

Present and Future of TMDs

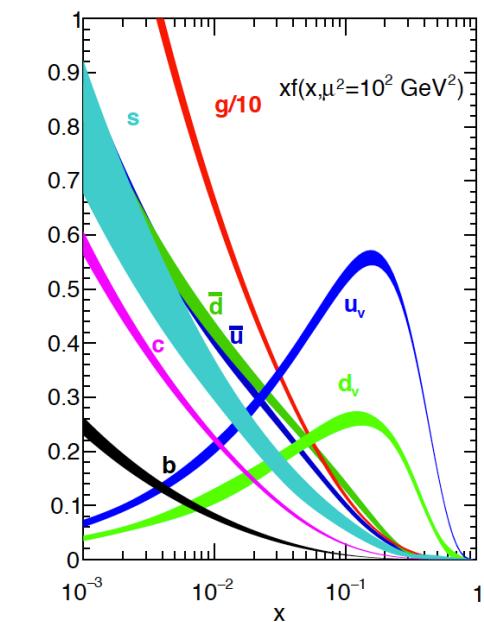
Marco Contalbrigo – INFN Ferrara

European Nuclear Physics Conference - Santiago de Compostela, 24-28 October 2022

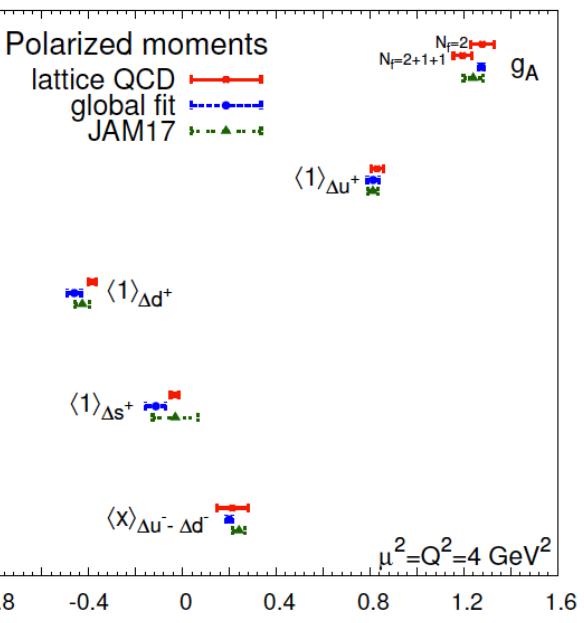
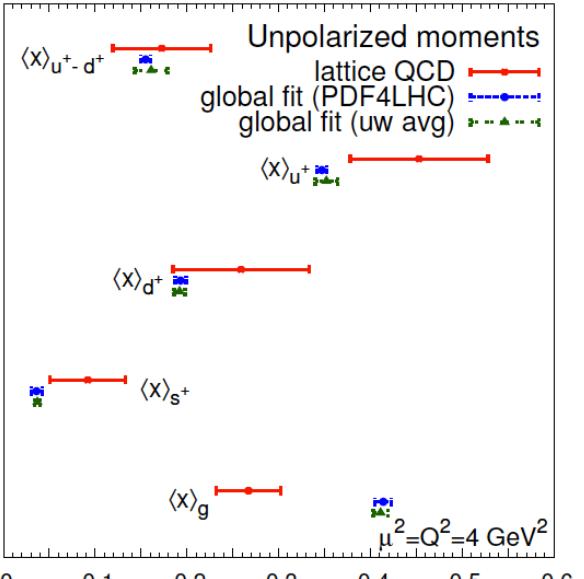
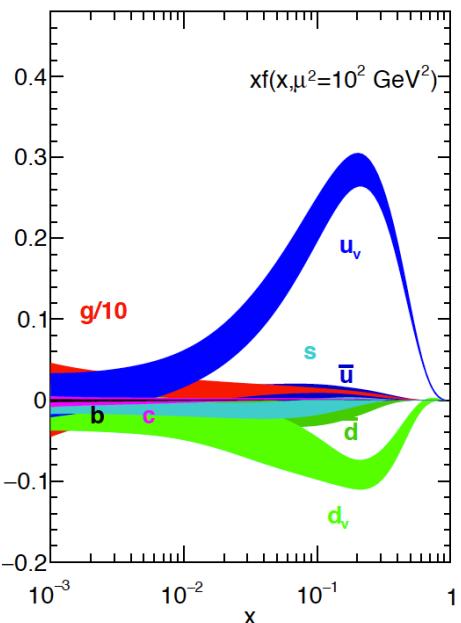
Parton Content

Unpolarized
moments

H-W Lin++ [1711.07916]



Polarized (helicity)
moments



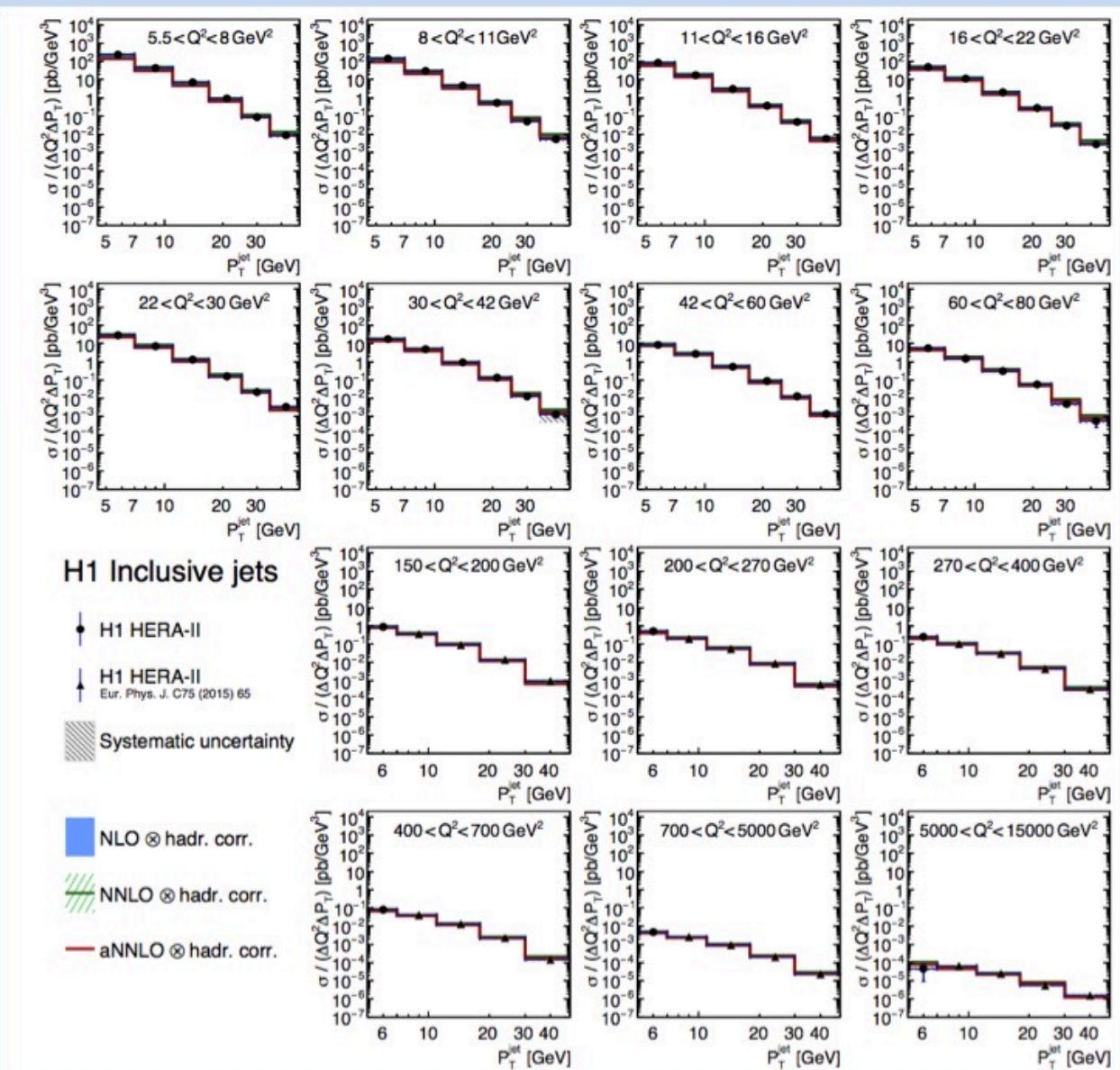
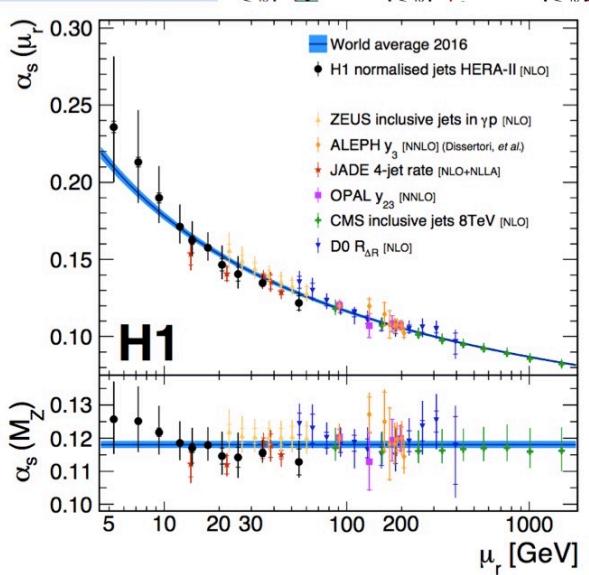
HERA Legacy and Perturbative QCD

Good perturbative description
(hard gluon emission)

$p_T > 5 \text{ GeV}$ $Q^2 > 5 \text{ GeV}^2$

Part in a $P_T \ll Q$ TMD regime

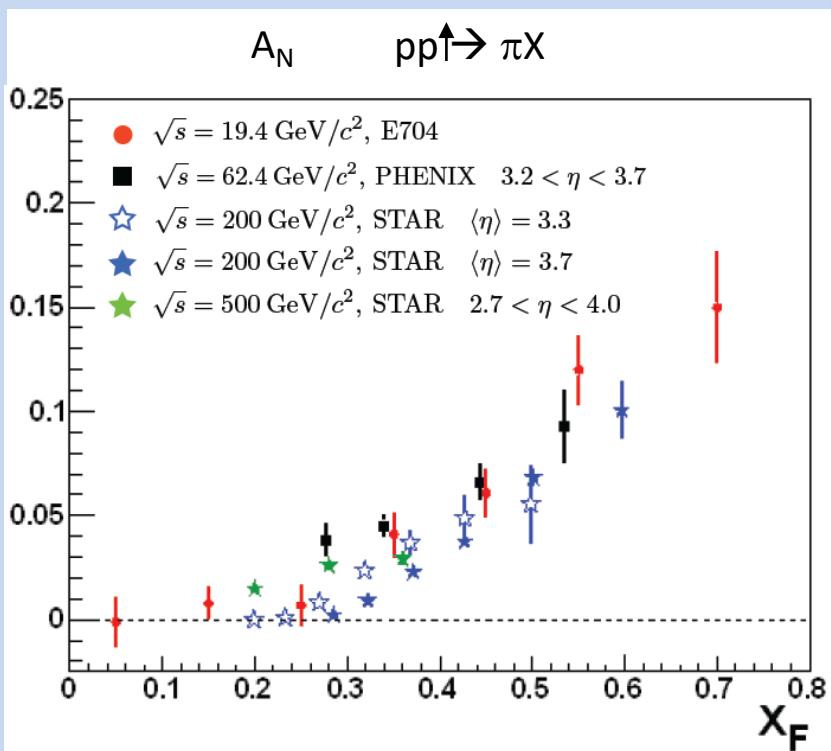
H1 [arXiv: 1611.03421]



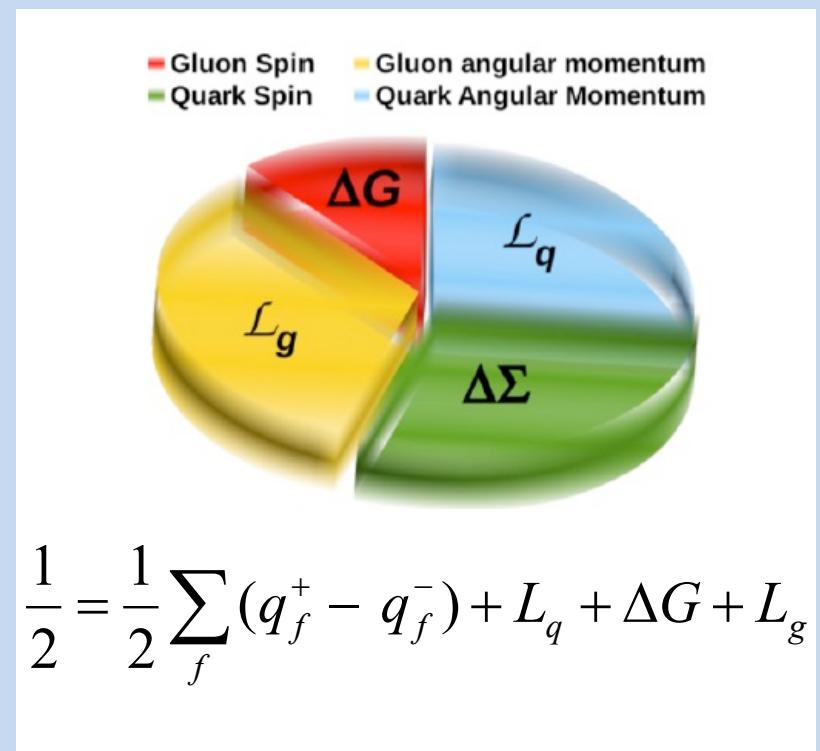
Can QCD be a precision science ?

