Studies of Evolution of TMDs

Harut Avakian (JLab)

Resummation, Evolution, Factorization 2020

Dec 9, 2020

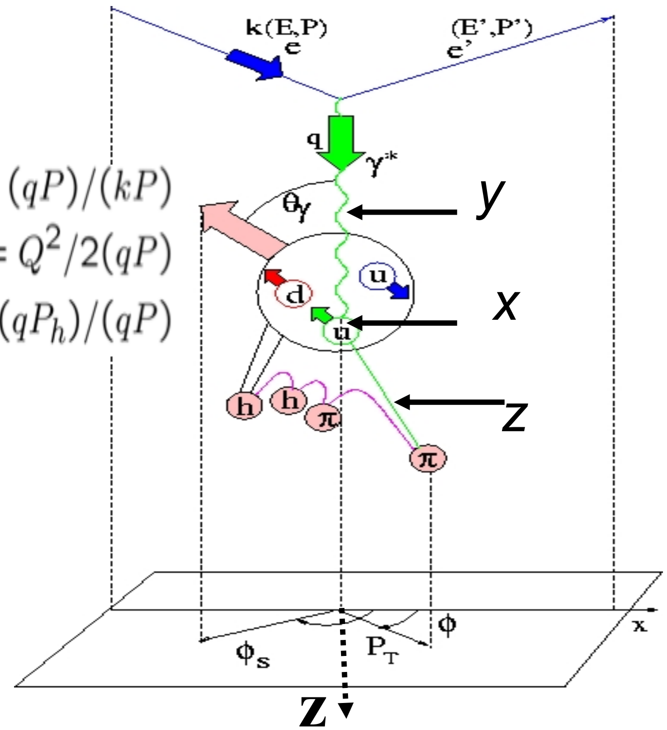
- Measuring the transverse momentum in SIDIS
- The role of MC in understanding the systematics
- SF-based MC (dedicated) vs LUND-MC (full events)
- P_T-distributions of hadrons and evolution measurements
- LUND-MC vs CLAS12 data
  - Single hadron and P_T/Q correlations
  - Di-hadron
  - Q^2-dependence of SSAs
- EIC simulations: TMD evolution and low y
- Summary

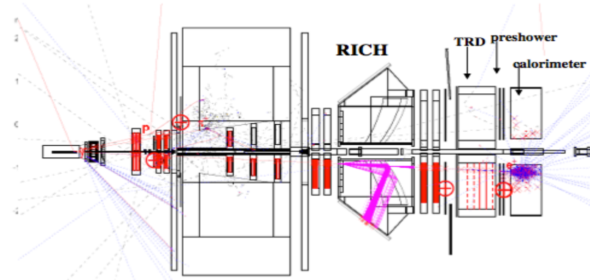
Semi Inclusive DIS

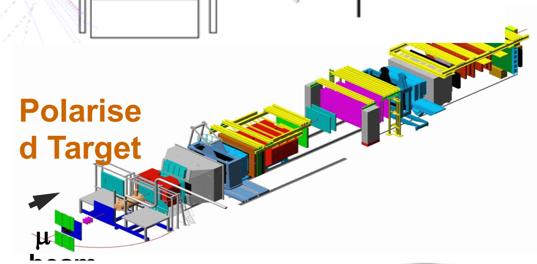
$y = (qP)/(kP)$

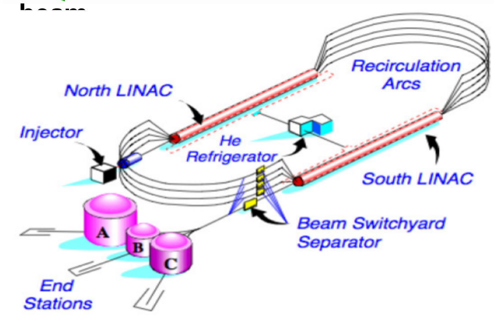
$x = Q^2/2(qP)$

$z = (qP_h)/(qP)$









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

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

beam polarization

target polarization

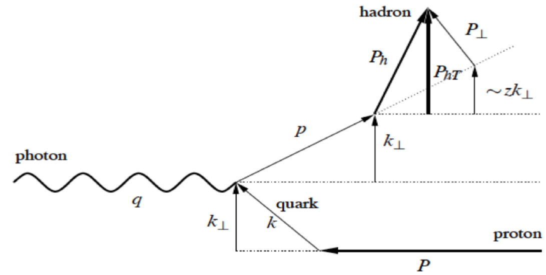
Distribution & Fragmentation Functions

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

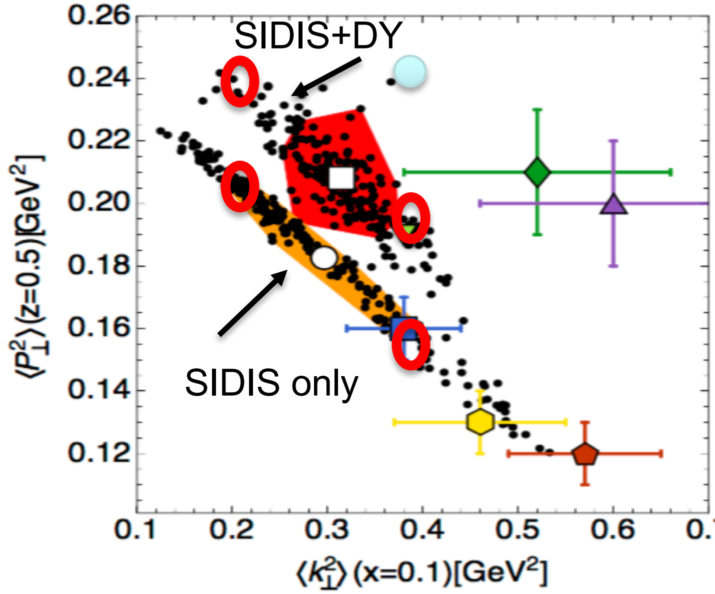
Extracting the average transverse momenta

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

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



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



- Extraction very sensitive to input (replicas)
- Most sensitive to parameters is the large P_T
- Why DY gives higher values
- Why the large P_T are not described
- How to reconcile data with 1pion MC?

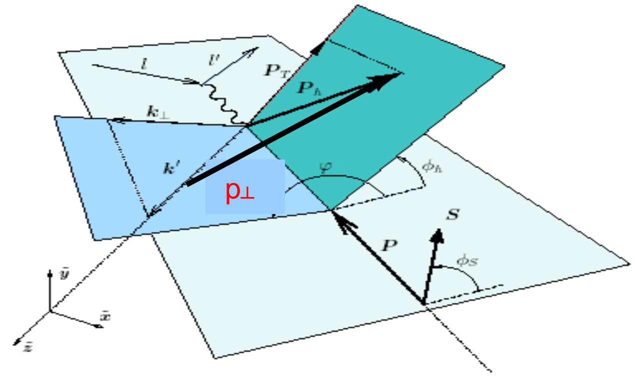
$$m_N^h(x,z,\boldsymbol{P}_{hT}^2)=\frac{\pi}{\sum_a e_a^2 f_1^a(x)} \times \sum_a e_a^2\, f_1^a(x)\, D_1^{a\to h}(z)\,\frac{e^{-\boldsymbol{P}_{hT}^2/\left(z^2\langle \boldsymbol{k}_{\perp,a}^2\rangle+\langle \boldsymbol{P}_{\perp,a\to h}^2\rangle\right)}}{\pi\left(z^2\langle \boldsymbol{k}_{\perp,a}^2\rangle+\langle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

- Theory: FFs include all possible sources of a given hadron, including fragmentation and diffractive VMs!
- How do we get the TMD FFs and what are their $P_\perp$ and Q^2 dependence?

Sea is not divided to perturbative and non-perturbative

Reproduce SIDIS output with MC

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



$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP^2_{h\perp}} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h}$$

$$+\varepsilon\cos(2\phi_h)F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}$$

$$+S_\parallel\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)F_{UL}^{\sin 2\phi_h}\right]$$

Theory

Provide an input set of SF_l

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

Output counts for a given energy and detector setup

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

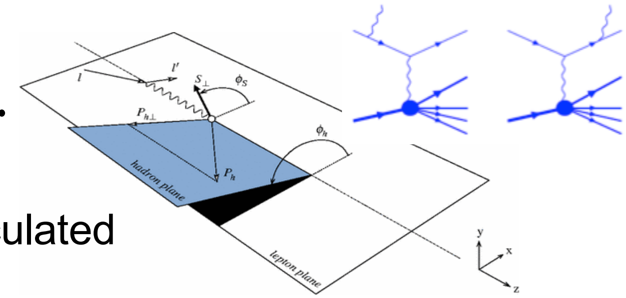
step-2 (for a given E_{beam},λ,Λ) P_i^{el}, P_i^h

step-3 (detected for a given Detector configuration) $x_j, Q_j^2 z_j P^2_{hT,j} \phi_h^j \phi_l^j \phi_s^j$

Additional complications: Experiment can't measure just 1 SF

I. Akushevich et al

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



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

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

Correction to DSA

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

COMPASS and HERMES provided first estimates for practically all SFs
Different SFs will have different P_T and Q^2 dependence
Simultaneous extraction of all moments is important also because of correlations!

MC simulations

MC is crucial, and not only for acceptance studies!

To understand the measurement we should be able to simulate, at least basic features we are trying to study (P_T and Q^2, in particular)

If we can't simulate the process of the interest (with it's physics backgrounds) we will never be able to estimate properly the systematics of the measurement

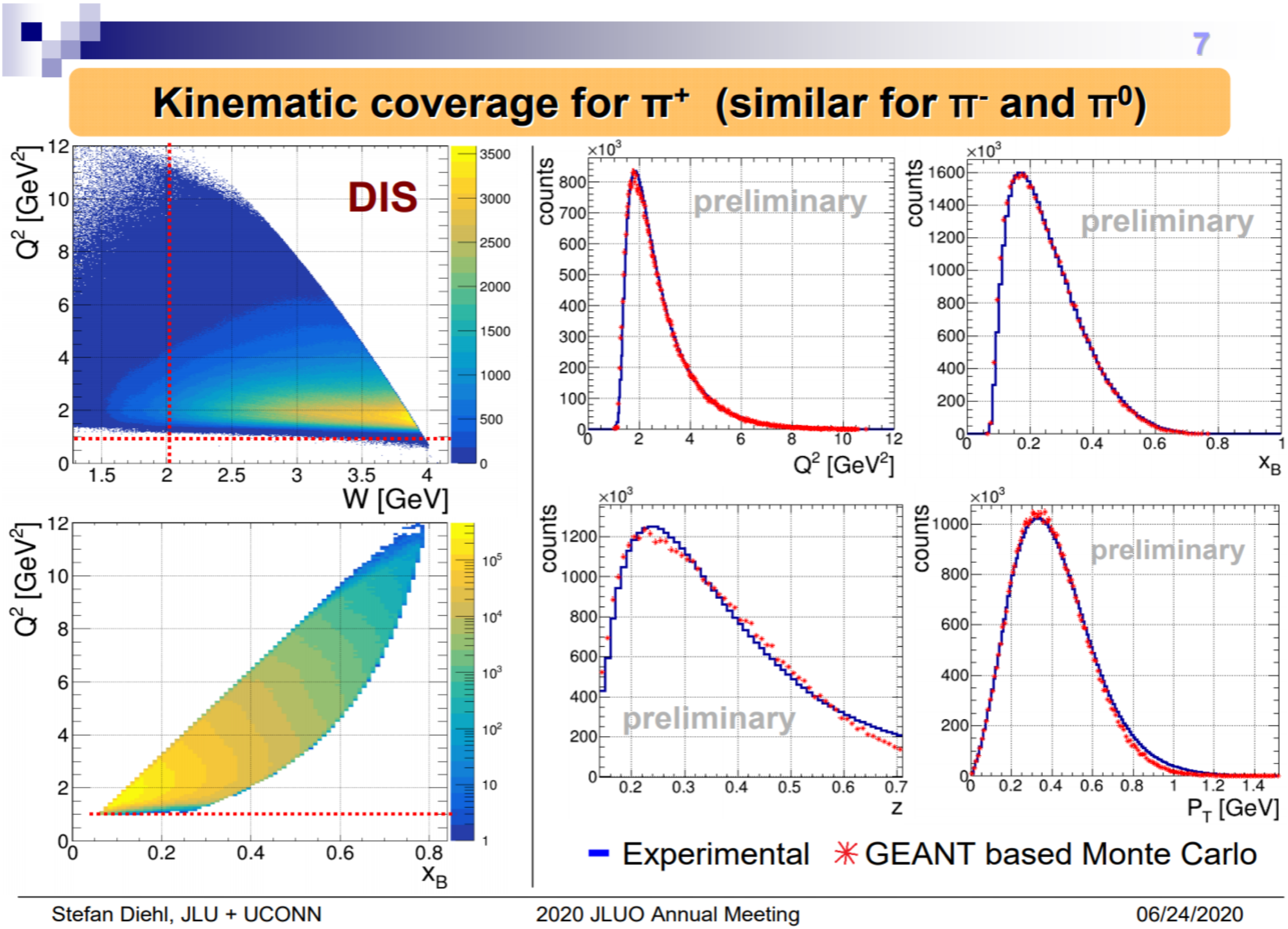
Main options in MC

- Full event generation: more realistic, describes full accessible energy range, but less freedom in proper accounting of correlations between different SFs

- Single hadron generators: can include all SFs with proper evolution properties and account for correlations, also involving RC, but so far failed to describe the data in the accessible P_T and Q^2 range

