TMDs from Hard Scattering Processes

Umberto D'Alesio
University and INFN, Cagliari

- TMDs & Unpolarized cross sections:

evolution, accuracy and non perturbative inputs

- TMDs & Transverse single-spin asymmetries:

Universality, evolution, and (factorization in) inclusive processes

- Conclusions

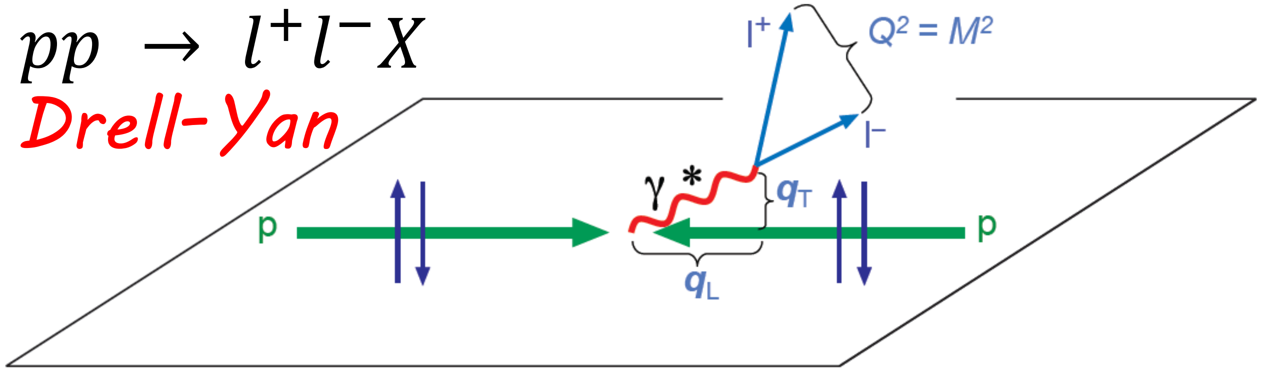
3D Parton Distributions: path to the LHC

TMDs: How can we access them?

Two-scale processes: $Q^2 \gg p_T^2 \geq \Lambda_{QCD}^2$

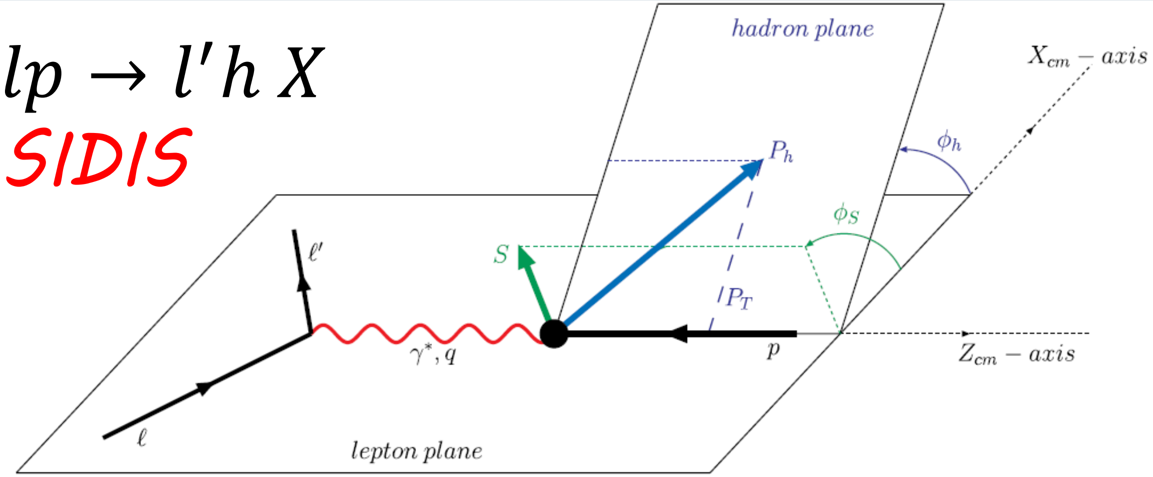
$pp \to l^+ l^- X$

Drell-Yan

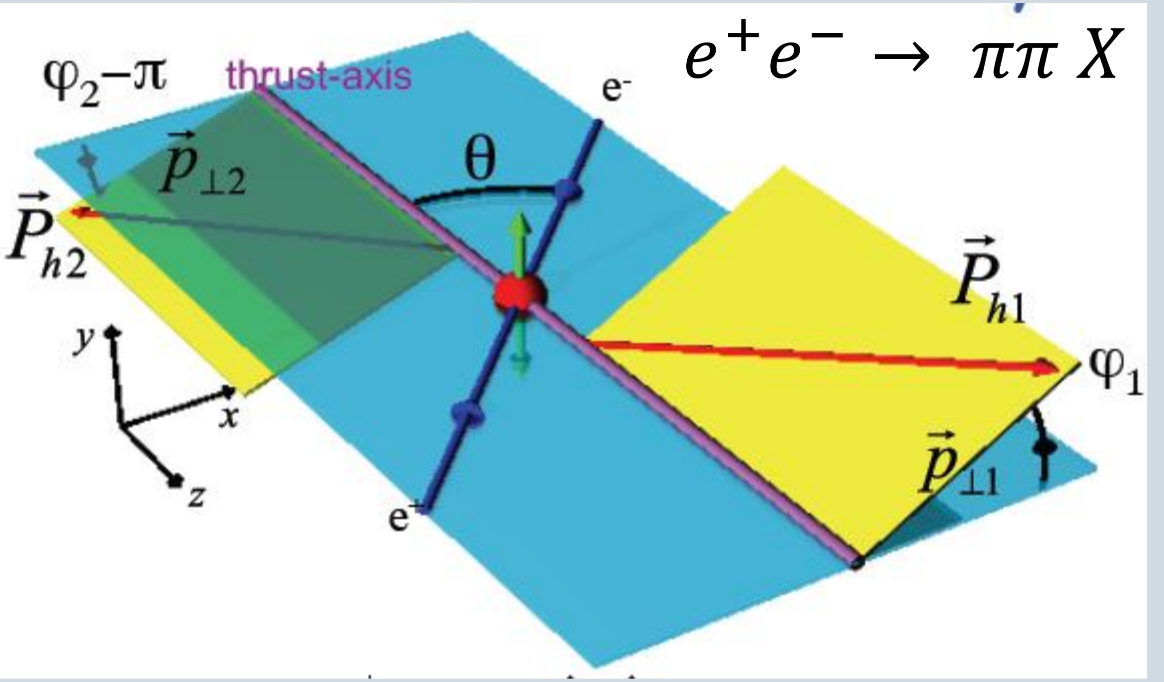


$lp \to l' h X$

SIDIS

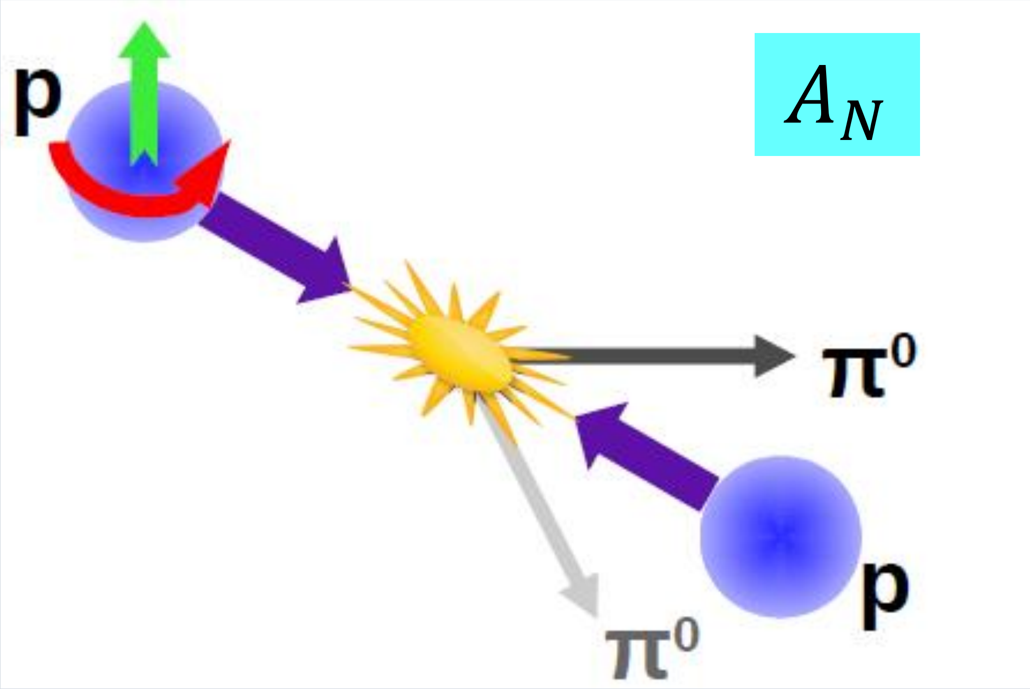


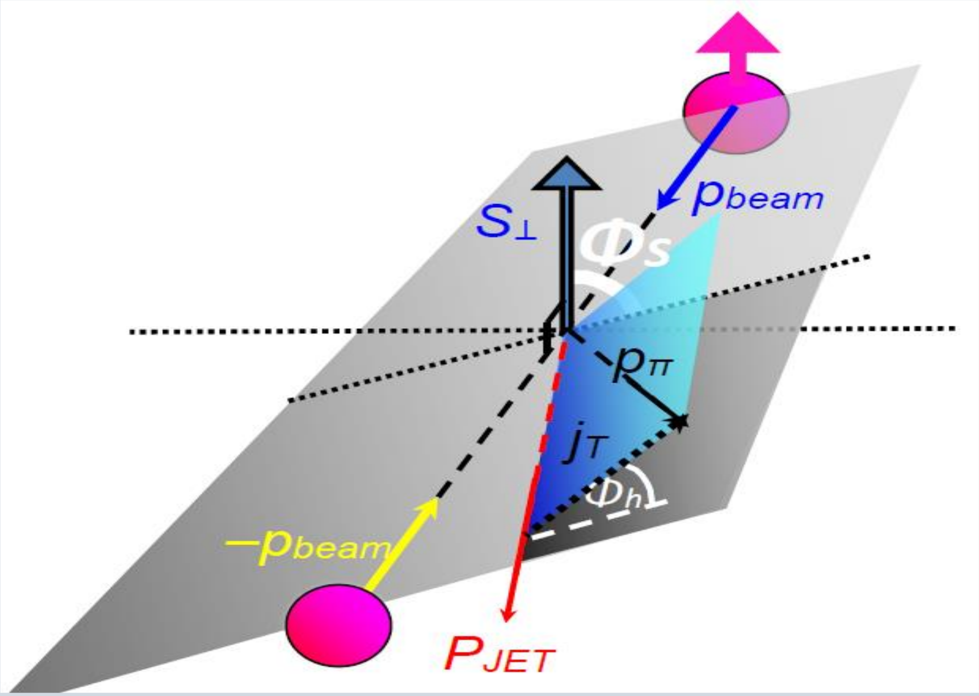
$e^+ e^- \to \pi\pi X$



TMD factorization proven

And possibly in processes like





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

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

Single scale processes

And more

TMDs and unpolarized cross sections

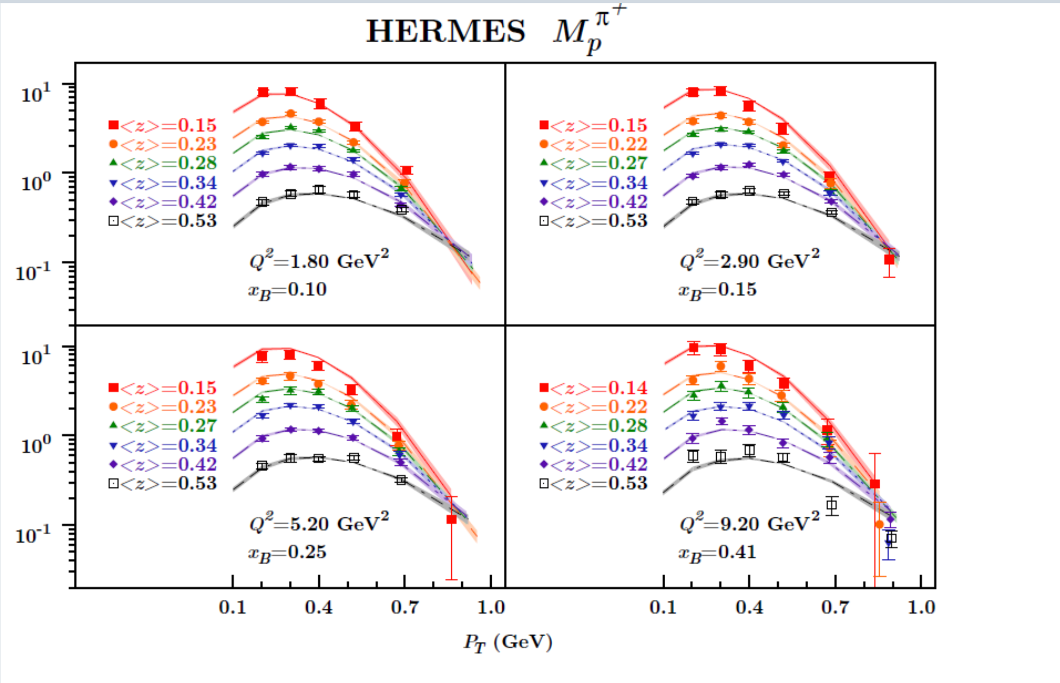
SIDIS multiplicities

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

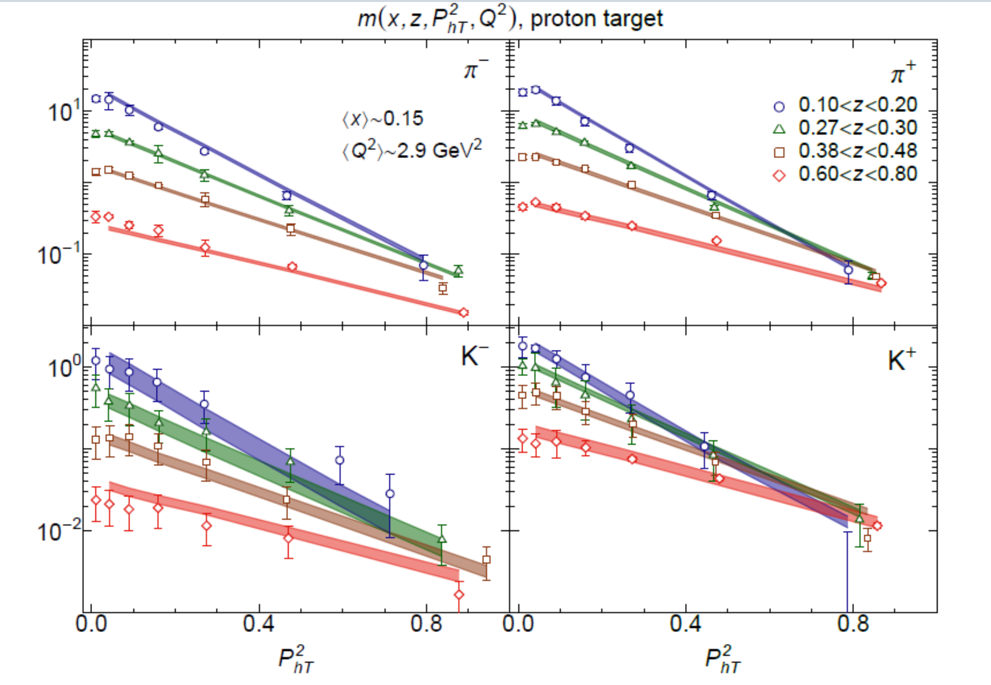
$$f_{q/p}(x,k_\perp) = f_{q/p}(x)\,\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle}}{\pi\langle k_\perp^2\rangle}$$

