Correlation Effects in Hadronization

Harut Avakian (JLab)

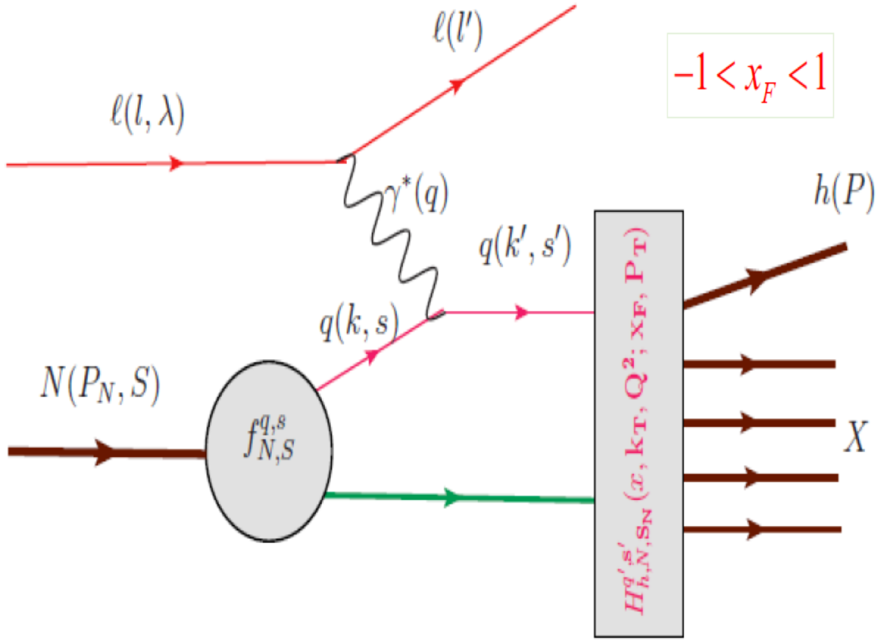
QCD Evolution Workshop 2021
May 14, 2021

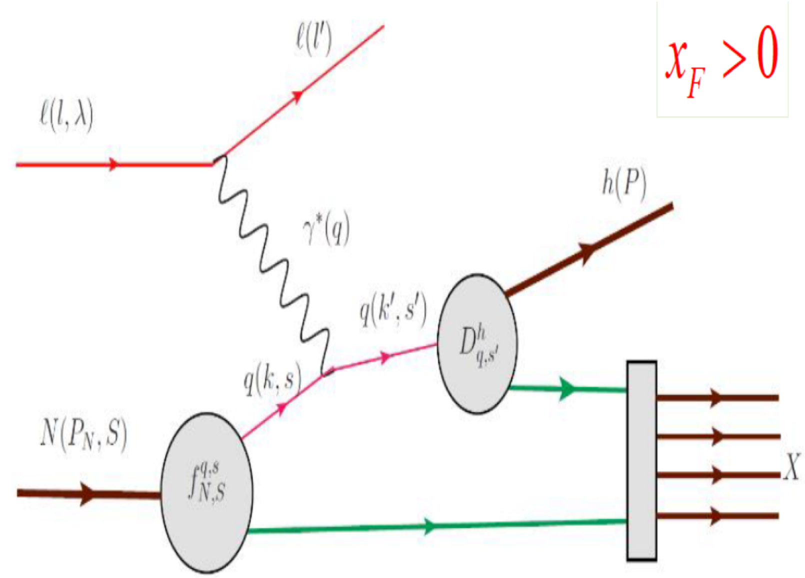
- Production of pair of hadrons in SIDIS
- Measurements of SSAs in dihadron production
- The role of vector mesons
  - MC simulations vs data
  - Extraction of k_T-dependences
  - Possible impact on spin-observables
- Correlations of hadrons in current and target fragmentation regions
- Summary

Hadronization

$Q^2 \gg M_p^2$

A.Kotzinian FF2019





Hadronization Function
→ conditional probability to produce hadron $\boldsymbol{h}$

$$H_{h/N}^{q'}\left(x,\mathbf{k}_T,Q^2;x_F,\mathbf{P}_T^h;\mathbf{s}_q',\mathbf{S}_N\right)$$

Quark Fragmentation Functions

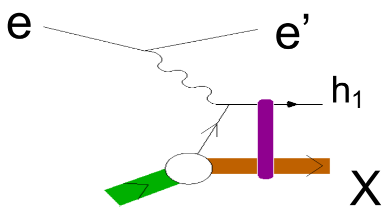
$$D_{q,s'}^{h}\left(z,\mathbf{p}_T,Q^2\right)$$

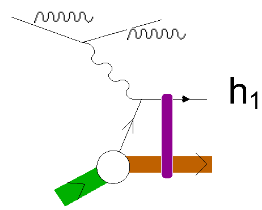
Where this works?

electro-production of hadrons

single hadron in CFR (Current Fragmentation Region)

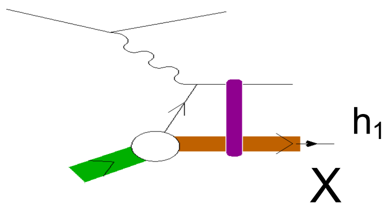
with additional radiation

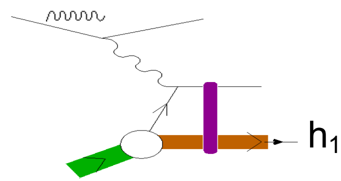




Does it matter what is the source of the single hadron, and if yes, where?

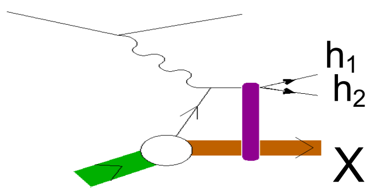
single hadron in TFR(Target Fragmentation Region)

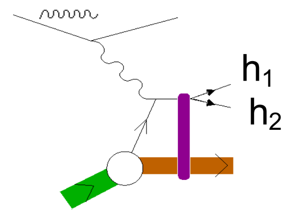




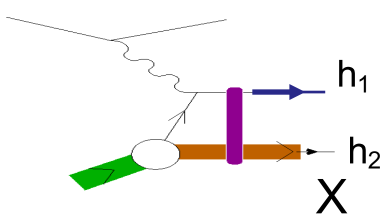
radiation mixes contributions from different structure functions and complicates separation of exclusive from semi-inclusive

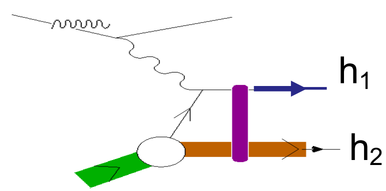
correlated hadrons(dihadron,rho,..) in CFR





correlated hadrons in CFR+TFR

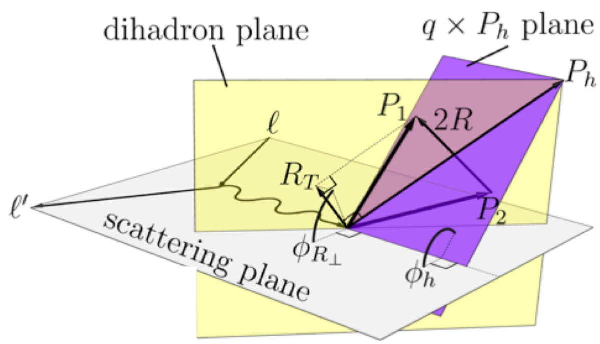


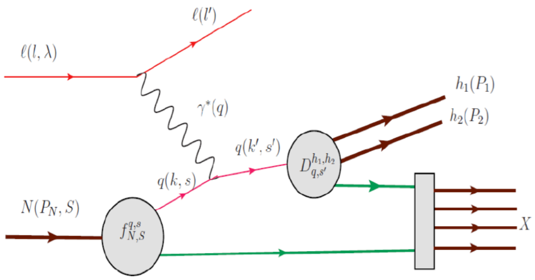


Correlated hadron production in hard scattering

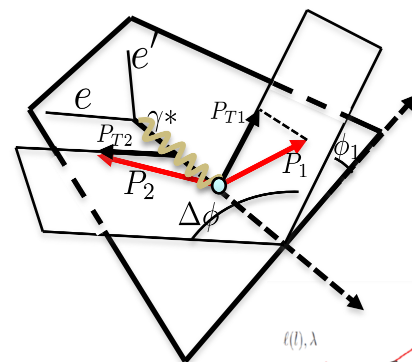
Dedicated CLAS12 proposals: E12-06-112B/E12-09-008B

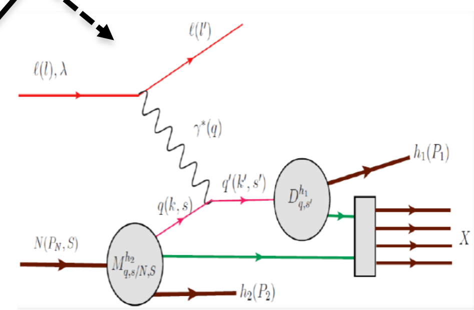
2 hadrons in current fragmentation





hadrons in current & target fragmentation





$$P_h = P_1 + P_2,$$

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

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*

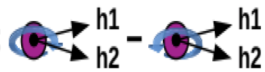
$\phi_R - \phi_h$ -accessing leading twist polarized fragmentation functions *Matevosyan,Kotzinian,Thomas*

$\phi_1 - \phi_2$ -accessing correlations in current and target regions *Anselmino, Barone, Kotzinian*

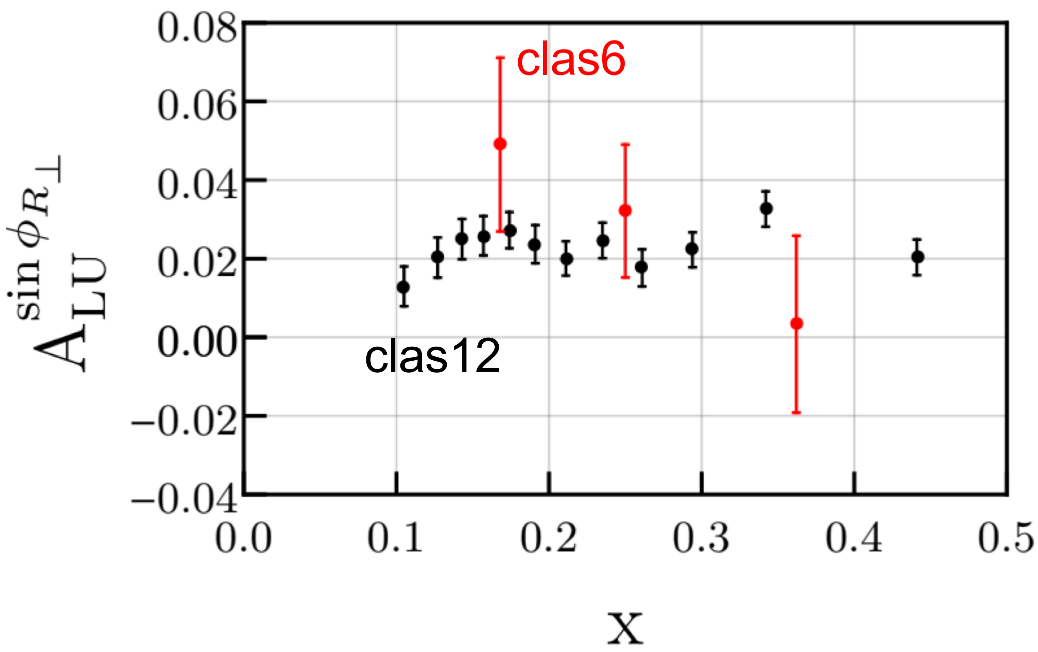
2h production in SIDIS provides access to correlations inaccessible in simple SIDIS

Observation of SSAs in ep→e'$\pi^+\pi^-$X

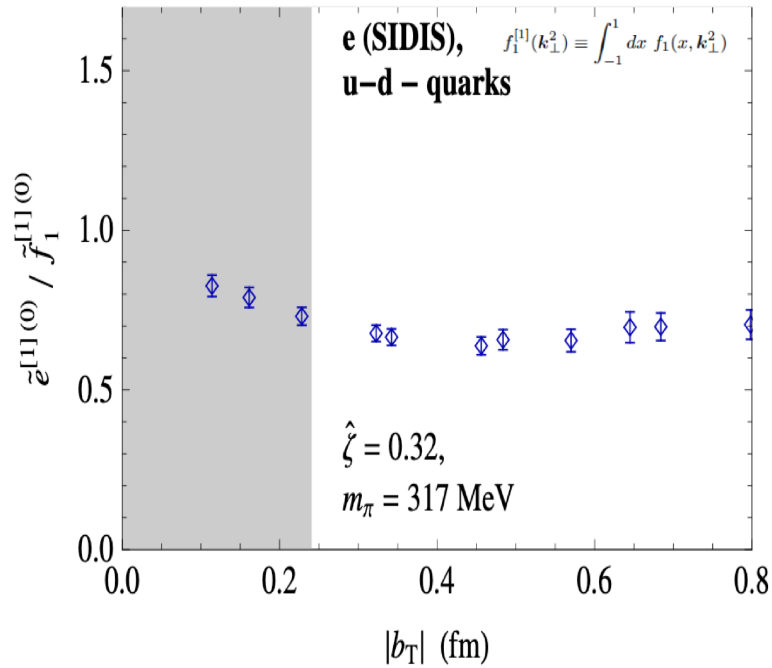
T. Hayward et al. Phys. Rev. Lett. 126, 152501 (2021)

