ExtreMe Matter Institute

EMMI

EMMI Rapid Reaction Task Force: Impact of Vector Mesons on the studies of the 3D structure of the nucleon

CERN, June 15-19, 2026

Harut Avakian (JLab)

- EMMI-supported RRTF is essentially a **"think tank"** locking a small group of experts in a room for a few days to crack a critical, time-sensitive scientific puzzle.
- **Fully exploiting vector meson production to map the nucleon's 3D structure requires: a) complex theoretical frameworks that are still highly debated, b) establish systematic ways to analyse the data via multi-differential cross-section and polarization measurements, c) develop robust Monte Carlo simulation frameworks and advanced phenomenological tools for global data extraction, such as neural-network-based fitting and modern amplitude analysis packages.**

- **Targeted Objective:** It is convened "rapidly" when an urgent scientific question arises.
- **Restricted Participation:** Attendance is **by invitation only**. It brings together a limited number of experts who are directly working on the specific problem.
- **Working Format:** Instead of a long schedule of standard presentations, RRTFs prioritize active collaboration, featuring brief introductory talks followed by **extensive round-table discussions** and **debates.**
- **The Deliverable:** The ultimate goal is to produce a concrete output. Within a few months of the meeting, the group publishes a **Final RRTF Report** or a joint scientific paper that outlines the consensus, resolves the discrepancy, or sets the roadmap for future research.

EMMI Rapid Reaction Task Force: Impact of Vector Mesons on the studies of the 3D structure of the nucleon

https://indico.gsi.de/event/24556/overview

Jun 15 – 19, 2026
CERN
Europe/Berlin timezone

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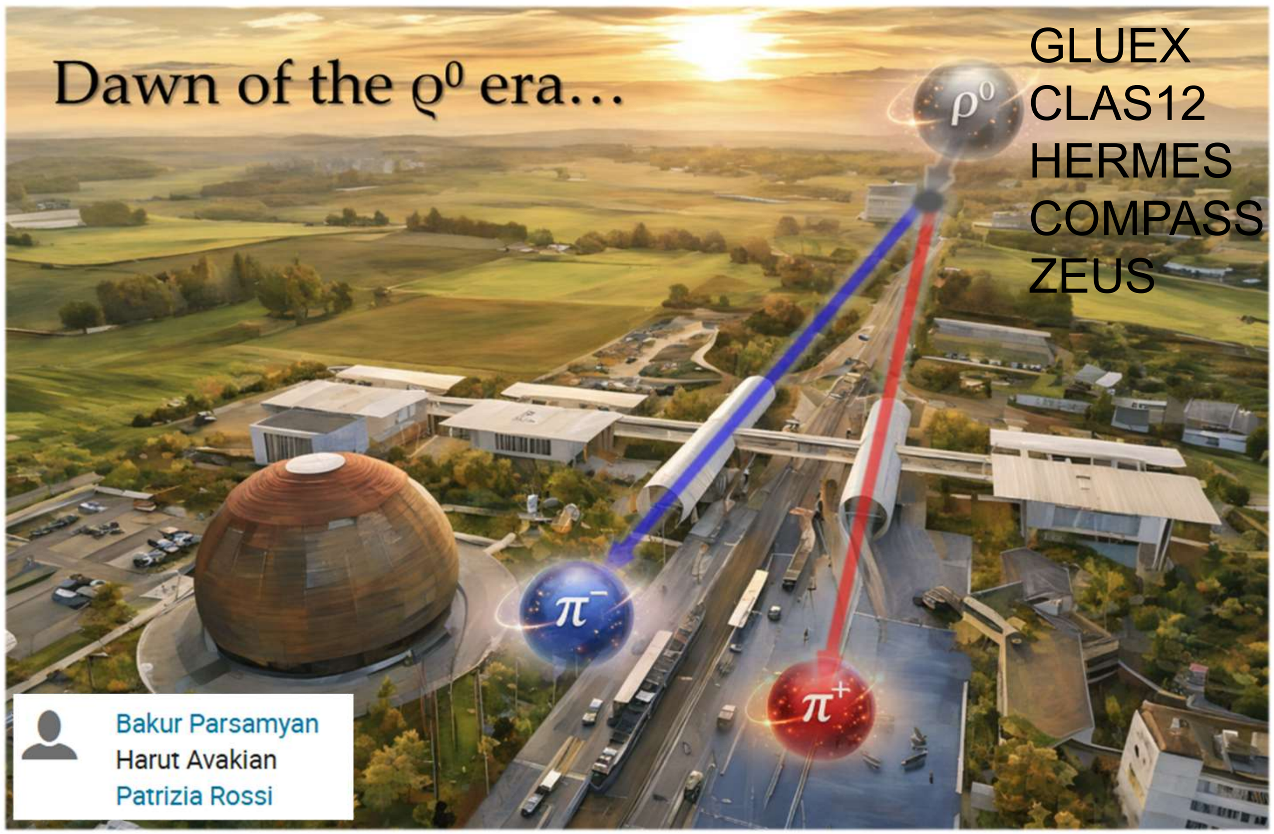
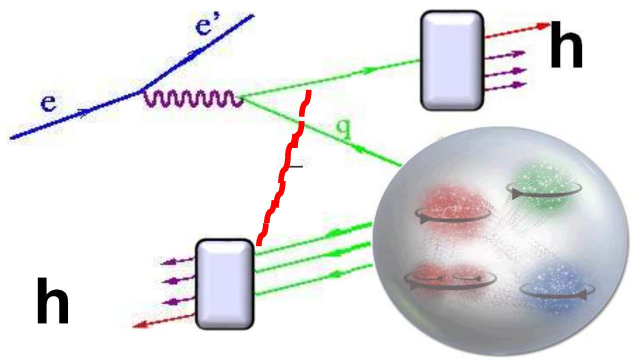


3D PDFs: Electroproduction of hadrons

Current Fragmentation Region (CFR)

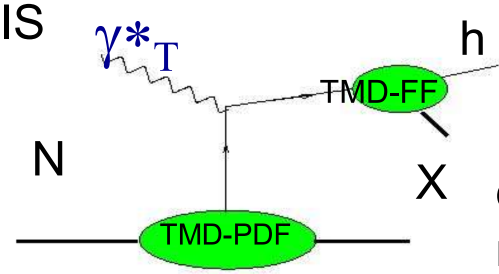
$x_F>0$



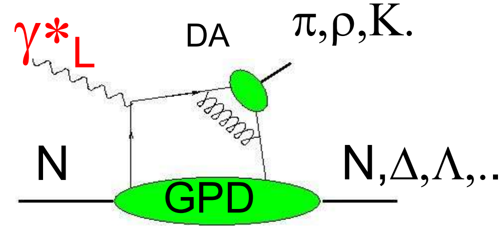
$x_F<0$

Target Fragmentation Region (TFR)

SIDIS



HEP



Study

x,Q^2,z,P_T,ϕ,ϕ_S ~$1/Q^4$

Flavor and polarization dependence of transverse momentum distributions

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

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 relevant with several independent variables involved
- Cross contributions make studies based on a given set of assumptions challenging

One-photon exchange cross sections for eh→e'hX

$$\frac{d\sigma^{lN\to l'hX}}{dx_B dQ^2 dz dP^2_{h\perp} d\phi_h} = \frac{K(x,y)}{Q^4}\left\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi} + \varepsilon\cos(2\phi_h) F_{UU}^{\cos 2\phi} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi}\right\}$$

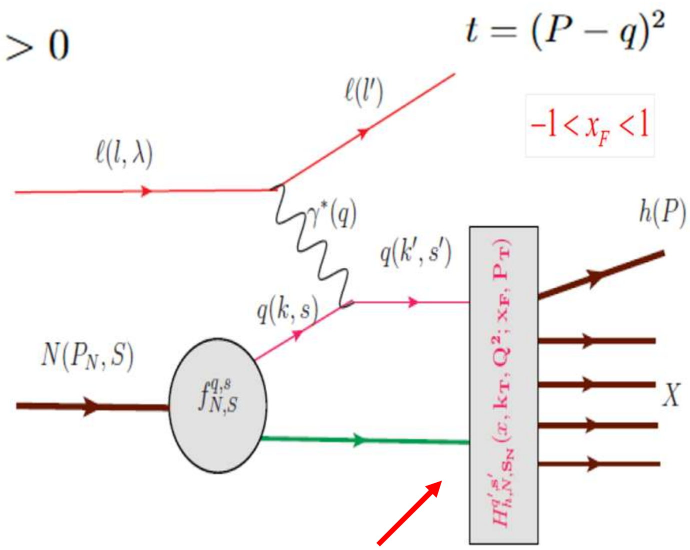
The only difference with exclusive production is the $M_X^2 - M_p^2 > 0$

$t = (P-q)^2$

$$-t = M_p^2 - M_X^2 + \frac{Q^2}{x_{\rm Bj}}(1-z)$$

$$\int dz\, \delta(M_X^2(z,t) - M_p^2) = \frac{1}{|\partial M_X^2/\partial z|} = \frac{x_{\rm Bj}}{Q^2}$$

probability to produce π+



Hadronization function **describes the probability to produce a hadron** (π,K,…) **for a given leftover configuration with spin and flavor content**

Additional 1/Q² appears after replacement of z with t

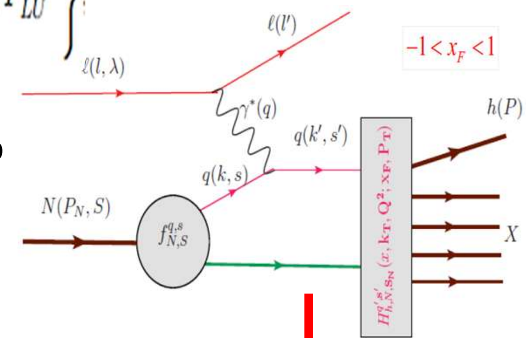
Event generators such as PYTHIA (based on string fragmentation) are for years describing semi-inclusive production of hadrons in the full energy range of experiments and also exclusive limit (extension to polarization critical!!!)

One-photon exchange cross sections for eh→e'hX

0 for low P_Ts

$$\frac{d\sigma^{lN\to l'hX}}{dx_B\, dQ^2\, dz\, dP_{h\perp}^2\, d\phi_h} = \frac{K(x,y)}{Q^4}\left\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi}+\varepsilon\cos(2\phi_h)F_{UU}^{\cos 2\phi}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi}\right\}$$

Hadronization function



SIDIS phenomenology

$$lN \to l'\pi^+X$$
$$lN \to l'\rho^0X$$
....

$$lN \to l'\pi^+X$$

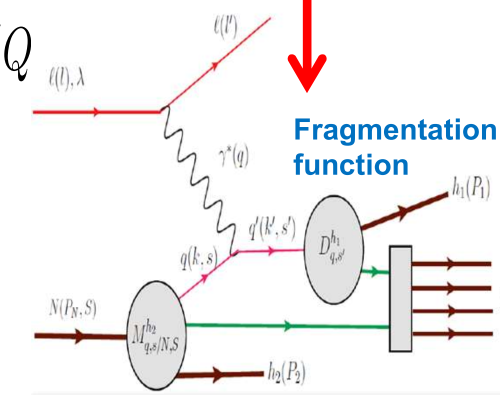
probability to produce π+

TMD Fragmentation Function

$$F_{XY}^h(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}(M/Q)$$

TMD PDF

Fragmentation function



$$\gamma_T^* p \to \pi^+ X(\pi^+ n, \pi^+\Delta, \pi^+\pi^- p, \pi^+\pi^0\pi^- \ldots)$$
....

missing in SIDIS

$$\gamma_L^* p \to \pi^+ X(\pi^+ n, \pi^+\Delta, p\rho^0, \pi^+\pi^0\pi^- \ldots)$$

$$\gamma_L^* p \to p\rho_L^0$$

→ most significant
→ increases at higher energies

$$lN \to l'\pi^+X$$

experiment

What type of exclusive processes should we cut out from experiment to have an adequate comparison with theory which doesn't have longitudinal photon contributions?

