Hall-B Studies with JLab20+

Marco Contalbrigo – INFN Ferrara

Opportunities with JLab Energy and Luminosity Upgrade - ECT* 26-30 September 2022

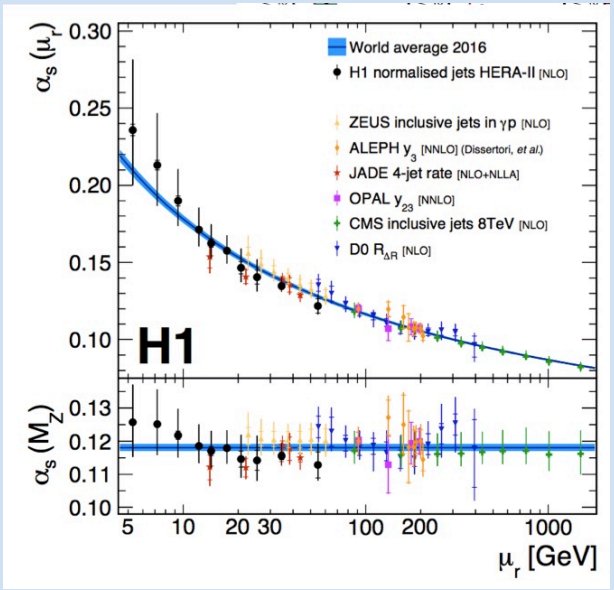
HERA Legacy and Perturbative QCD

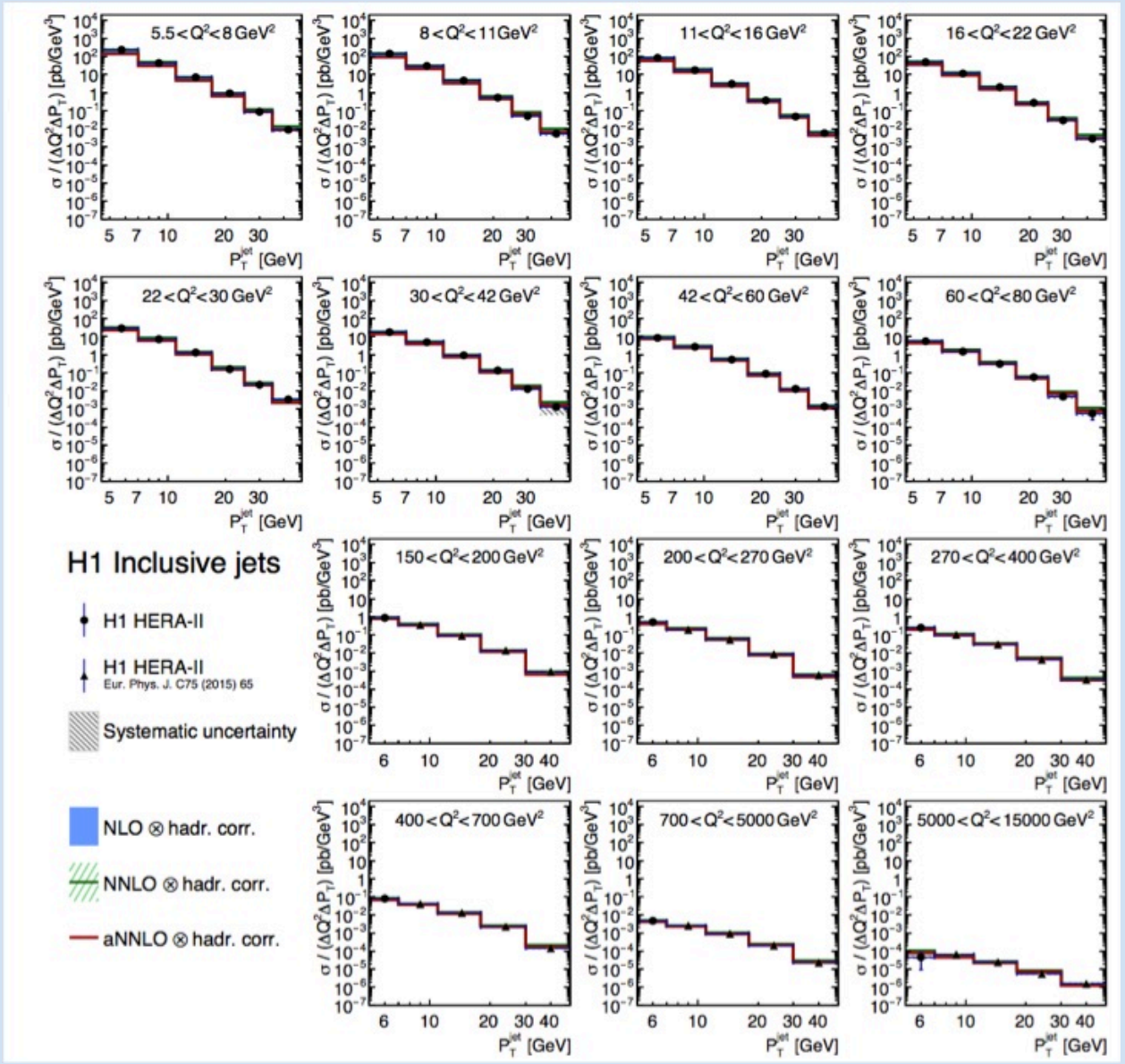
Good perturbative description (hard gluon emission)

p_T>5 GeV Q^2>5 GeV^2

Part in a P_T<<Q TMD regime

H1 [arXiv: 1611.03421]



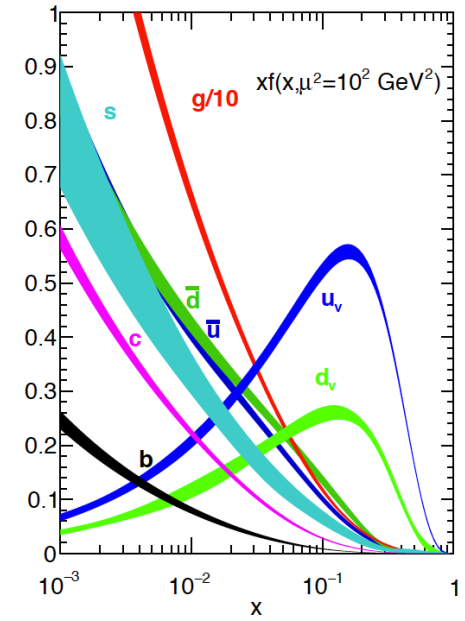


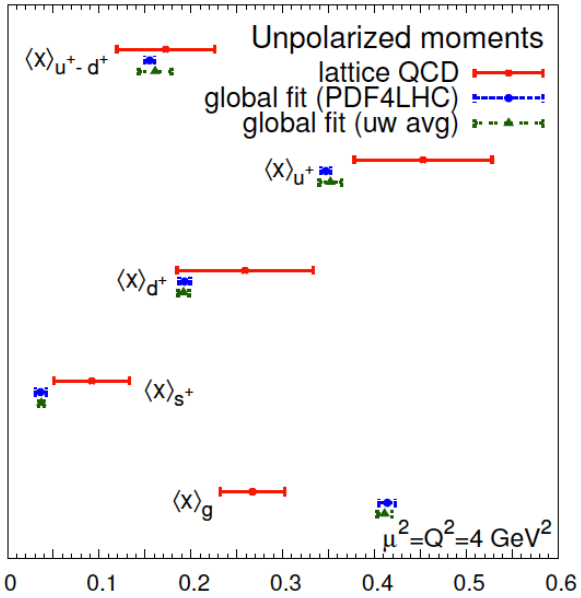
Parton Content

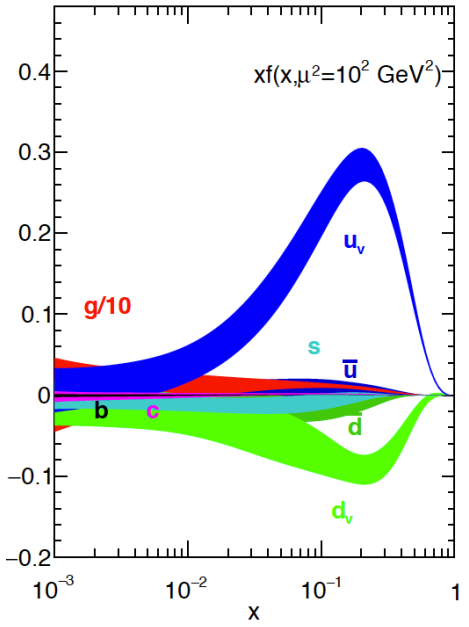
Unpolarized moments

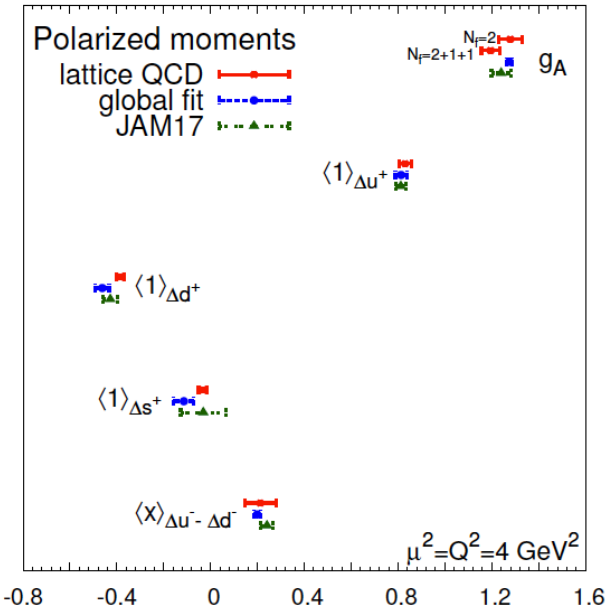
H-W Lin++ [1711.07916]

Polarized (helicity) moments



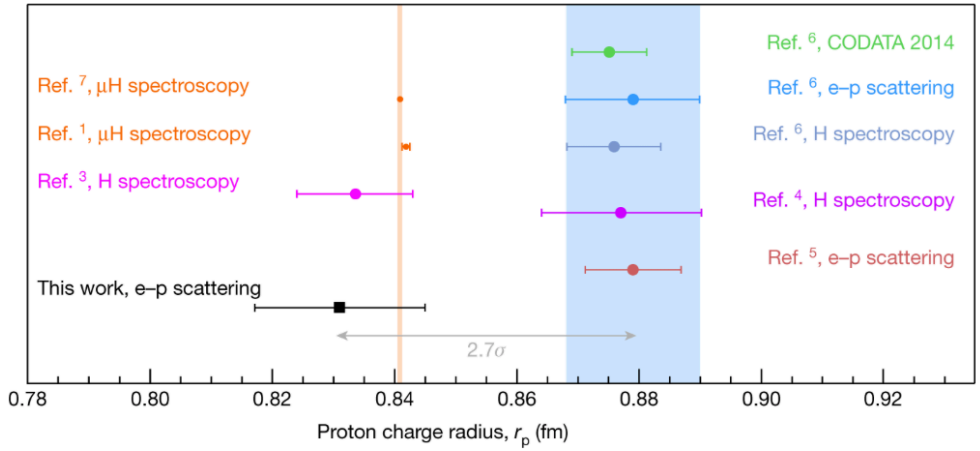




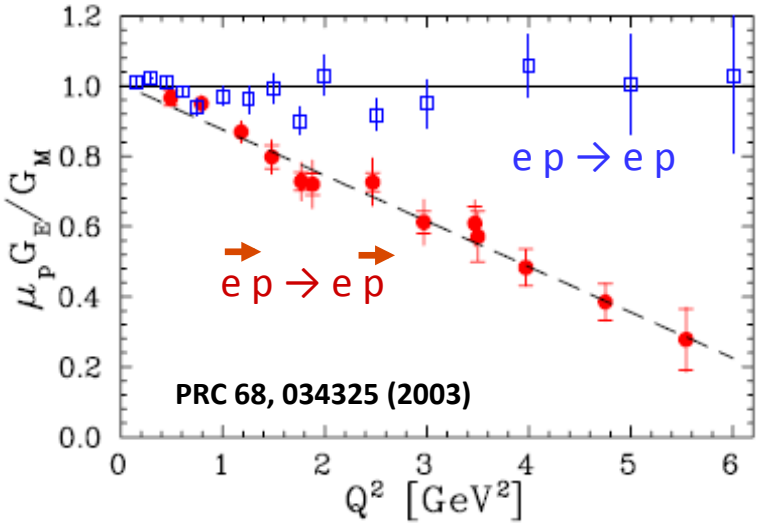


Still Surprising Proton

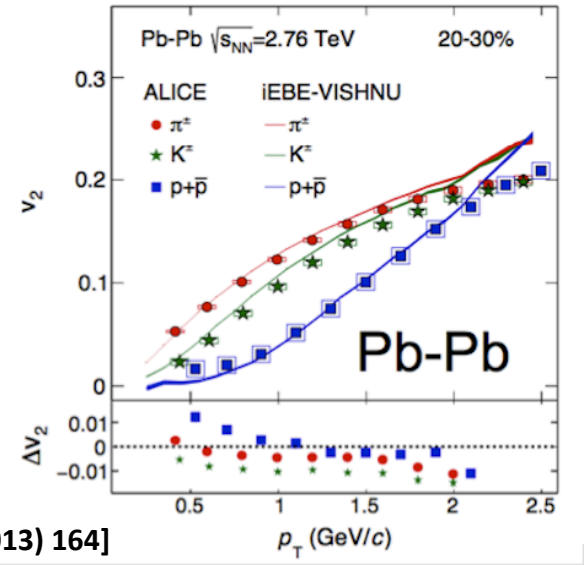
Do we control the proton form factor and radius ?



Nature 575 147 (2019)

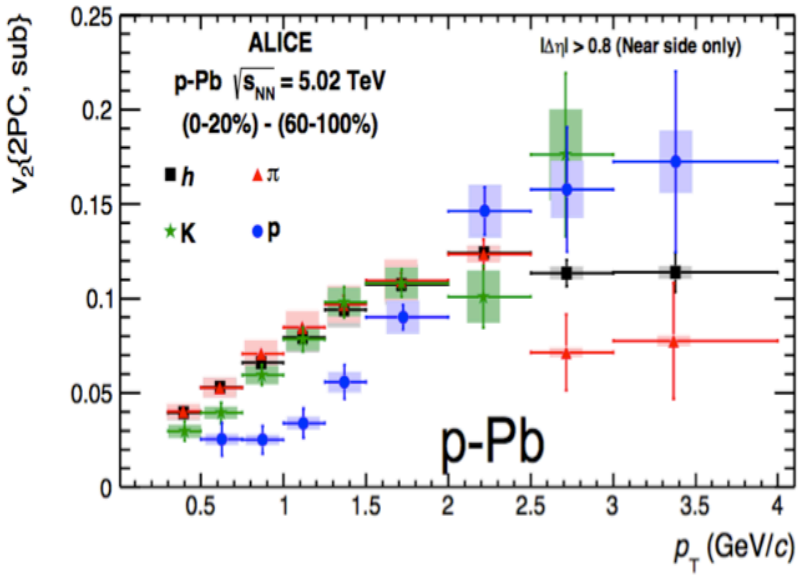


Is there a collective motion in small systems ?