$H_1^{\sphericalangle}$ = 

$$d\sigma_{LU} \propto \lambda_e \sin(\phi_{R_\perp}) \left(xe(x)H_1^{\sphericalangle}(z,M_h) + \frac{1}{z} f_1(x)\tilde{G}^{\sphericalangle}(z,M_h) \right)$$



Engelhardt: TMDs from JLab to EIC



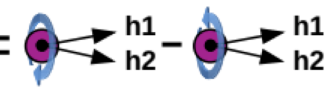
Doubling the JLab beam energy, opens the phase space for dihadrons

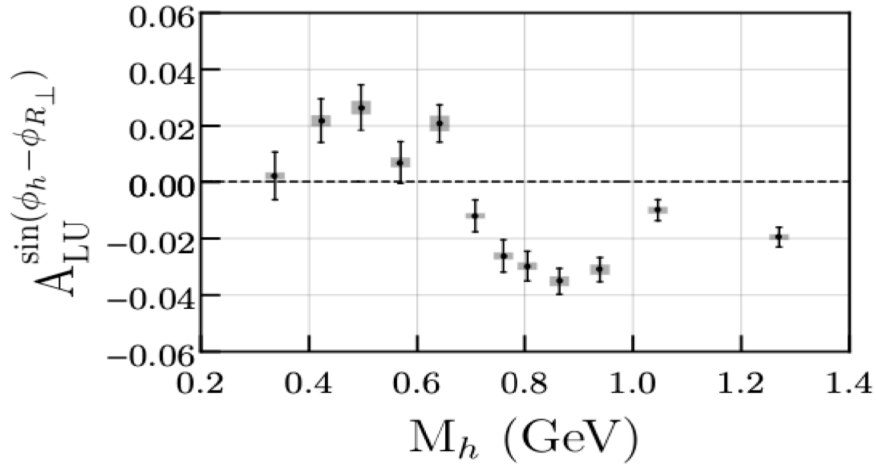
Quark gluon correlations may be very significant

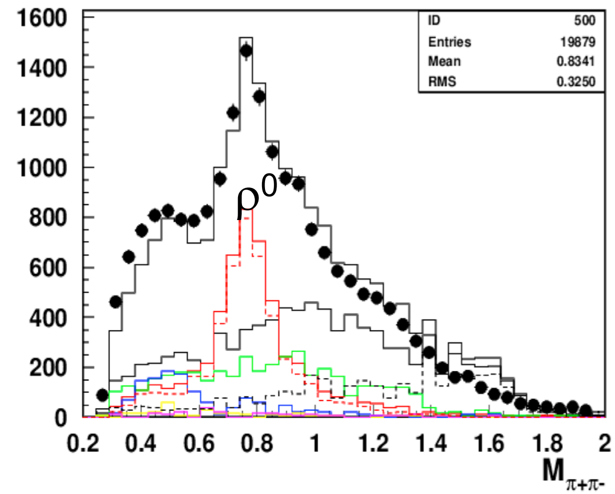
Observation of SSAs in ep→e'$\pi^+\pi^-$X

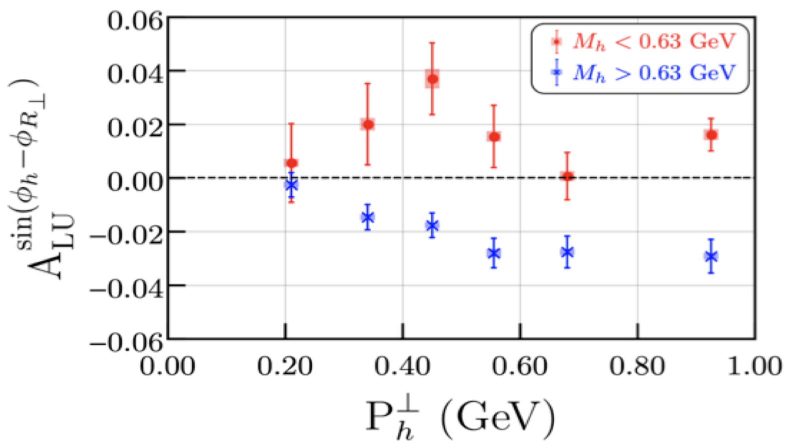
T. Hayward et al. Phys. Rev. Lett. 126, 152501 (2021)

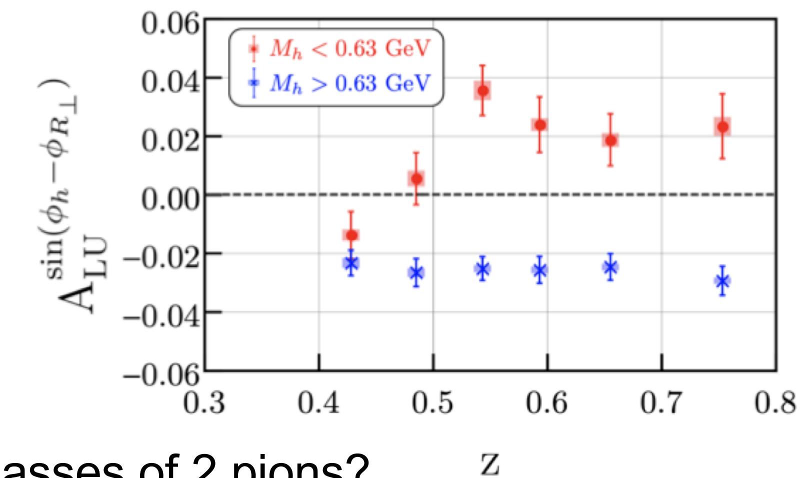
$$d\sigma_{LU} \propto \ C\lambda_e \sin(\phi_h - \phi_{R_\perp})\mathcal{I}\left[f_1 G_1^\perp\right] + \ldots$$

$G_1^\perp =$  a TMD FF





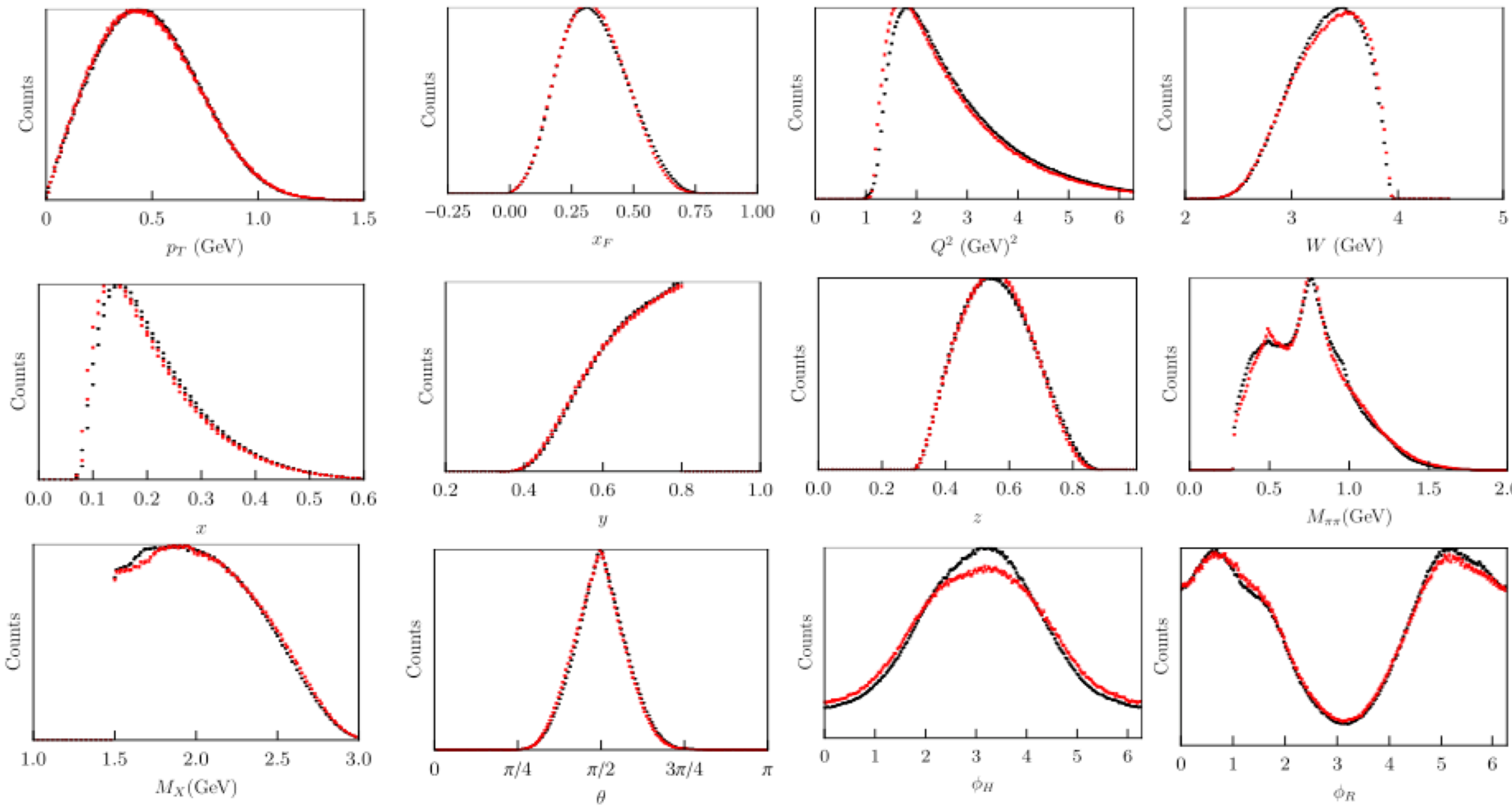




What is so special about the low invariant masses of 2 pions?

