3D structure and spin-orbit correlations

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JLEIC SIDIS Working group meeting, Nov 25, 2019

- TMDs: measurements, extractions, interpretation
- Old observables new possibilities
- New observables
- EIC simulations
- Tools available and needed to accomplish studies of 3D dynamics
- Conclusions

Main publications on EIC related to 3D

Transverse Momentum Dependent Parton Distribution/Fragmentation Functions at an Electron-Ion Collider
M. Anselmino (INFN, Turin & Turin U.) et al.. Jan 2011. 44 pp.
Published in Eur.Phys.J. A47 (2011) 35] (citations: 41)

Gluons and the quark sea at high energies: Distributions, polarization, tomography
Daniel Boer (Groningen U.) et al.. 547pp
e-Print: arXiv:1108.1713 [nucl-th] (citations: 479)

Electron Ion Collider: The Next QCD Frontier : Understanding the glue that binds us all
A. Accardi (Jefferson Lab & Hampton U.) et al.. Published in Eur.Phys.J. A52 (2016) no.9, 268 (citations: 661)

- Get predictions, which can be checked by future measurements (used)
- Make measurements in different kinematical domain to shed light on things we already know we don't understand (suggested)

Need to define priorities to focus on advantages of EIC (JLEIC) version with highest priority on 3D physics, requiring lower energies and higher luminosities

Tables of golden measurements

arXiv:1108.1713

Three-dimensional structure of the nucleon and nuclei: transverse momentum dependence				
Deliverables	Observables	What we learn	Phase I	Phase II
Sivers and unpolarized TMDs for quarks and gluon	SIDIS with transv. polarization/ions; di-hadron (di-jet) heavy flavors	quantum interference multi-parton and spin-orbit correlations	valence+sea quarks, overlap with fixed target experiments	3D Imaging of quarks and gluon; Q^2 ($P_\perp$) range QCD dynamics

QCD matter in nuclei				
Deliverables	Observables	What we learn	Phase I	Phase II
integrated gluon distributions	$F_{2,L}$	nuclear wave function; saturation, Q_s	gluons at $10^{-3} \leq x \leq 1$	explore sat. regime
k_T-dep. gluons; gluon correlations	di-hadron correlations	non-linear QCD evolution/universality	onset of saturation; Q_s	RG evolution
transp. coefficients in cold matter	large-x SIDIS; jets	parton energy loss, shower evolution; energy loss mech.	light flavors, charm bottom; jets	precision rare probes; large-x gluons

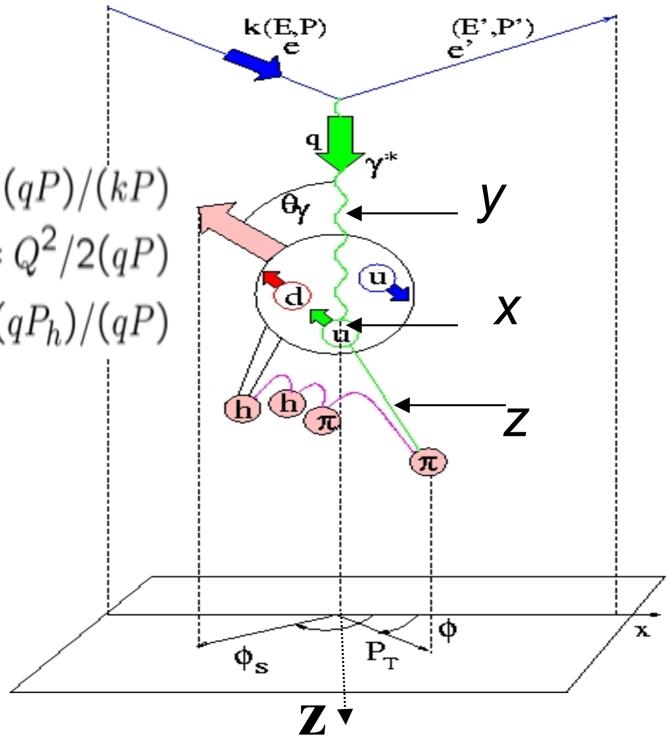
JLAB12 collected data which can, and should be used in defining the future measurements at JLEIC related to 3D distribution and fragmentation functions

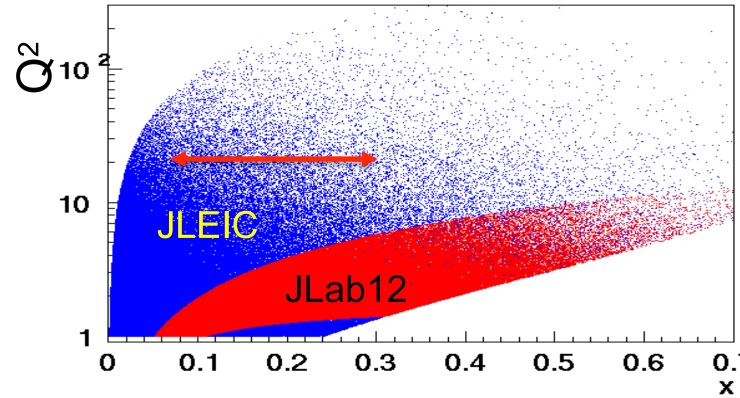
SIDIS kinematical plane and observables

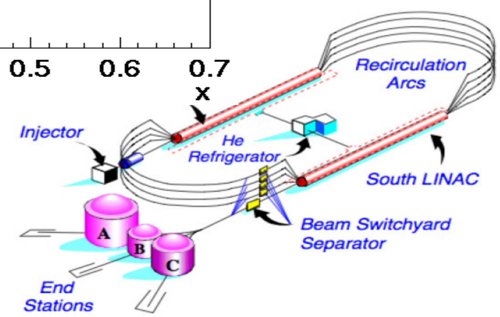
$y = (qP)/(kP)$

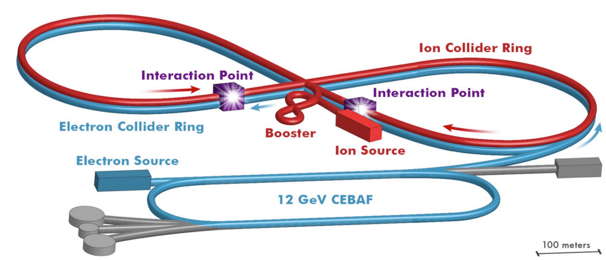
$x = Q^2/2(qP)$

$z = (qP_h)/(qP)$









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

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

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

beam polarization

target polarization

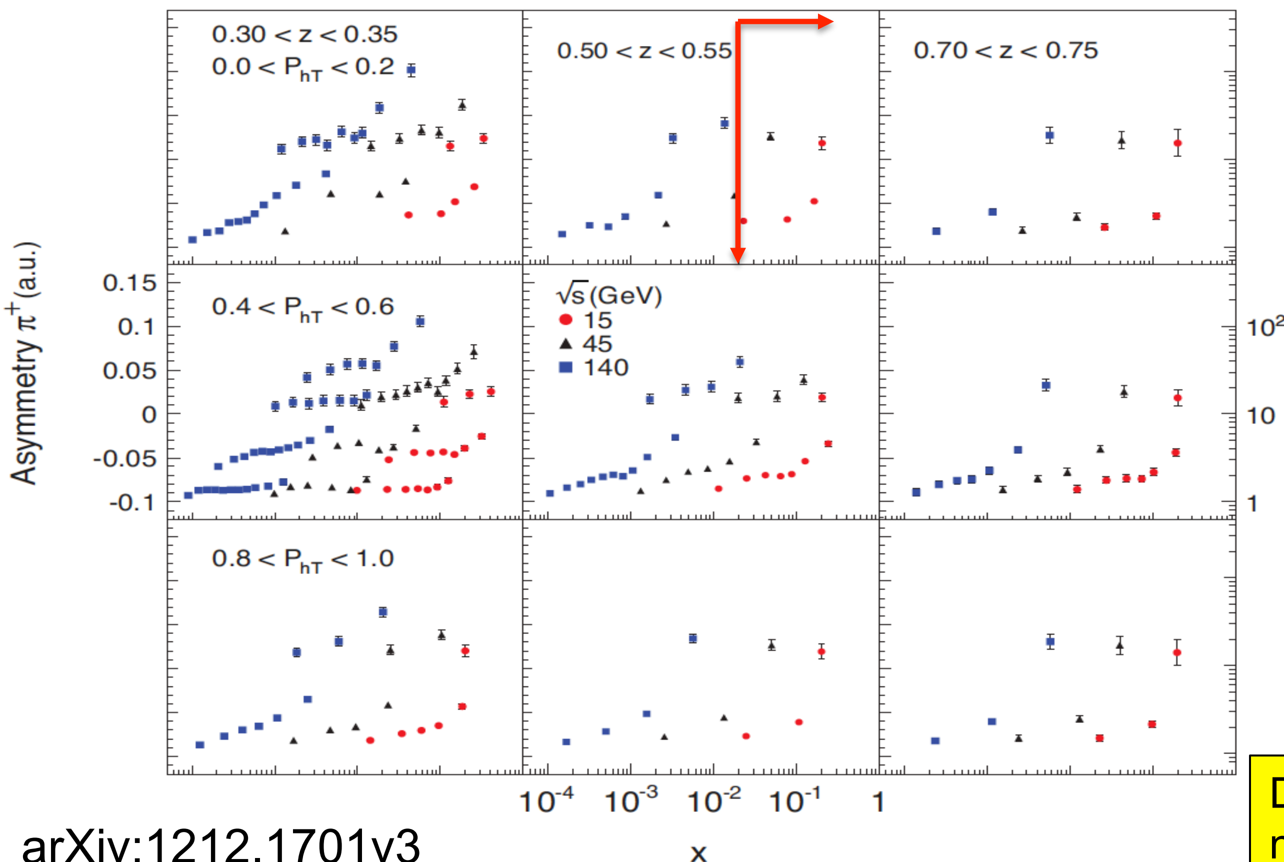
corrections for the region of large kT~Q

Overlap in 0.05<x<0.25 crucial for interpretation of 3D

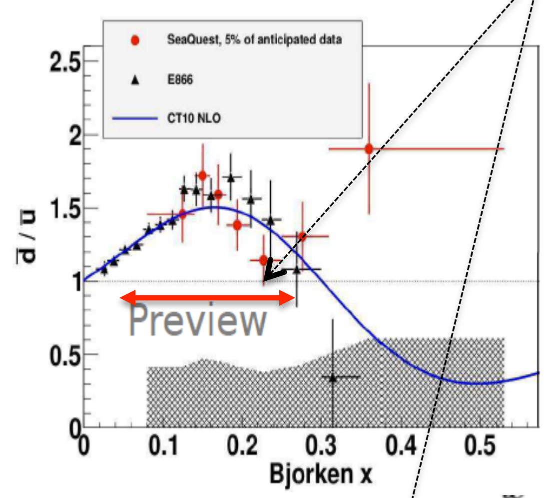
Non-perturbative physics as a key for understanding the dynamics

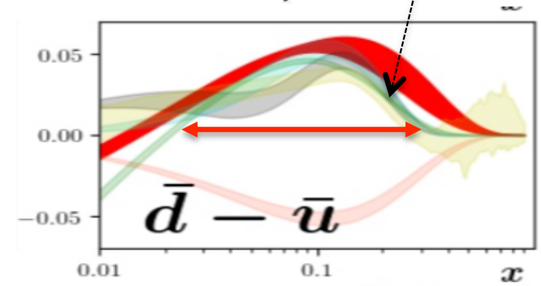
luminosity of 10 fb^{-1} $\sqrt{s} = 140$ GeV, $\sqrt{s} = 45$ GeV and $\sqrt{s} = 15$

0.05<x<0.25



arXiv:1212.1701v3





Define kinematics, where the non-perturbative effects matter

- Explore the transverse momentum dependence of the SSA in a wide range
- Cover the kinematics where the non-perturbative see is relevant
- With increasing z and P_T the x>0.01 becomes increasingly inaccessible at large **s**

Possible activities: what is needed

1) More detailed studies of possible underlying systematics for projections appearing as "golden" observables of EIC related to 3D structure(Ex. Sivers Effects) in complex azimuthal asymmetries, to define additional observables, which may clarify the picture

2) Adding more observables sensitive to the structure of nucleon and nuclei, and underlying QCD dynamics

Do we have tools needed for systematical studies of the 3D structure?

Simulation of spin-orbit observables is the only way to understand the systematics of any kind of measurements and their interpretation based on any kind of formalism

what is needed

1. MC generators, both full event and dedicated, including spin-orbit correlations. With all the complexity of multiple SFs involved in the structure of azimuthal distribution understanding of correlations will be critical to make any kind of useful projections.
2. Development of full Extraction and VAlidation MC chain (EVA) to understand all consequences of various simplifications and assumptions (ignoring RC, other SF contributions, various correlations in the distributions and final hadronization process,...). Understanding of systematics of measurements and extraction procedures is crucial

Possible activities

1) More detailed studies of possible underlying systematics for projections appearing as "golden" observables of EIC related to 3D structure(Ex. Sivers Effects) in complex azimuthal asymmetries (ex. Sivers effect coming purely from RC)

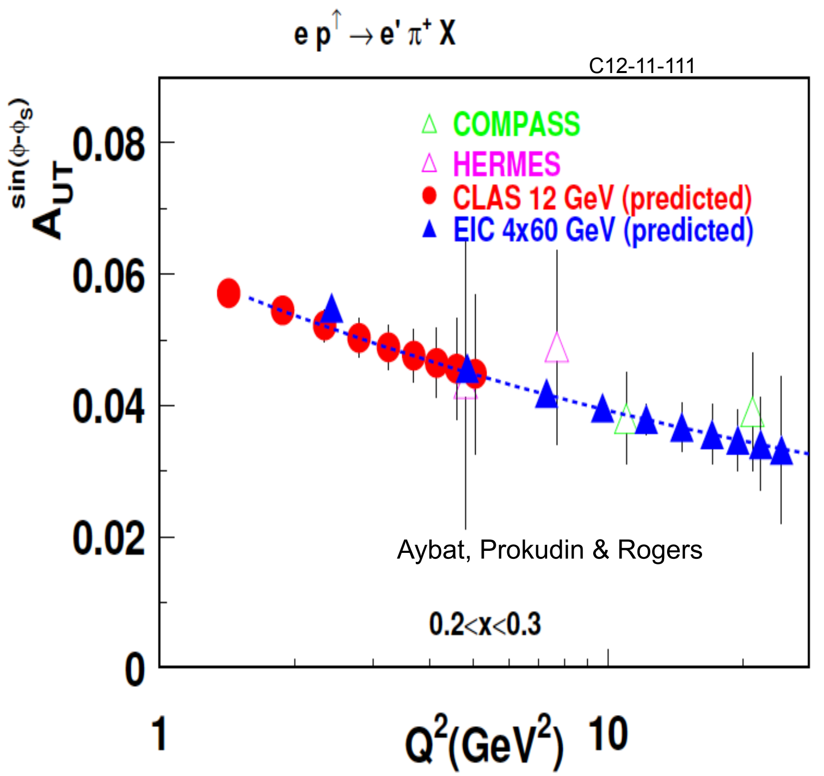
- measurements of Q^2-dependence of observables, testing the current understanding of evolution properties of involved TMDs. So far we measure the A_LU Q^2-dependence, and already get some surprises.
- measurements of P_T-dependences of observables, to understand the role of different factors, including correlations in hadronization process (for ex. SSA generated in VM decays.)
- understand the role of radiative corrections accounting for structure functions, which can contribute

2) Adding more observables sensitive to the structure of nucleon and nuclei:

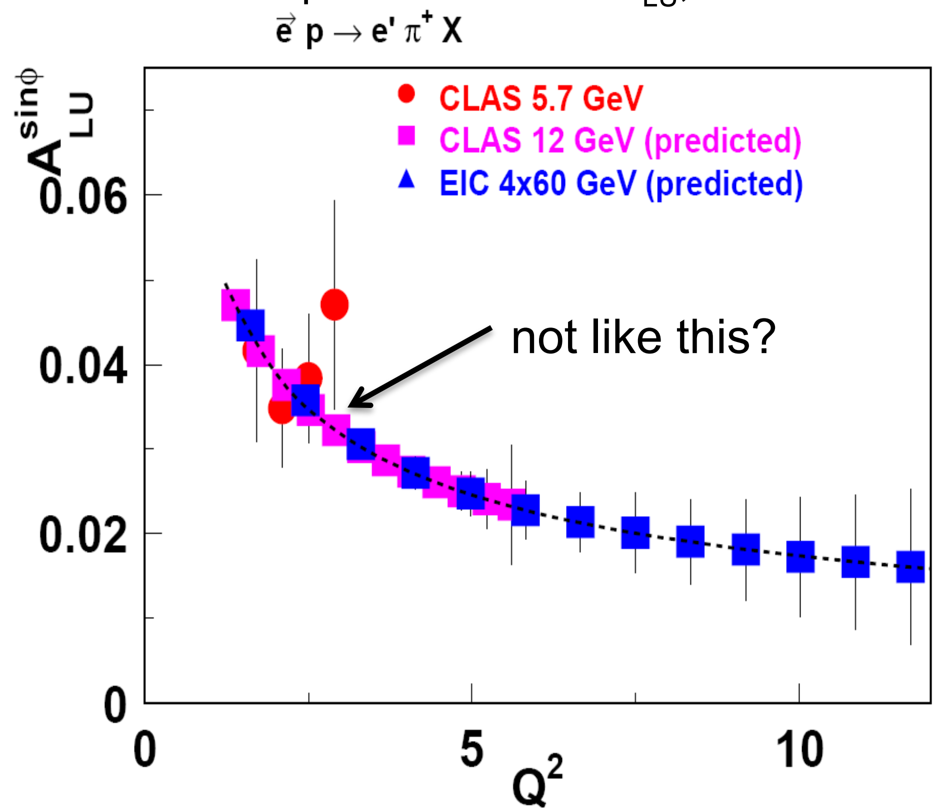
- More final states, like Lambda, di-hadrons, including also SSA from polarization of the final state particles
- Correlations in target and current fragmentation. Ex. possible tagging of strange quarks with detection of Lambdas in target and Kaons in forward direction, proton pion correlations,…
- medium modifications of TMDs and GPDs. This we need already for NH3 target measurements with CLAS12, as most of the events are coming from nitrogen

Evolution and k_T-dependence of TMDs: from CLAS12 to JLEIC

Q^2-dependence of Sivers A_{UT}, $f_1^{\perp}(x, k_T)$

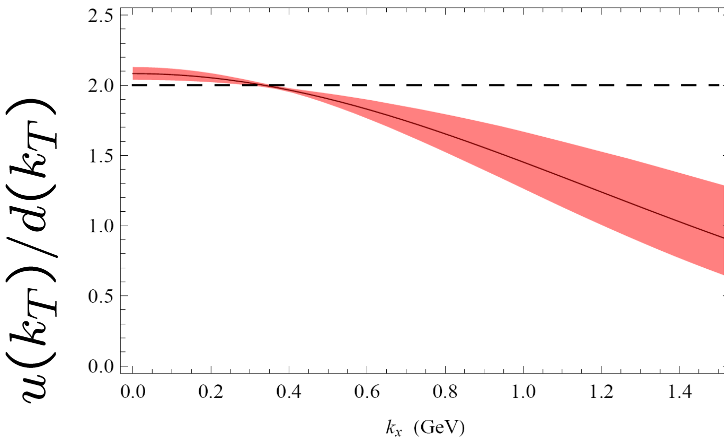


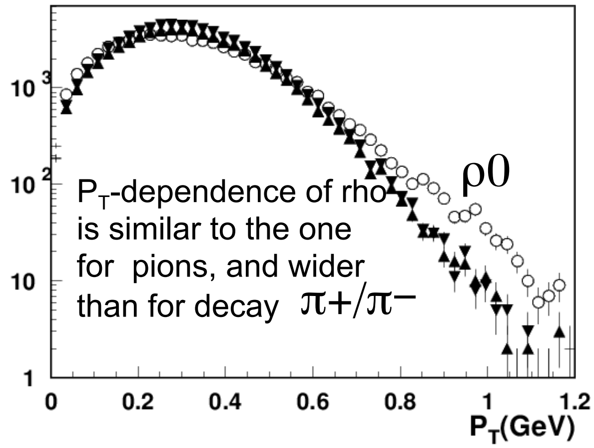
Q^2-dependence of HT A_{LU},

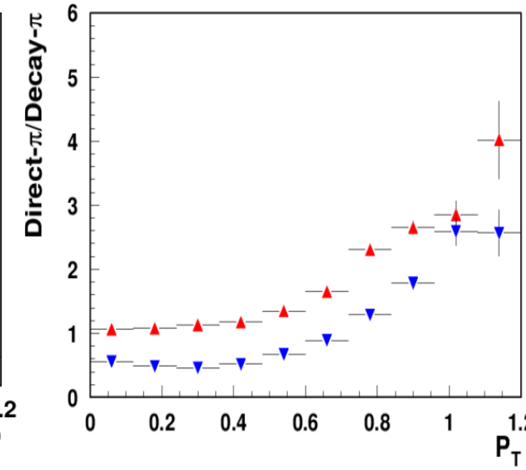


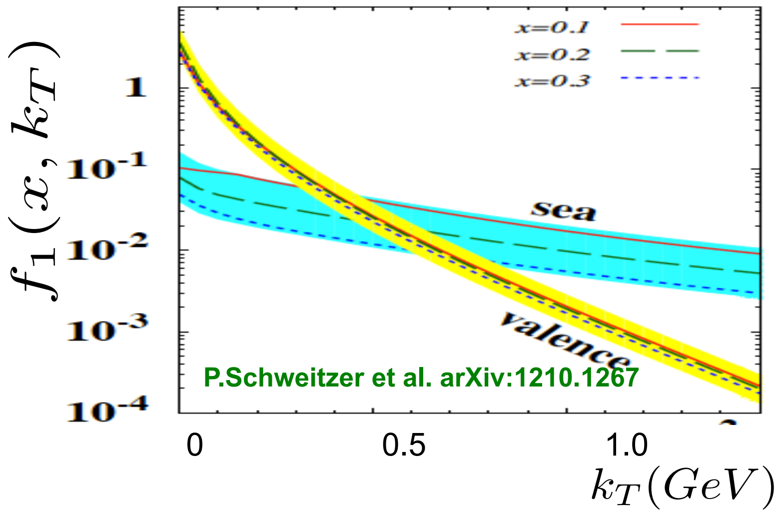
- Measurements of Q^2-dependence of multiplicities and in particular of SSAs in a wide kinematic range (most critical for TMD studies)

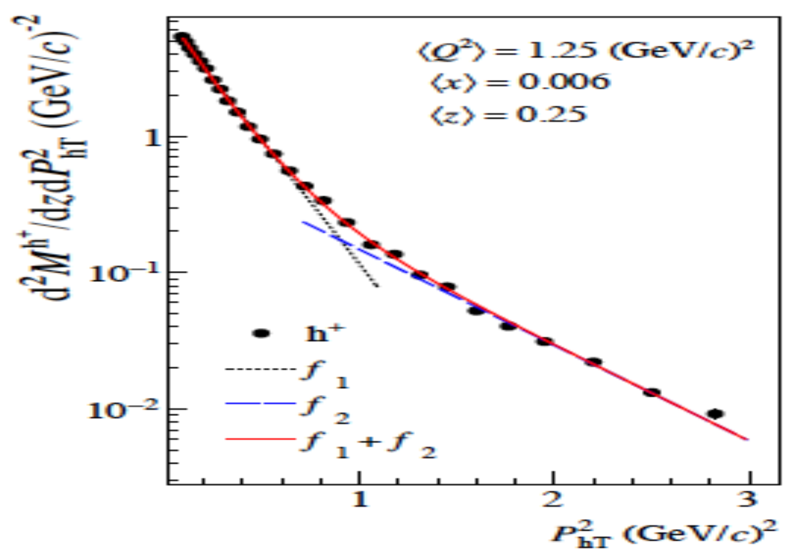
Accessing k_T–distributions in SIDIS





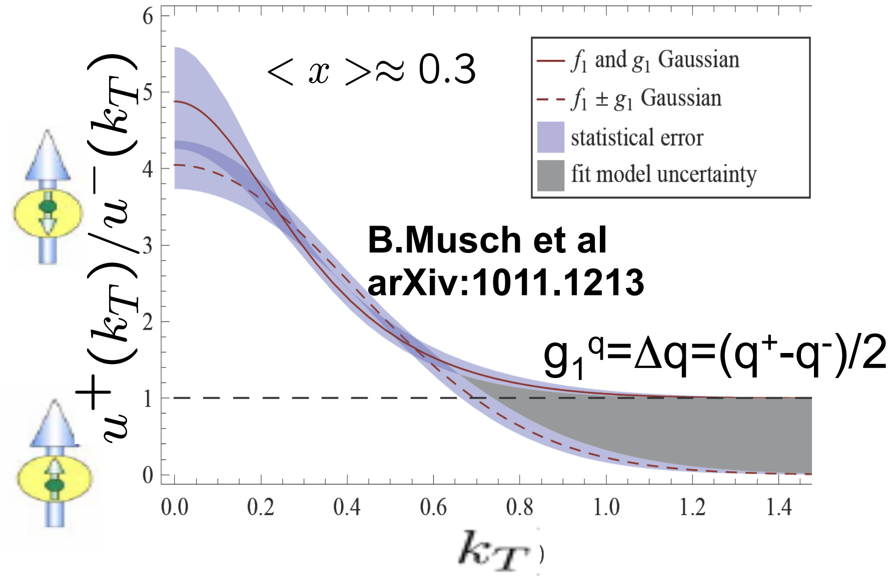


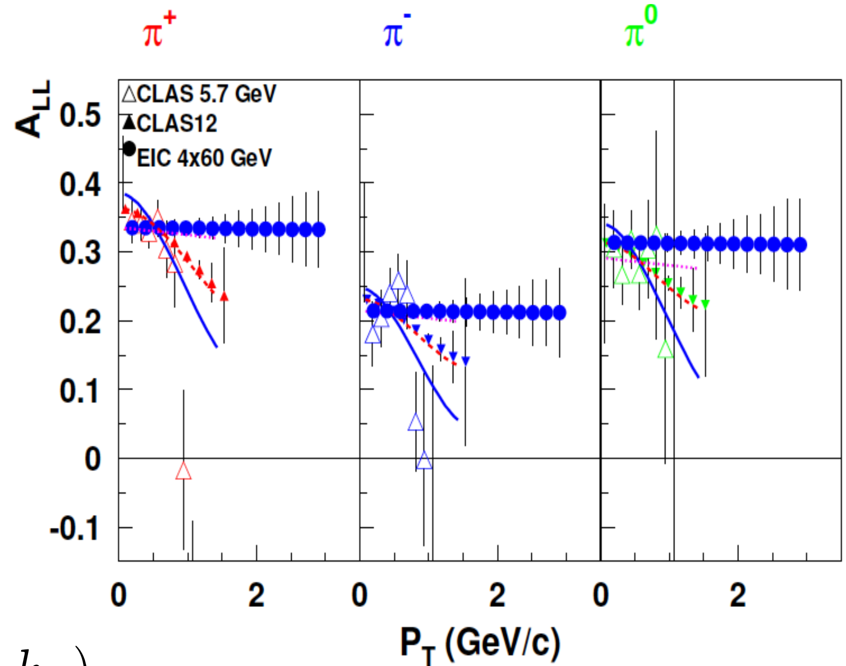




Understanding of the high P_T fraction of SIDIS (non-perturbative) is crucial for modeling of SIDIS and extraction of k_T-distributions of TMDs (may depend on flavor and spin)

k_T-dependence of TMDs: from CLAS12 to JLEIC



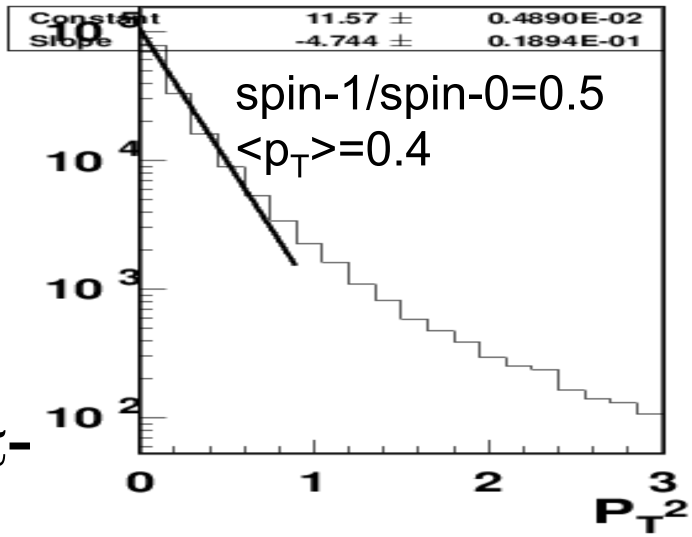


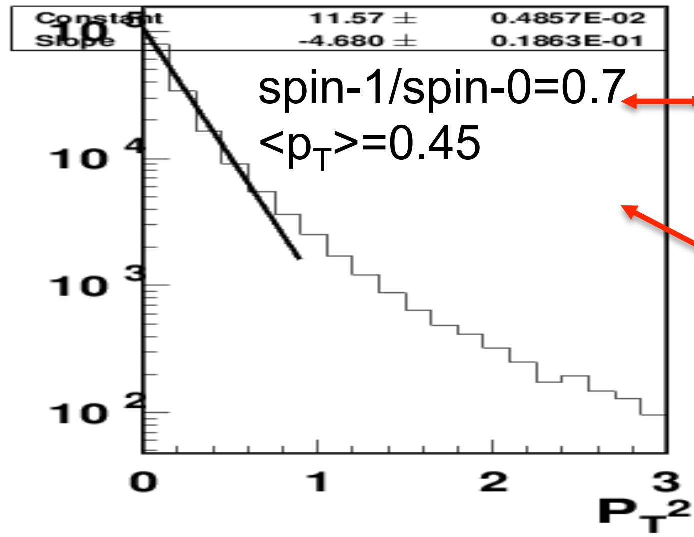
Accessing k_T-dependence of $g_1(x, k_T)$

- Spin orbit correlations may change significantly k_T (hence P_T) distributions of flavors, and their relative magnitude (critical for TMD studies)
- Understanding of large k_T-dependence of flavor distributions may require combination of unpolarized and longitudinally polarized target measurements, as they measure sum and difference of different TMDs

