TMD studies at JLab: present and future

Giovanni Angelini (GWU) *

Sar WorS 2021 Sardinian Workshop on Spin

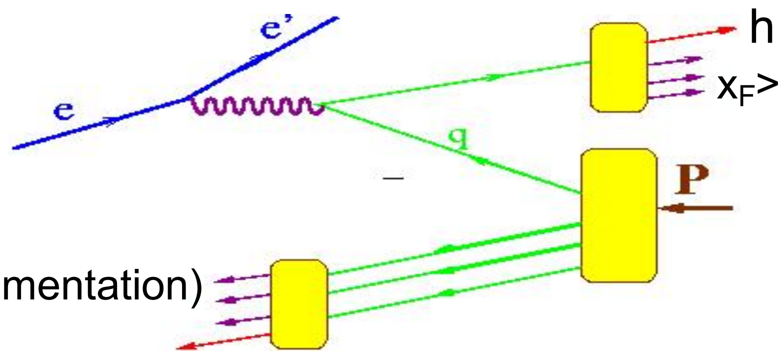
Sep 6-8, 2021

- Introduction
- SIDIS program at JLab
- Present some CLAS12 data
- Studies of transverse momentum of hadrons
  - multiplicities
  - azimuthal modulations
- Interpretations & challenges
- Future measurements
- Summary

*** In collaboration with Harut Avakian (JLab)**

Electroproduction: extending 1D PDFs

x_F – fractional momentum in the CM frame

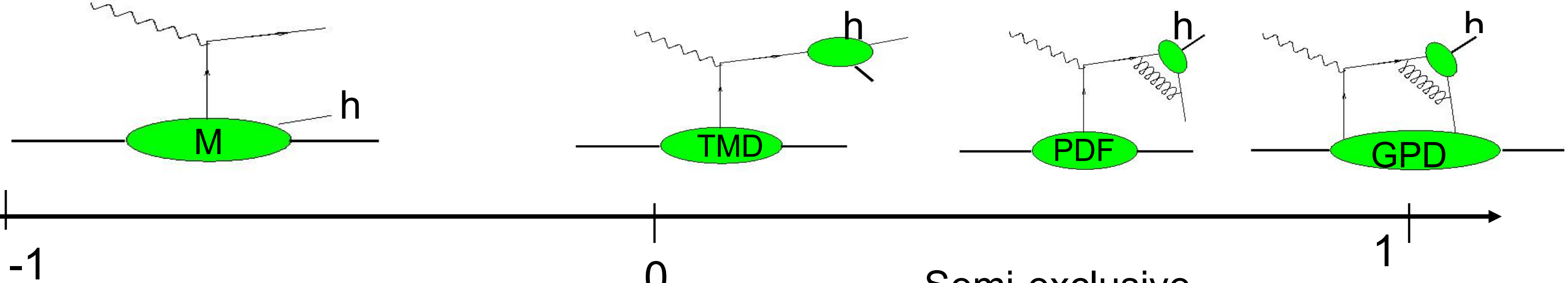


$x_F>0$ (current fragmentation)

$x_F<0$ (target fragmentation)

Target fragmentation

Current fragmentation



Fracture Functions

k_T-dependent PDFs

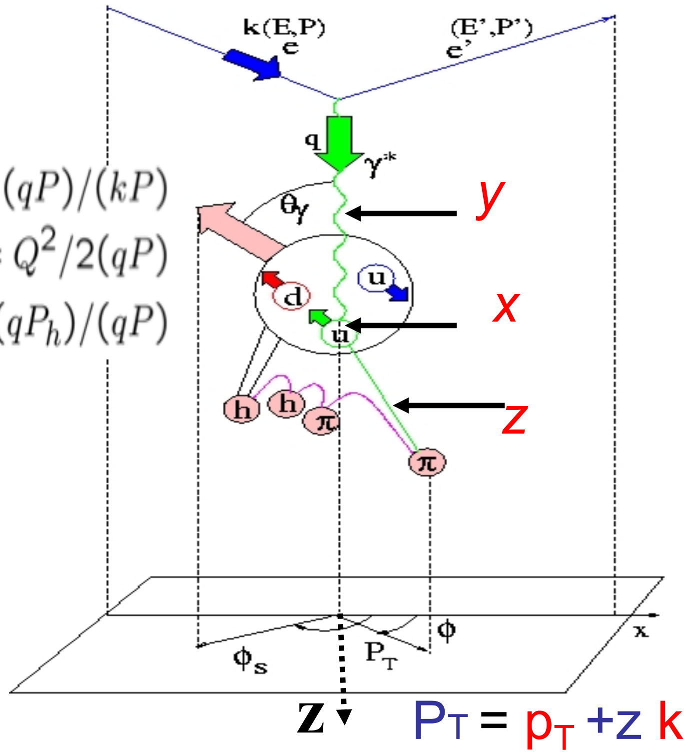
Semi-exclusive production

Generalized PDFs

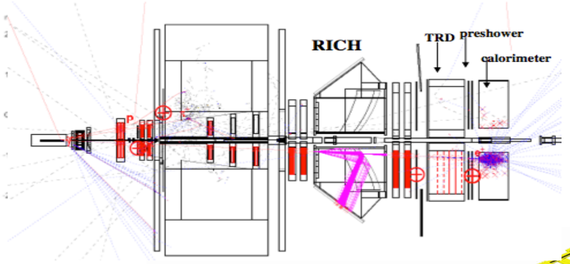
Wide kinematic coverage of large acceptance detectors allows studies of semi-inclusive and exclusive processes simultaneously

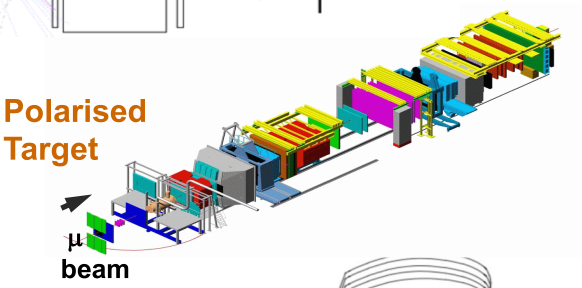
Semi Inclusive DIS

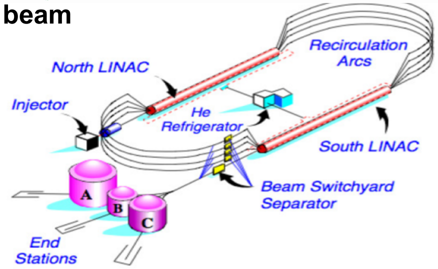
$$y = (qP)/(kP)$$
$$x = Q^2/2(qP)$$
$$z = (qP_h)/(qP)$$



$P_T = p_T + z\, k_T$







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

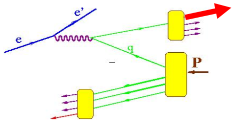
Azimuthal modulations depend on structure functions, providing information on underlying correlations of spins with partonic momentum distributions

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

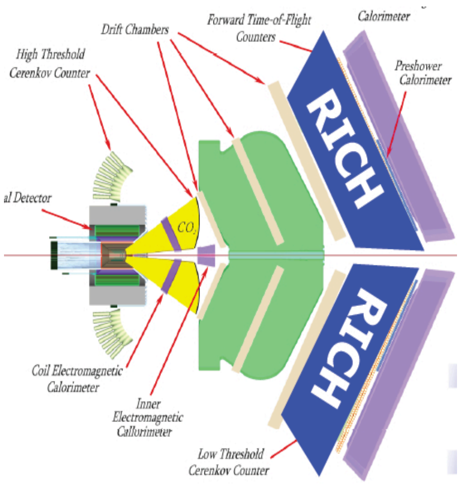
target polarization

beam polarization

Distribution & Fragmentation Functions



SIDIS at JLab12



CLAS12

E12-06-112: π^+,π^-,π^0
E12-09-008: K^+, K^-,K^0

E12-07-107: π^+,π^-,π^0
E12-09-009: K^+,K^-,K^0

C12-11-111: π^+,π^-,π^0 K^+, K^-

H_2, NH_3, HD

Proton

Quark spin polarization

Nucleon polarization

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 $h_{1T}^\perp$

Hall C | Hall A

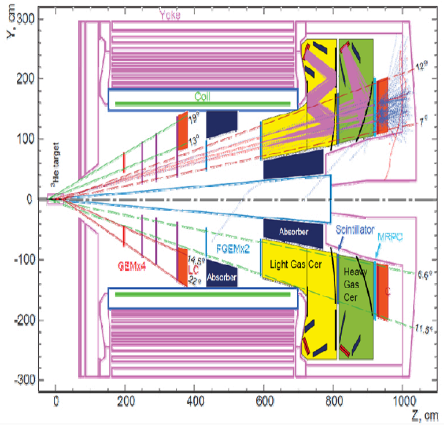
E12-09-017: π^+,π^-, K^+,K^-
C12-11-102: π^0

HMS
SHMS

C12-11-108: π^+,π^-

Solid

H_2 | NH_3



CLAS12

E09-008: π^+,π^-,π^0 K^+, K^-,K^0

E07-107: π^+,π^-,π^0
E09-009: K^+,K^-,K^0

D_2, ND_3

D_2

Quark spin polarization

Nucleon polarization

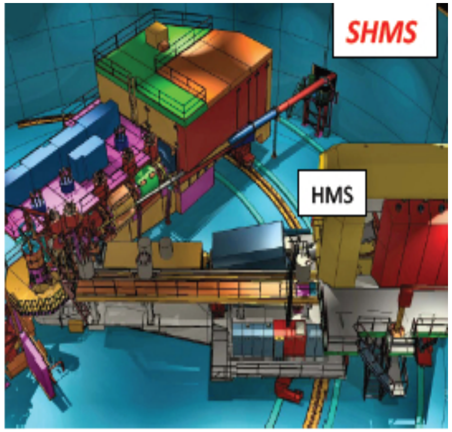
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Hall C

E12-09-017: π^+,π^-, K^+,K^-
C12-11-102: π^0

HMS
SHMS

D_2



C12-20-002
$\pi^+,\pi^-.\pi^0$,K+

^{3}He

Quark spin polarization

Nucleon polarization

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 $h_{1T}^\perp$

Hall A

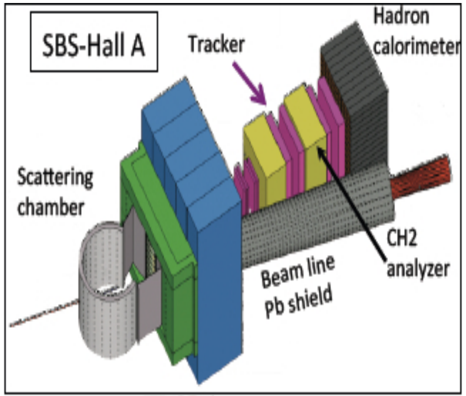
E12-07-007: π^+, π^-

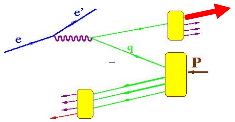
Solid

E10-006: π^+,π^-
E12-09-018: π^+,π^-, K^+,K^-

Solid
SBS

^{3}He

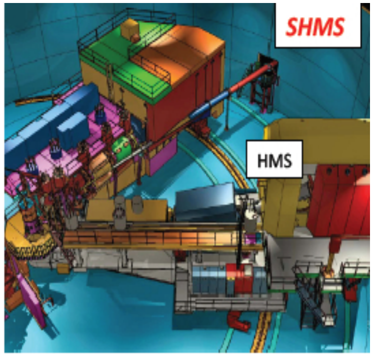


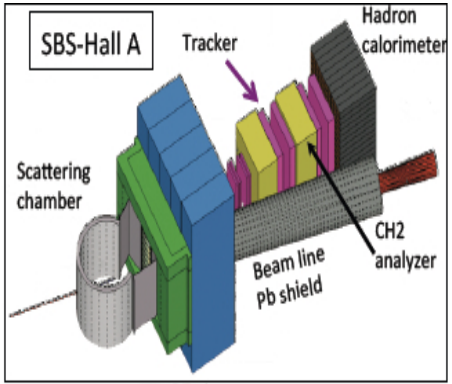


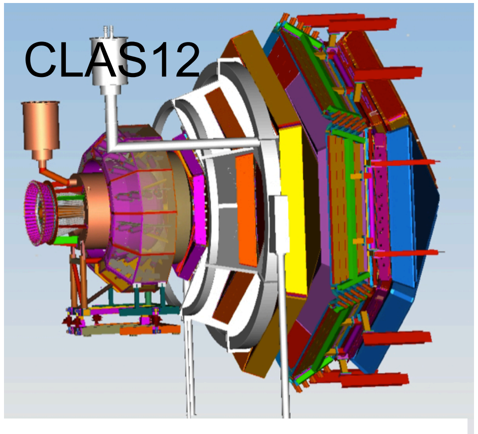
SIDIS at JLab12

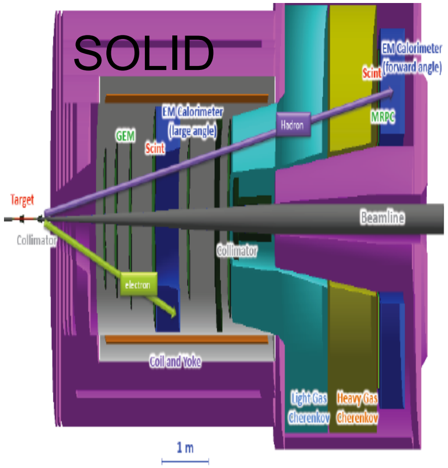
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

Complementary measurements with different targets

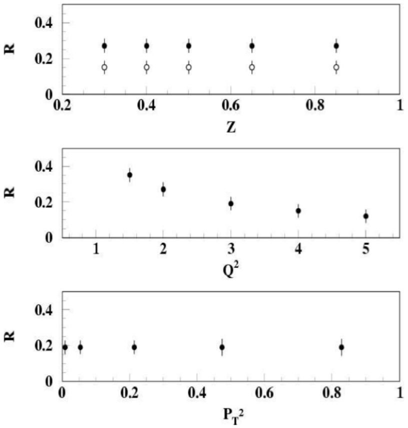


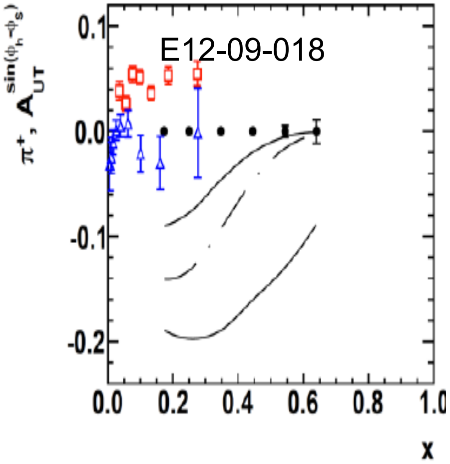


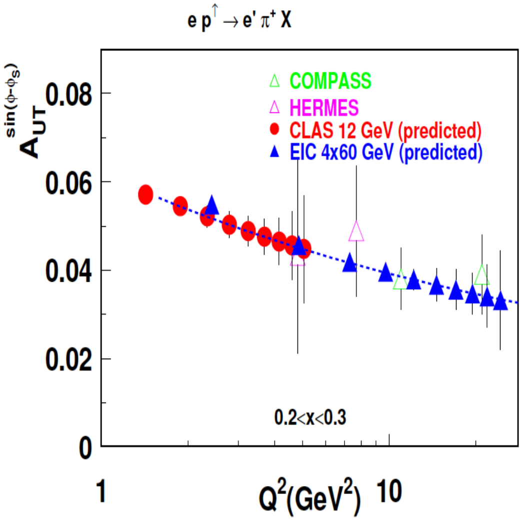


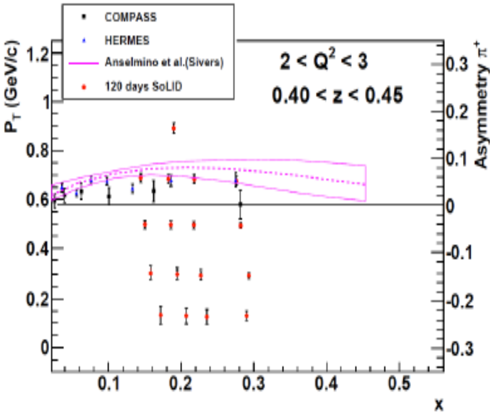


L/T-separation









Combination of high resolution measurements from spectrometers combined with large acceptance data from CLAS12 and SOLID would allow to study TMDs in details in the valence region

