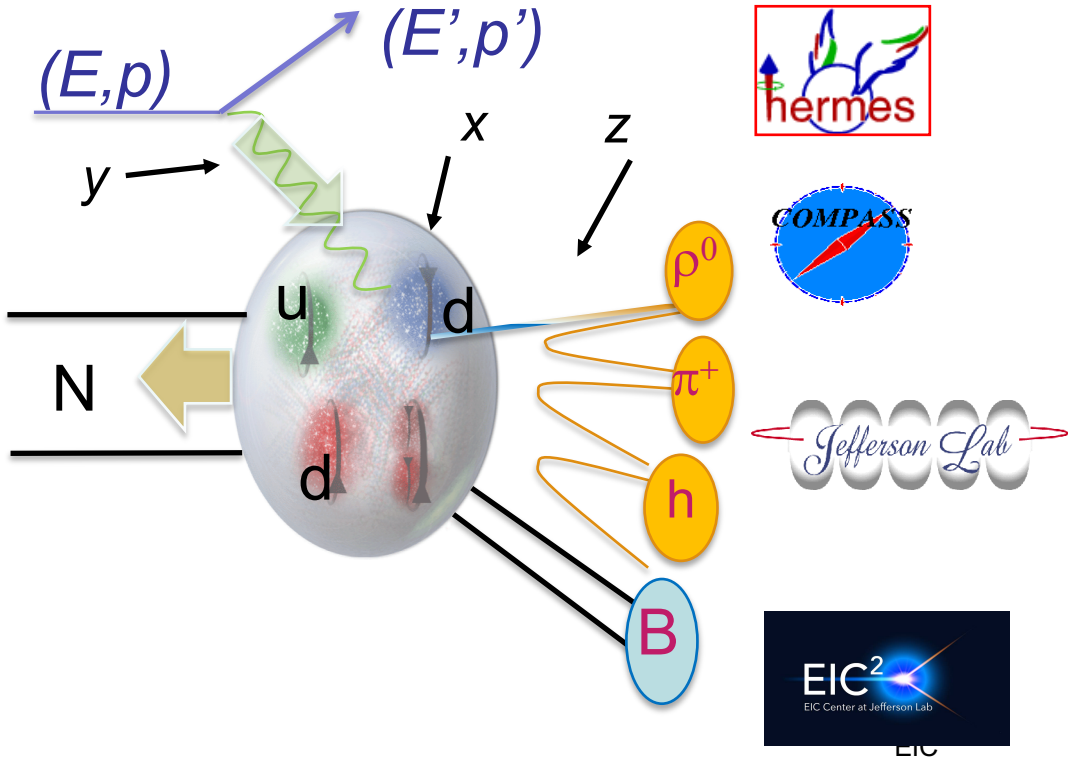
TMD Studies in SIDIS

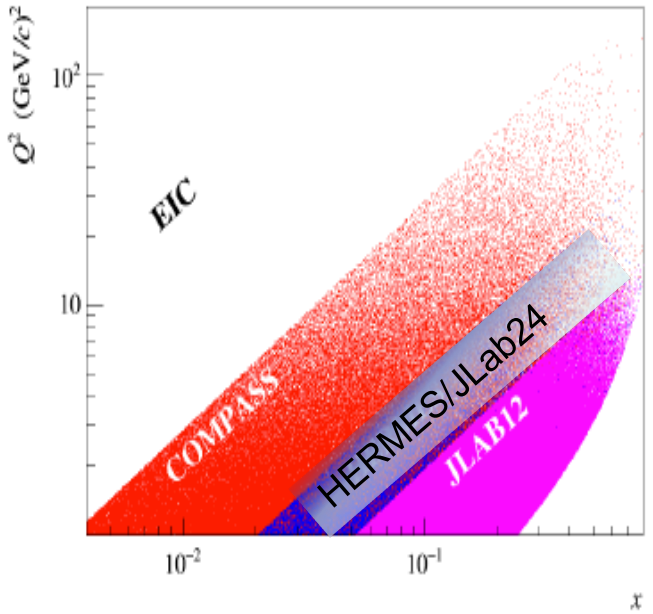
Harut Avakian (JLab)

Strong QCD from Hadron Structure Experiments
June 7-10, 2021

- Introduction
- Recent results from CLAS12 in SIDIS
- Limitations in theory description
- The role of vector mesons in SIDIS
- The role of high P_T
- Summary

SIDIS kinematical coverage and observables





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

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

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

beam polarization

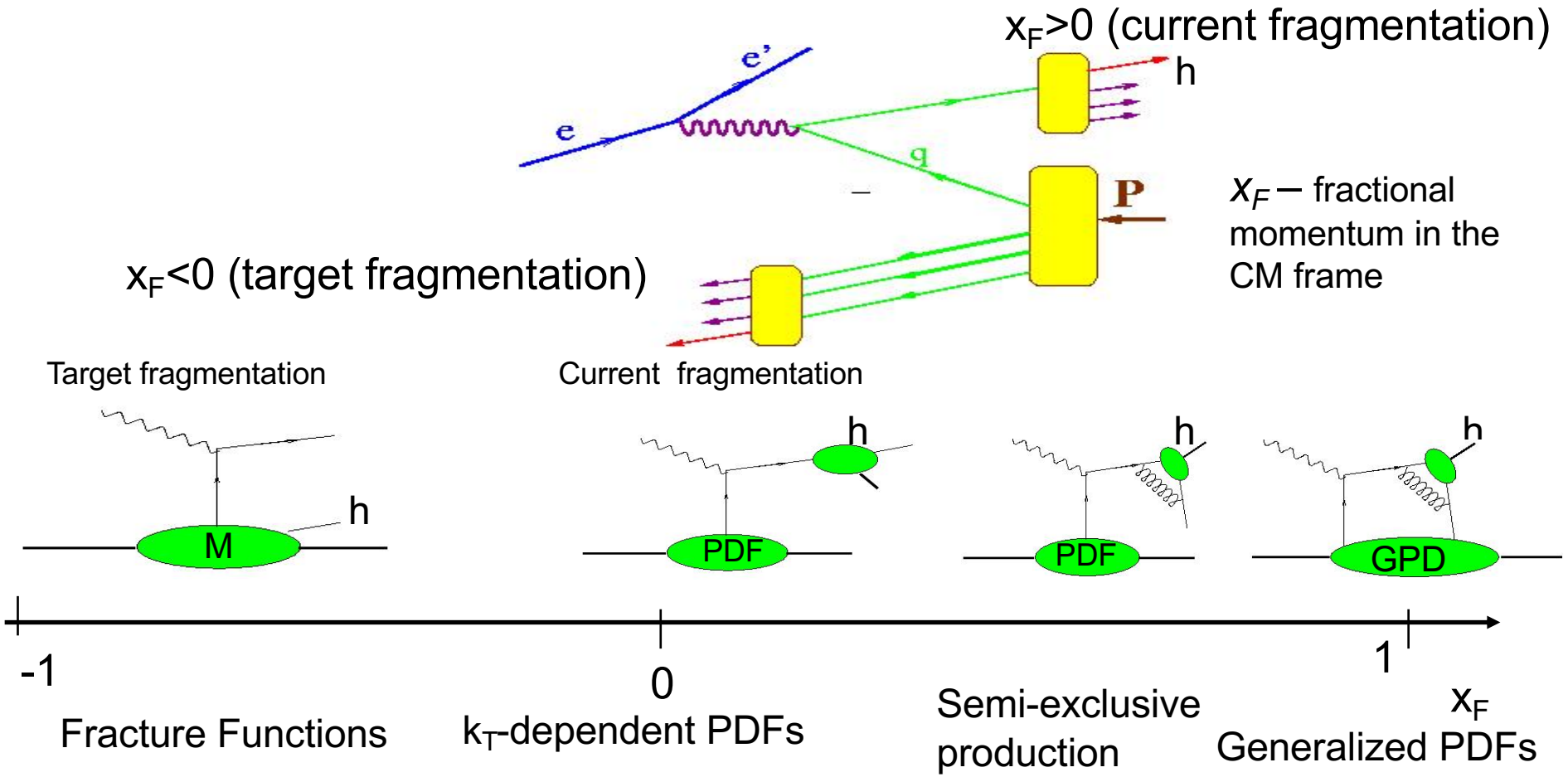
target polarization

corrections for the region of large kT~Q

$q_T = P_T/z$

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Single pion production in hard scattering

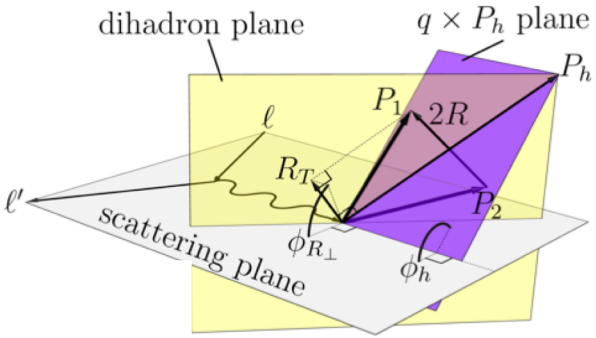


Wide kinematic coverage of large acceptance detectors allows studies of hadronization both in the target and current fragmentation regions

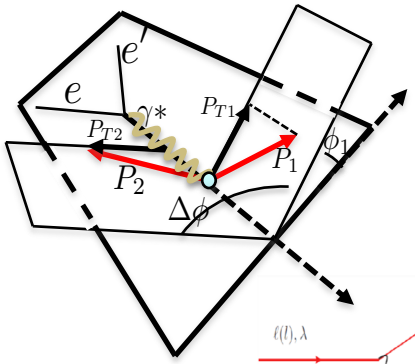
Correlated hadron production in hard scattering

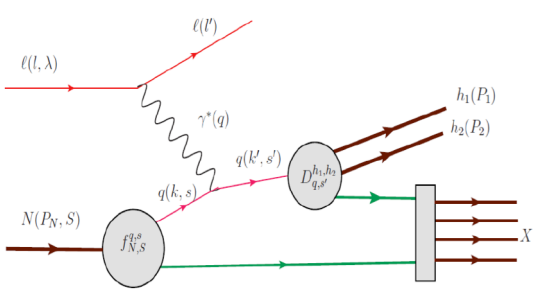
Dedicated CLAS12 proposals: E12-06-112B/E12-09-008B

2 hadrons in current fragmentation

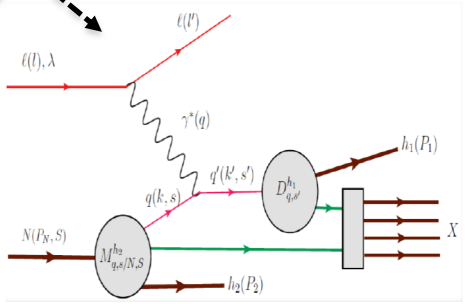


hadrons in current & target fragmentation





$$P_h = P_1 + P_2,$$
$$R = \frac{1}{2}(P_1 - P_2).$$



With ϕ_S, ϕ_1, ϕ_2, ϕ_R, ϕ_h several observables have been identified to study correlations

$\phi_R - \phi_S$, ϕ_R -accessing transversity and quark-gluon correlations *Radici & Bacchetta*

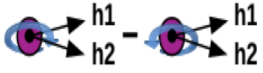
$\phi_R - \phi_h$ -accessing leading twist polarized fragmentation functions *Matevosyan,Kotzinian,Thomas*

$\phi_1 - \phi_2$ -accessing correlations in current and target regions *Anselmino, Barone, Kotzinian*

2h production in SIDIS provides access to correlations inaccessible in simple SIDIS

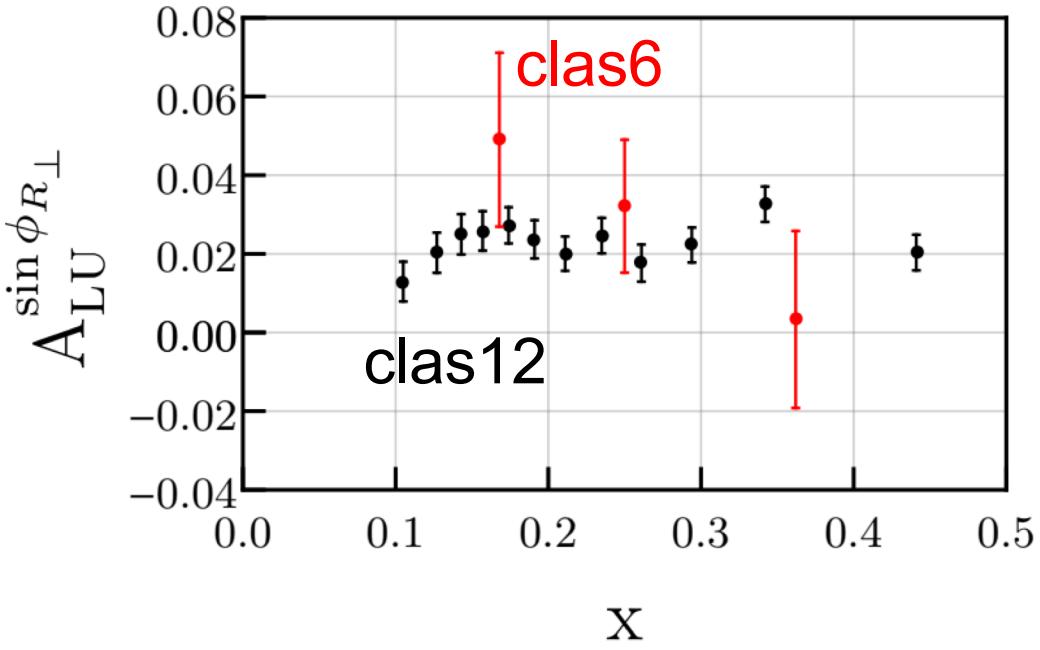
Observation of SSAs in ep→e'$\pi^+\pi^-$X

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

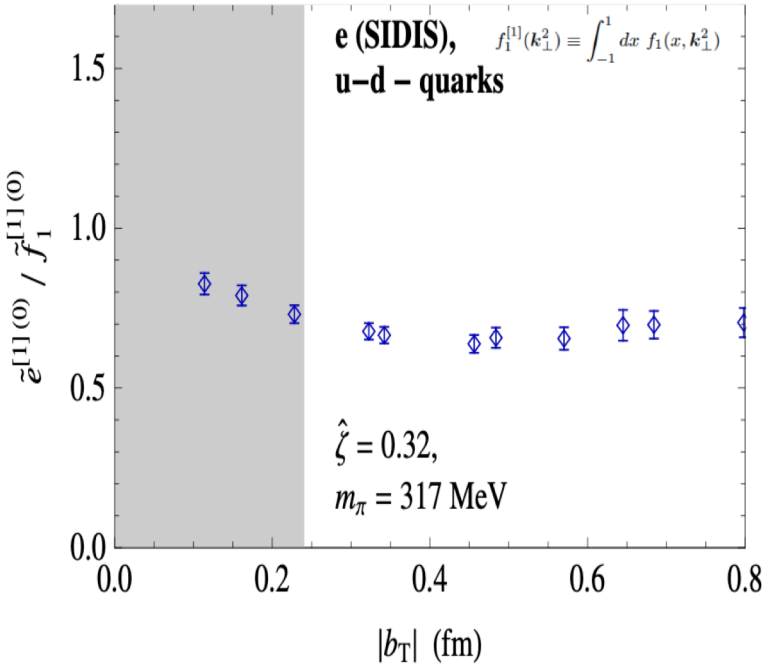
$H_1^{\sphericalangle}$ = 

$$d\sigma_{LU} \propto \lambda_e \sin(\phi_{R\perp}) \left(xe(x) H_1^{\sphericalangle}(z, M_h) + \frac{1}{z} f_1(x) \tilde{G}^{\sphericalangle}(z, M_h) \right)$$

