Spin effects in QCD and 3D nucleon structure

- Motivations
- 3D nucleon structure
- TMDs (Transverse momentum dependent distributions)
- Transverse single-spin asymmetries in various processes
- GPDs (Generalized parton distributions)
- Open issues

Disclaimer/apologies

Not covered in this talk:

- Models of TMDs and GPDs
- Lattice calculations
- Parton orbital angular momentum
- GPD phenomenology
- TMDs/GPDs in nuclei
- Double Parton Distribution Functions

Motivations (general statements)

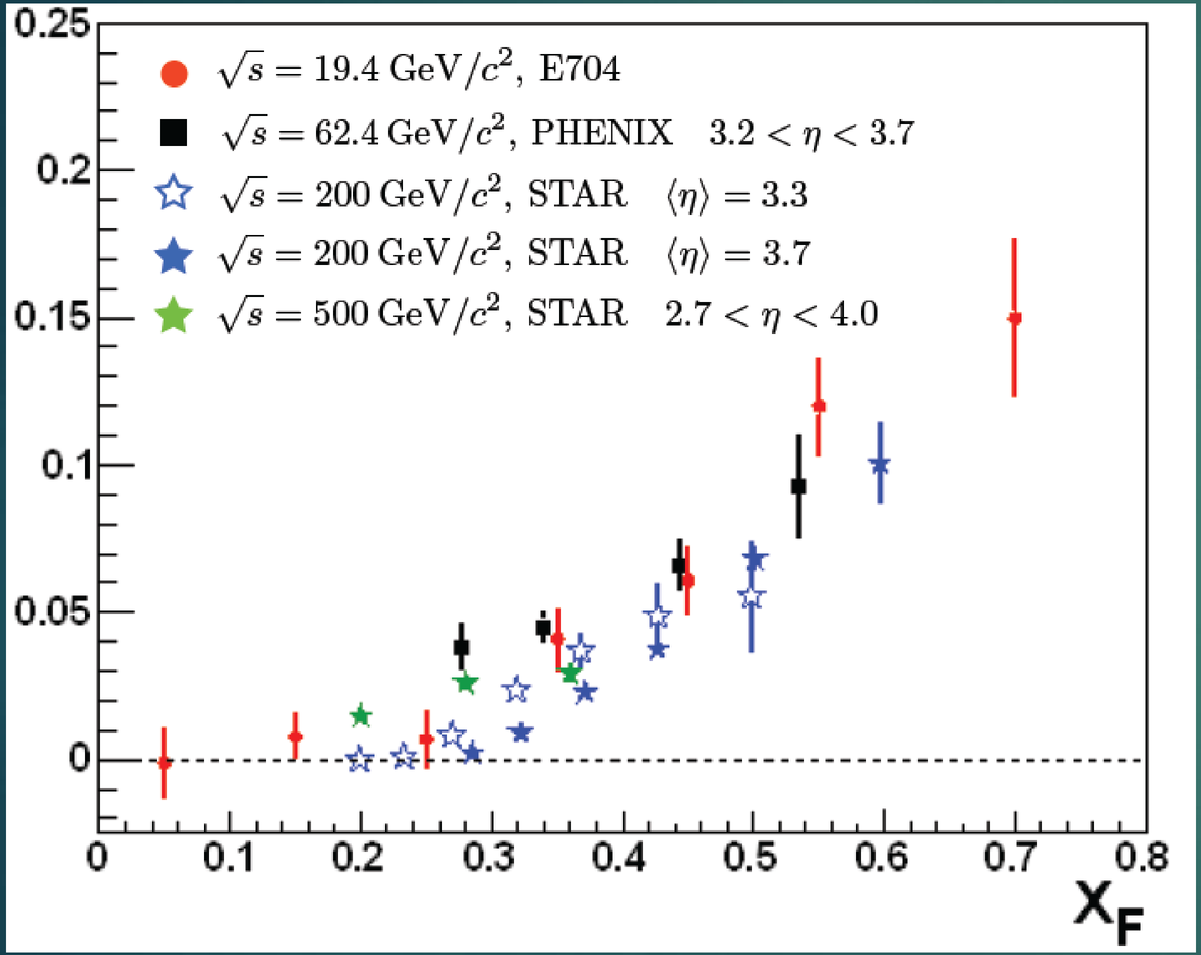
Nucleon: still a mysterious object despite 50 years of studies

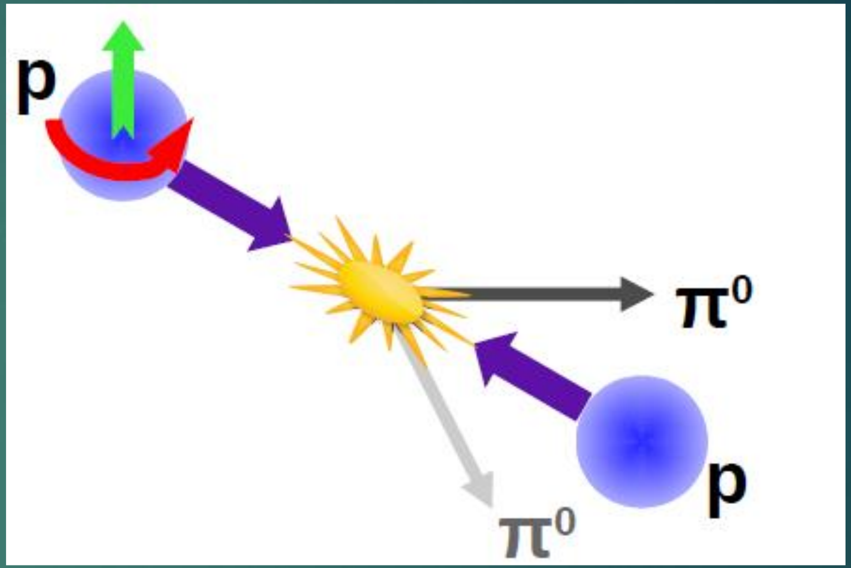
QCD and confinement: still to be understood

Spin: fundamental quantum degree of freedom

A tool to study the inner structure of composite systems

Transverse Spin effects: A_N in $p^{\uparrow}p \rightarrow \pi$ X… a long-standing puzzle



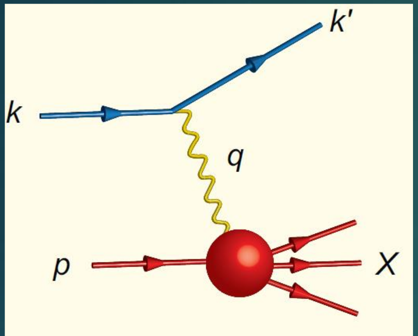


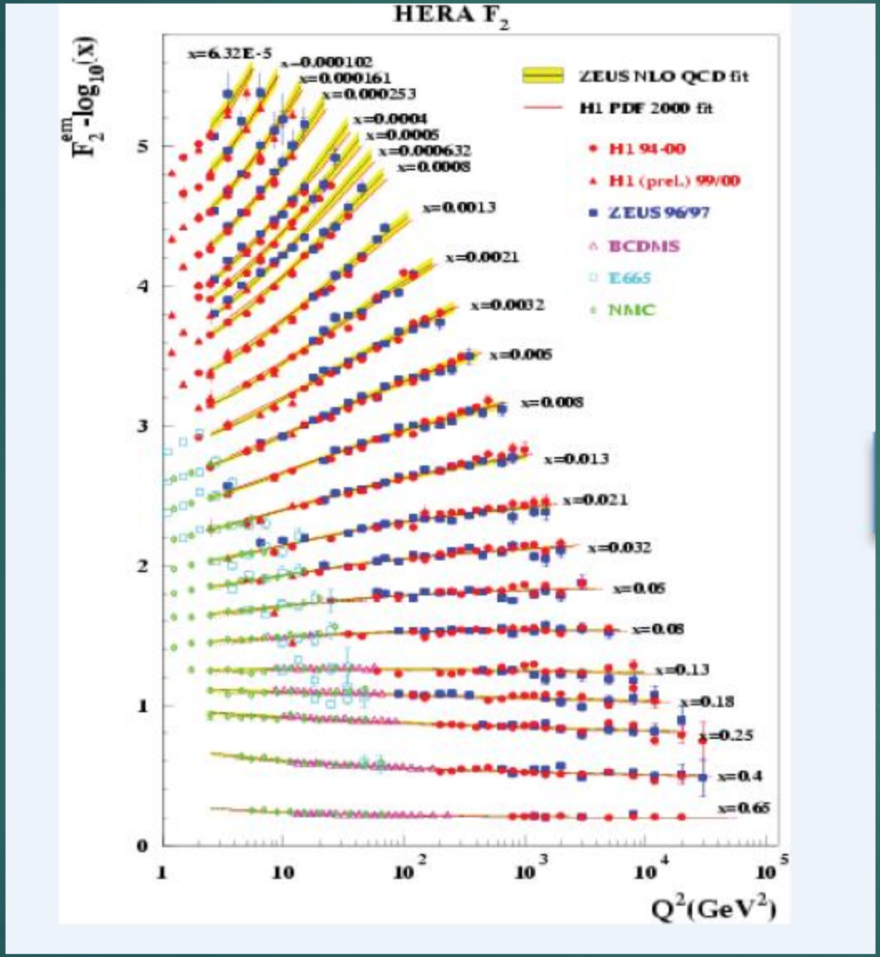
Almost energy independent

Collinear twist-2 QCD
$A_N \leq$ few %

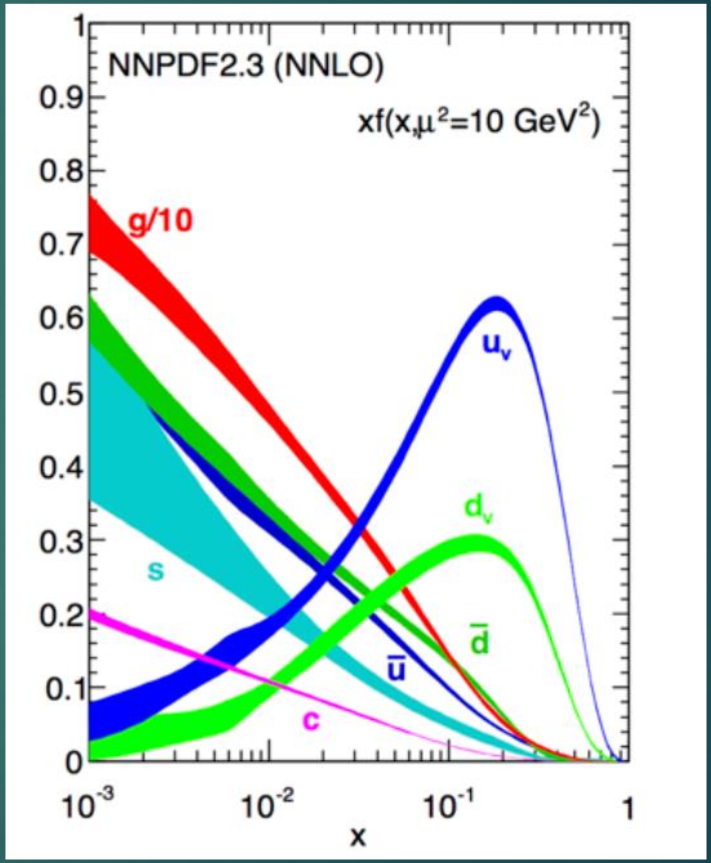
1-D picture of the nucleon

inclusive DIS





DIS Structure Function



Collinear PDFs

(open) Physics issues

Orbital motion of quarks/gluons
Its correlation to proton spin
Intrinsic transverse momentum of quarks/gluons
Spatial distribution of quarks/gluons

3D structure

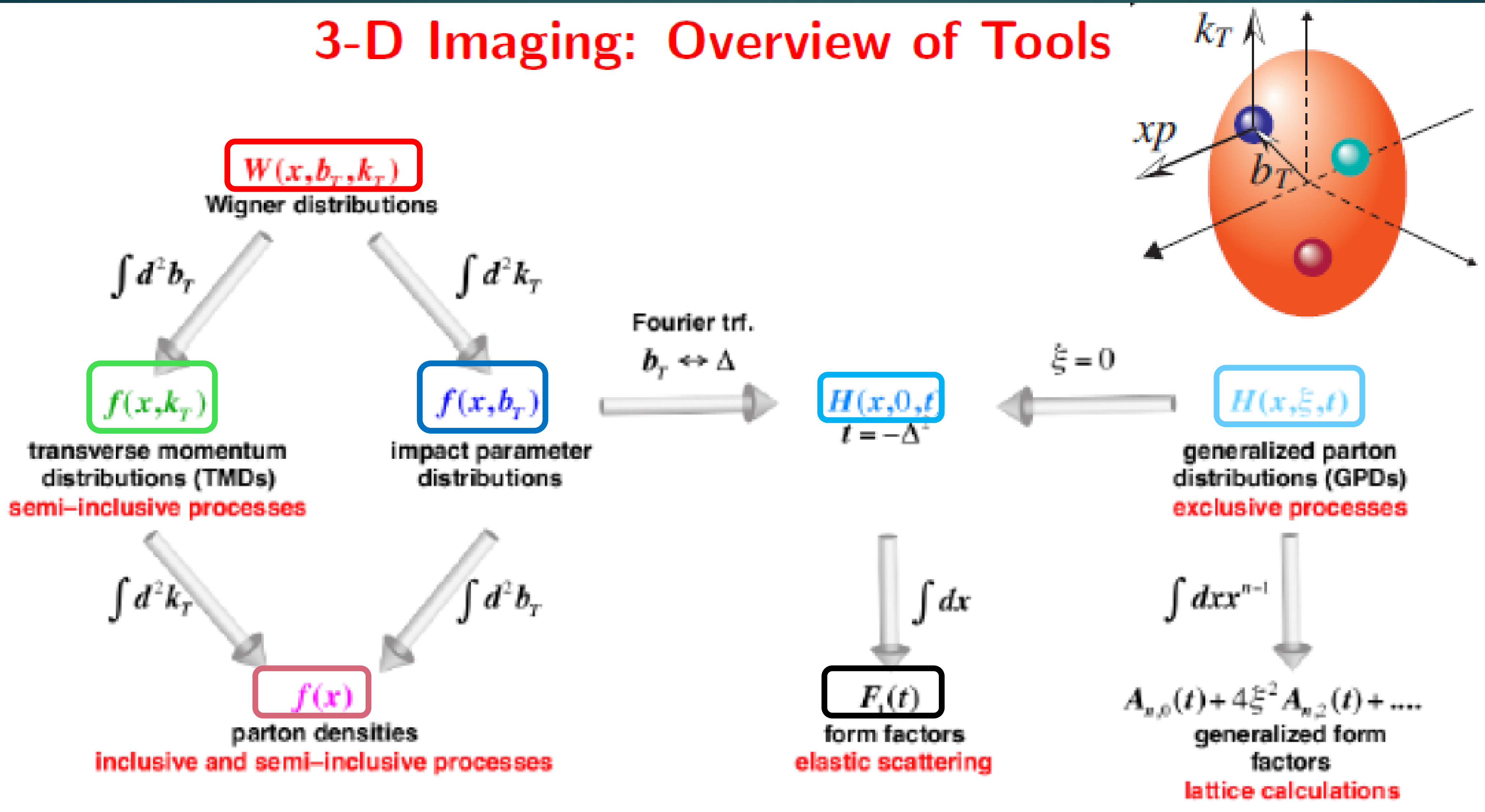
Non perturbative effects in high-energy processes
Origin of transverse/azimuthal spin asymmetries

Observables

Role of local color gauge invariance of QCD
Factorization, universality, resummation

QCD at work

3-D Imaging: Overview of Tools

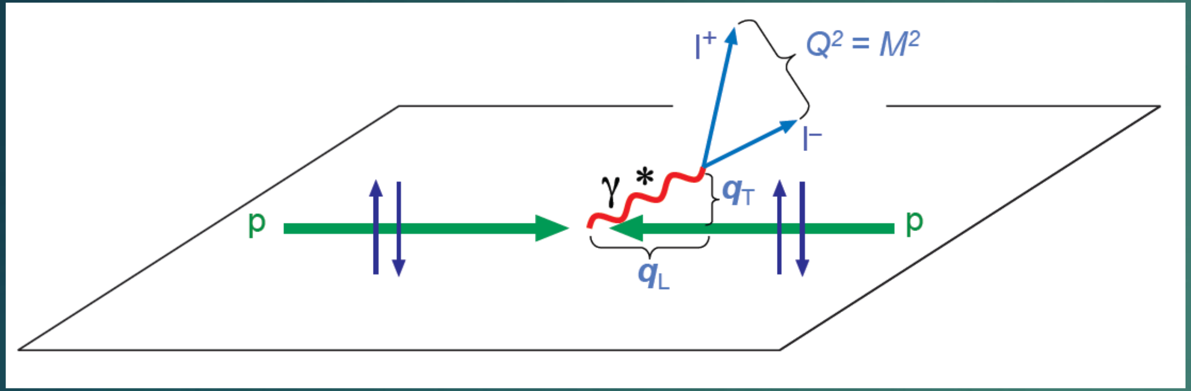


(from arXiv:1212.1701)

