Understanding Exclusive VM production

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DPWG, March 11, 2026

- Measurements of VM
- From helicity amplitudes → spin density matrix elements → structure function
- Challenges in interpretation of exclusive rhos
  - separation of exclusive rhos from semi-exclusive rhos
  - separation of transverse rho from longitudinal rhos
  - separation of transverse photon contributions from longitudinal
- Rho-MC
- What we learned (ZEUS/H1/HERMES/COMPASS/JLAB)
- Summary

Precision measurements in SIDIS and HEP

Some requirements in interpretation of precision multidimensional measurements in hadron production in SIDIS and HEP, needed for proper interpretations in termes of 3D partonic distributions (TMDs and GPDs)

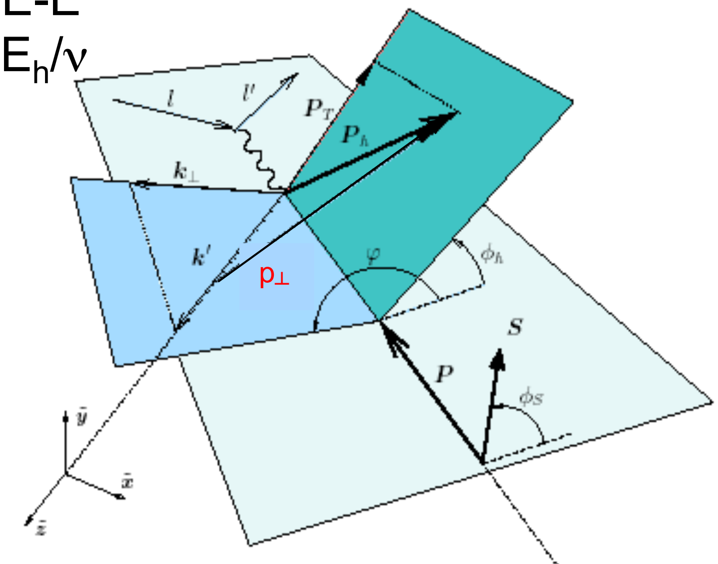
- SIDIS interpretation requires detailed understanding of exclusive VM contributions
- Measurements of VM observables, require detailed understanding of multidimensional acceptances
- Detailed MC describing VMs is critical, also for AI-enabled inference of helicity amplitudes
- Validation of claims on separating different dynamical contributions through measurements of target and beam spin asymmetries important advantage of JLab
- Combination of different beam energies, good resolutions, high statistics, makes JLab a unique place for VM studies

Dedicated workshops on impact of VMs (https://indico.cern.ch/event/1657528/overview)

DIS kinematical coverage and observables

$\nu = E - E'$

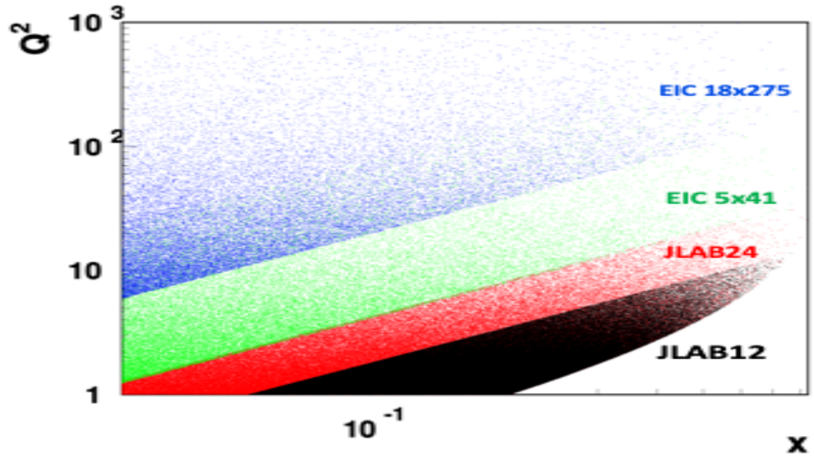
$z = E_h/\nu$

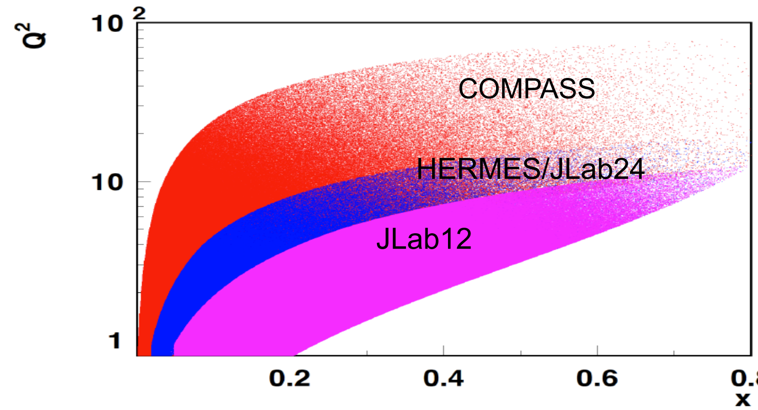


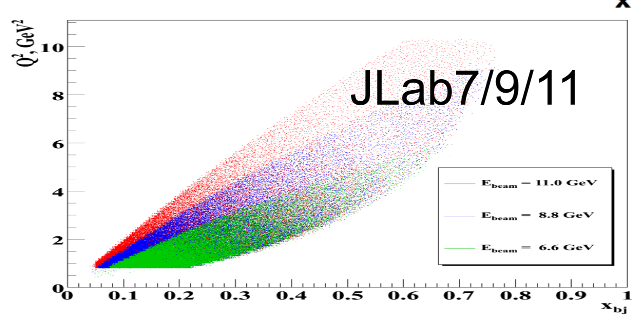
t (HEP) or z, P_{hT} (SIDIS)

EIC

$$\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = {} & \frac{\alpha^2}{x\,y\,Q^2}\frac{y^2}{2(1-\varepsilon)}\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\,F_{UU}^{\cos\phi_h}+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\
& + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\Big[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big] \\
& + S_L\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big] \\
& + S_T\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big)+\varepsilon\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
& + \varepsilon\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
& + \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
& + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S\,F_{LT}^{\cos\phi_S}+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}
\end{aligned}$$



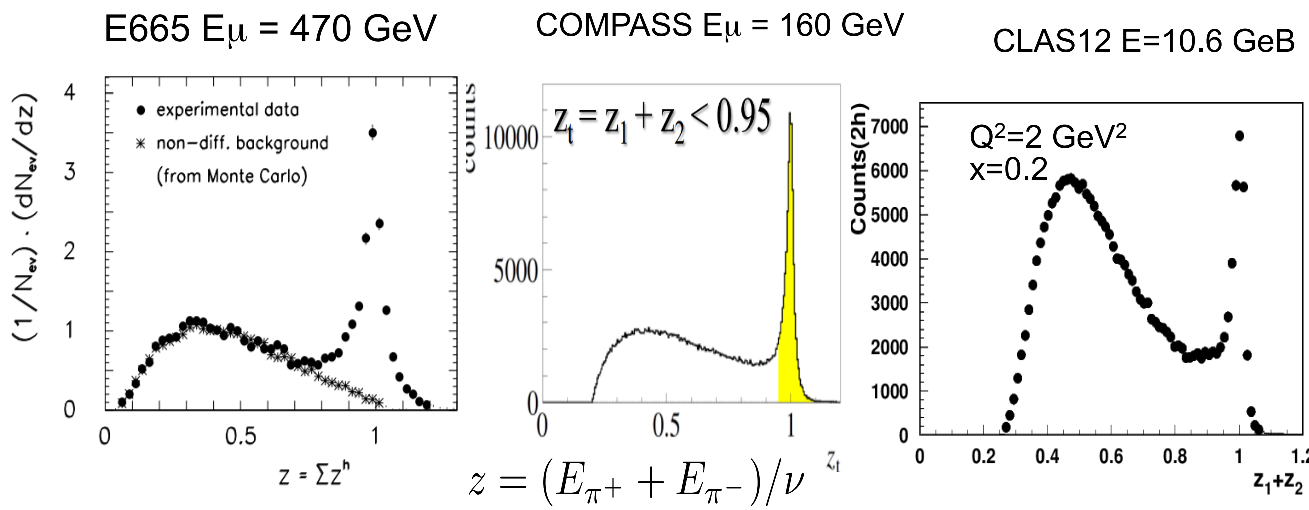


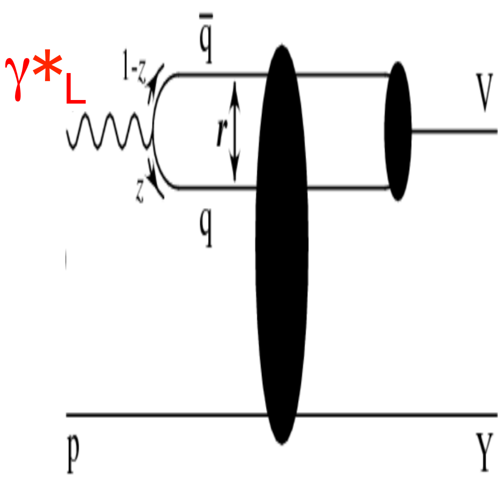


Exclusive VMs (ρ^0, ω,ϕ, J/Ψ,…)

$$\gamma^*(\mu) + p(\lambda) \rightarrow \rho(\nu) + p(\sigma)$$

$\mu, \nu, \lambda, \sigma$ → helicities





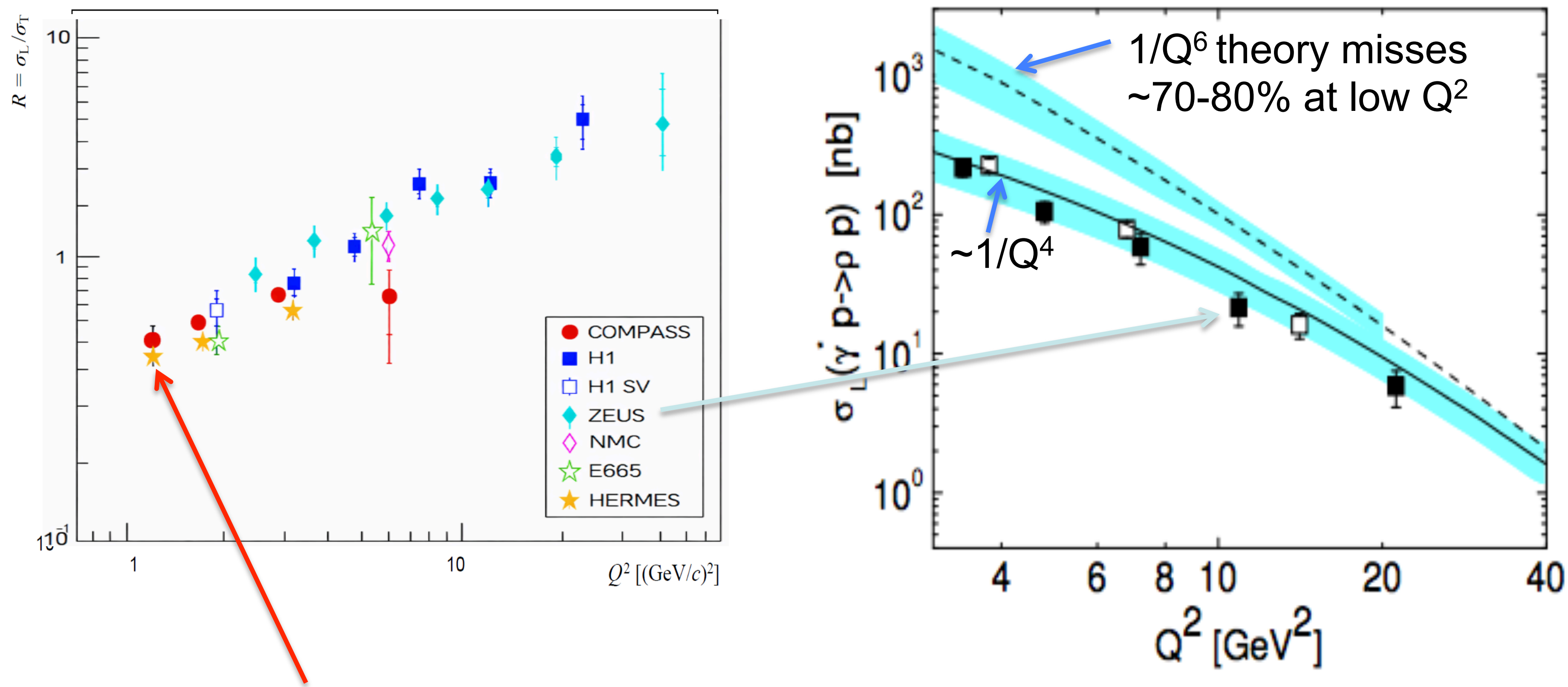
Estimated ~20% contributions from rho to charged pion SIDIS, consistent with ~10% of diffractive DIS in inclusive DIS

indication: most longitudinally polarized ρ^0

For GPD based interpretation need experimental separation of contributions

Studies of exclusive processes require high resolution and multidimensional measurements !!!

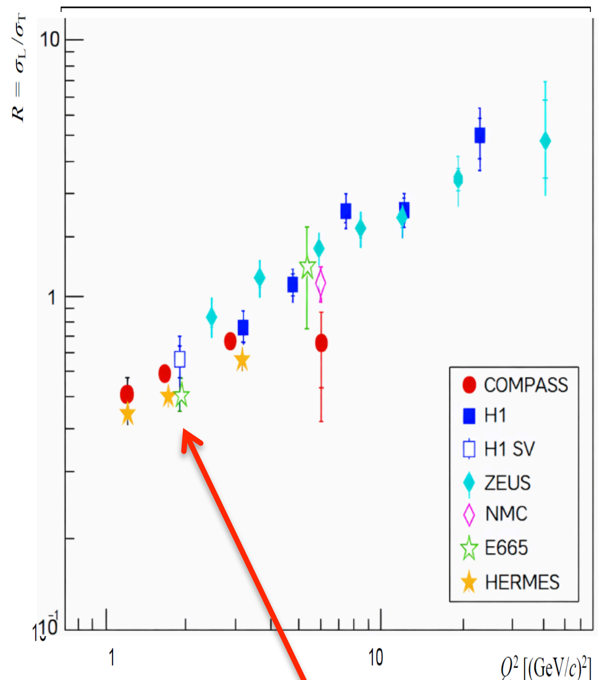
Separating Longitudinal photon contributions

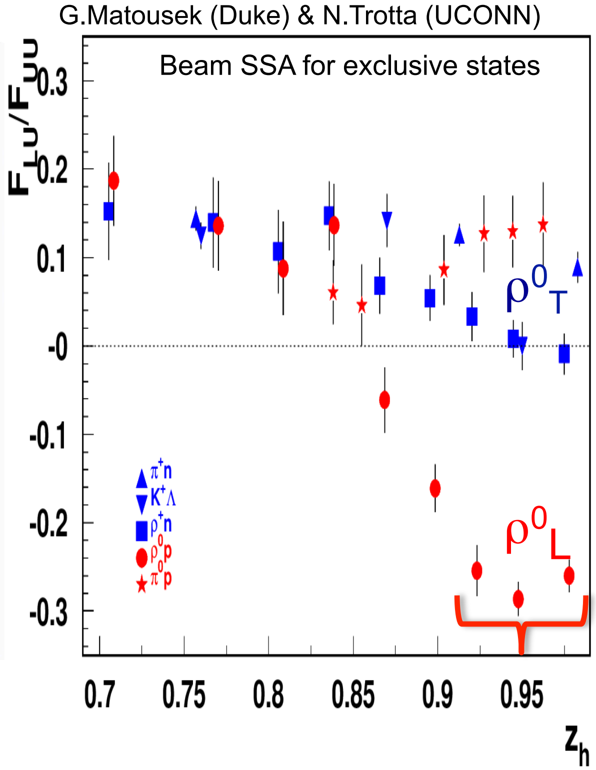


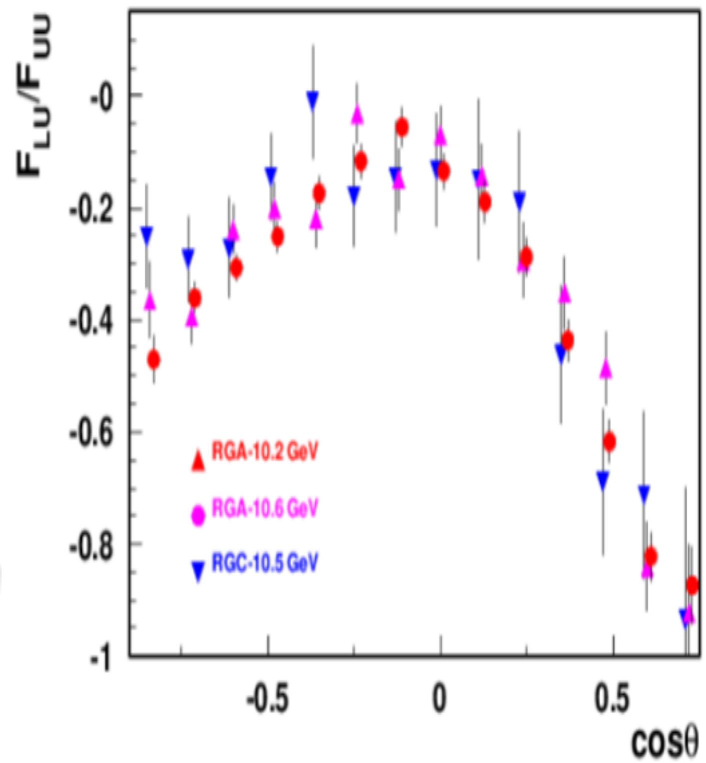
L/T separation Assuming SCHC

The ZEUS measurements, followed by others, indicated that the longitudinal photon contributions (diffractive rho) drop as $\sim 1/Q^4$ → dramatically underestimate JLab ρ^0s

L/T photons producing T/L VMs







L/T separation Assuming SCHC→ SSA of rho should be 0←clearly violated

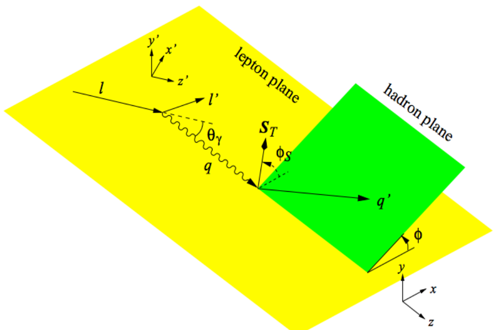
To separate L and T-photon contributions detailed measurements are needed for L/T interference observables, which are practically impossible at higher energies!!!

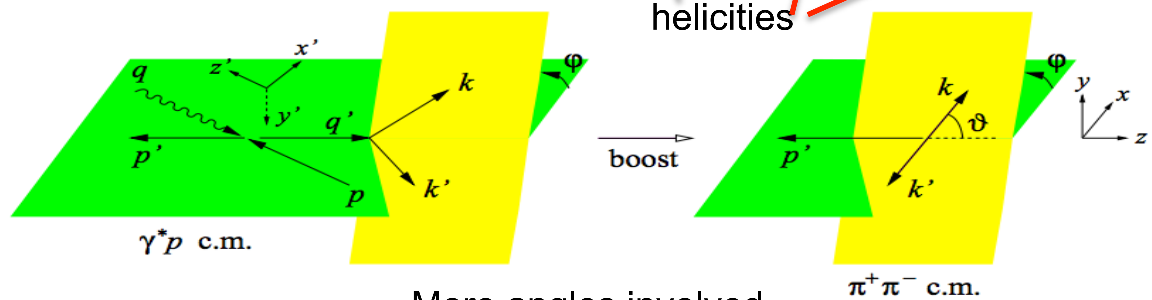
Structure functions case of VMs decaying to h+h-

Diehl: 0704.1565

$T^{\nu\sigma}_{\mu\lambda}$ helicity amplitudes describing $\gamma^*(\mu)+p(\lambda)\to\rho(\nu)+p(\sigma)$ depend on x,Q^2,t

helicities





More angles involved

$$\frac{d\sigma}{d\psi\, d\phi\, d\varphi\, d(\cos\vartheta)\, dx_B\, dQ^2\, dt} = \frac{1}{(2\pi)^2}\frac{d\sigma}{dx_B\, dQ^2\, dt}$$
$$\times\left(W_{UU}+P_\ell W_{LU}+S_L W_{UL}+P_\ell S_L W_{LL}+S_T W_{UT}+P_\ell S_T W_{LT}\right)$$

with

$$\frac{d\sigma}{dx_B\, dQ^2\, dt} = \frac{\alpha_{\rm em}}{2\pi}\frac{y^2}{1-\epsilon}\frac{1-x_B}{x_B}\frac{1}{Q^2}\left(\frac{d\sigma_T}{dt}+\epsilon\frac{d\sigma_L}{dt}\right),$$

spin density matrix

$$\rho^{\nu\nu'}_{\mu\mu',\lambda\lambda'} = (N_T+\epsilon N_L)^{-1}\sum_\sigma T^{\nu\sigma}_{\mu\lambda}\left(T^{\nu'\sigma}_{\mu'\lambda'}\right)^*$$

$$N_T = \tfrac{1}{2}\sum_{\lambda,\nu,\sigma}\left|T^{\nu\sigma}_{+\lambda}\right|^2$$

$$N_L = \tfrac{1}{2}\sum_{\lambda,\nu,\sigma}\left|T^{\nu\sigma}_{0\lambda}\right|^2$$

beam and target polarizations

All W_{XY} depend on Q^2,x_B,t,ϕ,θ,φ

longitudinal rho

transverse rho

$$W_{XY}(\phi,\varphi,\vartheta) = \frac{3}{4\pi}\left[\cos^2\vartheta\, W^{LL}_{XY}(\phi)+\sqrt{2}\cos\vartheta\,\sin\vartheta\, W^{LT}_{XY}(\phi,\varphi)+\sin^2\vartheta\, W^{TT}_{XY}(\phi,\varphi)\right]$$

interference between
longitudinal and transverse ρ

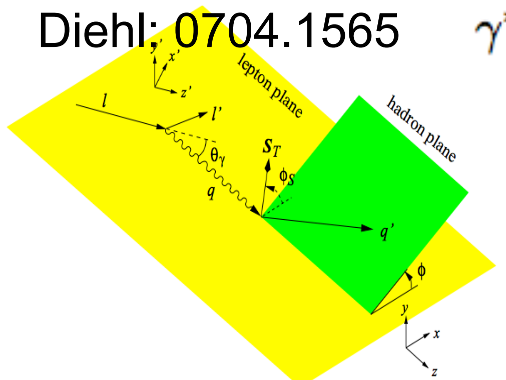
Structure functions case of VMs

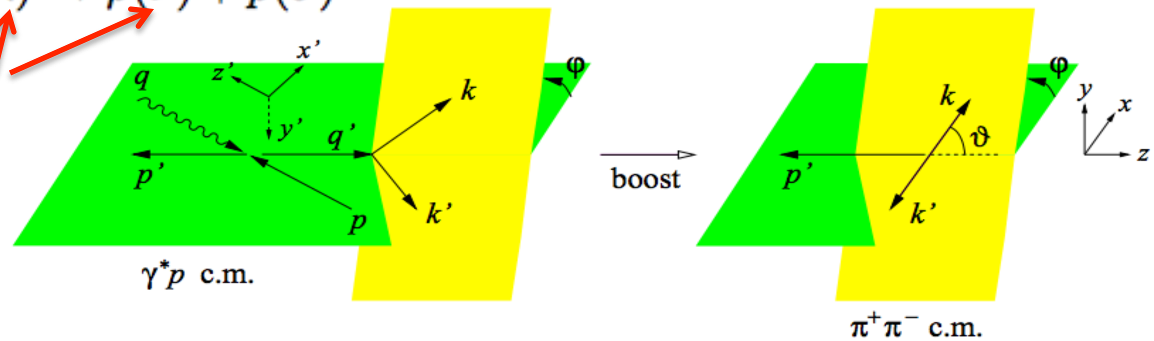
Diehl: 0704.1565

$\gamma^*(\mu) + p(\lambda) \rightarrow \rho(\nu) + p(\sigma)$

helicities

More angles involved





cross section could be presented in terms of combinations of helicity amplitudes

$$u^{\nu\nu'}_{\mu\mu'} = \tfrac{1}{2}\left(\rho^{\nu\nu'}_{\mu\mu',++} + \rho^{\nu\nu'}_{\mu\mu',--}\right)$$ unpol

$$l^{\nu\nu'}_{\mu\mu'} = \tfrac{1}{2}\left(\rho^{\nu\nu'}_{\mu\mu',++} - \rho^{\nu\nu'}_{\mu\mu',--}\right)$$ long.pol

In the forward limit of small t

$$u^{\nu\nu'}_{\mu\mu'}, l^{\nu\nu'}_{\mu\mu'} \underset{t\to t_0}{\sim} (t_0 - t)^{p/2}$$

	matrix elements		$p_{\min}$
	$u^{00}_{++} + \epsilon u^{00}_{00}$		0
	$u^{0+}_{0+} - u^{-0}_{0+}$	$l^{0+}_{0+} - l^{-0}_{0+}$	0
	$u^{++}_{++} + u^{--}_{++} + 2\epsilon u^{++}_{00}$	$l^{++}_{++} + l^{--}_{++}$	0
	u^{-+}_{-+}	l^{-+}_{-+}	0
	u^{00}_{0+}	l^{00}_{0+}	1
W^{LL}_{LU} →	u^{00}_{0+}	l^{00}_{0+}	1
	u^{0+}_{-+}	l^{0+}_{-+}	1
W^{TT}_{LU} →	$u^{++}_{0+} + u^{--}_{0+}$	$l^{++}_{0+} + l^{--}_{0+}$	1

To measure any observables integrated over the photon (μ) and VM (ν) polarizations (cross sections and spin asymmetries) one has to integrate in the multidimensional space the experimental observables corrected for acceptance in θ, φ

Structure functions for VMs: integrated case

Diehl: 0704.1565

$$\gamma^*(\mu) + p(\lambda) \to \rho(\nu) + p(\sigma)$$

helicities

$$\frac{d\sigma}{d\psi\, d\phi\, d\varphi\, d(\cos\vartheta)\, dx_B\, dQ^2\, dt} = \frac{1}{(2\pi)^2} \frac{d\sigma}{dx_B\, dQ^2\, dt} \times \Big(W_{UU} + P_\ell W_{LU} + S_L W_{UL} + P_\ell S_L W_{LL} + S_T W_{UT} + P_\ell S_T W_{LT} \Big)$$

$$u^{\nu\nu'}_{\mu\mu'} = \tfrac{1}{2}(\rho^{\nu\nu'}_{\mu\mu',++} + \rho^{\nu\nu'}_{\mu\mu',--})$$

unpolarized part involves several dynamical contributions

$W_{UU}(\phi,\varphi,\vartheta)$ longitudinal rho transverse rho

$$= \frac{3}{4\pi}\Big[\cos^2\vartheta\, W^{LL}_{UU}(\phi) + \sqrt{2}\cos\vartheta\,\sin\vartheta\, W^{LT}_{UU}(\phi,\varphi) + \sin^2\vartheta\, W^{TT}_{UU}(\phi,\varphi)\Big]$$

r^{04}_{00} SDME (mixes L and T with different x,Q^2,t-dependences)

$$W^{LL}_{UU}(\phi) = \big(u^{0\,0}_{++} + \epsilon u^{0\,0}_{0\,0}\big) - 2\cos\phi\,\sqrt{\epsilon(1+\epsilon)}\,\mathrm{Re}\, u^{0\,0}_{0+} - \cos(2\phi)\,\epsilon u^{0\,0}_{-+}$$

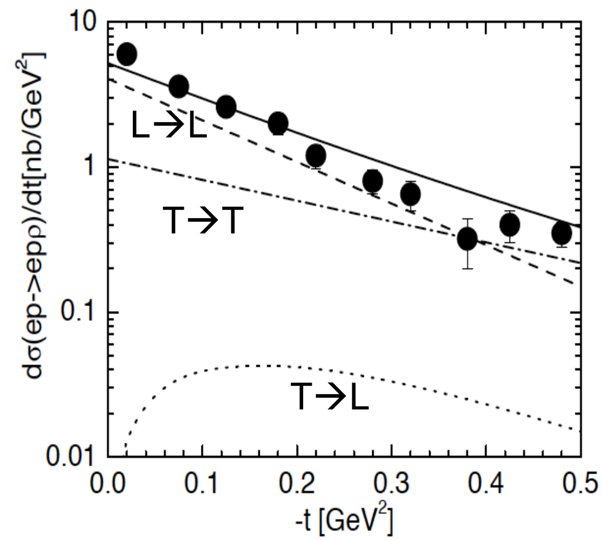
longitudinal photon (L) with 0 helicity producing longitudinal ρ_L

transverse photon (T) with + helicity producing longitudinal ρ_L

$$W^{TT}_{UU}(\phi,\varphi) = \tfrac{1}{2}\big(u^{++}_{++} + u^{--}_{++} + 2\epsilon u^{++}_{0\,0}\big)$$

$1 - r^{04}_{00}$ (keep normalization)

GK:0501242



Looking for L→L physics
focus on low t large Q^2

Structure functions: case of VMs

Diehl: 0704.1565 $\gamma^*(\mu) + p(\lambda) \to \rho(\nu) + p(\sigma)$

More angles involved

$$\frac{d\sigma}{d\psi\, d\phi\, d\varphi\, d(\cos\vartheta)\, dx_B\, dQ^2\, dt} = \frac{1}{(2\pi)^2} \frac{d\sigma}{dx_B\, dQ^2\, dt}$$

$$\times \Big(W_{UU} + P_\ell W_{LU} + S_L W_{UL} + P_\ell S_L W_{LL} + S_T W_{UT} + P_\ell S_T W_{LT} \Big)$$

$$u^{\nu\nu'}_{\mu\mu'} = \tfrac{1}{2}\big(\rho^{\nu\nu'}_{\mu\mu',++} + \rho^{\nu\nu'}_{\mu\mu',--}\big)$$

beam SSA involves several dynamical contributions

$$W_{LU}(\phi, \varphi, \theta)$$

After integration over φ two terms survive

$$\cos^2\theta W^{LL}_{LU}(\phi,\theta) + \sin^2\theta W^{TT}_{LU}(\phi,\theta)$$

$$W^{LL}_{LU}(\phi) = -2\sin\phi\sqrt{\epsilon(1-\epsilon)}\,\mathrm{Im}\, u^{0\,0}_{0+}\,,$$

$$W^{LT}_{LU}(\phi,\varphi) = \sin(\phi+\varphi)\sqrt{\epsilon(1-\epsilon)}\,\mathrm{Im}\big(u^{0+}_{0+} - u^{-0}_{0+}\big)$$
$$- \sin\varphi\sqrt{1-\epsilon^2}\,\mathrm{Im}\big(u^{0+}_{++} - u^{-0}_{++}\big)$$
$$- \sin(\phi-\varphi)\sqrt{\epsilon(1-\epsilon)}\,\mathrm{Im}\big(u^{0-}_{0+} - u^{+0}_{0+}\big)\,,$$

interference of transverse and longitudinal ρ from transverse photons

$$W^{TT}_{LU}(\phi,\varphi) = -\sin\phi\sqrt{\epsilon(1-\epsilon)}\,\mathrm{Im}\big(u^{++}_{0+} + u^{--}_{0+}\big) + \sin(\phi+2\varphi)\sqrt{\epsilon(1-\epsilon)}\,\mathrm{Im}\, u^{-+}_{0+}$$
$$- \sin(2\varphi)\sqrt{1-\epsilon^2}\,\mathrm{Im}\, u^{-+}_{++}$$
$$+ \sin(\phi-2\varphi)\sqrt{\epsilon(1-\epsilon)}\,\mathrm{Im}\, u^{+-}_{0+}\,.$$

Detector has acceptances in angles, and integration should account that to be interpretable by theory

MC implementation: generator

MC code written by Gagik Gavalian using the full set of helicity amplitudes from Diehl: 0704.1565 (works for polarized beams and longitudinally and transversely polarized targets)!!!

https://github.com/gavalian/simulations/

$$\sigma_{LL}/\sigma_{TT}(t) \propto e^{t(B_{LL}-B_{TT})}$$

$$B_{LT}^{V} = 2B_{TT}^{V} = B_{LL}^{V}$$

wider T→T !!!

real parts, imaginary part

```
// LL part
   ph.u[Wkernels::h('0')][Wkernels::h('0')][Wkernels::h('0')][Wkernels::h('0')] = {30.0*exp(3*t)*xdepl , 0.0000};   // x-section-L
   ph.u[Wkernels::h('0')][Wkernels::h('0')][Wkernels::h('0')][Wkernels::h('+')] = {0.0, 5.000*exp(2.5*t)/Q};   // only sin u^00_0+
//
// TT part
   ph.u[Wkernels::h('+')][Wkernels::h('+')][Wkernels::h('+')][Wkernels::h('+')] = {5*exp(1.5*t)*xdept, 0.0000};   // x-section-T
   ph.u[Wkernels::h('+')][Wkernels::h('+')][Wkernels::h('0')][Wkernels::h('+')] = {0.0, -0.7500*exp(1.5*t)/Q};   // only sin u^++_0+
//-cos2    ph.u[Wkernels::h('0')][Wkernels::h('0')][Wkernels::h('-')][Wkernels::h('+')] = {0.025*exp(0.3*t), 0.0000};
```

Particular example has 4-5 times higher longitudinal photon contributions

GK: arXiv:0708.3569

$$\gamma_L^* \to \rho_L \propto 1$$

$$\gamma_T^* \to \rho_L \propto \sqrt{(1-z)/x}$$

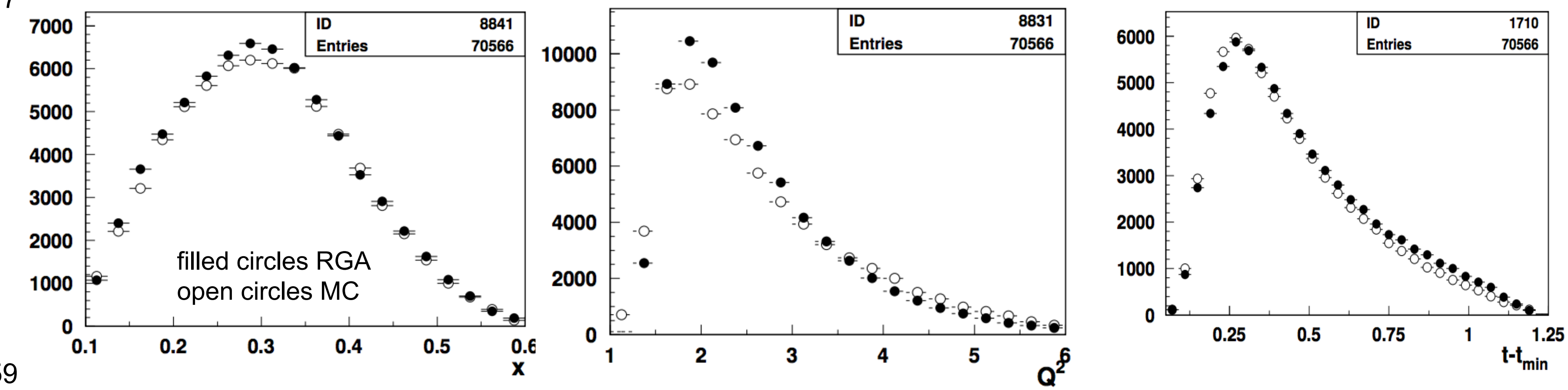
$$\gamma_L^* \to \rho_T \propto \sqrt{<k_\perp^2>(1-z)/x}$$

x,Q^2,t-dependences currently include some predictions from theory, but eventually should be parameterized with parameters extracted, using multidimensional fits, preferably AI based

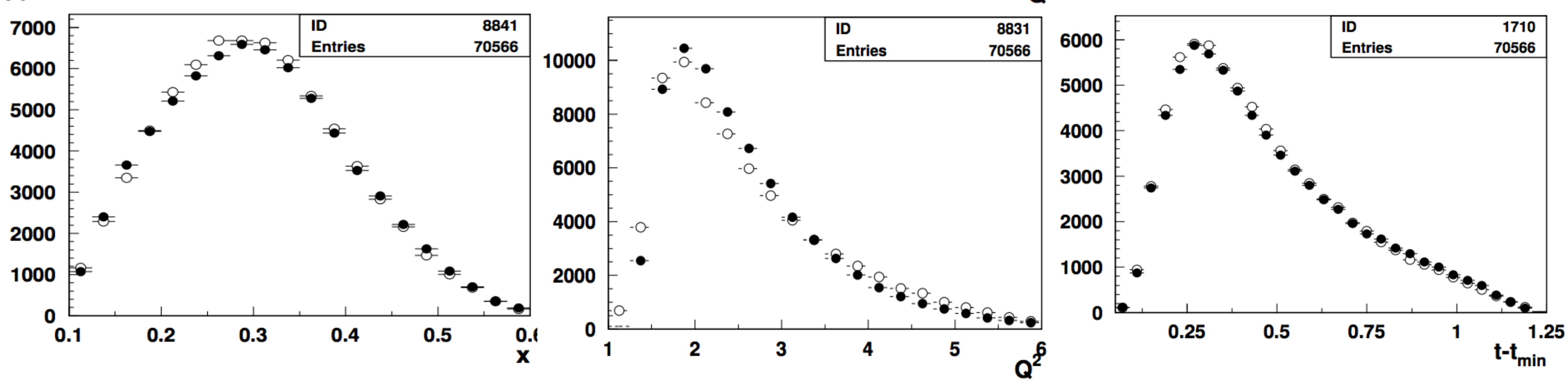
Comparing the MC with RGA data (ep→e'p'ρ)

use the rho-generator-gemc-coatjava chain to compare with RGA inbending Fall18 (filled symbols) vs 2 MC models (open symbols)

10277



10359



- With proton detected and exclusivity cuts applied no major background left
- Good agreement for distributions on relevant variables

$$\cos\varphi Re u^{0+}_{++} + \sin\varphi Im u^{0+}_{++}\sqrt{1-\epsilon^2}$$

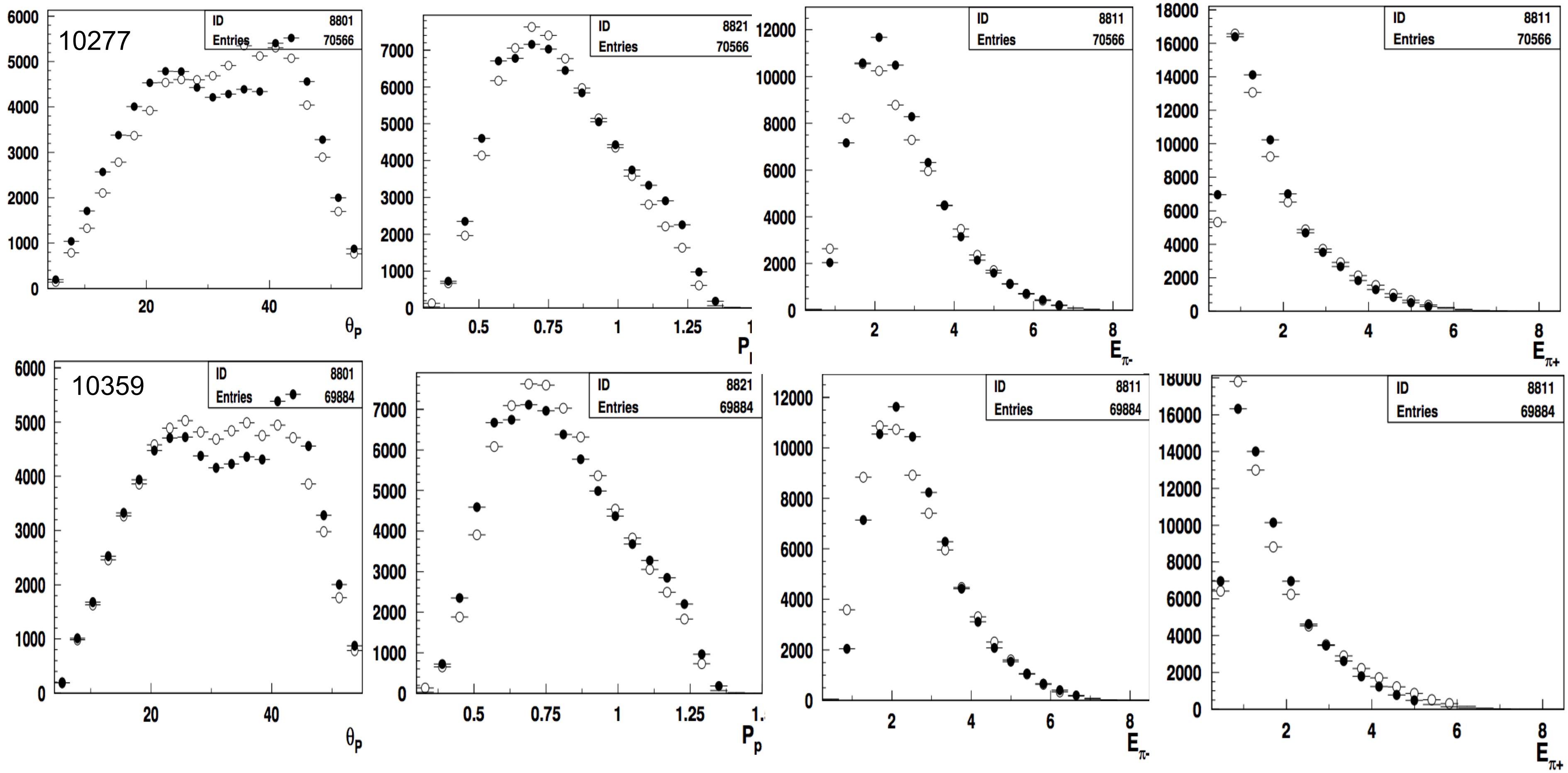
10359 has additional terms in $W^{LT}_{LU}(\phi,\varphi)$ from interference of transverse and longitudinal rho produced by transverse photons

Comparing the MC(gemc) with RGA data

After a preliminary tune and testing use the rho-generator-gemc-coatjava chain to compare with RGA inbending Fall18 (/volatile/clas12/osg/avakian/10277 vs 10359

filled circles RGA

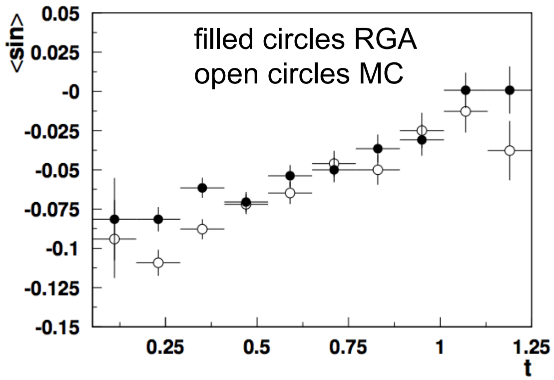
open circles MC

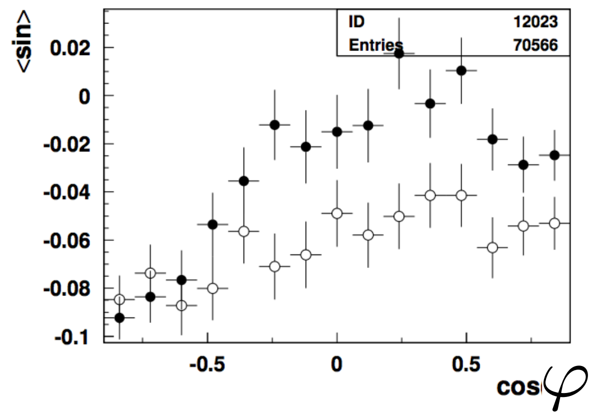


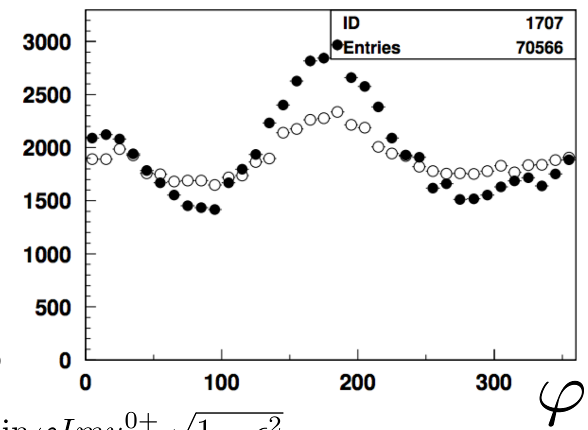
Comparing the MC versions with RGA data

use the rho-generator-gemc-coatjava chain to compare with RGA inbending Fall18 (/volatile/clas12/osg/avakian/10277 vs 10359

10277

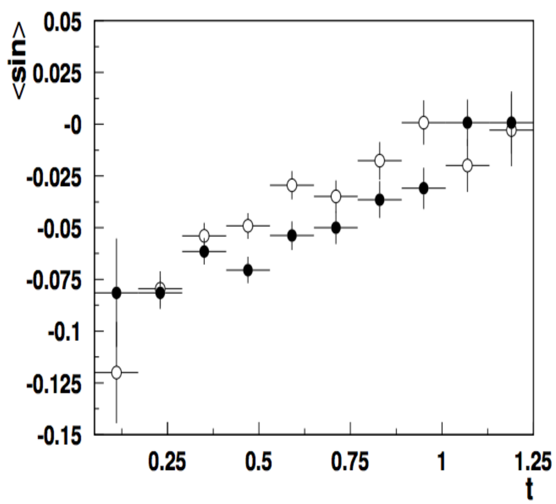


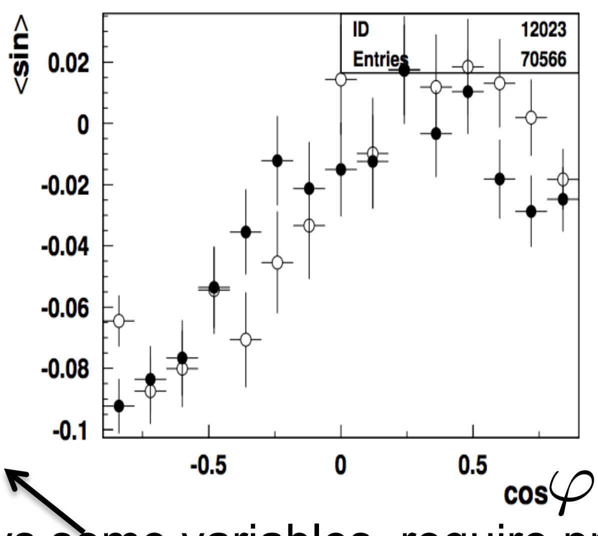


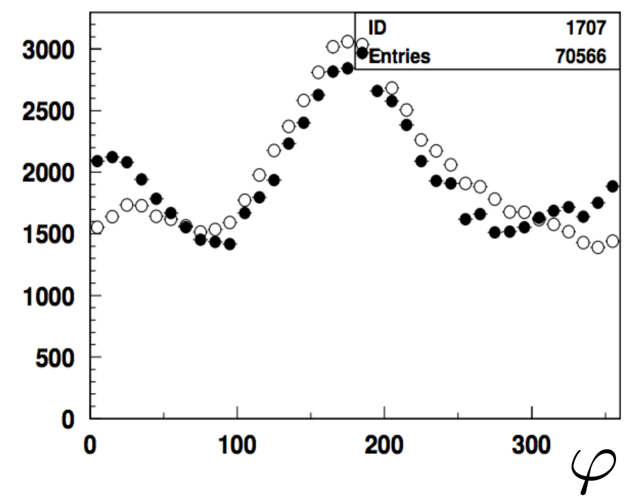


10359

$$\cos\varphi Reu^{0+}_{++} + \sin\varphi Imu^{0+}_{++}\sqrt{1-\epsilon^2}$$







SSA dependence described vs some variables, require proper integration over others

φ -dependence of the beam SSA likely comes from interference of L/T ρ^0s

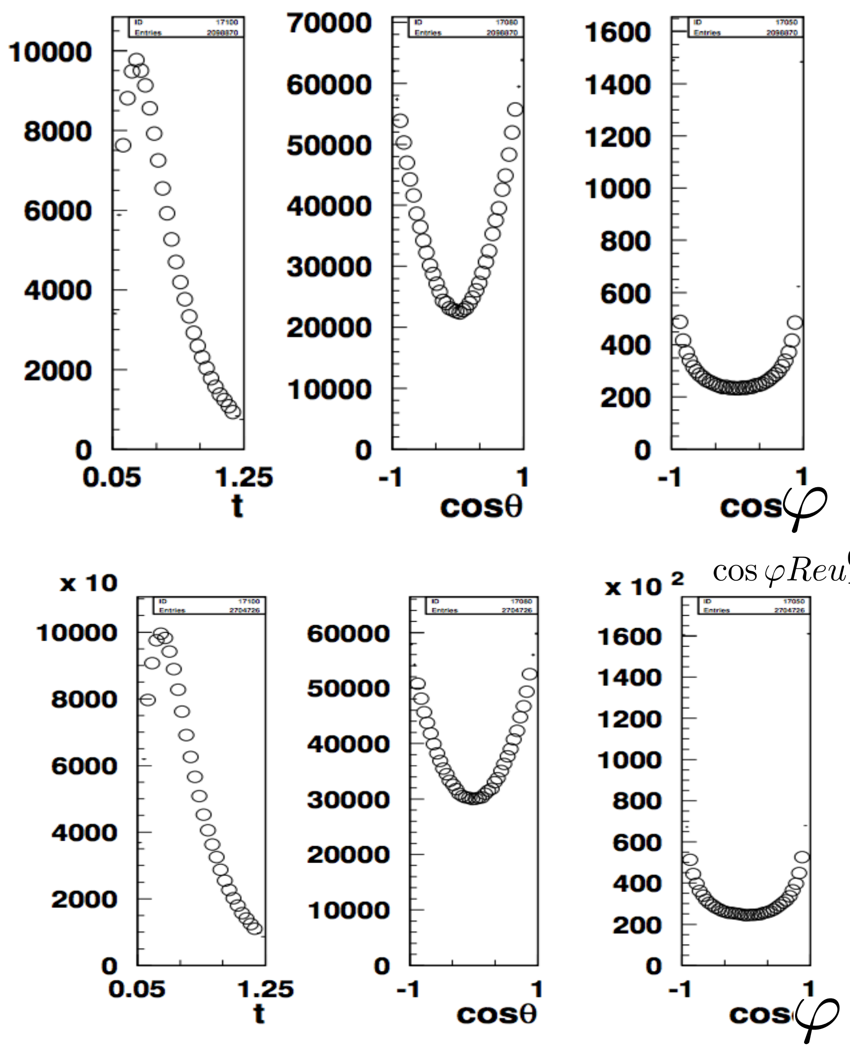
Comparing the MC v4 with RGA data

Generated

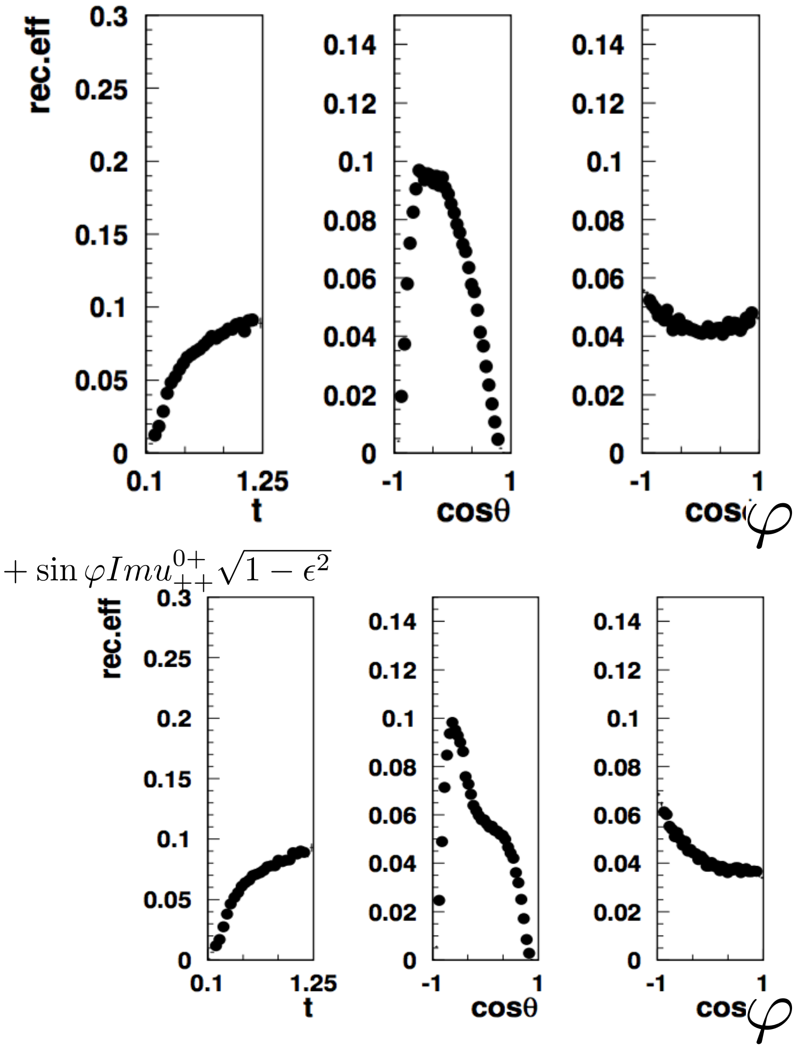
Reconstruction efficiencies

10277

10359



$\cos\varphi Reu^{0+}_{++} + \sin\varphi Imu^{0+}_{++}\sqrt{1-\epsilon^2}$



Comparing acceptances for MC model inputs

use the rho-generator-gemc-coatjava chain to compare with RGA inbending Fall18 (/volatile/clas12/osg/avakian/10277 vs 10359

