NUCLEON STRUCTURE PHENOMENOLOGY

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- MOTIVATIONS
- 3D NUCLEON STRUCTURE
- HARD SEMI-INCLUSIVE/EXCLUSIVE (POLARIZED) PROCESSES
- OPEN ISSUES

Motivations (general statements)

- Nucleon: the most abundant piece of matter in the visible Universe... still a mysterious object (charge radius, spin content…??)

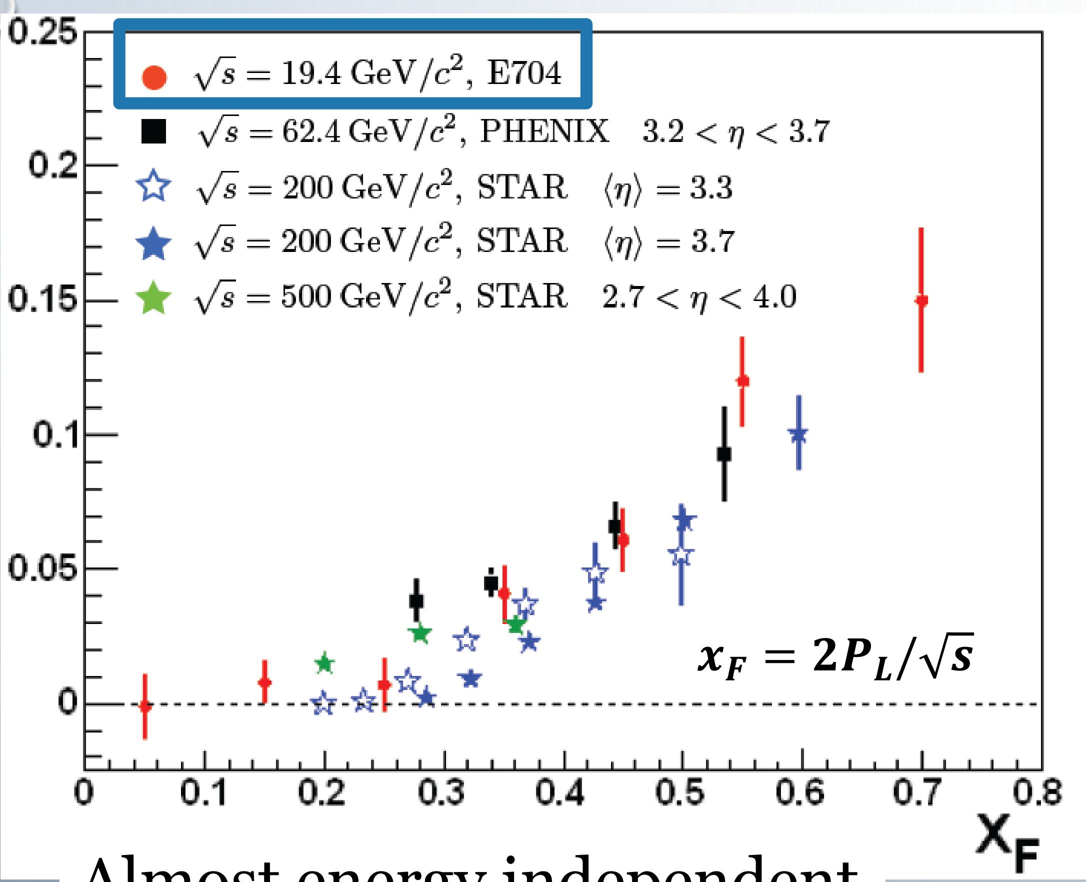
- QCD and confinement: still to be understood

- Semi-inclusive/exclusive processes w/wo spin:
  tools to study the inner structure of a composite system

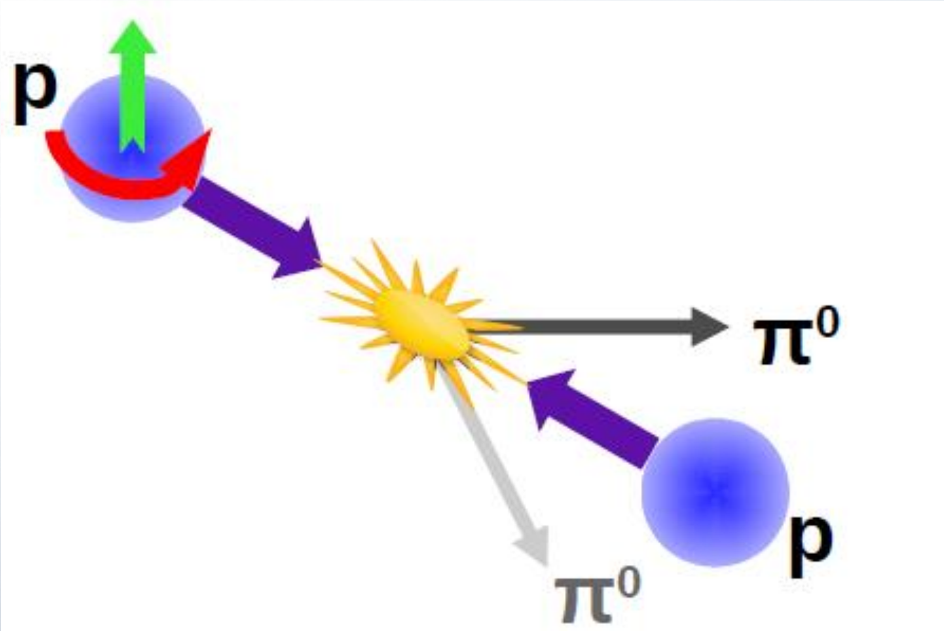
such as a nucleon

Transverse Spin effects

A_N in $p^{\uparrow}p \to \pi X$... "the origin"...a long-standing puzzle



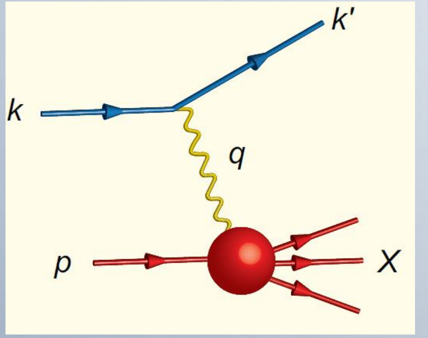
Almost energy independent



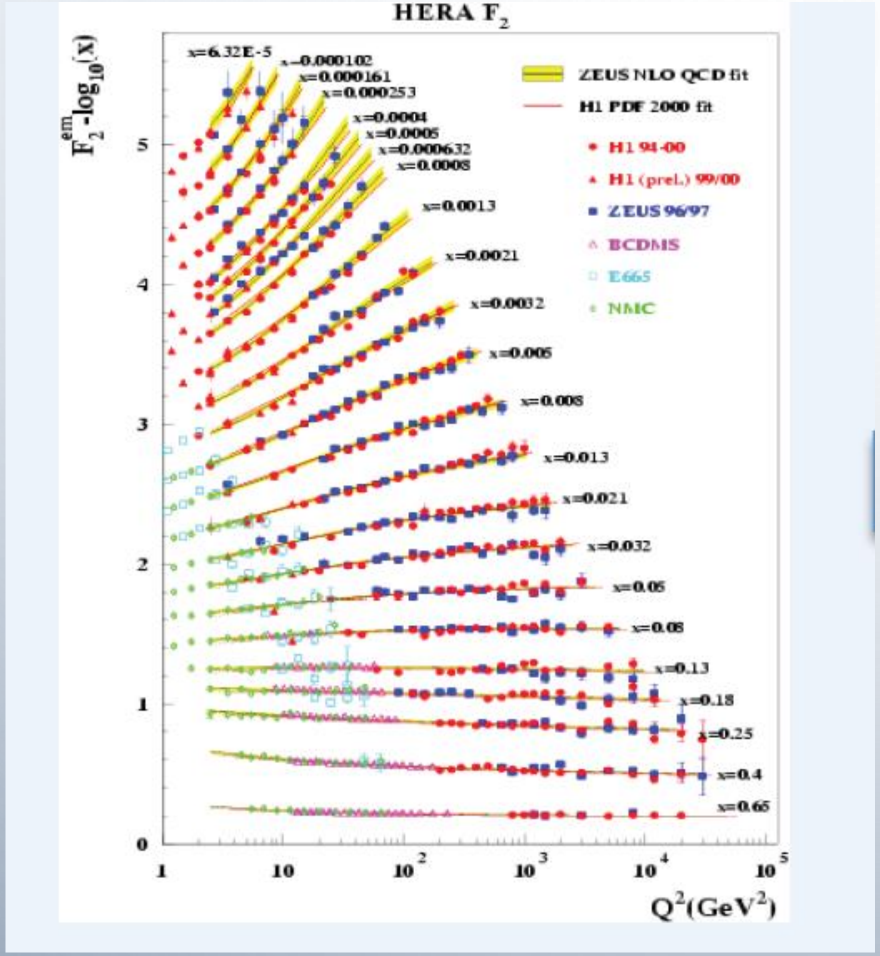
Collinear twist-2 QCD:
$A_N \leq$ few %

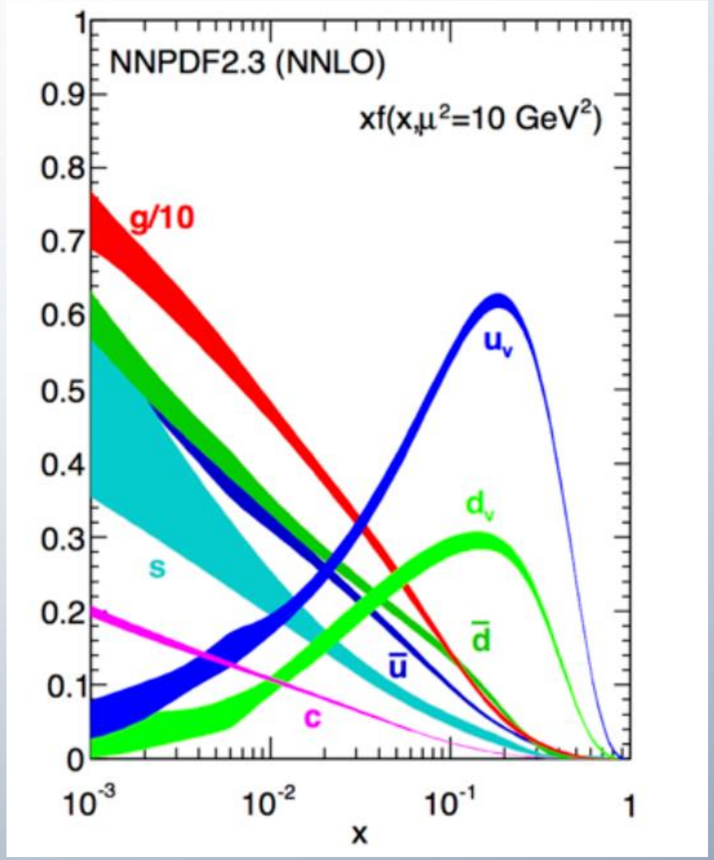
1-D picture of the nucleon

inclusive DIS



DIS Structure Functions





Collinear PDFs

(open) Physics issues

Parton orbital motion and its correlation to the nucleon spin
Parton intrinsic transverse momentum
Spatial distribution of partons and the nucleon shape

3D structure

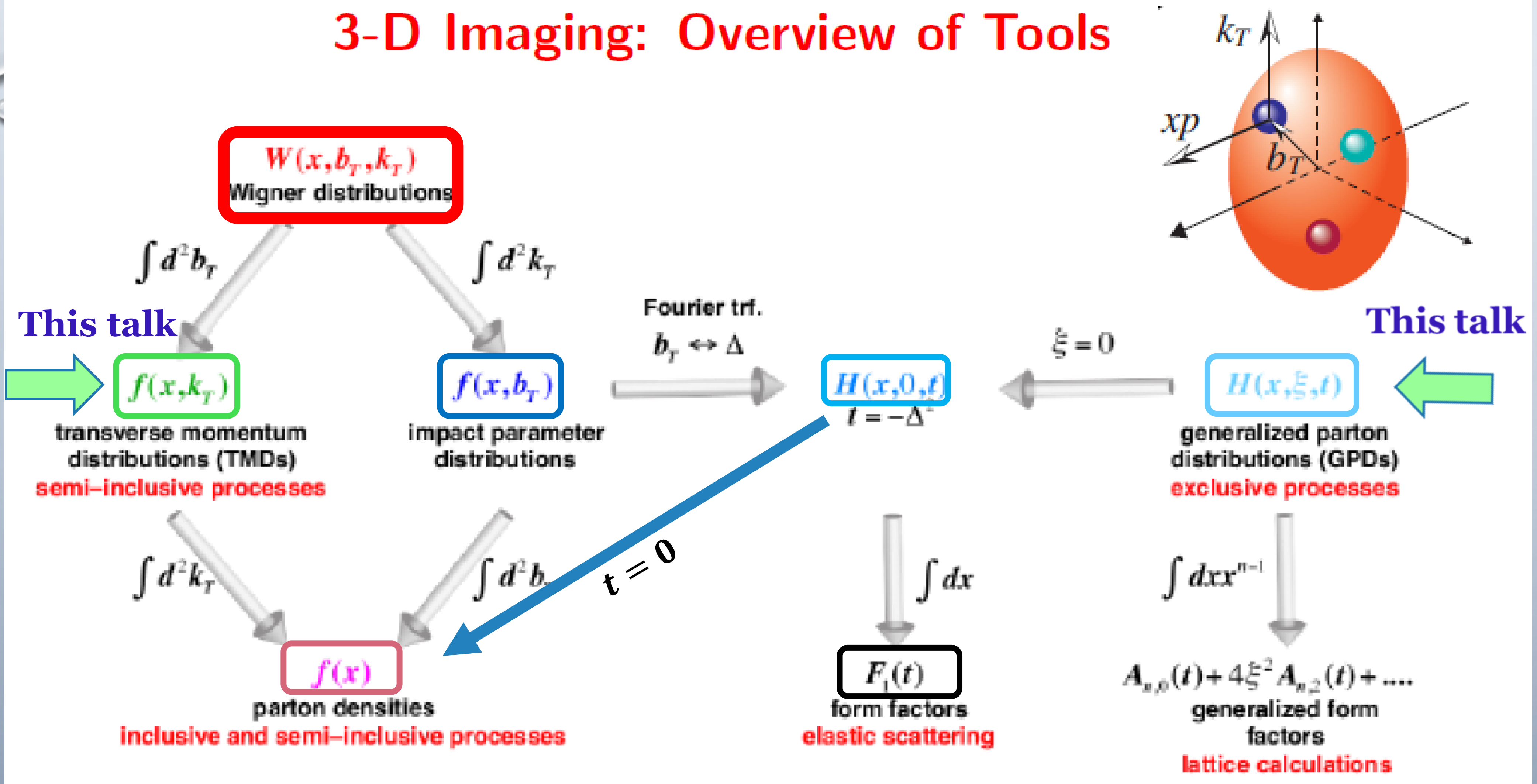
Non perturbative effects in high-energy processes
Origin of transverse/azimuthal spin asymmetries

Observables

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

QCD at work

3-D Imaging: Overview of Tools



(from arXiv:1212.1701)

Proton spin puzzle

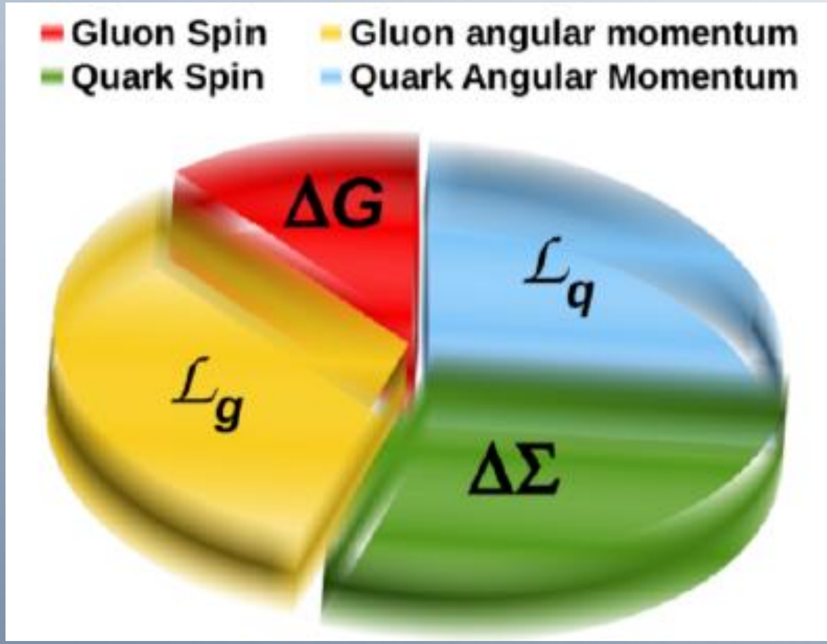
Proton Spin

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

(Anti)quark Contribution: 0.15-0.20

Gluon Contribution: 0.2 in x>0.05

Parton Orbital Momentum: ???

