The TMD Physics Program at JLab

Marco Contalbrigo – INFN Ferrara

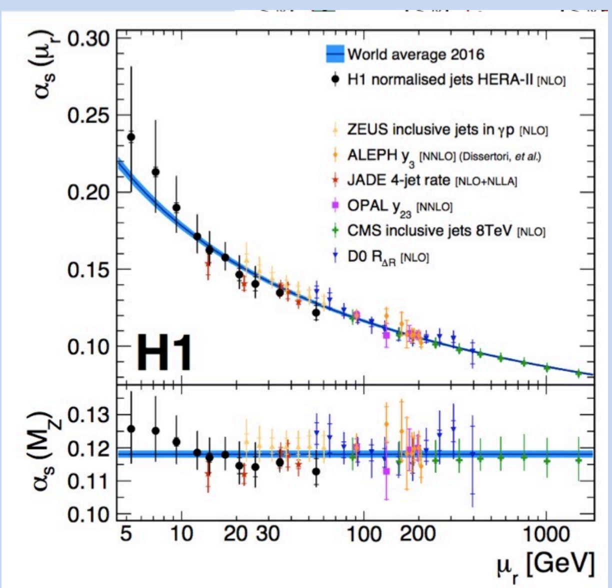
Sar Wors 2023 - 4-7 Giugno 2023

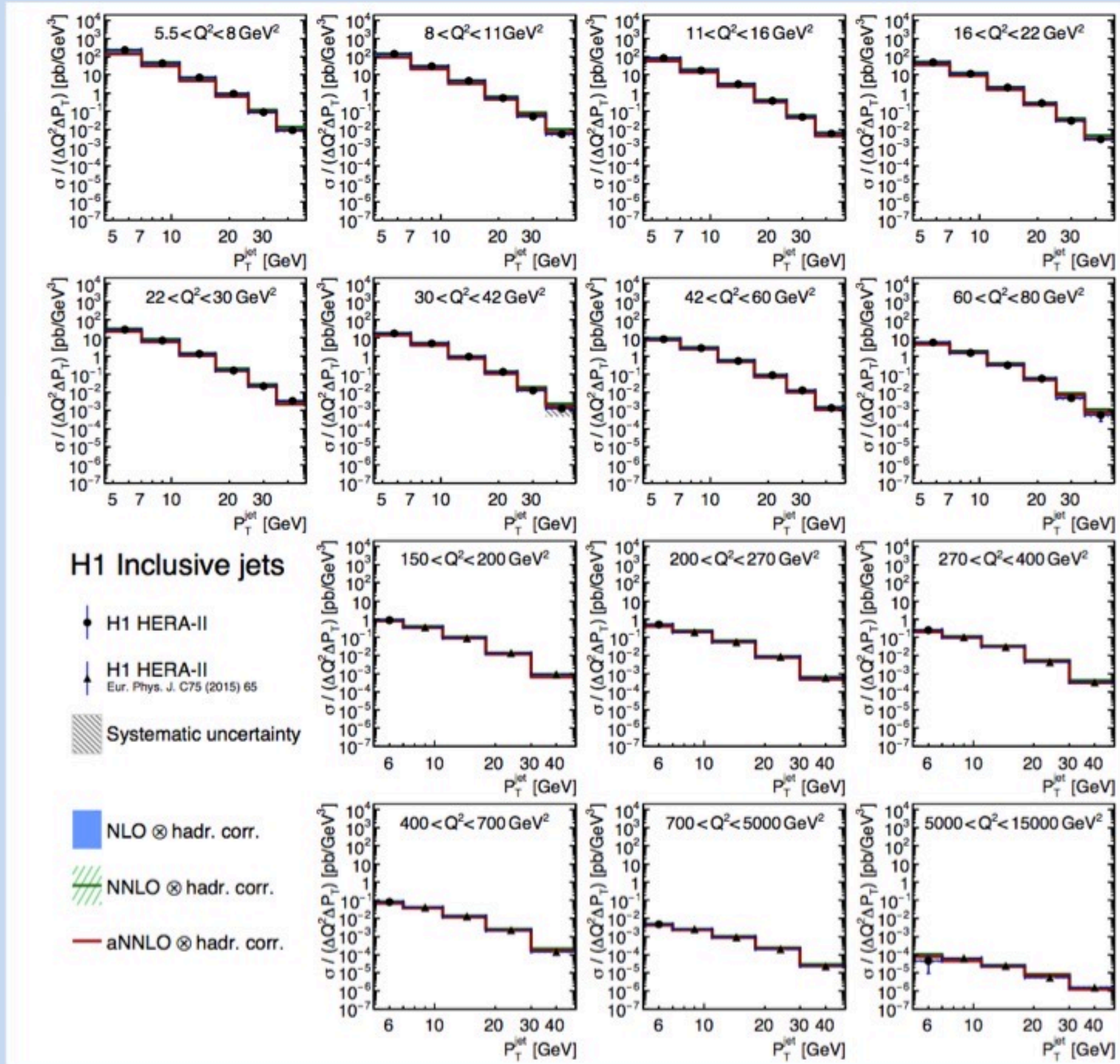
Good perturbative description
(hard gluon emission)

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

Part in a P_T<<Q TMD regime

H1 [arXiv: 1611.03421]

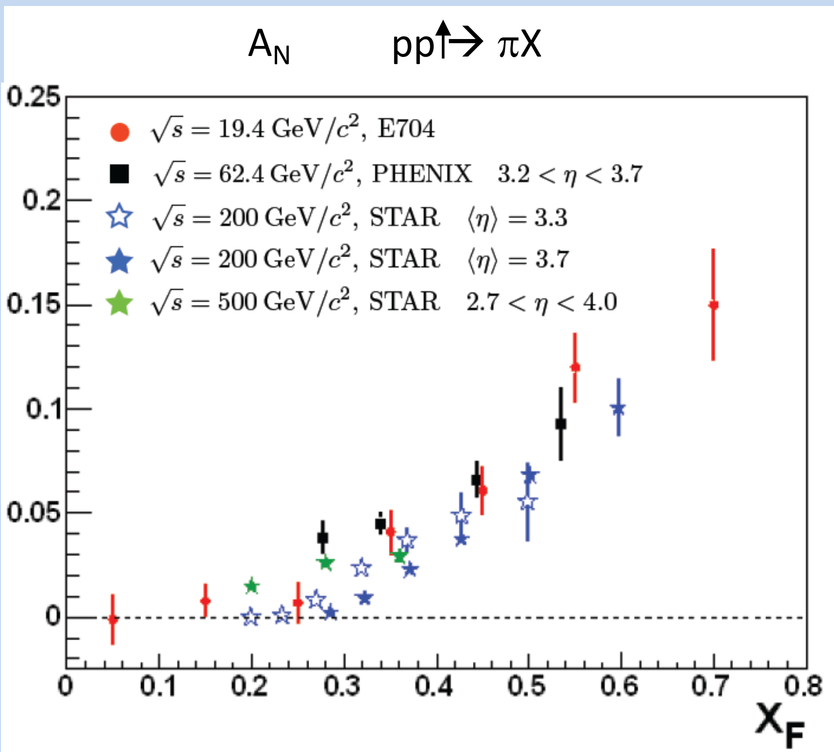




Can QCD be a precision science ?

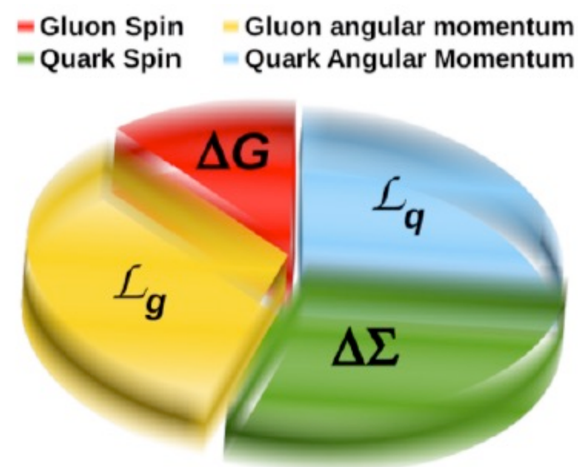
Should not be confused with pQCD, which already can,
but is not touching the intimate nature of the strong interaction

Single Spin Asymmetries

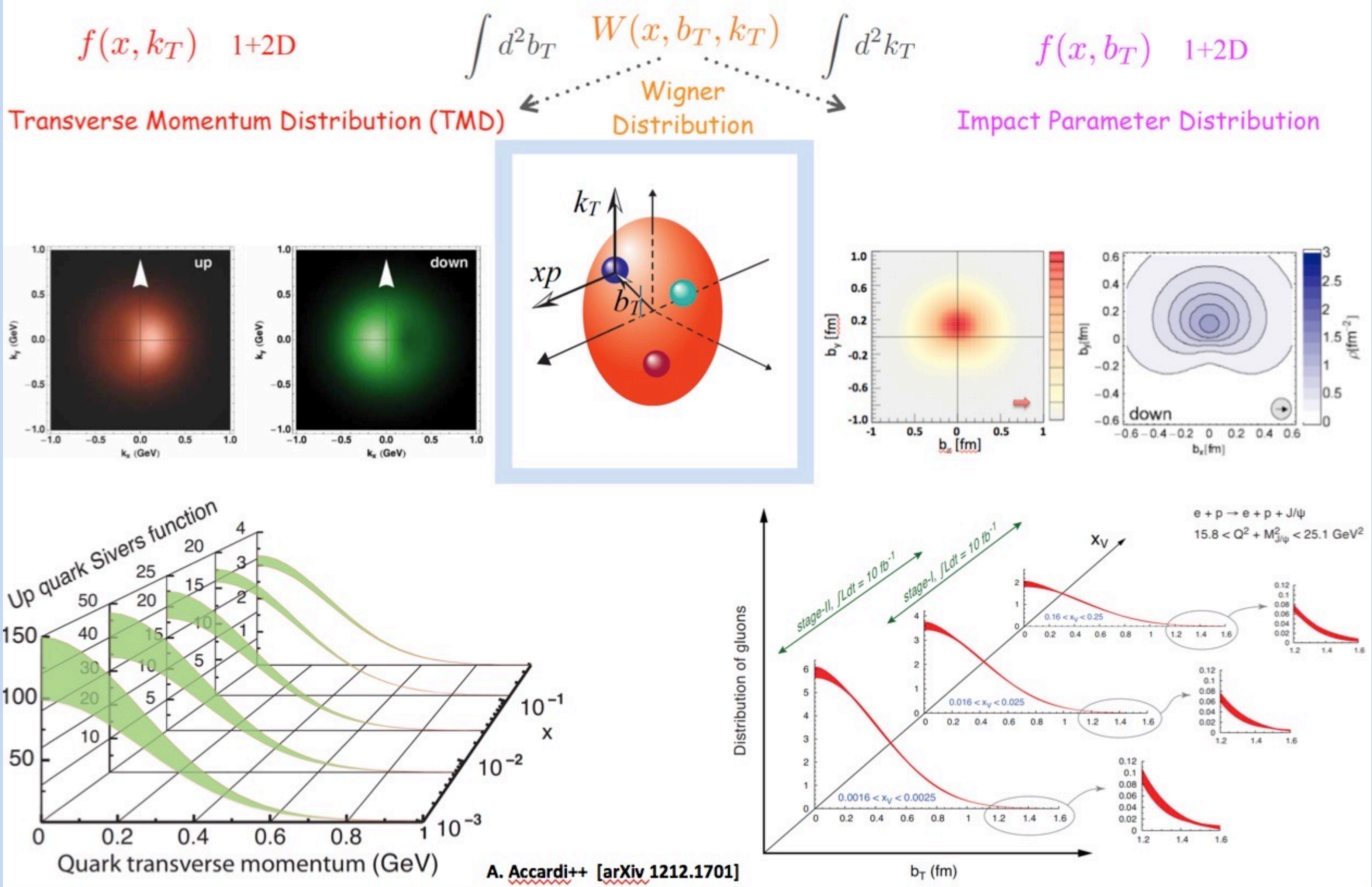


?

Proton Spin Budget



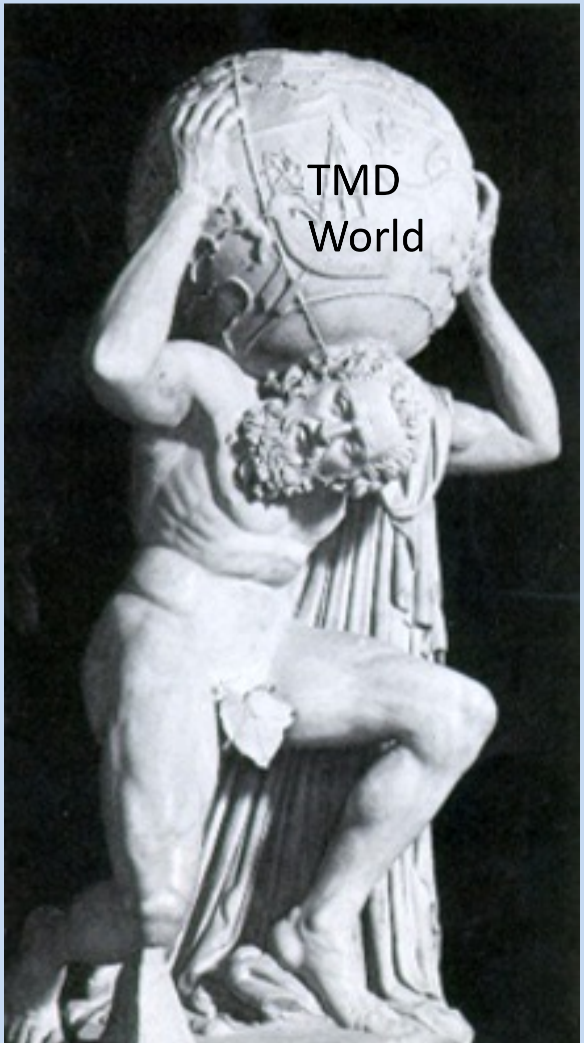
$$\frac{1}{2} = \frac{1}{2}\sum_f (q_f^+ - q_f^-) + L_q + \Delta G + L_g$$