JLEIC (5x50) P_T-dependences for pions

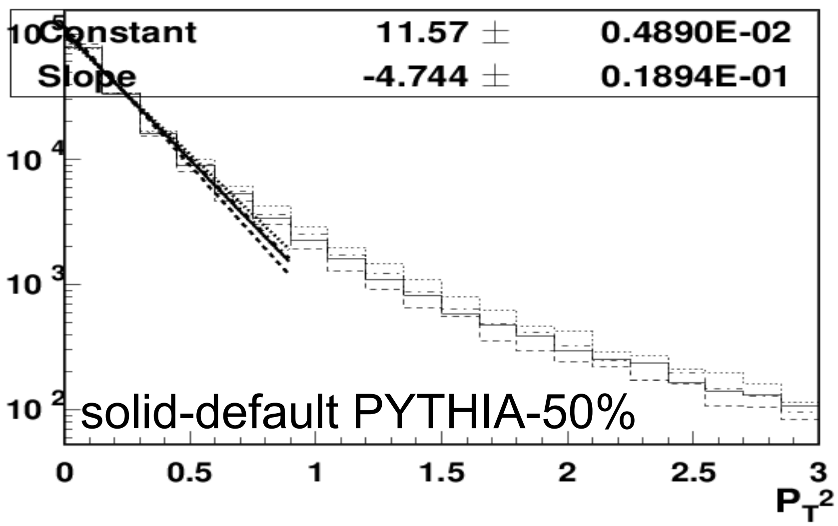
π-

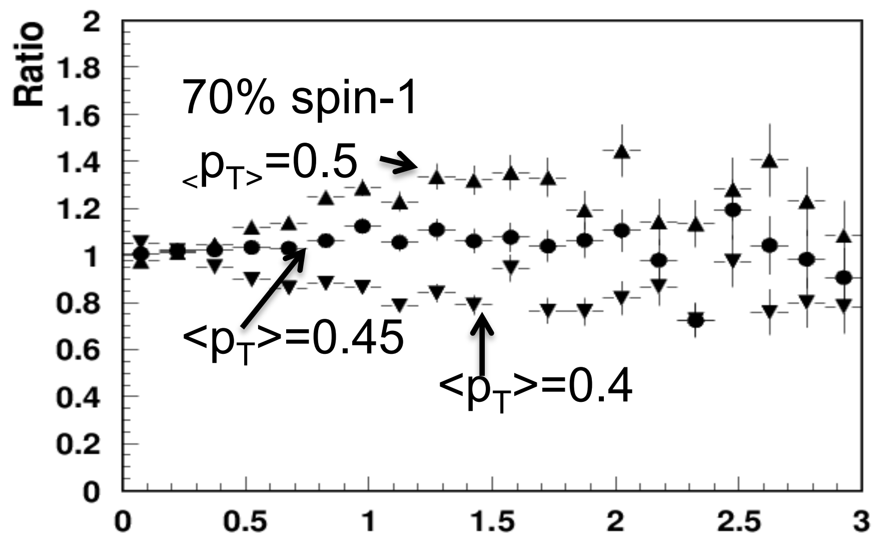




Fraction of spin-1

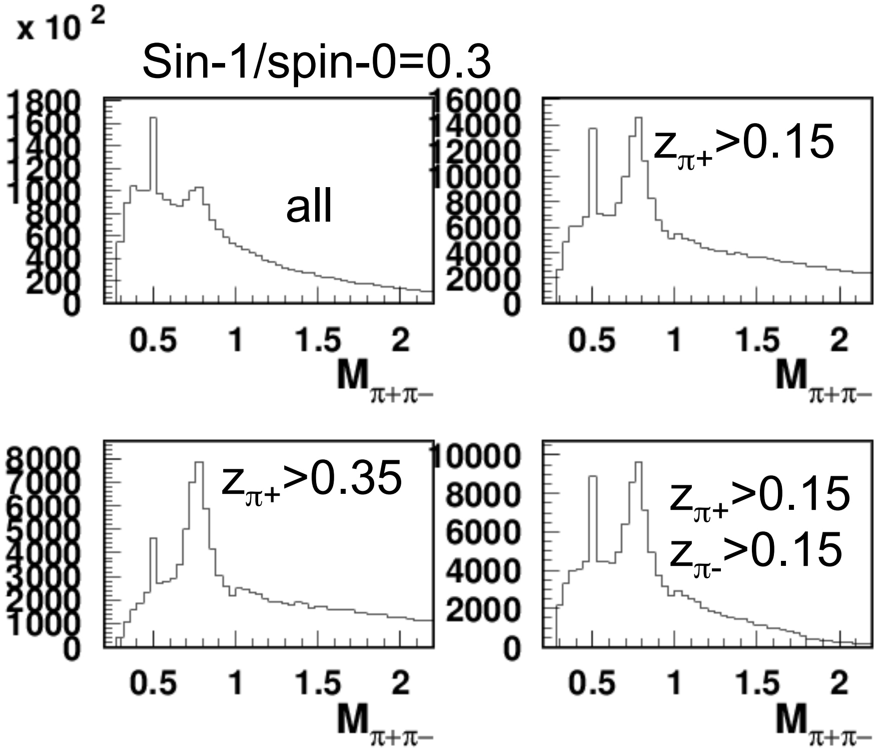
Intrinsic transverse momentum

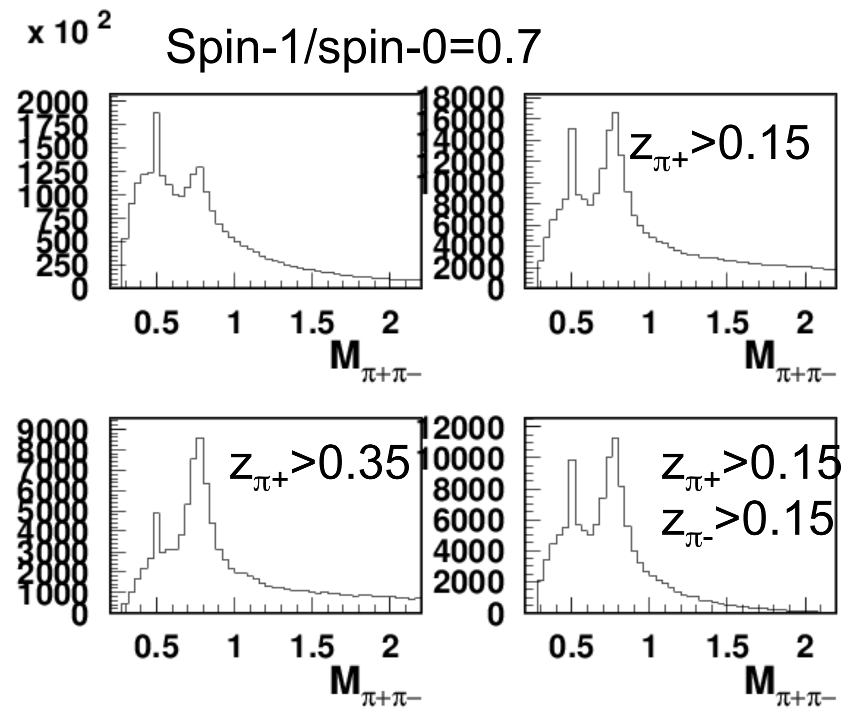


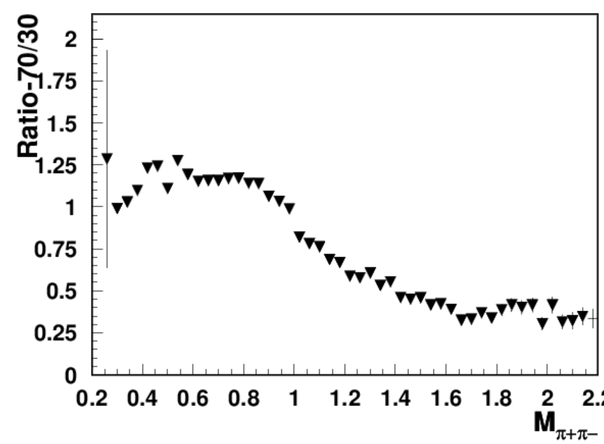


The same π+ P_T-dependence may be achieved with different initial transverse momenta

JLEIC (5x50) 2-hadron mass spectra







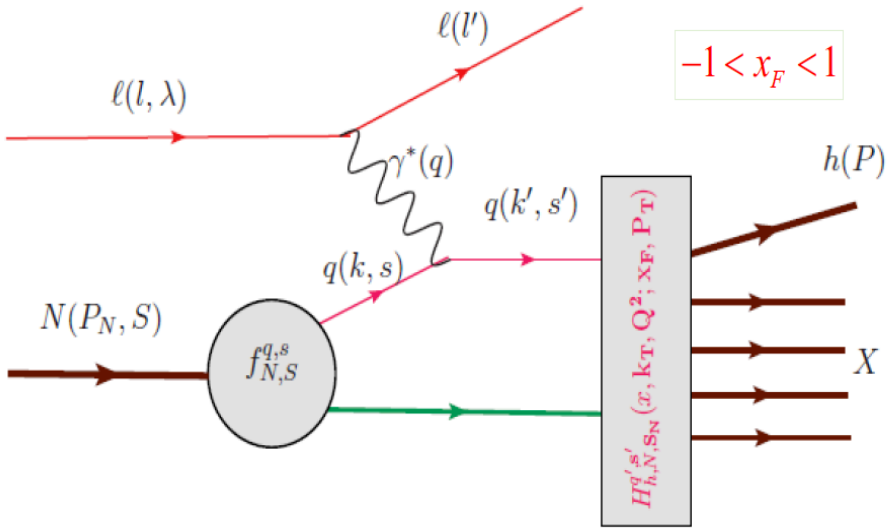
The rho peak is not increasing visually with increase of the fraction of VMs, as most of the background comes from low momentum particles at large Mππ

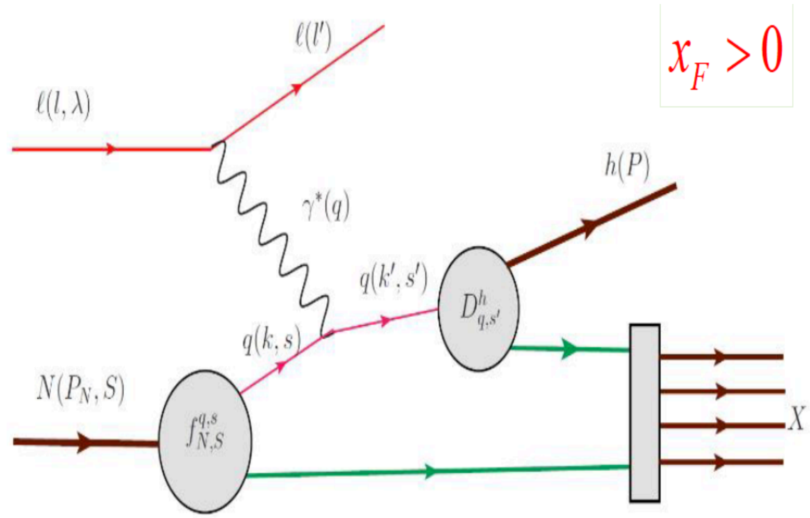
Hadronization and factorization

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

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

$Q^2 \gg M_p^2$





Hadronization Function
→ conditional probability to produce hadron ***h***

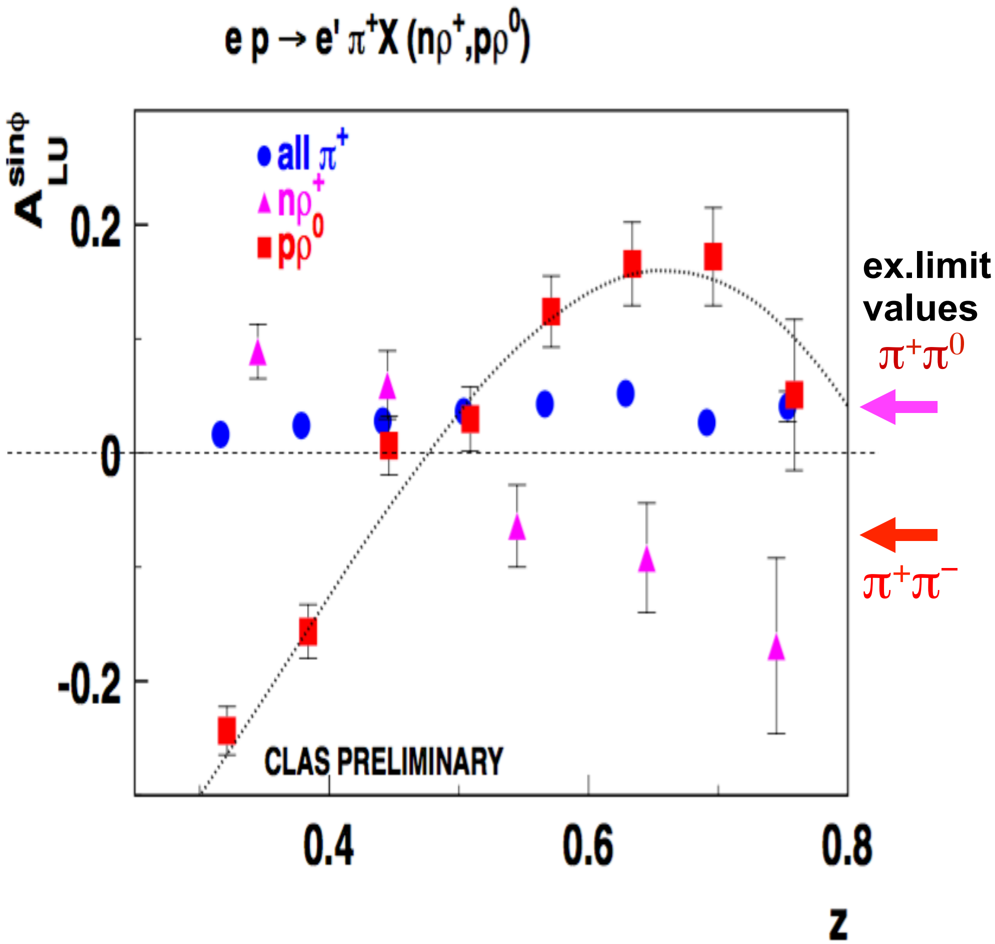
$$H^{q'}_{h/N}\left(x,\mathbf{k}_T,Q^2;x_F,\mathbf{P}^h_T;\mathbf{s}'_q,\mathbf{S}_N\right)$$

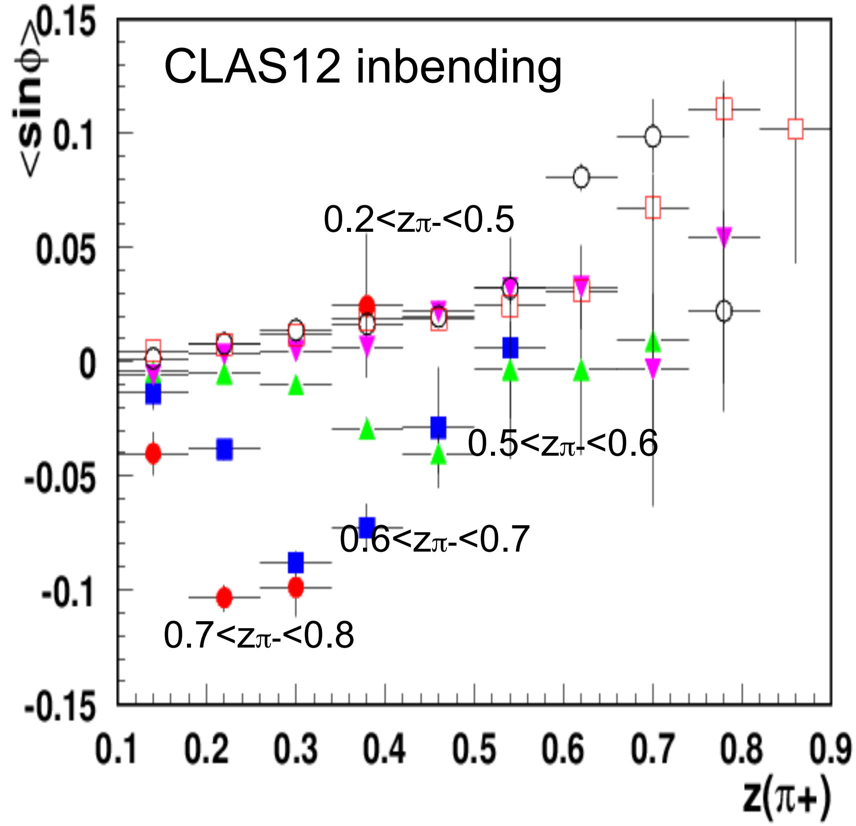
Quark Fragmentation Functions
(*universal and independent*)

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

Where this works?

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



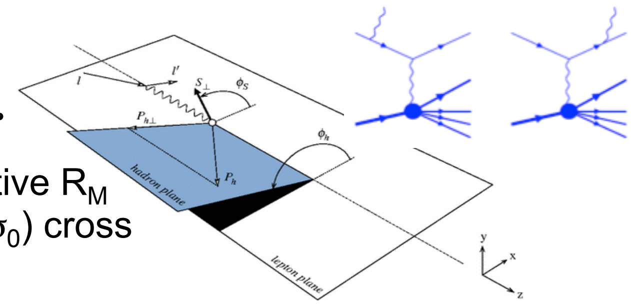


Inclusive pion SSA depend on unobserved hadron as observed SSA for the inclusive π+ changes significantly with the π- z
Understanding the source of SSAs is important for modeling, interpretation,RC,..

Experiment measures full sum of several SF with radiative effects

I. Akushevich et al

$$\sigma = \sigma_{UU} + \sigma_{UU}^{\cos\phi} cos\phi + S_T \sigma_{UT}^{\sin\phi_S} \sin\phi_S + ...$$



Due to radiative corrections, ϕ-dependence of x-section will get multiplicative R_M and additive R_A corrections, which could be calculated from the full Born (σ_0) cross section for the process of interest

$$\sigma_{Rad}^{ehX}(x,y,z,P_T,\phi,\phi_S) \rightarrow \sigma_0^{ehX}(x,y,z,P_T,\phi,\phi_S) \times R_M(x,y,z,P_T,\phi) + R_A(x,y,z,P_T,\phi,\phi_S)$$

Due to radiative corrections, ϕ-dependence of x-section will get more contributions
- Some moments will modify
- New moments may appear, which were suppressed before in the x-section

Simplest rad. correction
$R(x,z,\phi_h) = R_0(1 + r\cos\phi_h)$

Correction to normalization

$$\sigma_0(1+\alpha\cos\phi_h)R_0(1+r\cos\phi_h) \rightarrow \sigma_0 R_0(1+\alpha r/2)$$

Correction to SSA

$$\sigma_0(1+sS_T\sin\phi_S)R_0(1+r\cos\phi_h) \rightarrow \sigma_0 R_0(1+sr/2S_T\sin(\phi_h-\phi_S)+sr/2S_T\sin(\phi_h+\phi_S))$$

can be very significant

Correction to DSA

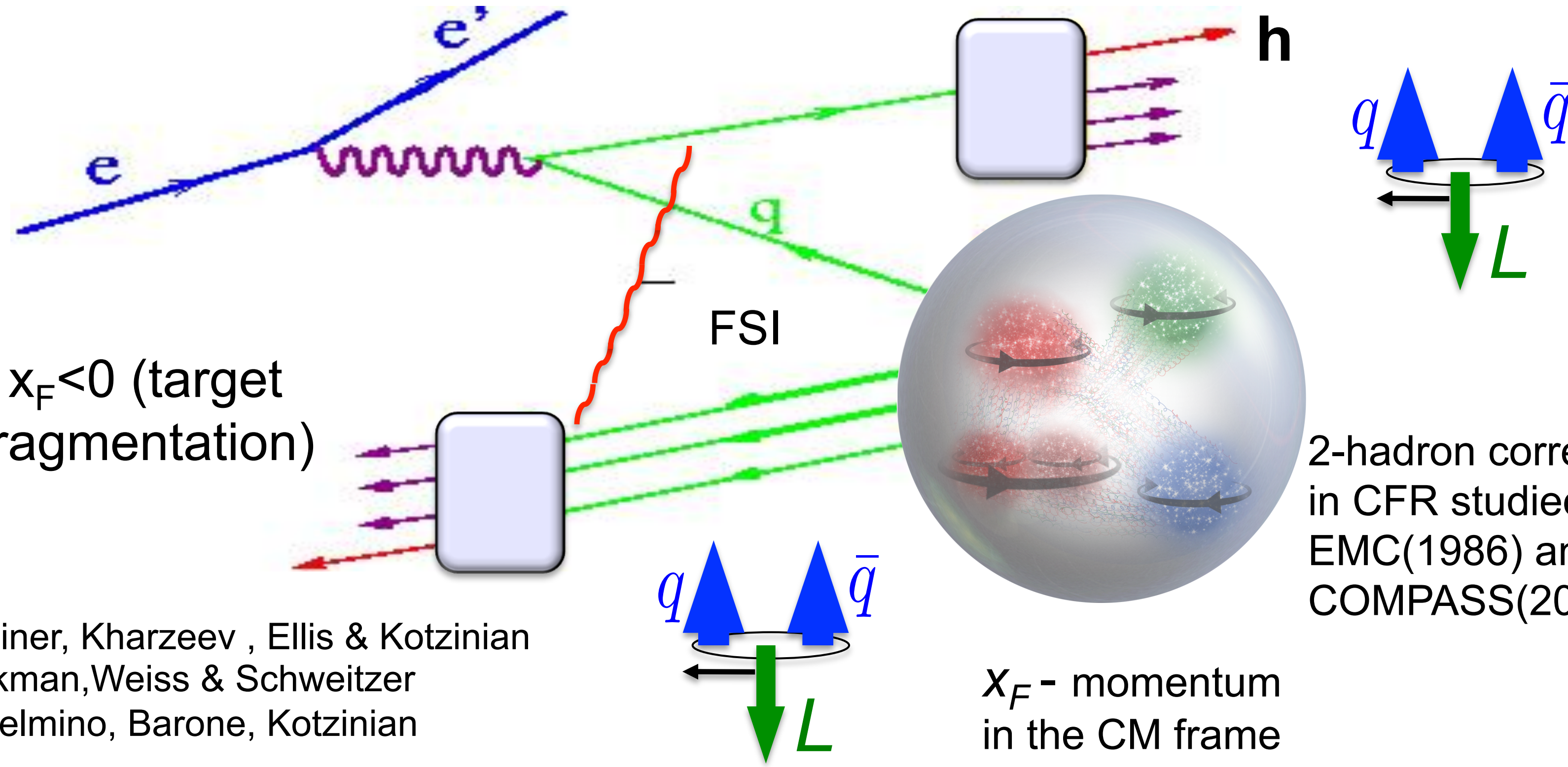
$$\sigma_0(1+g\lambda\Lambda+f\lambda\Lambda\cos\phi_h)R_0(1+r\cos\phi_h) \rightarrow \sigma_0 R_0(1+(g+fr/2)\lambda\Lambda)$$

We measure the ϕ-dependent radiative cross section, not moments!!!
Simultaneous extraction of all moments is important also because of correlations!

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)

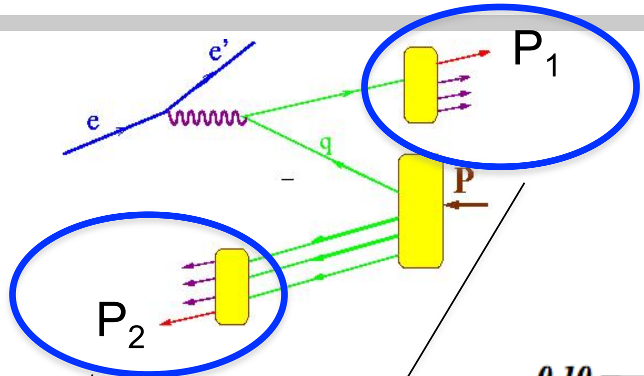
Karliner, Kharzeev , Ellis & Kotzinian
Strikman,Weiss & Schweitzer
Anselmino, Barone, Kotzinian

x_F - momentum in the CM frame

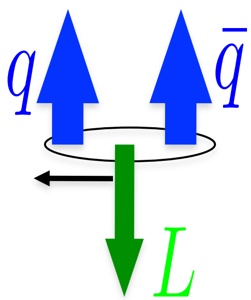
Modeling of q-q-bar correlations with spins and momenta in the process (not in PYTHIA) will be important for understanding of the dynamics

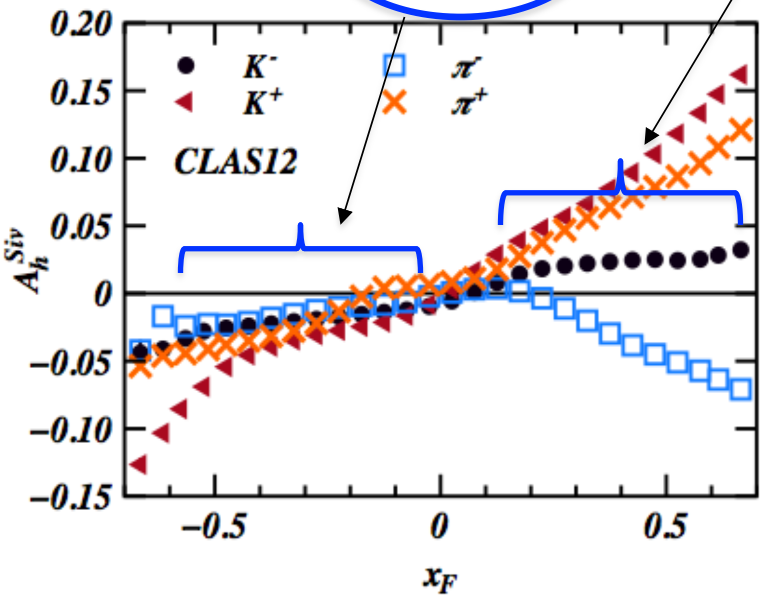
Sivers effect in Target fragmentation

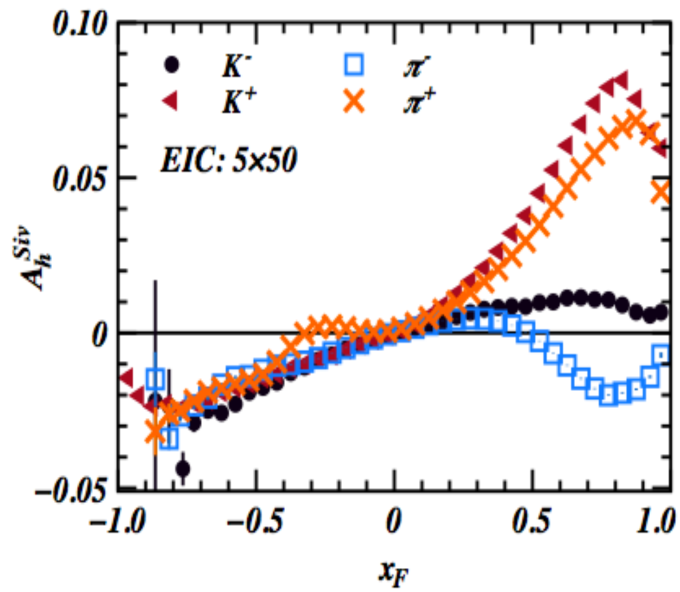
H. Matevosyan et al.
arXiv:1502.02669



Sivers effect is a correlation between target and current fragments

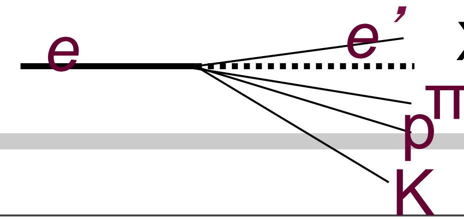


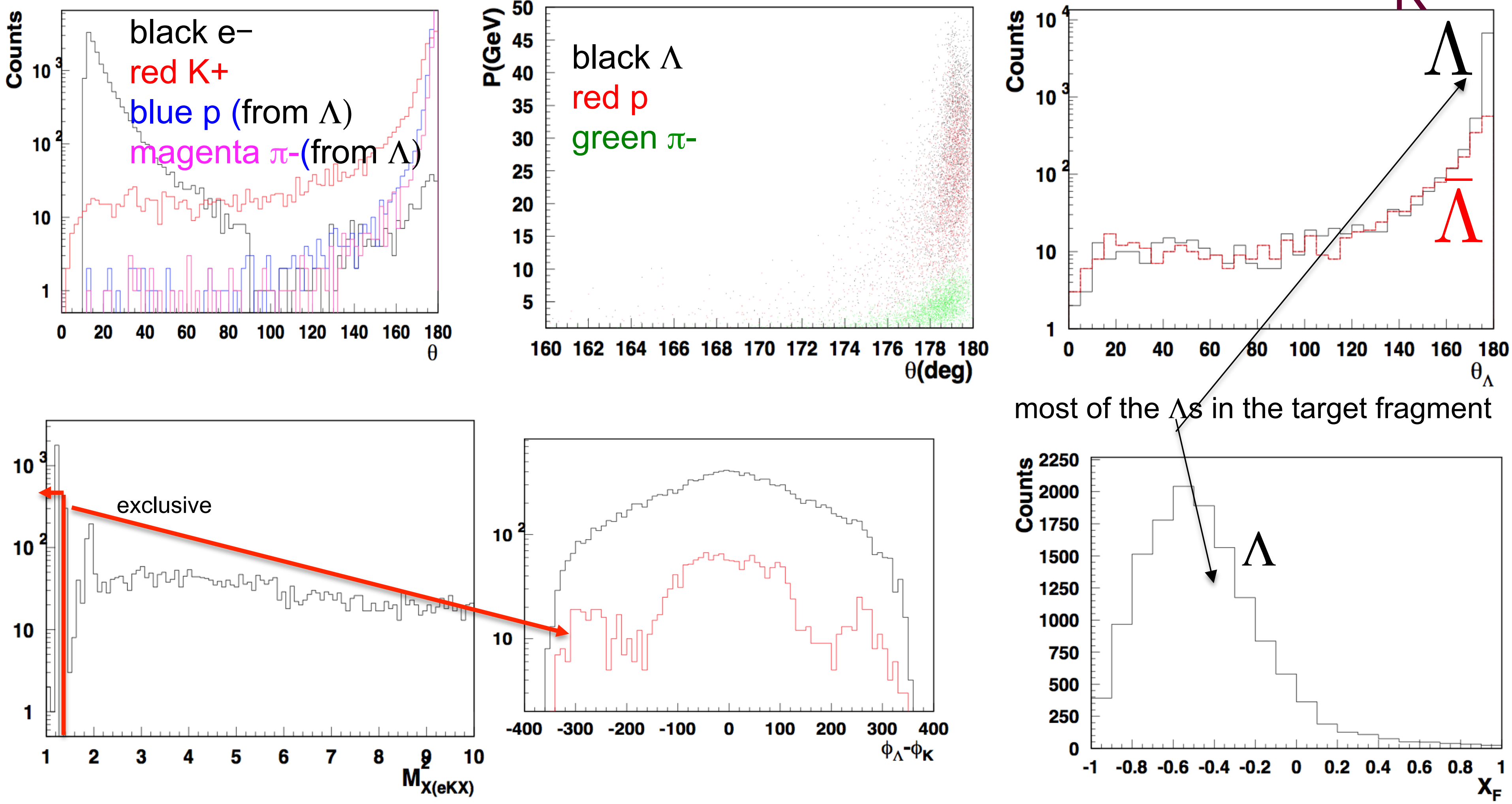




Wide coverage of CLAS12 and EIC will allow studies of kinematic dependences of the Sivers effect, both in current and target fragmentation regions