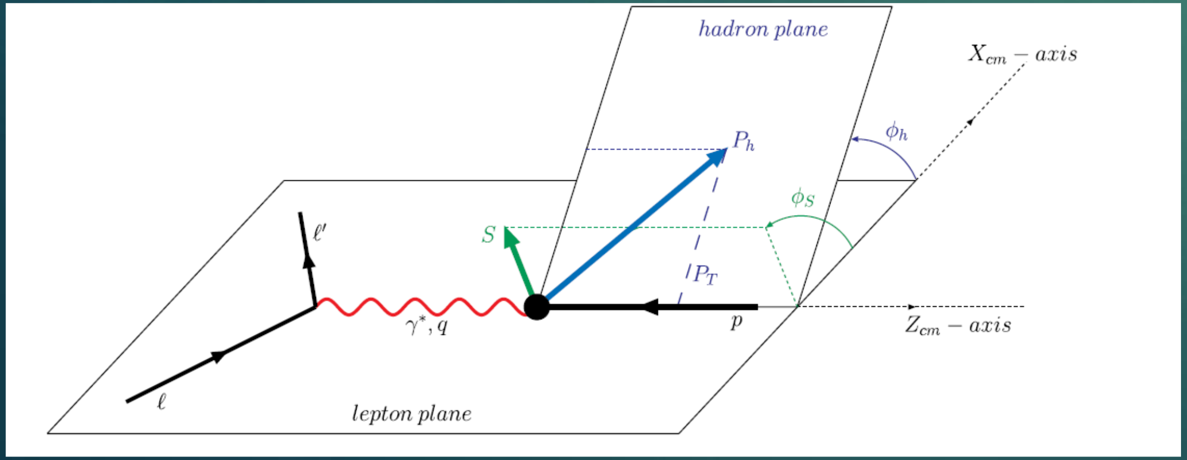
TMDs: How can we access them?

Two-scale processes: $Q^2 \ll k_T^2 \approx \Lambda_{QCD}^2$

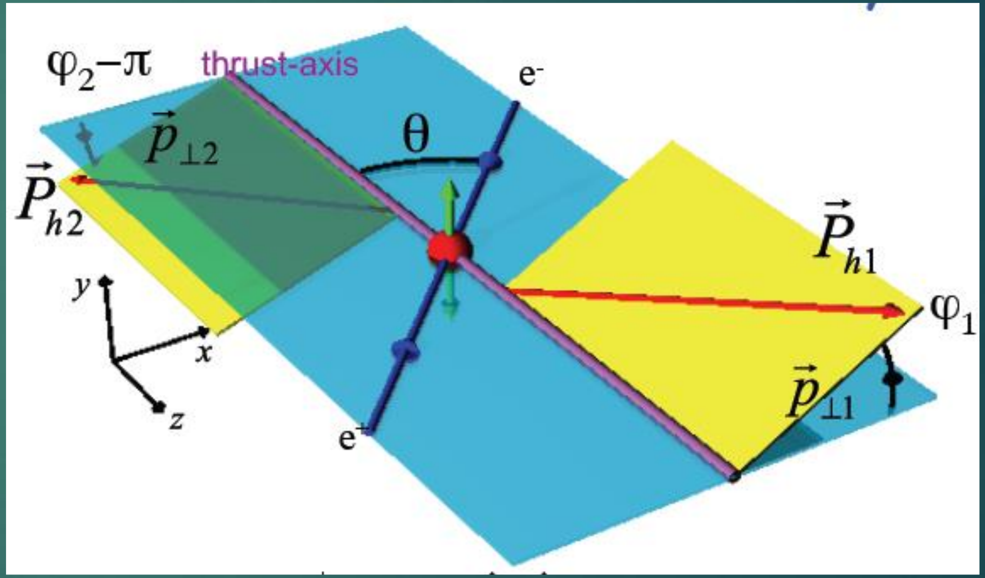
Drell-Yan $pp \rightarrow l^+ l^- X$



SIDIS $lp \rightarrow l' h X$

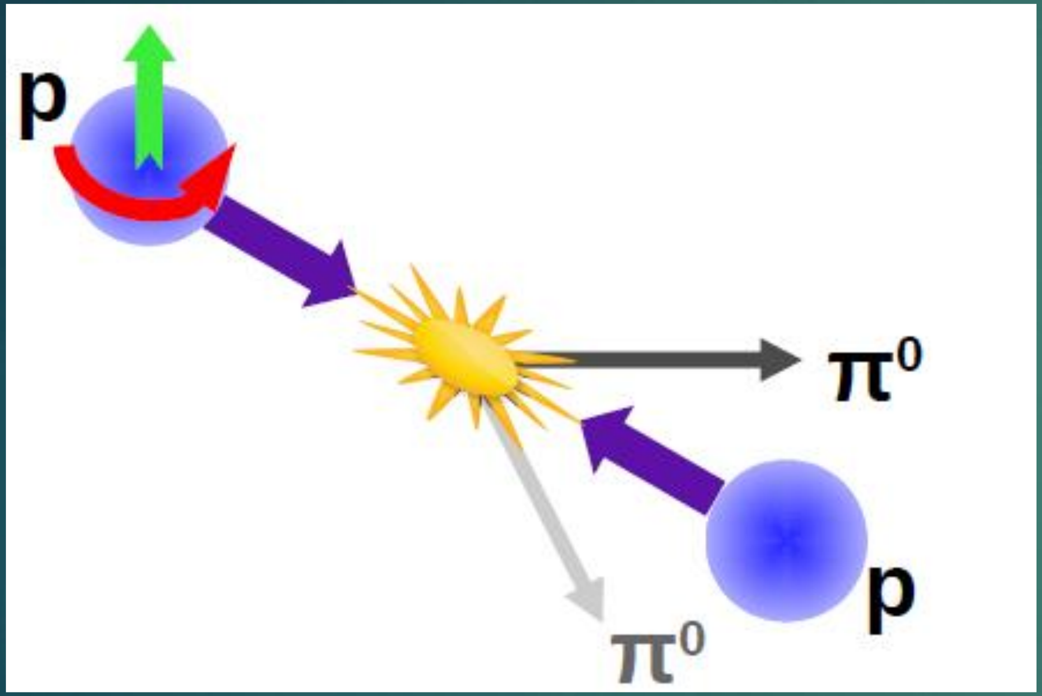


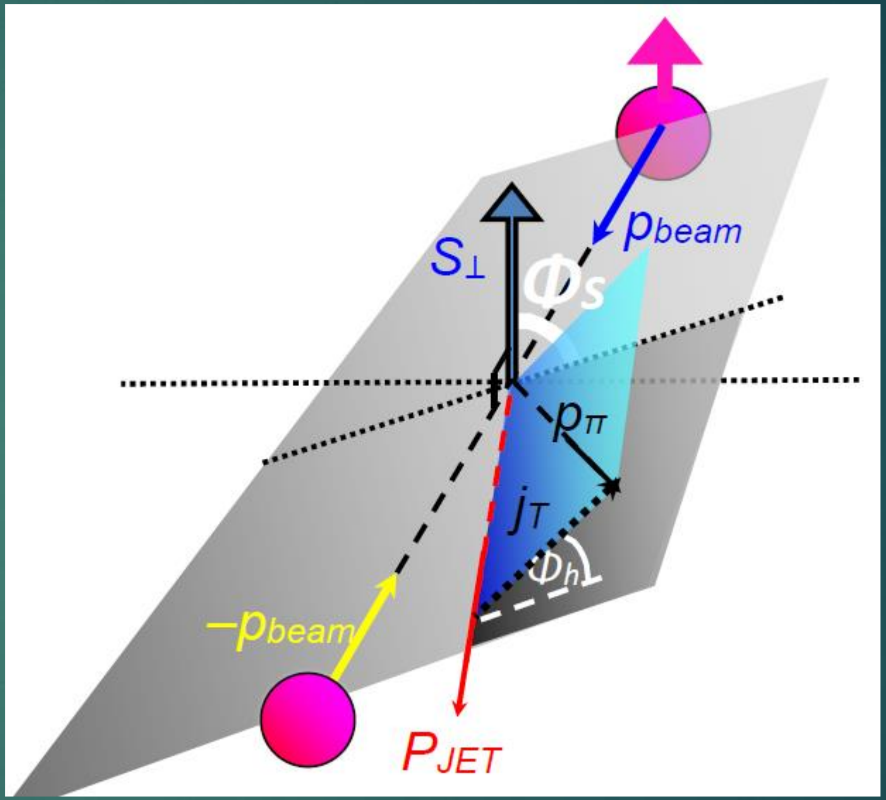
$e^+e^- \rightarrow \pi\pi X$



TMD factorization proven

And possibly in processes like





$pp \to \pi X$

$(pp \to \gamma X, pp \to jet X)$

Single scale processes

$pp \to \pi \, jet \, X$

And more

Where can we access TMDs?

SIDIS — hermes, COMPASS, Jefferson Lab, EIC

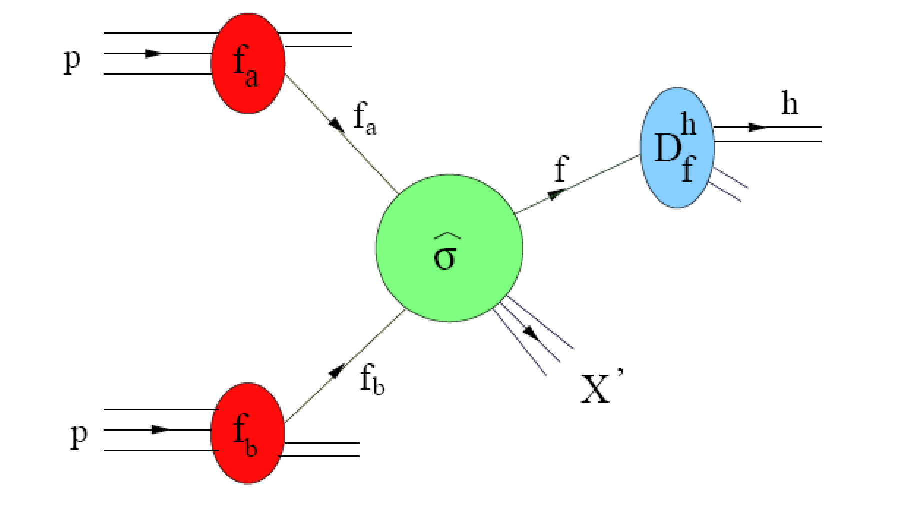
Drell-Yan — Fermilab, LHC, COMPASS

$e^+e^- \to \pi\,\pi\,X$ — BELLE, BABAR, BESIII

$pp \to \pi X\,,\ pp \to \pi\ jet\ X$ — BROOKHAVEN NATIONAL LABORATORY

Theory: factorization and evolution

Collinear approach

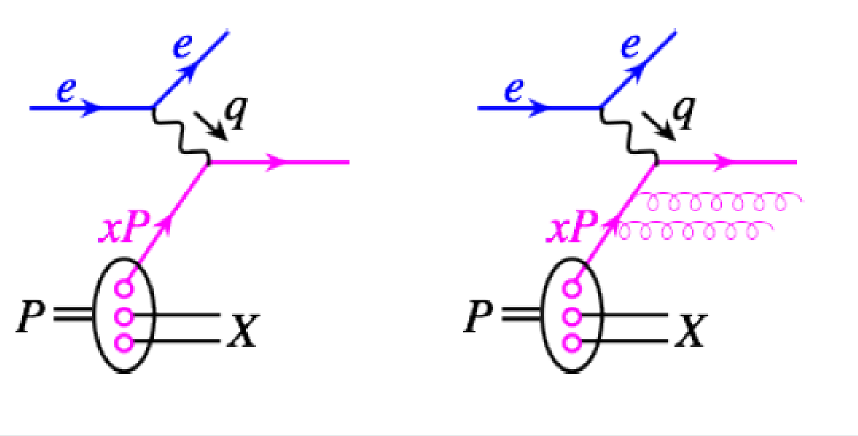


Factorization

$$\sigma(pp \to hX) \sim f_a(x_1) \otimes f_b(x_2) \otimes \hat{\sigma}^{f_a f_b \to f}(\hat{s}) \otimes D_f^h(z)$$

Parton Distribution Func.	Partonic x-section	Fragmentation Func.
from experiment	from pQCD	from experiment
Universal	Process dependent	**Universal**

Evolution → DGLAP eqs.



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

A cornerstone in pQCD

TMD approach…more involved

TMD Factorization and evolution

$$\frac{d\sigma_{\rm DY}}{dq_T} \sim \mathcal{H}_{\rm DY} \int d^2\vec{k}_{aT}\, d^2\vec{k}_{bT}\, \delta(\vec{q}_T - \vec{k}_{aT} - \vec{k}_{bT})\, f_1^q(x_a, \vec{k}_{aT}^{\,2})\, f_1^{\bar{q}}(x_b, \vec{k}_{bT}^{\,2}) + Y_{\rm DY}$$

DY processes

$$f_1^a(x, k_\perp; \mu^2) = \frac{1}{2\pi} \int d^2 b_\perp e^{-ib_\perp \cdot k_\perp} \widetilde{f}_1^a(x, b_\perp; \mu^2)$$

Collins approach (2011)

$$\widetilde{f}_1^a(x, b_T; \mu^2) = \sum_i (\tilde{C}_{a/i} \otimes f_1^i)(x, b_*; \mu_b) e^{\tilde{S}(b_*;\mu_b,\mu)} e^{g_K(b_T) \ln \frac{\mu}{\mu_0}} \hat{f}_{\rm NP}^a(x, b_T)$$

Collinear PDF

pQCD

Non perturbative parts

In SCET analogous expression in *b* space: Echevarria, Idilbi, Scimemi (2012)

Theor. equivalent but potentially different in phen.