ALICE [PLB 726 (2013) 164]

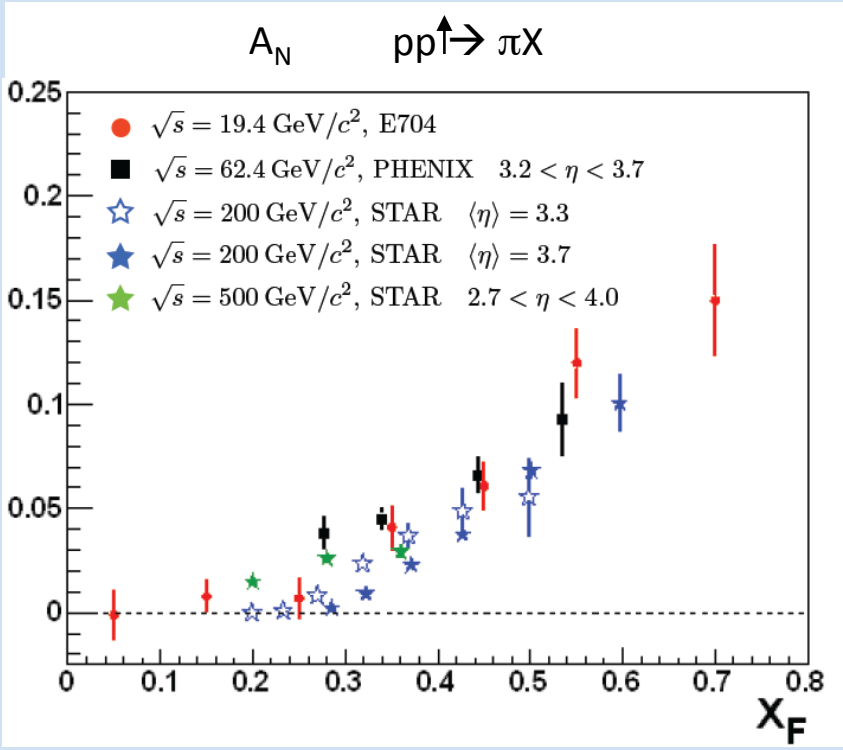
$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + \dots\right)$$



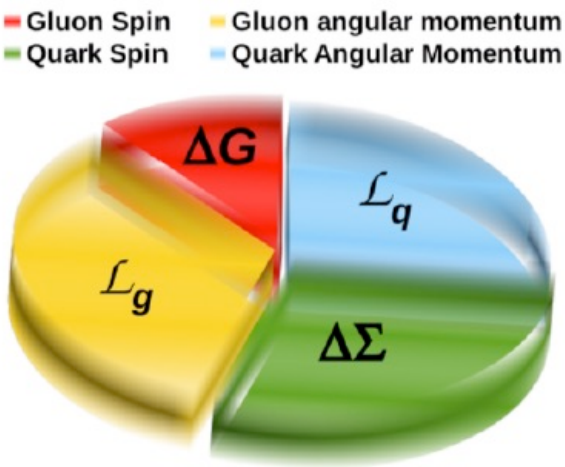
Can QCD be a precision science ?

Should not be confused with pQCD, which already can,
but is not touching the intimate nature of the strong interaction

Single Spin Asymmetries



Proton Spin Budget



$$\frac{1}{2} = \frac{1}{2}\sum_f (q_f^+ - q_f^-) + L_q + \Delta G + L_g$$

3D Imaging

$f(x, k_T)$ 1+2D

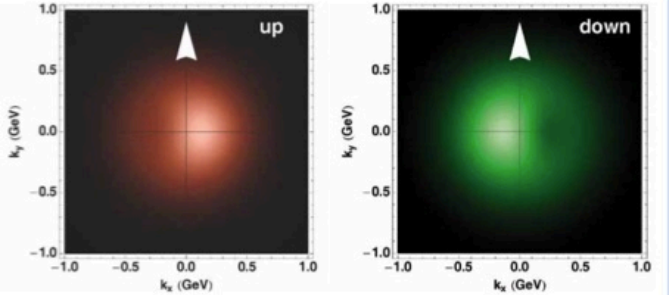
$\int d^2 b_T$ $W(x, b_T, k_T)$ $\int d^2 k_T$

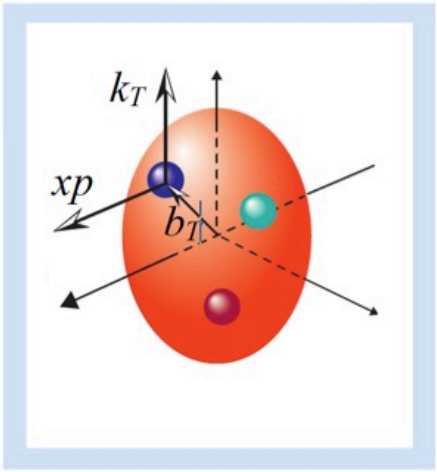
Wigner Distribution

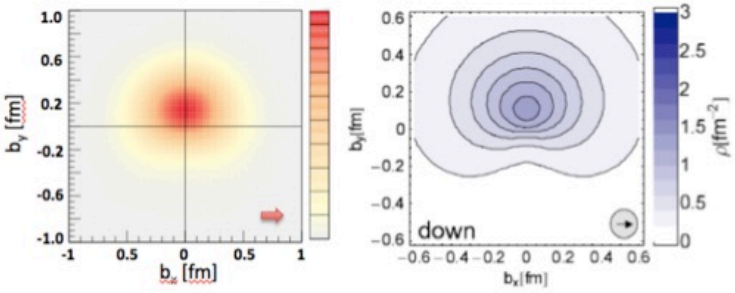
$f(x, b_T)$ 1+2D

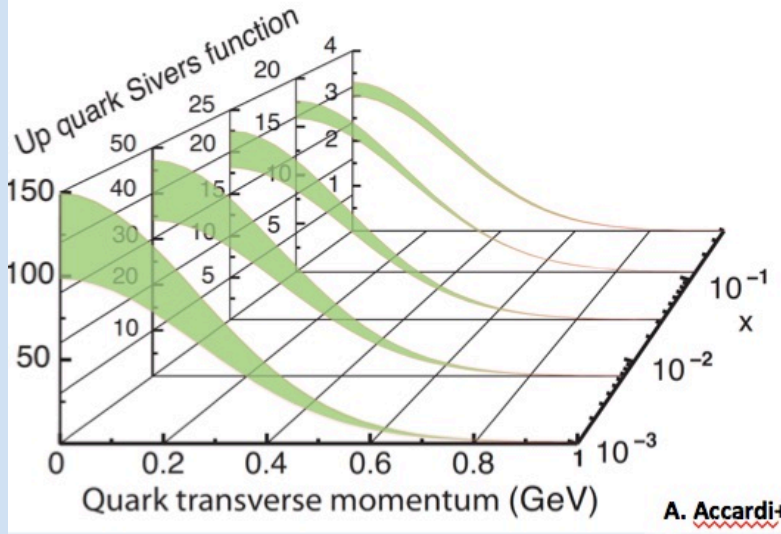
Transverse Momentum Distribution (TMD)

Impact Parameter Distribution

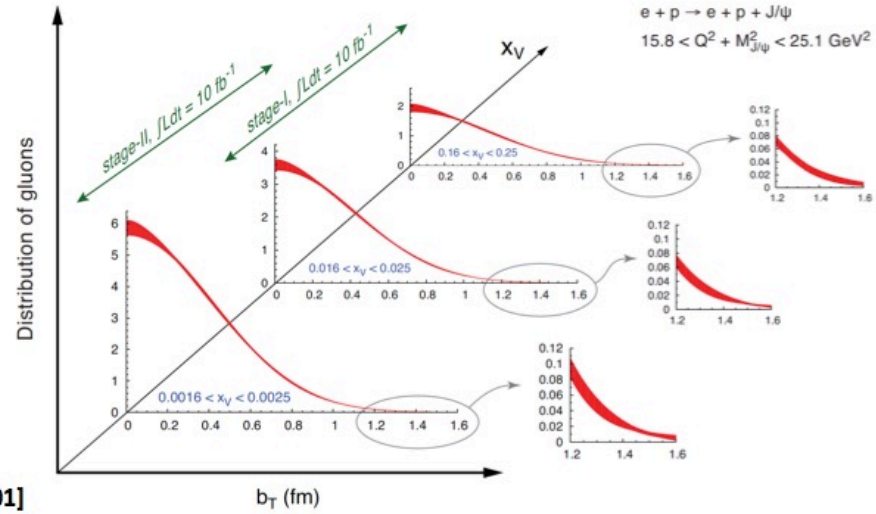






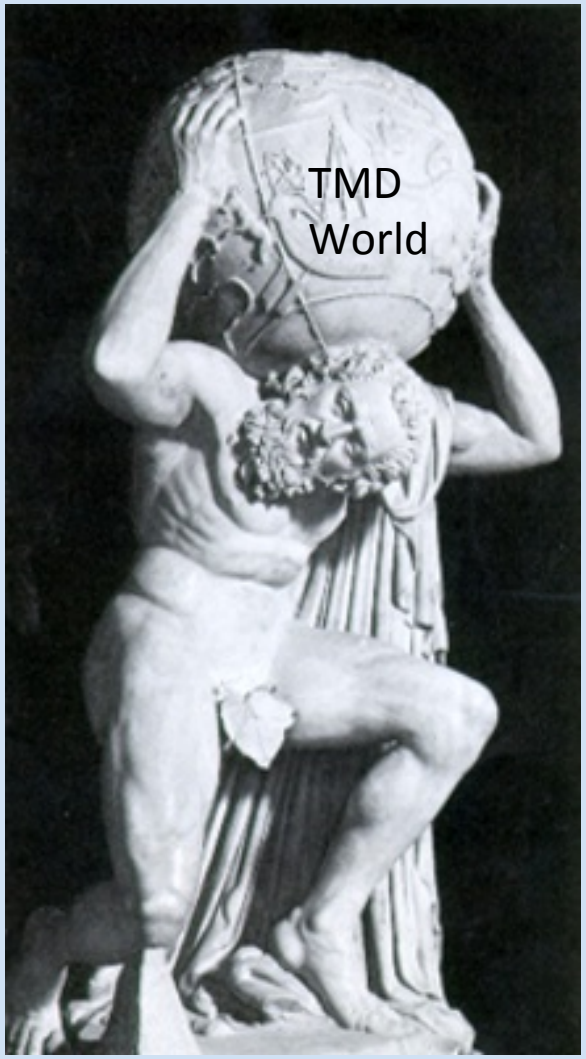


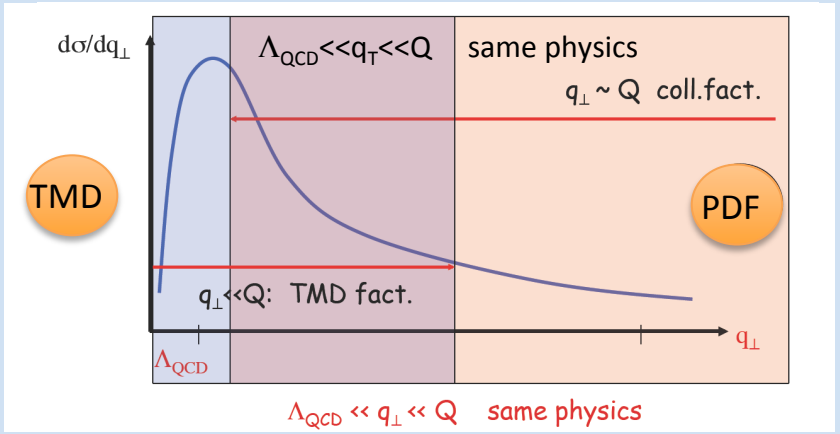
A. Accardi++ [arXiv 1212.1701]



Parton Correlators

Beauty and complexity of the unique strong-interacting world





quark polarisation

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

quark polarisation

N/q	U	L	T
U	D_1		$H_1^\perp$

SIDIS Landscape

SIDIS Cross-Section

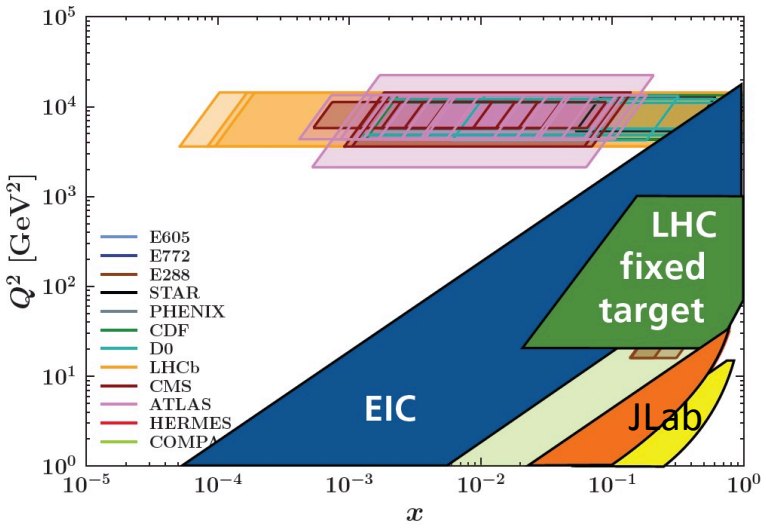
$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Big\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}$$
$$+ \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big]$$
$$+ S_L\,\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big]$$
$$+ S_T\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}$$
$$+ \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}$$
$$+ \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}$$
$$+ \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}$$

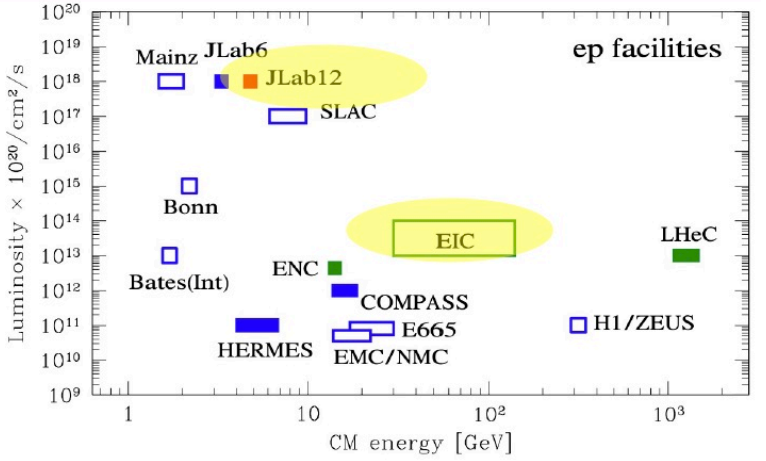
TMD Factorization

$$F_{UT}^{\sin(\phi_h-\phi_S)} = \sum_q e_q^2\,|C_V(Q)|^2\,[R(Q,\mu_0)\otimes f_{1T}^{\perp q}(x;\mu_0)\otimes D_1^q(z;\mu_0)]$$

