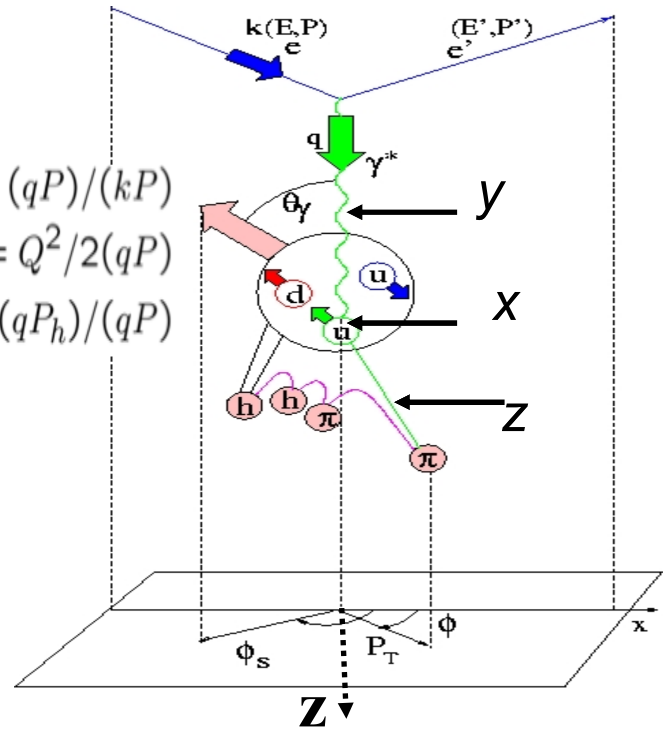
Studies of transverse momentum distributions in SIDIS

Harut Avakian (JLab)

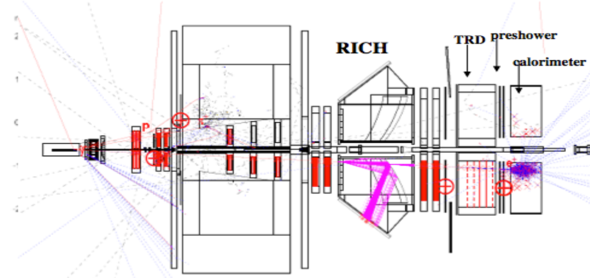
IWHSS-2020
November 16-18, 2020

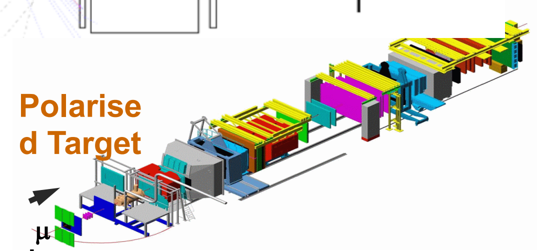
- Introduction
- LUND-MC and data
  - Single hadron
  - Di-hadron
  - Target fragmentation
- Accessing k_T in P_T-distributions of hadrons
  - Phase space
  - Contributions in SIDIS
  - Fitting the P_T-distributions
- CLAS12 multiplicity studies
- From Jlab 12 to EIC simulations
- Conclusions

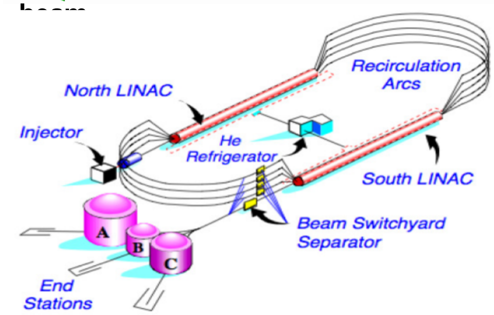
Semi Inclusive DIS



$$y = (qP)/(kP)$$
$$x = Q^2/2(qP)$$
$$z = (qP_h)/(qP)$$







EIC Center at Jefferson Lab

$$\sigma = F_{UU} + P_t F_{UL}^{\sin\phi} \sin 2\phi + P_b F_{LU}^{\sin\phi} \sin\phi \ldots$$

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

beam polarization

target polarization

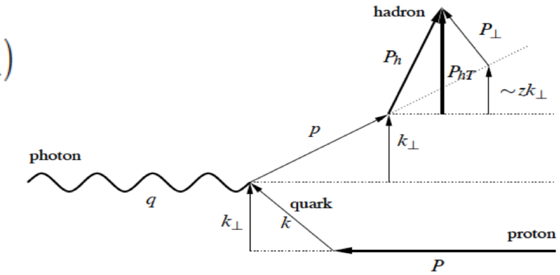
Distribution & Fragmentation Functions

$P_{hT} = P_T = P_\perp + z\, k_\perp$

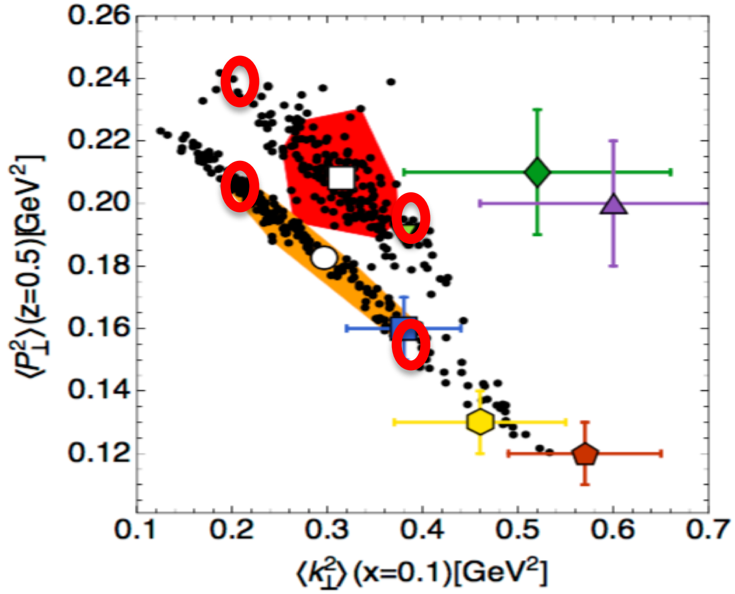
Extracting the average transverse momenta

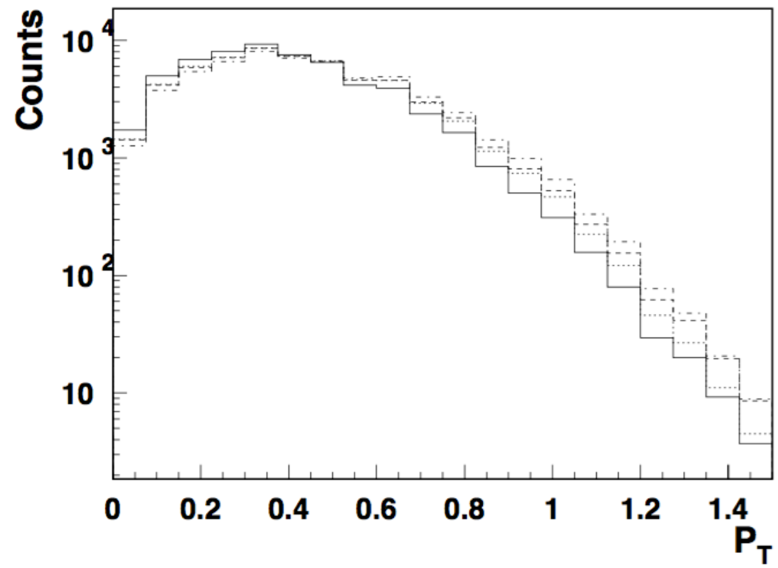
Andrea Signori,[1,*] Alessandro Bacchetta,[2,3,†] Marco Radici,[3,‡] and Gunar Schnell[4,5,§]

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



$$\langle \boldsymbol{P}_{hT,a}^2 \rangle = z^2 \langle \boldsymbol{k}_{\perp,a}^2 \rangle + \langle \boldsymbol{P}_{\perp,a\to h}^2 \rangle$$





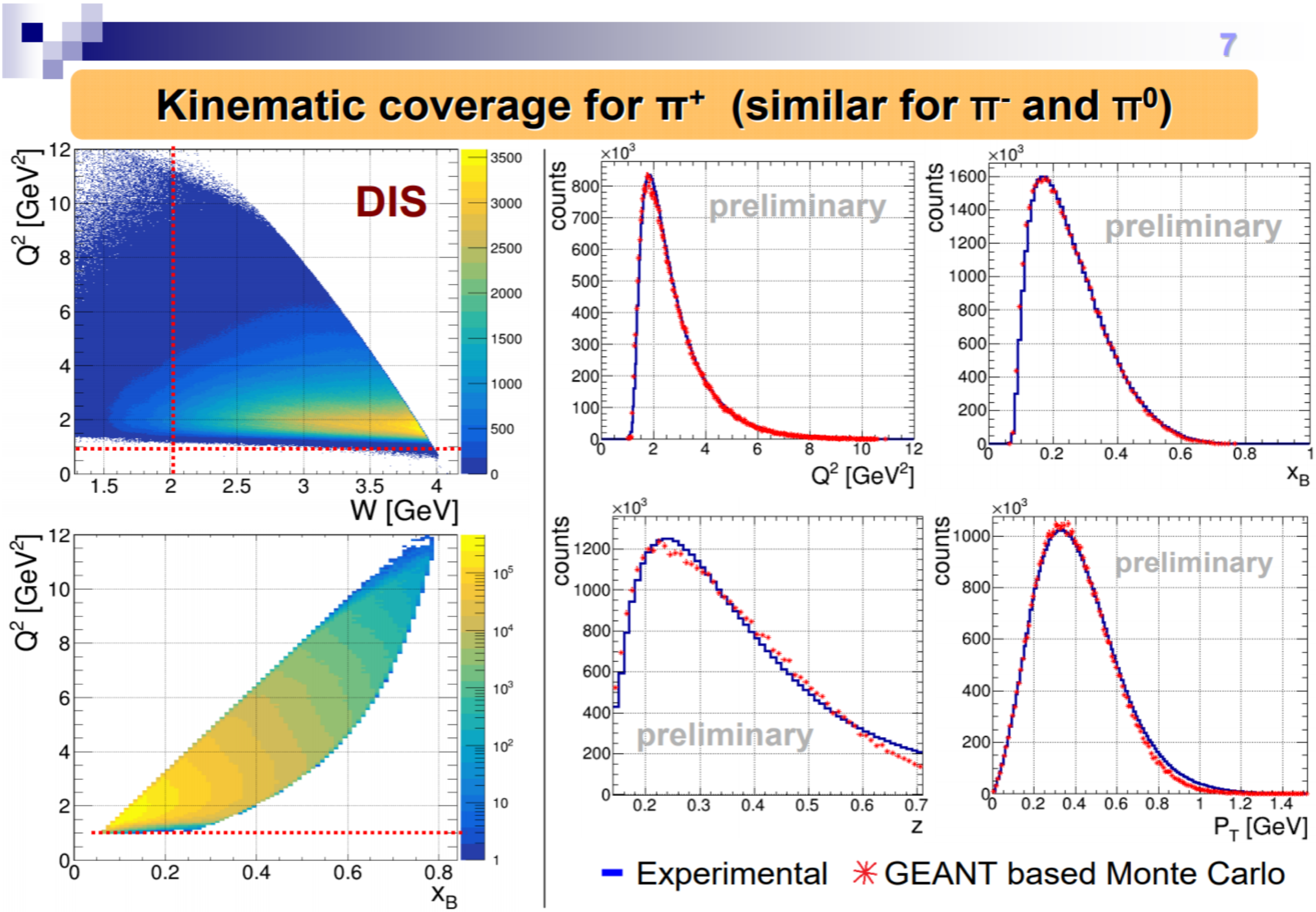
$$m_N^h(x,z,\boldsymbol{P}_{hT}^2) = \frac{\pi}{\sum_a e_a^2 \, f_1^a(x)} \times \sum_a e_a^2 \, f_1^a(x)\, D_1^{a\to h}(z)\, \frac{e^{-\boldsymbol{P}_{hT}^2/\left(z^2\langle \boldsymbol{k}_{\perp,a}^2\rangle + \langle \boldsymbol{P}_{\perp,a\to h}^2\rangle\right)}}{\pi\left(z^2\langle \boldsymbol{k}_{\perp,a}^2\rangle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

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

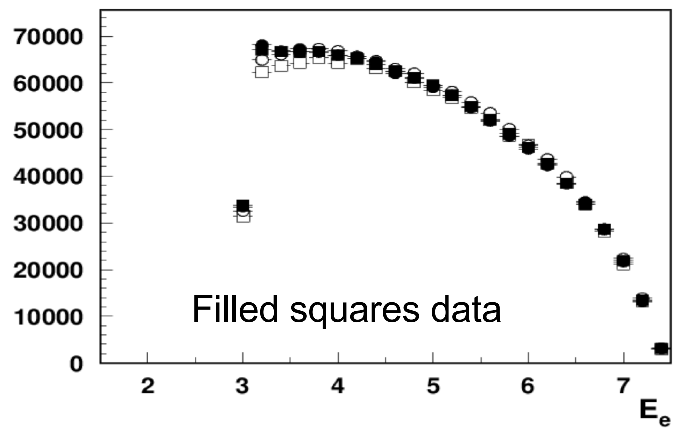
Sea is not divided to perturbative and non-perturbative

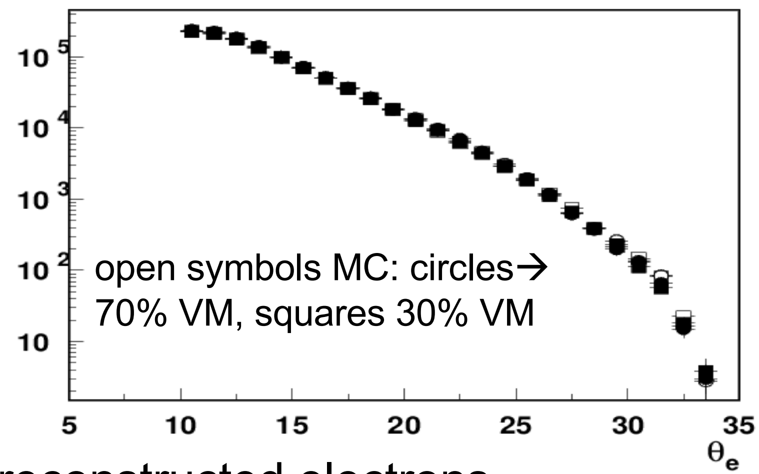
SIDIS ehX: CLAS12 data vs MC

CLAS12 single hadron note: in review for publication

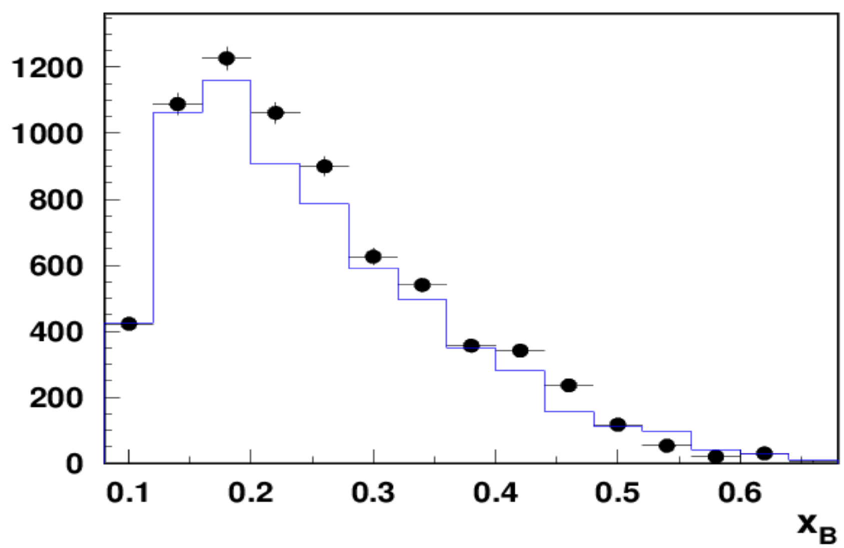


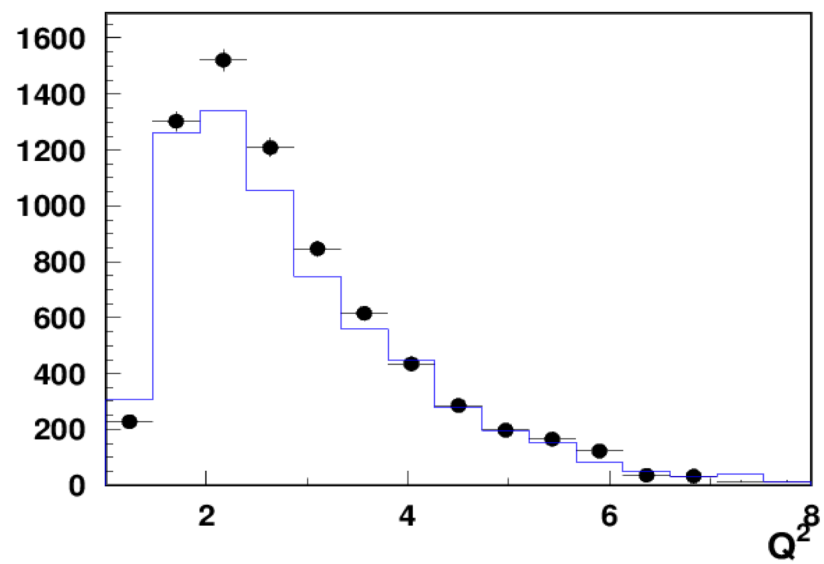
CLAS12(RGA): $ep \rightarrow e'\pi^+\pi^-X$





Normalizing sets to the same number of reconstructed electrons

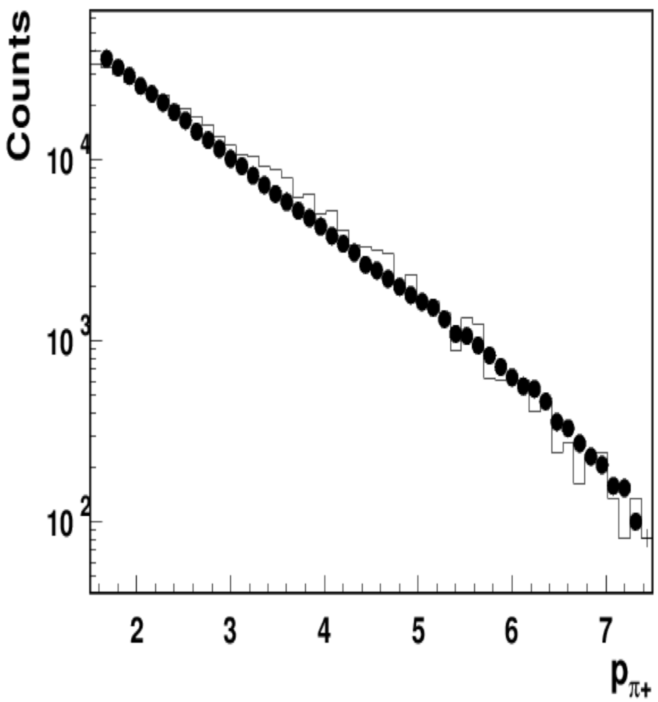


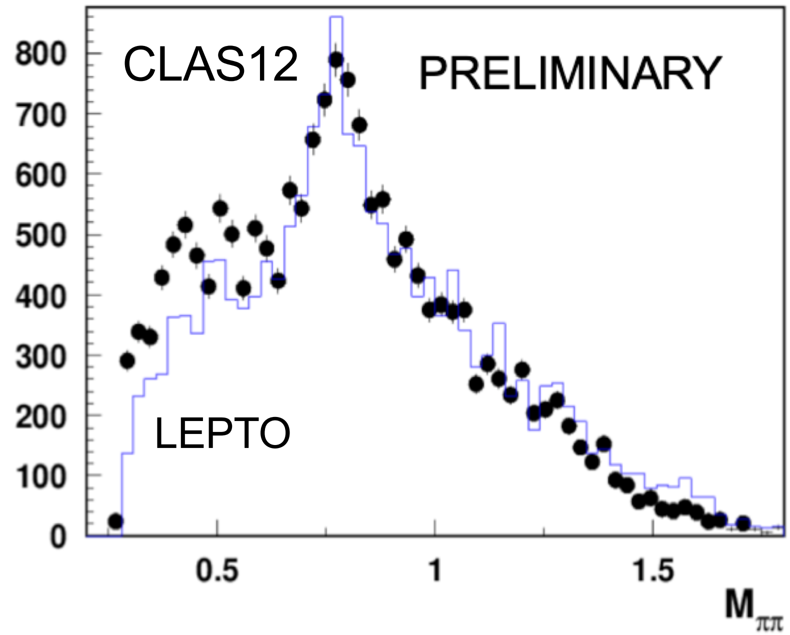


x, Q^2-dependences for $e'\pi^+\pi^-X$ MC (line) in good agreement with low lumi data