Role of NON perturbative input

TMDs and unpolarized cross sections

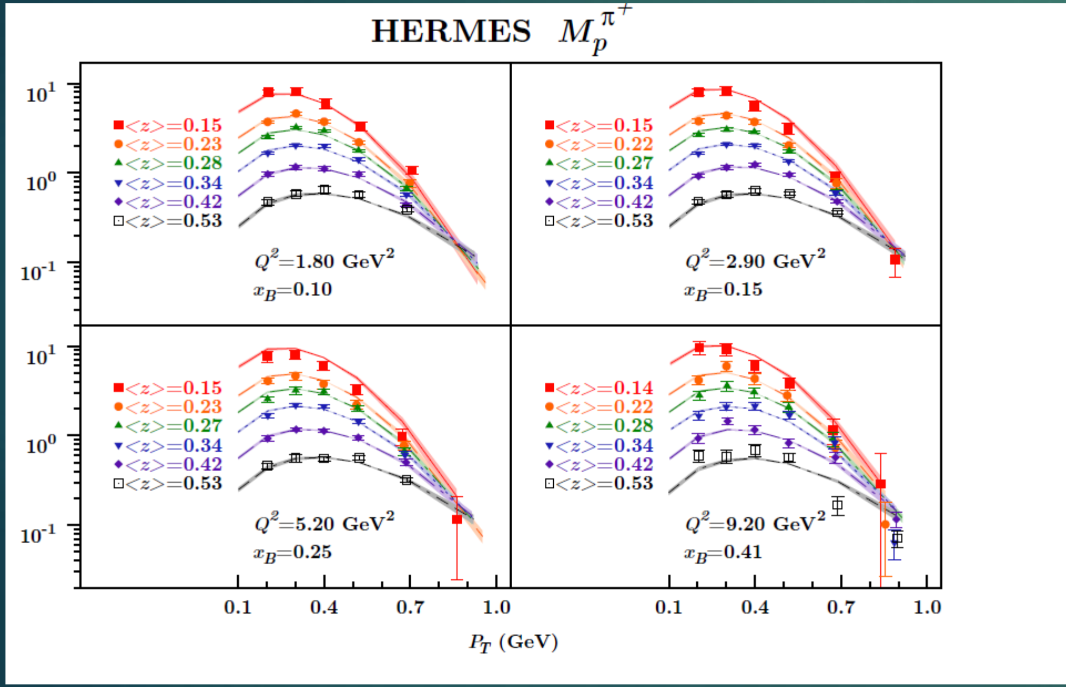
SIDIS multiplicities

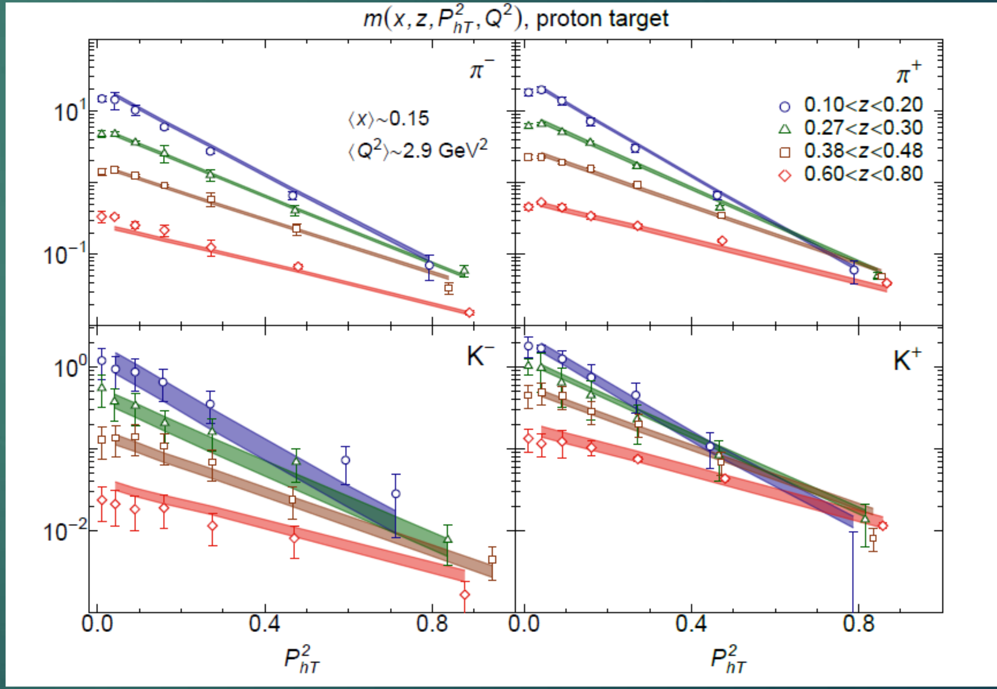
$$\frac{d\sigma_N^h / dx\,dz\,d\boldsymbol{P}_{hT}^2\,dQ^2}{d\sigma_{\rm DIS}/dx\,dQ^2},$$

$$f_{q/p}(x,k_\perp) = f_{q/p}(x)\,\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle}}{\pi\langle k_\perp^2\rangle}$$

$$D_{h/q}(z,p_\perp) = D_{h/q}(z)\,\frac{e^{-p_\perp^2/\langle p_\perp^2\rangle}}{\pi\langle p_\perp^2\rangle}\,.$$

without TMD evolution (limited Q^2 range)



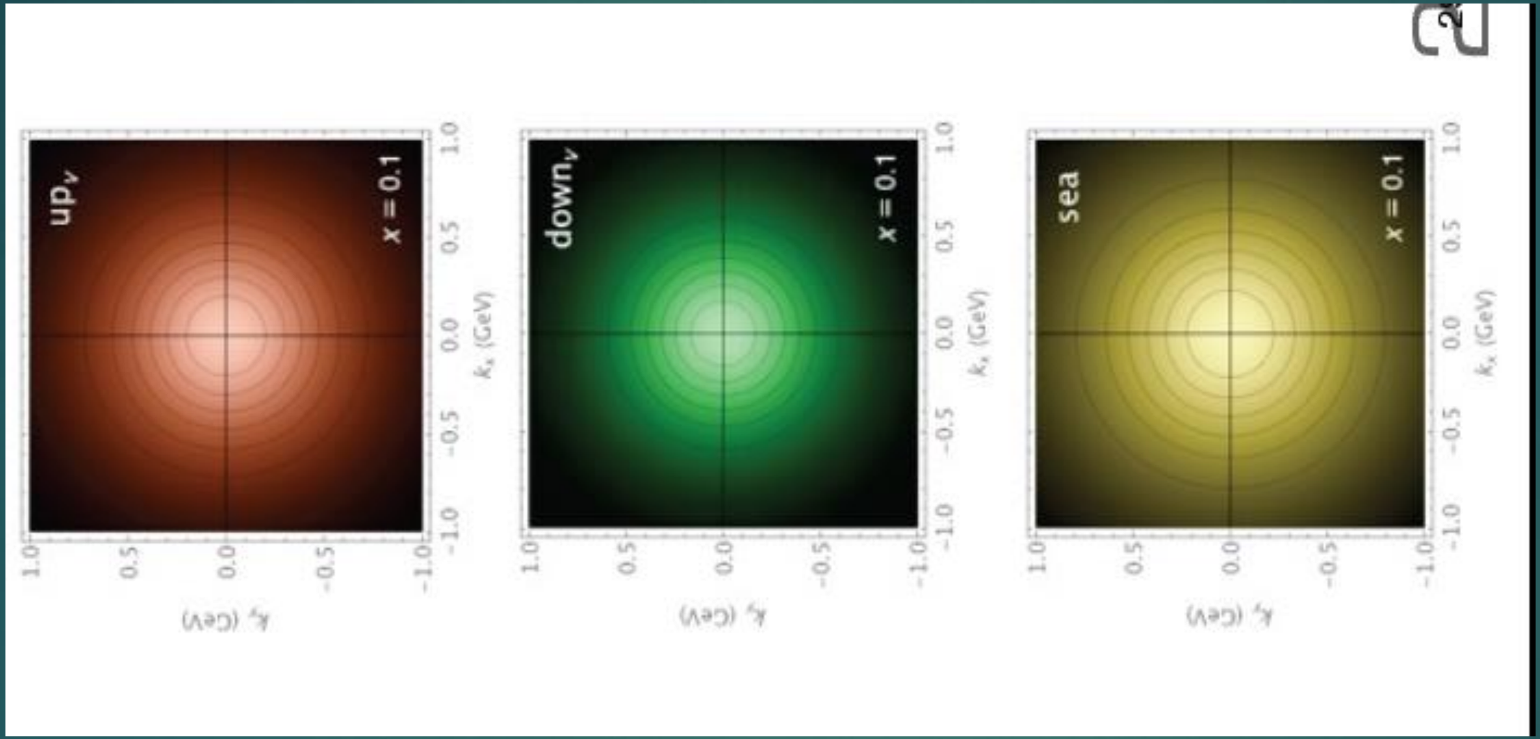


Anselmino, Boglione, Gonzalez, Melis, Prokudin (2014)

Signori, Bacchetta, Radici, Schnell (2013)

TMDs: flavour structure

Gaussian widths



Signori, Bacchetta, Radici, Schnell (2013)

up < down < sea ????

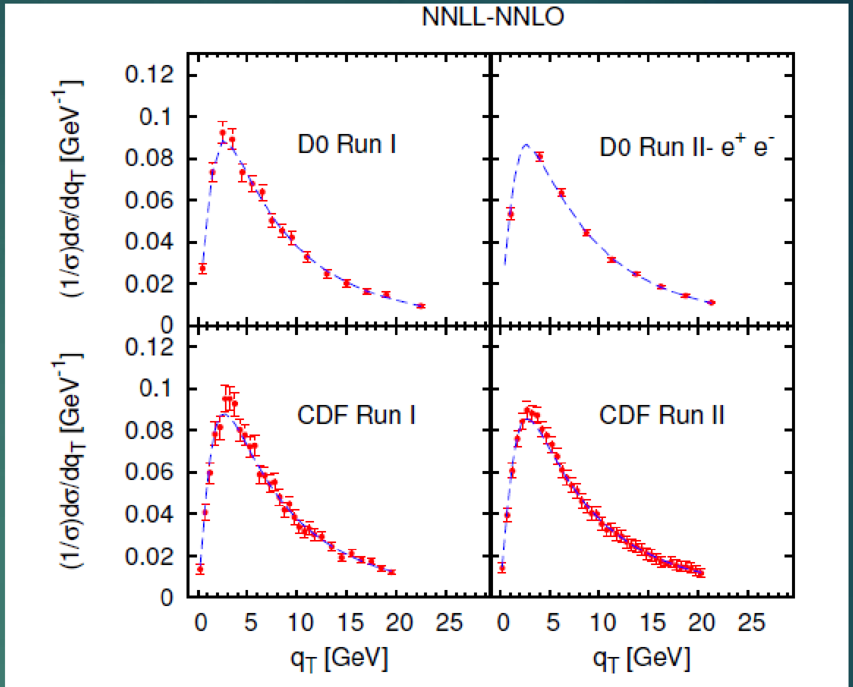
to be further explored

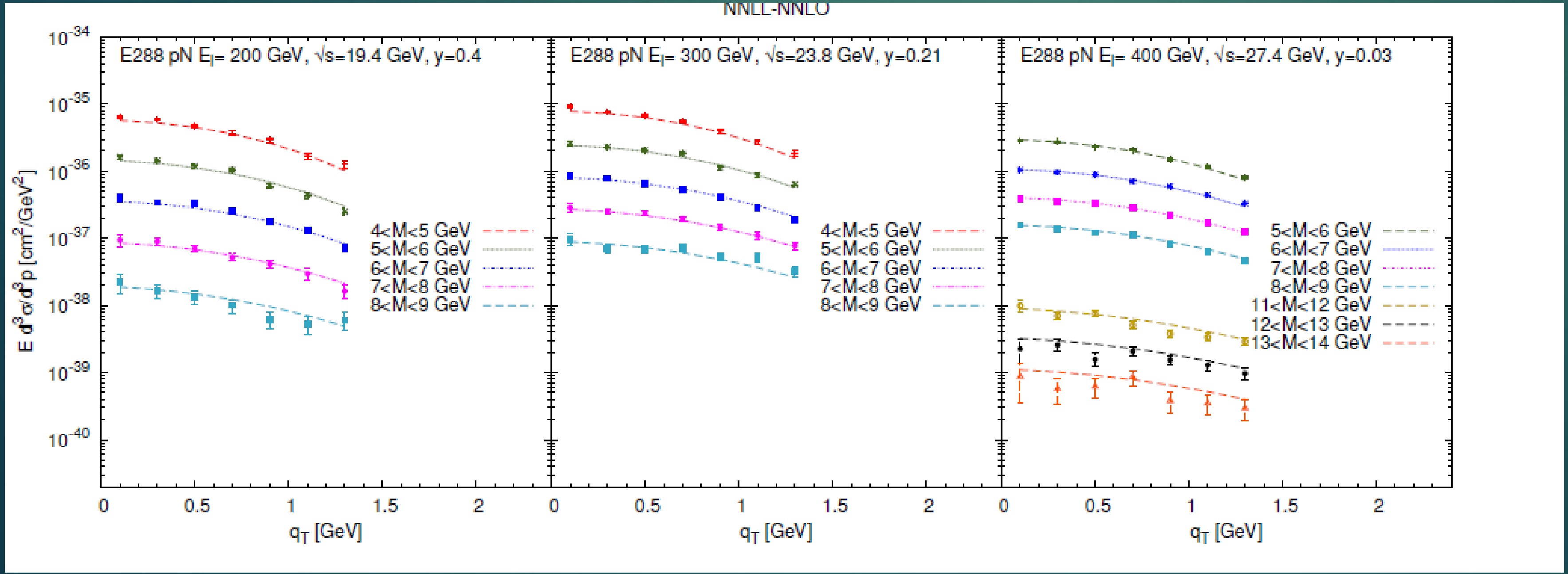
Fit to Drell-Yan and Z^0 production data

TMD evolution at NNLL (SCET)
UD, Echevarria, Melis, Scimemi (2014)
(223 data points)

$$\chi^2/\text{d.o.f.} = 1.12$$

Tevatron



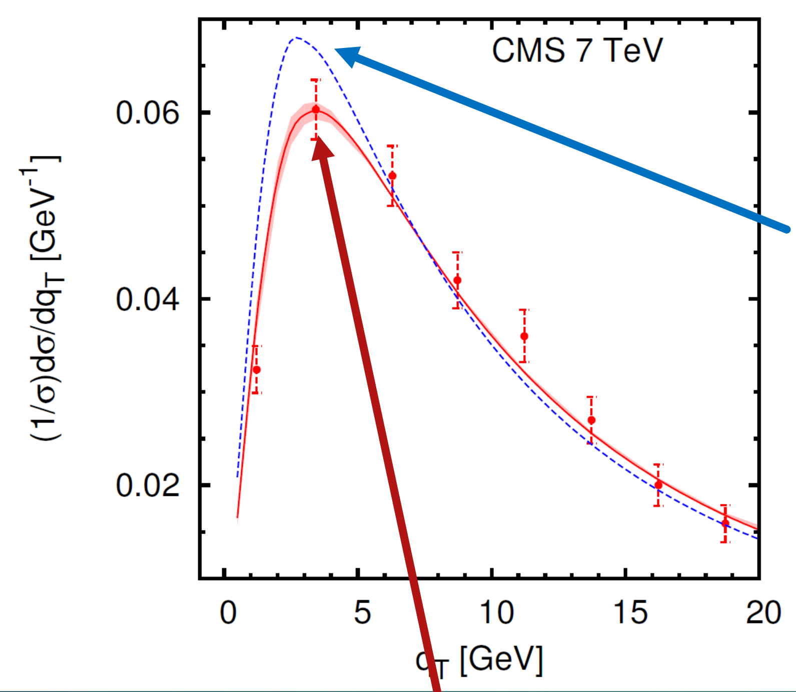


Low energy

TMDs at LHC

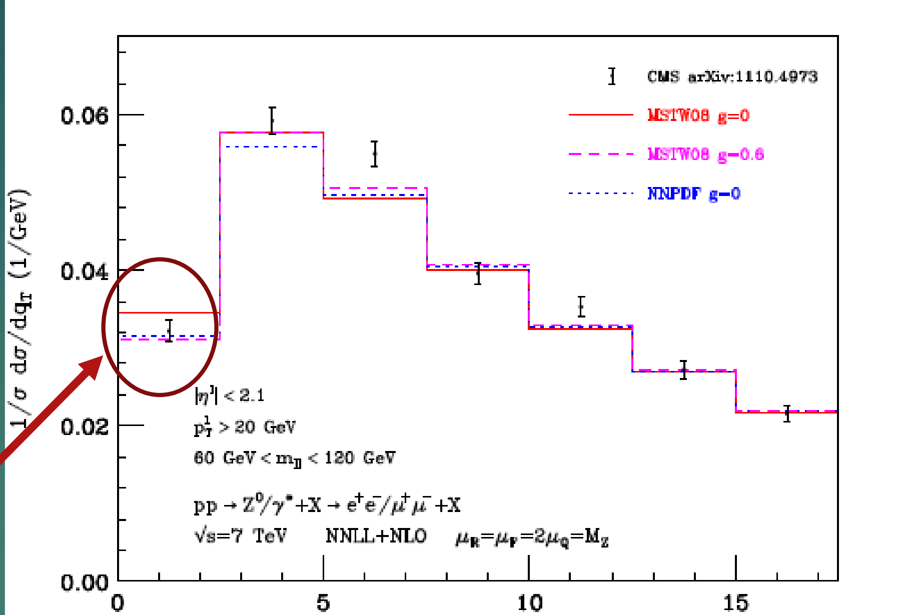
Predictions from NNLL fit

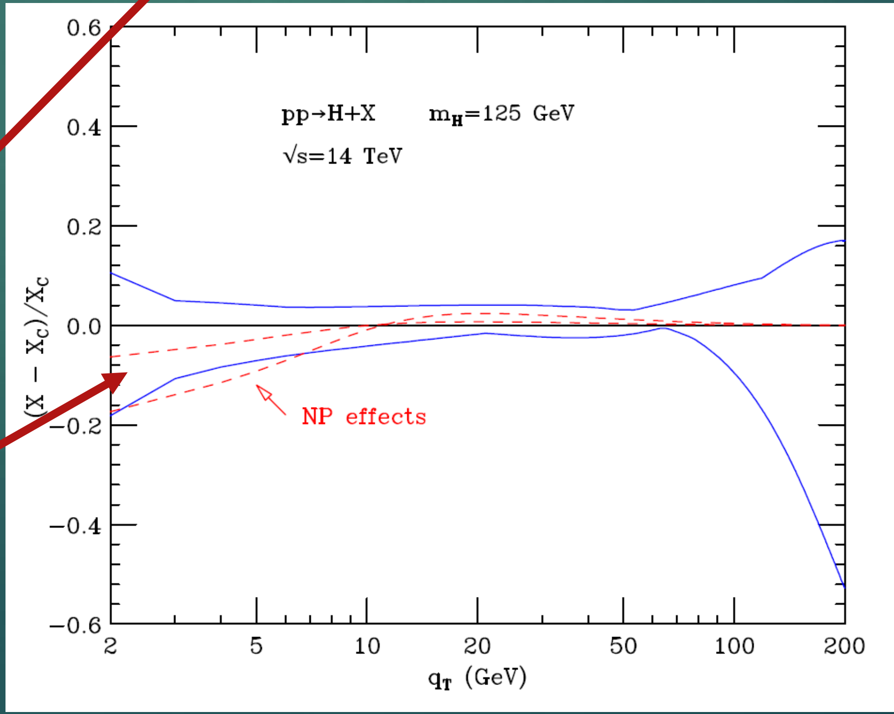
$pp \rightarrow Z\ X$



UD, Echevarria, Melis, Scimemi (2014)

