Overview and Recent Progress in TMDs

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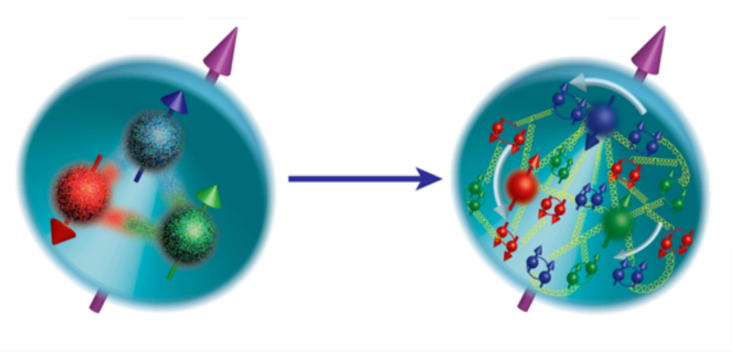
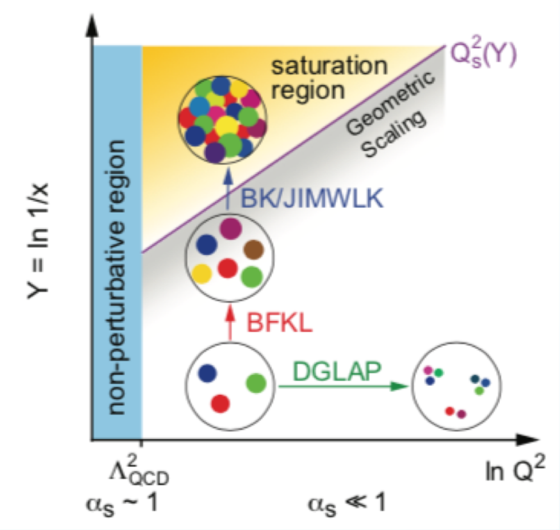
The proton in QCD

- Proton is made of
  - 2 up quarks + 1 down quarks ➡ **valence quarks**
  - + any number of quark-antiquark pairs ➡ **sea quarks**
  - + any number of gluons





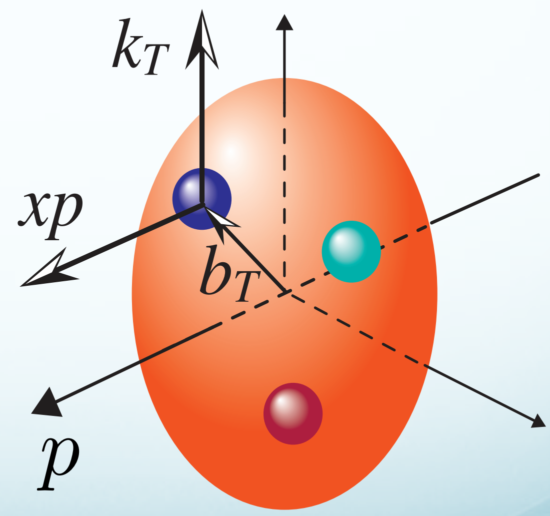
✓ **Infinite many body dynamic system of quarks and gluons**
✓ **By changing *x* and *Q*, we probe different aspects of the proton wave function**

Quark and gluon structure of the nucleon

- Goal: quantum tomography in terms of quarks and gluons
  - **Momentum**: how do the quarks, antiquarks, gluons move inside?
  - **Position**: where are they located?
  - **Orbit**: do they orbit, carry orbital angular momentum?
  - **Correlation**: quantum correlations between motion and overall nucleon properties, e.g., spin? How do they respond to the external probes?

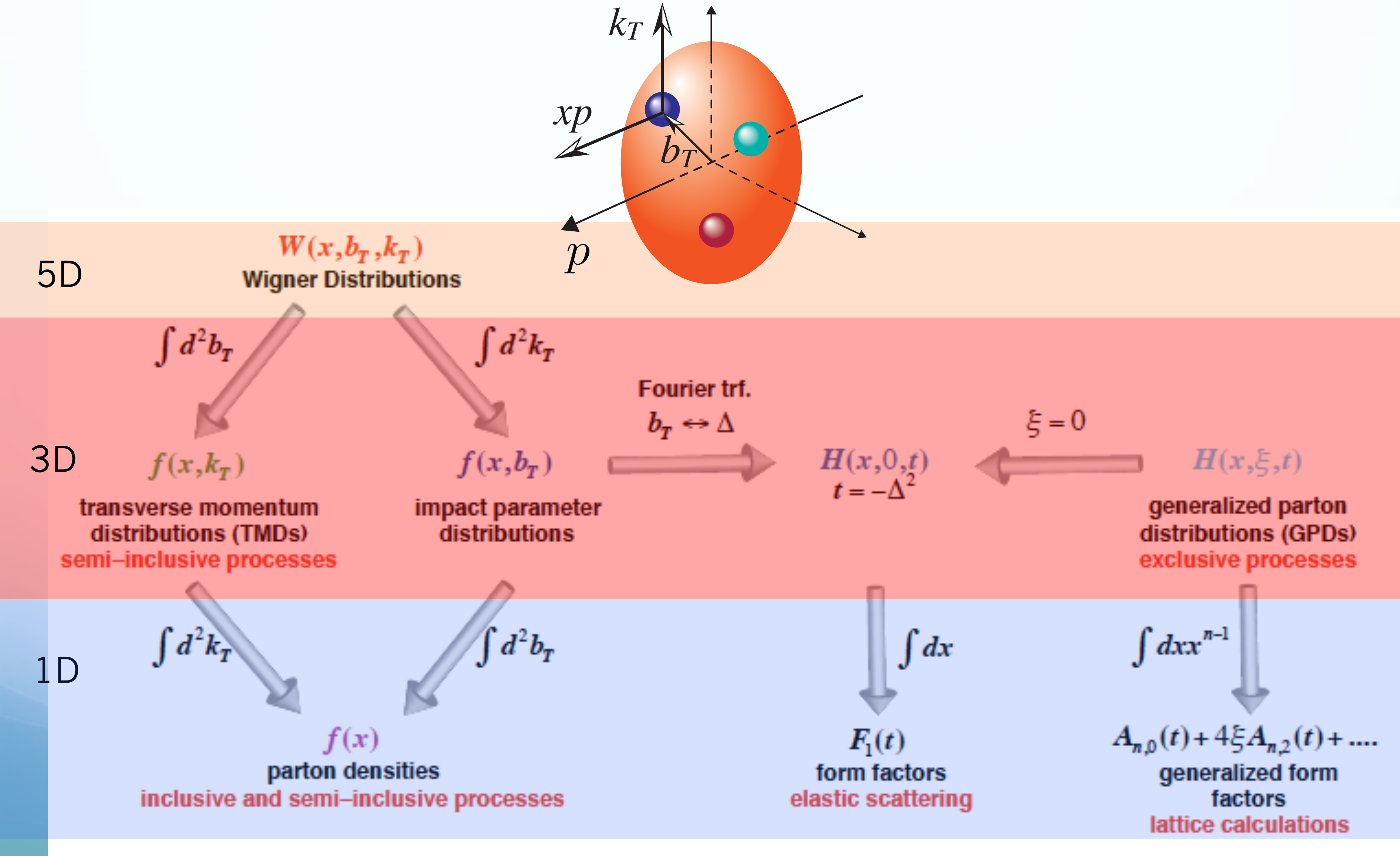
Internal landscape of the nucleon

Such information are defined as a set of **parton distribution functions**



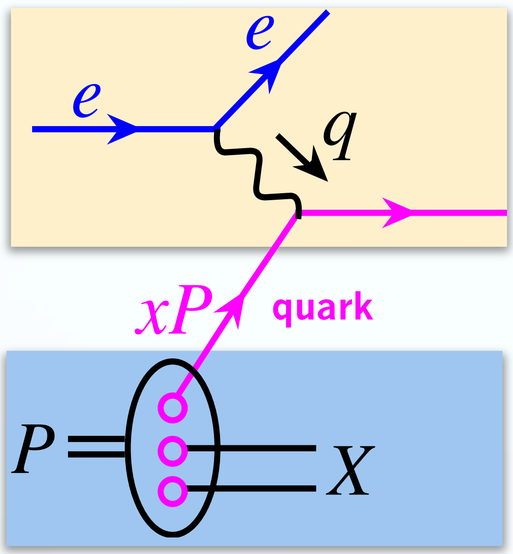
Unified view: internal landscape

- Wigner distributions: a quantum version of phase-space distribution



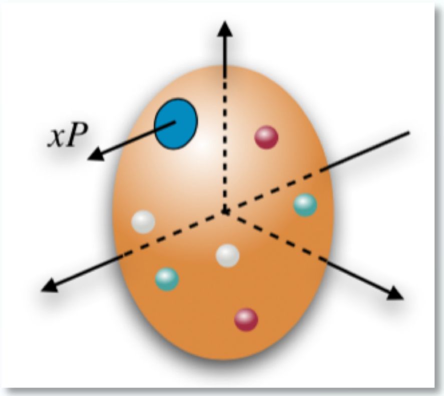
QCD factorization

- Take deep inelastic scattering as an example



$\hat{\sigma}_{q,g}(Q)$

$f_{q,g}(x,Q)$



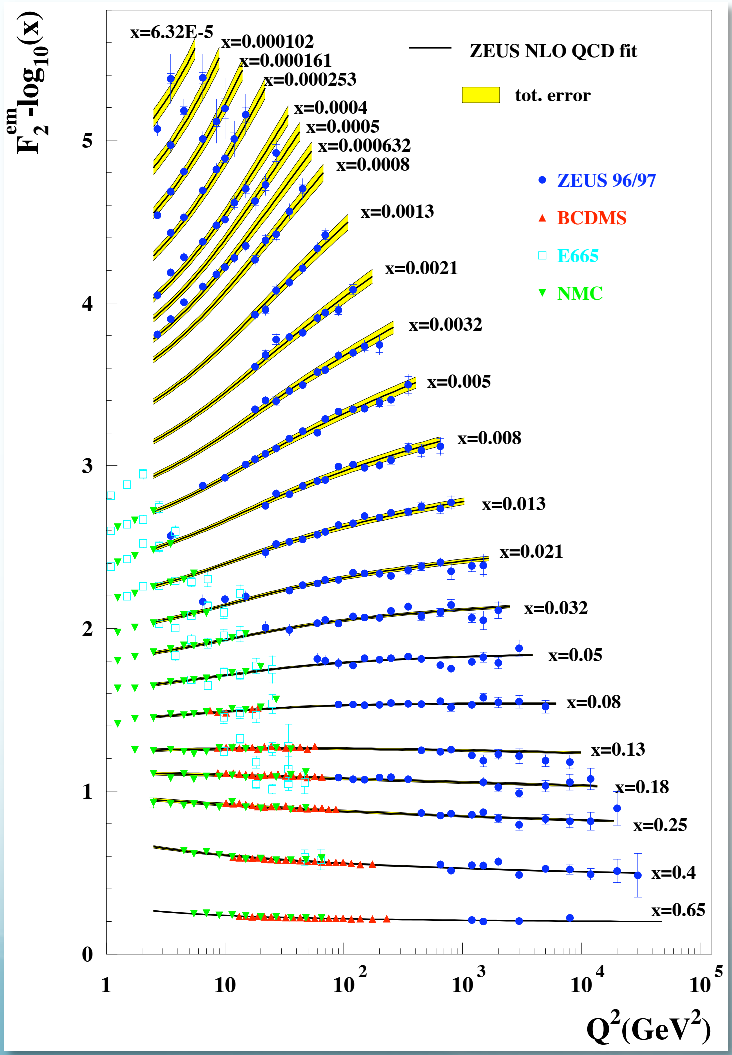
$$\sigma_{\text{proton}}(Q) = \hat{\sigma}_{q,g}(Q) \otimes f_{q,g}(x,Q)$$