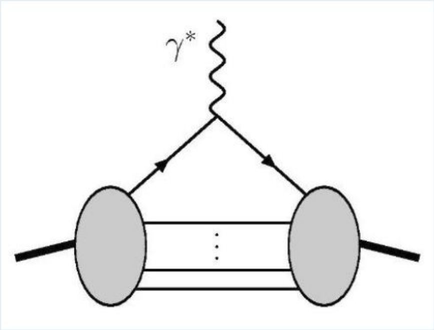


Role of TMDs and GPDs

Non trivial decomposition [Leader, Lorcé (2014)]

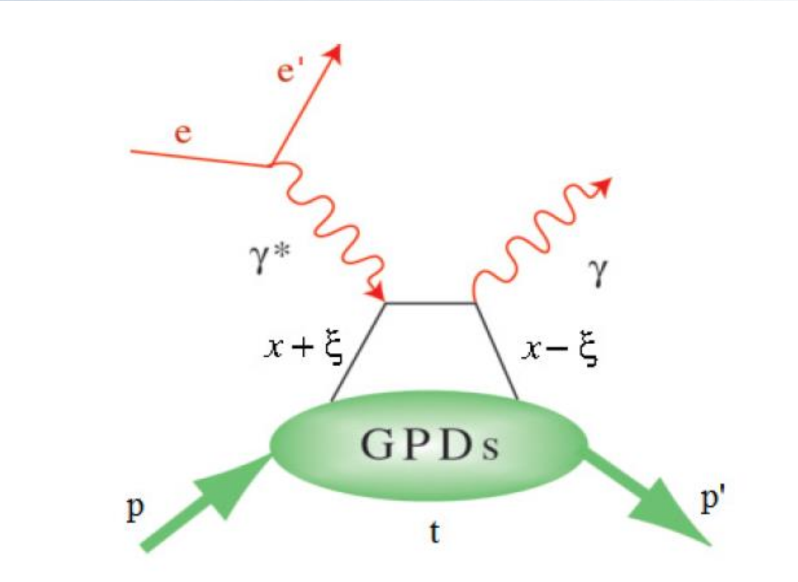
GPDs

Elastic scattering



Form Factors:
Information on position
not on quark momentum

Virtual Compton scattering



unpolarized quark
and nucleon

unpolarized quark and
transversely polarized
nucleon

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

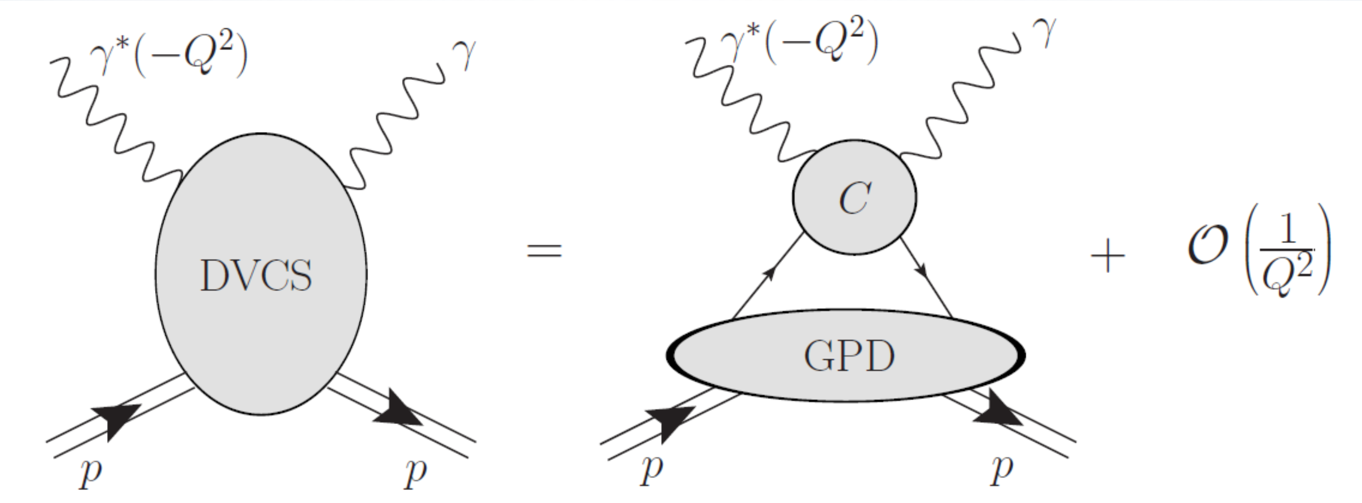
$$\int_{-1}^{1} dx \tilde{H}(x,\xi,t) = G_A(t); \int_{-1}^{1} dx \tilde{E}(x,\xi,t) = G_P(t)$$

GPDs: Information on position
and quark momentum fraction

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.

DVCS Factorization

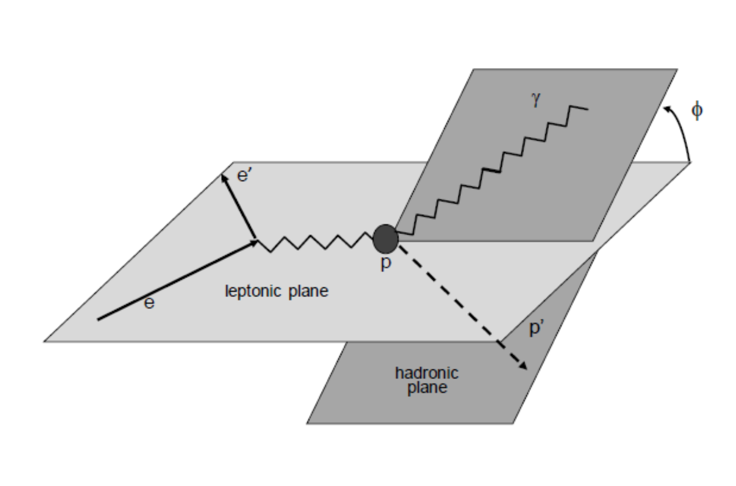
Collins et al. (1998)



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

Physics issues in GPDs

- **DVCS: golden channel**. HERMES, COMPASS, JLab, H1, ZEUS → Silvia Niccolai

- DVMP (virtual meson production): uncertainty on meson distribution amplit.

- Extraction of GPDs: model-dependent (4 GPDs in DVCS & integrated over x → CFFs)

- 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 (1997)

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

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

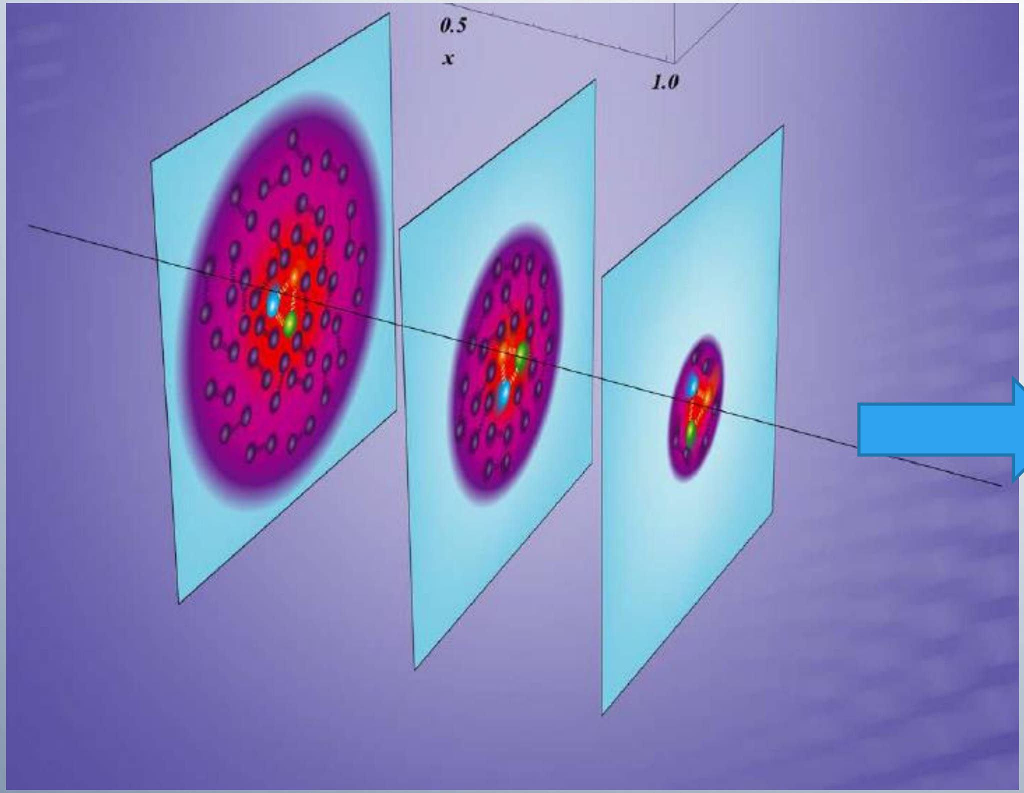
H, E non-flip GPDs

Proton tomography from JLab data

Dupré et al (2017)

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

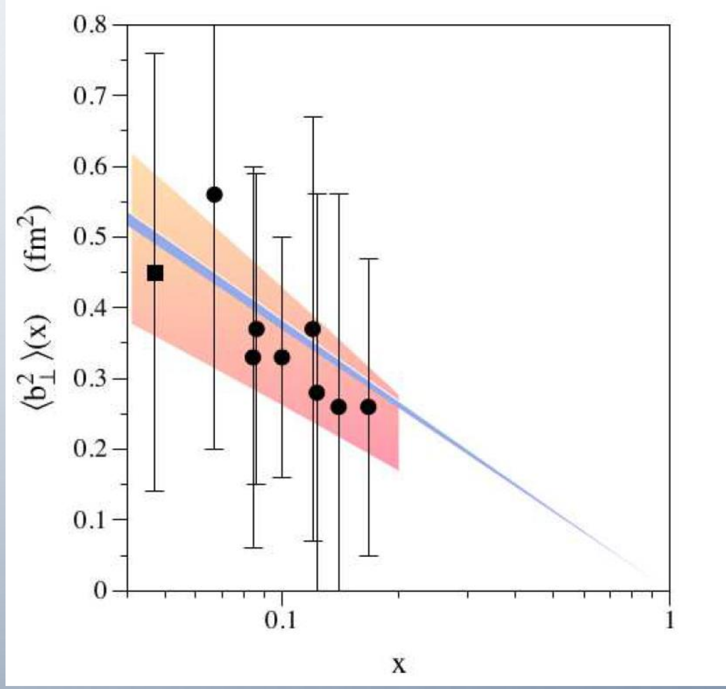
Distribution in the transversal space



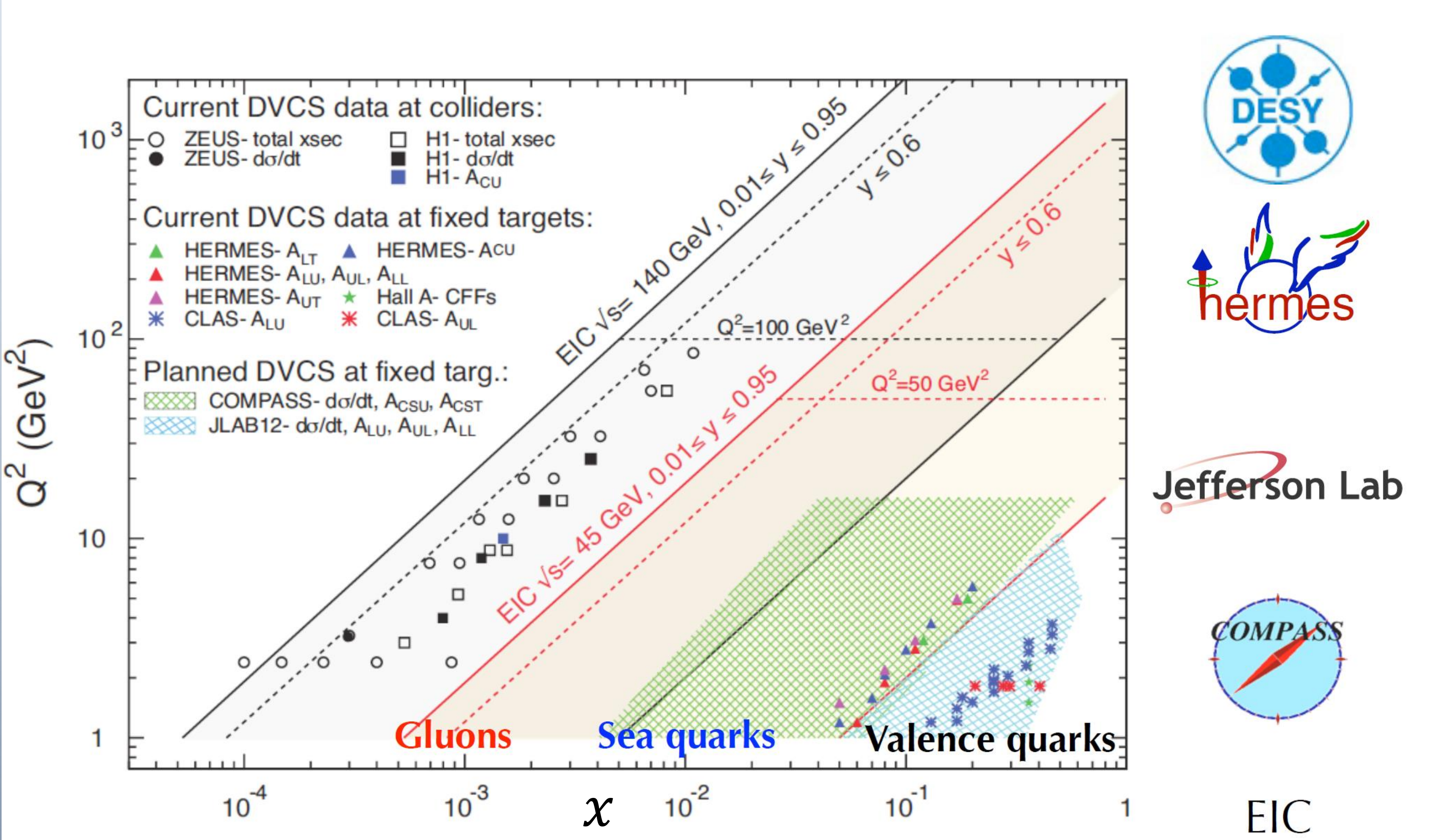
Silvia Niccolai

$$\langle b_\perp^2\rangle^q(x) = \frac{\int d^2\mathbf{b}_\perp \mathbf{b}_\perp^2 \rho^q(x,\mathbf{b}_\perp)}{\int d^2\mathbf{b}_\perp \rho^q(x,\mathbf{b}_\perp)}.$$

Mean squared radius in the T space

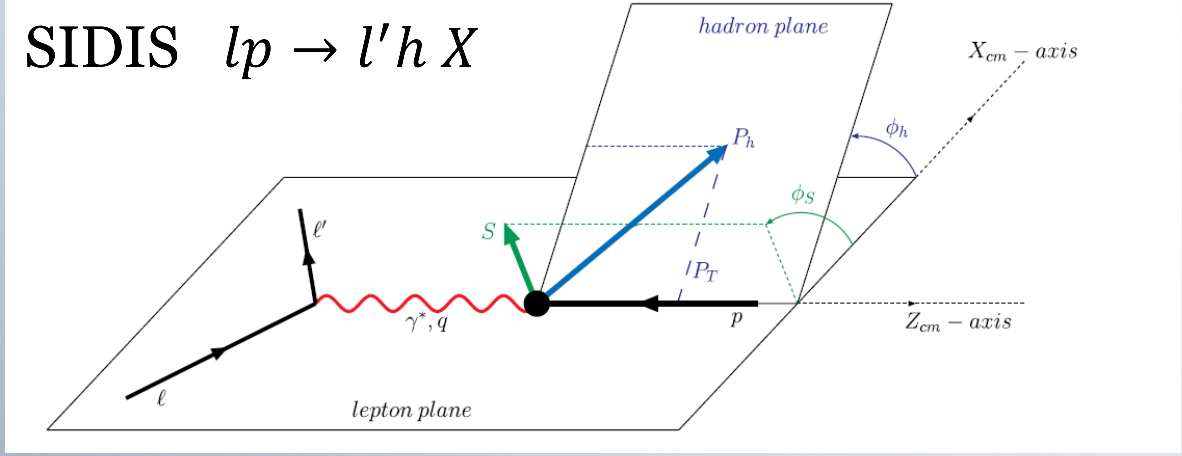


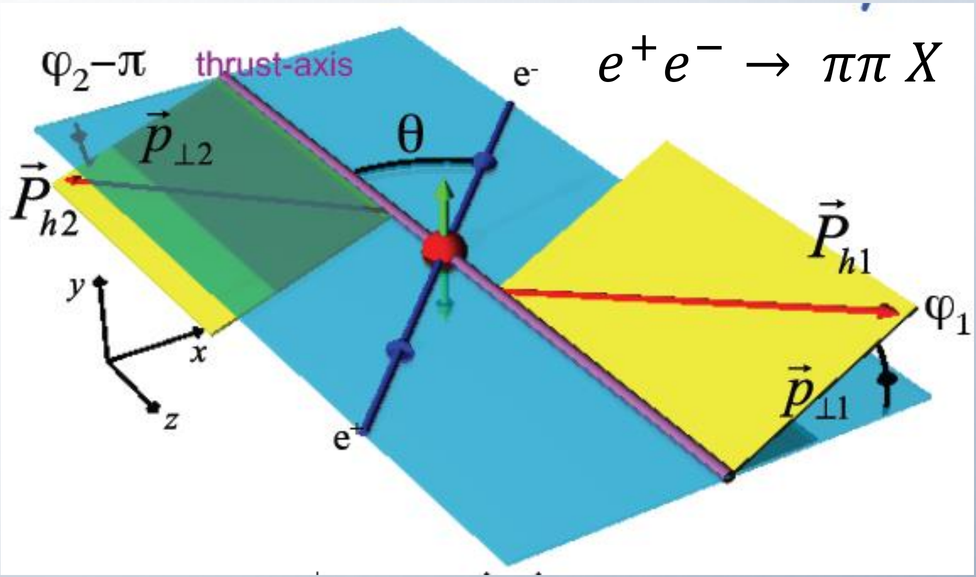
GPD measurements

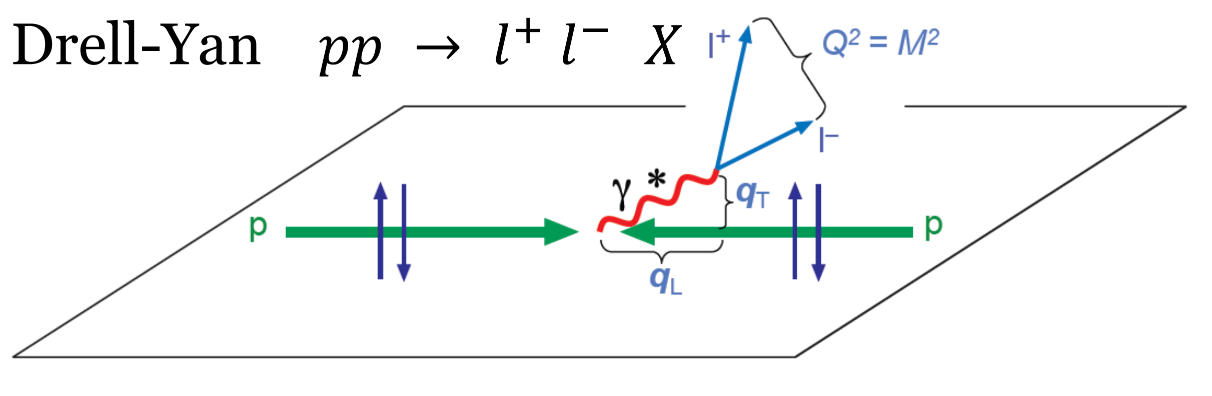


Direct access to TMDs:

