Studies of 3D Structure of the Nucleon

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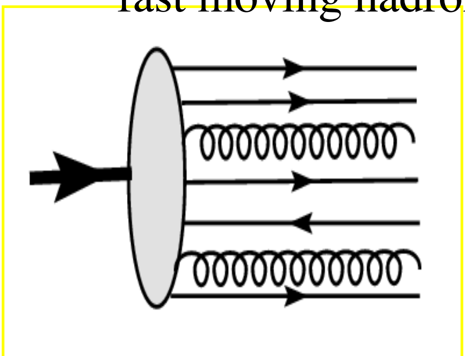
ISMD2021
July 12-16, 2021

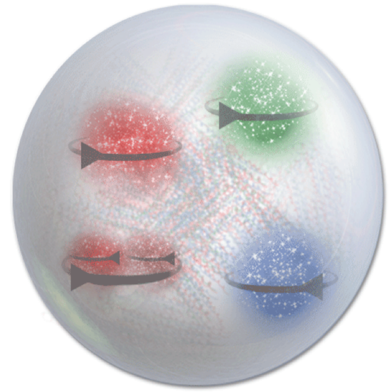
- Introduction
- Measurements at JLab12
- Extraction of 3D PDFs
- Interpretations
- Challenges
- Summary

Proton structure from 1D to 3D

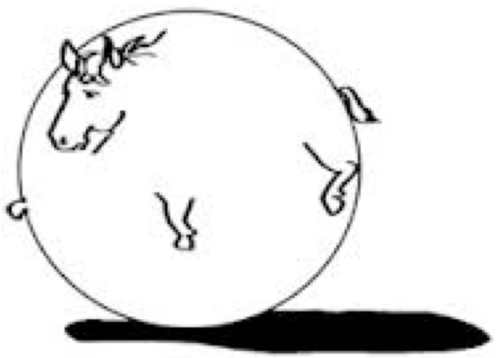
fast moving hadron



real life



spherical horse in vacuum

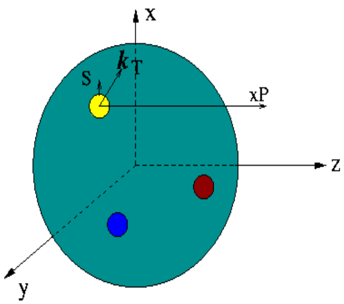


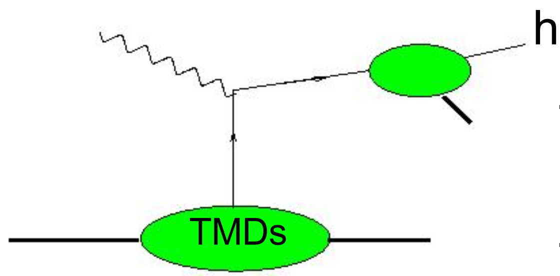
To understand better the dynamics we need to

- Study orbital motion, move from 1D to 3D
- Study interactions and correlations of spin, longitudinal and transverse degrees of freedom

3D structure of the nucleon

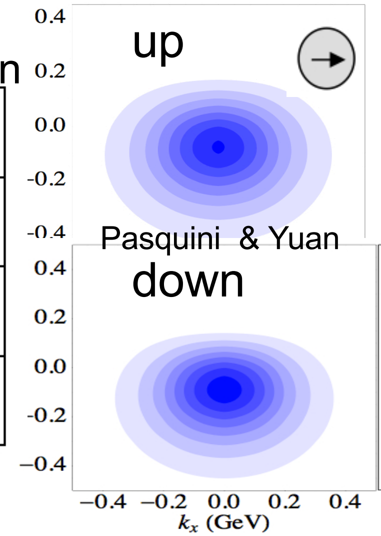
Semi-Inclusive processes and transverse momentum distributions



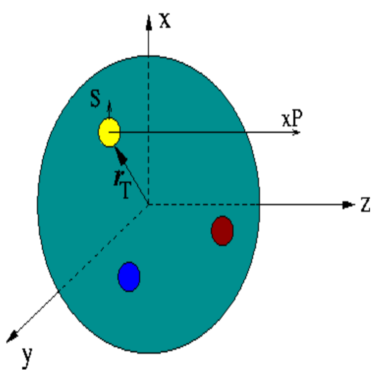


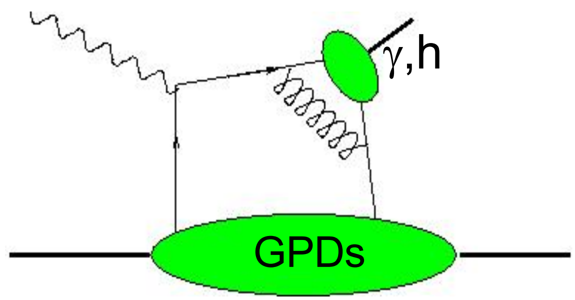
quark polarization

N/q (nucleon pol.)	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	$h_1, h_{1T}^{\perp}$

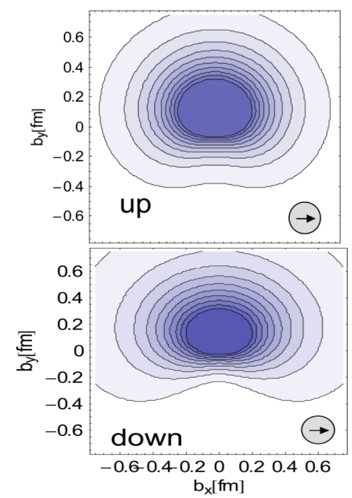


Hard exclusive processes and spatial distributions of partons





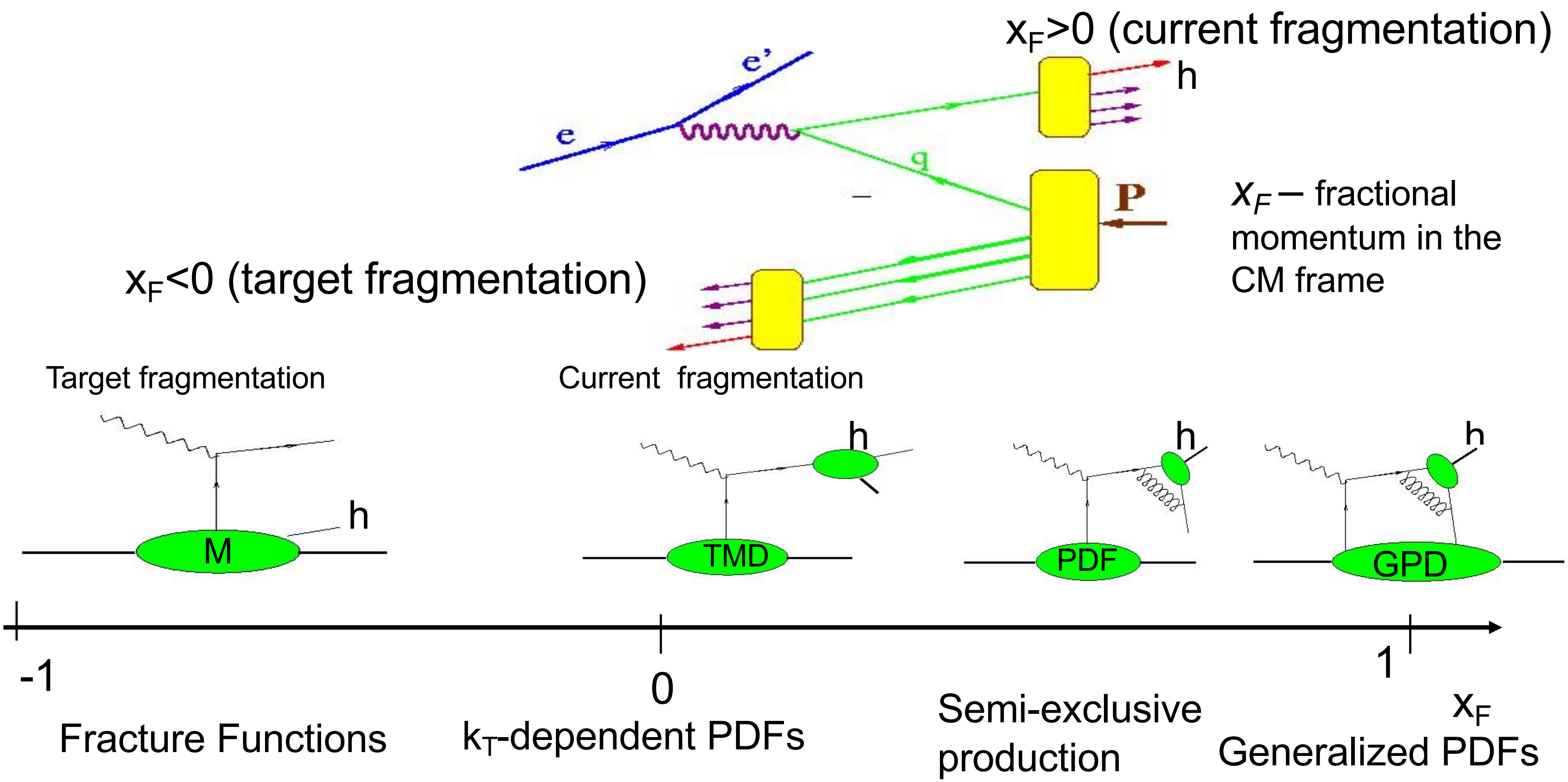
N/q	U	L	T
U	H		$\mathcal{E}_T$
L		$\widetilde{H}$	
T	E		$H_T, \widetilde{H}_T$



(QCDSF)

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

Electroproduction: extending 1D PDFs



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

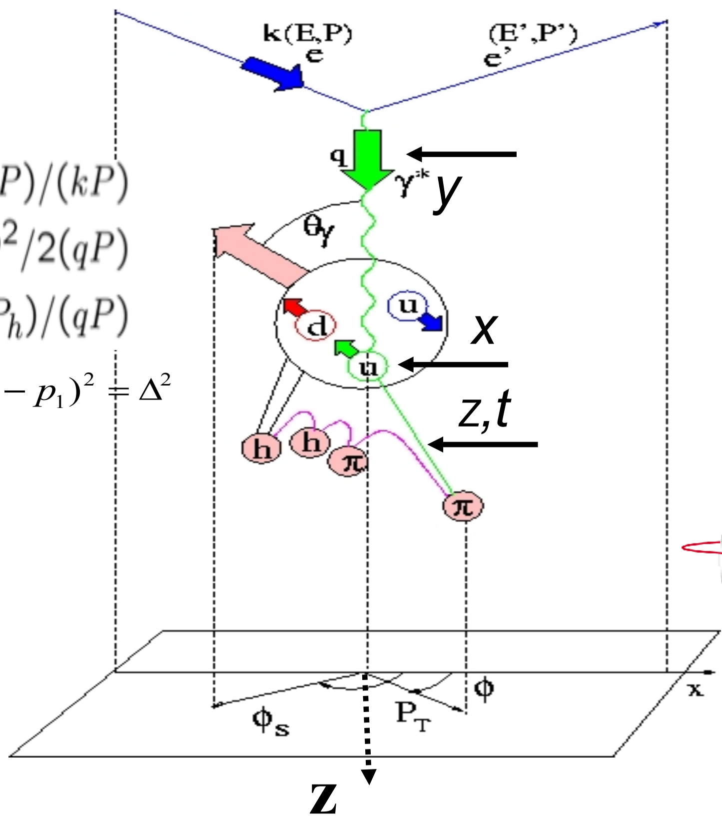
Electroproduction: kinematics and detectors

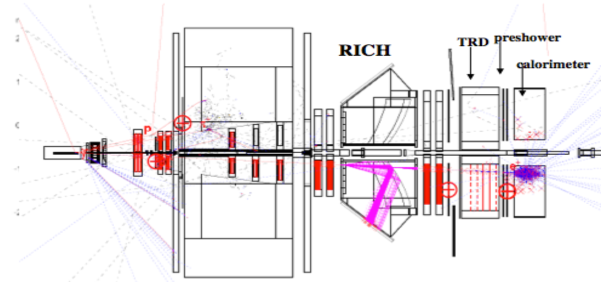
$y = (qP)/(kP)$

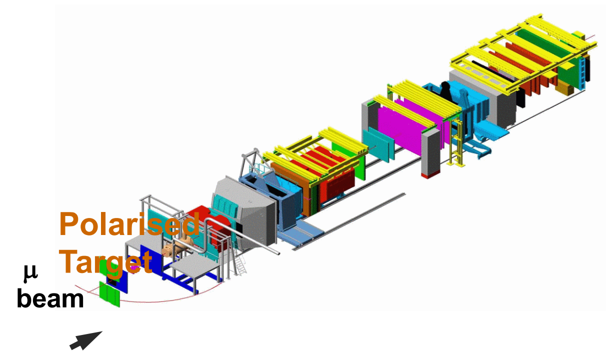
$x = Q^2/2(qP)$

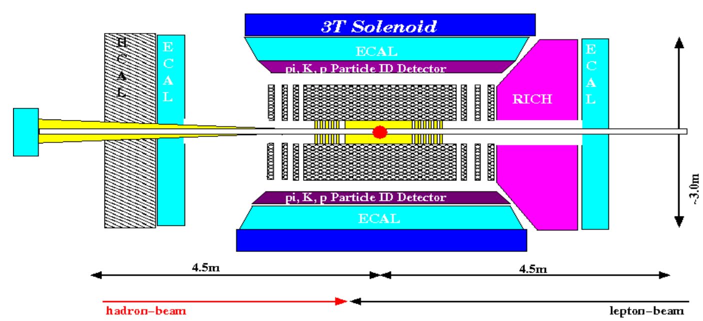
$z = (qP_h)/(qP)$

$t = (p_2 - p_1)^2 = \Delta^2$









x-section/multiplicity

spin-azimuthal asymmetries

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

Azimuthal modulations depend on structure functions, providing information on underlying correlations of spins with partonic momentum and space distributions

