TMDs at Electron Ion Collider

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FUTURE


LAW & CRIME
LANGUAGES

Why Electron Ion Collider?

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THE EUROPEAN PHYSICAL JOURNAL A

Review

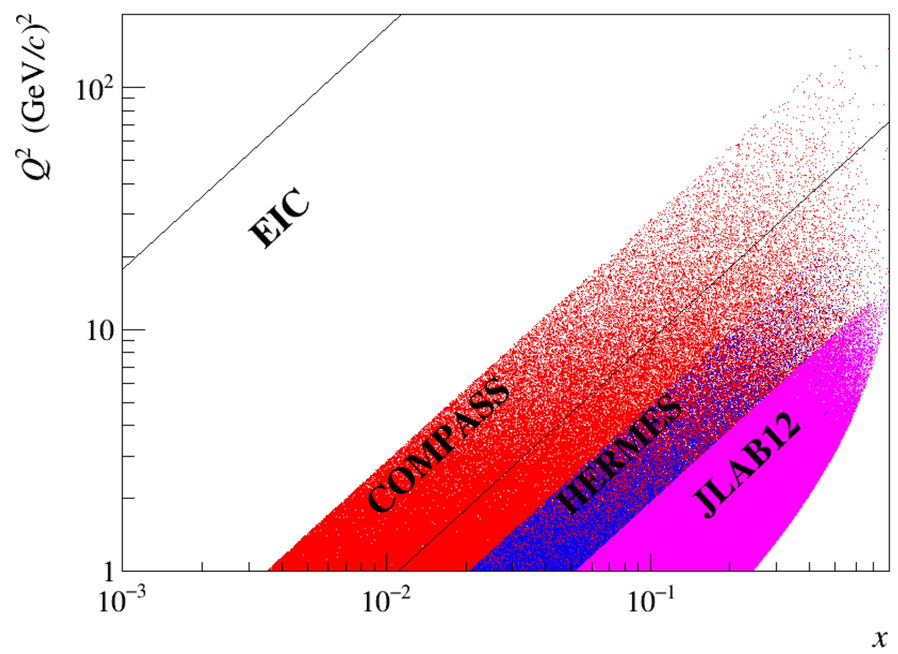
Electron-Ion Collider: The next QCD frontier

Understanding the glue that binds us all

PennState Berks

Why do we need an Electron Ion Collider?

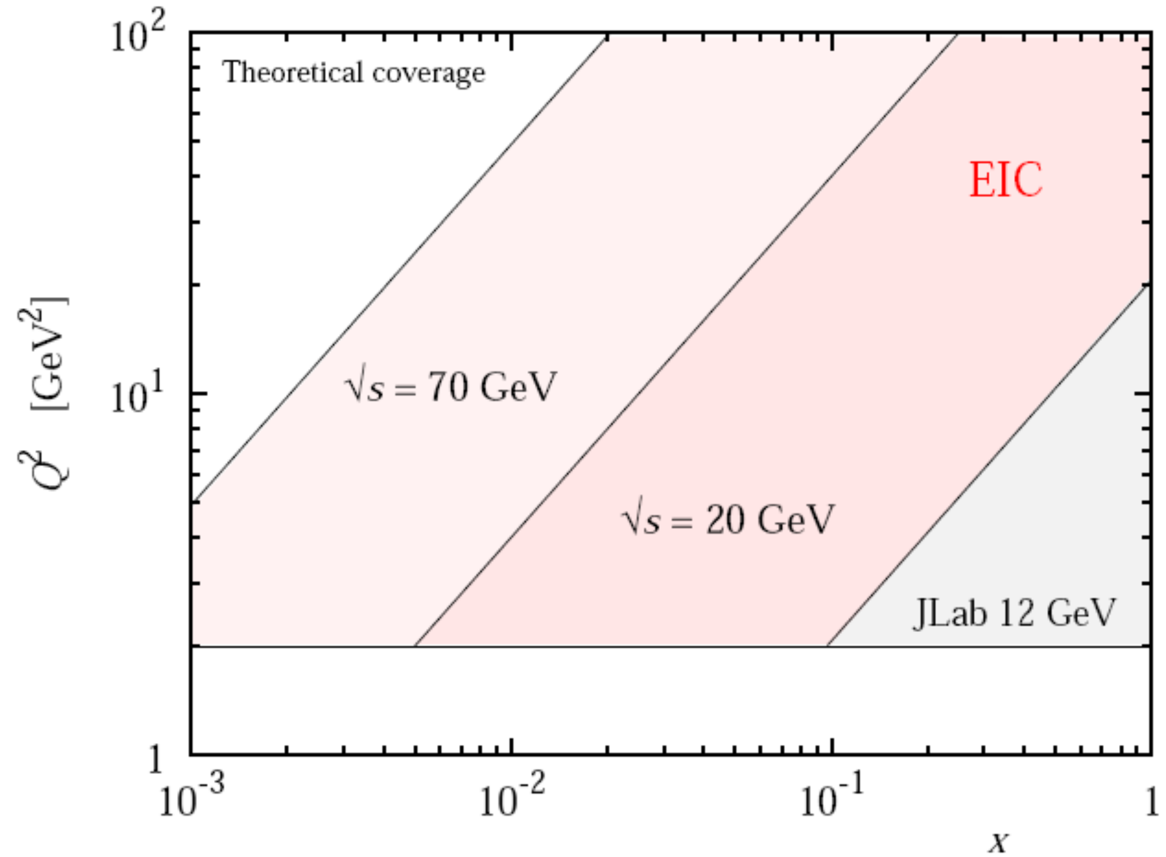
EIC is a *unique* facility that is capable of performing a well defined set of measurements in yet unexplored region and reveal details of dynamics of sea quarks and gluons in the nucleon.

