Target fragmentation in fixed-target experiments

Harut Avakian (JLab)

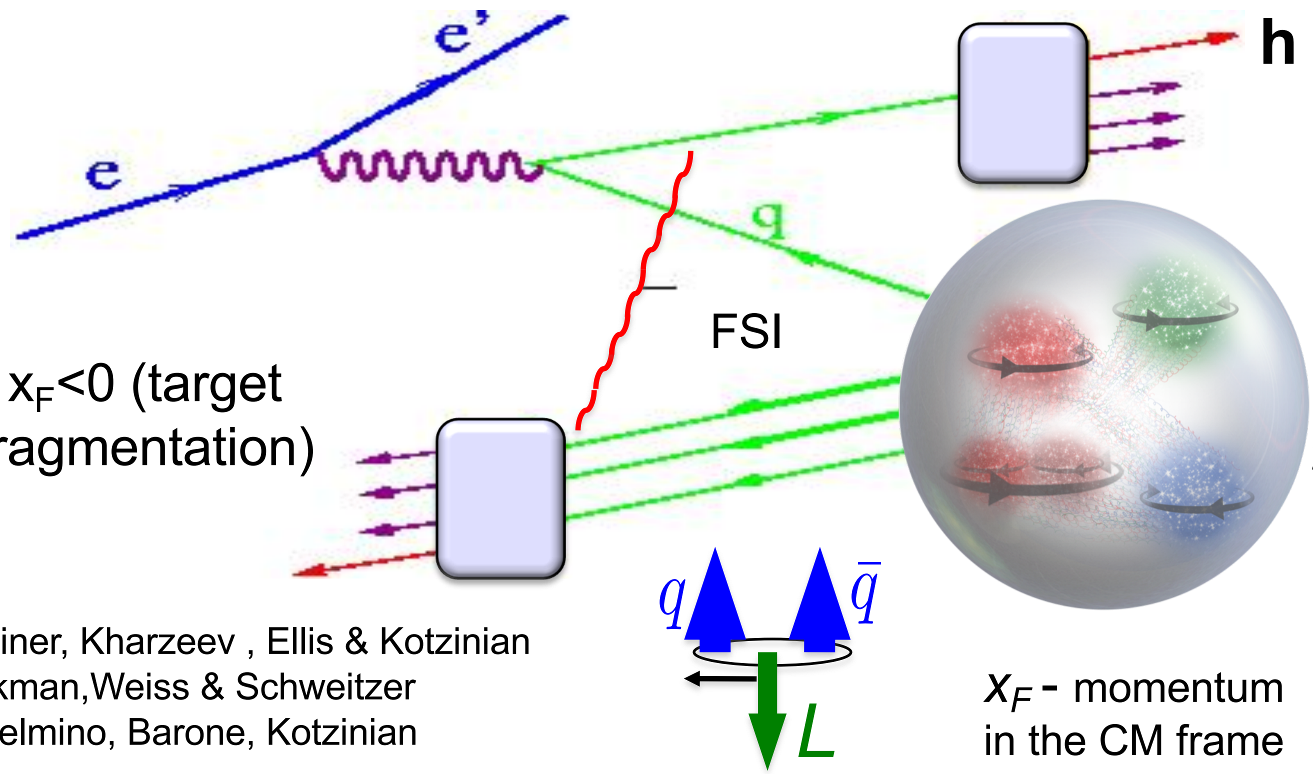
Target fragmentation physics with EIC
September 28-30, 2020

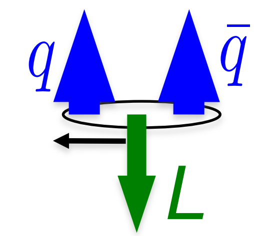
- Target fragmentation as a source for k_T-structure
- LUND-MC (CLAS12/COMPASS/EMC)
  - Single hadron
  - Di-hadron
- Accessing k_T in P_T-distributions of hadrons
- EIC simulations
- Polarization effects, and correlations with current
- Conclusions

Hadron production in hard scattering

$x_F>0$ (current fragmentation)

X. Artru & Z. Belghobsi





$x_F<0$ (target fragmentation)

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

Modeling of q-q-bar correlations with spins and momenta in the process (not in PYTHIA) will be important for understanding of the dynamics

EMC Studies

M. Arneodo *et al.* [European Muon Collaboration], Phys. Lett. B **150**, 458 (1985)

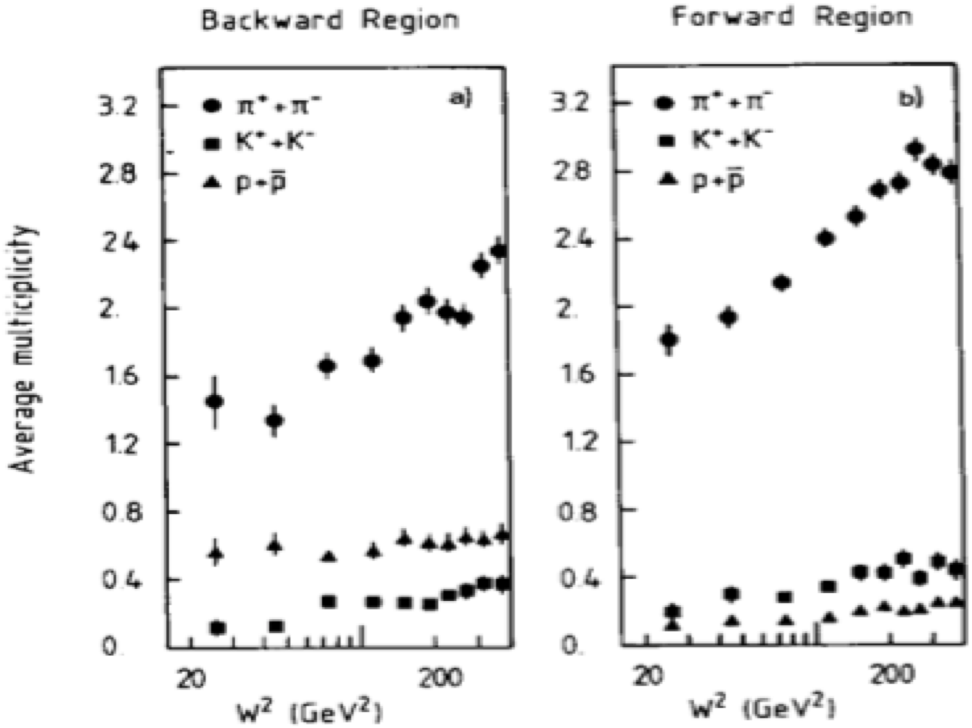
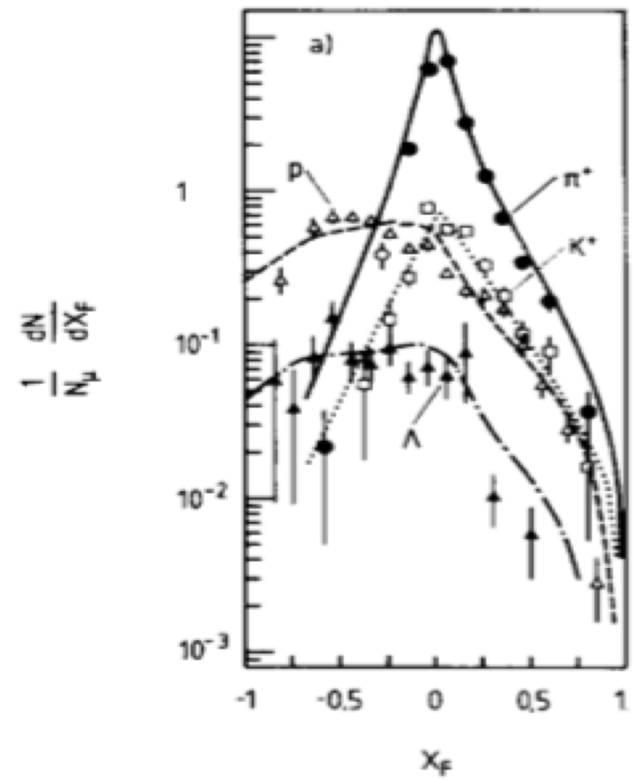


Fig. 1. Average multiplicity of pions, kaons and protons as a function of W^2, (a) backward multiplicity ($x_F < 0$), (b) forward multiplicity ($x_F > 0$).

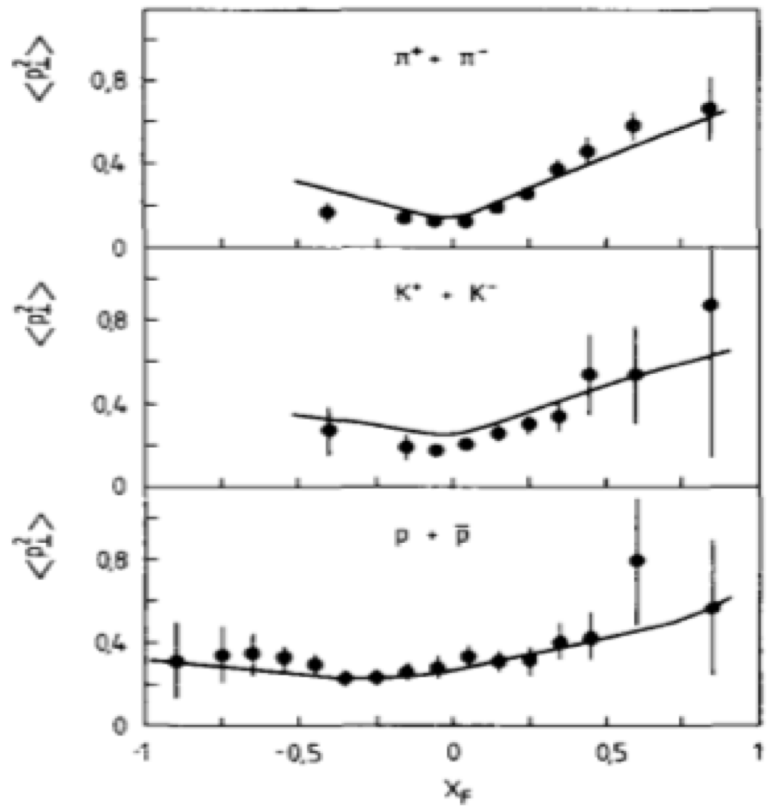


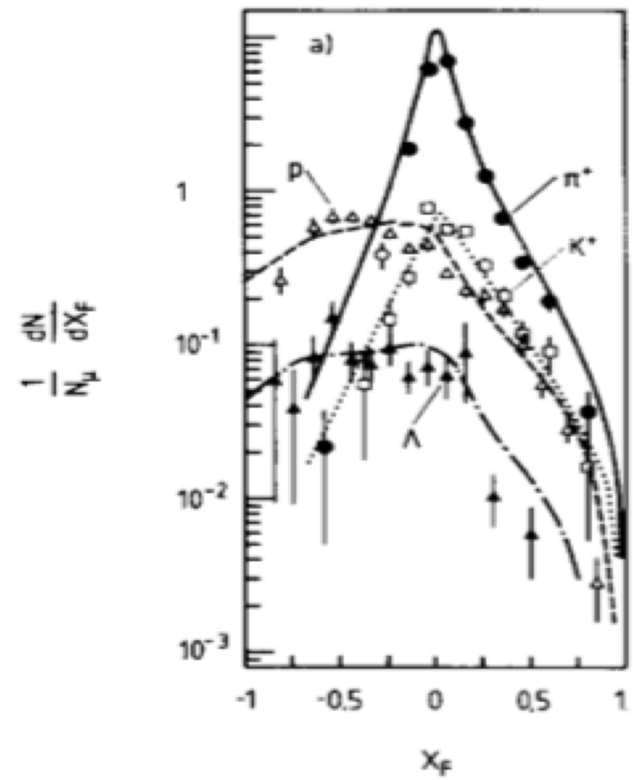
Proton multiplicities in target fragmentation ~0.5

The curves represent the predictions of the Lund model.

This can be interpreted as diquark fragmentation into baryons

EMC Studies

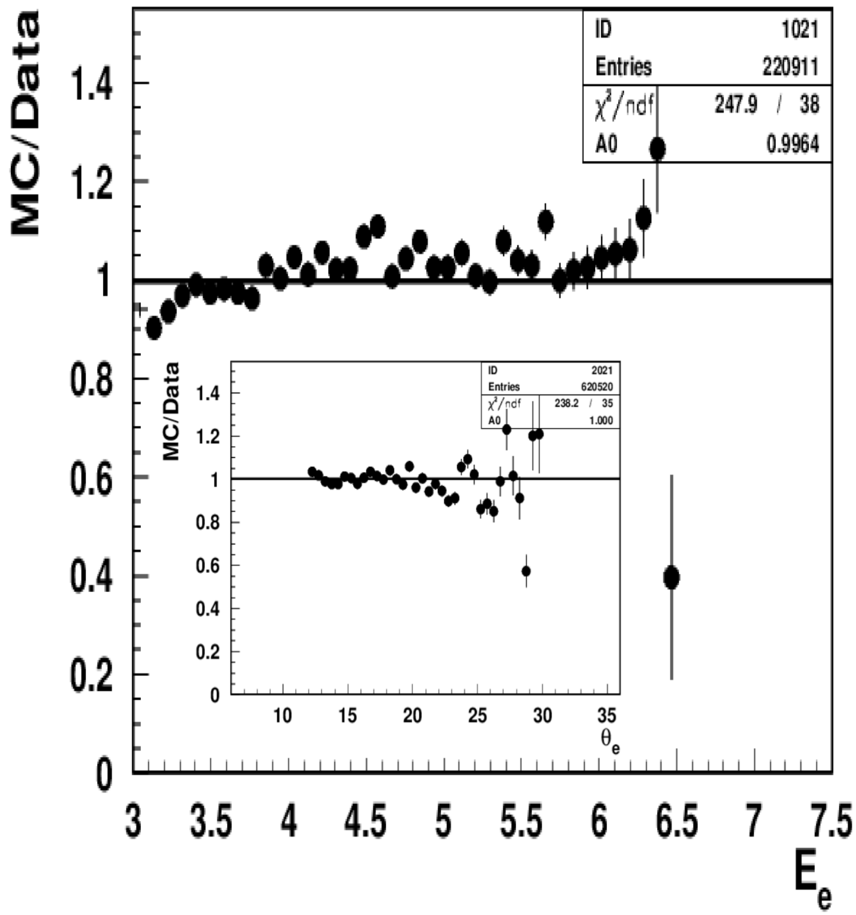


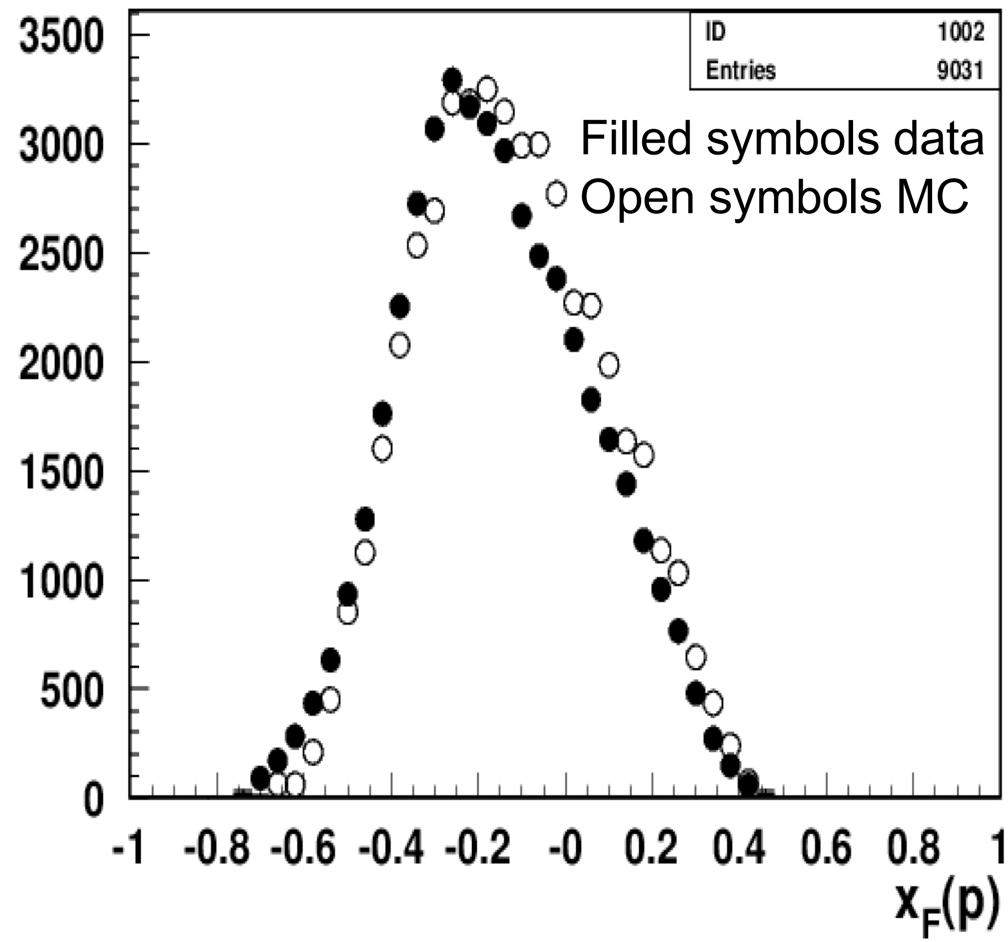


In the central x_F region, $\langle P_T^2 \rangle$ depends on particle mass, being larger for heavier particles. Tile main trends of the data are qualitatively reproduced by the Lund model.

CLAS12 Studies:Data vs MC

Using PEPSI (LUND) generator



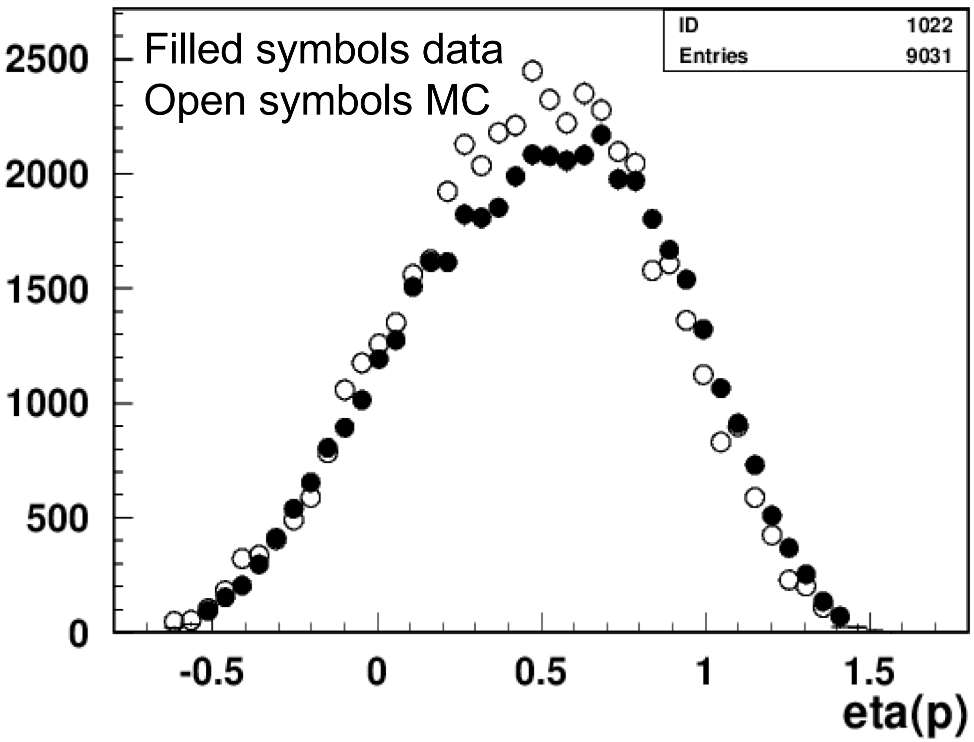


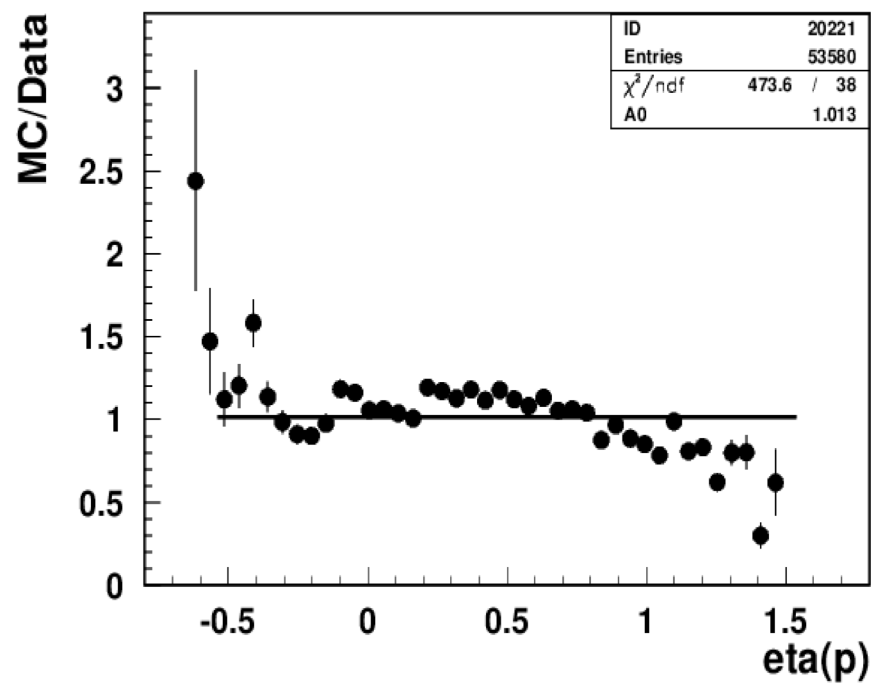
Multliplicity of protons in good agreement with JETSET
Normalized multiplicity ~0.5