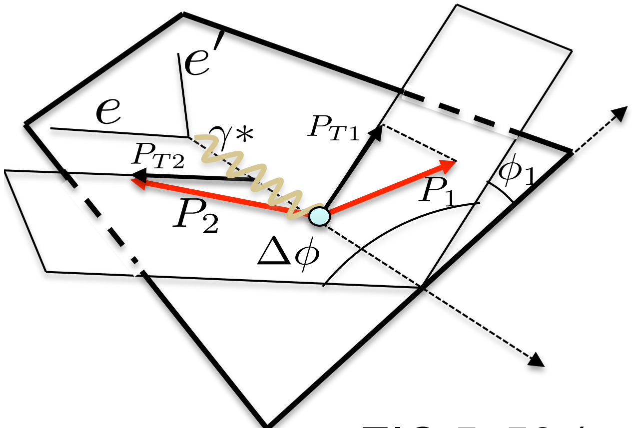
Lambda production in EIC (5x50 GeV)

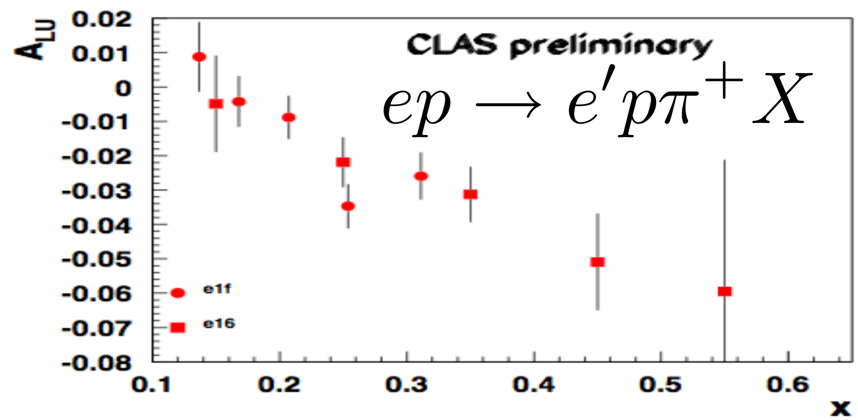




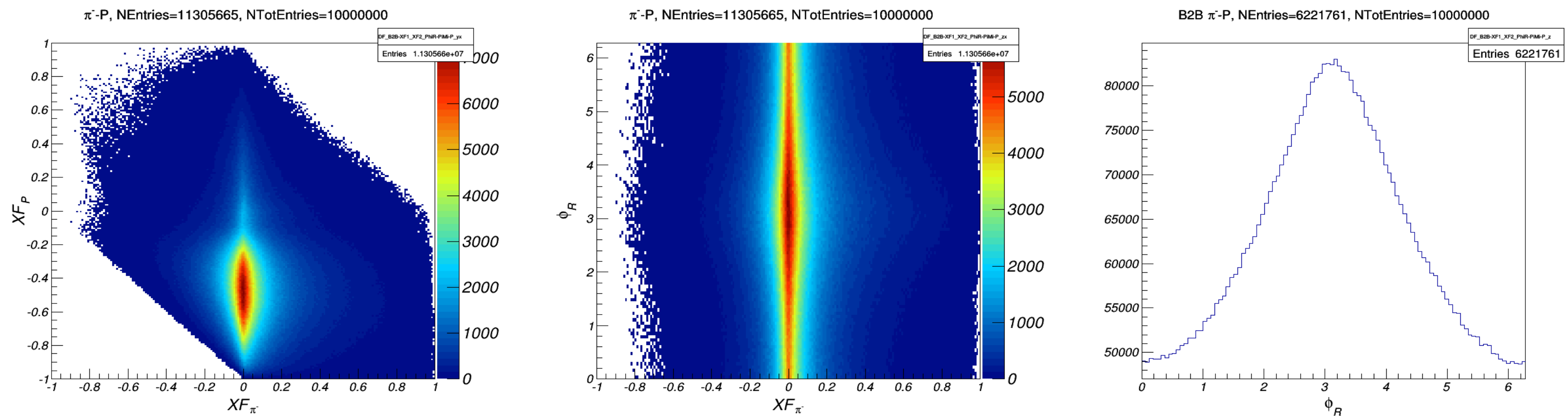
At forward angles Lambdas are mainly from target fragments

Back to back (B2B) correlations and SSA A_{LU}





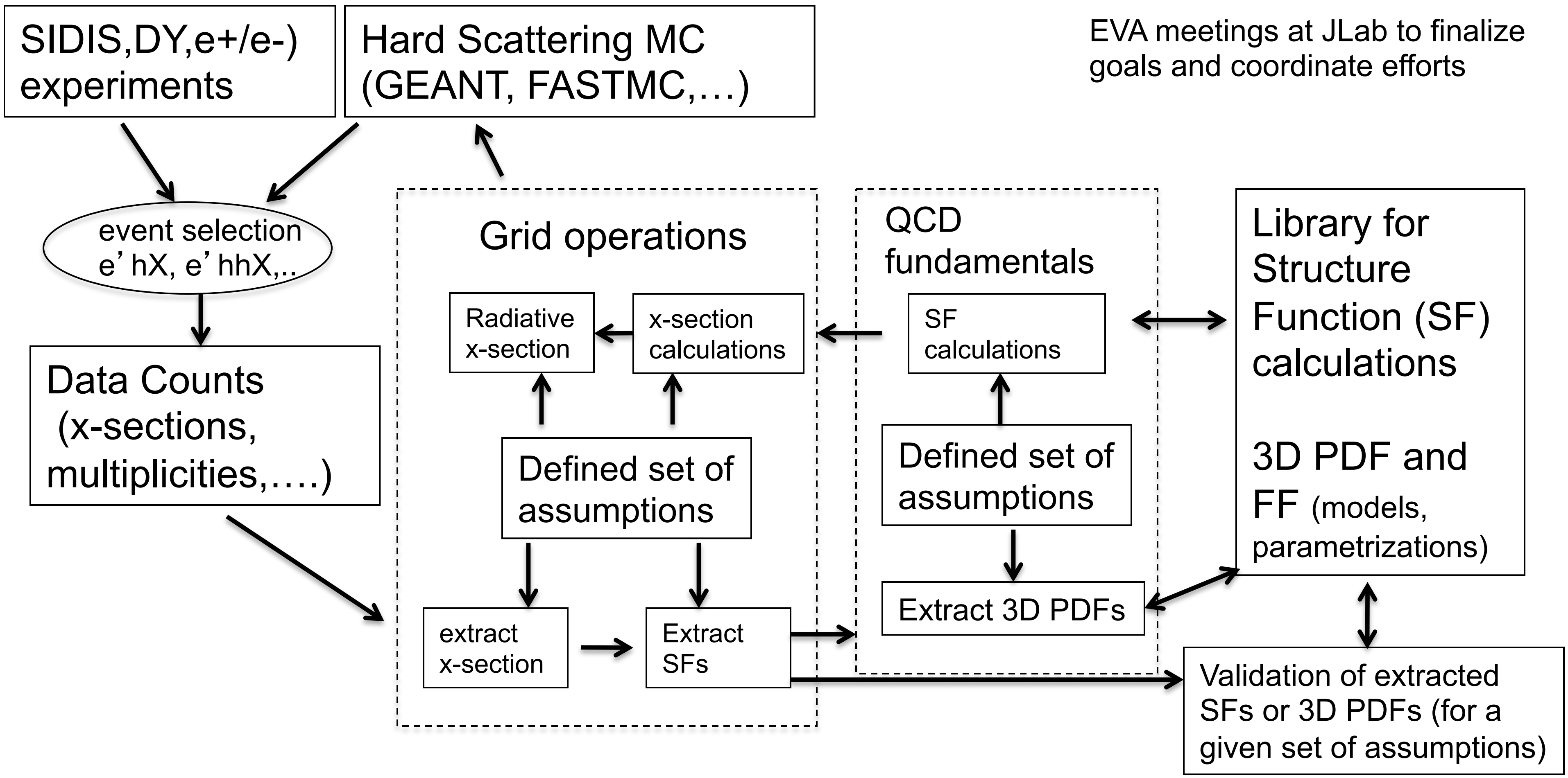
EIC 5x50 (proton-pion)



- b2b correlations could be measured for meson in the current and barion in the target region

3D PDF Extraction and VAlidation (EVA) framework

EVA meetings at JLab to finalize goals and coordinate efforts



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

Assumptions and approximations to be validated in EVA

The list of different experimental and theoretical items includes things like:

1) Effects from limited kinematic acceptance, both due to limited beam energies, and due to limited acceptances of detectors
2) Contributions from Vector Mesons
3) Contributions from target fragmentation
4) Self consistency of radiative corrections and possible effects of other azimuthal moments
5) Sensitivity to used parameterizations, showing up even for 1D analysis, and promising to be much bigger for 3D
6) Systematics in extraction due to binning of data on extraction of P_T and Q^2-dependence of SIDIS observables and possibly underlying TMDs
7)Effects from ignored HT contributions
8)Modification of TMDs in medium
……..

Unaccounted items may be more or less critical for measurements of observables in general, and extraction of TMDs, in particular, and only detailed simulations can help to identify their relevance.

SUMMARY

- The CLAS12 data supports predictions from different MCs of 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
- The observables for pions from rhos have peculiar spin and momentum dependences and may <u>require different RC, modeling, and interpretation</u>
- Understanding of exclusive production of hadrons, in particular, at large t, where they show similar behavior, will be important for SIDIS
- 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 with JLab12 will be critical for interpretation of JLab12 data, as well as COMPASS and DY</u>

The simulation of spin-orbit correlations in single and di-hadro SIDIS is crucial for estimates of contributions from different factors and final interpretation of SIDIS observables in general, and extraction of 3D structure from observed multiplicities and SSAs, in particular

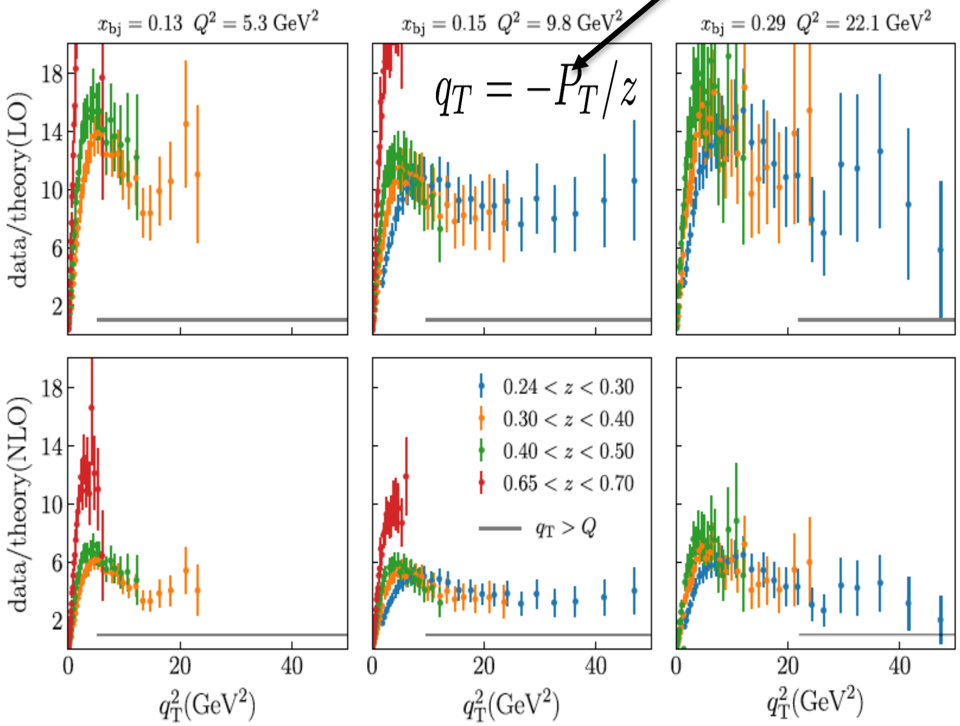
Support slides

FO vs data for $q_T \gtrsim Q$ (“qT-crisis”)

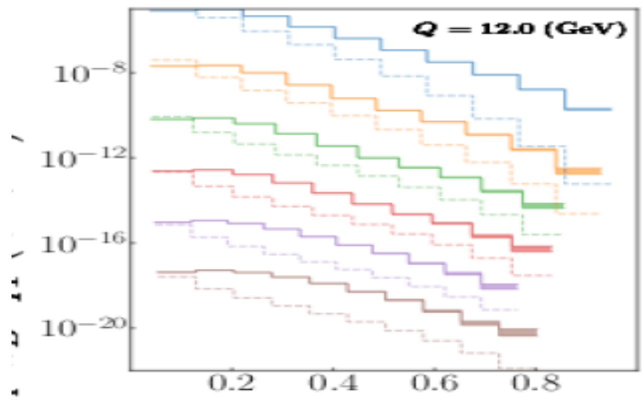
$$F^h_{XY}(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}(M/Q)$$

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

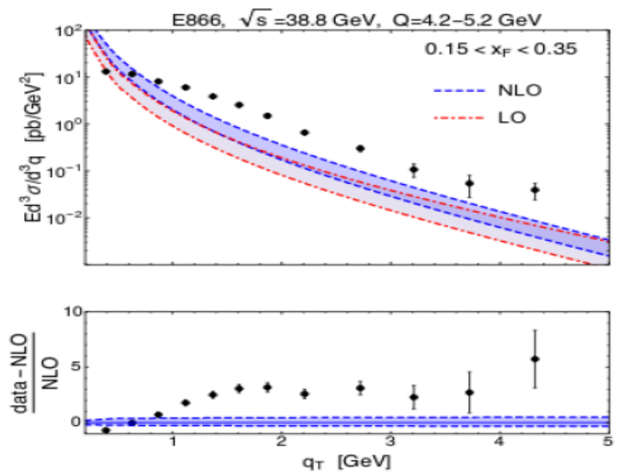
quark transverse momentum



$e^+e^- \to h_1 h_2 X$ - Moffat et. al 1909.02951



Drell Yan - Bacchetta et. al 1901.06916



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.

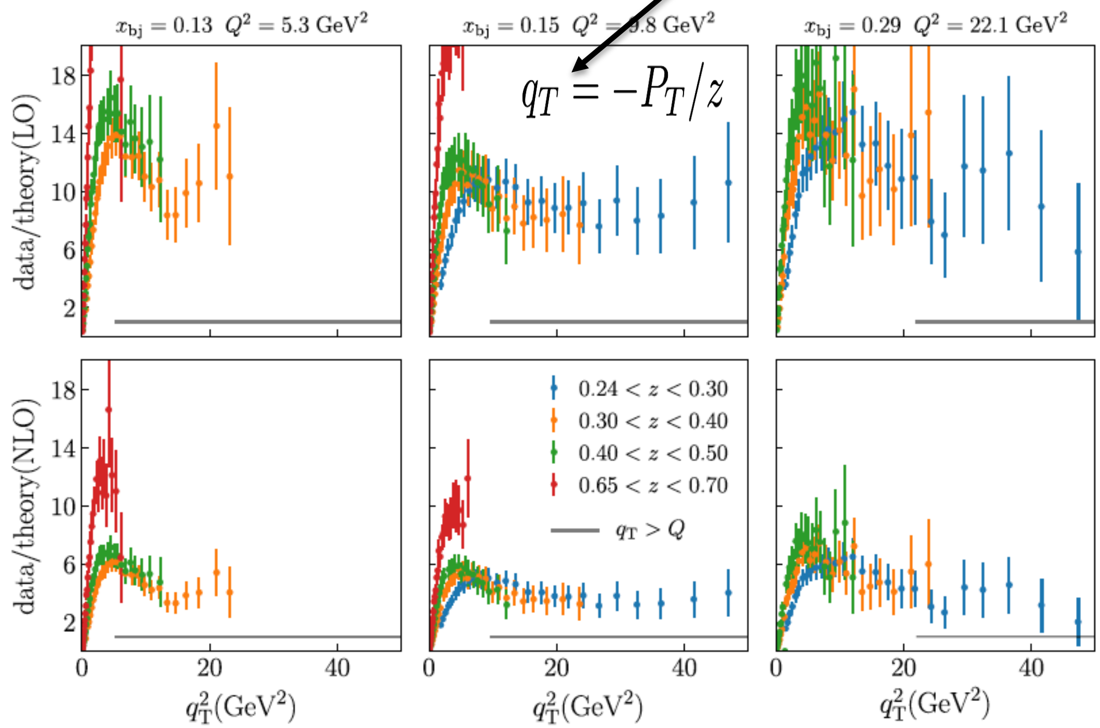
Gonzalez-Hernandez et al, PRD 98, 114005 (2018)

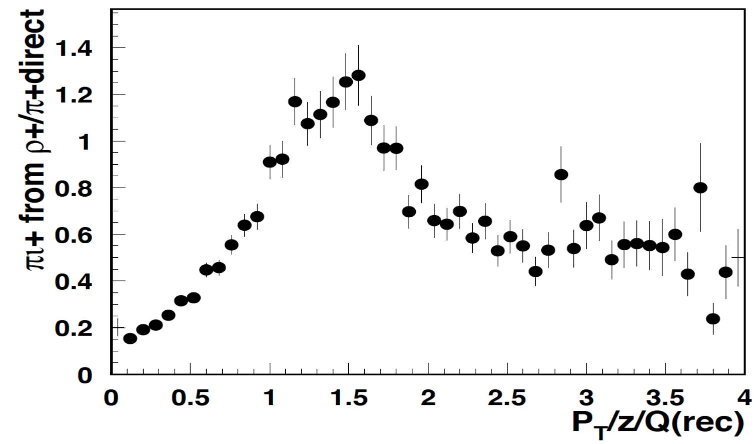
TMD formalism applicability

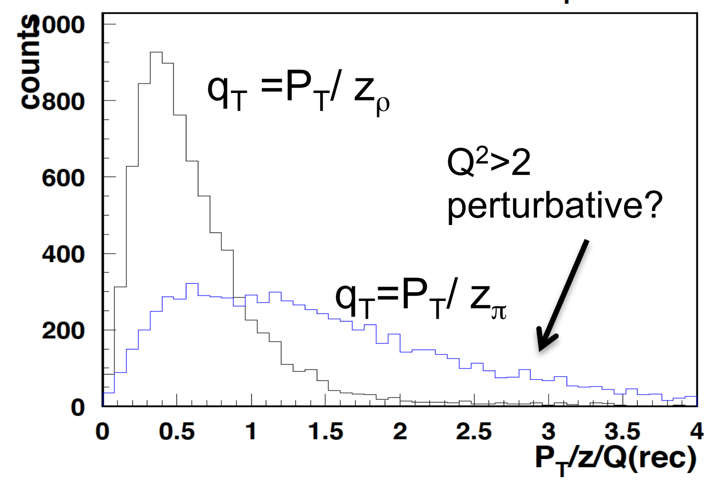
$$F^h_{XY}(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}(M/Q)$$

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

quark transverse momentum





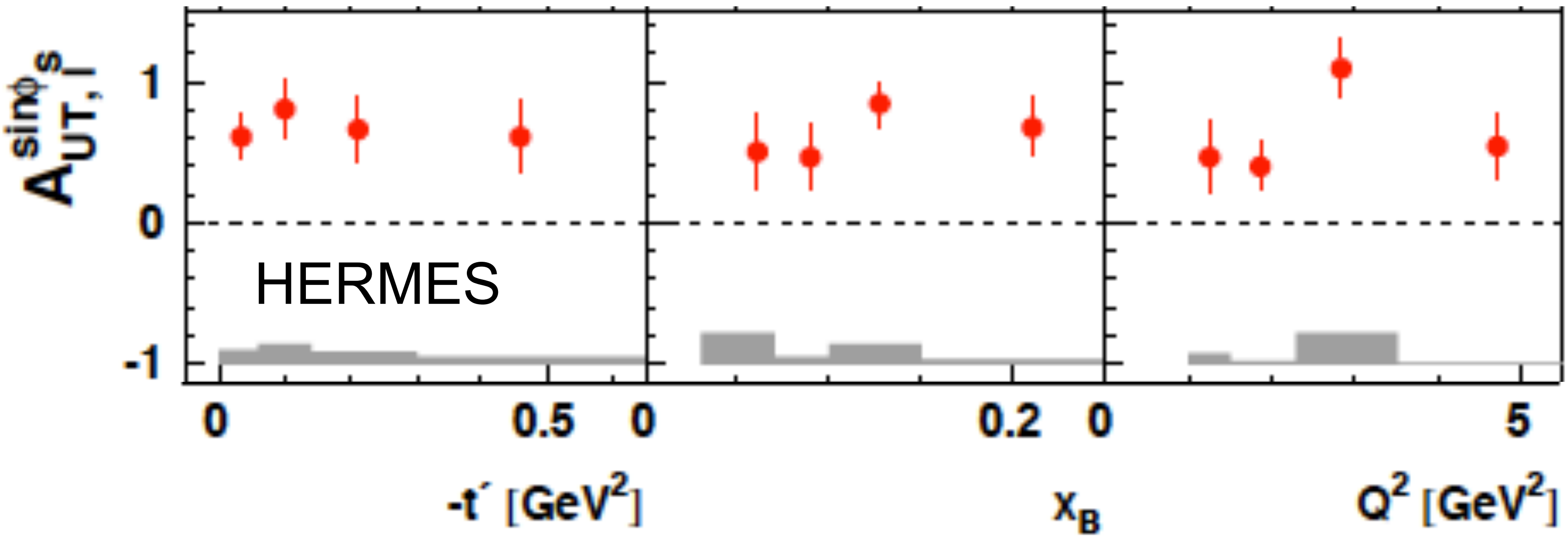


The measurements disagree with leading order and next-to-leading order calculations most significantly at the more moderate values of **x** close to the valence region.

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

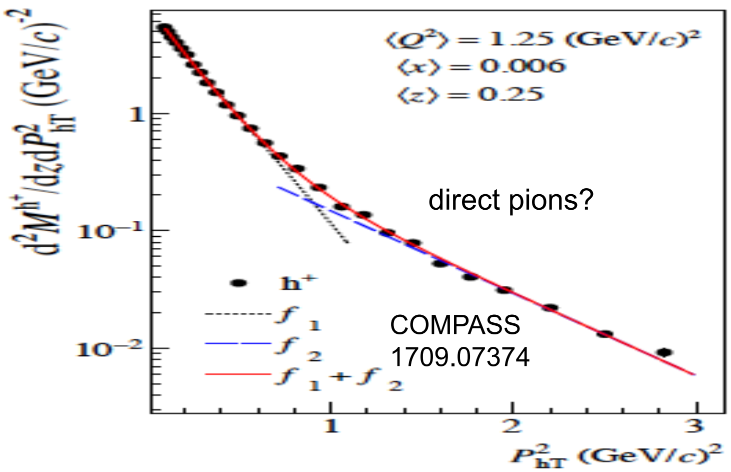
understanding the fraction of pions from "correlated dihadrons" will be important to make sense out of q_T distributions

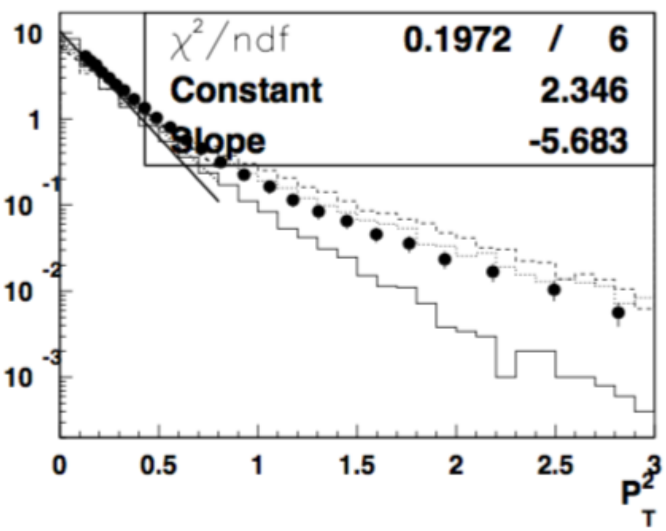
Phys. Lett. B 682 (2010) 345



Dihadrons: key to hadronization?

Origin of non-Gaussian tails





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
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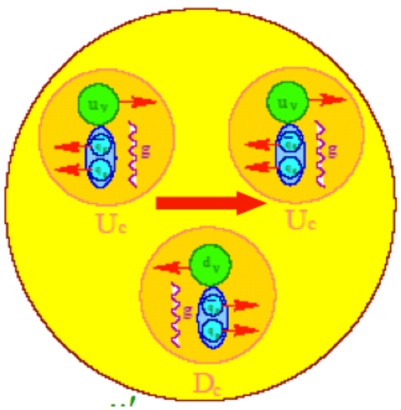
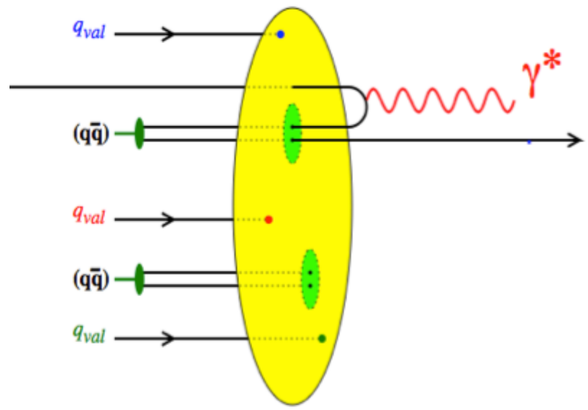
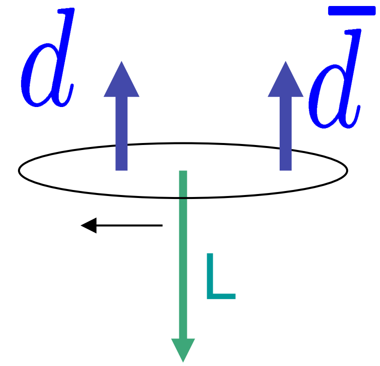
   - contributions to pions from target fragmentation may be less relevant

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

Correlations between target and current



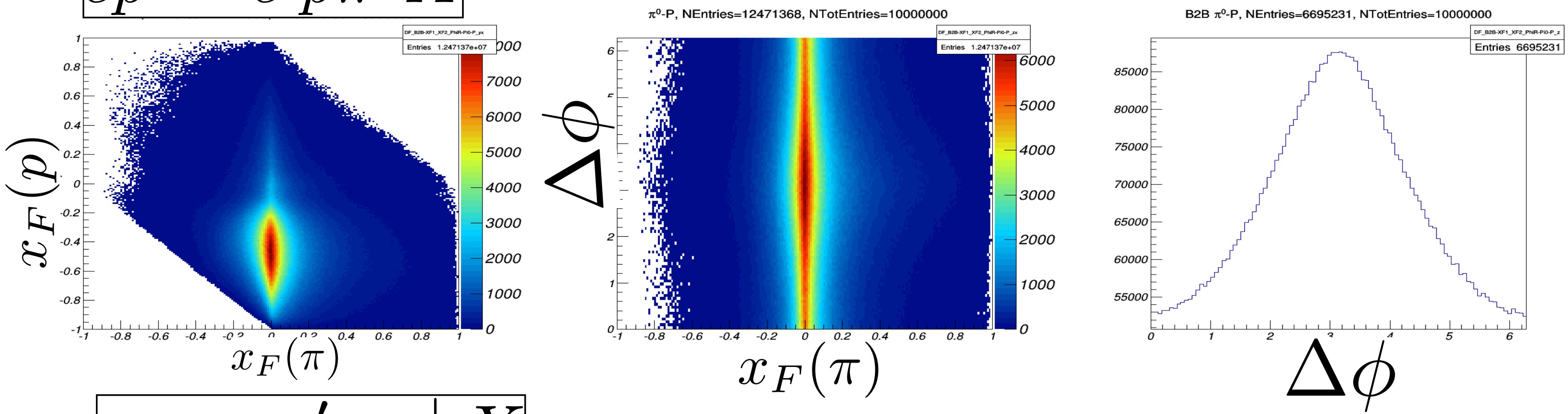




- how the remnant system dresses itself up to become a full-fledged hadron
- correlation with the spin of the target or/and the produced particles

b2b distributions: EIC 5x50 (proton-pion)

$$ep \to e'p\pi^0 X$$



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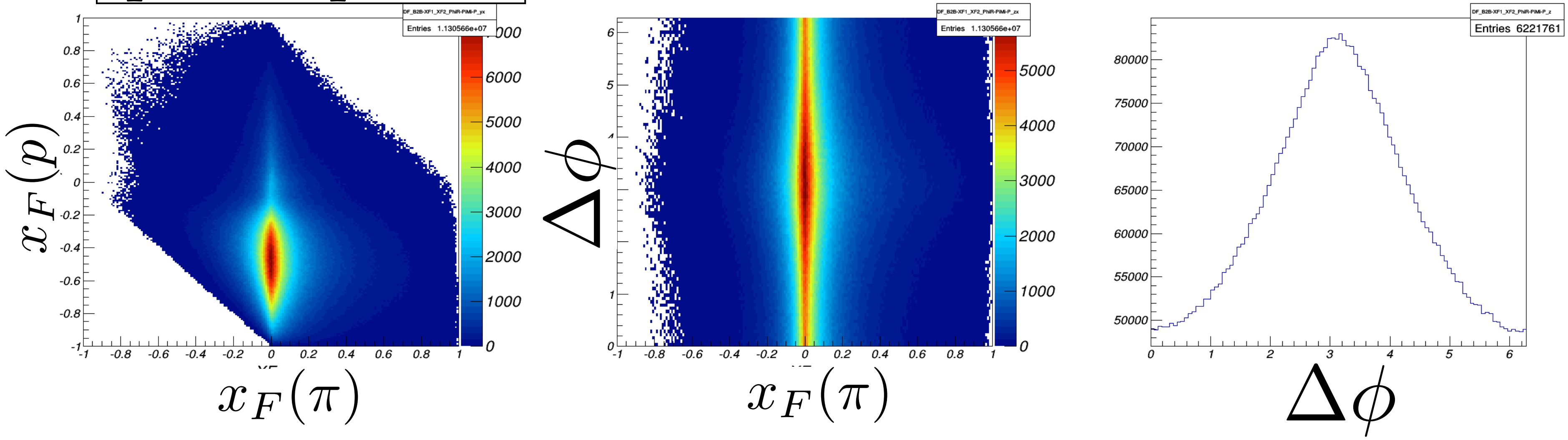
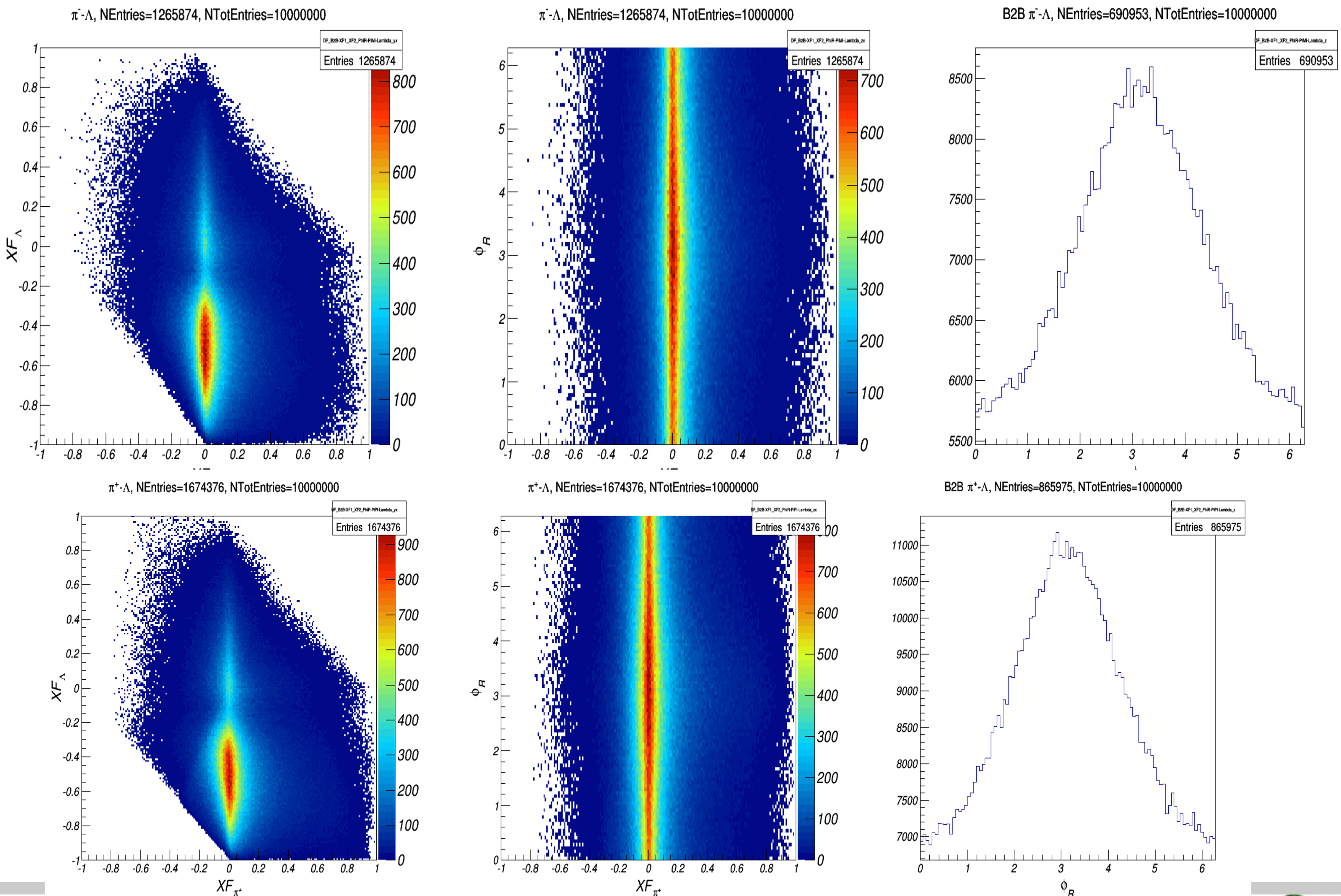
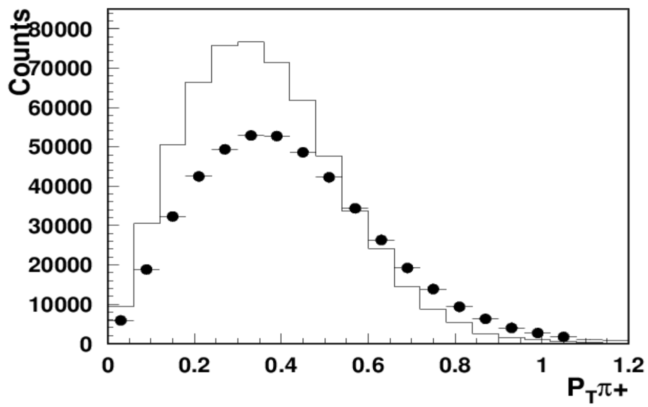
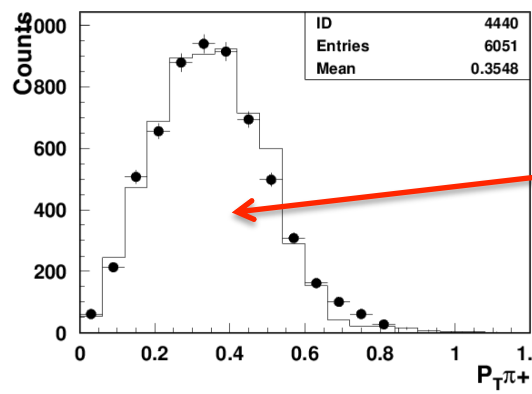


