Transverse spin structure: from experiment to theory

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Quantum Chromodynamics

There is no doubt that QCD is the right theory for hadron physics

However, many fundamental questions…

- How does the nucleon mass emerge from the light quarks dynamically?
- Why quarks and gluons are confined inside the nucleon?
- How do the fundamental nuclear forces arise from QCD?
- …

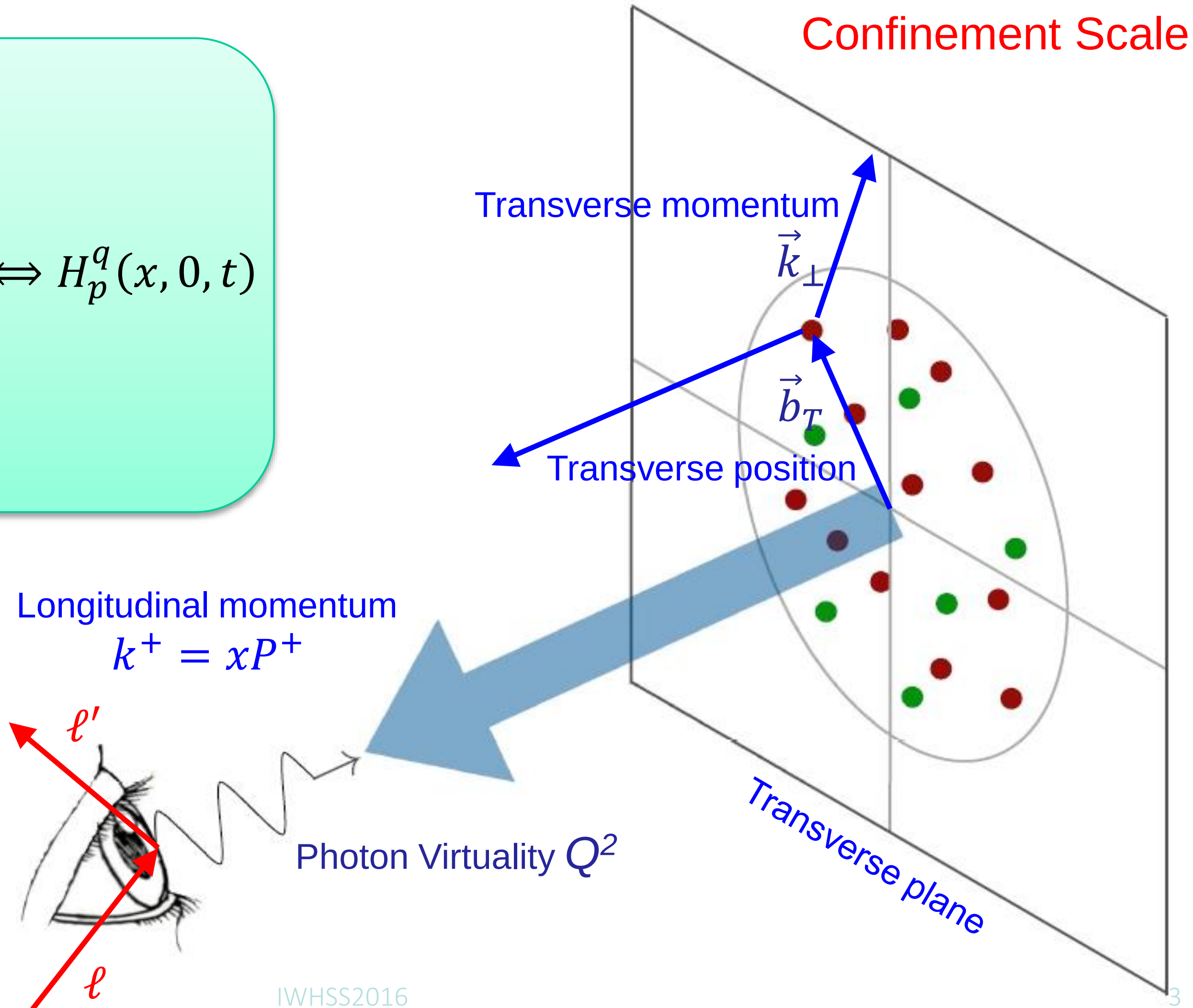
We don’t have a comprehensive picture of the nucleon structure as we don’t have a QCD nucleon wave function

THE 3D VIEW OF THE PROTON (from TMDs and GPDs) ALLOWS NEW INSIGHTs TO QCD

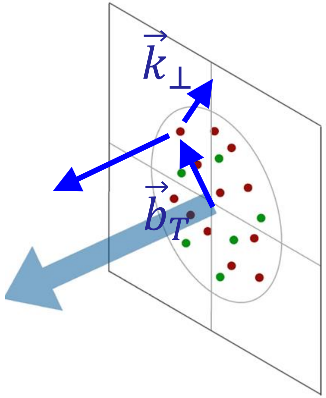
Transverse structure of the Nucleon

$$\begin{tikzcd}
& W_p^q(x,\vec{k}_\perp,\vec{b}_T) \arrow[dl, "d^2b_T"'] \arrow[dr, "d^2k_\perp"] & \\
f_p^q(x,\vec{k}_\perp) \arrow[dr, "d^2k_\perp"'] & & f_p^q(x,\vec{b}_T) \Leftrightarrow H_p^q(x,0,t) \arrow[dl, "d^2b_T"] \\
& f_p^q(x) &
\end{tikzcd}$$

High Energy Probe
Hard Scale



Confined parton motion in a hadron



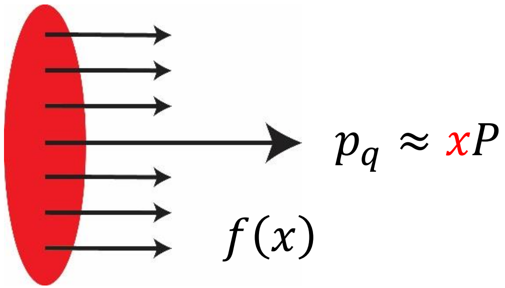
- Scattering with a large momentum transfer
  - Momentum scale of the hard probe $Q \gg {}^1/_R \sim \Lambda_{QCD} \sim 1\ \mathrm{fm}$
  - Combined motion $\sim {}^1/_R$ is too week to be sensitive to the hard probe
  - Collinear factorization – integrated into PDFs
- Scattering with multiple momentum scales observed
  - Two-scale observables (such as SIDIS, low p_T Drell-Yan) $Q \gg q_T \sim {}^1/_R \sim \Lambda_{QCD} \sim 1\ \mathrm{fm}$
  - “Hard” scale Q localizes the probe to see the quark or gluon d.o.f.
  - “Soft” scale q_T could be sensitive to the confined motion
  - TMD factorization: the confined motion is encoded into TMDs

The orbital motion:

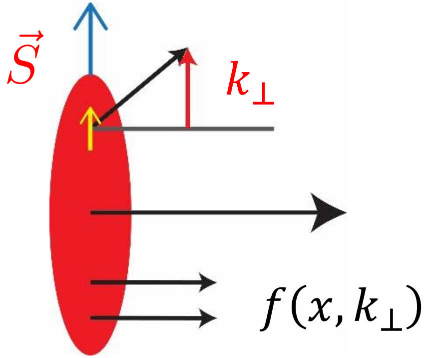
- Orbital motion of quarks and gluons must be significant inside the nucleons!
  - This is in contrast to the naive non-relativistic quark model, which was the motivation to introduce the color quantum number!
- Orbital motion shall generate direct orbital Angular Momentum which must contribute to the spin of the proton
- Orbital motion can also give rise to a range of interesting physical effects (Single Spin Asymmetries)

Structure of proton

- Transverse Momentum Dependent parton distribution (TMDs)



Longitudinal motion only



Longitudinal + transverse motion

- Sivers function: an asymmetric parton distribution in a transversely polarized nucleon ($k_\perp$ correlated with the spin of the nucleon)

$$f_{q/h\uparrow}(x, k_\perp, \vec{S}) = f_{q/h}(x, k_\perp) - \frac{1}{M} f_{1T}^{\perp q}(x, k_\perp) \vec{S} \cdot (\hat{p} \times \vec{k}_\perp)$$

- Boer-Mulders function: an asymmetric parton distribution in an unpolarised nucleon ($k_\perp$ correlated with the spin of the quark)

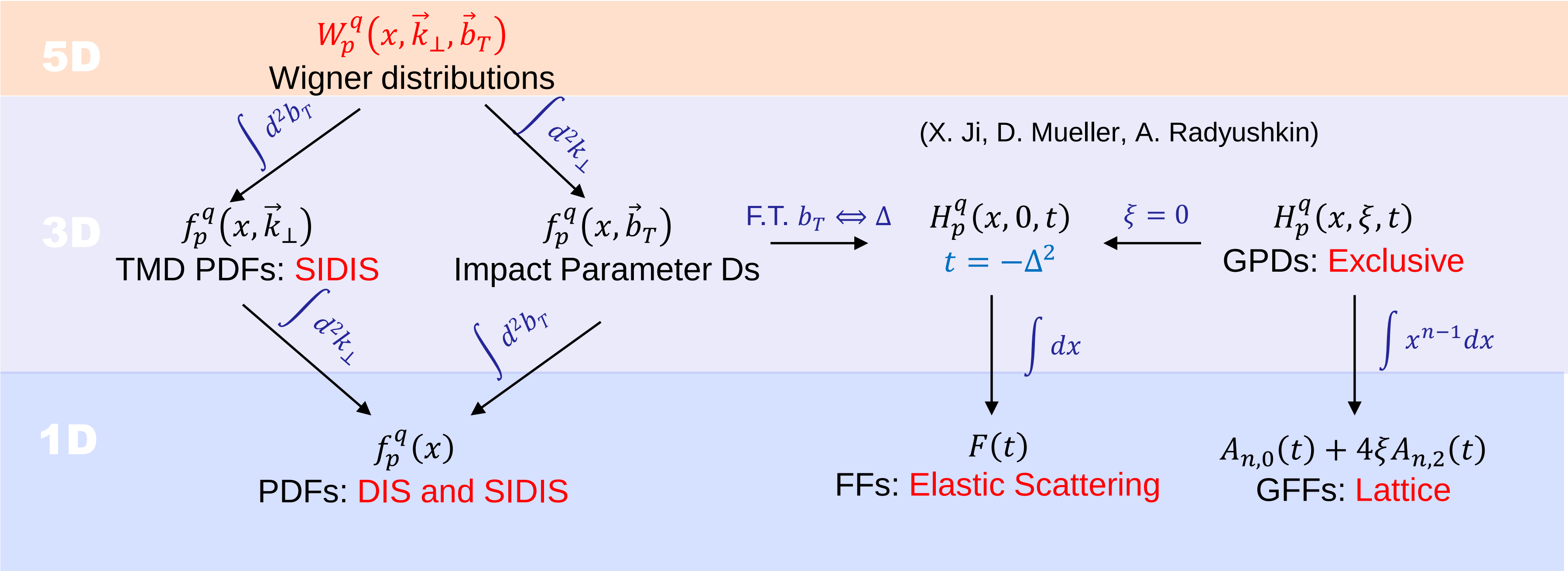
$$f_{q/h\uparrow}(x, k_\perp, \vec{s}) = f_{q/h}(x, k_\perp) - \frac{1}{M} h_{1T}^{\perp q}(x, k_\perp) \vec{s} \cdot (\hat{p} \times \vec{k}_\perp)$$

New ways to look at partons

- We not only need to know that partons have longitudinal momentum, but must have transverse degrees of freedom as well
- Partons in transverse coordinate space
  - Generalized parton distributions (GPDs)
- Partons in transverse momentum space
  - Transverse-momentum distributions (TMDs)
- Both? Wigner distributions!

Unified view of the Nucleon

- Wigner distributions (Belitsky, Ji, Yuan)



5D

$W_p^q(x,\vec{k}_\perp,\vec{b}_T)$

Wigner distributions

$\int d^2b_T$

$\int d^2k_\perp$

(X. Ji, D. Mueller, A. Radyushkin)

3D

$f_p^q(x,\vec{k}_\perp)$

TMD PDFs: SIDIS

$f_p^q(x,\vec{b}_T)$

Impact Parameter Ds

F.T. $b_T \Leftrightarrow \Delta$

$H_p^q(x,0,t)$

$t = -\Delta^2$

$\xi = 0$

$H_p^q(x,\xi,t)$

GPDs: Exclusive

$\int d^2k_\perp$

$\int d^2b_T$

$\int dx$

$\int x^{n-1}dx$

1D

$f_p^q(x)$

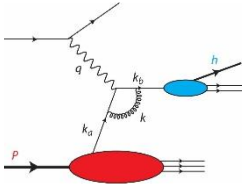
PDFs: DIS and SIDIS

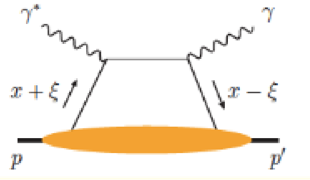
$F(t)$

FFs: Elastic Scattering

$A_{n,0}(t) + 4\xi A_{n,2}(t)$

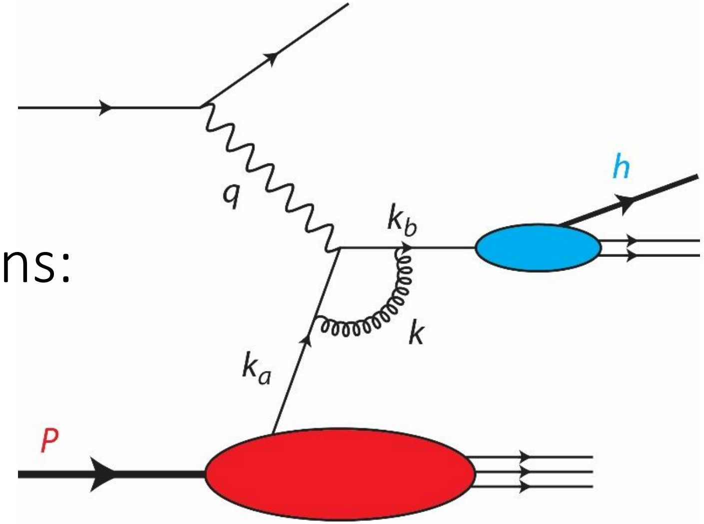
GFFs: Lattice





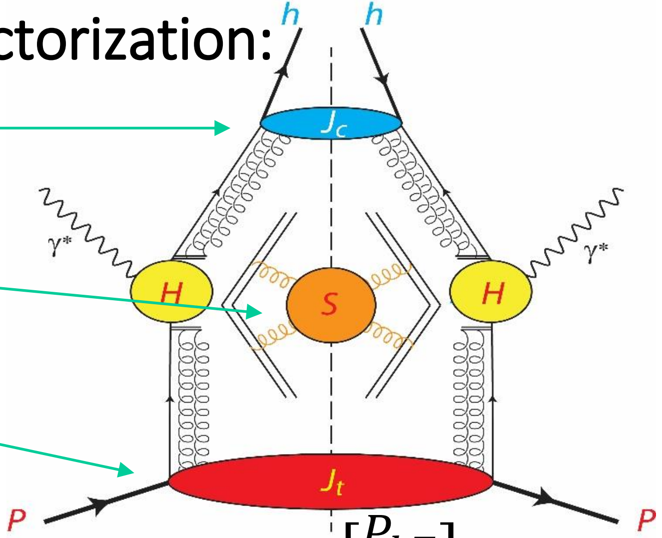
Factorization in QCD – SIDIS

- Parton model – LO QCD
  - Parton distribution function in a hadron
  - parton-to-hadron fragmentation function
- QCD interaction and leading power regions:
  - Collinear regions: $k \parallel P \ \ and\ k \parallel h$
  - Soft regions: $k^{\mu} \to 0$



Factorization in QCD – SIDIS

- Perturbative definition – in terms of TMD factorization:



TMD Fragmentation

Soft Factor

TMD Distribution

- Low P_{hT} – TMD factorization:

$$\sigma(Q, P_{hT}, x, z) = \hat{H}(Q) \otimes \phi_f(x, k_\perp) \otimes D_{f\to h}(z, p_\perp) \otimes S(k_{s\perp}) + \mathcal{O}\left[\frac{P_{hT}}{Q}\right]$$