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

Single Spin Asymmetries

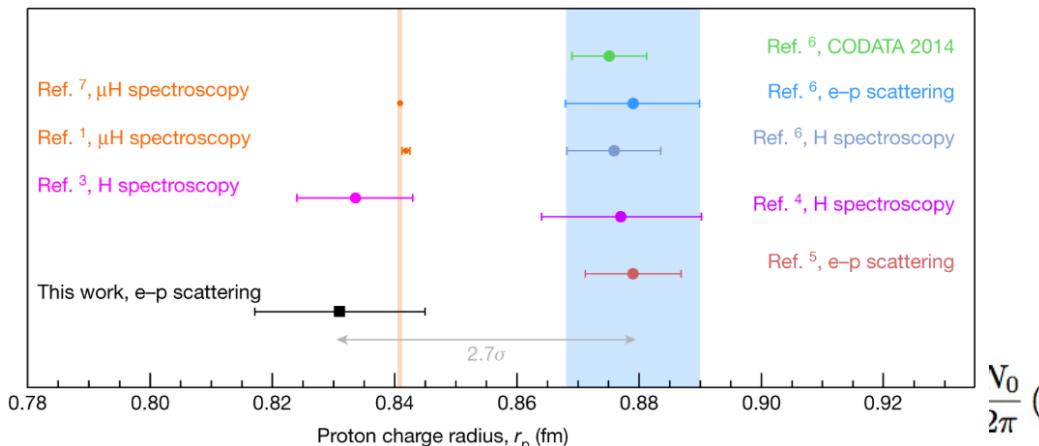


Proton Spin Budget

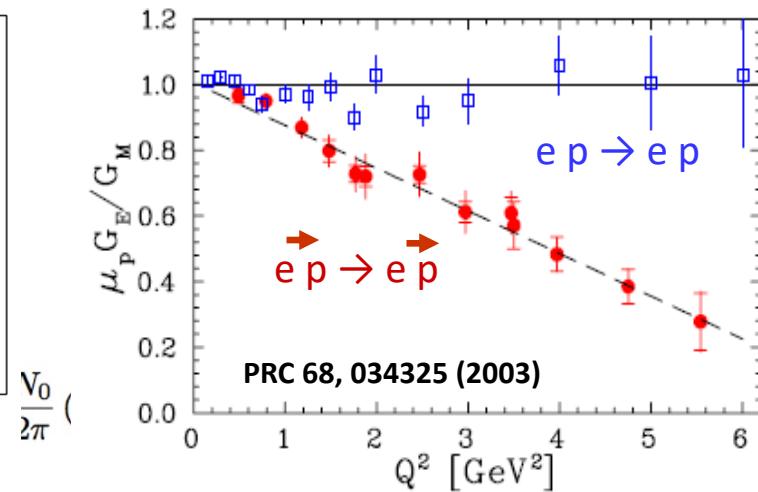


Still Surprising Proton

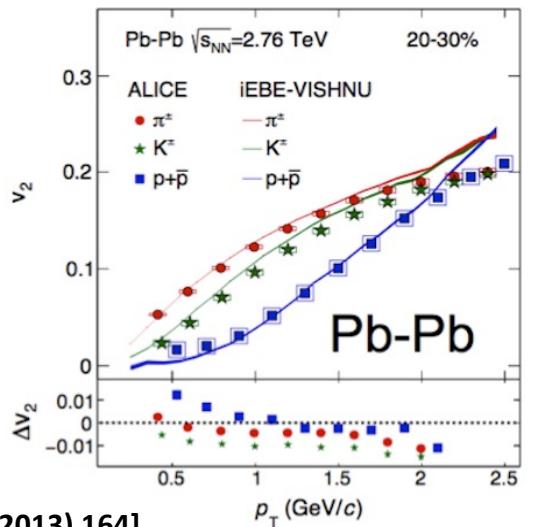
Do we control the proton form factor and radius ?



Nature 575 147 (2019)

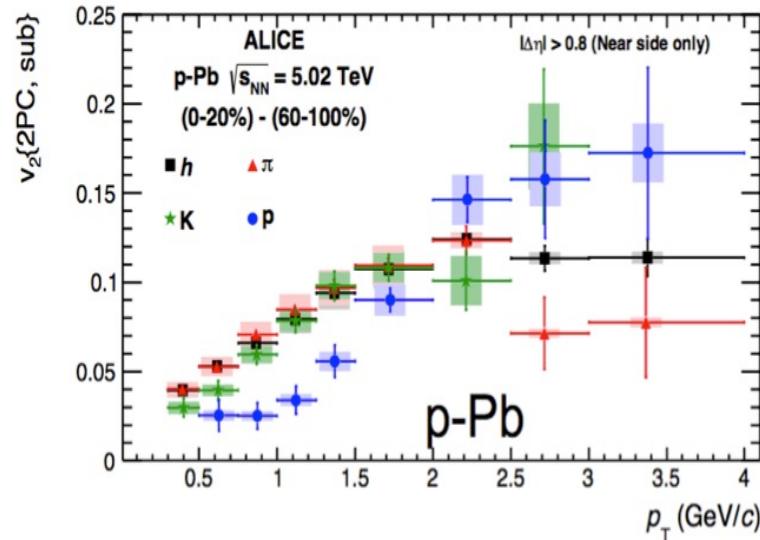


Is there a collective motion in small systems ?

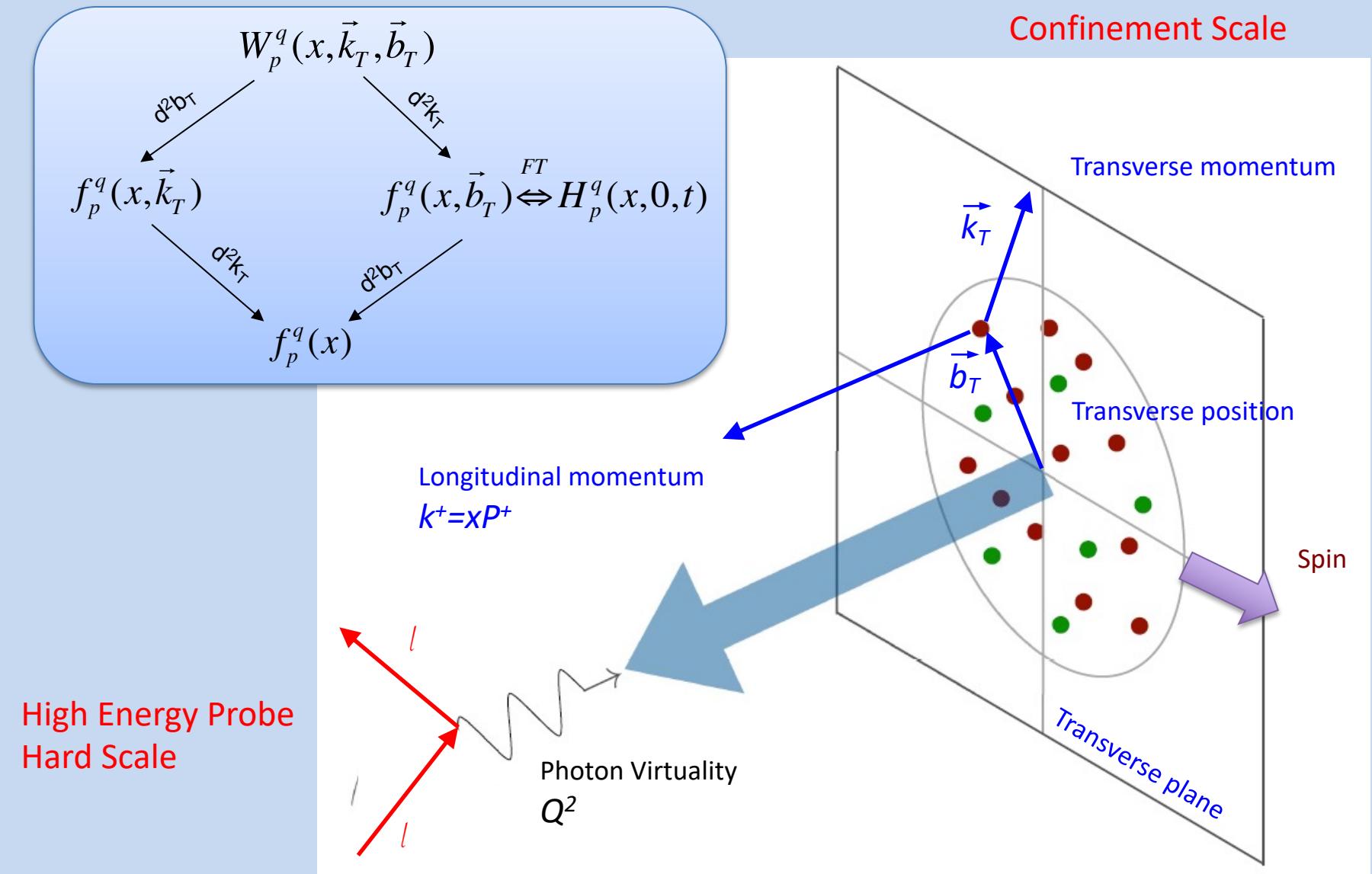


ALICE [PLB 726 (2013) 164]

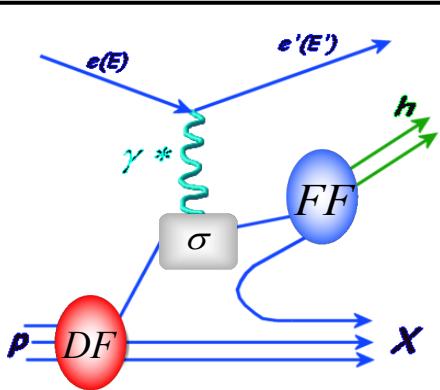
$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi} (1 + 2v_1 \cos(\varphi - \Psi_1) + 2v_2 \cos[2(\varphi - \Psi_2)] + \dots)$$



The 3D Nucleon Structure

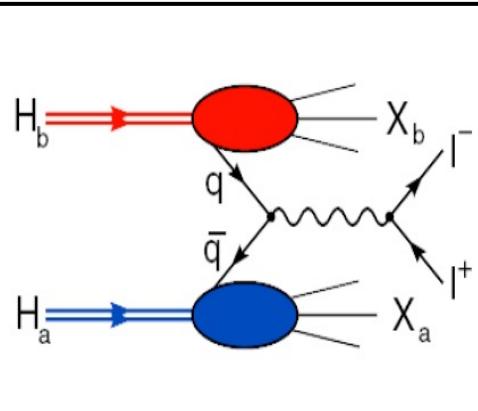


Physics Channels



SIDIS: rich phenomenology, the most explored so far

$$\text{SIDIS} \quad \sigma^{ep \rightarrow ehX} = \sum_q DF \otimes \sigma^{eq \rightarrow eq} \otimes FF$$

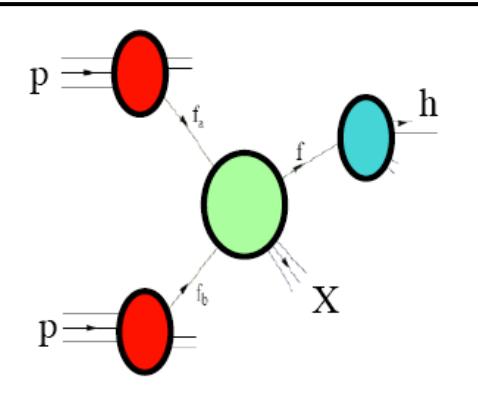


e^+e^- colliders: powerful fragmentation laboratories

$$e^+e^- \quad \sigma^{ee \rightarrow hhX} = \sum_q \sigma^{qq \rightarrow ee} \otimes FF \otimes FF$$

DY: challenging for experiments (only unpolarized so far)

$$\text{DY} \quad \sigma^{pp \rightarrow eeX} = \sum_q DF \otimes DF \otimes \sigma^{qq \rightarrow ee}$$



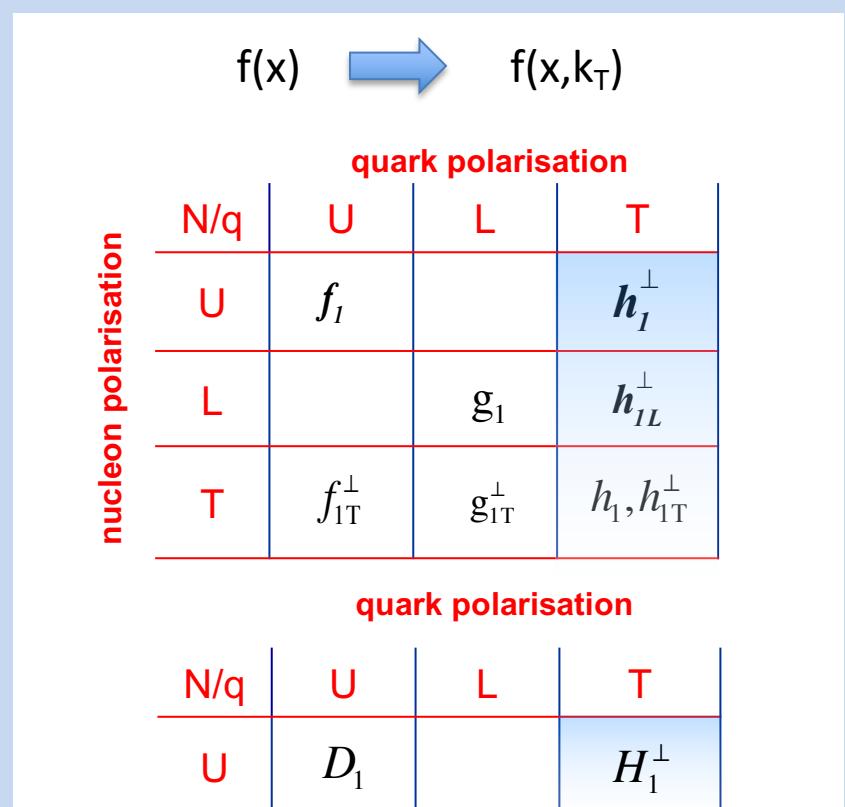
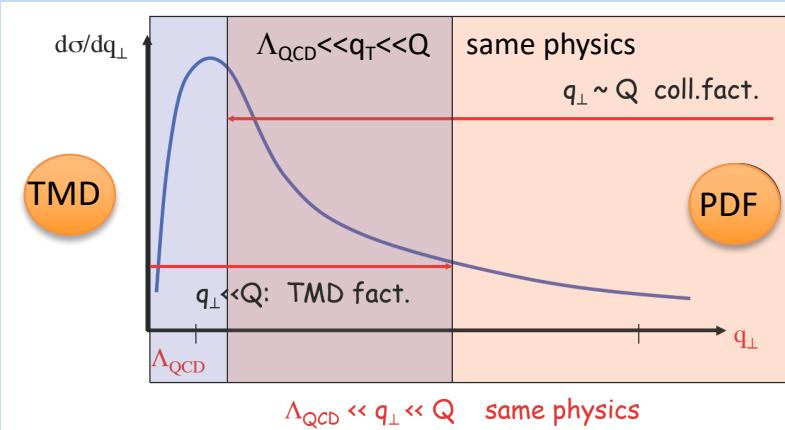
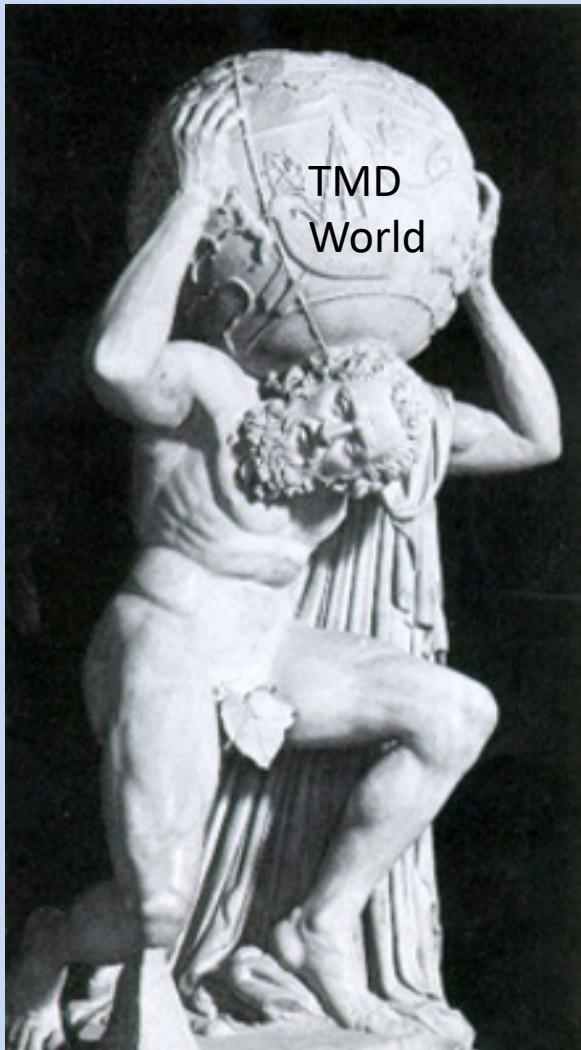
Hadron reactions: challenging for theory (ISI + FSI)

$$pp \quad \sigma^{pp \rightarrow hX} = \sum_q DF \otimes DF \otimes \sigma^{qq \rightarrow qq} \otimes FF$$



