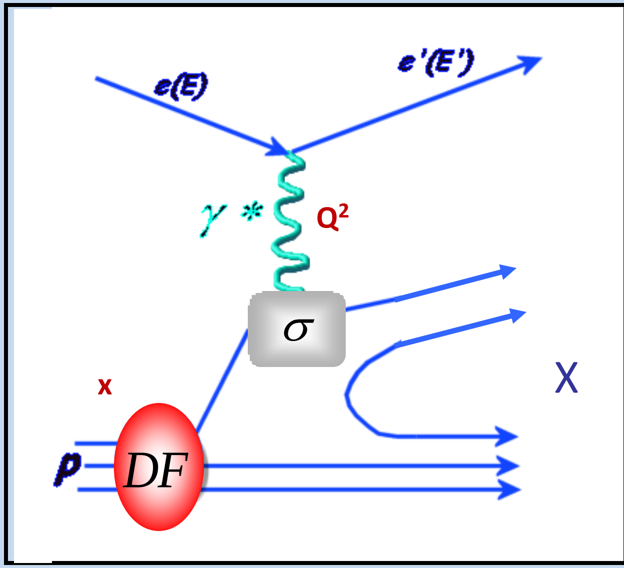
Hadron Structure from Deep-Inelastic Scattering Experiments

Marco Contalbrigo – INFN Ferrara

GGI School – Frontiers in Nuclear and Hadronic Physics - Firenze, 28 February 2025

Inclusive



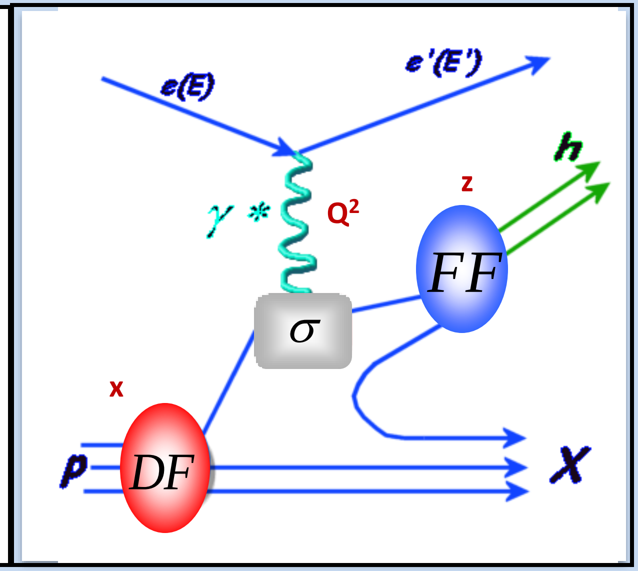
SFs (x,Q^2)

Structure functions
(unpolarized, helicity)

Sum over quark charges

$$d^2\sigma \propto F_2 \left(= \sum_q e_q^2 q(x)\right)$$

Semi-inclusive



DFs (x,Q^2) + FF(z,Q^2)

Parton distributions + fragmentation

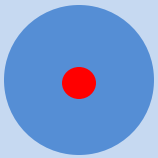
$$D_u^{\pi+}(z) > D_u^{\pi-}(z)$$

Flavor sensitivity

$$d^3\sigma^h \propto \sum_q e_q^2 q(x) D_q^h(z)$$

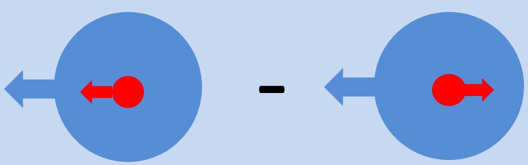
Parton Content

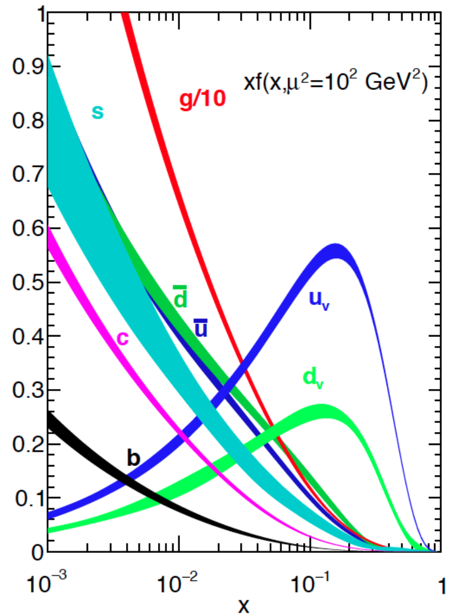
Unpolarized moments

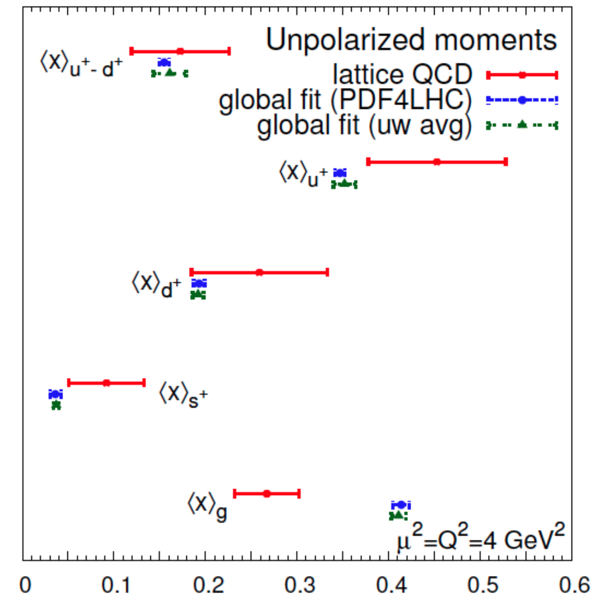


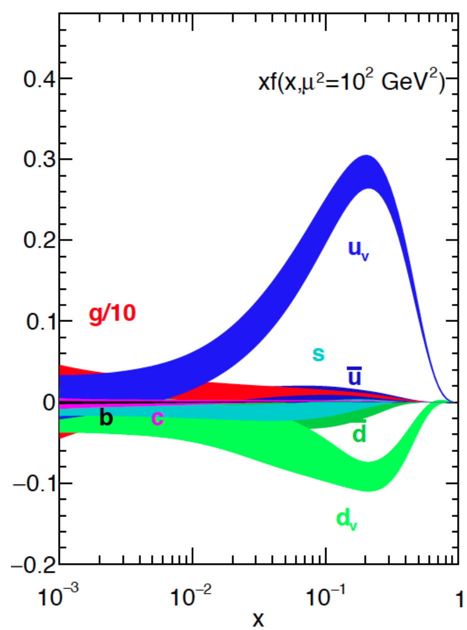
H-W Lin++ [1711.07916]

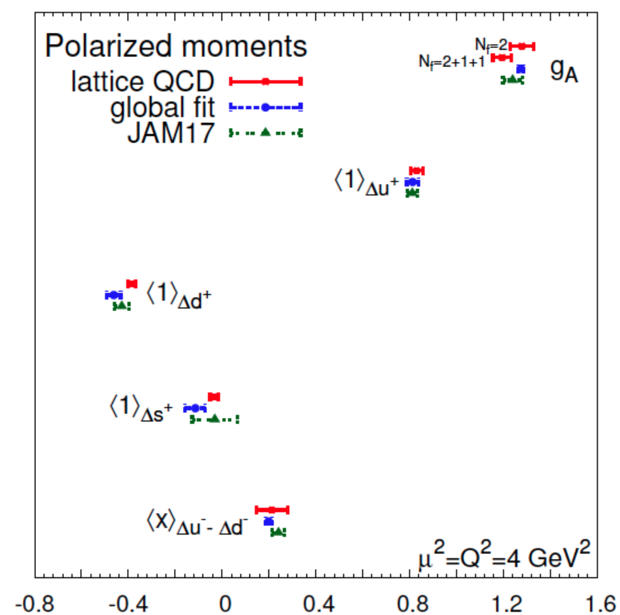
Polarized (helicity) moments











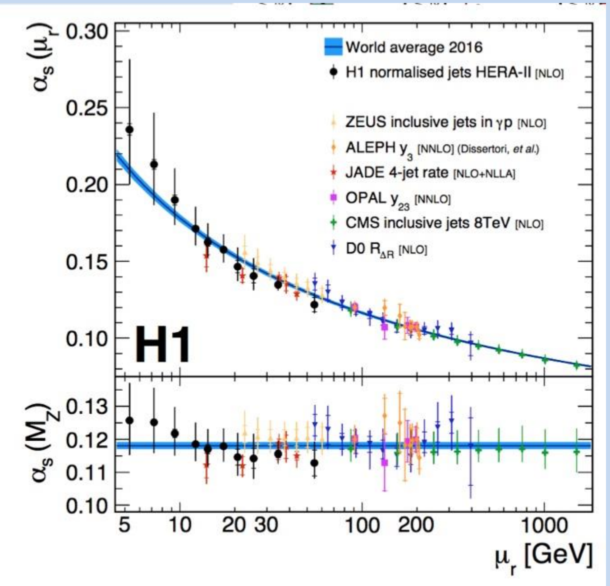
High-Energy e-p

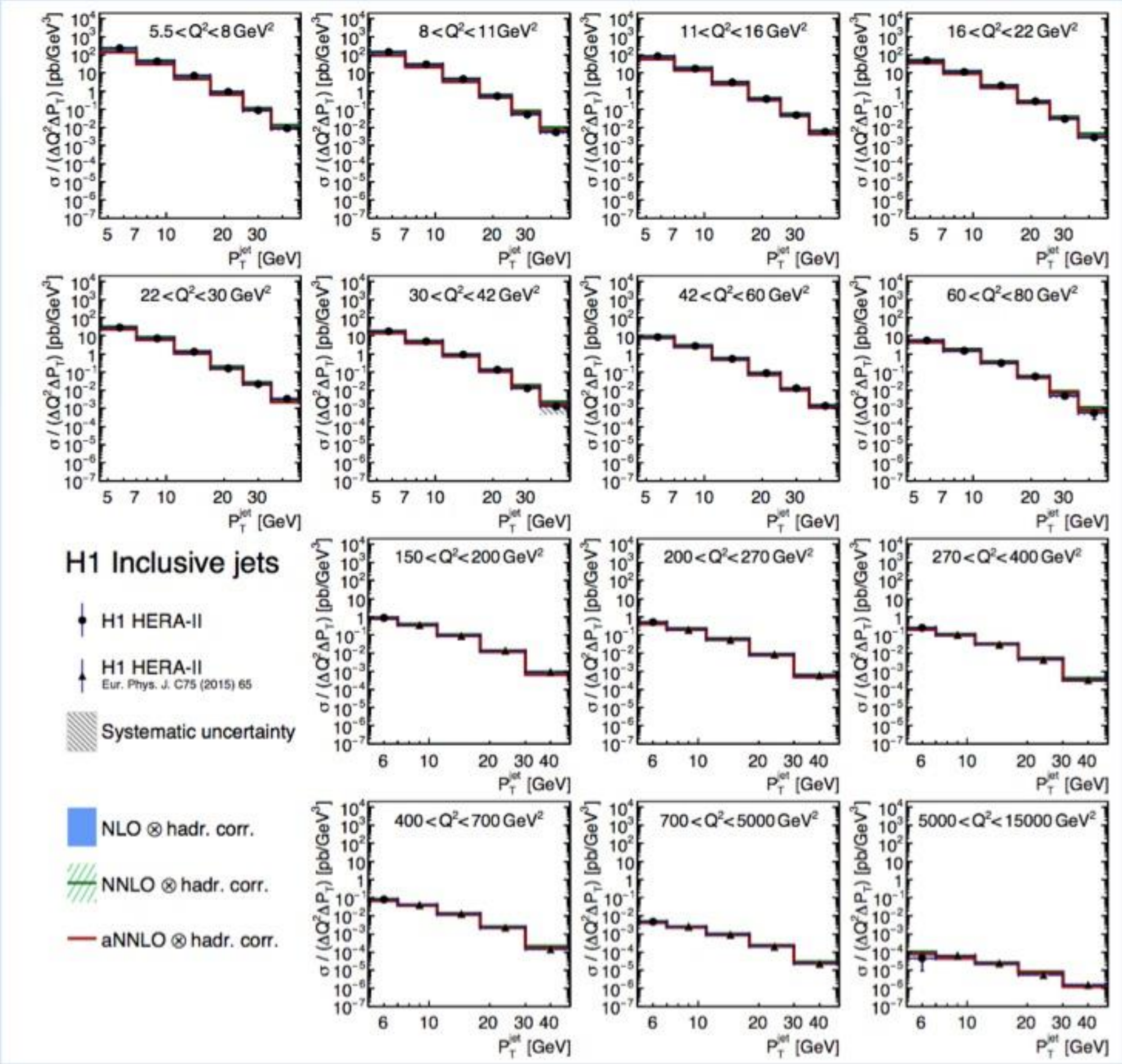
Good perturbative description
(hard gluon emission)

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

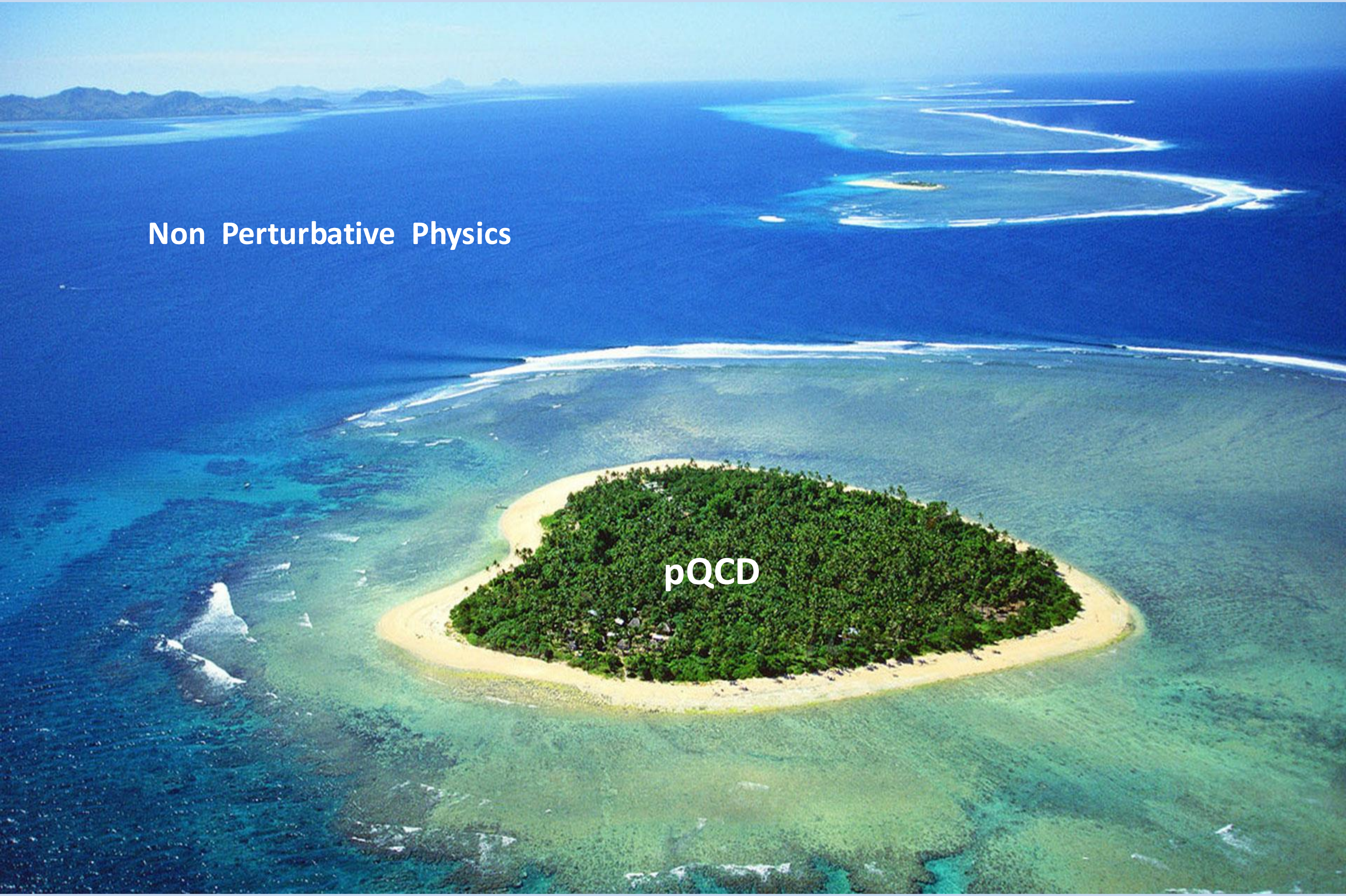
Part in a $P_T \ll Q$ TMD regime

H1 [arXiv: 1611.03421]





The QCD View

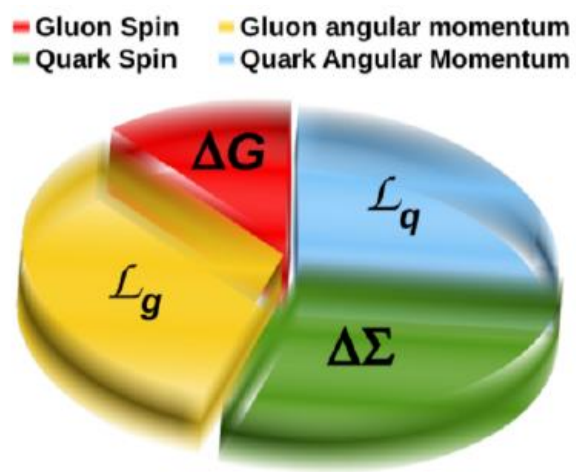


QCD vs pQCD

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

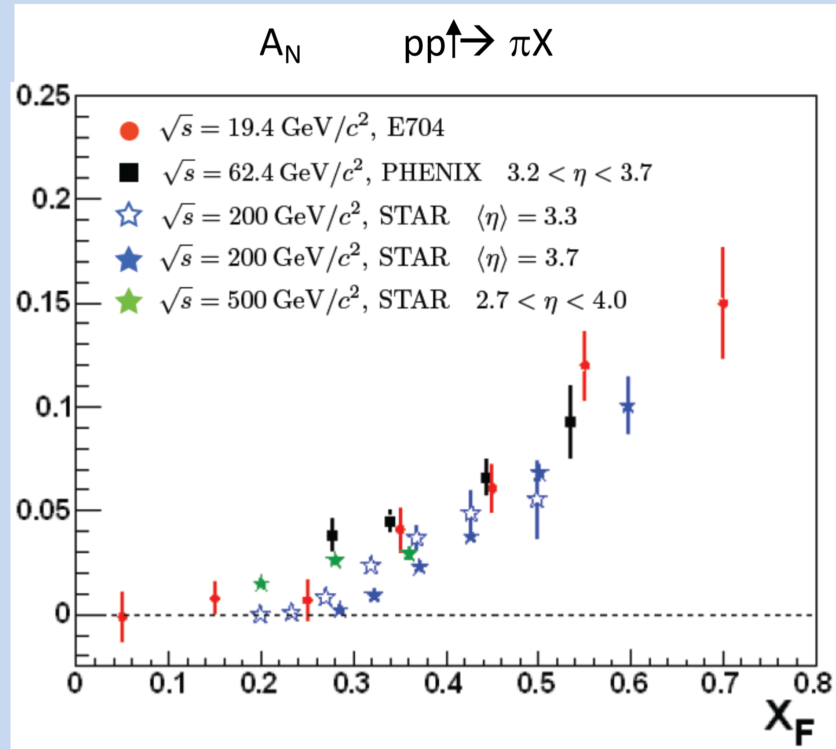
Proton Spin Budget



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

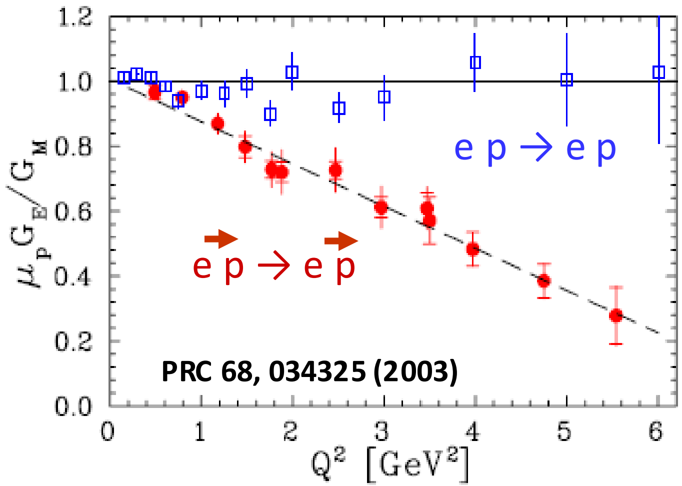
?

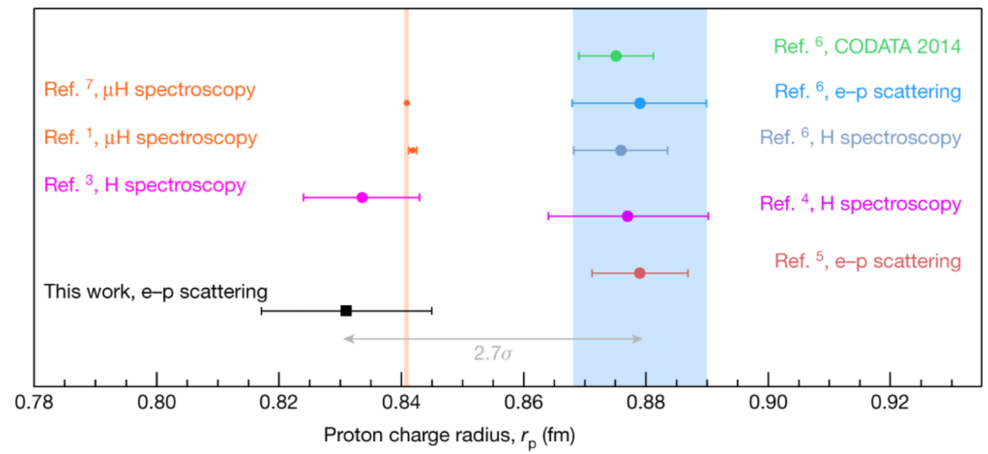
Single Spin Asymmetries



Still Surprising Proton

Do we control the proton form factor and radius ?

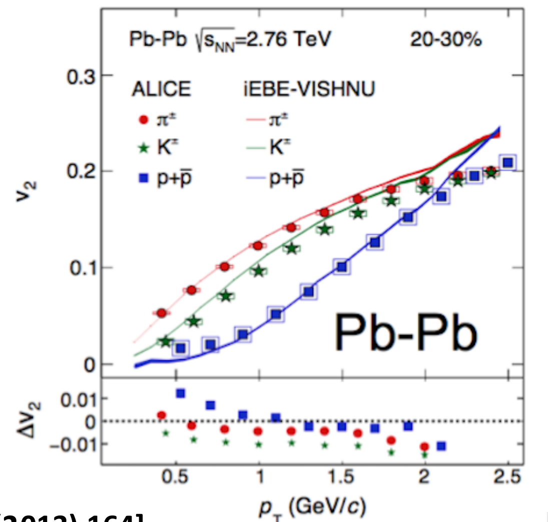




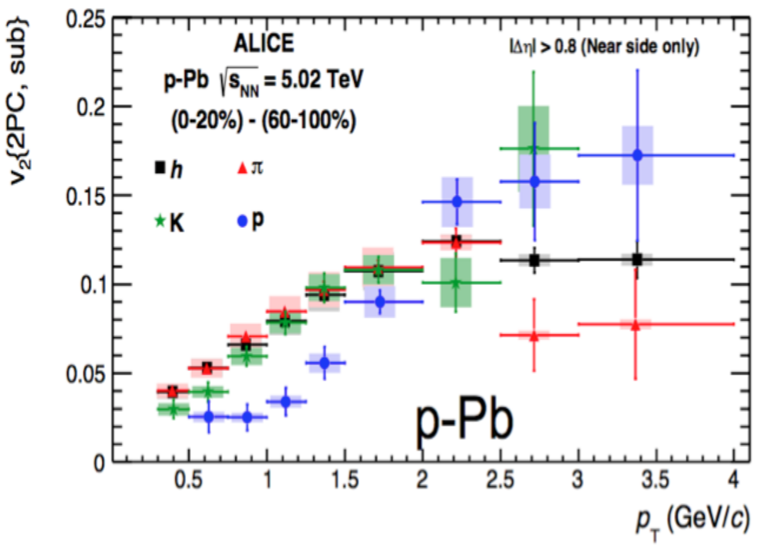
Nature 575 147 (2019)

Is there a collective motion in small systems ?