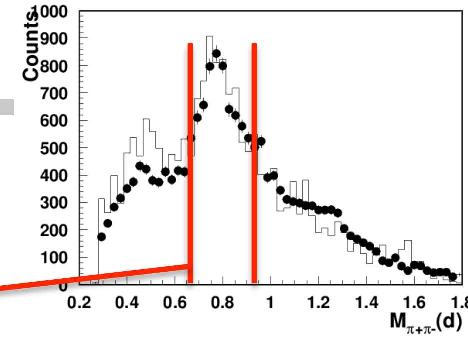
b2b distributions: EIC 5x50 (Lambda-pi)

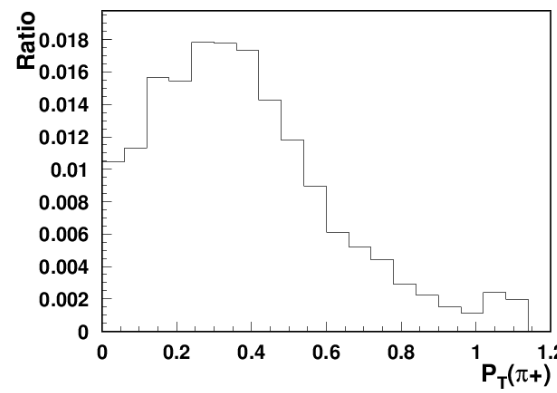


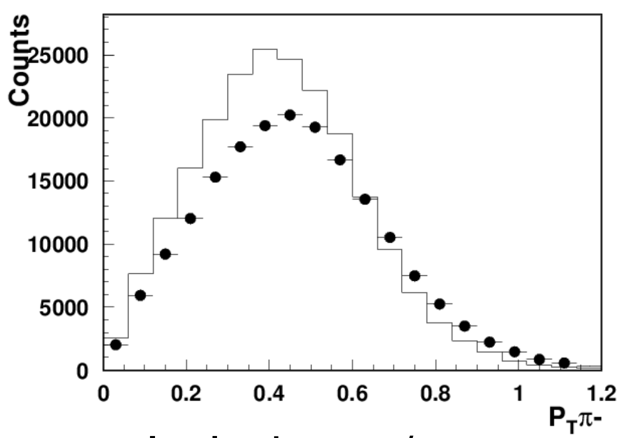
P_T distributions in the rho region



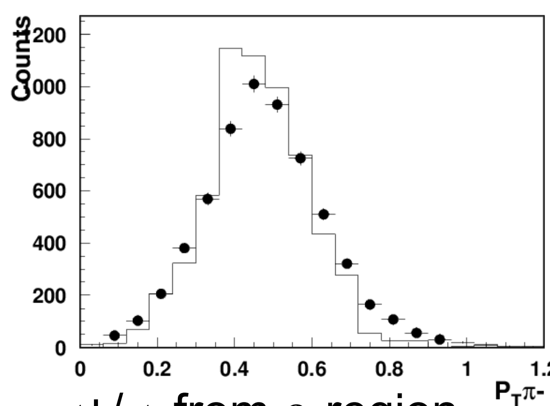




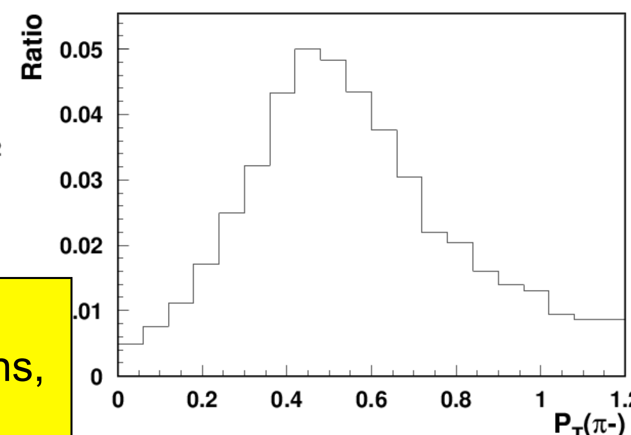




Inclusive π+/π−

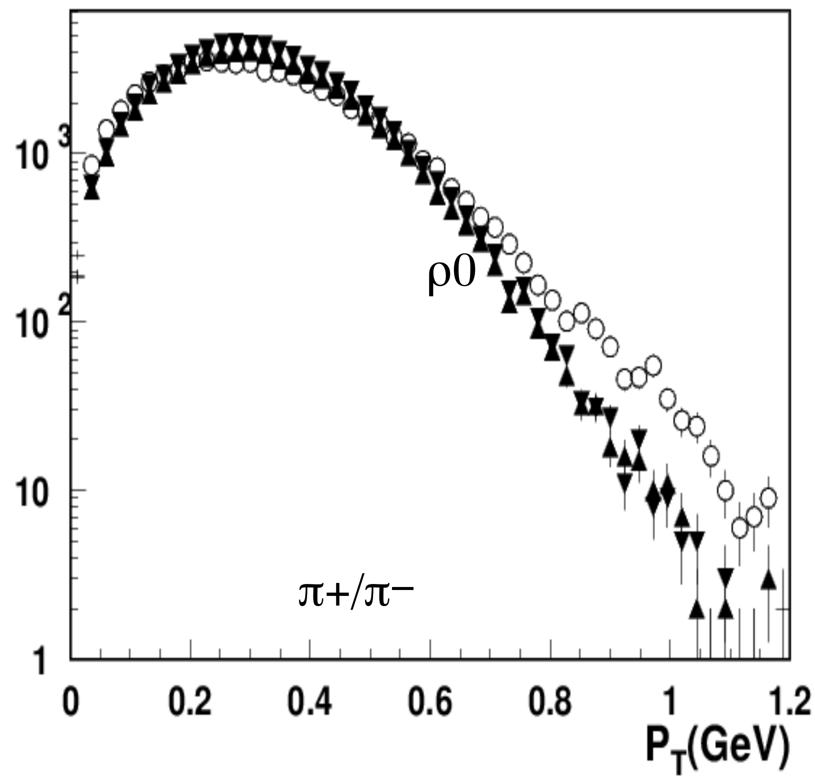


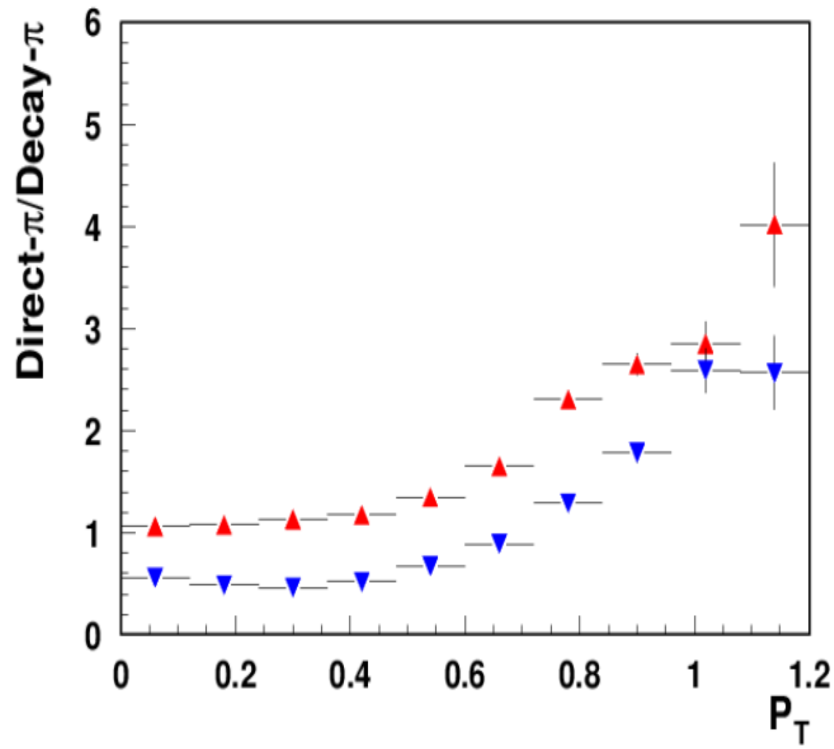
π+/π−from ρ-region



P_T- distributions of pions in the rho region look like low P_T Gaussian, while unrelated (direct) pions have a wider distributions, which can be described by a wider Gauss similar to original VMs

P_T of pions from rho decays: LUND string fragmentation





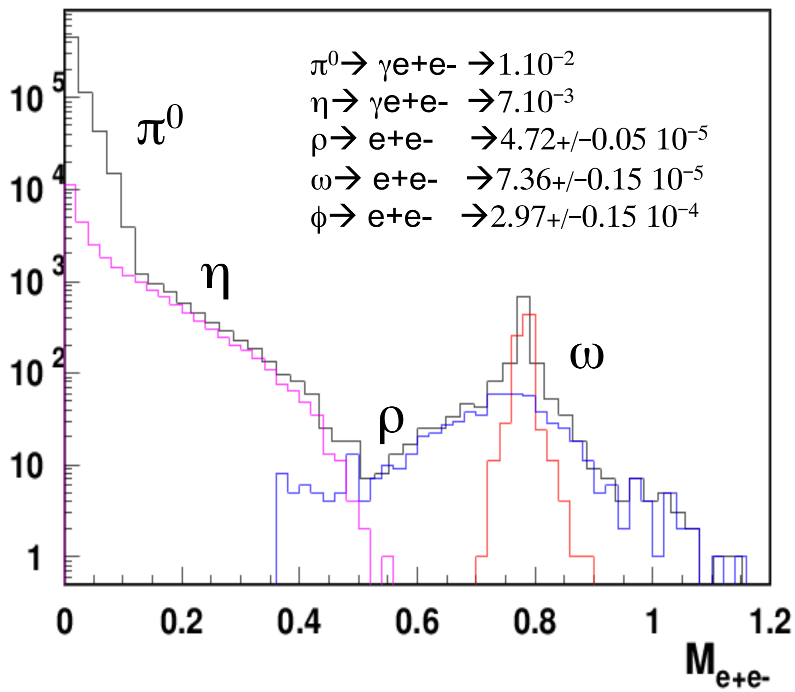
P_T-dependence of rho is similar to the one for decay pions

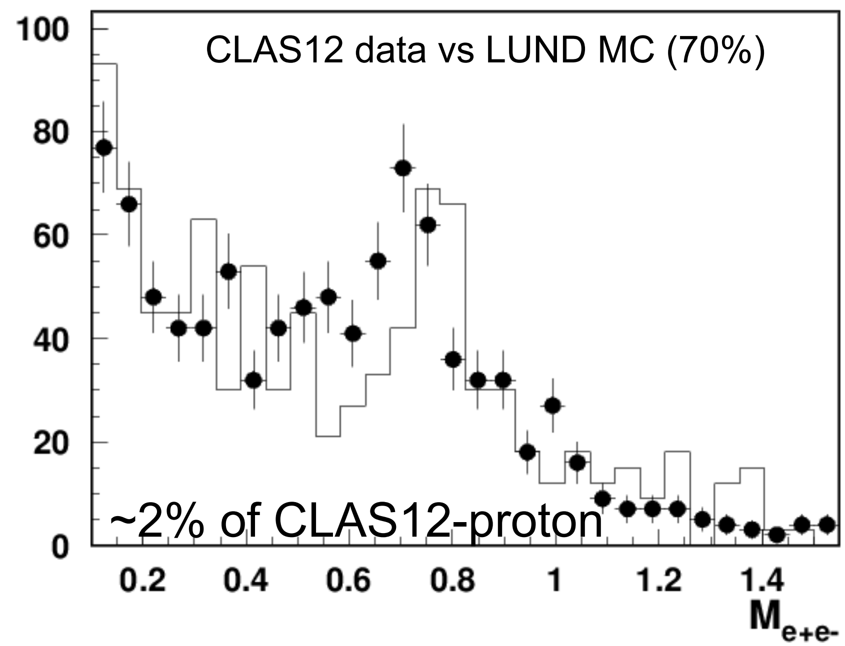
Fraction of direct π+ increases with P_T

Using e+e- to estimate vector mesons

<u>The invariant mass of dihadrons is contaminated by other vector mesons, with shape not changing significantly with hadronization fraction to spin-1 vs spin-0 mesons</u>

decays of π and η are kinematically separeated from ω and ρ^0





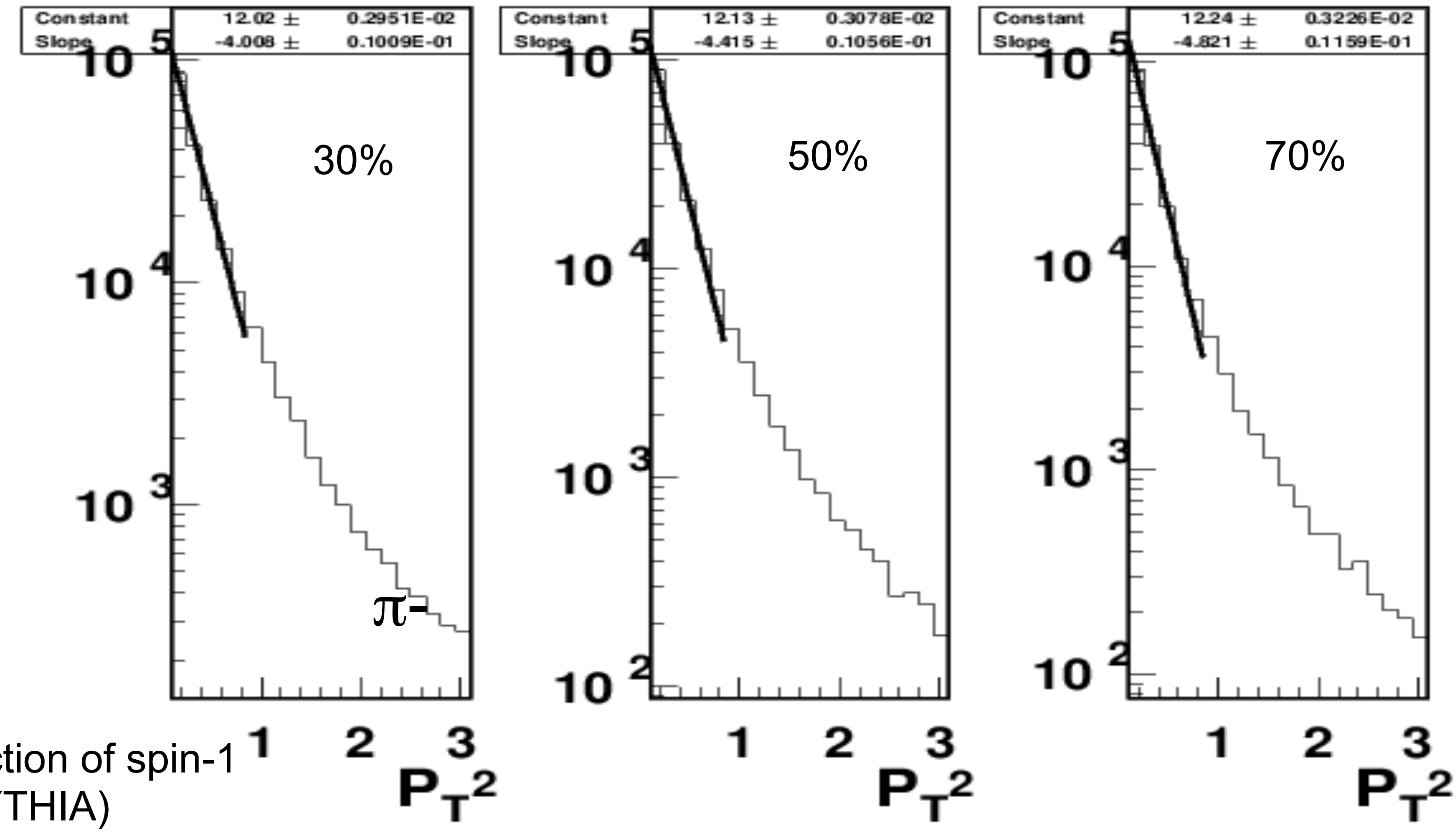
Vector meson per electron can be independently estimated from ep→e'e+e-X

Correlated hadron production: Where it matters

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

- Most pions coming from VM decays will change:
    - number of e+e-/μ+μ- pairs produced in hadronization process (may be relevant for DY)
    - 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

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

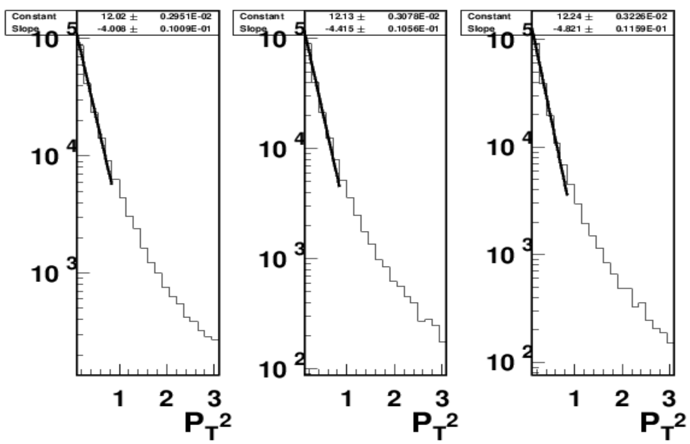


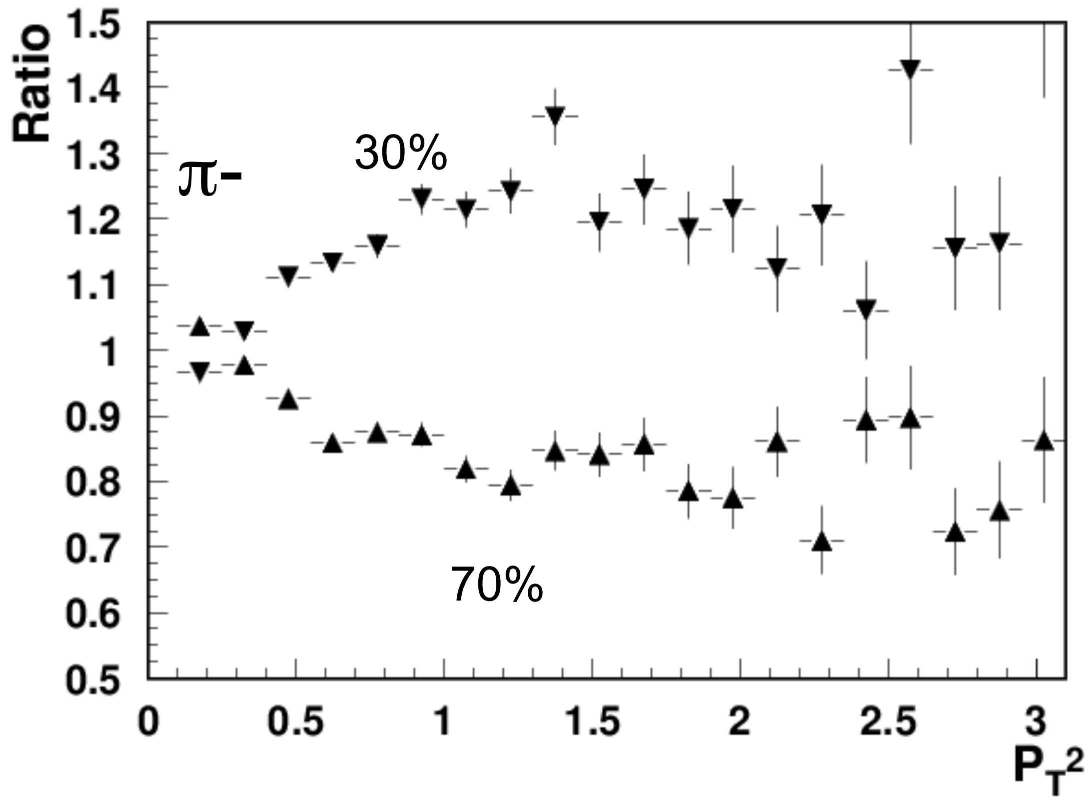
fraction of spin-1
(PYTHIA)

For the same average transverse momentum in PYTHIA increasing the fraction of spin-1 particles, increases the fraction of low PT hadrons

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

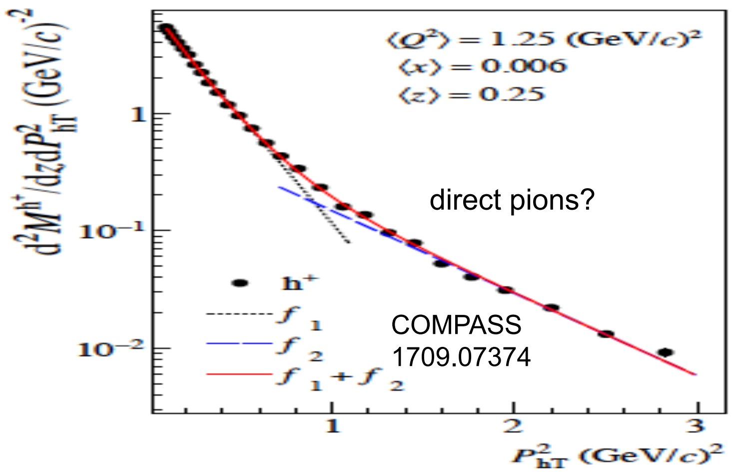
fraction of spin-1
PYTHIA-parj(11)

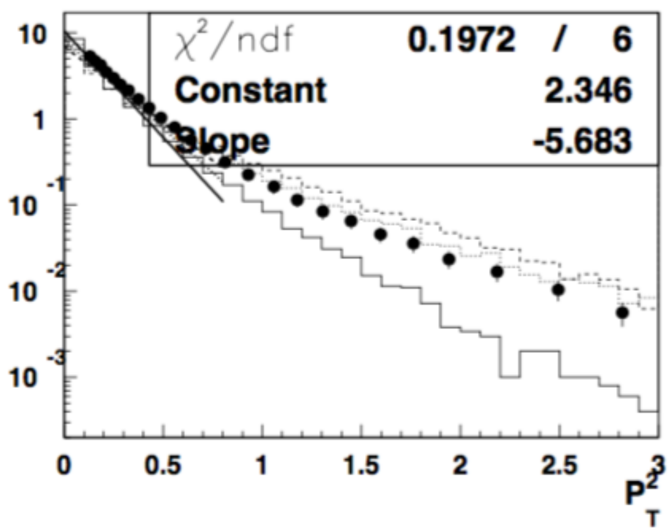




Smaller the fraction of spin-1 particles (for the same quark transverse momenta), more high P_T pions → the same low P_T distributions will have much wider large P_T-distributions depending on the fraction of VMs

Transverse momentum distributions: COMPASS





Origin of non-Gaussian tails

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
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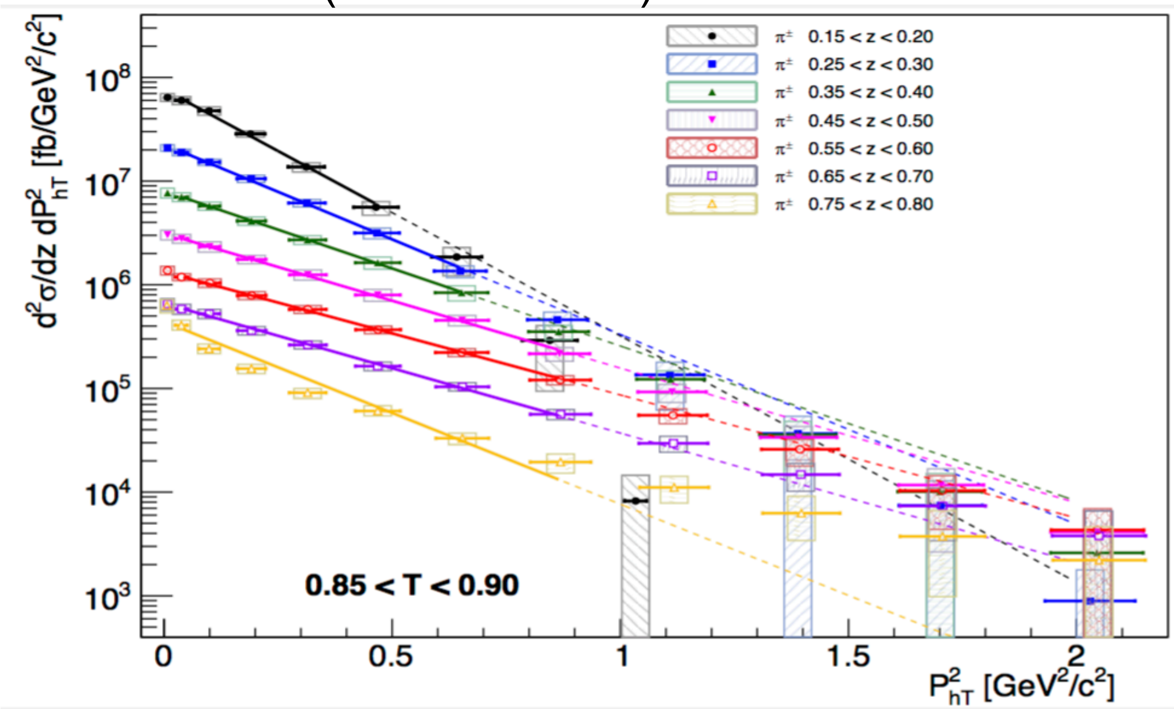
   - contributions to pions from target fragmentation may be less relevant

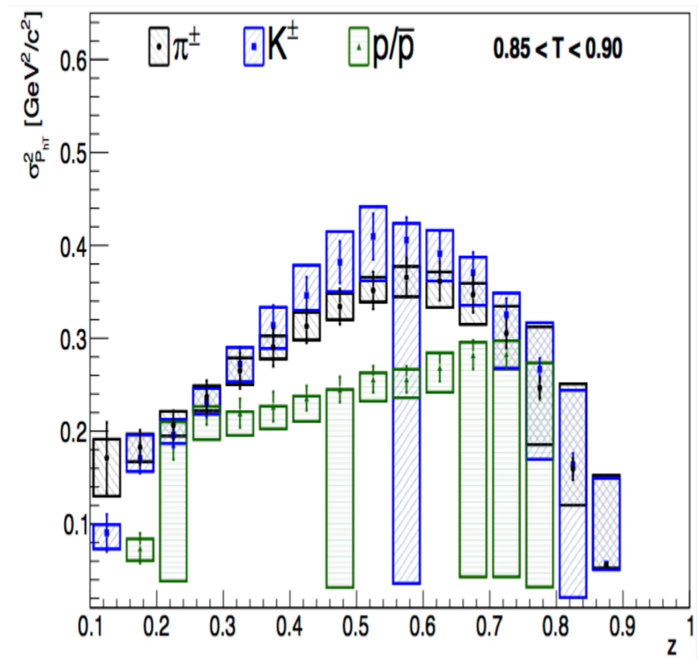
2) Combined increase of average transverse momentum and fraction of VMs allows description of non Gaussian tails at large P_T indicating most hadrons come from TMD region

3) A single Gaussian in PYTHIA applied to VMs and pions, creates a ”Low-P_T” Gaussian for decay pions