SIDIS ehX,ehhX: CLAS12 data vs MC

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

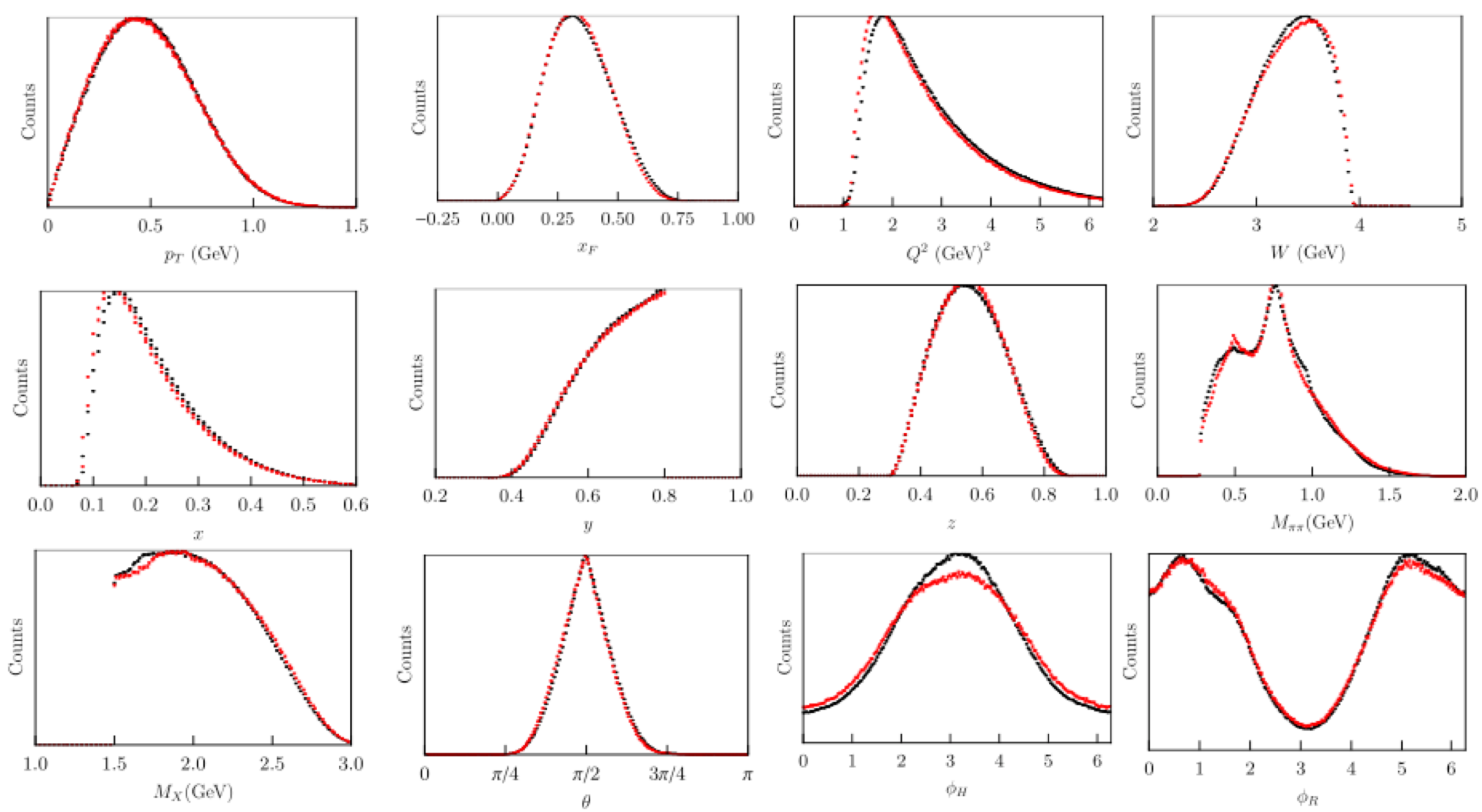




- Most of the single hadron sample (from 50-70%) is coming from VM decays
- Pion counts for normalized e'X events are consistent with clas12 LUND MC (VM 70%)
- Simulation describes well both single (e'hX) and di-hadron (e'hhX) counts in CLAS12
- MC data can be used to make conclusions about the source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

SIDIS ehhX: CLAS12 data vs MC

CLAS12 dihadron production ep→ehhX (T.Hayward)

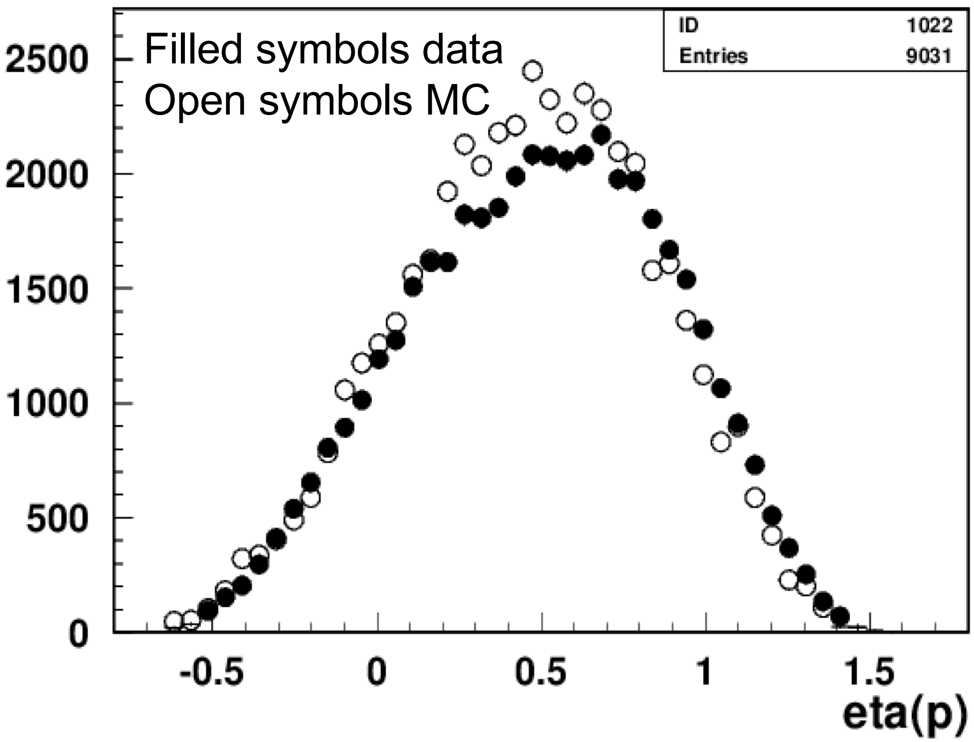


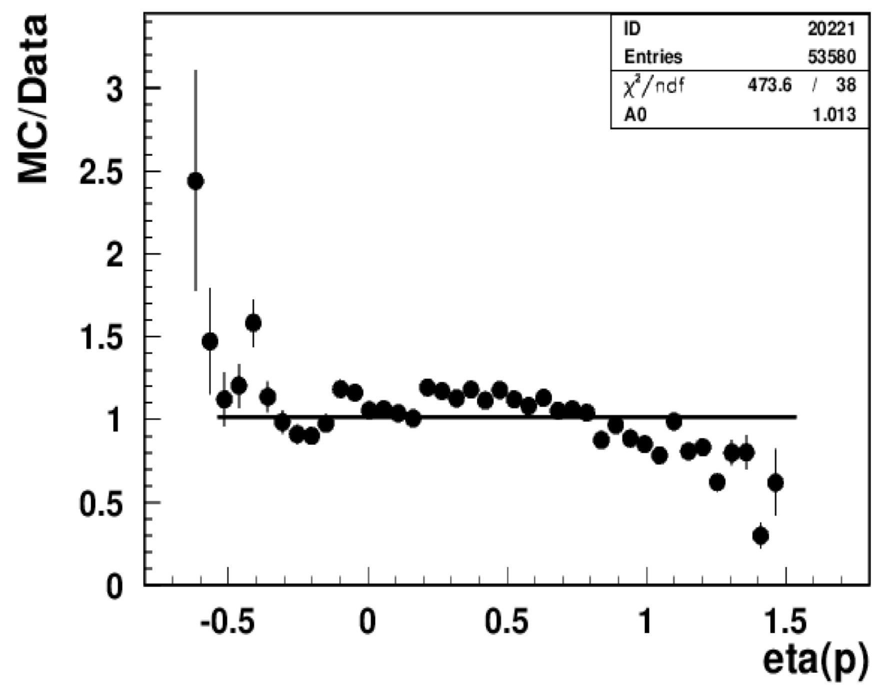
CLAS12 MC, based on the PEPSI(LEPTO) simulation with <u>most parameters "default"</u> is in a good agreement with CLAS12 measurements for all relevant distributions

CLAS12 Studies: Data vs MC

Using PEPSI (LUND) generator rapidity in Breit frame

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

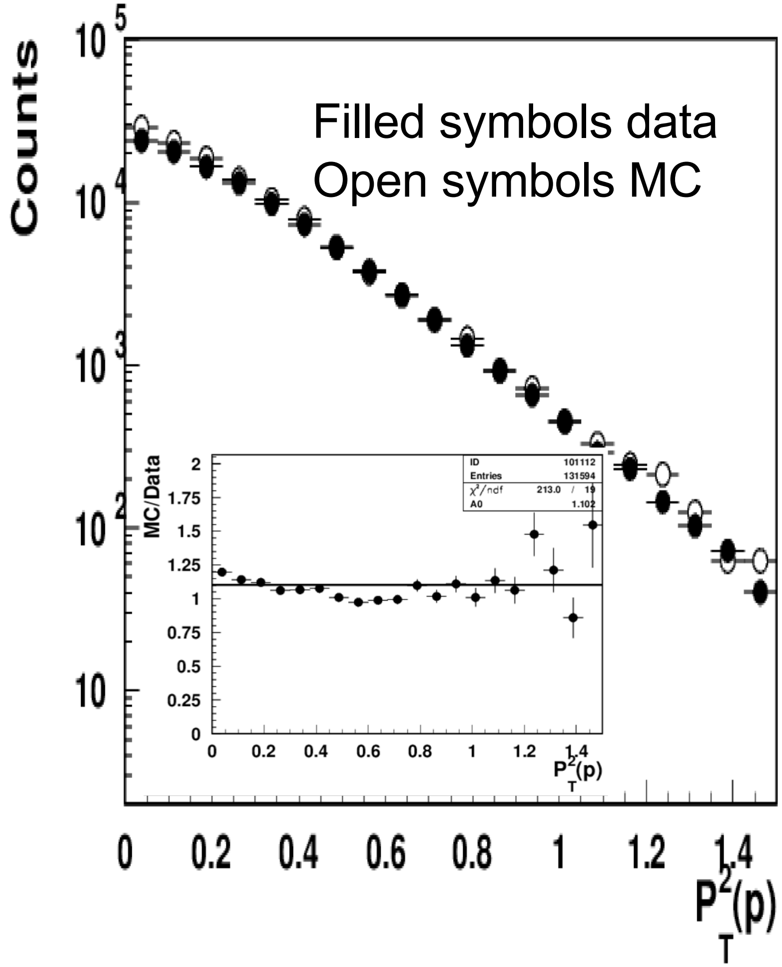


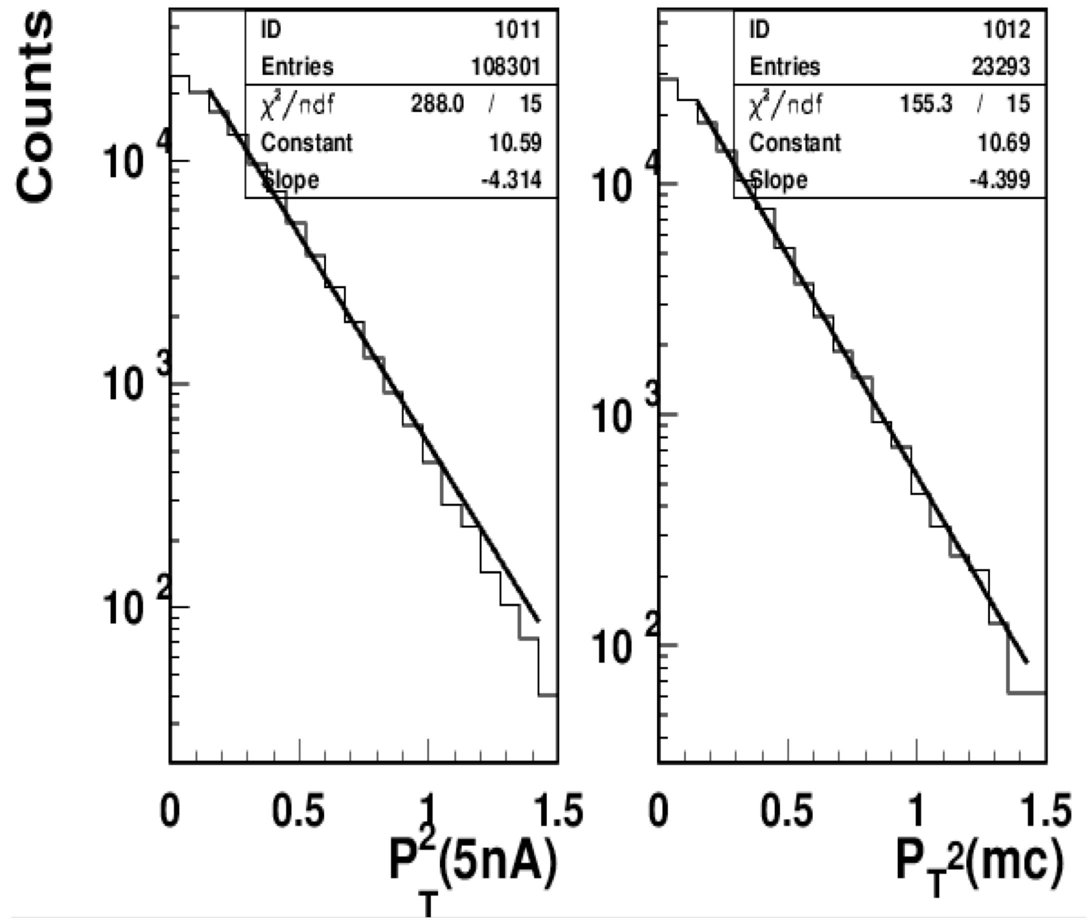


Distributions of protons vs rapidity in good agreement with LUND-MC (LEPTO) in most of the kinematics

CLAS12 Studies: Data vs MC

Using PEPSI (LUND) generator





- P_T-distributions of protons, and widths are in good agreement with LEPTO
- May be a source for widths in hadronization

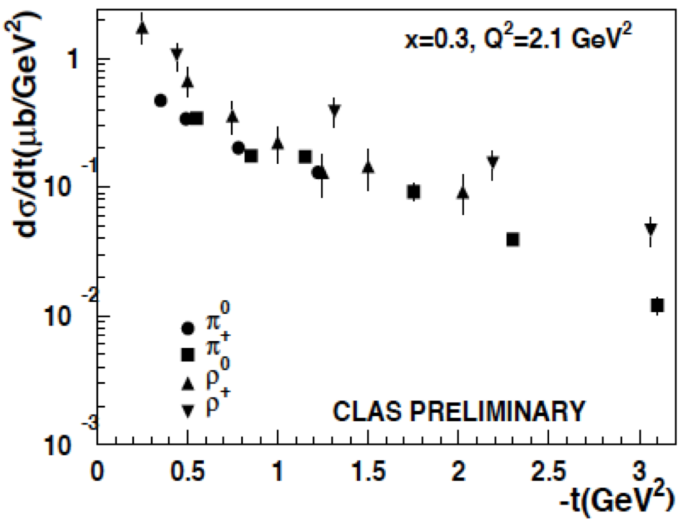
JETSET

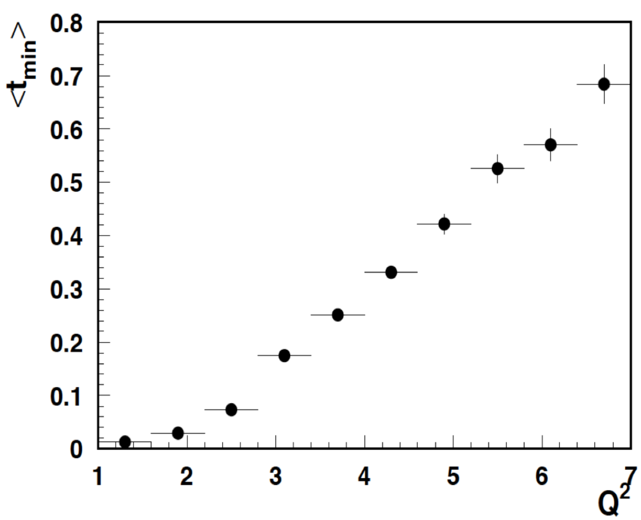
Test: It is not trivial to achieve agreement with data, when using in the single-pion MC with widths of k_T-distributions of pions extracted from the same data

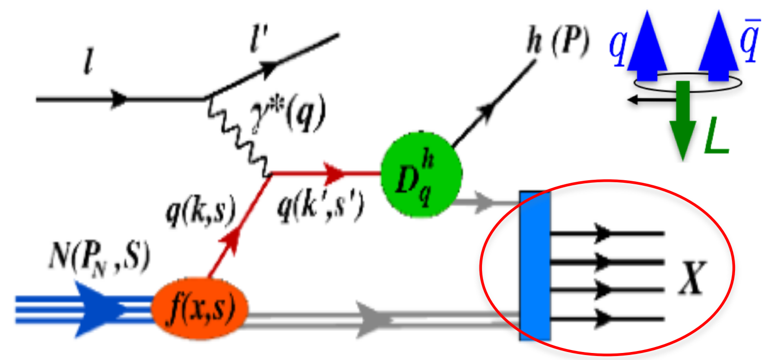
So why the LUND-MCs are so successful in description of hard scattering processes, and SIDIS in the first place?

- The hadronization into different hadrons, in particular Vector Mesons is accounted (full kinematics)
- The correlations between target and current fragments included (mainly lower z)
- ……….