12 GeV Approved Experiments by Physics Topics

Topic (status: May 2021)	Hall A	Hall B	Hall C	Hall D	Other	Total
Hadron spectra as probes of QCD	0	2	1	4	0	**7**
Transverse structure of the hadrons	7	4	3	1	0	**15**
longitudinal structure of the hadrons	1	3	7	1	0	**12**
3D structure of the hadrons	5.5	9	6.5	0	0	**21**
Hadrons and cold nuclear matter	9	6	7	1	0	**23**
Low-energy tests of the Standard Model and Fundamental Symmetries	3	1	0	1	1	**6**
Total	**25.5**	**25**	**24.5**	**8**	**1**	**84**
Total Experiments Completed	**9.0**	**9.7**	**7.3**	**1.5**	**0**	**27.5**
Total Experiments Remaining	**16.5**	**15.3**	**17.2**	**6.5**	**1.0**	**56.5**

~10 years

JLab 2015 Science & Technology review closeout bullets:
- develop an integrated picture of what measurements are necessary and will be conducted in determining the GPDs and TMDs
- develop milestones for extraction of GPDs and TMDs from experiment

GPDs and CFFs: Accessing OAM

$$\left\{\mathcal{H},\mathcal{E},\mathcal{H}^3_+,\mathcal{E}^3_+,\widetilde{\mathcal{H}}^3_-,\widetilde{\mathcal{E}}^3_-\right\}(\xi) = \int_{-1}^{1} dx\, C^{(-)}(\xi,x)\left\{H,E,H^3_+,E^3_+,\widetilde{H}^3_-,\widetilde{E}^3_-\right\}(x,\eta)_{|\eta=-\xi}$$

$$\left\{\widetilde{\mathcal{H}},\widetilde{\mathcal{E}},\widetilde{\mathcal{H}}^3_+,\widetilde{\mathcal{E}}^3_+,\mathcal{H}^3_-,\mathcal{E}^3_-\right\}(\xi) = \int_{-1}^{1} dx\, C^{(+)}(\xi,x)\left\{\widetilde{H},\widetilde{E},\widetilde{H}^3_+,\widetilde{E}^3_+,H^3_-,E^3_-\right\}(x,\eta)_{|\eta=-\xi}$$

Perturbatively calculable coefficients

$$C^{(\mp)}F \to \sum_{i=u,d,s} C_i^{(\mp)}F_i$$

Recover GPDs from CFFs

Calculate angular momentum distribution (Ji)

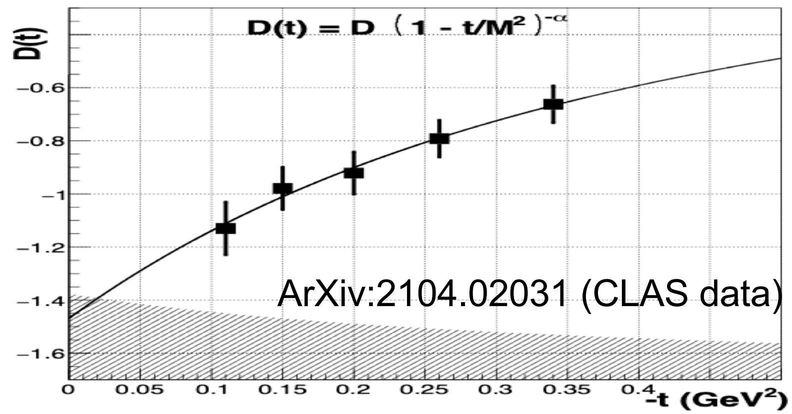
$$\lim_{t\to 0}\int_{-1}^{1} dx\, x\left(H^a(x,\xi,t)+E^a(x,\xi,t)\right) = 2J^a(0)$$

Mellin moments of unpolarized GPDs yield the EMT form factors (1805.06596)

$$\int_{-1}^{1} dx\, x\, H^a(x,\xi,t) = A^a(t) + \xi^2 D^a(t)$$

Extract force and pressure distributions

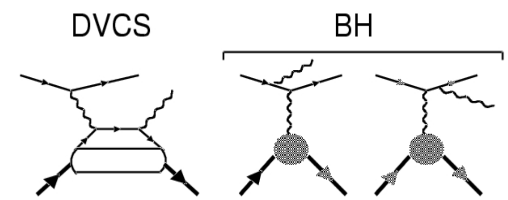
$$D = -\frac{4m}{15}\int d^3r\, r^2\, s(r) = m\int d^3r\, r^2\, p(r)$$



ArXiv:2104.02031 (CLAS data)

- Extraction of CFFs from data allows extractions of GPDs and EMT form factors opening access to fundamental properties, like mass, pressure, forces in nucleon
- Understanding of the systematics in extraction of CFFs in limited kinematics and further propagation to other observables requires detailed simulations !!!

Deeply Virtual Compton Scattering ep→e'p'γ



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

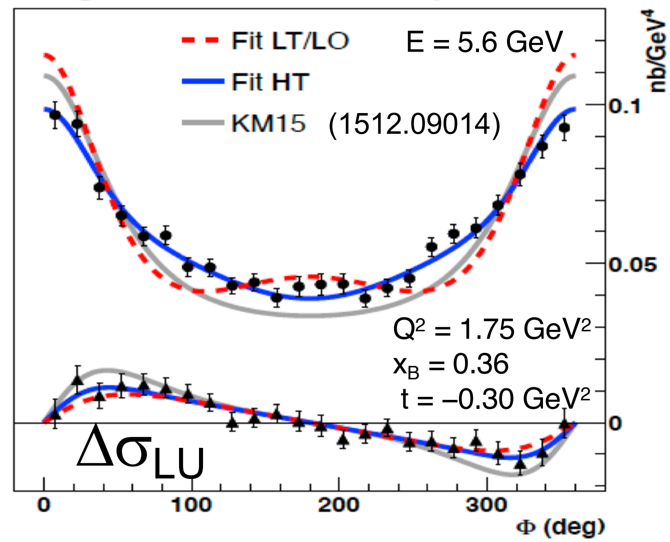
$$\mathcal{I} = \frac{\pm e^6}{x_{\rm B} y^3 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\mathcal{I}} + \sum_{n=1}^{3} \left[c_n^{\mathcal{I}} \cos(n\phi) + s_n^{\mathcal{I}} \sin(n\phi) \right] \right\},$$

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

s_2^I

$$\Delta\sigma_{LU} \sim \sin\phi\{F_1 H(\xi,\xi,t) + \xi(F_1+F_2)\tilde{H} + kF_2 E\}$$

$$\Delta\sigma_{UL} \sim \sin\phi\{F_1 \tilde{H} + \xi(F_1+F_2)(H + ..\ \}$$



Hall-A: 1504.05453 (LU)
Hall-B: 1501.07052 (UL)

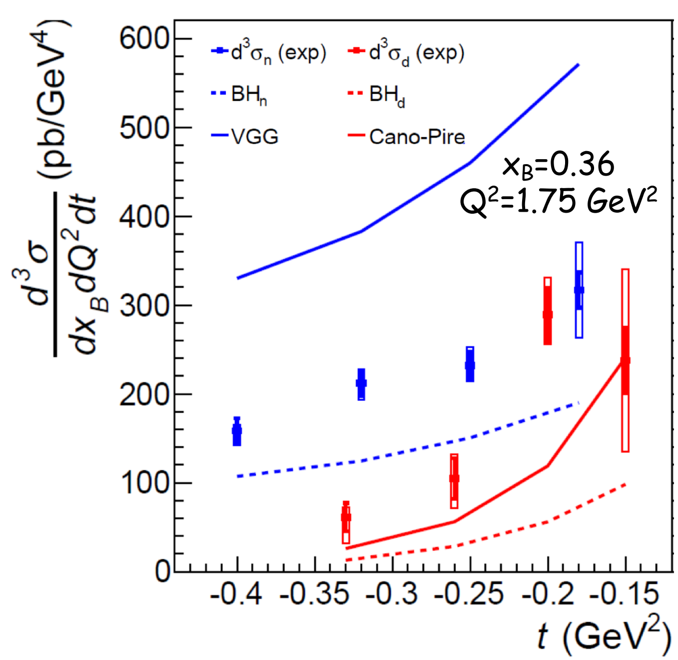
- Interference responsible for SSA, contain the same lepton propagator $P_1(\phi)$ as BH
- Different contributions have different kinematical dependences
- Higher twist contributions may be important in separation of DVCS

Hall-A:DVCS off the neutron (en→enγ)

C.M. Camacho

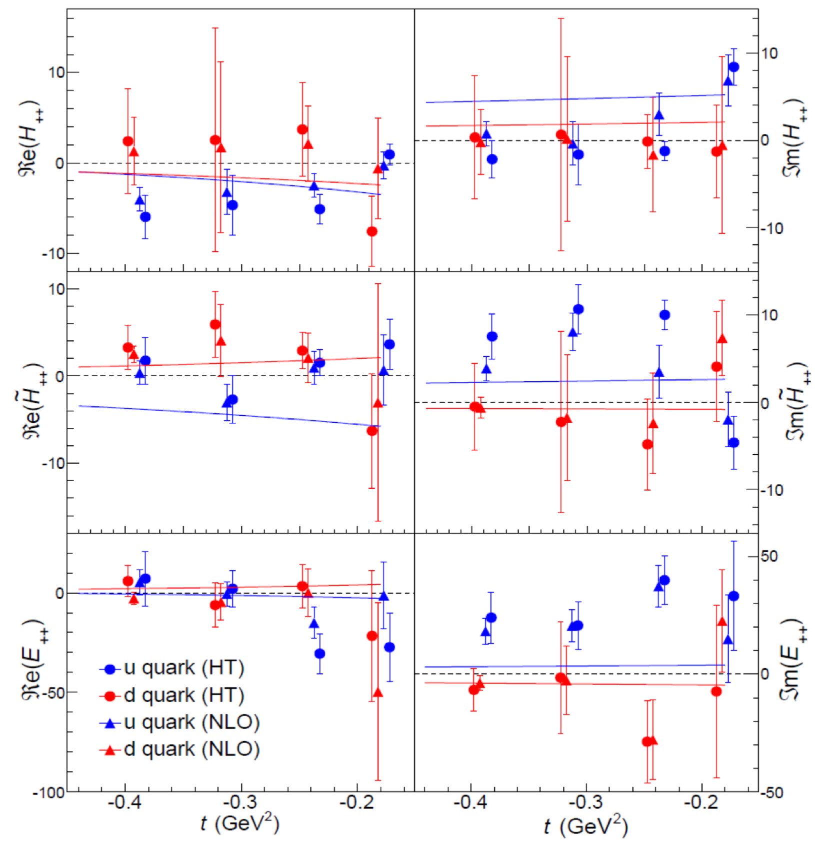
$$D(e,e\gamma)X - p(e,e\gamma)p = n(e,e\gamma)n + d(e,e\gamma)d$$

- JLab Hall A experiment E08-025: DVCS off an LD2 target
- Quasi-free *p* events subtracted using normalized LH2 data
- Coherent DVCS off *d* separated using $ed \to e\gamma X$ missing mass



Nature Physics 16, 191 (2020)

- 1st observation of DVCS off the neutron
- Sizeable cross section (significantly larger than BH)

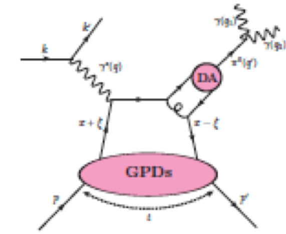


- Flavor separation of Compton Form Factors by combining proton and neutron DVCS data
- Uncertainties dominated by correlations originating from the (partial) separation of the coherent *d*-DVCS channel

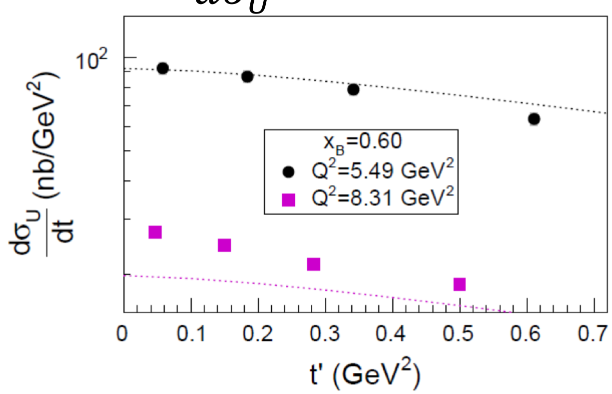
Hall-A: Exclusive π^0 electroproduction ($ep \to ep\pi^0$)