TMD Evolution

Evolution kernel (with CS non-perturbative kernel)





TMD Probes

SIDIS Cross-Section

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$$+ \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big]$$
$$+ S_L\,\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big]$$
$$+ S_T\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}$$
$$+ \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}$$
$$+ \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}$$
$$+ \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}$$

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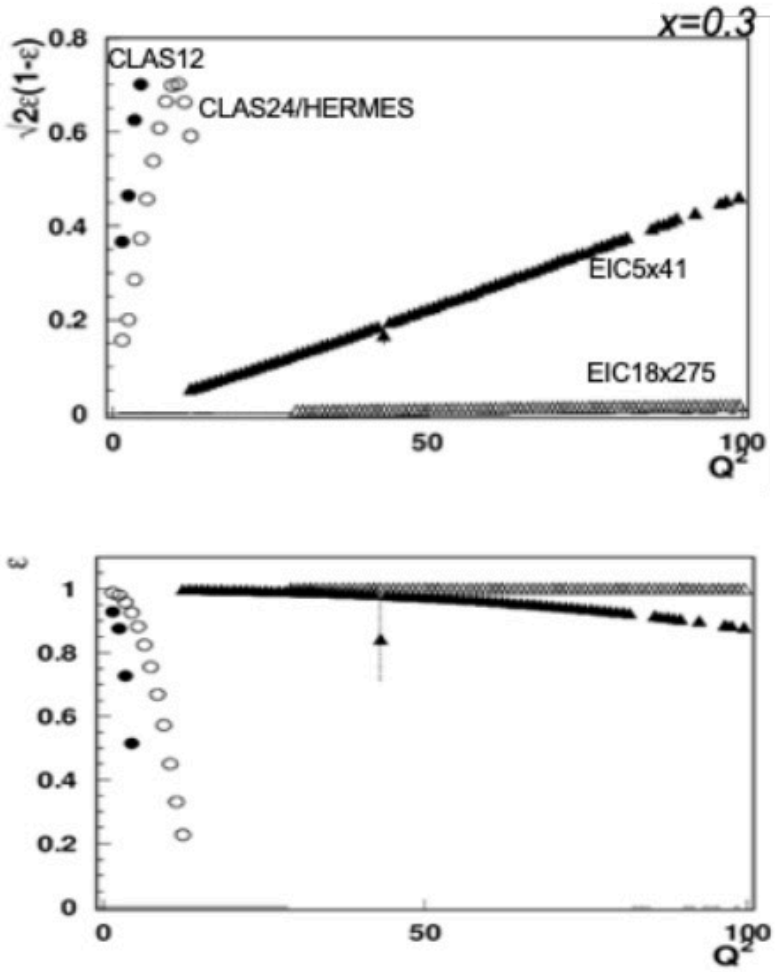
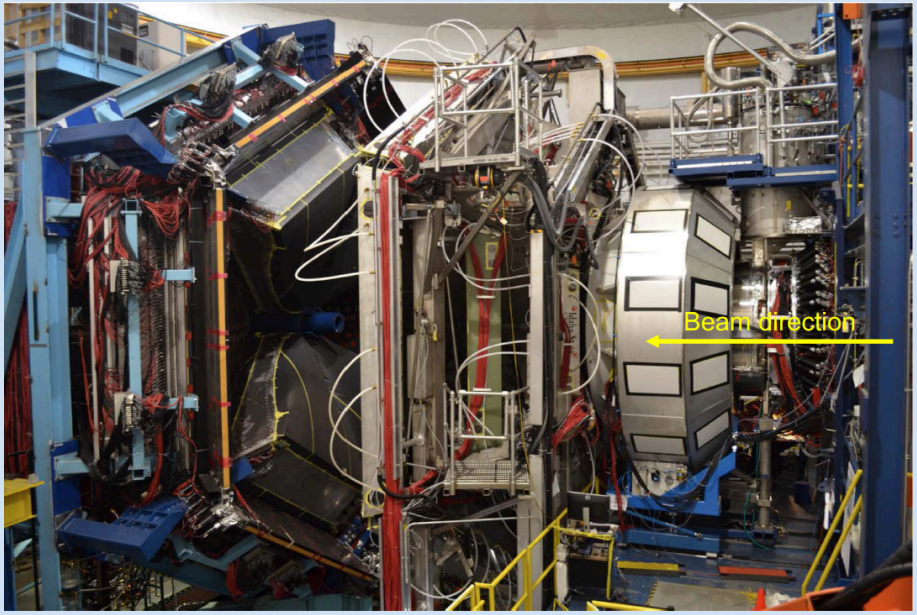
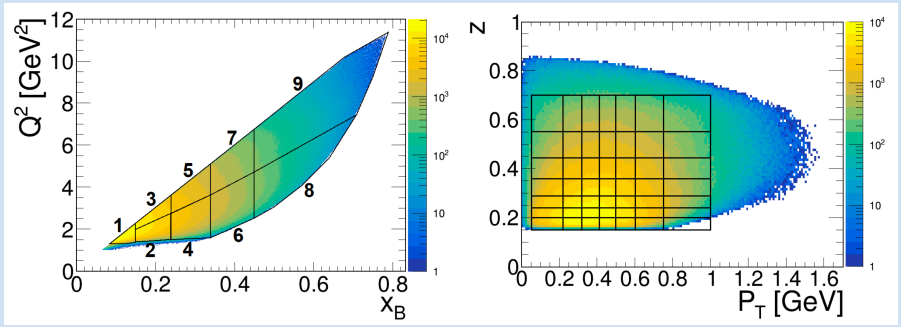


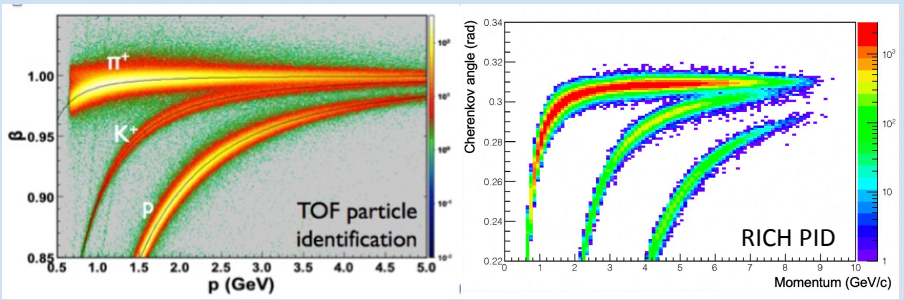
H. Avakian at Transversity 2022

CLAS12 @ JLab

CLAS12 wide coverage, excellent PID, various polarized targets, high luminosity

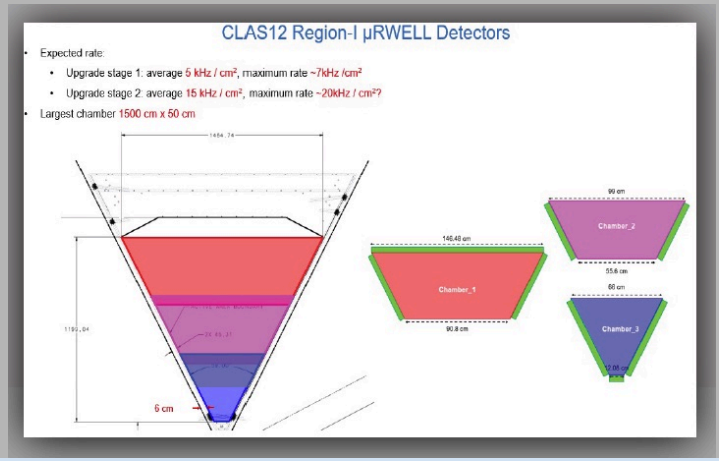






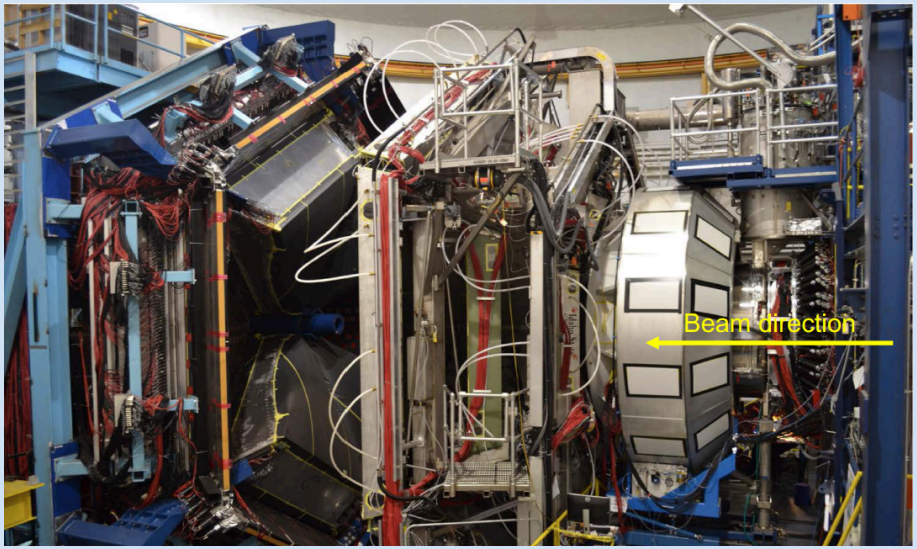
Year	Period	Run	Target	Polarization	Beam
2018	Spring-Fall	RGA	Proton	-	10.6 GeV
	Fall	RGK	Proton	-	6.5-7.5 GeV
2019	Spring	RGA	Proton	-	10.6 GeV
2019	Spring-Fall	RGB	Deuteron	-	10.6 GeV
2020	Spring-Fall	RGF	Deuteron	-	10.6 GeV
2021	Fall	RGM	Nuclear	-	Several GeV
2022	Spring-Fall	RGC	NH_3-ND_3	Longitudinal	10.6 GeV
> 2022		RGH	NH_3-ND_3	Transverse	10.6 GeV
> 2022			^{3}He	Longitudinal	10.6 GeV
> 2022		RGG	^{7}LiD, ^{6}LiH	Longiudinal	10.6 GeV

Luminosity upgrade Stage-1: 2×10^{35} cm^{-2}s^{-1} 3 years
Stage-2: $> 10^{37}$ cm^{-2}s^{-1} 7-10 years



CLAS12 Features

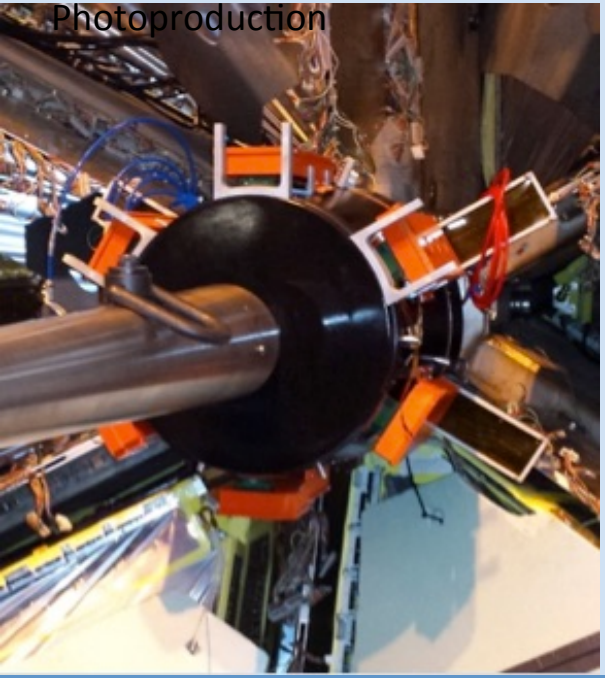
Large-acceptance comprehensive detector

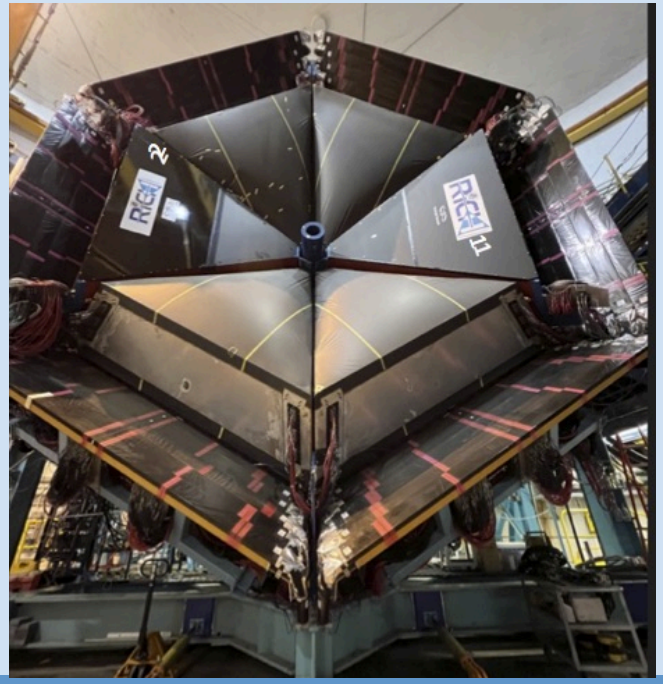


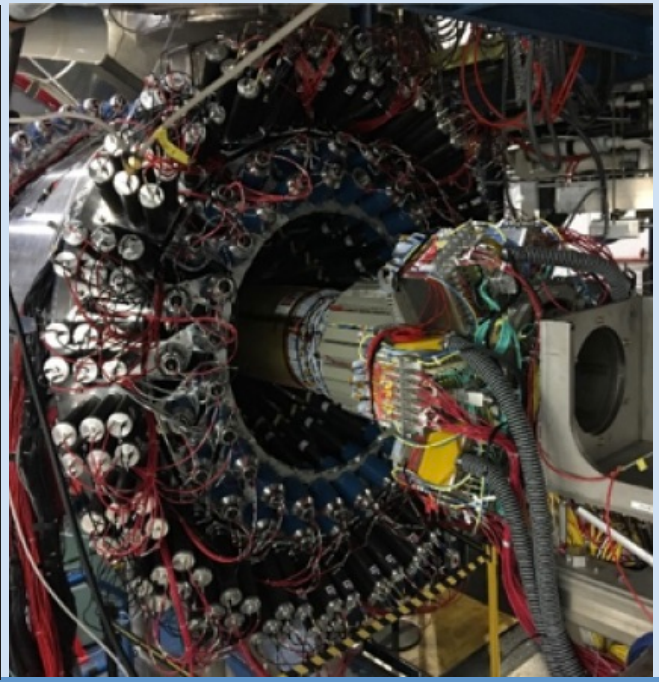
Forward Tagger
(low-θ spectrometer)
Bethe-Heitler
Low-Q^2
Photoproduction