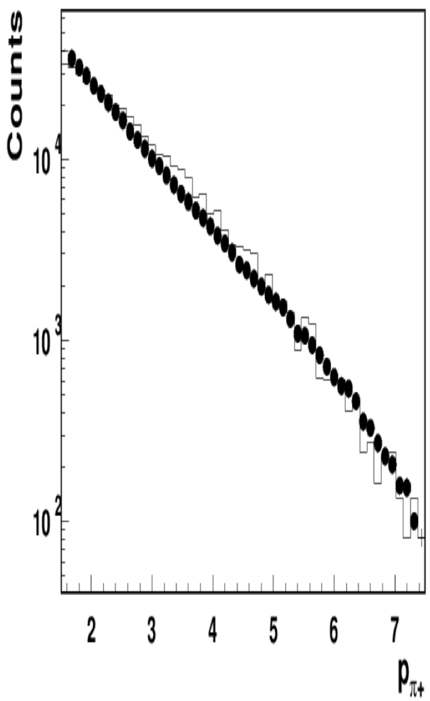
SIDIS ehX: CLAS12 data vs MC

CLAS12 single hadron: data vs LUND MC

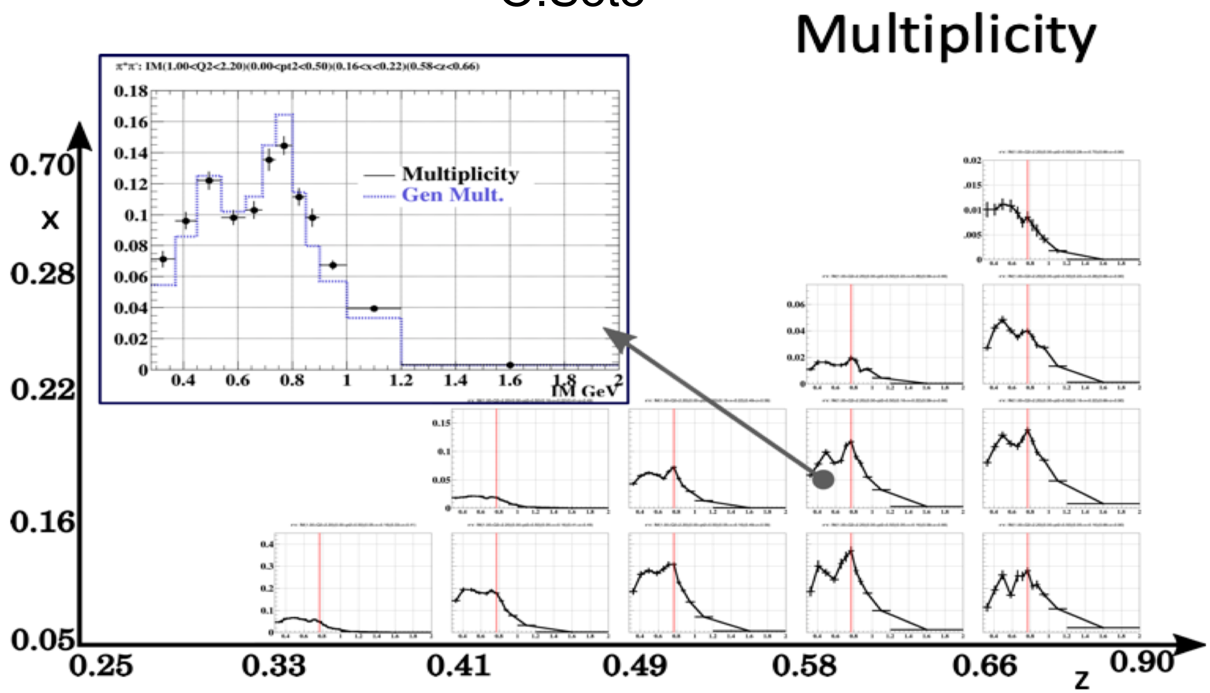


SIDIS ehX,ehhX: CLAS12 data vs MC

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



O.Soto



- 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 dihadrons vs LUND-MC

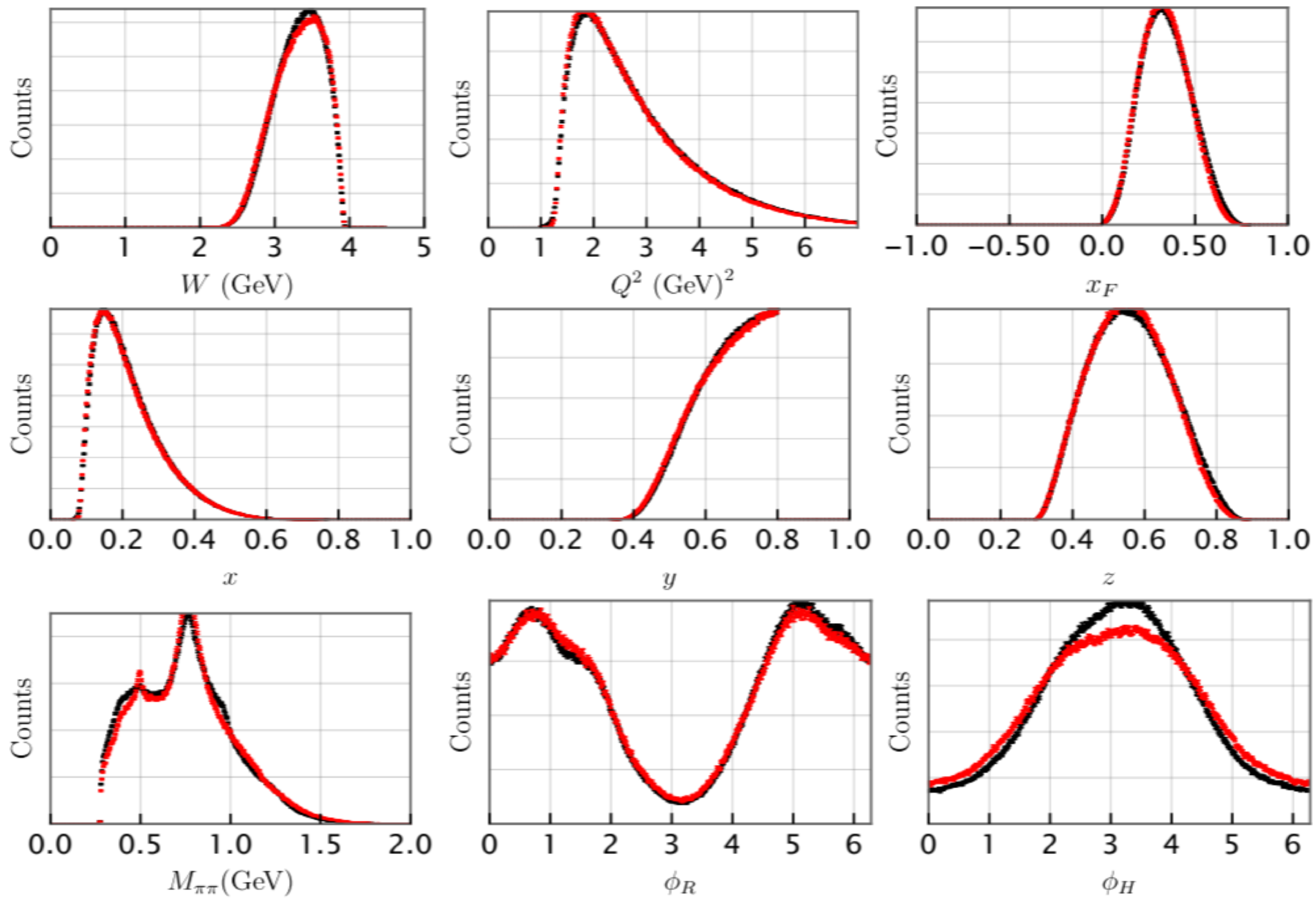
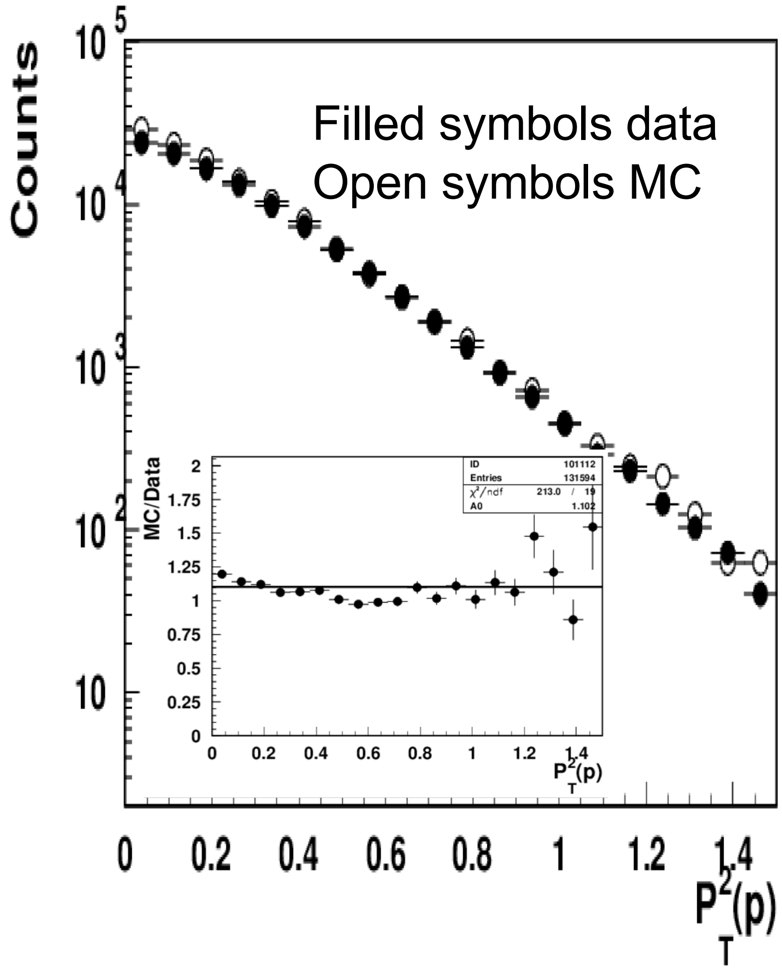
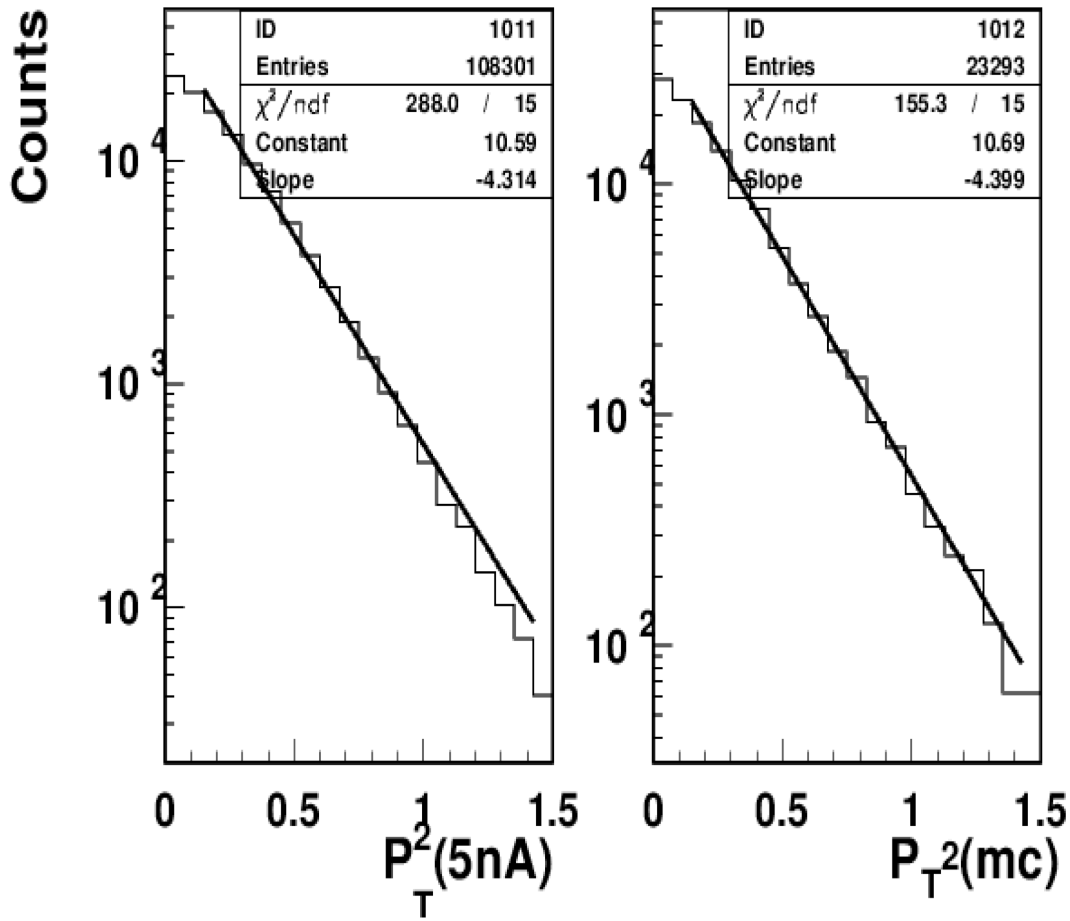


FIG. 26: (Color online). Comparison between the mass-produced OSG Monte Carlo (red) and data (black). From top to bottom and left to right the figures are: W, Q^2, x, y, z, $M_{\pi\pi}$, phi_R and ϕ_h.

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

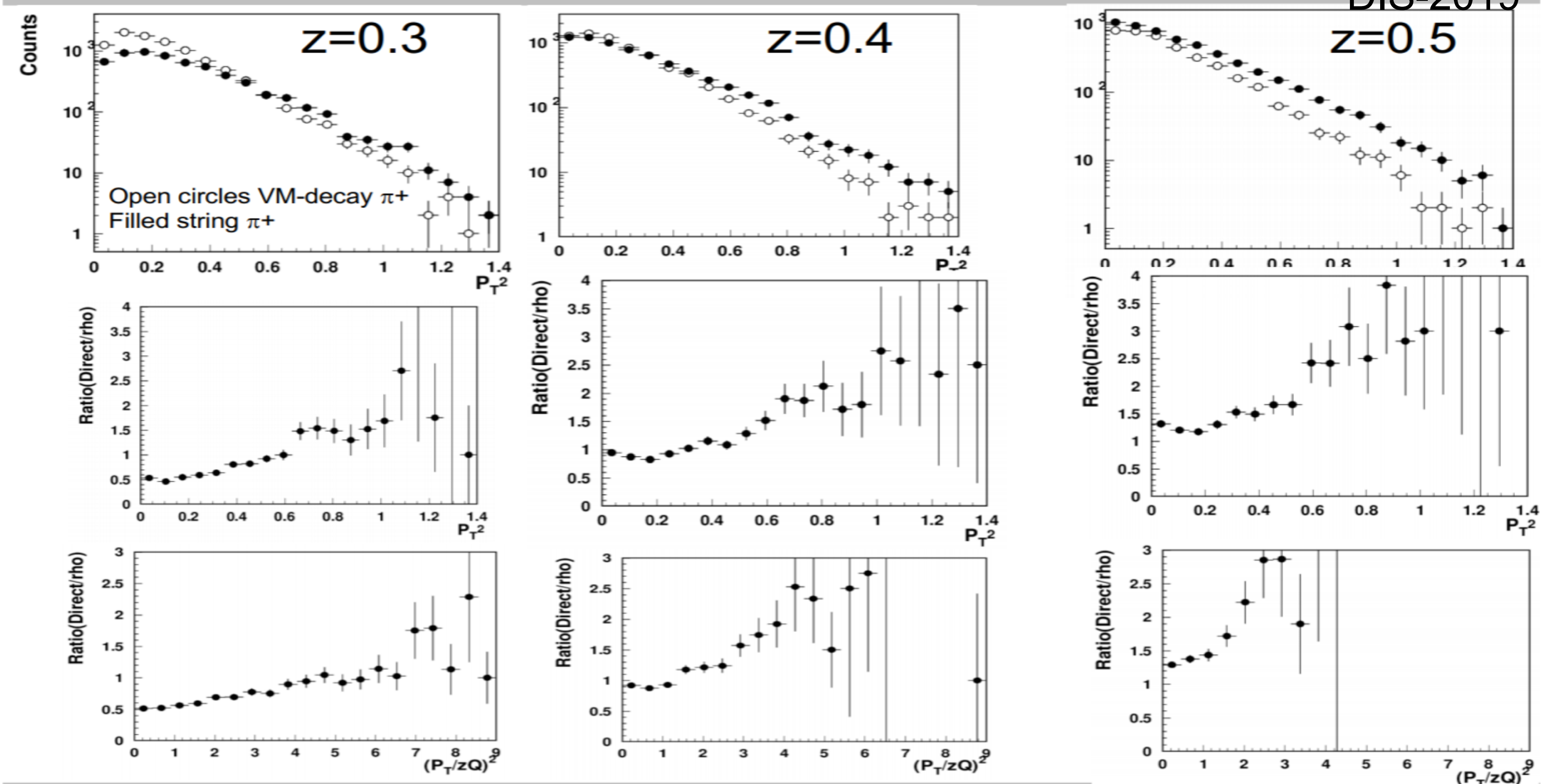
JETSET: LUND Fragmentation

Test results: It is not trivial to achieve agreement with data, when using 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)
- ……….

JLab12: SIDIS and P_T



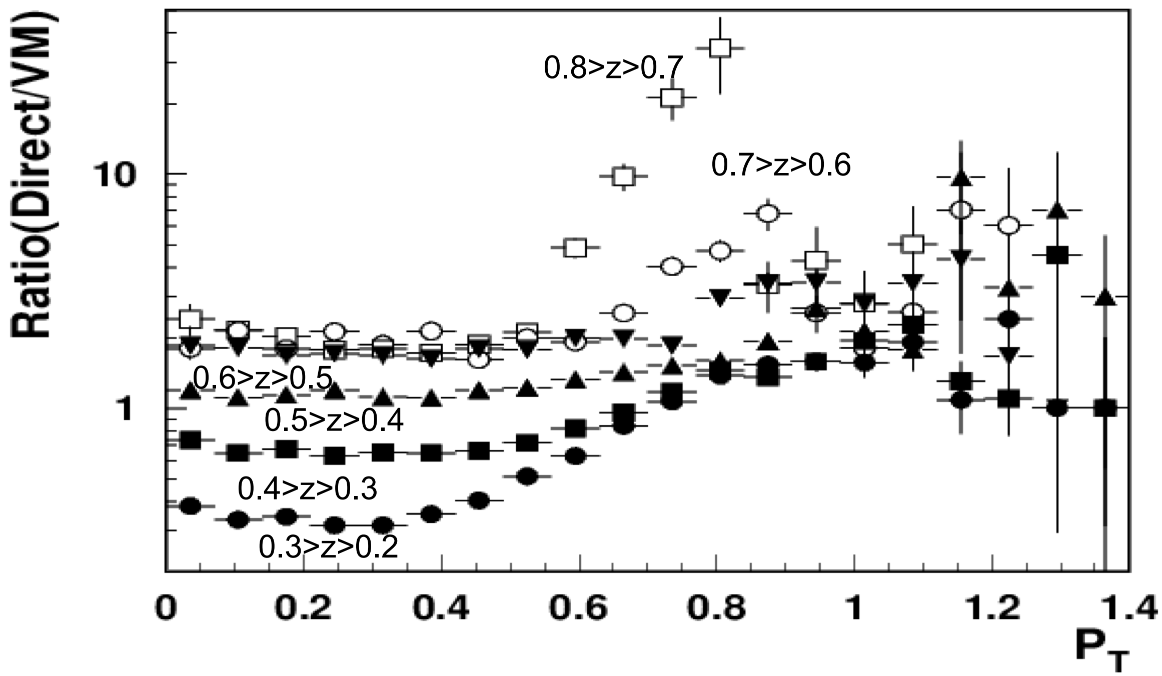
Important note: VM means VMs from quark fragmentation (not diffractive)

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)
Could this info be used to model the complex z/P_T-dependence of FFs, Q^2?

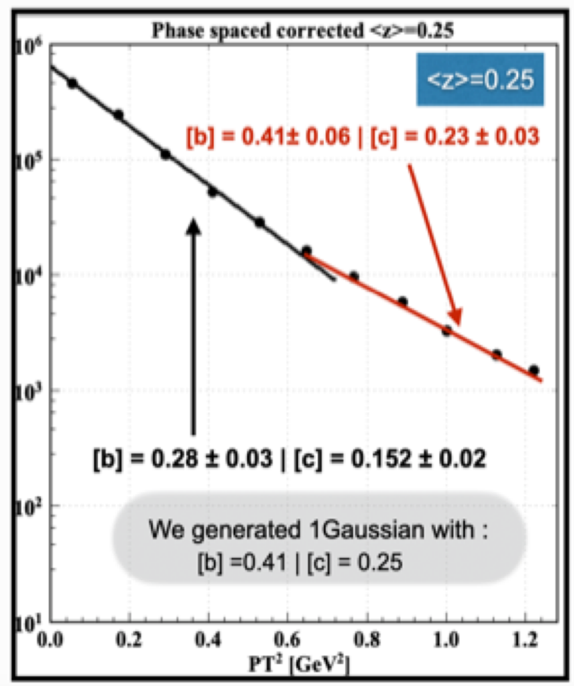
CLAS12 Multiplicities: the role of high P_T

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

G. Angelini (GW)



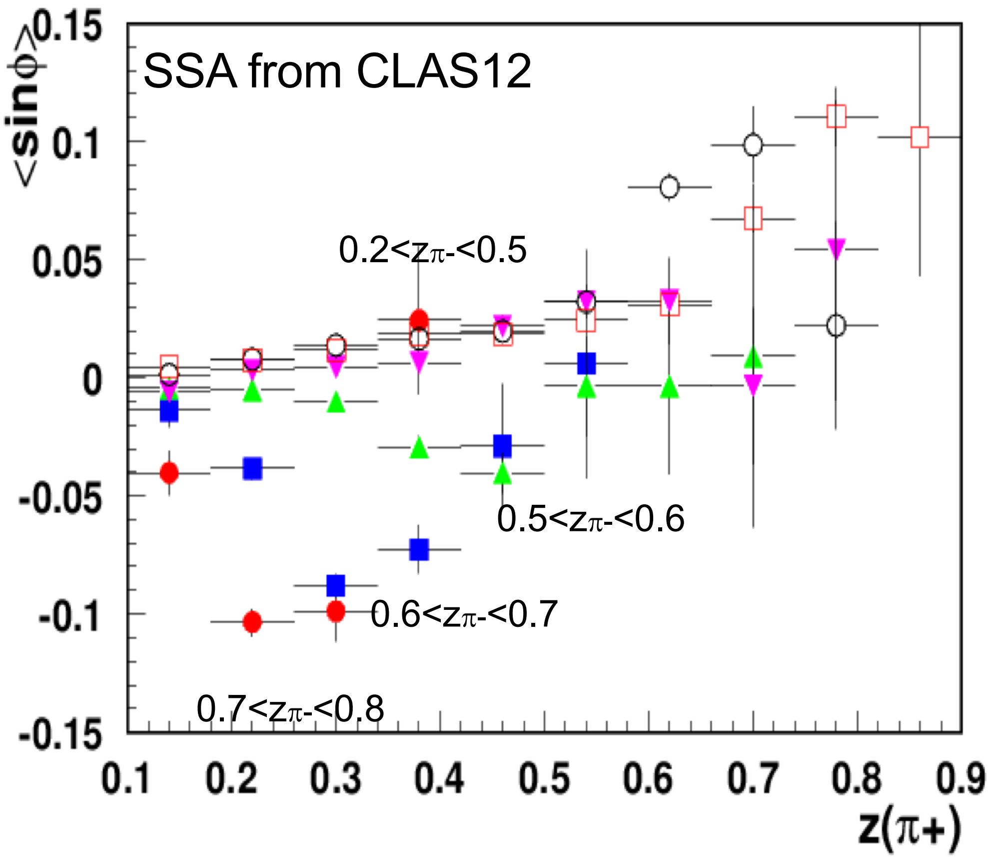
Fit : [a]*exp(-x/(<z>^{2}*[b]+[c]))