Exclusive ρ production at large t







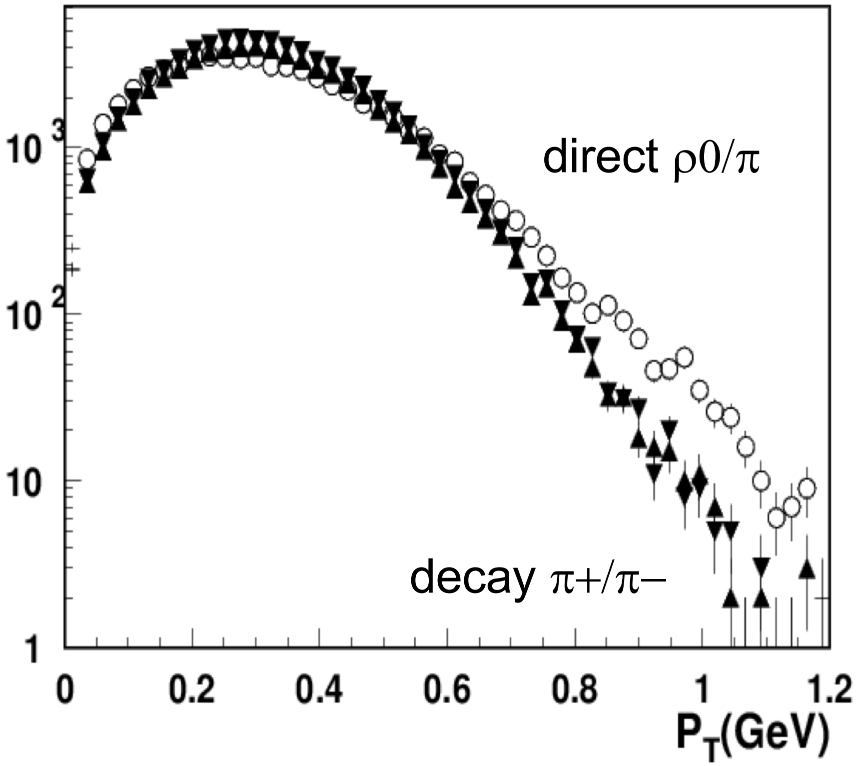
p,n

Implications

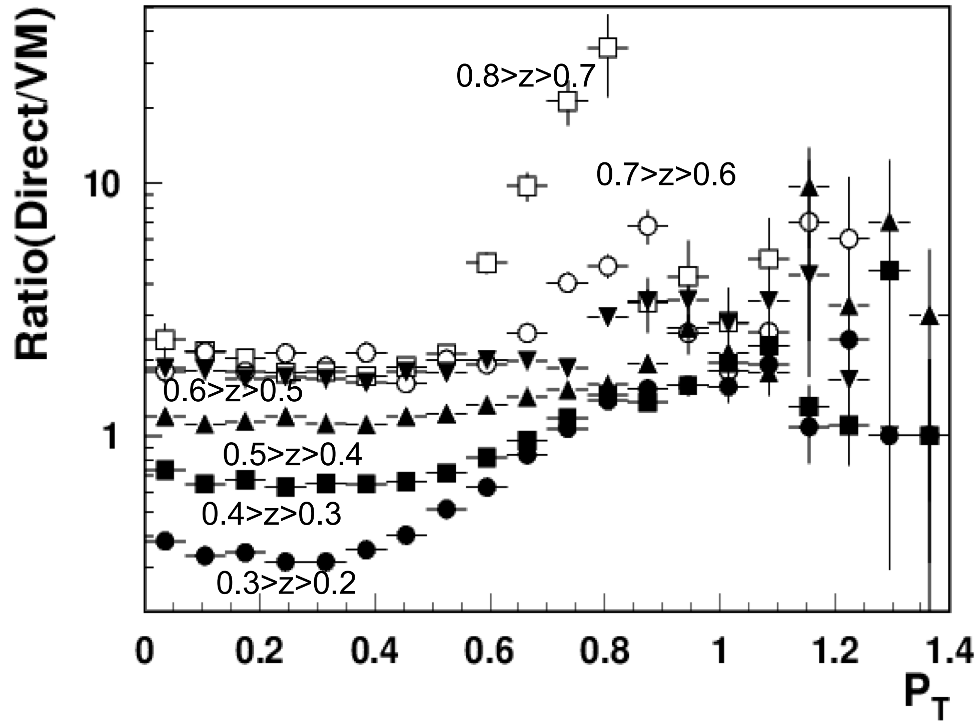
- x-section of measured exclusive process at large t (t_{min})exhibit similar pattern
- $\rho+>\rho^0$ →Diffractive production suppressed
- at large t production mechanism most likely is similar to SIDIS, better at lower energies
- Slightly higher rho x-sections indicate the fraction of SIDIS pions from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

P_T of pions from rho decays: LUND string fragmentation

Note: LUND-MCs use a single Gauss in k_T

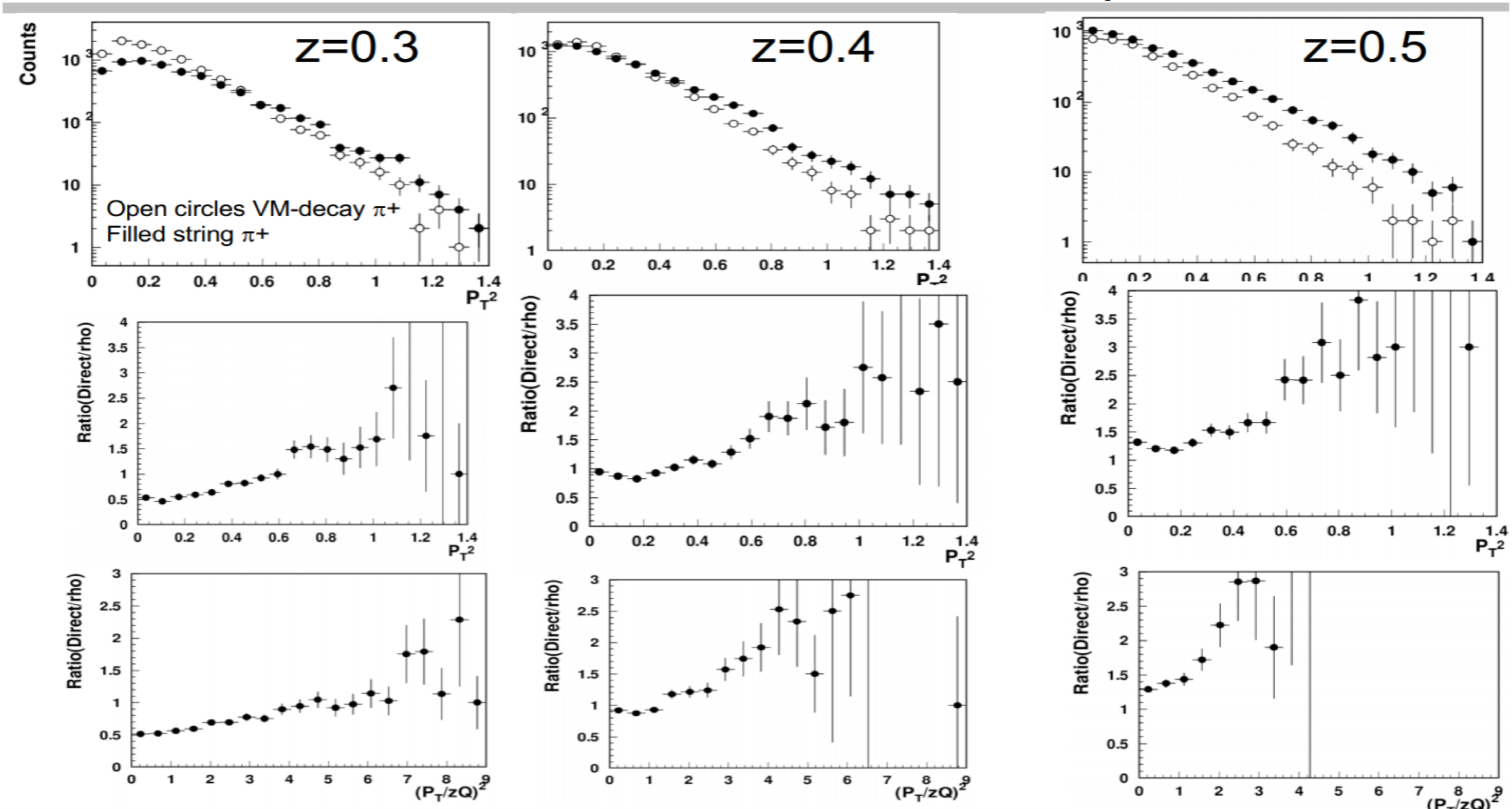


Fraction of direct $\pi+$ increases with P_T and z



- 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 challenging
- Understanding of dihadron production is crucial for interpretation of single-hadron SIDIS, in particular, k_T-dependence of PDFs

JLab12: SIDIS and P_T



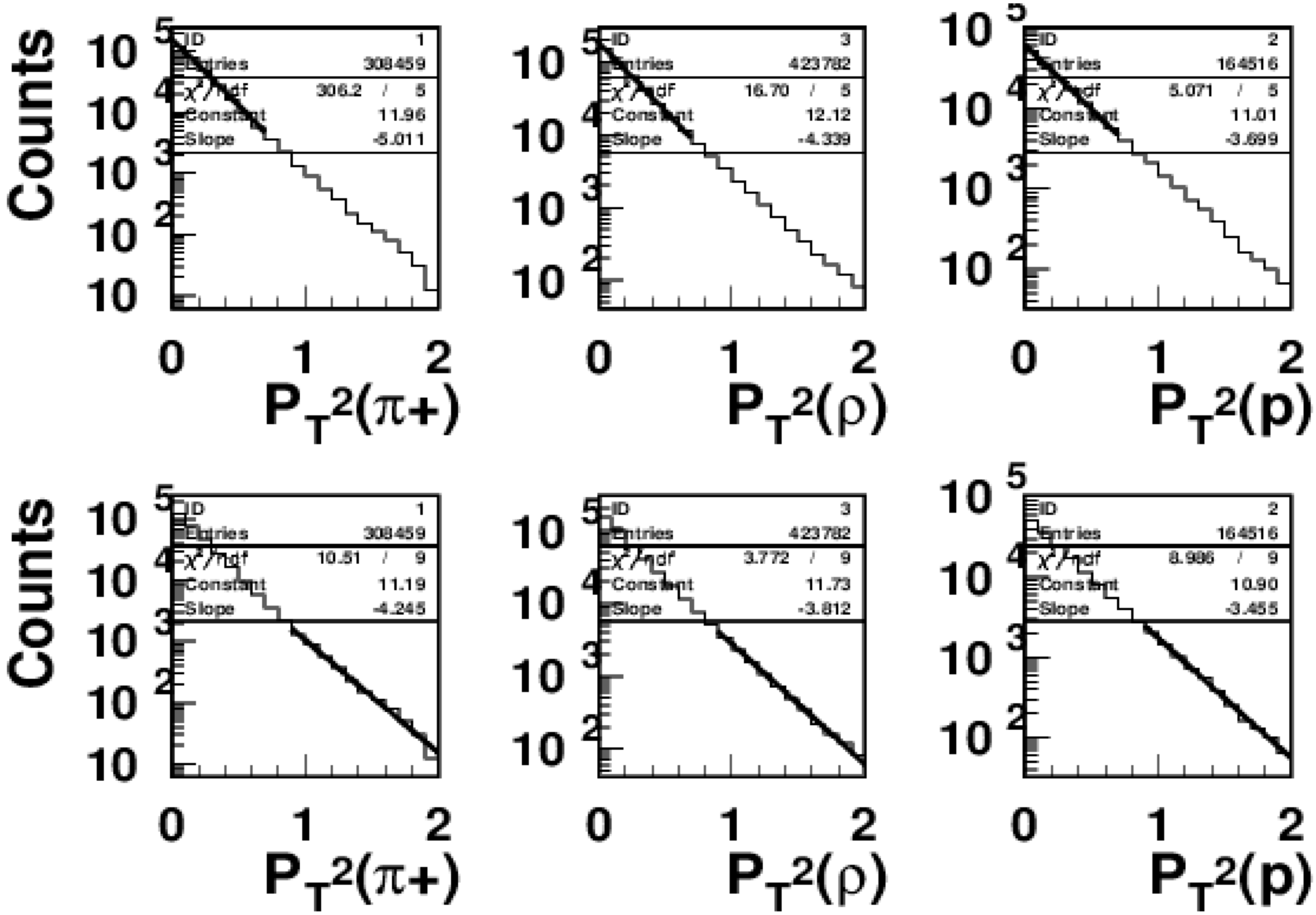
Important note: VM means VMs from quark fragmentation (not diffractive)

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)

Accessing the k_T (JLab)

