Hadron transverse momentum distributions from SIDIS and pp

Andrea Bressan
University of Trieste and INFN

3D PARTON DISTRIBUTIONS: PATH TO THE LHC, 29/11 - 2/12/2016
INFN-Laboratori Nazionali di Frascati

Transverse structure of the Nucleon

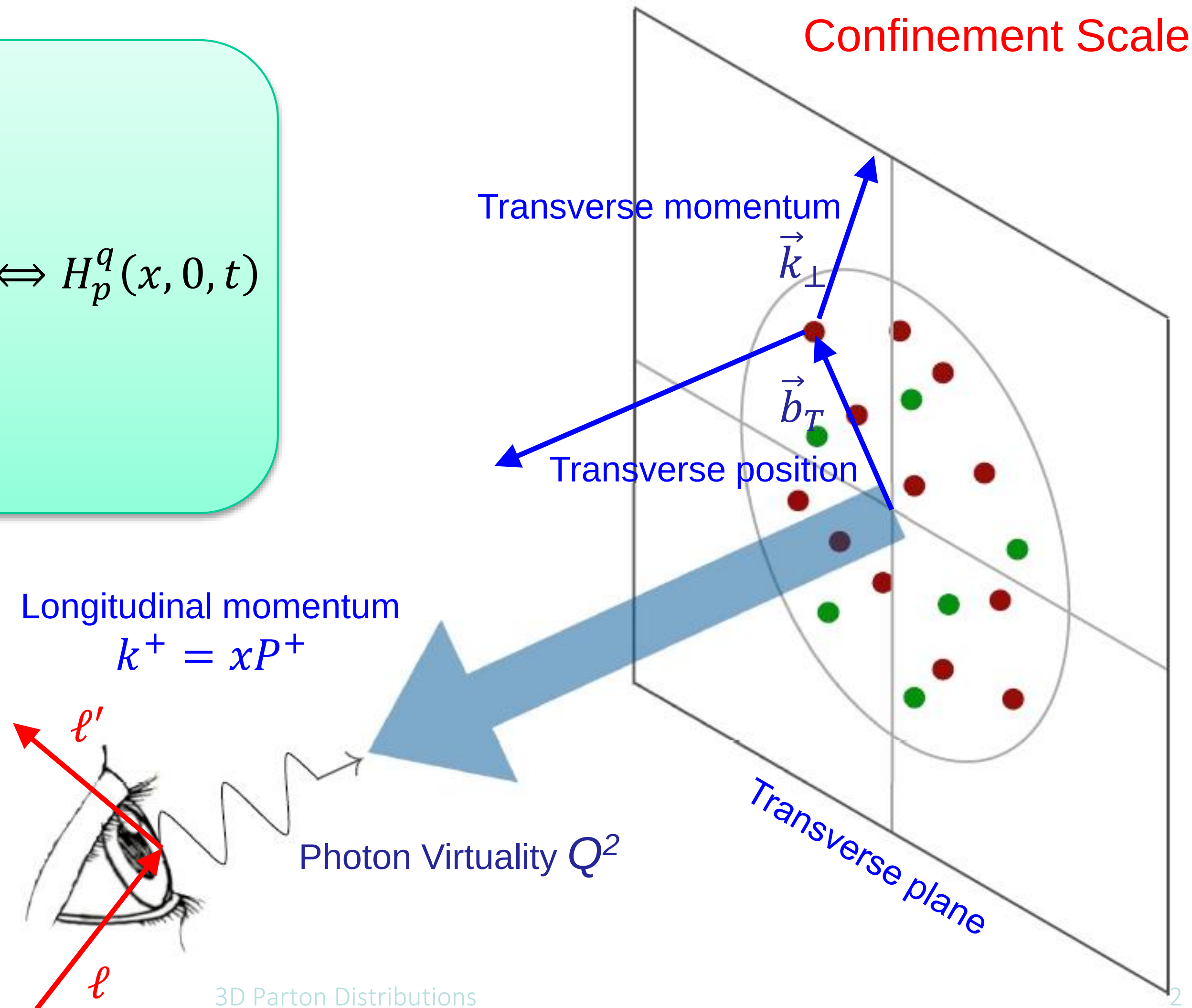
$$W_p^q(x, \vec{k}_\perp, \vec{b}_T)$$

$\xrightarrow{d^2 b_T}$ $f_p^q(x, \vec{k}_\perp)$ $\qquad$ $\xrightarrow{d^2 k_\perp}$ $f_p^q(x, \vec{b}_T) \Leftrightarrow H_p^q(x, 0, t)$

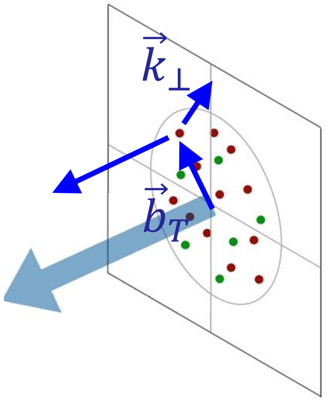
$f_p^q(x, \vec{k}_\perp) \xrightarrow{d^2 k_\perp}$ $\qquad$ $f_p^q(x, \vec{b}_T) \xrightarrow{d^2 b_T}$

$$f_p^q(x)$$

High Energy Probe
Hard Scale



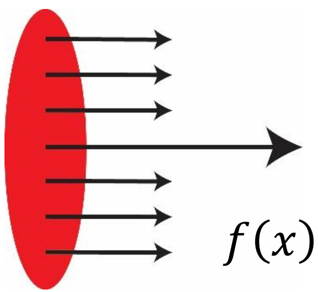
Confined parton motion in a hadron



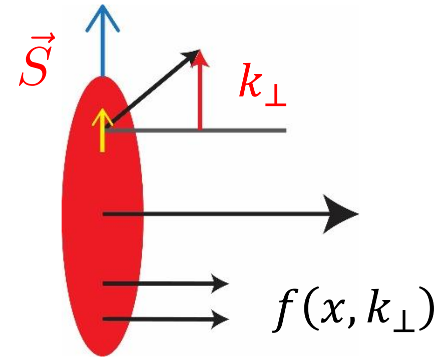
- Scattering with a large momentum transfer
  - Momentum scale of the hard probe $Q \gg {}^1/_R \sim \Lambda_{QCD} \sim 1\ \mathrm{fm}$
  - Combined motion $\sim {}^1/_R$ is too week to be sensitive to the hard probe
  - Collinear factorization – integrated into PDFs
- Scattering with multiple momentum 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

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)

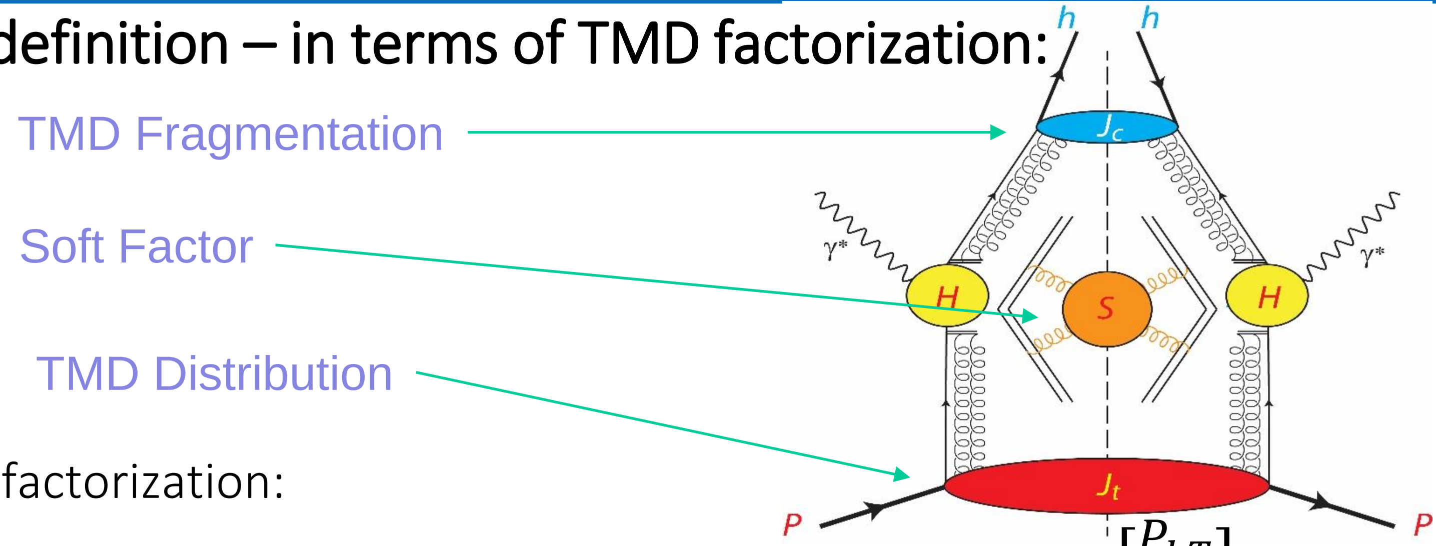
$$f_{q/h\uparrow}(x, k_\perp, \vec{s}) = f_{q/h}(x, k_\perp) - \frac{1}{M} h_{1T}^{\perp q}(x, k_\perp) \vec{s} \cdot (\hat{p} \times \vec{k}_\perp)$$

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!