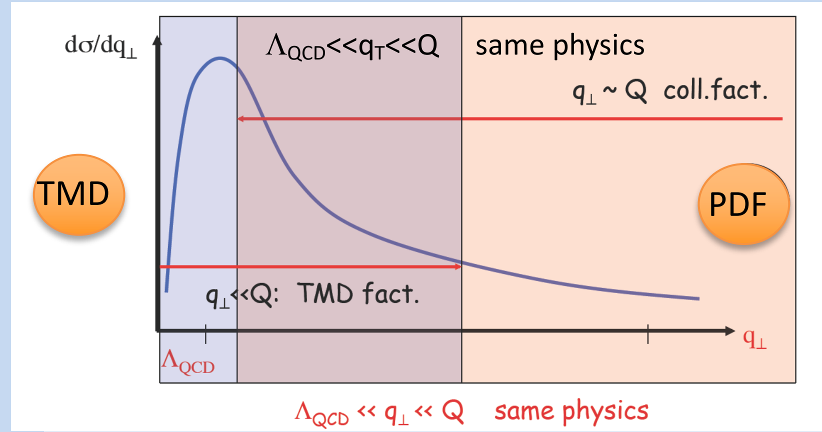


A. Accardi++ [arXiv 1212.1701]

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 Cross-Section

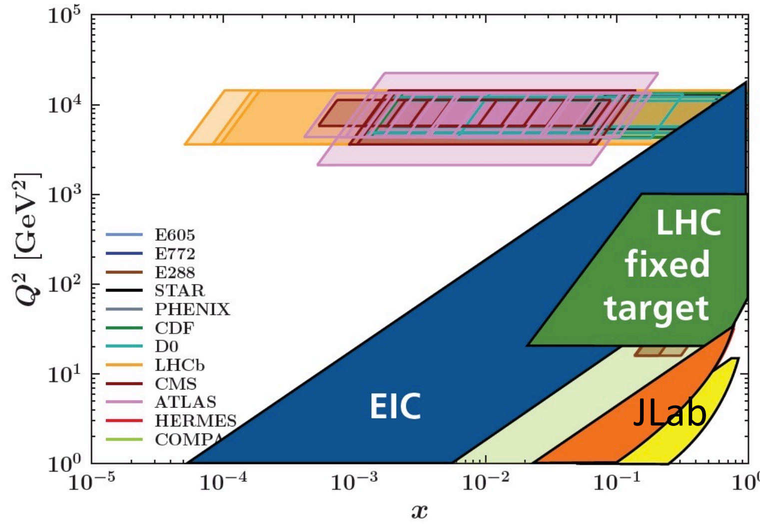
$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2}$$
$$= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Big\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}$$
$$+ \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\s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

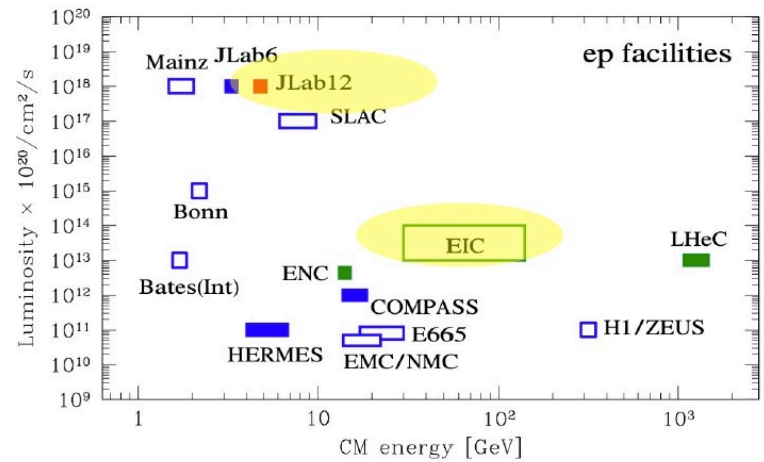
TMD Factorization

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

TMD Evolution

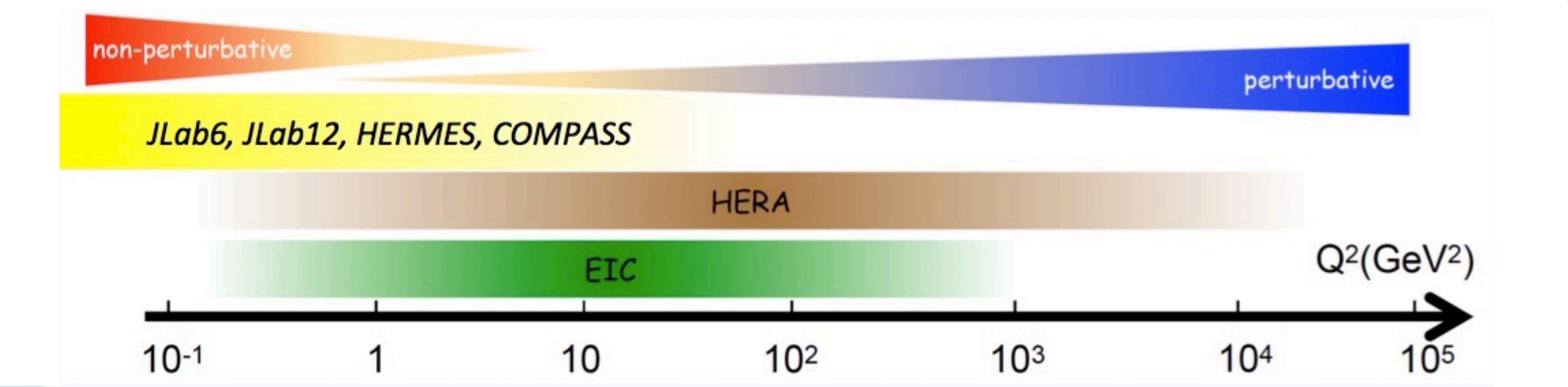
Evolution kernel (with CS non-perturbative kernel)



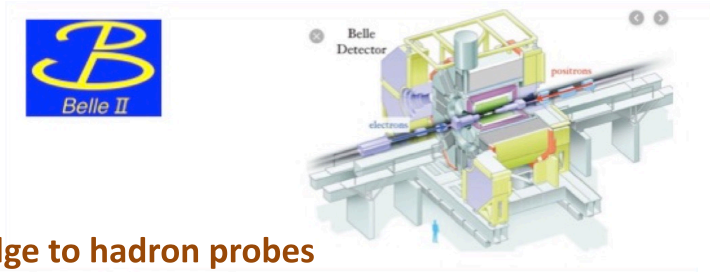


TMD Baseline

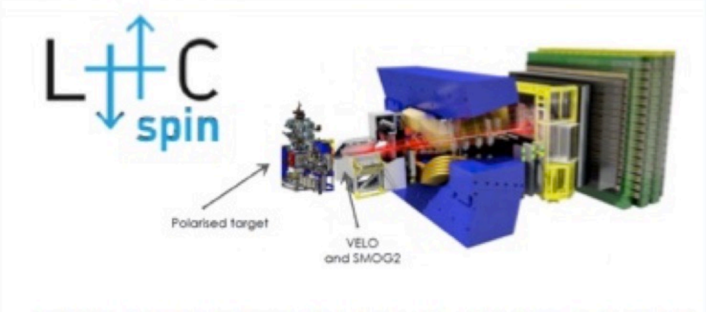
Energy range matching perturbative and non-perturbative regimes



Unprecedented fragmentation information

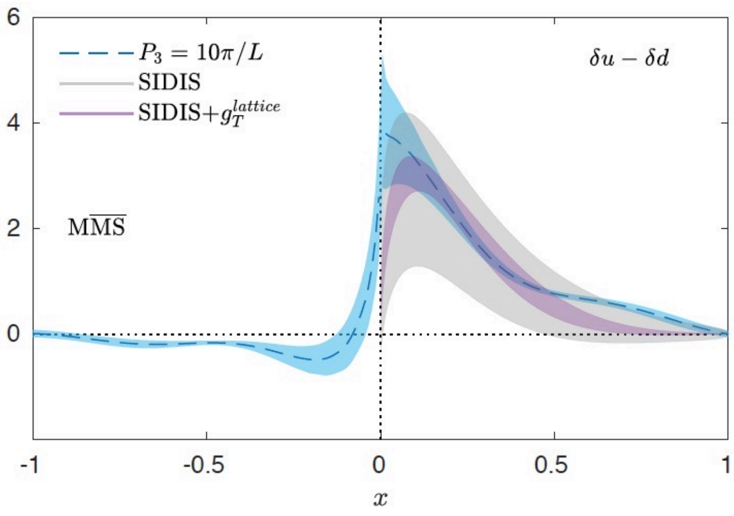


Bridge to hadron probes

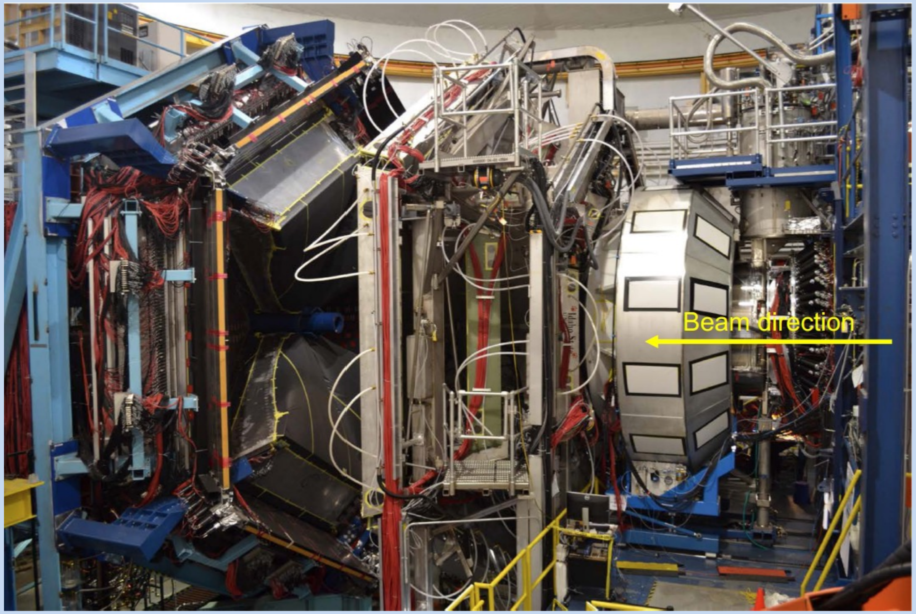


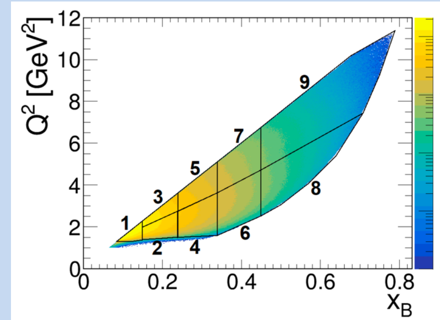
New lattice achievements

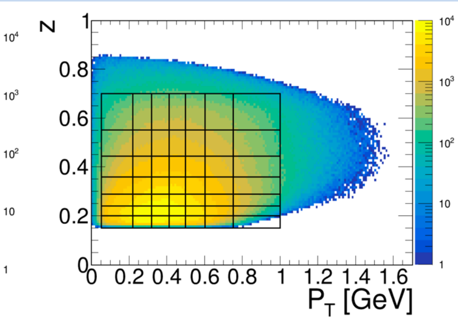
C. **Alexandrou++ [arXiv: 1902.00857]**

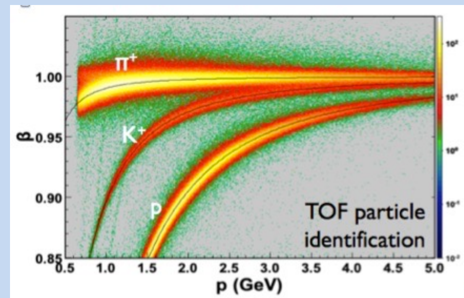


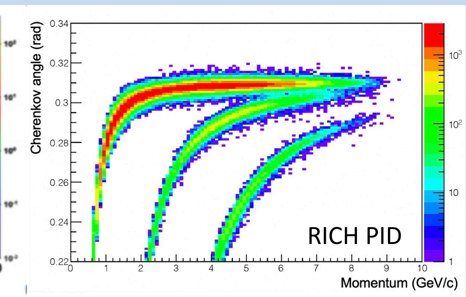
CLAS12 wide coverage, excellent PID, various polarized targets, high luminosity







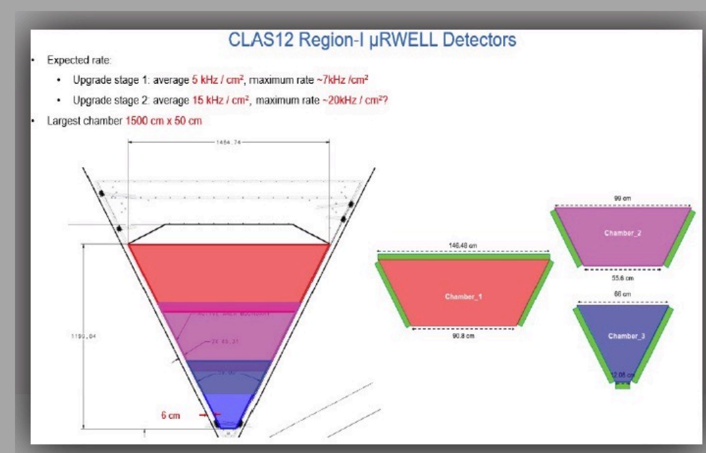




Year	Period	Run	Target	Polarization	Beam
2018	Spring-Fall	RGA	Proton	-	10.6 GeV
	Fall	RGK	Proton	-	6.5-7.5 GeV
2019	Spring	RGA	Proton	-	10.6 GeV
2019	Spring-Fall	RGB	Deuteron	-	10.6 GeV
2020	Spring-Fall	RGF	Deuteron	-	10.6 GeV
2021	Fall	RGM	Nuclear	-	Several GeV
2022	Spring-Fall	RGC	NH_3-ND_3	Longitudinal	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