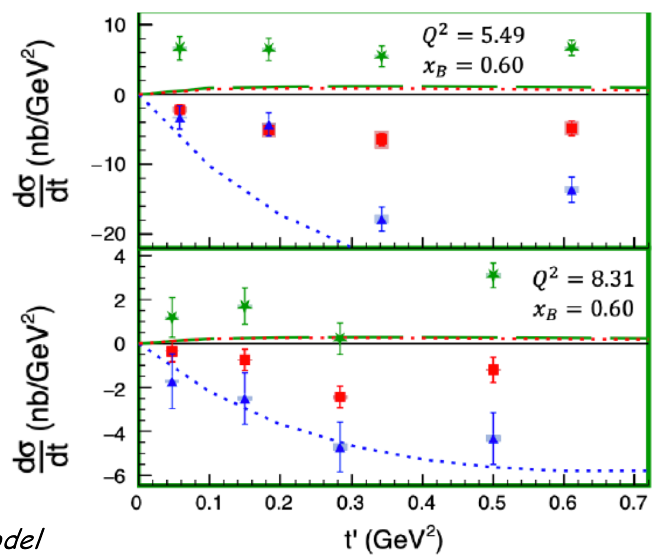
C.M.Camacho

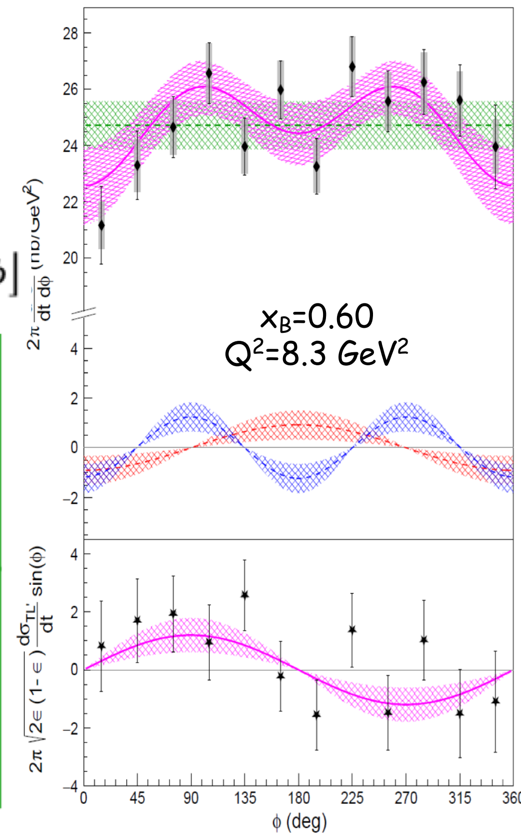
- JLab Hall A experiment E12-06-114 at 11 GeV
- Cross-section measurements up to large values of x_B and Q^2
- Dominance of the transverse cross section ($d\sigma_{TT} \gg d\sigma_{TL}, d\sigma_{TL'}$)
- Values well described by the modified factorization approach (Goloskokov, Kroll): access to *transversity GPDs*



$$d^4\sigma = \frac{\Gamma}{2\pi}\left[\underbrace{d\sigma_T + \epsilon d\sigma_L}_{d\sigma_U} + \sqrt{2\epsilon(1+\epsilon)}\,d\sigma_{TL}\cos\phi + \epsilon\, d\sigma_{TT}\cos\phi + h\sqrt{2\epsilon(1-\epsilon)}\,d\sigma_{TL'}\sin\phi\right]$$







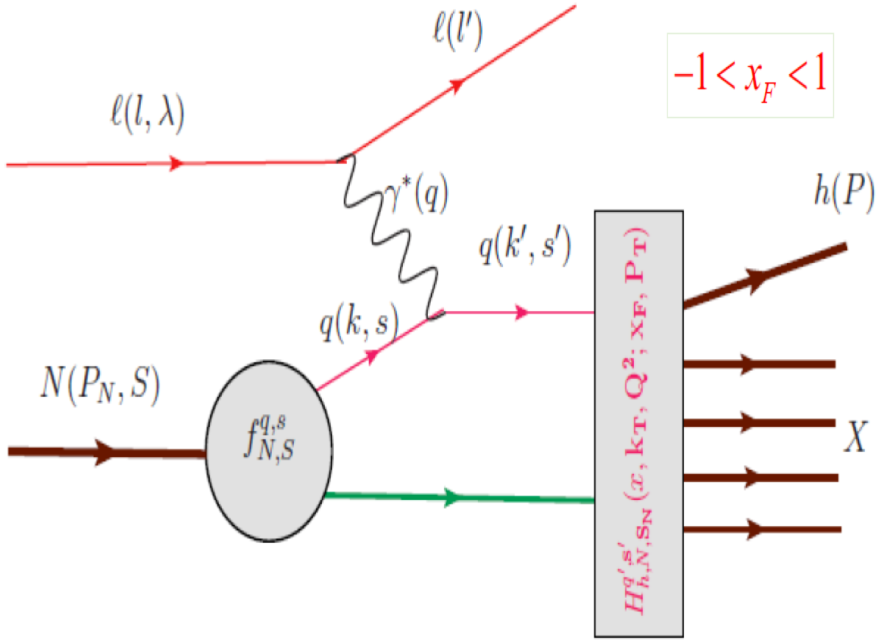
Dotted lines: GK model

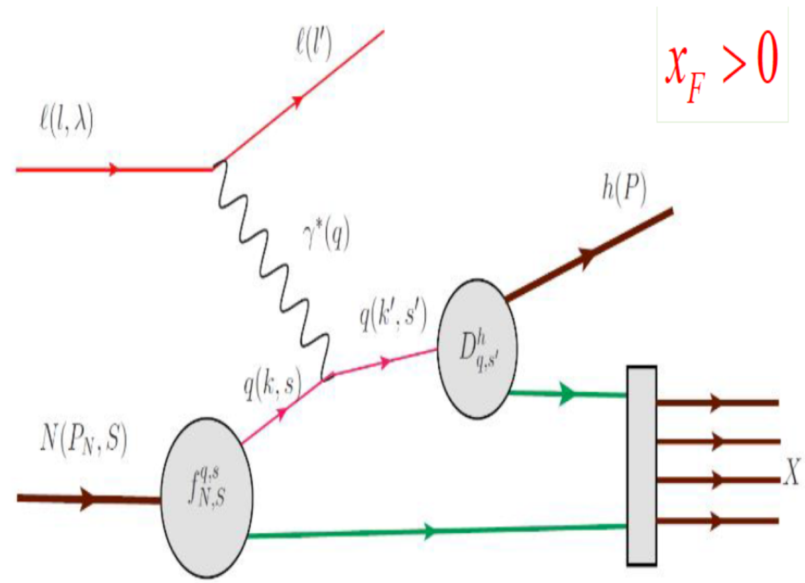
ArXiv:2011.11125

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

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

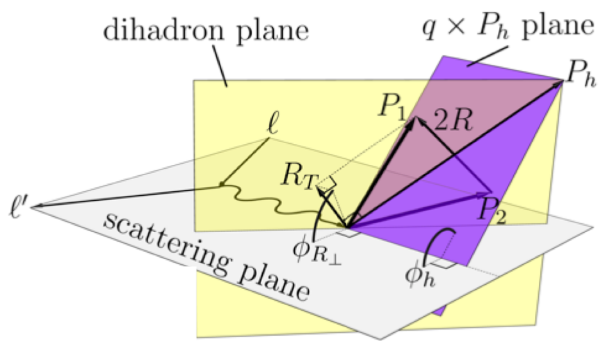
Where this works?

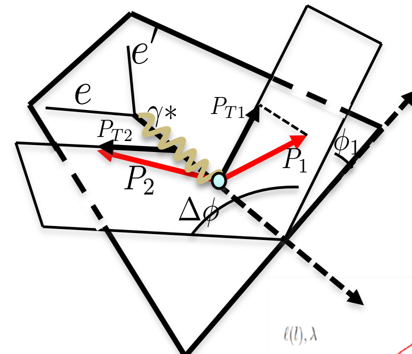
Correlated hadron production in hard scattering

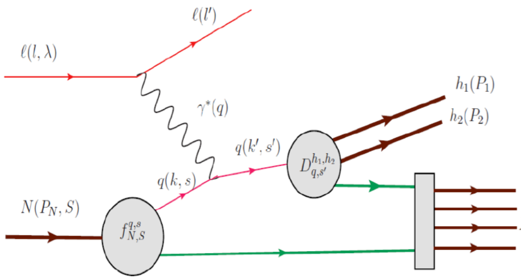
Dedicated CLAS12 proposals: E12-06-112B/E12-09-008B

2 hadrons in current fragmentation

hadrons in current & target fragmentation

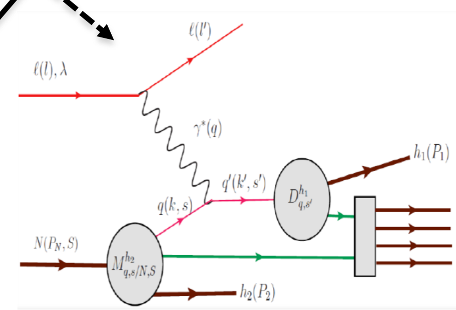






$$P_h = P_1 + P_2,$$

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



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*

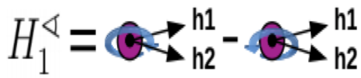
$\phi_R - \phi_h$ -accessing leading twist polarized fragmentation functions *Matevosyan,Kotzinian,Thomas*

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

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

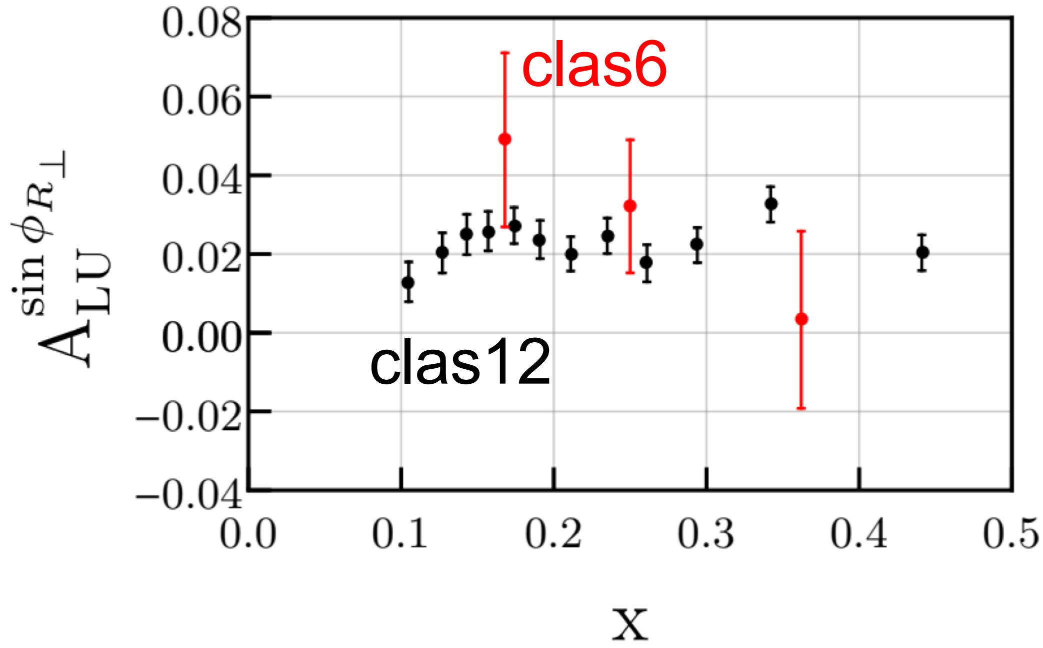
Observation of SSAs in ep→e'$\pi^+\pi^-$X

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

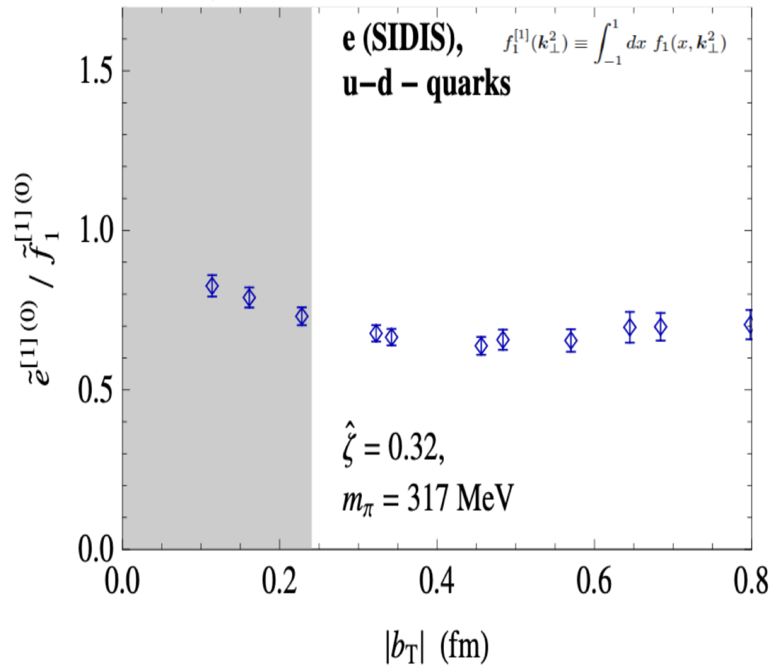


$$d\sigma_{LU} \propto \lambda_e \sin(\phi_{R_\perp}) \left(xe(x) H_1^{\sphericalangle}(z, M_h) + \frac{1}{z} f_1(x) \tilde{G}^{\sphericalangle}(z, M_h) \right)$$

Bacchetta&Radici: arXiv:hep-ph/0311173



Engelhardt: TMDs from JLab to EIC

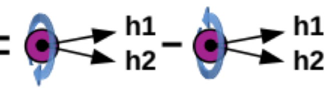


- Doubling the JLab beam energy, opens the phase space for SIDIS dihadrons
- Quark gluon correlations may be very significant
- PDF e describes the force on the transversely polarized quark after scattering

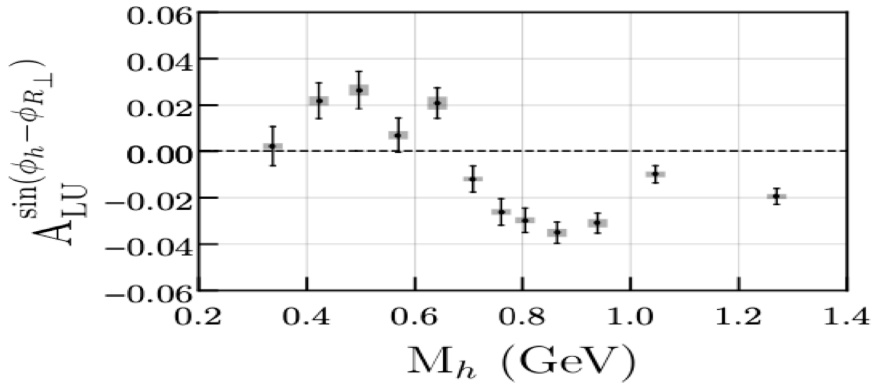
Observation of SSAs in $ep \rightarrow e'\pi^+\pi^-X$

