BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

RBRC

RIKEN BNL Research Center

How was matter formed after the Big Bang? Scientists at the RBRC are pursuing this ultimate question of modern physics to understand the origin of matter and the universe. Their goal is to establish a new field of physics by coordinating theoretical and experimental research.

3D Tomography of Parton Motion inside Hadrons

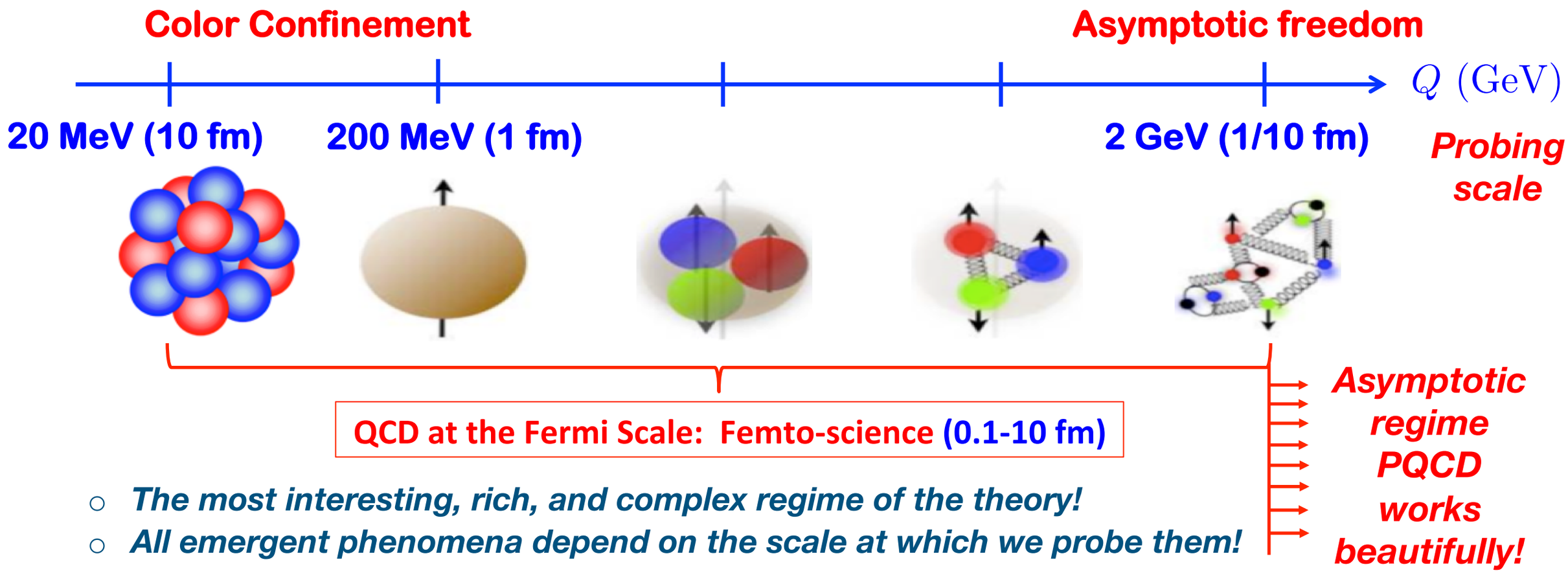
Jianwei Qiu

Theory Center, Jefferson Lab

Acknowledgement: This talk was prepared based on publications and progresses made by members of TMD collaboration. Unfortunately, a lot of materials could not be covered in one talk.

QCD and Structure of Hadrons and Nuclei

- **QCD – Color Confinement:**
  - ✧ Do not see any quarks and gluons in isolation
  - ✧ The structure of nucleons and nuclei – emergent properties of QCD



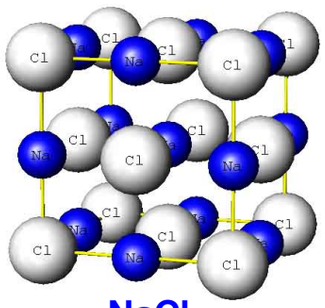
  - ○ *The most interesting, rich, and complex regime of the theory!*
  - ○ *All emergent phenomena depend on the scale at which we probe them!*

- **QCD – Asymptotic Freedom:**
  - ✧ Force becomes weaker at a shorter-distance – Controllable "Probes"
  - ✧ Explore the structure of nucleons and nuclei **indirectly** by using "local", "sharp", and "controllable" probes, …

“See” the Structure of Nucleons and Nuclei

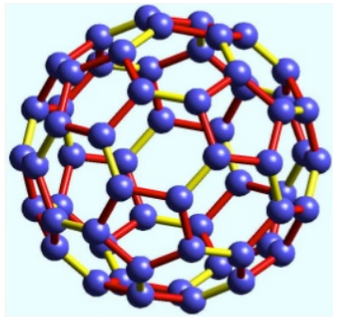
- **Structure – “a still picture”:**

Crystal Structure:



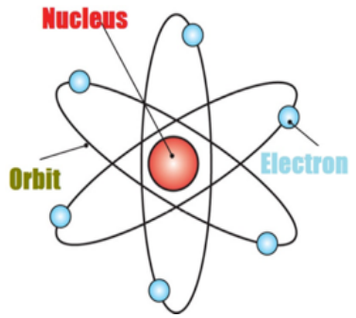
NaCl,
B1 type structure

Nano-material:



Fullerene, C60

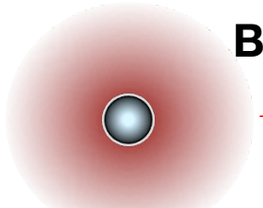
Atomic structure



Quantum orbits

Motion of nuclei is much slower than the speed of light, neutral photon!

- **No “still picture” for hadron’s partonic structure!**



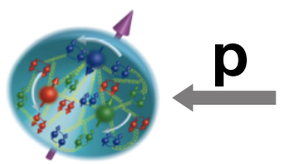
B-meson
$B^+(u\bar{b})$

Brown-Muck

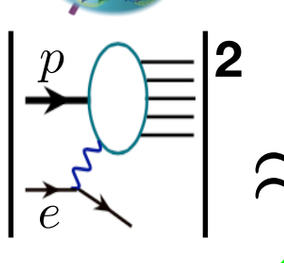
*Quarks and gluons are moving **relativistically**, color is fully entangled!*

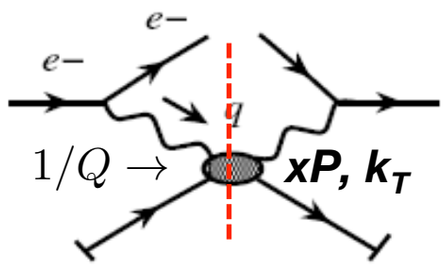
Partonic structure = “Quantum Probabilities”: $\langle P,S|\mathcal{O}(\psi,\psi,A^\mu)|P,S\rangle$

