March 15-17, 2017
Jefferson Lab, Newport News, VA

TMD Theory
and
TMD Topical Collaboration

Jianwei Qiu
Theory Center, Jefferson Lab

3D Nucleon Tomography Workshop
Modeling and Extracting Methodology

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TMD Collaboration

Why TMDs?
What is the TMD Topical Collaboration?
What does the collaboration want to achieve?

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Theory Center, Jefferson Lab

Hadron and Hadron Structure

- **Nucleons are the fundamental building blocks of all atomic nuclei, and make up essentially almost all the mass of the visible universe**

- **Understanding the structure of hadrons in terms of QCD's quarks and gluons is one of the central goals of modern nuclear physics –** *The 2015* ***LONG RANGE PLAN*** *for* ***NUCLEAR SCIENCE***

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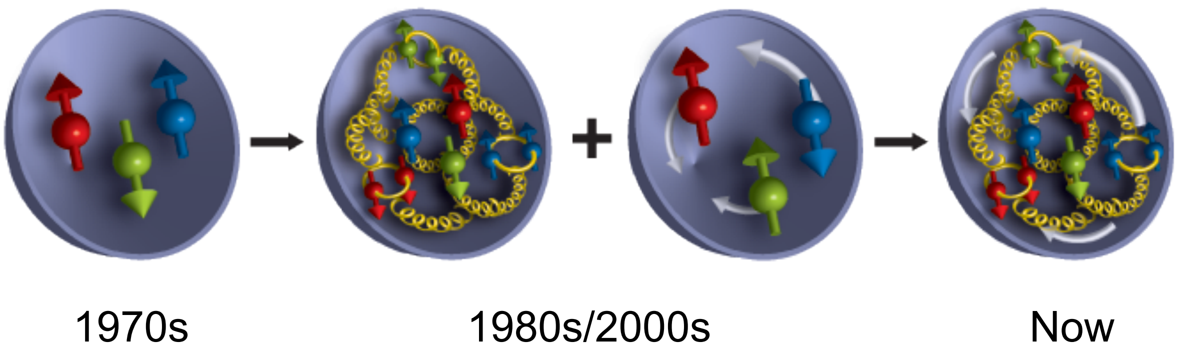
- **Our understanding of hadron evolves**



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Hadron and Hadron Structure

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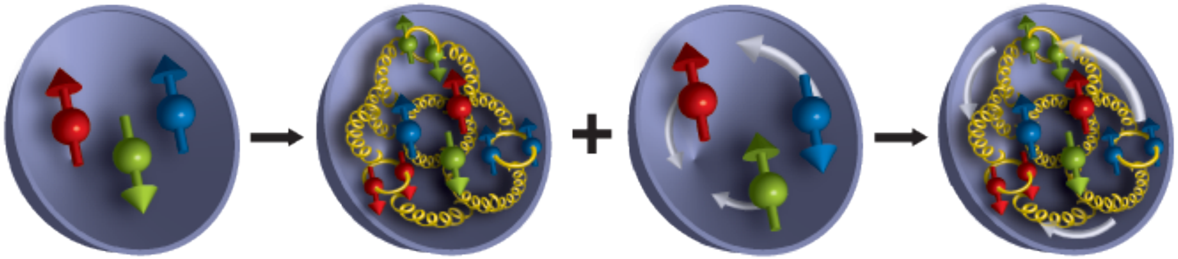
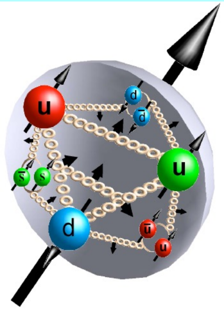


1970s 1980s/2000s Now

In QCD, nucleon emerges as a strongly interacting, relativistic bound state of quarks and gluons

- This has been identified as a major theme and the great intellectual challenge of the DOE Nuclear Theory subprogram

Hadron structure in QCD



- **What do we need to know for the structure?**
  - **In theory:** $\langle P, S | \mathcal{O}(\overline{\psi}, \psi, A^\mu) | P, S \rangle$ – **Hadronic matrix elements**

    with all possible operators: $\mathcal{O}(\overline{\psi}, \psi, A^\mu)$
  - **In fact:** ***None of these matrix elements is a direct physical observable in QCD – color confinement!***
  - **In practice:** **Accessible hadron structure**
    = hadron matrix elements of quarks and gluons, which

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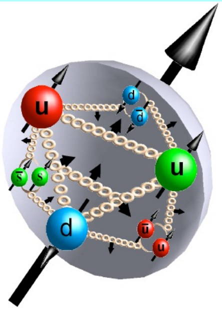
    2) **can be calculated in lattice QCD**

Hadron structure in QCD



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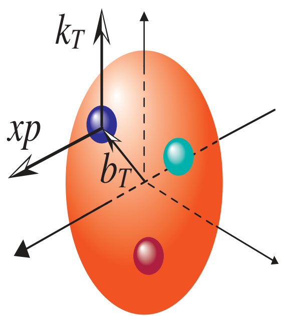
- **Single-parton structure "seen" by a short-distance probe:**
  - **5D structure:**

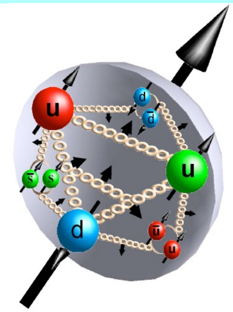


1) $\int d^2b_T$ → $f(x, k_T, \mu)$ – **TMDs:** ***2D confined motion!***

2) $\int d^2k_T$ → $F(x, b_T, \mu)$ – **GPDs:** ***2D spatial imaging!***

3) $\int d^2k_T d^2b_T$ → $f(x, \mu)$ – **PDFs:** ***Number density!***

Hadron structure in QCD



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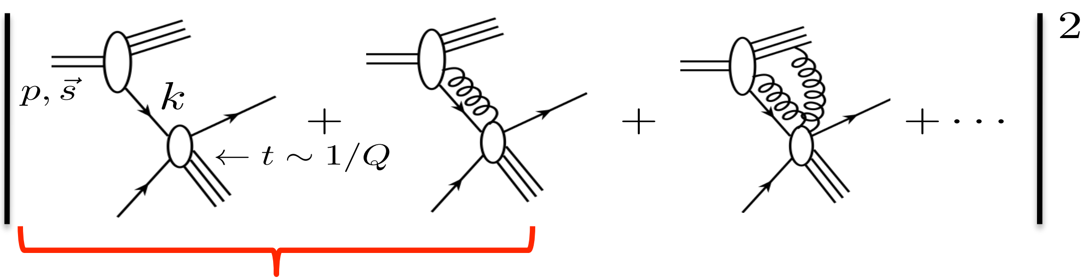
❑ Multi-parton correlations:

$\sigma(Q,\vec{s}) \propto$

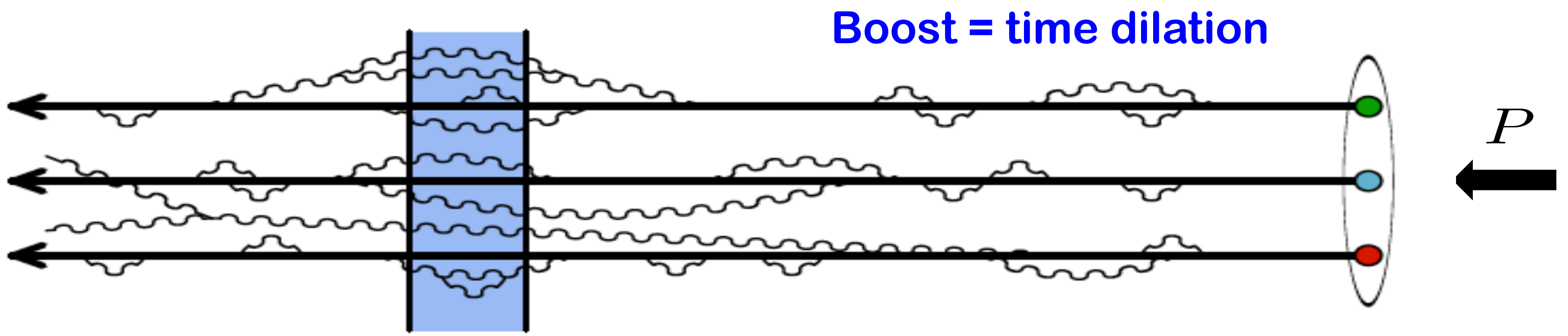


$\left(\frac{\langle k_\perp\rangle}{Q}\right)^n$ – Expansion

Quantum interference ➡ 3-parton matrix element – not a probability!

How to “see” the hadron structure?

- Need high energy probes to “see” the boosted structure:



Hard probe (t ~ 1/Q < fm): *Catches the quantum fluctuation!*

- ✧ Longitudinal momentum fraction – *x* : $xP \sim Q$
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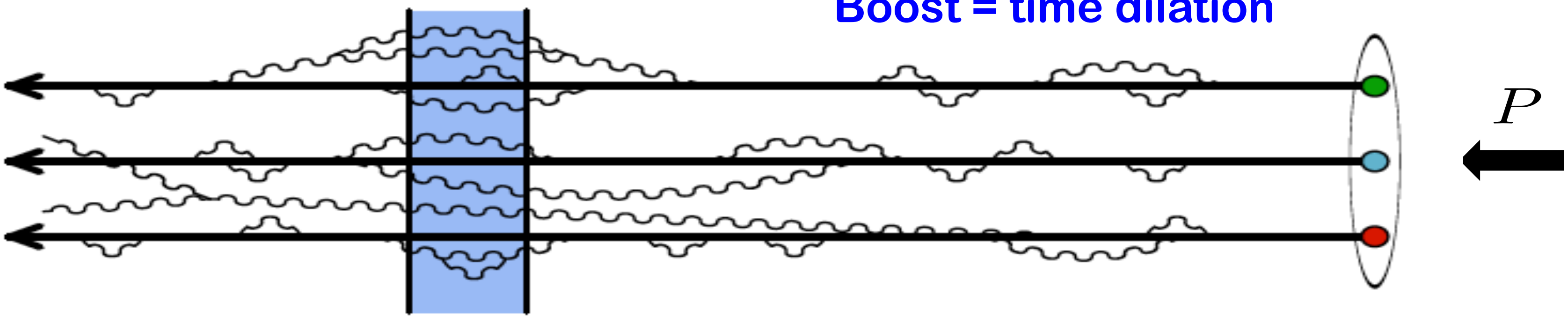

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No modern detector can see quarks and gluons in isolation!

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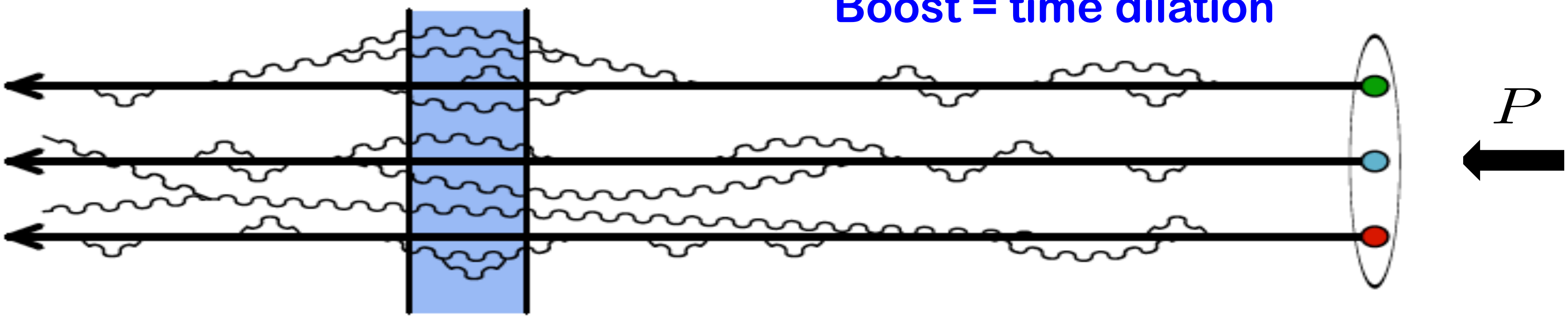
Boost = time dilation



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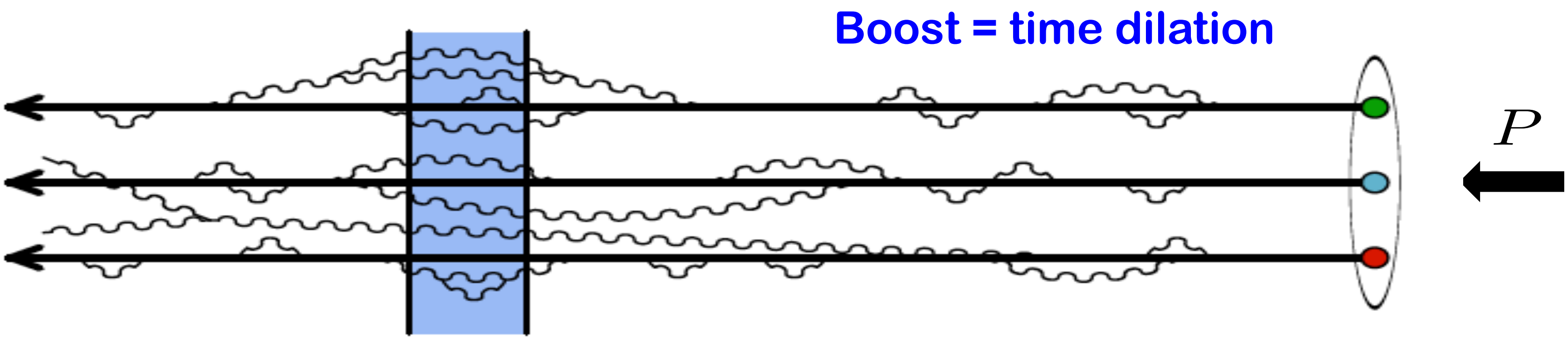

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- Question:

  How to quantify the hadron structure if we cannot see quarks and gluons?