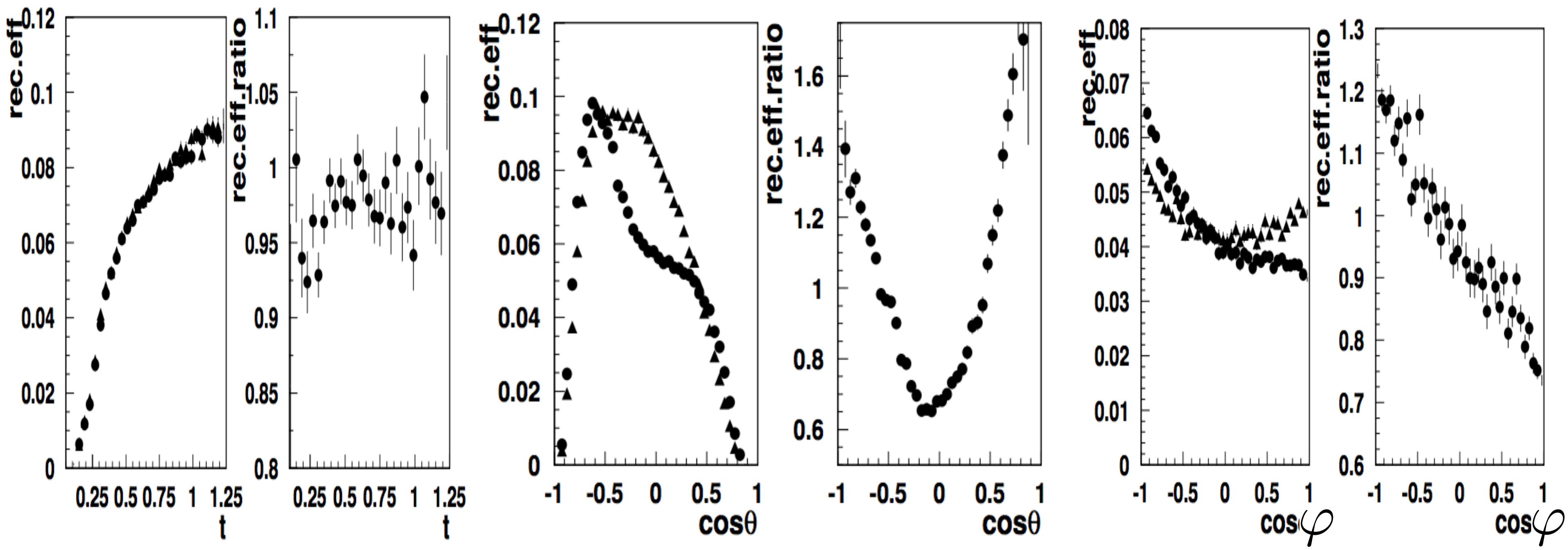
10359 has additional terms in $W_{LU}^{LT}(\phi,\varphi)$ from interference of transverse and longitudinal rho produced by transverse photons

$$\cos\varphi Re u_{++}^{0+} + \sin\varphi Im u_{++}^{0+}\sqrt{1-\epsilon^2}$$

in HERMES/COMPASS ~ +10%

0-within errors

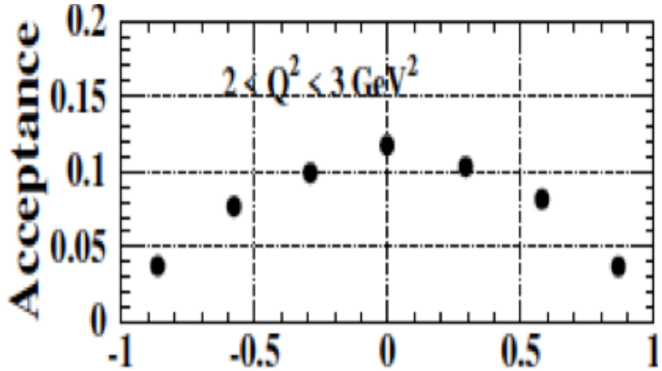
10277 vs 10359

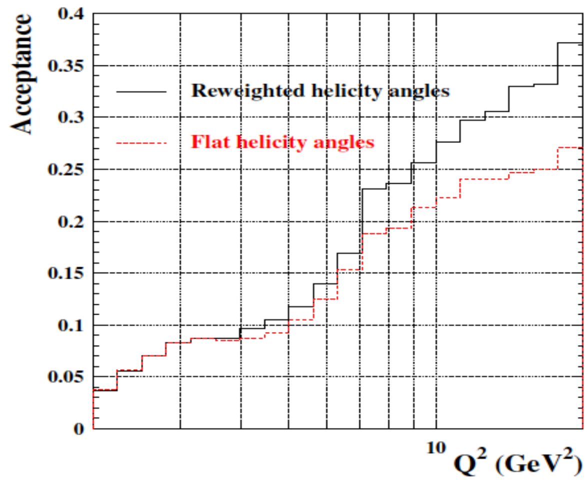


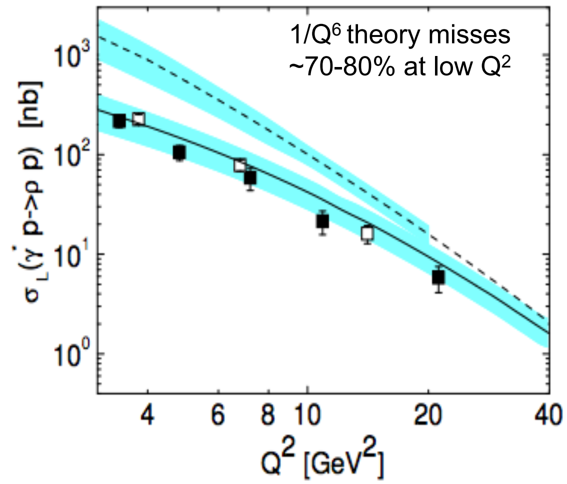
While overall distributions over relevant variables look similar, the acceptances integrated over wide bins may be very different

Impact of acceptances in cos θ

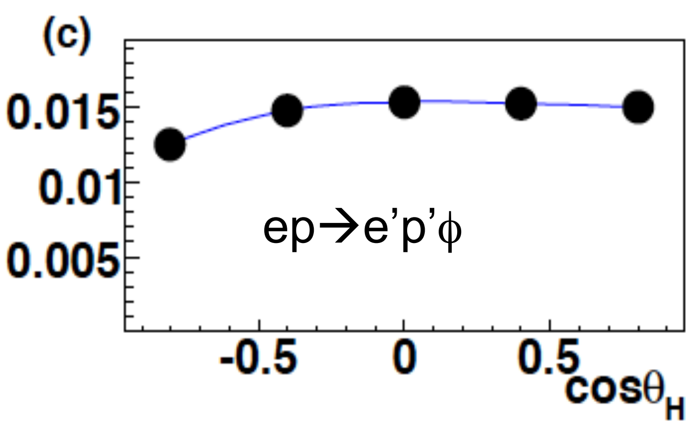
ZEUS rho (0708.1478)

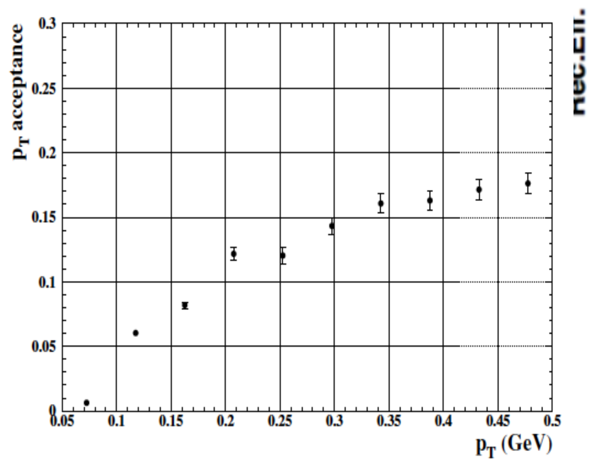


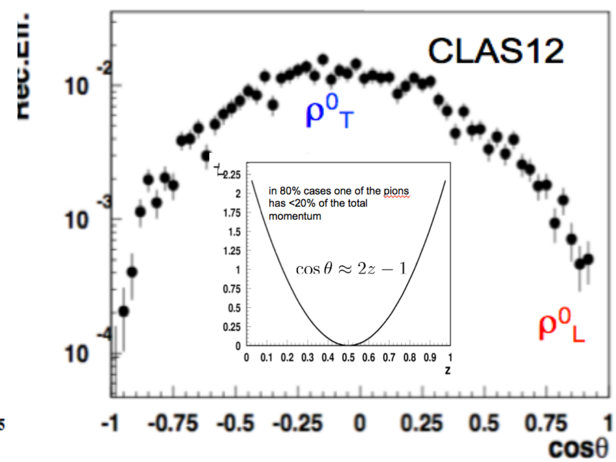




CLAS6 0803.3537







- Proper acceptance account requires fine multidimensional binning, high statistics
- ZEUS 7-bins with acceptance at |cosθ|>0.8 reducing ~2 times (integrated over t?)
- Situation even worse for electroproduction of ϕ-mesons

SUMMARY

Measurements of exclusive ρ and, longitudinal rho, in particular, with polarized beams and targets will be crucial for completeness of the measurements of 3D structure, including GPD and TMD based interpretations

- Studies of exclusive rho, indicate several strong dynamical contributions from different interference terms, *including longitudinal photon contributions*
- Measurements of rho, are classical demonstration of how *critical multidimensional measurements with high precision* could be
- CLAS12 has significant advantage compared to higher energy experiments in *resolution and statistics, required for proper separation of exclusive VMs* from semi-exclusive VMs, and separation of transverse rhos from longitudinal
- *Target and beam SSAs and DSA* can help to separate diffractive rho from other exclusive and semi-exclusive processes, and extract kinematic dependences of helicity amplitudes
- The diffractive VM contributions, violate the factorized picture of SIDIS based on the dominance of the leading twist contributions, and *detailed understanding of exclusive rho contributions in the multi-D space will be critical to address the challenges of SIDIS*

- Develop MC, produce large samples for cross section studies, extract Helicity amplitudes/SDMEs from RGK/RGA/RGC/RGB data sets
- Combine efforts of CLAS+COMPASS communities (ex. generator development) in understanding the diffractive $\rho,\phi,..$ and sort out the impact on OAM, TMD-PDFs, ….
- Prepare a proposal for AI-enabled Inference of helicity amplitudes (Genesis,...)

support

Genesis: Unifying Physics from Quarks to Cosmos

AI-Enabled Inference of Helicity Amplitudes and Spin-Density Matrix Elements in Vector-Meson Production

[PI Name], [PI Institution]
[Co-I Names / Institutions]

Proposed Period: 36 months Total Cost: [TBD after NOFO]
Target Program/NOFO: [TBD: Office/Program after NOFO]

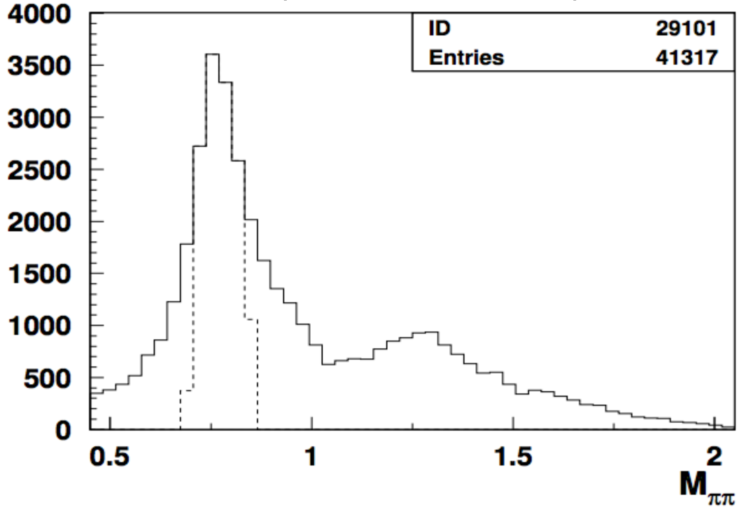
Project Summary (1 page max; draft)

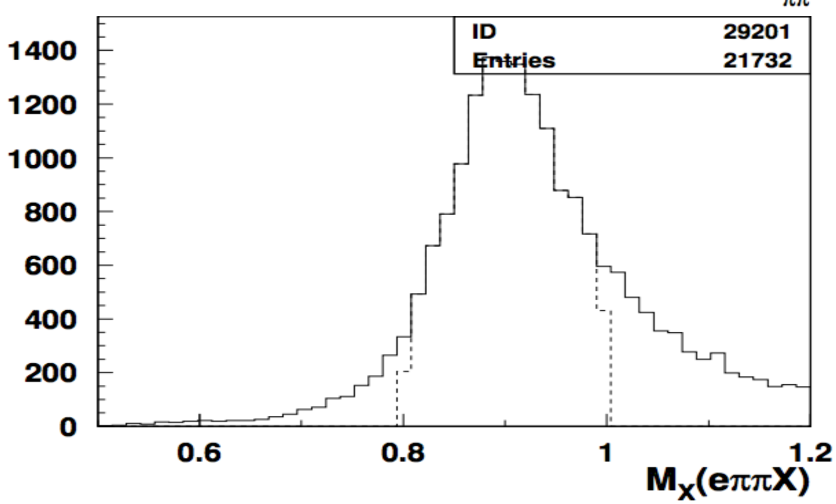
Modern nuclear and particle-physics experiments infer fundamental reaction mechanisms by fitting high-dimensional distributions of measured final-state particles. In exclusive vector-meson electroproduction (e.g., $\gamma^* p \to \rho^0 p$ with $\rho^0 \to \pi^+\pi^-$), the underlying dynamics are encoded in complex helicity amplitudes whose bilinear combinations appear as spin-density matrix elements (SDMEs) and structure functions. Extracting amplitudes and SDMEs from multi-dimensional angular and kinematic distributions is an inverse problem that is statistically and computationally intensive, and often bottlenecked by acceptance effects, backgrounds, and correlations across many observables.

We propose an AI-enabled, physics-constrained inference framework that learns the map from detector-level observables (angles, invariant masses, Q^2, x_B, t, beam/target polarization states, etc.) to helicity amplitudes and SDMEs, using a validated Monte Carlo (MC) generator as a controlled "forward model." The approach combines (i) simulation-driven training on large ensembles spanning physically allowed amplitude space, (ii) differentiable surrogate modeling of the MC to accelerate likelihood-based inference, and (iii) uncertainty-quantified inversion (e.g., normalizing flows and Bayesian neural inference) that produces calibrated posteriors for amplitudes/SDMEs rather than point estimates. We will deliver open, reusable tools and demonstrated performance on both simulated and experimental datasets, enabling faster and more comprehensive physics interpretation across kinematic space and across experiments.

Cuts on Invariant/Missing masses

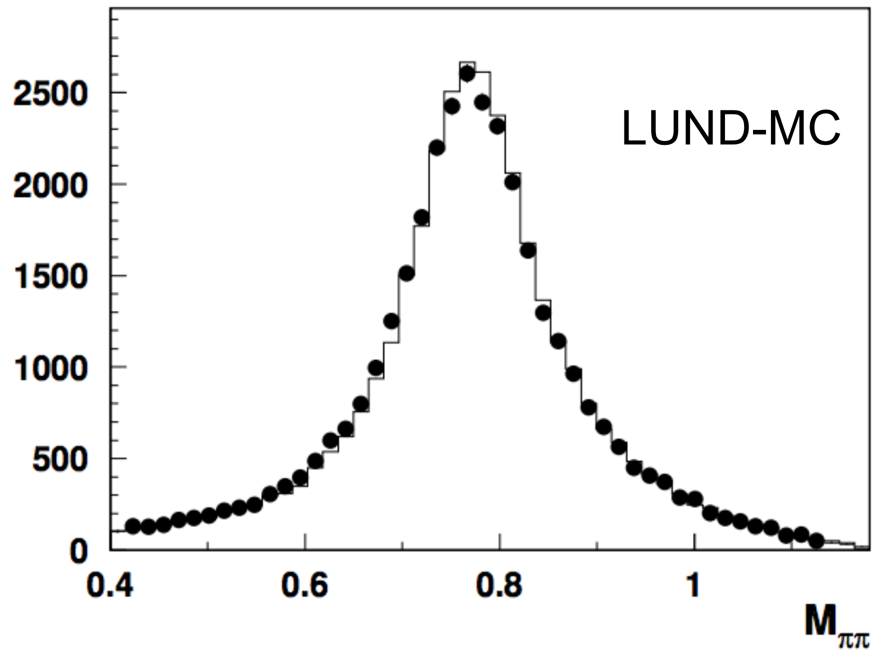
bin 0.235<x<0.265 (RGA 10.2 GeV)





With proton detected and exclusivity cuts applied no major background left

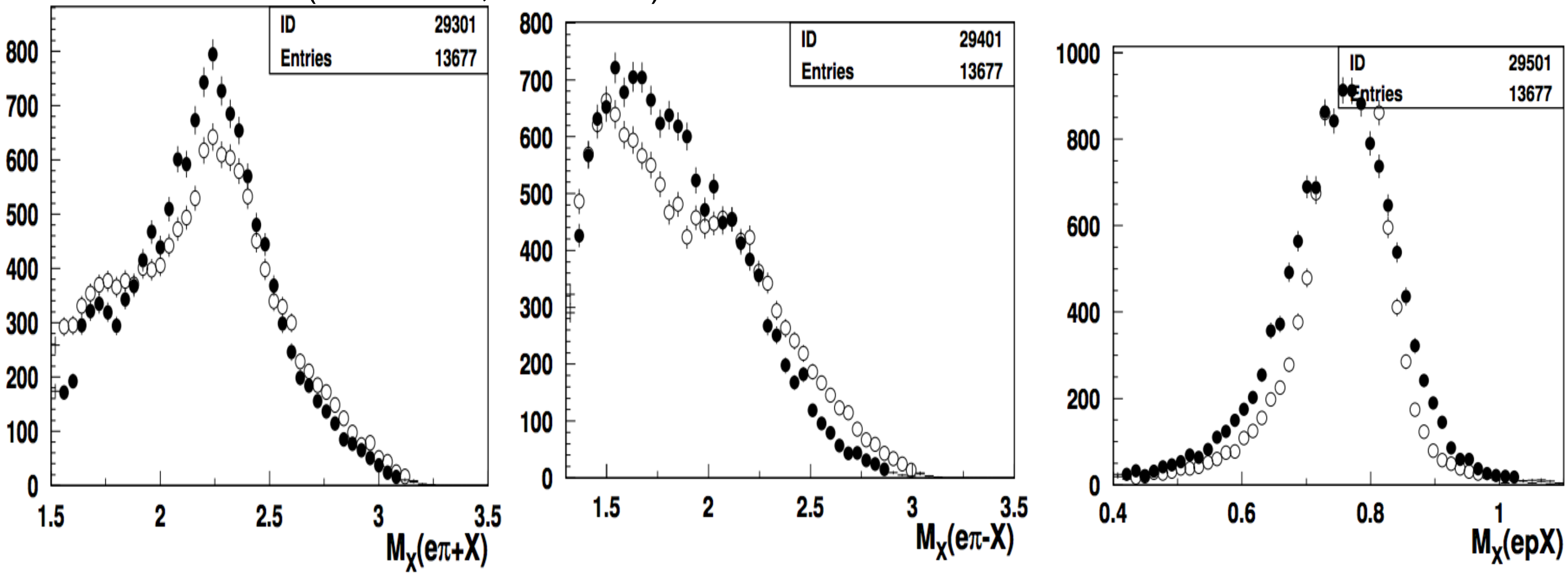
- With tight exclusivity cuts background is minor
- Wide rho peak makes problematic proper background subtraction



Solid line correspond to reconstructed set, using generated values in LUND-MC
Points correspond to reconstructed values
→Width is wider than resolution effects

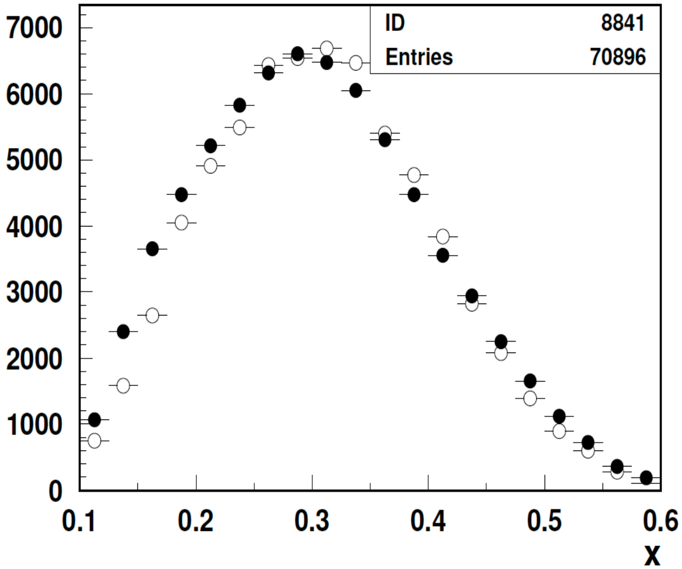
Cuts on Invariant/Missing masses

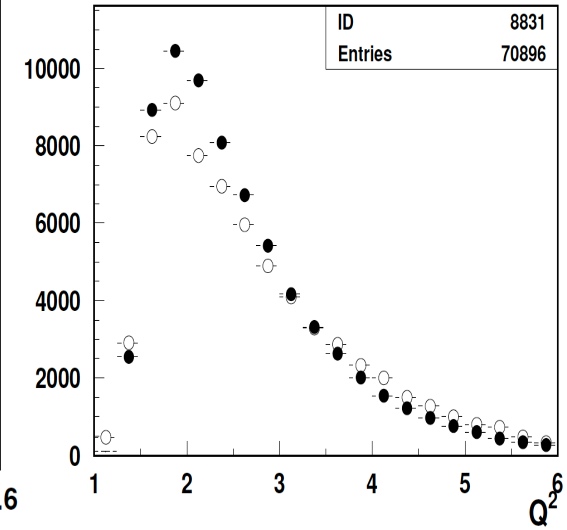
bin 0.235<x<0.265 (RGA 2019, 10.2 GeV)

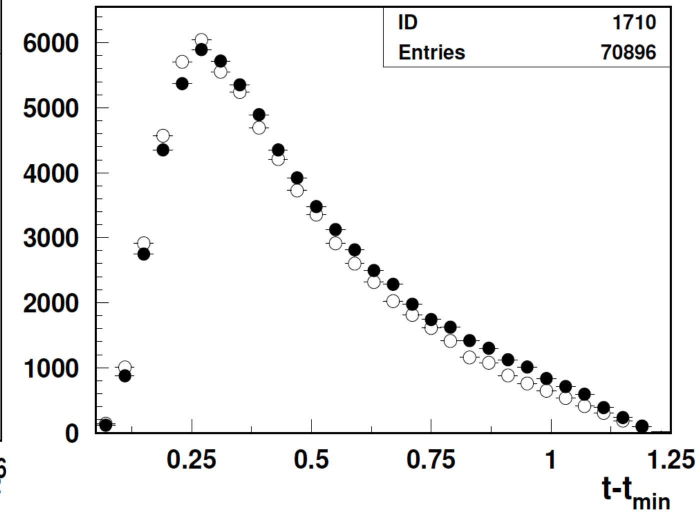


Qualitative agreement between MC and Data
in a given bin in 0.235<x<0.265

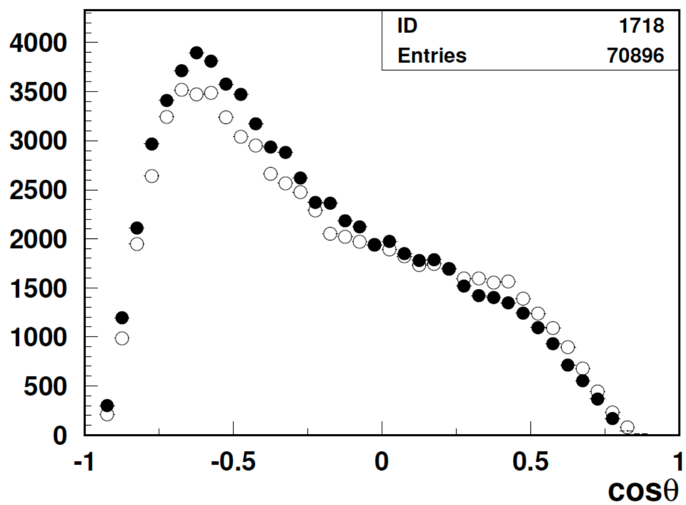
Comparing the MC v4 with RGA data

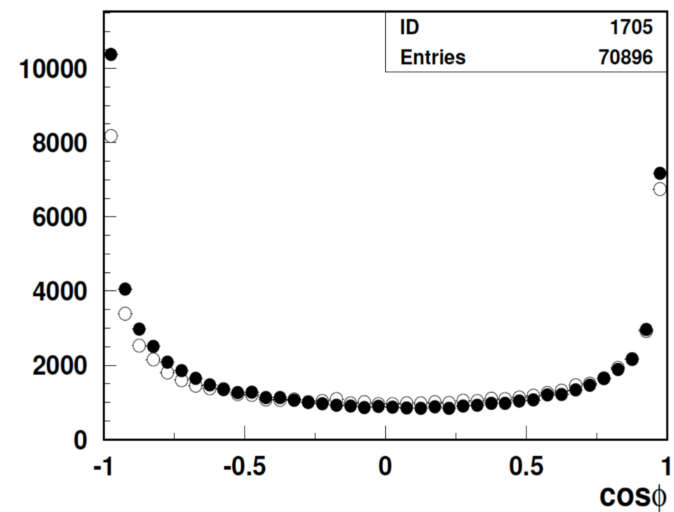






Relative contributions from longitudinal and transverse described well with Longitudinal rhos dominating ~5-6 times



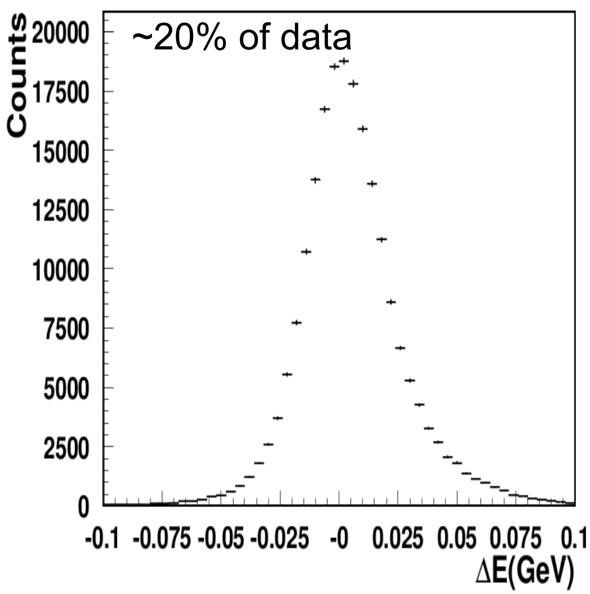


CLAS12 Experiments involved: Exclusive rhos

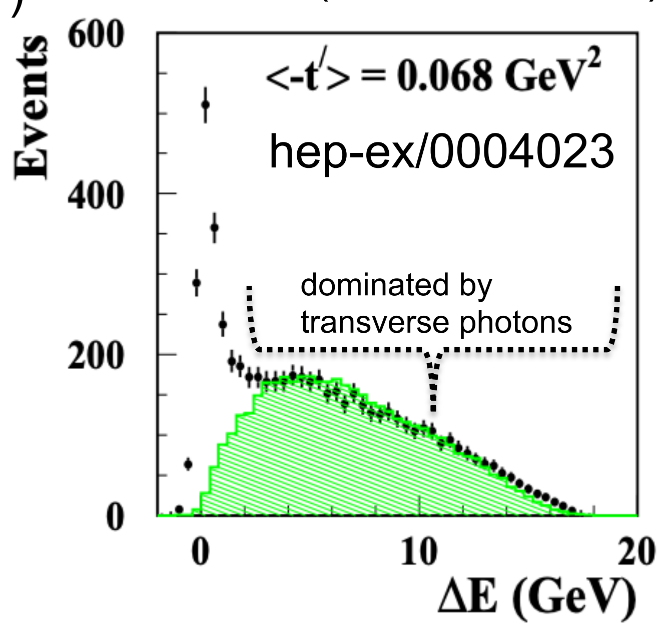
Exclusivity condition defined by the missing Energy:

$$M_X^2 = (p + q - p_{\pi^+} - p_{\pi^-})^2 \qquad E_{miss} = \frac{M_X^2 - M^2}{2M}$$

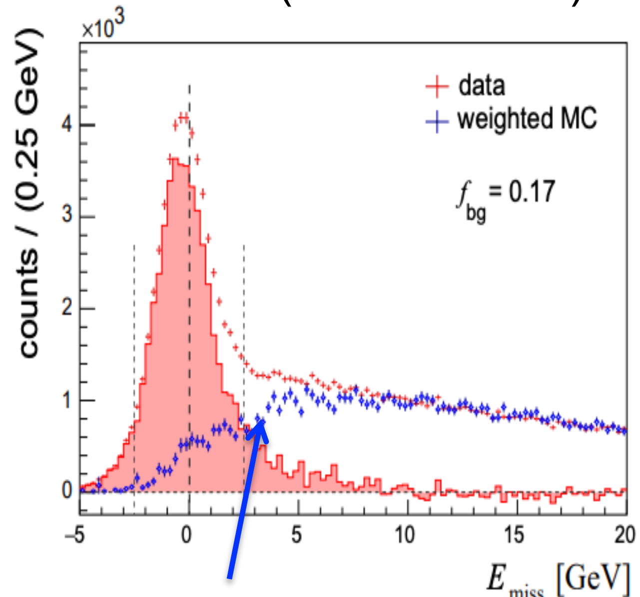
CLAS12 (width <0.1GeV)



HERMES(width ~0.6GeV)



COMPASS(width ~2GeV)



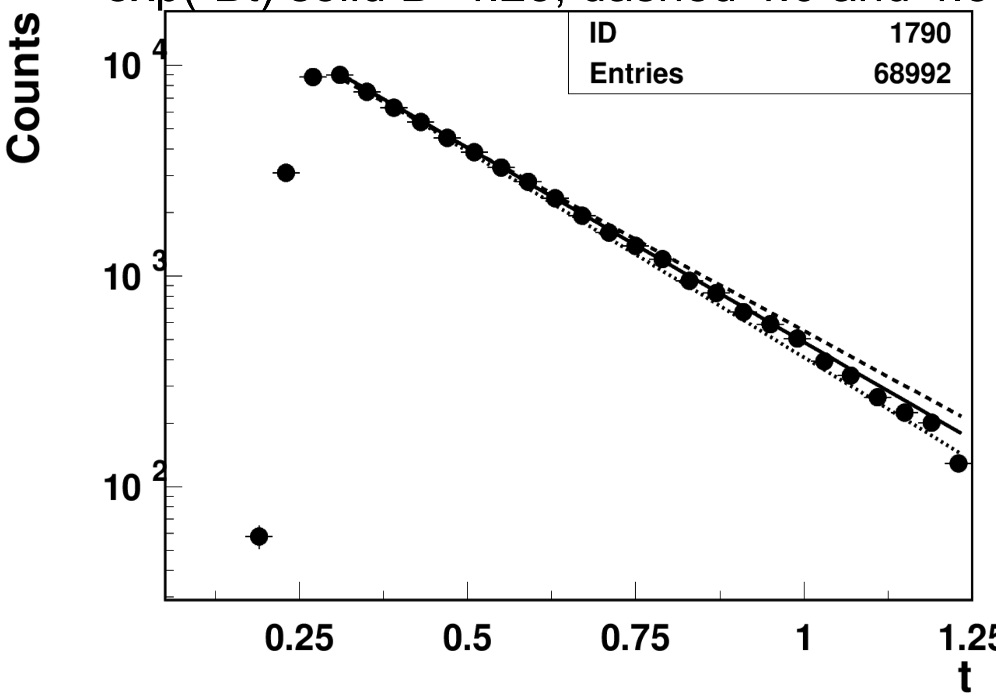
what are cosθ distributions of those?

- Guarantying the "exclusivity" requires good resolutions (gets worse at higher energies)
- Subtraction procedure relays on normalization, based on exclusive limit of LUND-MC
- All distributions have tails, indicating the RC may not be negligible
- Extraction of SDMEs, will require validation in the multi-D space (significant samples)

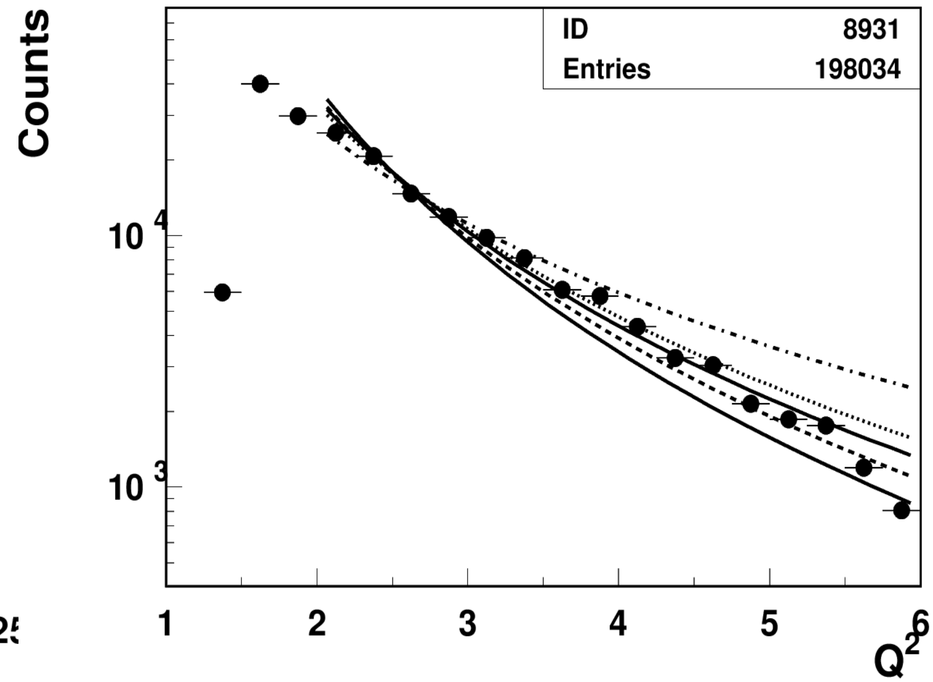
MC sensitivity for a given x-bin

0.34<x<0.36 (solid lines 1/Q^6, exp(-4.25t)

exp(-Bt) solid B=4.25, dashed 4.0 and 4.5



1/Q^(2N) solid N=3,
dashed 2.2,2.8,3.2,3.5



Extraction of parameters B and N ($Q^{2N}{}_L$ and $Q^{2N}{}_T$, B_L and B_T) require proper integration in the multidimensional phase space!!!
Implementing in the MC predictions from GK for B_L and B_T

Structure functions: case of VMs

Diehl: 0704.1565 $\gamma^*(\mu) + p(\lambda) \to \rho(\nu) + p(\sigma)$

$$\frac{d\sigma}{d\psi\, d\phi\, d\varphi\, d(\cos\vartheta)\, dx_B\, dQ^2\, dt} = \frac{1}{(2\pi)^2} \frac{d\sigma}{dx_B\, dQ^2\, dt} \times \Big(W_{UU} + P_\ell W_{LU} + S_L W_{UL} + P_\ell S_L W_{LL} + S_T W_{UT} + P_\ell S_T W_{LT} \Big)$$

$$u^{\nu\nu'}_{\mu\mu'} = \tfrac{1}{2}\big(\rho^{\nu\nu'}_{\mu\mu',++} + \rho^{\nu\nu'}_{\mu\mu',--}\big)$$

unpolarized part involves several dynamical contributions

$$W_{LU}(\phi, \varphi, \theta)$$

$$W^{LL}_{UU}(\phi) = \big(u^{0\,0}_{++} + \epsilon u^{0\,0}_{0\,0}\big) - 2\cos\phi\, \sqrt{\epsilon(1+\epsilon)}\, \mathrm{Re}\, u^{0\,0}_{0+} - \cos(2\phi)\, \epsilon u^{0\,0}_{-+}\,,$$

$$\begin{aligned} W^{LT}_{UU}(\phi,\varphi) = {} & \cos(\phi+\varphi)\, \sqrt{\epsilon(1+\epsilon)}\, \mathrm{Re}\big(u^{0+}_{0+} - u^{-0}_{0+}\big) \\ & - \cos\varphi\, \mathrm{Re}\big(u^{0+}_{++} - u^{-0}_{++} + 2\epsilon u^{0+}_{0\,0}\big) + \cos(2\phi+\varphi)\, \epsilon\, \mathrm{Re}\, u^{0+}_{-+} \\ & - \cos(\phi-\varphi)\, \sqrt{\epsilon(1+\epsilon)}\, \mathrm{Re}\big(u^{0-}_{0+} - u^{+0}_{0+}\big) + \cos(2\phi-\varphi)\, \epsilon\, \mathrm{Re}\, u^{+0}_{-+}\,, \end{aligned}$$

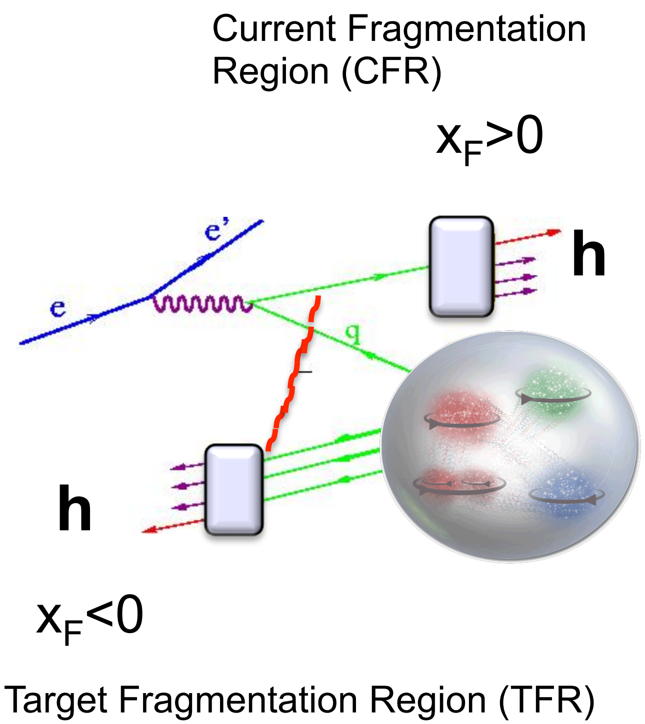
$$\begin{aligned} W^{TT}_{UU}(\phi,\varphi) = {} & \tfrac{1}{2}\big(u^{++}_{++} + u^{--}_{++} + 2\epsilon u^{++}_{0\,0}\big) + \tfrac{1}{2}\cos(2\phi+2\varphi)\, \epsilon u^{-+}_{-+} \\ & - \cos\phi\, \sqrt{\epsilon(1+\epsilon)}\, \mathrm{Re}\big(u^{++}_{0+} + u^{--}_{0+}\big) + \cos(\phi+2\varphi)\, \sqrt{\epsilon(1+\epsilon)}\, \mathrm{Re}\, u^{-+}_{0+} \\ & - \cos(2\varphi)\, \mathrm{Re}\big(u^{-+}_{++} + \epsilon u^{-+}_{0\,0}\big) - \cos(2\phi)\, \epsilon\, \mathrm{Re}\, u^{++}_{-+} \\ & + \cos(\phi-2\varphi)\, \sqrt{\epsilon(1+\epsilon)}\, \mathrm{Re}\, u^{+-}_{0+} + \tfrac{1}{2}\cos(2\phi-2\varphi)\, \epsilon u^{+-}_{-+}\,. \end{aligned}$$

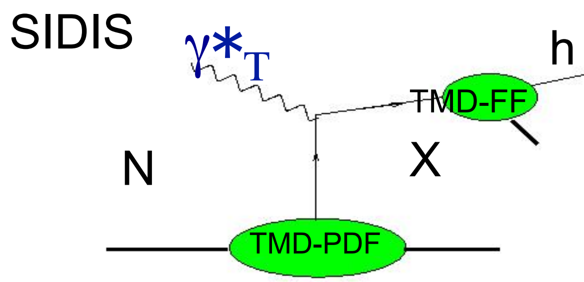
After integration over φ
few terms survive

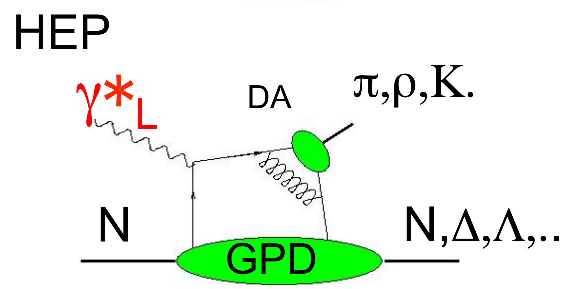
$$\cos^2\theta W^{LL}_{UU}(\phi,\theta) + \sin^2\theta W^{TT}_{UU}(\phi,\theta)$$

The GPD based description is applicable for separate matrix elements

3D PDFs: Electroproduction of hadrons







Study

x,Q^2,z,P_T,ϕ,ϕ_S $\sim 1/Q^4$

Flavor and polarization dependence of transverse momentum distributions

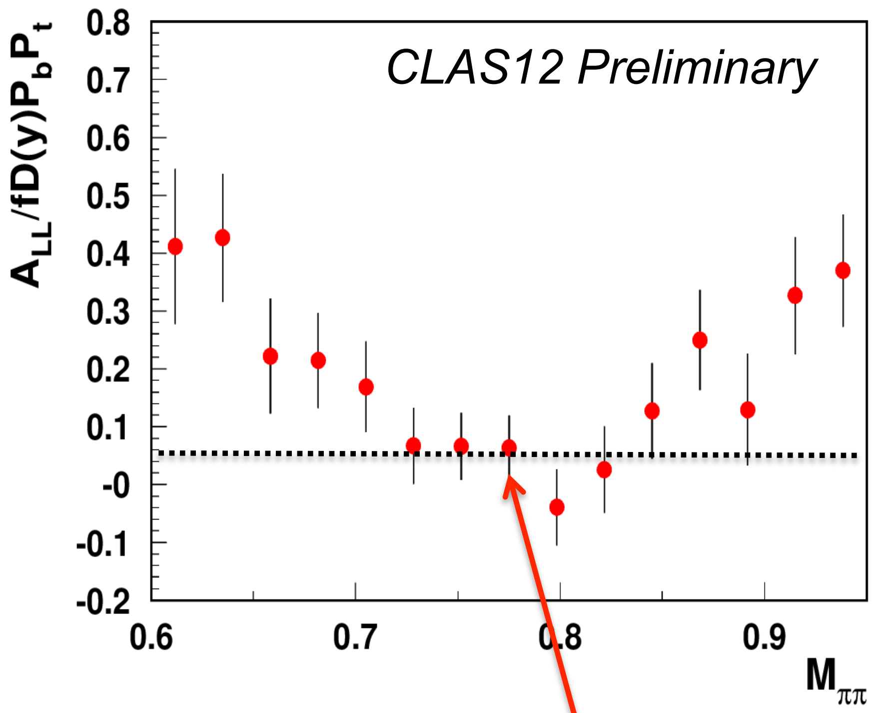
$x,Q^2,t,\phi,\phi_S+\phi,\theta$ $\sim 1/Q^6$

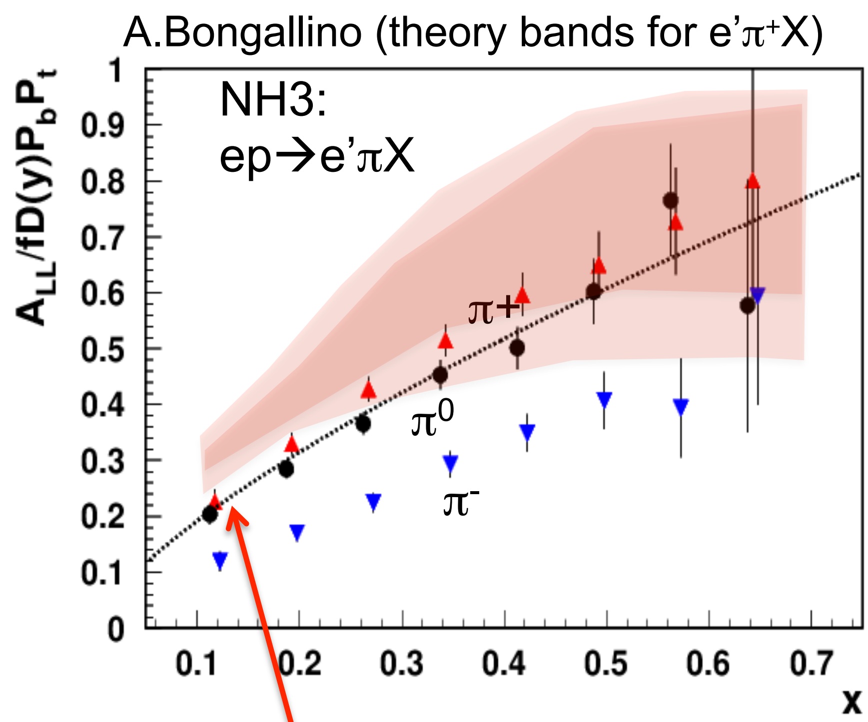
Flavor and polarization dependence of transverse space distributions

Phenomenology tends to ignore contributions from longitudinal photons to SIDIS and transverse photons to HEP→ practically no attempts to understand sin and cosine modulations in cross sections!!!

- Different non-perturbative objects may be involved with several independent variables involved
- Cross contributions make studies based on a given set of assumptions challenging

Exclusive ρ0s: impact on double spin asymmetries (NH_3 target)





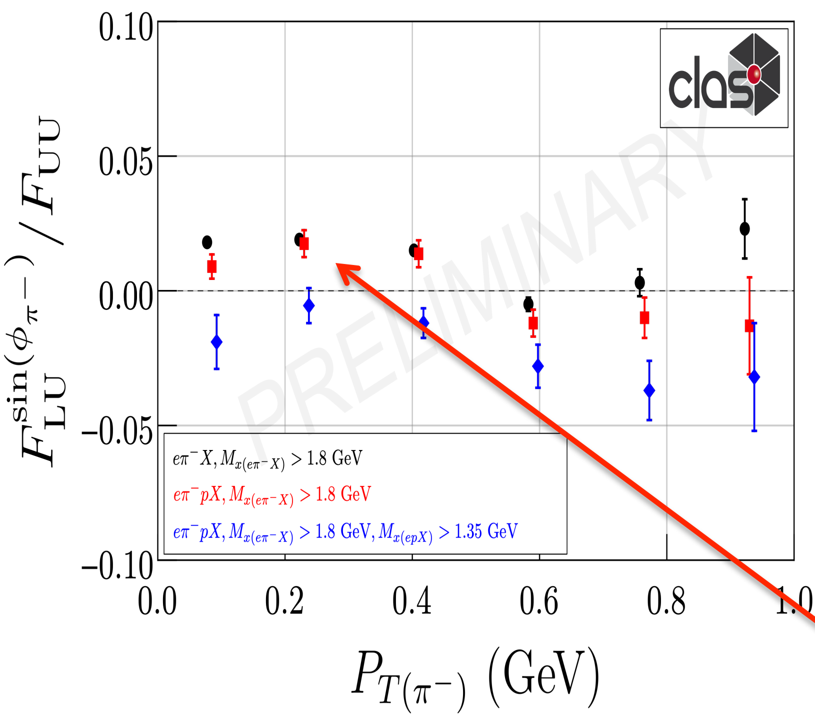
$\gamma_T^* \to \rho_L \propto \sqrt{(1-z)/x}$

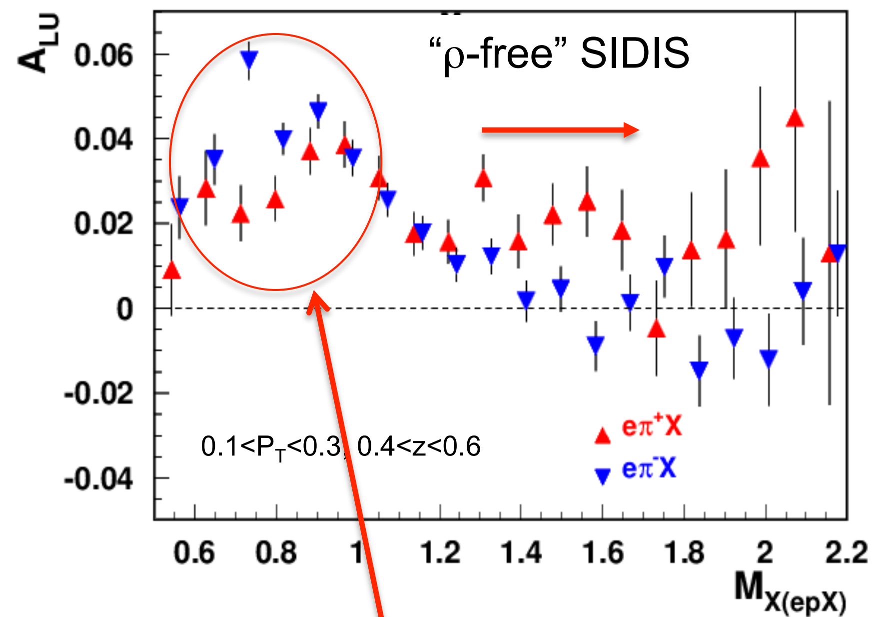
- DSA suppressed for exclusive rho as
- longitudinal photon cross section is P-odd

→ contribution appears only in the SSA, a P-odd observable, and does not appear in DSA

DSA of charged pions affected by the rho introducing dilution in measured DSAs (will affect all kinds of extractions of helicity PDFs in SIDIS and DIS), in particular at small x

Exclusive ρ0s: impact on SIDIS SSAs

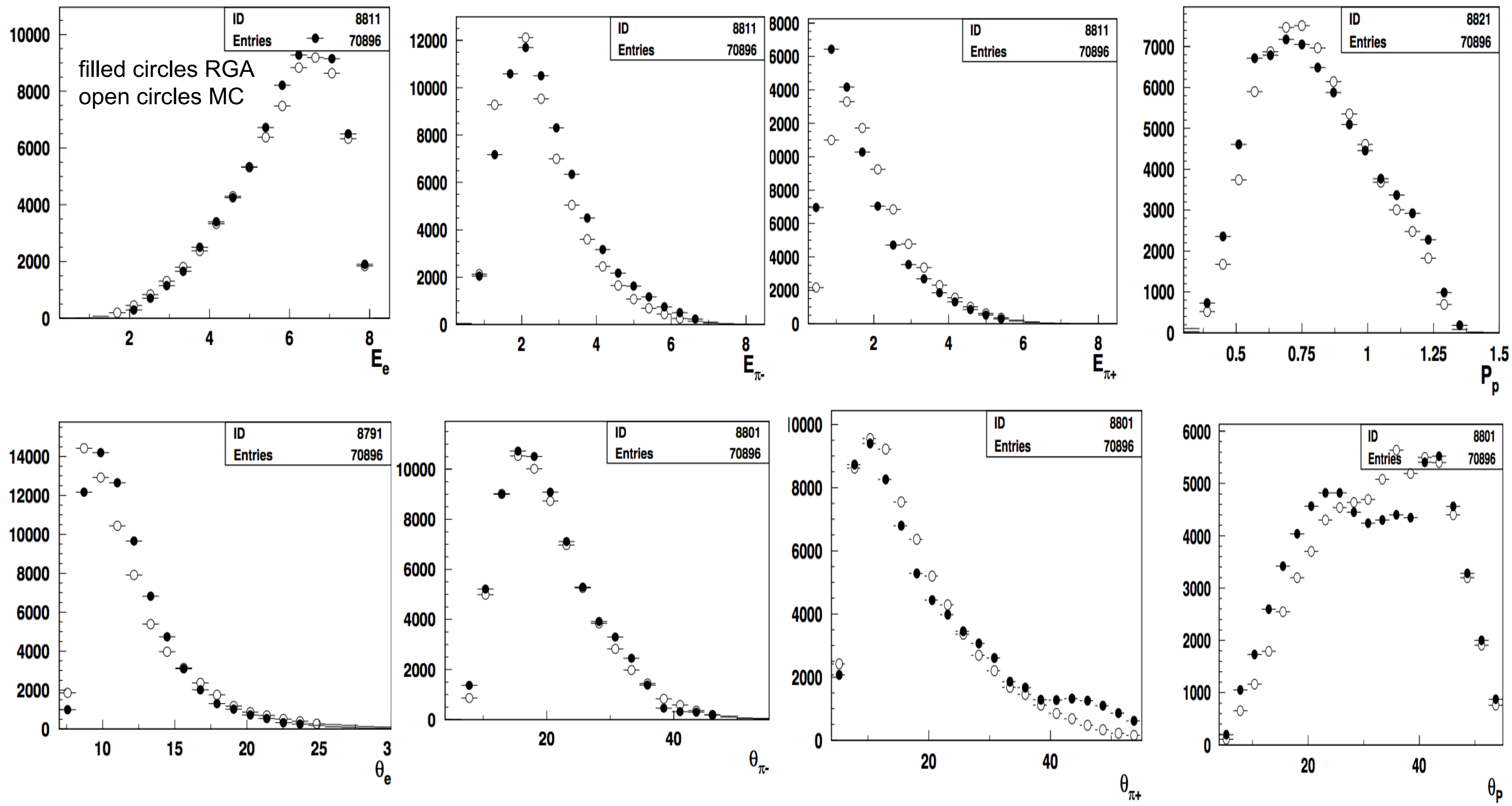




- Can change the pion SSAs, in particular at small P_T
- The same sign and size of π+ and π- SSA indicates the rho0 may be significant, subtraction will require detailed MC studies, which require proper SDMEs
- While VM contributions are ~20% in multiplicities in SSA they can be >100%
- Detection of the target proton allows to clean up the SIDIS sample from exclusive rho contributions

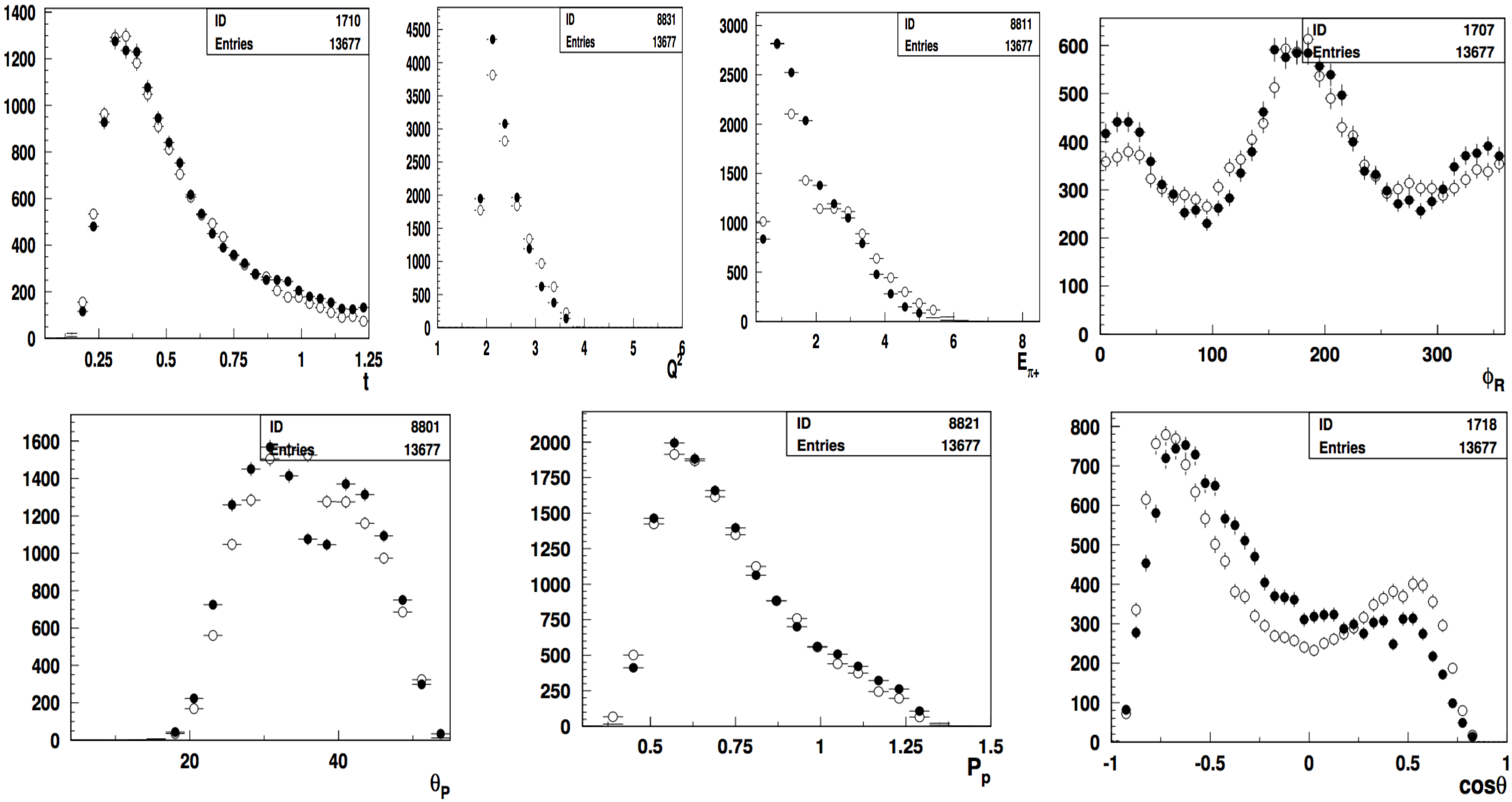
Comparing the MC(gemc) with RGA data

After a preliminary tune and testing use the rho-generator-gemc-coatjava chain to compare with RGA inbending Fall22 (/volatile/clas12/osg/avakian/10277 vs 10359