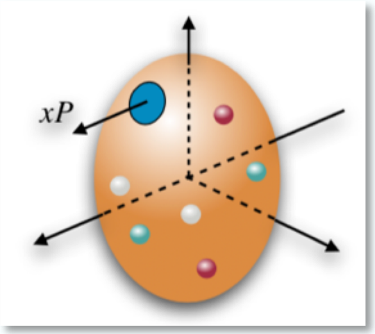
measured **calculable** **extracted**

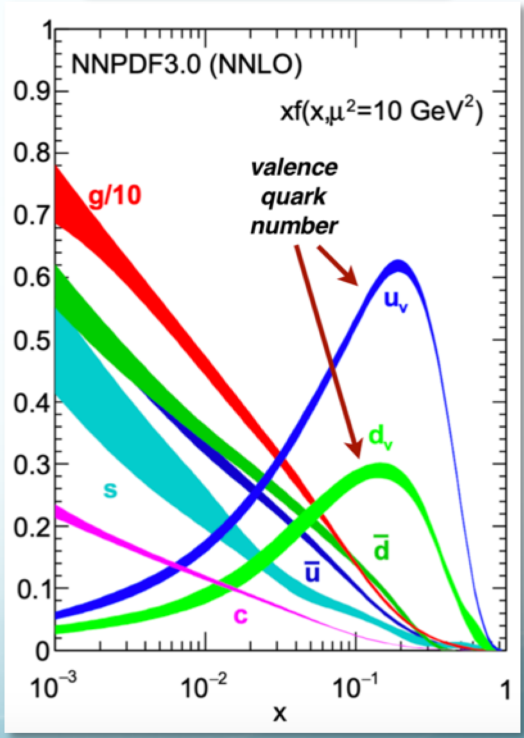
- Proton structure: encoded in PDFs
- QCD dynamics at high-energy scale Q

Colinear PDFs

- One dimensional structure of the proton: longitudinal motion





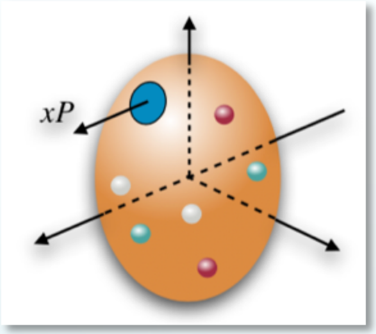


See E. R. Nocera talk

Moving forward

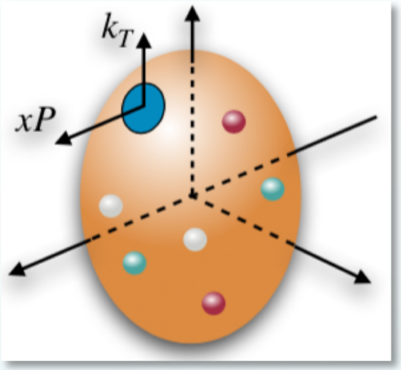
- 30+ years' study, good knowledge about parton's longitudinal motion: 1D
- Nucleon 3D structure: both longitudinal + transverse momentum dependent structure

Transverse Momentum Dependent parton distributions (TMDs)



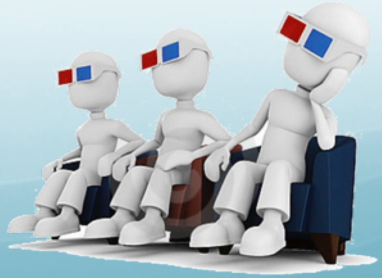
$f(x)$

Longitudinal motion only



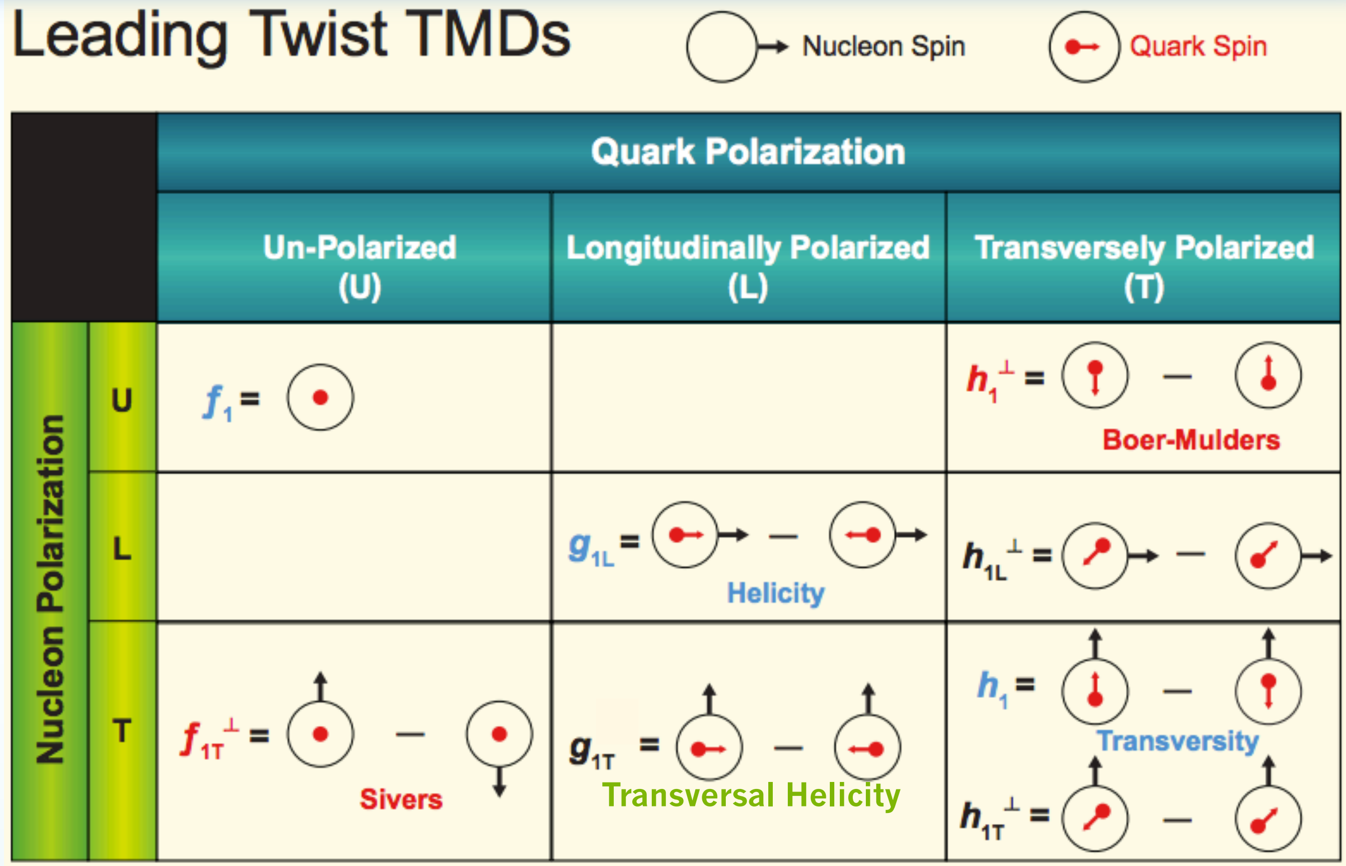
$f(x, k_T)$

Longitudinal + transverse motion



TMDs: rich quantum correlations

TMD parton distribution



TMD fragmentation function

	Quark Polarization U	L	T
Pion	D_1		$H_1^\perp$ **Collins**

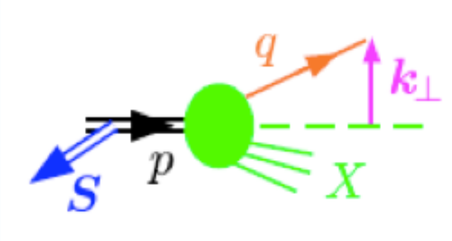
Novel insights from TMDs

- Quantum correlation: spin-spin, spin-momentum (orbit) correlations
  - Akin to those in hydrogen atoms and topological insulators
- 3D imagining
  - Both longitudinal and transverse motion
- Orbital motion
  - Most TMDs would vanish in the absence of parton orbital angular momentum
- Color gauge invariance at a very deep level
  - Akin to Aharonov-Bohm Effect

Using the nucleon as a QCD "laboratory"

Sivers function: non-universal

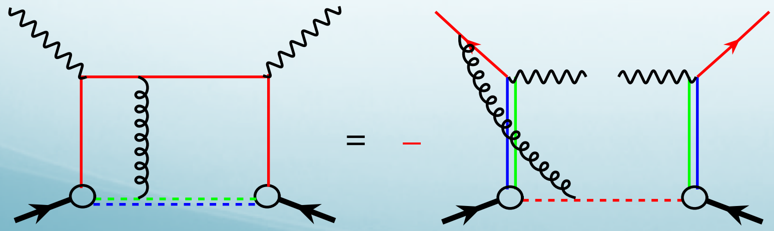
- Sivers function: unpolarized quark distribution inside a transversely polarized proton



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

Spin-independent   Spin-dependent

- ✓ 1990: introduced by D. Sivers, to describe the large single spin asymmetry measured in inclusive hadron production in p+p collisions at Fermilab
- ✓ 1993: J. Collins shows Sivers function has to vanish due to time-reversal invariance
- ✓ 2002: Brodsky, Hwang, Schmidt performed an explicit model calculation, showed the existence of the Sivers function
- ✓ 2002: Original proof missed the gauge link (needed to properly define gauge invariant distribution), once added, found Sivers function in SIDIS is opposite to that in Drell-Yan



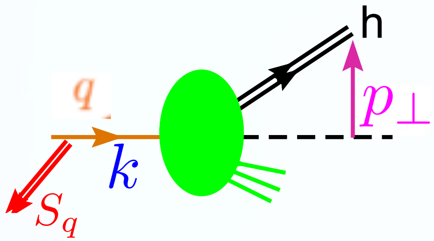
SIDIS = − DY

$$f_{1T}^{\perp \mathrm{DIS}}(x, k_\perp) = -f_{1T}^{\perp \mathrm{DY}}(x, k_\perp)$$

Collins 02, Boer-Mulders-Pijlman 03, Kang-Qiu, 09 ...