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



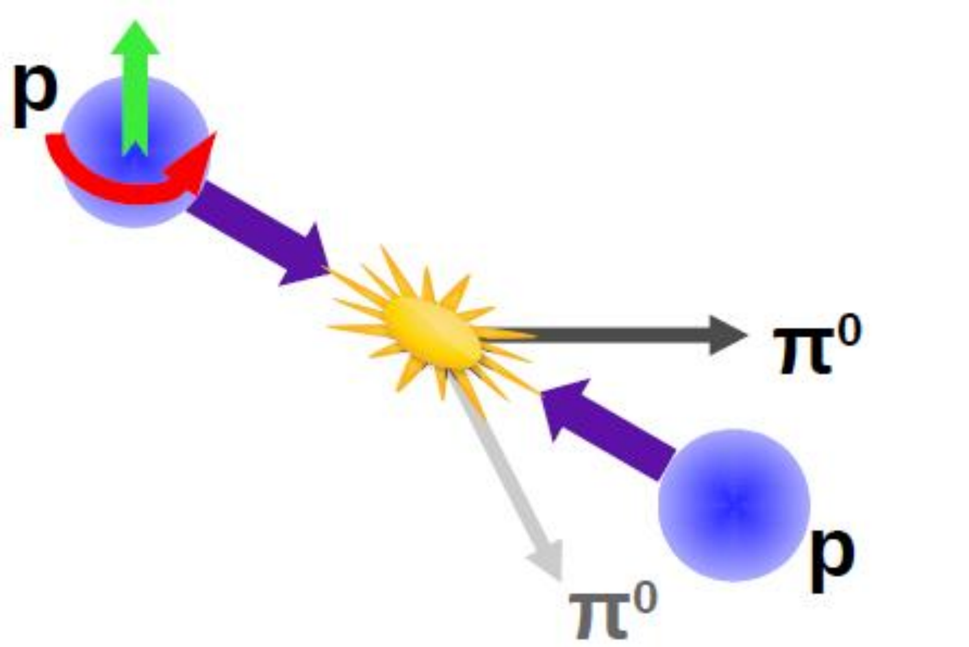




TMD factorization proven

And possibly in processes like

Single-scale processes: large P_T



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

$$pp \to J/\psi X$$
$$pp \to D X$$

Access to Gluon TMD

$pp \to \pi \; jet \; X$ **Two-scale process**

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

$pp \to h\,X\,,\; pp \to \;\pi\; jet\; X$ BROOKHAVEN NATIONAL LABORATORY AFTER@LHC

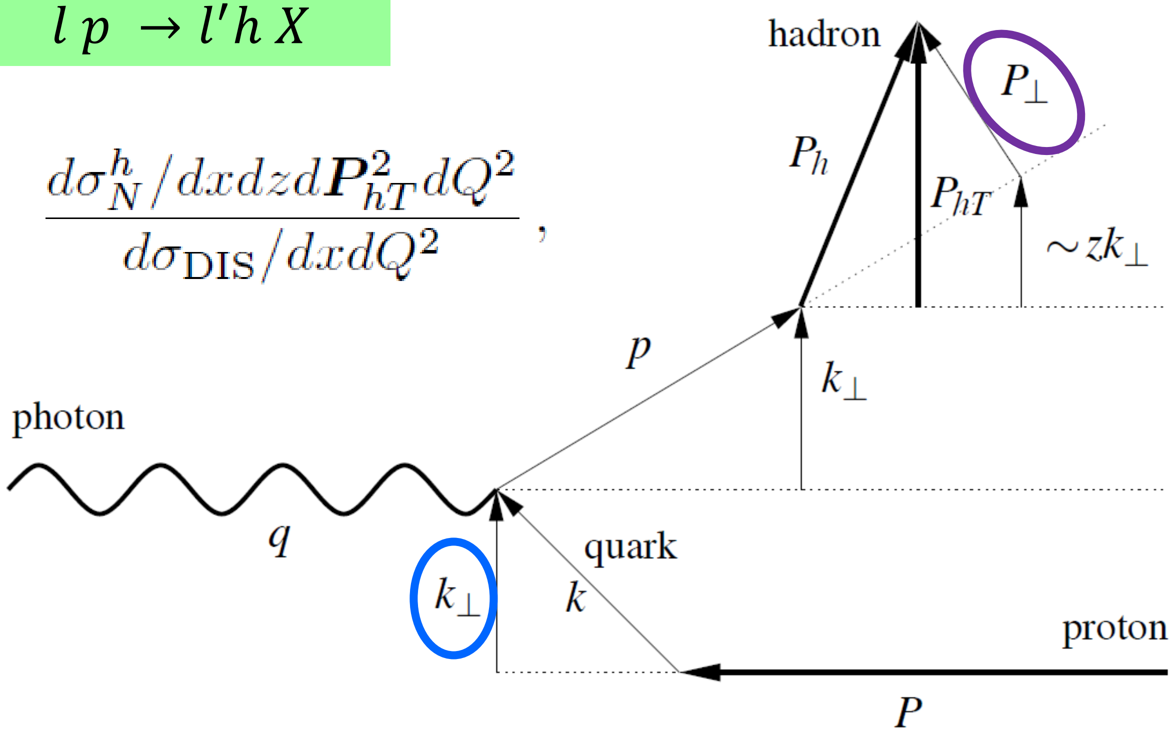
TMDs and unpolarized cross sections

SIDIS multiplicities

Current fragmentation region: large z…to be reconsidered

$l\,p \rightarrow l'\,h\,X$

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



Factorized Gaussian forms

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

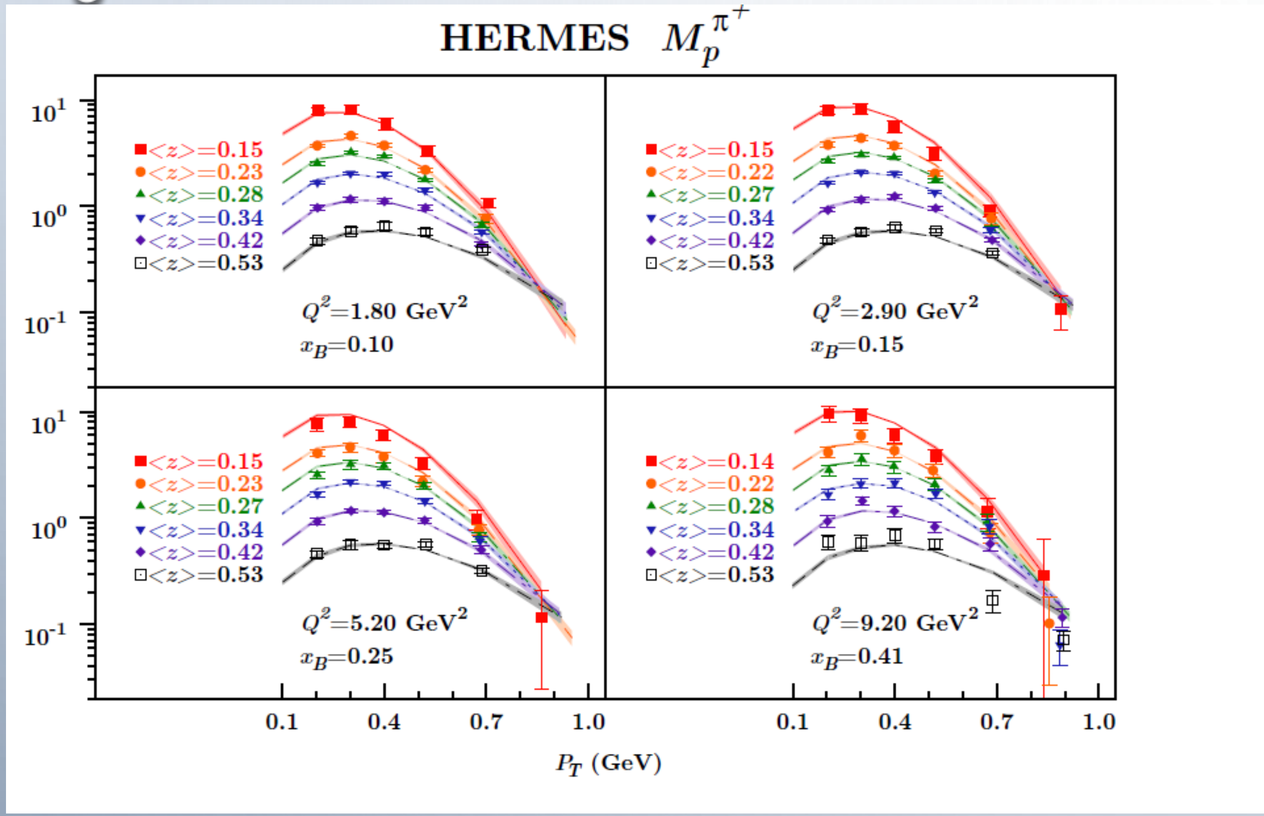
$$D_{h/q}(z,p_\perp) = D_{h/q}(z)\,\frac{e^{-p_\perp^2/\langle p_\perp^2\rangle}}{\pi\langle p_\perp^2\rangle}\,.$$

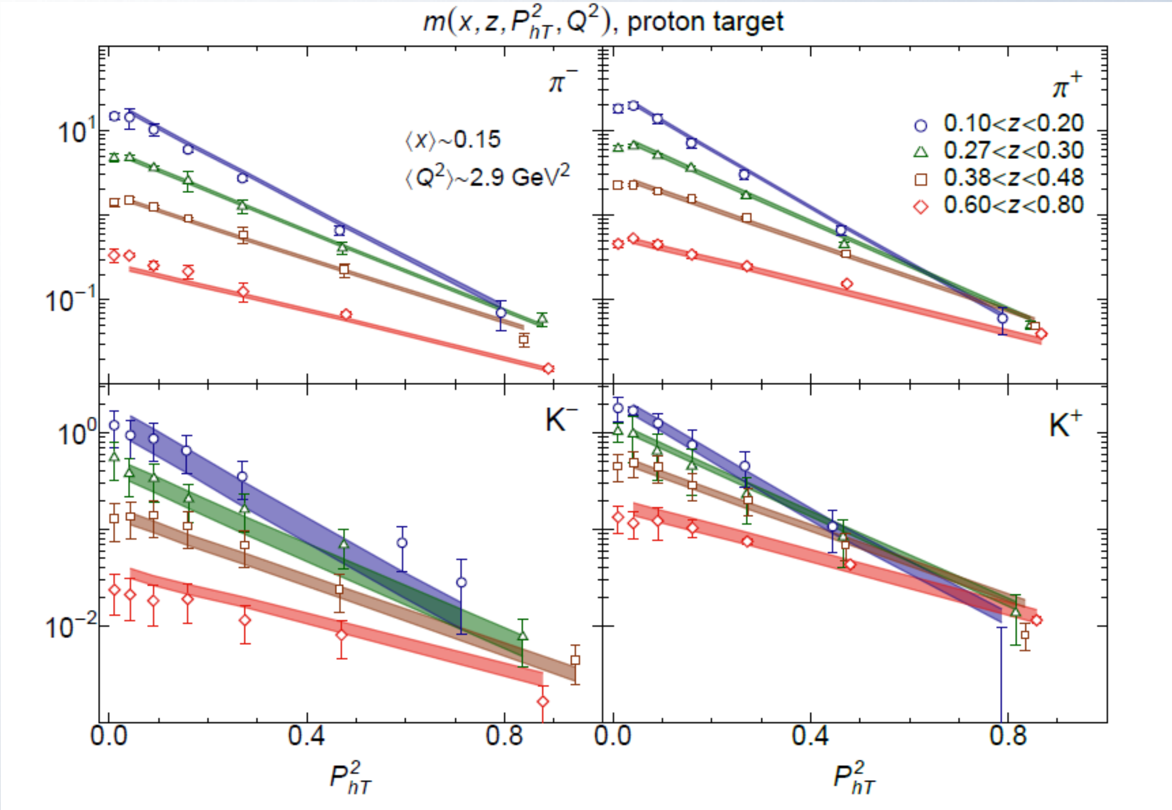
TMD-PDFs — hard scattering — TMD-FFs

$$d\sigma^{\ell p\to\ell hX} = \sum_q f_q(x,\boldsymbol{k}_\perp;Q^2)\otimes d\hat\sigma^{\ell q\to\ell q}(y,\boldsymbol{k}_\perp;Q^2)\otimes D_q^h(z,\boldsymbol{p}_\perp;Q^2)$$

$< k_\perp^2 > = 0.57\text{-}0.38\ GeV^2$

$< p_\perp^2 > = 0.12\text{-}0.18\ GeV^2$



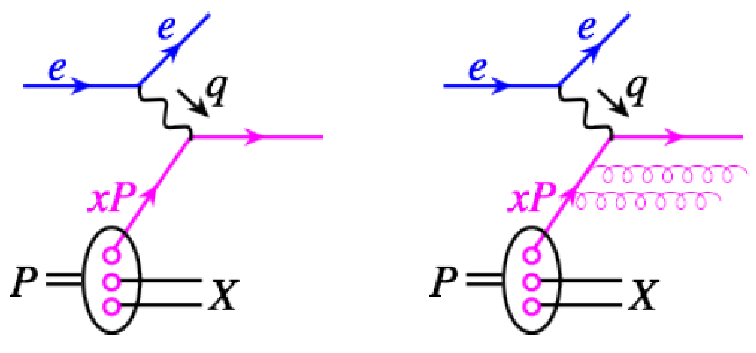


Anselmino, et al. (2014)

Signori, Bacchetta, Radici, Schnell (2013)

Theory: factorization and evolution

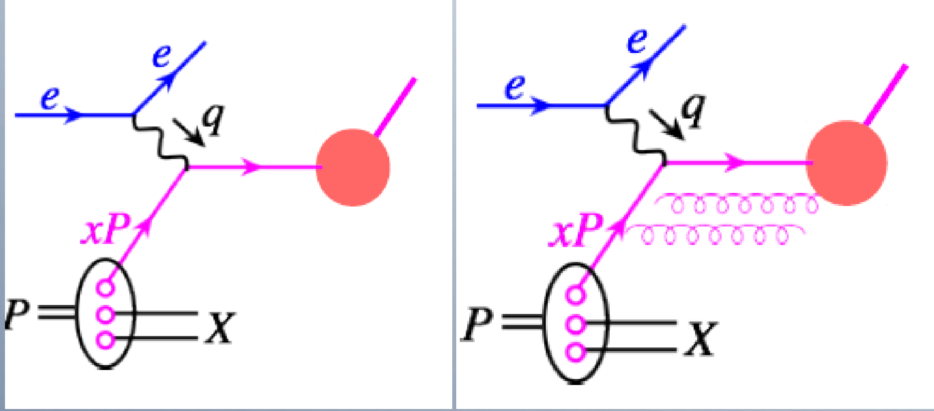
Collinear approach



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

Evolution $\rightarrow$ DGLAP eqs.

TMD approach…more involved



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

$$Q_T \ll Q$$

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)

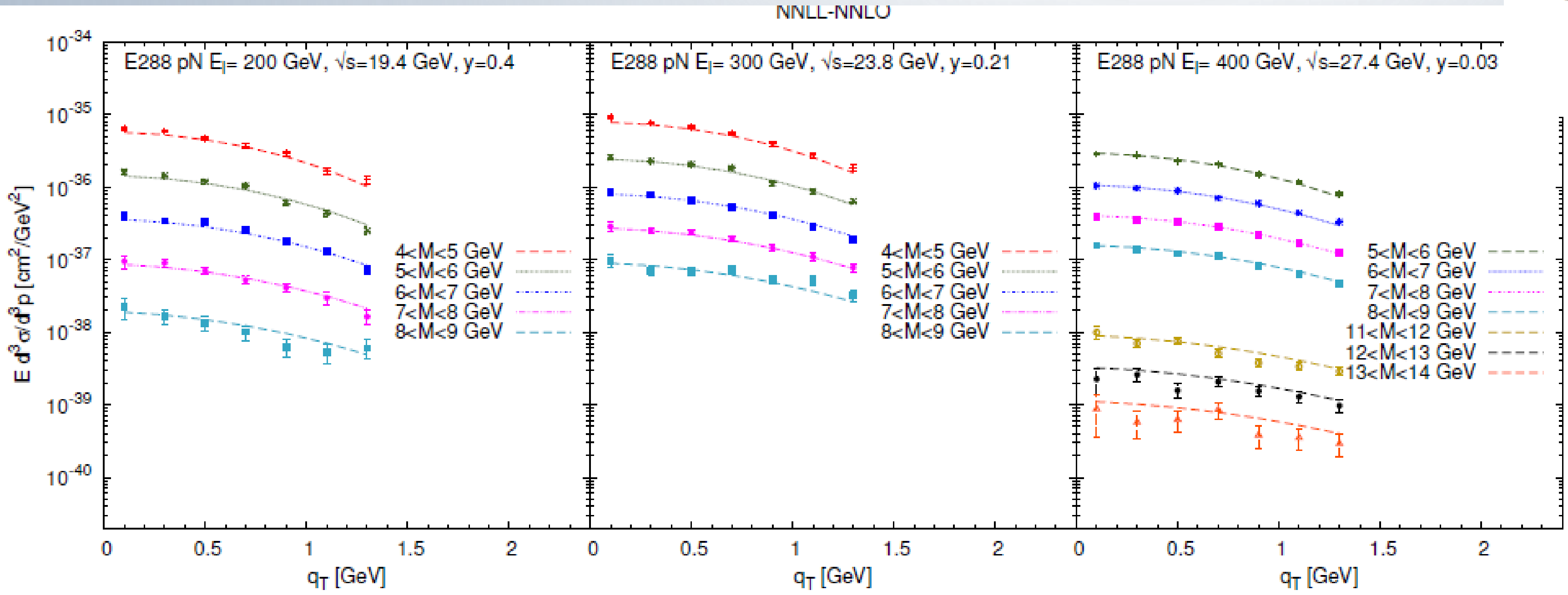
Echevarria-Idilbi-Schafer-Scimemi 2012
D'Alesio-Echevarria-Melis-Scimemi 2014
Echevarria-Scimemi-Vladimirov 2016