- Answer:

  QCD factorization! *Not exact, but, controllable approximation!*

QCD factorization - approximation

- ❑ **Cross section with identified hadron(s) is NON-Perturbative!**

QCD factorization - approximation

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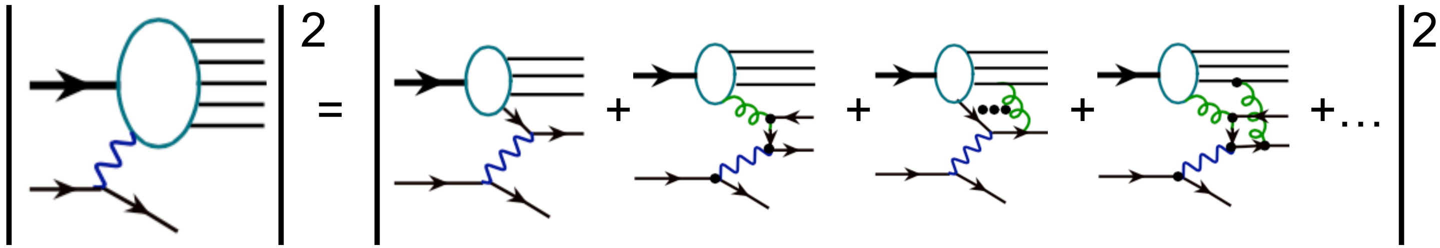
$$\sigma_{\rm DIS}(x,Q^2) =$$



QCD factorization - approximation

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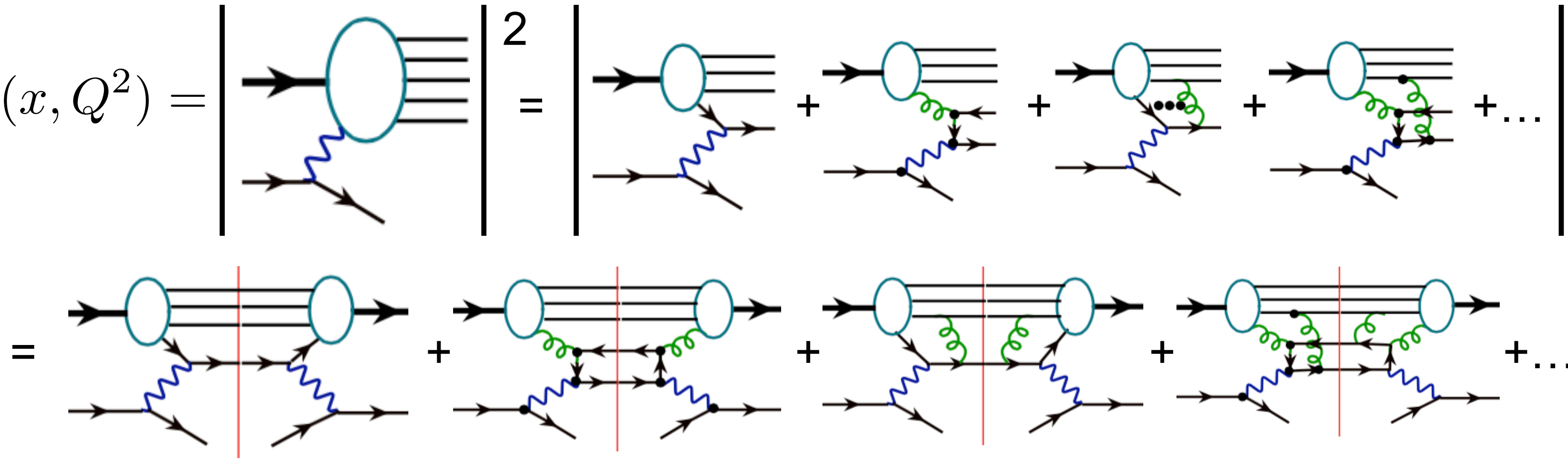

$$= c_q \otimes q(x,Q^2) + c_g \otimes g(x,Q^2) + c_{qg} \otimes T_{qg}(\{x\},Q^2) + c_{gg} \otimes T_{gg}(\{x\},Q^2)$$

$$+\mathcal{O}\left(\langle k_T^n \rangle / Q^n, \langle F^{2n} \rangle / Q^n\right) + \ldots$$

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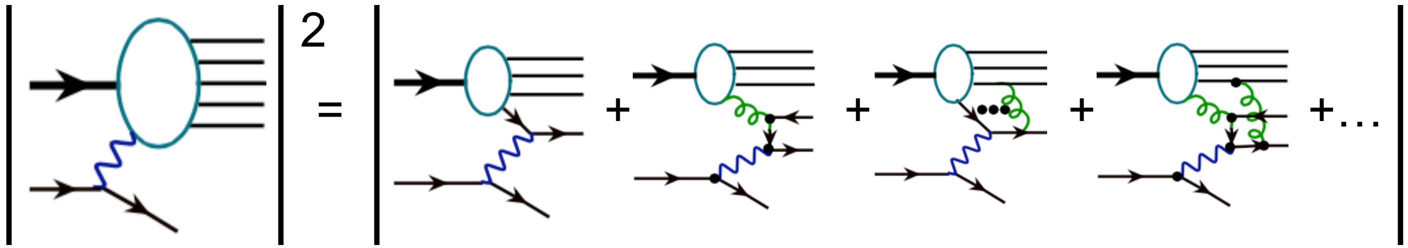

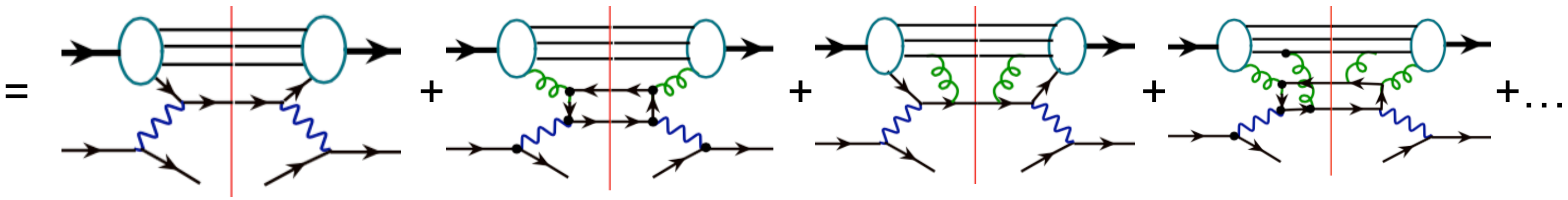

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Leading power
Linear contribution
DGLAP regime
...

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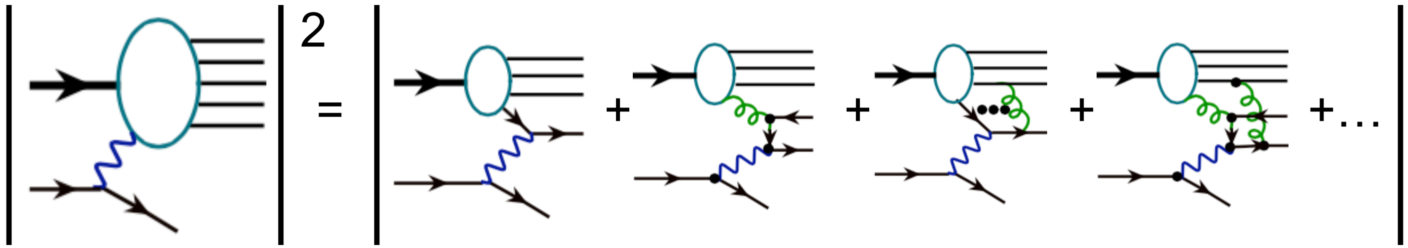

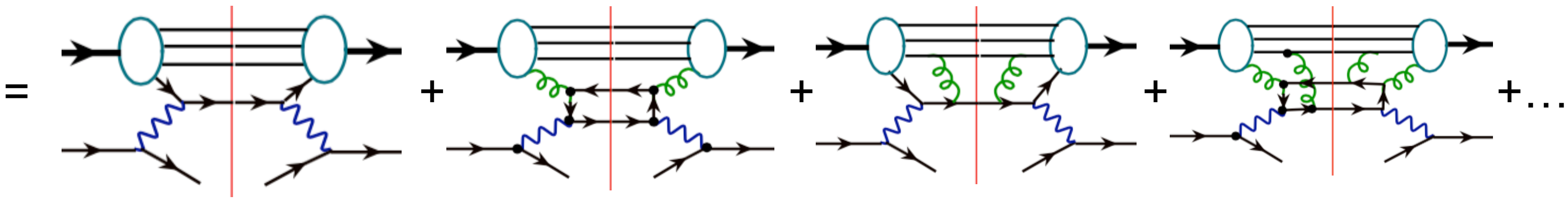

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Power corrections
Non-Linear contribution
Multi-parton correlations

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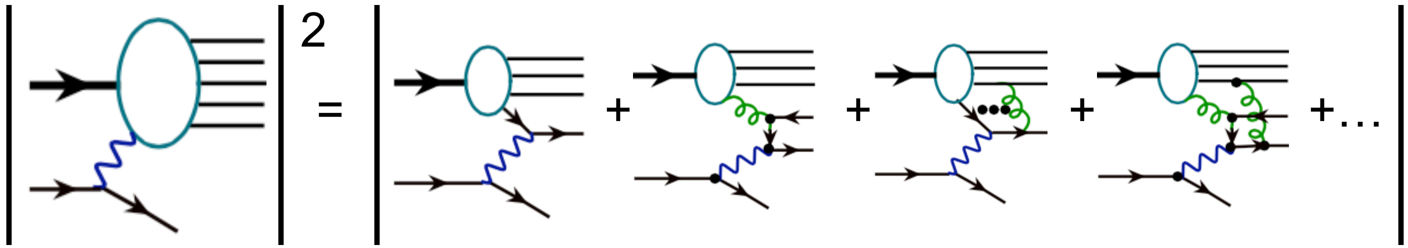

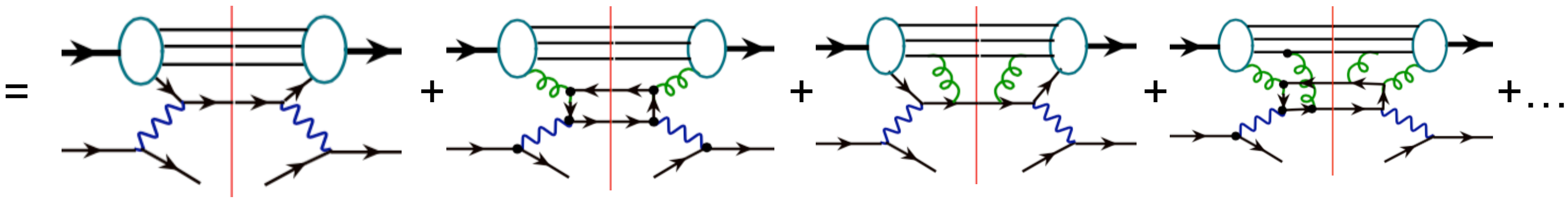

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Approximation – Leading power/twist factorization!

QCD factorization - approximation

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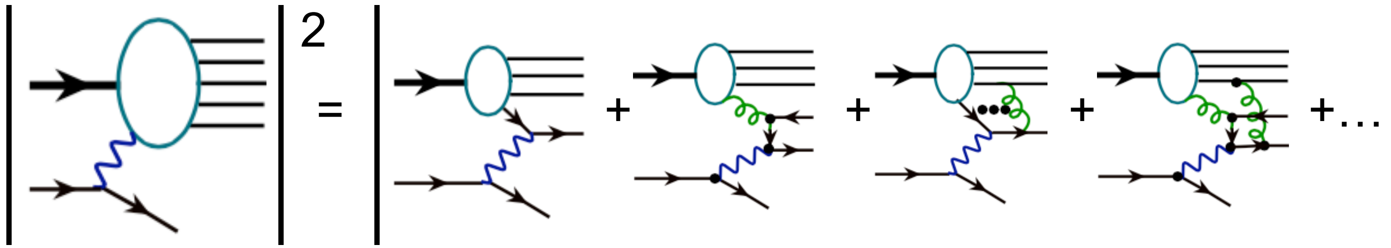

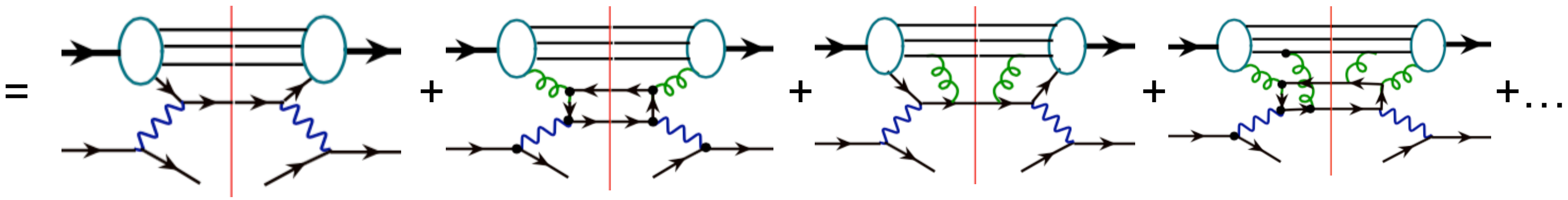

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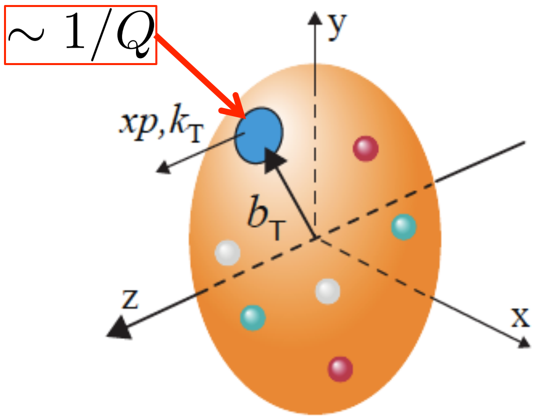
Approximation – Leading power/twist factorization!

Non-perturbative physics neglected or in input PDFs!

How to quantify the hadron structure?

- Quantifying the "structure":



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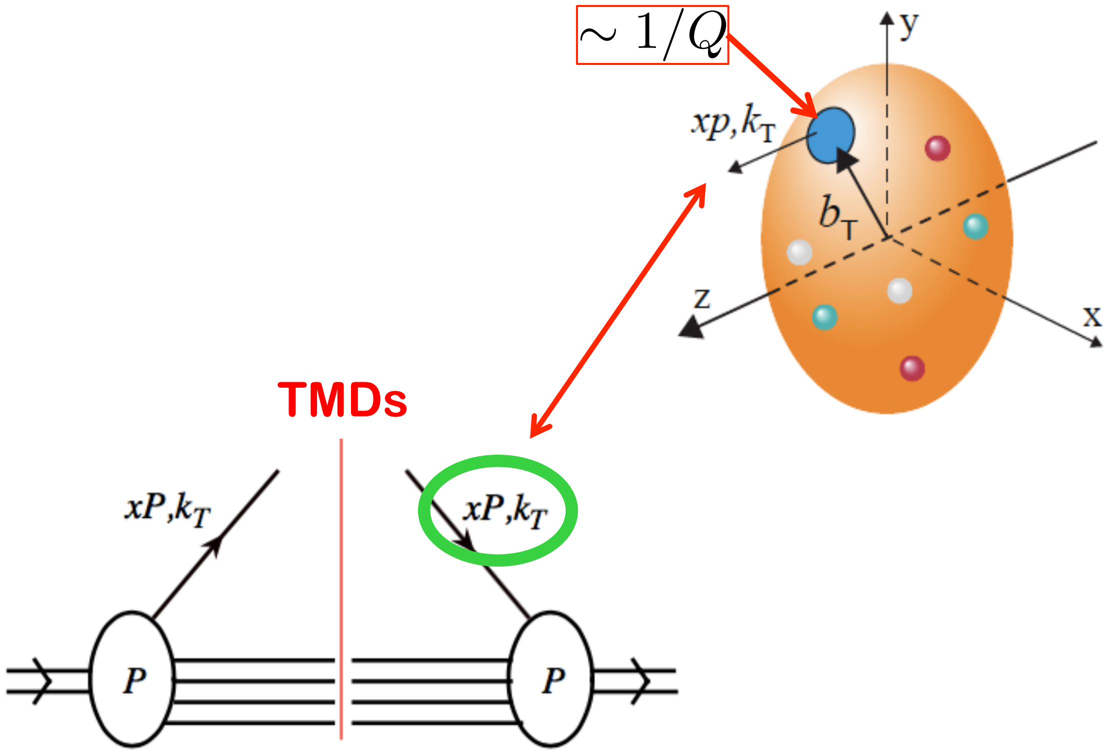

