3D Structure of the Nucleon: from JLab12 to JLab24

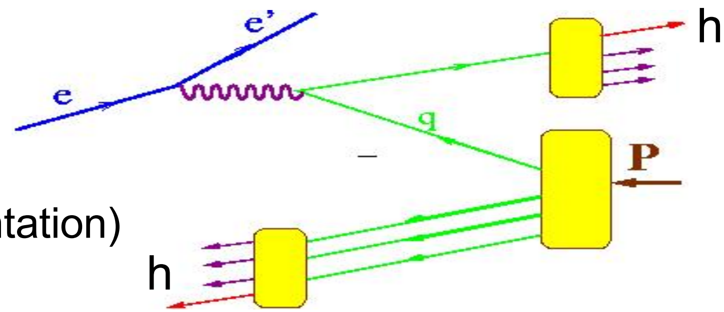
Harut Avakian (JLab)

Light Cone 2021: Physics of Hadrons on the Light Front

- Studies of 3D structure
- Semi-Inclusive hadrons
- Di-hadrons and correlations in hadronization from CLAS12
- Complementarity with JLab24 and EIC
- Exclusive processes
- Summary

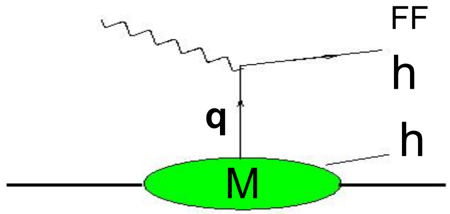
Electroproduction: extending 1D PDFs

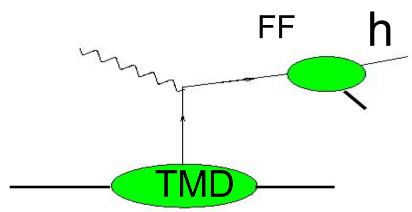
x_F – fractional momentum in the CM frame

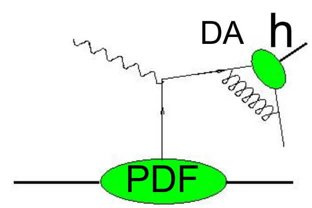


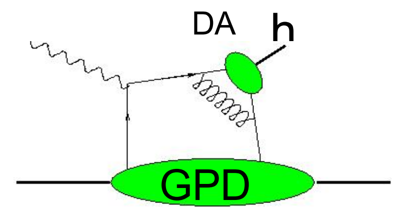
$x_F>0$ (current fragmentation)

$x_F<0$ (target fragmentation)









-1 Fracture Functions (target fragmentation) 0 Semi-exclusive production 1 x_F

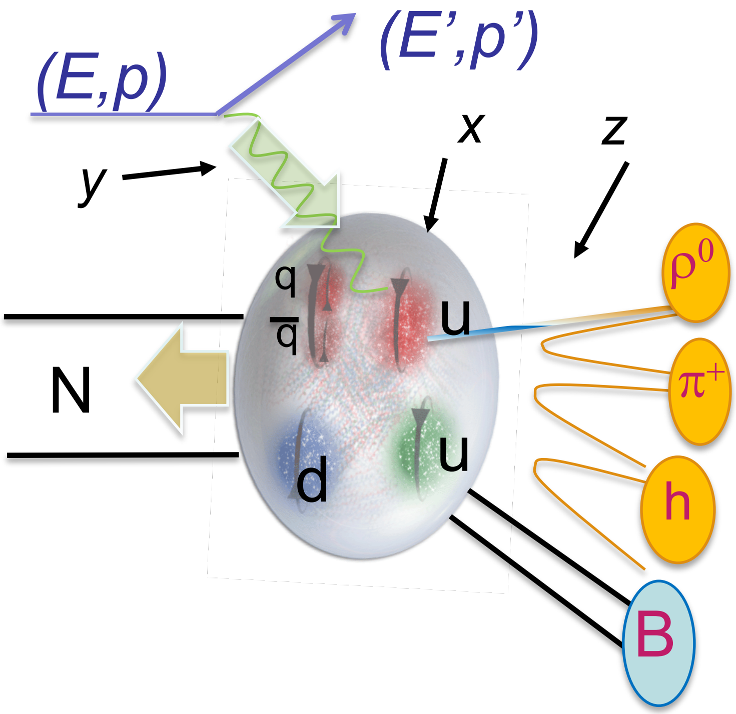
N/q	U	L	T
U	$\hat{u}_1$	$\hat{l}_1^{\perp h}$	$\hat{t}_1^h, \hat{t}_1^{\perp}$
L	$\hat{u}_{1L}^{\perp h}$	$\hat{l}_{1L}$	$\hat{t}_{1L}^h, \hat{t}_{1L}^{\perp}$
T	$\hat{u}_{1T}^h, \hat{u}_{1T}^{\perp}$	$\hat{l}_{1T}^h, \hat{l}_{1T}^{\perp}$	$\hat{t}_{1T}, \hat{t}_{1T}^{hh}, \hat{t}_{1T}^{\perp\perp}, \hat{t}_{1T}^{\perp h}$

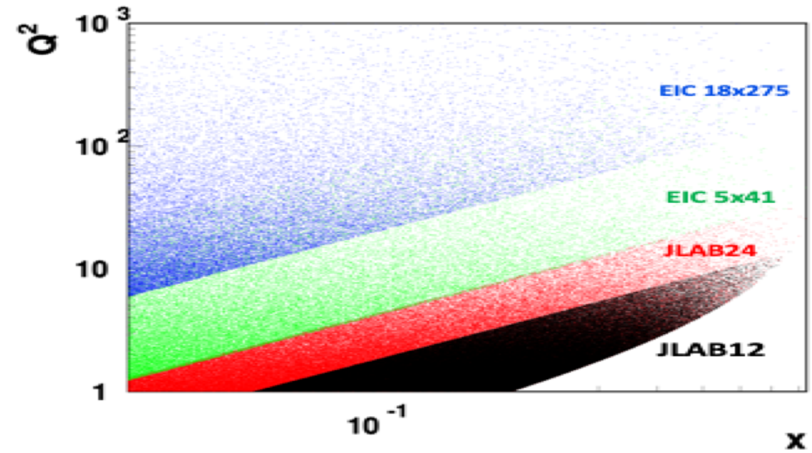
N/q	U	L	T
U	f_1	X	$h_1^{\perp}$
L	X	g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	$h_1, h_{1T}^{\perp}$

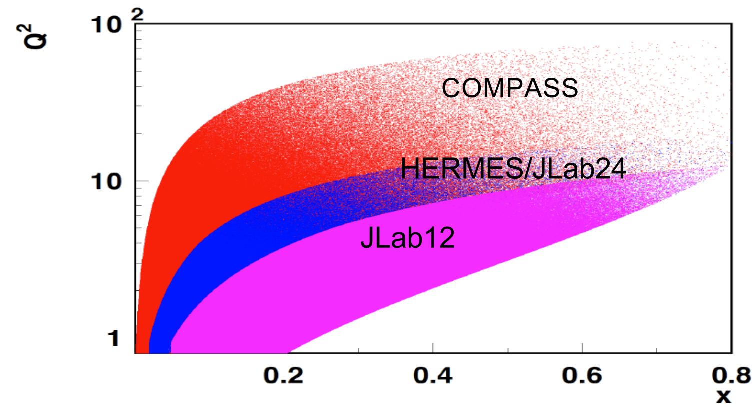
N/q	U	L	T
U	H	X	$\mathcal{E}_T$
L	X	$\widetilde{H}$	
T	E		$H_T, \widetilde{H}_T$

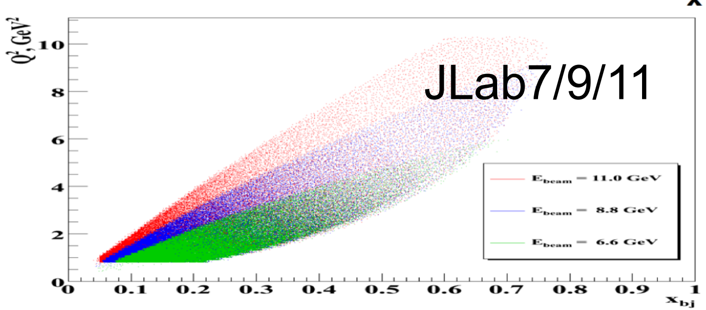
Wide kinematic coverage of large acceptance detectors allows studies of semi-inclusive and exclusive processes simultaneously

SIDIS kinematical coverage and observables









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

Studies of azimuthal modulations give access to underlying 3D partonic distributions

Azimuthal distributions in SIDIS (unpolarized)

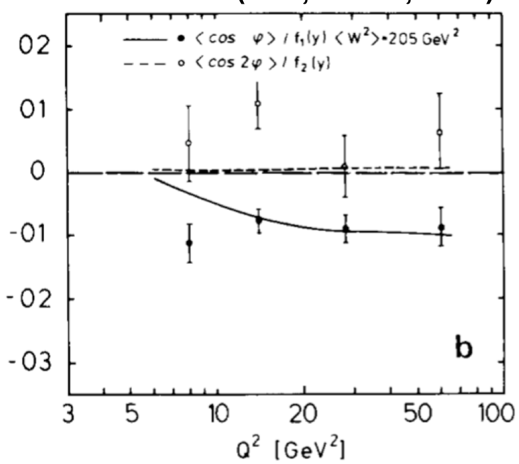
H.T.

H.T.

$$\frac{d\sigma}{dx_B\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\left\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\,F_{LU}^{\sin\phi_h}\right\},$$

H.T.

EMC-1983 (PL,v130,118)



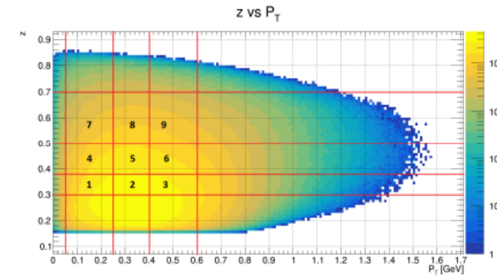
Observables: - Azimuthal Moments - Multiplicity

$$\boxed{\frac{d^4M^{\pi^\pm}(x,Q^2,z,P_T^2)}{dx\,dQ^2\,dz\,dP_T^2} = \left(\frac{d^4\sigma^{\pi^\pm}}{dx\,dQ^2\,dz\,dP_T^2}\right)\Big/\left(\frac{d^2\sigma^{DIS}}{dx\,dQ^2}\right)}$$

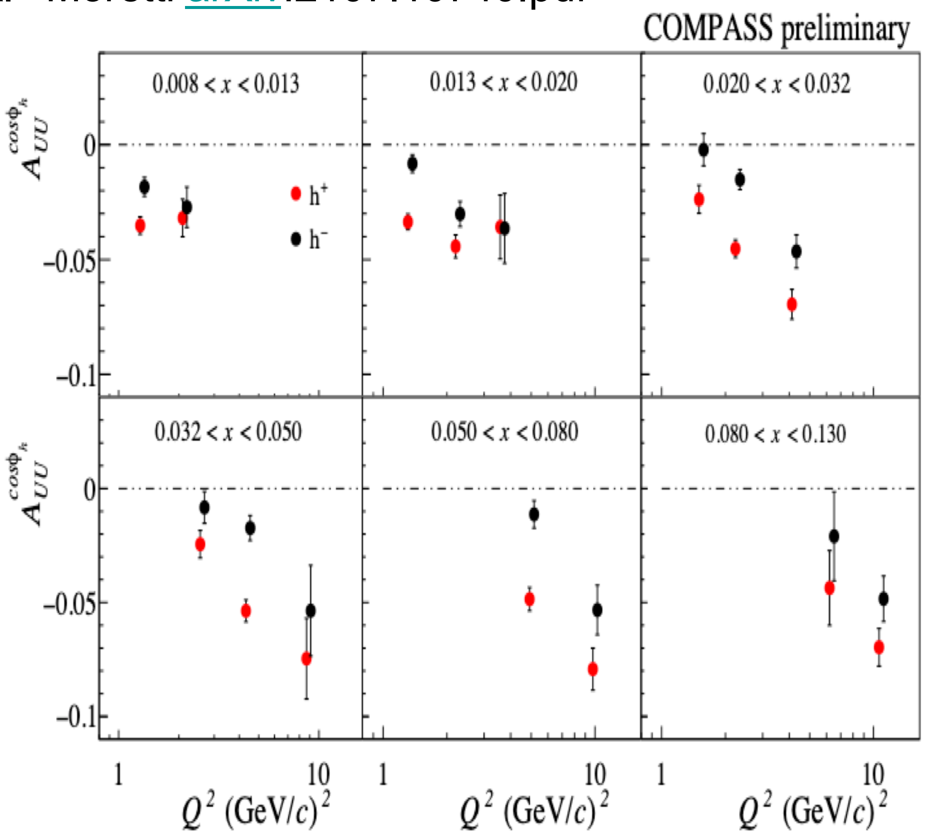
$$m^h(x,z,P_T^2,Q^2) = \frac{\pi F_{UU,T}(x,z,P_T^2,Q^2) + \pi\epsilon F_{UU,L}(x,z,P_T^2,Q^2)}{F_T(x,Q^2)+\epsilon F_L(x,Q^2)}$$

- SIDIS experiments measure the ϕ-dependent cross sections (multiplicities)
- Quark-gluon correlations are significant in electro production experiments (even at high energies).
- Large cosϕ modulations observed in electroproduction (EMC, COMPASS, HERMES) may be a key in understanding of the QCD dynamics.