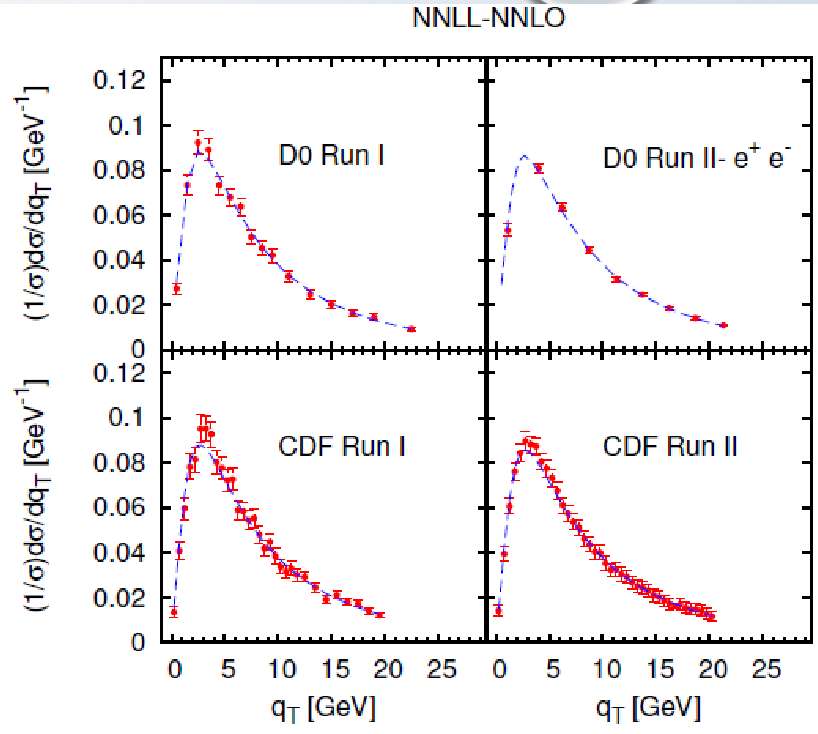
Tremendous progress

An example: Fit to Drell-Yan and Z^0 production data

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

Low energy





Tevatron

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

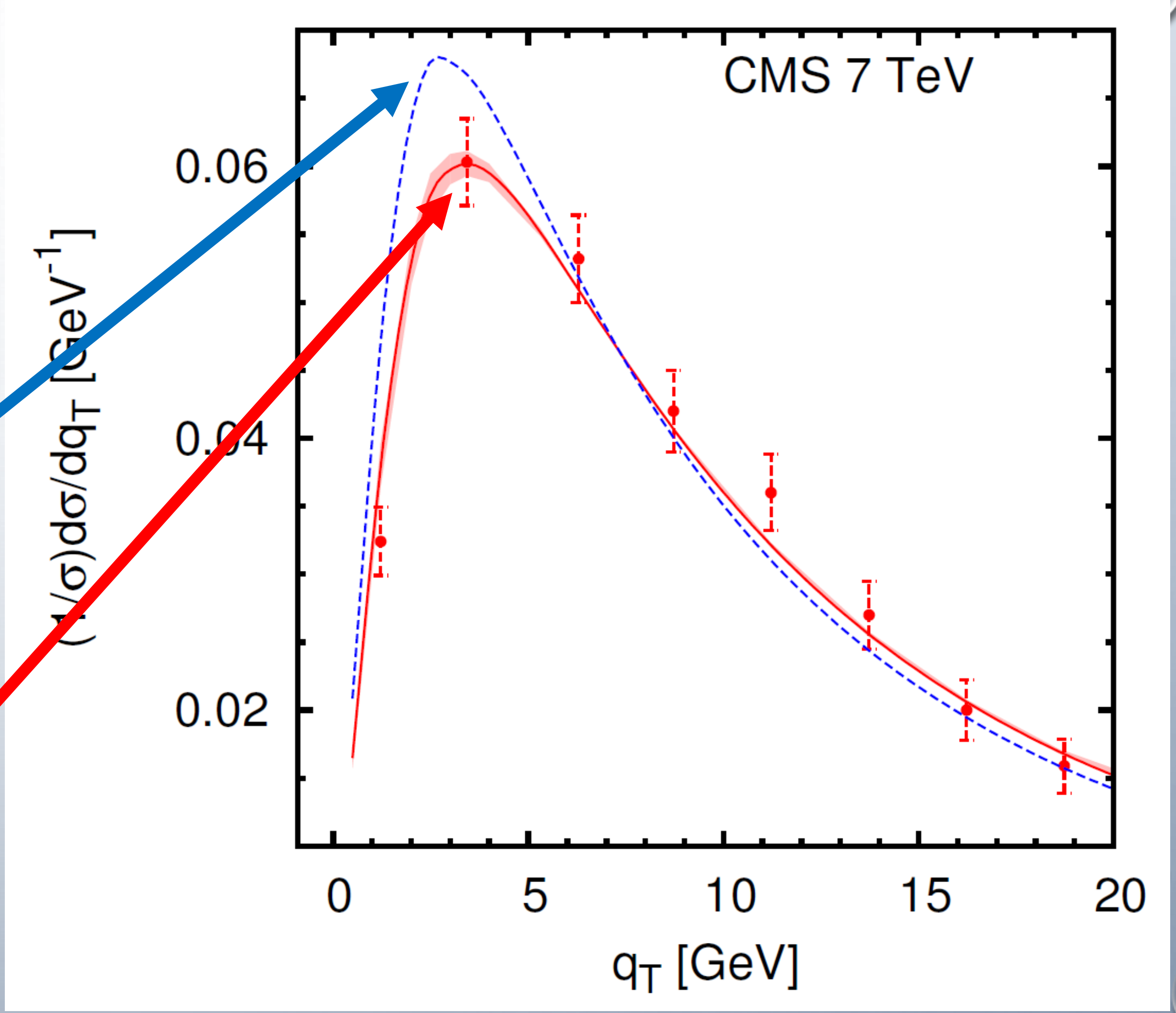
TMDs at LHC

Predictions from NNLL fit

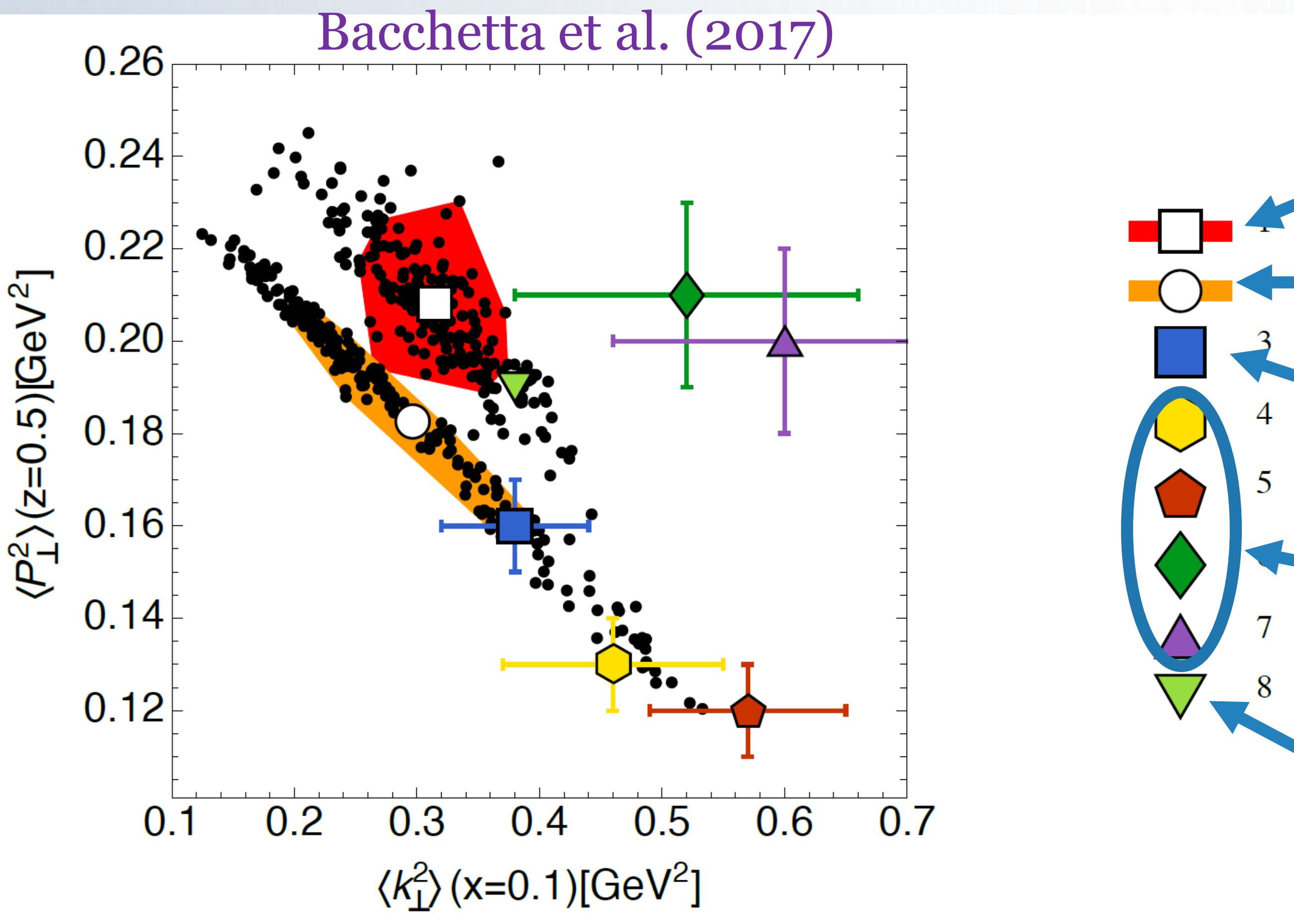
$$pp \to Z\ X$$

Pure resummed pQCD

Inclusion of the non Perturbative piece (k_T)



Gaussian width correlations



Fit of DY, Z and SIDIS + TMD evol.
Bacchetta et al (2017)

Fit of SIDIS - NO TMD evol.
Signori et al (2013)

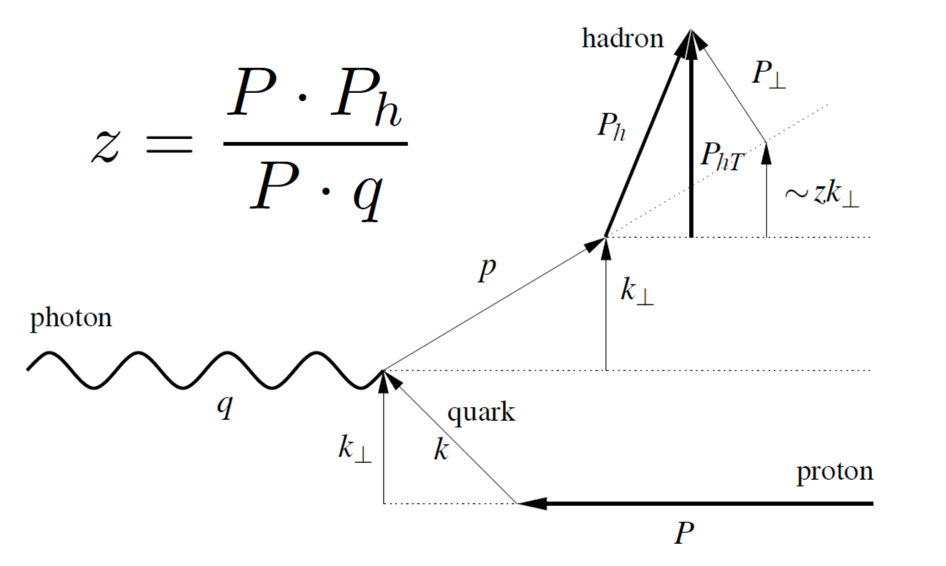
Fit of SIDIS - NO TMD evol.
Schweitzer et al (2010)

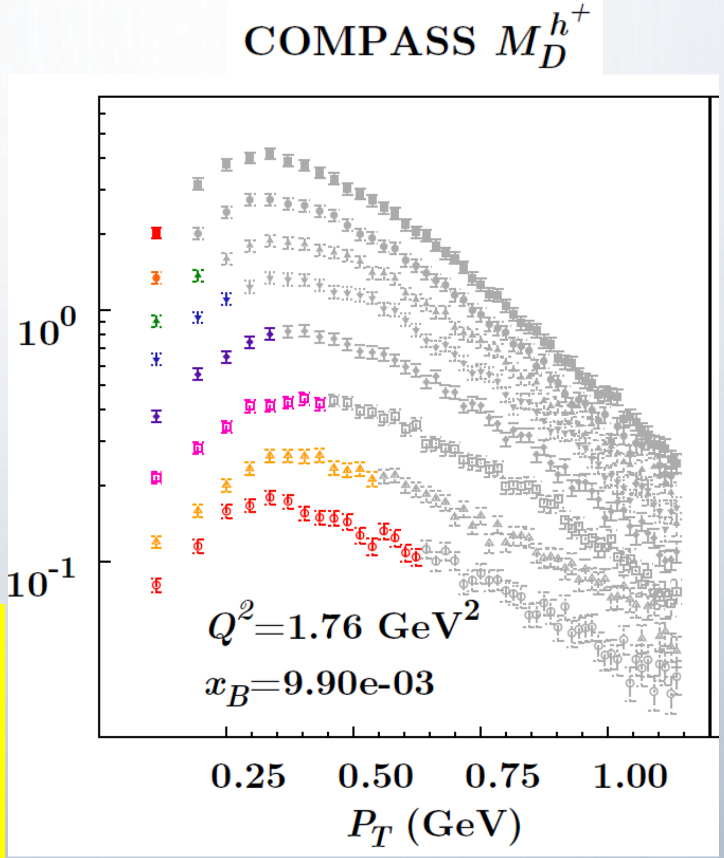
Fit of SIDIS - NO TMD evol.
Anselmino et al (2014)

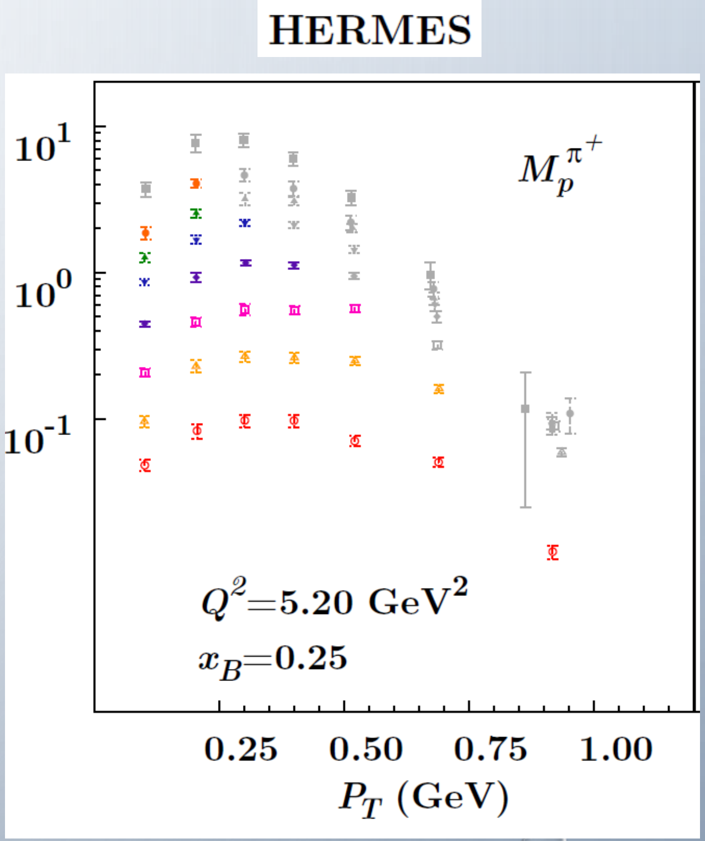
Fit of SIDIS, DY, Z + TMD evol.
Echevarria et al (2014)

$$\boldsymbol{P}_{hT} \approx z\boldsymbol{k}_\perp + \boldsymbol{P}_\perp$$

Current fragmentation region in SIDIS







Recent study by Boglione et al (2017)

- Large z is not enough
- Relevance of the hadron rapidity
- CFR: even small z if P_T is small
- NO CFR if large z and large P_T
- NO CFR if $P_T \approx Q$

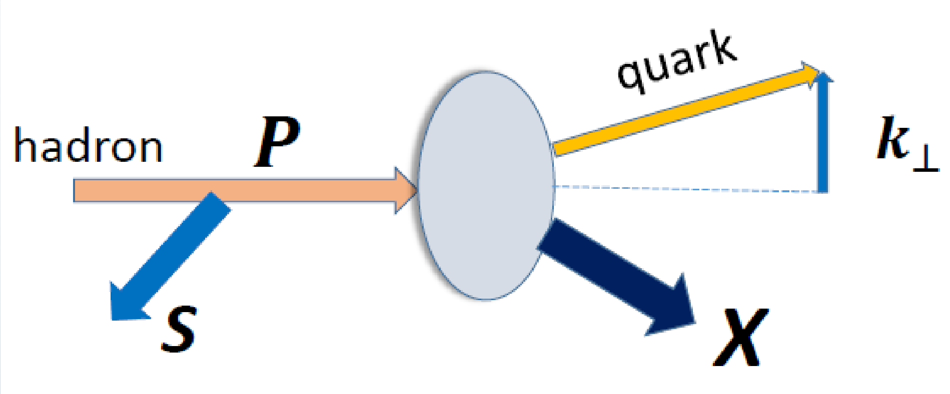
To be further explored

TMDs and SPIN

Collinear: unpol (f_1), helicity (g_1) and transversity (h_1) distributions,
TMD approach: 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

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

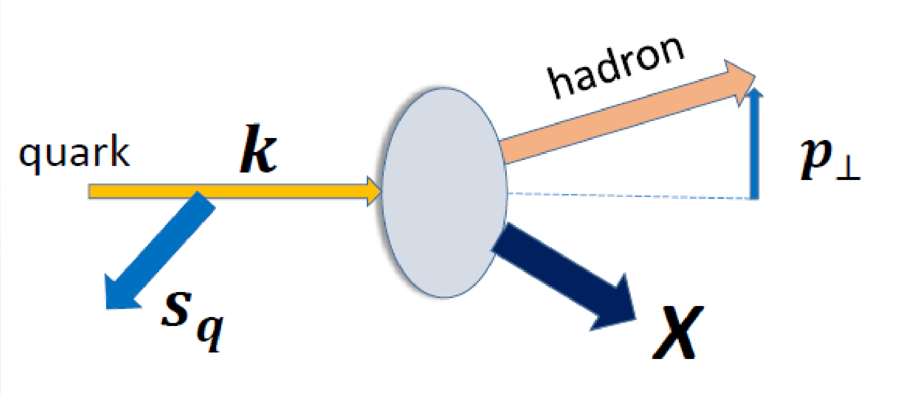
Spin independent

Spin dependent

As well, a relevant TMD in the fragmentation process:

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

Collins (1992)

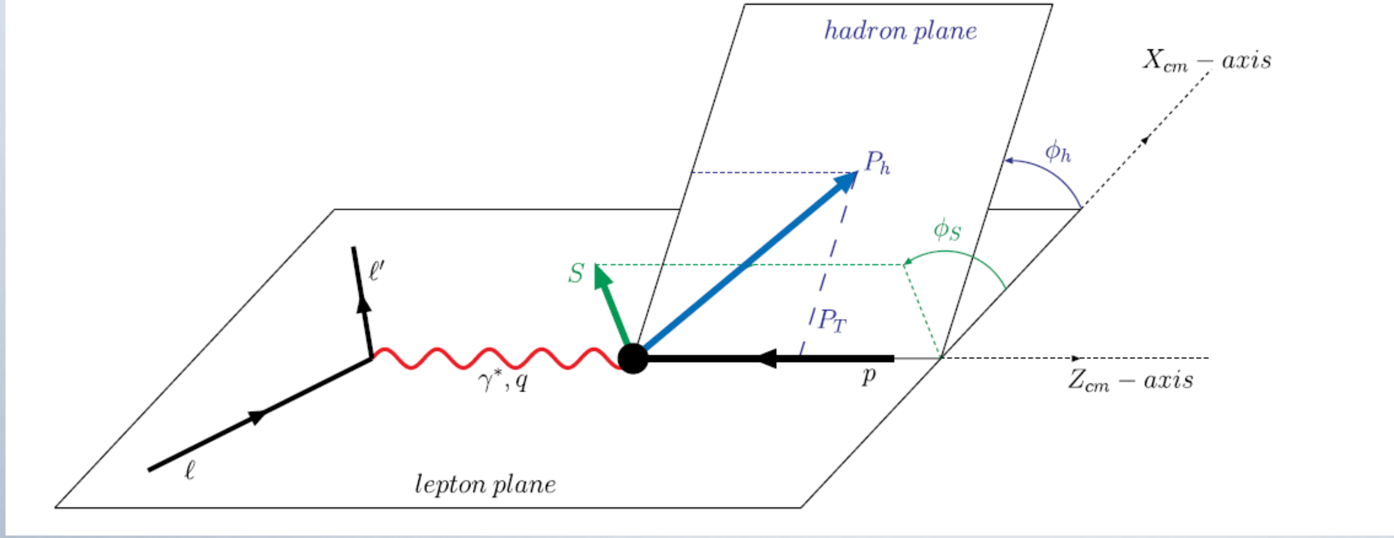


Correlation between the spin of the fragmenting quark and the hadron transverse momentum

