Correlated di-hadron production

Harut Avakian (JLab)

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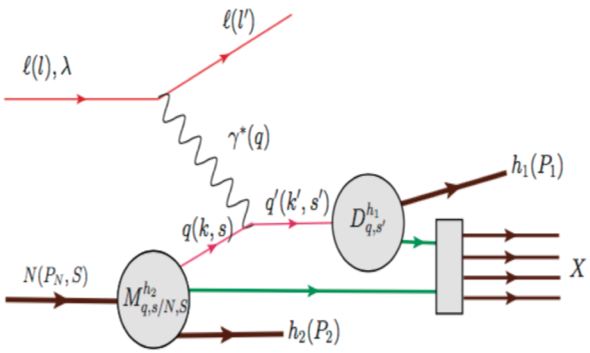
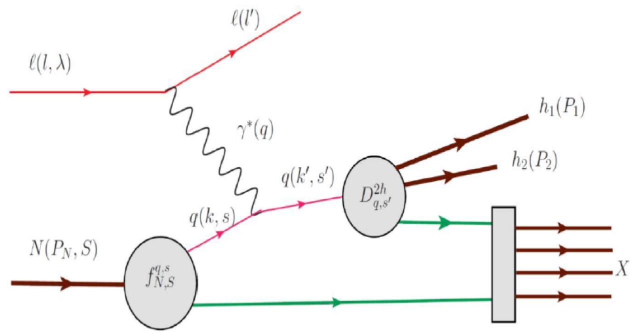
Workshop on Novel Probes of the Nucleon Structure in SIDIS, e+e- and pp

- Introduction
- Correlated di-hadron production
- The role of dihadrons in single hadron observables
- Dihadron production at CLAS12
- Di-hadron multiplicities
- Data MC comparison
- Conclusions

Di-hadron production in SIDIS

2h production in SIDIS provides access to correlations inaccessible in simple SIDIS (dihadron fragmentation, correlations of target and current regions, entanglement....)





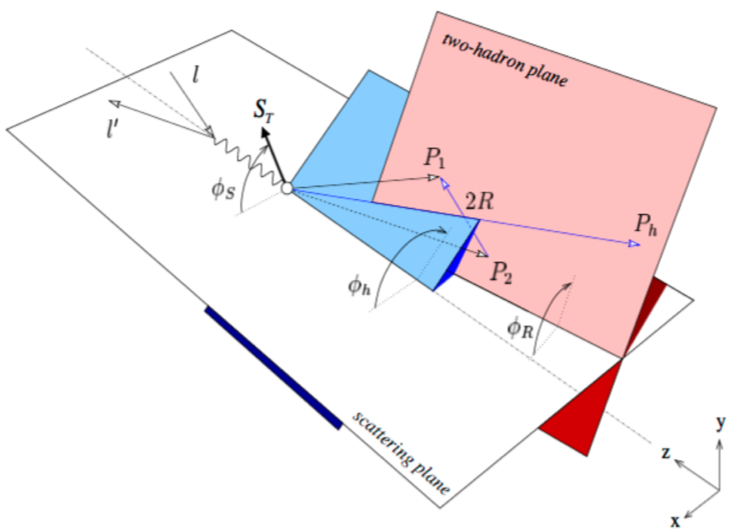
$$P_h = P_1 + P_2,$$
$$R = \frac{1}{2}(P_1 - P_2).$$

Beam SSA provides access to quark helicity in SIDIS via dihadron correlations using the helicity-dependent dihadron fragmentation function (DiFF) .

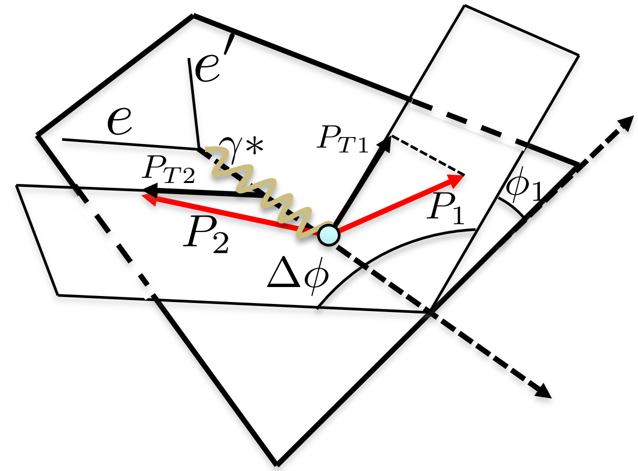
Dedicated CLAS12 proposals: E12-06-112B/E12-09-008B

Correlated hadron production in hard scattering

2 hadrons in current fragmentation



hadrons in current & target fragmentation

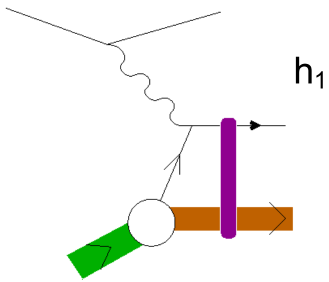


With ϕ_S, ϕ_1, ϕ_2, ϕ_R, ϕ_h several observables have been identified to study correlations

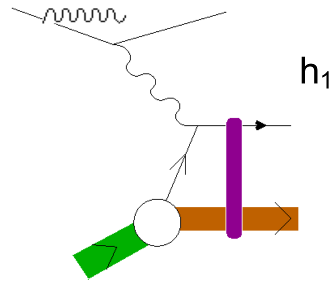
$\phi_R-\phi_S$, ϕ_R -accessing transversity and quark-gluon correlations *Radici & Bacchetta*
$\phi_R-\phi_h$ -accessing leading twist polarized fragmentation functions *Matevosyan,Kotzinian,Thomas*
$\phi_1-\phi_2$ -accessing correlations in current and target regions *Anselmino, Barone, Kotzinian*

Sources of inclusive hadron electro-production

single hadron in CFR

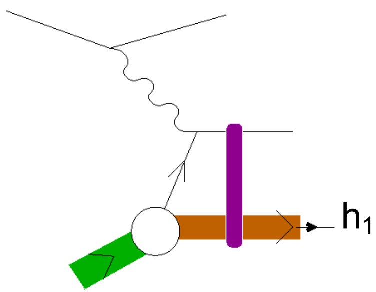


with additional radiation
single hadron in CFR

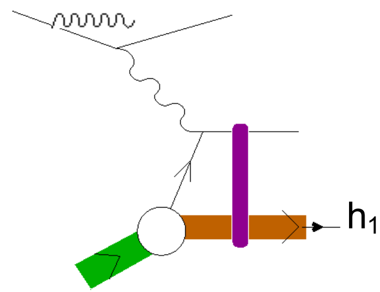


radiation mixes contributions from different structure functions and complicates separation of exclusive from semi-inclusive

single hadron in TFR

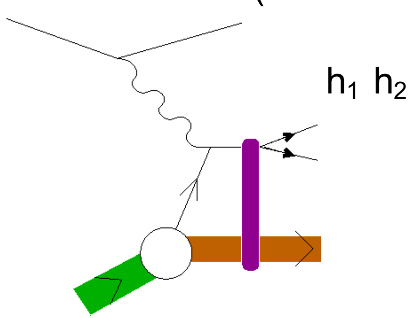


single hadron in TFR

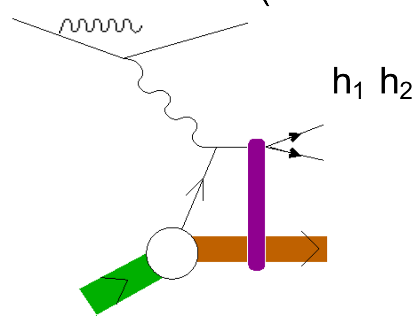


Does it matter what is the source of the single hadron, and if yes, where?

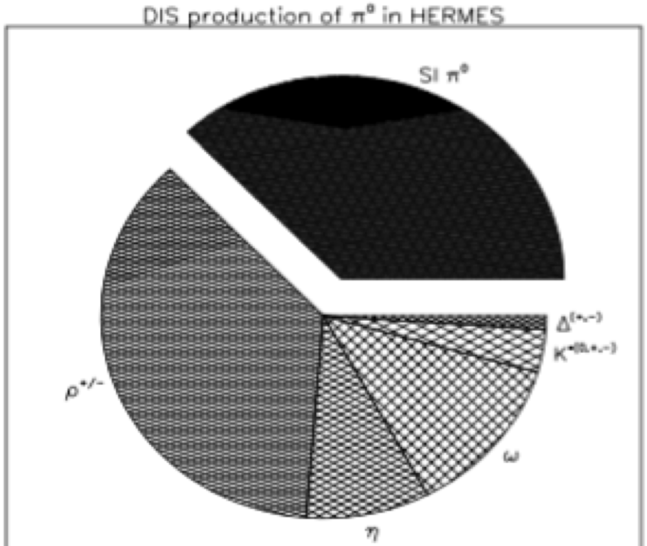
correlated hadrons(dihadron,rho,..) in CFR



correlated hadrons(dihadron,rho,..) in CFR



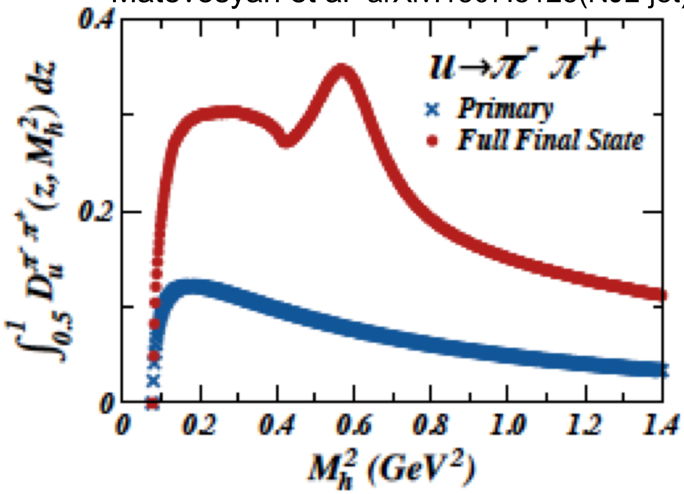
Dihadron production

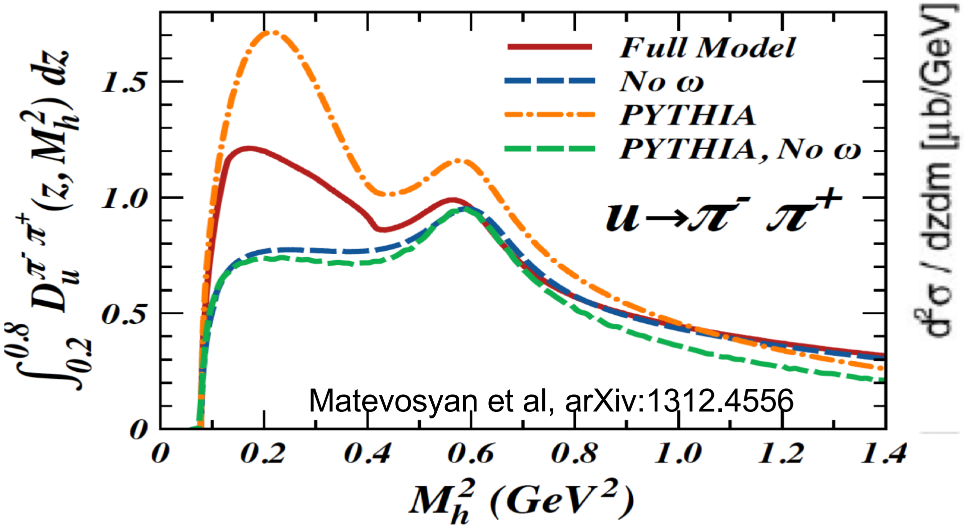


HERMES-note-96.059

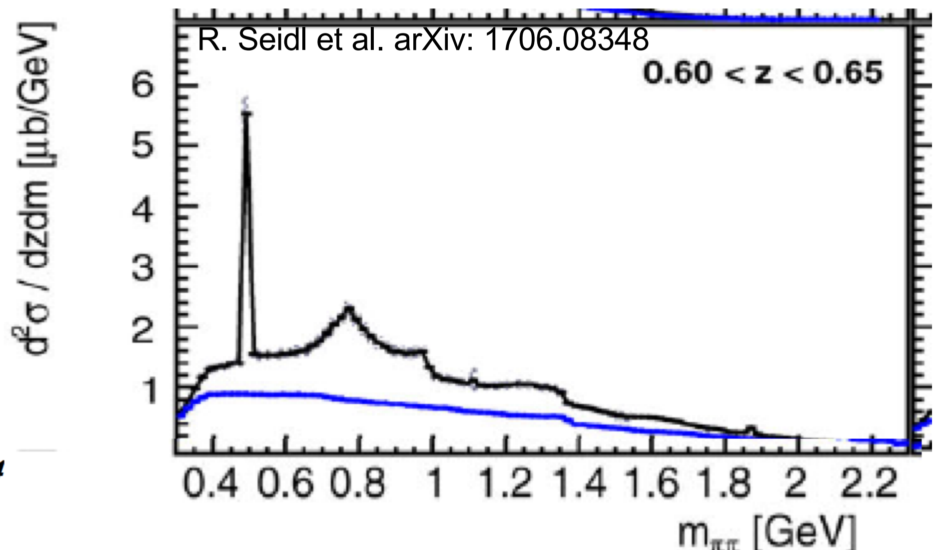
What is the origin of dihadrons? What is a single hadron?

Matevosyan et al arXiv:1307.8125(NJL-jet)



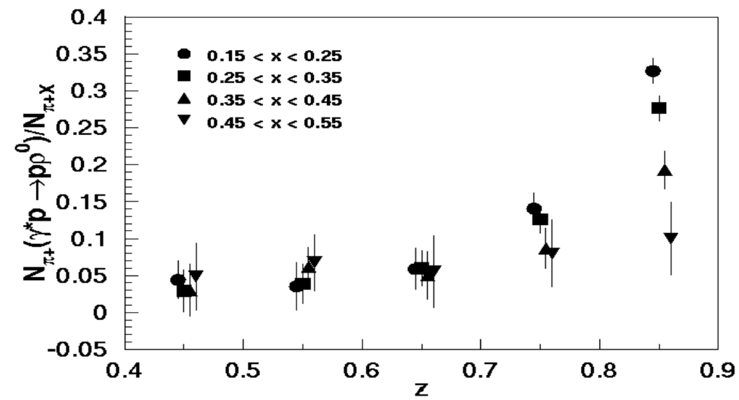


Matevosyan et al, arXiv:1312.4556



Dihadrons and Vector meson contributions

1) Should we worry about pions/kaons coming from vector meson decays?
2) What about ρ+ and ρ-
3) What do we know about relevant observables for pions specifically coming from vector meson decays
4) What about SIDIS rhos (can we measure?)
5) What is radiative correction due to rho?
6) Vector meson as resonance in dihadron production?



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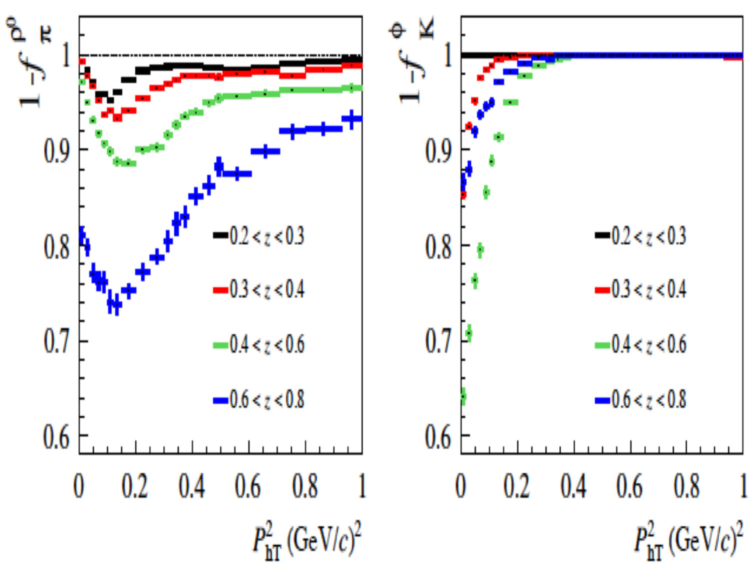
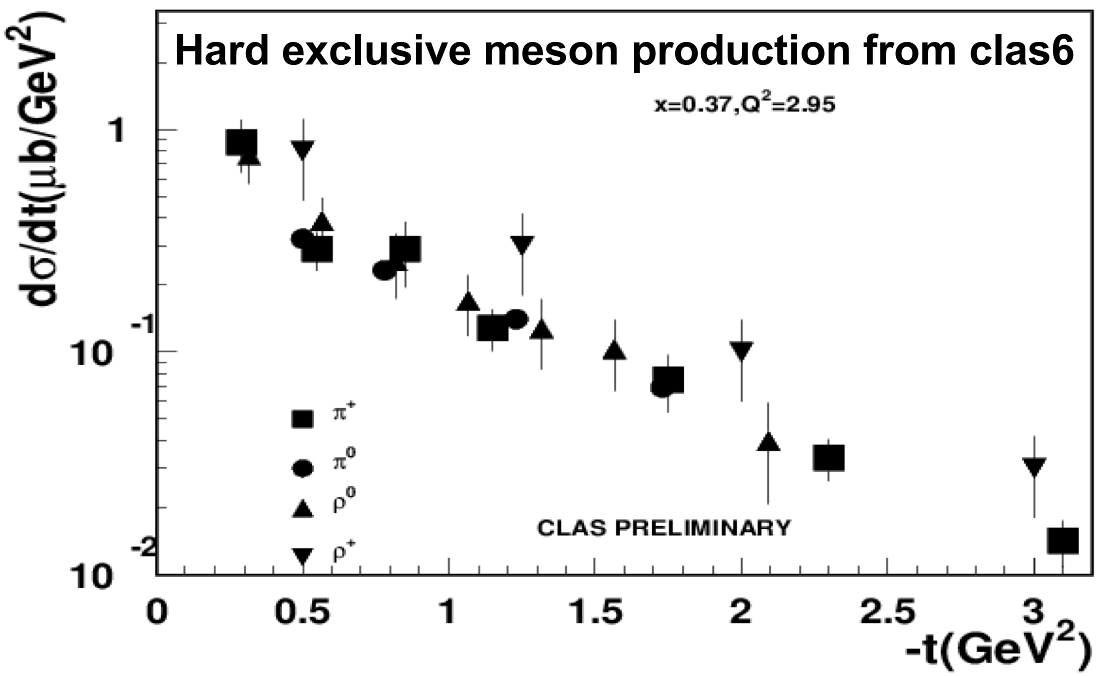
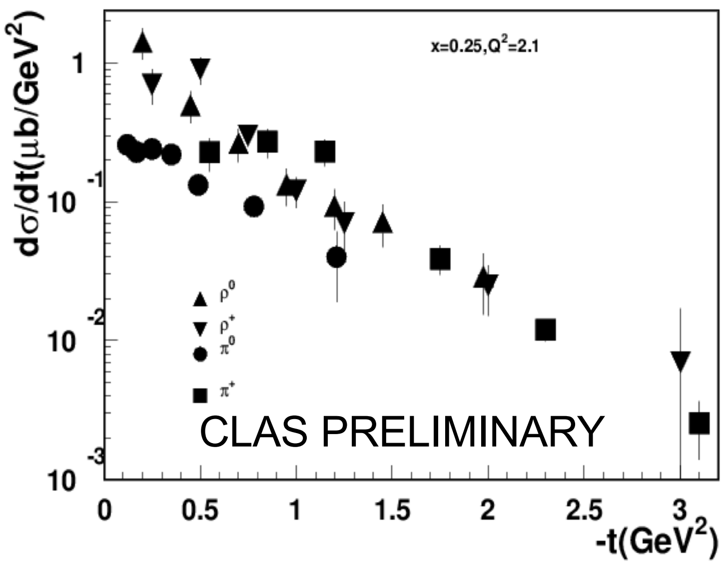
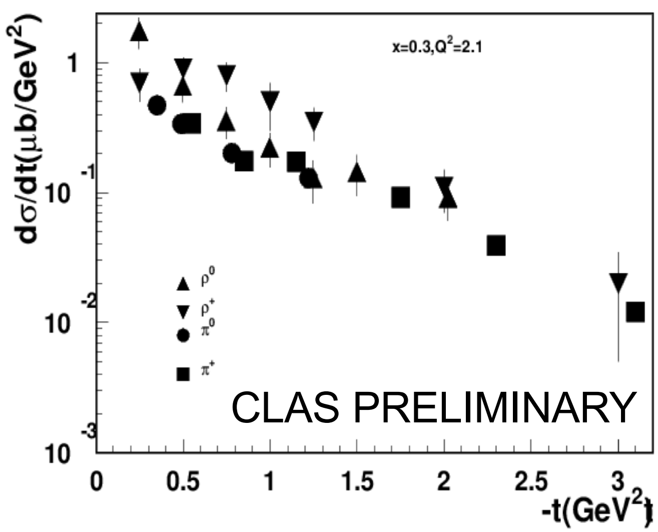
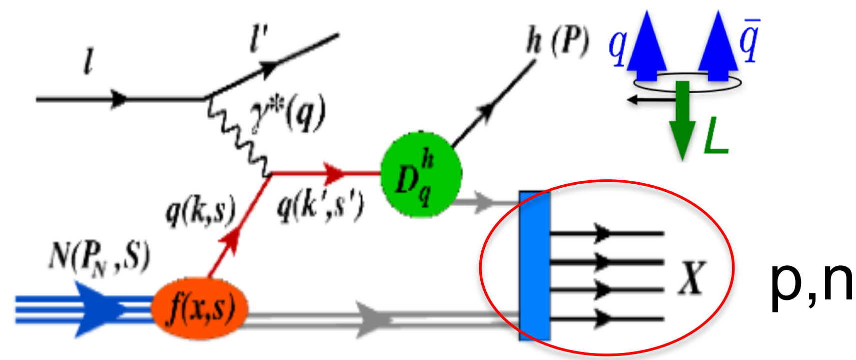