CLAS12 Studies: Data vs MC

Using PEPSI (LUND) generator rapidity in Breit frame

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

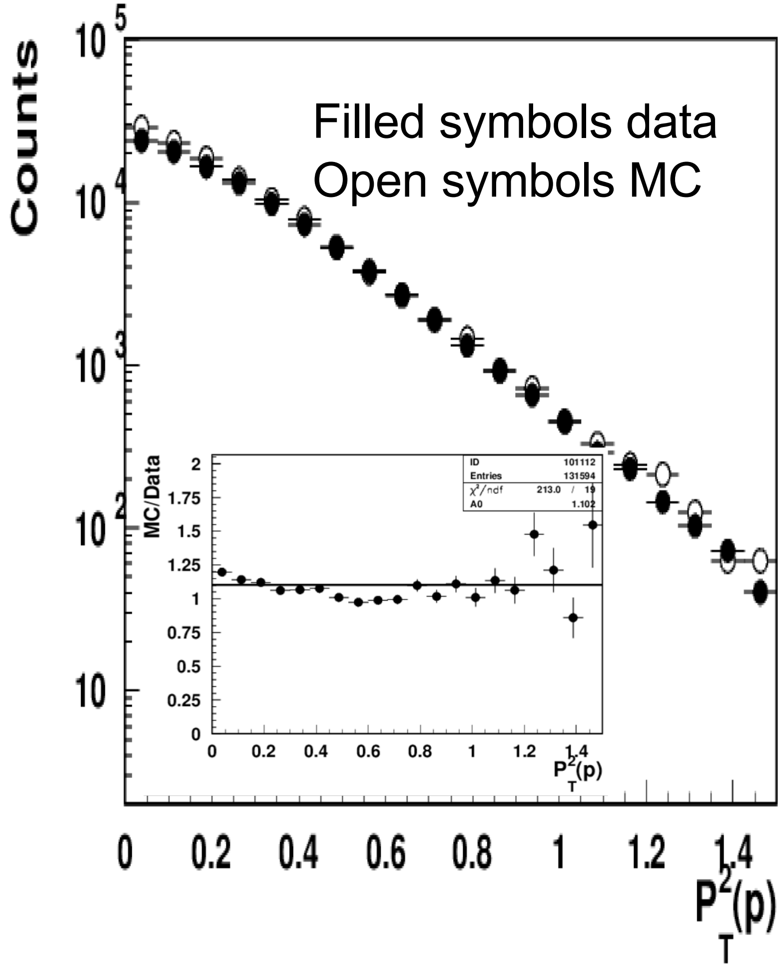


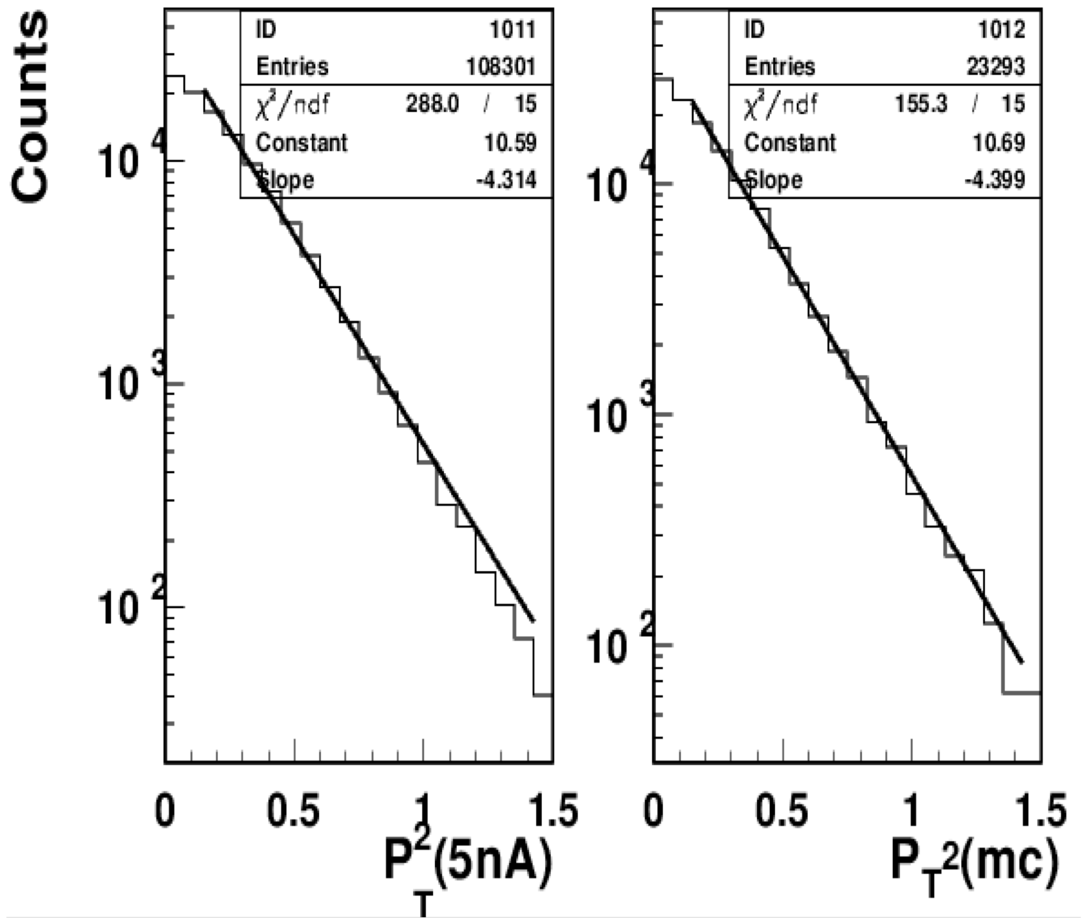


Multiliplicity of protons vs rapidity in good agreement with JETSET in most of the kinematics

CLAS12 Studies: Data vs MC

Using PEPSI (LUND) generator





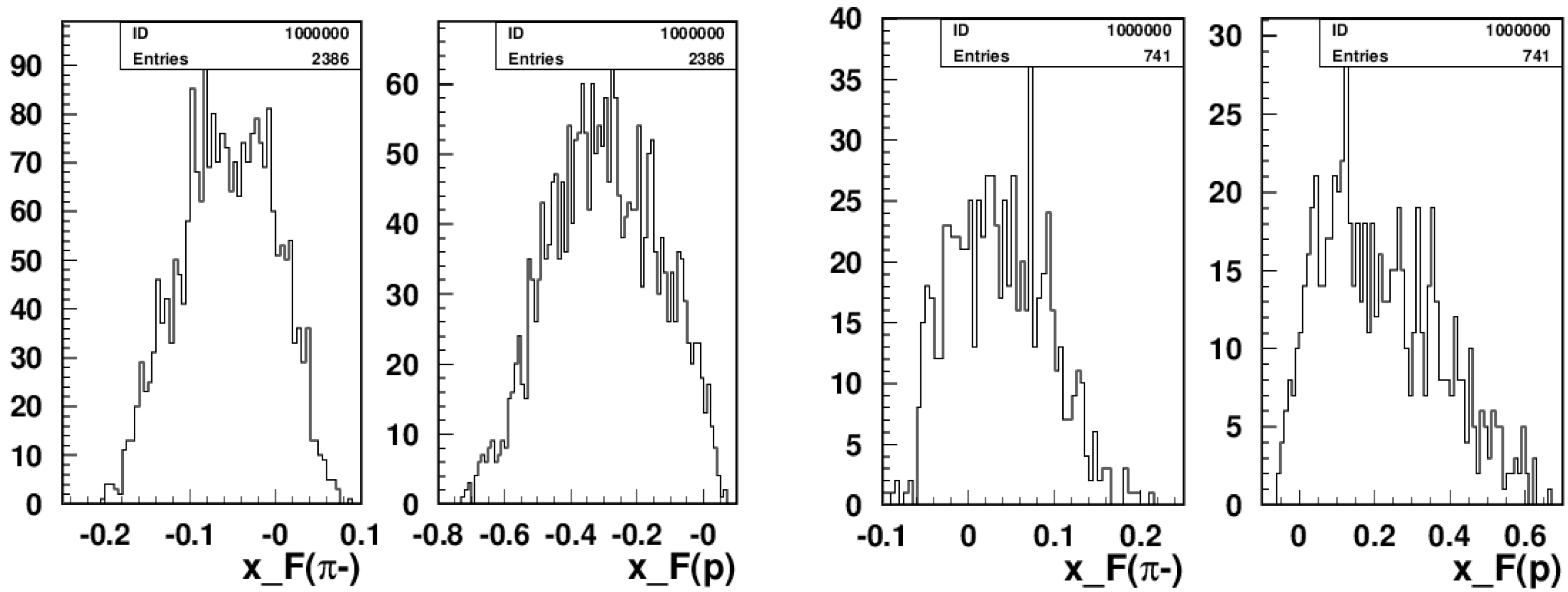
Mutliplicity of protons, and widths of distributions in good agreement with JETSET
May be a source for widths in fragmentation

CLAS12 Studies

Using PEPSI (LUND) generator: checking xF of decay products ($\Lambda \rightarrow p\pi-$)

$x_F(\Lambda)<0$

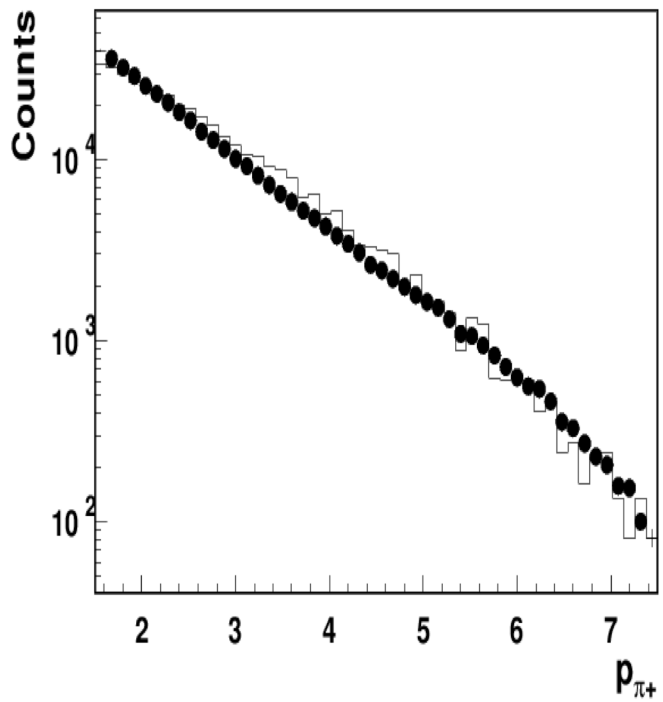
$x_F(\Lambda)>0$

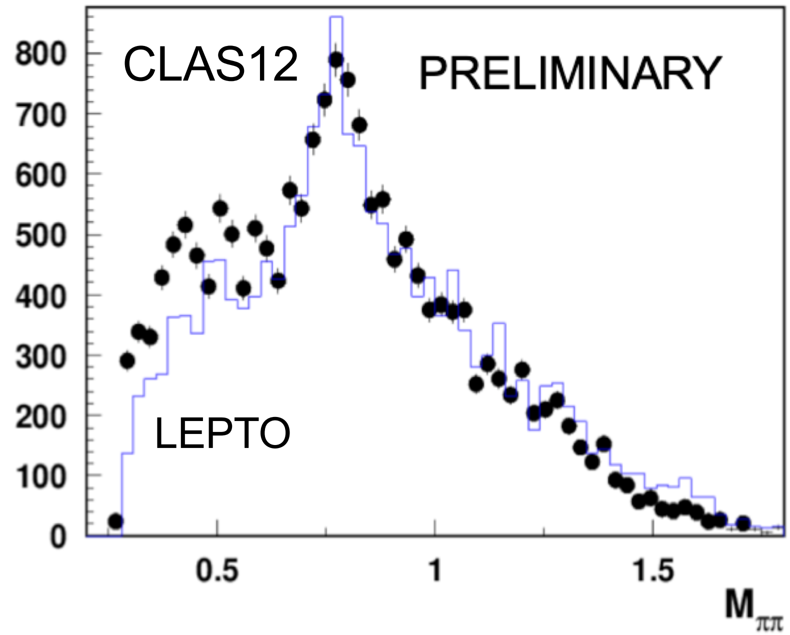


X_F-can approximately represent the current/target fragmentation regions, with decay products introducing corrections

SIDIS ehX,ehhX: CLAS12 data vs MC

ep→e'hX (RGB/RGA CLAS12 Data/MC <u>normalized to the same number of electrons</u>)

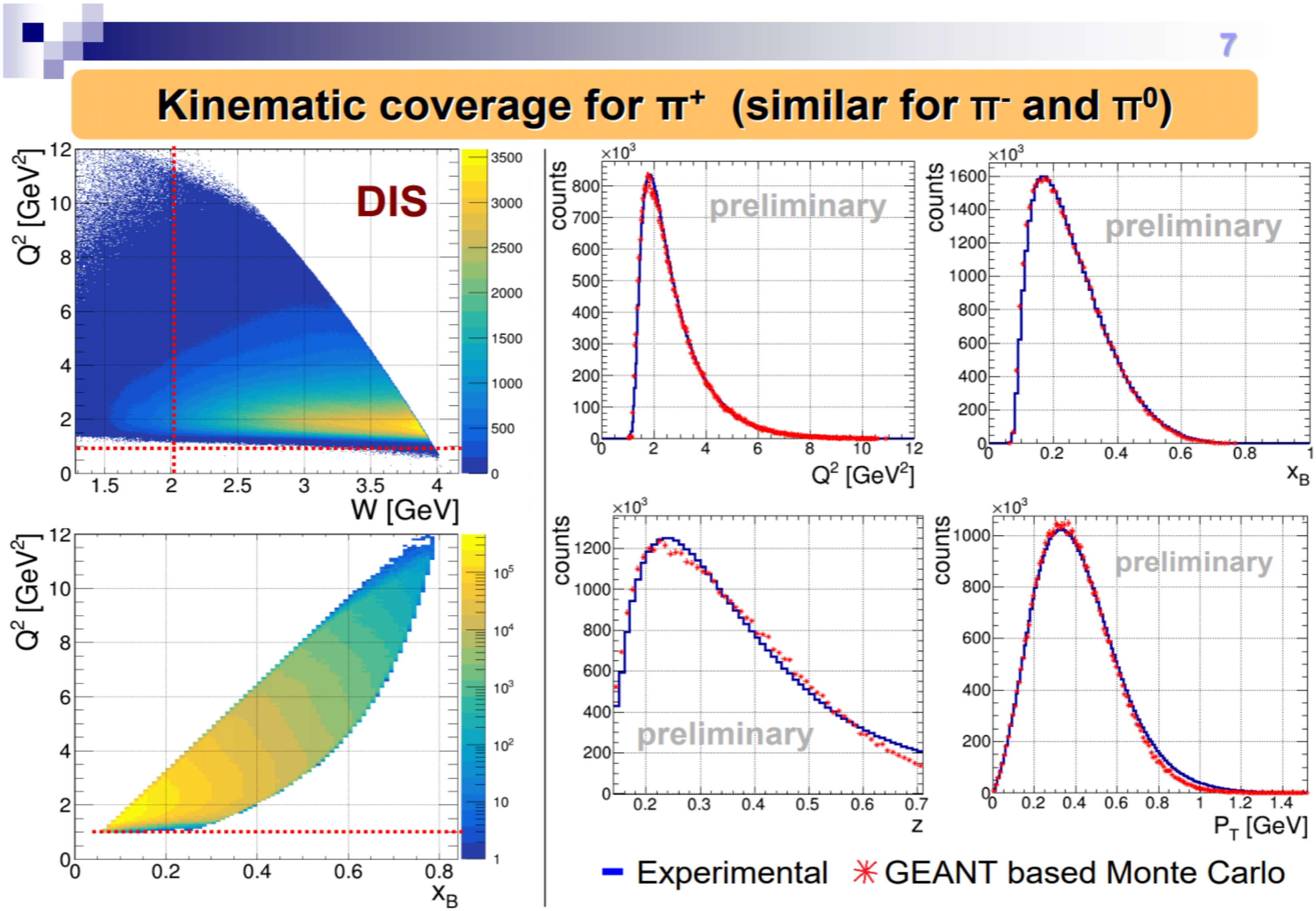




- Most of the single hadron sample (from 50-70%) is coming from VM decays
- Pion counts for normalized e'X events are consistent with clas12 LUND MC (VM 70%)
- Simulation describes well both single (e'hX) and di-hadron (e'hhX) counts in CLAS12
- MC data can be used to make conclusions about the source of hadrons