- High P_{hT} – Collinear factorization:

$$\sigma(Q, P_{hT}, x, z) = \hat{H}(Q, P_{hT}, \alpha_s) \otimes \phi_f(x) \otimes D_{f\to h}(z) + \mathcal{O}\left[\frac{1}{P_{hT}}, \frac{1}{Q}\right]$$

- P_{hT} Integrated – Collinear factorization:

$$\sigma(Q, x, z) = \hat{H}(Q, \alpha_s) \otimes \phi_f(x) \otimes D_{f\to h}(z) + \mathcal{O}\left[\frac{1}{Q}\right]$$

Transverse-Momentum Dependent PDFs

- **Inclusive** processes → collinear factorisation: one or less hadrons detected
- **“More inclusive”** processes → TMD factorisation: two or more hadrons in the initial or final state detected

- **Collinear factorisation**: longitudinal momenta of the patrons are intrinsic, transverse momenta can be created by perturbative radiation effects (parton showers)
- **TMD factorisation**: a unifying QCD-based framework with both mechanisms of the transverse-momentum creation taken into account: intrinsic (essentially non-perturbative) and perturbative radiation

Wilson Lines

- Parton Distribution Functions must be:
  - Gauge-invariant
  - Universal
  - Renormalizable
- Wilson lines are crucial for everything! BUT introduce path-dependence:
  - **Path-dependence**: the structure of the Wilson lines is process-dependent; universality (and/or factorisation) may be broken
  - **Factorisation scale** is arbitrary: transition from one scale to another (different experiments have different characteristic scales) by means of evolution equations; Wilson lines complicate renormalizability

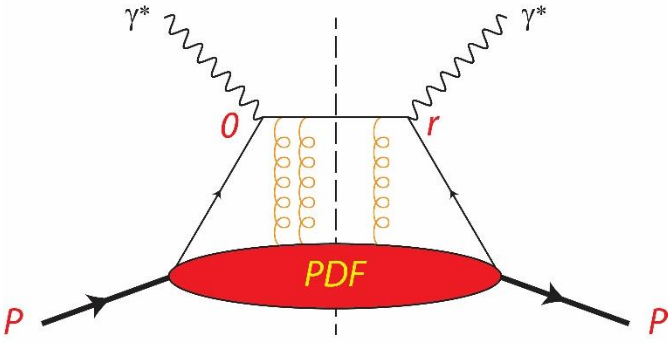
Ordinary PDFs

- The Bj limit ($Q^2, \nu \to \infty$ with $x = Q^2/2M\nu$ fixed) selects scattering on a single parton in the target. $\sigma_{DIS}(\ell N \to \ell' X)$ determines the ordinary PDF

$$f_{q/N}(x) = \frac{1}{8\pi}\int dr^- e^{-iMxr^-/2}\langle N(P)|\bar{q}(r^-)\gamma^+ W[r^-,0] q(q)|N(P)\rangle \,\Big|_{\substack{r^+\sim 1/\nu\to 0\\ r_\perp\sim 1/Q\to 0}}$$

- The Wilson line W arises from scattering of the struck quark in the target. It does not cancel between the amplitude and (amplitude)* since the photon vertices are separated by r^-… In the light-cone gauge, $A^+ = 0$, the Wilson link reduces to unity and can be omitted

- $W[r^-,0] \equiv P\exp\left[\frac{ig}{2}\int_0^{r^-} dx^- A^+(x^-)\right]$



TMD PDFs

- When we consider the TMD we take into account also the transverse motion of the quark $k_\perp$ The field-theoretical expression is quite complicated due to the structure of the gauge link, which now connects two space-time points with a transverse separation

$$f_{q/N}(x, k_\perp) = \frac{1}{8\pi}\int dr^- \frac{dr_\perp^2}{(2\pi)^2} e^{-iMxr^-/2+ik_\perp\cdot r_\perp}$$

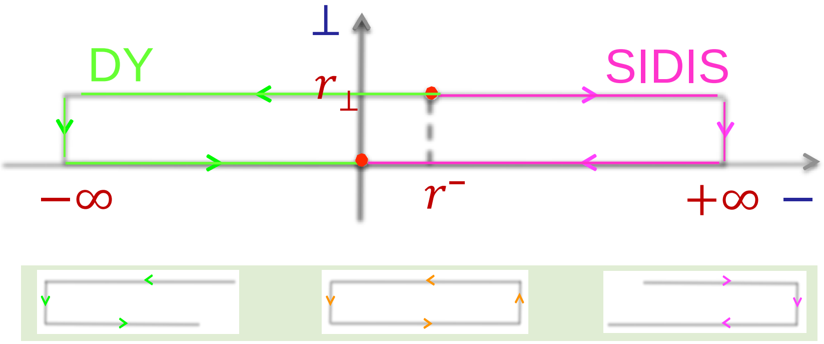
$$\langle N(P)|\bar{q}(r^-, r_\perp)\gamma^+ W[r^-, r_\perp; 0]q(0)|N(P)\rangle|_{r^+\sim 1/\nu\to 0}$$

- The Wilson line W is no longer on the light-cone axis and may introduce a **process dependence**

Parity and Time reversal invariance ⇒

$$\left(f_{1Tq}^{\perp}\right)_{DY} = -\left(f_{1Tq}^{\perp}\right)_{SIDIS}$$

Most critical test to TMD approach to SSA



Energy dependence of TMDs

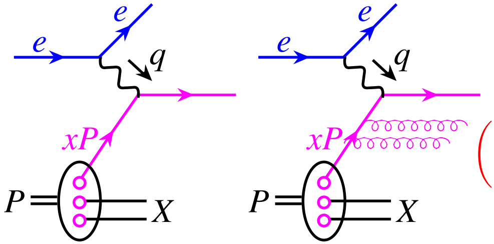
- Experiments operate in very different kinematic ranges
  - Typical hard scale Q is different: $Q \sim 1\text{–}5$ GeV in SIDIS, $Q{\sim}4\text{–}90$ GeV for DY, $Q{\sim}3\text{–}10$ GeV in e^+e^-
  - Also center-of-mass energy is different
- Such energy dependence (evolution) has to be taken into account for any reliable QCD description/prediction
- Both collinear PDFs and TMDs depend on the energy scale Q at which they are measured, such dependences are governed by QCD evolution equations

Collinear PDFs $F(x, Q)$

TMDs $F(x, k_\perp; Q)$

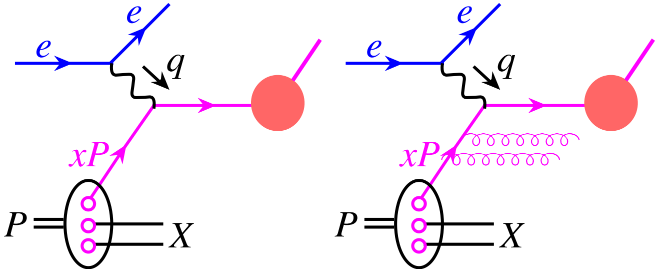
QCD evolution: meaning

- Evolution = include important perturbative corrections
  - DGLAP evolution of collinear PDFs: what it does is to resum the so-called single logarithms in the higher order perturbative calculations



$$\left(\alpha_s \ln \frac{Q^2}{\mu^2}\right)^n$$

- TMD factorization works in the situation where there are two observed momenta in the process, $Q \gg q_T$: resums the so-called double logarithms in the higher order perturbative corrections



$$\left(\alpha_s \ln^2 \frac{Q^2}{q_T^2}\right)^n$$

Main difference between collinear and TMD evolution

- Collinear PDFs (DGLAP): the evolution kernel is purely perturbative

$$\frac{\partial f_a(x,Q)}{\partial \ln Q^2} = \sum_b \int_z^1 \frac{dz}{z} P_{a\leftarrow b}\left(\frac{x}{z},Q\right) f_b(z,Q)$$

$$f(x,Q_i) \longrightarrow R_{\text{Coll}}(x,Q_i,Q_f) \longrightarrow f(x,Q_f)$$

- TMDs: the evolution kernels are not. They contain non-perturbative component, which makes the evolution much more complicated
  - $k_\perp$ can run into non-perturbative region

$$F(x,k_\perp,Q_i) \longrightarrow R_{\text{TMD}}(x,k_\perp,Q_i,Q_f) \longrightarrow F(x,k_\perp,Q_f)$$

TMD evolution

$$F(x, k_\perp; Q_i)$$

- We have a TMD above measured at a scale Q. It is easier to deal in the Fourier transformed space

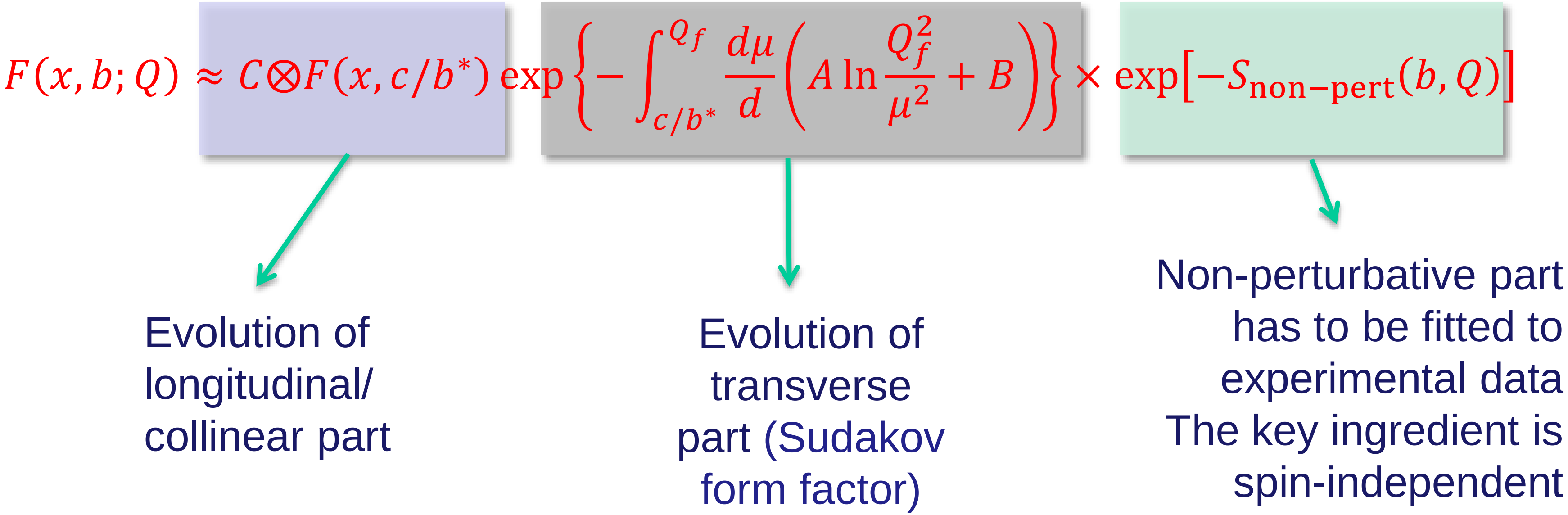
$$F(x, b; Q_i) = \int d^2\boldsymbol{k}_\perp e^{-i,k_\perp \cdot b} F(x, k_\perp; Q_i)$$

- In the small b region, one can then compute the evolution to this TMDs, which goes like

$$F(x, b; Q_f) = F(x, b; Q_i) \exp\left\{-\int_{Q_i}^{Q_f} \frac{d\mu}{d}\left(A \ln\frac{Q_f^2}{\mu^2} + B\right)\right\}\left(\frac{Q_f^2}{Q_i^2}\right)^{-\int_{c/b}^{Q_i} \frac{d\mu}{d} A}$$

TMD evolution:

- QCD evolution of TMDs in Fourier space (solution of equation)



$$F(x,b;Q) \approx C\otimes F(x,c/b^{*})\,\exp\left\{-\int_{c/b^{*}}^{Q_f}\frac{d\mu}{d}\left(A\ln\frac{Q_f^2}{\mu^2}+B\right)\right\}\times\exp\left[-S_{\text{non-pert}}(b,Q)\right]$$

Evolution of longitudinal/ collinear part

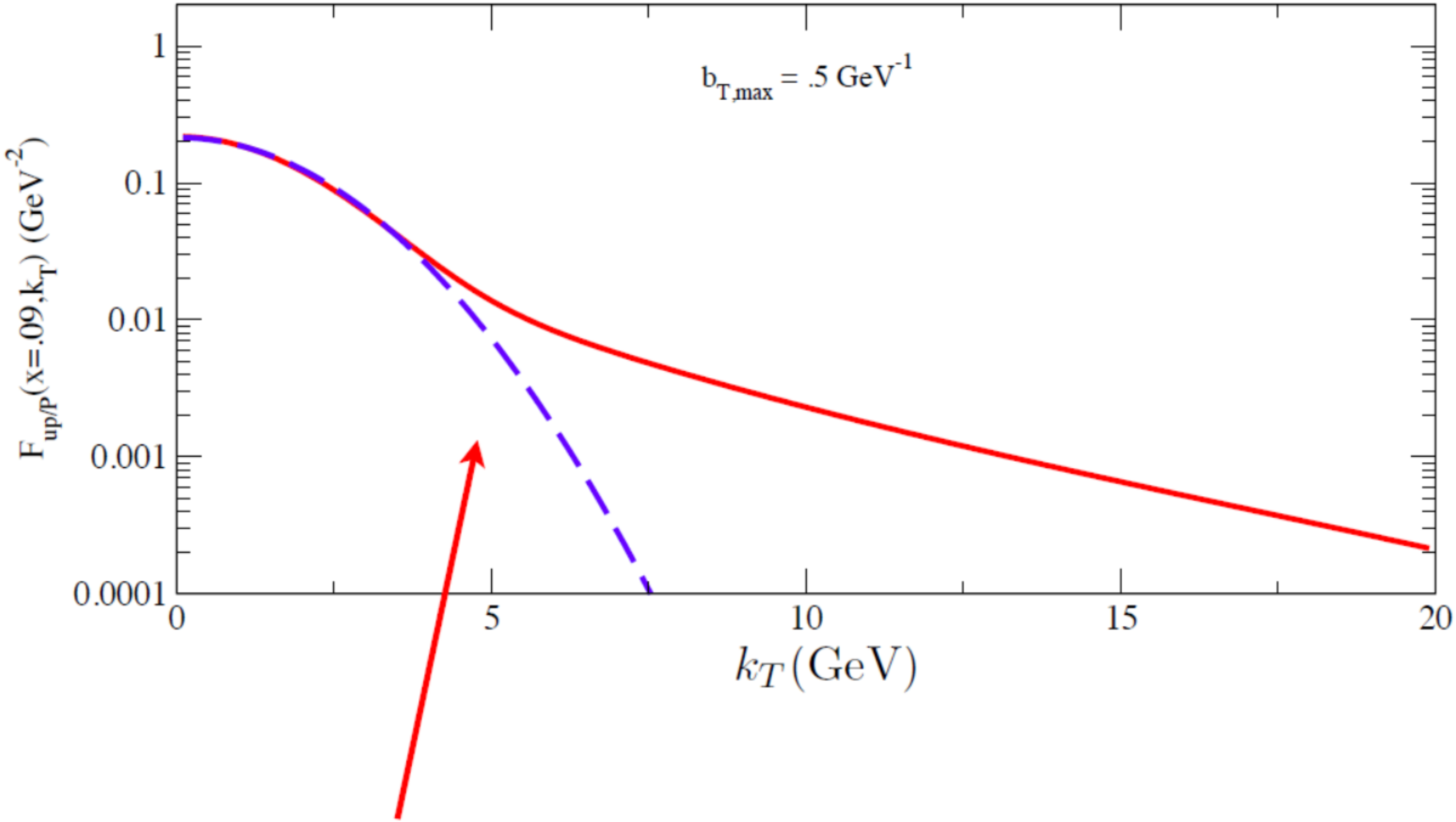
Evolution of transverse part (Sudakov form factor)

Non-perturbative part has to be fitted to experimental data

The key ingredient is spin-independent

- Polarized scattering data comes as ratio: e.g. $A_{UT}^{\sin(\phi_h-\phi_s)} = F_{UT}^{\sin(\phi_h-\phi_s)}/F_{UU}$
- Unpolarized data is very important to constrain/extract the key ingredient for the non-perturbative part

Effect of QCD evolution



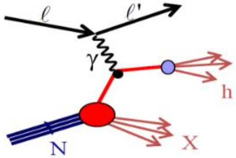
gaussian fit does not capture the effects of evolution quite well

TMD evolution

- High-energy DIS: rise of the proton structure function at small-x. As parton longitudinal momentum fractions x become small, the transverse degrees of freedom becomes increasingly important.
- The strong corrections at small-x come from multiple radiation of gluons over long intervals in rapidity, and are present in all higher orders of perturbation theory. TMD evolution provides an appropriate framework to resum such corrections.