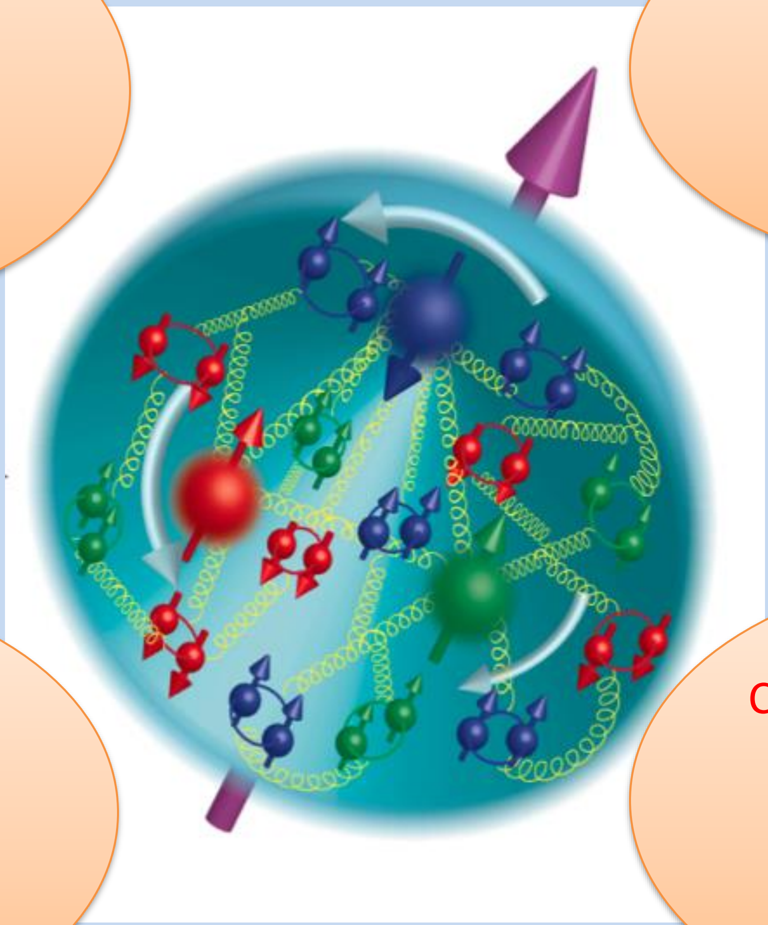
$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + \ldots\right)$$



ALICE [PLB 726 (2013) 164]



The QCD View



Dynamic Spin
- Parton polarization
- Orbital motion
- Form Factors
- Magnetic Moment

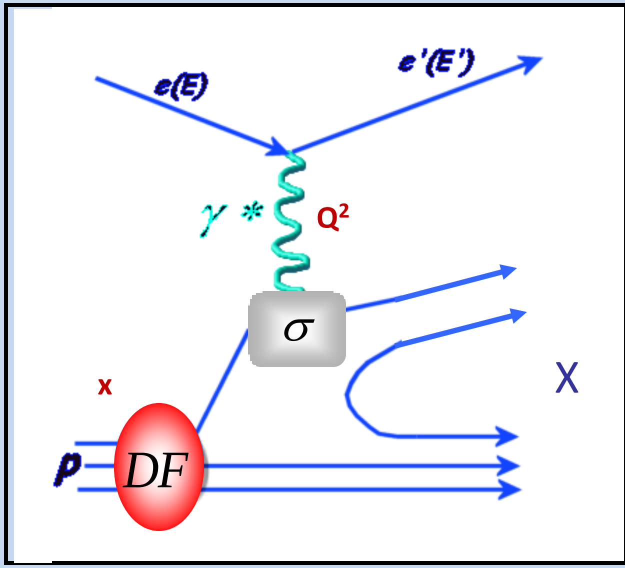
Parton Correlations
- dPDFs
- Short range
- MPI

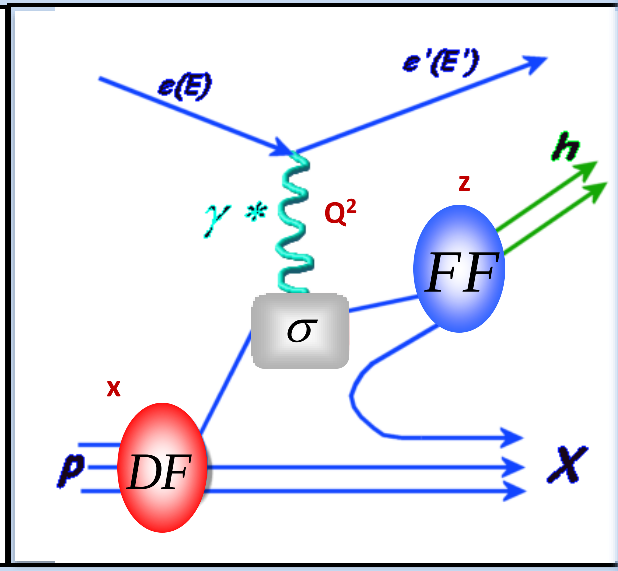
Hadronization
- Spin-orbit effects
- Parton energy loss
- Jet quenching

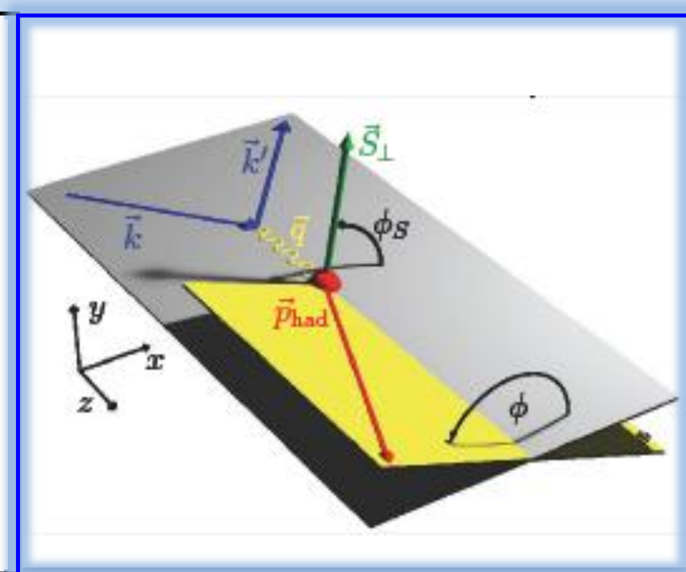
Color charge density
- Nucleon tomography
- Diffractive physics
- Gluon saturation
- Color force

Deep-Inelastic Scattering

Inclusive	Semi-inclusive	Semi-inclusive







Inclusive

SFs (x,Q^2)

Structure functions (unpolarized, helicity)

Sum over quark charges

$$d^2s \ \mu \ F_2 (= \text{å}_q \ e_q^2 q(x))$$

Semi-inclusive

DFs (x,Q^2) + FF(z,Q^2)

Parton distributions + fragmentation

$$D_u^{p+}(z) > D_u^{p-}(z)$$

Flavor sensitivity

$$d^3s^h \ \mu \ \text{å}_q \ e_q^2 q(x) D_q^h(z)$$

Semi-inclusive

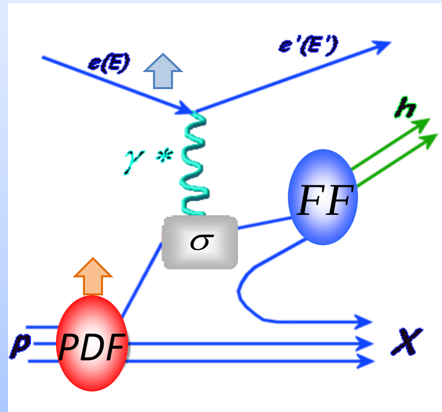
TMDs $(x,z,P_{h\perp},Q^2)$

Transverse momentum dependent parton functions

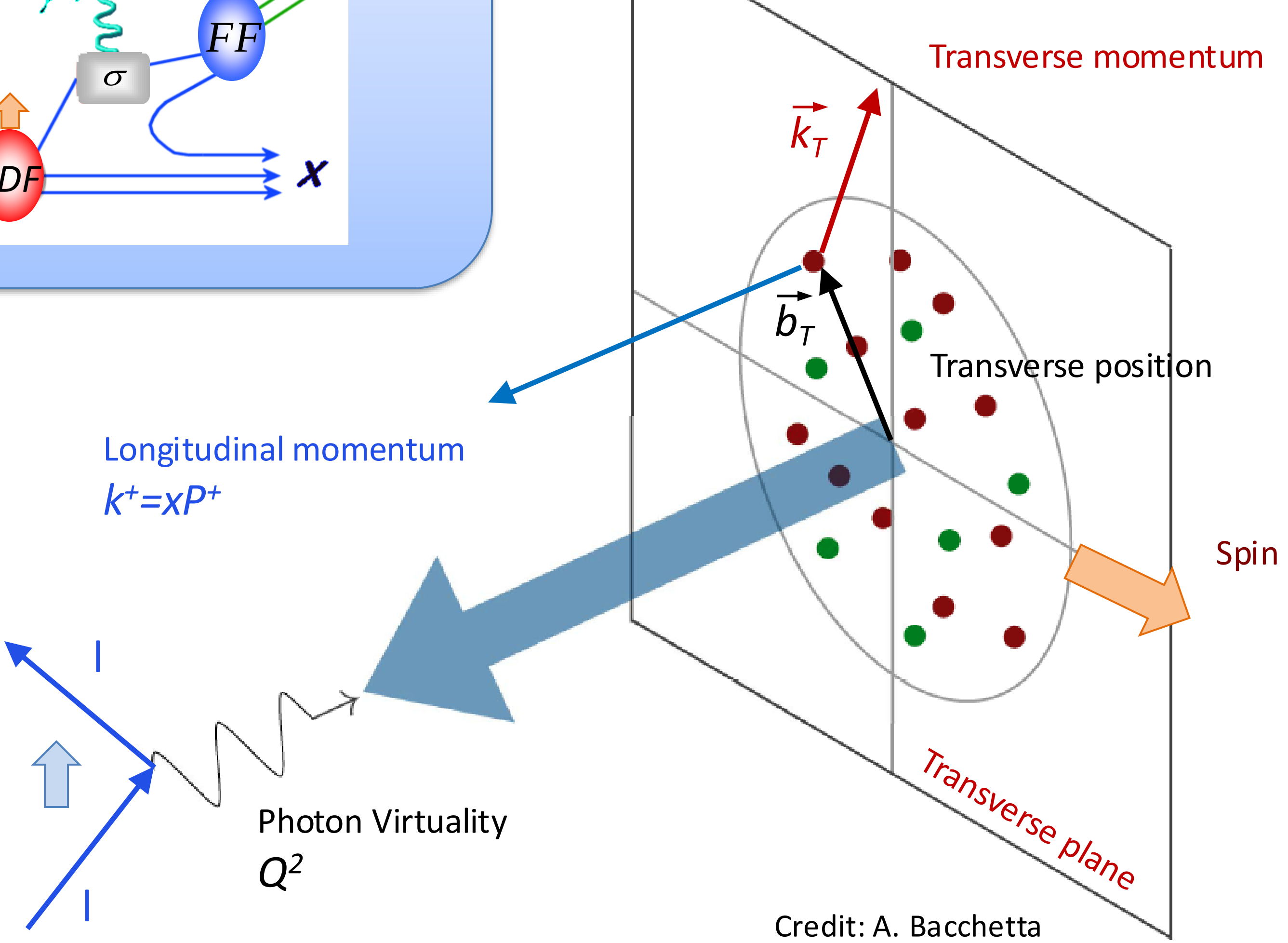
Spin-Orbit effects

$$d^6s^h \ \mu \ \text{å}_q \ e_q^2 q(x,k_T) \text{Ä} \ D_q^h(z,p_T)$$

Rich and Involved phenomenology !!

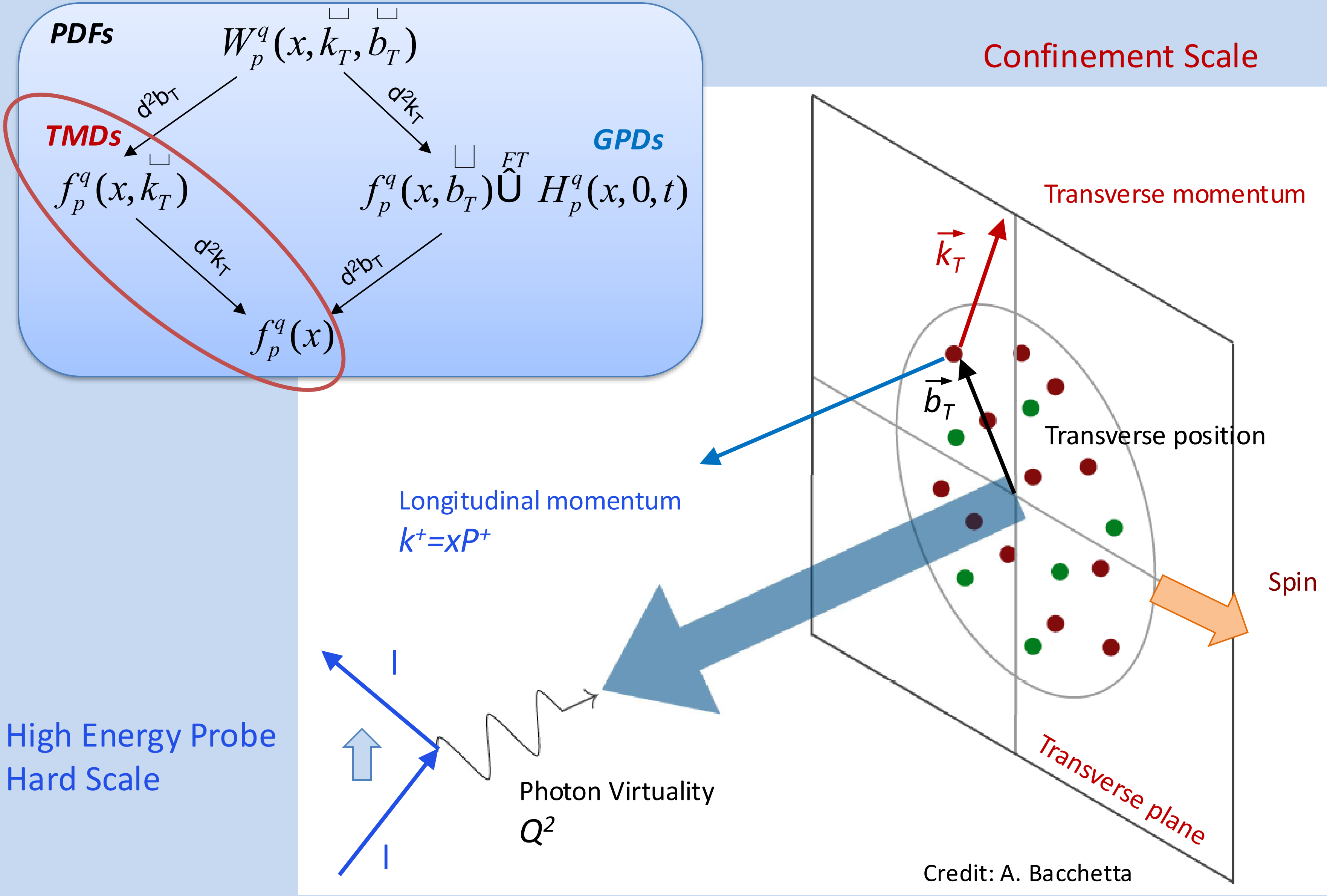


Confinement Scale

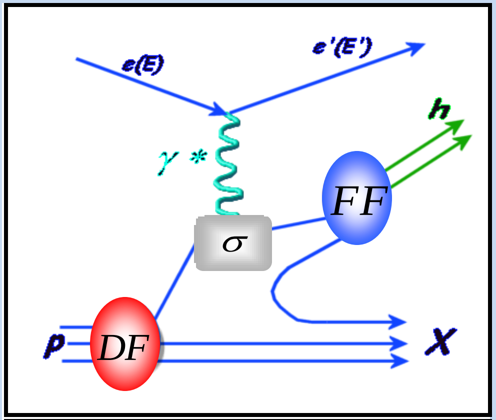


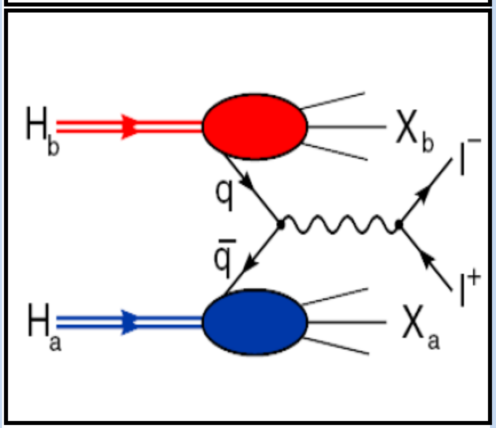
Credit: A. Bacchetta

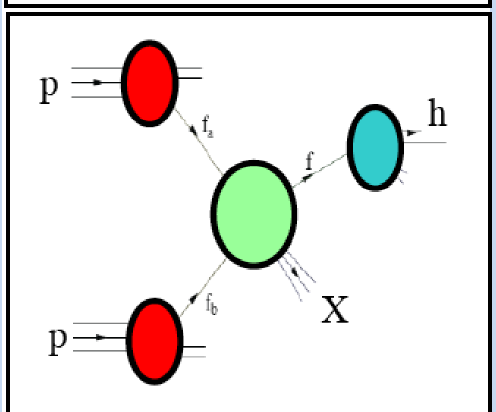
High Energy Probe
Hard Scale


PDFs
$W_p^q(x, \vec{k}_T, \vec{b}_T)$
d²b_T
d²k_T
TMDs
GPDs
$f_p^q(x, \vec{k}_T)$
$f_p^q(x, \vec{b}_T) \xleftrightarrow{FT} H_p^q(x, 0, t)$
d²k_T
d²b_T
$f_p^q(x)$
Confinement Scale
Transverse momentum
$\vec{k}_T$
$\vec{b}_T$
Transverse position
Longitudinal momentum
$k^+ = xP^+$
Spin
High Energy Probe
Hard Scale
l
l
Photon Virtuality
Q^2
Transverse plane
Credit: A. Bacchetta

Physics Channels







SIDIS: rich phenomenology, the most explored so far

SIDIS $$\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$$

e^+e^- colliders: powerful fragmentation laboratories

e^+e^- $$\sigma^{ee\to hhX} = \sum_q \sigma^{q\bar{q}\to ee} \otimes FF \otimes FF$$

DY: challenging for experiments (only unpolarized so far)

DY $$\sigma^{pp\to eeX} = \sum_q DF \otimes DF \otimes \sigma^{q\bar{q}\to ee}$$

Hadron reactions: challenging for theory (ISI + FSI)

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

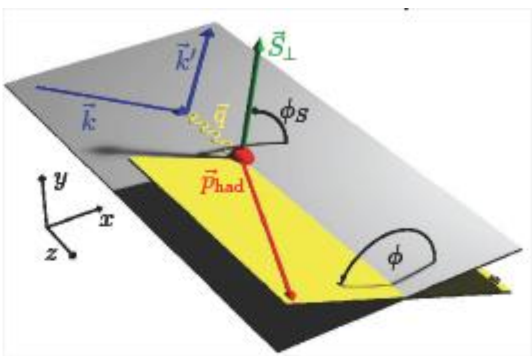
EIC

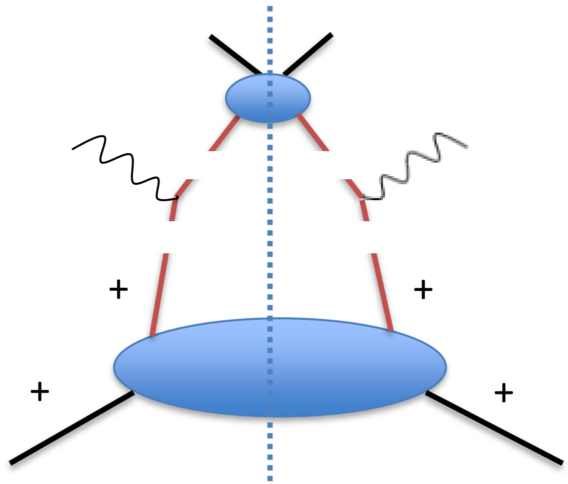
SIDIS Cross-Section and TMDs

$$\frac{d^6\sigma}{dx\,dQ^2\,dz\,dP_h\,d\phi\,d\phi_S} \overset{LT}{\propto} \left[F_{UU} + \varepsilon\cos(2\phi)F_{UU}^{\cos(2\phi)}\right] + S_L\left[\varepsilon\sin(2\phi)F_{UL}^{\sin(2\phi)}\right]$$

$$+ S_T\left[\sin(\phi-\phi_S)F_{UT}^{\sin(\phi-\phi_S)} + \varepsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)}\right]$$

$$+ S_L\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}\right] + S_T\lambda_e\left[\sqrt{1-\varepsilon^2}\,\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)}\right] + O\left(\frac{1}{Q}\right)$$





Quark fragmentation

TMD Factorization holds for $p_T \ll Q$

Quark parton distribution

Wide kinematic coverage is needed to resolve the convolution

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

$$\frac{d^6\sigma}{dx\,dQ^2\,dz\,dP_{h\perp}\,d\phi\,d\phi_S} \propto \left[F_{UU} + \varepsilon\cos(2\phi)F_{UU}^{\cos(2\phi)}\right] + S_L\left[\varepsilon\sin(2\phi)F_{UL}^{\sin(2\phi)}\right]$$

$$+ S_T\left[\sin(\phi-\phi_S)F_{UT}^{\sin(\phi-\phi_S)} + \varepsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)}\right]$$

$$+ S_L\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}\right] + S_T\lambda_e\left[\sqrt{1-\varepsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)}\right] + O\left(\frac{1}{Q}\right)$$

(F_{UU}: f_1; $F_{UU}^{\cos(2\phi)}$: $h_1^\perp$; $F_{UL}^{\sin(2\phi)}$: $h_{1L}^\perp$; $F_{UT}^{\sin(\phi-\phi_S)}$: $f_{1T}^\perp$; $F_{UT}^{\sin(\phi+\phi_S)}$: h_1; $F_{UT}^{\sin(3\phi-\phi_S)}$: $h_{1T}^\perp$; F_{LL}: g_1; $F_{LT}^{\cos(\phi-\phi_S)}$: $g_{1T}^\perp$)

Access to independent correlators bringing information on the confinement dynamics

$f(x) \rightarrow f(x,k_T)$ $\qquad$ $D(x) \rightarrow D(z,p_T)$

quark polarisation (columns) / **nucleon polarisation** (rows)

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		$H_1^\perp$

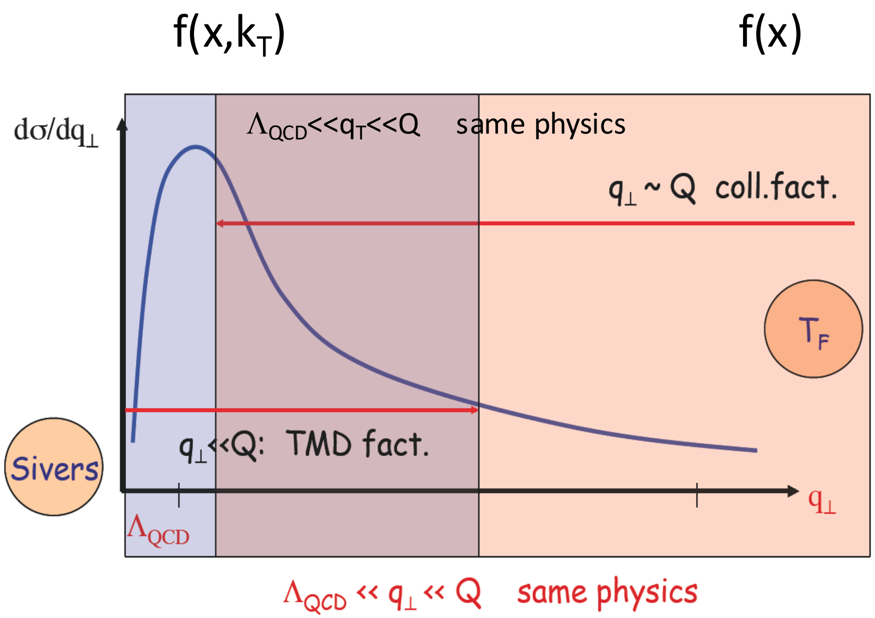
SIDIS Cross-Section and TMDs

$$\frac{d^6\sigma}{dx\,dQ^2\,dz\,dP_{h\perp}\,d\phi\,d\phi_S} \propto \left[F_{UU} + \varepsilon\cos(2\phi)F_{UU}^{\cos(2\phi)}\right] + S_L\left[\varepsilon\sin(2\phi)F_{UL}^{\sin(2\phi)}\right]$$

$$+ S_T\left[\sin(\phi-\phi_S)F_{UT}^{\sin(\phi-\phi_S)} + \varepsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)}\right]$$

$$+ S_L\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}\right] + S_T\lambda_e\left[\sqrt{1-\varepsilon^2}\,\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)}\right] + O\left(\frac{1}{Q}\right)$$

Labels on the terms: f_1, $h_1^\perp$, $h_{1L}^\perp$, $f_{1T}^\perp$, h_1, $h_{1T}^\perp$, g_1, $g_{1T}^\perp$



TMD Factorization:

Holds for p_T << Q

--> Proper domain of phenomenological fits ?