Exclusive π/ρ production at large t





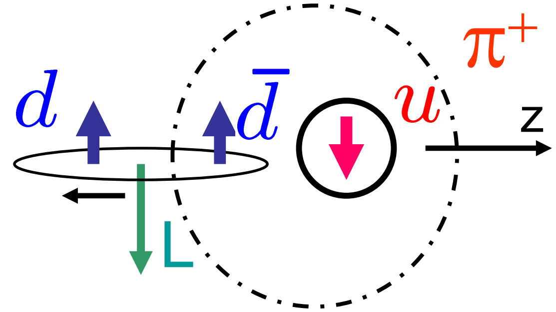


Implications

- x-section of measured exclusive process at large t exhibit similar pattern
- $\rho+>\rho^0$ →Diffractive production suppressed
- at large t production mechanism most likely is similar to SIDIS
- Slightly higher rho x-sections indicate the fraction of SIDIS pions from VM > 60%
- consistent with LUND-MC in fraction of pions from rho
- ………

Collins effect

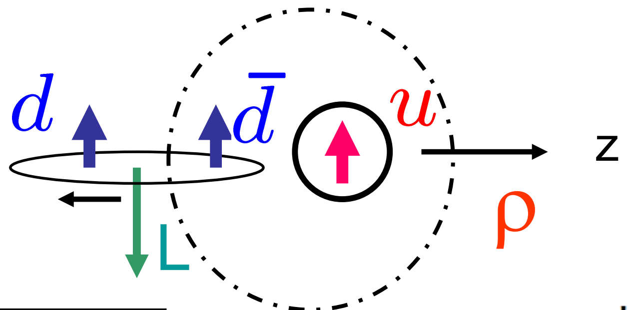
Simple string fragmentation for pions (Artru model)



leading pion out of page

$$h_1 H_1^{\perp u \to \pi}$$

ρ production may produce an opposite sign A_{UT}



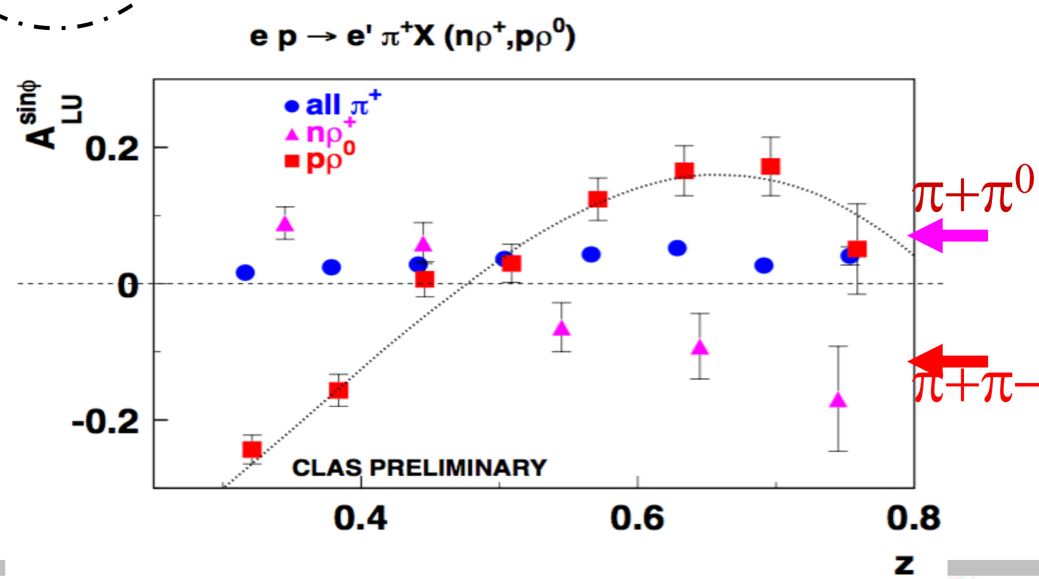
Leading ρ opposite to leading π(into page)

$$H_1^{\perp u \to \rho} \sim -\frac{1}{3} H_1^{\perp u \to \pi}$$

hep-ph/9606390

Fraction of ρ in eπX	% left from eπX asm
20%	~75%
40%	~50%

Pions from rho decays may require special treatment for understanding of certain observables



Radiative DIS

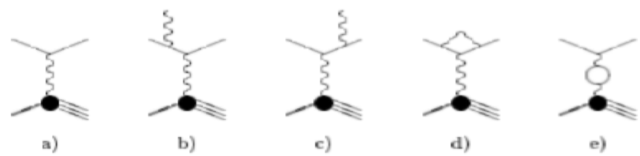


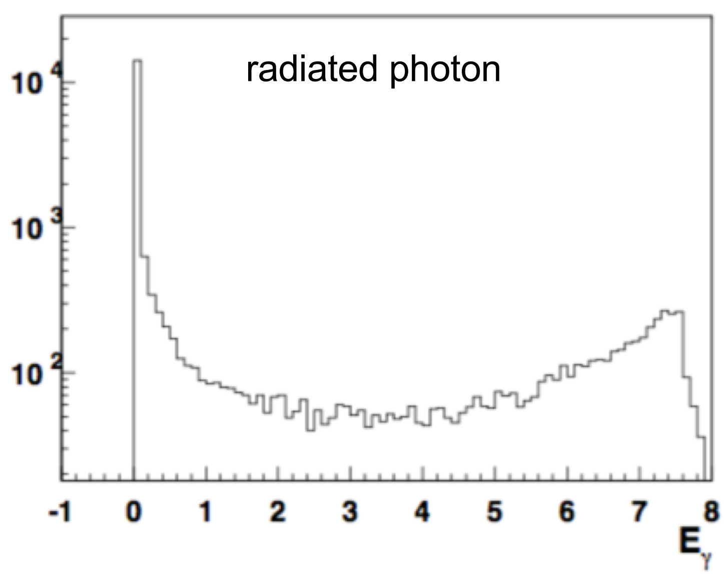
Figure 1: Feynman diagrams contributing to the Born and the radiative correction cross sections in lepton-nucleus scattering.

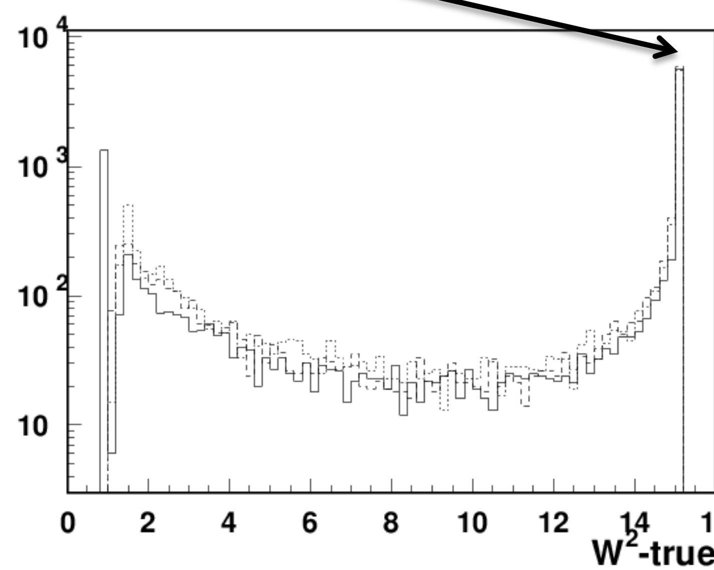
Akushevich et al. http://www.jlab.org/RC/radgen/

generate a single kinematical point at E_b=10.6 GeV with e'=2.0 GeV, θ=0.3
→ **x,y,Q^2,W^2(0.12,0.8,1.9,15.1)**
Integrated over all **Eγ** **$\sigma_{Rad}/\sigma_{Born}$=1.24**

For SIDIS may need "ρ" x-sections in the full W range, including exclusive part

original W^2



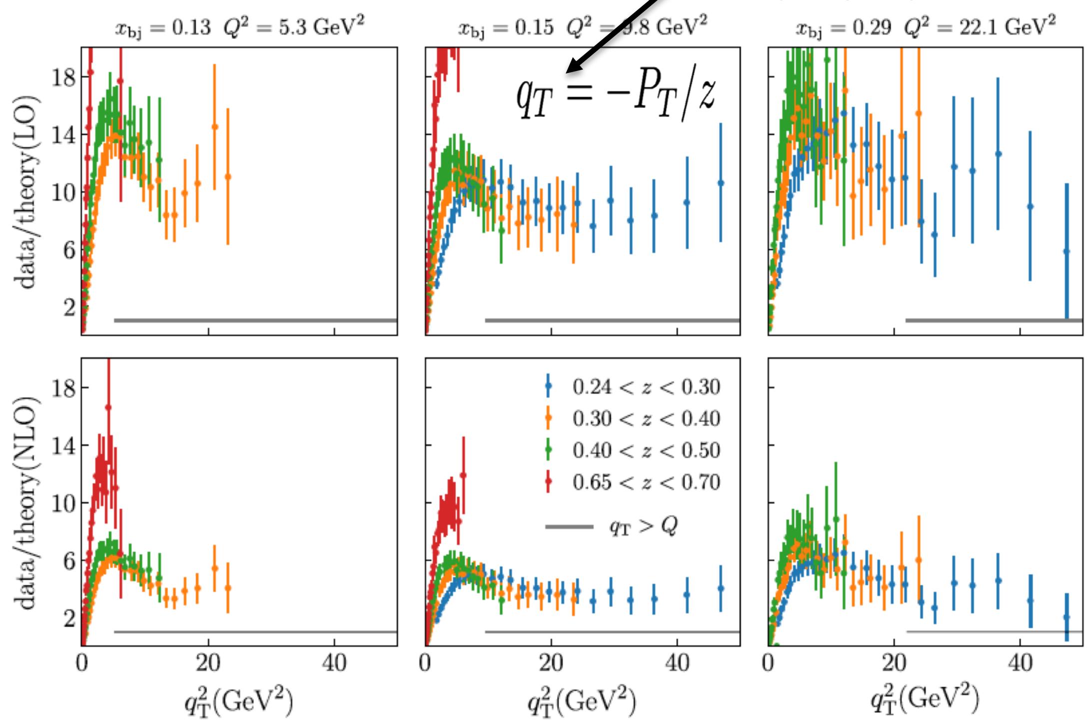


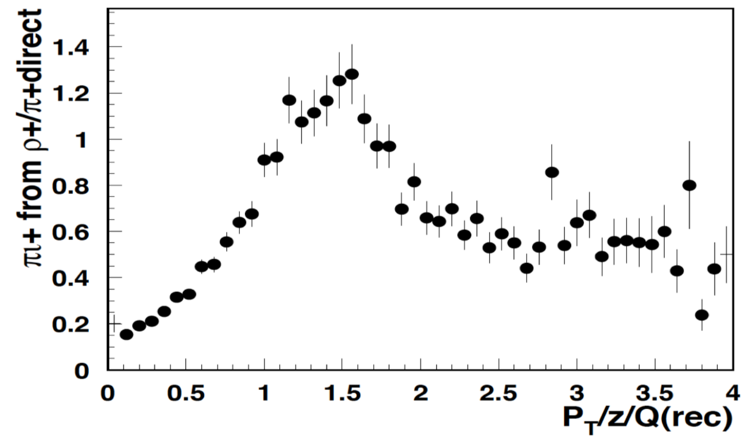
Does it matter if the pion comes from correlated pairs?

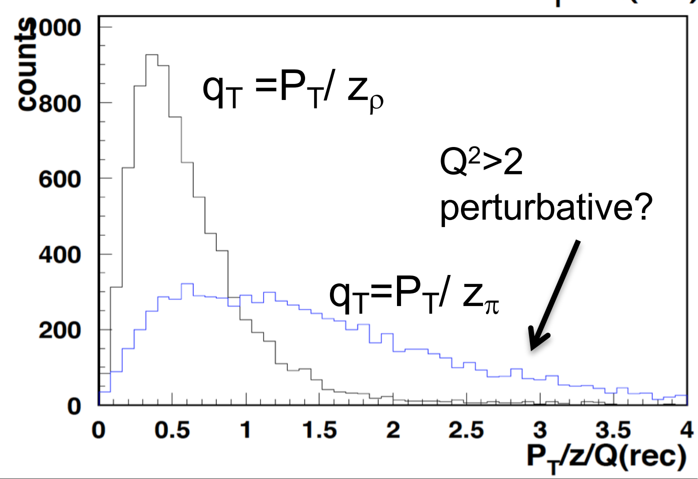
$$F^h_{XY}(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}(M/Q)$$

$$\int d^2\vec{k}_T d^2\vec{p}_T \delta^{(2)}(z\vec{k}_T + \vec{p}_T - \vec{P}_T)$$

quark transverse momentum







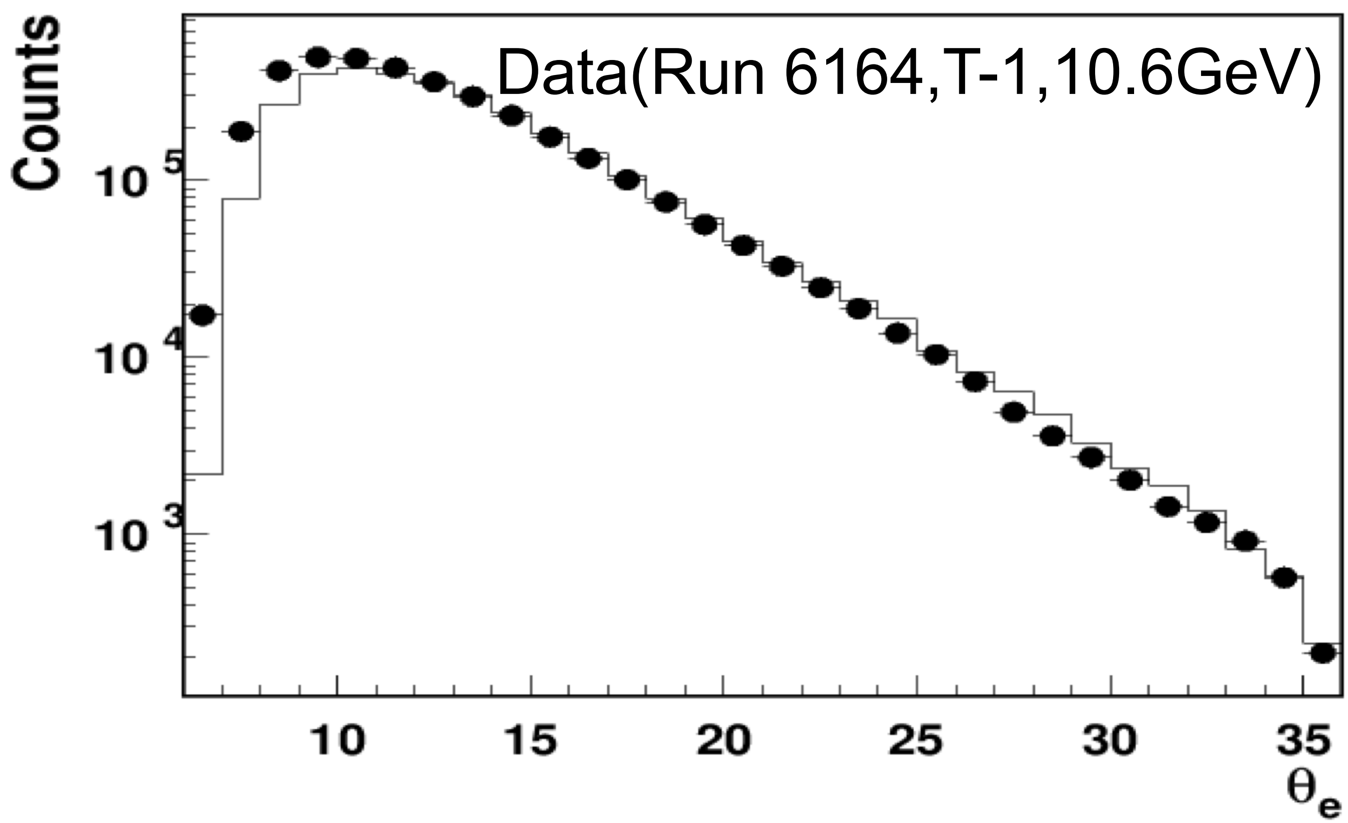
The measurements disagree with leading order and next-to-leading order calculations most significantly at the more moderate values of **x** close to the valence region.

Gonzalez-Hernandez et al, PRD 98, 114005 (2018)

understanding the fraction of pions from "correlated dihadrons" will be important to make sense out of qT distributions

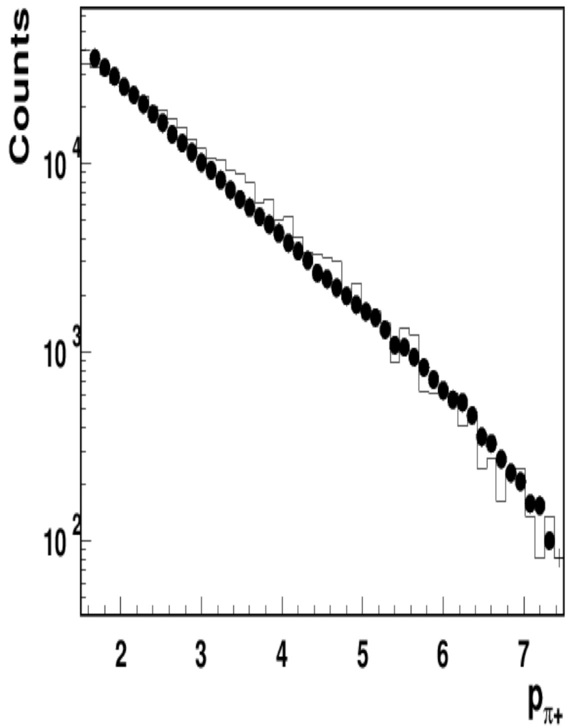
Generators for MC simulations

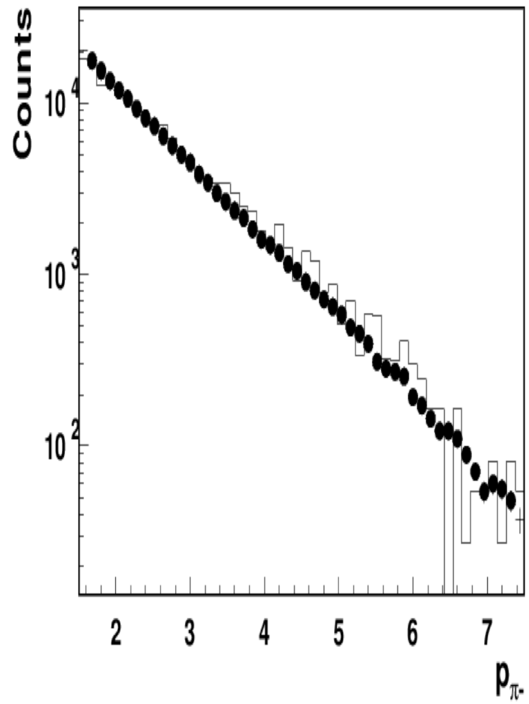
- Full event generators (LUND-MC PEPSI, LEPTO)
- Dedicated event generators for e’ hhx (TMDGen T.Hayward)

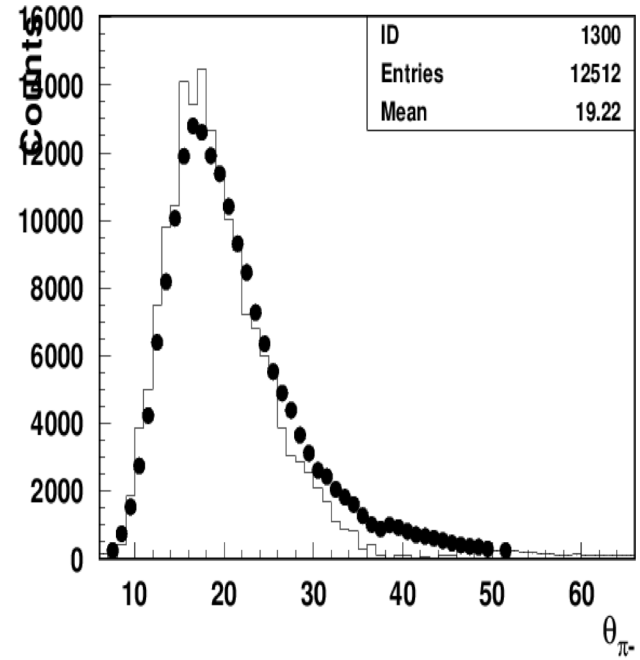


SIDIS ehX: CLAS12 data

ep→e'hX (Data/MC normalized to number of electrons)
(<1% of deuteron 2019 sample))