Accessing TMD PDFs and FFs

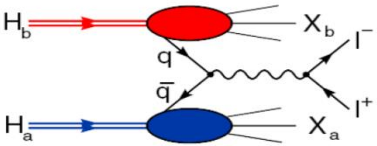
- TMD factorization works in the domain where there are two observed momenta in the process, such as SIDIS, DY, e^+e^-. $Q \gg q_T$: Q is large to ensure the use of pQCD, q_T is much smaller such that it is sensitive to parton's transverse momentum
- SIDIS off polarized p, d, n targets



HERMES
COMPASS
JLab
future: ***eN colliders?***

$\sigma^{\ell p\to\ell' hX} \sim q(x) \otimes \hat{\sigma}^{\gamma q\to q} \otimes D_q^h(z)$

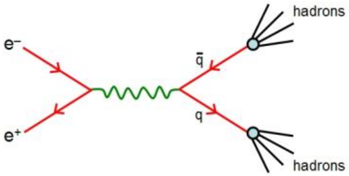
- polarised Drell-Yan



COMPASS
RHIC
FNAL
future: ***FAIR, JPark, NICA***

$\sigma^{hp\to\mu\mu} \sim \bar{q}_h(x_1) \otimes q_p(x_2) \otimes \hat{\sigma}^{\bar{q}q\to\mu\mu}(\hat{s})$

- $e^+e^- \to h_1 h_2$



BaBar
Belle
Bes III

$\sigma^{e^+e^-\to h_1 h_2} \sim \hat{\sigma}^{\ell\ell\to\bar{q}q}(\hat{s}) \otimes D_q^{h_1}(z_1) \otimes D_q^{h_2}(z_2)$

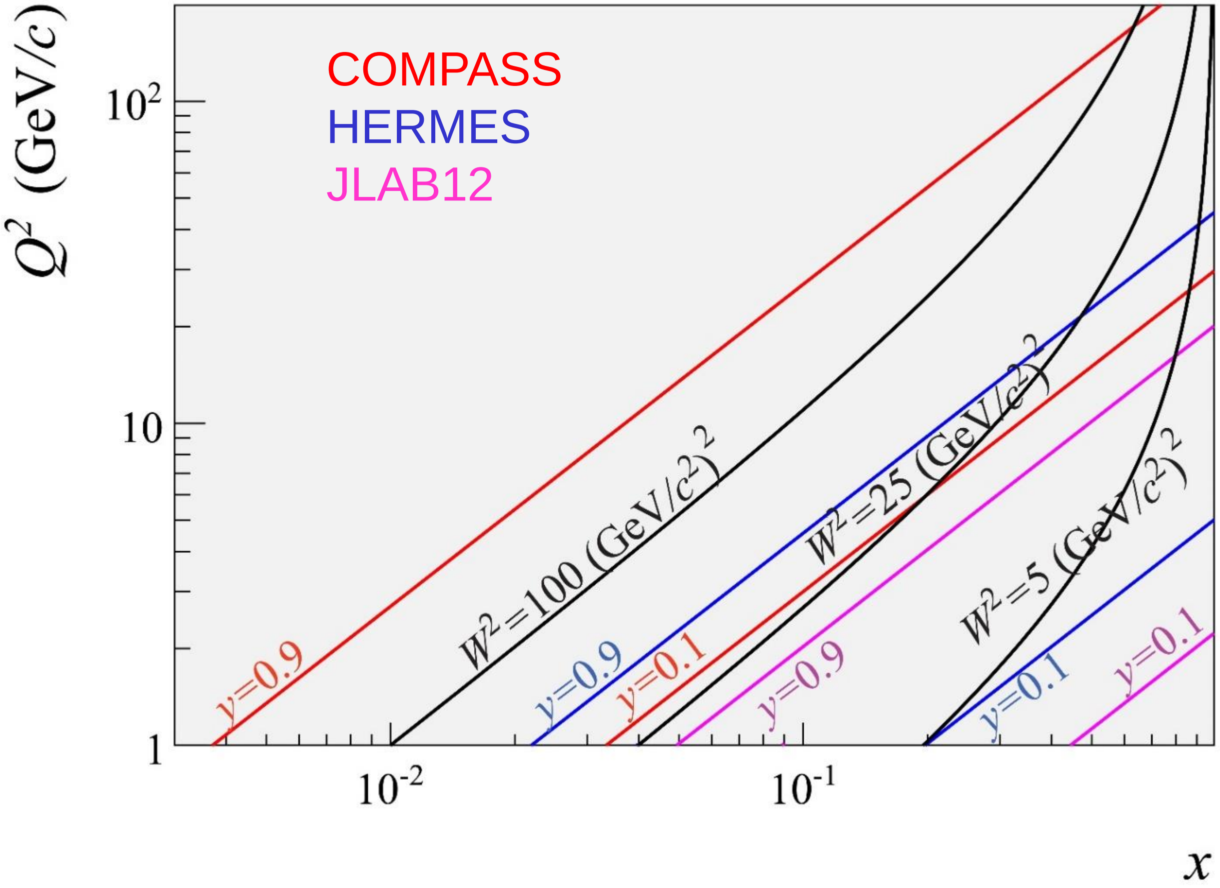
SIDIS Experiments

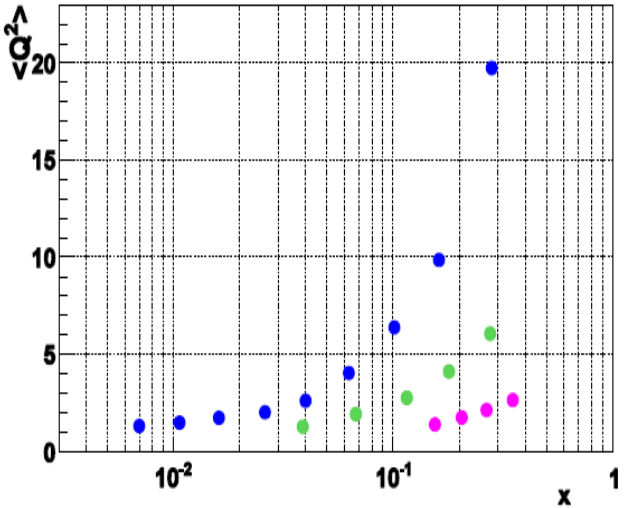
SIDIS Experiment must:

- Have large acceptances on all the relevant variables x, Q^2, z, P_{hT}, ϕ
- Use different targets (p, d, n) and identify hadrons to allow flavour separation
- Be ad different energies for to cover PDFs from the valence region down to small-x
- Large luminosity to allow multidimensional results needed by the complexity of TMDs

- **The polarized lepton-nucleon collider will be a mandatory tool to reach the level of ordinary PDF**

Kinematic coverage





SIDIS access to TMDs

Factorisation (Collins & Soper, Ji, Ma, Yuan,
Qiu & Vogelsang, Collins & Metz...)

$$\sigma(\ell p \rightarrow \ell' h X) \sim q(x) \otimes \hat{\sigma}^{\gamma q \rightarrow q} \otimes D_q^h(z)$$

chiral odd

T odd

Nucleon polarization

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

Hadron polarization

Parton polarization	U	T	L
U	D_1	$D_{1T}^{\perp}$	
T	$H_1^{\perp}$	H_1 , $H_{1T}^{\perp}$	$H_{1T}^{\perp}$
L		G_{1T}	G_{1L}

- NOT directly accessible
- Their extractions require measurements of x-sections and asymmetries in **a large kinematic domain of** x, Q^2, z, P_{hT}

Measurements with the target transversely polarized:

Year	Obs	
2005	$A^{h}_{Siv,d}, A^{h}_{Col,d}$	First ^{6}LiD data
2006	$A^{h}_{Siv,d}, A^{h}_{Col,d}$	Full ^{6}LiD statistics
2009	$A^{\pi^\pm, K^\pm, K^0_S}_{Siv,d}, A^{\pi^\pm, K^\pm, K^0_S}_{Col,d}$	Full ^{6}LiD statistics
2010	$A^{h}_{Siv,p}, A^{h}_{Col,p}$	2007 NH_3 data
2012	$A^{sin\phi_{RS}}_{UT,d}, A^{sin\phi_{RS}}_{UT,p}$	Full ^{6}LiD
2012	$A^{h}_{Siv,p}, A^{h}_{Col,p}$	Full NH_3statistics
2012	$A^{sin(\phi_\rho - \phi_S)}_{UT,d}, A^{sin(\phi_\rho - \phi_S)}_{UT,p}$	Exclusive ρ^0
2013	$A^{(\phi_\rho, \phi_S)}_{UT,d}, A^{(\phi_\rho, \phi_S)}_{UT,p}$	Exclusive ρ^0, all asyms.
2014	$A^{sin\phi_{RS}}_{UT,d}, A^{sin\phi_{RS}}_{UT,p}$	Full ^{6}LiD and NH_3
2014	$A^{\pi^\pm, K^\pm, K^0_S}_{Siv,d}, A^{\pi^\pm, K^\pm, K^0_S}_{Col,d}$	Full NH_3 statistics
2015	Interplay $A^{sin\phi_{RS}}_{UT,p}$ vs $A^{h}_{Col,p}$	Full NH_3 statistics

Measurements with unpolarised targets:

Year	Obs	
2013	$dn^h/(dN^\mu dz\, dp_T^2)$	Unpolarized multiplicities on d, 2004
2014	$A_{UU,d}^{\cos\phi_h}, A_{UU,d}^{\cos 2\phi_h}, A_{LU,d}^{\sin\phi_h}$	2004, part
2016	$dn^\pi/(dN^\mu dz)$	Unpolarized multiplicities on d, 2006
2016	$dn^h/(dN^\mu dz\, dp_T^2)$	Unpolarized multiplicities on d, 2006
2016	$dn^K/(dN^\mu dz)$	Unpolarized multiplicities on d, 2006

Multiplicity distributions

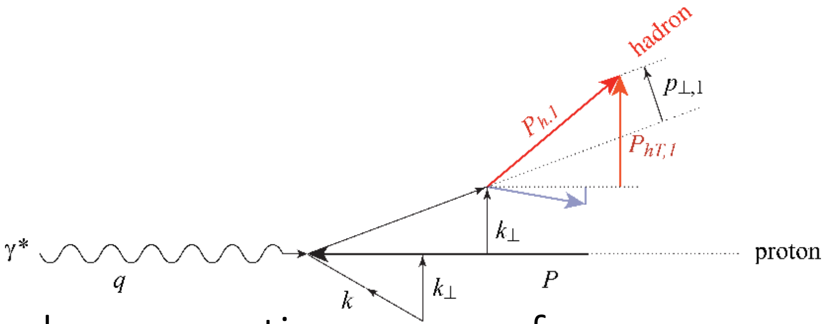
- Unpolarized hadron multiplicity distributions are the basic material for studying the mechanisms of P_{hT} generation and the applicability of TMD factorization.

- It is important to have differential distributions in kinematic variables x, Q^2, z besides P_{hT}

- Not only low P_{hT}. Tails at $P_{hT} > 1$GeV carries important perturbative & non-perturbative information

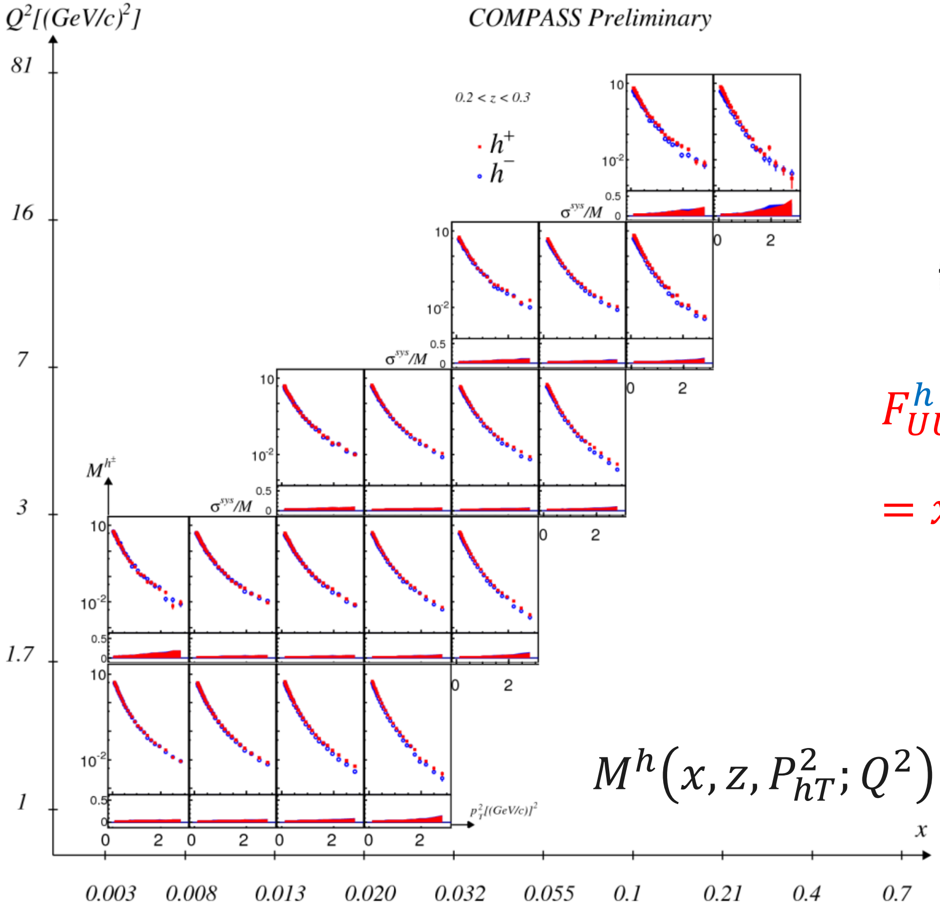
Importance of unpolarized SIDIS

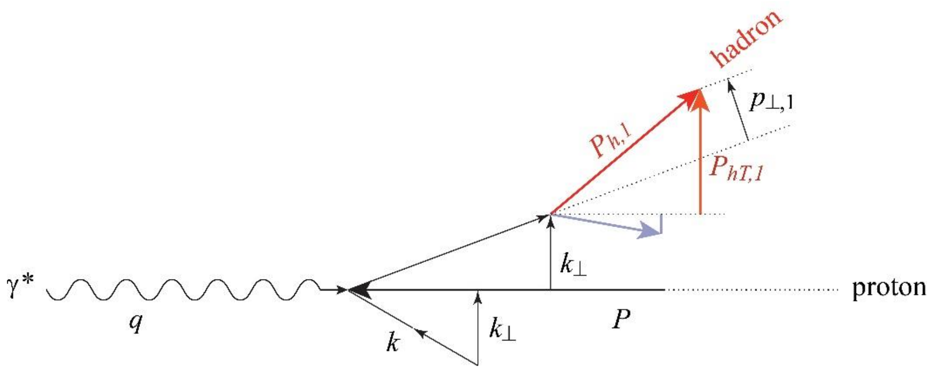
- The cross-section dependence from p_T^h results from:
  - intrinsic $k_\perp$ of the quarks
  - $p_\perp$ generated in the quark fragmentation
  - A Gaussian ansatz for $k_\perp$ and $p_\perp$ leads to
  - $\langle p_{T,h}^2 \rangle = z^2 \langle k_\perp^2 \rangle + \langle p_\perp^2 \rangle$