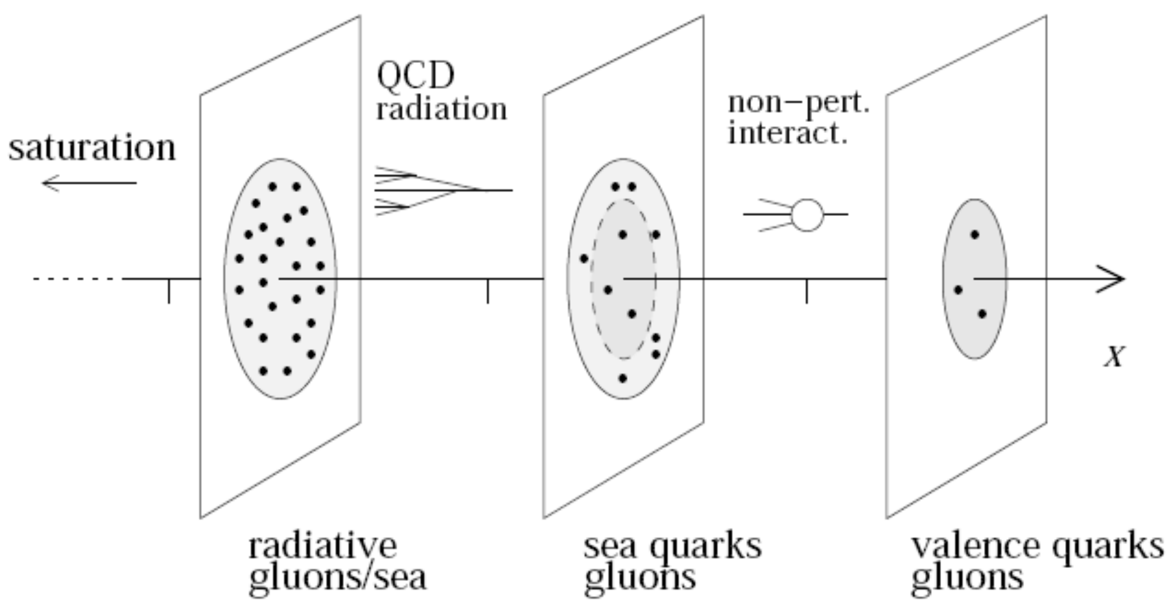


Importance of these studies is corroborated by the interest of Nuclear Physics community in the USA and the rest of the world.

Why is it so important for theory?

We are a data-driven science!





Nucleon is a many body dynamical system of quarks and gluons

Changing x we probe different aspects of nucleon wave function

How partons move and how they are distributed in space is one of the directions of development of nuclear physics

Technically such information is encoded into Generalised Parton Distributions (GPDs) and Transverse Momentum Dependent distributions (TMDs)

These distributions are also referred to as 3D (three-dimensional) distributions

PennState
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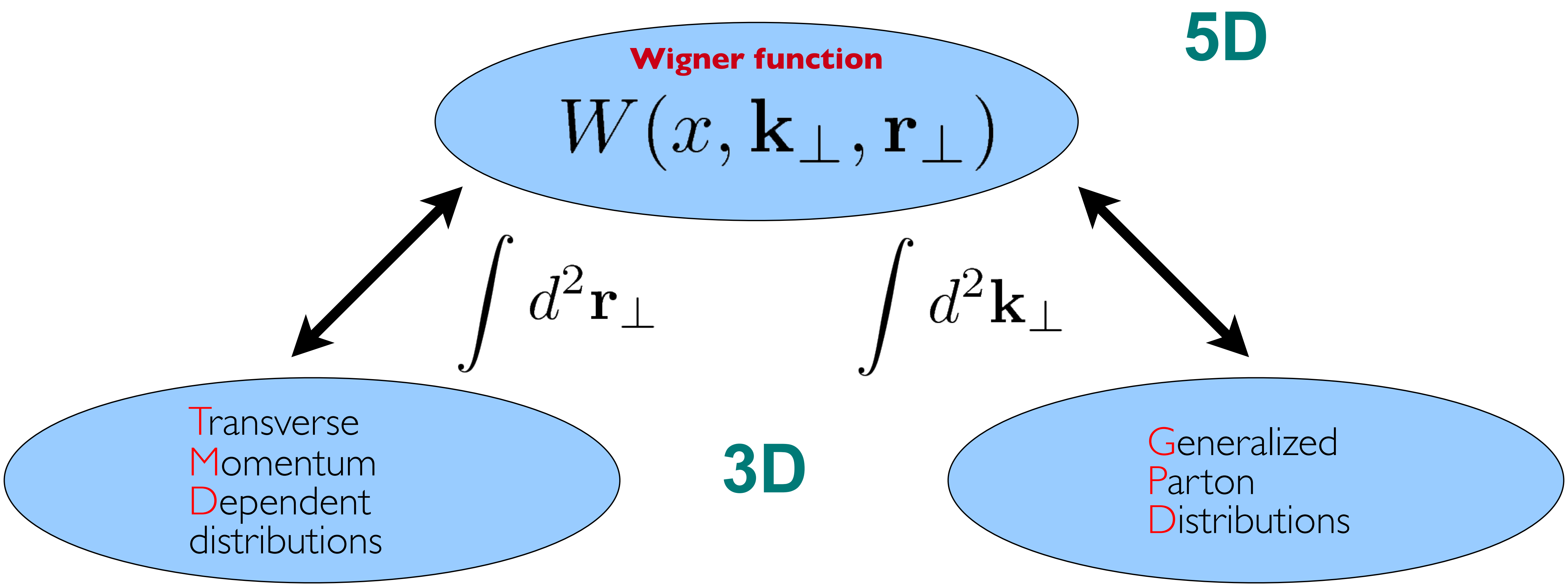
Unified View of Nucleon Structure