Factorization in QCD – SIDIS

- Perturbative definition – in terms of TMD factorization:



- Low P_{hT} – TMD factorization:

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

- High P_{hT} – Collinear factorization:

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

- P_{hT} Integrated – Collinear factorization:

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

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

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

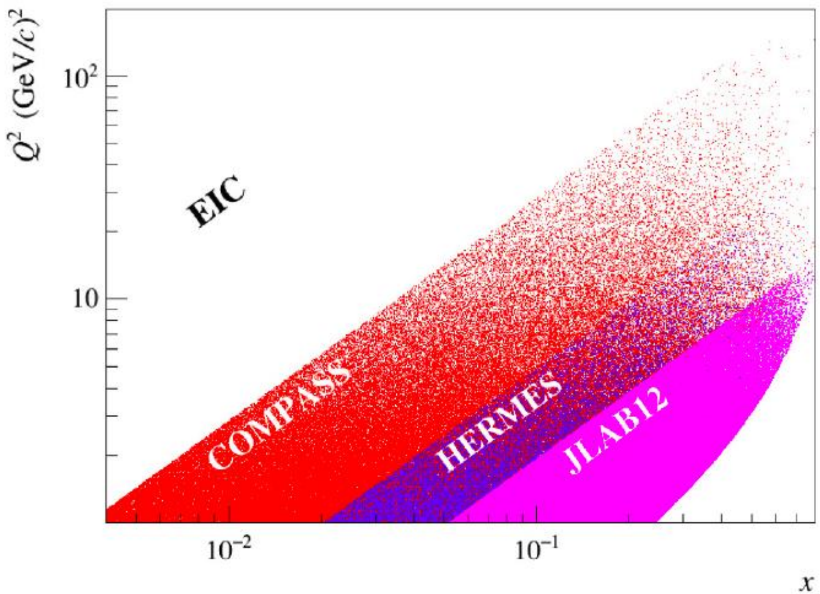
SIDIS Experiments

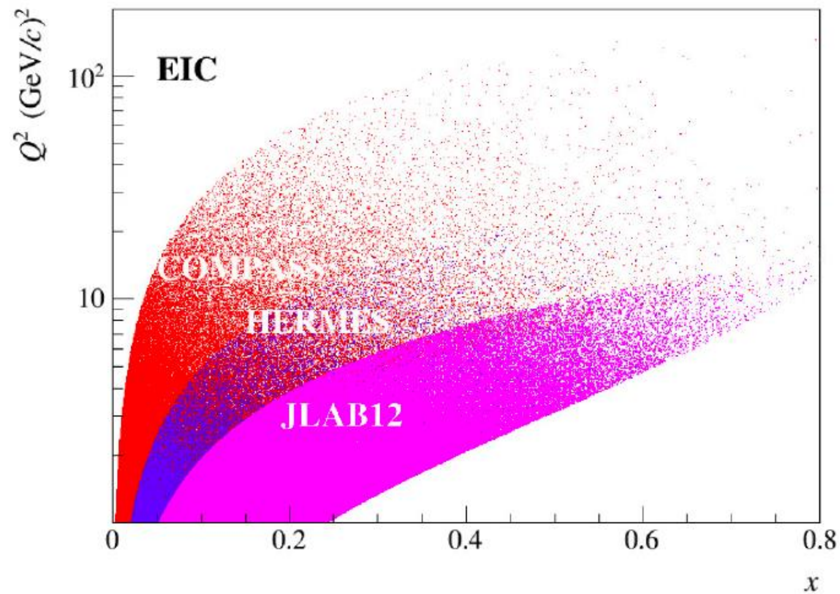
SIDIS Experiment must:

- 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

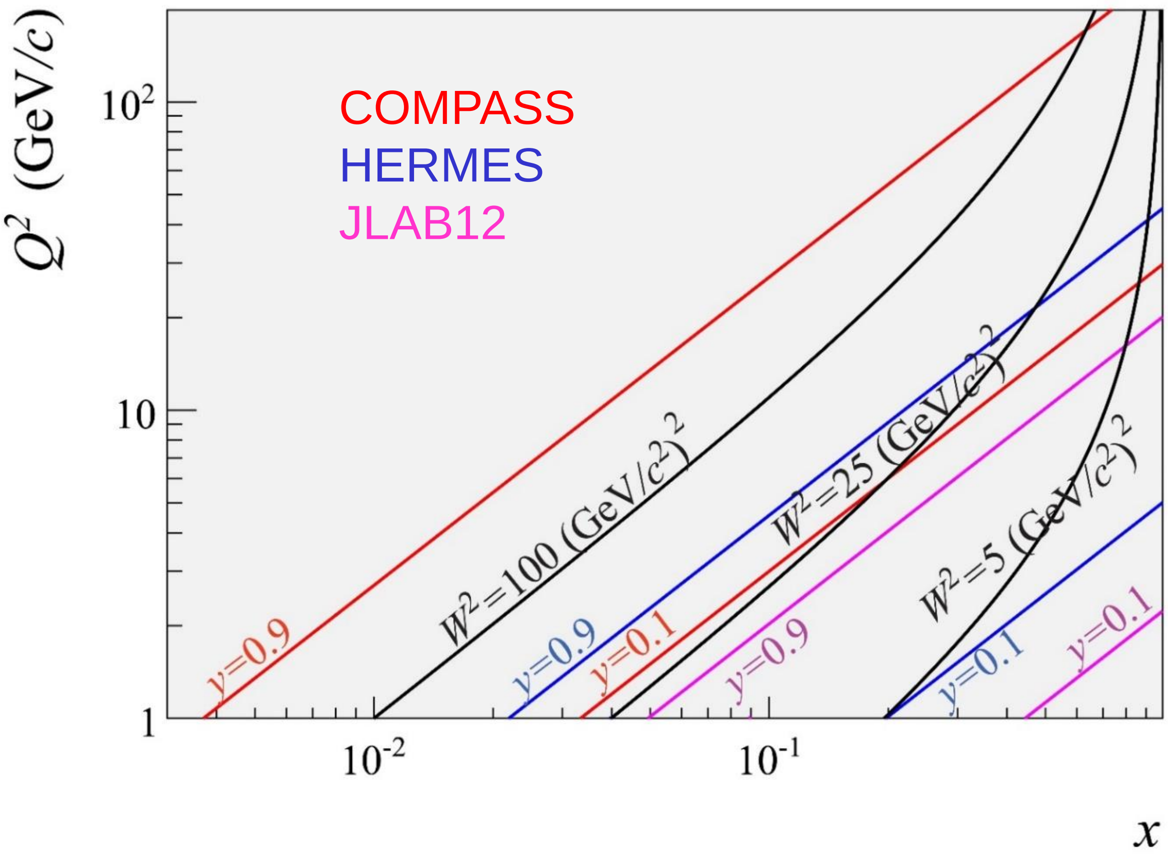
- **The polarized lepton-nucleon collider will be a mandatory tool to reach the level of ordinary PDF**

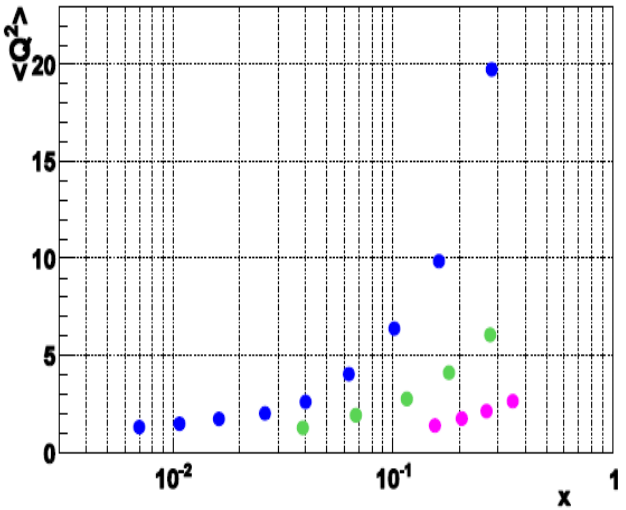
Kinematic coverage

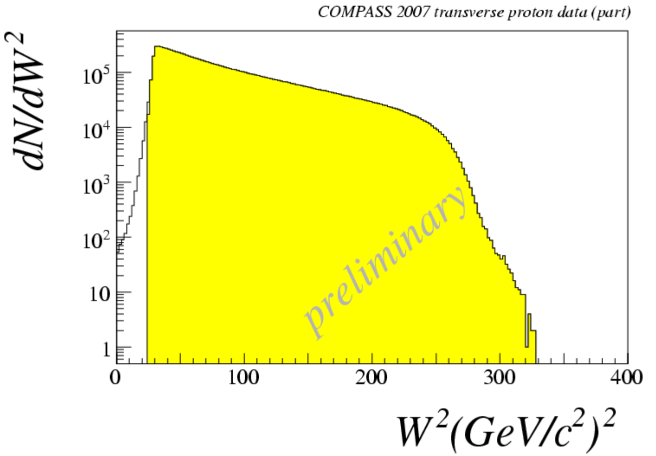




Kinematic coverage



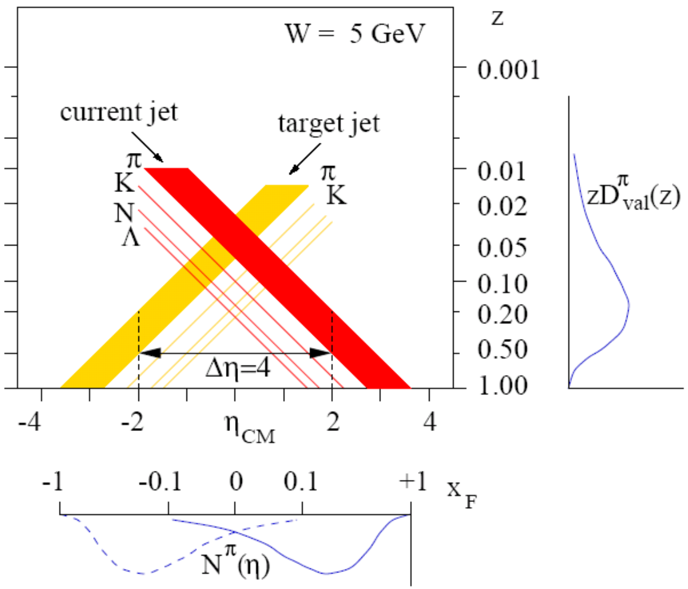




Berger criterion (separation of CFR &TFR)

The typical hadronic correlation length in rapidity is

$$\Delta y_h \simeq 2$$



if the dynamics of quark fragmentation is to be studied independently of "contamination" from target fragmentation, it is necessary that $Y \gtrsim 4$, or, equivalently, that

$$W_X = \left[\frac{Q^2(1-x)}{x}\right]^{1/2} \gtrsim 7.4\text{GeV}. \qquad (17)$$

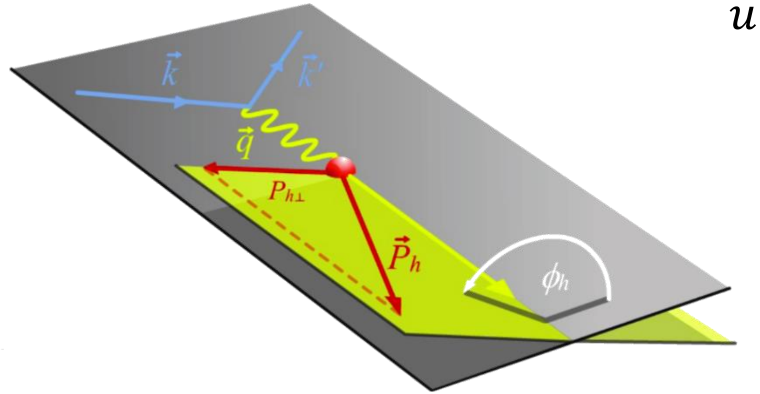
If the inequality Eq. (17) is satisfied, it should be possible to measure fragmentation functions $D(z, Q^2)$ over essentially the full range of z, $0 < z < 1$. Somewhat smaller values of W_X may be adequate if attention is restricted to the large z region. As Y is increased above 2, or

$$W_X \gtrsim 3 \text{ GeV}, \qquad (18)$$

the quark and target fragmentation regions begin to separate. As long as $Y \gtrsim 2$, the hadrons with the largest values of z are most likely quark fragments. Data[14] from $e^+e^- \to h\,X$ show that a distinct function $D(z)$ may have developed for $z \gtrsim 0.5$ at $W = 3$ GeV. The region extends to $z \simeq 0.2$ for $W = 4.8$ GeV, and to $z \simeq 0.1$ for $W = 7.4$ GeV. For $z > 0.3$, fragmentation functions have been obtained from data[15] on $ep \to e'\pi^\pm X$ at $E = 11.5$ GeV, with $3 < W_X < 4$ GeV.