TMD Parton Correlators

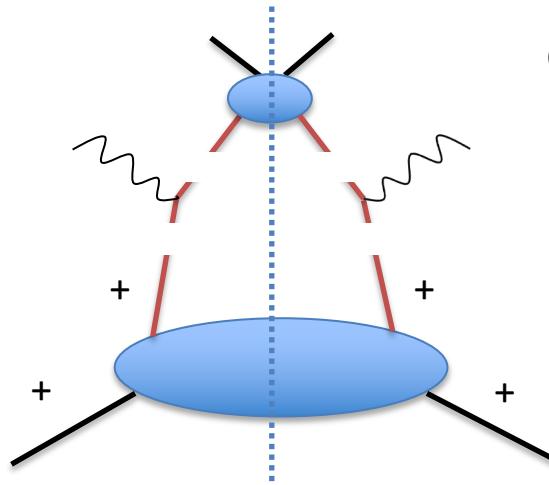
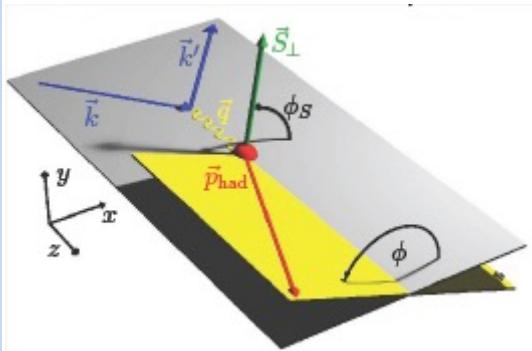
Beauty and complexity of the unique strong-interacting world



SIDIS Cross-Section and TMDs

$$\begin{aligned}
 \frac{d^6\sigma}{dx dQ^2 dz dP_{h_\perp} d\phi d\phi_S} \stackrel{LT}{\propto} & \left[F_{UU} + \varepsilon \cos(2\phi) F_{UU}^{\cos(2\phi)} \right] + S_L \left[\varepsilon \sin(2\phi) F_{UL}^{\sin(2\phi)} \right] \\
 & + S_T \left[\sin(\phi - \phi_S) F_{UT}^{\sin(\phi - \phi_S)} + \varepsilon \sin(\phi + \phi_S) F_{UT}^{\sin(\phi + \phi_S)} + \varepsilon \sin(3\phi - \phi_S) F_{UT}^{\sin(3\phi - \phi_S)} \right] \\
 & + S_L \lambda_e \left[\sqrt{1 - \varepsilon^2} F_{LL} \right] + S_T \lambda_e \left[\sqrt{1 - \varepsilon^2} \cos(\phi - \phi_S) F_{LT}^{\cos(\phi - \phi_S)} \right] + O\left(\frac{1}{Q}\right)
 \end{aligned}$$

f₁ h₁[⊥] h_{1L}[⊥]
f_{1T}[⊥] h₁ h_{1T}[⊥]
g₁ g_{1T}[⊥]



Quark fragmentation

TMD Factorization
Holds for $p_T \ll Q$
Not trivial gauge invariance
Peculiar Q^2 evolution (DGLAP)

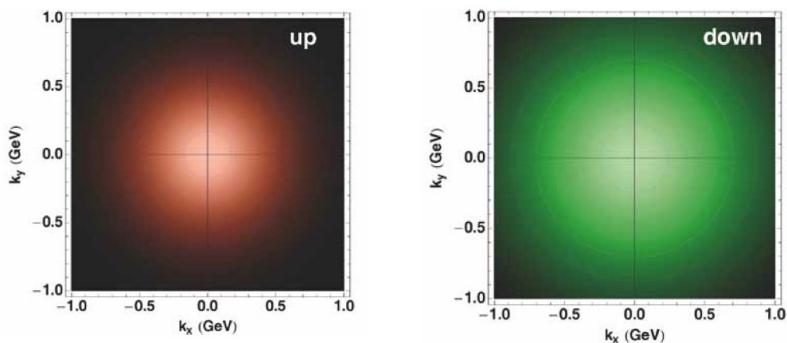
Quark parton distribution

Wide kinematic coverage is needed to resolve the convolution

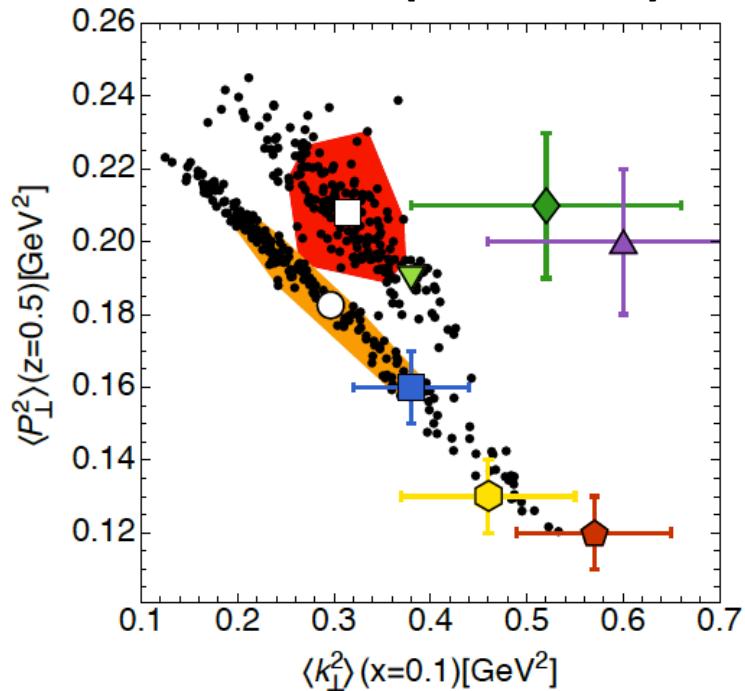
$$F_{UU} = f \otimes D = x \sum_q e_q^2 \int d^2 p_T d^2 k_T \delta^{(2)}(\mathbf{P}_{h_\perp} - z \mathbf{k}_T - \mathbf{p}_T) w(\mathbf{k}_T, \mathbf{p}_T) f^q(x, k_T^2) D^q(z, p_T^2)$$

Unpolarized TMDs

$$\left\langle P_{h\perp}^2 \right\rangle = z^2 \left\langle k_T^2 \right\rangle + \left\langle p_T^2 \right\rangle$$



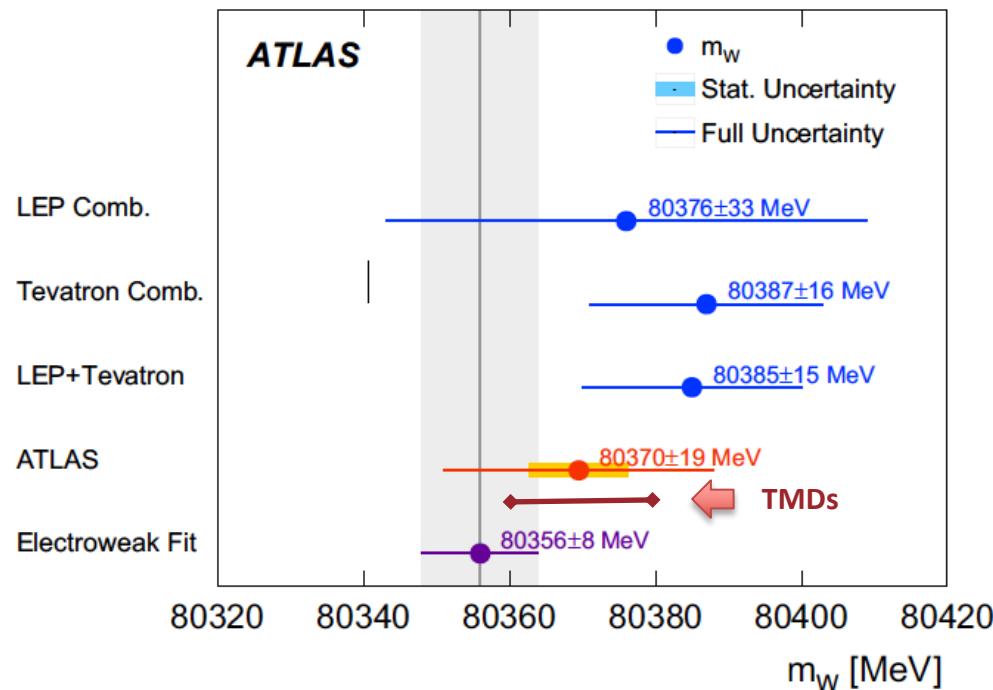
A. Bacchetta++ [arXiv:1703.10157]



A. Bacchetta++ [arXiv:1807.02101]

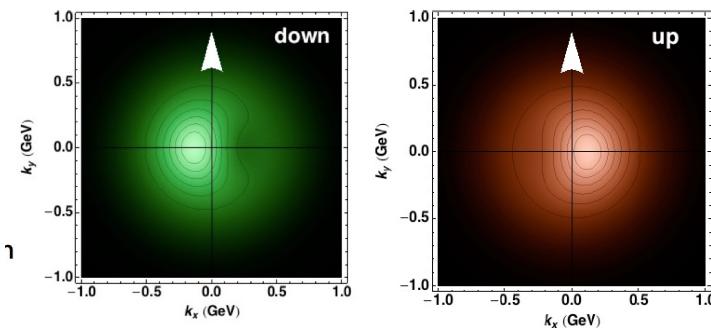
$m_W = 80370 \pm 7 \text{ (stat.) MeV}$
 $\pm 11 \text{ (exp. syst.)}$
 $\pm 14 \text{ (mod. syst.)}$
+9 / -6 (TMDs)

ATLAS++ [arXiv:1701.07240]



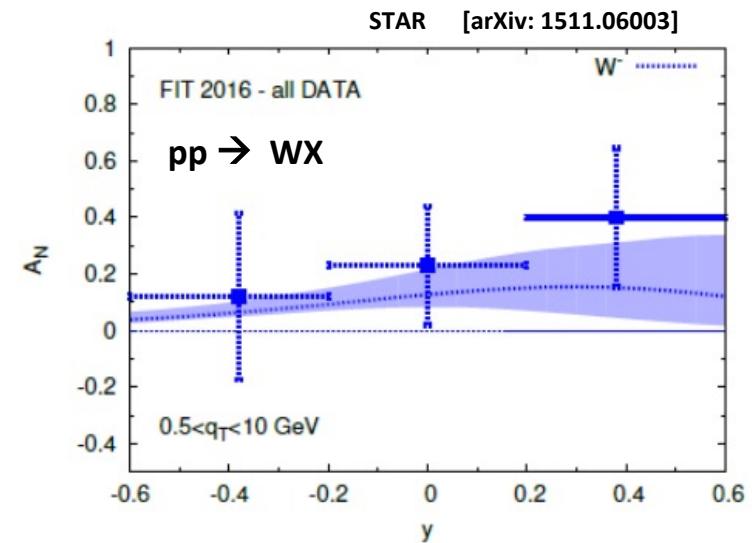
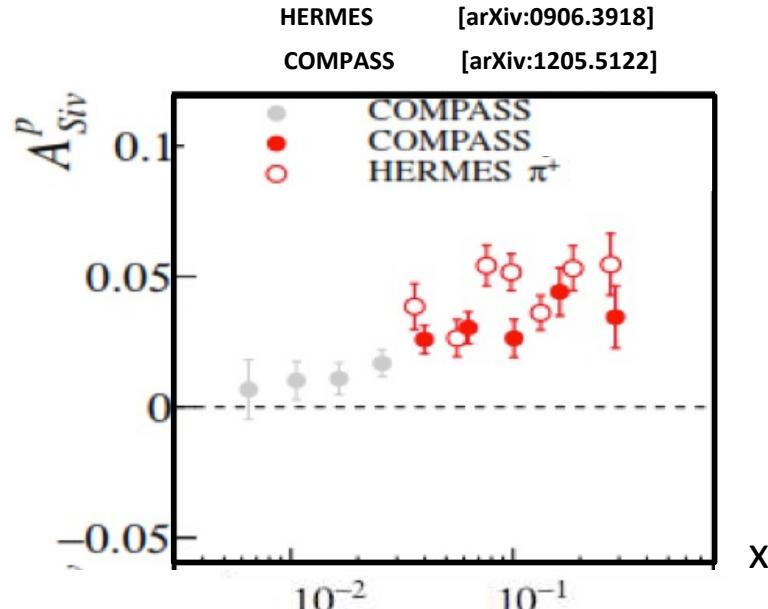
Spin-Orbit Effect: Sivers