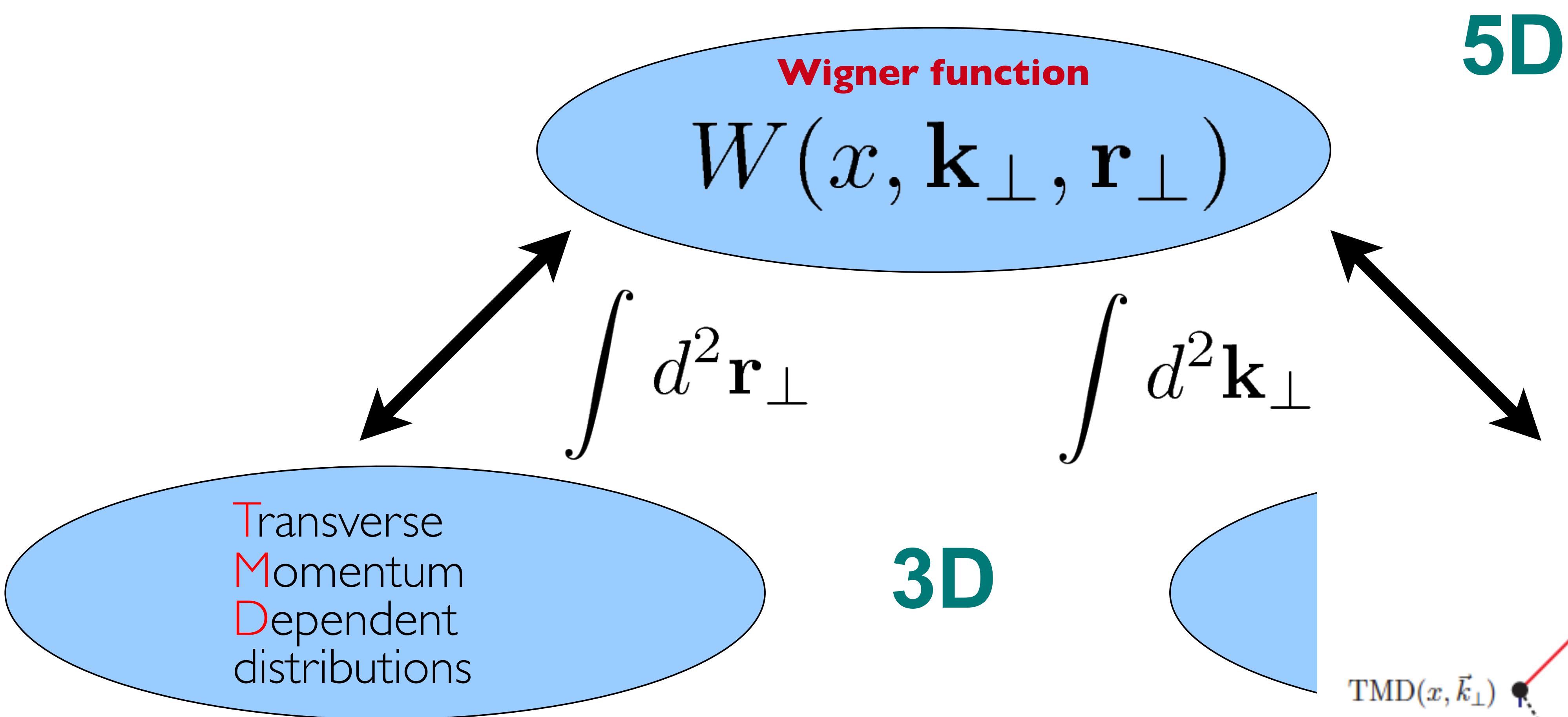


We hope to be able to combine the knowledge on GPDs and TMDs and access Wigner functions or GTMDs (F.T. of Wigner distributions)

7 years ago possible experimental measures of GTMDs were not know, now we have some proposed avenues to measure

A. Metz

Unified View of Nucleon Structure



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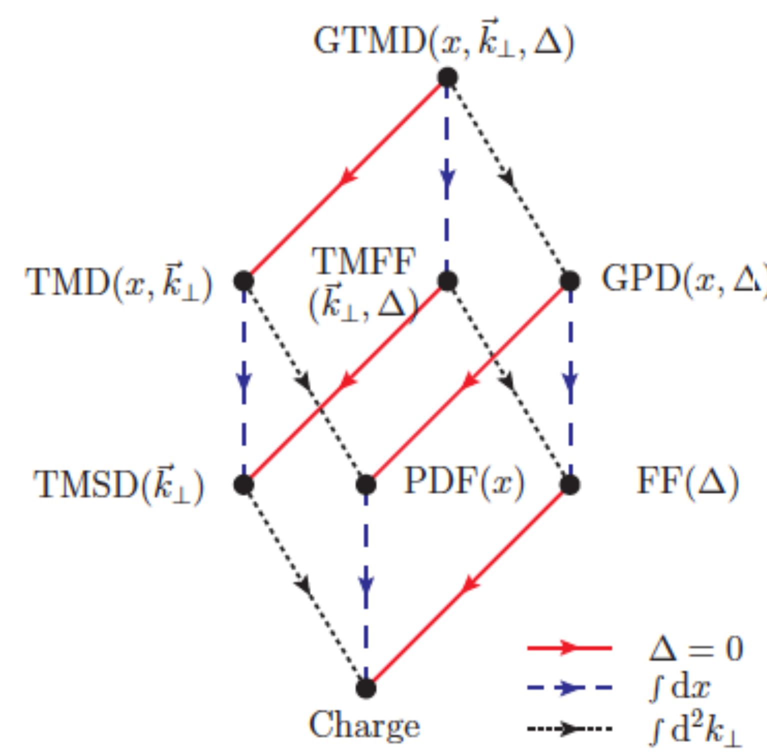


(diagram from Lorcé, Pasquini, Vanderhaeghen, 2011)

- GTMDs describe the most general two-parton structure of hadrons

A. Metz

Are There Novel Views on Nucleon Structure

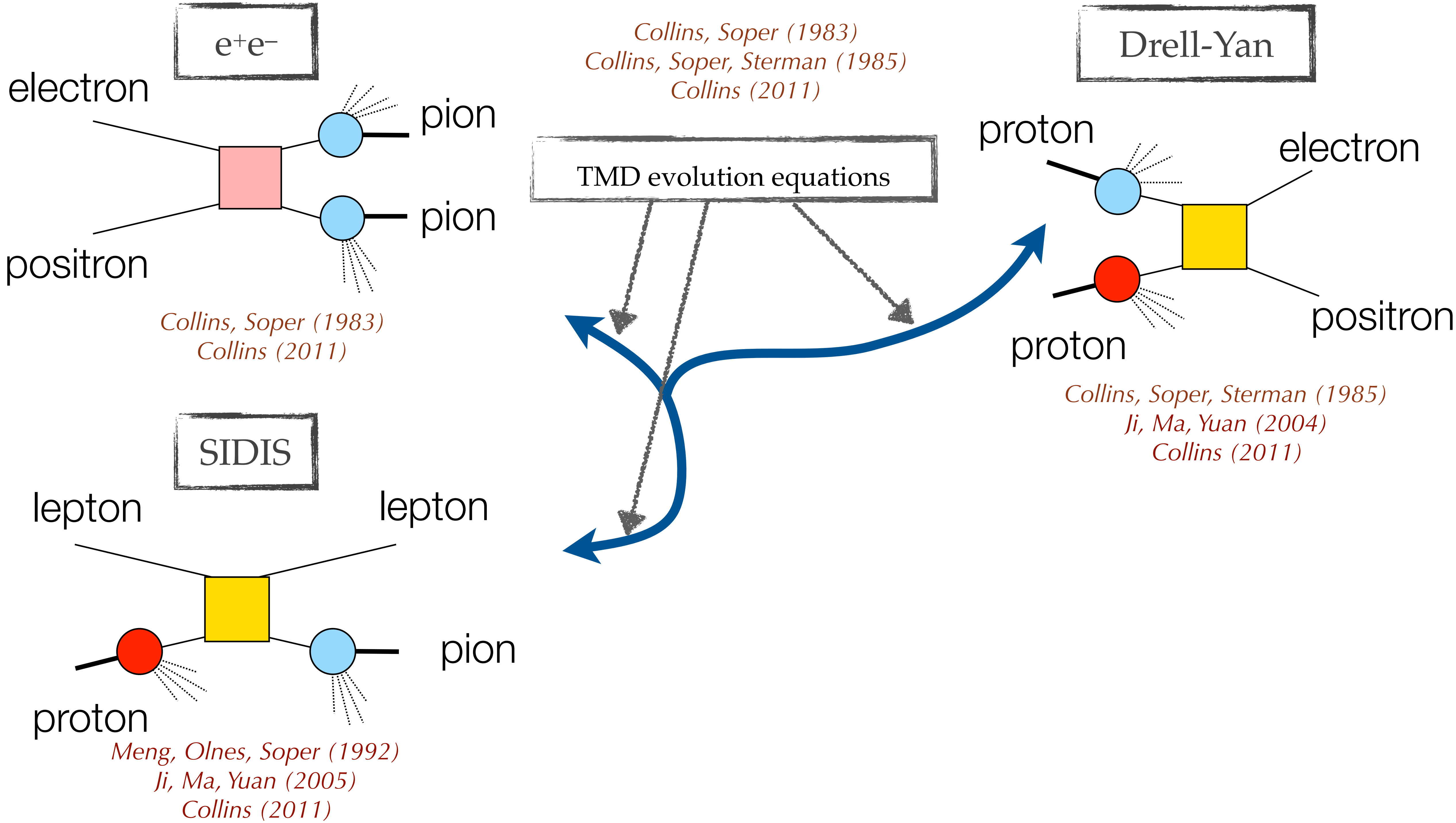
The proton as an entangled multipartite state?