Bacchetta&Radici: arXiv:hep-ph/0311173



Engelhardt: TMDs from JLab to EIC



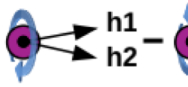
Doubling the JLab beam energy, opens the phase space for SIDIS dihadrons

Quark gluon correlations may be very significant

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

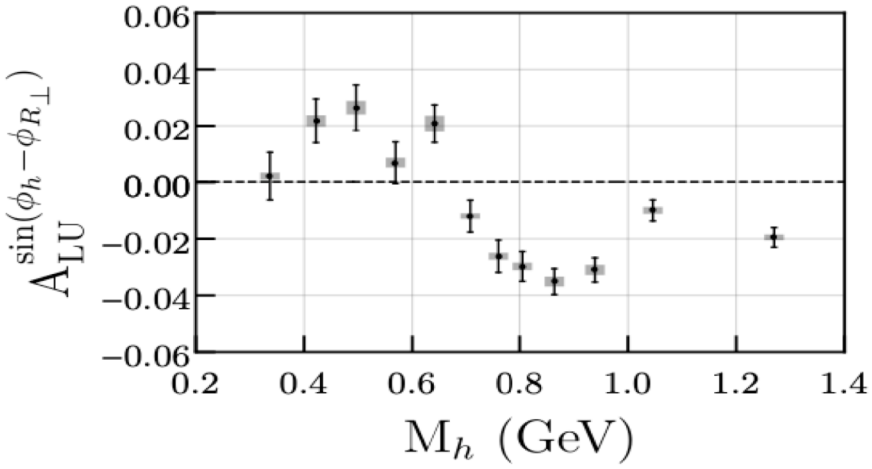
T. Hayward et al. Phys. Rev. Lett. 126, 152501 (2021)

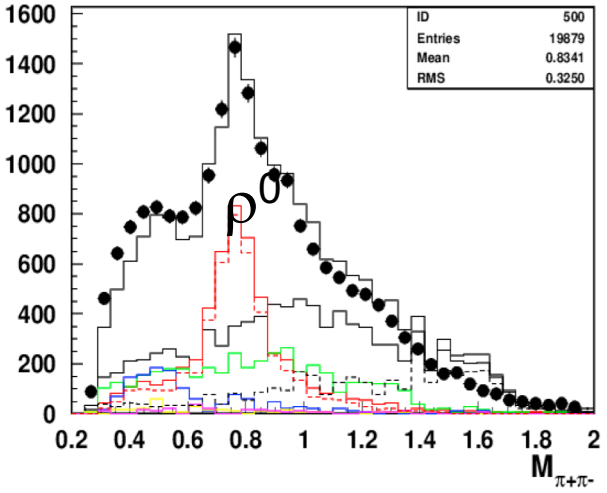
$$d\sigma_{LU} \propto C\lambda_e \sin(\phi_h - \phi_{R_\perp})\mathcal{I}\left[f_1 G_1^\perp\right] + \ldots$$

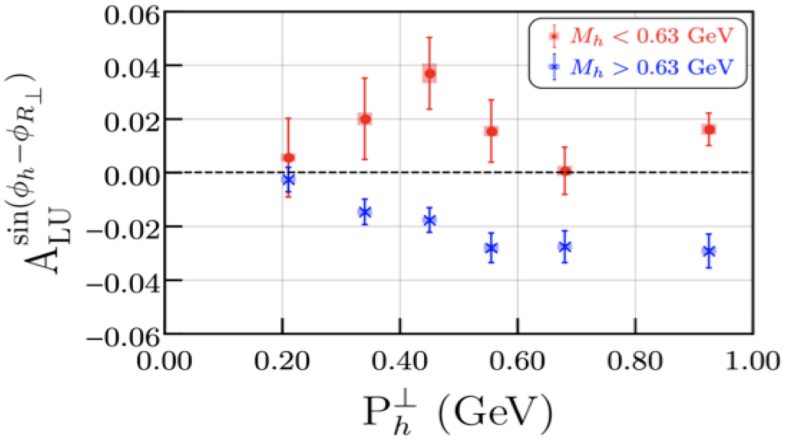
$G_1^\perp$ = 

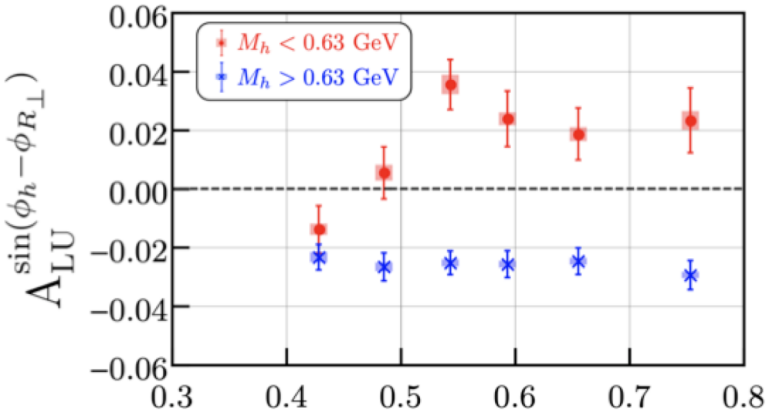
a TMD FF

Matevosyan et al, arXiv:1707.04999





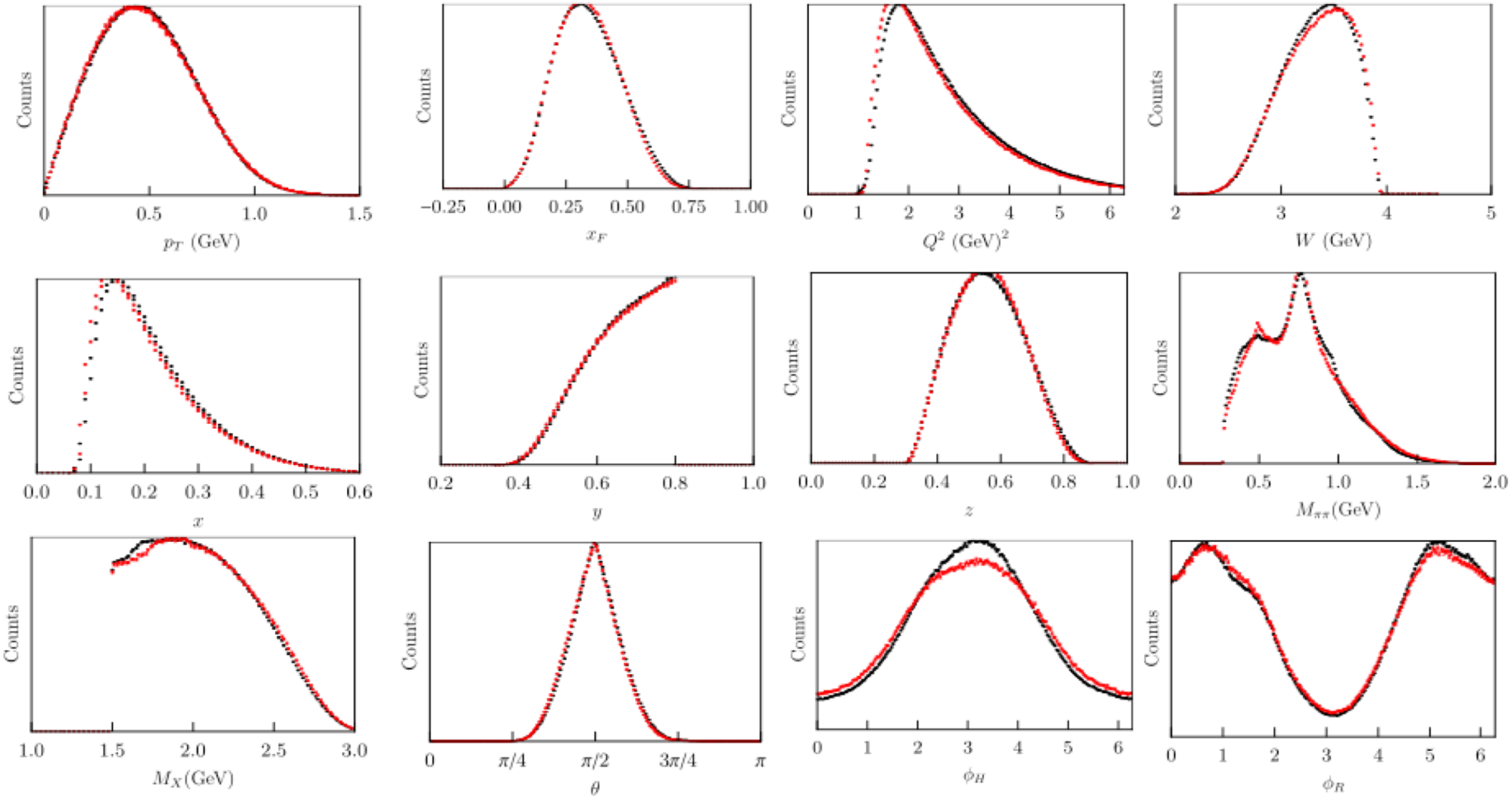




What is so special about the low invariant masses of 2 pions?

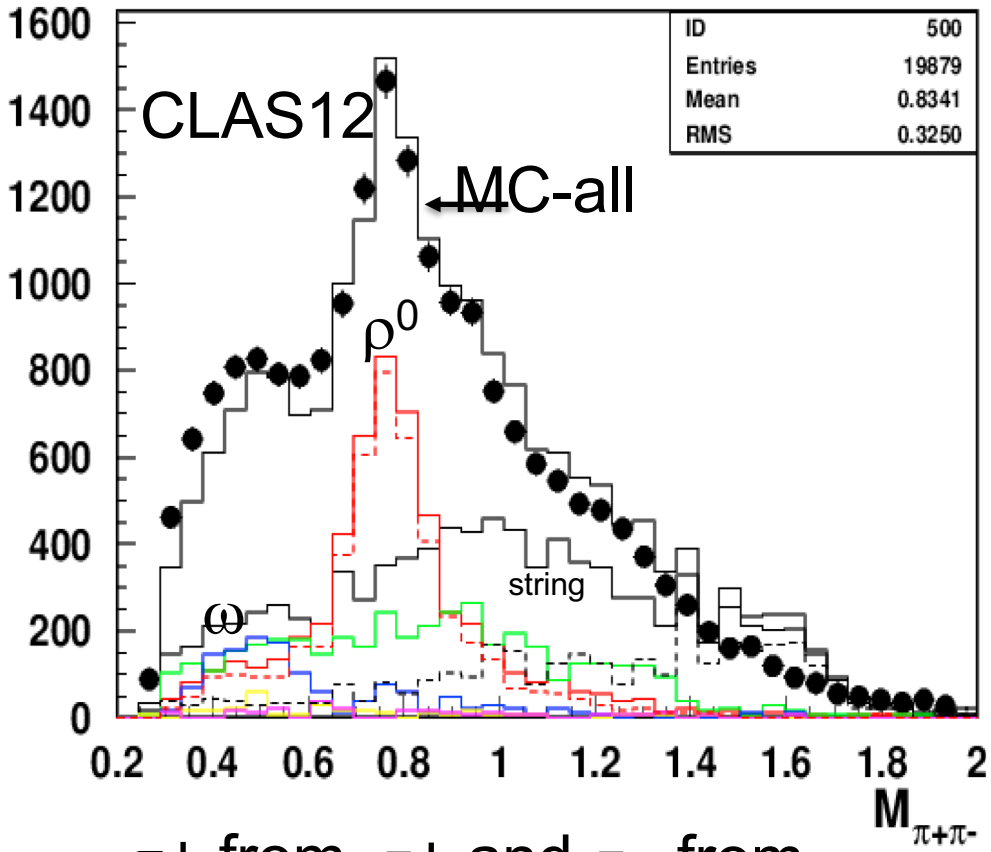
SIDIS ehhX: CLAS12 data vs MC

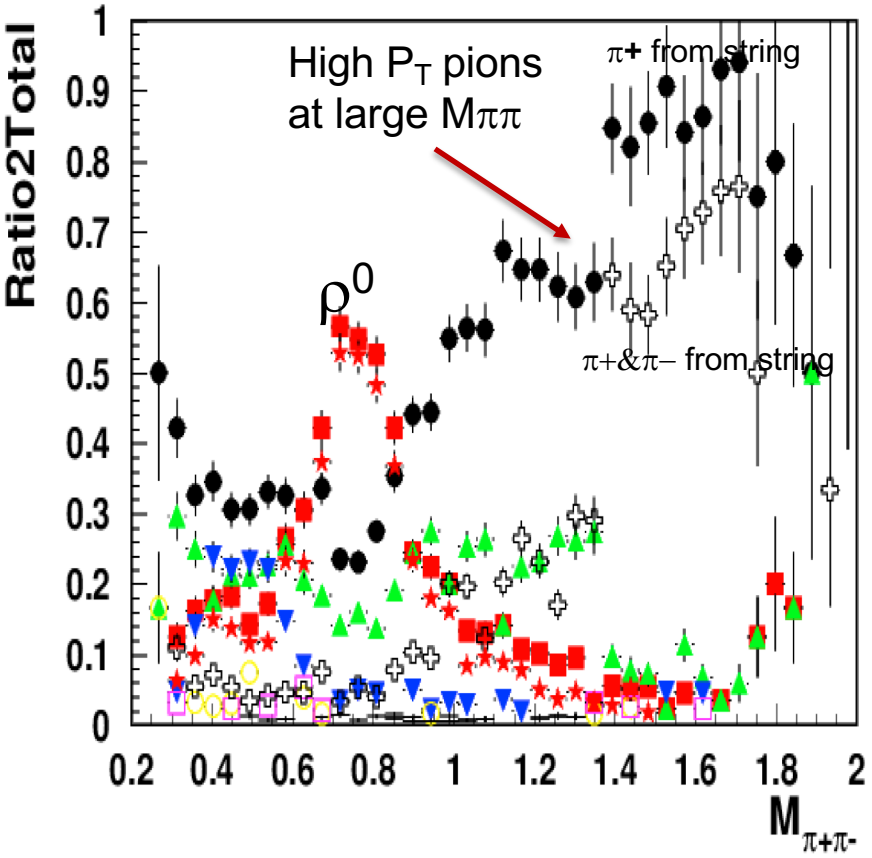
CLAS12 dihadron production ep→ehhX (T.Hayward)