Transverse momentum distributions in e+e-

A. Vossen (POETIC-2019)





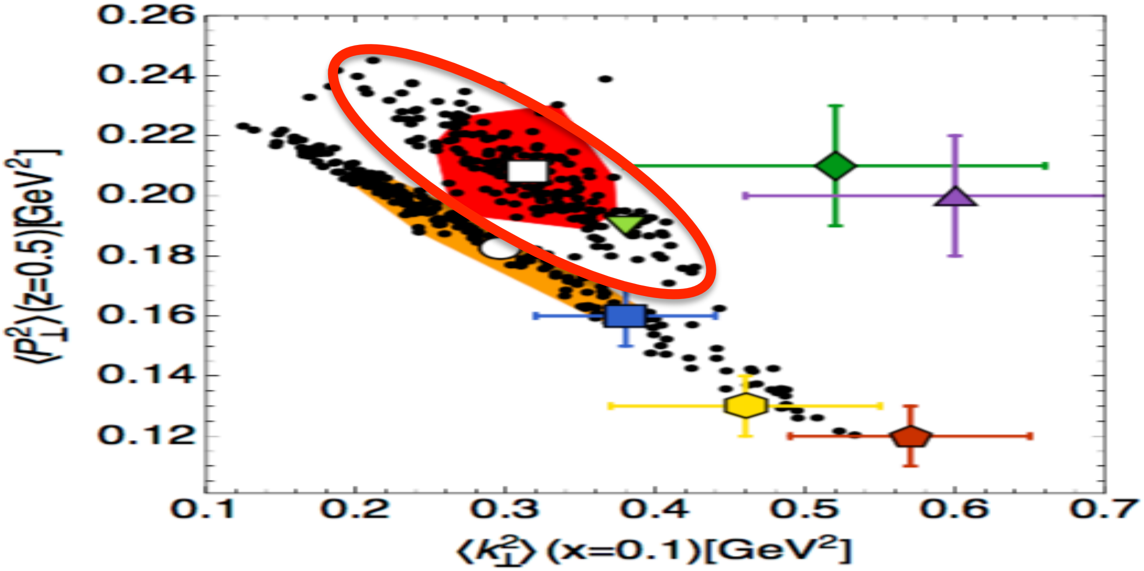
•Fit Gauss to low P_T data
•Mostly well described with possible exception at high z
•Deviation from Gauss at large P_T
•Clear increase in width with z for low values of z

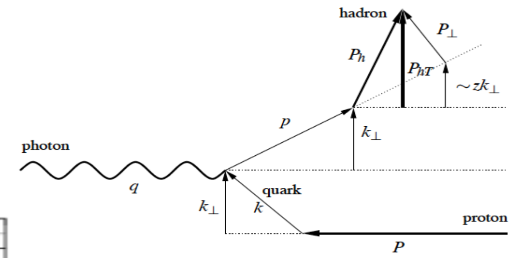
General increase with z with turnover at larger values of z for mesons

Extracting the average transverse momenta

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

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

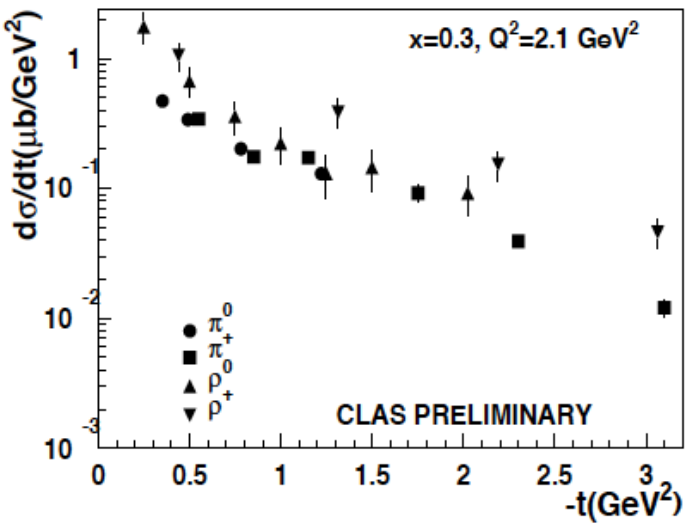


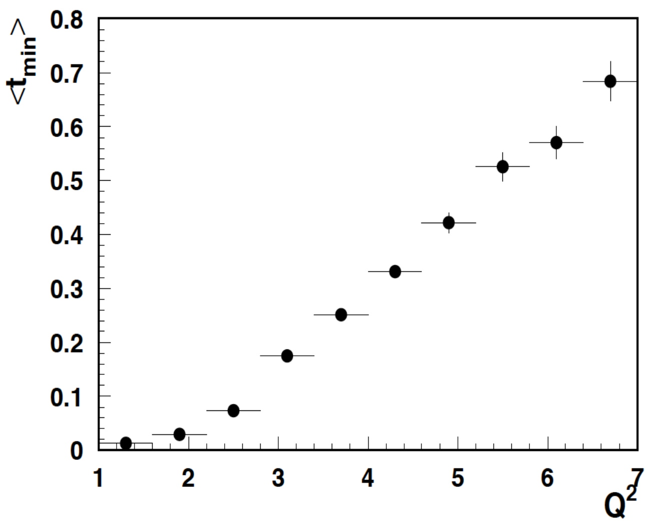


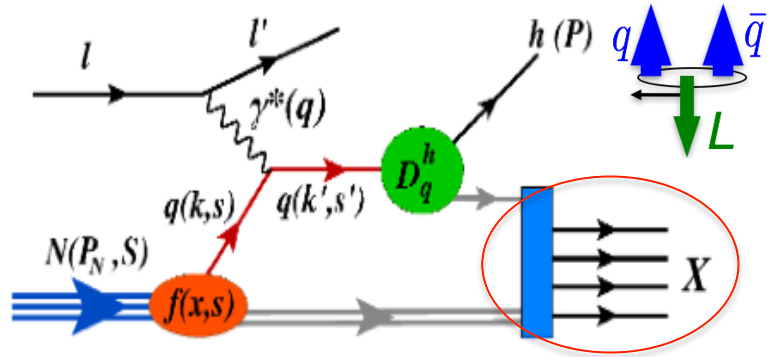
$$m_N^h(x,z,P_{hT}^2) = \frac{\pi}{\sum_a e_a^2 f_1^a(x)} \times \sum_a e_a^2 \, f_1^a(x)\, D_1^{a\to h}(z) \, \frac{e^{-P_{hT}^2/\left(z^2\langle k^2_{\perp,a}\rangle + \langle P^2_{\perp,a\to h}\rangle\right)}}{\pi\left(z^2\langle k^2_{\perp,a}\rangle + \langle P^2_{\perp,a\to h}\rangle\right)}$$

- Adding DY data shifts up the values of transverse momenta
- Multiplicity alone may not be enough to separate $\langle k_T \rangle$ from average $\langle p_T \rangle$
- Suggestion: perform fits for P_T>0.7-0.8 GeV, where independent fragmentation safer

Exclusive π/ρ production at large t





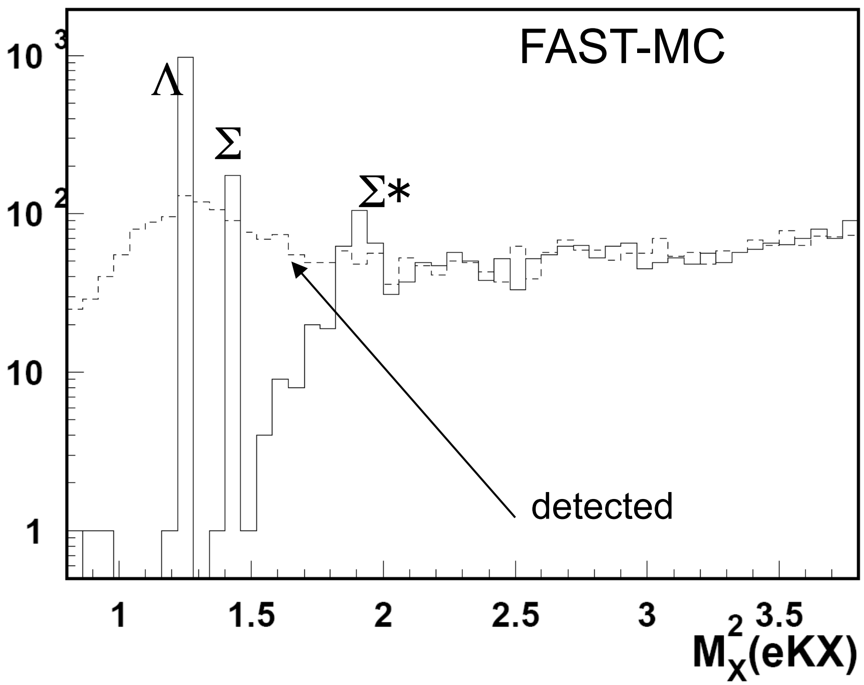


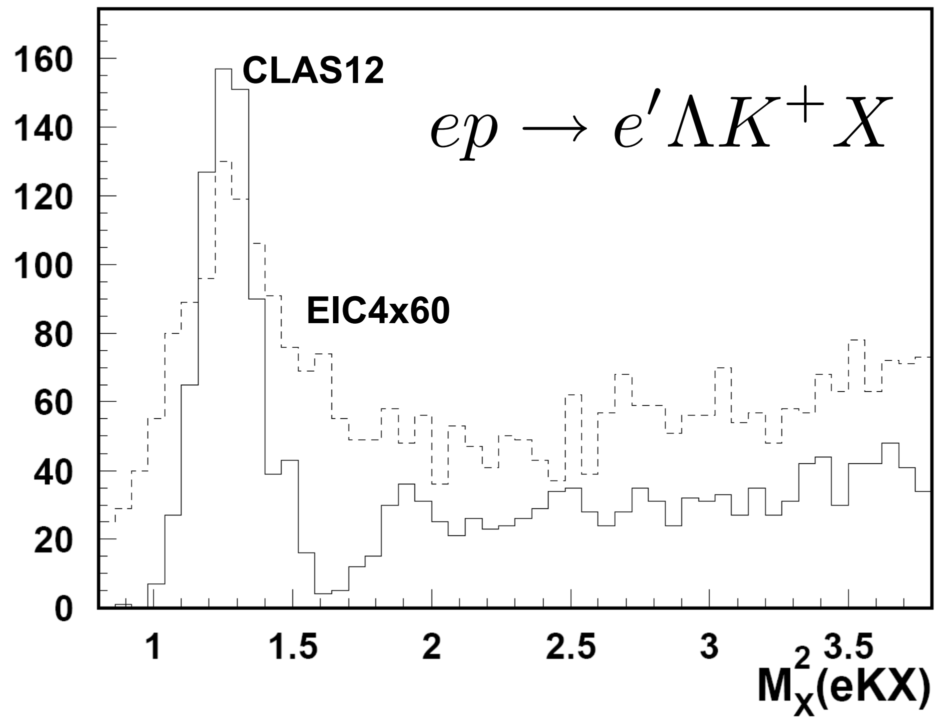
p,n

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, 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 rho
- ....

Kaon production in SIDIS

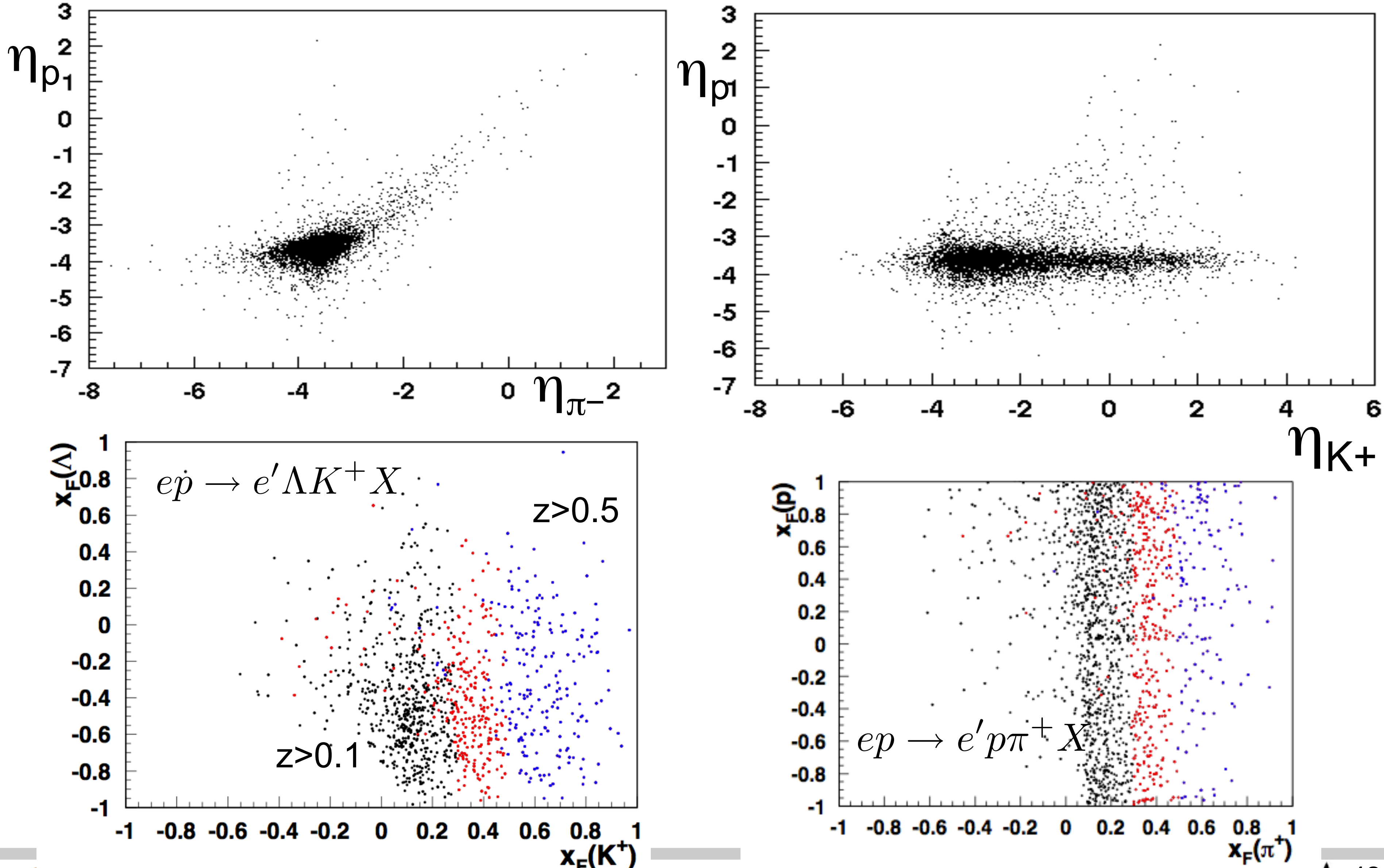




$\sigma(p) = 0.05 + 0.06*p$ [GeV] %

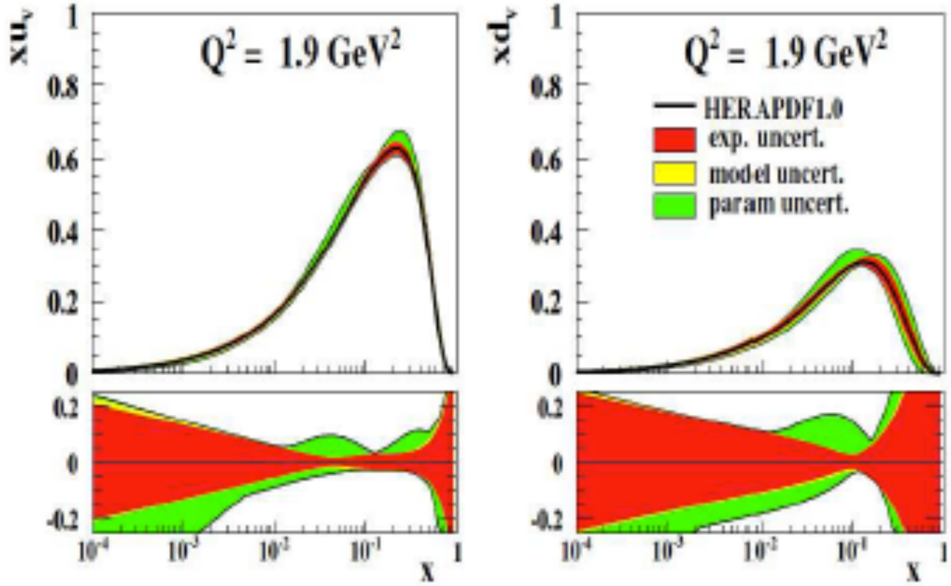
Identification using the missing mass may be possible

EIC 5x50 GeV: Kinematic distributions of Lambdas and Kaons

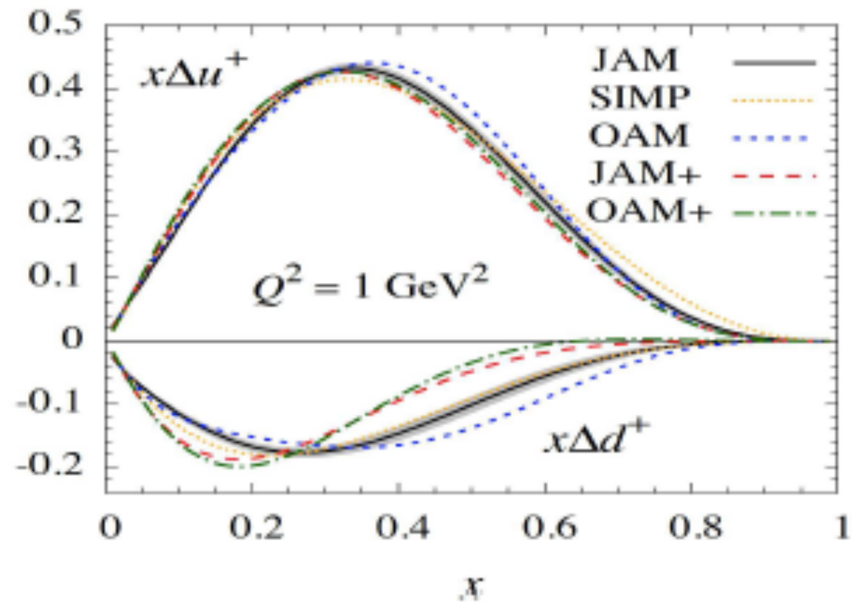


Studies of 1D PDFs

F. Aaron et al., JHEP 1001 (2010)



P. Jimenez-Delgado et al (2014), 1403.3355.



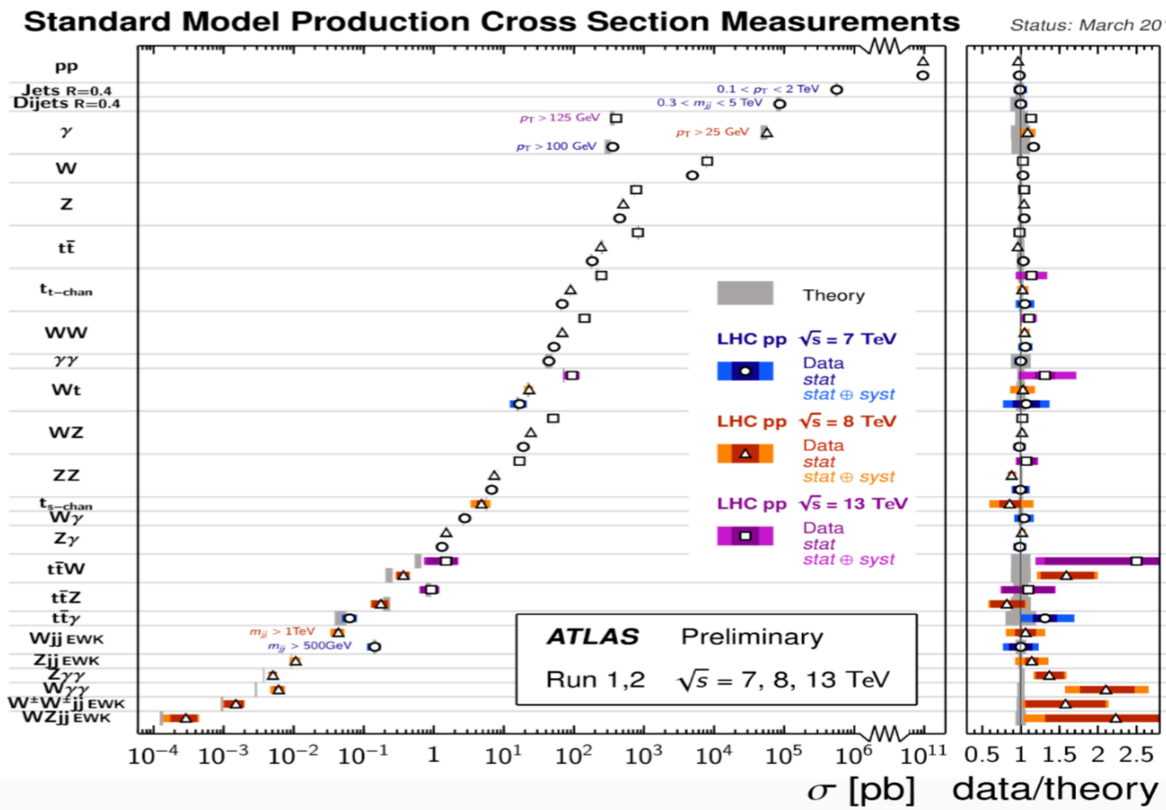
- Strong model and parametrization dependence observed already for 1D PDFs
- Positivity requirement may change significantly the PDF (need self consistent fits of polarized and unpolarized target data!!!)

Standard model successes:

X.Ji (POETIC-2019)

- The standard model itself has been hugely successful in explaining many physics phenomena
  - Electroweak processes
  - High-energy QCD processes

Perturbation theory works! (LHC)



All moments are relevant

$$F_L(x,Q^2) = (1+\gamma^2)F_2(x,Q^2) - 2xF_1(x,Q^2)$$

F_L

$$\int d^2k_T k_T^2 f^{\perp}(x,k_T^2) = 2F_L(x) - F_1(x) + \mathcal{M}_4$$

Tw 3 Tw 4 Tw 2

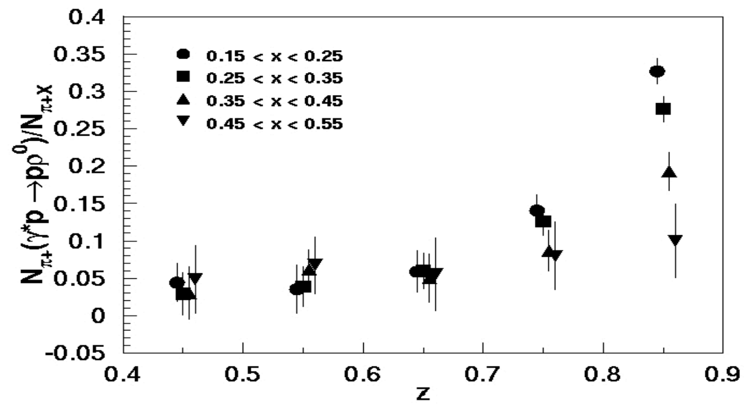
Connection with SIDIS cross section

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\Big[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\Big(xh\,H_1^{\perp} + \frac{M_h}{M}\,f_1\frac{\tilde{D}^{\perp}}{z}\Big) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\Big(xf^{\perp}D_1 + \frac{M_h}{M}\,h_1^{\perp}\frac{\tilde{H}}{z}\Big)\Big]$$

Simonetta Liuti (UVA) CTEQ Fall Meeting, Nov 10

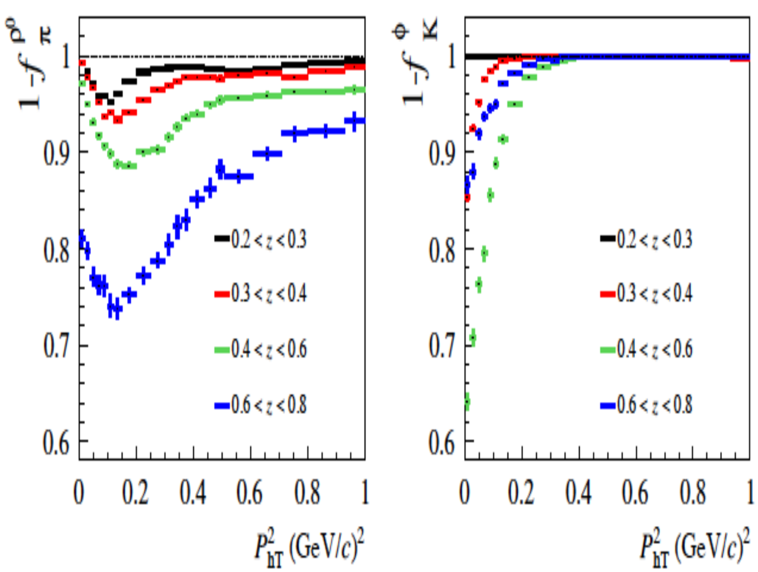
Dihadrons and Vector meson contributions

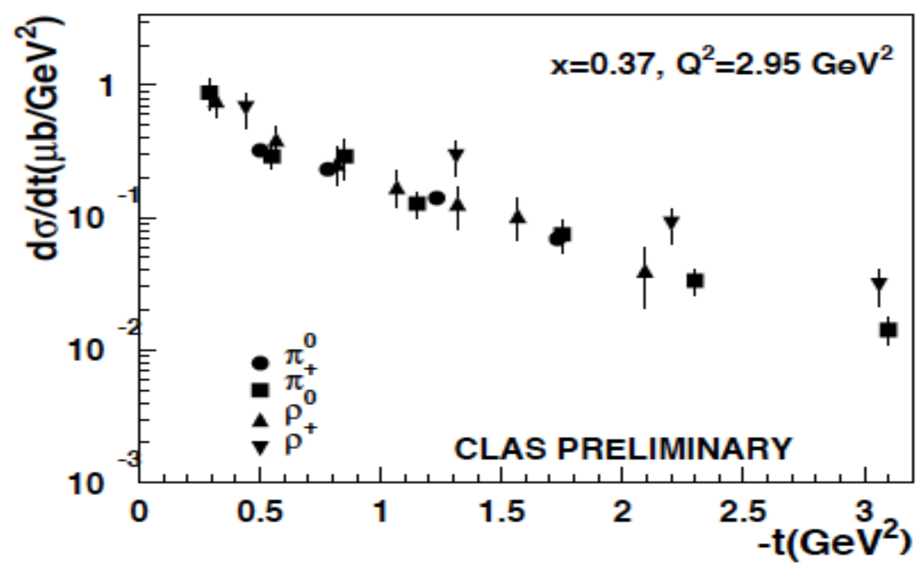
1) Should we worry about pions/kaons coming from vector meson decays?
2) What about ρ+ and ρ-
3) What do we know about relevant observables for pions specifically coming from vector meson decays
4) What about SIDIS rhos (can we measure?)
5) What is radiative correction due to rho?
6) Vector meson as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



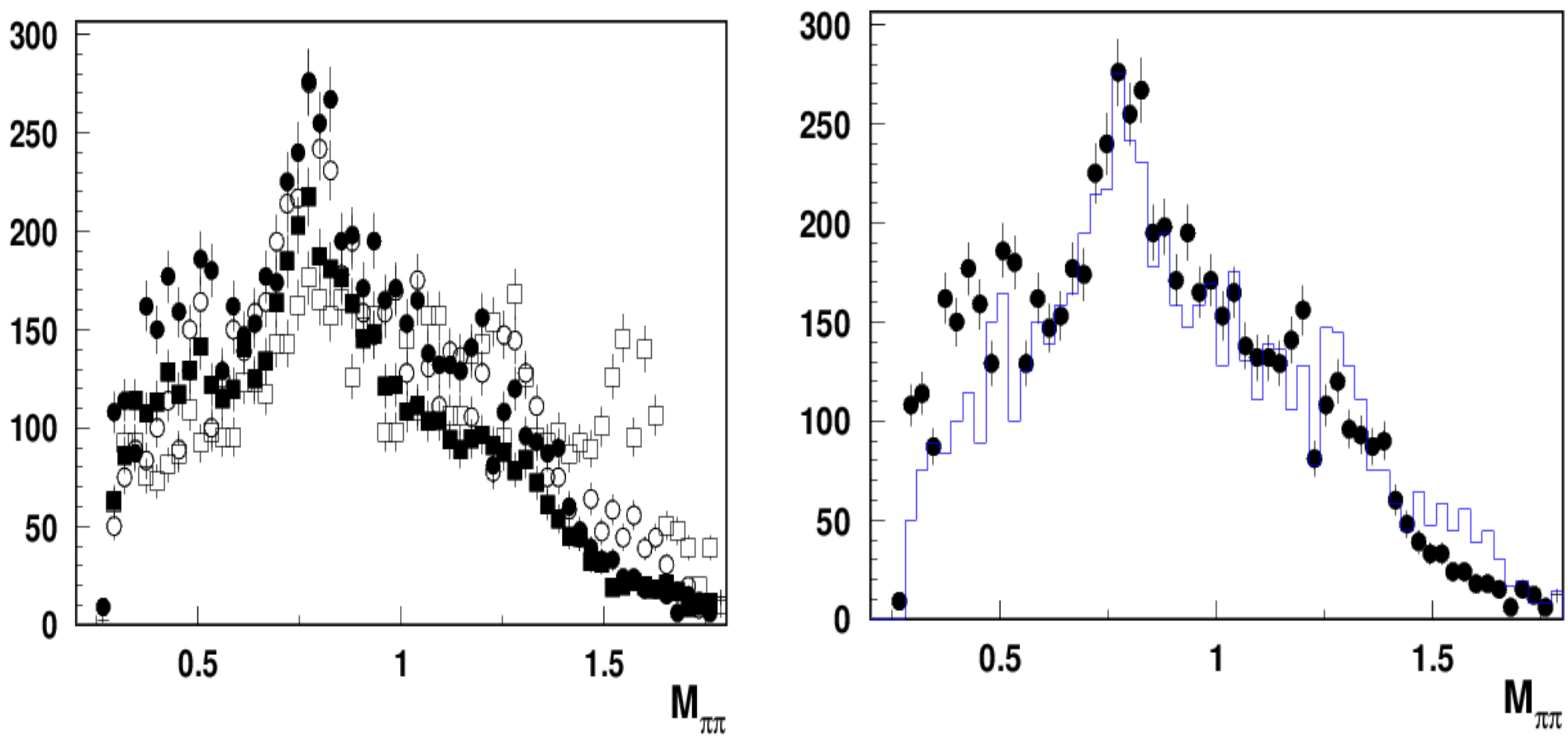
Hard exclusive meson production from clas6