$$\propto \langle P|\overline{\psi}\ [\text{Spin}]\ \psi|P\rangle$$

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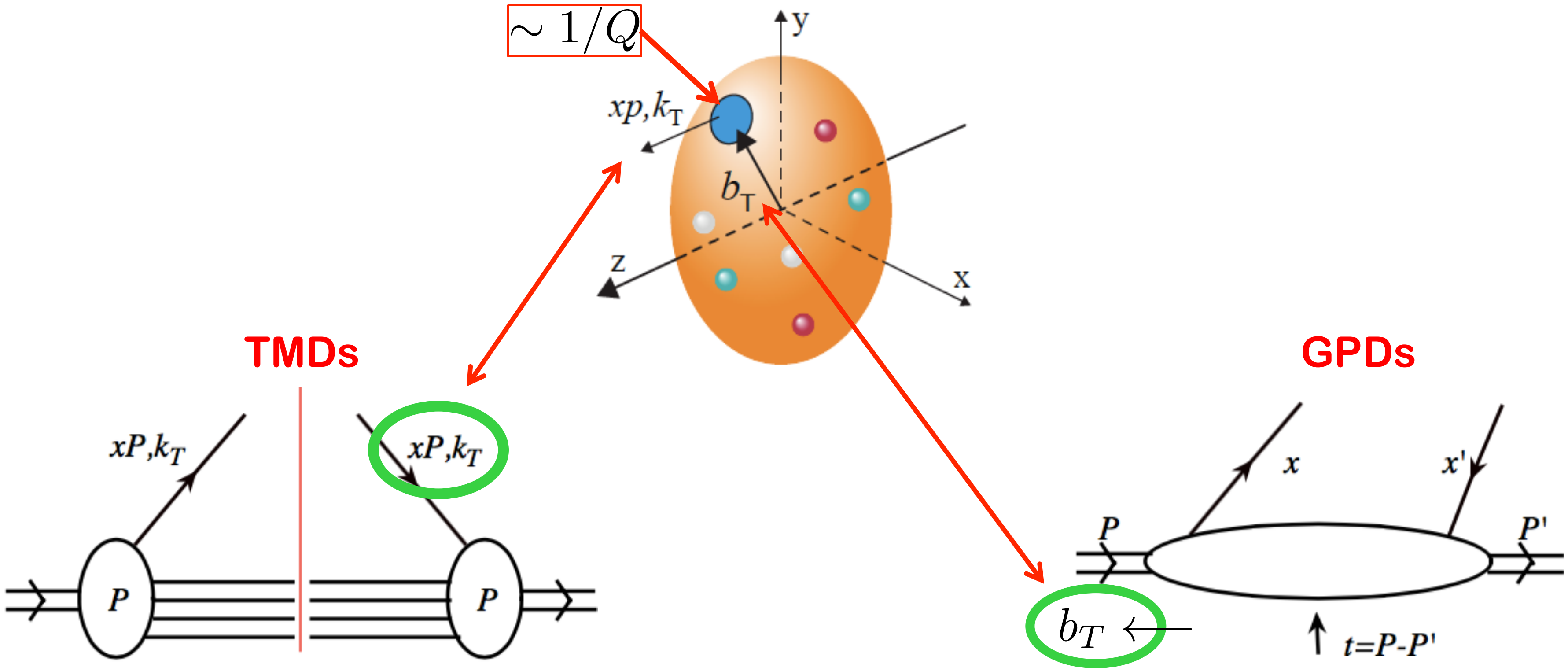

$$\propto \langle P|\overline{\psi}\ [\mathrm{Spin}]\ \psi|P\rangle \qquad \propto \langle P'|\overline{\psi}\ [\mathrm{Spin}]\ \psi|P\rangle$$

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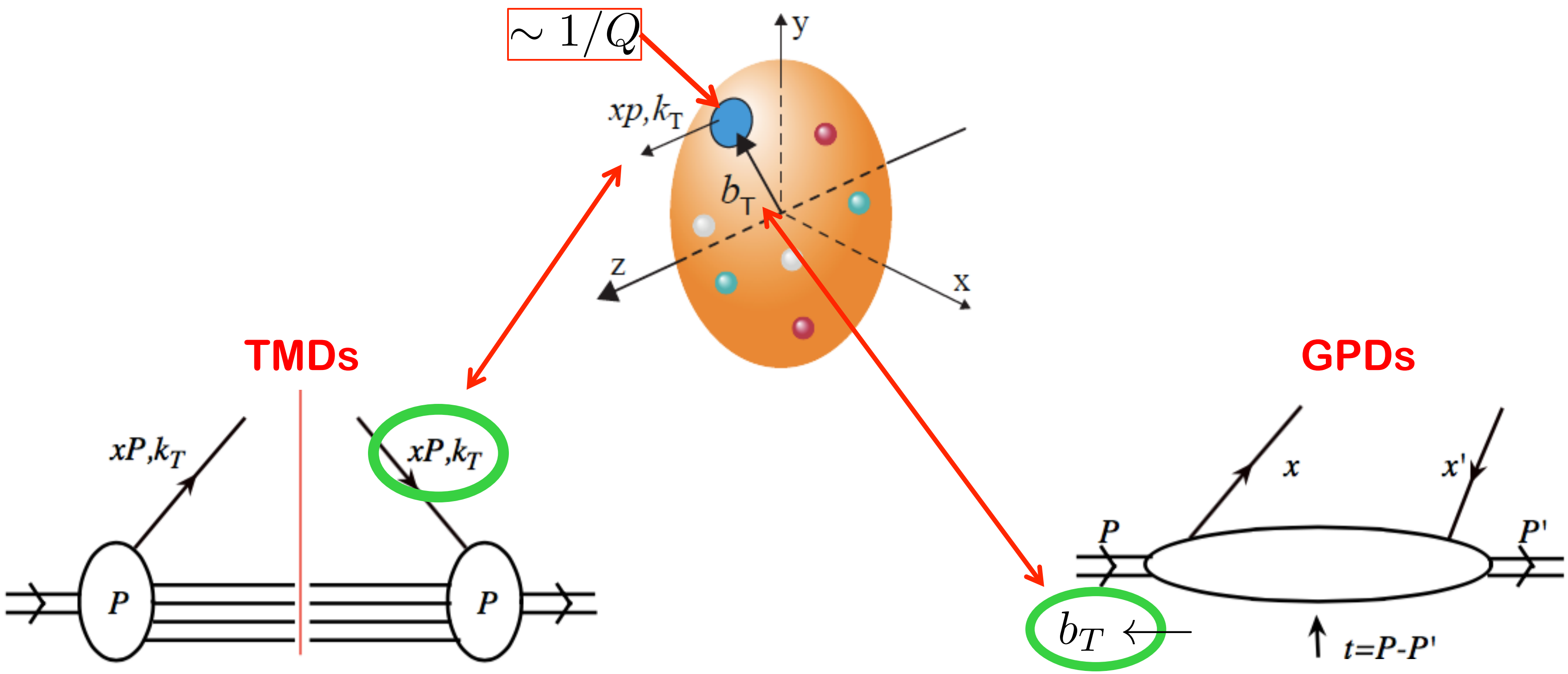

$\propto \langle P | \overline{\psi}\ [\text{Spin}]\ \psi | P \rangle$

Cross sections

$\propto \langle P' | \overline{\psi}\ [\text{Spin}]\ \psi | P \rangle$

Amplitudes

How to quantify the hadron structure?

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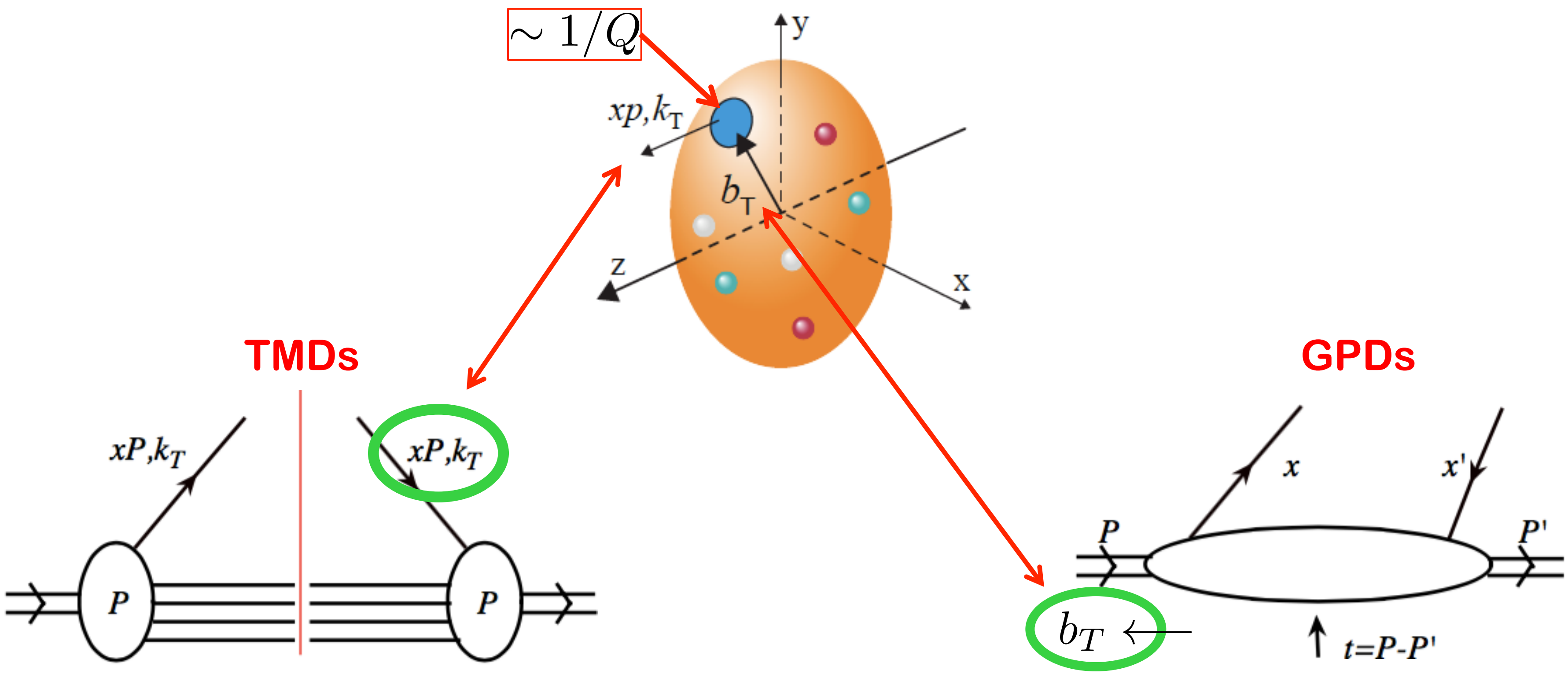

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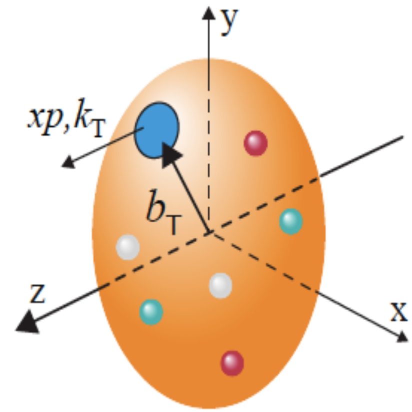
Cross sections   *Amplitudes*

Confined transverse motion
is encoded in the TMDs – the focus of TMD collaboration

Two-momentum-scale observables

❑ Cross sections with two-momentum scales observed:

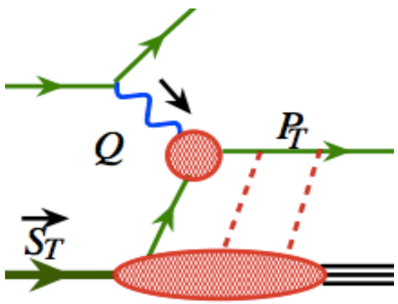
$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\rm QCD}$$



✧ Hard scale: Q_1 localizes the probe
to see the quark or gluon d.o.f.

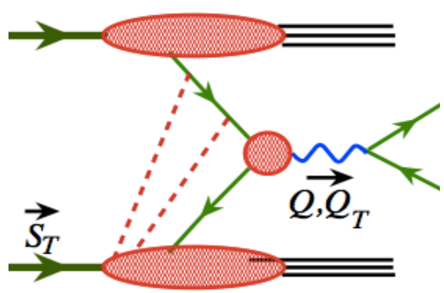
✧ "Soft" scale: Q_2 could be more sensitive to
hadron structure, e.g., confined motion

❑ Two-scale observables with the hadron broken:



SIDIS: Q>>P_T

+



DY: Q>>P_T

+ Two-jet momentum imbalance in SIDIS, …

➡

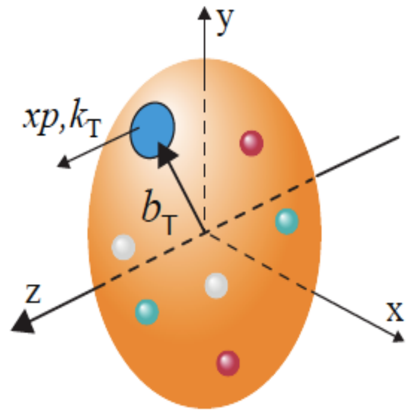
✧ Natural observables with TWO very different scales

✧ TMD factorization: partons' confined motion is encoded into TMDs

Two-momentum-scale observables

❑ **Cross sections with two-momentum scales observed:**

$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\rm QCD}$$



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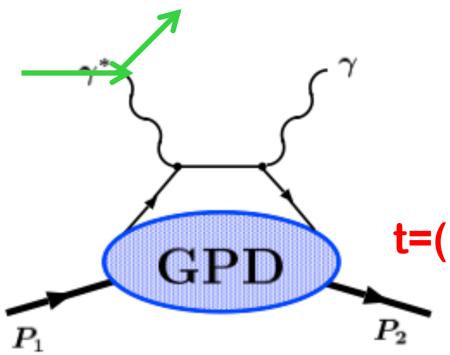
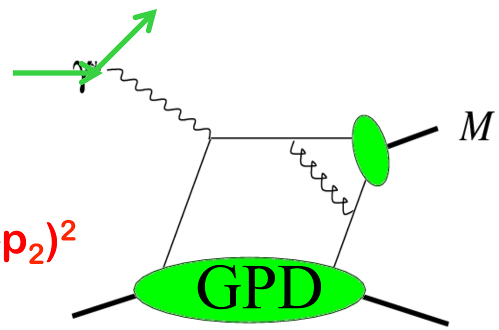
❑ **Two-scale observables with the hadron unbroken:**



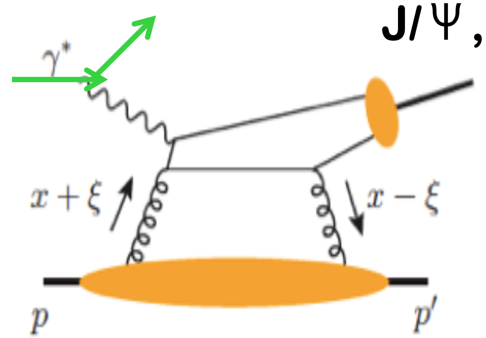
DVCS: $Q^2 \gg |t|$

+ $t=(p_1-p_2)^2$



DVEM: $Q^2 \gg |t|$

+ J/Ψ, Φ, …



EHMP: $Q^2 \gg |t|$

+ …

✧ **Natural observables with TWO very different scales**

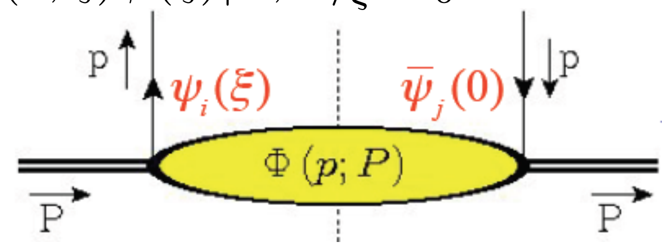
✧ **GPDs: Fourier Transform of t-dependence gives spatial b_T-dependence**

Definition of TMDs

❑ Non-perturbative definition:

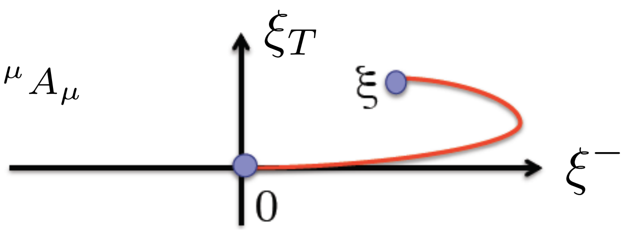
✧ In terms of matrix elements of parton correlators:

$$\Phi^{[U]}(x, p_T; n) = \int \frac{d\xi^- d^2\xi_T}{(2\pi)^3} e^{i\,p\cdot\xi} \langle P, S|\overline{\psi}(0)U(0,\xi)\psi(\xi)|P, S\rangle_{\xi^+=0}$$



✧ Depends on the choice of the gauge link:

$$U(0,\xi) = e^{-ig\int_0^\xi ds^\mu A_\mu}$$



✧ Decomposes into a list of TMDs:

$$\Phi^{[U]}(x, p_T; n) = \Big\{ f_1^{[U]}(x, p_T^2) - f_{1T}^{\perp[U]}(x, p_T^2)\frac{\epsilon_T^{p_T S_T}}{M} + g_{1s}^{[U]}(x, p_T)\gamma_5$$
$$+ h_{1T}^{[U]}(x, p_T^2)\,\gamma_5\,\not{S}_T + h_{1s}^{\perp[U]}(x, p_T)\frac{\gamma_5\,\not{p}_T}{M} + i h_1^{\perp[U]}(x, p_T^2)\frac{\not{p}_T}{M}\Big\}\frac{\not{P}}{2},$$

❑ Gives "unique" TMDs, IF we knew proton wave function!