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

Sources of inclusive pions: CLAS12 vs MC





π+ from ρ0 ——

string ——

ρ+ ——

ω ——

π+ and π– from ---- ----

- Dominant fraction of inclusive pions come from VM decays

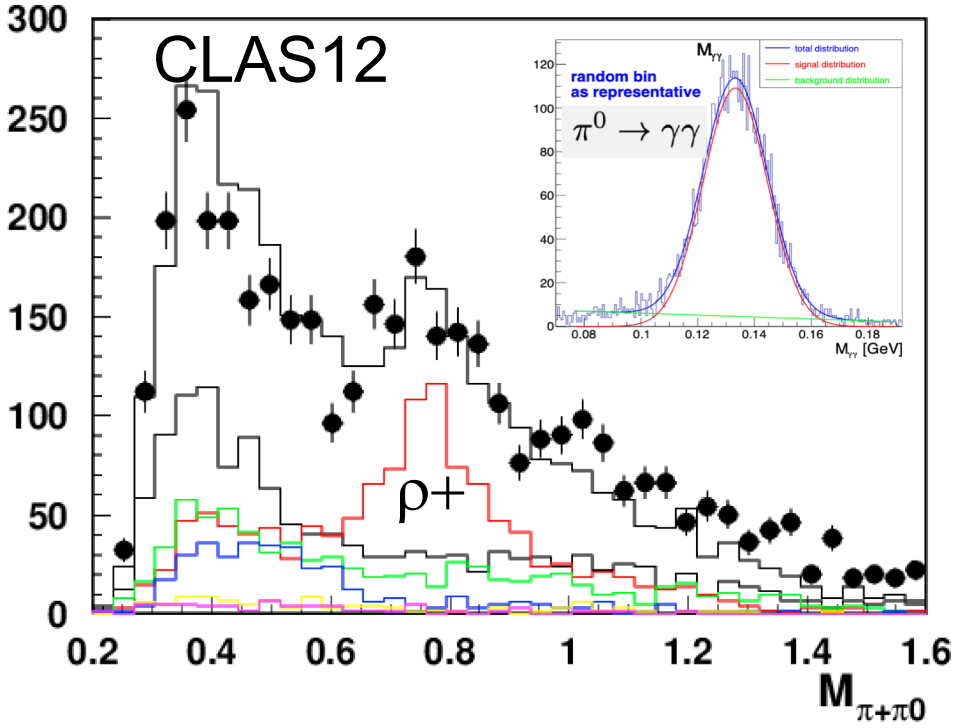
Very important to have multidimensional TMD Fragmentation Functions!

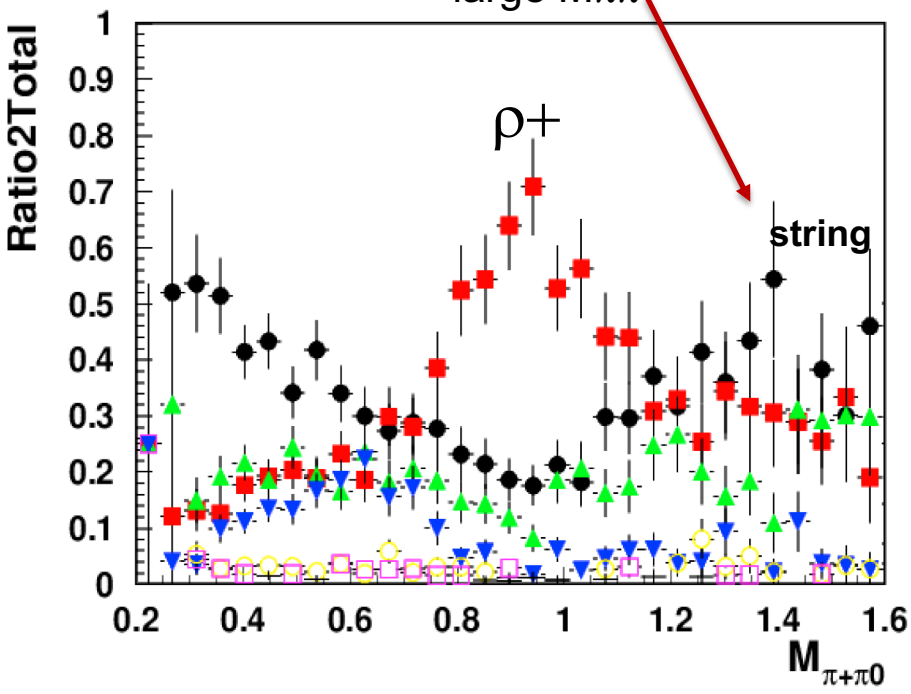
Sources of inclusive pions: CLAS12 vs MC

$\rho^{\pm} \rightarrow \pi^0 + \pi^{\pm}$

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

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





Dominant fraction of inclusive pions come from VM decays

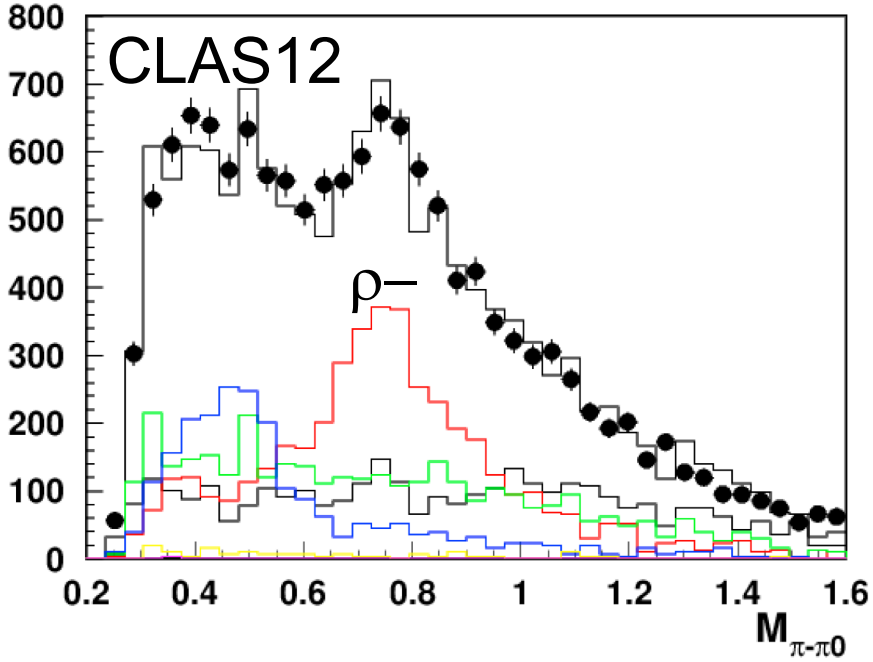
π+ from
- ρ+
- string
- ρ0
- ω

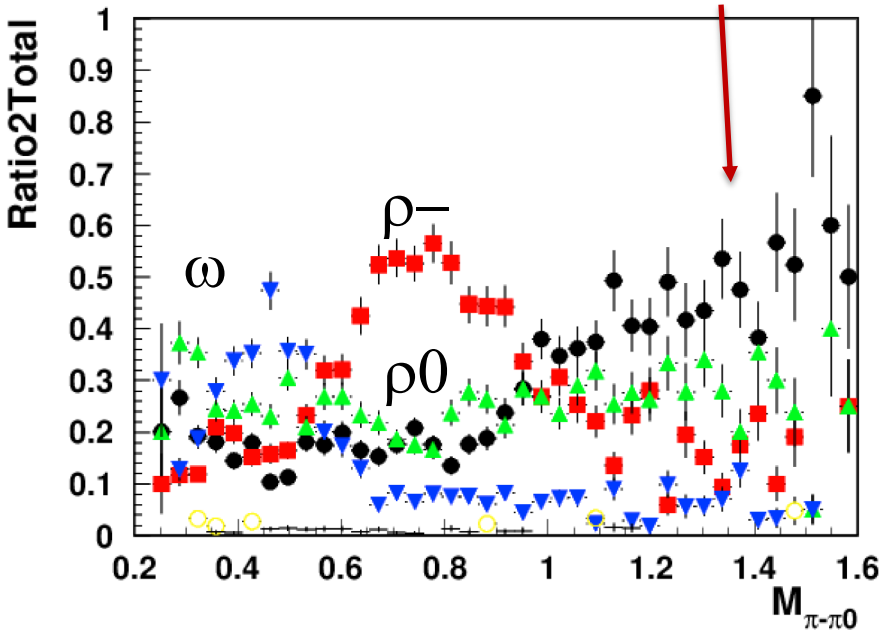
CLAS12 due to unique capability for precision measurements of neutral pions, will provide measurements of multiplicities of variety of semi-inclusive and exclusive hadron pairs (could be also VMs).

Sources of inclusive pions: CLAS12 vs MC

$\rho^{\pm} \rightarrow \pi^0 + \pi^{\pm}$ Detection of π^0s allows studies of $\rho^{\pm}$

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





π– from:

- ρ–
- string
- ρ0
- ω

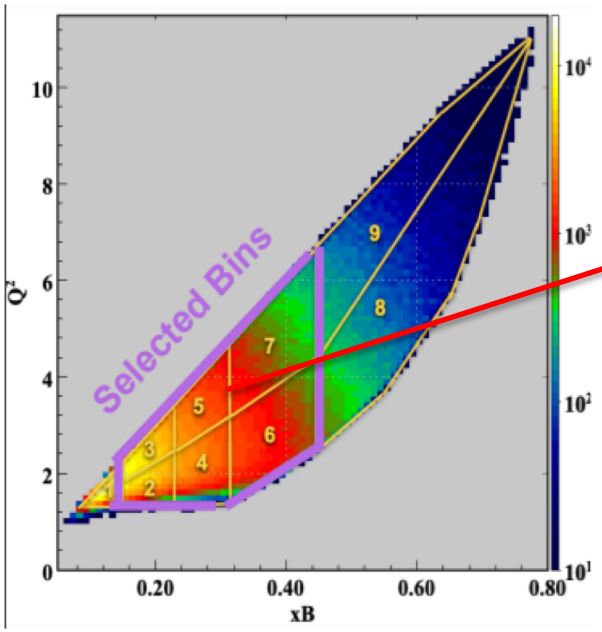
Dominant fraction of inclusive pions come from VM decays

Precision measurements of all combination of pion pairs is crucial for separation of multiplicities of different vector mesons

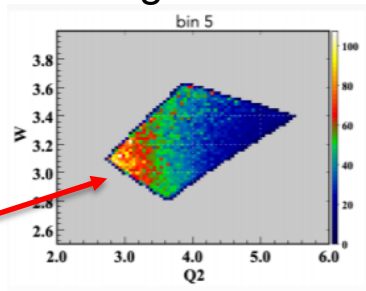
CLAS12 high P_T : impact of vector mesons

G. Angelini (GW)

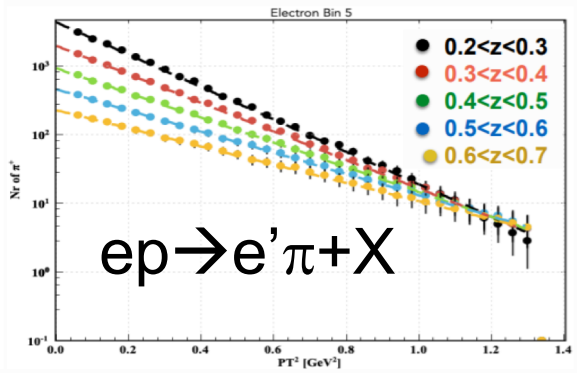
Generate direct pions with Gaussian

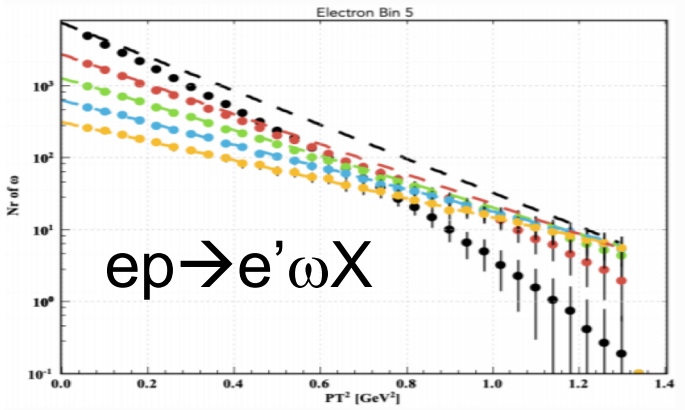


Higher W



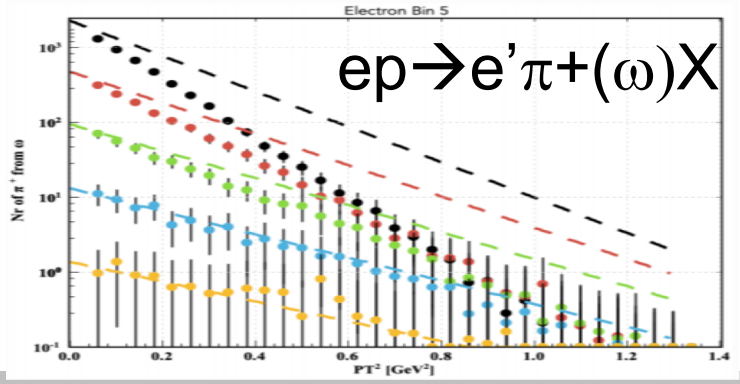
Generate pions from ω produced with the same Gaussian
Phase space effects more pronounced





- The low P_T sample of pions is dominated by VM decays

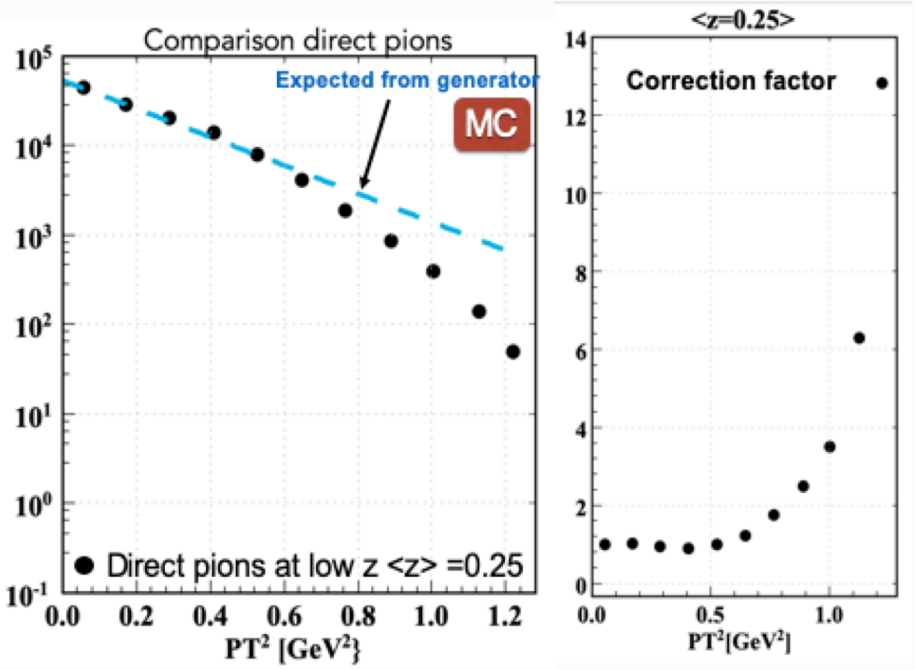
Decay pions from ω have significantly lower transverse momentum for the same z