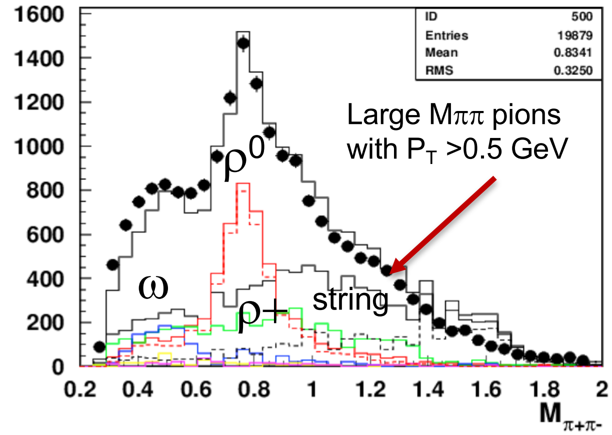
T. Hayward et al. Phys. Rev. Lett. 126, 152501 (2021)

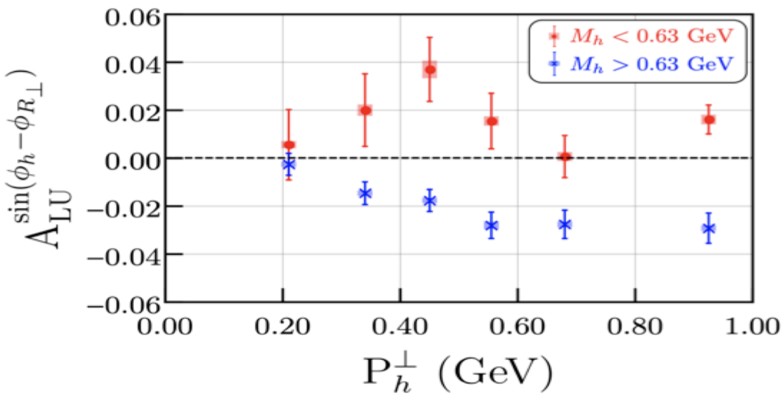
$$d\sigma_{LU} \propto C\lambda_e \sin(\phi_h - \phi_{R_\perp})\mathcal{I}\left[f_1 G_1^\perp\right] + \ldots$$

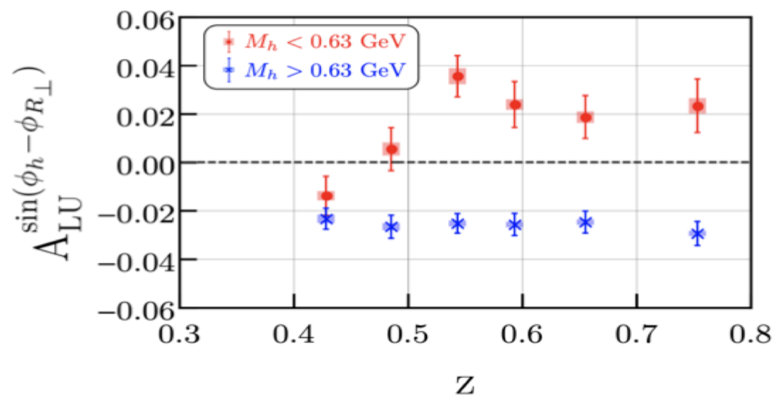
$G_1^\perp =$  a TMD FF

Matevosyan et al, arXiv:1707.04999







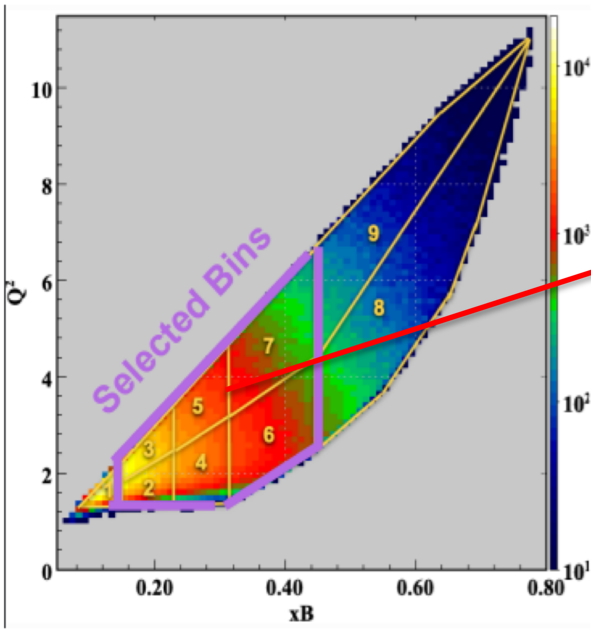


- The 2 hadron sample is dominated by correlated hadrons (VM-decays)
- Spin-orbit correlations change with the source of the hadrons
- TMD theory can't handle currently the P_T of hadrons >~0.5 GeV

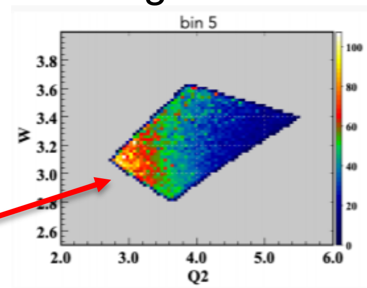
CLAS12 high P_T : impact of vector mesons

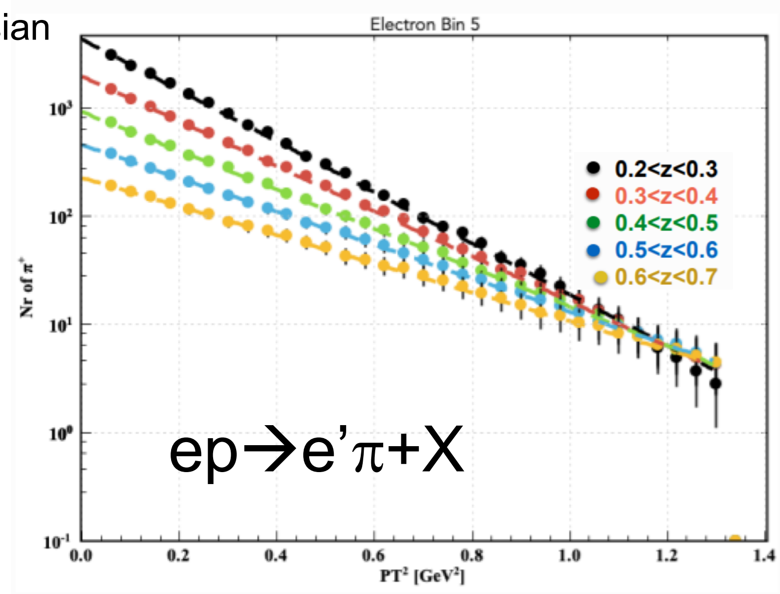
G. Angelini (GW)

Generate direct pions with Gaussian

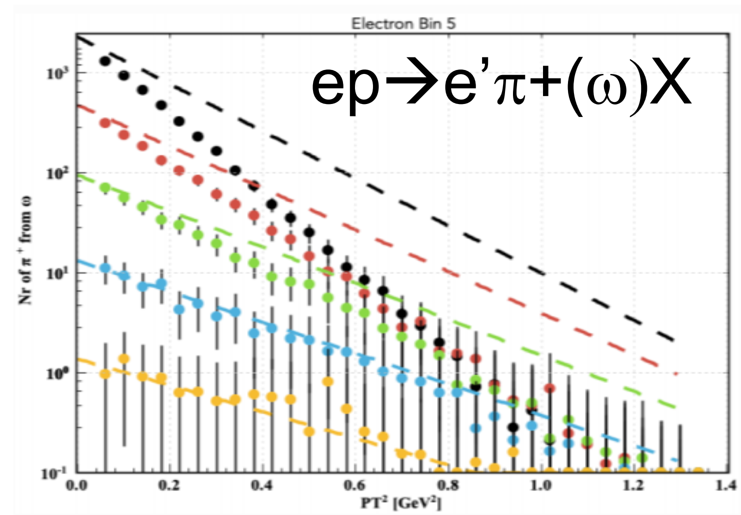


Higher W





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 VMs have significantly lower transverse momentum for the same z

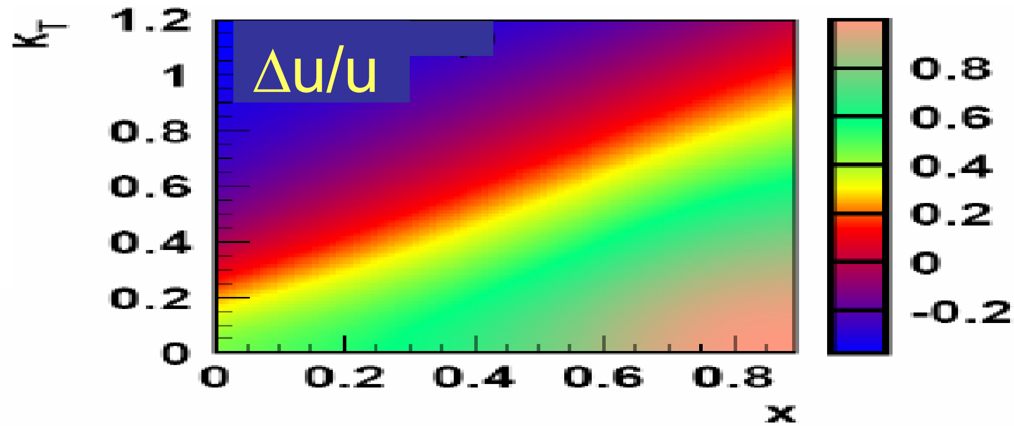
Quark longitudinal polarization

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

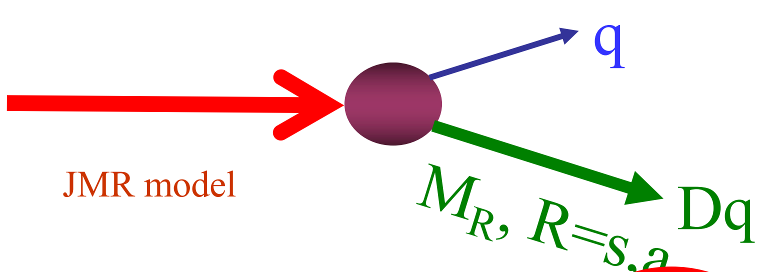
$u^{-}(x,k_T) = f_1^u(x,k_T^2) - g_1^u(x,k_T^2)$

	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)**

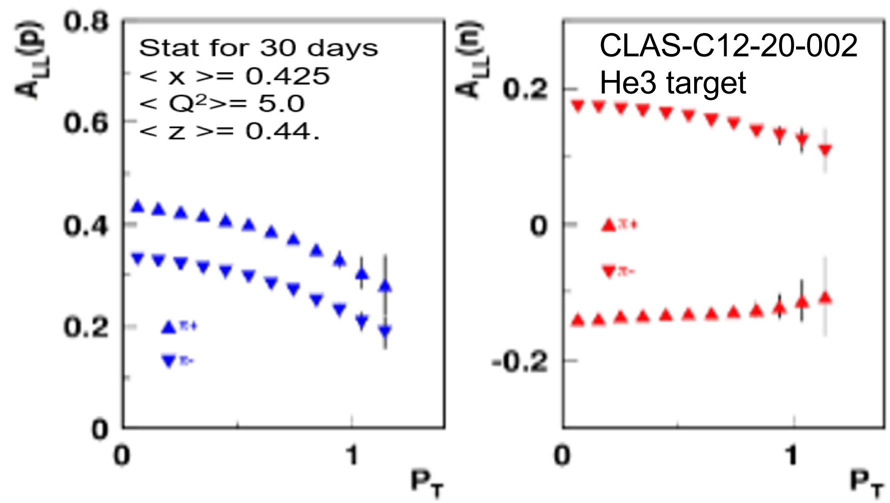


(dipole formfactor), J.Ellis, D-S.Hwang, A.Kotzinian



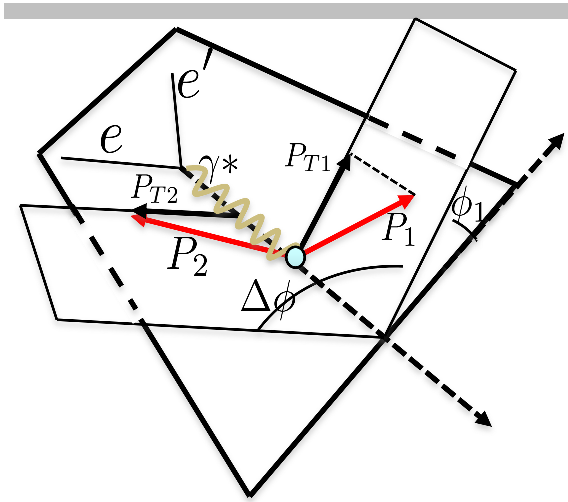
$$f_1(x,\mathbf{k}_T^2) = A\frac{(xM+m)^2 + \mathbf{k}_T^2}{(\mathbf{k}_T^2+\lambda_R^2)^{2a}},$$

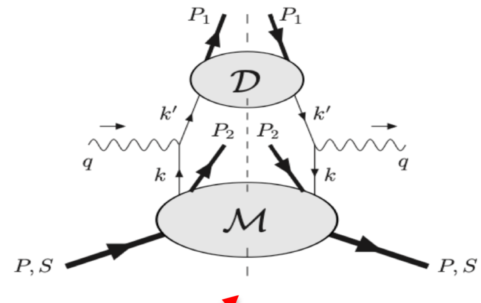
$$g_1(x,\mathbf{k}_T^2) = A\frac{(xM+m)^2 - \mathbf{k}_T^2}{(\mathbf{k}_T^2+\lambda_R^2)^{2a}},$$



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

Back-to-back SSAs ep→pπ$^+$X





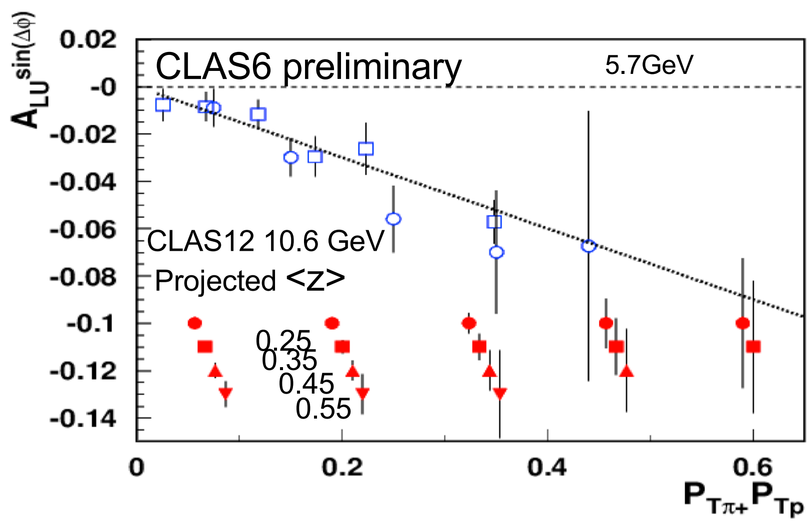
Fracture Functions define the probability for hadron production (P2) given the struck quark q. Combined with the fragmentation function (defining probability for quark q to produce a hadron (P1) defines the x-section for 2 hadron production.