But, we do NOT know proton wave function (calculate it on lattice?)

TMDs are NOT direct physical observables!

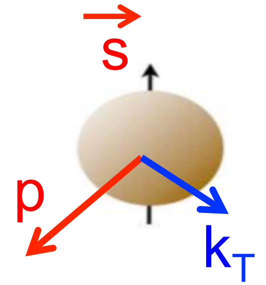
TMDs: confined motion, its spin correlation

- **Power of spin – many more correlations:**

		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	f_1 =		$h_1^\perp$ = − Boer-Mulders
	L		g_{1L} = − Helicity	$h_{1L}^\perp$ = −
	T	$f_{1T}^\perp$ = − Sivers	$g_{1T}^\perp$ = −	h_1 = − Transversity $h_{1T}^\perp$ = −

Nucleon Spin — Quark Spin

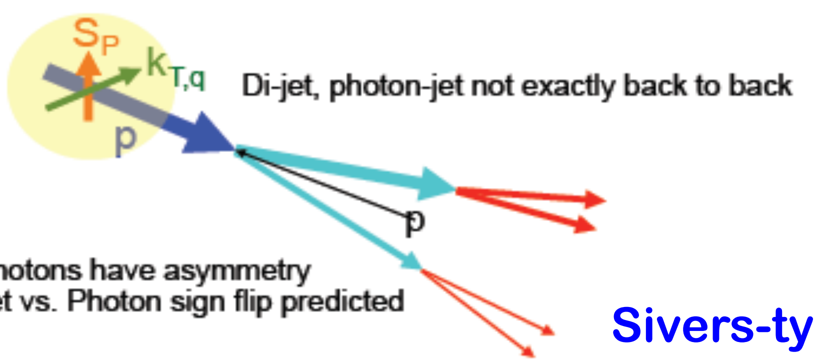
Similar for gluons



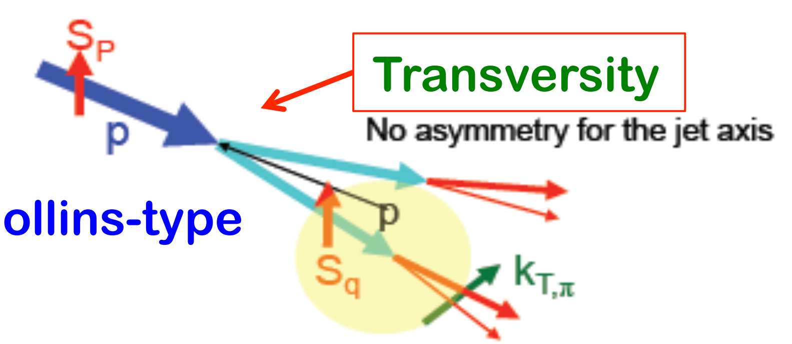
Require two Physical scales

More than one TMD contribute to the same observable!

- **A_N – single hadron production:**



Sivers-type

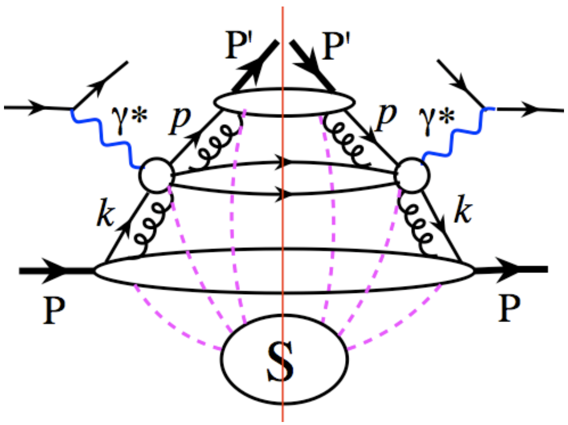


Collins-type

TMDs extracted from data

❑ **Perturbative definition – in terms of TMD factorization:**

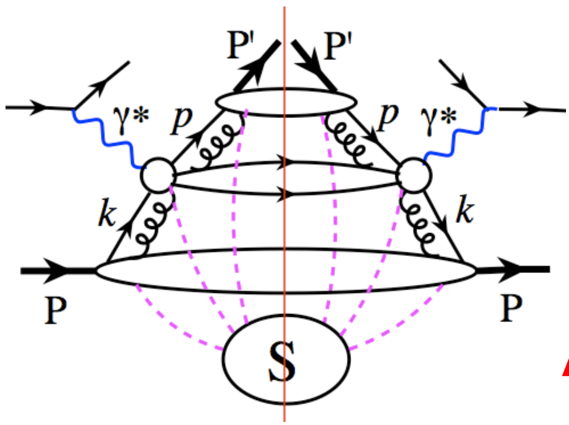
SIDIS as an example:



TMDs extracted from data

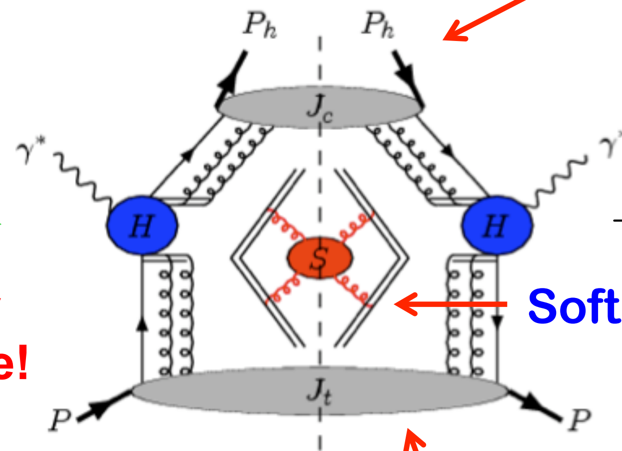
❑ **Perturbative definition – in terms of TMD factorization:**

SIDIS as an example:



Theory Advance!

TMD fragmentation



$$+\,\mathcal{O}\left(\frac{\langle k^2\rangle}{Q^2},\frac{\langle p^2\rangle}{Q^2}\right)$$

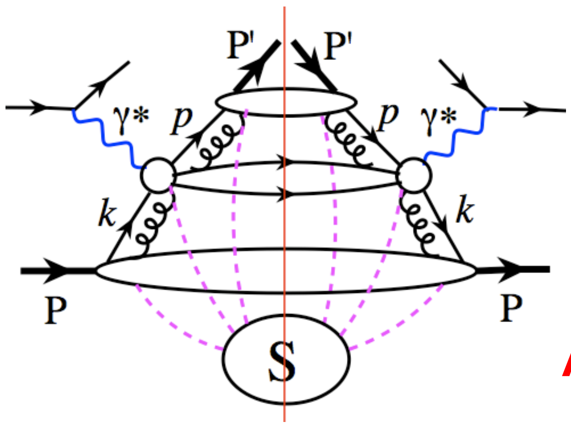
Soft factors

TMD parton distribution

TMDs extracted from data

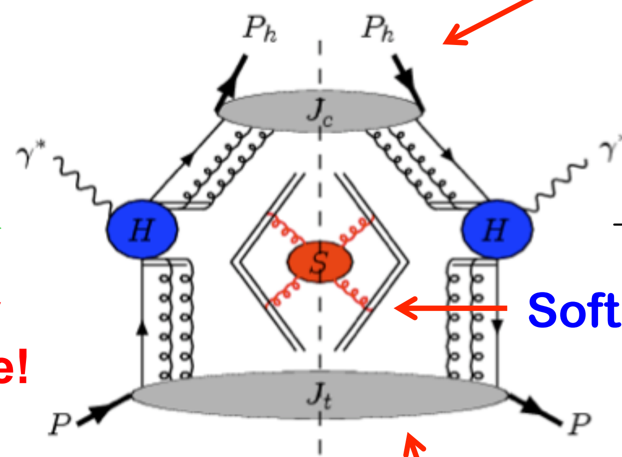
❑ **Perturbative definition – in terms of TMD factorization:**

SIDIS as an example:



Theory Advance!

TMD fragmentation



$$+\,\mathcal{O}\left(\frac{\langle k^2\rangle}{Q^2},\frac{\langle p^2\rangle}{Q^2}\right)$$

Soft factors

TMD parton distribution

❑ **Extraction of TMDs:**

$$\sigma_{\rm SIDIS}(Q,P_{h\perp},x_B,z_h)=\hat{H}(Q)\otimes\Phi_f(x,k_\perp)\otimes\mathcal{D}_{f\to h}(z,p_\perp)\otimes\mathcal{S}(k_{s\perp})+\mathcal{O}\left[\frac{P_{h\perp}}{Q}\right]$$

TMDs are extracted by fitting DATA using the factorization formula

✧ Depending on the perturbatively calculated $\hat{H}(Q;\mu)$
perturbative orders, renormalization, factorization schemes, …

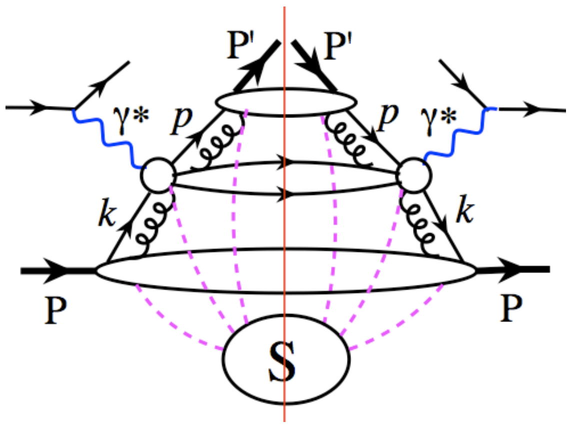
✧ Depending on the approximation of neglecting the power corrections, ..

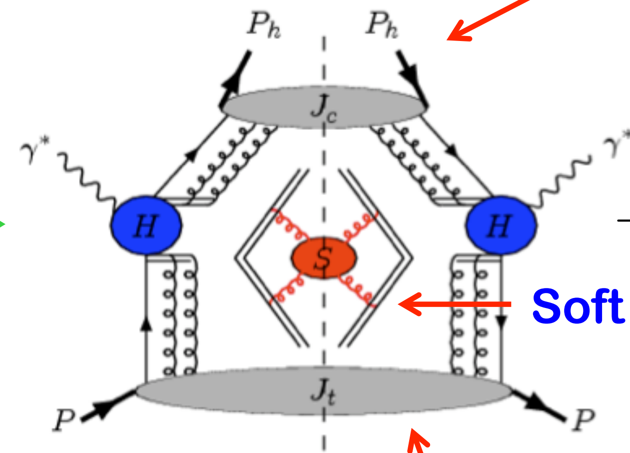
→ *Importance of lattice QCD calculations, …*

TMDs extracted from data

- **Perturbative definition – in terms of TMD factorization:**

SIDIS as an example:





$$+\,\mathcal{O}\left(\frac{\langle k^2\rangle}{Q^2},\frac{\langle p^2\rangle}{Q^2}\right)$$

TMD fragmentation

Soft factors

TMD parton distribution

- **Low P_{hT} – TMD factorization:**

$$\sigma_{\rm SIDIS}(Q,P_{h\perp},x_B,z_h)=\hat{H}(Q)\otimes\Phi_f(x,k_\perp)\otimes\mathcal{D}_{f\to h}(z,p_\perp)\otimes\mathcal{S}(k_{s\perp})+\mathcal{O}\left[\frac{P_{h\perp}}{Q}\right]$$

- **High P_{hT} – Collinear factorization:**

$$\sigma_{\rm SIDIS}(Q,P_{h\perp},x_B,z_h)=\hat{H}(Q,P_{h\perp},\alpha_s)\otimes\phi_f\otimes D_{f\to h}+\mathcal{O}\left(\frac{1}{P_{h\perp}},\frac{1}{Q}\right)$$

- **P_{hT} Integrated - Collinear factorization:**

$$\sigma_{\rm SIDIS}(Q,x_B,z_h)=\tilde{H}(Q,\alpha_s)\otimes\phi_f\otimes D_{f\to h}+\mathcal{O}\left(\frac{1}{Q}\right)$$

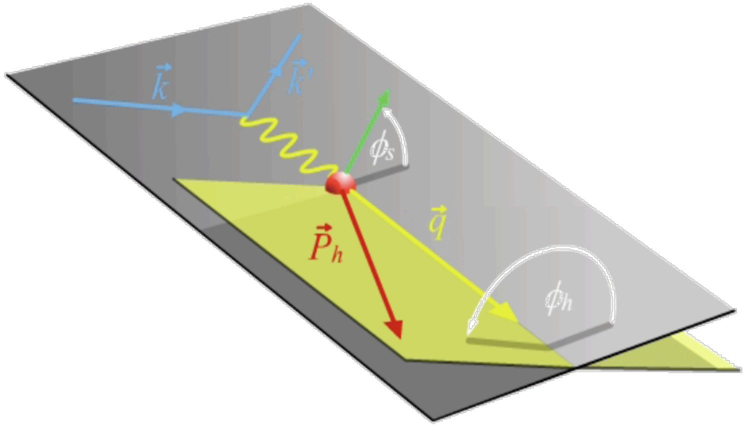
SIDIS is the best for probing TMDs

- Naturally, two scales & two planes:

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

$$= A_{UT}^{Collins}\sin(\phi_h + \phi_S) + A_{UT}^{Sivers}\sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity}\sin(3\phi_h - \phi_S)$$



- Separation of TMDs:

$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S)\rangle_{UT} \propto h_1 \otimes H_1^\perp$$

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S)\rangle_{UT} \propto f_{1T}^\perp \otimes D_1$$

$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S)\rangle_{UT} \propto h_{1T}^\perp \otimes H_1^\perp$$

Collins frag. Func. from e$^+$e$^-$ collisions

Hard, if not impossible, to separate TMDs in hadronic collisions

Using a combination of different observables (not the same observable): jet, identified hadron, photon, …