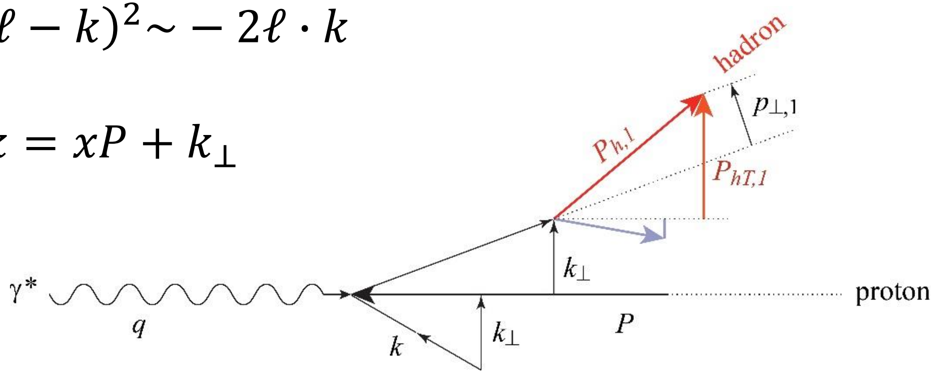
Unpolarised Azimuthal Modulation

The semi inclusive cross-section for $\ell p \rightarrow \ell' h X$ is given by $d\sigma^{\ell p \rightarrow \ell' h X} = \sum_q f_q(x, Q^2) \otimes d\sigma^{\ell q \rightarrow \ell' q} \otimes D_q^h(z, Q^2)$. The cross section for the partonic process is simply given by $d\sigma^{\ell q \rightarrow \ell' q} = \hat{s}^2 + \hat{u}^2$



$$s \coloneqq (\ell + k)^2 \sim 2\ell \cdot k$$
$$u \coloneqq (\ell - k)^2 \sim -2\ell \cdot k$$

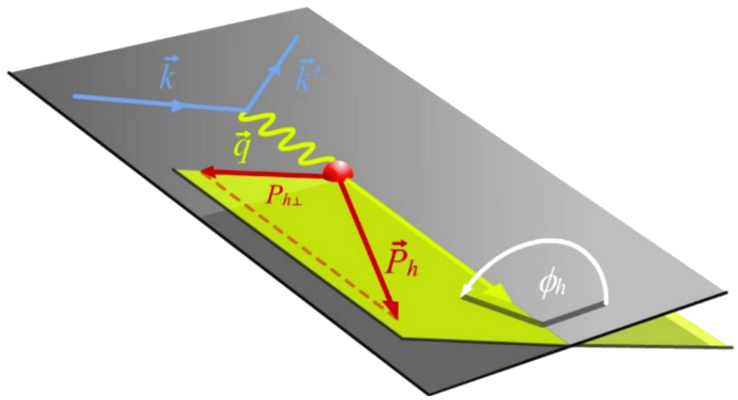
$$k = xP + k_\perp$$



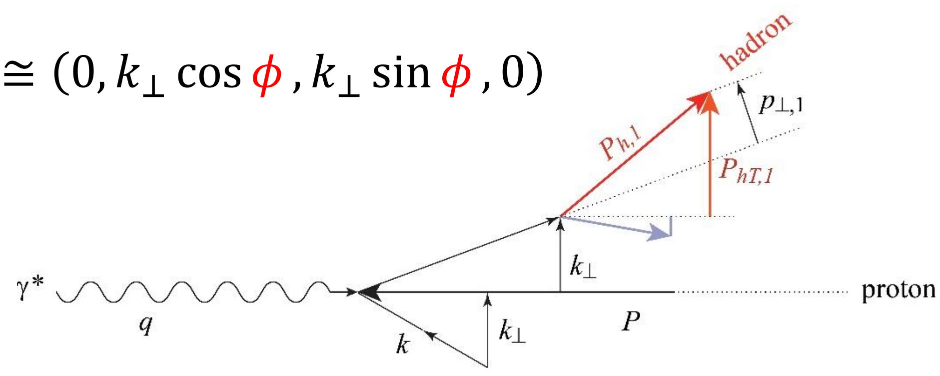
In collinear PM $d\sigma^{\ell q \rightarrow \ell' q} = \hat{s}^2 + \hat{u}^2 = x[1 + (1 - y)^2]$, i.e. no ϕ_h dependence.

Unpolarised Azimuthal Modulation

$k_\perp$ has only components outside the lepton scattering plane:



$$k_\perp \cong (0, k_\perp \cos\phi, k_\perp \sin\phi, 0)$$



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

Unpolarised Azimuthal Modulation

The full cross section for the unpolarised case is written as:

$$\frac{d\sigma}{dx\,dy\,dz\,dP_{hT}^2\,d\phi_h\,d\psi} = \left[\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\cos\phi_h\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\right.$$

Bacchetta, Diehl, Goeke, Metz, Mulders and Schlegel JHEP 0702:093 (2007)

$$A_{UU}^{x}\left(x,z,dP_{hT}^2,Q^2\right) = \frac{F_{UU}^{x}}{F_{UU,T}+\varepsilon F_{UU,L}}$$

$$\varepsilon = \frac{1-y-\frac{1}{4}y^2\gamma^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}y^2\gamma^2} \quad and \quad \gamma = \frac{2xM}{Q}$$

$$F_{UU} = C[f_1D_1] = x\sum_q e_q^2\int d\vec{p}_\perp d\vec{k}_\perp\,\delta^2\left(z\vec{k}_\perp+\vec{p}_\perp-\vec{P}_{hT}\right)f_1^q(x,k_\perp,Q^2)D_{1,q}^h(z,p_\perp,Q^2)$$

Unpolarised Azimuthal Modulation

When looking at the content of the structure functions/modulations in terms of TMD PDFs for the $\cos\phi_h$ and $\cos 2\phi_h$ we can write:

$$F_{UU}^{\cos\phi_h} = -\frac{2M}{Q} C\left[\frac{\hat{h}\cdot\vec{k}_\perp}{M} f_1 D_1 - \frac{p_\perp k_\perp}{M}\frac{\vec{P}_{hT} - z(\hat{h}\cdot\vec{k}_\perp)}{zM_h M} h_1^\perp H_1^\perp\right] + \text{twists} > 3$$

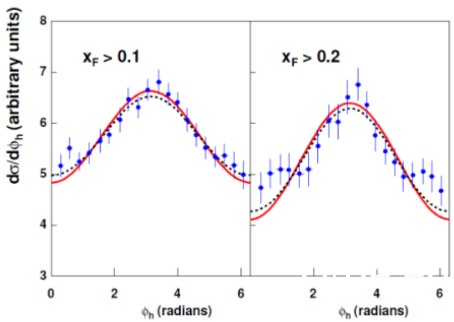
$$F_{UU}^{\cos 2\phi_h} = C\left[\frac{(\hat{h}\cdot\vec{k}_\perp)(\hat{h}\cdot\vec{p}_\perp) - \vec{p}_\perp\cdot\vec{k}_\perp}{MM_h} h_1^\perp H_1^\perp\right] + \text{twists} > 3$$

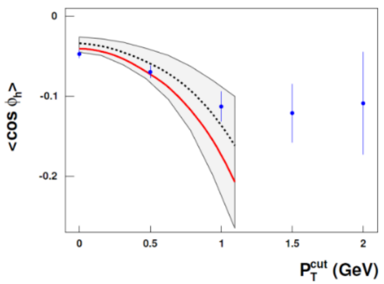
In the $\cos 2\phi_h$ Cahn effects enters only at twist4

$$F_{\text{Cahn}}^{\cos 2\phi_h} \approx \frac{2}{Q^2} C\left[\left\{2(\hat{h}\cdot\vec{k}_\perp)^2 - k_\perp^2\right\} f_1 D_1\right]$$

Experimental status

- Azimuthal modulations in $\ell p \to \ell' h X$ measured by
  - EMC
  - E665





Fits from M. Anselmino, V. Barone, E. Boglione,U. D’Alesio, F. Murgia, A. Prokudin, A. Kotzinian, and C. Turk

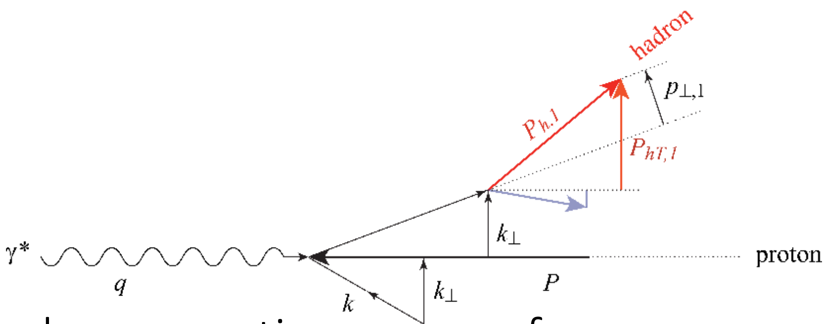
- Large modulations up to 40% for $\cos\phi$, while $\cos 2\phi \sim 5\%$