- **Need a probe to “see” quarks and gluons!**

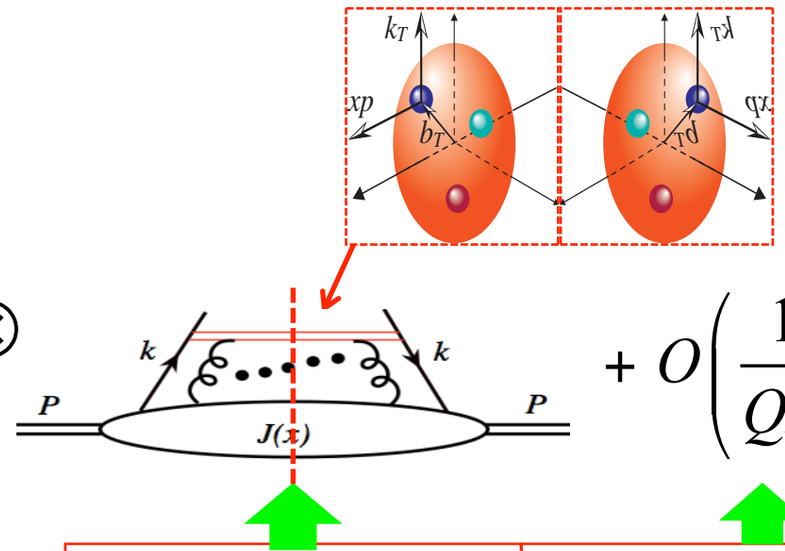


$$\sigma_{\rm DIS}(x,Q^2) = \left|\;\right|^2 \approx$$





$\otimes$



$$+\,O\left(\frac{1}{QR}\right)$$

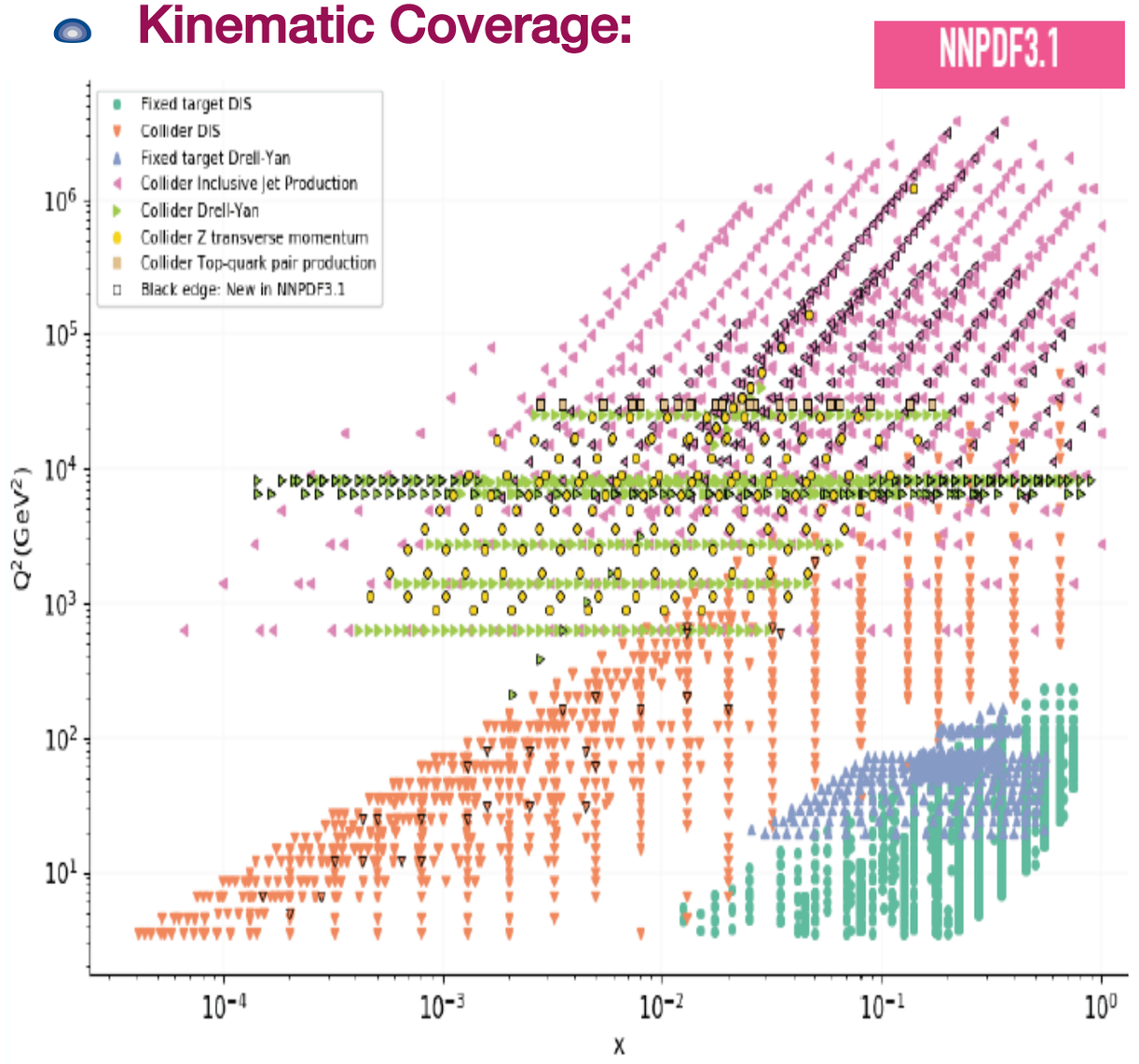
Factorization | **Hard-part Probe** | **Parton-distribution Structure** | **Power corrections Approximation**

QCD Factorization Works to the Precision

Data sets for Global fits:

	Process	Subprocess	Partons	x range
Fixed Target	$\ell^\pm\{p,n\} \to \ell^\pm + X$	$\gamma^* q \to q$	$q, \bar{q}, g$	$x \gtrsim 0.01$
	$\ell^\pm n/p \to \ell^\pm + X$	$\gamma^* d/u \to d/u$	d/u	$x \gtrsim 0.01$
	$pp \to \mu^+\mu^- + X$	$u\bar{u}, d\bar{d} \to \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
	$pn/pp \to \mu^+\mu^- + X$	$(u\bar{d})/(u\bar{u}) \to \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
	$\nu(\bar{\nu})N \to \mu^-(\mu^+) + X$	$W^* q \to q'$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
	$\nu N \to \mu^-\mu^+ + X$	$W^* s \to c$	s	$0.01 \lesssim x \lesssim 0.2$
	$\bar{\nu} N \to \mu^+\mu^- + X$	$W^* \bar{s} \to \bar{c}$	$\bar{s}$	$0.01 \lesssim x \lesssim 0.2$
Collider DIS	$e^\pm p \to e^\pm + X$	$\gamma^* q \to q$	$g, q, \bar{q}$	$0.0001 \lesssim x \lesssim 0.1$
	$e^+ p \to \bar{\nu} + X$	$W^+\{d,s\} \to \{u,c\}$	d, s	$x \gtrsim 0.01$
	$e^\pm p \to e^\pm c\bar{c} + X$	$\gamma^* c \to c, \gamma^* g \to c\bar{c}$	c, g	$10^{-4} \lesssim x \lesssim 0.01$
	$e^\pm p \to e^\pm b\bar{b} + X$	$\gamma^* b \to b, \gamma^* g \to b\bar{b}$	b, g	$10^{-4} \lesssim x \lesssim 0.01$
	$e^\pm p \to \text{jet} + X$	$\gamma^* g \to q\bar{q}$	g	$0.01 \lesssim x \lesssim 0.1$
Tevatron	$p\bar{p} \to \text{jet} + X$	$gg, qg, qq \to 2j$	g, q	$0.01 \lesssim x \lesssim 0.5$
	$p\bar{p} \to (W^\pm \to \ell^\pm\nu) + X$	$u\bar{d} \to W^+, \bar{u}d \to W^-$	$u, d, \bar{u}, \bar{d}$	$x \gtrsim 0.05$
	$p\bar{p} \to (Z \to \ell^+\ell^-) + X$	$uu, dd \to Z$	u, d	$x \gtrsim 0.05$
	$p\bar{p} \to t\bar{t} + X$	$qq \to t\bar{t}$	q	$x \gtrsim 0.1$
LHC	$pp \to \text{jet} + X$	$gg, qg, q\bar{q} \to 2j$	g, q	$0.001 \lesssim x \lesssim 0.5$
	$pp \to (W^\pm \to \ell^\pm\nu) + X$	$u\bar{d} \to W^+, d\bar{u} \to W^-$	$u, d, \bar{u}, \bar{d}, g$	$x \gtrsim 10^{-3}$
	$pp \to (Z \to \ell^+\ell^-) + X$	$q\bar{q} \to Z$	$q, \bar{q}, g$	$x \gtrsim 10^{-3}$
	$pp \to (Z \to \ell^+\ell^-) + X, p_\perp$	$gq(\bar{q}) \to Zq(\bar{q})$	$g, q, \bar{q}$	$x \gtrsim 0.01$
	$pp \to (\gamma^* \to \ell^+\ell^-) + X$, Low mass	$q\bar{q} \to \gamma^*$	$q, \bar{q}, g$	$x \gtrsim 10^{-4}$
	$pp \to (\gamma^* \to \ell^+\ell^-) + X$, High mass	$q\bar{q} \to \gamma^*$	$\bar{q}$	$x \gtrsim 0.1$
	$pp \to W^+\bar{c}, W^-c$	$sg \to W^+c, \bar{s}g \to W^-\bar{c}$	$s, \bar{s}$	$x \sim 0.01$
	$pp \to t\bar{t} + X$	$gg \to t\bar{t}$	g	$x \gtrsim 0.01$
	$pp \to D, B + X$	$gg \to c\bar{c}, b\bar{b}$	g	$x \gtrsim 10^{-6}, 10^{-5}$
	$pp \to J/\psi, \Upsilon + pp$	$\gamma^*(gg) \to c\bar{c}, b\bar{b}$	g	$x \gtrsim 10^{-6}, 10^{-5}$
	$pp \to \gamma + X$	$gq(\bar{q}) \to \gamma q(\bar{q})$	g	$x \gtrsim 0.005$