Transverse & Longitudinal photons

Structure function	γ^* helicity	prefactor	low-P_{hT} twist	low-P_{hT} PDF	high-P_{hT} calculation twist	order	power	JLab	EIC
$F_{UU,T}$	TT	1	2	f_1	2	α_s	$1/P_{hT}^2$	+	+
$F_{UU,L}$	LL	ϵ	4		2	α_s	$1/Q^2$	+	=
$F_{UU}^{\cos\phi_h}$	LT	$\sqrt{2\epsilon(1+\epsilon)}$	3	$h,\ f^\perp$ + tw. 2	2	α_s	$1/(QP_{hT})$	+	=
$F_{UU}^{\cos 2\phi_h}$	TT	ϵ	2	$h_1^\perp$	2	α_s	$1/Q^2$ [*]	+	+
$F_{LU}^{\sin\phi_h}$	LT	$\sqrt{2\epsilon(1-\epsilon)}$	3	$e,\ g^\perp$ + tw. 2	2	α_s^2	$1/(QP_{hT})$	+	−
$F_{UL}^{\sin\phi_h}$	LT	$\sqrt{2\epsilon(1+\epsilon)}$	3	$h_L,\ f_L^\perp$ + tw. 2	2	α_s^2	$1/(QP_{hT})$	+	=
$F_{UL}^{\sin 2\phi_h}$	TT	ϵ	2	$h_{1L}^\perp$	2	α_s^2	$1/Q^2$ [*]	+	=
F_{LL}	TT	$\sqrt{1-\epsilon^2}$	2	g_1	2	α_s	$1/P_{hT}^2$	+	−
$F_{LL}^{\cos\phi_h}$	LT	$\sqrt{2\epsilon(1-\epsilon)}$	3	$e_L,\ g_L^\perp$ + tw. 2	2	α_s	$1/(QP_{hT})$	+	−
$F_{UT,T}^{\sin(\phi_h-\phi_S)}$	TT	1	2	$f_{1T}^\perp$	3	α_s	$1/P_{hT}^3$	+	=
$F_{UT,L}^{\sin(\phi_h-\phi_S)}$	LL	ϵ	4		3	α_s	$1/(Q^2P_{hT})$	+	−
$F_{UT}^{\sin(\phi_h+\phi_S)}$	TT	ϵ	2	h_1	3	α_s	$1/P_{hT}^3$	+	=
$F_{UT}^{\sin(3\phi_h-\phi_S)}$	TT	ϵ	2	$h_{1T}^\perp$	3	α_s	$1/(Q^2P_{hT})$ [*]	=	−
$F_{UT}^{\sin\phi_S}$	LT	$\sqrt{2\epsilon(1+\epsilon)}$	3	$f_T,\ h_T,\ h_T^\perp$ + tw. 2	3	α_s	$1/(QP_{hT}^2)$	+	=
$F_{UT}^{\sin(2\phi_h-\phi_S)}$	LT	$\sqrt{2\epsilon(1+\epsilon)}$	3	$f_T^\perp,\ h_T,\ h_T^\perp$ + tw. 2	3	α_s	$1/(QP_{hT}^2)$	=	−
$F_{LT}^{\cos(\phi_h-\phi_S)}$	TT	$\sqrt{1-\epsilon^2}$	2	g_{1T}	3	α_s	$1/P_{hT}^3$	+	=
$F_{LT}^{\cos\phi_S}$	LT	$\sqrt{2\epsilon(1-\epsilon)}$	3	$g_T,\ e_T,\ e_T^\perp$ + tw. 2	3	α_s	$1/(QP_{hT}^2)$	=	−
$F_{LT}^{\cos(2\phi_h-\phi_S)}$	LT	$\sqrt{2\epsilon(1-\epsilon)}$	3	$g_T^\perp,\ e_T,\ e_T^\perp$ + tw. 2	3	α_s	$1/(QP_{hT}^2)$	=	−

Need a similar table for exclusive Helicity Structure Functions!!!

Bacchetta-0611265

$$-t = M_p^2 - M_X^2 + \frac{Q^2}{x_{Bj}}(1-z)$$

$$P_T^2(t) \simeq -(1-x_B)t = (1-x_B)|t|$$

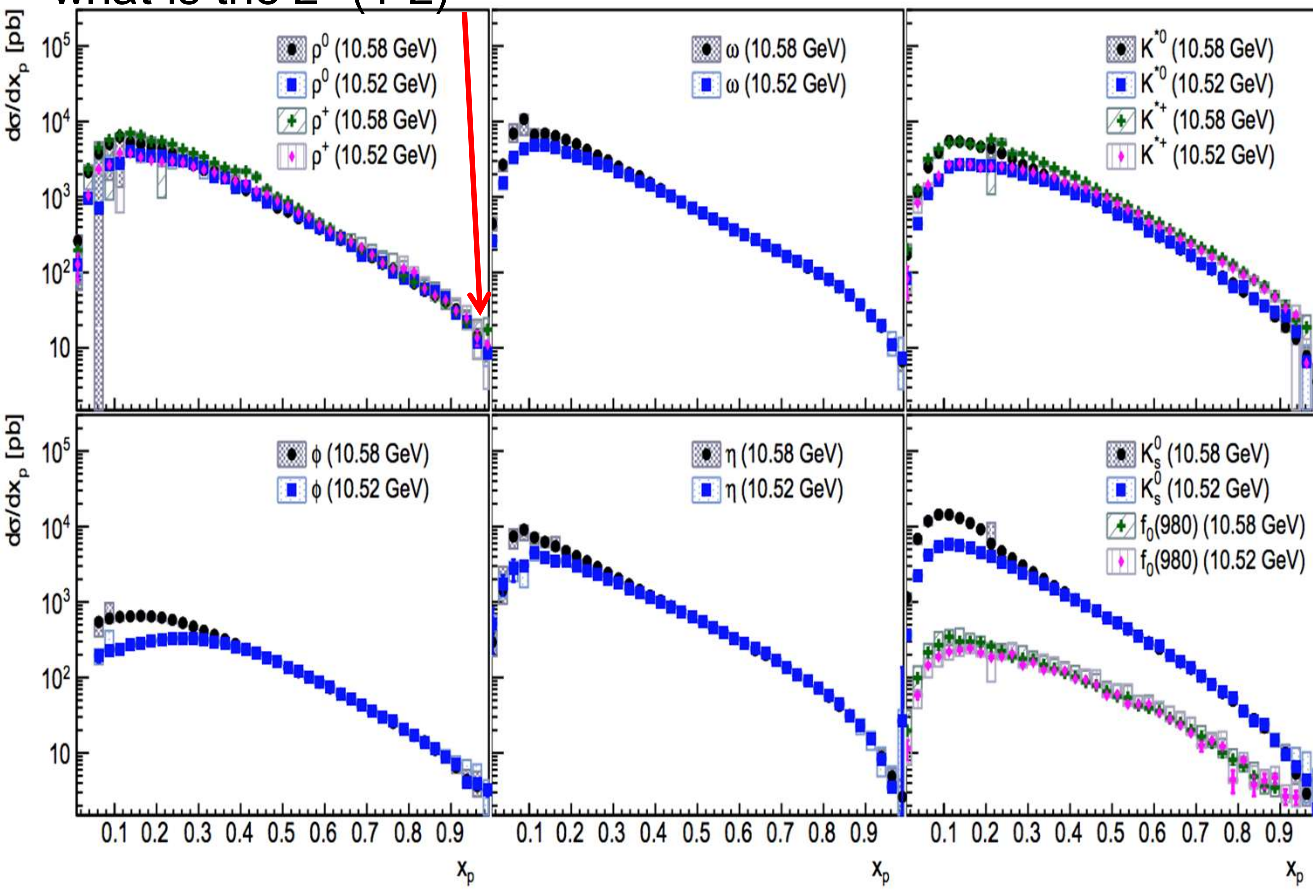
Important features to notice

- No L in Double Spin 0 moment
- Some critical observables (cross sections, $\sin(\phi-\phi_S)$) containl contributions from TT/LL and can't be separated easily
- Several TT terms, may provide info on T-amplitudes
- P_{hT} and k_T critical for understanding of transverse x-sections

cross sections in the z→1 limit from e+e-

2411.12216

what is the z^{α} (1-z) $^{\beta}$



Belle: production cross sections as a function of x_p

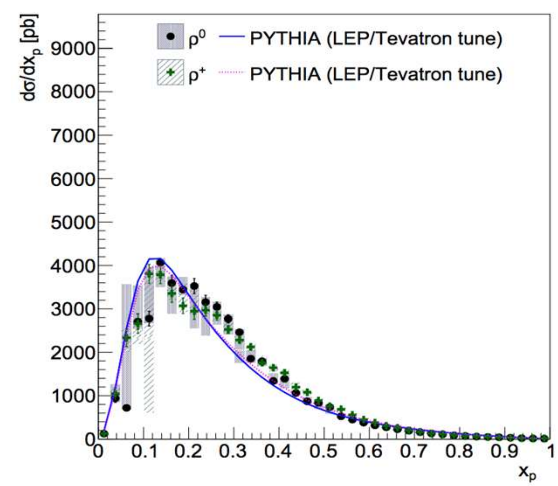
hadron momentum in e+e- CM

$$x_p = \frac{2|\vec{p}_h|}{\sqrt{s}} \quad z_h = \frac{E_h}{\nu}.$$

$$z_P = \frac{\text{hadron light-cone momentum}}{\text{fragmenting parton light-cone momentum}}$$

$$z_h \approx z_P \left[1 + \frac{M_h^2 + P_T^2}{z_P^2 Q^2}\right]^{-1}$$

$$z_P \approx \frac{1}{2}\left[x_p + \sqrt{x_p^2 + \frac{4m_h^2}{s}}\right]$$



Possible contribution from γ^*_T

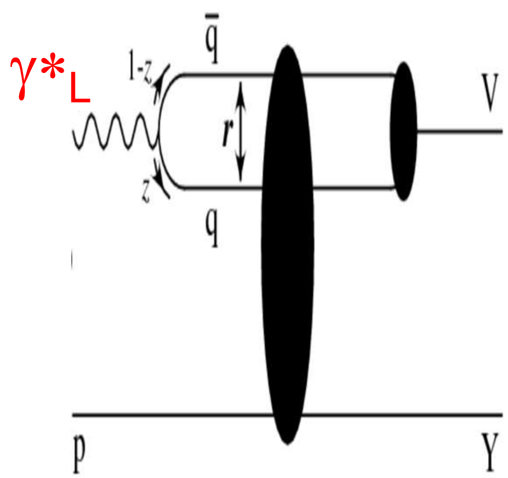
Is the γ^*_T contribution from ρ0 ρ+ comparable?

slightly more rho+!