SIDIS ehX: CLAS12 data vs MC

CLAS12 single hadron note: in review for publication



SIDIS ehhX: CLAS12 data vs MC

CLAS12 dihedron note: in review for publication

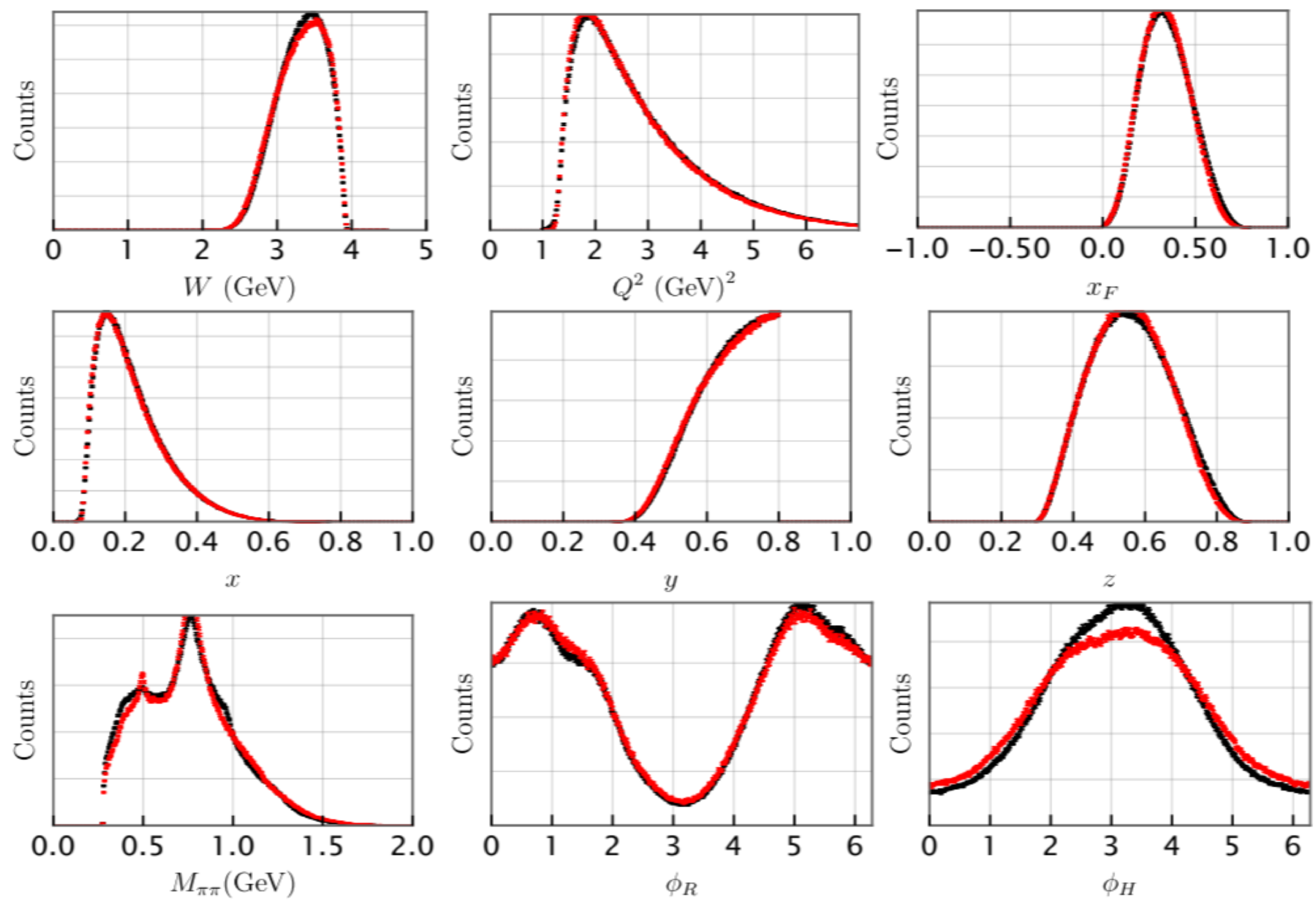
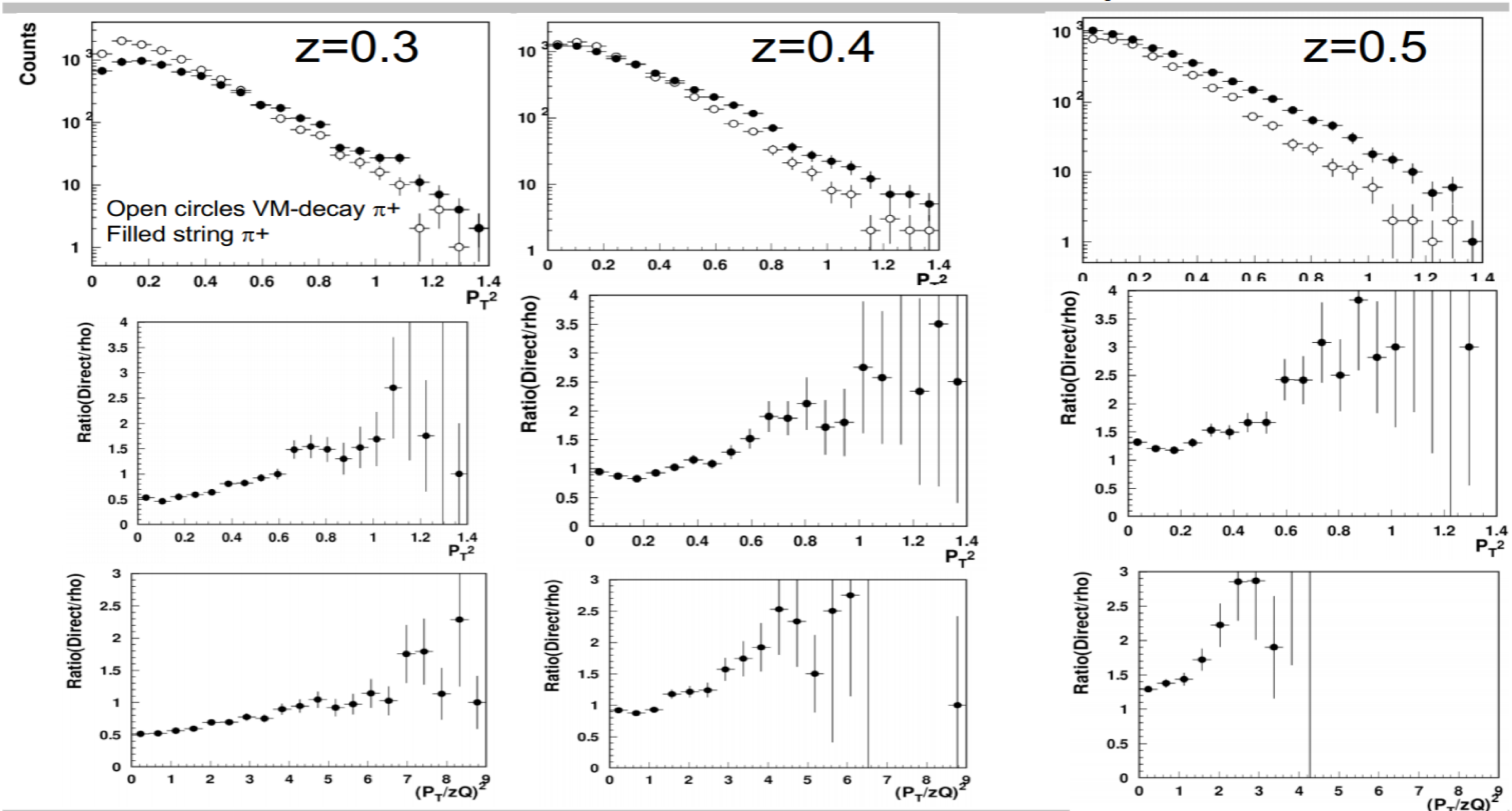


FIG. 26: (Color online). Comparison between the mass-produced OSG Monte Carlo (red) and data (black). From top to bottom and left to right the figures are: W, Q^2, x, y, z, $M_{\pi\pi}$, phi_R and ϕ_h.

JLab12: SIDIS and P_T

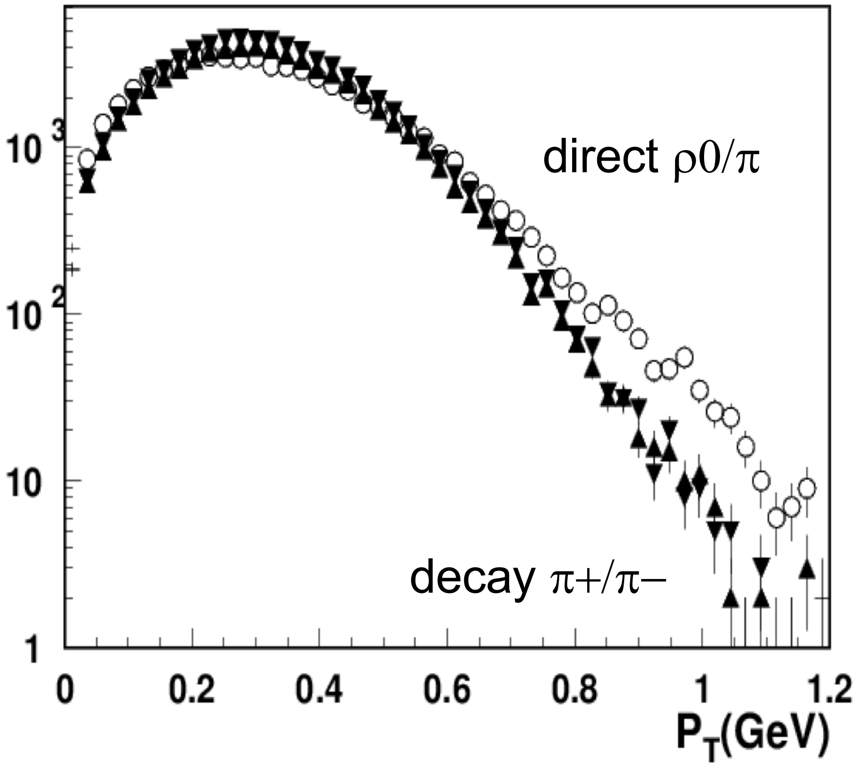


Important note: VM means VMs from quark fragmentation (not diffractive)

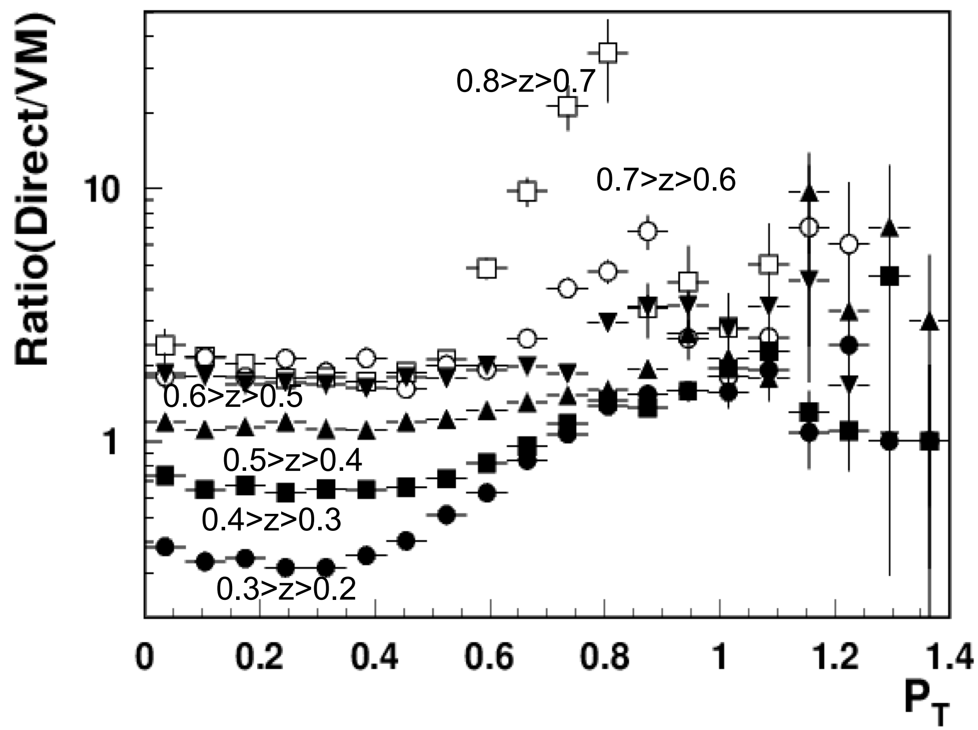
P_T-distribution of hadrons, for a given value of z, can't be used alone to extract information about the underlying k_T-structure (fraction of VMs relevant)

P_T of pions from rho decays: LUND string fragmentation

Note: PYTHIA uses a single Gauss in k_T

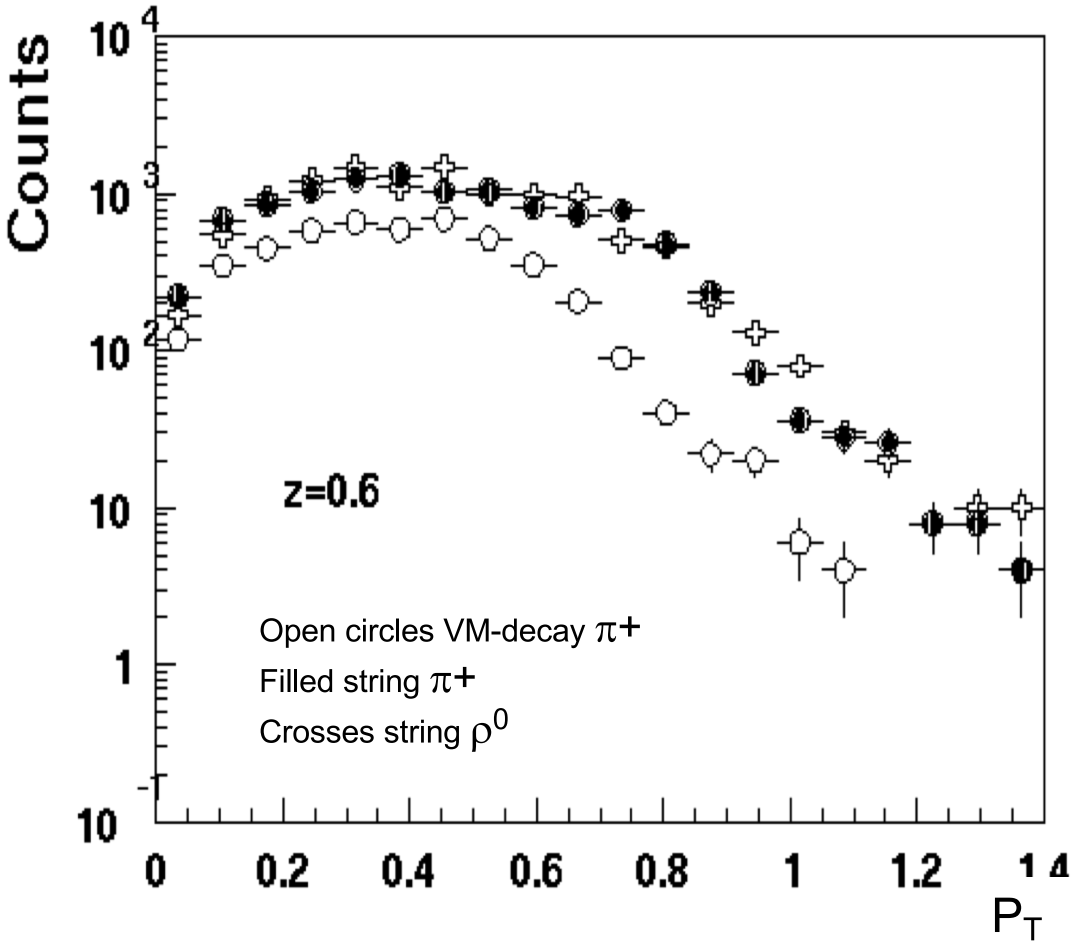


Fraction of direct π+ increases with P_T and z



- P_T-dependence of direct hadrons (ρ+/−0, π+/−/0) is wider than the one from decay pions, making studies of k_T-structure using low P_T hadrons <u>challenging</u>
- Understanding of dihadron production is crucial for interpretation of single-hadron SIDIS, in particular, k_T-dependence of PDFs

JLab12: SIDIS and P_T

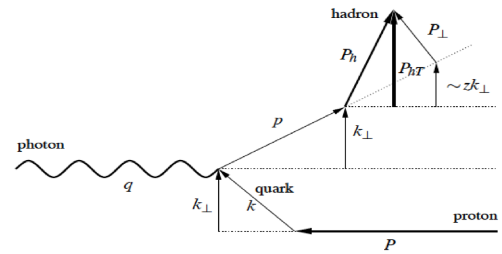


Direct pions and rhos have the same P_T-distributions carrying direct information about the k_T-structure of the initial quarks

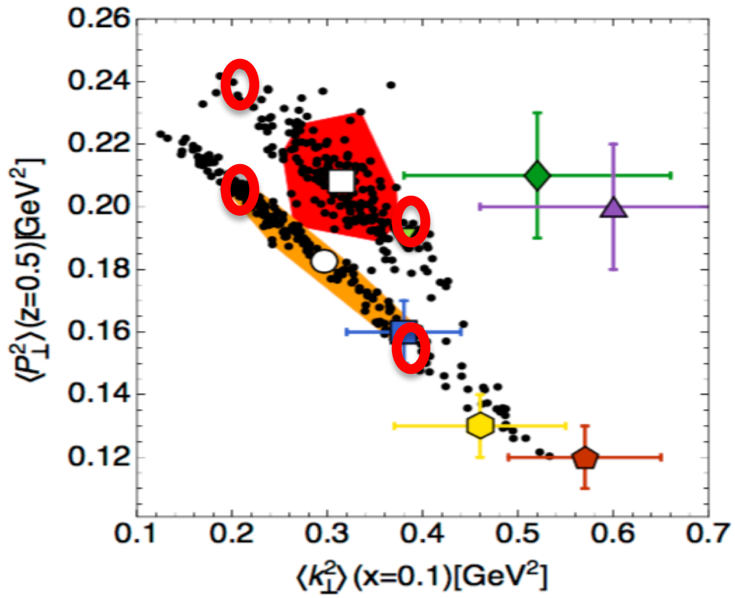
Hadrons produced from decays will have in average much lower P_T for the same z, and studies of k_T-structure will require additional input

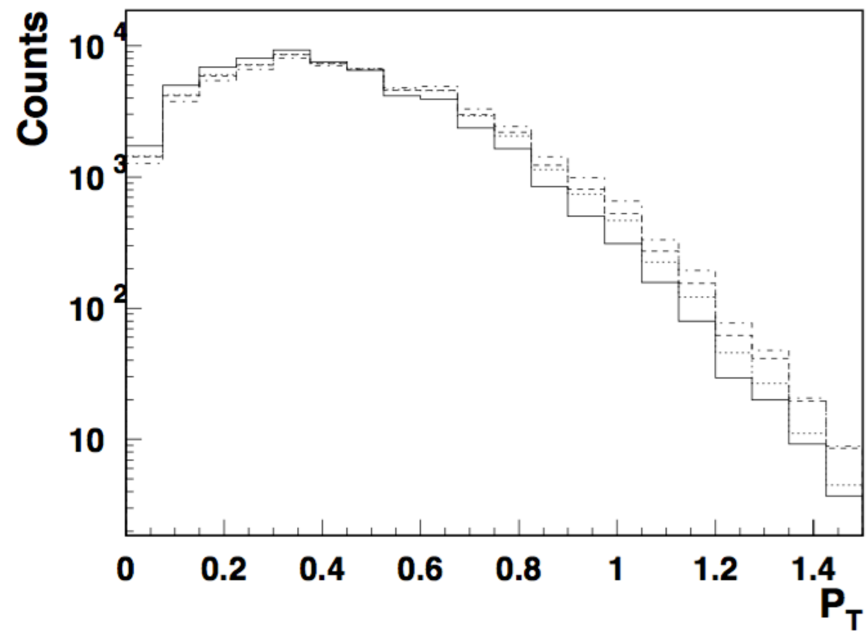
Extracting the average transverse momenta

Andrea Signori,[1,*] Alessandro Bacchetta,[2,3,†] Marco Radici,[3,‡] and Gunar Schnell[4,5,§]



$$F_{UU,T}(x,z,P_{hT}^2,Q^2) = \sum_a \mathcal{H}^a_{UU,T}(Q^2;\mu^2) \int dk_\perp \, dP_\perp \, f_1^a(x,k_\perp^2;\mu^2)\, D_1^{a\to h}(z,P_\perp^2;\mu^2)\,\delta(zk_\perp - P_{hT} + P_\perp)$$
$$+ Y_{UU,T}(Q^2,P_{hT}^2) + \mathcal{O}(M/Q).$$



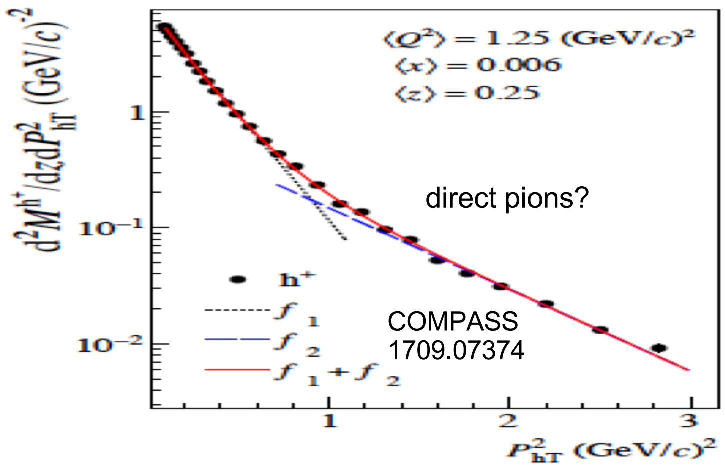


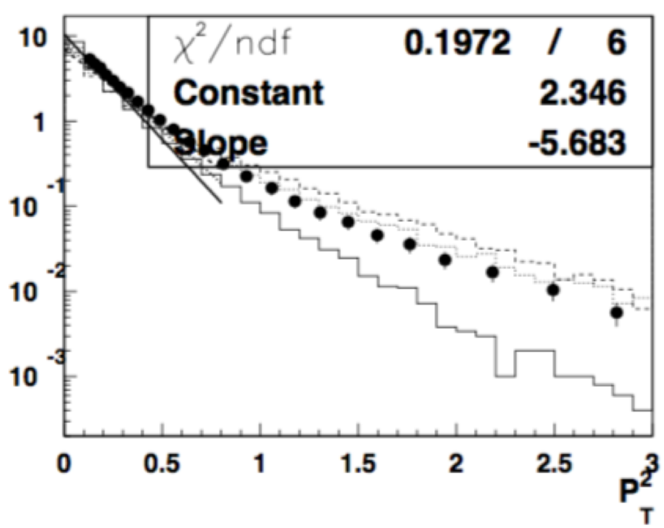
$$m_N^h(x,z,P_{hT}^2) = \frac{\pi}{\sum_a e_a^2\, f_1^a(x)}$$
$$\times \sum_a e_a^2\, f_1^a(x)\, D_1^{a\to h}(z)\, \frac{e^{-P_{hT}^2/\left(z^2\langle k_{\perp,a}^2\rangle + \langle P_{\perp,a\to h}^2\rangle\right)}}{\pi\left(z^2\langle k_{\perp,a}^2\rangle + \langle P_{\perp,a\to h}^2\rangle\right)}$$

Sea is not divided to perturbative and non-perturbative

- Extraction very sensitive to input (replicas)
- Most sensitive to parameters is the large P_T region
- Multiplicity alone may not be enough to separate $\langle k_T\rangle$ from average $\langle p_T\rangle$

Origin of non-Gaussian tails





1 hadron 2 Gausses or 1 Gauss 2 hadrons?