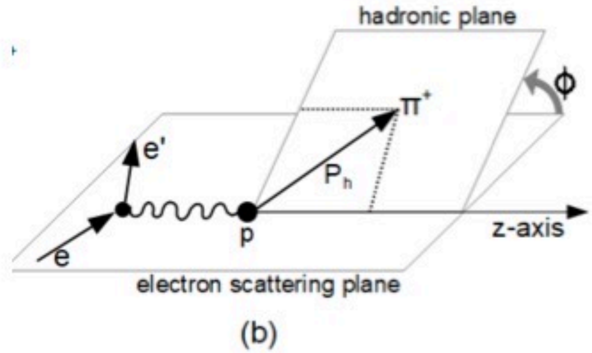
Beam Spin Asymmetry @ CLAS12

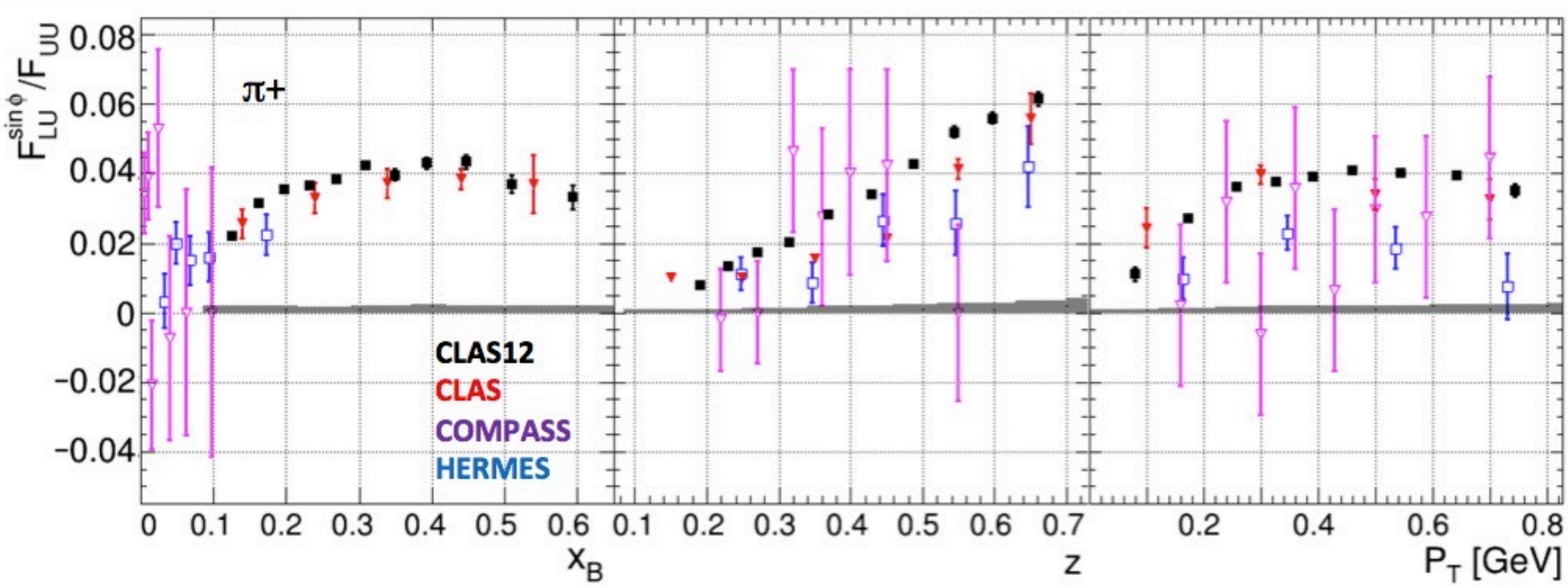
CLAS12 proton data (RGA)

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

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

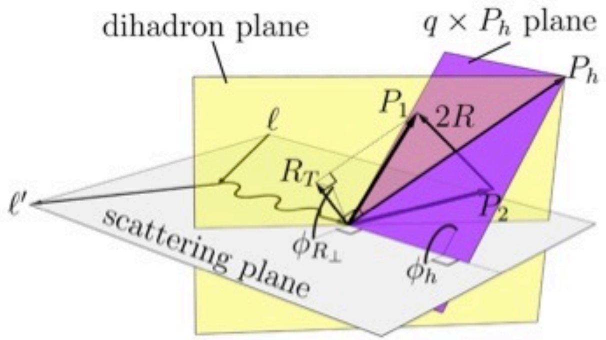
86.9±2.6 %





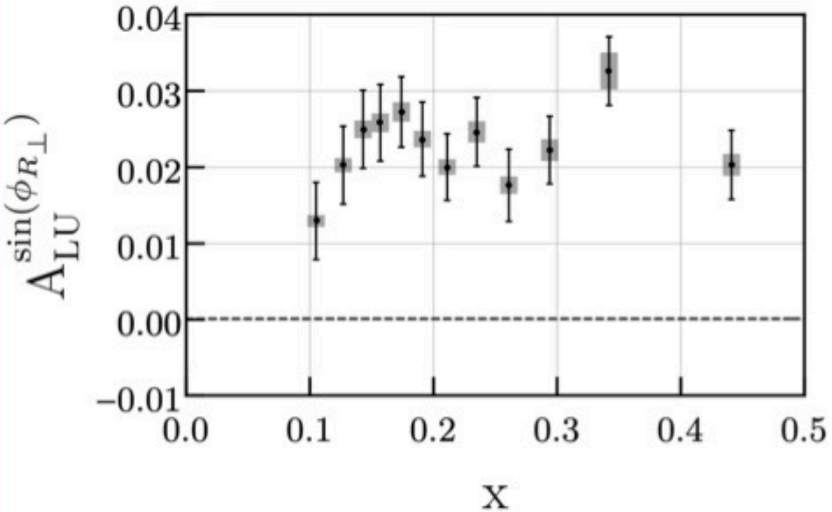
CLAS12 proton data (RGA)

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

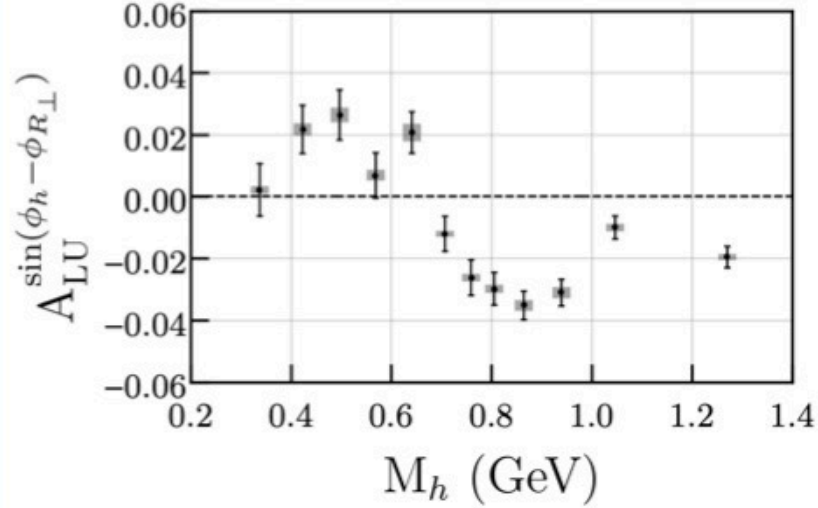


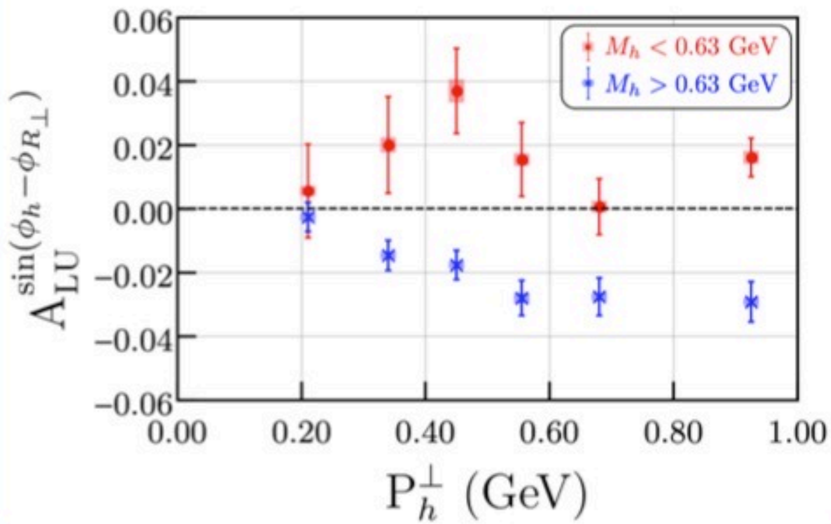
$$d\sigma_{LU} \propto$$

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



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



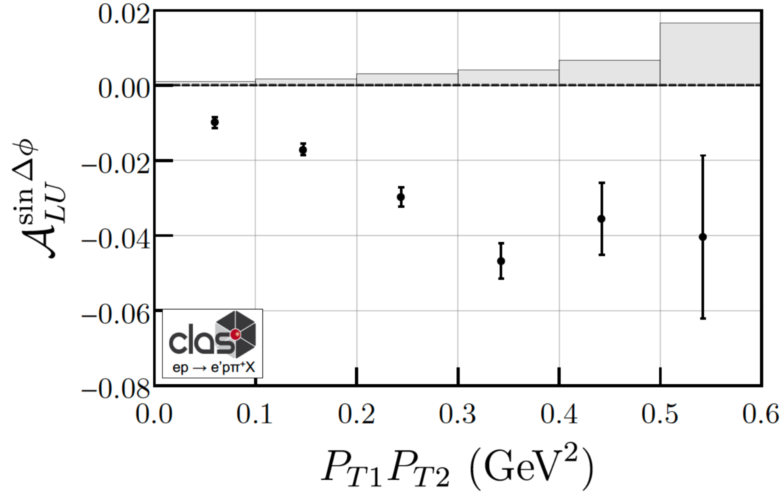


Fracture Functions @ CLAS12

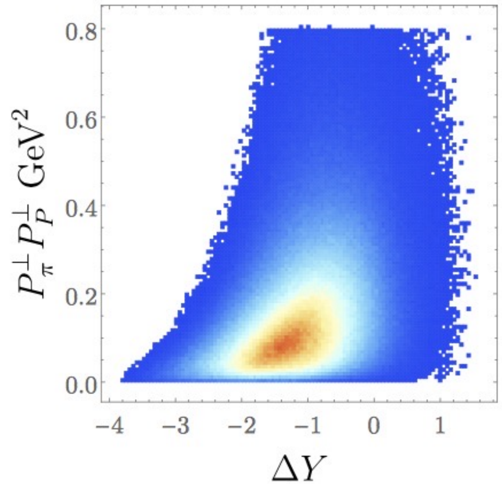
- Fracture function $\hat{l}_1^{\perp h}$ depends on ζ.
- Fragmentation function D_1 depends on z_π.

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

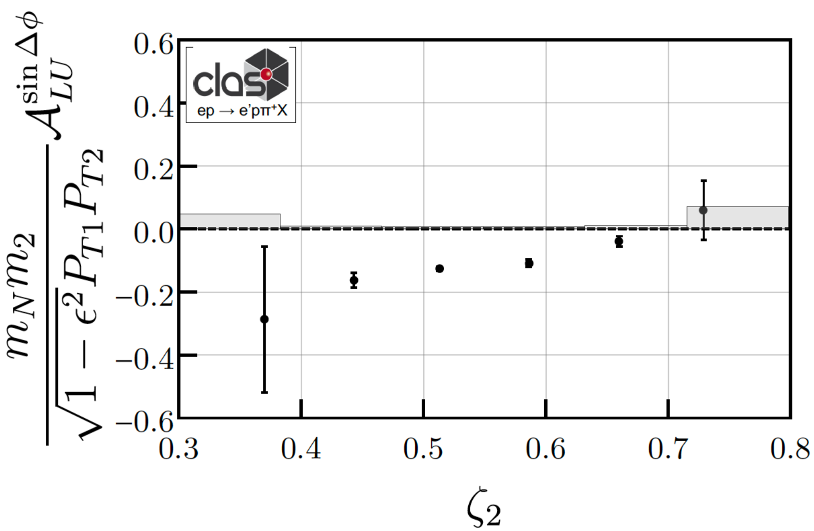
$$\zeta = E_P/E \quad z_\pi = E_\pi/\nu$$