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

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

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

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



- 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,..)

Summary

- Studies of azimuthal distributions of finals state semi-inclusive and exclusive hadrons and photons provide access to complex 3D nucleon structure with variety of spin-orbit correlations

- Spin dependent and independent cross sections have been measured by JLab experiments (Hall-A,HallB) for exclusive photon and pi0 production off proton and neutron allowing flavor separation of underlying chiral even and chiral odd GPDs (CFFs)

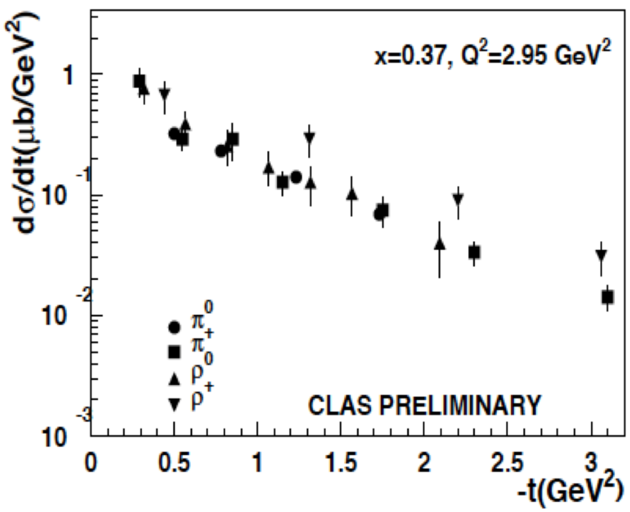
- Measurements of dihadron multiplicities at JLab indicate that hadronization of quarks goes predominantly through production of Vector Mesons (applies to Kaons a well)

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

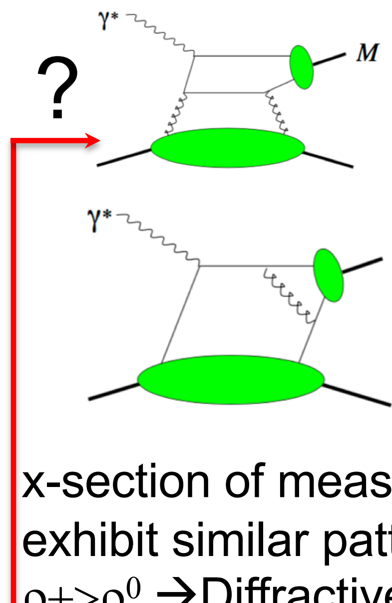
- Progress in theory and lattice calculations in describing the higher twist observables will be crucial for future precision studies of the 3D structure of nucleon using the GPD and TMD formalisms.

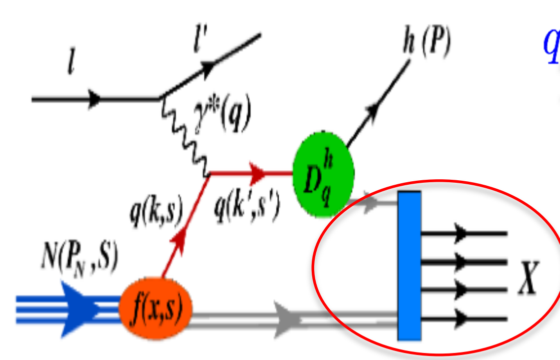
- Detailed simulations of the full ϕ-dependent cross section will be important for proper estimates of the systematics of extracted moments, and final extraction of physics observables (space and momentum distributions, forces, pressure,…)

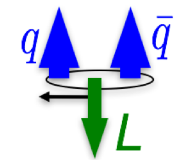
Exclusive π/ρ production at large x/t



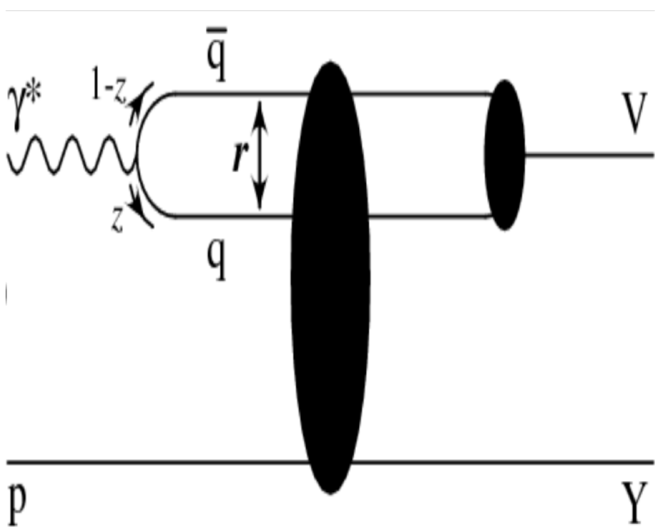
?







p,n



Implications

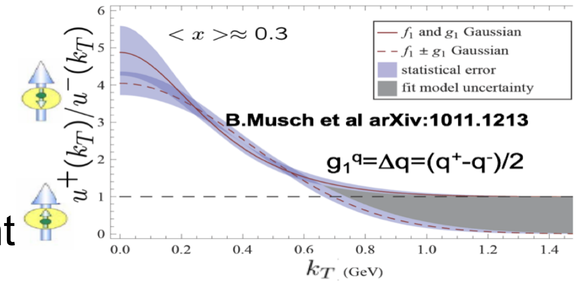
x-section of measured exclusive process at large t exhibit similar pattern

- $\rho^+ > \rho^0$ →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)?
- ....

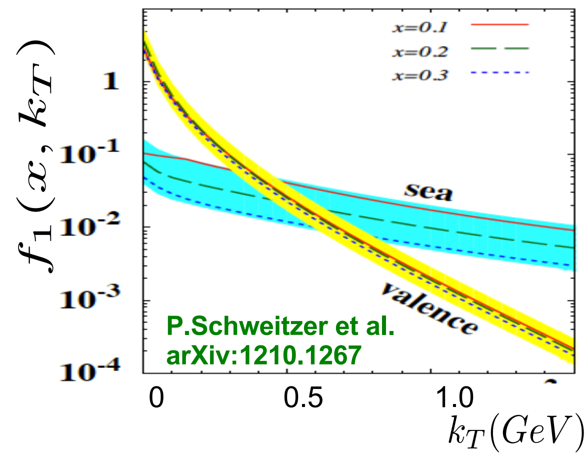
Extending to small x, large Q2 and large P_T

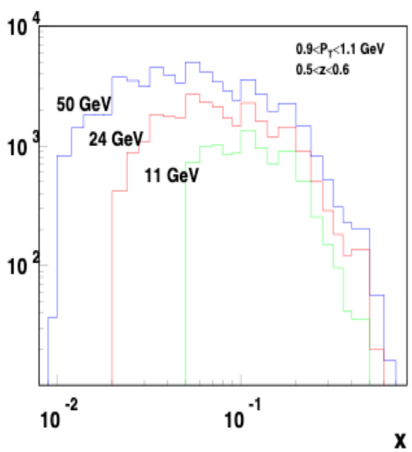
Non-perturbative sea ("tornado") in nucleon is a key to understand the nucleon structure

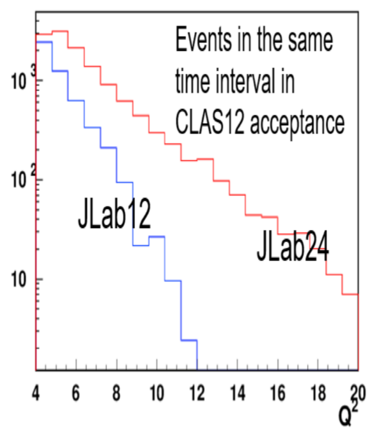
$\bar{d} > \bar{u}$

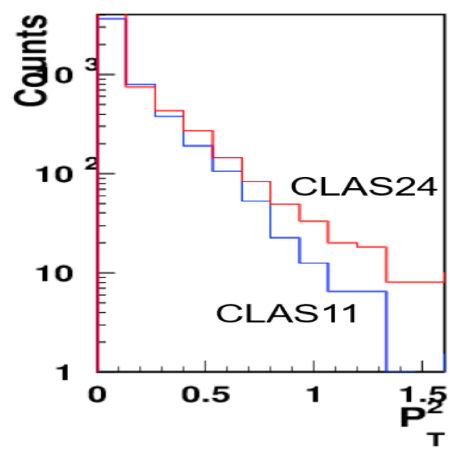


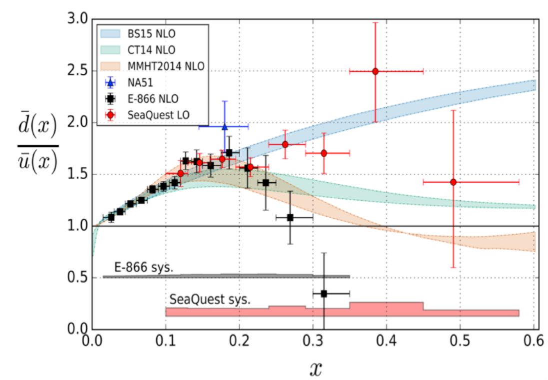
- Spin and momentum of struck quarks are correlated with remnant
- Correlations of spins of q-q-bar with valence quark spin and transverse momentum will lead to observable effects
- Spin-Orbit correlations so far were shown (measurements and model calculations) to be significant in the region where non-perturbative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







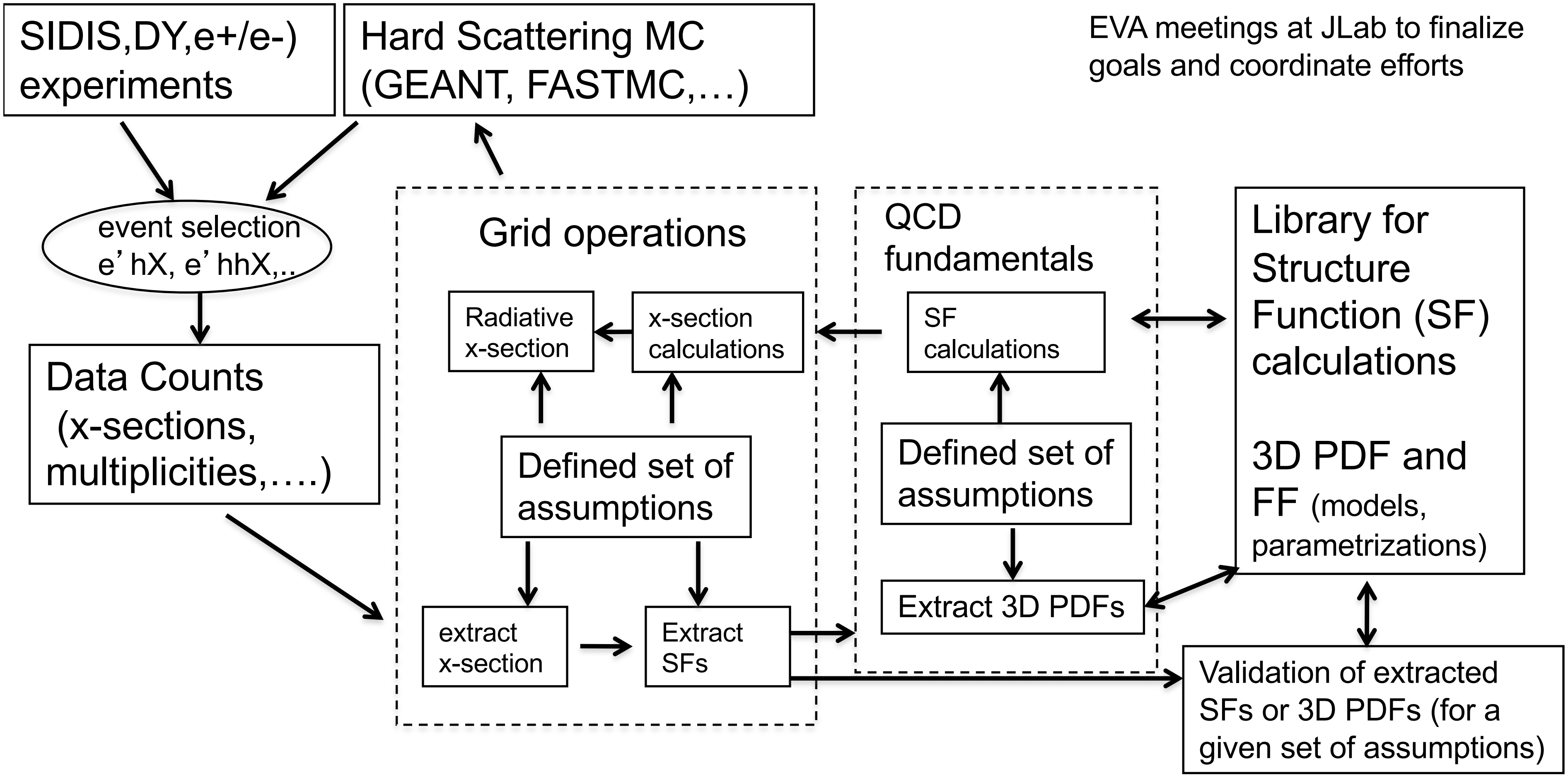




Upgrade to 24 GeV will qualitatively increase the JLab phase space, opening access to large P_T, high Q^2 and low x (sea) region