- It could shed light on the transition from collinear → 3D picture
  - At level of partons/good fields: transition from PDFs to TMDs with staple gauge links
  - Role of Wilson loops in unifying dipole and TMD pictures at small x
- Many open ends remain!

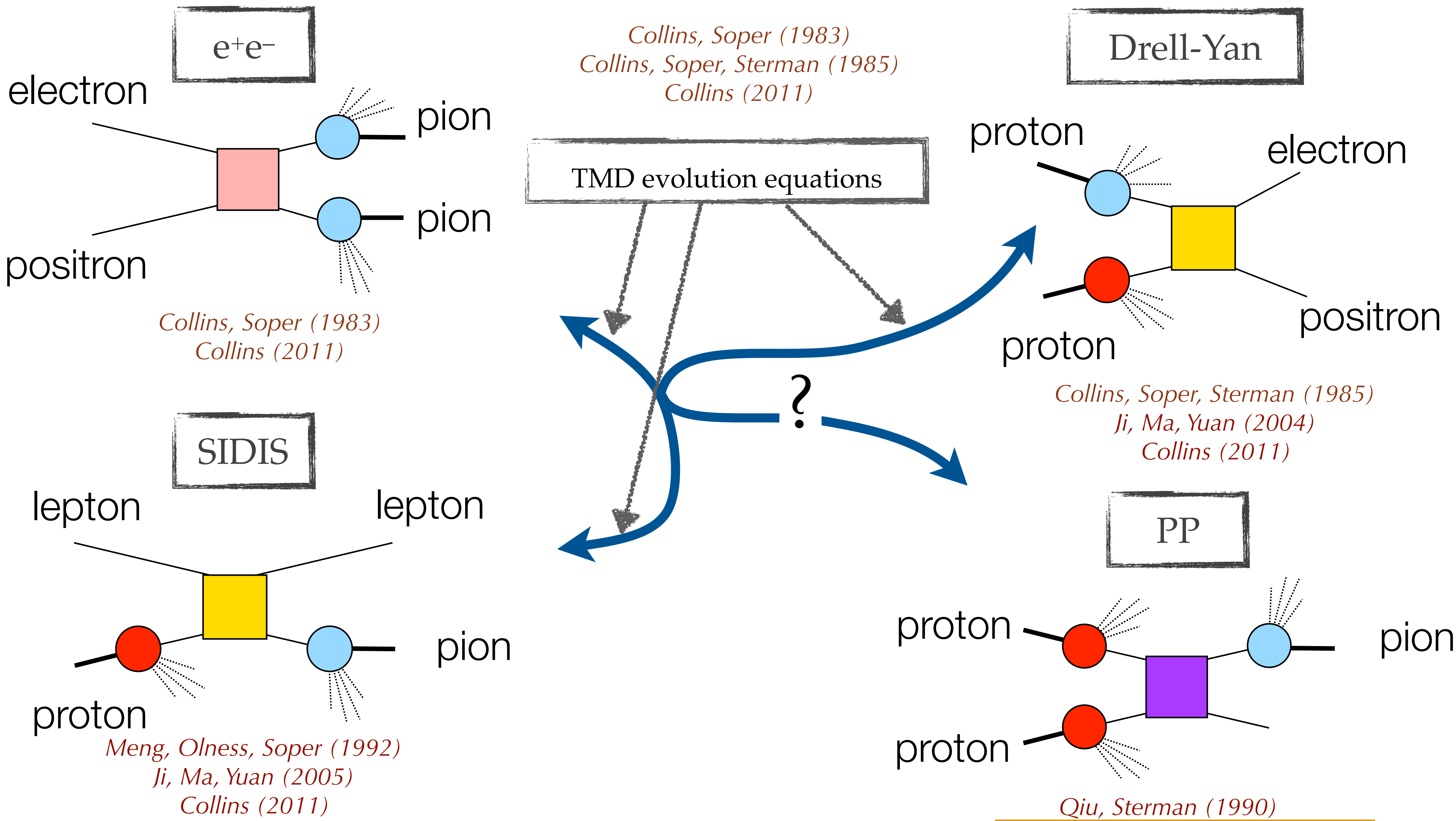
P. Mulders

Why TMDs, factorization, and evolution

TMD factorization

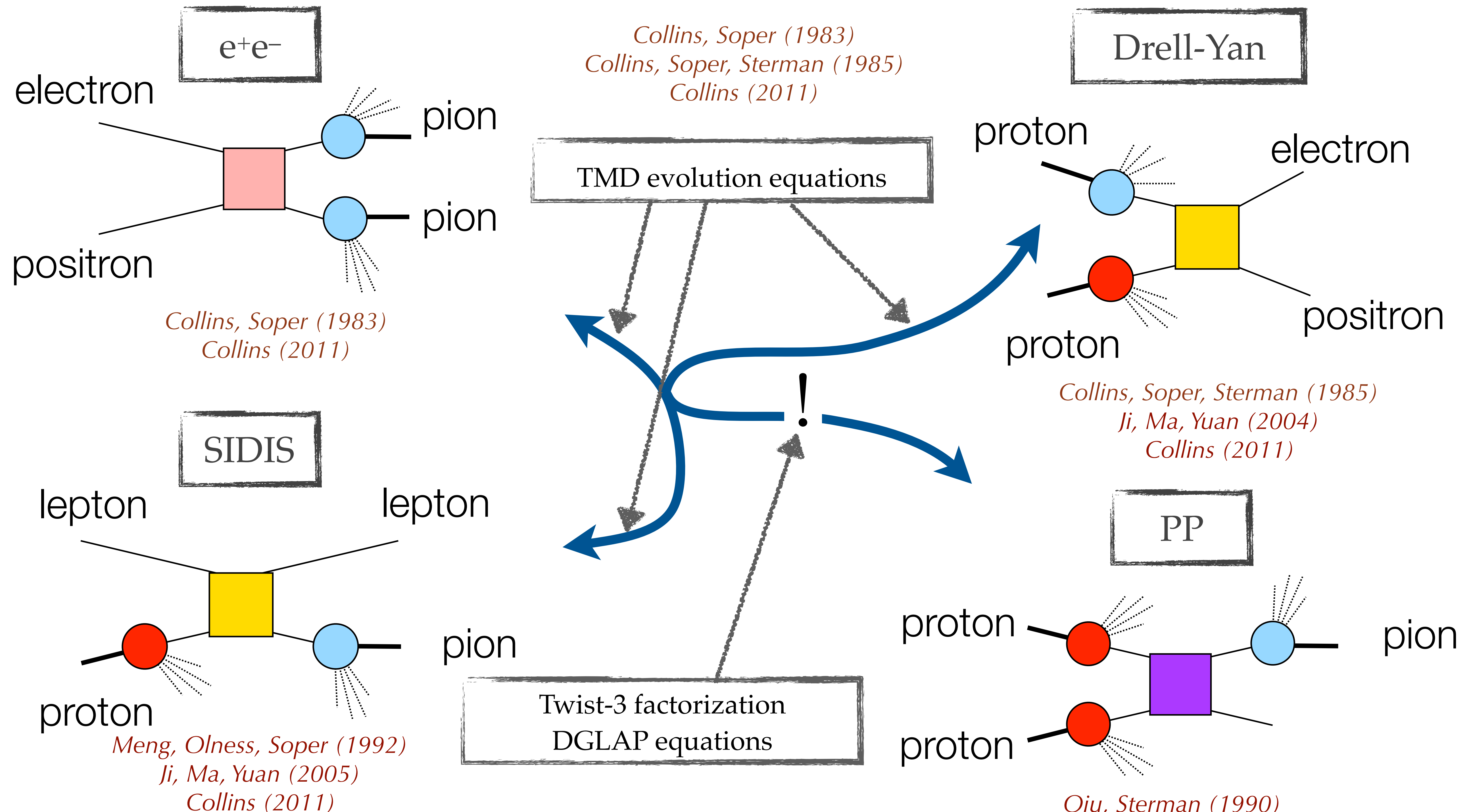


TMD factorization



Only one scale is measured in PP
TMD factorization is not applicable?

TMD factorization



- Twist-3 functions are related to TMD via OPE