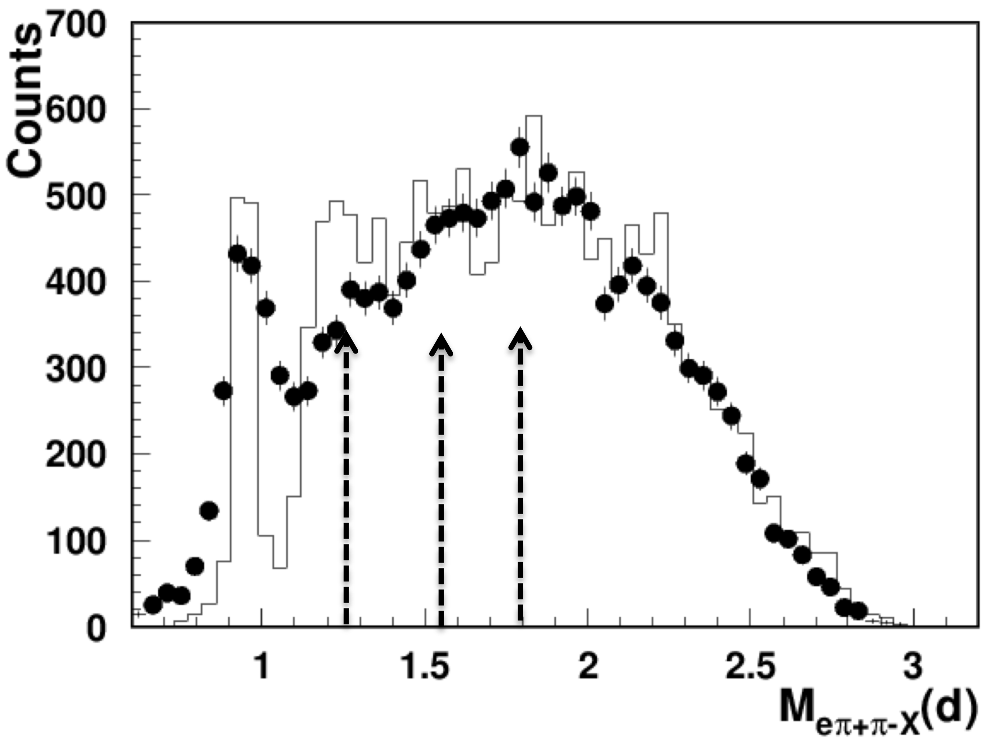


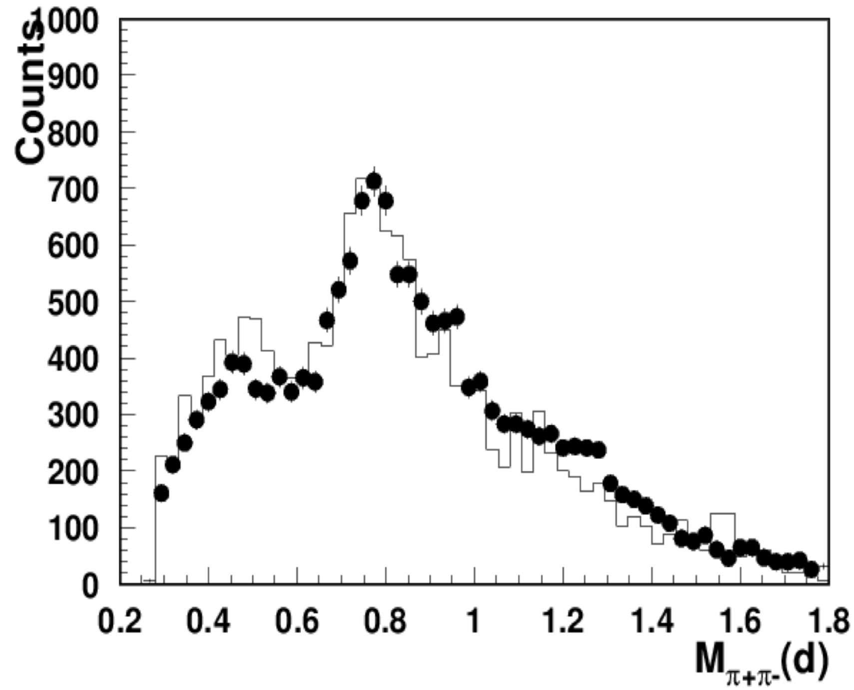
- Pion counts for normalized e'X events consistent with clas12 LUND MC

Correlated pairs: CLAS12 Data

ep→e'hhX

CLAS12 deuteron-2019, 10.6GeV



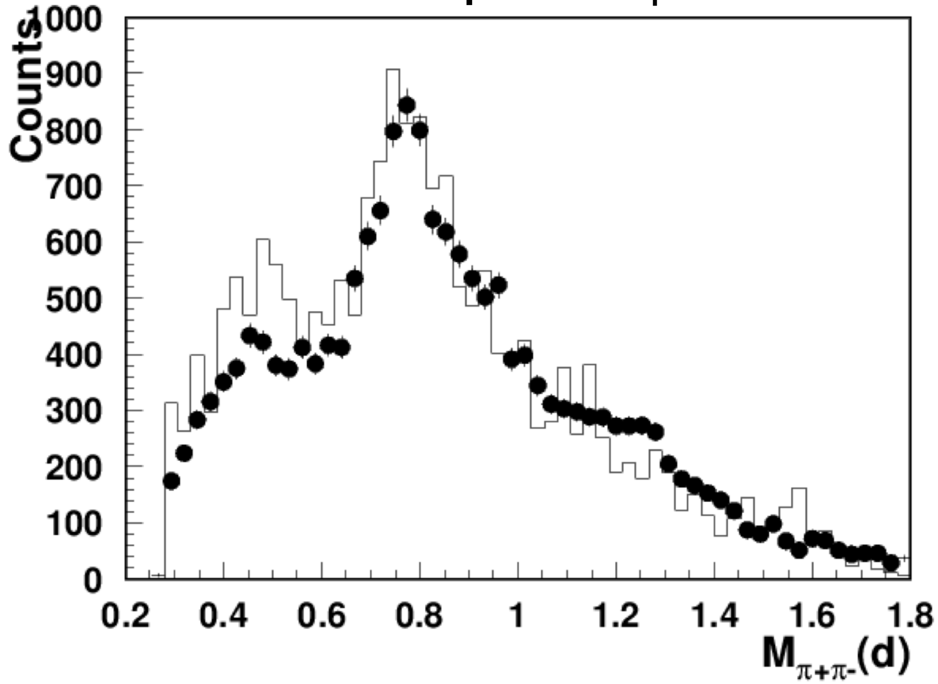


- Normalized to number of electrons pion pair multiplicities consistent with LUND-MC
- Fraction of exclusive states may be significant

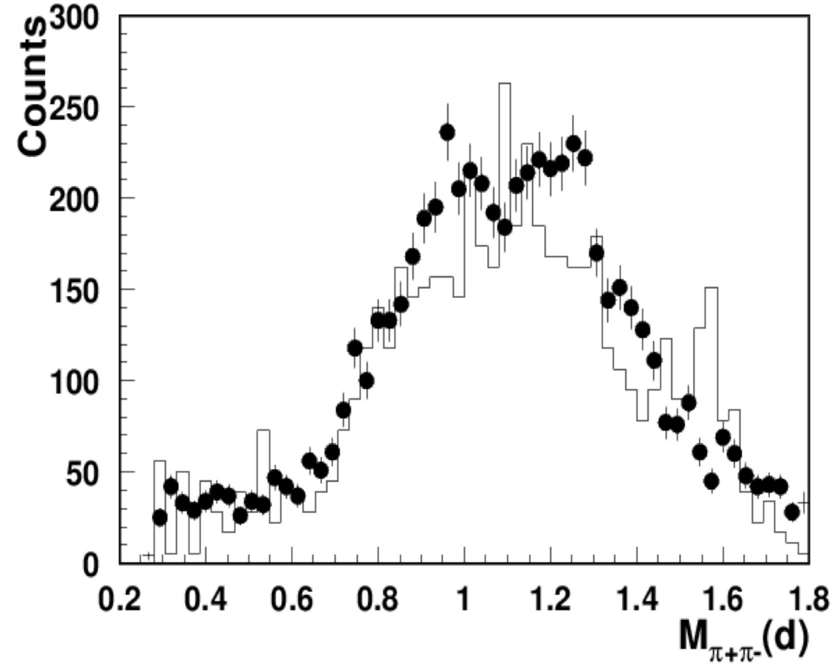
Correlated pairs: Data(Run 6144,T-1,10.6GeV)

ep→e'hhX

All pion P_T

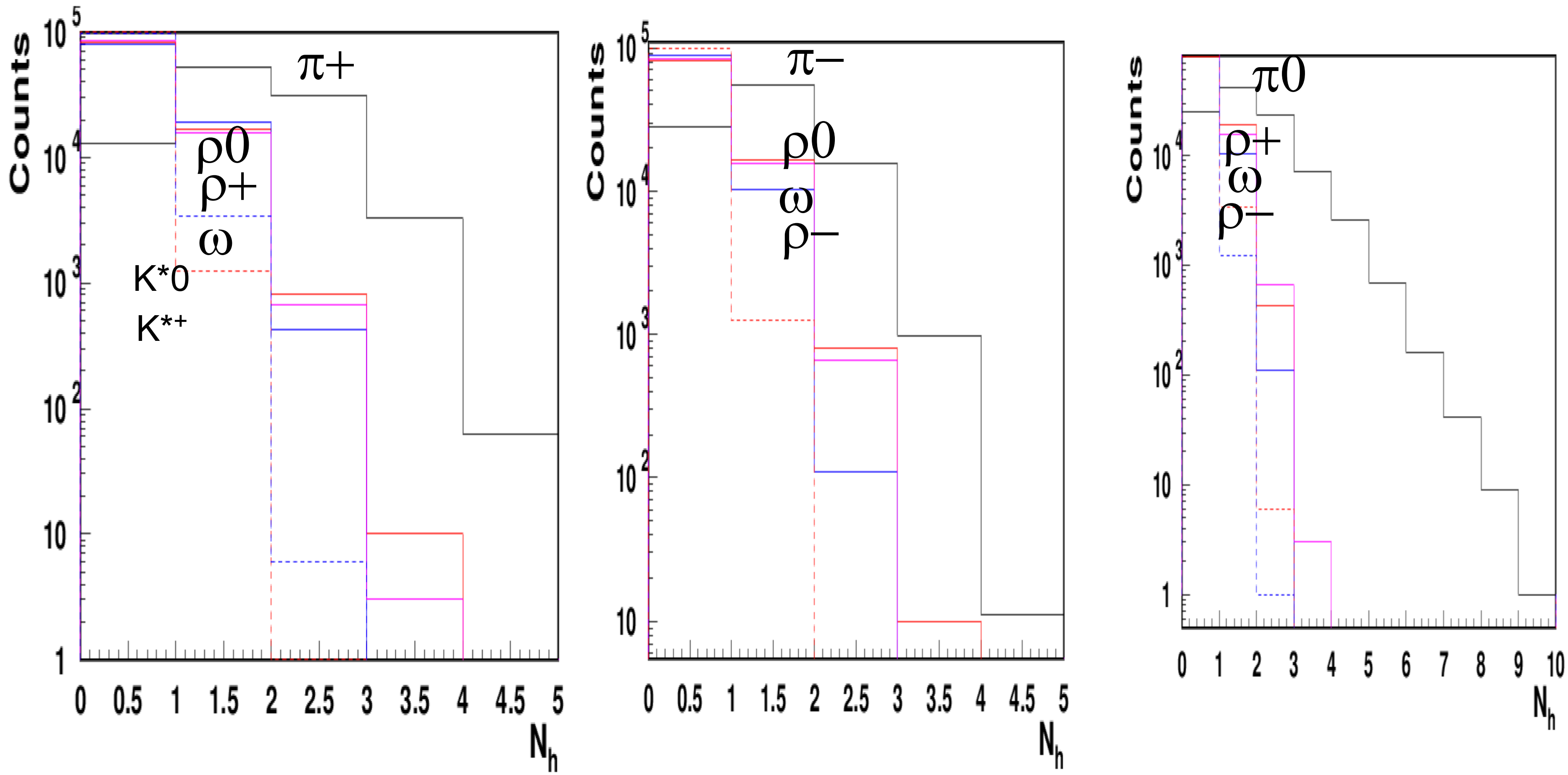


only P_T>0.4



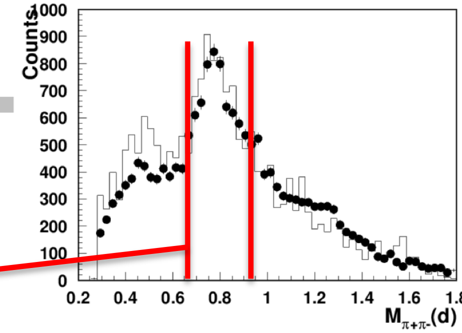
- Cut on large P_T (right plot has $P_T(\pi+)>0.4$ GeV, $P_T(\pi-)>0.4$ GeV) practically eliminates the rho region.
- Similar effect observed also for MC

Background events

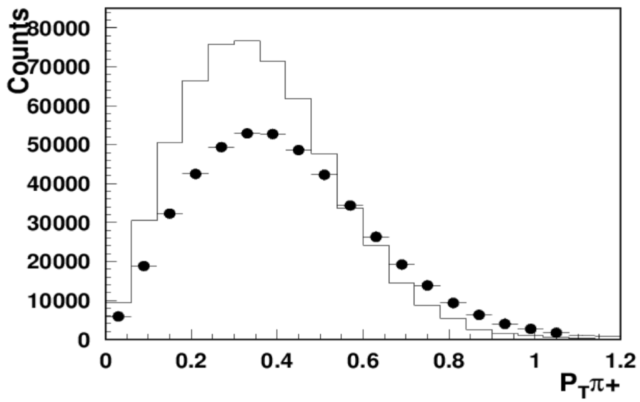


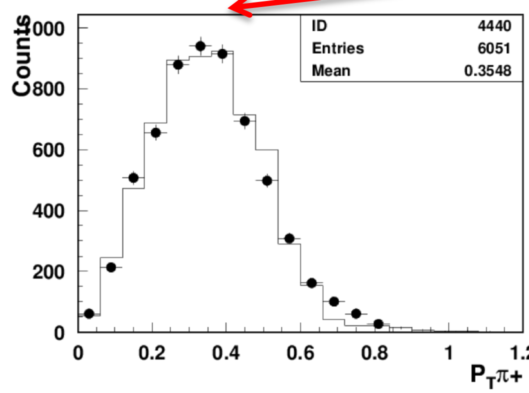
There are ~10% with 2 rho+/rho0/rho- (dashed show K*0 and K*+)

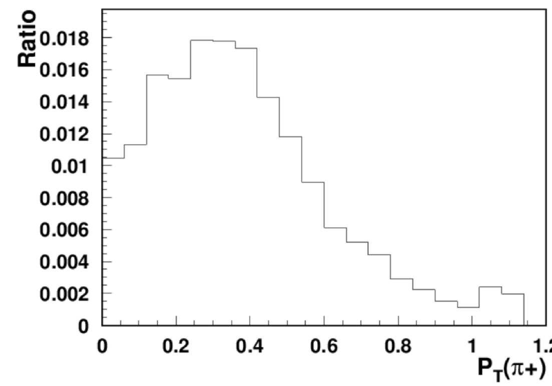
P_T distributions in the rho region

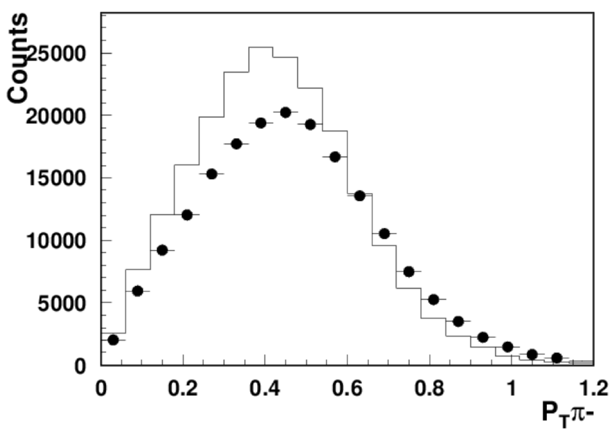


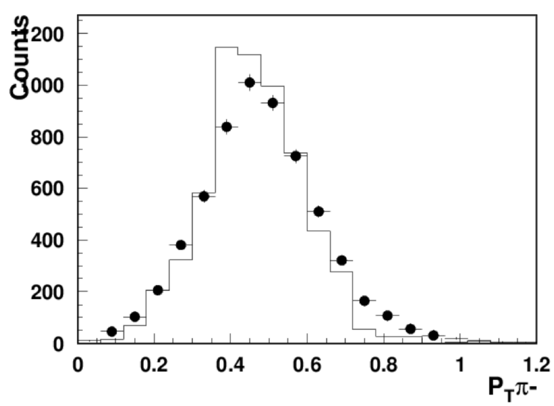
P_T- distributions of pions in the rho region look like Gaussian