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

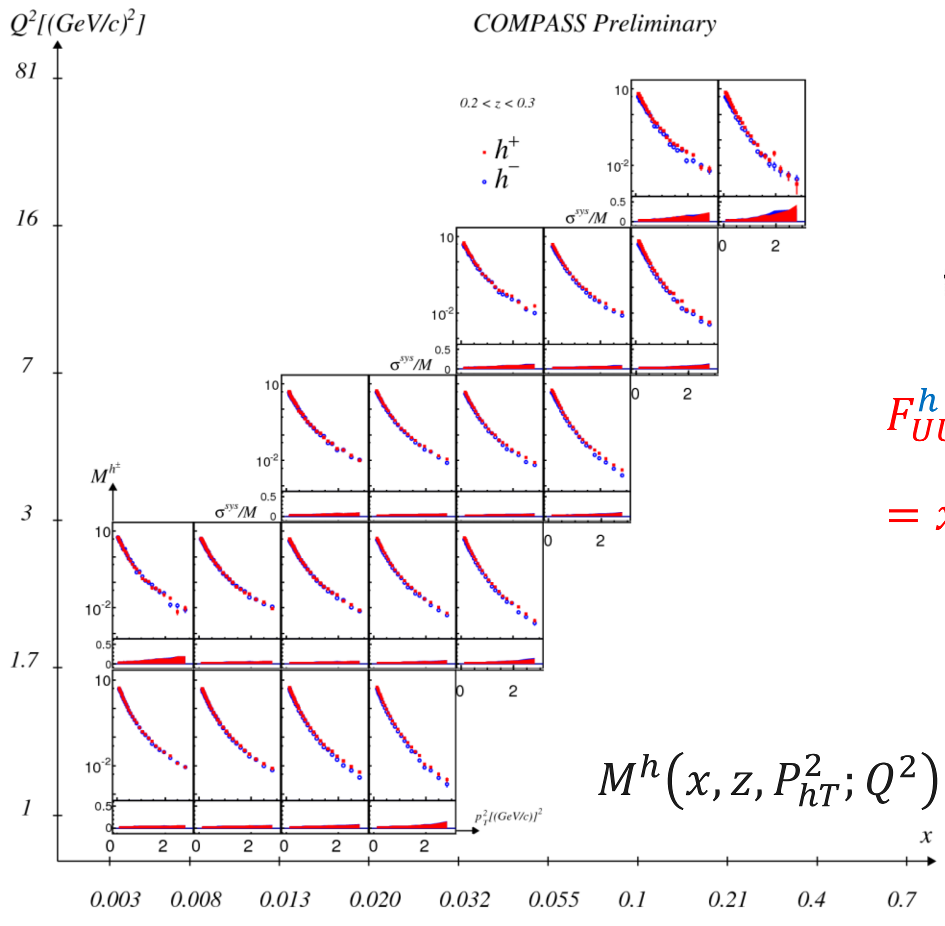
Importance of unpolarized SIDIS

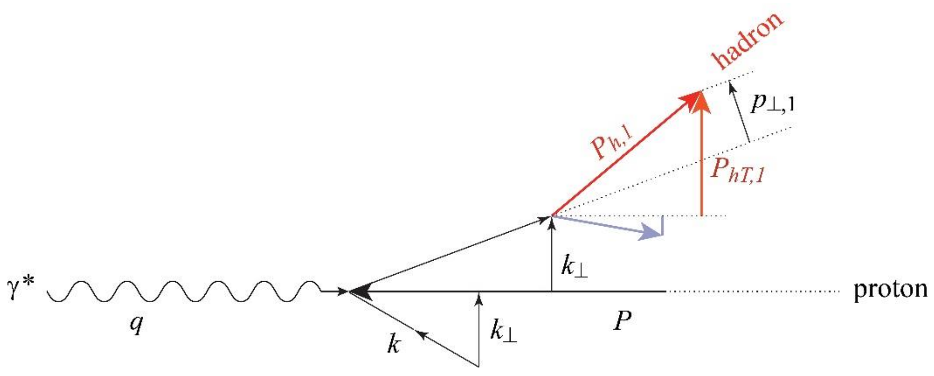
- The cross-section dependence from p_T^h results from:
    - intrinsic $k_\perp$ of the quarks
    - $p_\perp$ generated in the quark fragmentation
    - A Gaussian ansatz for $k_\perp$ and $p_\perp$ leads to
    - $\langle P_{hT}^2 \rangle = z^2 \langle k_\perp^2 \rangle + \langle p_\perp^2 \rangle$



- 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 and on p (Hermes only)
    - No COMPASS 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

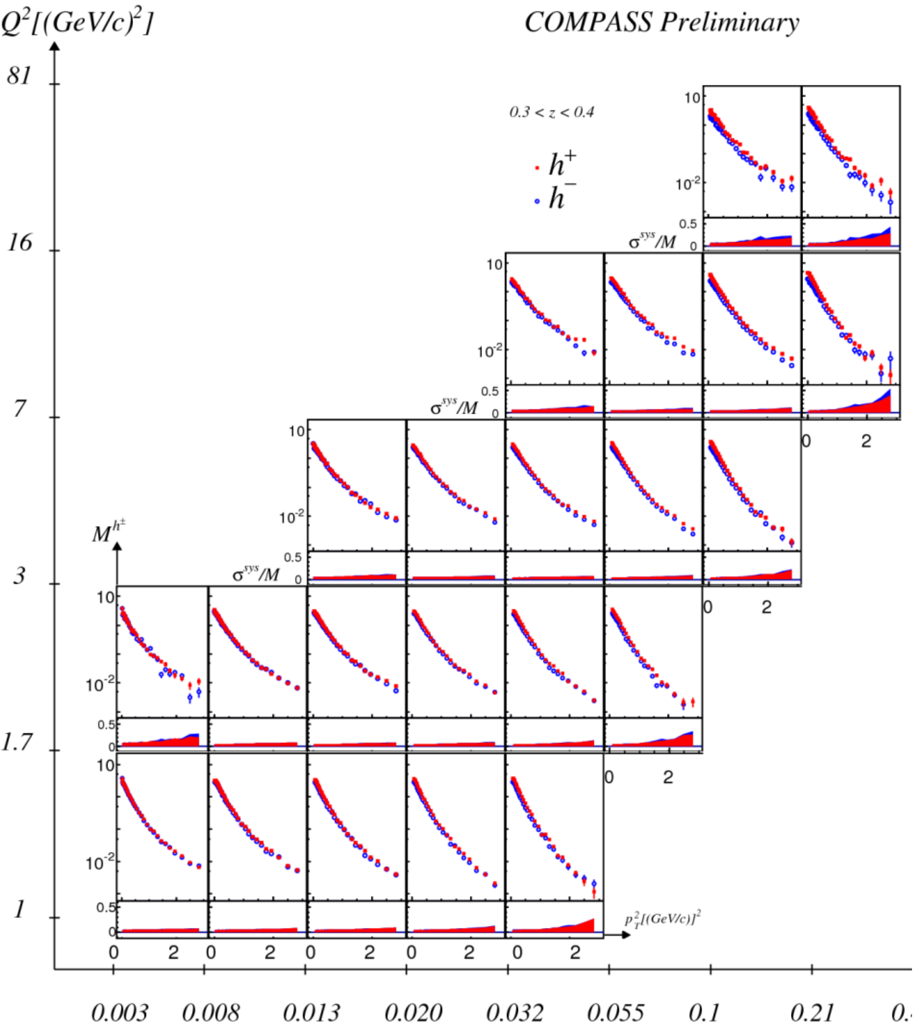


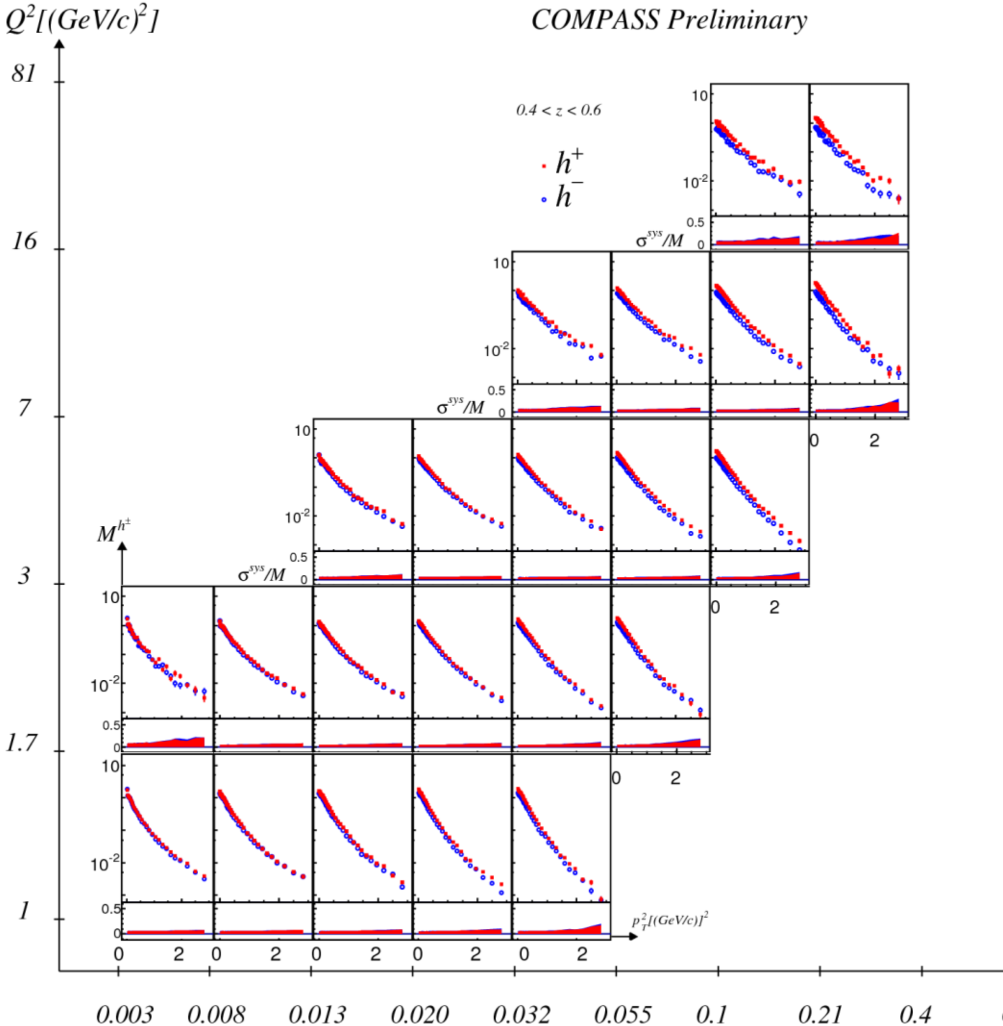


$$F_{UU}^{h}(x, z, P_{hT}^2;\ Q^2)$$
$$= x \sum_q e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp \delta(\vec{p}_\perp - z\vec{k}_\perp$$