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

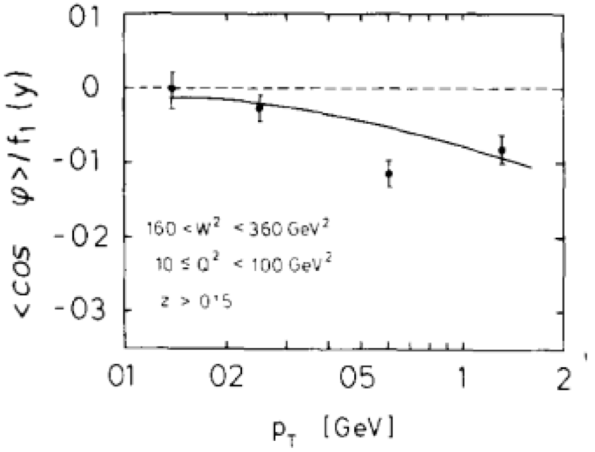
Azimuthal distributions in SIDIS (unpolarized)

$$\frac{d\sigma}{dx_B\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{x_B y Q^2}\,\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\Bigg\{F_{UU,T}+\varepsilon\,\overset{\text{H.T.}}{\overset{\downarrow}{F_{UU,L}}}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,\overset{\text{H.T.}}{\overset{\downarrow}{F_{UU}^{\cos\phi_h}}}$$

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}\Bigg\} \xleftarrow{} \text{H.T.},$$

EMC-1983 (PL,v130,118)



Observables: - Azimuthal Moments - Multiplicity

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

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

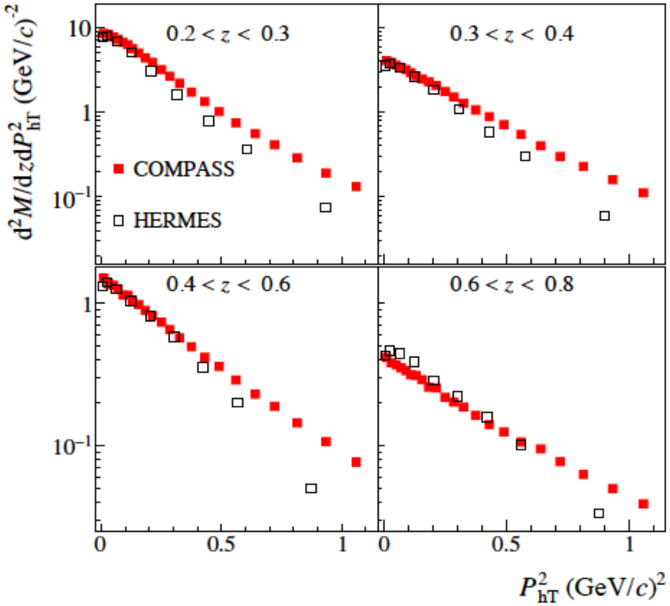
- Quark-gluon correlations are significant in electro production experiments (even if at high energy).
- Large cosϕ modulations observed in electroproduction (EMC, COMPASS, HERMES) may be a key in understanding of the QCD dynamics.

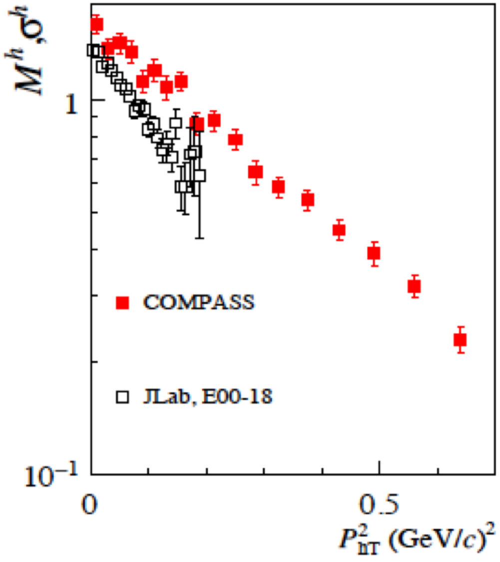
Multiplicities of hadrons in SIDIS

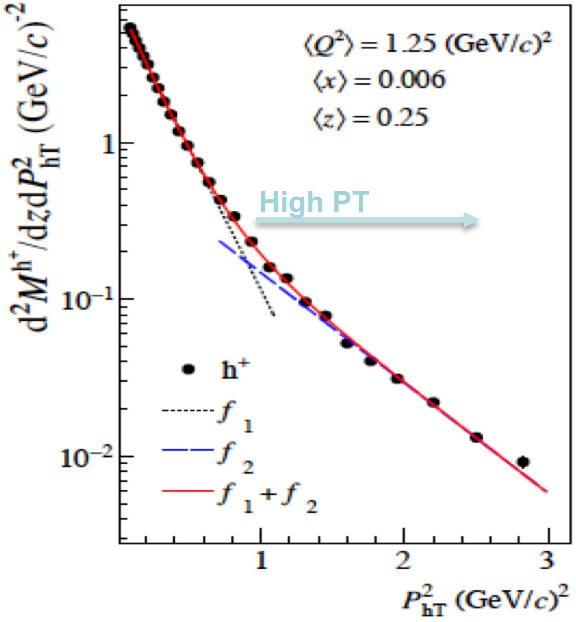
Gaussian Ansatz $$\boxed{f_1^q} \otimes \boxed{D_1^{q\to h}} = x f_1^q(x)\, D_1^{q\to h}(z) \frac{e^{-P_{hT}^2/<P_{hT}^2>}}{\pi < P_{hT}^2 >}$$

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

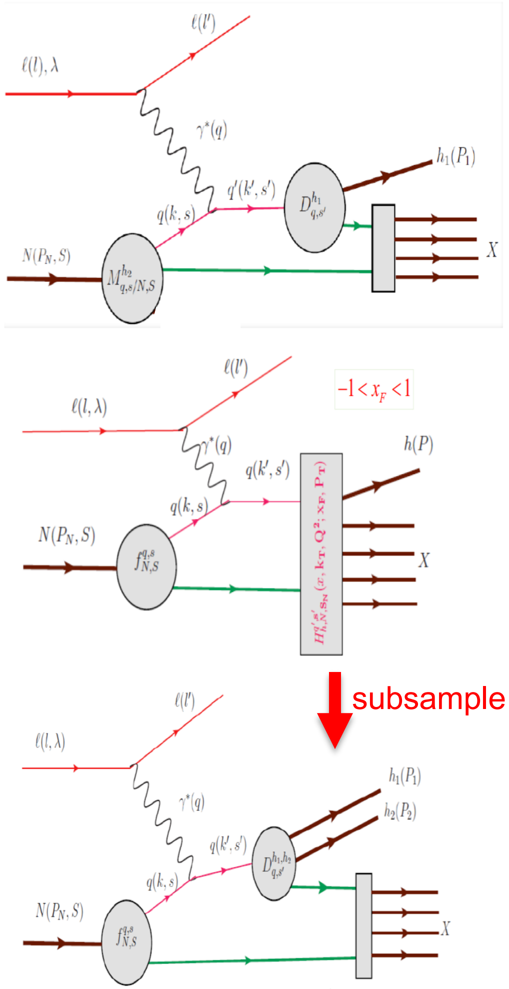
- What is the origin of the “high” PT tail?
  1) Perturbative contributions?
  2) Non perturbative contributions? (TMDs dependence not 1 Gaussian)

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
- ….

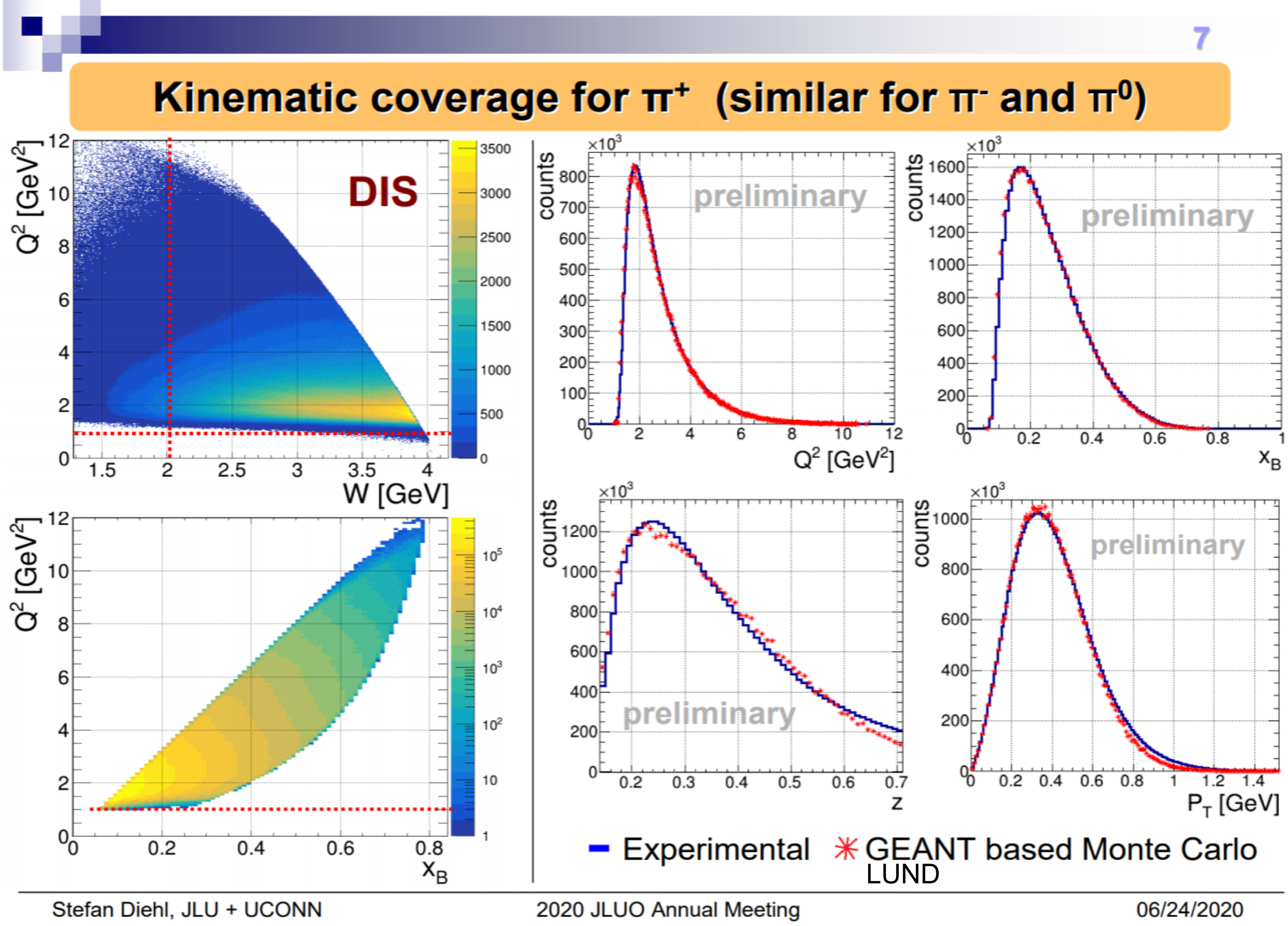


To understand the measurements we should be able to simulate, at least the basic features we are trying to study (P_T and Q^2,-dependences in particular)

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

SIDIS ehX: CLAS12 data

CLAS12 single hadron distributions $ep \rightarrow e'\pi^+X$



7

Kinematic coverage for π^+ (similar for π^- and π^0)