1) the "real" multiplicity may be lower with most hadrons produced from struck quark with large z, and low z fraction filled by VM decay pions
   - intrinsic k_T may be higher
   - the z-dependence enhanced at large z (may be tuned better to describe single and di-hadron distributions)
   - contributions to pions from target fragmentation may be less relevant

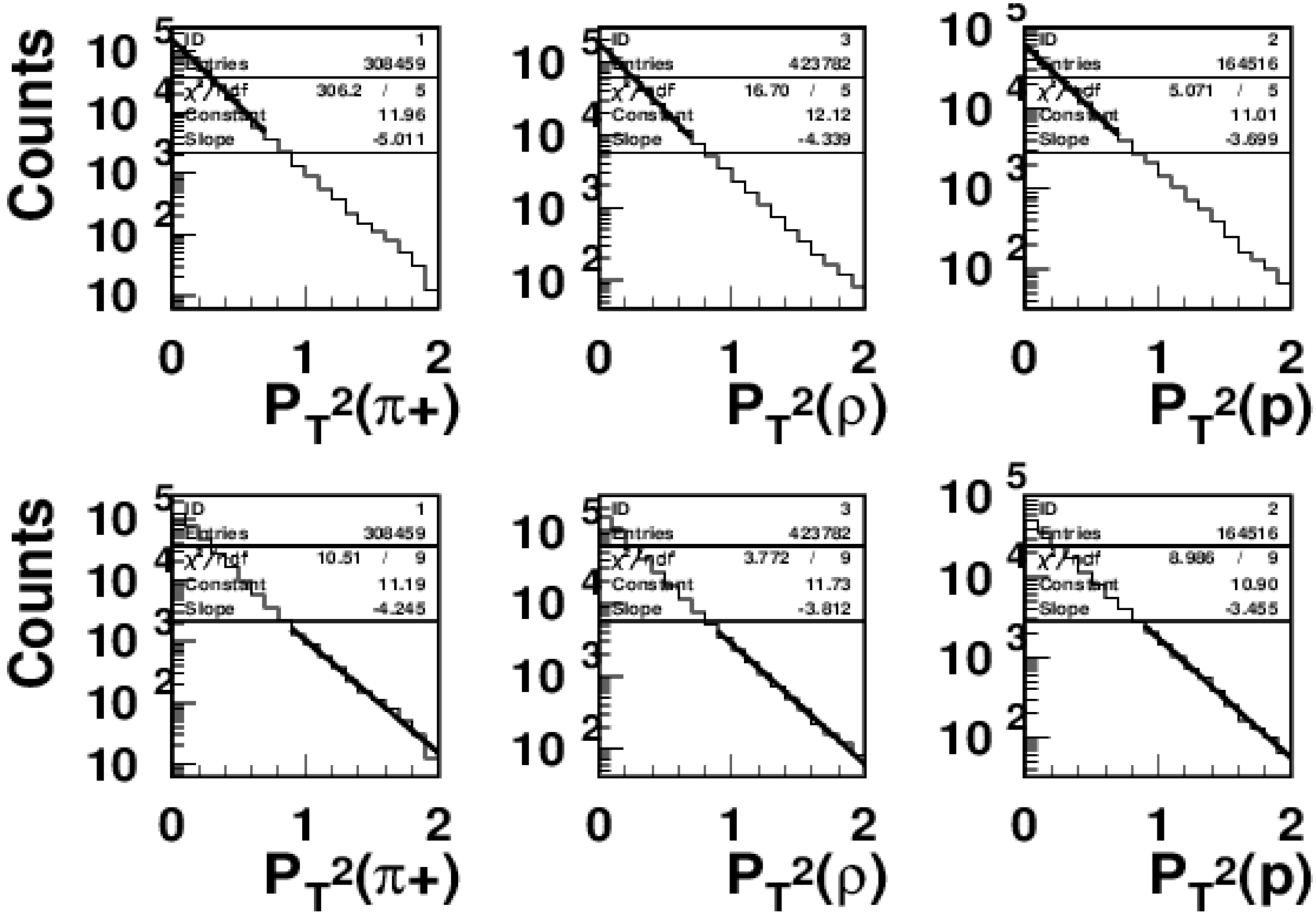
2) Combined increase of average transverse momentum and fraction of VMs allows description of non Gaussian tails at large P_T indicating most hadrons come from TMD region

Extractions of k_T-widths ignoring VMs will underestimate the $\langle k_T^2\rangle$

Accessing the k_T (JLab)

Fit $0<P_T<0.8$

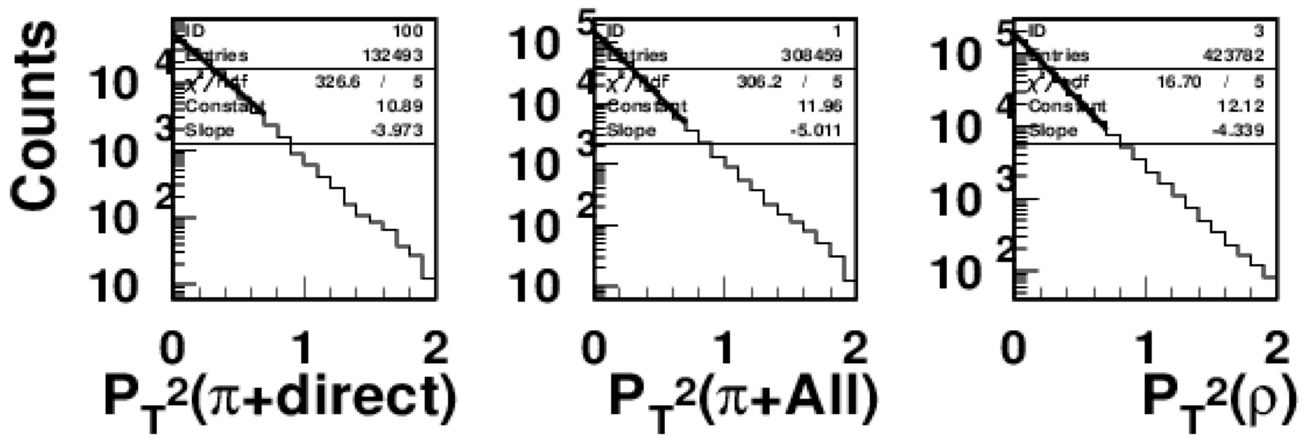
Fit $0.9<P_T<1.5$



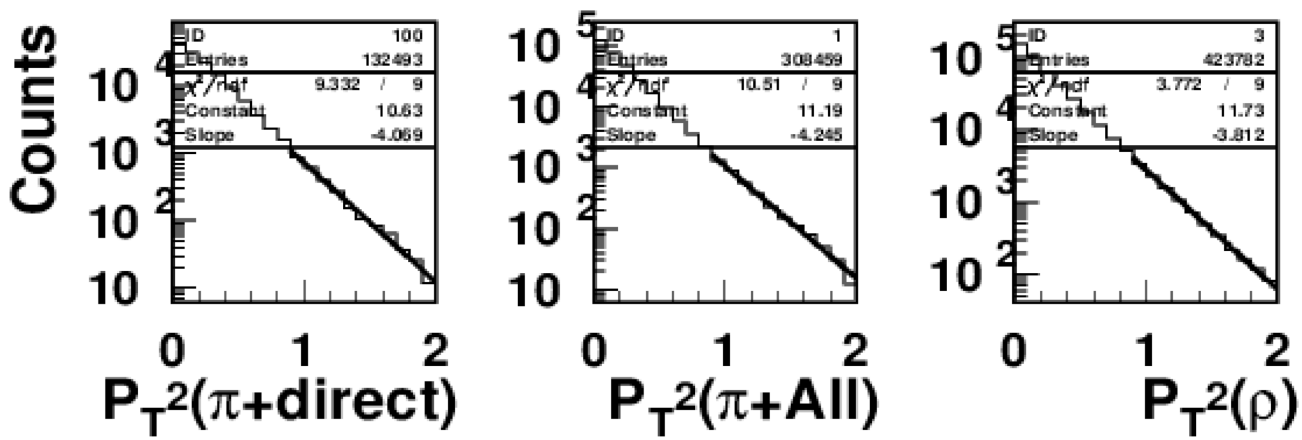
Fit to P_T gives significantly wider P_T for larger P_T pions

Accessing the k_T (JLab)

Fit $0<P_T<0.8$



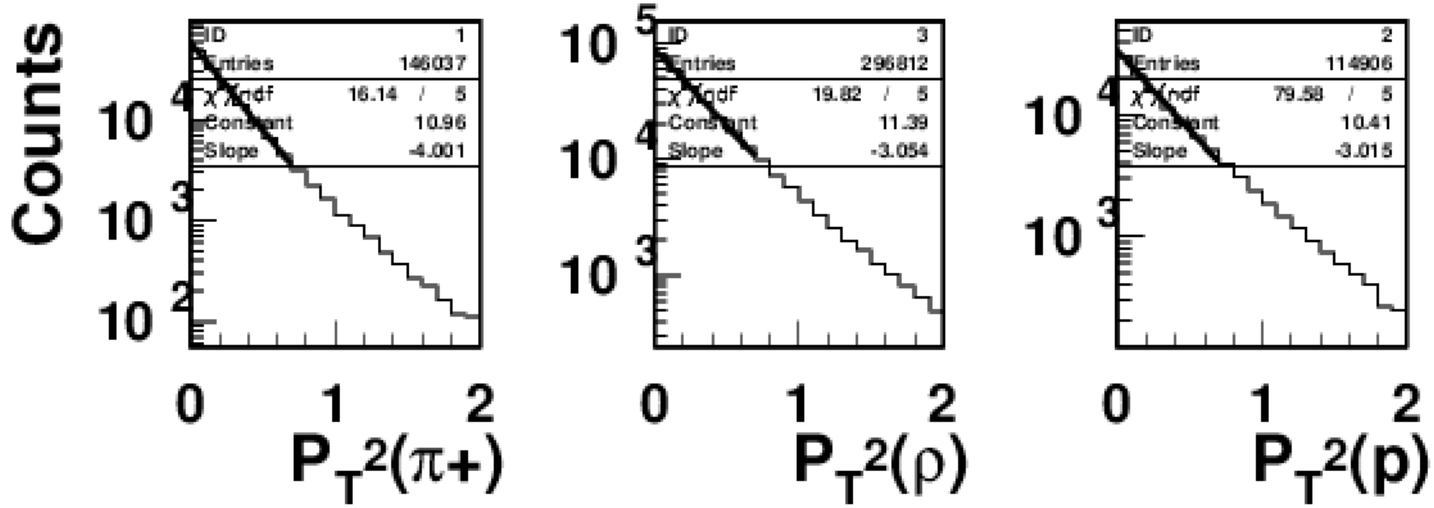
Fit $0.9<P_T<1.5$



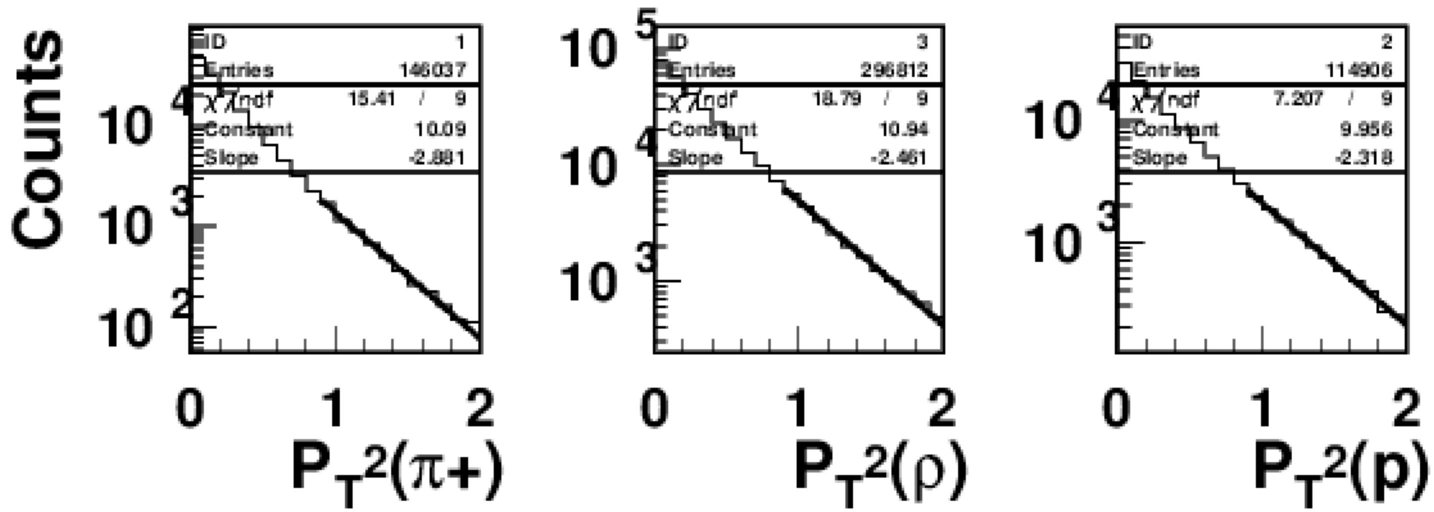
Fit to P_T gives practically the same value for direct pions, similar to one for rhos

Accessing the k_T (COMPASS)

Fit $0<P_T<0.8$



Fit $0.9<P_T<1.5$

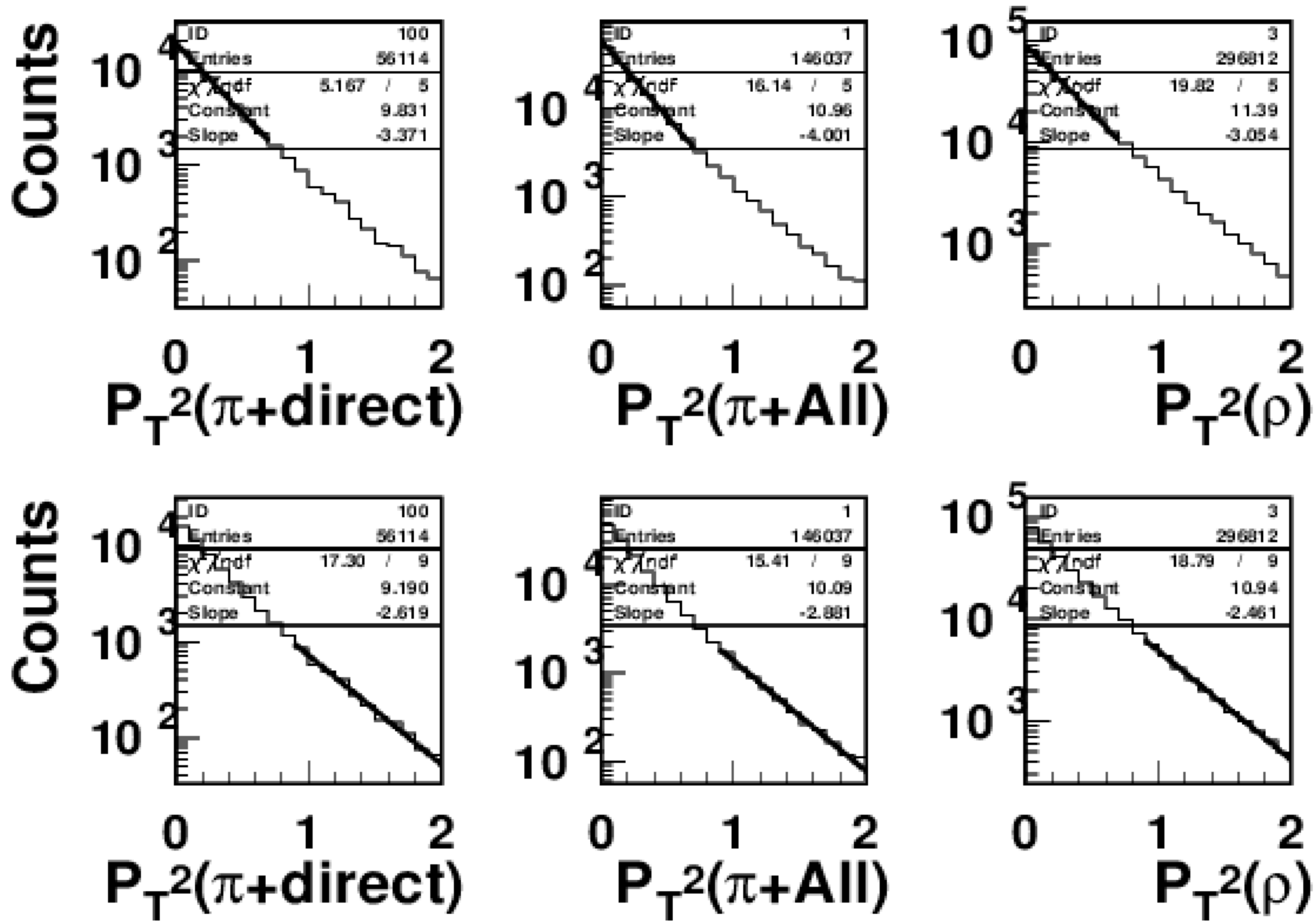


Fit to P_T gives significantly wider P_T for larger PT (bigger effect for pions)

Accessing the k_T (COMPASS)