Kinematic Coverage:

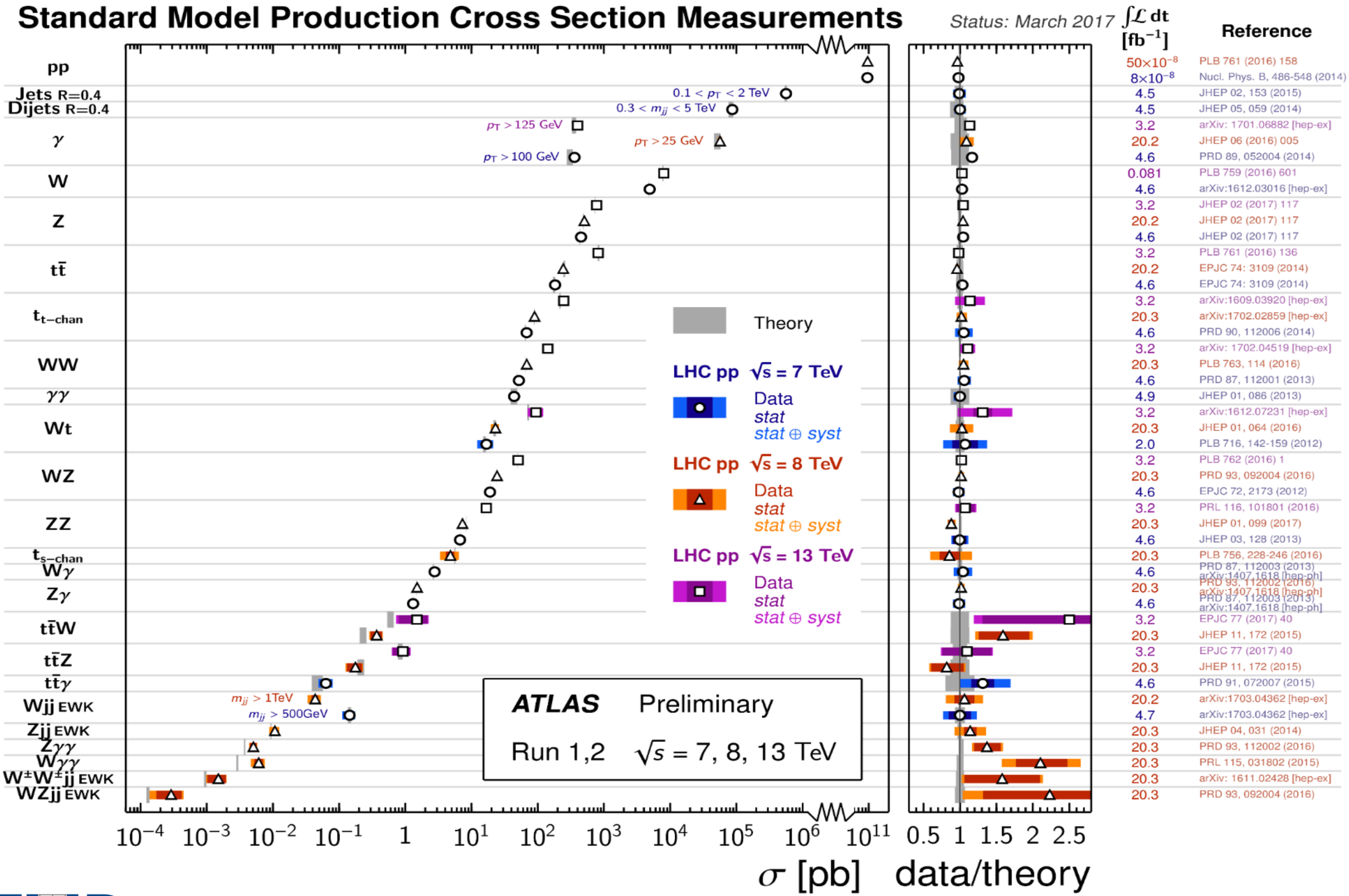


Fit quality:

$\chi^2/\text{dof} \sim 1 \Rightarrow$ Non-trivial check of QCD

	LO	NLO	NNLO
All data sets	3706 / 2763	3267 / 2996	2717 / 2663

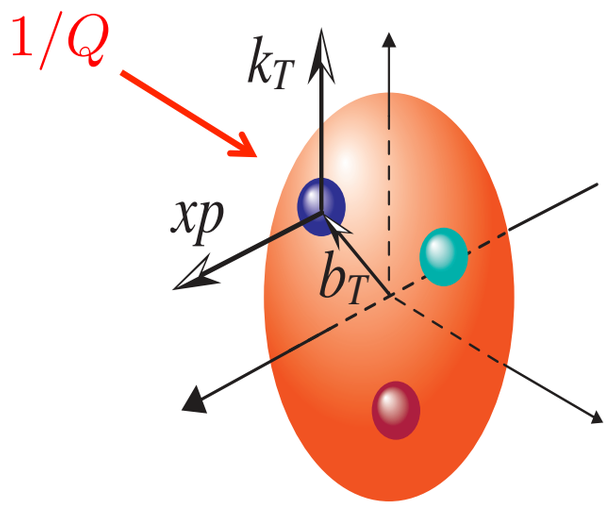
Unprecedent Success of QCD and Standard Model



SM: Electroweak processes + QCD perturbation theory works!

New-Type Probes for 3D Partonic Structure of Hadrons

- **Single-scale hard probe is too "localized"!**

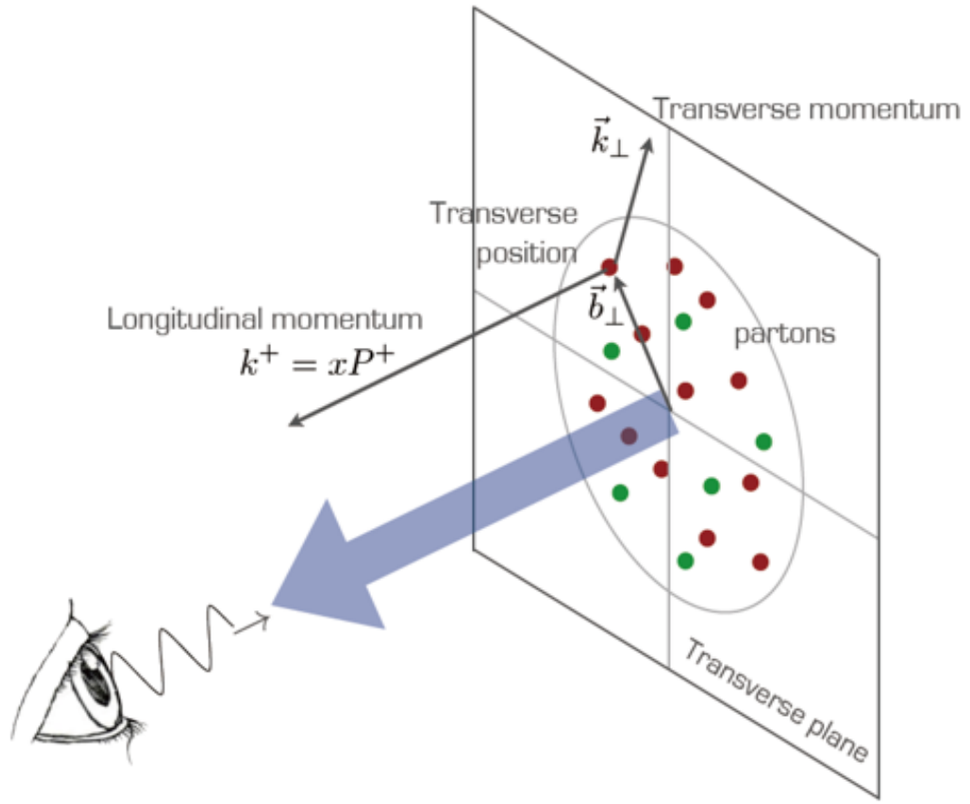


  - It pins down the particle nature of quarks and gluons
  - But, not very sensitive to the detailed structure of hadron ~ fm
  - Transverse confined motion: k_T ~ 1/fm << Q (> 10^{-1} fm)
  - Transverse spatial position: b_T ~ fm << Q (> 10^{-1} fm)