Experimental ✱ GEANT based Monte Carlo

LUND

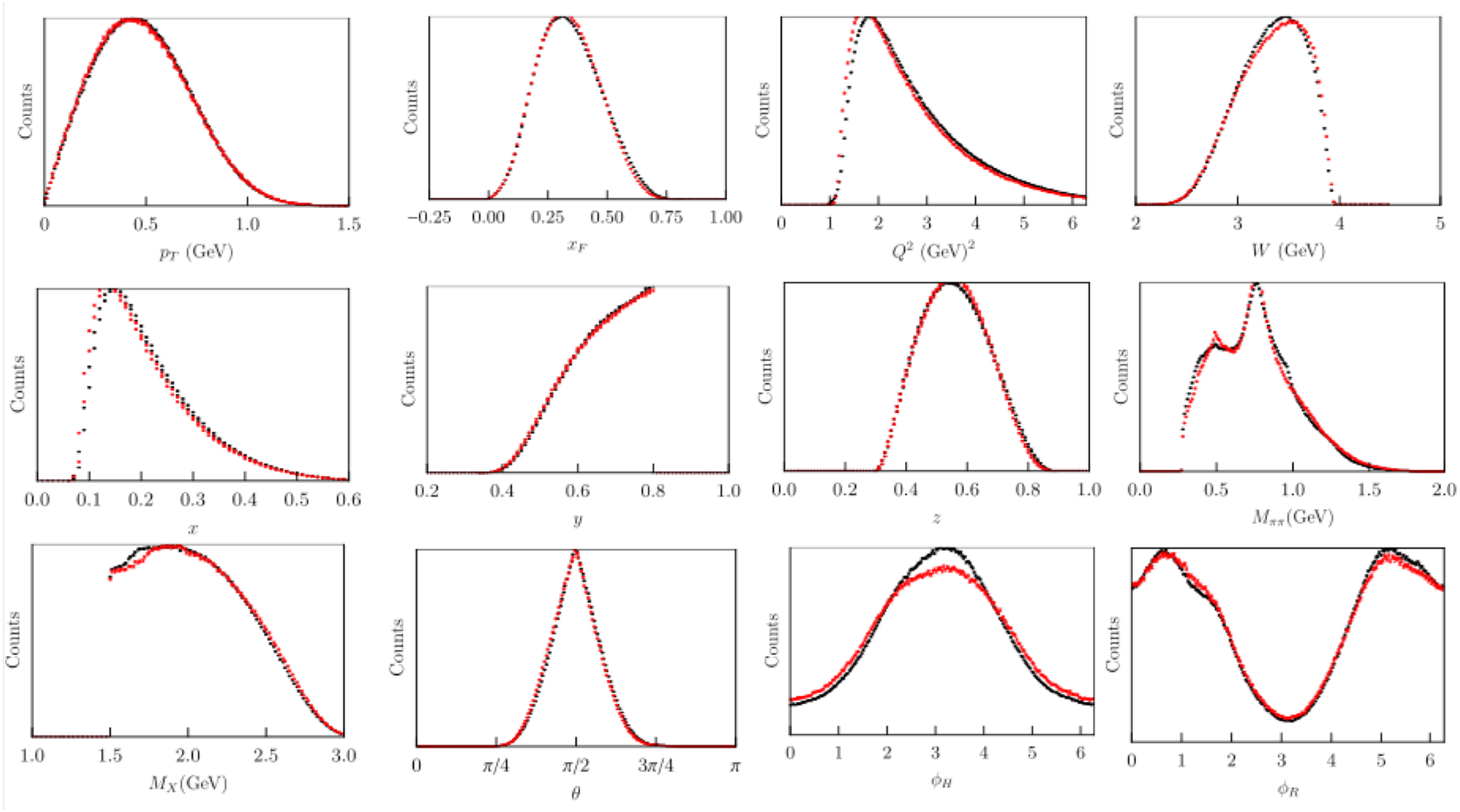
Stefan Diehl, JLU + UCONN

2020 JLUO Annual Meeting

06/24/2020

SIDIS ehhX: CLAS12 data vs MC

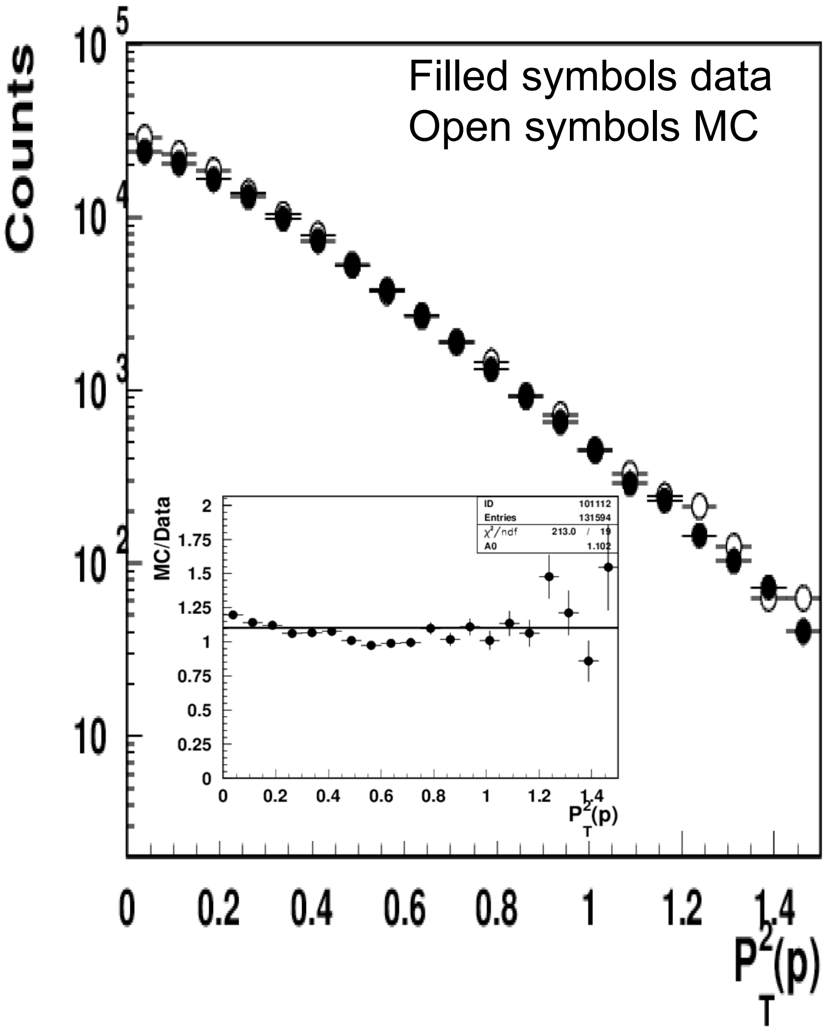
CLAS12 dihadron production ep→ehhX

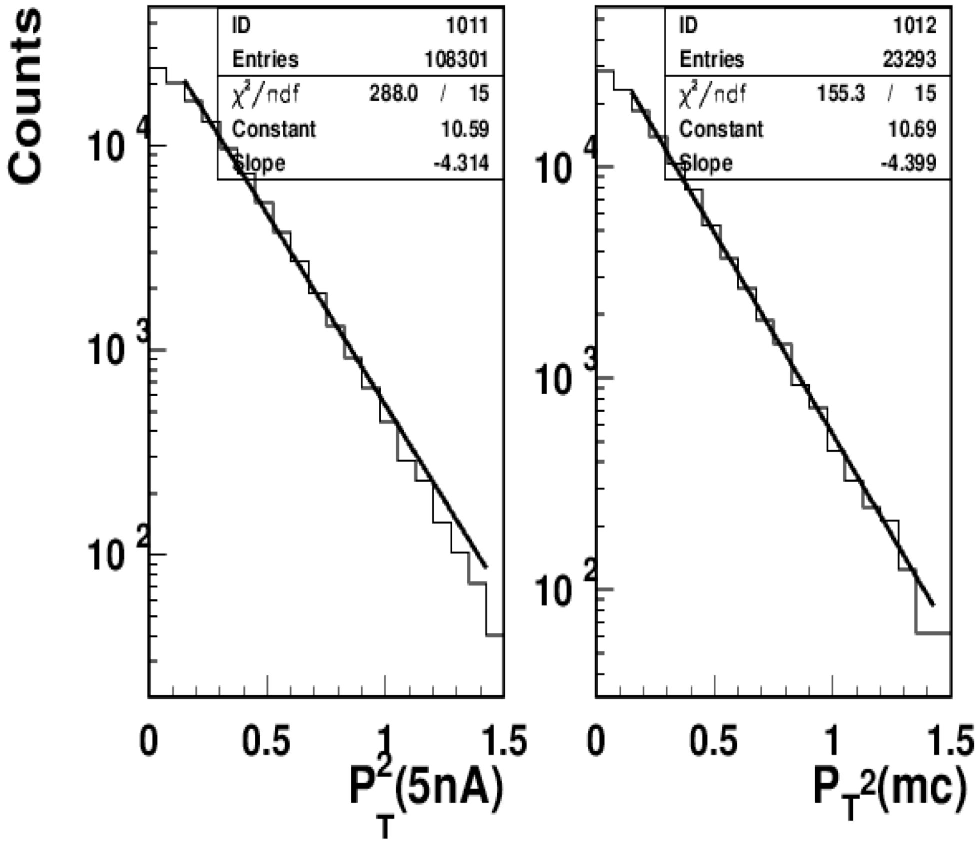


CLAS12 MC, based on the PEPSI(LEPTO) simulation with <u>most parameters ”default”</u> is in a good agreement with CLAS12 measurements for all relevant distributions

CLAS12 Studies: Data vs MC

Using PEPSI (LUND) generator





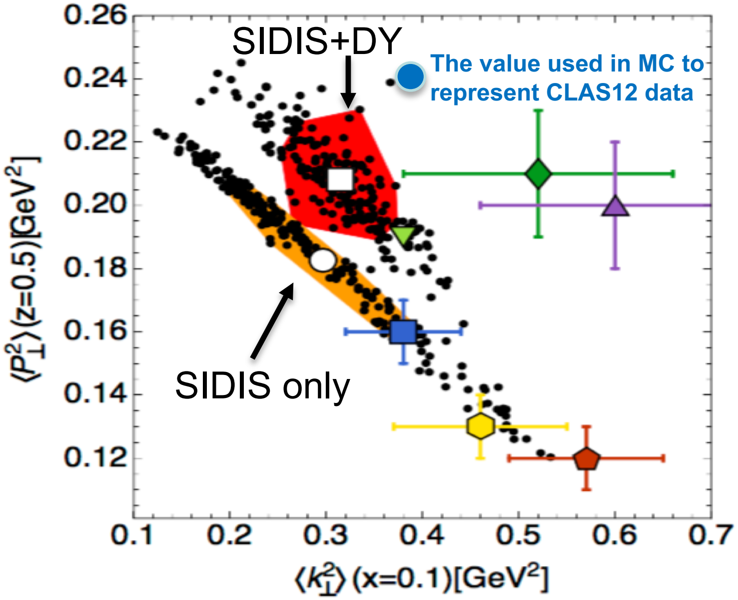
- P_T-distributions of protons, and widths are in good agreement with LEPTO
- May be a source for widths in hadronization

Extracting the average transverse momenta

Andrea Signori,[1,*] Alessandro Bacchetta,[2,3,†] Marco Radici,[3,‡] and Gunar Schnell[4,5,§] 10.1007/JHEP11(2013)194

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

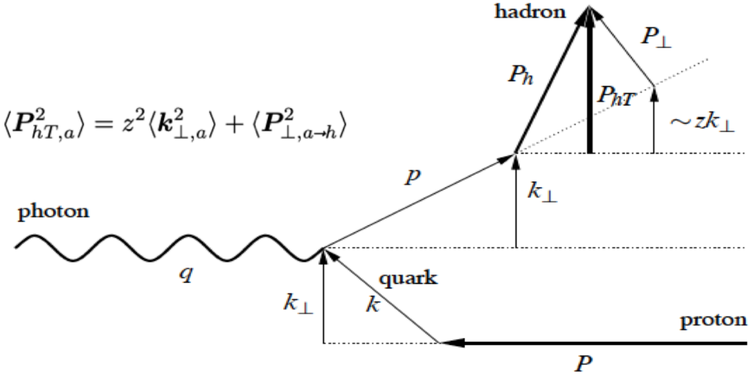
$$+ Y_{UU,T}(Q^2,P_{hT}^2) + \mathcal{O}(M/Q)\,.$$



SIDIS+DY

The value used in MC to represent CLAS12 data

SIDIS only



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

- Extraction very sensitive to input (replicas)
- Why DY gives higher values ?
- How to reconcile data with 1 pion MC?

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

Sea is not divided to perturbative and non-perturbative

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

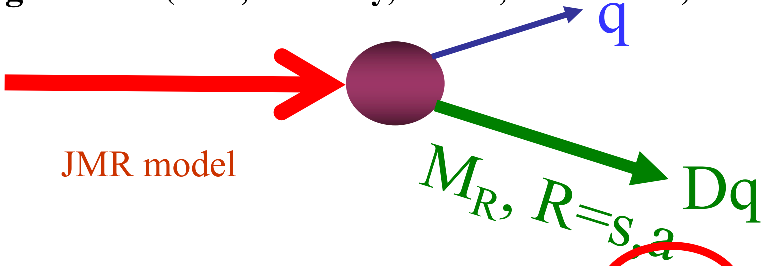
Unknown “known” f_1,g_1 TMDs

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

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

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

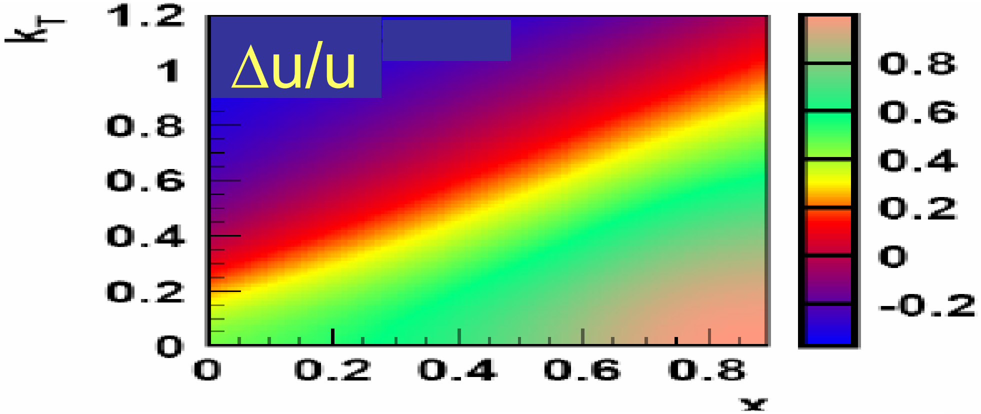
Effect of the orbital motion on the q- may be significant **(H.A.,S.Brodsky, A.Deur, F.Yuan 2007)**

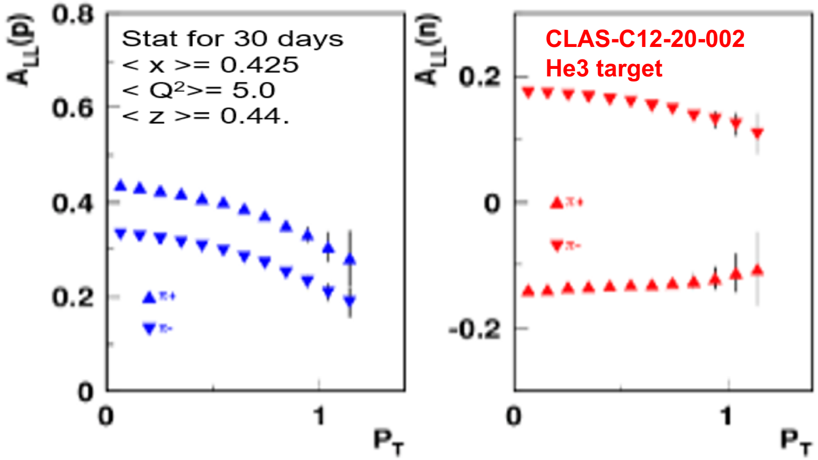


$$f_1(x,\mathbf{k}_T^2) = A\frac{(xM+m)^2 \boxed{+\mathbf{k}_T^2}}{(\mathbf{k}_T^2+\lambda_R^2)^{2\alpha}},$$

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

(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 $g_1(x,k_T)$-studies CLAS12 proposal with He3 target approved by PAC

Flavor dependent TMD Fragmentation functions

https://www.phy.anl.gov/nsac-lrp/Whitepapers/StudyOfFragmentationFunctionsInElectronPositronAnnihilation.pdf

$$F_{UU} \propto \sum_q f_{1,q}(x,k_\perp) \otimes D_1^{q\to h}(z,p_\perp)$$

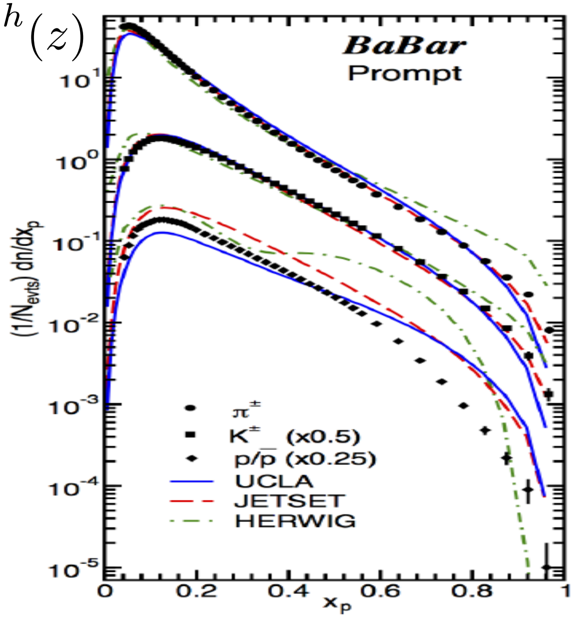
Even simple approximations require an additional set of parameters

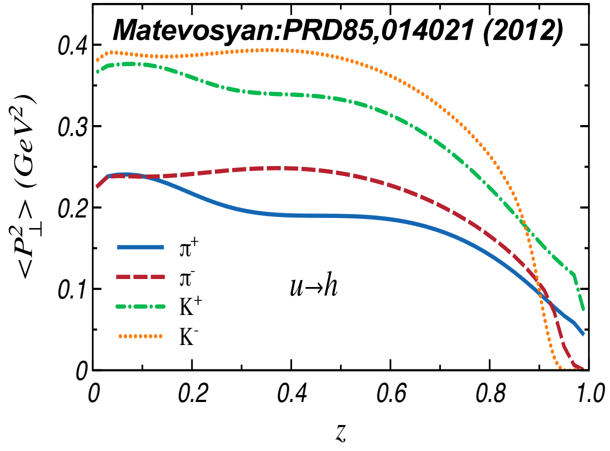
$$D_1^{q\to h,fav}(z,p_\perp) = D_1^{q\to h}(z) \times \frac{e^{-\frac{p_\perp^2}{\langle p_{\perp,fav}^2(z)\rangle}}}{\pi\langle p_{\perp,fav}^2(z)\rangle}$$

$$D_1^{q\to h,unf}(z,p_\perp) = D_1^{q\to h}(z) \times \frac{e^{-\frac{p_\perp^2}{\langle p_{\perp,unf}^2(z)\rangle}}}{\pi\langle p_{\perp,unf}^2(z)\rangle}$$

$$\langle p_{\perp,unf}^2(z)\rangle > \langle p_{\perp,fav}^2(z)\rangle$$

$D_1^{q\to h}(z)$





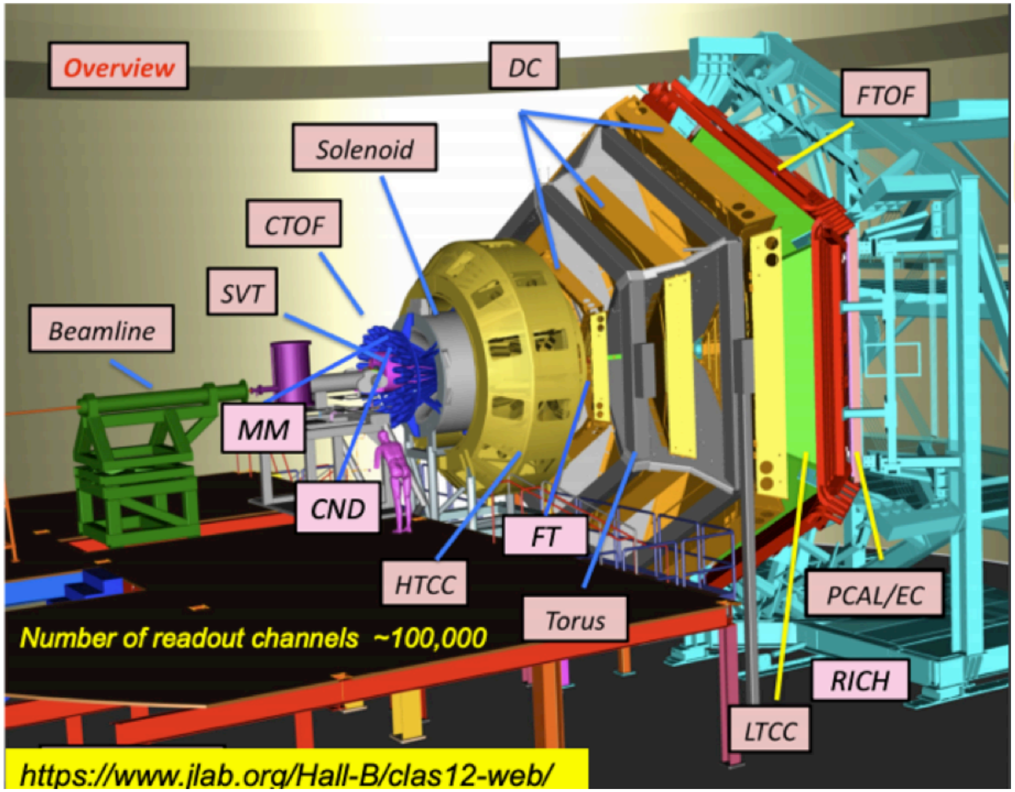
Measurements of flavor and spin dependence of transverse momentum dependent fragmentation functions will provide critical input to TMD extraction

CLAS12 (JLAB) Detector

CLAS allows measuring multi-particle final state detection, opening unique possibilities to study correlation in hadron production.