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

without TMD evolution (limited Q^2 range)



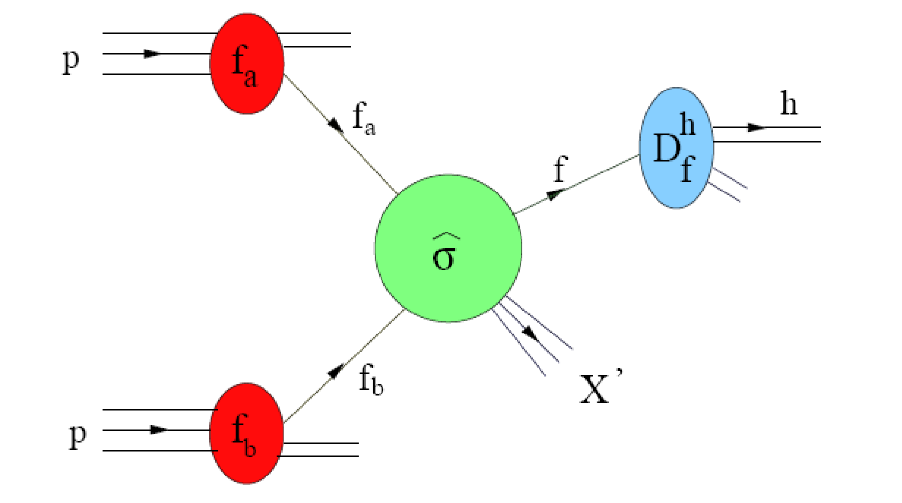
Anselmino et al. (2014)



Signori, Bacchetta, Radici, Schnell (2013)

Theory: factorization and evolution

Collinear approach



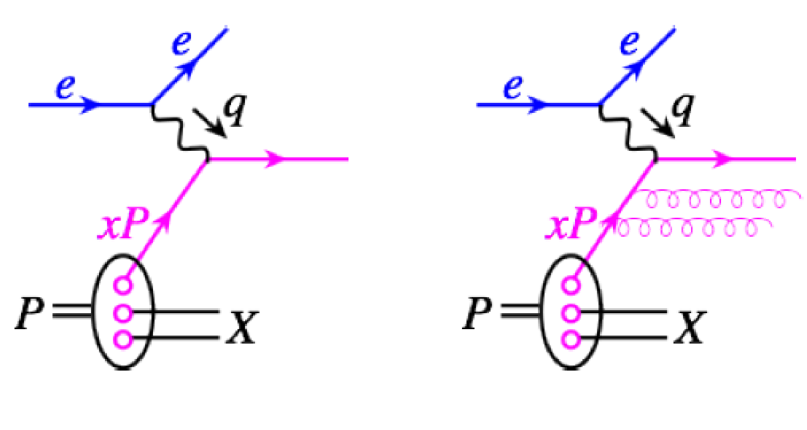
Factorization

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

Parton Distribution Func.
from experiment
Universal

Partonic x-section
from pQCD
Process dependent

Fragmentation Func.
from experiment
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

$$\frac{d\sigma}{dQ\,dq_T} \sim H(Q^2,\mu^2) \int d^2\boldsymbol{k}_{AT}\, d^2\boldsymbol{k}_{BT}\, F_A(x_A, \boldsymbol{k}_{AT}; \zeta_A, \mu)\, F_B(x_B, \boldsymbol{k}_{BT}; \zeta_B, \mu)\, \delta^{(2)}(\boldsymbol{k}_{AT} + \boldsymbol{k}_{BT} - \boldsymbol{q}_T)$$

DY processes

Echevarria, Idilbi, Scimemi (2012,13,14)

UD, Echevarria, Melis, Scimemi (2014)

$$\tilde{F}_{q/N}(x, b_T; \zeta, \mu) = \tilde{F}^{\rm pert}_{q/N}(x, b_T; \zeta, \mu)\tilde{F}^{\rm NP}_{q/N}(x, b_T; \zeta)$$

TMD in b space

$$e^{-\lambda_1 b_T}\left(1 + \lambda_2 b_T^2\right)$$

Scale independent

$$\sim \left(\frac{\zeta}{\zeta_b}\right)^{-D(b_T;\mu)} \sum_j \int_x^1 \frac{d\tau}{\tau} \tilde{C}^{Q}_{q\leftarrow j}(x/\tau, b_T; \zeta_b, \mu) f_{j/N}(\tau, \mu)$$

Collinear PDF

$$\frac{dD}{d\ln\mu} = \Gamma_{\rm cusp}$$

RG eq

Theo. Equiv. with Collins approach

Non-perturbative input and accuracy

$$\tilde{F}^{\rm NP}_{q/N}(x, b_T; Q) = e^{-\lambda_1 b_T}\left(1 + \lambda_2 b_T^2\right)$$

Relevant for Z^0 data

Sensitive to low-energy/low-q_T data

Both needed

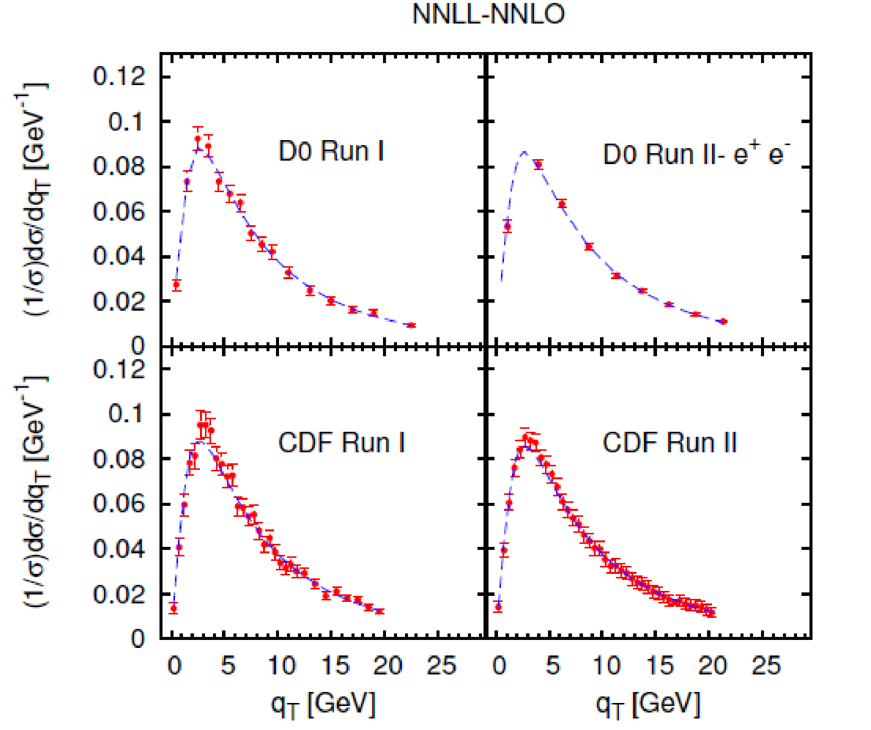
Order	H	$\hat{C}_{q\leftarrow j}$	$\Gamma_{\rm cusp}$	γ^V	D^R
LL	α_s^0	α_s^0	α_s^1	α_s^0	α_s^0
NLL	α_s^0	α_s^0	α_s^2	α_s^1	α_s^1
NNLL	α_s^1	α_s^1	α_s^3	α_s^2	α_s^2

Fit to Drell-Yan and Z^0 production data

TMD evolution at NNLL (SCET)

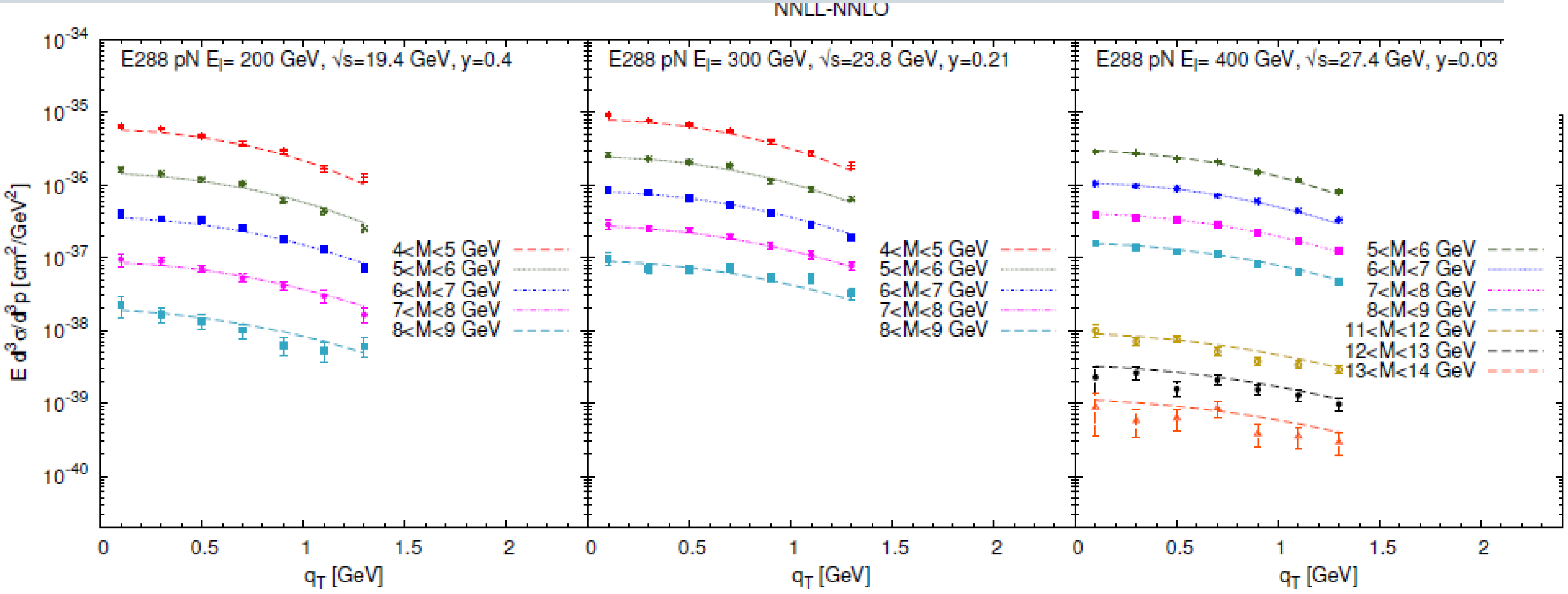
UD, Echevarria, Melis, Scimemi (2014)

(223 data points)