Forward Detector current region

Central Detector
Exclusivity
Fracture functions
Target region







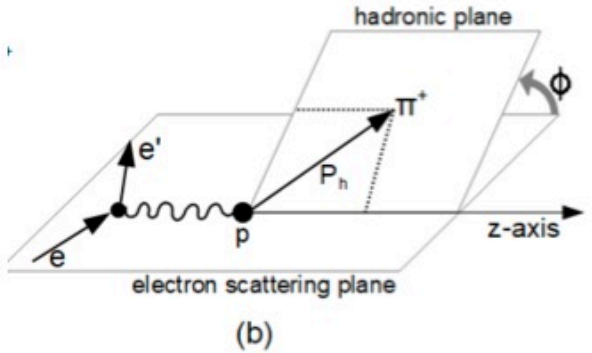
Beam Spin Asymmetry @ CLAS12

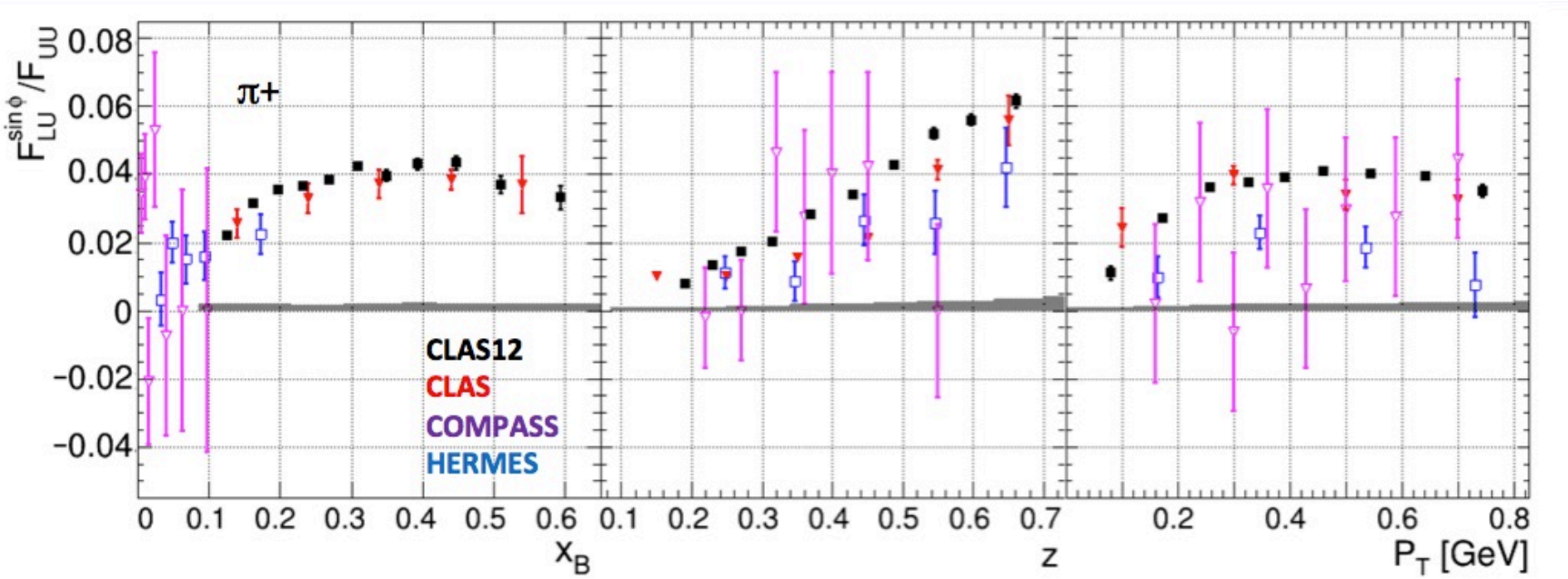
CLAS12 proton data (RGA)

S. Diehl et al., e-Print: 2101.03544

$$F_{LU}^{\sin\phi} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{h}\cdot k_T}{M_h}\left(x_B e H_1^{\perp} + \frac{M_h}{M} f_1 \frac{\tilde{G}^{\perp}}{z} \right) + \frac{\hat{h}\cdot P_T}{M}\left(x_B g^{\perp} D_1 + \frac{M_h}{M} h_1^{\perp} \frac{\tilde{E}}{z} \right) \right]$$

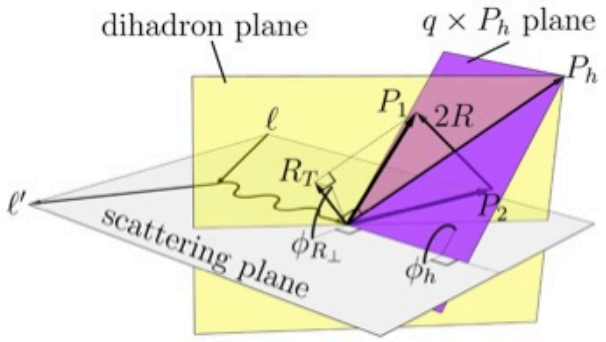
86.9 ± 2.6 %



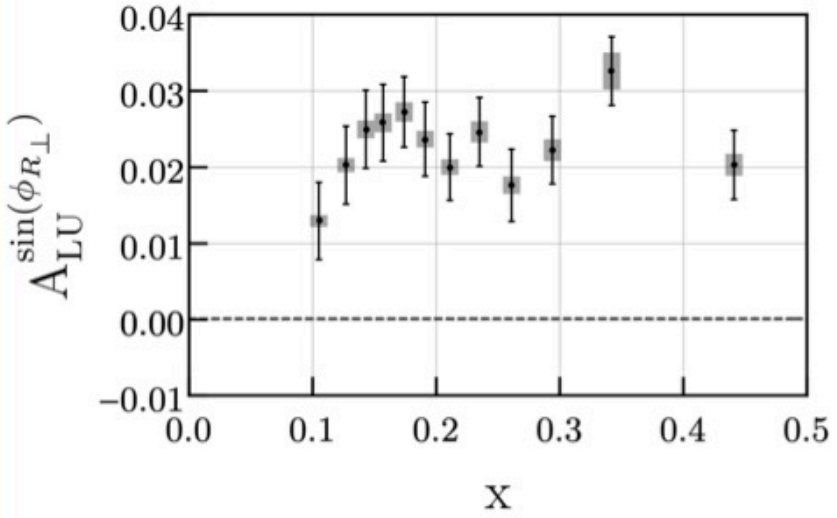


CLAS12 proton data (RGA)

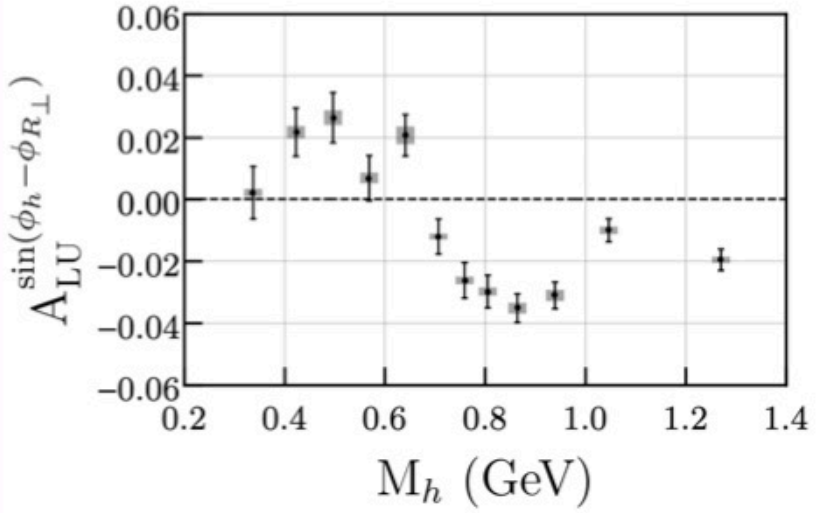
T.B. Hayward et al., PRL 126 (2021) 152501

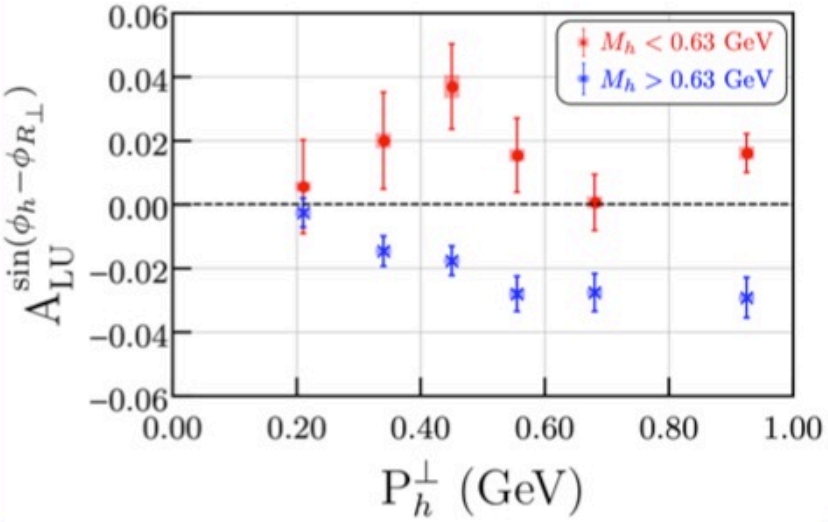


$$d\sigma_{LU} \propto W \lambda_e \sin(\phi_{R_\perp}) \left(x e(x) H_1^{\sphericalangle}(z, M_h) + \frac{1}{z} f_1(x) \tilde{G}^{\sphericalangle}(z, M_h) \right)$$



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





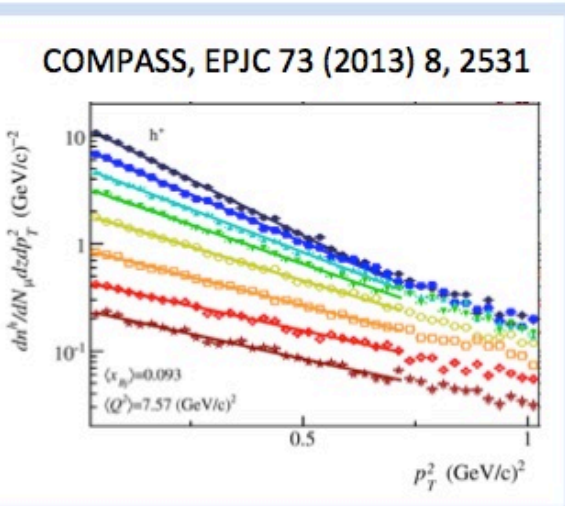
Multiplicities @ CLAS12

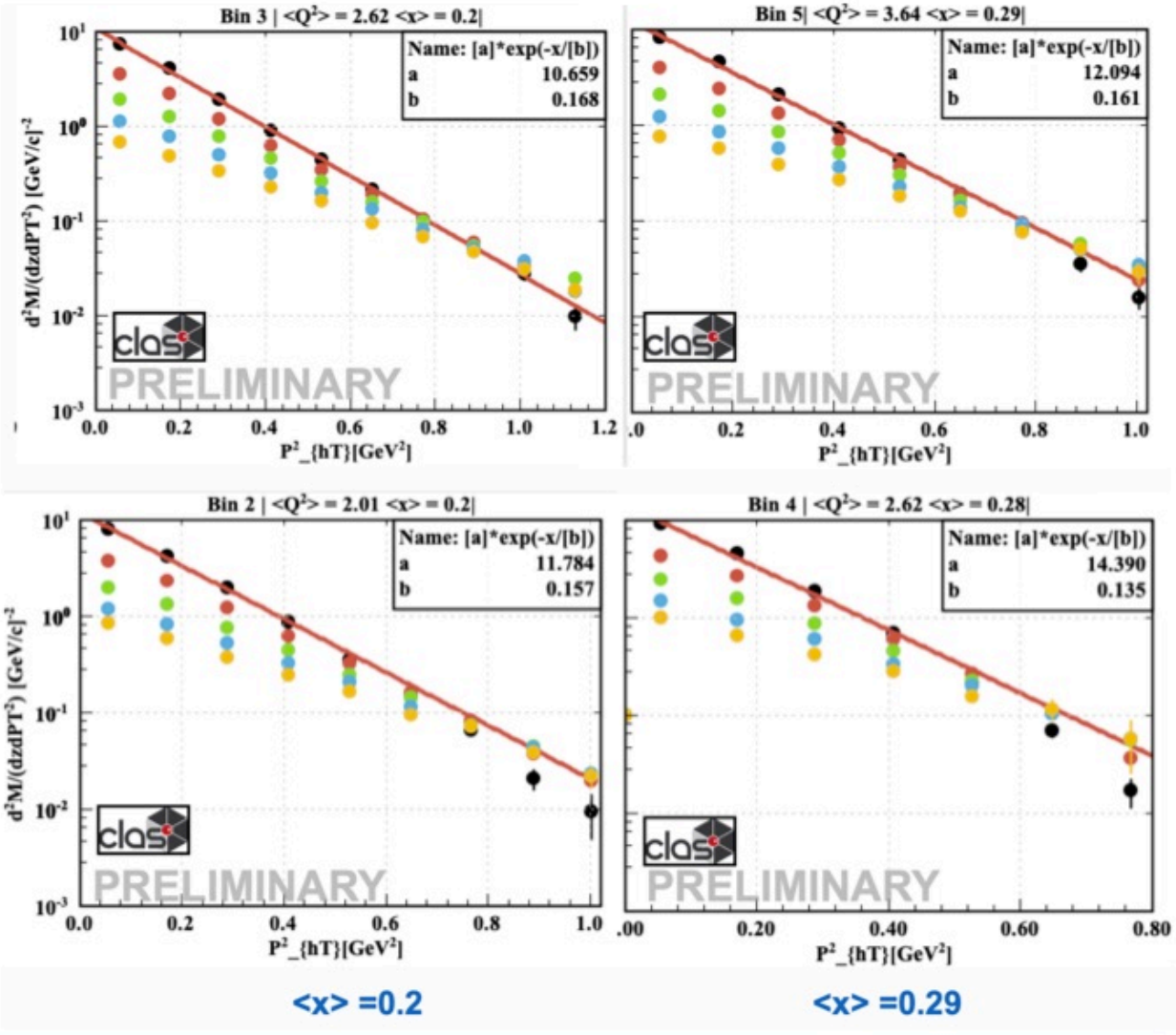
Transverse momentum dependence and phase space