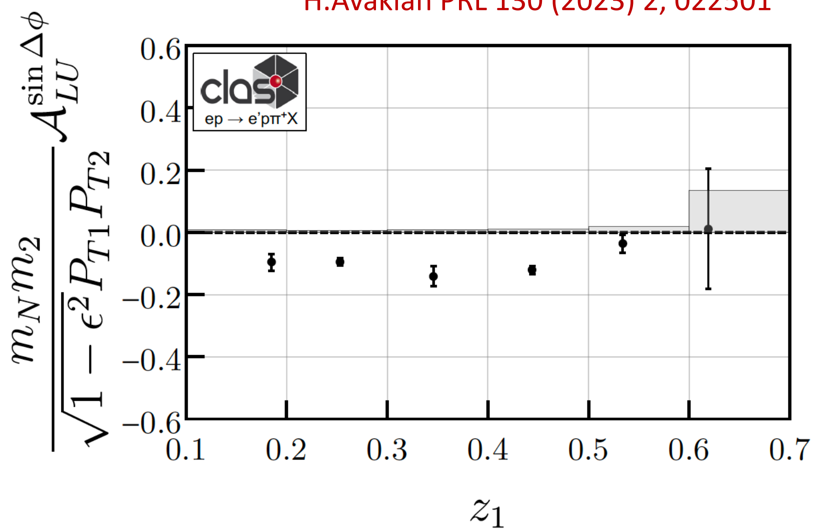


ep → e'pπ⁺X



H.Avakian PRL 130 (2023) 2, 022501



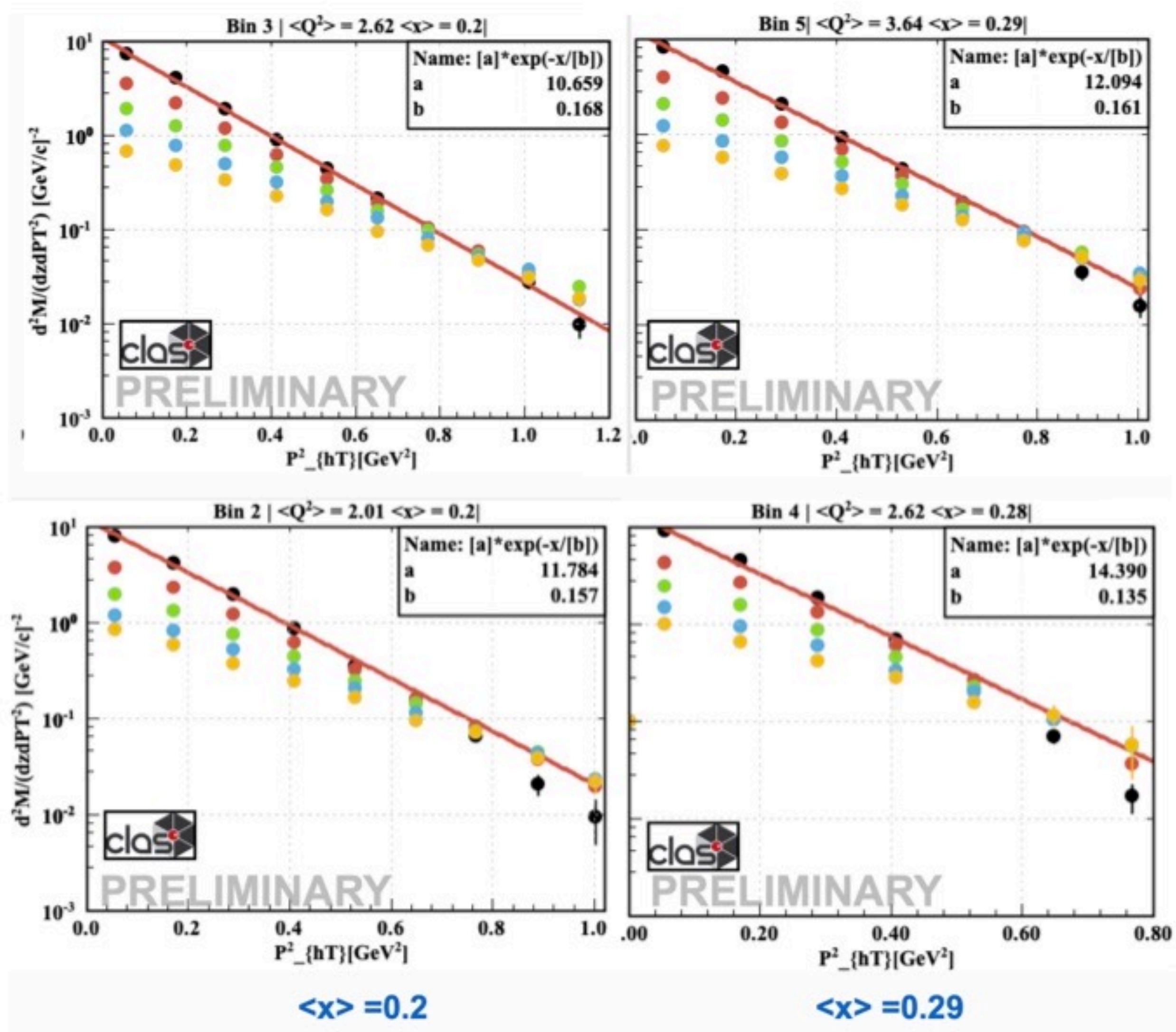


Transverse momentum dependence and phase space

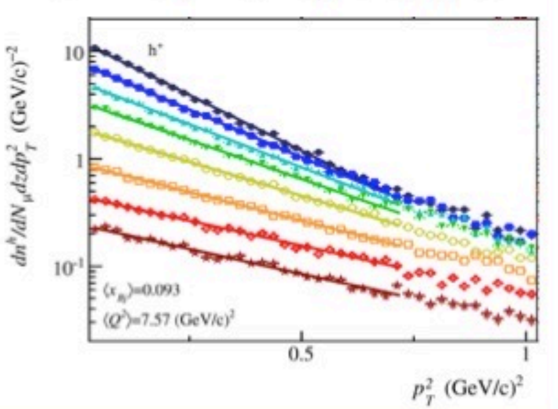
ep->eπ+X

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



COMPASS, EPJC 73 (2013) 8, 2531



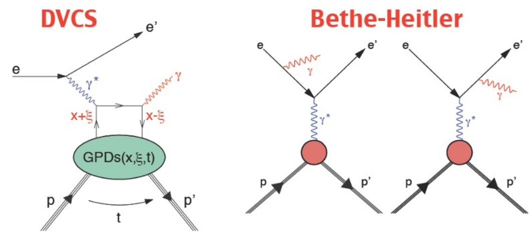
Being extended to π^0, k, dihadrons, vector mesons

Acceptance being unfolded with a multidimensional kinematic binning and improving MC

Exclusive Physics @ CLAS12

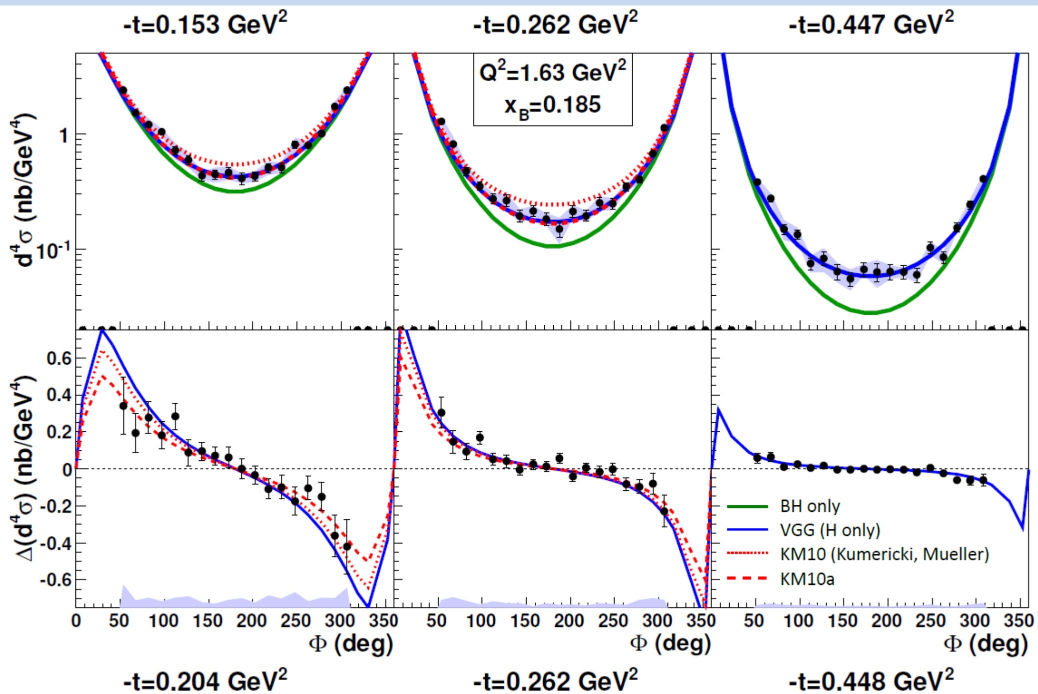
Informations on the real and imaginary part of the QCD scattering amplitude

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



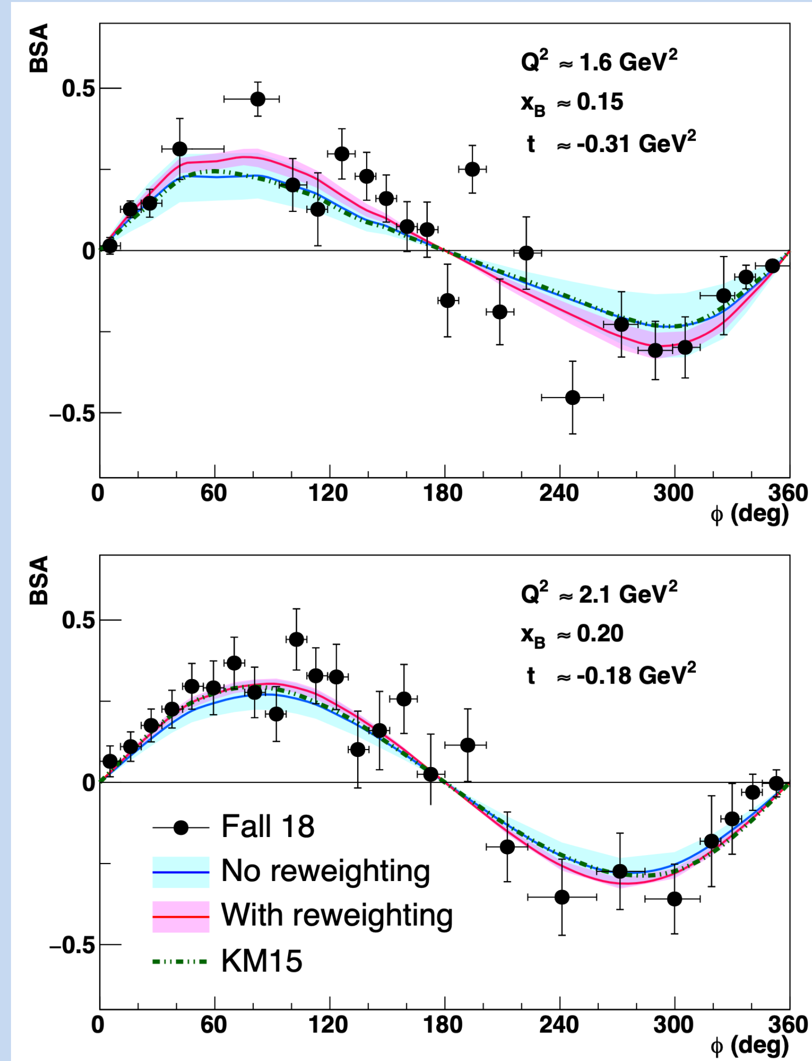
CLAS

H.-S. Jo et. al. [arXiv: 1504.02009]