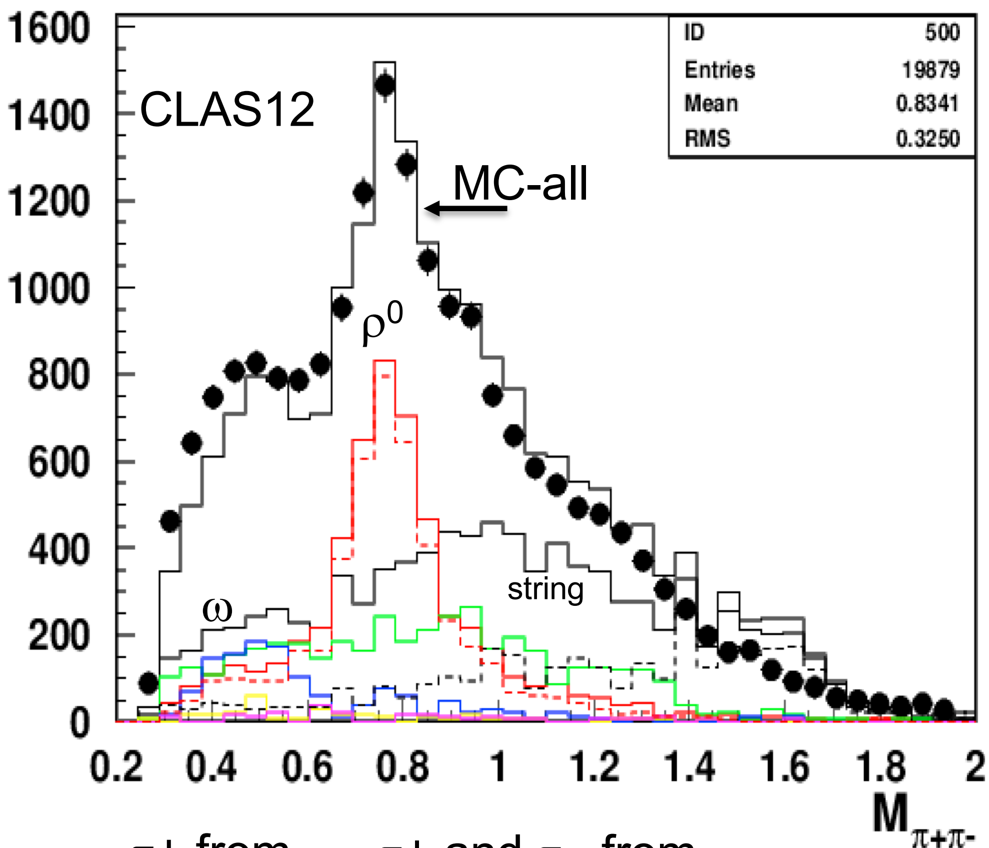
SIDIS ehhX: CLAS12 data vs MC

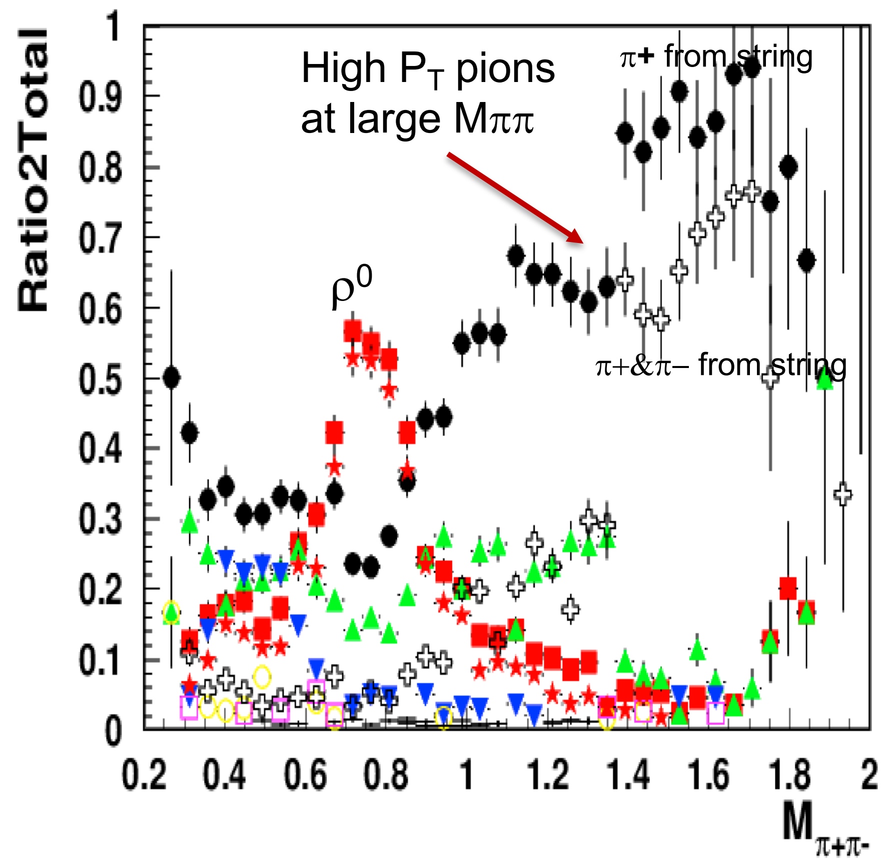
CLAS12 dihadron production ep→ehhX (T.Hayward)



CLAS12 MC, based on the PEPSI(LEPTO) simulation with <u>most parameters "default"</u> is in a good agreement with CLAS12 measurements for all relevant distributions

Sources of inclusive pions: CLAS12 vs MC





	π+ from	π+ and π– from
ρ0	red solid line	red dashed line
string	black solid line	black dashed line
ρ+	green line	
ω	blue line	

- Dominant fraction of inclusive pions come from VM decays
- Relative fraction by default in JETSET ~50%

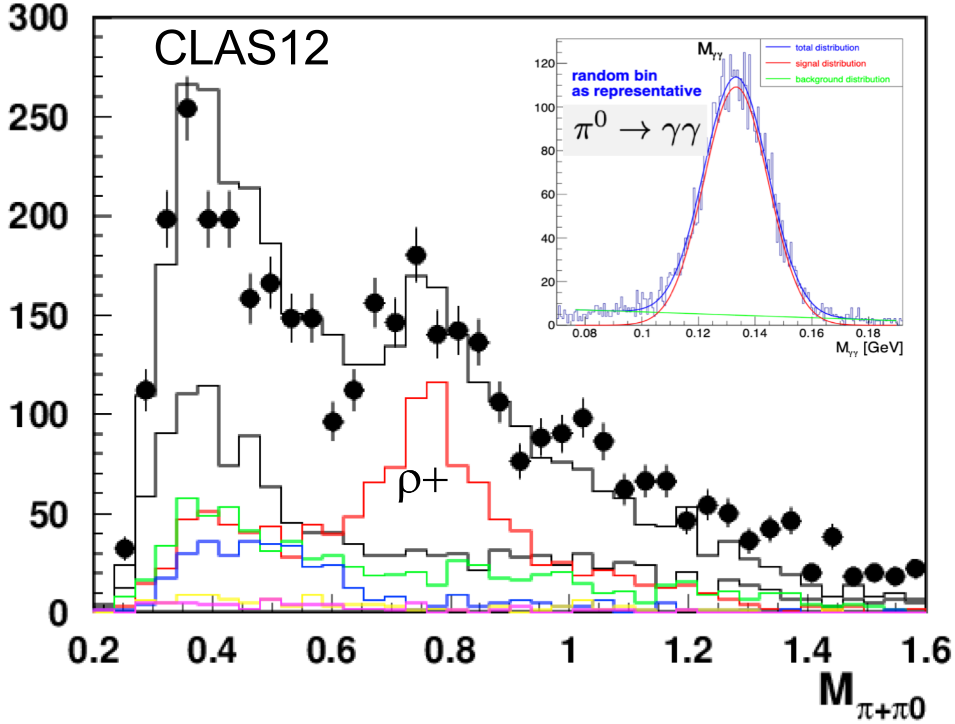
Very important to have multidimensional TMD Fragmentation Functions!

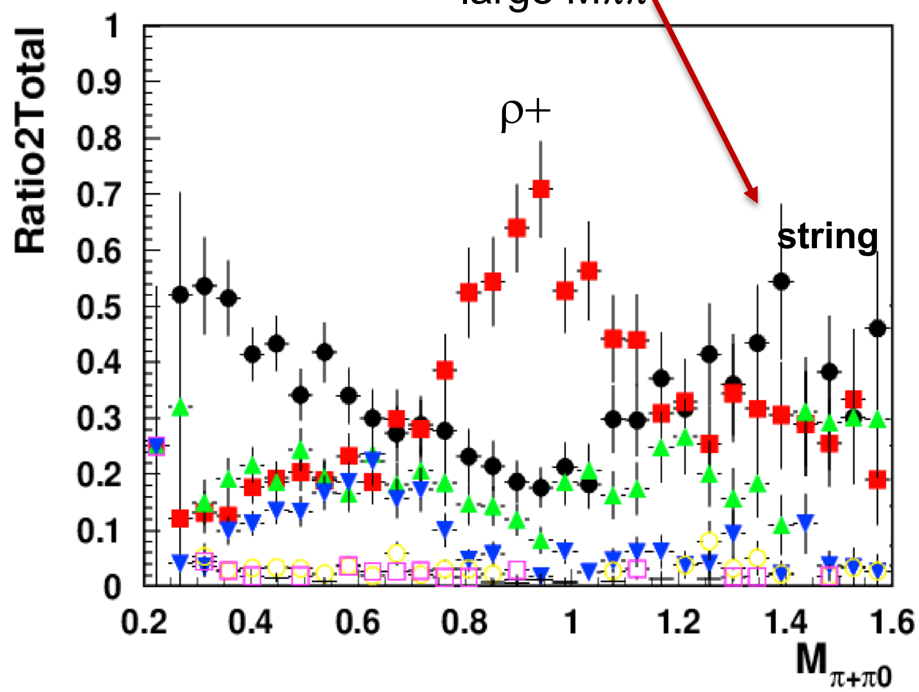
Sources of inclusive pions: CLAS12 vs MC

$\rho^{\pm} \to \pi^0 + \pi^{\pm}$

Detection of π^0s allows studies of $\rho^{\pm}$

High P_T pions at large $M_{\pi\pi}$





π+ from
- ρ+ (red)
- string (black)
- ρ0 (green)
- ω (blue)

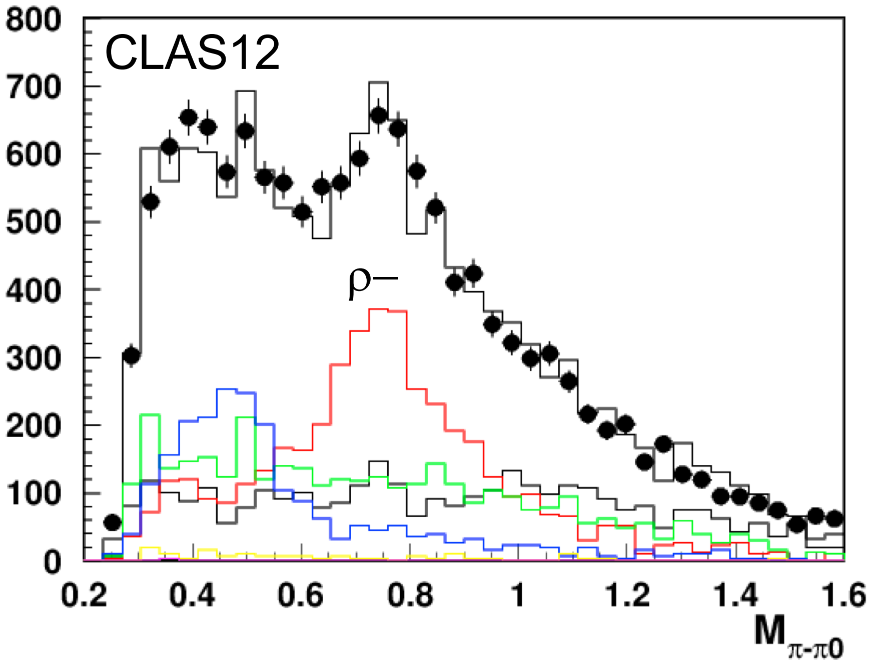
Dominant fraction of inclusive pions come from VM decays

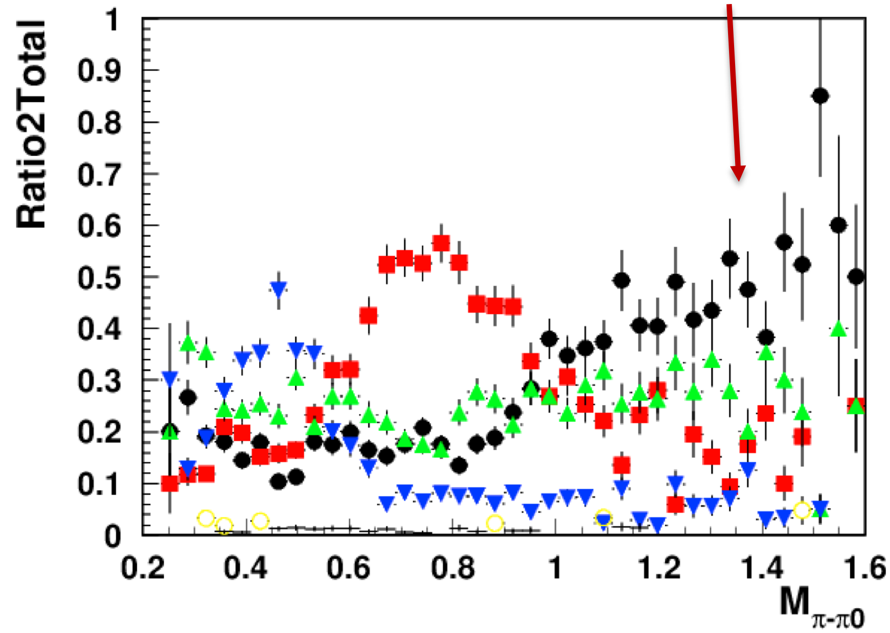
CLAS12 due to unique capability for precision measurements of neutral pions, will provide measurements of multiplicities of variety of semi-inclusive and exclusive hadron pairs (could be also VMs).