Forward Detector:
- *TORUS magnet*
- *HT Cherenkov Counter*
- *Drift chamber system*
- *LT Cherenkov Counter*
- *RICH detector*
- *Forward ToF System*
- *Pre-shower calorimeter*
- *E.M. calorimeter (EC)*
- *Forward Tagger*

Central Detector:
- *SOLENOID magnet*
- *Barrel Silicon Tracker*
- *Micromegas*
- *Central ToF system*
- *Neutron detector*
- *Backward Angle Neutron detector*

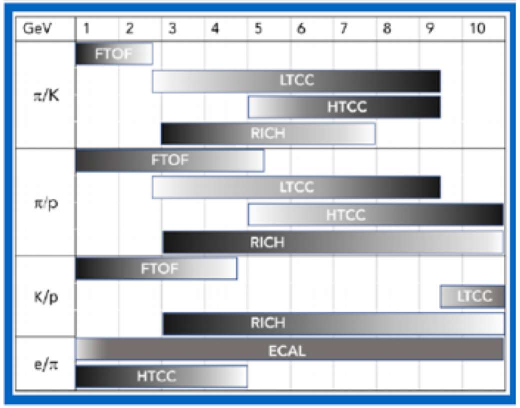


Number of readout channels ~100,000

https://www.jlab.org/Hall-B/clas12-web/

The CLAS12 Spectrometer at Jefferson Laboratory,
V.D. Burkert, et al. Nucl. Instrum. Meth. A, Volume 959, 2020, 163419

PID @ CLAS12



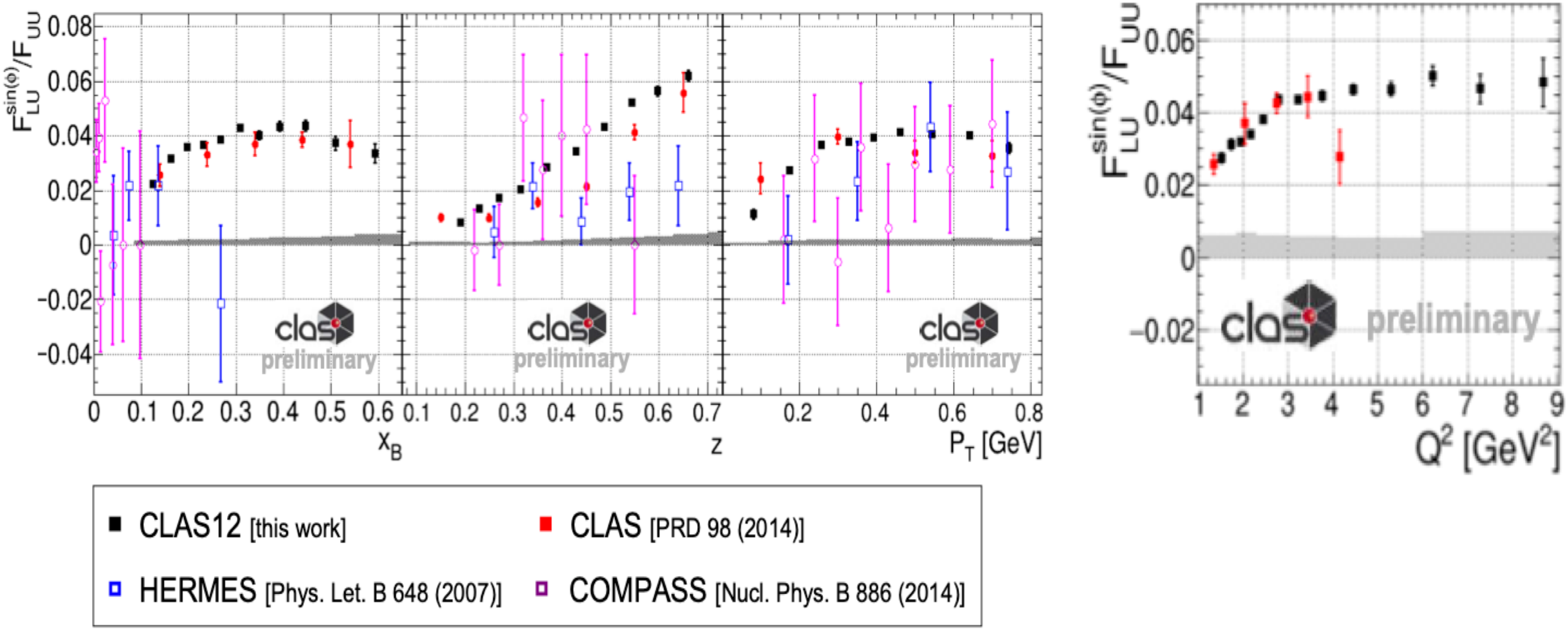
- Large acceptance detector
- Polarized beam (85% average polarization)
- Operates with polarized and unpolarized targets.
- Luminosity up to $10^{35}\ cm^{-2} s^{-1}$
- Beam energy up to 10.6 GeV

SSA from CLAS12

S. Diehl et al (in publication) arXiv:2101.03544

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

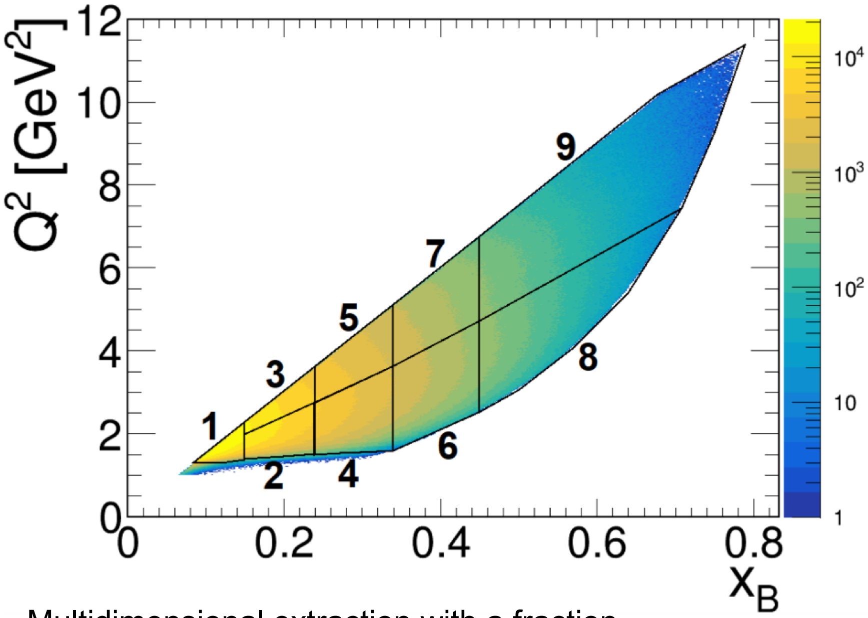
$$\langle \sin\phi\rangle \propto F_{LU}^{\sin\phi}/F_{UU} \propto 1/Q$$



- Superior statistics in large x-region most relevant for spin-orbit correlation studies
- Unexpected Q^2-dependence is under study in fine multidimensional bins x,z,P_T

SSA from CLAS12

S. Diehl et al (in publication) arXiv:2101.03544

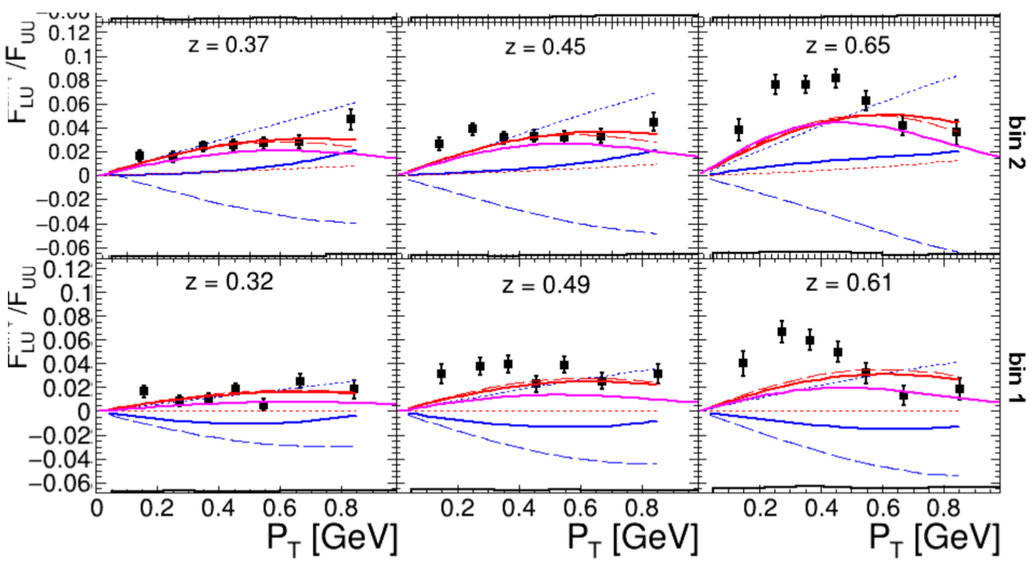


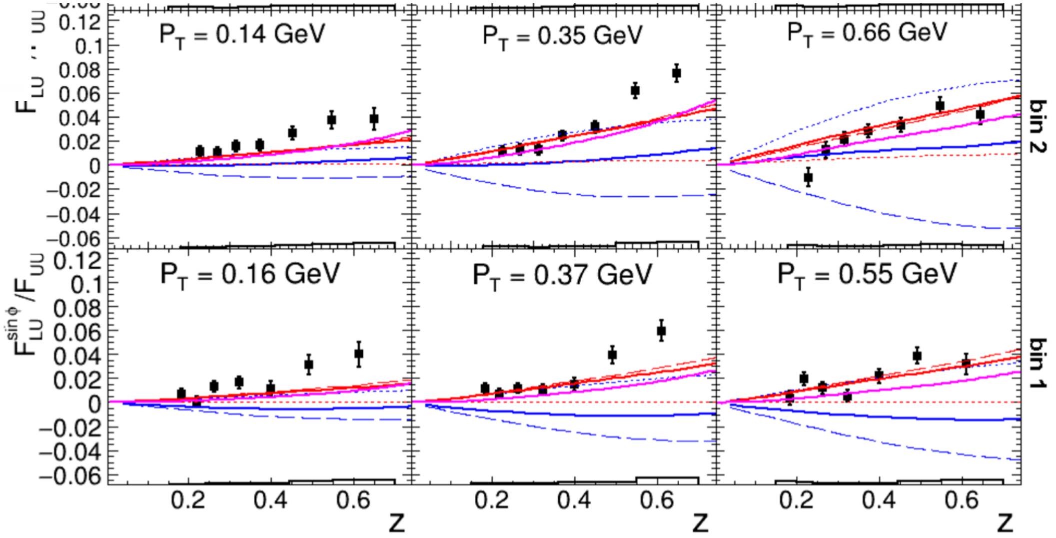
Multidimensional extraction with a fraction
of the total approved statistics for the experiment.

Model 1:W. Mao and Z. Lu, Eur. Phys. J. C 73, 2557 (2013)

Model 2:W. Mao and Z. Lu, Eur. Phys. J. C 74, 2910 (2014).

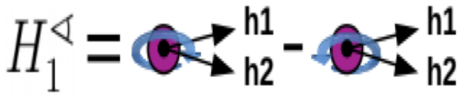
$eH_1^\perp$ (dashed line) and $g^\perp D_1$ (dotted line)





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

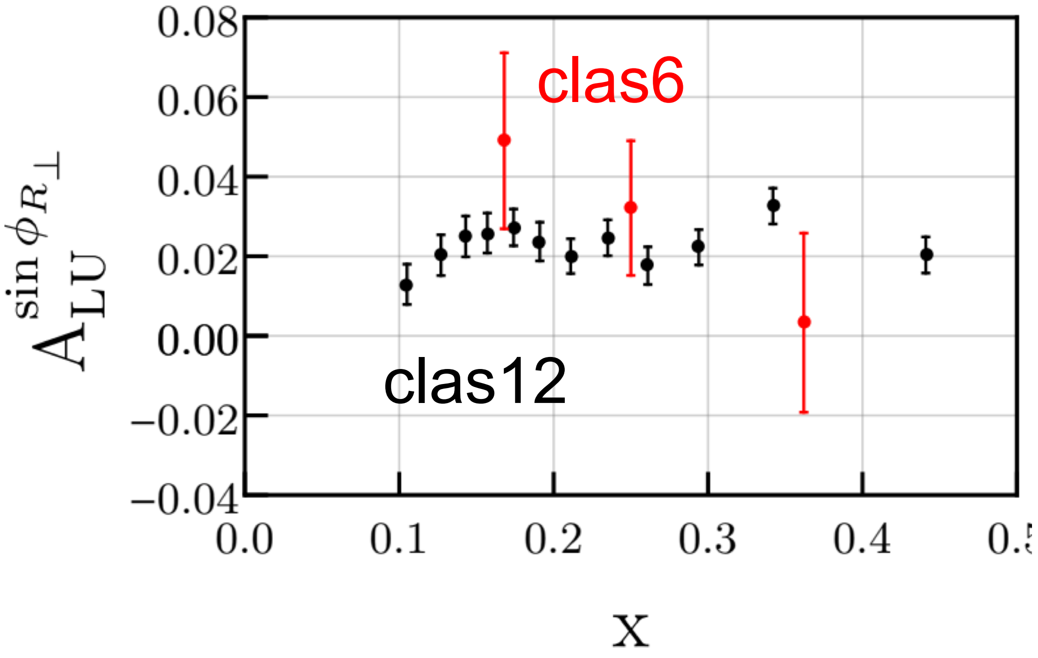
T. Hayward et al. Phys. Rev. Lett. 126, 152501 (2021)