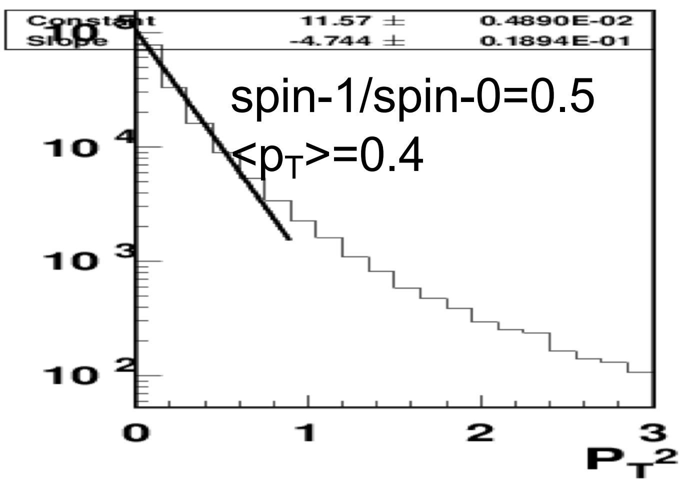
Fit $0<P_T<0.8$

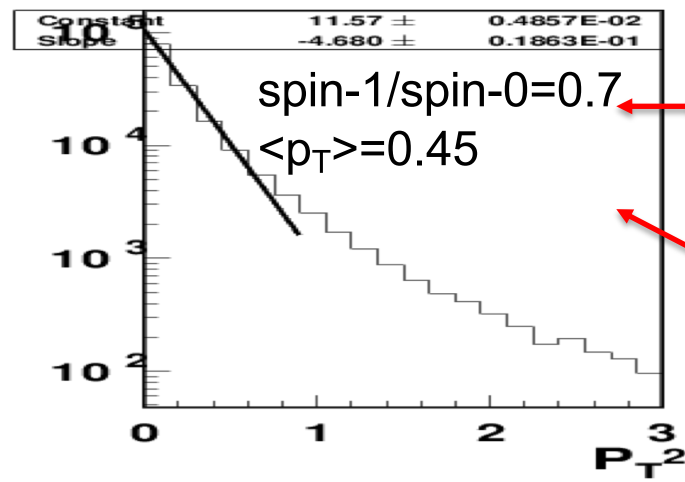
Fit $0.9<P_T<1.5$



Fit to P_T gives similar P_T for direct pions and rhos

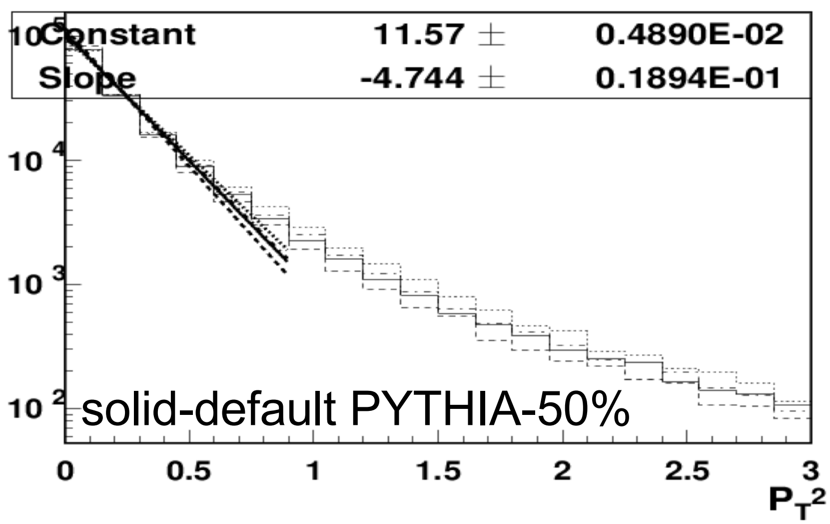
JLEIC (5x50) P_T-dependences for pions

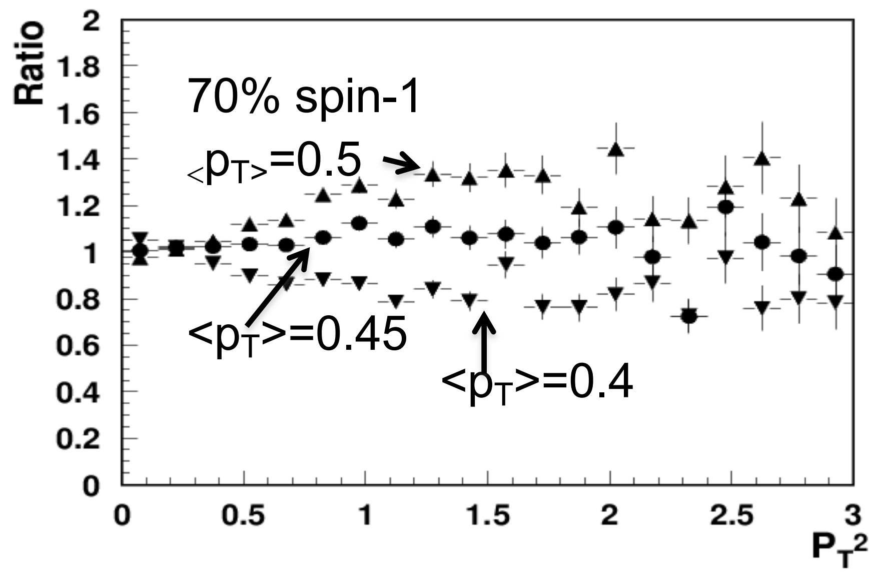




Fraction of spin-1

Intrinsic transverse momentum

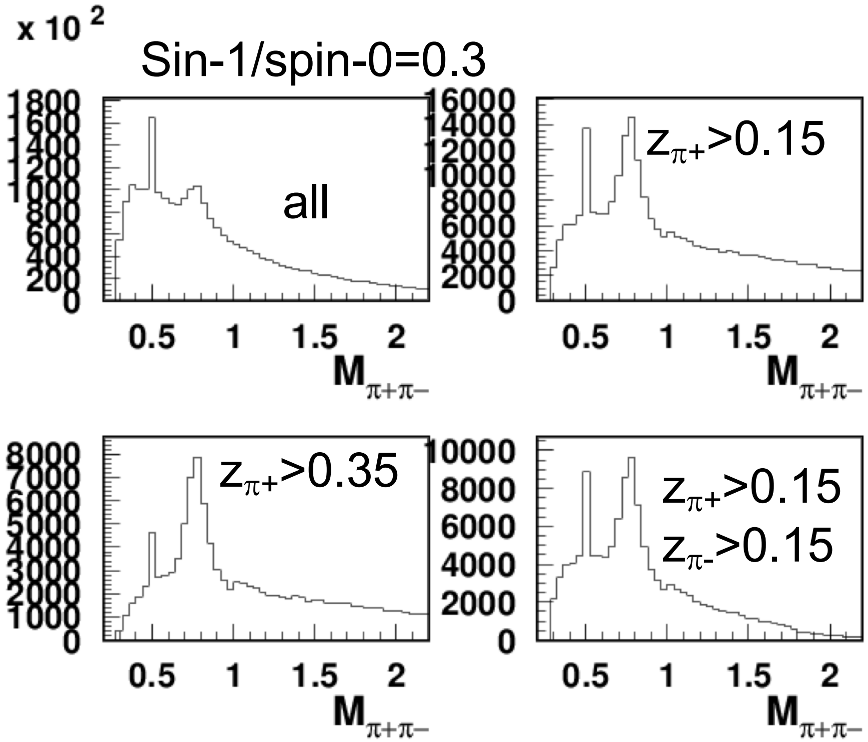


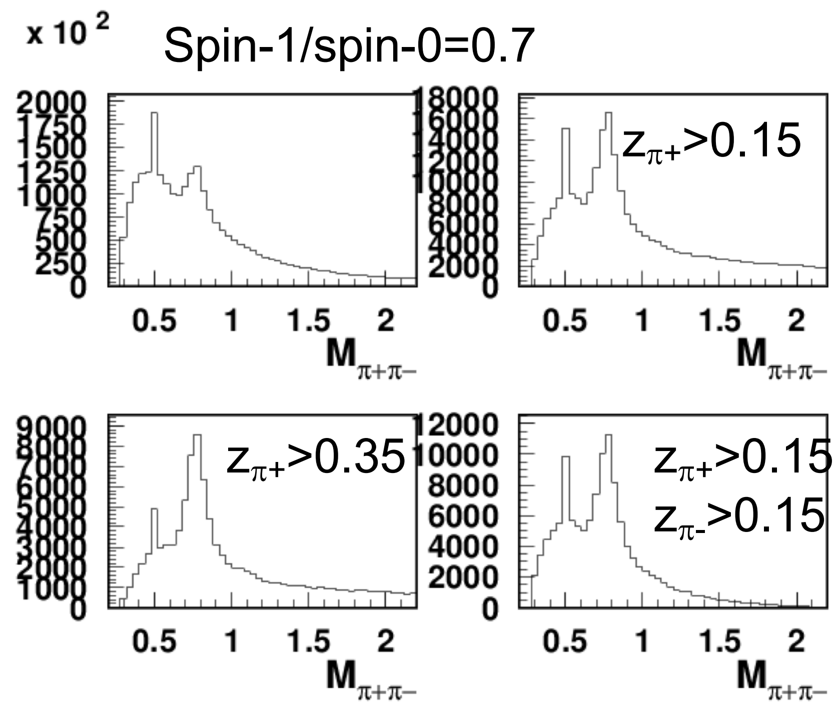


The same π+ P_T-dependence may be achieved with different initial transverse momenta

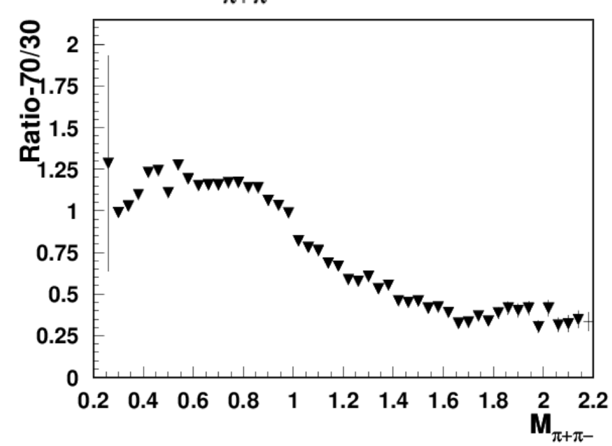
P_Ts above 0.6 most sensitive to the intrinsic k_T-distributions

JLEIC (5x50) 2-hadron mass spectra





- The rho peak is not increasing visually with increase of the fraction of VMs, as higher number of VMs create comb.bck.
- Most of the background comes from low momentum particles at large $M_{\pi\pi}$



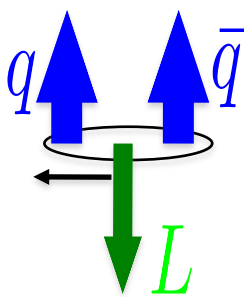
Correlated hadron production: Where it matters

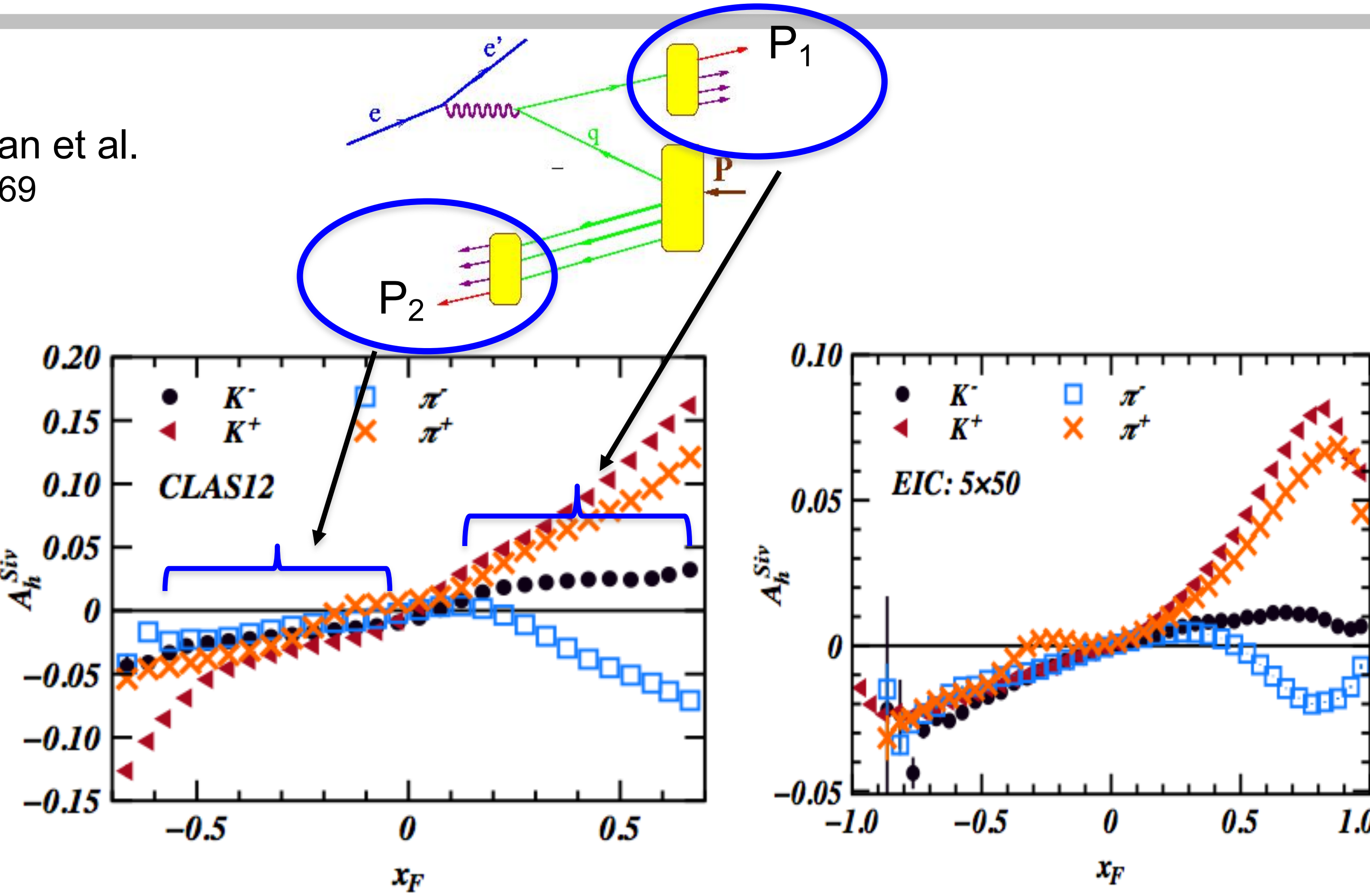
- CLAS12 data supports predictions from different MCs of a very significant fraction of inclusive pions coming from correlated dihadrons (large VM fraction supported by latest e+e- studies).

- Most pions in ehX, coming from VM decays will change:
  - account of radiative corrections will require a different set of SFs (exclusive VMs may contribute)
  - modeling of spin effects will be different (opposite sign for Collins predicted)
  - decay pions may dominate low z and low P_T
  - interpretation has to account lower P_T/z in case $z=E_h/\nu$ involves the energy of rho instead of pion
  - The range in P_T for pions will extend to higher values, than predicted from fits to data at P_T<1 GeV
  - number of e+e-/μ+μ- pairs produced in hadronization process (may be relevant for DY,W,…)

Target fragmentation: Sivers effect

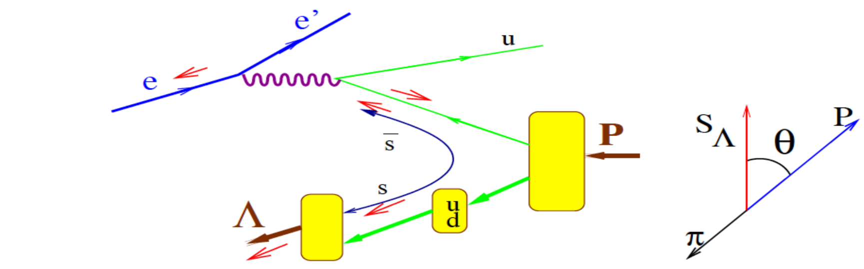
H. Matevosyan et al.
arXiv:1502.02669



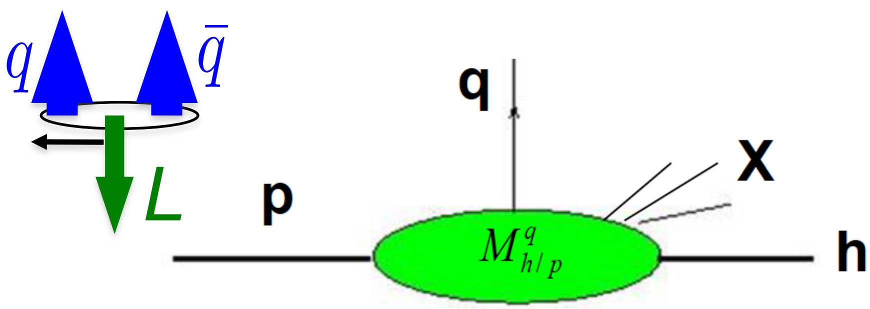


Wide coverage of CLAS12 and EIC will allow studies of kinematic dependences of the Sivers effect, both in current and target fragmentation regions

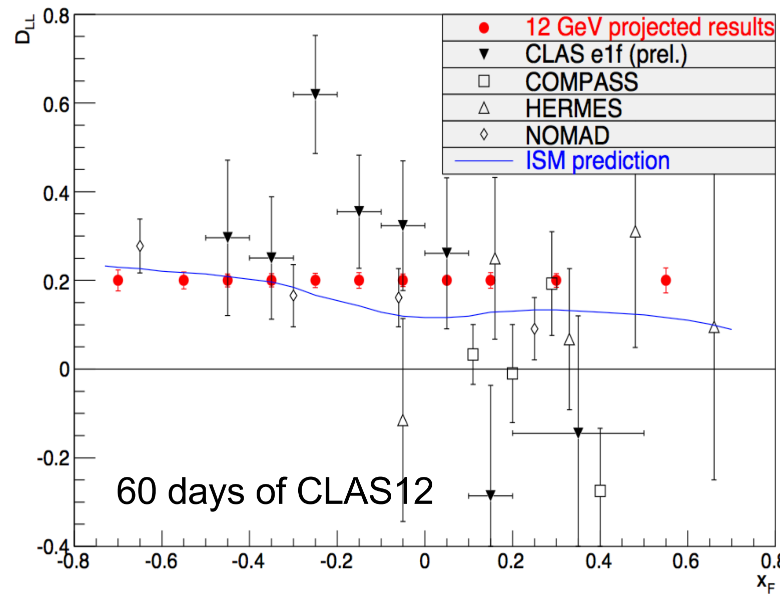
Target fragmentation region: Λ production



$$D^{LL} = \frac{\sum_a e_a^2 \Delta M^L}{\sum_a e_a^2 M}$$



polarization transfer coefficient



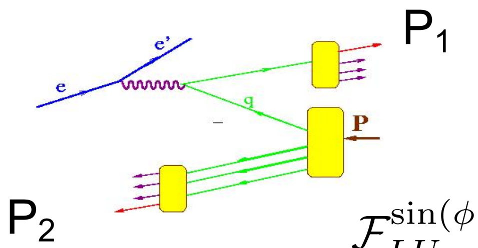
probability to produce the hadron h when a quark q is struck in a proton target

Measurements of fracture functions opens a new avenue in studies of the structure of the nucleon in general and correlations between current and target fragmentation in particular

$$A_{LUL}^{TFR} = hS_{\parallel}\frac{y\left(1-\frac{y}{2}\right)\sum_a e_a^2 \Delta M^L}{\left(1-y+\frac{y^2}{2}\right)\sum_a e_a^2 M}$$

- Large acceptance of CLAS12 and EIC provide a unique possibility to study the nucleon structure in target fragmentation region
- First measurements already performed using the CLAS data at 6 GeV.

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

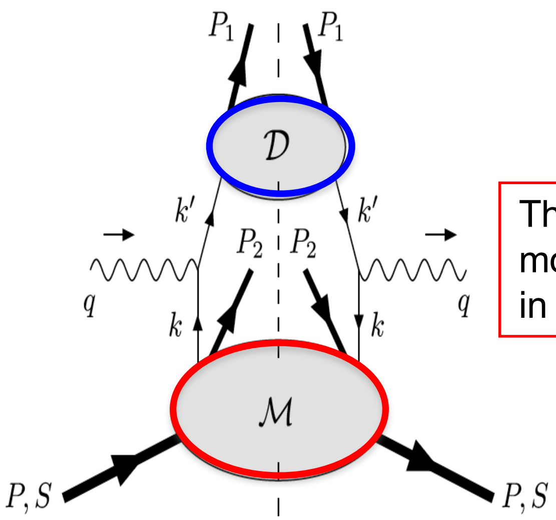


M. Anselmino, V. Barone and A. Kotzinian, Physics Letters B 713 (2012)

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

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.

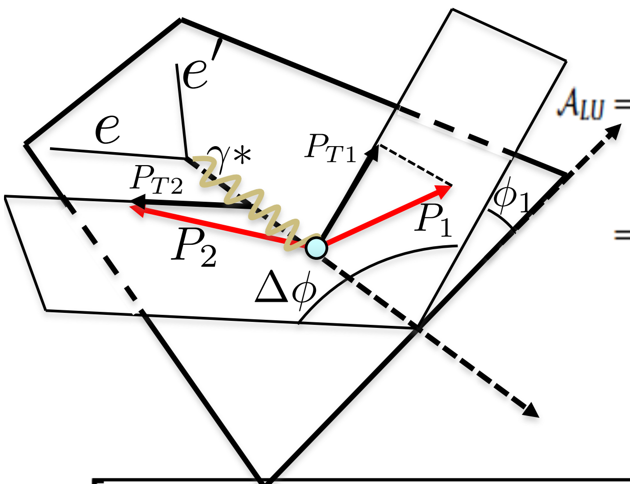
$$\mathcal{A}_{LU} = -\frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)}\frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}}\sin\Delta\phi$$

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)
- ...

B2B hadron production in SIDIS: First measurements

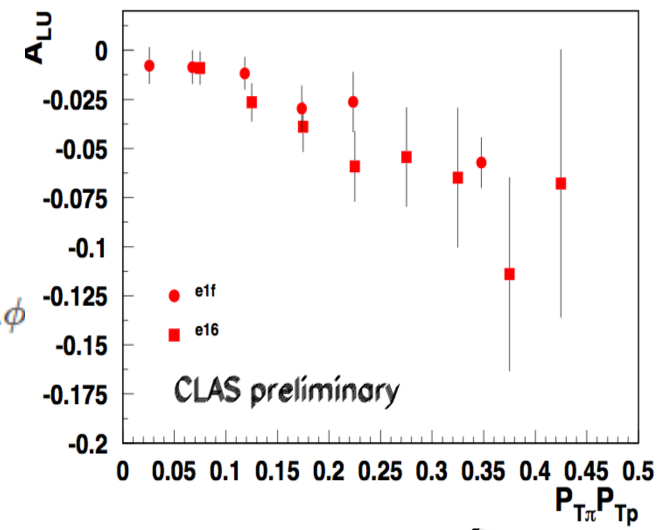
M. Anselmino, V. Barone and A. Kotzinian,
Physics Letters B 713 (2012)

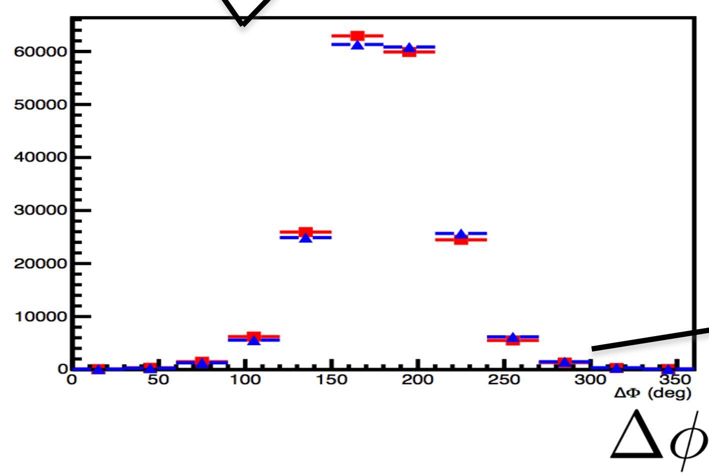
$$ep \longrightarrow e' p \pi^+ X$$

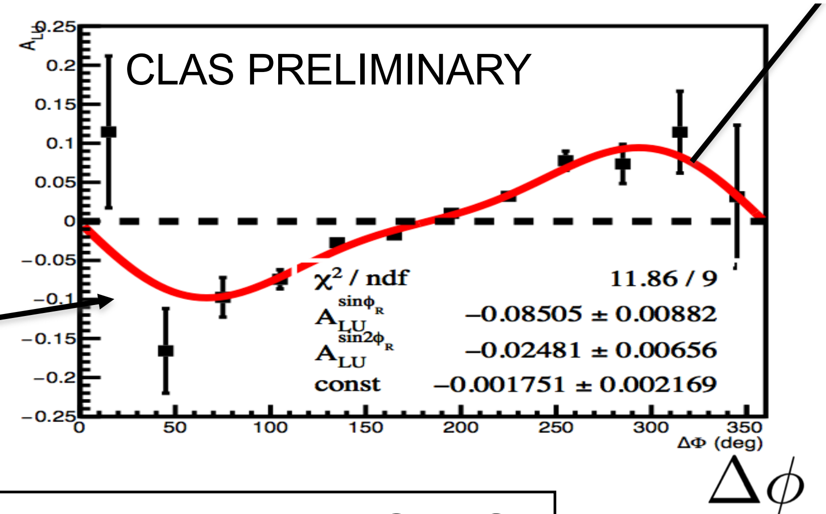


$$A_{LU} = -\frac{y(1-\frac{y}{2})}{(1-y+\frac{y^2}{2})}\frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}}\sin\Delta\phi$$

$$= -\frac{|\boldsymbol{P}_{1\perp}||\boldsymbol{P}_{2\perp}|}{m_N m_2}\frac{y(1-\frac{y}{2})}{(1-y+\frac{y^2}{2})}\frac{\mathcal{C}[w_5 M_L^{\perp,h} D_1]}{\mathcal{C}[MD_1]}\sin\Delta\phi$$