Sources of inclusive pions: CLAS12 vs MC

$\rho^{\pm} \rightarrow \pi^0 + \pi^{\pm}$ Detection of π^0s allows studies of $\rho^{\pm}$

High P_T pions at large $M_{\pi\pi}$





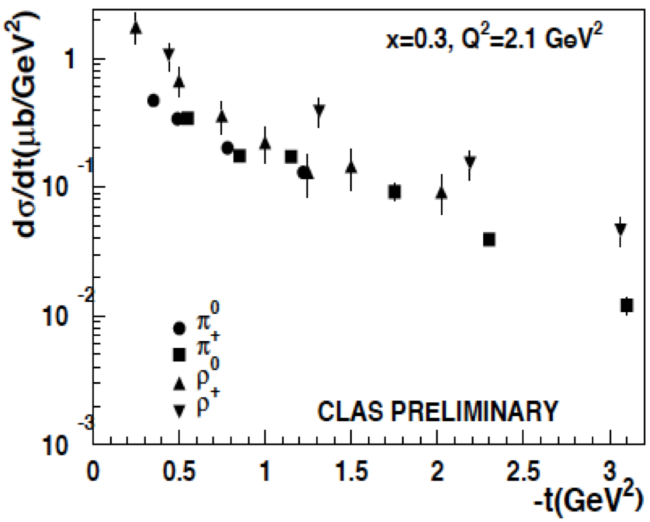
π− from:

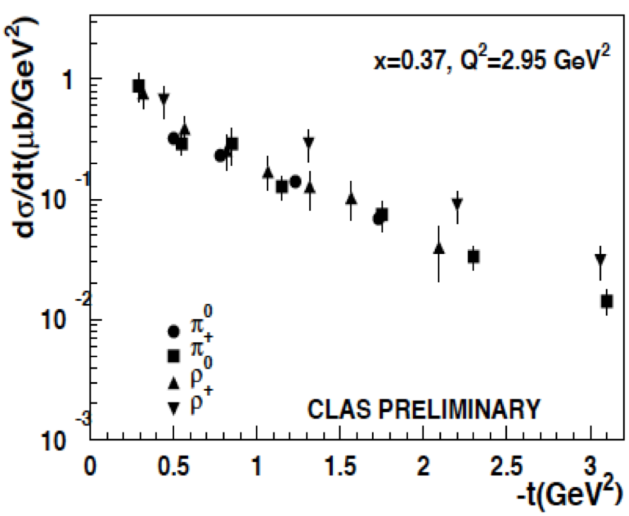
- ρ−
- string
- ρ0
- ω

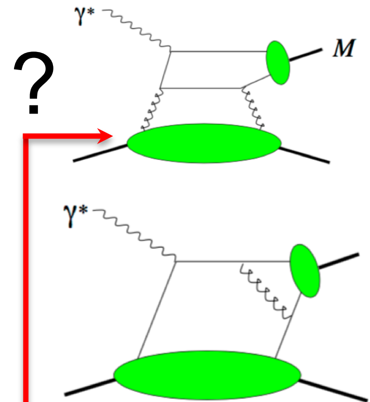
Dominant fraction of inclusive pions come from VM decays

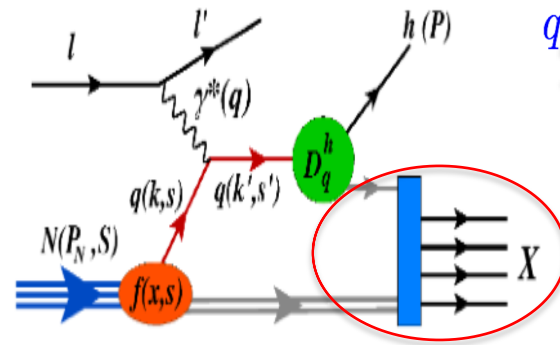
Precision measurements of all combination of pion pairs is crucial for separation of multiplicities of different vector mesons

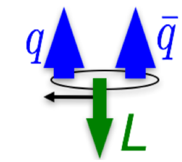
Exclusive π/ρ production at large t











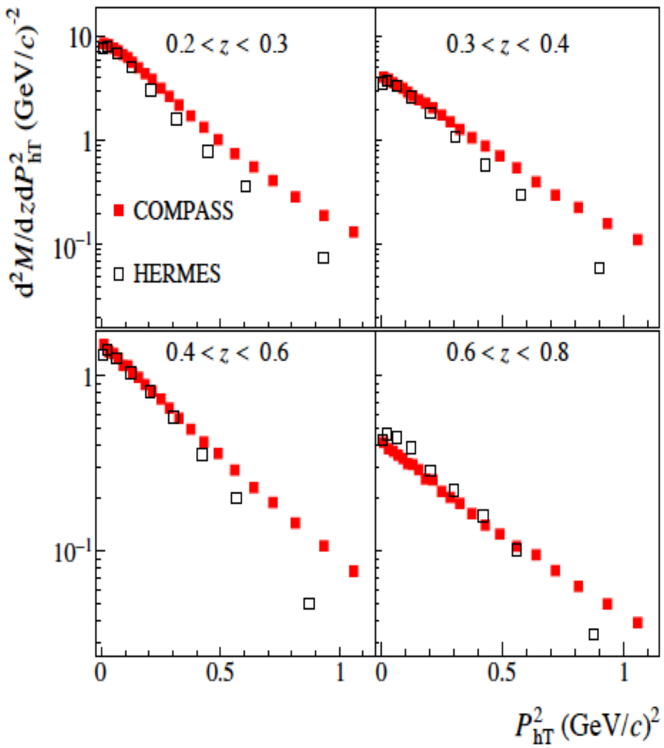
Implications

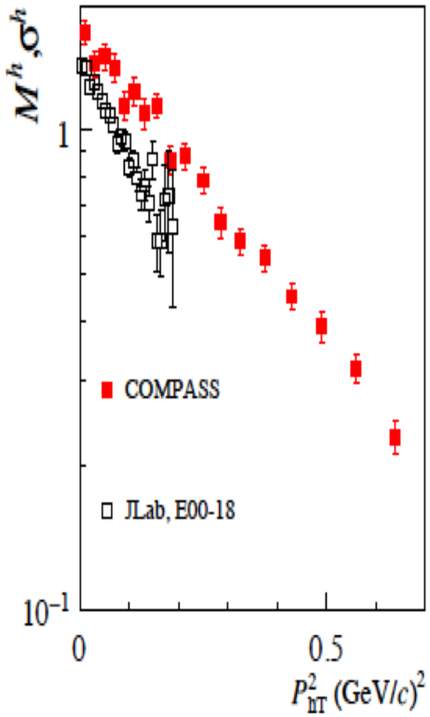
x-section of measured exclusive process at large t exhibit similar pattern

- $\rho^+ > \rho^0$ →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 VMs
- Integrating in total counts (different Q^2-dependence)?
- ………

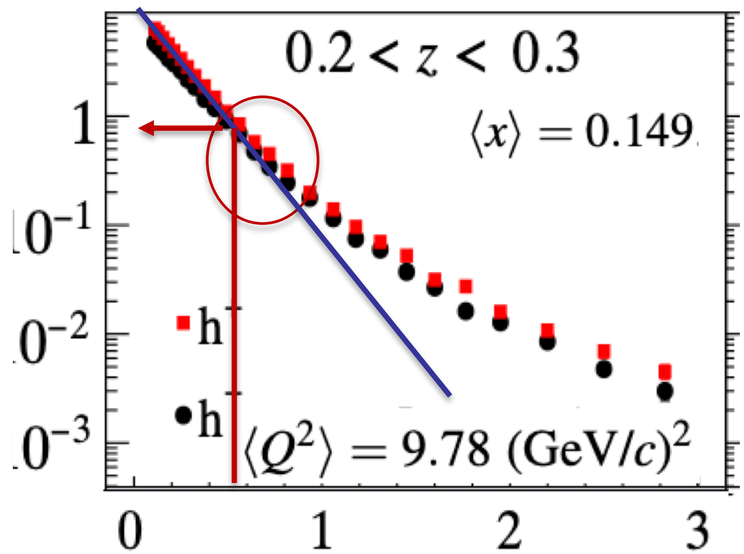
Multiplicities in SIDIS

COMPASS:1709.07374





Theory only describing only low P_T



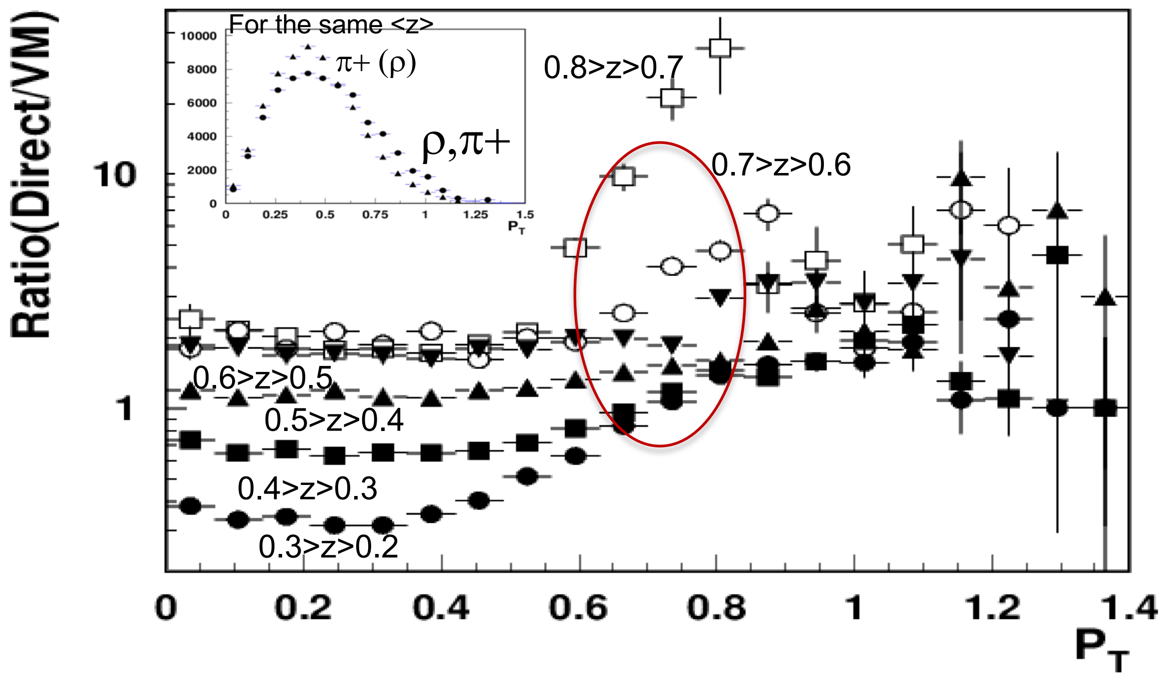
Lower the beam energy, less phase space for high $P_{T,}$ Impact can be simulated, more significant for heavier VMs

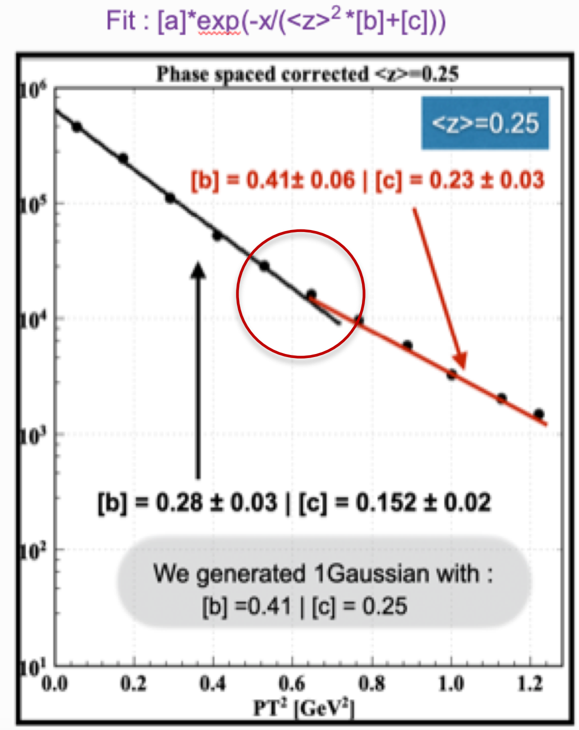
Main question: What is the origin of the tail starting at P_T~0.6-0.7?