- TMD and twist-3 factorizations are related in high QT region
- Global analysis of TMDs and twist-3 is possible:

All four processes can be used.

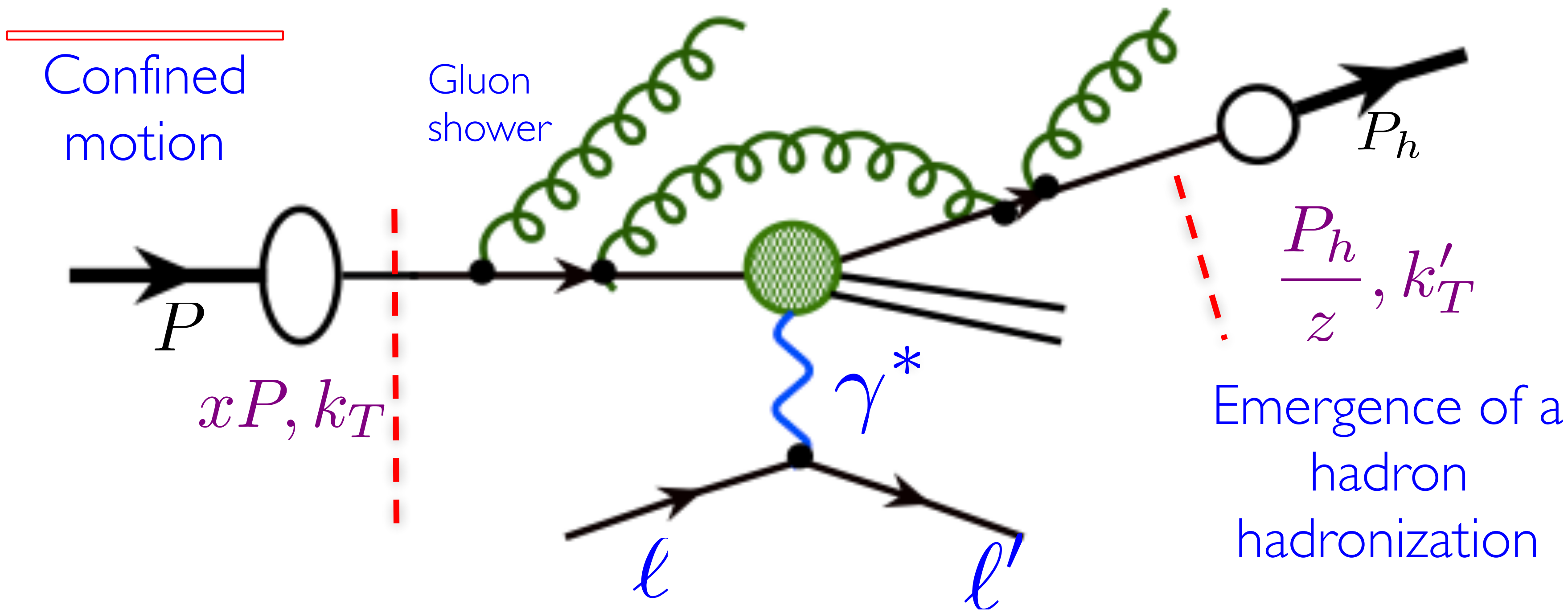
- Data are from HERMES, COMPASS, JLab,

BaBar, Belle, RHIC, LHC, Fermilab

Global fit is needed.
Work in progress

Studies of TMD evolution happened after EIC White paper!

Study of evolution gives us insight on different aspects and origin of confined motion of partons, gluon radiation, parton fragmentation



Evolution allows to connect measurements at very different scales.