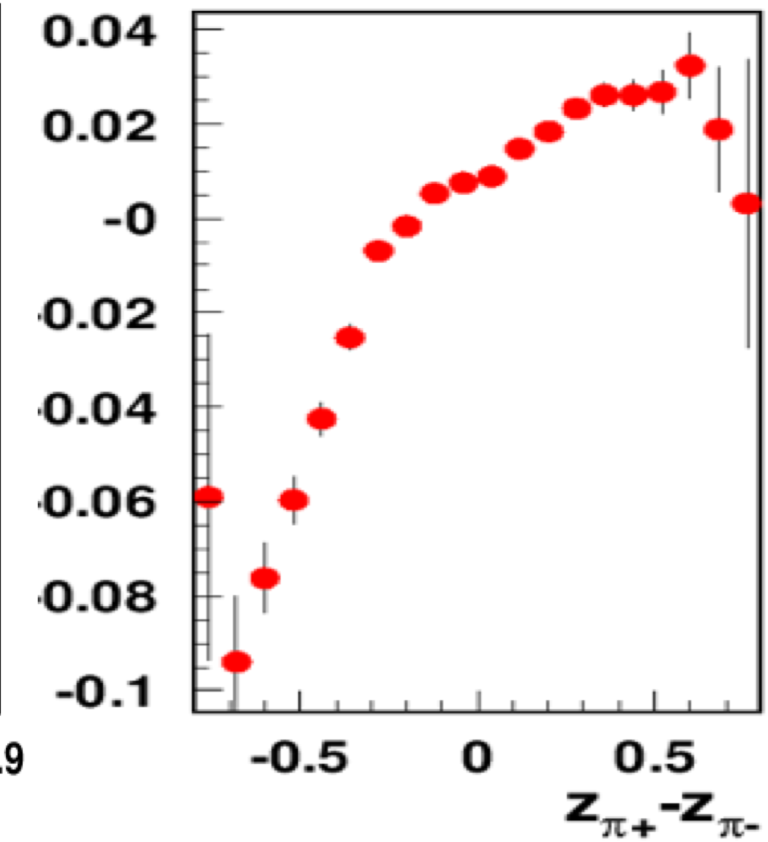


- Corrections due to phase space (energy needed to produce a hadron with a given z,P_T at given x,Q^2) are detector and model independent
- Corrections due to fraction of fragmentation VMs and diffractive VMs are model dependent, but can be extracted from MC (work in progress)

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

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





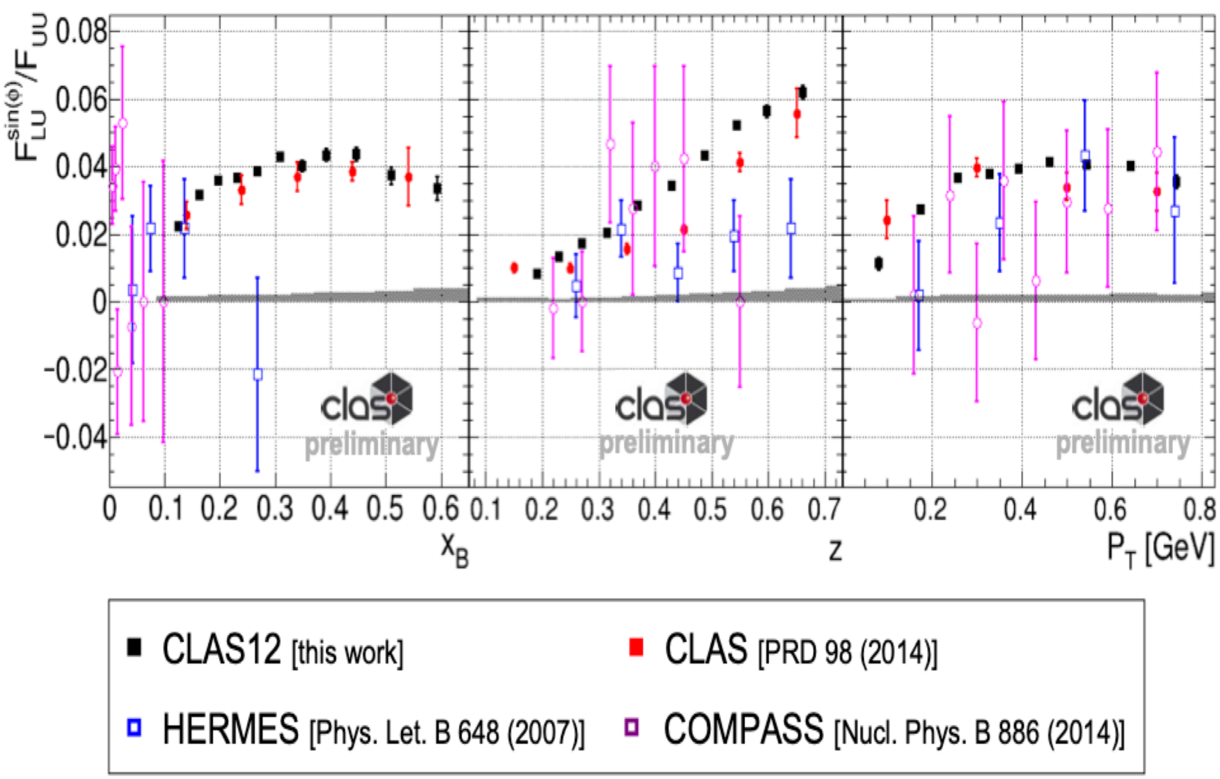
Observed SSA for the inclusive π+ changes significantly with the π- z

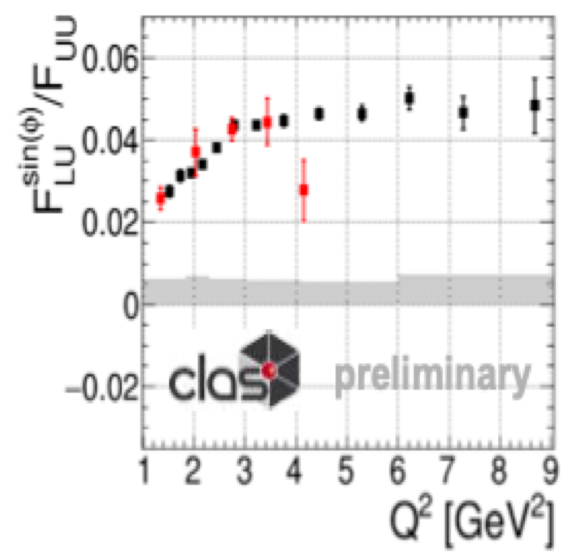
Q^2-dependence of SSA from CLAS12

S. Diehl (DNP-2020)

$$BSA_i = \frac{1}{P_e} \cdot \frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

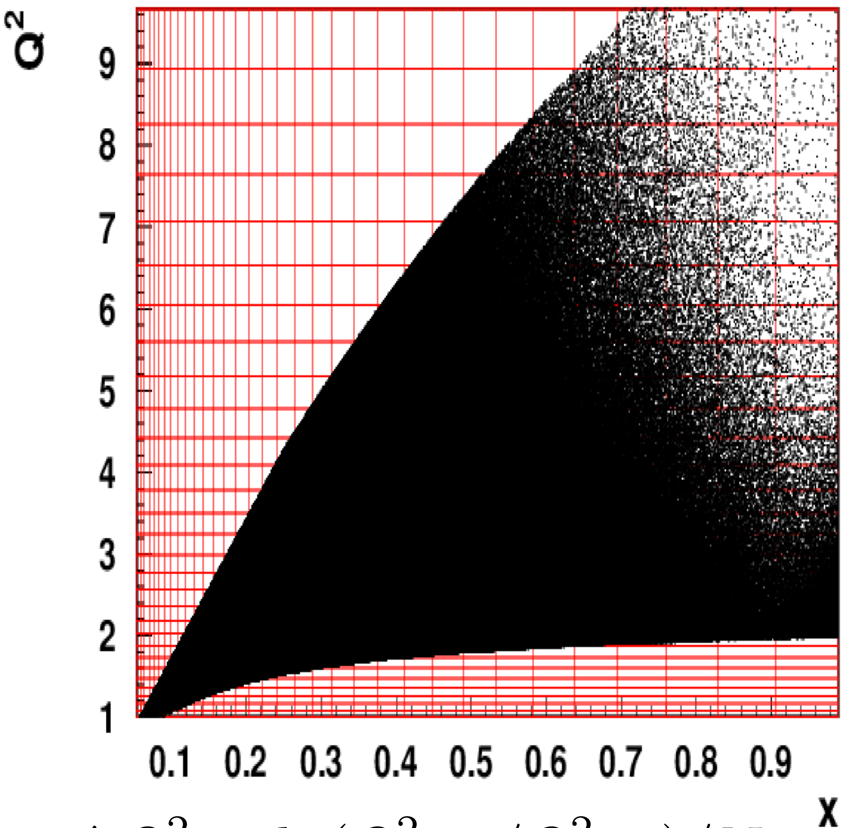
$$\langle \sin\phi \rangle \propto F_{LU}^{\sin\phi}/F_{UU} \propto 1/Q$$

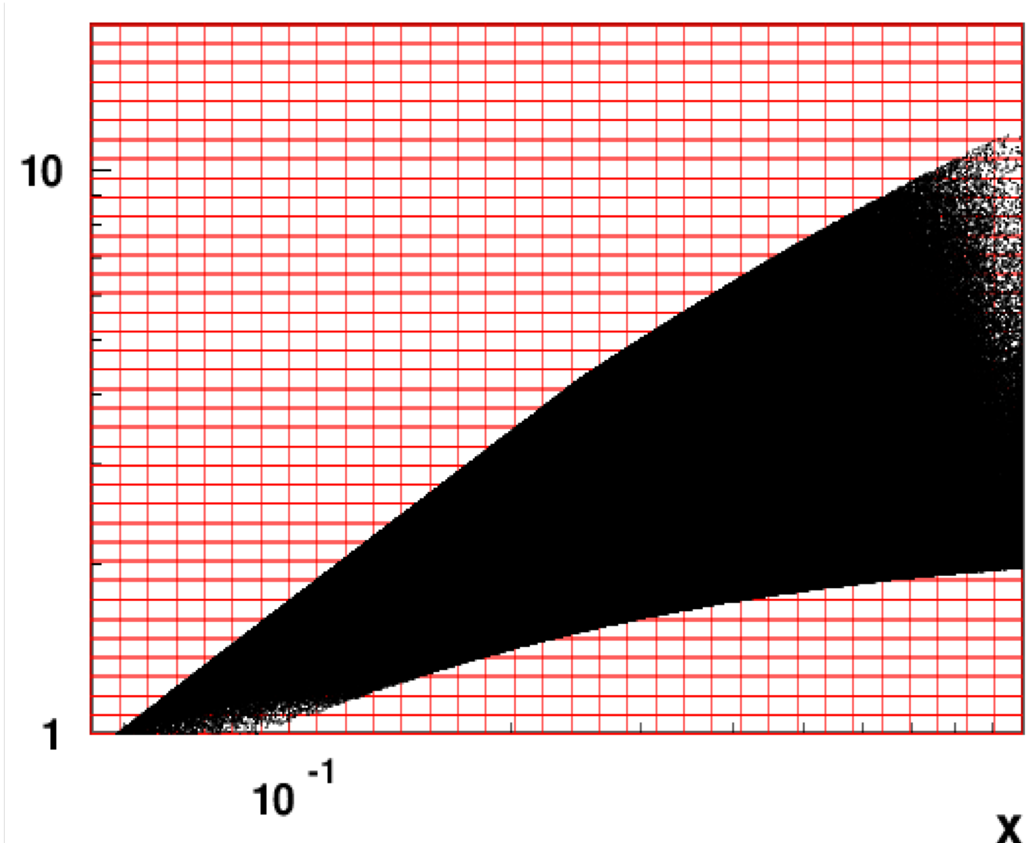




Unexpected Q^2-dependence is under study in fine multidimensional bins and P_T, in particular

Reconstructed Data table: details





$$\Delta Q^2 = ln(Q^2_{max}/Q^2_{min})/N_q$$

$$Q^2_i = Q^2_{min} e^{i\Delta Q^2}$$

$$x_i = x_{min} e^{i\Delta x}$$

DIS Structure functions and x-sections

JSON file for $f_1(x, Q^2, k_T)$

```
{
        "model": "PV17"
        "reference": "A. Bacchetta et al. [arXiv:1703.
        "function": "unpolarized TMD PDF f1(x,k_\perp^
        "Beam Energy": 10.400
        "f.s.hadron": "pi+"
        "target": "proton"
        "flavors: "[-3,-2,-1,1,2,3]"
        "variables":["fl","x","Q2","k_perp"]
        "x min": 0.0004
        "x max": 0.8
        "x number of interval logarithmic": 50
        "Q2 max": 1.0
        "Q2 min": 11.0
        "Q2 interval": 0.5
        "k_\perp min": 0.1
        "k_\perp max": 2.0
        "k_\perp interval": 0.1
}
```

JSON file for $F_{UU,T} = \mathcal{C} f_1(x, Q^2, k_T) \times D_1(z, Q^2, p_T)$

```
{
        "model": "PV17"
        "reference": "A. Bacchetta et al. [arXiv:1703.10157]"
        "function": "F_T, F_UUT, F_UTT^sin(\phi_h - \phi_S)"
        "Beam Energy": 10.400
        "f.s.hadron": "pi+"
        "target": "proton"
        "variables":["x","Q2","y","z","PhT"]
        "x min": 0.0004
        "x max": 0.8
        "x number of interval logarithmic": 50
        "z min": 0.2
        "z max": 0.8
        "z interval": 0.01
        "Q2 min": 1.0
        "Q2 max": 11.
        "Q2 interval": 0.5
        "P_hT min": 0.01
        "P_hT max": 2
        "P_hT interval": 0.1
}
```

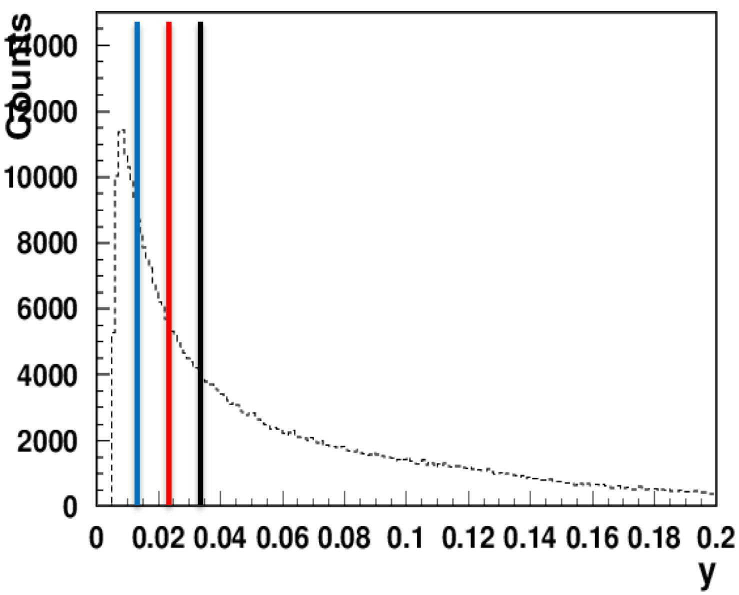
x	Q2	y	z	phT	F_T	F_UUT	F_{UTT}
0.0004	1.0000	-5.4822	0.2000	0.0100		793.268606	0.888651
0.0004	1.0000	-5.4822	0.2000	0.0400		793.268606	0.893171
0.0004	1.0000	-5.4822	0.2000	0.0700		793.268606	0.893232
0.0004	1.0000	-5.4822	0.2000	0.1000		793.268606	0.874783
0.0004	1.0000	-5.4822	0.2000	0.1300		793.268606	0.831029
0.0004	1.0000	-5.4822	0.2000	0.1600		793.268606	0.766942
0.0004	1.0000	-5.4822	0.2000	0.1900		793.268606	[illegible]

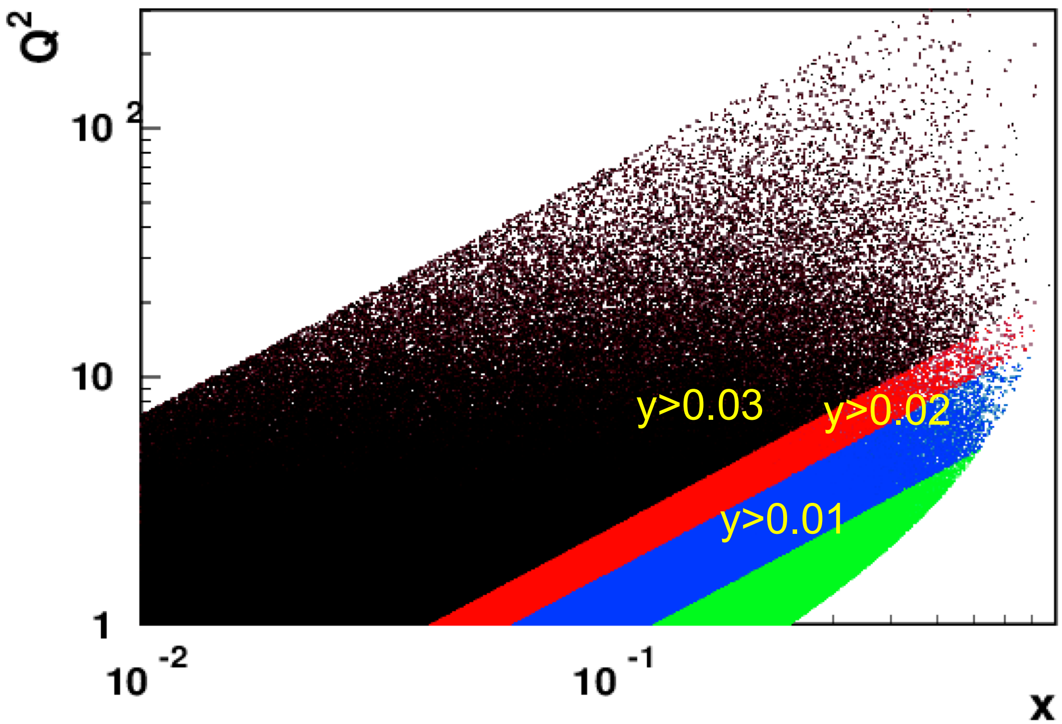
Low Q^2 and large x kinematics in EIC

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

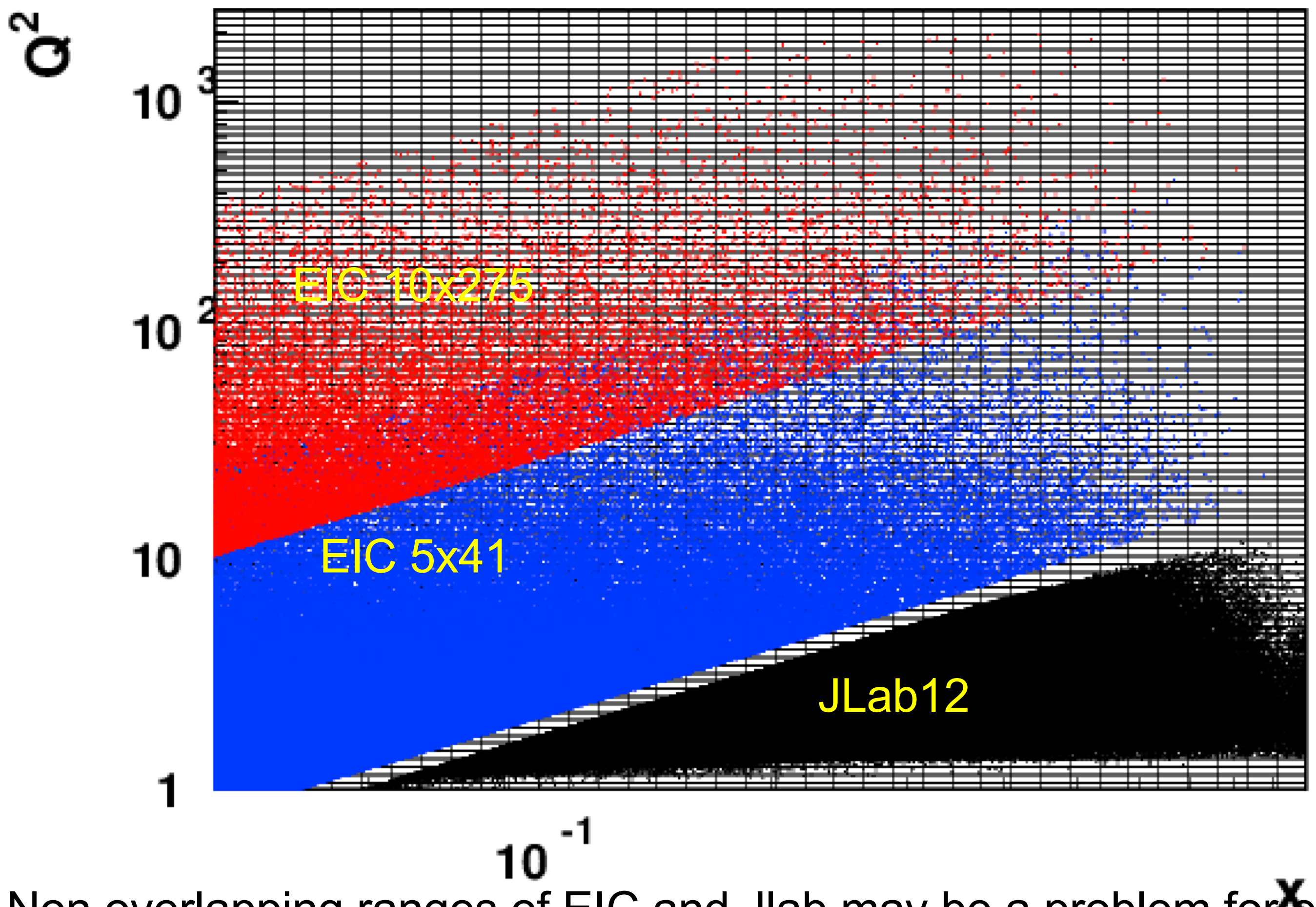




Small y are critical to access wide range in Q2 for large x, where the non-perturbative effects are relevant