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

Sivers and Collins functions extensively studied theoretically, experimentally and phenomenologically

SIDIS



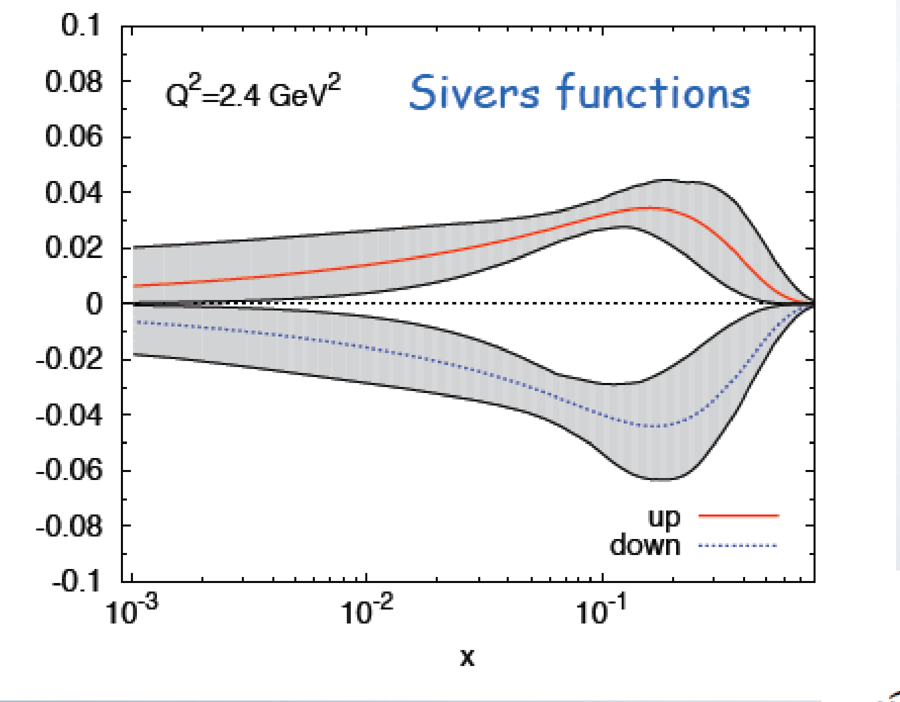
CLEAR evidence from data
HERMES, COMPASS

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

Collins — Sivers

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

→ Marco Contalbrigo



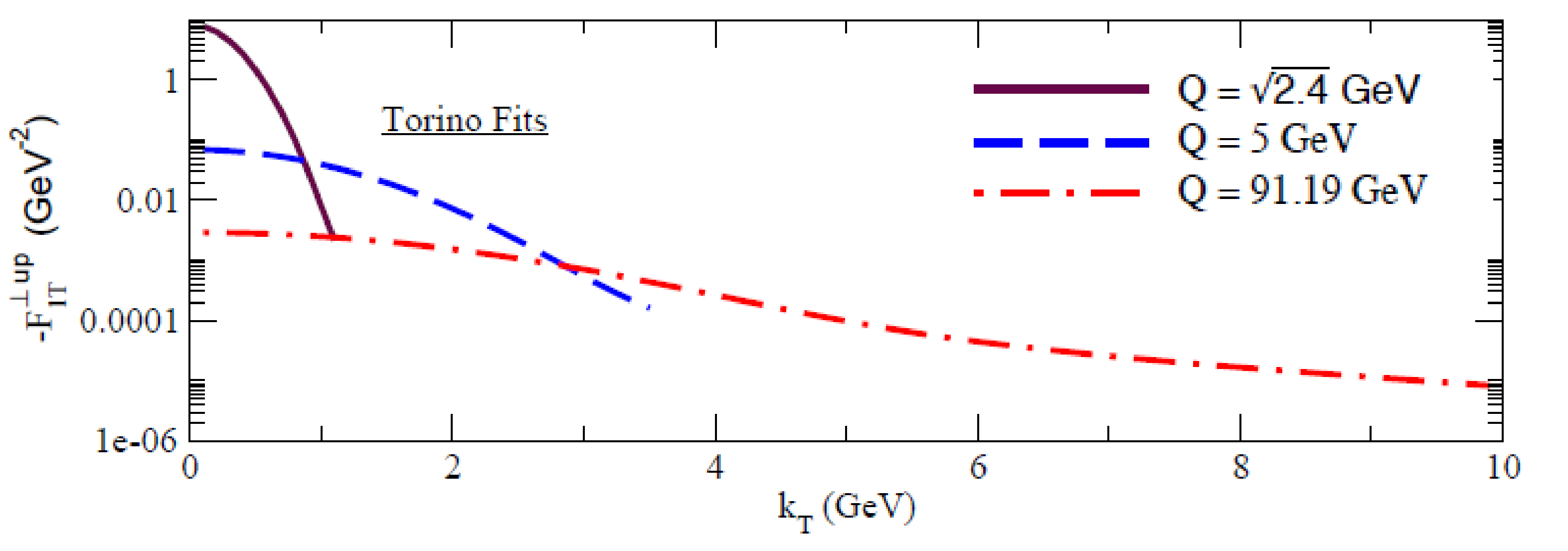
Extracted Sivers functions

TO-CA and PV groups

large-x region: unconstrained [→ JLab]

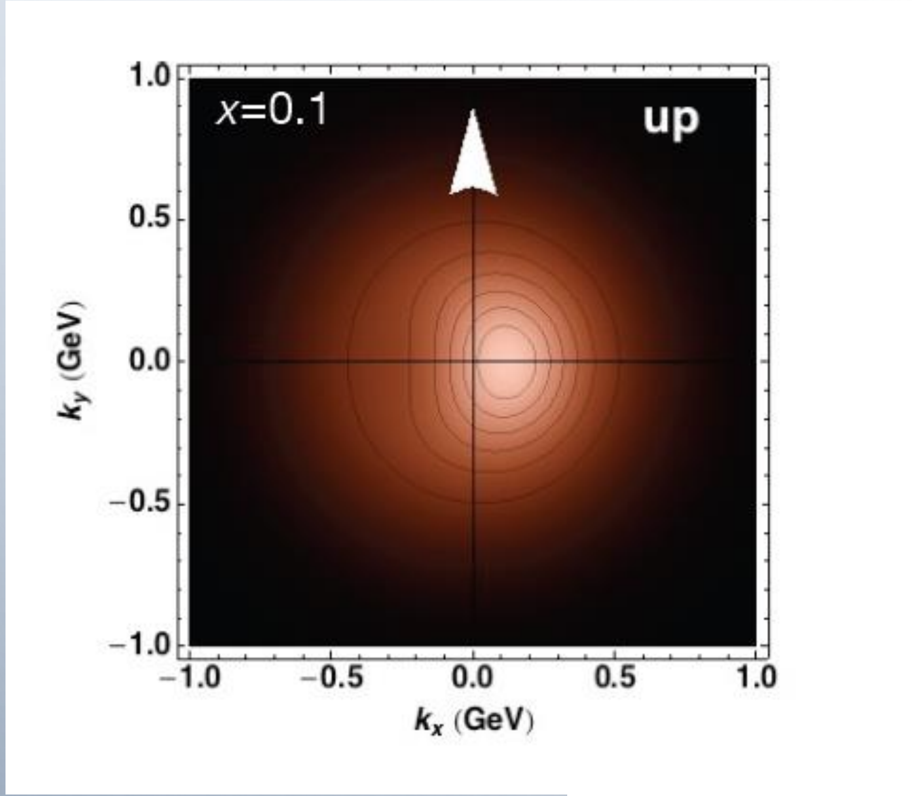
sea region: unconstrained [→ EIC]

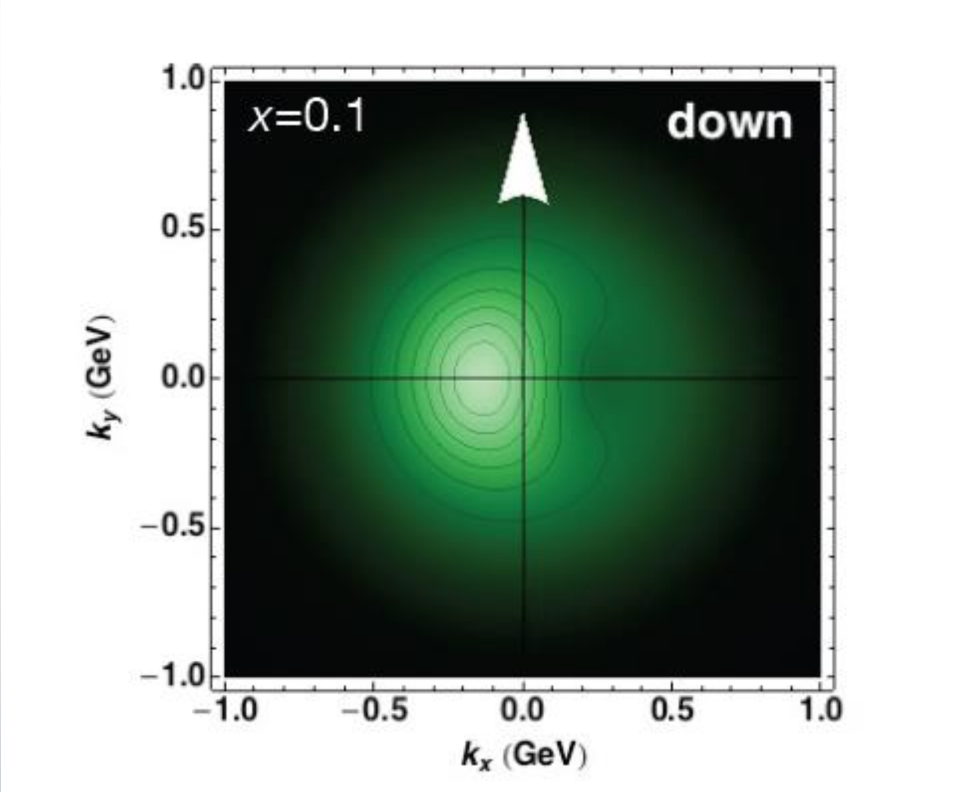
Aybat, Collins, Qiu, Rogers (2012)



Effect of the TMD evolution

Distortion in the transverse plane

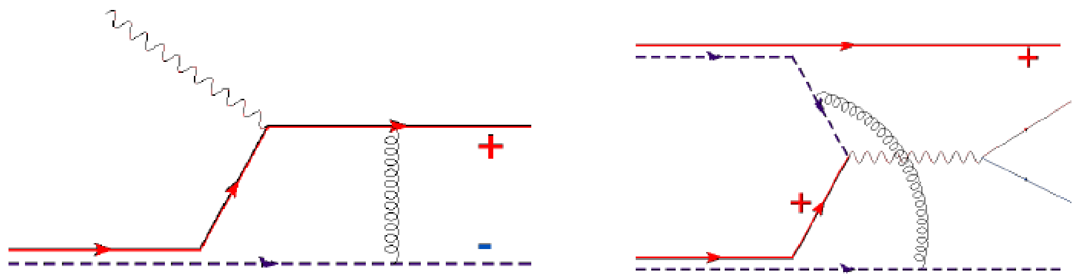




picture from A. Bacchetta, M. Contalbrigo,

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)

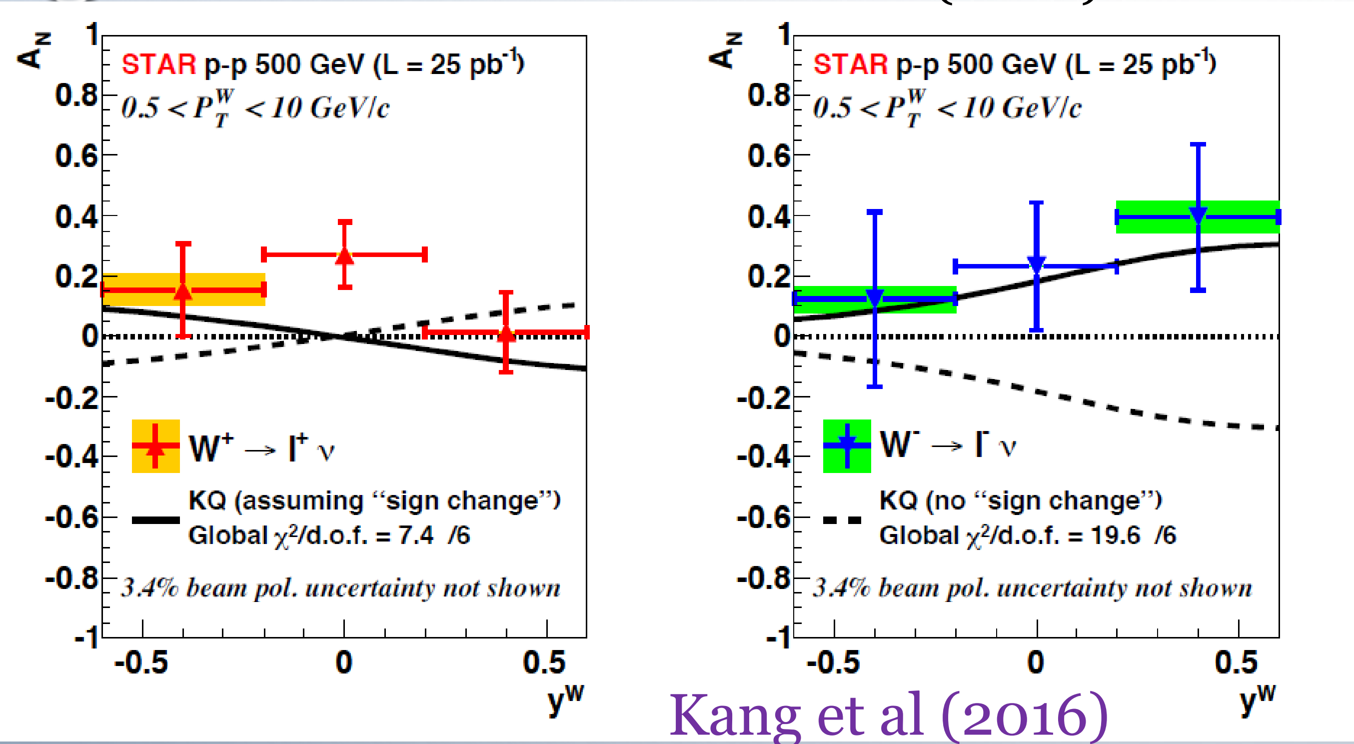
Final state interactions in **SIDIS**
Initial state interactions in **DY**

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: $p^{\uparrow}p \rightarrow W^{\pm}\ X$

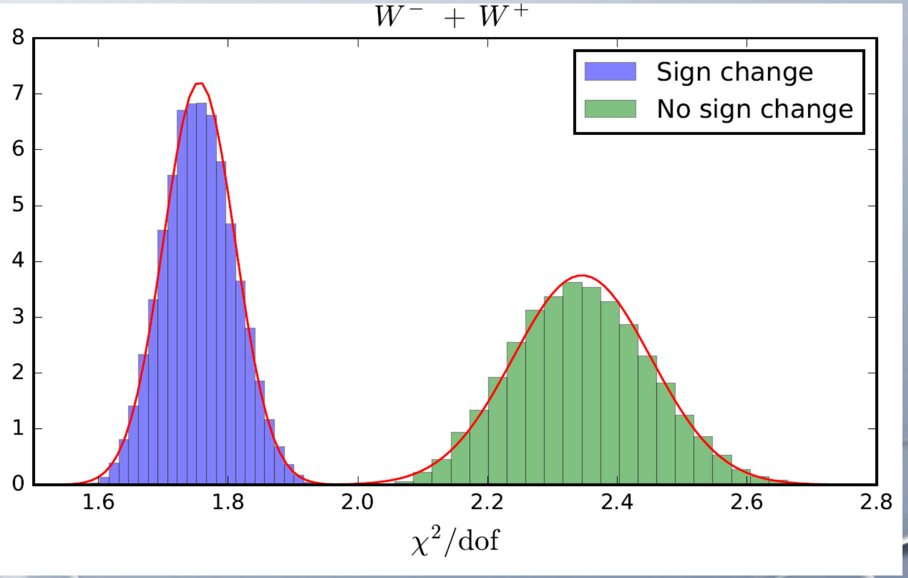
STAR Collaboration (2016)



Kang et al (2016)

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

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



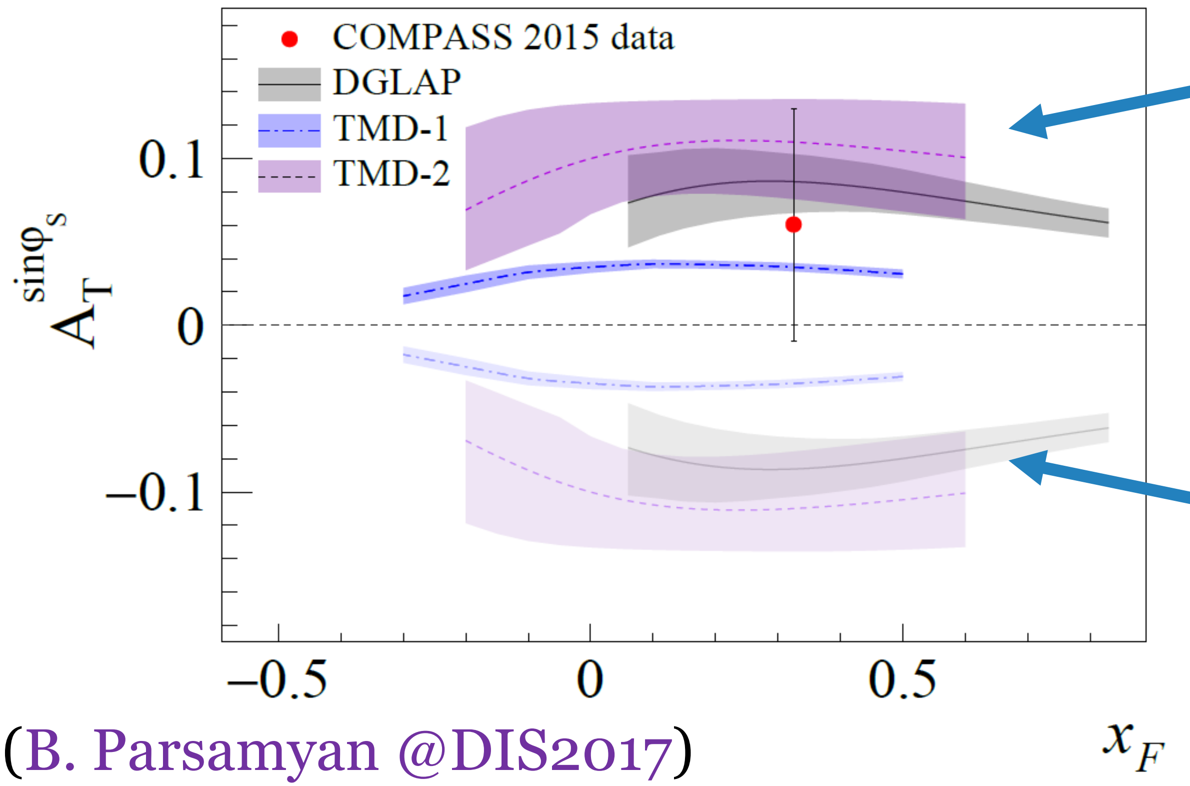
- Sign change $\chi^2/d.o.f \sim 1.2$
- No sign change $\chi^2/d.o.f \sim 3.2$