$$\sigma_{UT}^{\sin(\phi - \phi_S)} \propto f_{1T}^\perp \otimes D_1$$

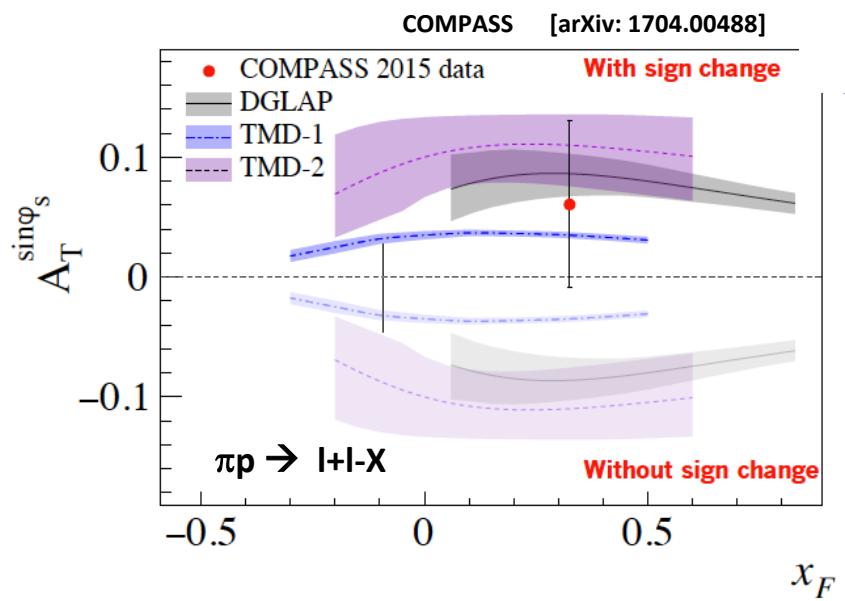


$\times (-1)$

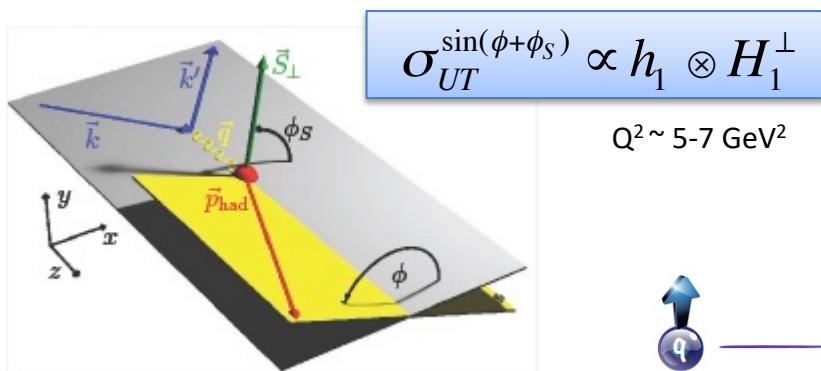
Sivers from polarized SIDIS



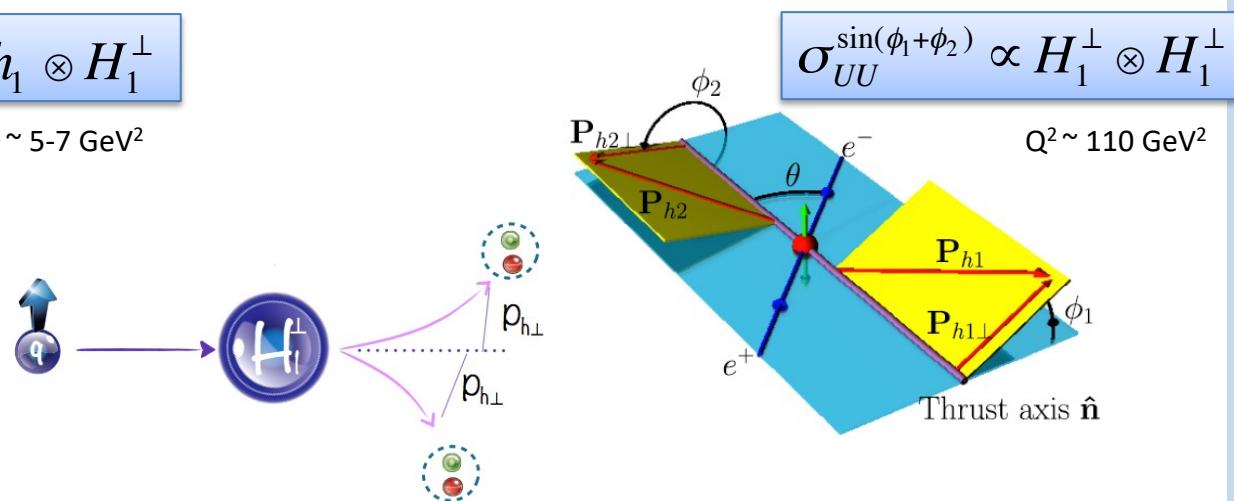
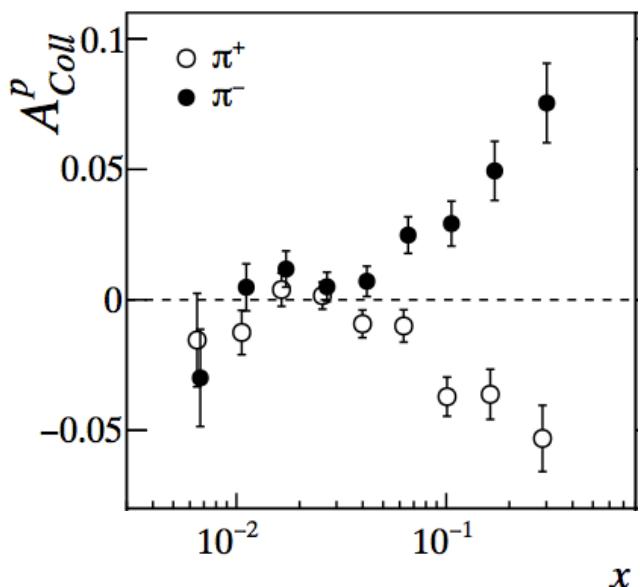
Sivers from hadronic reactions



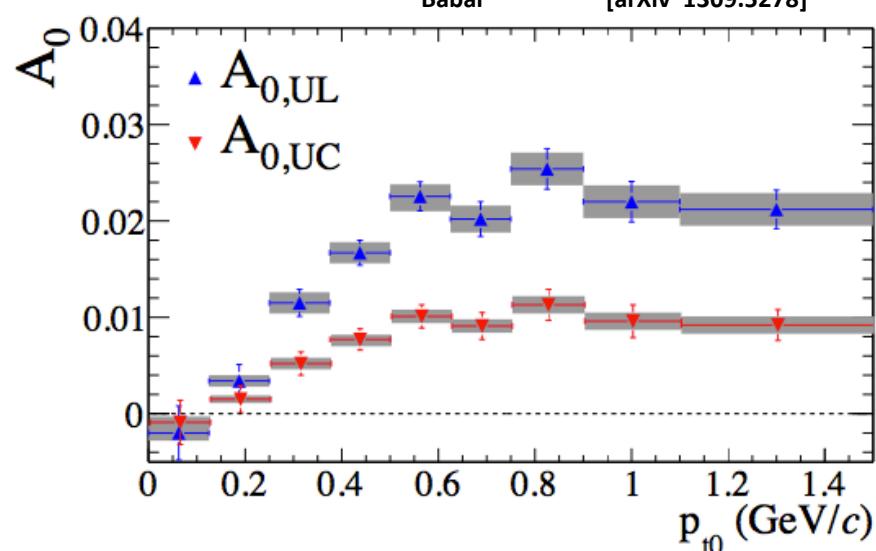
Spin-Orbit Effect: Collins



HERMES [arXiv 0408013]
 HERMES [arXiv 0906.3918]
 COMPASS [arXiv 1005.5609]
 COMPASS [arXiv 1408.4405]

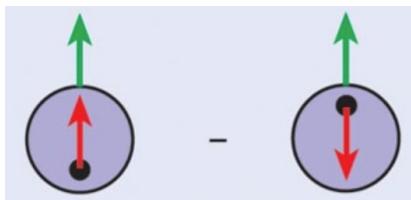
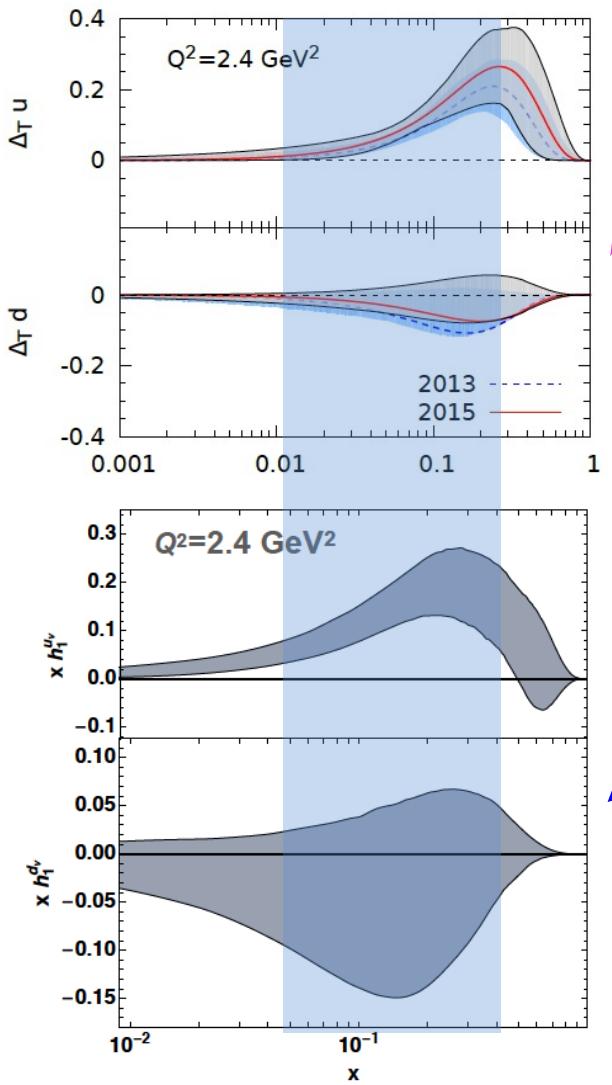


Belle [talk at DIS2014]
 BESIII [arXiv 1507.06824]
 Babar [arXiv 1309.5278]



Transversity and Tensor Charge

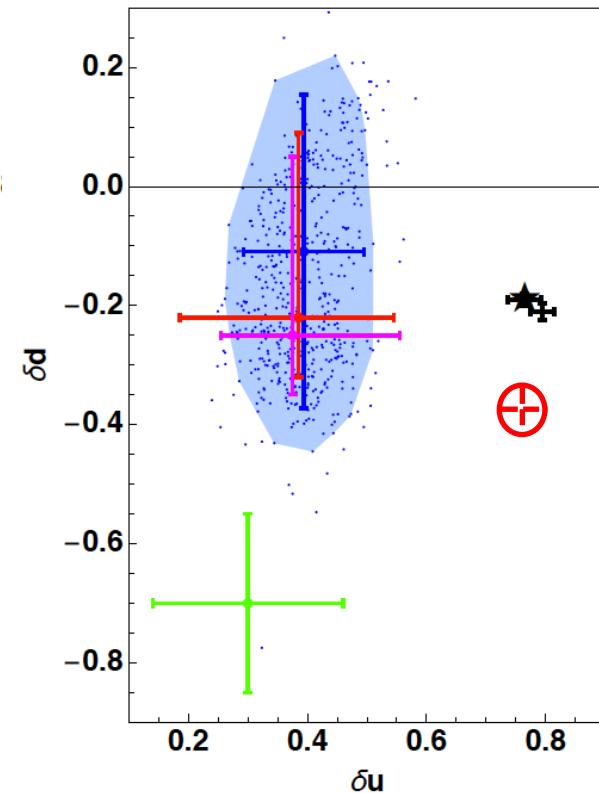
Distributions:



Charges:

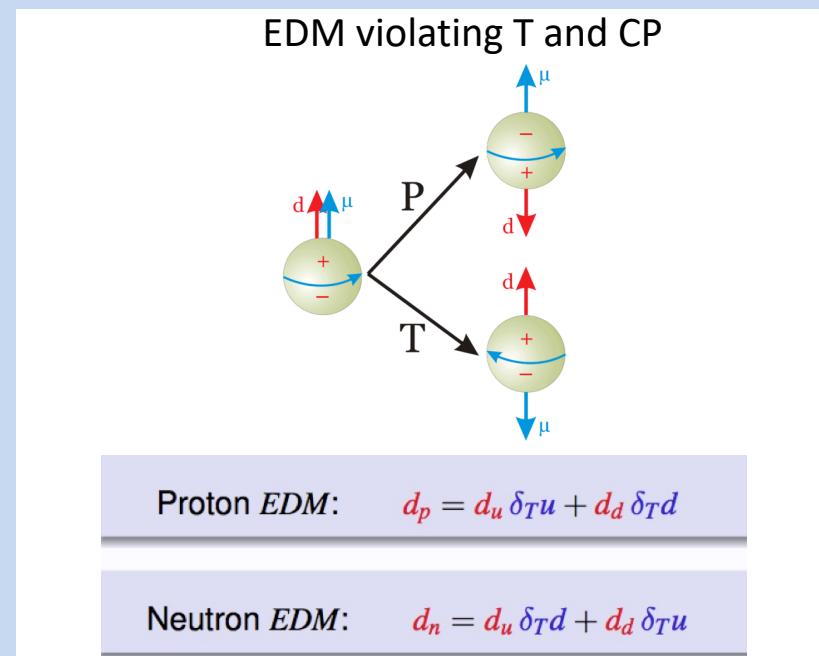
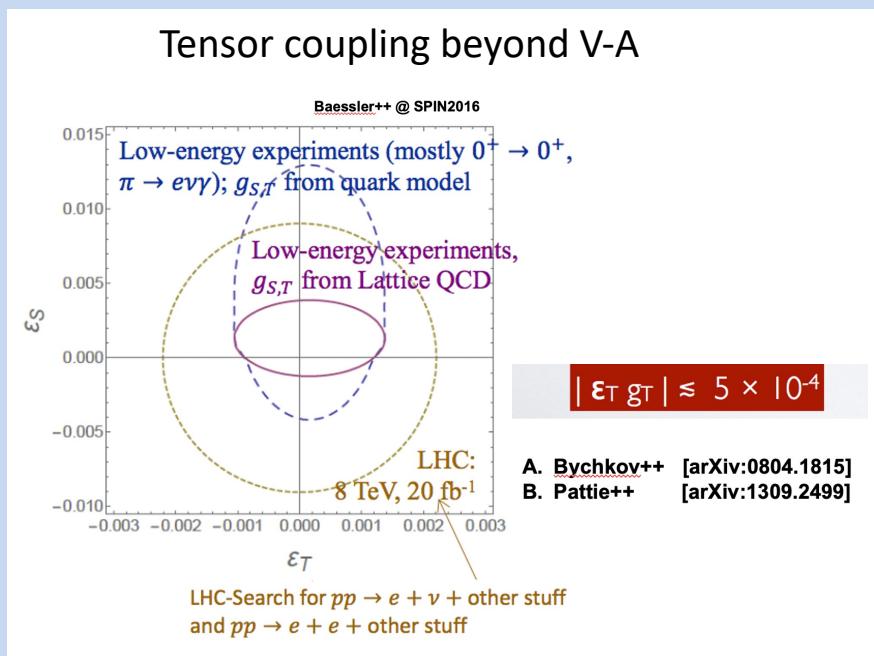
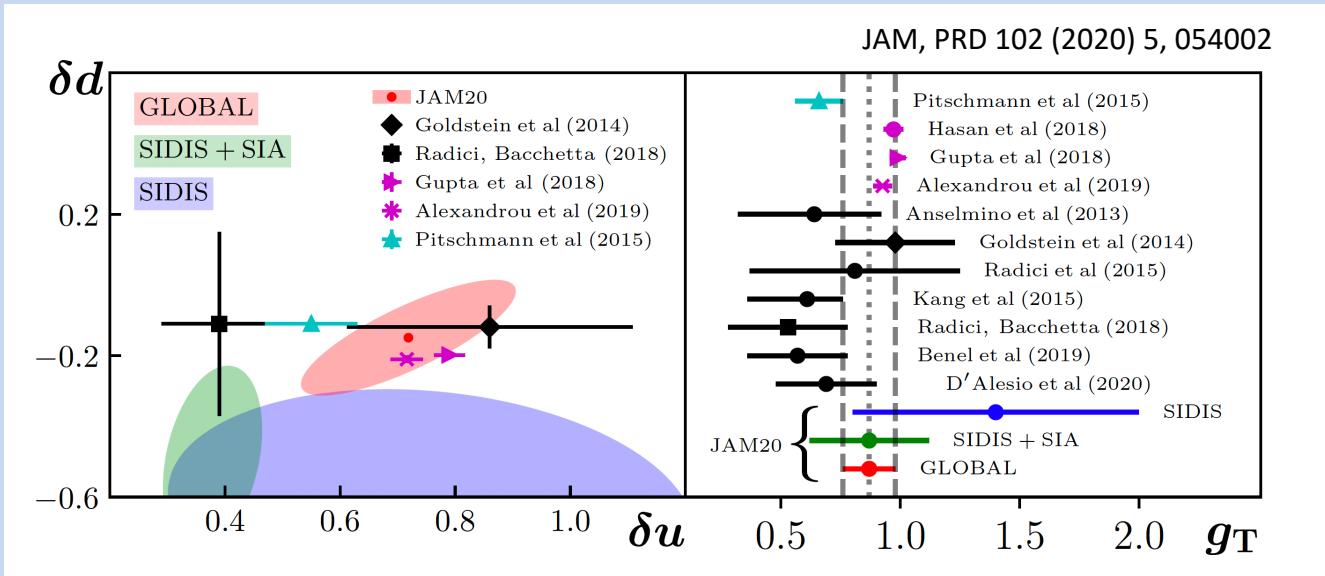
$$\delta q \equiv \int_0^1 dx [\Delta_T q(x) - \Delta_T \bar{q}(x)]$$