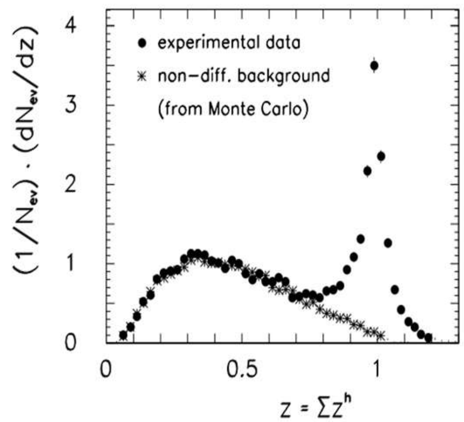
Exclusive VMs (ρ^0, ω,ϕ, J/Ψ,□)

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

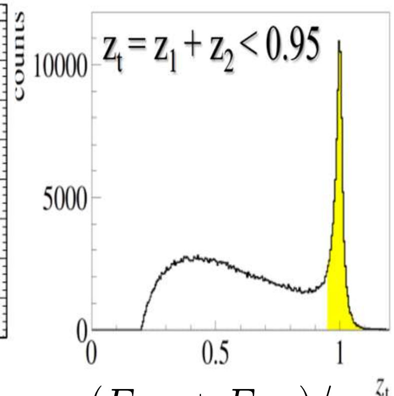
$\mu, \nu, \lambda, \sigma$ → helicities



E665 Eμ = 470 GeV

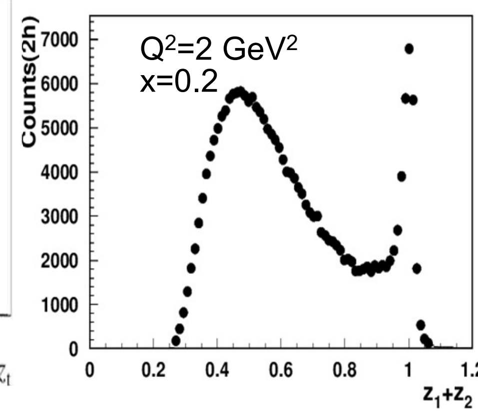


COMPASS Eμ = 160 GeV



$$z = (E_{\pi^+} + E_{\pi^-})/\nu$$

CLAS12 E=10.6 GeB



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

→seem to have no major impact in $\pi+\pi 0$

For GPD based interpretation need experimental separation of contributions

indication: most longitudinally polarized ρ^0

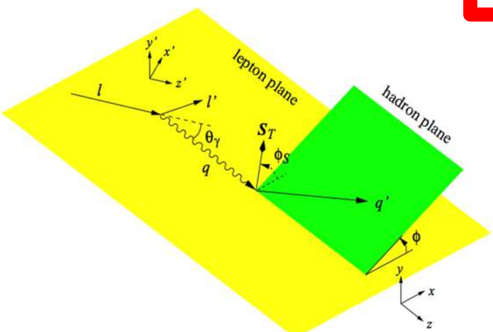
Studies of exclusive processes require high resolution and multidimensional measurements !!!

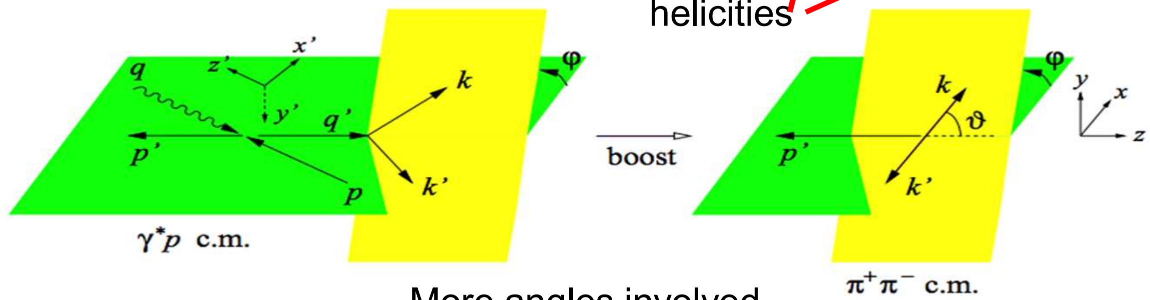
Structure functions case of VMs decaying to h+h-

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

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

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

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

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

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

beam and target polarizations

All W_{XY} depend on Q^2, x_B, t, ϕ, θ, Π

longitudinal rho

transverse rho

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

interference between

longitudinal and transverse ρ

Modeling helicity amplitudes of VMs

K.Passek-Kumericki

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

helicities

GK helicity amplitudes

$$P^2_{h\perp} = -z(t - t_{\min})$$

$$\gamma^*_T \to V_L \propto \frac{\sqrt{-t}}{Q},$$

$$\gamma^*_L \to V_T \propto \frac{\sqrt{-t}\,\langle k_\perp^2\rangle^{1/2}}{Q^2},$$

$$\gamma^*_T \to V_{-T} \propto \frac{-t\,\langle k_\perp^2\rangle^{1/2}}{Q^3}.$$

$$\underbrace{\gamma^*_L \to V_L}_{\text{twist-2 collinear, clean}} > \underbrace{\gamma^*_T \to V_T}_{\text{important for } \sigma_T \text{ and } R},$$

$$\underbrace{\gamma^*_T \to V_L}_{\text{helicity flip; SDME and GTMD-sensitive interference}} > \underbrace{\gamma^*_L \to V_T,\ \gamma^*_T \to V_{-T}}_{\text{more suppressed}}.$$

Understanding of model independent dependences of amplitudes important for modeling

Structure functions for VMs: integrated case

Diehl: 0704.1565

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

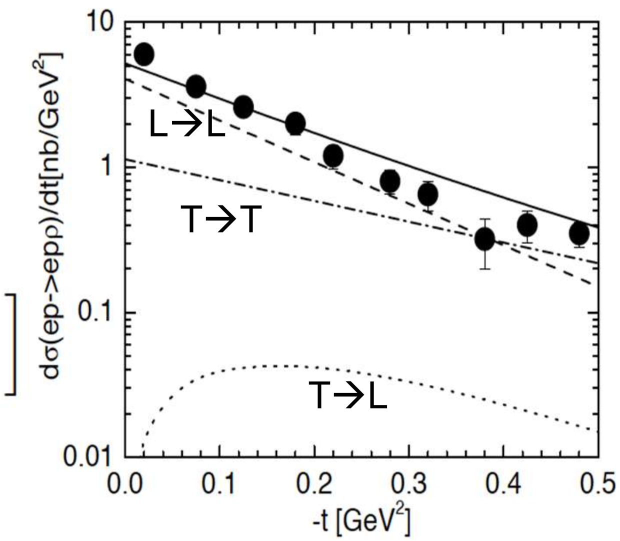
helicities

The GPD based description is applicable for certain helicity amplitudes

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

unpolarized part involves several dynamical contributions

GK:0501242



longitudinal rho

transverse rho

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

longitudinal photon (L) with 0 helicity

producing predominanly longitudinal ρ_L

Looking for L→L physics
t-dependences very different
focus on low t large Q^2
Extrapolation to t=0 not trivial!

SDMEs: different combinations in experiment

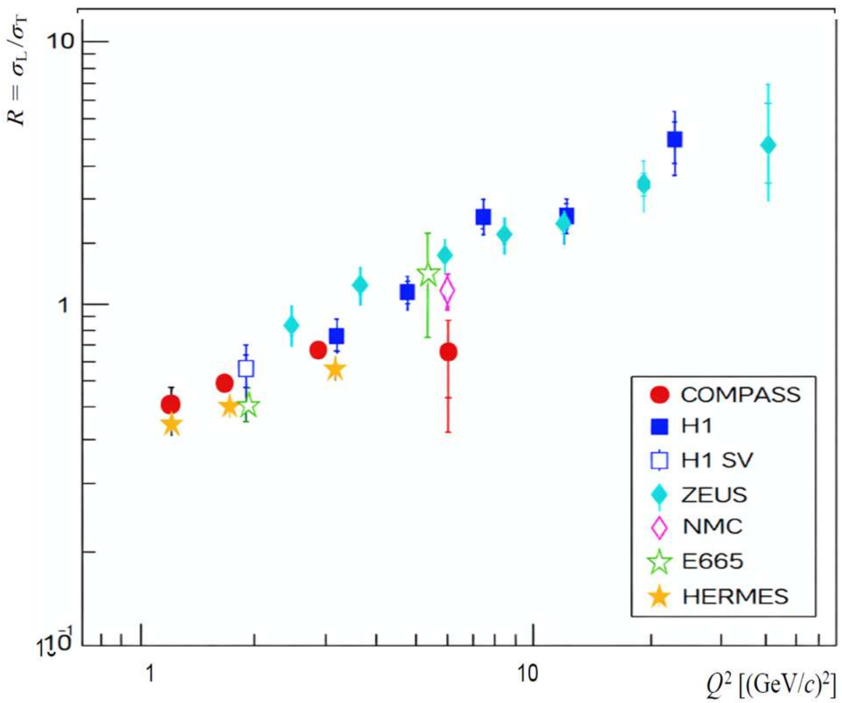
Diehl: 0704.1565 $\gamma^*(\mu) + p(\lambda) \to \rho(\nu) + p(\sigma)$

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

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

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

$$u^{0\,0}_{++} + \epsilon u^{0\,0}_{0\,0} = r^{04}_{00} = \frac{d\sigma(\gamma^*_T \to V_L) + \varepsilon d\sigma^N(\gamma^*_L \to V_L)}{d\sigma}$$



Given very much suppressed detection of longitudinal rho, the longitudinal photon contribution may be underestimated

Example for unpolarized beam and target: ψ

Helicity Amplitude Formalism for Vector Meson Leptonic Decays in Photoproduction

A.Pilloni

For unpolarized target and beam we have

Decay to leptons for longitudinally polarization VMs become $\sin^2\theta$

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

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

$$\begin{aligned} W_{UU}'^{TT}(\phi) &= \left(u_{++}^{++} + u_{++}^{--} + 2\,\mathrm{Re}\,u_{++}^{-+} + 2\varepsilon u_{0\,0}^{++} + 2\varepsilon\,\mathrm{Re}\,u_{0\,0}^{-+}\right) \\ &+ \cos(2\phi)\,\varepsilon\left(u_{-+}^{-+} + u_{-+}^{+-} + 2\,\mathrm{Re}\,u_{-+}^{++}\right) \\ &- 2\cos\phi\sqrt{\varepsilon(1+\varepsilon)}\,\mathrm{Re}\left(u_{0+}^{++} + u_{0+}^{--} + u_{0+}^{-+} + u_{0+}^{+-}\right) \end{aligned}$$