X vs Q2 from Jlab to EIC

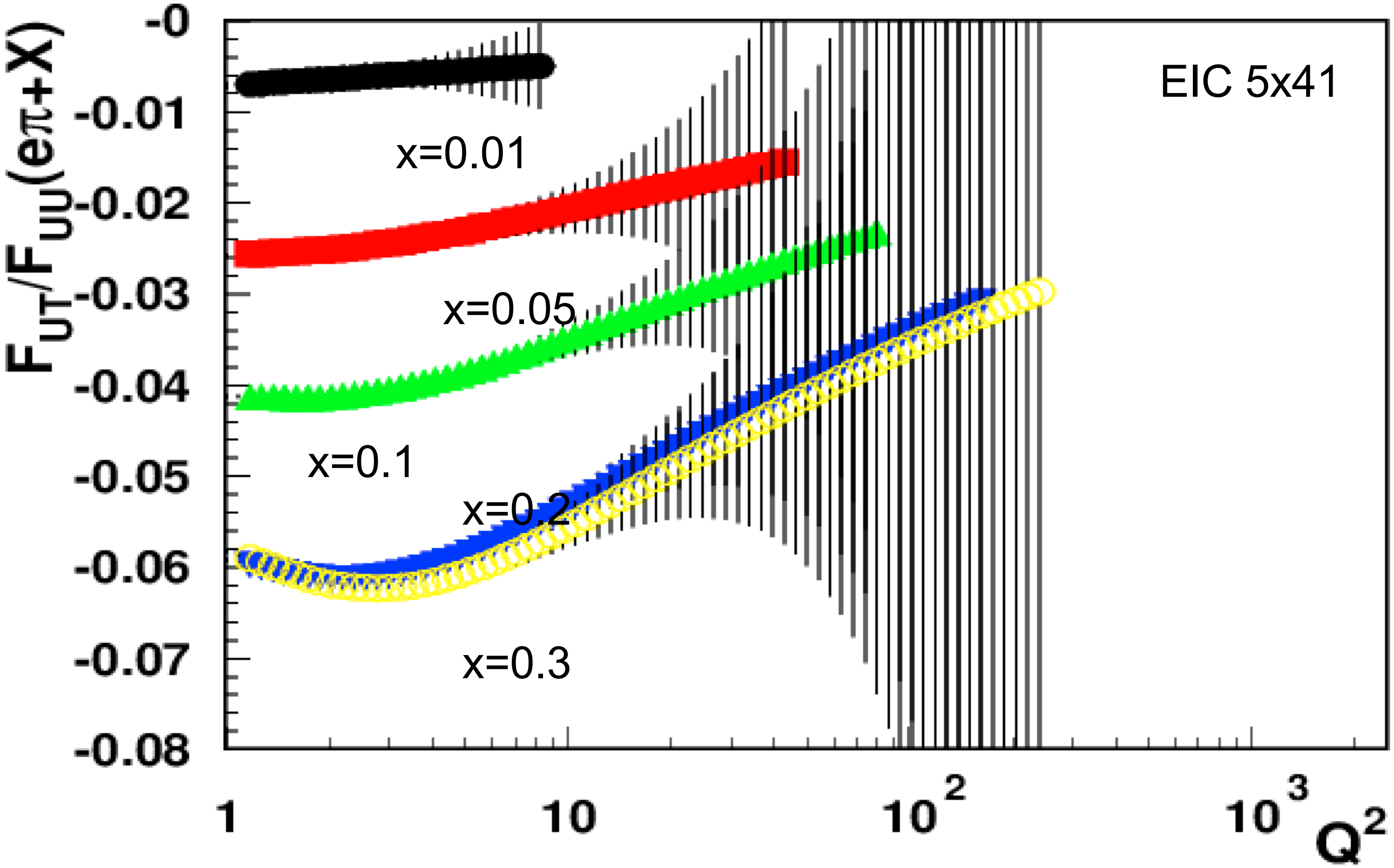
The same binning covers JLab and EIC



$y_{min}>0.025$

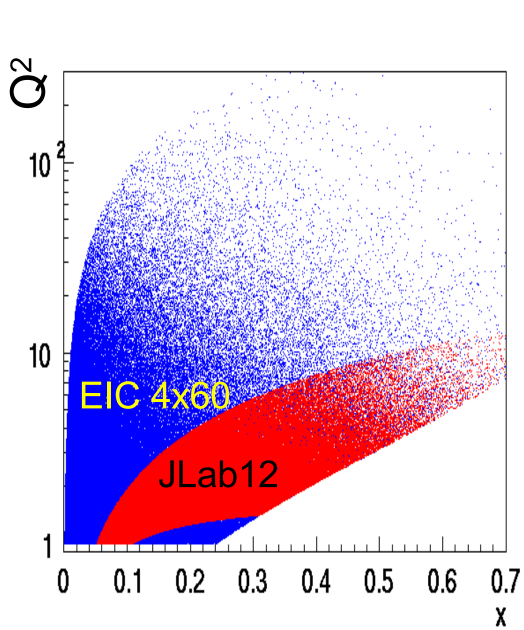
Non overlapping ranges of EIC and Jlab may be a problem for evolution studies, which are most critical for the 3D structure (to be checked)

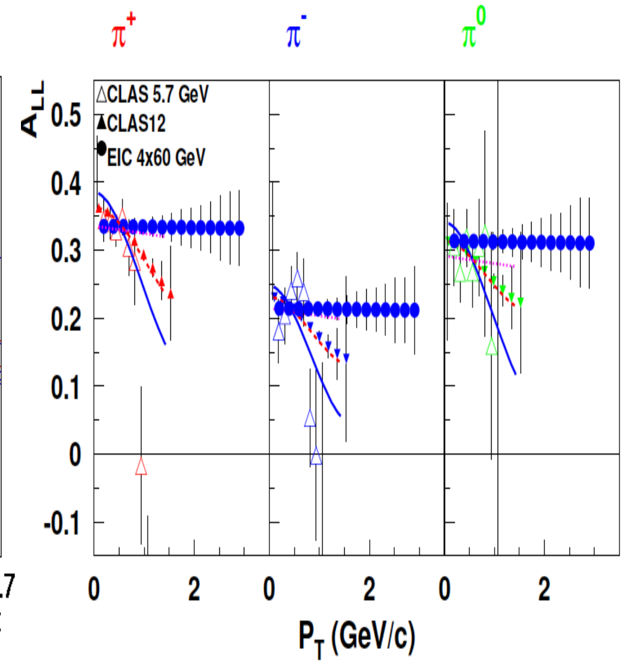
Sivers Effect vs Q^2 (Pavia)

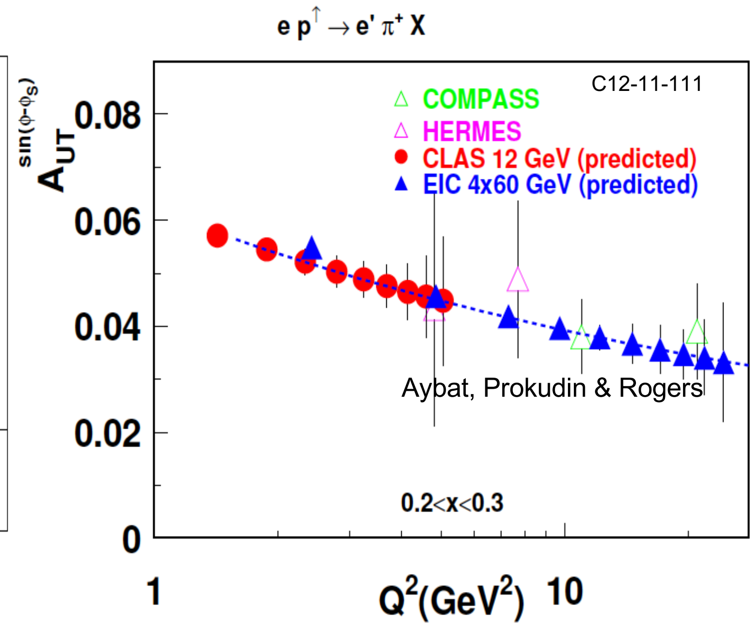


Measuring Sivers evolution may need large x, low y and large statistics in a wide range Q^2

CLAS12: Evolution and k_T-dependence of TMDs



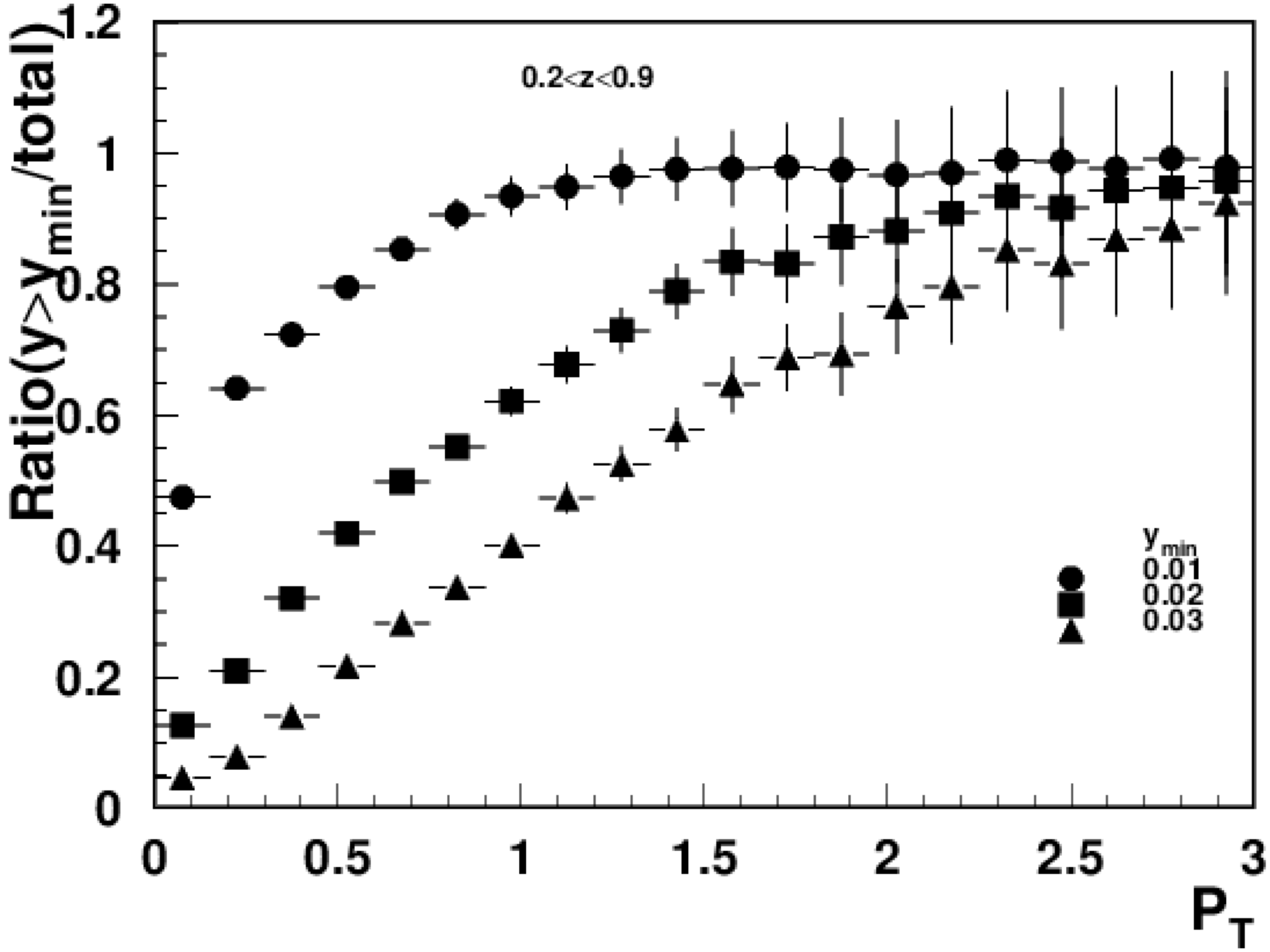




CLAS12 kinematical coverage $\quad$ k_T-dependence of $g_1(x, k_T)$ $\quad$ Q^2-dependence of Sivers, $f_1^{\perp}(x, k_T)$

- 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.

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

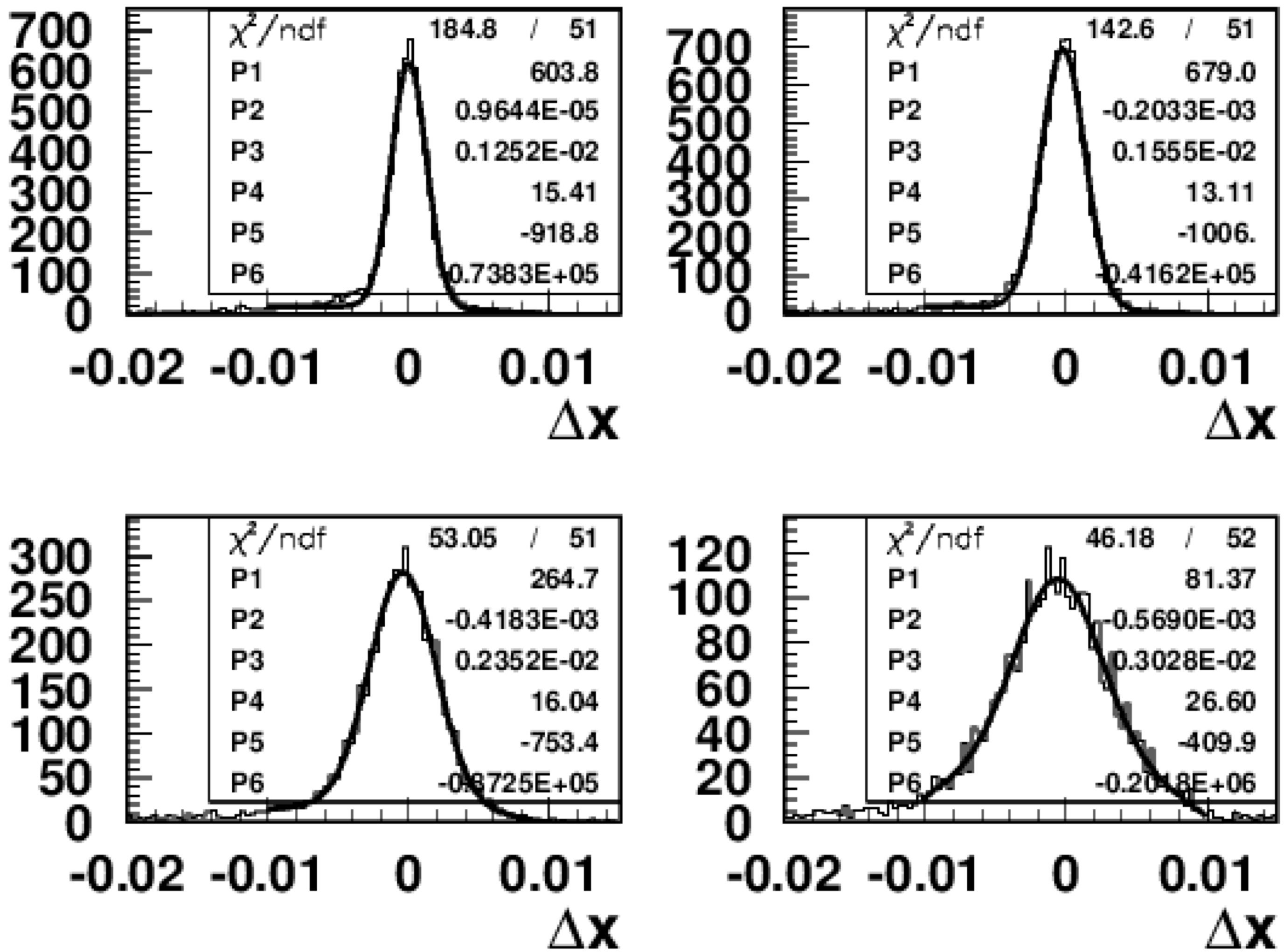
Summary

- MC reproduction of processes of interest is crucial for understanding of the systematics of measured observables (need fine grids with SFs!)
- Evolution of transverse momentum dependence of partonic distributions, in particular of Sivers effect, will require detailed understanding of z, P_T, Q^2-dependences of underlying fragmentation functions.
- Contributions to multiplicities and SSAs in SIDIS from different sources and SFs, may have completely different Q^2 and P_T-dependences
- Combination of JLa12 and EIC will be important for evolutions studies and will require control over reconstruction of the lepton kinematics at low y and low P_T