Collins function: universal

- Collins function: unpolarized hadron from a transversely polarized quark



$$D_{h/q}(z,p_\perp) = D_1^q(z,p_\perp^2) + \frac{1}{zM_h} H_1^{\perp q}(z,p_\perp^2)\vec{S}_q \cdot \left(\hat{k} \times p_\perp\right)$$

Spin-independent Spin-dependent

- ✓ 2002: Metz studied the universality property of Collins function in a model-dependent way – very subtle – finally found it is universal between SIDIS and e+e-
- ✓ 2004: Collins and Metz have general arguments
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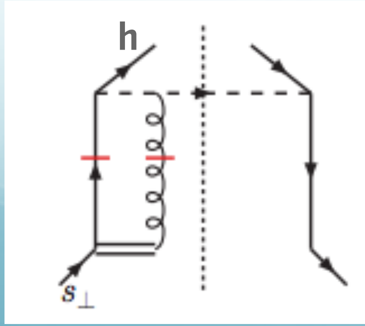
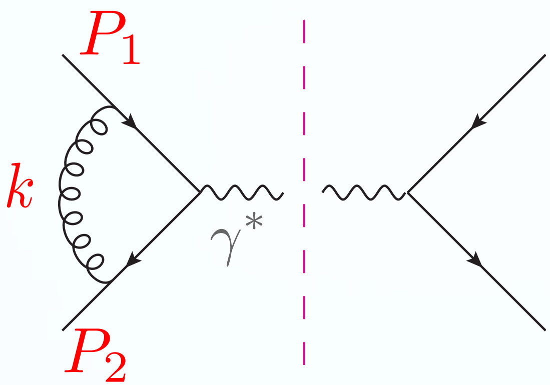


$$H_1^{\perp \mathrm{SIDIS}}(z,p_\perp^2) = H_1^{\perp e^+e^-}(z,p_\perp^2) = H_1^{\perp \mathrm{pp}}(z,p_\perp^2)$$

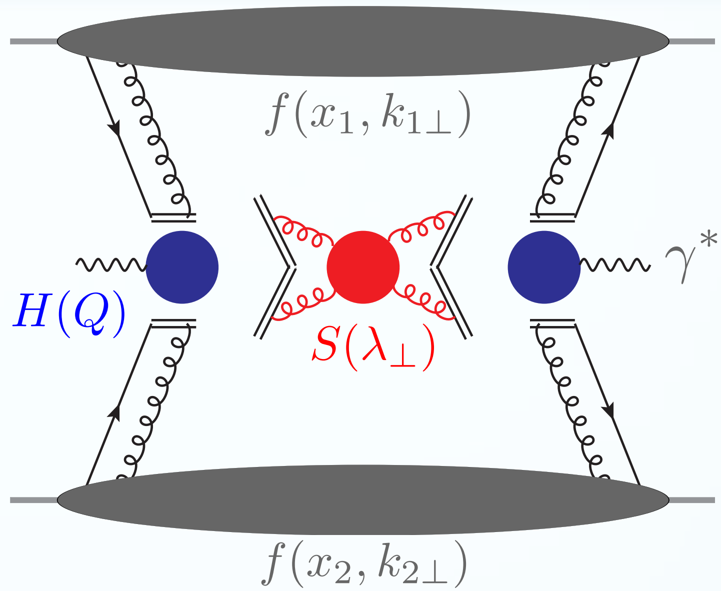
Metz 02, Collins, Metz 04, Yuan 08, Yuan, Zhou 09, Boer, Kang, Vogelsang, Yuan, PRL 10, ...

TMD factorization in a nut-shell

- Drell-Yan: $p+p \to [\gamma^* \to \ell^+\ell^-] + X$



Factorization of regions:
(1) k//P$_1$, (2) k//P$_2$, (3) k soft, (4) k hard



- Factorized form and mimic "parton model"

$$\frac{d\sigma}{dQ^2 dy d^2 q_\perp} \propto \int d^2k_{1\perp}\, d^2k_{2\perp}\, d^2\lambda_\perp H(Q) f(x_1, k_{1\perp}) f(x_2, k_{2\perp}) S(\lambda_\perp) \delta^2(k_{1\perp} + k_{2\perp} + \lambda_\perp - q_\perp)$$

$$= \int \frac{d^2b}{(2\pi)^2} e^{iq_\perp \cdot b} H(Q) f(x_1, b) f(x_2, b) S(b)$$

$$F(x,b) = f(x,b)\sqrt{S(b)}$$

$$= \int \frac{d^2b}{(2\pi)^2} e^{iq_\perp \cdot b} H(Q) F(x_1, b) F(x_2, b)$$

mimic "parton model"

TMD evolves

- 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 in a nutshell

$$F(x, k_\perp; Q) = \frac{1}{(2\pi)^2} \int d^2b e^{ik_\perp \cdot b} F(x, b; Q) = \frac{1}{2\pi} \int_0^\infty db\, b J_0(k_\perp b) F(x, b; Q)$$

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

longitudinal/collinear part

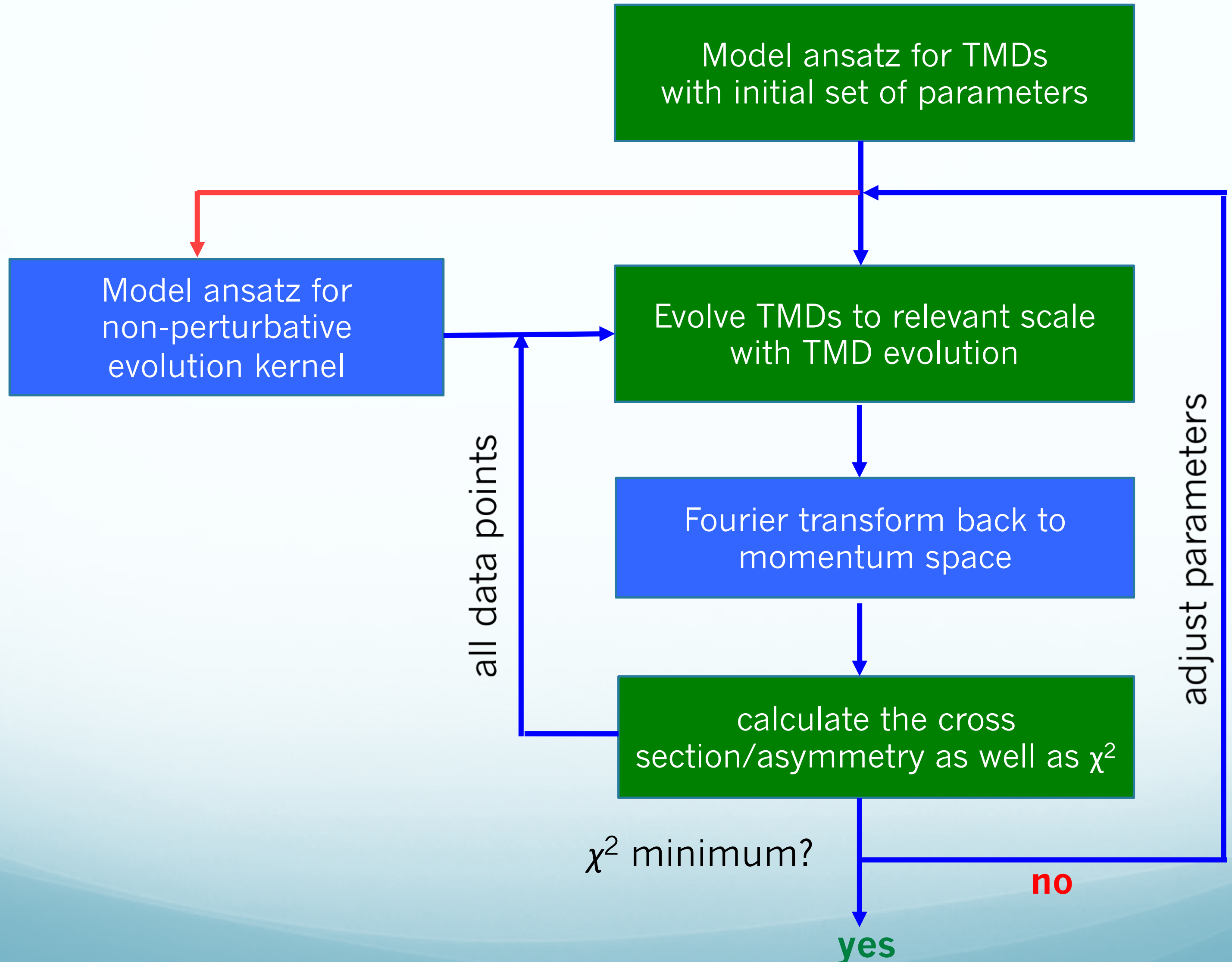
transverse part

- ✓ Non-perturbative: fitted from data
- ✓ The key ingredient – ln(Q) piece is spin-independent

The presence of non-perturbative evolution kernel makes TMD global analysis much more involved