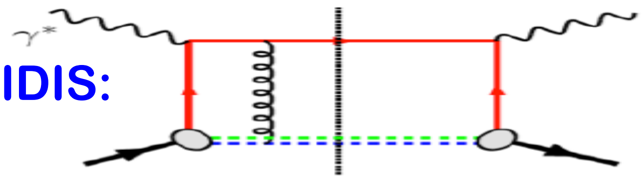
Modified universality for TMDs

❑ Definition:

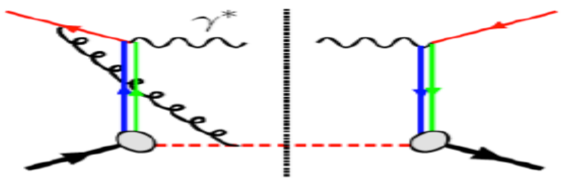
$$f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) = \int \frac{dy^- d^2y_\perp}{(2\pi)^3}\, e^{ixp^+y^- - i\,\mathbf{k}_\perp\cdot\mathbf{y}_\perp} \langle p,\vec{S}|\overline{\psi}(0^-,\mathbf{0}_\perp)\,\boxed{\text{Gauge link}}\,\frac{\gamma^+}{2}\psi(y^-,\mathbf{y}_\perp)|p,\vec{S}\rangle$$

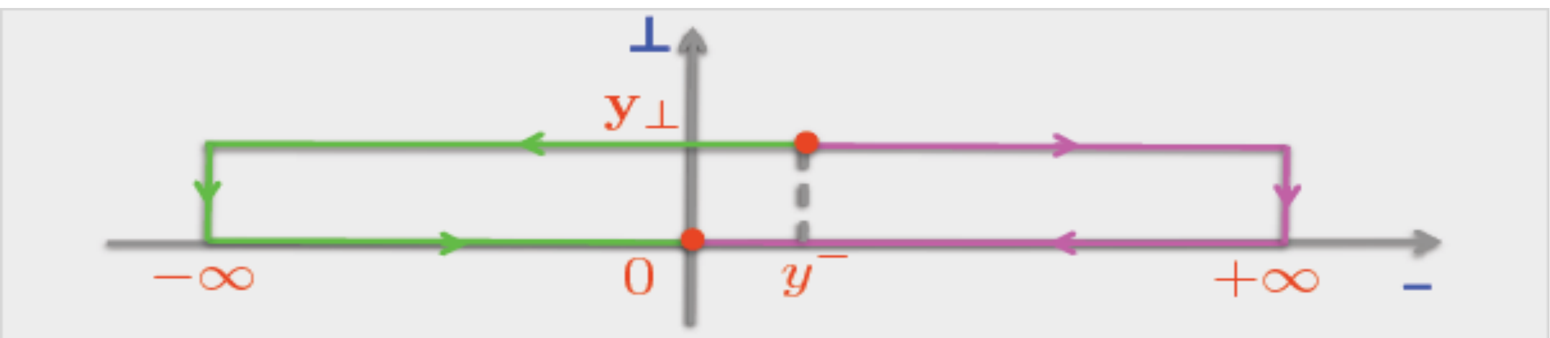
❑ Gauge links:

SIDIS:



DY:





❑ Process dependence:

$$f^{\text{SIDIS}}_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) \neq f^{\text{DY}}_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S})$$

Collinear factorized PDFs are process independent

Critical test of TMD factorization

- Parity – Time reversal invariance:

$$f_{q/h^\uparrow}^{\rm SIDIS}(x, \mathbf{k}_\perp, \vec{S}) = f_{q/h^\uparrow}^{\rm DY}(x, \mathbf{k}_\perp, -\vec{S})$$

- Definition of Sivers function:

$$f_{q/h^\uparrow}(x, \mathbf{k}_\perp, \vec{S}) \equiv f_{q/h}(x, k_\perp) + \frac{1}{2}\Delta^N f_{q/h^\uparrow}(x, k_\perp)\, \vec{S} \cdot \hat{p} \times \hat{\mathbf{k}}_\perp$$

- Modified universality:

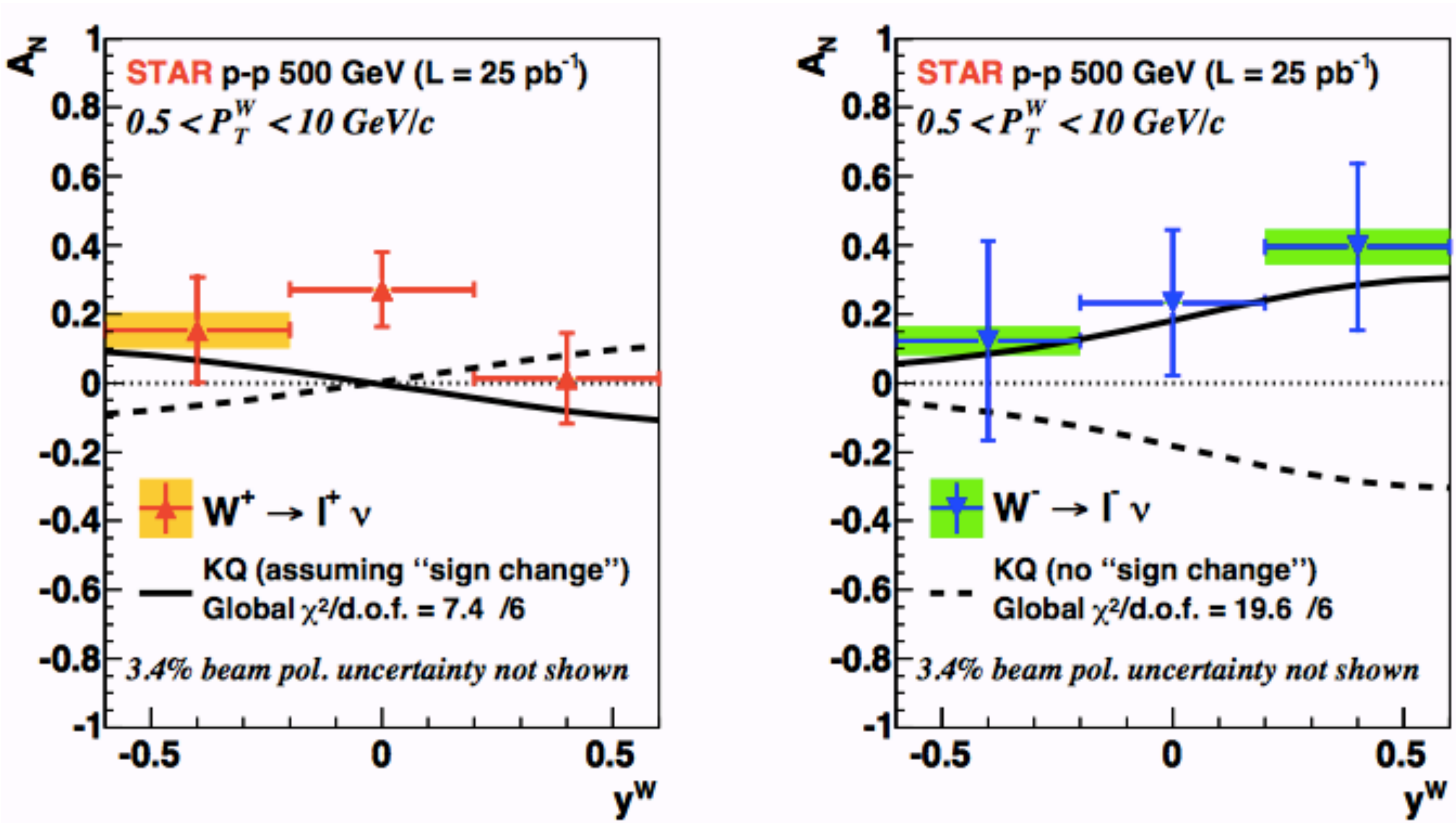
$$\Delta^N f_{q/h^\uparrow}^{\rm SIDIS}(x, k_\perp) = -\Delta^N f_{q/h^\uparrow}^{\rm DY}(x, k_\perp)$$

The spin-averaged part of this TMD is process independent,

but, spin-averaged Boer-Mulder's TMD requires the sign change!

Same PT symmetry examination needs for TMD gluon distributions!

Hint of the sign change: A_N of W production



Data from STAR collaboration on A_N for W-production are consistent with a sign change between SIDIS and DY

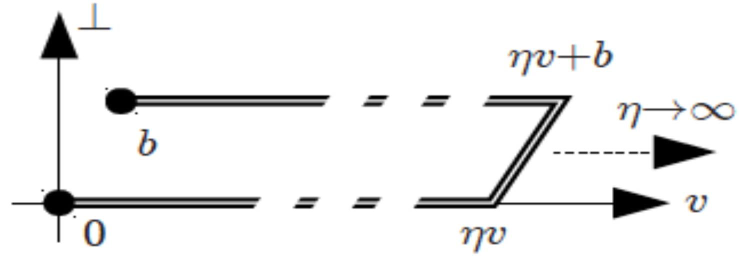
STAR Collab. Phys. Rev. Lett. 116, 132301 (2016)

Hint of the sign change from lattice QCD

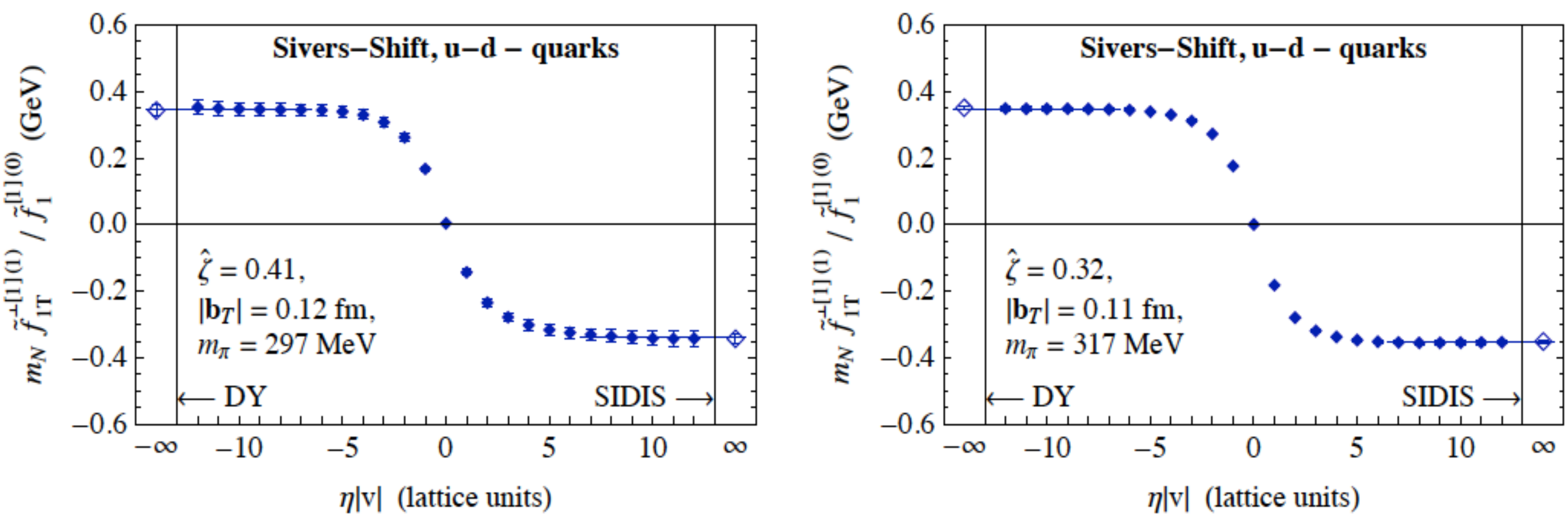
Engelhardt@TMD
Collaboration meeting

❑ Gauge link for lattice calculation:

Staple-shaped gauge link $\mathcal{U}[0, \eta v, \eta v + b, b]$



❑ Normalized moment of Sivers function – at given b_T:

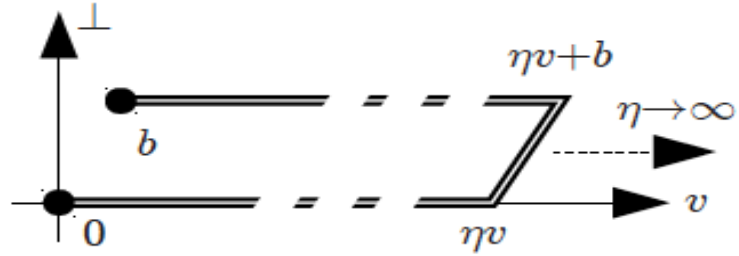


Hint of the sign change from lattice QCD

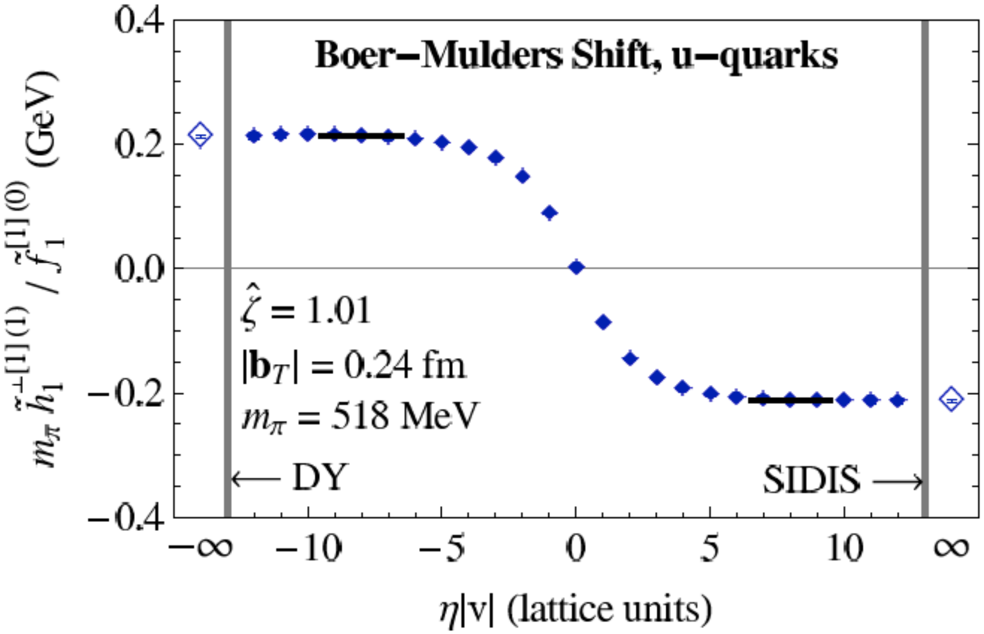
Engelhardt@TMD Collaboration meeting

- **Gauge link for lattice calculation:**

Staple-shaped gauge link $\mathcal{U}[0, \eta v, \eta v + b, b]$

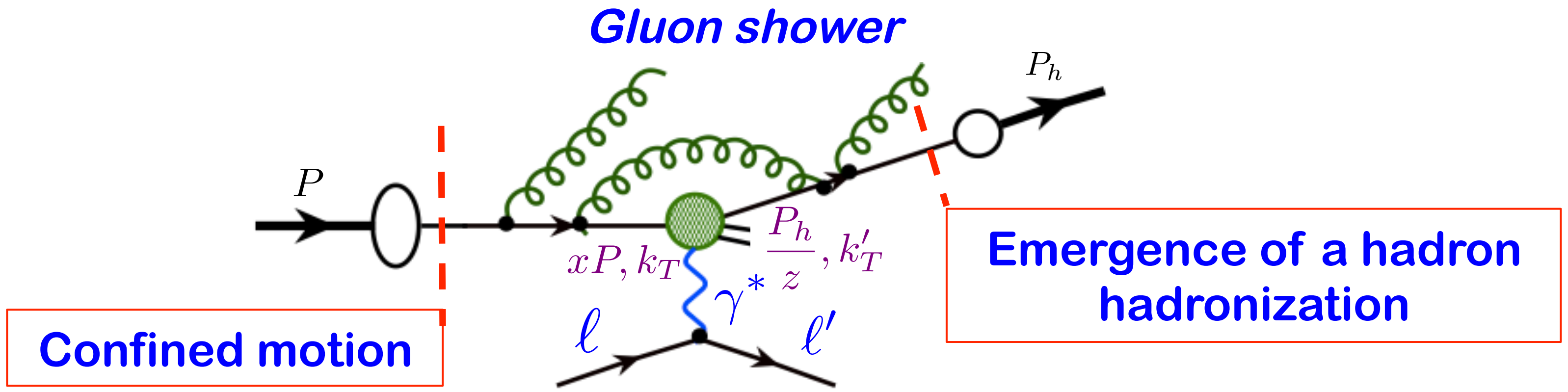


- **Normalized moment of Boer-Mulders function – at given b_T:**



Parton k_T at the hard collision

❑ **Sources of parton k_T at the hard collision:**



❑ **Large k_T generated by the shower (caused by the collision):**

✧ Q^2-dependence – linear evolution equation of TMDs in b-space

✧ The evolution kernels are perturbative at small b, but, not large b

➡ The nonperturbative inputs at large b could impact TMDs at all Q^2

❑ **Challenge: to extract the "true" parton's confined motion:**

✧ Separation of perturbative shower contribution from nonperturbative hadron structure – QCD evolution - not as simple as PDFs