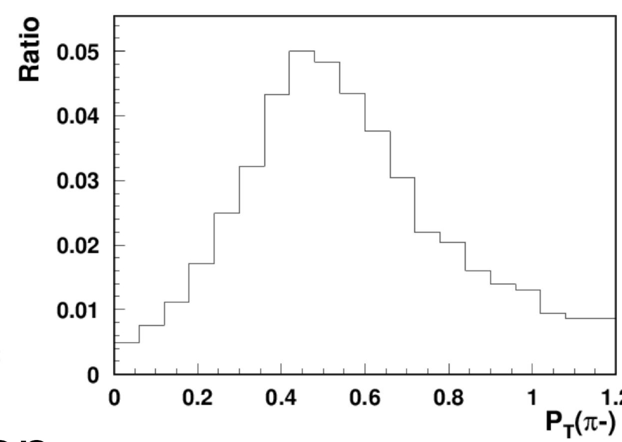










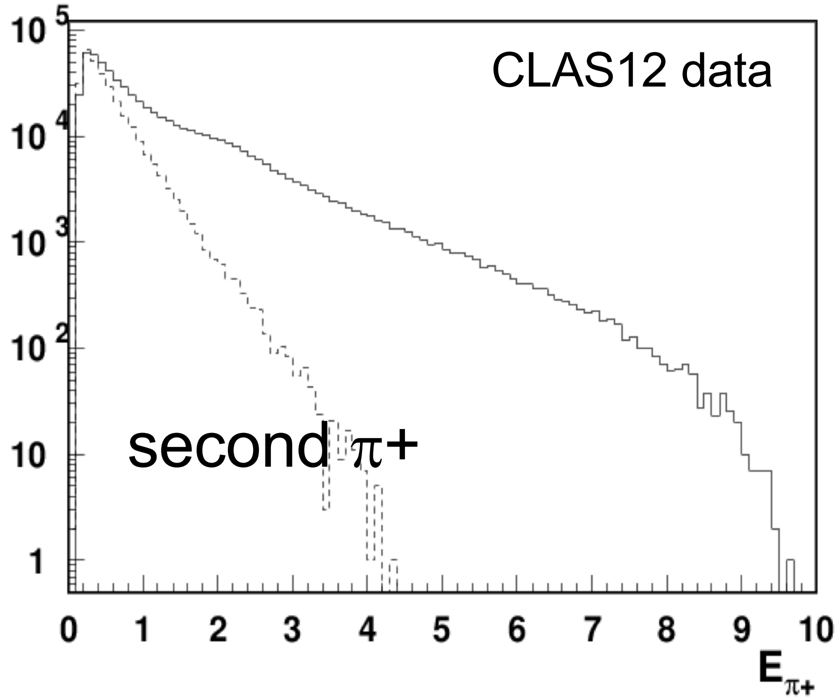


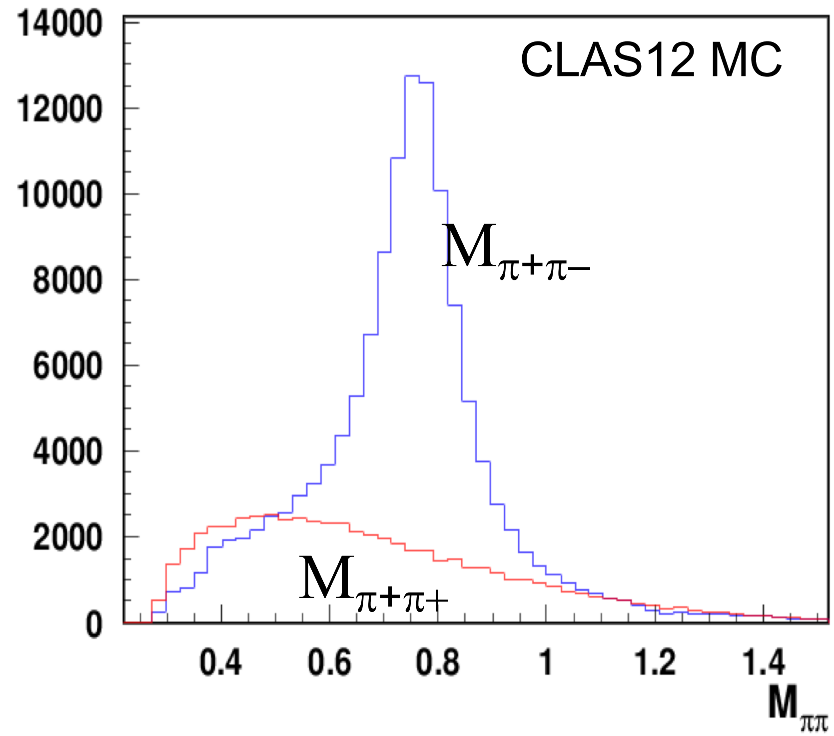
Inclusive $\pi+/\pi-$

$\pi+/\pi-$from ρ-region

Invariant mass distributions for 2π+

All events with parent of π+ is ρ0

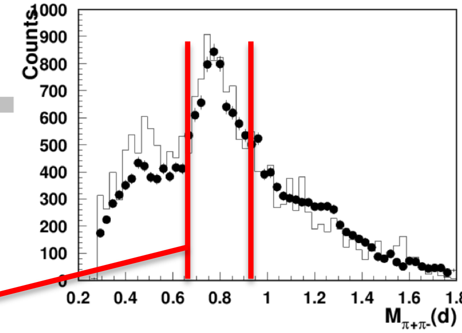


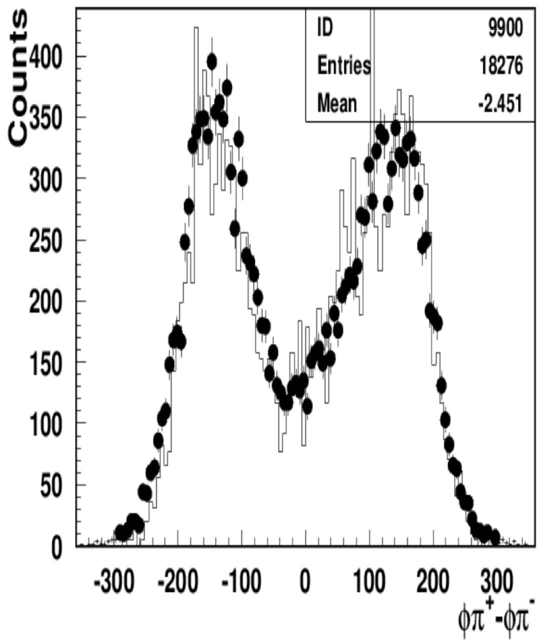


The π+/π– pairs out of ρ-region may still be generated by ρs

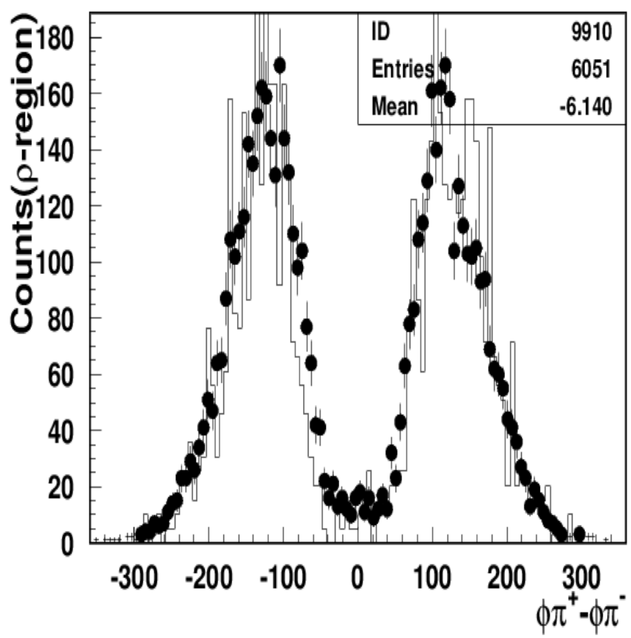
ϕ–distributions of hadrons in CM system

Most energetic π+ and π–appear back-to-back

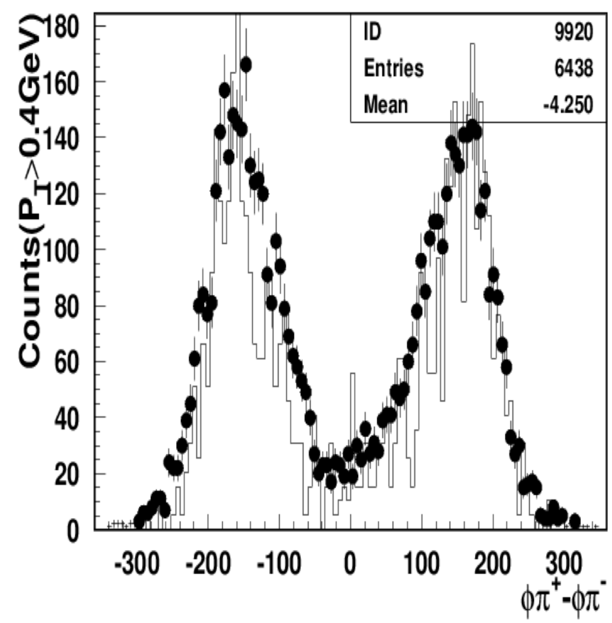




Inclusive π+π–



π+π–from ρ-region



π+π–from P_T>0.4 GeV
"high P_T"-region

SUMMARY

- CLAS12 (Fall) proton and deuteron (Spring) data compared with MC based on the LUND string fragmentation
- Data supports predictions from different MCs of very significant fraction of inclusive pions coming from rhos.
- The observables for pions from rhos have peculiar spin and momentum dependences and require different RC, modeling, and interpretation
- Understanding of exclusive production of hadrons, in particular, at large t, where they show similar behavior, will be important for SIDIS

The interpretation of di-hadron production in SIDIS, as well as interpretation of single-hadron production is intimately related to contributions to those samples from correlated semi-iclusive and exclusive di-hadrons in general, and vector mesons, in particular.

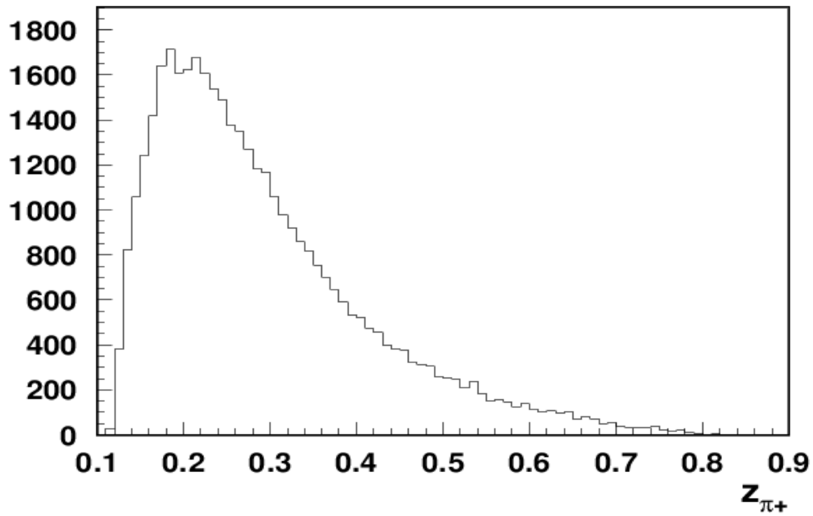
TODO:

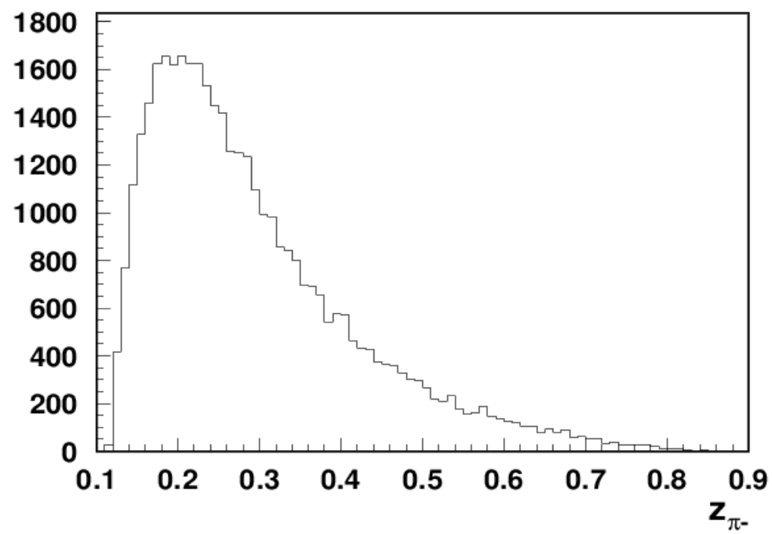
measure multiplicity of exclusive and semi-iclusive dihadrons $\pi^+\pi^0, \pi^+\pi^-, \pi^-\pi^0$ for proton and deuteron targets

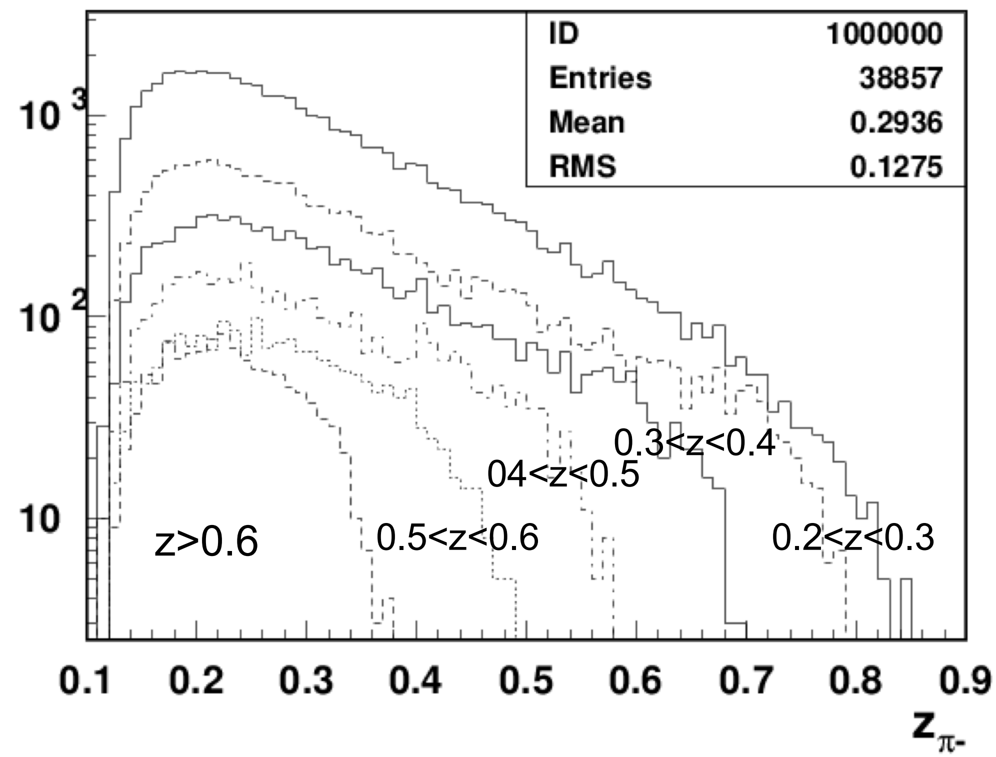
Support slides

Correlated pairs: Data(Run 5038,T-1,10.6GeV)

ep→e'hhX

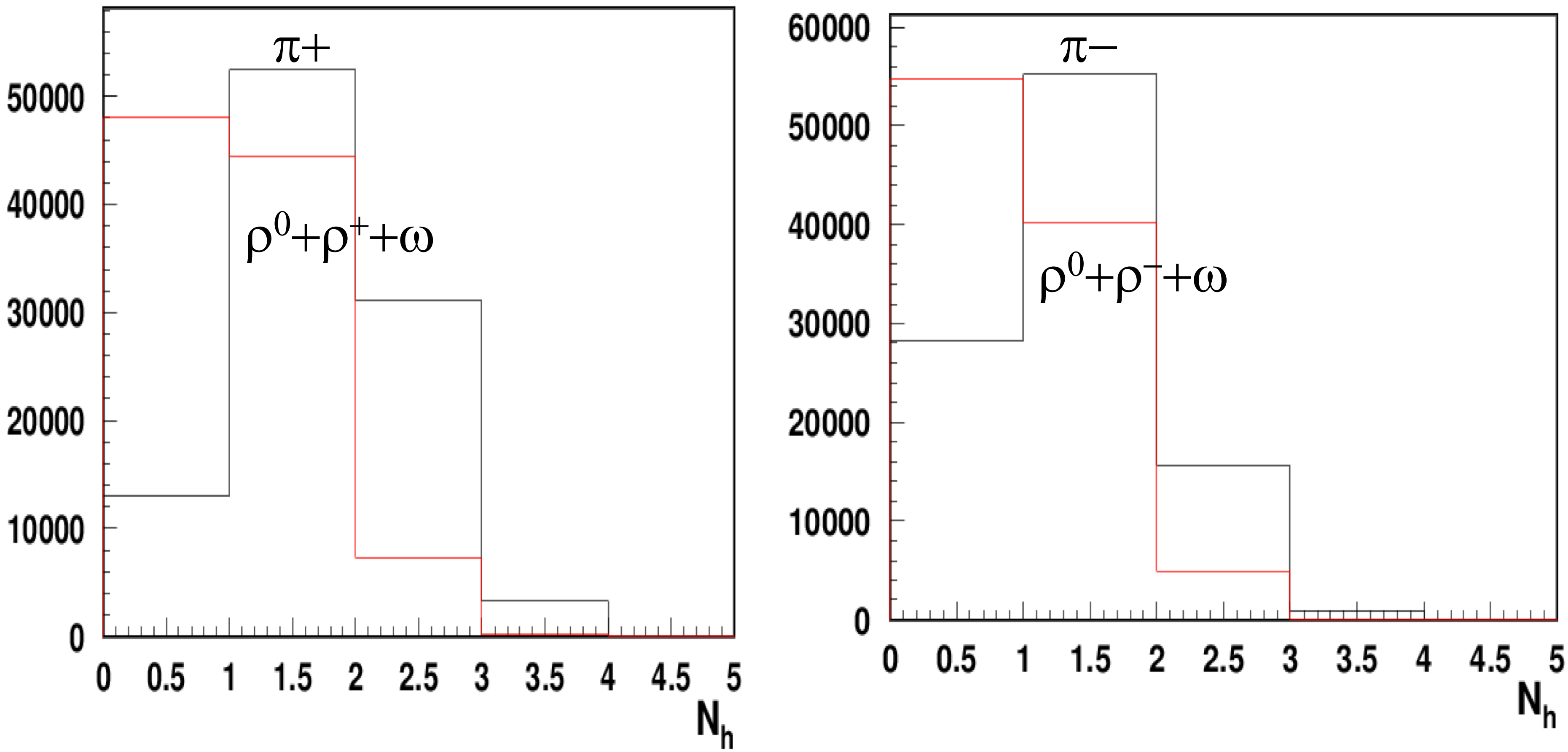






- Similar z-distributions for dihadrons

Background events: integrated for all VM



Note: pion sample include the contributions from VMs

Event generators for DIS/SIDIS/HEP studies

Main classes of event generators:

a)Full event generators where sets of outgoing particles are produced in the interactions between two incoming particles and a complete event is generated

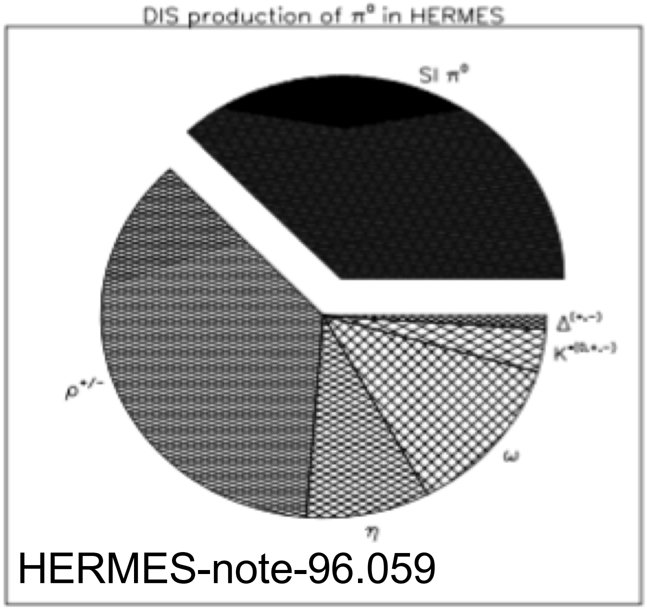
Applications: attempt to reproduce the raw data
understand background conditions
estimating rates of certain types of events
planning and optimizing detector performances,…

b) **Specific event generators (single hadron, di-hadron, DVCS…) , where only the final state particles of interest are generated**

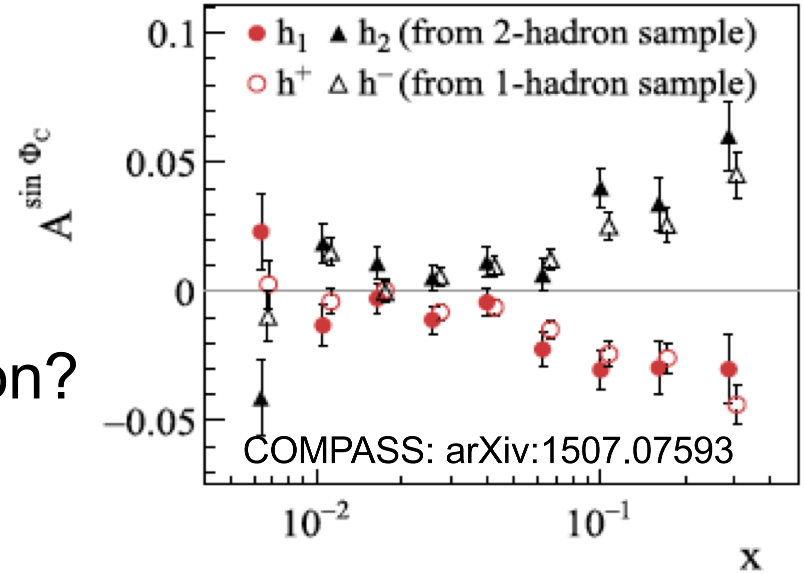
Applications: providing fast tests of analysis procedures with relatively simple
integration of different input models.
developing analysis frameworks.

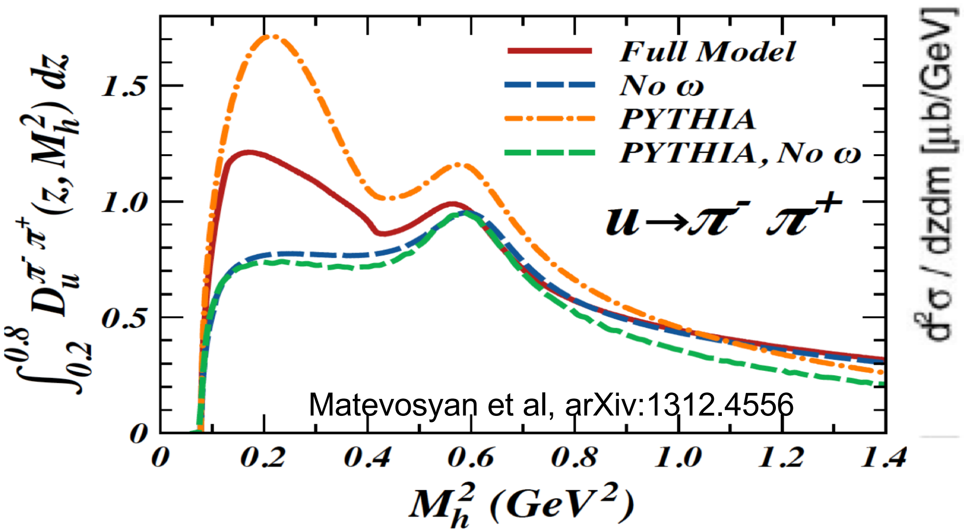
1) Providing events with cross section
2) Phase space with realistic x-sections provided as weight factors
+unfolding measured data for acceptance and detector resolution effects
3) Easier implementation of Radiative Effects

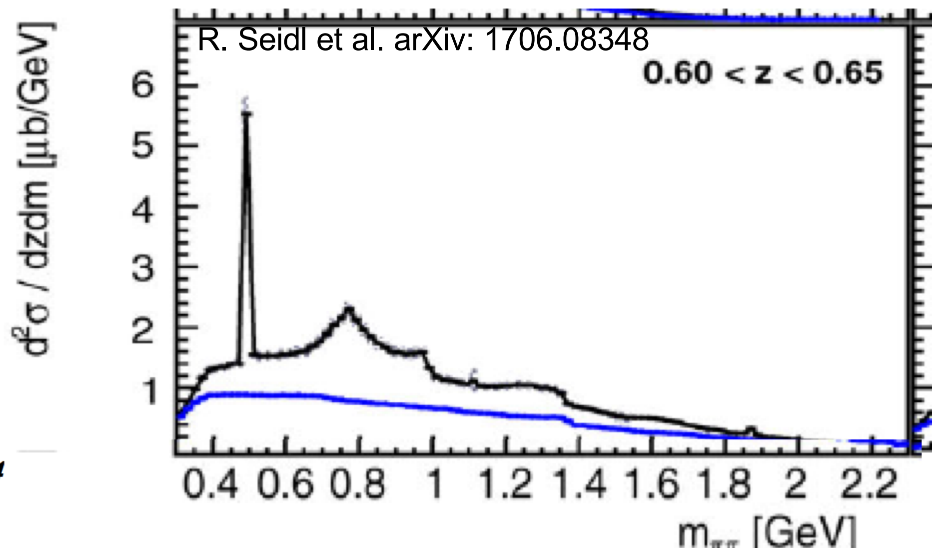
Dihadron production



What is the origin of dihadrons?
What is a single hadron?