CLAS12 Multiplicities: the role of high P_T

LUND MC at 12 GeV using a single Gauss for all hadrons

G. Angelini (GW)

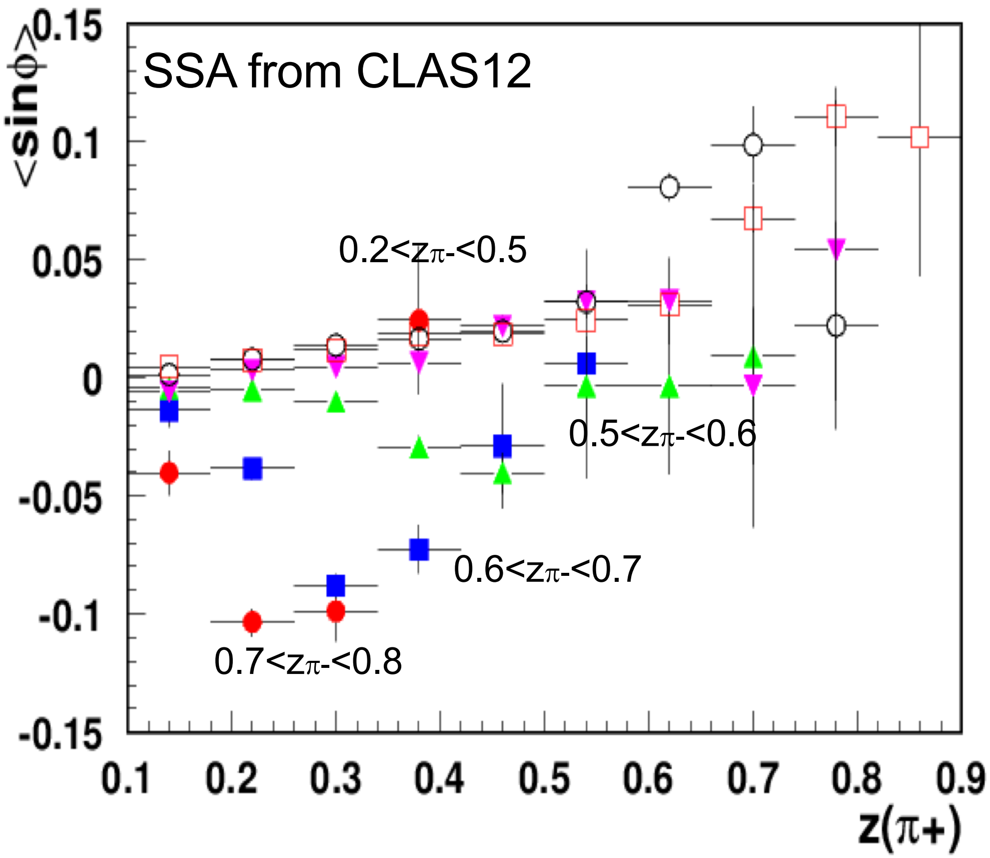


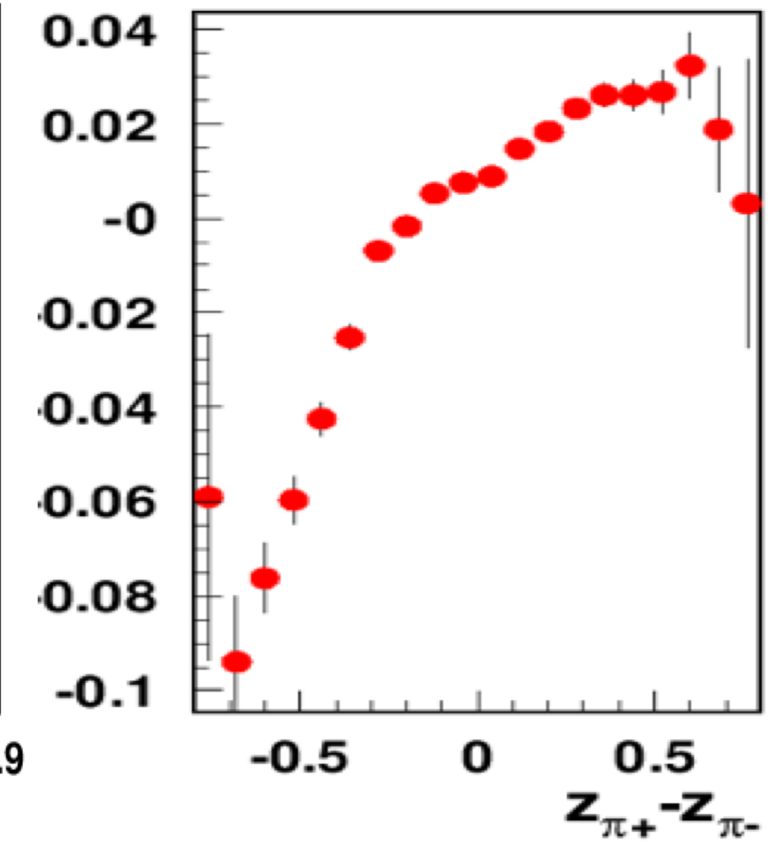


- Corrections due to phase space (energy needed to produce a hadron with a given z,P_T at given x,Q^2) are detector and model independent
- Corrections due to fraction of fragmentation VMs and diffractive VMs are model dependent, but can be extracted from MC (work in progress)

At low z, only the high P_T shows the generated Gaussian transverse momentum distribution.

Disecting the SSA in ep→e'π+X from CLAS12

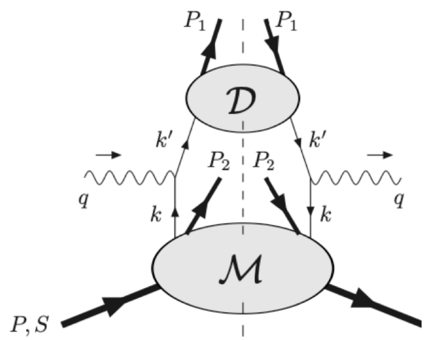




Observed SSA for the inclusive π+ changes significantly with the π- z
The polarization of the ρ itself may be relevant (no SSA for symmetric case)

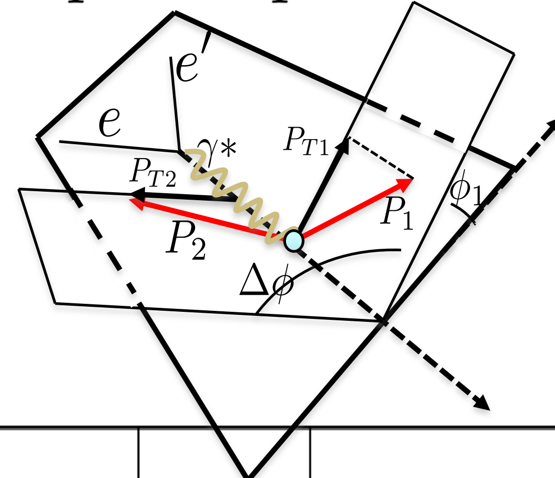
B2B hadron production in SIDIS: Theory

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



$$\mathcal{A}_{LU} = -\frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)} \frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}} \sin\Delta\phi$$
$$= -\frac{|\mathbf{P}_{1\perp}||\mathbf{P}_{2\perp}|}{m_N m_2} \frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)} \times \frac{\mathcal{C}[w_5\, \hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]} \sin\Delta\phi,$$

$ep \longrightarrow e' p \pi^+ X$



Fracture Functions define the probability for hadron production (P2) given the struck quark q. Combined with the fragmentation function (defining probability for quark q to produce a hadron (P1) defines the x-section for 2 hadron production.

	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	$\hat{u}_{1T}^h, \hat{u}_{1T}^{\perp}$	$\hat{l}_{1T}^h, \hat{l}_{1T}^{\perp}$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$

$$\mathcal{F}_{UU} = \mathcal{C}\left[\hat{u}_1 D_1\right]$$

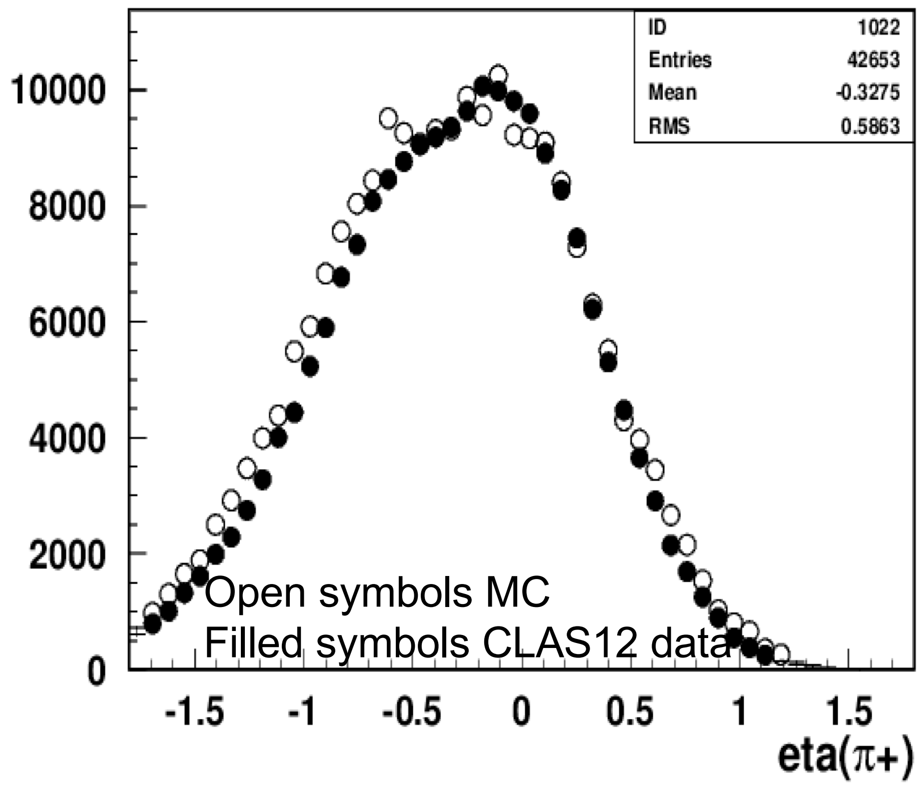
$$\mathcal{C}\left[f(\mathbf{k}_\perp, \mathbf{k}'_\perp, \ldots)\right] \equiv \sum_a e_a^2 x_B \int \mathrm{d}^2\mathbf{k}_\perp \int \mathrm{d}^2\mathbf{k}'_\perp \times \delta^2(\mathbf{k}_\perp - \mathbf{k}'_\perp - \mathbf{P}_{1\perp}/z_1)\, f(\mathbf{k}_\perp, \mathbf{k}'_\perp, \ldots).$$

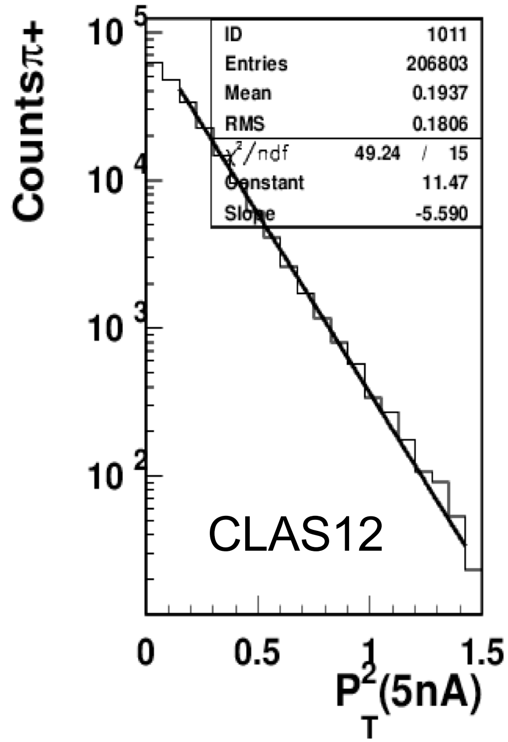
Probability to produce a hadron for a given longitudinally polarized quark

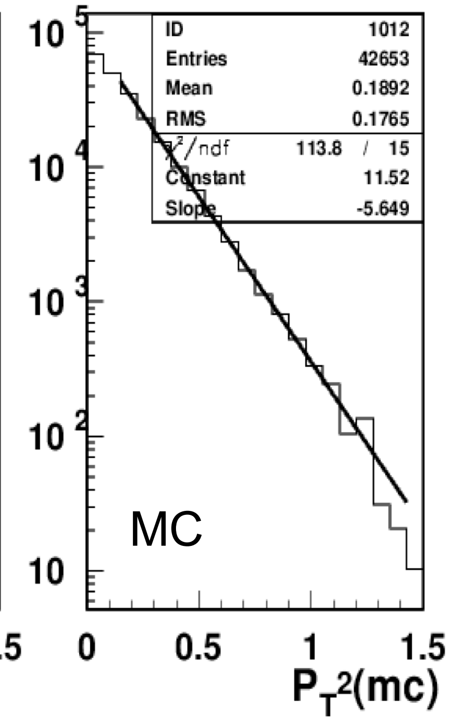
CLAS12 Studies: pions

Using PEPSI (LUND) generator rapidity in Breit frame

Boglione et al
https://arxiv.org/pdf/1904.12882.pdf







Distributions of pions vs rapidity in good agreement with LUND-MC (LEPTO) in most of the kinematics