COMPASS:1709.07374



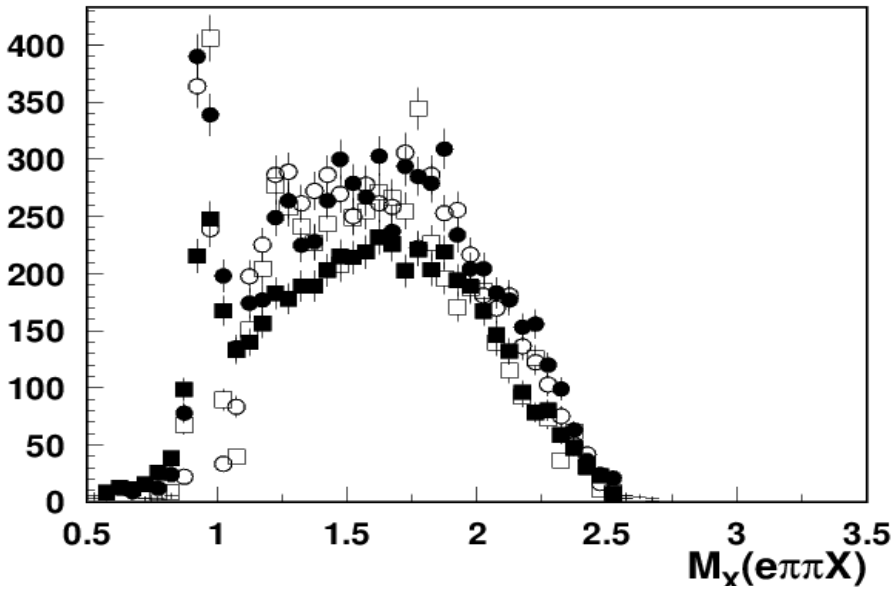


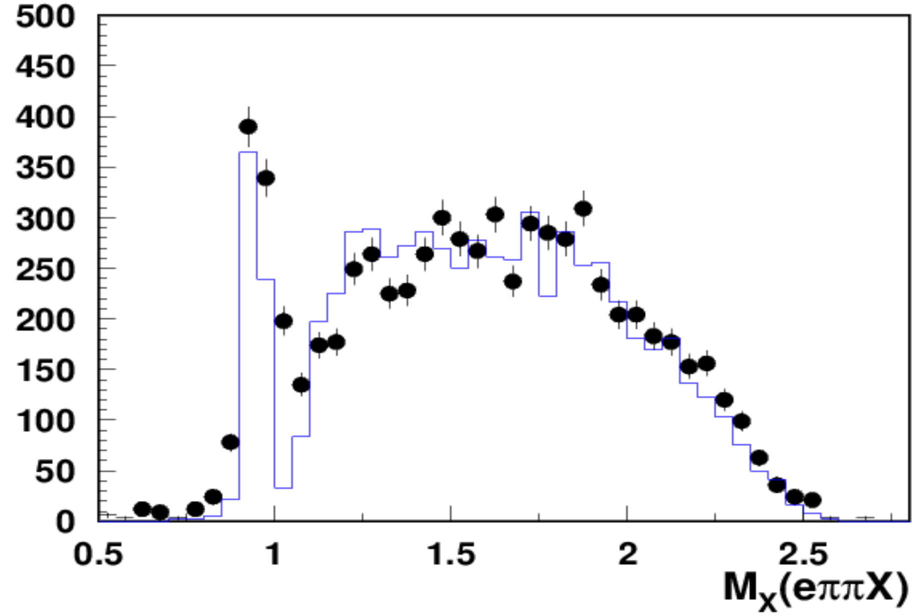
CLAS12-RGA: ep→e'$\pi^+\pi^-$X

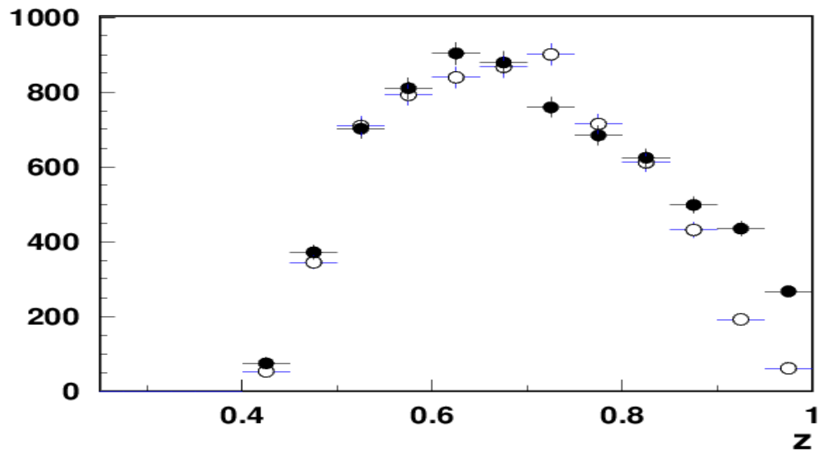


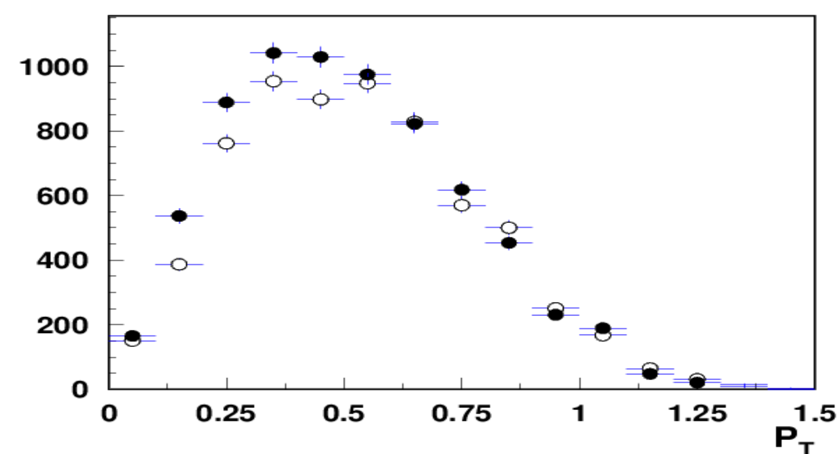
Filled circles low lumi data, filled squares high lumi data
open symbols MC: circles→ 70% VM, squares 30% VM

RGA: ep→e'$\pi^+\pi^-$X







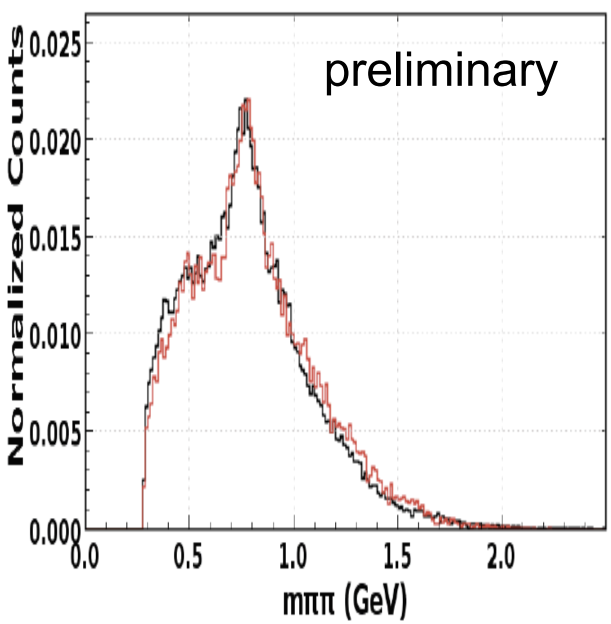


Filled circles low lumi data, filled squares high lumi data
open symbols MC: circles→ 70% VM, squares 30% VM

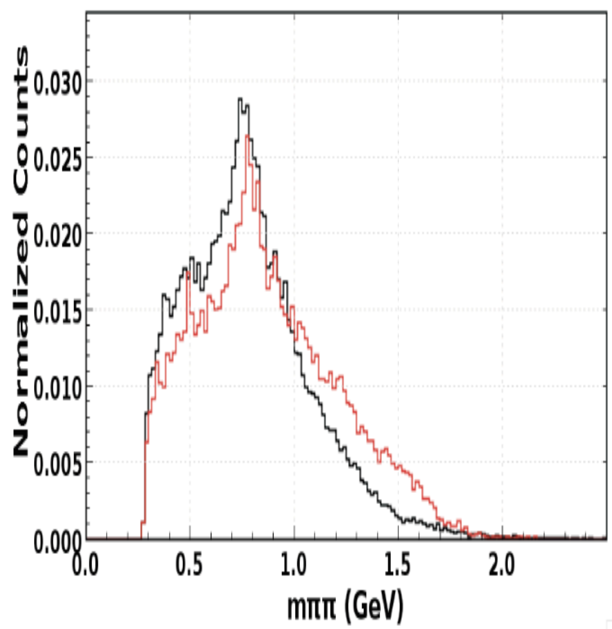
VM contributions: MC vs CLAS12 Data

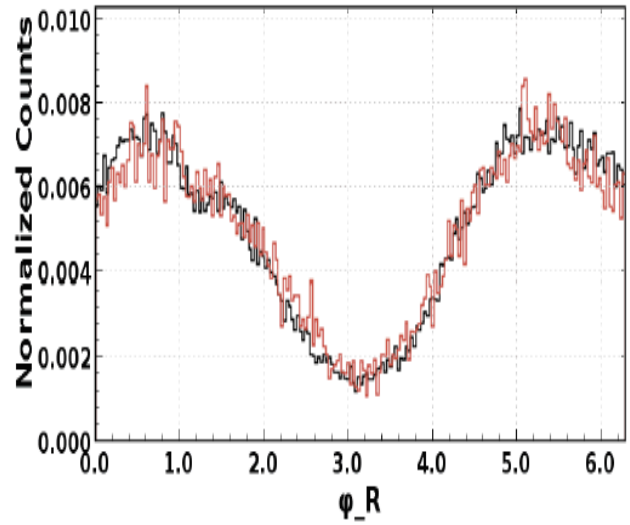
Timothy B. Hayward W&M

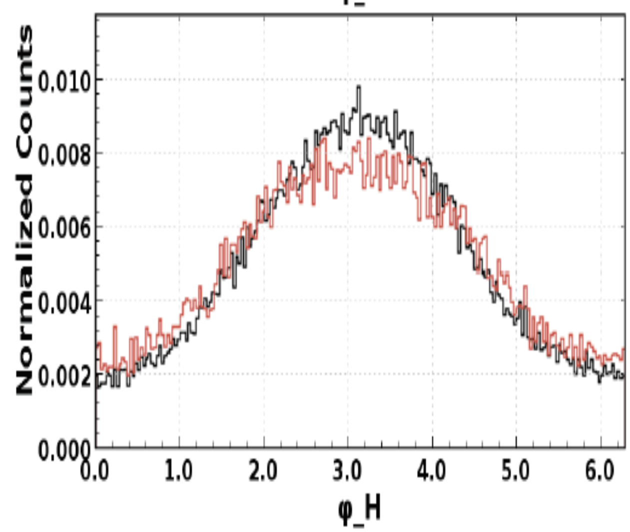
70% VM Production



30% VM Production

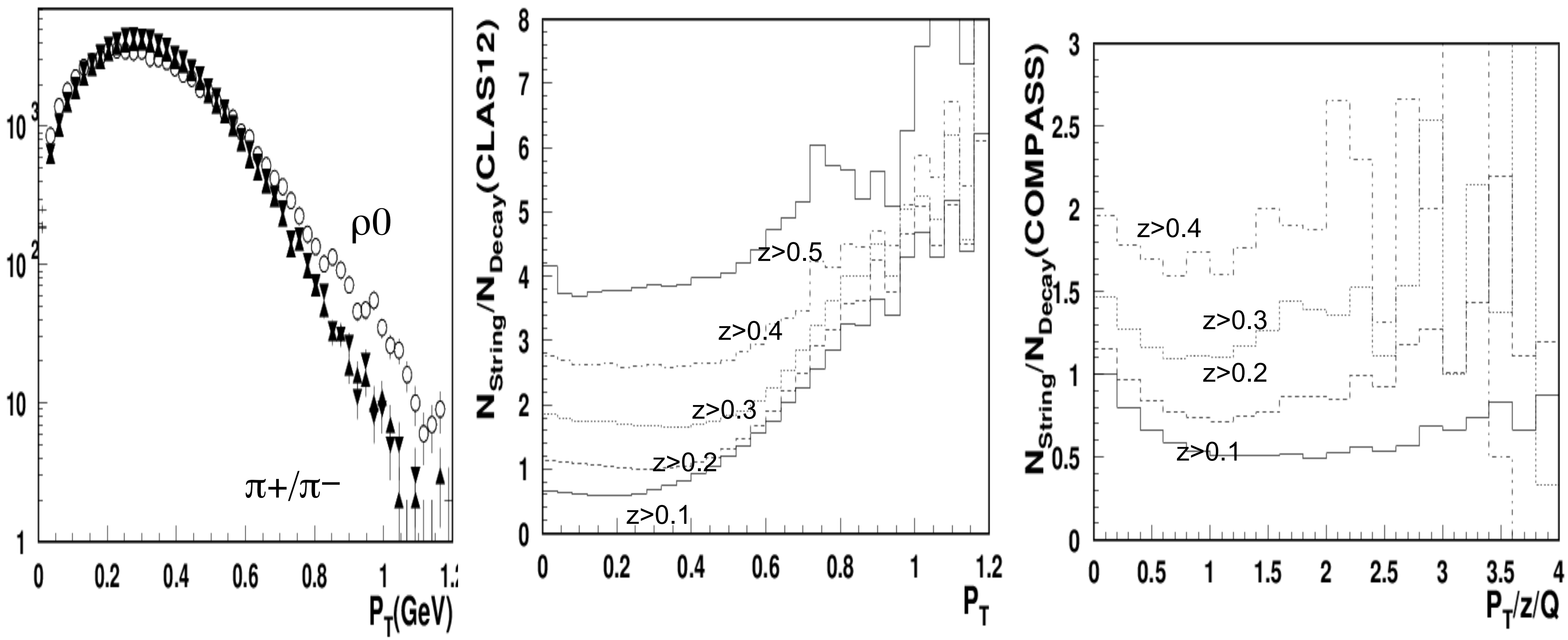






The 70% contribution much more closely matches the data.

P_T of pions from rho decays: LUND string fragmentation



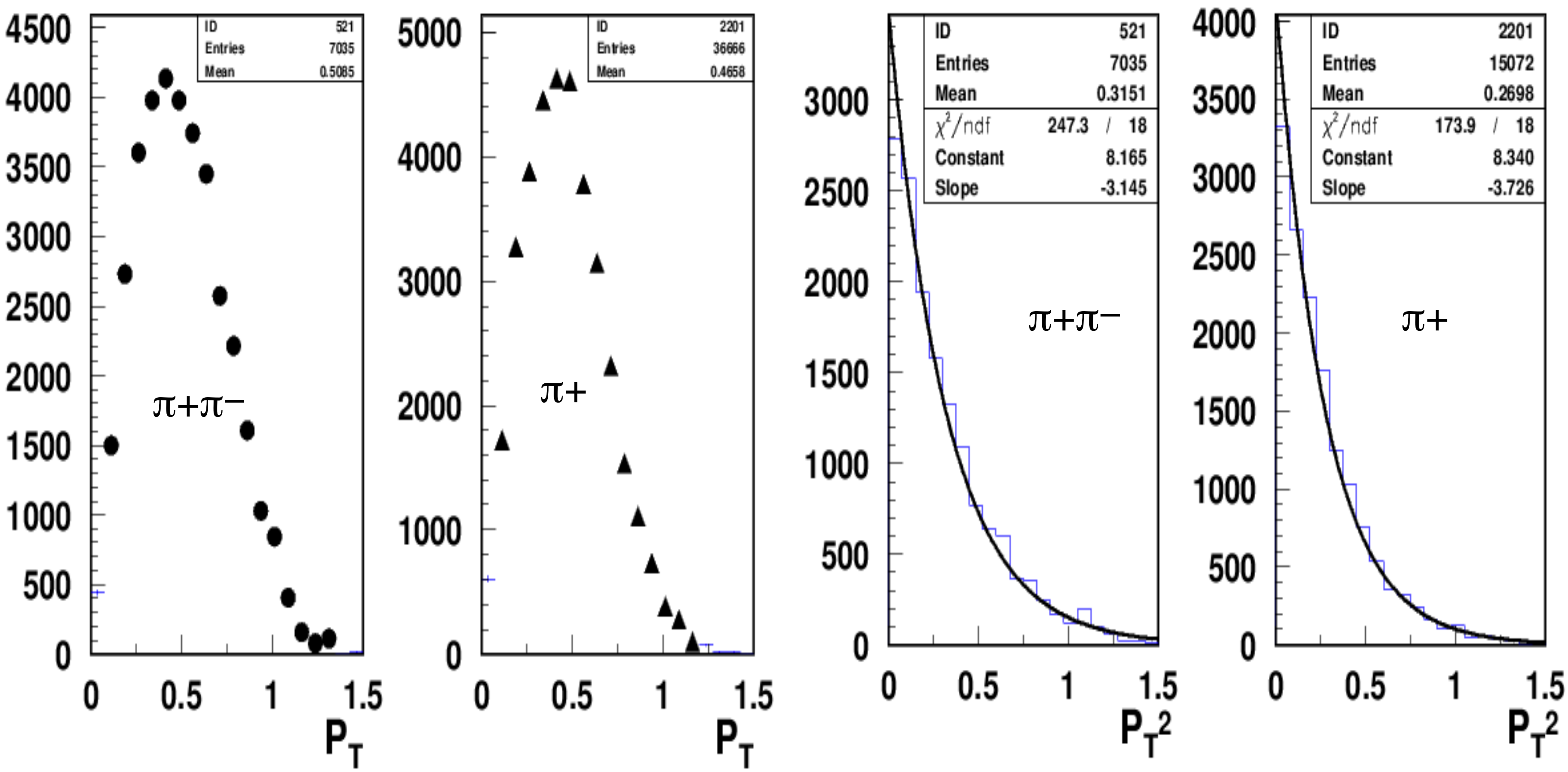
P_T-dependence of rho is similar to the one for decay pions at low P_T

Fraction of direct π+ increases with P_T

Fraction of direct π+ decreases with P_T/z/Q

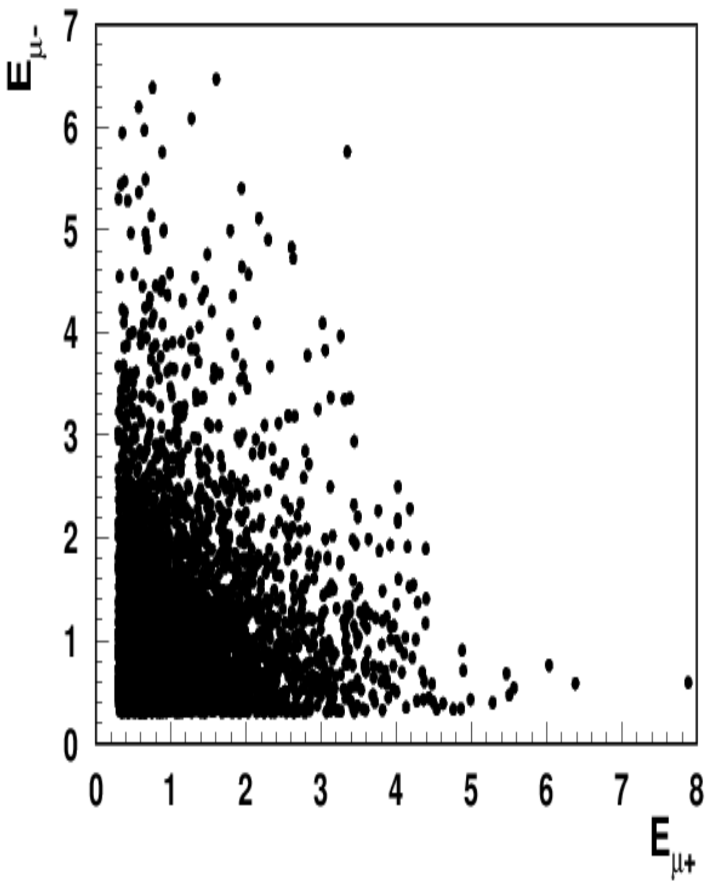
Gaussian fits in low P_T-range are dominated by VM decay pions!

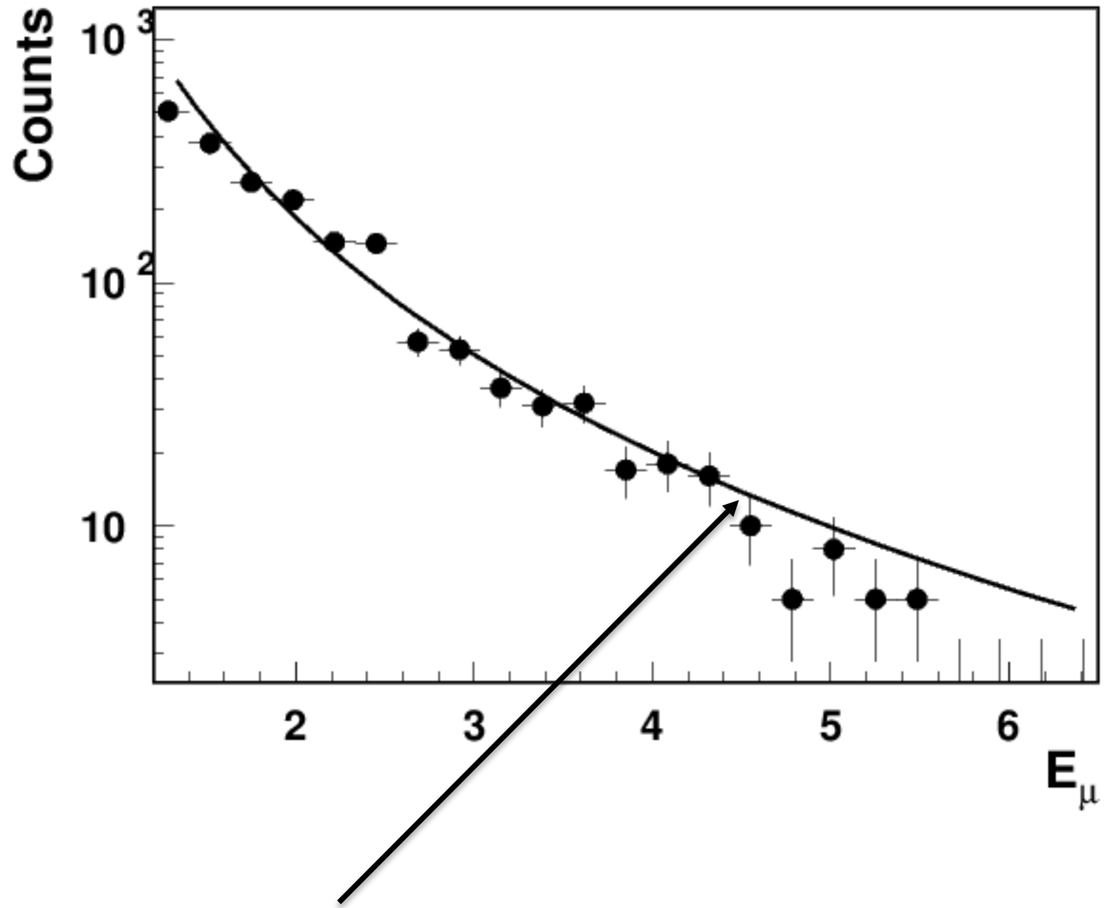
P_T of pions from VM decays: CLAS12 data



For the same average value of z, $\pi+\pi-$ pair has a wider P_T-distribution

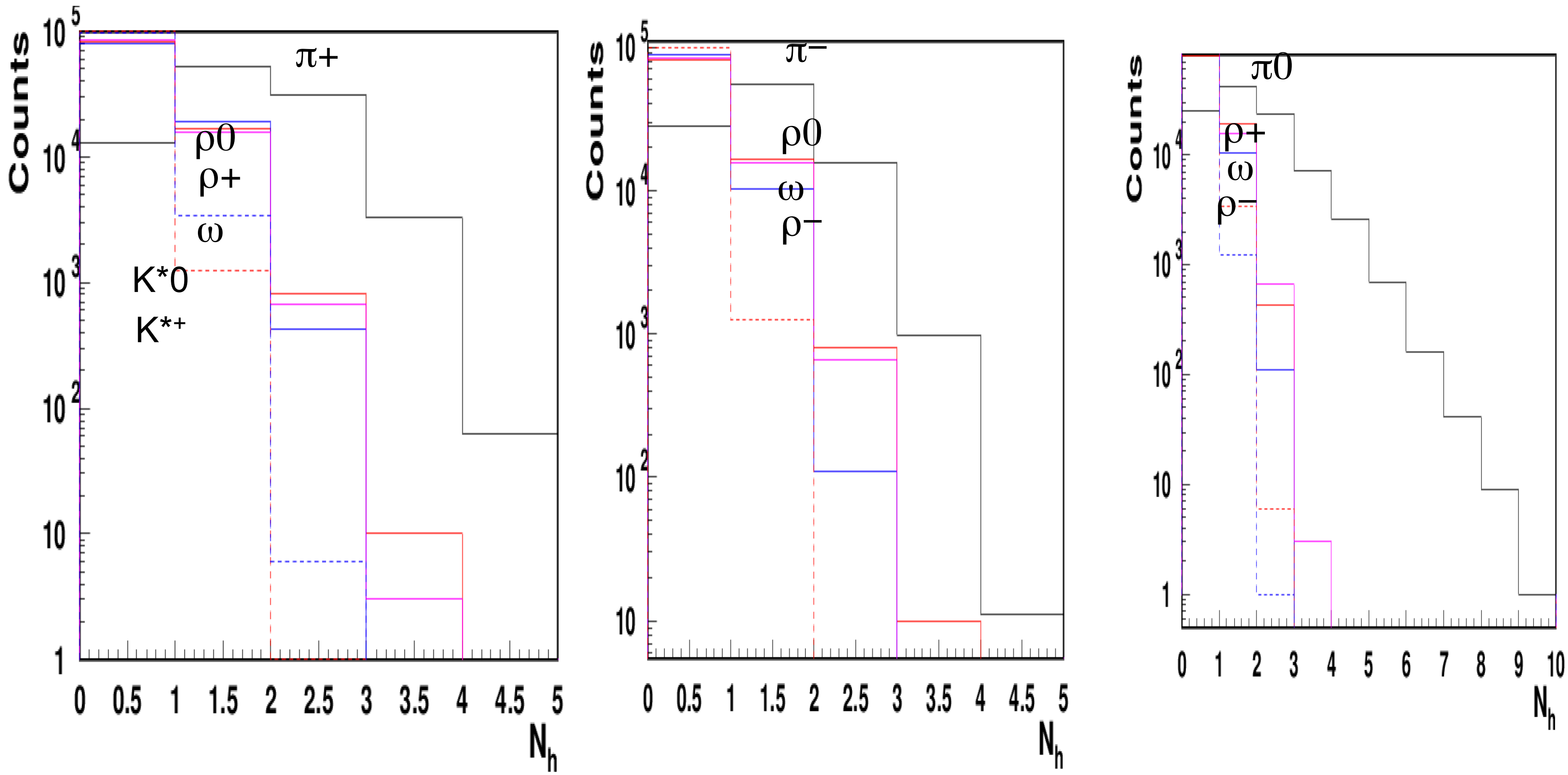
Kinematical distributions of Muons at clas12





Muons from rho decays in clas12 follow $E^{-3.2}$
Similar behavior for cosmic e+e- PhysRevLett. 113.221102 (H.Dembinski and Co)
EPJ **52**, 02001 (2013) (Ostapchenko)

Background events



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

Radiative DIS

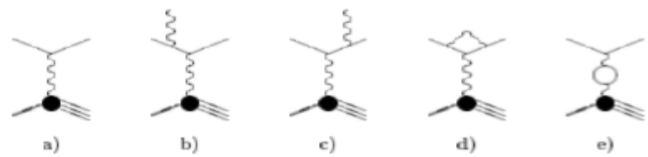


Figure 1: Feynman diagrams contributing to the Born and the radiative correction cross sections in lepton-nucleus scattering.