Pure pQCD





Ferrera (2014)

Uncertainty in $pp \rightarrow H\ X$

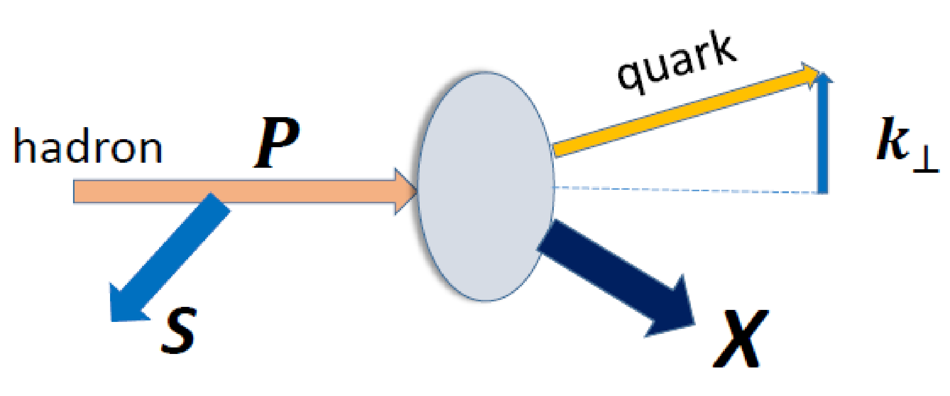
Inclusion of the non perturbative piece (k_T)

TMDs and spin

Beyond the unpol (f_1), helicity (g_1) and transversity (h_1) distributions, surviving in the collinear limit, there are 5 TMDs more, in particular

The Sivers function $f_{1T}^{\perp}$

Sivers (1989)



Correlation between the spin of the proton and the parton transverse momentum

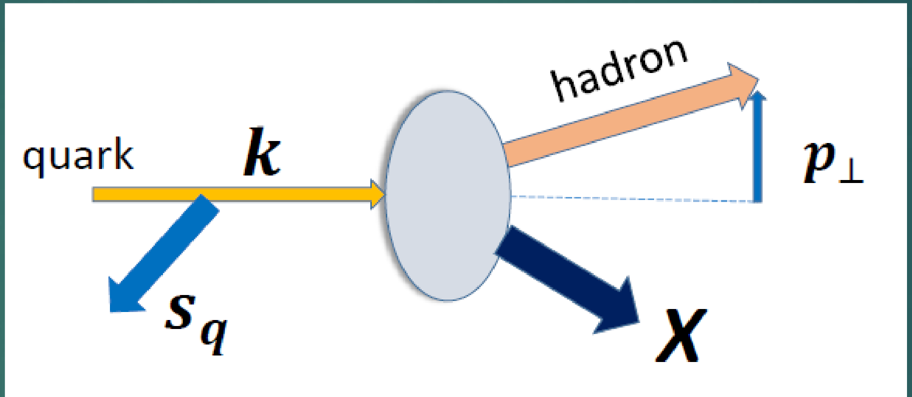
$$f_{q/h^\uparrow}(x,\vec{k}_\perp,\vec{S}) = f_{q/h}(x,k_\perp^2) - \frac{1}{M} f_{1T}^{\perp q}(x,k_\perp^2)\vec{S}\cdot(\hat{P}\times\vec{k}_\perp)$$

Spin independent — Spin dependent

Analogously, one can define TMDs in the fragmentation process.
In particular, for its relevance

The Collins function $H_1^{\perp q}$

Collins (1992)



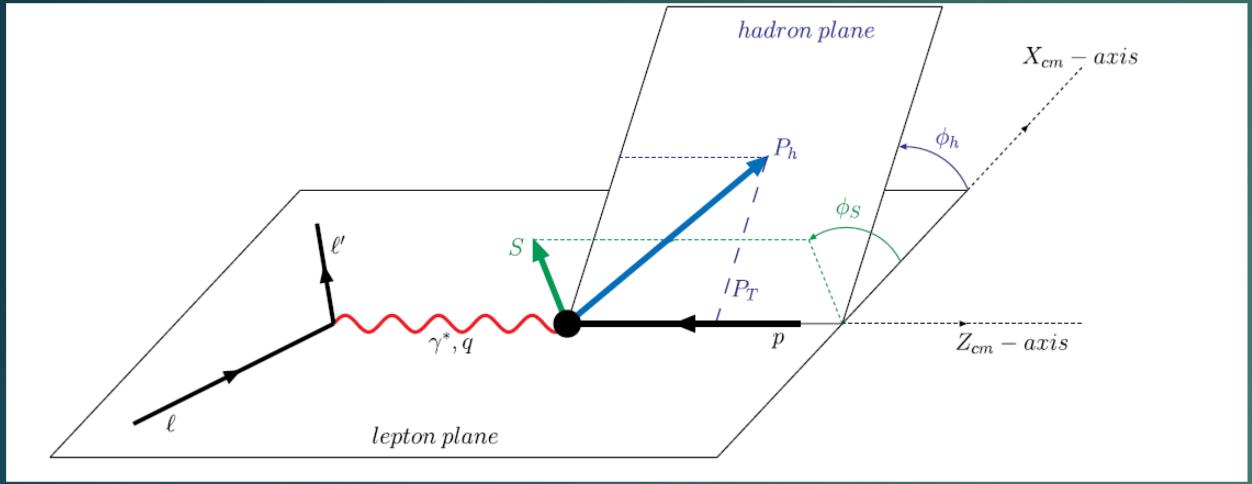
Correlation between the spin of the fragmenting quark and the hadron transverse momentum

$$D_{q/h}(z,\vec{p}_\perp,\vec{s}_q) = D_{q/h}(z,p_\perp^2) + \frac{1}{zM_h} H_1^{\perp q}(z,p_\perp^2)\,\vec{s}_q \cdot (\hat{k} \times \vec{p}_\perp)$$

Crucial for the first ever extraction of the transversity distribution

Sivers and Collins functions extensively studied theoretically, experimentally and phenomenologically

SIDIS

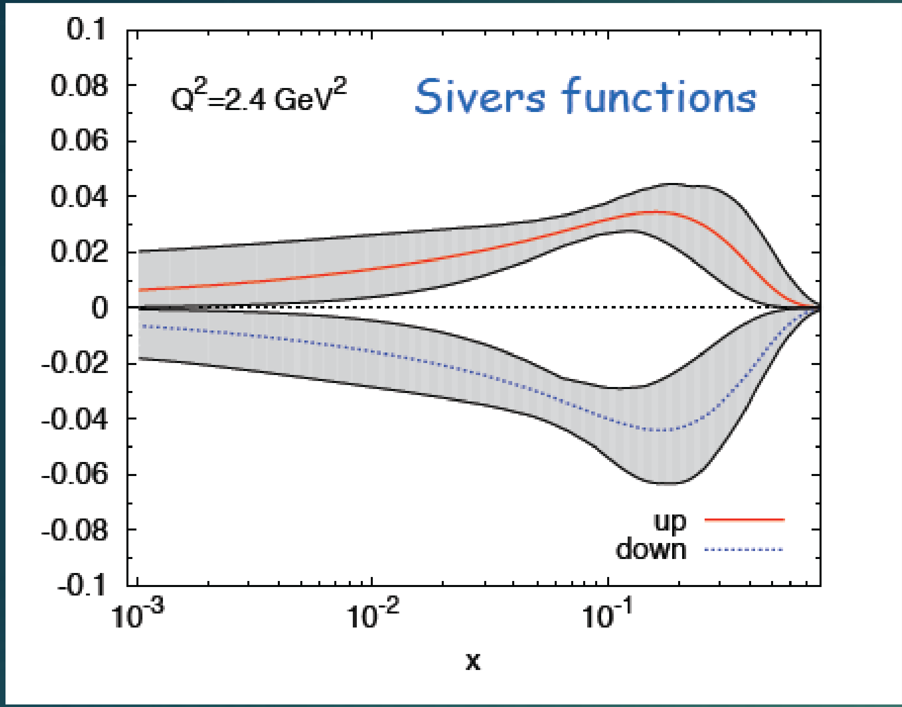


CLEAR evidence from data
HERMES, COMPASS

$$d\sigma(S) \sim \sin(\phi_h + \phi_S) h_1 \otimes H_1^{\perp} + \sin(\phi_h - \phi_S) f_{1T}^{\perp} \otimes D_1 + \ldots$$

Collins Sivers

First phase: analysis with DGLAP evolution
Second phase (just started): TMD evolution

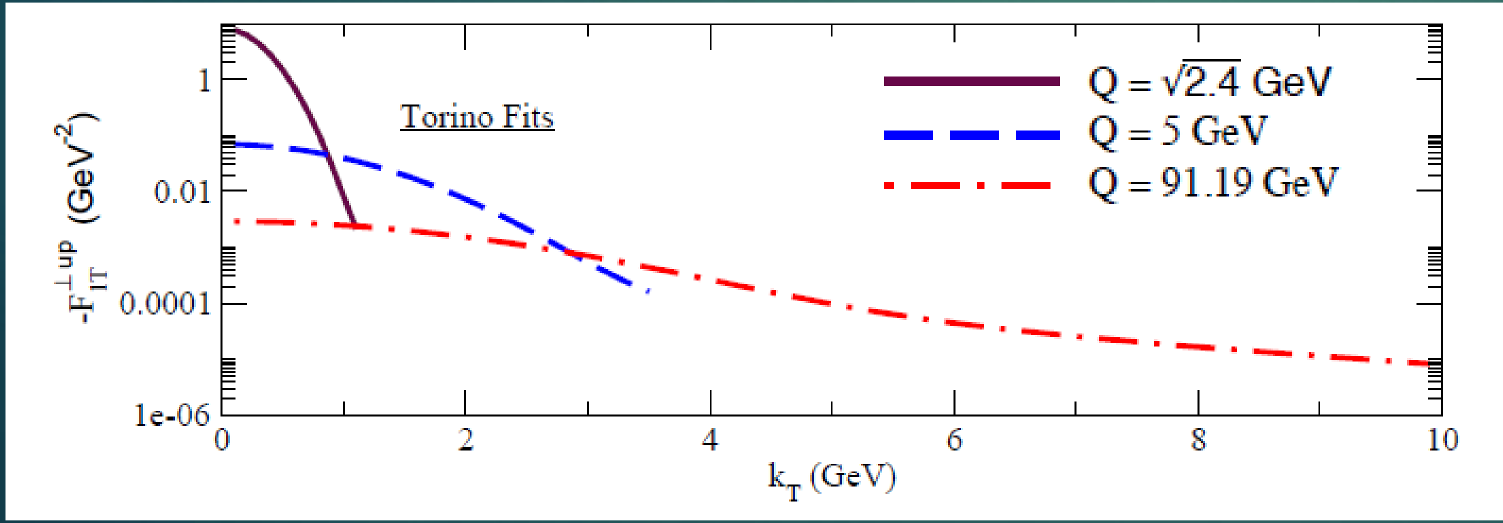


Extracted Sivers functions

TO-CA and PV groups

large-x region: unconstrained [→JLab]

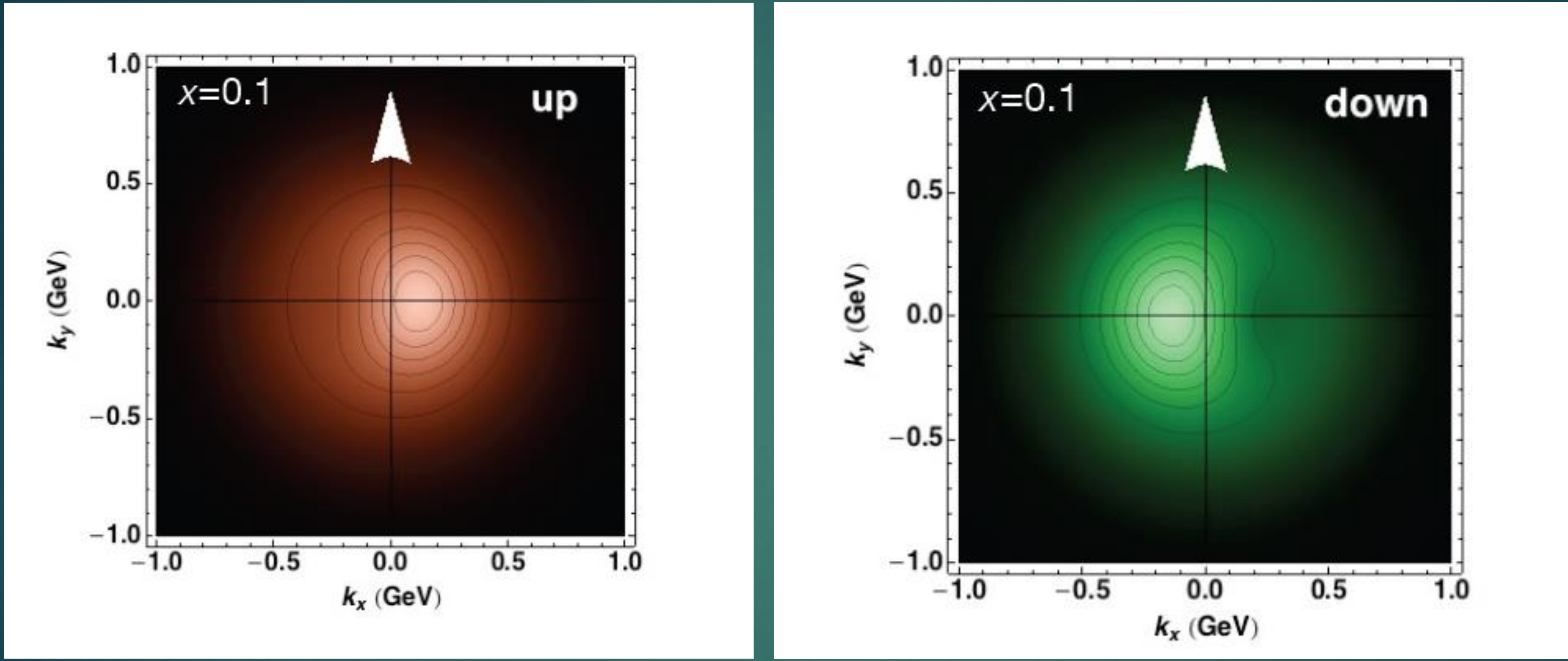
sea region: unconstrained [→EIC]



Effect of
TMD evolution

Aybat, Collins, Qiu, Rogers (2012)

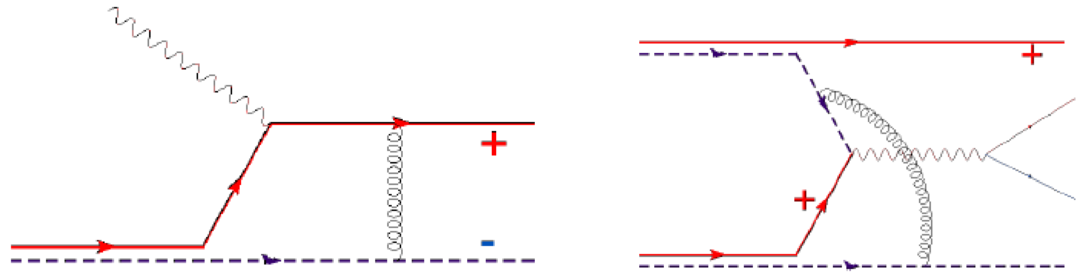
Distortion in the transverse plane



picture from A. Bacchetta, M. Contalbrigo,

Non zero Sivers effect related to parton orbital angular momentum

Modified universality of the Sivers function



$$f_{1T}^{\perp SIDIS} = -f_{1T}^{\perp DY}$$

Collins (2012)