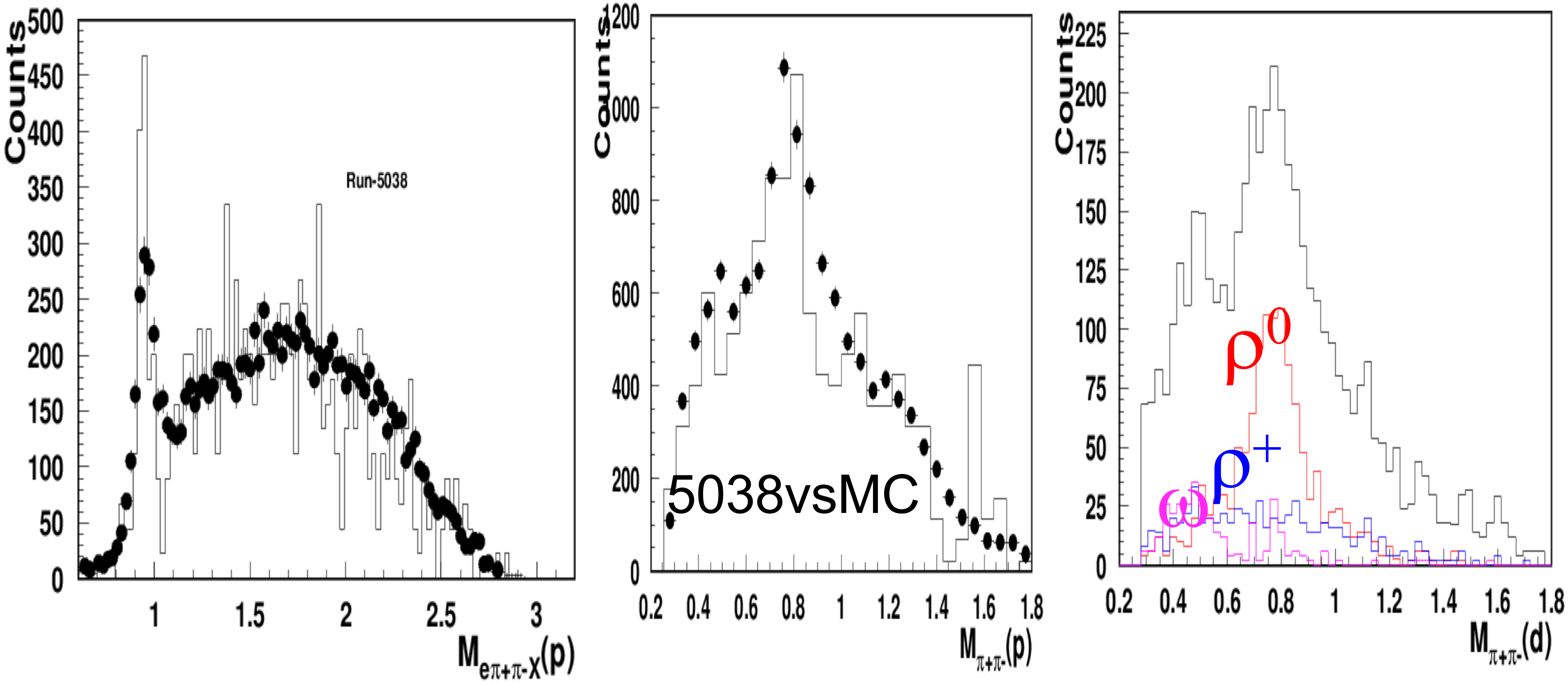






Correlated pairs: Data/MC(Run 5038,T-1,10.6GeV)

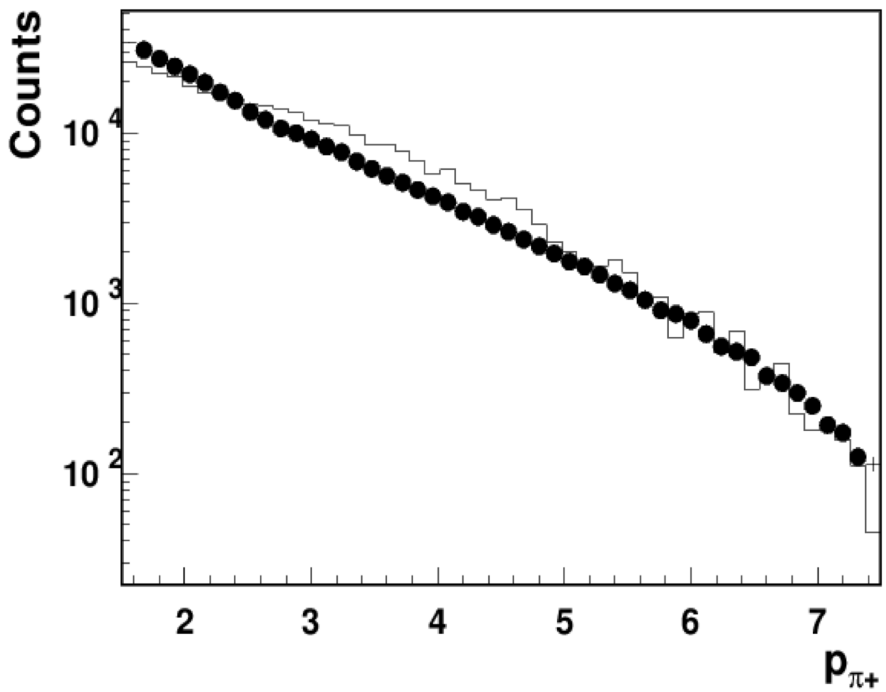
Data/MC normalization by number of reconstructed e'X events

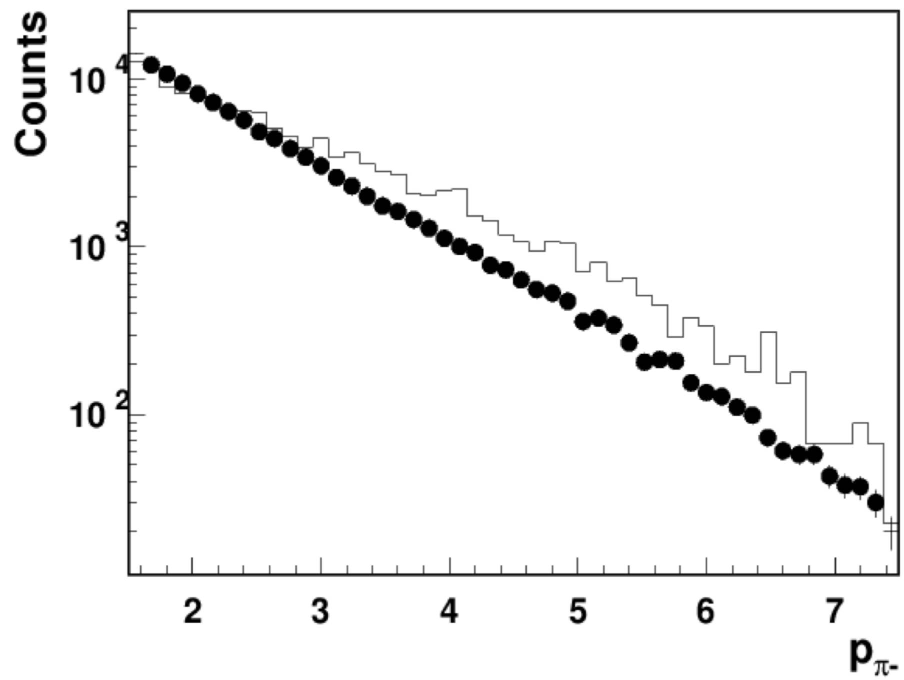


- Fraction of exclusive pairs could be separated
- Most of the pion pairs comes from SIDIS VM decays
  - those are mostly SIDIS VM

Correlated pairs: Data(Run 5038,T-1,10.6GeV)

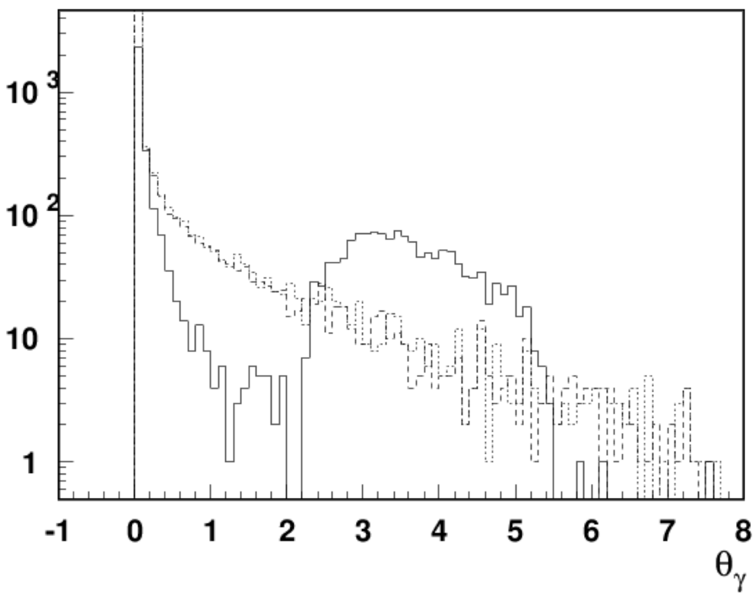
ep→e'hX

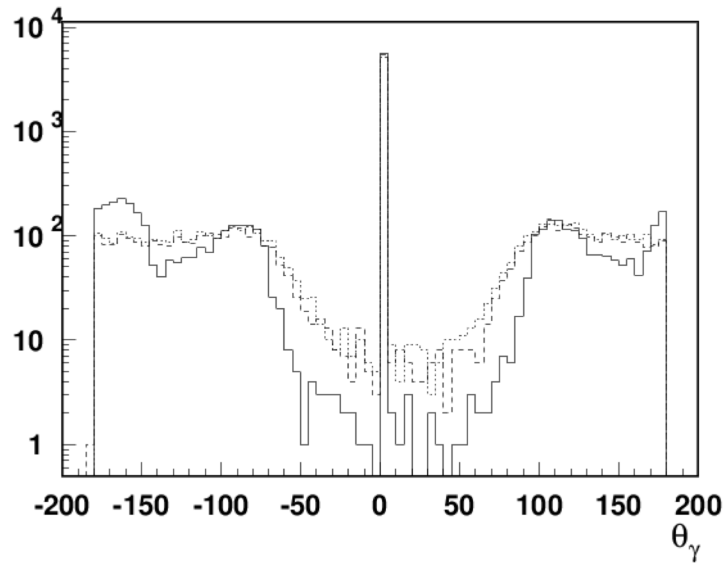




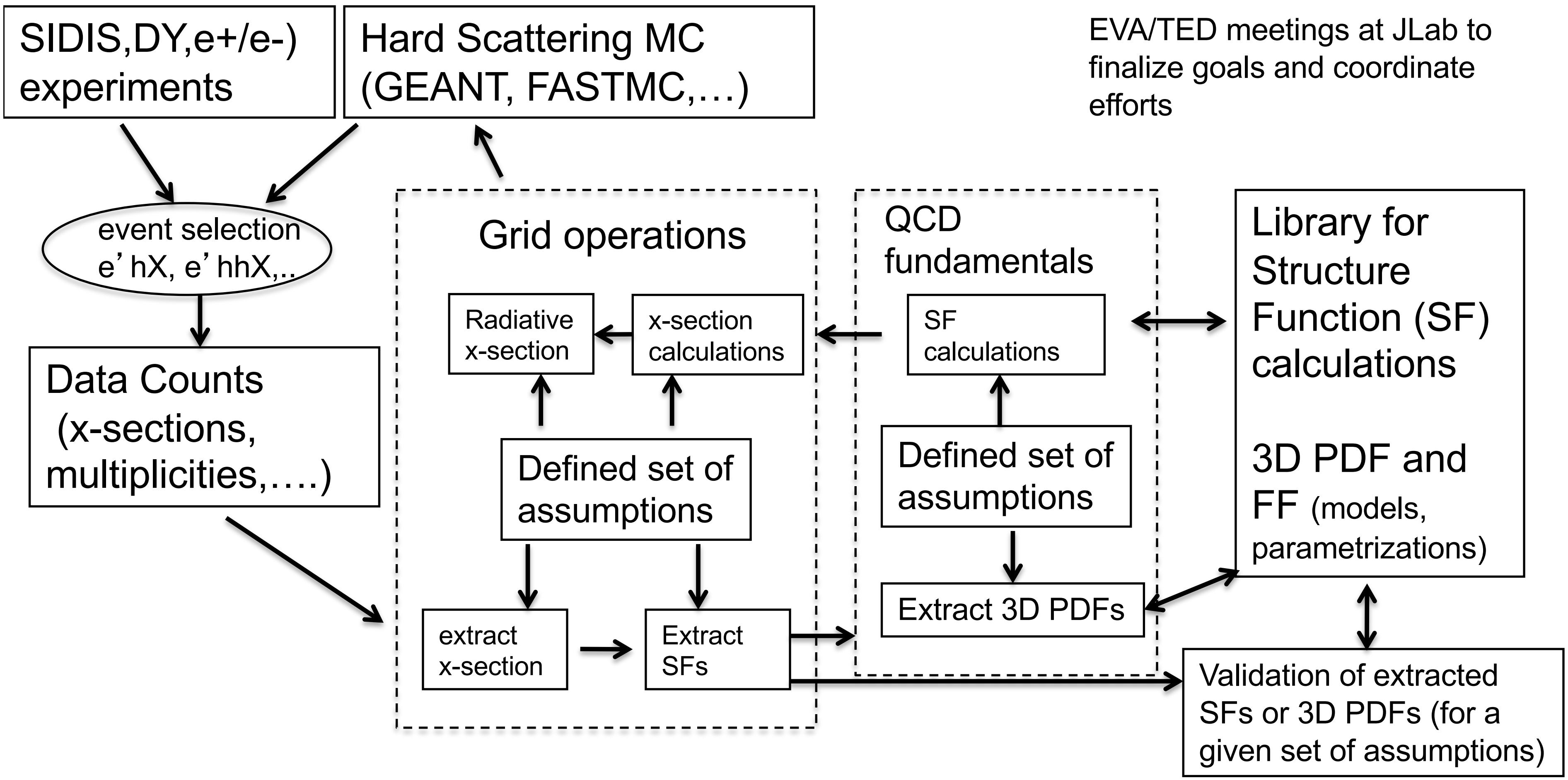
- Data/MC normalized by number of e'X events
- Reasonable agreement for pi+ (apart from region 3<p<5)

RC using radgen





3D PDF Extraction and VAlidation (EVA) framework



Development of a reliable techniques for the extraction of 3D PDFs and fragmentation functions from the multidimensional experimental observables with controlled systematics requires close collaboration of experiment, theory and computing

Event generators for DIS/SIDIS/HEP studies

https://github.com/JeffersonLab/clasdis-nocernlib
https://github.com/JeffersonLab/inclusive-dis-rad
https://github.com/JeffersonLab/dvcsgen

……..

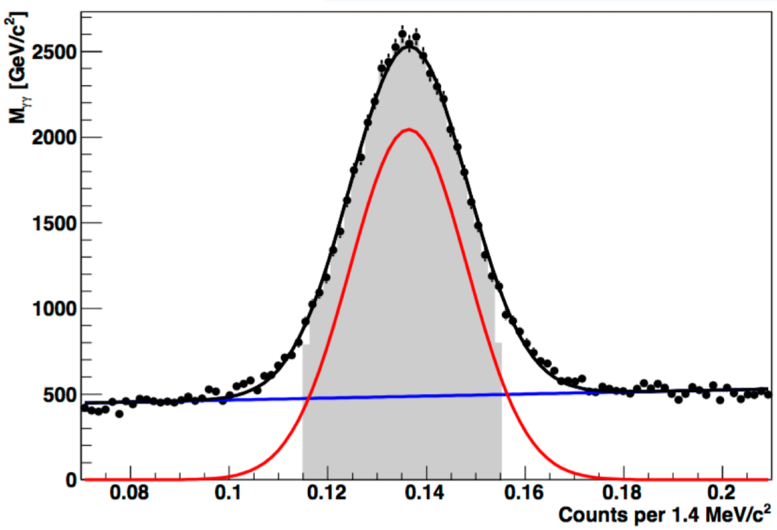
More generators announced
Exclusive 2 pion
HEPGEN /group/gpd/sidis/hepgen/
Manual:
http://project-gpd-full-chain-mc.web.cern.ch/project-gpd-full-chain-mc/hepgen/

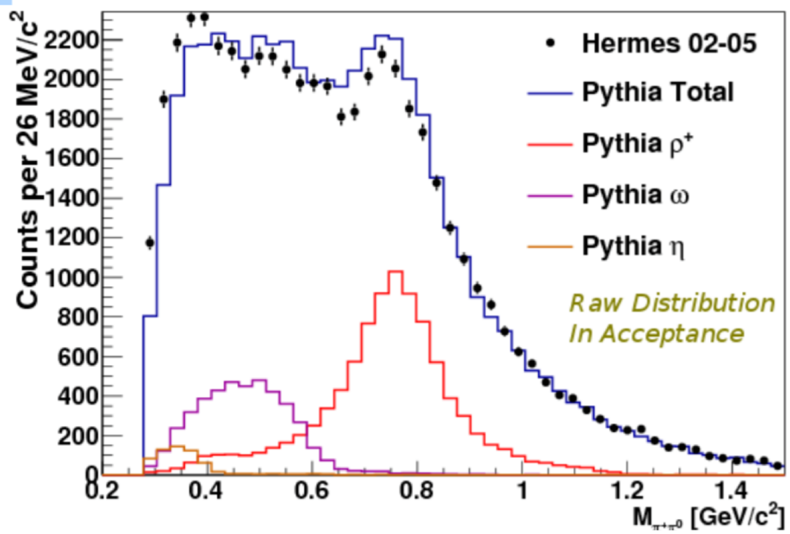
-- single photon production (DVCS + BH)
-- exclusive π^0 production and decay $\pi^0 \to \gamma + \gamma$
-- exclusive ρ^0 production and decay $\rho^0 \to \pi^+ + \pi^-$
-- exclusive φ production and decay $\varphi \to K^+ + K^-$
-- exclusive ω production and decays $\omega \to \pi^+ + \pi^- + \pi^0$
--- exclusive ρ^+ production and decay $\rho^+ \to \pi^+ + \pi^0$,
-- exclusive J/ψ production and decays $J/\psi \to e^+ + e^-$ or $J/\psi \to \mu^+ + \mu^-$

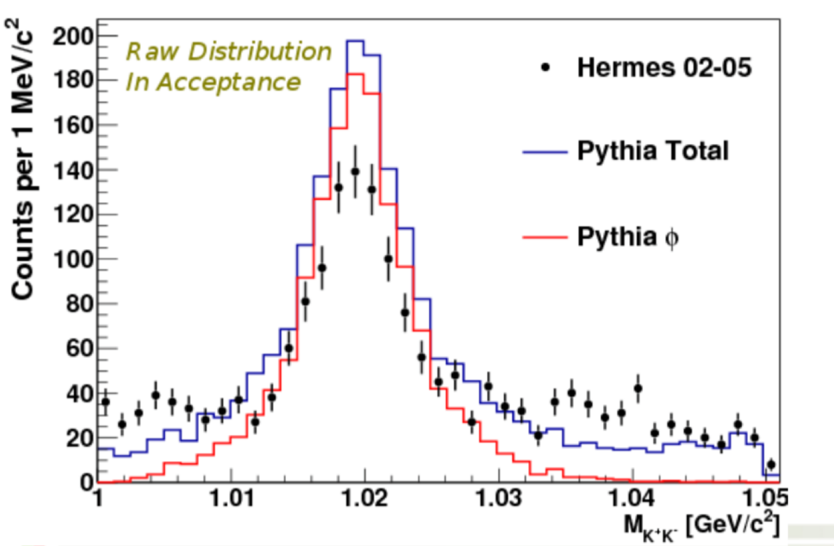
Radiative corrections for all relevant processes should be done with MC generating a radiative photon with account of proper SF set involved.