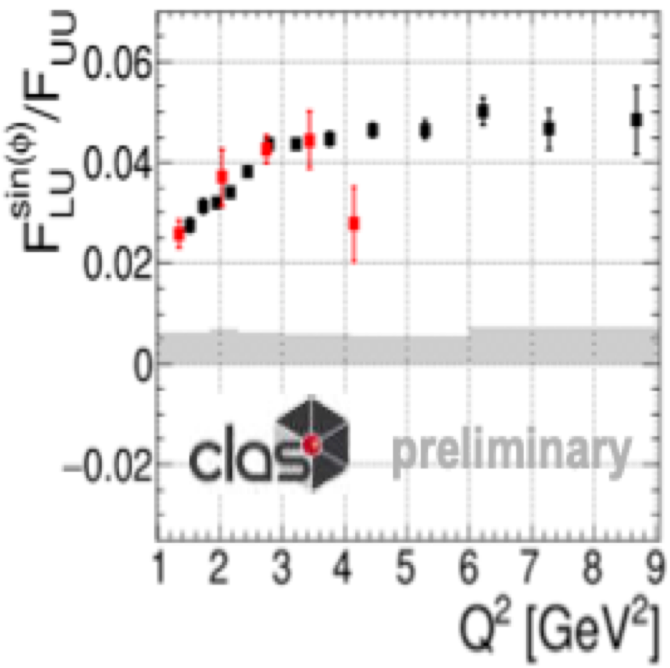
HT at COMPASS and CLAS12



A. Moretti arXiv:2107.10740.pdf



S. Diehl et al arXiv:2101.03544



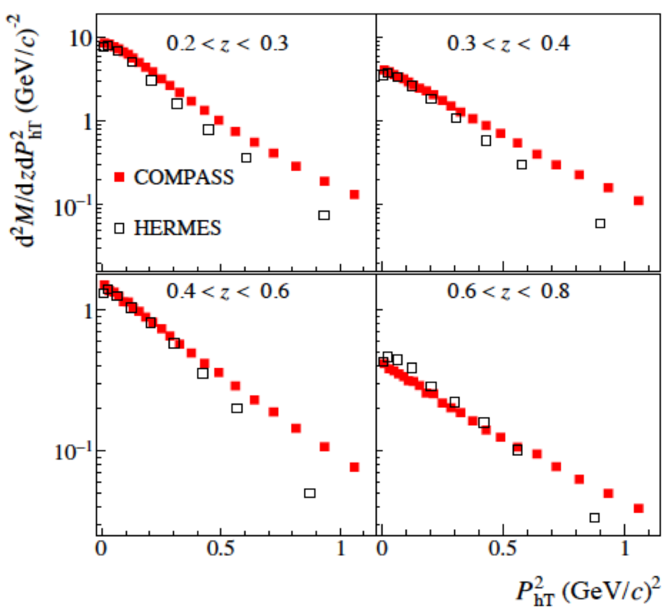
The ratios of SFs (to F_{UU}) are not really decreasing with Q!!!
The HT observables, don't look much like HT observables, something missing in understanding
Understanding of these behavior can be a key to understanding of other inconsistencies

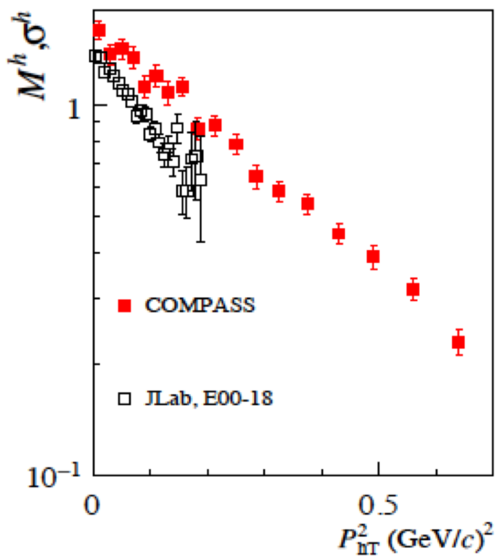
Multiplicities of hadrons in SIDIS

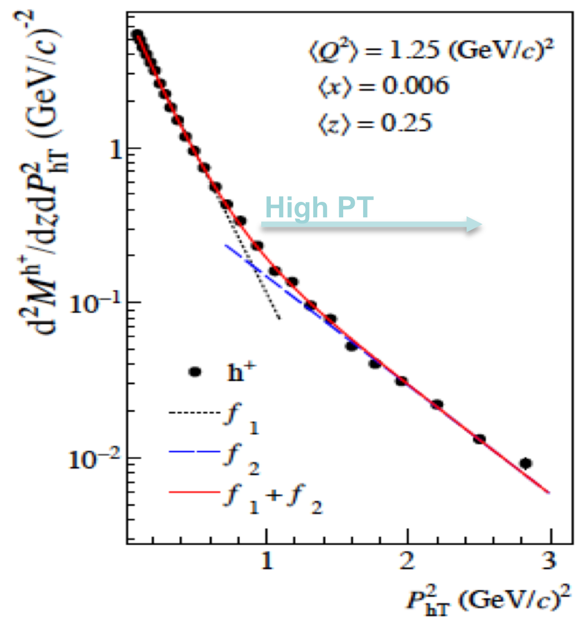
Gaussian Ansatz $\boxed{f_1^q} \otimes \boxed{D_1^{q\to h}} = x f_1^q(x)\, D_1^{q\to h}(z) \dfrac{e^{-P_{hT}^2/<P_{hT}^2>}}{\pi < P_{hT}^2 >}$

TMDs universal, so what is the origin of the differences observed ?

COMPASS:1709.07374



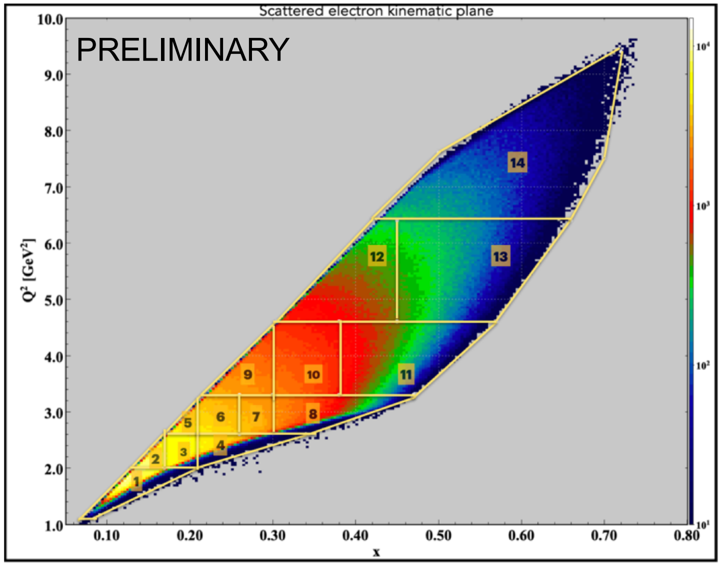


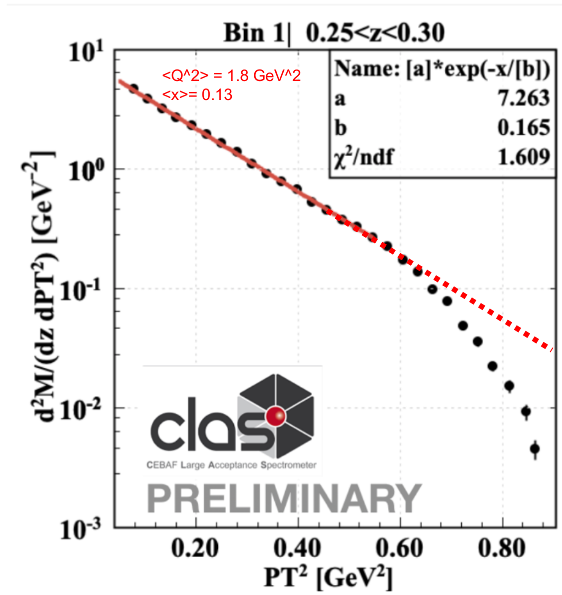


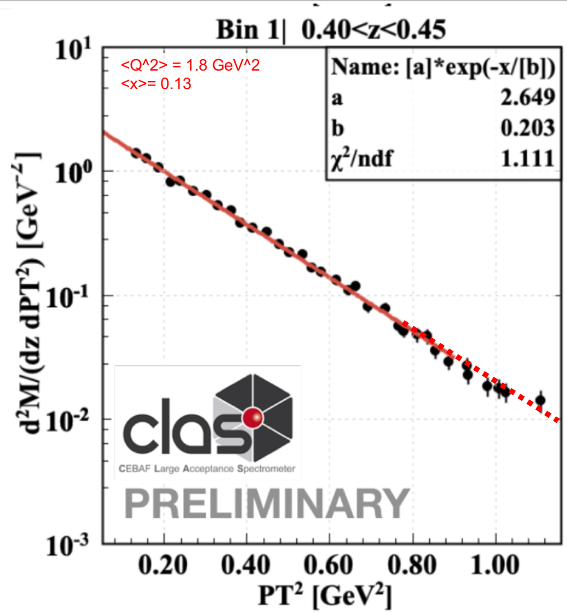
- TMDs evolution makes distribution wider
- Lower the beam energy, less phase space for high P_T

- What is the origin of the “high” PT tail?
  1) Perturbative contributions?
  2) Non perturbative contributions? (TMDs dependence not 1 Gaussian)