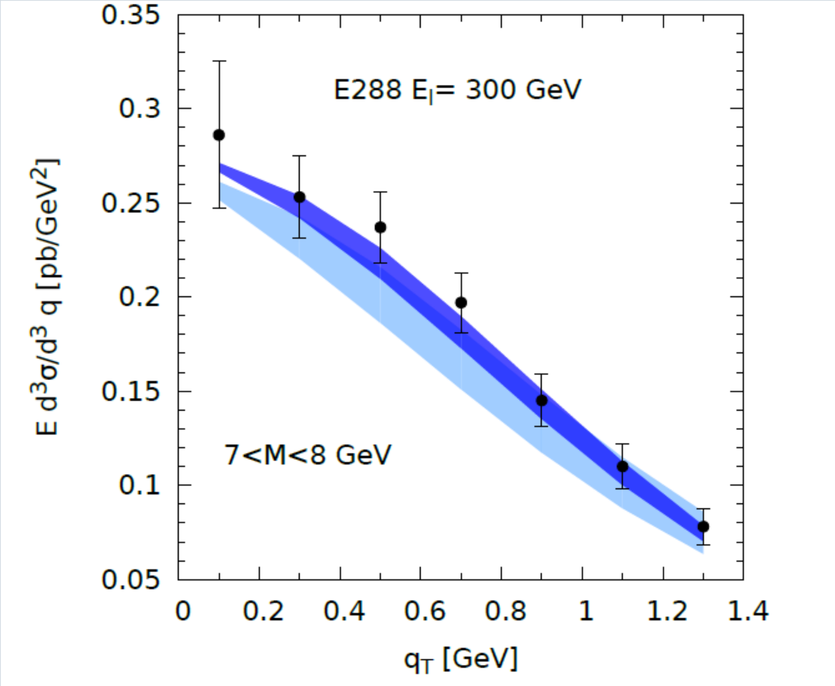
Tevatron

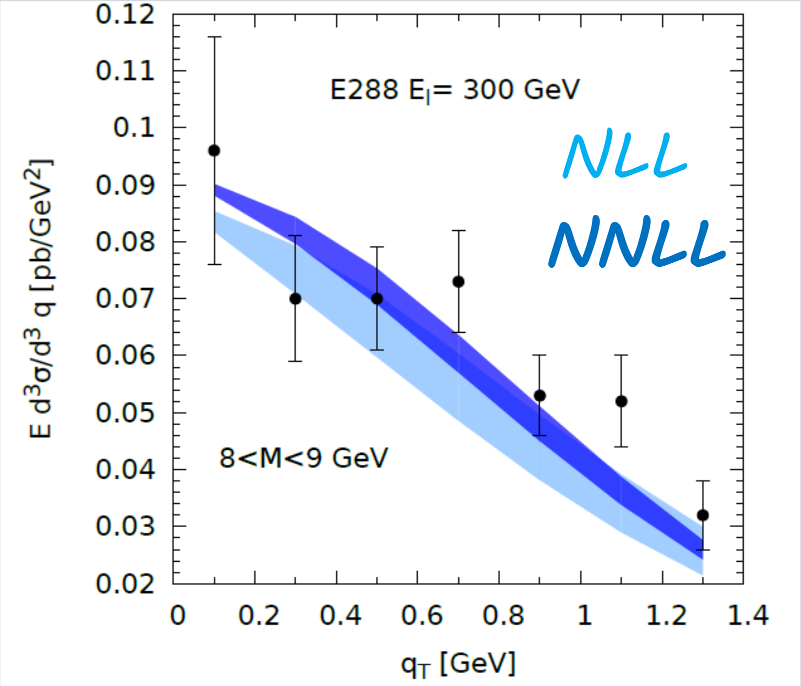
$\chi^2/\text{d.o.f.} = 1.12$



Low energy

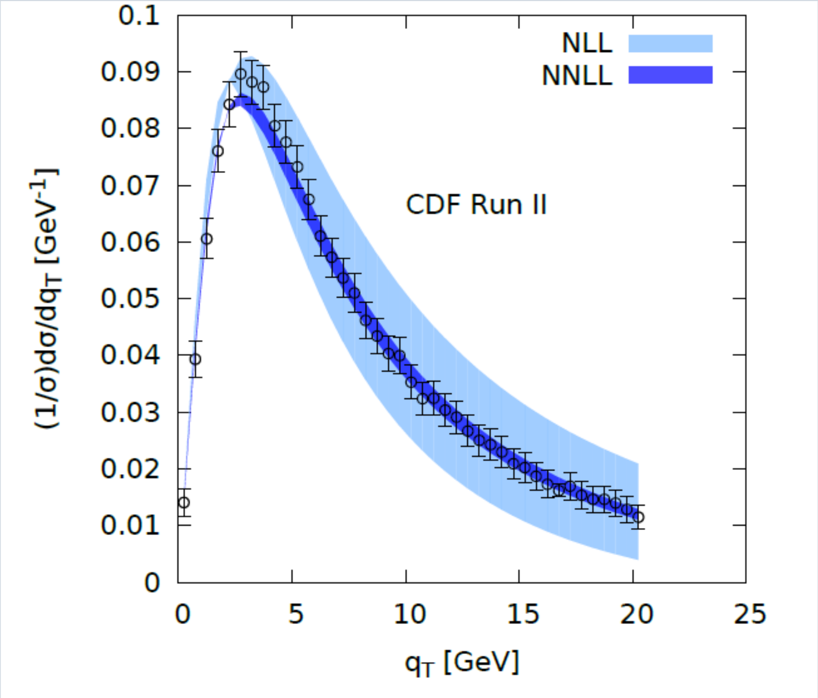
Scale dependence: NLL vs. NNLL





Low energy

Tevatron



Strong reduction at NNLL

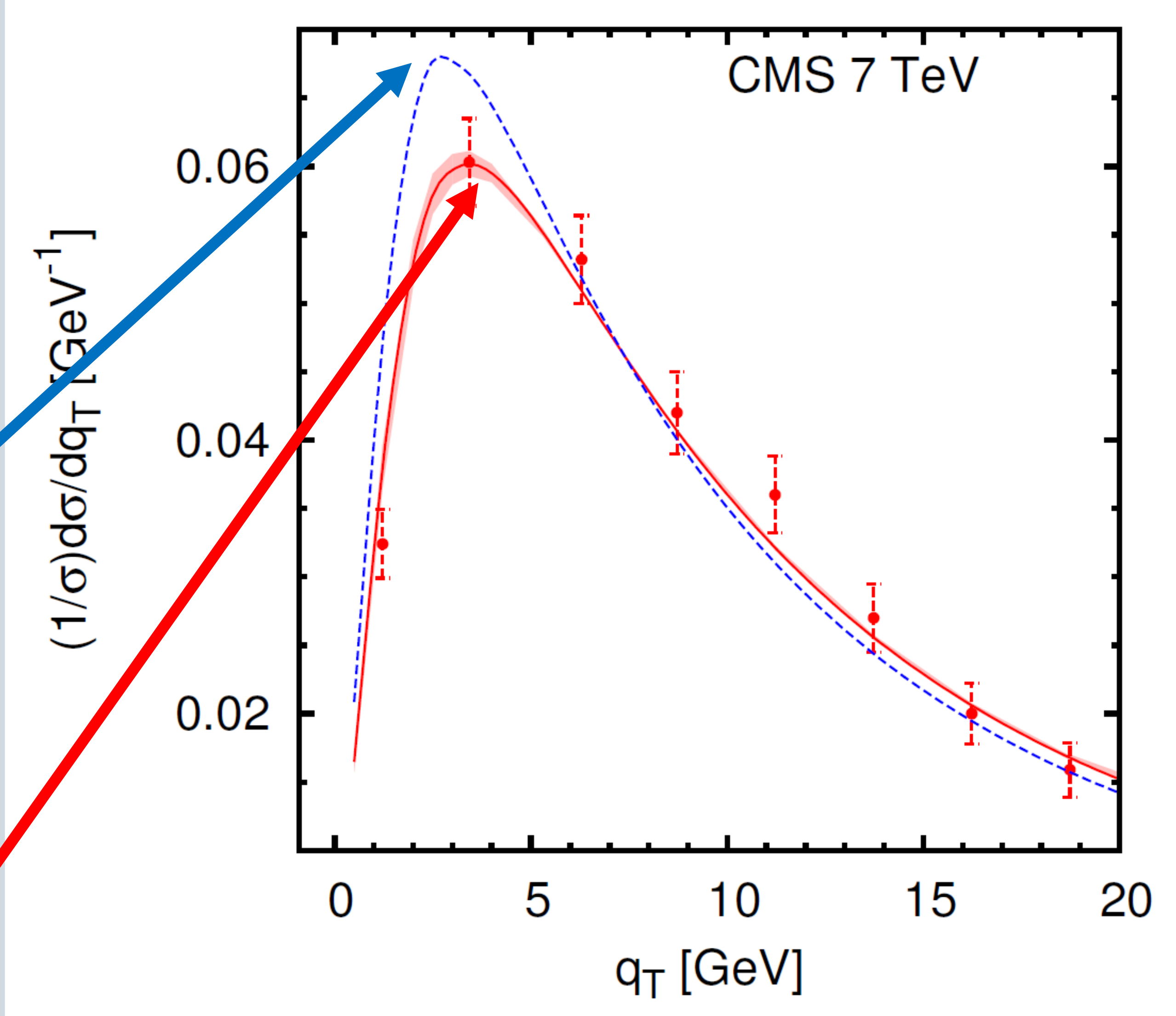
TMDs at LHC (I)

Predictions from NNLL fit

$$pp \rightarrow Z\,X$$

Pure resummed pQCD

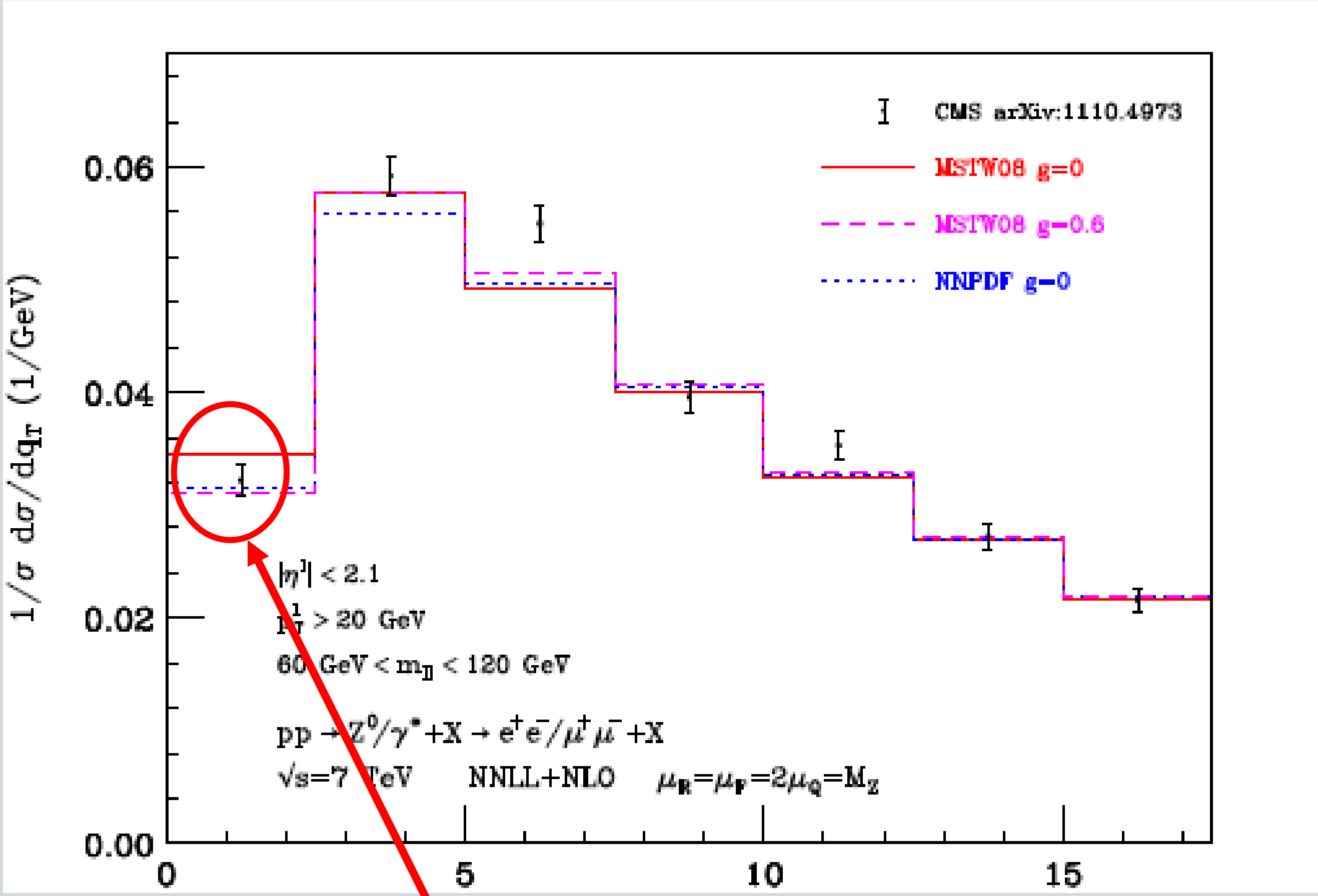
Inclusion of the non Perturbative piece (k_T)

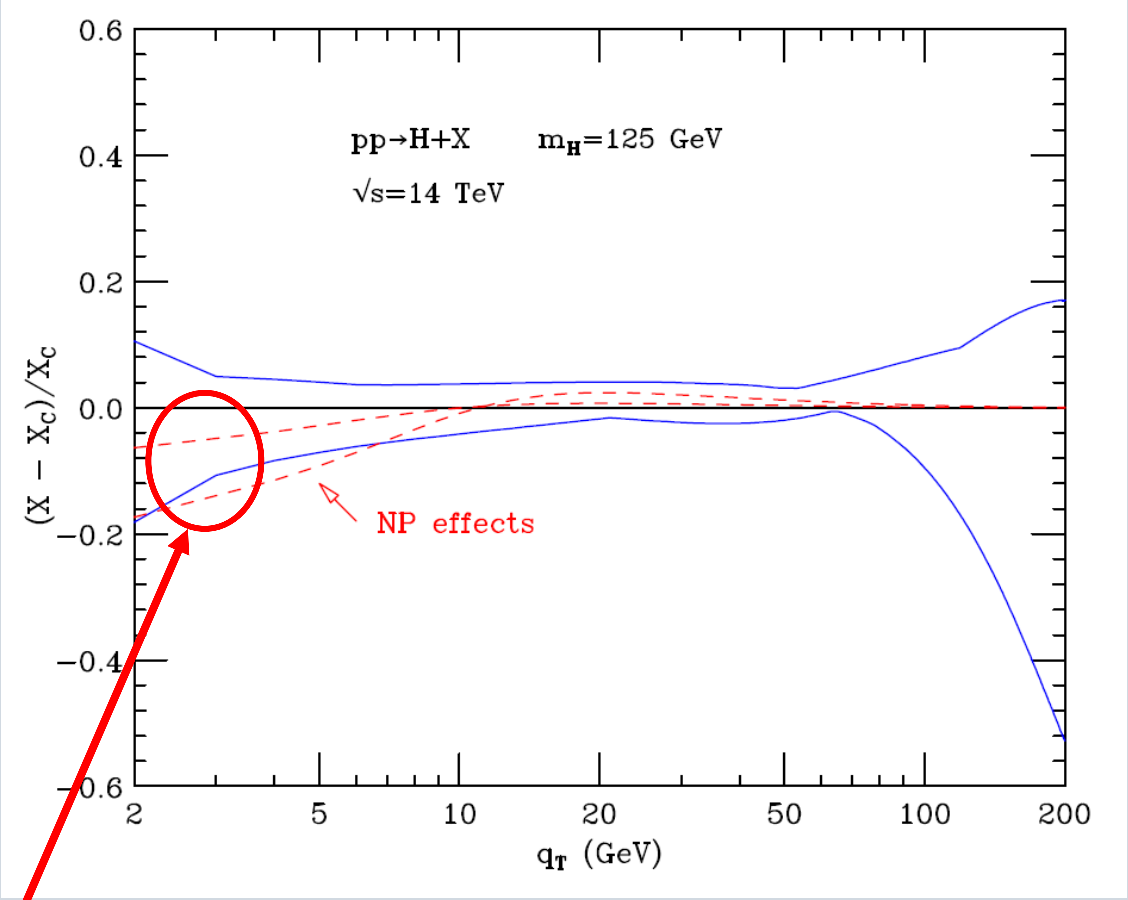


TMDs at LHC (II)

Ferrera (2014)

$pp \rightarrow Z\ X$





Inclusion of the non perturbative piece

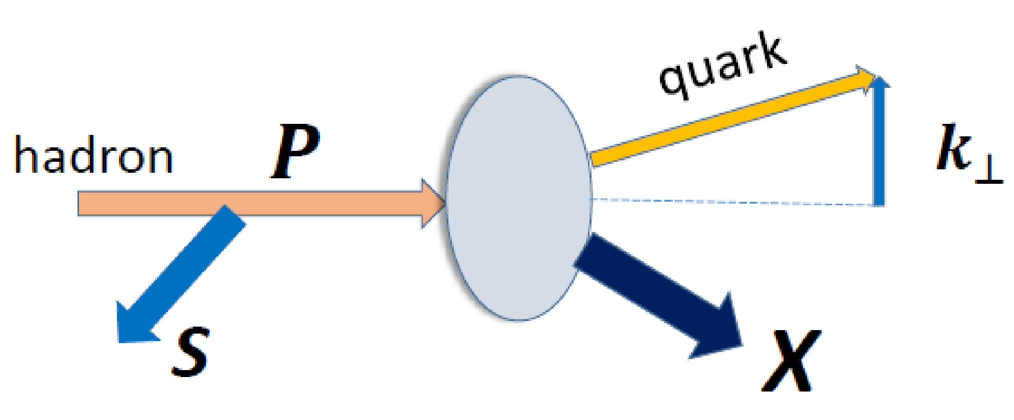
uncertainties in $pp \rightarrow H\ X$

TMDs and spin

For its relevance, among the eight TMD-PDFs

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

Sivers (1989)



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

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

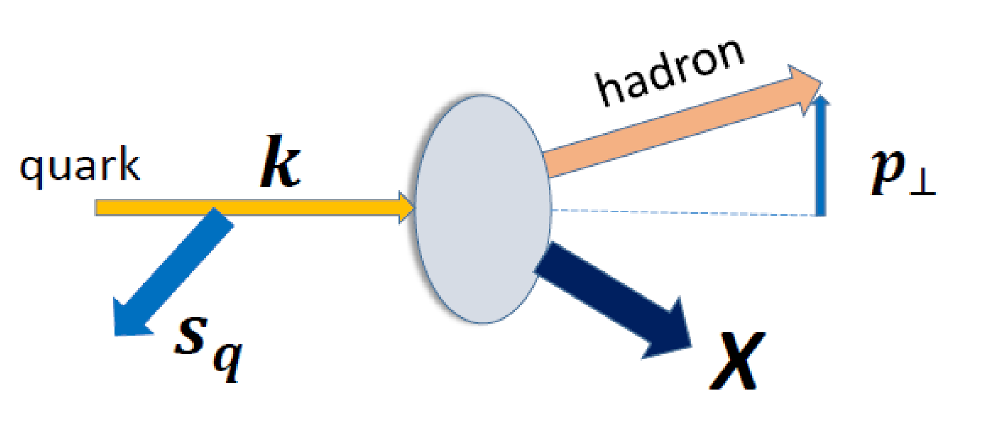
Spin independent

Spin dependent

Analogously, among the TMD-FFs, for its relevance

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

Collins (1992)