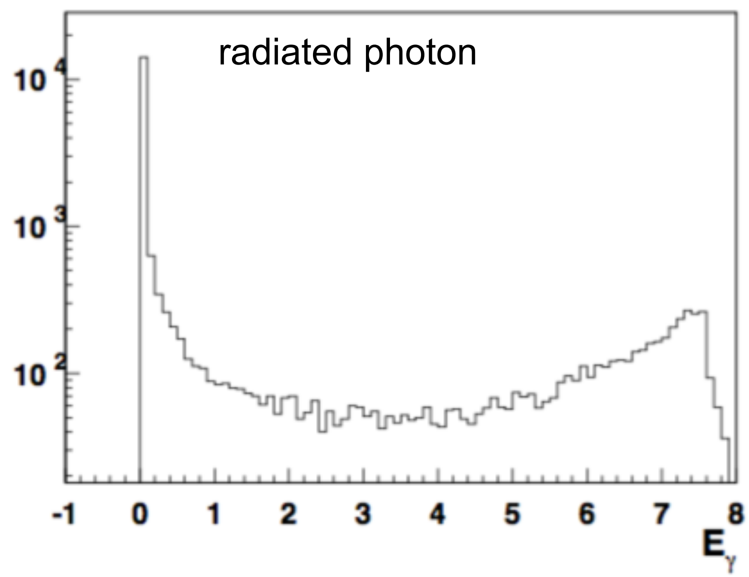
Akushevich et al. http://www.jlab.org/RC/radgen/

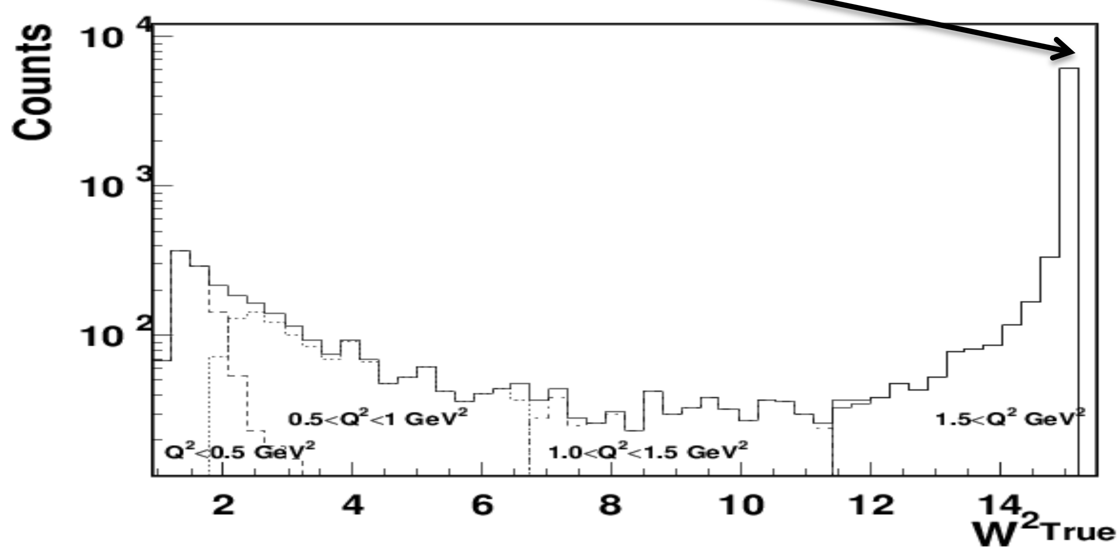
SIDIS version: JLAB-PHY-19-2938

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

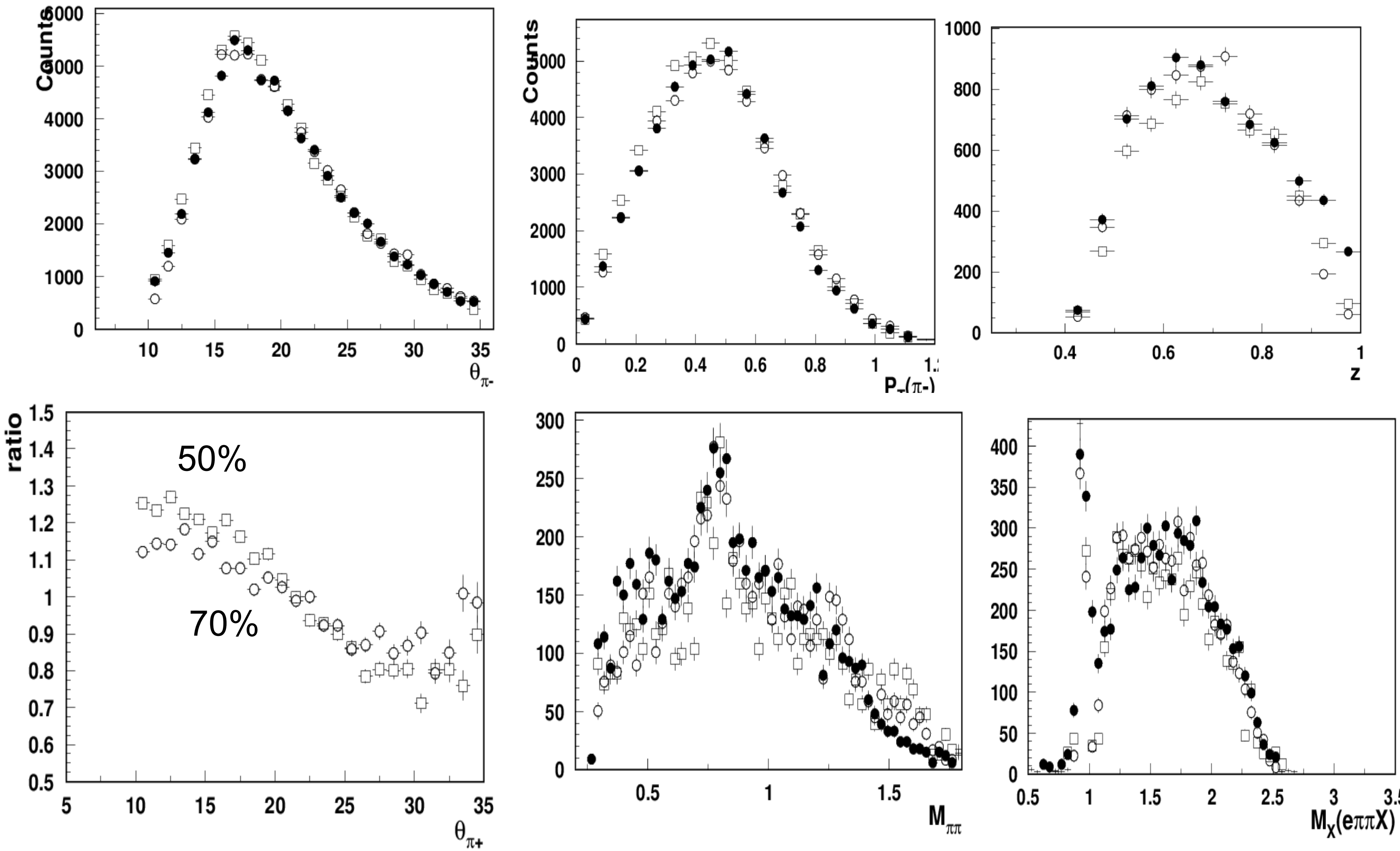
generate a single kinematical point at E_b=10.6 GeV with e'=2.0 GeV, θ=0.3
→ **x,y,Q^2,W^2(0.12,0.8,1.9,15.1)**
Integrated over all **Eγ** **$\sigma_{Rad}/\sigma_{Born}$=1.24**

original
Q^2,W^2(1.9,15.1)

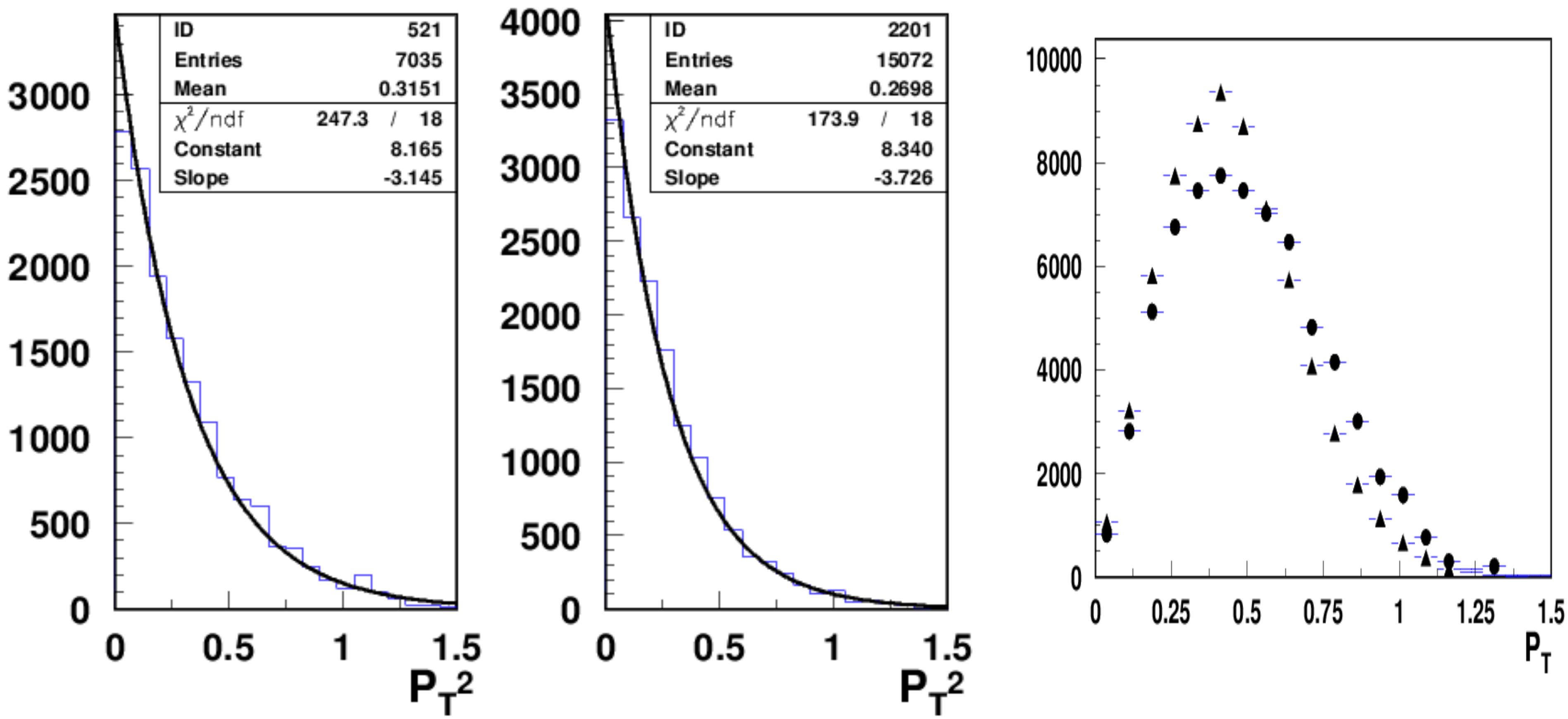




compare different distributions: 70% vs 50%



P_T-widths



For the same <z> rho (pi+pi-) is wider than pi+

cl_parj11=0.7 ! default PARJ(11) fraction of spin 1 light mesons (rho)
cl_parj12=0.4 ! default PARJ(12) fraction of spin 1 strange mesons (affects K*s)
cl_parj14=0.0 ! default PARJ(14) : (D = 0.) is the probability that a spin = 0 meson is produced with an orbital angular momentum 1, for a total spin = 1.
cl_parj15=0.0 ! defaultPARJ(15) : (D = 0.) is the probability that a spin = 1 meson is produced with an orbital angular momentum 1, for a total spin = 0.
cl_parj16=0.0 ! defaultPARJ(16) : (D = 0.) is the probability that a spin = 1 meson is produced with an orbital angular momentum 1, for a total spin = 1.
cl_parj17=0.0 ! defaultPARJ(17) : (D = 0.) is the probability that a spin = 1 meson is produced with an orbital angular momentum 1, for a total spin = 2.
c
cl_parj21=0.4 ! default PARJ(21) for the width of P_T distribution default in JETSET 0.36

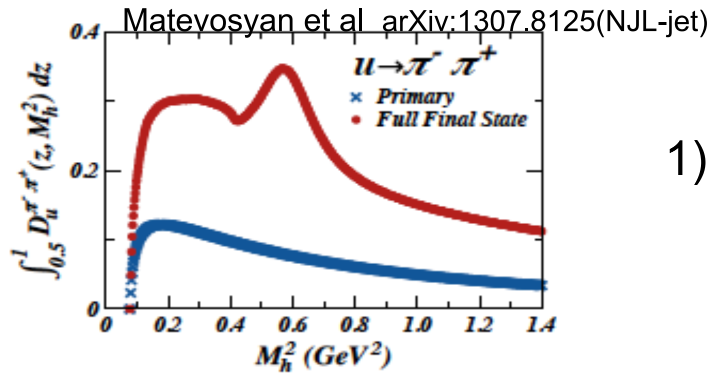
cl_parj41=0.30 ! default parameter a in (1-z)^a large z-suppression in FF
cl_parj42=0.58 ! default parameter b in exp(-bm_\perp^2/z) in FF

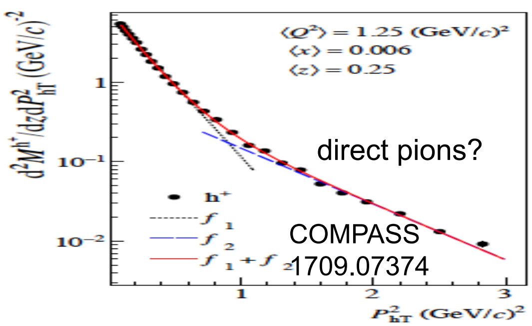
Parameter affecting single pion P_T(parj21), z(parj41)

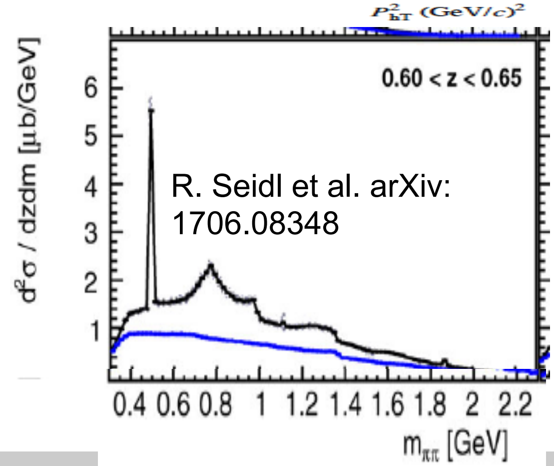
Main parameters to describe the fragmentation function:

- the width of the transverse momentum distribution
- the ratio of strange to nonstrange pair creation
- the ratio of vector to pseudoscalar meson production

Dihadrons: key to hadronization?







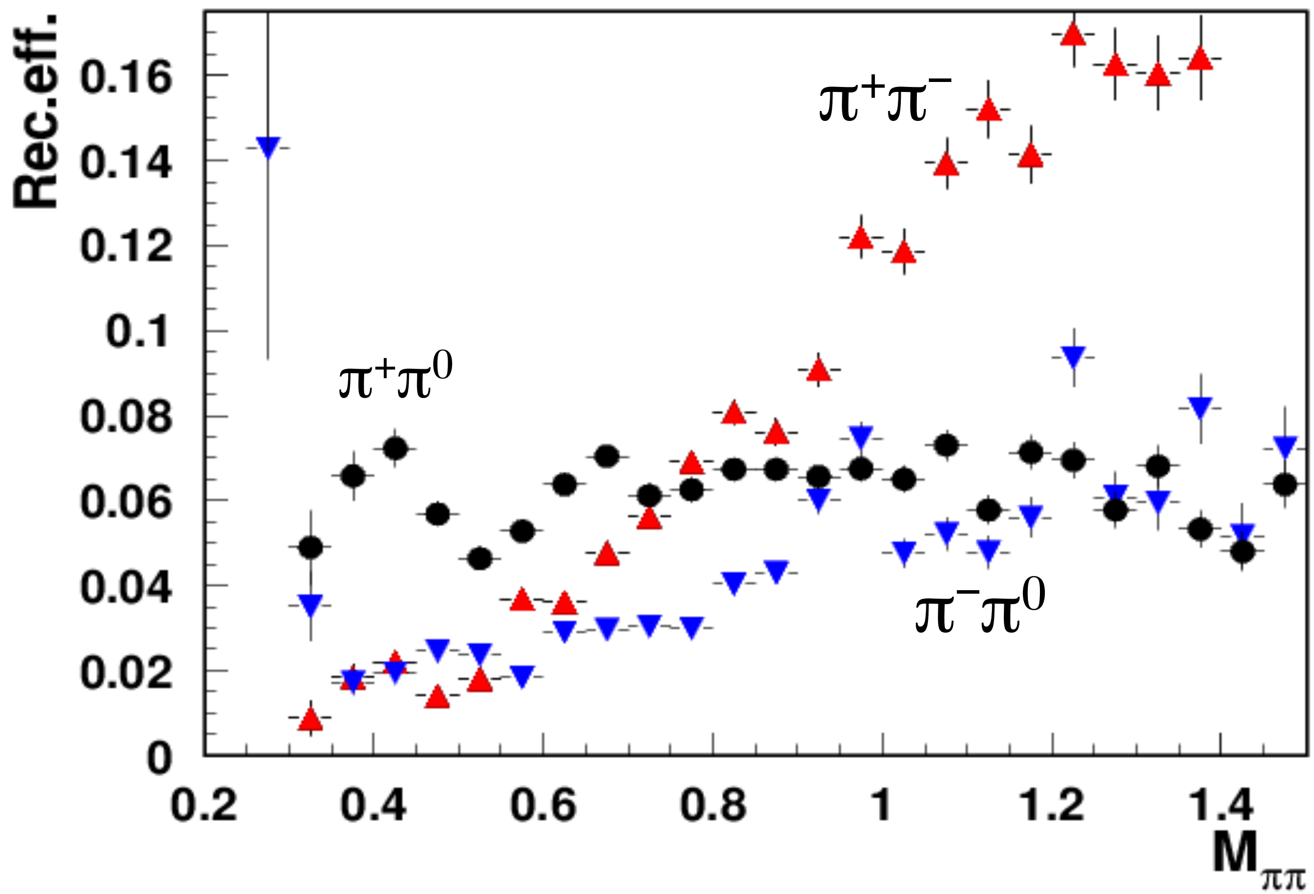
How quarks hadronise?

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) Most hadrons at accessible in SIDIS P_Ts come from non-perturbative region, with direct pions dominating only the high P_T fraction
3) Fragmentation functions (production probability) of VMs, both unpolarized and polarized should be extracted from SIDIS and e+e- and compared to check the "independence" and "universality"

R.Seidl (preliminary) → at least 40% of dihadrons in e+e- are from rhos(good for universality)

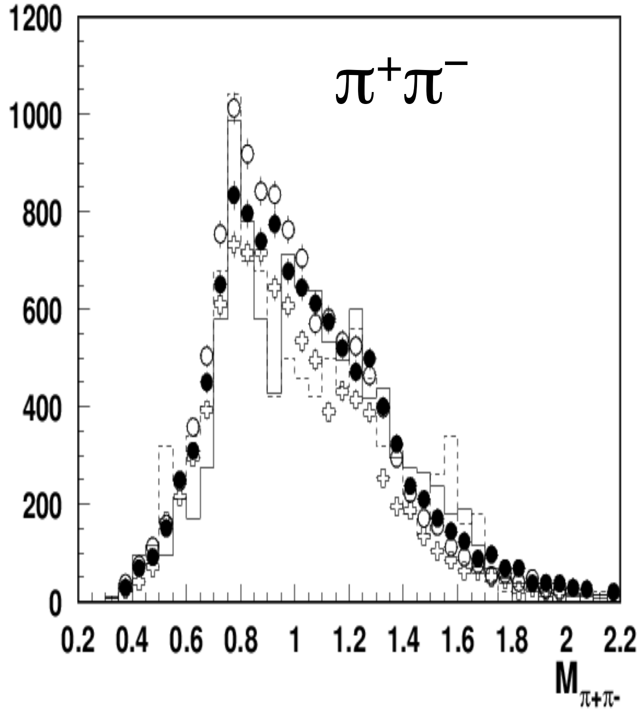
Invariant mass of pion pairs Mππ

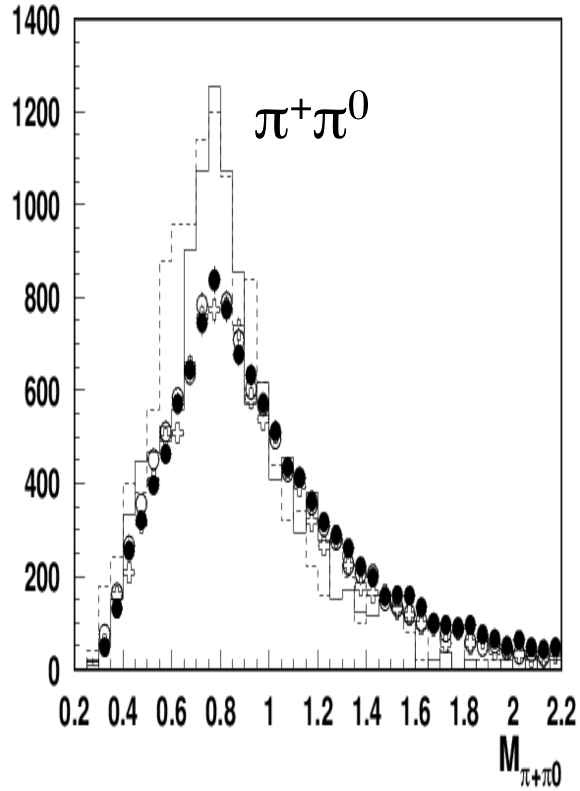


Reconstruction efficiencies extracted from LUND-MC with full GEANT4 simulation of CLAS12

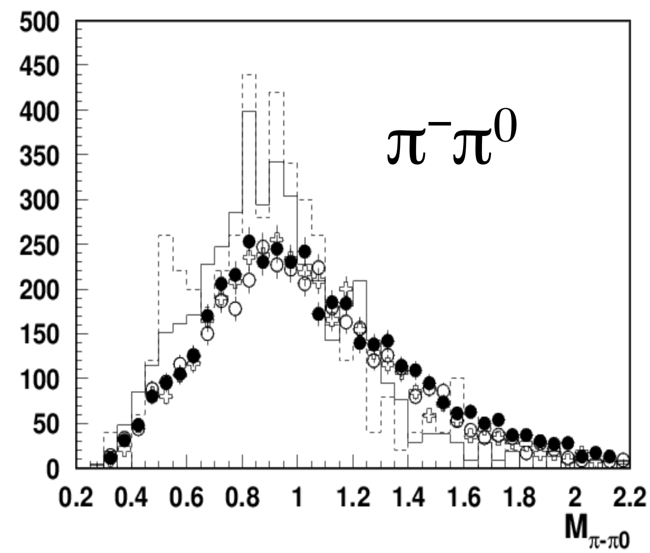
In the range 0.7<Mππ <0.9 efficiencies for ρ0 and ρ+ comparable

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

Quark flavours and transverse momenta in PYTHIA

field energy between them can be transformed into the sum of the two transverse masses $\mathbf{m_T}$. quarks created in one point and then tunnel out to the classically allowed region. The probability is given by

$$\exp\left(-\frac{\pi m_\perp^2}{\kappa}\right) = \exp\left(-\frac{\pi m^2}{\kappa}\right)\exp\left(-\frac{\pi p_\perp^2}{\kappa}\right)$$

the string tension $\kappa \approx 1\ \mathrm{GeV/fm} \approx 0.2\ \mathrm{GeV}^2$

The factorization of the transverse momentum and the mass terms leads to a flavour independent Gaussian spectrum for the **p**x and **p**y

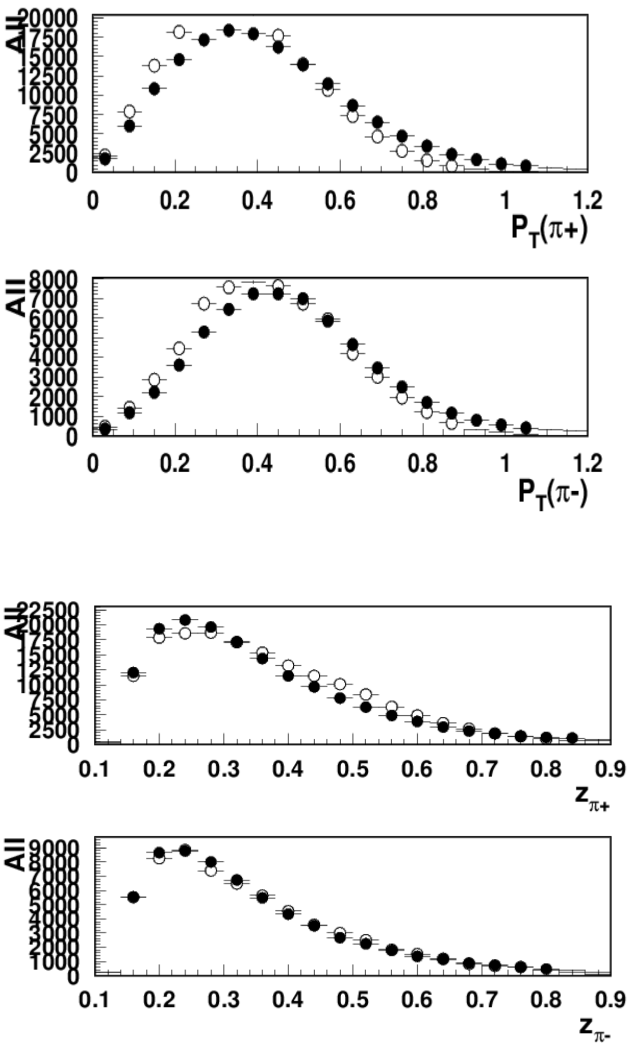
The **p**T of a meson $q_{i-1}\, q_i$ is given by the vector sum of the **p**T's of the q_{i-1} and q_i constituents, which implies Gaussians in $\mathbf{p_x}$ and $\mathbf{p_y}$ with a width \sqrt(2) that of the quarks themselves

flavor dependence u : d : s : c → 1 : 1 : 0.3 : 10^{-11}

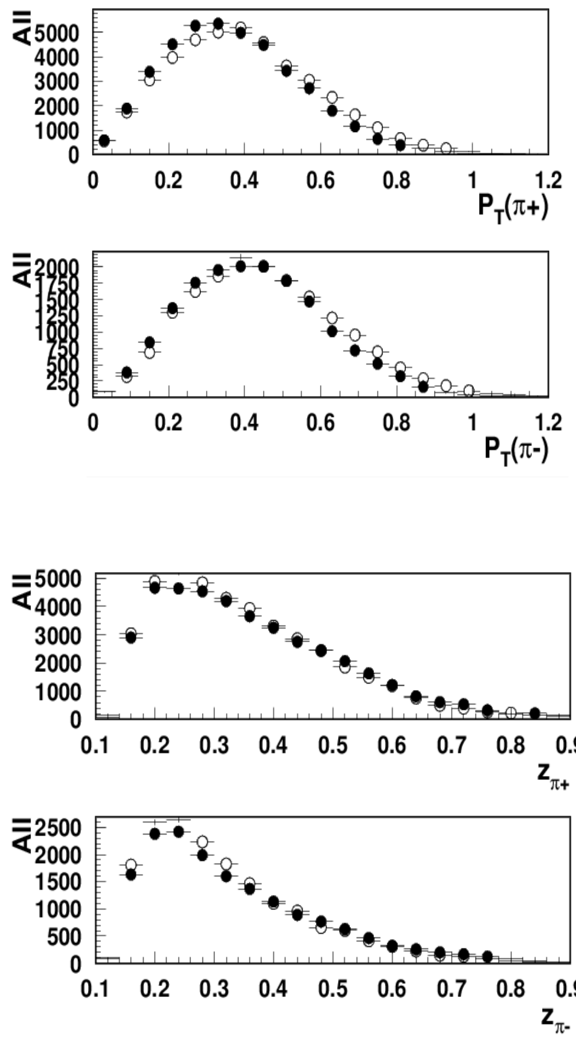
Spin counting arguments would then suggest a 3:1 mixture between the lowest lying vector and pseudoscalar multiplets. Wave function overlap arguments lead to a relative enhancement of the lighter pseudoscalar states

comparing clas12 data with MC

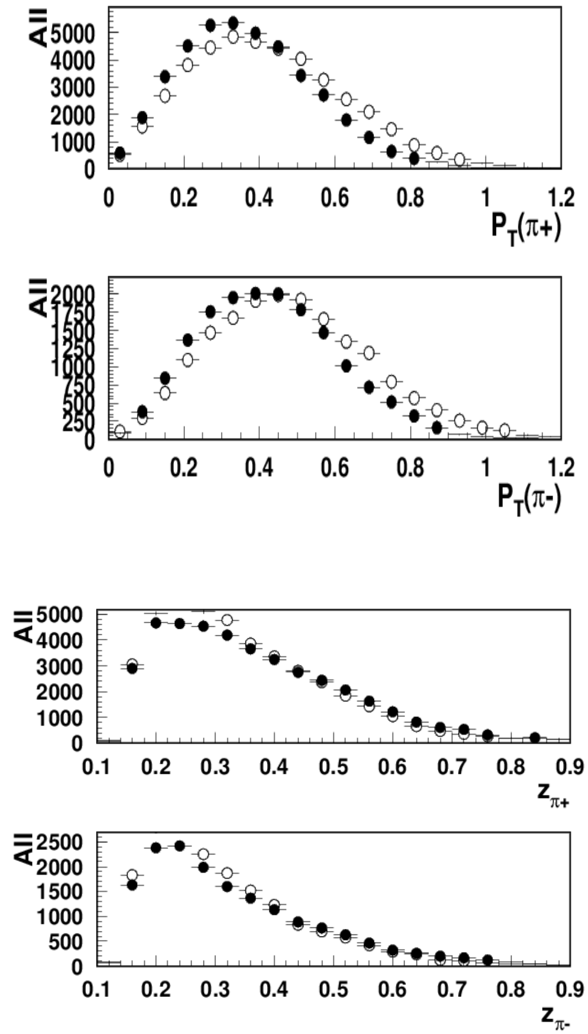
data vs parj41=0.3/parj21=0.4



parj21=0.4 parj41=0.3 vs parj21=0.5parj41=1.2



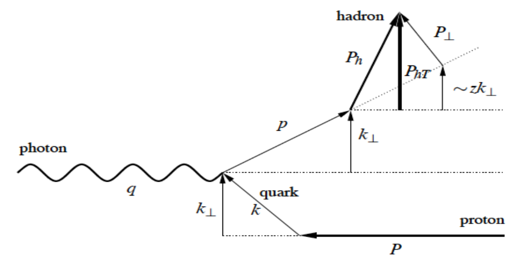
parj21=0.4 parj41=0.3 vs parj21=0.6, parj41=2.0

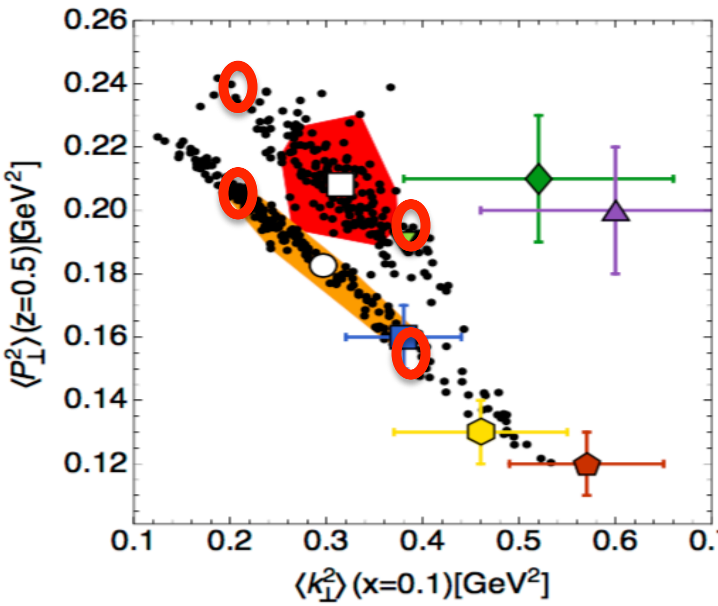


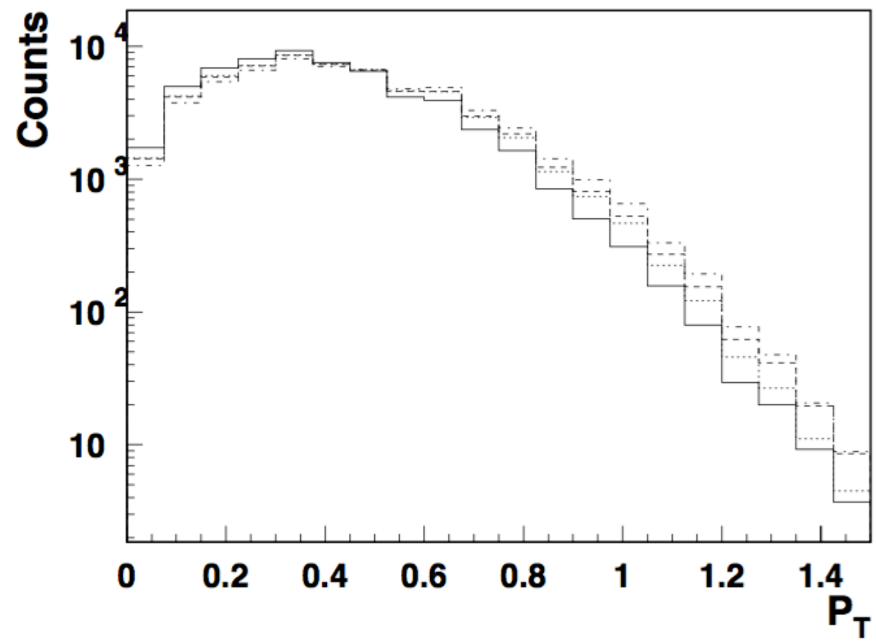
Extracting the average transverse momenta

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

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





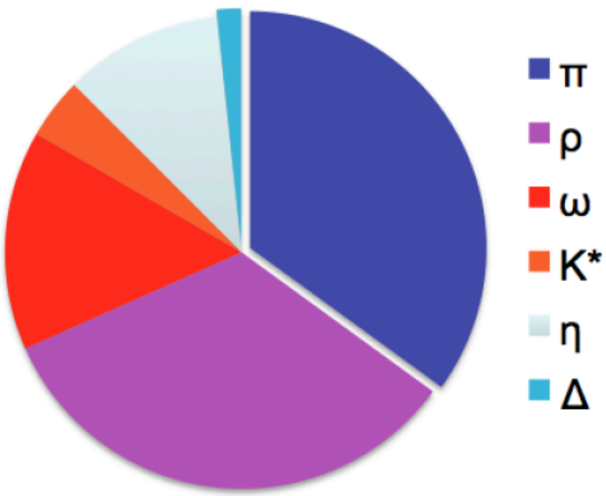


$$m_N^h(x,z,P_{hT}^2) = \frac{\pi}{\sum_a e_a^2 f_1^a(x)} \times \sum_a e_a^2 \, f_1^a(x) \, D_1^{a\to h}(z) \, \frac{e^{-P_{hT}^2/\left(z^2\langle k_{\perp,a}^2\rangle + \langle P_{\perp,a\to h}^2\rangle\right)}}{\pi\left(z^2\langle k_{\perp,a}^2\rangle + \langle P_{\perp,a\to h}^2\rangle\right)}$$