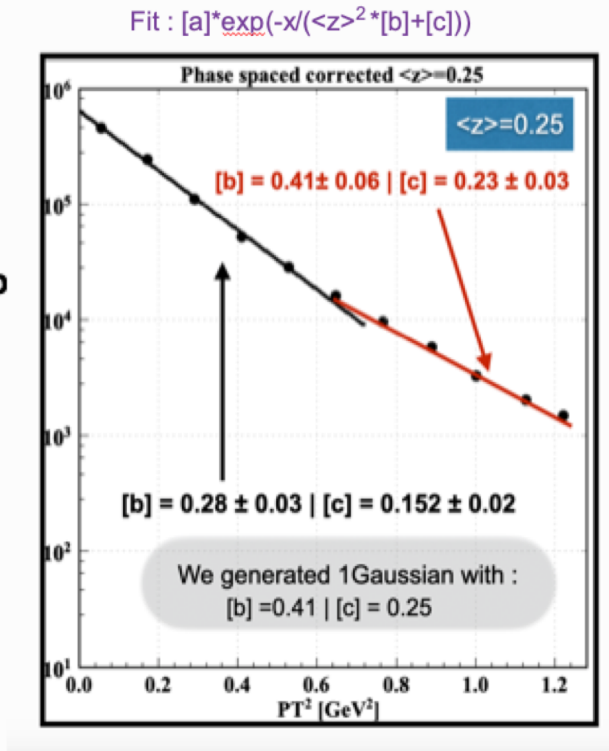
CLAS12 Multiplicities: the role of high P_T

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

G. Angelini (GW)



Applied to all pion samp



- 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

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

Current theory limitations (q_T/Q)

JLab/HERMES/COMPASS/EIC talks

estimates of their effects. For example, the TMD description of SIDIS is valid in the small-p_T regime when $p_T^2/(zQ)^2 \ll 1$, and in a recent study [JHEP 06 (2020) 137] finding that $p_T^2/(zQ)^2 \lesssim 0.06$ approximately demarcates the boundary to large p_T, where a description in terms of TMD PDFs may not be trustworthy. By comparison, values for this ratio as

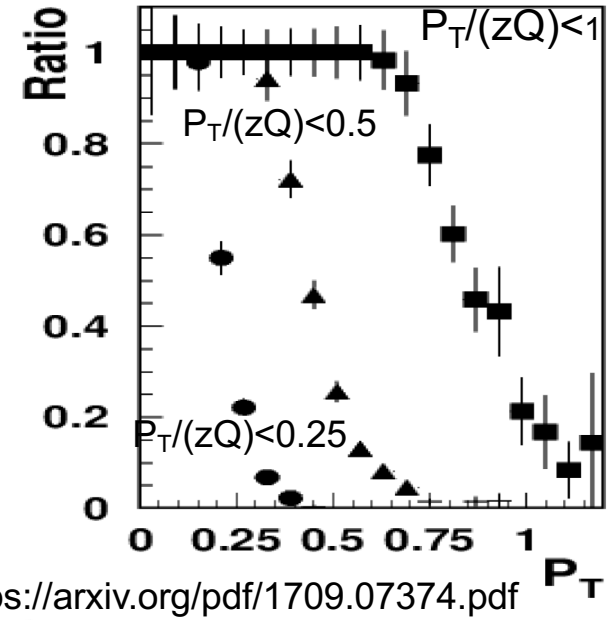
The $q_T=P_T/z$ theory "trustworthy" cut:

1) Suppresses moderate Q^2 and large P_T (sensitive to k_T), where all kind of azimuthal modulations are most significant
2) Enhances large z region (ex. Exclusive Events) in TMD and low z in FO calculations

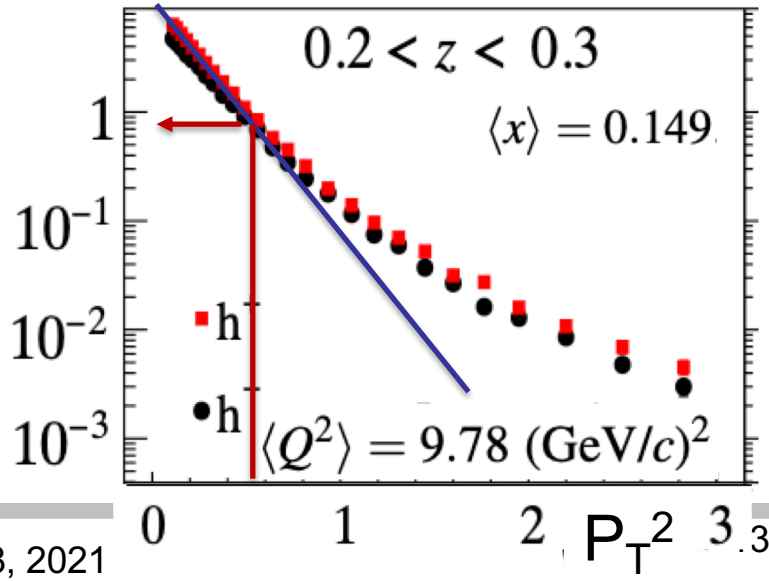
3) Cuts not only most of the JLab data, but practically all accessible in polarized SIDIS large P_T samples , including ones from HERMES COMPASS, and even EIC.

Details available from https://indico.jlab.org/event/439/

JLab12



https://arxiv.org/pdf/1709.07374.pdf

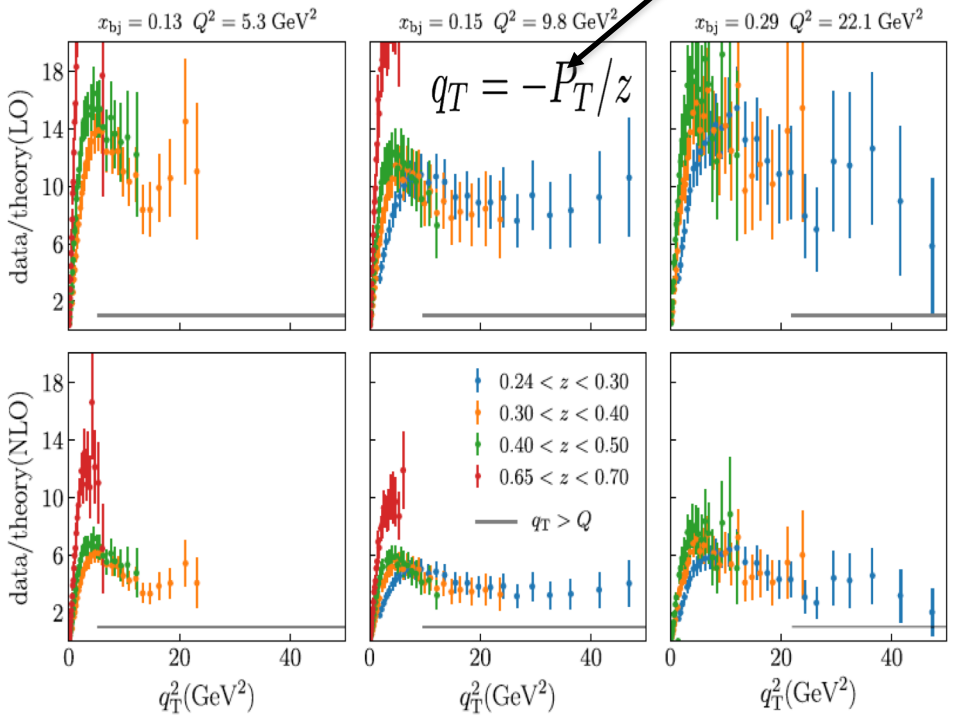


FO vs data for $q_T \gtrsim Q$

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

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

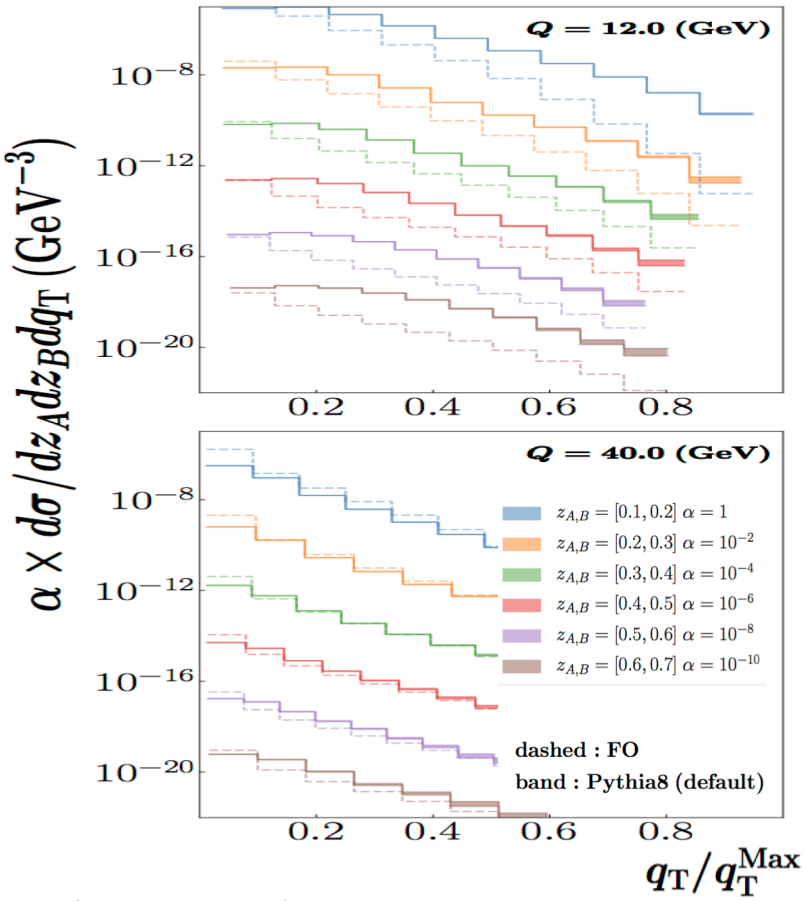
quark transverse momentum



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)

$e^+e^- \to h_1h_2X$ - Moffat et. al 1909.02951



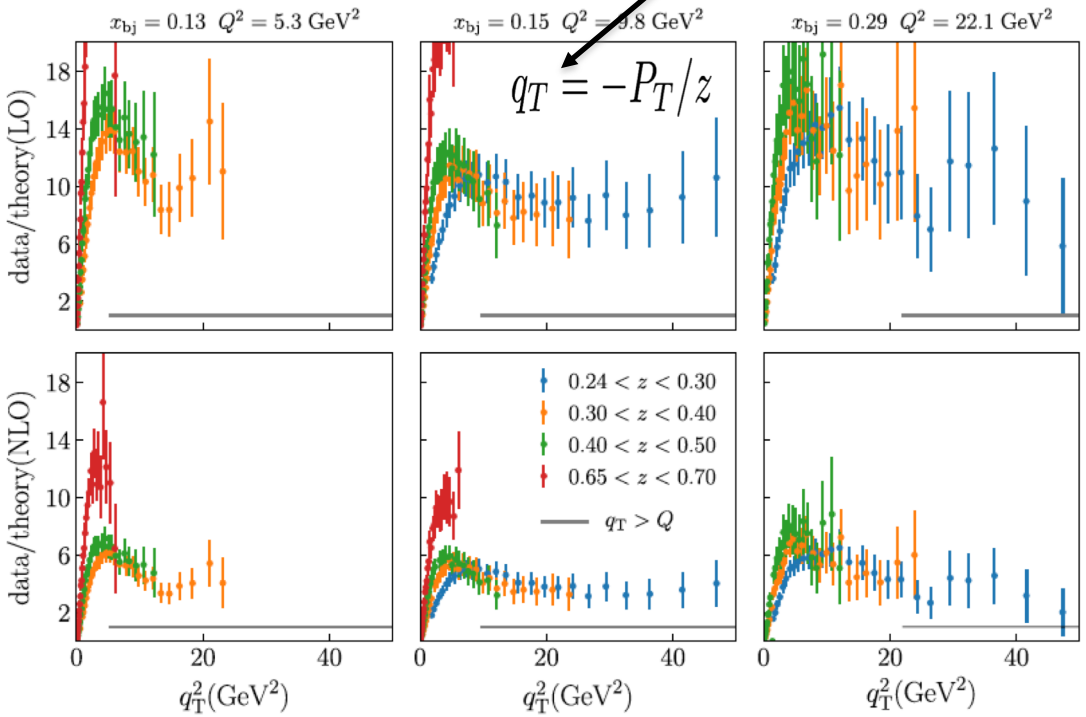
Suggestion: Check agreement with PYTHIA for SIDIS at EIC energies?