Final state interactions in **SIDIS**
Initial state interactions in **DY**

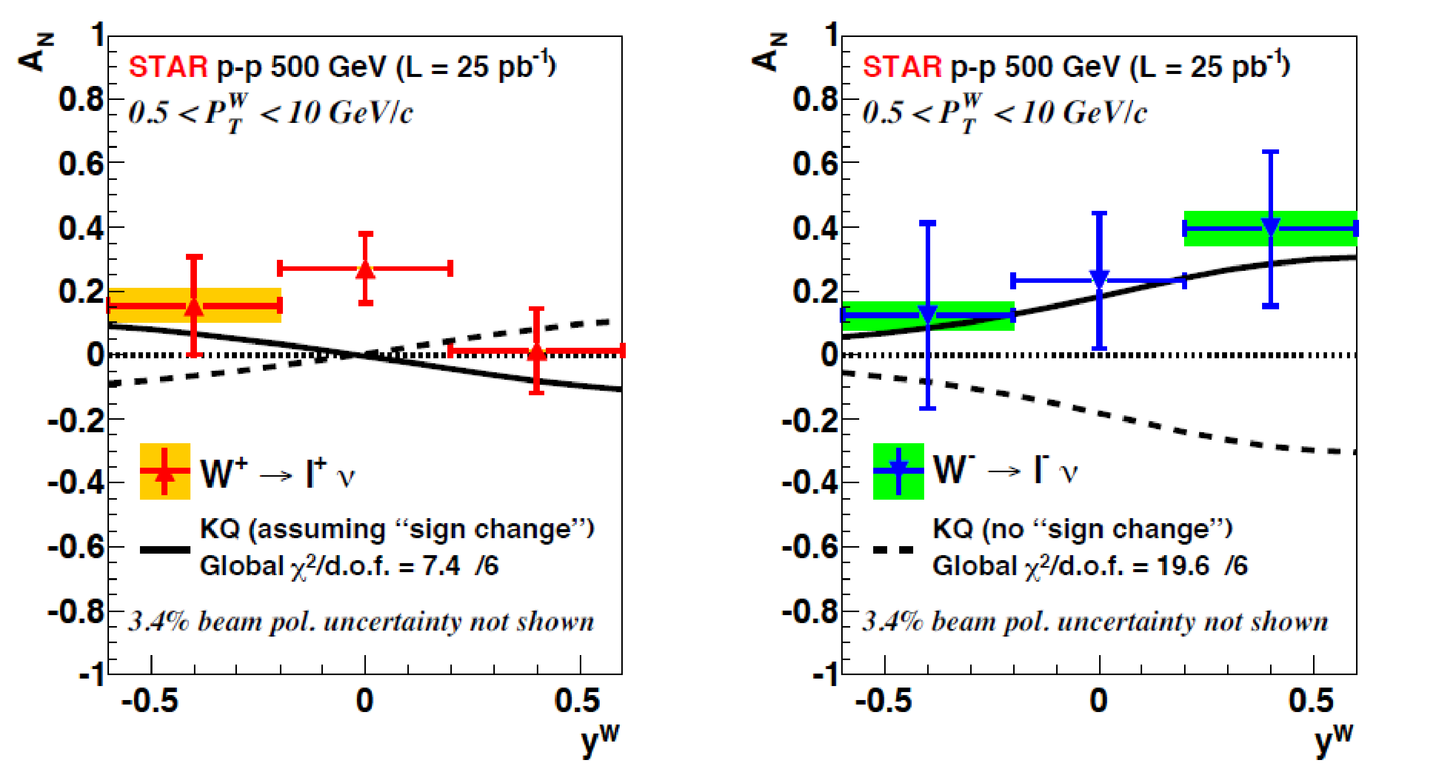
A clear-cut test

If falsified:

- misunderstanding of final-state interacts. leading to T-odd effects
- missing points in QCD factorization (TMD and collinear) [most severe scenario]

First results from RHIC: $p^{\uparrow}p \to W^{\pm}\, X$

STAR Collaboration (2016)



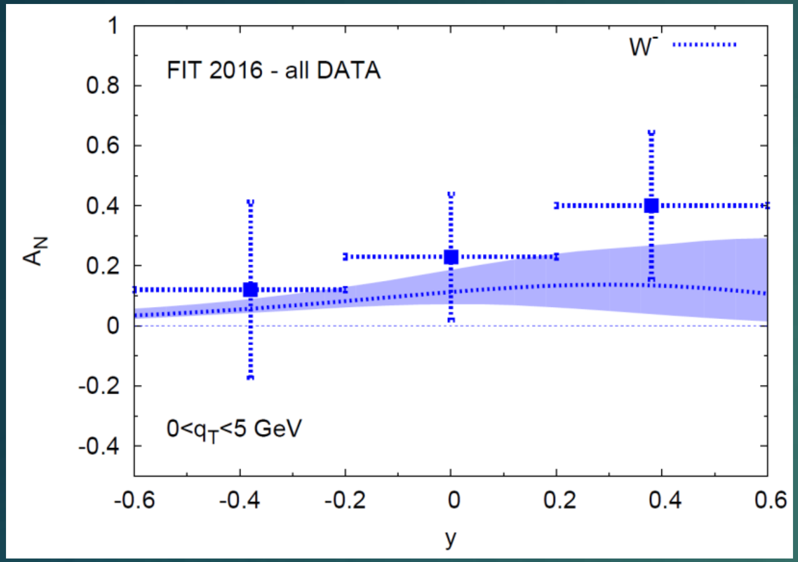
No TMD evolution

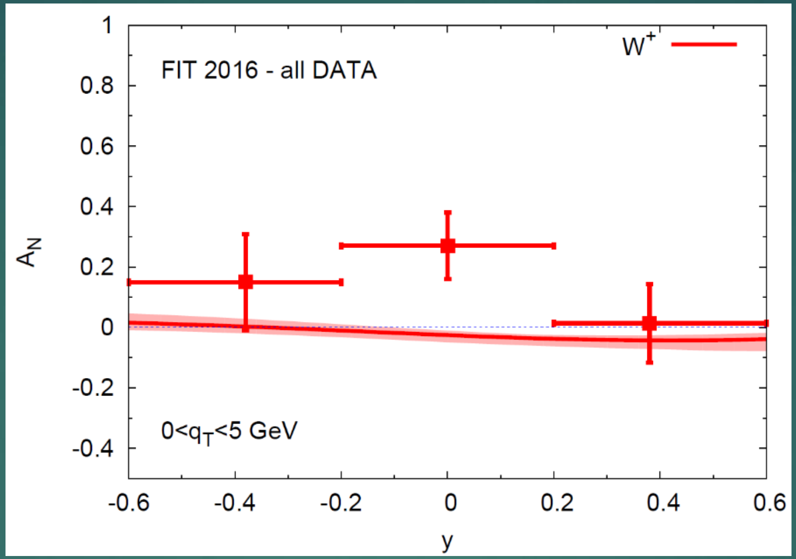
First hint at the sign change, but large exp. errors and …

- Sign change $\chi^2/d.o.f \sim 1.2$
- No sign change $\chi^2/d.o.f \sim 3.2$

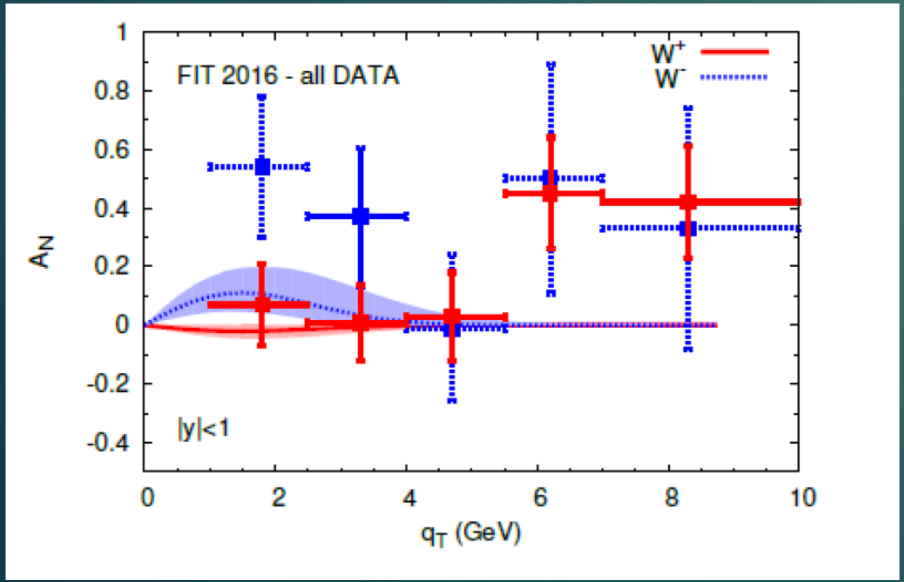
Kang et al (2016)

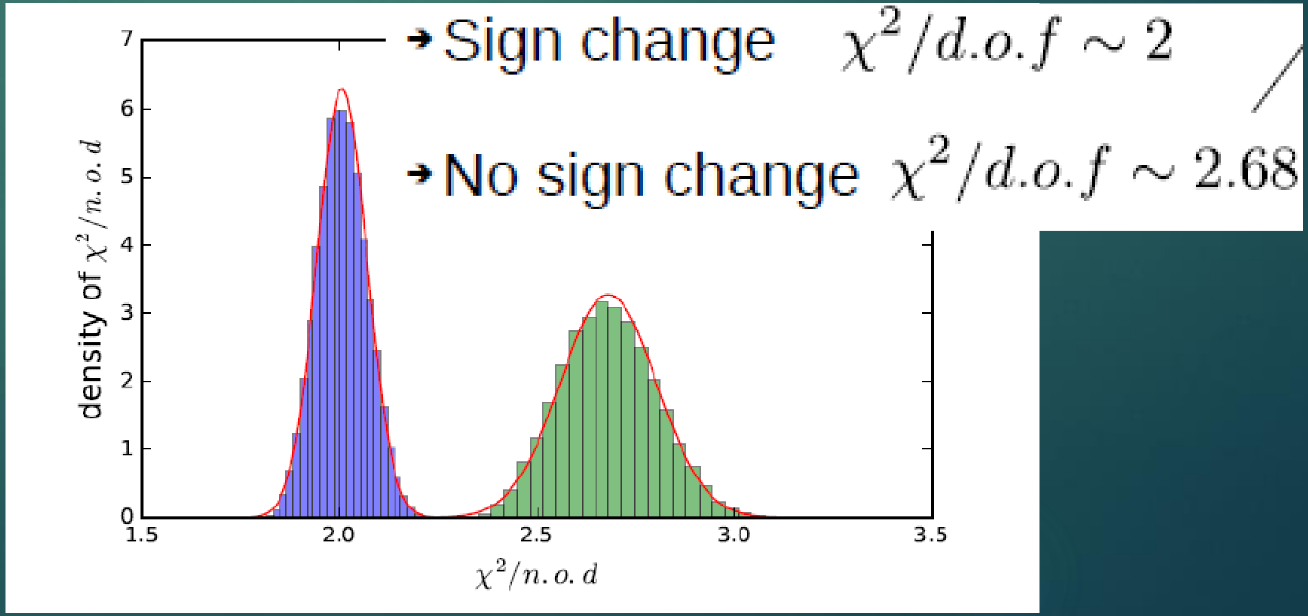
New analysis: (in progress) Anselmino, Boglione, UD, Murgia, Prokudin (2016)