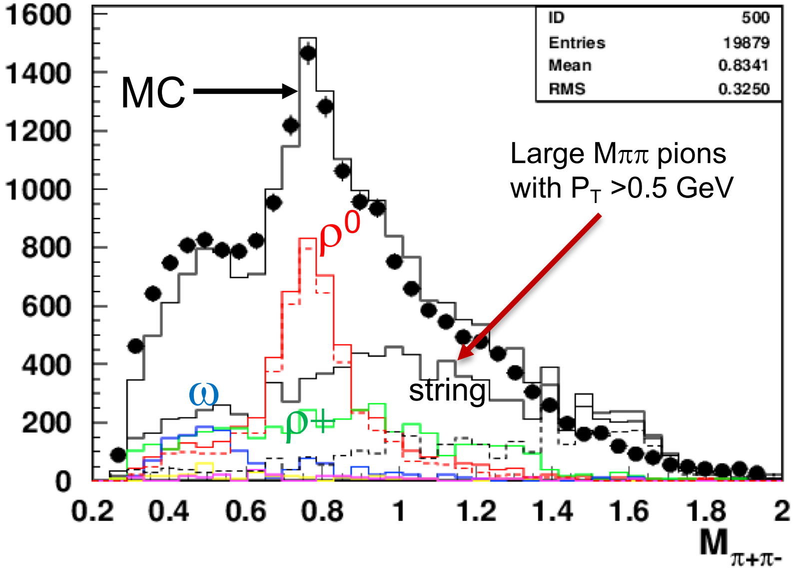


$$d\sigma_{LU} \propto \lambda_e \sin(\phi_{R_\perp}) \left(xe(x) H_1^{\sphericalangle}(z, M_h) + \frac{1}{z} f_1(x) \tilde{G}^{\sphericalangle}(z, M_h) \right)$$

Bacchetta&Radici: arXiv:hep-ph/0311173

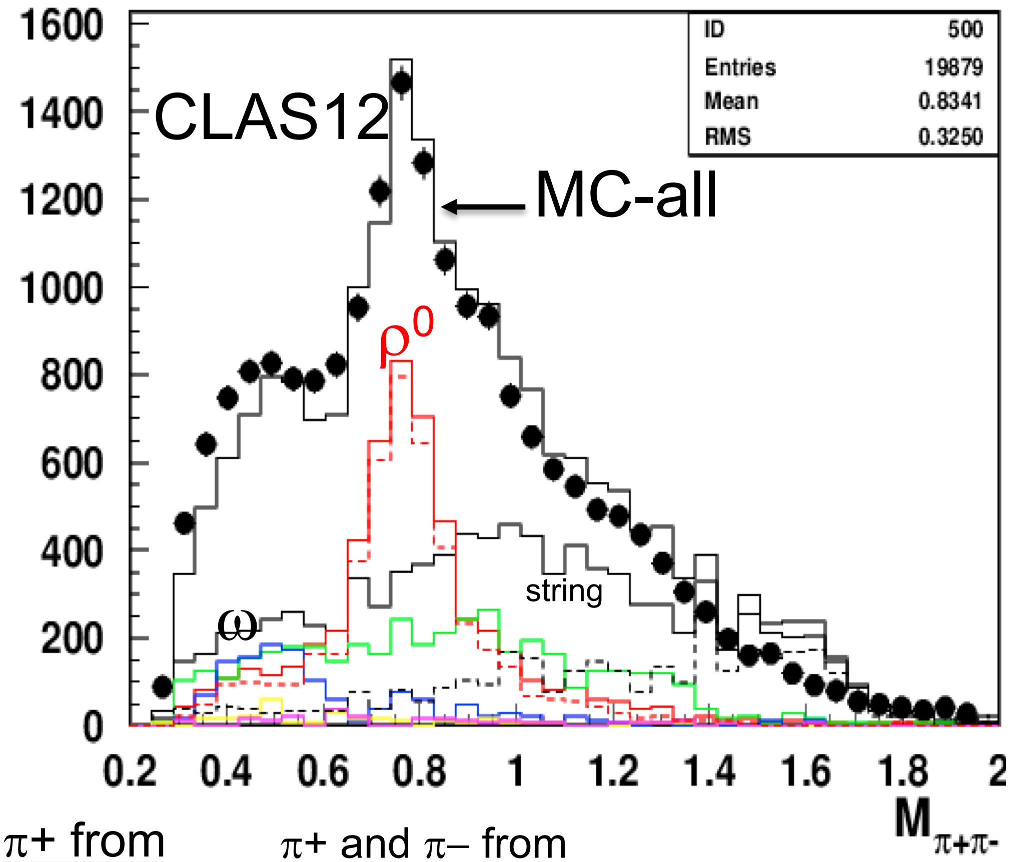
PDF e describes the force on the transversely polarized quark after scattering

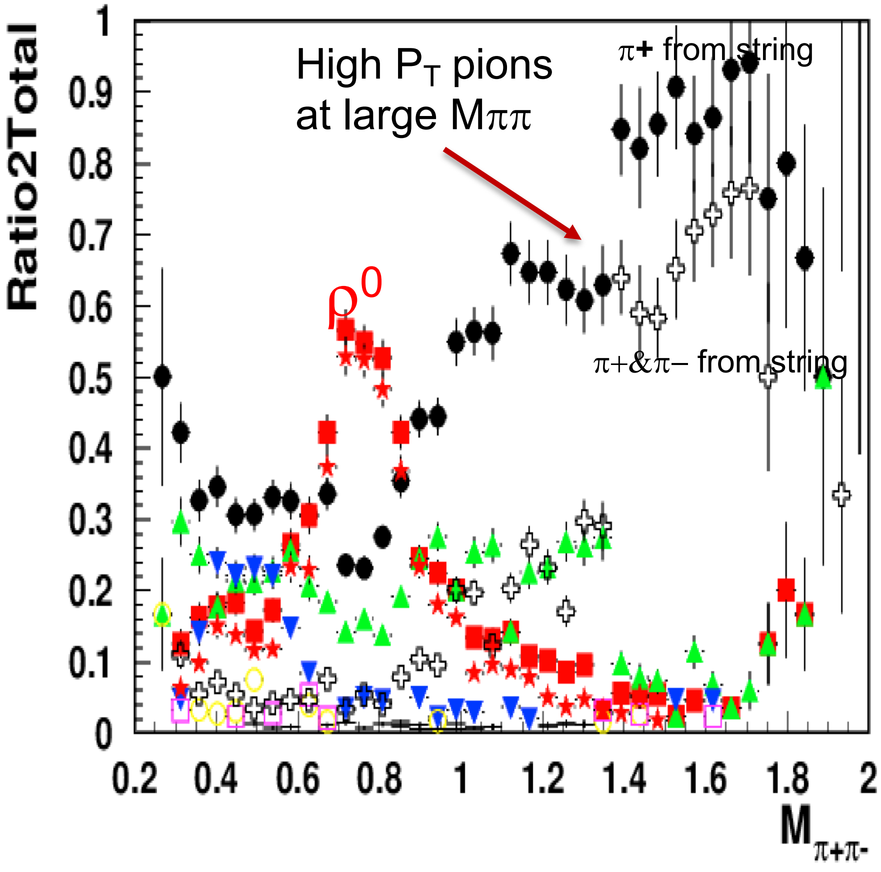




- Spin-azimuthal correlations in hadron pair production are very significant
- Hadron pairs in SIDIS (true from JLab to LHC) are dominated by VM decays (therefore single hadron channel too)

Sources of inclusive pions: CLAS12 vs MC





High P_T pions at large Mππ

π+ from		π+ and π– from
—	ρ0	----
—	string	----
—	ρ+	
—	ω	

- Dominant fraction of inclusive pions come from VM decays
- Relative fraction by default in JETSET ~50%

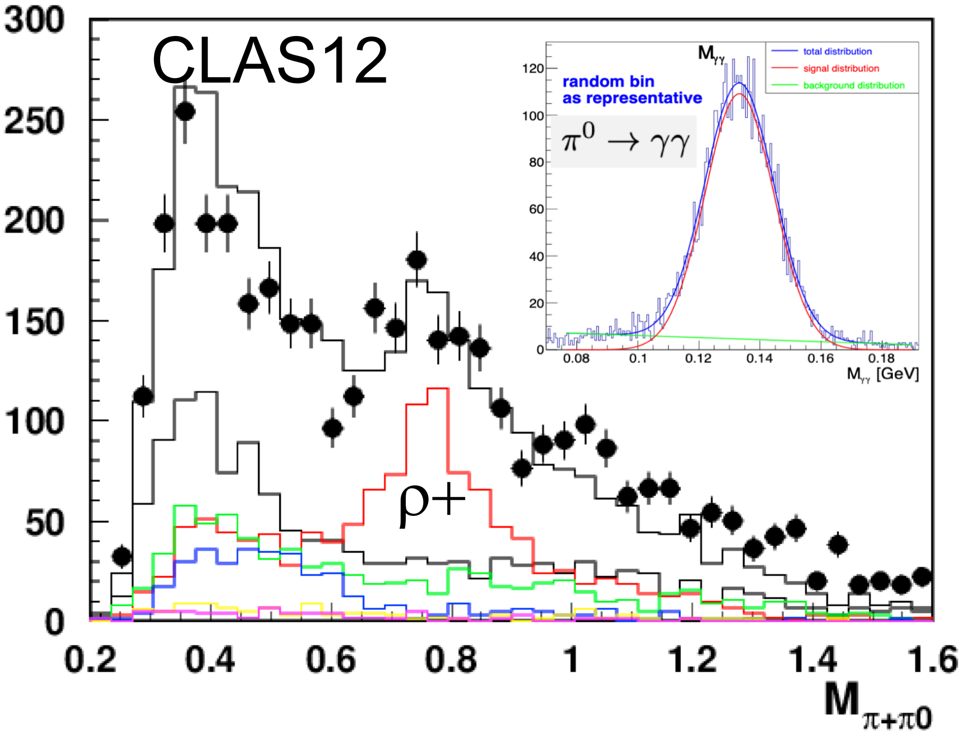
Very important to have multidimensional TMD Fragmentation Functions!

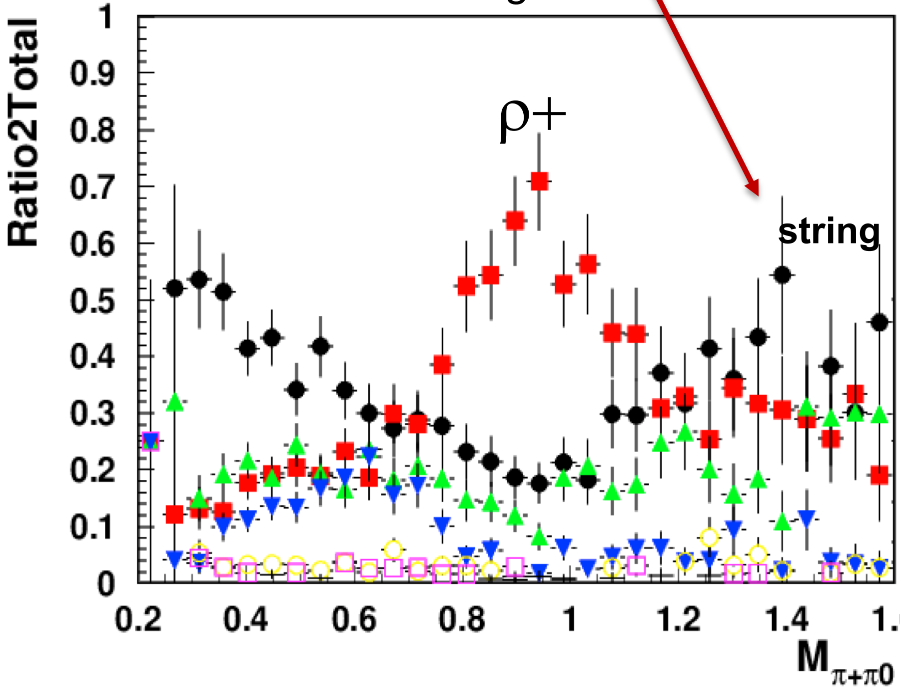
Sources of inclusive pions: CLAS12 vs MC

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

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

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





— ρ+
— string
— ρ0
— ω

Dominant fraction of inclusive pions come from VM decays

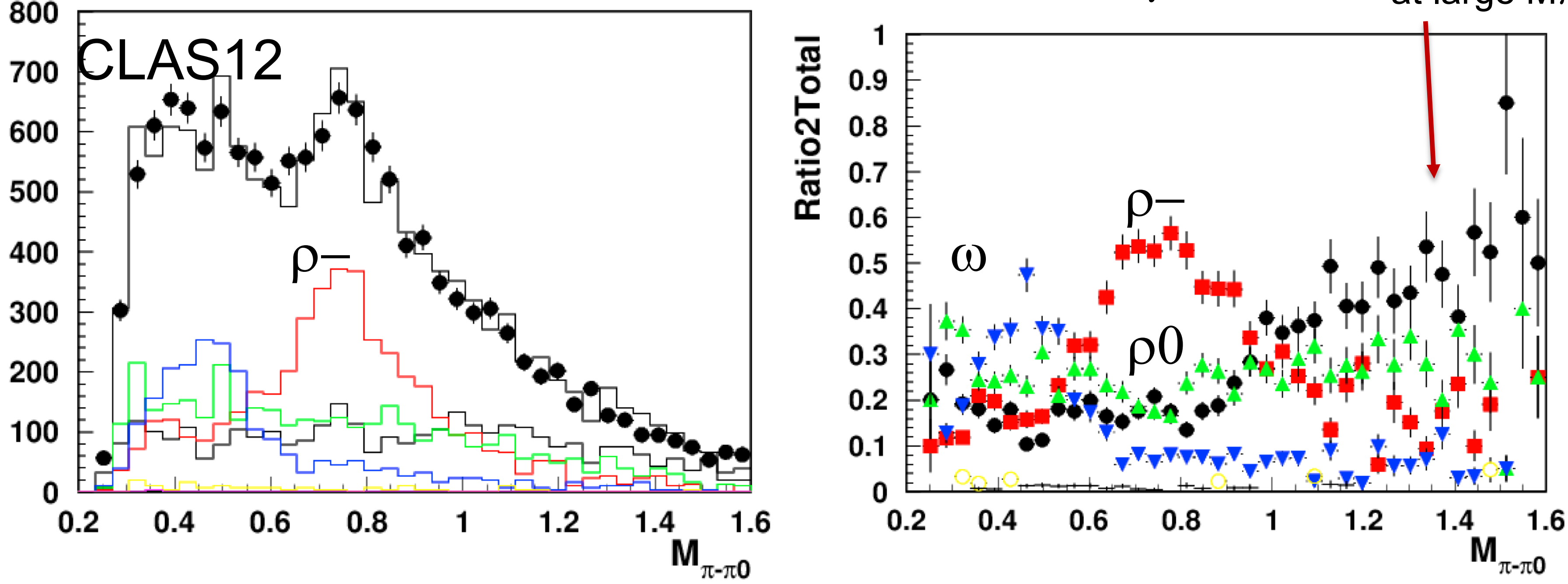
CLAS12 due to unique capability for precision measurements of neutral pions, will provide measurements of multiplicities of variety of semi-inclusive and exclusive hadron pairs (could be also VMs).