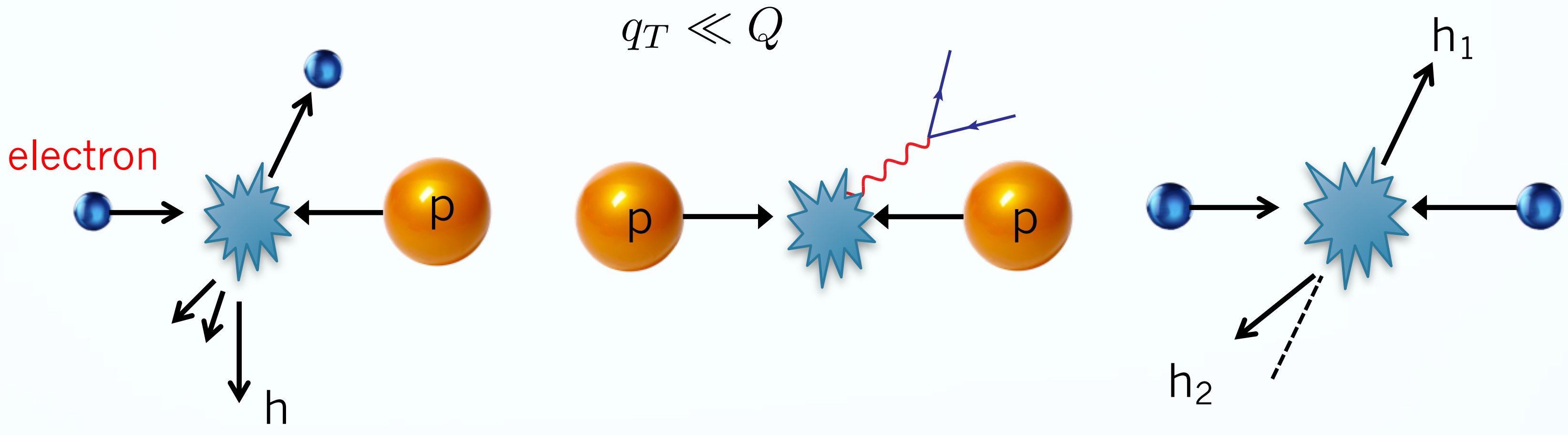
TMD global analysis

- Outline of a TMD global analysis: numerically more heavy



Standard processes to extract TMDs

- SIDIS, Drell-Yan, dihadron in e^+e^-



- They have a well-established TMD factorization formalism

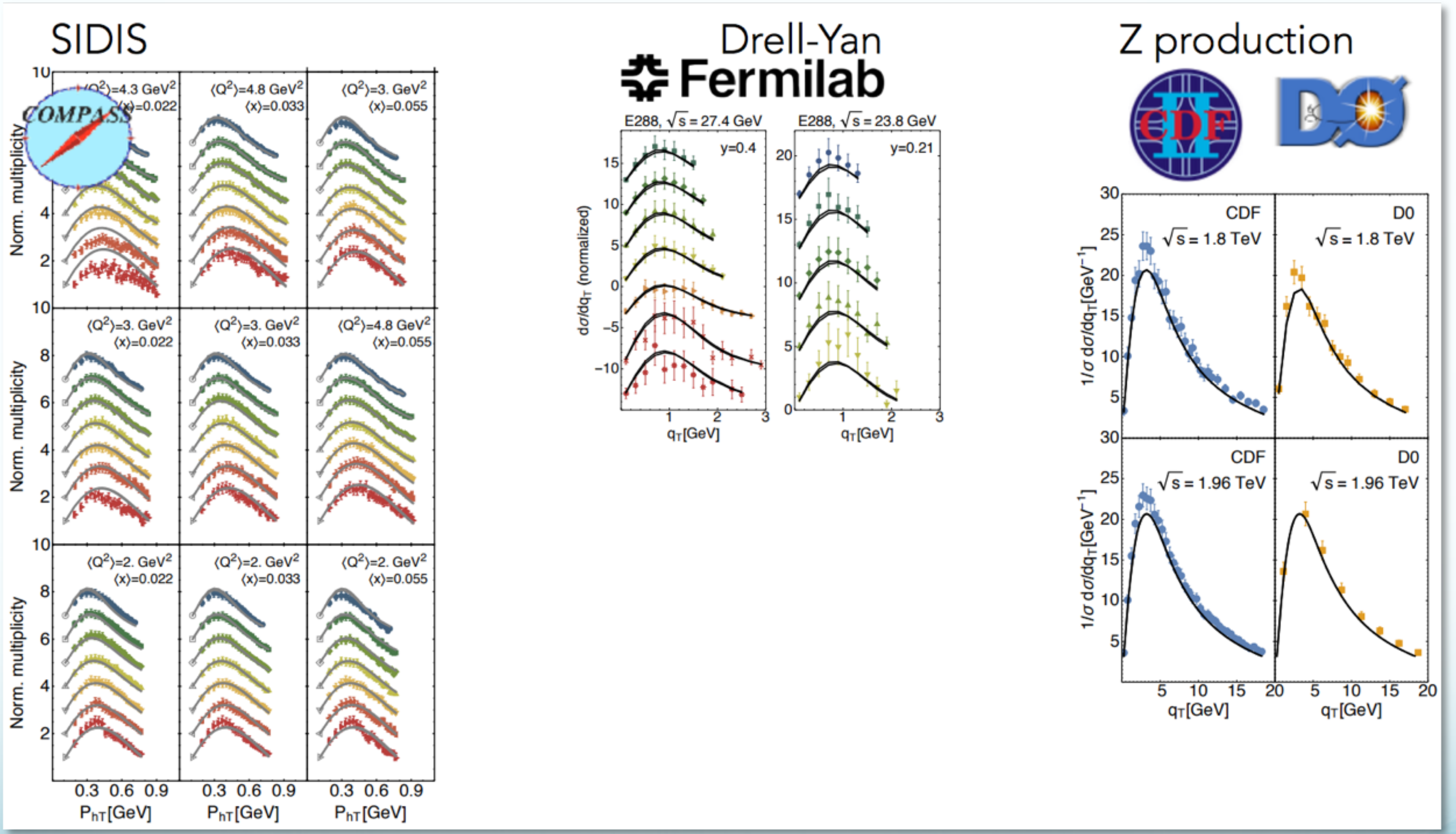
Extremely active phenomenology - 1

- Examples: Pavia, Torino, EIKV, KSPY, DEMS, SV...

	Framework	W+Y	HERMES	COMPASS	DY	Z production	N of points
KN 2006 hep-ph/0506225	LO-NLL	W	✘	✘	✔	✔	98
QZ 2001 hep-ph/0506225	NLO-NLL	W+Y	✘	✘	✔	✔	28 (?)
RESBOS resbos@msu	NLO-NNLL	W+Y	✘	✘	✔	✔	>100 (?)
Pavia 2013 arXiv:1309.3507	LO	W	✔	✘	✘	✘	1538
Torino 2014 arXiv:1312.6261	LO	W	✔ (separately)	✔ (separately)	✘	✘	576 (H) 6284 (C)
DEMS 2014 arXiv:1407.3311	NLO-NNLL	W	✘	✘	✔	✔	223
EIKV 2014 arXiv:1401.5078	LO-NLL	W	1 (x,Q^2) bin	1 (x,Q^2) bin	✔	✔	500 (?)
SIYY 2014 arXiv:1406.3073	NLO-NLL	W+Y	✘	✔	✔	✔	200 (?)
Pavia 2017 arXiv:1703.10157	LO-NLL	W	✔	✔	✔	✔	8059
SV 2017 arXiv:1706.01473	NNLO-NNLL	W	✘	✘	✔	✔	309
BSV 2019 arXiv:1902.08474	NNLO-NNLL	W	✘	✘	✔	✔	457