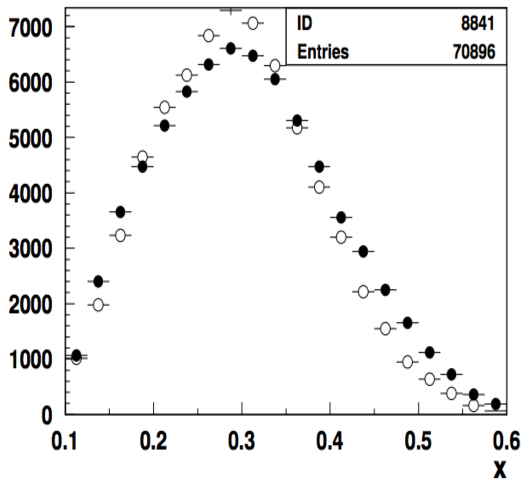
Kinematical distributions of final state exclusive rhos

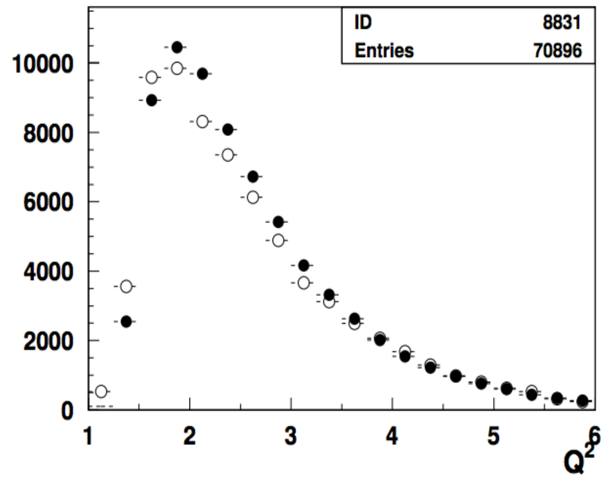
bin 0.235<x<0.265

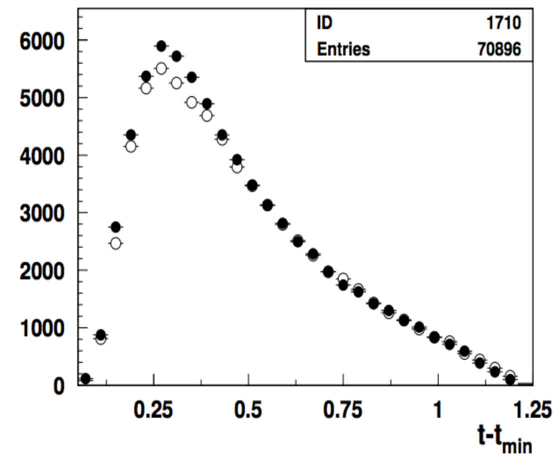


→Kinematical distributions consistent also in small bins

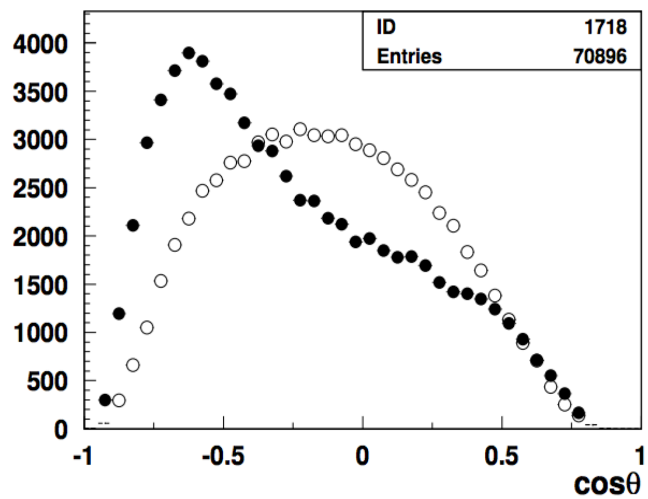
Comparing the MC v1 with RGA data

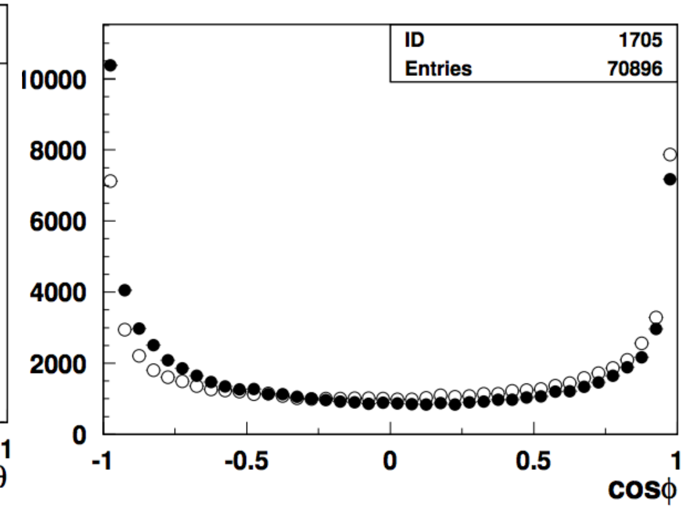






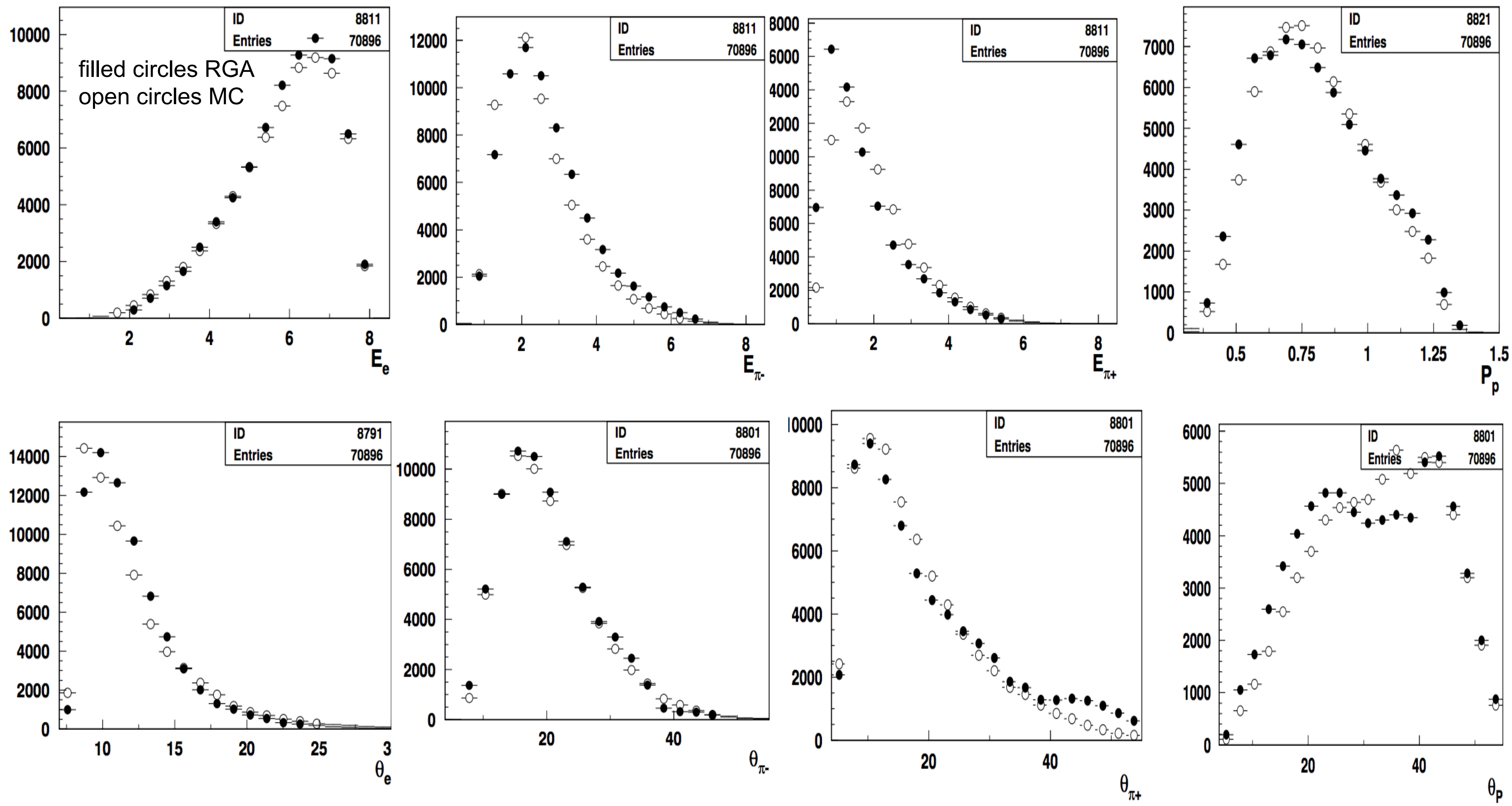
Relative contributions from longitudinal and transverse rhos messed up





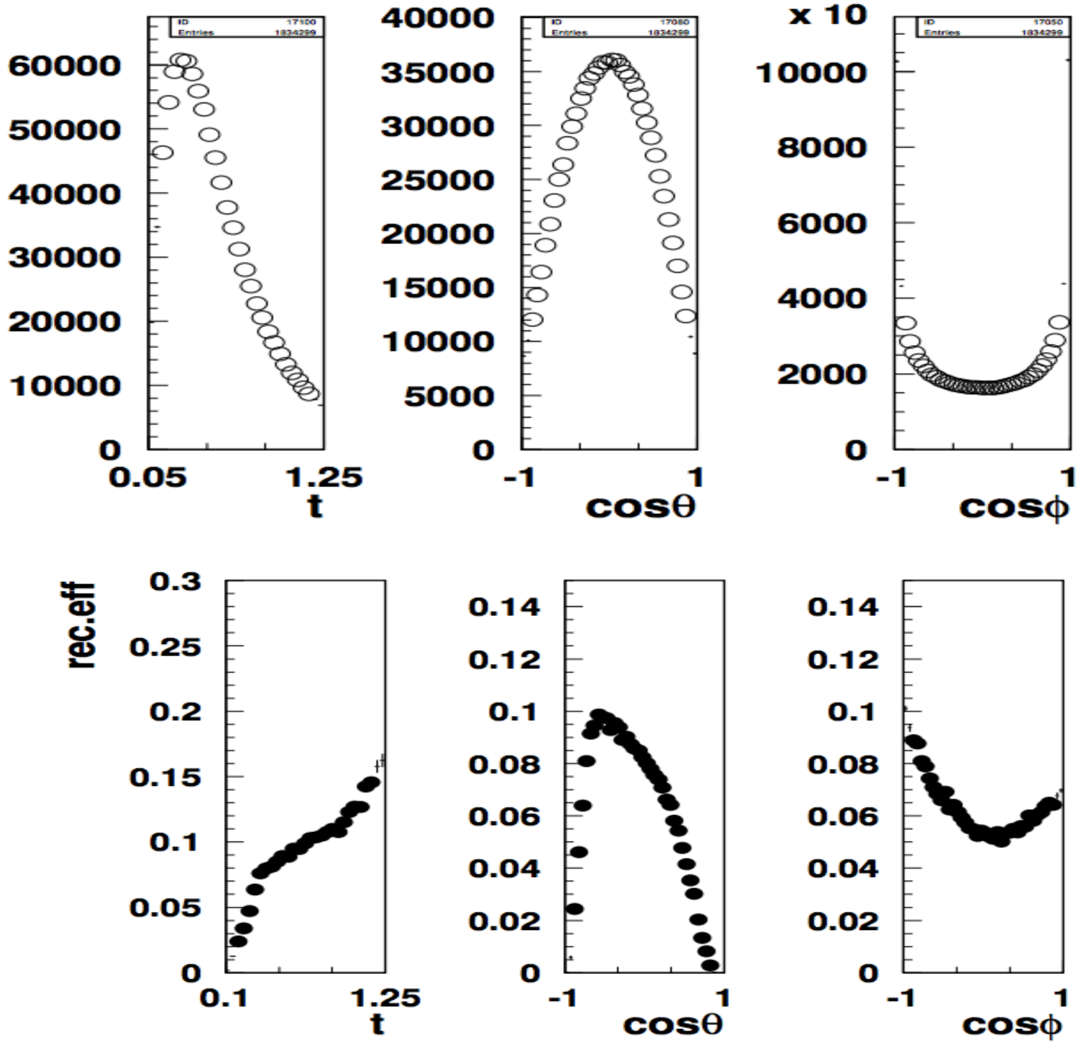
Comparing the MC(gemc) with RGA data

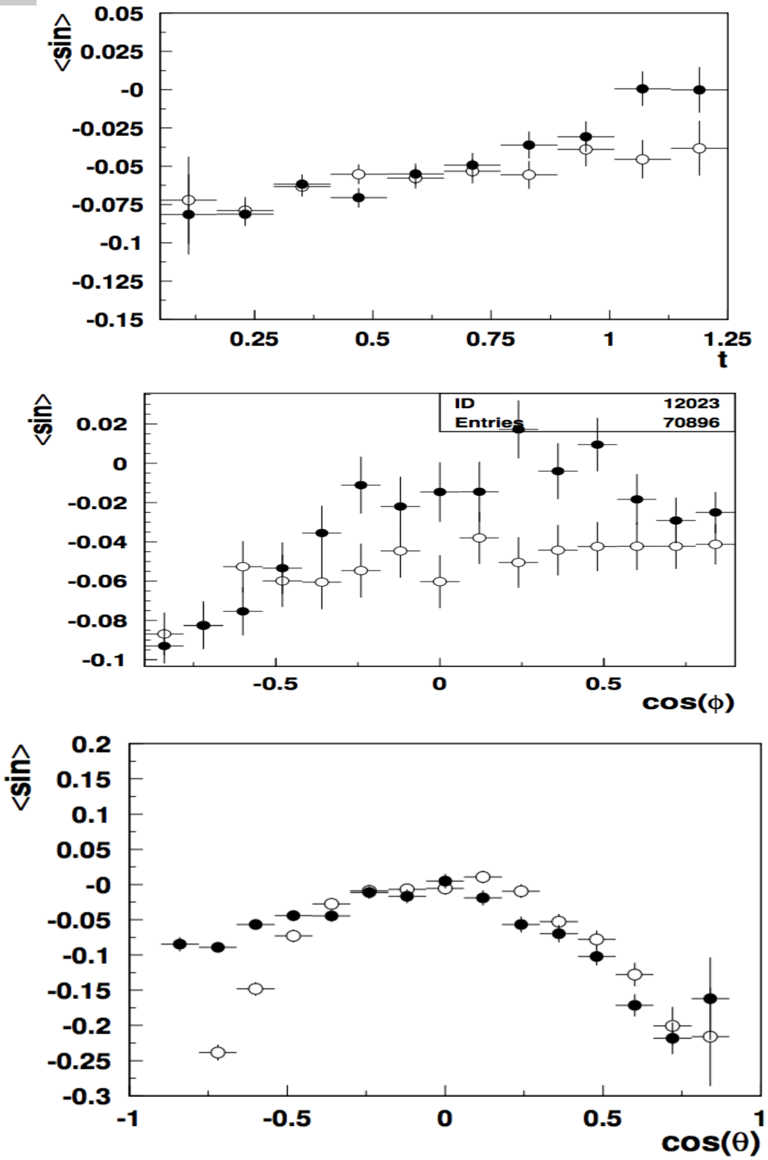
After a preliminary tune and testing use the rho-generator-gemc-coatjava chain to compare with RGA inbending Fall22 (/volatile/clas12/osg/avakian/10228(V1)/34/44/50(V4)



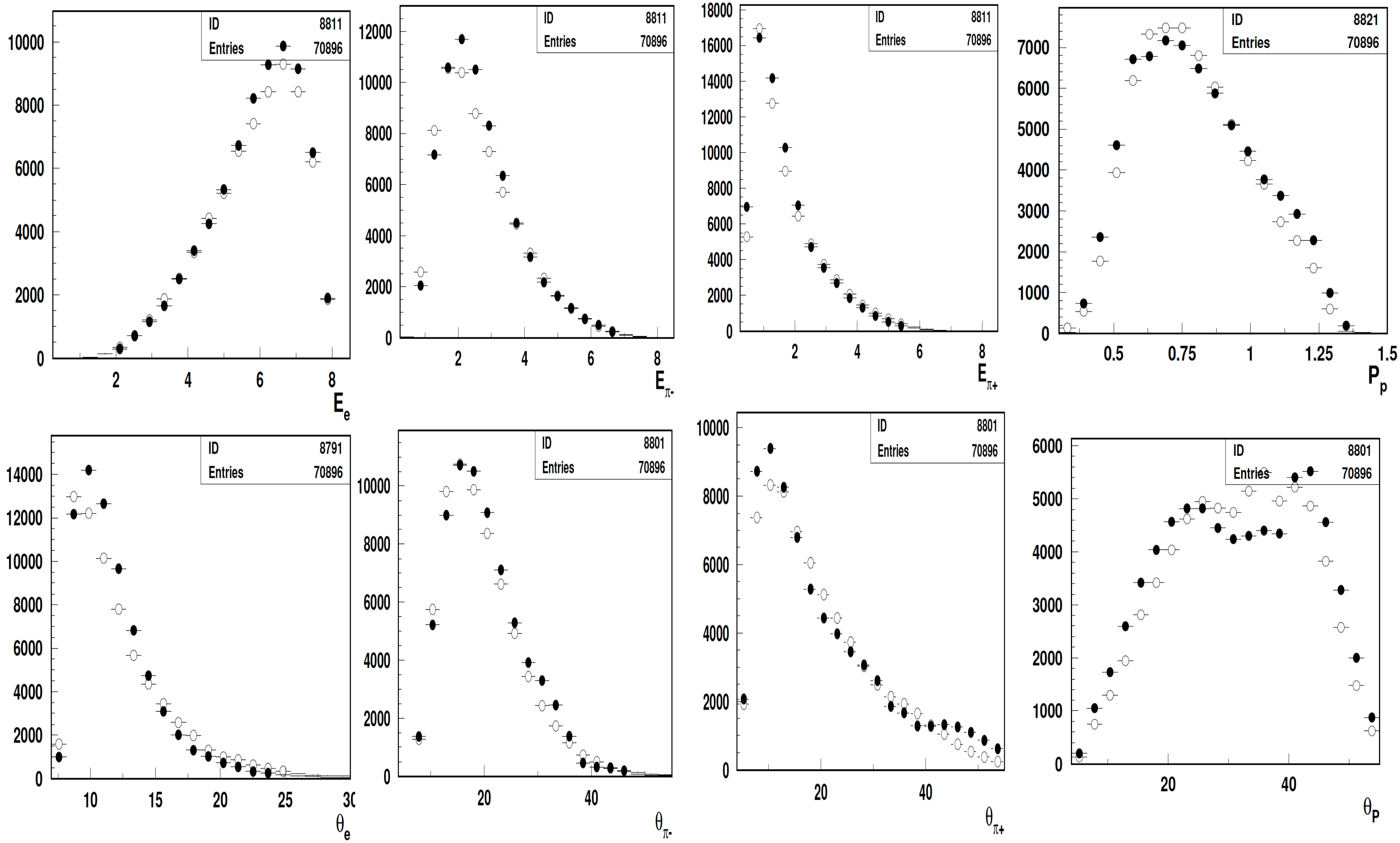
Comparing the v1 MC with RGA data

Transverse ρ dominated



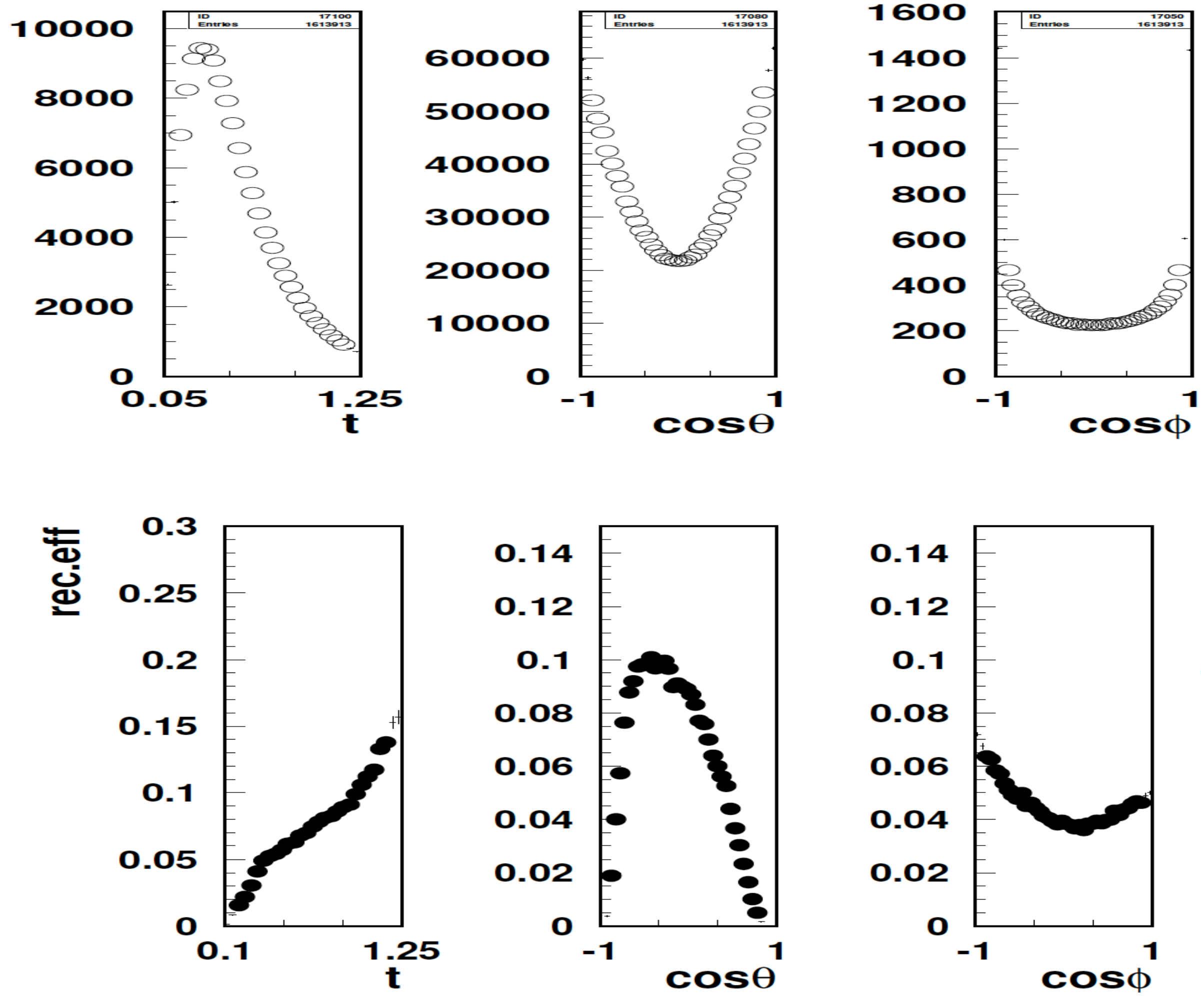


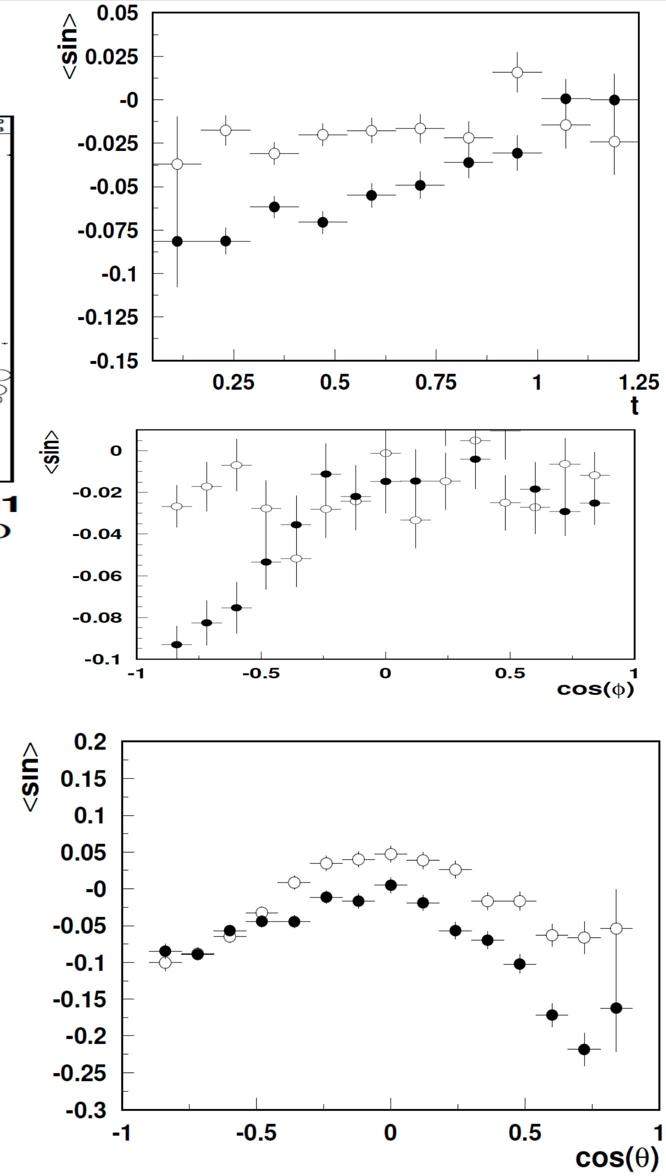
Comparing the MC v4 with RGA data



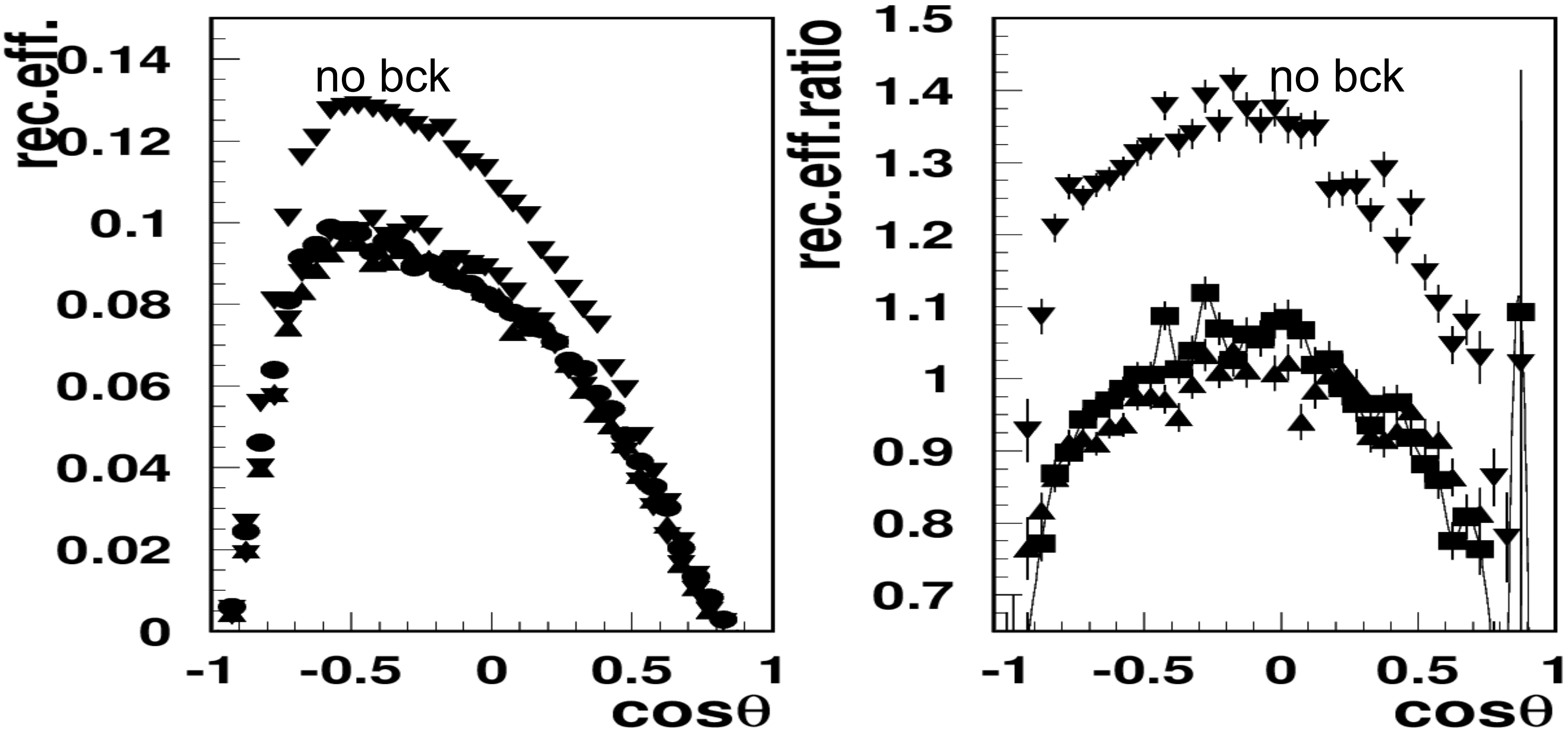
Comparing the MC v4 with RGA data

Longitudinal ρ dominated





Model dependence of the acceptance

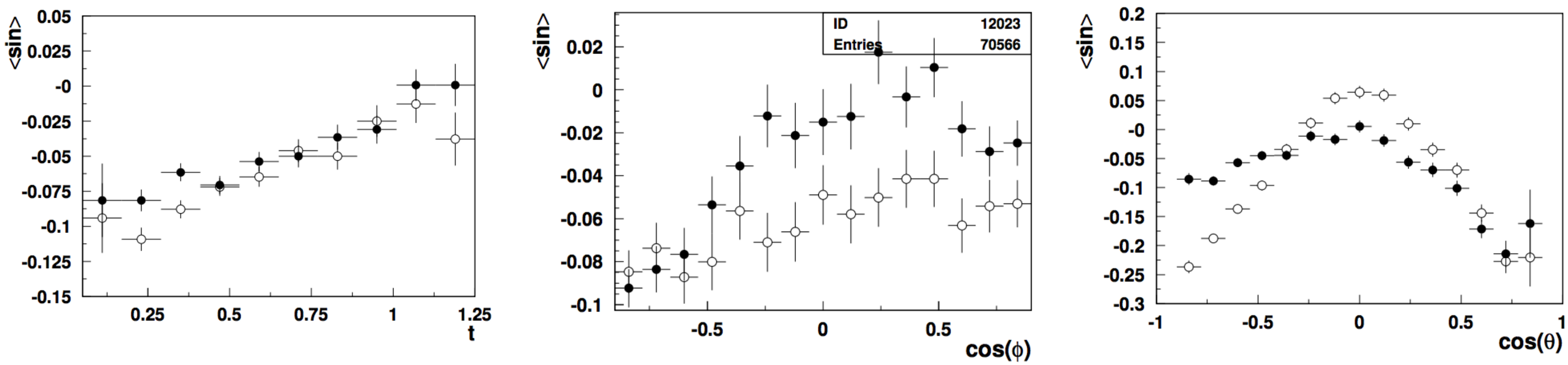


- Four versions of MC (v1-v4) with reasonable description of all kinematic dependences, carry different physics content, very different L/T parts
- Acceptance indeed is a very strong function of the angle and even small variations change the acceptance for 20-30% for wide bins in $\mathbf{Q^2}$,$\mathbf{x}_B$,**t**,ϕ,θ,φ

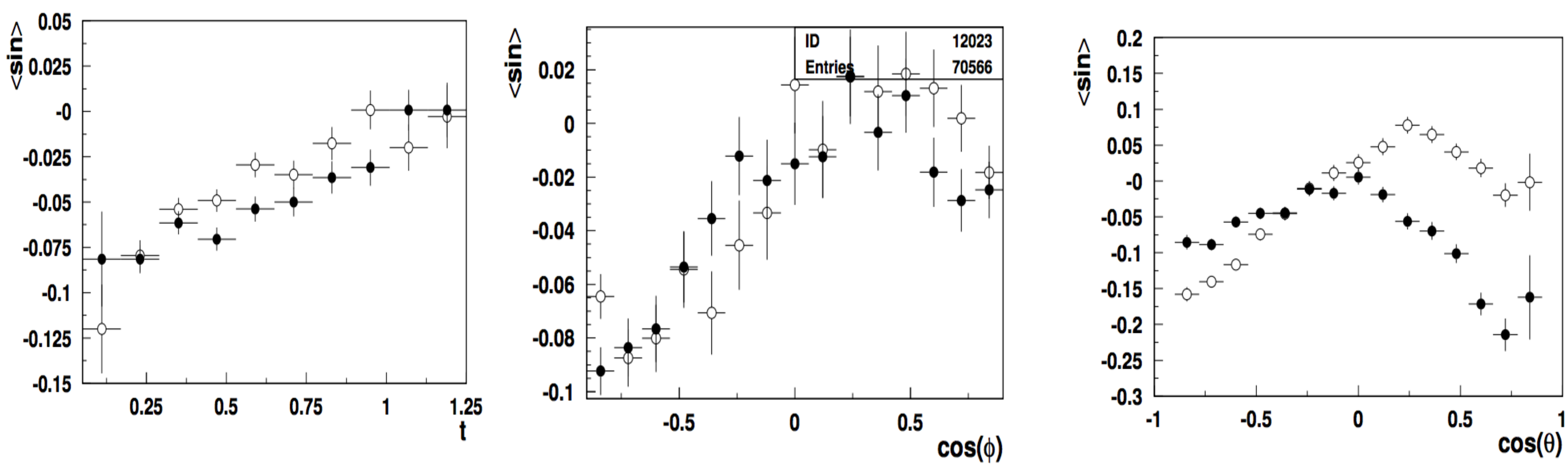
Comparing the MC versions with RGA data

use the rho-generator-gemc-coatjava chain to compare with RGA inbending Fall18 (/volatile/clas12/osg/avakian/10277 vs 10359

10277



10359

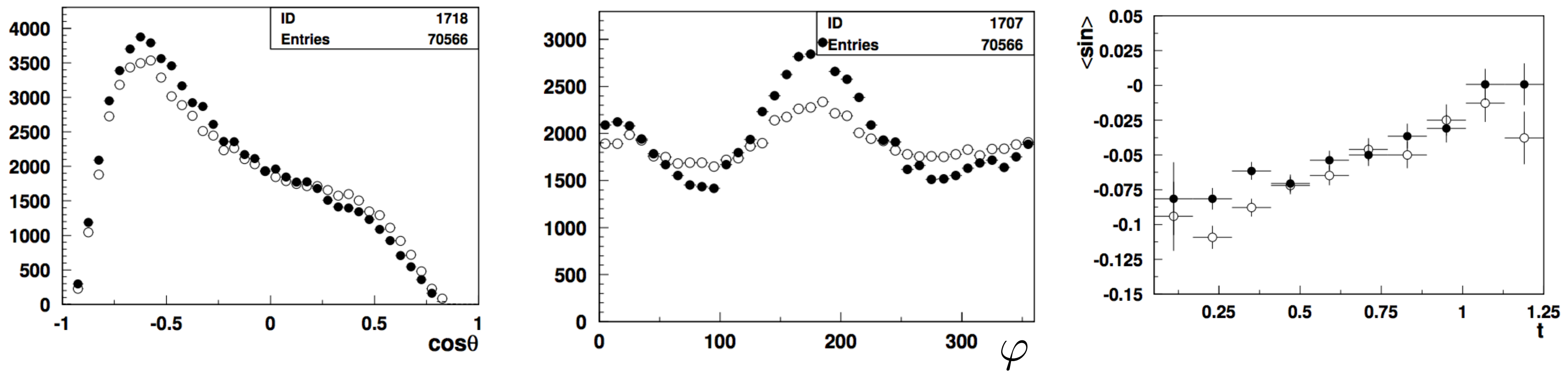


SSA dependence described vs some variables, off vs some other

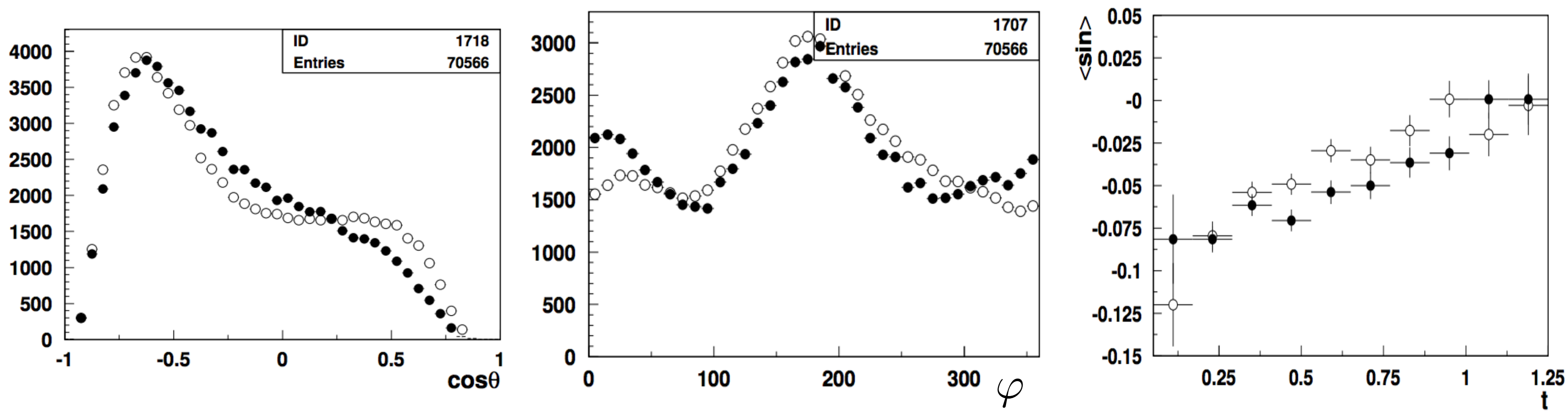
Comparing the MC versions with RGA data

use the rho-generator-gemc-coatjava chain to compare with RGA inbending Fall18 (/volatile/clas12/osg/avakian/10277 vs 10359

10277



10359



Relative contributions from longitudinal and transverse rhos messed up

Structure functions for VMs: integrated case

Diehl: 0704.1565

$$\gamma^*(\mu) + p(\lambda) \to \rho(\nu) + p(\sigma)$$

helicities

$$\frac{d\sigma}{d\psi\, d\phi\, d\varphi\, d(\cos\vartheta)\, dx_B\, dQ^2\, dt} = \frac{1}{(2\pi)^2} \frac{d\sigma}{dx_B\, dQ^2\, dt} \times \left(W_{UU} + P_\ell W_{LU} + S_L W_{UL} + P_\ell S_L W_{LL} + S_T W_{UT} + P_\ell S_T W_{LT} \right)$$

$$u^{\nu\nu'}_{\mu\mu'} = \tfrac{1}{2}\left(\rho^{\nu\nu'}_{\mu\mu',++} + \rho^{\nu\nu'}_{\mu\mu',--}\right)$$

unpolarized part involves several dynamical contributions

longitudinal rho — transverse rho

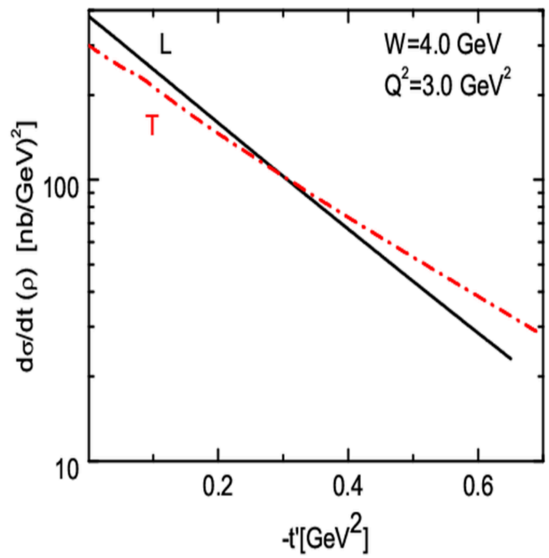
$$W_{UU}(\phi,\varphi,\vartheta) = \frac{3}{4\pi}\left[\cos^2\vartheta\, W^{LL}_{UU}(\phi) + \sqrt{2}\cos\vartheta\,\sin\vartheta\, W^{LT}_{UU}(\phi,\varphi) + \sin^2\vartheta\, W^{TT}_{UU}(\phi,\varphi)\right]$$

r^{04}_{00} SDME (mixes L and T with different x,Q^2,t-dependences)

$$W^{LL}_{UU}(\phi) = \left(u^{00}_{++} + \epsilon u^{00}_{00}\right) - 2\cos\phi\sqrt{\epsilon(1+\epsilon)}\,\mathrm{Re}\, u^{00}_{0+} - \cos(2\phi)\,\epsilon u^{00}_{-+}$$

longitudinal photon (L) with 0 helicity producing longitudinal ρ_L

transverse photon (T) with + helicity producing longitudinal ρ_L



$$W^{TT}_{UU}(\phi,\varphi) = \tfrac{1}{2}\left(u^{++}_{++} + u^{--}_{++} + 2\epsilon u^{++}_{00}\right)$$

$1 - r^{04}_{00}$ (keep normalization)

Looking for L→L physics focus on low t large Q^2

SDMEs: different combinations in experiment

Diehl: 0704.1565 $\gamma^*(\mu) + p(\lambda) \to \rho(\nu) + p(\sigma)$

$$u_{\mu\mu'}^{\nu\nu'} = \frac{1}{2}\left(\rho_{\mu\mu',++}^{\nu\nu'} + \rho_{\mu\mu',--}^{\nu\nu'}\right)$$

$$\frac{d\sigma}{d\psi\, d\phi\, d\varphi\, d(\cos\vartheta)\, dx_B\, dQ^2\, dt} = \frac{1}{(2\pi)^2} \frac{d\sigma}{dx_B\, dQ^2\, dt} \times \left(W_{UU} + P_\ell W_{LU} + S_L W_{UL} + P_\ell S_L W_{LL} + S_T W_{UT} + P_\ell S_T W_{LT}\right)$$

$$u_{++}^{0\,0} + \epsilon u_{0\,0}^{0\,0} = r_{00}^{04} = \frac{d\sigma(\gamma_T^* \to V_L) + \varepsilon d\sigma^N(\gamma_L^* \to V_L)}{d\sigma}$$

Valuable source of info on longitudinal photon!!!

sinusoidal modulations(~0 at COMPASS)

$$\mathrm{Im}\, u_{0+}^{0\,0} = r_{00}^{8}/\sqrt{2}\,,$$

$$\mathrm{Re}\, u_{0+}^{0\,0} = -r_{00}^{5}/\sqrt{2}$$

→ Interference of $\gamma_T^* \to \rho_L$ and $\gamma_L^* \to \rho_L$

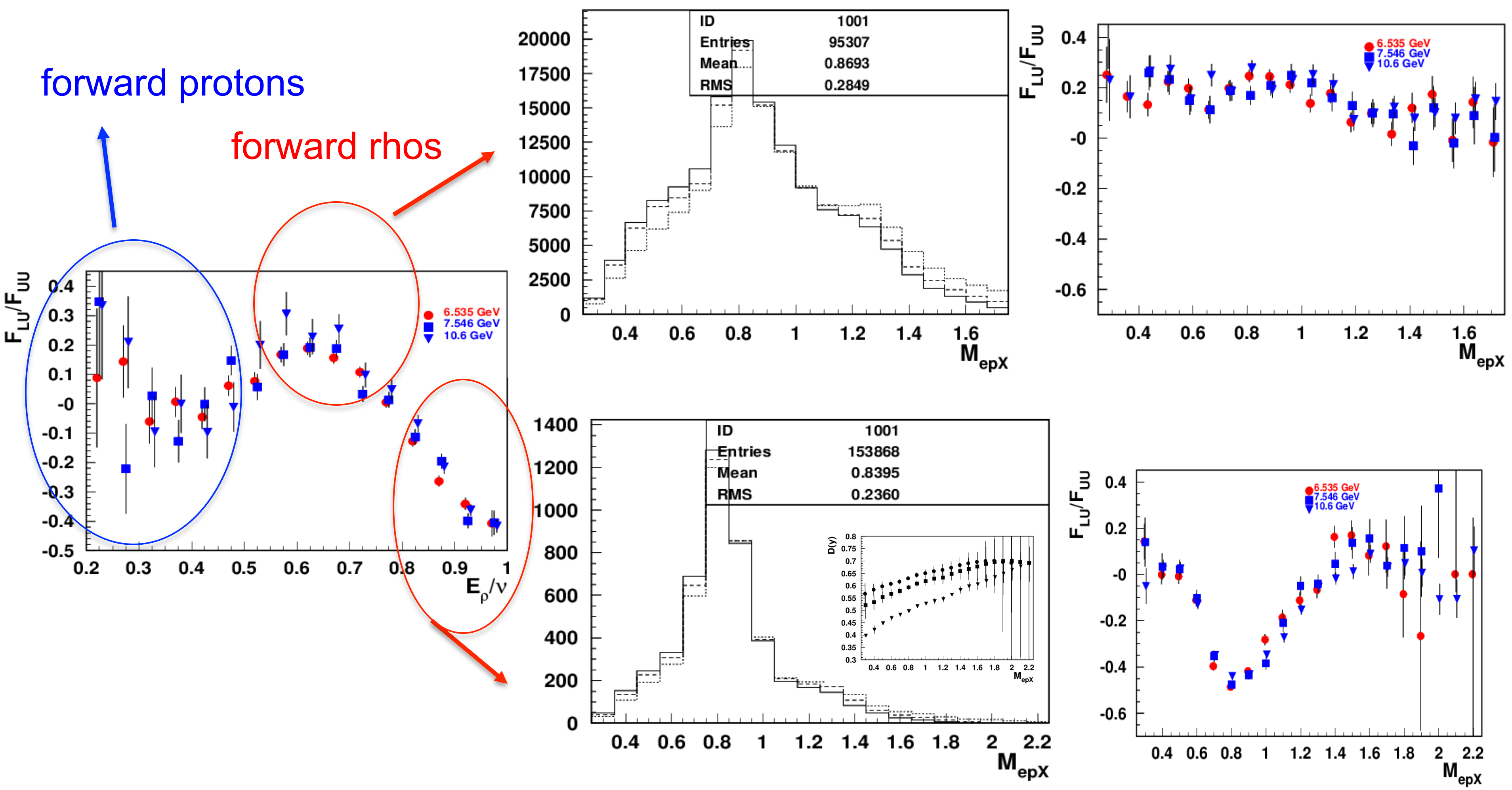
cosine modulations(huge at COMPASS)

$$\mathrm{Im}\left(u_{0+}^{++} + u_{0+}^{--}\right) = \sqrt{2}\, r_{11}^{8}$$ *(>0 at COMPASS)*

→ Interference of $\gamma_T^* \to \rho_T$ and $\gamma_L^* \to \rho_T$

$$\mathrm{Re}\left(u_{0+}^{++} + u_{0+}^{--}\right) = -\sqrt{2}\, r_{11}^{5}$$ *(~0 at COMPASS)*

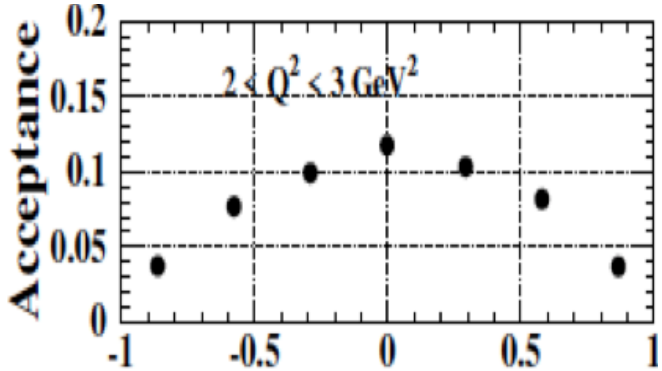
Exclusive π+π−: missing mass dependence

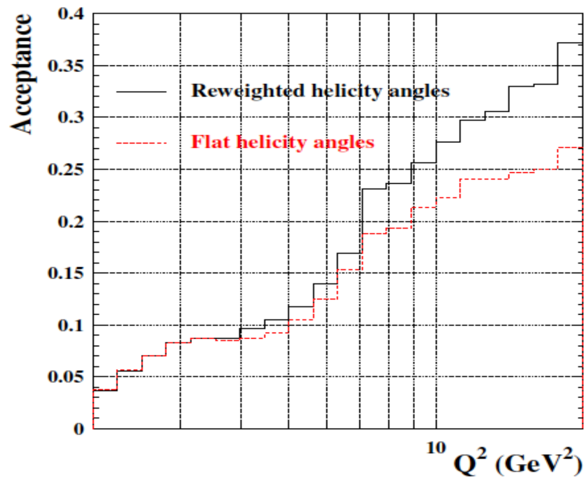


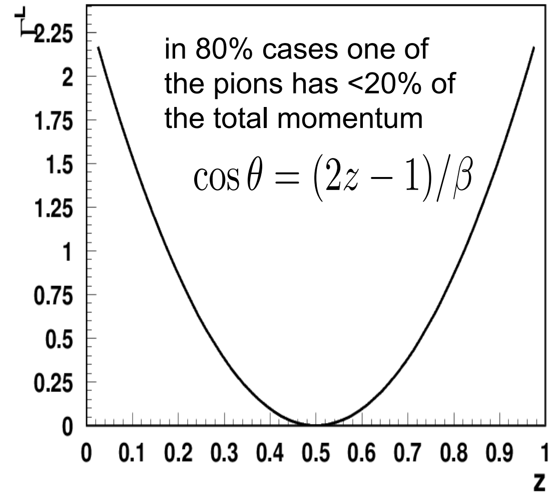
- ρs dominate both exclusive dihadron samples, contributing differently depending on z
- SSA can be used as a tool to check dominance of different dynamical contributions

Acceptances in cos\theta

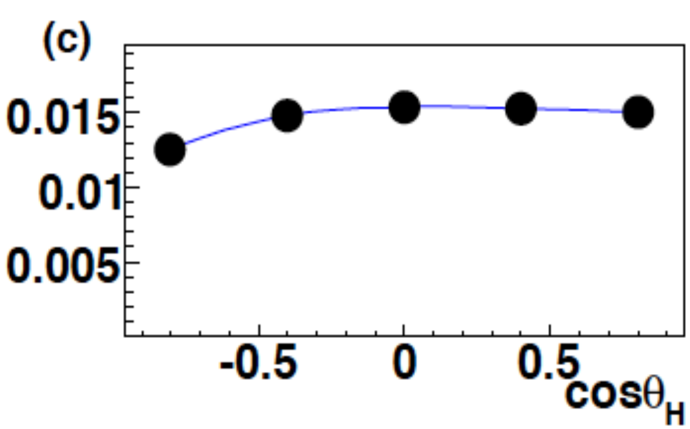
ZEUS rho (0708.1478)

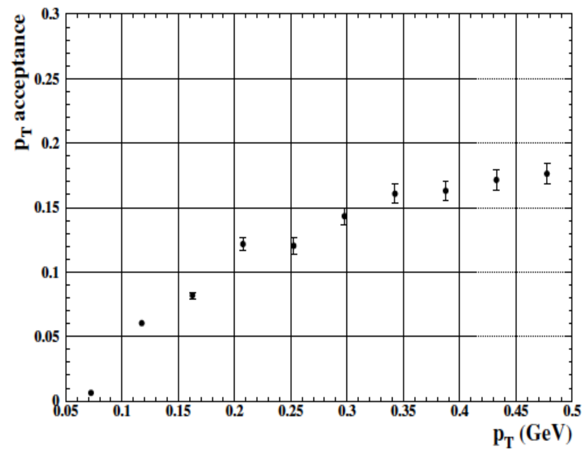


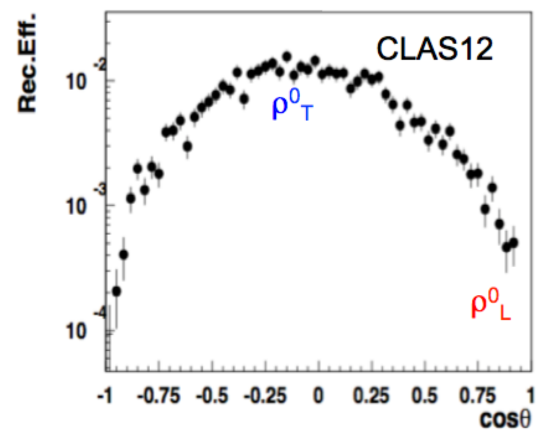




CLAS6 0803.3537







- Proper acceptance account requires fine multidimensional binning, high statistics
- 7-bins with acceptance at $|\cos\theta|>0.8$ reducing ~2 times (integrated over t?)
- Situation much worse for electroproduction of ϕ-mesons

DDIS and rho from ZEUS

ZEUS diffraction $1/Q^6$ at low M_X

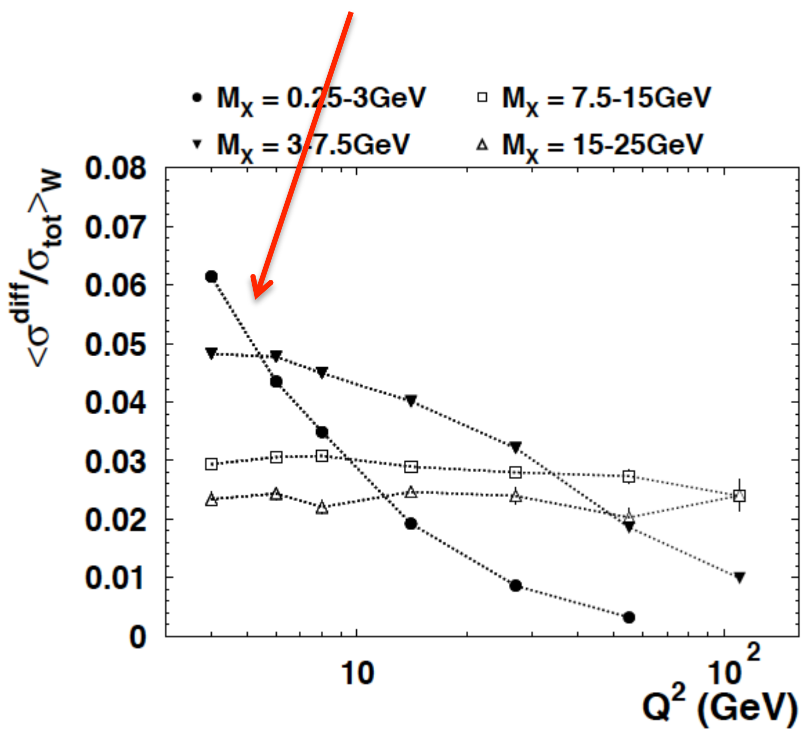
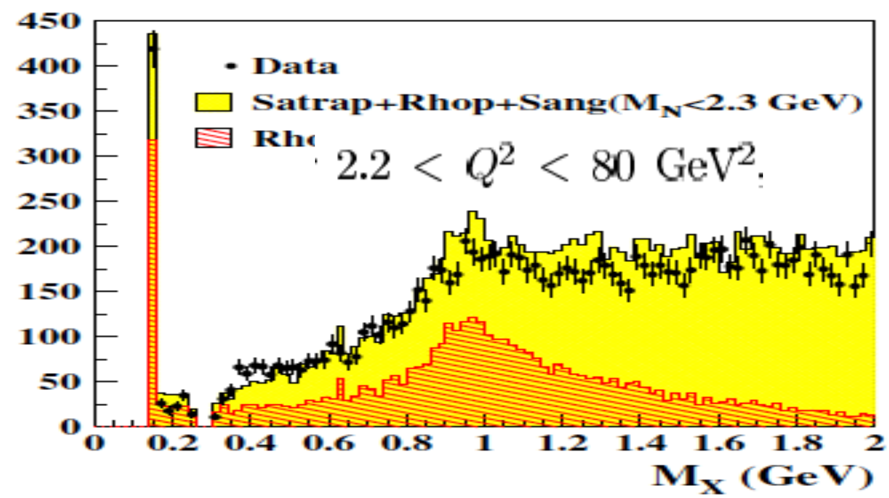
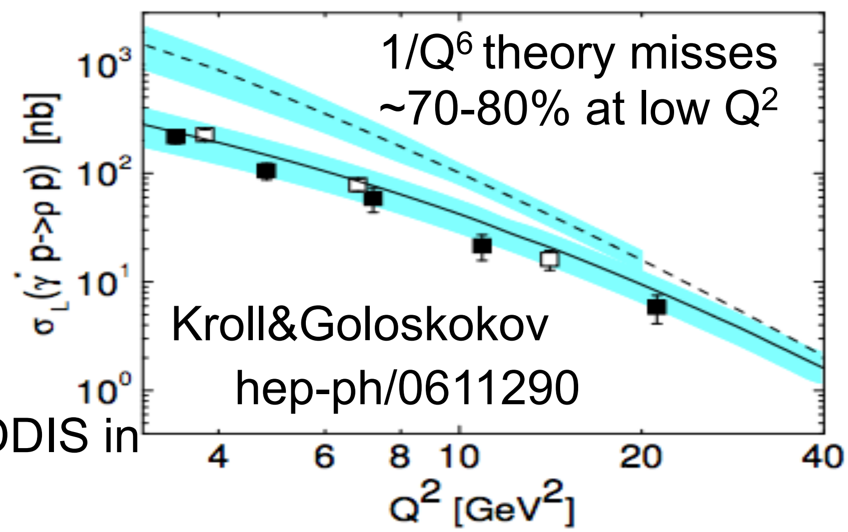


Figure 11.7: The ratio of the diffractive cross section σ^{diff} and the total $\gamma^* p$ cross section σ^{tot} is shown as a function of Q^2 for different bins of M_X. To guide the eye the dotted lines connect points corresponding to the same M_X values.