- **Need new type of "Hard Probes" – physical observables with TWO scales:**

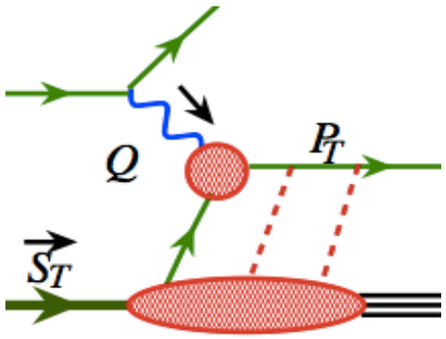
$$Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{\rm QCD}$$

  - Hard scale: Q_1 To localize the probe particle nature of quarks/gluons
  - "Soft" scale: Q_2 could be more sensitive to the hadron structure ~ 1/fm
  - Hit the hadron "very hard" without breaking it, clean information on the structure!

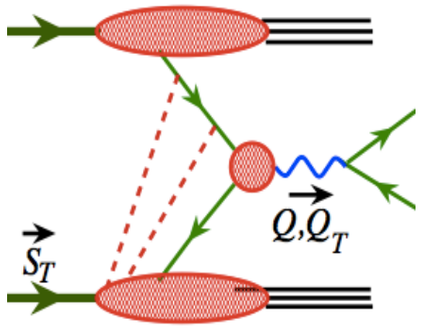


Unprecedent Challenge – "True" Hadron Structure

- **Natural two-scale observables in hard collisions:**

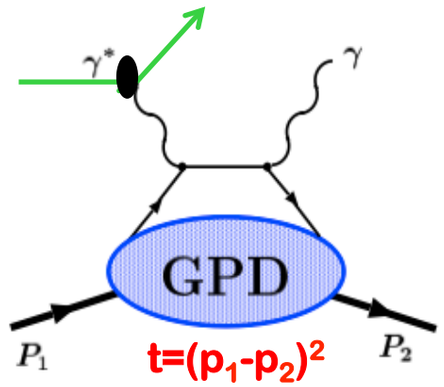


+

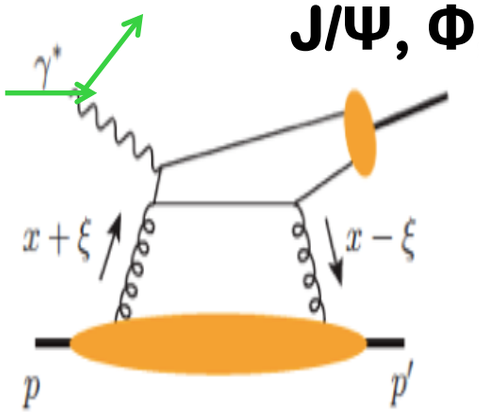


+ …

SIDIS: $Q \gg P_T$ DY: $Q \gg P_T$



+



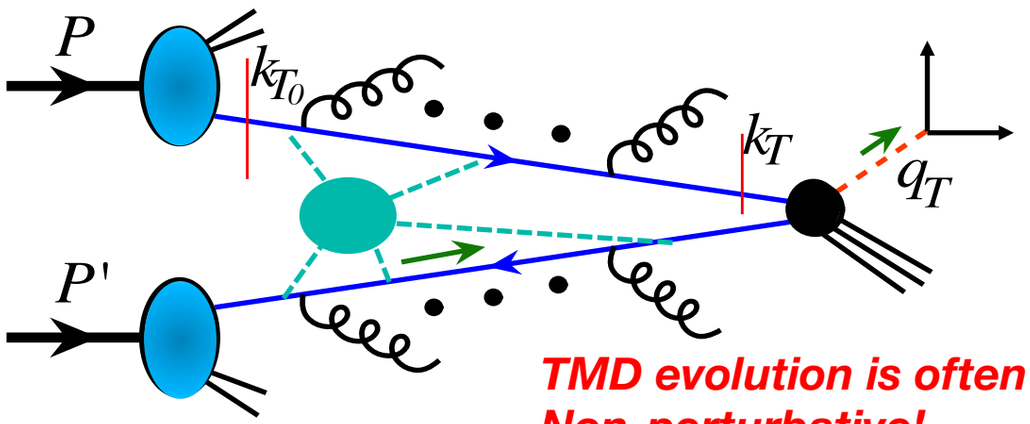
+ …

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

Parton's confined motion encoded into TMDs
Colliding hadron is *broken*

Parton's spatial imaging from Fourier transform of GPDs' t-dependence – hadron is *not broken*

- **Challenge to separate "collision effect" from "true" hadron structure:**



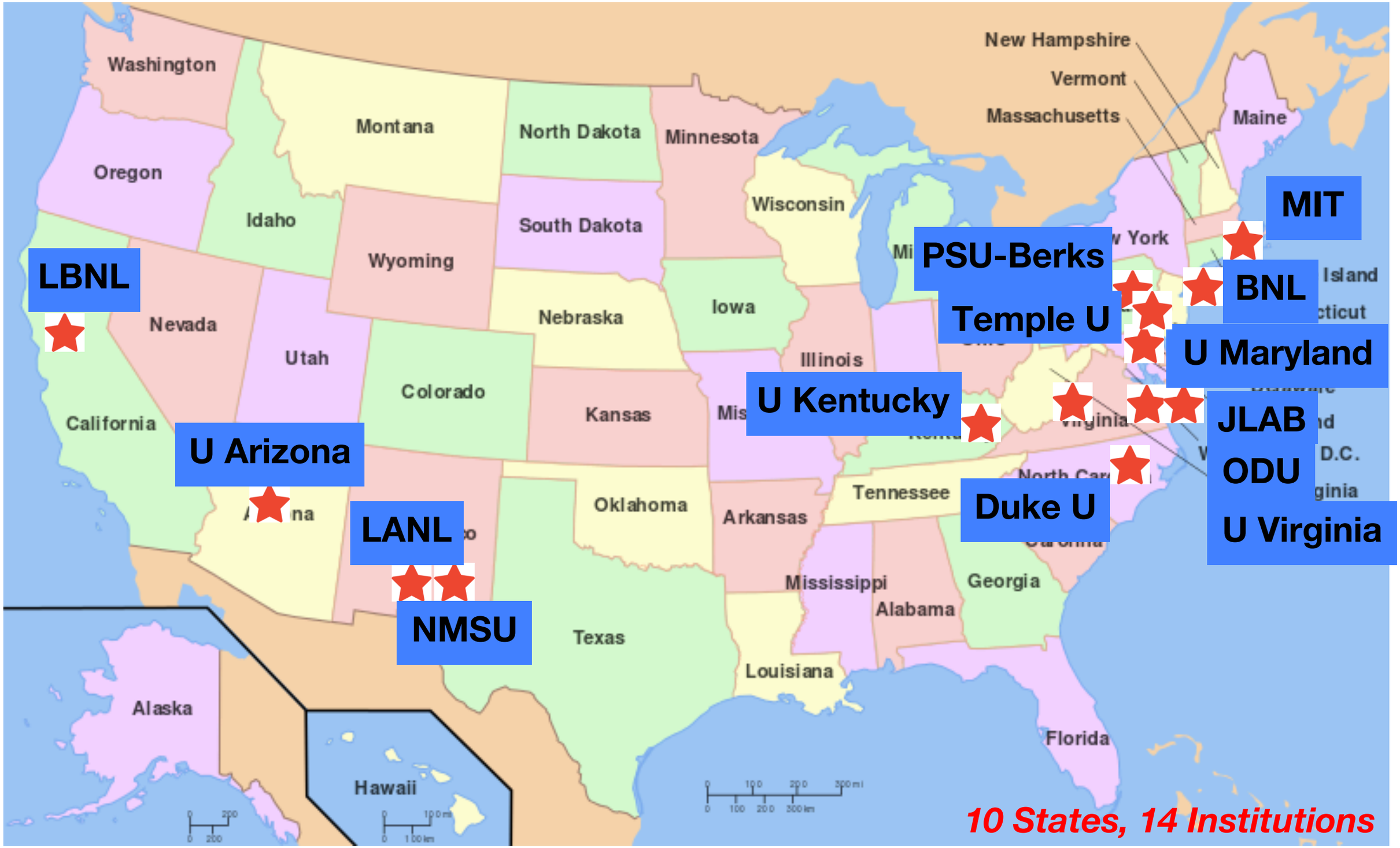
TMD evolution is often Non-perturbative!