A. Bacchetta @ DIS219



- ⊕ Helicity
- ★ Alexandrou et al., arXiv:1703.08781
- Gupta et al., arXiv:1806.09006
- Anselmino et al., arXiv:1303.3822
- Kang et al., arXiv:1505.05589
- Lin et al., arXiv:1710.09858
- Radici et al., arXiv:1802.05212

Tensor Charge and BSM Physics



SIDIS Landscape

To solve the TMD puzzle an interplay of luminosity and energy is required

SIDIS Cross-Section

$$\frac{d\sigma}{dx dy d\phi_S dz d\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{x y Q^2} \frac{y^2}{2(1-\varepsilon)} \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} \right.$$

$$+ \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} + S_L \left[\sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_h F_{UL}^{\sin \phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{\sin 2\phi_h} \right]$$

$$+ S_L \lambda_e \left[\sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_h F_{LL}^{\cos \phi_h} \right]$$

$$+ S_T \left[\sin(\phi_h - \phi_S) (F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)}) + \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} \right.$$

$$+ \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} + \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_S F_{UT}^{\sin \phi_S}$$

$$+ \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \left. \right] + S_T \lambda_e \left[\sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} \right.$$

$$+ \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_S F_{LT}^{\cos \phi_S} + \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \left. \right\}$$

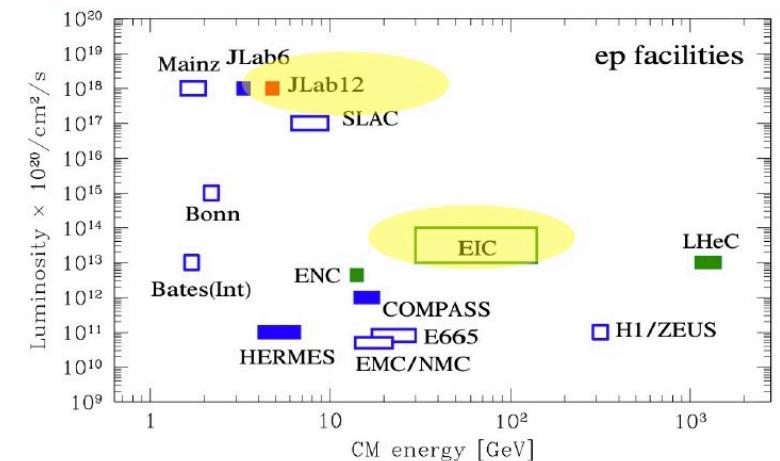
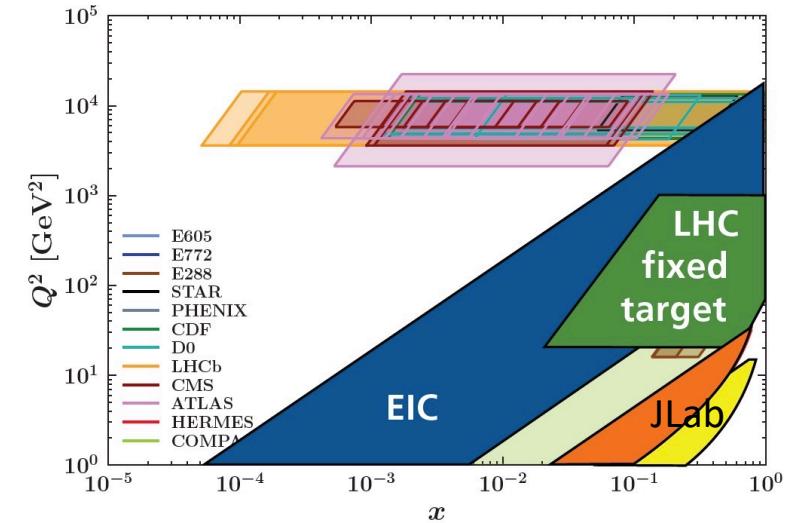
TMD Factorization

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

TMD Evolution

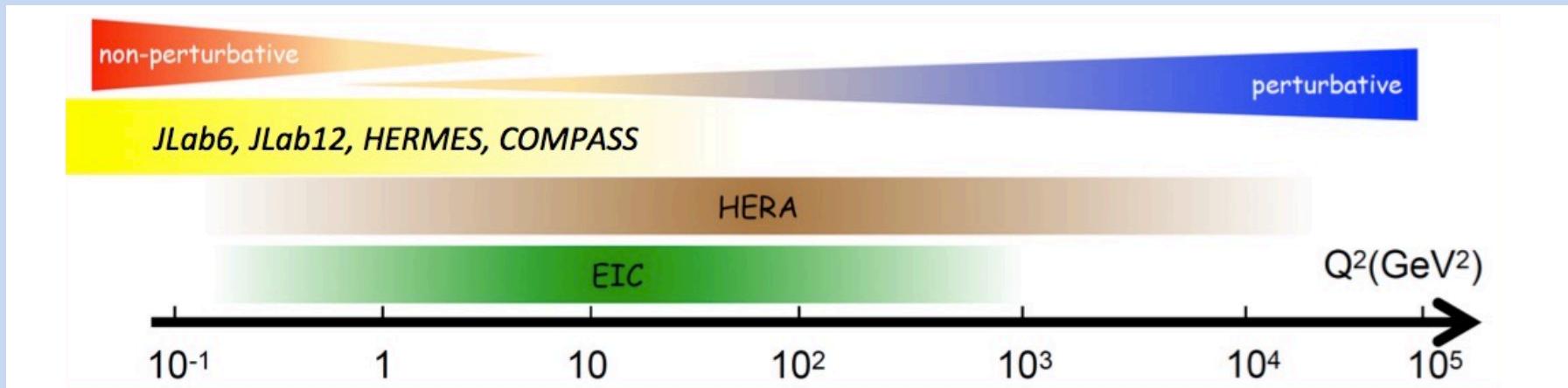
Evolution kernel (with CS non-perturbative kernel)

Subleading
1/Q suppressed

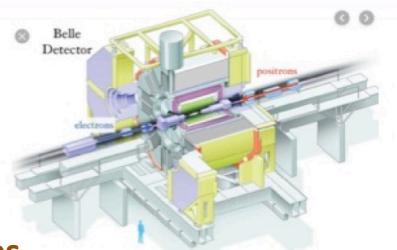


TMD Baseline

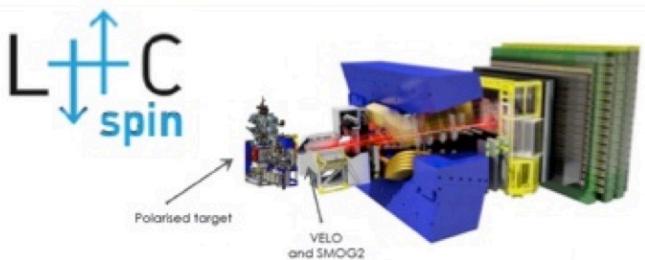
Energy range matching perturbative and non-perturbative regimes



Unprecedented fragmentation information

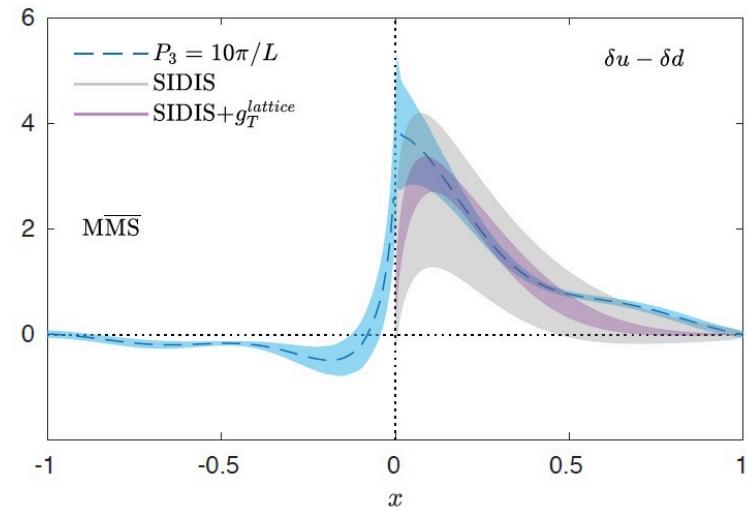


Bridge to hadron probes



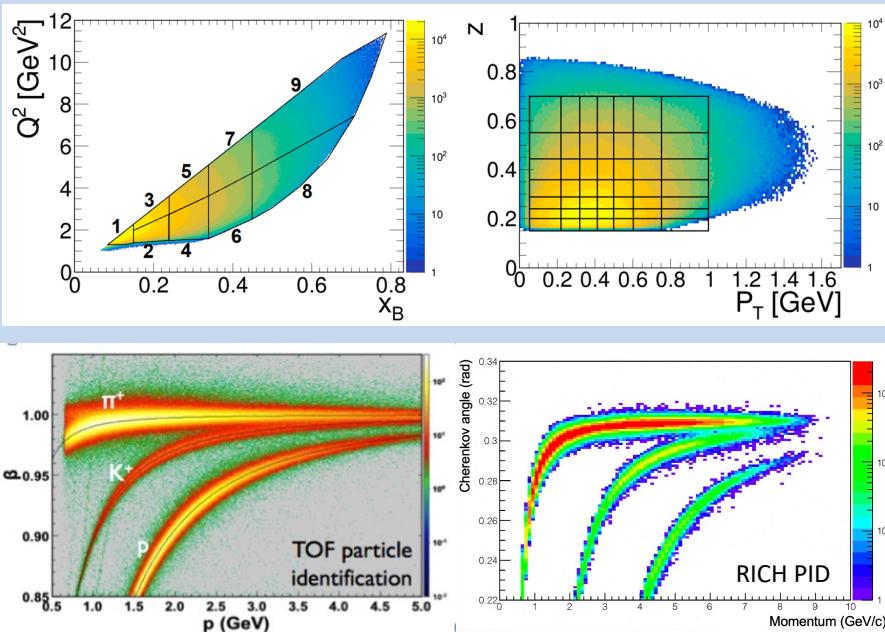
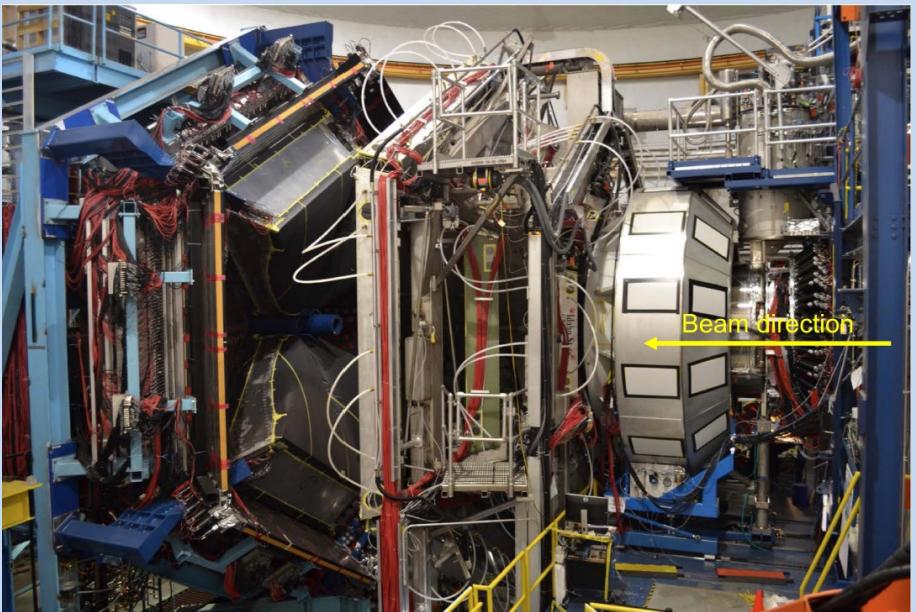
New lattice achievements

C. Alexandrou++ [arXiv: 1902.00857]



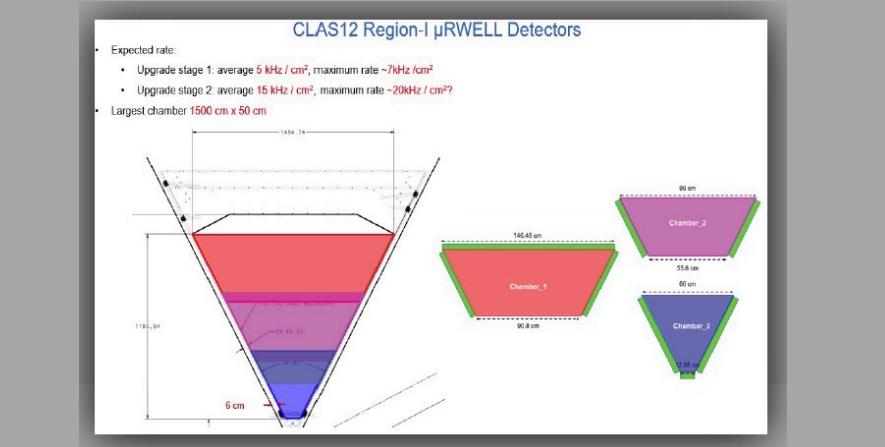
CLAS12 @ JLab

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	Longitudinal	10.6 GeV

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



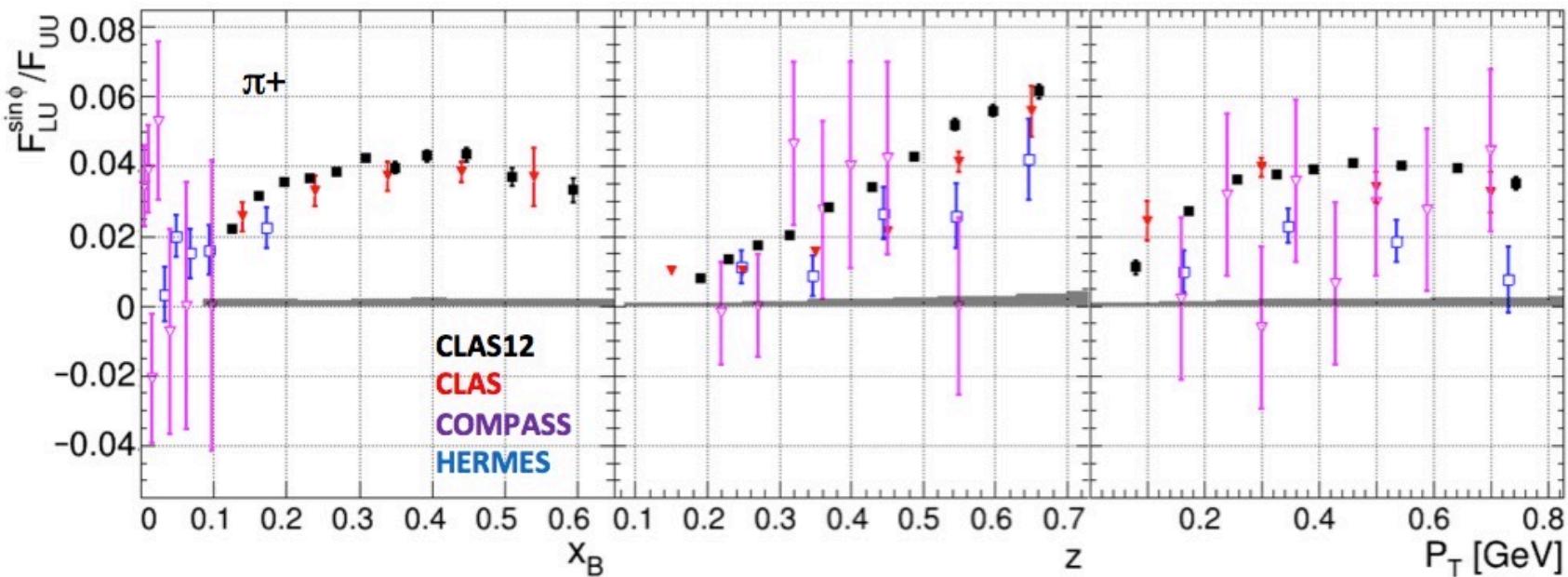
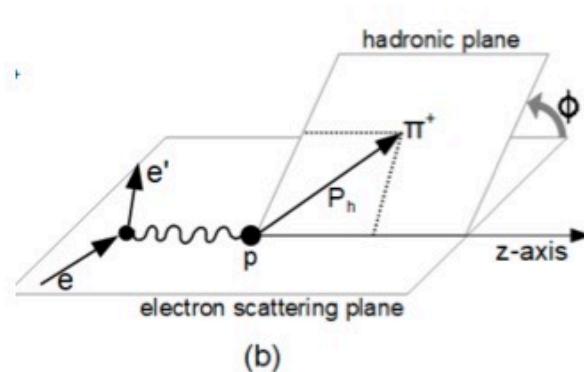
Beam Spin Asymmetry @ CLAS12