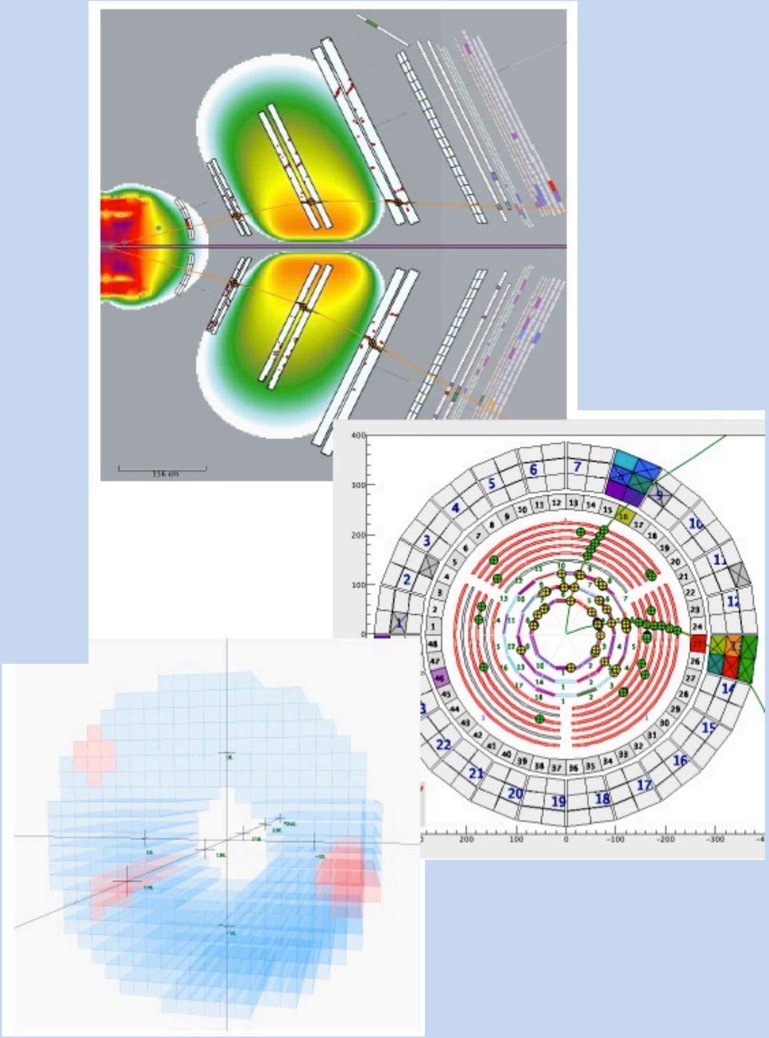
CLAS12

G. Christiaens et. al. [arXiv: 2211.11274]

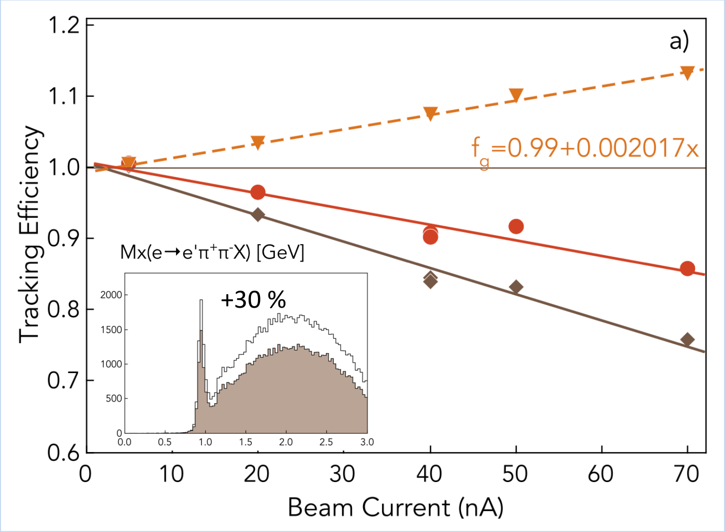


CLAS12 Data Pass-2

CLAS12 pass2 data re-processing
Started in May’23 with RGB (Deuteron run) data

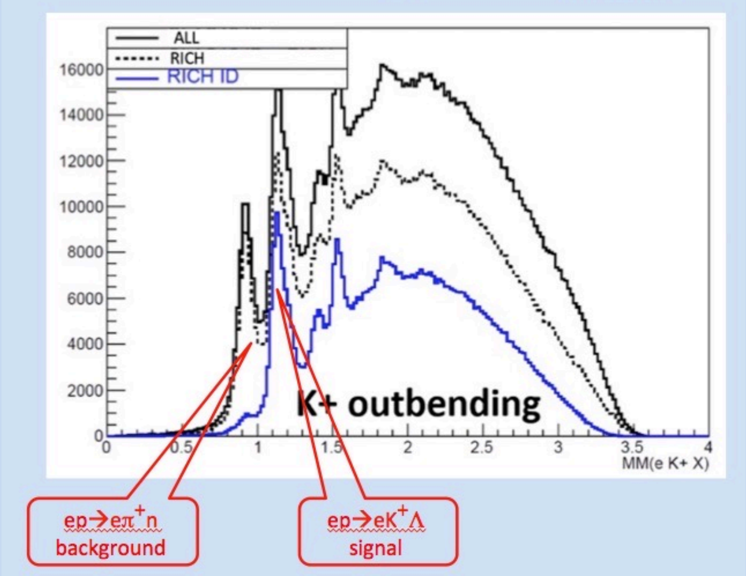


Improved central and forward tracking

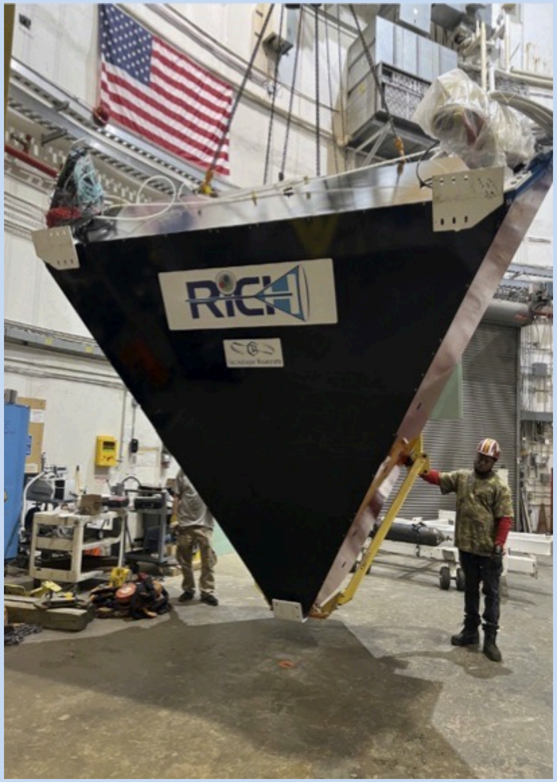


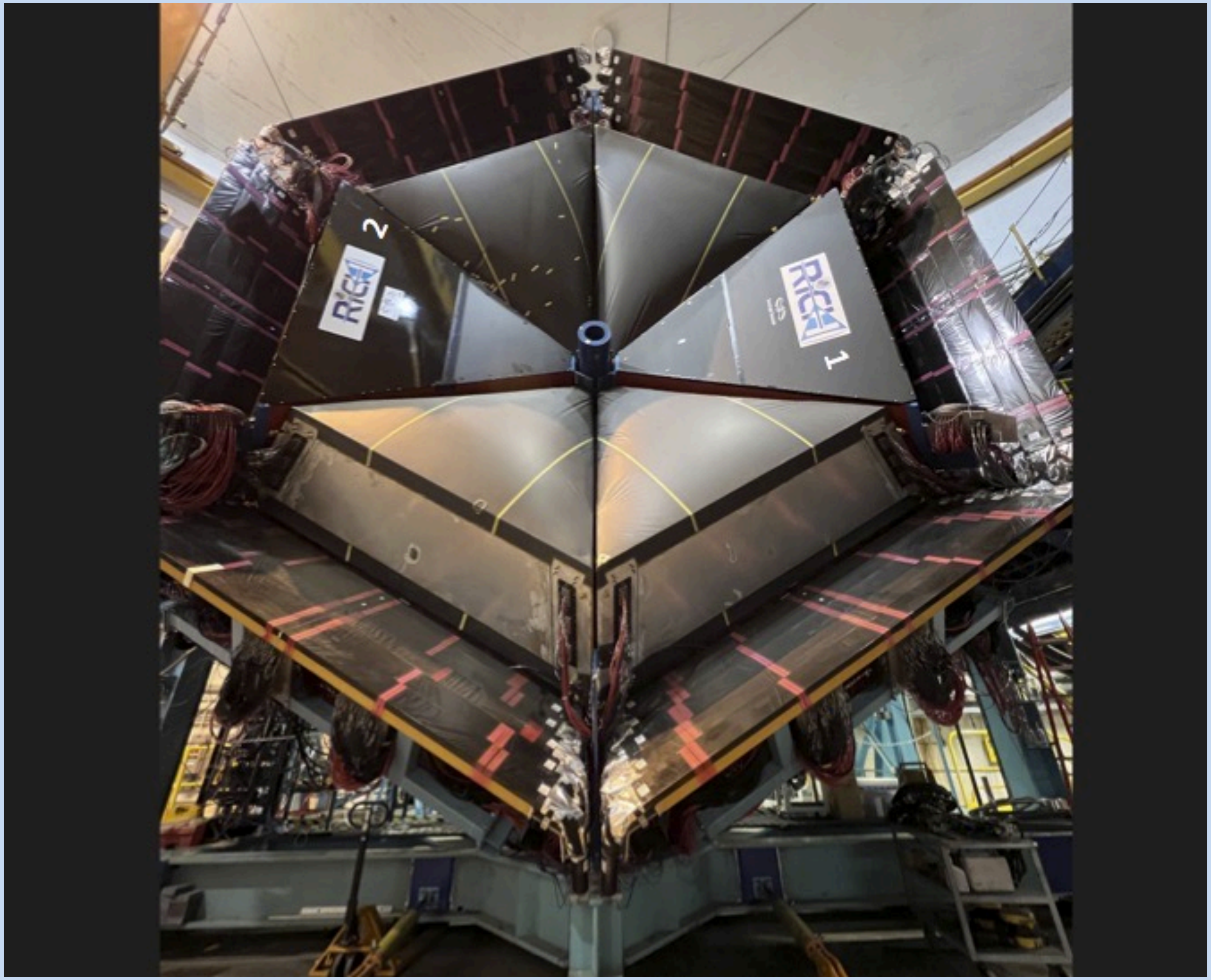
G. Gavalian, arXiv: 2205.02616

Improved PID and calorimetry



Completed in June 2022 with the symmetric configuration dedicated to the runs with polarized targets (now ongoing)



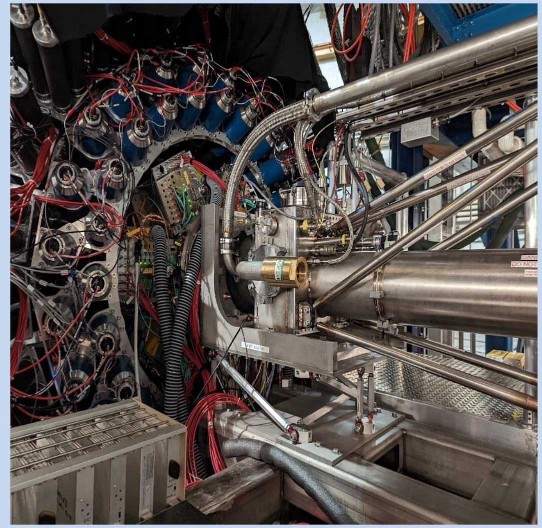


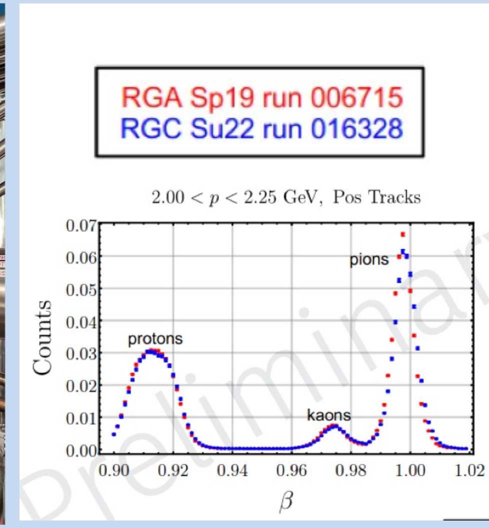
RCG: Longitudinal Pol. Target

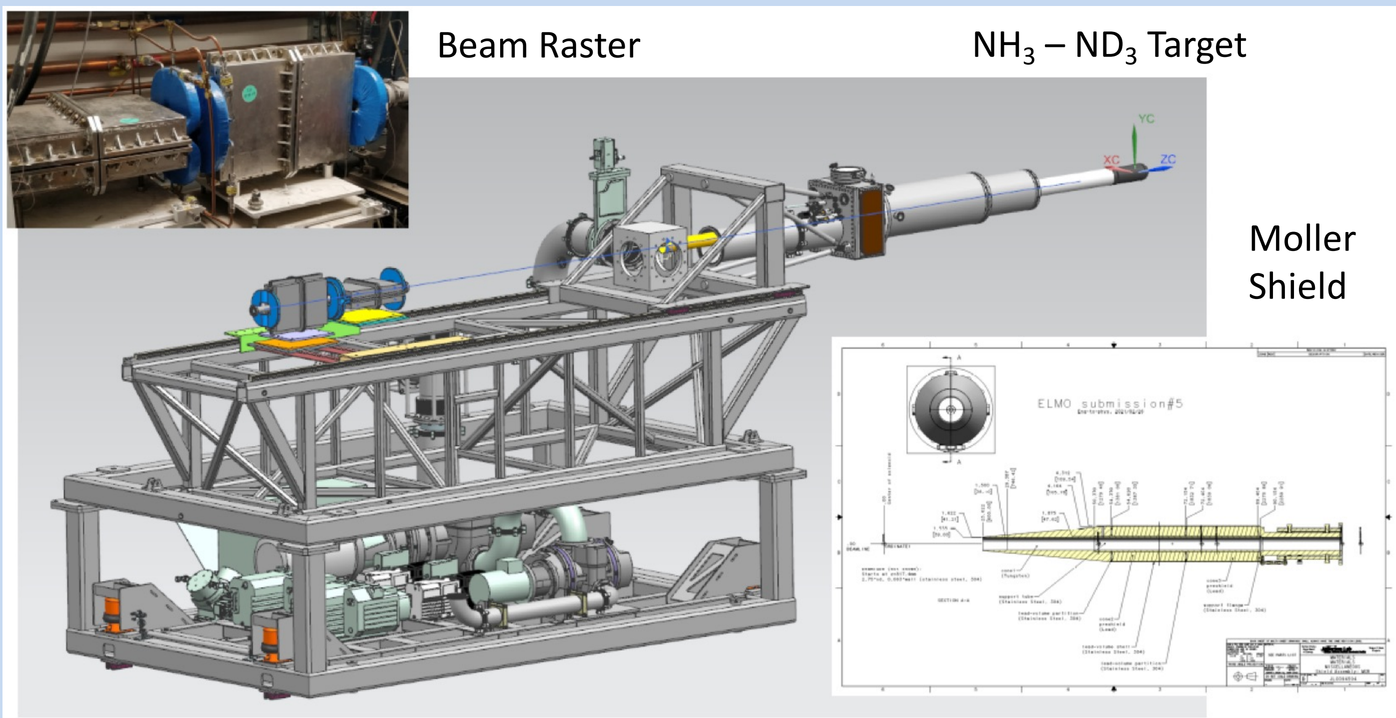
Succesfull run in summer 2022 – spring 2023

Detector performance and data prev-view as expected

Calibration and processing ongoing







Transverse Target @ CLAS12

HDice: pros: minimize the dilution and nuclear background (due to not-polarizable material)

pros: maximize acceptance (thanks to the light magnetic system)

cons: beam heating and radiation damage

cons: long preparation time

NH_3/ND_3 : pros: consolidated technology and infrastructure at JLab

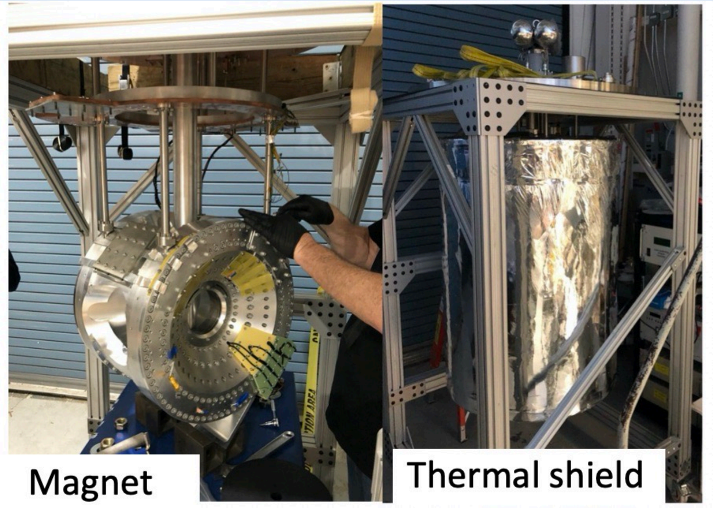
cons: increased systematic effect (nuclear effects, non uniform target density)

cons: impact on the experimental setup
(massive magnet of strong field and reduce acceptance)

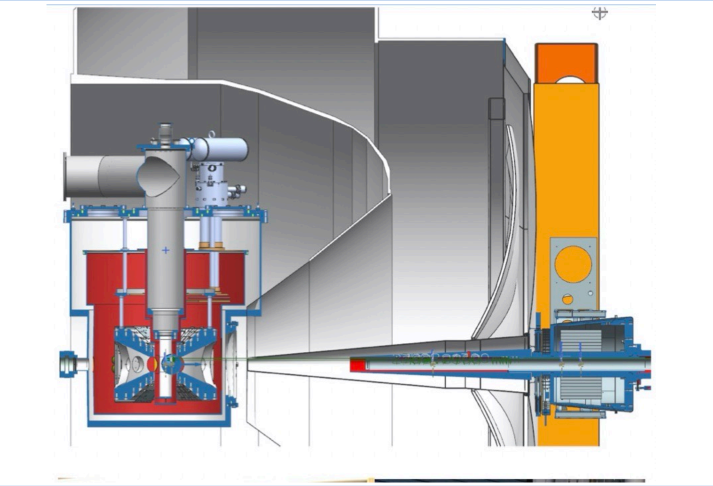
Target	HDice	NH3/ND3
Average polarization	41%	86%
Overhead	10%	3-5%
Dilution	1/3	3/17
FOM	13%	15%

Transverse Target @ CLAS12

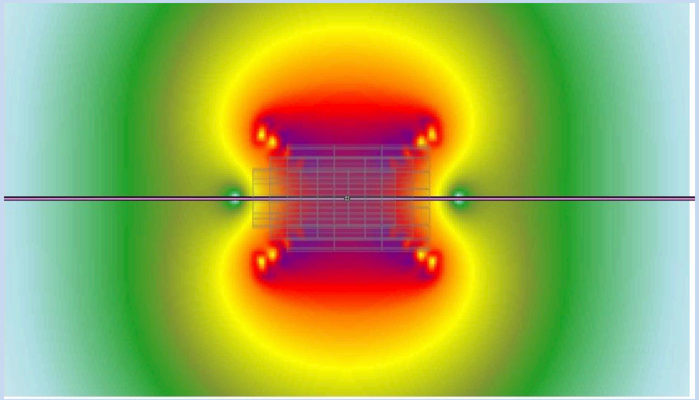
Low risk:
5T magnet being prepared for Hall-C



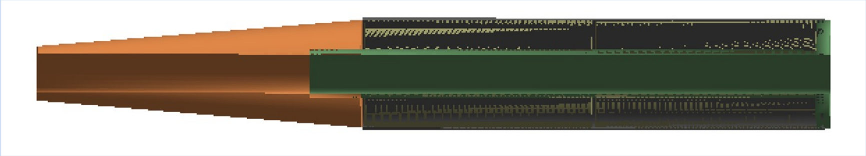
Major impact on CLAS12:
Incompatible with central detector



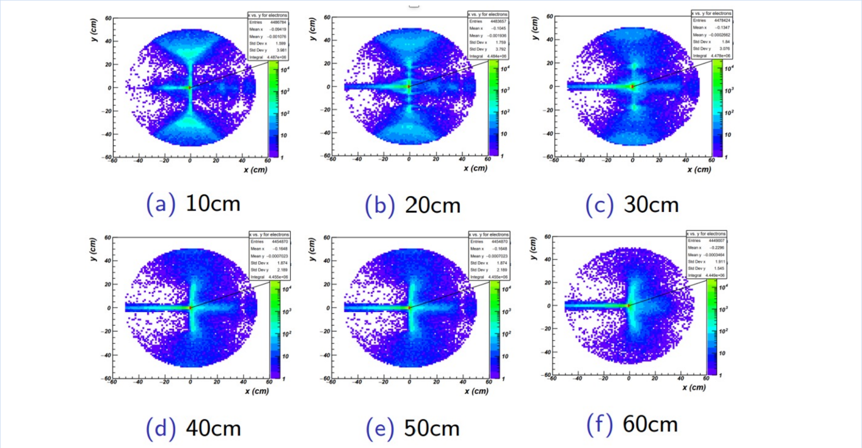
Side view



ELMO GEMC Cross-section (without Tungsten Tip)



Moller distribution along dummy tracking planes

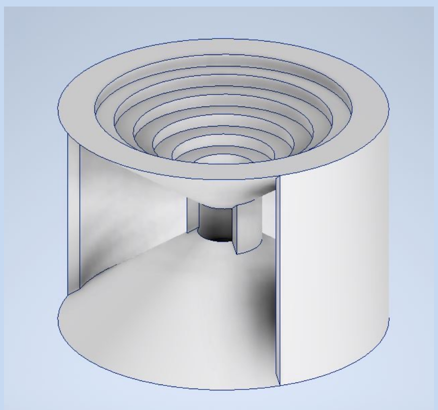


Alternate Target Holding Magnet

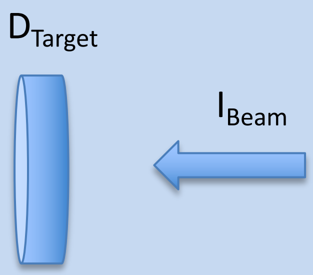
Goal: maximize the physics outcome

* design for a short target (Lumi $\propto$ D_{Target} x I_{beam})
* optimize acceptance
* reduce integrated field → simplify beam chicane
  → limit Moeller dispersion ?