Not trivial gauge invariance

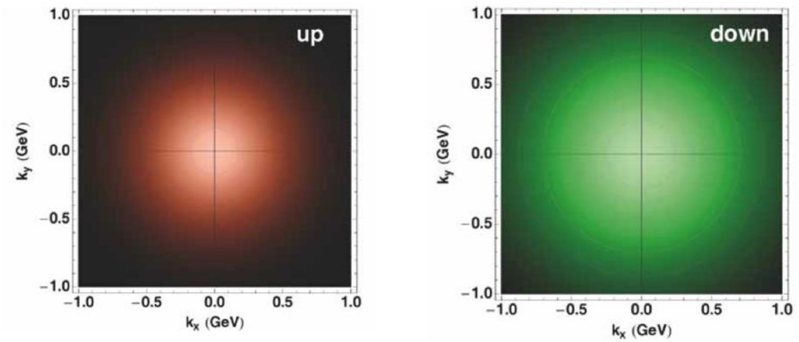
--> Sign change from SIDIS to DY ($f_{1T}^\perp$, $h_{1L}^\perp$)

Peculiar Q^2 evolution (~~DGLAP~~)

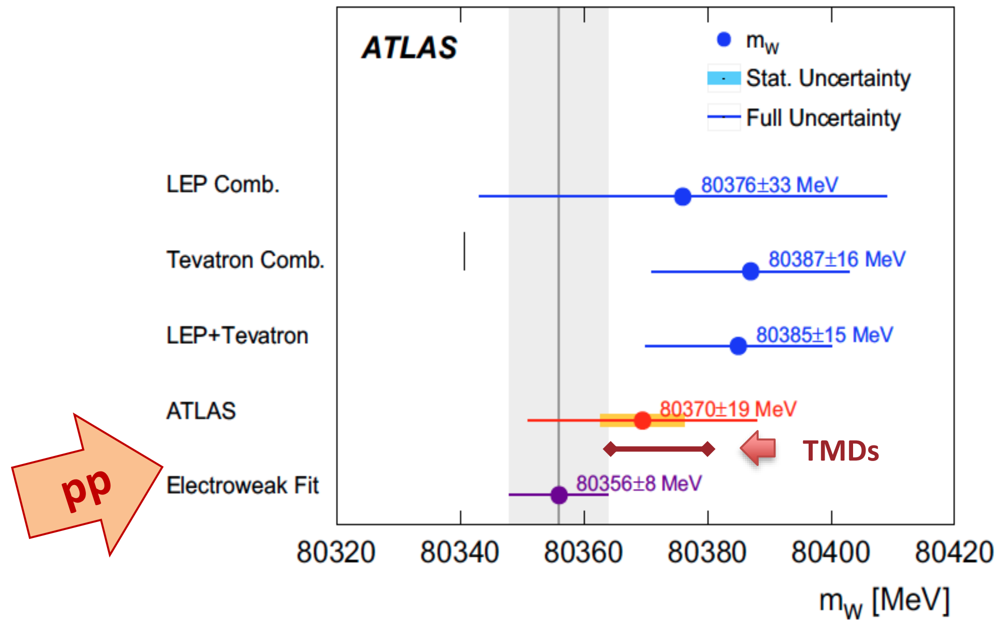
--> Non-perturbative inputs from data

Parton Number Density

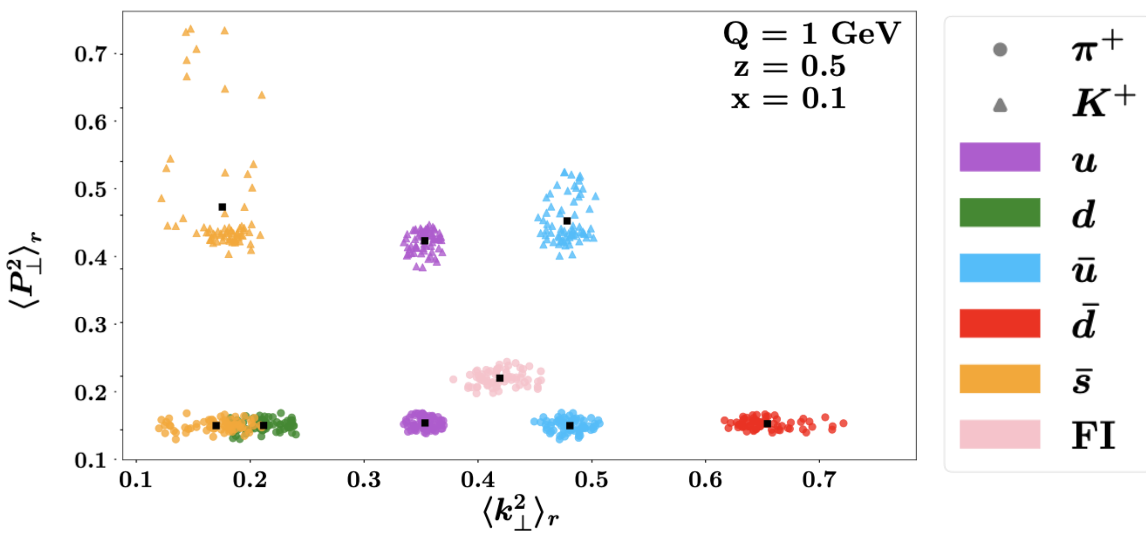
$$\langle P_{h\perp}^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle$$



ATLAS++ [arXiv:1701.07240]



A. Bacchetta++ [arXiv:2405.13833]



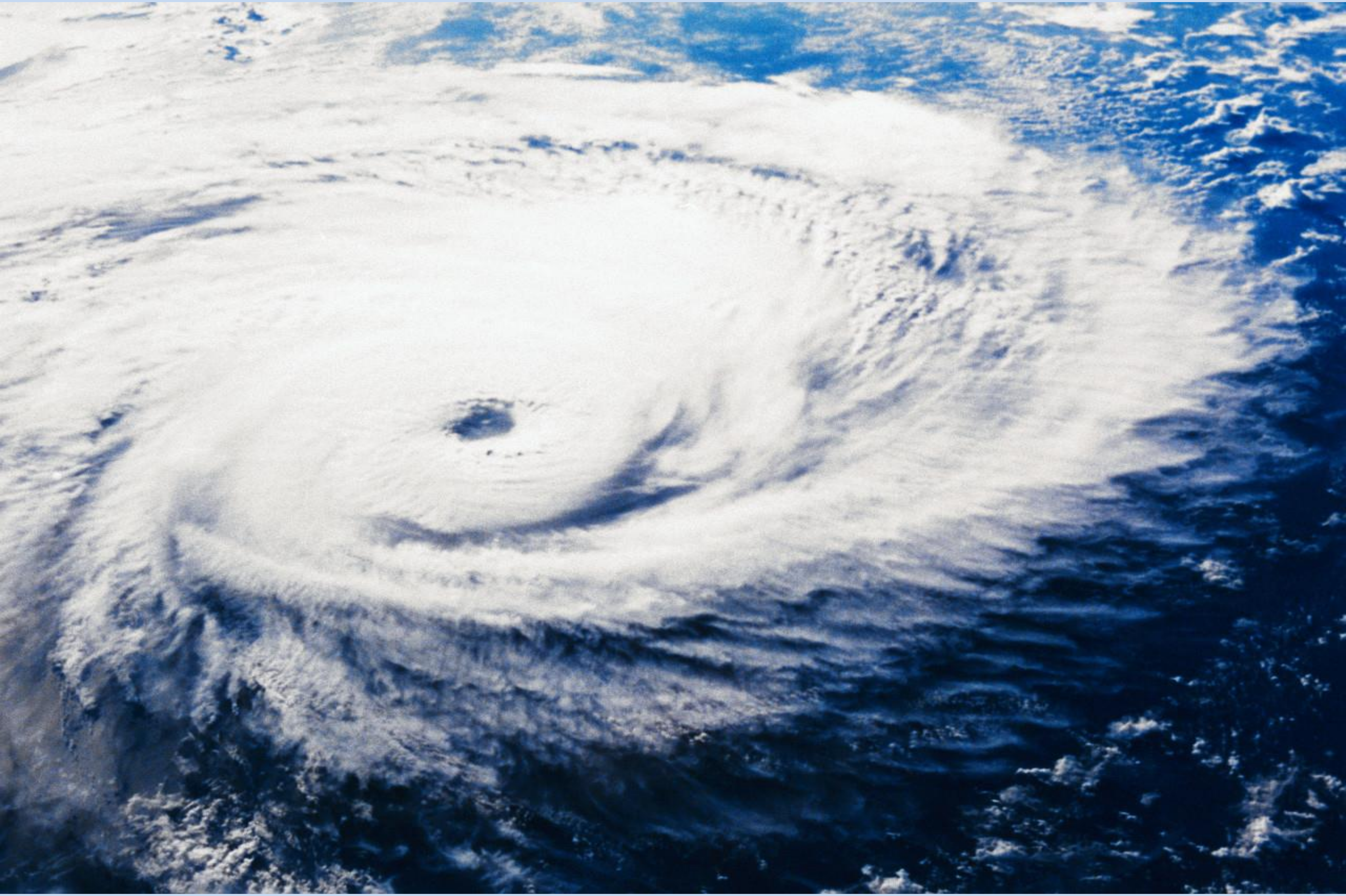
A. Bacchetta++ [arXiv:1807.02101]

MeV

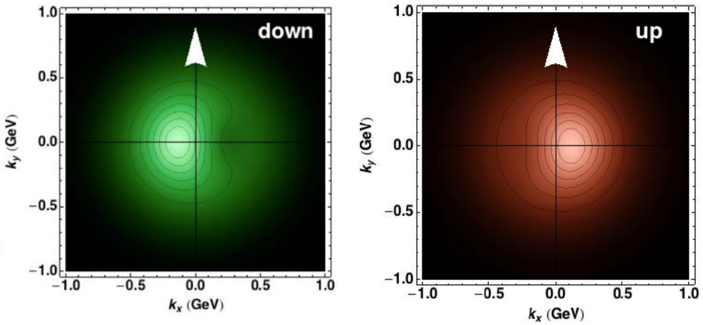
$$m_W = 80370 \pm 7\,(\text{stat.}) \pm 11\,(\text{exp. syst.}) \pm 14\,(\text{mod. syst.})$$

+9 / -6 (TMDs)

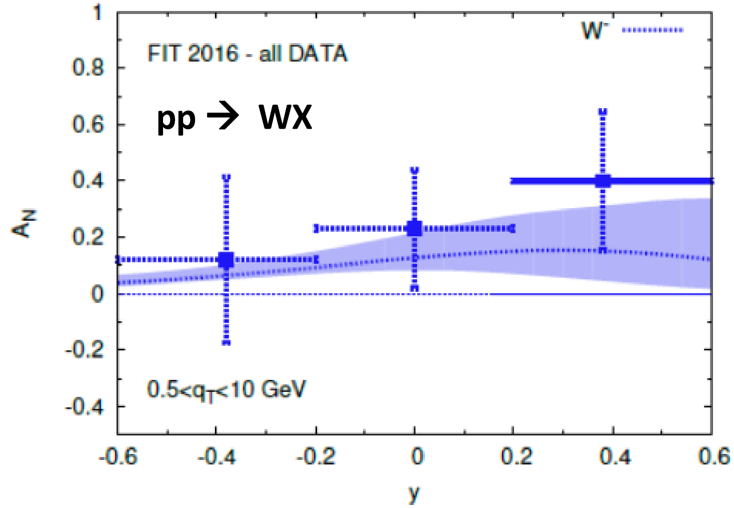
Spin-Orbit Effect



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



STAR [arXiv: 1511.06003]



(-1)

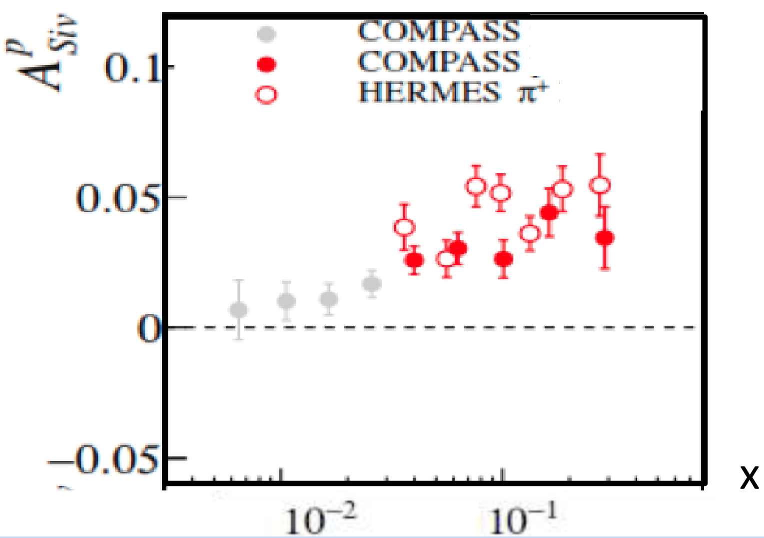
Sivers from polarized SIDIS

DY

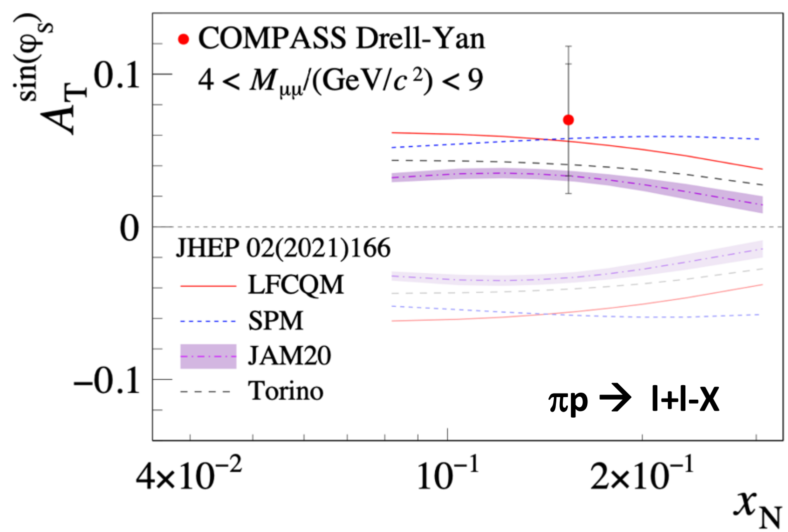
Sivers from hadronic reactions

HERMES [arXiv:0906.3918]

COMPASS [arXiv:1205.5122]



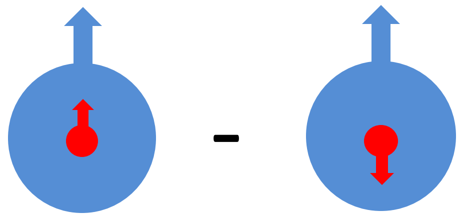
COMPASS [arXiv: 2312.17379]

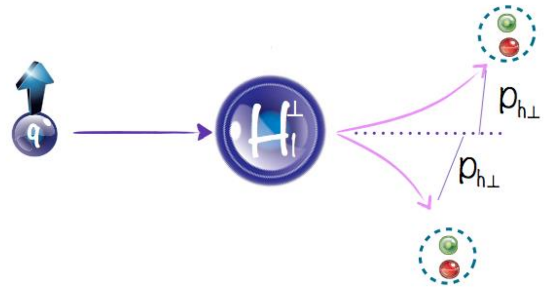


Spin-Orbit Effect: Collins

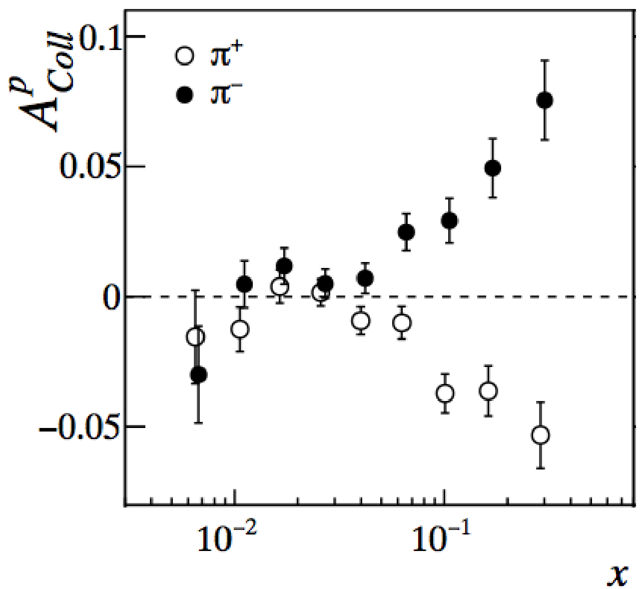
$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 \otimes H_1^{\perp}$

$Q^2 \sim$ 5-7 GeV^2



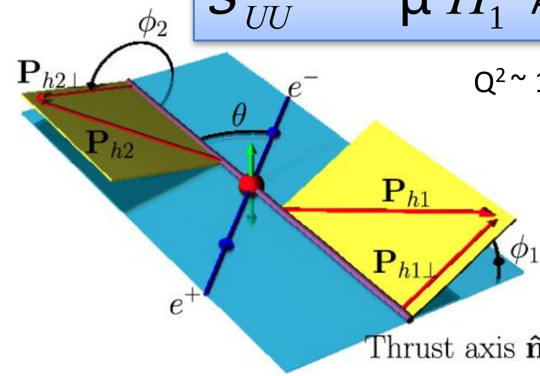


HERMES	[arXiv 0408013]
HERMES	[arXiv 0906.3918]
COMPASS	[arXiv 1005.5609]
COMPASS	[arXiv 1408.4405]



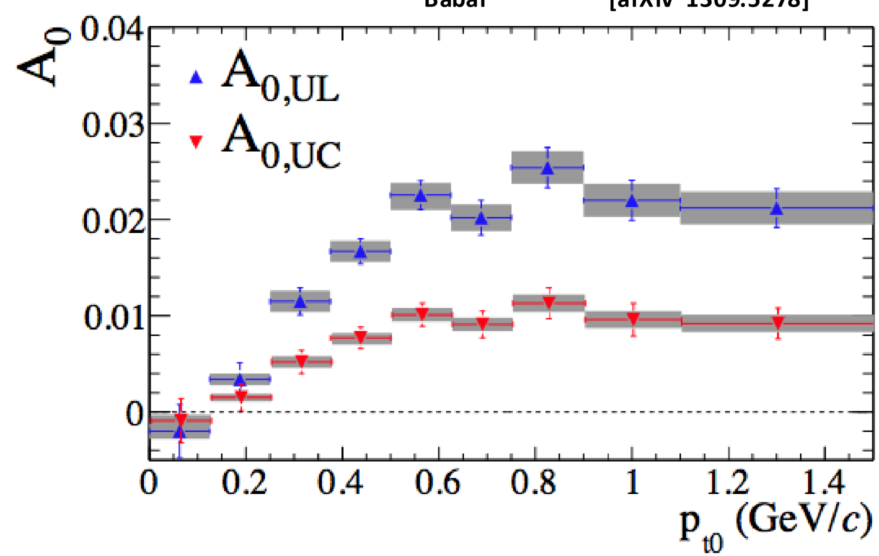
$\sigma_{UU}^{\sin(\phi_1+\phi_2)} \propto H_1^{\perp} \otimes H_1^{\perp}$

$Q^2 \sim$ 110 GeV^2

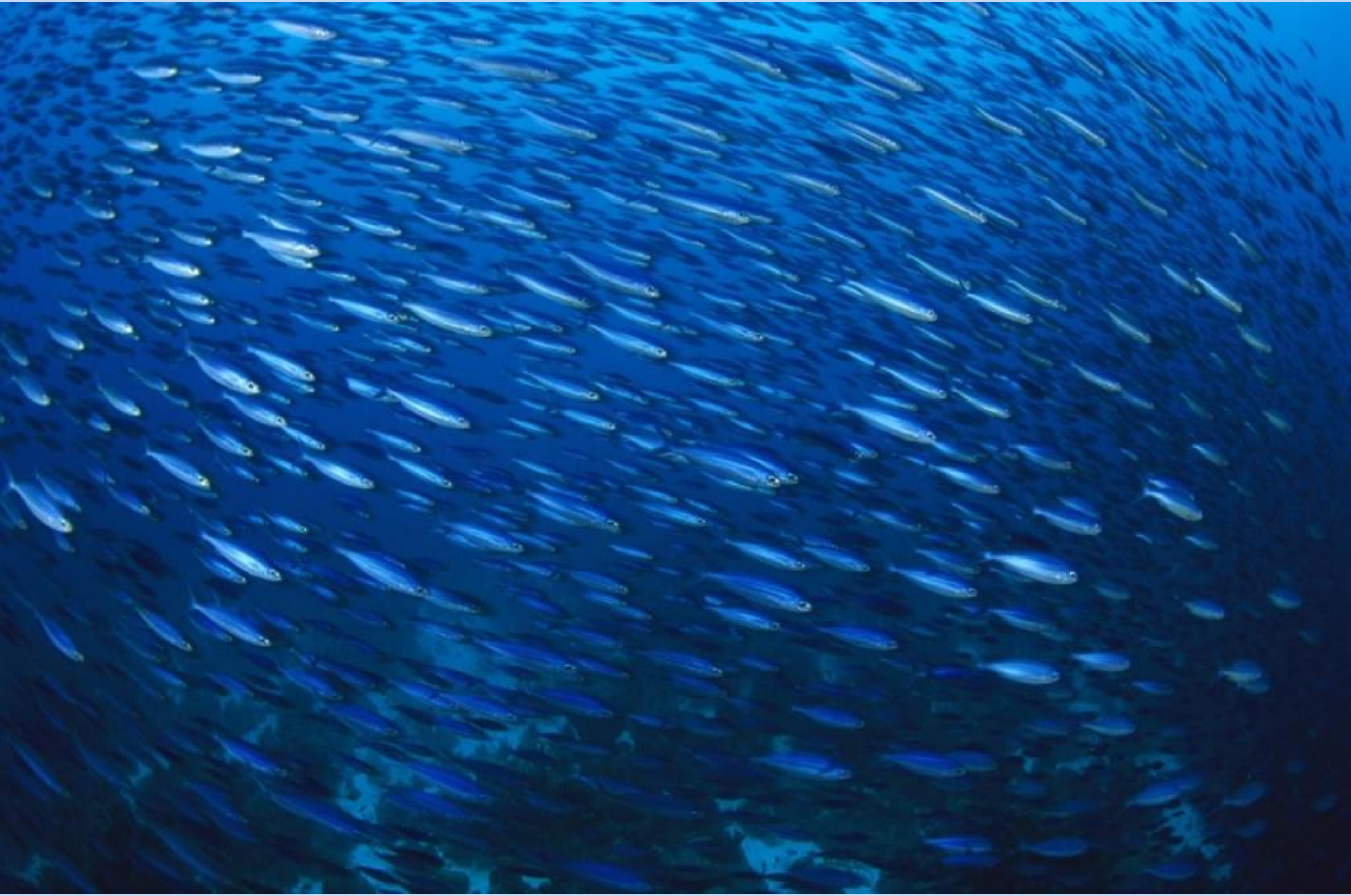


Belle	[talk at DIS2014]
BESIII	[arXiv 1507.06824]
Babar	[arXiv 1309.5278]