No TMD evolution

gliari University & INFN)

Sivers asymmetry for Drell-Yan at COMPASS

$\pi^- p \to \mu^+ \mu^- X$



(B. Parsamyan @DIS2017)

Change of sign

Without Sign change

Same kinematical region as that for SIDIS extraction

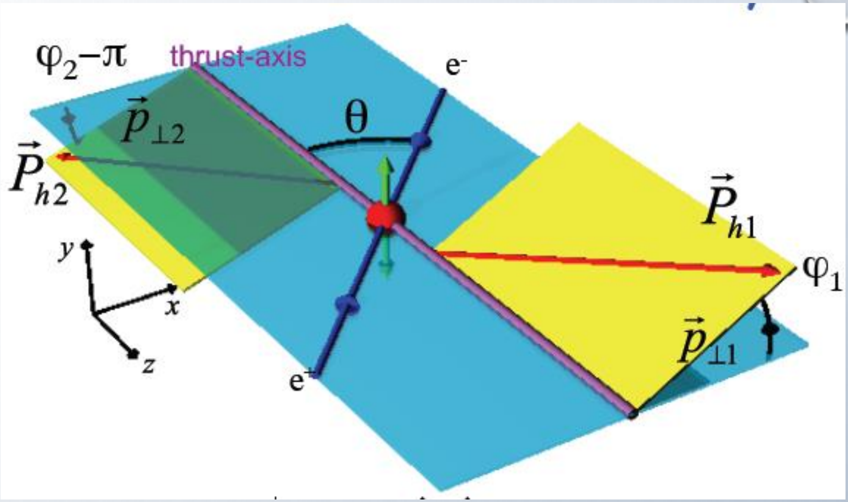
Collins function & transversity

Combined analysis of

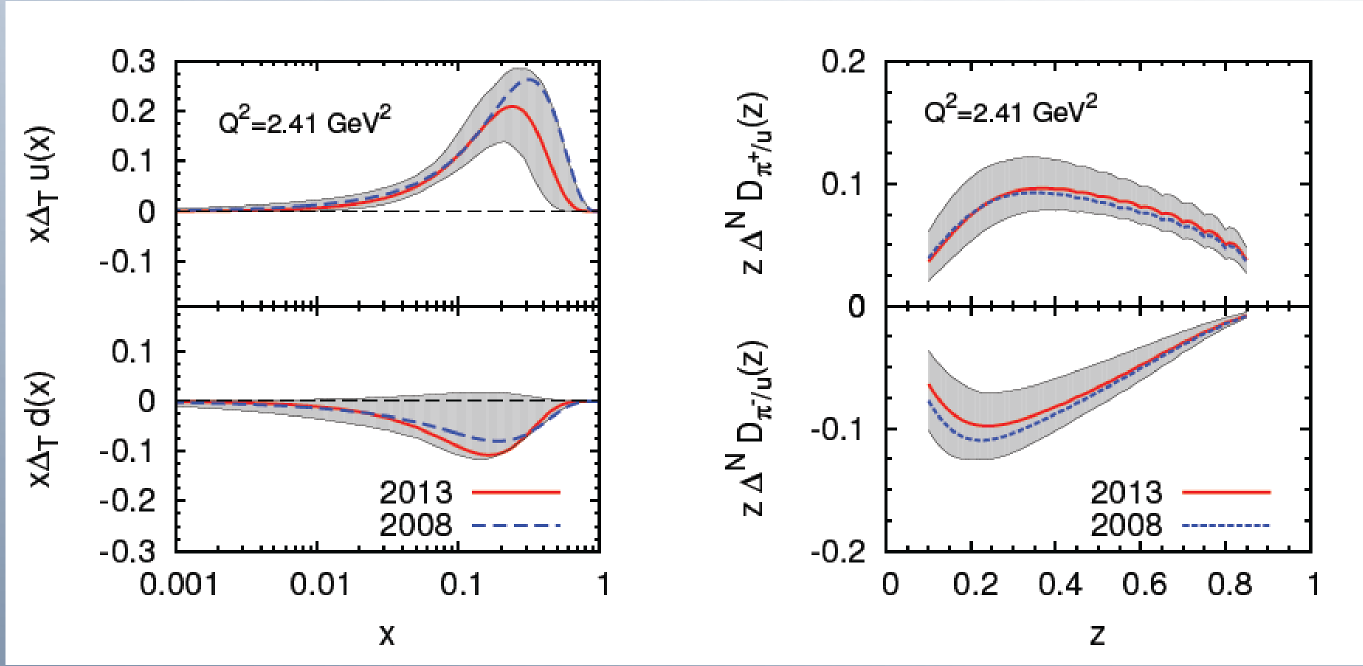
SIDIS and $e^+e^- \to \pi\pi X$

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

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



Without TMD evolution



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

Same analysis but with TMD evolution

Kang, Prokudin, Sun, Yuan (2015)

Compatible with LO analysis
No compelling TMD evolution yet
Remember: SSAs are ratios….

Back to A_N : further evidence of Sivers and Collins effects

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

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

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

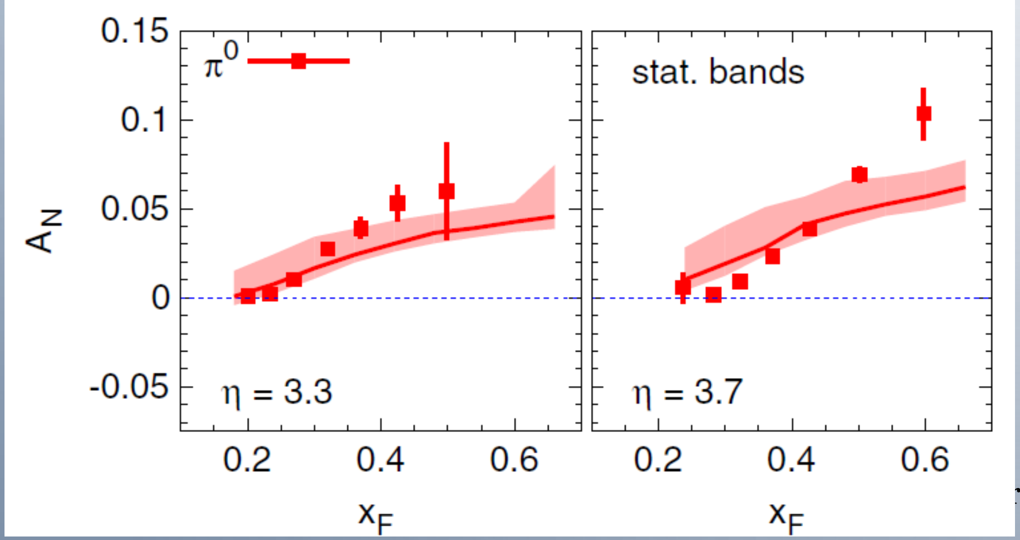
~ Sivers
+ transversity $\otimes$ Collins + ...

Non separable

In a phenomenological TMD scheme (GPM)

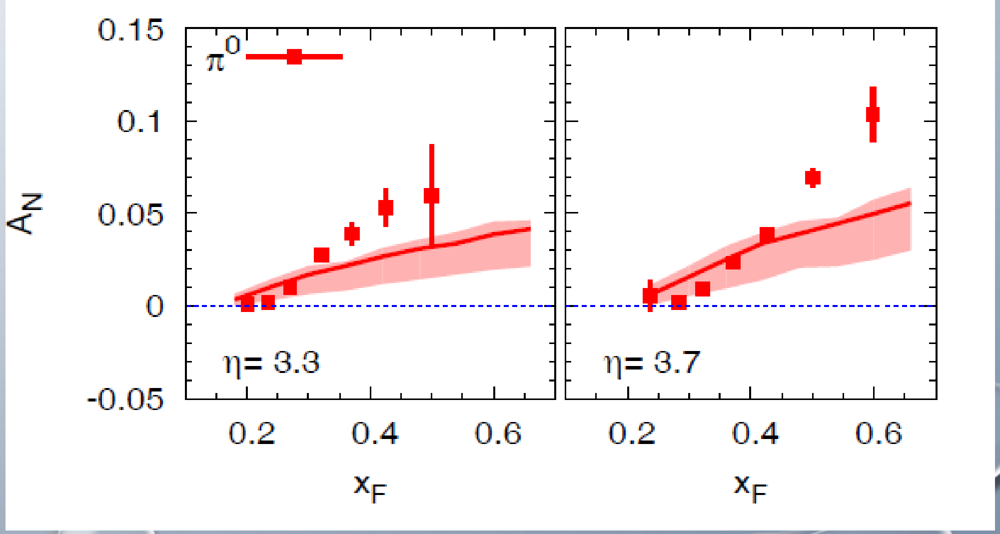
From SIDIS extractions to *pp* data (STAR (2008)):
Anselmino, Boglione, UD, Leader, Melis, Murgia, Prokudin (2012 & 13)

Sivers effect alone



Proper combination? in progress

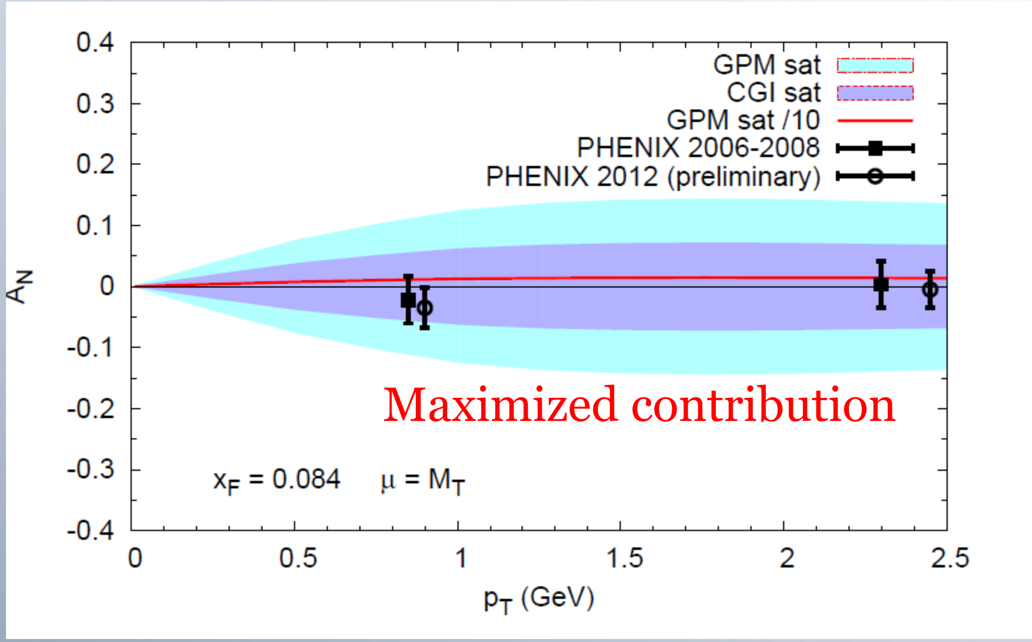
Collins effect alone

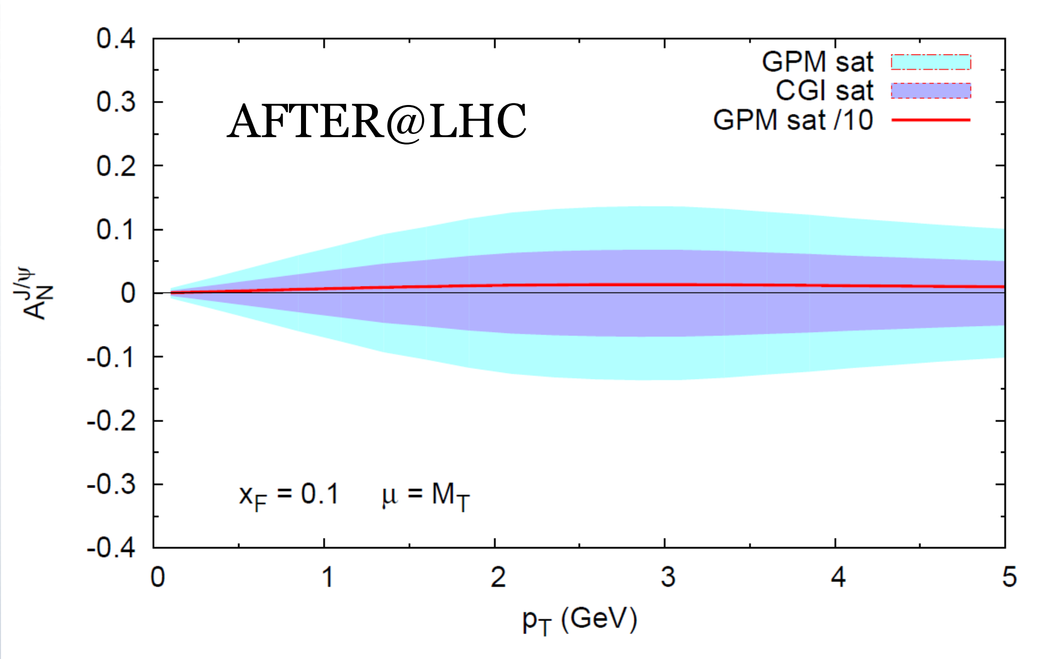


SSAs for Quarkonium production:
direct access to the GLUON Sivers function

UD, Murgia, Pisano, Taels (2017)

$$g\,g \to J/\psi\,g$$





GPM: parton model with universal TMDs

CGI: TMD approach with initial/final state interactions (DY/SIDIS sign change)

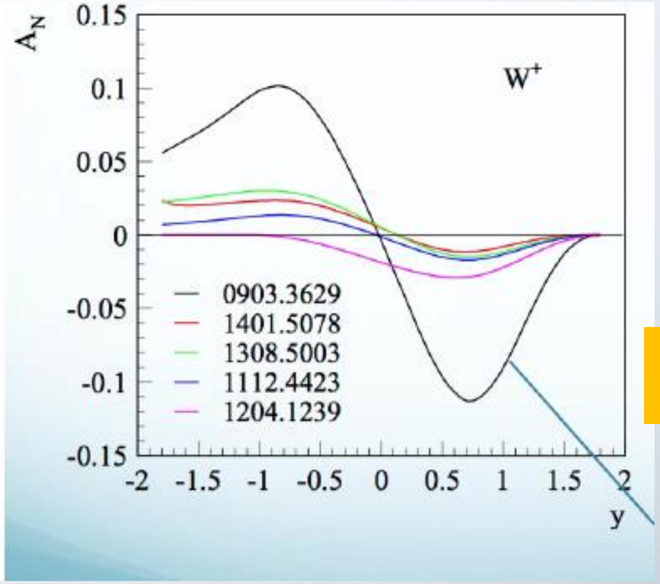
→ Luciano Pappalardo

Open issues in TMD phenomenology

- ❑ TMD evolution and its relevance

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

- ❑ Role of non perturbative input choices

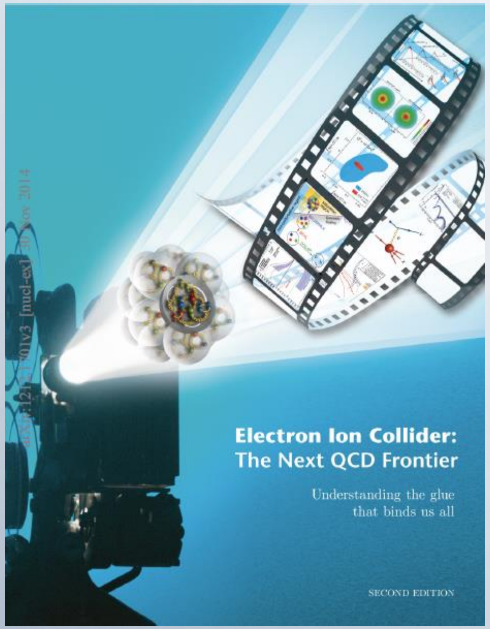


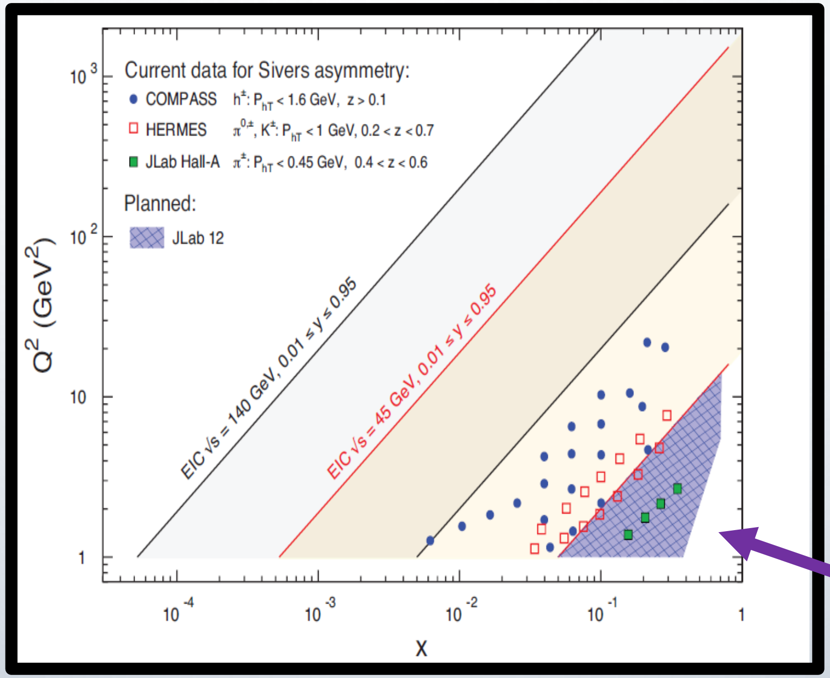
Kang (2015)

w/o TMD evolution

- ❑ Transverse momentum dependence in SIDIS and its consistency with DY
- ❑ Proper definition/selection of the current fragmentation region in SIDIS
- ❑ TMD factorization breaking effects in $pp \to \pi X$, $pp \to jet\ jet\ X$ (sizeable???)
- ❑ Gluon TMDs at low x, TMD factorization vs. Color Glass Condensate

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

Marco Radici

CONCLUSIONS AND OPEN ISSUES

- NUCLEON STRUCTURE: MYSTERIOUS AND FASCINATING

EXPERIMENTAL EVIDENCE TO GO BEYOND A SIMPLE COLLINEAR (1D) PICTURE

DATA INTERPRETATION TOWARDS A TRUE 3D IMAGE OF THE NUCLEON

- SPIN-TMD EFFECTS AND GPDS WELL ESTABLISHED: ORBITAL ANGULAR MOMENTUM
- TRANSVERSE SINGLE-SPIN ASYMMETRIES: CHALLENGING AND TOOL TO LEARN DEEPER ON THE NUCLEON STRUCTURE AND QCD
- WAITING FOR COMPASS, JLAB-12, RHIC, AND EVENTUALLY EIC RESULTS
- PHENOMENOLOGY ISSUES

- GPDS: MODELLING, ALGORITHMS IN FITTING,...