- The azimuthal modulations in the unpolarized cross-sections comes from:
  - Intrinsic $k_\perp$ of the quarks
  - The Boer-Mulders PDF
- Difficult measurements were one has to correct for the apparatus acceptance
- COMPASS and HERMES have
  - results on ^6LiD $(\sim d)$ and d
  - No measurements on p since on NH_3 $(\sim p)$ nuclear effects may be important
- ⇒COMPASS-II, measurements on LH_2 in parallel with DVCS

Importance of unpolarized SIDIS

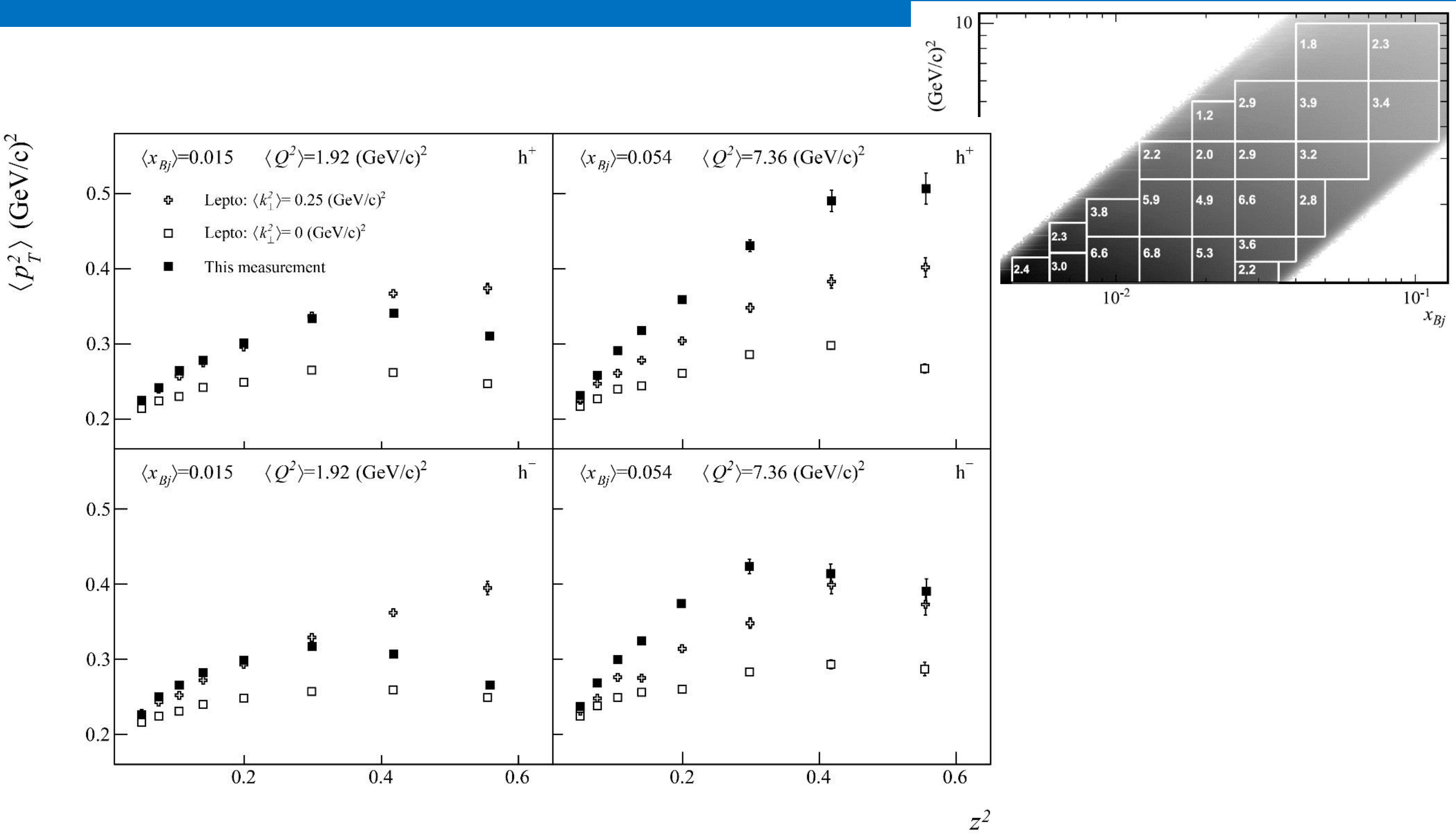




$$F_{UU}^{h}(x,z,P_{hT}^2;\ Q^2)$$
$$= x\sum_q e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp \delta(\vec{p}_\perp - z\vec{k}_\perp)$$

$$M^h(x,z,P_{hT}^2;Q^2) = \frac{d^5\sigma^h/dxdQ^2dzd^2\vec{p}_T}{d^2\sigma^{DIS}/dxdQ^2} \sim \frac{F_{UU}^{h}(x,z,P_{hT}^2;\ Q^2)}{F_{UU,T}+\varepsilon F_{UU,L}}$$

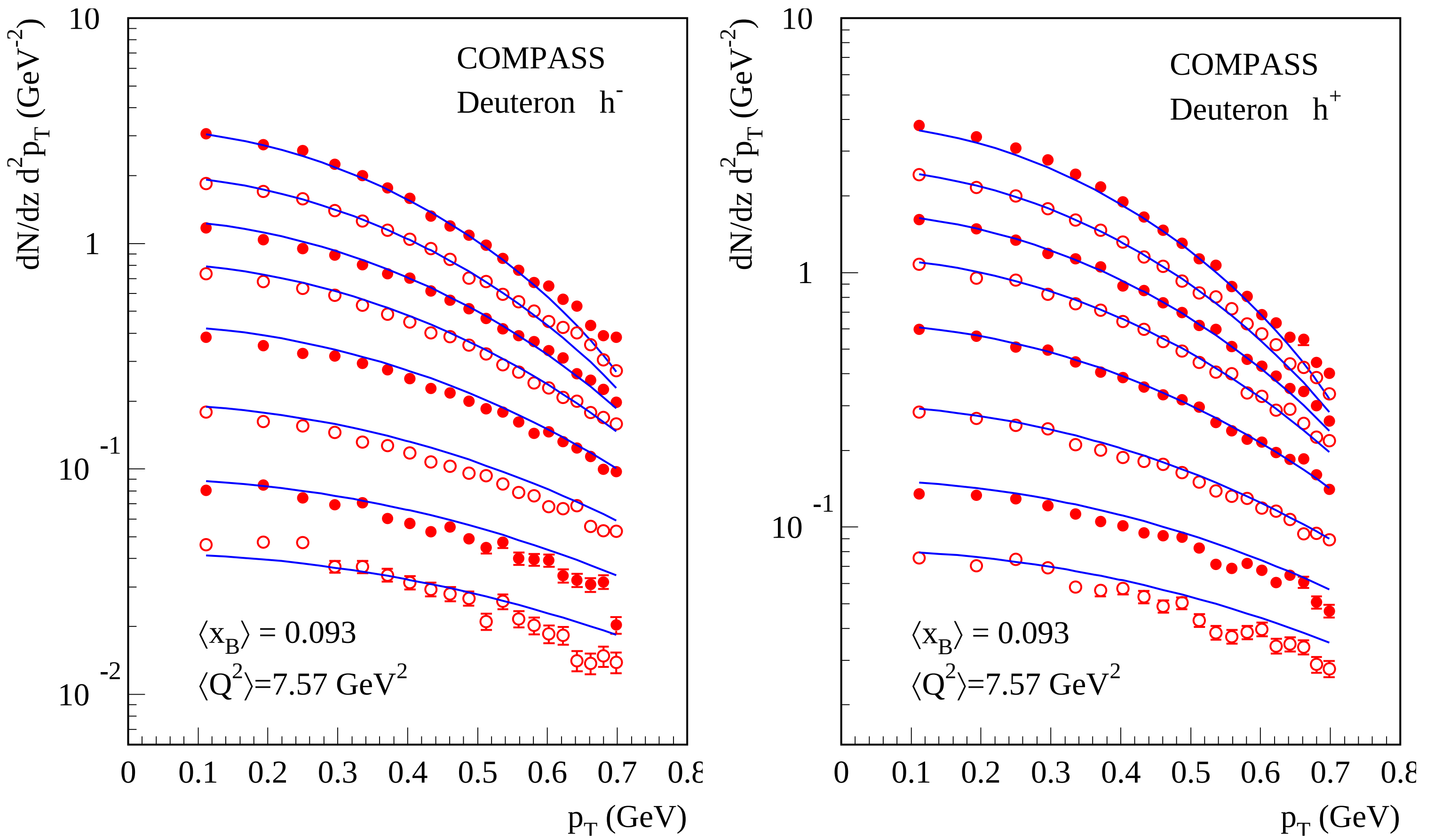
Mean values


$\langle p_T^2 \rangle$ (GeV/c)^2
$\langle x_{Bj} \rangle$=0.015 $\langle Q^2 \rangle$=1.92 (GeV/c)^2 h$^+$
$\langle x_{Bj} \rangle$=0.054 $\langle Q^2 \rangle$=7.36 (GeV/c)^2 h$^+$
$\langle x_{Bj} \rangle$=0.015 $\langle Q^2 \rangle$=1.92 (GeV/c)^2 h$^-$
$\langle x_{Bj} \rangle$=0.054 $\langle Q^2 \rangle$=7.36 (GeV/c)^2 h$^-$
✚ Lepto: $\langle k_\perp^2 \rangle$= 0.25 (GeV/c)^2
☐ Lepto: $\langle k_\perp^2 \rangle$= 0 (GeV/c)^2
■ This measurement
0.2
0.3
0.4
0.5
0.2
0.4
0.6
z^2
10
(GeV/c)^2
10^{-2}
10^{-1}
x_{Bj}
1.8
2.3
1.2
2.9
3.9
3.4
2.2
2.0
2.9
3.2
3.8
5.9
4.9
6.6
2.8
2.3
6.6
6.8
5.3
3.6
2.4
3.0
2.2

TMD evolution works: multiplicity distribution in SIDIS

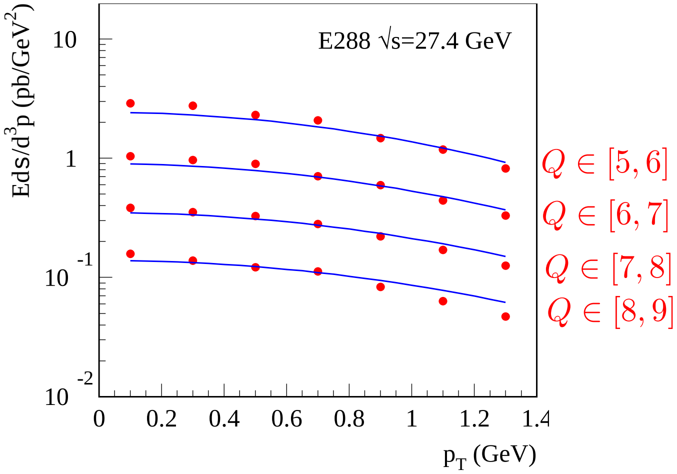
- Comparison to COMPASS data

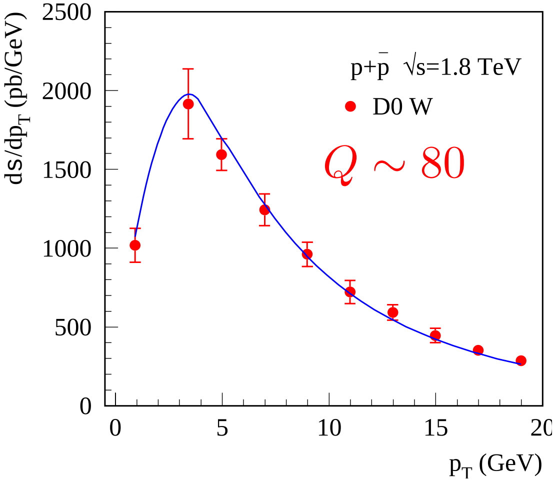
Echevarria, Idilbi, Kang, Vitev

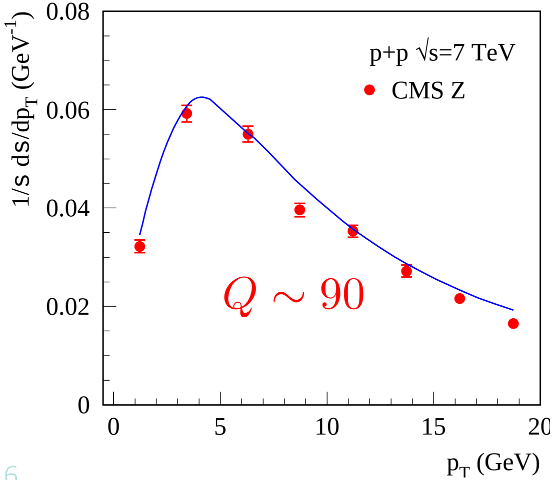


TMD evolution works: Drell-Yan and W/Z production

- Comparison with DY, W/Z pt distribution





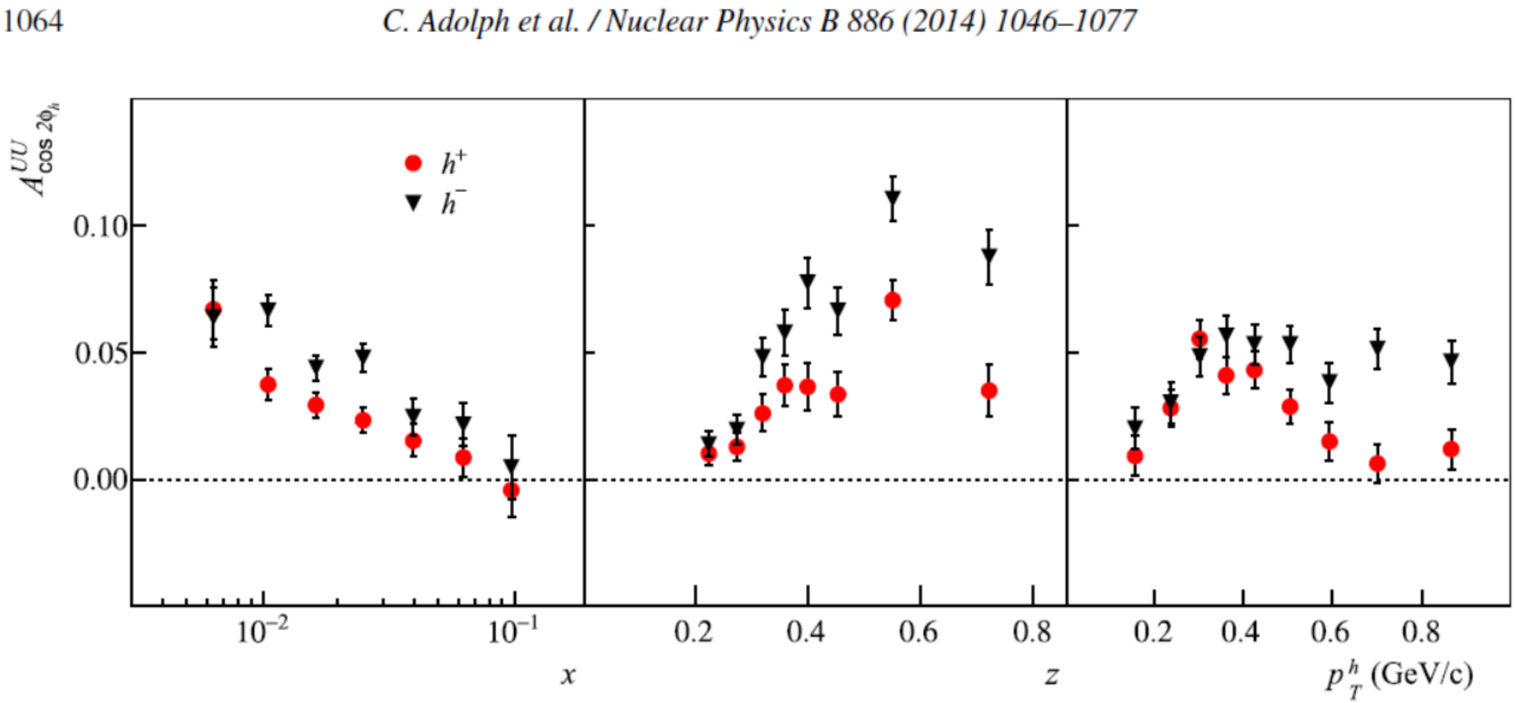


- Works for SIDIS, DY, and W/Z in all the energy ranges
- Make predictions for future JLab 12, COMPASS, Fermilab, RHIC experiments