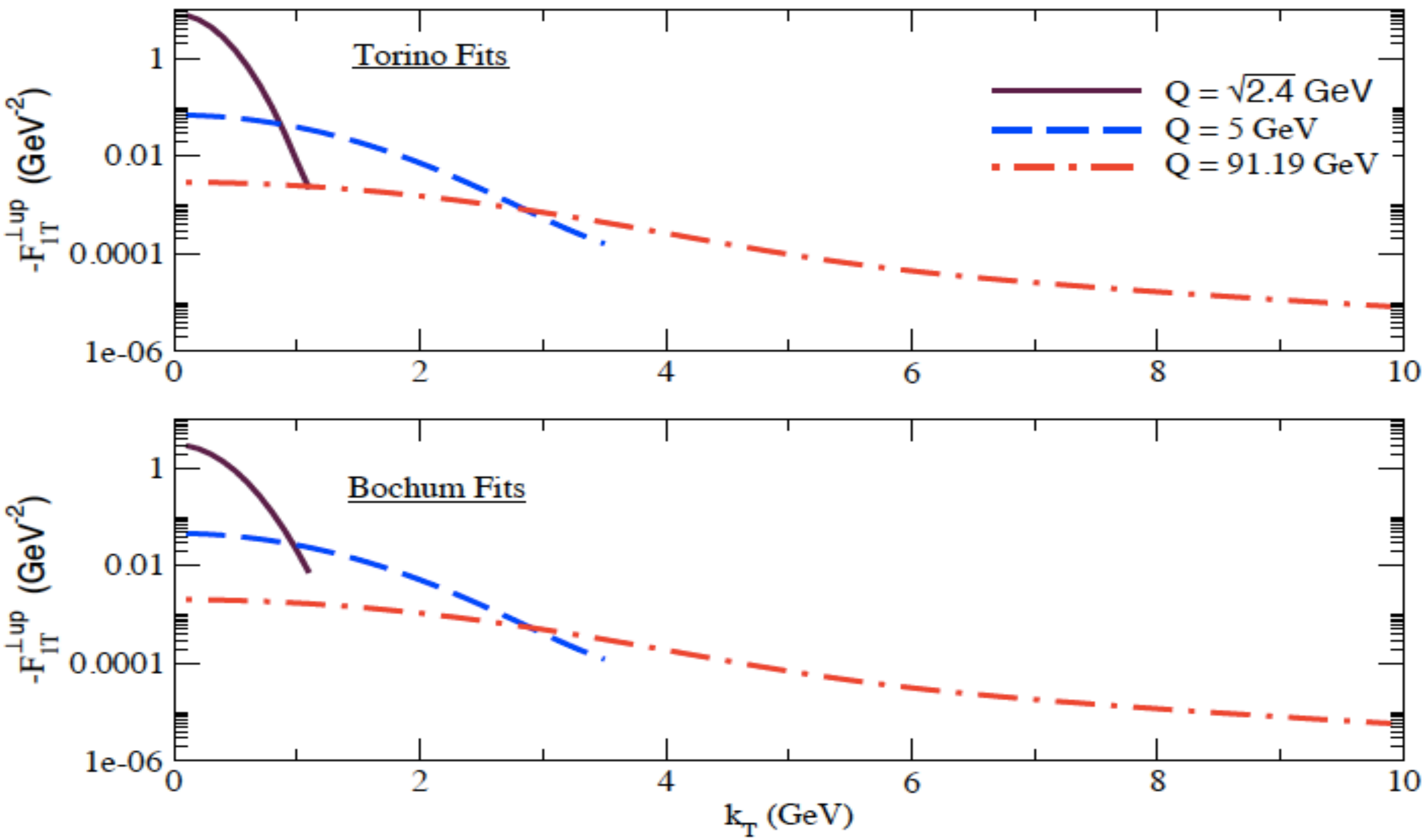
✧ Role of lattice QCD?

Task of the DOE supported TMD collaboration

Evolution of Sivers function

Aybat, Collins, Qiu, Rogers, 2011

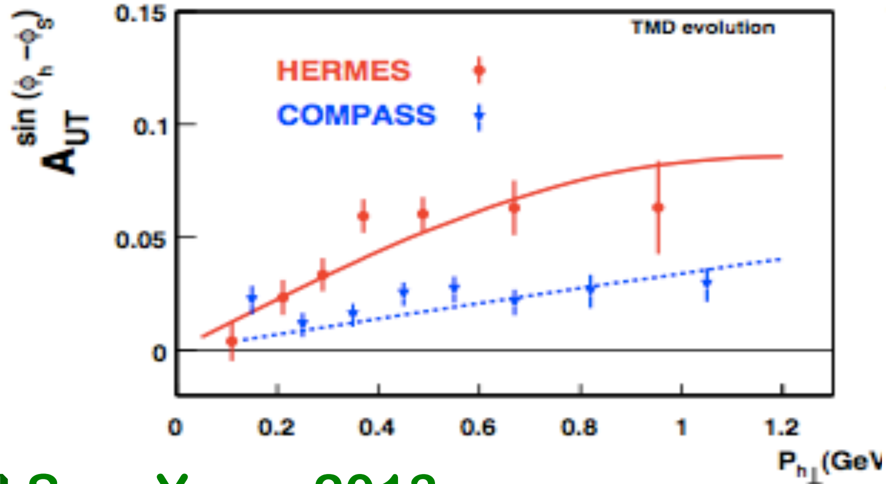
- **Up quark Sivers function:**

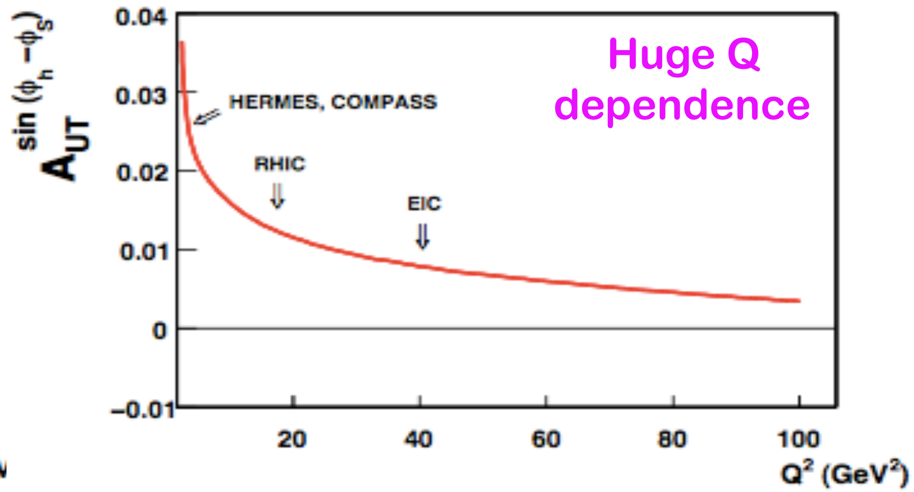


Very significant growth in the width of transverse momentum

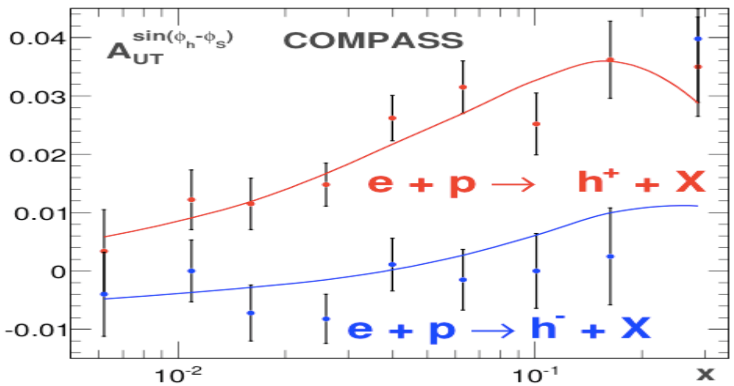
Different fits – different Q-dependence

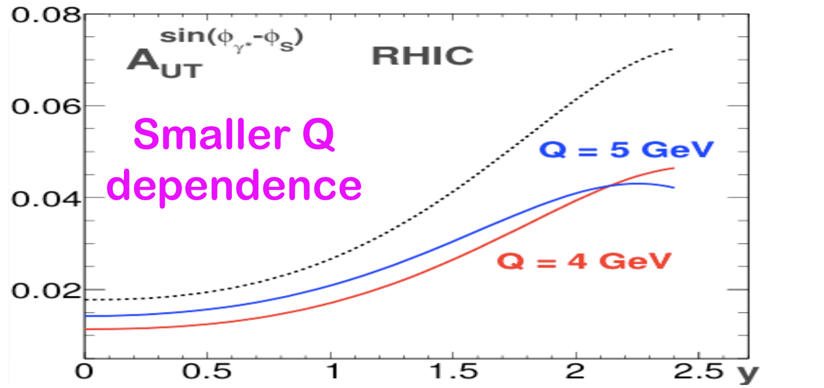
- Aybat, Prokudin, Rogers, 2012:





- Sun, Yuan, 2013:





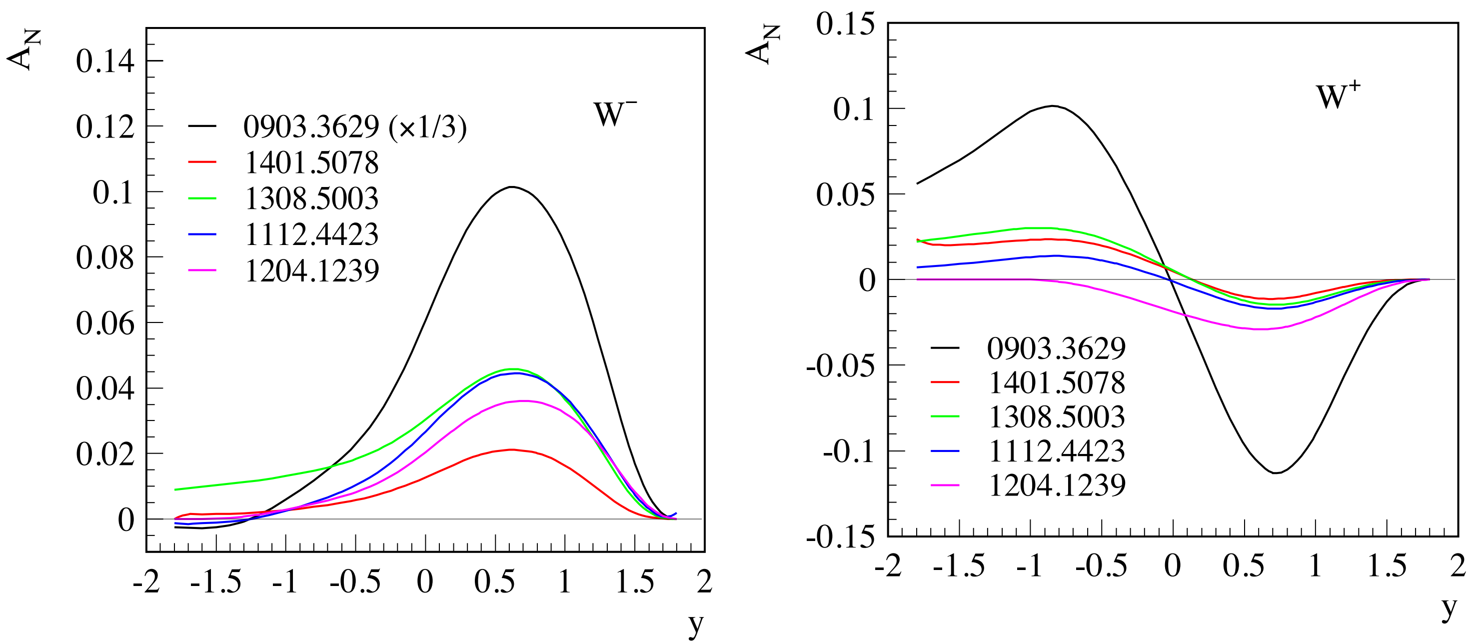
No disagreement on evolution equations!

Issues: Extrapolation to non-perturbative large b-region
Choice of the Q-dependent "form factor"

“Predictions” for A_N of W-production at RHIC?

See also talk by Marcia Quaresma on Wed. for COMPASS

- **Sivers Effect:**
  - ✧ Quantum correlation between the spin direction of colliding hadron and the preference of motion direction of its confined partons
  - ✧ QCD Prediction: Sign change of Sivers function from SIDIS and DY
- **Current “prediction” and uncertainty of QCD evolution:**



TMD collaboration proposal: Lattice, theory & Phenomenology

RHIC is the excellent and unique facility to test this (W/Z – DY)!

What happened?

- **Sivers function:**

Differ from PDFs!

$$F_{1T}^{\perp f}(x, k_T; \mu, \zeta_F) = \frac{-1}{2\pi k_T} \int_0^\infty db_T\, b_T\, J_1(k_T b_T) \tilde{F}_{1T}^{\prime\perp f}(x, b_T; \mu, \zeta_F)$$

Need non-perturbative large b_T information for any value of Q! **$Q = \mu$**

What happened?

- Sivers function:

Differ from PDFs!

$$F_{1T}^{\perp f}(x, k_T; \mu, \zeta_F) = \frac{-1}{2\pi k_T} \int_0^\infty db_T\, b_T\, J_1(k_T b_T) \tilde{F}_{1T}^{\prime \perp f}(x, b_T; \mu, \zeta_F)$$

Need non-perturbative large b_T information for any value of Q! **$Q = \mu$**

- What is the "correct" Q-dependence of the large b_T tail?

$$\tilde{F}_{f/P}(x, \mathrm{b}_T; Q, Q^2) = \overbrace{\sum_j \int_x^1 \frac{d\hat{x}}{\hat{x}} \tilde{C}_{f/j}(x/\hat{x}, b_*; \mu_b^2, \mu_b, g(\mu_b)) f_{j/P}(\hat{x}, \mu_b)}^{\mathrm{AA}}$$

$$\times \overbrace{\times \exp\left\{ \ln \frac{Q}{\mu_b} \tilde{K}(b_*; \mu_b) + \int_{\mu_b}^{Q} \frac{d\mu'}{\mu'} \left[\gamma_F(g(\mu'); 1) - \ln \frac{Q}{\mu'} \gamma_K(g(\mu')) \right] \right\}}^{\mathrm{BB}}$$

$$\times \overbrace{\exp\left\{ g_{f/P}(x, b_T) + g_K(b_T) \ln \frac{Q}{Q_0} \right\}}^{\mathrm{CC}}$$

Nonperturbative "form factor"

$$g_{f/P}(x, b_T) + g_K(b_T) \ln \frac{Q}{Q_0} \equiv -\left[g_1 + g_2 \ln \frac{Q}{2Q_0} + g_1 g_3 \ln(10x) \right] b_T^2$$

What happened?