CLAS12 proton data (RGA)

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

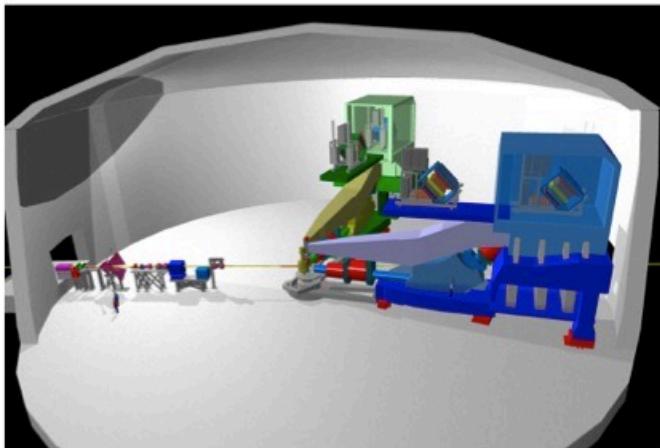
$$F_{LU}^{\sin \phi} = \frac{2M}{Q} \mathcal{C} \left[-\frac{\hat{h} \cdot k_T}{M_h} \left(x_B e H_1^\perp + \frac{M_h}{M} f_1 \frac{\tilde{G}^\perp}{z} \right) + \frac{\hat{h} \cdot P_T}{M} \left(x_B g^\perp D_1 + \frac{M_h}{M} h_1^\perp \frac{\tilde{E}}{z} \right) \right]$$

86.9 \pm 2.6 %



Upcoming @ JLab

SBS: Spectrometer Pair



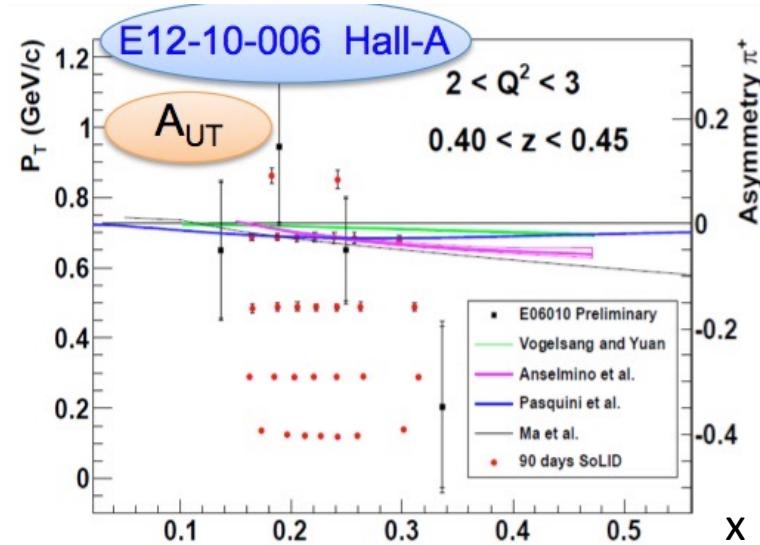
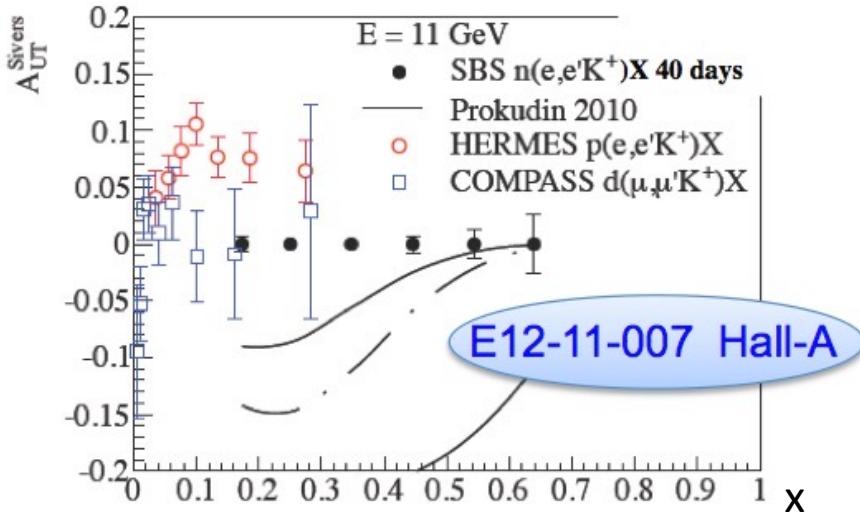
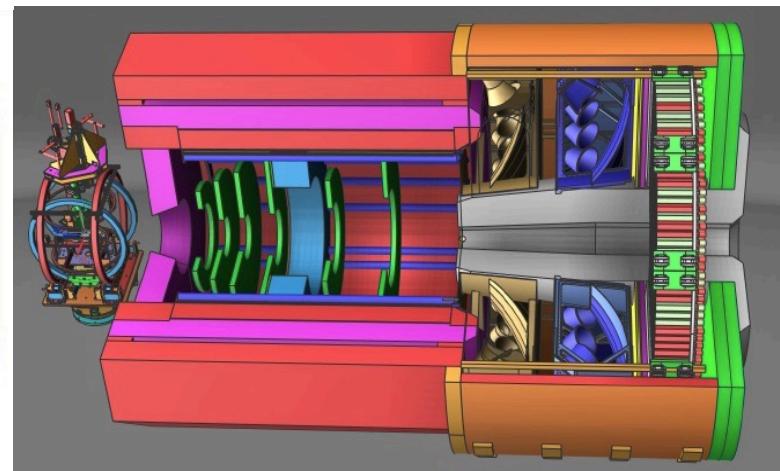
Hall-A:

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

^3He targets

Wide coverage

SOLID: Large Acceptance Detector



+ precision higher-twist and low pT physics in Hall-C

Multiplicities @ CLAS12

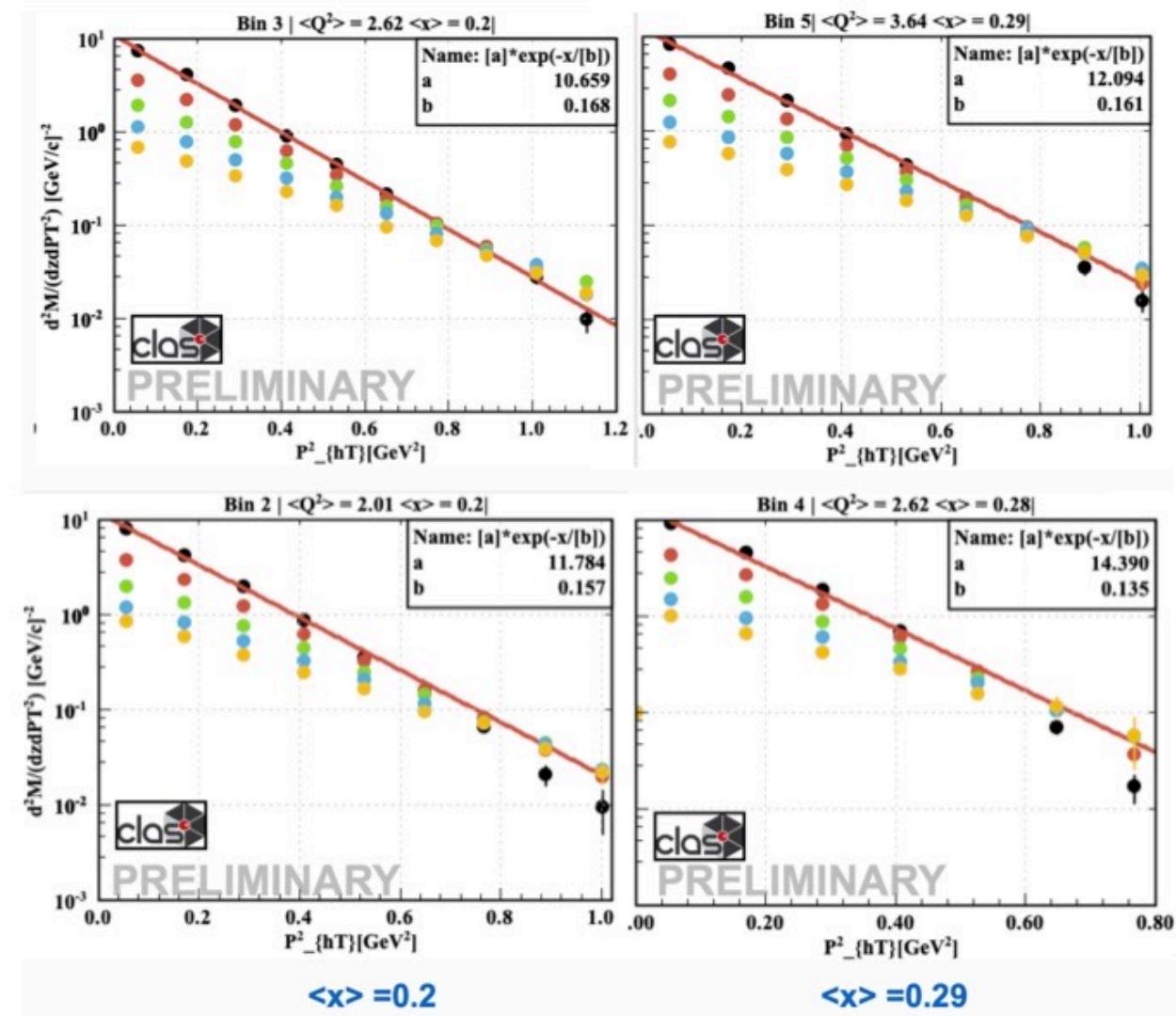
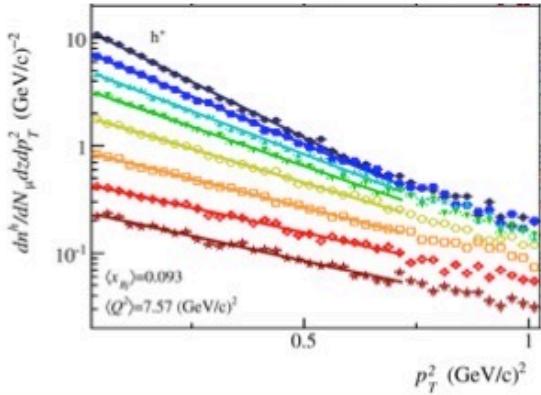
Transverse momentum dependence and phase space

$e\mu \rightarrow e\pi + X$

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

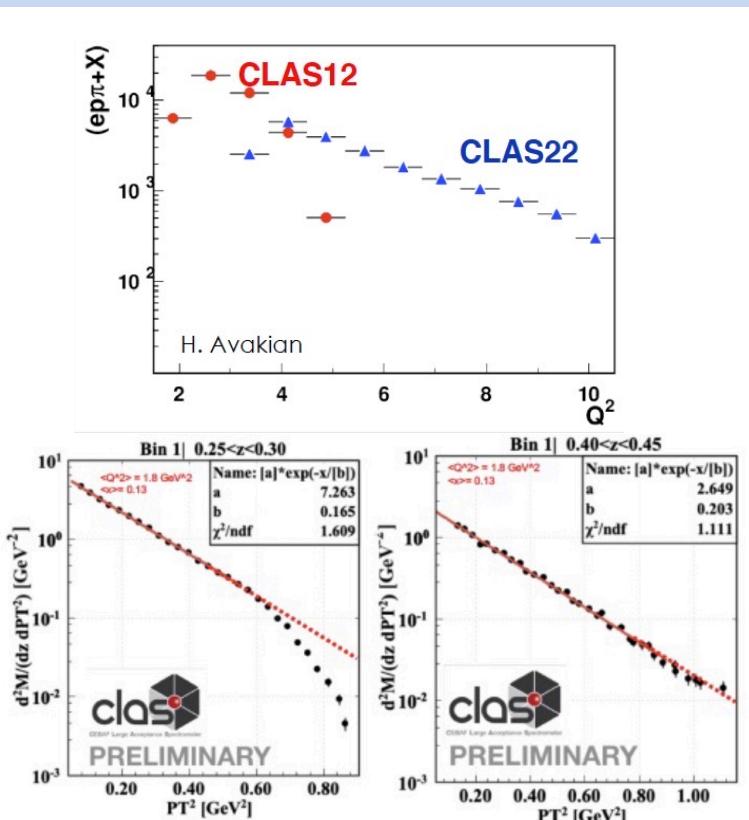


Extend the reach in Q^2 and p_T to exploit an unique facility at the intensity frontier