- With the hard collision, hadron is broken
- A parton *shower* develops during collision
- *Parton k_T probed at the hard collision is NOT the same as "confined motion" in a hadron*
- The difference is encoded in QCD evolution
- TMD evolution *is different* from that of PDFs

→ **Need for TMD Collaboration!**

Three-pronged approach: *QCD Theory, Phenomenology & Lattice QCD*

The Team - TMD Topical Collaboration



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

The Team - TMD Topical Collaboration

- **Co-Spokespersons:**

  W. Detmold (MIT), J.-W. Qiu (JLab)

- **Institutions & Members: 21 Members + Postdocs + Students + Affiliate Members**

  Brookhaven National Lab (R. Venugopalan)

  Duke University (T. Mehen)

  Jefferson Lab (J.-W. Qiu)

  Lawrence Berkeley National Lab (F. Yuan)

  Los Alamos National Lab (C. Lee, I. Vitev)

  Massachusetts Institute of Technology (W. Detmold, J. Negele, I.W. Stewart)

  New Mexico State University (M. Burkardt, M. Engelhardt, M. Schlegel)

  Old Dominion University (T. Rogers, joint with JLab)

  Penn State University at Berks (L. Gamberg, A. Prokudin, bridged with JLab)

  Temple University (M. Constantinou, A. Metz)

  University of Arizona (S. Fleming)

  University of Kentucky (K.-F. Liu)

  University of Maryland (X.-D. Ji)

  University of Virginia (S. Liuti)

4 National Labs, 10 Universities

The Team - TMD Topical Collaboration

- **Bridged Faculty:**

  M. Constantinou (Fall 2016, Temple U),

  M. Schlegel (Spring 2018, NMSU)

- **Postdocs:**

  D. Pitonyak (2016-18,PSU-Berks/ODU ➔ Assist. Prof. Lebanon Valley College),

  Y. Yang (2016-17, Kentucky U ➔ Staff, ITP, Chinese Academy of Science),

  Y. Zhao (2016-19, MIT), J. Liang (2017-2018, Kentucky), L. Dai (2018-2020, Duke U),

  N. Sato (2018-19, ODU➔Nathan Isgur Fellow, JLab), A. Tarasov (2018-19, BNL),

  Z. Liu (2018-2020, LANL), Y. Zhao (2019-2021, BNL)

- **Students:**

  M. Albright, S. Dolan, Z. Scalyer (PSU-Berks), K. Lee (Stony Brook),

  Ou Labun (Arizona), A. Rajan (UVa ➔ PD, BNL), …

- **Affiliate members – Network:**

  J.-W. Chen (NTU, Taiwan), J.C. Collins (PSU), Z.-B. Kang (UCLA),

  L. Jin (Connecticut), D. Lin (NSTU, Taiwan), H.-W. Lin (MSU), A. Schaefer (Regensburg),

  P. Schweitzer (Connecticut), P. Shanahan (MIT), G. Sterman (Stony Brook),

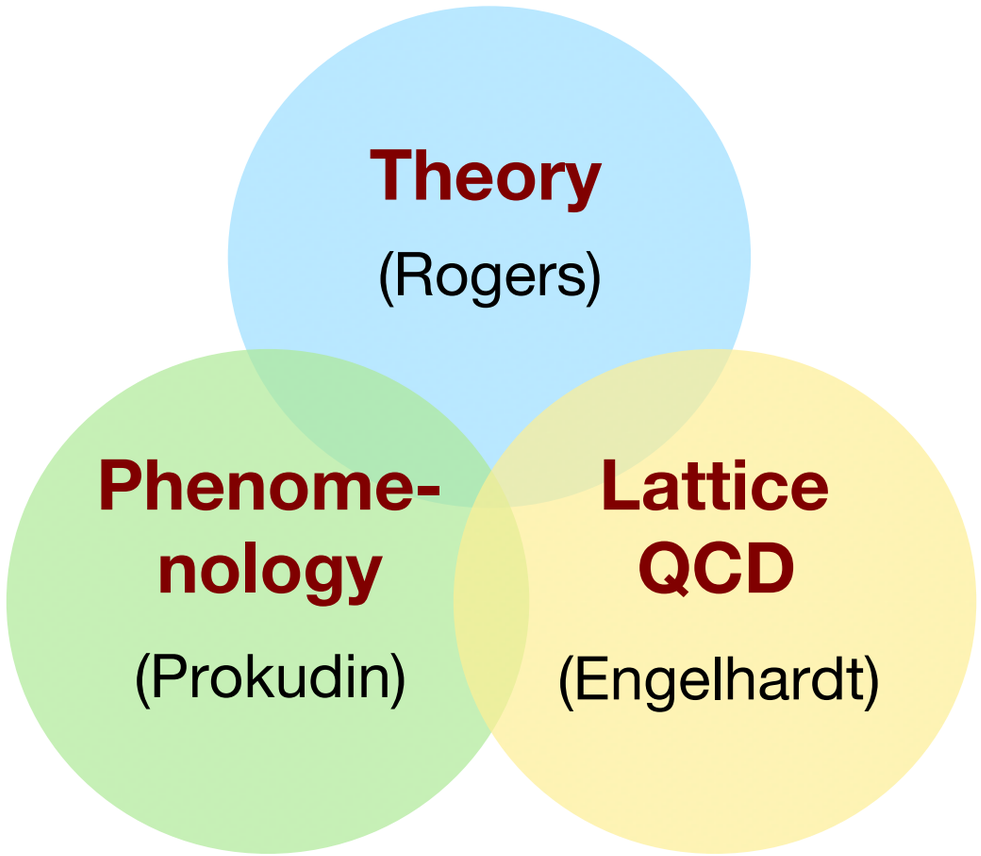
  H.-X. Zhu (Zhejiang U), D. Neill (Feynman Fellow, LANL), **M. Ebert (MIT),**

  Y.-S. Lin (SJTU, China), Y. Makris (LANL), M. Sievert (LANL), M. Wagman (MIT),

  S. Yoshida (LANL), J.-H. Zhang (Regensburg), Y. Hatta (BNL), Y. Kovchegov (OSU), …

The Mission, the Method, and the Service

- **Coherent three-pronged approach:**



Theory

– Strengthen the theoretical foundation of TMD physics;

- Scrutinize the definition and factorization
- Identify new observables and broaden impact of TMDs
- Devise new ways to access them
  – connection to facilities, JLab, RHIC, the LHC, EIC

Phenomenology

– Extract TMD knowledge from experimental data

- Develop fast software to do global fit of TMDs
- Produce extensive TMDs from global fitting data
- Make them available to the community