Sign reversed





Underestimated at large

Collins function & transversity

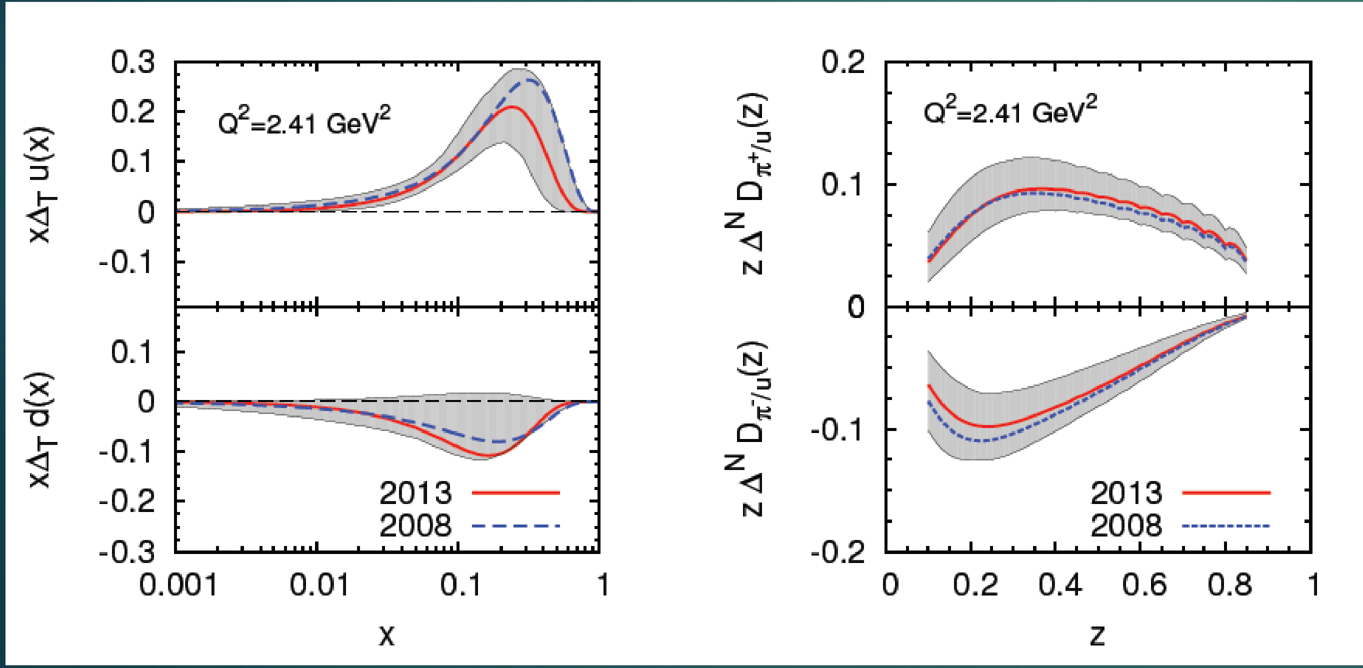
Combined analysis of

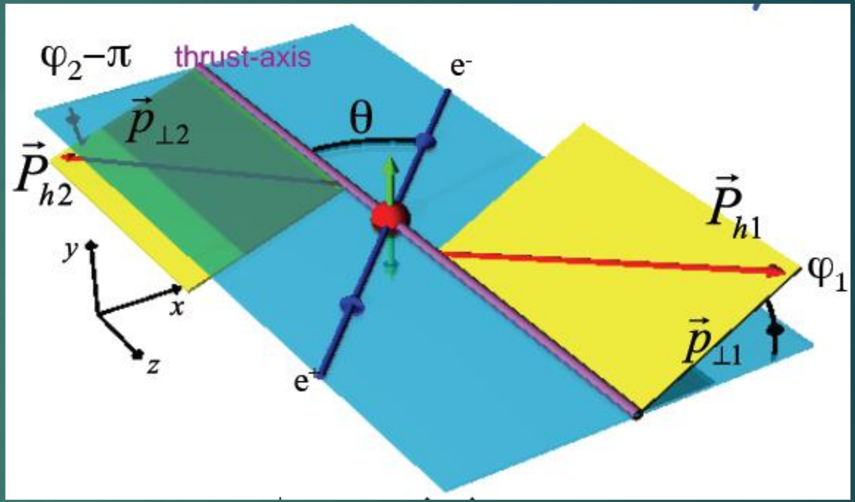
SIDIS and $e^+ e^- \to \pi\pi X$

$h_1(x_B, k_\perp) H_1^\perp(z_h, p_\perp)$

$H_1^\perp(z_1, p_{1\perp}) H_1^\perp(z_2, p_{2\perp})$

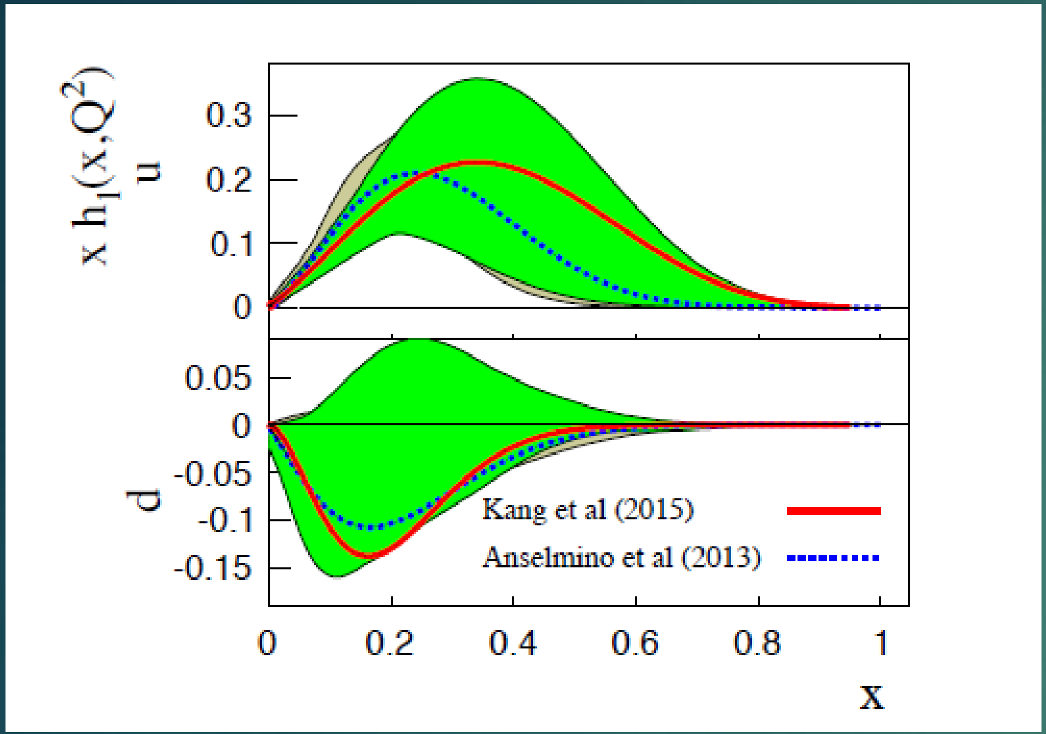
Without TMD evolution

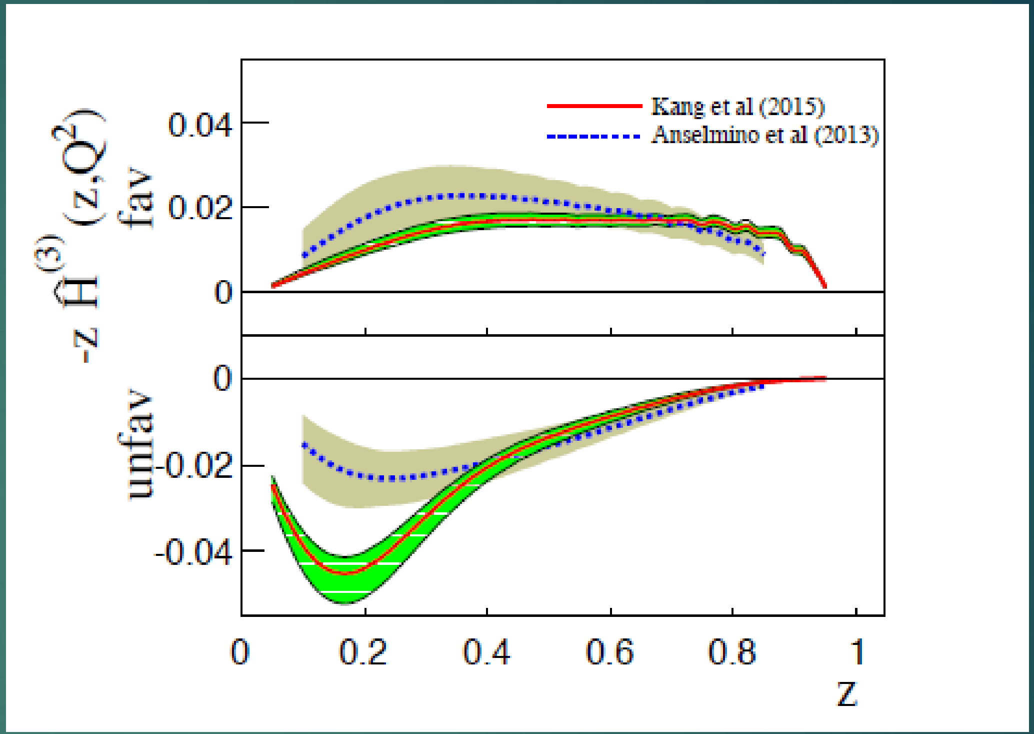




Anselmino, Boglione, UD, Melis, Murgia, Prokudin (2015)

Same analysis but with TMD evolution   Kang, Prokudin, Sun, Yuan (2015)





Compatible with LO extraction
Anselmino et al 2009, 2013, 2015

No compelling TMD evolution yet
Remember: SSAs are ratios….

Back to A_N : further evidences of Sivers and Collins effects

$$p^{\uparrow}\, p \to \pi\, X$$

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

$$d\sigma^{\uparrow} - d\sigma^{\uparrow}$$

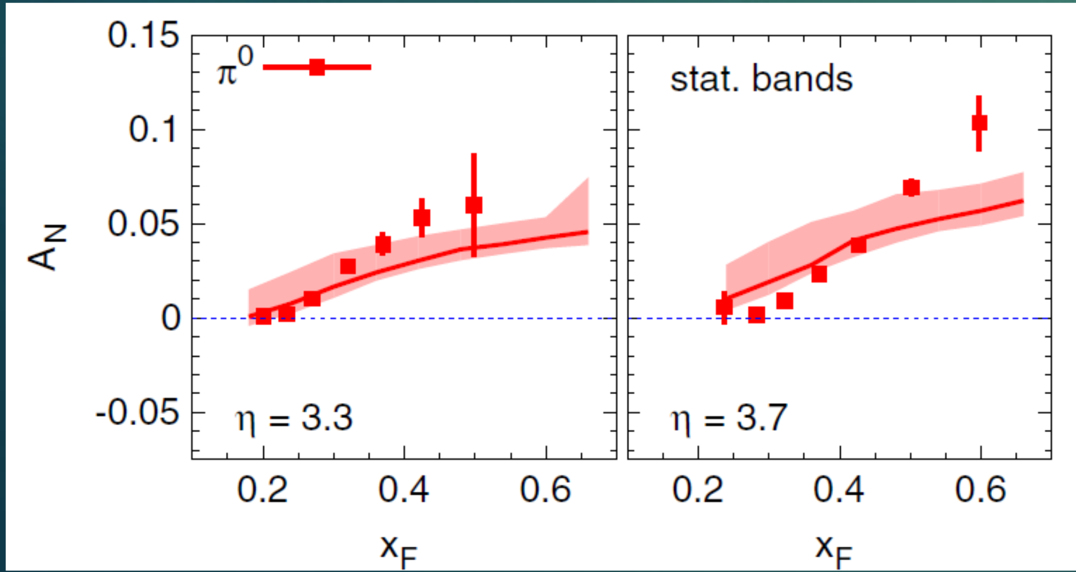
$\sim$ Sivers
\+ transversity $\otimes$ Collins + …

In a phenomenological TMD scheme

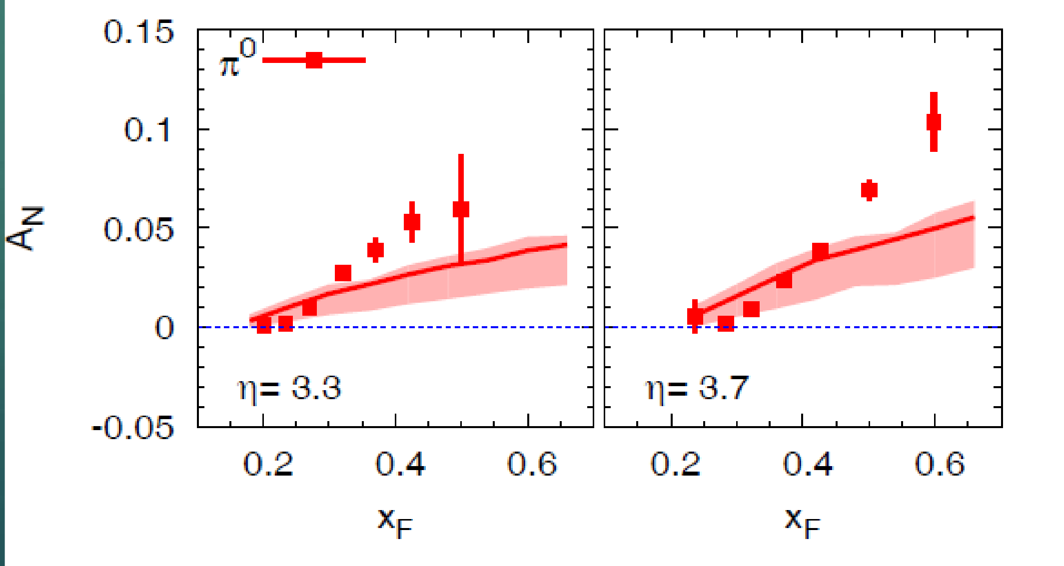
Non separable

From SIDIS extractions to RHIC *pp* data (STAR (2008))
(Anselmino, Boglione,UD, Leader, Melis, Murgia, Prokudin (2012 & 2014))

Sivers effect alone



Collins effect alone



Higher-twist contributions to A_N

Collinear factorization: proven Qiu, Sterman (1991)

Twist-three functions corresponding, and related, to the TMDs, like

$$T_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\text{SIDIS}}$$ Boer, Mulders, Piljman (2003)

Using these relations one is not able to describe A_N (sign mismatch issue)

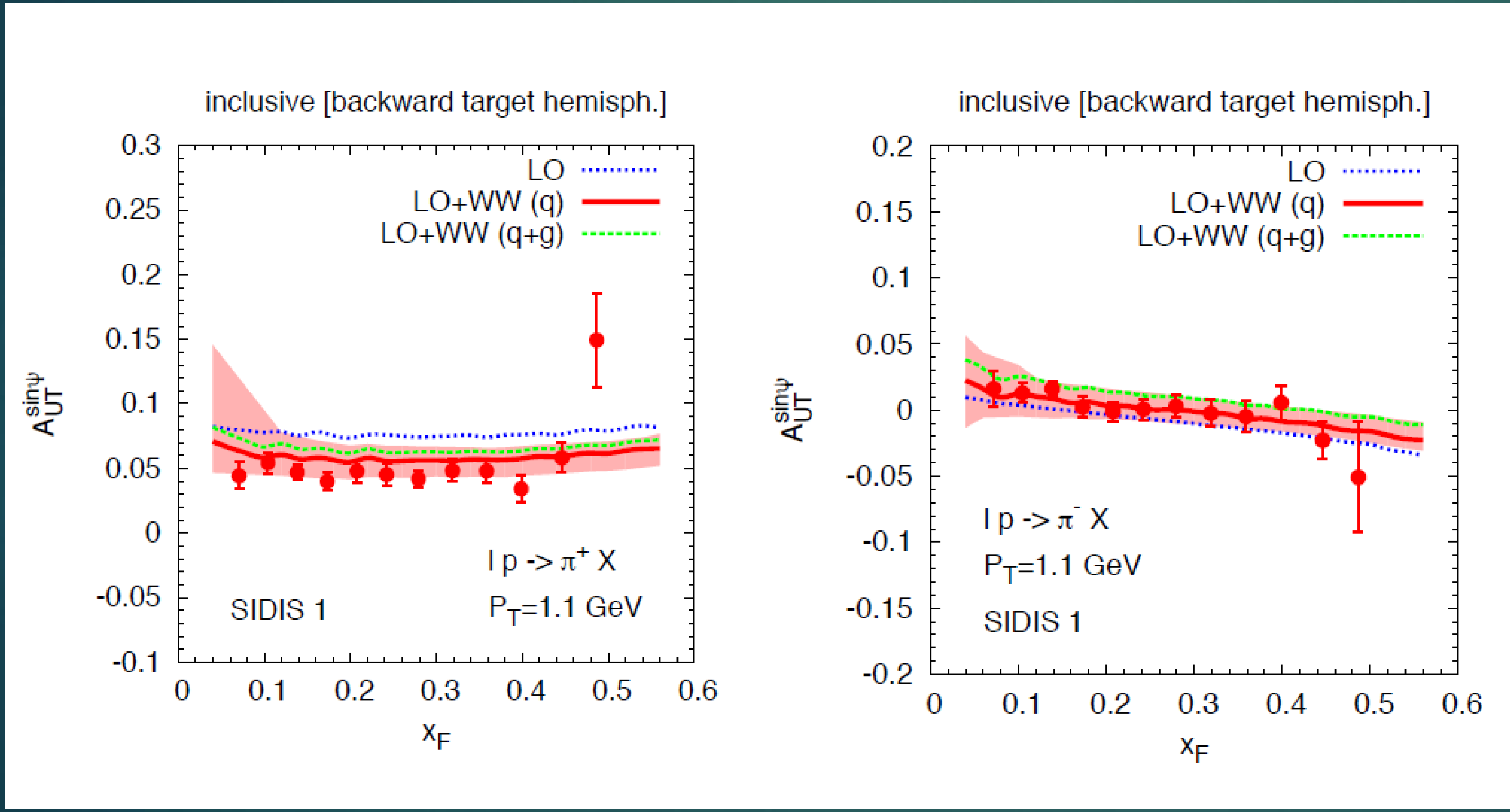
A completely new twist-3 fragm. function seems to be able to explain A_N

(Kanazawa, Koike, Metz, Pitonyak, PRD 89 (2014) 111501)

A_N in $pp \to \gamma\, X$ ideal to disentangle the two approaches (A_N with different sign)

In the meantime …. another successfully description within a TMD scheme of a SSA for a single -inclusive process: $l\,p \;\rightarrow\; \pi\, X$

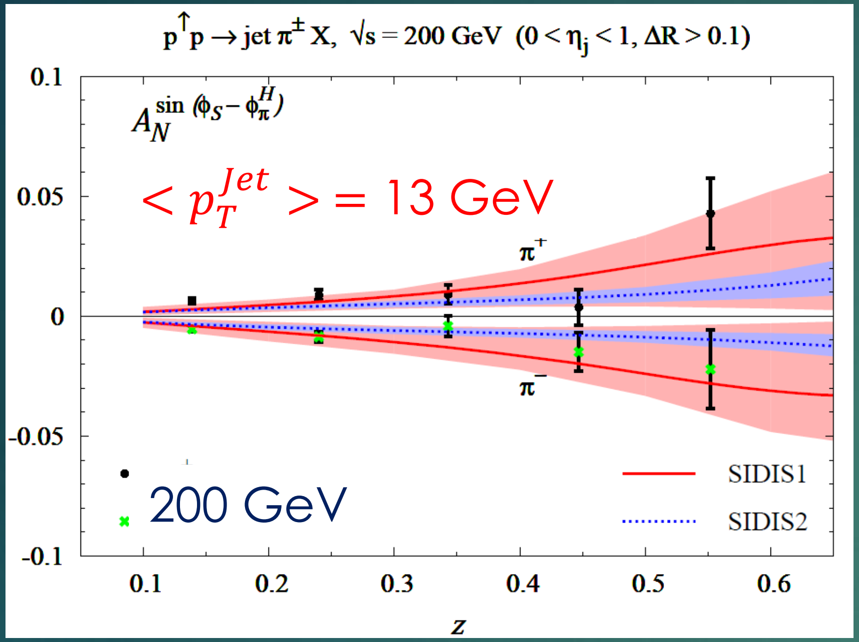
Predictions from TMD fact. at LO + Weizsäcker-Williams approximation