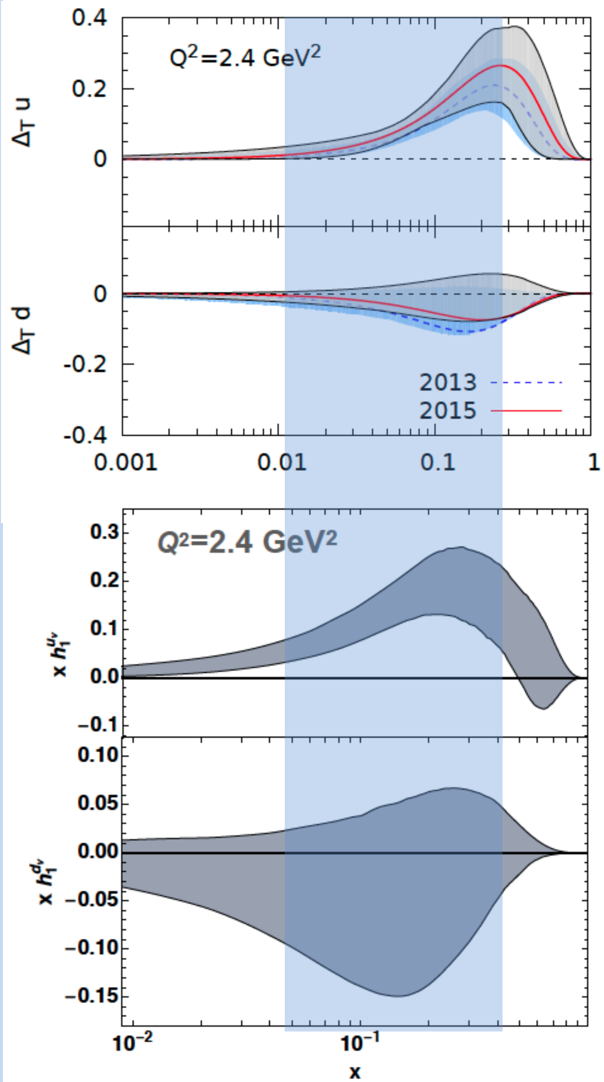
e^+e^-



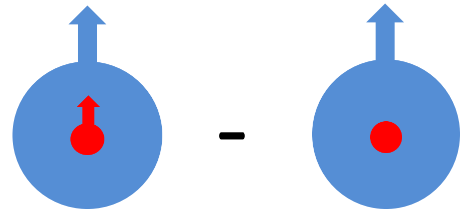
Parton Polarization



Distributions:

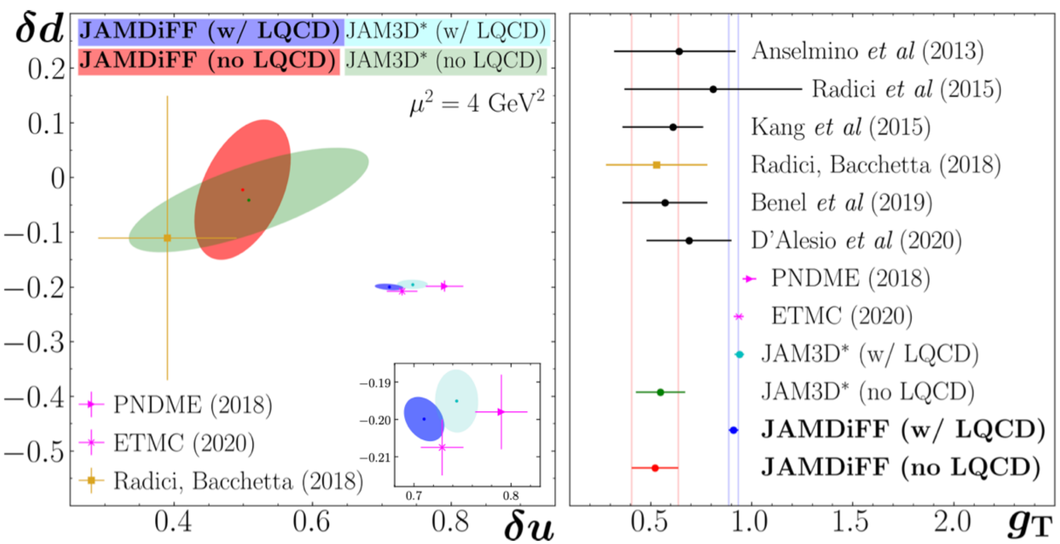


Charges:



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

JAM, 2306.12998



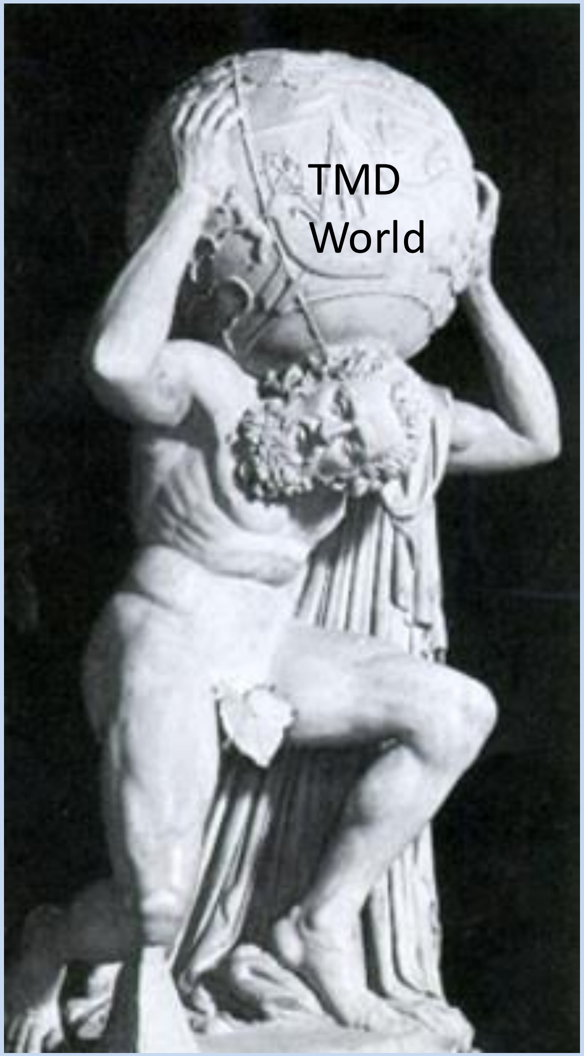
Connected to Beyond Standard Model physics:

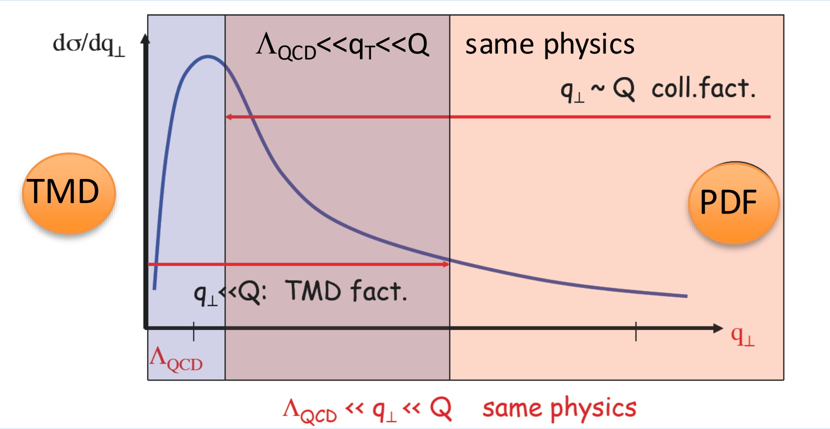
- Electric Dipole Moment of particles

- Tensor coupling (beyond V-A)

TMD Parton Correlators

Beauty and complexity of the unique strong-interacting world





$f(x)$ → $f(x,k_T)$

quark polarisation (columns); **nucleon polarisation** (rows)

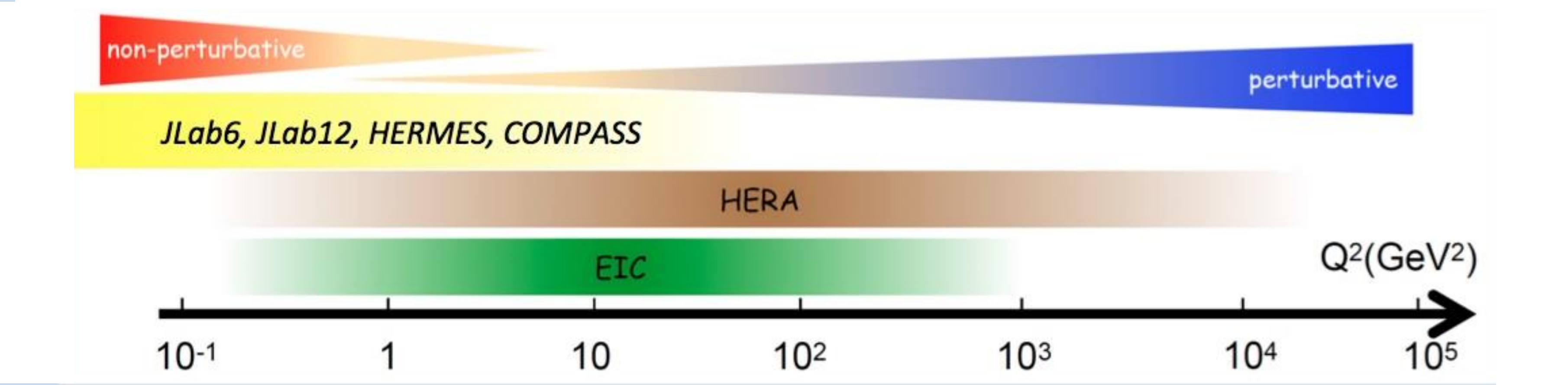
N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\wedge}$	$g_{1T}^{\wedge}$	$h_1, h_{1T}^{\wedge}$

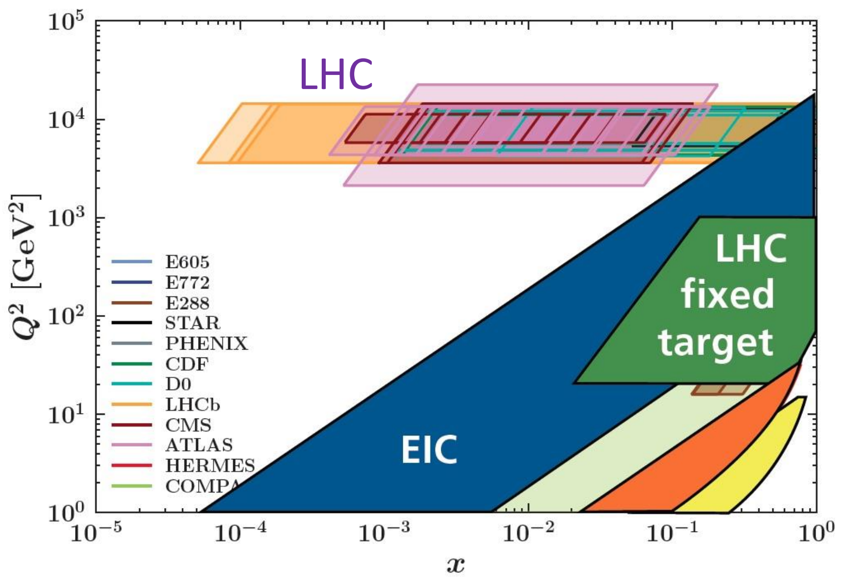
quark polarisation

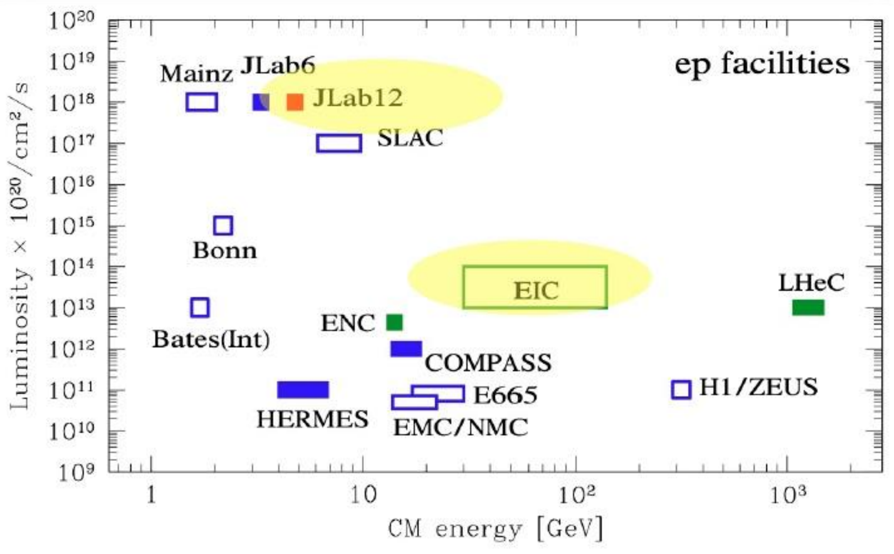
N/q	U	L	T
U	D_1		$H_1^{\wedge}$

TMD Baseline

Energy range matching perturbative and non-perturbative regimes



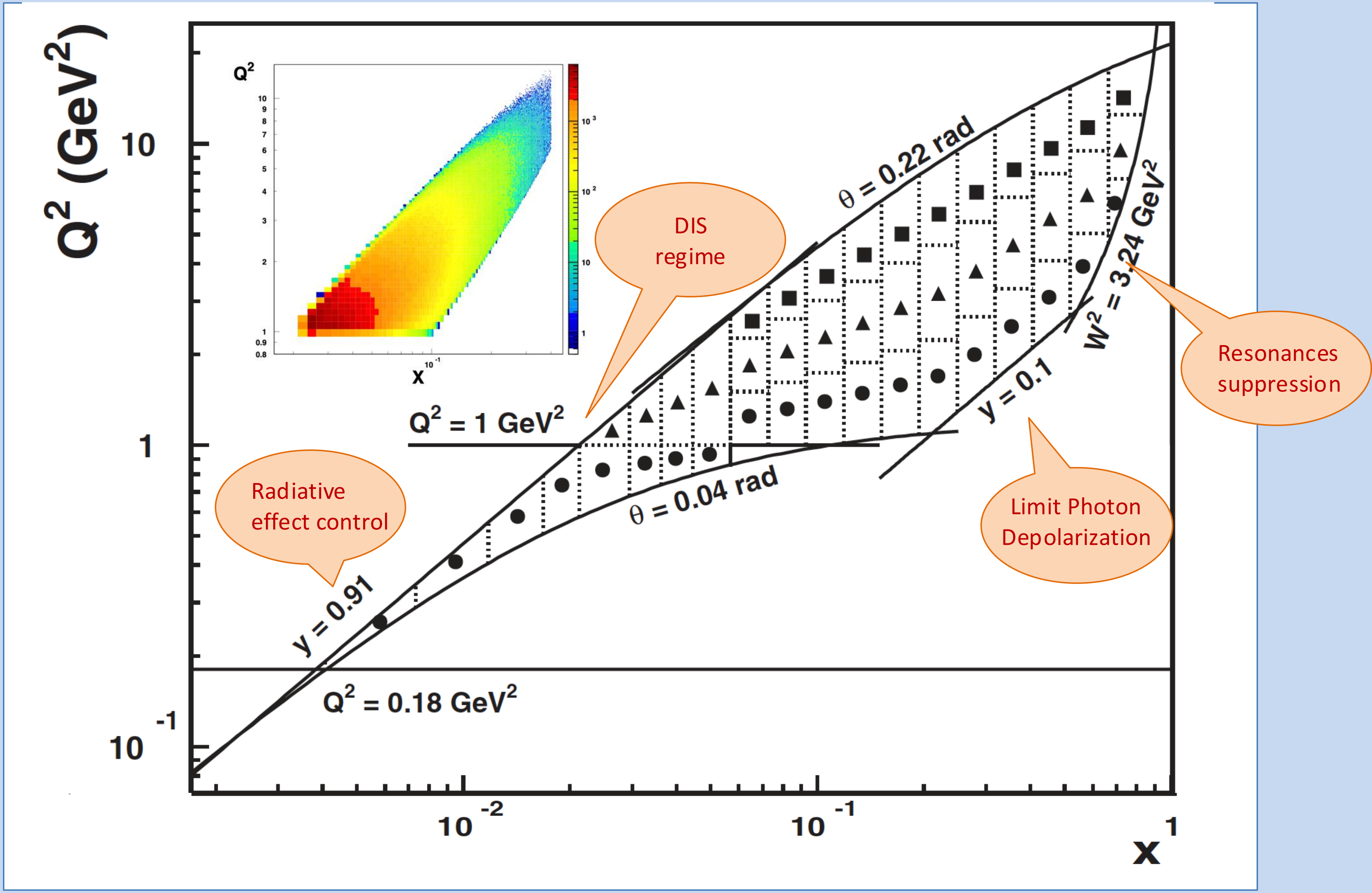




SIDIS Kinematic Variables

$k = (E, \vec{k}),\ k' = (E', \vec{k}')$	4-momenta of the initial and final-state leptons
θ, ϕ	Polar and azimuthal angle of the scattered lepton
$P \stackrel{\text{lab}}{=} (M, 0)$	4-momentum of the initial target nucleon
$q = k - k'$	4-momentum of the virtual photon
$Q^2 \equiv -q^2 \stackrel{\text{lab}}{=} 4EE' \sin^2 \frac{\theta}{2}$	Negative squared 4-momentum transfer
$\nu \equiv \frac{P \cdot q}{M} \stackrel{\text{lab}}{=} E - E'$	Energy of the virtual photon
$x = \frac{Q^2}{2P \cdot q} = \frac{Q^2}{2M\nu}$	Bjorken scaling variable
$y \equiv \frac{P \cdot q}{P \cdot k} \stackrel{\text{lab}}{=} \frac{\nu}{E}$	Fractional energy of the virtual photon
$W^2 = (P + q)^2 = M^2 + 2M\nu - Q^2$	Squared invariant mass of the photon-nucleon system
$p = (E_h, \vec{p})$	4-momentum of a hadron in the final state
$z = \frac{P \cdot p}{P \cdot q} \stackrel{\text{lab}}{=} \frac{E_h}{\nu}$	Fractional energy of the observed final-state hadron
$x_F = \frac{p_{CM}^{\parallel}}{\lvert\vec{q}\rvert} \stackrel{\text{lab}}{\simeq} \frac{2p_{CM}^{\parallel}}{W}$	Longitudinal momentum fraction of the hadron

Electron Kinematic Range

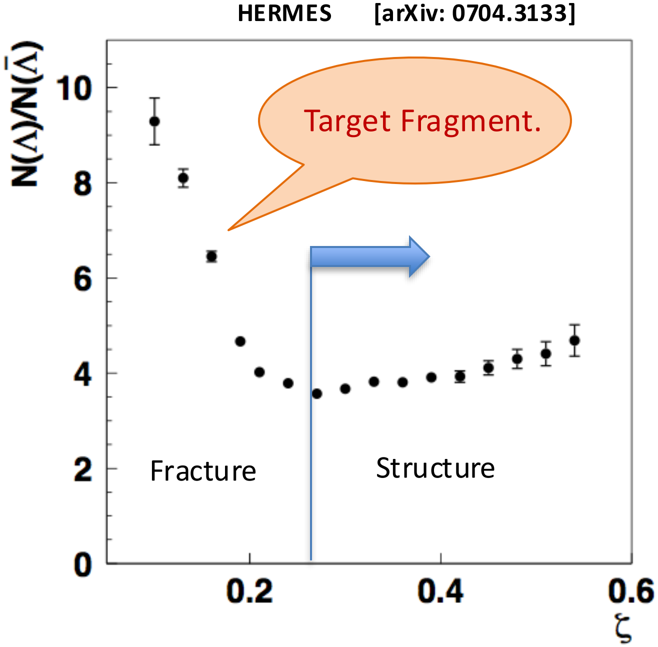


Proper Fragmentation Range

How to ensure we are not in target fragmentation ?

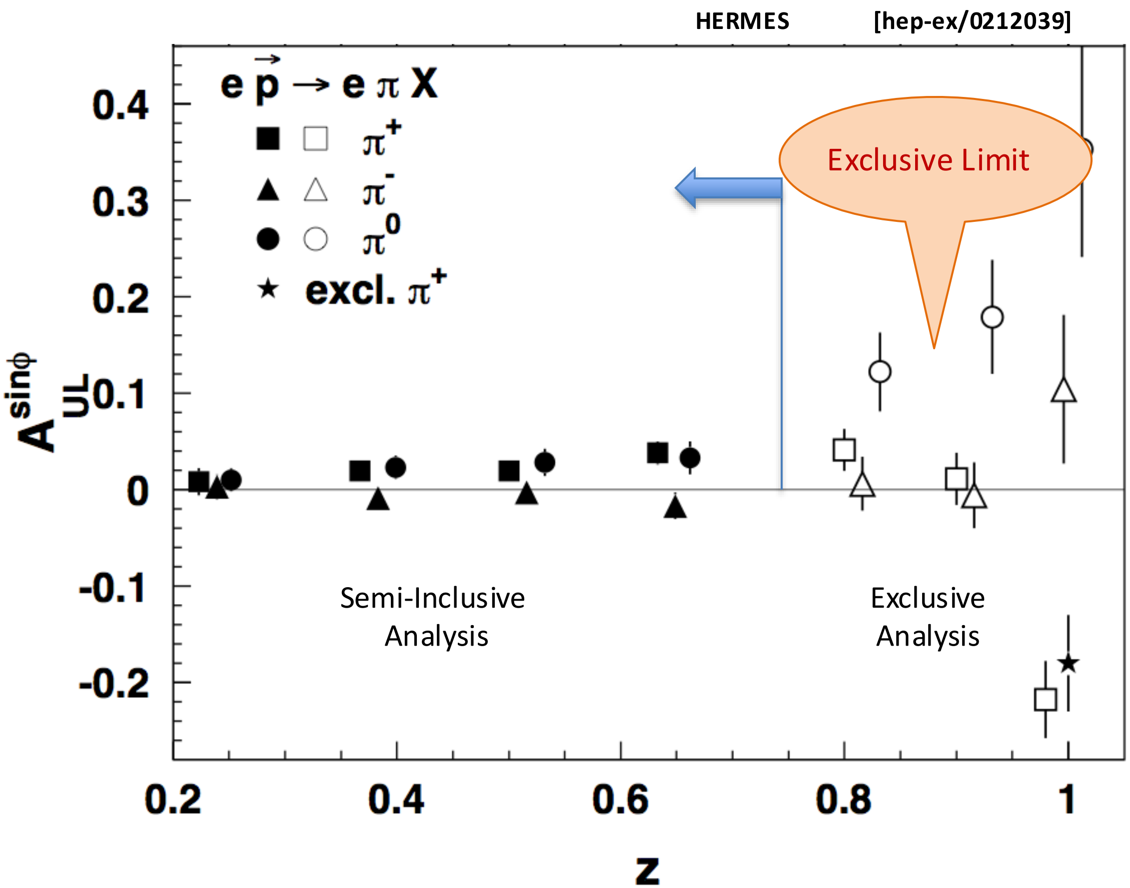
When the exclusive is no more part of the semi-inclusive ?