Fit $0<P_T<0.8$

Fit $0.9<P_T<1.5$

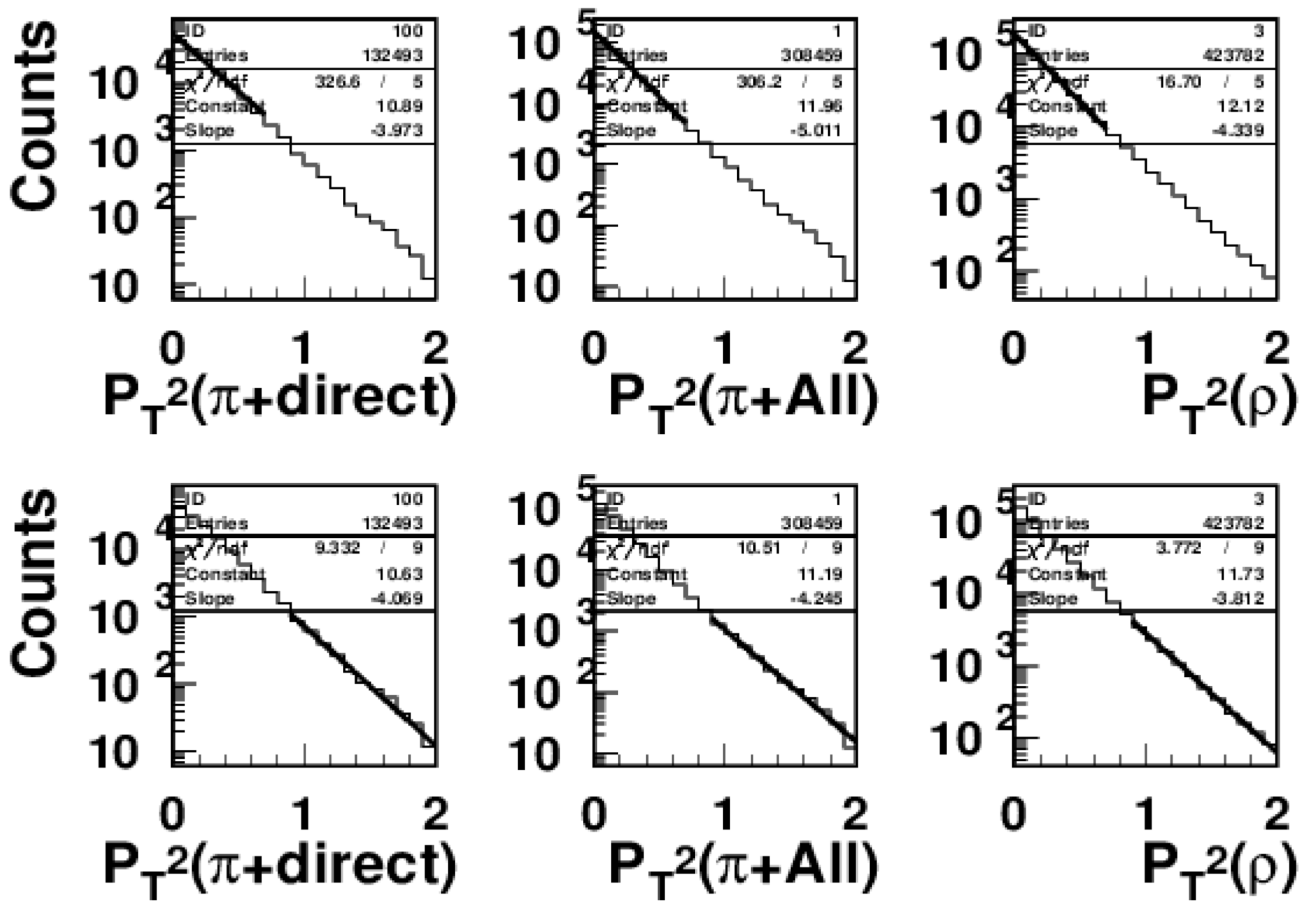


Fit to P_T gives significantly wider P_T for larger P_T pions

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

G. Angelini (GW)

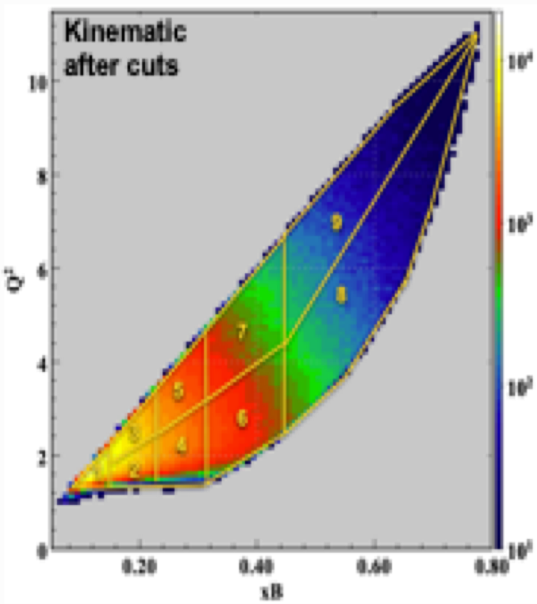
Multiplicities from CLAS12

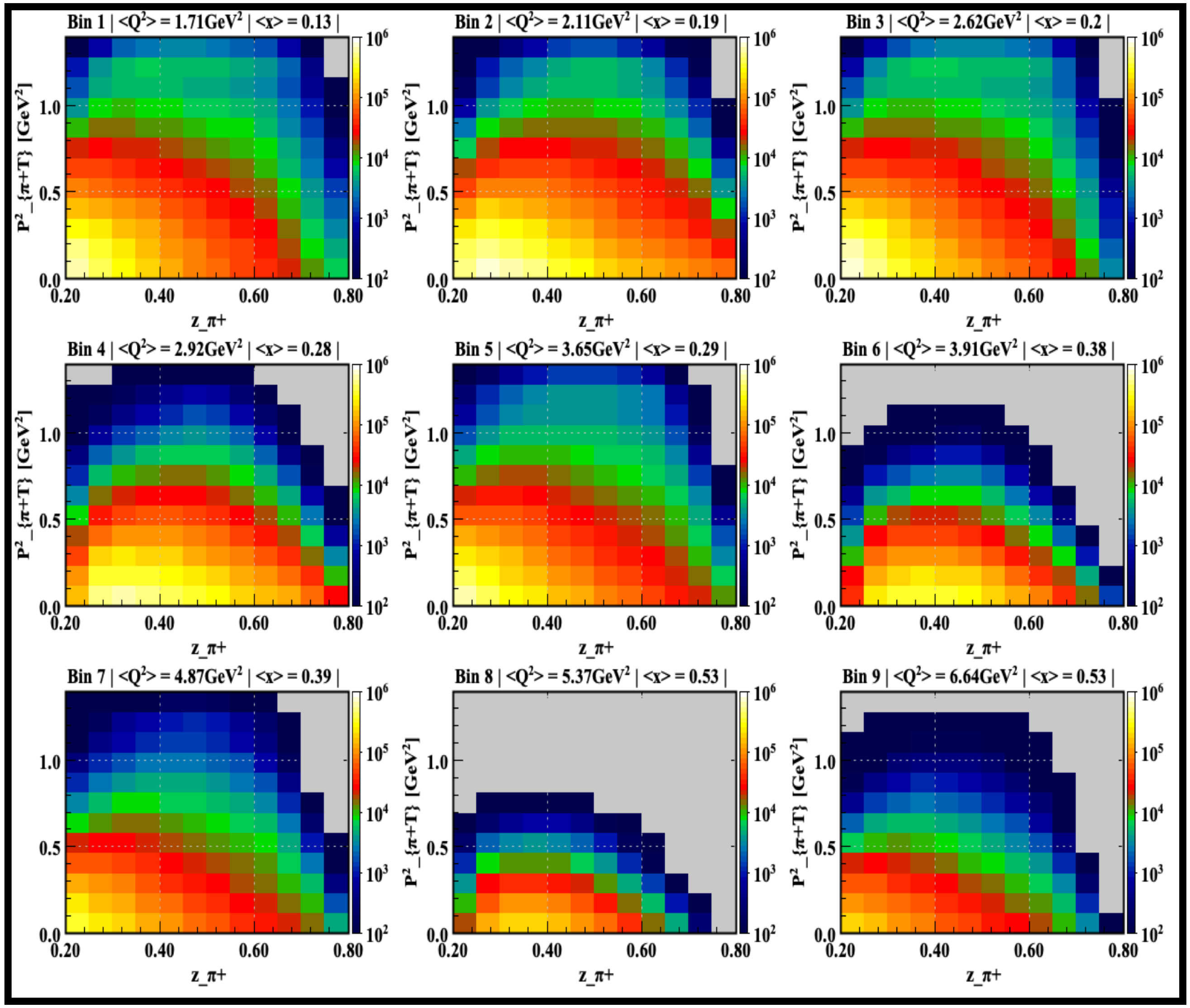
$Q^2 > 1$ GeV^2 | W > 2GeV | y < 0.75

+PID Cuts
+ Missing Mass> 1.5 GeV/c
+ Fiducial cuts
+$x_F > 0$

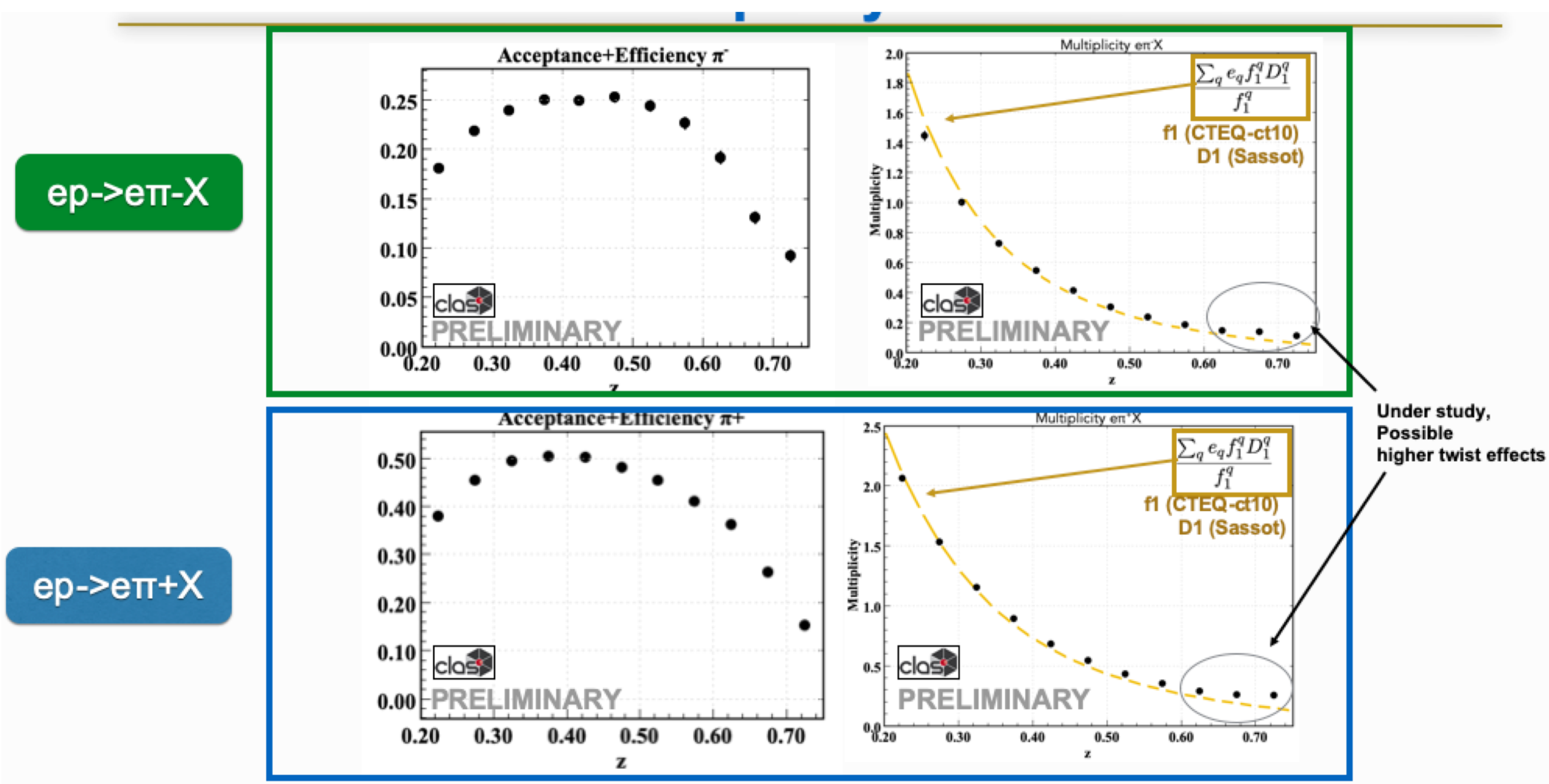
9 x 14 x 14 = 1764 bins

(Q^2, x)   Z   PT2





CLAS12 Multiplicities: z-dependence



Simple leading order seem to work reasonably well for z-dependence of multiplicity

G. Angelini (GW)

CLAS12 Multiplicities: P_T-dependence

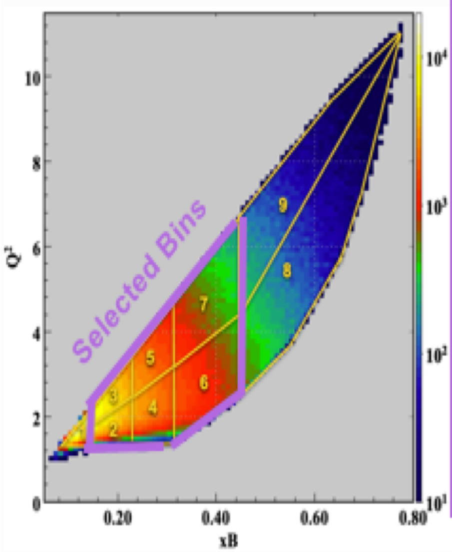
$$m_N^h(x,z,P_{hT}^2) = \frac{\pi}{\sum_a e_a^2 f_1^a(x)} \times \sum_a e_a^2 f_1^a(x)\, D_1^{a\to h}(z)\, \frac{e^{-P_{hT}^2/(z^2\langle k_{\perp,a}^2\rangle + \langle P_{\perp,a\to h}^2\rangle)}}{\pi(z^2\langle k_{\perp,a}^2\rangle + \langle P_{\perp,a\to h}^2\rangle)}$$

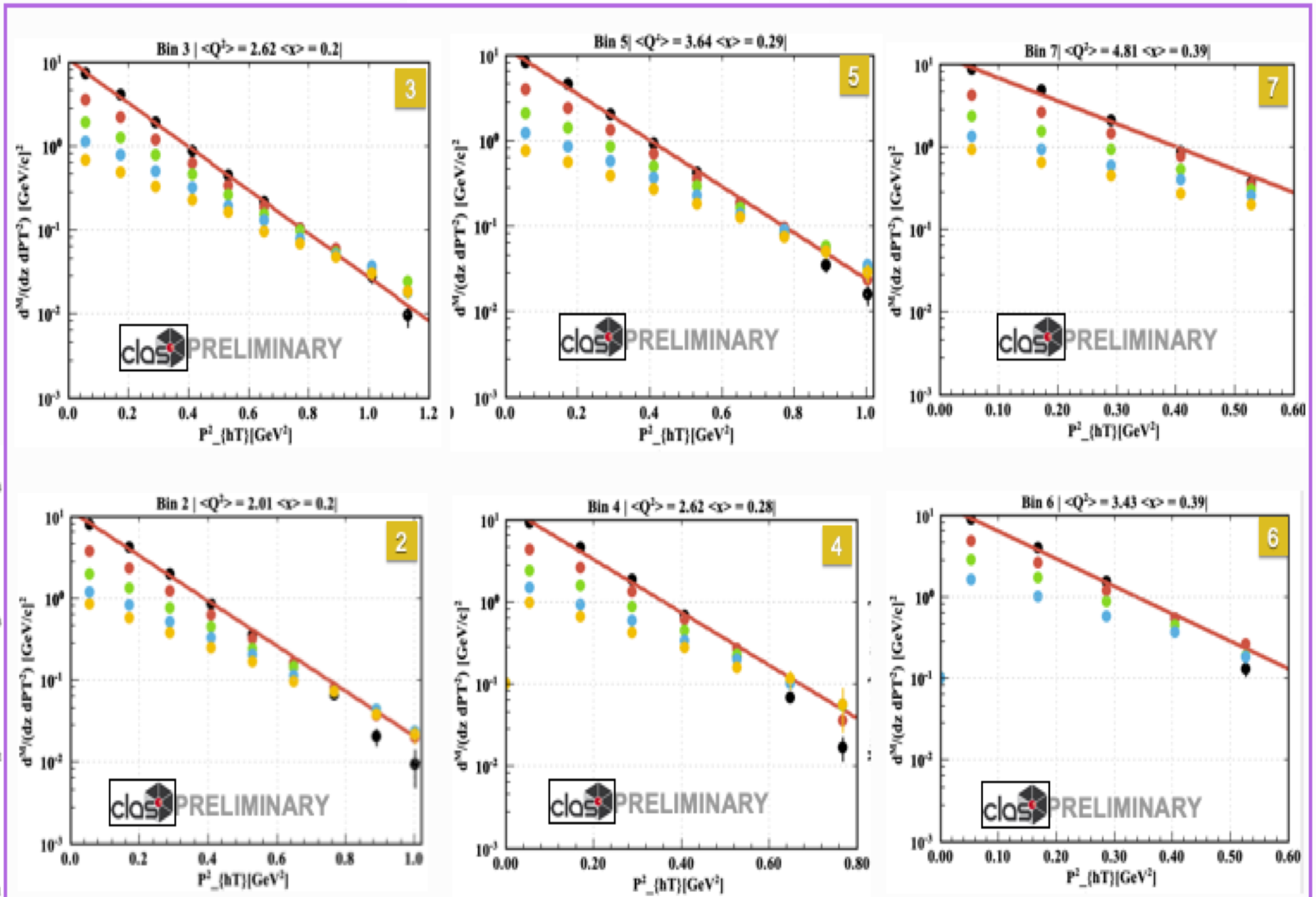
Fitted in the plots

ep->eπ+X

Color legend

- 0.2<z<0.3
- 0.3<z<0.4
- 0.4<z<0.5
- 0.5<z<0.6
- 0.6<z<0.7

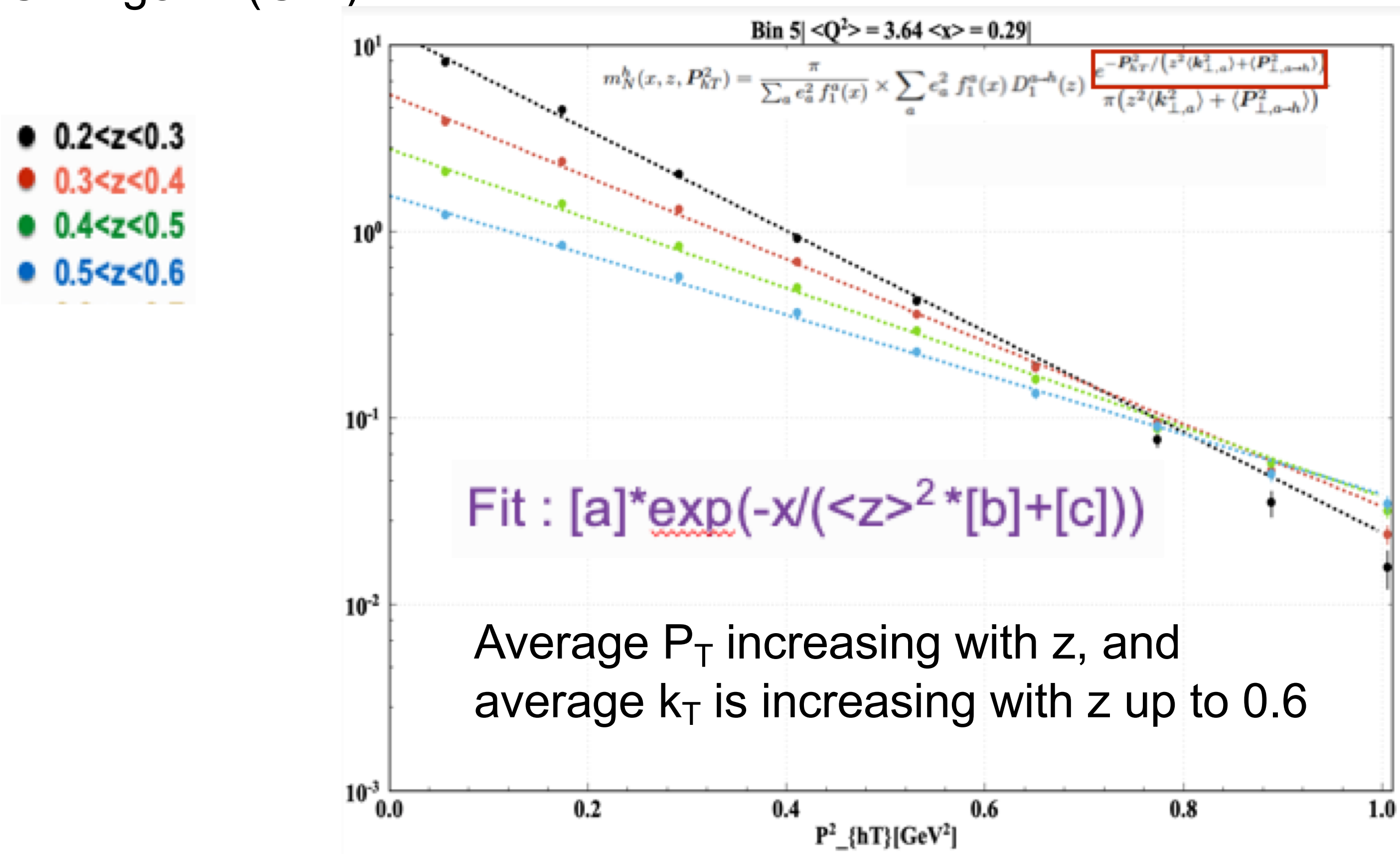




<x> =0.2 <x> =0.29 <x> =0.39

CLAS12 Multiplicities: fits to P_T-dependence

G. Angelini (GW)



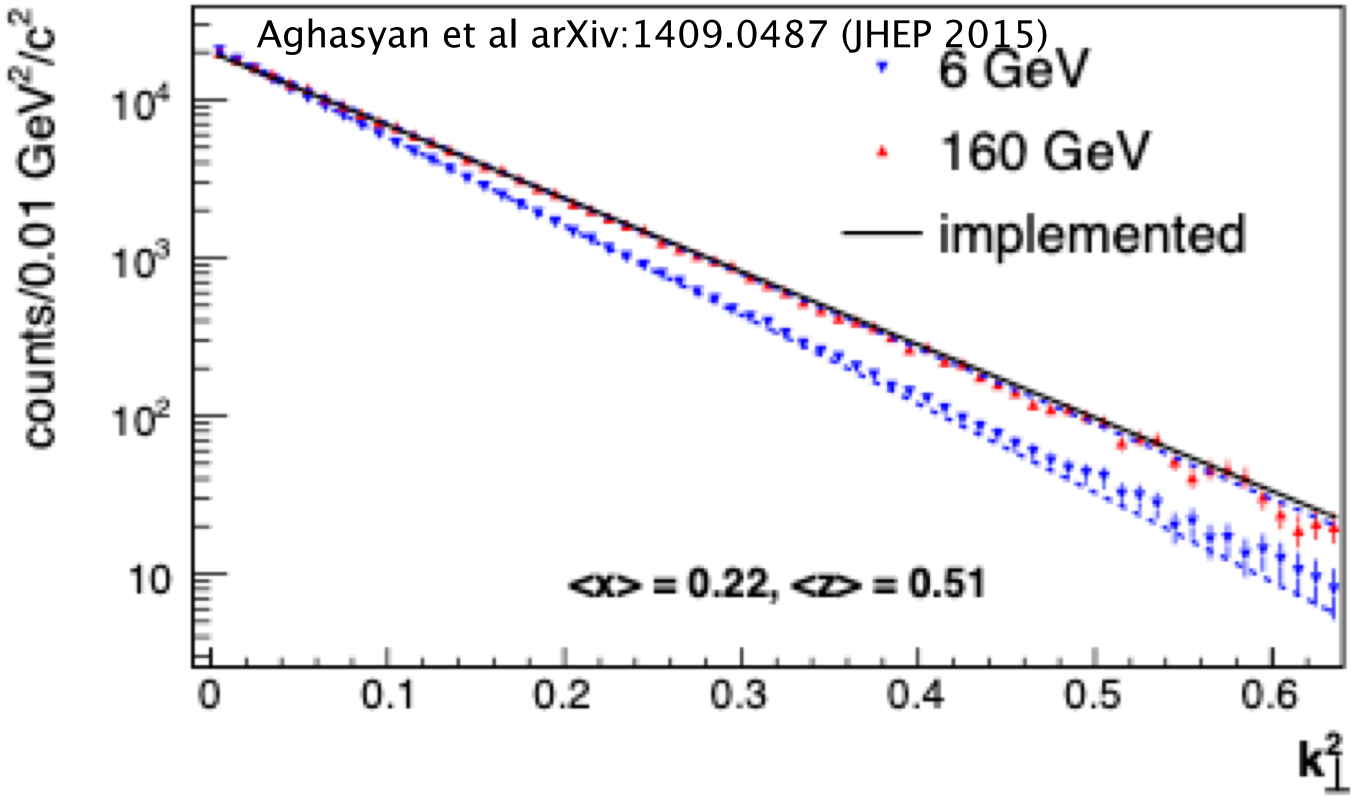
Fit procedure gives different values for different ranges in P_T

Possible reasons:

- Phase space limitations are function of z
- VM contributions are function of z

Energy conversation and the phase space

For a given x,Q^2,z kinematics put limits on the hadron P_T and underlying k_T



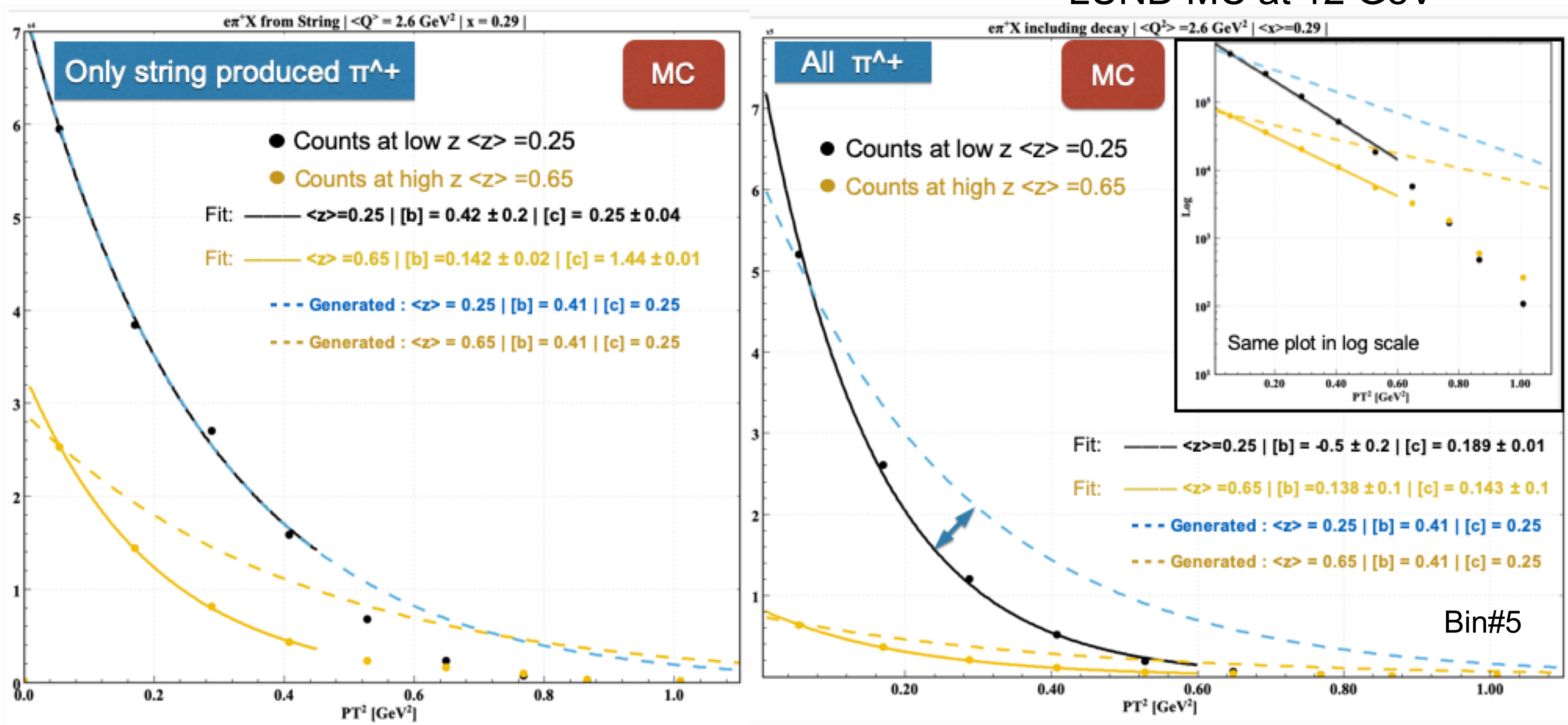
Effect of phase space is more significant at lower beam energies, increases with **z**, but could and should be accounted

Note: The effect is detector/model independent

CLAS12 Multiplicities: fits to P_T-dependence

G. Angelini (GW)

LUND MC at 12 GeV



Procedure: Use the direct pions, generated with $\langle k_T^2\rangle=0.41$ (dashed lines) and try to look at the distributions of pions (solid lines) and extract the $\langle k_T^2\rangle$

Effect is more significant at small x, large z and at high P_T

CLAS12 Multiplicities: the role of high P_T

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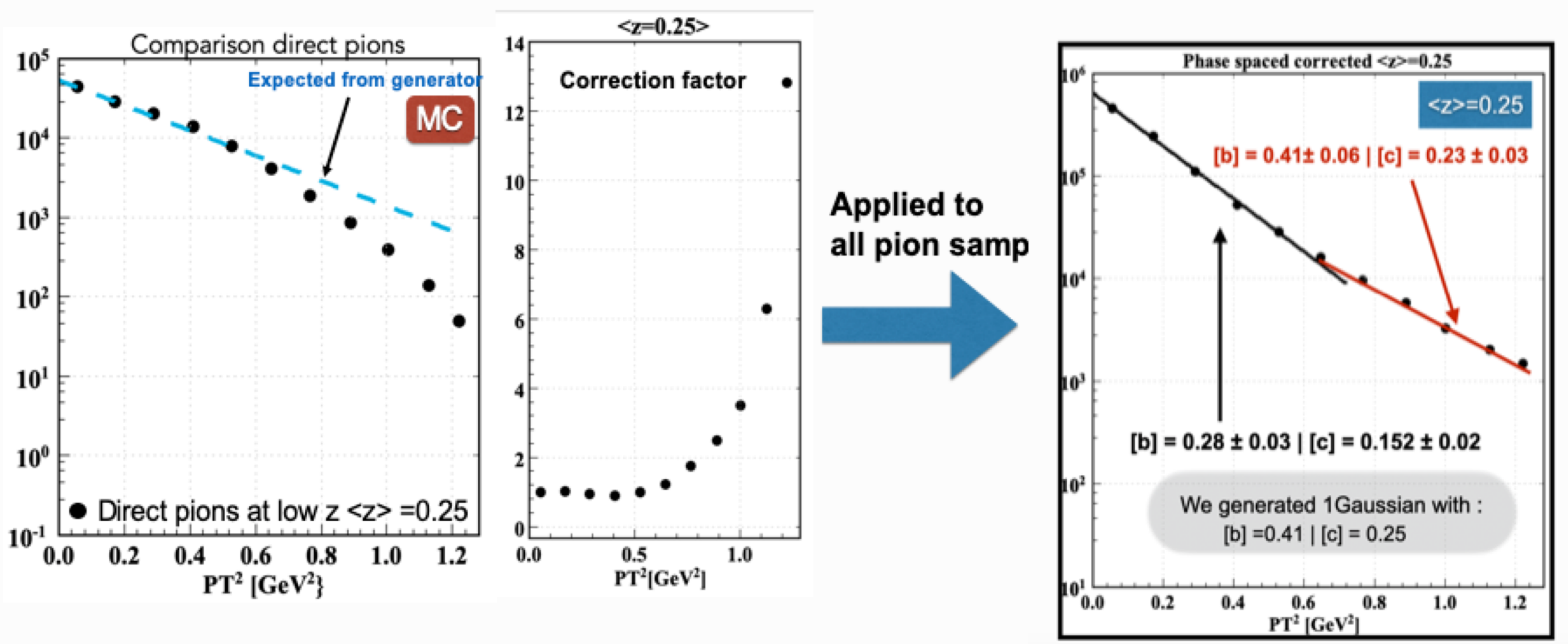
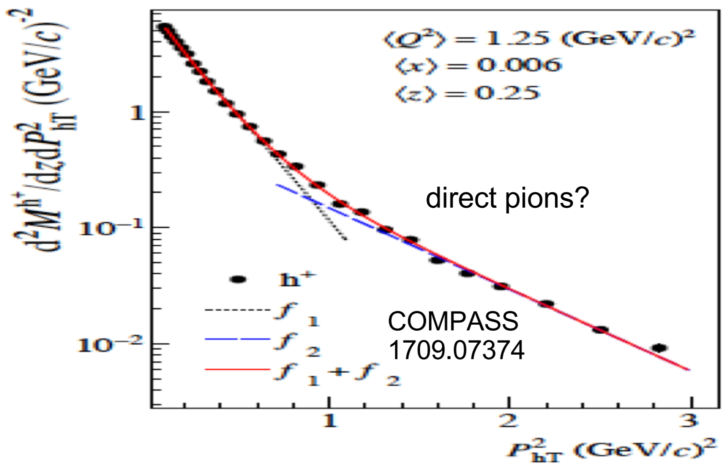
LUND MC at 12 GeV

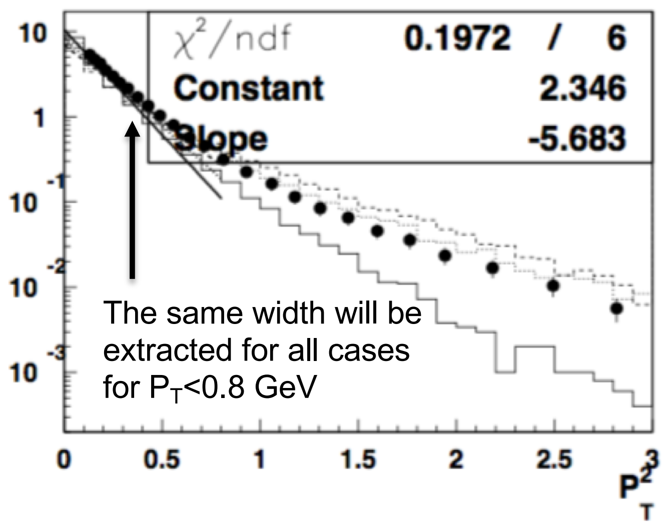


- Corrections due to phase space (energy needed to produce a hadron with a given z, P_T at given x, Q^2) are detector and model independent
- Corrections due to fraction of fragmentation VMs and diffractive VMs are model dependent, but can be extracted from MC (work in progress)

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

Origin of non-Gaussian tails





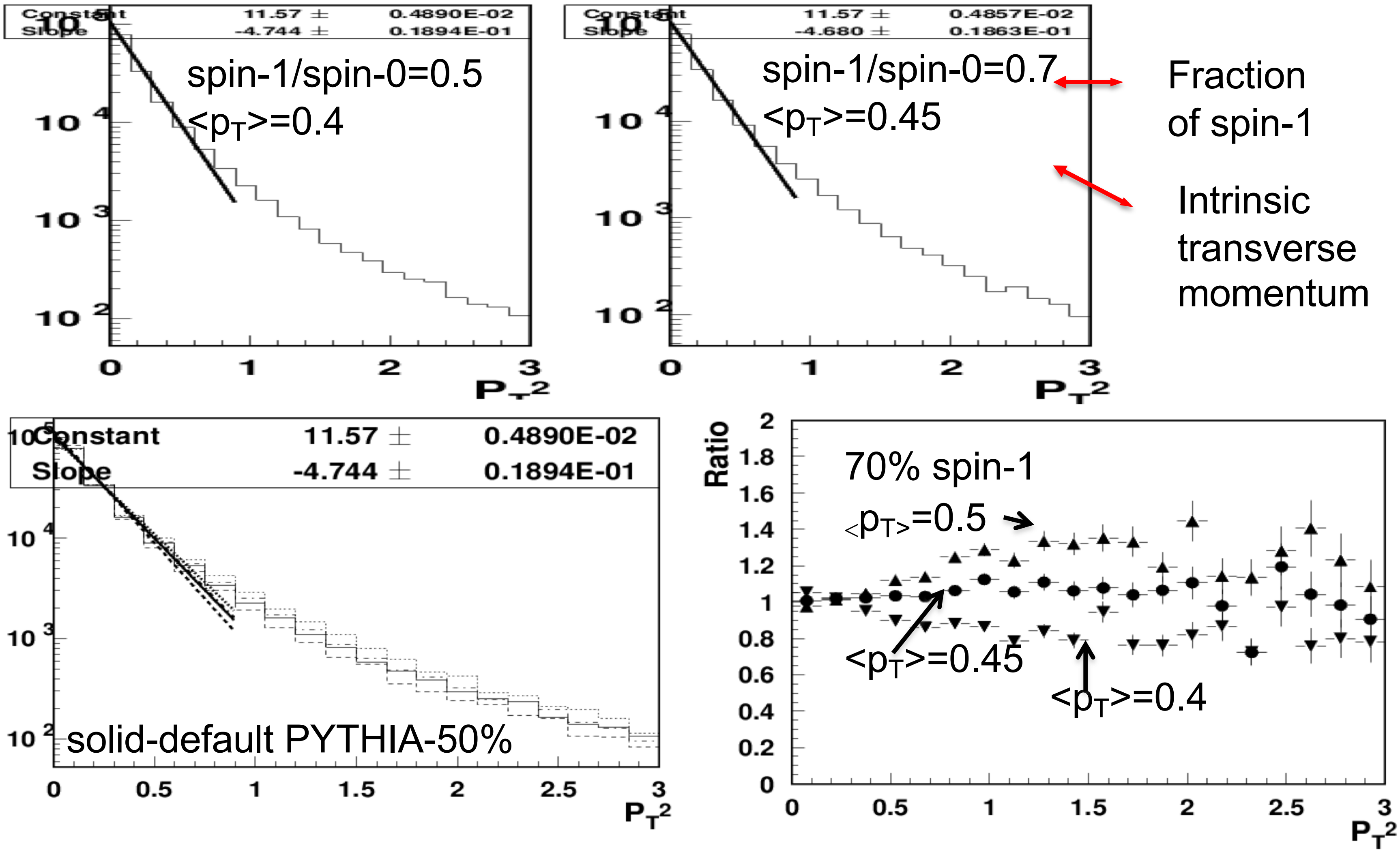
1 hadron 2 Gausses or 1 Gauss 2 hadrons?

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 $<k_T^2>$

EIC (5x50) P_T-dependences for pions



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

More dynamical input in fits

Ex.: fit the f_1 and g_1/h_1, as independent functions (ignoring SB) requires bunch of parameters, serves in fitting data, but useless outside of the region of fit
So far worked for f1 and g1 using some polynoms, trying to use the information on small and large x limits, and sometimes the info about different x-dependences of q+ and q- (BBS,ABDY,..)

More physics information we put in fits more chances that those fits will be useful outside of the kinematical region covered by data used in the fit

Accounting more knowledge in fits will be even more important for TMDs with more degrees of freedom and bigger number of possible parameters

The situation is even more critical for fragmentation functions, as much less is known about p_T-dependences of fragmentation functions, including flavor dependences, even for spin-0 mesons (warning for future attempts to introduce complex parameterizations of FFs)

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 require different RC, modeling, and interpretation
- Modeling of spin-orbit correlation will help to understand the dynamics and define the regions where independent fragmentation is most applicable
- Corrections due to phase space (detector, model independent) and fractions of pions from VMs may be critical for interpretation of data and can help to extract the underlying k_T-distribtions

- 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

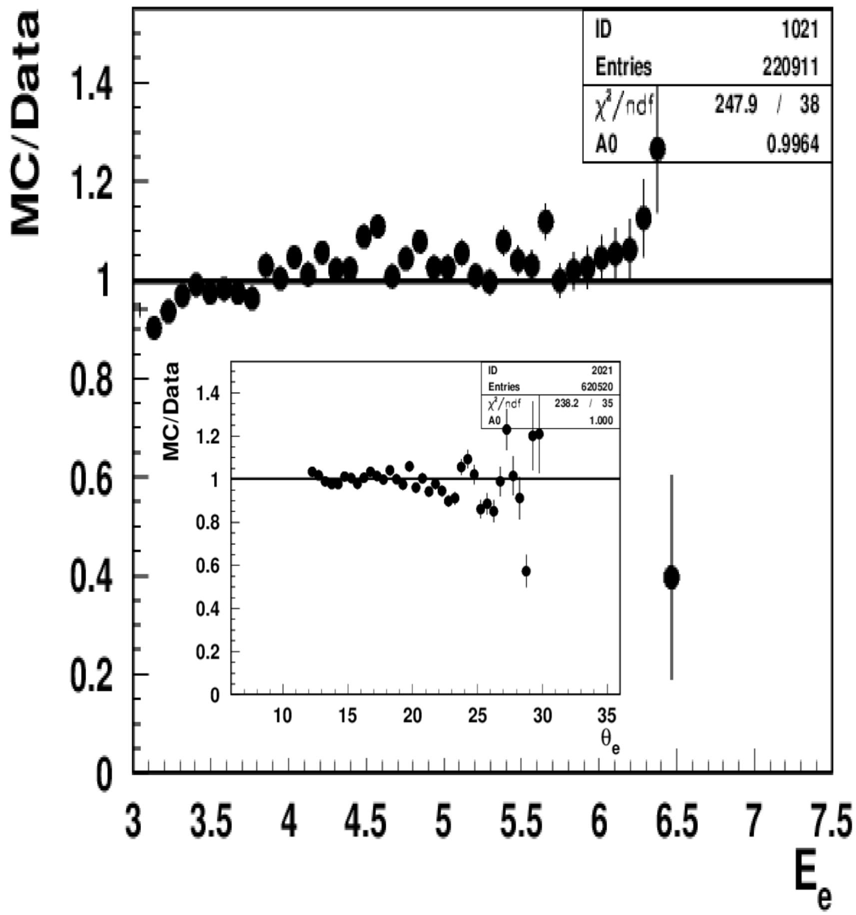
Correlated hadron production: Where it matters

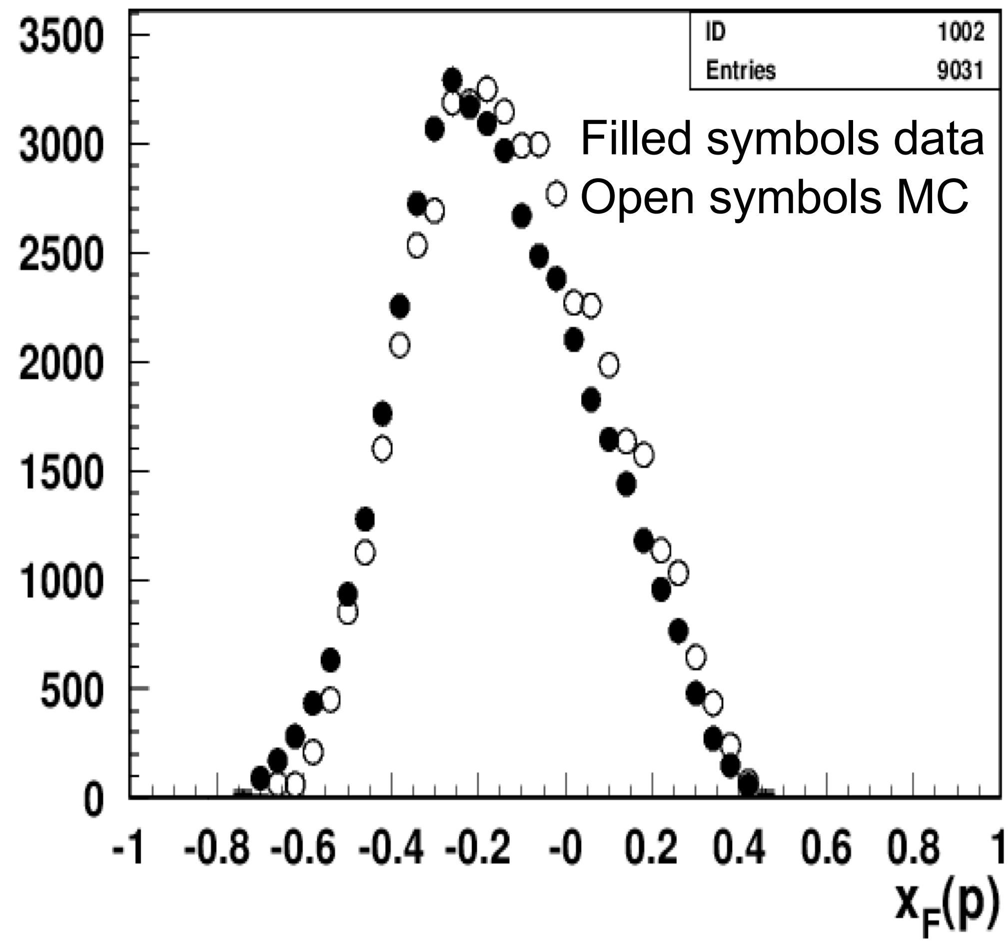
- CLAS12 data supports predictions from different MCs of a very significant fraction of inclusive pions coming from correlated dihadrons (large VM fraction supported by latest e+e- studies).