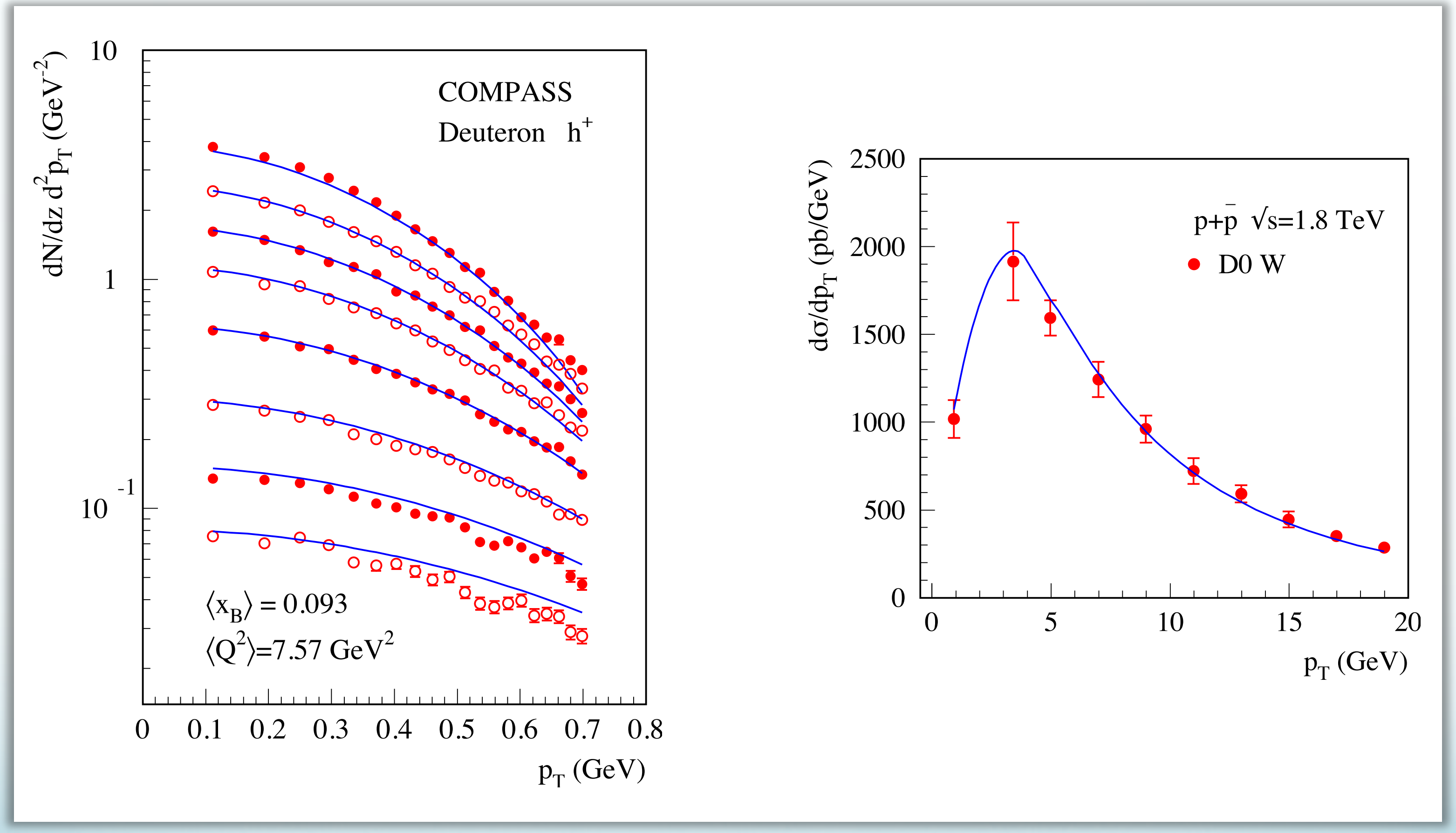
Extremely active phenomenology - 2

- Example: Pavia group



Extremely active phenomenology - 3

- Example: our group

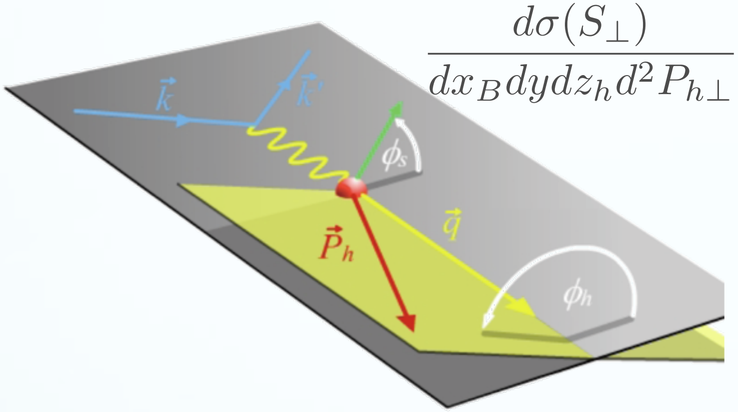


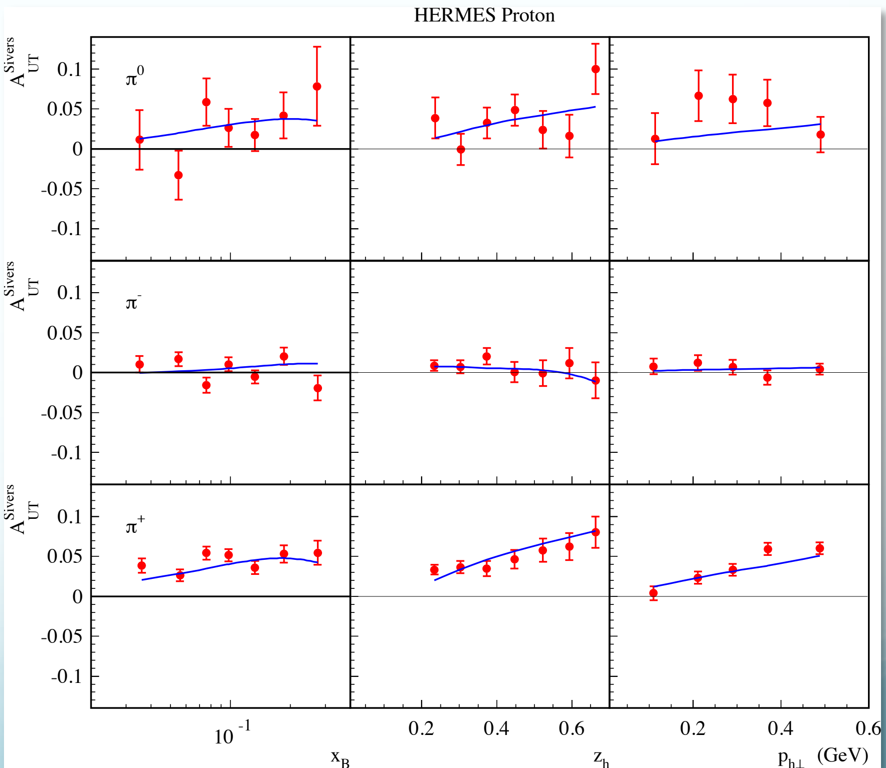
Sivers asymmetry from SIDIS

- Sivers asymmetry has been measured in SIDIS process: HERMES, COMPASS, JLab

$$\ell + p^{\uparrow} \rightarrow \ell' + \pi(p_T) + X$$

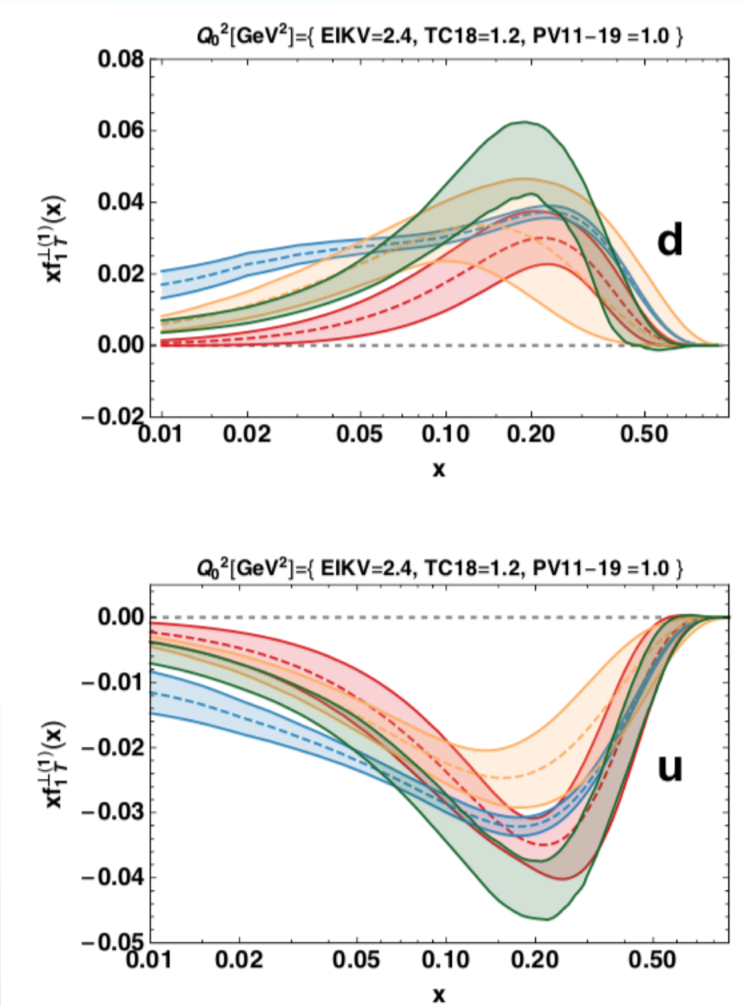
$$\frac{d\sigma(S_\perp)}{dx_B dy dz_h d^2 P_{h\perp}} = \sigma_0(x_B, y, Q^2)\left[F_{UU} + \sin(\phi_h - \phi_s)\, F_{UT}^{\sin(\phi_h - \phi_s)} + \ldots\right]$$





Current status of Sivers extraction

- Large uncertainties

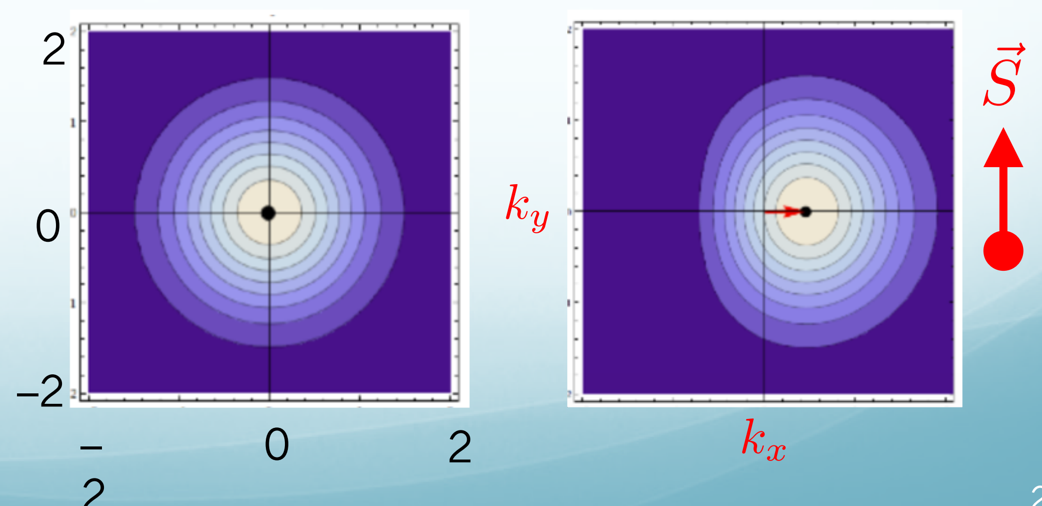


EIKV [1401.5078]

PV11 [1107.5755]

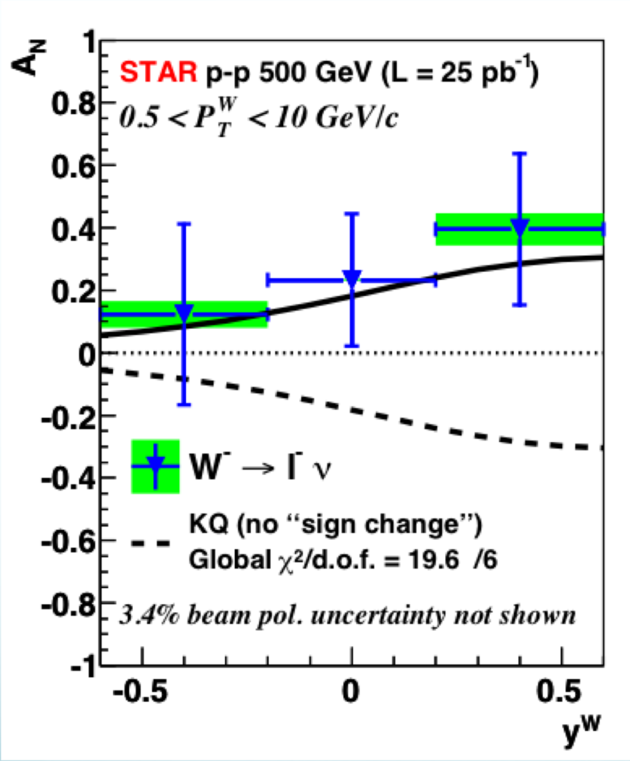
TC18 [1806.10645]

PV19 **preliminary** ≈ UCLA preliminary

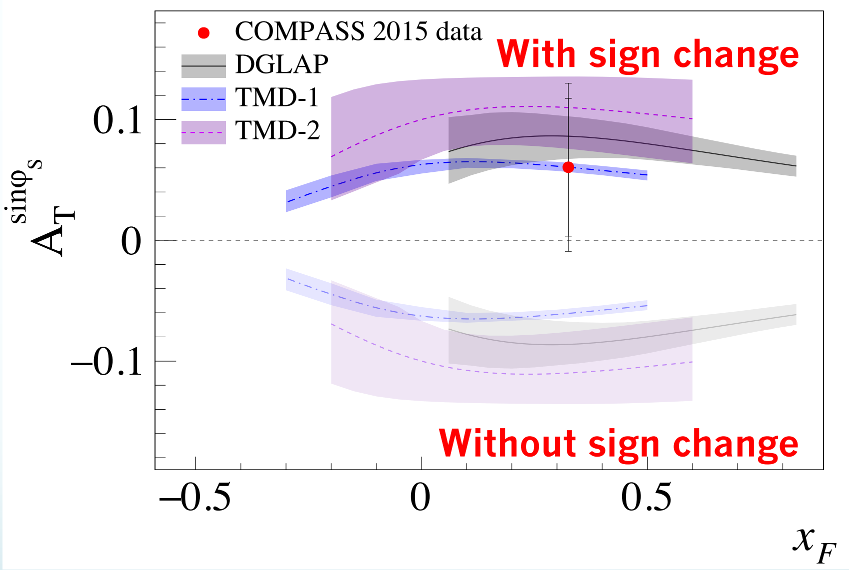


Experimental evidence of sign change

- STAR measurements: the data favors sign change
- Both theory and experiment has large uncertainty: will be improved with 2017 run



DY lepton pair



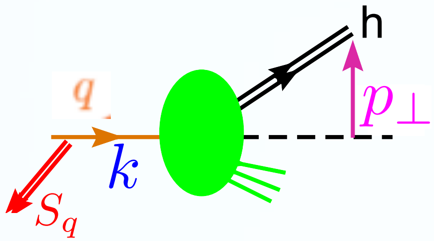
KQ = Kang, Qiu

STAR, arXiv:1511.06003, PRL

COMPASS, 1704.00488

Collins function: universal

- Collins function: unpolarized hadron from a transversely polarized quark



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Spin-independent   Spin-dependent