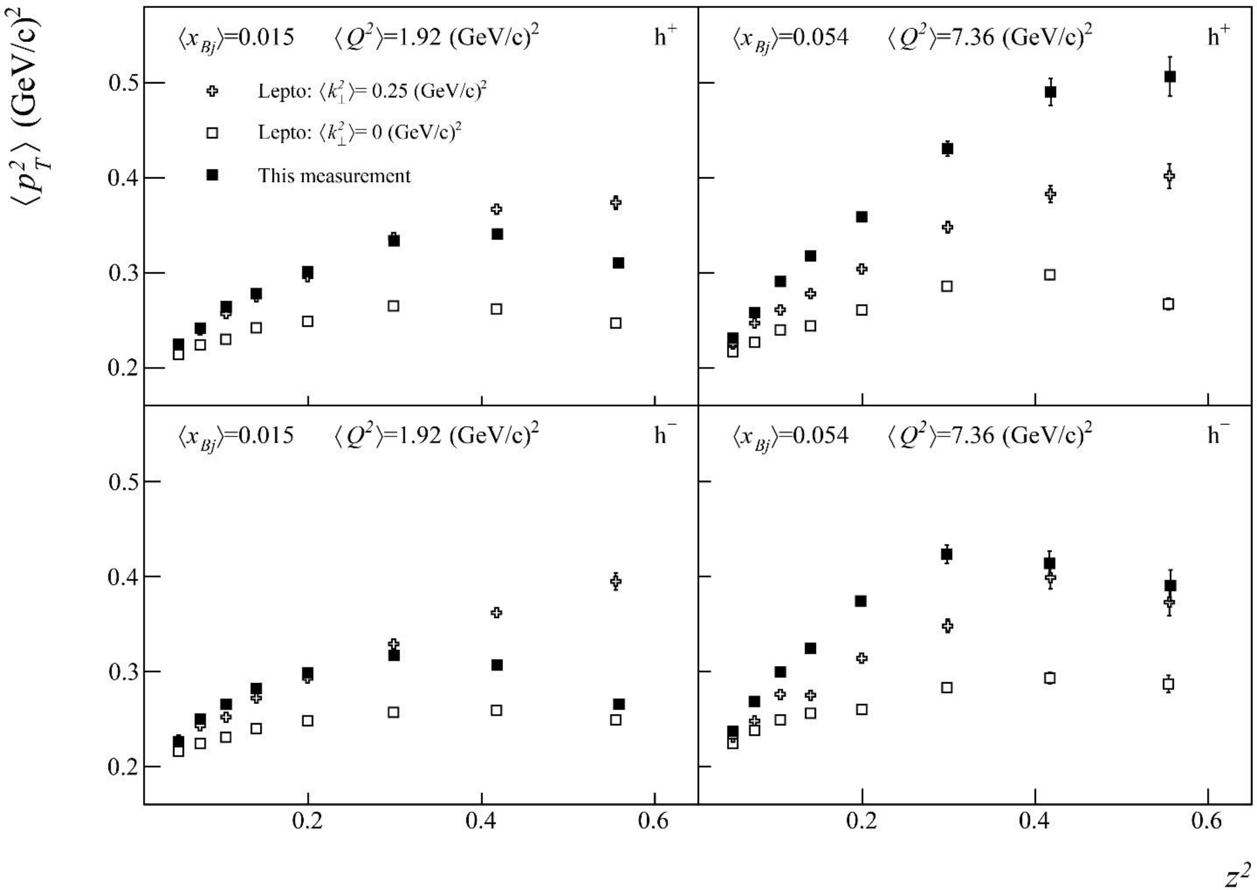
$$M^h(x, z, P_{hT}^2; Q^2) = \frac{d^5\sigma^h/dxdQ^2dzd^2\vec{p}_T}{d^2\sigma^{DIS}/dxdQ^2} \sim \frac{F_{UU}^{h}(x, z, P_{hT}^2;\ Q^2)}{F_{UU,T} + \varepsilon F_{UU,L}}$$

Importance of unpolarized SIDIS

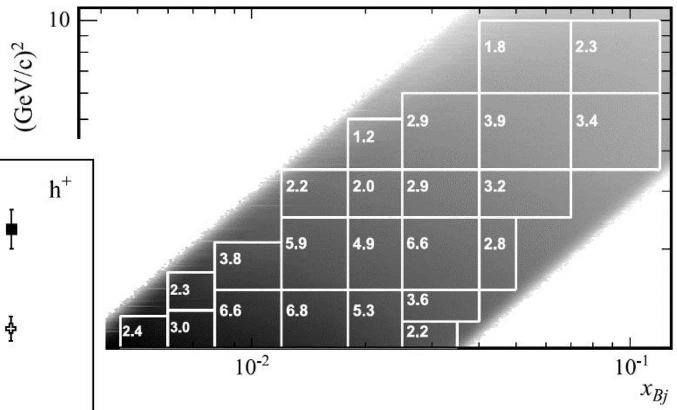




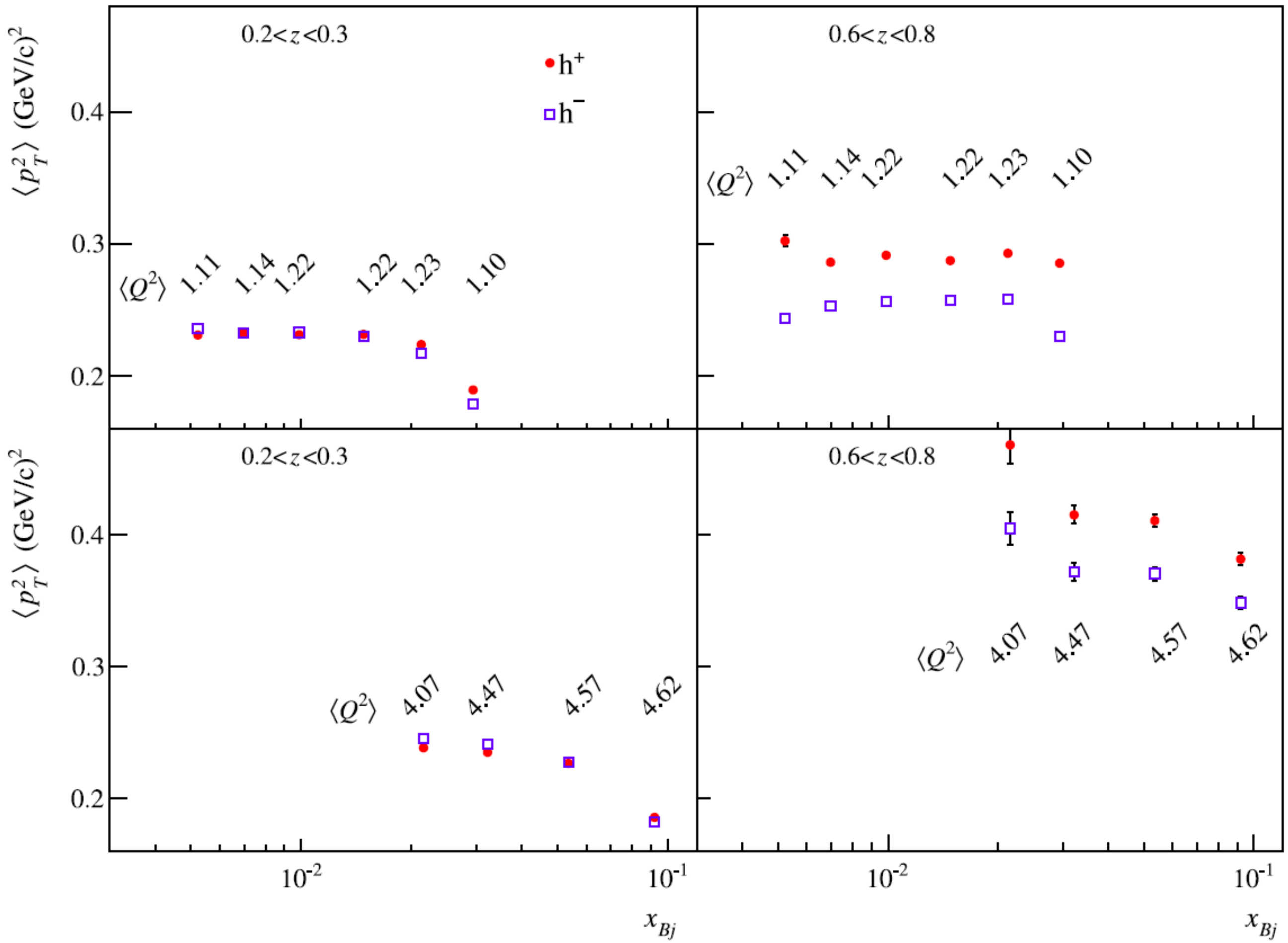
Mean values



$\langle x_{Bj}\rangle$=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
$\langle p_T^2\rangle$ (GeV/c)^2
0.2
0.3
0.4
0.5
0.2
0.4
0.6
z^2