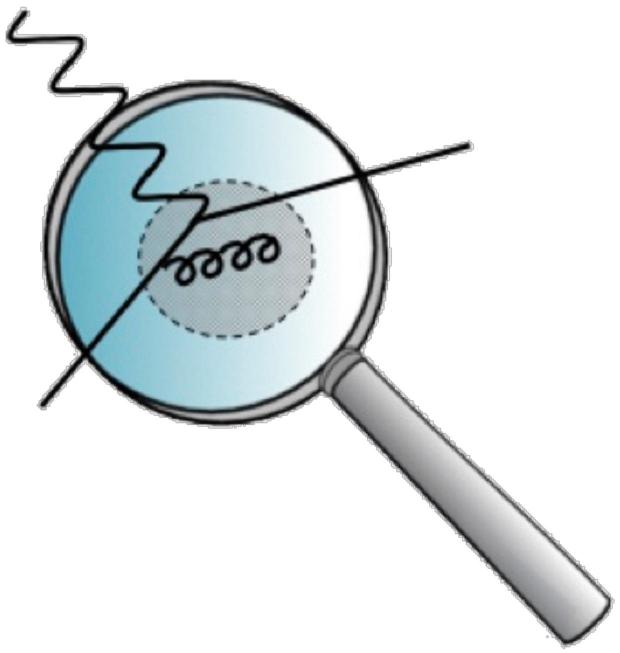
TMD evolution has also a universal non-perturbative part. The result of evolution cannot be uniquely predicted using evolution equations until the non-perturbative part is reliably extracted from the data.

Just like collinear PDFs, TMDs also depend on the scale of the probe = evolution

Collinear PDFs

$F(x, Q)$

- ✓ DGLAP evolution
- ✓ Resum $\left[\alpha_s \ln(Q^2/\mu^2)\right]^n$
- ✓ Kernel: purely perturbative



TMDs

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

- ✓ Collins-Soper/rapidity evolution equation
- ✓ Resum $\left[\alpha_s \ln^2(Q^2/k_\perp^2)\right]^n$
- ✓ Kernel: can be non-perturbative when $k_\perp \sim \Lambda_{\rm QCD}$

$$F(x, Q_i) \downarrow R^{\rm coll}(x, Q_i, Q_f) \downarrow F(x, Q_f)$$

$$F(x, k_\perp, Q_i) \downarrow R^{\rm TMD}(x, k_\perp, Q_i, Q_f) \downarrow F(x, k_\perp, Q_f)$$

TMD evolution and non-perturbative component

- Fourier transform back to the momentum space, one needs the whole b region (large b): need some non-perturbative extrapolation
  - Many different methods/proposals to model this non-perturbative part

$$F(x,k_\perp;Q)=\frac{1}{(2\pi)^2}\int d^2b e^{ik_\perp\cdot b}F(x,b;Q)=\frac{1}{2\pi}\int_0^\infty db\, bJ_0(k_\perp b)F(x,b;Q)$$

Collins, Soper, Sterman 85, ResBos, Qiu, Zhang 99, Echevarria, Idilbi, Kang, Vitev, 14, Aidala, Field, Gamberg, Rogers, 14, Sun, Yuan 14, D'Alesio, Echevarria, Melis, Scimemi, 14, Rogers, Collins, 15, Vladimirov, Scimemi 17…

- Eventually evolved TMDs in b-space

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

longitudinal/collinear part

transverse part

✓ Non-perturbative: fitted from data

✓ The key ingredient – ln(Q) piece is spin-independent

Since the polarized scattering data is still limited kinematics, we can use unpolarized data to constrain/extract key ingredients for the non-perturbative part

A. Bacchetta, A. Vladimirov, A. Signori, L. Gamberg

Quark TMDs

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

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

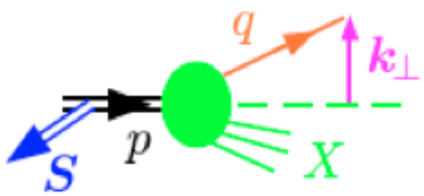
Gluon TMDs

	GLUON POLARIZATION			WILSON LOOP
	Unpolarized	**Circular**	**Linear**	
TARGET SPIN U	f_1		$h_1^\perp$	e
TARGET SPIN L		g_1	$h_{1L}^\perp$	
TARGET SPIN T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$	e_T

Sabrina Cotogno, Cristian Pisano

Sivers function: unpolarized quark distribution inside a transversely polarized nucleon

Sivers 1989



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

Spin independent

Spin dependent

Sivers function: $f_{1T}^{\perp q}$ describes strength of correlation $\vec{S} \cdot (\hat{P} \times \vec{k}_\perp)$

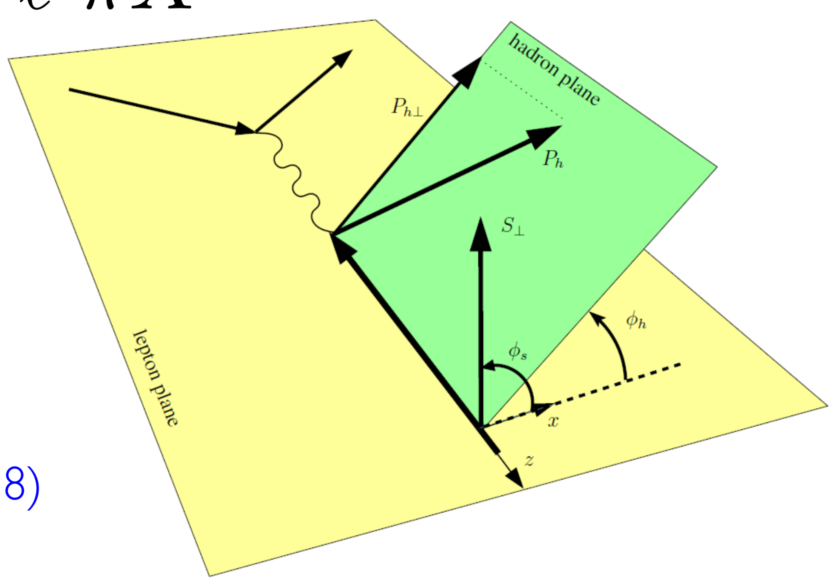
Sivers 1989

This function is extensively studied experimentally, phenomenologically, theoretically

$$\ell P \to \ell' \pi X$$

Sivers function gives rise to Single Spin Asymmetries in scattering processes. For instance in Semi Inclusive Deep Inelastic process

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



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

Sivers function

Large – N_c result $$f_{1T}^{\perp u} = -f_{1T}^{\perp d}$$ Pobylitsa 2003

→ Confirmed by phenomenological extractions

→ Confirmed by experimental measurements

Relation to GPDs (E) and anomalous magnetic moment Burkardt 2002

$$f_{1T}^{\perp q} \sim \kappa^q$$

→ Predicted correct sign of Sivers asymmetry in SIDIS

→ Shown to be model-dependent

Meissner, Metz, Goeke 2007

→ Used in phenomenological extractions

Bacchetta, Radici 2011

Sivers function

Sum rule

Burkardt 2004

→ Conservation of transverse momentum

→ Average transverse momentum shift of a quark inside a transversely polarized nucleon

$$\langle k_T^{i,q} \rangle = \varepsilon_T^{ij} S_T^j f_{1T}^{\perp(1)q}(x)$$

$$f_{1T}^{\perp(1)q}(x) = \int d^2k_\perp \frac{k_\perp^2}{2M^2} f_{1T}^{\perp q}(x, k_\perp^2)$$