- 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,…)

CLAS12 Studies:Data vs MC

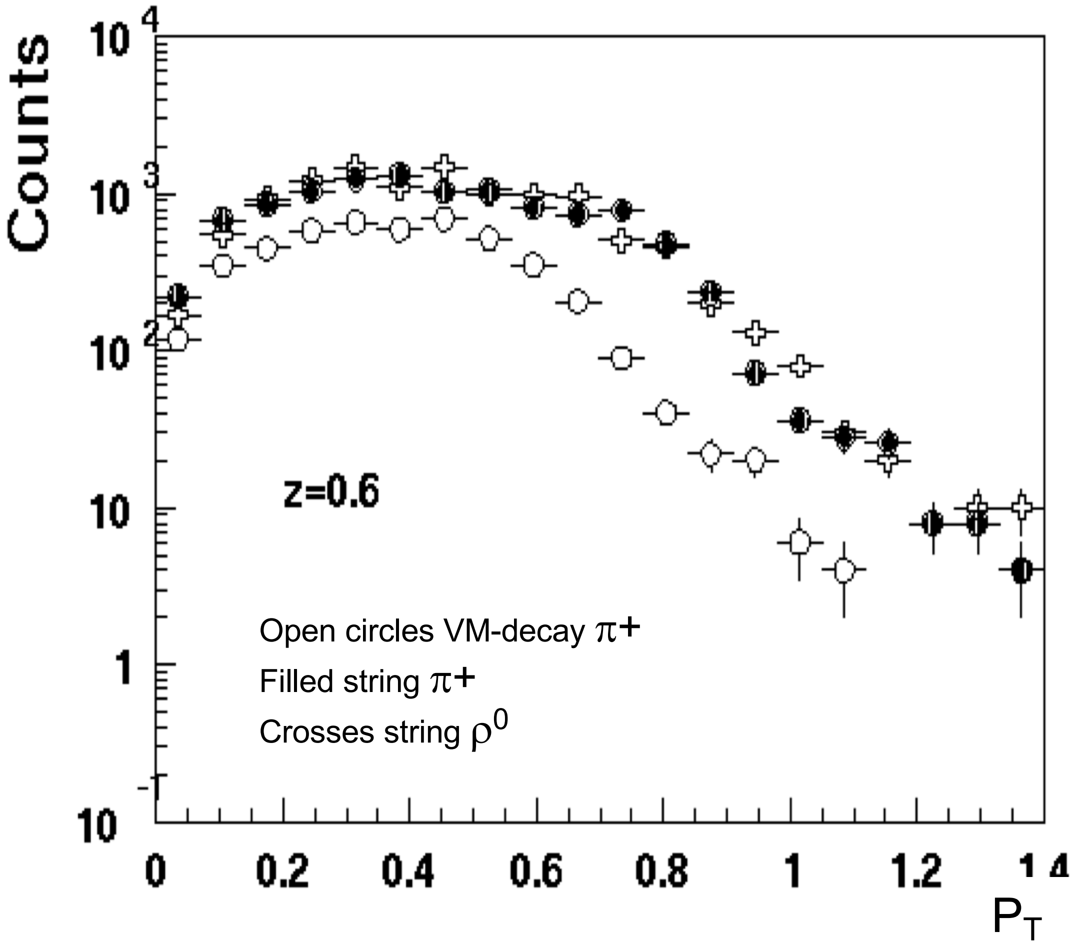
Using PEPSI (LUND) generator





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

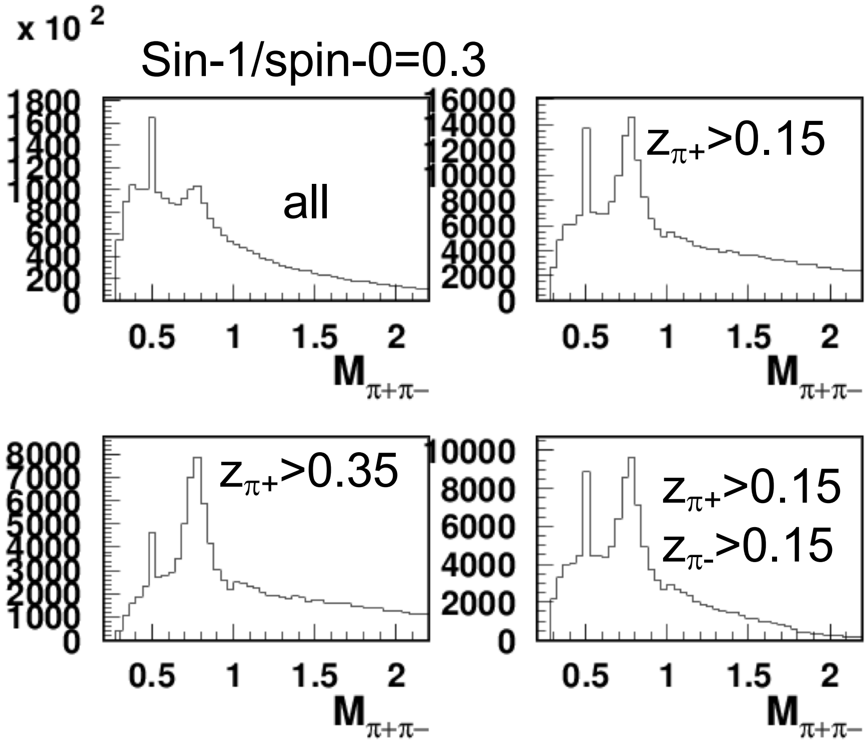
JLab12: SIDIS and P_T

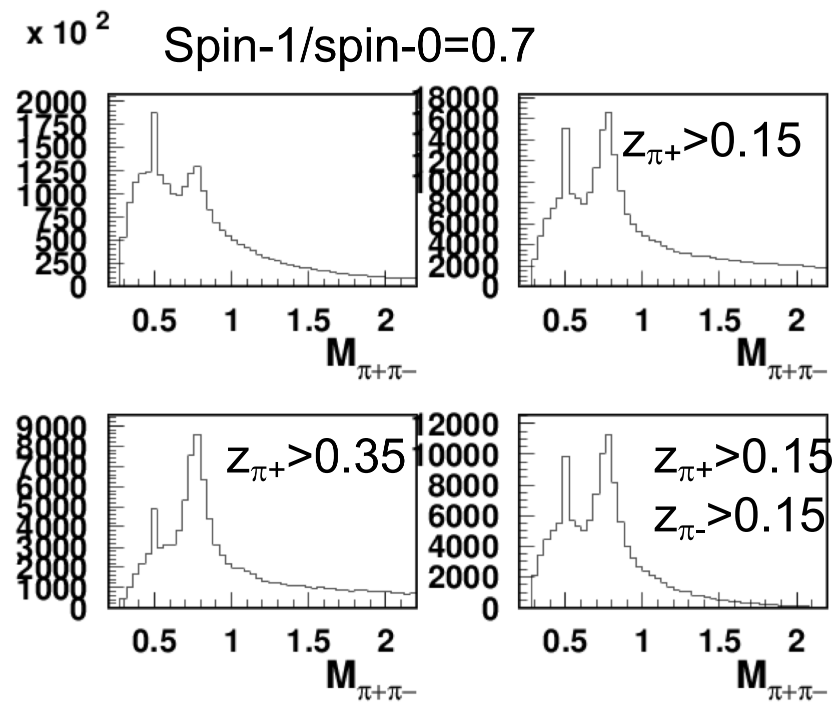


Direct pions and rhos have the same P_T-distributions carrying direct information about the k_T-structure of the initial quarks

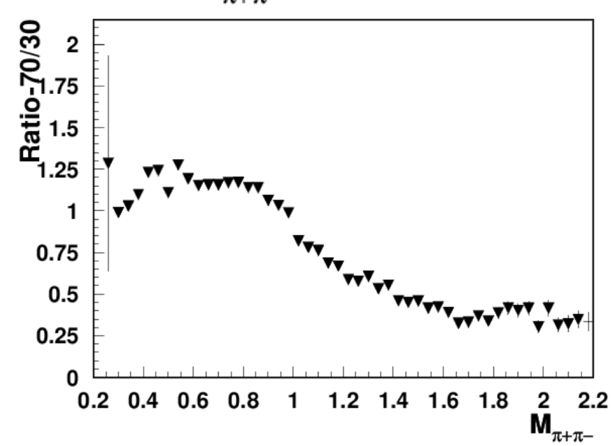
Hadrons produced from decays will have in average much lower P_T for the same z, and studies of k_T-structure will require additional input

EIC (5x50) 2-hadron mass spectra





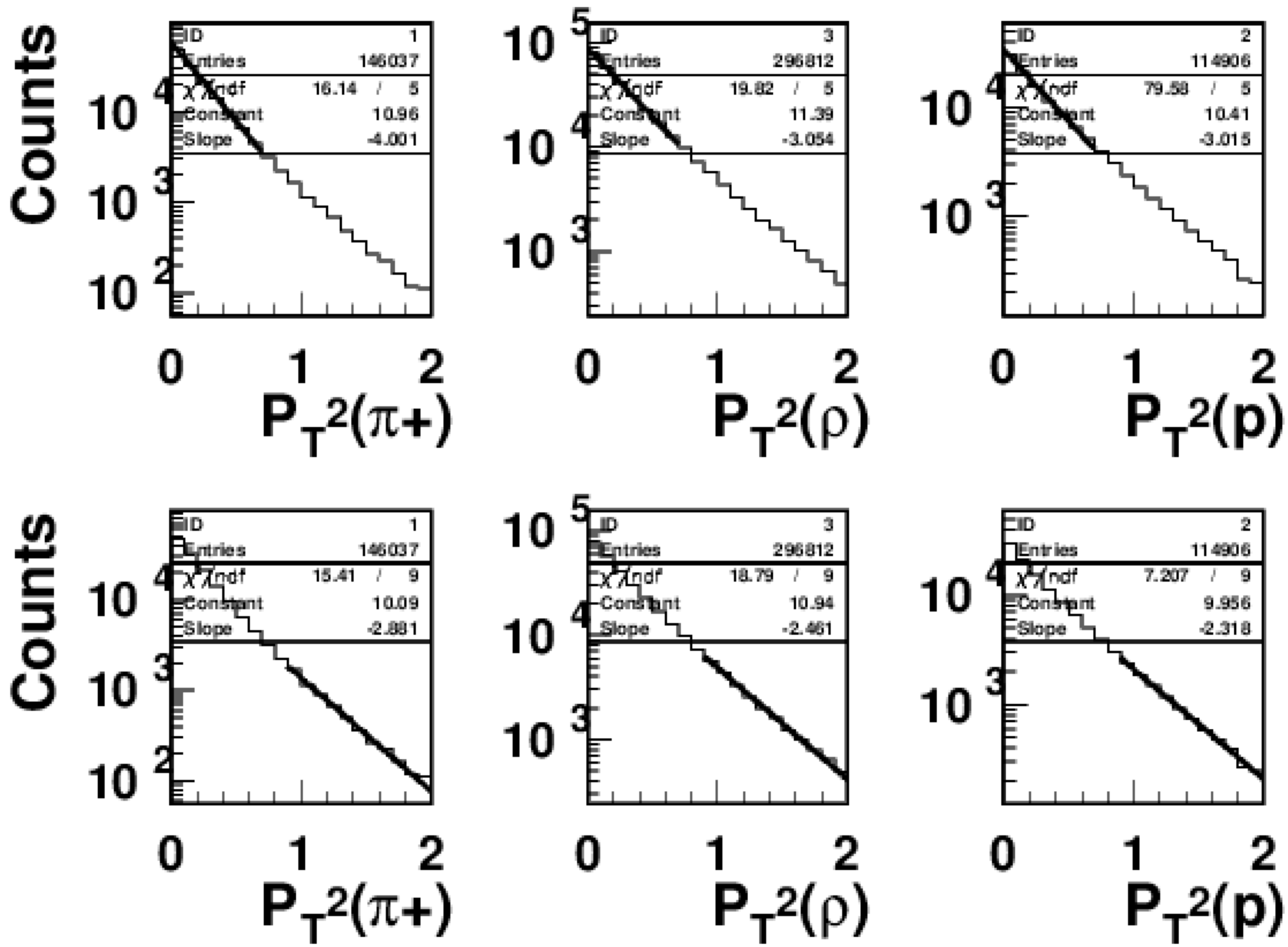
- The rho peak is not increasing visually with increase of the fraction of VMs, as higher number of VMs create comb.bck.
- Most of the background comes from low momentum particles at large $M_{\pi\pi}$



Accessing the k_T (COMPASS)

Fit $0<P_T<0.8$

Fit $0.9<P_T<1.5$

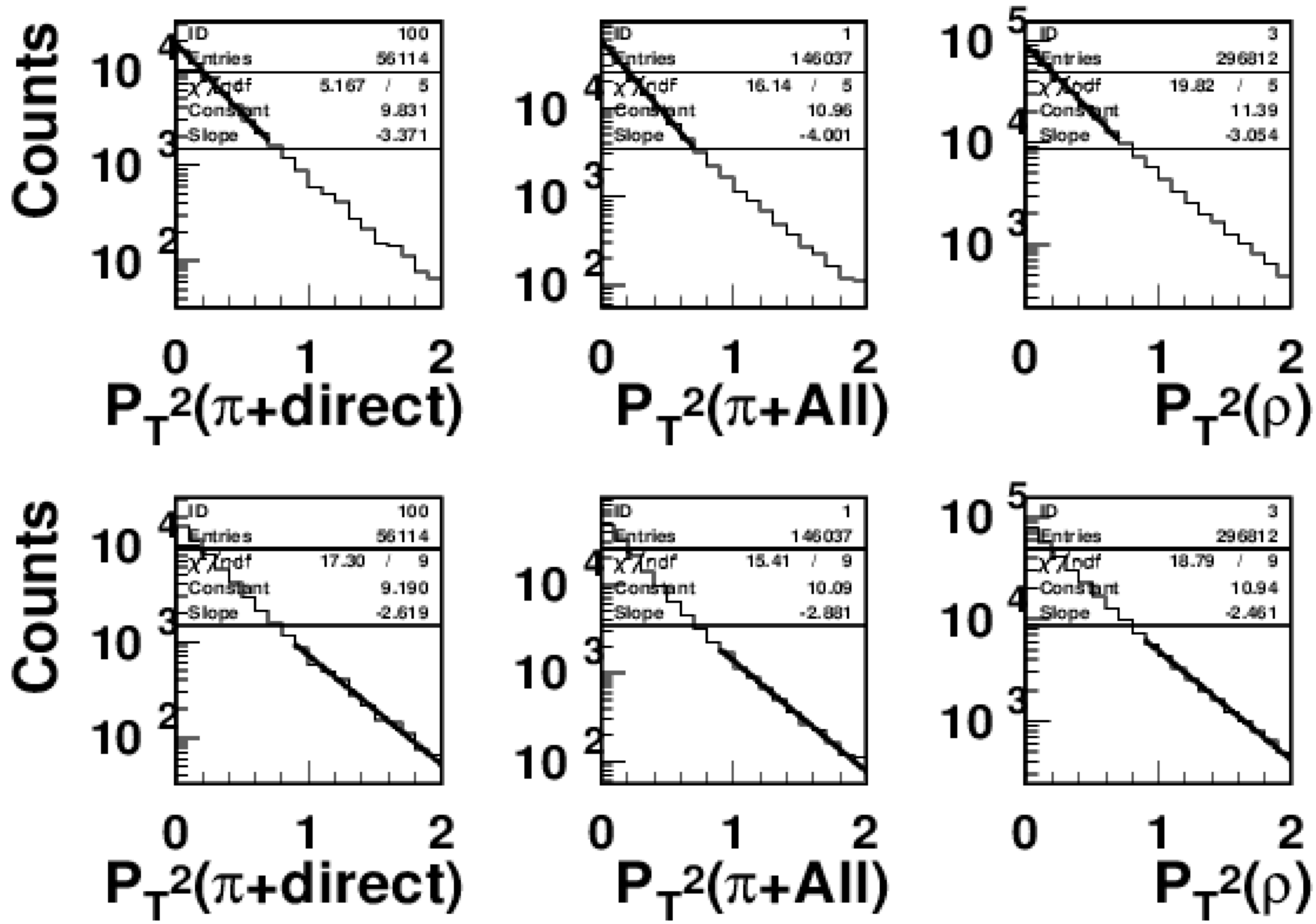


Fit to P_T gives significantly wider P_T for larger PT (bigger effect for pions)

Accessing the k_T (COMPASS)