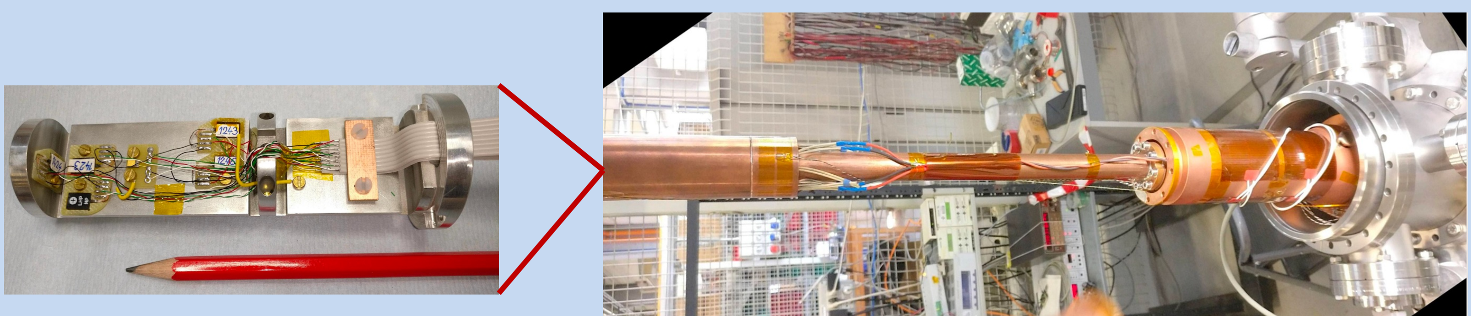
Challenges: preserve 100 ppm uniformity, cope with strong forces
Goal: match the CLAS12 high-luminosity upgrade



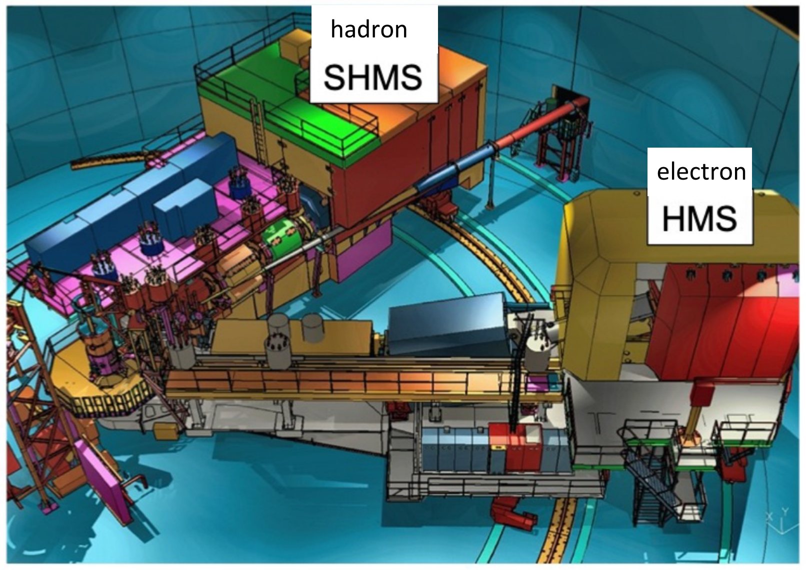
Massive magnet



Light magnet



SIDIS Cross Section



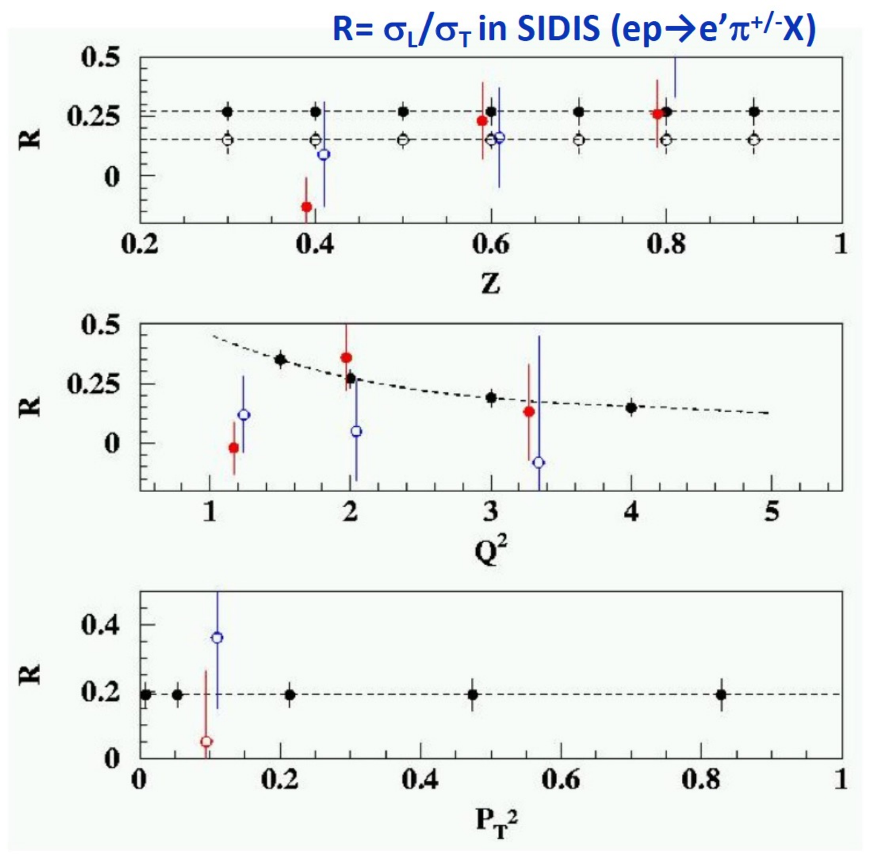
$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{K(x,y)}{Q^2}\left\{F_{UU,T} + \varepsilon F_{UU,L} + \ \ldots\right\}$$

$R=\sigma_L/\sigma_T$

Assumed similar to DIS. Requires validation from experiments as any other SIDIS term.

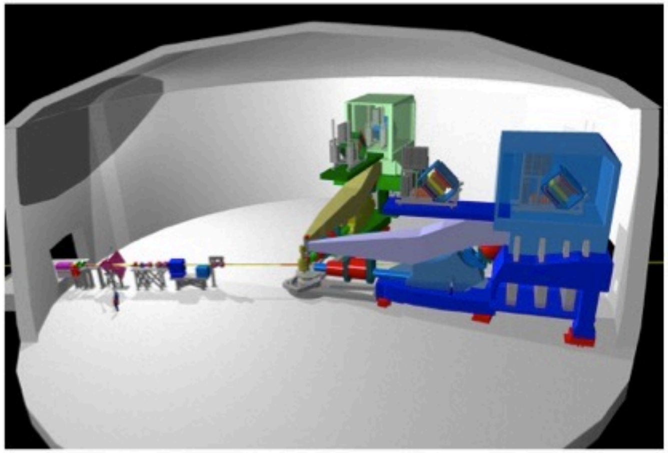
- Excellent control of point-to-point systematic uncertainties required for **precise L-T separation**

Crucial measurement as it yields the **fundamental quantity of R** which relates the cross sections (experimental observables) to the structure functions (objects of theoretical models)



+ precision higher-twist and low pT physics

SBS: Spectrometer Pair



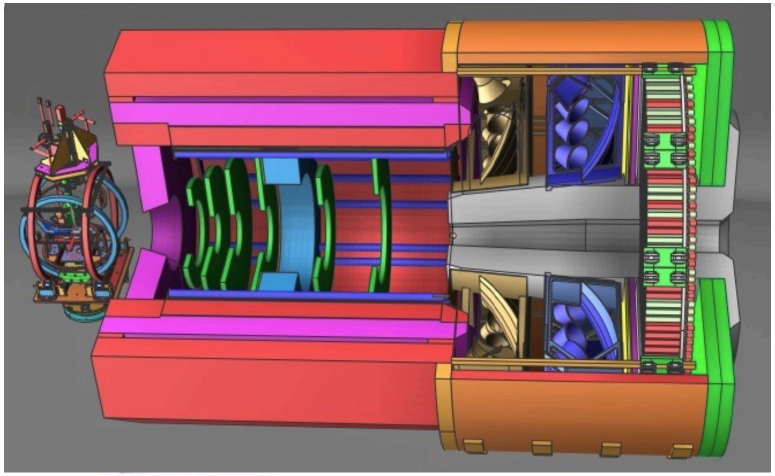
Hall-A:

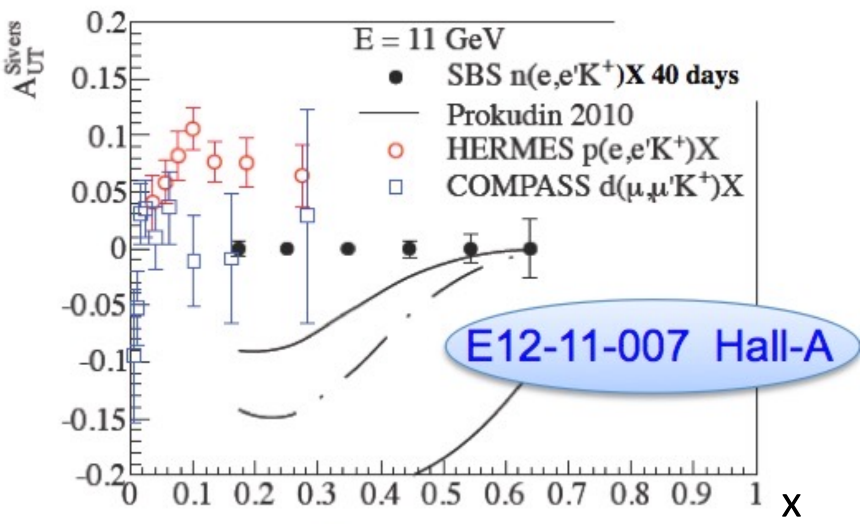
High-luminosity $10^{38}\ cm^{-2}s^{-1}$

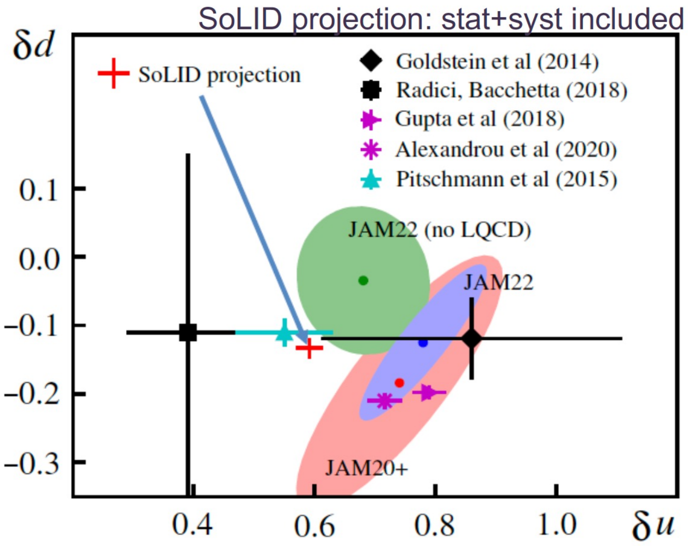
^3He targets

Wide coverage

SOLID: Large Acceptance Detector







The ultimate precision in the valence region, ^3He targets, suitable for possible energy upgrades

CEBAF Energy Upgrade

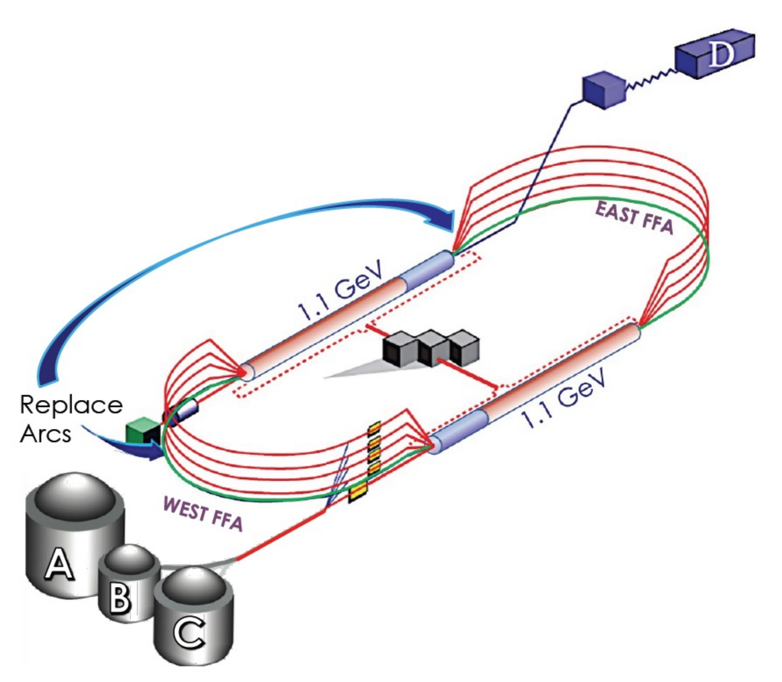
Extend the reach of an unique facility at the intensity frontier