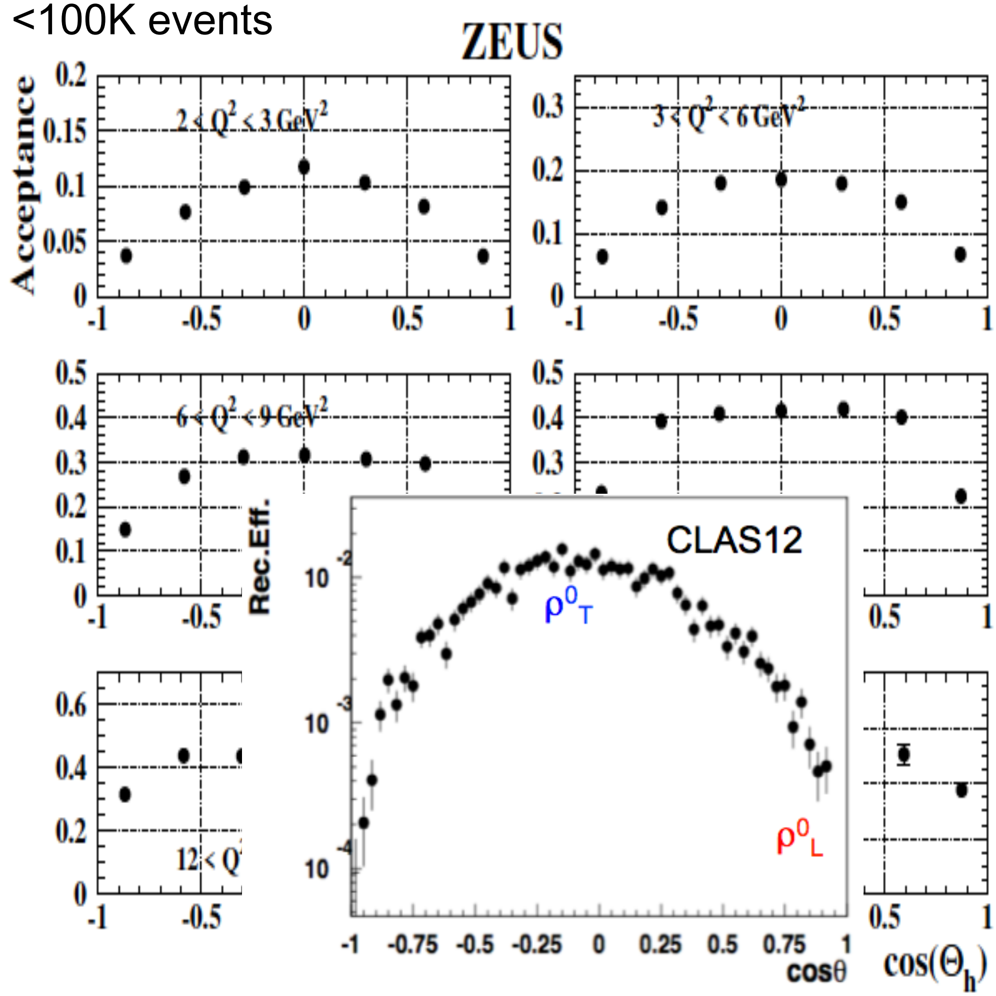
~20-30% of DDIS comes from rho
What about the Q^2~4GeV^2?



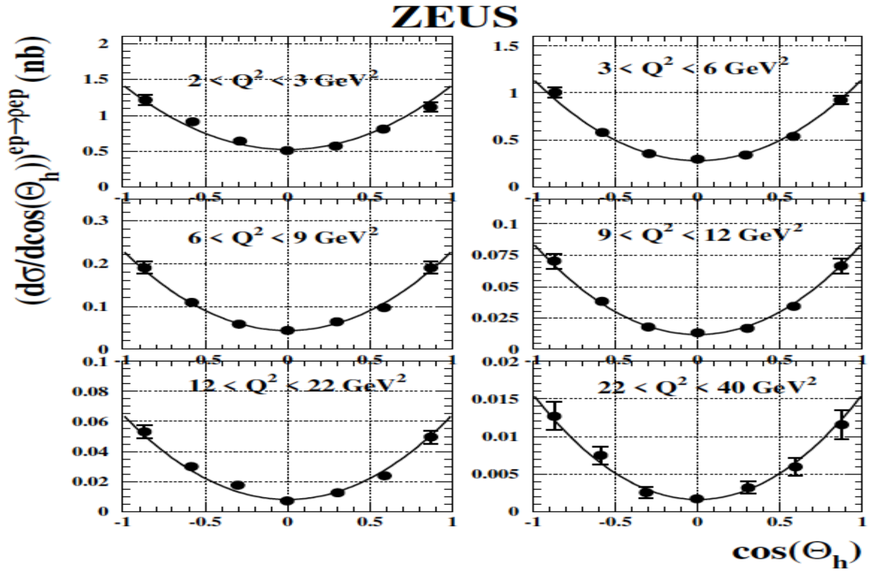
What are the other ~70-80% contributions to DDIS in the low MX bin, at low Q^2, in particular?

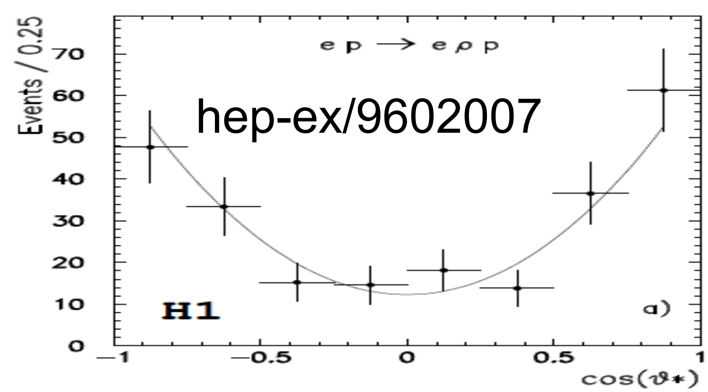
Measuring exclusive VMs: ZEUS and H1

<100K events



ZEUS rho (0708.1478)

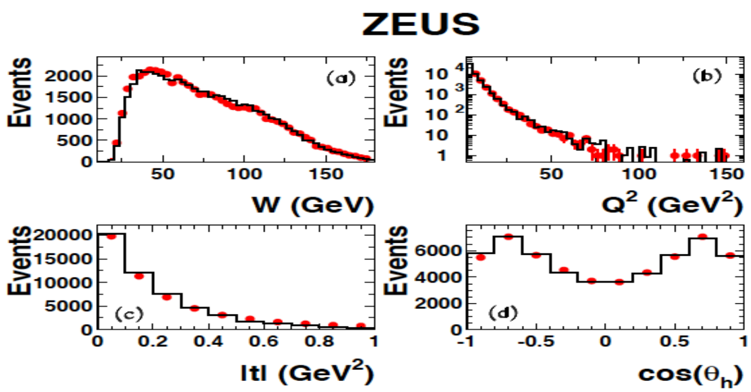


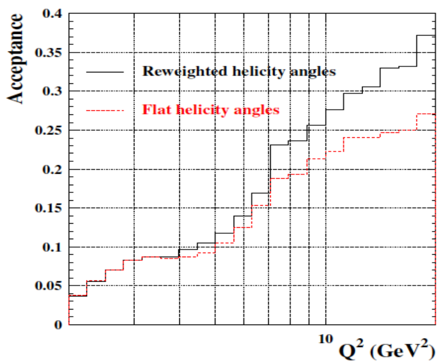


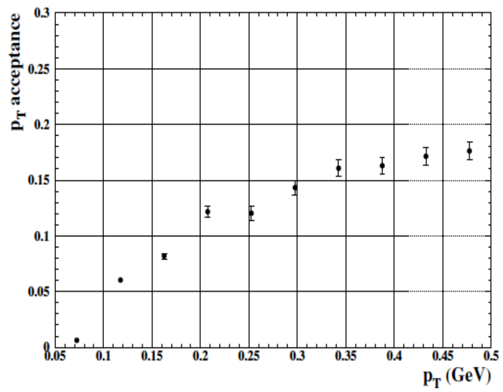
Proper acceptance account requires fine multidimensional binning, high statistics
7-bins with acceptance at |cosθ|>0.8 reducing ~2 times (integrated over t?)

More plots from ZEUS

ZEUS rho (0708.1478)







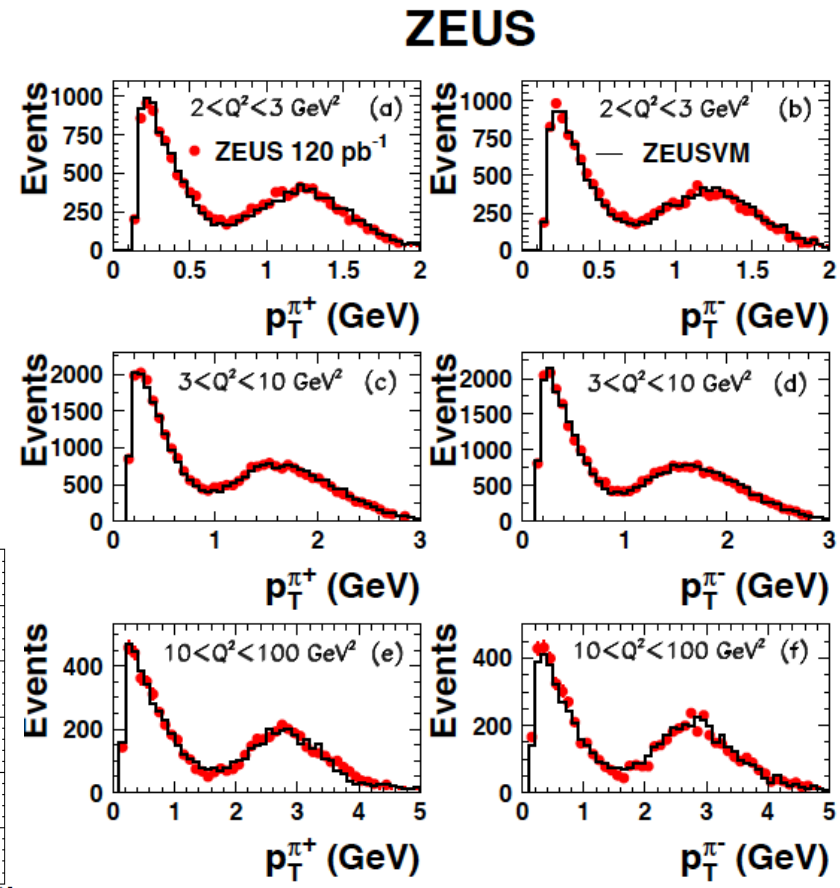


Figure 2: *Comparison between the data and the ZEUSVM MC distributions for the transverse momentum, p_T, of π^+ and π^- particles, for different ranges of Q^2, as indicated in the figure. The events are selected to be within $0.65 < M_{\pi\pi} < 1.1$ GeV and $|t| < 1.0$ GeV^2. The MC distributions are normalised to the data.*

The acceptance low at low P_T, (low t?) and Q^2, increasing with Q^2 (agreement with LT theory also improving at large Q^2).

Exclusive rhos and SDMEs from COMPASS

$$\mathcal{W}^U(\Phi,\phi,\cos\Theta)$$

$$+\ \sqrt{2\epsilon(1+\epsilon)}\cos\Phi\left(r^5_{11}\sin^2\Theta + r^5_{00}\cos^2\Theta\right.$$

corr. with r_{10}^5 (Hermes) no corr (COMPASS)

$$\mathcal{W}^L(\Phi,\phi,\cos\Theta)$$

$$+\ \sqrt{2\epsilon(1-\epsilon)}\sin\Phi\left(r^8_{11}\sin^2\Theta + r^8_{00}\cos^2\Theta\right.$$

corr. with r_{1-1}^8 (Hermes) no corr (COMPASS)

$$\gamma^*_T \to \rho^0_L \qquad \tau_{01} \approx \sqrt{\epsilon}\frac{\sqrt{(r^5_{00})^2+(r^8_{00})^2}}{\sqrt{2r^{04}_{00}}}$$

$$\mathrm{Im}\, u^{0\,0}_{0+} = r^8_{00}/\sqrt{2}, \qquad \mathrm{Re}\, u^{0\,0}_{0+} = -r^5_{00}/\sqrt{2}$$

Since the decay angle is correlated with the polarization of the rho, then r_{00}^8 and r_{00}^5 will be responsible for longitudinal rho, so tiny beam SSA expected for longitudinal rho

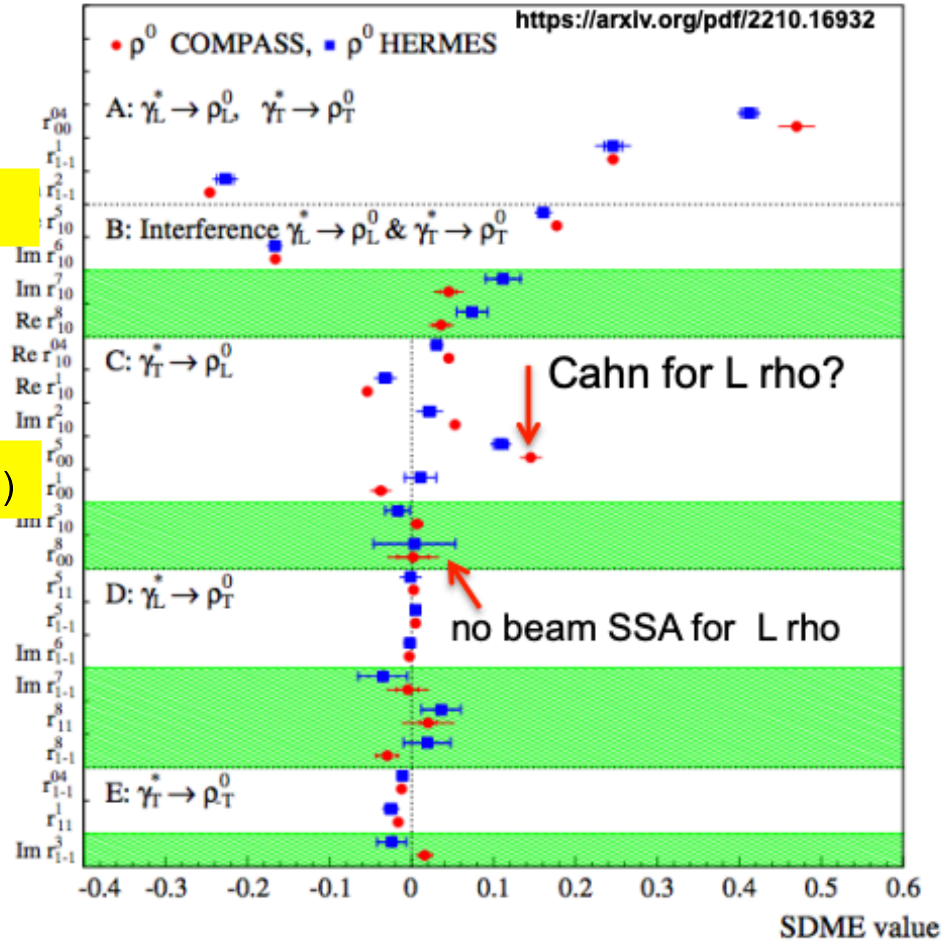
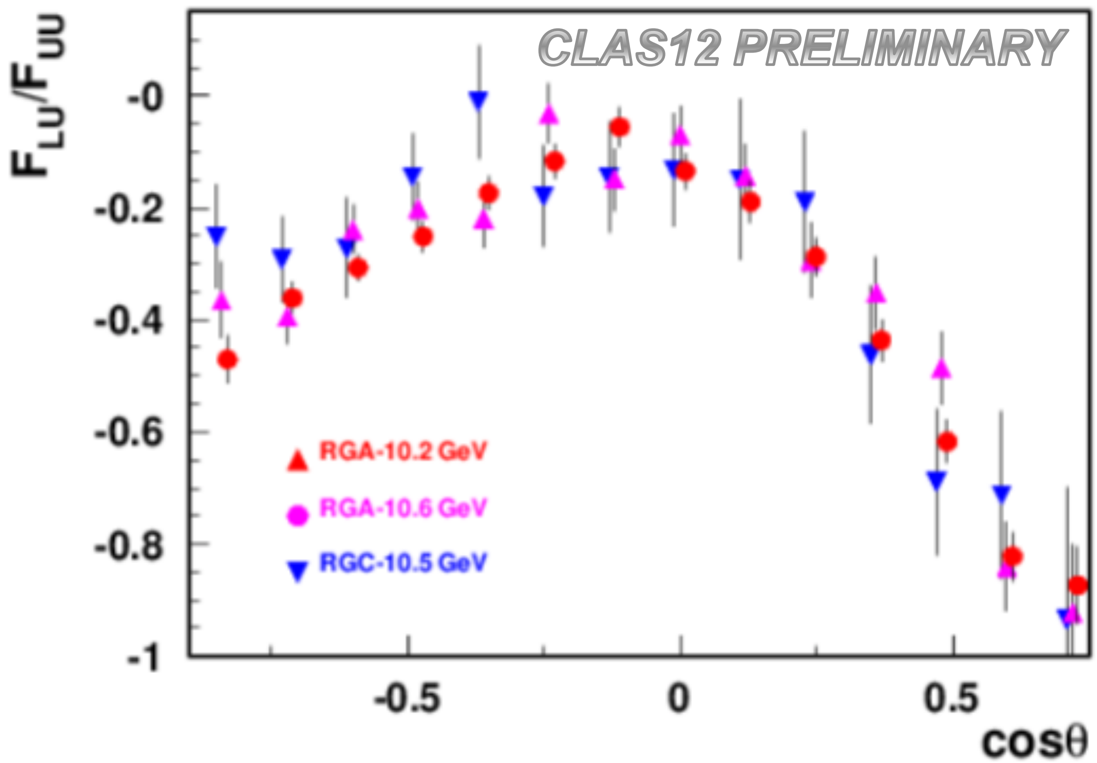
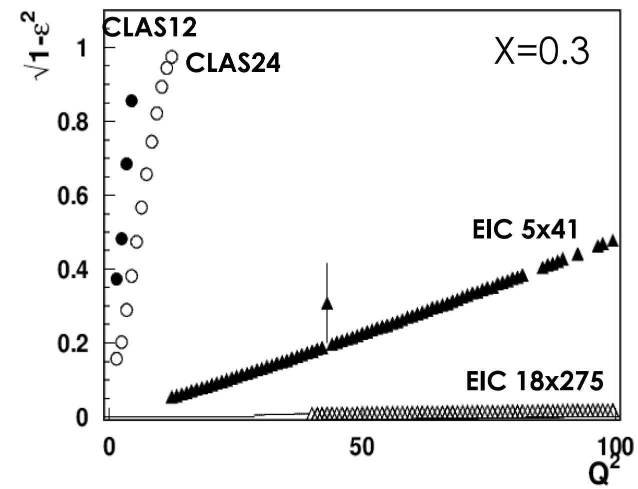


Fig. 12: Comparison of the 23 SDMEs for exclusive ρ^0 leptoproduction on the proton extracted in the entire kinematic regions of the HERMES and COMPASS experiments. For HERMES the average kinematic values are $\langle Q^2\rangle = 1.96$ (GeV/c)^2, $\langle W\rangle = 4.8$ GeV/c^2, $\langle|t'|\rangle = 0.13$, while those for COMPASS are $\langle Q^2\rangle = 2.40$ (GeV/c)^2, $\langle W\rangle = 9.9$ GeV/c^2, $\langle p_T^2\rangle = 0.18$ (GeV/c)^2. Inner error bars represent statistical uncertainties and outer ones statistical and systematic uncertainties added in quadrature. Unpolarised (polarised) SDMEs are displayed in unshaded (shaded) areas.

SSA: ρ^0 A_{LU}

Large cosines correspond to higher fractions of longitudinal rho from unpolarized target runs (RGA) and polarized target runs (RGC)





$$\mathrm{Im}\, u^{0\,0}_{0+} = r^8_{00}/\sqrt{2}\,,$$

Some modulations (ex. SSAs and DSAs) suppressed at large x kinematically at higher energies due to $\varepsilon \rightarrow 1$

SSA is very significant and has cosine shape, likely indicating significant contributions from longitudinal ρ0s

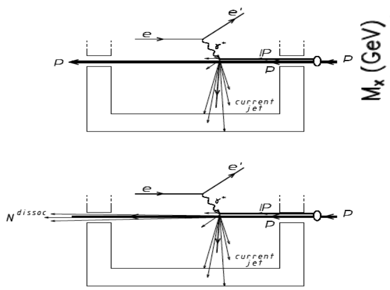
SUMMARY

Measurements of exclusive ρ and, longitudinal rho, in particular, with polarized beams and targets will be crucial for completeness of the measurements of 3D structure, including GPDs and TMDs

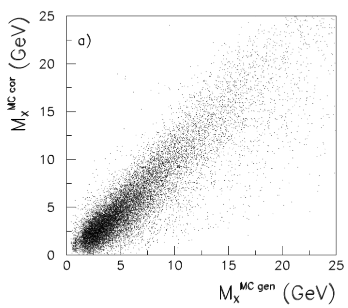
- Studies of exclusive rho, indicate several strong dynamical contributions from different interference terms, *including longitudinal photon contributions*
- Measurements of rho, are classical demonstration of how *critical multidimensional measurements with high precision* could be
- CLAS12 has significant advantage compared to higher energy experiments in *resolution and statistics, required for proper separation of exclusive VMs* from semi-exclusive VMs, and separation of transverse rhos from longitudinal
- *Target and beam SSAs and DSA* can help to separate diffractive rho from other exclusive and semi-exclusive processes, and extract kinematic dependences of helicity amplitudes
- The diffractive VM contributions, violate the factorized picture of SIDIS based on the dominance of the leading twist contributions, and *detailed understanding of exclusive rho contributions in the multi-D space will be critical to address the challenges of SIDIS*

- Develop MC, produce large samples for cross section studies, extract SDMEs from RGK/RGA/RGC/RGB data sets
- Combine efforts of CLAS+COMPASS communities (ex. generator development) in understanding the diffractive ρ and sort out the impact on OAM, TMD-PDFs, ….

Measured x-section: DDIS vs DIS

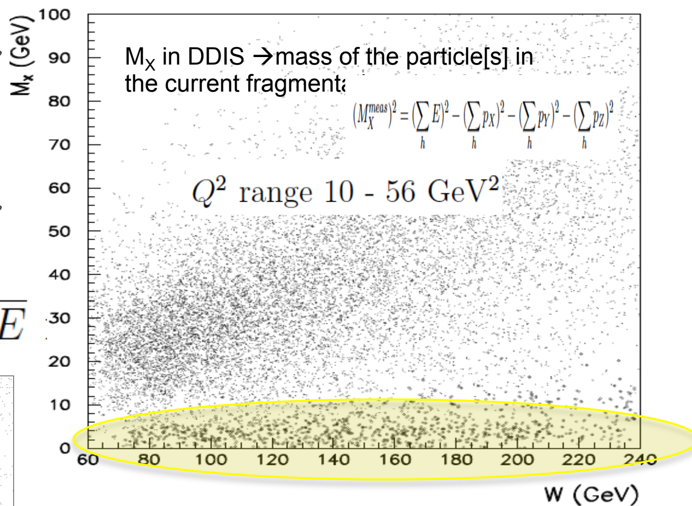


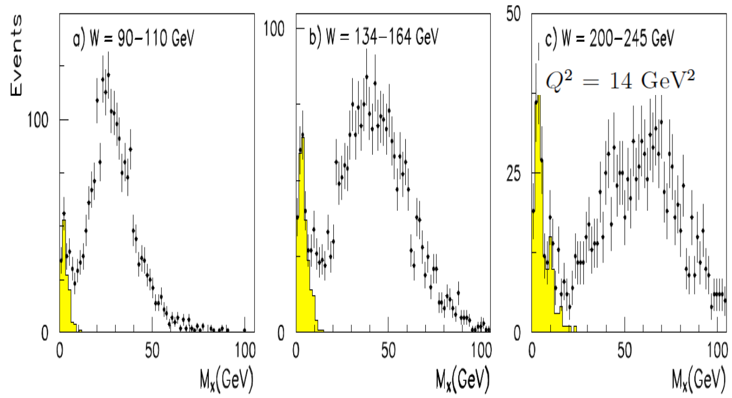
$$\sigma_E/E = 18\%/\sqrt{E}$$



Week increase with W in photoproduction
Strong increase in electroproduction (longitudinal rho?)

η is defined as $-\ln(\tan\frac{\theta}{2})$.





For $\eta_{max} < 1.5$ the contribution from nondiffractive scattering is expected to be negligible

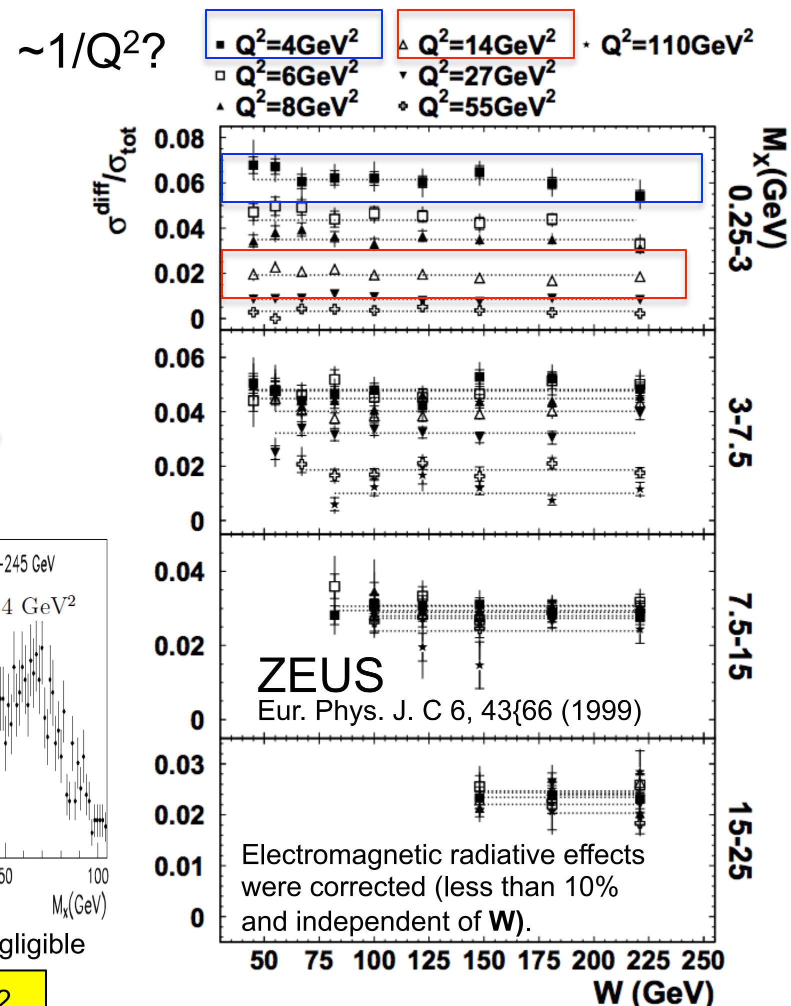


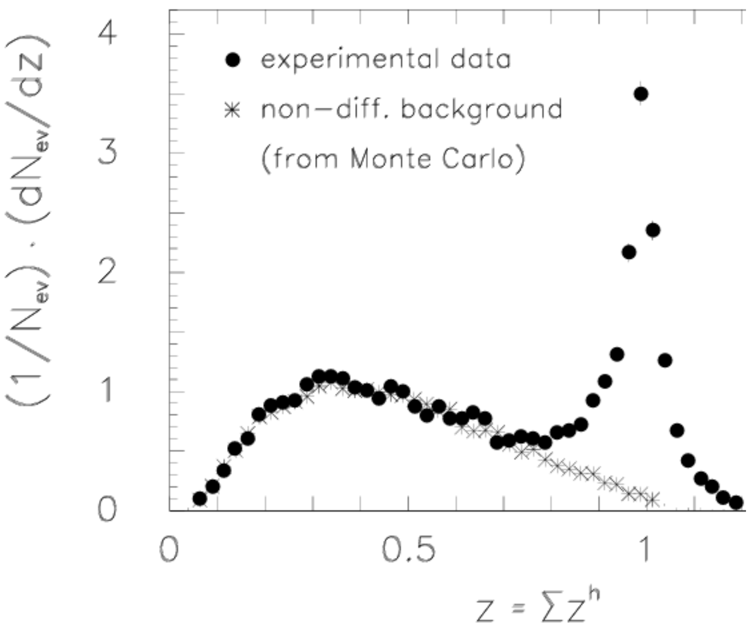
Figure 11.6: The ratio of the diffractive cross section σ^{diff}, integrated over the bin width $M_a < M_X < M_b$, and the total $\gamma^* p$ cross section σ^{tot} is shown as a function of W for different bins of M_X and Q^2. The dotted lines indicate the average values of $\sigma^{diff}/\sigma^{tot}$ in the measured W region for each bin in Q^2 and M_X.

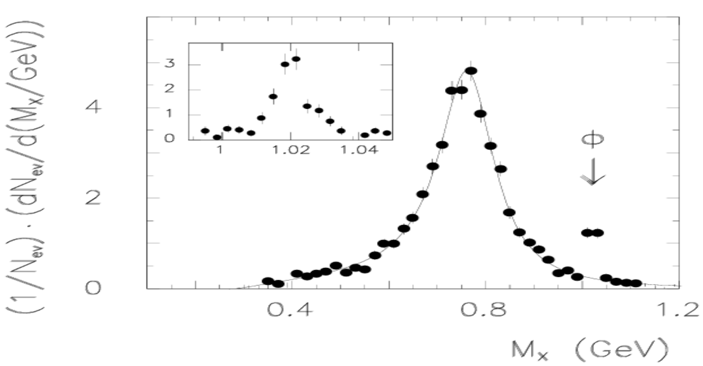
No dependence of DDIS/DIS on W, decrease with Q^2 indicating the VMs can be the main contributor
At lowest M_X seem to be ~$1/Q^2$, at higher M_X there seem to be no Q^2-dependence

Measurements of rho: E665

https://inspirehep.net/files/58cfd687d71fffa160843650967cdd61

Z.Phys.C 74 (1997) 237-261





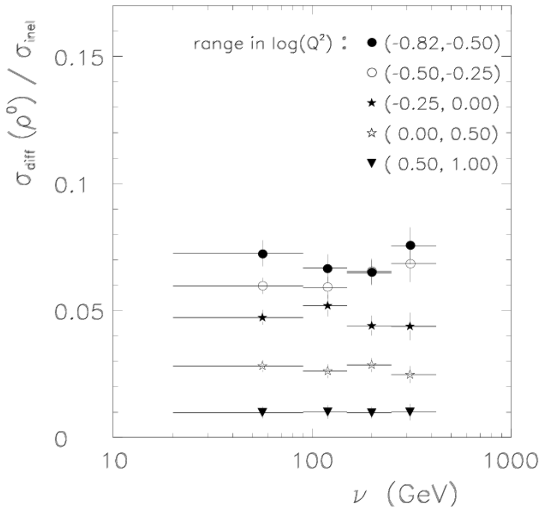


Fig. 21. Th
bins of Q^2

3. What the acceptance magnitude looked like

From those thesis MC plots (typical values):

cosθ	acceptance (approx)
−1	~0.2–0.3
−0.5	~0.6
0	~1
0.5	~0.6
1	~0.2–0.3

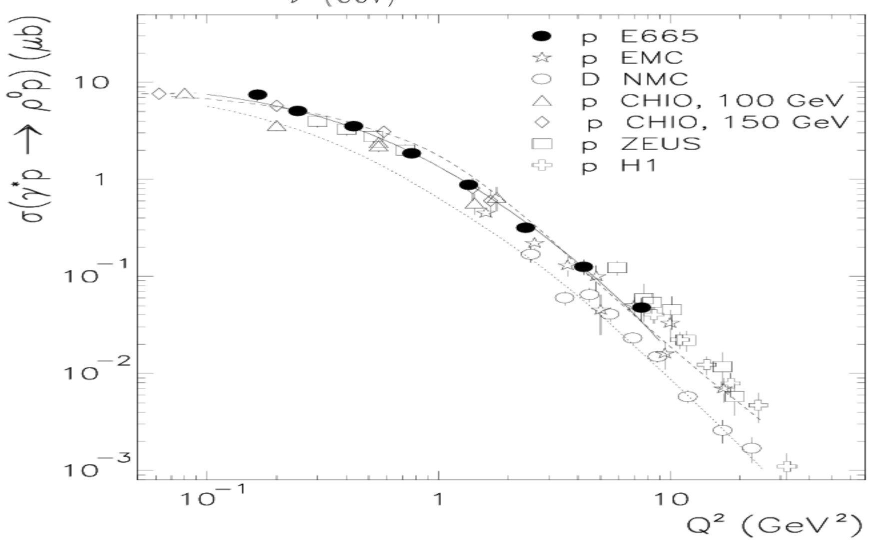


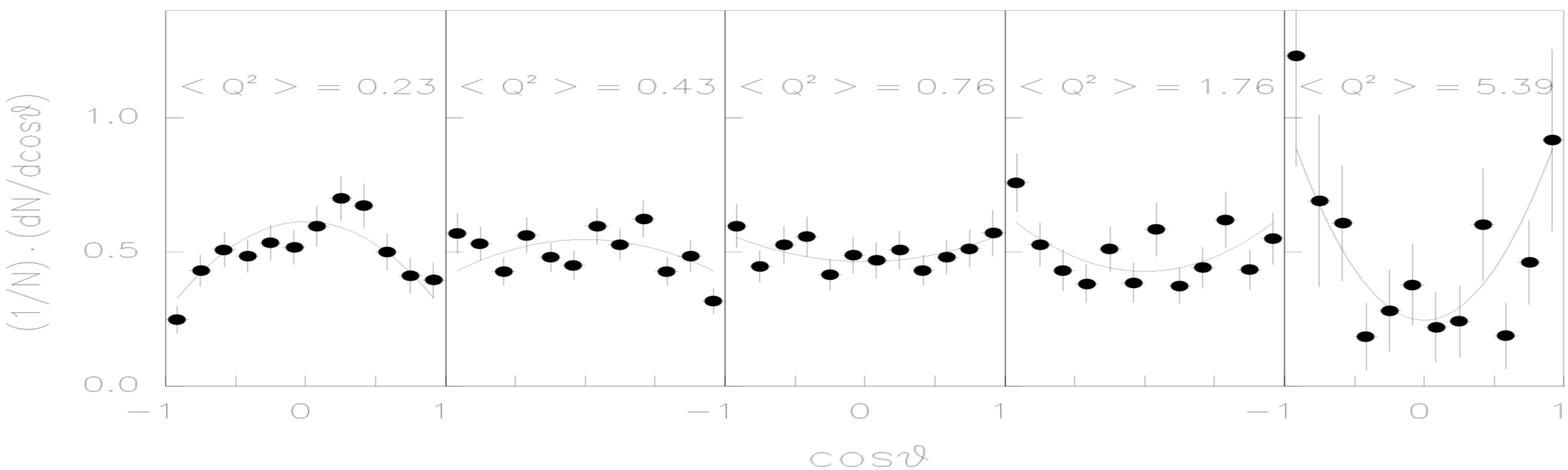
Fig. 23. $\sigma_{diff}(\gamma^* p \to \rho^0 p)$ as a function of Q^2: E665 data (full circles) and the results from the CHIO [22], EMC [24], NMC [26], H1 [16] and ZEUS [15, 17, 18] experiments. The solid line represents

Measurements of rho: E665

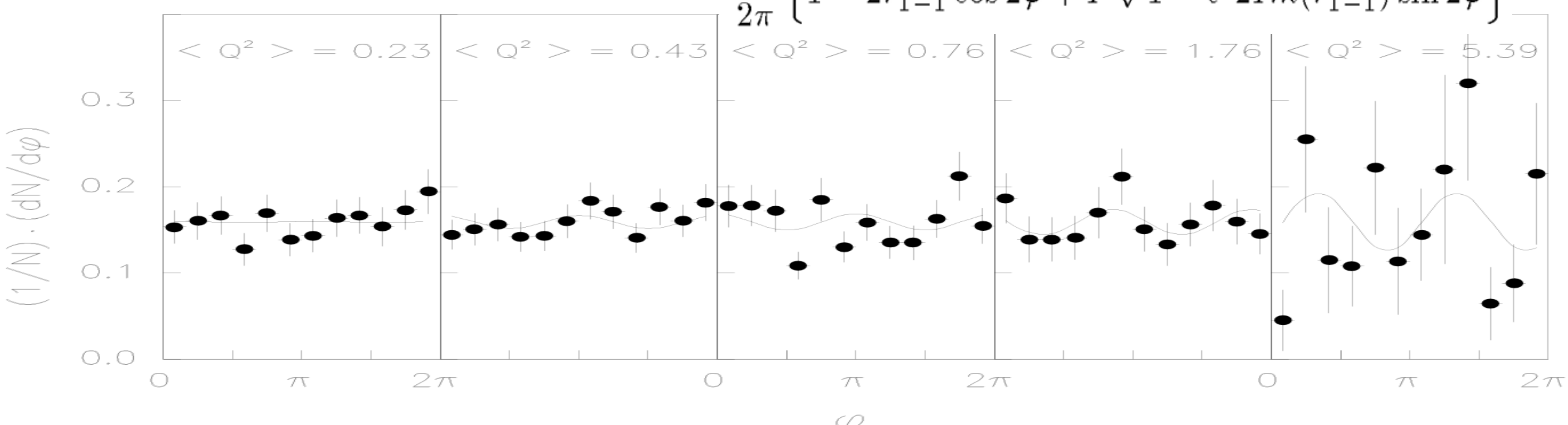
https://inspirehep.net/files/58cfd687d71fffa160843650967cdd61

Z.Phys.C 74 (1997) 237-261

$$\frac{dN}{d\cos\vartheta} \approx \frac{3}{4}\left\{1 - r_{00}^{04} + \left(3r_{00}^{04} - 1\right)\cos^2\vartheta\right\}$$



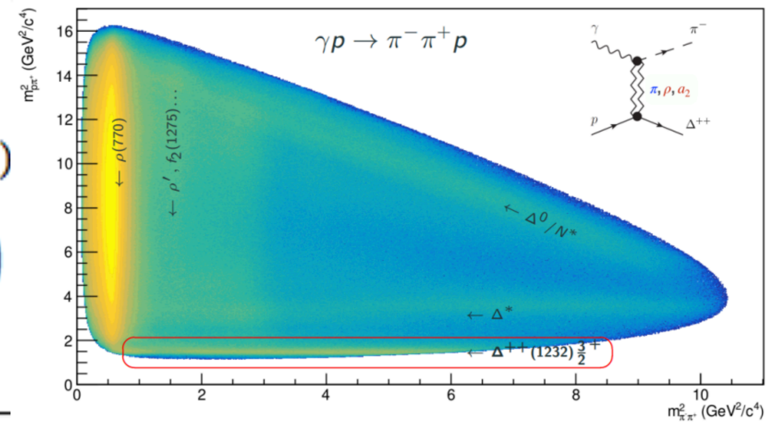
$$\frac{1}{2\pi}\left\{1 - 2r_{1-1}^{04}\cos 2\varphi + P\sqrt{1-\epsilon^2}\,2Im(r_{1-1}^{3})\sin 2\varphi\right\}$$

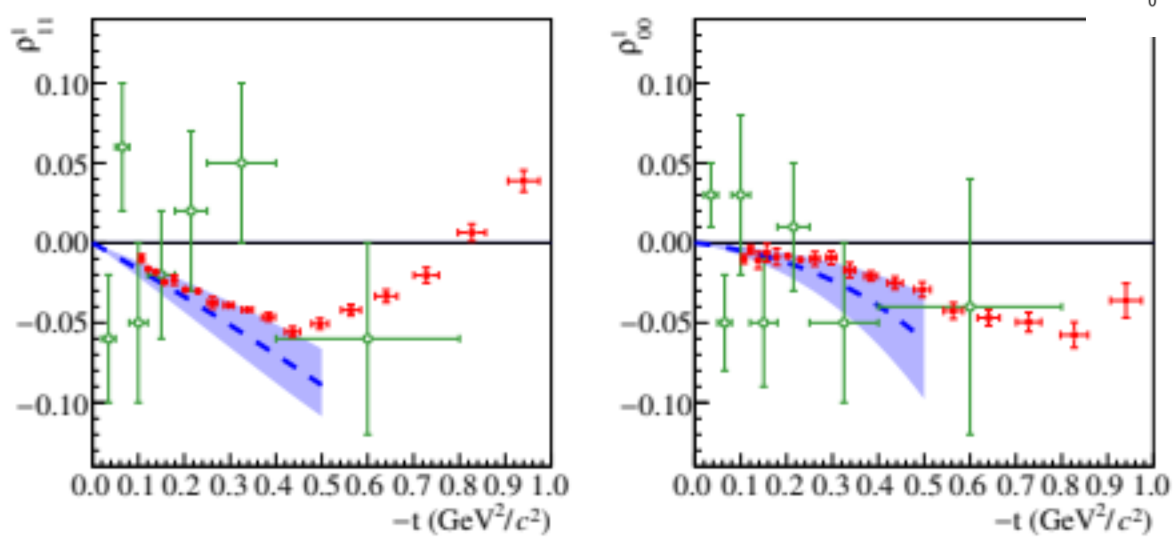


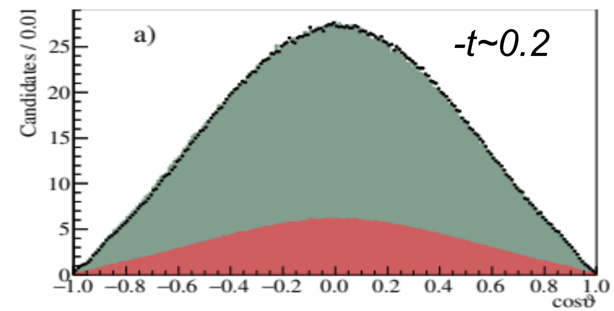
SDMEs from photoproduction

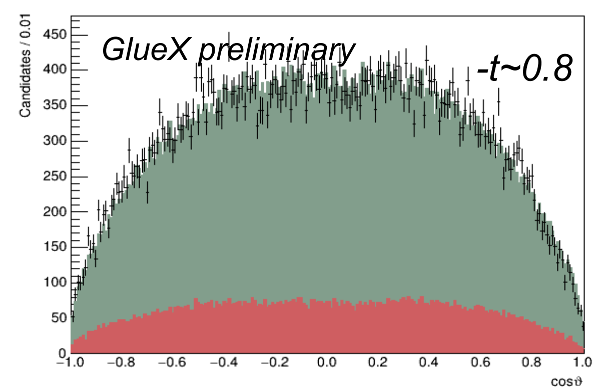
JLab/GlueX, S. Adhikari et al, Phys.Rev.C 108 (2023), 055204: ArXiv:2305.09047

$$W^1(\cos\vartheta,\varphi) = \frac{3}{4\pi}\Big(\rho^1_{11}\sin^2\vartheta + \rho^1_{00}\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^1_{10}\sin 2\vartheta\cos\varphi - \rho^1_{1-1}\sin^2\vartheta\cos 2\varphi\Big) \quad (11)$$





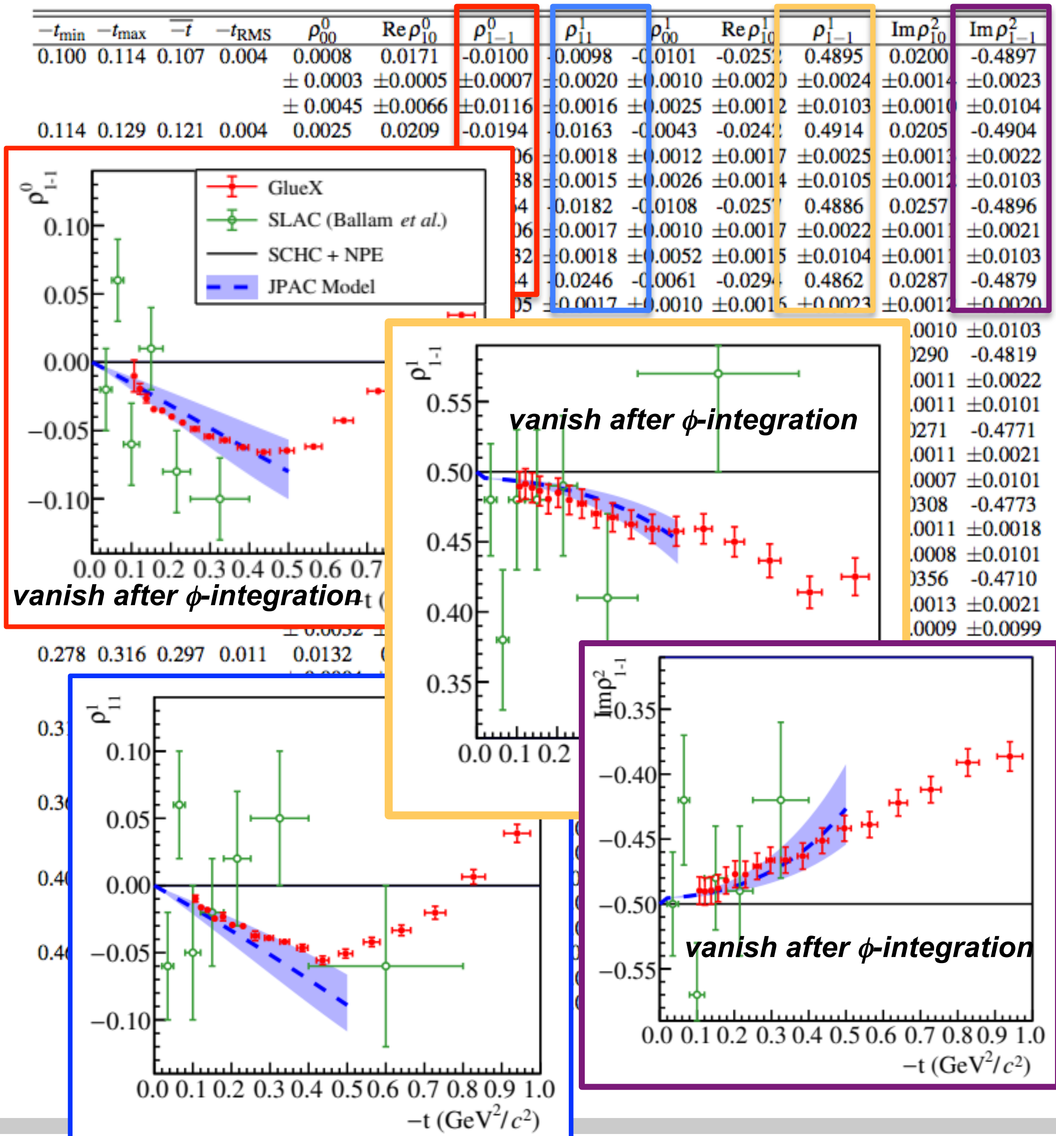


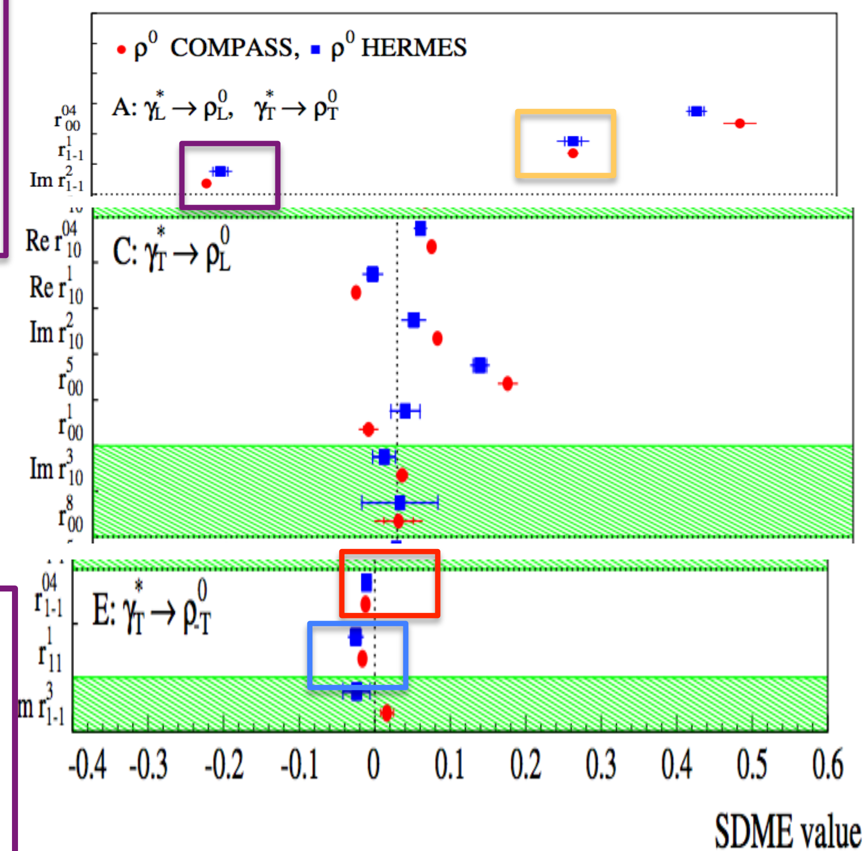


While at small t (dominant part of the statistics) the transverse rhos dominate, at large t the contribution from transverse photons going to longitudinal rho becomes more significant

SDMEs from photoproduction

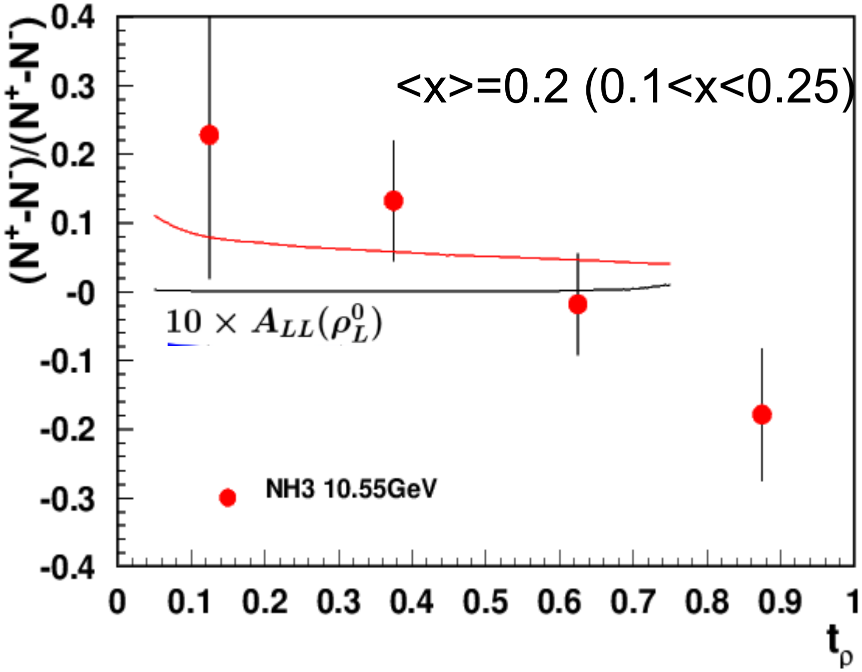
JLab/GlueX, S. Adhikari et al: https://arxiv.org/pdf/2305.09047

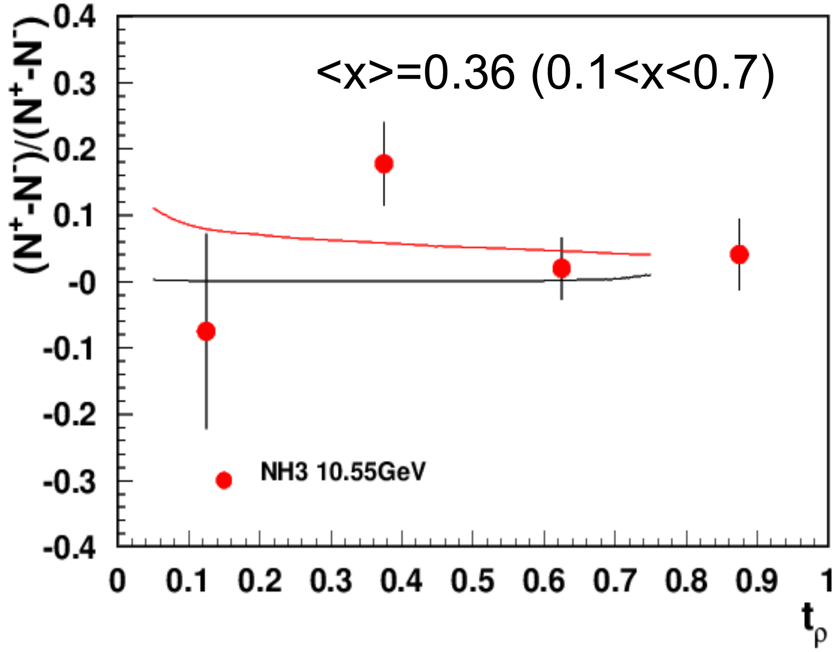




The SDMEs for transverse photons with $\sin^2\theta$ (to transverse rho?) at $Q^2>0$ seem to be smaller (detailed comparison vs Q^2).