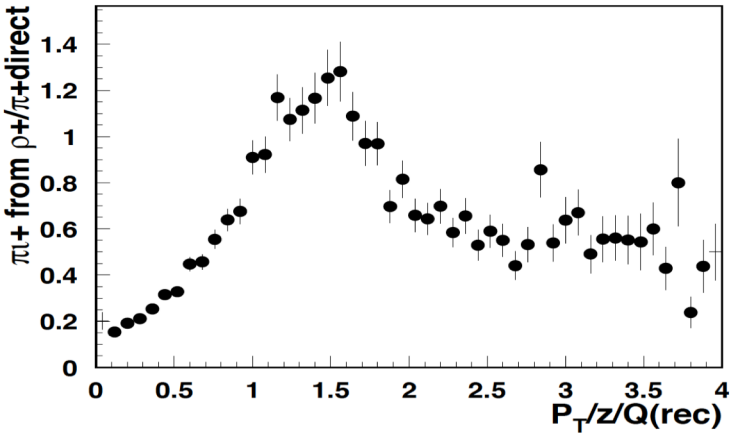
TMD formalism applicability and the impact of q_T cut

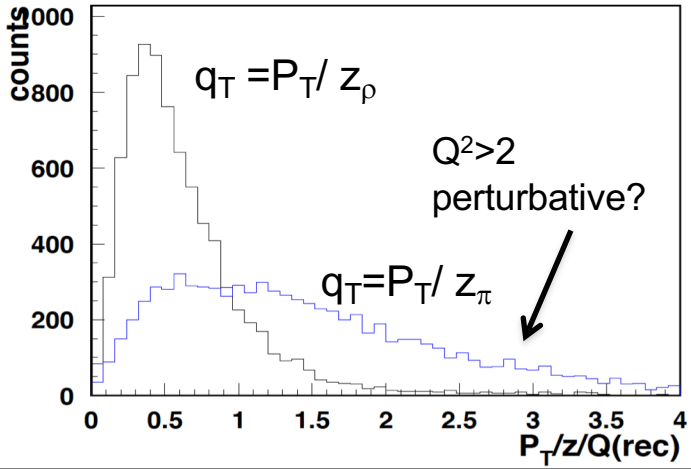
$$F^h_{XY}(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}(M/Q)$$

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

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

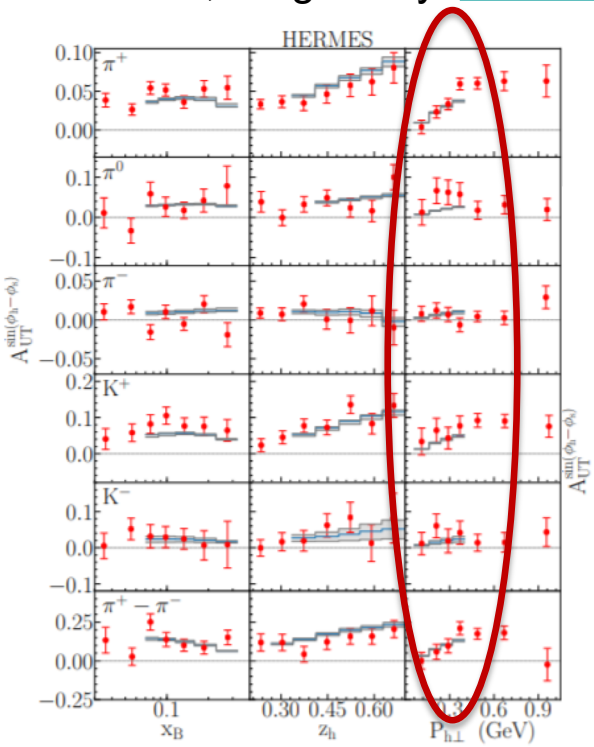
Extracting the average transverse momenta

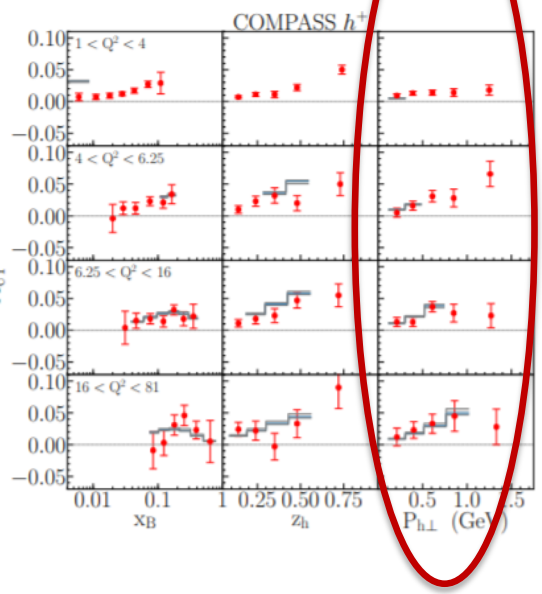
Sivers functions at NLO+NNLL

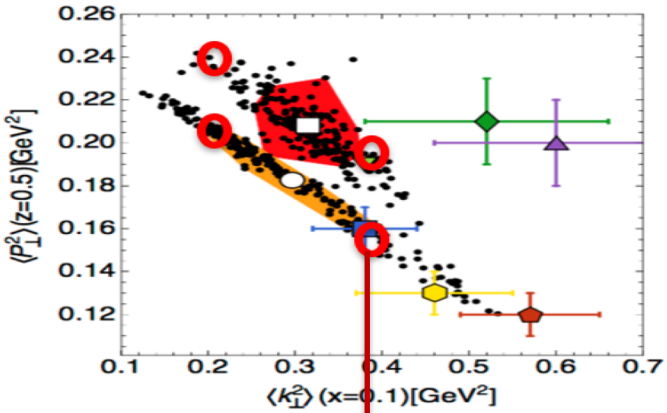
Echevarria,Kang&Terry: JHEP01(2021)126

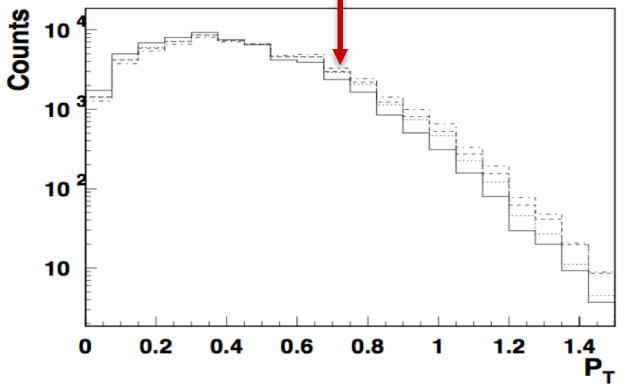
Andrea Signori,[1,*] Alessandro Bacchetta,[2,3,†] Marco Radici,[3,‡] and Gunar Schnell[4,5,§]

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









Fits even for COMPASS include only the small fraction of the low P_T-data, with trivial linear dependence

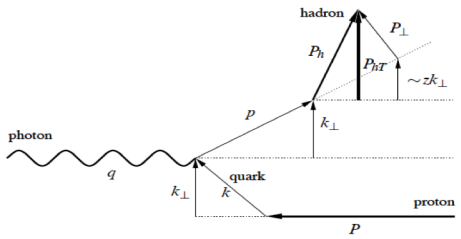
What exactly we learn about high P_T, and can we extrapolate?

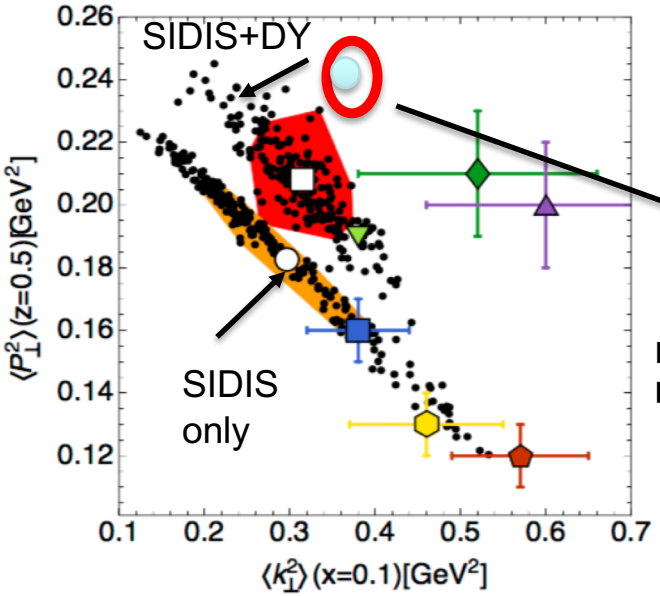
- Extraction very sensitive to input (replicas)
- Most sensitive to parameters is the large P_T region

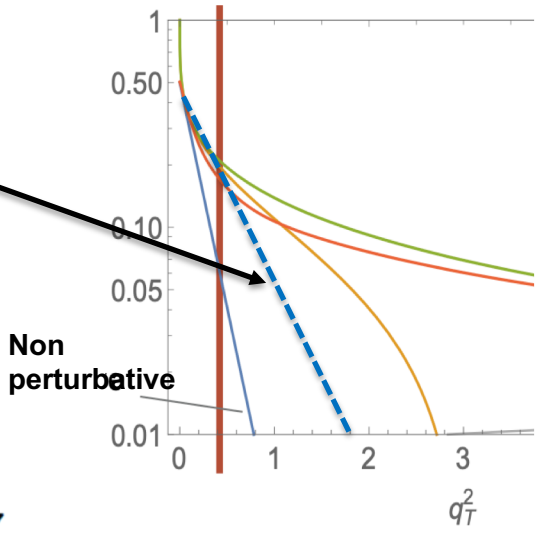
Limitations of current TMD theory

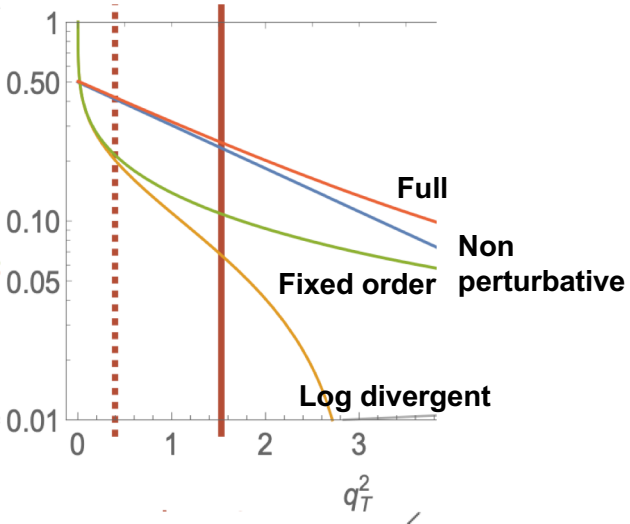
Andrea Signori,[1,*] Alessandro Bacchetta,[2,3,†] Marco Radici,[3,‡] and Gunar Schnell[4,5,§]

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



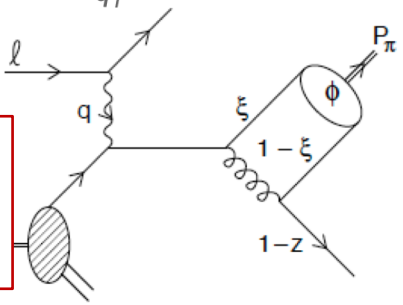






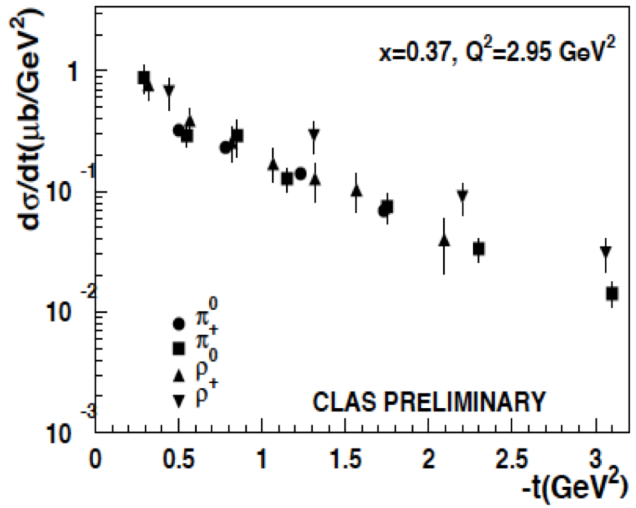
Sea is not divided to perturbative and non-perturbative

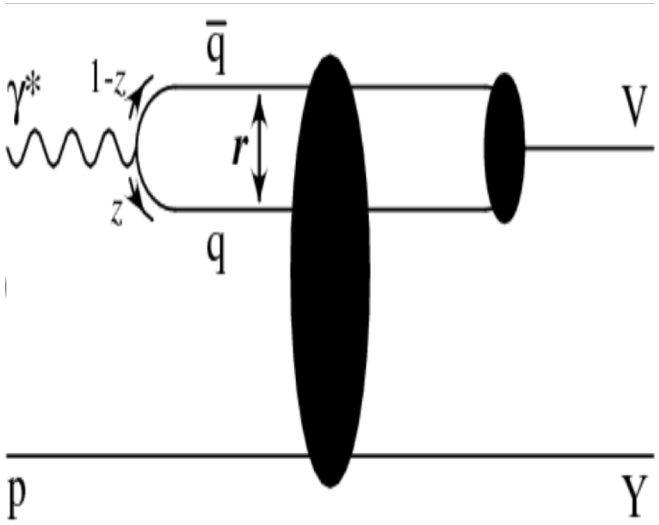
- Crucial to extend the theory to large q_T
- Higher Twist account may help
- Linking SIDIS with exclusive