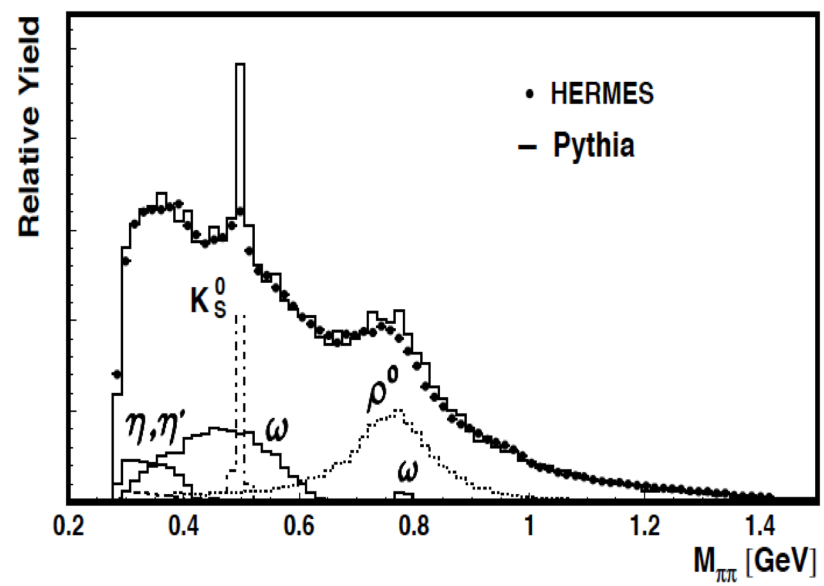
HERMES dihadrons

Particle Reconstruction

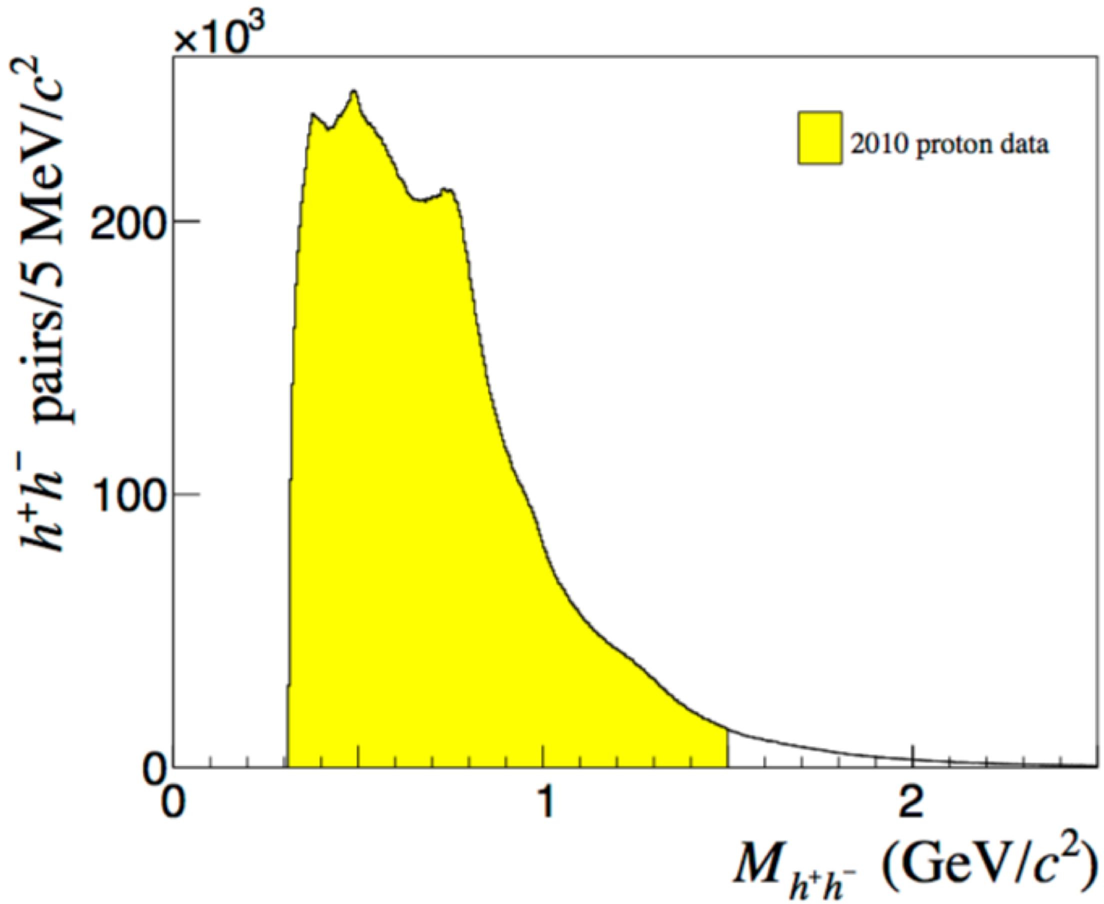




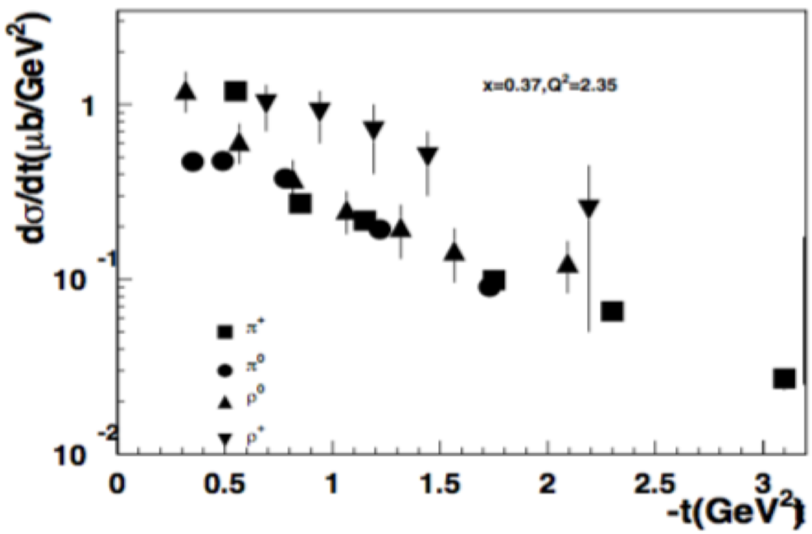


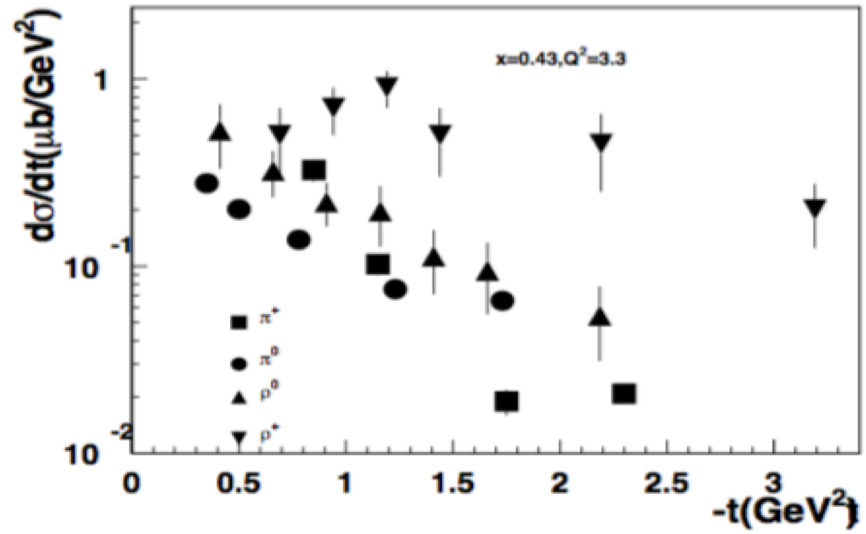


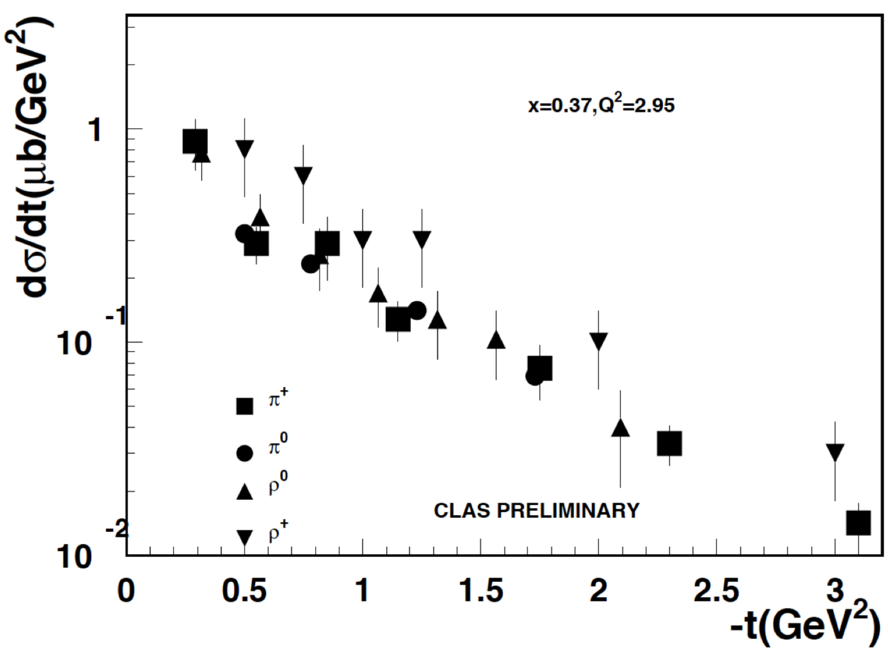
COMPASS dihadrons

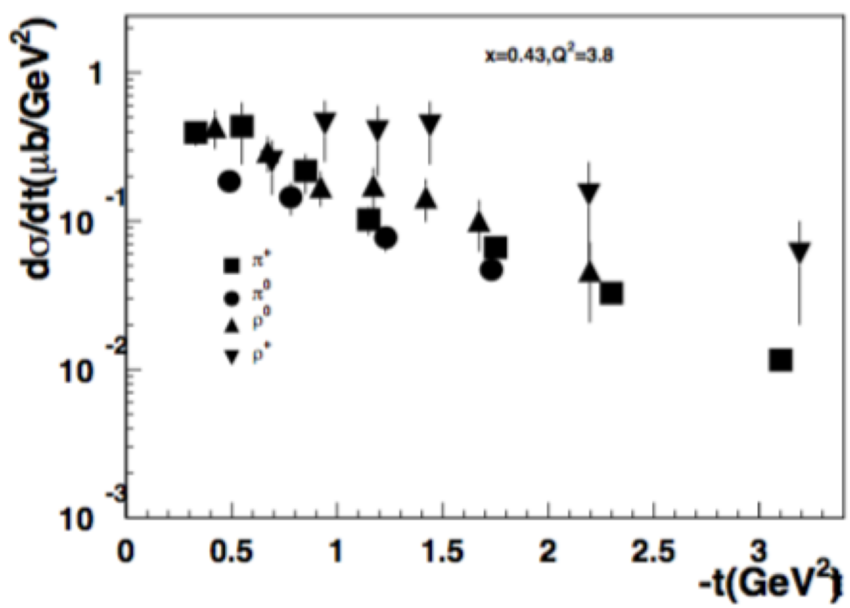


Higher energy, higher the probability to pick up pions from different rhos

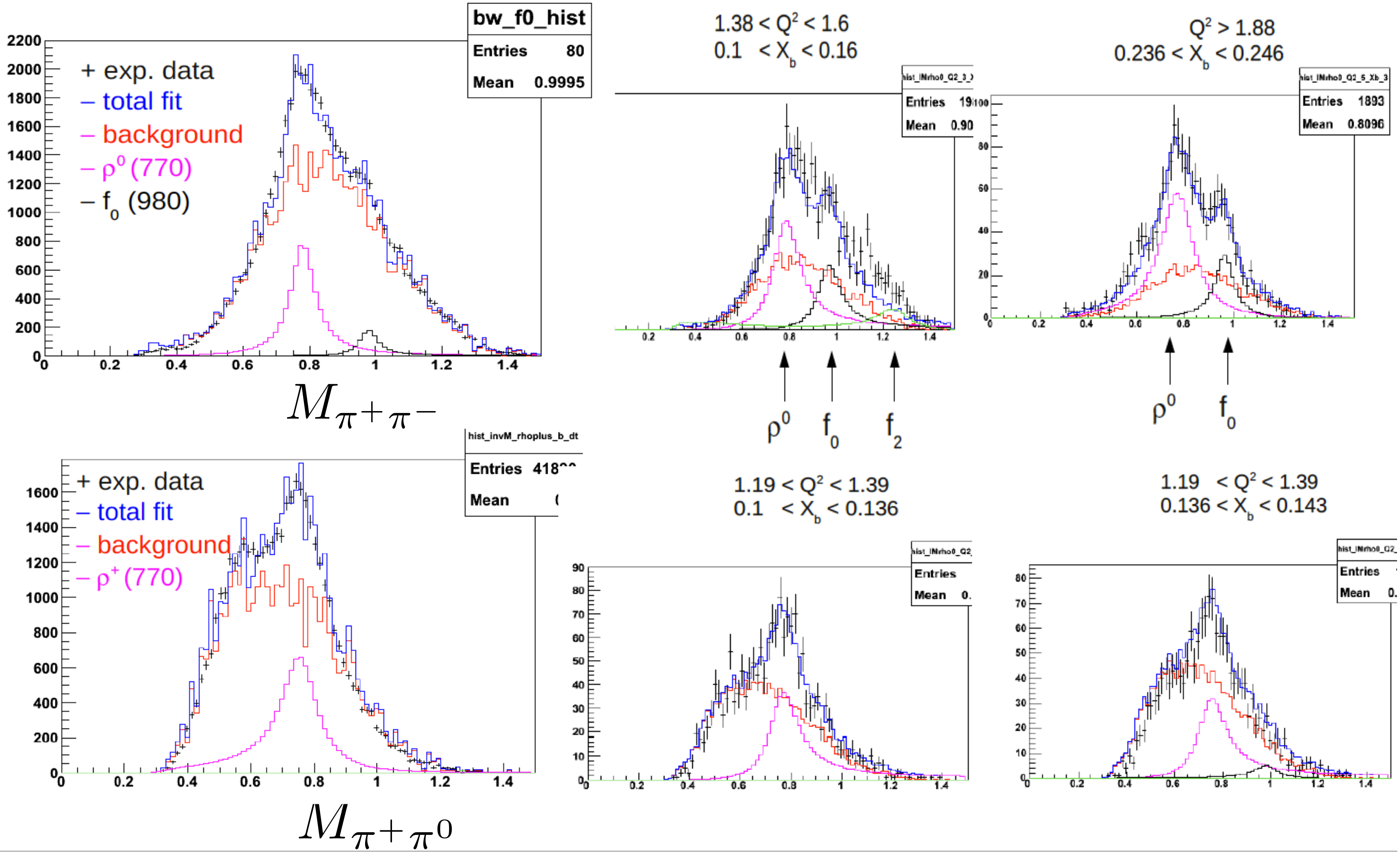

x=0.37,Q²=2.35
dσ/dt(μb/GeV²)
-t(GeV²)
π⁺
π⁰
ρ⁰
ρ⁺


x=0.43,Q²=3.3
dσ/dt(μb/GeV²)
-t(GeV²)
π⁺
π⁰
ρ⁰
ρ⁺


x=0.37,Q²=2.95
dσ/dt(μb/GeV²)
-t(GeV²)
π⁺
π⁰
ρ⁰
ρ⁺
CLAS PRELIMINARY


x=0.43,Q²=3.8
dσ/dt(μb/GeV²)
-t(GeV²)
π⁺
π⁰
ρ⁰
ρ⁺

Dihadron simulations with LUND-MC @6 GeV

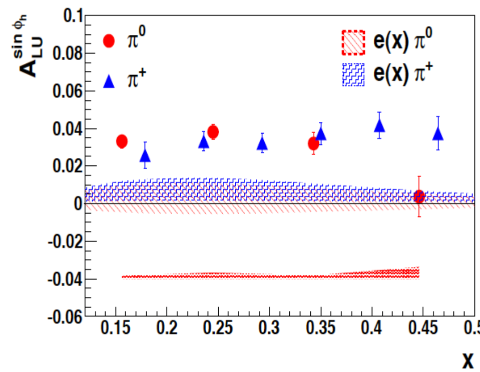


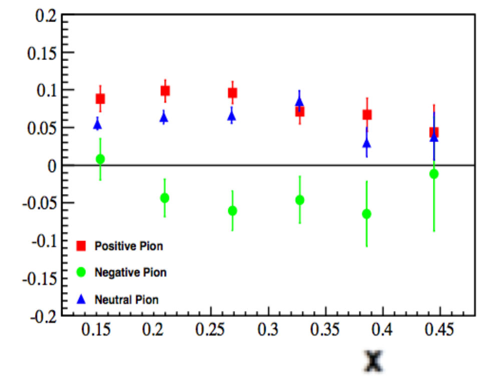
Quark-gluon correlations: flavor dependence

Higher Twist PDFs

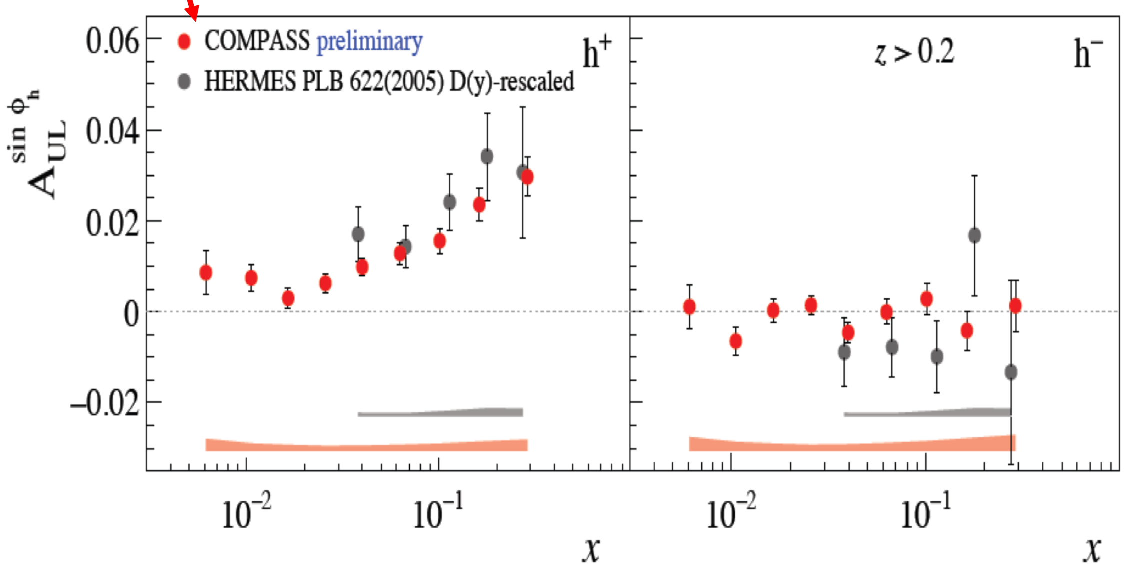
N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	h, e
L	$f_L^{\perp}$	$g_L^{\perp}$	h_L, e_L
T	$f_T, f_T^{\perp}$	$g_T, g_T^{\perp}$	$h_T, e_T, h_T^{\perp}, e_T^{\perp}$

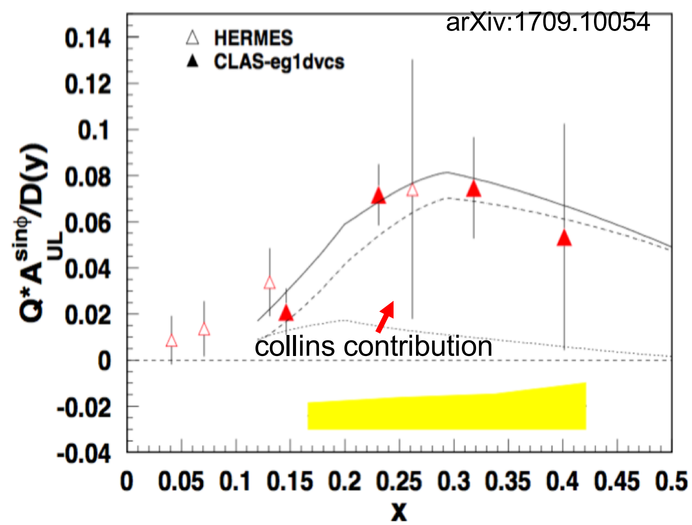
1) roughly equal $\pi^+\pi^0$ SSA
2) π^- SSA much smaller, consistent with 0 or<0