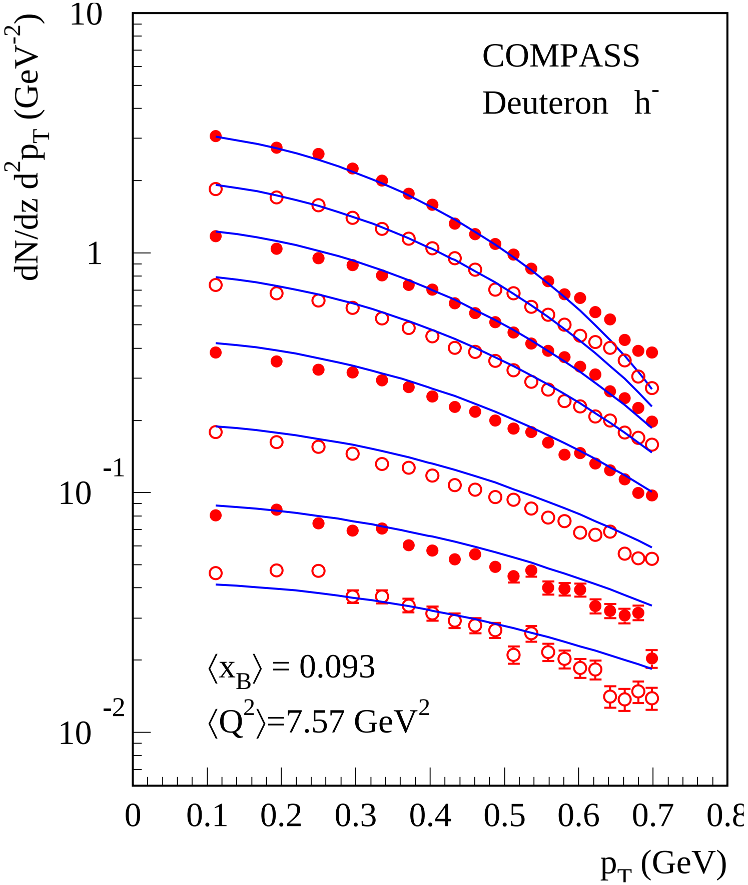
10
(GeV/c)^2
10^{-2}
10^{-1}
x_{Bj}
1.8 2.3
2.9 3.9 3.4
1.2
2.2 2.0 2.9 3.2
5.9 4.9 6.6 2.8
3.8
2.3
6.6 6.8 5.3 3.6
2.4 3.0 2.2

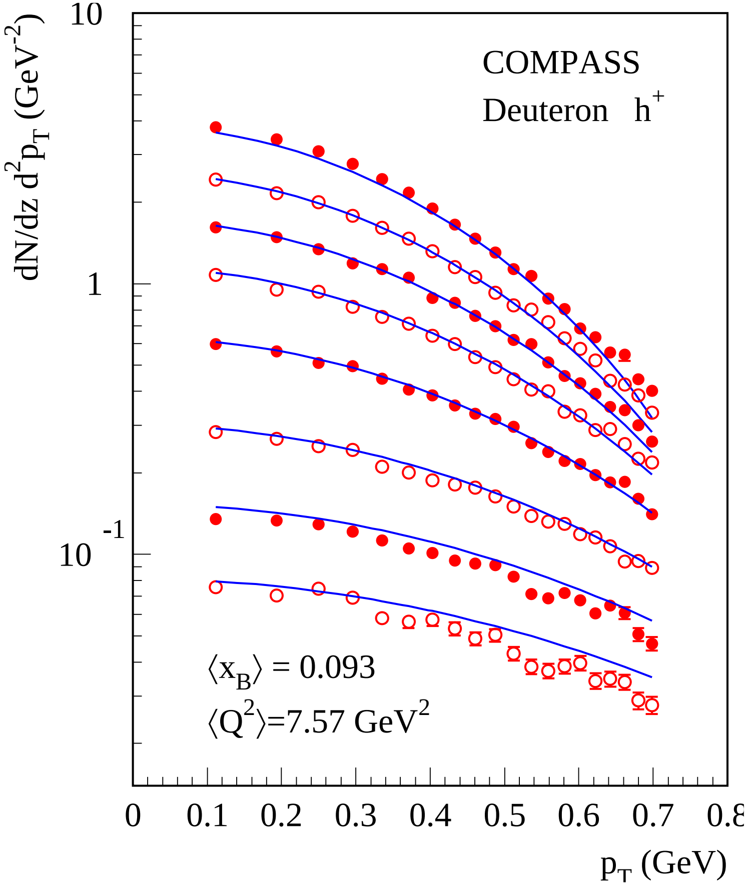

0.2<z<0.3
0.6<z<0.8
h+
h−
⟨Q²⟩ 1.11 1.14 1.22 1.22 1.23 1.10
⟨Q²⟩ 4.07 4.47 4.57 4.62
⟨p_T²⟩ (GeV/c)²
0.2
0.3
0.4
10⁻²
10⁻¹
x_Bj

TMD evolution: multiplicity distribution in SIDIS

- Comparison to COMPASS data

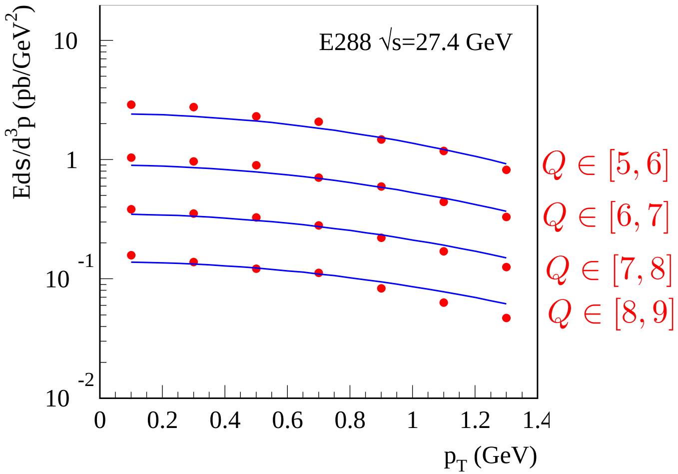
Echevarria, Idilbi, Kang, Vitev

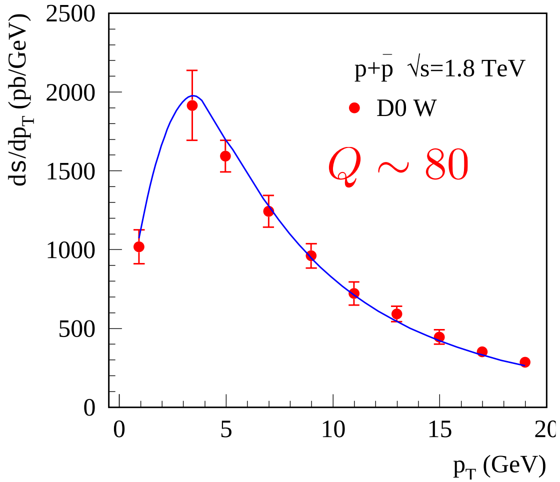


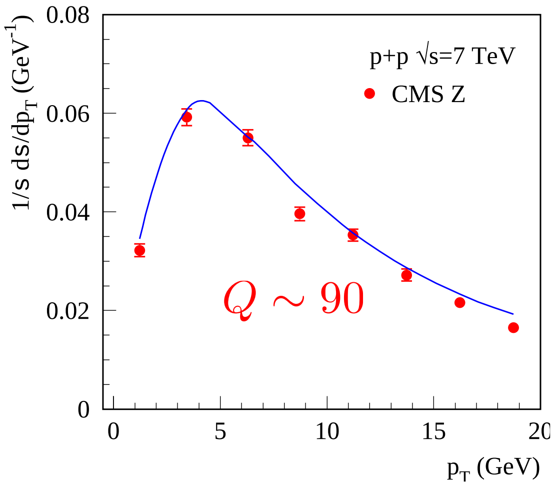


TMD evolution works: Drell-Yan and W/Z production

- Comparison with DY, W/Z P_T distribution







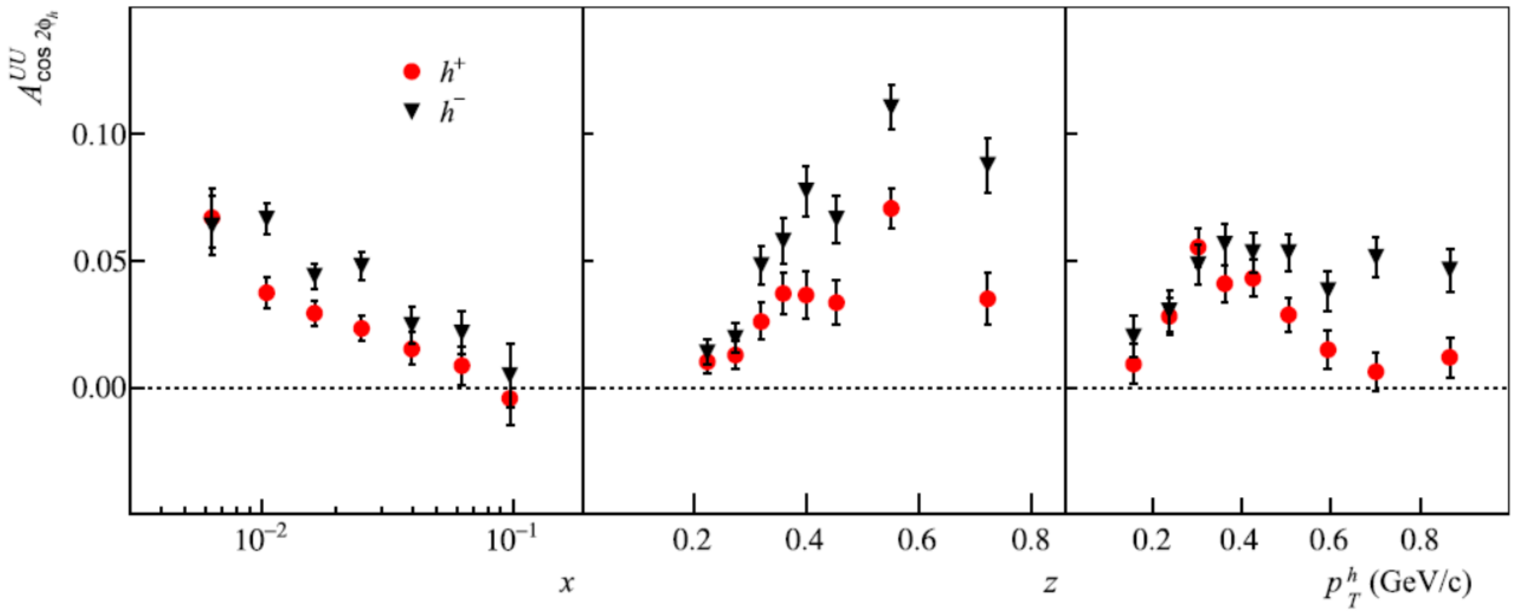
- Works for SIDIS, DY, and W/Z in all the energy ranges
- Make predictions for future JLab 12, COMPASS, Fermilab, RHIC experiments