Significant correlation asymmetries observed by CLAS will be extended to CLAS12 and possibly EIC

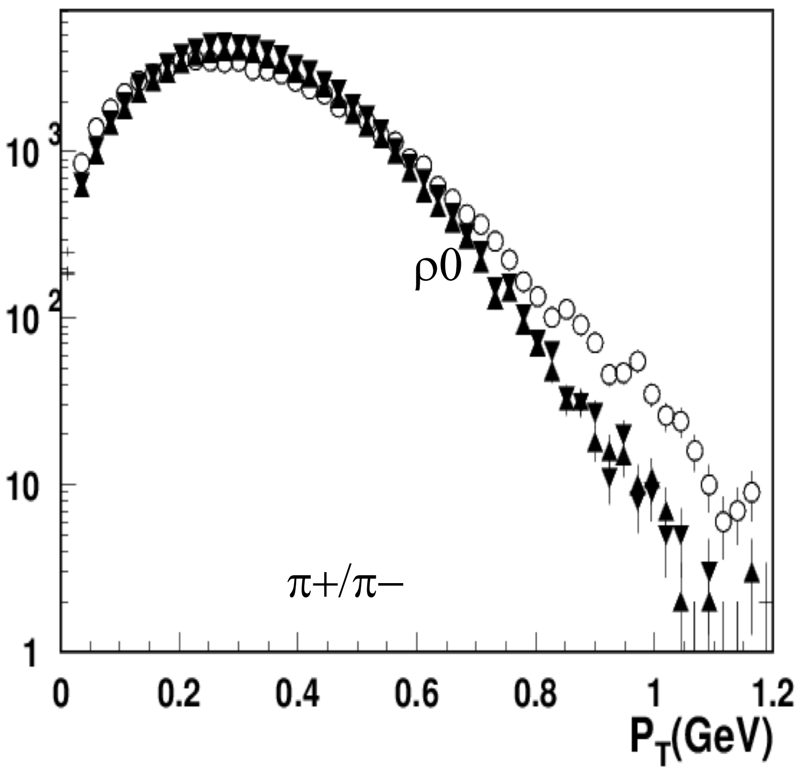
SUMMARY

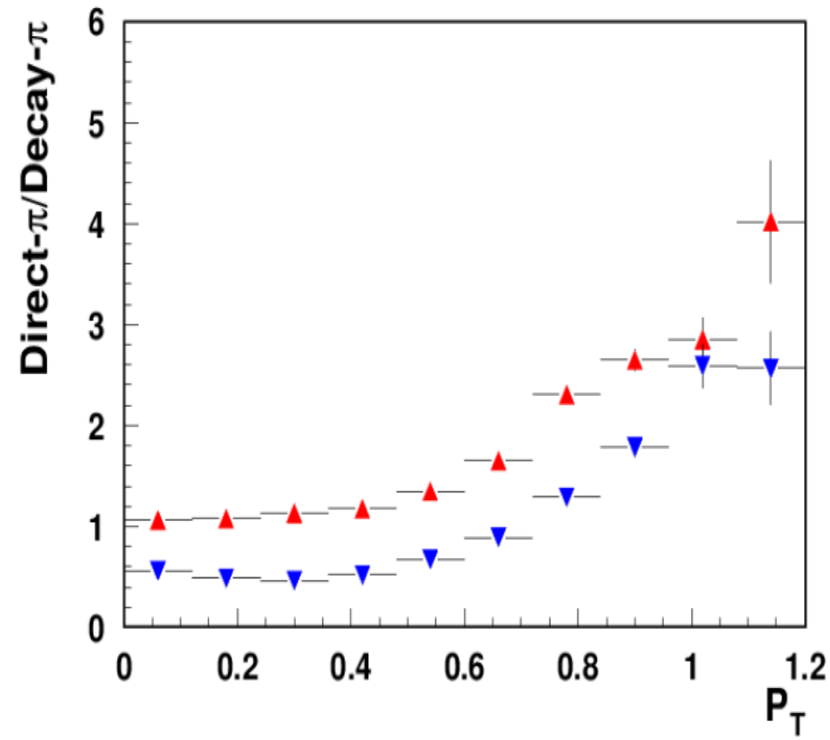
- LUND-MC describes well the data in a full accessible energy range (Jlab/COMPASS/EMC) and can be used to test methods to study the k_T-structure
- The CLAS12 data supports predictions from different MCs of a very significant fraction of inclusive pions coming from correlated dihadrons.
- Higher fraction of hadrons with spin-1 vs spin-0 in hadronization will have a number of implications and may <u>require different RC, modeling, and interpretation</u>
- Modeling of spin-orbit correlation will help to understand the dynamics and define the regions where independent fragmentation is most applicable
- <u>Overlap in kinematics for EIC (large x, Q^2<100-200 challenging) with JLab12 well as with COMPASS and DY will be critical for interpretation of data</u>

- The interpretation of di-hadron production in SIDIS, as well as interpretation of single-hadron production, the independent fragmentation, in particular, are intimately related to contributions to those samples from correlated semi-inclusive and exclusive di-hadrons in general, and rho mesons, in particular.
- Target fragmentation may provide important complementary information on the 3D structure

Support slides

P_T of pions from rho decays: LUND string fragmentation

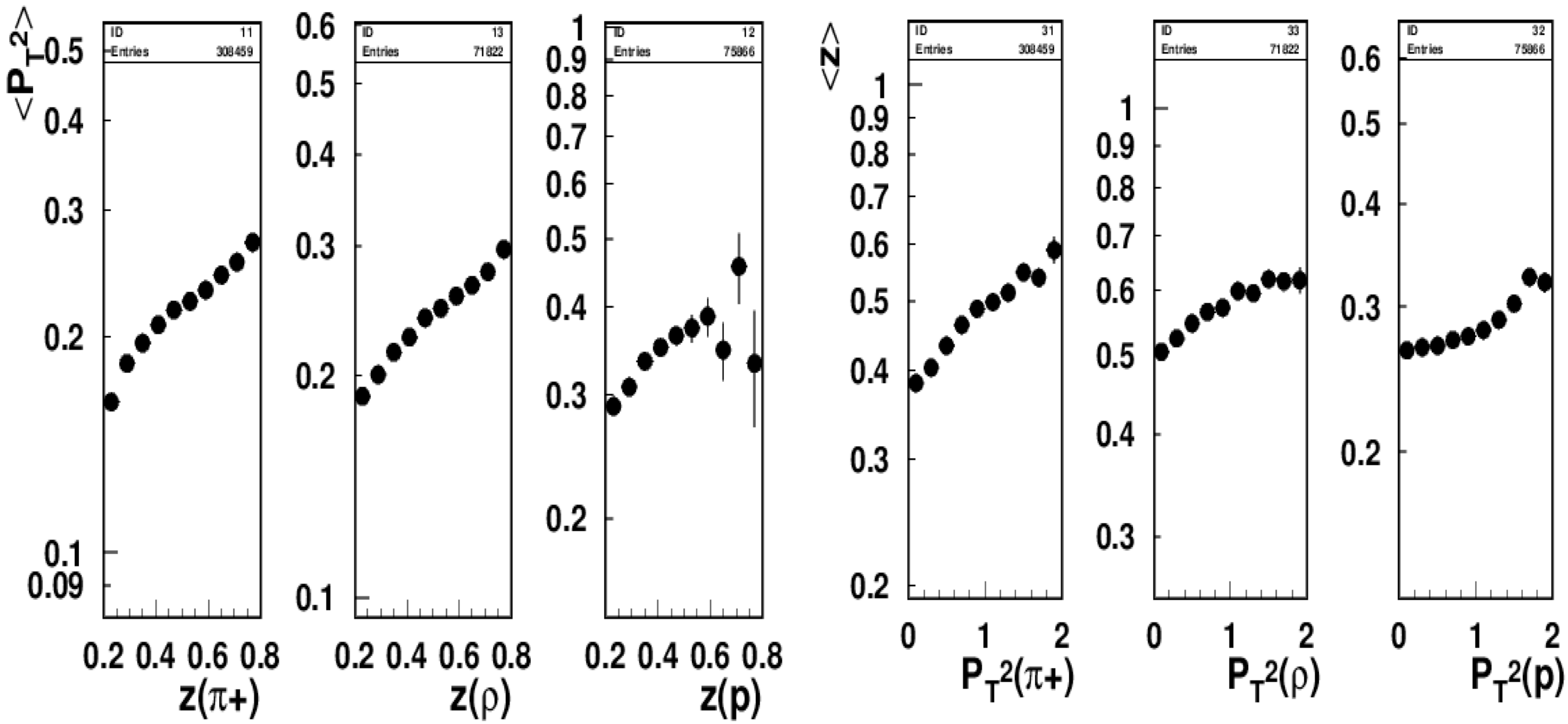




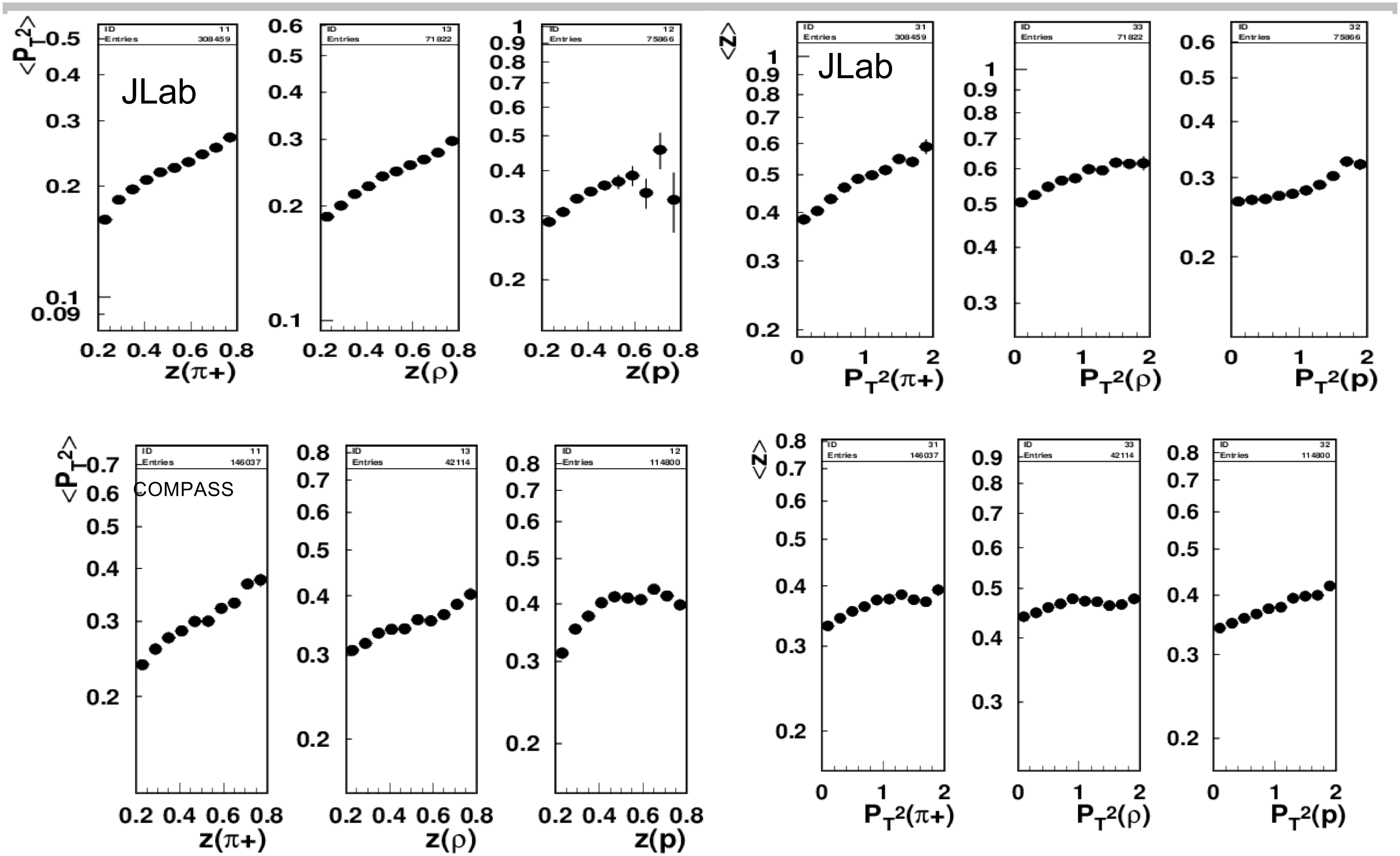
P_T-dependence of rho is similar to the one for decay pions

Fraction of direct $\pi+$ increases with P_T

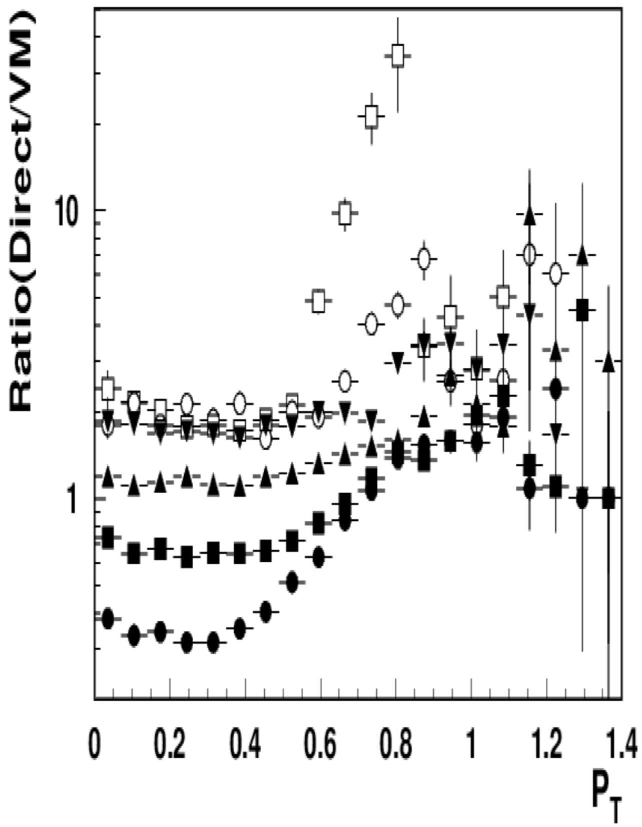
Kinematical averages (JLab)

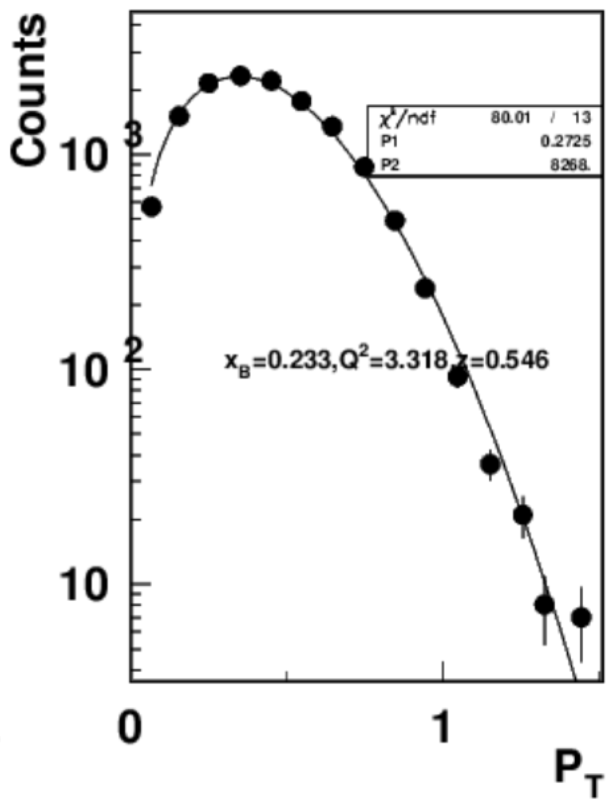


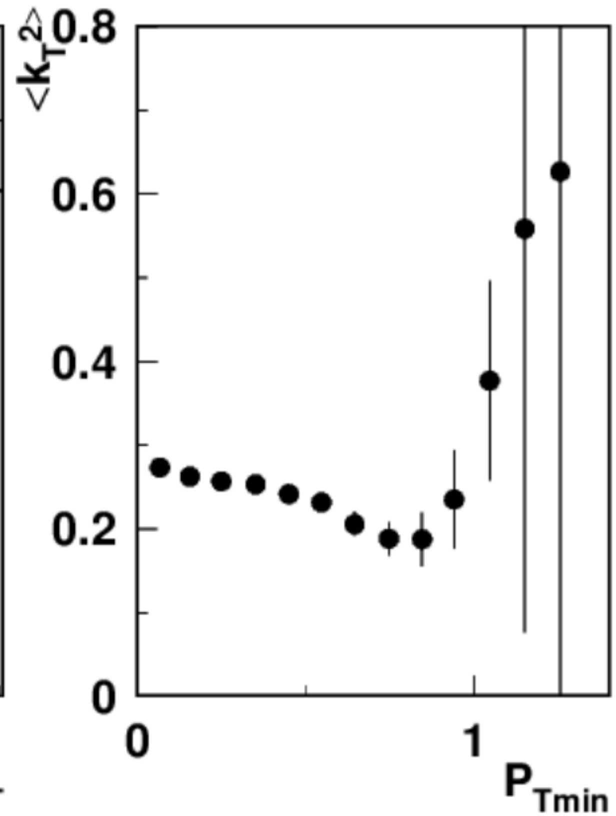
Kinematical averages (Jlab vs COMPASS)



Accessing the kT







Higher PT, closer tooriginal distribution for pions

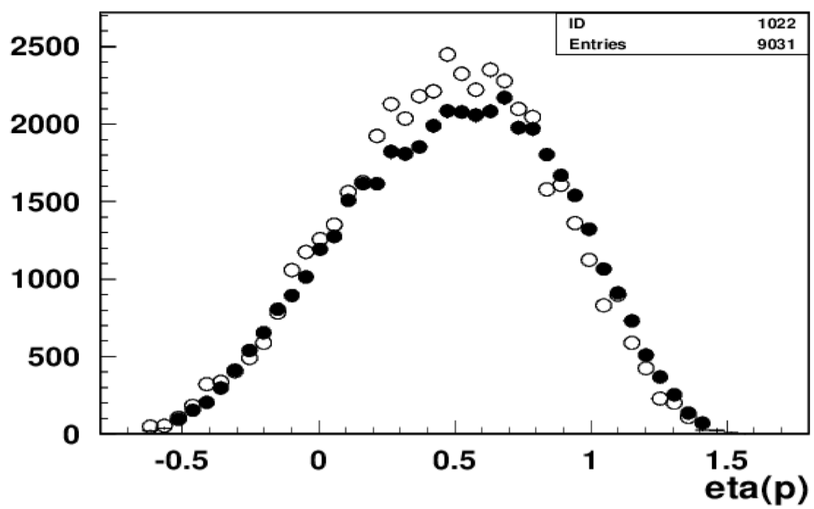
Fit with a single Gauss, starting from some Ptmin
Higher Ptmin less the decay fraction, closer to original k_T-width of distribution for pions

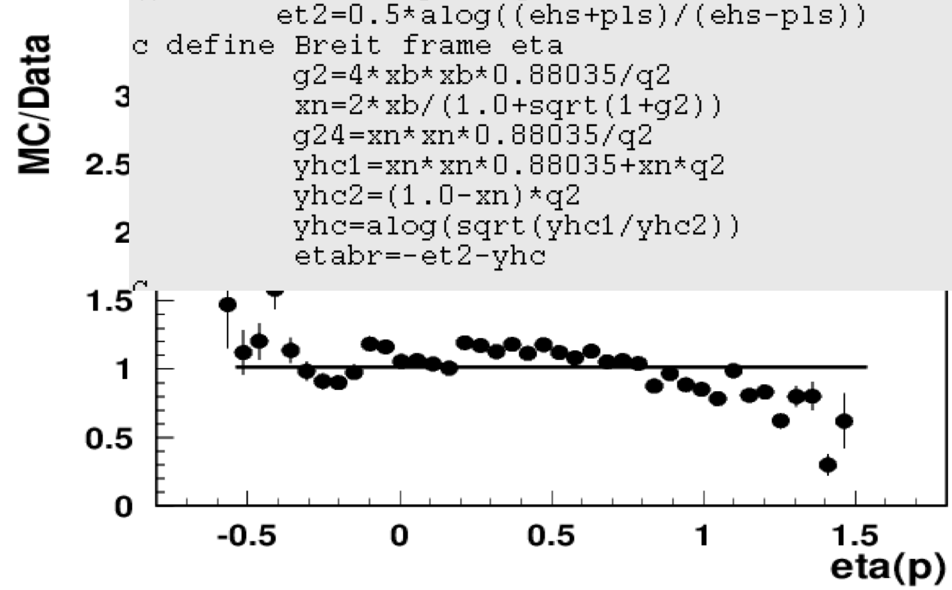
CLAS12 Studies

Using PEPSI (LUND) generator rapidity in Breit frame

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

$$y^{\pm}_{\mathrm{B,b}} = \ln\left[\frac{Q z_{\mathrm{h}}\left(Q^2 - x_{\mathrm{N}}^2 M_p^2\right)}{2x_{\mathrm{N}}^2 M^2 M_{\mathrm{B,T}}} \pm \frac{Q}{x_{\mathrm{N}} M}\sqrt{\frac{z_{\mathrm{h}}^2\left(Q^2 - x_{\mathrm{N}}^2 M^2\right)^2}{4x_{\mathrm{N}}^2 M^2 M_{\mathrm{B,T}}^2} - 1}\,\right] \approx \ln\left(\frac{M_{\mathrm{B,T}}}{z_{\mathrm{h}} Q}\right)$$