ep->eπ+X

Color legend

- 0.2<z<0.3
- 0.3<z<0.4
- 0.4<z<0.5
- 0.5<z<0.6
- 0.6<z<0.7





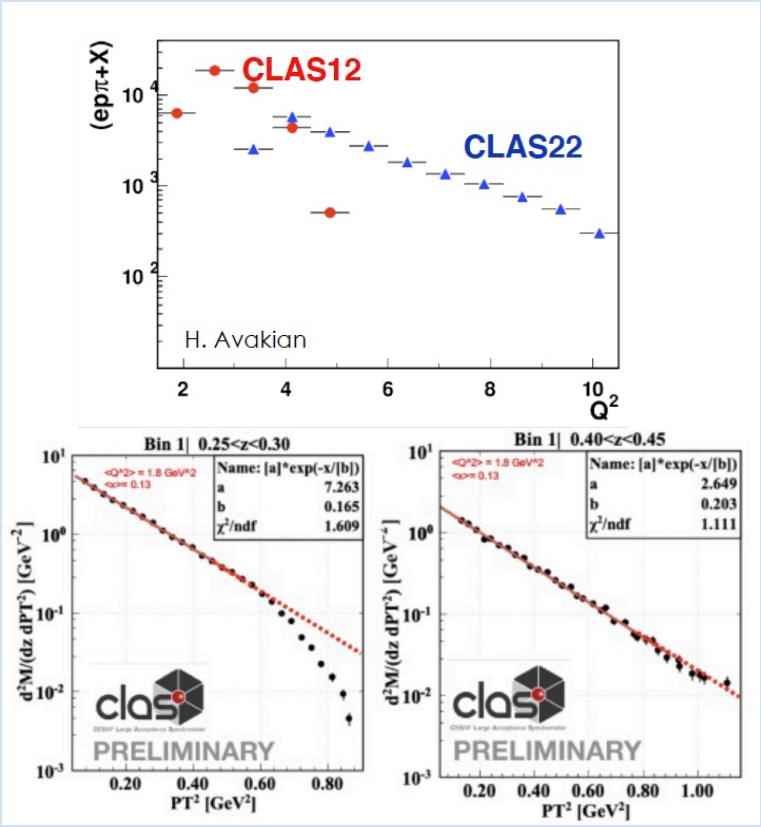
JLab Future

Extend the reach in Q^2 and p_T to exploit an unique facility at the intensity frontier

Energy increase to 20++ GeV

SOLID and CLAS12+

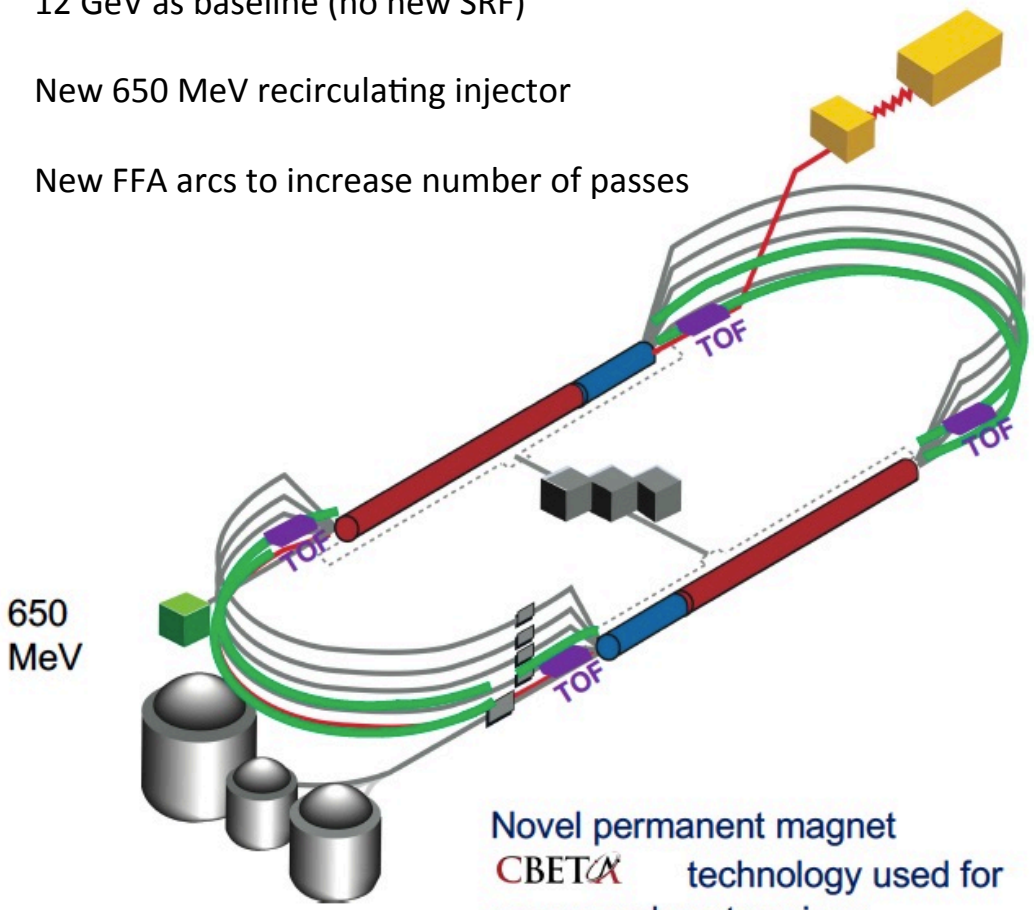
Positron source



12 GeV as baseline (no new SRF)

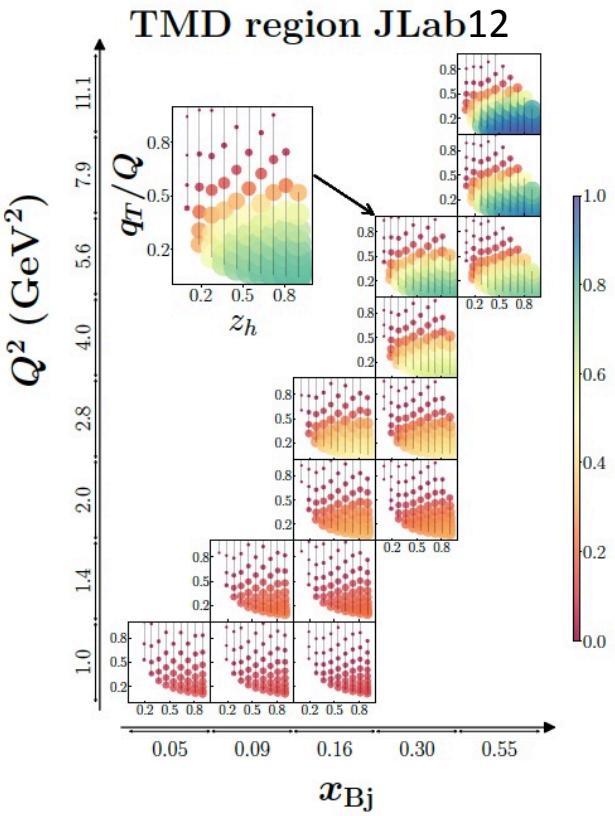
New 650 MeV recirculating injector

New FFA arcs to increase number of passes

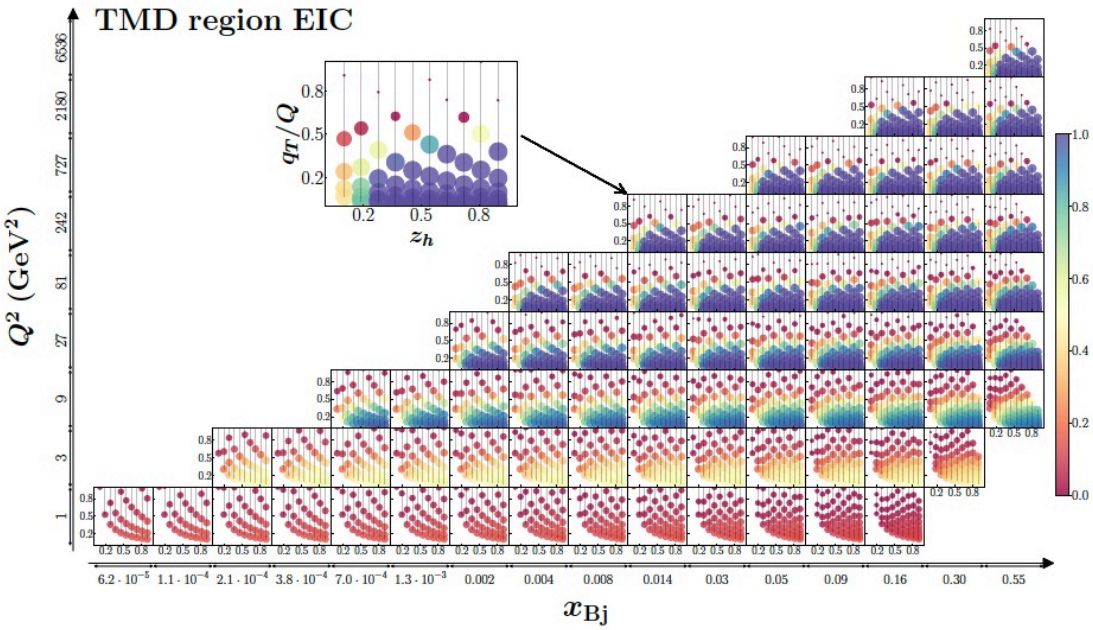


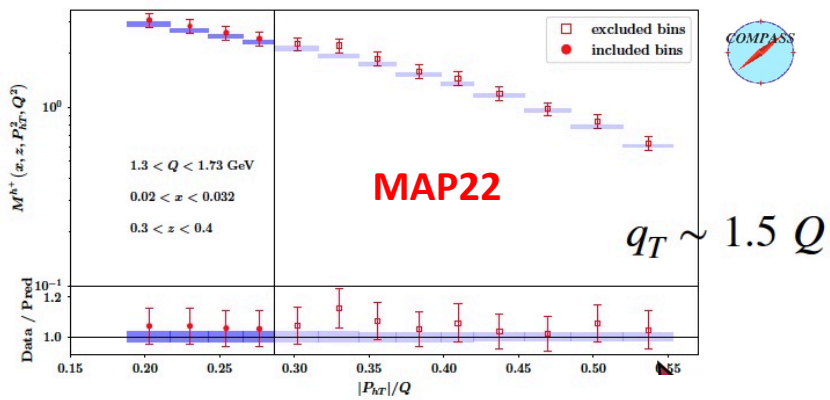
TMD Regimes

TMD sensitivity (Affinity) as q_T/Q



M. Boglione++ [arXiv: 2201.12197]





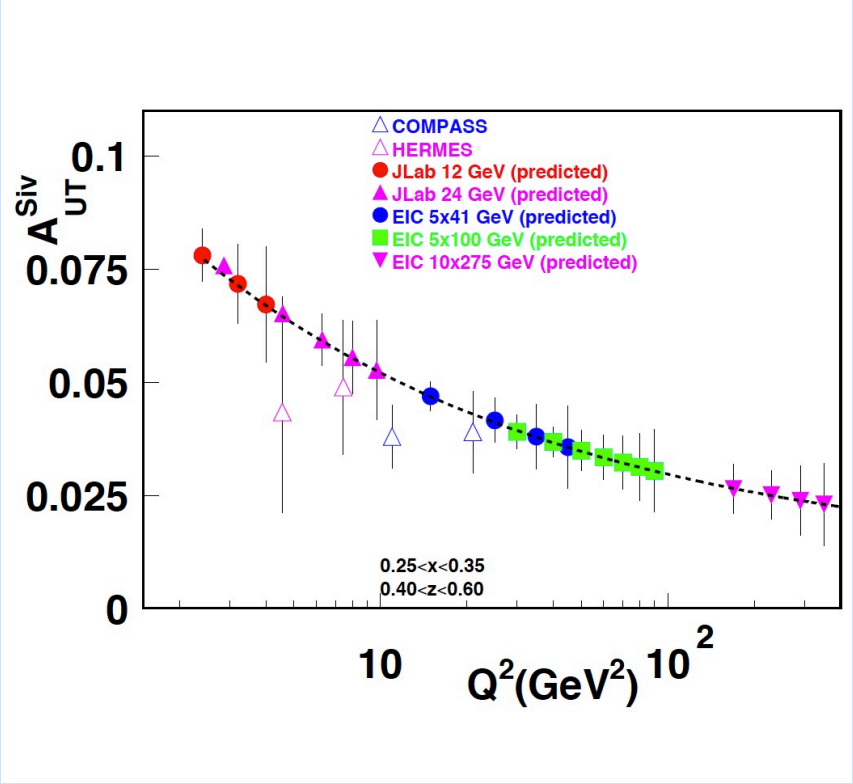
A. Bacchetta @ JLab workshop 22

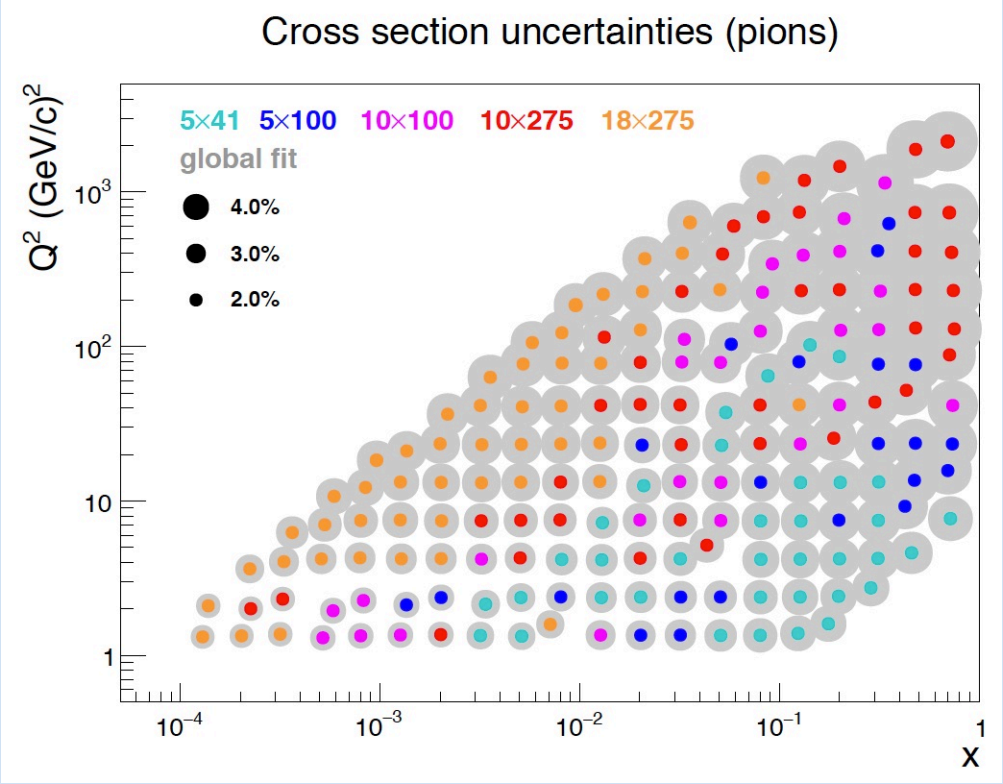
The perturbative part should be under control before accessing the non-perturbative