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
- $$A_{U(L),T}^{w(\phi_h,\phi_S)}(x)=\frac{\int_{Q^2_{min}}^{Q^2_{max}}dQ^2\int_{z_{min}}^{z_{max}}dz\int_{p_{T,min}}^{p_{T,max}}d^2\vec{p}_T F_{U(L),T}^{w(\phi_h,\phi_S)}}{\int_{Q^2_{min}}^{Q^2_{max}}dQ^2\int_{z_{min}}^{z_{max}}dz\int_{p_{T,min}}^{p_{T,max}}d^2\vec{p}_T\left(F_{UU,T}+\varepsilon F_{UU,L}\right)}$$

Boer-Mulders in $\cos 2\phi$

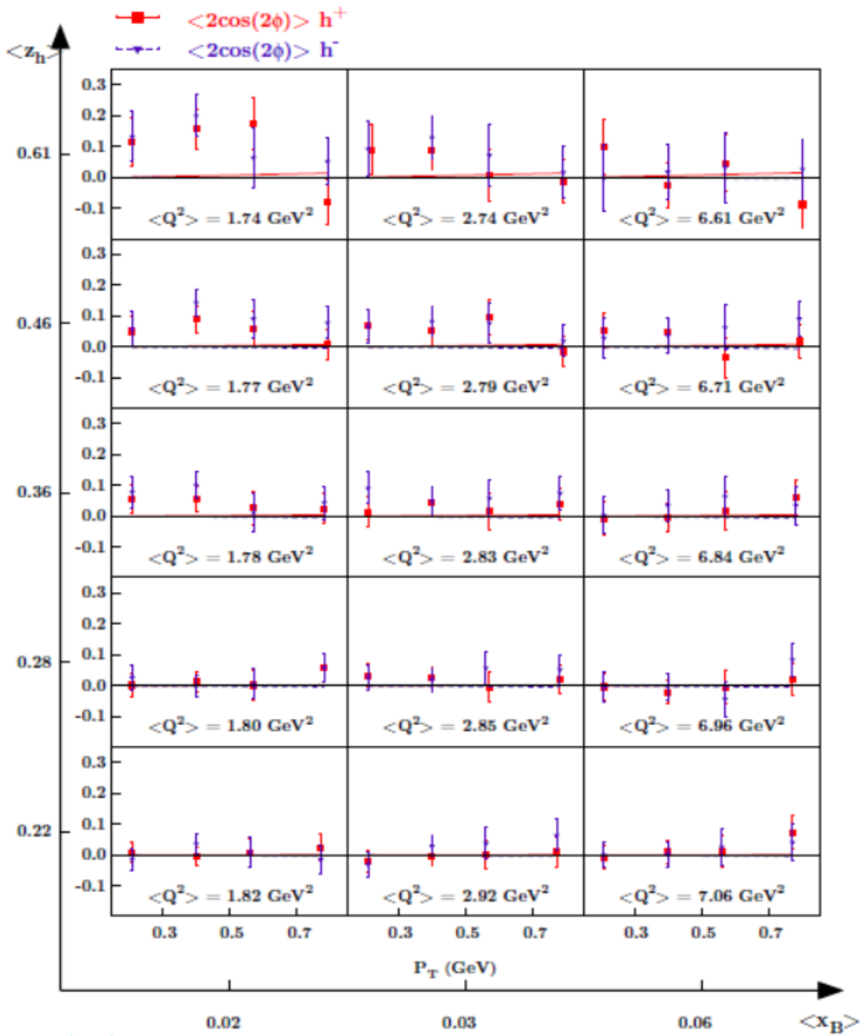
1064 *C. Adolph et al. / Nuclear Physics B 886 (2014) 1046–1077*

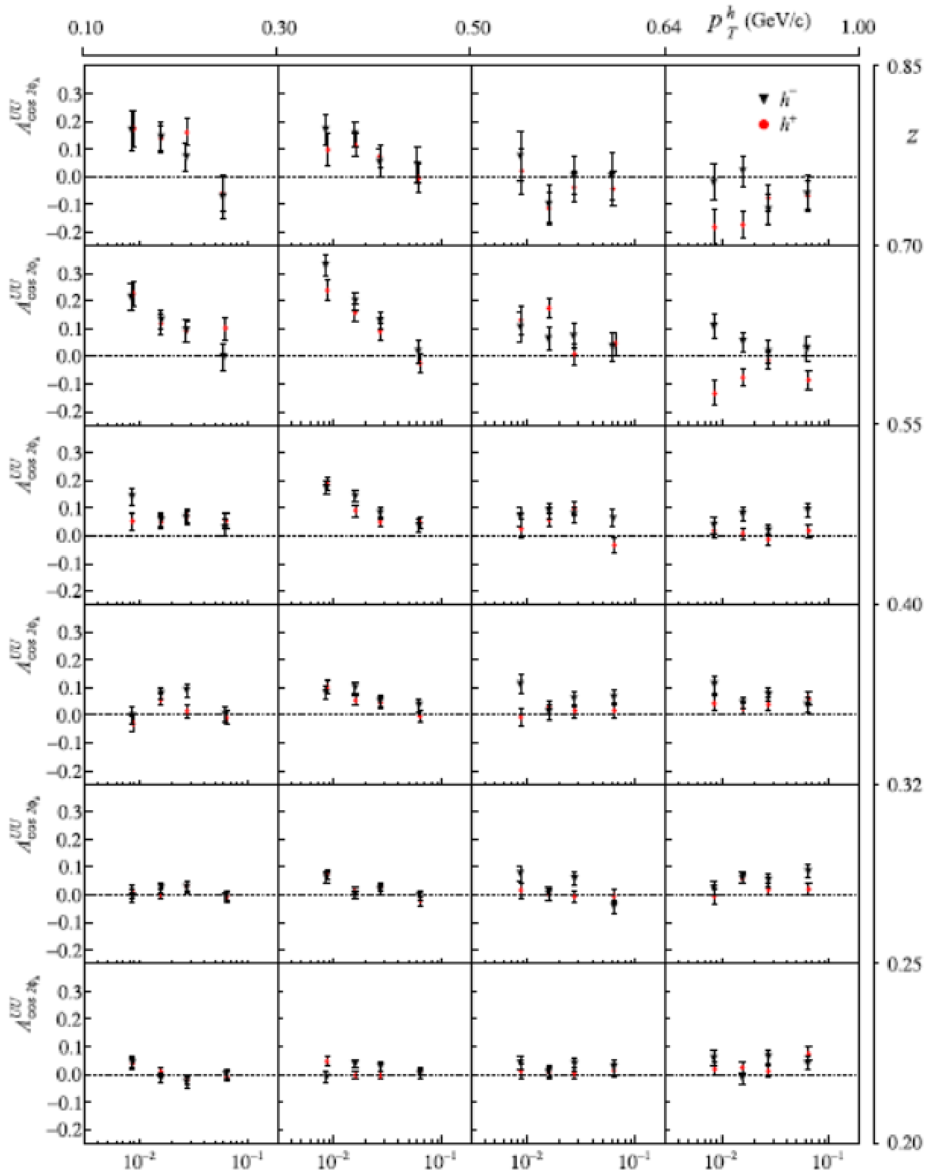


$$F_{UU}^{\cos 2\phi}(x, z, P_{hT}^2;\ Q^2)$$

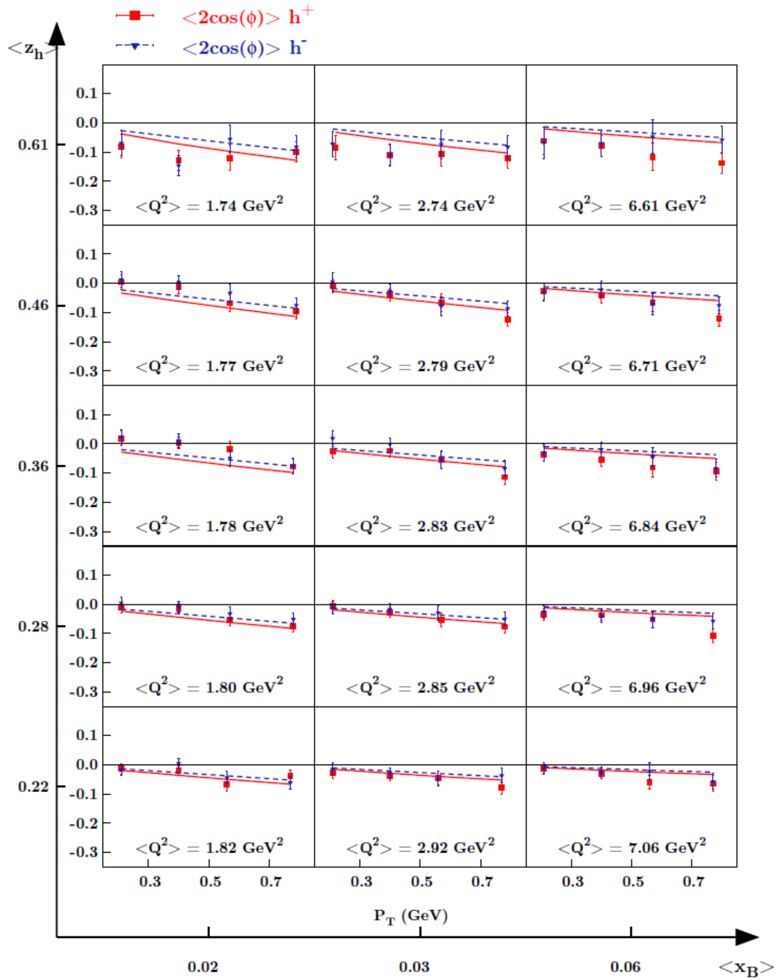
$$= -x \sum_q e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp \frac{2(\hat{h}\cdot\vec{k}_\perp)(\hat{h}\cdot\vec{k}_\perp) - \vec{k}_\perp\cdot\vec{p}_\perp}{M m_h}\ h_1^{\perp,q}(x, k_\perp^2; Q^2) H_1^{\perp,q\to h}(z, p_\perp^2; Q^2)$$