Lattice QCD

– Pursue non-perturbative calculations of TMDs

- Establish LQCD capability to study partonic structure
- Understand nonperturbative input to TMD evolution
- Calculate non-perturbative evolution kernels, …

- **Service to the community and productivity:**

Provide compelling research, training and career opportunities for young nuclear theorists

– including the undergraduate and graduate students, postdocs, and junior faculty

– TMD summer school, TMD handbook, …

– Numerous TMD publications, invited talks, QCD global analysis of TMDs, …

TMDs from Two-Scale Observables

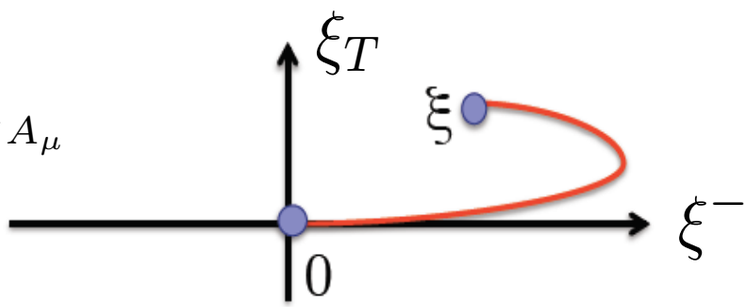
- **From PDFs to TMDs:**

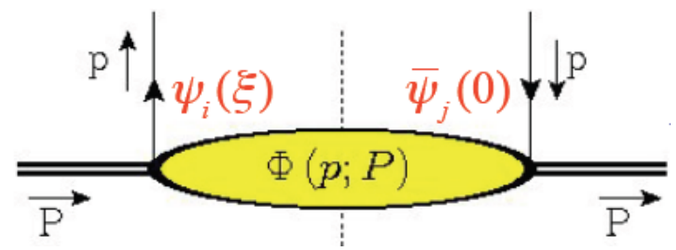
$f_{q/P}(x)$ longitudinal → **TMD:** $f_{q/P}(x, k_T)$ longitudinal & Transverse

- **TMDs depends on how color flows from scattering amplitude to its complex conjugate:**

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

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

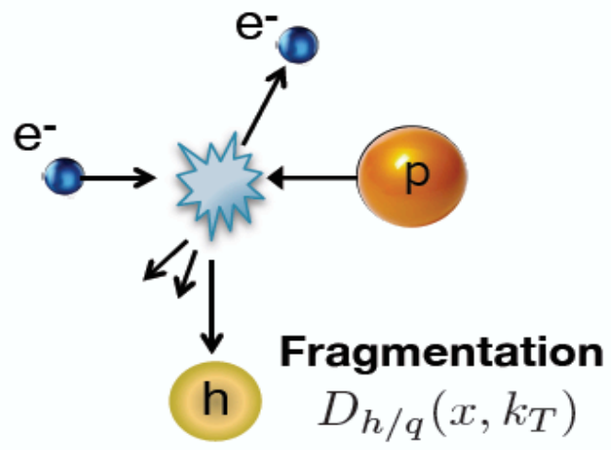




- **Classical two-scale observables:**

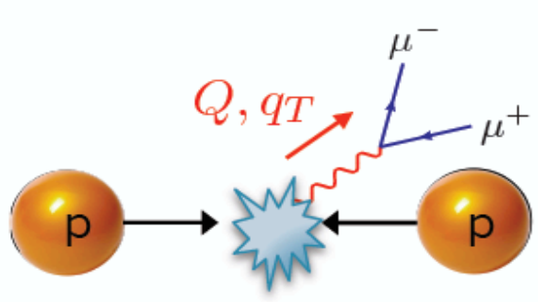
Semi-Inclusive DIS

$\sigma \sim f_{q/P}(x, k_T) D_{h/q}(x, k_T)$



Drell-Yan

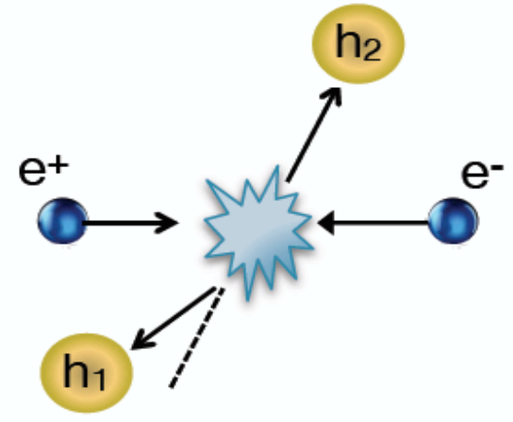
$\sigma \sim f_{q/P}(x, k_T) f_{q/P}(x, k_T)$



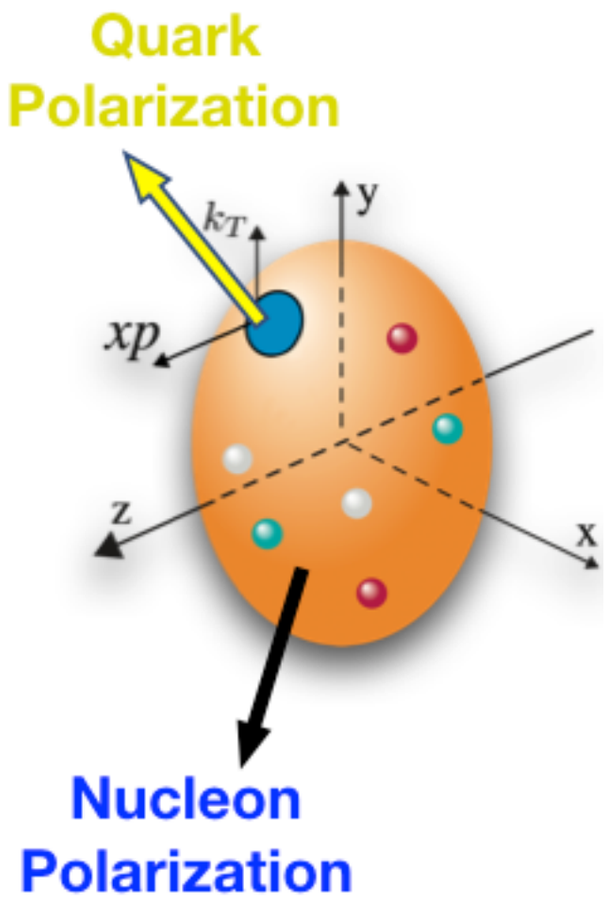
$q_T \ll Q$

Dihadron in e⁺e⁻

$\sigma \sim D_{h_1/q}(x, k_T) D_{h_2/q}(x, k_T)$



TMDs with Polarization



Nucleon Polarization	Quark Polarization: Unpolarized (U)	Quark Polarization: Longitudinally Polarized (L)	Quark Polarization: Transversely Polarized (T)
U	$f_1(x,k_T^2)$		$h_1^\perp(x,k_T^2)$ Boer-Mulders
L		$g_1(x,k_T^2)$ Helicity	$h_{1L}^\perp(x,k_T^2)$ Long-Transversity
T	$f_1^\perp(x,k_T^2)$ Sivers	$g_{1T}(x,k_T^2)$ Trans-Helicity	$h_1(x,k_T^2)$ Transversity; $h_{1T}^\perp(x,k_T^2)$ Pretzelosity

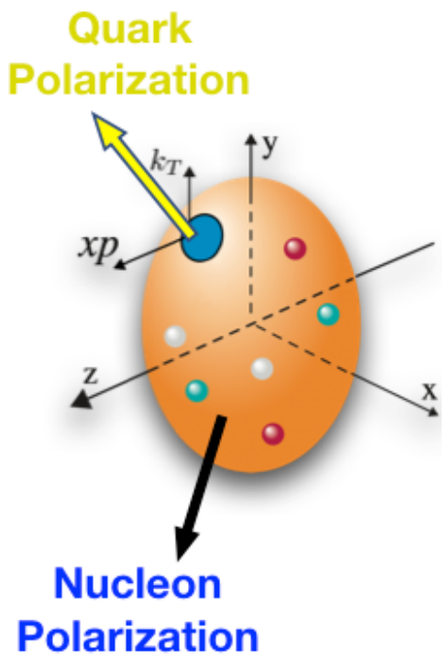
- **Questions:**
  - **What do we learn?**
  - **How to separate them?**