Support slides…

Resolutions

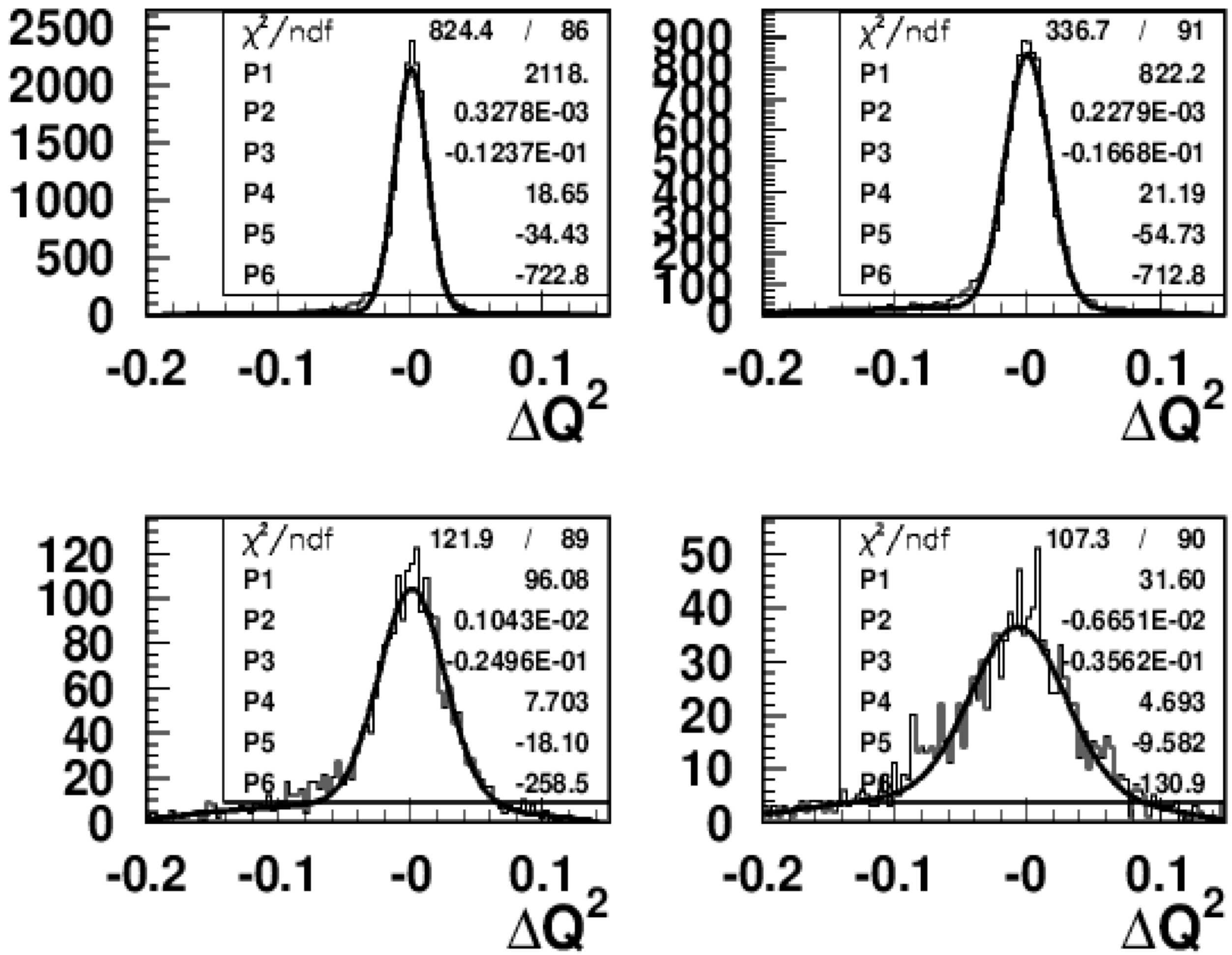
X-bins
0.0540
0.0590
0.0644
0.0704
0.0768
0.0839
0.0917
0.1001
0.1093
0.1194
0.1304
0.1424
0.1555
0.1699
0.1855
0.2026
0.2213
0.2417
0.2639
0.2882
0.3148
0.3438
0.3755
0.4101
0.4479
0.4891
0.5342
0.5834
0.6372
0.6959
0.7600



Bins ~4sigma

1.000
1.0814
1.1694
1.2646
1.3675
1.4788
1.5991
1.7292
1.8700
2.0222
2.1867
2.3647
2.5571
2.7652
2.9903
3.2336
3.4968
3.7814
4.0891
4.4219
4.7818
5.1709
5.5917
6.0468
6.5389
7.0711
7.6465
8.2688
8.9418
9.6695
10.4564
11.3074
12.2276
13.2227
14.2988
15.4625
16.7209
18.0816

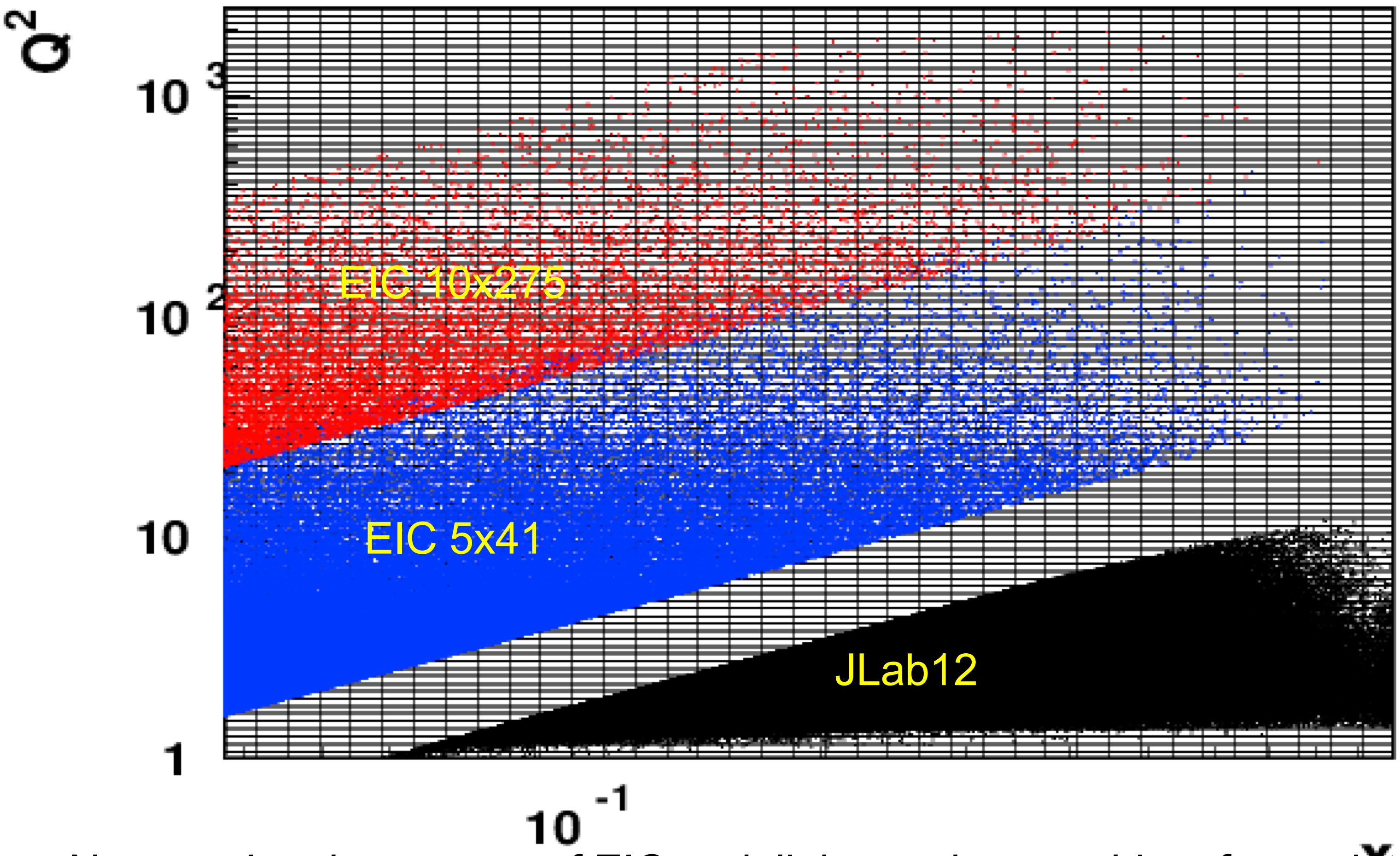
Resolutions



Bins ~5sigma

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)

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

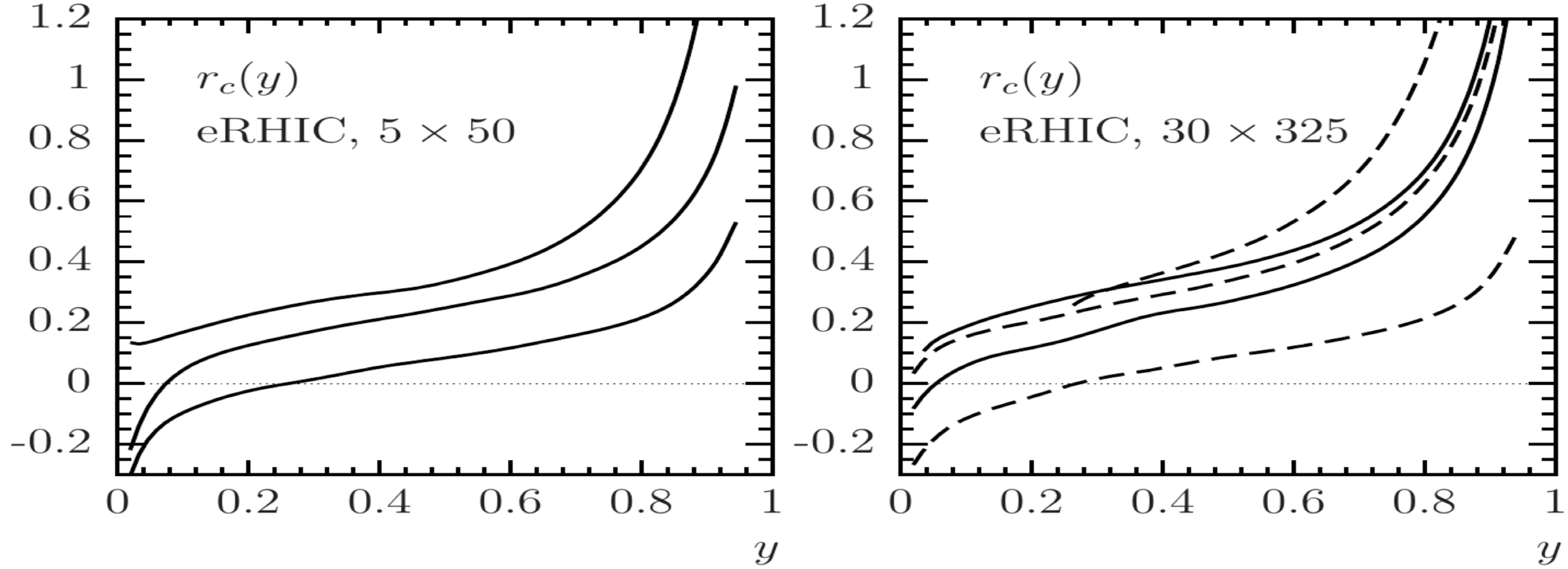
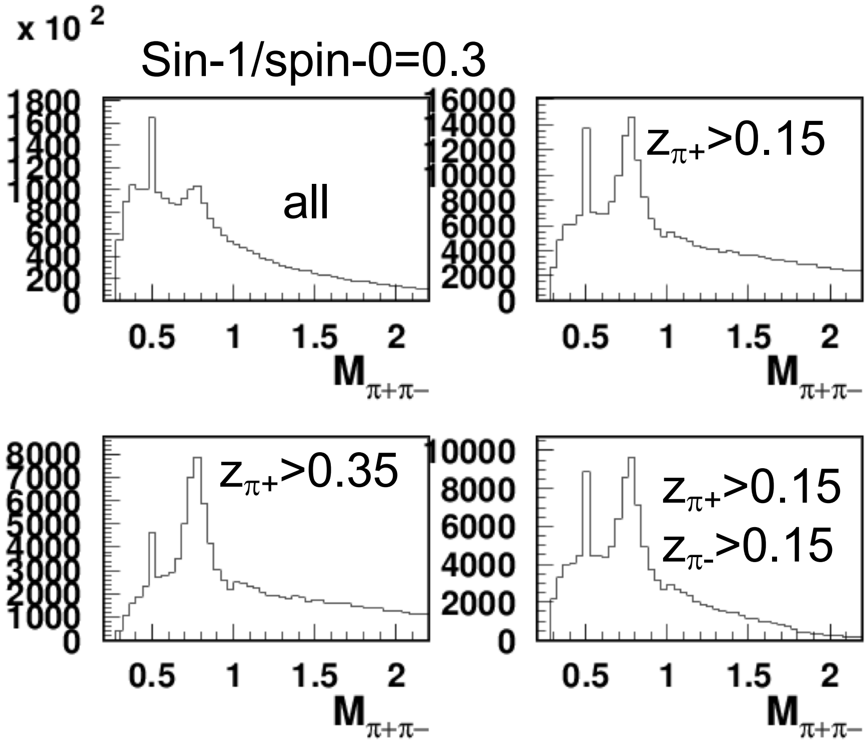


Figure 7.25. y-dependence of the leptonic radiative correction factor for electron proton scattering with different beam energies and in different x_B ranges. Left: $E_e = 5$ GeV, $E_p = 30$ GeV and the curves from the bottom up correspond to $0.1 < x_B < 0.4$, $10^{-2} < x_B < 10^{-1}$, $10^{-3} < x_B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

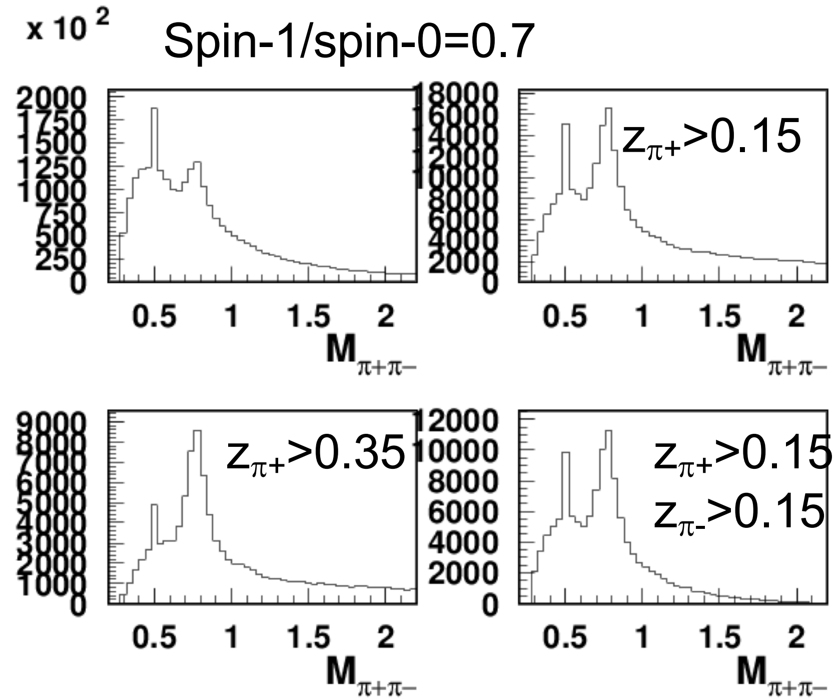
What are the RC in the region of y<0.05 (x>0.02) for SIDIS case ?

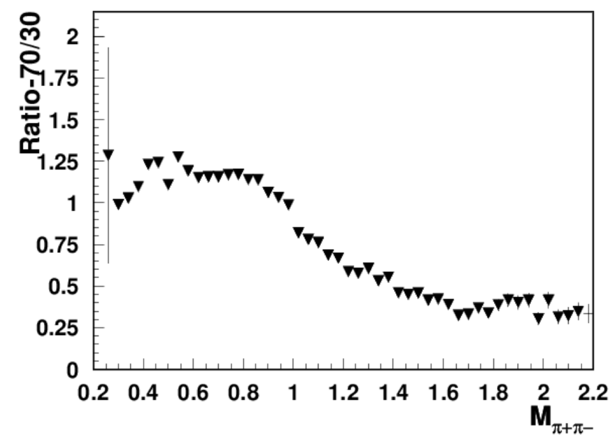
JLEIC (5x50) 2-hadron mass spectra

Sin-1/spin-0=0.3



Spin-1/spin-0=0.7





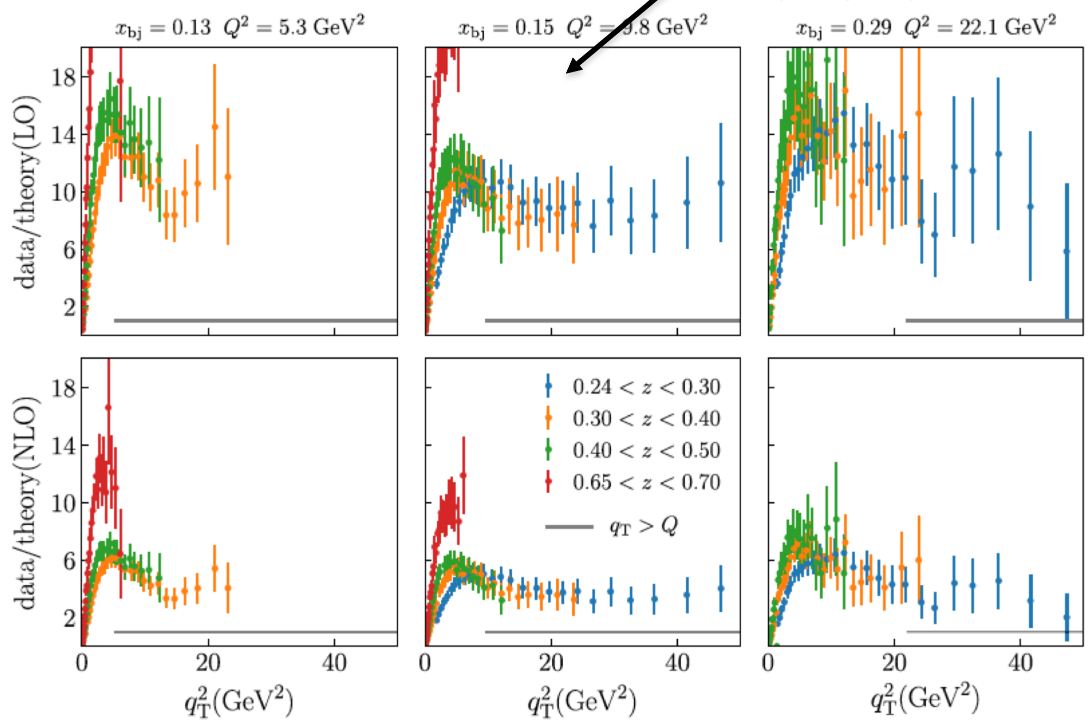
The rho peak is not increasing visually with increase of the fraction of VMs, as most of the background comes from low momentum particles at large $M_{\pi\pi}$