Energy increase to 20++ GeV

SOLID and CLAS12+

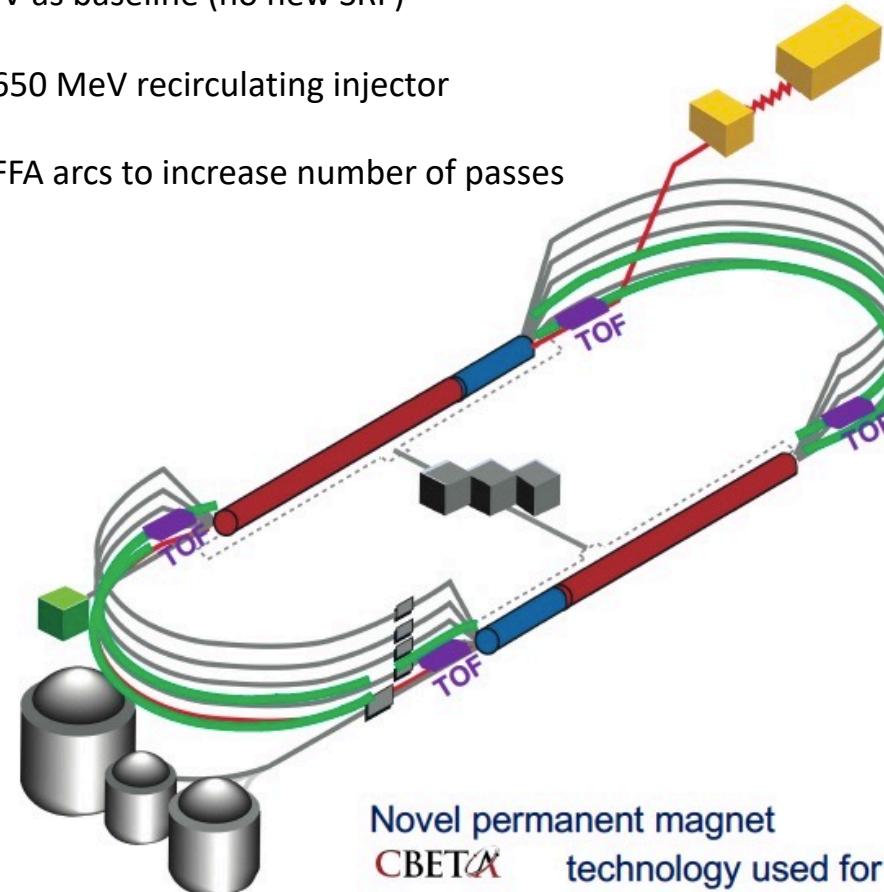
Positron source



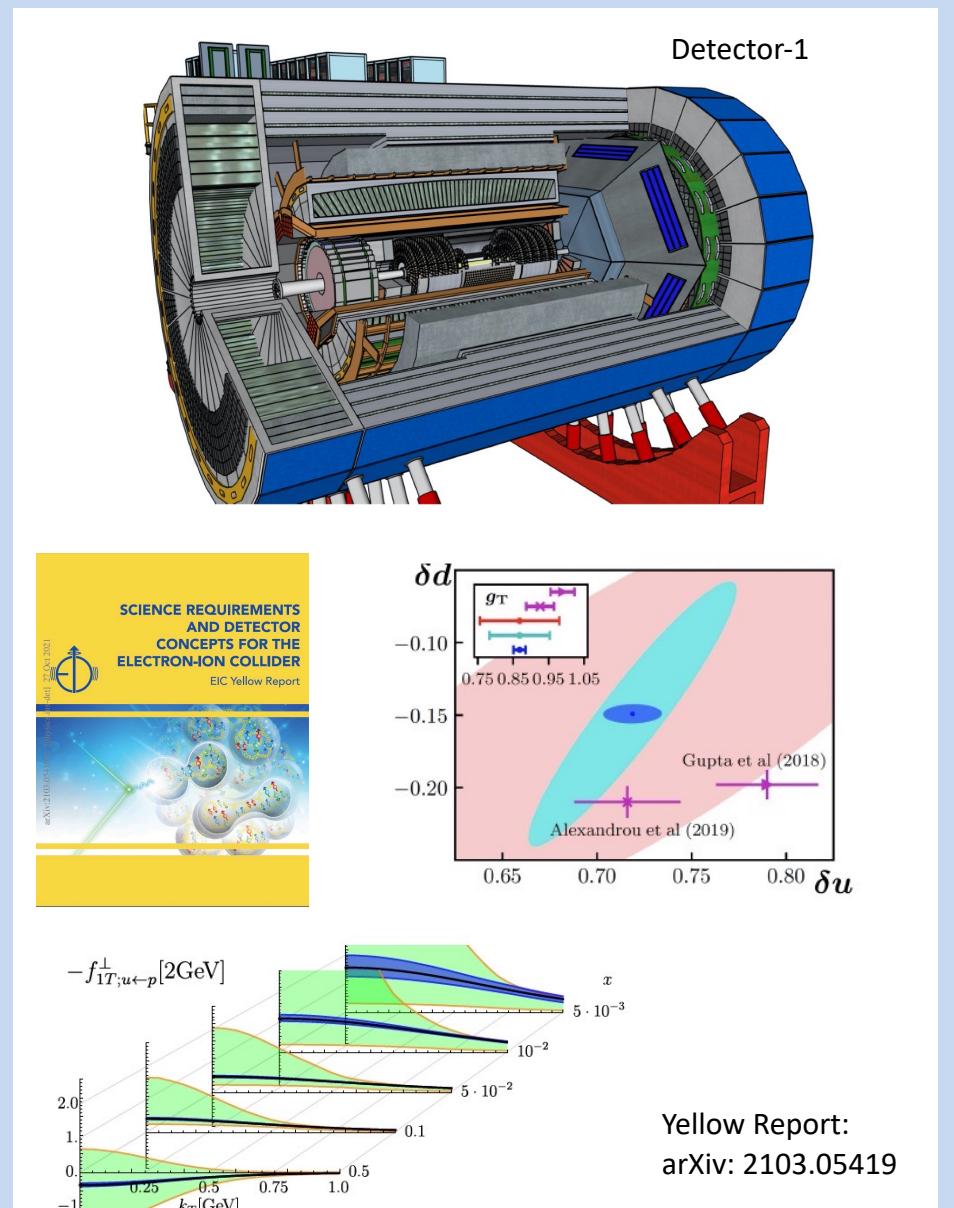
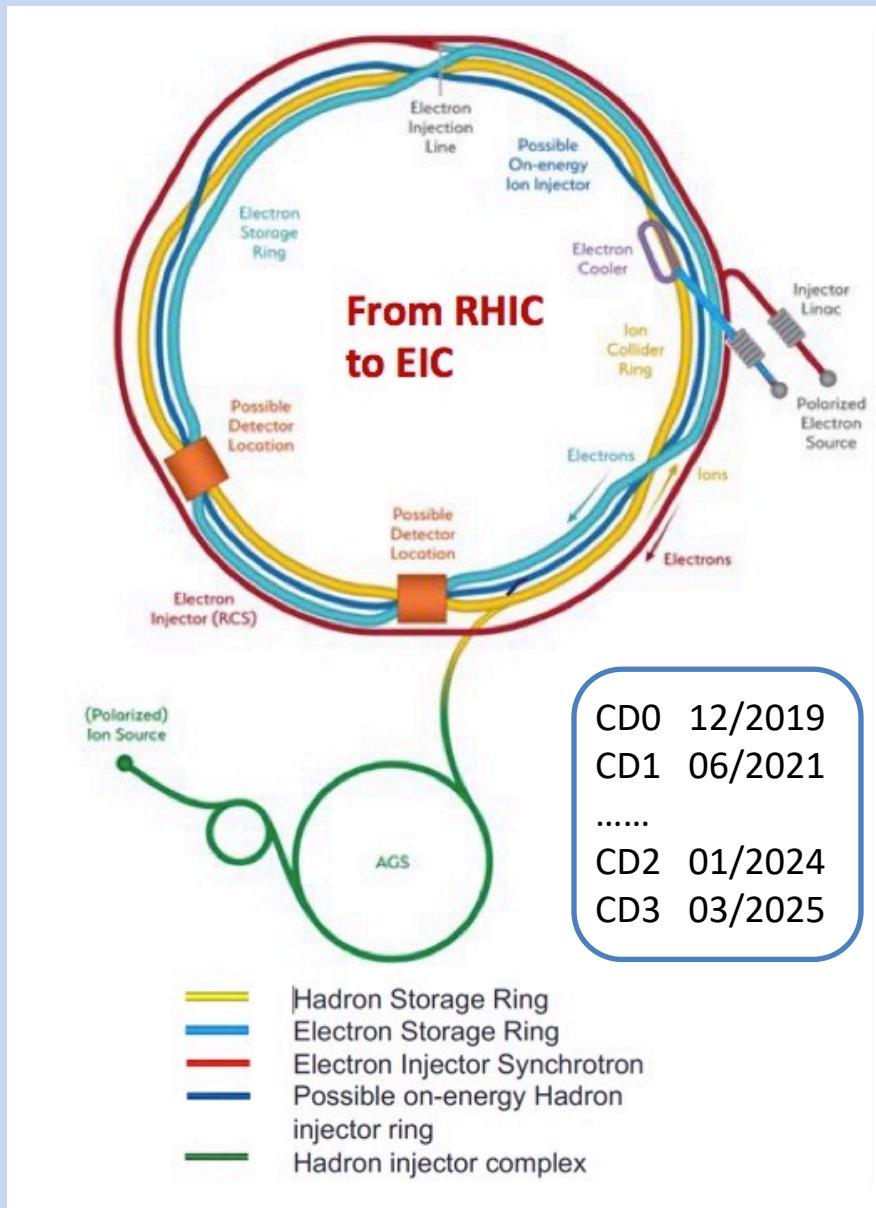
12 GeV as baseline (no new SRF)