3D PDF Extraction and VAlidation (EVA) framework

EVA meetings at JLab to finalize goals and coordinate efforts



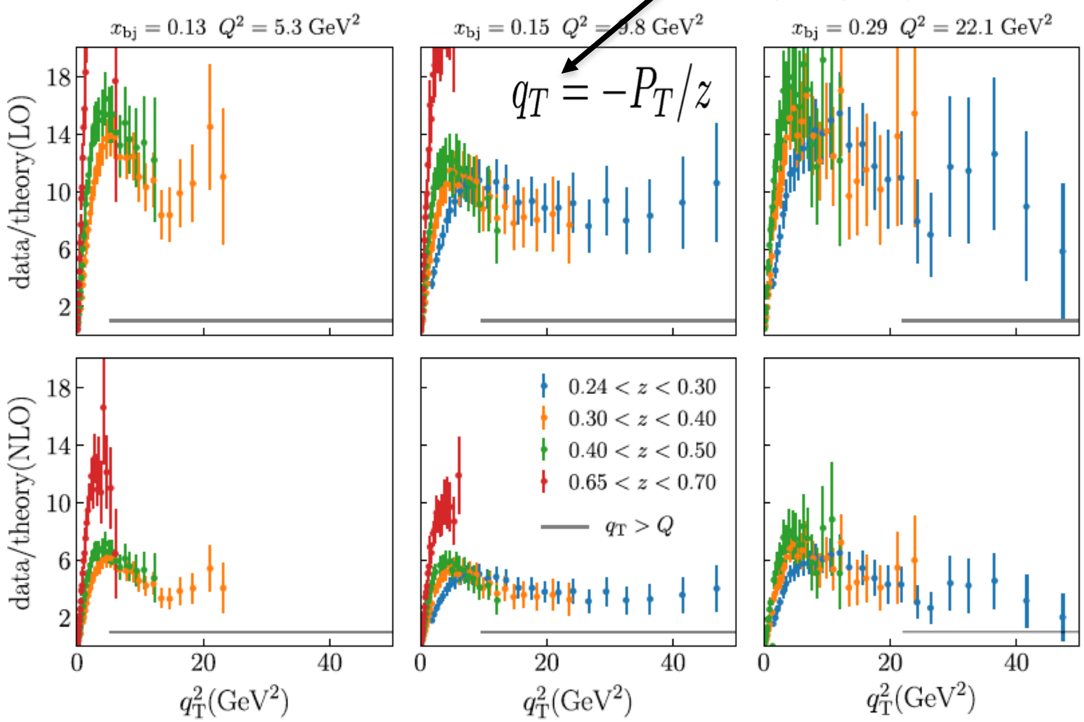
Development of a reliable techniques for the extraction of 3D PDFs and fragmentation functions from the multidimensional experimental observables with controlled systematics requires close collaboration of experiment, theory and computing

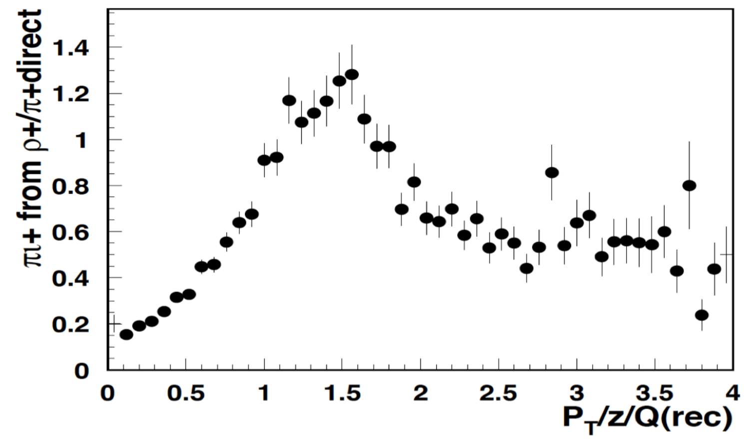
TMD formalism applicability and the impact of q_T cut

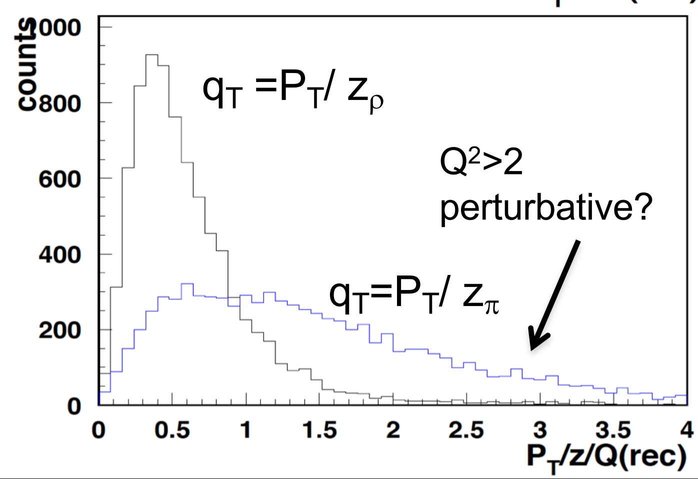
$$F^h_{XY}(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}(M/Q)$$

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

quark transverse momentum







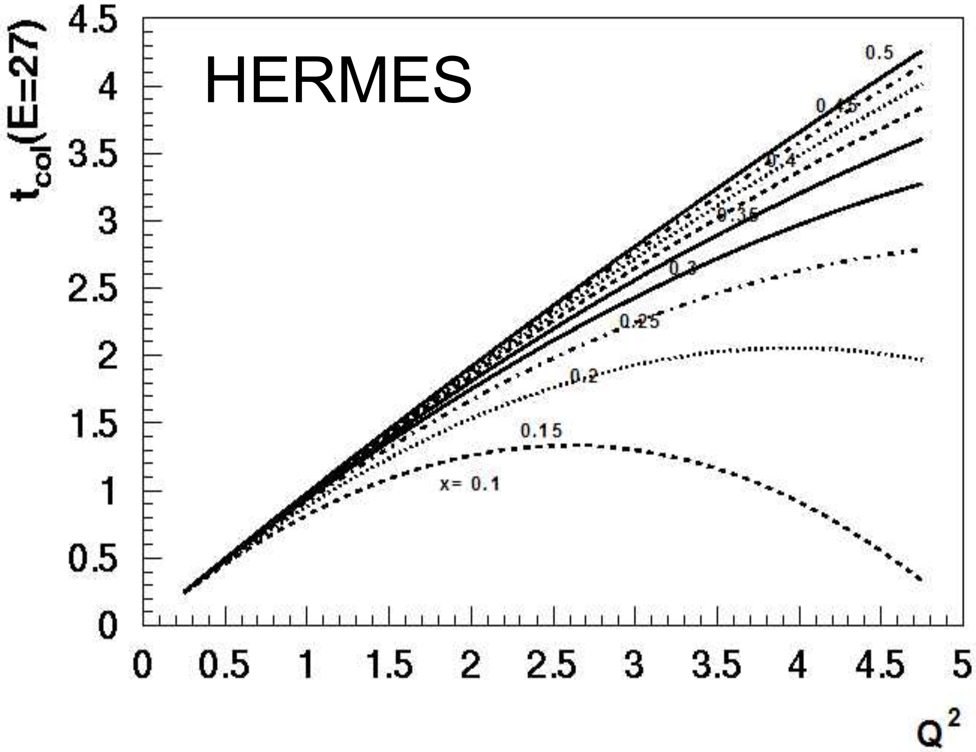
The measurements disagree with leading order and next-to-leading order calculations most significantly at the more moderate values of **x** close to the valence region.

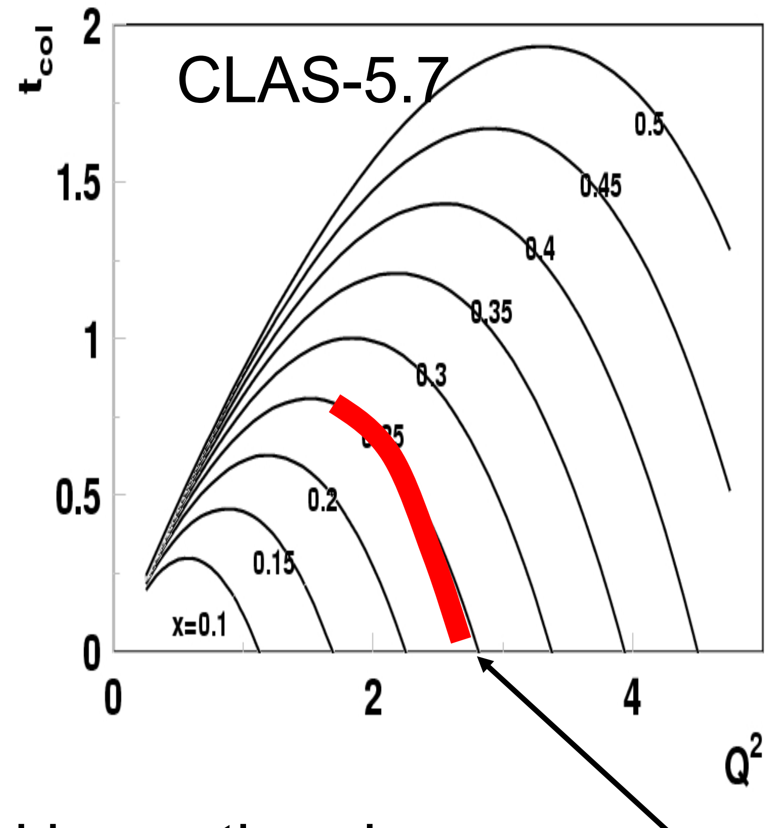
Gonzalez-Hernandez et al, PRD 98, 114005 (2018)

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

Collinearity kinematics

$$y_{col} = \frac{Q^2 - t}{Q^2 - xt} = y \quad \longrightarrow \quad t_{col} = \frac{Q^2(Q^2 - 2xME)}{(Q^2 - 2ME)x}$$

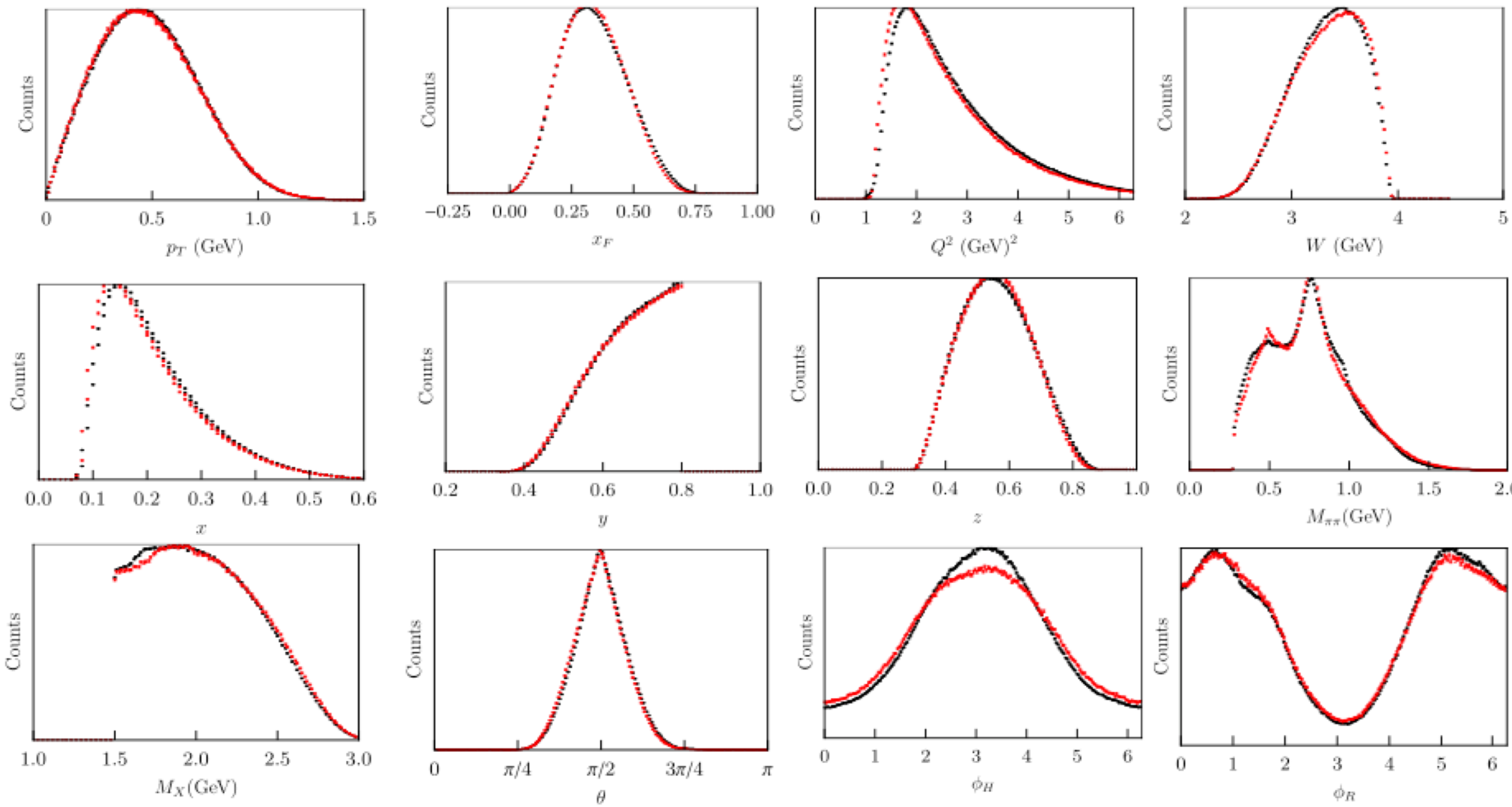




Strong dependence of collinearity kinematics changes region of enhanced **t** as afunction of beam energy