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 Mππ



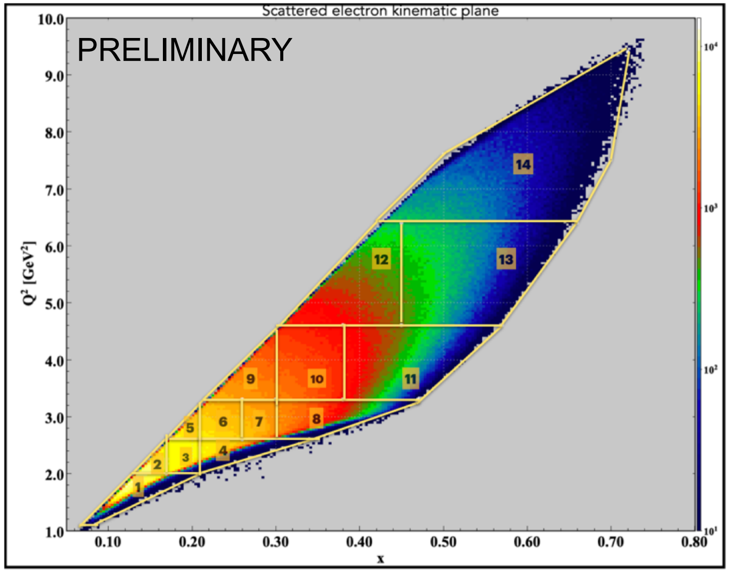
π− from:

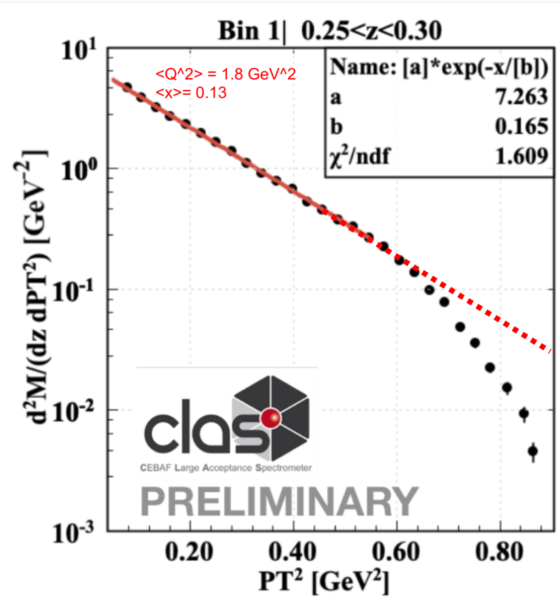
- ρ−
- string
- ρ0
- ω

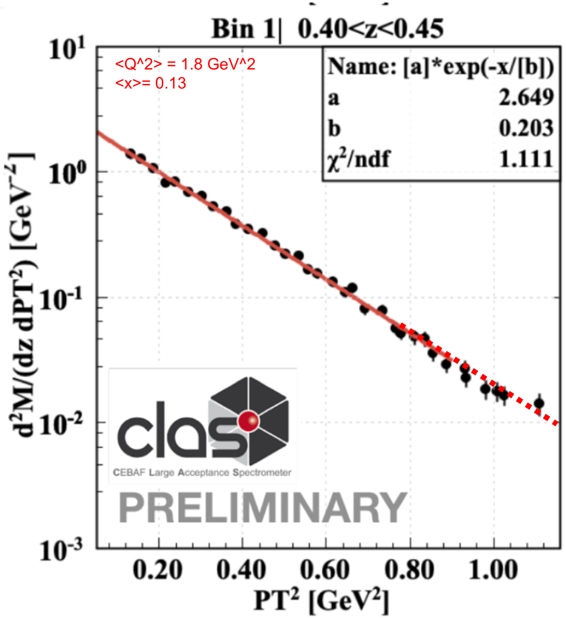
Dominant fraction of inclusive pions come from VM decays

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

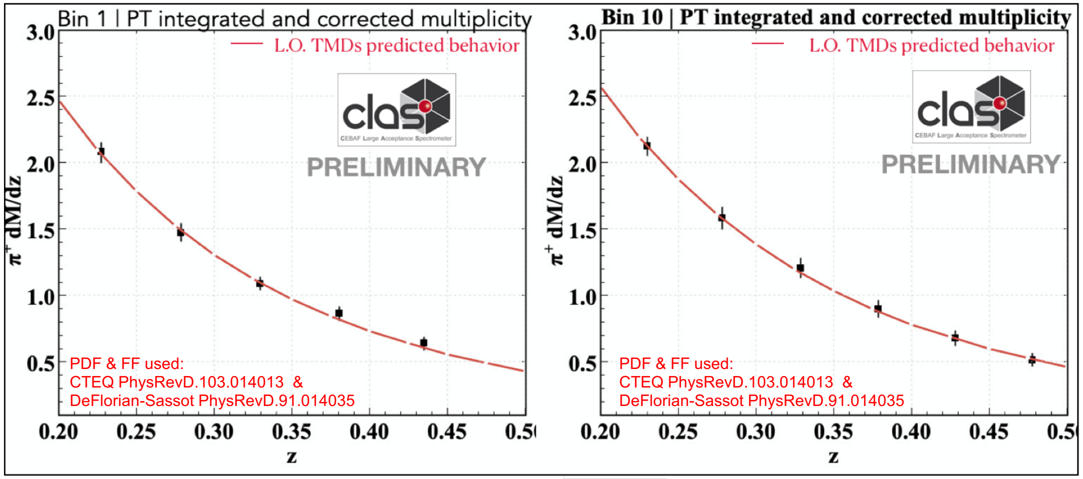
CLAS12 1h Multiplicities: high P_T & phase space



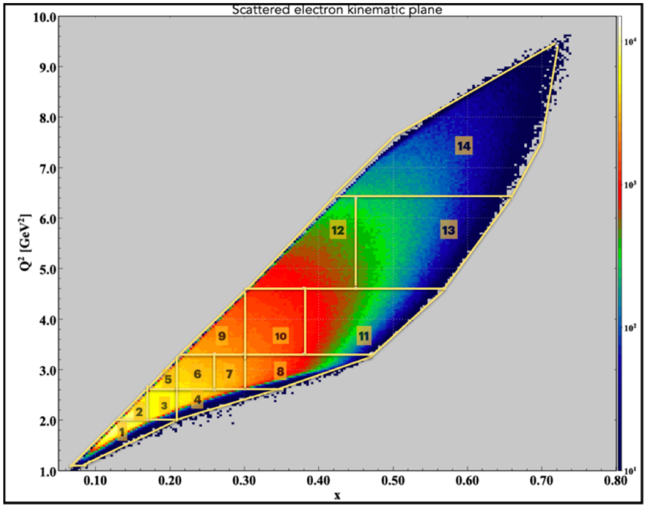




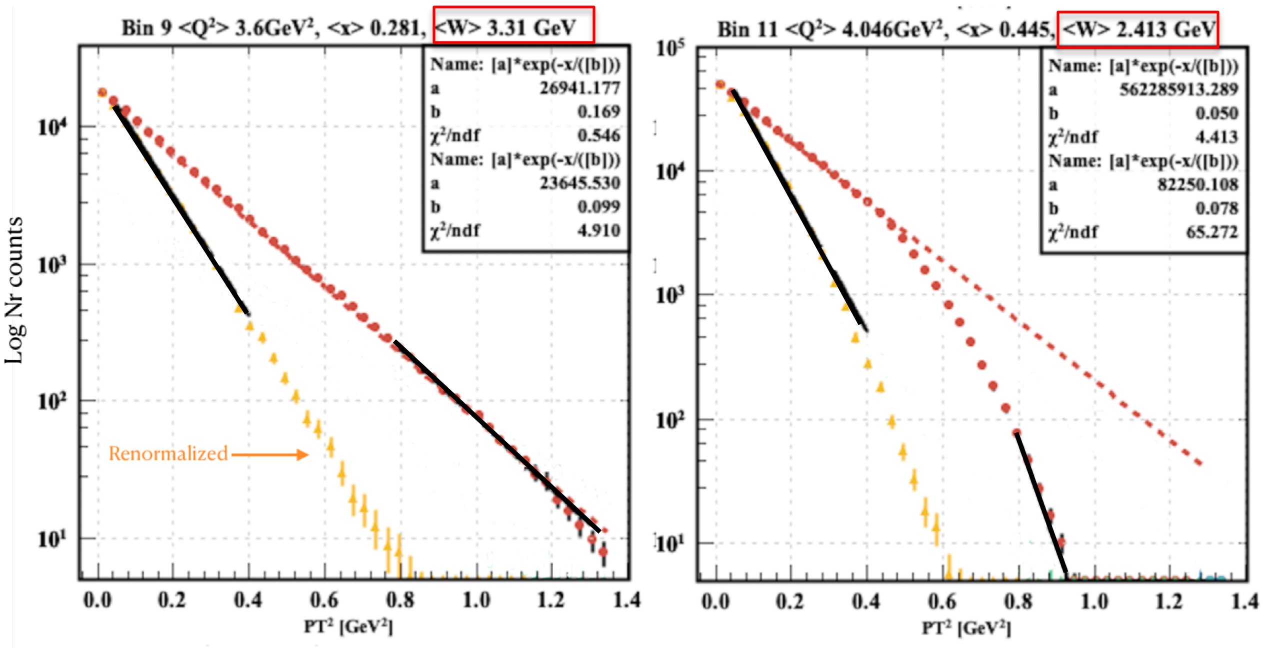
For some kinematic regions, at low z, the high P_T distribution appear suppressed: there is no enough energy in the system to produce hadron with high transverse momentum (phase space effect).
If the effect is accounted, the CLAS data follows global fits.



CLAS12 1h Multiplicities: high P_T & phase space



We binned the MC Phase space as for the CLAS12 multiplicity analysis, we used a single hadron generator with PDFs, FFs, and Gaussian Ansatz for transverse momentum and looked at the produced distribution.



– – – Coded PT distribution in generator (0.2<z<0.25)

● Directly Generated π+ (0.2 <z<0.25)

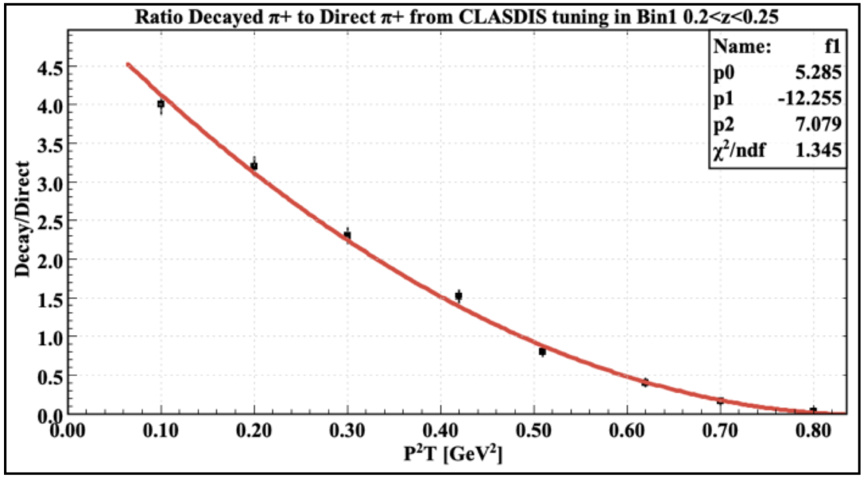
▲ π+ decayed from ω (0.2 <z<0.25)

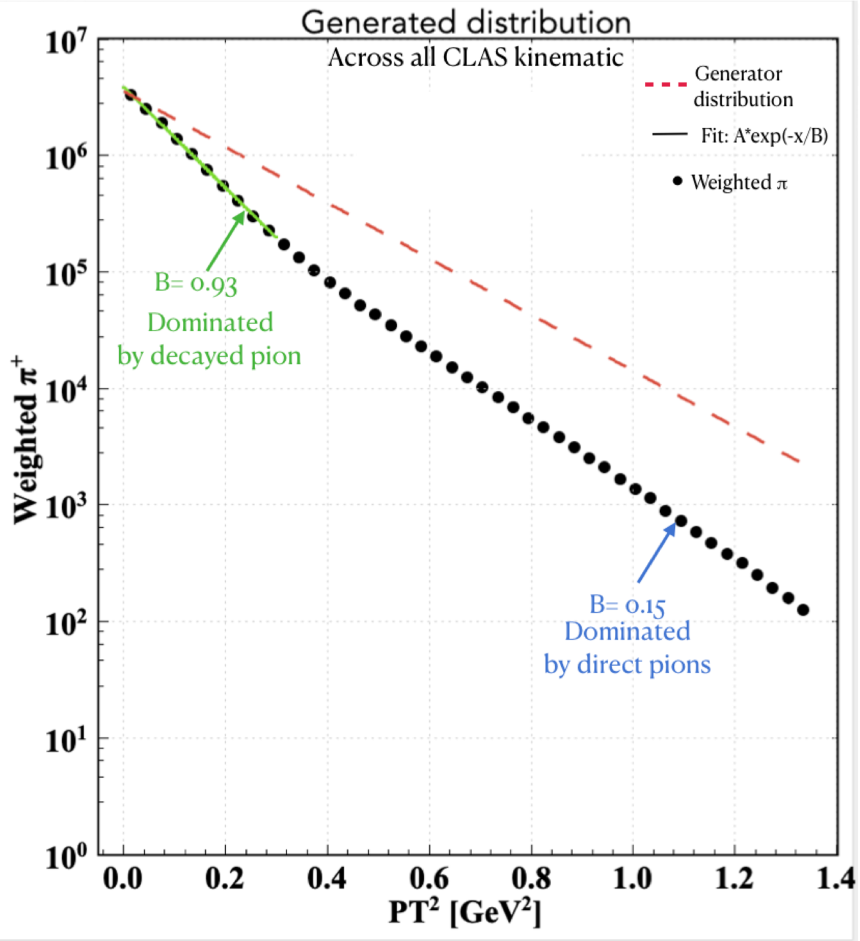
——— Gaussian Fit

- Phase space limitations for direct pion production more significant at low W, and low z
- Decayed pions have a much steeper P_T distribution at the same z

CLAS12 high P_T : impact of vector mesons

We consider the ratio of Decayed to Direct pions from the LEPTO MC (that well describes our data) and reweighted the distribution of pions accordingly.

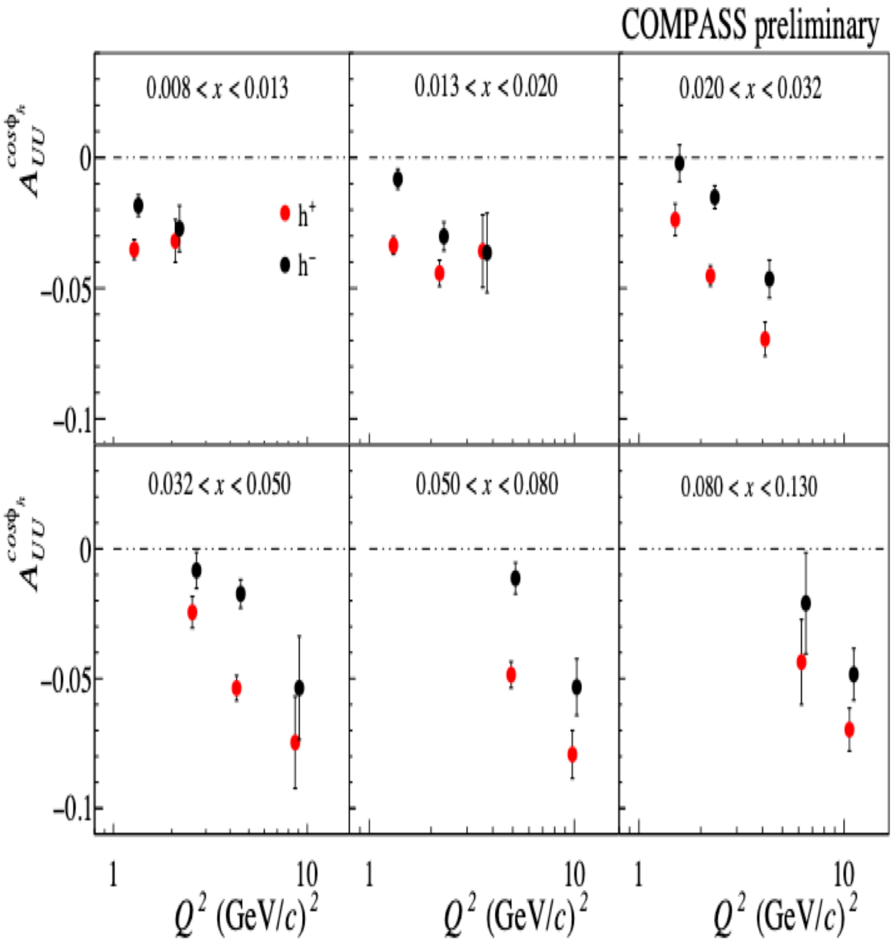


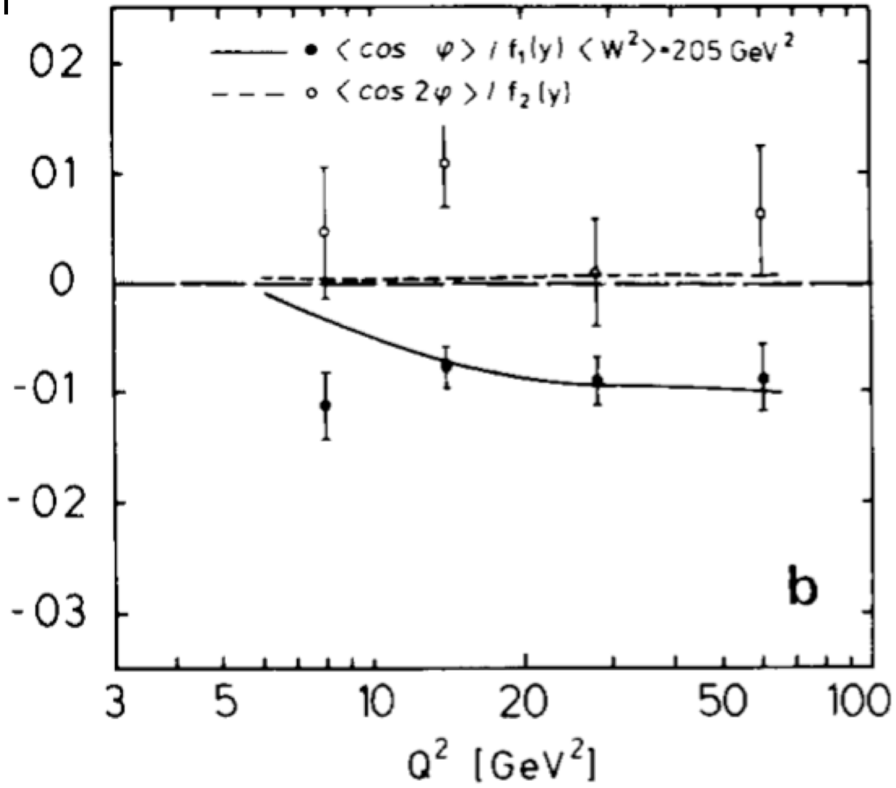


By combining the directly produced pions and the decayed pions, two Gaussian slopes are effectively generated even if we started with one single gaussian

Large cosines from EMC to COMPASS

A. Moretti: https://arxiv.org/pdf/2107.10740.pdf





J. Aubert *et al.*, "Measurement of Hadronic Azimuthal Distributions in Deep Inelastic Muon Proton Scattering," *Phys. Lett. B*, vol. 130, pp. 118–122, 1983.