What is the gluon polarization at large x?



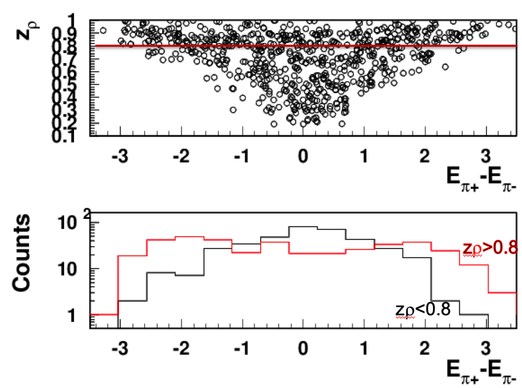


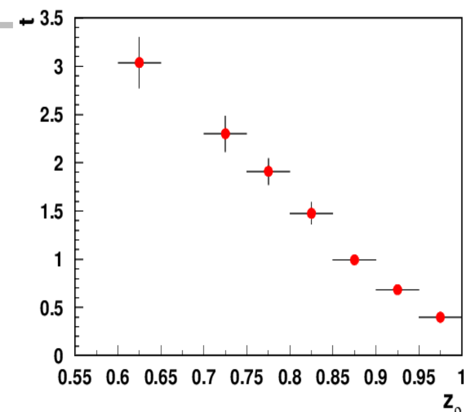
Curves calculated by Kroll&Goloskokov (x=0.12)

The full sample would allow fine binning in

and separation of longitudinal/transverse ρ

Polarization of rho

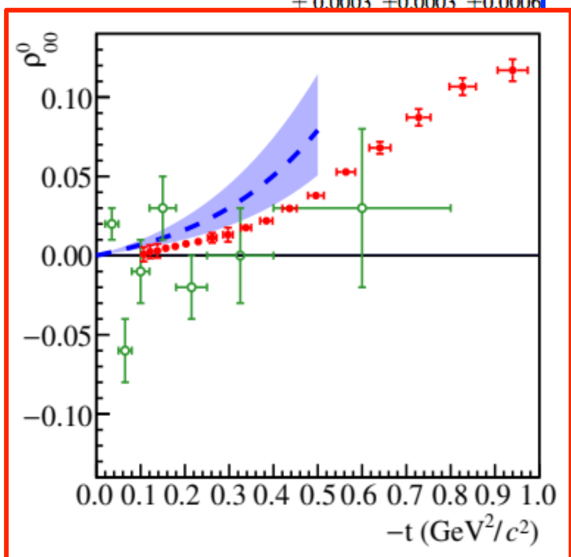


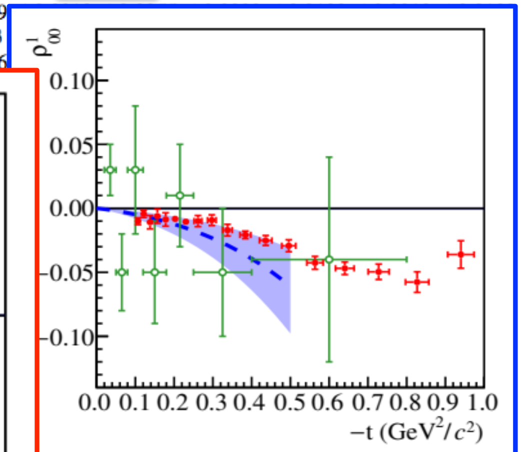


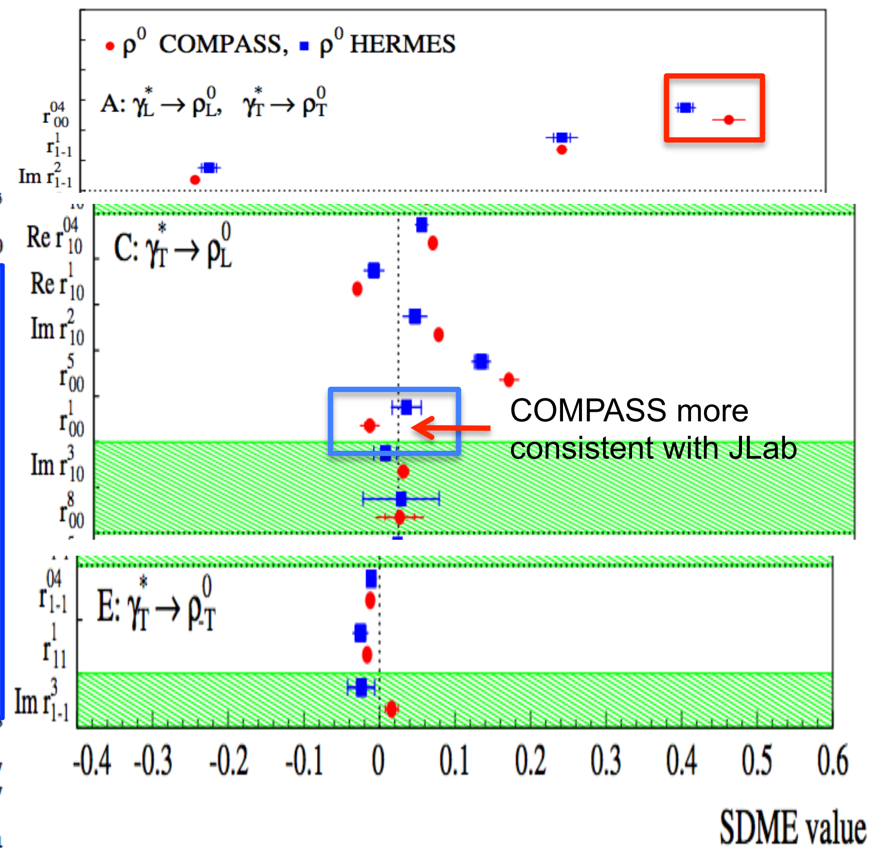
SDMEs from photoproduction

JLab/GlueX, S. Adhikari et al: https://arxiv.org/pdf/2305.09047

$-t_{min}$	$-t_{max}$	$-\overline{t}$	$-t_{RMS}$	ρ^0_{00}	$\mathrm{Re}\,\rho^0_{10}$	ρ^0_{1-1}	ρ^1_{11}	ρ^1_{00}	$\mathrm{Re}\,\rho^1_{10}$	ρ^1_{1-1}	$\mathrm{Im}\,\rho^2_{10}$	$\mathrm{Im}\,\rho^2_{1-1}$
0.100	0.114	0.107	0.004	0.0008	0.0171	-0.0100	-0.0098	-0.0101	-0.0252	0.4895	0.0200	-0.4897
				± 0.0003	±0.0005	±0.0007	±0.0020	±0.0010	±0.0020	±0.0024	±0.0014	±0.002
				± 0.0045	±0.0066	±0.0116	±0.0016	±0.0025	±0.0012	±0.0103	±0.0010	±0.010
0.114	0.129	0.121	0.004	0.0025	0.0209	-0.0194	-0.0163	-0.0043	-0.0242	0.4914	0.0205	-0.4904
				± 0.0003	±0.0004	±0.0006	±0.0018	±0.0012	±0.0017	±0.0025	±0.0013	±0.002
				± 0.0042	±0.0030	±0.0038	±0.0015	±0.0026	±0.0014	±0.0105	±0.0012	±0.010
0.129	0.147	0.138	0.005	0.0030	0.0244	-0.0264	-0.0182	-0.0108	-0.0257	0.4886	0.0257	-0.4896
				± 0.0003	±0.0004	±0.0006	±0.0017	±0.0010	±0.0017	±0.0022	±0.0011	±0.002
				± 0.0044	±0.0023	±0.0032	±0.0018	±0.0052	±0.0015	±0.0104	±0.0011	±0.0103
0.147	0.167	0.157	0.006	0.0047	0.0283	-0.0344	-0.0246	-0.0061	-0.0294	0.4862	0.0287	-0.4879
				± 0.0002	±0.0004	±0.0005	±0.0017	±0.0010	±0.0016	±0.0023	±0.0012	±0.0020
				± 0.0022	±0.0011	±0.0009						
0.167	0.190	0.178	0.007	0.0058	0.0295	-0.0353						
				± 0.0003	±0.0003	±0.0006						
							.0464	-0.0208	-0.0449	0.4624	0.0378	-0.4631
							.0022	±0.0017	±0.0017	±0.0031	±0.0014	±0.0027
							.0014	±0.0025	±0.0010	±0.0097	±0.0011	±0.0097
							.0557	-0.0251	-0.0507	0.4592	0.0366	-0.4513
							.0026	±0.0020	±0.0020	±0.0036	±0.0017	±0.0024
							.0018	±0.0033	±0.0016	±0.0098	±0.0012	±0.0095
0.464	0.527	0.496	0.018	0.0379	0.0480	-0.0647	-0.0507	-0.0293	-0.0519	0.4575	0.0356	-0.4417
				± 0.0006	±0.0005	±0.0008	±0.0029	±0.0029	±0.0020	±0.0042	±0.0019	±0.0033
				± 0.0022	±0.0019	±0.0013	±0.0017	±0.0037	±0.0015	±0.0097	±0.0014	±0.0093







The SDMEs for transverse photons with $\cos^2\theta$ (to longitudinal rho?) at $Q^2>0$ different, in particular r_{00}^1 (relevant for BM).

Understanding exclusive rhos and SDME validations

$$\mathcal{W}^U(\Phi,\phi,\cos\Theta)$$

$$+ \quad \sqrt{2\epsilon(1+\epsilon)}\cos\Phi\left(r^5_{11}\sin^2\Theta + r^5_{00}\cos^2\Theta\right.$$

corr. with r^5_{1-1} , r^6_{1-1} ,r^5_{00} (Hermes, COMPASS)

$$\mathcal{W}^L(\Phi,\phi,\cos\Theta)$$

$$+ \quad \sqrt{2\epsilon(1-\epsilon)}\sin\Phi\left(r^8_{11}\sin^2\Theta + r^8_{00}\cos^2\Theta\right.$$

$$\left. -\sqrt{2}\mathrm{Re}\{r^8_{10}\}\sin 2\Theta\cos\phi - r^8_{1-1}\sin^2\Theta\cos 2\phi\right)\Big].$$

corr. with r^8_{1-1} ,r^8_{00} (Hermes, COMPASS)

$$\gamma^*_L \to \rho^0_T, \quad \tau_{10} \approx \frac{\sqrt{(r^5_{11} + \mathrm{Im}\{r^6_{1-1}\})^2 + (\mathrm{Im}\{r^7_{1-1}\} - r^8_{11})^2}}{\sqrt{2(r^1_{1-1} - \mathrm{Im}\{r^2_{1-1}\})}}$$

$$\mathrm{Im}(u^{++}_{0+} + u^{--}_{0+}) = \sqrt{2}\, r^8_{11} \qquad \mathrm{Re}(u^{++}_{0+} + u^{--}_{0+}) = -\sqrt{2}\, r^5_{11}$$

Since the decay angle is correlated with the polarization of the rho, then r_{11}^8 and r_{11}^5 will be responsible for transverse rho (no Cahn?)

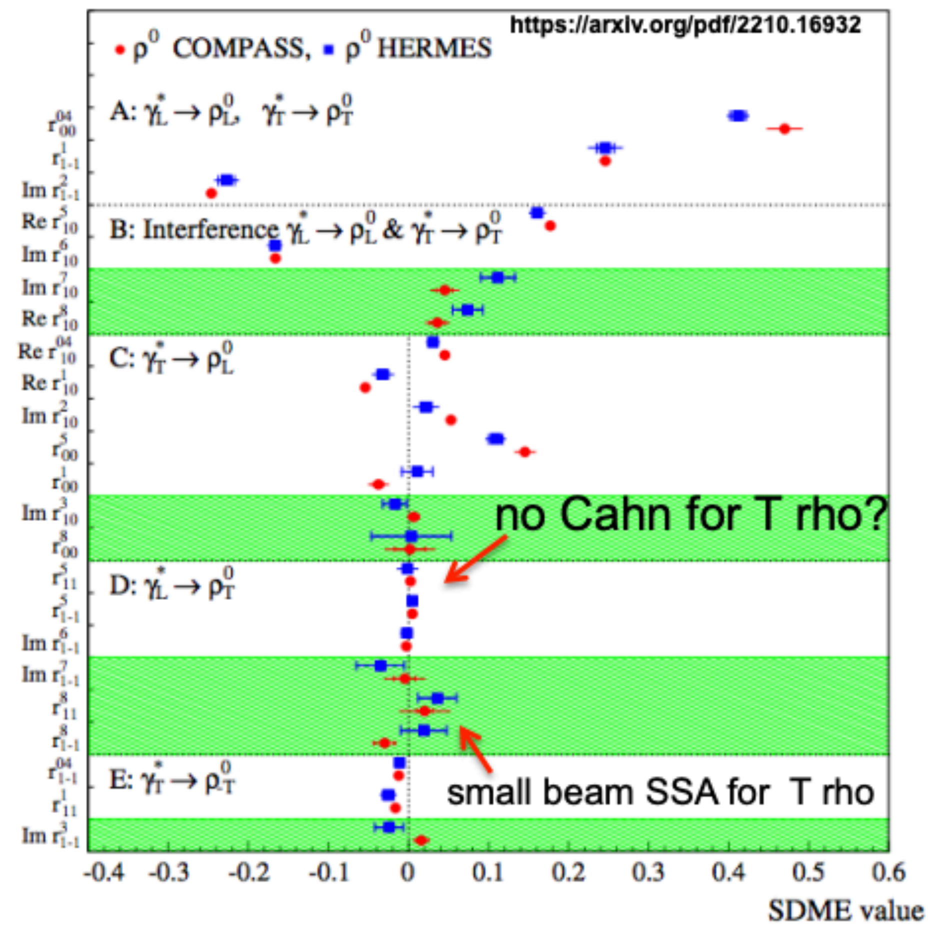


Fig. 12: Comparison of the 23 SDMEs for exclusive ρ^0 leptoproduction on the proton extracted in the entire kinematic regions of the HERMES and COMPASS experiments. For HERMES the average kinematic values are $\langle Q^2\rangle = 1.96$ (GeV/c)^2, $\langle W\rangle = 4.8$ GeV/c^2, $\langle |t'|\rangle = 0.13$, while those for COMPASS are $\langle Q^2\rangle = 2.40$ (GeV/c)^2, $\langle W\rangle = 9.9$ GeV/c^2, $\langle p_T^2\rangle = 0.18$ (GeV/c)^2. Inner error bars represent statistical uncertainties and outer ones statistical and systematic uncertainties added in quadrature. Unpolarised (polarised) SDMEs are displayed in unshaded (shaded) areas.

VM contributions

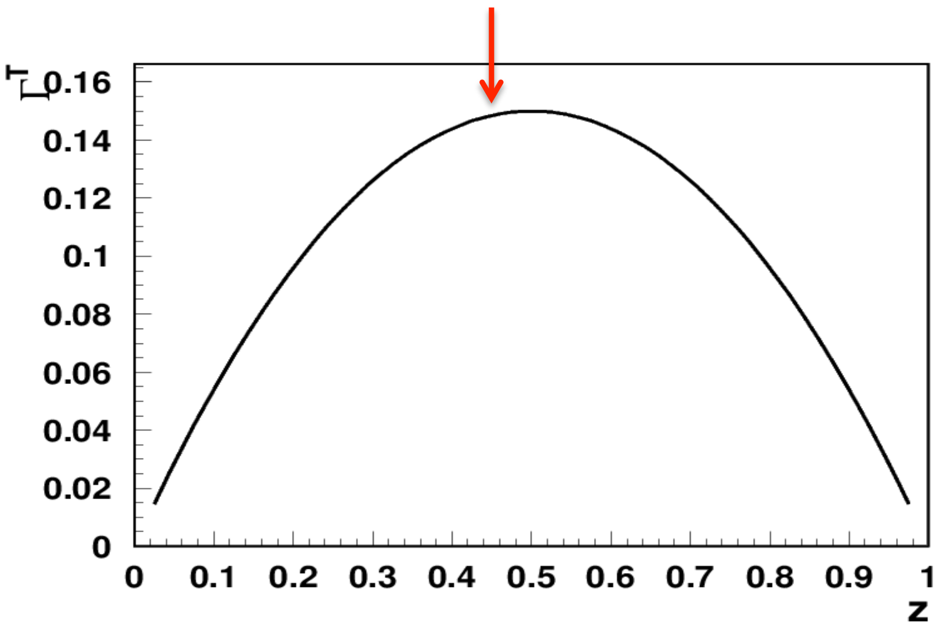
$\rho^0 \to \pi^+\pi^-$

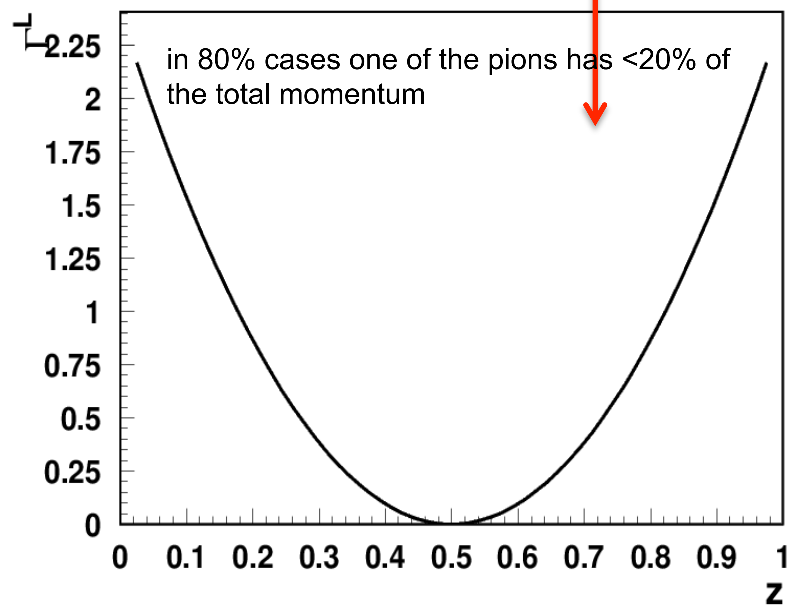
Yuri Kovchegov

$$k_T^2 = z(1-z)\, M_\rho^2 - m_\pi^2.$$

$$\Gamma^L_{\rho^0\to\pi^+\pi^-} \sim |M^L_{\rho^0\to\pi^+\pi^-}|^2 \sim \left| \frac{k_\perp^2 + m_\pi^2}{M_\rho} \left(\frac{1}{z} - \frac{1}{1-z} \right) + M_\rho\,(1-2z) \right|^2 = 4\, M_\rho^2\,(1-2z)^2.$$

$$\Gamma^T_{\rho^0\to\pi^+\pi^-} \sim k_T^2 \sim z(1-z)\, M_\rho^2 - m_\pi^2$$





Asymmetric decays of longitudinal rho lead to much smaller acceptance
Similar but inverted distributions for e+e- decays

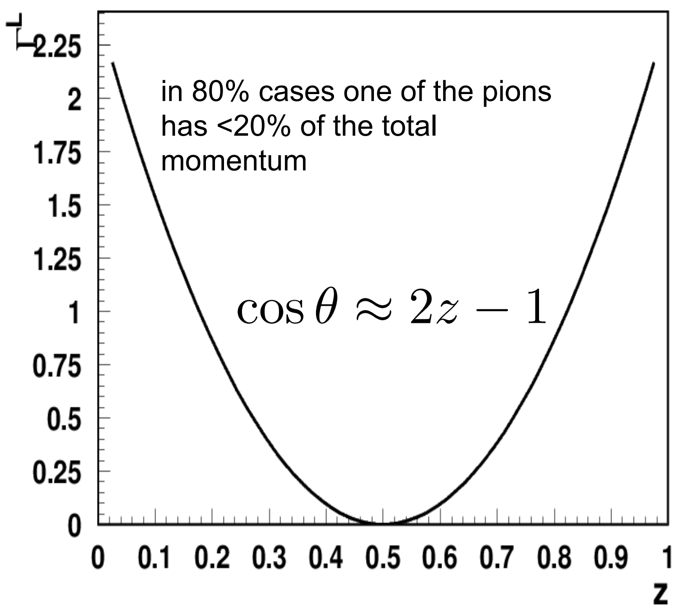
VM contributions

$\rho^0 \to \pi^+\pi^-$

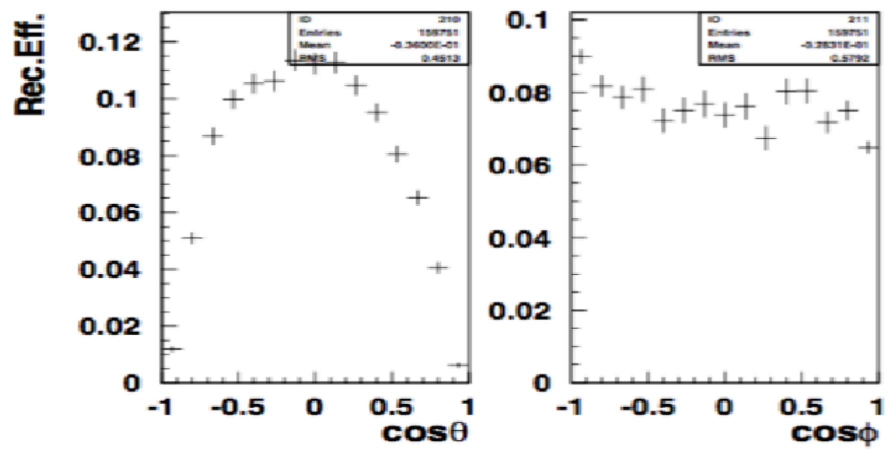
Yuri Kovchegov

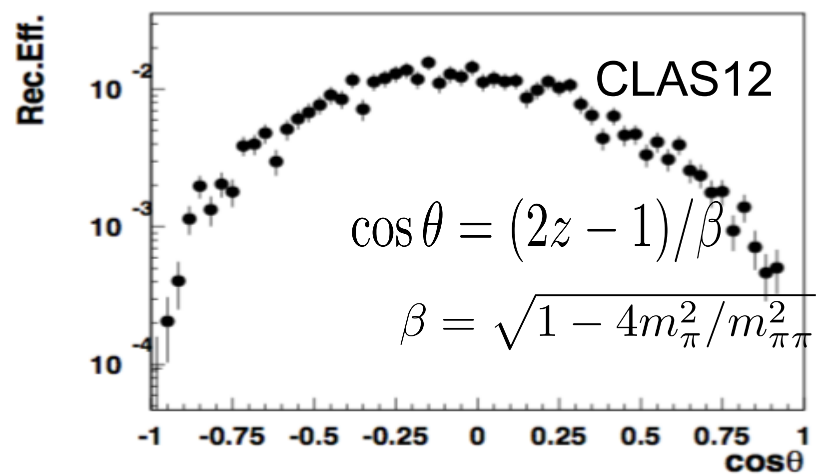
$$k_T^2 = z(1-z)\,M_\rho^2 - m_\pi^2.$$

$$\Gamma^L_{\rho^0\to\pi^+\pi^-} \sim |M^L_{\rho^0\to\pi^+\pi^-}|^2 \sim \left|\frac{k_\perp^2+m_\pi^2}{M_\rho}\left(\frac{1}{z}-\frac{1}{1-z}\right)+M_\rho\,(1-2z)\right|^2 = 4\,M_\rho^2\,(1-2z)^2.$$



Asymmetric decays of longitudinal rho lead to much smaller acceptance, more than order of magnitude

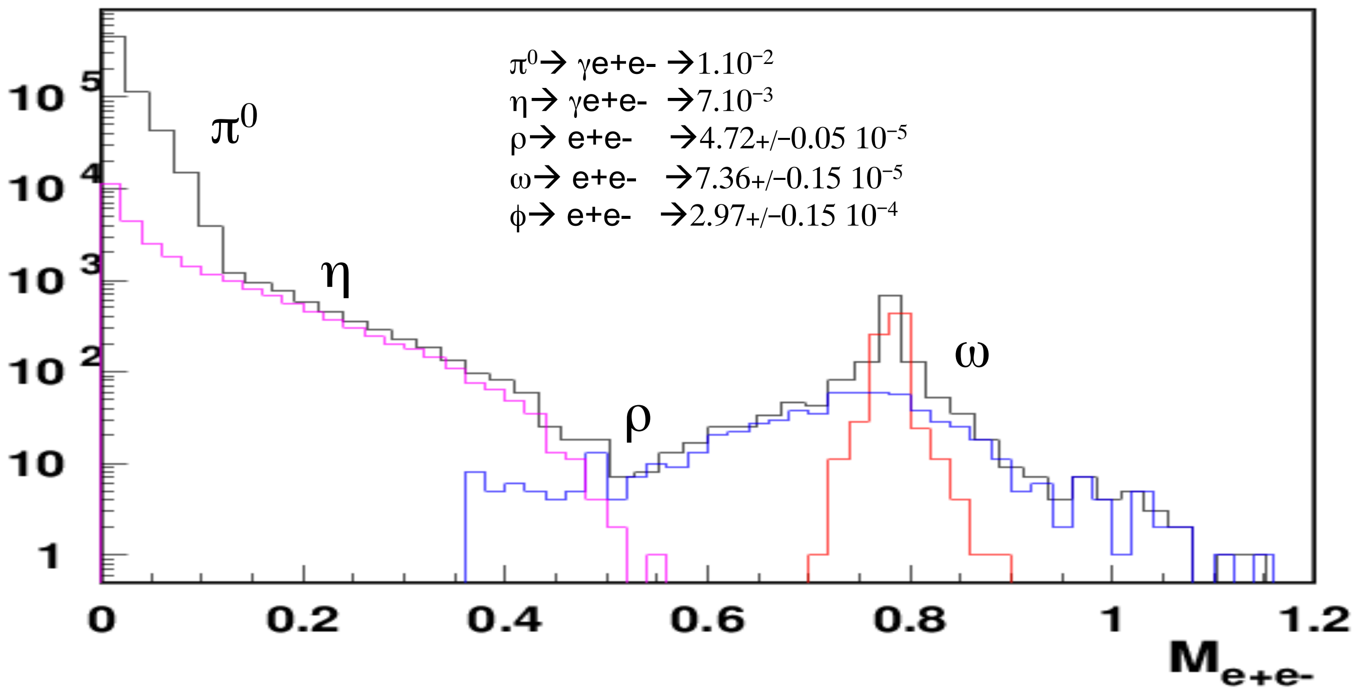




Using e+e- to estimate vector mesons

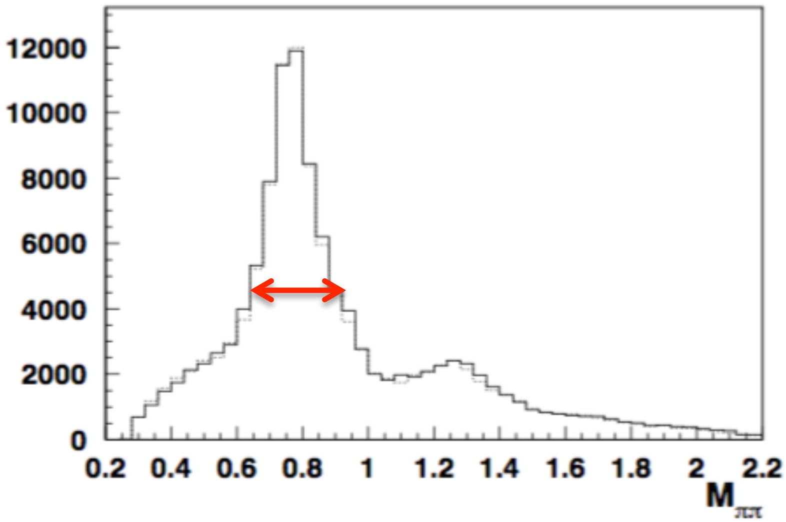
The invariant mass of dihadrons is contaminated by other vector mesons, with shape not changing significantly with hadronization fraction to spin-1 vs spin-0 mesons

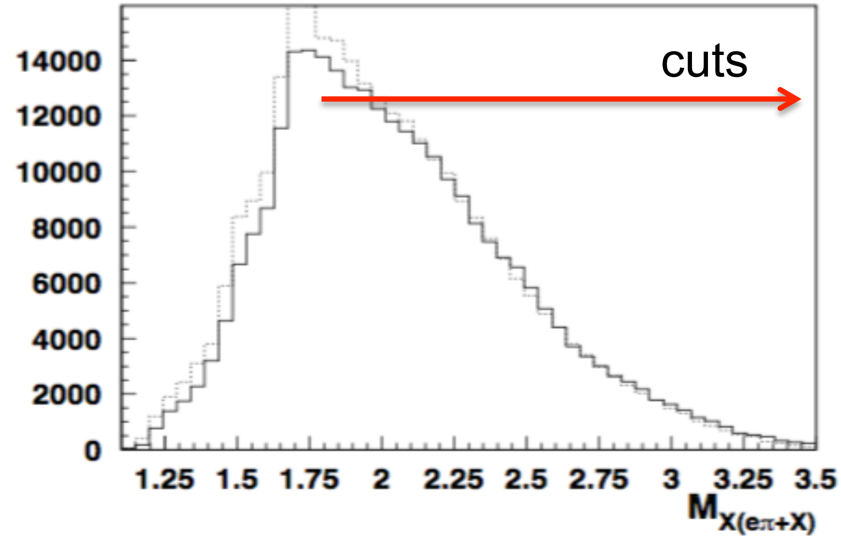
decays of π and η are kinematically separeated from ω and ρ^0

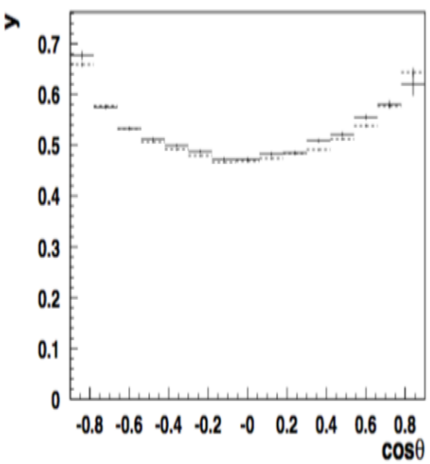


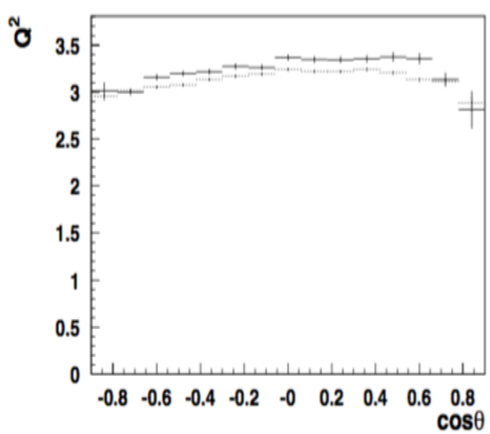
Vector meson per electron can be independently estimated from ep→e'e+e-X
Significant fraction of VM may affect DY studies.

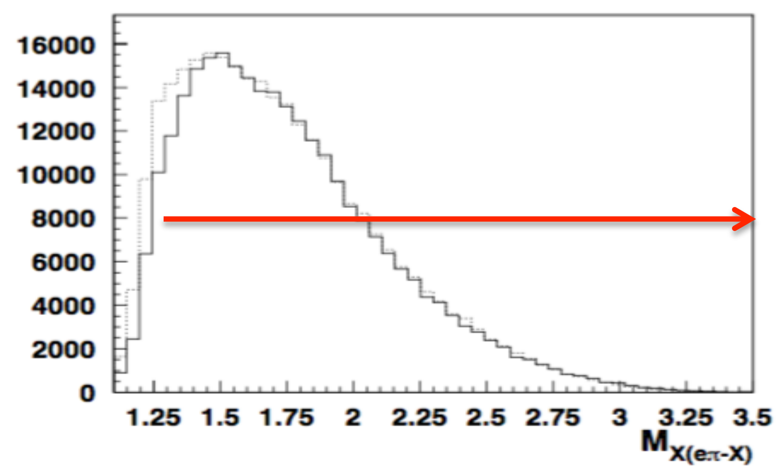
supporting plots







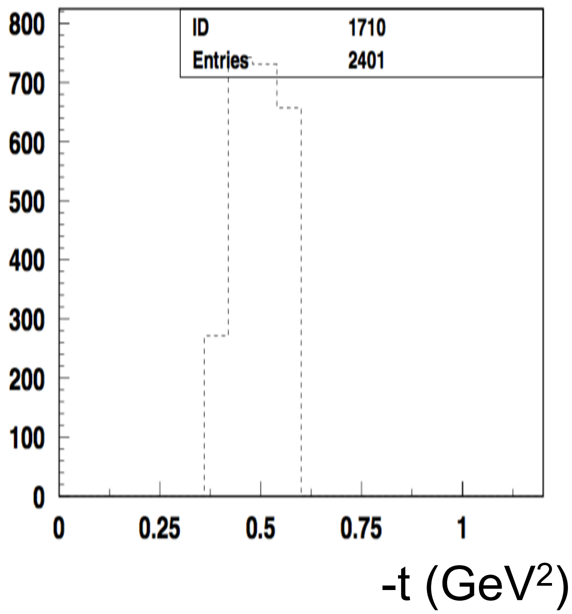


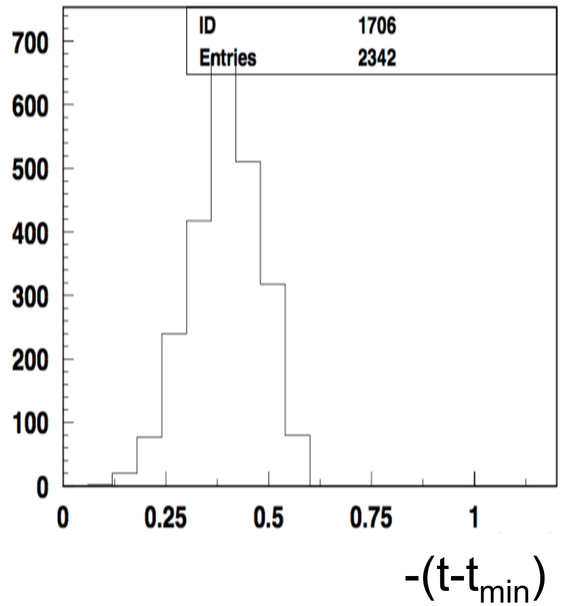


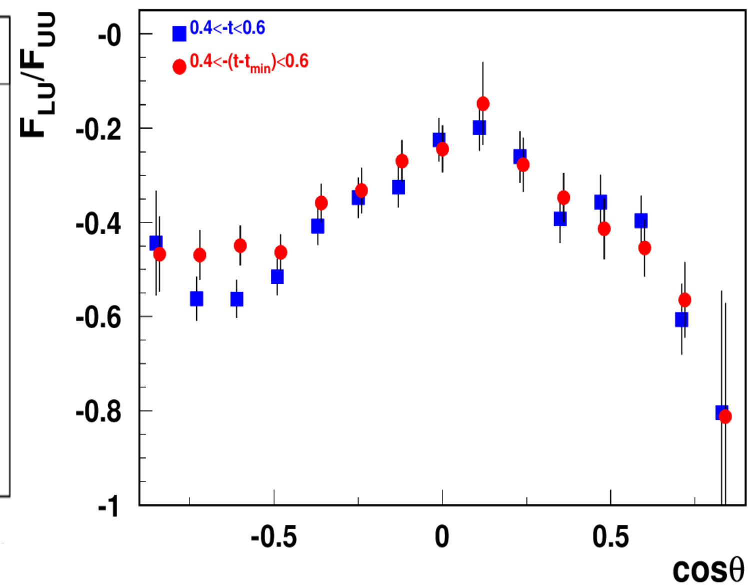
RGC-Fall and RGA inbending 10.6 consistent

t vs $t\text{-}t_{min}$

bin I t, -0.6<t<-0.4

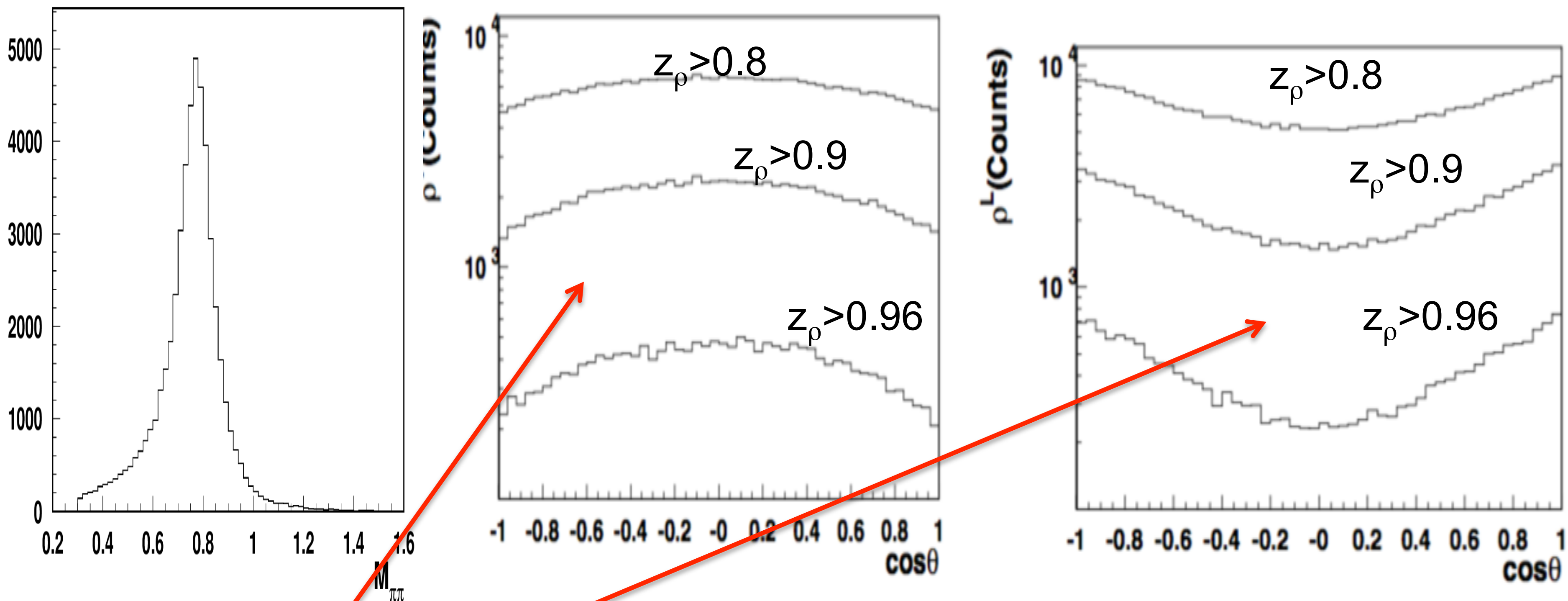






Stringspinner rhos

$|GL/GT|=0$ -> $fL=0:\theta_{LT}=0$ $|GL/GT|=20$ -> $fL=0.995\theta_{LT}=0$



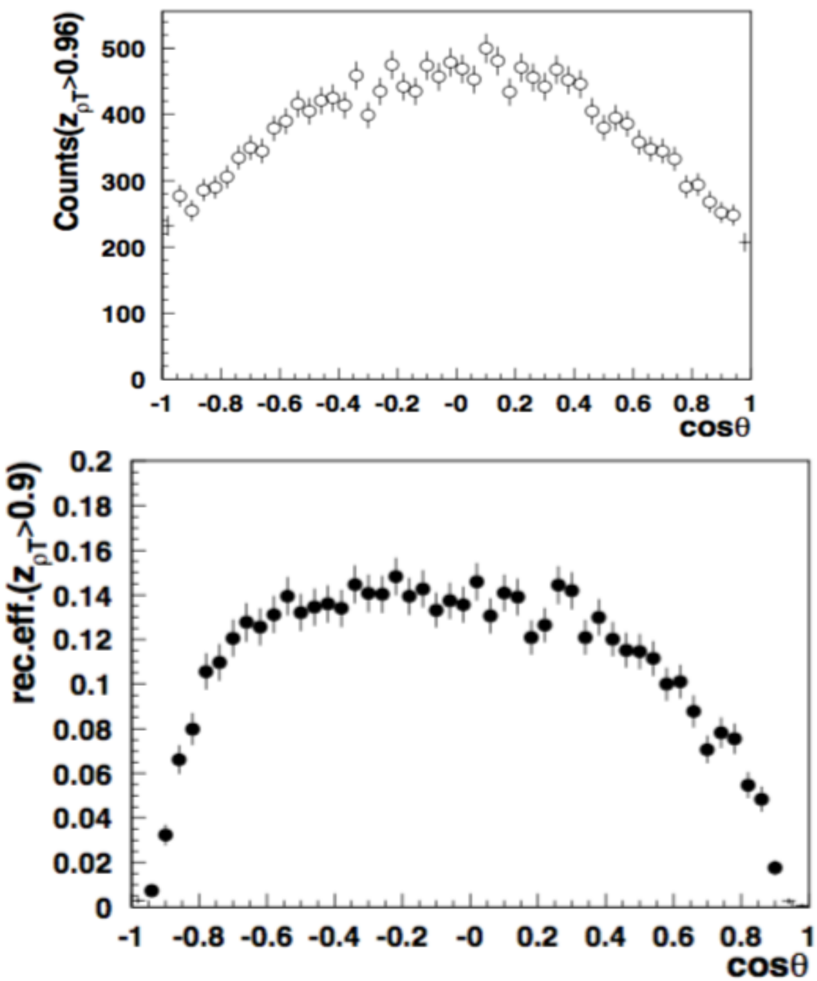
The pedestal in addition to $\cos^2\theta$ for longitudinal rho and $\sin^2\theta$ for transverse disappears for $z\rightarrow1$. What exactly is that pedestal?

- the more you sweat in times of peace the less you bleed in war

Monte Carlo simulation is crucial for *understanding* of systematics of all steps and assumptions used in extraction of complex 3D nucleon structure

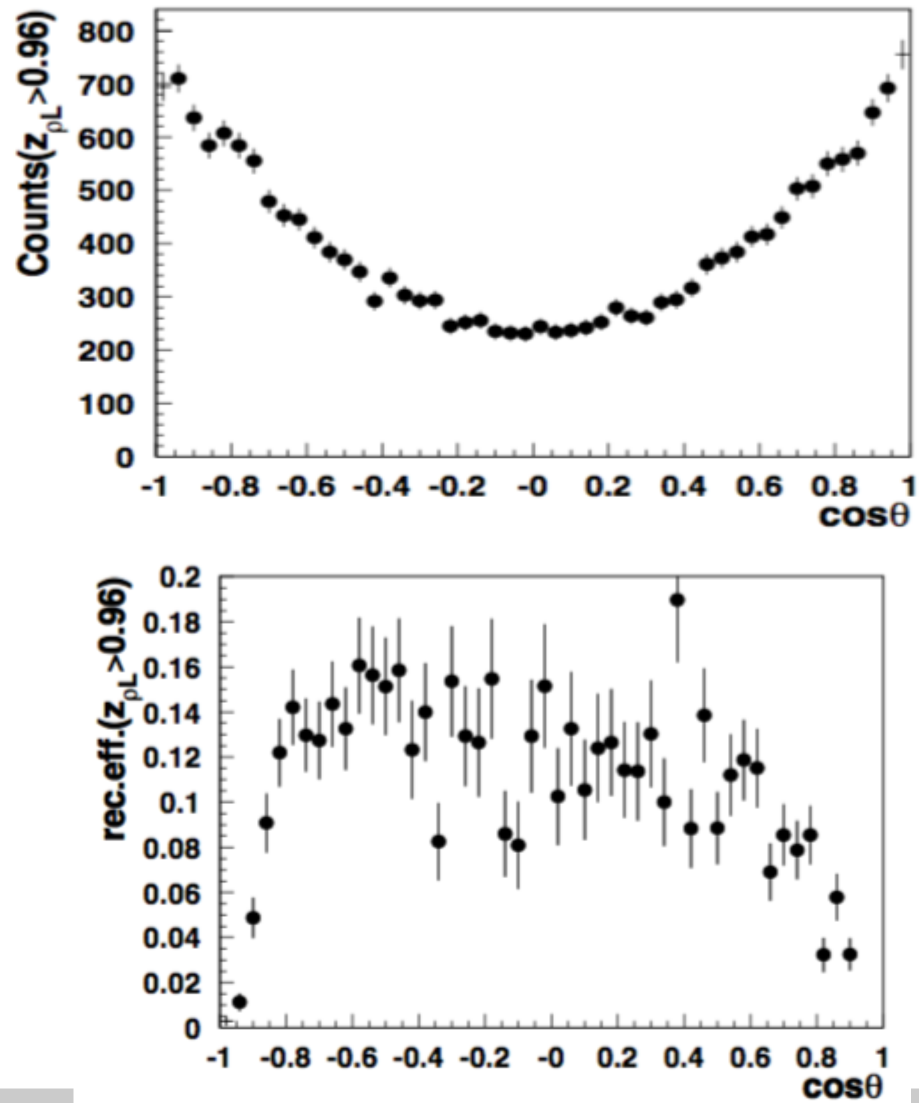
Stringspinner: rhos cosθ

|GL/GT|=0 -> fL=0:θ_{LT}=0



Strong suppression for asymmetric decays

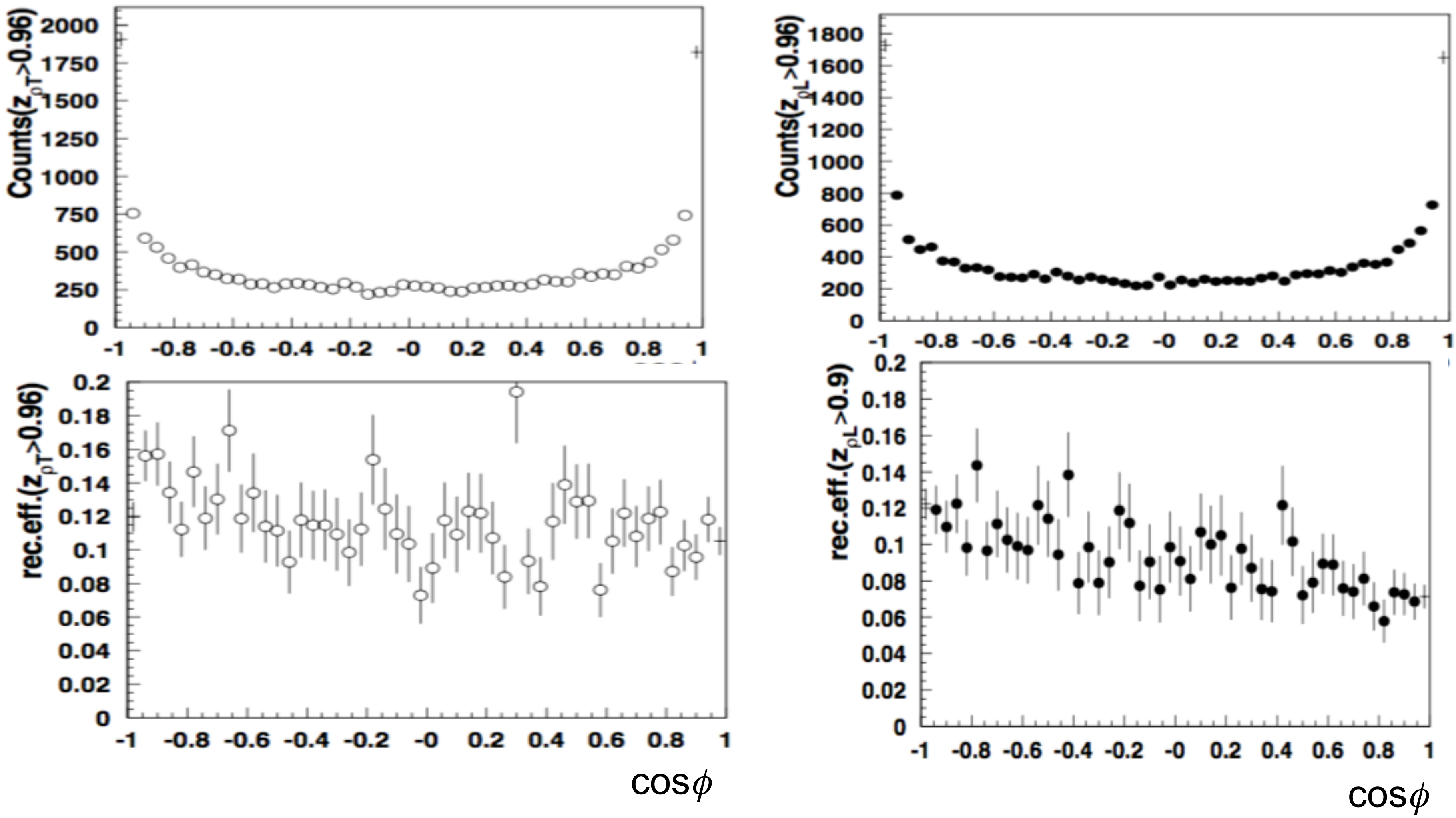
|GL/GT|=20 -> fL=0.995θ_{LT}=0



Stringspinner: rho decay plane phi

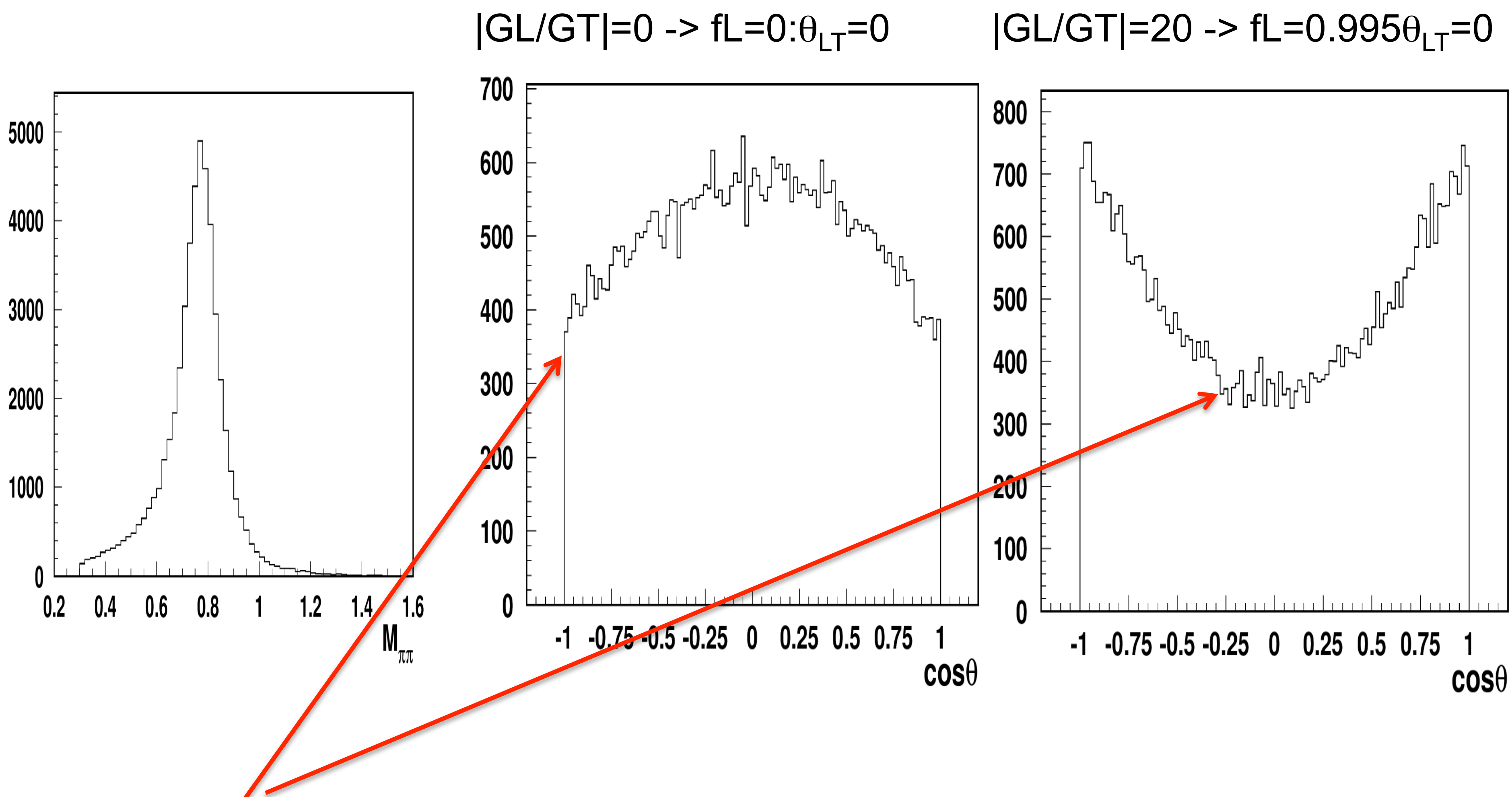
|GL/GT|=0 -> fL=0:θ_{lT}=0

|GL/GT|=20 -> fL=0.995θ_{LT}=0



Practically no dependence of acceptance on azimuthal angle of decay plane cosϕ

Stringspinner rhos



The pedestal in addition to cos^2\theta for longitudinal rho and sin^2\theta for transverse disappears for z→1. What exactly is that pedestal?