In preparation of **Long Range Plan (2023)**

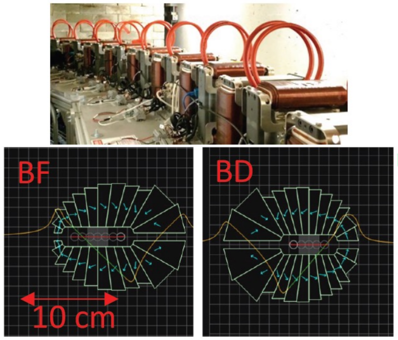
Replace higest energy arcs with Fixed-Field Alternating Gradient (FFA) arcs
- Permament, multi function magnets
- Current design assumes 6 passes through single pair of FFA arcs

Nominal linac energy 1100 MeV/pass
10 total passes in machine → **20-24 GeV final energy**

Upgraded injector if 650 MeV and **positron source**



Permanent FFA Magnets
- Small transverse size, slightly longer than 1 m each
- Demonstrated at CBETA (Cornell)
- Electromagnetic correctors



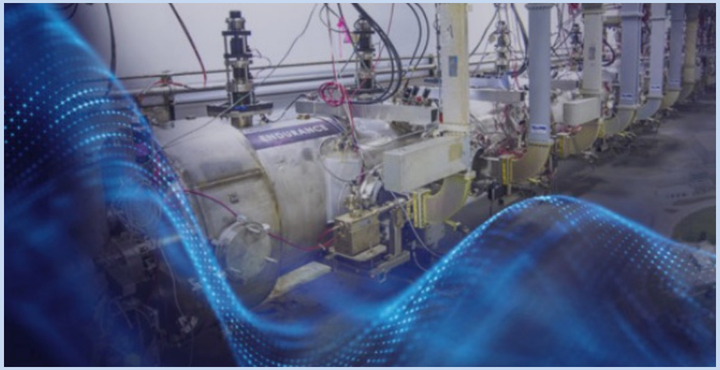
Magnets by Stephen Brooks, BNL

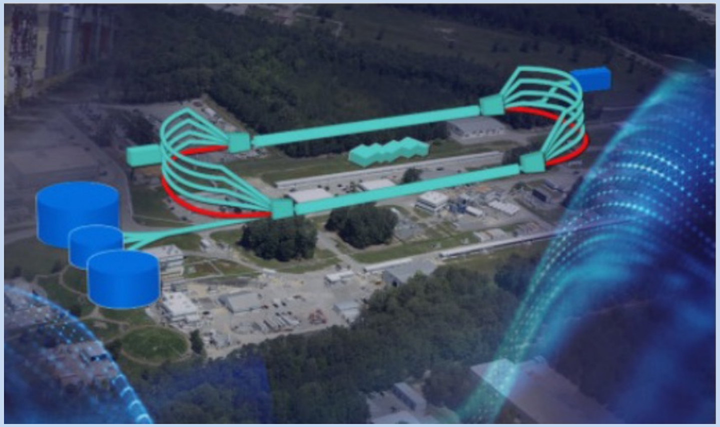
Future Opportunities

Internationally

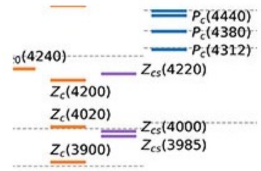
- **J-FUTURE**
  Messina (Italy) March 28-30, 2022
- **Hadron Physics Opportunities with JLab Energy and Luminosity Upgrade**
  Pohang (Korea) July 18-21, 2022
- **Opportunities with Jlab Energy and Luminosity Upgrade**
  ECT* Trento (Italy) September 26-30, 2022

Sience at the luminosity frontier:
Jefferson Lab at 22 GeV — 23-25 Jan 2023



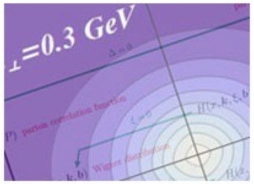


@ JLab Workshop Summer Series



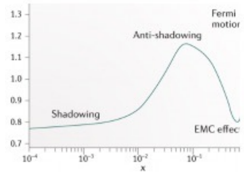
Hadron Spectroscopy with a CEBAF Energy Upgrade
June 16 & 17
Marco Battaglieri, Sean Dobbs, Derek Glazier, Alessandro Pilloni, Just

Recent observations in heavy-quark spectroscopy have provided numerous candid
Pc states. With a CEBAF energy upgrade to 20-24 GeV these states and other char



The Next Generation of 3D Imaging
July 7 & 8
Harut Avagyan, Carlos Munoz Camacho, Jian-Ping Chen, Xiangdong Ji, .

Studies of azimuthal distributions of hadrons and photons in exclusive and semi-inclu
of observables helping to elucidate the way the properties of the proton emerge dyn
JLab 12 GeV program, and driving force behind the construction of the future Electr



Science at Mid x: Anti-shadowing and the Role of the Sea
July 22,23
John Arrington, Mark Dalton, Thia Keppel, Wally Melnitchouk, Jianwei Qiu

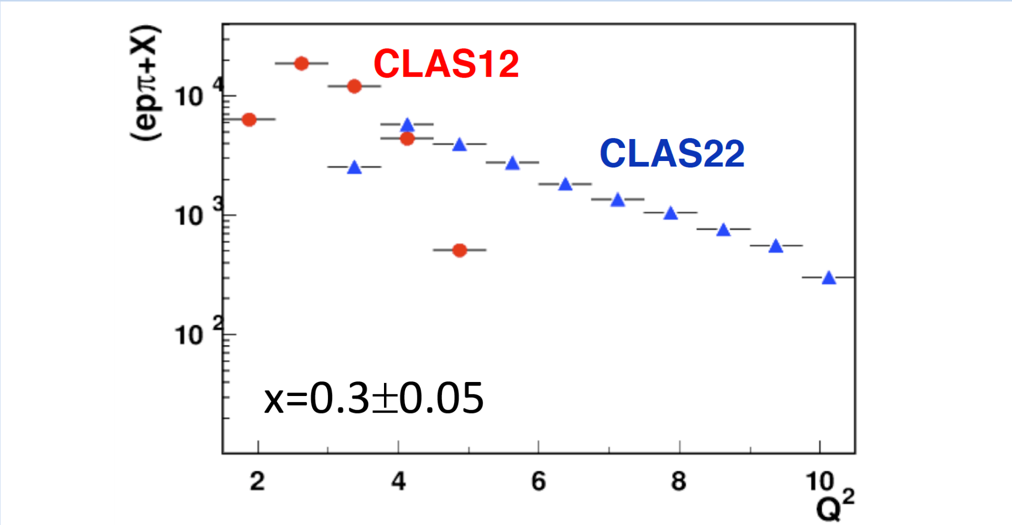
An upgrade of CEBAF at Jefferson Lab beyond 20 GeV will open up key science that is not
most possible is in the "middle" Bjorken x regime around x~0.1, where the available mome
several exciting measurements. Here, for example, the long-standing mystery of anti-shad

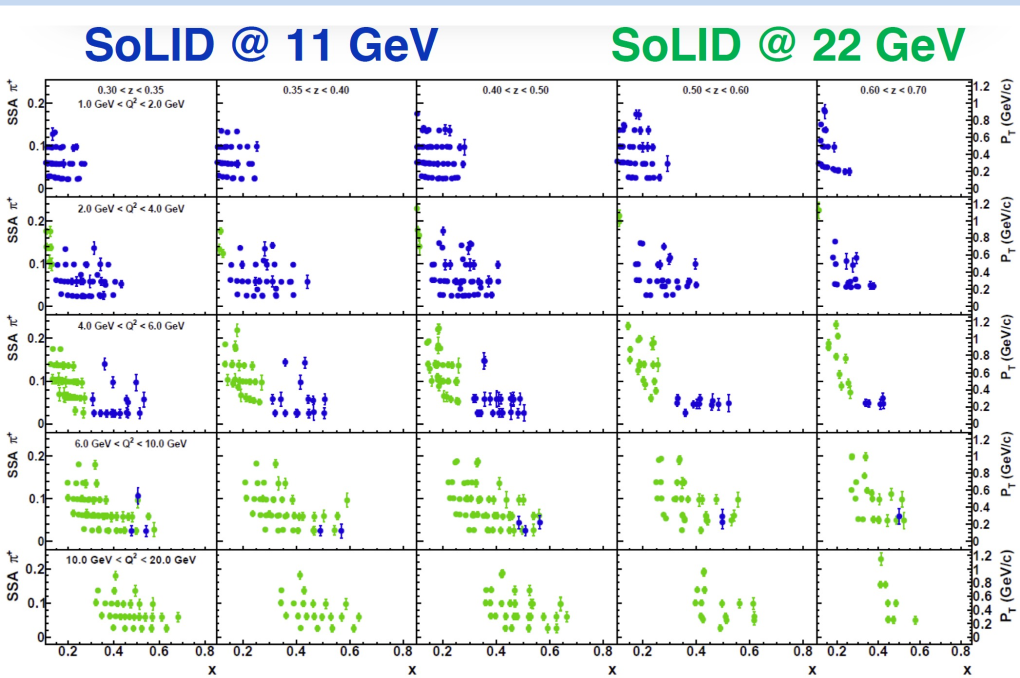
Physics Beyond the Standard Model
August 1
Marco Battaglieri, Bob McKeown, Xiaochao Zheng, Patrizia Rossi

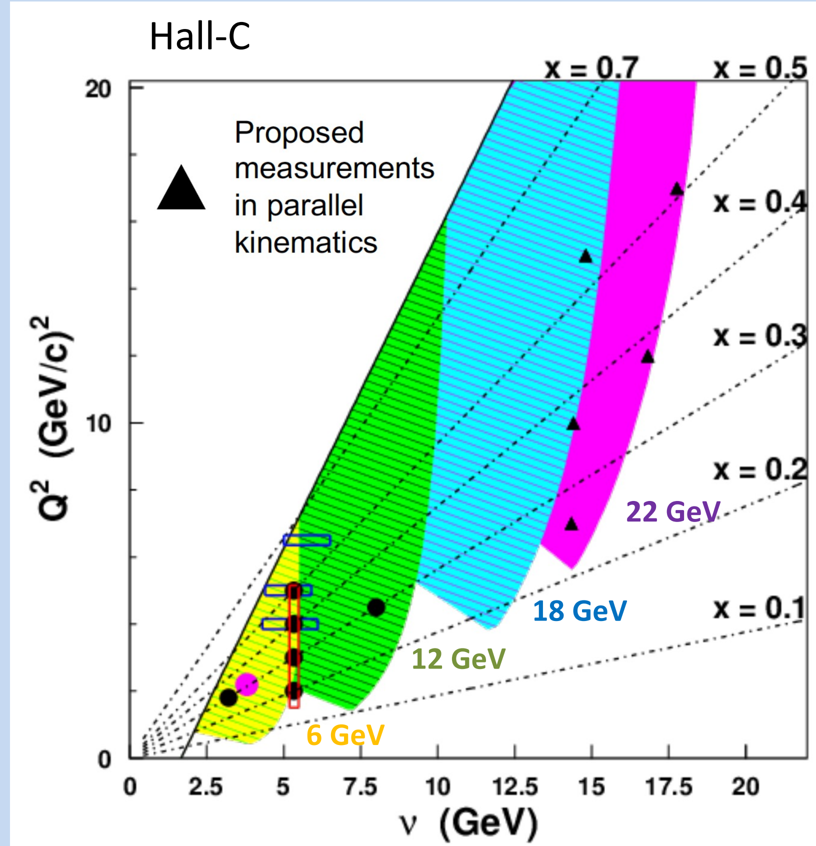
Possibilities for testing the Standard Model and searching for new physics bey
discussed. There will be opportunities for presentations and discussions where

J/Psi and Beyond
August 16 & 17 9am - 1pm
Ed Brash, Ian Cloet, Zein-Eddine Meziani, Jianwei Qiu, Patrizia Rossi

Measurements of J/psi near threshold with high statistics, for both electro and pho
the community. A CEBAF energy increase (to ~24 GeV) will allow us to ask new que
nuclear and particle physics, thus enhancing the physics output of all four experime