A. Konig and P. Kroll, "A Realistic Calculation of the Azimuthal Asymmetry in Semi-inclusive Deep Inelastic Scattering," *Z. Phys. C*, vol. 16, p. 89, 1982.

Cosine moments do not really follow the expected Q-behavoir

Unpolarized x-section: F_{UU}^{Cahn}

Anselmino et al arXiv:hep-ph/0412316

assume, both for the parton densities and the fragmentation functions, a factorized Gaussian dependence

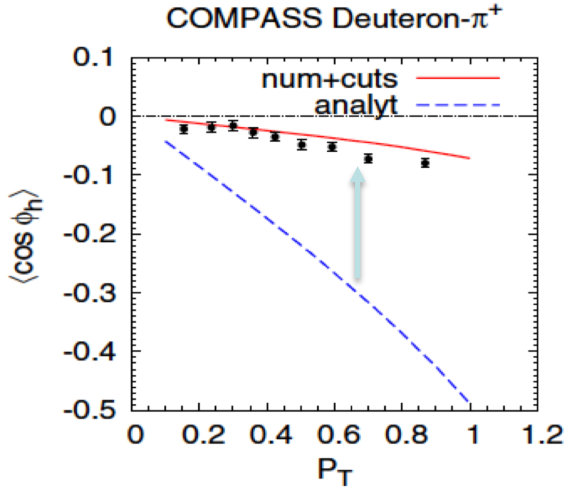
$$\langle P_T^2\rangle = \langle p_\perp^2\rangle + z_h^2\langle k_\perp^2\rangle$$

$$\frac{d^5\sigma^{\ell p\to \ell h X}}{dx_B\, dQ^2\, dz_h\, d^2\boldsymbol{P}_T} \simeq \sum_q \frac{2\pi\alpha^2 e_q^2}{Q^4}\, f_q(x_B)\, D_q^h(z_h)\Bigg[(1+(1-y)^2) - 4\,\frac{(2-y)\sqrt{1-y}\,\langle k_\perp^2\rangle\, z_h\, P_T}{\langle P_T^2\rangle\, Q}\,\cos\phi_h\Bigg]\frac{1}{\pi\langle P_T^2\rangle}\, e^{-P_T^2/\langle P_T^2\rangle}\,,$$

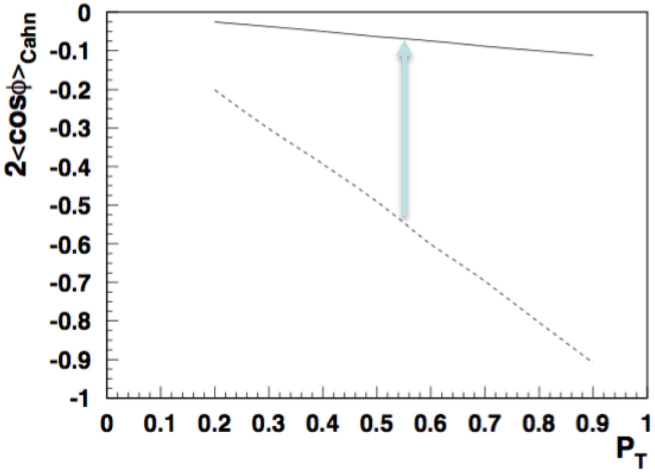
Cahn effect, within assumptions can be the most sensitive observable for intrinsic k_T

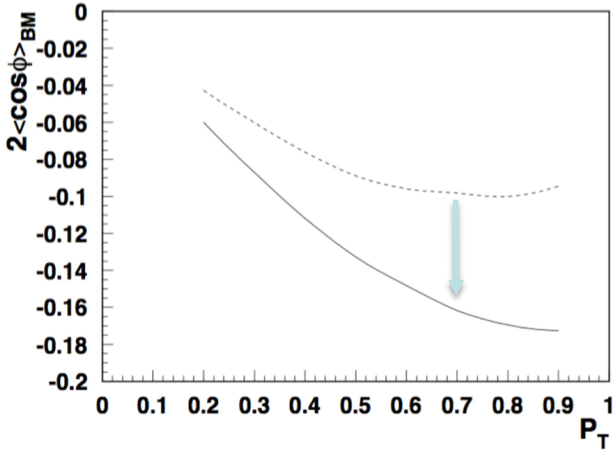
k_T-max: Effect on BM vs Cahn

M. Boglione, S. Melis & A. Prokudin
Phys. Rev. D 84, 034033 2011

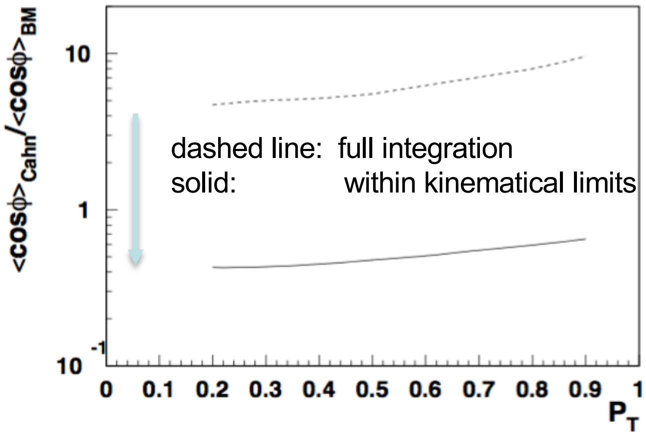


EVA tests from JLAB: Cahn & BM





$$C[w, fD] = x\sum_a e_a^2 \int d^2\boldsymbol{p}_\perp\, d^2\boldsymbol{k}_\perp\, \delta^{(2)}(z\boldsymbol{k}_\perp + \boldsymbol{p}_\perp - \boldsymbol{P}_{h\perp})\, w(\boldsymbol{k}_\perp,\boldsymbol{p}_\perp) f^a(x,\boldsymbol{k}_\perp^2)\, D^a(z,\boldsymbol{p}_\perp^2)$$



$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[\frac{\hat{h}\cdot p_\perp}{zM_h}\frac{k_\perp^2}{M^2} h_1^\perp H_1^\perp - \frac{\hat{h}\cdot k_\perp}{M} z f_1 D_1\right]$$

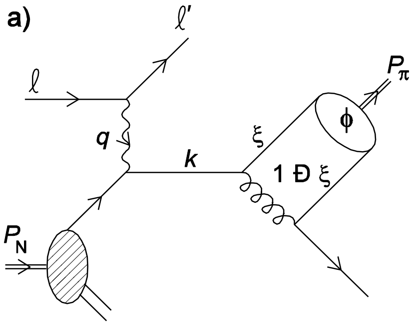
BM contribution seem to be less sensitive to phase space limitations
PRELIMINARY: Need cross checks.

Azimuthal Asymmetries in semi-exclusive limit

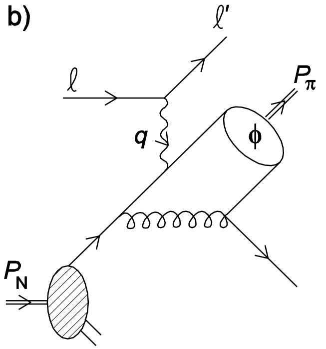
•*Phys.Lett.B* 347 (1995) 413-418

- Higher twists (Berger 1980, Brandenburg et al 1995) z→1 dominant contribution u+e- →e- π+ d

a)



b)



$$H_1 \ = \mathcal{N}\, \frac{1}{2x_B} \left(\, [I_2(z,p_T/Q)]^2 \ + \ \frac{p_T^4}{Q^4}[I_1(z,p_T/Q)]^2 \, \right),$$

$$H_2 \ = \mathcal{N} \left(\, [I_2(z,p_T/Q)]^2 \ + \ 4\frac{p_T^2}{Q^2}z^2[I_1(z,p_T/Q)]^2 \ + \frac{p_T^4}{Q^4}[I_1(z,p_T/Q)]^2 \, \right)$$

$$I_1(z,p_T/Q) \ = \ z \int_0^1 d\xi \frac{\phi(\xi)}{z \ - \ \xi(z^2-p_T^2/Q^2)};$$

$$I_2(z,p_T/Q) \ = \ \int_0^1 d\xi \frac{\phi(\xi)}{1-\xi} \ - \ z^2 I_1(z,p_T/Q)$$

$$\frac{Q^2 \, d\sigma}{dx_B dy dz dp_T^2 d\varphi} = \frac{4\pi\alpha^2 ME}{Q^2} \left(x_B y^2 \ H_1 \ + \ (1-y) \ H_2 \right.$$

$$\left. + \ \frac{p_T}{Q}(2-y)\sqrt{1-y} \ H_3 \ \cos\varphi \ + \ \frac{p_T^2}{Q^2}(1-y) \ H_4 \ \cos 2\varphi \right)$$

Significant contributions at large z and P_T also for H_1/F_{UU}

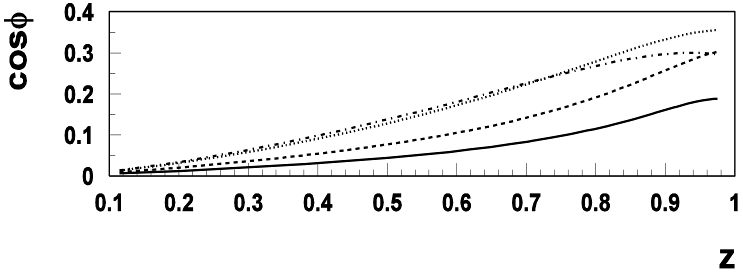
$$F_{UU,T} = 2xH_1$$

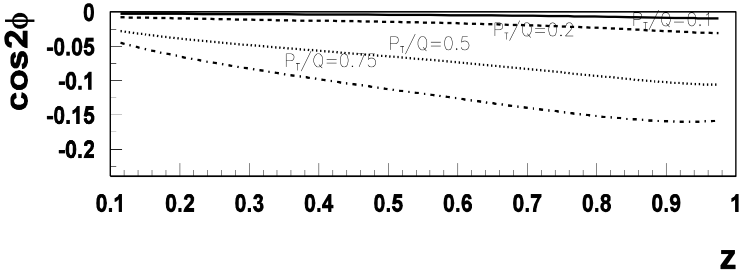
Azimuthal Asymmetries in semi-exclusive limit

- Higher twists (Berger 1980, Brandenburg et al 1995)
  z→1 dominant contribution u+e- →e- π+/ρ0 d/u

$$\langle \cos\varphi\rangle = \frac{1}{2}\,\frac{p_T}{Q}\,\frac{(2-y)\sqrt{1-y}\;H_3}{x_B y^2\,H_1 \;+\; (1-y)\,H_2},$$

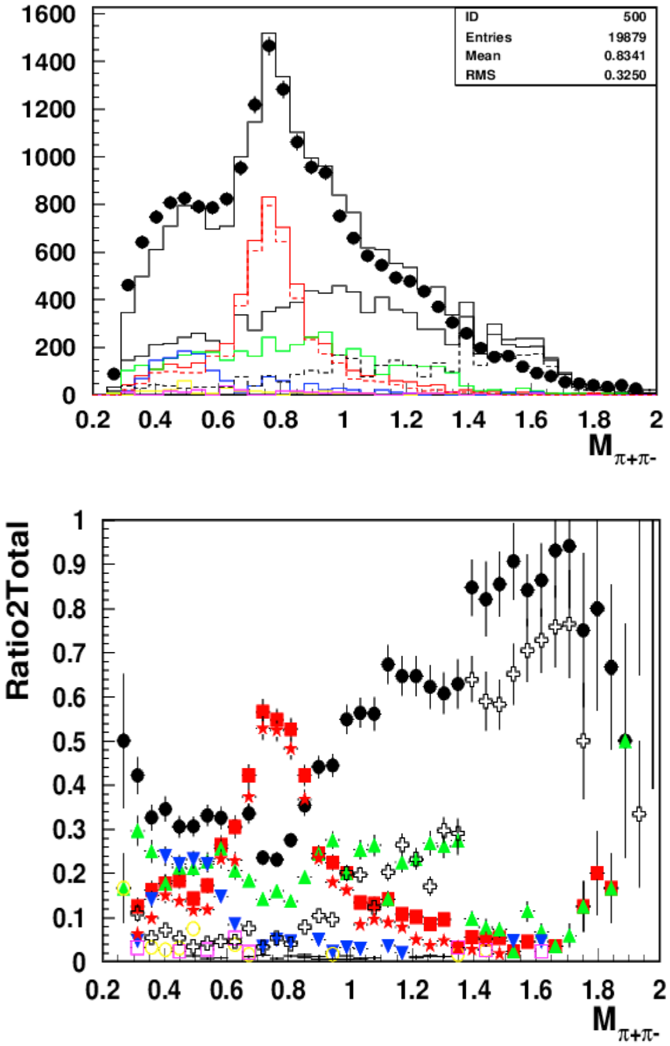
$$\langle \cos 2\varphi\rangle = \frac{1}{2}\,\frac{p_T^2}{Q^2}\,\frac{(1-y)\;H_4}{x_B y^2\,H_1 \;+\; (1-y)\,H_2}$$





- **Semi-exclusive production of pions and even more for VMs will be crucial to understand**
- Dominant contribution to meson wave function is the perturbative one gluon exchange and approach is valid at factor ~3 lower Q^2 than in case of hard exclusive scattering (Afanasev & Carlson 1997)

Azimuthal modulations in SIDIS: decay pions



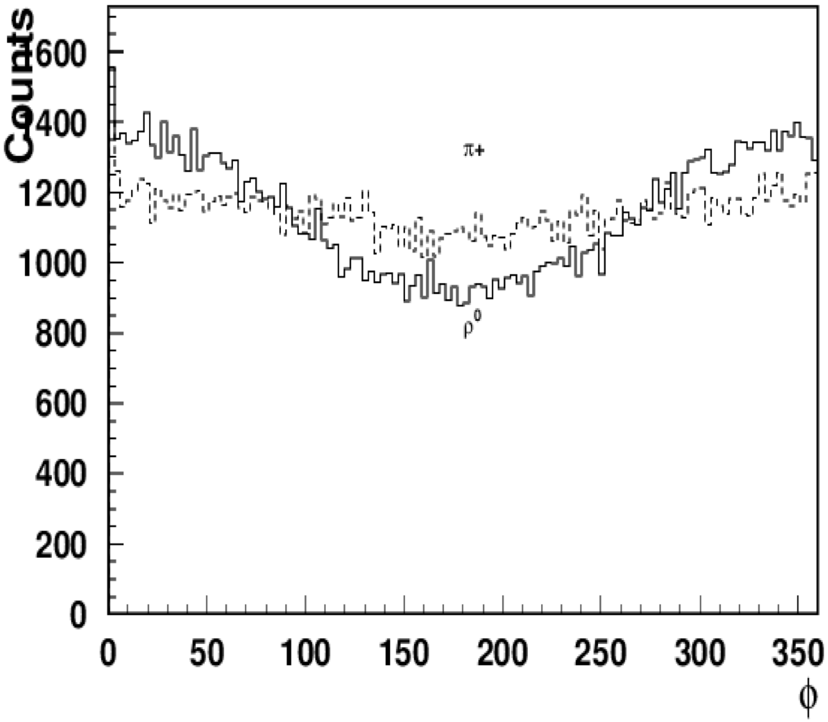
Significant fraction of pions are from VM decays.