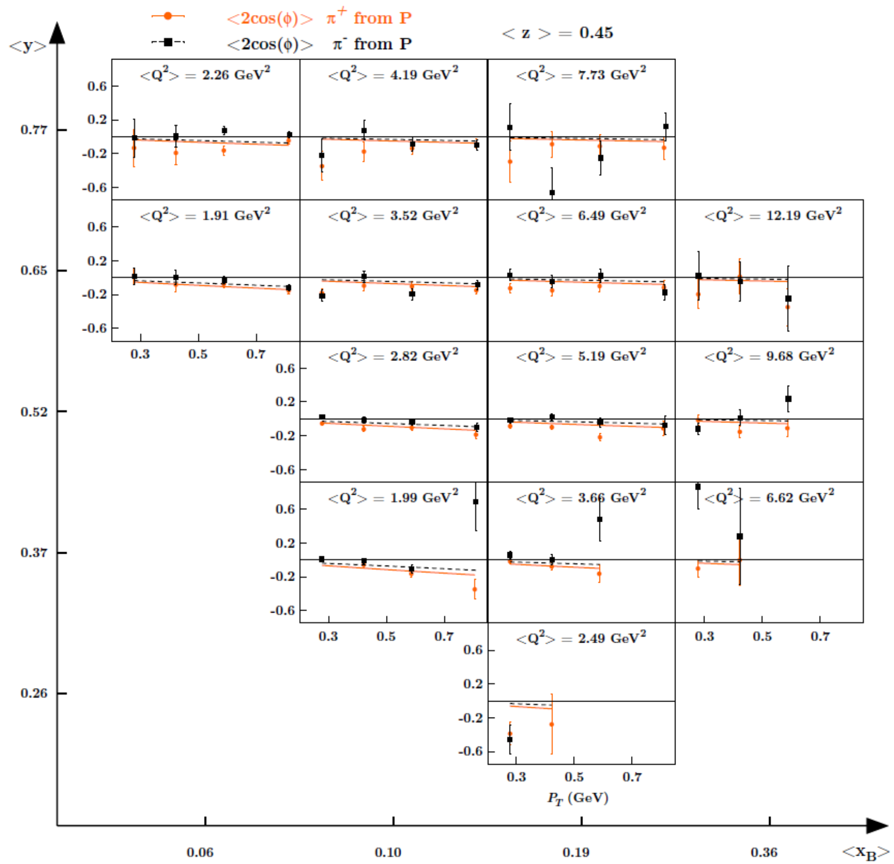
Boer-Mulders in cos 2ϕ





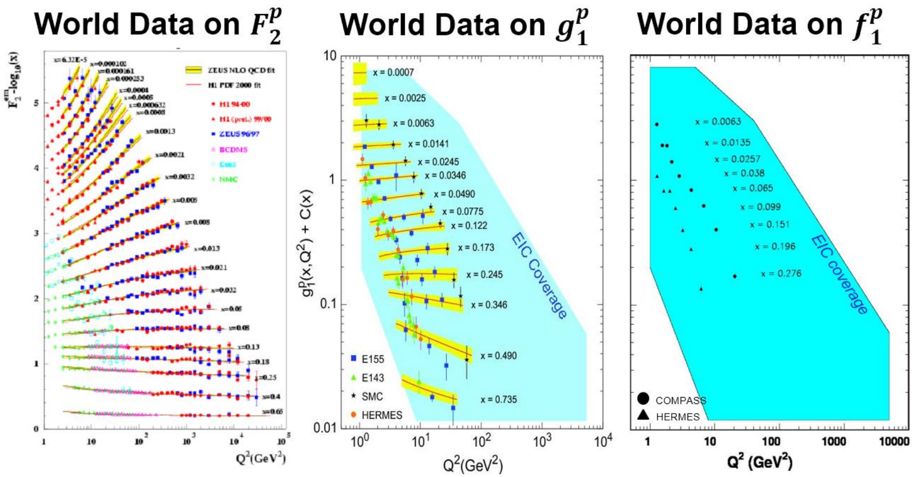
cos ϕ modulation





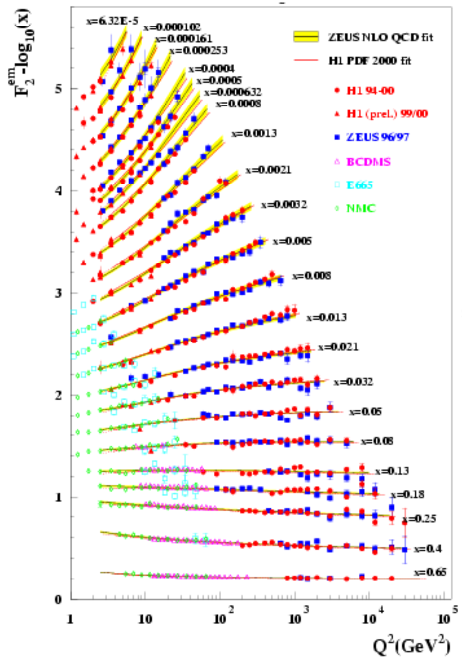
Conclusions

- The study of TMDs has entered the phase of multidimensional analysis
- An important step in this direction is the large sample of precise unpolarised data, both as multiplicities and as azimuthal modulations
- In the next years more of such data will be available both from COMPASS and from JLab12
- Waiting for the EIC to extend the accessible phase space, the description of such data is a mandatory task for the theory of TMDs

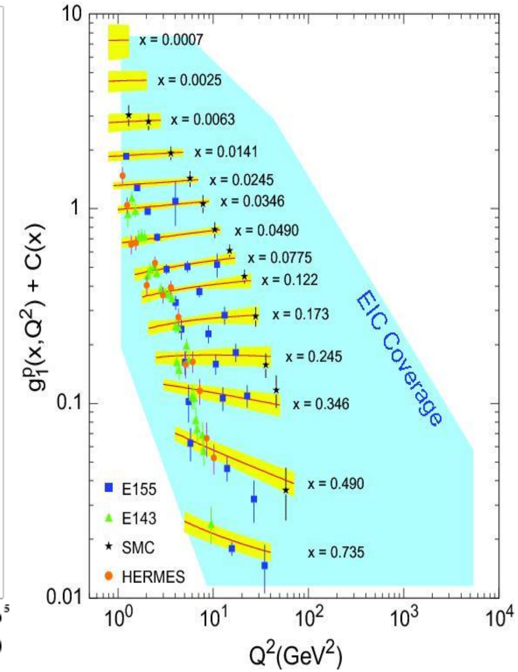


Far Future perspective

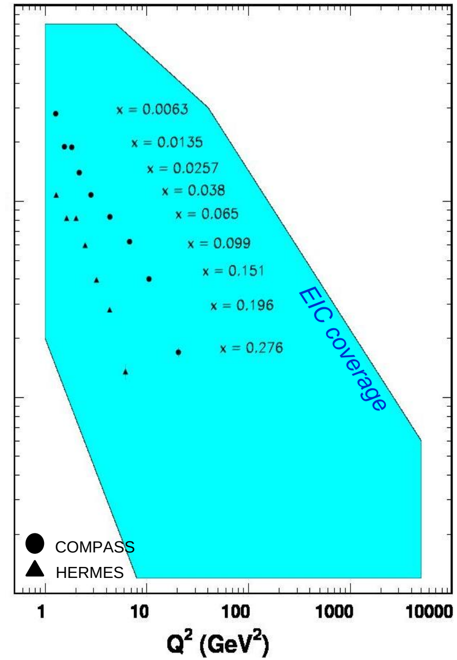
World Data on F_2^p



World Data on g_1^p



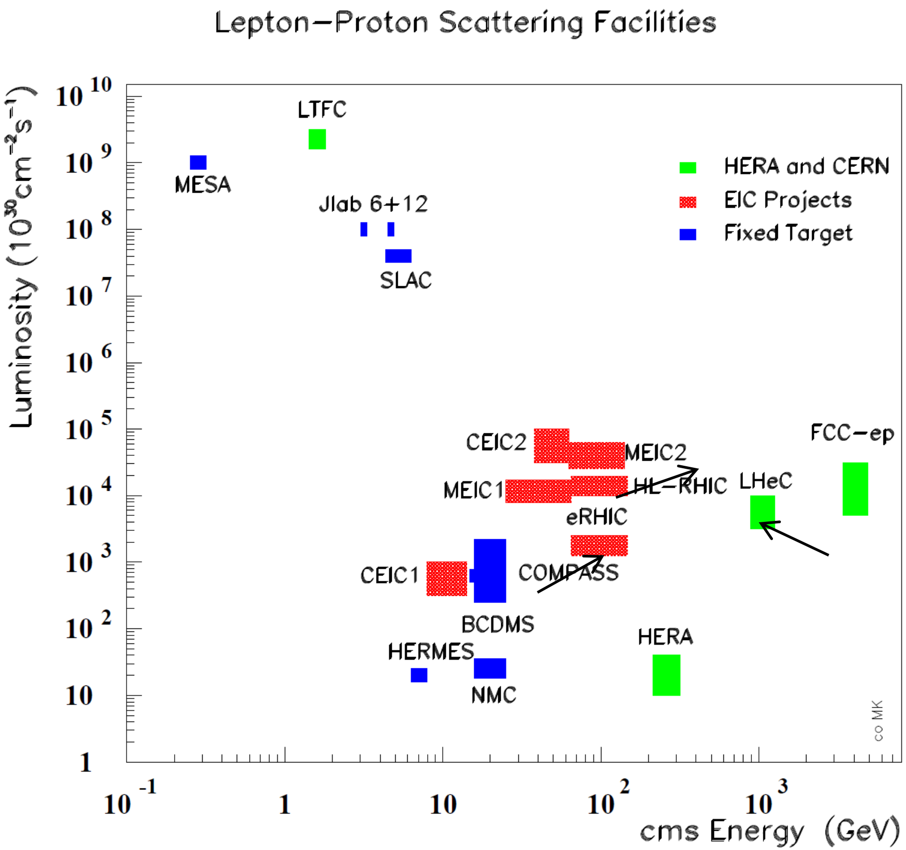
World Data on f_1^p



Thank you

and see you all in Trieste for the EICUG meeting (July 18-22, 2017)

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