The Q^2 Game

Wide leverage (at given x) to: isolate higher-twists
probe evolution
disentangle x dependence

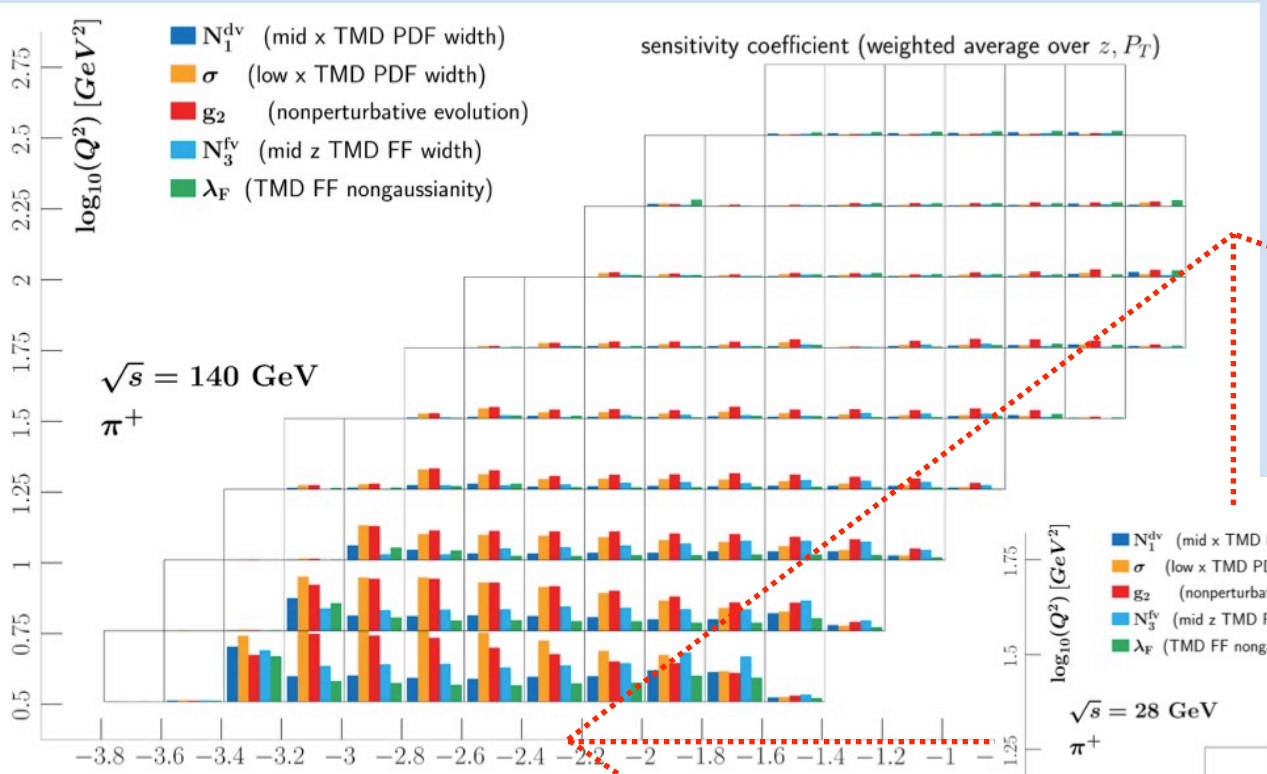
Keep Q^2 moderate to: avoid perturbative dilution



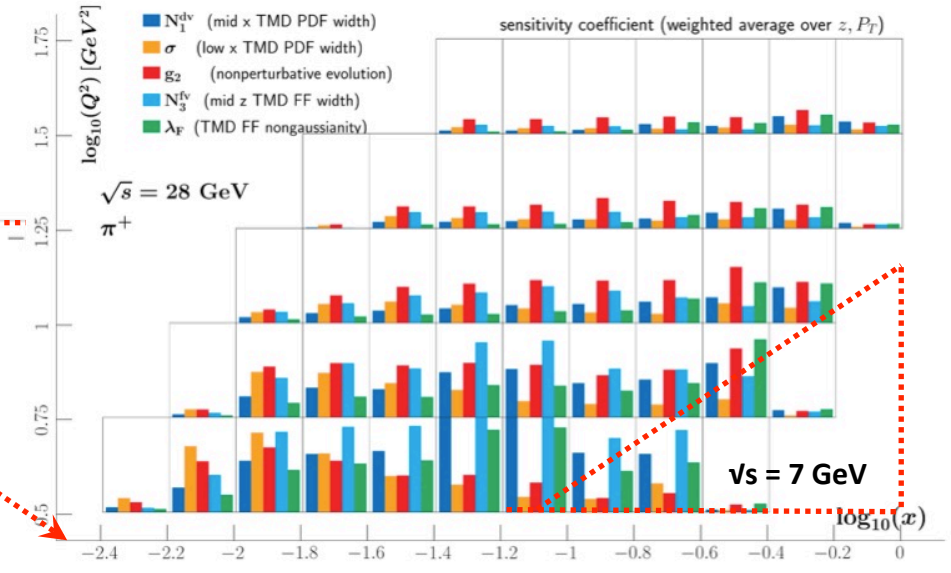


TMDs Description

The sensitivity on the relevant parameters changes with center of mass energy



Yellow Report [arXiv: 2103.05419]



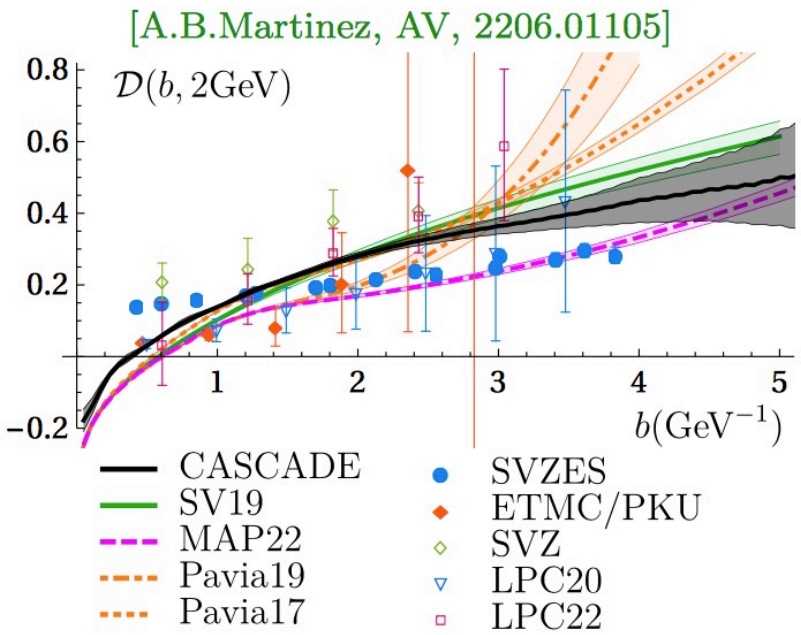
$S(\langle x \rangle_{\text{bin}}, \langle Q^2 \rangle_{\text{bin}})$ with weighted average over z, P_T

TMD Evolution

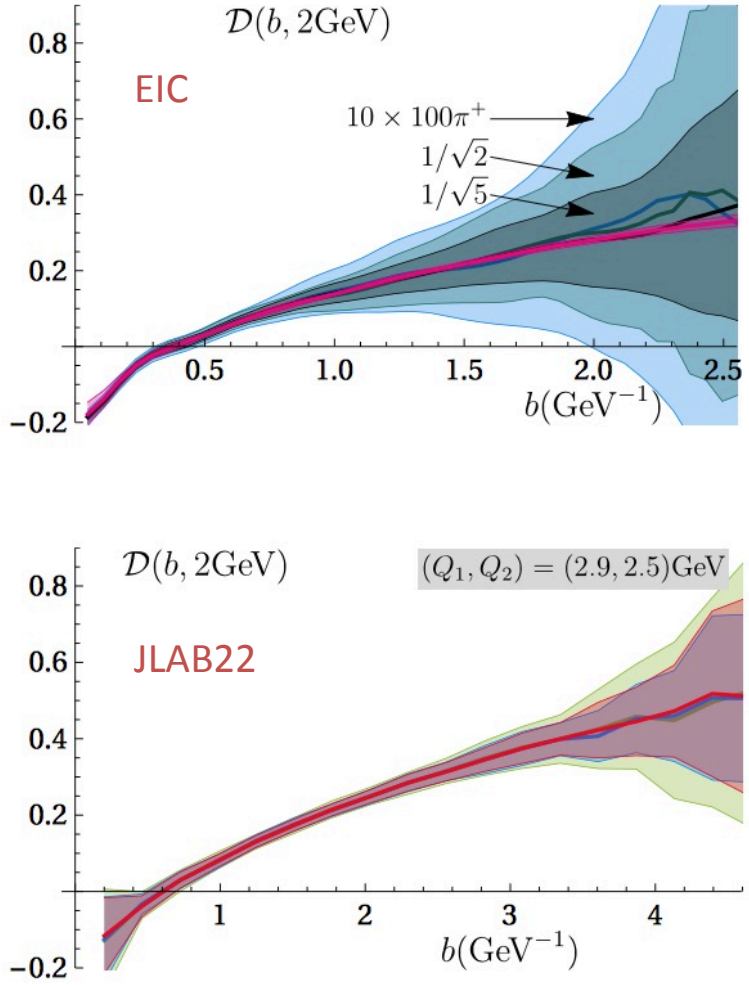
With b as Fourier conjugate of PT/z

$$F_{UT}^{\sin(\phi_h-\phi_S)} = \sum_q e_q^2 |C_V(Q)|^2 \int \frac{d^2b}{(2\pi)^2} e^{i(b\cdot P_T)/z} R(Q,b,\mu_0) f_{1T}^{\perp q}(x,b;\mu_0) D_1^q(z,b;\mu_0)$$

Collins-Soper non-perturbative evolution kernel



Complementarity in Q^2 and b coverage



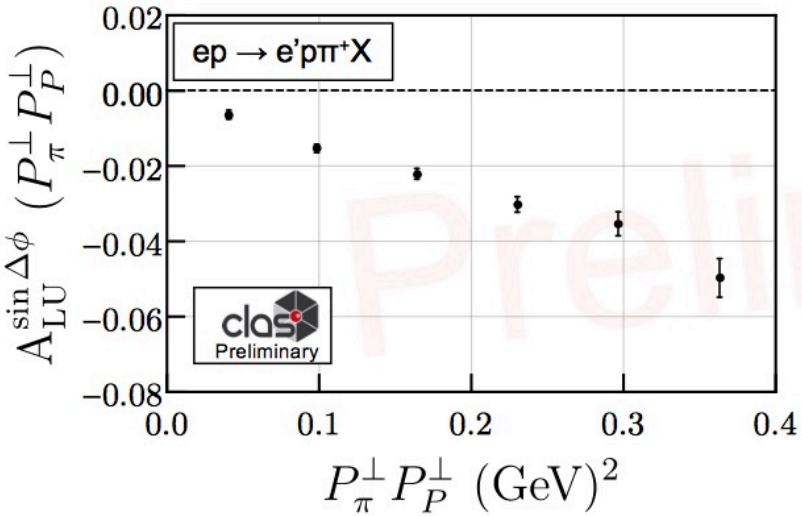
A. Vladimirov @ APCTP22 workshop

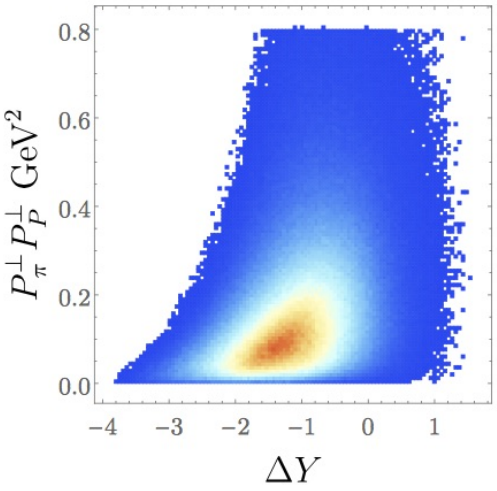
Fracture Functions

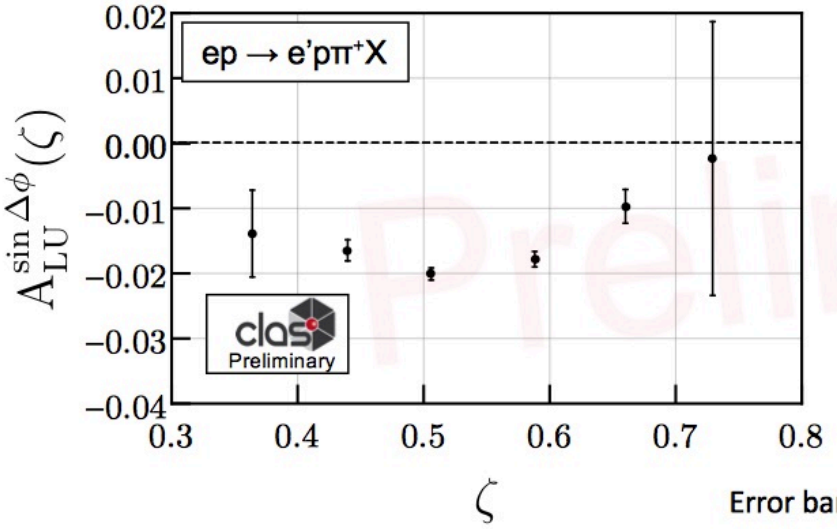
- Fracture function $\hat{l}_1^{\perp h}$ depends on ζ.
- Fragmentation function D_1 depends on z_π.