- **Sivers function:**

Differ from PDFs!

$$F_{1T}^{\perp f}(x,k_T;\mu,\zeta_F) = \frac{-1}{2\pi k_T}\int_0^\infty db_T\, b_T\, J_1(k_T b_T)\tilde{F}_{1T}^{\prime\perp f}(x,b_T;\mu,\zeta_F)$$

Need non-perturbative large b_T information for any value of Q! *$Q = \mu$*

- **What is the "correct" Q-dependence of the large b_T tail?**

$$\tilde{F}_{f/P}(x,\mathrm{b}_T;Q,Q^2) = \overbrace{\sum_j \int_x^1 \frac{d\hat{x}}{\hat{x}} \tilde{C}_{f/j}(x/\hat{x}, b_*; \mu_b^2, \mu_b, g(\mu_b)) f_{j/P}(\hat{x},\mu_b)}^{\mathrm{AA}}$$

$$\times \overbrace{\times \exp\left\{ \ln\frac{Q}{\mu_b}\tilde{K}(b_*;\mu_b) + \int_{\mu_b}^{Q}\frac{d\mu'}{\mu'}\left[\gamma_F(g(\mu');1) - \ln\frac{Q}{\mu'}\gamma_K(g(\mu'))\right]\right\}}^{\mathrm{BB}}$$

$$\times \overbrace{\exp\left\{ g_{f/P}(x,b_T) + g_K(b_T)\ln\frac{Q}{Q_0}\right\}}^{\mathrm{CC}}$$

Nonperturbative "form factor"

$$g_{f/P}(x,b_T) + g_K(b_T)\ln\frac{Q}{Q_0} \equiv -\left[g_1 + g_2\ln\frac{Q}{2Q_0} + g_1 g_3\ln(10x)\right] b_T^2$$

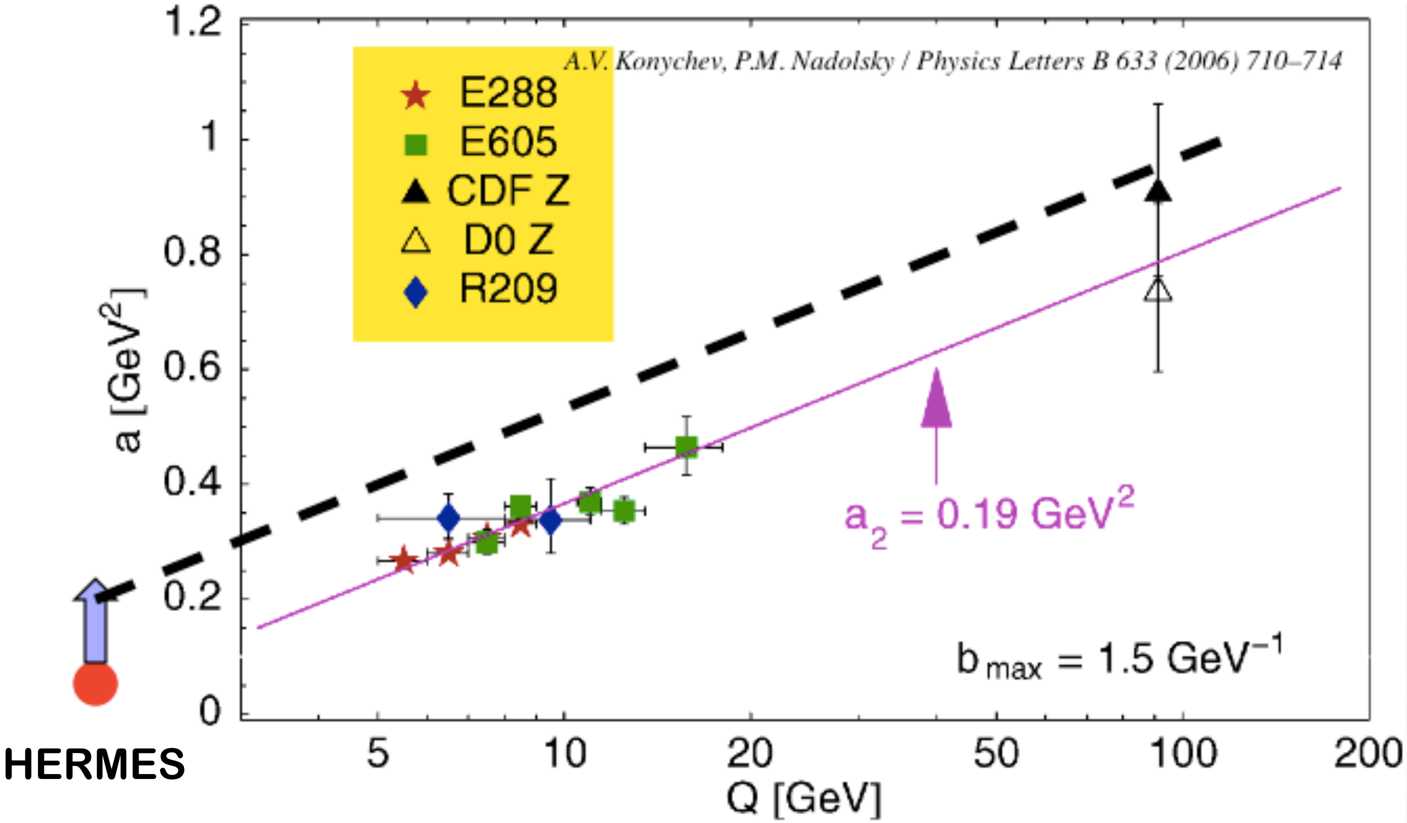
Is the log(Q) dependence sufficient? Choice of g_2 & b_* affects Q-dep.

The "form factor" and b_* change perturbative results at small b_T!

Q-dependence of the "form" factor

Konychev, Nadolsky, 2006

- ❑ Q-dependence of the "form factor" :



$$\mathcal{F}^{\rm NP}(b,Q) = a(Q^2)\,b^2$$

At Q ~ 1 GeV, ln(Q/Q_0) term may not be the dominant one!

$$\mathcal{F}^{\rm NP} \approx b^2(a_1 + a_2 \ln(Q/Q_0) + a_3 \ln(x_A x_B) + \ldots) + \ldots$$

Power correction? **($(Q_0/Q)^n$-term?** ***Better fits for HERMES data?***

Global QCD analysis: extraction of TMDs

❑ QCD TMD factorization:

– Connect cross sections, asymmetries to TMDs

✧ Factorization is known or expected to be valid for SIDIS, Drell-Yan (Υ^*, W/Z, H^0,…), 2-Jet imbalance in DIS, …

✧ *Same level of reliability as collinear factorization for PDFs, up to the sign change*

❑ QCD evolution of TMDs:

– TMDs evolve when probed at different momentum scales

✧ Evolution equations are for TMDs in b_T-space (Fourier Conjugate of k_T)

FACT: QCD evolution does NOT fully fix TMDs in momentum space, even with TMDs fixed at low Q – large b_T-input!!!

✧ *Very different from DGLAP evolution of PDFs – in momentum space*

FACT: QCD evolution uniquely fix PDFs at large Q, once the PDFs is determined at lower Q – linear evolution in momentum space

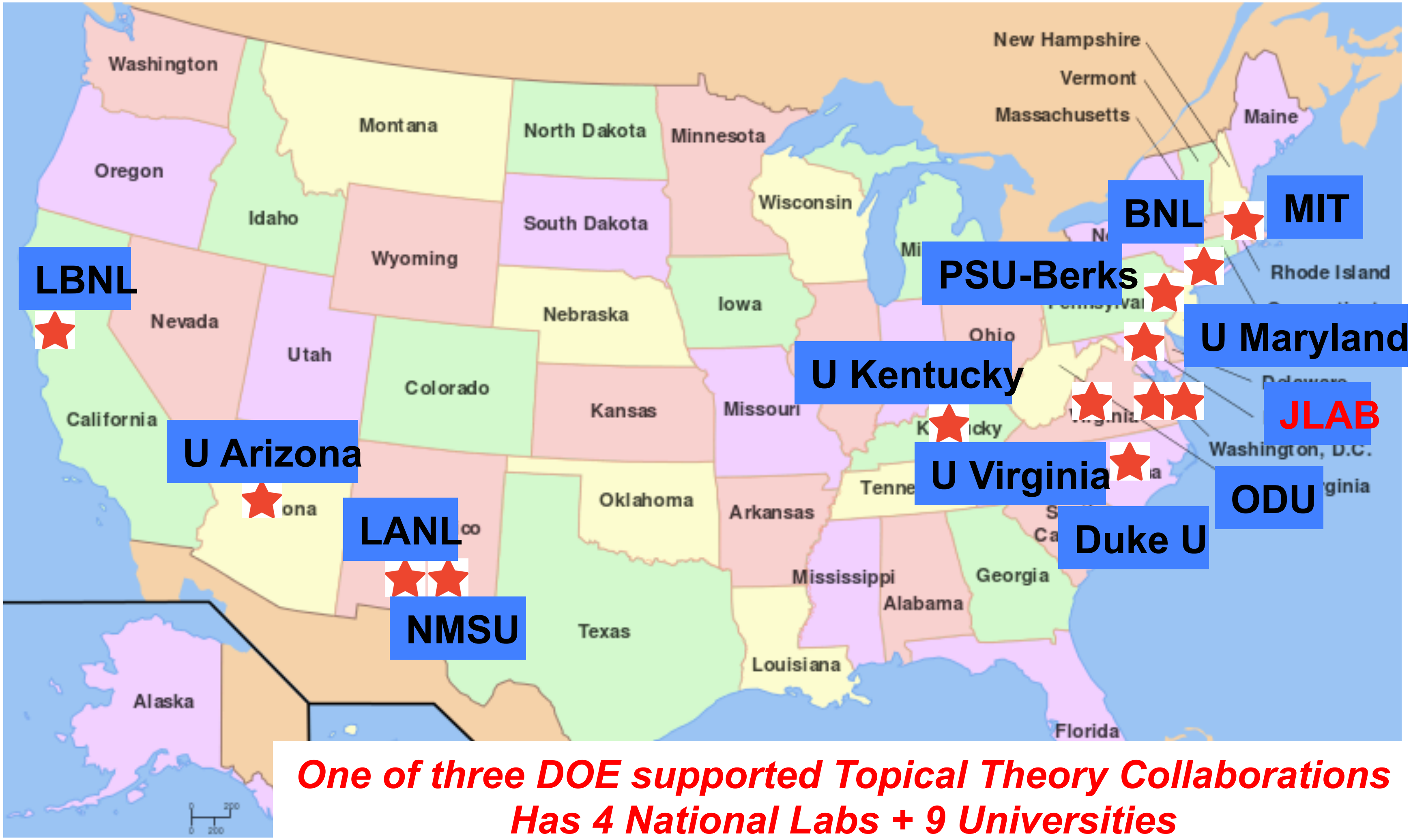
❑ Challenges:

Predictive power, extraction of hadron structure, …

TMD Topical Theory Collaboration

Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD (TMD Collaboration)

Co-spokespersons: W. Detmold, J.W. Qiu



One of three DOE supported Topical Theory Collaborations
Has 4 National Labs + 9 Universities

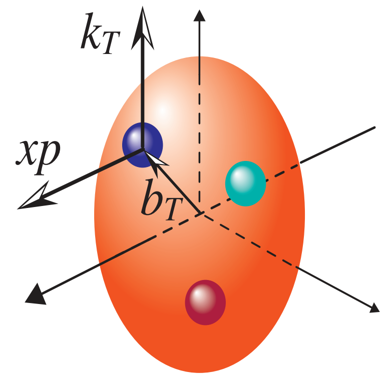
TMD Topical Theory Collaboration

❑ Objectives/Deliverables – 3D Confined Motion:

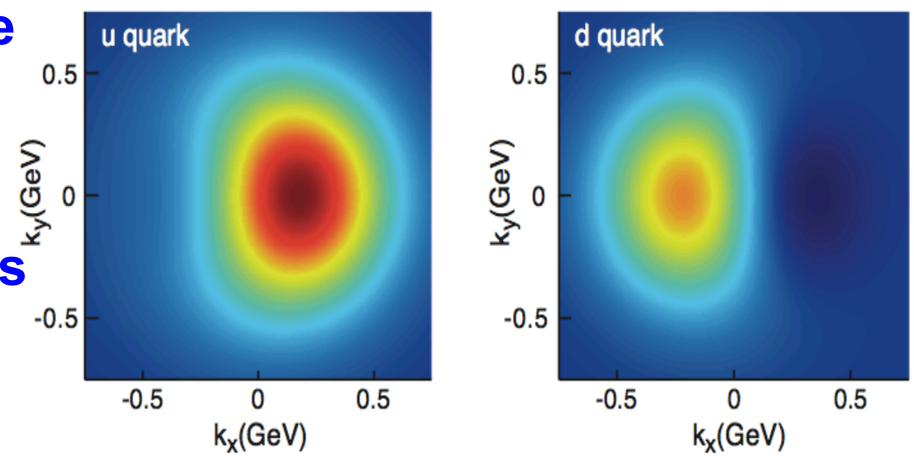
Unique three pronged scientific effort:
(1) theory, (2) phenomenology and
(3) lattice QCD, to explore 3D hadron
structure – 3D confined motion!