Inclusive $\overline{\Lambda}/\Lambda$ yield
at W~5 GeV (HERMES)



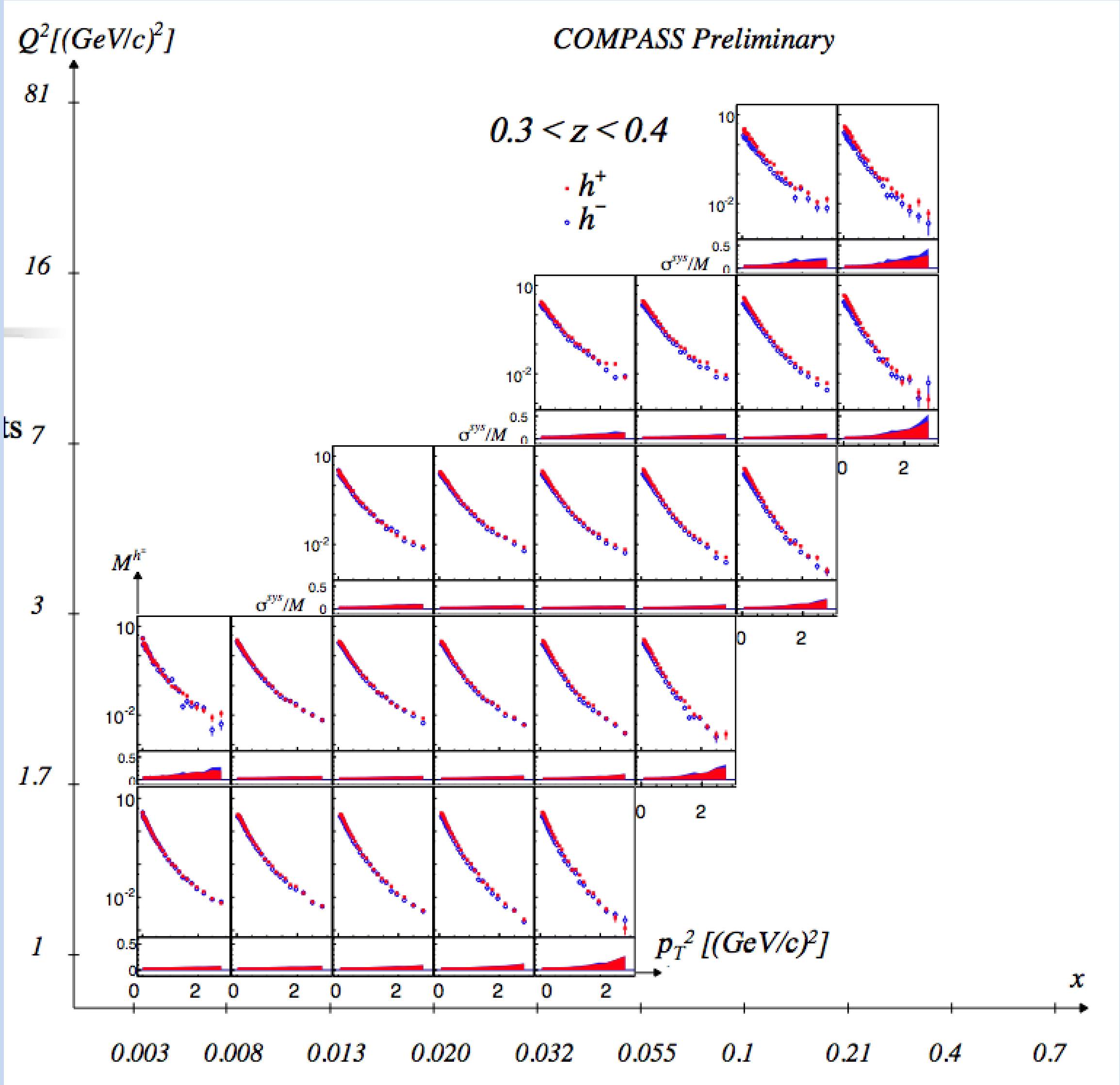
$$\zeta \equiv (E_\Lambda + p_{z\Lambda})/(E_e + p_e)$$

Highly correlated to z, x_F



Multi-D Investigation

Achieve the maximum phase space coverage with:



Disentanglement

✓ kinematic dependences

✓ dynamical regimes
- twist in Q^2
- perturbative in p_T

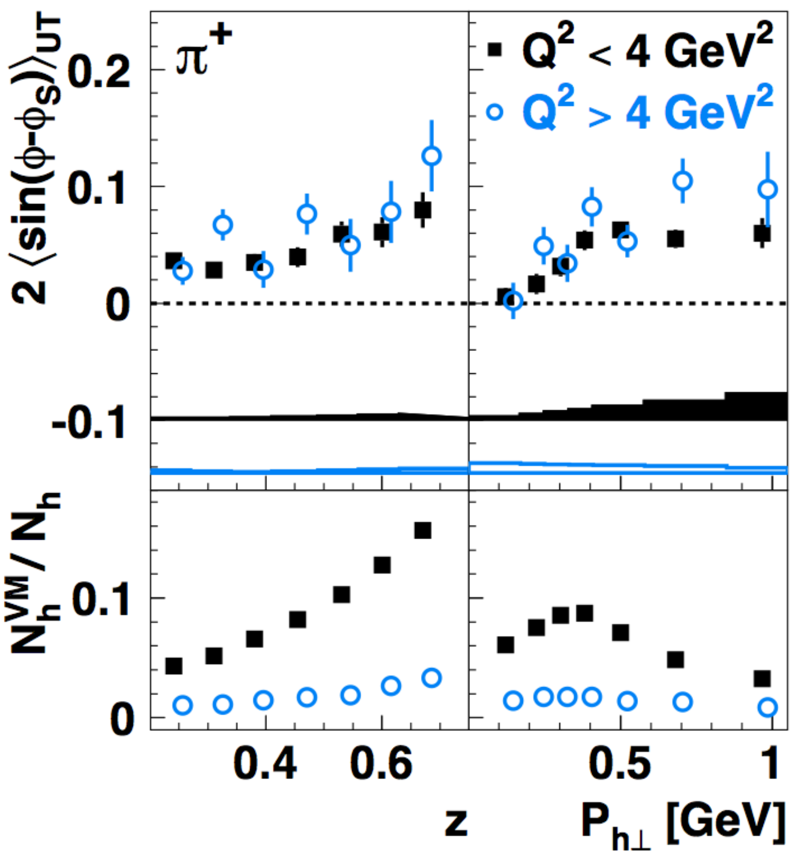
Asymmetries so far used to suppress systematics effects

$$A_{LL} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

$$A_{LL} = \frac{1}{f P_T P_B} \frac{N^+ - N^-}{N^+ + N^-}$$

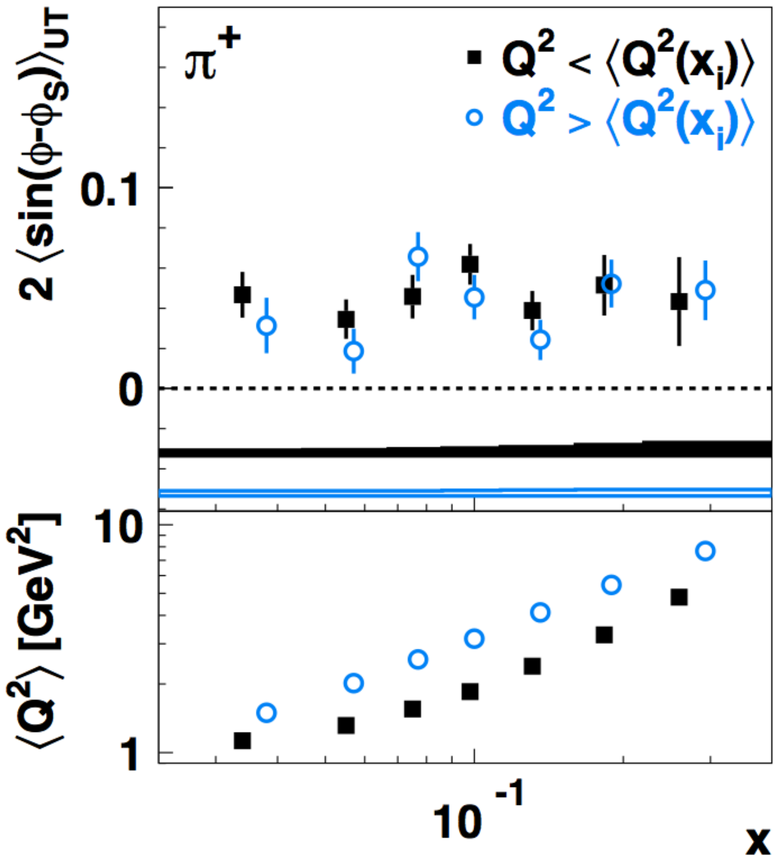
They suppress also physics (i.e. evolution)

Test of exclusive channel influence



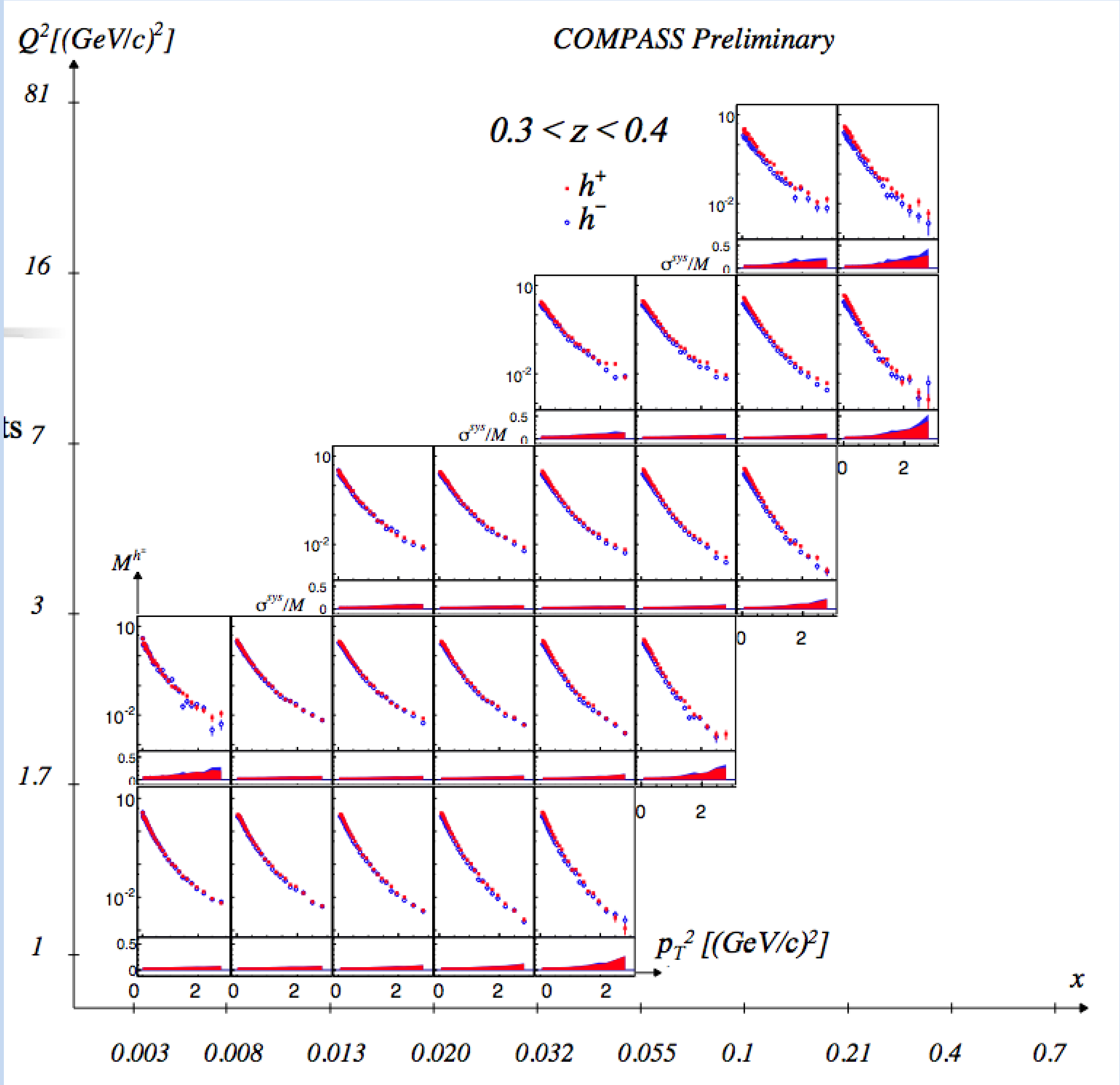
Test of higher-twist contribution

HERMES [arXiv:0906.3918]



Multi-D Investigation

Achieve the maximum phase space coverage with:

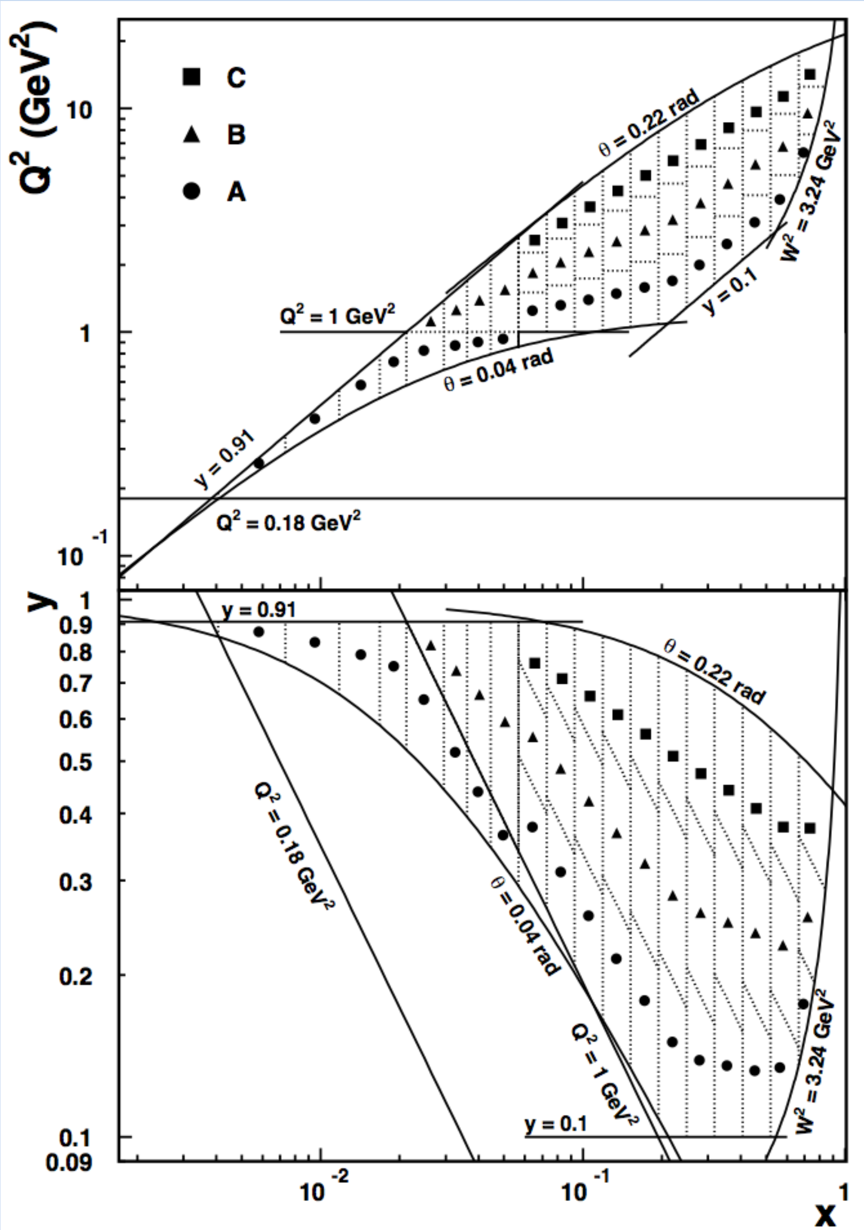


Disentanglement

- ✓ kinematic dependences
- ✓ dynamical regimes
  - twist in Q^2
  - perturbative in p_T
- ✓ kinematical dilutions
- ✓ instrumental dilutions

radiative smearing & x-talk

acceptance effects



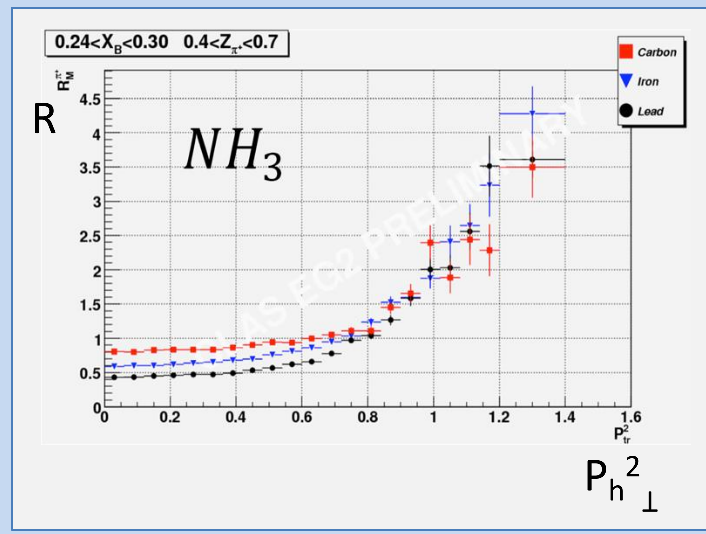
Analyzing power matters

Goes like y

$$A_{LL} \propto \frac{\sqrt{1-\varepsilon^2}\,F_{LL}}{F_{UU,T}+\varepsilon F_{UU,L}}$$

Nuclear effects from real (^{6}LiD, NH_3, ^{3}He) targets

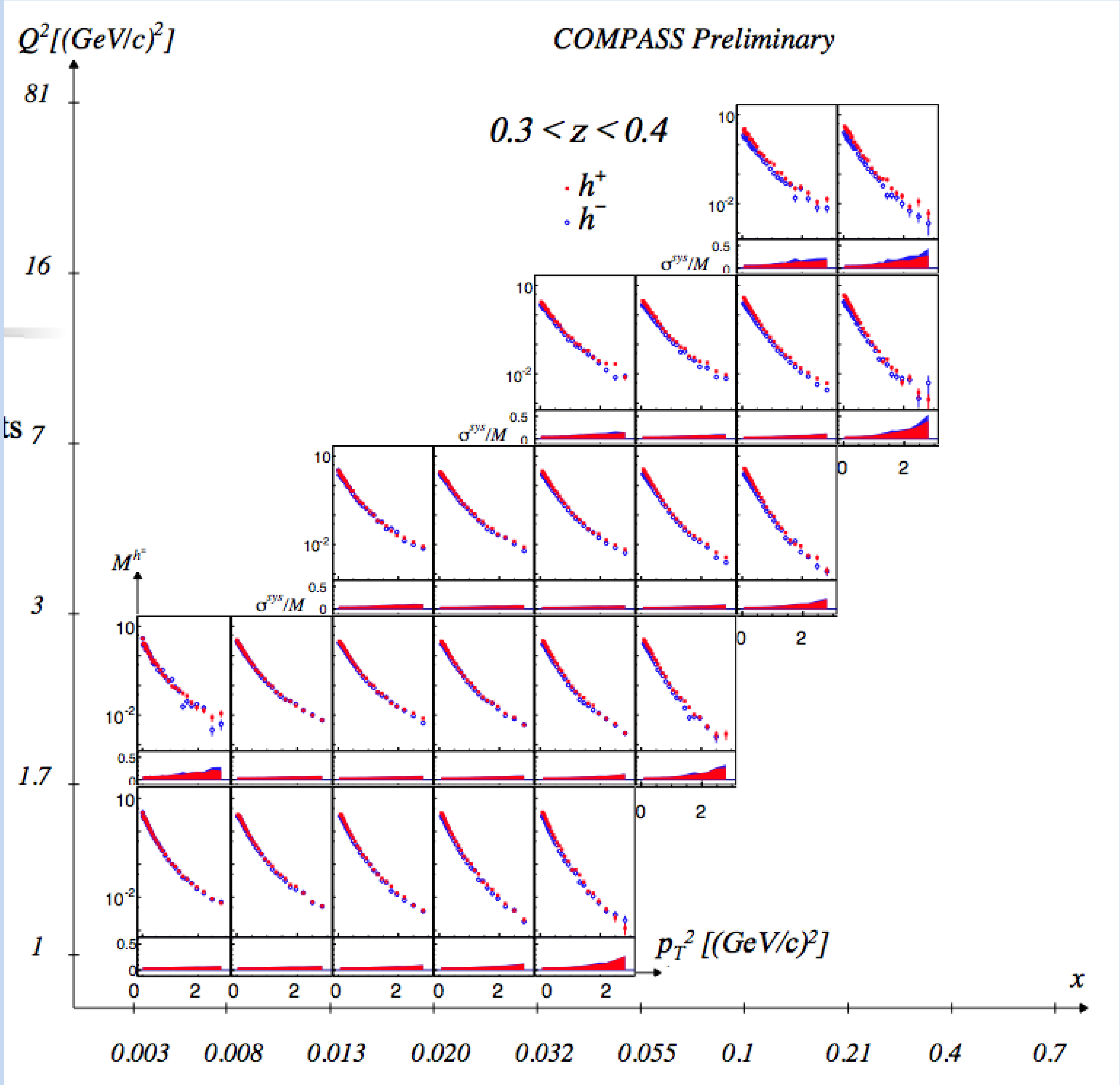
$$A_{LL} = \frac{1}{f P_T P_B}\,\frac{N^+ - N^-}{N^+ + N^-}$$



Dilution goes with N

Precision improves with √N

Achieve the maximum phase space coverage with:

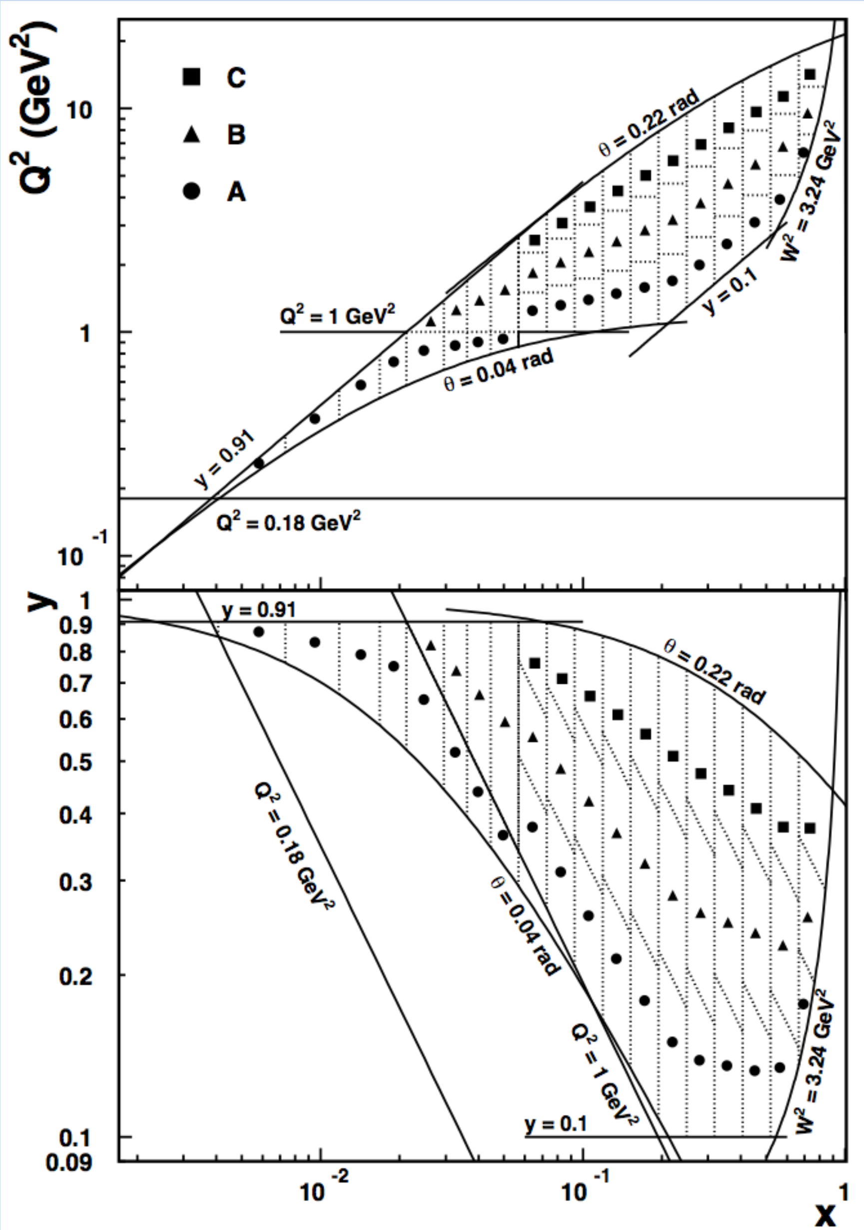


Disentanglement

- ✓ kinematic dependences
- ✓ dynamical regimes
  - twist in Q^2
  - perturbative in p_T
- ✓ kinematical dilutions
- ✓ instrumental dilutions
- ✓ radiative smearing & x-talk

acceptance effects

Smearing Effect



What about event migration ?