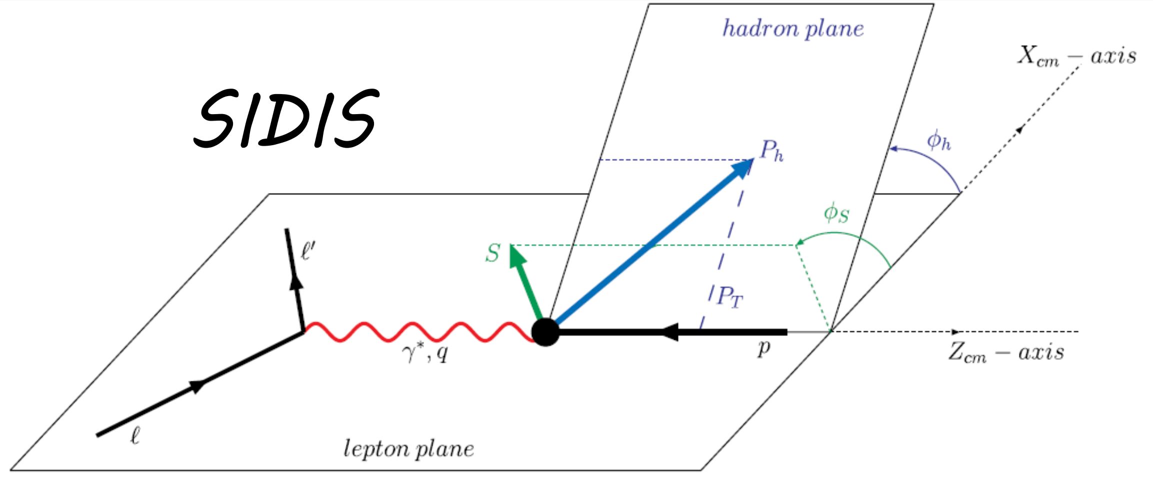
Correlation between the spin of the fragmenting quark and the hadron transverse momentum

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

Crucial for the first ever extraction of transversity

Sivers and Collins functions extensively studied theoretically, experimentally and phenomenologically

SIDIS



CLEAR evidence from data HERMES, COMPASS, JLab

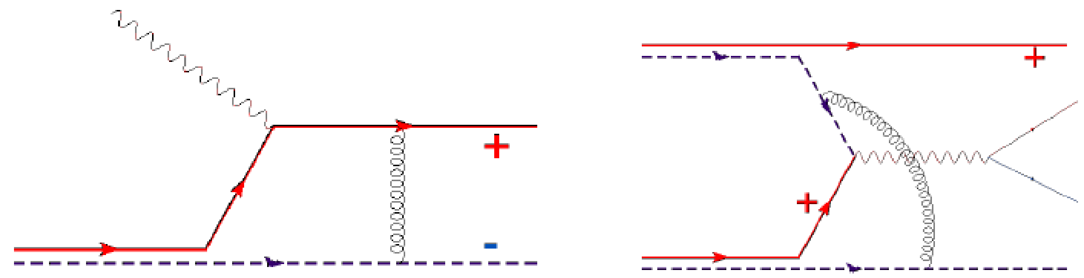
$$d\sigma(S) \sim \sin(\phi_h + \phi_S) h_1 \otimes H_1^{\perp} + \sin(\phi_h - \phi_S) f_{1T}^{\perp} \otimes D_1 + \ldots$$

Collins   Sivers

First phase: analysis with DGLAP evolution

Second phase (just started): TMD evolution

Modified universality of the Sivers function



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

Collins (2002)

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

A clear-cut test

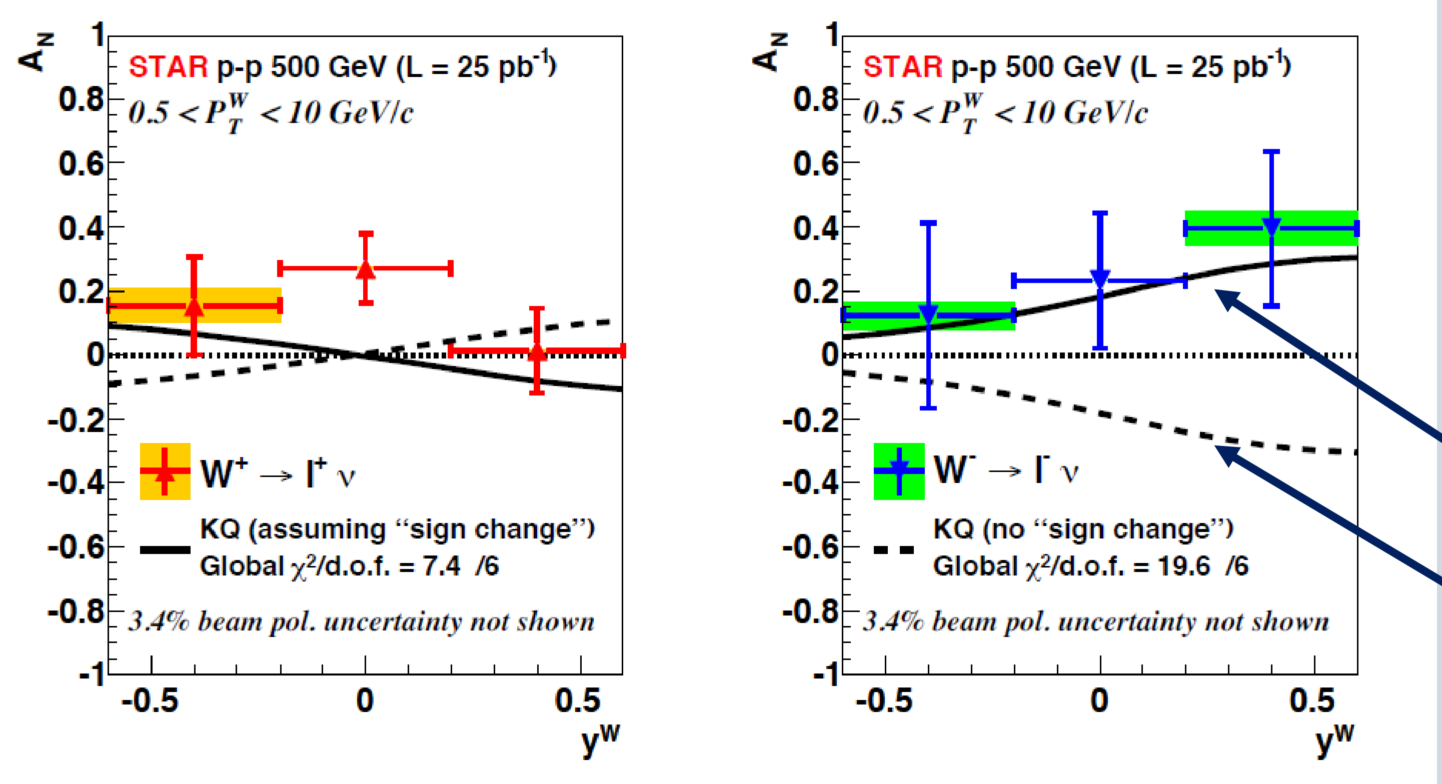
If falsified:

- misunderstanding of I/F state interact. → T-odd effects
- missing points in QCD factorization (TMD and collinear)

[most severe scenario]

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

STAR Collaboration (2016)



Kang et al. (2016)

without TMD evolution

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

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

New analysis: Anselmino, Boglione, UD, Murgia, Prokudin, in progress

- *New extraction of the Sivers funct.: why? Role of antiquarks*

- A_N *in* W^+ *production*

dominant

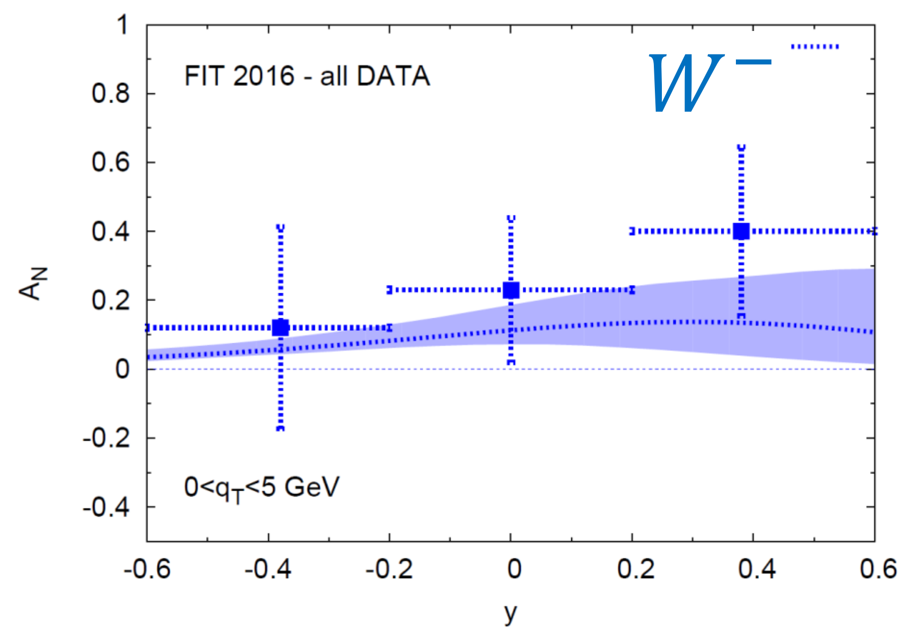
$$\cos^2\theta_C\,\Delta^N f_{u/p^\uparrow}\otimes f_{\bar d/p}+\cos^2\theta_C\,\Delta^N f_{\bar d/p^\uparrow}\otimes f_{u/p}$$

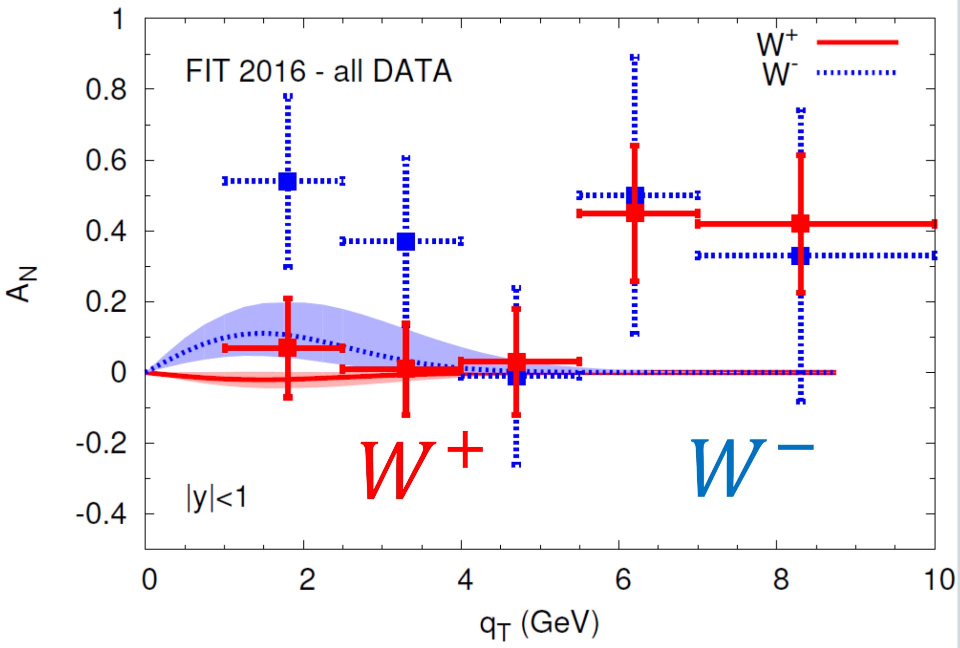
$$+\sin^2\theta_C\,\Delta^N f_{u/p^\uparrow}\otimes f_{\bar s/p}+\sin^2\theta_C\,\Delta^N f_{\bar s/p^\uparrow}\otimes f_{u/p}$$

STAR: $-0.4 < y < 0.4$

$x_{1,2} = 0.1 - 0.24$

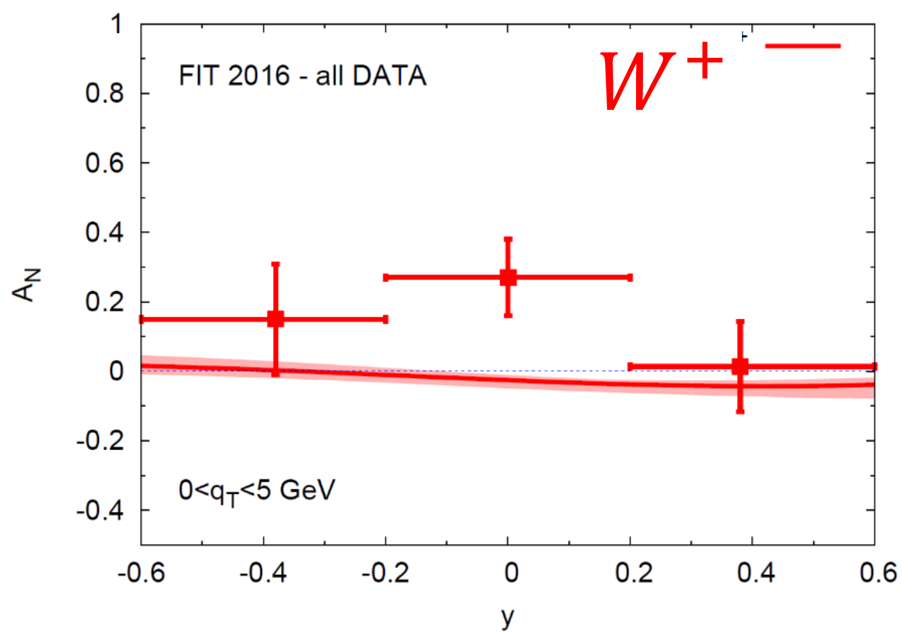
Role of unpolarized TMDs

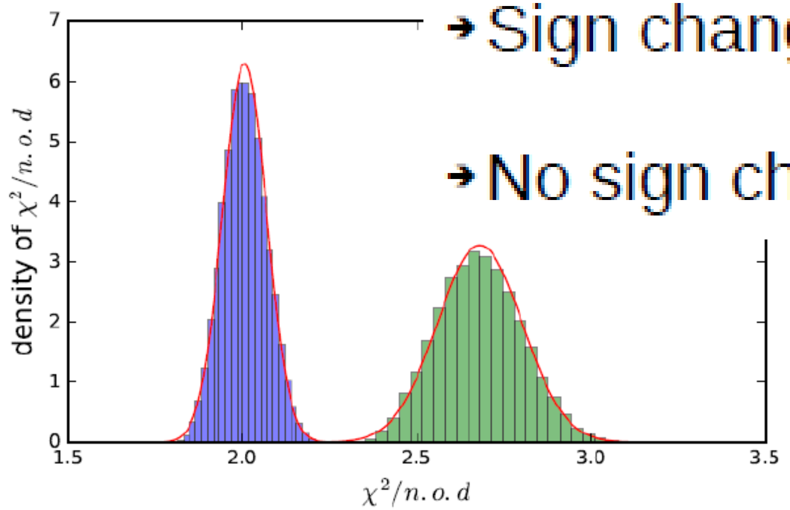




- ❑ *Sign reversed*
- ❑ *Without TMD evolution*

Underestimated at large q_T





→ Sign change $\chi^2/d.o.f \sim 2$

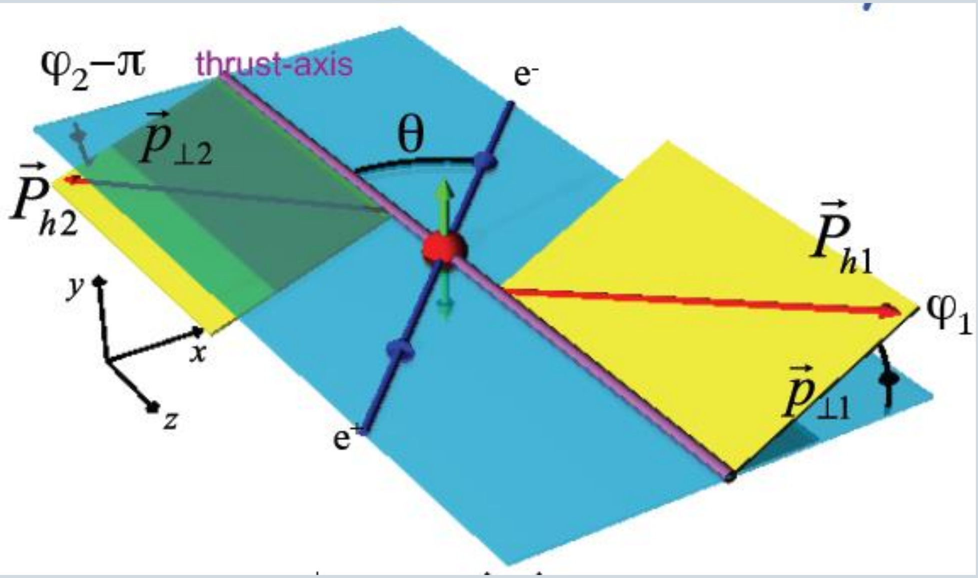
→ No sign change $\chi^2/d.o.f \sim 2.68$