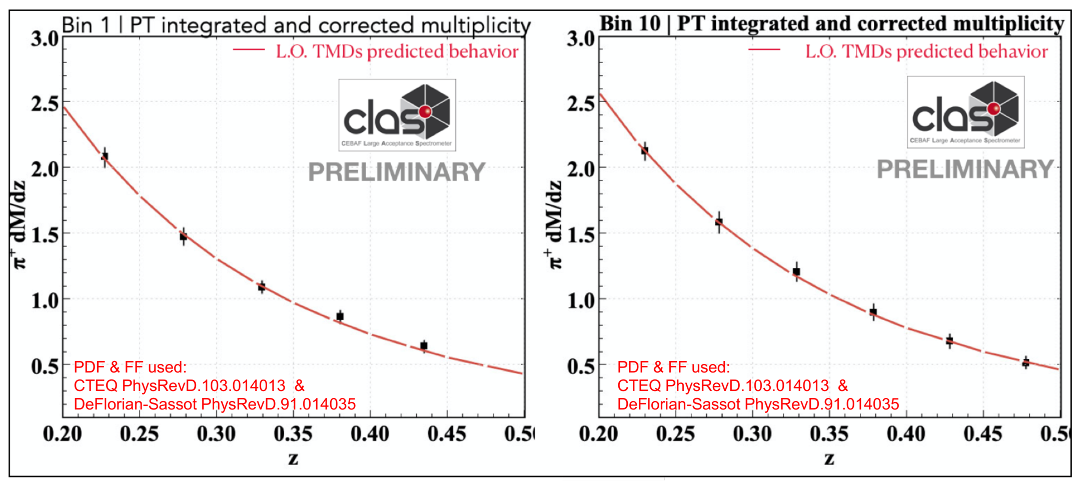
CLAS12 1h Multiplicities: high P_T & phase space





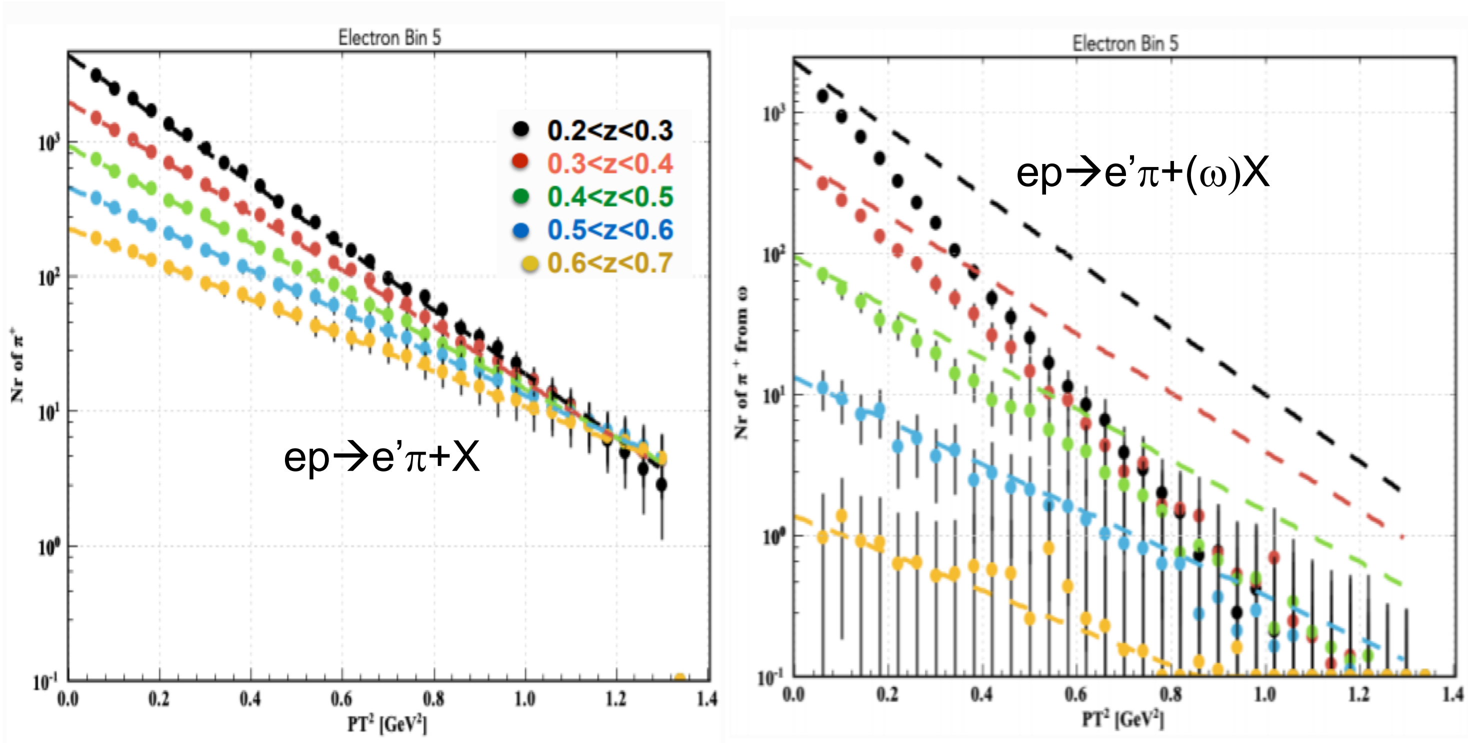


For some kinematic regions, at low z, the high P_T distribution appear suppressed: there is no enough energy in the system to produce hadron with high transverse momentum (phase space effect).
If the effect is accounted, the CLAS data follows global fits.



CLAS12 1h Multiplicities: high P_T & phase space

The same Gaussian Ansatz for transverse momentum used for pions and VMs to see the impact on P_T distribution.



- Phase space limitations for direct pion production more significant at lower W, and lower z
- Decayed pions have a much steeper P_T distribution at the same z
- JLab24 would allow to extend measurements to higher P_T, to support the novel understanding of hadronization process suggested by the CLAS12 measurements

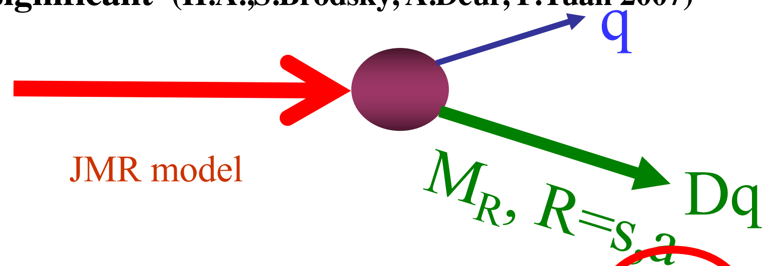
Unknown "known" f_1,g_1 TMDs

$$u^{+}(x,k_T) = f_1^u(x,k_T^2) + g_1^u(x,k_T^2)$$

$$u^{-}(x,k_T) = f_1^u(x,k_T^2) - g_1^u(x,k_T^2)$$

	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

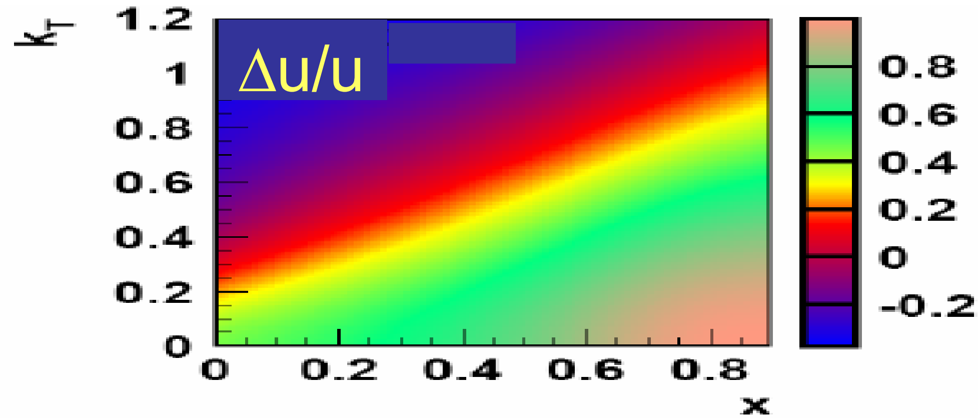
Effect of the orbital motion on the q- may be significant (H.A.,S.Brodsky, A.Deur, F.Yuan 2007)

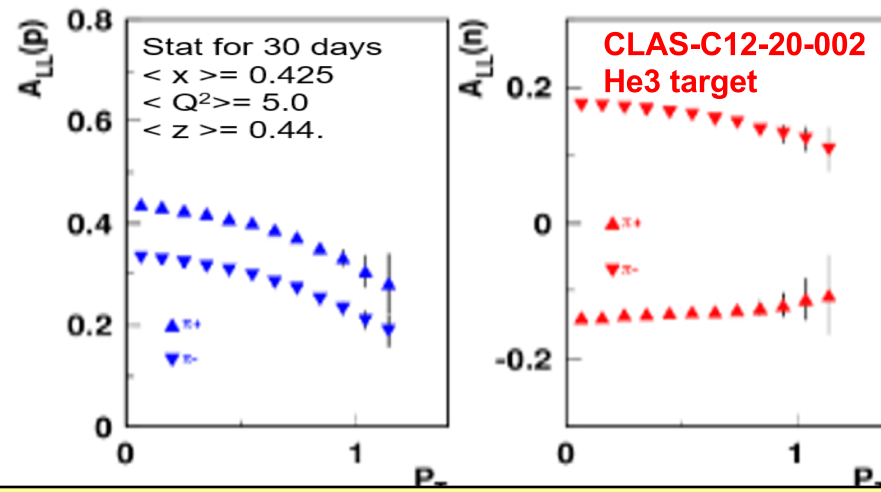


$$f_1(x,\mathbf{k}_T^2) = A\frac{(xM+m)^2 + \mathbf{k}_T^2}{(\mathbf{k}_T^2+\lambda_R^2)^{2\alpha}},$$

$$g_1(x,\mathbf{k}_T^2) = A\frac{(xM+m)^2 - \mathbf{k}_T^2}{(\mathbf{k}_T^2+\lambda_R^2)^{2\alpha}},$$

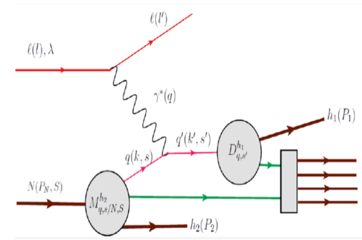
(dipole formfactor), J.Ellis, D-S.Hwang, A.Kotzinian



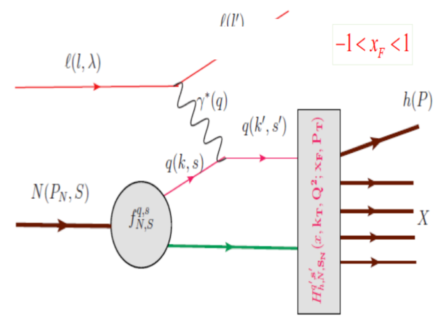


Models and lattice predict very significant spin and flavor dependence for TMDs
Large transverse momenta are crucial to access the large k_T of quarks
A dedicated to g1(x,k_T)-studies CLAS12 proposal with He3 target approved by PAC

MC simulations: Why LUND works?



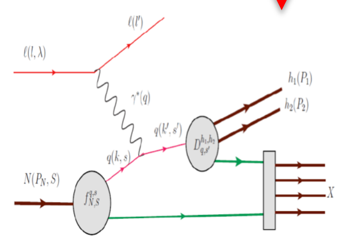
- A single-hadron MC with the SIDIS cross-section where widths of k_T-distributions of pions are extracted from the data is not reproducing well the data.
- LUND fragmentation based MCs were successfully used worldwide from JLab to LHC, showing good agreement with data.

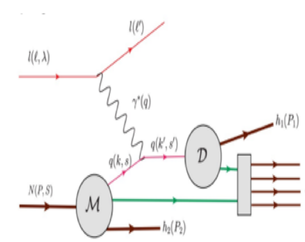


So why the LUND-MCs are so successful in description of hard scattering processes, and SIDIS in the first place?