- define bins larger than resolution

  but keep in mind non-linearities!!!

$$\frac{dx}{x} \mu \frac{1}{y} \frac{dp}{p}$$

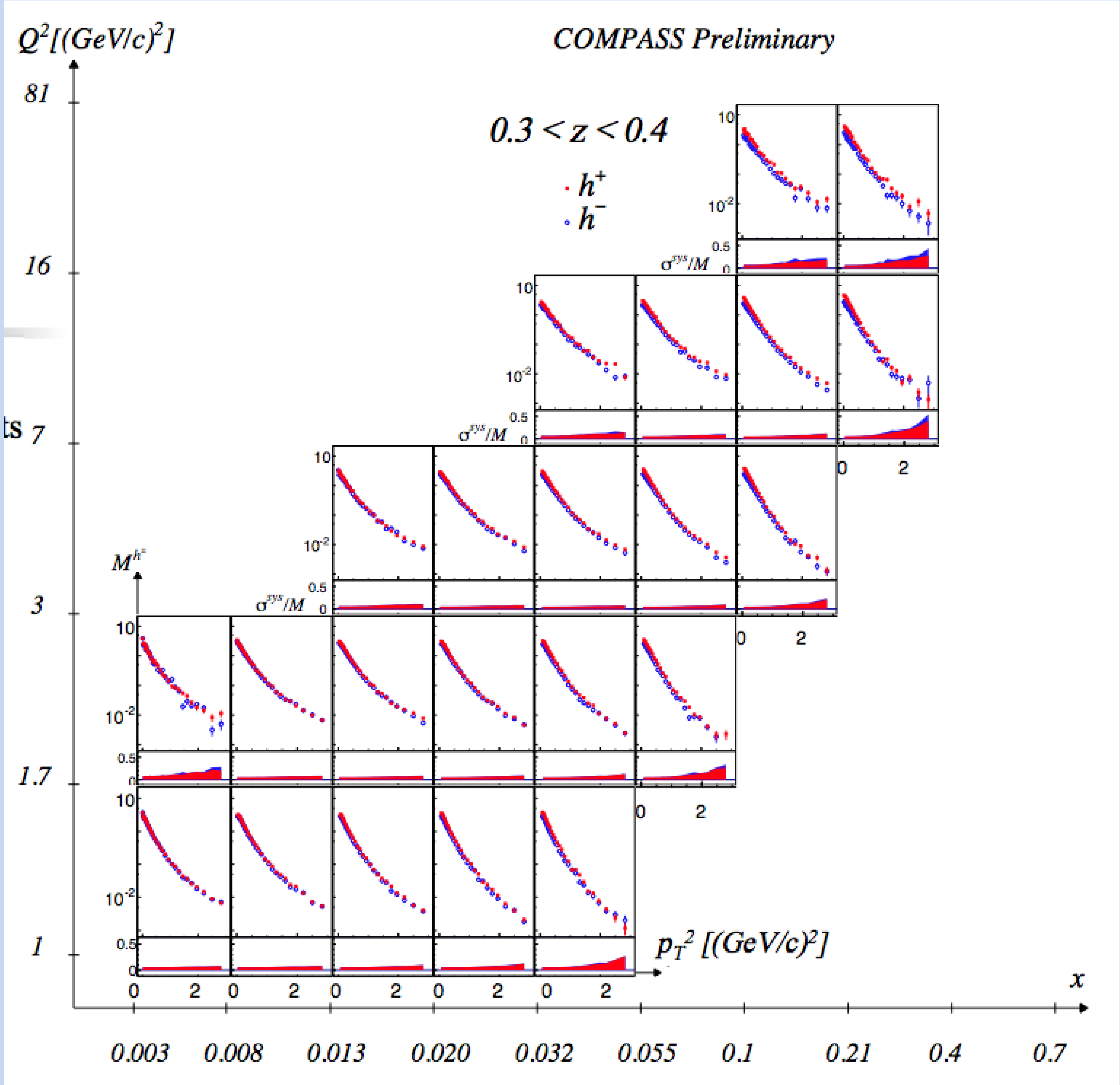
- radiative effects change the kinematics (larger y) and introduce a x-talk between modulations

  a full knowledge of the hadronic tensor is in principle required

- unfold smearing and radiative effects introduce a statistical correlation

Multi-D Investigation

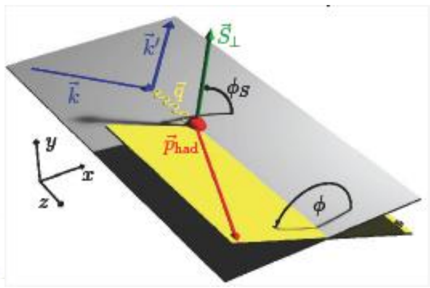
Achieve the maximum phase space coverage with:

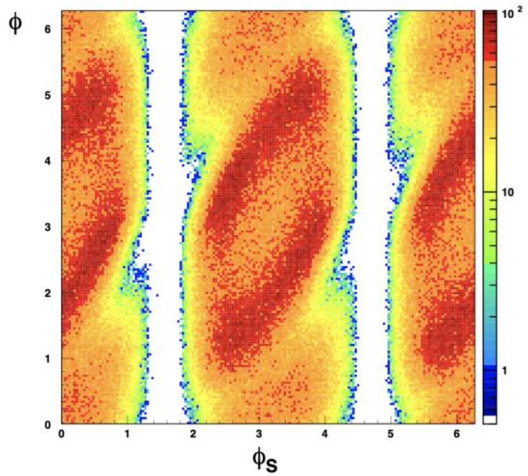


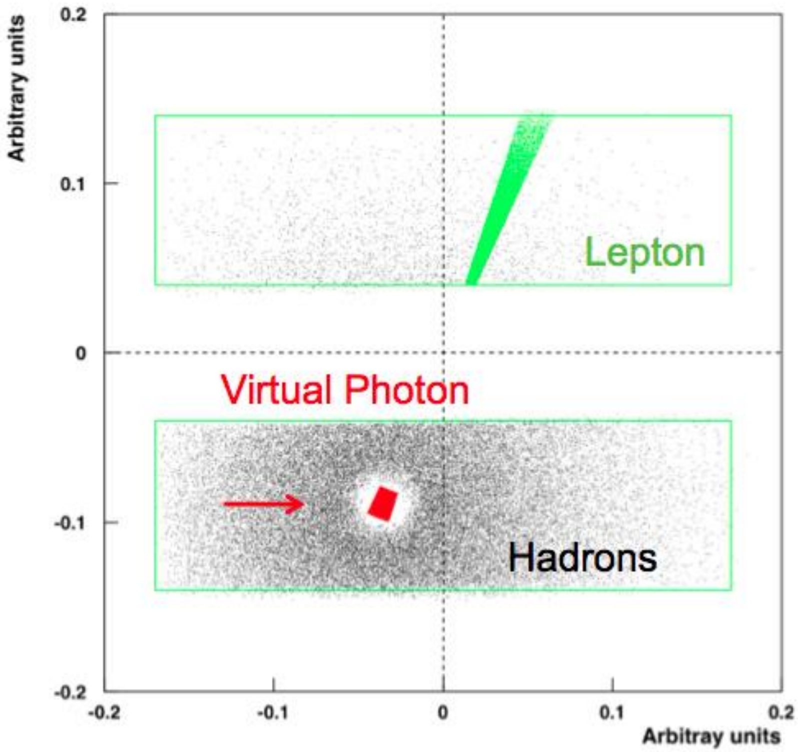
Disentanglement

- ✓ kinematic dependences
- ✓ dynamical regimes
  - twist in Q^2
  - perturbative in p_T
- ✓ kinematical dilutions
- ✓ instrumental dilutions
- ✓ radiative smearing & x-talk
- ✓ acceptance effects

Do we have enough (ϕ,ϕ_S) coverage in each bin ?







(x, Q^2)

($z, P_{h_\perp}$)

Partial coverage in phi at a given detected event kinematics

Acceptance introduce azimuthal modulations in the measured yields !

Unbinned Maximum likelihood possible for spin-asymmetries

Next-Gen DIS Facilities: JLab

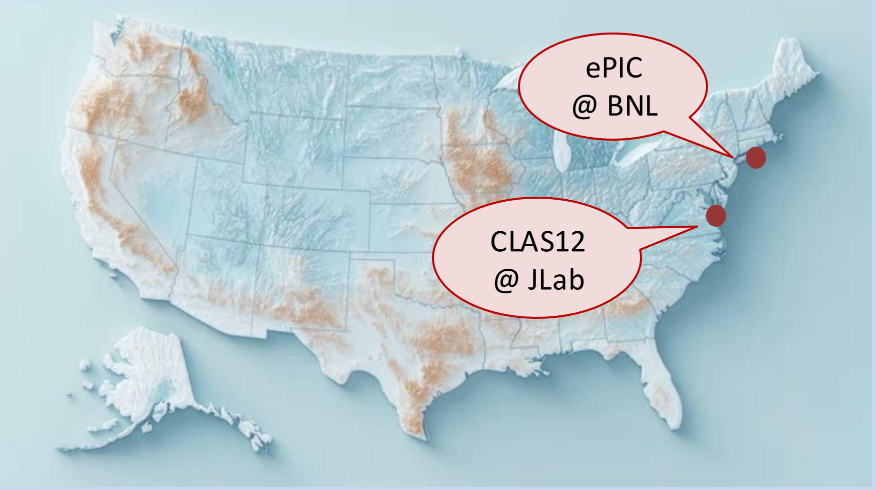
Jefferson Laboratory (JLab)
Continuous Electron Beam Accelerator Facility

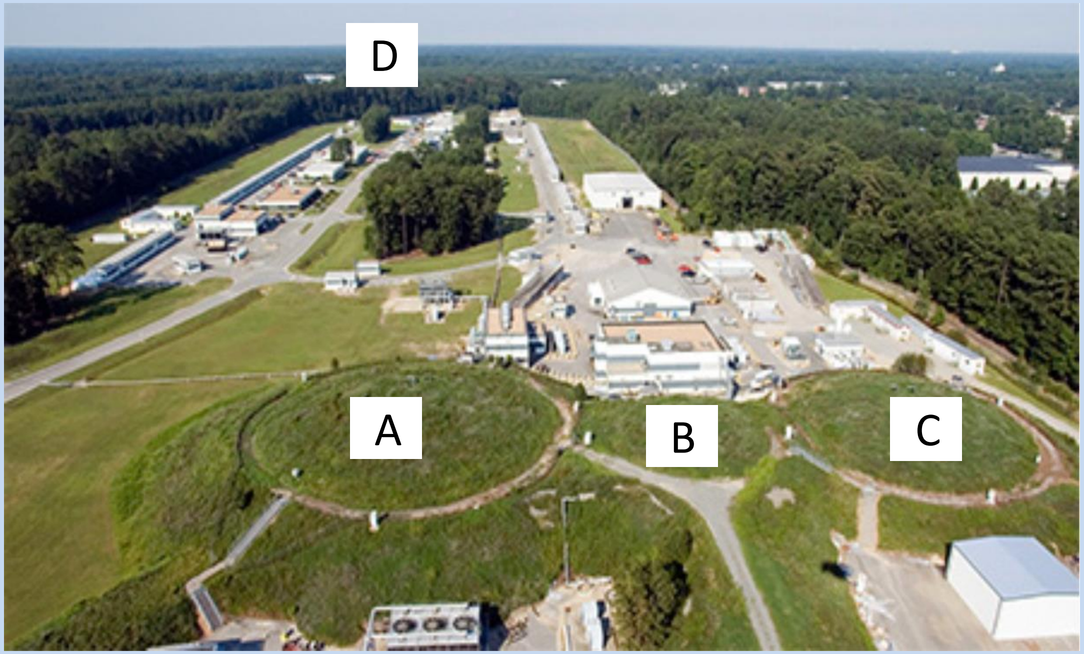
12 GeV energy

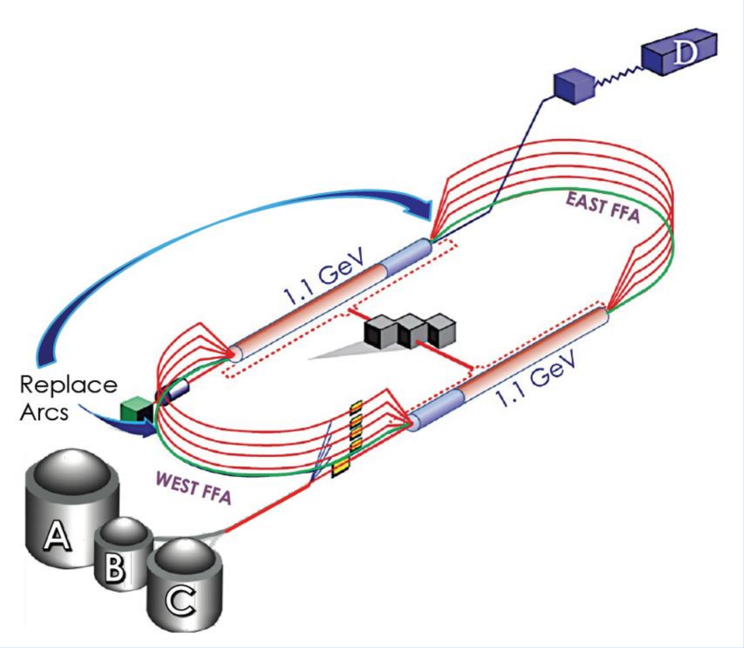
90 μA Beam Current

85 % Polarization

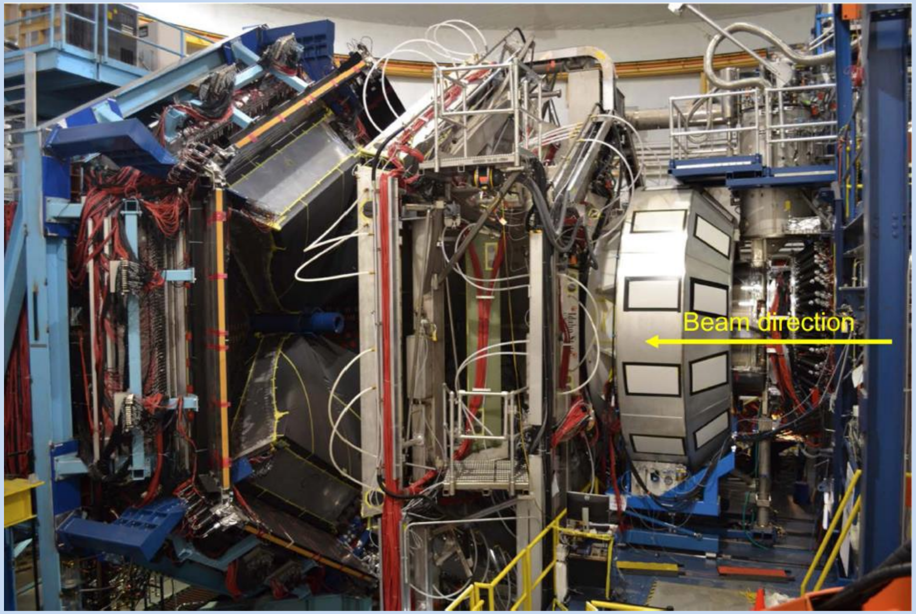
4 experimental Halls (A-D)

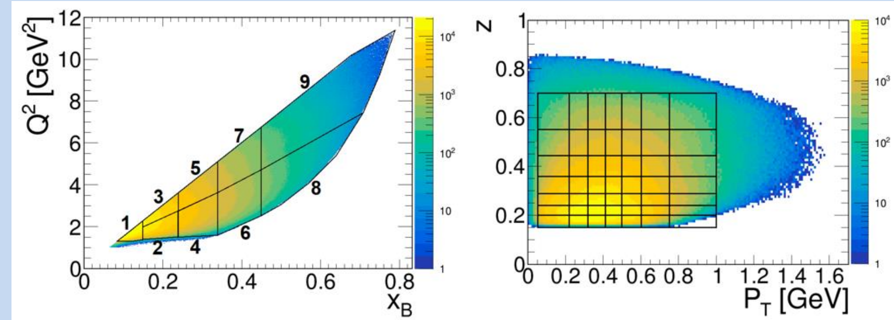


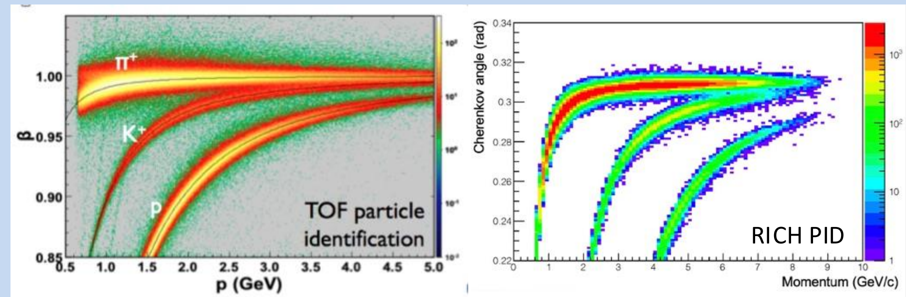




CLAS12 wide coverage, excellent PID, various polarized targets, high luminosity

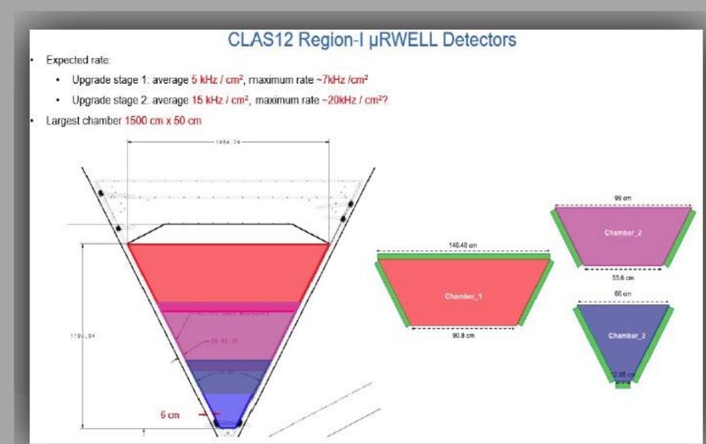






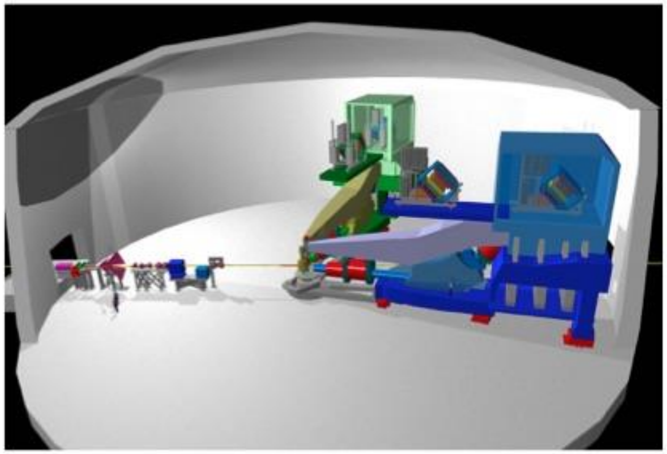
Year	Period	Run	Target	Polarization	Beam
2018	Spring-Fall	RGA	Proton	-	10.6 GeV
	Fall	RGK	Proton	-	6.5-7.5 GeV
2019	Spring	RGA	Proton	-	10.6 GeV
2019	Spring-Fall	RGB	Deuteron	-	10.6 GeV
2020	Spring-Fall	RGF	Deuteron	-	10.6 GeV
2021	Fall	RGM	Nuclear	-	Several GeV
2022	Spring-Fall	RGC	NH_3-ND_3	Longitudinal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



Upcoming @ JLab

SBS: Spectrometer Pair



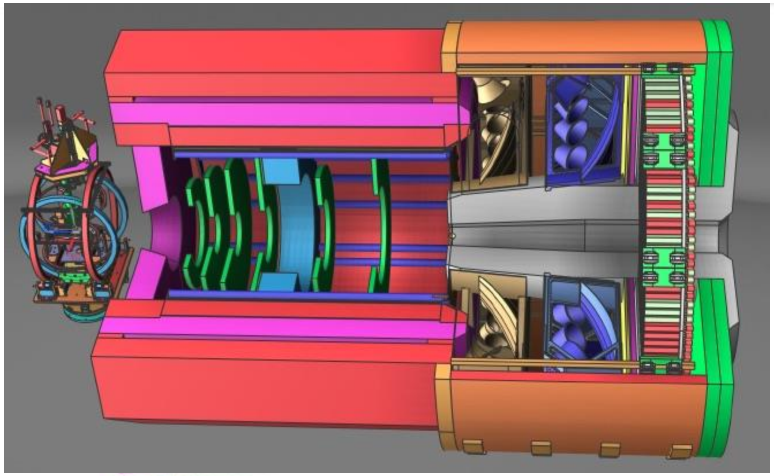
Hall-A:

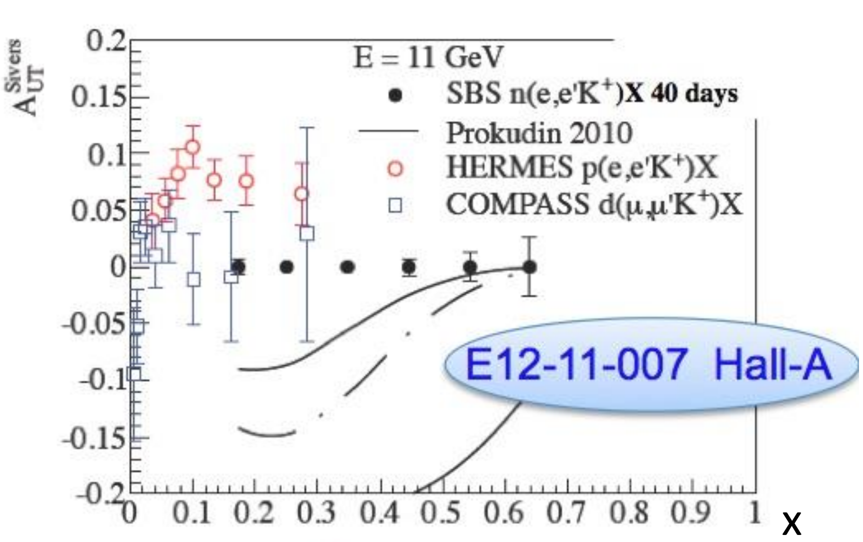
High-luminosity
10^{38} cm^{-2}s^{-1}

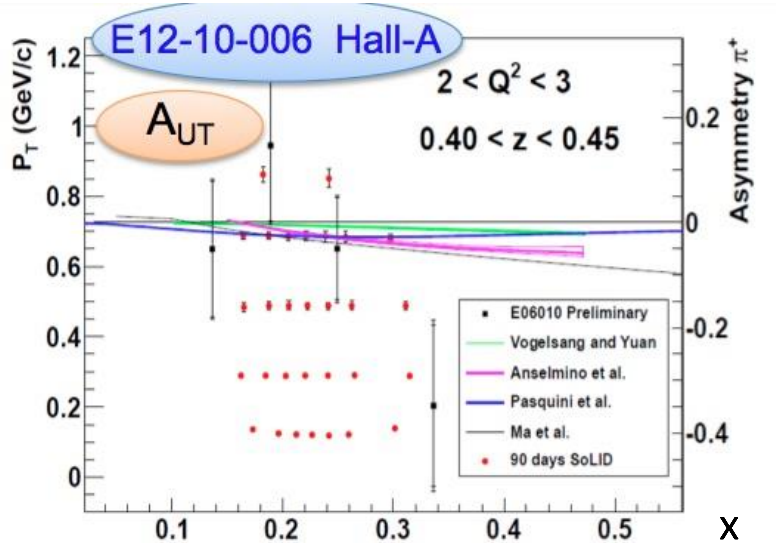
^{3}He targets

Wide coverage

SOLID: Large Acceptance Detector







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

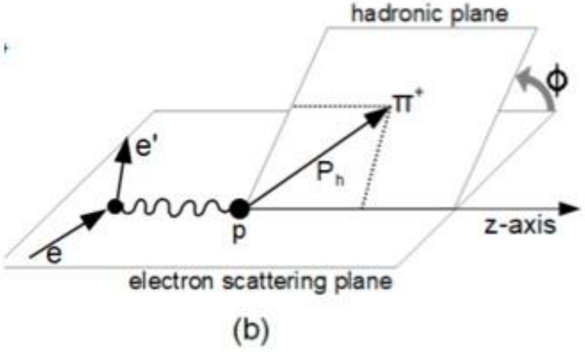
Beam Spin Asymmetry @ CLAS12

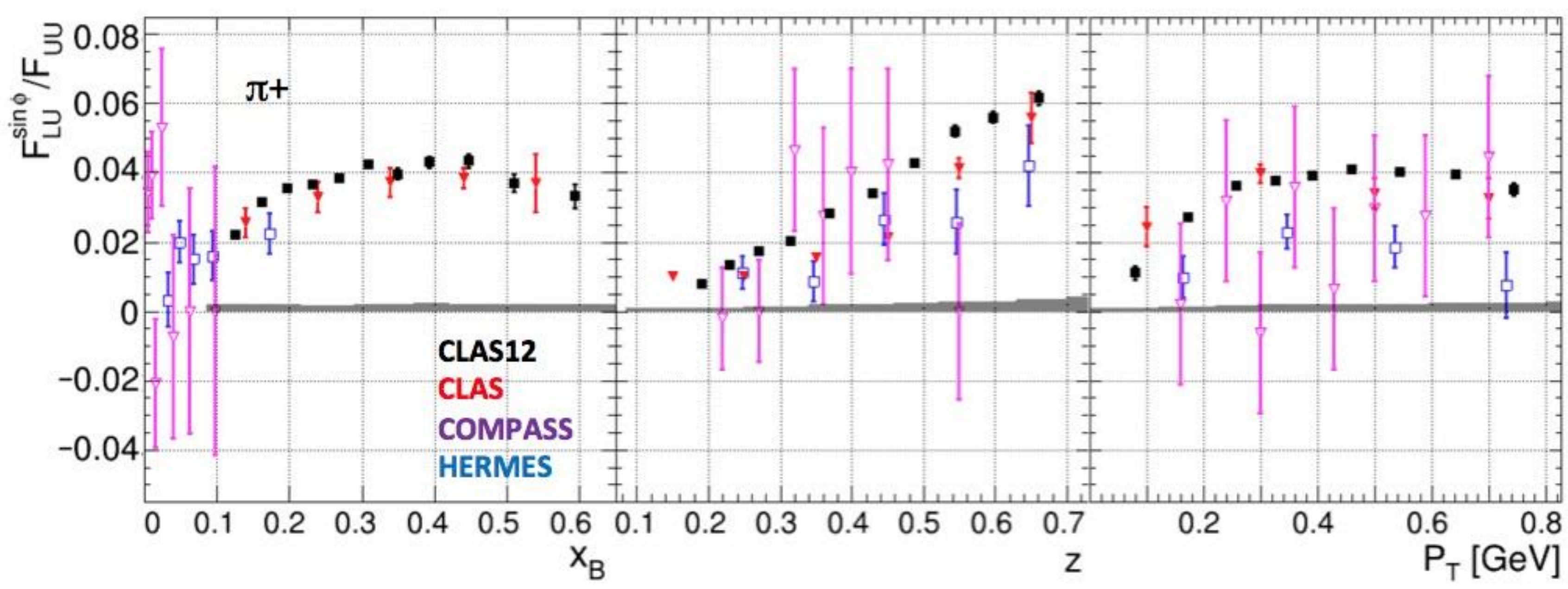
CLAS12 proton data (RGA)

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 %





Multiplicities @ CLAS12

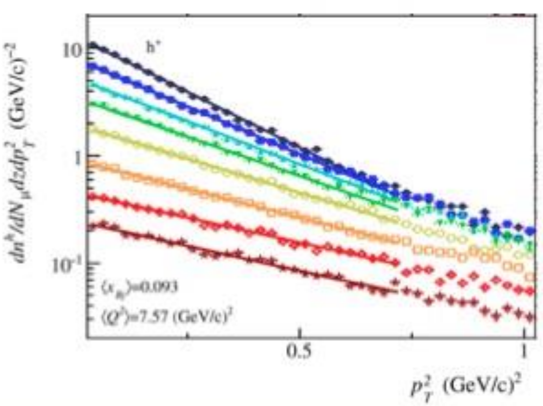
Transverse momentum dependence and phase space

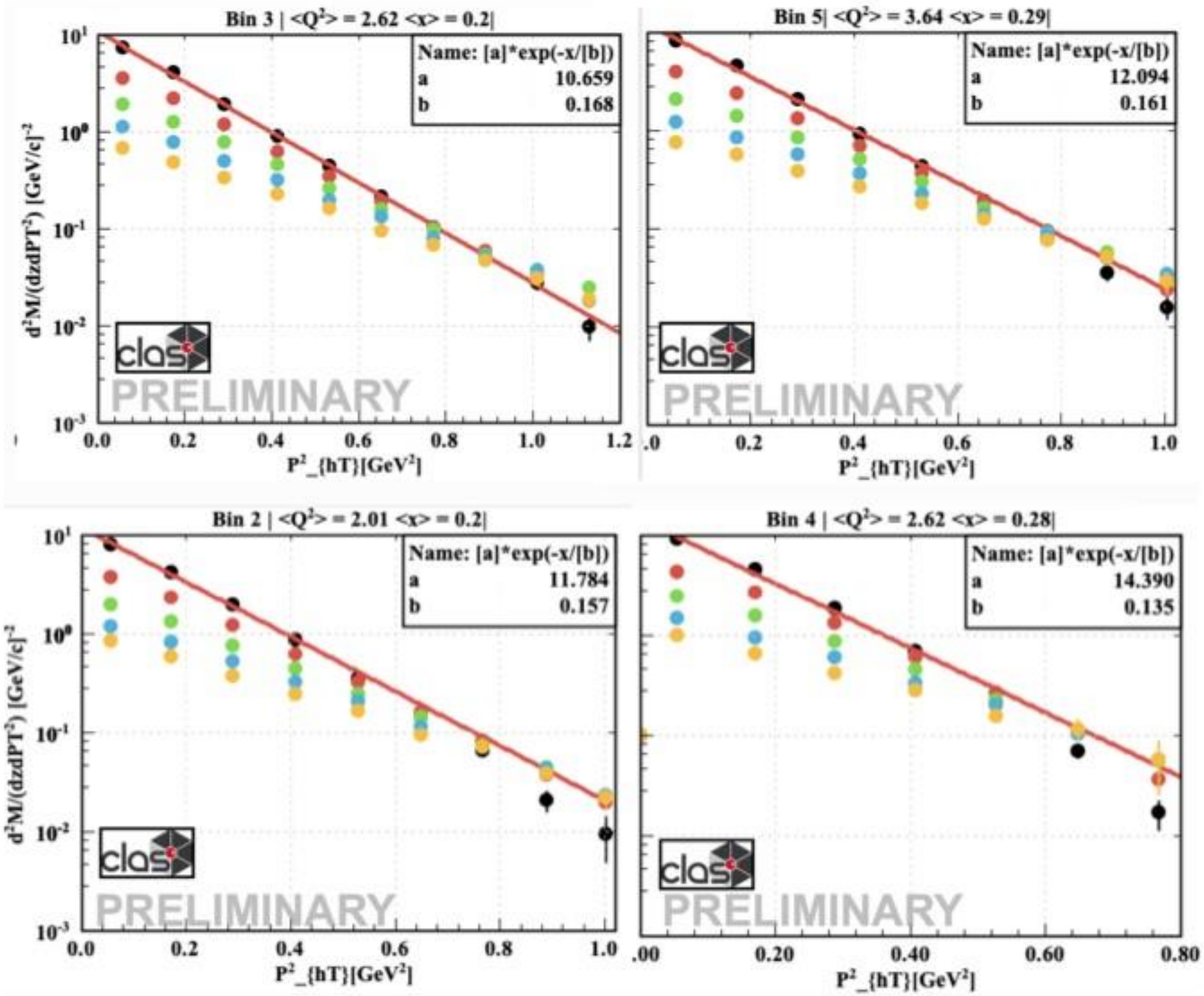
ep->eπ+X

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

COMPASS, EPJC 73 (2013) 8, 2531





<x> =0.2

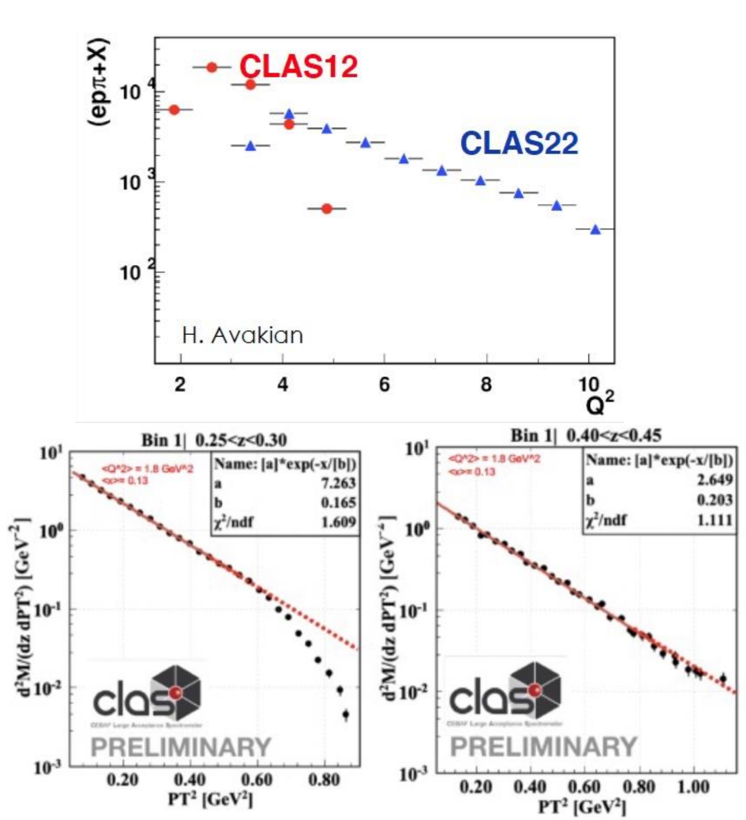
<x> =0.29

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+

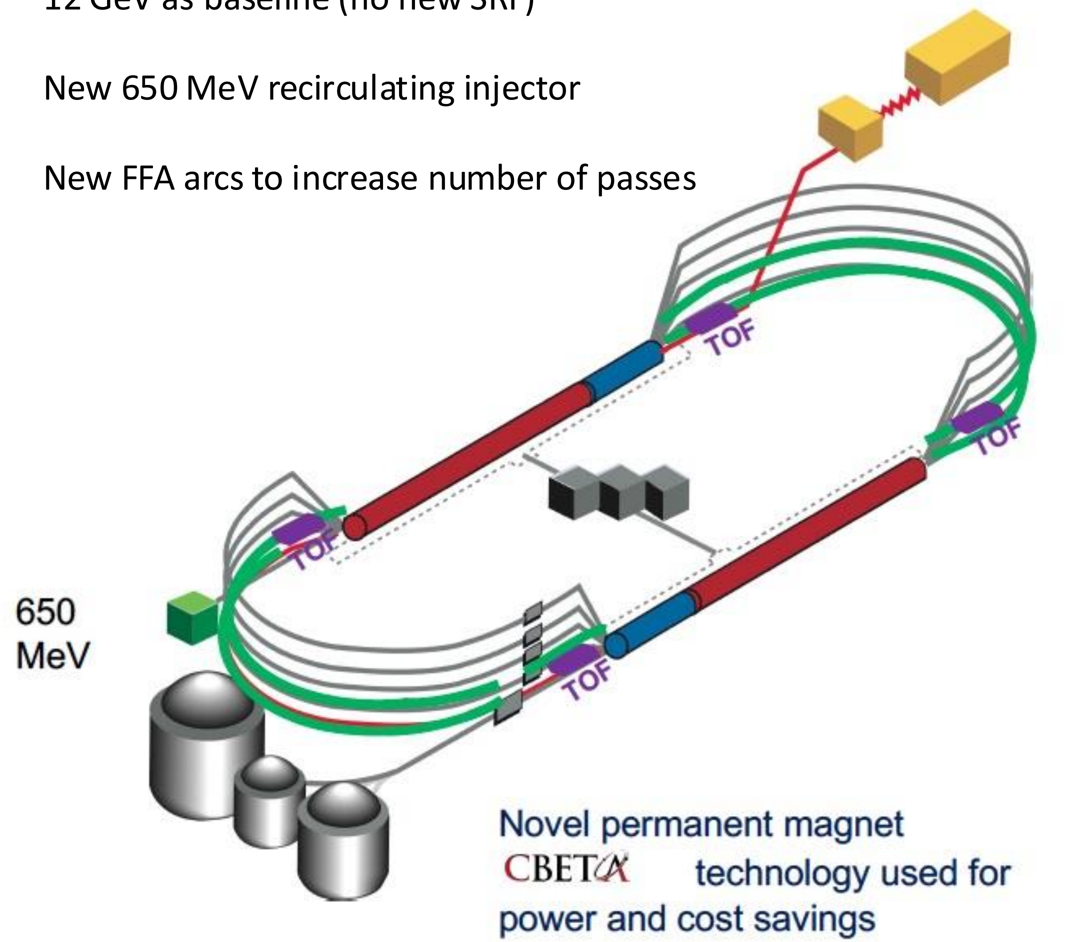
Positron source



12 GeV as baseline (no new SRF)

New 650 MeV recirculating injector

New FFA arcs to increase number of passes



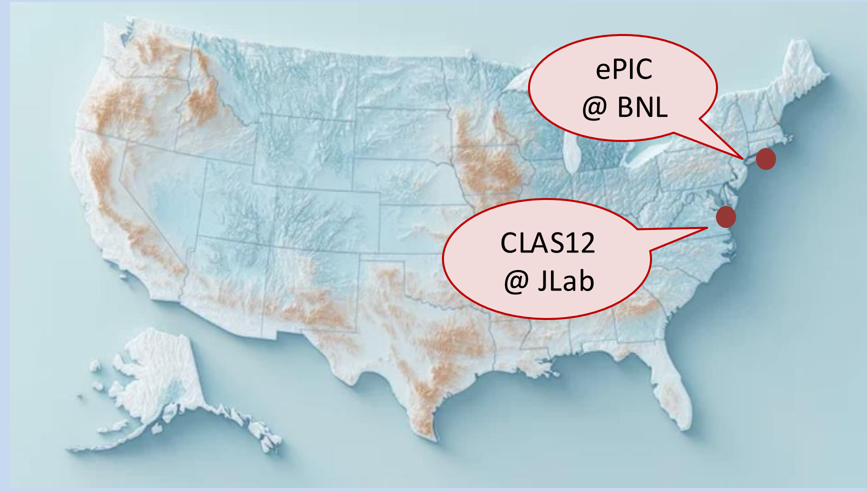
Brookhaven National Laboratory (BNL)
Electron-Ion Collider

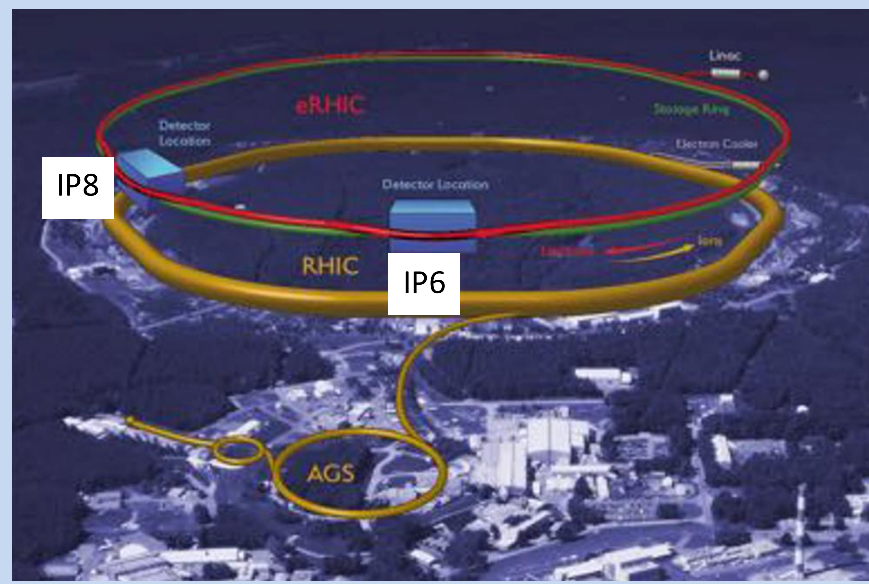
Hadron Beam 41-275 GeV

Electron Beam 5 -18 GeV

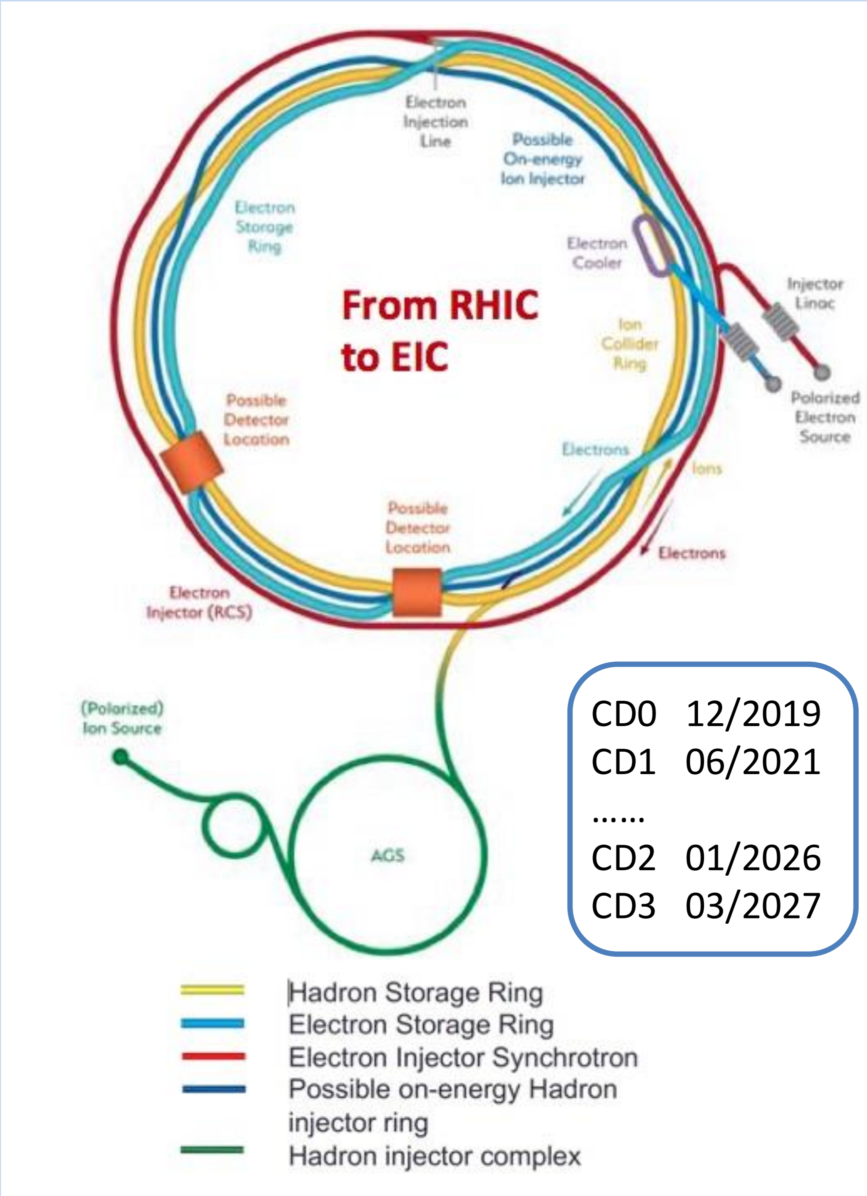
Polarized Electron and Light Ions

2 Interaction Points (IP6, IP8)



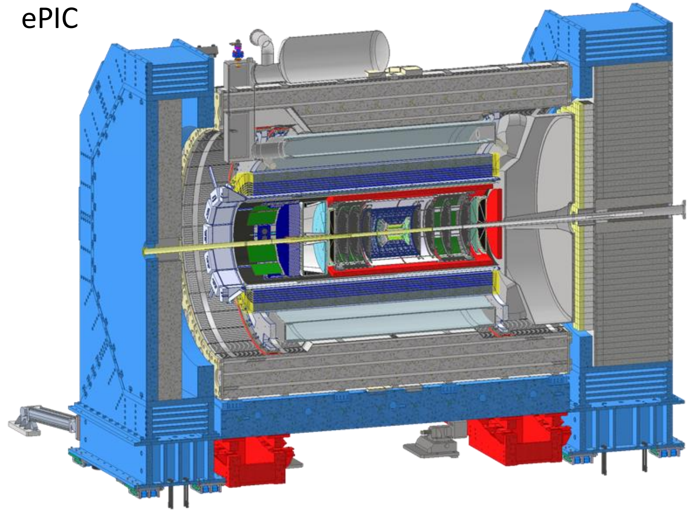


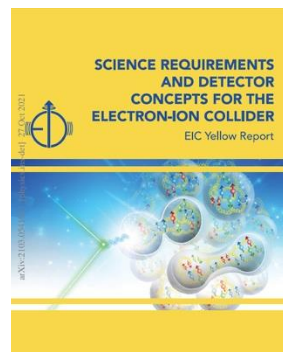
Electron-Ion Collider

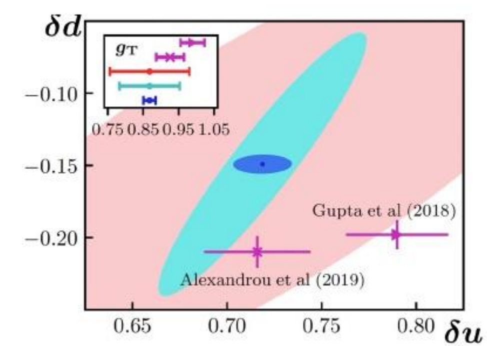


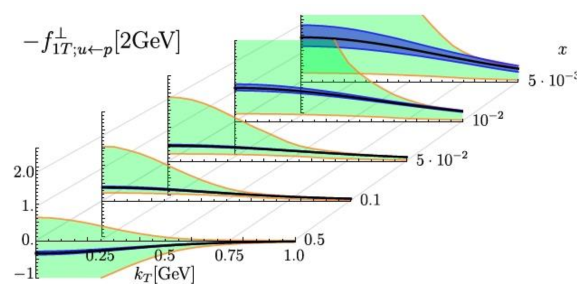
CD0 12/2019
CD1 06/2021
……
CD2 01/2026
CD3 03/2027