VM decays dominates the low PT region and shows steeper PT distributions.

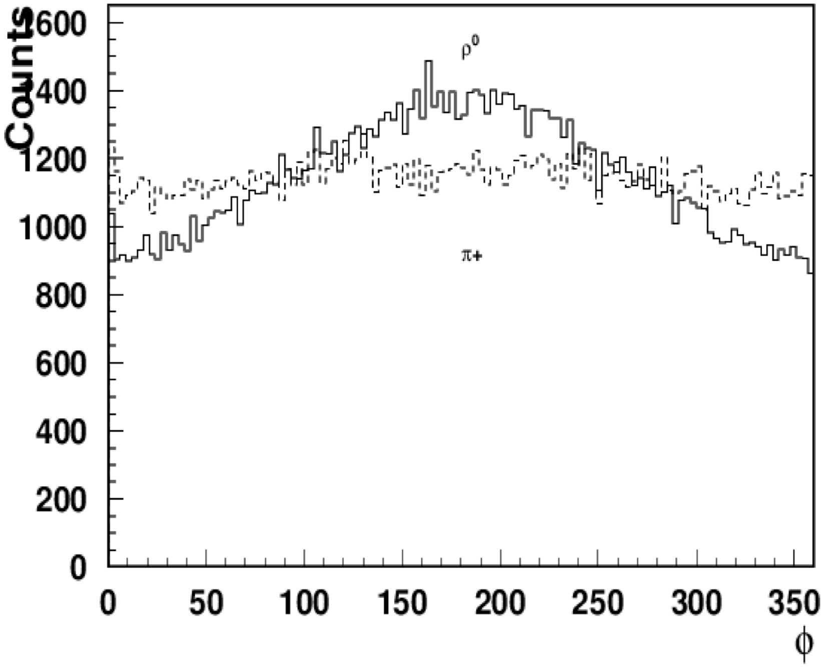
What is the impact on azimuthal distributions?

Azimuthal Asymmetries: impact of rho

Berger HT for rho

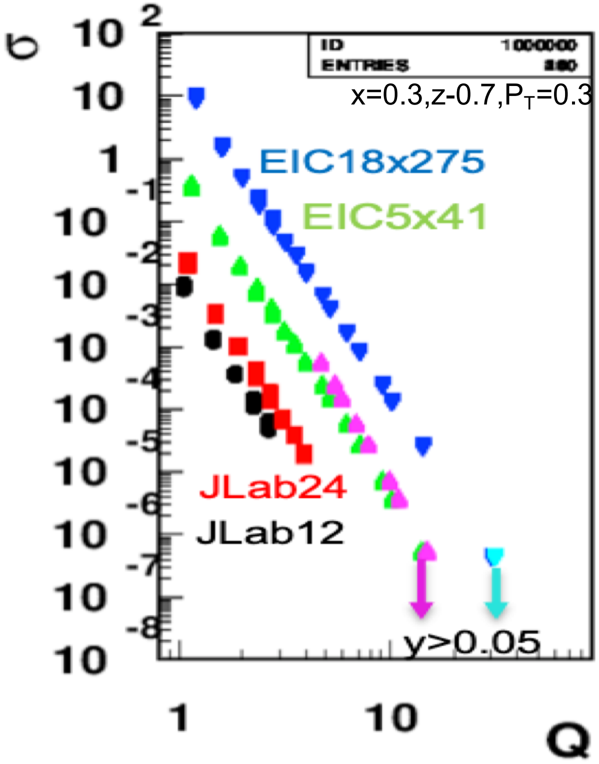


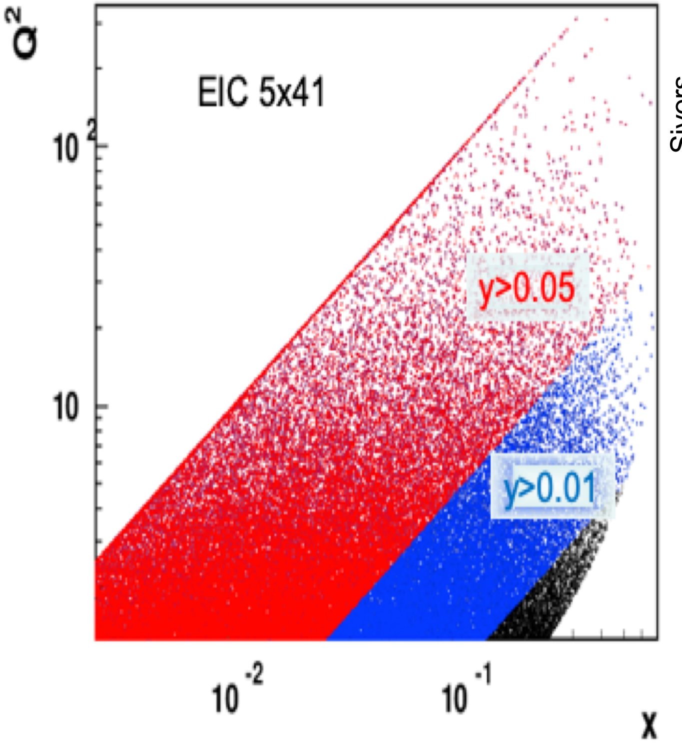
Cahn HT for rho

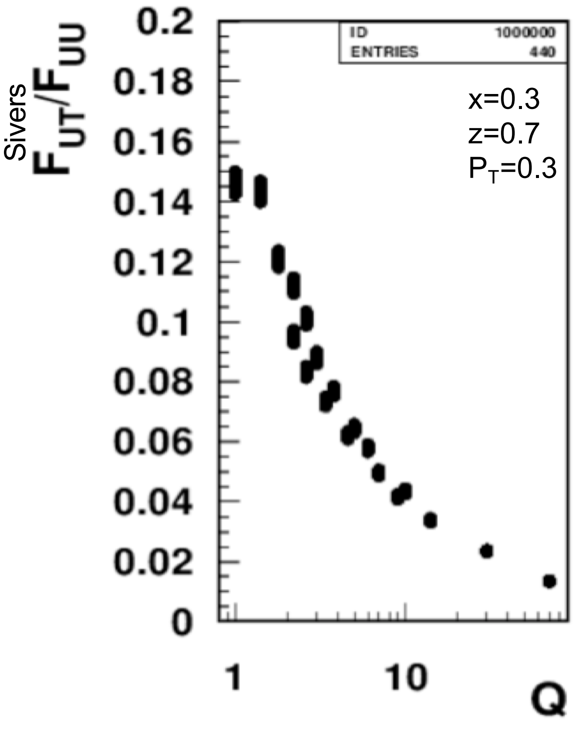


- **For the $0.2<z<0.4$, $P_T<0.5$ there will be a significant dilution in azimuthal modulations for decay pions.**

From JLab to EIC: complementarity



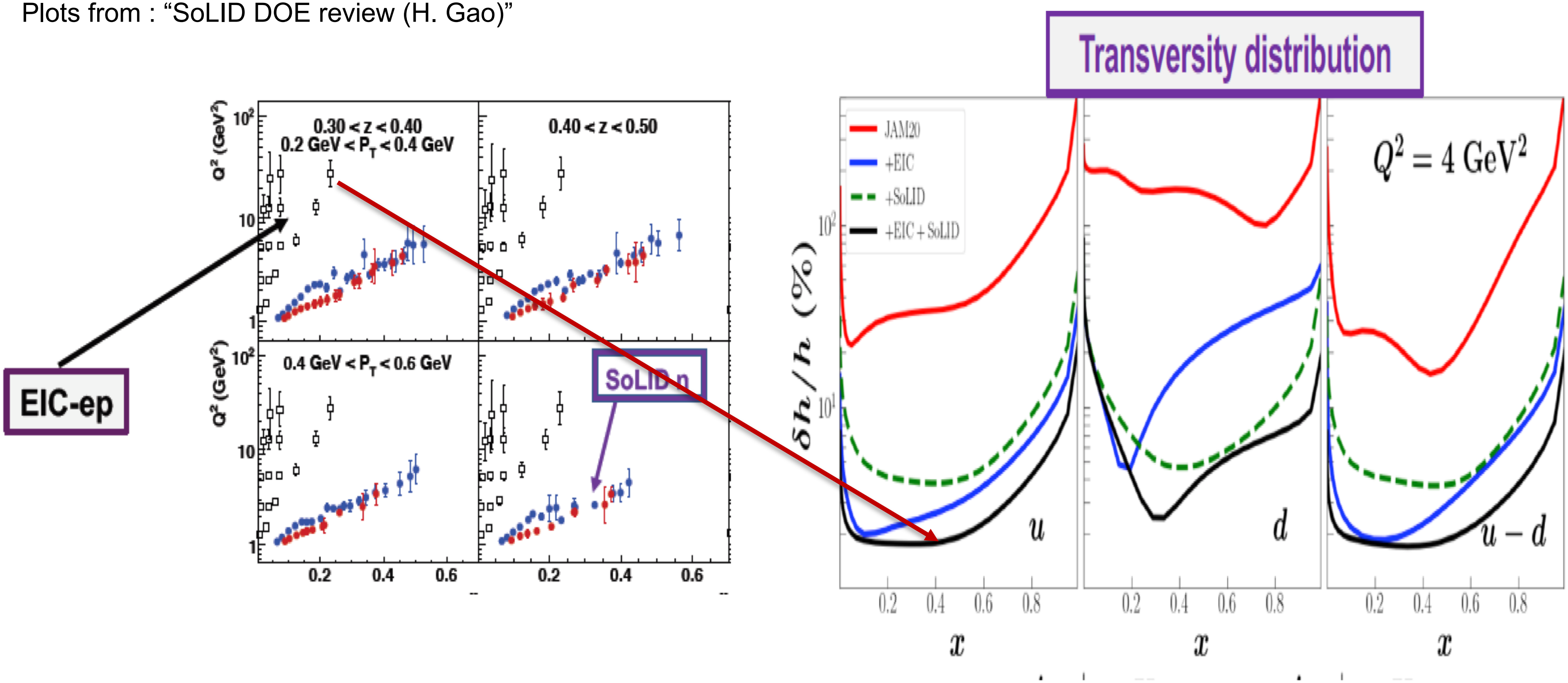




- Understanding of Q^2-dependence of multiplicities crucial for interpretation
- Proper evaluation of systematics, will require definition of fiducial kinematics
- JLab at 24 GeV will provide critical input in evolution studies of TMDs
- Higher Q^2-coverage of “Low s” EIC running will provide validation of evolution studies at JLab at large x

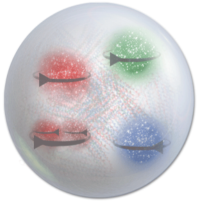
TMDs sensitivity to transversity: large x

Plots from : “SoLID DOE review (H. Gao)”



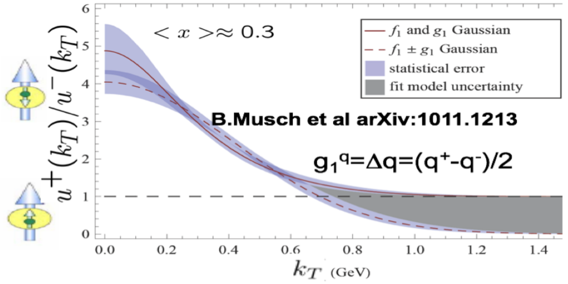
- SOLID measurements with transversely polarized targets will provide crucial input at large x
- Complementarity of JLab and EIC at large x should be carefully examined for better coordination

Extending to small x, large Q2 and large P_T



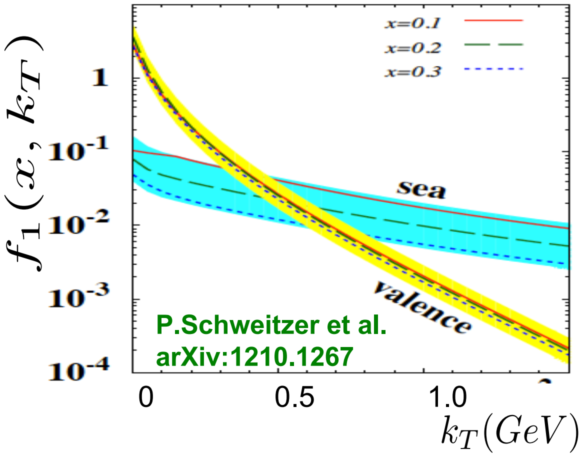
Non-perturbative sea (“tornado”) in nucleon is a key to understand the nucleon structure

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

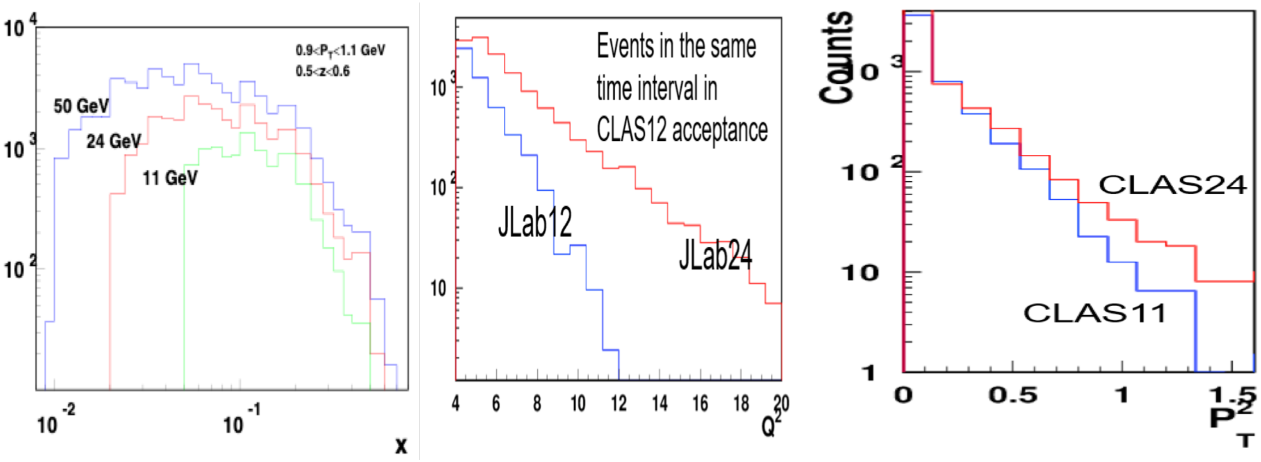


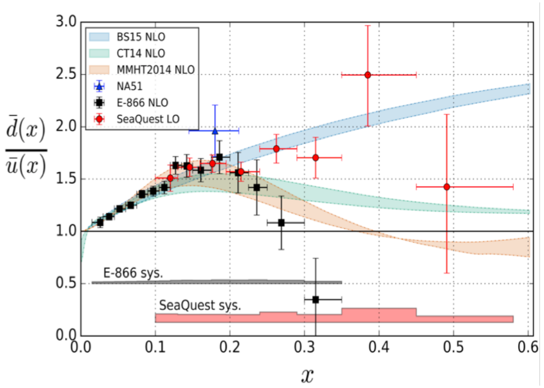
B.Musch et al arXiv:1011.1213

- 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



P.Schweitzer et al. arXiv:1210.1267





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 and asymmetries provide qualitatively new possibilities for understanding the structure of the nucleon and the process of hadronization, allowing experimental studies of the fractions and distributions of pions coming from vector meson decays. CLAS12 provides high statistical multidimensional measurements.

Extraction of multiplicities and spin-azimuthal asymmetries in multidimensional space is critical for interpretation of results and understanding of the systematics of TMD extractions

The extraction of universal 3D PDFs requires a clear understanding of the impact of the phase space in polarized electroproduction experiments, especially at JLab.

Understanding contributions from VM (with stronger phase space dependence) will be important to understand the systematics of TMD extraction and maybe provide a possible explanation for the single hadron PT distribution.

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