CLAS12 Studies: protons

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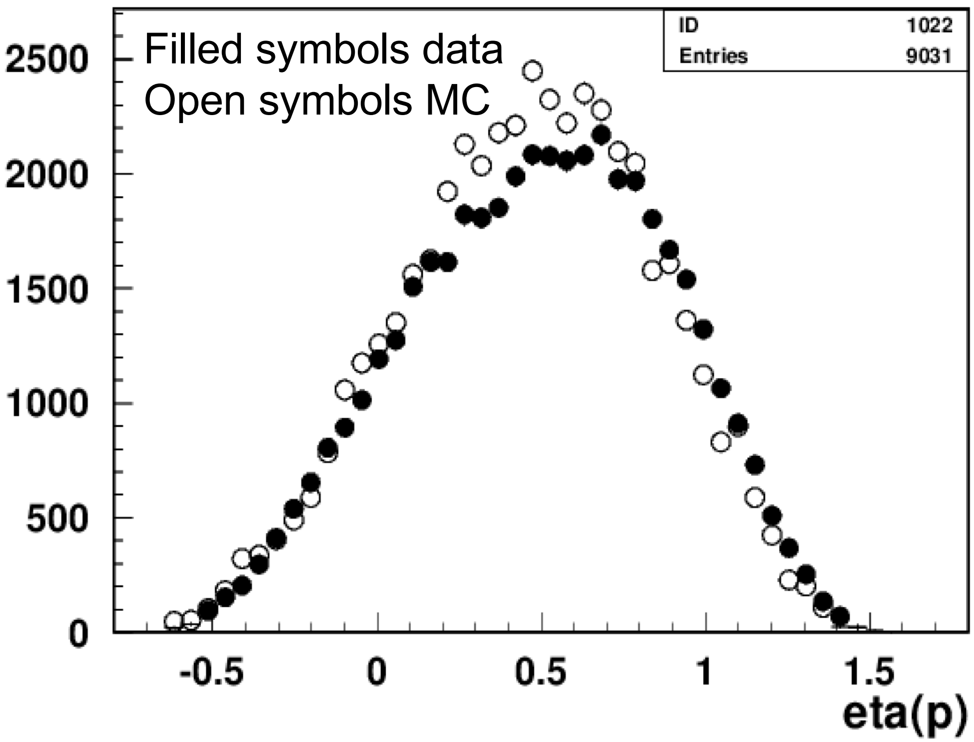
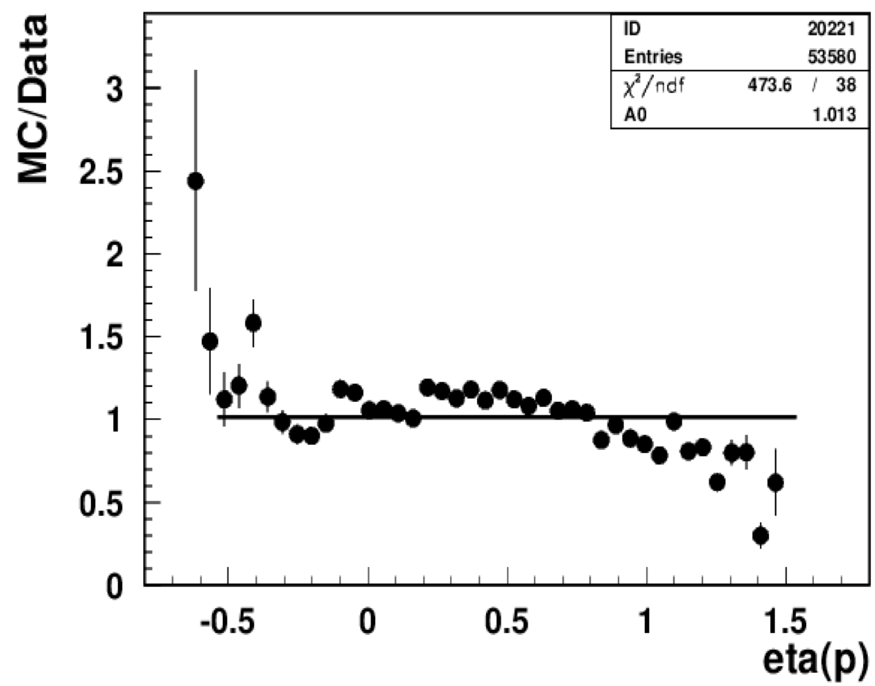
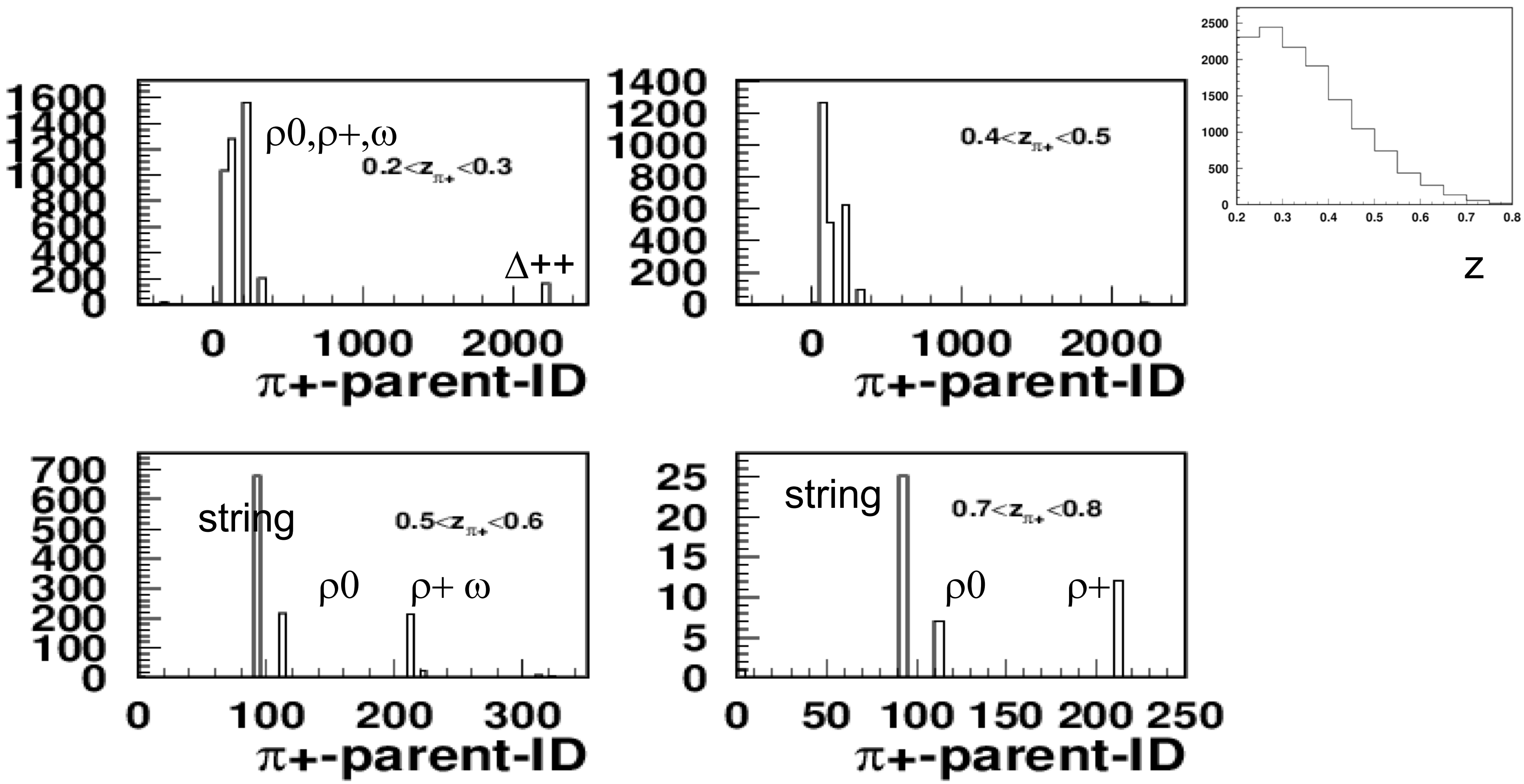




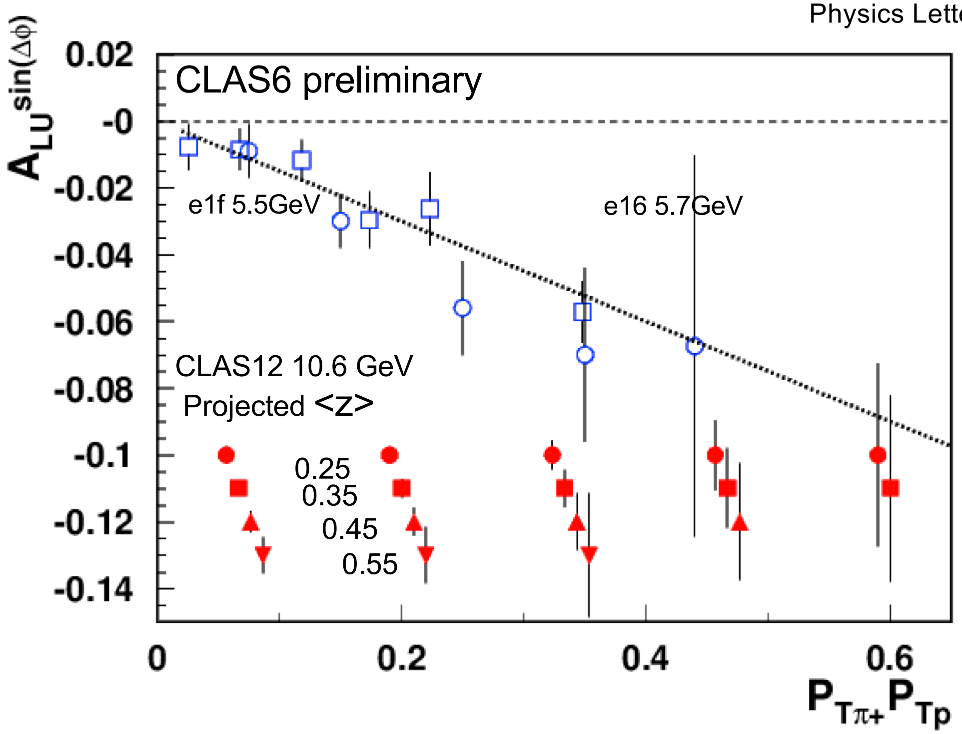
Distributions of protons vs rapidity in good agreement with LUND-MC (LEPTO) in most of the kinematics

π+ parents in ep→e'pπ^+X events



Tiny fraction of pions come from Δ++ at z~0.2, and at large z mainly from string and ρ

B2B SSAs ep→pπ+X



M. Anselmino, V. Barone and A. Kotzinian,
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$$= -\frac{|\mathbf{P}_{1\perp}||\mathbf{P}_{2\perp}|}{m_N m_2} \frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)}$$

$$\times \frac{\mathcal{C}[w_5\, \hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]} \sin\Delta\phi,$$

May be canceling out in large x
(true for u-quark dominance)

$$\hat{l}_1^{\perp h}(x_B, \zeta_2, \mathbf{k}_\perp^2, \mathbf{P}_{2\perp}^2, \mathbf{k}_\perp \cdot \mathbf{P}_{2\perp})$$
$$\simeq a(x_B, \zeta_2, \mathbf{k}_\perp^2, \mathbf{P}_{2\perp}^2)$$
$$+ b(x_B, \zeta_2, \mathbf{k}_\perp^2, \mathbf{P}_{2\perp}^2)\, \mathbf{k}_\perp \cdot \mathbf{P}_{2\perp}$$

$$\mathcal{A}_{LU}(x_B, z_1, \zeta_2, \mathbf{P}_{1\perp}^2, \mathbf{P}_{2\perp}^2, \Delta\phi)$$
$$= A(x_B, z_1, \zeta_2, \mathbf{P}_{1\perp}^2, \mathbf{P}_{2\perp}^2)\, \sin\Delta\phi$$
$$+ B(x_B, z_1, \zeta_2, \mathbf{P}_{1\perp}^2, \mathbf{P}_{2\perp}^2)\, \sin(2\Delta\phi)$$

- Significant SSA observed consistent with linear behavior with P_T-product
- Indicates significant correlations between hadrons in SIDIS in CFR and TFR
- Superior statistics of CLAS12 allows multidimensional binning (x,z,P_T,..)

Summary

- Significant beam spin asymmetries measured by CLAS in two pion production indicating significant correlations in forward going hadrons, and providing access to underlying polarized fragmentation functions and quark-gluon correlations
- Significant beam spin asymmetries measured by CLAS in pion proton production indicating significant correlations between hadrons produced in the CFR and TFR
- Measurements of dihadron multiplicities would allow to constrain experimentally the fractions and distributions of pions coming from vector meson decays (tune JETSET as well)

- Publications of SSAs in b2b, and single hadron and dihadrons multiplicities in SIDIS from CLAS12 expected by the end of 2021

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

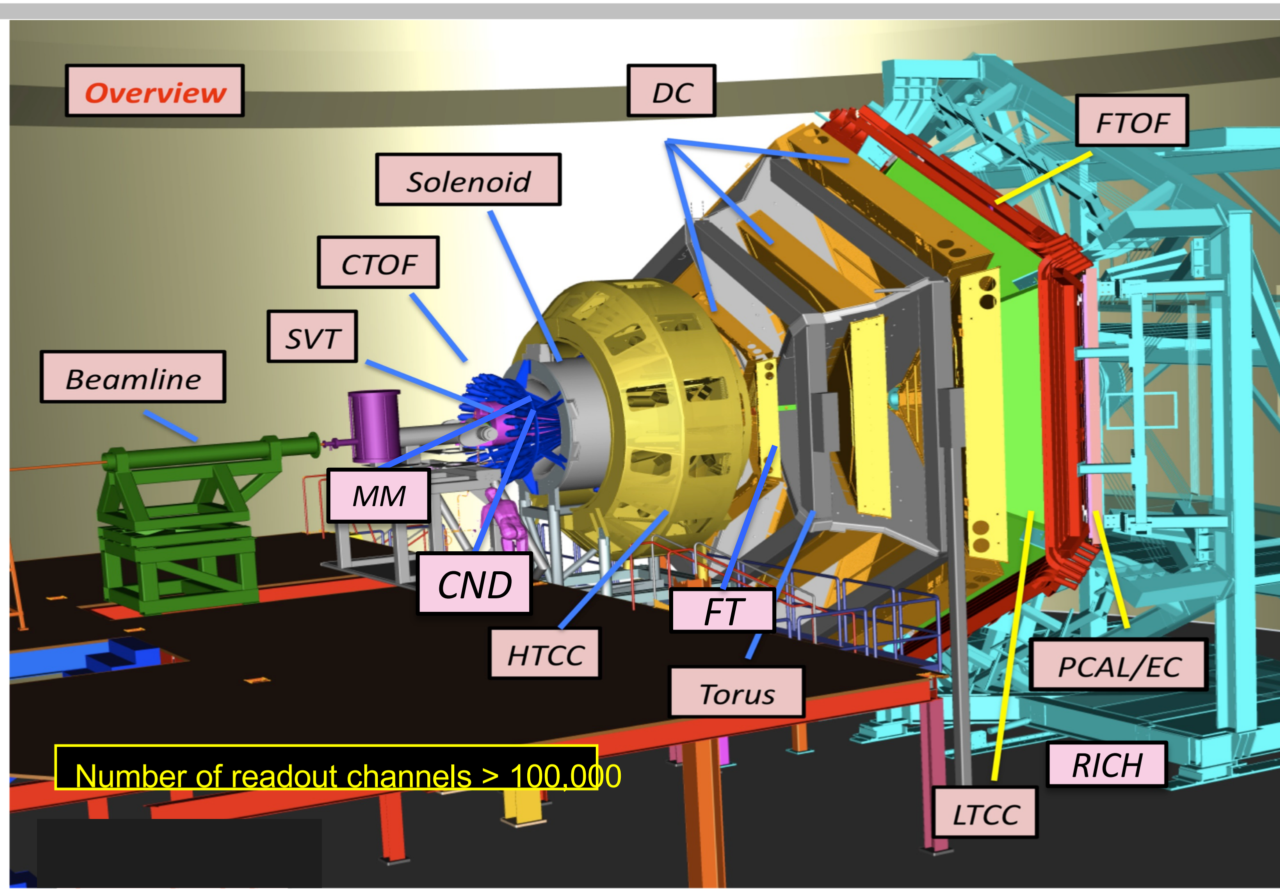
Support slides

CLAS12 Detector Systems

Forward Detector (FD)
- TORUS magnet
- HT Cherenkov Counter
- Drift chamber system
- LT Cherenkov Counter
- Forward ToF System
- Pre-shower calorimeter
- E.M. calorimeter
- Forward Tagger
- RICH detector