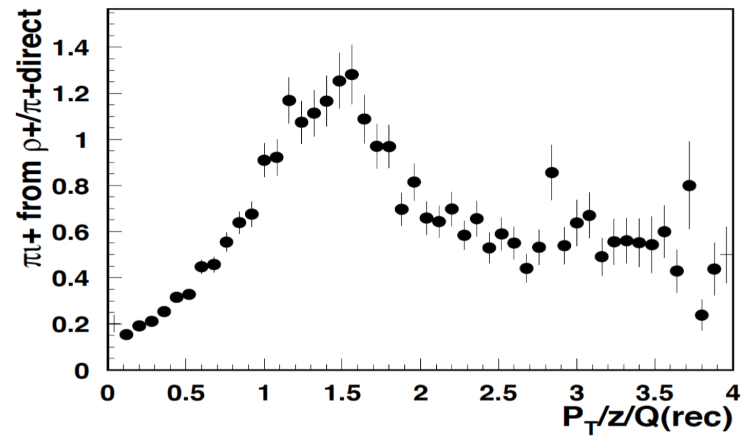
TMD formalism applicability

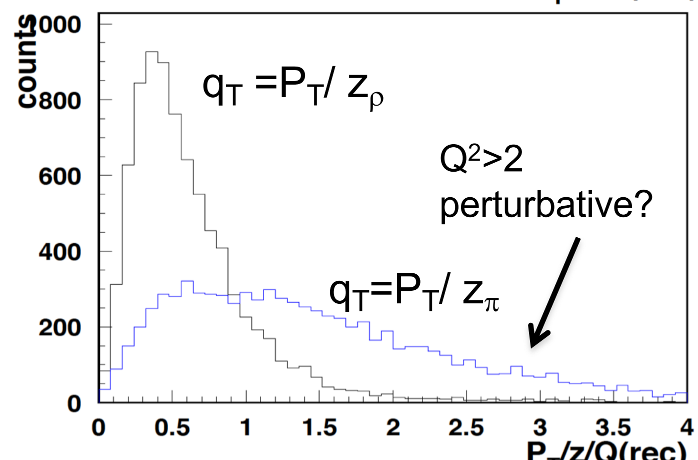
$$F^h_{XY}(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}(M/Q)$$

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

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)

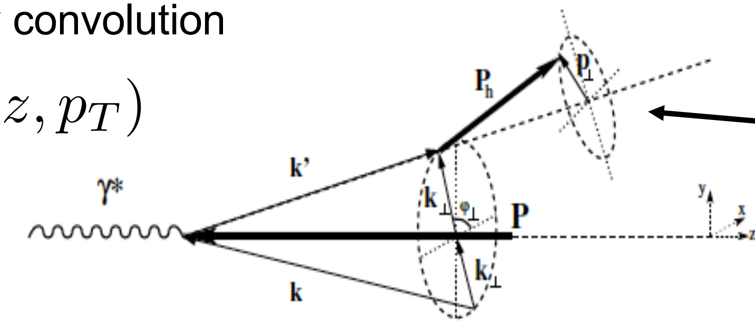
understanding the fraction of pions from "correlated dihadrons" will be important to make sense out of q_T distributions

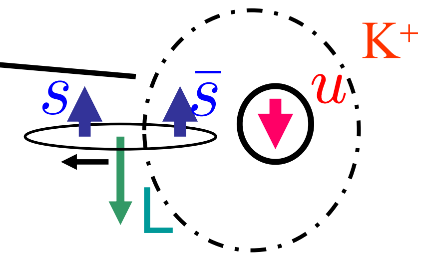
N/q	U	L	T
U	f_1		
L		g_1	
T			h_1

Flavor dependence of transverse momentum

SIDIS x-section defined by convolution

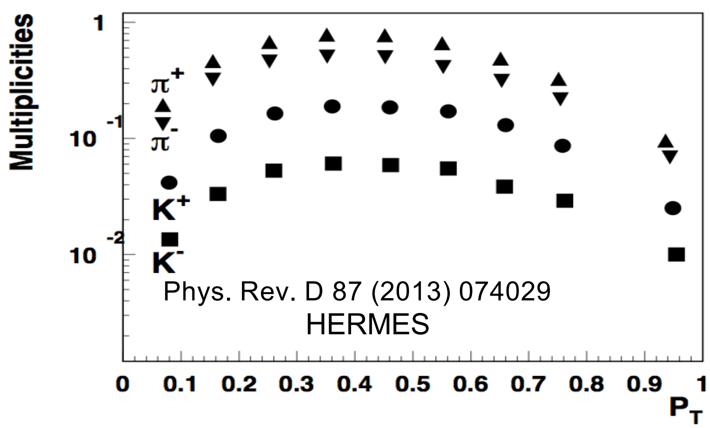
$$f_1^q(x, k_T) \otimes D_1^{q\to h}(z, p_T)$$

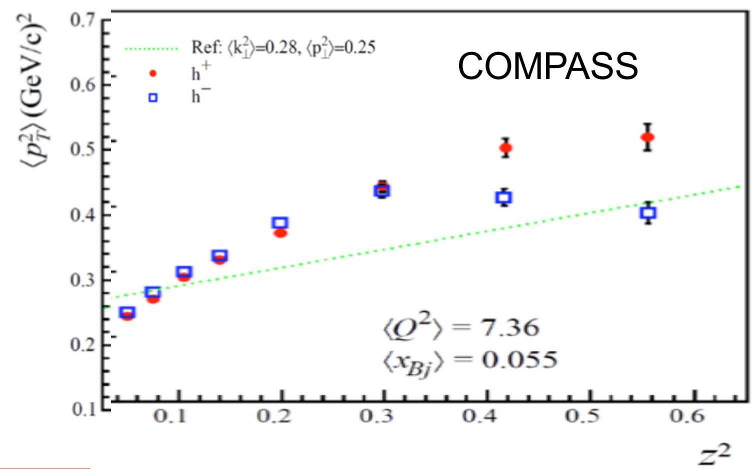




Disentanglement of z and P_{hT} : provides access to the transverse intrinsic quark k_T and fragmentation p_T,

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

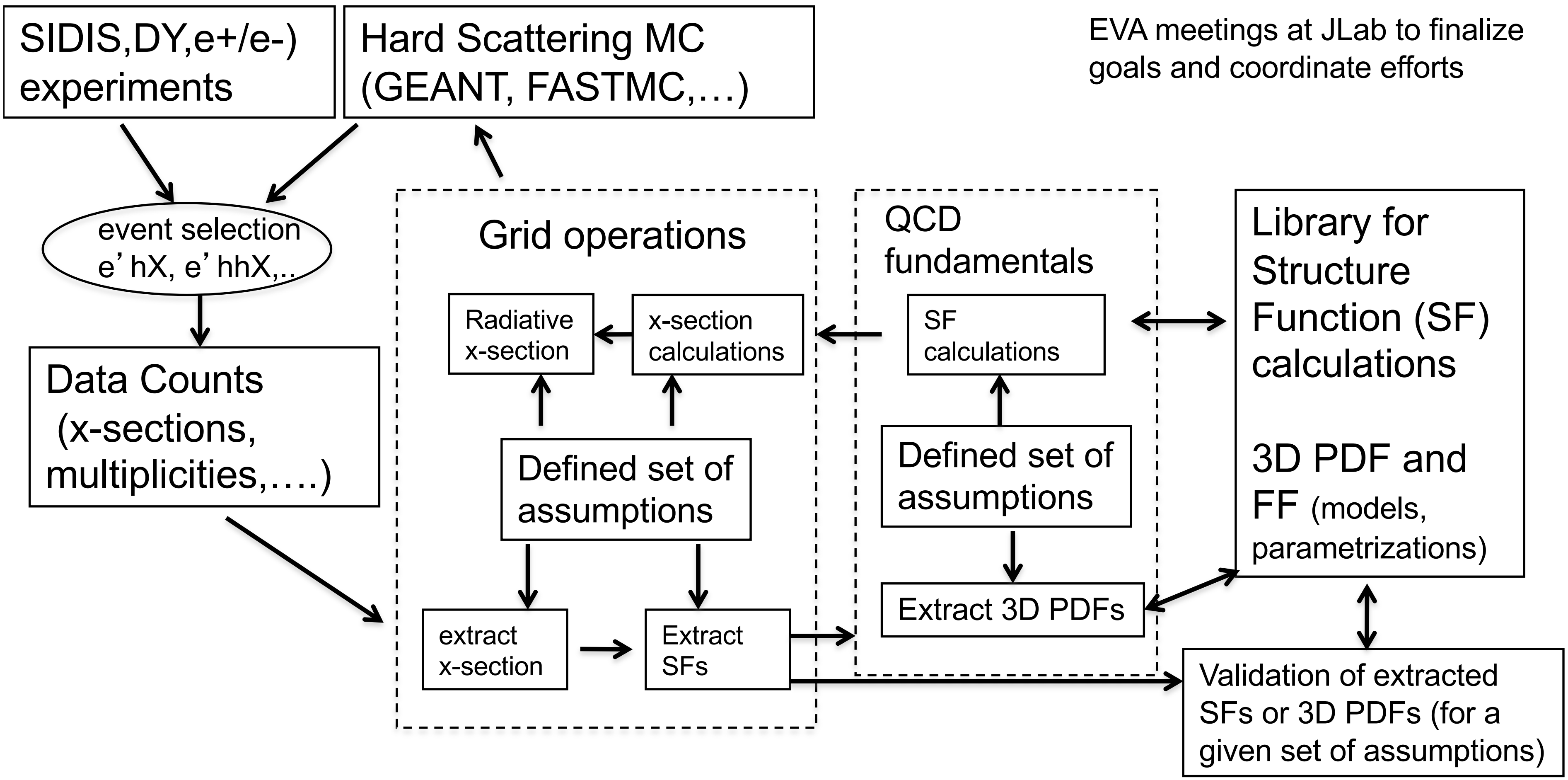




Multiplicities deviate from simple Gaussian distributions already at small P_T
Data indicating flavor dependence of widths of partonic distributions

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

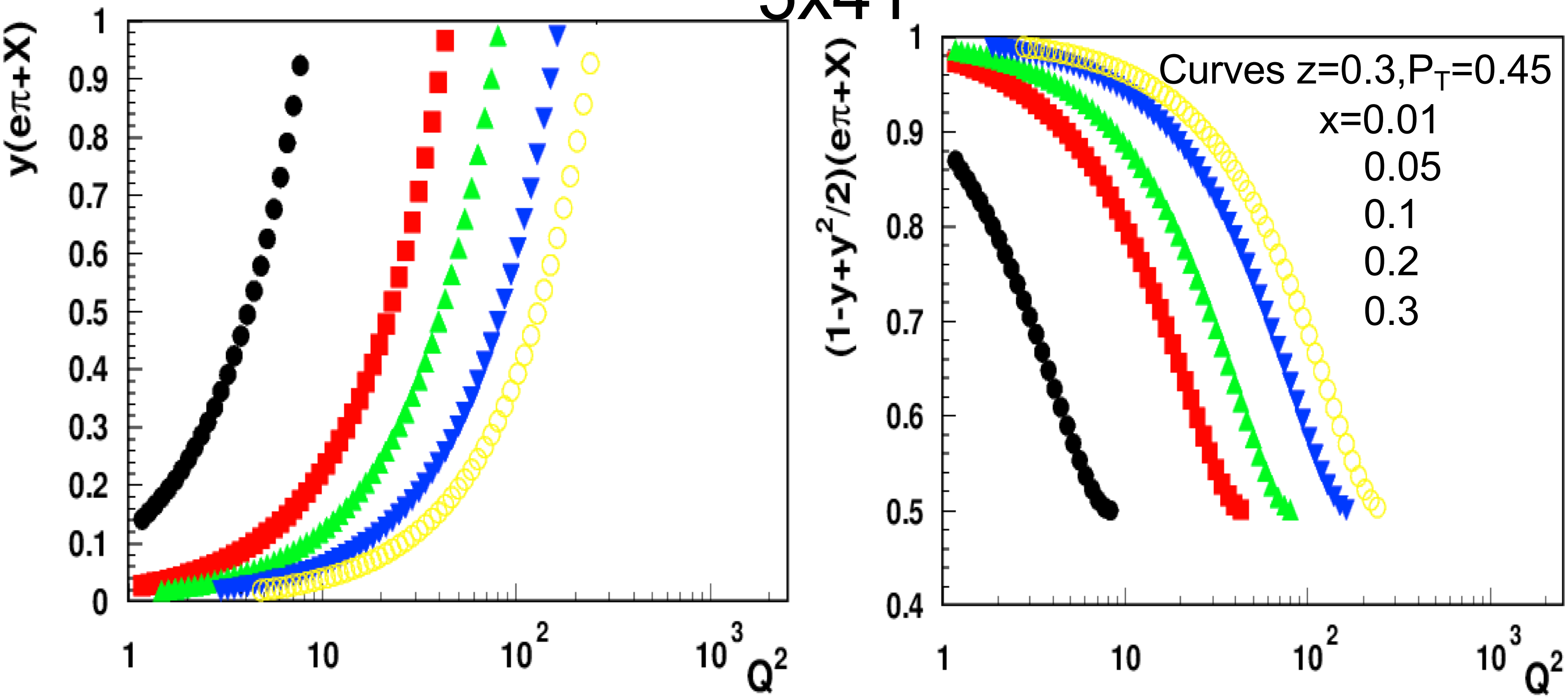
3D PDF Extraction and VAlidation (EVA) framework



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

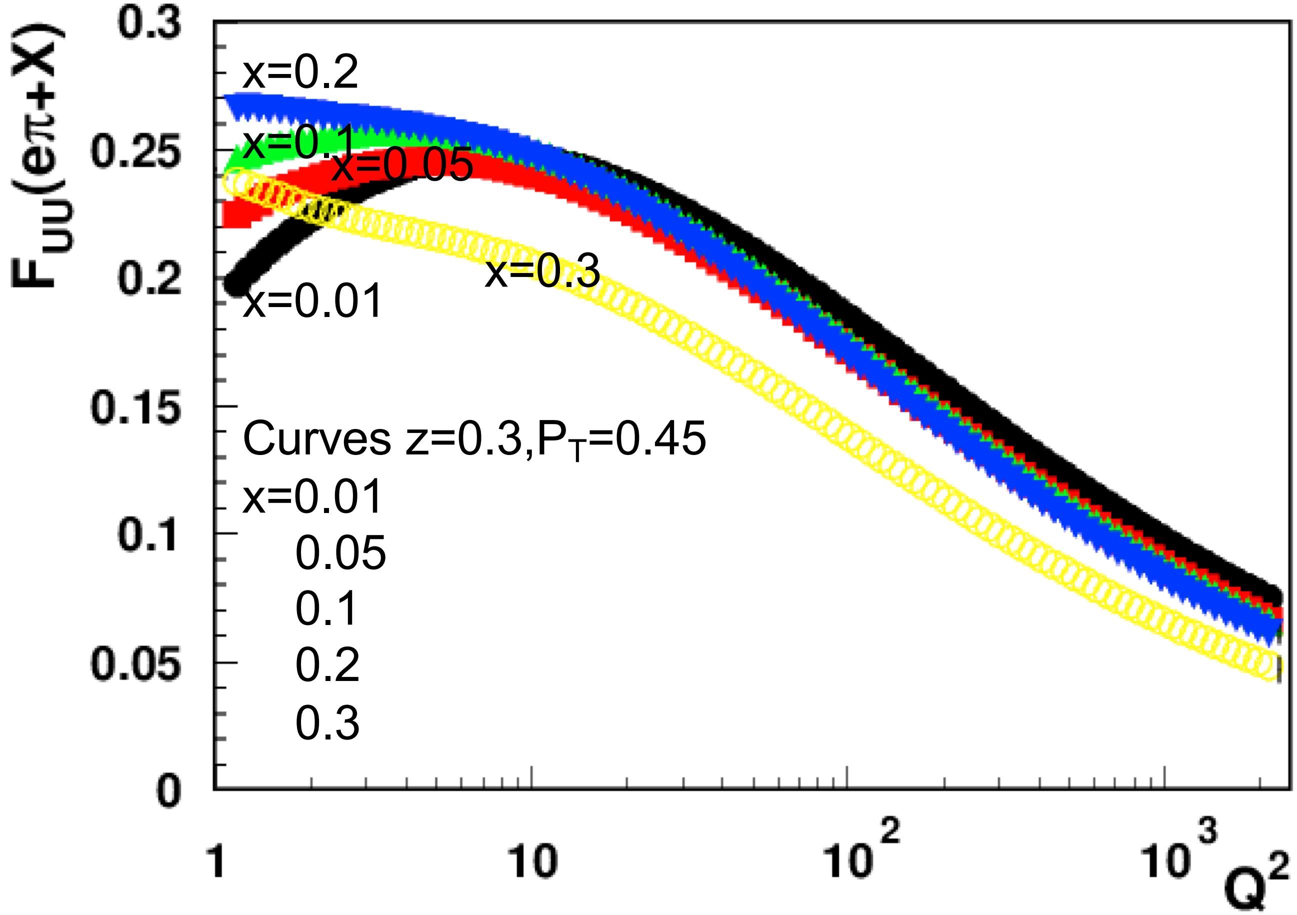
Accessible kinematics

5x41



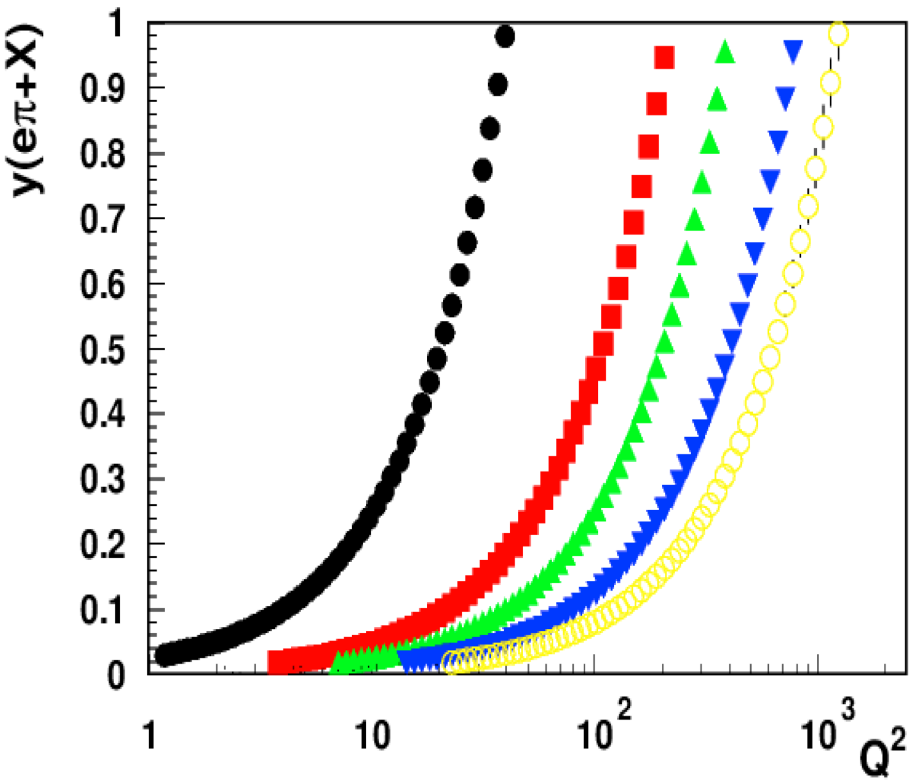
y<1 defines the accessible kinematical limits