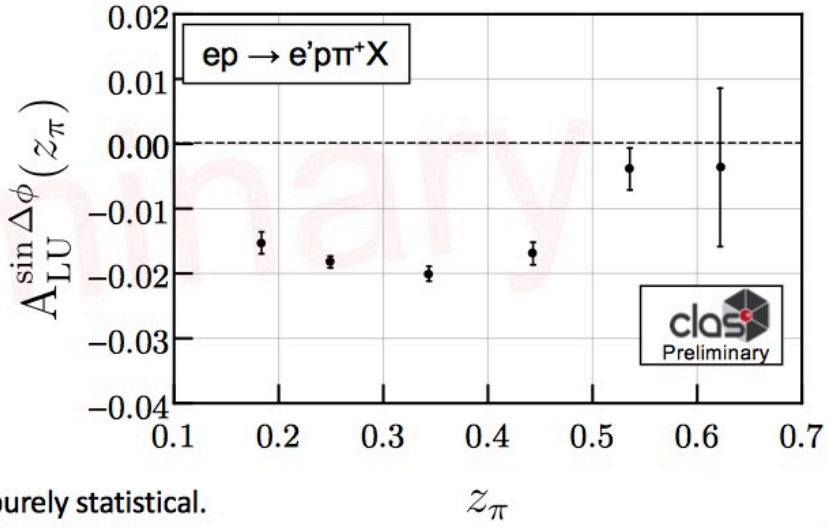
$$\mathcal{F}_{LU}^{\sin(\Delta\phi)} = \frac{|p_{\pi^+}^{\perp}||p_P^{\perp}|}{m_P m_{\pi^+}} \mathcal{C}\left[w_5 \hat{l}_1^{\perp h} D_1\right]$$

$$\zeta = E_P/E \quad z_\pi = E_\pi/\nu$$







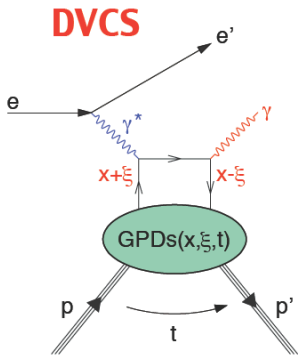


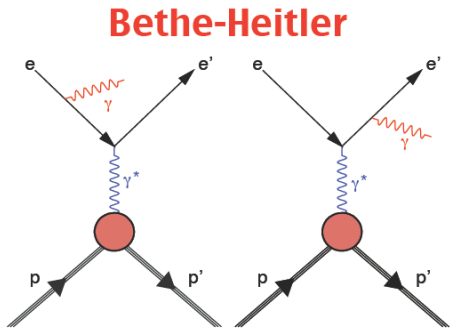
Error bars purely statistical.

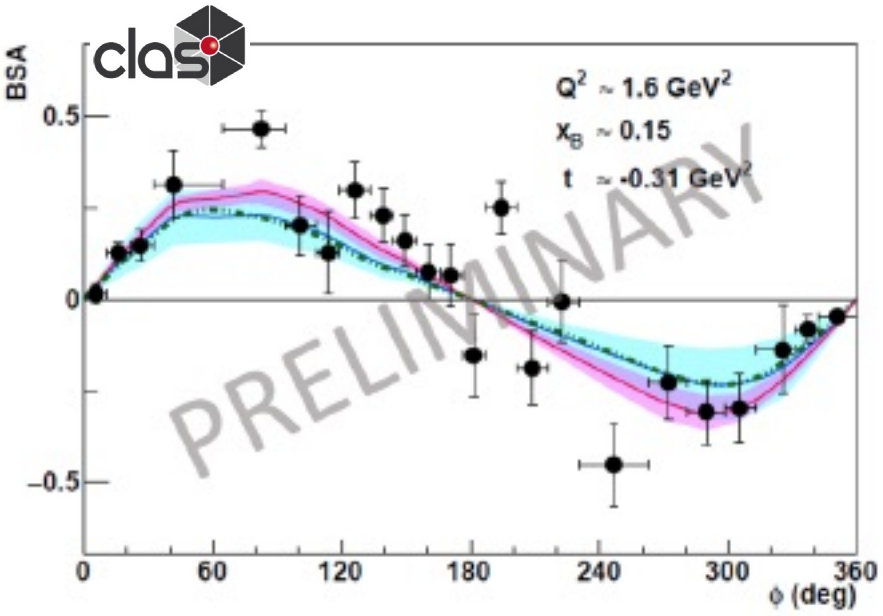
DVCS Cross Section

Informations on the real and imaginary part of the QCD scattering amplitude

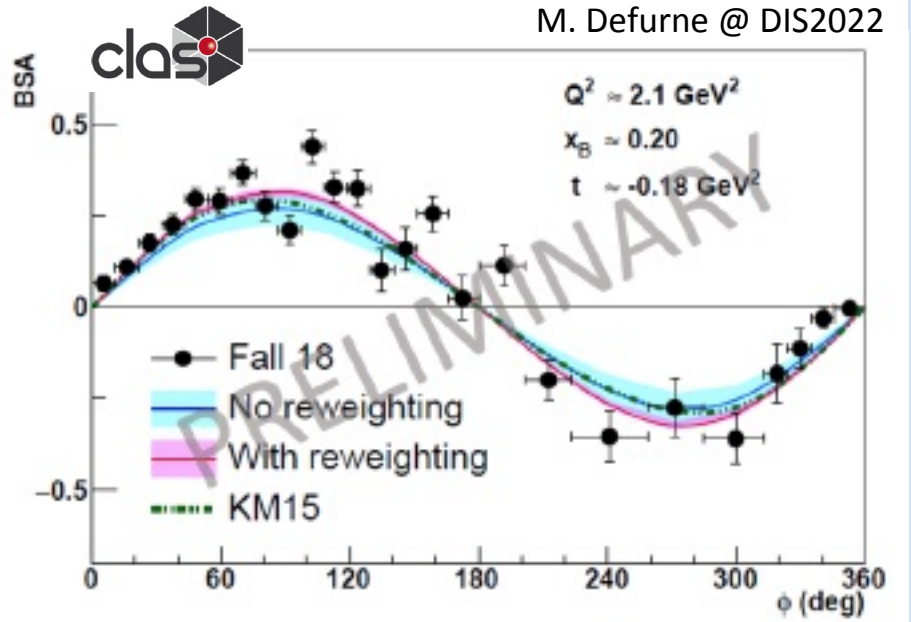
$$\frac{d^4\sigma}{dQ^2\, dx_B\, dt\, d\phi} \propto \left(|\mathcal{T}_{DVCS}|^2 + |\mathcal{T}_{BH}|^2 + \mathcal{I}\right)$$







M. Defurne @ DIS2022



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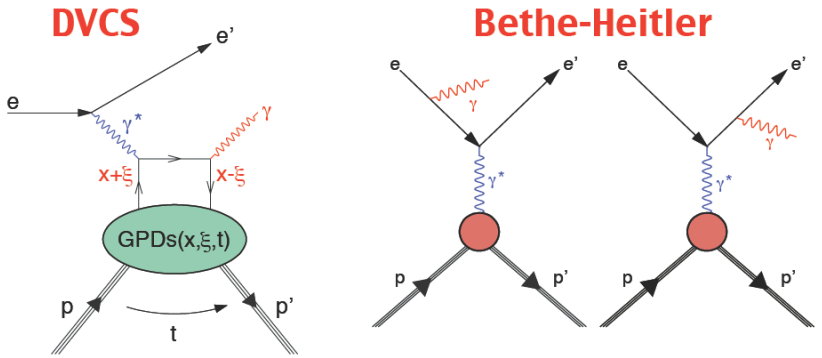
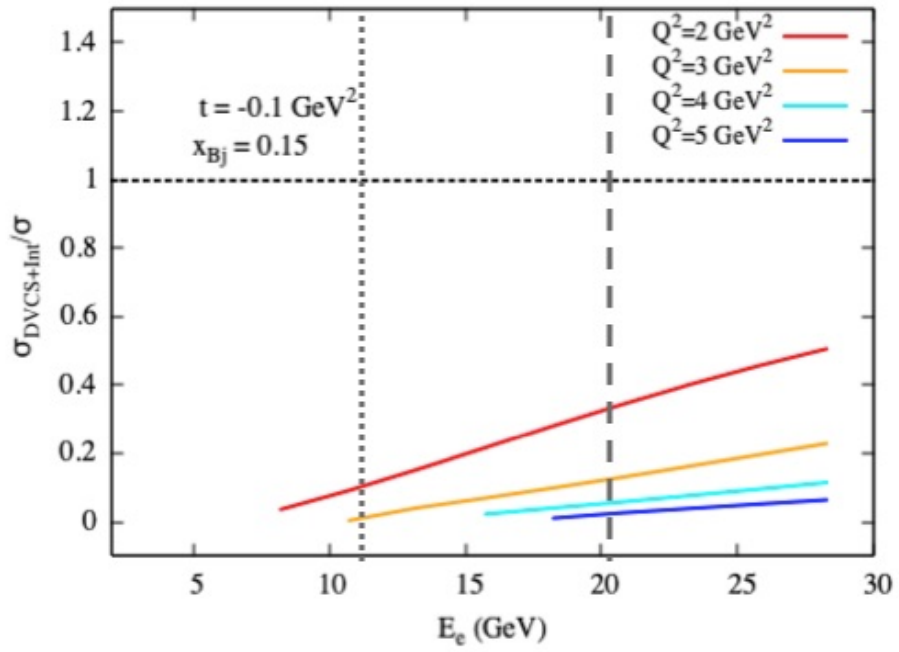
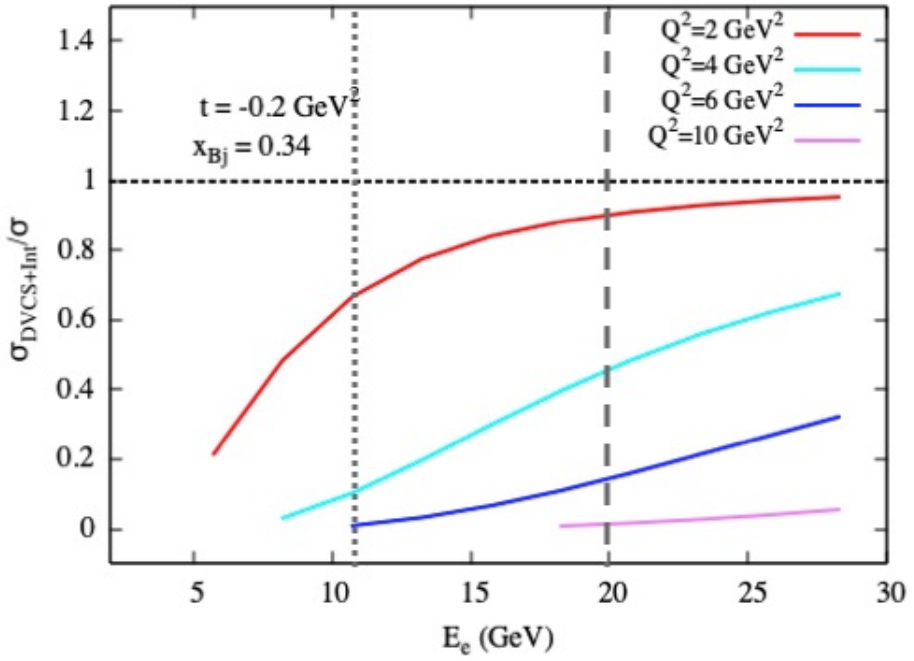


Sensitivity change with c.m. energy and Q^2. At JLab20+ range extended towartds low-x