The asymmetries

- The asymmetries are:
- $A_{U(L),T}^{w(\phi_h,\phi_S)}(x,z,p_T;Q^2) = \frac{F_{U(L),T}^{w(\phi_h,\phi_S)}}{F_{UU,T}+\varepsilon F_{UU,L}}$
- When we measure on 1D
- $A_{U(L),T}^{w(\phi_h,\phi_S)}(x) = \frac{\int_{Q^2_{min}}^{Q^2_{max}} dQ^2 \int_{z_{min}}^{z_{max}} dz \int_{p_{T,min}}^{p_{T,max}} d^2\vec{p}_T F_{U(L),T}^{w(\phi_h,\phi_S)}}{\int_{Q^2_{min}}^{Q^2_{max}} dQ^2 \int_{z_{min}}^{z_{max}} dz \int_{p_{T,min}}^{p_{T,max}} d^2\vec{p}_T (F_{UU,T}+\varepsilon F_{UU,L})}$

Boer-Mulders in cos 2ϕ

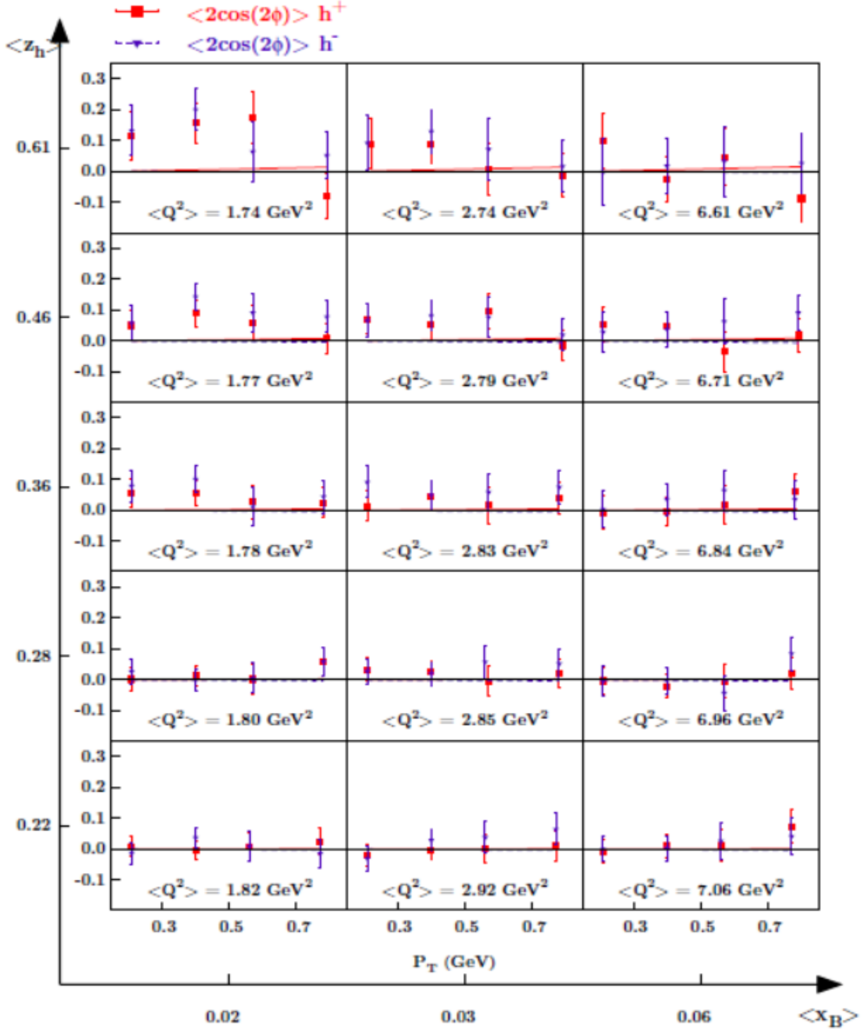


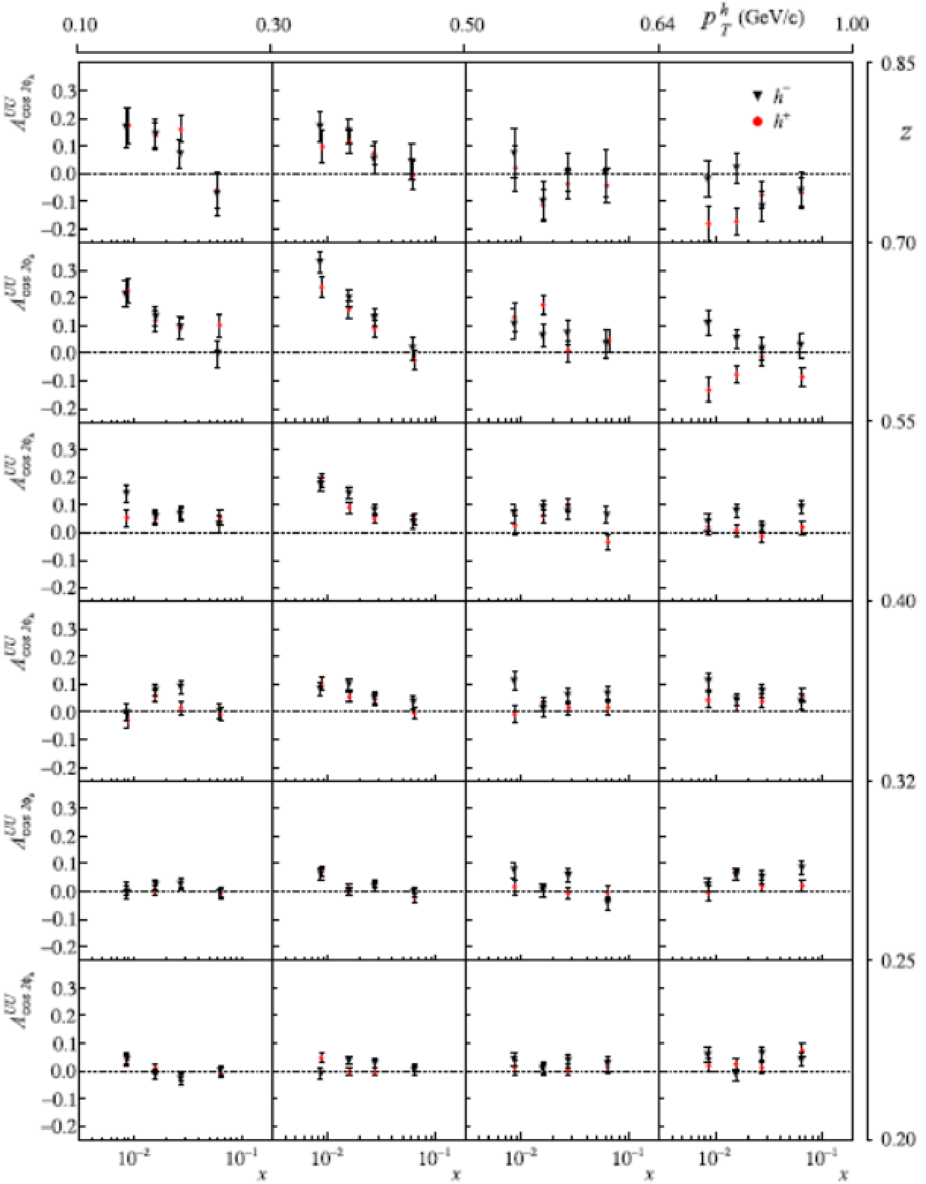
1064 C. Adolph et al. / Nuclear Physics B 886 (2014) 1046–1077

$$F_{UU}^{\cos 2\phi}(x, z, P_{hT}^2;\ Q^2)$$

$$= -x \sum_q e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp \frac{2(\hat{h}\cdot\vec{k}_\perp)(\hat{h}\cdot\vec{k}_\perp) - \vec{k}_\perp\cdot\vec{p}_\perp}{M m_h}\ h_1^{\perp,q}(x, k_\perp^2; Q^2) H_1^{\perp,q\to h}(z, p_\perp^2; Q^2)$$