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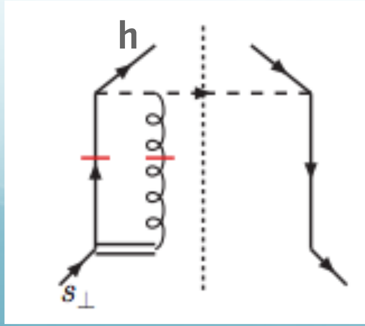
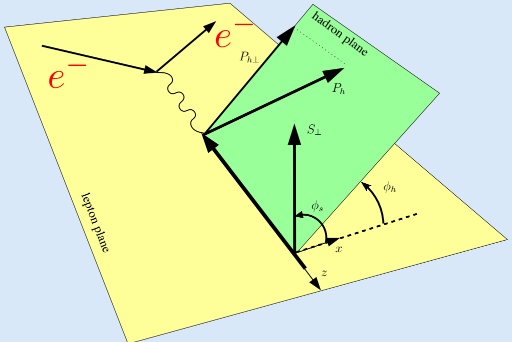


$$H_1^{\perp \mathrm{SIDIS}}(z,p_\perp^2) = H_1^{\perp e^+e^-}(z,p_\perp^2) = H_1^{\perp \mathrm{pp}}(z,p_\perp^2)$$

Metz 02, Collins, Metz 04, Yuan 08,
Boer, Kang, Vogelsang, Yuan, PRL 10, ...

Collins asymmetry from SIDIS and e+e-

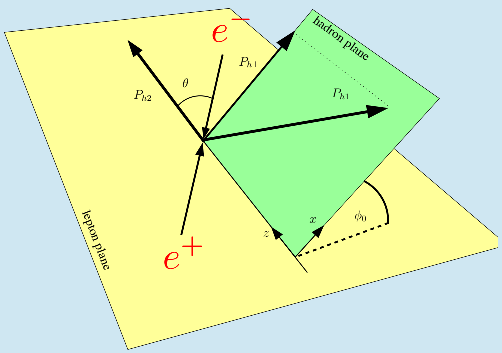
- SIDIS and e+e-: combined global analysis



$$F_{UT}^{\sin(\phi_h+\phi_s)} \sim h_1(x_B, k_\perp) H_1^\perp(z_h, p_\perp)$$

transversity — Collins function

$$\frac{d\sigma(S_\perp)}{dx_B dy dz_h d^2 P_{h\perp}} = \sigma_0(x_B, y, Q^2)\left[F_{UU} + \sin(\phi_h+\phi_s)\,\frac{2(1-y)}{1+(1-y)^2}\,F_{UT}^{\sin(\phi_h+\phi_s)} + \ldots\right]$$



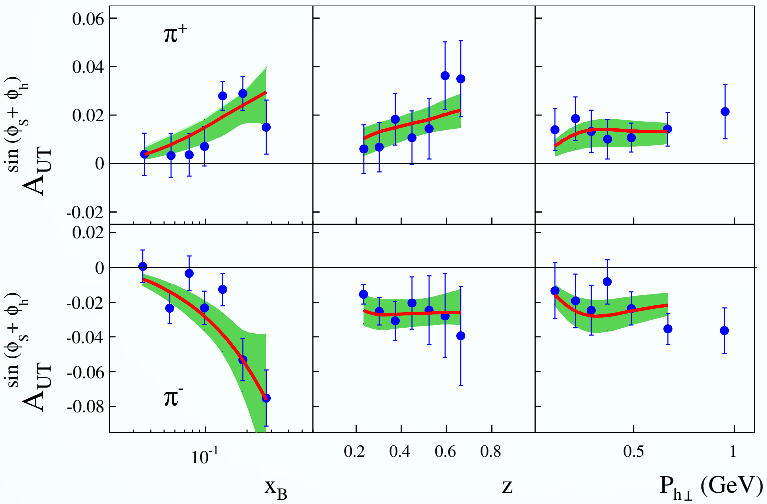
$$Z_{\rm collins}^{h_1 h_2} \sim H_1^\perp(z_1, p_{1\perp}) H_1^\perp(z_2, p_{2\perp})$$

Collins function

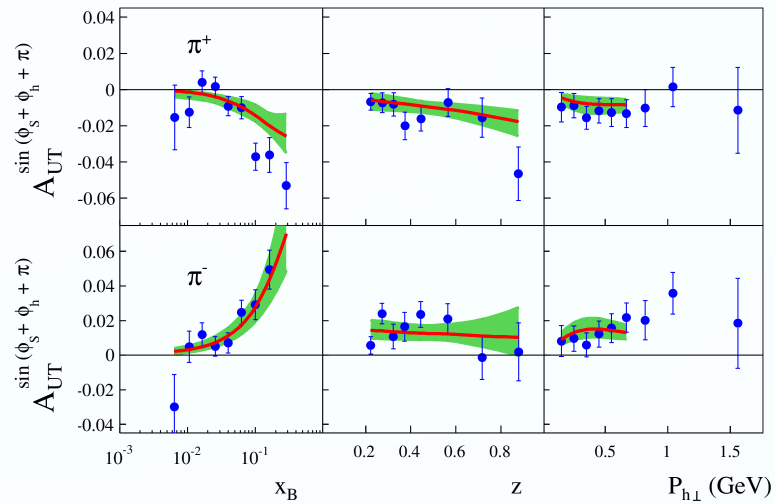
$$\frac{d\sigma^{e^+e^-\to h_1 h_2 + X}}{dz_{h1} dz_{h2} d^2 P_{h\perp}\, d\cos\theta} = \frac{N_c \pi \alpha_{\rm em}^2}{2Q^2}\left[\left(1+\cos^2\theta\right) Z_{uu}^{h_1 h_2} + \sin^2\theta\cos(2\phi_0) Z_{\rm collins}^{h_1 h_2}\right]$$