Analogous tables for:

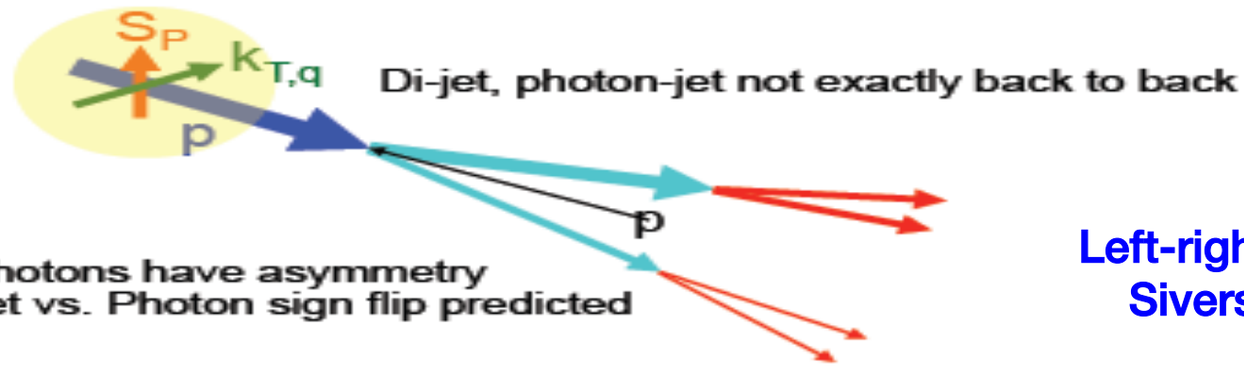
- **Gluons** $f_1 \to f_1^g$ etc
- **Fragmentation functions**
- **Nuclear targets** $S \neq \frac{1}{2}$

Physics of TMDs

- **Intrinsic & confined parton motion:**

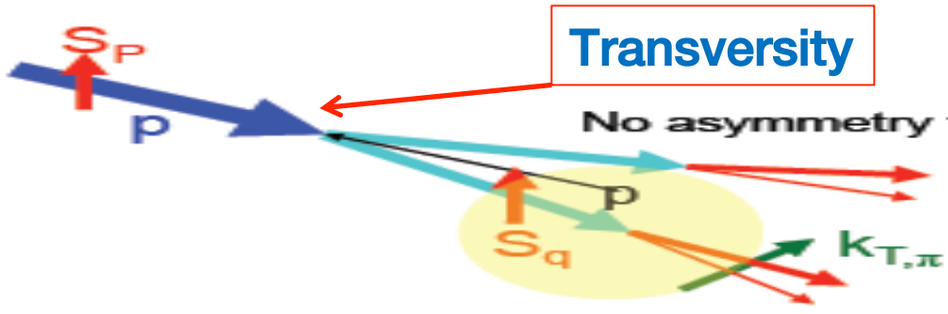


- Fundamental information sensitive to how partons are bound together
- Responsible for dynamical contribution to emergent hadron properties, such as spin, mass, ..
- Correlation between hadron spin and preference of parton motion, …



Left-right asymmetries
Sivers-type effect

- Correlation between parton spin and direction preference for emergence of hadron, …



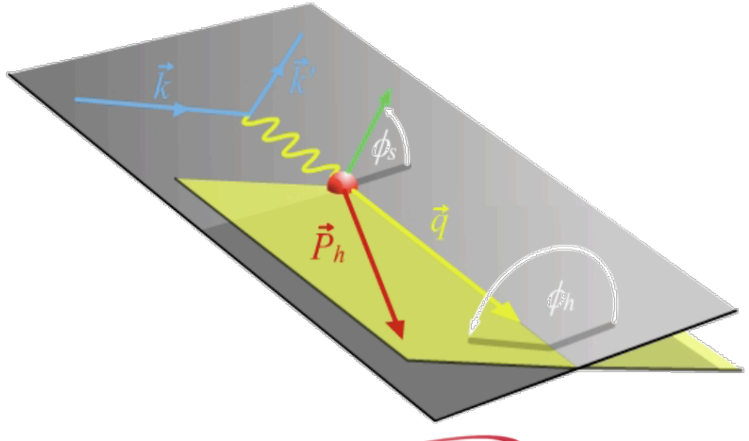
Left-right asymmetries
Collins-type effect

- **How to distinguish them?**

Lepton-hadron SIDIS is ideal for distinguishing different TMDs

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

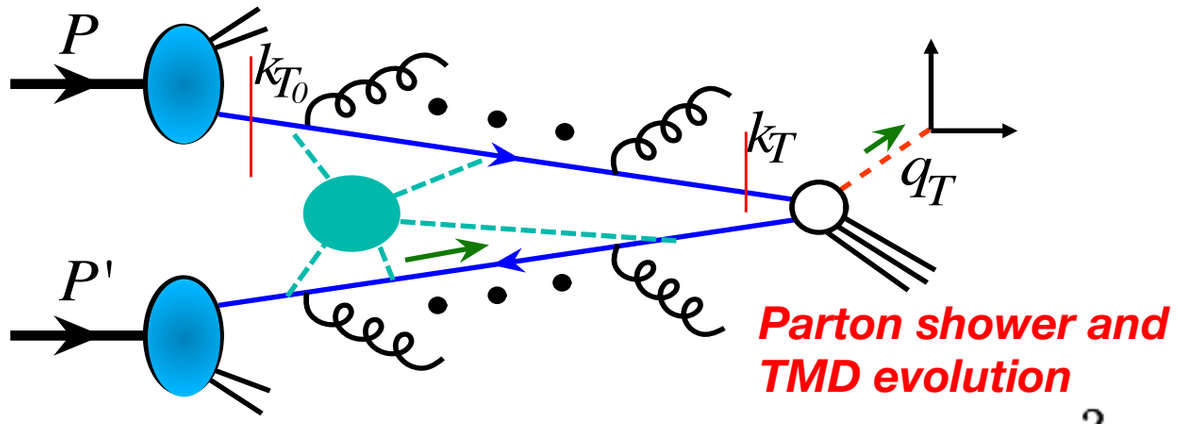
$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_s) \rangle_{UT} \propto f_{1T}^\perp \otimes D_1$$



TMD Factorization and Evolution

- **"Drell-Yan" as an example:**

  CSS (Collins, Soper, Sterman)
  SCET (Soft Collinear Effective Theory)



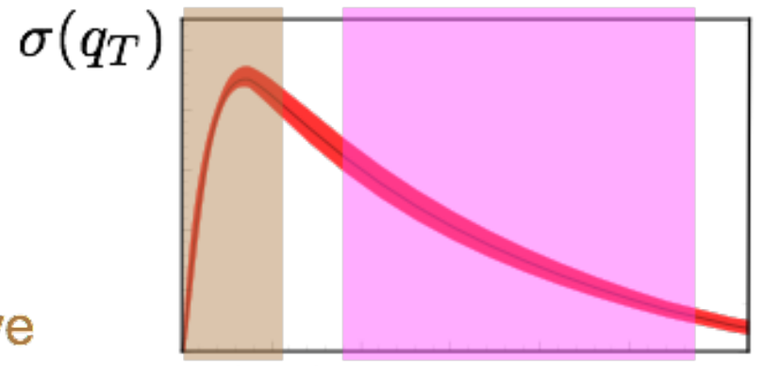
Parton shower and TMD evolution

$$\sigma(q_T) = H(Q,\mu) \int d^2\vec{b}_T\, e^{i\vec{q}_T\cdot\vec{b}_T}\, f_q(x_a,\vec{b}_T,\mu,\zeta_a)\, f_q(x_b,\vec{b}_T,\mu,\zeta_b) + \mathcal{O}\left(\frac{q_T^2}{Q^2}\right)$$

Hard virtual corrections

FT

$$f_q(x_a,\vec{k}_T,\mu,\zeta_a)$$



- $k_T \sim b_T^{-1} \sim \Lambda_{\rm QCD}$ $\quad f_q(x,\vec{k}_T)$ nonperturbative