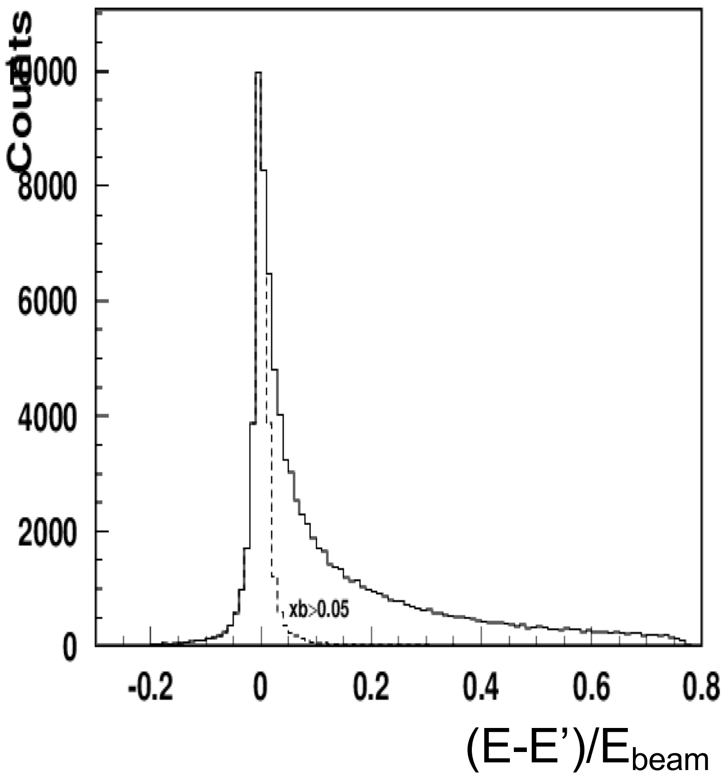

```
c        ptrann=pts
^        xfhad=2*pls/sqrt(ww2)
         et2=0.5*alog((ehs+pls)/(ehs-pls))
c define Breit frame eta
          g2=4*xb*xb*0.88035/q2
          xn=2*xb/(1.0+sqrt(1+g2))
          g24=xn*xn*0.88035/q2
          yhc1=xn*xn*0.88035+xn*q2
          yhc2=(1.0-xn)*q2
          yhc=alog(sqrt(yhc1/yhc2))
          etabr=-et2-yhc
```

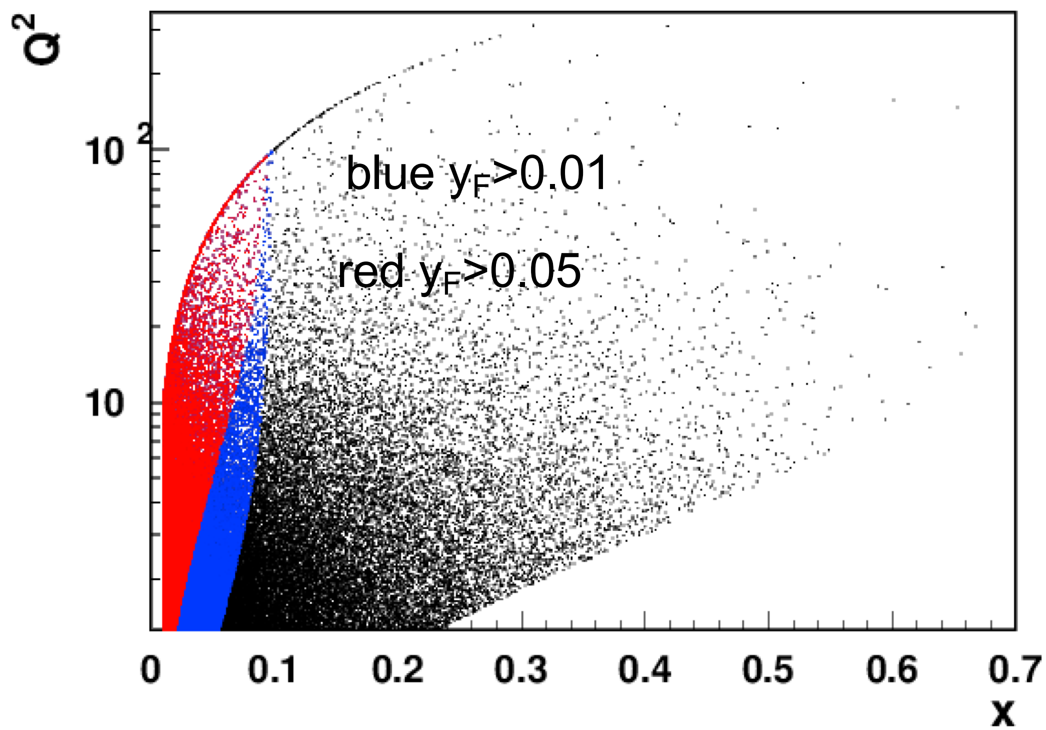
Multiliplicity of protons vs rapidity in good agreement with JETSET in most of the kinematics

Low Q2 events for evolution studies

EIC 5x41

Large x events all in region of small y_F=1.0-E'/Ebeam





- Small phase space for radiation, as E and E' roughly equal
- Large x are washed out with y cut

RC in the low y region (large x and low Q2)

$$r_c(y) = \frac{\mathrm{d}\sigma/\mathrm{d}y|_{O(\alpha)}}{\mathrm{d}\sigma/\mathrm{d}y|_{Born}} - 1$$

EIC-white-paper.1108.1713

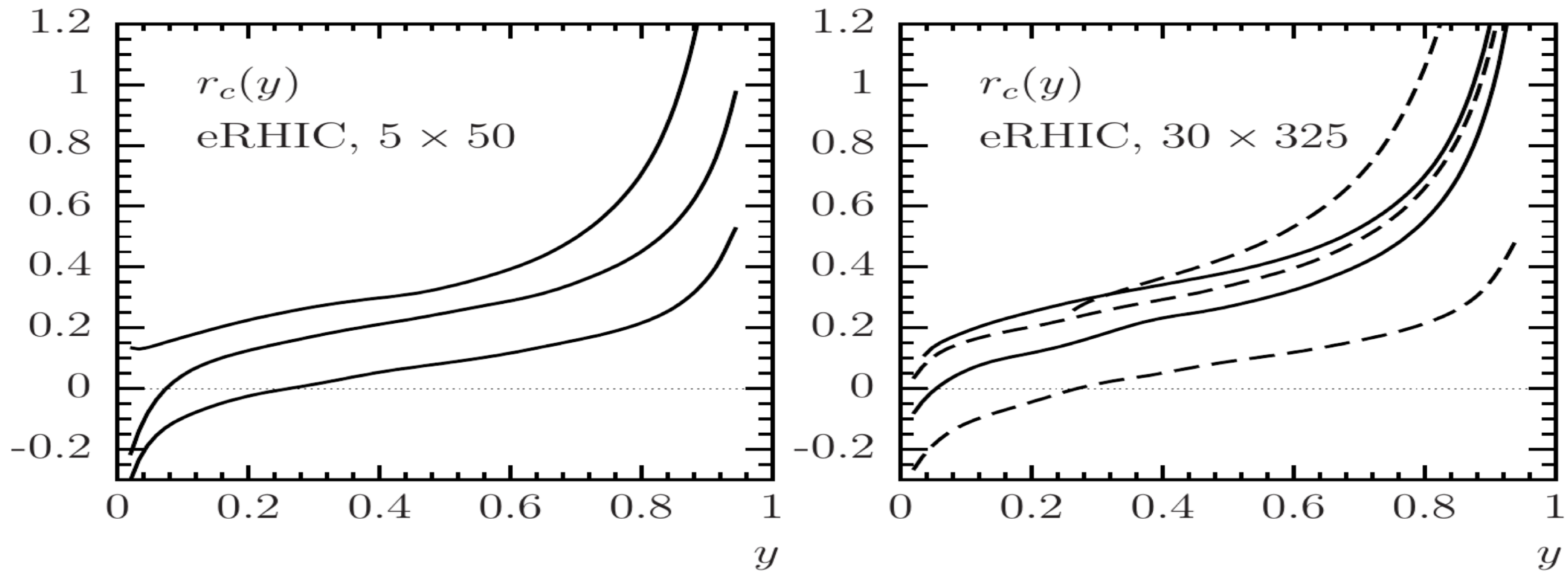
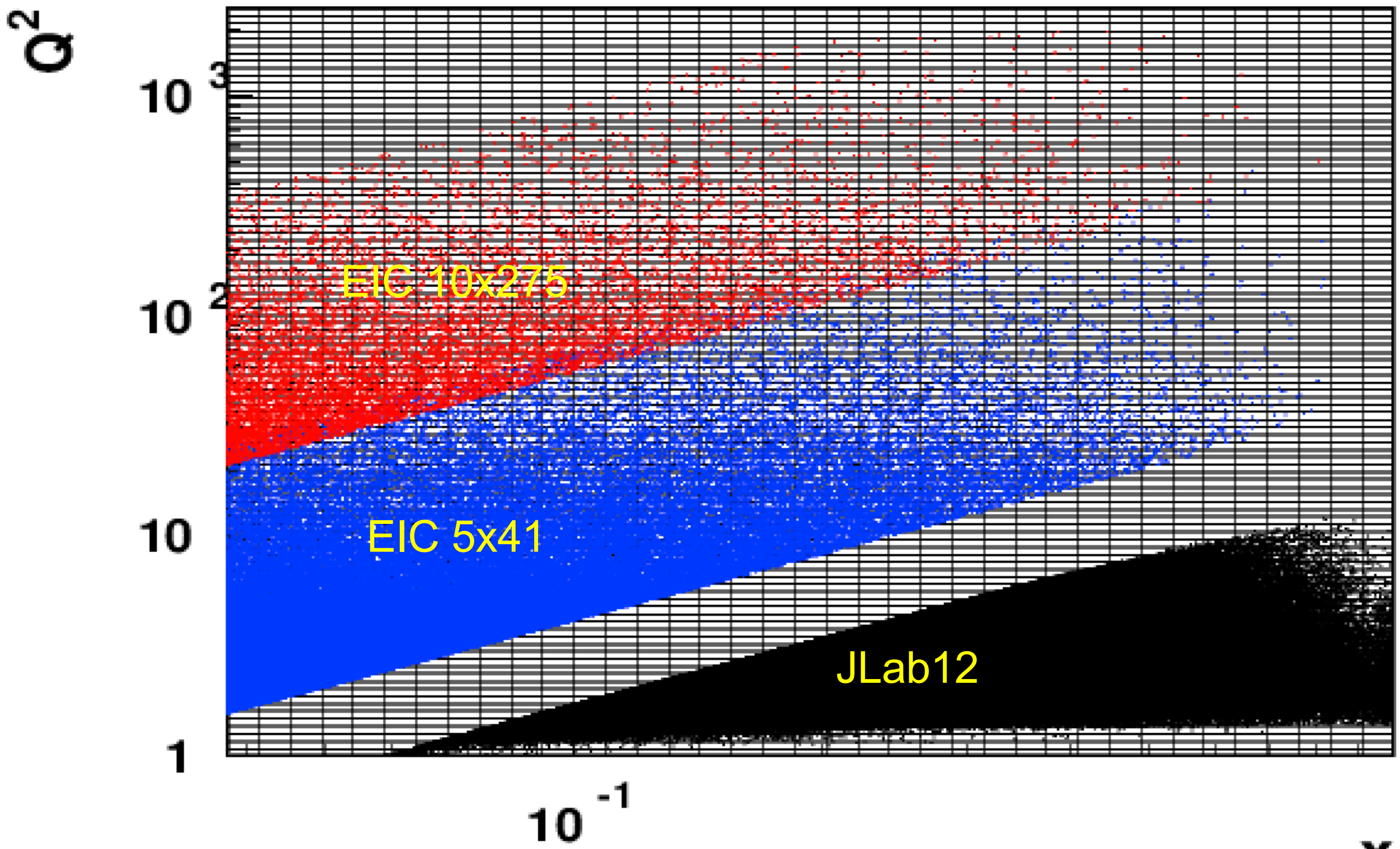


Figure 7.25. y-dependence of the leptonic radiative correction factor for electron proton scattering with different beam energies and in different x_B ranges. Left: $E_e = 5$ GeV, $E_p = 30$ GeV and the curves from the bottom up correspond to $0.1 < x_B < 0.4$, $10^{-2} < x_B < 10^{-1}$, $10^{-3} < x_B < 10^{-2}$; Right: $E_e = 30$ GeV, $E_p = 325$ GeV and $0.1 < x_B < 0.4$, $10^{-2} < x_B < 10^{-1}$, $10^{-3} < x_B < 10^{-2}$, $10^{-4} < x_B < 10^{-3}$, $10^{-5} < x_B < 10^{-4}$ (full and dashed lines alternating for better visibility).

What are the RC in the region of y<0.05 (x>0.02) for SIDIS case ?

X vs Q2 from Jlab to EIC

The same binning covers JLab and EIC



y_{min}>0.05

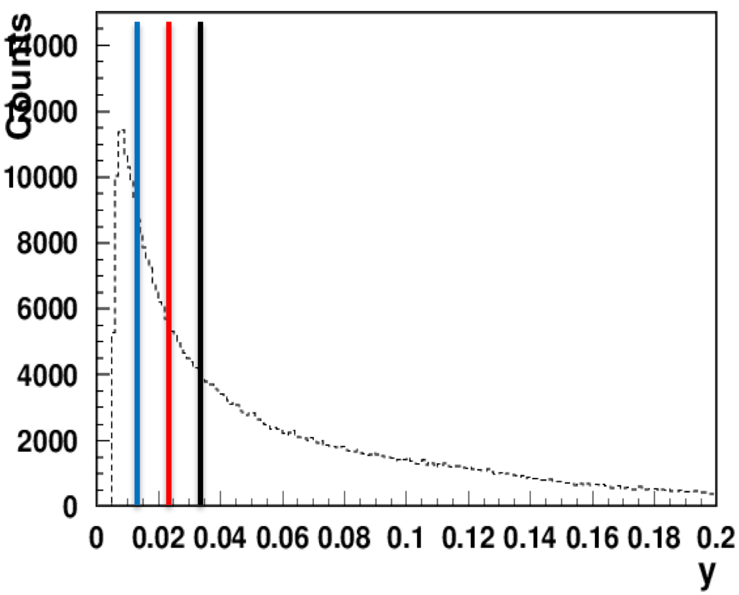
Non overlapping ranges of EIC and Jlab may be a problem for evolution studies, which are most critical for the 3D structure (to be checked)

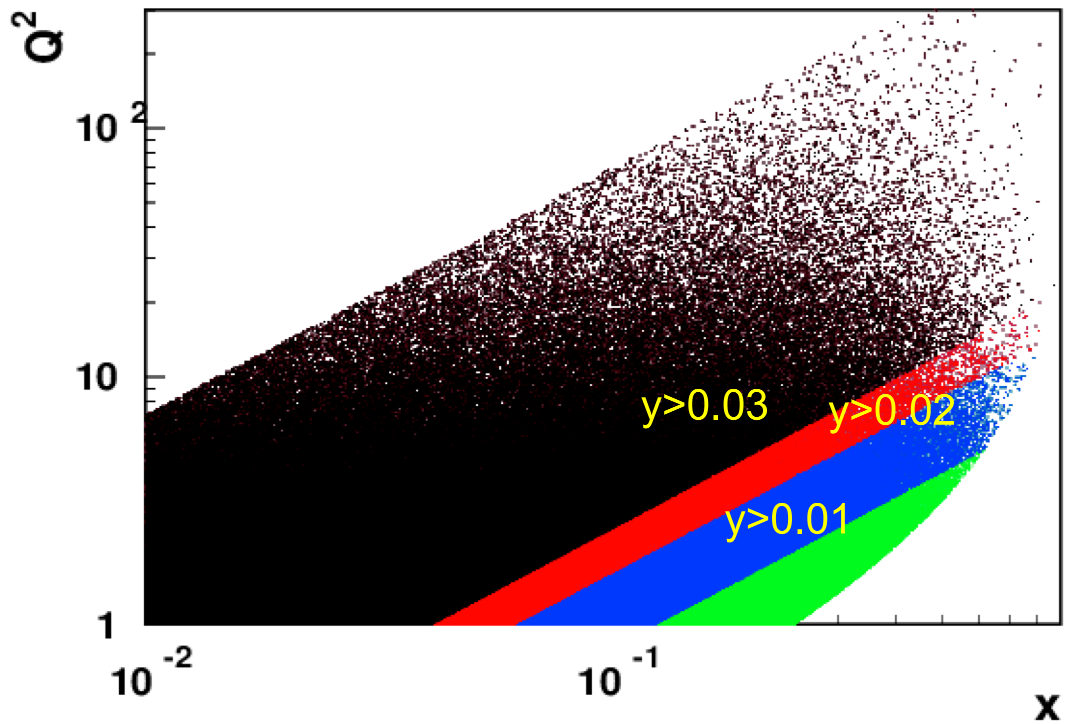
Low Q^2 and large x kinematics in EIC

The same binning covers JLab and EIC

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

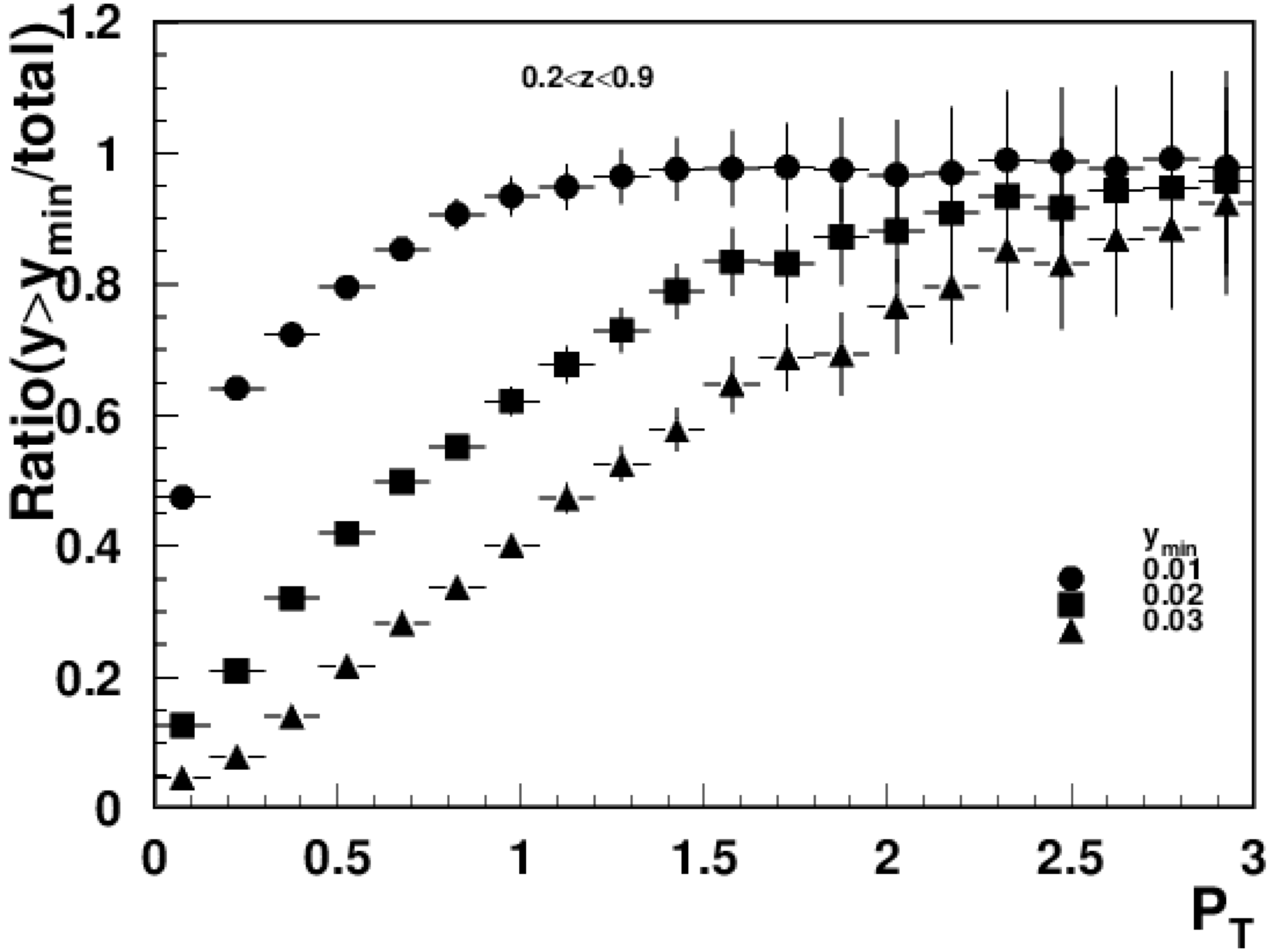
EIC 5x41





Small y are critical to access wide range in Q^2 for large x, where the non-perturbative effects are relevant (electron kinematics not well defined)