Global fitting of Collins asymmetry

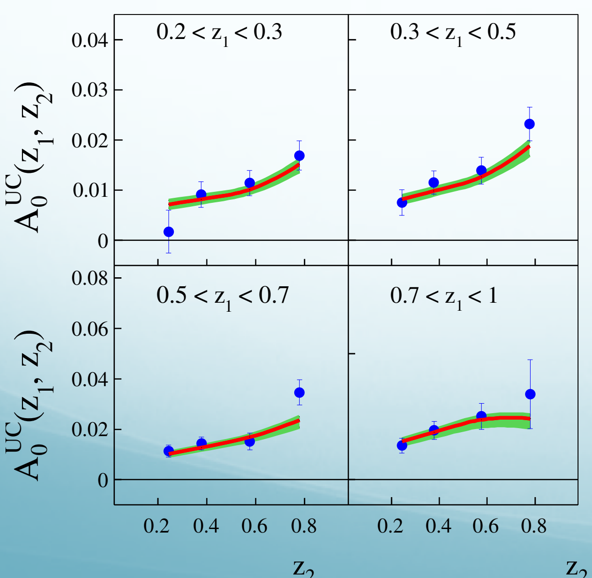
HERMES



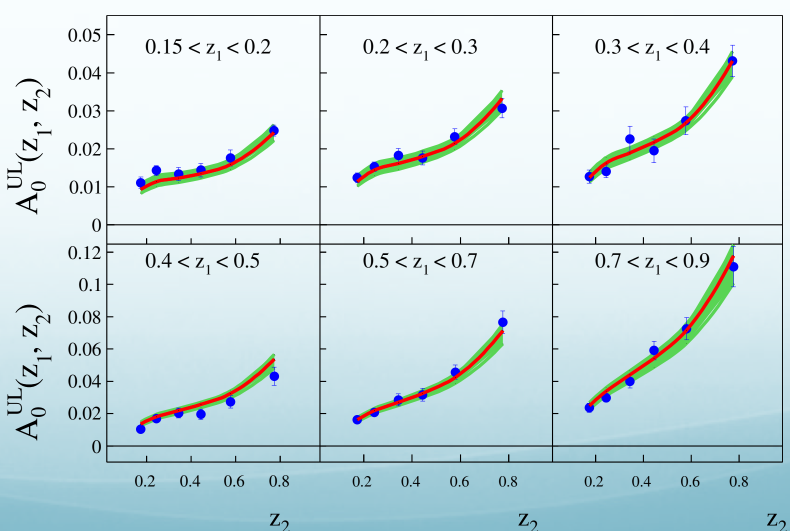
COMPASS



BELLE



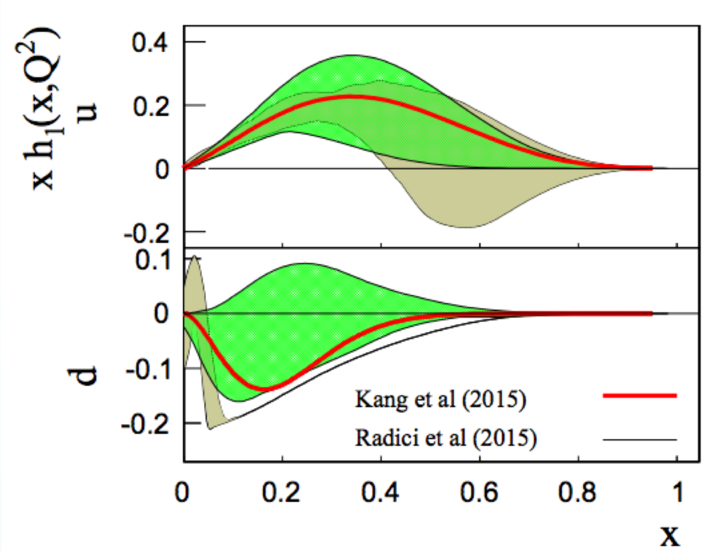
BaBar

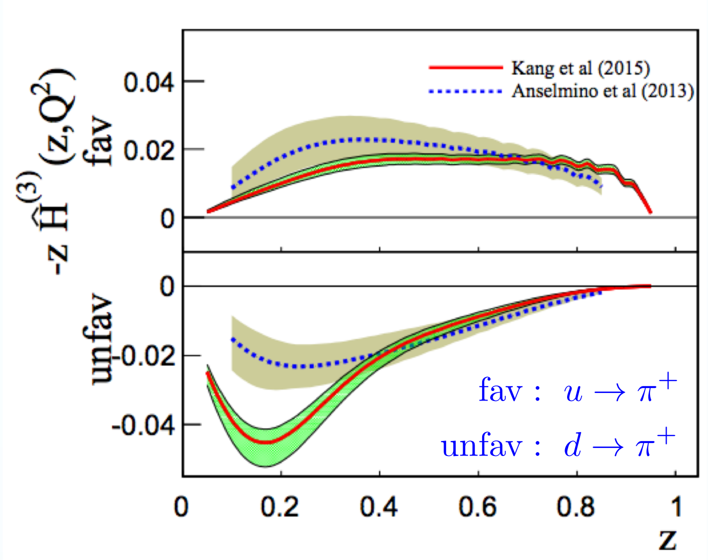


Kang, Prokudin, Sun, Yuan, PRD 15 & 16

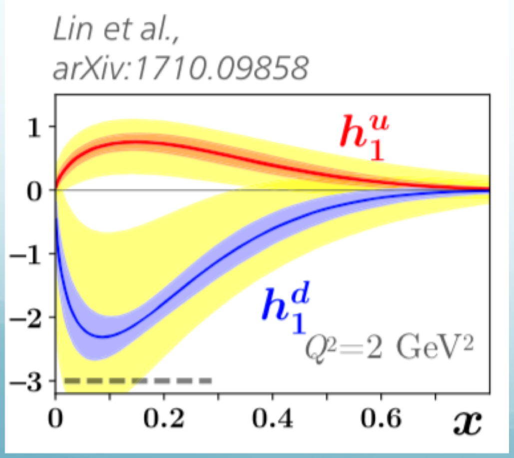
Fitted TMDs

- Fitted quark transversity and Collins function



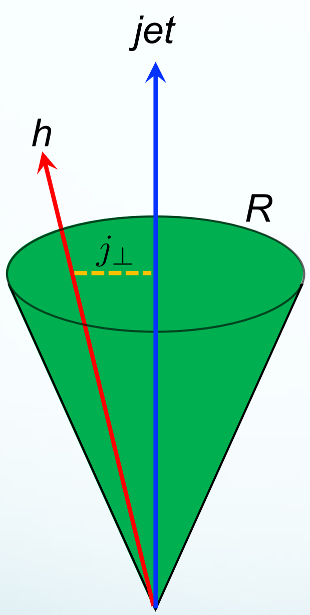


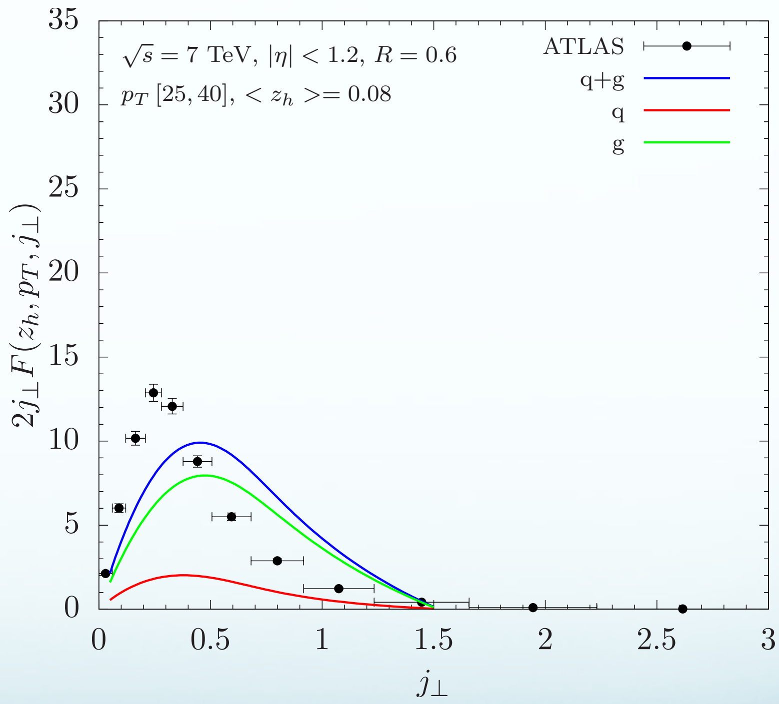
- Using lattice data (tensor charge) to constrain transversity



Novel opportunities: TMDs through jets

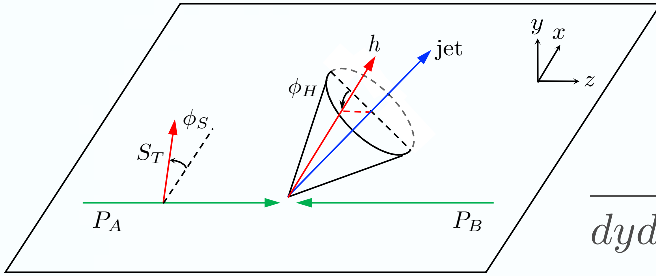
- Study transverse momentum distribution of hadrons inside a fully reconstructed jet
  - Probe TMD fragmentation functions
  - Sensitive to gluon TMDs: for inclusive jet production at the LHC





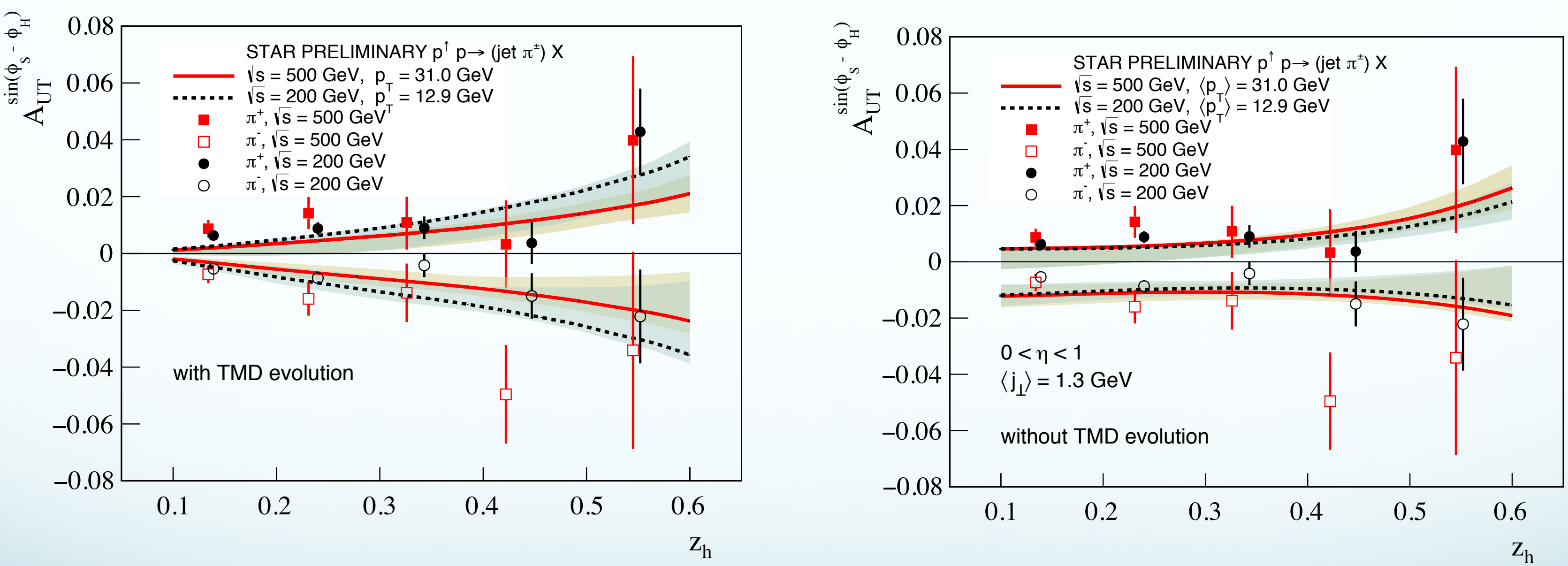
Kang, Liu, Ringer, Xing, 1705.08443

Collins azimuthal asymmetry



$$p^{\uparrow}\left[\vec{S}_{\perp}(\phi_S)\right] + p \to [\text{jet}\, h(\phi_H)] + X$$

$$\frac{d\sigma}{dy d^2 p_{\perp}^{\text{jet}} dz d^2 j_T} = F_{UU} + \sin(\phi_S - \phi_H) F_{UT}^{\sin(\phi_S - \phi_H)}$$



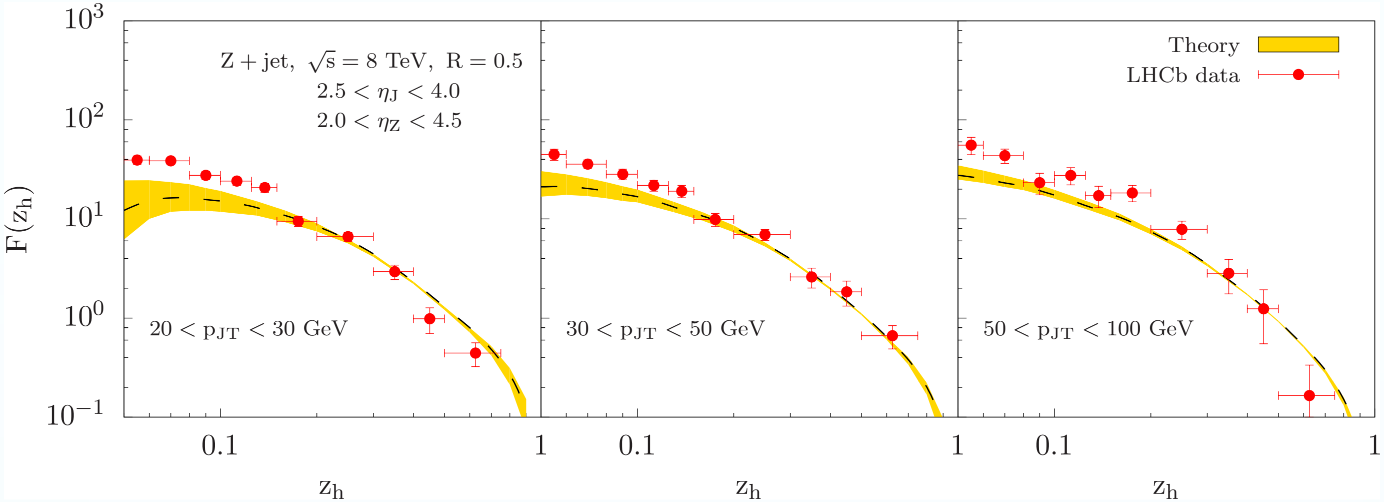
- *Test universality of Collins function between e+p, e+e, and p+p*
- *Test TMD evolution*