To be further explored

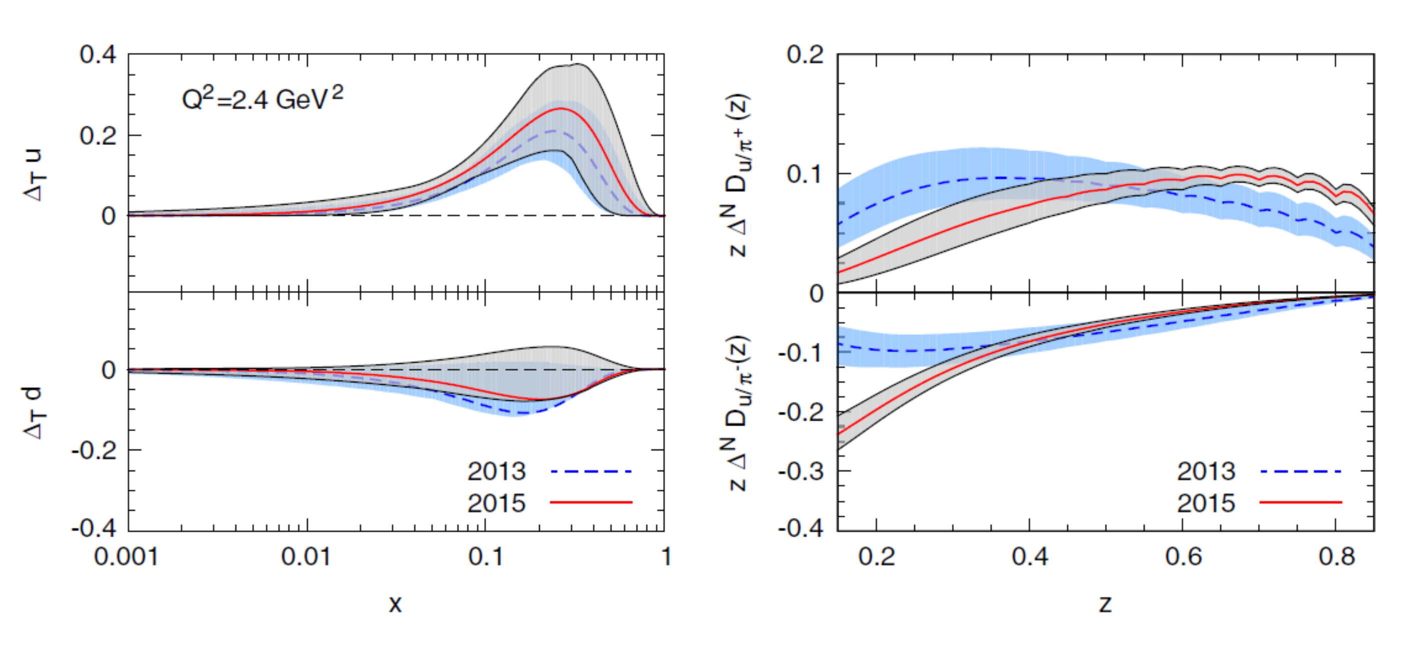
Collins function & transversity

Combined analysis of
SIDIS and $e^+e^- \to \pi\pi X$

$h_1(x_B, k_\perp) H_1^\perp(z_h, p_\perp)$ $H_1^\perp(z_1, p_{1\perp}) H_1^\perp(z_2, p_{2\perp})$



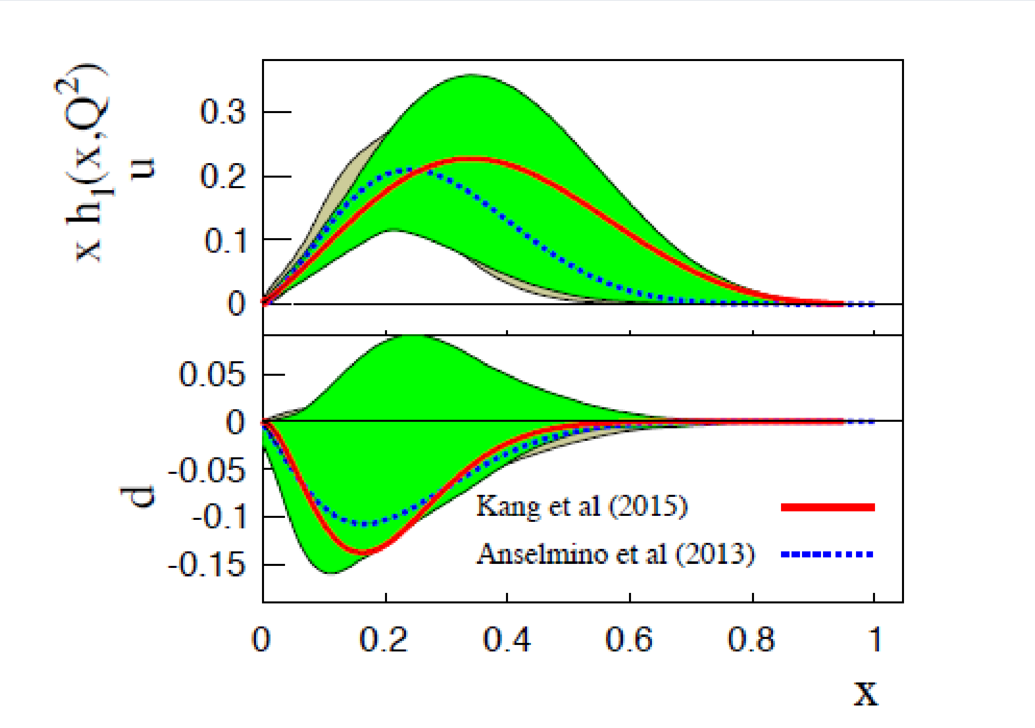
without TMD evolution

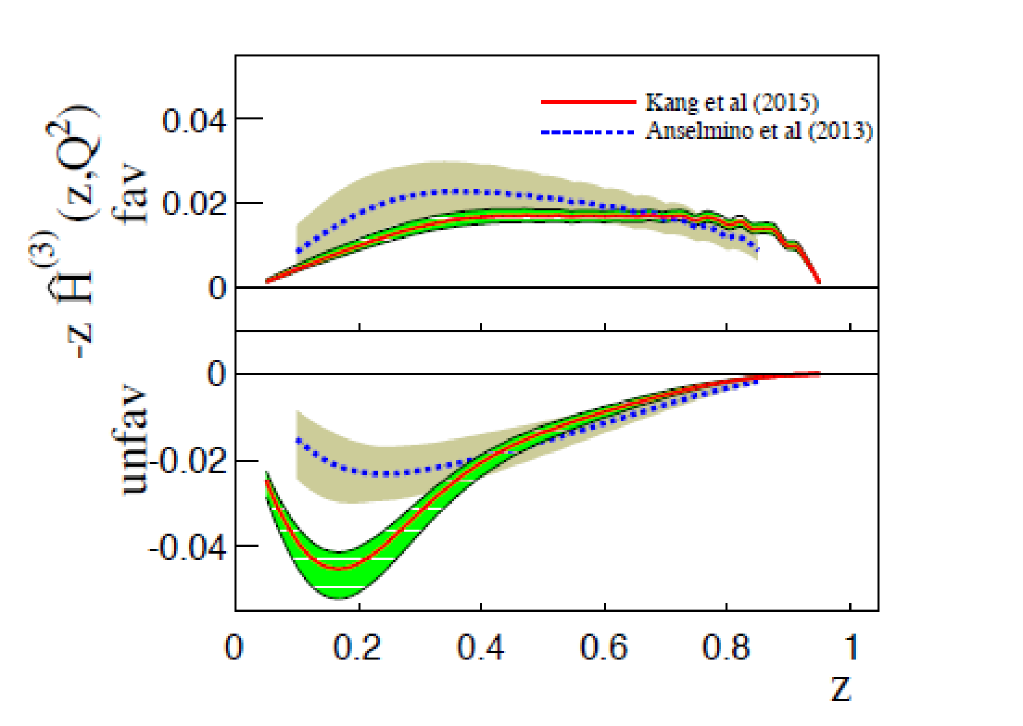


Anselmino, Boglione, UD, Gonzalez, Melis, Murgia, Prokudin (2007, 09, **13, 15**)

Differences due to a more flexible Collins param.

Analysis with TMD evolution
Kang, Prokudin, Sun, Yuan (2015)





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

NO evidence of TMD evolution yet
SSAs are (double)ratios…

Back to A_N : further evidence of Sivers and Collins effects

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

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

$$d\sigma^{\uparrow} - d\sigma^{\uparrow} \sim \text{Sivers} + \text{transversity} \otimes \text{Collins} + \ldots$$

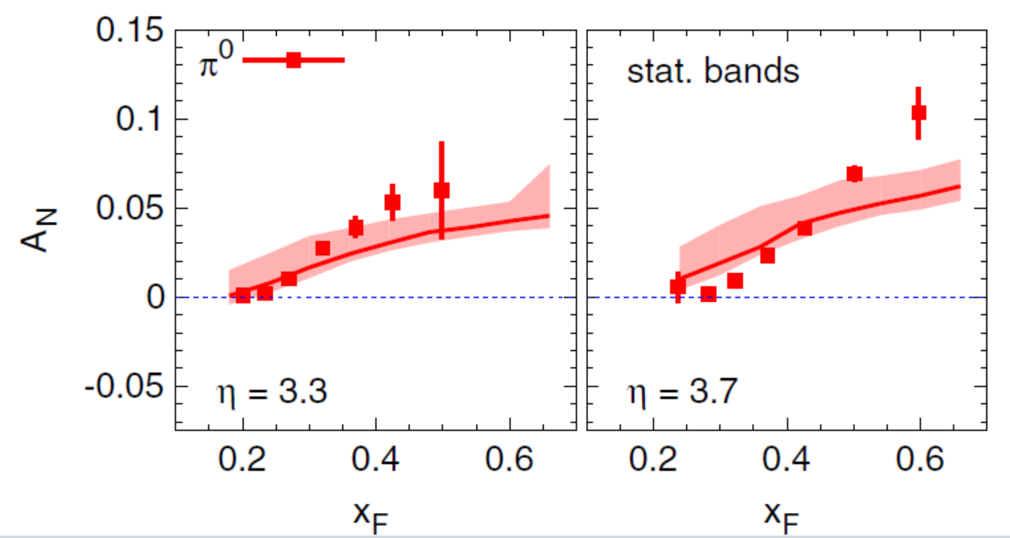
Non separable

In a phenomenological TMD scheme

From SIDIS extractions to pp data (STAR (2008))

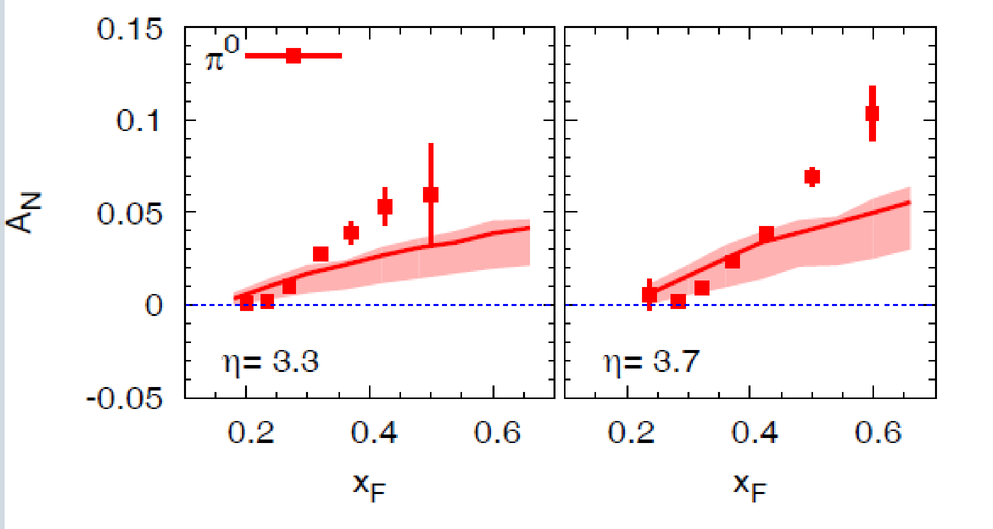
Anselmino, Boglione, UD, Leader, Melis, Murgia, Prokudin (2012 & 13)

Sivers effect alone



Proper combination? in progress

Collins effect alone



Higher-twist contributions to A_N

- Collinear factorization: proven Qiu, Sterman (1991)
- Twist-3 funct.s corresponding, and related, to TMDs, like

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

Boer, Mulders, Piljman (2003)

- Using these relations within the HT approach A_N cannot be described (sign mismatch issue)
- A new twist-3 fragm. function needed to explain A_N

Kanazawa, Koike, Metz, Pitonyak (2014)