- 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 $\langle p_T\rangle$

Sea is not divided to perturbative and non-perturbative

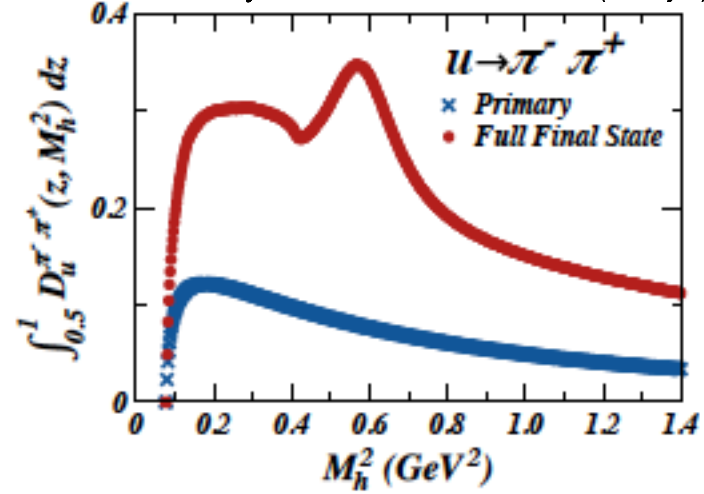
Dihadron production

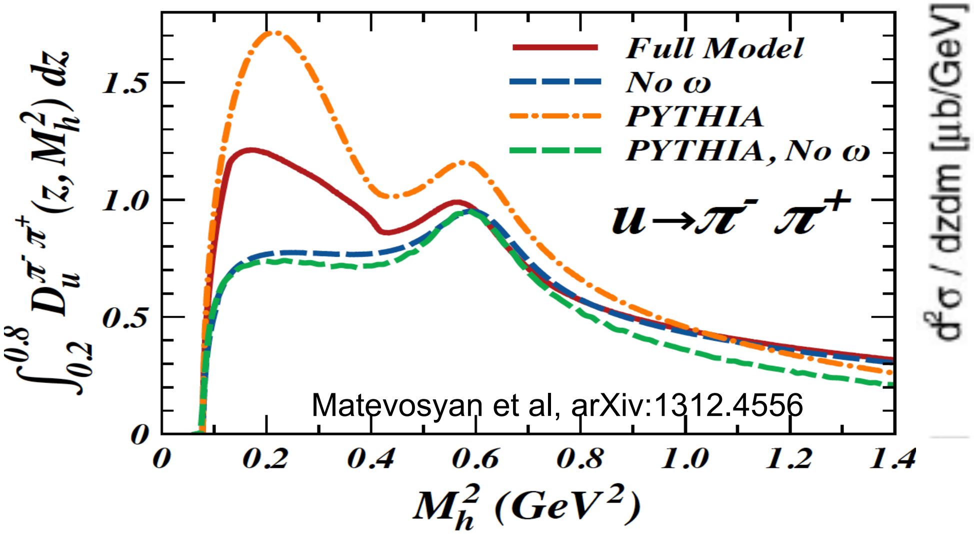


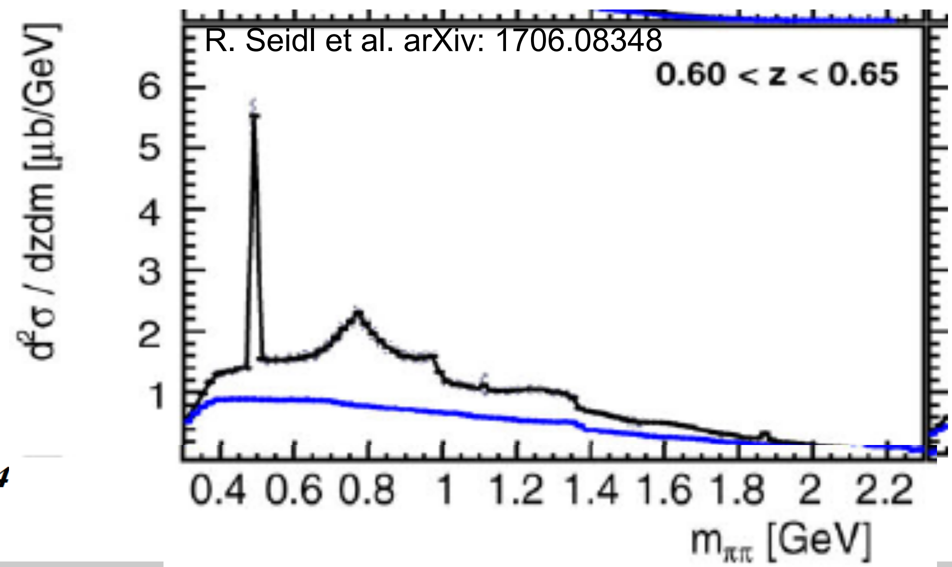
HERMES-note-96.059

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

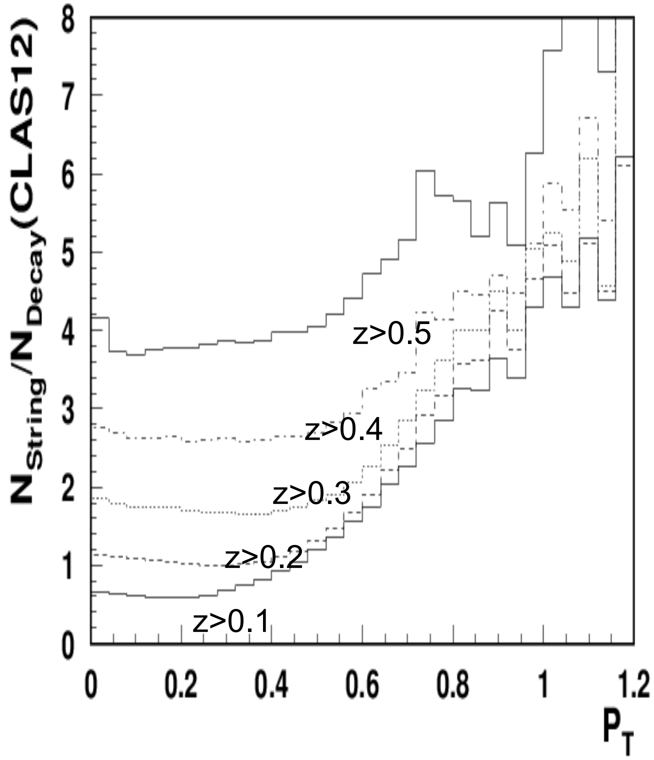
Matevosyan et al arXiv:1307.8125(NJL-jet)

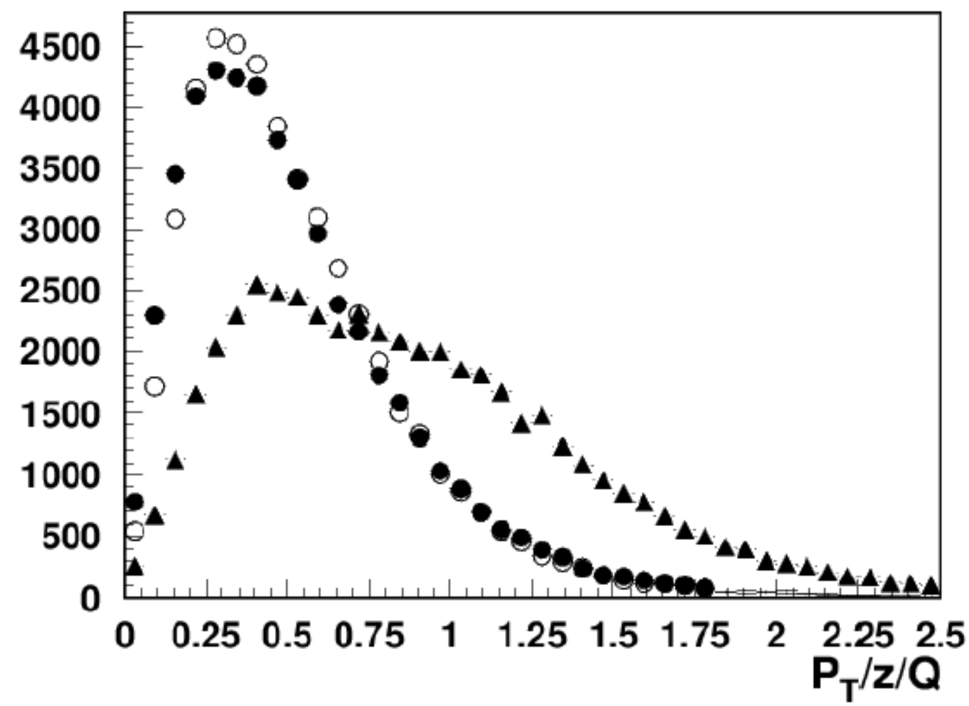






P_T of pions from rho decays: LUND string fragmentation



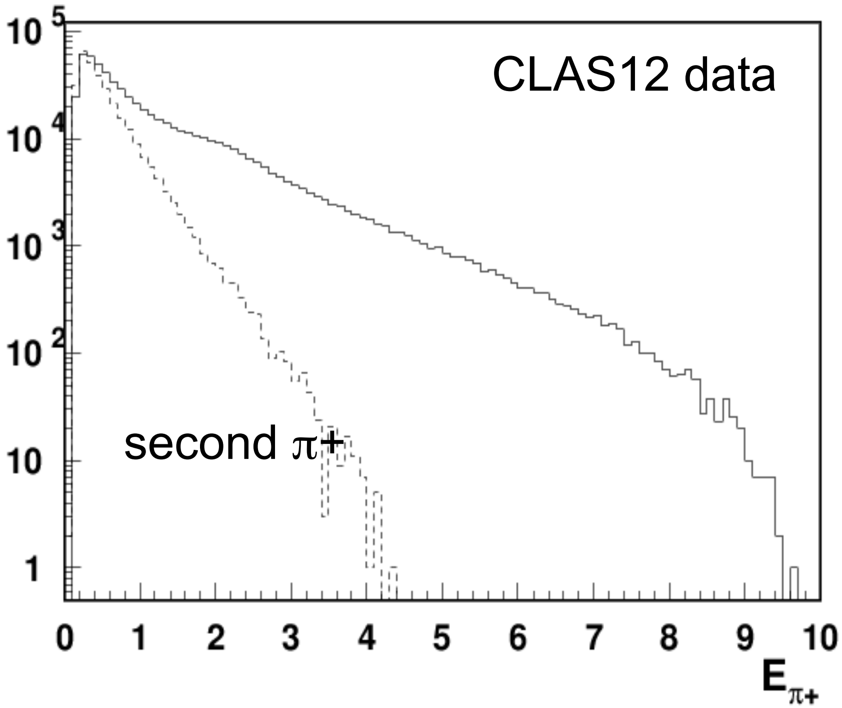


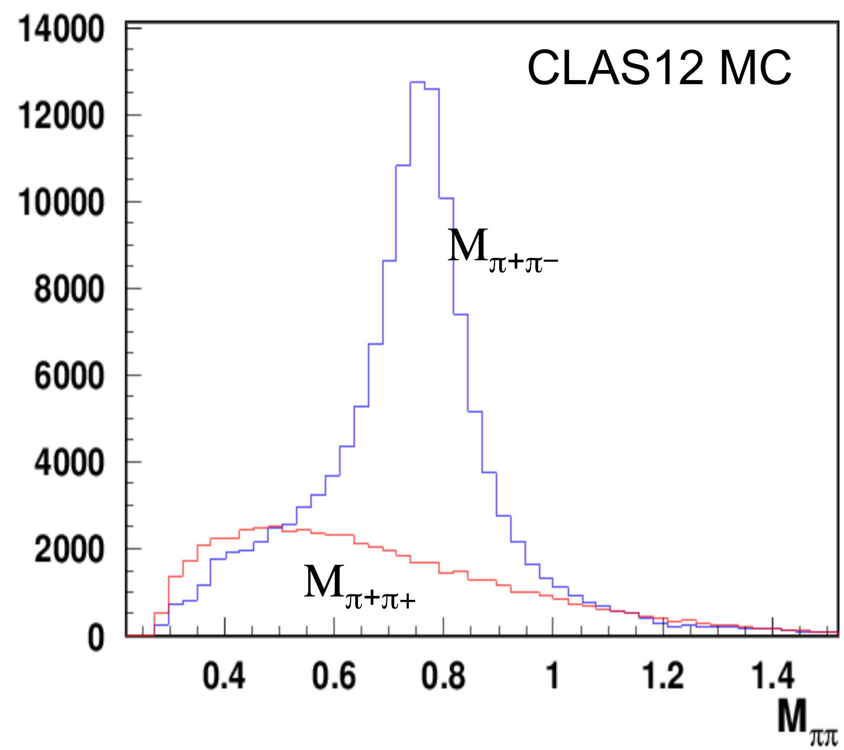
Fraction of direct π+ increases with P_T

Fraction of direct π+ decreases with P_T/z/Q

Invariant mass distributions for 2π+

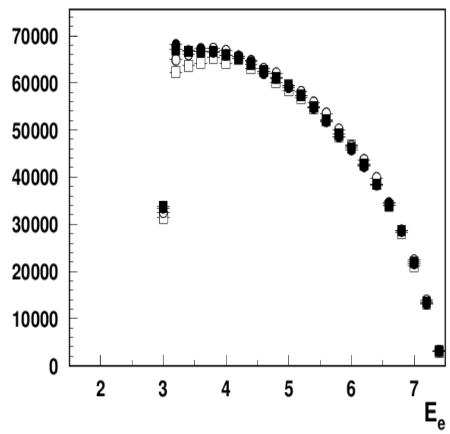
All events with parent of π+ is ρ0

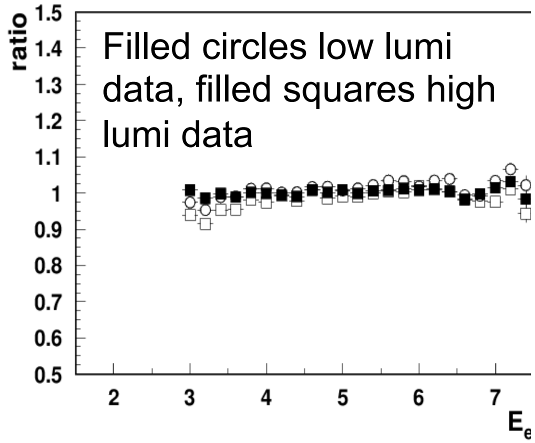


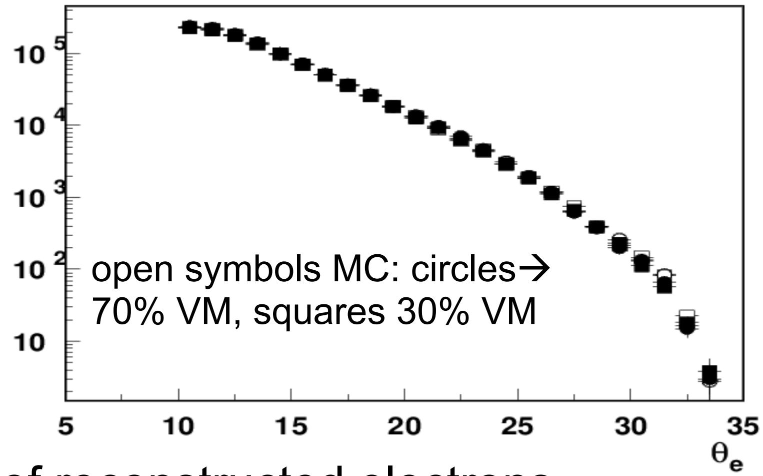


The π+/π− pairs out of ρ-region may still be generated by ρs

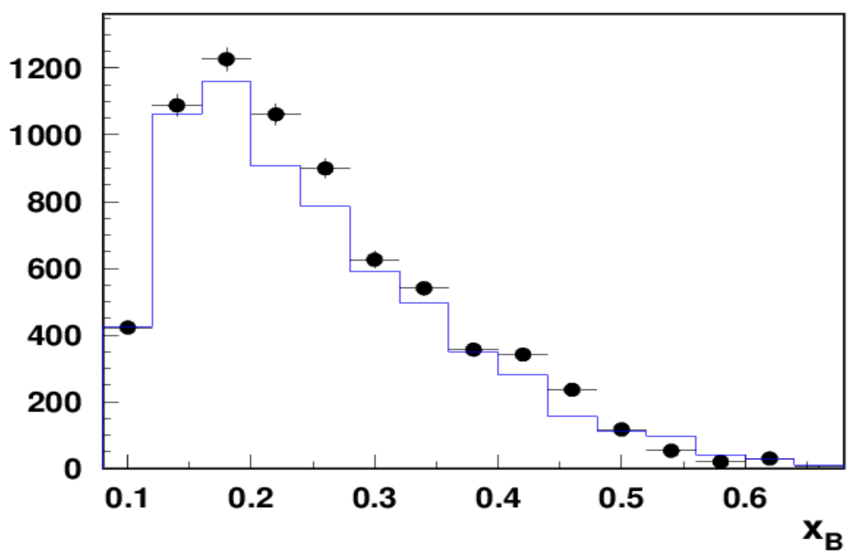
RGA: ep→e'$\pi^+\pi^-$X

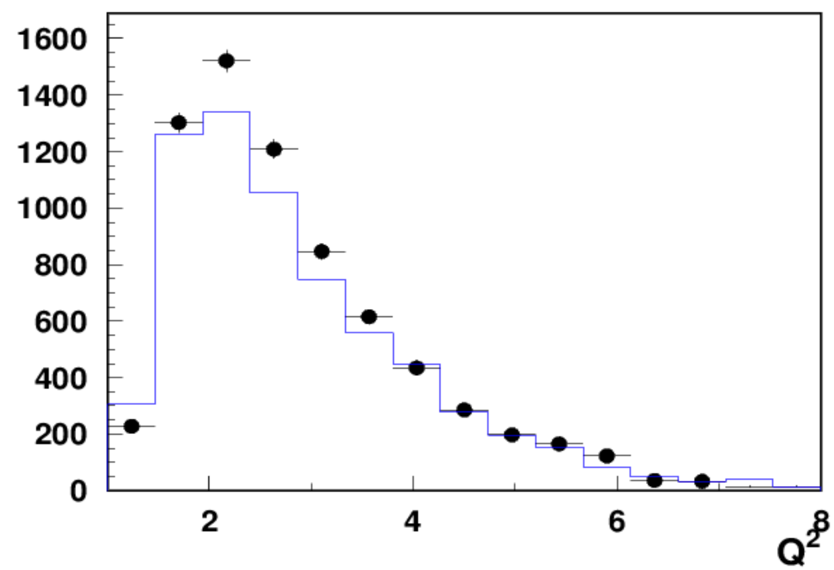






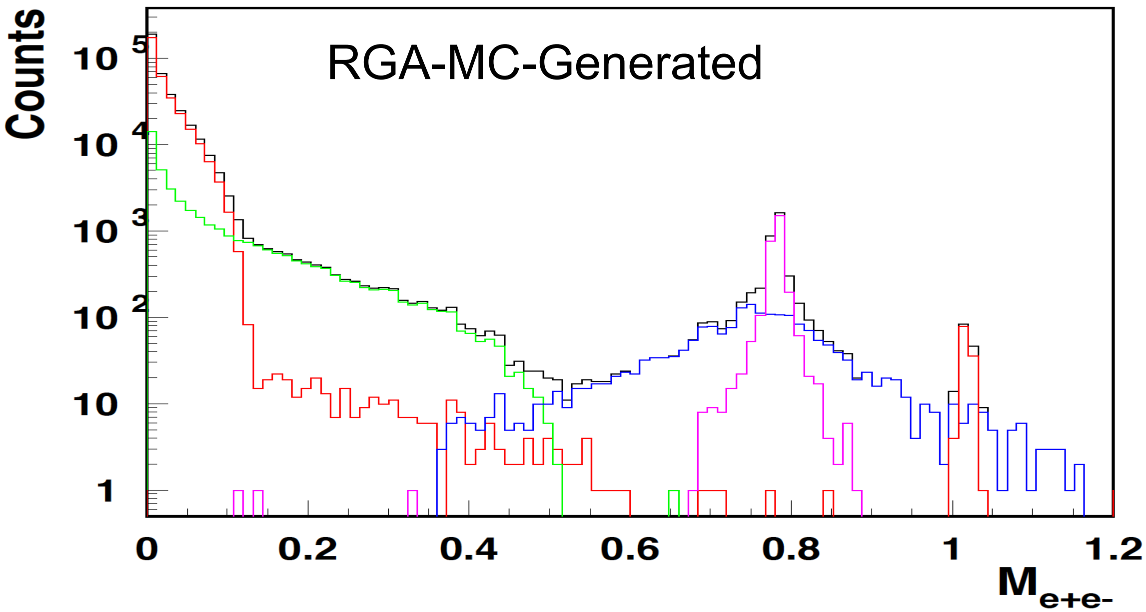
Normalizing all sets to the same number of reconstructed electrons

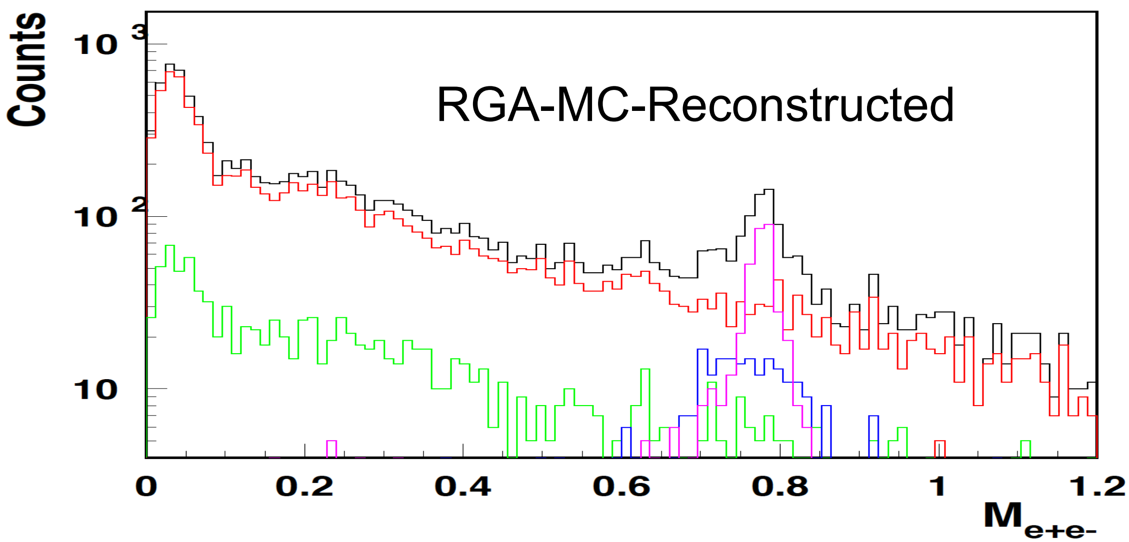




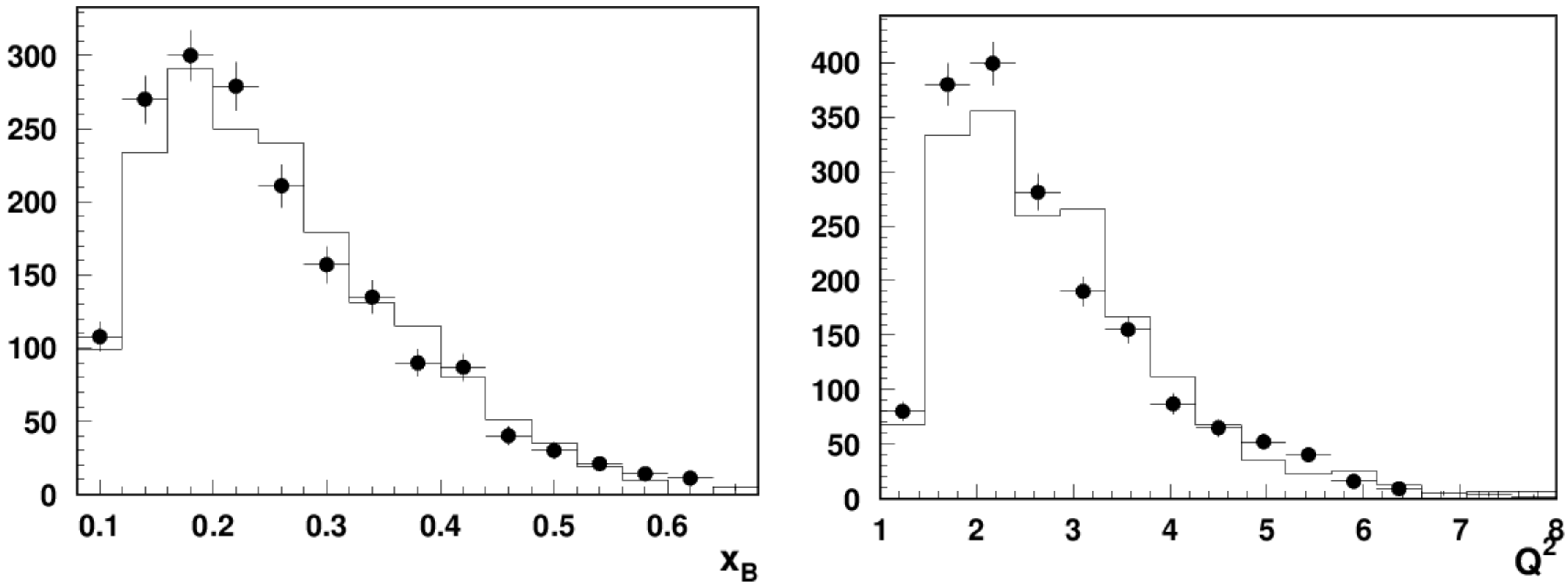
x, Q^2-dependences for e'$\pi^+\pi^-$X MC (line) in good agreement with low lumi data

e+e- distributions in ep→e' e+e-X



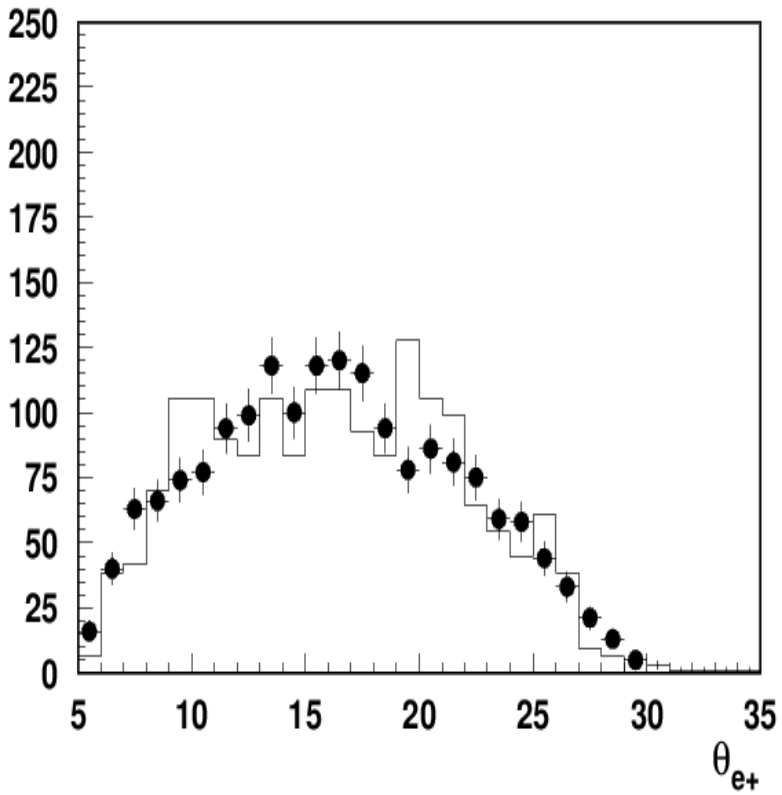


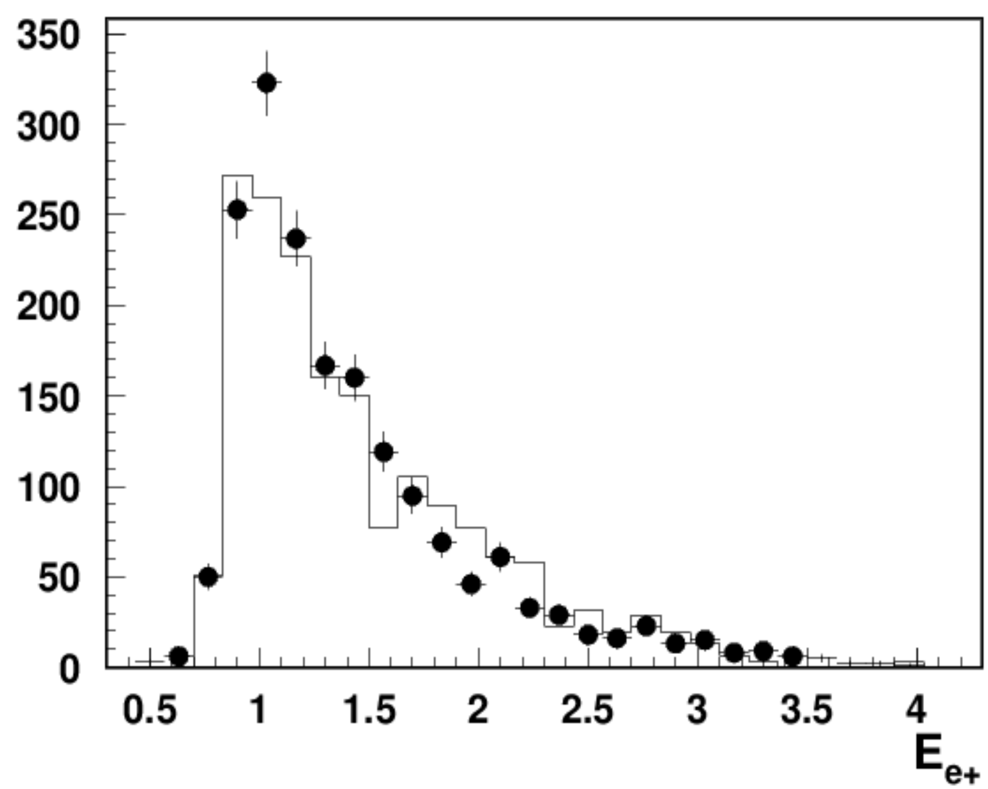
e+e- distributions in ep→e' e+e-X



x,Q^2-distributions of ep→e' e+e-X events from MC consistent with data

e+e- distributions in ep→e' e+e-X





Meson-decay positrons consistent with CLAS12 data