S+W vs Diehl in VM production in MC

S+W modulations for unpolarized target (P_l-lepton polarization) **Integrated over φ**

$$\mathcal{W}^{UU}(\Phi,\cos\Theta) = \frac{3}{8\pi^2}\Big[\frac{1}{2}(1-r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00}-1)\cos^2\Theta + \sqrt{2\epsilon(1+\epsilon)}\cos\Phi\left(r^5_{11}\sin^2\Theta + r^5_{00}\cos^2\Theta\right) - \epsilon\cos 2\Phi\left(r^1_{11}\sin^2\Theta + r^1_{00}\cos^2\Theta\right) + P_l\sqrt{2\epsilon(1-\epsilon)}\sin\Phi\left(r^8_{11}\sin^2\Theta + r^8_{00}\cos^2\Theta\right)\Big]$$

$$u^{00}_{++} + \epsilon u^{00}_{00} = r^{04}_{00}\,,$$
$$u^{++}_{++} + u^{--}_{++} + 2\epsilon u^{++} = 1 - r^{04}_{00}$$

Diehl's modulations ($\Phi = -\phi$) with normalization difference of 2π using $\int \frac{d\phi}{2\pi}$:

$$W_{UU}(\phi,\Theta) = \frac{3}{4\pi}\Big[\left(u^{00}_{++} + \epsilon u^{00}_{00}\right)\cos^2\Theta + \tfrac{1}{2}\left(u^{++}_{++} + u^{--}_{++} + 2\epsilon u^{++}_{00}\right)\sin^2\Theta - \sqrt{2\epsilon(1+\epsilon)}\cos\phi\left[\tfrac{1}{\sqrt{2}}\,\mathrm{Re}\left(u^{++}_{0+} + u^{--}_{0+}\right)\sin^2\Theta + \sqrt{2}\,\mathrm{Re}\,u^{00}_{0+}\cos^2\Theta)\right] - \epsilon\cos(2\phi)\left(\mathrm{Re}\,u^{++}_{-+}\sin^2\Theta + u^{00}_{-+}\cos^2\Theta\right) - P_L\sin\phi\sqrt{2\epsilon(1-\epsilon)}\left[\tfrac{1}{\sqrt{2}}\,\mathrm{Im}\left(u^{++}_{0+} + u^{--}_{0+}\right)\sin^2\Theta + \sqrt{2}\,\mathrm{Im}\,u^{00}_{0+}\cos^2\Theta\right]\Big]$$

L/T photon interference to produce Longitudinal ρ

In Diehl's formalism, connection between modulations and polarization more clear

→We effectively extract Cahn and B&M effects for different polarizations of VM!!!

Modeling of VM production in MC: Modified Diehl's formalism

Standard SDME approach

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

$$\int \frac{d\phi}{2\pi}\int d\varphi\, d(\cos\vartheta)\, W_{UU}(\phi,\varphi,\vartheta) = 1\,.$$

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

with

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

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

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

Ex. cross section of L→L in terms of SDMEs will be

$$\frac{d\sigma^{\gamma_L p\to p\rho_L}}{d(\cos\vartheta)\, dx_B\, dQ^2\, dt} = \frac{3\Gamma}{4}\epsilon\cos^2\theta\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right)u^{00}_{00}$$

Moving the UNKNOWN σ_{Total} makes modeling challenging and confusion in cross contributions

Modified approach with **Helicity Structure Functions (HSFs)** H_{XY}

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

$$r^{\nu\nu'}_{\mu\mu',\lambda\lambda'} = \sum_\sigma T^{\nu\sigma}_{\mu\lambda}\left(T^{\nu'\sigma}_{\mu'\lambda'}\right)^*$$

$$v^{\nu\nu'}_{\mu\mu'} = \left(r^{\nu\nu'}_{\mu\mu',++} + r^{\nu\nu'}_{\mu\mu',--}\right)$$

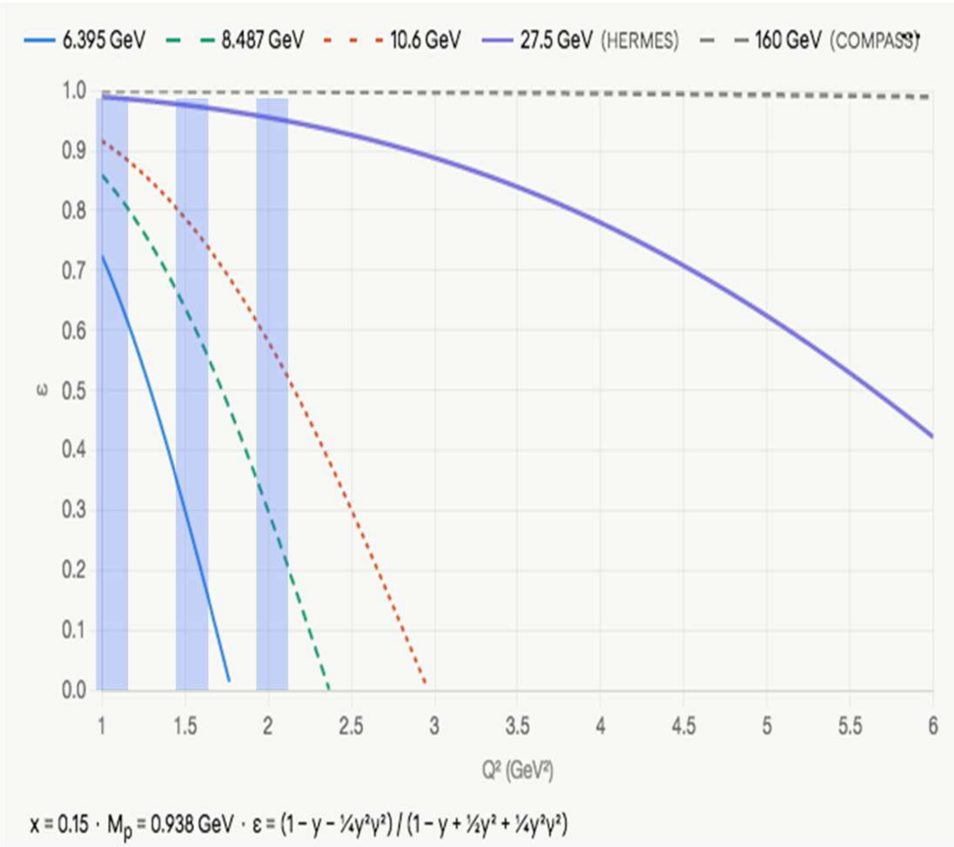
with Γ defined using Hand's convention for virtual photon flux.

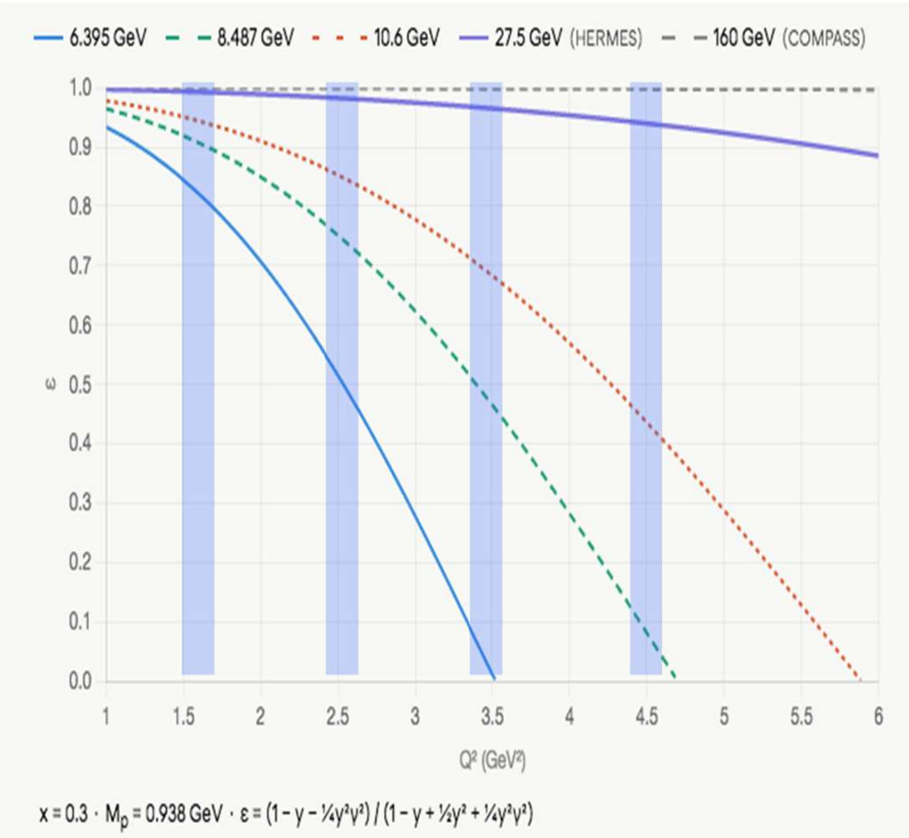
$$\Gamma = \frac{\alpha_{\rm em}}{2\pi}\frac{y^2}{1-\epsilon}\frac{1-x_B}{x_B}\frac{1}{Q^2}$$

$$\frac{d\sigma^{\gamma_L p\to p\rho_L}}{d(\cos\vartheta)\, dx_B\, dQ^2\, dt} = \frac{3\Gamma}{4}\epsilon\cos^2\theta\, v^{00}_{00}$$

ε-dependence for electroproduction experiments

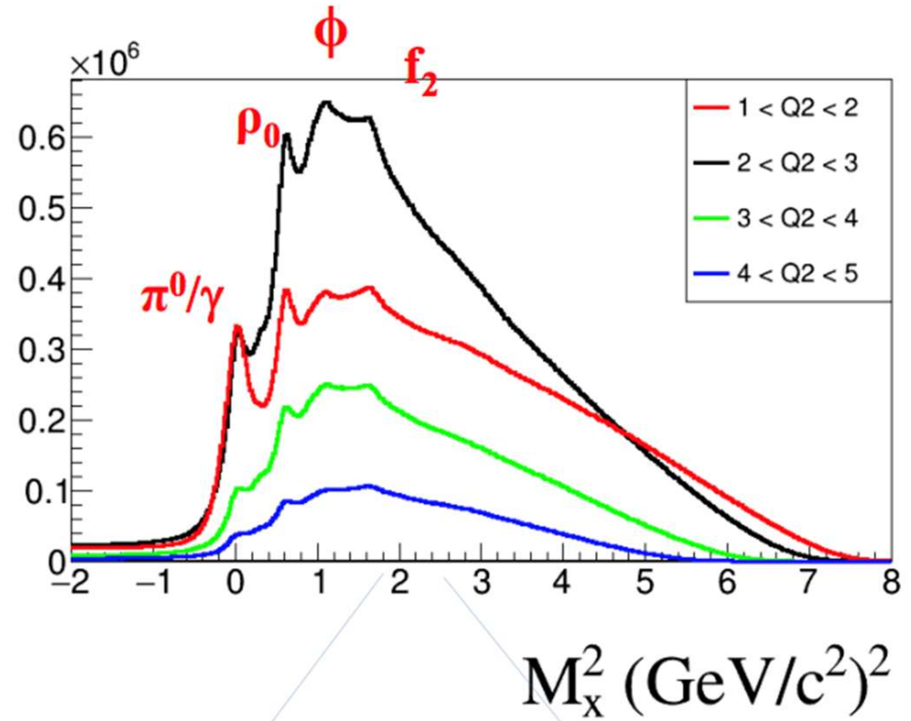
CLAS12 already collected data on proton for 6.4,6.5,7.5.8.5.10.2,10.6 GeV