- The hadronization into different hadrons, in particular Vector Mesons is accounted (full kinematics)
- Accessible phase space properly accounted
- The correlations between hadrons, as well a as target and current fragments accounted
- ….

subsamples

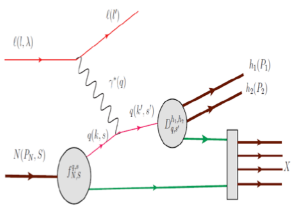




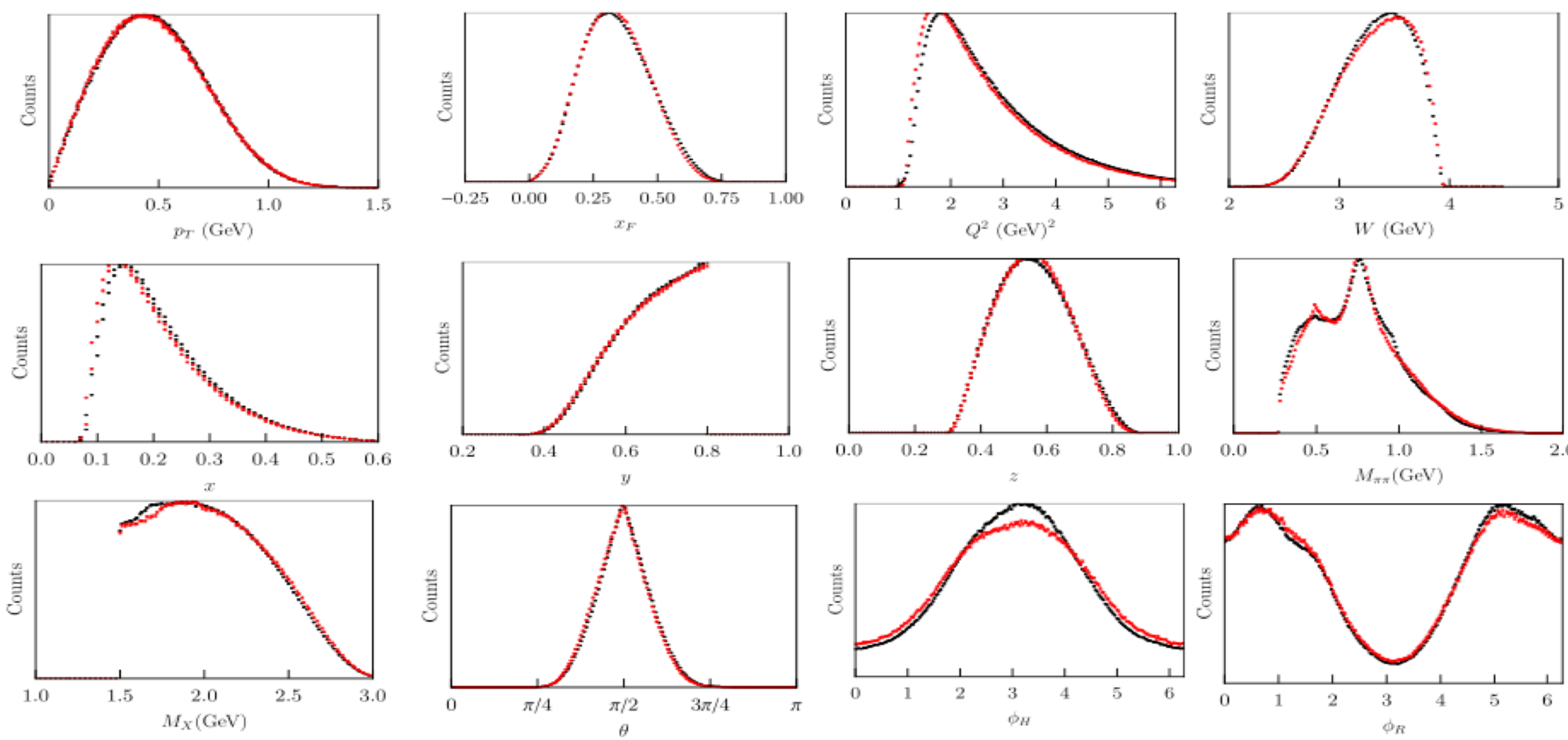
To understand the measurements we should be able to simulate, at least the basic features we are trying to study (P_T and Q^2,-dependences in particular)

The studies of correlated hadron pairs in SIDIS may be a key for proper interpretation !!!

SIDIS ehhX: CLAS12 data vs MC



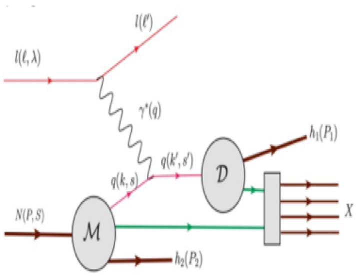
CLAS12 dihadron production ep→ehhX

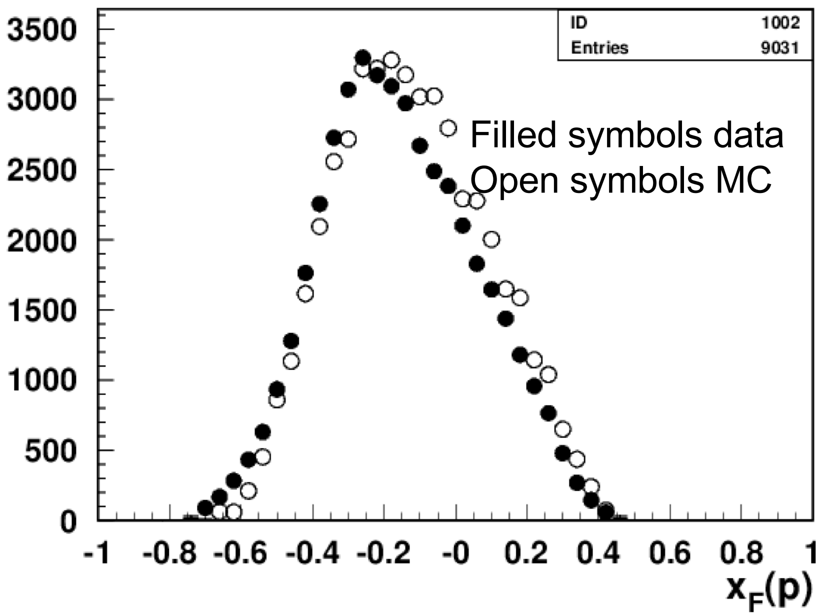


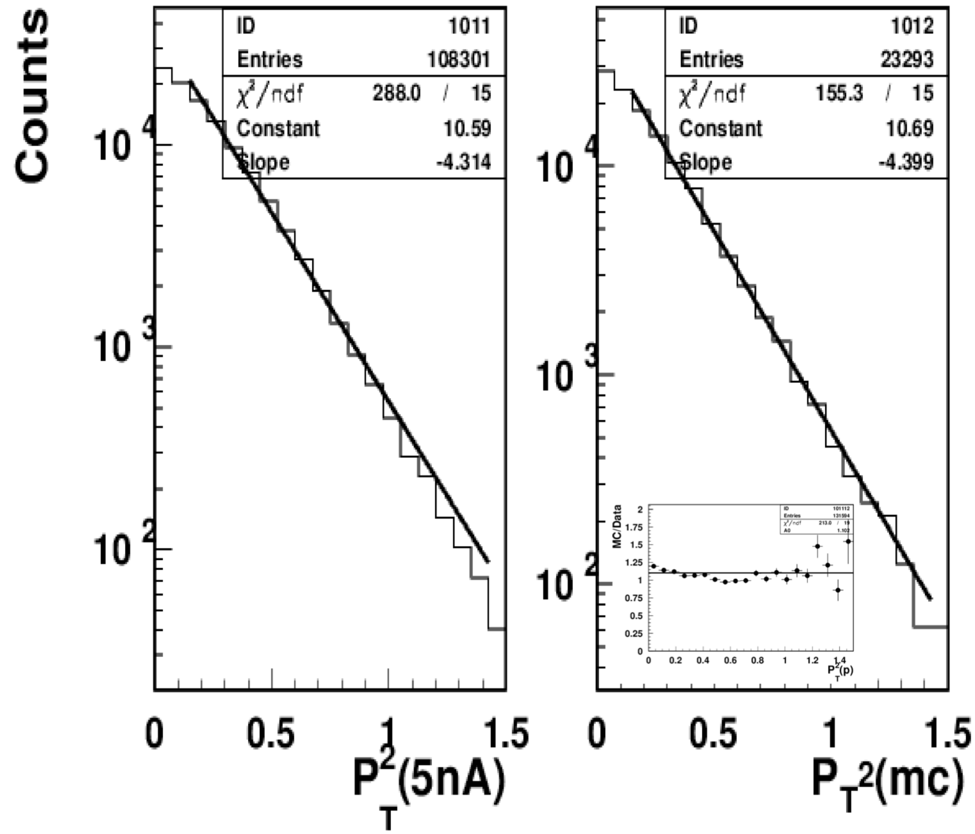
CLAS12 MC, based on the PEPSI(LEPTO) simulation with most parameters ”default” is in a good agreement with CLAS12 measurements for all relevant distributions

CLAS12 Studies: Data vs MC

Using PEPSI (LUND) generator





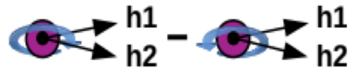


- Kinematic distributions, z, x_F, P_T-distributions of protons, and widths are in good agreement with LEPTO
- TFR may be a valuable source for studies of widths in hadronization
- Expect significantly better separation of TFR and CFR at JLab24

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

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

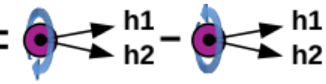
$d\sigma_{LU} \propto e(x) H_1^{\sphericalangle}(z, M_h)$ $\quad H_1^{\sphericalangle} =$



Bacchetta&Radici: arXiv:hep-ph/0311173

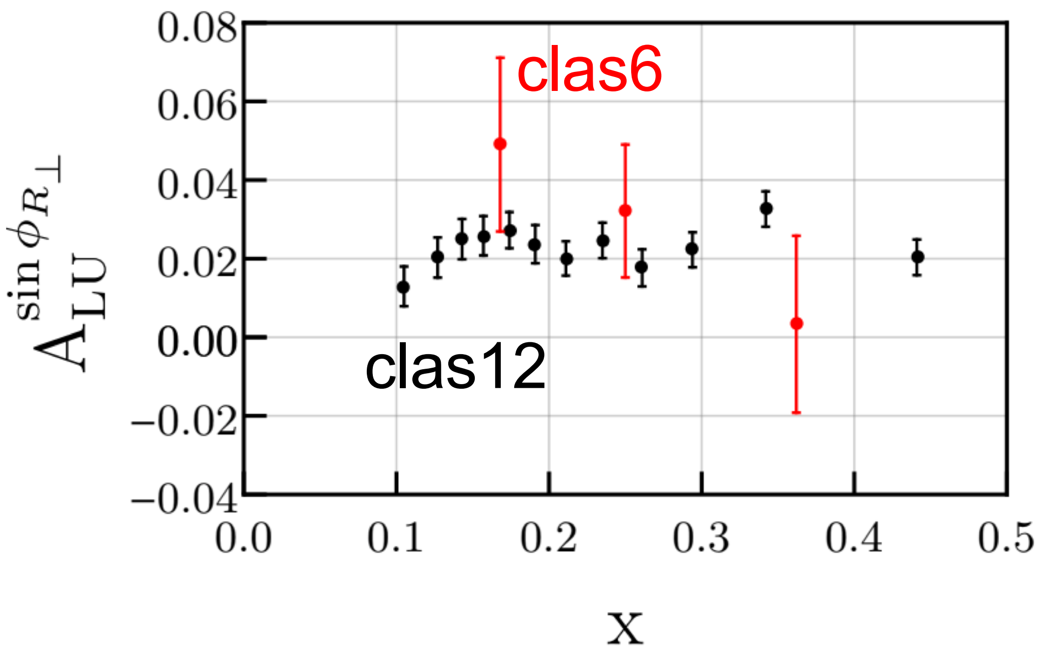
$d\sigma_{LU} \propto \lambda_e \sin(\phi_h - \phi_{R_\perp}) \mathcal{I}\left[f_1 G_1^\perp\right] + \ldots$