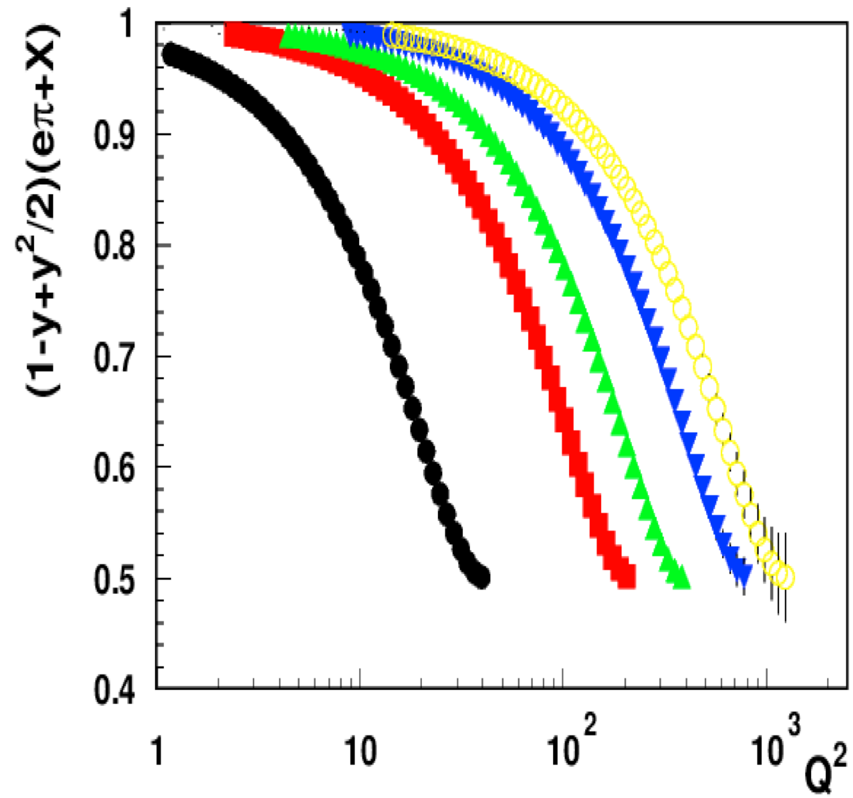
Structure Functions (Pavia)



Accessible kinematics

EIC: 10x100

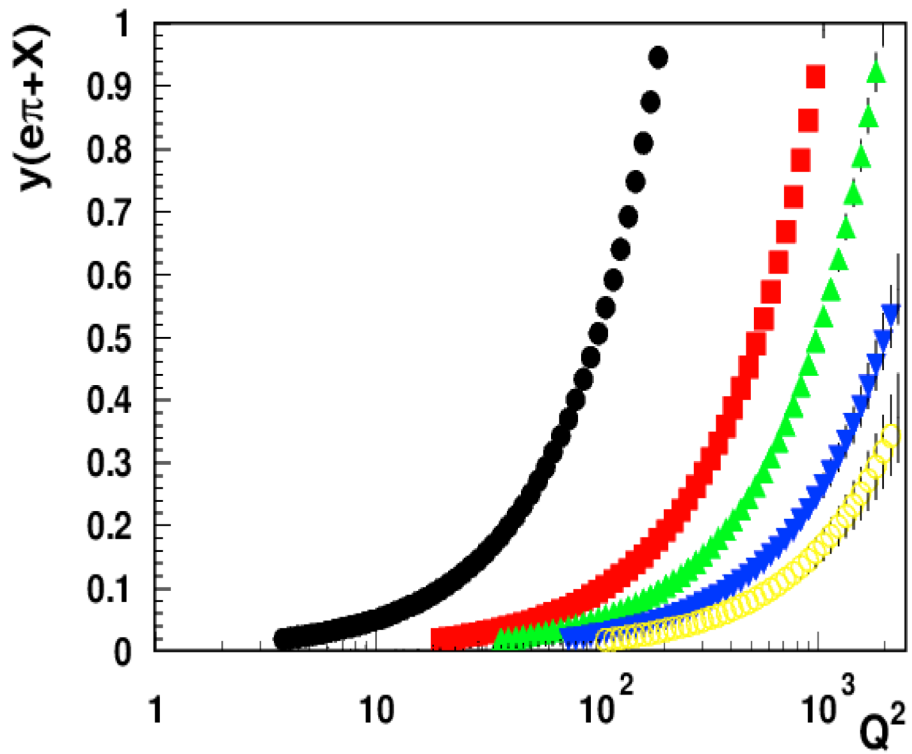


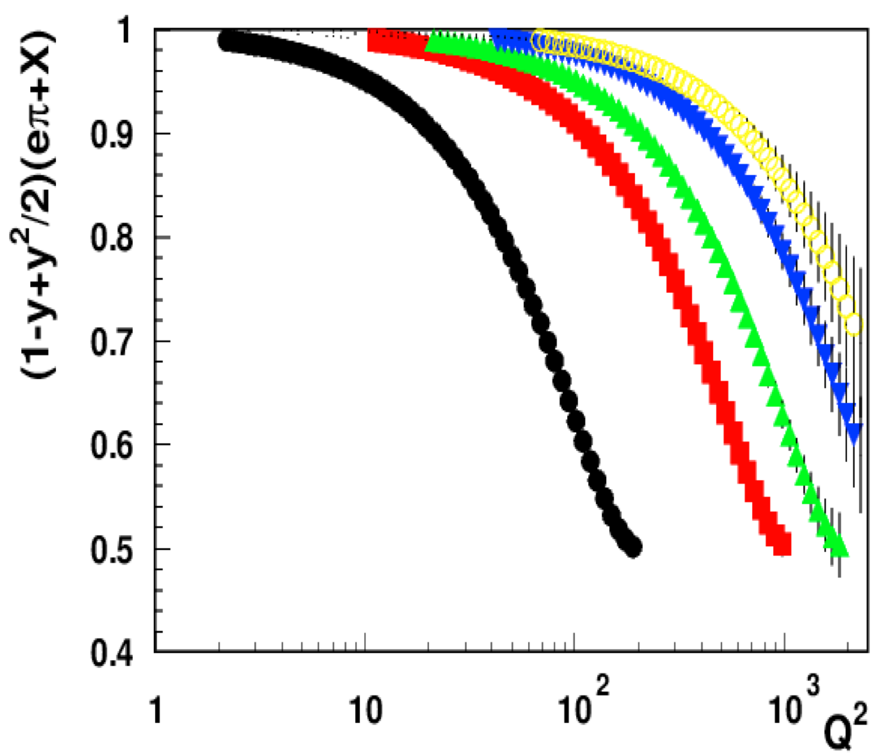


y<1 defines the accessible kinematical limits

Accessible kinematics

EIC:18x275

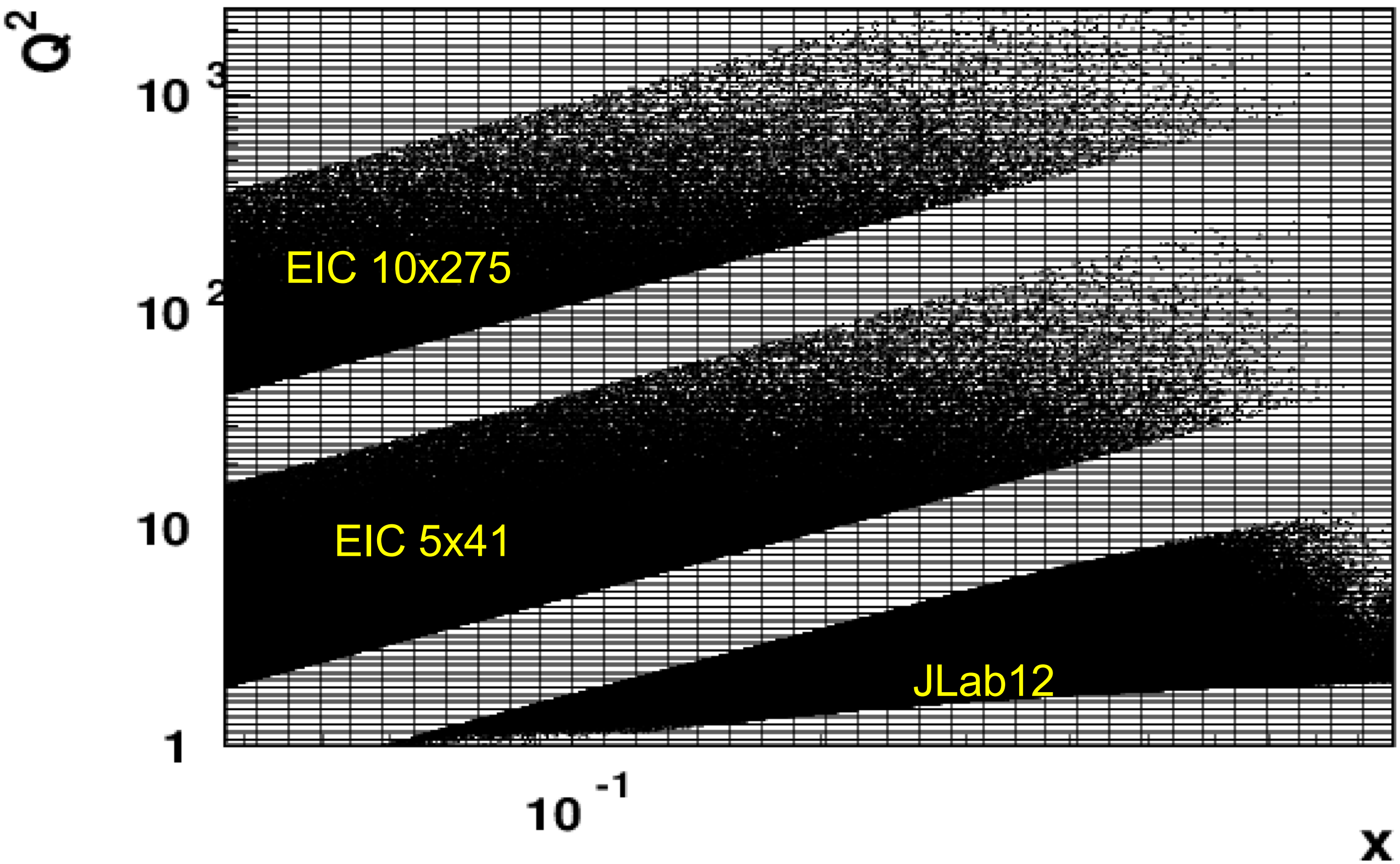




y<1 defines the accessible kinematical limits

Reconstructed Data table: details

The same binning covers JLab and EIC



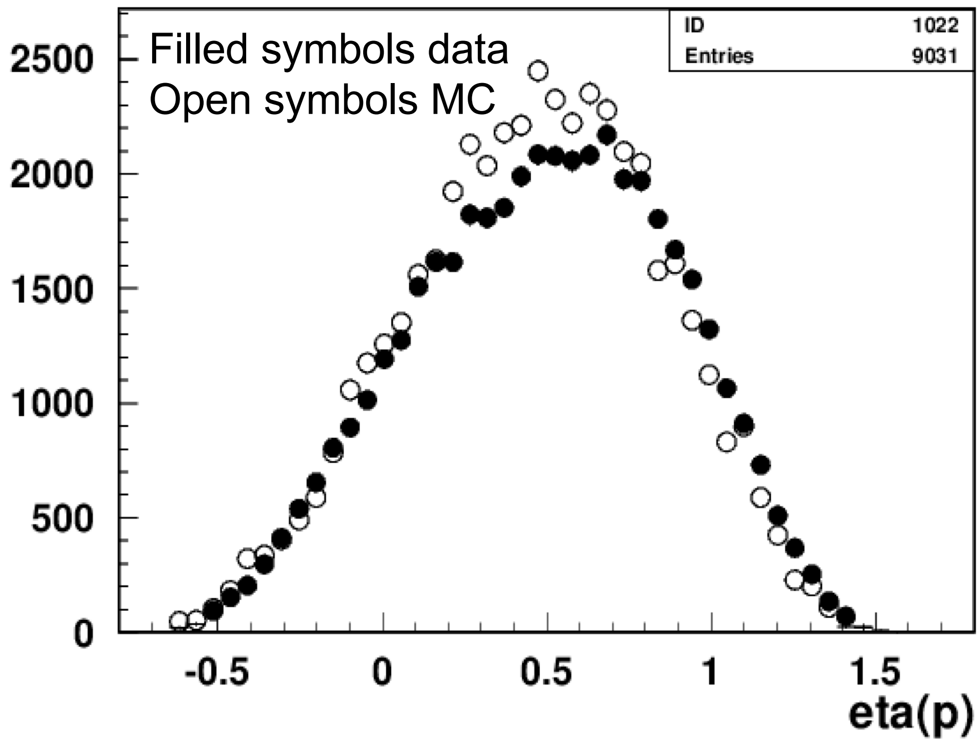
y>0.05

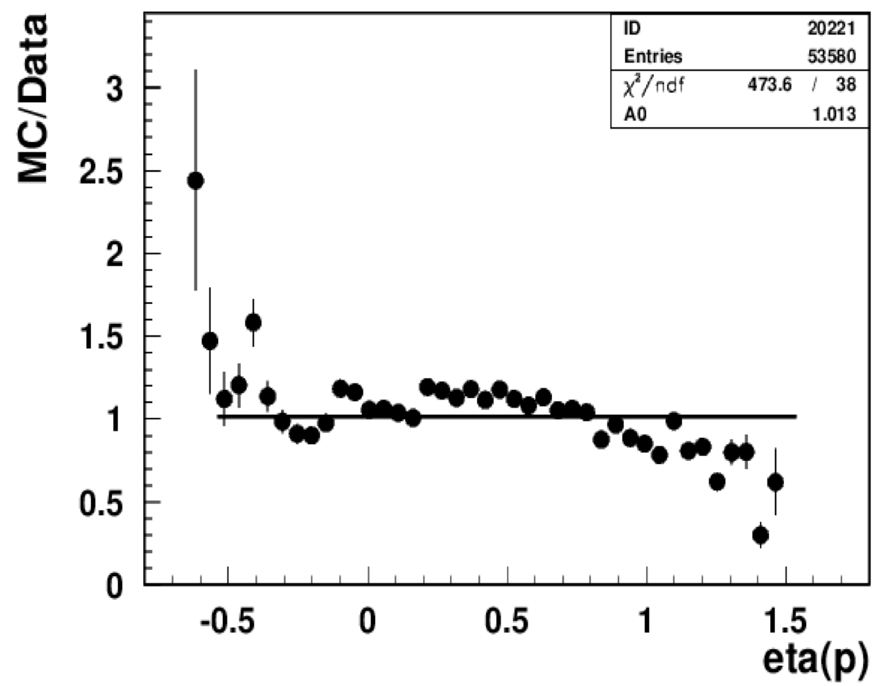
Non overlapping ranges of EIC and Jlab may be a problem for evolution studies, which are most critical for the 3D structure (to be checked)

CLAS12 protons: Data vs MC

Using PEPSI (LUND) generator rapidity in Breit frame

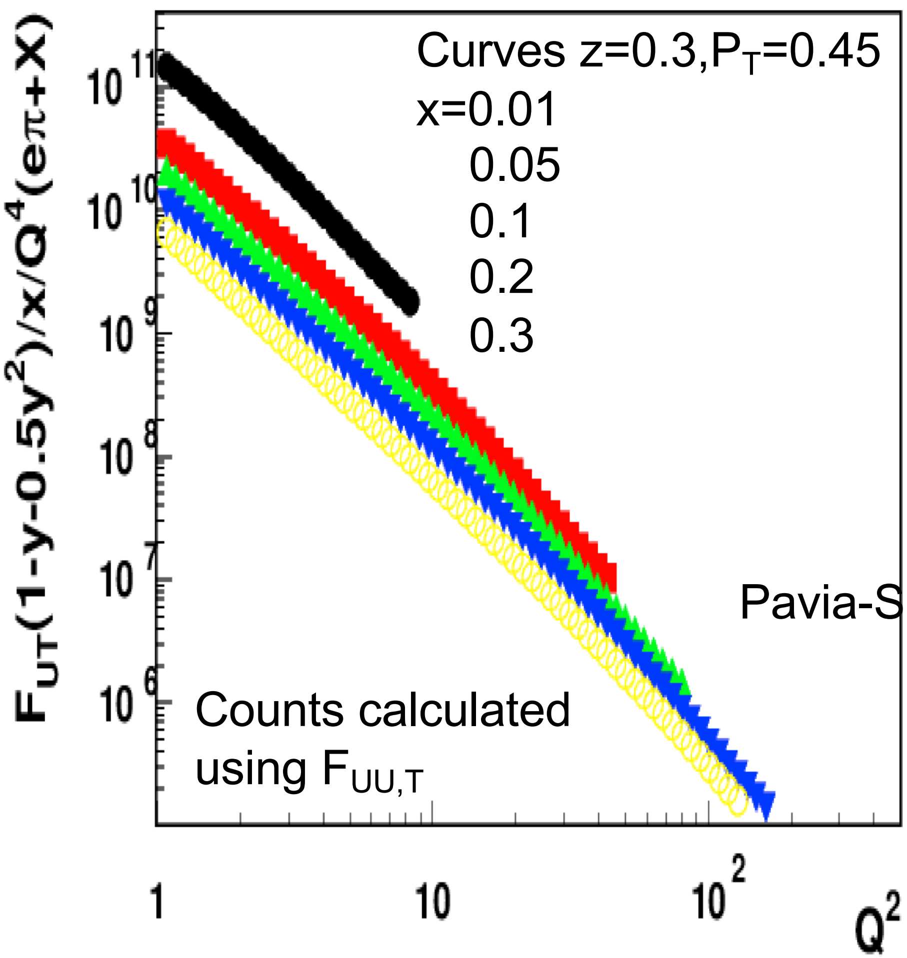
Boglione et al
https://arxiv.org/pdf/1904.12882.pdf

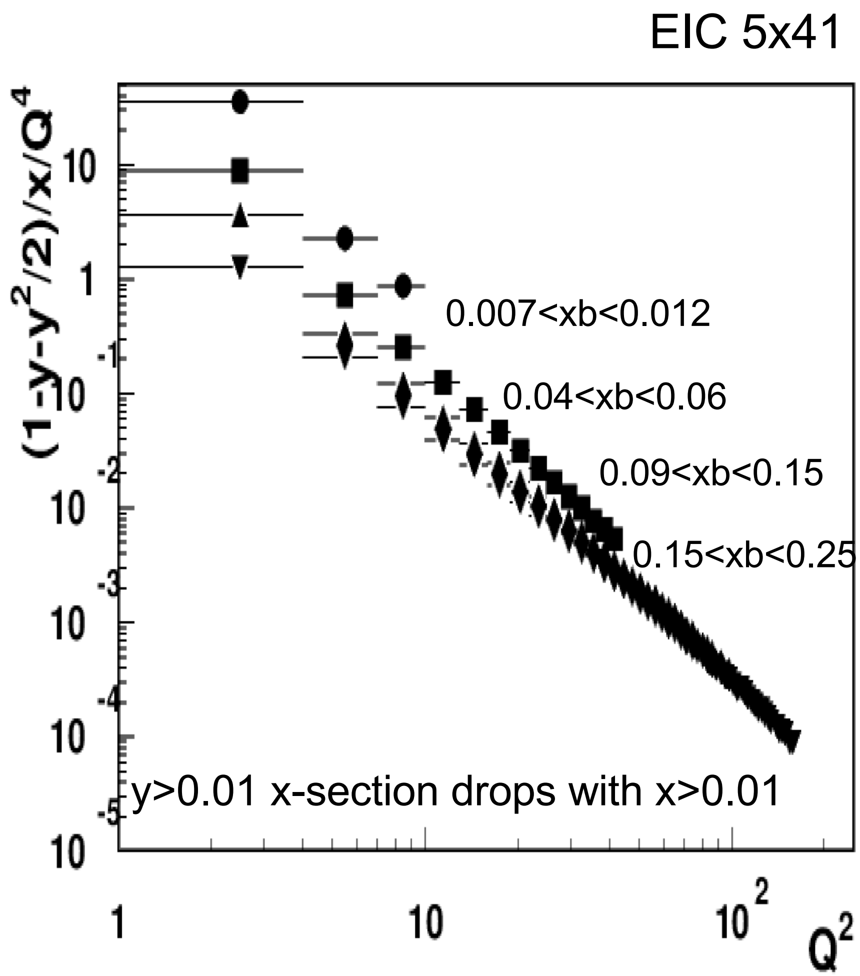




Multiliplicity of protons vs rapidity in good agreement with JETSET in most of the kinematics