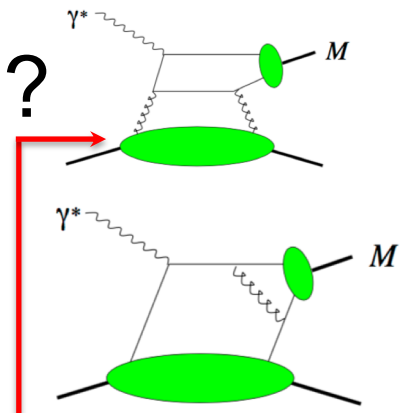


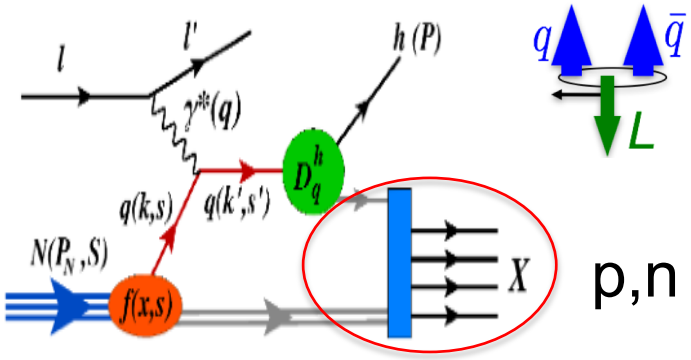
Semi-exclusive production

Exclusive π/ρ production at large x/t







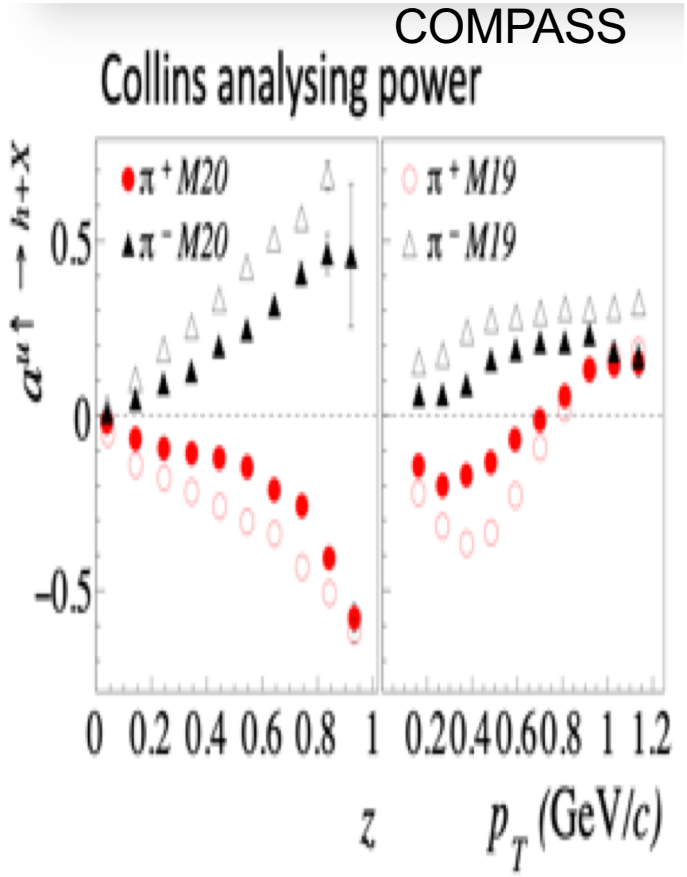


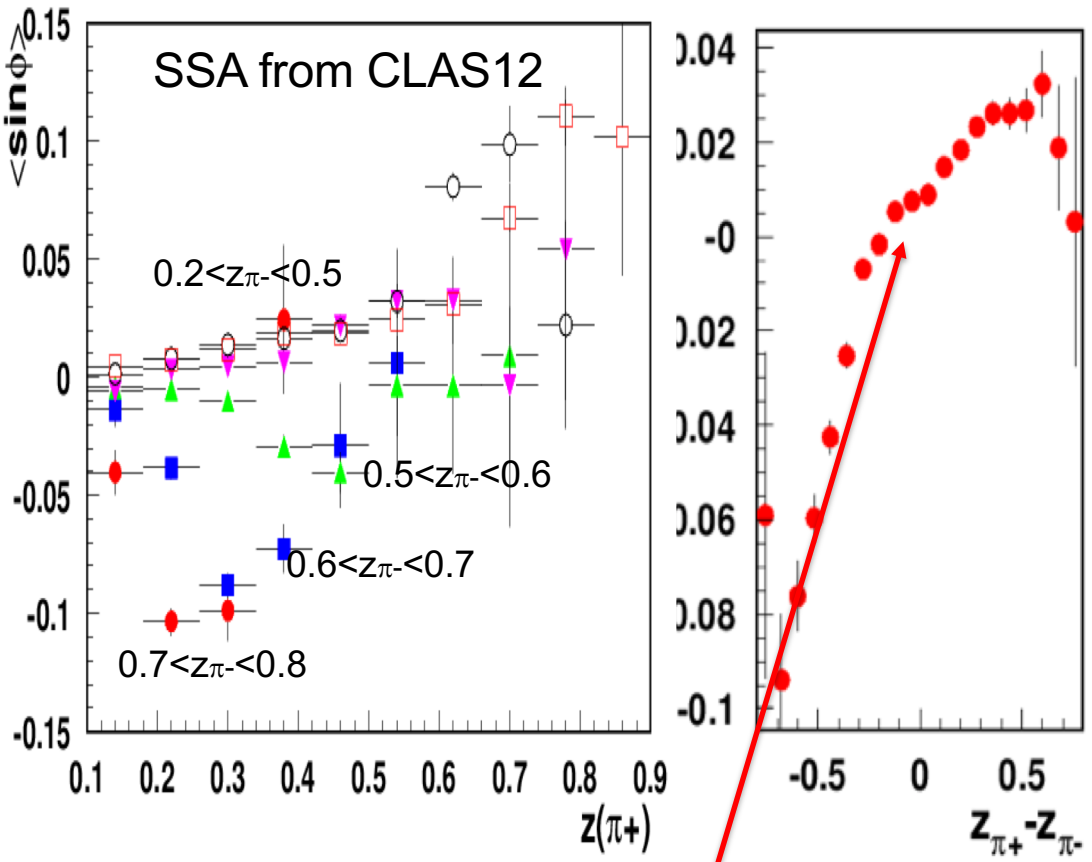
p,n

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)?
- ……..

Disecting the SSA in ep→e'πX





VM contributions may change significantly the interpretation of Collins analyzing power

A. Kerbizi: TMD Studies: from JLab to EIC

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

The polarization of the ρ itself may be relevant (no SSA for symmetric case)

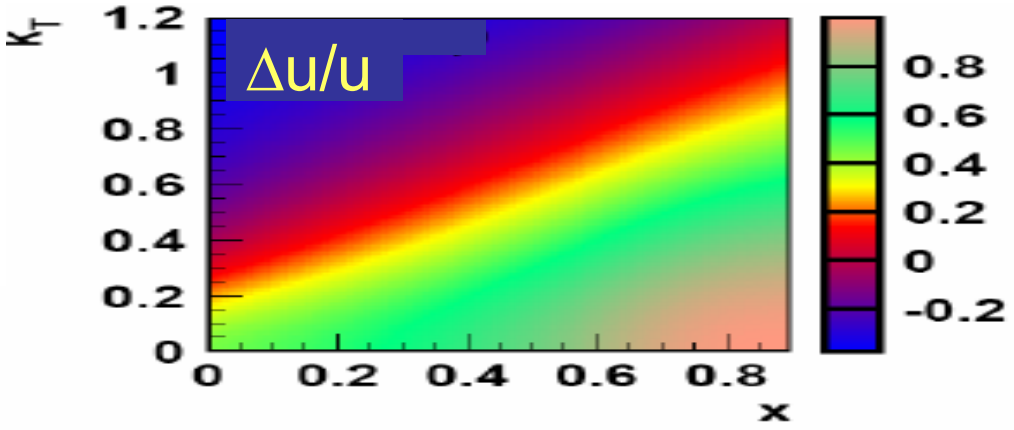
Quark longitudinal polarization

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

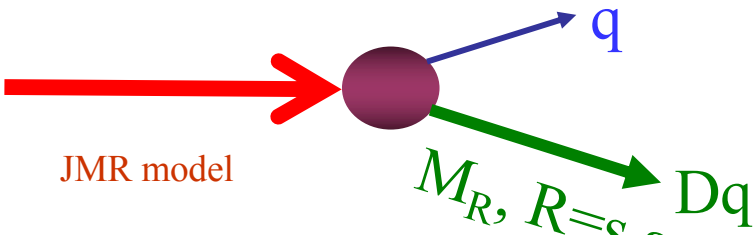
$$u^{-}(x,k_T) = f_1^u(x,k_T^2) - g_1^u(x,k_T^2)$$

	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)

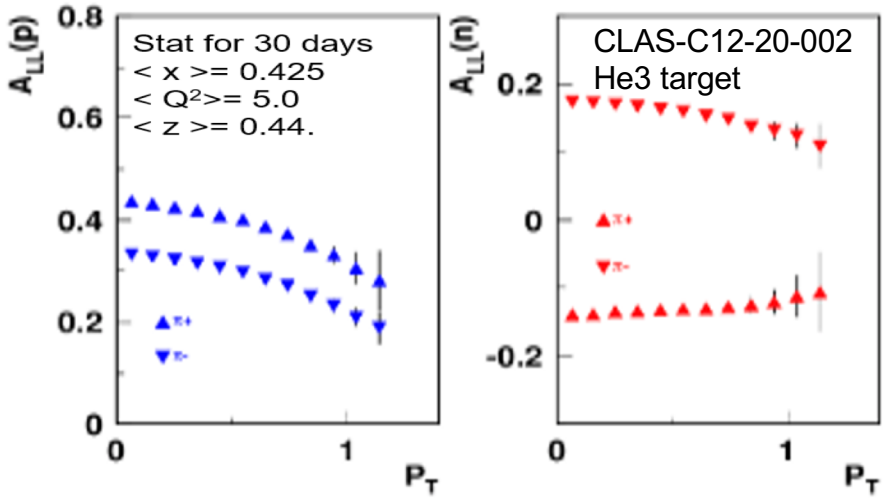


(dipole formfactor), J.Ellis, D-S.Hwang, A.Kotzinian



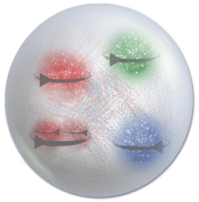
$$f_1(x,\mathbf{k}_T^2) = A\,\frac{(xM+m)^2+\mathbf{k}_T^2}{(\mathbf{k}_T^2+\lambda_R^2)^{2\alpha}},$$

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



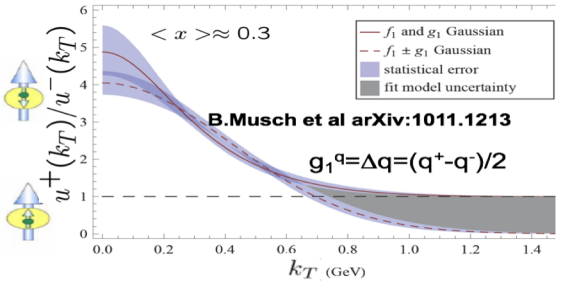
Large transverse momenta are crucial to access the large k_T of quarks

Extending to small x, large Q2 and large P_T

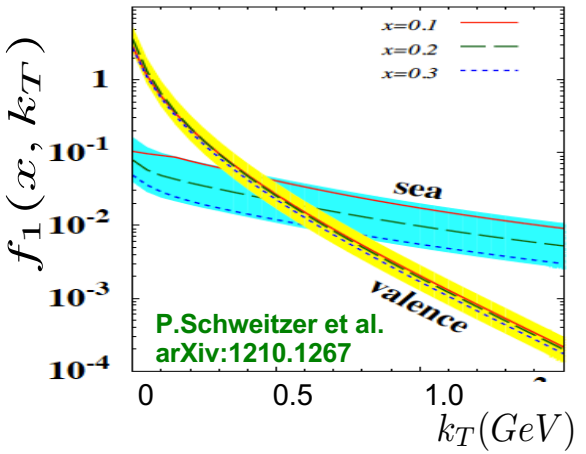


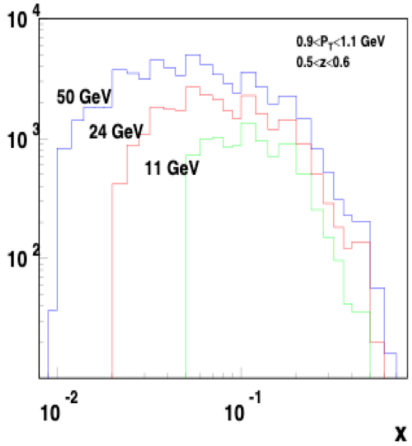
Non-perturbative sea ("tornado") in nucleon is a key to understand the nucleon structure

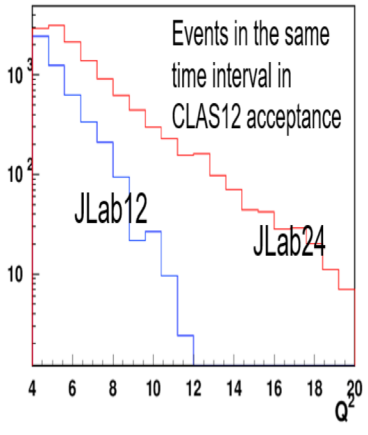
$\bar{d} > \bar{u}$

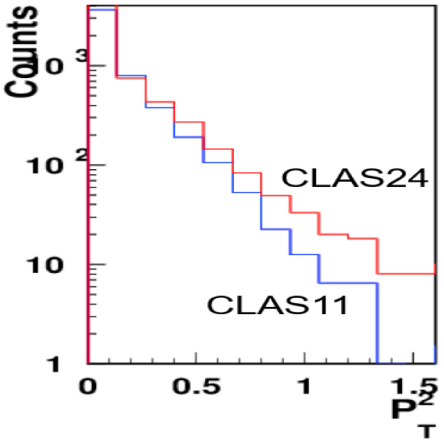


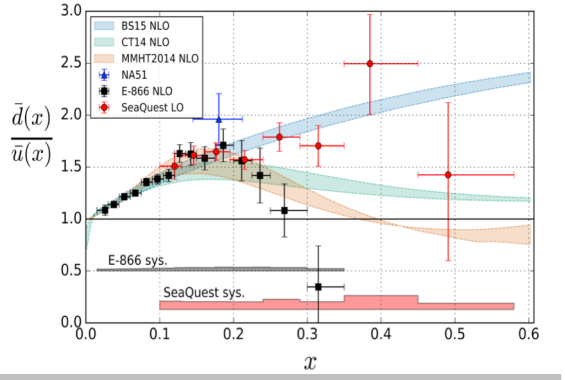
- Spin and momentum of struck quarks are correlated with remnant
- Correlations of spins of q-q-bar with valence quark spin and transverse momentum will lead to observable effects
- Spin-Orbit correlations so far were shown (measurements and model calculations) to be significant in the region where non-perturbative effects dominate











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

Summary

- Measurements of dihadron multiplicities with CLAS12 indicate that hadronization of quarks goes predominantly through production of Vector Mesons (applies to Kaons a well)

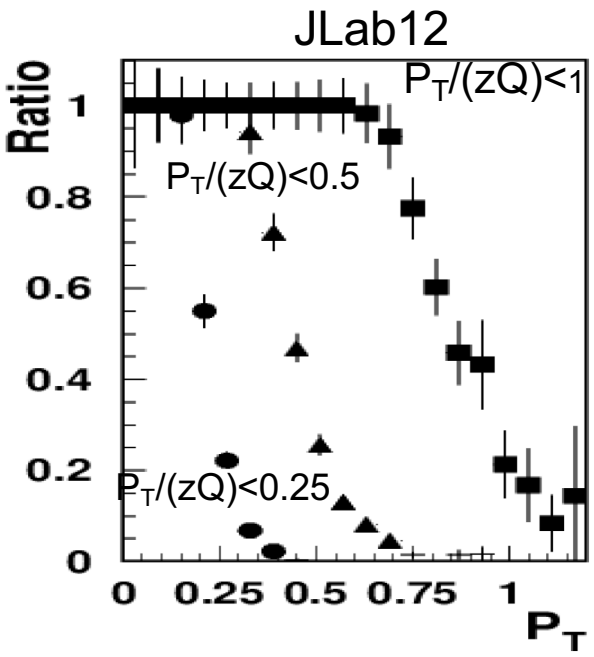
- Significant beam spin asymmetries measured by CLAS12 in two hadron production indicates significant correlations in final hadrons, and large quark-gluon correlations

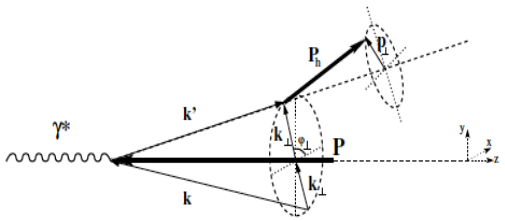
- CLAS12 data would allow to constrain experimentally the fractions and distributions of pions coming from vector meson decays (tune JETSET as well), and that will change significantly the interpretation of the SIDIS data in general, and polarized SIDIS data in particular

- Large transverse momenta of hadrons, currently excluded from TMD analysis, are most sensitive to the flavor and spin dependence of partonic distributions.