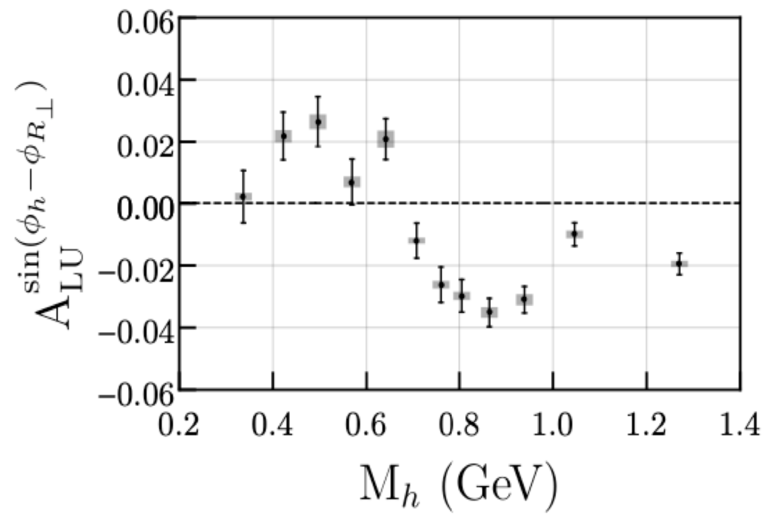
$G_1^\perp =$



a TMD FF

Matevosyan et al, arXiv:1707.04999



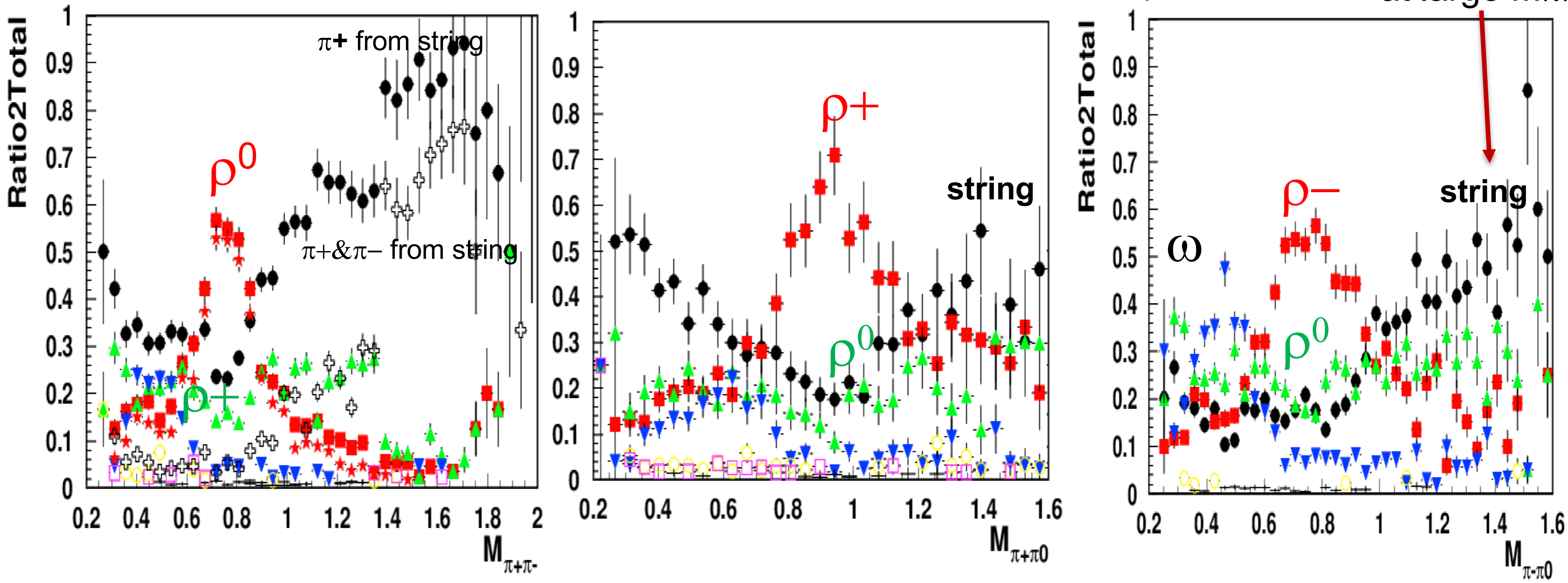


- Doubling the JLab beam energy, opens the phase space for SIDIS dihadrons
- Quark gluon correlations may be very significant
- PDF e describes the force on the transversely polarized quark after scattering
- Extended range in Q^2 for JLab24 will be crucial in interpretation of higher twist effects

Sources of inclusive pions: CLAS12 MC

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

High P_T pions at large $M\pi\pi$



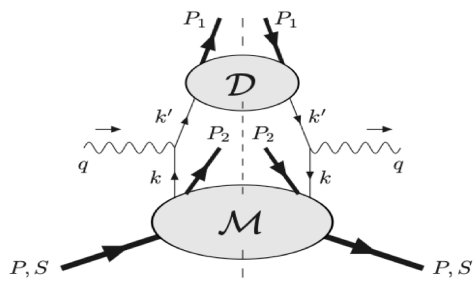
Dominant fraction of 2 pion combinations come from VM decays

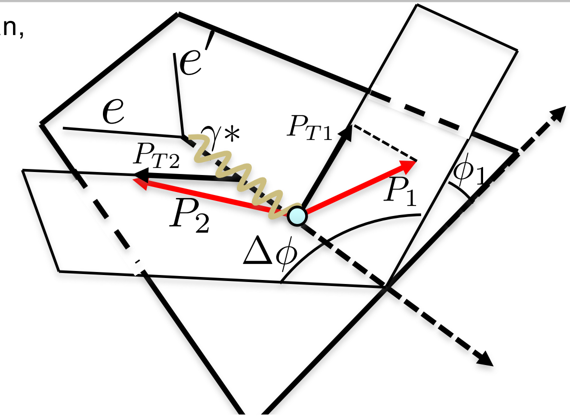
ρ
string
ω

All measured 2 pion combinations are dominated by VM decays, indicate that all inclusive pions are dominated by VM decays at small P_Ts, and in particular at lower z!!!

Correlations in 2 hadron production

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

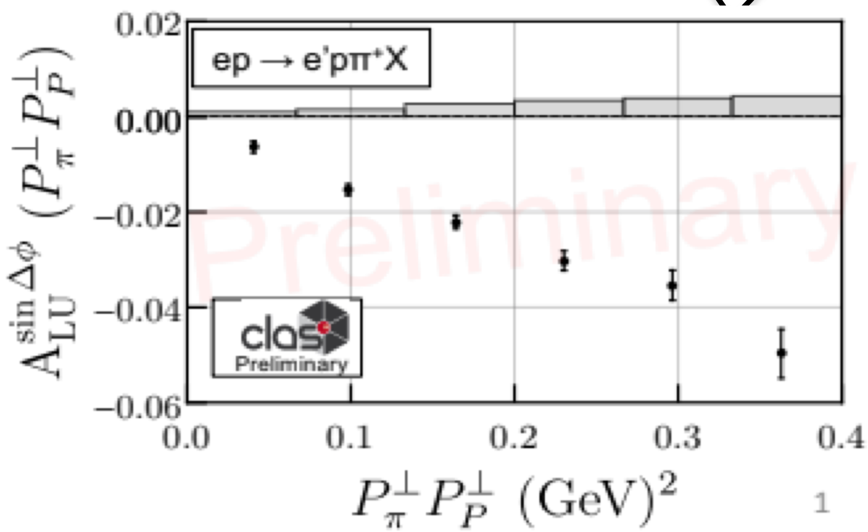


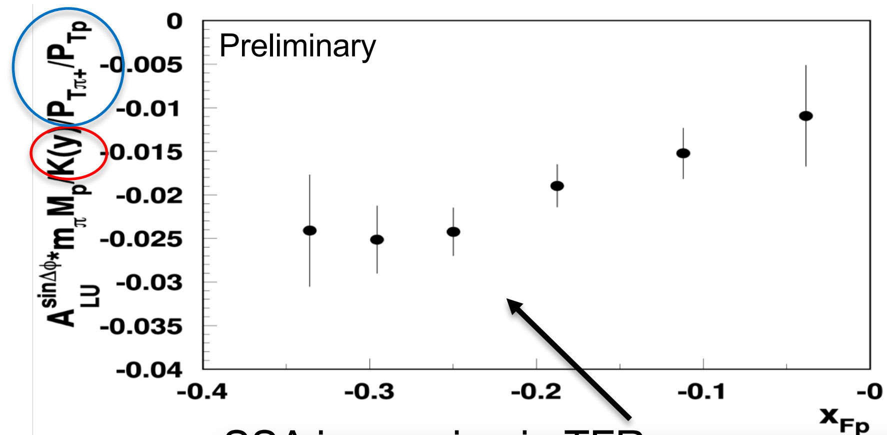


$$\mathcal{A}_{LU} = -\frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)} \frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}} \sin\Delta\phi$$

$$= -\frac{|\mathbf{P}_{1\perp}||\mathbf{P}_{2\perp}|}{m_N m_2} \frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)}$$