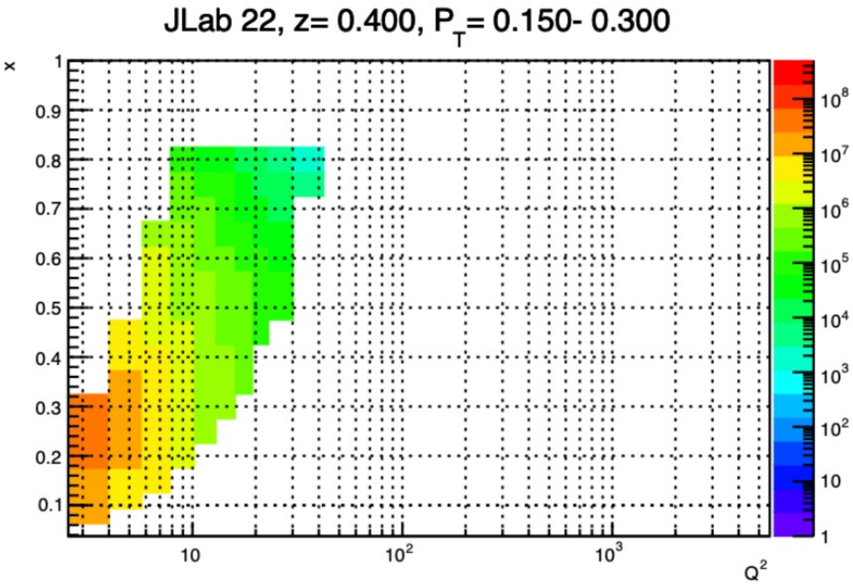


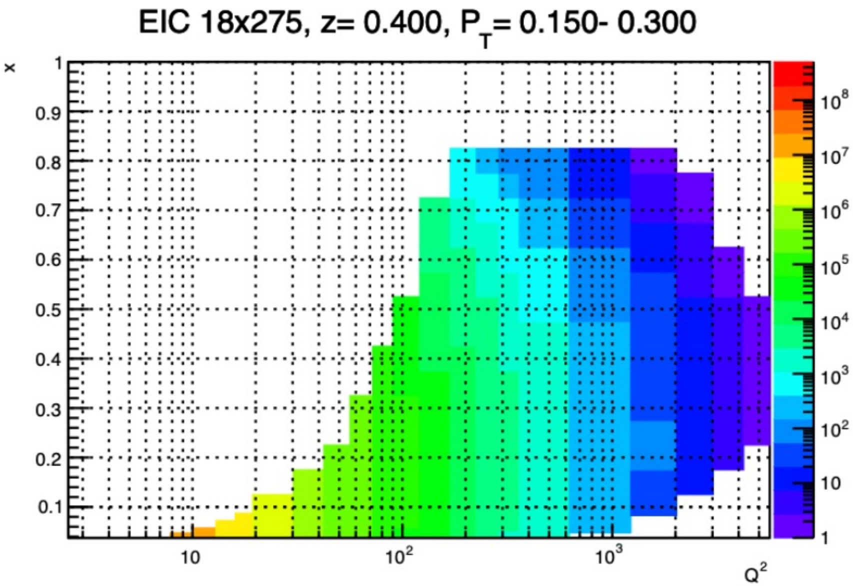


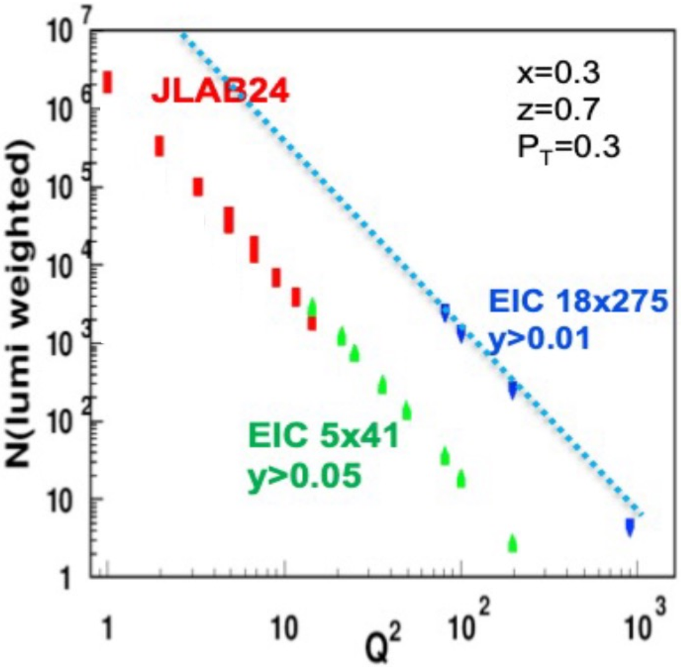


With Enhanced Beam Energy
Boost of Q^2 Evolution Study

JLab Domain







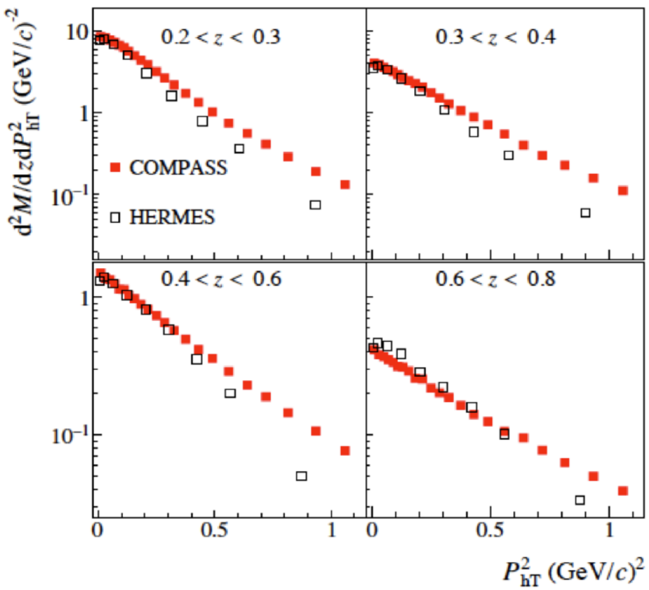
x-section from Bacchetta et al, 1703.10157

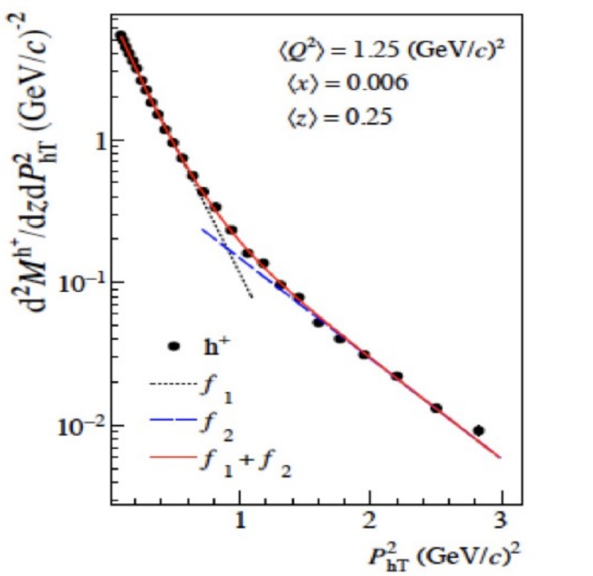
H. Avakian
M. Mirazita

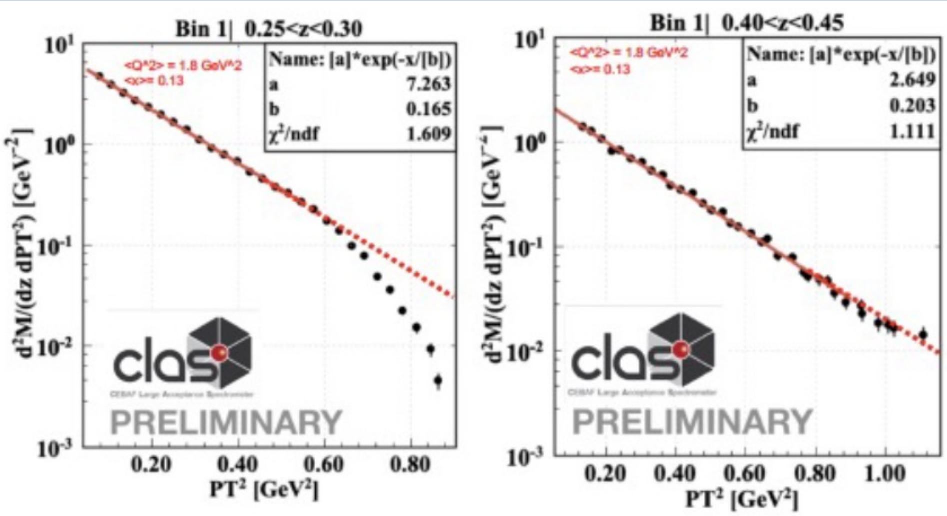
Counts / year

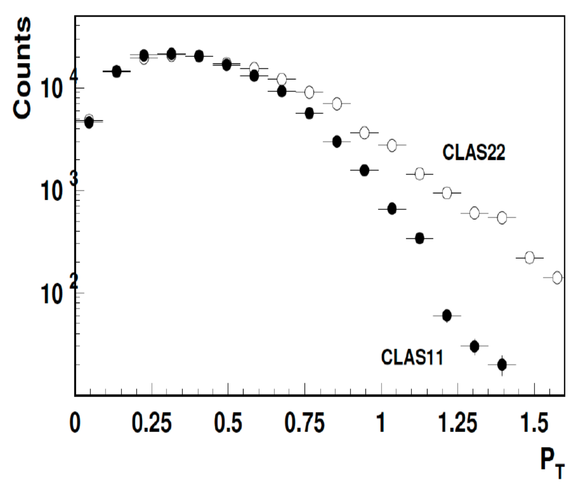
JLab: Unique precision in the valence region

P_T tail is a key element: perturbative contribution, matching, phase space









SIDIS Cross-Section

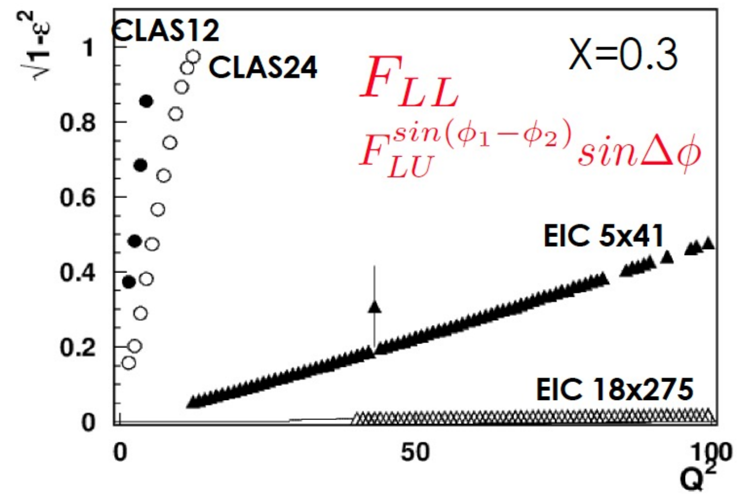
$$\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2}$$
$$= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Big\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}$$
$$+ \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\s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

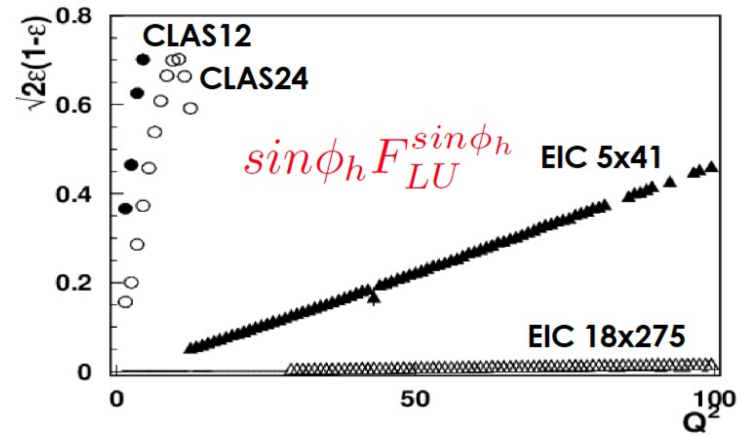
TMD Factorization

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

TMD Evolution

Evolution kernel (with CS non-perturbative kernel)





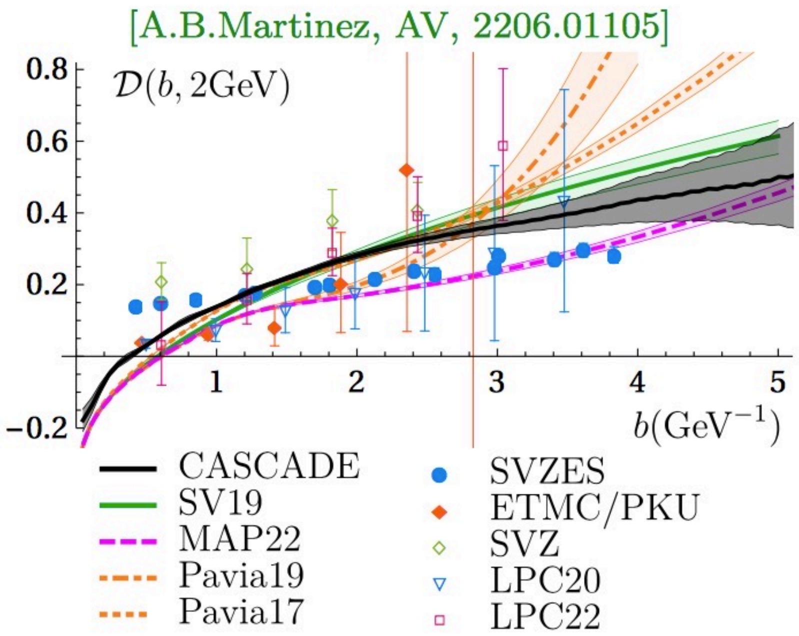
H. Avakian at Transversity 2022

TMD Evolution

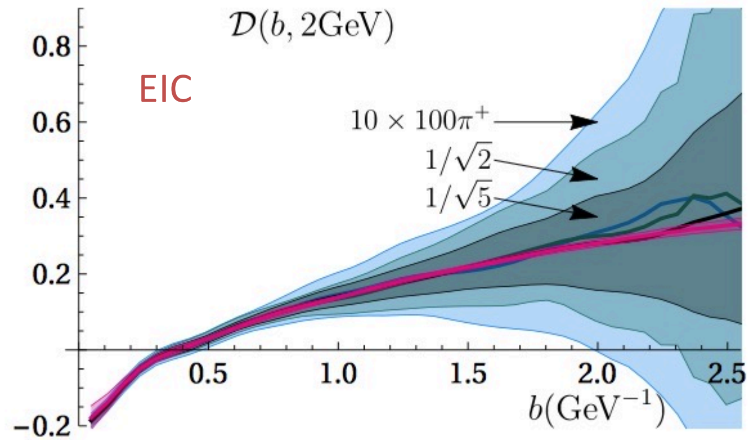
With b as Fourier conjugate of PT/z

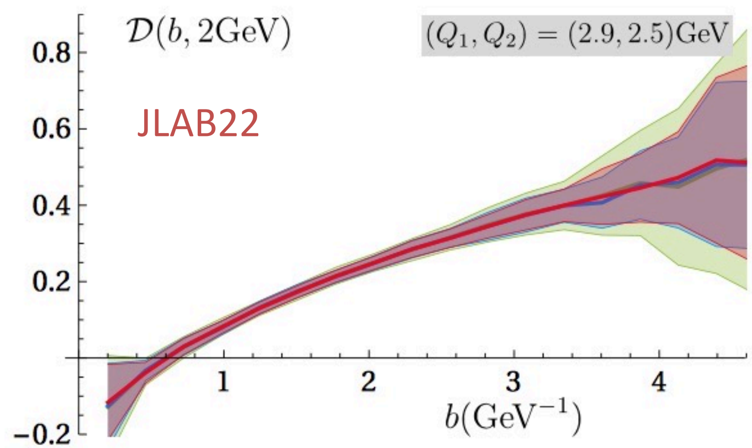
$$F_{UT}^{\sin(\phi_h-\phi_S)} = \sum_q e_q^2 |C_V(Q)|^2 \int \frac{d^2b}{(2\pi)^2} e^{i(b\cdot P_T)/z} R(Q,b,\mu_0) f_{1T}^{\perp q}(x,b;\mu_0) D_1^q(z,b;\mu_0)$$

Collins-Soper non-perturbative evolution kernel



Complementarity in Q² and b coverage





A. Vladimirov @ APCTP22 workshop

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