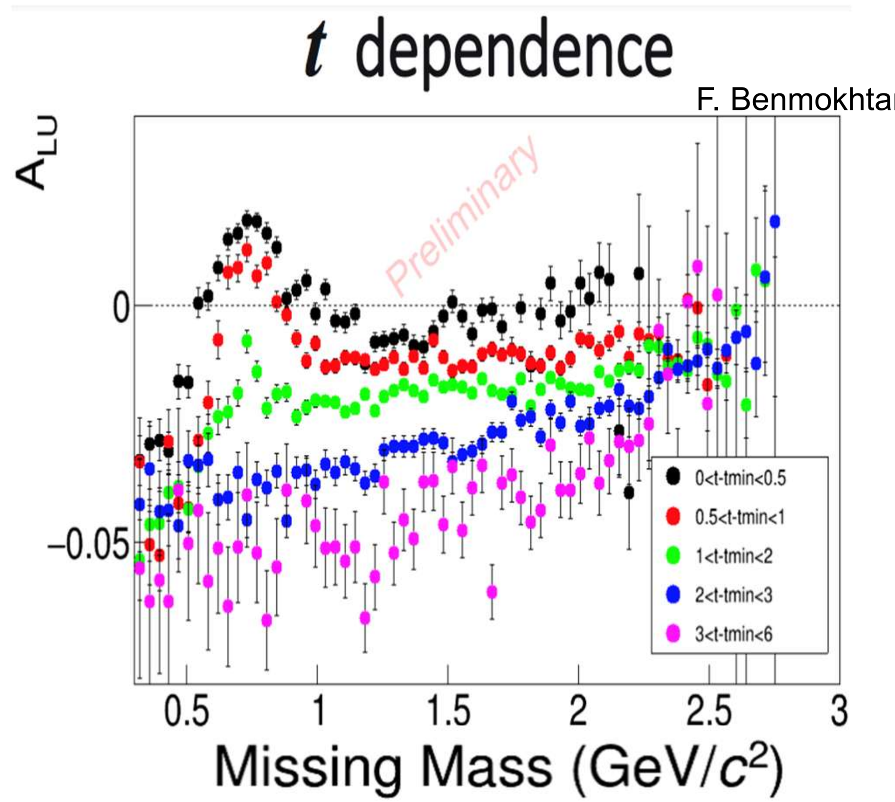




Combining SDME measurements (may need "event base" analysis) at CLAS12 and HERMES/COMPASS will be important for model independent separation of longitudinal part

Alternative measurements with epX





Longitudinal rho disappears in epX at large t

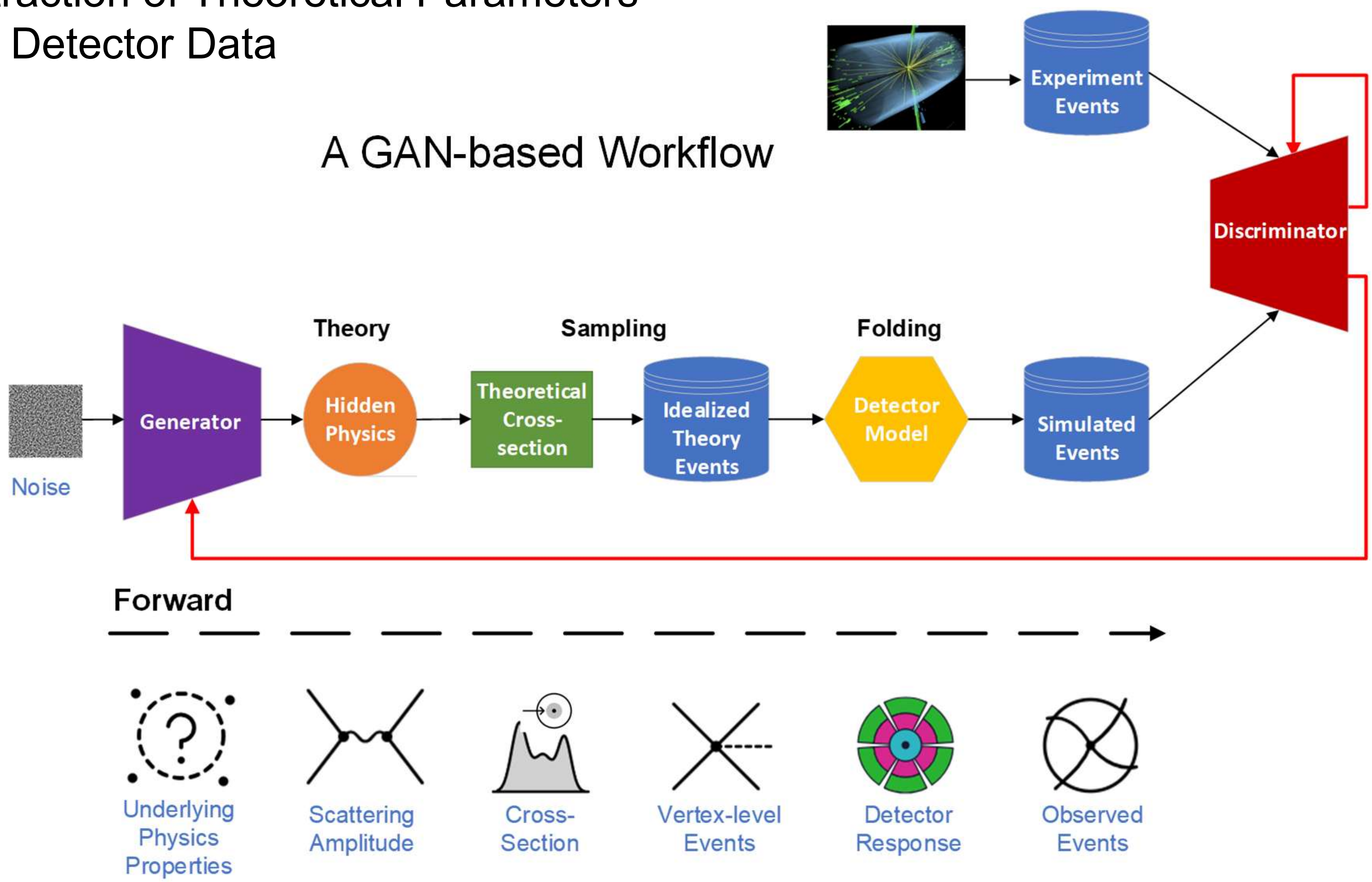
Inclusive proton measurements provide access to exclusive VMs, for cross sections integrated over decay variables (θ and ϕ)
Different backgrounds and systematics and will require good resolutions to separate different contributions

A Model-Independent Framework

GENESIS proposal: AI-Driven Framework for Direct Extraction of Theoretical Parameters from Raw Detector Data

Yaohang Li

A GAN-based Workflow



Summary of main decisions

- Use the same formalism for Master Formula for eN->e'hX both for SIDIS and exclusive limit (Alessandro Bacchetta, Leonard Gamberg)
- In MC development use the Helicity Structure Functions instead of SDMEs (Derek, Harut, Valery)
- Use model independent kinematic dependences in modeling of amplitudes (Kornelija Passek, Shohini Bhattacharya)
- Add proper description of exclusive rhos in the polarized PYTHIA (Albi Kerbizi)
- In inference of helicity amplitudes combine diffusion approach with likelihood (Bhawani Singh, Yaohang Li)
- Use the latest fragmentation functions from Belle to evaluate the σ_T in exclusive limit from PYTHIA, compare with σ_{Total} for different final state VMs
- Run the full generation, reconstruction, and amplitude extraction chain for different beam energies at JLab and COMPASS, check the L/T ratio extraction with direct Rosenbluth separation, combining JLab and COMPASS data

SUMMARY

Development of realistic MC is absolutely critical for measurements of exclusive VMs and, longitudinal rhos, in particular, with polarized beams and targets, which are crucial for proper interpretation of the measurements of 3D structure, including GPD and TMD based formalisms

- 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, including the acceptance in 7D
- 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 rhos from transverse and longitudinal photons
- *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*

- A program for AI-enabled Inference of helicity amplitudes with validation in development
  - Develop MC, produce large samples for cross section studies, extract helicity amplitudes/SDMEs from RGK (6.5,7.5,8.5)/RGA(10.6)/RGC(LPol)/RGB(D) data sets
  - **Most critical: sort out Q^2-dependences of relevant amplitudes/HSFs**
  - Combine efforts of CLAS+GLUEX+COMPASS communities (ex. generator development) in understanding the diffractive ρ,ϕ, J/Ψ.. and sort out the impact on OAM, TMD-PDFs, ….

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

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

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

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

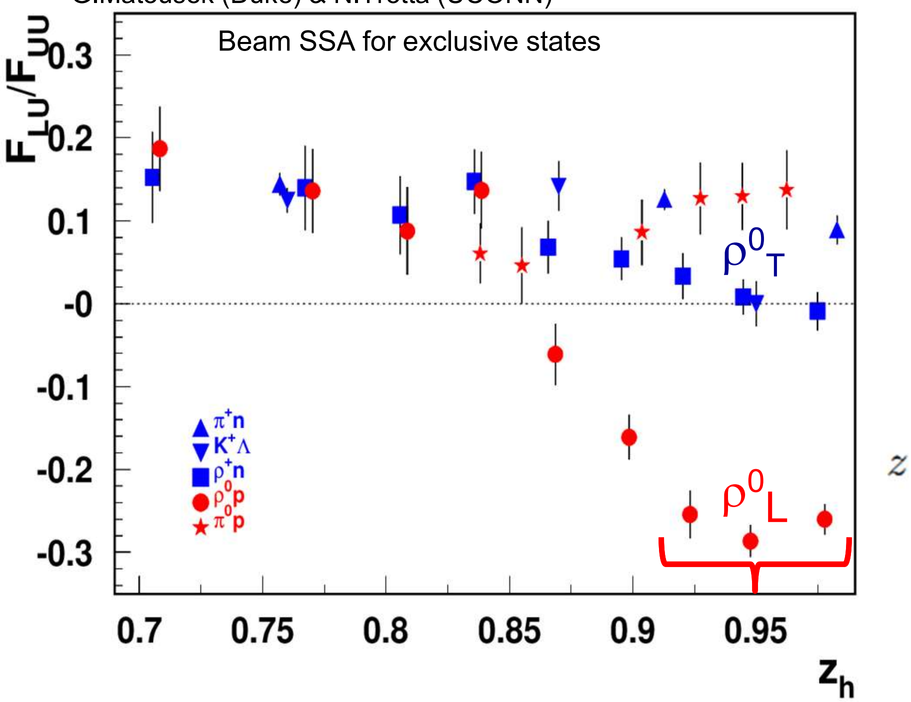
interference of transverse and longitudinal ρ from transverse photons

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

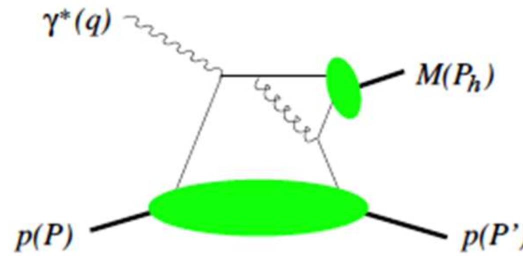
Detector has acceptances in angles, and integration should account that to be interpretable by theory