- TMDS: EVOLUTION, NON PERTURBATIVE INPUTS,...

THANK YOU

BACK-UP SLIDES

TMD Factorization and evolution (I)

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

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

Calculation is perturbative, valid only in region $b \ll 1/\Lambda_{QCD}$

Fourier transform in momentum space involves non-perturbative region

$$f(x, k_\perp; Q) = \int_0^\infty \frac{bdb}{2\pi} J_0(k_\perp b) \tilde{f}(x, b; Q)$$

TMD Factorization and evolution (II)

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

DY processes: $pp \to l^+ l^- X$

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

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

- The non perturbative part of evolution is the main reason of different predictions

Non-perturbative input and accuracy

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

Both needed

Relevant for Z^0 data

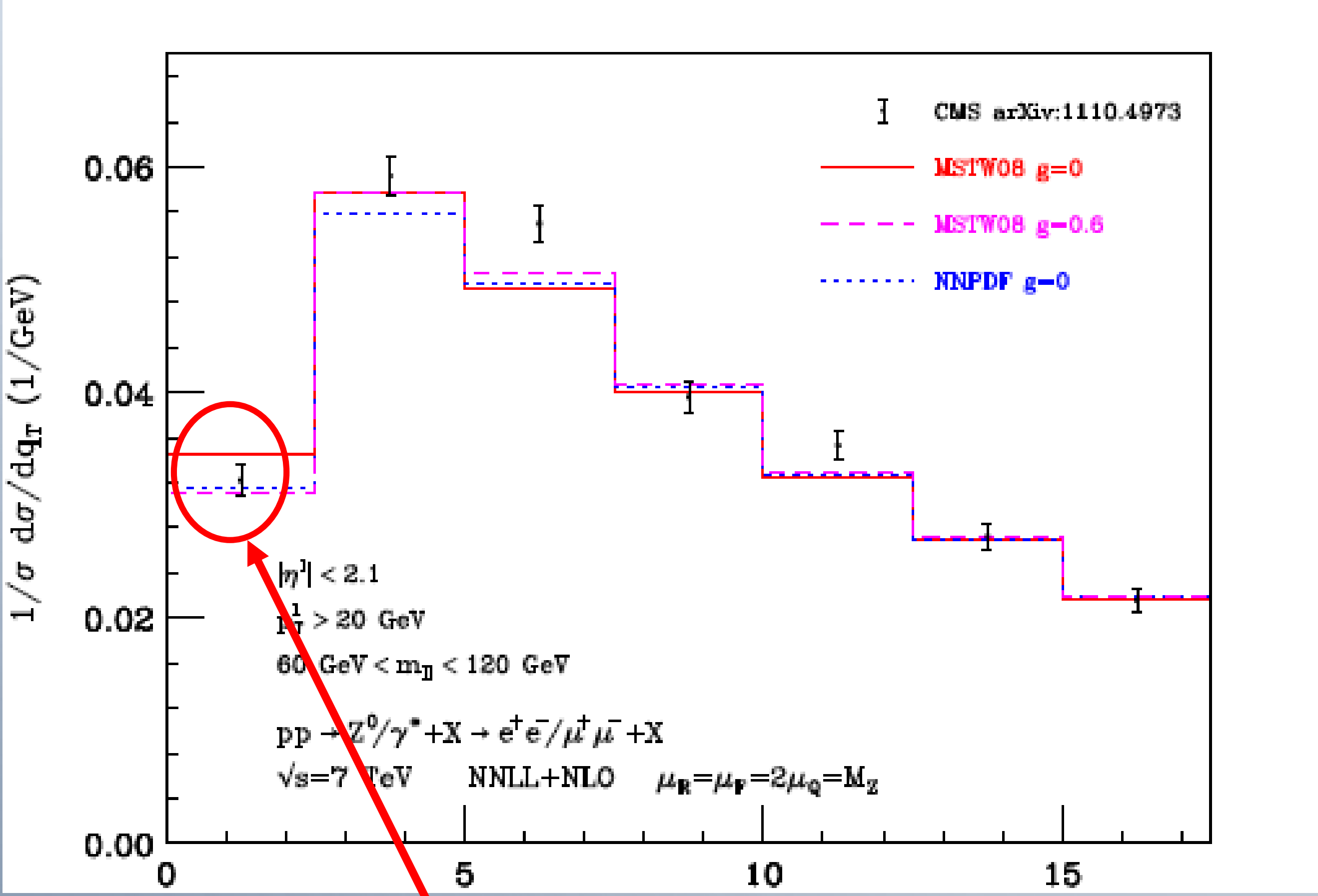
Sensitive to low-energy/low-q_T data

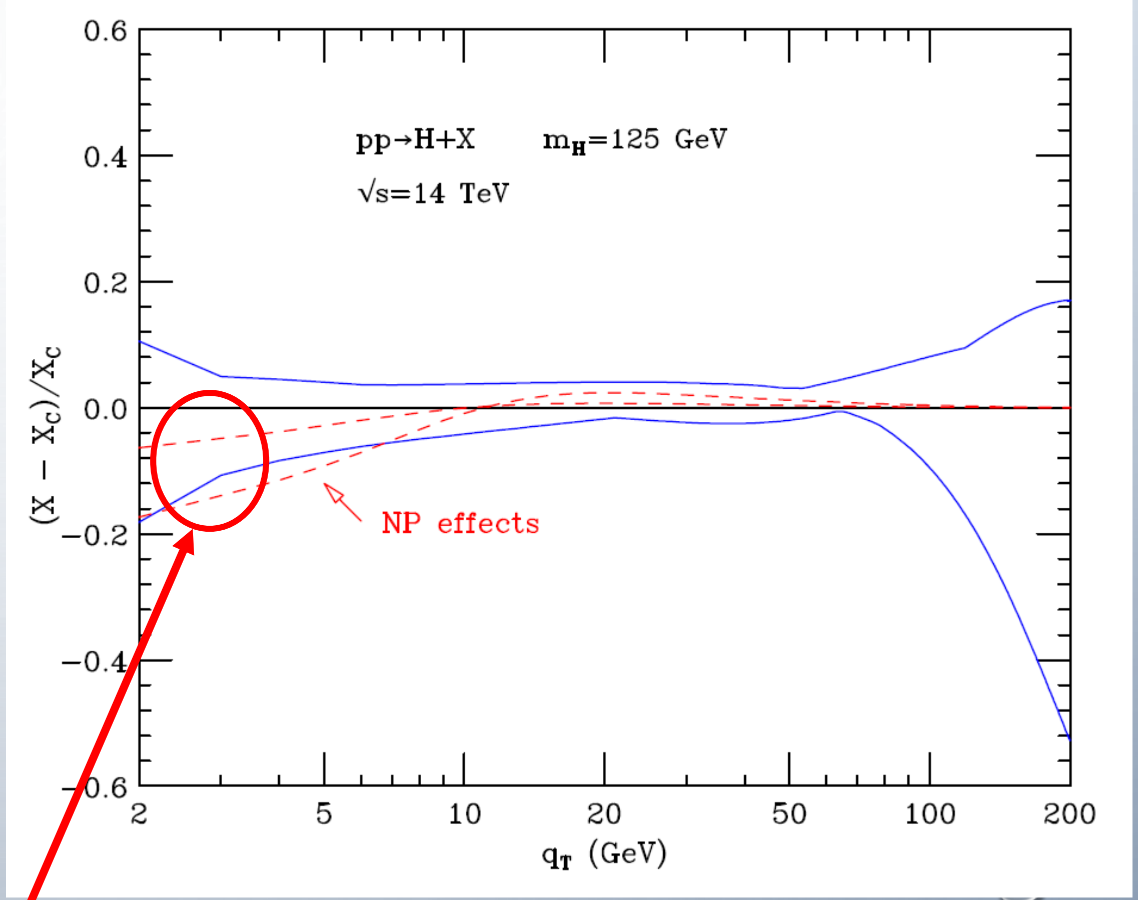
Order	H	$\hat{C}_{q\leftarrow j}$	Γ_{cusp}	γ^V	D^R
LL	α_s^0	α_s^0	α_s^1	α_s^0	α_s^0
NLL	α_s^0	α_s^0	α_s^2	α_s^1	α_s^1
NNLL	α_s^1	α_s^1	α_s^3	α_s^2	α_s^2

TMDs at LHC (II)

Ferrera (2014)

$pp \rightarrow Z\,X$





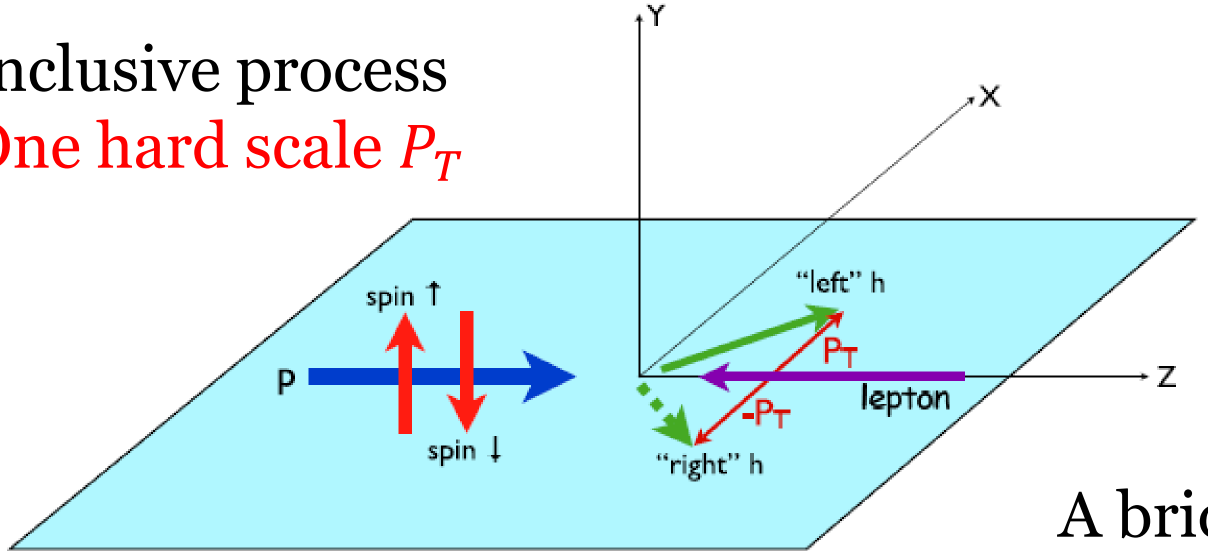
Inclusion of the non perturbative piece

uncertainties in $pp \rightarrow H\,X$

A_N in $l\, p \to \pi\, X$ (single-scale process)

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

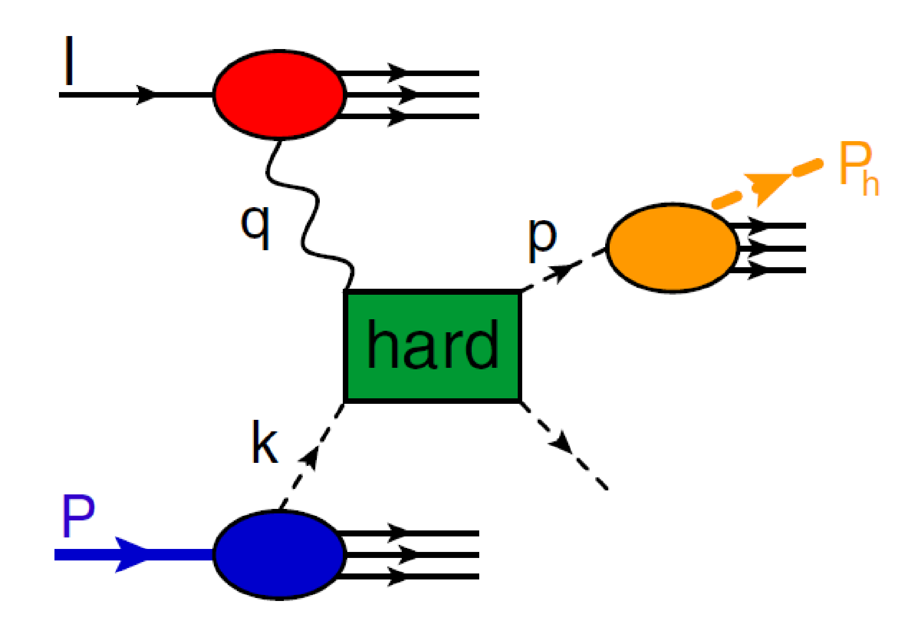
LO: $lq \to lq$

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

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

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

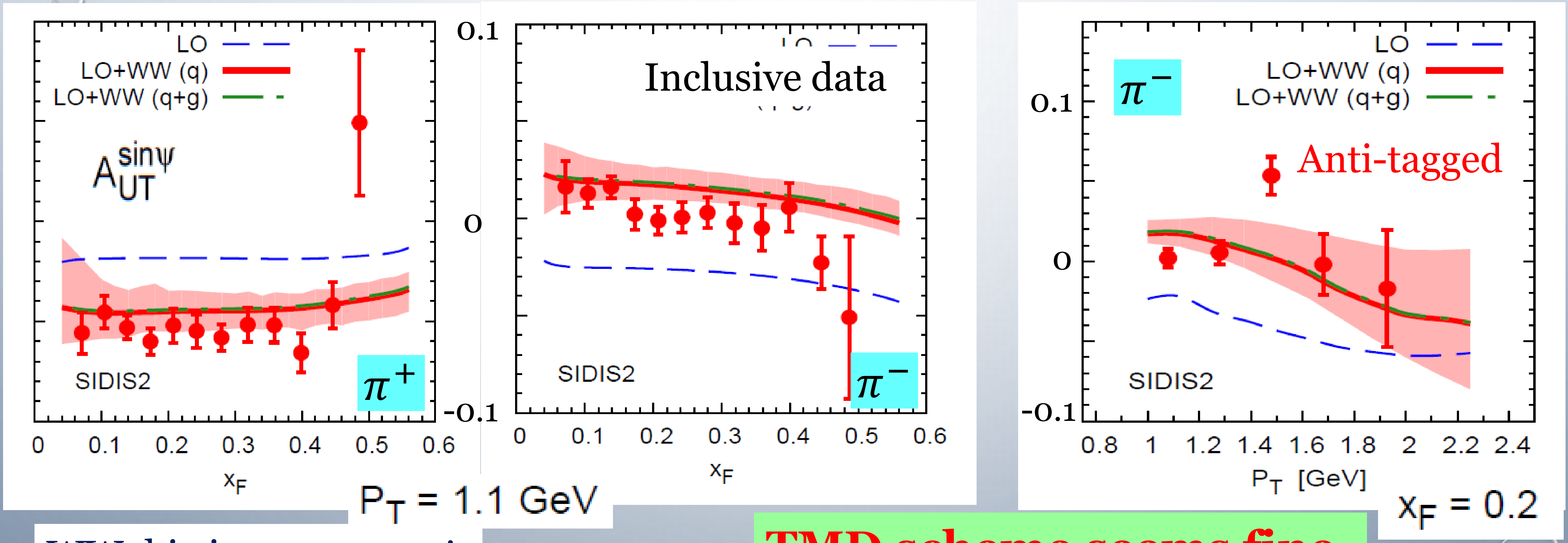
Weizsäcker-Williams approximation

Reanalysis of SSAs (and unpol. xsecs): UD, Flore, Murgia 2017

SSAs: Only Sivers and (marginally) Collins effects sizeable

Predictions from SIDIS extractions

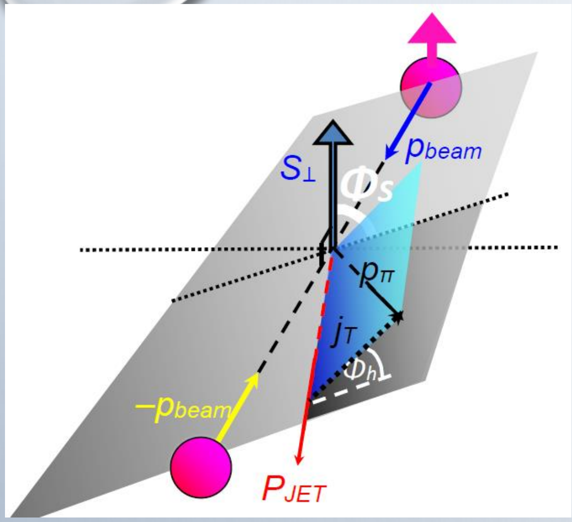
HERMES data (2014)



WW: big improvement!