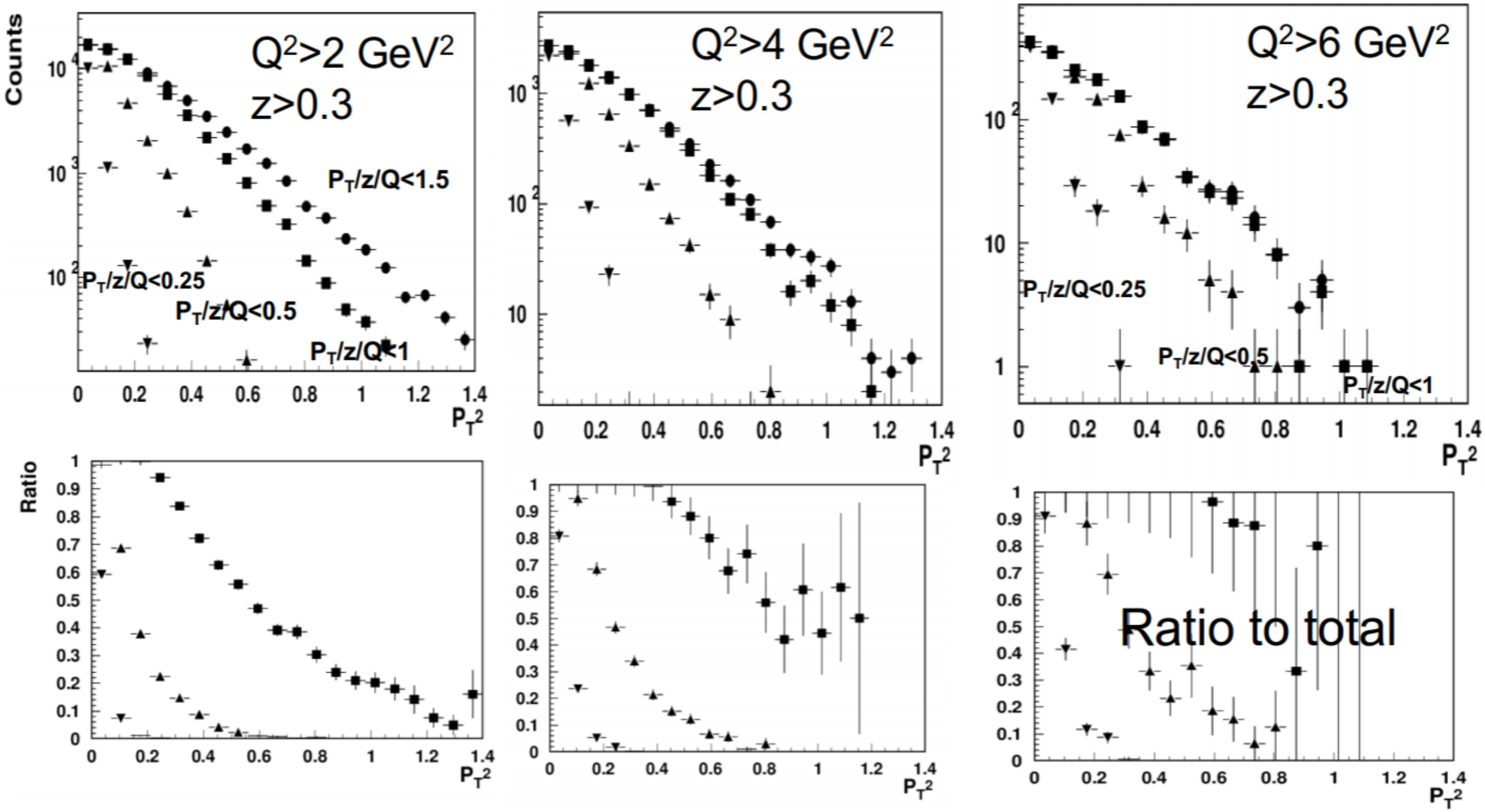
Low Q^2 and large x kinematics in EIC: P_T-distributions



EIC 5x41
x>0.01

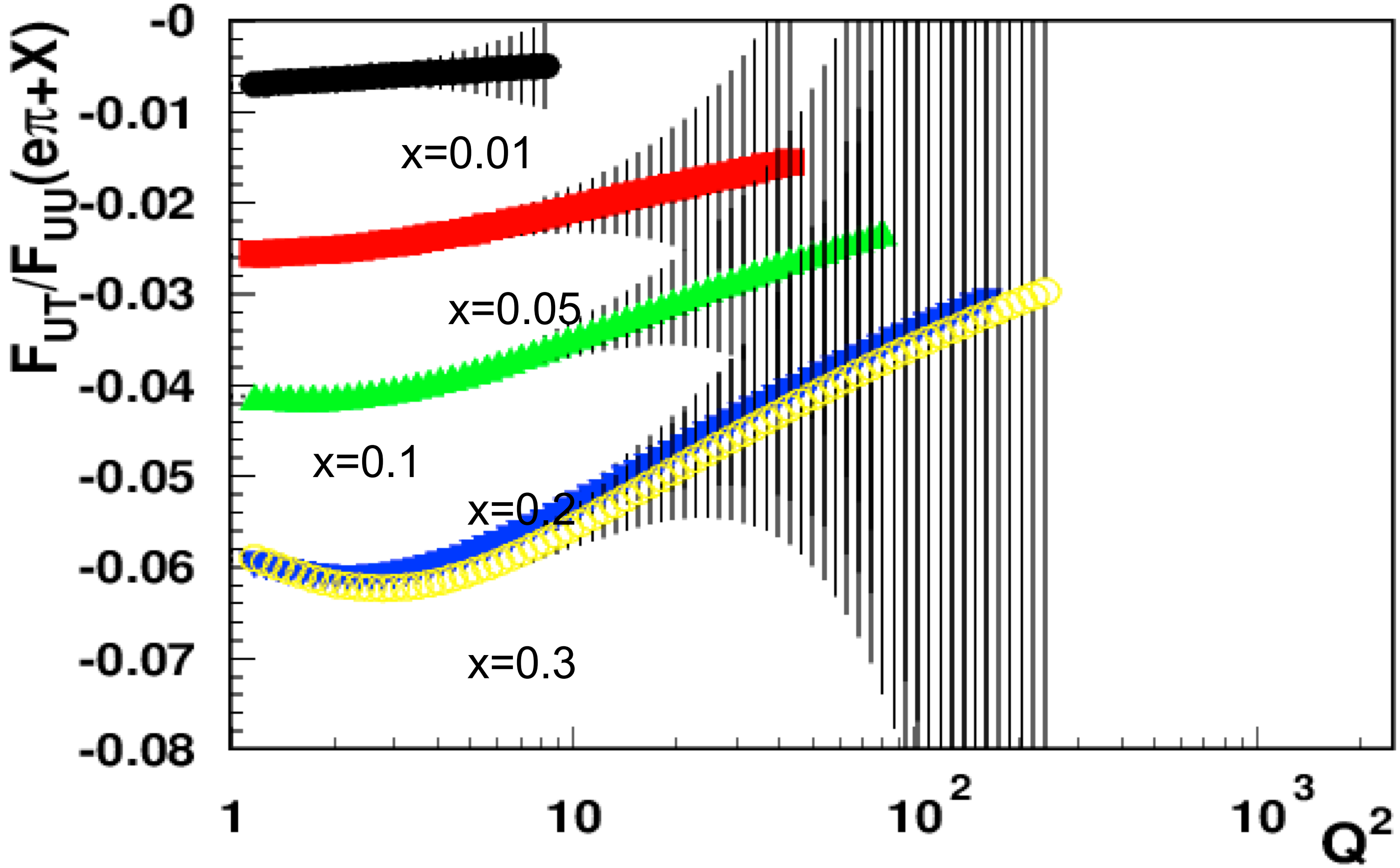
For large x(x>0.05) large y cuts can significantly change P_T-distributions

JLab12: SIDIS and $P_T/z/Q$ cuts



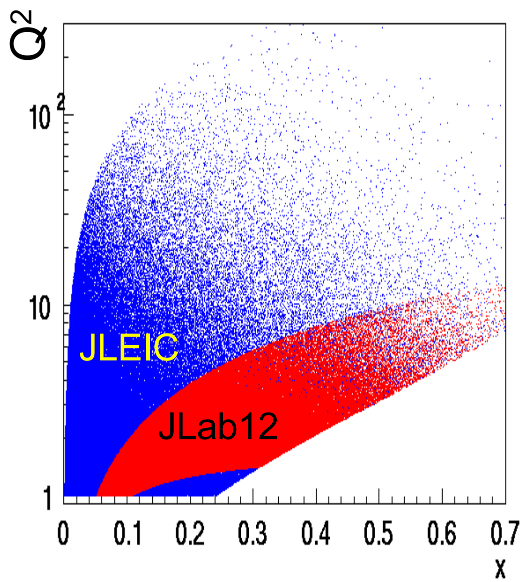
Lower cuts on $P_T/(zQ)$ eliminate all events except few coming from VM decays (very low P_T)

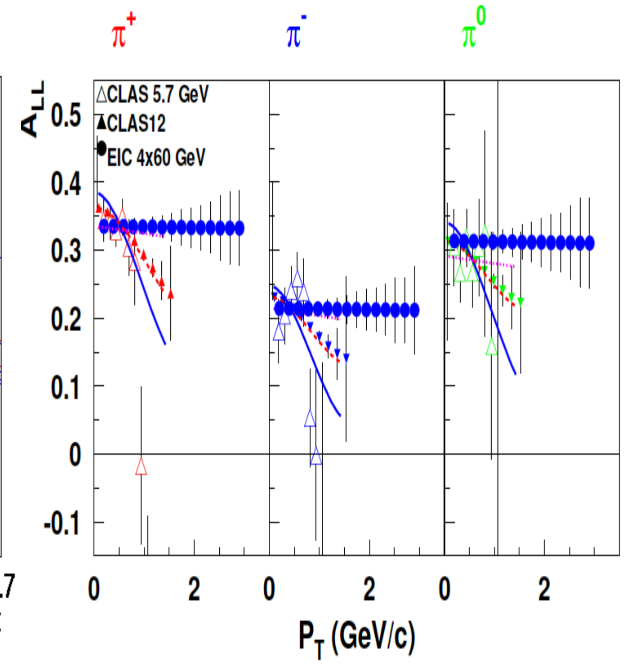
Sivers Effect vs Q^2 (Pavia)

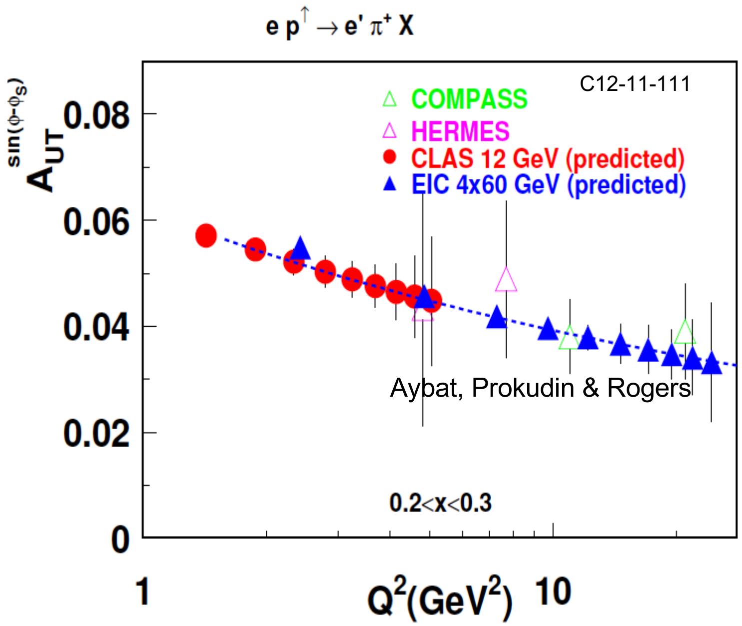


Measuring Sivers evolution requires largex, low y and large statistics in a wide range Q^2

CLAS12: Evolution and k_T-dependence of TMDs



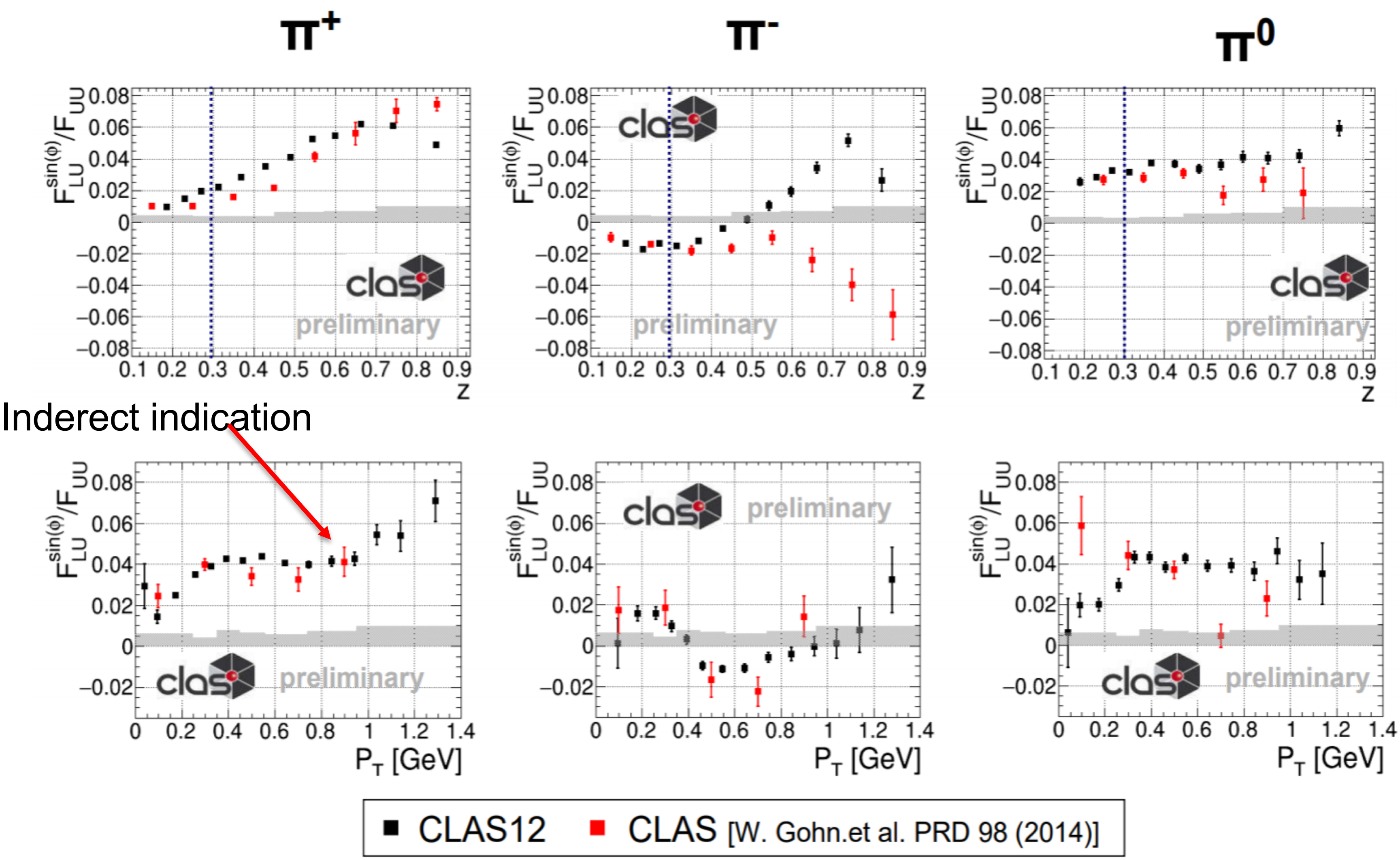




CLAS12 kinematical coverage k_T-dependence of $g_1(x, k_T)$ Q^2-dependence of Sivers, $f_1^{\perp}(x, k_T)$

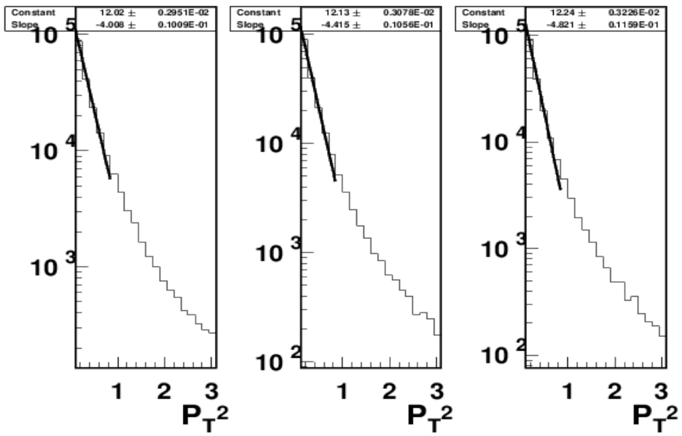
- Large acceptance of CLAS12 allows studies of P_T and Q^2-dependence of SSAs in a wide kinematic range (most critical for TMD studies)
- Comparison of JLab12 data with HERMES, COMPASS and EIC will pin down transverse momentum dependence and the non-trivial Q^2 evolution of TMD PDFs in general, and Sivers function in particular.

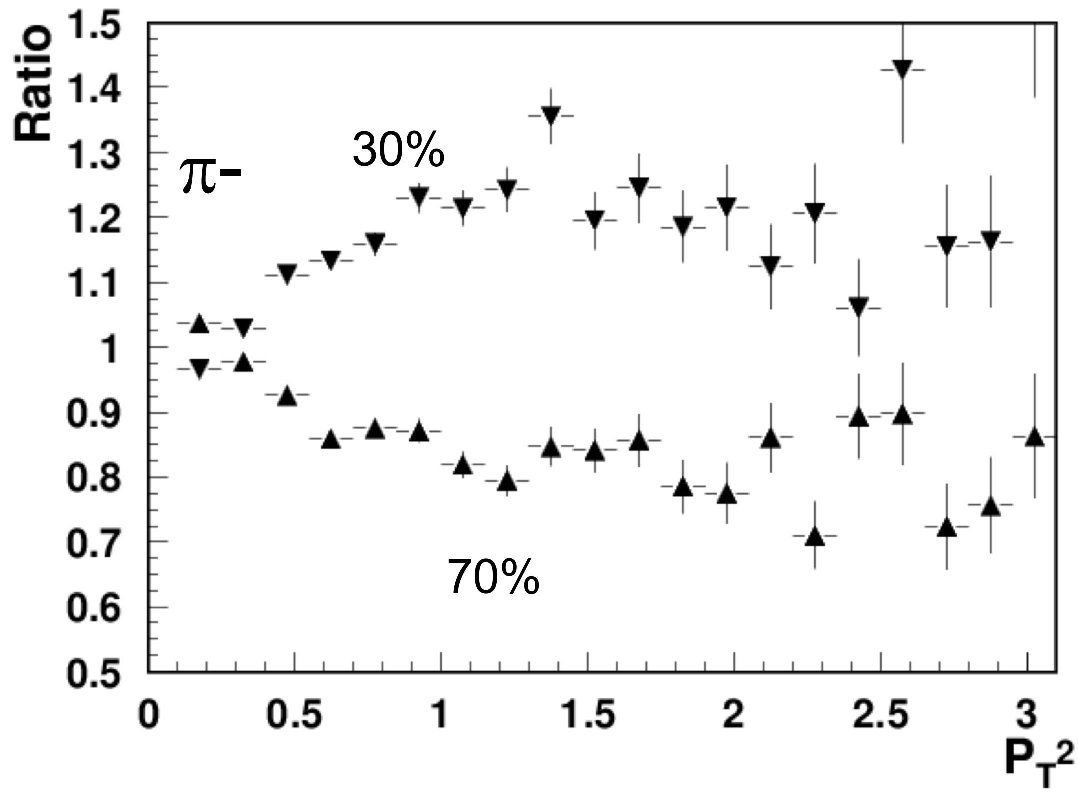
$F_{LU}^{\sin\phi} / F_{UU}$ for a **z** and **P$_T$** binning



JLEIC (5x50) P_T-dependences vs fraction of spin-1

fraction of spin-1
PYTHIA-parj(11)





Smaller the fraction of spin-1 particles (for the same quark transverse momenta), more high P_T pions → the same low P_T distributions will have much wider large P_T-distributions depending on the fraction of VMs