Central Detector (CD)
- Solenoid magnet
- Silicon Vertex Tracker
- Central Time-of-Flight
- Central Neutron Detector
- MicroMegas

Beamline
- Diagnostics
- Shielding
- Targets
- Polarimeter
- Faraday Cup

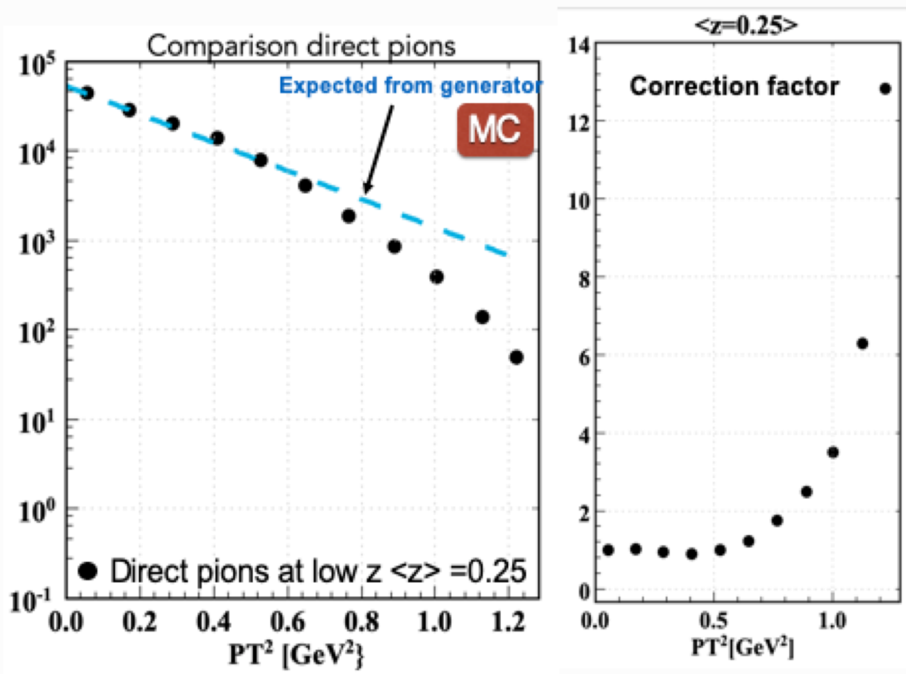


Sources of systematics (defining the "fiducial" region):

1. Background processes (photoproduction, e+e- pairs,diffractive?)
2. Inefficiencies (Detector components, Reconstruction, Lumiosity)
3. Misidentification (e- with π-, π+/- with K+/- and e+/e-)
4. Modeling of the CLAS12 response in GEANT (resolutions,…)
5. …..

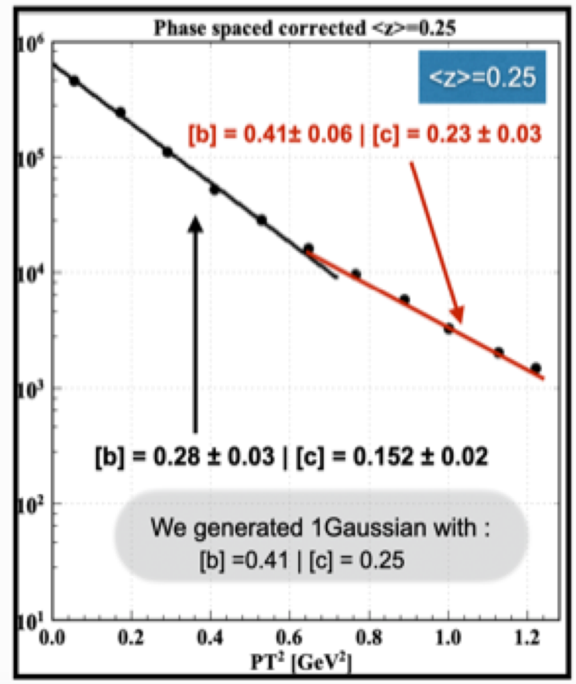
CLAS12 Multiplicities: the role of high P_T

G. Angelini (GW)



Applied to all pion samp

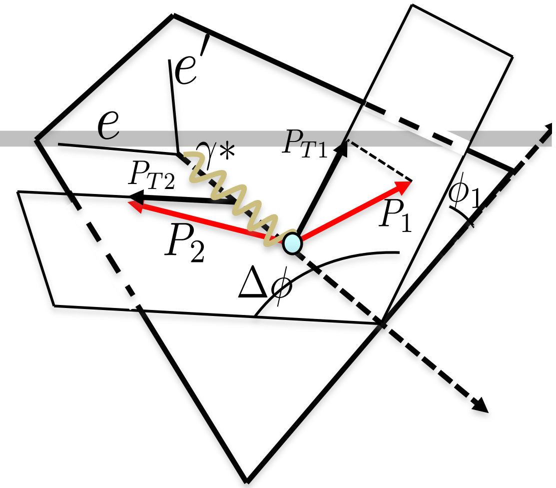
LUND MC at 12 GeV



- Corrections due to phase space (energy needed to produce a hadron with a given z, P_T at given x, Q^2) are detector and model independent
- Corrections due to fraction of fragmentation VMs and diffractive VMs are model dependent, but can be extracted from MC (work in progress)

At low z, only the high P_T shows the generated Gaussian transverse momentum distribution.

Proton z(ζ_2)

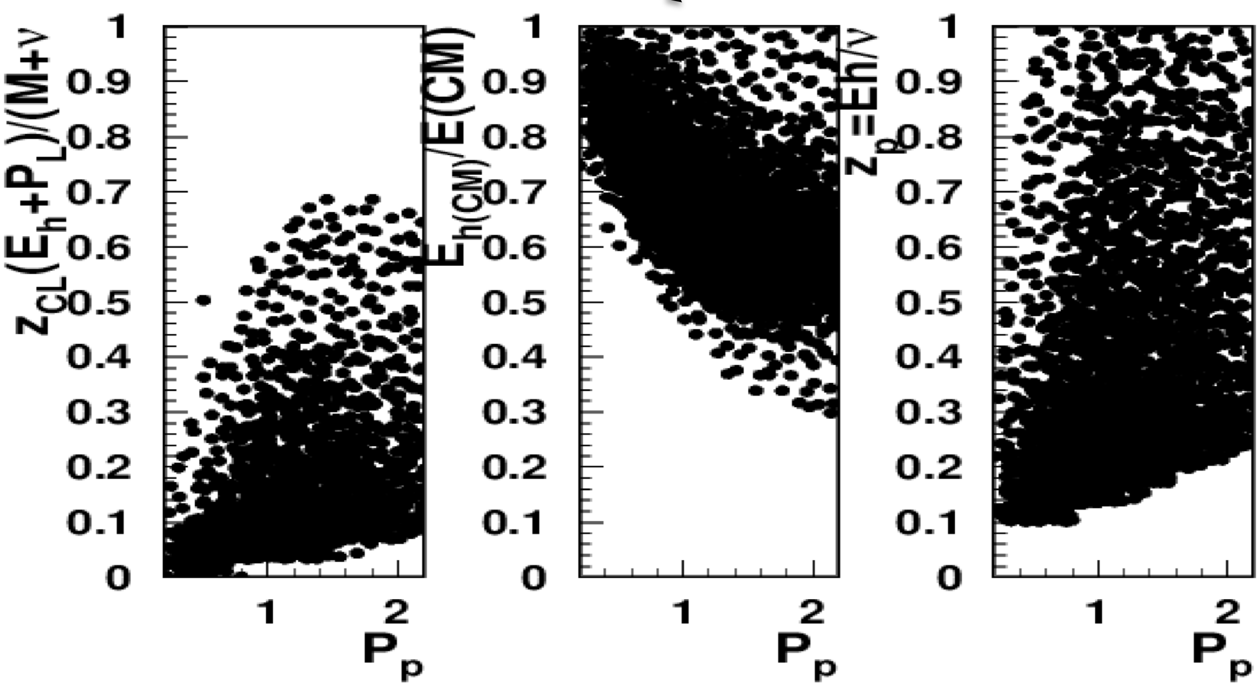


$$A_{LU}(x, z_1, \zeta_2, P_{1\perp}^2, P_{2\perp}^2, \Delta\phi) = \frac{\int d\phi_2\, \sigma_{LU}}{\int d\phi_2\, \sigma_{UU}} = \frac{-\frac{P_{1\perp}P_{2\perp}}{m_2 m_N} F_{k1}^{\hat{l}^{\perp h}\cdot D_1} \sin(\Delta\phi)}{F_0^{\hat{u}\cdot D_1}}$$

$$x, z_1, \zeta_2, P_{1\perp}^2, P_{2\perp}^2, \boldsymbol{P}_{1\perp}\cdot\boldsymbol{P}_{2\perp}$$