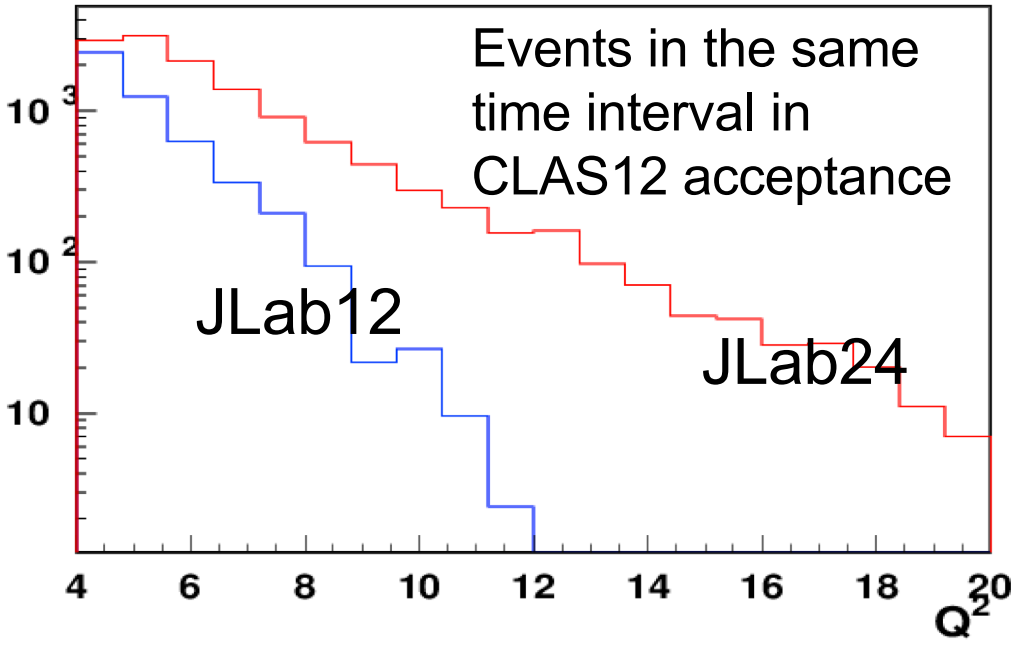
- JLab upgrade to 24 GeV will open qualitatively new opportunities to study the transverse momentum dependence and evolution properties of partonic distributions

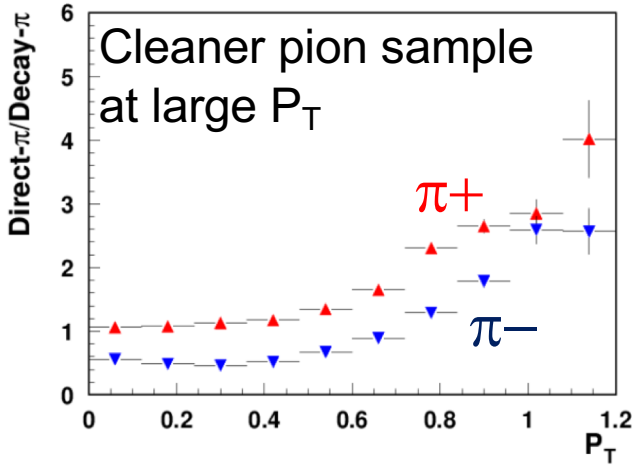
From JLa12 to JLab24 Larger Q^2 at large P_T





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



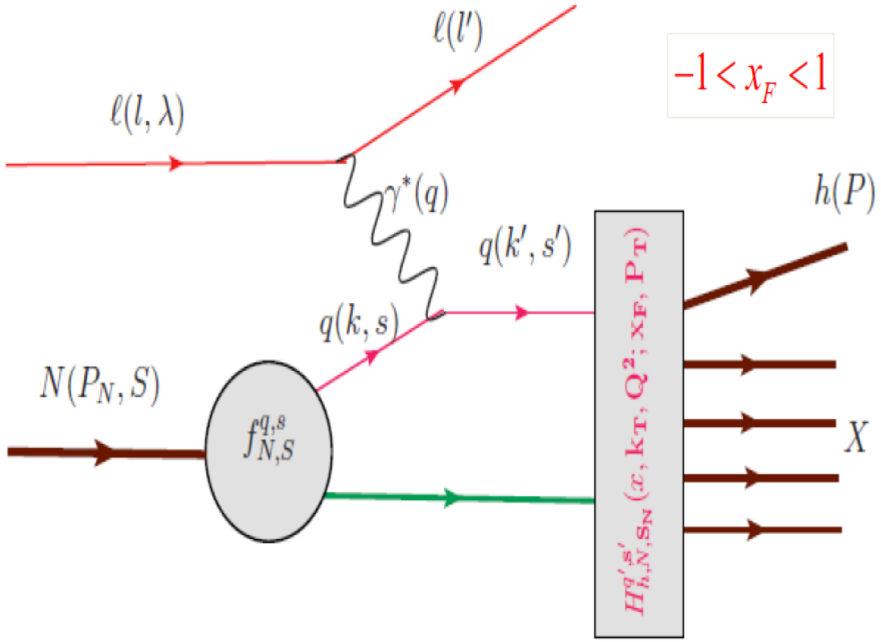


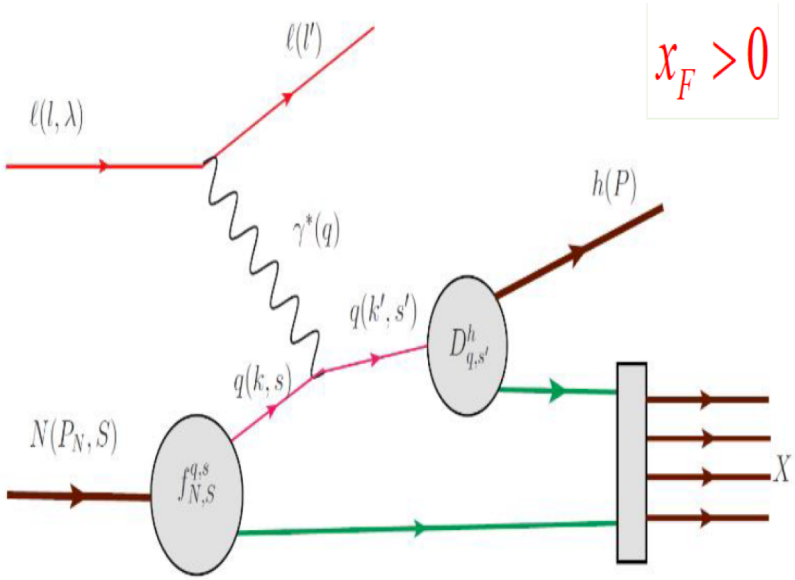
JLab24 will significantly increase the the Q^2 range, allowing detailed separation of higher twist SFs, needed for understanding the QCD

Hadronization

$Q^2 \gg M_p^2$

A.Kotzinian FF2019





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

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

Quark Fragmentation Functions

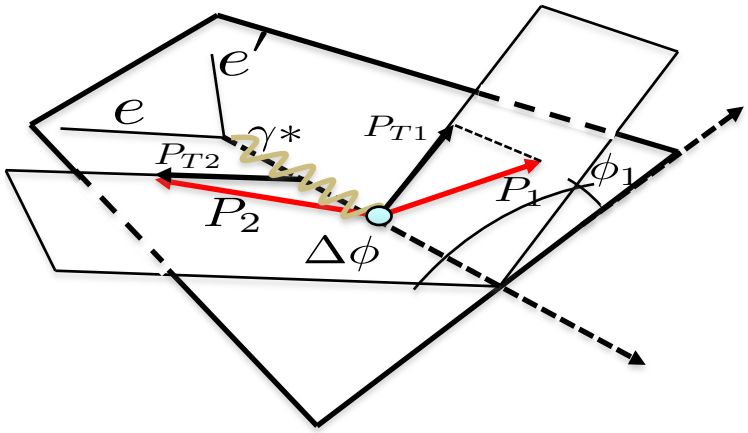
$$D_{q,s'}^h\left(z,\mathbf{p}_T,Q^2\right)$$

Where this works?

B2B hadron production in SIDIS: First measurements

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

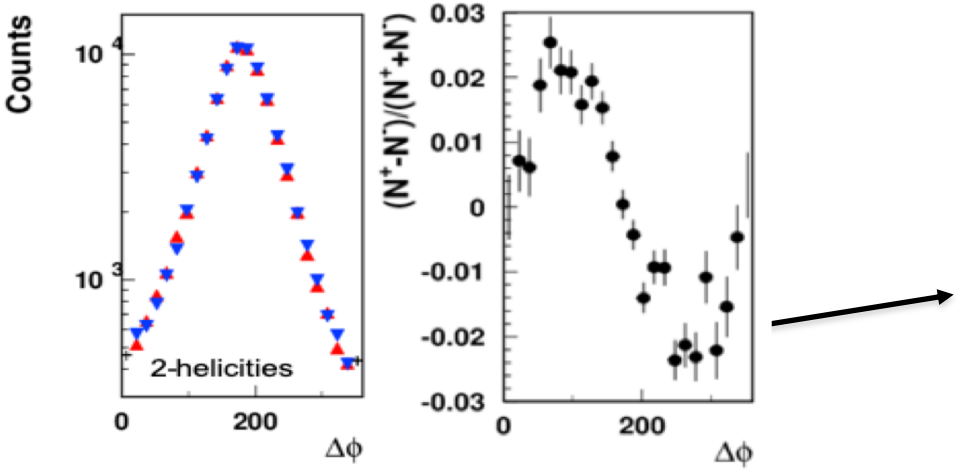
$$ep \to e' p \pi^+ X$$

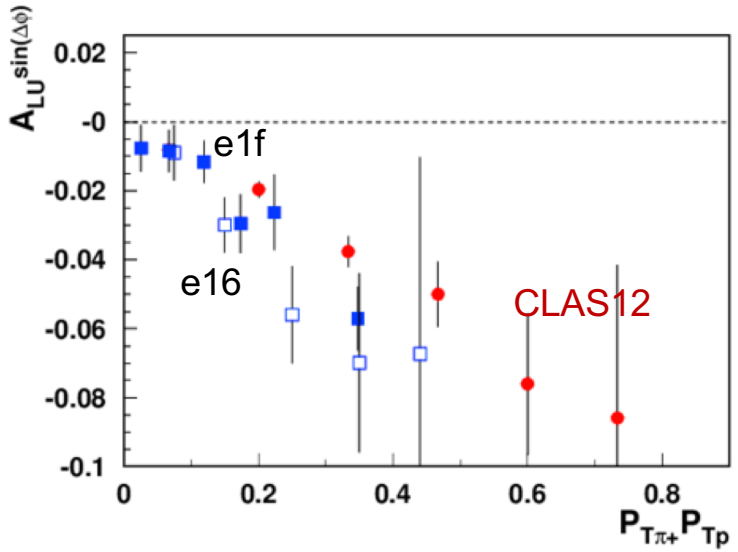


$$A_{LU} = -\frac{y(1-\frac{y}{2})}{(1-y+\frac{y^2}{2})}\frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}}\sin\Delta\phi$$

$$= -\frac{|\boldsymbol{P}_{1\perp}||\boldsymbol{P}_{2\perp}|}{m_N m_2}\frac{y(1-\frac{y}{2})}{(1-y+\frac{y^2}{2})}\frac{\mathcal{C}[w_5 \hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]}\sin\Delta\phi,$$

kinematics — modulation — Correlation



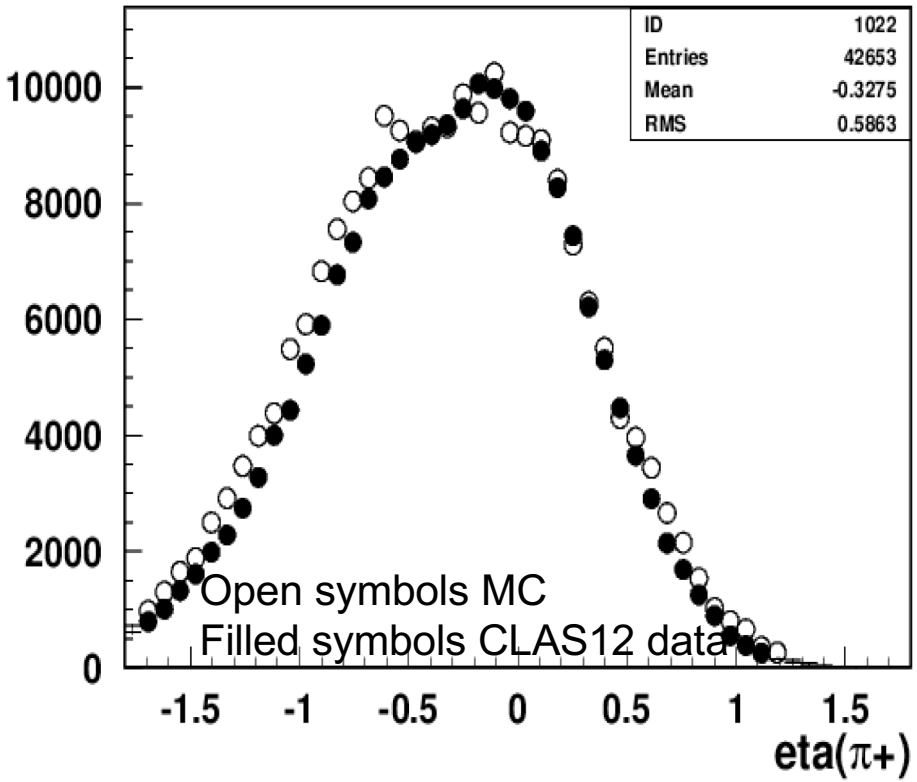


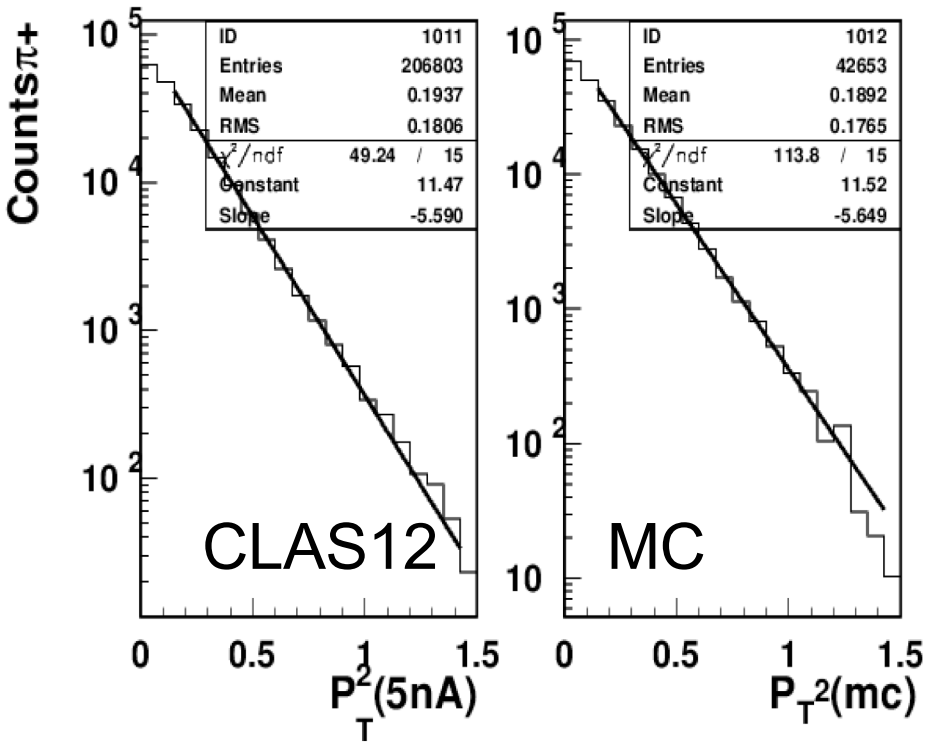
Significant single-spin asymmetries observed by CLAS12 (talk by T. Hayward) indicating strong correlations between hadrons