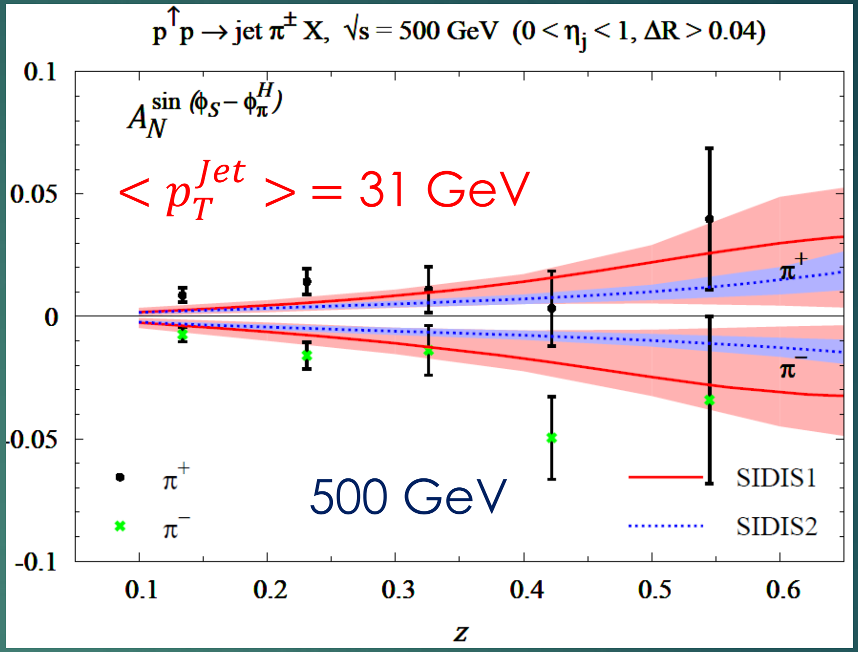


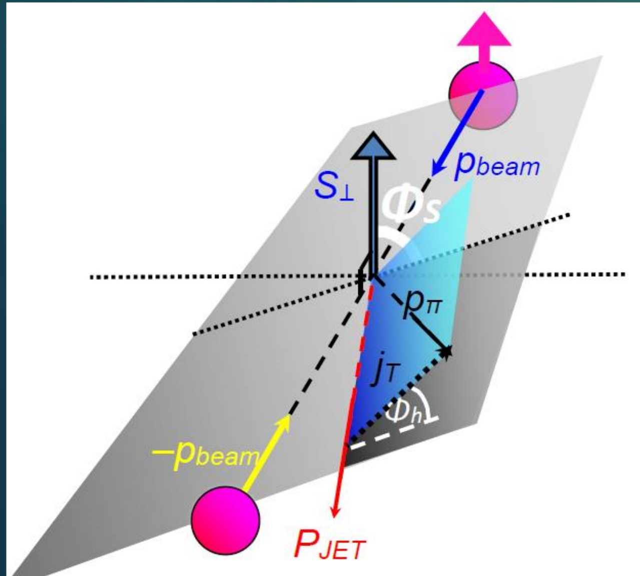
HERMES data (2014)

UD, Flore, Murgia (2016) [LO] Anselmino, Boglione, UD, Melis, Murgia, Prokudin (2010&2014)

Collins function: from SIDIS to $pp \to \pi\, jet\, X$







Data from STAR Collaboration (2015)

UD, Murgia, Pisano (2011, 2016)

without TMD evolution

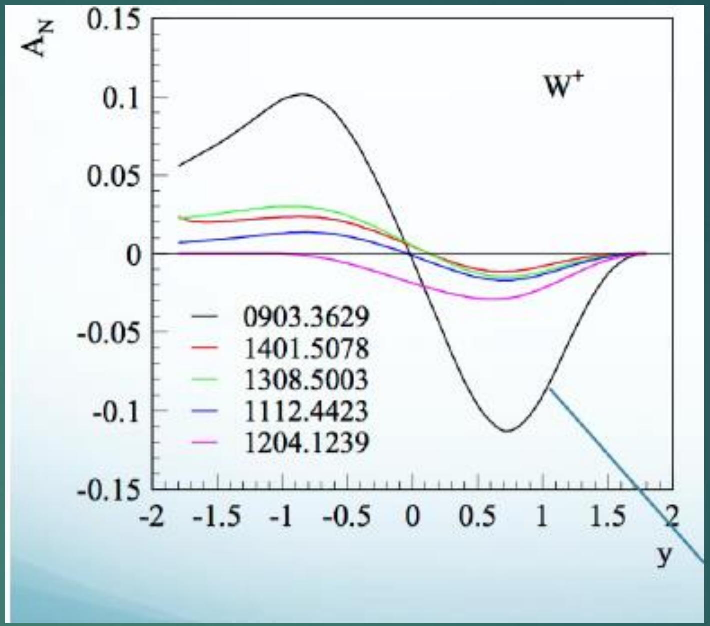
Universality of the Collins function and mild (or no) TMD evolution

Open issues in TMD phenomenology

TMD evolution and its relevance
An example

A_N for $p^{\uparrow} p \to W^{\pm} X$

w/o TMD evolution



Kang (2015)

Role of non perturbative input choices

Transverse momentum dependence in SIDIS and its consistency with DY

TMD factorization breaking effects in $pp \to \pi X$, $pp \to jet\, jet\, X$ (sizeable???)

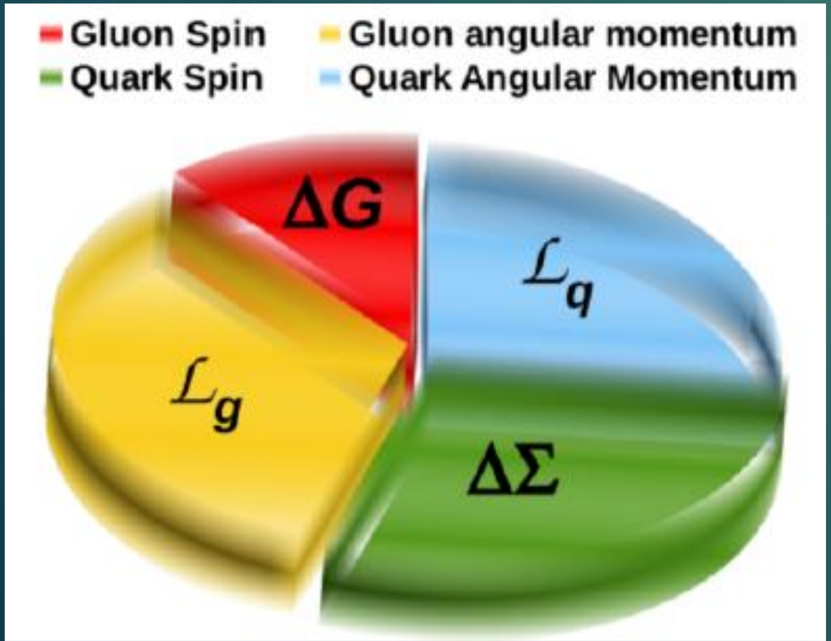
Gluon TMDs at low x and parton saturation,
TMD factorization vs. Color Glass Condensate

Proton spin puzzle

Proton Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

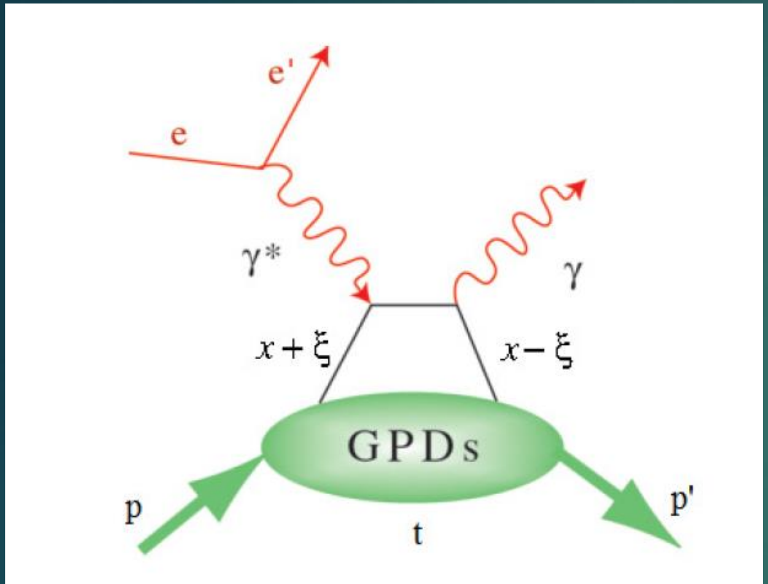
(Anti)quark Contribution:	Gluon Contribution:	Parton Orbital Momentum:
0.15-0.20	0.2 in x>0.05	???



Non trivial decomposition [Leader, Lorcé (2014)]

GPDs: few hints

Virtual Compton scattering

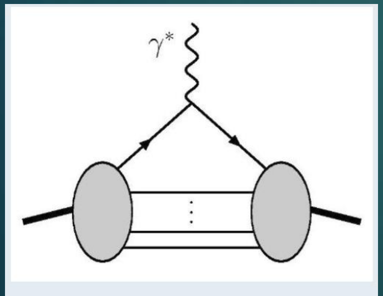


$$\int_{-1}^{1} dx H(x,\xi,t) = F_1(t); \int_{-1}^{1} dx E(x,\xi,t) = F_2(t)$$
$$\int_{-1}^{1} dx \widetilde{H}(x,\xi,t) = G_A(t); \int_{-1}^{1} dx \widetilde{E}(x,\xi,t) = G_P(t)$$

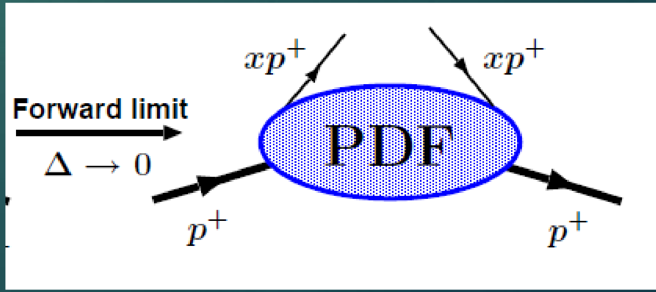
where $F_1(t)$ and $F_2(t)$ are the Dirac and Pauli FFs, and $G_A(t)$ and $G_P(t)$ are the axial and pseudoscalar FFs.

GPDs: Information on position and quark momentum fraction

Elastic scattering

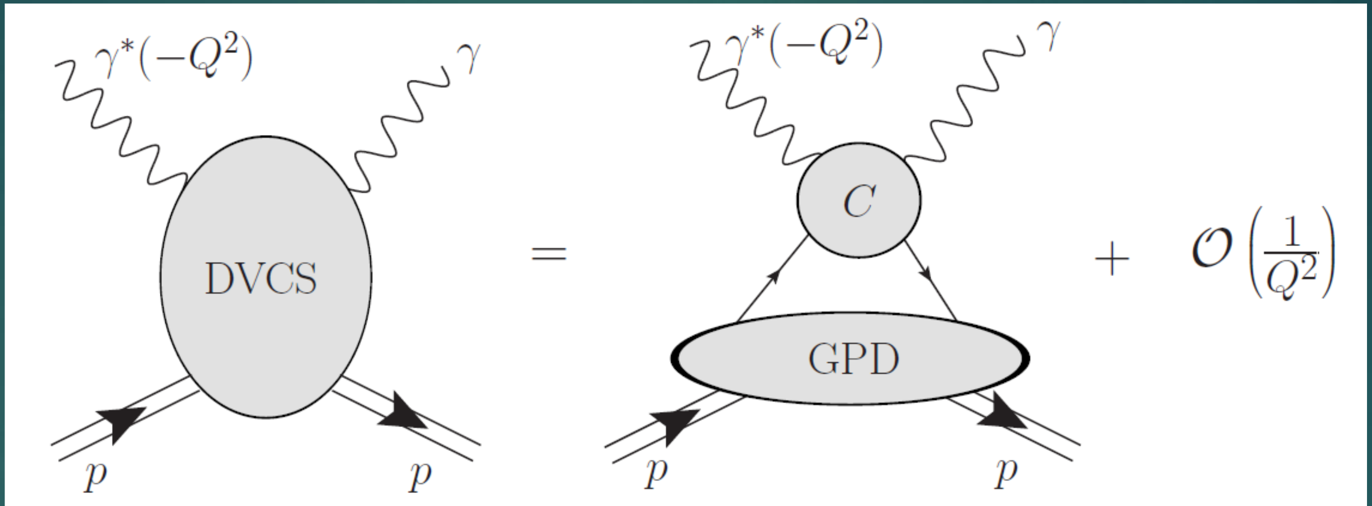


Form Factor: Position information
No sensitivity to quark momentum



DVCS Factorization

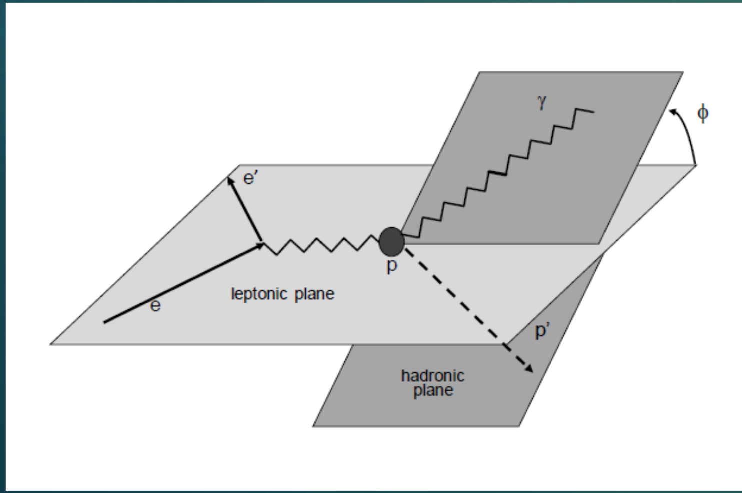
Collins et al. (1998)



Compton
Form Factor

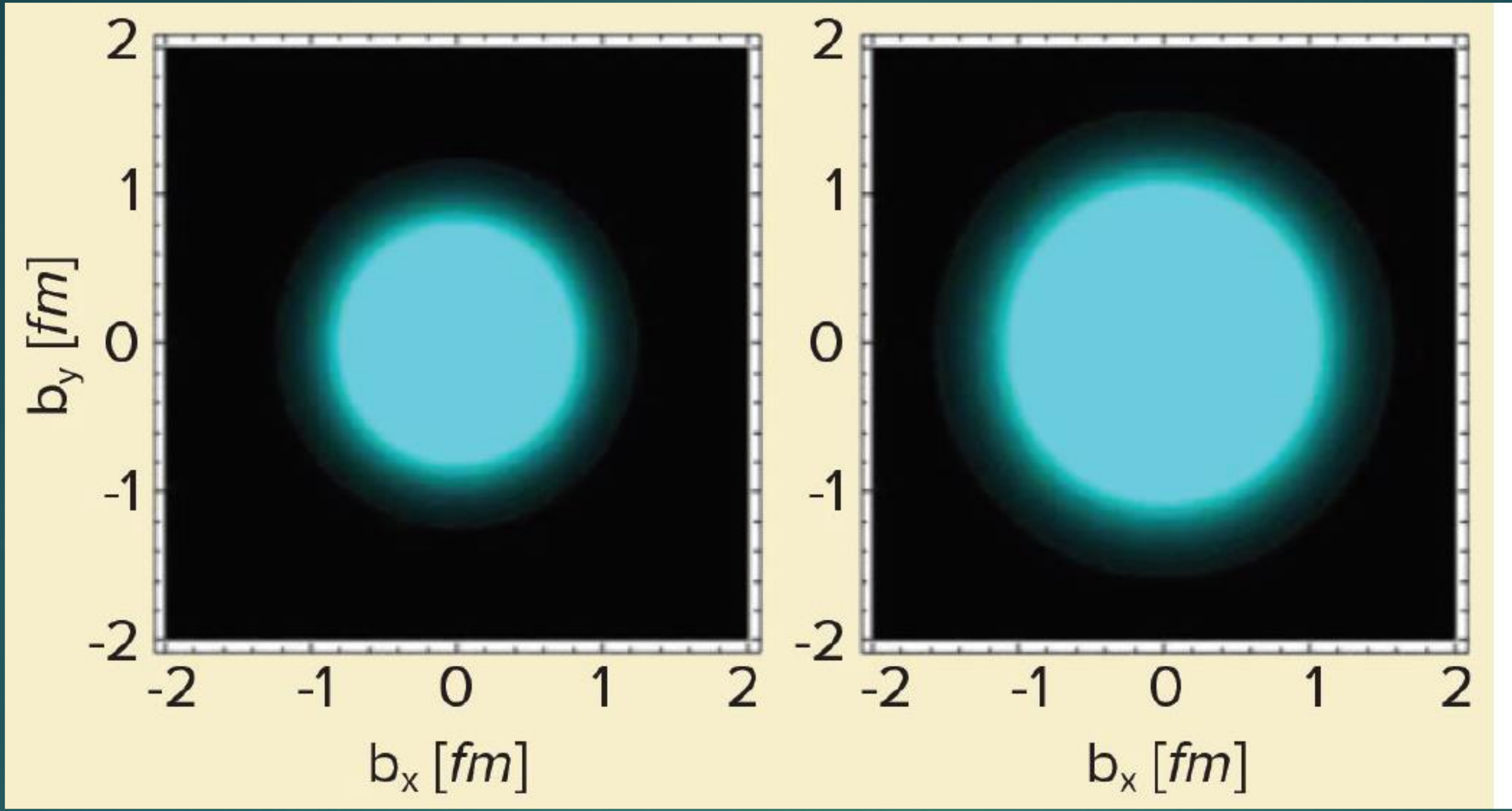
$$ {}^a\mathcal{H}(x_B, t, Q^2) = \int dx \; C^a\left(x, \frac{x_B}{2 - x_B}, \frac{Q^2}{Q_0^2}\right) H^a\left(x, \frac{x_B}{2 - x_B}, t, Q_0^2\right) $$

GPD



Different Φ modulations give access to different combinations of GPDs

From 2015 Long Range Plan for Nuclear Science



$x = 0.25$ $\quad$ $x = 0.09$

- Distribution of partons in transversal space

$$\rho(x, \vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} e^{-i\vec{b}_\perp \cdot \vec{\Delta}_\perp} H(x, 0, -\vec{\Delta}_\perp^2)$$

Physics issues in GPDs

- DVCS: golden channel. Measured at HERMES, COMPASS, CLASS, H1, ZEUS

- DVMP (virtual meson product): uncertainty on meson distr. amplit.