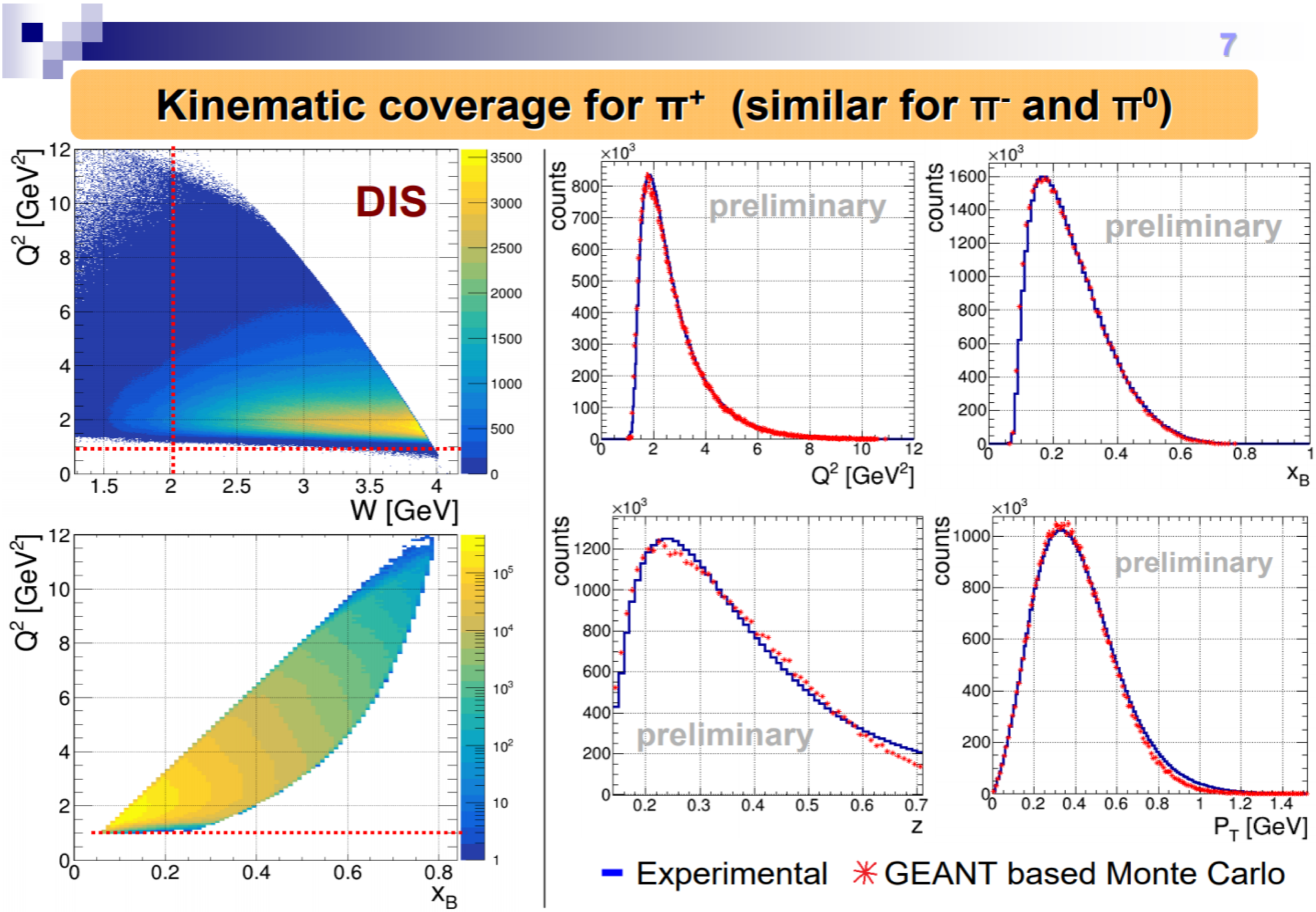
$$\zeta = P_h^- / P^- \simeq E_h/E$$

in the $\gamma^* - N$ c.m. frame



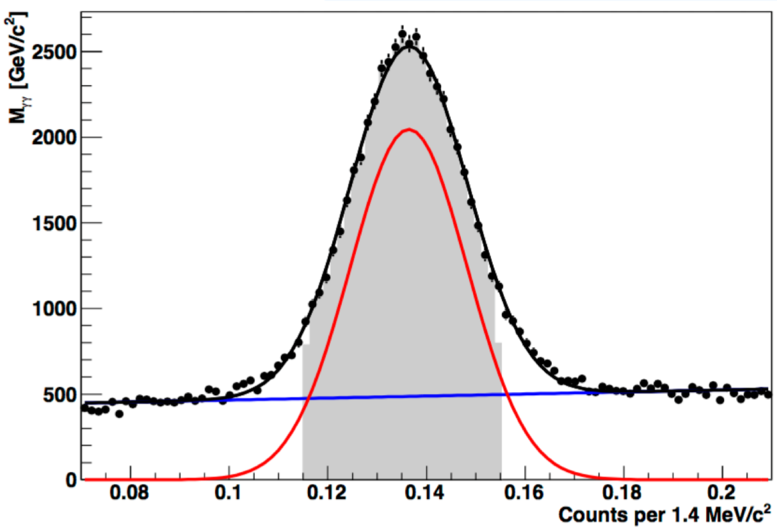
SIDIS ehX: CLAS12 data vs MC

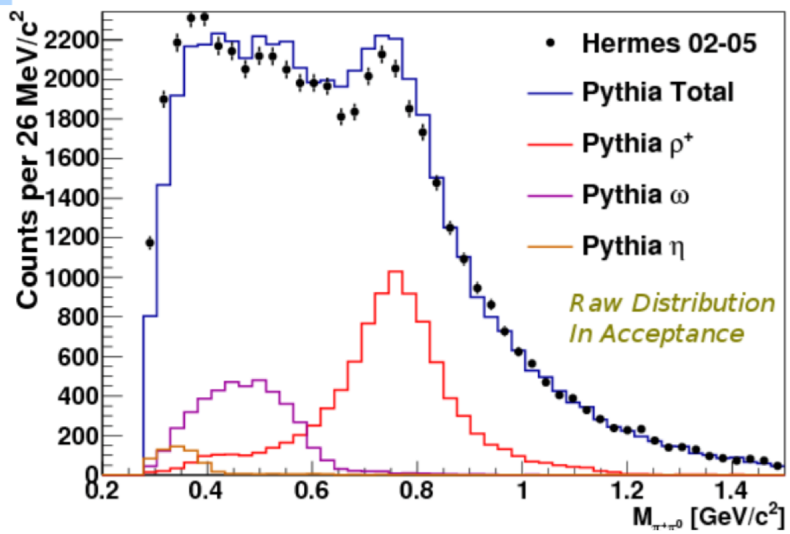
CLAS12 single hadron note: in review for publication

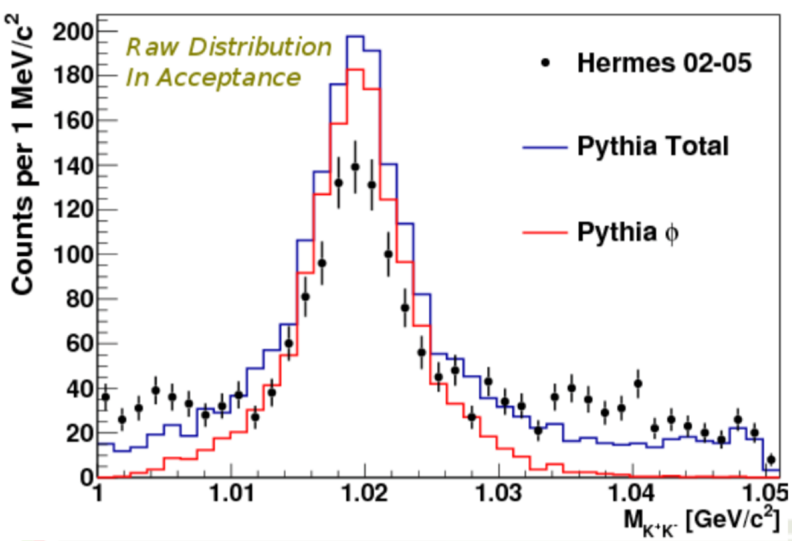


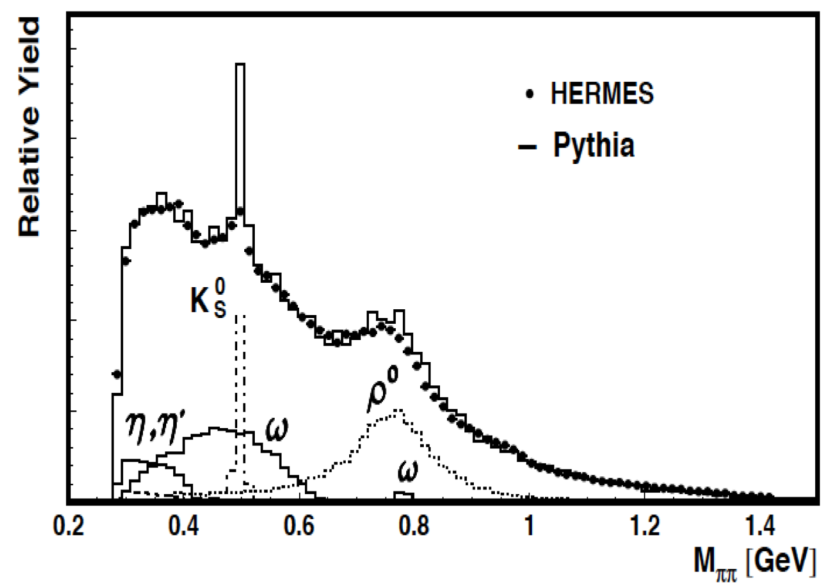
HERMES dihadrons

Particle Reconstruction

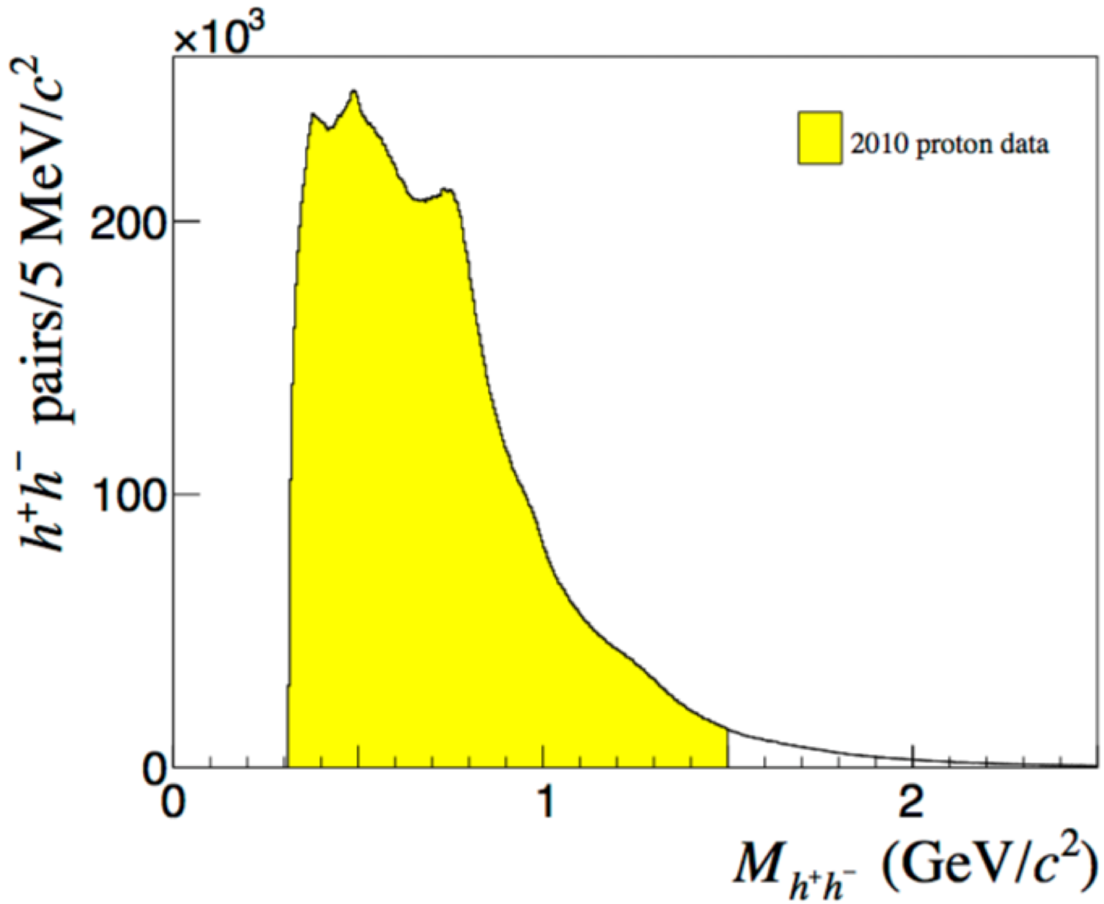








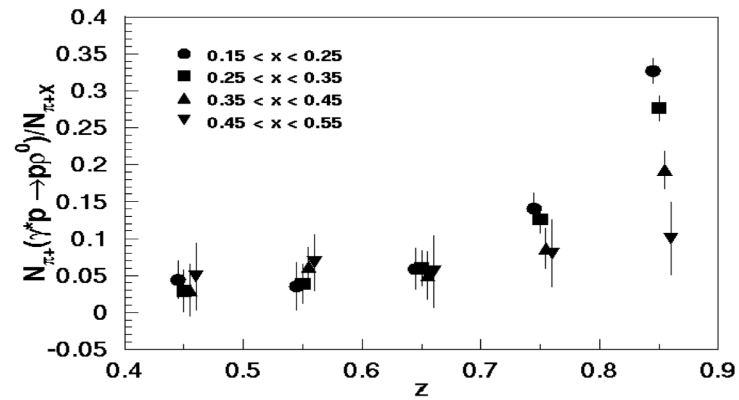
COMPASS dihadrons



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

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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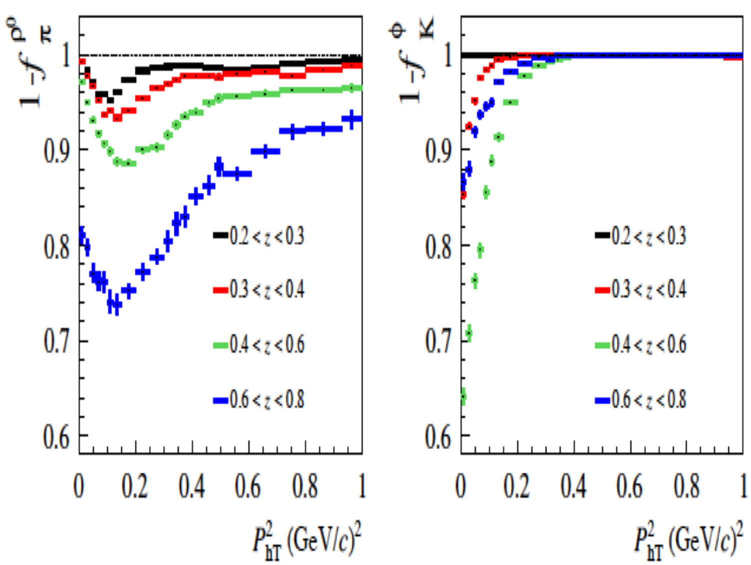

Hard exclusive meson production from clas6