Structure functions case of VMs

Diehl: 0704.1565 $\gamma^*(\mu) + p(\lambda) \to \rho(\nu) + p(\sigma)$

helicities

cross section could be presented in terms of combinations of helicity amplitudes

$$u^{\nu\nu'}_{\mu\mu'} = \tfrac{1}{2}\left(\rho^{\nu\nu'}_{\mu\mu',++} + \rho^{\nu\nu'}_{\mu\mu',--}\right)$$ unpol

$$l^{\nu\nu'}_{\mu\mu'} = \tfrac{1}{2}\left(\rho^{\nu\nu'}_{\mu\mu',++} - \rho^{\nu\nu'}_{\mu\mu',--}\right)$$ long.pol

$$n^{\nu\nu'}_{\mu\mu'} = \tfrac{1}{2}\left(\rho^{\nu\nu'}_{\mu\mu',+-} - \rho^{\nu\nu'}_{\mu\mu',-+}\right)$$ trans.pol

In the forward limit of small t $u^{\nu\nu'}_{\mu\mu'}, l^{\nu\nu'}_{\mu\mu'} \underset{t\to t_0}{\sim} (t_0 - t)^{p/2}$

	matrix elements		$p_{\min}$
	$u^{0\,0}_{++} + \epsilon u^{0\,0}_{0\,0}$		0
	$u^{0+}_{0+} - u^{-0}_{0+}$	$l^{0+}_{0+} - l^{-0}_{0+}$	0
	$u^{++}_{++} + u^{--}_{++} + 2\epsilon u^{++}_{0\,0}$	$l^{++}_{++} + l^{--}_{++}$	0
	u^{-+}_{-+}	l^{-+}_{-+}	0
	$u^{0\,0}_{0+}$	$l^{0\,0}_{0+}$	1
W^{LL}_{LU} →	$u^{0\,0}_{0+}$	$l^{0\,0}_{0+}$	1
	u^{0+}_{-+}	l^{0+}_{-+}	1
W^{TT}_{LU} →	$u^{++}_{0+} + u^{--}_{0+}$	$l^{++}_{0+} + l^{--}_{0+}$	1

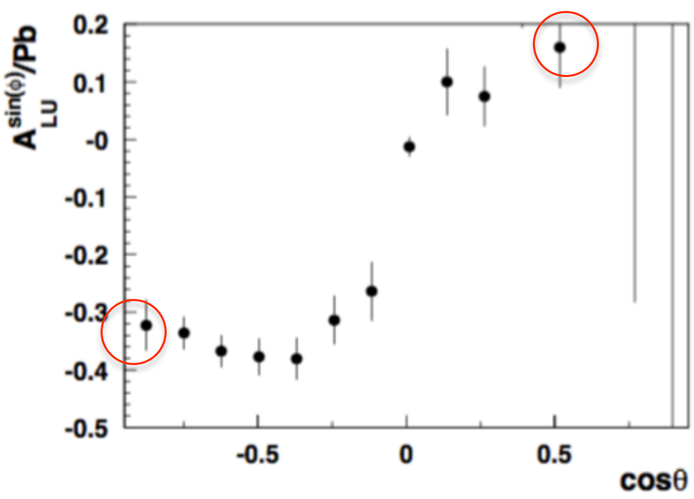
$$n^{\nu\nu'}_{\mu\mu'}, s^{\nu\nu'}_{\mu\mu'} \underset{t\to t_0}{\sim} (t_0 - t)^{q/2}$$

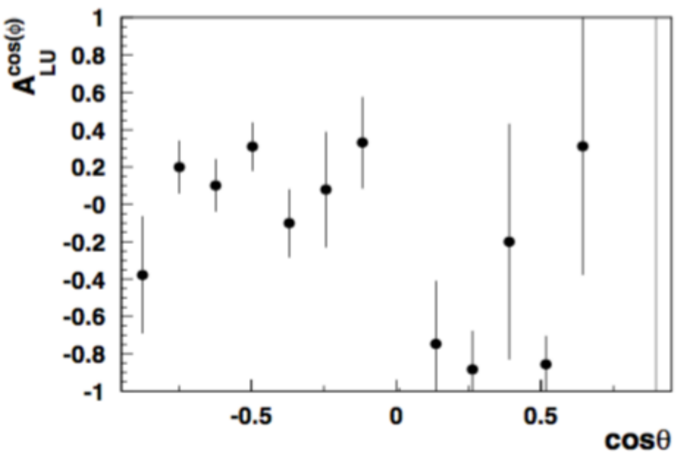
matrix elements		$q_{\min}$
$n^{0\,0}_{++} + \epsilon n^{0\,0}_{0\,0}$		1
$n^{0+}_{0+} - n^{-0}_{0+}$	$s^{0+}_{0+} - s^{-0}_{0+}$	1
$n^{++}_{++} + n^{--}_{++} + 2\epsilon n^{++}_{0\,0}$	$s^{++}_{++} + s^{--}_{++}$	1
n^{-+}_{-+}	s^{-+}_{-+}	1
$n^{0\,0}_{0+}$	$s^{0\,0}_{0+}$	0

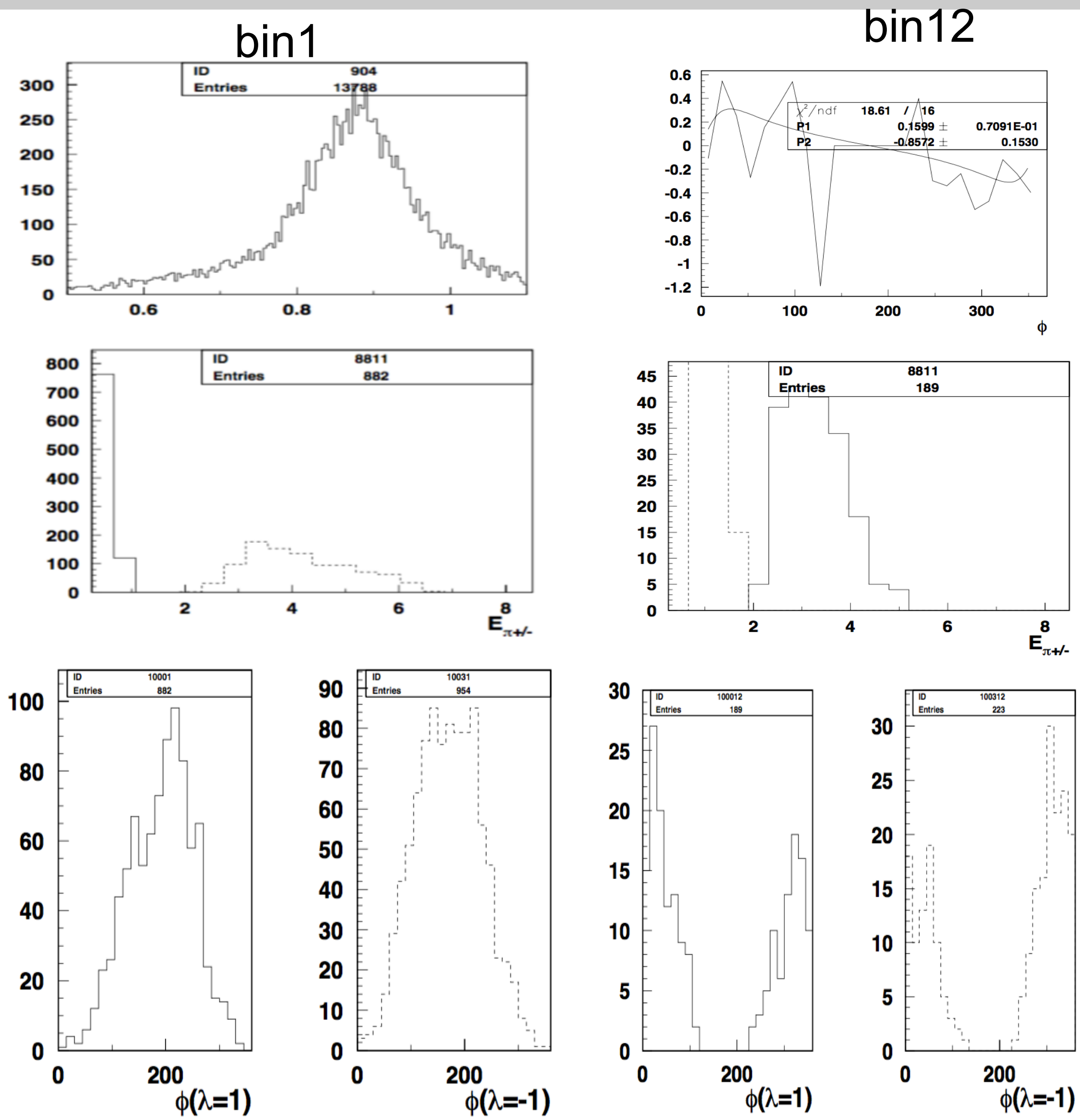
At leading twist the transition from a longitudinal photon to a longitudinal ρ becomes dominant, and transverse spin asymmetry can be defined as

$$\frac{\operatorname{Im} n^{0\,0}_{0\,0}}{u^{0\,0}_{0\,0}} = \frac{\sqrt{t_0 - t}}{M_N}\,\frac{\sqrt{1-\xi^2}\,\operatorname{Im}(\mathcal{E}^*\mathcal{H})}{(1-\xi^2)\,|\mathcal{H}|^2 - \left(\xi^2 + t/(4M_N^2)\right)|\mathcal{E}|^2 - 2\xi^2\operatorname{Re}(\mathcal{E}^*\mathcal{H})}$$

Theta dependence $-0.99 < \cos\varphi < -0.75$



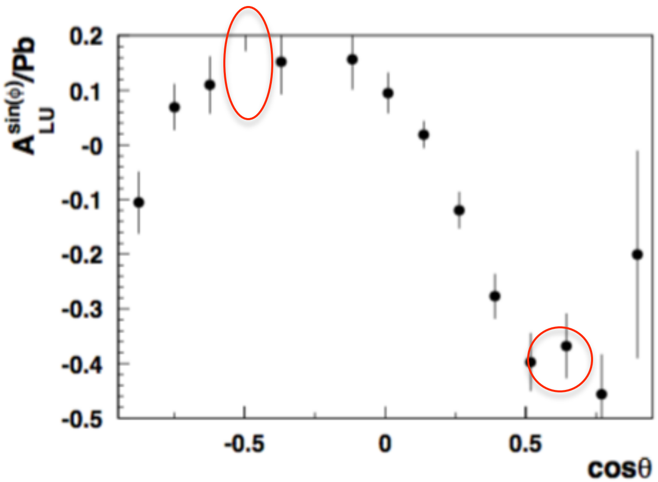


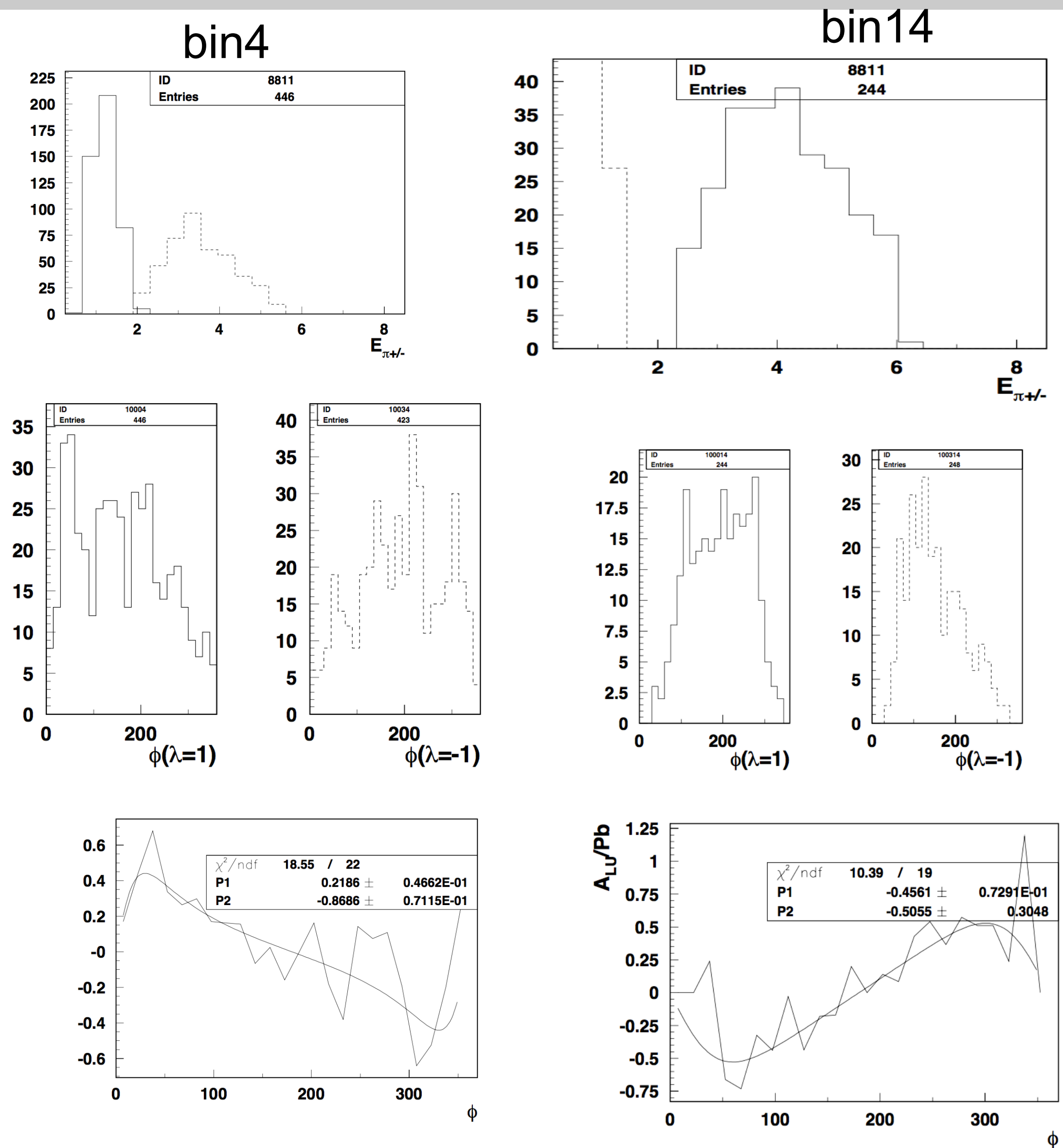


Interference of transverse and longitudinal rhos may be significant

Theta dependence

$0.25 < \cos\varphi < 0.75$

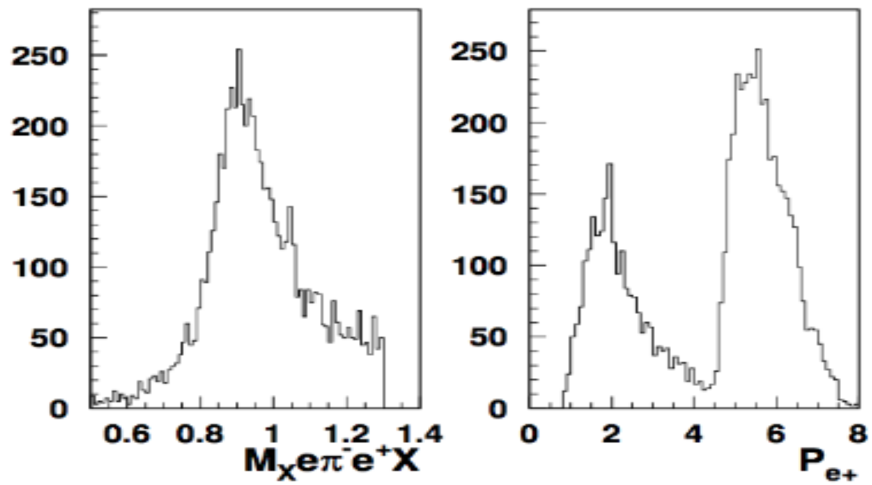


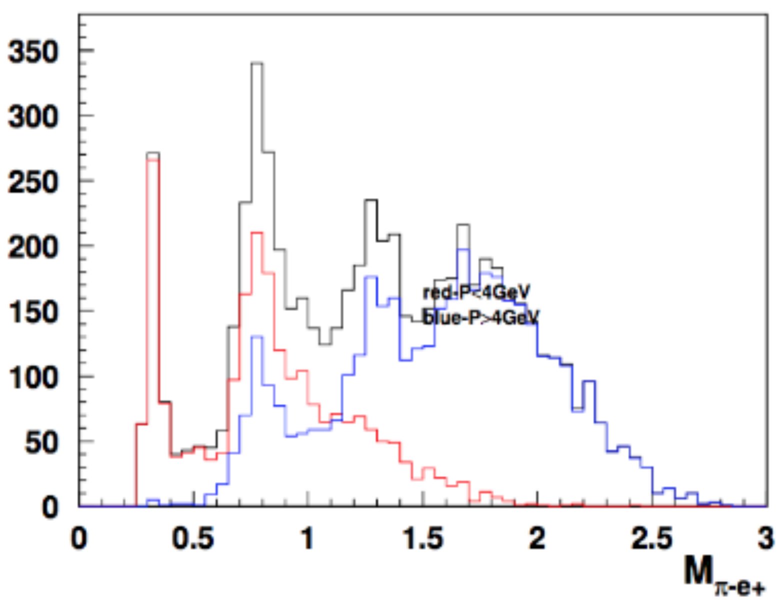


Strong variations with phi

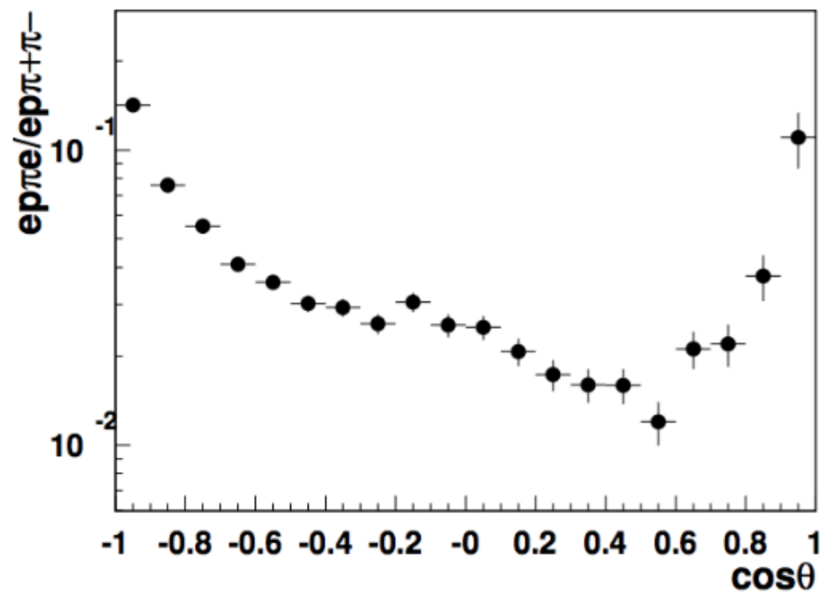
With relatively uniform acceptance in phi the contribution from different modulations cancels to large extent (to be properly quantified for final publication!)

More systematics



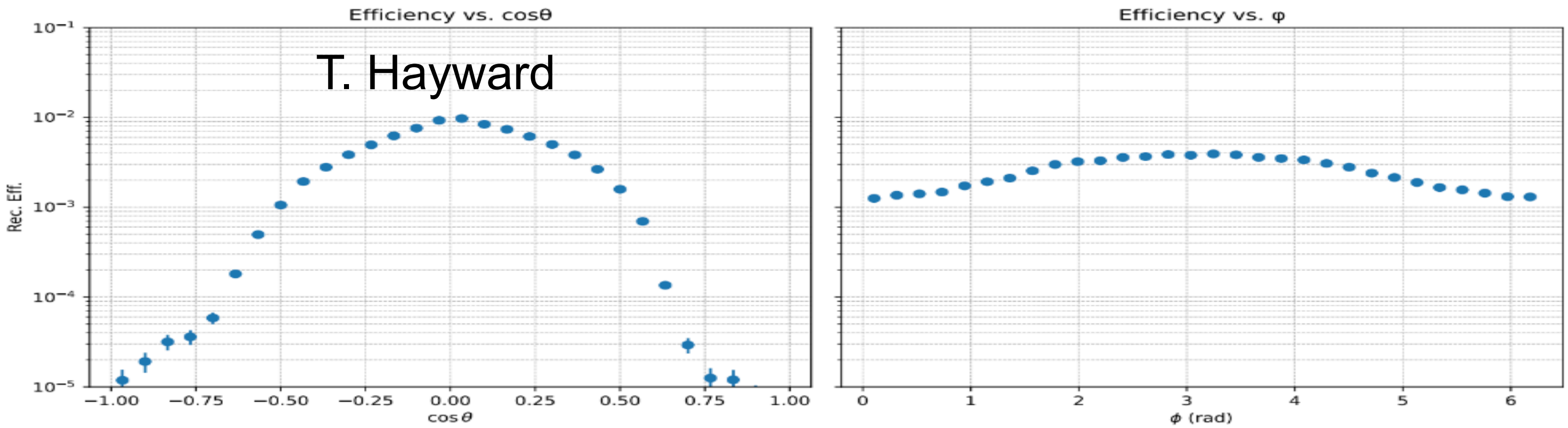


Using PID from DSTs



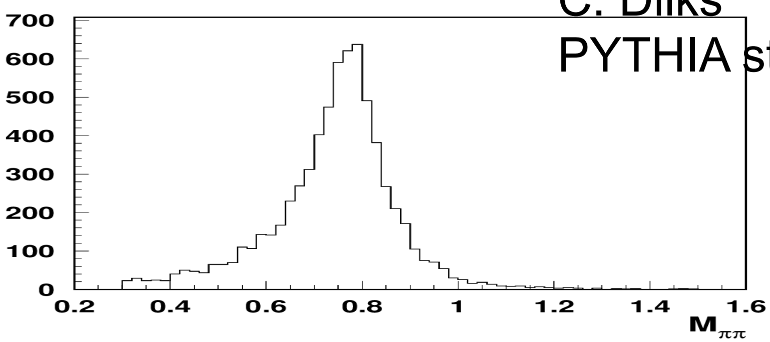
We loose a fraction of exclusive rhos due to misidentification of pion >10% in asymmetric decay case (to accounted in x-section studies)

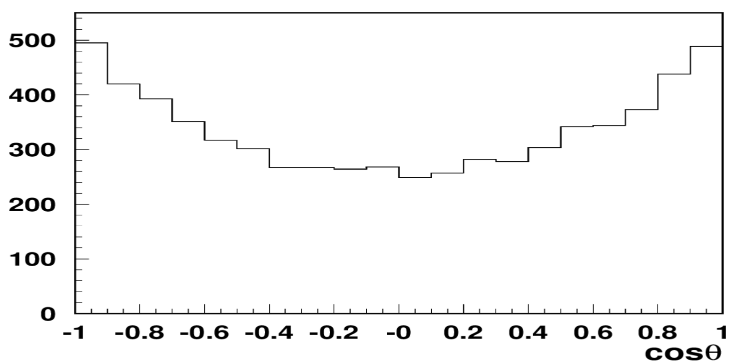
MC studies

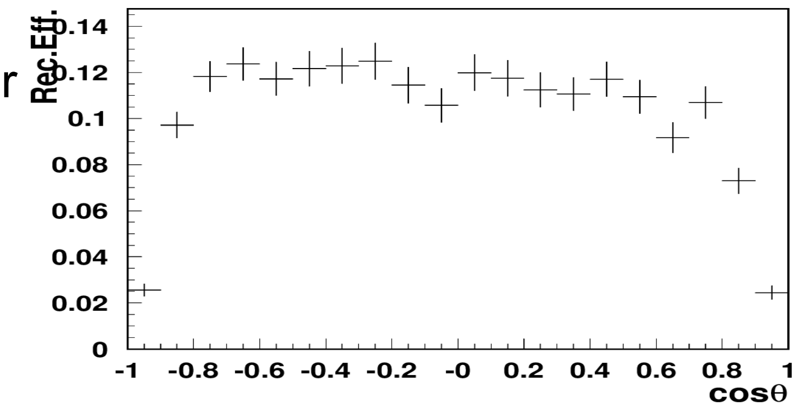


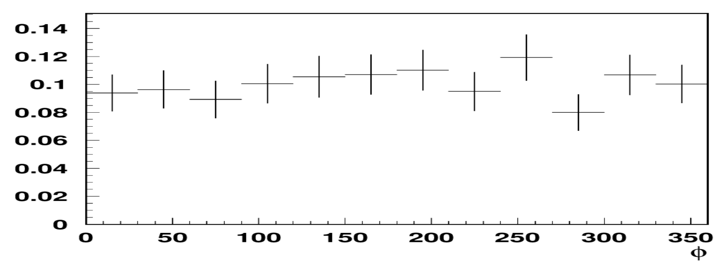
T. Hayward

C. Dilks
PYTHIA stringspinner





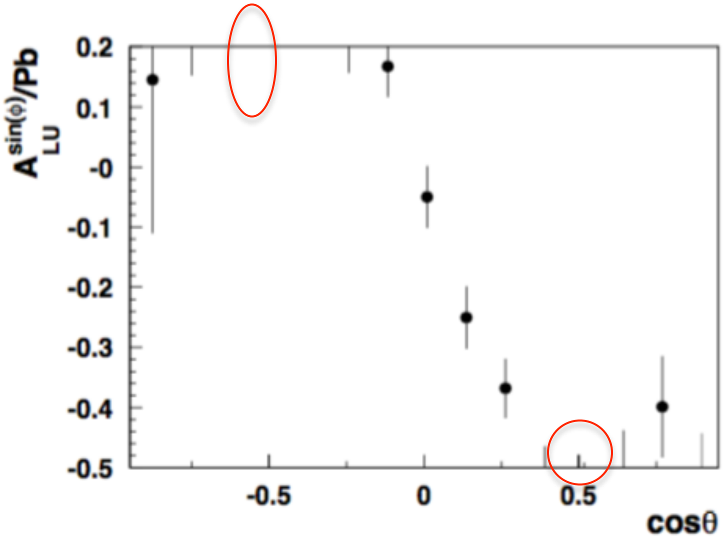




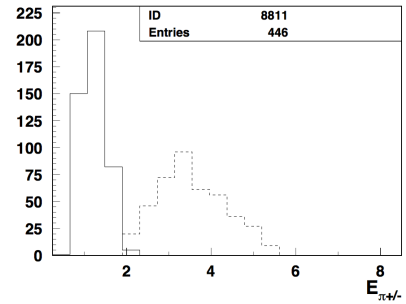
Consistent with week acceptance dep. for phi

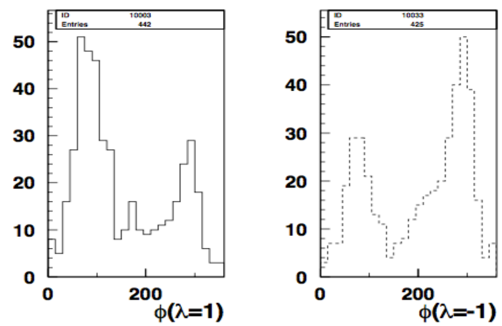
Theta dependence

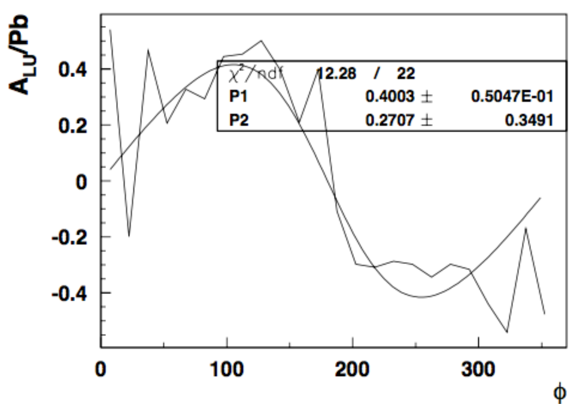
$0.75<\cos\phi<1$



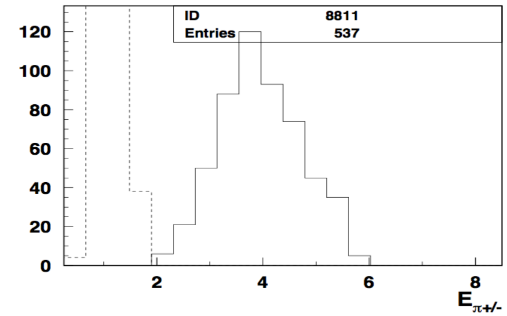
bin3

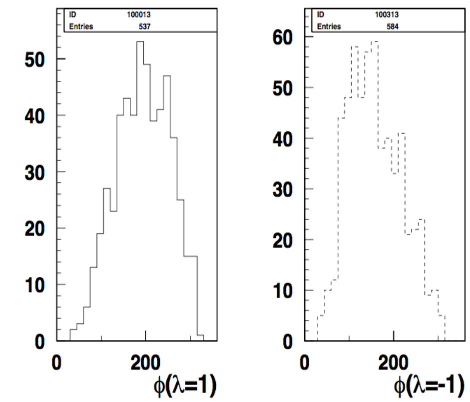


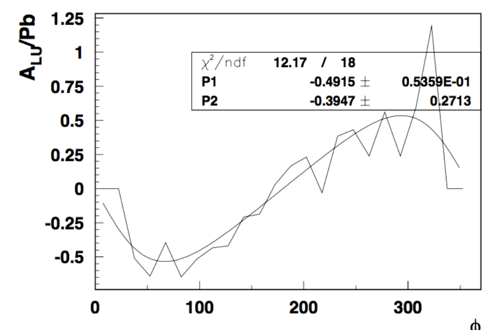




bin13





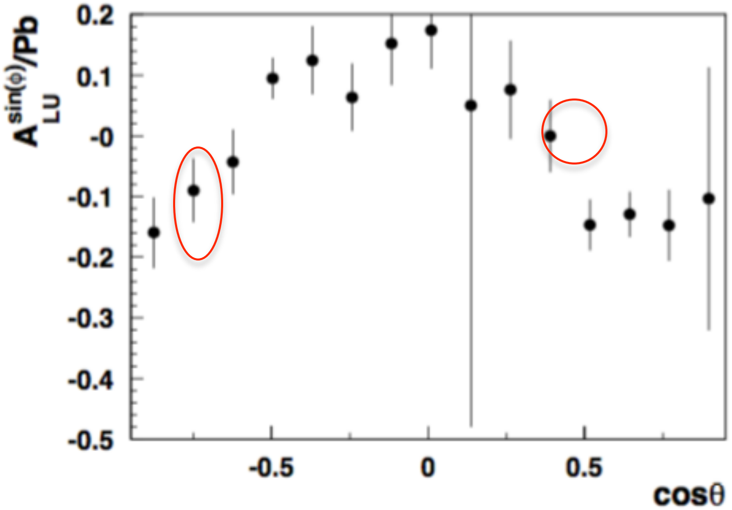


Strong variations with phi

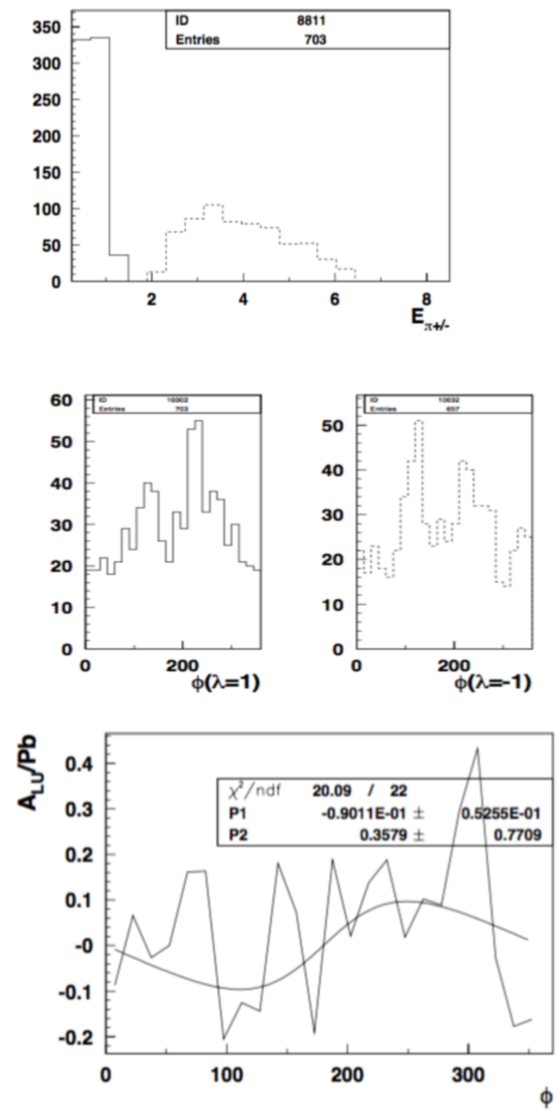
With relatively uniform acceptance in phi the contribution from different modulations cancels to large extent (to be properly quantified for final publication!)

Theta dependence

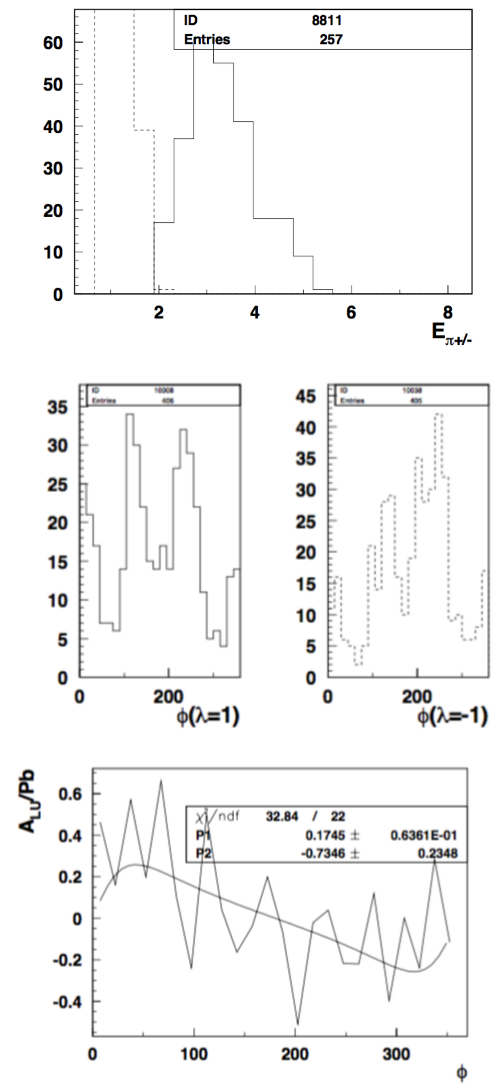
$-0.25<\cos\phi<0.25$



bin2



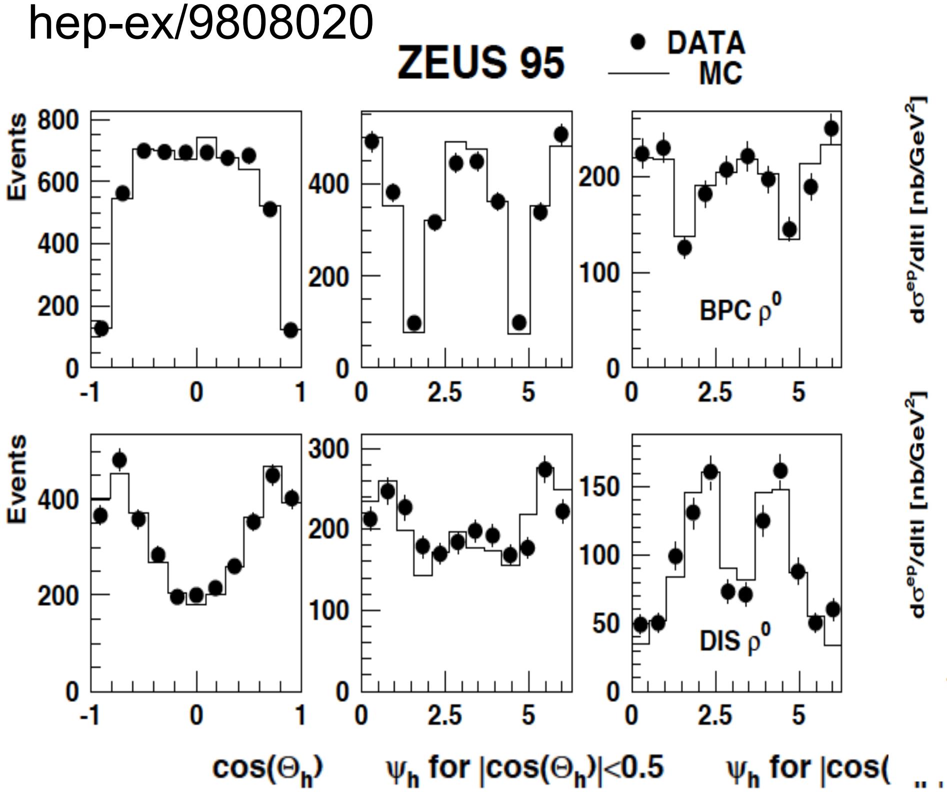
bin8

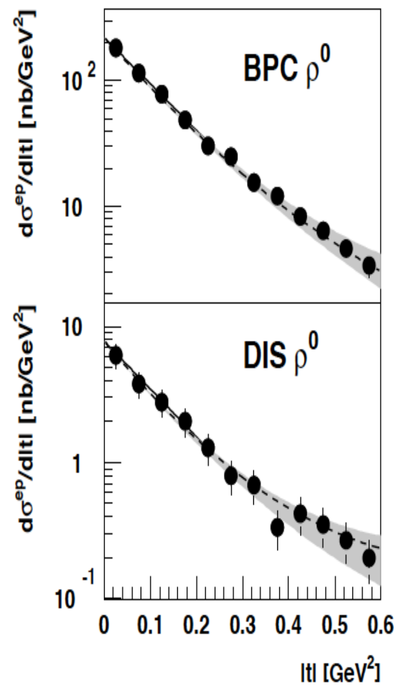


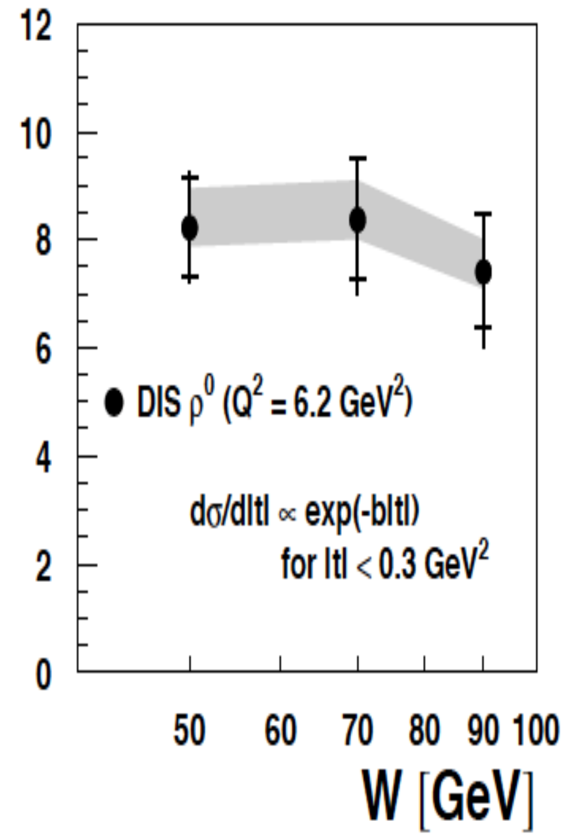
Strong variations with phi

More plots from ZEUS

hep-ex/9808020







Wide bins in t, what is the minimum energy of pi+/pi- detected?:
What is the resolution in t ?
What is the fraction of events for t<0.1 ?
What is the acceptance in cos\theta for low Q^2 bin for lowest t?
What is the total statistics of rho H1+ ZEUS, anyway to do 4D (x,Q^2,t,theta) analysis?

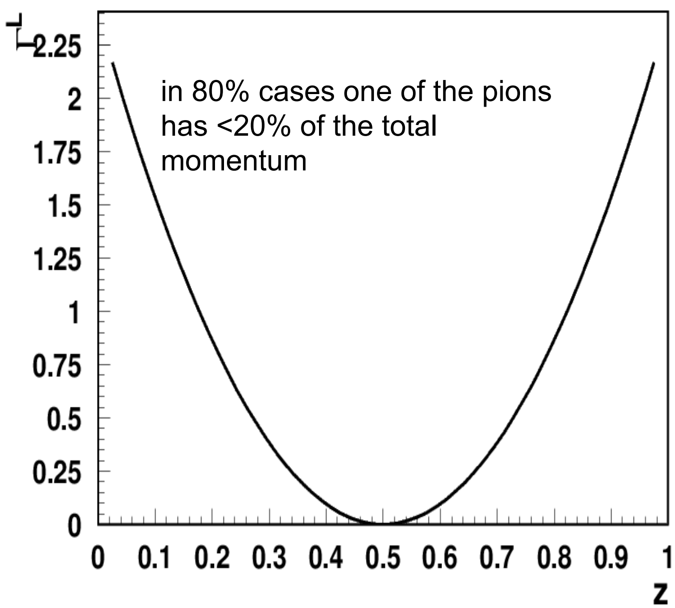
VM contributions

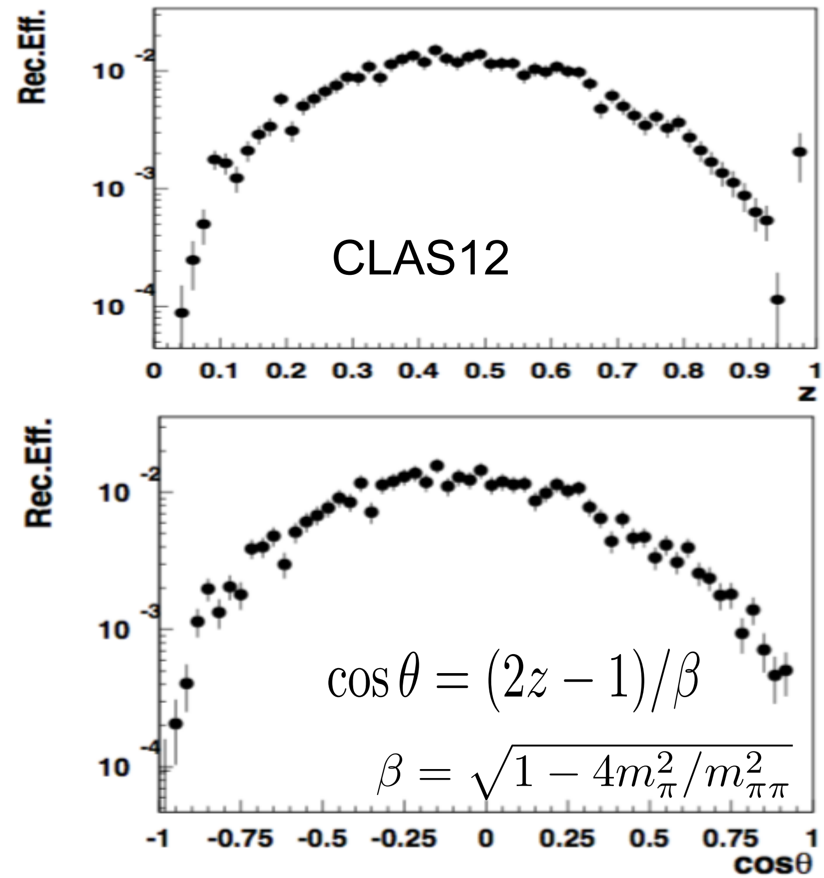
$$\rho^0 \to \pi^+\pi^-$$

Yuri Kovchegov

$$k_T^2 = z(1-z)\,M_\rho^2 - m_\pi^2.$$

$$\Gamma^L_{\rho^0\to\pi^+\pi^-} \sim |M^L_{\rho^0\to\pi^+\pi^-}|^2 \sim \left|\frac{k_\perp^2 + m_\pi^2}{M_\rho}\left(\frac{1}{z} - \frac{1}{1-z}\right) + M_\rho\,(1-2z)\right|^2 = 4\,M_\rho^2\,(1-2z)^2.$$

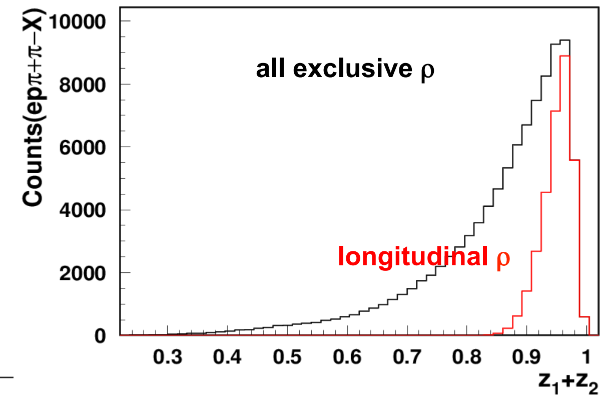


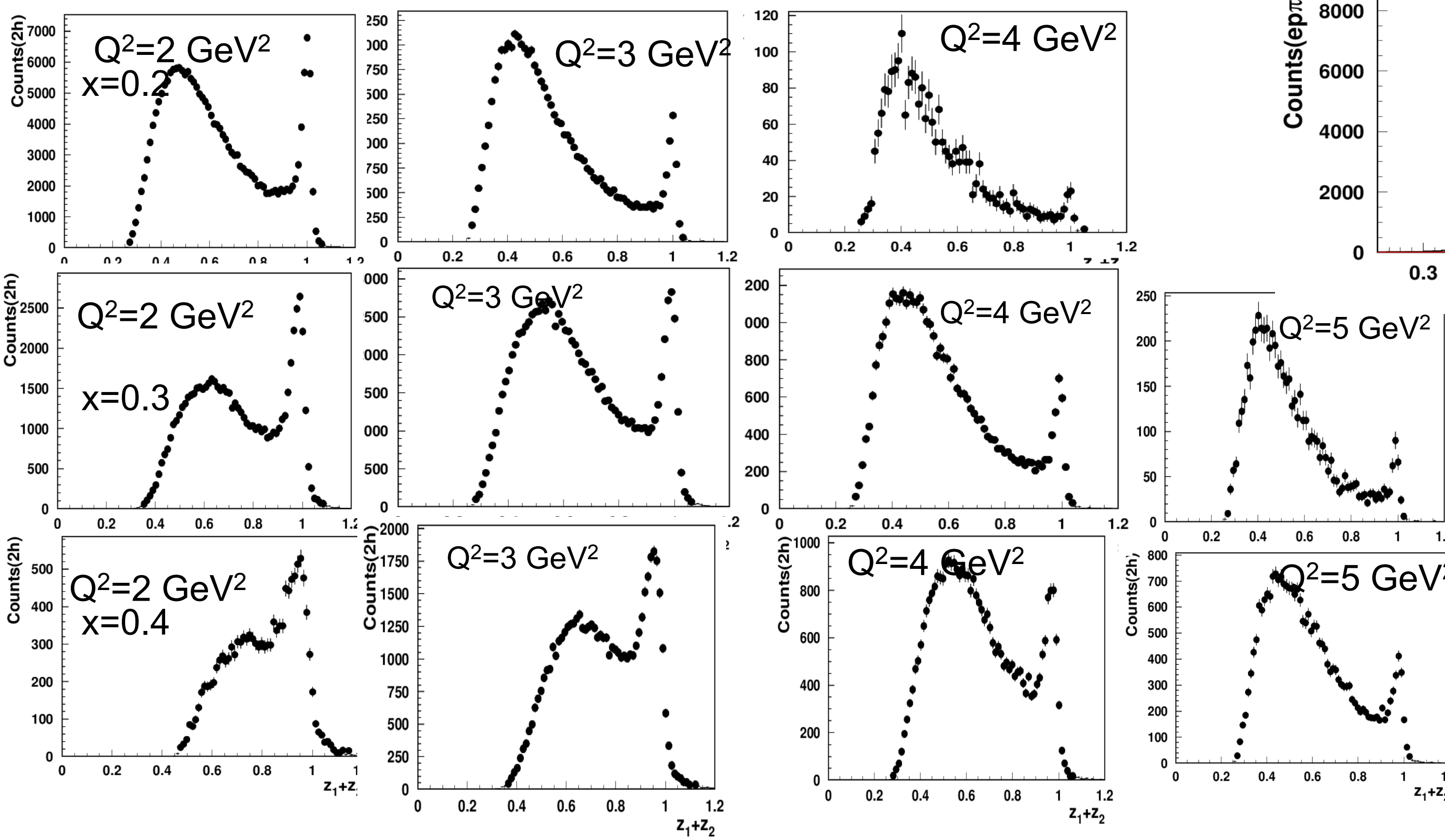


Asymmetric decays of longitudinal rho lead to much smaller acceptance, more than order of magnitude

Exclusive dihadrons from CLAS12

$t_{min} \approx -M^2x^2/(1-x)$





GK: arXiv:0708.3569

$$\gamma_L^* \to \rho_L \propto 1$$

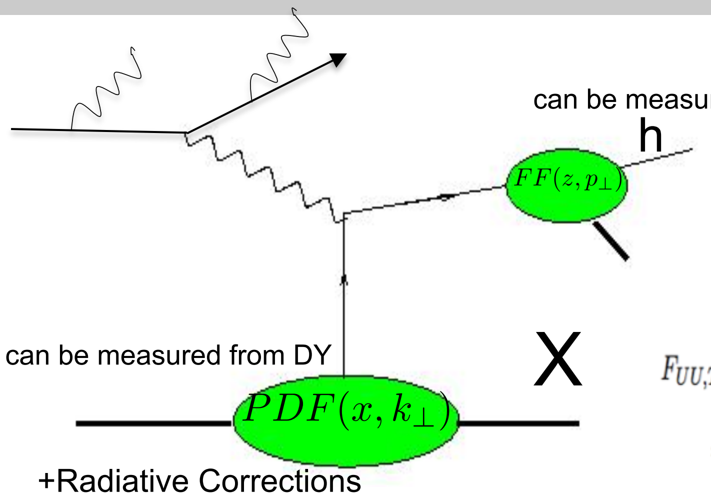
$$\gamma_T^* \to \rho_L \propto \sqrt{(1-z)/x}$$

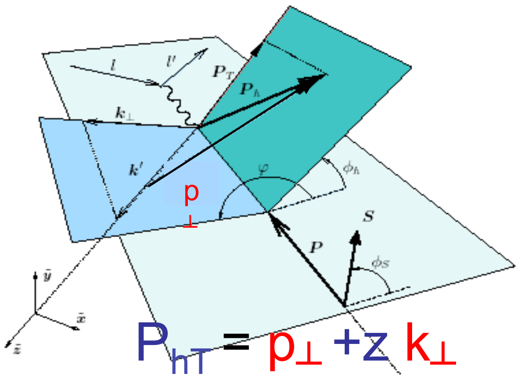
$$\gamma_L^* \to \rho_T \propto \sqrt{<k_\perp^2>(1-z)/x}$$

at lower x
need higher z

The exclusive rho contributions in SIDIS (multiplicity) drop with Q^2 ($\sim 1/Q^2$)
At large $z=z_1+z_2$ the transverse photon contributions to ρ_L suppressed

SIDIS as THE theory describes it





Probability to produce 1 or 2 hadrons in single photon exchange

$$\frac{d\sigma^{eN\to e'hX}}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2}$$

TMD Parton Distribution Functions

TMD Parton Fragmentation Functions

$$F_{UU,T}(x,z,P_{hT}^2,Q^2) = x\sum_q \mathcal{H}^q_{UU,T}(Q^2,\mu^2)\int d^2\boldsymbol{k}_\perp\, d^2\boldsymbol{P}_\perp\, f_1^a(x,\boldsymbol{k}_\perp^2;\mu^2)\, D_1^{a\to h}(z,\boldsymbol{P}_\perp^2;\mu^2)\,\delta(z\boldsymbol{k}_\perp - \boldsymbol{P}_{hT}+\boldsymbol{P}_\perp) + Y_{UU,T}(Q^2,\boldsymbol{P}_{hT}^2) + \mathcal{O}(M^2/Q^2)$$

hard part

Factorization allowing description using distribution functions (TMD-PDF) and fragmentation functions (TMD FF)
X→ multiplicity of unobserved hadrons LARGE, and x-section doesn't depend on X (independent fragmentation)
Leading twist dominates, $Q^2 >> 1$, $k_\perp/Q << 1$

"much bigger/smaller" defined in comparison with experiment

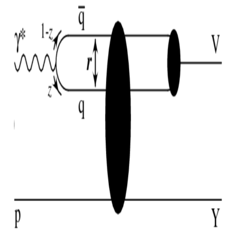
Conclusions in case of apparent disagreement:

1)factorization is broken?
2)<u>unaccounted terms may contribute (assumptions are not good in certain kinematics,…)</u>

Data has it all!!! Dealing with unaccounted terms:
- Theory accounts for them (ex. VMs)
- Experiment measures and excludes them!!! (ex.VMs)

Theory predictions for transverse SSAs for rho

Goeke et al: hep-ph/0106012



$$A_{\rho_L^0 p} = \int_{-1}^{1} dx \, \frac{1}{\sqrt{2}} \left(e_u \, H^u - e_d \, H^d\right) \left\{ \frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right\}$$

$$B_{\rho_L^0 p} = \int_{-1}^{1} dx \, \frac{1}{\sqrt{2}} \left(e_u \, E^u - e_d \, E^d\right) \left\{ \frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right\}$$