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

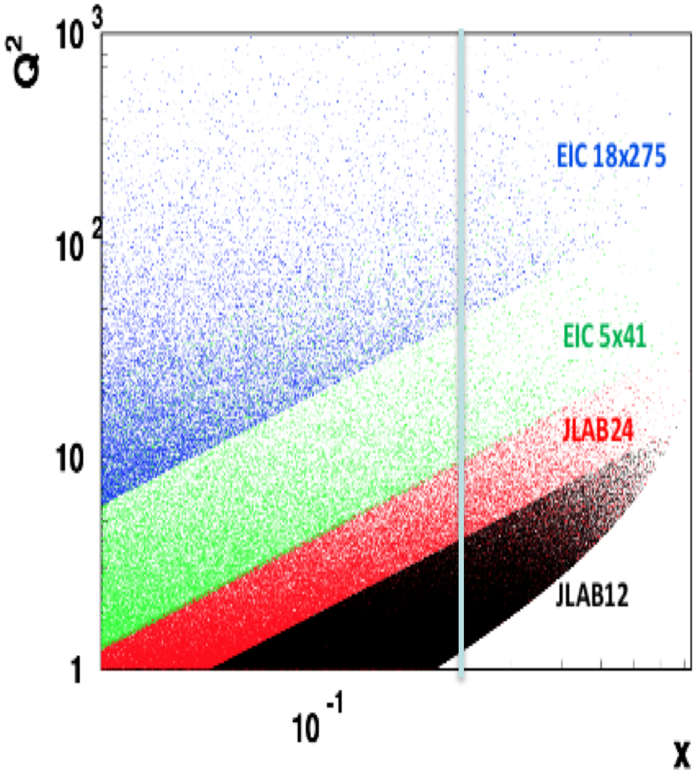


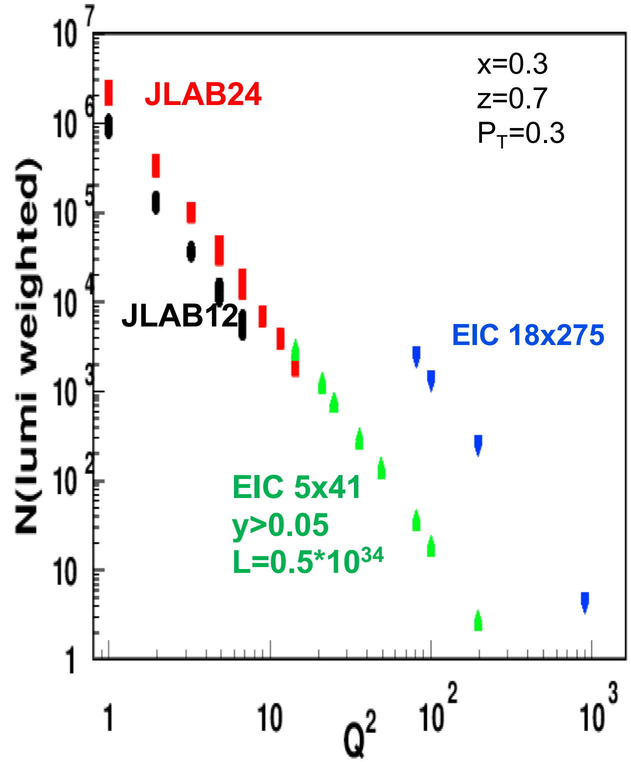


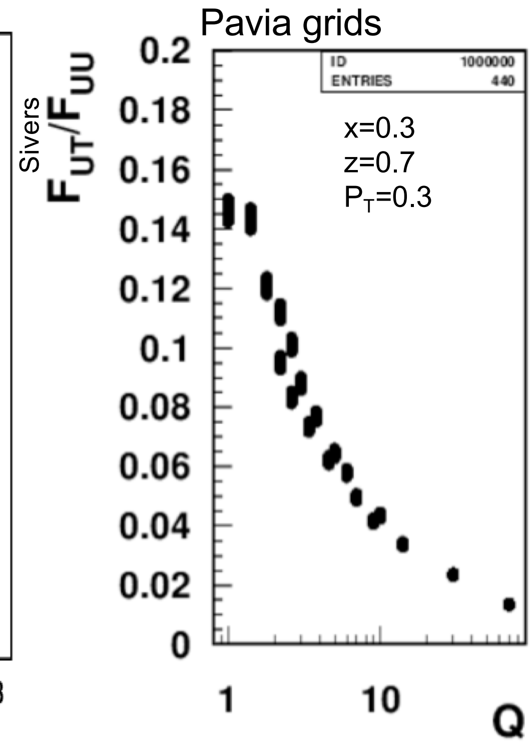
SSA increasing in TFR

- Spin-azimuthal correlations in hadron pair production in CFR and TFR are very significant
- Phase space accessible at JLab24 would allow the coverage in high PTs
- Phase space accessible at JLab24 would allow the coverage in wider rapidity gaps

From JLab to EIC: complementarity





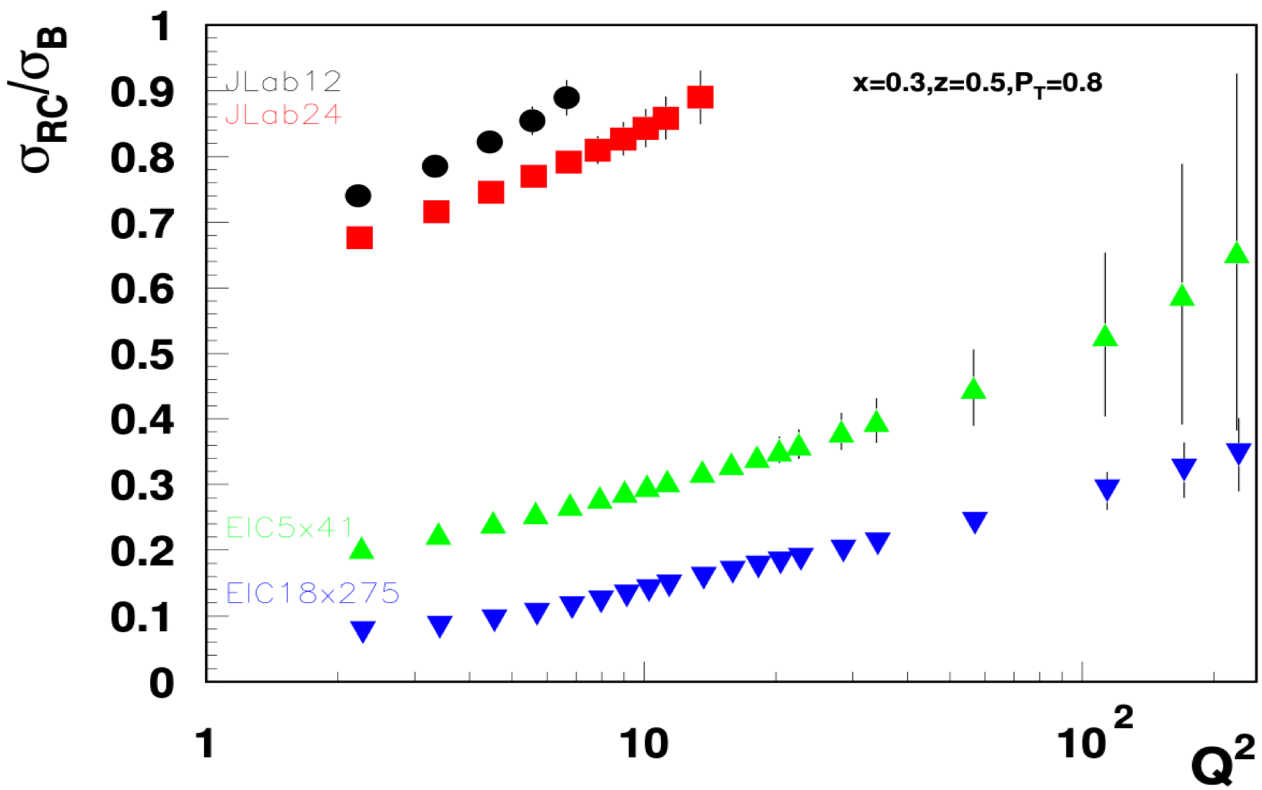


- The counts in a given bin, and the size of the effect will define the expected sensitivity.
- Proper evaluation of systematics, will require definition of fiducial kinematics, and the impact of the multidimensionality
- JLab at 24 GeV will provide critical input in evolution studies of TMDs
- Higher Q^2-coverage of “Low s” EIC running will provide validation of evolution studies at JLab at large x (will require high luminosity)

From JLab to EIC: complementarity

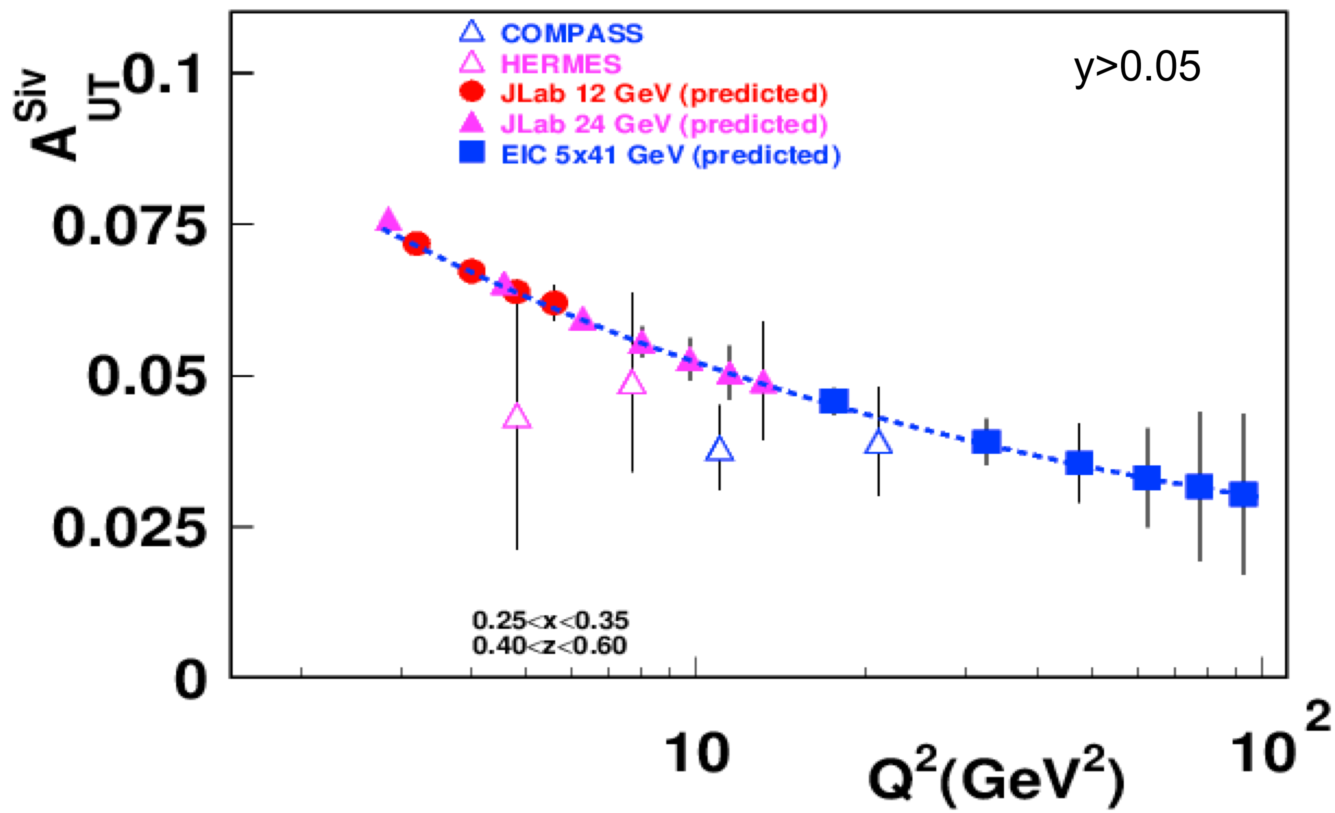
The ratio of radiative cross (σ_{RC}) section to Born (σ_B) in SIDIS

T. Liu et al
JHEP 11 (2021) 157
Gaussian F_{UU} (ϕ_h=0)



- The radiative effects in SIDIS may be very significant and measurements in multidimensional space at different facilities will be crucial for understanding the systematics in evolution studies.

Contributions for 3D structure studies: Sivers

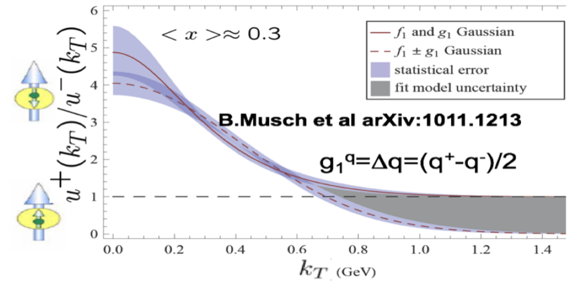


JLab24 will be crucial to bridge the TMD studies between JLab12 and EIC in the valence region

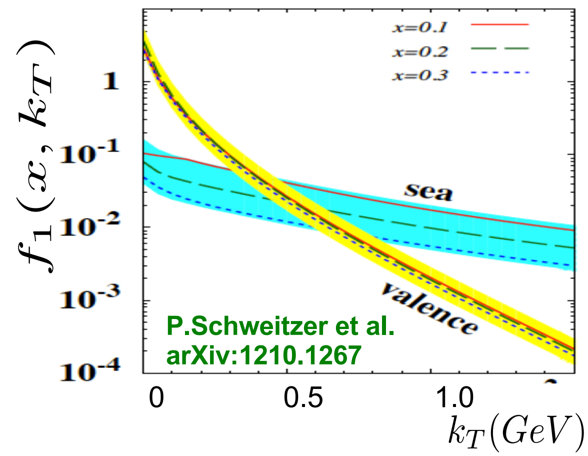
Extending to small x, large Q^2 and large P_T