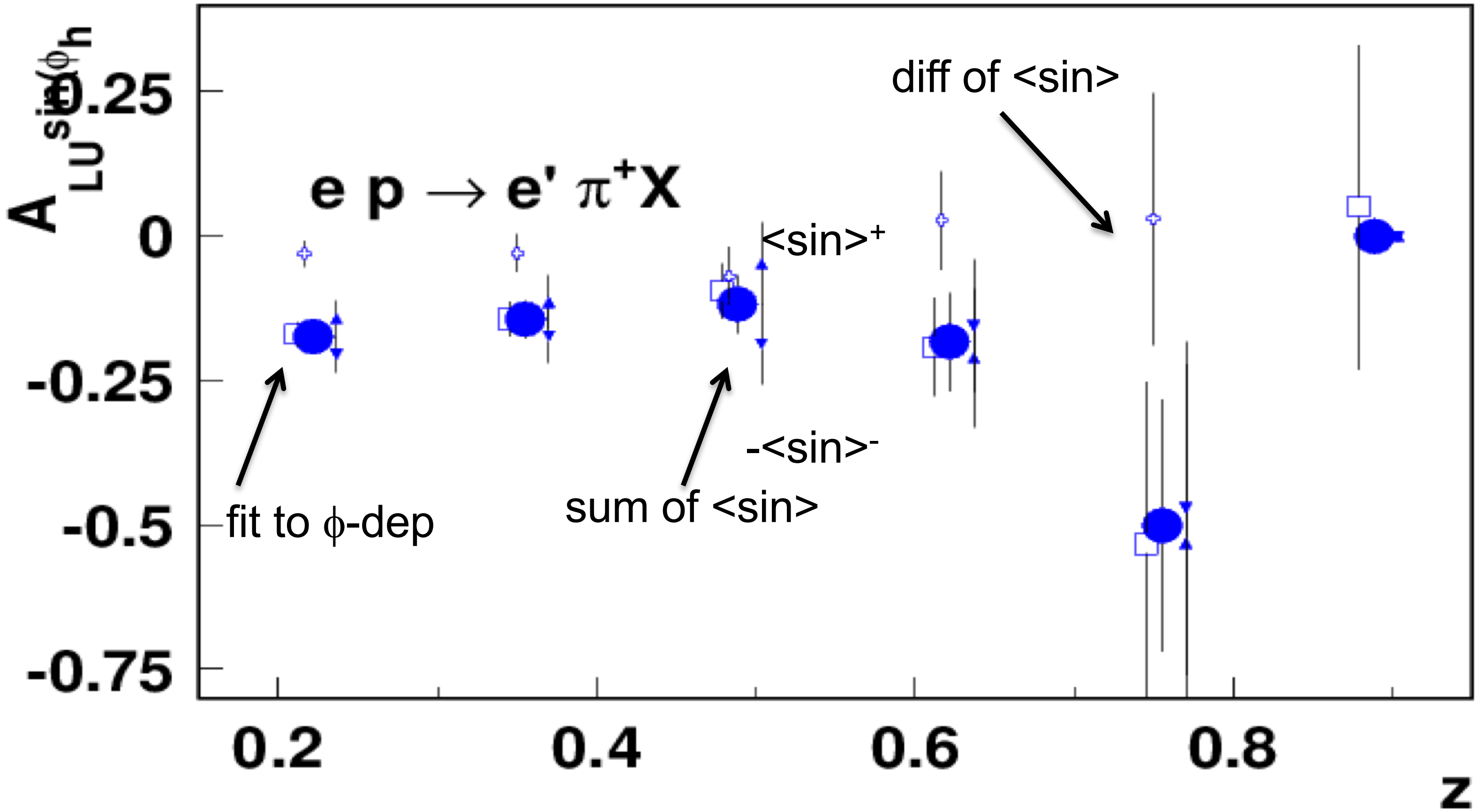
CLAS/HERMES





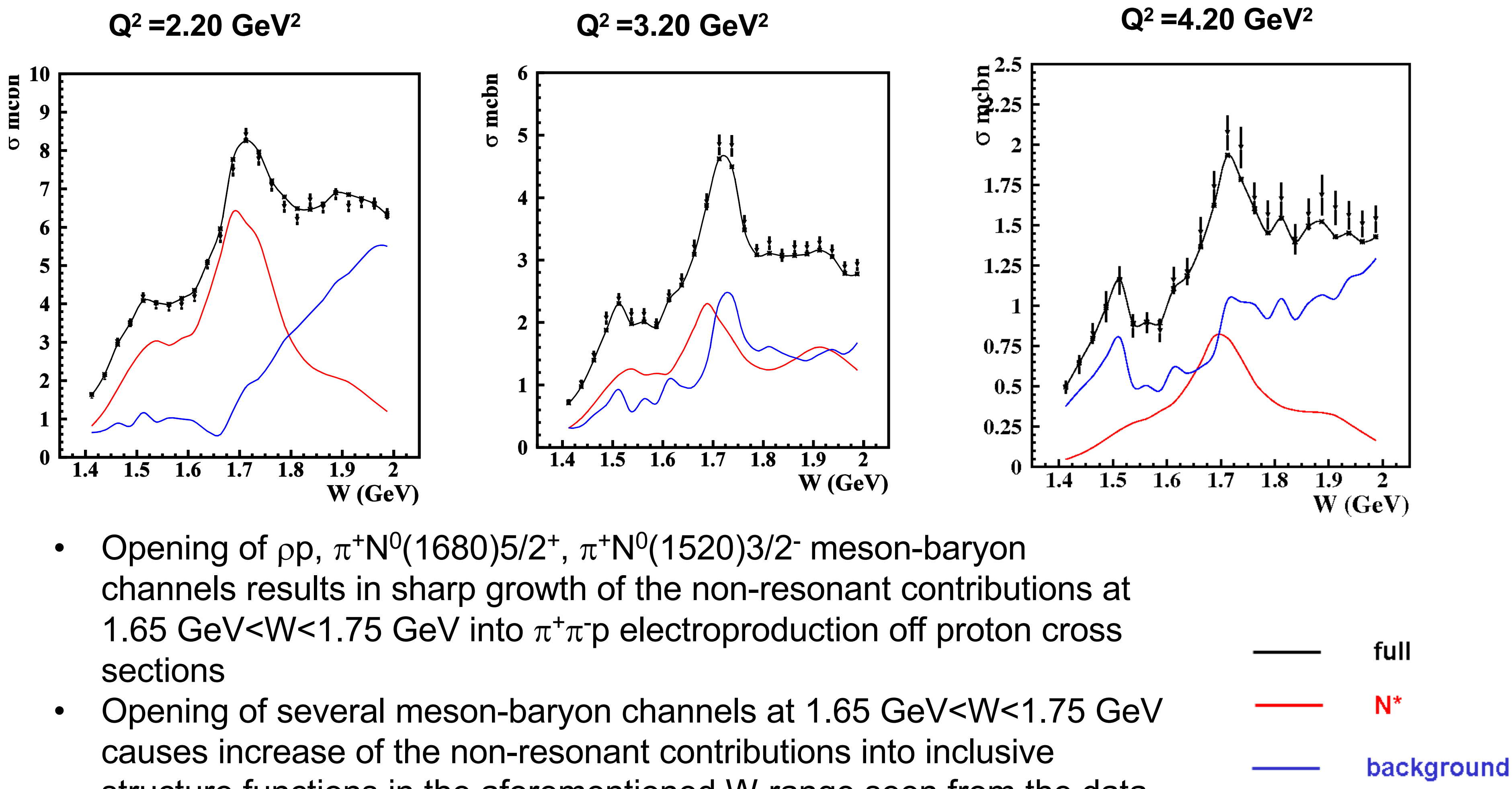
• Significant longitudinal beam and target SSA measured at HERMES, JLab and COMPASS may be related to higher twist distribution functions
• sinϕ modulations for $\pi^+\pi^0$ consistent with dominance of Sivers mechanism
• Subleading asymmetries comparable with leading ones (1/Q terms should be accounted)

Beam SSA for single pions



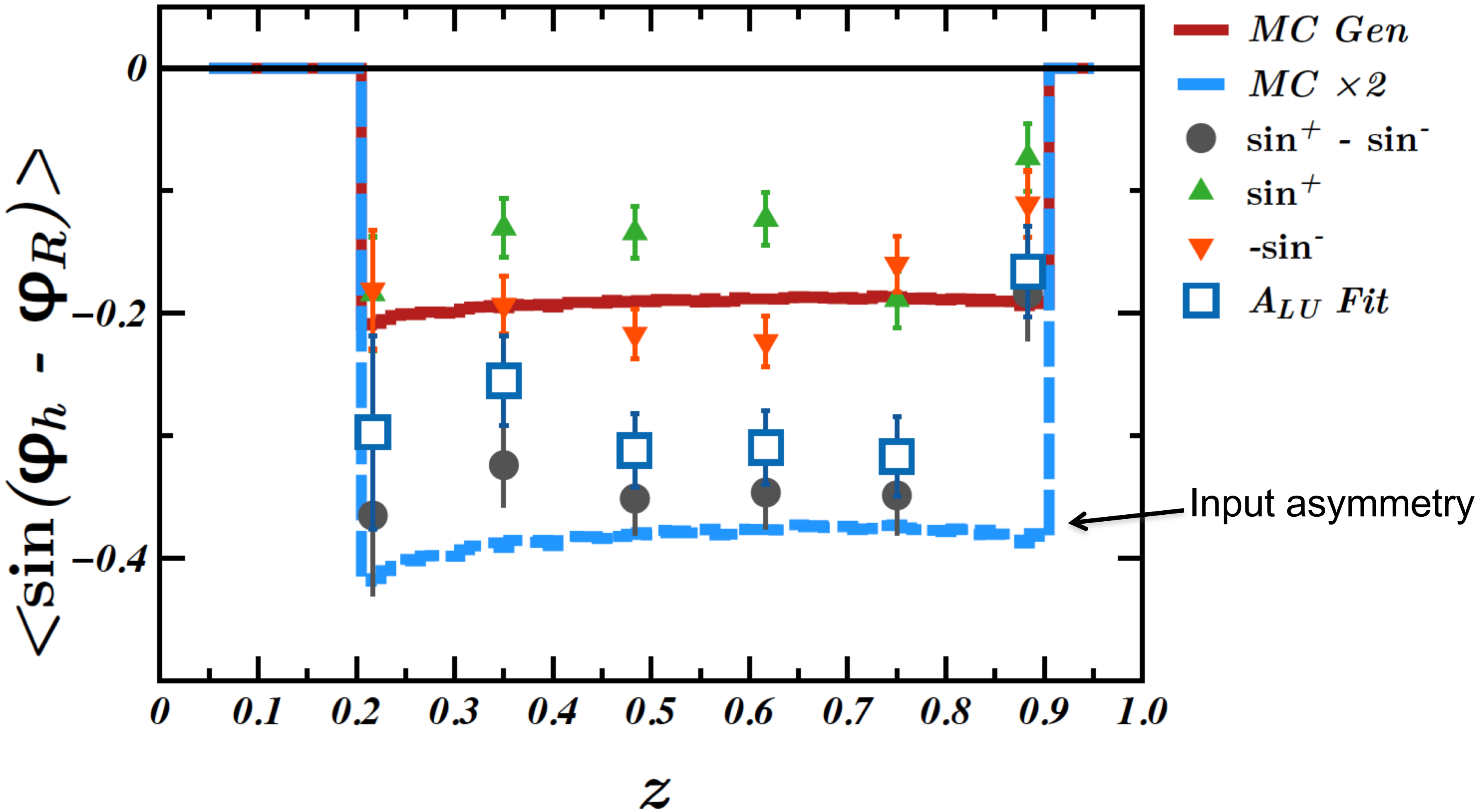
Significant beam SSA generated for single pions by the dihadron SSA input

Resonant vs Non-resonant Contributions in $\pi^+\pi^-p$ Electroproduction off Protons



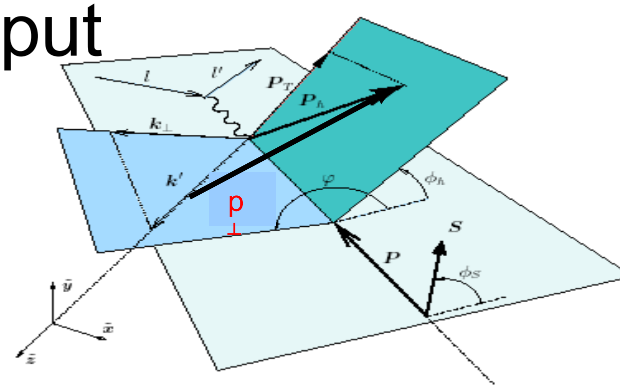
- Opening of ρp, $\pi^+N^0(1680)5/2^+$, $\pi^+N^0(1520)3/2^-$ meson-baryon channels results in sharp growth of the non-resonant contributions at 1.65 GeV<W<1.75 GeV into $\pi^+\pi^-p$ electroproduction off proton cross sections
- Opening of several meson-baryon channels at 1.65 GeV<W<1.75 GeV causes increase of the non-resonant contributions into inclusive structure functions in the aforementioned W-range seen from the data (slide # 24)

Extracting beam SSA: cross check



Generated curves in reasonable agreement with extraction
Small systematic difference (likely from acceptance) under investigation

MC Generator to simulate SIDIS output



SIDIS MC in 7D (10D)

$$\frac{d\sigma_{\lambda\Lambda}^{eN\to e'hX}}{dx\,dQ^2\,dz\,dP_{hT}^2\,d\phi_h\,d\phi_l\,d\phi_s} = \sum_{l=1}^{L} SF_l$$

Theory

Provide a set of SF_l

For a given model/theory based on underlying non-perturbative input and assumptions calculate SF_l

$F_l(x_1, x_2, x_3, ...x_N, P_1, P_2, ...P_M)$

step-1 $x_i, Q_i^2 z_i P_{hT}^{i2} \phi_h^i \phi_l^i \phi_s^i$

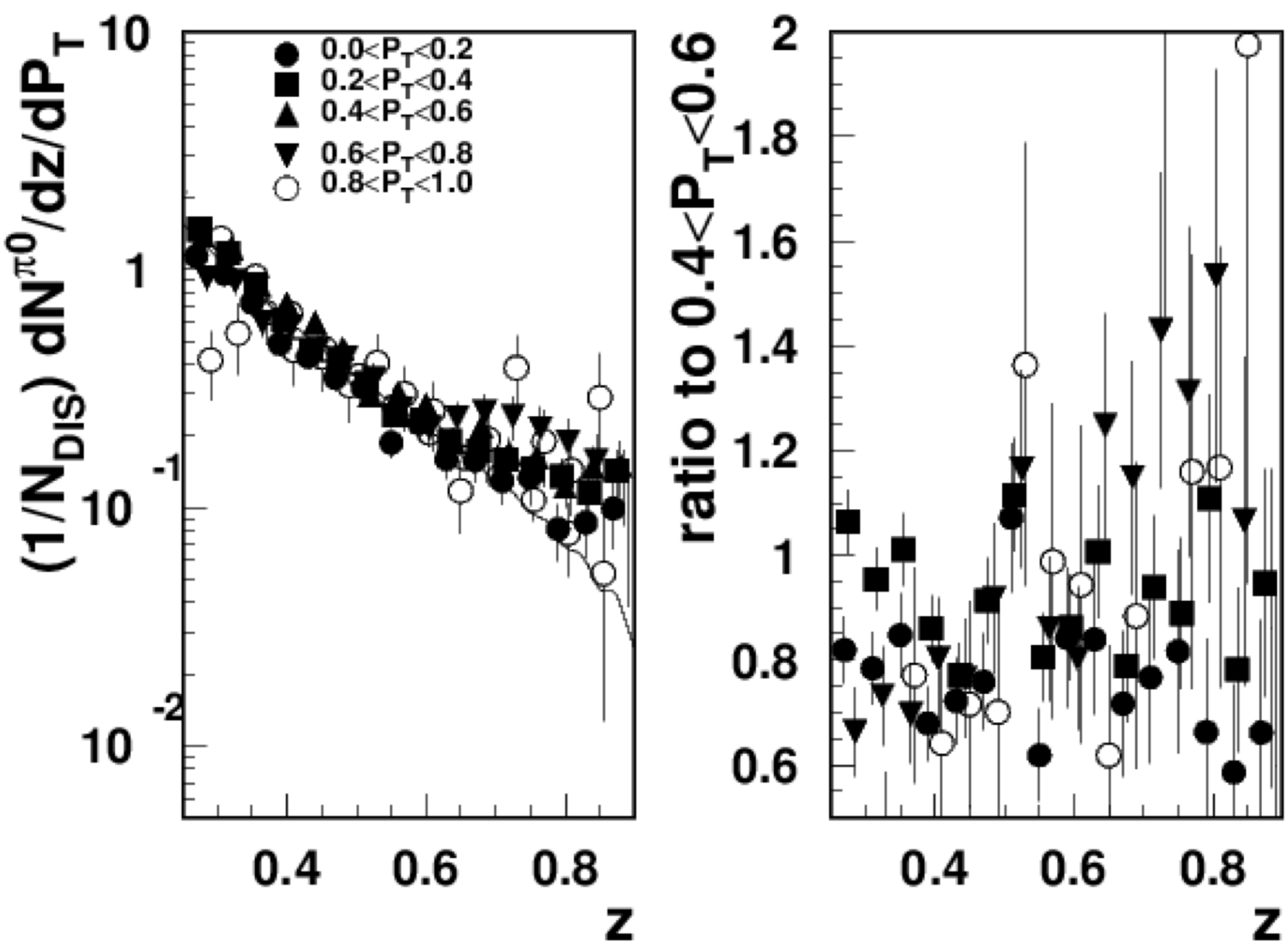
step-2 (for a given E_{beam}, λ, Λ) P_i^{el}, P_i^h

step-3 (detected for a given Detector configuration)

$x_j, Q_j^2 z_j P_{hT,j}^2 \phi_h^j \phi_l^j \phi_s^j$

$F_l(x_1, x_2, x_3, ...x_N, P_1^*, P_2^*, ...P_M^*)$

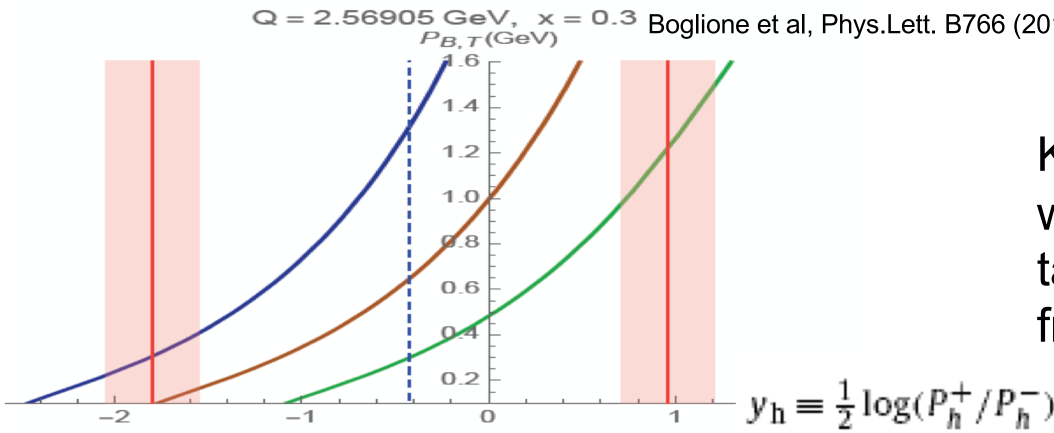
Need criteria to compare the input and output parameter spaces (validate)