- Extraction of GPDs: model-dependent

- Parameterizations: different families, not always able to describe all data, qualitatively good (different observables, few parameters and assumptions)

- Major role in the nucleon spin decomposition

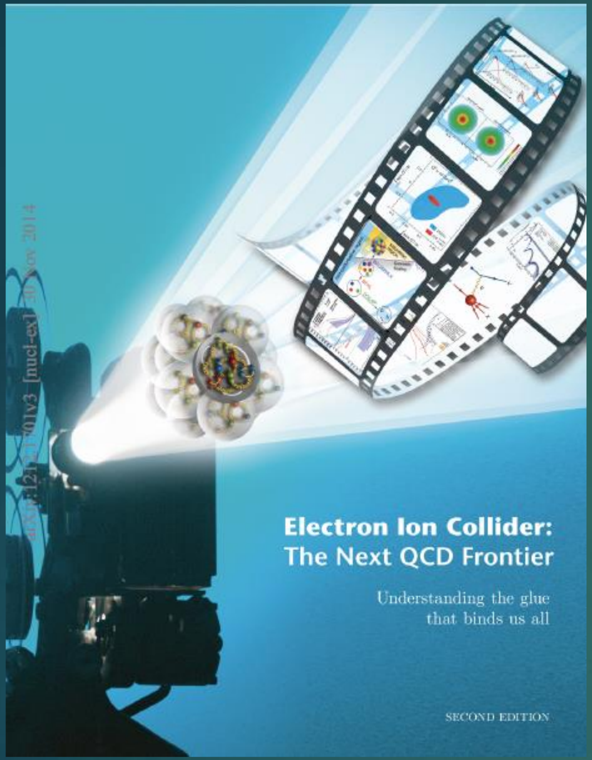
- "Ji's sum rule" (related to proton spin problem)

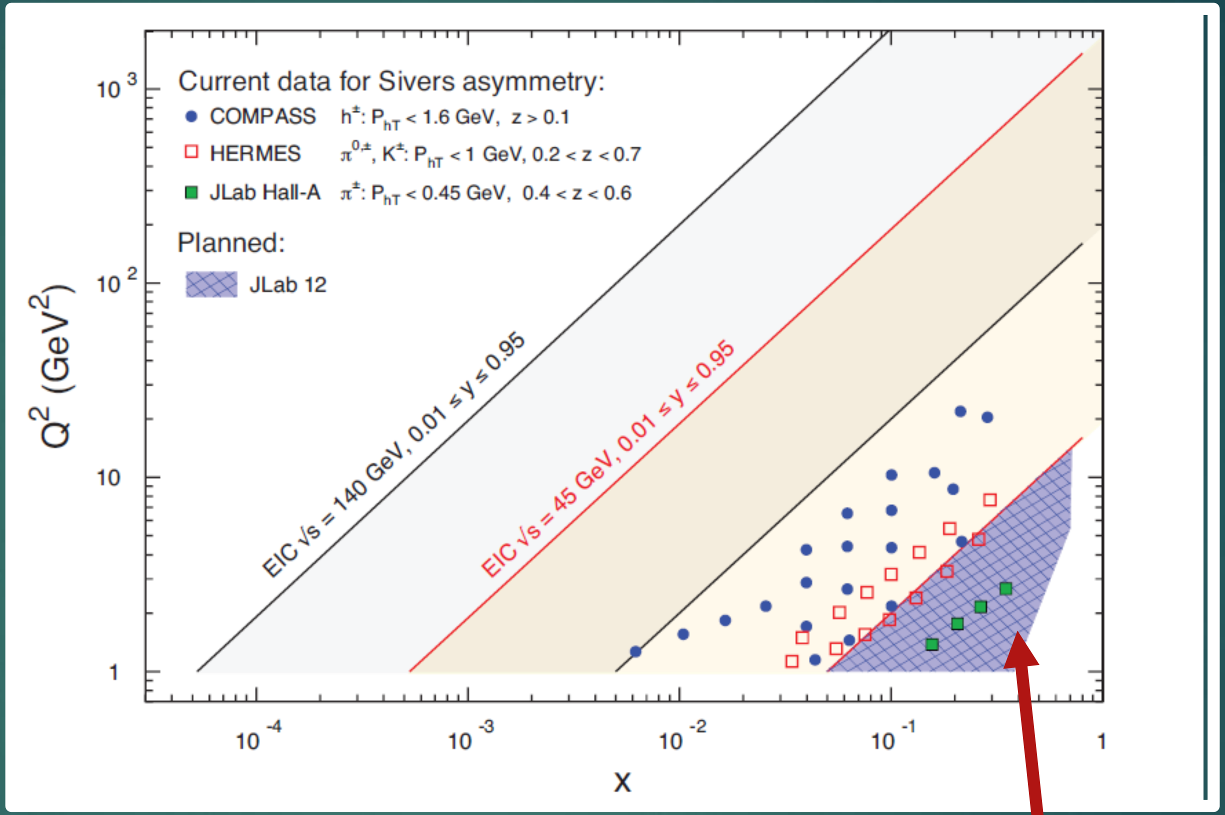
$$J^q = \frac{1}{2}\int_{-1}^{1} dx\, x\left[H^q(x,\eta,t) + E^q(x,\eta,t)\right]_{t\to 0}$$

Ji (1997)

H, E non-flip GPDs

Future → EIC





JLAB

access to small-x domain:

Space, (transv.) momentum and spin distributions of gluon and sea quarks

Missing and complementary information on TMDs and GPDs

Conclusions and open issues

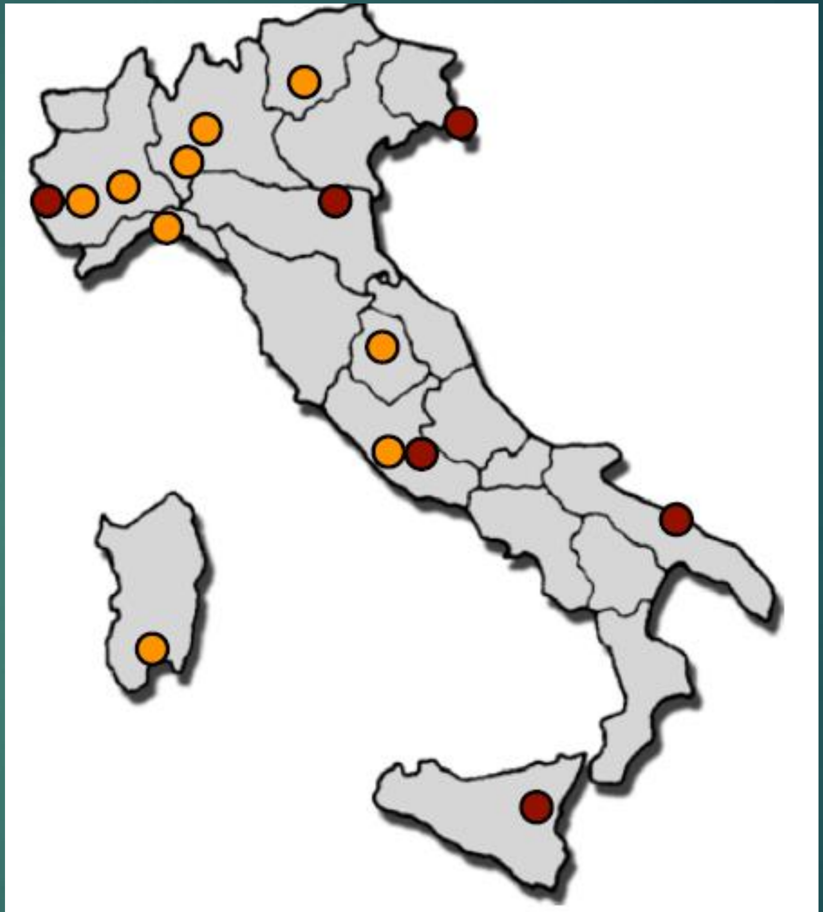
- Experimental evidence to go beyond a simple collinear (1D) picture

  3D image of the nucleon: tremendous progress
- Transverse single-spin asymmetries: challenging and tool to learn deeper on the nucleon structure and QCD
- Spin-TMD effects ad GPDs well established
- Orbital angular momentum: TMDs (indir.) and GPDs (directly)
- More data expected: COMPASS, Jlab, RHIC, and eventually EIC
- Phenomenological and theoretical analysis to be improved:

  factorization and non perturbative inputs
- TMD approach and low-x physics: still to be pursued
- TMD and GPD community: very active and spread all over the world (USA, Japan, China, Russia, Netherlands, Belgium, France, Germany, and ITALY)

Research activities in Italy

Theory NINPHA
National Initiative on Physics of Hadrons

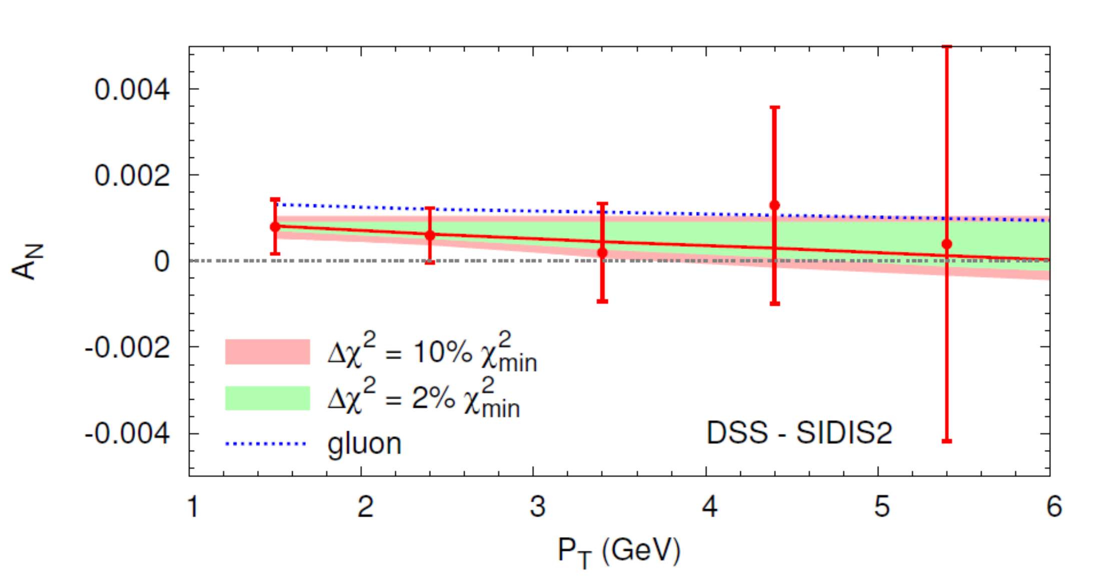


Experiments
COMPASS JLAB

Thank you

BACK-UP SLIDES

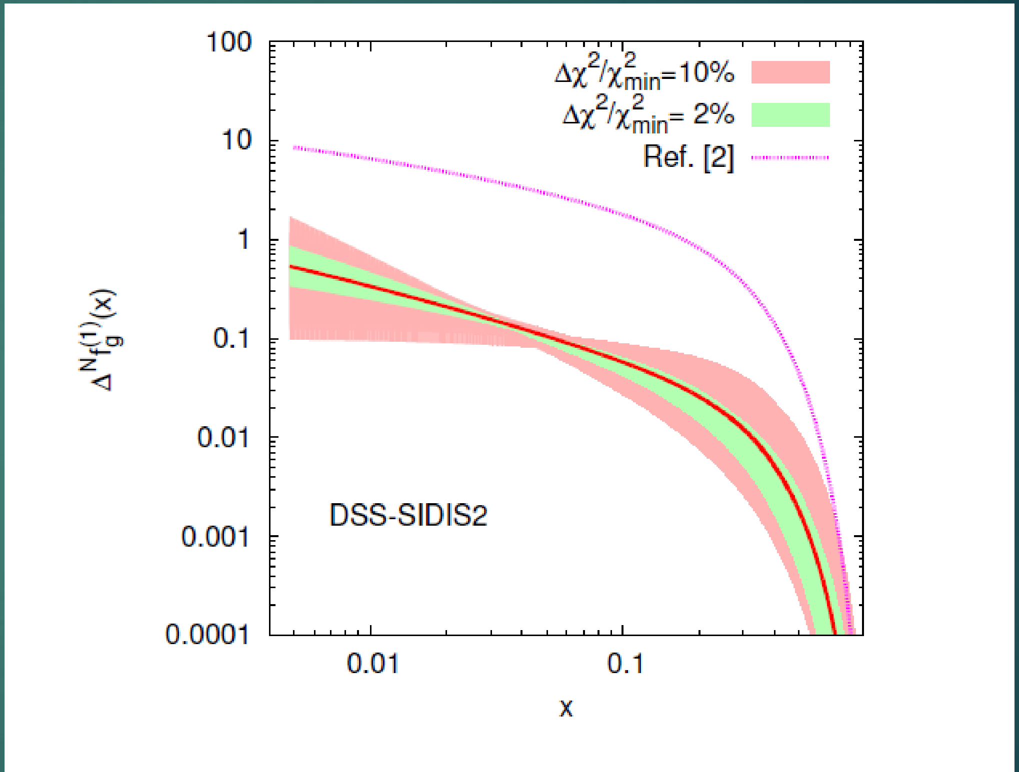
Access to the gluon Sivers function



PHENIX Collaboration data (2014)

All other effects are washed out

A_N at mid-rapidity



UD, Murgia, Pisano JHEP09 (2015)

TMD factorization approaches

Collins-Soper-Sterman (CSS) resummation framework

Seminal paper

Collins-Soper-Sterman 1985
ResBos: C.P. Yuan, P. Nadolsky
Qiu-Zhang 1999, Vogelsang, etc...
Kang-Xiao-Yuan 2011
Sun-Yuan 2013

TMD framework

"New" Collins approach

Collins 2011
Aybat-Rogers 2011,
Aybat-Collins-Rogers-Qiu, 2012
Aybat-Prokudin-Rogers 2012
Anselmino-Boglione-Melis 2012
Prokudin-Bacchetta 2013
Echevarria-Idilbi-Kang-Vitev 2014
Collins-Rogers 2015
Kang-Prokudin-Sun-Yuan 2015
Collins et al 2016

Soft Collinear Effective Theory (SCET)

Echevarria-Idilbi-Schafer-Scimemi 2012
D'Alesio-Echevarria-Melis-Scimemi 2014
Echevarria-Scimemi-Vladimirov 2016

Tremendous progress