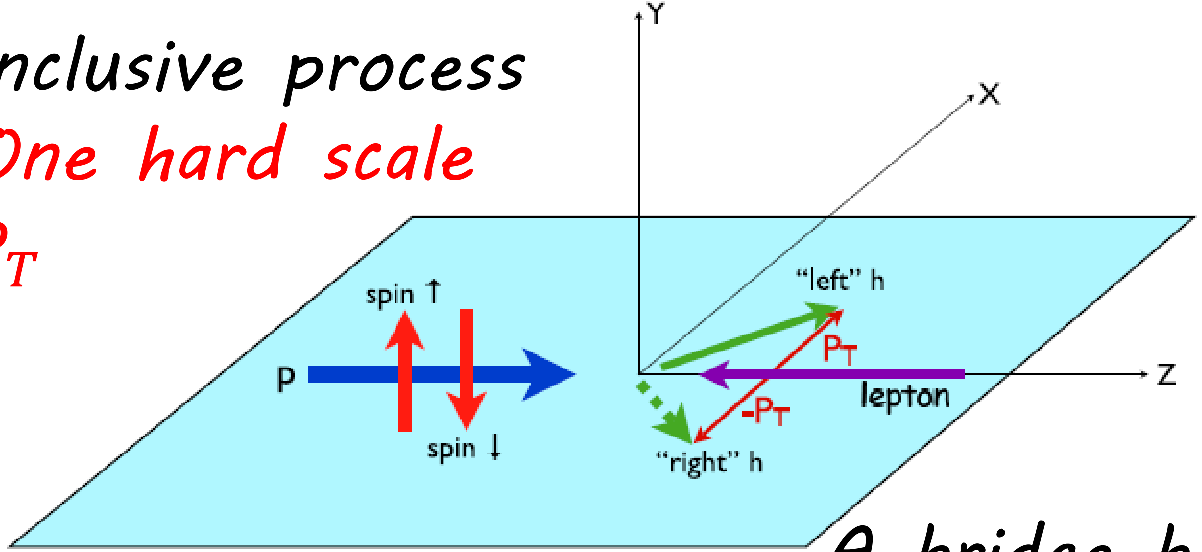
A_N in $pp \to \gamma X$ to disentangle the two schemes (A_N sign)

A_N in $l\,p \to \pi\,X$

Inclusive process

One hard scale

P_T



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

$$A(\phi_S, S_T) = \boldsymbol{S}_T \cdot (\hat{\boldsymbol{p}} \times \hat{\boldsymbol{P}}_T) = S_T \sin\phi_S\, A_N$$

A bridge between SIDIS and $pp \to h\,X$

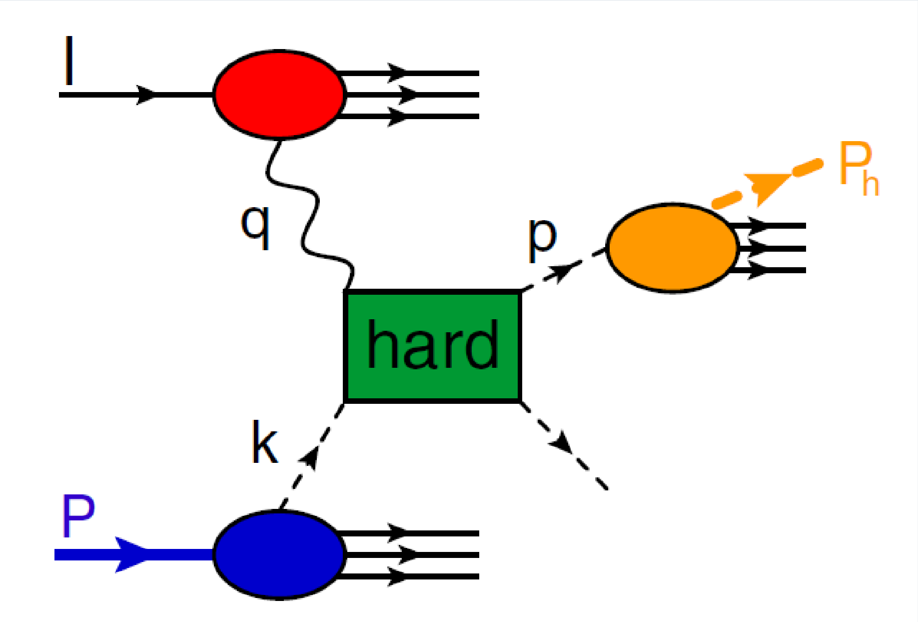
From SIDIS to $l\,p \to h\,X$: test of a unified TMD approach

LO: $lq \to lq$ Anselmino, Boglione, UD, Melis, Murgia, Prokudin (2010&14)

Fairly good description of HERMES data but

Inclusive events: final lepton scattered almost collinear $Q^2 \approx 0$

Quasi-real photon exchange



- *Lepton as a source of quasi-real γ*

  $l \to l' \gamma$ *final lepton almost collinear*

Hinderer, Schlegel, Vogelsang (2015)

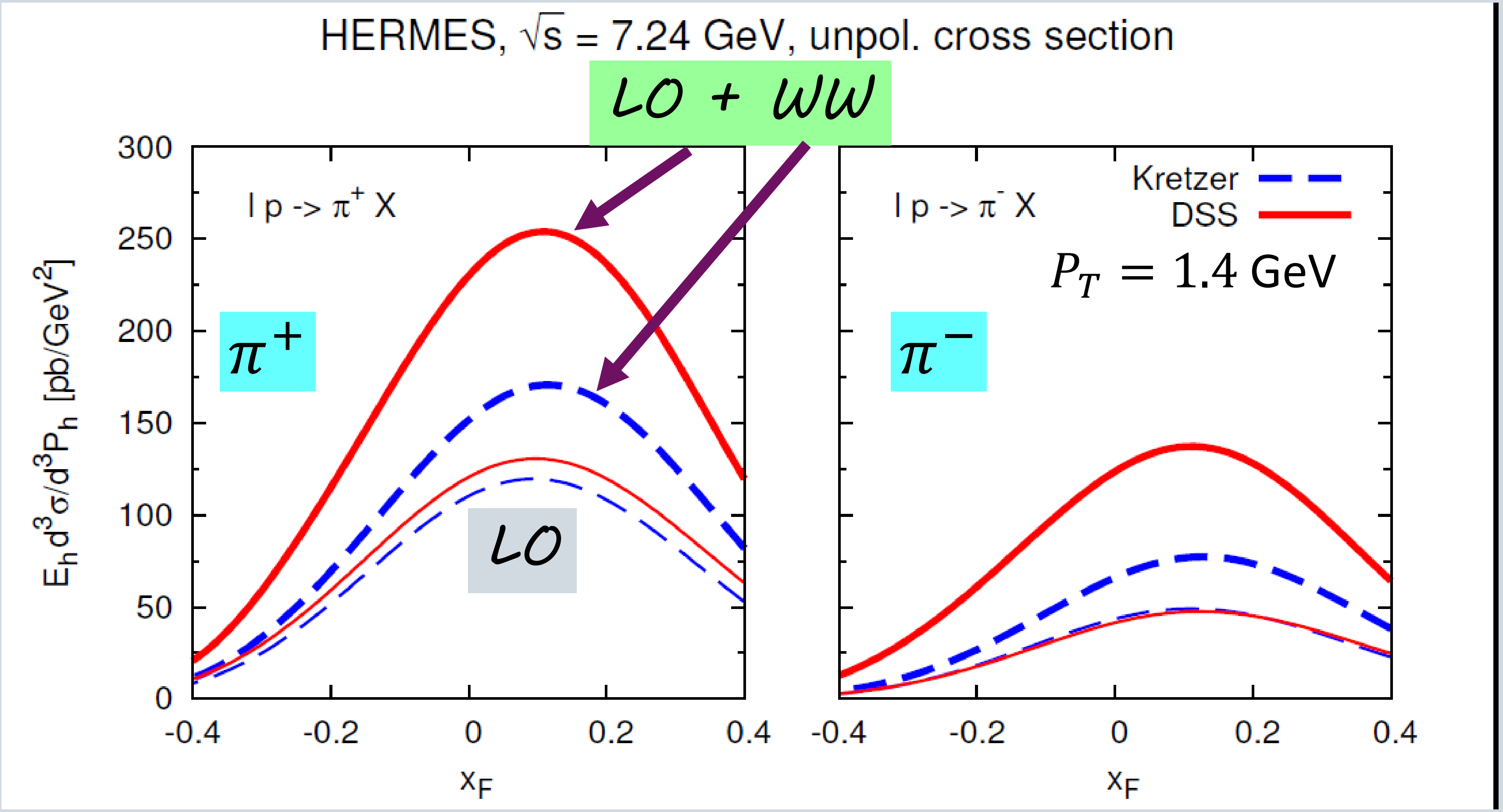
$$\sigma^{\rm WW}(\ell p \to hX) = \int dy\, f_{\gamma/\ell}(y)\, \sigma(\gamma p \to hX)$$

Weizsäcker-Williams approximation

$$f_{\gamma/\ell}(y) = \frac{\alpha}{2\pi} \frac{1+(1-y)^2}{y} \left[\ln\left(\frac{\mu^2}{y^2 m_\ell^2} \right) - 1 \right]$$

Reanalysis within a TMD scheme + Weizsäcker-Williams approx.

UD, Flore, Murgia (in preparation) - UD@QCD Evolution 2016



Unpolarized cross sections

LO $lq \to lq$

WW $\gamma q \to gq$ $\gamma g \to q\bar{q}$

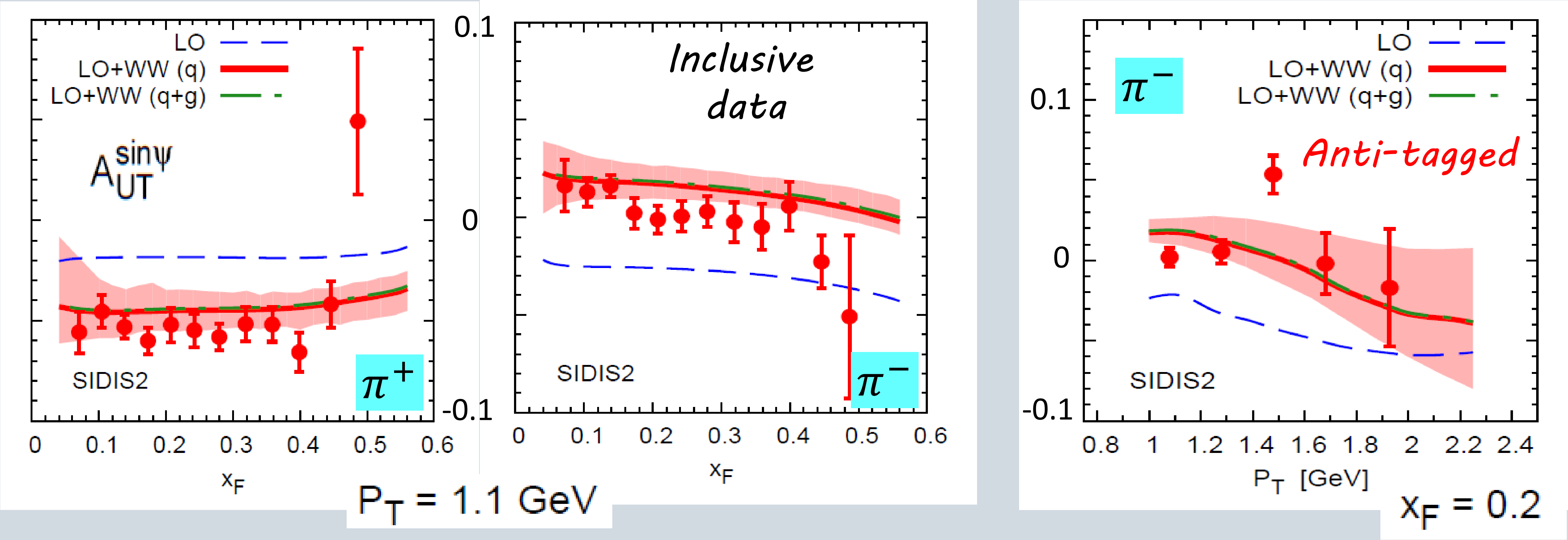
NOTICE $x_F > 0$ backward scattering

WW piece: 50-70% of the total

SSAs: Only Sivers and (marginally) Collins effects sizeable

Predictions from SIDIS extractions

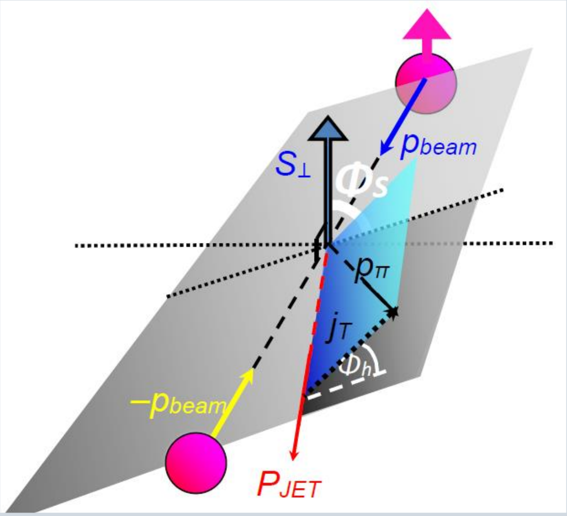
HERMES data (2014)



WW: big improvement!

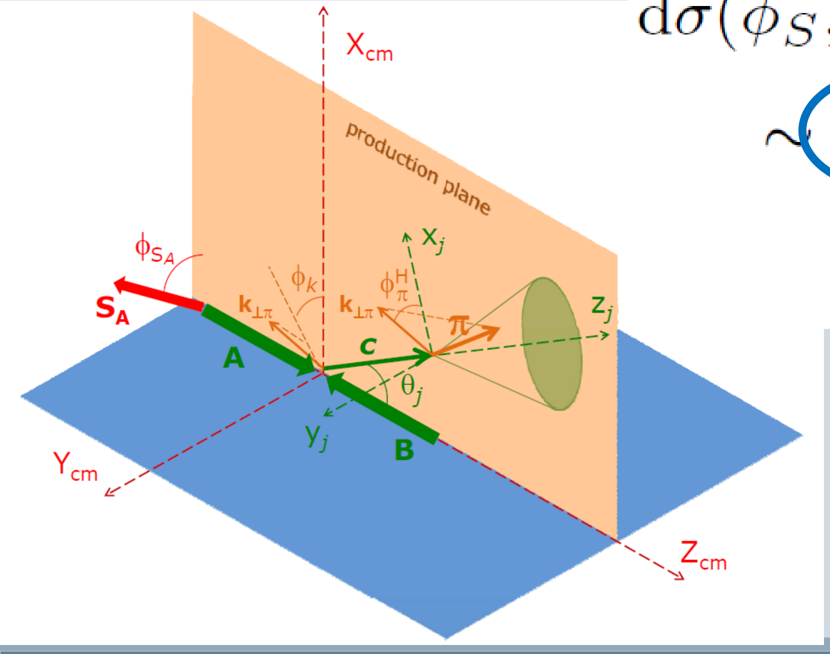
TMD scheme seems to work

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



$$A_N^W = 2\,\frac{\int d\phi_S d\phi_\pi^H\, W(\phi_S,\phi_\pi^H)[d\sigma(\phi_S) - d\sigma(\phi_S+\pi)]}{\int d\phi_S d\phi_\pi^H\,[d\sigma(\phi_S) + d\sigma(\phi_S+\pi)]}$$