Kang, Prokudin, Ringer, Yuan, 1707.00913

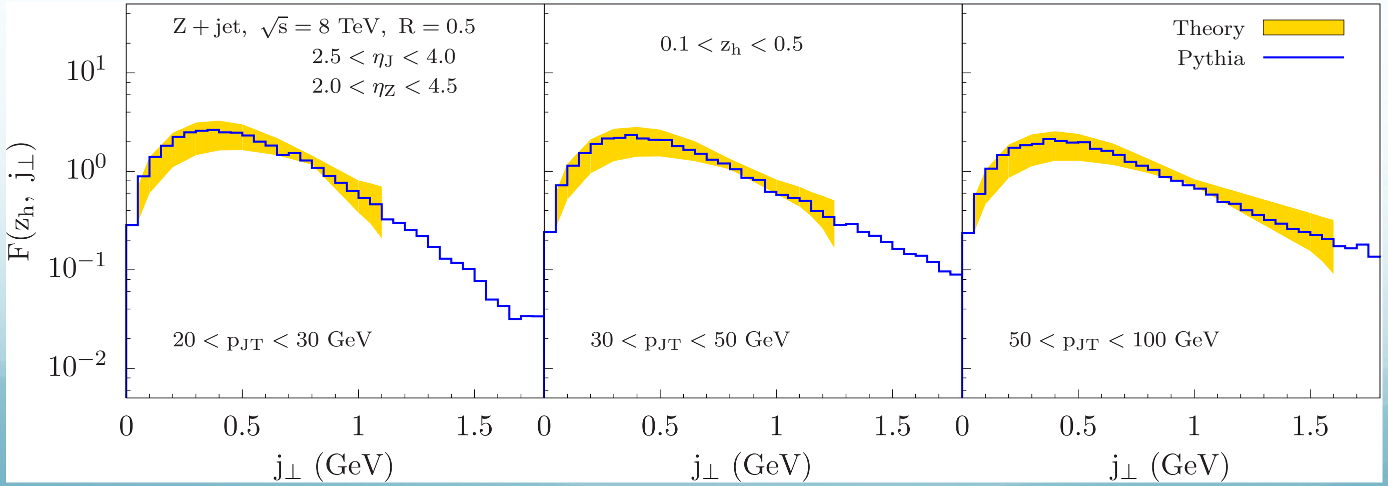
LHCb: Z-tagged jet – quark jet

- z_h distribution

Kang, Lee, Terry, Xing, arXiv:1906.07187

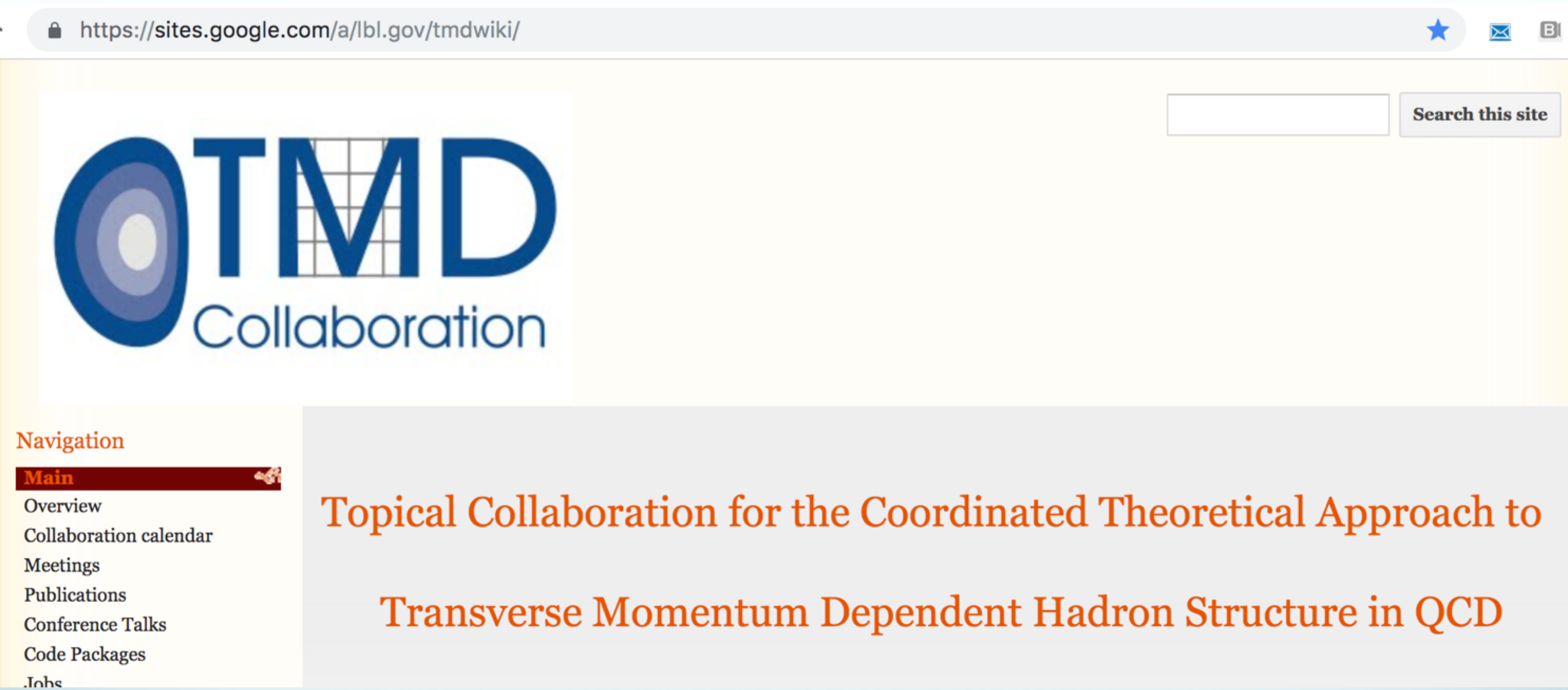


- j_T distribution does now work well with Pythia



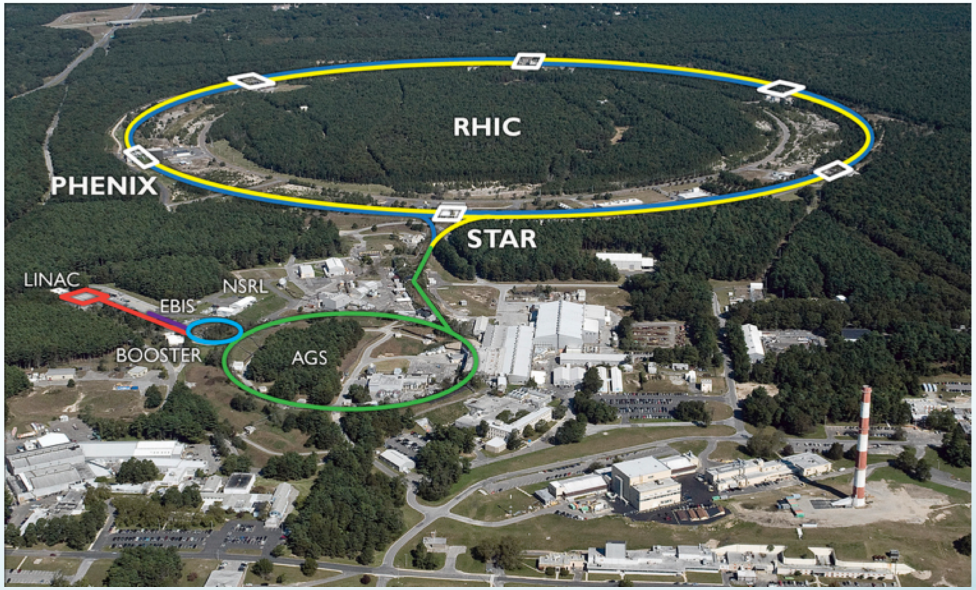
Very active theoretical research

- DOE TMD Collaboration



Active experimental programs

- US: Jefferson Lab 12 GeV + RHIC spin program
- COMPASS + HERMES + BELLE + BES



Electron Ion Collider

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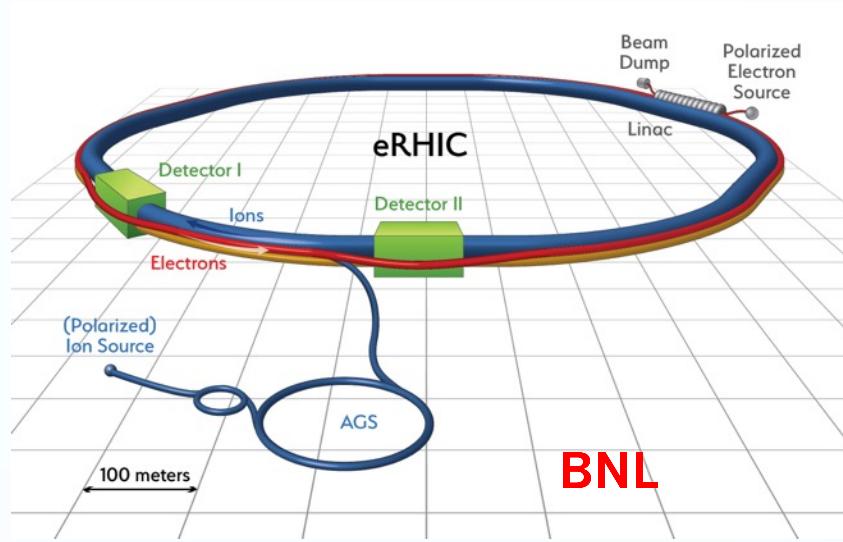
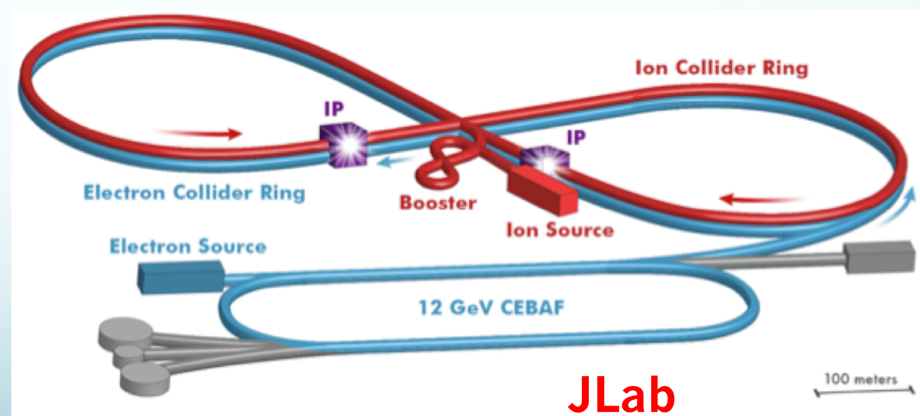
Brookhaven National Laboratory in New York is a potential host for the Electron-Ion Collider.

NUCLEAR PHYSICS

Billion-dollar collider gets thumbs up

Proposed US electron–ion smasher wins endorsement from influential nuclear-science panel.





Summary

- Study on TMDs are extremely active in the past few years, lots of progress have been made
- Nucleon as a QCD “laboratory”: in particular topics/ideas that are similar to those in AMO/Condensed Matter Physics
  - Quantum correlation: spin-spin correlation, spin-orbit correlation, orbital motion, quantum phase interference effects …
  - 3D imaging of the nucleon at the most fundamental level
- Exciting opportunities: lots of experiments activities/measurements being/to be performed/planned in current and future experimental facilities (most importantly, the EIC)

Thank you!