L/T photons producing T/L VMs

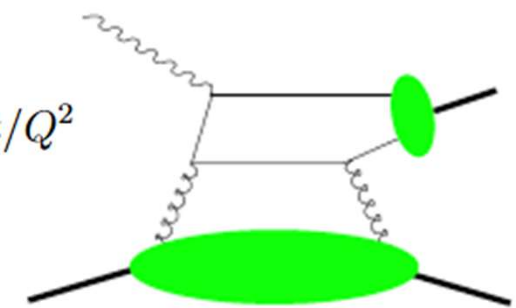
G.Matousek (Duke) & N.Trotta (UCONN)



Indication of different dynamical mechanism for ρ^0



$$z = 1 + x_B t/Q^2$$



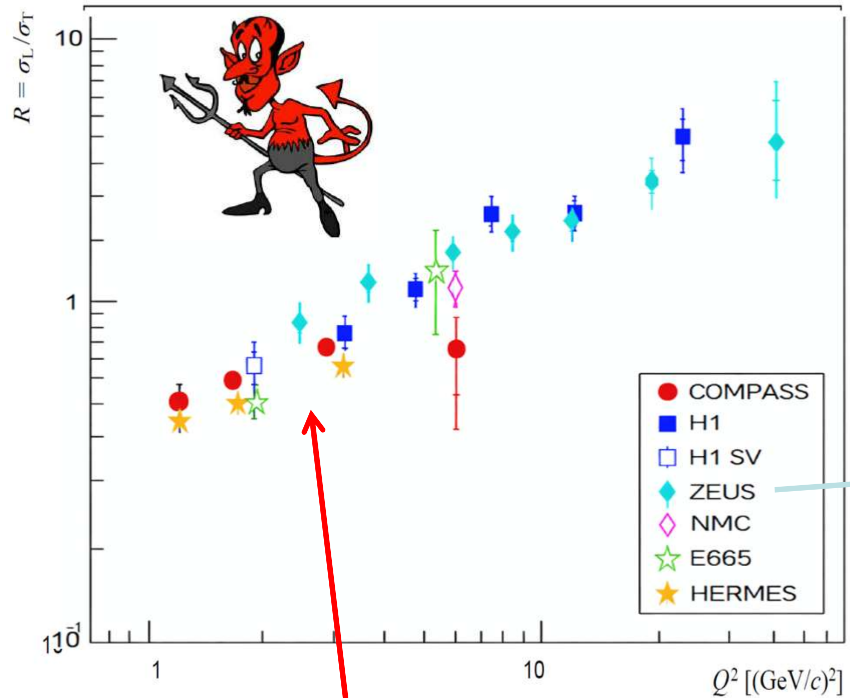
For modeling some intuition is needed on what are the relative contributions from T and L photons in different channels?

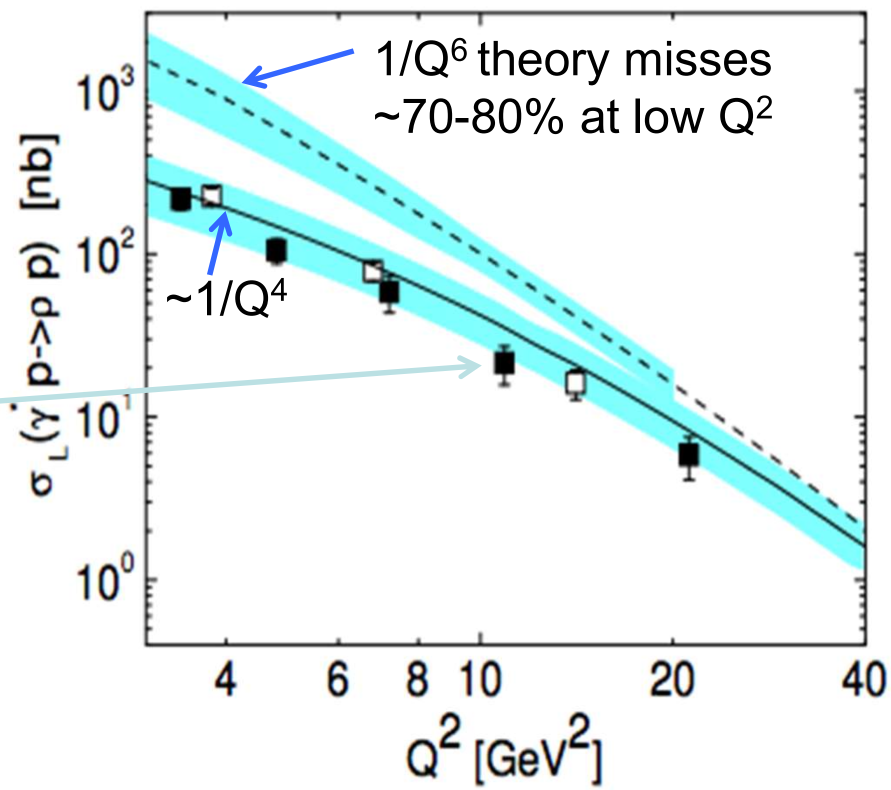
L/T separation and proper measurements of Q^2-dependences of all observables are critical for interpretation of different contributions

Realistic modeling is critical for understanding of the 7D acceptances!!!

Separating Longitudinal photon contributions

"The greatest enemy of knowledge is not ignorance, it is the illusion of knowledge." D.J. Boorstin





L/T separation Assuming SCHC

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

To be checked both, extraction of σ_L cross-section and evaluation of σ_L/σ_T

SDMEs: different combinations in experiment

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

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

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

$$u^{0\,0}_{++} + \epsilon u^{0\,0}_{0\,0} = r^{04}_{00} = \frac{d\sigma(\gamma^*_T \to V_L) + \varepsilon d\sigma^N(\gamma^*_L \to V_L)}{d\sigma}$$

sinusoidal modulations(~0 at COMPASS)

Valuable source of info on longitudinal photon!!!

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

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

cosine modulations(huge at COMPASS)

$$\mathrm{Im}\left(u^{++}_{0+} + u^{--}_{0+}\right) = \sqrt{2}\, r^{8}_{11}$$ *(>0 at COMPASS/HERMES)*

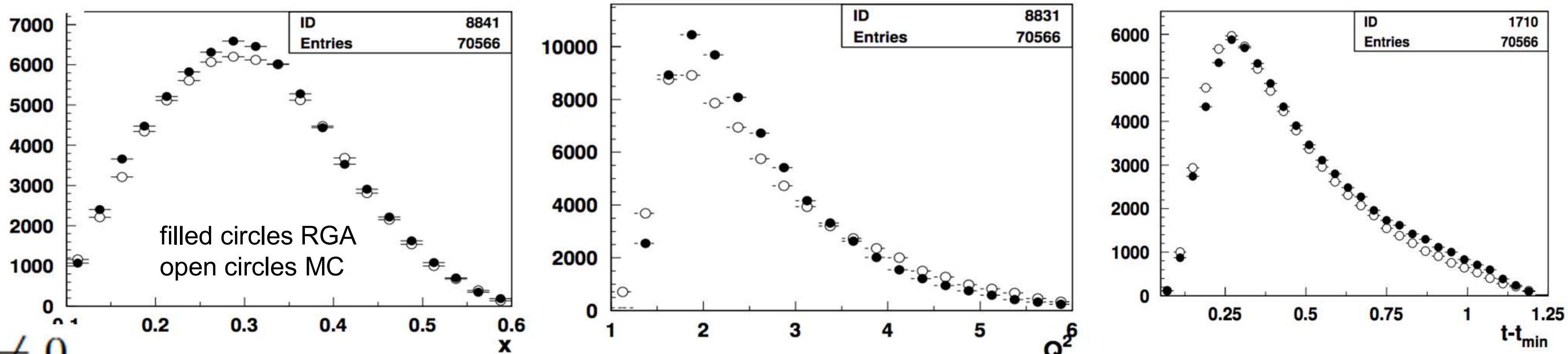
$$\mathrm{Re}\left(u^{++}_{0+} + u^{--}_{0+}\right) = -\sqrt{2}\, r^{5}_{11}$$ *(~0 at COMPASS/HERMES)*

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

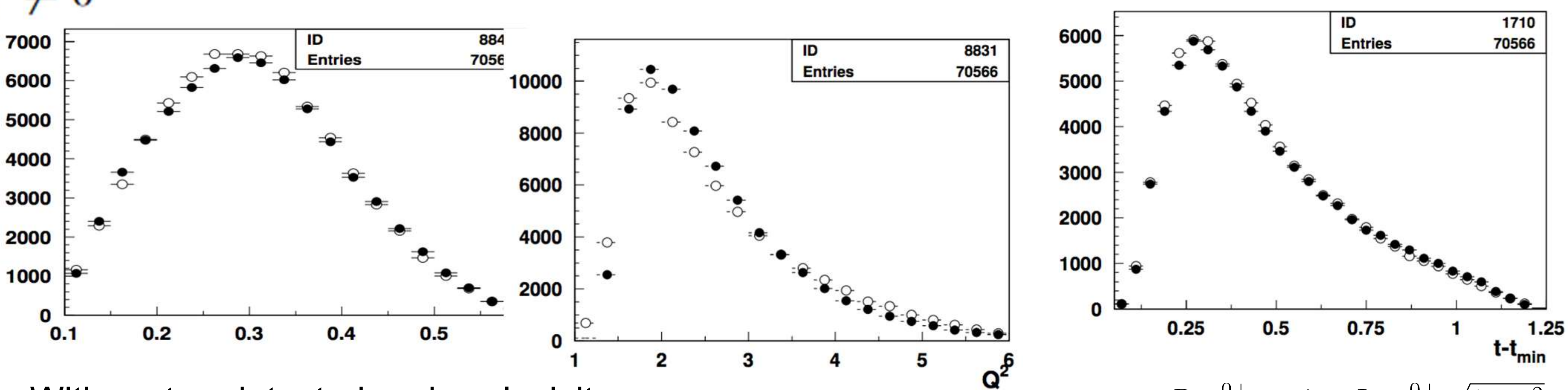
Comparing the MC with CLAS12 data (ep→e'p'ρ)

use the rho-generator-gemc-reconstruction chain to compare with CLAS12 10.6 GeV data vs 2 MC models