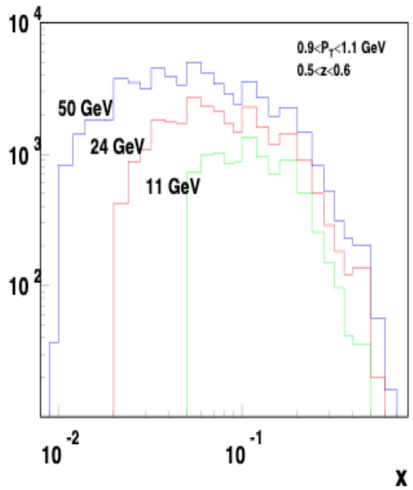
Non-perturbative sea ("tornado"/$^3P_0$) in nucleon is a key to understand the nucleon structure

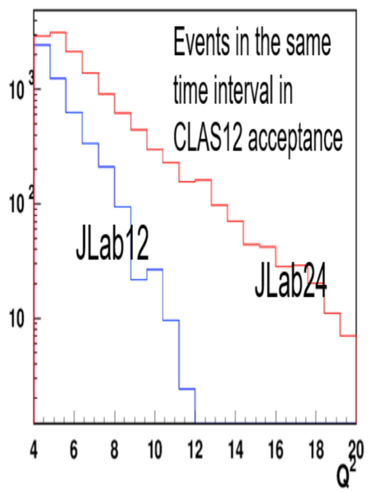
$$\bar{d} > \bar{u}$$

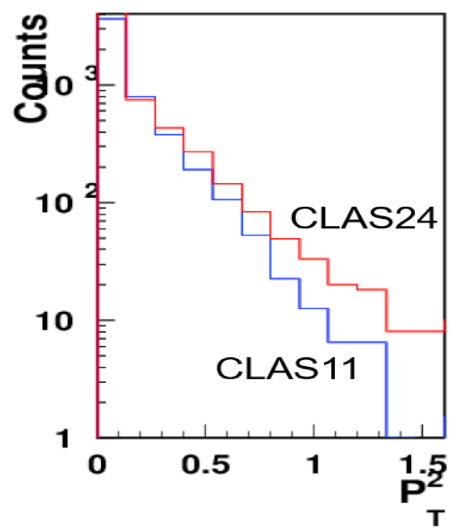


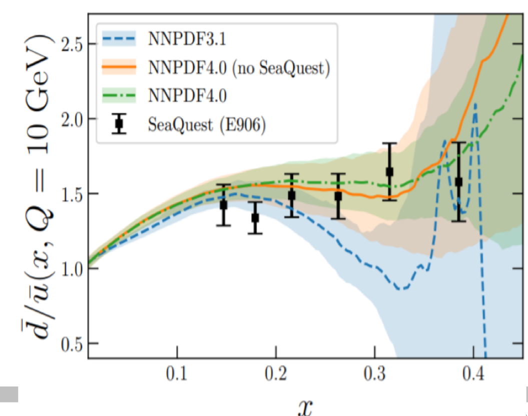
- Spin-Orbit correlations so far were shown (measurements and model calculations) to be significant in the region where non-perturbative effects dominate (x>0.02)
- Large transverse momenta of hadrons most relevant for understanding the non-perturbative QCD dynamics







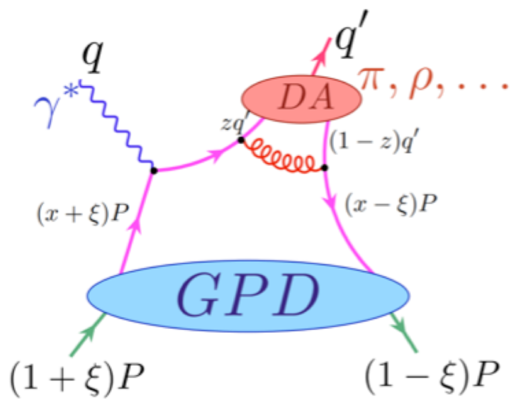




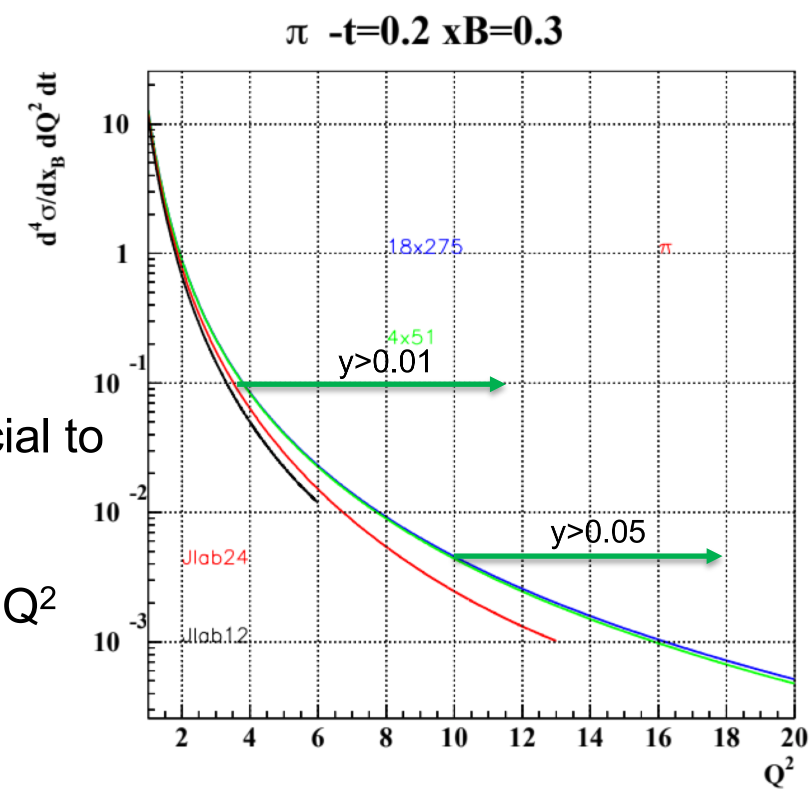
Upgrade to 24 GeV will qualitatively increase the JLab phase space, opening access to large P_T, high Q^2 and low x (sea) region

Deeply Virtual Meson Production

V. Kubarovsky, A.Kim



$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)|\langle H_T\rangle|^2 - \frac{t'}{8m^2}|\langle \bar{E}_T\rangle|^2\right]$$

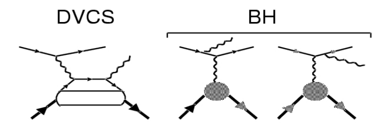


Large Q^2 accessible at JLab24 will be crucial to sort out different contributions to DVMP x-section

Lower energy EIC could extent further the Q^2 range

S. Niccolai

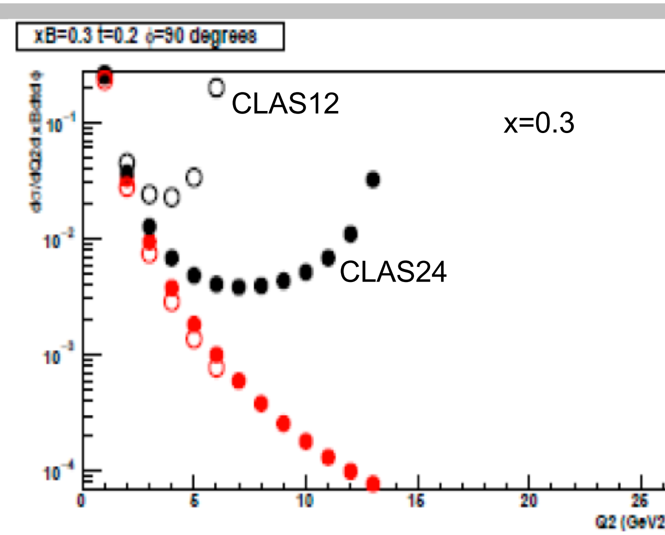
DVCS and BH



$$|\mathcal{T}_{\rm BH}|^2 = \frac{e^6}{\boxed{x_{\rm B}^2 y^2 (1+\epsilon^2)^2}\boxed{\Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}}\left\{c_0^{\rm BH} + \sum_{n=1}^{2} c_n^{\rm BH}\cos(n\phi) + s_1^{\rm BH}\sin(\phi)\right\}$$

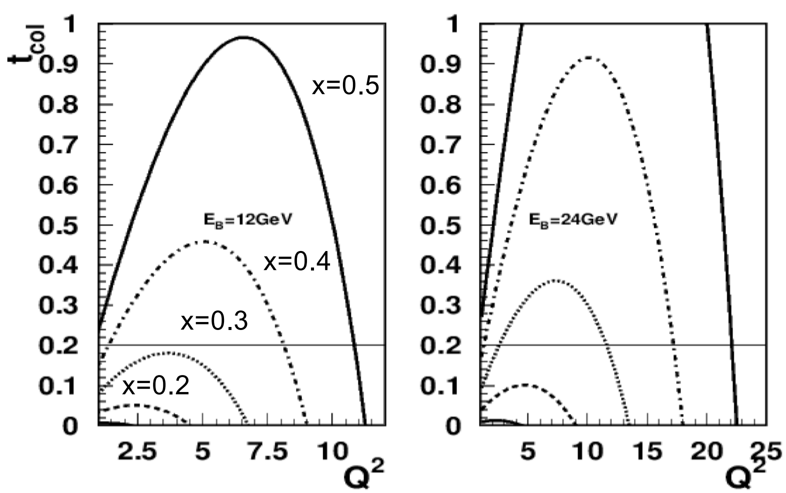
$$\mathcal{I} = \frac{\pm e^6}{\boxed{x_{\rm B} y^3}\boxed{\Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}}\left\{c_0^{\mathcal{I}} + \sum_{n=1}^{3}\left[c_n^{\mathcal{I}}\cos(n\phi) + s_n^{\mathcal{I}}\sin(n\phi)\right]\right\}$$

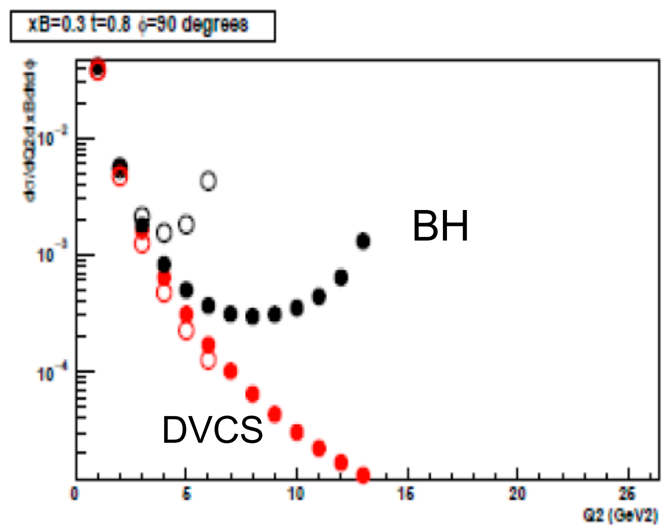
$$|\mathcal{T}_{\rm DVCS}|^2 = \frac{e^6}{y^2 Q^2}\left\{c_0^{\rm DVCS} + \sum_{n=1}^{2}\left[c_n^{\rm DVCS}\cos(n\phi) + s_n^{\rm DVCS}\sin(n\phi)\right]\right\}$$



$$y_{col} = \frac{Q^2 - t}{Q^2 - xt}$$

$$t_{col} = \frac{Q^2(Q^2 - 2xME)}{(Q^2 - 2ME)x}$$





- Higher twist contributions are relevant in GPD studies
- Large Q^2 accessible at JLab24 will be crucial to sort out different contributions from BH and DVCS

Summary

Upgrade to 24 GeV will qualitatively increase the JLab phase space, opening access to high Q^2 and low x (sea) region, as well as large P_T, t,…

Much wider range in Q^2 and P_T will be crucial in separation of higher twist contributions, critical for understanding the QCD dynamics