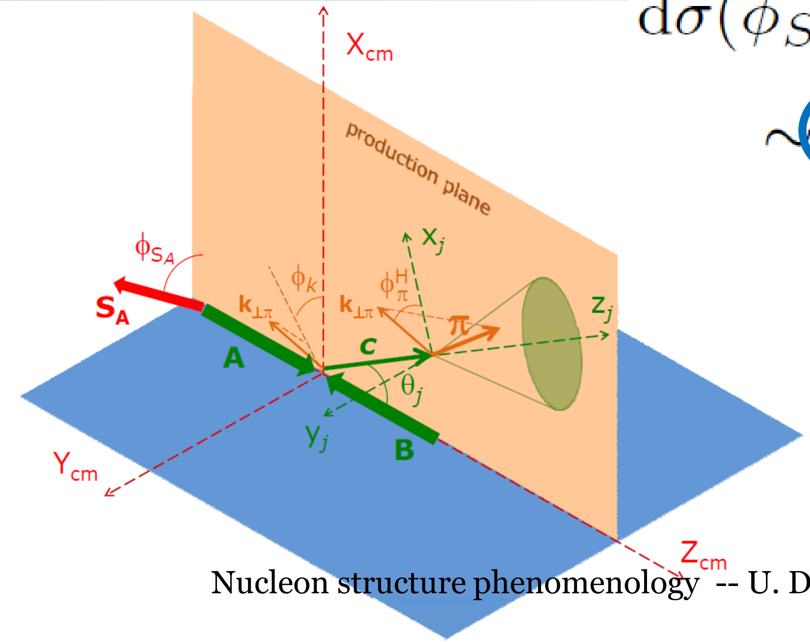
TMD scheme seems fine

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



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

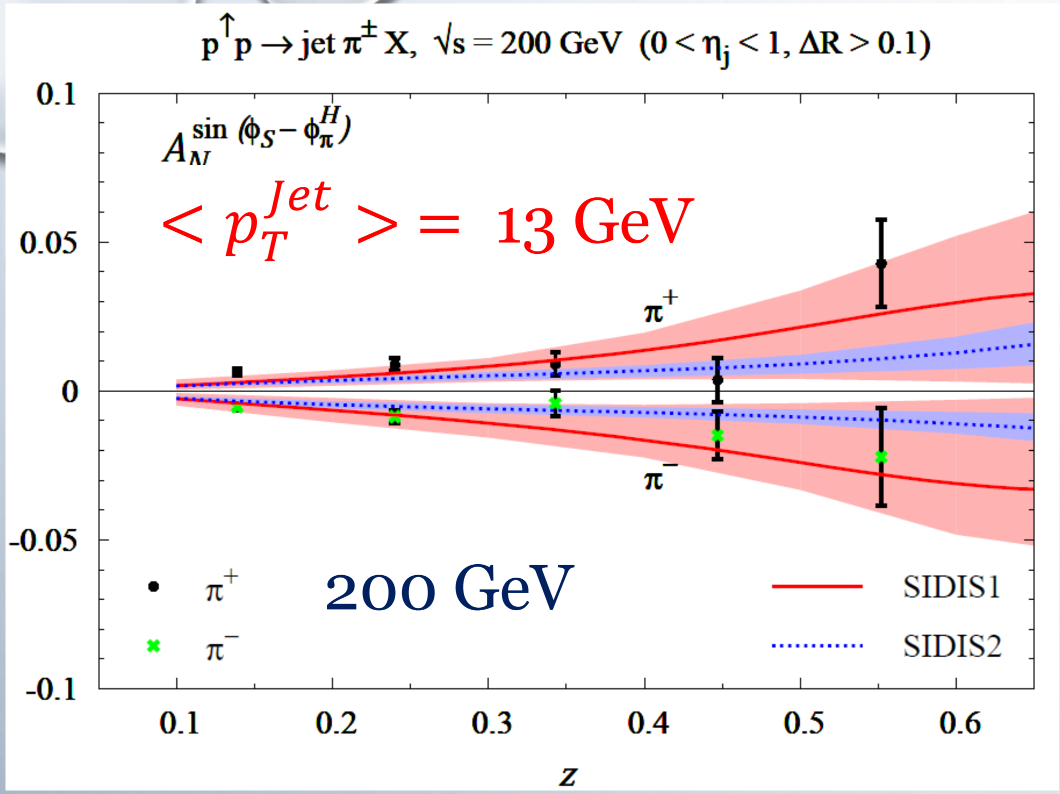
$$W(\phi_S,\phi_\pi^H) = \sin\phi_S,\ \sin(\phi_S - \phi_\pi^H),\ \ldots$$

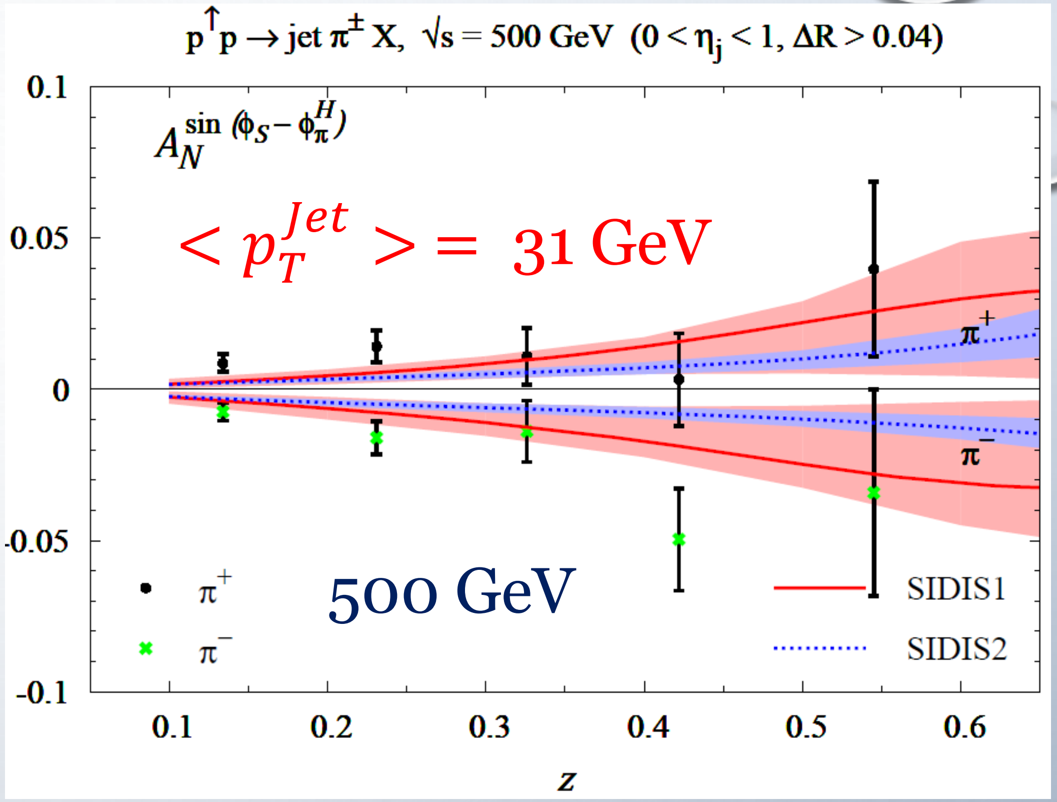


$$d\sigma(\phi_S,\phi_\pi^H) - d\sigma(\phi_S+\pi,\phi_\pi^H)$$
$$\sim d\Delta\sigma_0 \sin\phi_S + d\Delta\sigma_1^- \sin(\phi_S - \phi_\pi^H) + d\Delta\sigma_1^+ \sin(\phi_S + \phi_\pi^H)$$
$$+ d\Delta\sigma_2^- \sin(\phi_S - 2\phi_\pi^H) + d\Delta\sigma_2^+ \sin(\phi_S + 2\phi_\pi^H)$$

Sivers effect — **Collins-like effect** — **Collins effect**

UD, Murgia, Pisano (2011)





Predictions without TMD evolution

UD, Murgia, Pisano, in progress

Data: PHENIX Coll. (2015)

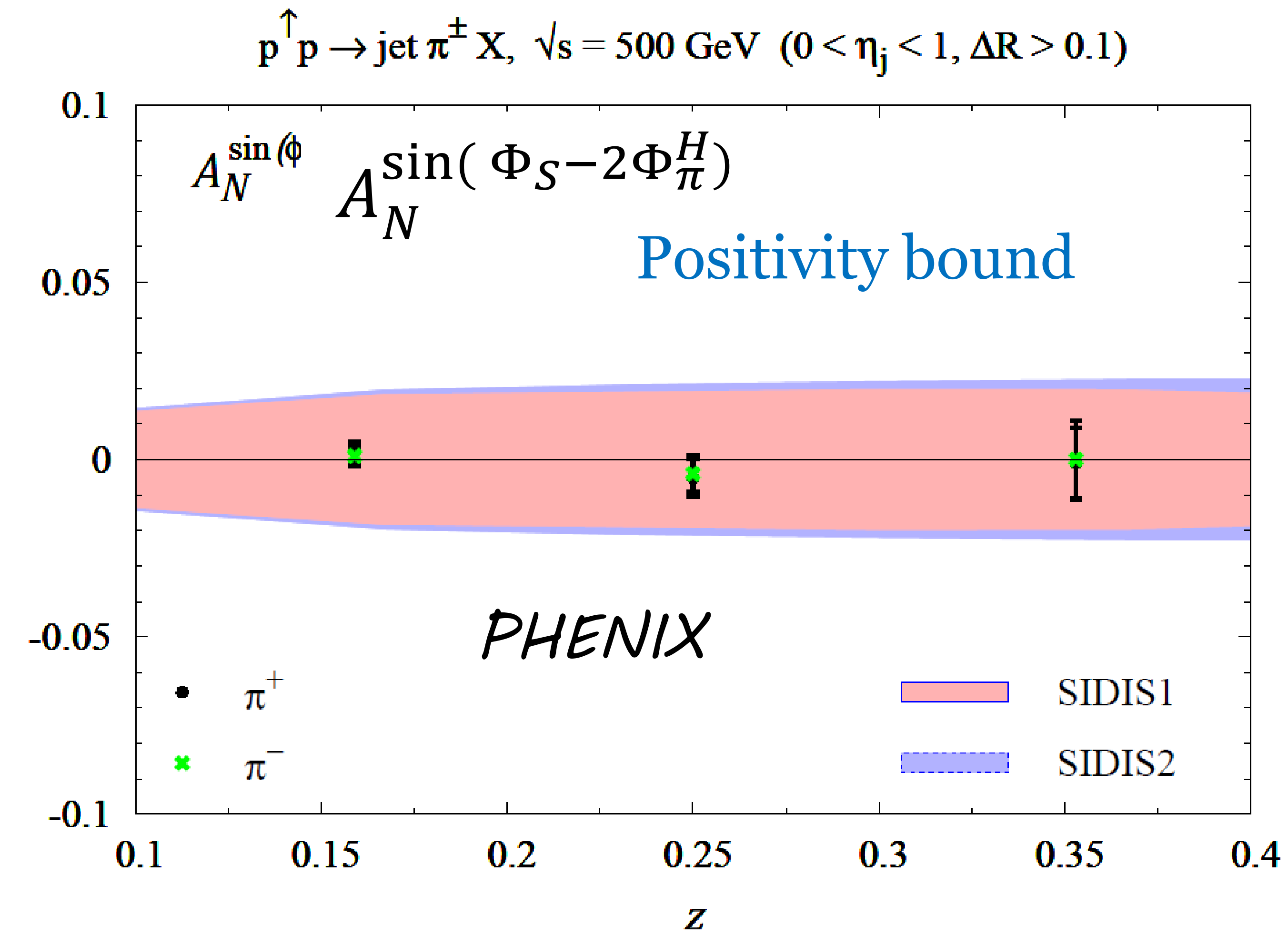
- Universality of the Collins function
- mild (or no) TMD evolution

Collins-like contribution

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

helicity flip of the gluon

Towards a first constraint of the product of TMDs for
linearly polarized gluons inside $p^\uparrow$
and
linearly pol. gluons fragm. into a π



TMDs and spin

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

8 functions in total (at leading twist)

Each represents different aspects of partonic structure

Each depends on Bjorken-x, transverse momentum, the scale

Each function is to be studied

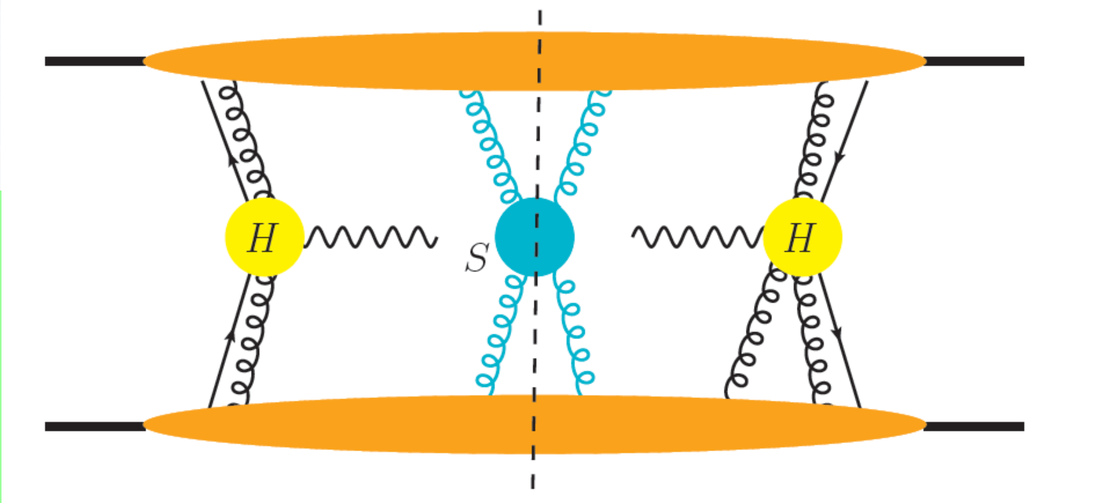
collinear

T-odd

Kotzinian (1995), Mulders, Tangerman (1995), Boer, Mulders (1998)

An example: DY process

Extra gluons:
- Wilson lines, operators between parton fields in the correlator function
- Soft factors, vacuum expectation values of further Wilson lines, absorbed in the TMDs)



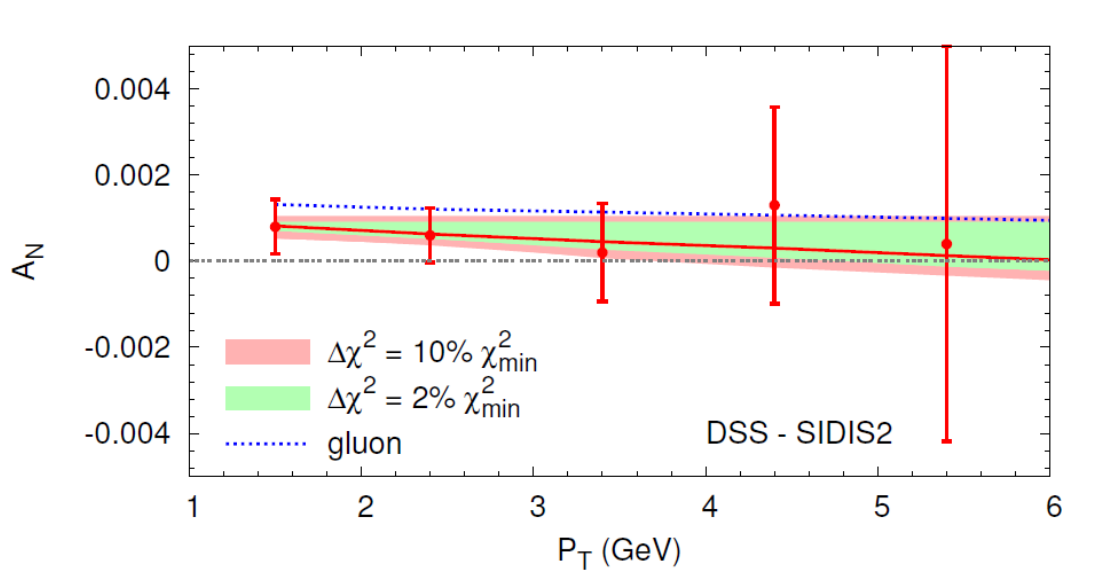
DY processes: $pp \to l^+ l^- X$

Wilson lines: path-ordered exponential of the gauge field ensuring local gauge invariance, but inducing some process dependence

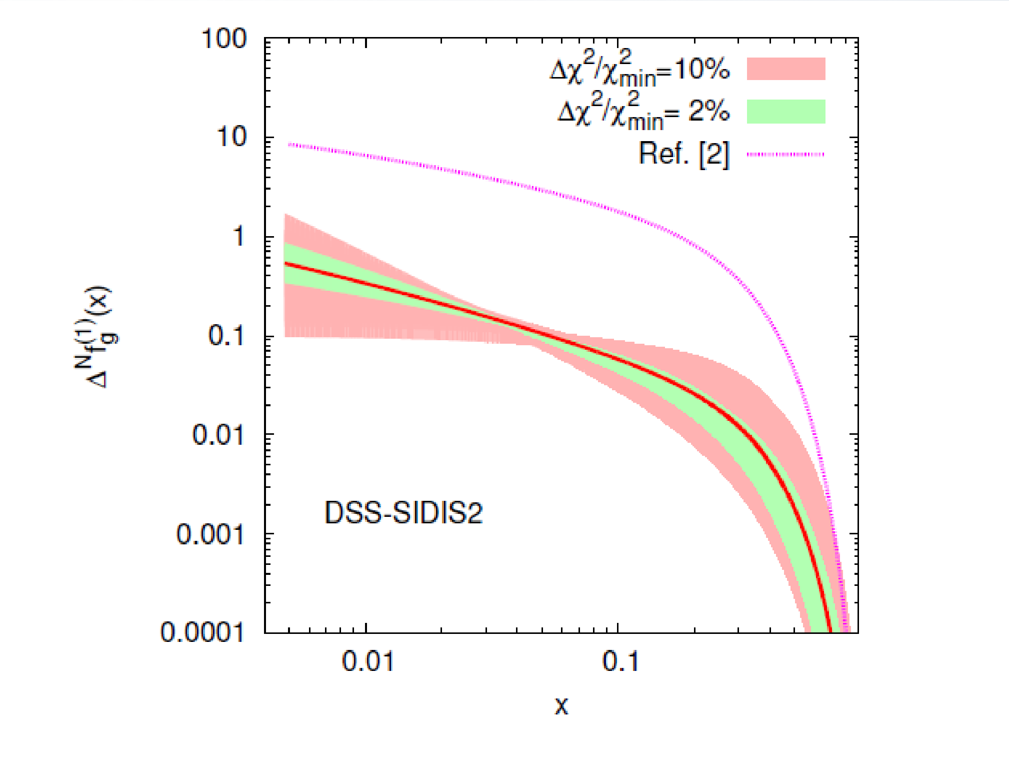
$$\mathcal{U}_{[\eta;\xi]} = \mathcal{P}\exp\left[-ig\int_C ds\cdot A^a(s)\,t^a\right]$$

$$\Phi_{ij}^{[\mathcal{U}]}(x,p_T;P,S) = \int \frac{d(\xi\cdot P)d^2\xi_T}{(2\pi)^3}\, e^{ip\cdot\xi}\, \langle P,S|\,\overline{\psi}_j(0)\,\mathcal{U}_{[0;\xi]}\,\psi_i(\xi)\,|P,S\rangle\big]_{\rm LF}\,.$$

Access to the gluon Sivers function



A_N at mid-rapidity



PHENIX Collaboration data (2014)

All other effects are washed out

UD, Murgia, Pisano JHEP09 (2015)

Higher-twist contributions to A_N

- Collinear factorization: proven Qiu, Sterman (1991)

- Twist-three functions could be related to TMDs:

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

Boer, Mulders, Piljman (2003)

- A completely new twist-3 fragm. function seems to be able (necessary) to explain A_N Kanazawa, Koike, Merz, Pitonyak (2014)

- Recent analysis with use of Lorentz Invariant Relations: Gamberg et al (2017)

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