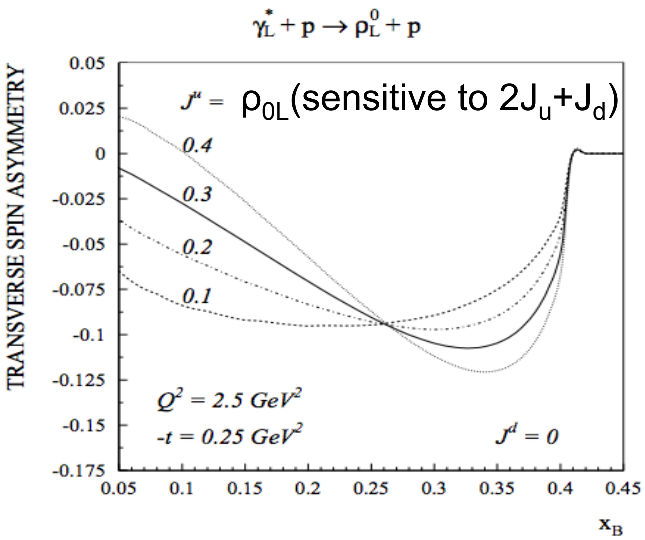
$$\frac{d\sigma_L}{dt} = \frac{1}{16\pi \, (s - m_N^2) \, \Lambda(s, -Q^2, m_N^2)} \, \frac{1}{2} \sum_{h_N} \sum_{h_N'} |\mathcal{M}^L(\lambda_M = 0, h_N'; h_N)|^2$$

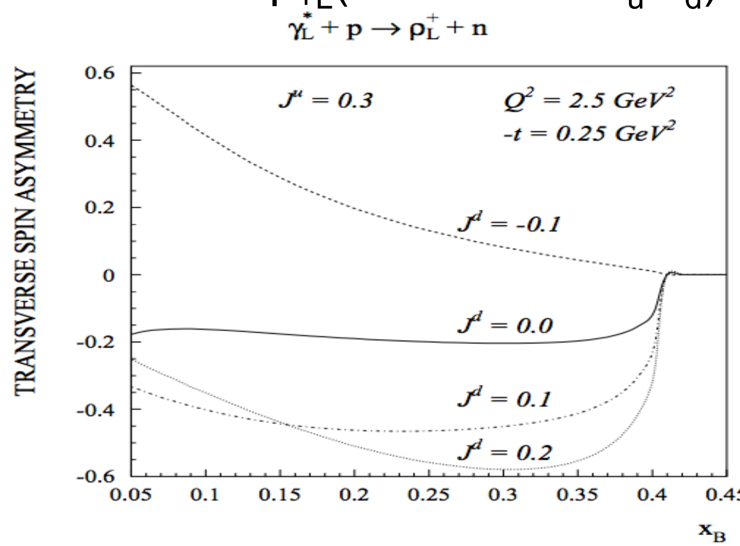
$$A_{\rho_L^+ n} = - \int_{-1}^{1} dx \, \left(H^u - H^d\right) \left\{ \frac{e_u}{x - \xi + i\epsilon} + \frac{e_d}{x + \xi - i\epsilon} \right\}$$

$$B_{\rho_L^+ n} = - \int_{-1}^{1} dx \, \left(E^u - E^d\right) \left\{ \frac{e_u}{x - \xi + i\epsilon} + \frac{e_d}{x + \xi - i\epsilon} \right\}.$$

$$\mathcal{A}_{V_L N} = - \frac{2\,|\Delta_\perp|}{\pi} \, \frac{\mathrm{Im}(AB^*)/m_N}{|A|^2 \, (1 - \xi^2) - |B|^2 \, (\xi^2 + t/(4m_N^2)) - \mathrm{Re}(AB^*) \, 2\,\xi^2}$$

ρ_{+L}(sensitive to J_u-J_d)





Significant SSAs predicted, sensitive to OAM contributions

Theory predictions for transverse SSAs for rho

Goloskokov&Kroll 0809.4126

$$t_{\min} = -\frac{2\xi}{1-\xi^2}\left[(1+\xi)M^2 - (1-\xi)m^2\right]$$

$$\frac{d\sigma_{L(T)}}{dt} = \frac{1}{16\pi(W^2-m^2)\sqrt{\Lambda(W^2,-Q^2,m^2)}} \sum_{\nu'} \left|\mathcal{M}_{0(+)\nu',0(+)+}\right|^2$$

$$\xi \simeq \frac{x_{\rm Bj}}{2-x_{\rm Bj}}\left[1+m_V^2/Q^2\right]$$

$$\Lambda(s,-Q^2,m_N^2) = 2m_N|\vec{q}_L|$$

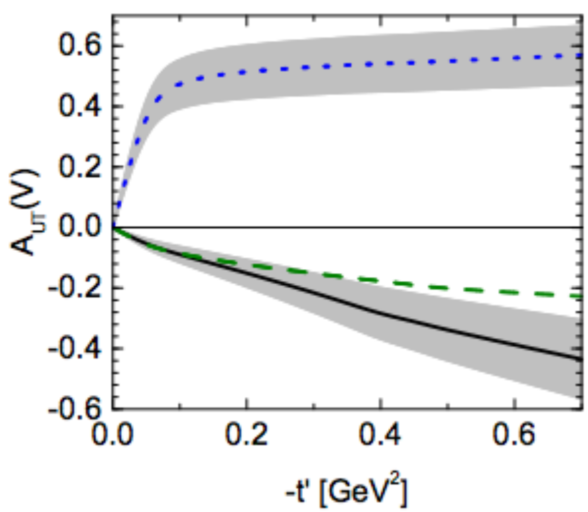
$$A_{UT} = -2\,\frac{\mathrm{Im}[\mathcal{M}^*_{+-,++}\,\mathcal{M}_{++,++}] + \varepsilon\,\mathrm{Im}[\mathcal{M}^*_{0-,0+}\,\mathcal{M}_{0+,0+}]}{\sum_{\nu'}\left[\,|\,\mathcal{M}_{+\nu',++}\,|^2 + \varepsilon\,|\,\mathcal{M}_{0\nu',0+}\,|^2\,\right]}$$

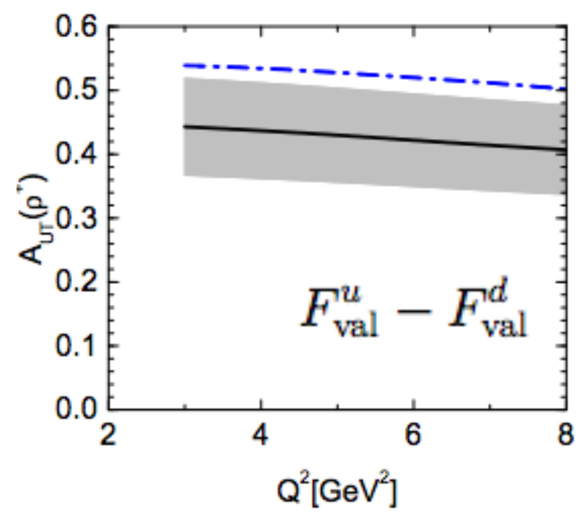
$$\mathcal{M}_{\mu-,\mu+}(\rho^0) \sim \langle e_u E^u_{\rm val} - e_d E^d_{\rm val}\rangle$$

Opposite signs from HERMES!!

$$A_{UT}(\rho^0_L) = 0.04 \pm 0.12$$

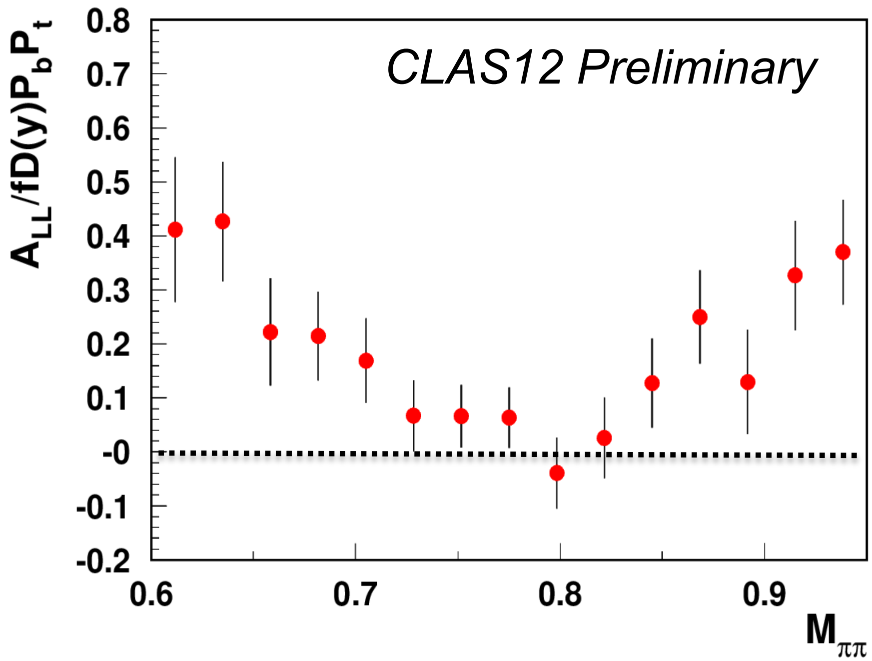
$$A_{UT}(\rho^0_T) = -0.08 \pm 0.10$$

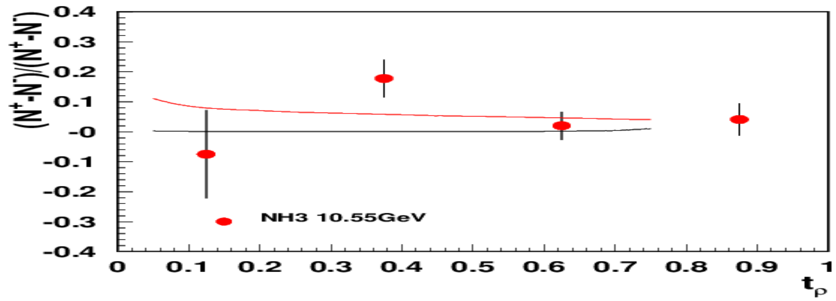


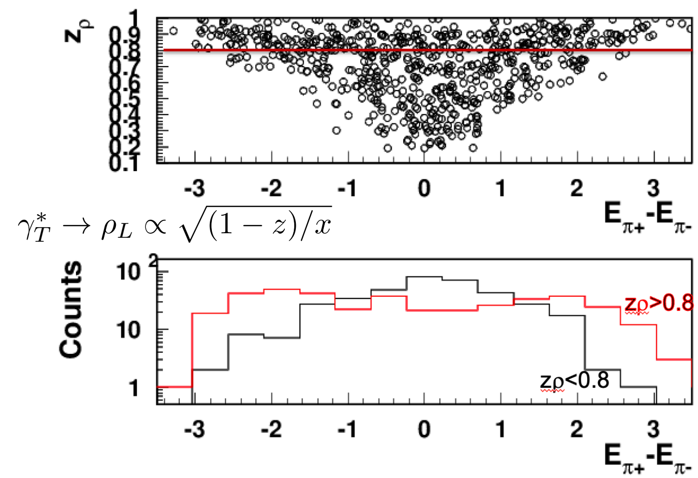


Significant SSAs for VMs

Studies of ρ^0 impact with longitudinally polarized NH_3 target





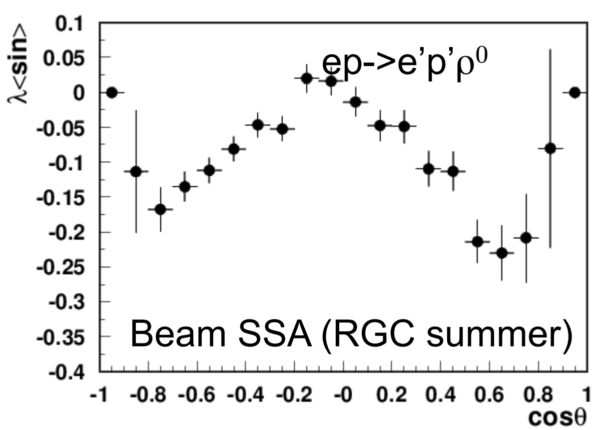


and diffractive exclusive ρ0s from exclusive π+π−

- DSA is P-even, SSA is P-odd
- longitudinal photon cross section is P-odd

→ contribution appears only in the SSA, a P-odd observable, and does not appear in DSA

With x10 less statistics than RGC, RGH can provide a significant measurement of ρ0 SSAs

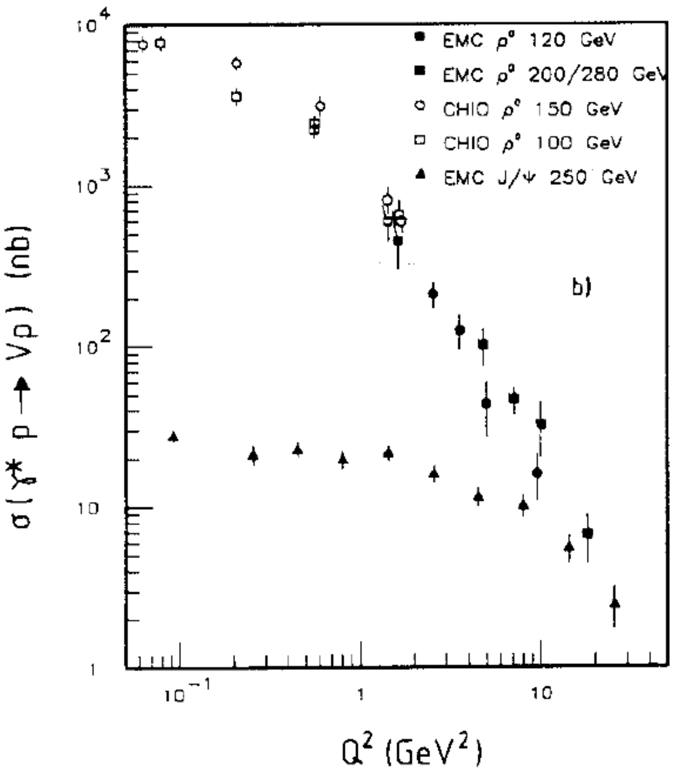


Experiments (EMC, NMC)

CERN-EP/87-231
December 23rd, 1987

EXCLUSIVE ρ^0 AND ϕ PRODUCTION IN DEEP INELASTIC MUON SCATTERING

The European Muon Collaboration

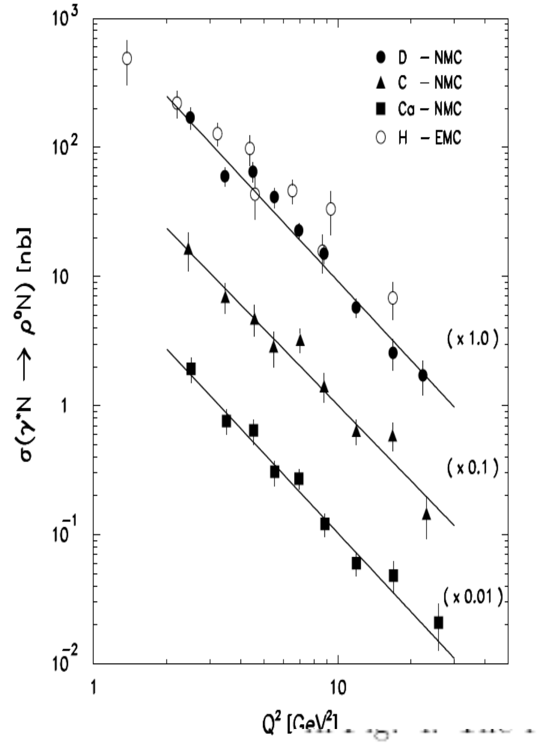


CERN-PPE/94-146
September 16, 1994

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Exclusive ρ^0 and ϕ Muoproduction at Large Q^2

THE NEW MUON COLLABORATION (NMC)

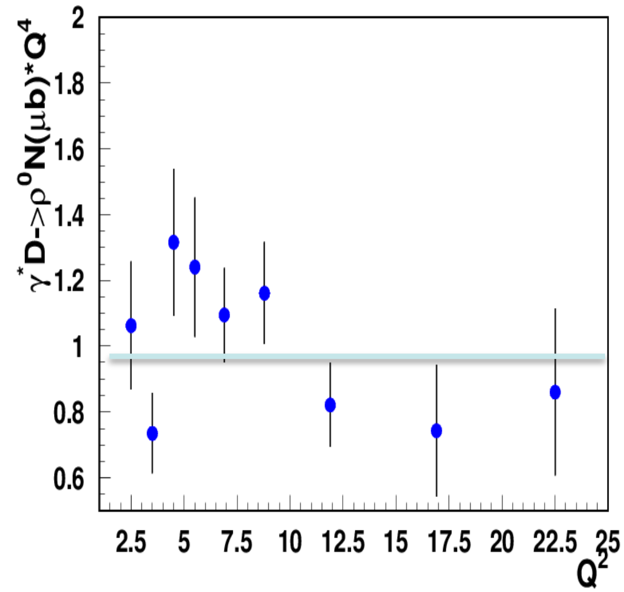


$\beta = 2.02 \pm 0.07.$

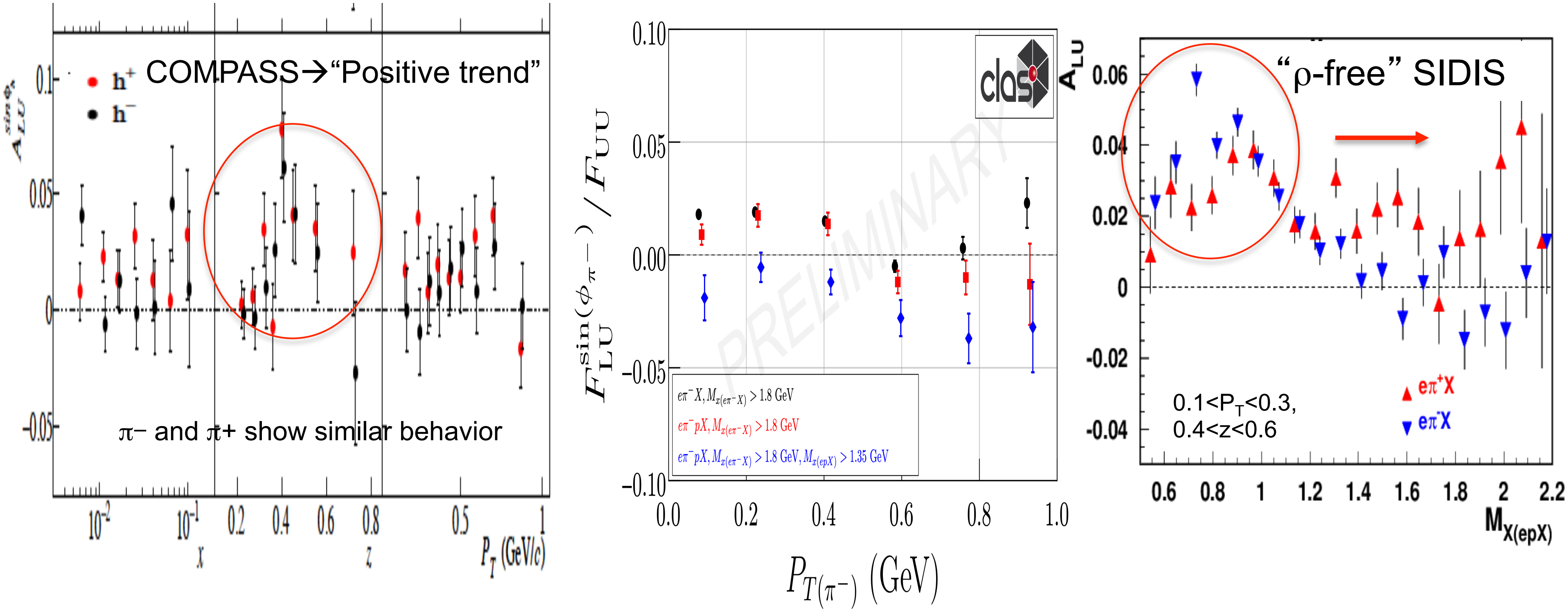
$$\sigma(Q^2) = \sigma_0\left(\frac{Q_0^2}{Q^2}\right)^\beta,$$

- Q^2 dependence of the type $1/Q^6$.

Q^2 $[GeV^2]$	$<\nu>$ $[GeV]$	$<\epsilon>$	$\sigma(\gamma^*N \to \rho^0 N)$ [nb]
Deuterium			
2.5	140	0.50	170 ± 31
3.5	116	0.66	60 ± 10
4.5	117	0.66	65 ± 11
5.5	106	0.72	41 ± 7
6.9	99	0.76	23 ± 3
8.8	93	0.78	15 ± 2
11.9	87	0.82	5.8 ± 0.9
16.9	87	0.81	2.6 ± 0.7
22.5	92	0.80	1.7 ± 0.5



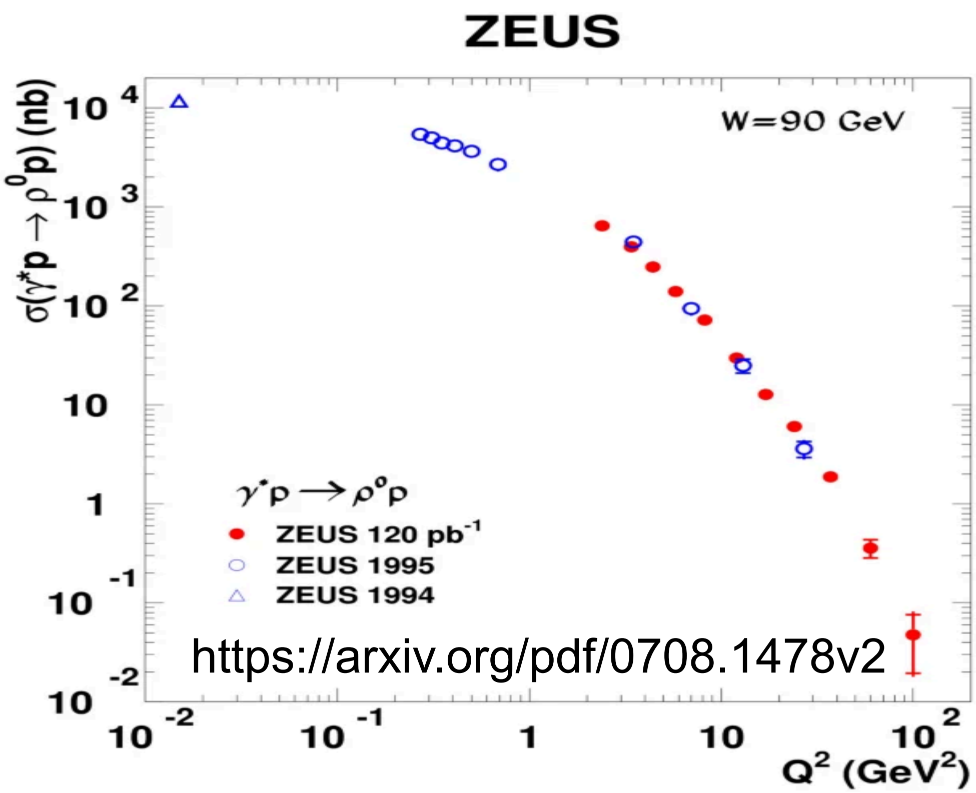
Exclusive ρ contributions to π: P_T-dependence

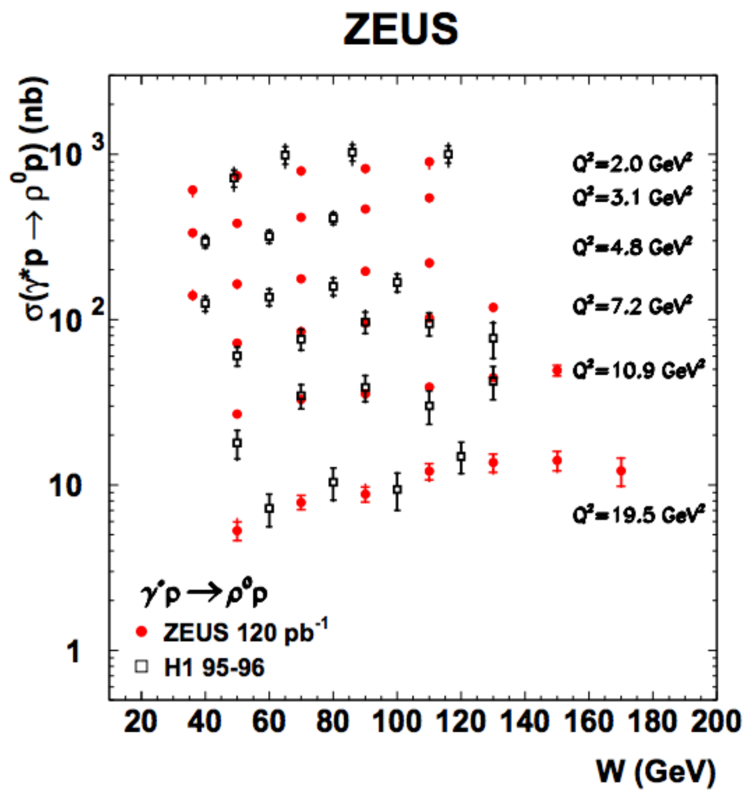


COMPASS→"Positive trend" also reproduced
when additional proton in TFR detected (red)

- The same sign and size of π+ and π- SSA indicates the rho0 may not be properly subtracted(require detailed MC studies, which require proper SDMEs)
- While VM contributions are ~20% in multiplicities in SSA they can be >100%
- Detection of the target proton introduces much smaller bias on the inclusive charged pion SSA, than the exclusive rho contributions

Experiments (ZEUS)





ıe Q^2 dependence of the cross section for exclusive ρ^0 electroproduction, at a γ^*p centre-of-mass ıergy $W = 90$ GeV. The ZEUS 1994 [53] and the ZEUS 1995 [10] data points have been extrapolated $W = 90$ GeV using the parameterisations reported in the respective publications. The inner error

$$\sigma(\gamma^* p \rightarrow \rho^0 p) \sim (Q^2 + m_\rho^2)^{-n},$$

- the Q^2 dependence of the cross-section, which for a longitudinally polarised photon is expected to behave as Q^{-6}, is moderated to become Q^{-4} by the rapid increase of the gluon density with Q^2;

what about fixed x?

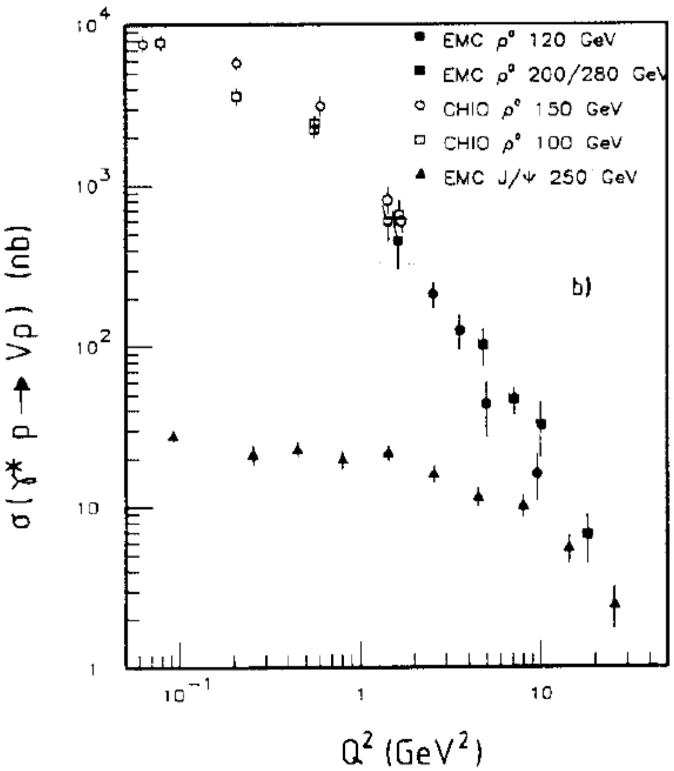
with the normalisation and n as free parameters, failed to produce results with an acceptable χ^2. The data appear to favour an n value which increases with Q^2.

Experiments (EMC, NMC)

CERN-EP/87-231
December 23rd, 1987

EXCLUSIVE ρ^0 AND ϕ PRODUCTION IN DEEP INELASTIC MUON SCATTERING

The European Muon Collaboration



CERN-PPE/94-146
September 16, 1994

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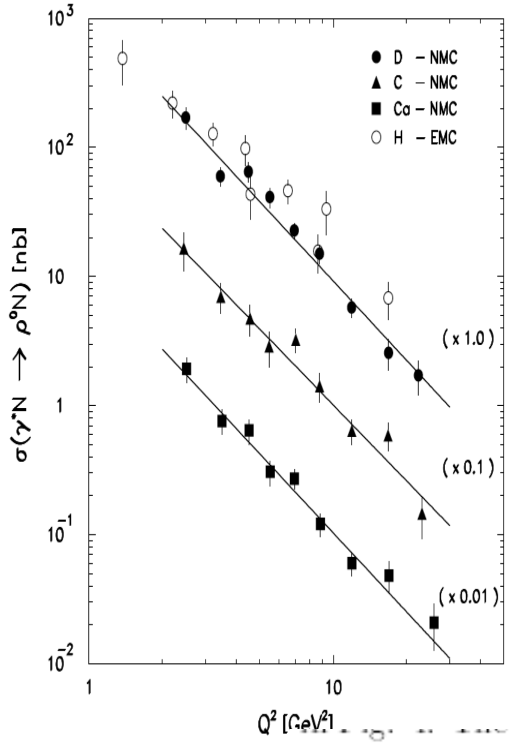

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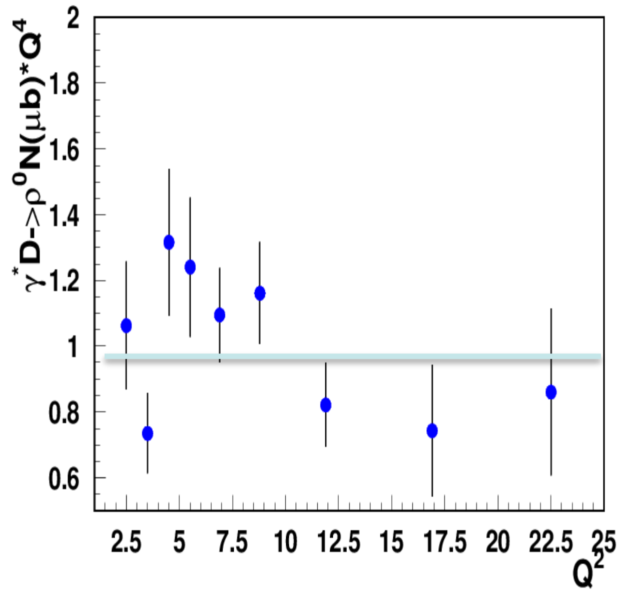


Response from theory

Hoyer, Paul G via jeffersonlab.onmicrosoft.com   6:05 AM (2 hours ago)

to Harut, Stanley, Valery

Dear Harut,

I agree that the decrease with Q^2 of the ZEUS cross section at fixed, low M_X is important and as expected for exclusive rho production. The 1/Q^4 of SIDIS comes from the inclusion of large M_X \propto Q^2 in the virtual photon fragmentation region (M_X being the mass of the mesonic system scattering off the intact nucleon target).

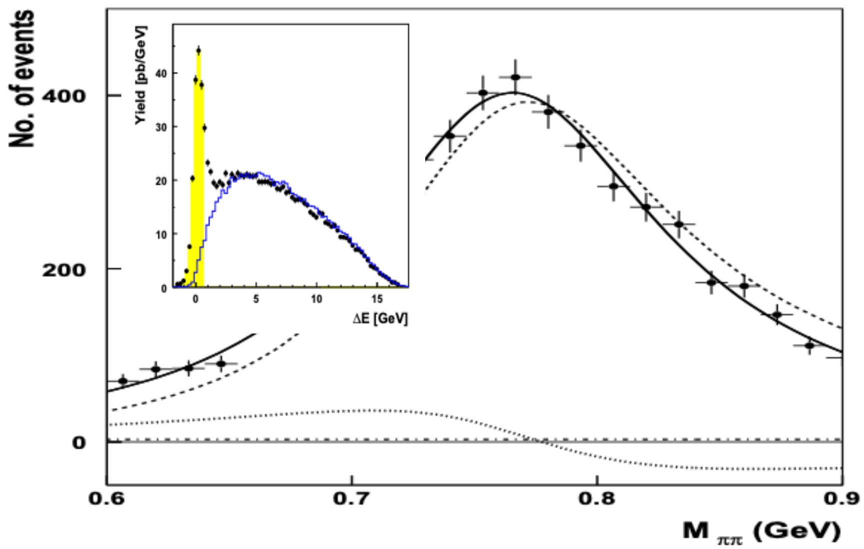
This need not mean that longitudinal virtual photons dominate. The transverse photon contribution arises from the end-point region (x = 0, 1) of the rho distribution amplitude, and may be suppressed only at very large Q^2. The PQCD prediction for the pion EM form factor is much smaller than the data at moderate Q^2, and starts to agree only at the highest Q^2 available to BABAR.

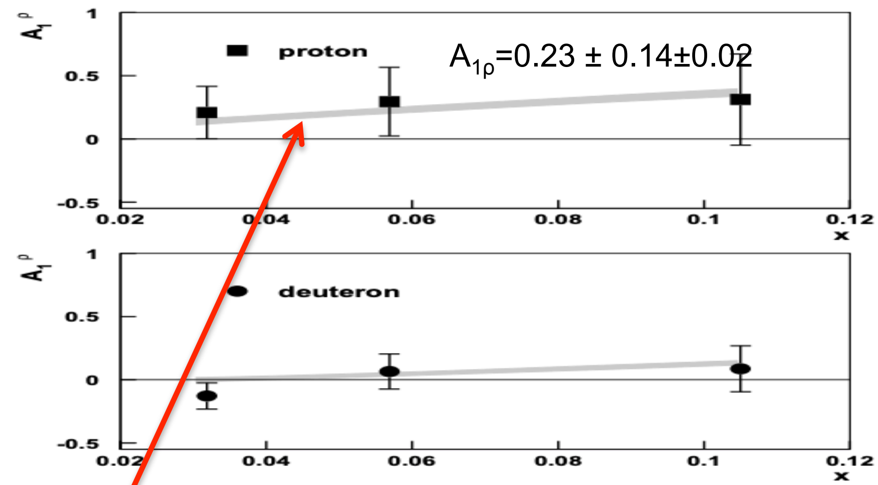
I don't have the experience to judge the importance of your argument concerning A_LL.

It would be interesting to study whether there is an analogy of Bloom-Gilman duality in DDIS. In DIS one keeps x_Bj, ie, Q^2/W fixed and extrapolates the scaling curve to low Q^2 and W. The curve averages the N^* resonance contributions at W= m_N^*. In DDIS transverse virtual photons dominate, so if the scaling curve agrees with the magnitude of the rho contribution it would suggest that the rho's are produced by transverse photons.

All the best from Paul

A_{LL} studies of exclusive ρ^0 : HERMES

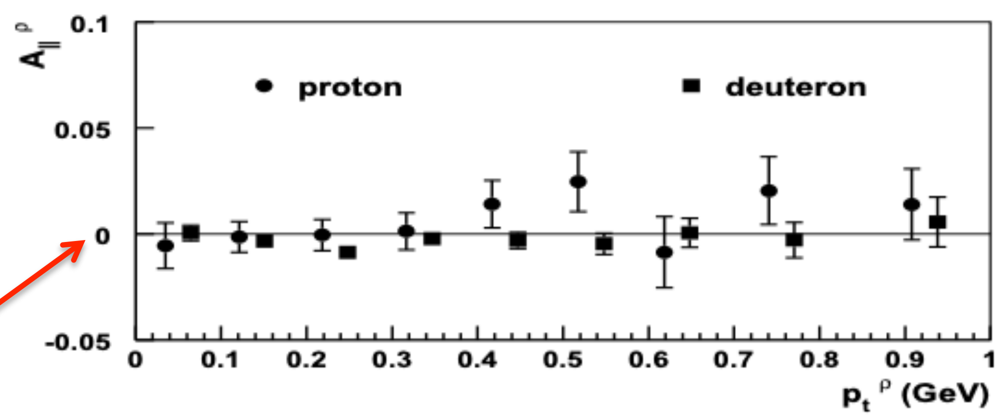




1D plots can be really misleading need multi-D

For a proper extraction of multiplicities and spin-azimuthal modulations of exclusive ρs, clean separation is needed for ρ^0, and longitudinally polarized ρ^0 signal, in particular

At low P_T, where the background is smaller, the asymmetry indeed tend to be negative



Accounting of ρ^0 will change the phenomenology of helicity distributions

Excluding the “diffractive” rho from SIDIS

Depending on how we exclude the exclusive rho we can have several versions of experimental samples of inclusive hadrons, each with their own bias:

1) Standard SIDIS (eN→ehX, h=π,K,..) within the full accessible kinematics, corrected for acceptance and RC, measured in the multidimensional space

→eπX biased with respect to theory by presence of contributions from diffractive rho, contributing to ~20% of counts, in low P_T, with contributions to SSA ~10 times higher

2) Standard SIDIS (eN→eπX) within the full accessible kinematics, corrected for acceptance and RC, measured in the multidimensional space, with subtracted in multi-D bins for rho0 contributions (“rho-subtracted SIDIS”)

→requires measurements of pions from diffractive rho in multidimensional space, means detailed studies of SDMEs of rhos, requiring good precisions and huge statistics, develop MC (ex. HEPGEN) also for all polarization observables, extensive validation needed, little known RC

3) SIDIS subsamples (eN→epπX, eN→e$\pi\pi$X) within the full accessible kinematics, allowing clear eliminiation of rho0 contributions using cuts on missing masses of epX or e$\pi\pi$X (“rho-free SIDIS”)

→biased by the presence of additional hadron in TFR (epX) or CFR (eppX), may need a new phenomenology

requires measurements of dependence on M_X to understand the bias,
Theory should be able to evaluate the bias from the presence of an additional hadron

SDMEs vs helicity amplitudes

with ϕ_S transverse polarization azimuthal angle.

$$W_{UU}^{LL}(\phi) = (u_{++}^{00} + \epsilon u_{00}^{00}) - 2\cos\phi\sqrt{\epsilon(1+\epsilon)}\,\mathrm{Re}\,u_{0+}^{00} - \cos(2\phi)\,\epsilon u_{-+}^{00},$$

$$\begin{aligned}
W_{UU}^{LT}(\phi,\varphi) = {}& \cos(\phi+\varphi)\sqrt{\epsilon(1+\epsilon)}\,\mathrm{Re}(u_{0+}^{0+} - u_{0+}^{-0}) \\
& - \cos\varphi\,\mathrm{Re}(u_{++}^{0+} - u_{++}^{-0} + 2\epsilon u_{00}^{0+}) + \cos(2\phi+\varphi)\,\epsilon\,\mathrm{Re}\,u_{-+}^{0+} \\
& - \cos(\phi-\varphi)\sqrt{\epsilon(1+\epsilon)}\,\mathrm{Re}(u_{0+}^{0-} - u_{0+}^{+0}) + \cos(2\phi-\varphi)\,\epsilon\,\mathrm{Re}\,u_{-+}^{+0},
\end{aligned}$$

$$\begin{aligned}
W_{UU}^{TT}(\phi,\varphi) = {}& \tfrac{1}{2}(u_{++}^{++} + u_{++}^{--} + 2\epsilon u_{00}^{++}) + \tfrac{1}{2}\cos(2\phi+2\varphi)\,\epsilon u_{-+}^{-+} \\
& - \cos\phi\sqrt{\epsilon(1+\epsilon)}\,\mathrm{Re}(u_{0+}^{++} + u_{0+}^{--}) + \cos(\phi+2\varphi)\sqrt{\epsilon(1+\epsilon)}\,\mathrm{Re}\,u_{0+}^{-+} \\
& - \cos(2\varphi)\,\mathrm{Re}(u_{++}^{-+} + \epsilon u_{00}^{-+}) - \cos(2\phi)\,\epsilon\,\mathrm{Re}\,u_{-+}^{++} \\
& + \cos(\phi-2\varphi)\sqrt{\epsilon(1+\epsilon)}\,\mathrm{Re}\,u_{0+}^{+-} + \tfrac{1}{2}\cos(2\phi-2\varphi)\,\epsilon u_{-+}^{+-}. \qquad (13)
\end{aligned}$$

The terms independent of ϕ and φ in W_{UU}^{LL} and W_{UU}^{TT} are related by

$$u_{++}^{++} + u_{++}^{--} + 2\epsilon u_{00}^{++} = 1 - (u_{++}^{00} + \epsilon u_{00}^{00}), \qquad (14)$$

$$W_{LU}^{LL}(\phi) = -2\sin\phi\sqrt{\epsilon(1-\epsilon)}\,\mathrm{Im}\,u_{0+}^{00},$$

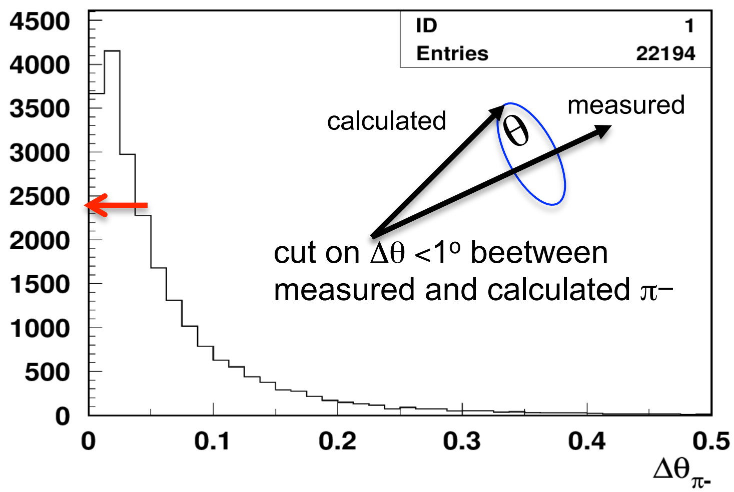
$$\begin{aligned}
W_{LU}^{LT}(\phi,\varphi) = {}& \sin(\phi+\varphi)\sqrt{\epsilon(1-\epsilon)}\,\mathrm{Im}(u_{0+}^{0+} - u_{0+}^{-0}) \\
& - \sin\varphi\sqrt{1-\epsilon^2}\,\mathrm{Im}(u_{++}^{0+} - u_{++}^{-0}) \\
& - \sin(\phi-\varphi)\sqrt{\epsilon(1-\epsilon)}\,\mathrm{Im}(u_{0+}^{0-} - u_{0+}^{+0}),
\end{aligned}$$

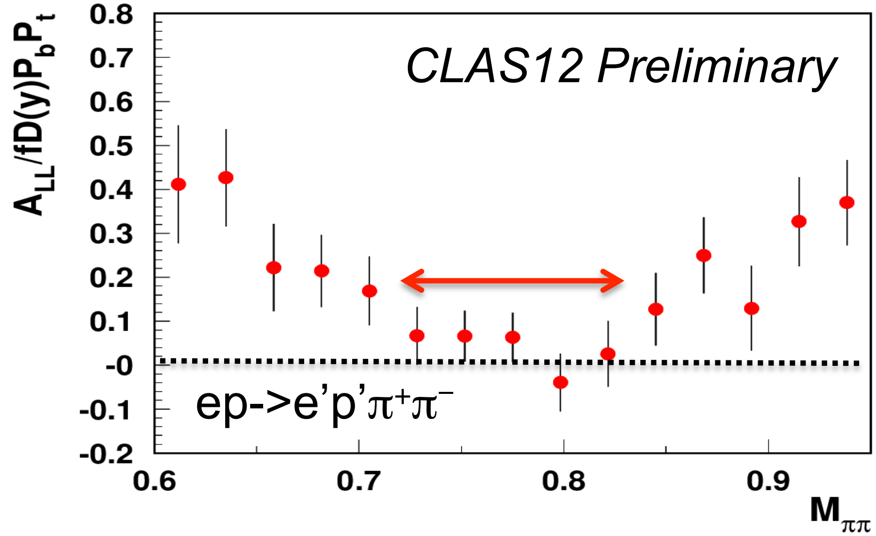
$$\begin{aligned}
W_{LU}^{TT}(\phi,\varphi) = {}& -\sin\phi\sqrt{\epsilon(1-\epsilon)}\,\mathrm{Im}(u_{0+}^{++} + u_{0+}^{--}) + \sin(\phi+2\varphi)\sqrt{\epsilon(1-\epsilon)}\,\mathrm{Im}\,u_{0+}^{-+} \\
& - \sin(2\varphi)\sqrt{1-\epsilon^2}\,\mathrm{Im}\,u_{++}^{-+} \\
& + \sin(\phi-2\varphi)\sqrt{\epsilon(1-\epsilon)}\,\mathrm{Im}\,u_{0+}^{+-}. \qquad (15)
\end{aligned}$$

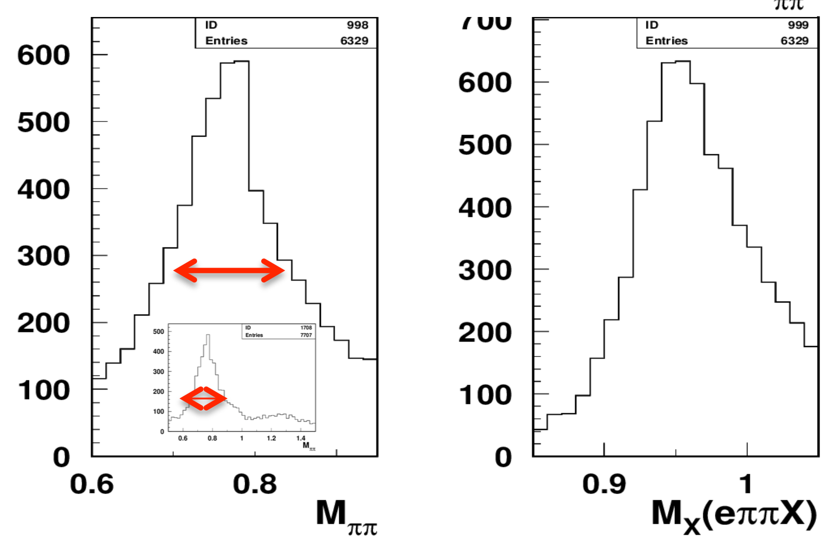
3

Studies of ρ^0 impact with longitudinally polarized NH_3 target

Separating exclusive dihadrons





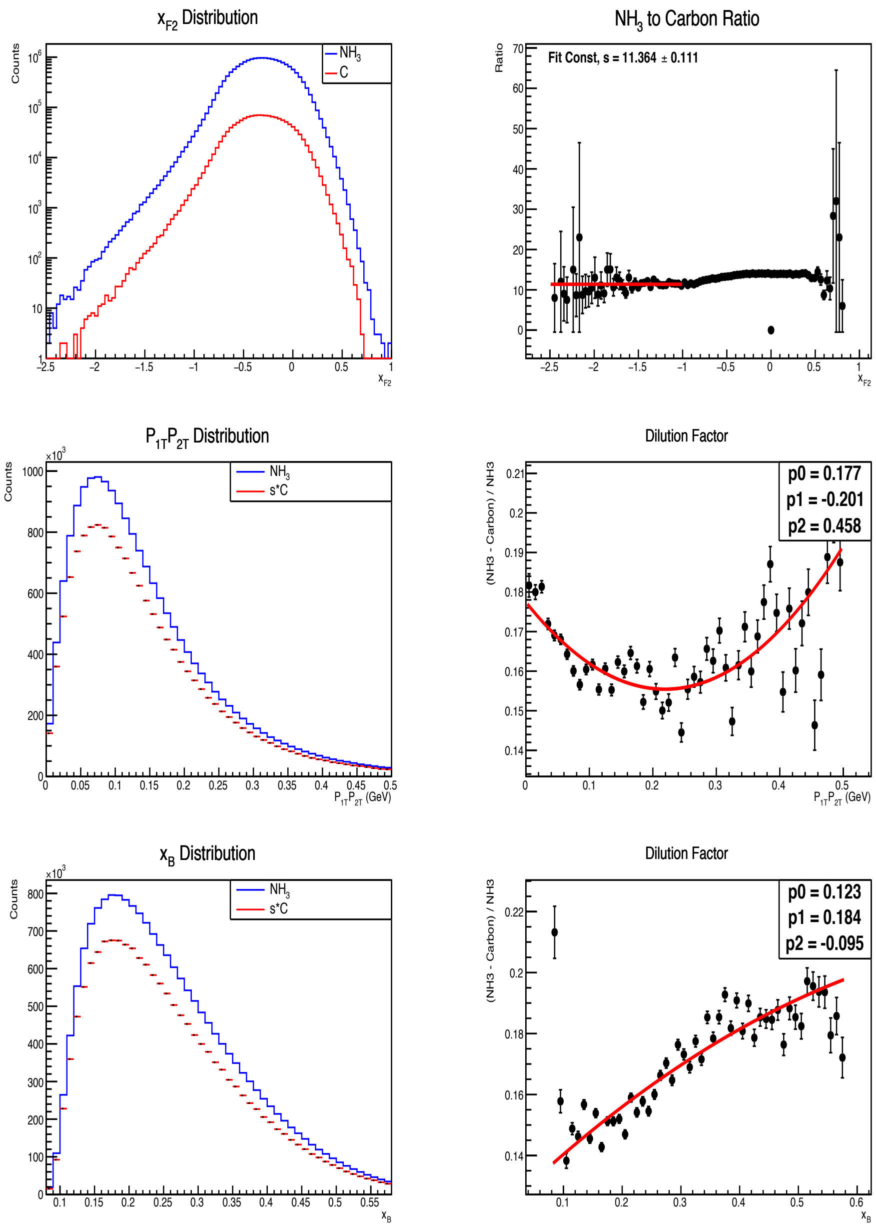


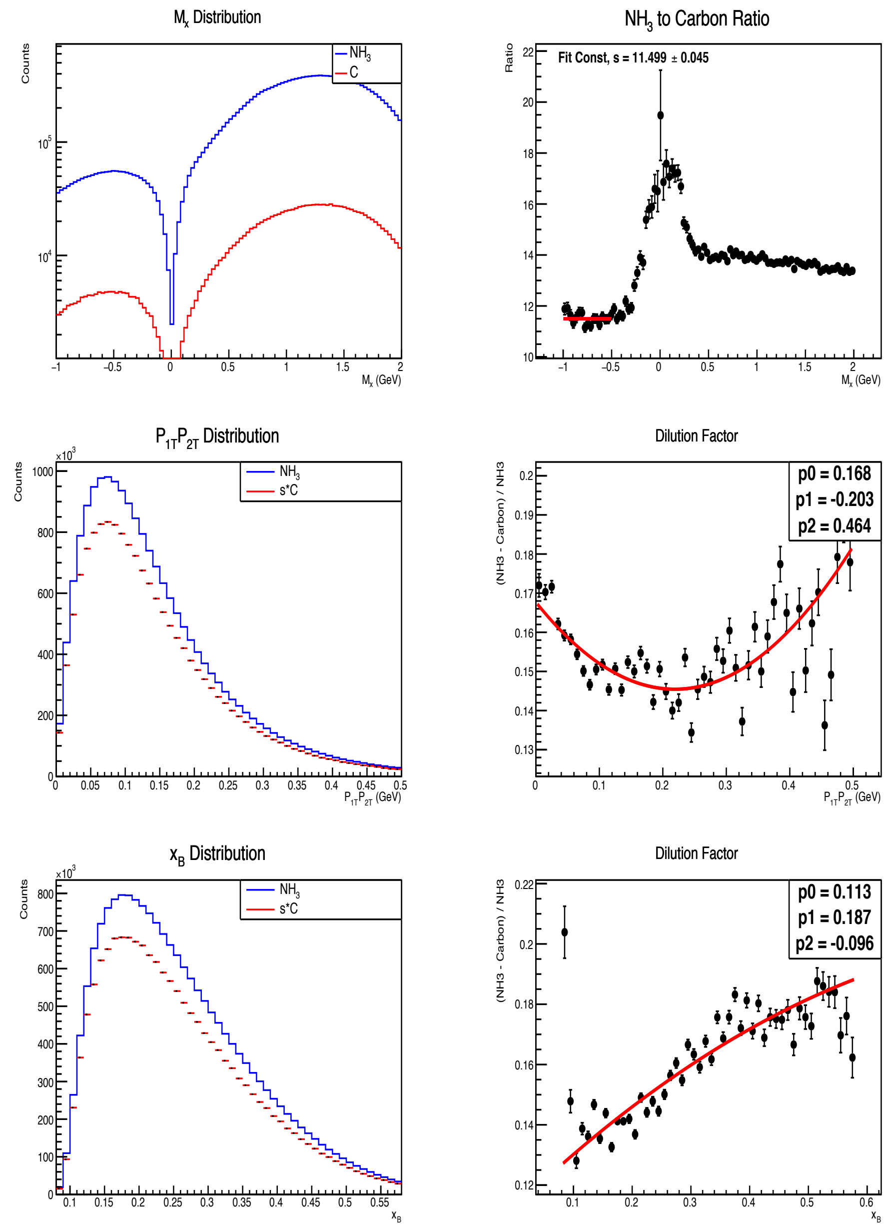
- Require the angle of negative pions is within a degree from calculated from e',p,π+ assuming exclusive e',p,$\pi+\pi$- event.
- Measurements of A_{LL} for ρ^0 indicate very small values (with ~10-20% bck, likely negative ~ -2-10%), and can be one of the reasons for higher A_{LL} with protons with a M_X cuts above 1.35 GeV (excluding exclusive ρ^0)

Request to theory→ evaluate the impact on $g_1(x,k_T)$ with all A_{LL}s increasing 10-20%

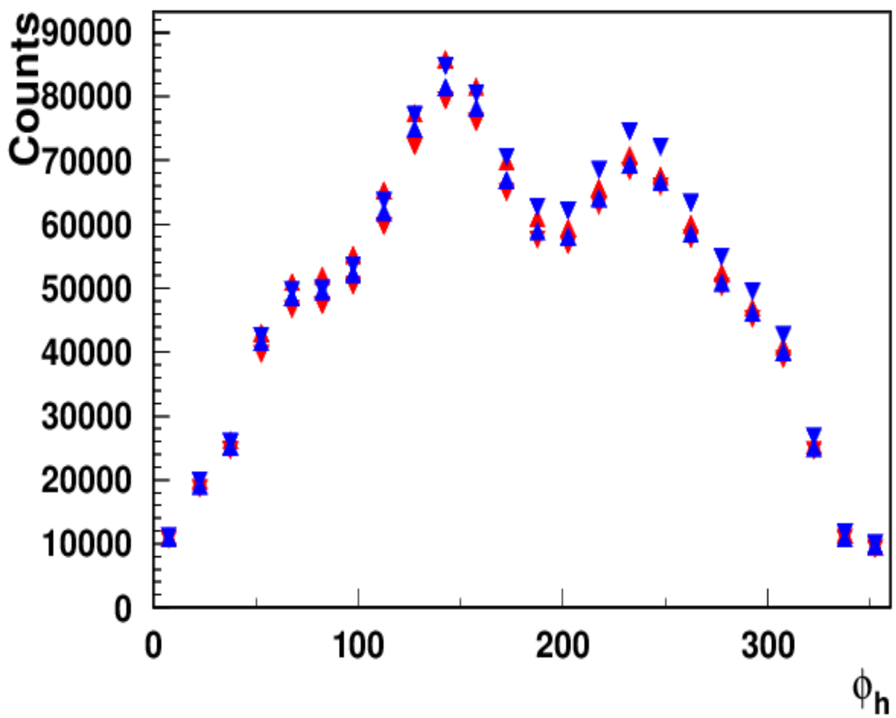
Need clear separation of hydrogen from NH_3 and diffractive exclusive ρ0s from exclusive $\pi+\pi-$