→ Sum rule

$$\sum_{a=q,g} \int_0^1 dx \langle k_T^{i,a} \rangle = 0 \qquad \sum_{a=q,g} \int_0^1 dx\, f_{1T}^{\perp(1)a}(x) = 0$$

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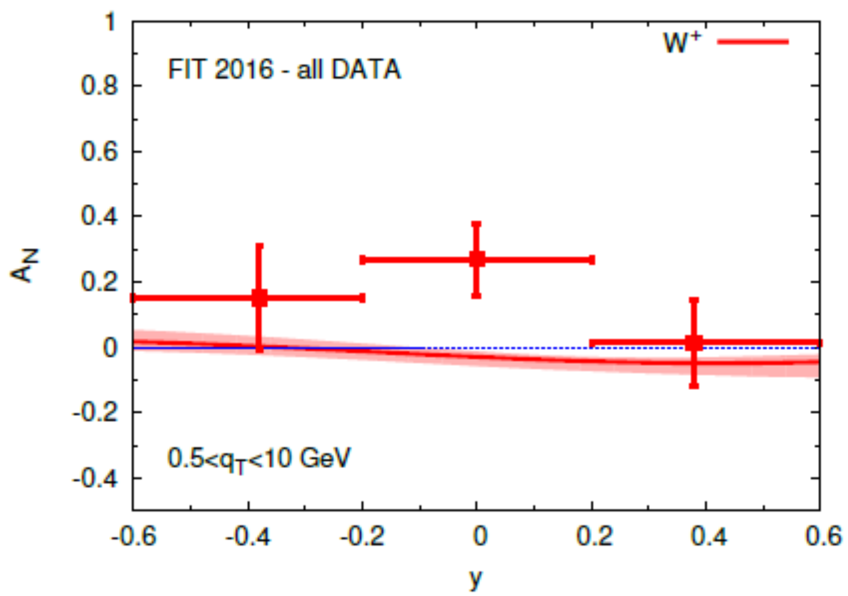
Process dependence of Sivers function

Anselmino et al 2016

- First experimental hint on the sign change: A_N in W and Z production



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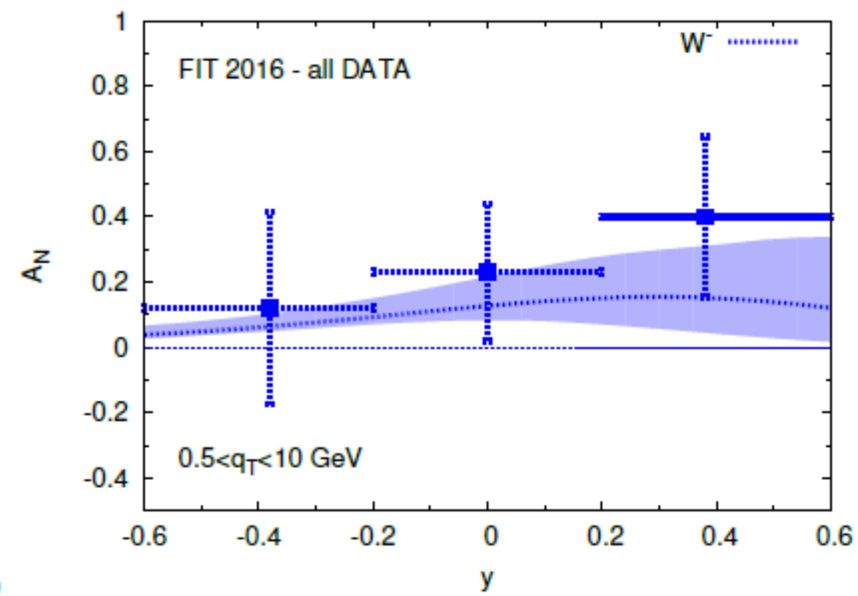
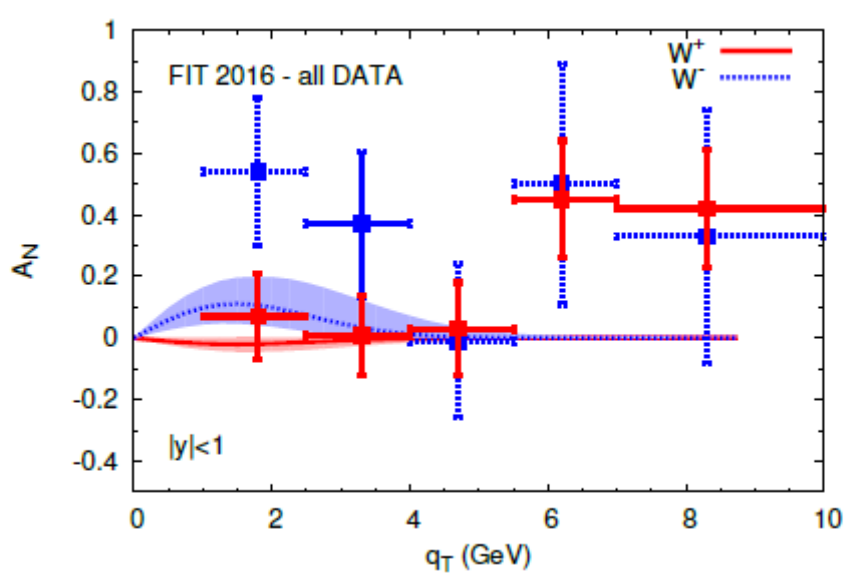