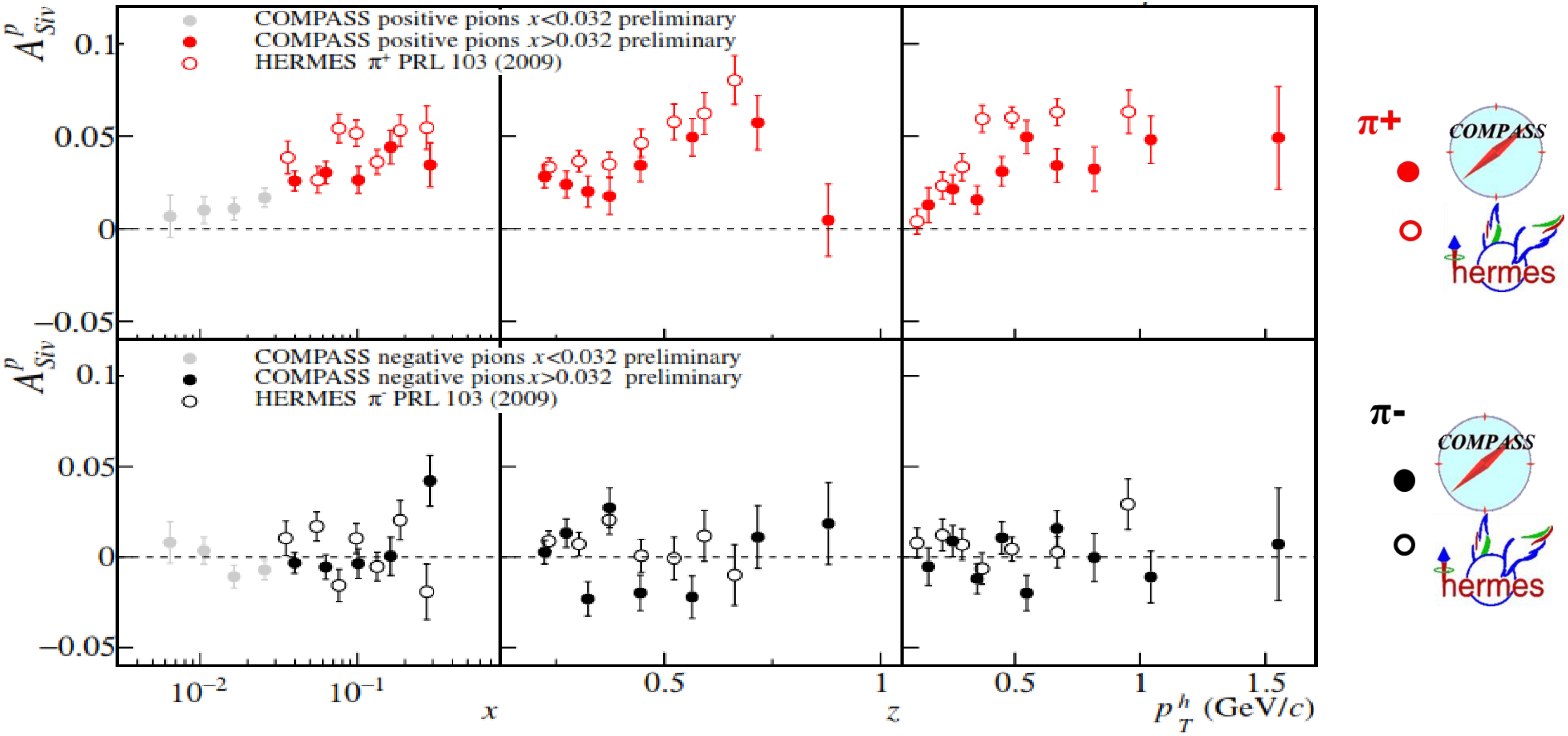
Boer-Mulders in $\cos 2\phi$



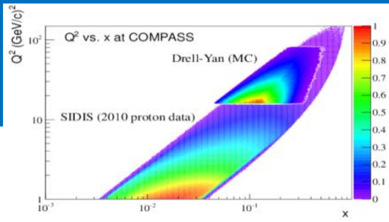


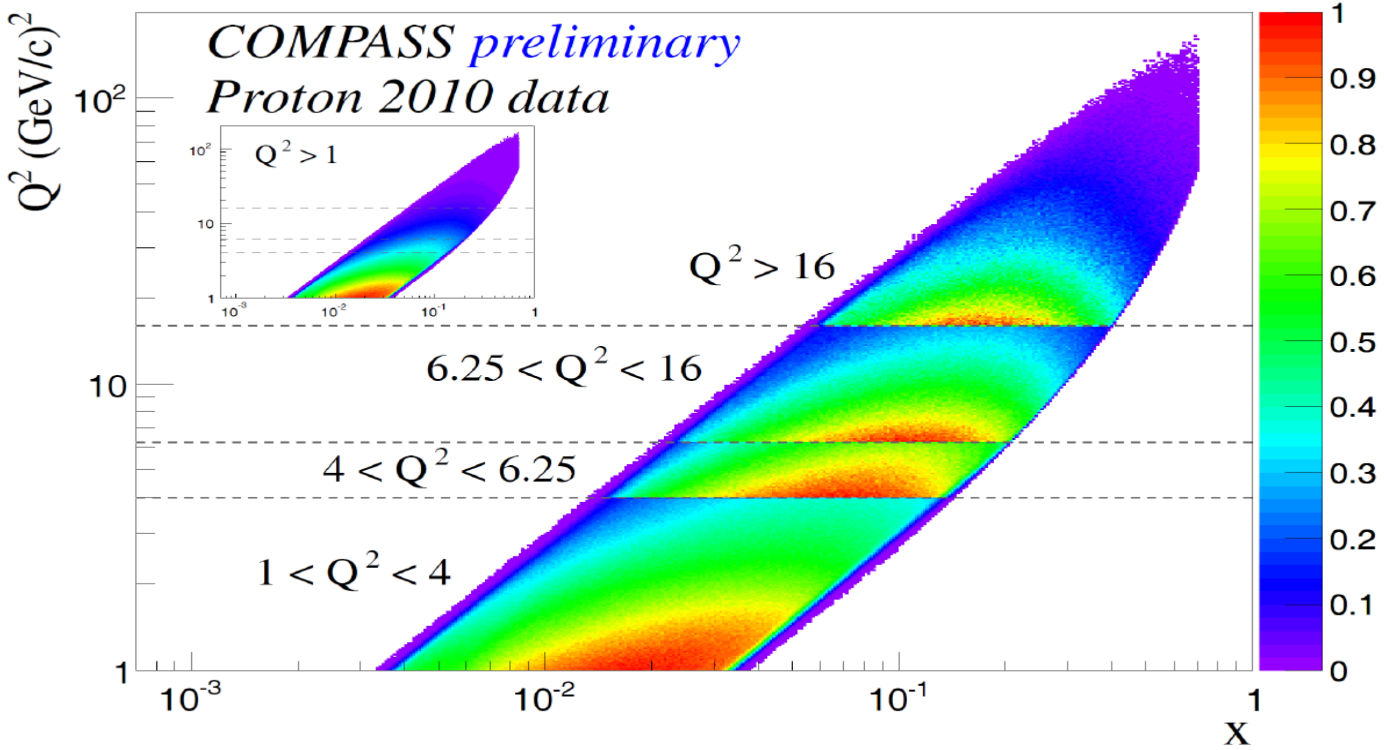
Sivers asymmetry on p

charged pions (and kaons), HERMES and COMPASS



Kinematic Coverage: SIDIS vs Drell-Yan

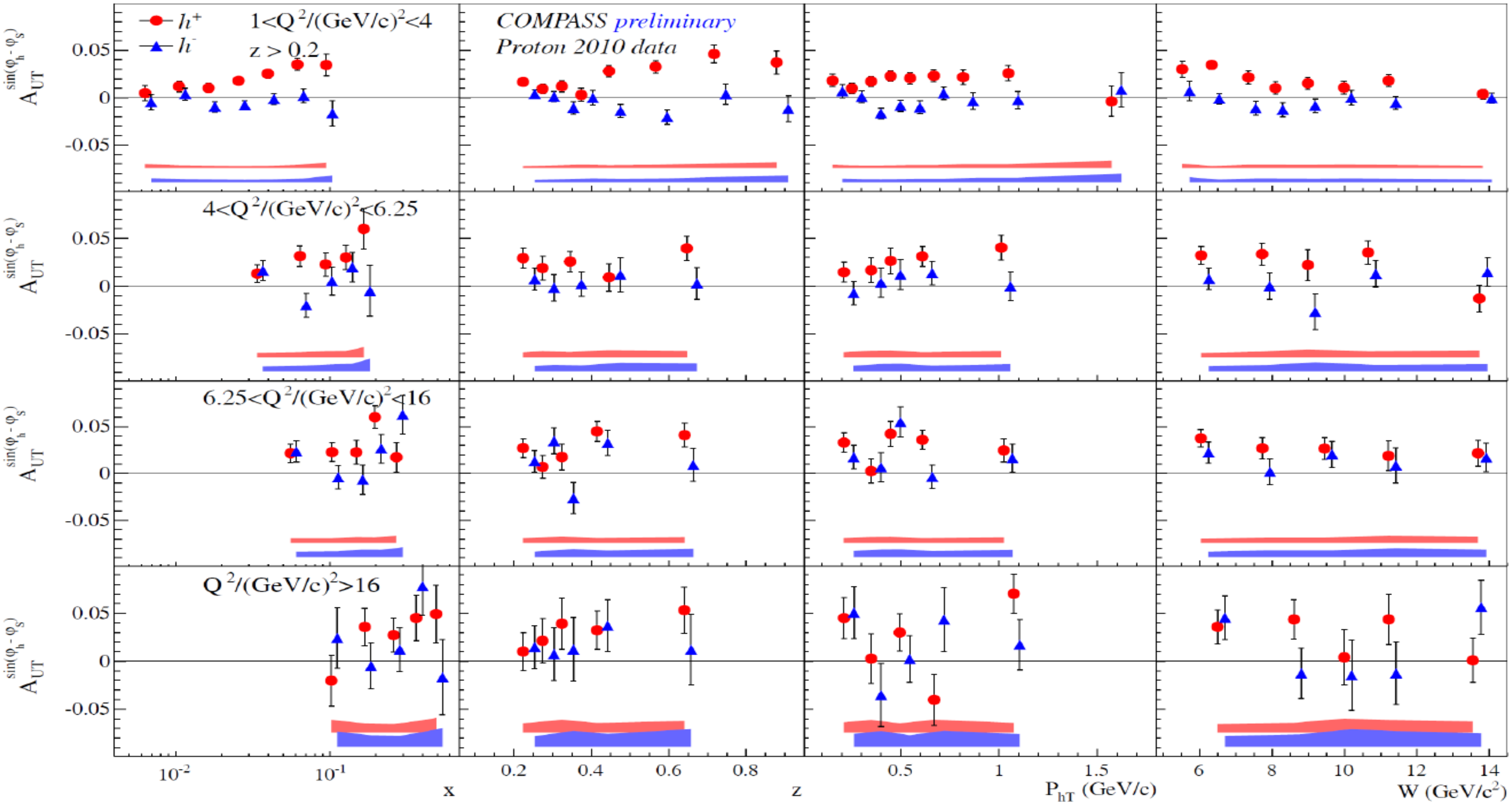




The phase spaces of the two processes overlap at COMPASS

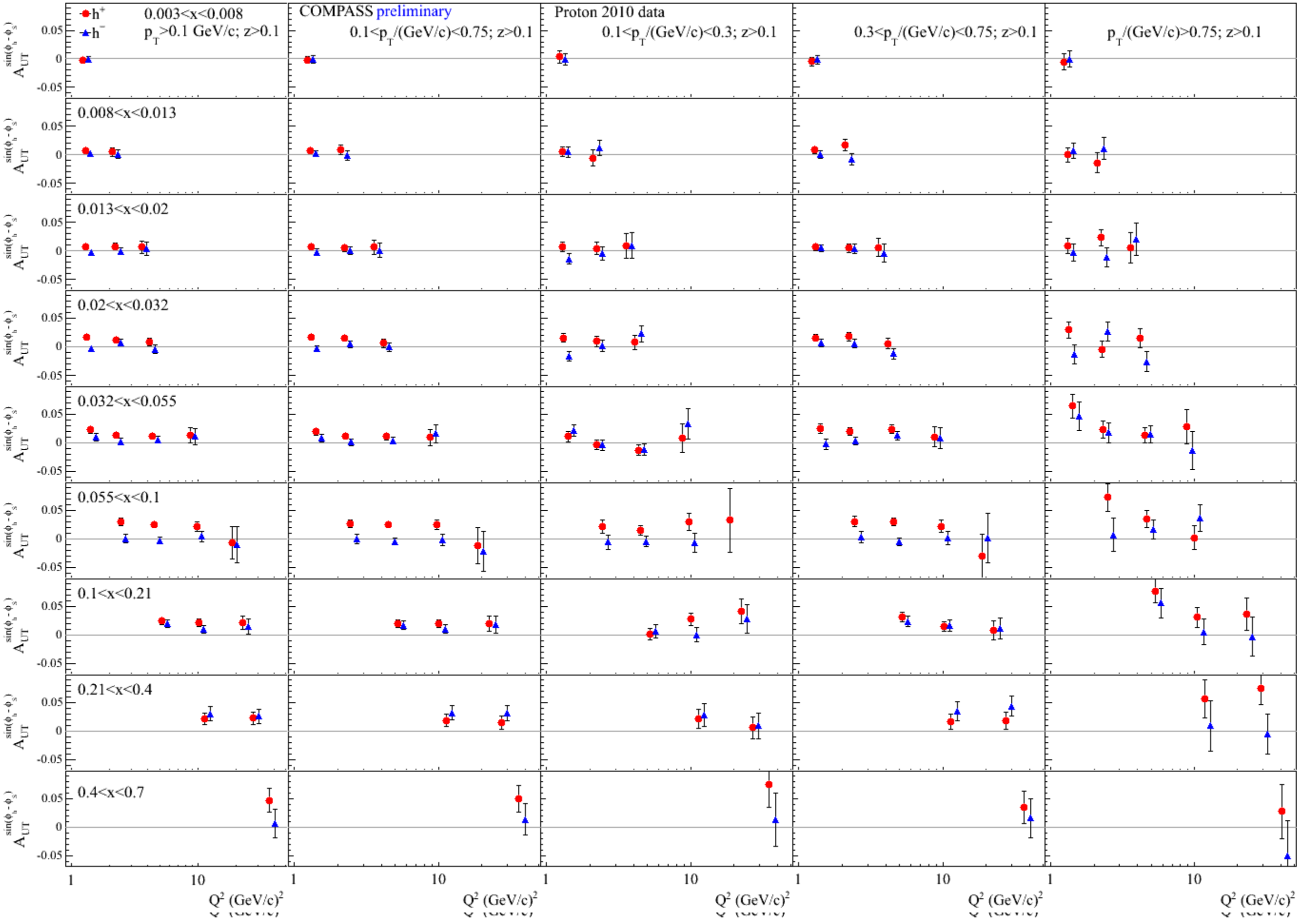
➔ Consistent extraction of TMD DPFs in the same region

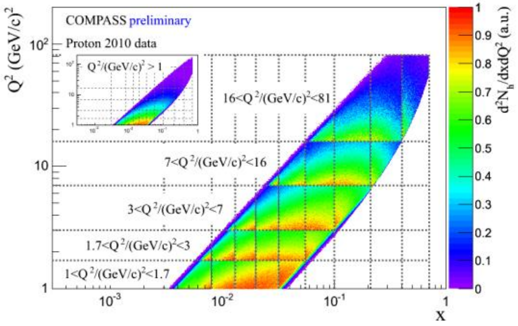
Sivers in DY range

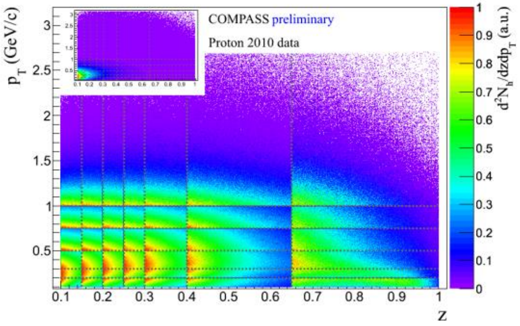


Sivers asymmetry on proton. Multidimensional

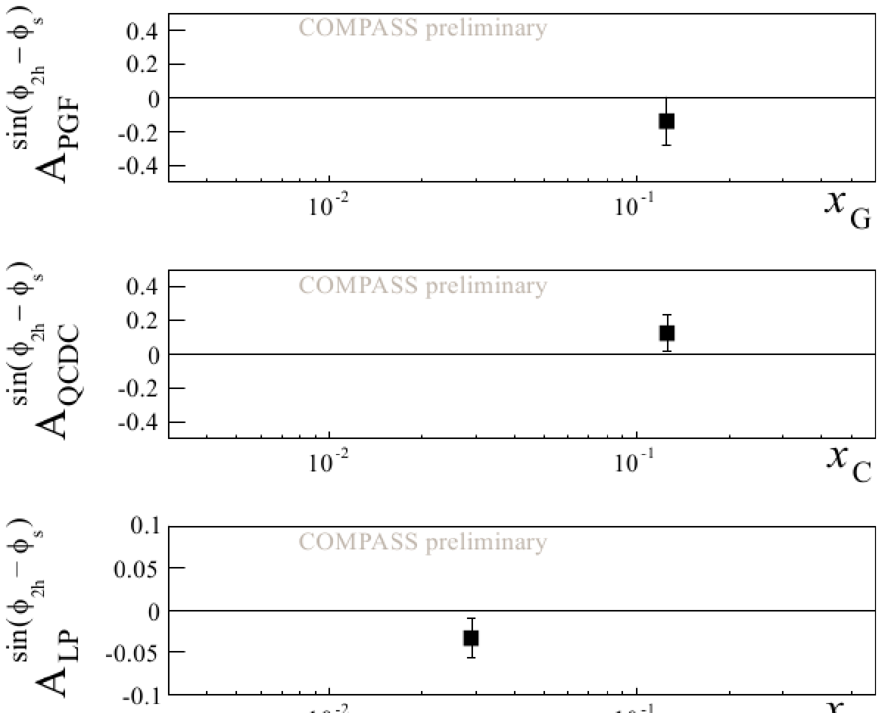
Extraction of TSAs with a Multi-D $\left(x\!:Q^2\!:z\!:p_T\right)$ approach

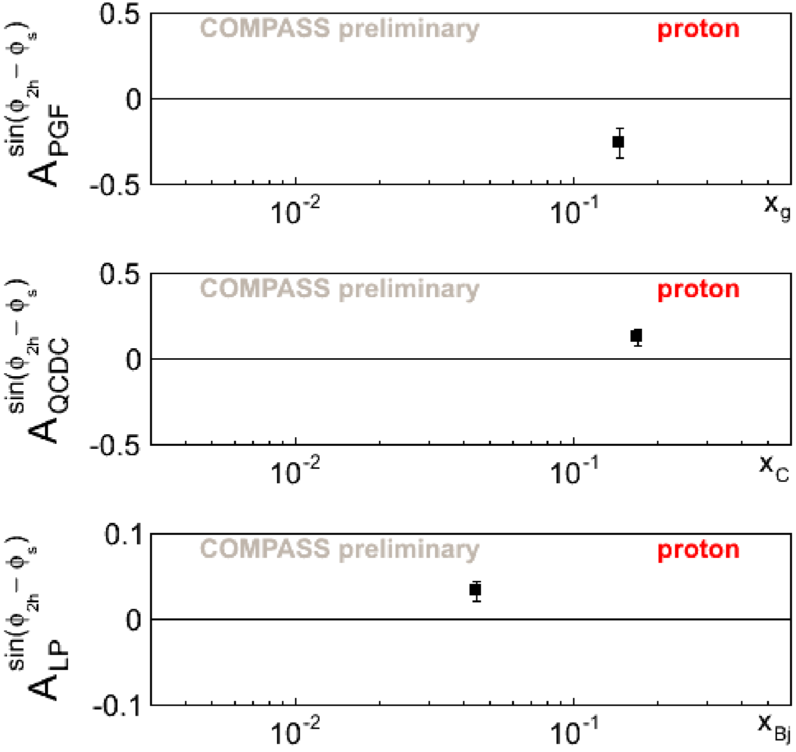






Sivers asymmetry on deuteron and proton for Gluons





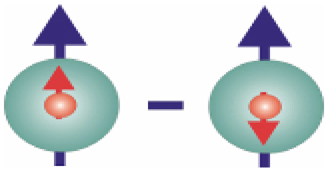
Transversity PDF

h_1^q **(x) = $q^{\uparrow\uparrow}$(x) - $q^{\uparrow\downarrow}$(x)**

$\Delta_T q(x)$,

$\delta q(x)$,

$\delta_T q(x)$



q=u_v, d_v, q_{sea}

quark with **spin** parallel to the nucleon spin in a transversely polarised nucleon

- probes the relativistic nature of quark dynamics
- no contribution from the gluons → simple Q^2 evolution
- Positivity: Soffer bound…………….. $2|h_1| \leq q + \Delta q$ *Soffer, PRL 74 (1995)*
- first moments: tensor charge………. $\delta q \equiv \int dx \left[h_1^q(x) - h_1^{\bar{q}}(x) \right]$
- sum rule for transverse spin in PM… $\frac{1}{2} = \frac{1}{2} \sum h_1^q + L_q + L_g$ *Bakker, Leader, Trueman, PRD 70 (04)*
- is chiral-odd: decouples from inclusive DIS