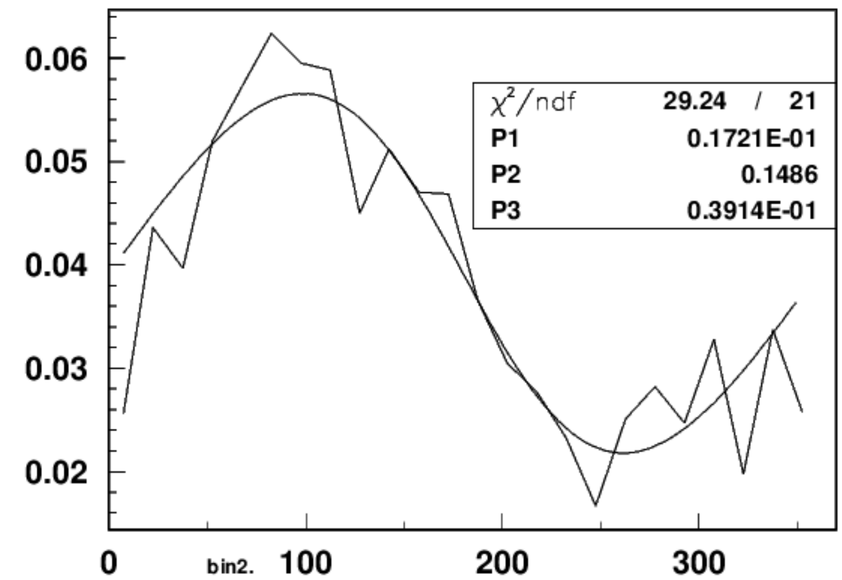
Scaling factor determined two different ways: x_{F2} and M_x; consistent results

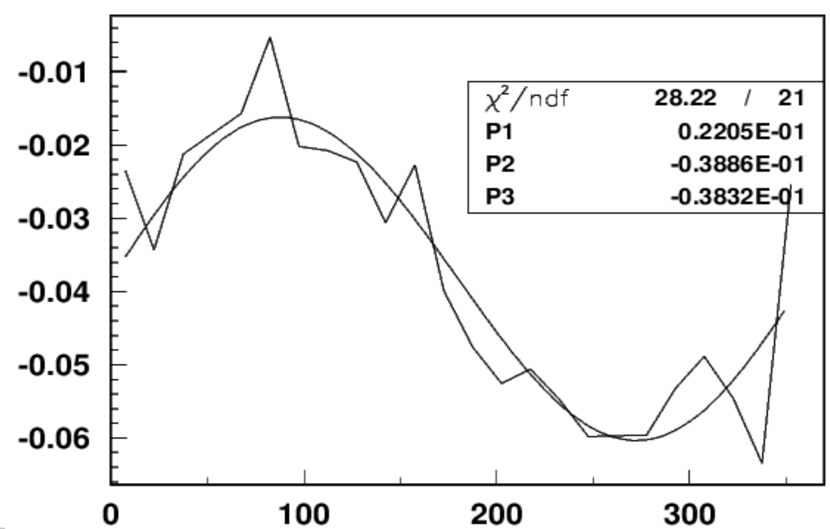




Single pions







ep->e'π+X Counts and asymmetries

Constant term corresponds to A_{LL}

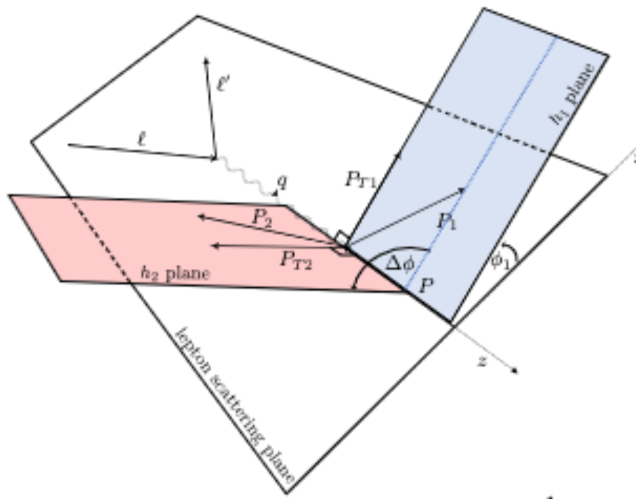
RGC: SSA in b2b hadron production

Using the sample ep→e'pπ+X

$$\frac{\alpha^2 x}{Q^4 y}\left(1+(1-y)^2\right)\begin{pmatrix}\sigma_{UU}+S_L\sigma_{UL}+S_T\sigma_{UT}+\\ \lambda D_{ll}\left(\sigma_{LU}+S_L\sigma_{LL}+S_T\sigma_{LT}\right)\end{pmatrix}$$

A. Kotzinian et al, arXiv:1107.2292

N/q	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^\perp$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^\perp$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^\perp$	$\hat{l}_{1T}^h, \hat{l}_{1T}^\perp$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$



$$\sigma_{LL} = F_0^{\hat{l}_1 \cdot D_1}$$

$$\sigma_{LU} = -\frac{P_{T1}P_{T2}}{m_N m_2} F_{k1}^{\hat{l}_1^{\perp h} \cdot D_1} \sin(\Delta\phi),$$

$$\sigma_{UL} = -\frac{P_{T1}P_{T2}}{m_N m_2} F_{k1}^{\hat{u}_{1L}^{\perp h} \cdot D_1} \sin(\Delta\phi)$$

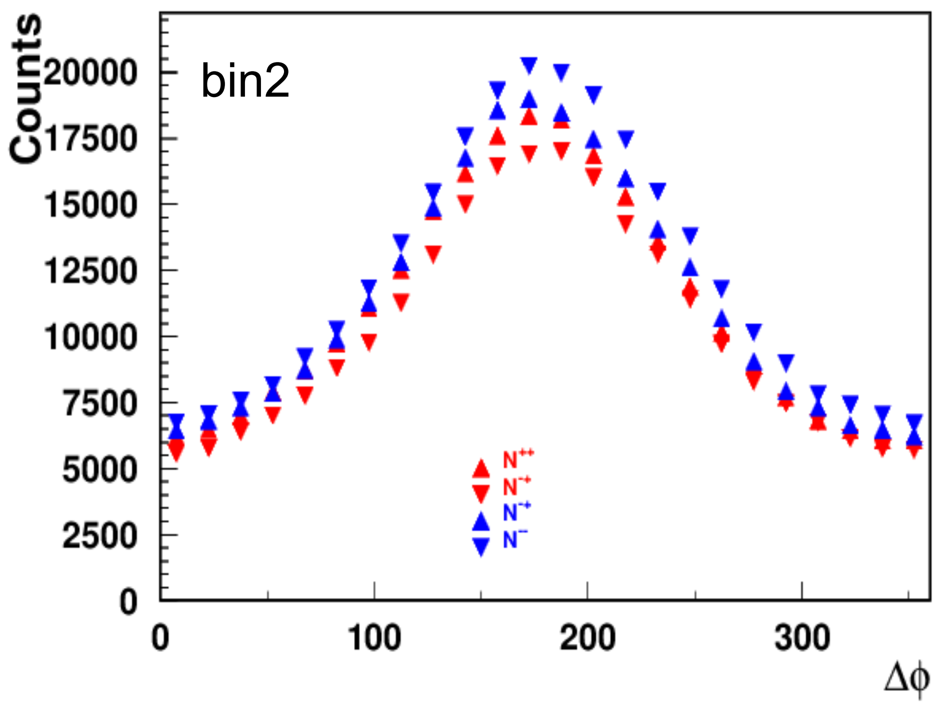
$$\sum_h \int \zeta d\zeta \int d^2 P_T \hat{l}_{1L} = (1-x) g_{1L}(x, k_T^2)$$

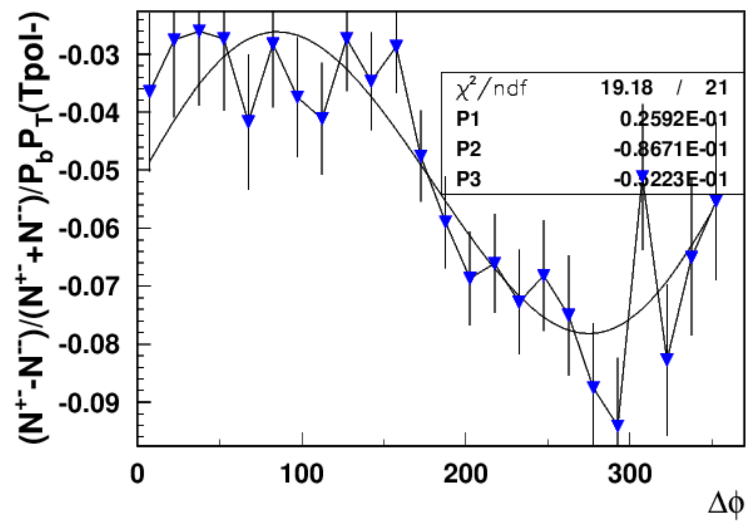
$$A_{UL} = -\frac{|\vec{P}_{T1}||\vec{P}_{T2}|}{m_N\, m_2} \frac{\mathcal{C}[w_5\, \hat{u}_{1L}^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]} \sin\Delta\phi.$$

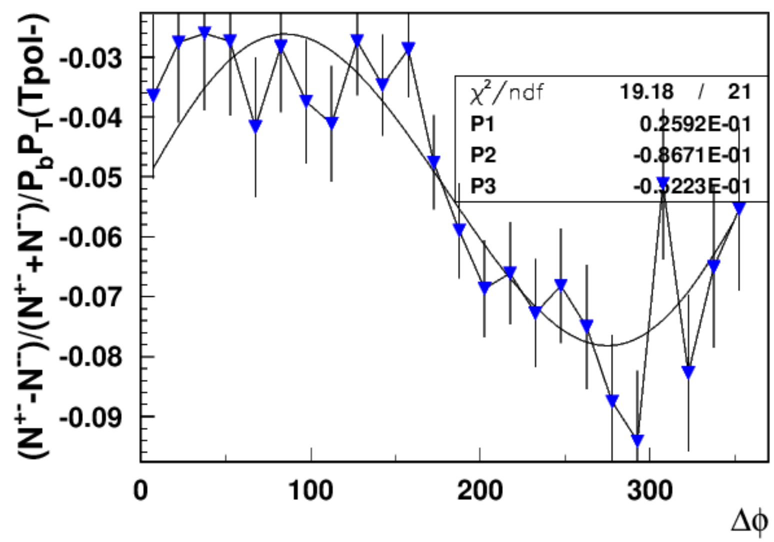
2 theory frameworks currently available to study b2b processes

Formalism based of fracture functions (Anselmino, Barone, Kotzinian
Semi-exclusive processes, involving GPDs on proton side (TFR) and TMDs on pion side (CFR) Yuan and Guo

b2b protons and pions



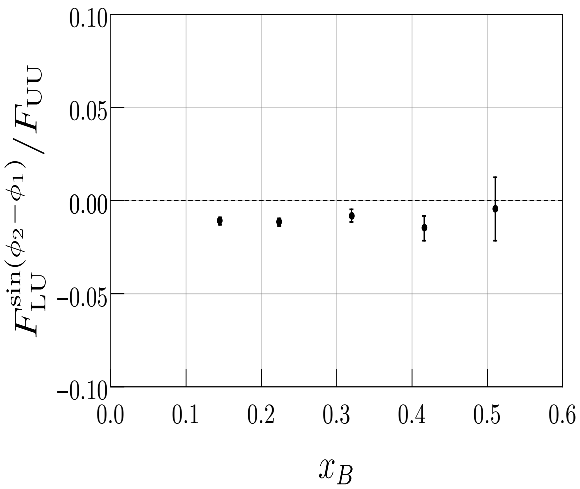




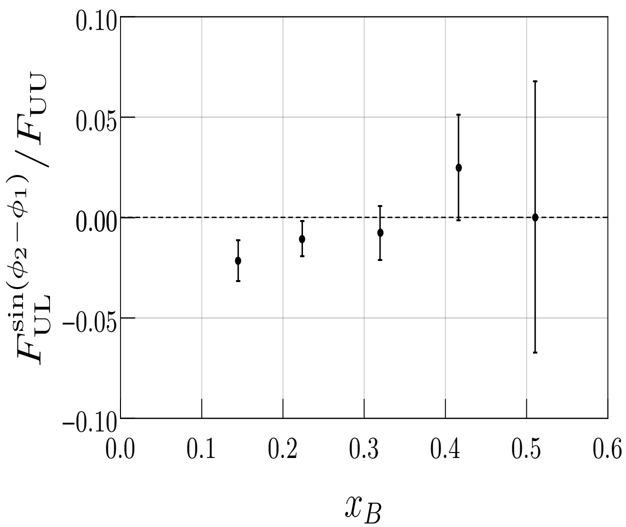
ep->e'pπ+X Counts and asymmetries

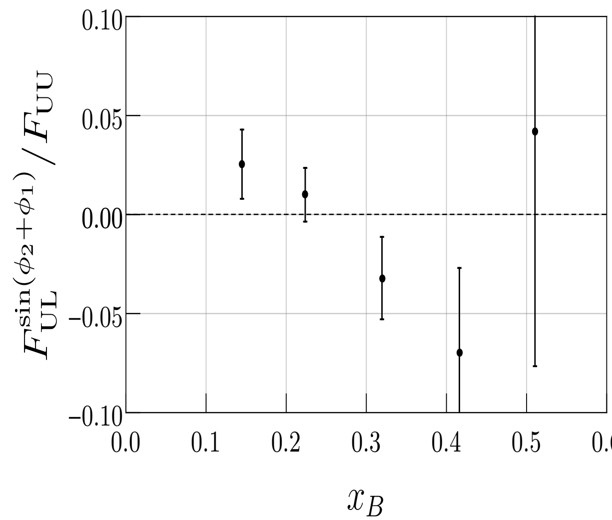
Constant term corresponds to A_{LL}

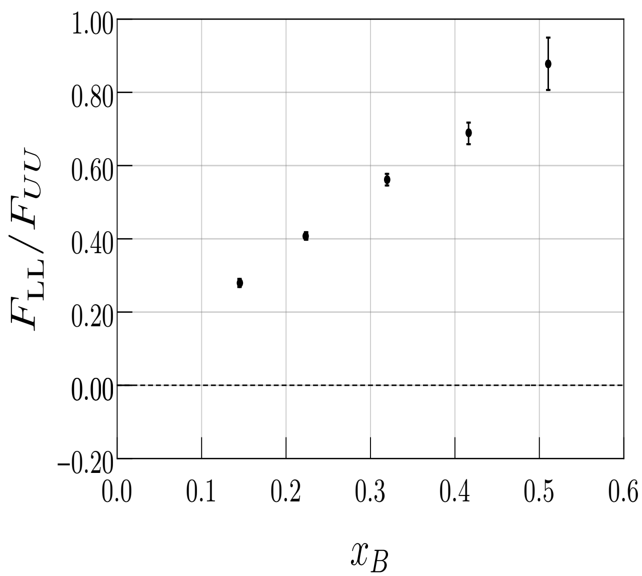
Extracting moments: x_B dependence



Cuts: DIS: $Q^2 > 1$, $W > 2$,
TFR/CFR: $z_1 > 0.2$, $x_{F1} > 0$, $x_{F2} < 0$
Inclusivity: $M_x > 0.95$, $M_{x1} > 1.8$, $M_{x2} > 1.4$





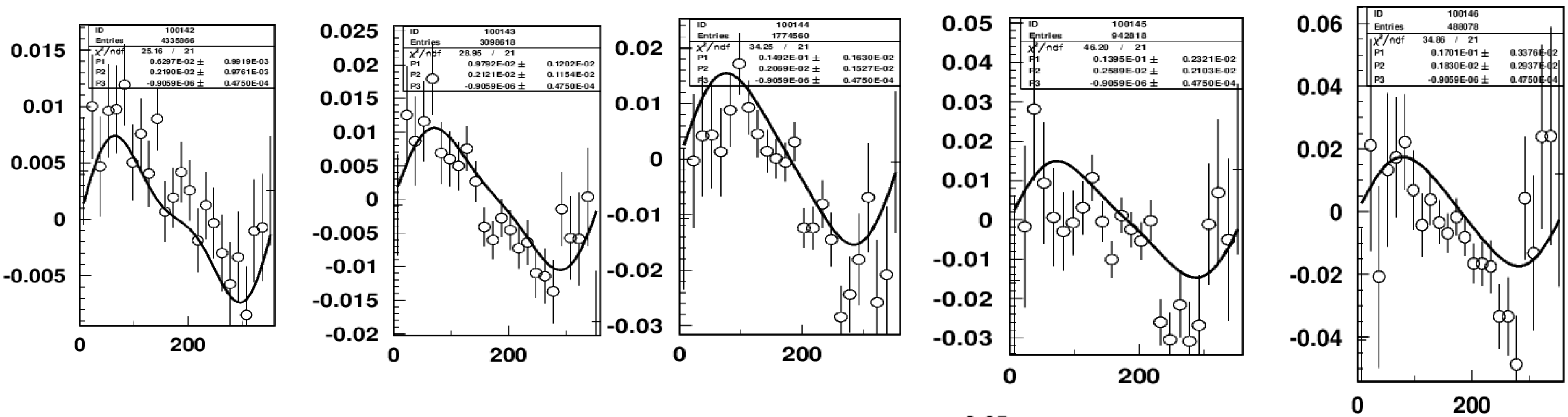


Bin	$< Q^2 >$	$< W >$	$< x_B >$	$< y >$	$< z1 >$	$< \zeta_2 >$	$< P_{1T} >$	$< P_{2T} >$	$< x_{F1} >$	$< x_{F2} >$
1	1.854	3.445	0.145	0.651	0.310	0.573	0.413	0.428	0.215	-0.324
2	2.612	3.147	0.224	0.591	0.306	0.544	0.362	0.389	0.208	-0.292
3	3.697	2.948	0.320	0.584	0.299	0.494	0.329	0.353	0.201	-0.260
4	4.984	2.798	0.416	0.605	0.292	0.439	0.307	0.318	0.194	-0.228
5	6.451	2.653	0.511	0.638	0.281	0.382	0.285	0.276	0.185	-0.195

Table 1: The mean kinematic variables in each of the bins for the extracted x_B asymmetries. Values given in GeV or GeV^2 where appropriate.

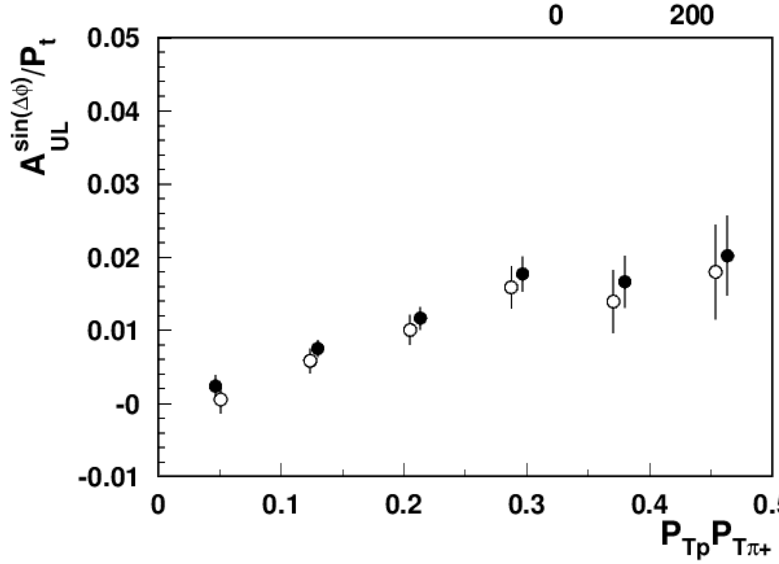
RGC SSA in b2b : PT-dependence

Using the sample ep→e'pπ+X



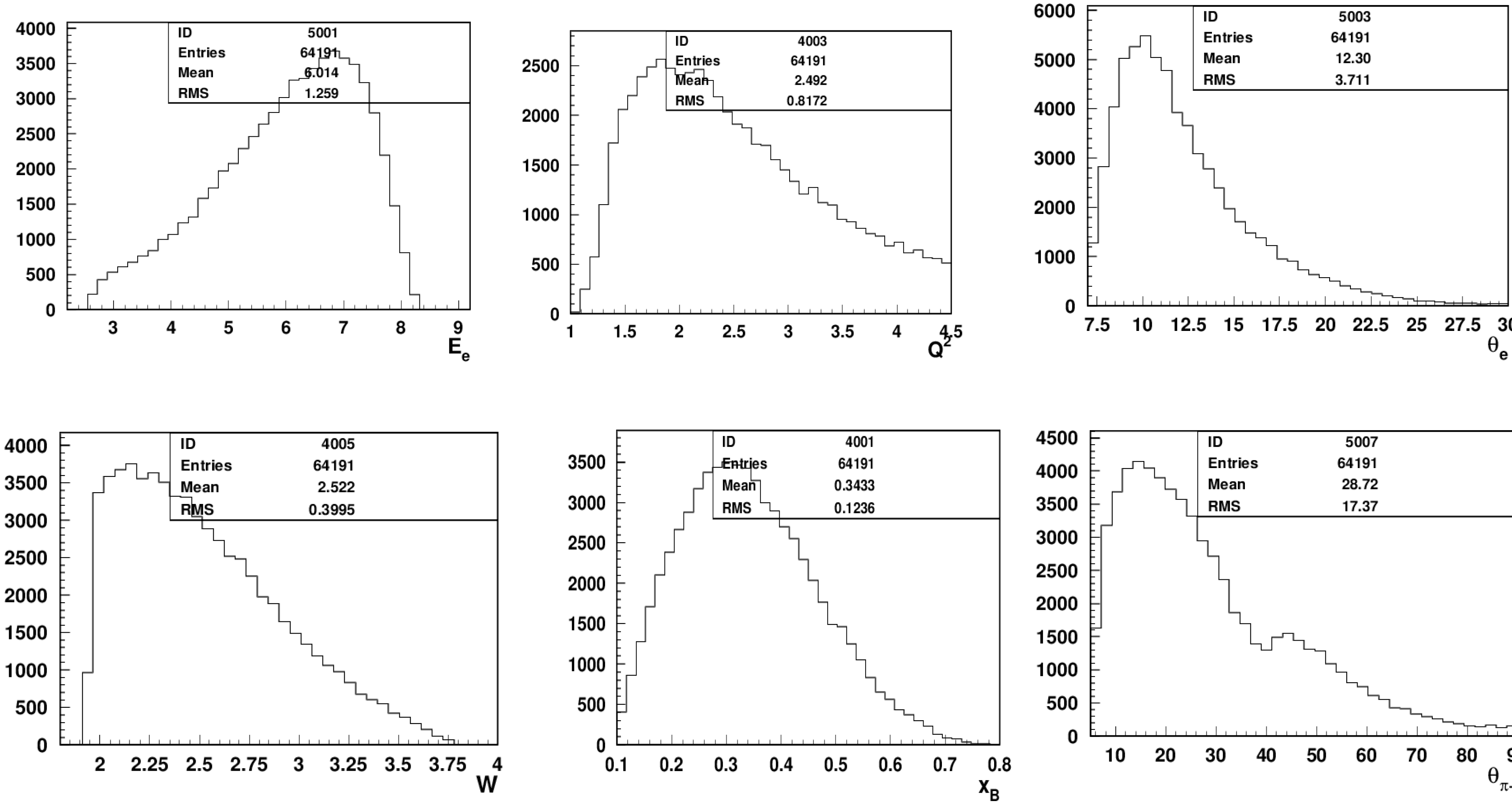
Target SSA extracted using fits to AUL(f) in bins of $P_T p P_T \pi+$

2 methods consistent



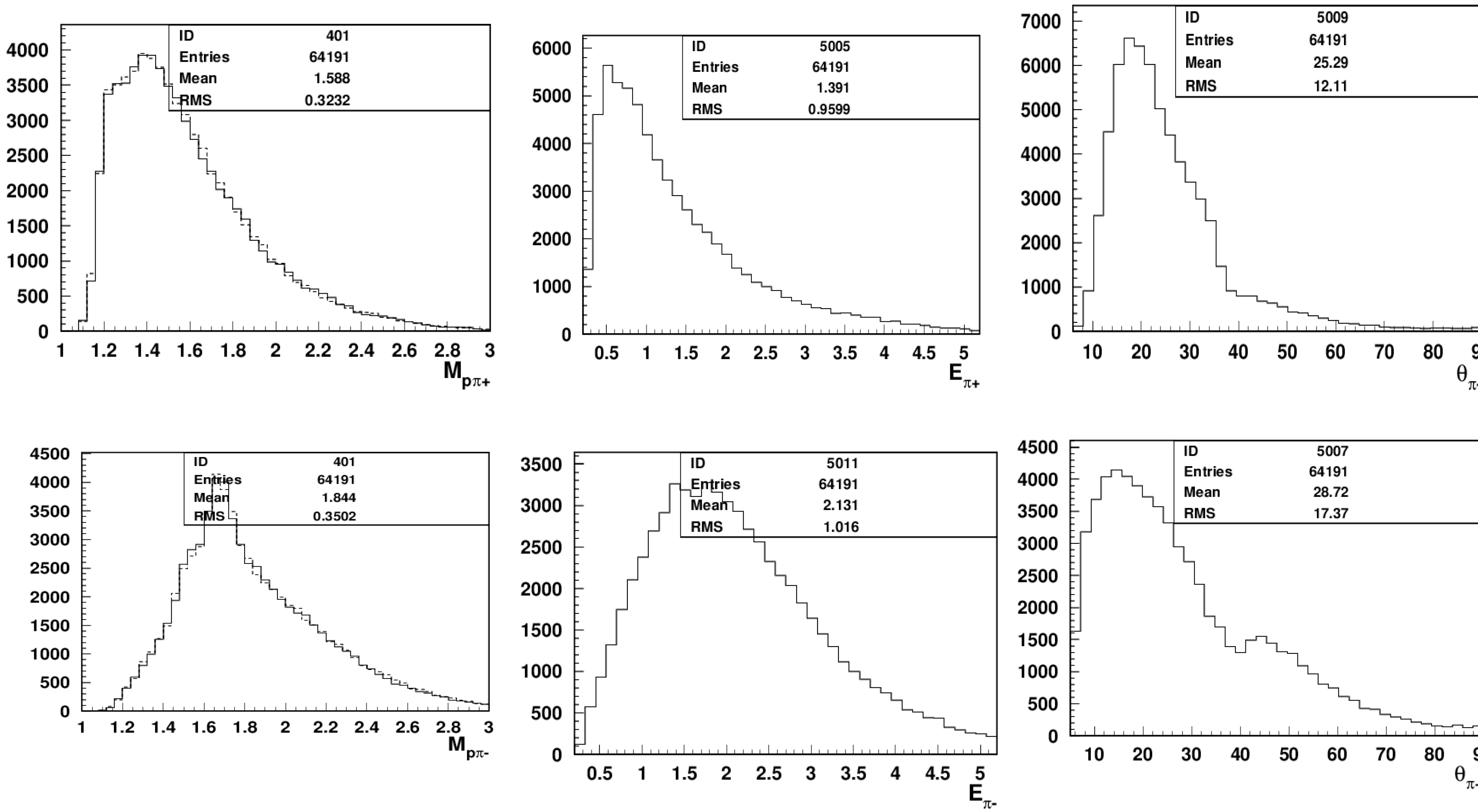
RGC: 2pion distributions

Using the sample ep→e'pπ+π−X



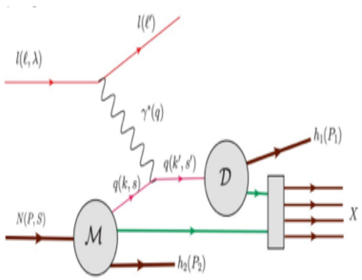
RGC: 2pion distributions

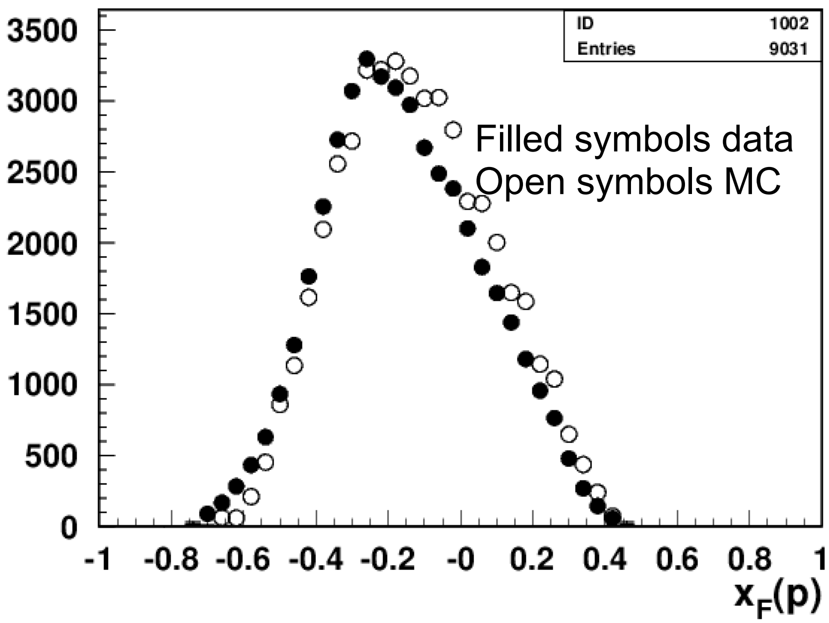
Using the sample ep→e'pπ+π−X

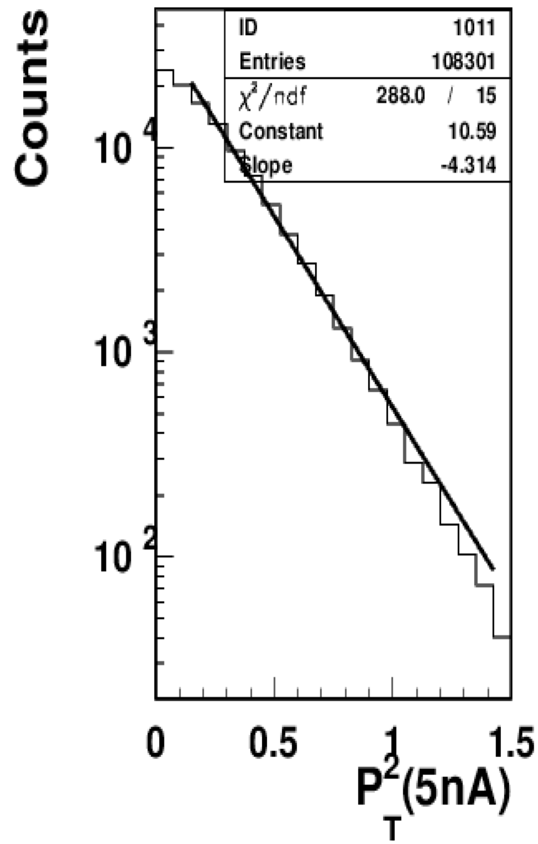


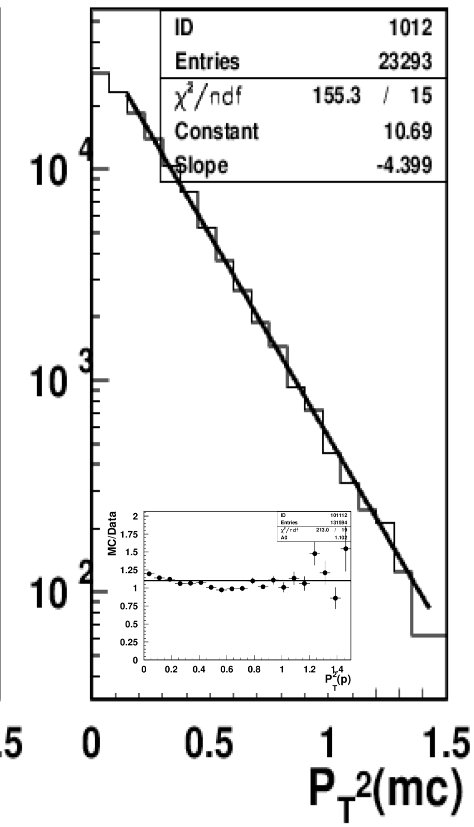
CLAS12 Studies: Data vs MC

Using PEPSI (LUND) generator









- Kinematic distributions, z,x_F,P_T-distributions of protons, and widths are in good agreement with LEPTO
- TFR may be a valuable source for studies of widths in hadronization
- Expect significantly better separation of TFR and CFR at JLab24

SIDIS cross section: separating $F_{UU,L}$

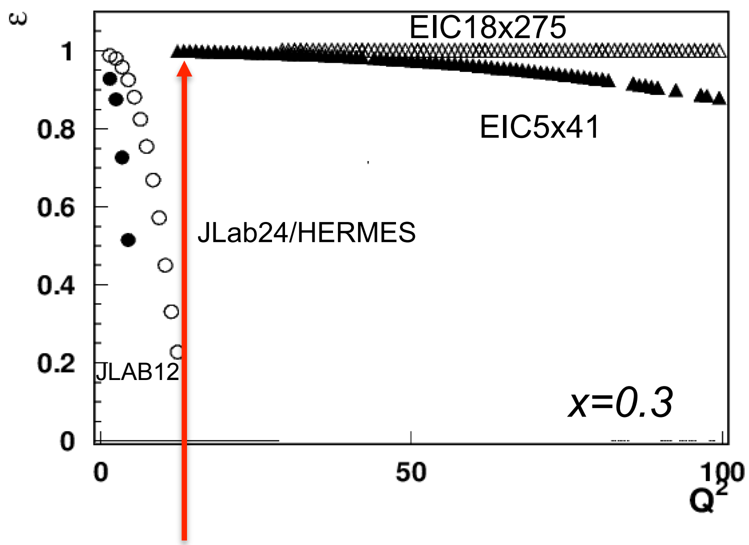
Semi-Inclusive:

ratio of longitudinal and transverse photon flux

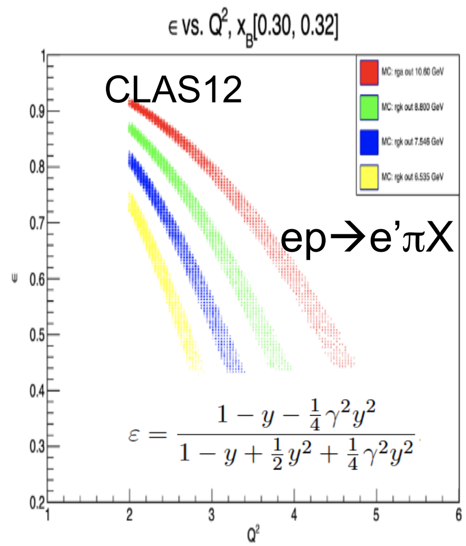
$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_\parallel\left[\sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] + S_\parallel\lambda_e\sqrt{1-\varepsilon^2}\,F_{LL}\Big\}$$

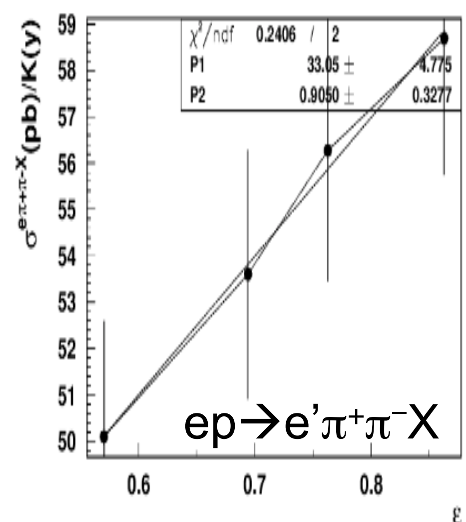
Hall-C E12-06-104
E12-23-014
Hall-B E12-16-010C

Separation of contributions from longitudinal and transverse photons critical for interpretation



Wide ε-coverage needed!!!



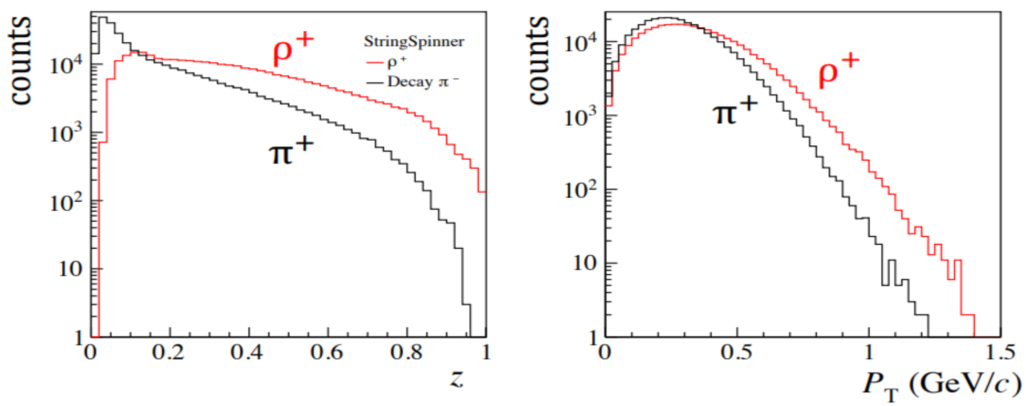


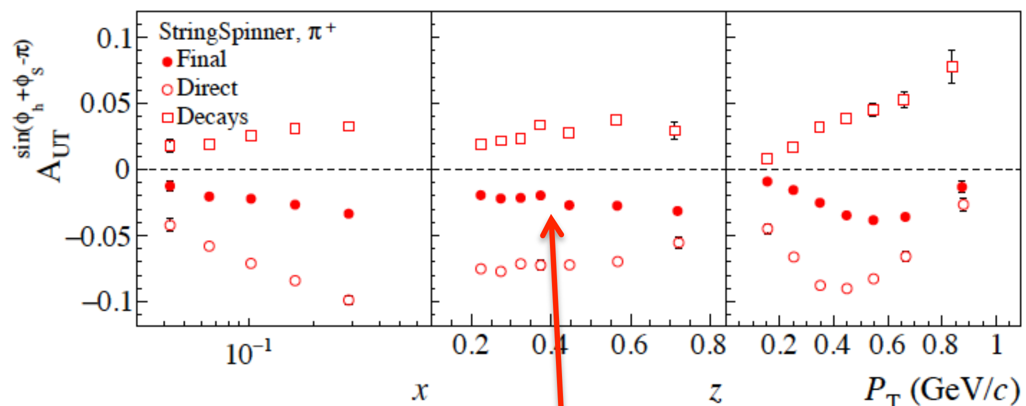
- At higher energies longitudinal photon contributions kinematically enhanced (at EIC 5 times bigger at Q^2~10)
- JLab studies critical for EIC data interpretation

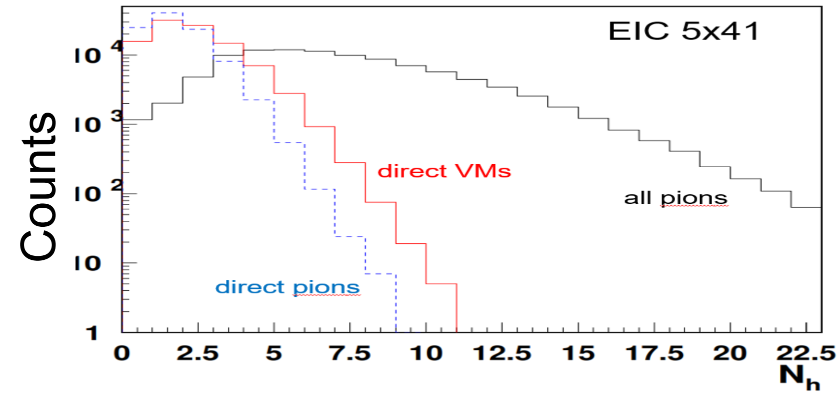
$R=F_{UU,L}/F_{UU,T}$ depend on the process, need for all relevant ones, in all kinematics!

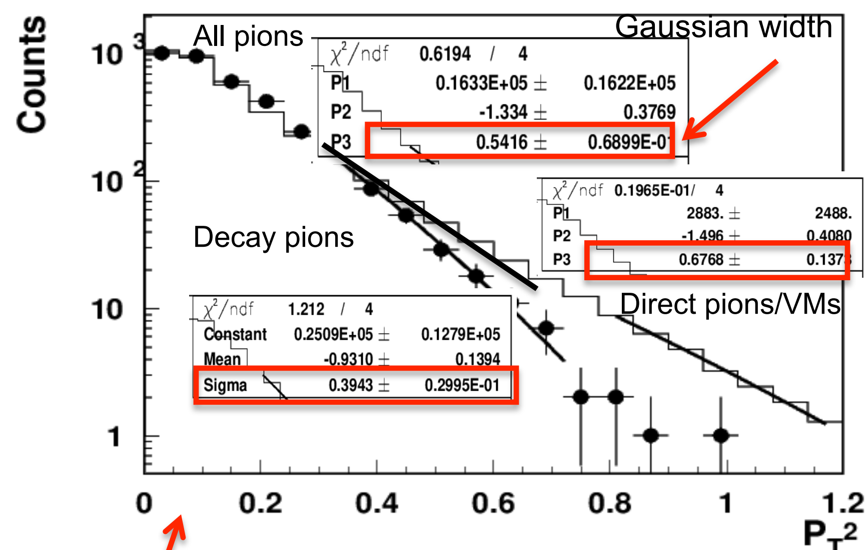
VM contributions

A. Kerbizi (Trieste U.)





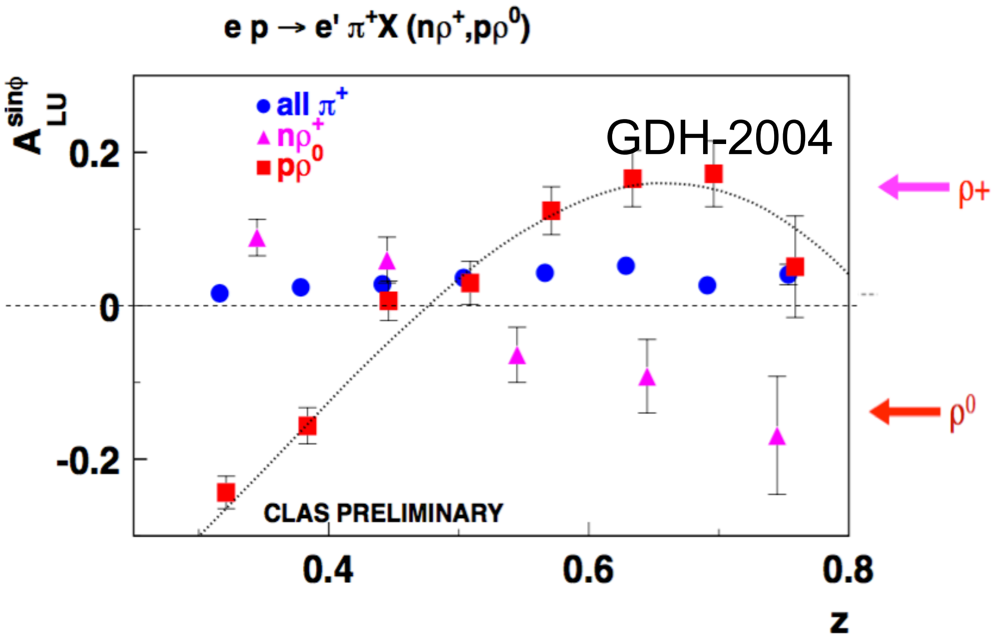


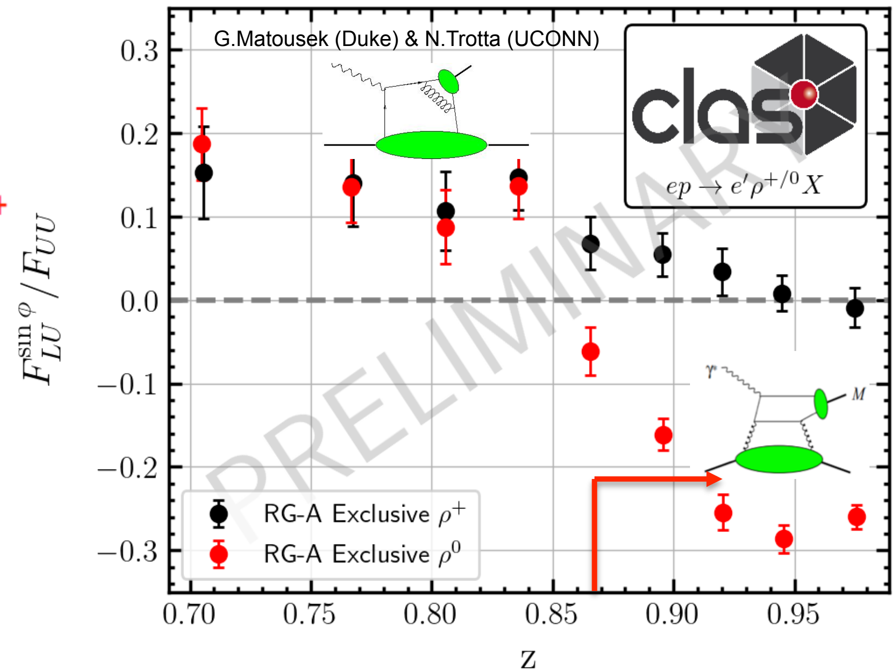


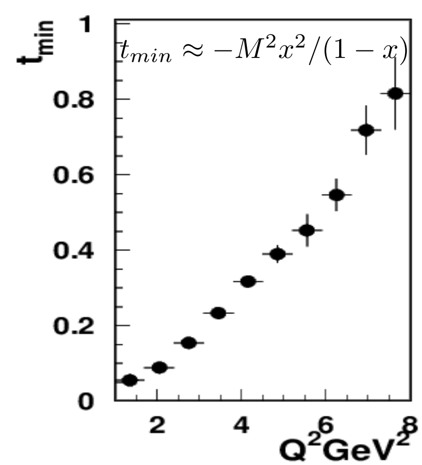
- Strong dilution of SSAs(3-5 for pions 2-3 for Kaons) due to VM decays
- Significant differences in pions vs Kaons from VMs(JLab can measure also K*, and their SSAs)

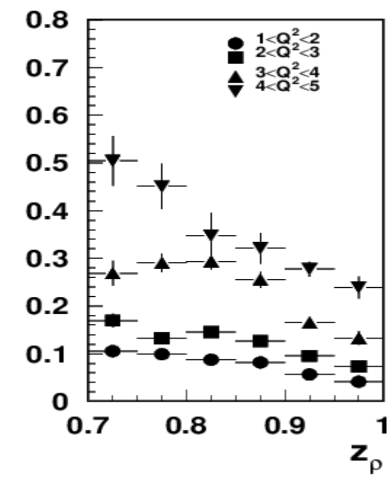
Understanding VMs is critical for interpretation even for unpolarized data

Quark-gluon correlations: impact of VMs





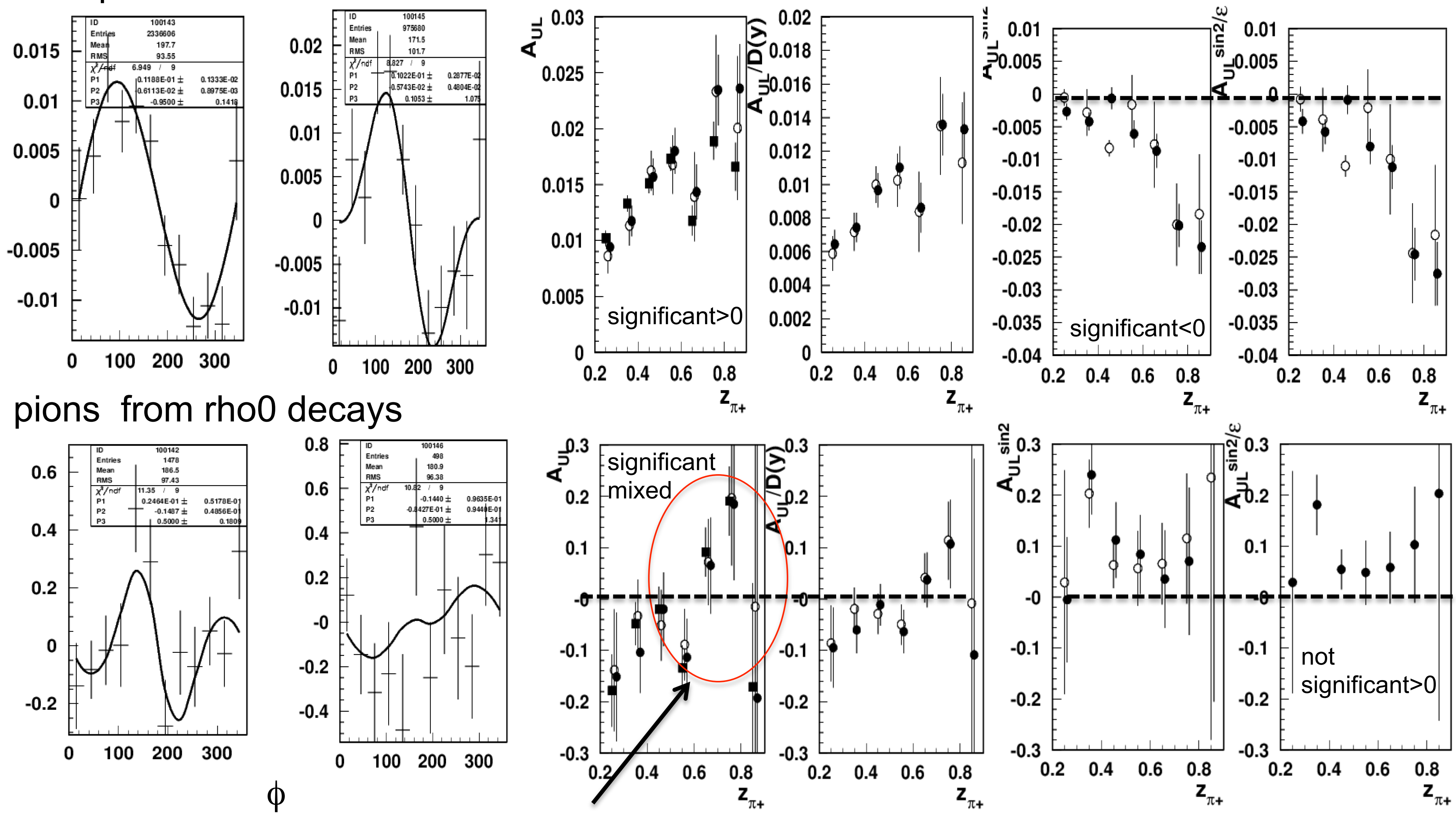




- Understanding of SSAs of VMs is critical in interpretation of the pion SIDIS
- A_{LU} sign change can define the dominating process!!!
- At large x the diffractive processes are suppressed by the minimum t

Exclusive rho: impact on $\pi+$ A_{UL} SSAs

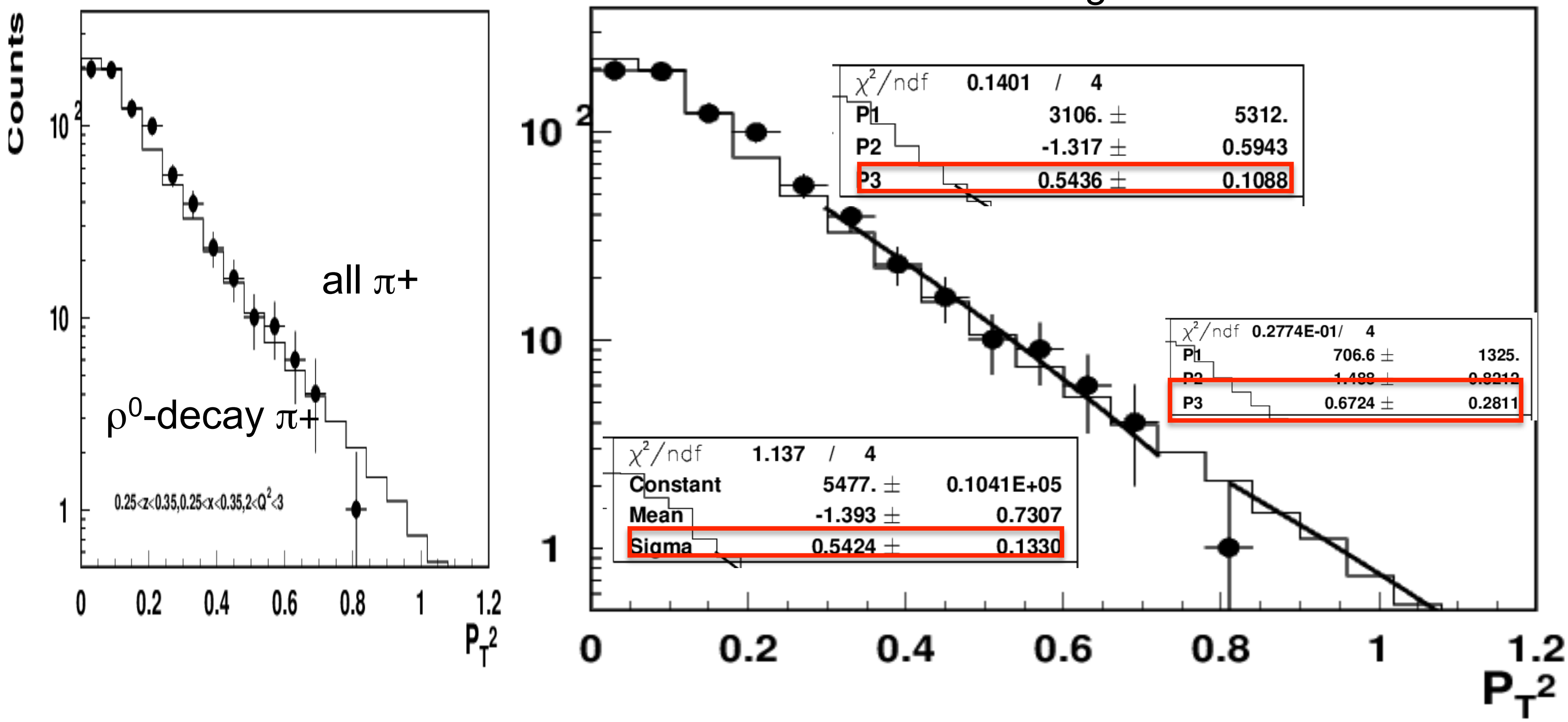
All pions



At large z the impact of rho may be significant, even if rho itself may not have significant SSA

VM contributions:3D space

Use a single Gaussian fit



Understanding VMs is critical for interpretation, extraction of P_T-widths, following extraction of k_T-widths (tails stay the same)

Similar situation with Kaons and K*