$$p^{\uparrow}p \to W^{\pm}X$$

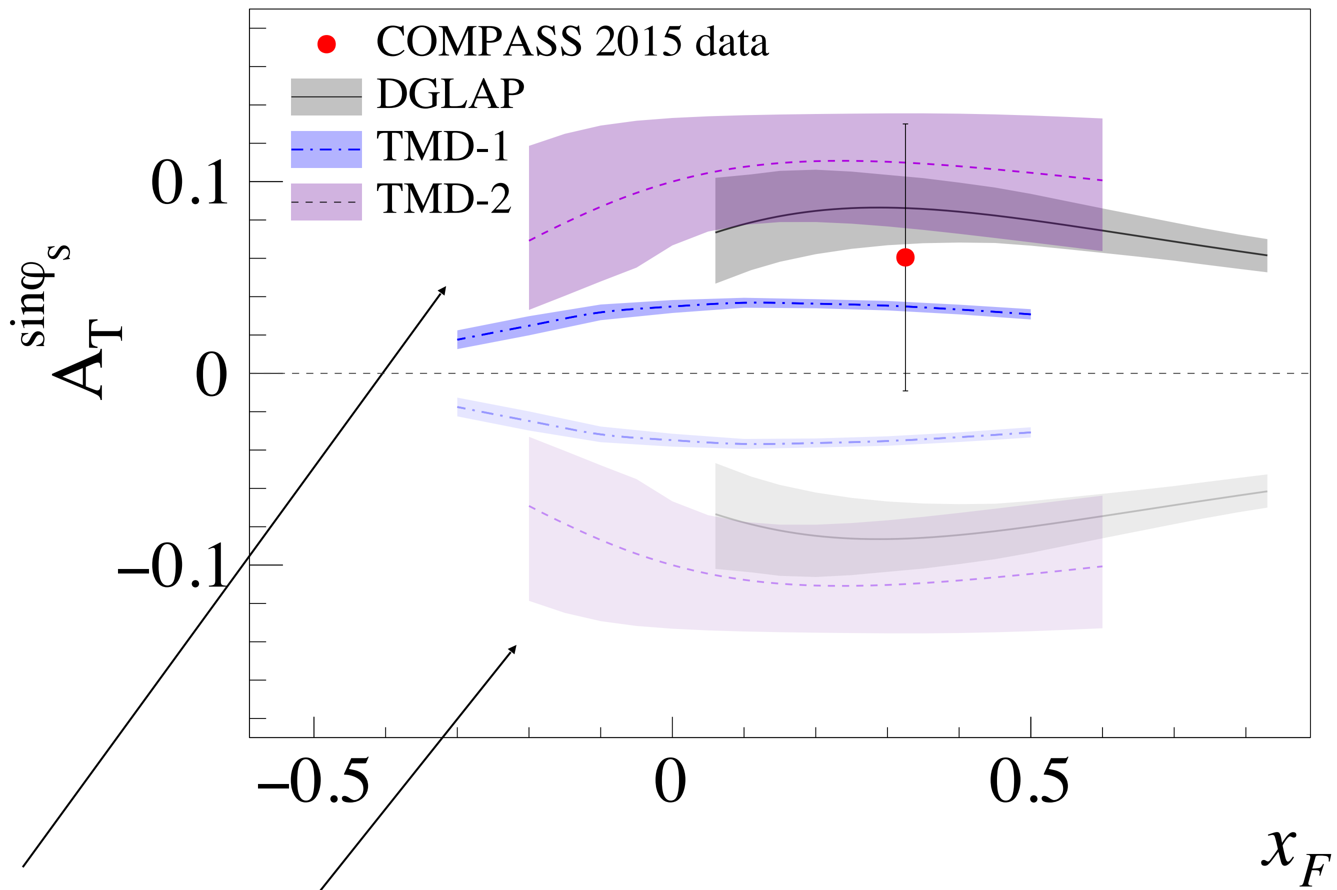


- Results with sign change
- No TMD evolution
- Antiquark Sivers functions included
- STAR results hint on sign change

Process dependence of Sivers function

COMPASS 2017

→ First experimental hint on the sign change in Drell-Yan



→ Sign change

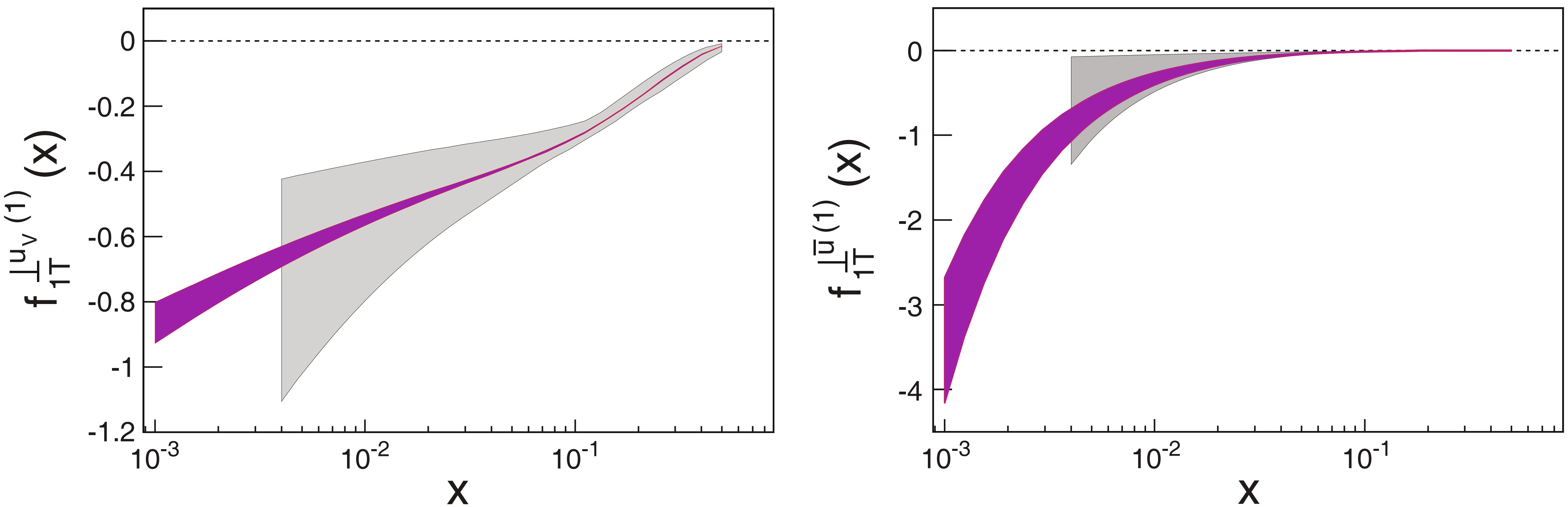
→ No sign change

→ COMPASS results hint on sign change

Sivers function

Expectation of EIC

AP 2010



Update of this and other estimates is needed and work is in progress

- There has been a lot of progress in the last few years in TMD physics
- TMD physics encompasses results of many different experimental facilities
- TMD physics is now extended to gluon TMD and small-x (not covered in this talk)
- Progress in lattice QCD is very exciting (not covered in this talk)

INT 2018

Probing Nucleons and Nuclei in High Energy Collisions (INT-18-3)
October 1 - November 16, 2018
Y. Hatta, Y. Kovchegov, C. Marquet, A. Prokudin

New developments of EIC related physics will be discussed, stay tuned for the program!