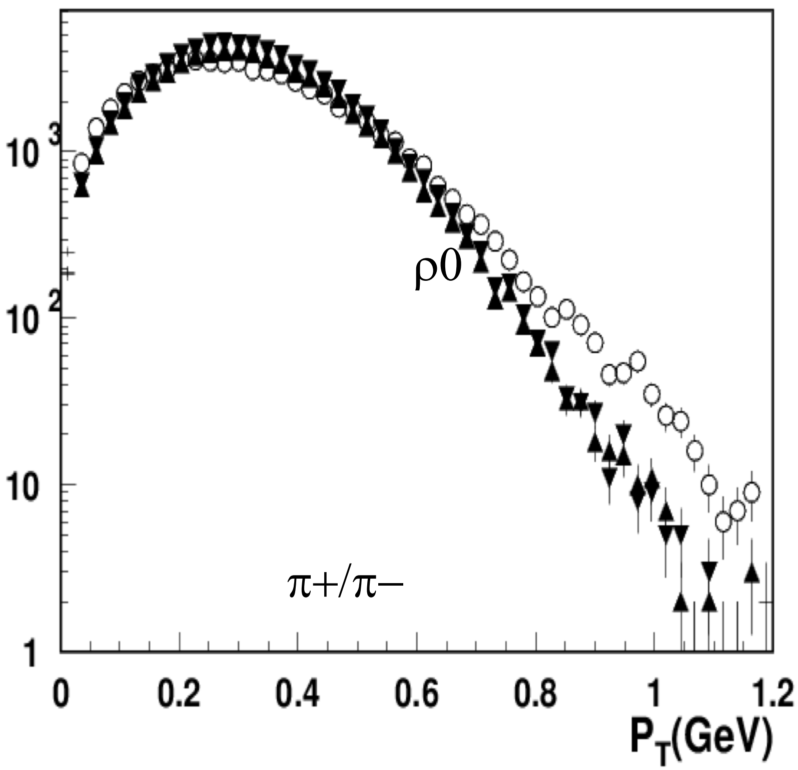
Fit $0<P_T<0.8$

Fit $0.9<P_T<1.5$

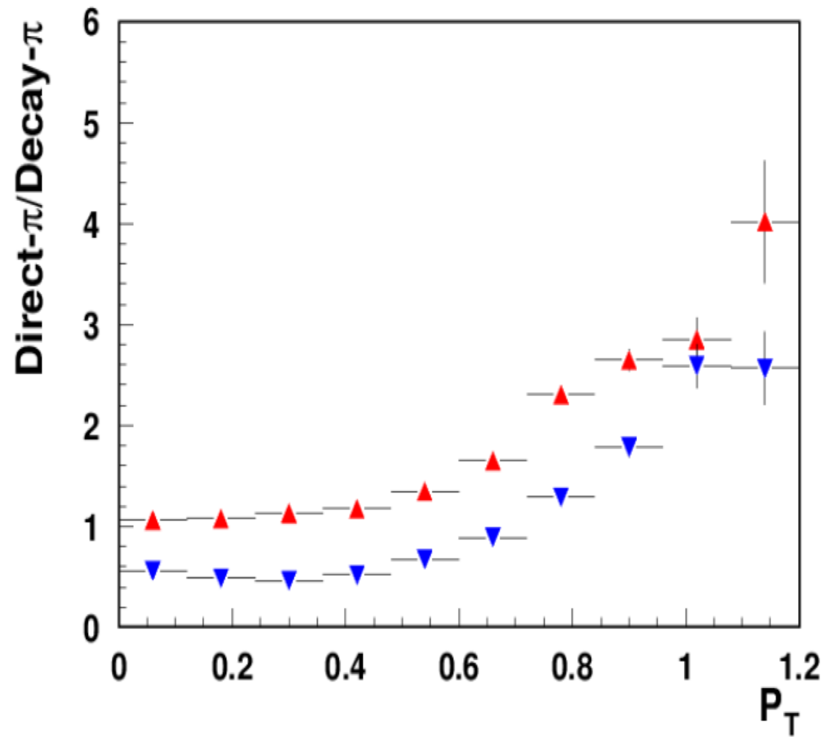


Fit to P_T gives similar P_T for direct pions and rhos

P_T of pions from rho decays: LUND string fragmentation

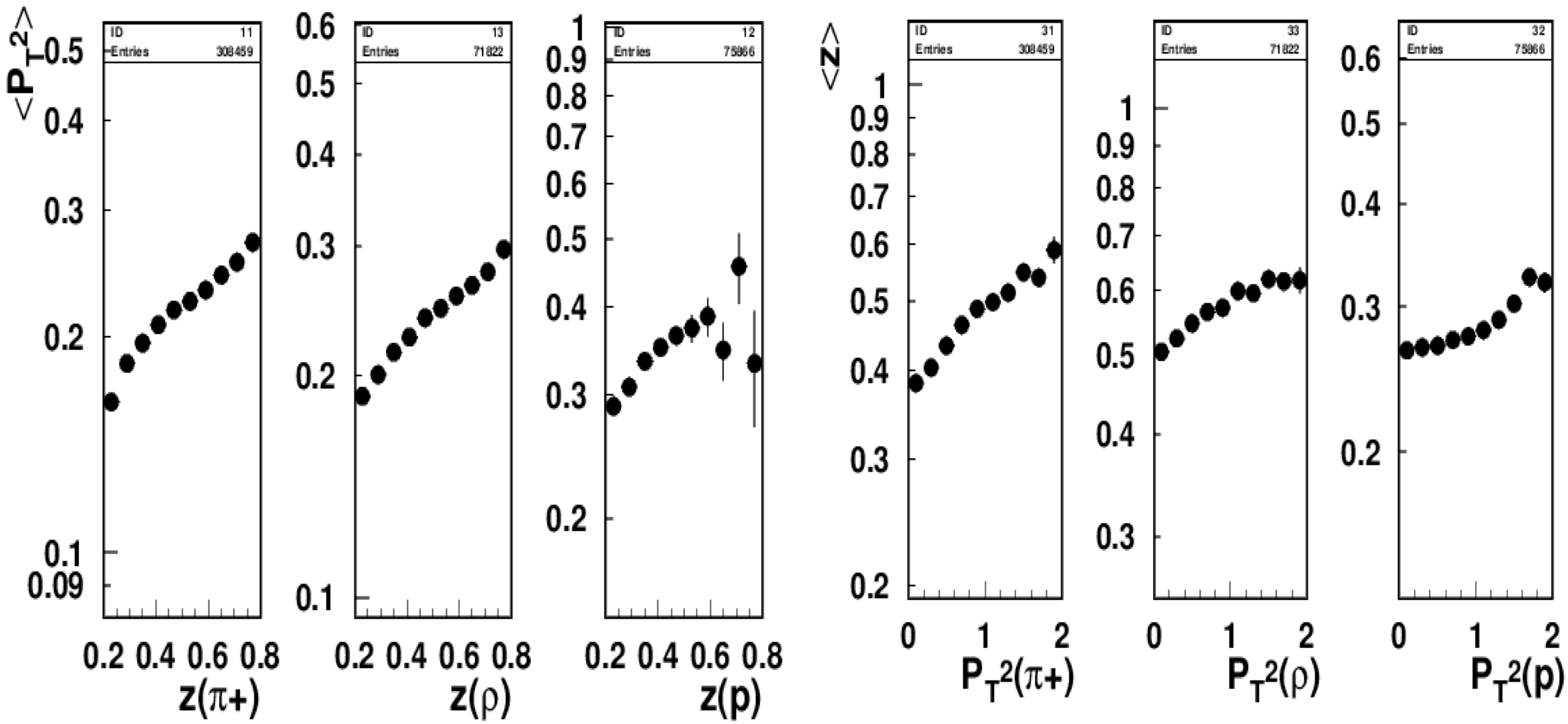


P_T-dependence of rho is similar to the one for decay pions

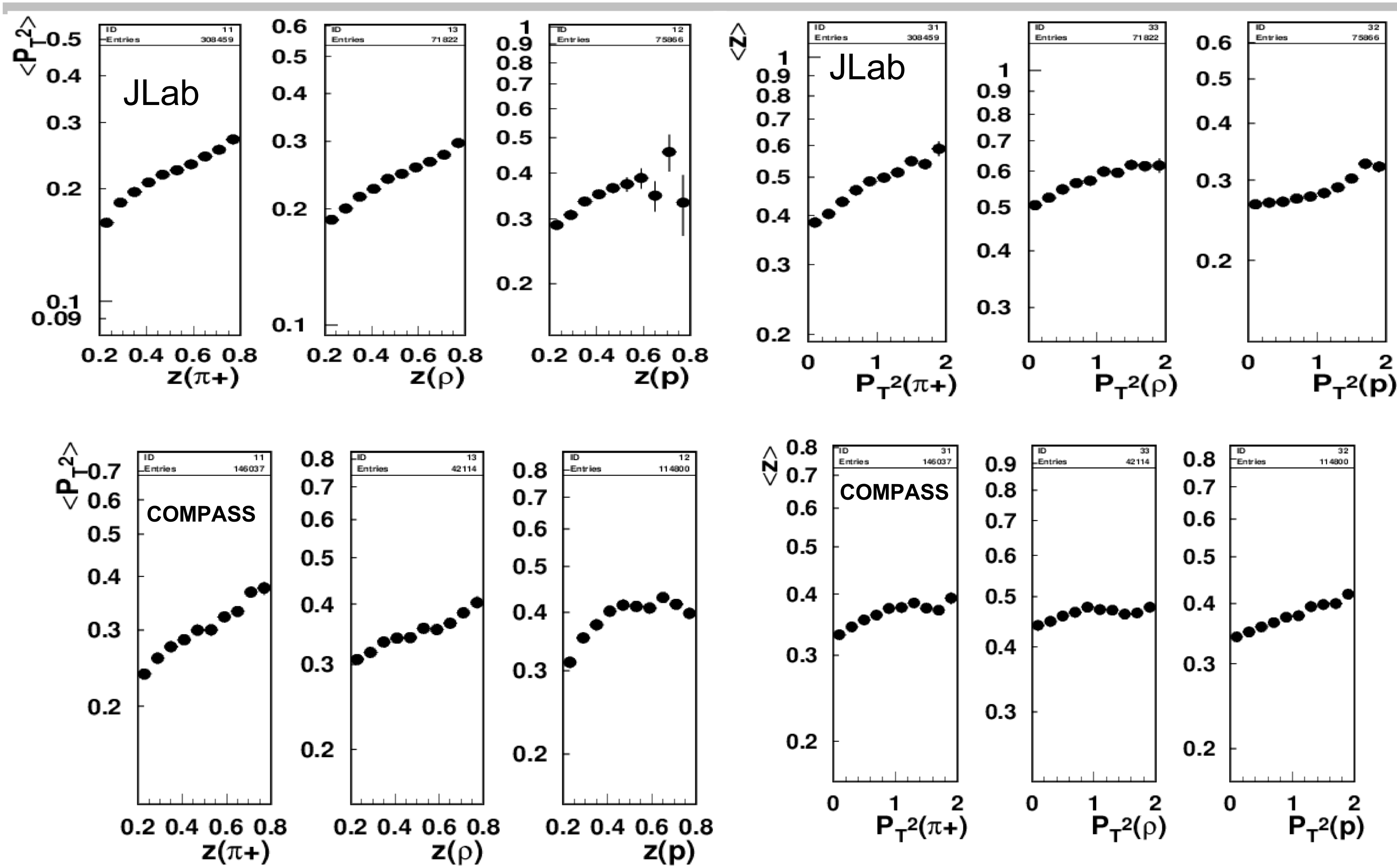


Fraction of direct $\pi+$ increases with P_T

Kinematical averages (JLab)



Kinematical averages (Jlab vs COMPASS)