CLAS12 Studies: pions

Using PEPSI (LUND) generator rapidity in Breit frame

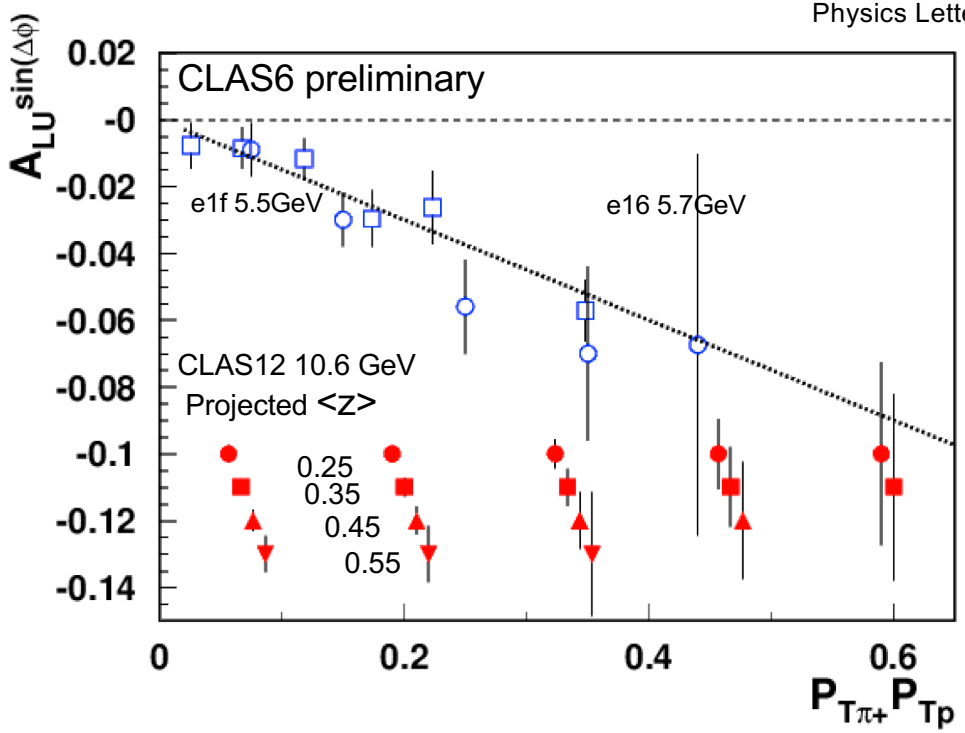
Boglione et al
https://arxiv.org/pdf/1904.12882.pdf





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

B2B SSAs ep→pπ+X



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

$$\mathcal{A}_{LU} = -\frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)}\frac{\mathcal{F}_{LU}^{\sin\Delta\phi}}{\mathcal{F}_{UU}}\sin\Delta\phi$$
$$= -\frac{|\mathbf{P}_{1\perp}||\mathbf{P}_{2\perp}|}{m_N m_2}\frac{y\left(1-\frac{y}{2}\right)}{\left(1-y+\frac{y^2}{2}\right)}$$
$$\times \frac{\mathcal{C}[w_5\,\hat{l}_1^{\perp h} D_1]}{\mathcal{C}[\hat{u}_1 D_1]}\sin\Delta\phi,$$

May be canceling out in large x
(true for u-quark dominance)

$$\hat{l}_1^{\perp h}(x_B,\zeta_2,\mathbf{k}_\perp^2,\mathbf{P}_{2\perp}^2,\mathbf{k}_\perp\cdot\mathbf{P}_{2\perp})$$
$$\simeq a(x_B,\zeta_2,\mathbf{k}_\perp^2,\mathbf{P}_{2\perp}^2)$$
$$+ b(x_B,\zeta_2,\mathbf{k}_\perp^2,\mathbf{P}_{2\perp}^2)\,\mathbf{k}_\perp\cdot\mathbf{P}_{2\perp}$$

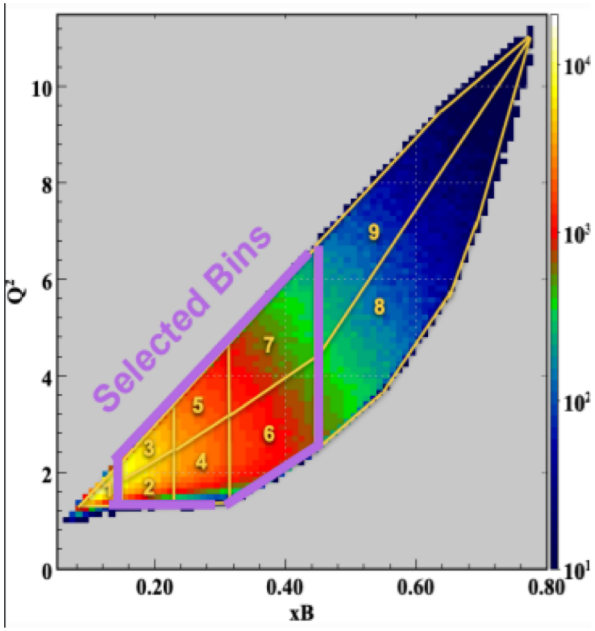
$$\mathcal{A}_{LU}(x_B,z_1,\zeta_2,\mathbf{P}_{1\perp}^2,\mathbf{P}_{2\perp}^2,\Delta\phi)$$
$$= A(x_B,z_1,\zeta_2,\mathbf{P}_{1\perp}^2,\mathbf{P}_{2\perp}^2)\,\sin\Delta\phi$$
$$+ B(x_B,z_1,\zeta_2,\mathbf{P}_{1\perp}^2,\mathbf{P}_{2\perp}^2)\,\sin(2\Delta\phi)$$

- Significant SSA observed consistent with linear behavior with P_T-product
- Indicates significant correlations between hadrons in SIDIS in CFR and TFR
- Superior statistics of CLAS12 allows multidimensional binning (x,z,P_T,..)

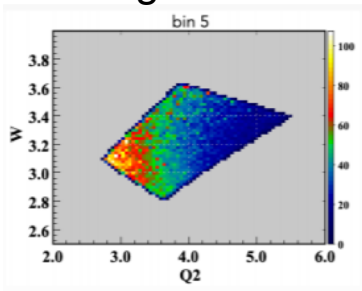
CLAS12 Multiplicities: high P_T & phase space

G. Angelini (GW)

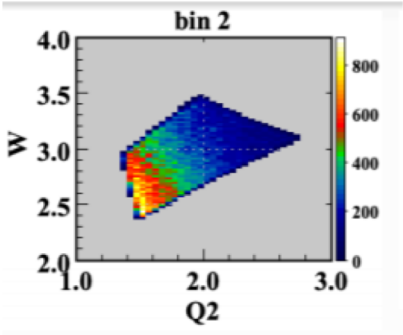
Generate direct pions with Gaussian

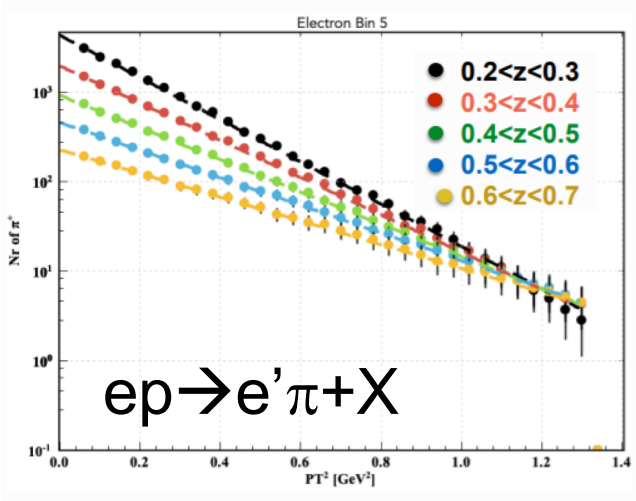


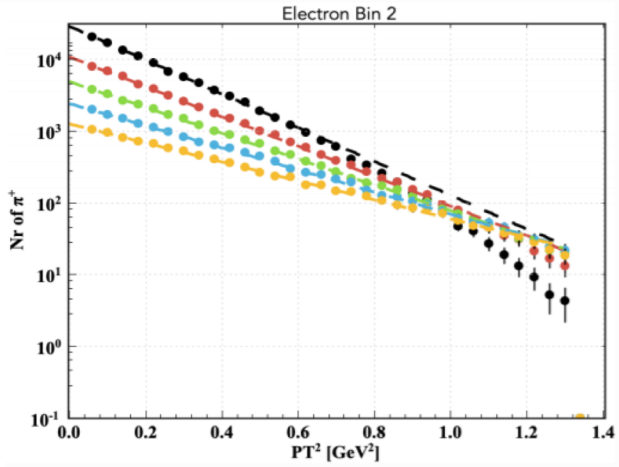
Higher W



Lower W







- Phase space limitations for direct pion production more significant at low W, and low z

At low z, and high P_T there is no enough energy in the system even for reproducing the Gaussian fall of (problem for studies of high P_T tails)

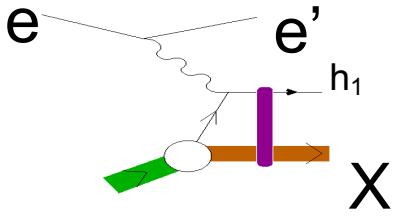
Opportunities with 24 GeV

Significantly wider phase space would allow

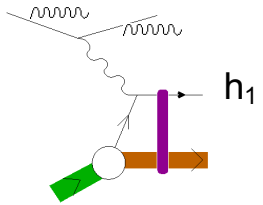
- Enhance the range in transverse momentum P_T of hadrons
  - Access to P_T-region where the dependence of the k_T-dependences of different flavors (valence and sea) and polarization states is most significant
- Enhance the Q^2 range
  - Increase significant the range of high Q2, where the theory is supposed to work better, and allow studies of evolution properties
- Enhance the x-range
  - Access the the full kinematical range (x>0.03-0.04) where the non-perturbative sea is expected to be significant

Electro-production of hadrons

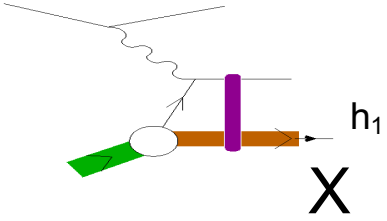
single hadron in CFR (Current Fragmentation Region)

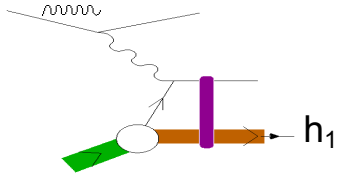


with additional radiation

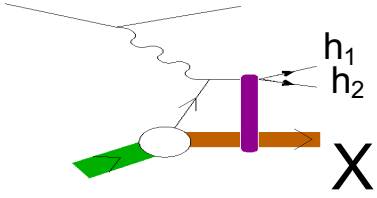


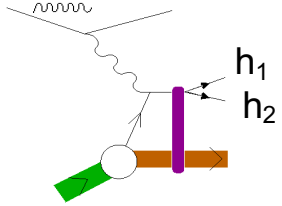
single hadron in TFR(Target Fragmentation Region)



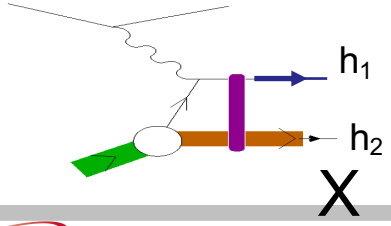


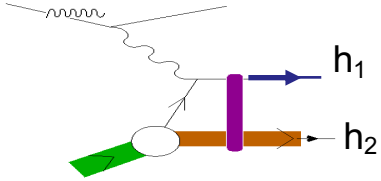
correlated hadrons(dihadron,rho,..) in CFR





correlated hadrons in CFR+TFR



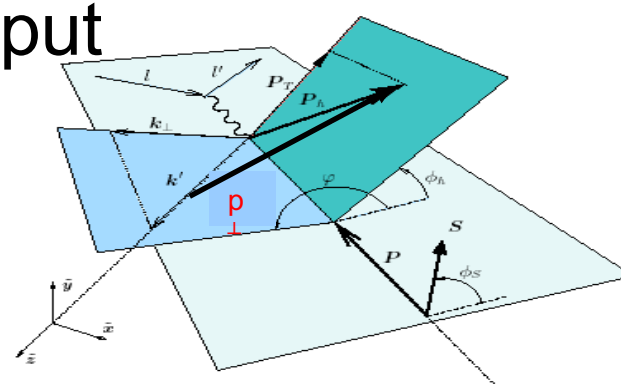


Does it matter what is the source of the single hadron, and if yes, where?

radiation mixes contributions from different structure functions and complicates separation of exclusive from semi-inclusive

MC Generator to simulate SIDIS output

SIDIS MC in 7D (10D)



$$\frac{d\sigma^{eN\to e'hX}_{\lambda\Lambda}}{dxdQ^2dzdP^2_{hT}d\phi_h d\phi_l d\phi_s} = \sum_{l=1}^{L} SF_l$$

Theory

Provide a set of SF_l

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

$$F_l(x_1, x_2, x_3, ...x_N, P_1, P_2, ...P_M)$$

step-1 $x_i, Q^2_i z_i P^{i2}_{hT} \phi^i_h \phi^i_l \phi^i_s$

step-2 (for a given E_{beam},λ,Λ) P^{el}_i, P^h_i

step-3 (detected for a given Detector configuration)

$$x_j, Q^2_j z_j P^2_{hT,j} \phi^j_h \phi^j_l \phi^j_s$$

$$F_l(x_1, x_2, x_3, ...x_N, P^*_1, P^*_2, ...P^*_M)$$

Need criteria to compare the input and output parameter spaces (validate)