SIDIS ehhX: CLAS12 data vs MC

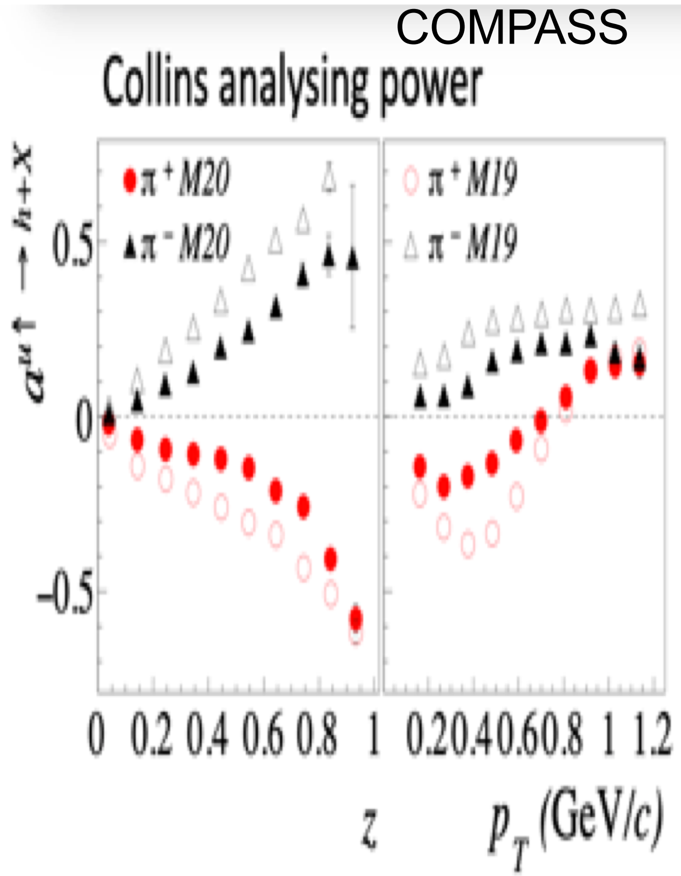
CLAS12 dihadron production ep→ehhX (T.Hayward)

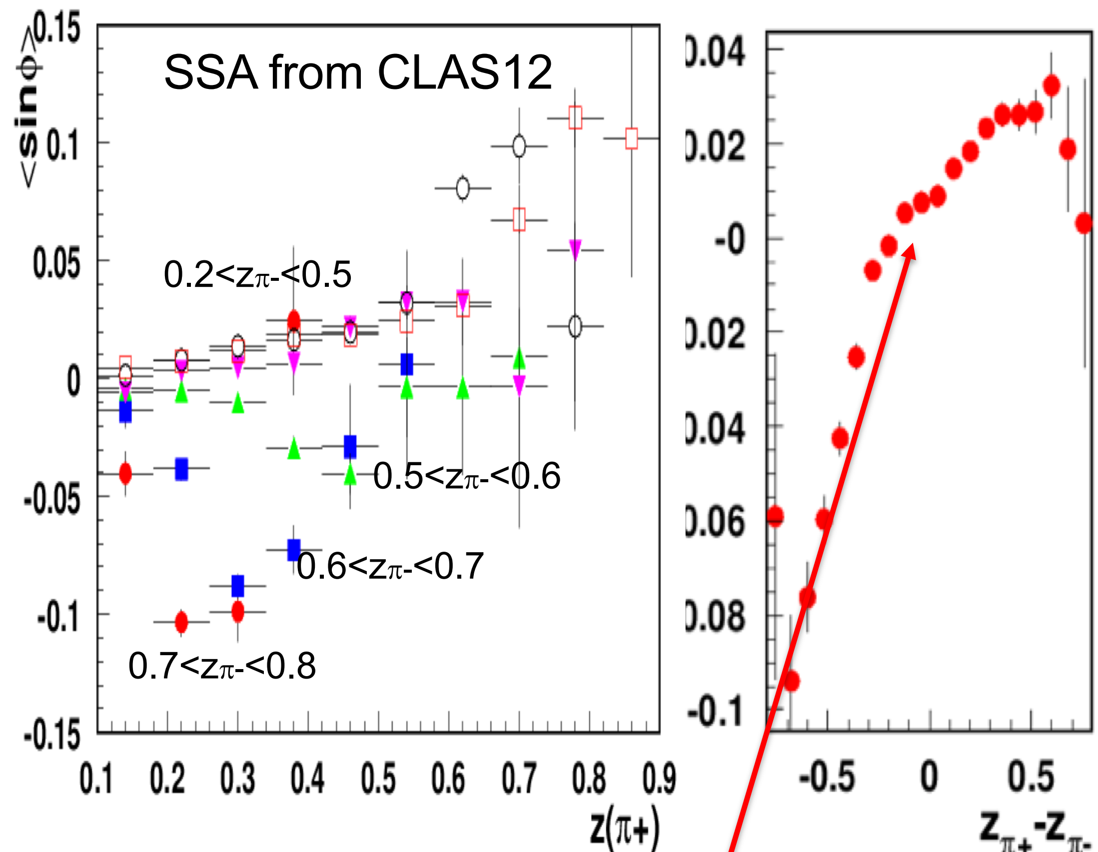


CLAS12 MC, based on the PEPSI(LEPTO) simulation with <u>most parameters "default"</u> is in a good agreement with CLAS12 measurements for all relevant distributions

Disecting the SSA in ep→e'πX

COMPASS





VM contributions may change significantly the interpretation of Collins analyzing power
A. Kerbizi: TMD Studies: from JLab to EIC

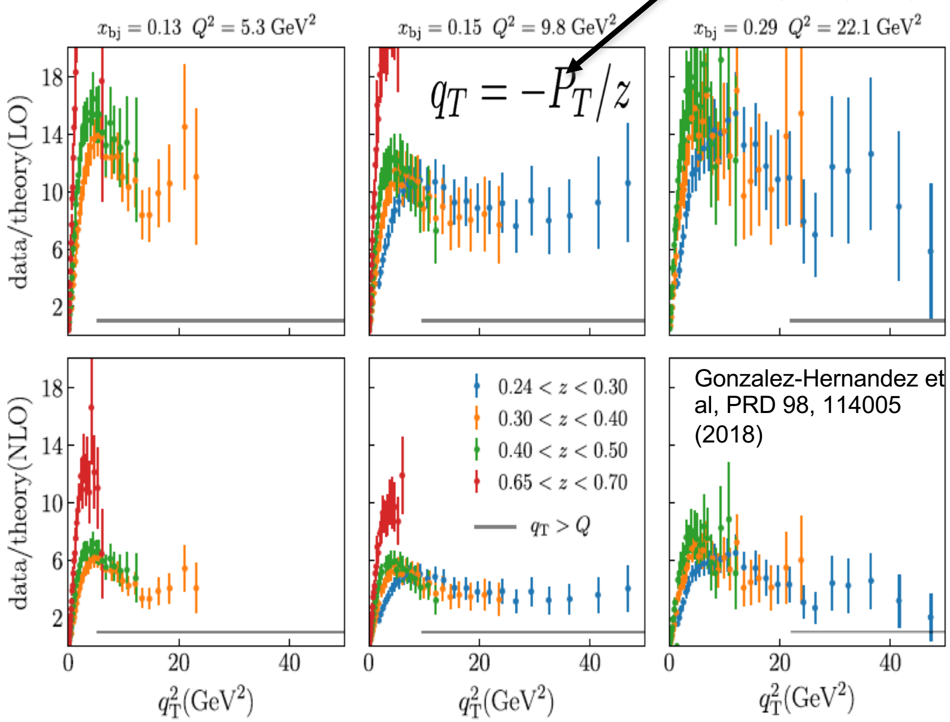
Observed SSA for the inclusive π+ changes significantly with the π- z
The polarization of the ρ itself may be relevant (no SSA for symmetric case)

FO vs data for $q_T \gtrsim Q$

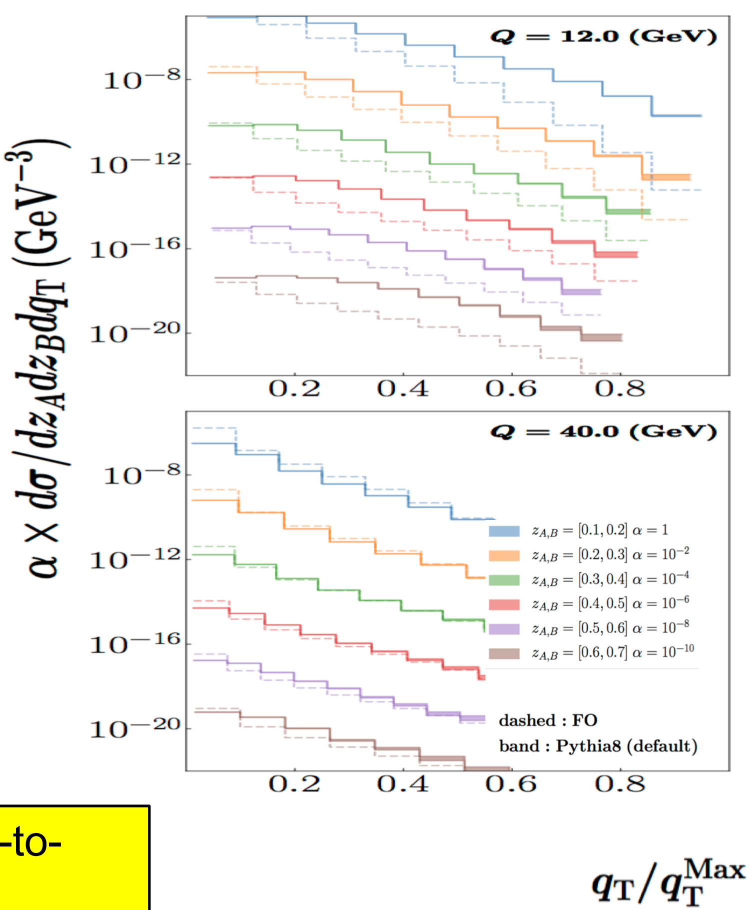
$$F^h_{XY}(x,z,P_T,Q^2) \propto \sum H^q \times f^q(x,k_T,..) \otimes D^{q\to h}(z,p_T,..) + Y(Q^2,P_T) + \mathcal{O}(M/Q)$$

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

quark transverse momentum



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

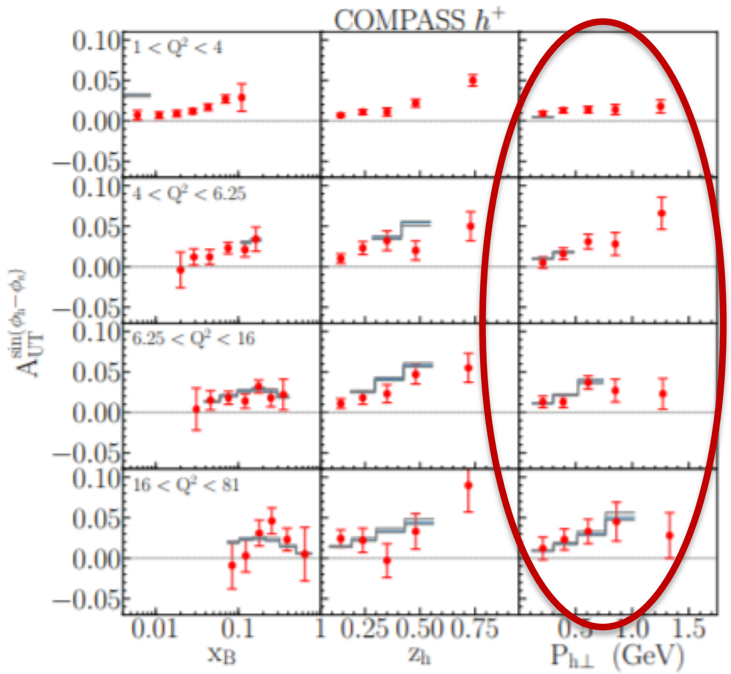


The measurements disagree with leading order and next-to-leading order calculations most significantly at the more moderate values of **x** close to the valence region.