ePIC









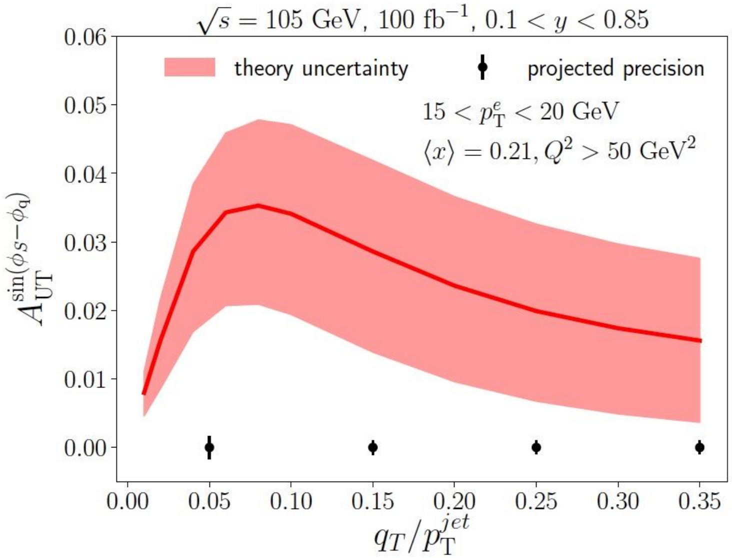
Yellow Report:
arXiv: 2103.05419

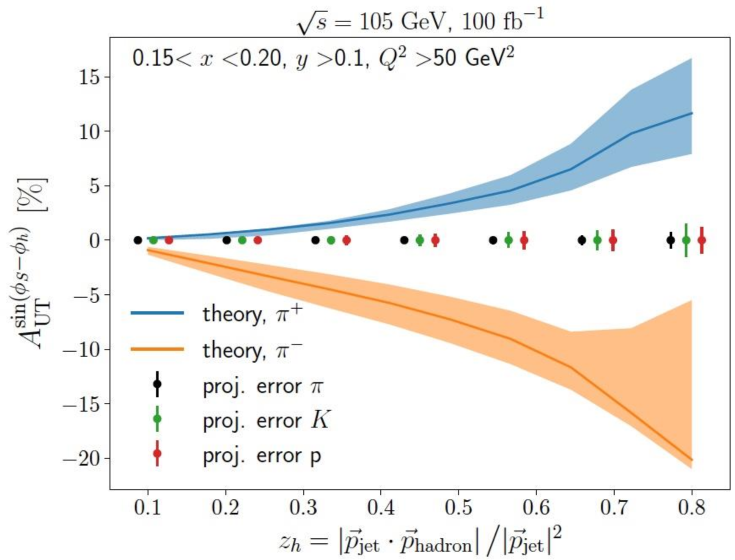
TMDs @ High Energy

Jets Sivers

Jets Collins

E.C. Aschenauer ++ [arXiv: 1708.01527]



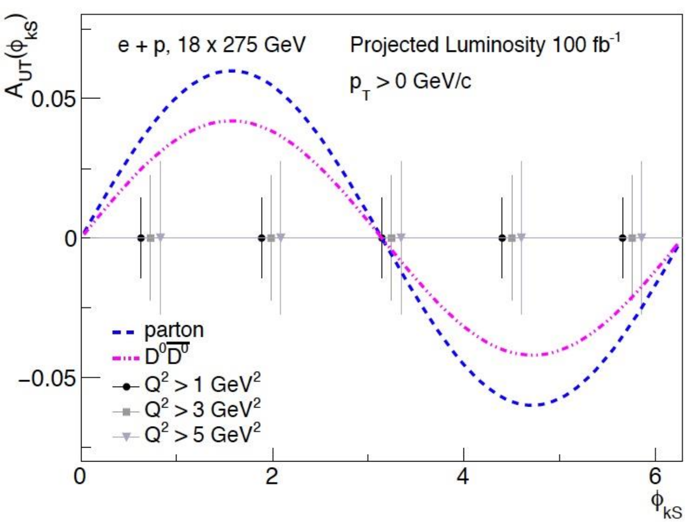


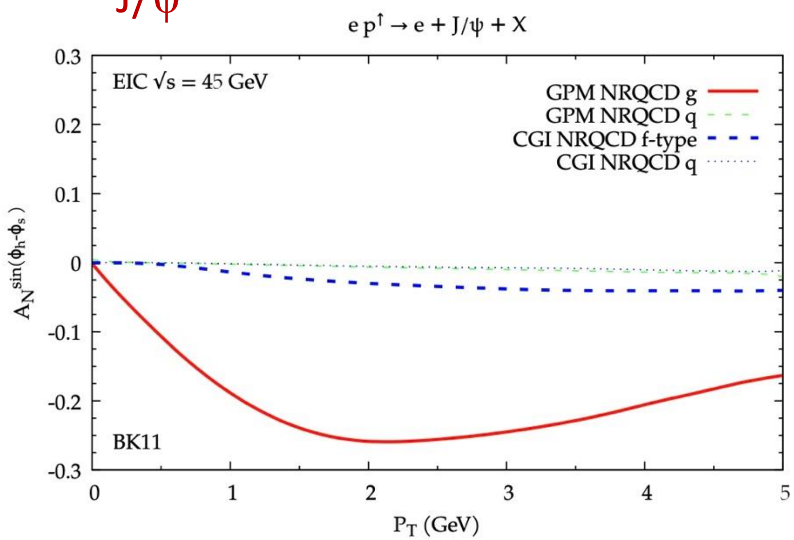
D^0

Gluon TMDs

J/ψ

U. D'Alesio++ [arXiv: 2203.03299]





SIDIS Cross-Section

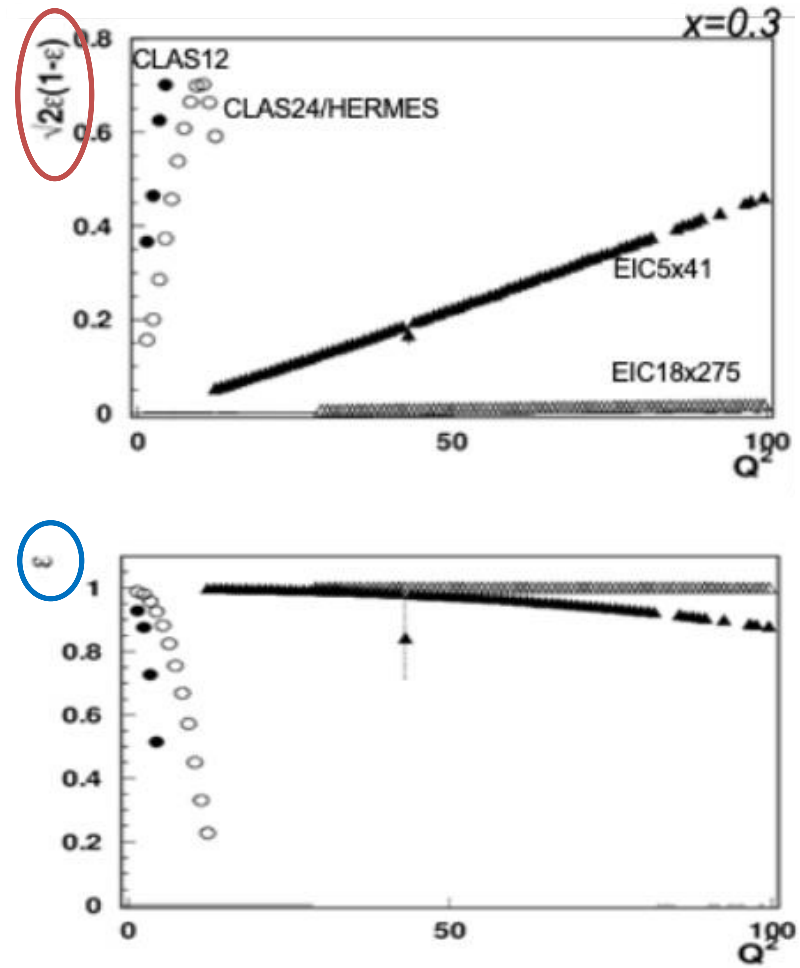
$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2}
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Big\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}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

Sub-Leading Terms

$$
F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\Big[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\Big(xh\,H_1^{\perp} + \frac{M_h}{M}\,f_1\frac{\tilde{D}^{\perp}}{z}\Big) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\Big(x f^{\perp} D_1 + \frac{M_h}{M}\,h_1^{\perp}\frac{\tilde{H}}{z}\Big)\Big]
$$

TMD Evolution

Evolution kernel (with CS non-perturbative kernel)

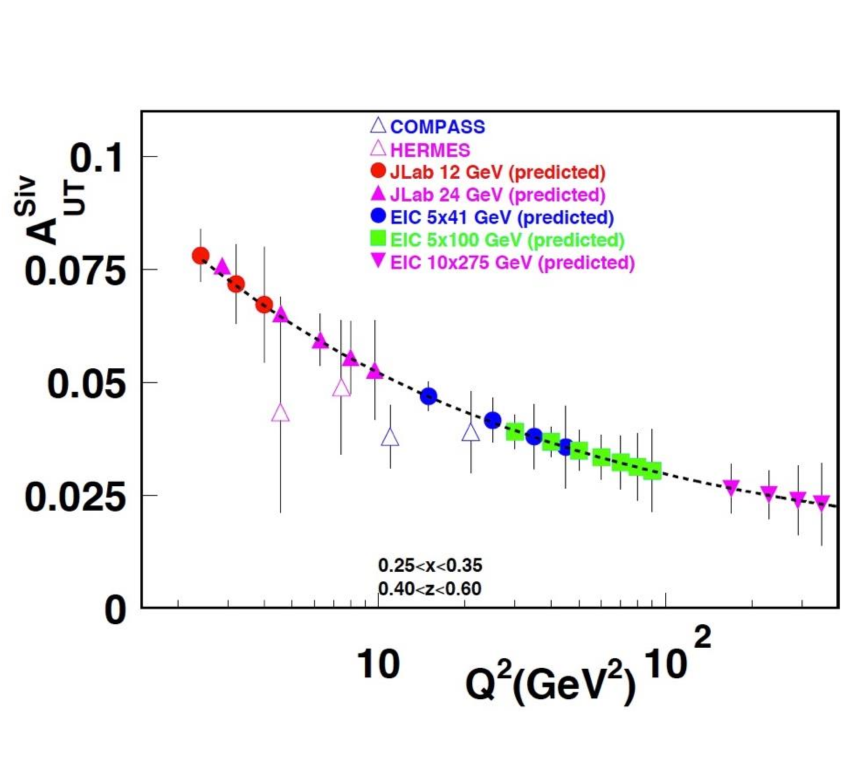


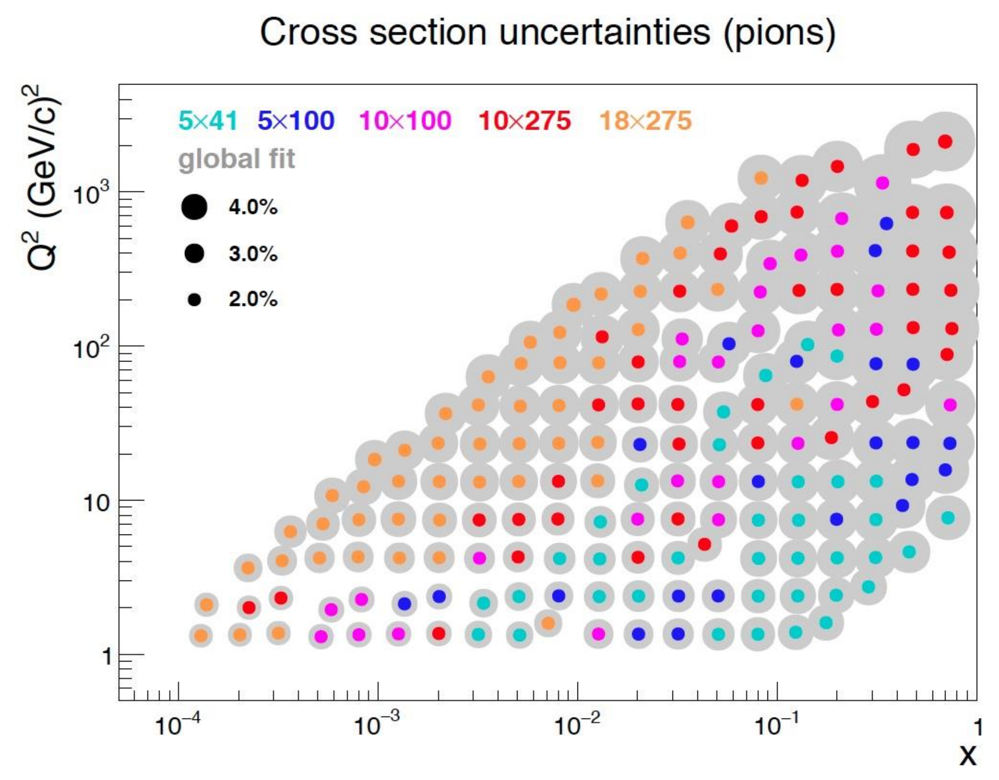
H. Avakian at Transversity 2022

The Q^2 Game

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

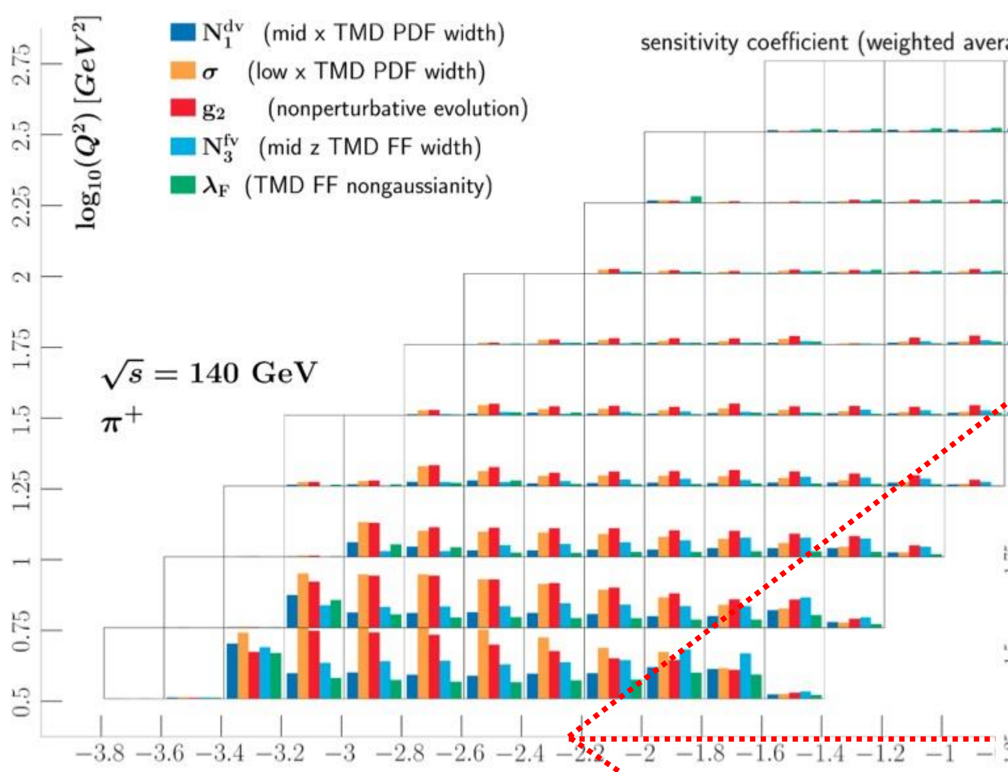
Keep Q^2 moderate to: avoid perturbative dilution

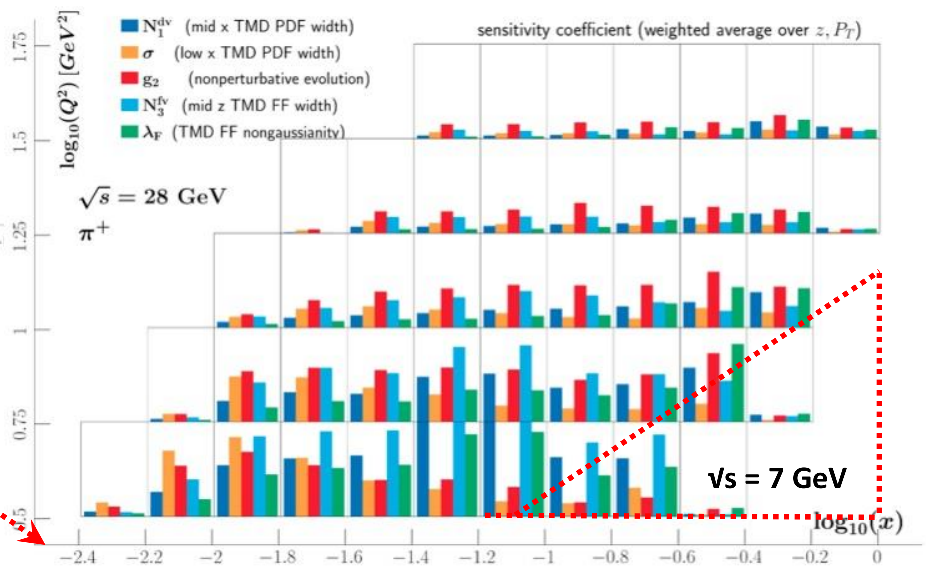




The sensitivity on the relevant parameters changes with center of mass energy

Yellow Report [arXiv: 2103.05419]





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

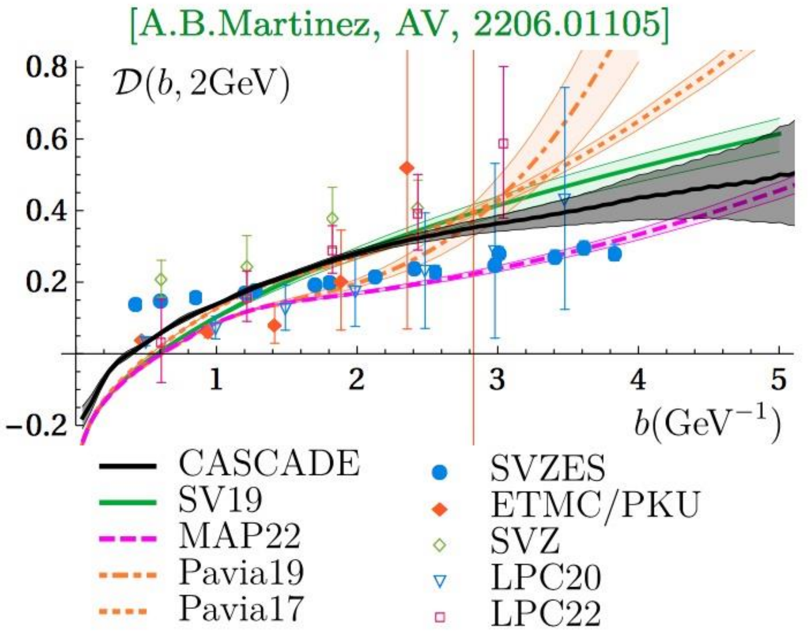
TMD Evolution

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

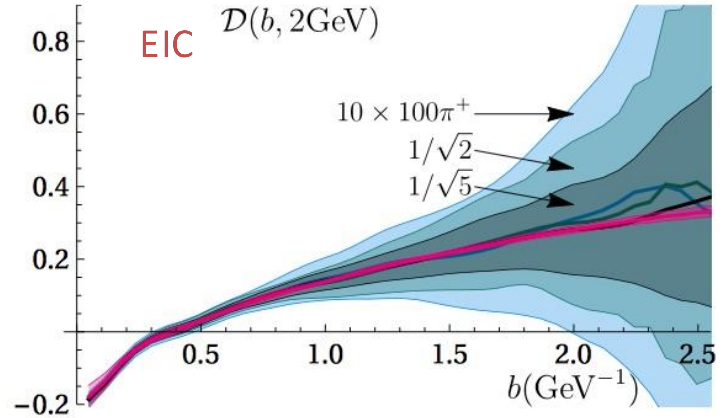
With b as Fourier conjugate of P_T/z

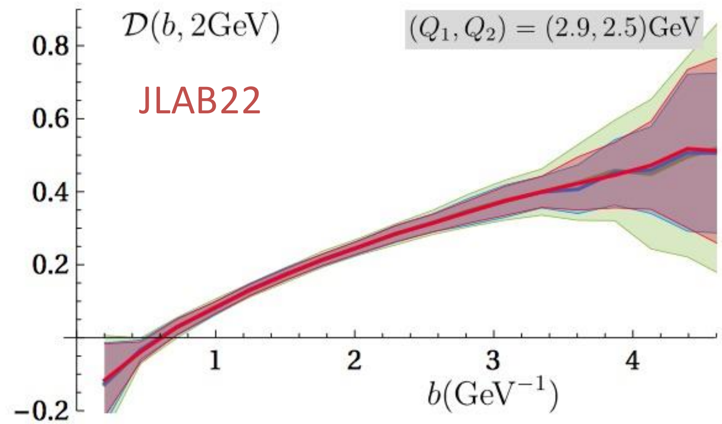
$$F_{UT}^{\sin(\phi_h-\phi_S)} = \sum_q e_q^2 |C_V(Q)|^2 \int \frac{d^2b}{(2\pi)^2} e^{i(b\cdot P_T)/z} R(Q,b,\mu_0) f_{1T}^{\perp q}(x,b;\mu_0) D_1^q(z,b;\mu_0)$$

Collins-Soper non-perturbative evolution kernel



Complementarity in Q^2 and b coverage





A. Vladimirov @ APCTP22 workshop

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