S. Liuti @ JLab workshop series

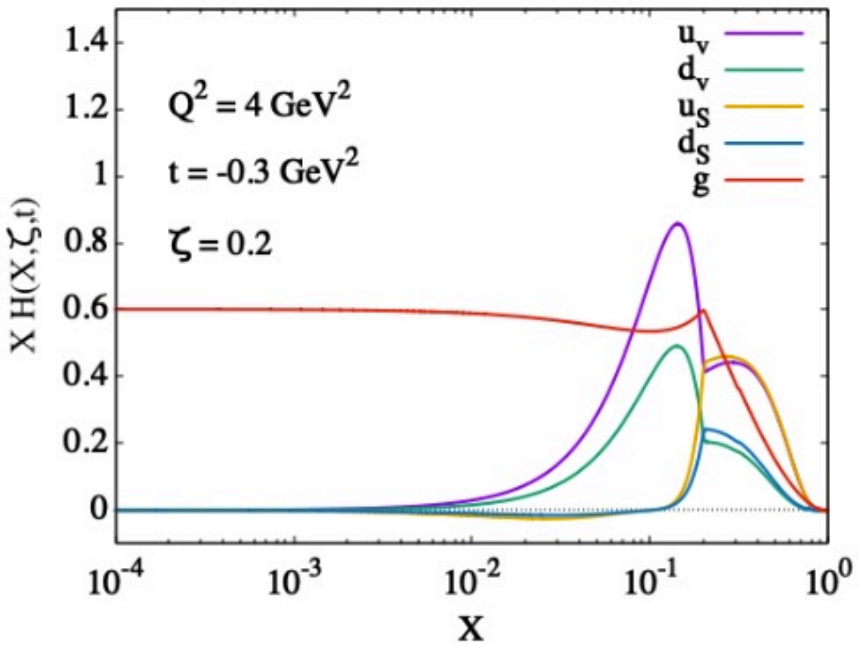


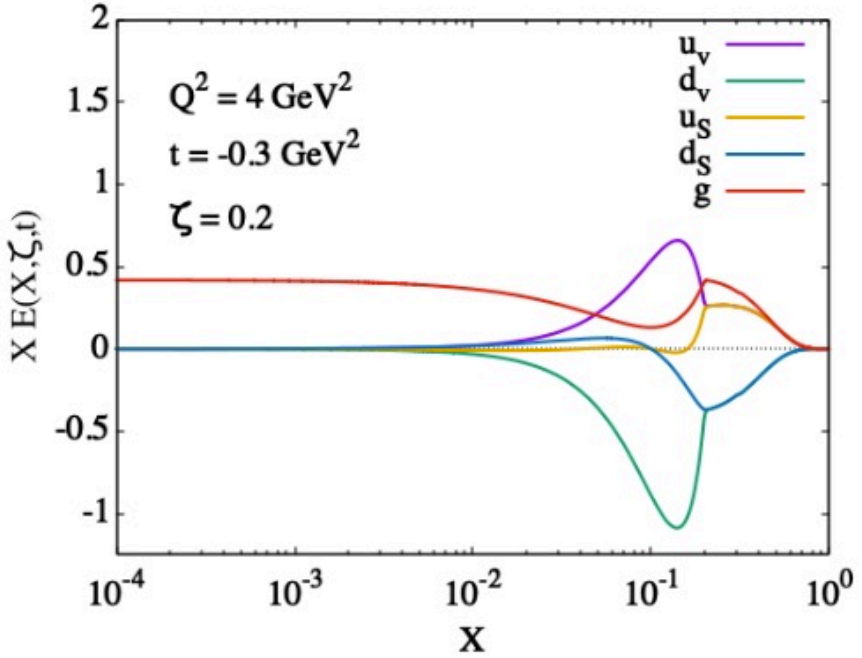


GPDs Description

JLab20+ can cover most relevant range for quarks and initiate probing gluons

PRD 105 (2022), arXiv:2101.01826





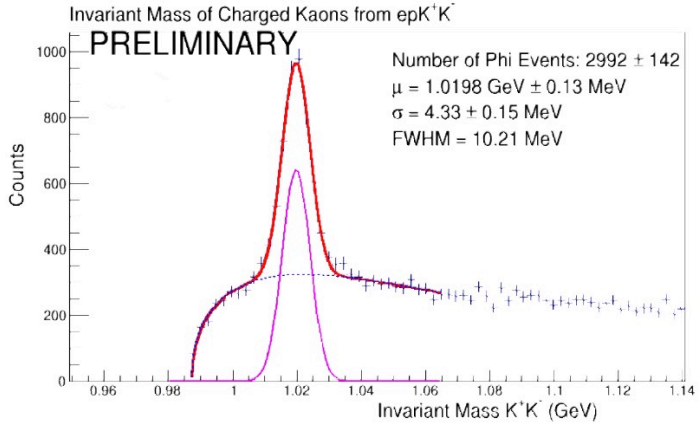
Meson Electro-production

Enhanced sensitivity to peculiar GPDs

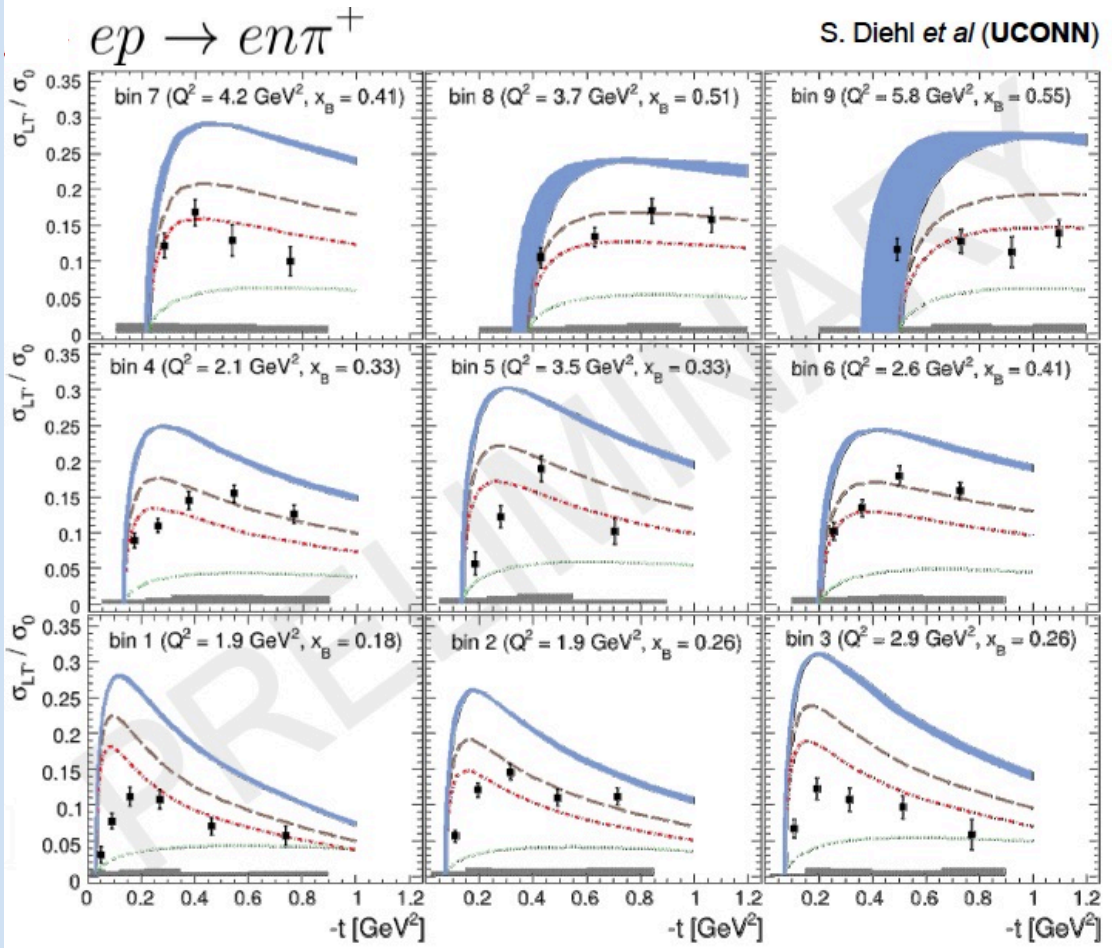
- 4 chiral-even GPDs: H, E, $\tilde{H}$, $\tilde{E}$
- 4 chiral-odd GPDs: H_T, E_T, $\tilde{H}_T$, $\tilde{E}_T$

	Meson	GPD flavor composition
$\tilde{H}$, $\tilde{E}$ H_T, $\bar{E}_T$	π^+	$\Delta u - \Delta d$
	π^0	$2\Delta u + \Delta d$
	η	$2\Delta u - \Delta d$
H, E	ρ^0	$2u + d$
	ρ^+	$u - d$
	ω	$2u - d$

$ep \to ep\phi \to epK^+K^-$

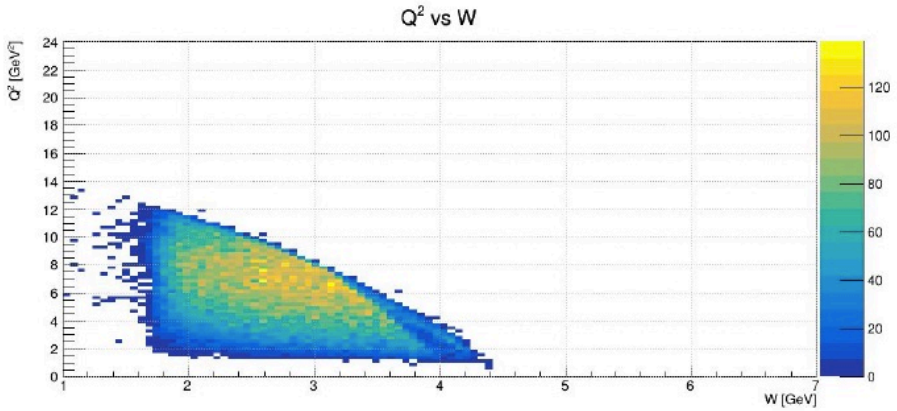


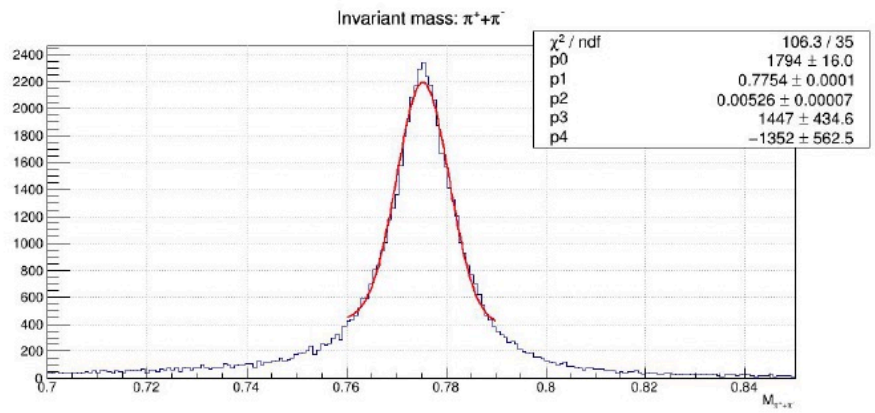
$ep \to en\pi^+$



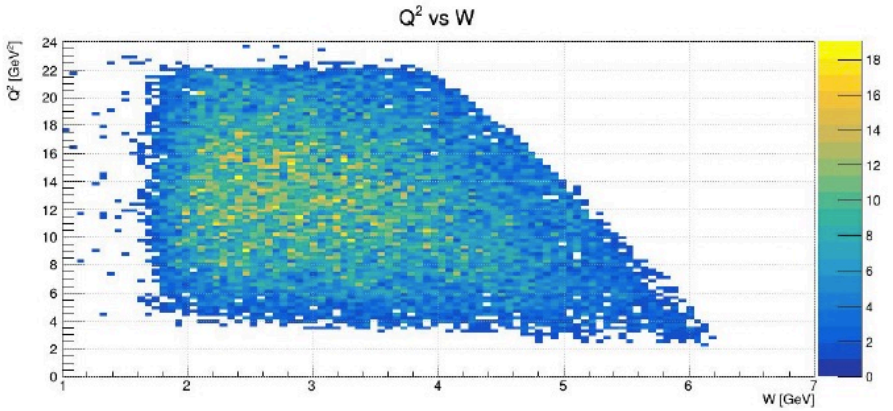
Meson Electro-production

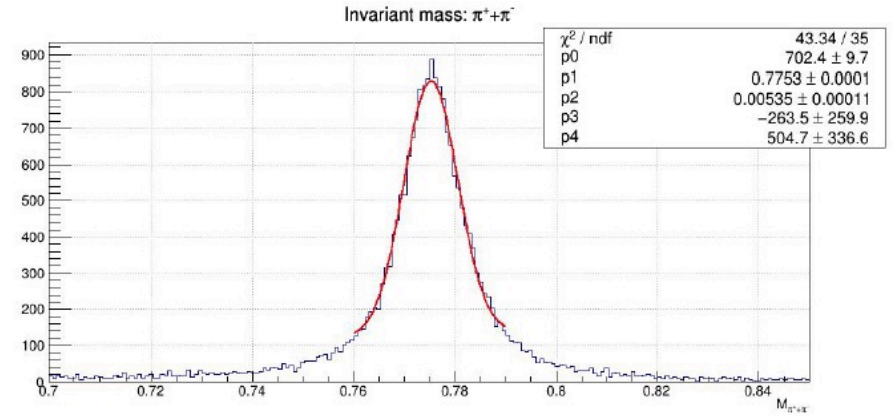
@ 10.6 GeV beam energy





@ 22 GeV beam energy

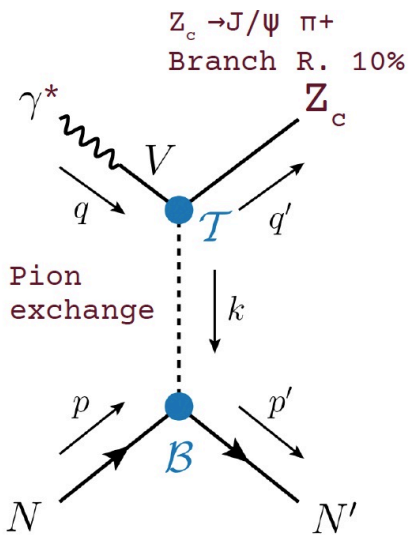


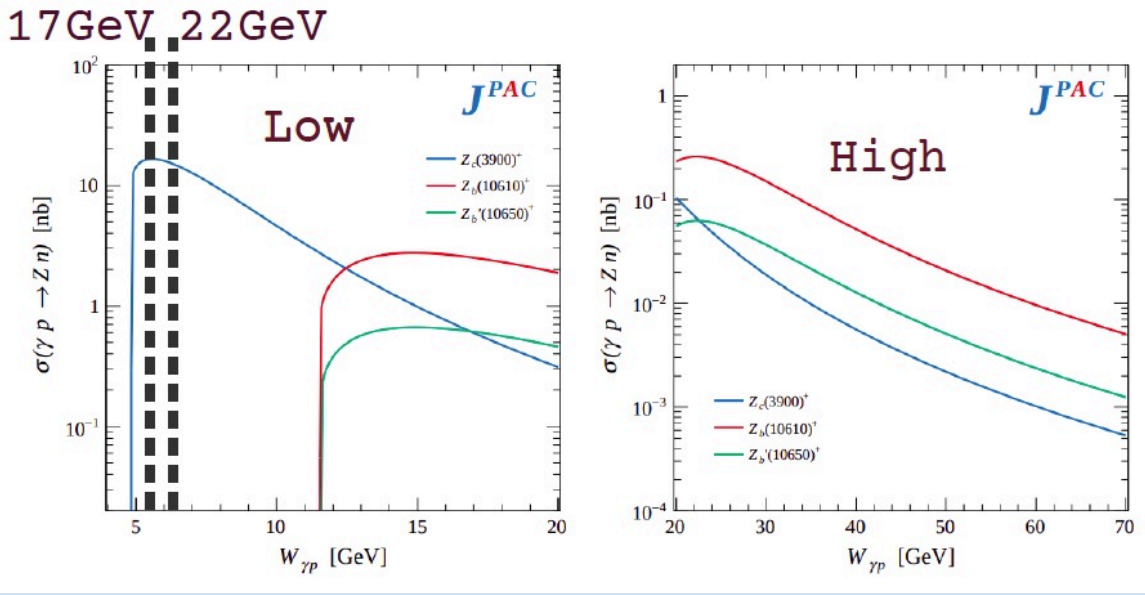


Spectroscopy

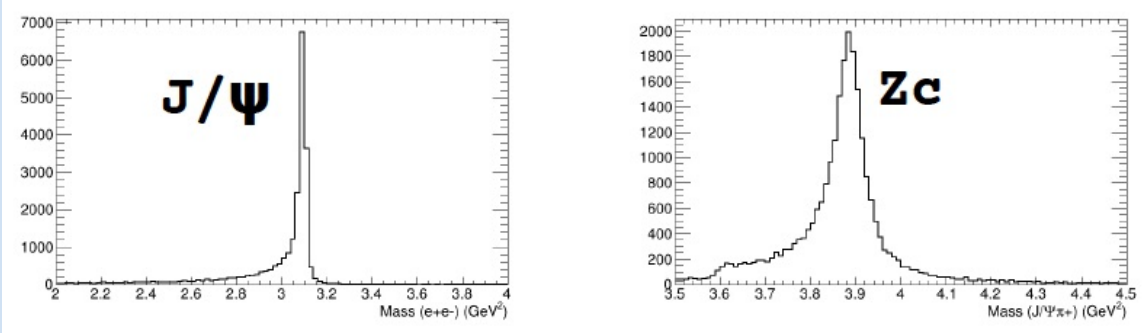
Stable states are a probe of QCD confinement (non perturbative QCD features)
Several new states with possible exotic contribution in the charmonium mass spectrum

Photoproduction as alternate production mechanism for a complete description





CLAS24 + zero degree spectrometer to tag scattered electron



Conclusions

The last decade provided many evidences that correlation of partonic transverse degrees of freedom in the nucleon do exist and manifest in hadronic interactions

Next step: Moving from phenomenology to rigorous treatment (predictive power)

New data coming from Jlab++ at high-luminosity and EIC at high-energy should allow to:

- Constrain models in the valence and sea region
- Test factorization, universality and evolution
- Study higher twist effects
- Investigate non-perturbative to perturbative transition (along P_T)
- Flavor separation via proton and deuteron targets and hadron ID
- Test of Lattice QCD calculations

A comprehensive study provides access to the peculiar dynamics of the QCD confined world