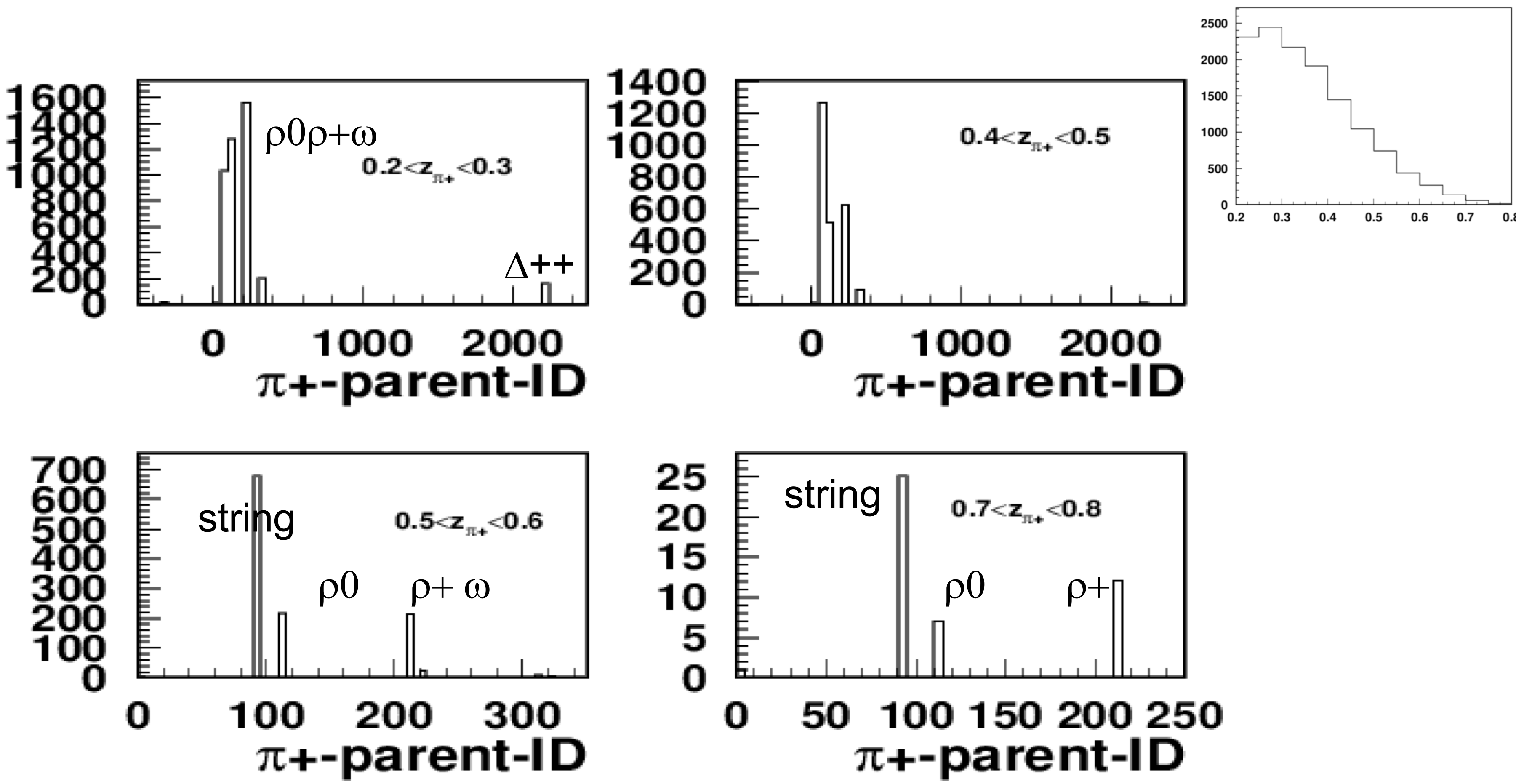
Measurements of dihadron multiplicities and asymmetries at large transverse momenta provide qualitatively new possibilities for understanding the structure of the nucleon, and the process of hadronization, including understanding of correlations leading to spin-azimuthal asymmetries in SIDIS

Extraction of multiplicities and spin-azimuthal asymmetries in multidimensional space is critical for interpretation of results and understanding of the systematics of extractions of 3D PDFs from SIDIS/DVMP

Defining the *complementarity* of measurements at JLab12/24,COMPASS and EIC will require development of extraction procedures with controlled systematics

support

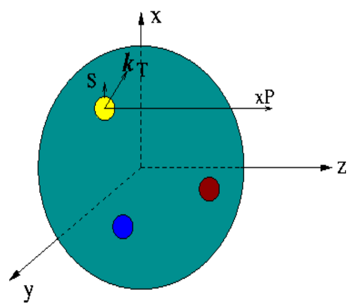
π+ parents in ep→e'pπ^+X events

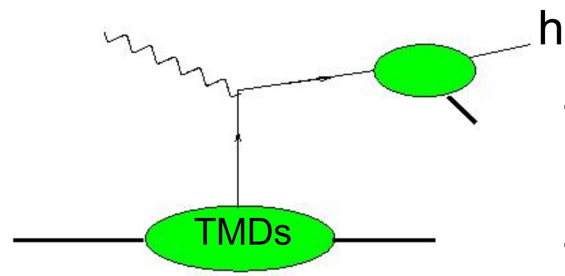


Tiny fraction of pions come from Δ++ at z~0.2, and at large z mainly from string and ρ

3D structure of the nucleon

Semi-Inclusive processes and transverse momentum distributions

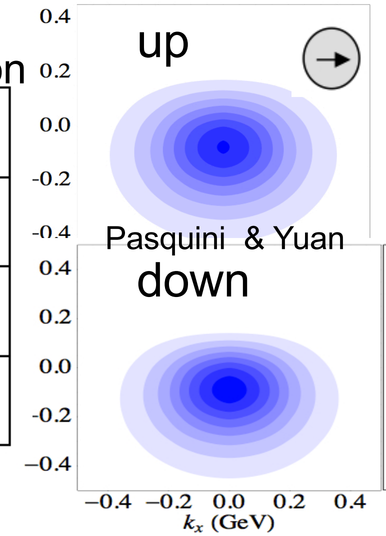




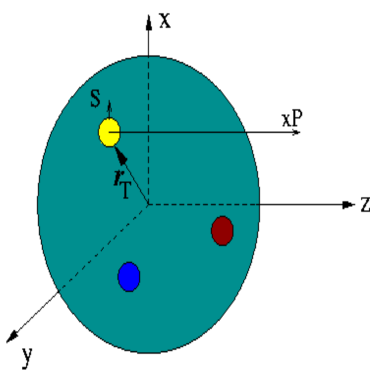
quark polarization

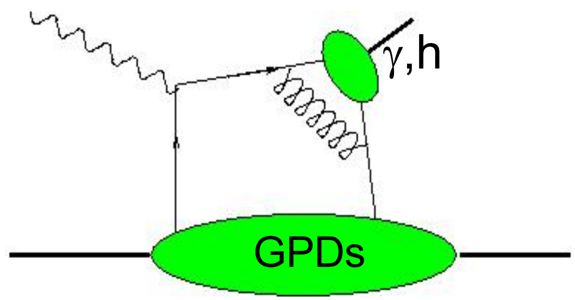
N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

nucleon pol.

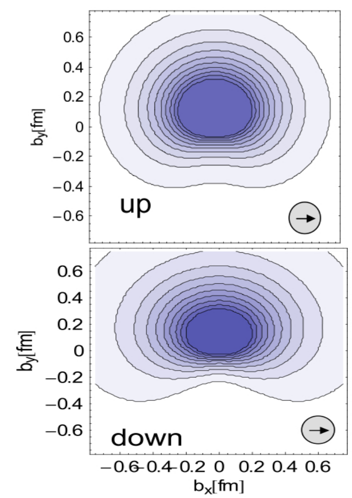


Hard exclusive processes and spatial distributions of partons





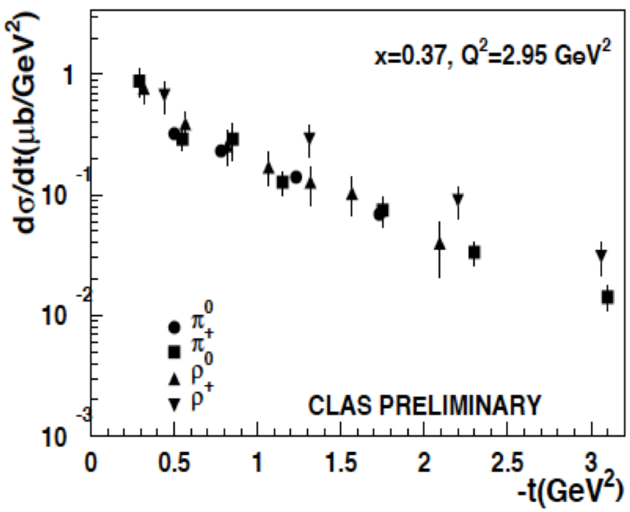
N/q	U	L	T
U	H		$\mathcal{E}_T$
L		$\widetilde{H}$	
T	E		$H_T, \widetilde{H}_T$

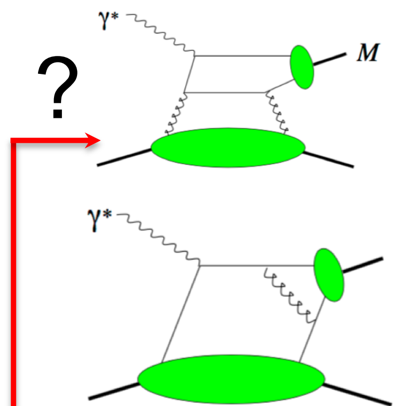


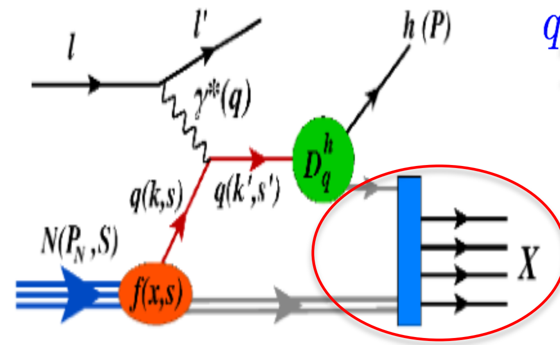
(QCDSF)

The quark-gluon dynamics manifests itself in a set of non-perturbative functions describing all possible spin-spin and spin-orbit correlations

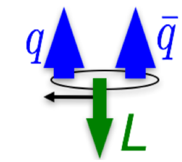
Exclusive π/ρ production at large x/t

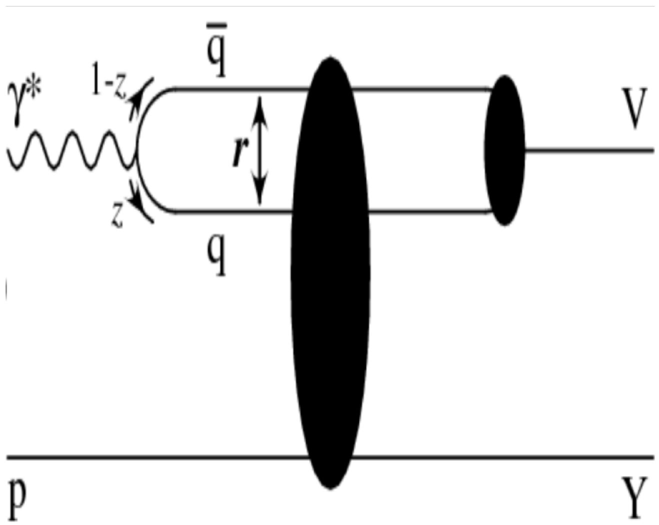






p,n





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
- Slightly higher rho x-sections indicate the fraction of SIDIS pions from VM > 60%
- consistent with LUND-MC in fraction of pions from VMs
- Integrating in total counts (different Q^2-dependence)?
- ………