Low Q^2 events for evolution studies

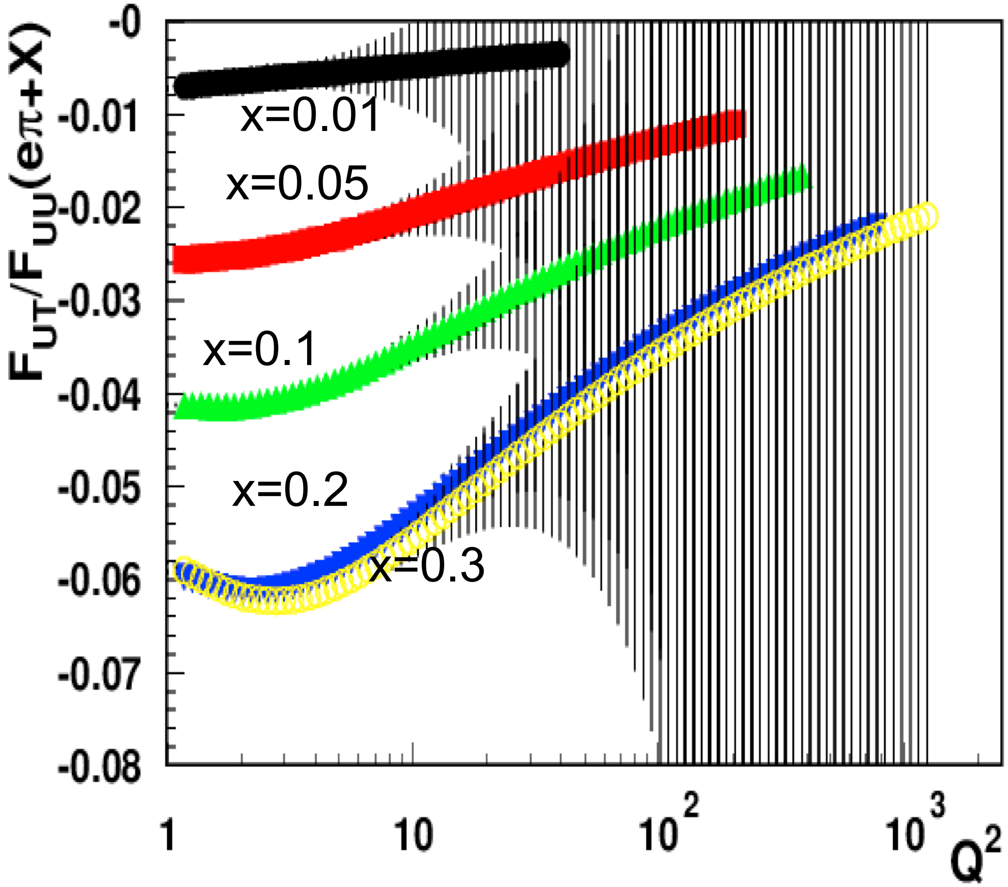




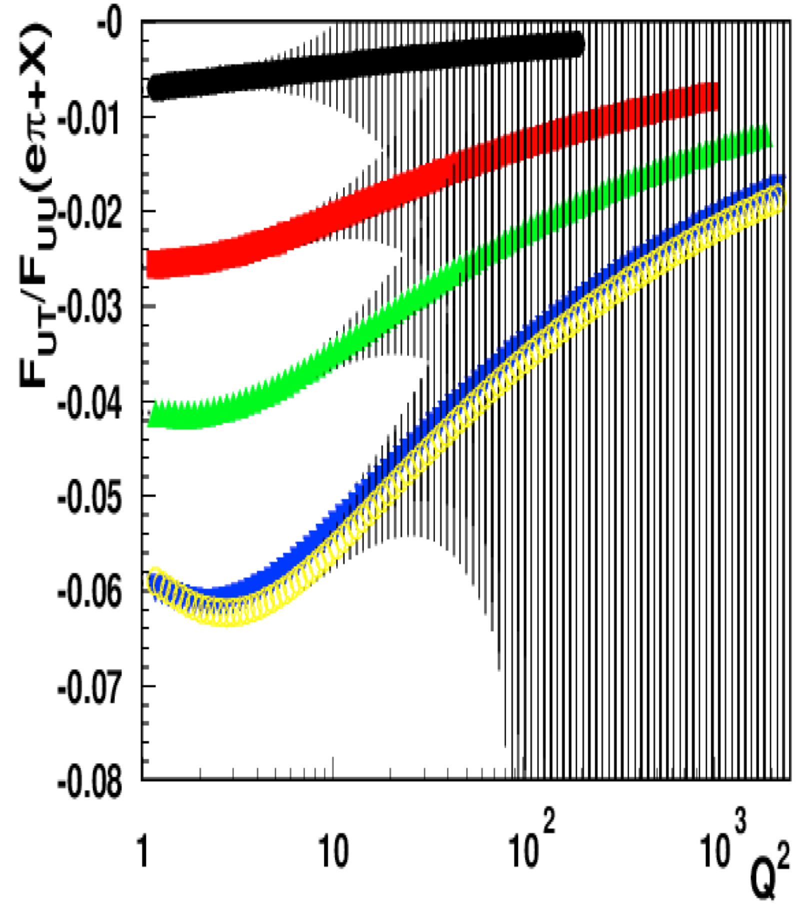
For evolution studies need a wide range in Q^2 for relatively large x, where the Sivers effect is significant region

Sivers Effect vs Q^2 (Pavia)

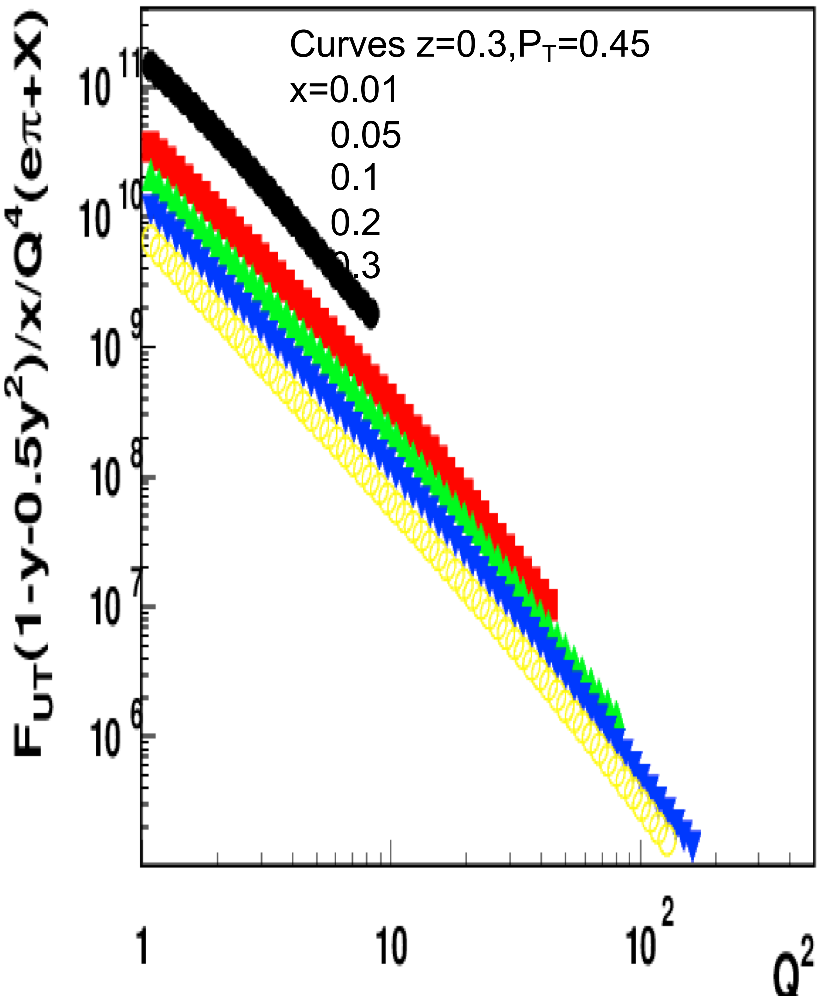
EIC:10x100

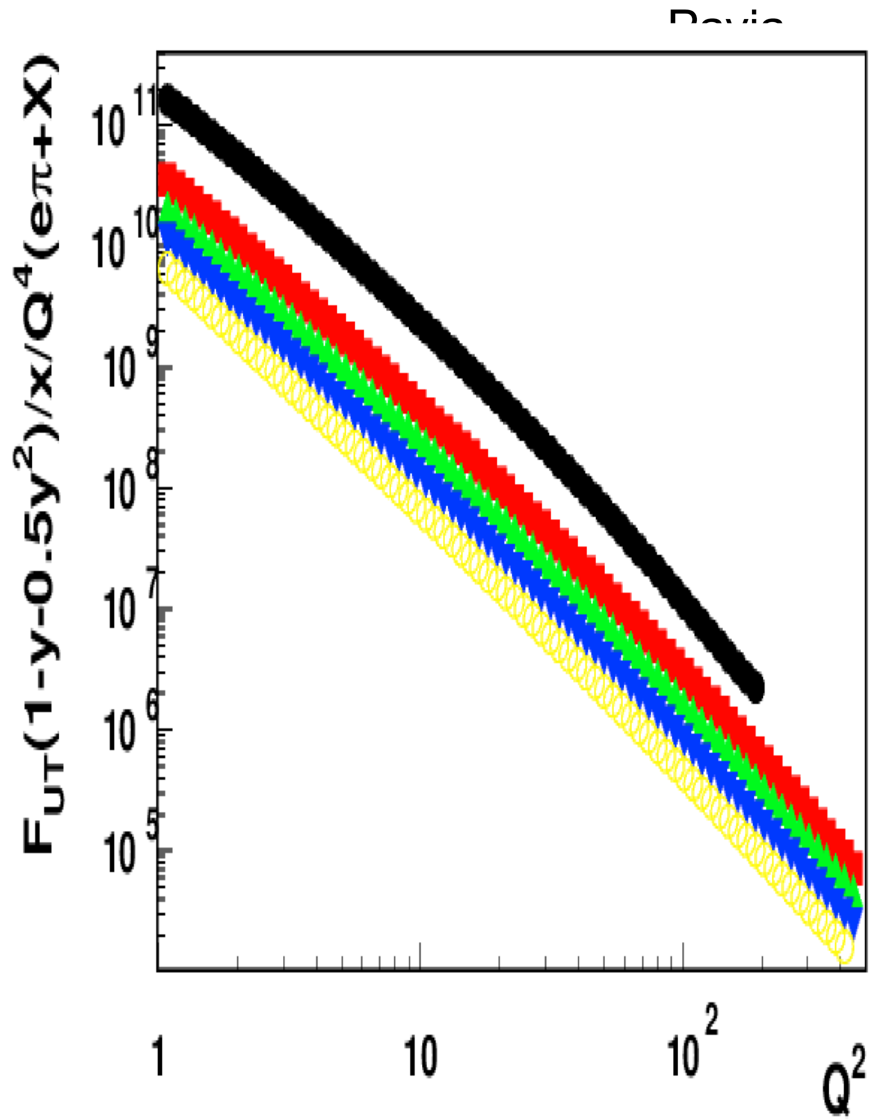


EIC:18x275



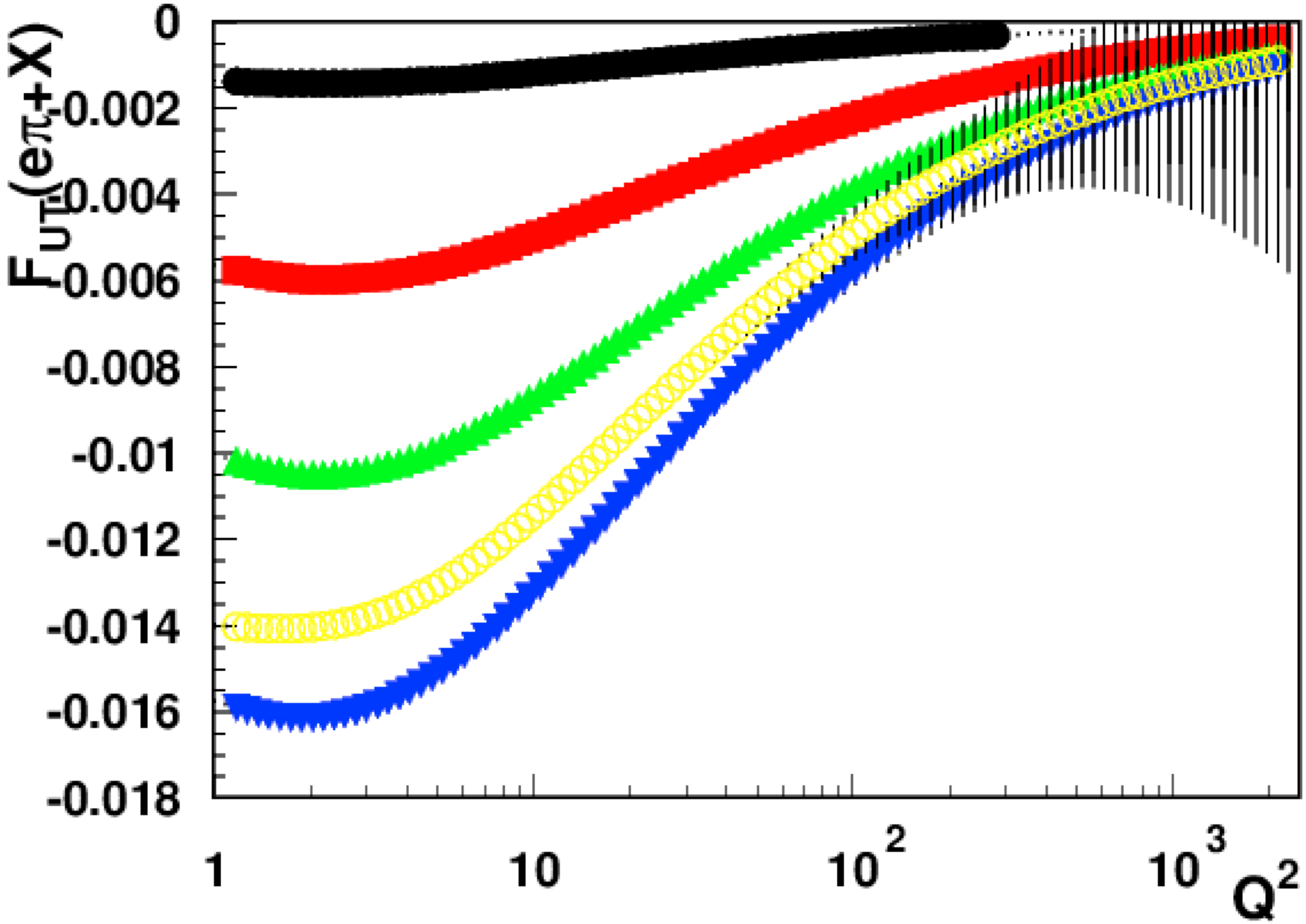
Low Q^2 events for evolution studies



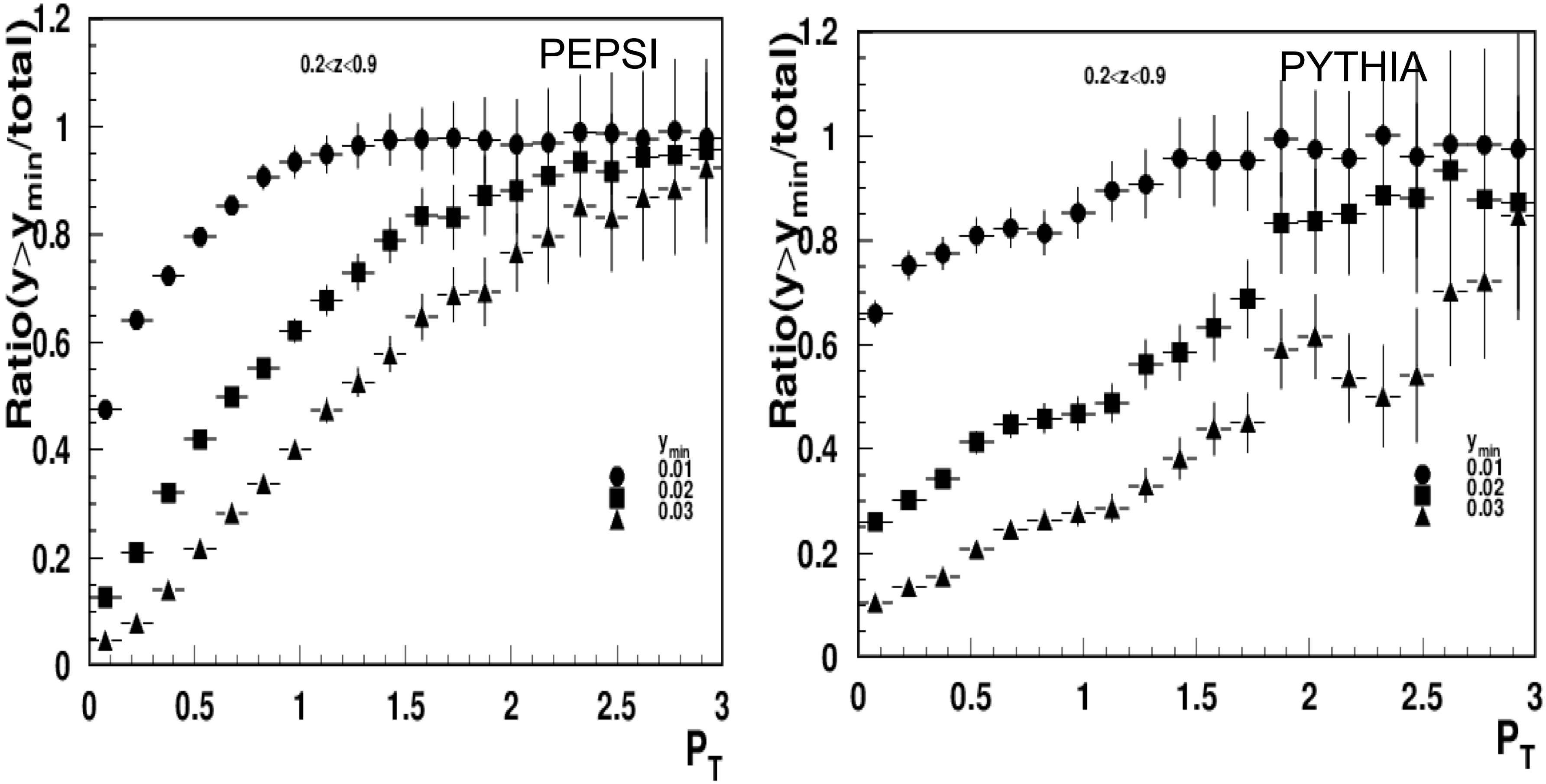


Access increases with s, but error too large in high Q^2

Structure Functions (Pavia)



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



EIC 5x41

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