Extracting the average transverse momenta

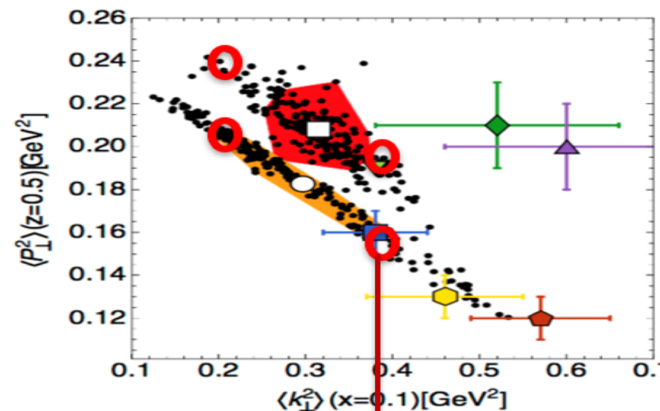
Sivers functions at NLO+NNLL

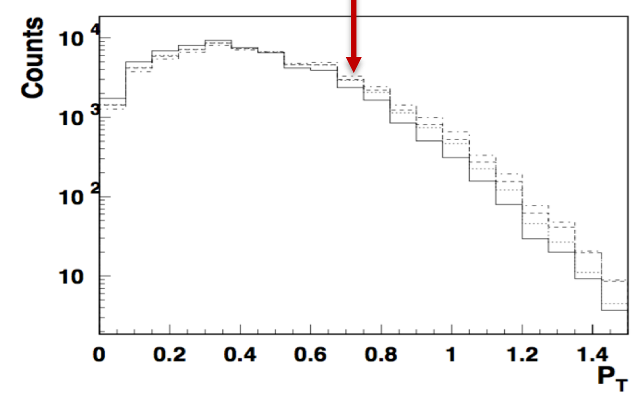
Echevarria,Kang&Terry: JHEP01(2021)126



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

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





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

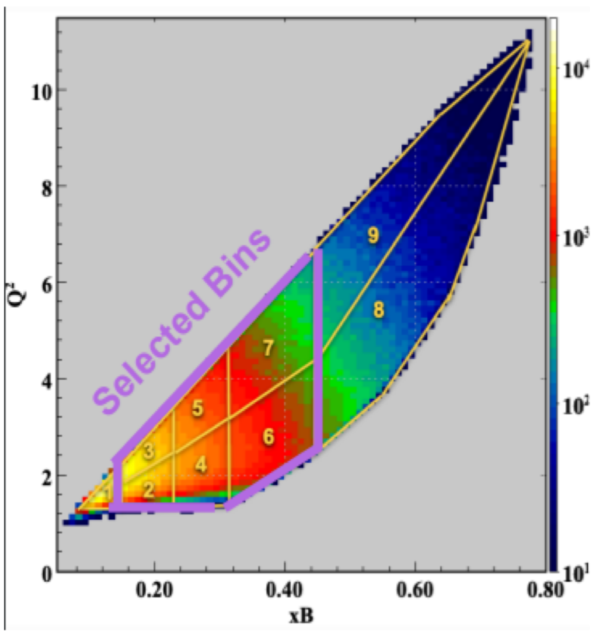
What exactly we learn about high P_T, and can we extrapolate?

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

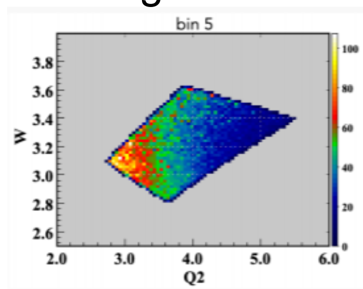
CLAS12 Multiplicities: high P_T & phase space

G. Angelini (GW)

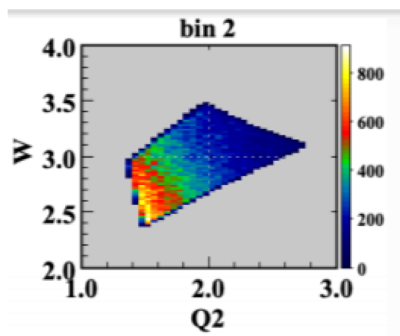
Generate direct pions with Gaussian

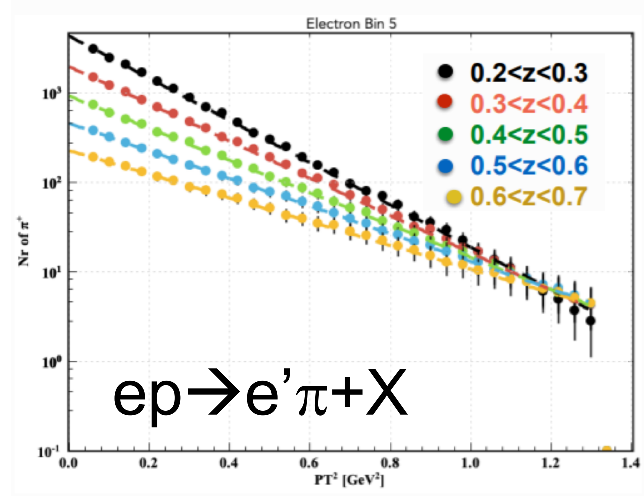


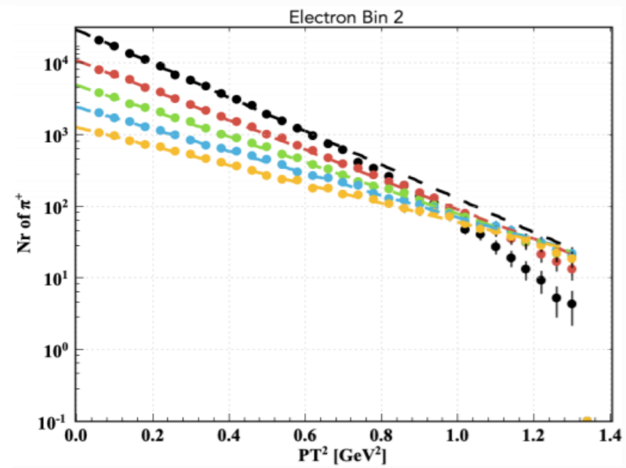
Higher W



Lower W







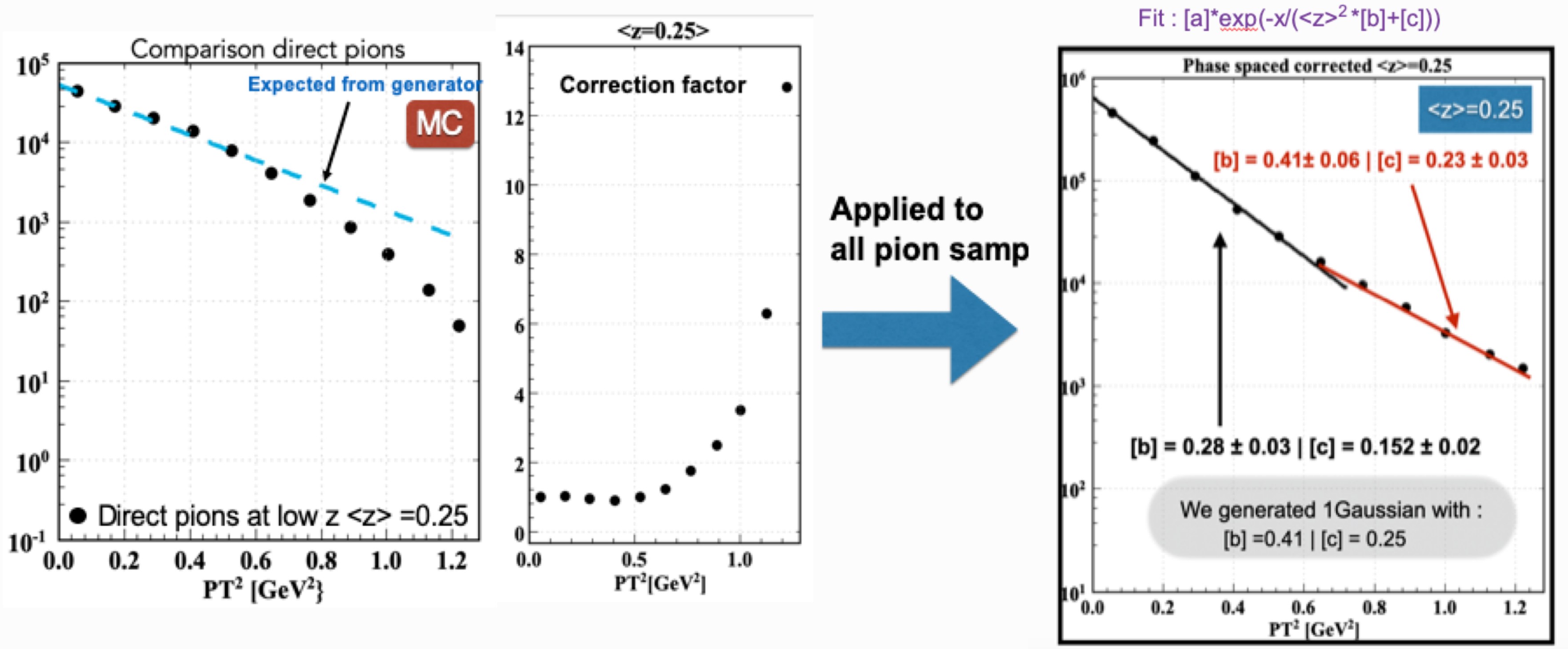
- Phase space limitations for direct pion production more significant at low W, and low z

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)

CLAS12 Multiplicities: the role of high P_T

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

G. Angelini (GW)



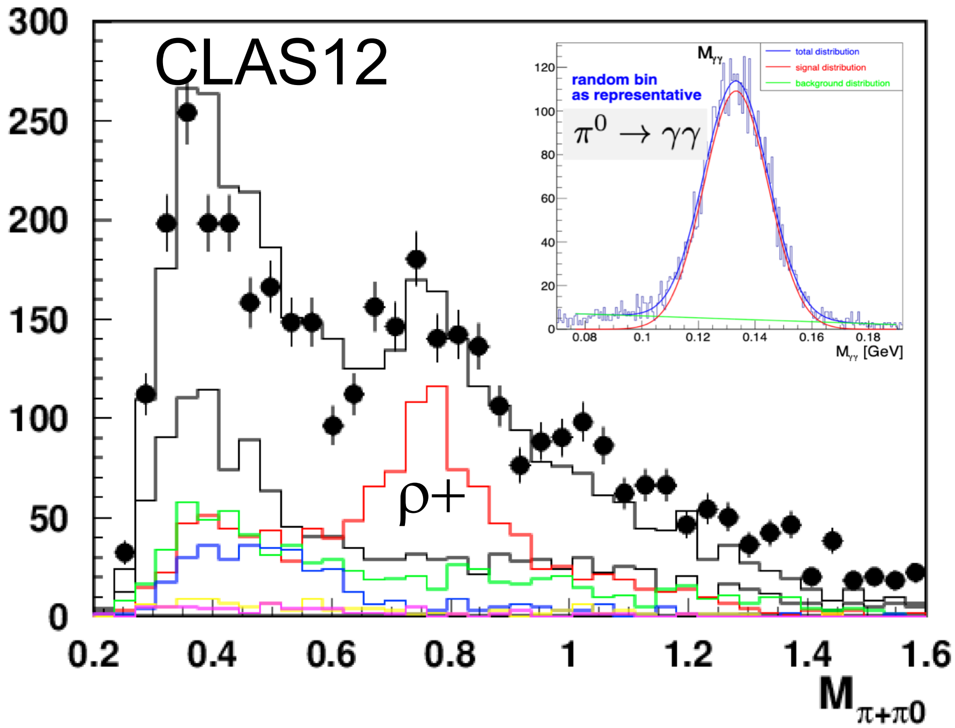
- Corrections due to phase space (energy needed to produce a hadron with a given z, P_T at given x, Q^2) are detector and model independent
- Corrections due to fraction of fragmentation VMs and diffractive VMs are model dependent, but can be extracted from MC

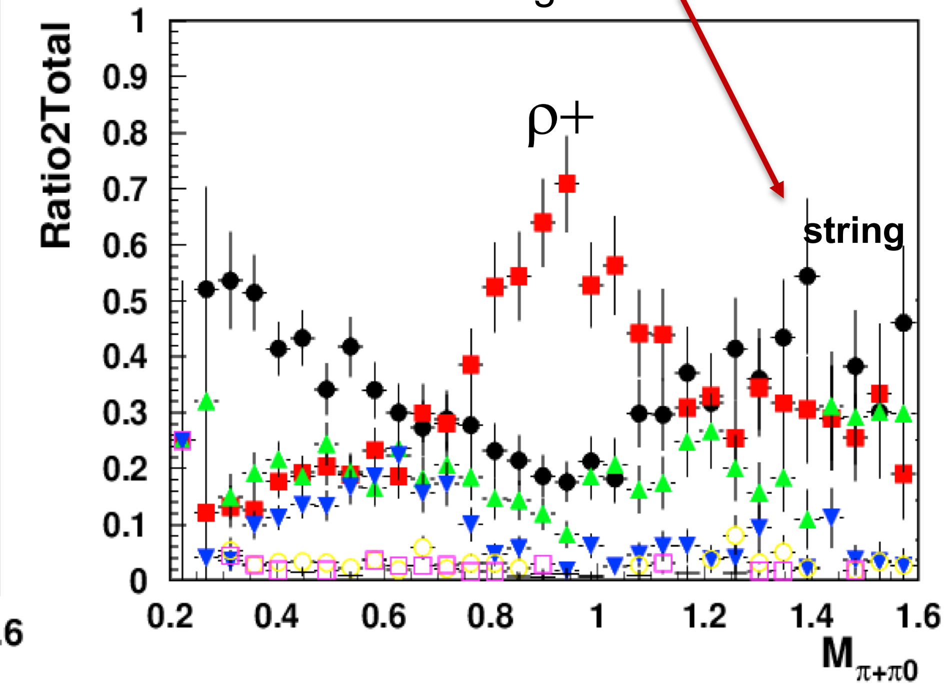
At low z, only the high P_T shows the generated Gaussian transverse momentum distribution.

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+ (red)
- string (black)
- ρ0 (green)
- ω (blue)

Dominant fraction of inclusive pions come from VM decays

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).