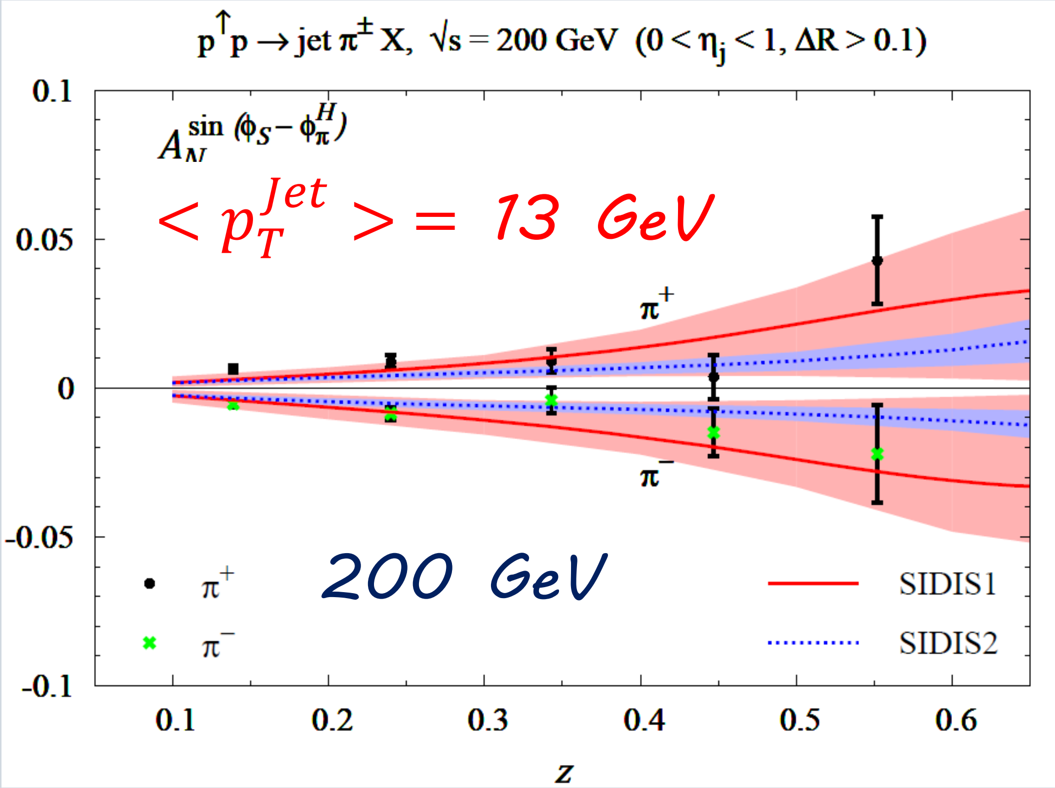
$$W(\phi_S,\phi_\pi^H) = \sin\phi_S,\ \sin(\phi_S - \phi_\pi^H),\ \ldots$$

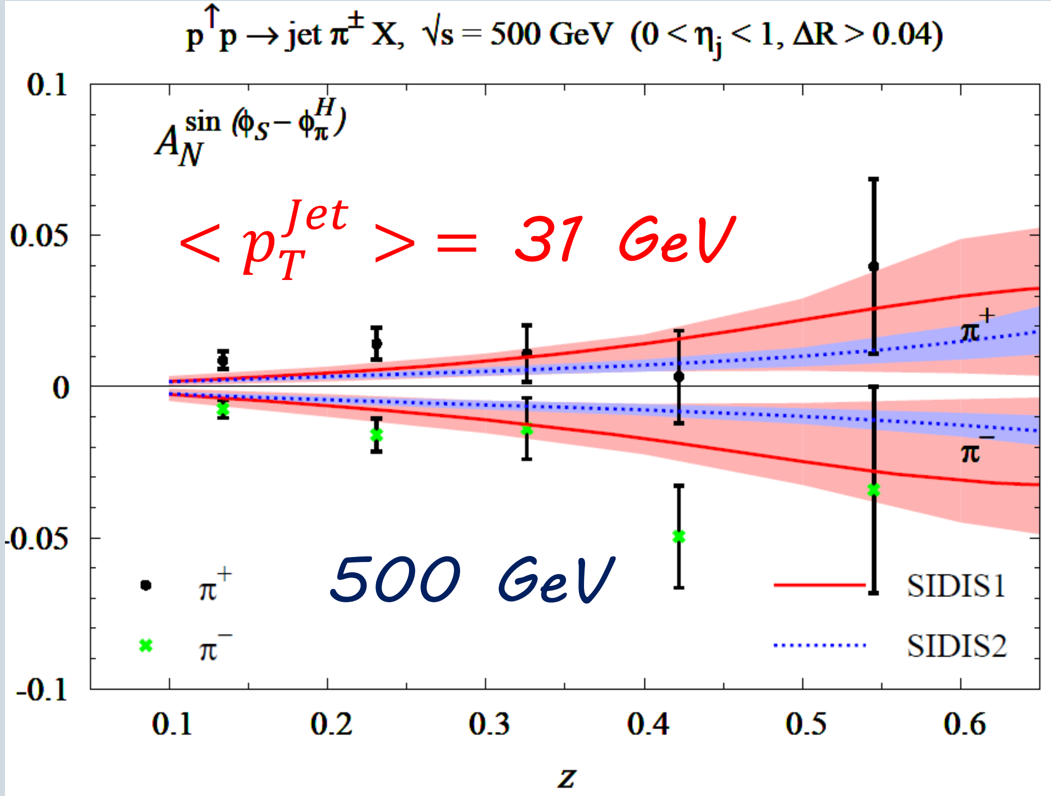


$$d\sigma(\phi_S,\phi_\pi^H) - d\sigma(\phi_S+\pi,\phi_\pi^H)$$
$$\sim d\Delta\sigma_0 \sin\phi_S + d\Delta\sigma_1^- \sin(\phi_S - \phi_\pi^H) + d\Delta\sigma_1^+ \sin(\phi_S + \phi_\pi^H)$$
$$+ d\Delta\sigma_2^- \sin(\phi_S - 2\phi_\pi^H) + d\Delta\sigma_2^+ \sin(\phi_S + 2\phi_\pi^H)$$

Sivers effect — Collins-like effect — Collins effect

UD, Murgia, Pisano (2011)





Predictions without TMD evolution

Data: PHENIX Collaboration (2015)

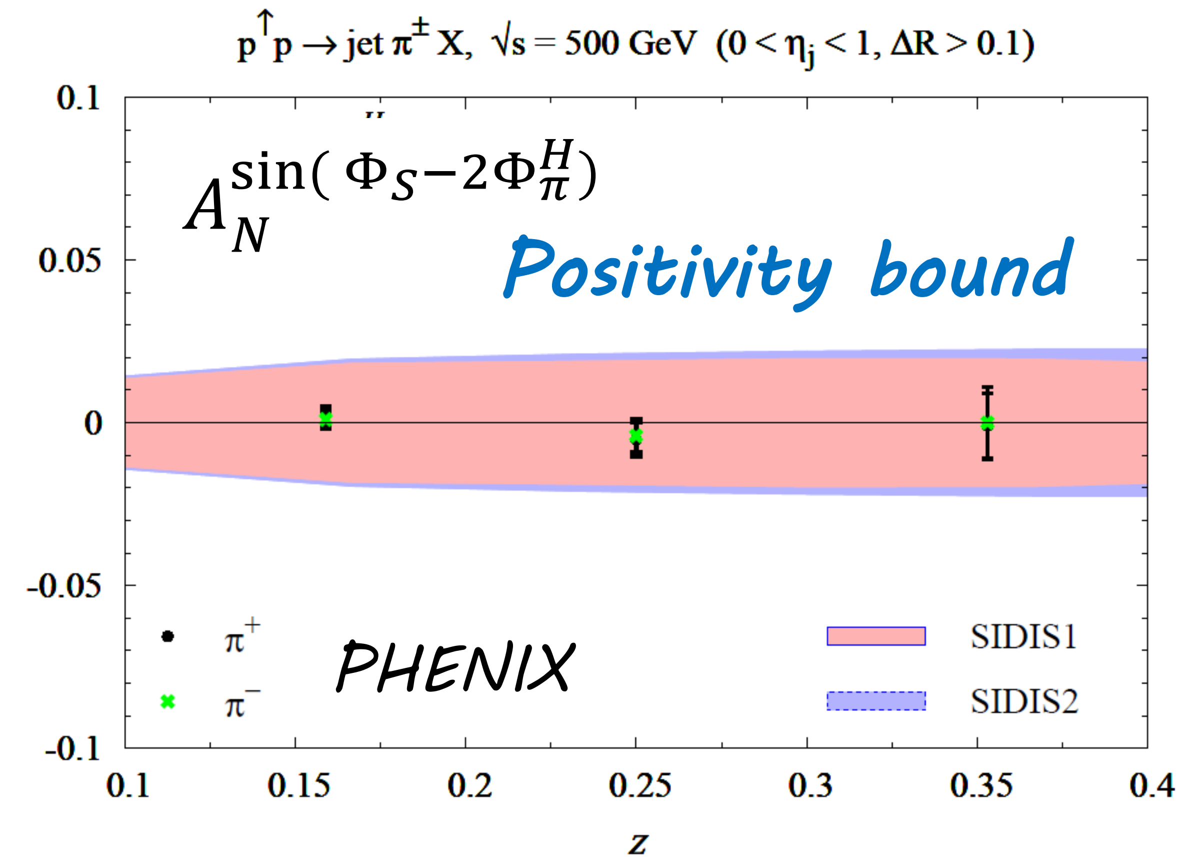
UD, Murgia, Pisano, in progress

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

Collins-like contribution

Defined modulation $\sin(\Phi_S - 2\Phi_\pi^H)$

helicity flip of the gluon



Towards a constraint of the product of TMDs for

linearly polarized gluons inside $p^\uparrow$

and

linearly pol. gluons fragm. into a π

Conclusions and open issues

THANK YOU!

- Tremendous progress of theory and phenomenology of TMDs
  factorization, evolution and universality
- Unpolarized cross sections:
  role of non perturbative inputs from low to high energies
  transv. momentum dependence in SIDIS and DY (consistency ???)
- Transverse single-spin asymmetries:
  NO compelling effects of TMD evolution from data
  NO evidence of factor. breaking in inclusive (one-large scale) processes
  Sign change of the Sivers funct. under study, Collins function universal
- More data expected: COMPASS, Jlab, RHIC, and eventually EIC

<u>In other words: more challenging and exciting work…</u>

BACK-UP SLIDES

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

"New" Collins approach

TMD framework

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

Collins approach (2011)

Theoretcal equivalent with SCET
but potentially different in phenomenology

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

Collinear PDF

pQCD

Non perturbative parts

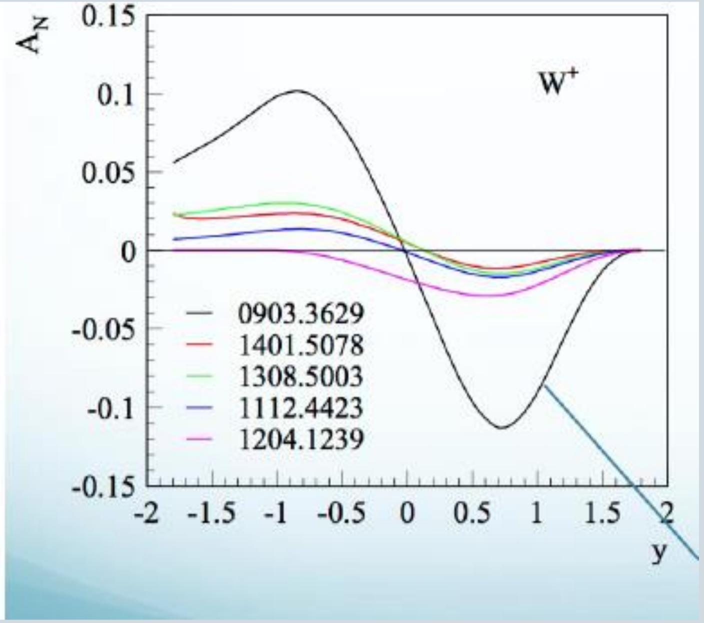
Role of NON perturbative input

Open issues in TMD phenomenology

TMD evolution and its releva

An example

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



w/o TMD evolution

Kang (2015)

Role of non perturbative input choices

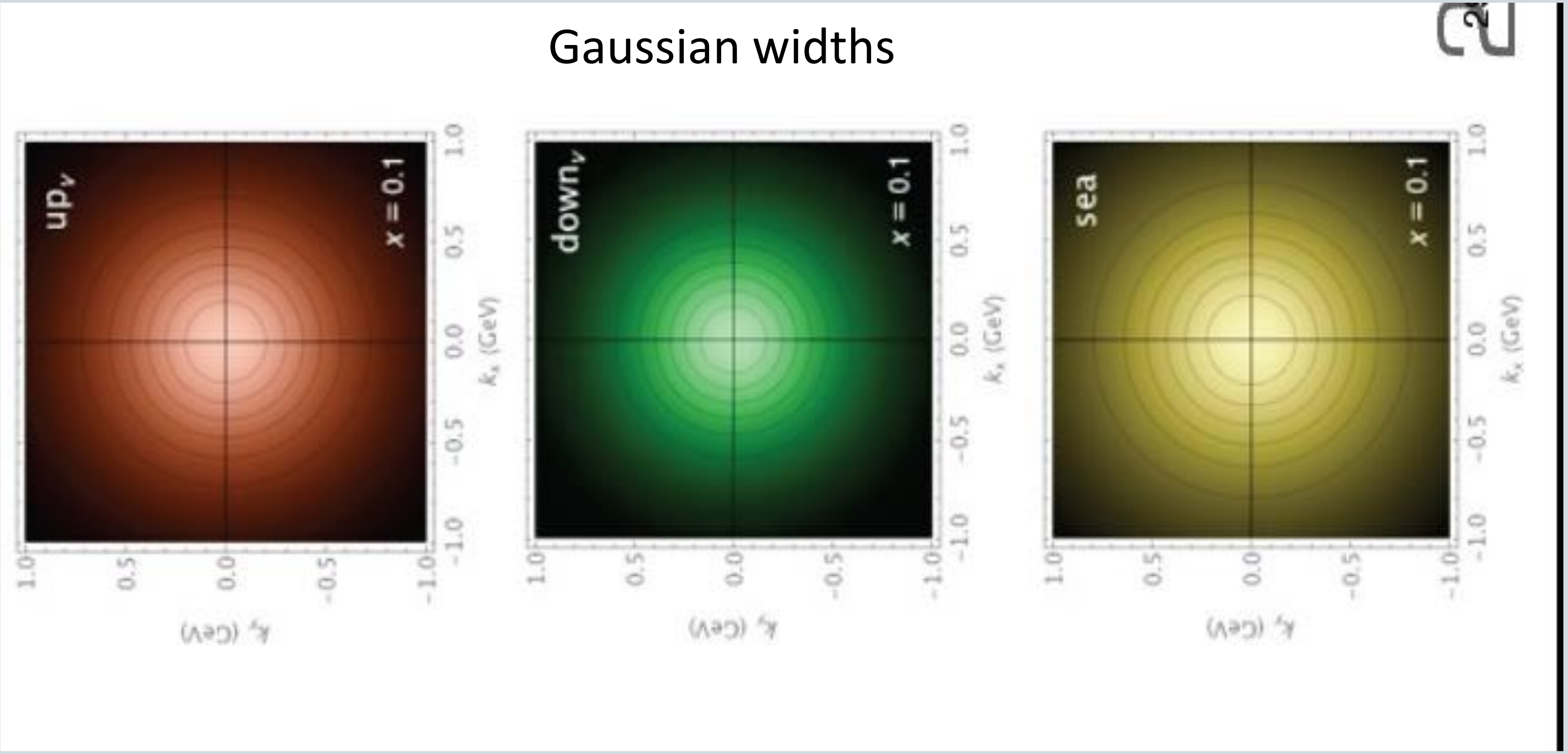
Transverse momentum dep. in SIDIS and its consistency with DY