- ✧ **Matching x-section to parton motion**
  - – **QCD factorization**
- ✧ **Parton motion vs. probing scale**
  - – **QCD quantum evolution**
  - – **RHIC Run17 – W program**
- ✧ **Lattice QCD calculation of TMDs**
  - – **QCD 1st principle prediction?**
- ✧ **Fast software to extract TMDs**
  - – **Service to community**
- ✧ **JLab12 data, …**

TMD Collaboration



Sivers function



Density distribution of an unpolarized
quark in a proton moving in z

Proposed research projects – examples

- **Factorization and definition of TMDs**

  Stewart (coordinator), Ji, Lee, Prokudin, Rogers, Vitev, Yuan, …

- **Evolution of TMDs**

  Prokudin (coordinator), Gamberg, Lee, Metz, Rogers, Yuan, …

- **Nonperturbative Input to TMD Evolution**

  Rogers (coordinator), Engelhardt, Fleming, Gamberg, Lee, Mehen, Qiu, Stewart, Vitev, Yuan, …

- **QCD Global Analysis of the TMDs**

  Yuan (coordinator), Gamberg, Lee, Metz, Prokudin, Qiu, Rogers, Vitev, Yuan, …

- **Relation between TMDs and collinear PDFs**

  Metz (coordinator), Qiu, Rogers, Sterman, Yuan, …

Proposed research projects – examples

- New physical observables sensitive to TMDs

  Gamberg (coordinator), Engelhardt, Mehen, Metz, Prokudin, Rogers, Stewart , …

- Lattice calculations of PDFs and TMDs – factorization

  Qiu (coordinator), Detmold, Fleming, Ji, Mehen, Stewart, …

- Lattice calculations of hadron structure – nonperturbative

  Detmold (coordinator), Engelhardt, Liu, Negele, …

- TMDs and parton orbital angular momentum

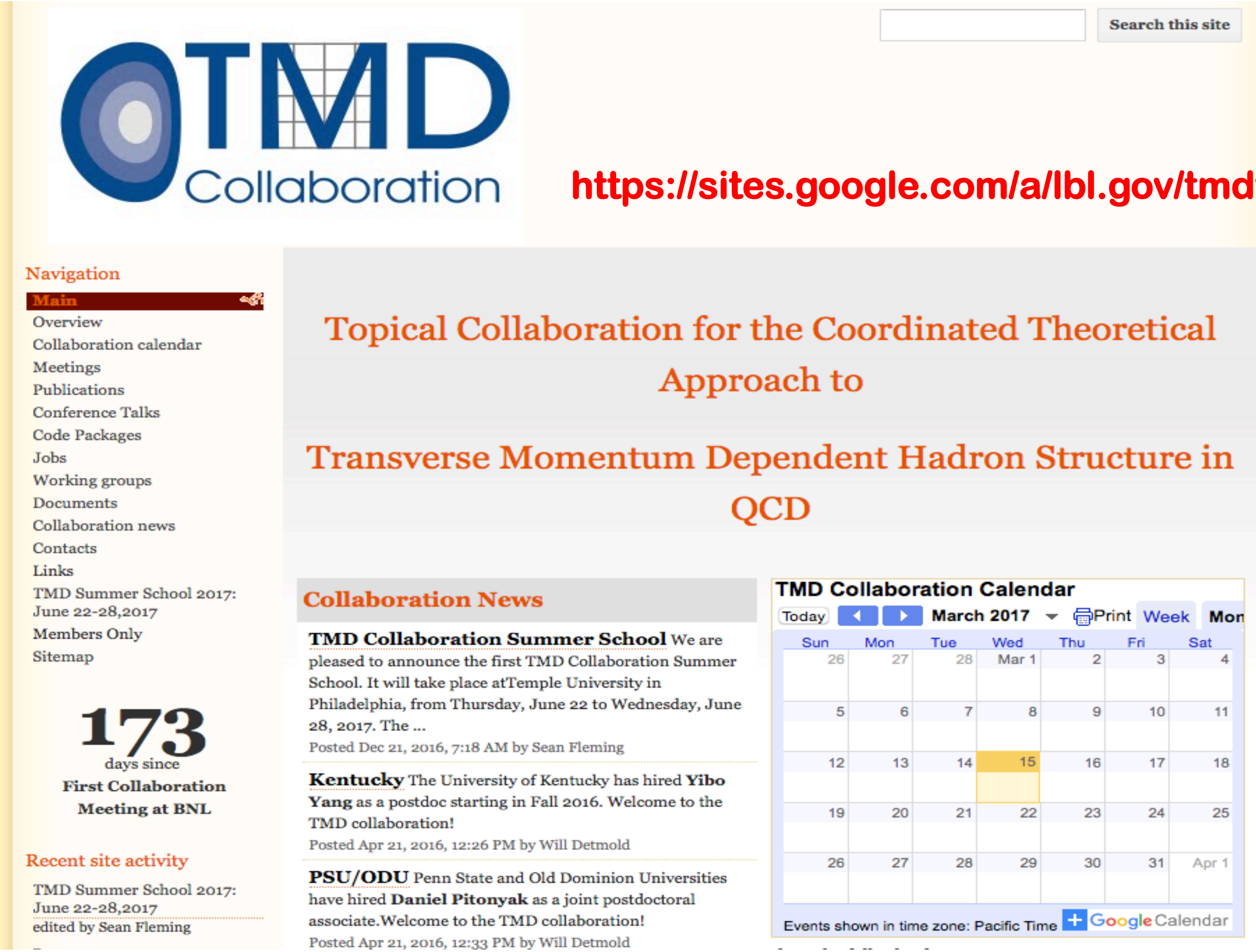
  Negele (coordinator), Burkardt, Engelhardt, Liu, Liuti, Metz, …

- TMDs at small-x and in nuclei

  Venugopalan (coordinator), Detmold, Fleming, Qiu, Stewart, Yuan, …

TMD WIKI page

https://sites.google.com/a/lbl.gov/tmdwiki/



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TMD Collaboration

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First Collaboration Meeting at BNL

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TMD Summer School 2017: June 22-28,2017
edited by Sean Fleming

Topical Collaboration for the Coordinated Theoretical Approach to

Transverse Momentum Dependent Hadron Structure in QCD

Collaboration News

TMD Collaboration Summer School We are pleased to announce the first TMD Collaboration Summer School. It will take place atTemple University in Philadelphia, from Thursday, June 22 to Wednesday, June 28, 2017. The ...
Posted Dec 21, 2016, 7:18 AM by Sean Fleming

Kentucky The University of Kentucky has hired **Yibo Yang** as a postdoc starting in Fall 2016. Welcome to the TMD collaboration!
Posted Apr 21, 2016, 12:26 PM by Will Detmold

PSU/ODU Penn State and Old Dominion Universities have hired **Daniel Pitonyak** as a joint postdoctoral associate.Welcome to the TMD collaboration!
Posted Apr 21, 2016, 12:33 PM by Will Detmold

TMD Collaboration Calendar

Today ◀ ▶ March 2017 ▾ Print Week Mon

Sun	Mon	Tue	Wed	Thu	Fri	Sat
26	27	28	Mar 1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30	31	Apr 1

Events shown in time zone: Pacific Time + Google Calendar

TMD Summer School @ Temple University

Travel

Program

Email Us

TMD Collaboration Summer School 2017

June 22 - 28, 2017
Temple University
Philadelphia, USA

Organizing Committee:

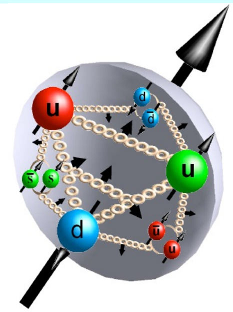
Matthias Burkardt (New Mexico State University)
Martha Constantinou (Temple University)
Sean Fleming, Co-Chair (University of Arizona)
Leonard Gamberg (Penn State University-Berks)
Keh-Fei Liu (University of Kentucky)
Andreas Metz, Co-Chair (Temple University)
Alexei Prokudin (Penn State University-Berks)

http://www.physics.arizona.edu/~fleming/Main.html

Topics and Speakers:

- QCD and Parton Model: Pavel Nadolsky (SMU)
- TMD Phenomenology: Alessandro Bacchetta (U. di Pavia) & Andrea Signori (JLAB)
- TMD Factorization and Evolution: Ted Rogers (ODU)
- TMDs in Experiement: Matthias Grosse-Perdekamp (UIUC)
- Lattice QCD: Will Detmold (MIT)
- SCET: Iain Stewart (MIT)
- Quasi-PDFs: Martha Constantinou (Temple U.)
- GPDs and Generalized TMDs: Cedric Lorce (Ecole Polytechnique)
- TMDs in Lattice QCD: Michael Engelhardt (NMSU)
- TMDs at small x: Feng Yuan (LBNL)

PDFs, TMDs, GPDs, and hadron structure



❑ What do we need to know for full hadron structure?

- ✧ **In theory:** $\langle P,S|\mathcal{O}(\overline{\psi},\psi,A^{\mu})|P,S\rangle$ – Hadronic matrix elements

  with ALL possible operators $\mathcal{O}(\overline{\psi},\psi,A^{\mu})$

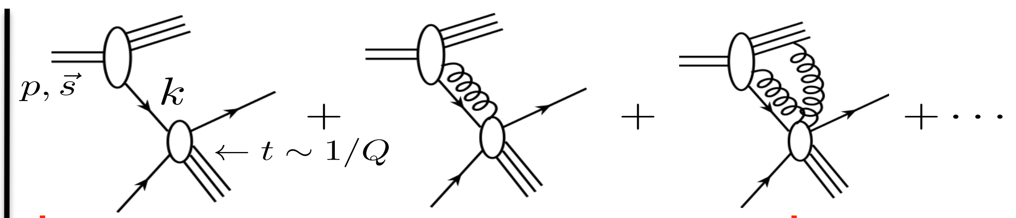
- ✧ **In fact:** *None of these matrix elements is a direct physical observable in QCD – color confinement! – need probes!!!*

- ✧ **In practice:** Accessible hadron structure
  = hadron matrix elements of quarks and gluons, which

  1) can be related to physical cross sections of hadrons and leptons with controllable approximation – factorization;
  2) can be calculated in lattice QCD

❑ Multi-parton correlations – beyond single parton distributions:

$\sigma(Q,\vec{s}) \propto \Big|$



$\Big|^2 \left(\frac{\langle k_\perp\rangle}{Q}\right)^n$ – Expansion

Quantum interference/correlation ➡ Multi-parton matrix elements

Summary

- ❑ TMDs and GPDs are NOT direct physical observables
  – could be defined differently

- ❑ Knowledge of nonperturbative inputs at large b_T is crucial in determining the TMDs from fitting the data

- ❑ QCD factorization is necessary for any controllable "probe" for hadron's quark-gluon structure!

- ❑ Jlab12, COMPASS, … will provide rich information on hadron structure via TMDs and/or GPDs in years to come!

- ❑ EIC is a ultimate QCD machine, and will provide answers to many of our questions on hadron structure, in particular, the confined transverse motions (TMDs), spatial distributions (GPDs), and multi-parton correlations, …

Thank you!

Backup slides

Evolution equations for TMDs

J.C. Collins, in his book on QCD

- TMDs in the b-space:

$$\tilde{F}_{f/P^\uparrow}(x, \mathrm{b_T}, S; \mu; \zeta_F) = \tilde{F}^{\mathrm{unsub}}_{f/P^\uparrow}(x, \mathrm{b_T}, S; \mu; y_P - (-\infty)) \sqrt{\frac{\tilde{S}_{(0)}(\mathrm{b_T}; +\infty, y_s)}{\tilde{S}_{(0)}(\mathrm{b_T}; +\infty, -\infty)\tilde{S}_{(0)}(\mathrm{b_T}; y_s, -\infty)}} Z_F Z_2$$

- Collins-Soper equation:

Renormalization of the soft-factor

$$\frac{\partial \tilde{F}_{f/P^\uparrow}(x, \mathrm{b_T}, S; \mu; \zeta_F)}{\partial \ln \sqrt{\zeta_F}} = \tilde{K}(b_T; \mu) \tilde{F}_{f/P^\uparrow}(x, \mathrm{b_T}, S; \mu; \zeta_F)$$

$$\zeta_F = M_P^2 x^2 e^{2(y_P - y_s)}$$

$$\tilde{K}(b_T; \mu) = \frac{1}{2} \frac{\partial}{\partial y_s} \ln \left(\frac{\tilde{S}(b_T; y_s, -\infty)}{\tilde{S}(b_T; +\infty, y_s)} \right)$$

Introduced to regulate the rapidity divergence of TMDs

- RG equations:

Wave function Renormalization

$$\frac{d\tilde{K}(b_T; \mu)}{d \ln \mu} = -\gamma_K(g(\mu))$$

Evolution equations are only valid when $b_T << 1/\Lambda_{QCD}$!

$$\frac{d\tilde{F}_{f/P^\uparrow}(x, \mathrm{b_T}, S; \mu; \zeta_F)}{d \ln \mu} = \gamma_F(g(\mu); \zeta_F/\mu^2) \tilde{F}_{f/P^\uparrow}(x, \mathrm{b_T}, S; \mu; \zeta_F).$$

- Momentum space TMDs:

Need information at large b_T for all scale μ !

$$F_{f/P^\uparrow}(x, \mathrm{k_T}, S; \mu, \zeta_F) = \frac{1}{(2\pi)^2} \int d^2\mathrm{b}_T \, e^{i\mathrm{k}_T \cdot \mathrm{b}_T} \, \tilde{F}_{f/P^\uparrow}(x, \mathrm{b_T}, S; \mu, \zeta_F)$$

Evolution equations for Sivers function

Aybat, Collins, Qiu, Rogers, 2011

- Sivers function:

$$F_{f/P^\uparrow}(x,k_T,S;\mu,\zeta_F) = F_{f/P}(x,k_T;\mu,\zeta_F) - F_{1T}^{\perp f}(x,k_T;\mu,\zeta_F)\frac{\epsilon_{ij}k_T^i S^j}{M_p}$$

- Collins-Soper equation:

Its derivative obeys the CS equation

$$\frac{\partial \ln \tilde{F}_{1T}^{\prime\perp f}(x,b_T;\mu,\zeta_F)}{\partial \ln\sqrt{\zeta_F}} = \tilde{K}(b_T;\mu)$$

$$\tilde{F}_{1T}^{\prime\perp f}(x,b_T;\mu,\zeta_F) \equiv \frac{\partial \tilde{F}_{1T}^{\perp f}(x,b_T;\mu,\zeta_F)}{\partial b_T}$$

- RG equations:

$$\frac{d\tilde{F}_{1T}^{\prime\perp f}(x,b_T;\mu,\zeta_F)}{d\ln\mu} = \gamma_F(g(\mu);\zeta_F/\mu^2)\tilde{F}_{1T}^{\prime\perp f}(x,b_T;\mu,\zeta_F)$$

$$\frac{d\tilde{K}(b_T;\mu)}{d\ln\mu} = -\gamma_K(g(\mu)) \quad \Rightarrow \quad \frac{\partial\gamma_F(g(\mu);\zeta_F/\mu^2)}{\partial\ln\sqrt{\zeta_F}} = -\gamma_K(g(\mu)),$$

- Sivers function in momentum space:

$$F_{1T}^{\perp f}(x,k_T;\mu,\zeta_F) = \frac{-1}{2\pi k_T}\int_0^\infty db_T\, b_T J_1(k_T b_T)\tilde{F}_{1T}^{\prime\perp f}(x,b_T;\mu,\zeta_F)$$

JI, Ma, Yuan, 2004
Idilbi, et al, 2004,
Boer, 2001, 2009,
Kang, Xiao, Yuan, 2011
Aybat, Prokudin, Rogers, 2012
Idilbi, et al, 2012,
Sun, Yuan 2013, …

Extrapolation to large b_T

❑ **CSS b*-prescription:**

Aybat and Rogers, arXiv:1101.5057
Collins and Rogers, arXiv:1412.3820

$$\tilde{F}_{f/P}(x, b_T; Q, Q^2) = \overbrace{\sum_j \int_x^1 \frac{d\hat{x}}{\hat{x}} \tilde{C}_{f/j}(x/\hat{x}, b_*; \mu_b^2, \mu_b, g(\mu_b)) f_{j/P}(\hat{x}, \mu_b)}^{AA}$$

$$\times \overbrace{\times \exp\left\{ \ln \frac{Q}{\mu_b} \tilde{K}(b_*; \mu_b) + \int_{\mu_b}^{Q} \frac{d\mu'}{\mu'} \left[\gamma_F(g(\mu'); 1) - \ln \frac{Q}{\mu'} \gamma_K(g(\mu')) \right] \right\}}^{BB}$$

$$\times \overbrace{\exp\left\{ g_{f/P}(x, b_T) + g_K(b_T) \ln \frac{Q}{Q_0} \right\}}^{CC}$$

Nonperturbative "form factor"

$$b_* = \frac{b_T}{\sqrt{1 + b_T^2/b_{max}^2}} \qquad \text{with } b_{max} \sim 1/2 \text{ GeV}^{-1}$$

❑ **Nonperturbative fitting functions**

Various fits correspond to different choices for $g_{f/P}(x, b_T)$ **and** $g_K(b_T)$
e.g.

$$g_{f/P}(x, b_T) + g_K(b_T) \ln \frac{Q}{Q_0} \equiv -\left[g_1 + g_2 \ln \frac{Q}{2Q_0} + g_1 g_3 \ln(10x) \right] b_T^2$$

Different choice of g_2 & b_* could lead to different over all Q-dependence!