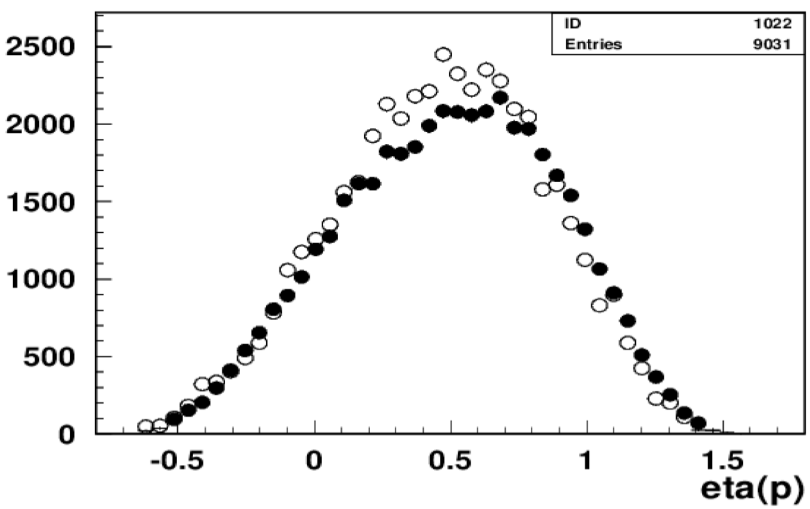


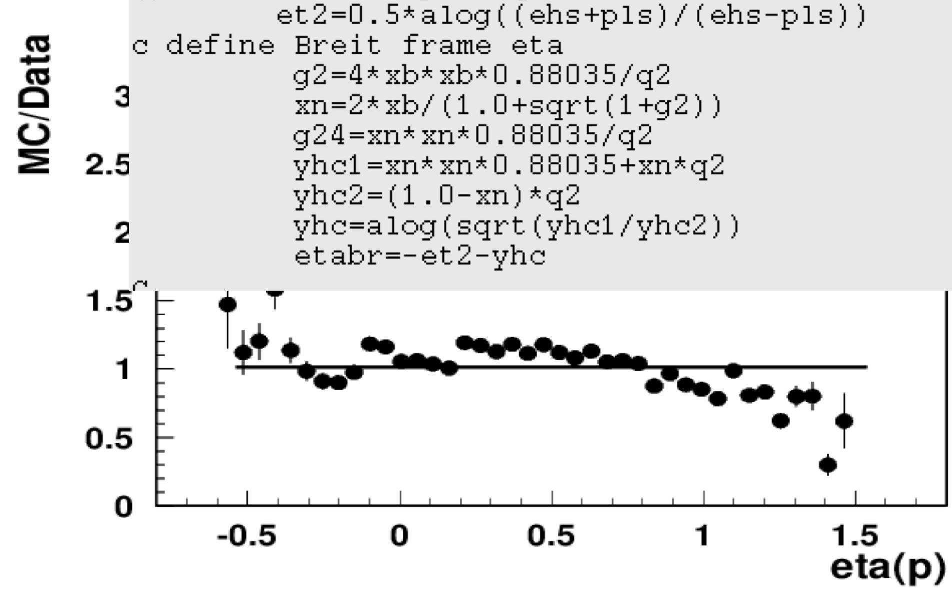
CLAS12 Studies

Using PEPSI (LUND) generator rapidity in Breit frame

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

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

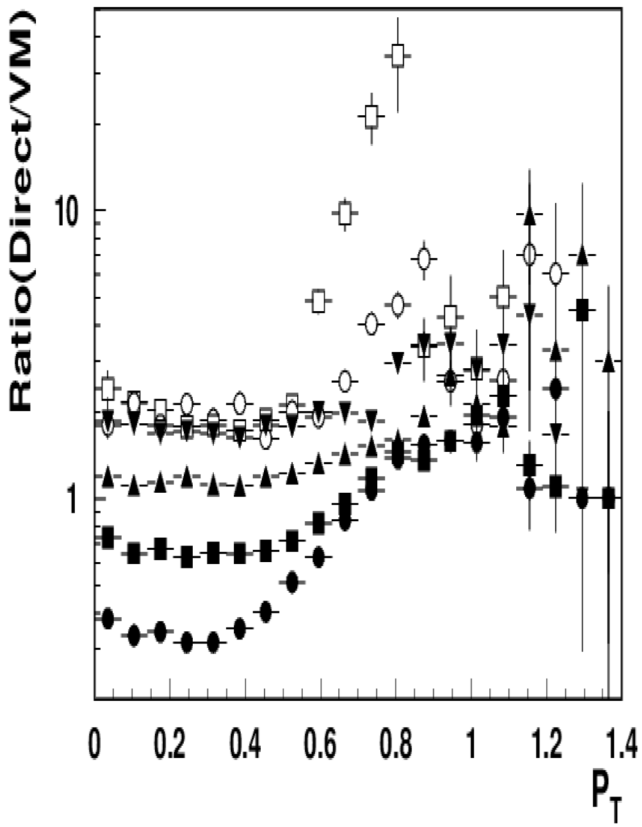


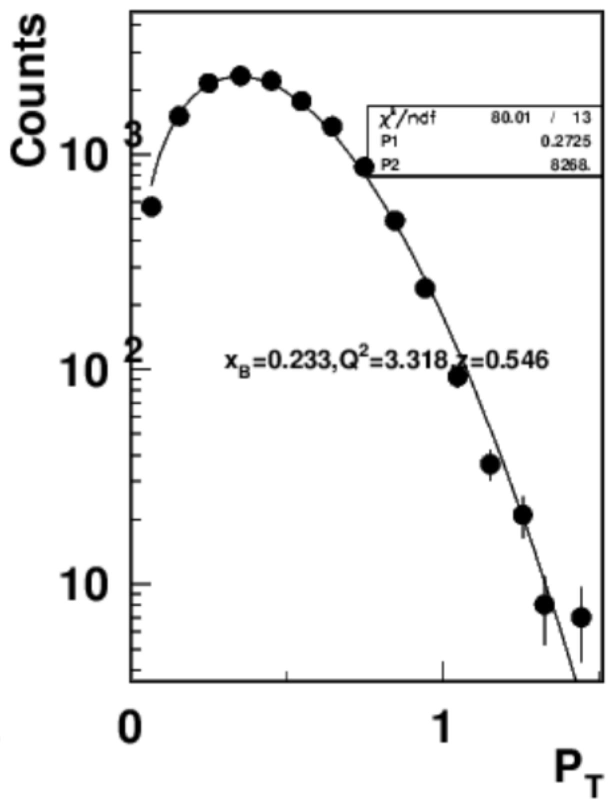


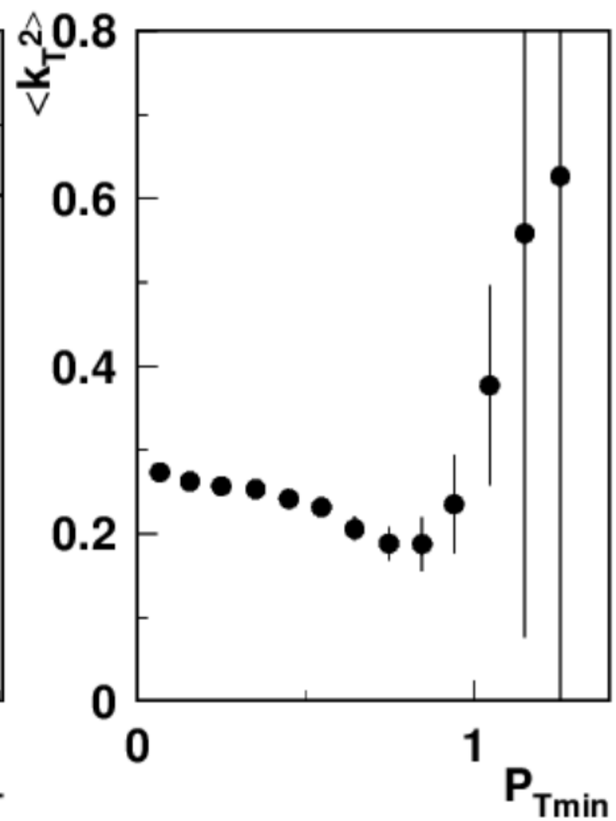

```
c        ptrann=pts
^        xfhad=2*pls/sqrt(ww2)
         et2=0.5*alog((ehs+pls)/(ehs-pls))
c define Breit frame eta
          g2=4*xb*xb*0.88035/q2
          xn=2*xb/(1.0+sqrt(1+g2))
          g24=xn*xn*0.88035/q2
          yhc1=xn*xn*0.88035+xn*q2
          yhc2=(1.0-xn)*q2
          yhc=alog(sqrt(yhc1/yhc2))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

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

Accessing the kT







Higher PT, closer
tooriginal distribution
for pions

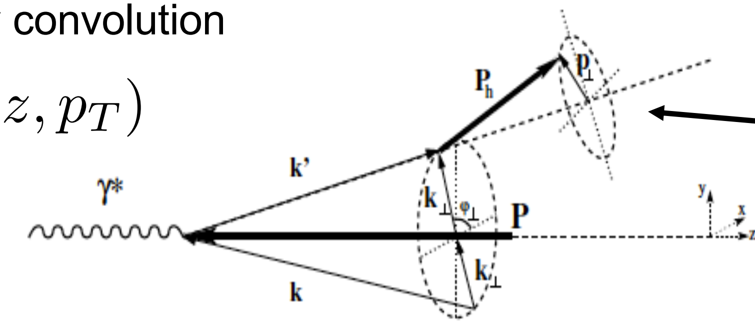
Fit with a single Gauss, starting from some Ptmin
Higher Ptmin less the decay fraction, closer to
original k_T-width of distribution for pions

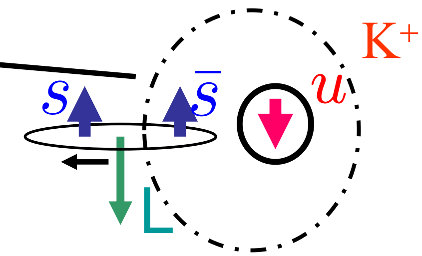
N/q	U	L	T
U	f_1		
L		g_1	
T			h_1

Flavor dependence of transverse momentum

SIDIS x-section defined by convolution

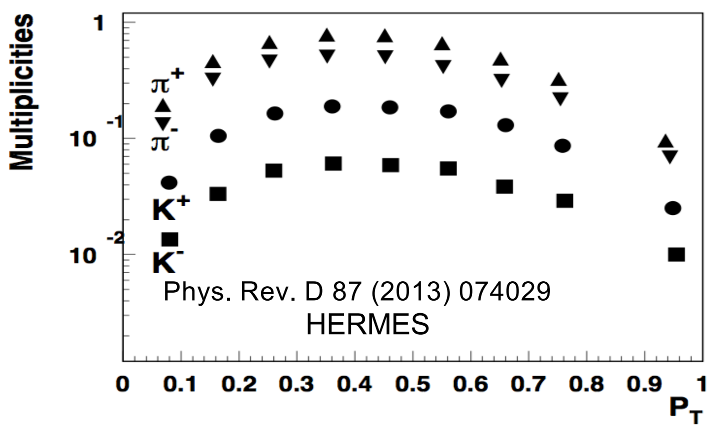
$$f_1^q(x, k_T) \otimes D_1^{q\to h}(z, p_T)$$

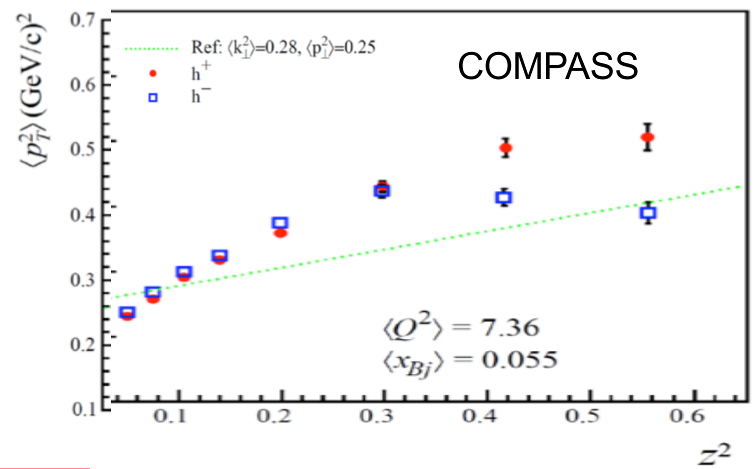




Disentanglement of z and P_{hT} : provides access to the transverse intrinsic quark k_T and fragmentation $p_{T,}$

$$\langle P_{h\perp}^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle$$





Multiplicities deviate from simple Gaussian distributions already at small P_T
Data indicating flavor dependence of widths of partonic distributions

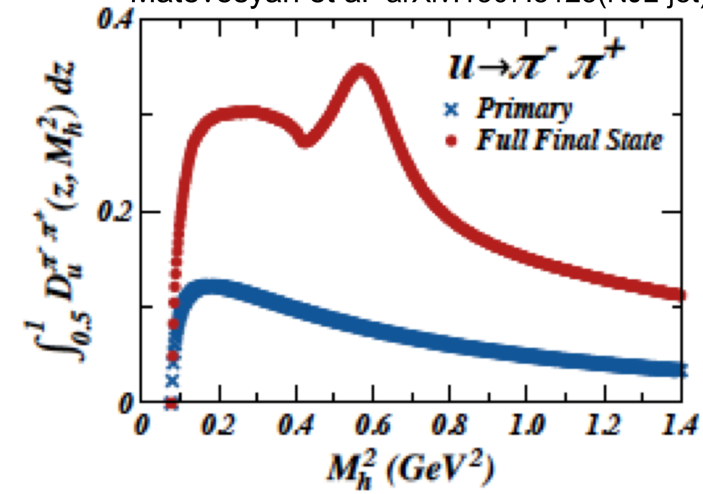
Precision studies of transverse momentum dependence of distribution and fragmentation functions are crucial for future SIDIS program at Jlab/COMASS/EIC

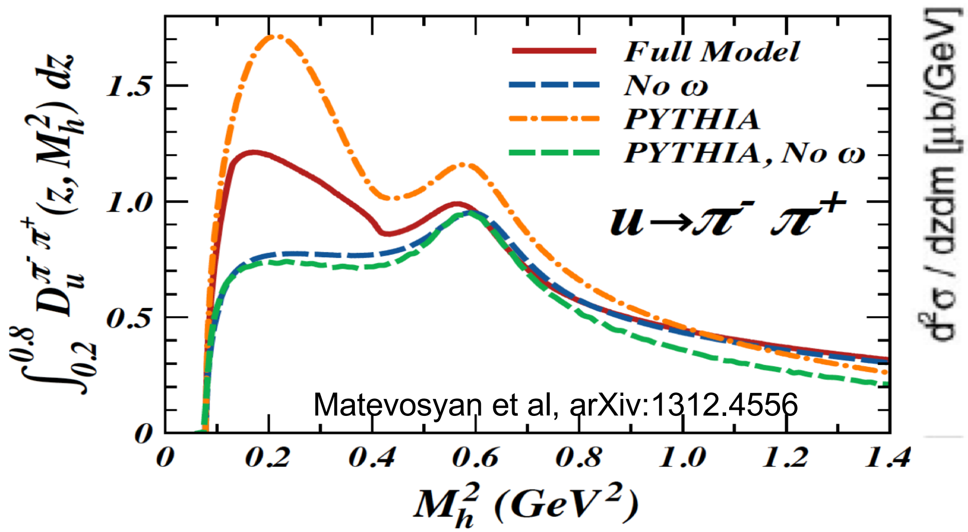
Dihadron production

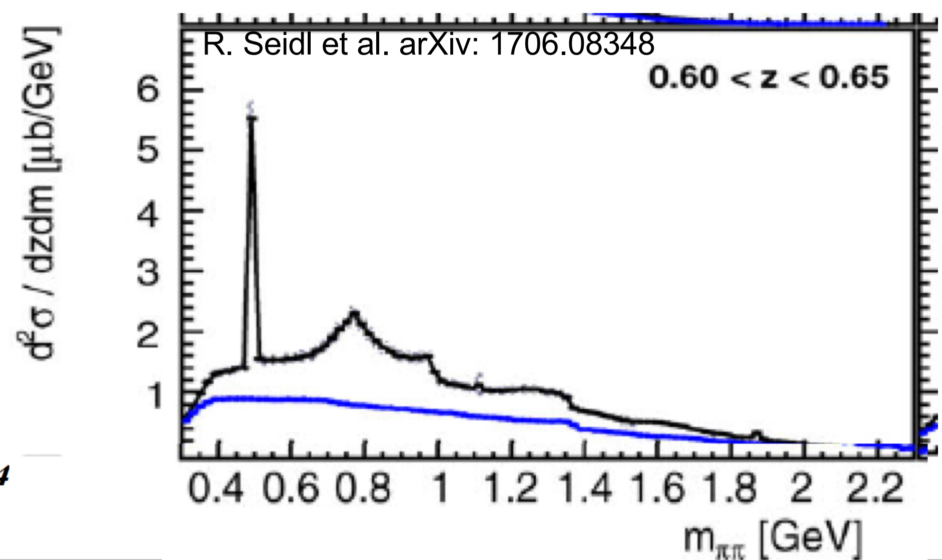
HERMES-note-96.059

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

Matevosyan et al arXiv:1307.8125(NJL-jet)





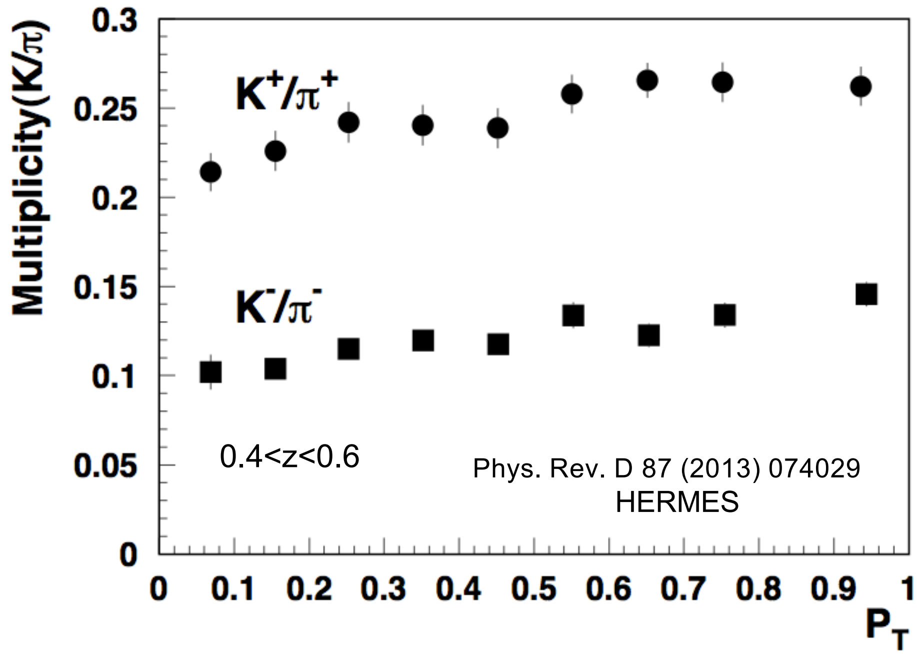


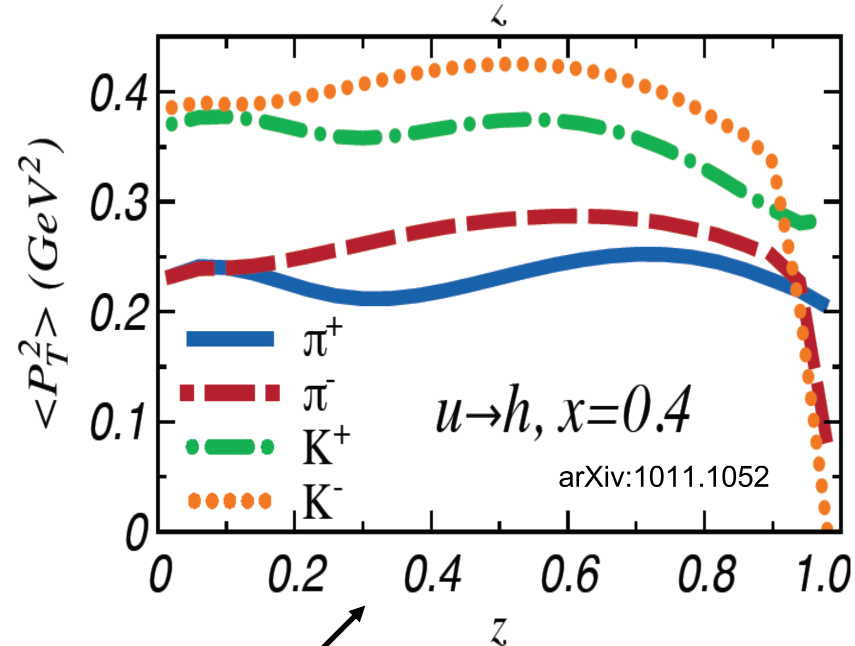
Hadronization effects

$$f_1^q(x,k_T)\otimes D_1^{q\to h}(z,p_T)$$

$$D_1^{u\to\pi^+}(z,p_T)$$
$$D_1^{u\to K^+}(z,p_T)$$

•Widths of fragmentation functions are flavor dependent. (H. Matevosyan, A. W. Thomas & W. Bentz)

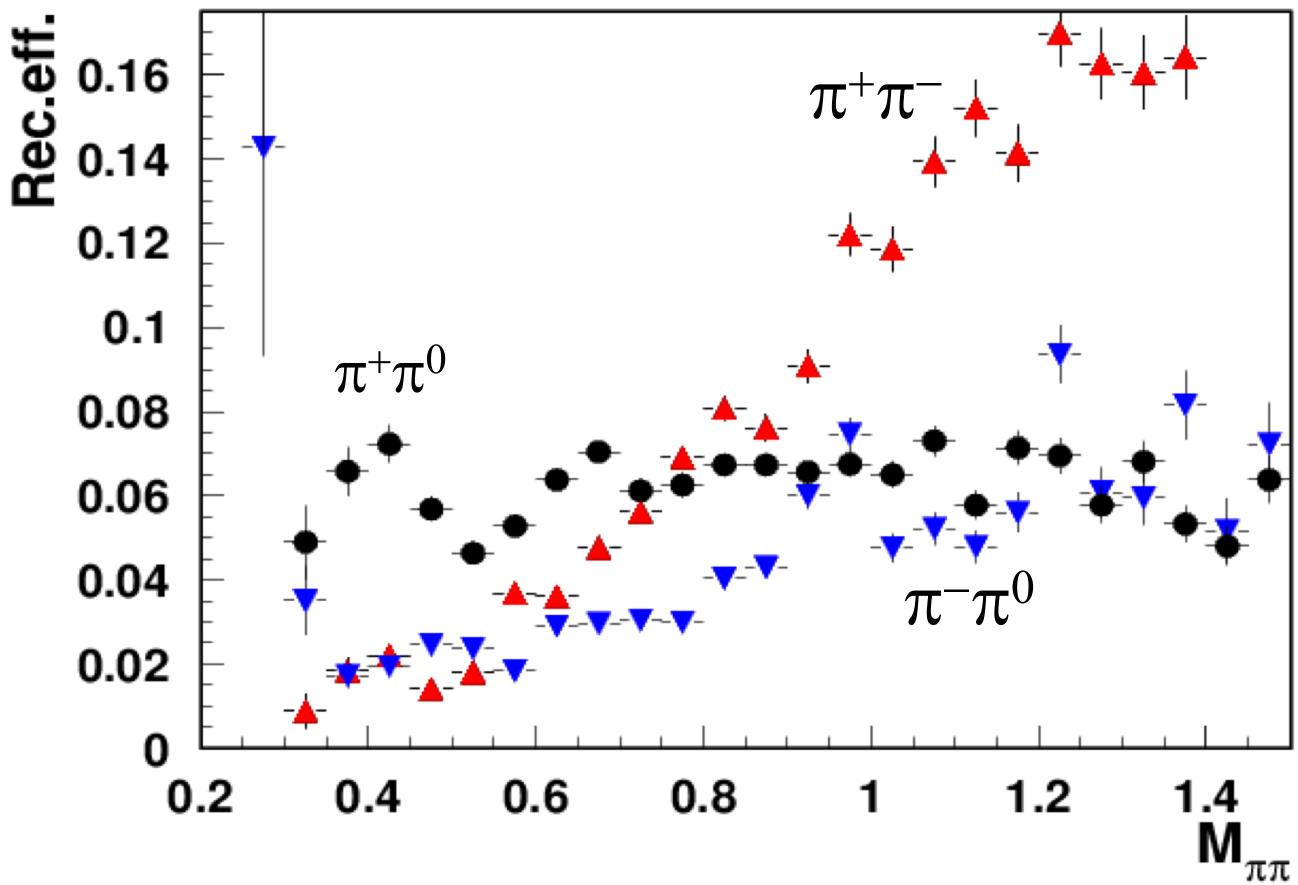




Assuming u-quark dominance the increase with P_T of the fraction of kaons in the final hadron sample is consistent with wider $D_1^{u\to K}$

Study of kaon multiplicities in SIDIS is crucial for understanding of spin-orbit effects in hadronization

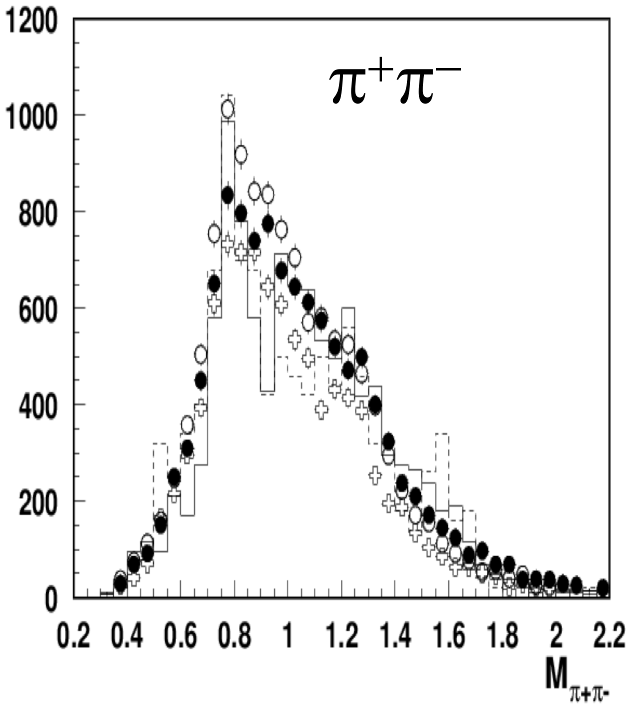
Invariant mass of pion pairs Mππ

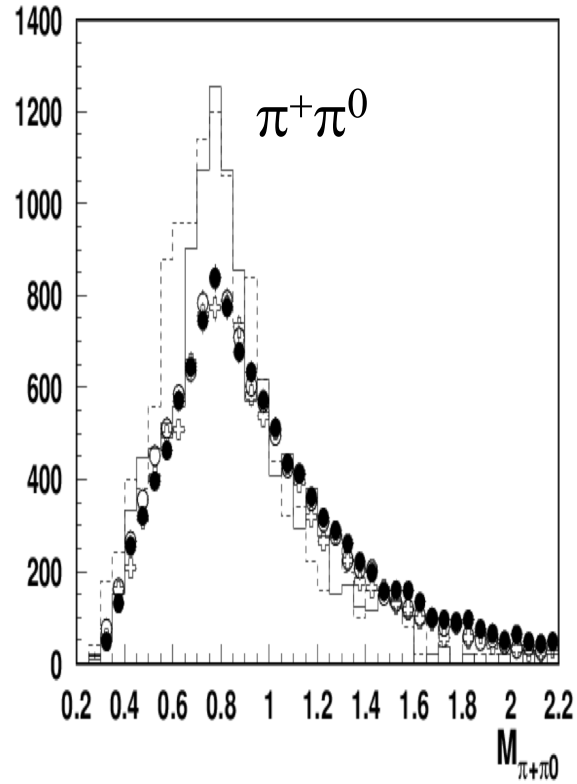


Reconstruction efficiencies extracted from LUND-MC with full GEANT4 simulation of CLAS12

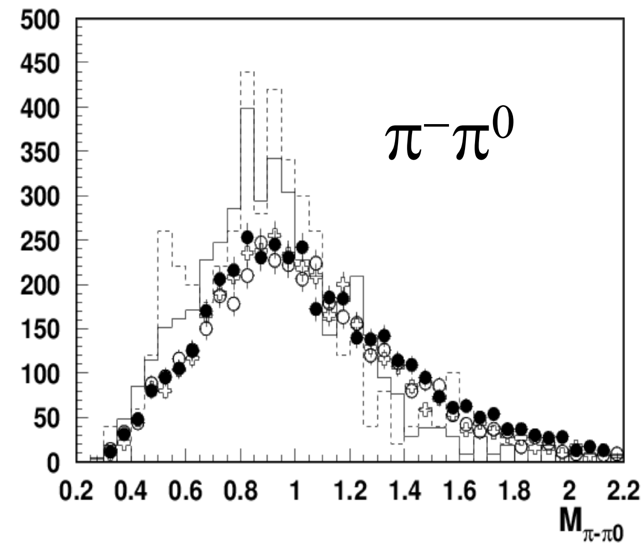
In the range 0.7<Mππ <0.9 efficiencies for ρ0 and ρ+ comparable

Invariant mass of pion pairs $M\pi\pi$





Number of ρ+ very significant



Curves 2 MC versions with 50 and 70% of spin-1
Circles 3 run sets RGA-Fall/Spring2019
5001(open), 5036 (full circles) 6715 (crosses)

should be redone with new cook of low lumi runs

Multiplicities from data consistent with multiplicities coming from CLAS12 LUND MC