Collins asymmetry on proton

x > 0.032 region

charged pions

COMPASS and HERMES results

π+

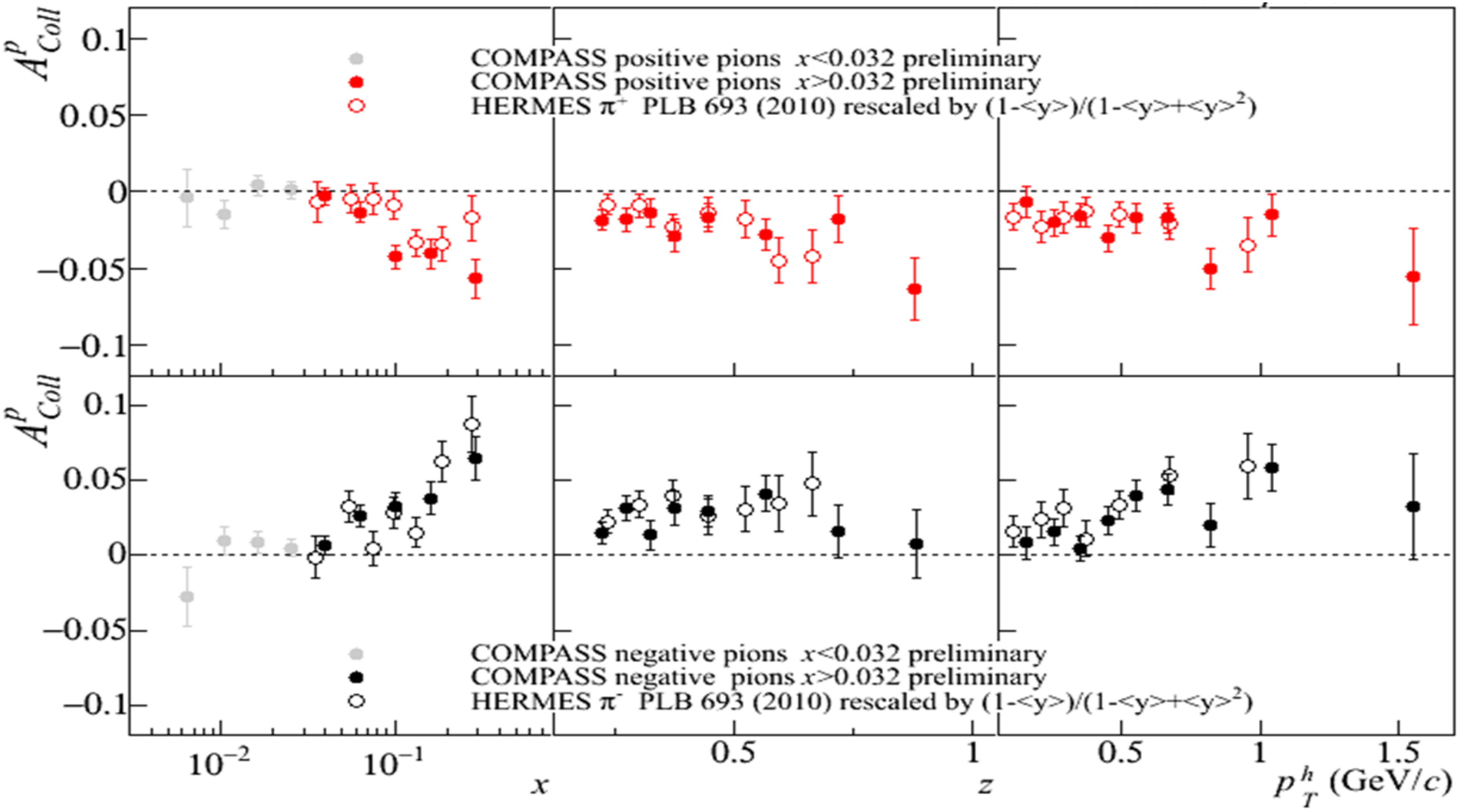
●

○

π-

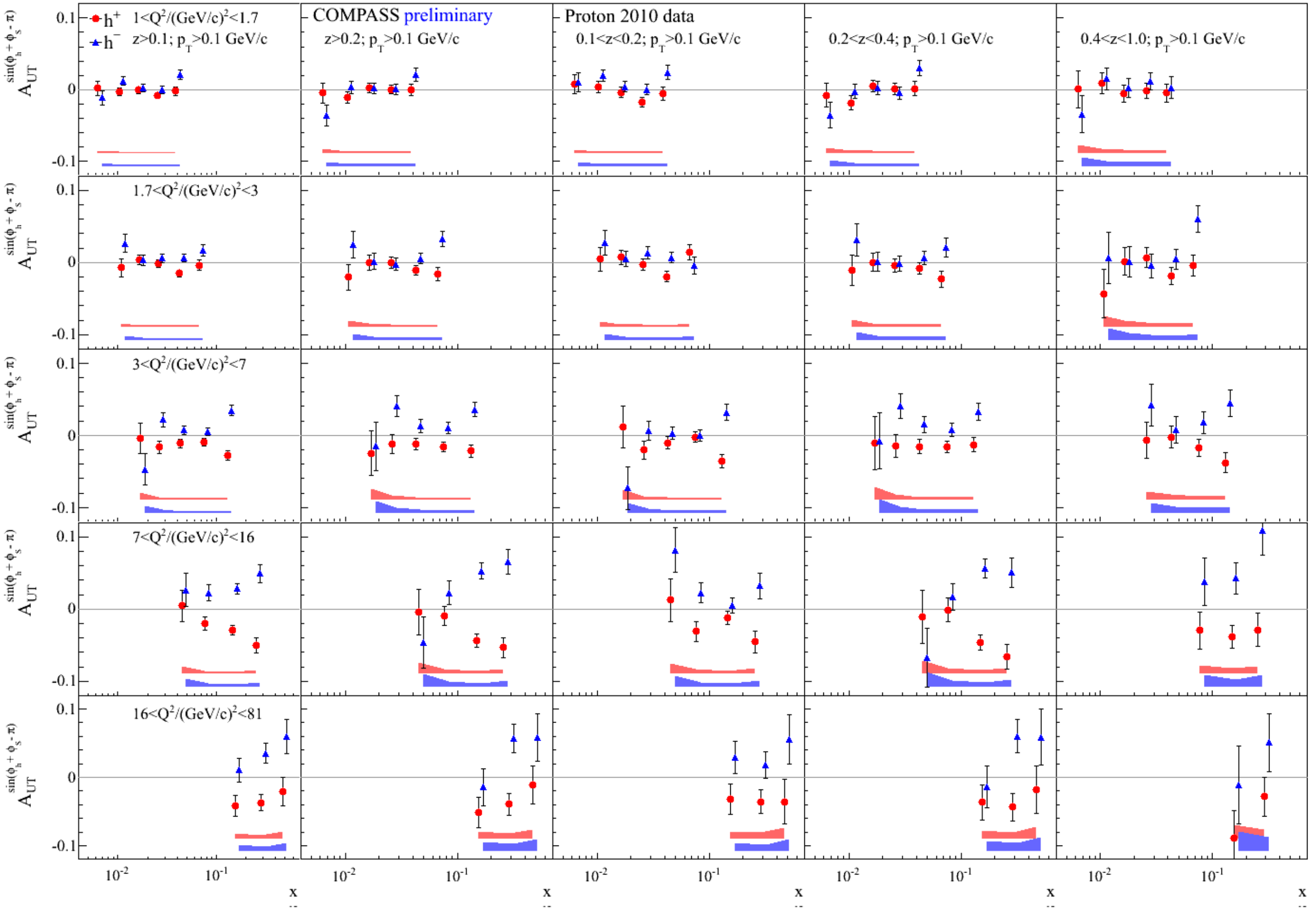
●

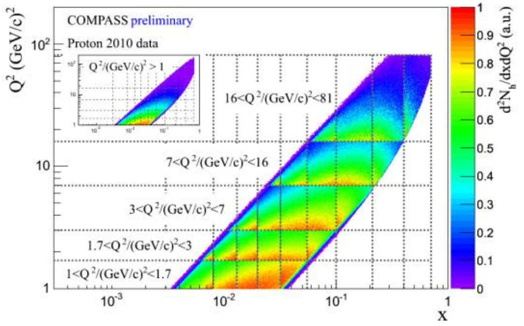
○



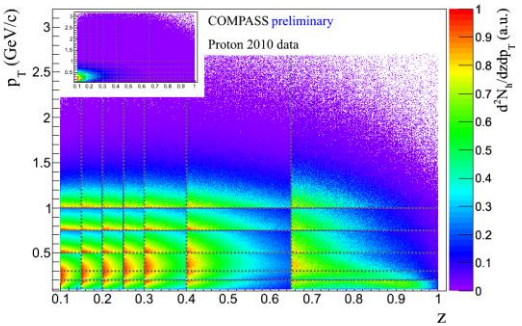
Collins asymmetry on proton. Multidimensional

Extraction of TSAs with a Multi-D $\left(x{:}\,Q^2{:}\,z{:}\,p_T\right)$ approach





One dense plot out of many

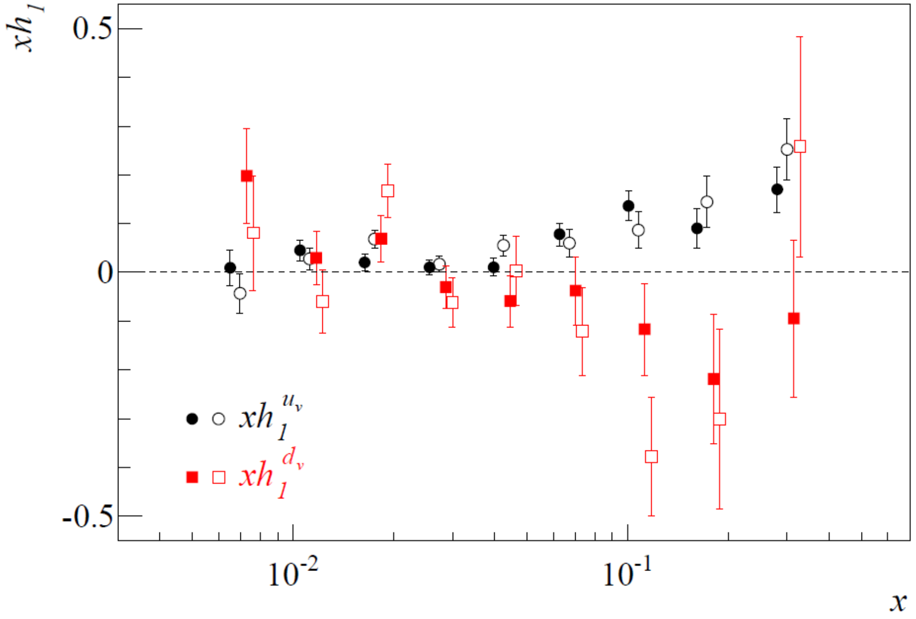


Transversity from our data

- Point-to-point extraction [Physical Review D 91, 014034 (2015)]
- Only COMPASS measured TSA on deuteron

Open points/squares – from dihadron

Closed points/squares – from Collins



ERRORS ON h_1^d ARE A FACTOR 4 LARGER THAT THE ONES ON h_1^u

From Collins asymmetries to transversity

- Following Physical Review D 91, 014034 (2015), in the valence region

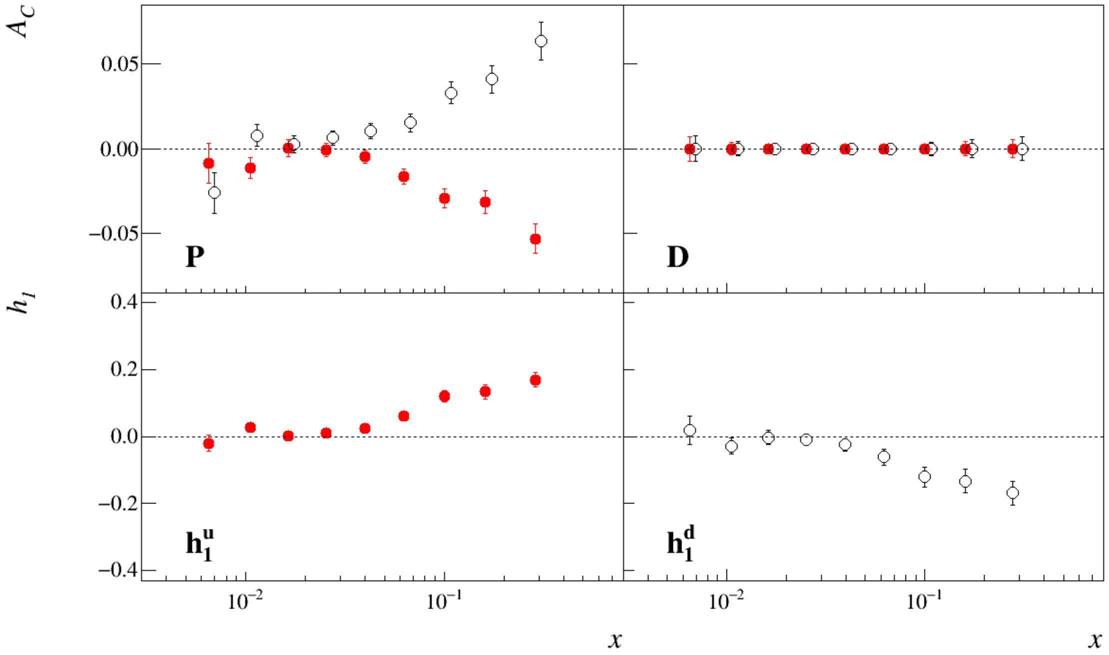
$$xh_1^u = \frac{1}{5}\frac{1}{\tilde{a}_P^h(1-\tilde{\alpha})}\left[\left(xf_p^+ A_p^+ - xf_p^- A_p^-\right) + \frac{1}{3}\left(xf_d^+ A_d^+ - xf_d^- A_d^-\right)\right]$$

$$xh_1^d = \frac{1}{5}\frac{1}{\tilde{a}_P^h(1-\tilde{\alpha})}\left[\frac{4}{3}\left(xf_d^+ A_d^+ - xf_d^- A_d^-\right) - \left(xf_p^+ A_p^+ - xf_p^- A_p^-\right)\right]$$

With $\tilde{a}_P^h$ and $\tilde{\alpha}$ constants

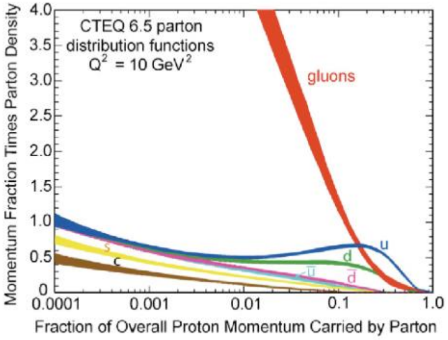
New deuteron data

- 1 full year (same as 2010).