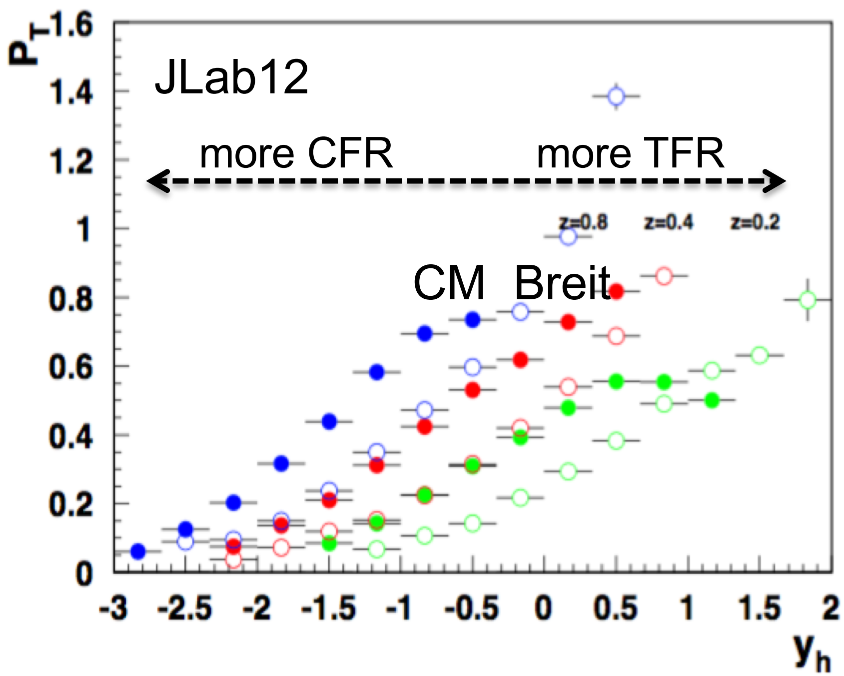
0.0<P_T<0.2
0.2<P_T<0.4
0.4<P_T<0.6
0.6<P_T<0.8
0.8<P_T<1.0
(1/N_DIS) dN^π0/dz/dP_T
ratio to 0.4<P_T<0.6
z
z

Additional complications: Experiment covers ranges described by different SFs

Boglione et al, Phys.Lett. B766 (2017) 245-253



Kinematics covers regions with different fractions from target and current fragmentation

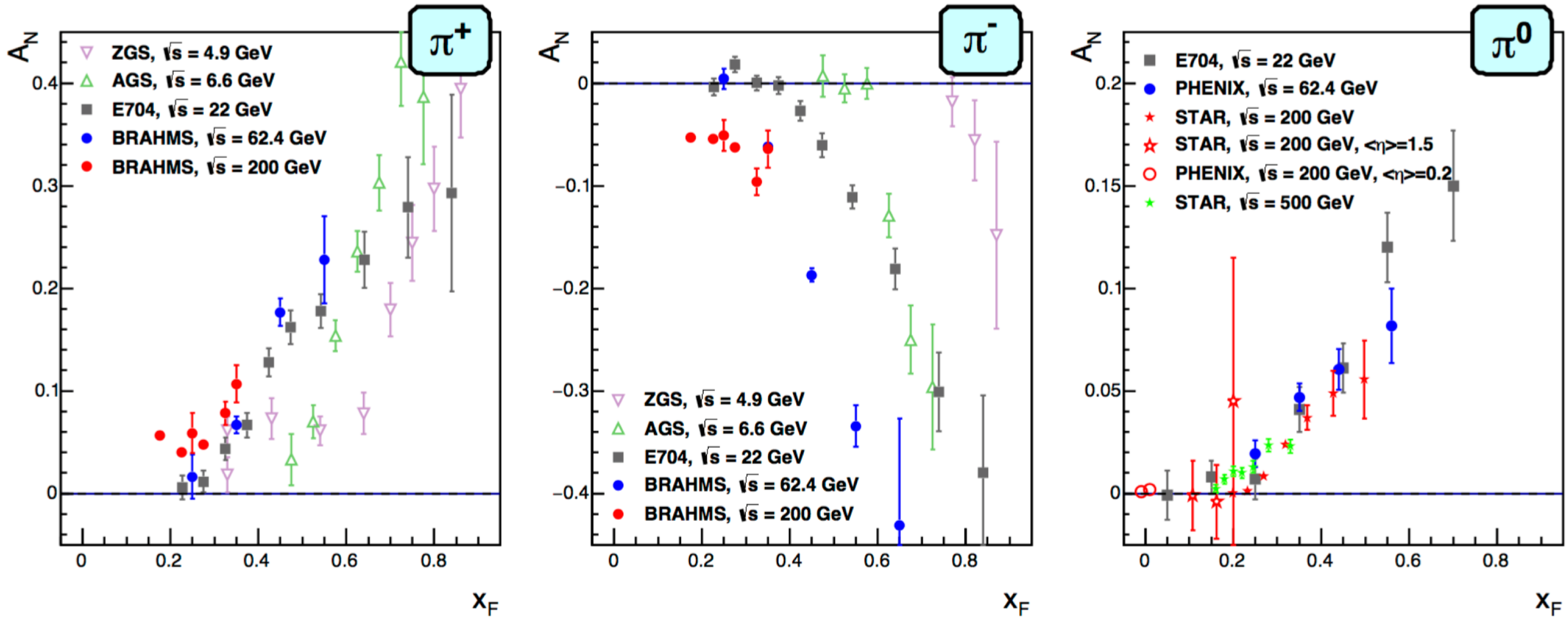


Understanding of the scale of ignored contributions (M/Q^2,P_T/Q^2, Target/Current correlations,…) will define the limits on precision for other involved contributions (ex. evolution).

Multidimensional bins (x,y,z,P_T,ϕ) are crucial for separation of different contributions

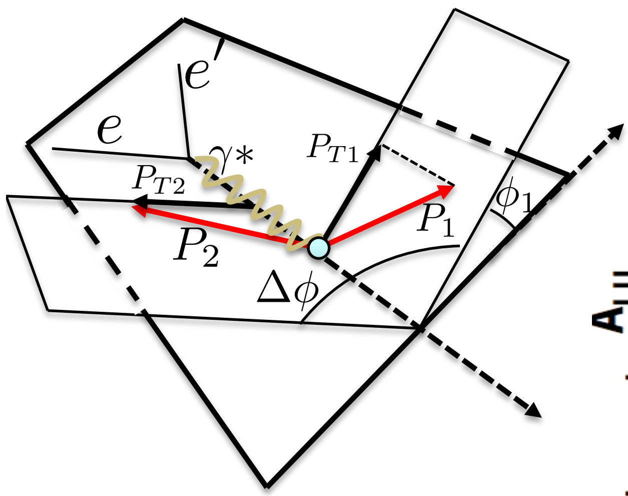
pi0s

https://arxiv.org/pdf/1512.05379.pdf



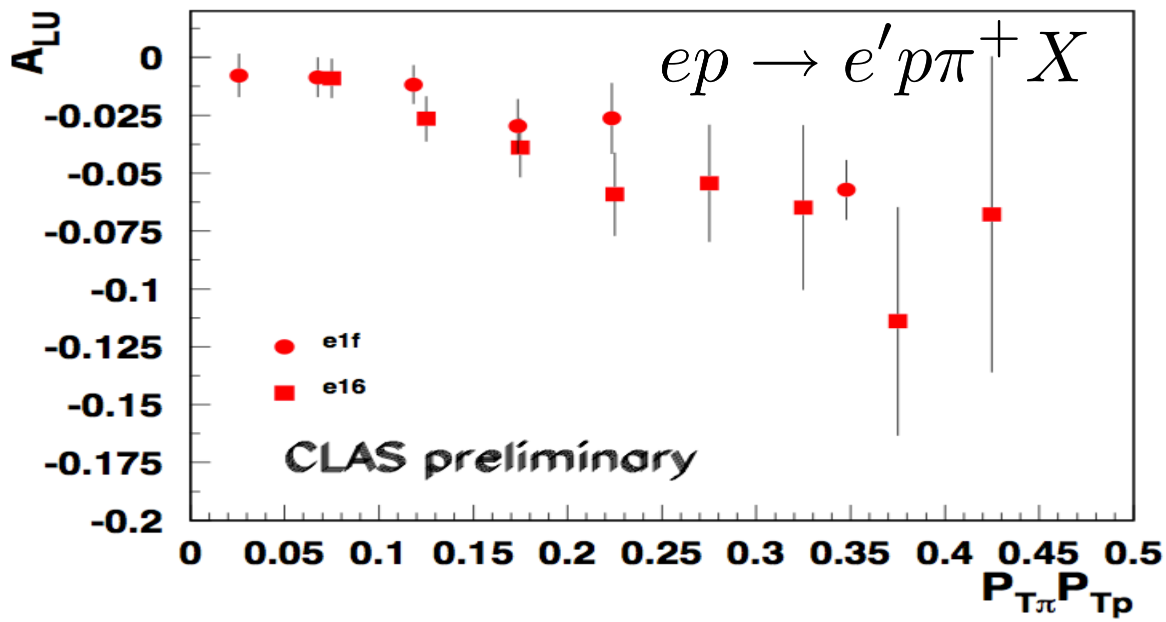
B2B hadron production in SIDIS: First measurements

M. Anselmino, V. Barone and A. Kotzinian,
Physics Letters B 713 (2012)



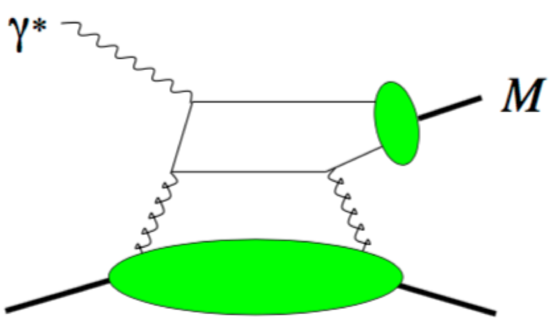
$$\mathcal{A}_{LU} = -\frac{y(1-\frac{y}{2})}{(1-y+\frac{y^2}{2})}\frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}}\sin\Delta\phi$$

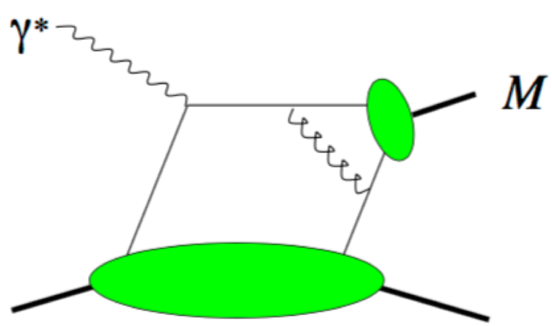
$$= -\frac{|\boldsymbol{P}_{1\perp}||\boldsymbol{P}_{2\perp}|}{m_N m_2}\frac{y(1-\frac{y}{2})}{(1-y+\frac{y^2}{2})}\frac{\mathcal{C}[w_5 M_L^{\perp,h} D_1]}{\mathcal{C}[M D_1]}\sin\Delta\phi.$$



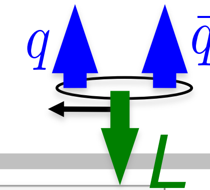
Asymmetry transverse momentum dependence (linear with $P_{T\pi}P_{Tp}$) consistent with theory prediction

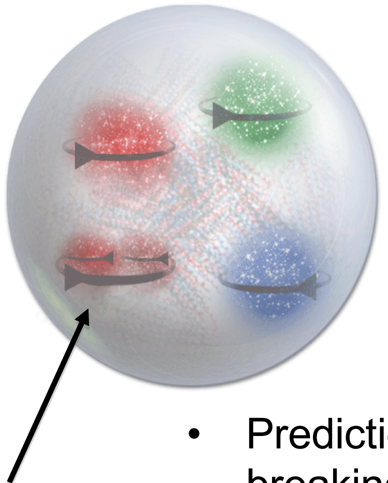
Production mechanism





Non-perturbative distributions

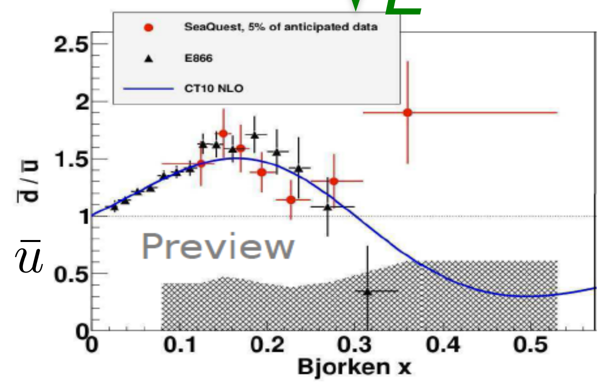




"Pion tornado"?

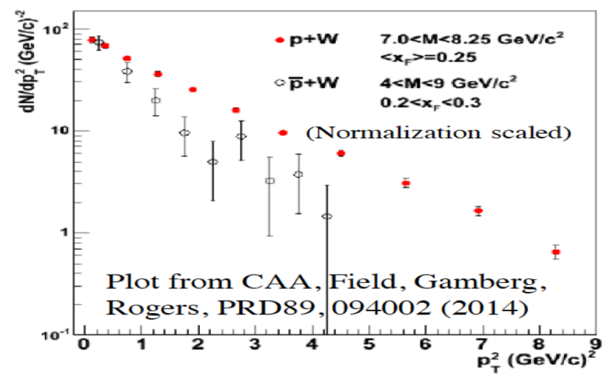
Non-perturbative sea in nucleon is a key to understand the nucleon structure

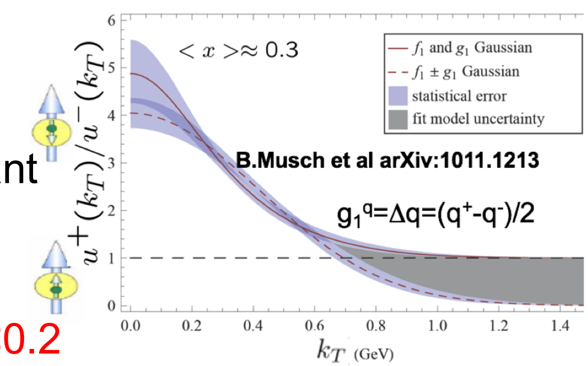
-- Large flavor asymmetry as evidence $\bar{d} > \bar{u}$ provides a hint for region where non-perturbative effects will be significant



- Predictions from dynamical model of chiral symmetry breaking [Schweitzer, Strikman, Weiss JHEP 1301 (2013) 163]

  -- k_T (sea) >> k_T (valence)
  -- short-range correlations between partons (small-size q-qbar pairs)
  -- directly observable in P_T-dependence of hadrons in SIDIS

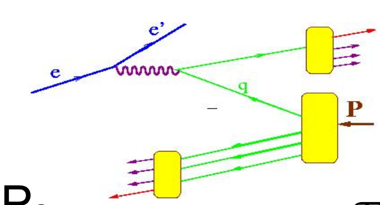




- spin and momentum of struck quarks are correlated with remnant
- correlations of spins of q-q-bar with valence quark spin and transverse momentum will lead to observable effects
- Non-perturbative sea most relevant for x>0.01, more for 0.1<x<0.2

Back-to-back hadron (b2b) production in SIDIS

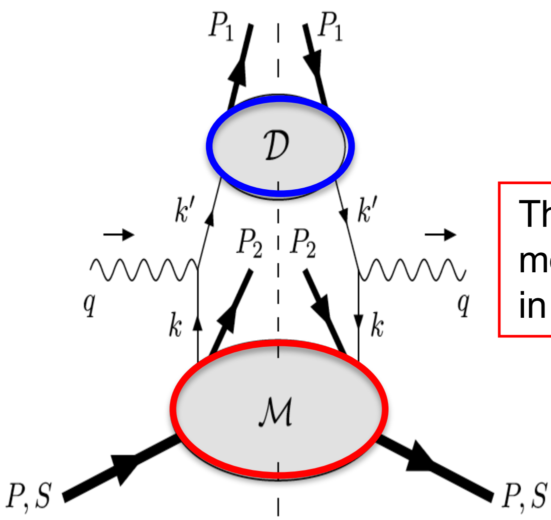
P$_1$



P$_2$

M. Anselmino, V. Barone and A. Kotzinian, Physics Letters B 713 (2012)

$$\mathcal{F}_{LU}^{\sin(\phi_1-\phi_2)} = \frac{|\vec{P}_{1\perp}\vec{P}_{2\perp}|}{m_N m_2}\mathcal{C}[w_5 M_L^{\perp h} D_1]$$



$$A_{LU} = -\frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)}\frac{F_{LU}^{\sin\Delta\phi}}{F_{UU}}\sin\Delta\phi$$

Leading Twist

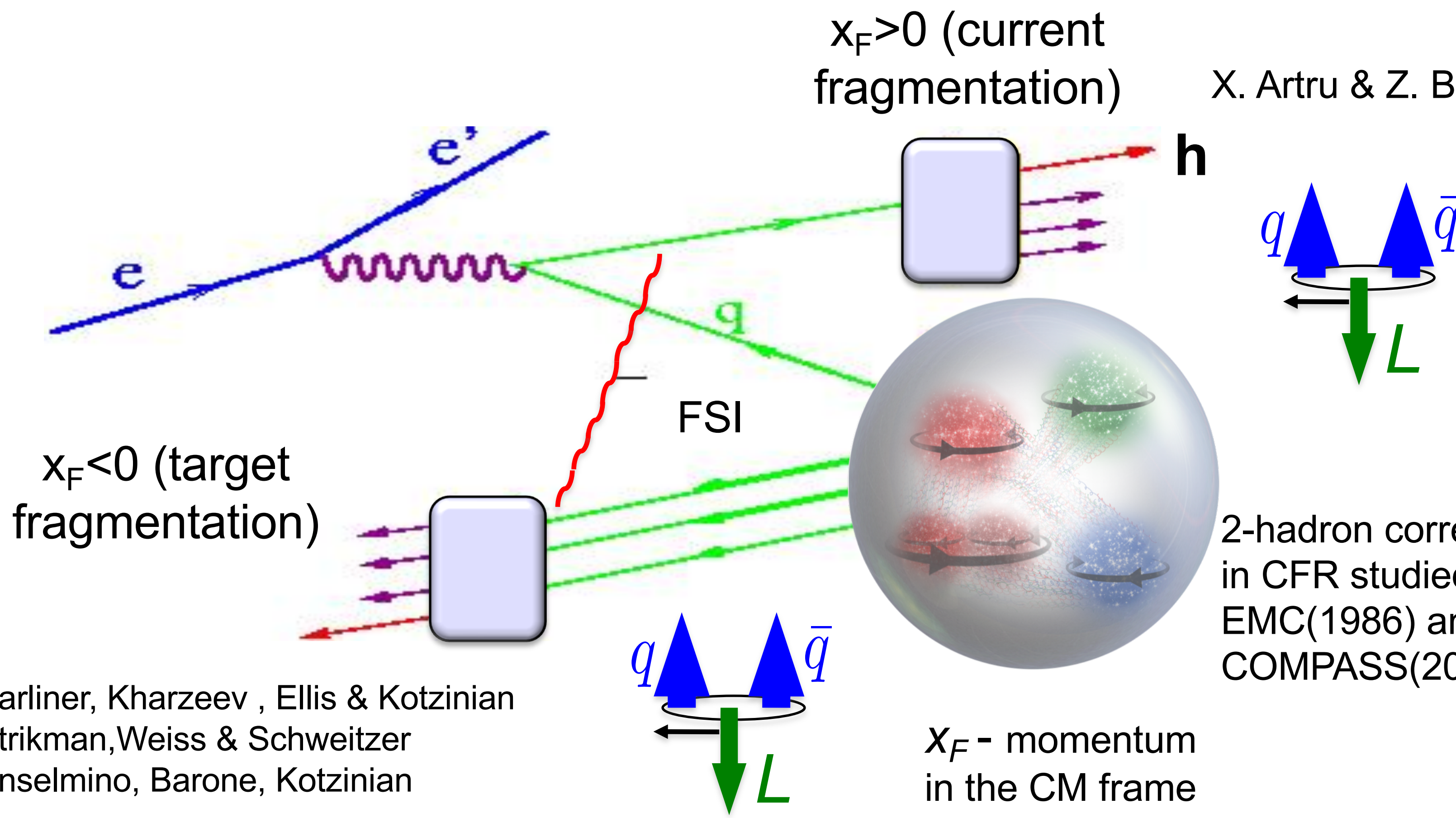
	U	L	T
U	M	$M_L^{\perp,h}$	$M_T^h, M_T^\perp$
L	$\Delta M^{\perp,h}$	ΔM_L	$\Delta M_T^h, \Delta M_T^\perp$
T	$\Delta_T M_T^h, \Delta_T M_T^\perp$	$\Delta_T M_L^h$ $\Delta_T M_L^\perp$	$\Delta_T M_T, \Delta_T M_T^{hh}$ $\Delta_T M_T^{\perp\perp}, \Delta_T M_T^{\perp h}$

The beam–spin asymmetry appears, at leading twist and low transverse momenta, in the deep inelastic inclusive lepto-production of two hadrons, one in the target fragmentation region and one in the current fragmentation region.

Back-to-back hadron production in SIDIS would allow:
- study SSAs not accessible in SIDIS at leading twist
- measure fracture functions
- control the flavor content of the final state hadron in current fragmentation (detecting the target hadron)
- study entanglement in correlations in target vs current
- access quark short-range correlations and χSB (Schweitzer et al)
- ...

Hadron production in hard scattering

X. Artru & Z. Belghobsi



2-hadron correlations in CFR studied in EMC(1986) and COMPASS(2015)

Karliner, Kharzeev , Ellis & Kotzinian
Strikman,Weiss & Schweitzer
Anselmino, Barone, Kotzinian

x_F - momentum in the CM frame

Correlations of the spin of the target or/and the momentum and the spin of quarks, combined with final state interactions define the azimuthal distributions of produced particles