TMD factor. 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

TMDs: flavour structure



Signori, Bacchetta, Radici, Schnell (2013)

up < down < sea ????

to be further explored

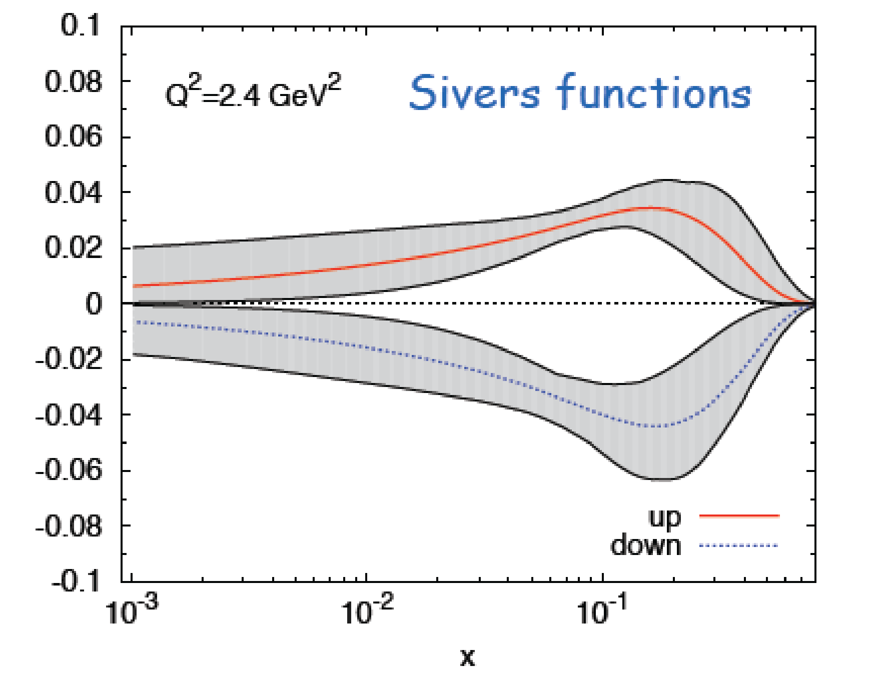
Where can we access TMDs?

SIDIS — hermes, COMPASS, Jefferson Lab, EIC

Drell-Yan — Fermilab, LHC, COMPASS

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

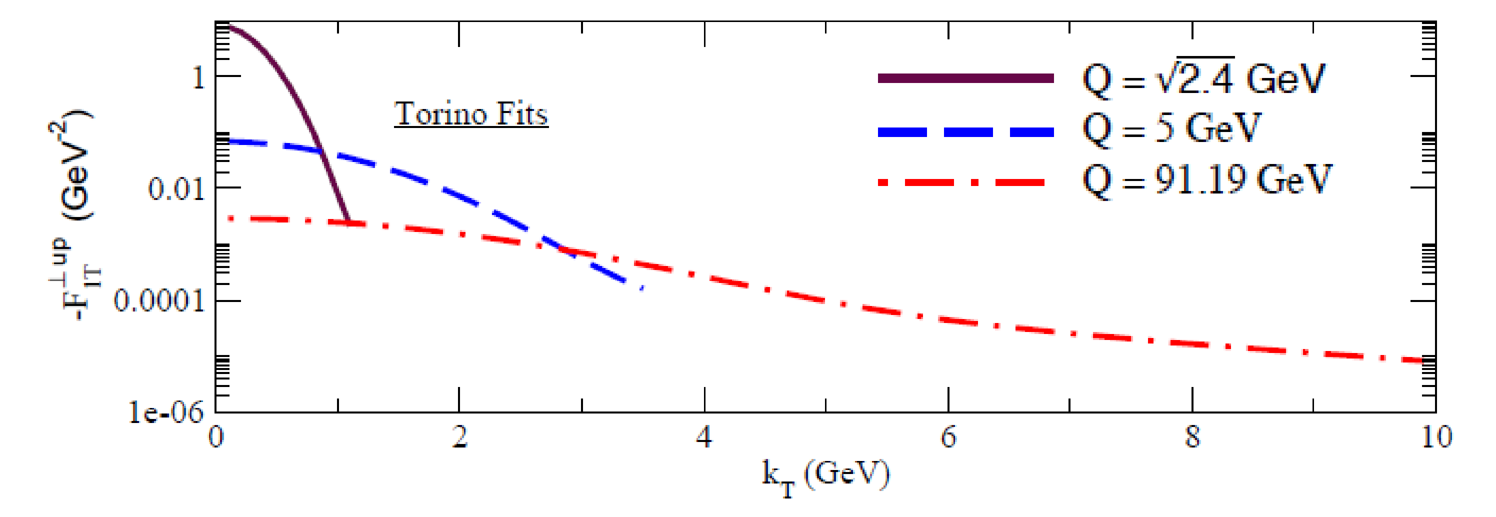
$pp \to \pi\, X\,,\ pp \to \pi\ jet\ X$ — BROOKHAVEN NATIONAL LABORATORY



Extracted Sivers functions
TO-CA and PV groups

large-x region: unconstrained [→JLab]

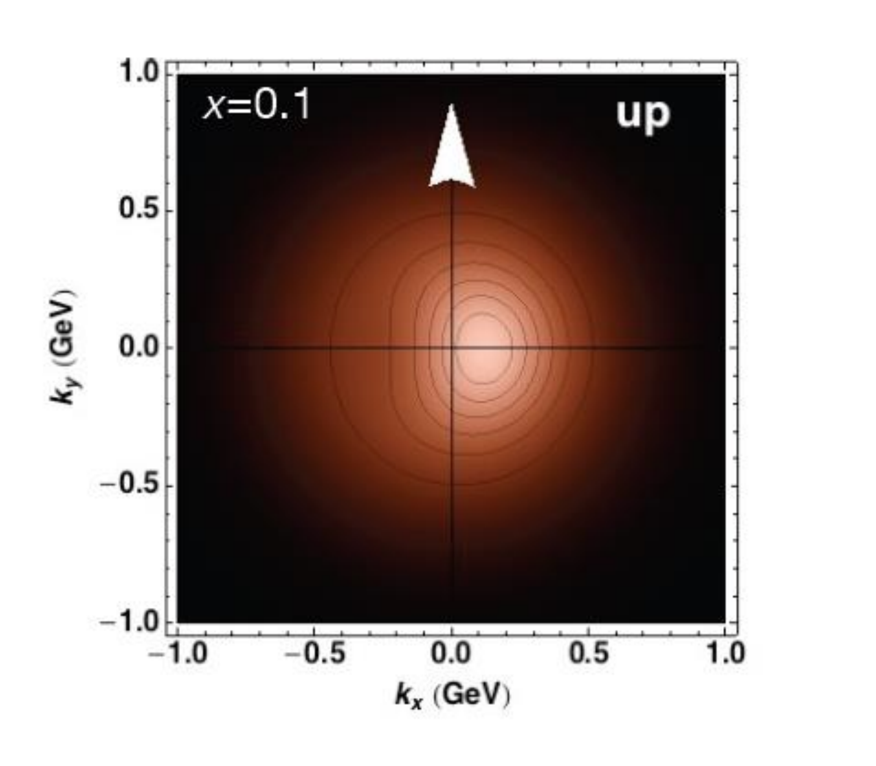
sea region: unconstrained [→EIC]

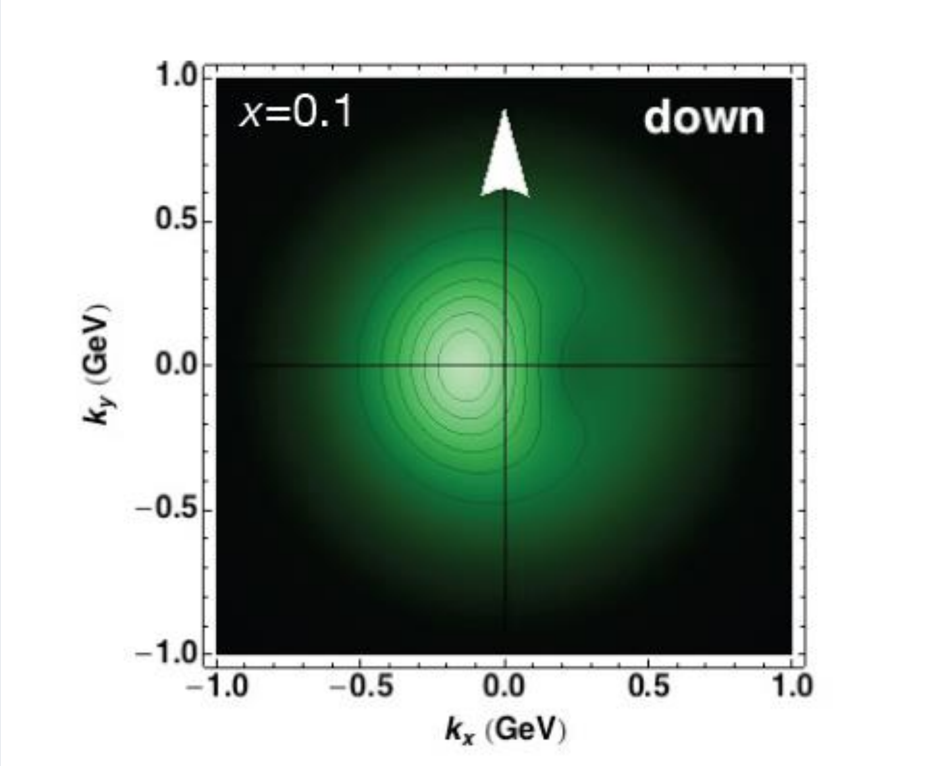


Effect of TMD evolution

Aybat, Collins, Qiu, Rogers (2012)

Distortion in the transverse plane

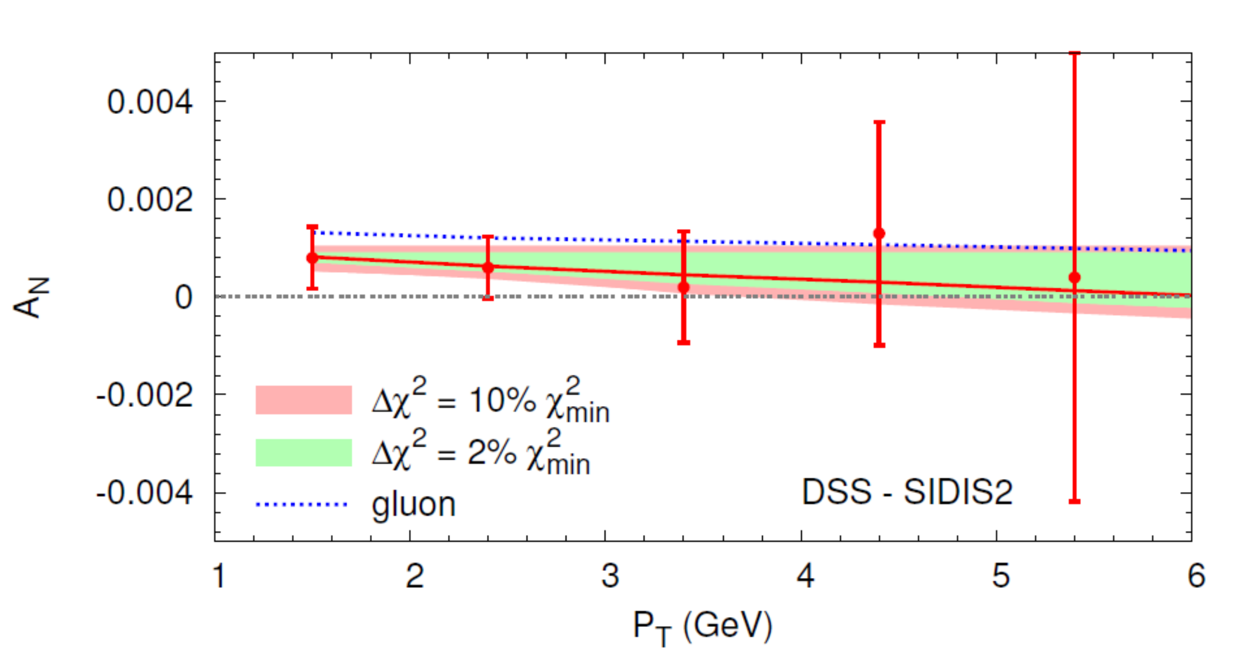




picture from A. Bacchetta, M. Contalbrigo,

Non zero Sivers effect related to parton orbital angular momentum

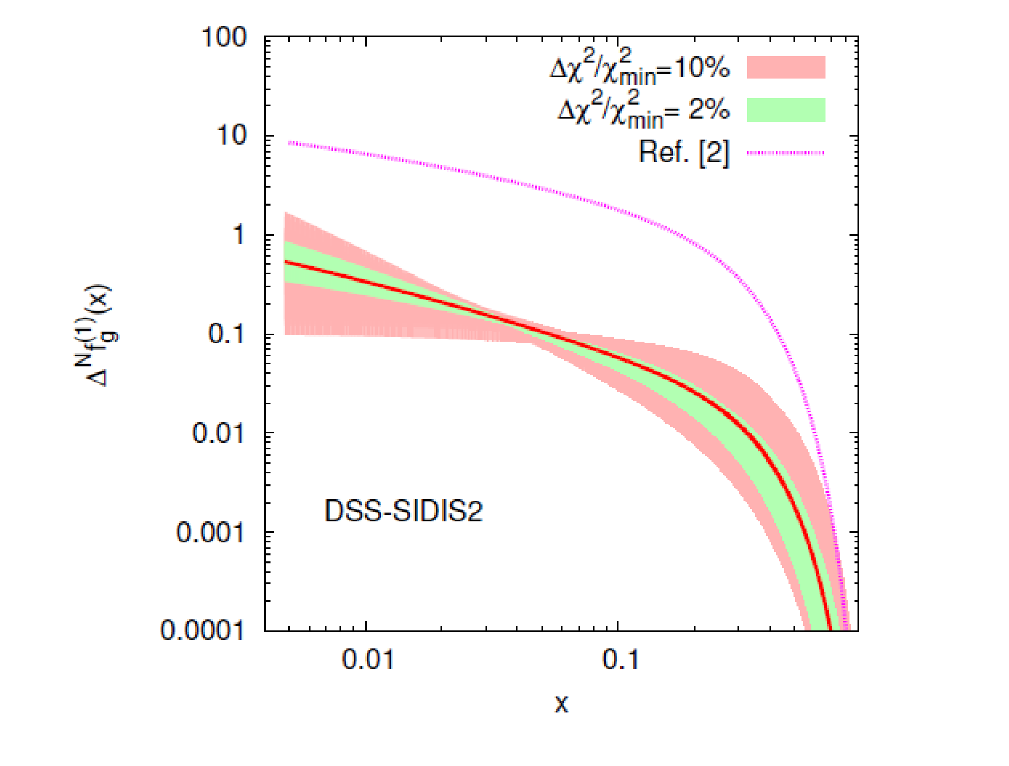
Access to the gluon Sivers function



PHENIX Coll data (2014)

All other effects are washed out

A_N at mid-rapidity



UD, Murgia, Pisano (2015)