New 650 MeV recirculating injector

New FFA arcs to increase number of passes

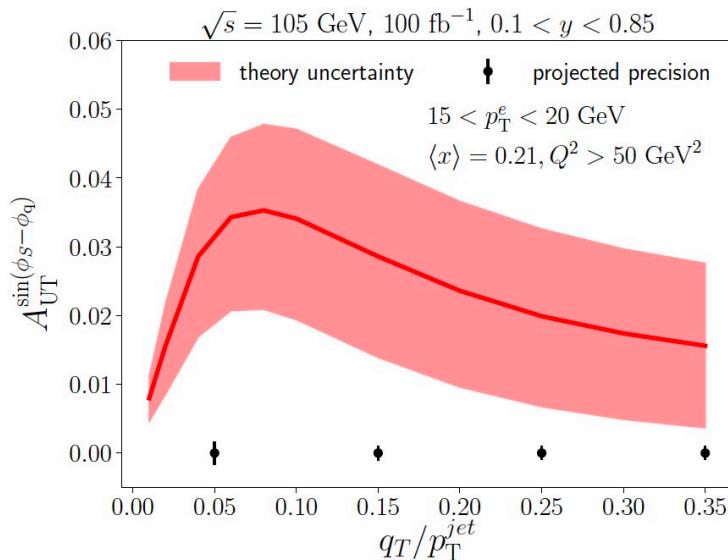


Electron-Ion Collider

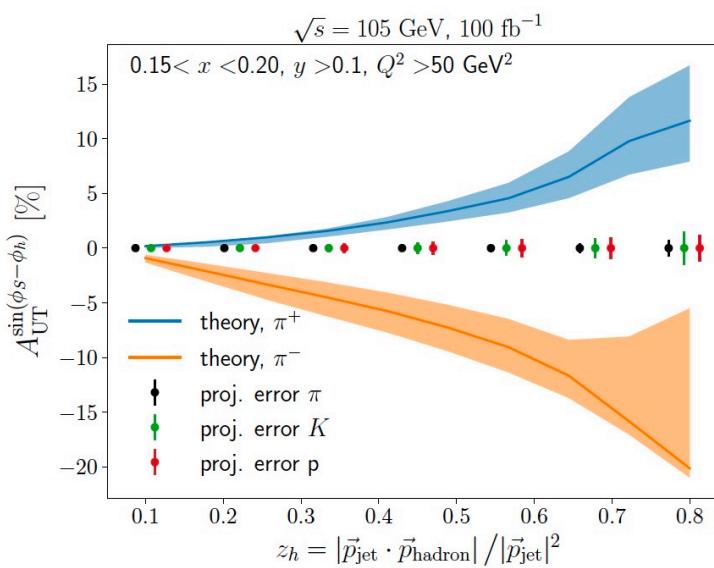


TMDs @ High Energy

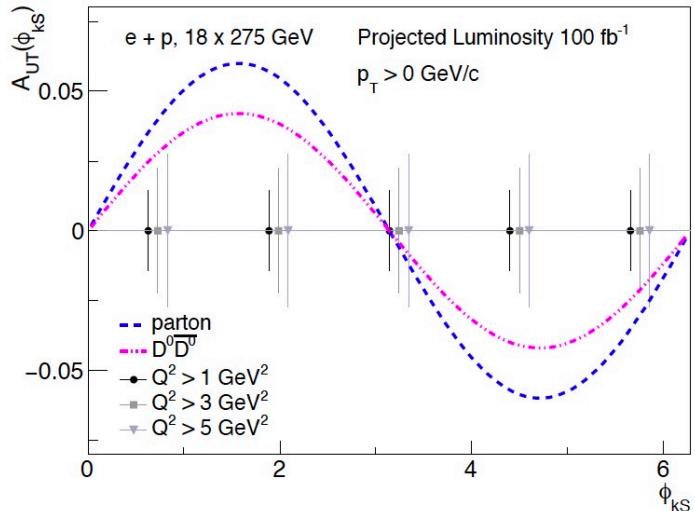
Jets Sivers



Jets Collins

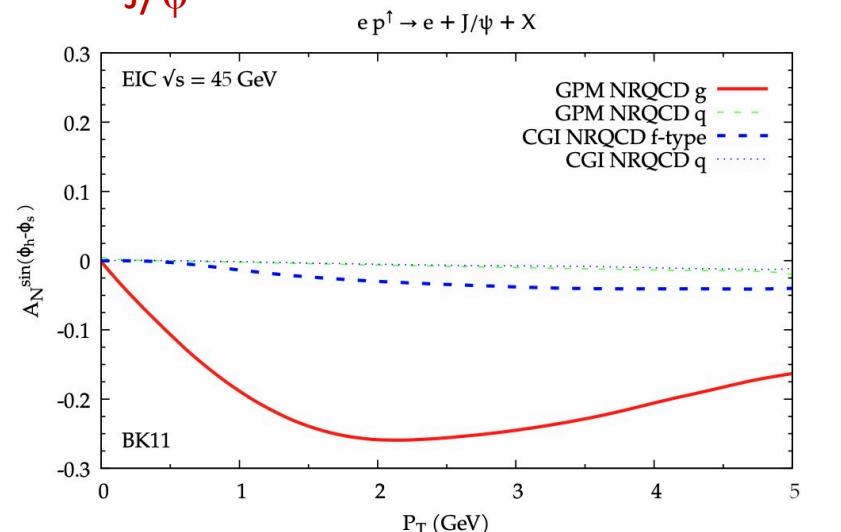


D⁰



Gluon TMDs

J/ψ



SIDIS Cross-Section

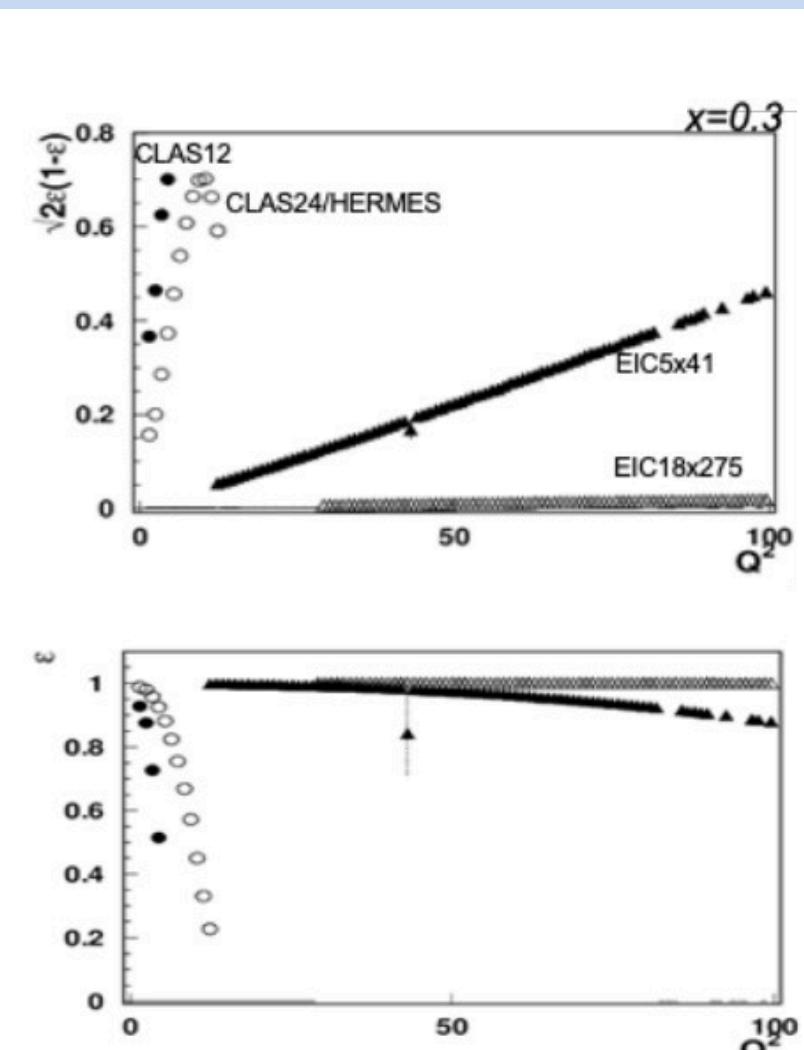
$$\begin{aligned}
 & \frac{d\sigma}{dx dy d\phi_S dz d\phi_h dP_{h\perp}^2} \\
 &= \frac{\alpha^2}{x y Q^2} \frac{y^2}{2(1-\varepsilon)} \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} \right.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

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

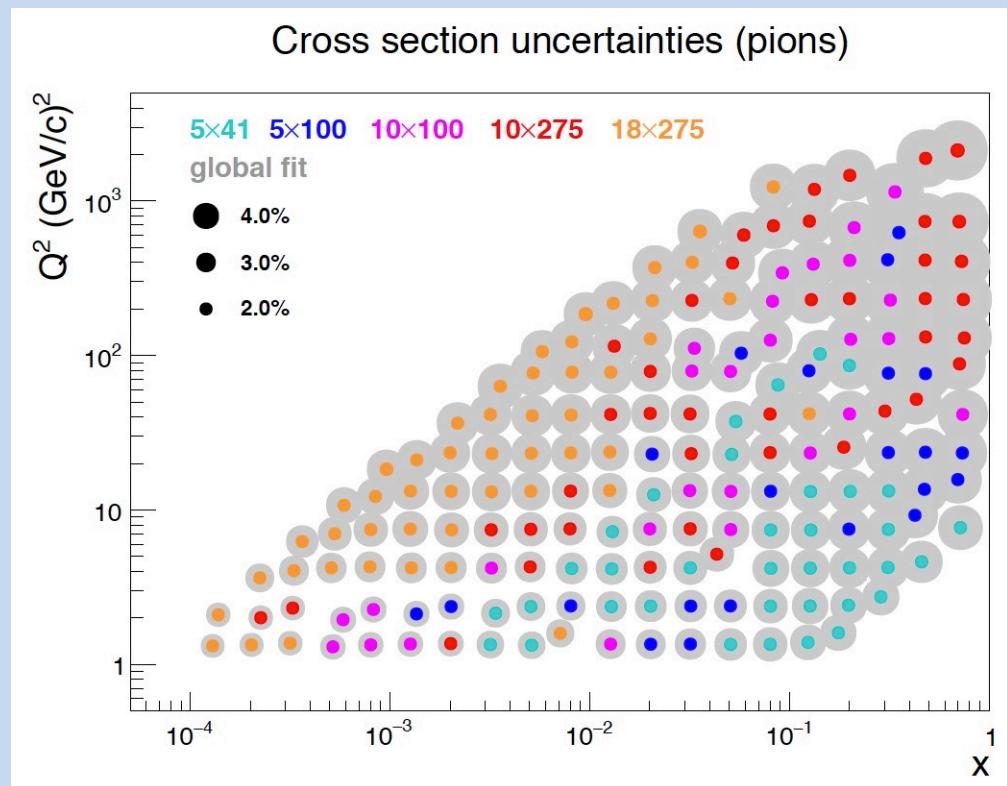
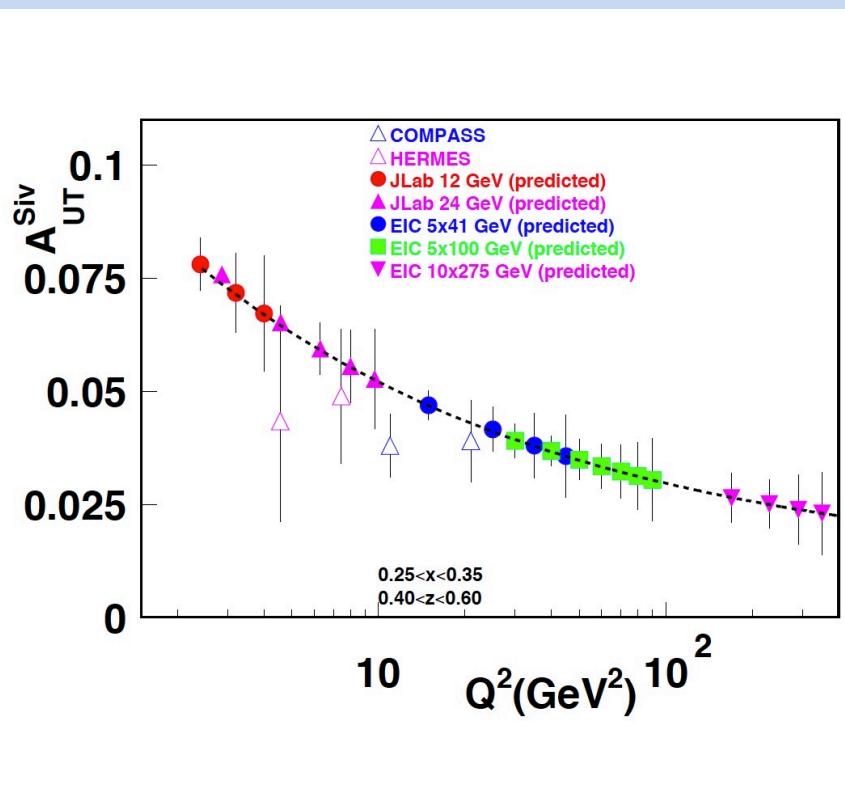
Evolution kernel (with CS non-perturbative kernel)



H. Avakian at Transversity 2022

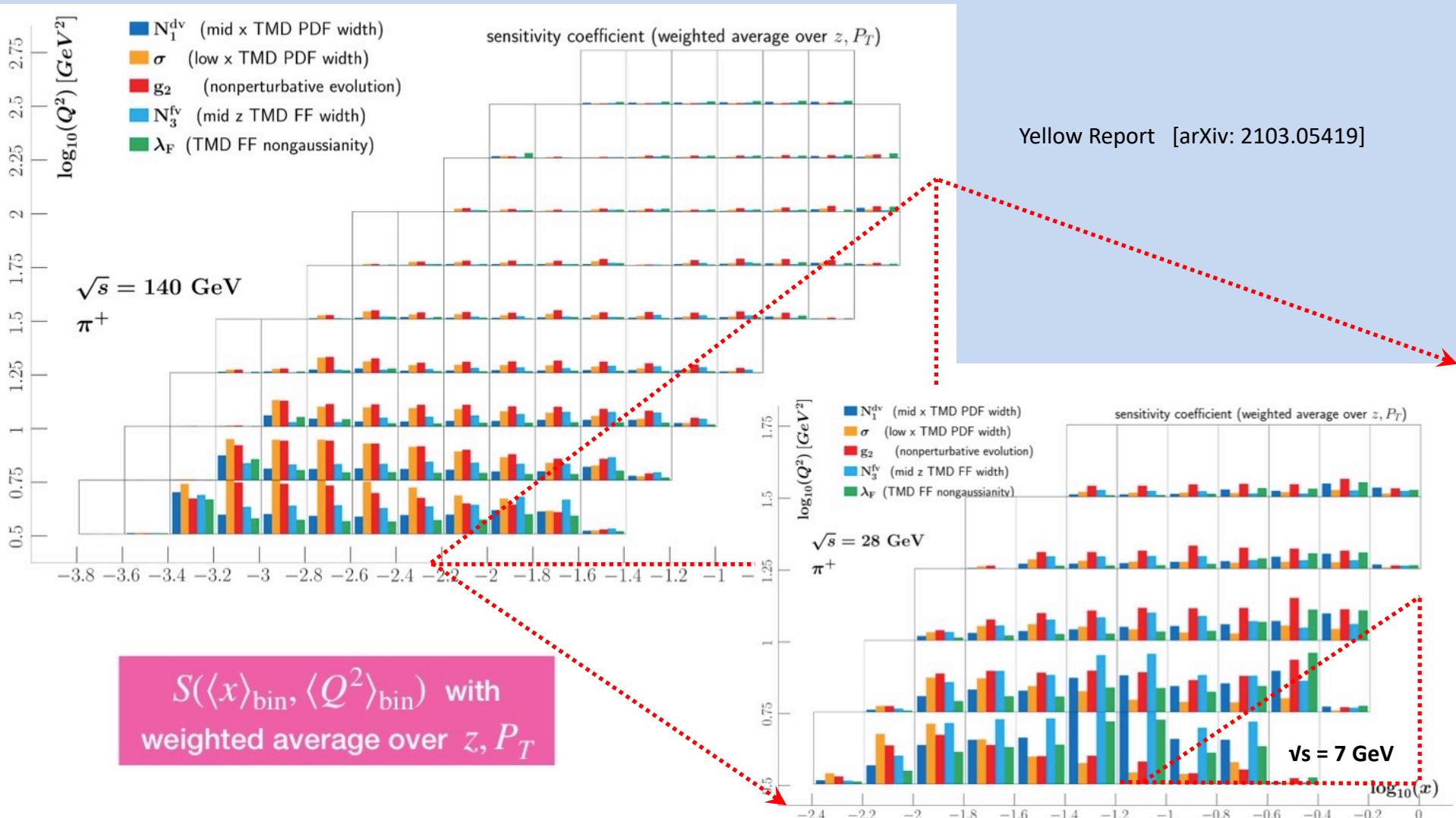
The Q^2 Game

- Wide leverage (at given x) to:
- isolate higher-twists ($1/Q$ suppressed terms)
 - probe Q^2 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



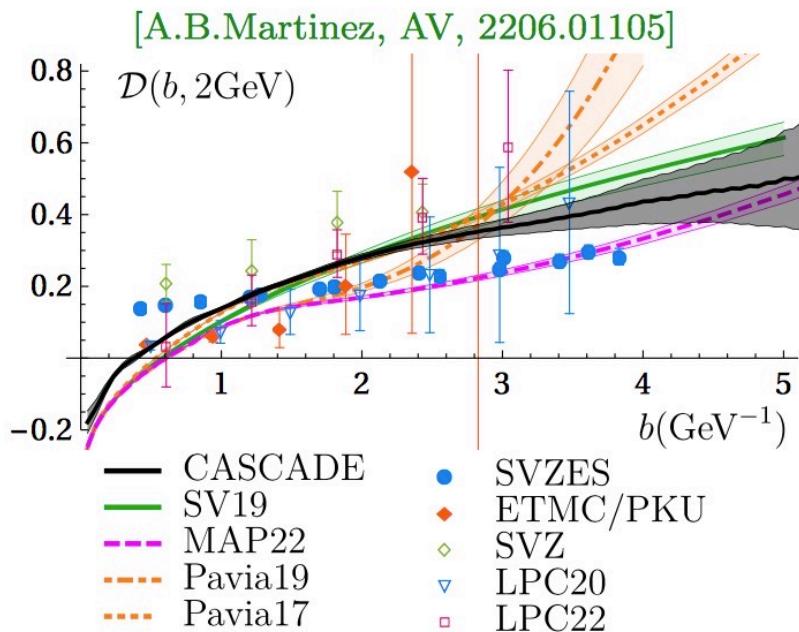
TMD Evolution

The missing non-perturbative universal piece can be extracted from data

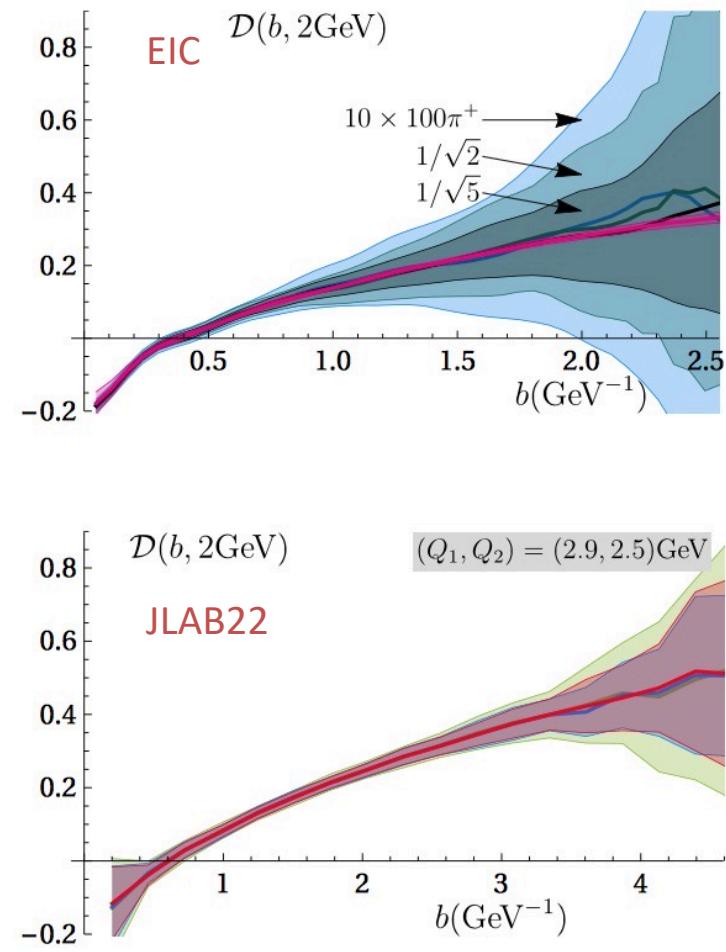
With b as Fourier conjugate of P_T/z

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

Collins-Soper non-perturbative evolution kernel



Complementarity in Q^2 and b coverage



A. Vladimirov @ APCTP22 workshop

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