$u_{00}^{0+} = 0$



$u_{00}^{0+} \neq 0$



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

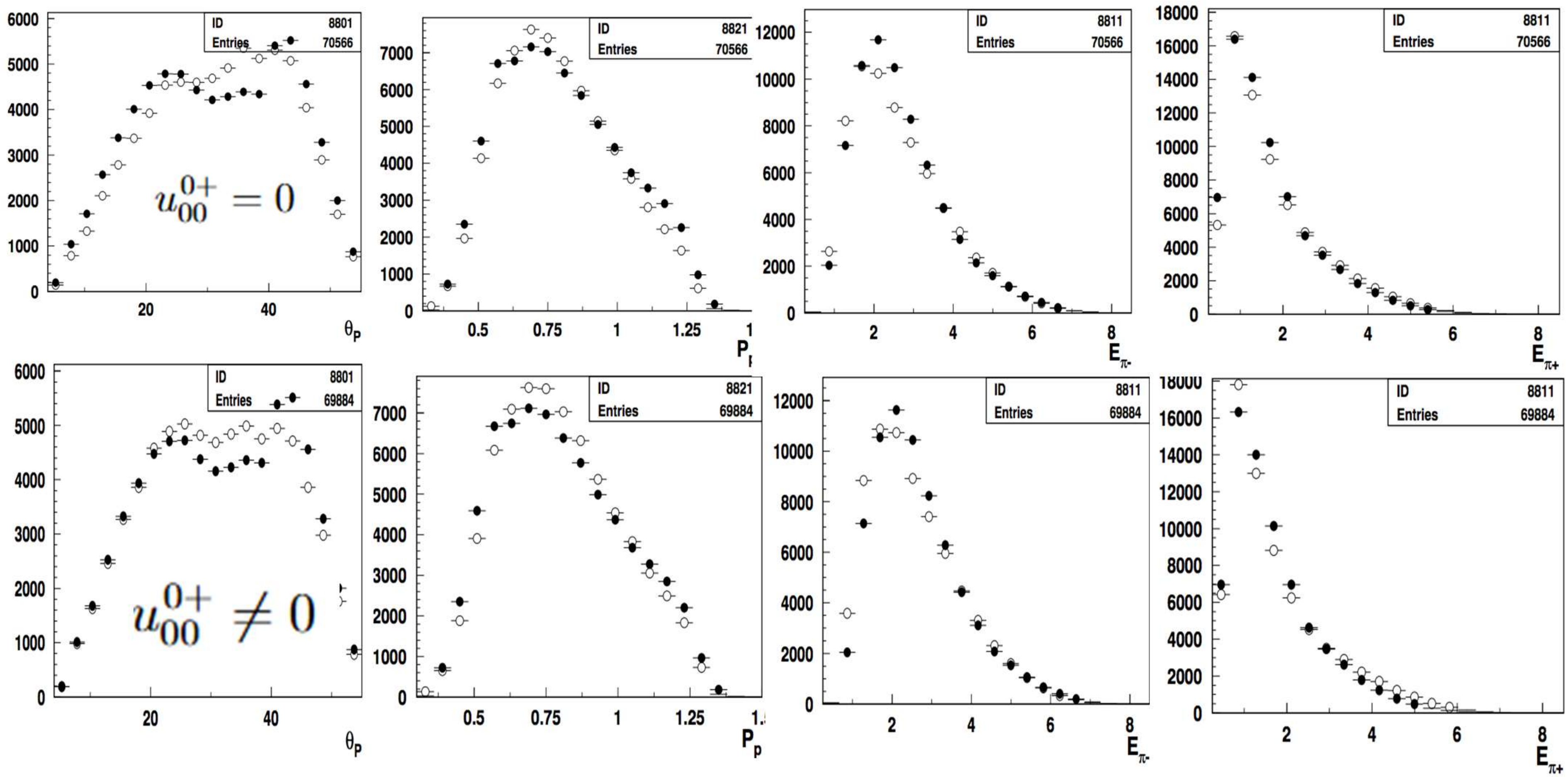
$\cos\varphi Re u_{++}^{0+} + \sin\varphi Im u_{++}^{0+} \sqrt{1-\epsilon^2}$

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

Comparing the MC(gemc) with CLAS12 data

After a preliminary tune and testing use the rho-generator-gemc-coatjava chain to compare with RGA inbending Fall18 for 2 versions different only for 1 amplitude

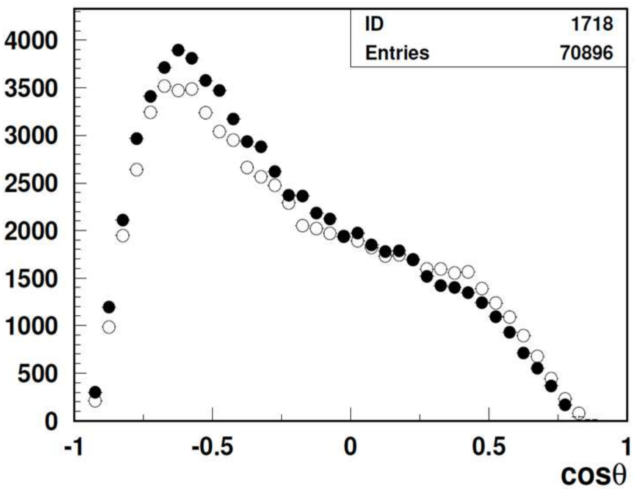
filled circles RGA
open circles MC

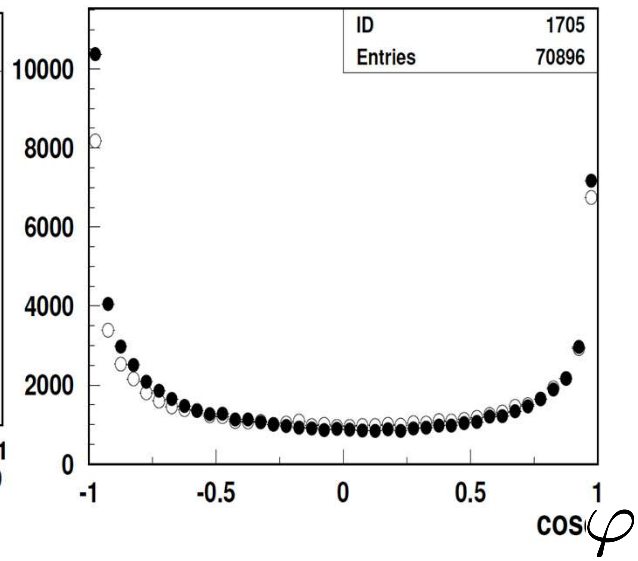


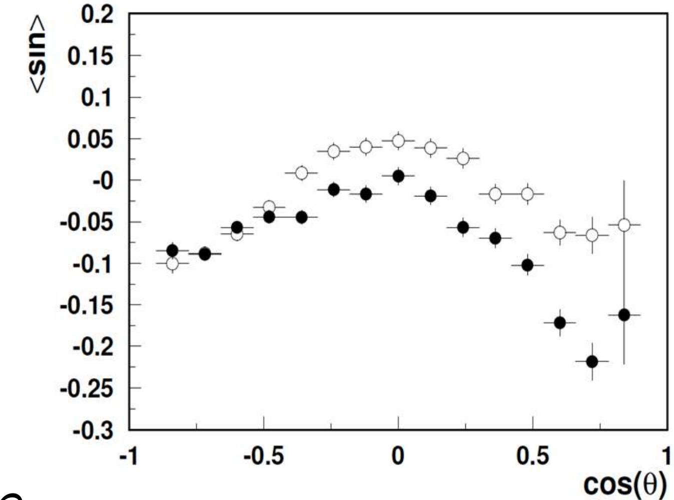
Comparing the MC with CLAS12 data

$u_{00}^{0+} = 0$

CLAS12 10.6 data set vs MC



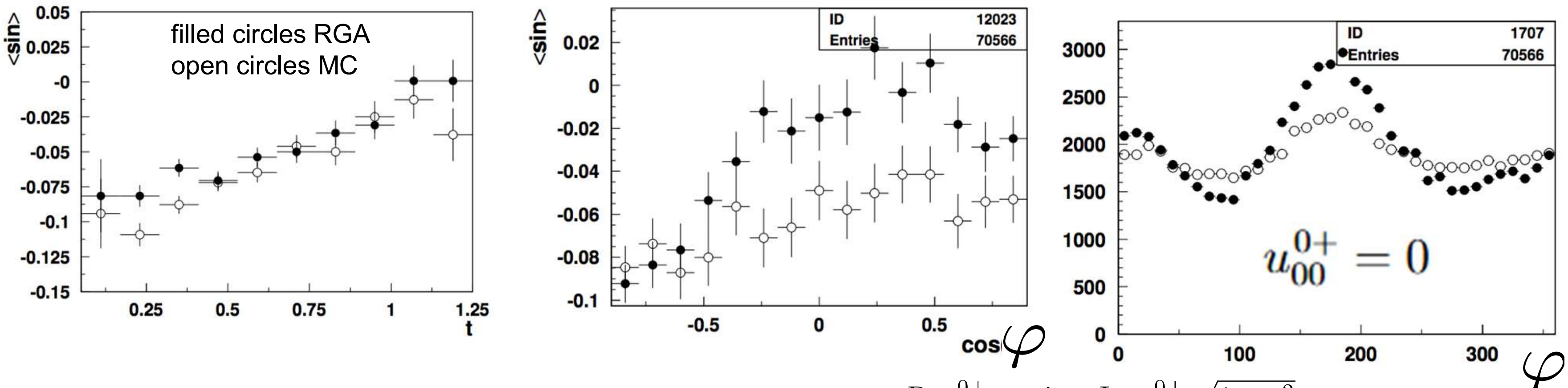




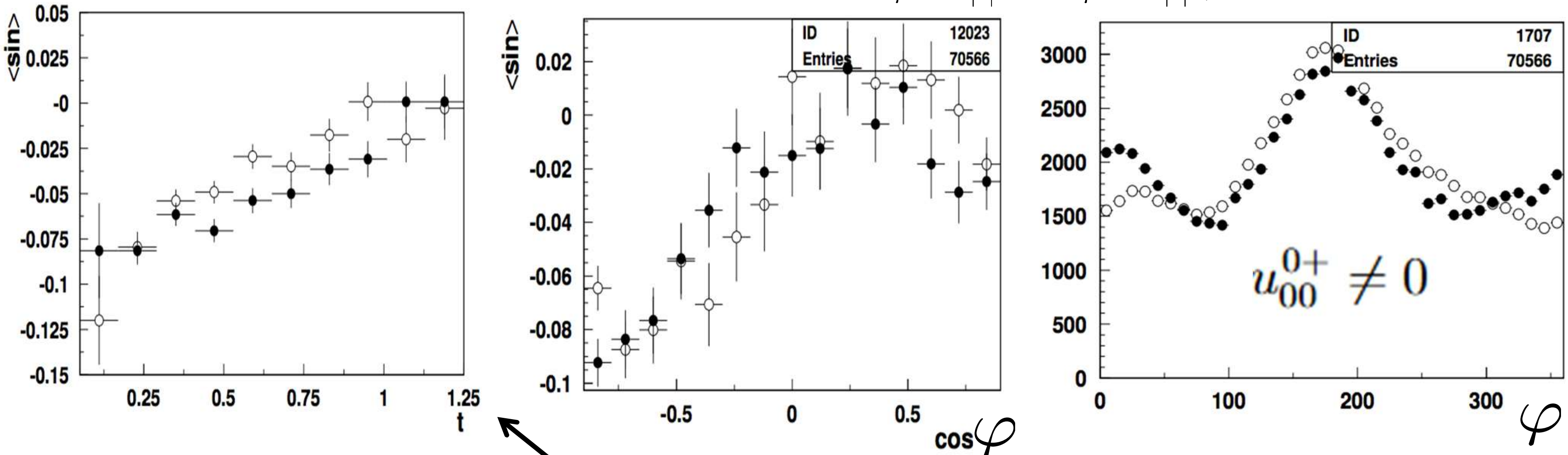
Relative contributions from longitudinal and transverse described well with Longitudinal rhos dominating ~5-6 times for Q^2~1.5