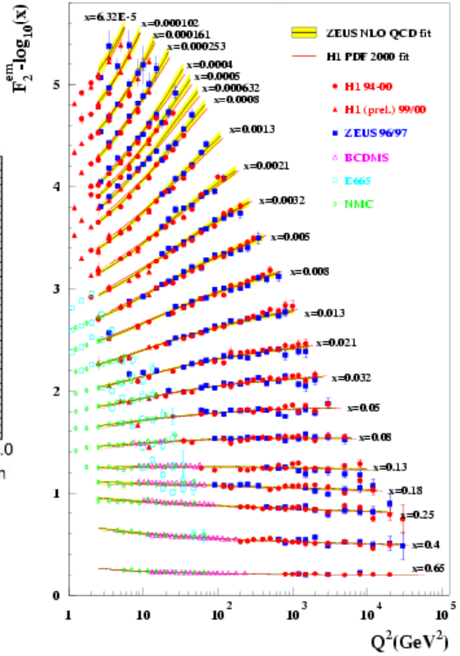


THIS IS A MEASUREMENT THAT WILL IMPACT OUR KNOWLEDGE,

Far Future perspective

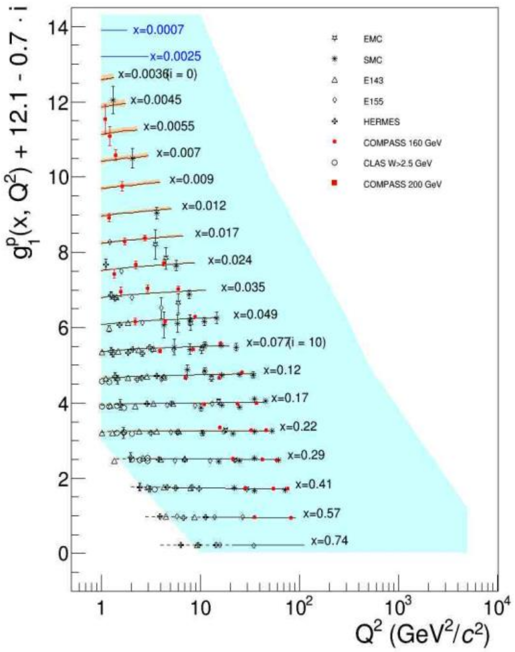


World Data on F_2^p



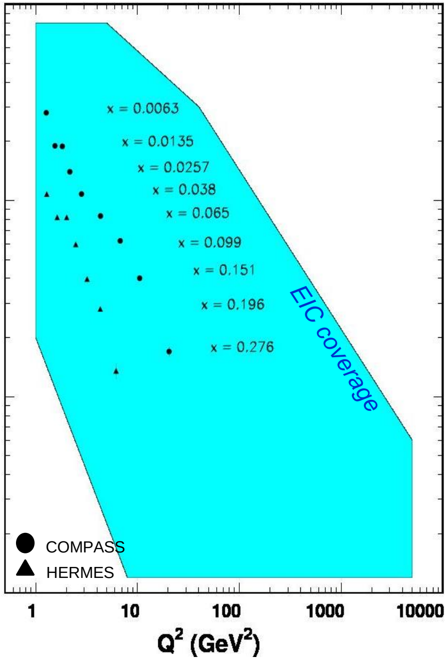
momentum

World Data on g_1^p



spin

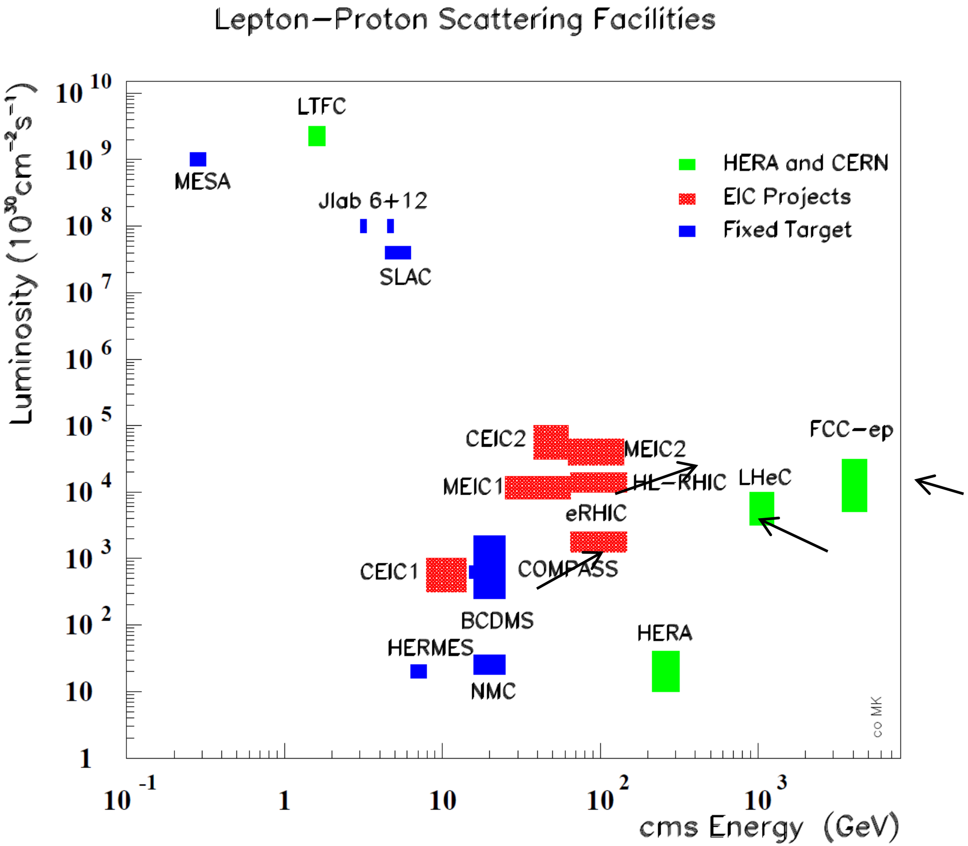
World Data on h_1^p



transverse spin ~ angular momentum

Thank you

The CM Energy vs Luminosity Landscape



CEIC1 = Chinese version
of Electron-Ion Collider
("A dilution-free mini-COMPASS")

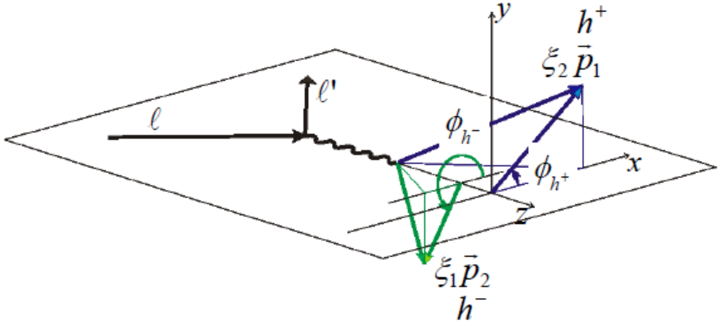
MEIC1 = EIC@Jlab

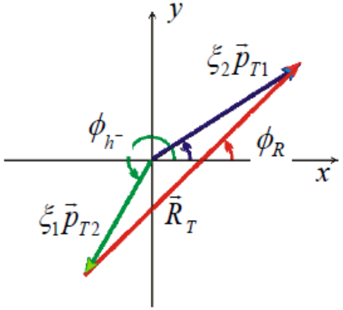
eRHIC = EIC@BNL

LHeC = ep/eA collider
@ CERN

CEIC2
MEIC2
HL-eRHIC
FCC-he

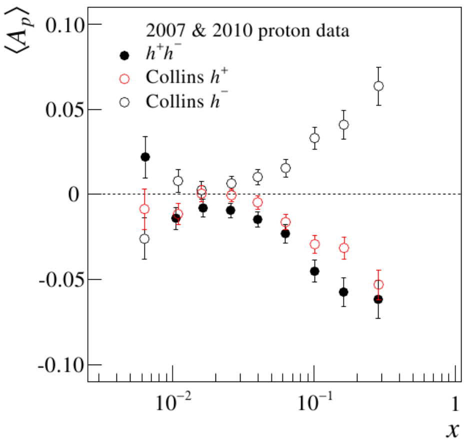
Hadron correlations

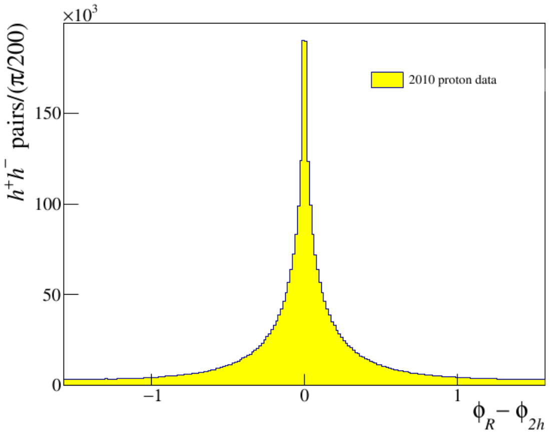


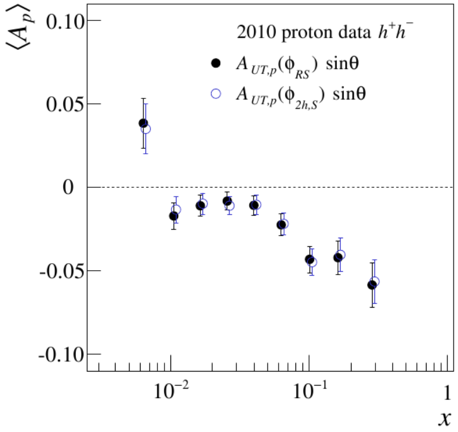


Interplay between Collins and IFF asymmetries

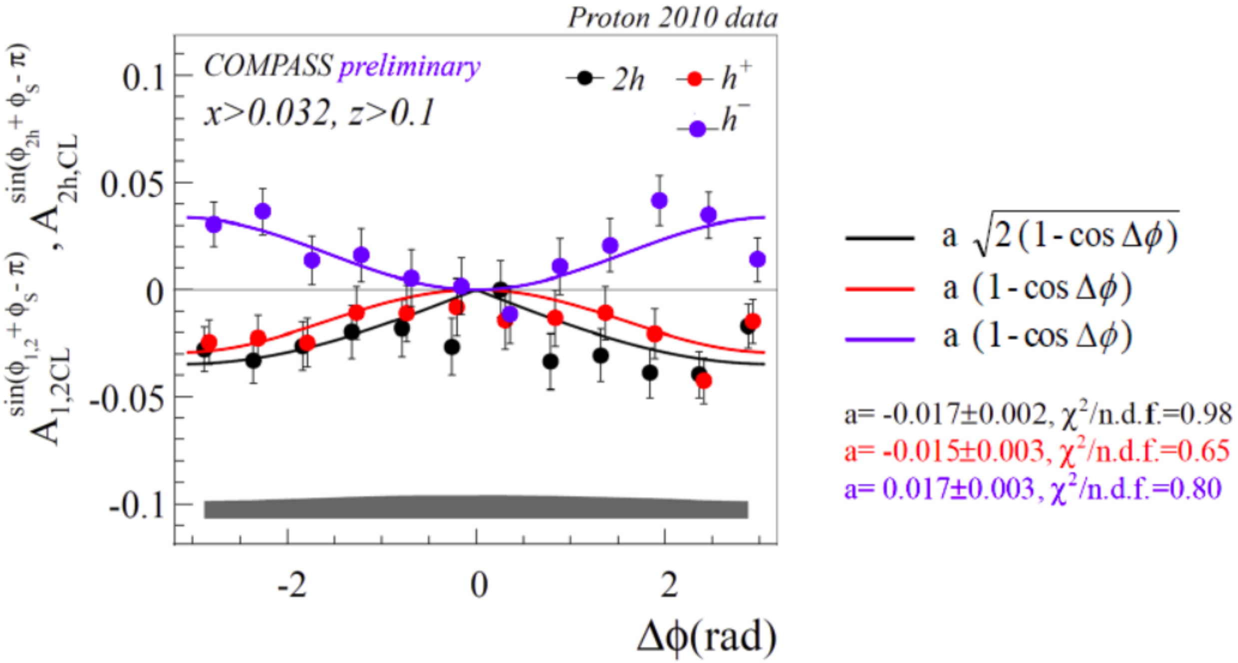
common hadron sample for Collins and 2h analysis







Asymmetries for $x > 0.032$ vs $\Delta\phi = \phi_{h^+} - \phi_{h^-}$

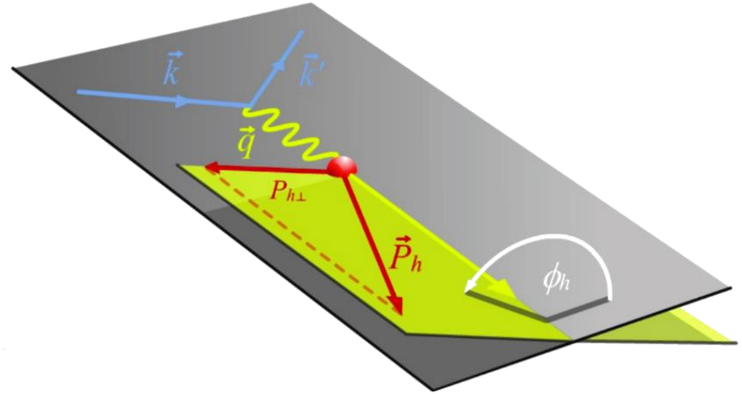


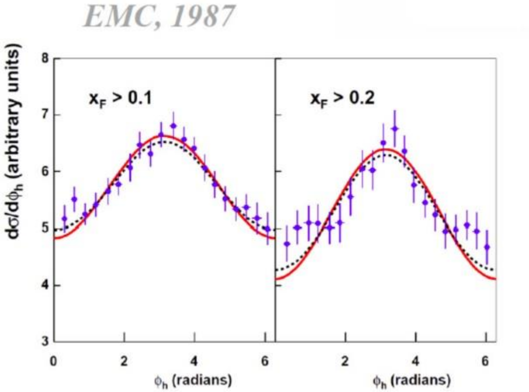
$$a = \frac{\sigma_{1C}^{h^+h^-}(\Delta\phi)}{\sigma_U(\Delta\phi)} = -\frac{\sigma_{2C}^{h^+h^-}(\Delta\phi)}{\sigma_U(\Delta\phi)}$$

ratio of the integrals compatible with $4/\pi$

Unpolarised Azimuthal Modulation

Huge azimuthal ϕ modulation on unpolrised target measured by EMC in 1987



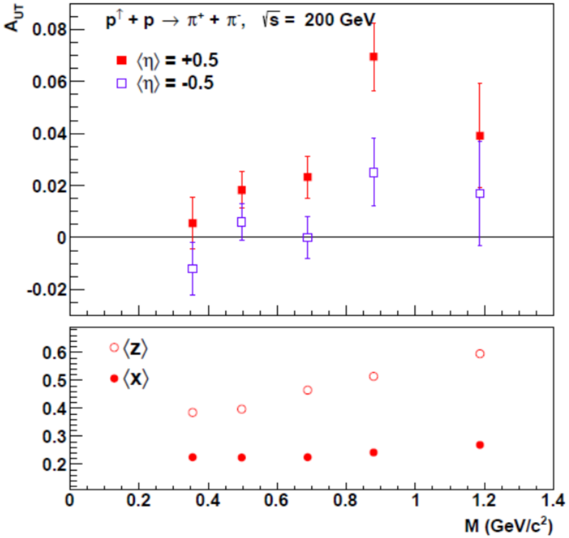


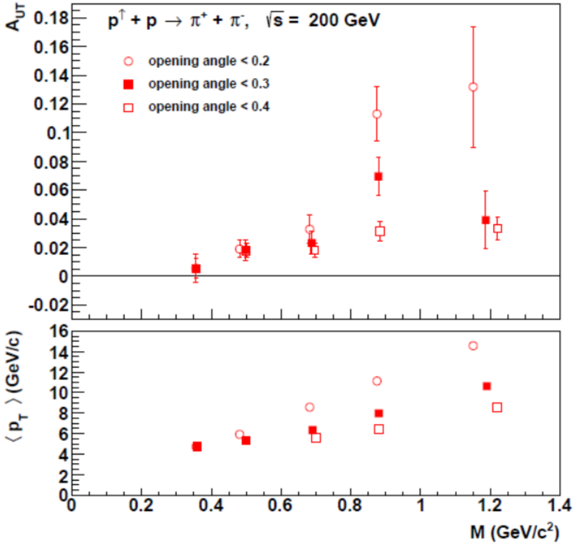
$d\sigma^{\ell p\to\ell' hX} = \sum_q f_q(x,Q^2)\otimes d\sigma^{\ell q\to\ell' q}\otimes D_q^h(z,Q^2)$ where, in collinear PM $d\sigma^{\ell q\to\ell' q} = \hat{s}^2 + \hat{u}^2 = x[1+(1-y)^2]$, i.e. no ϕ_h dependence. Taking into account the parton transverse momentum in the kinematics leads to:

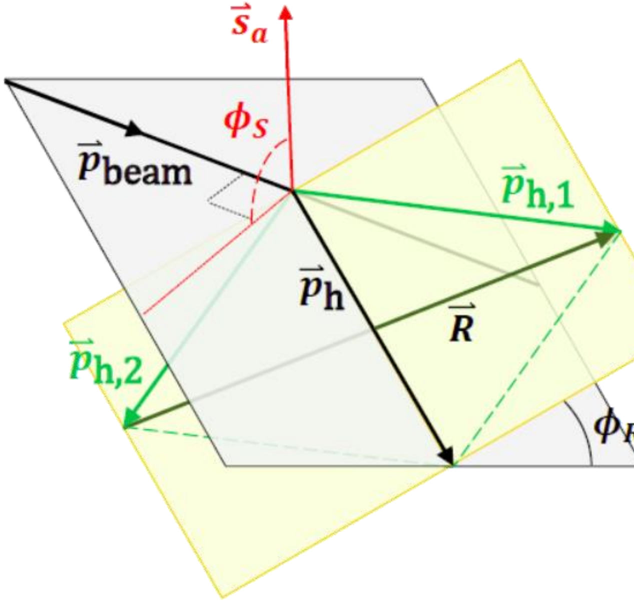
$$\hat{s} = sx\left[1-\frac{2k_\perp}{Q}\sqrt{1-y}\cos\phi_h\right]+\mathcal{O}\left(\frac{k_\perp^2}{Q}\right) \quad \hat{u} = sx(1-y)\left[1-\frac{2k_\perp}{Q\sqrt{1-y}}\cos\phi_h\right]+\mathcal{O}\left(\frac{k_\perp^2}{Q}\right)$$

Resulting in the $\cos\phi_h$ and $\cos 2\phi_h$ modulations observed in the azimuthal distributions

2h asymmetries in $p^{\uparrow}p \longrightarrow \pi\pi X$







$$d\sigma_{UT} \propto \sin\phi_{RS}\, f_1 \otimes h_1 \otimes \hat{\sigma}^{qq\to qq} \otimes H_{1,q}^{\measuredangle}(z,M)$$