Comparing the MC versions with CLAS12 data

use the rho-generator-gemc-coatjava chain to compare with RGA inbending Fall18



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



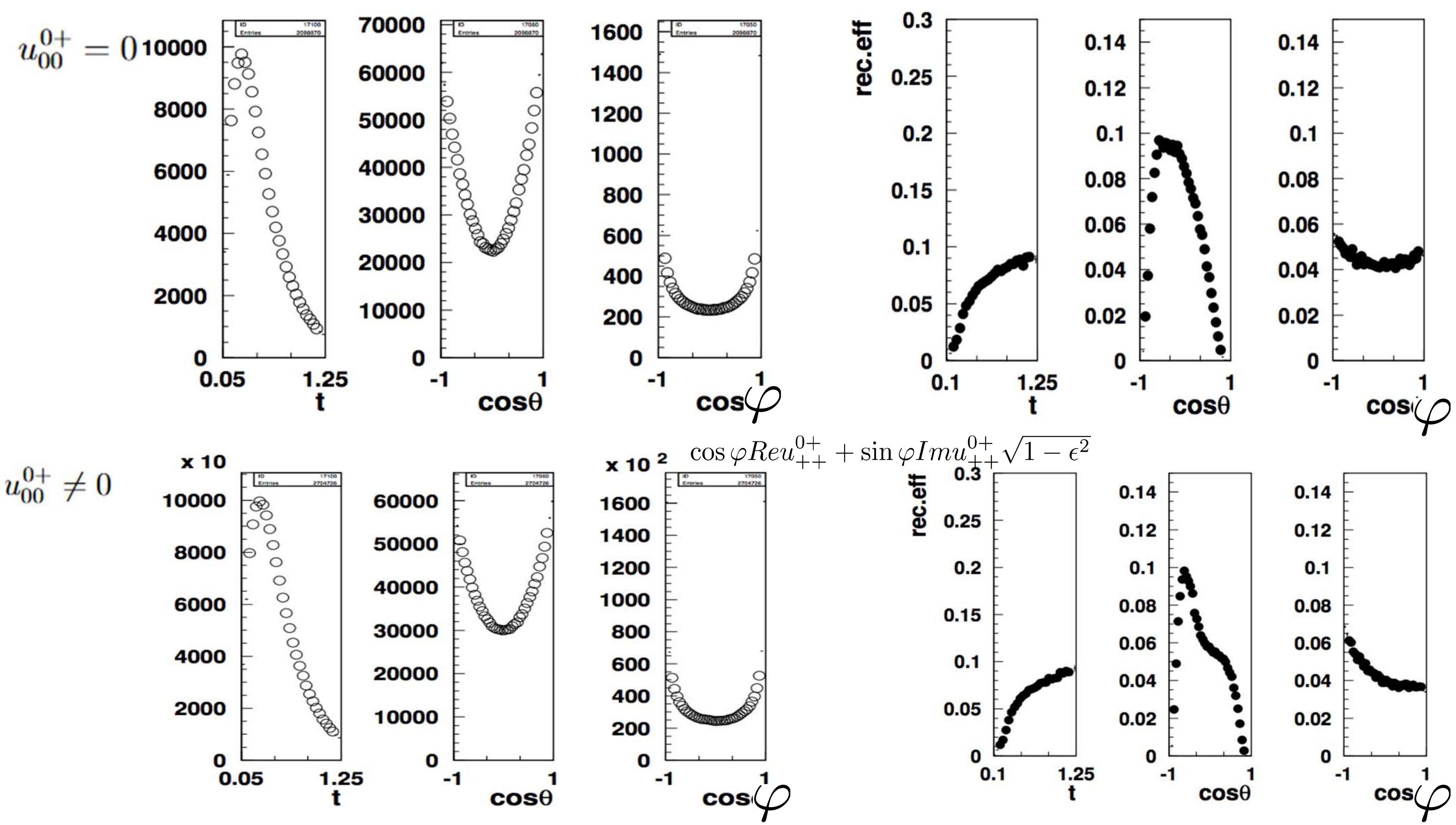
SSA dependence described vs some variables, require proper integration over others

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

Comparing the MC v4 with CLAS12 data

Generated

Reconstruction efficiencies



Comparing acceptances for MC model inputs

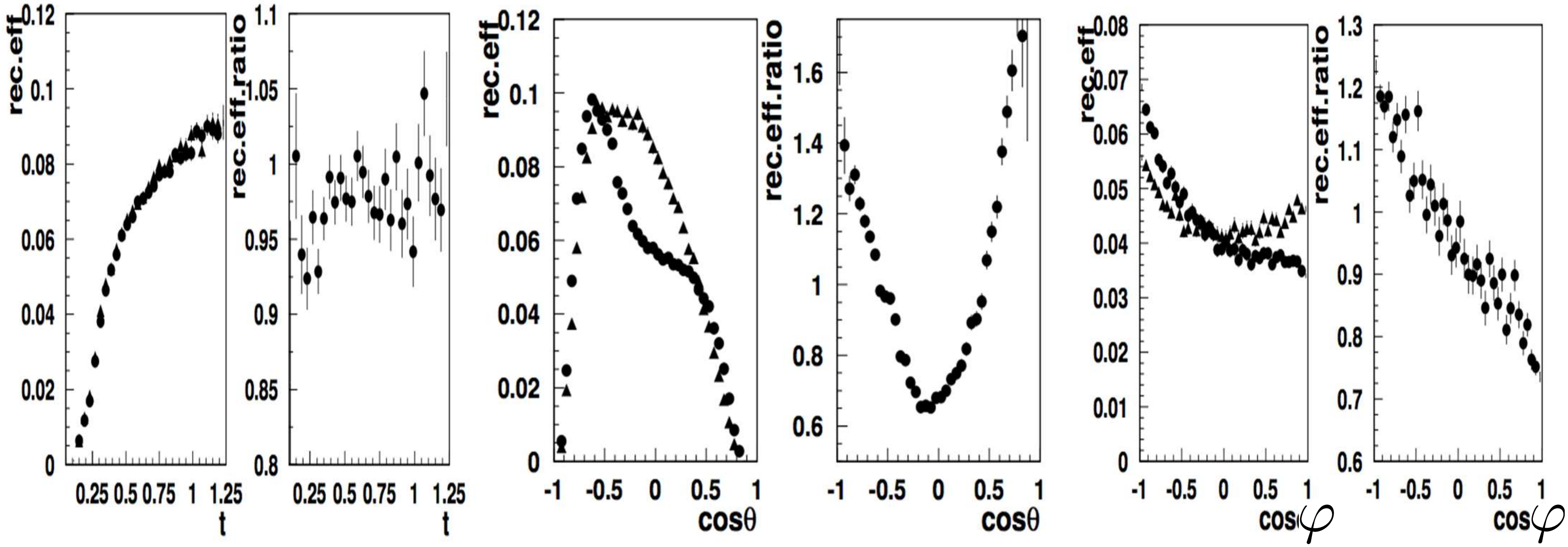
Acceptance difference for 2 MCs using the rho-generator-gemc-coatjava chain to compare with RGA inbending Fall18

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

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

in HERMES/COMPASS ~ +10%

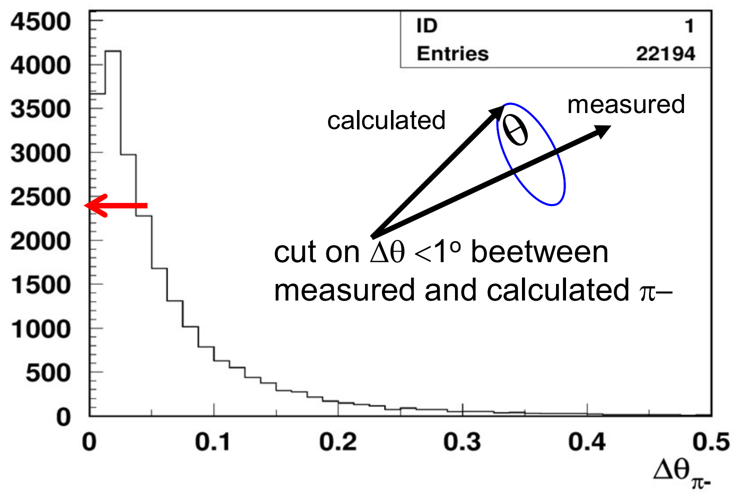
0-within errors



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

Studies of ρ^0 impact with longitudinally polarized NH_3 target

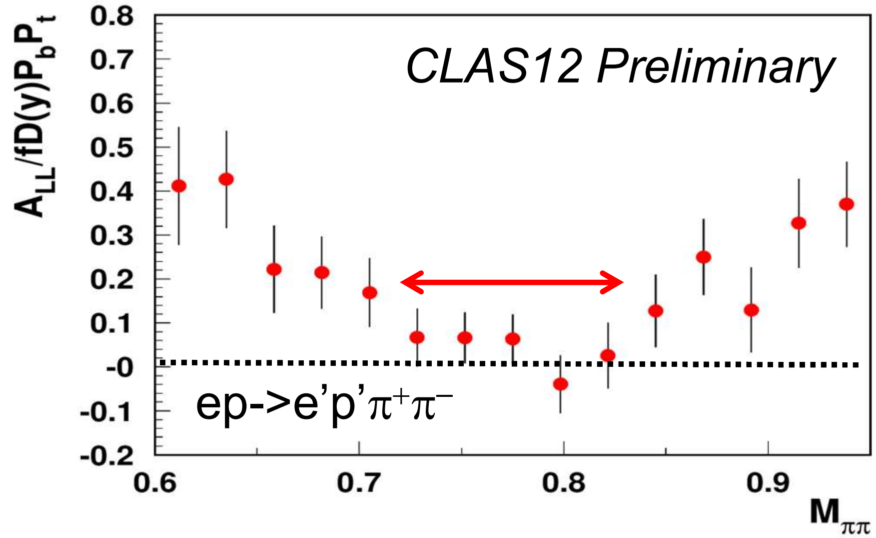
Separating exclusive dihadrons

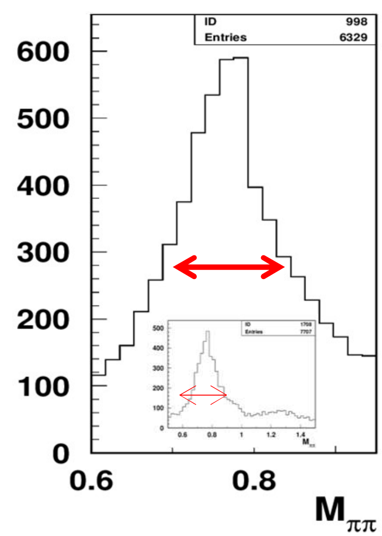


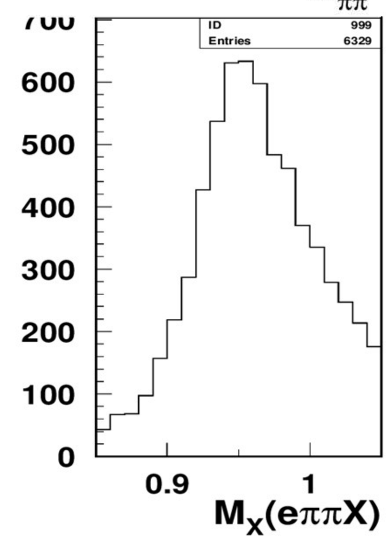
- Require the angle of negative pions is within a degree from calculated from e',p,π+ assuming exclusive e',p,π+π- event.

- 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 π+π–