- $k_T \sim b_T^{-1} \gg \Lambda_{\rm QCD}$ $\quad f_q(x,\vec{k}_T,\mu,\zeta) = \sum_i \int \frac{dy}{y}\, C_{qi}\left(\frac{x}{y},\vec{k}_T,\mu,\zeta\right) f_i(x,\mu)$

PDF

- **Evolution:**

$$\mu\frac{d}{d\mu}\ln f_q(x,\vec{b}_T,\mu,\zeta) = \gamma_\mu^q(\mu,\zeta)$$

$$\zeta\frac{d}{d\zeta}\ln f_q(x,\vec{b}_T,\mu,\zeta) = \gamma_\zeta^q(\mu,b_T)$$

Collins-Soper Equation

- **Matching to fixed order:** $q_T^2 \sim Q^2$

When $\mu, b_T^{-1} \gg \Lambda_{\rm QCD}$ ***, kernels are perturbative, LL, NLL, N2LL, N3LL***

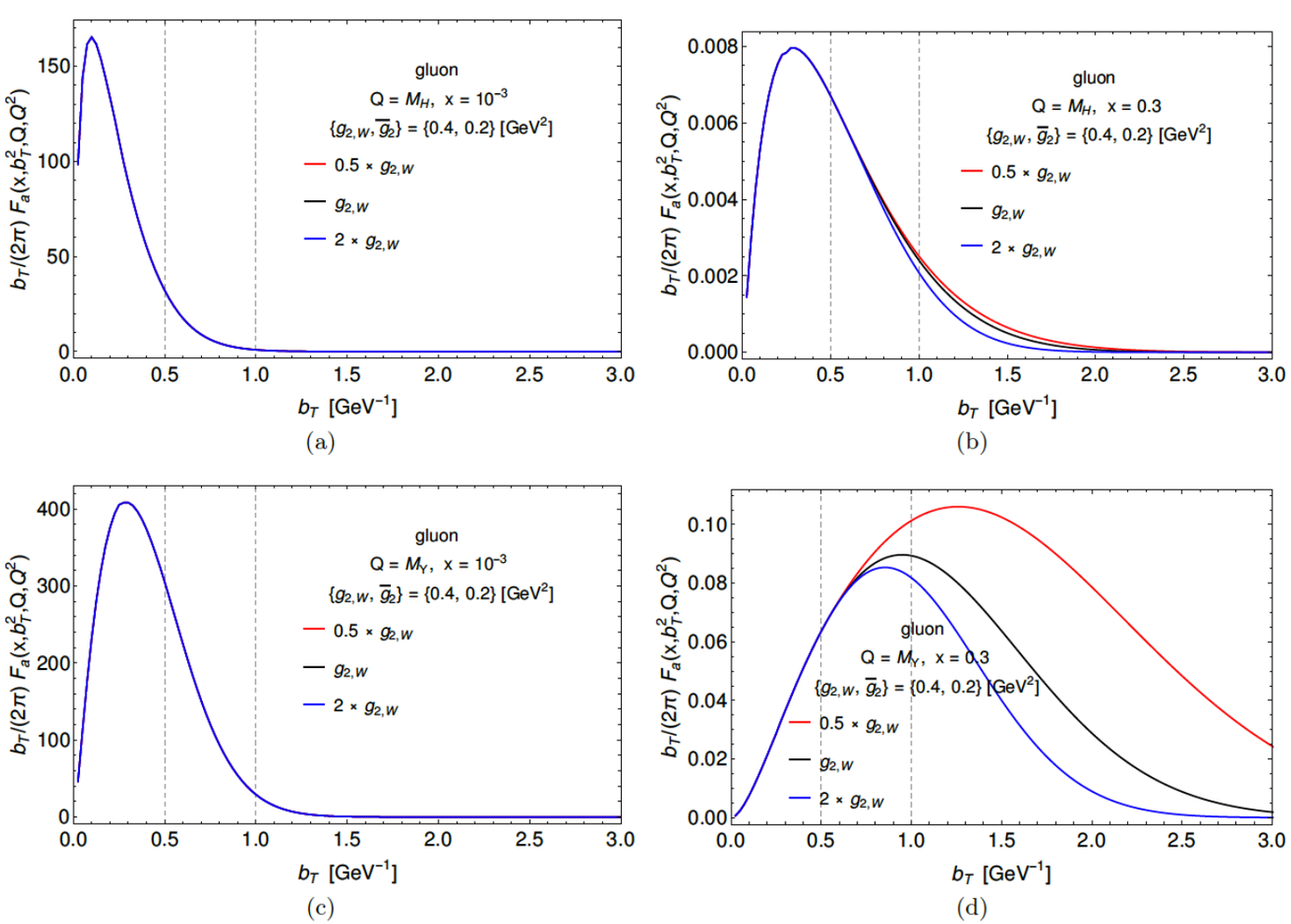
When $b_T^{-1} \sim \Lambda_{\rm QCD}$ ***, kernels are non-perturbative – LQCD effort !***

TMD Evolution is Very Different from PDF Evolution

- **DGLAP evolution is perturbative if Q^2 large enough:**
  - **Given a set of input PDFs:** $f_{i/h}(x, Q_0^2)$ **for** $x_{min} \le x \le 1$
  - **PDFs:** $f_{i/h}(x, Q^2)$ **are completely *determined* for all** $x > x_{min}$ **and** $Q^2 > Q_0^2$

- **With two scales:** Q **and** k_T **(or its F.T.** b_T**), TMD evolution is *non-perturbative***
  if $k_T \lesssim \Lambda_{\rm QCD}$ **or** $b_T \gtrsim 1/\Lambda_{\rm QCD}$ **even at large Q !**

- **TMDs have the most predictive power if TMD evolution is perturbative** Grewal et al. 2003.07453



- **If the area under the b_T-space TMDs are dominated by small-b_T**
- **That is, when shower is dominated by the large perturbative logarithms**
  – ideal for using SCET

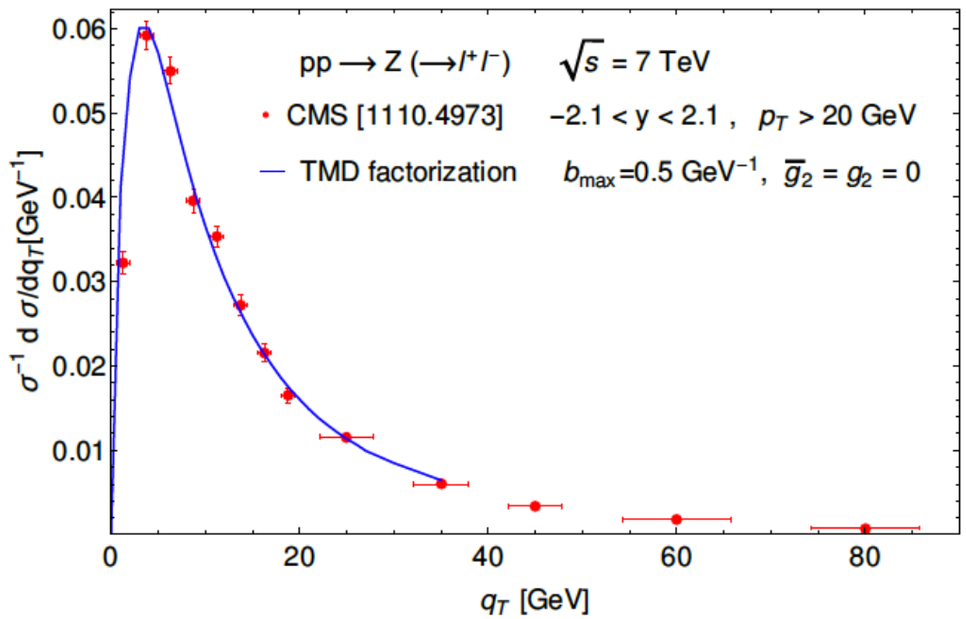
Large Q and small x regimes

Good for the LHC, not for hadron structure

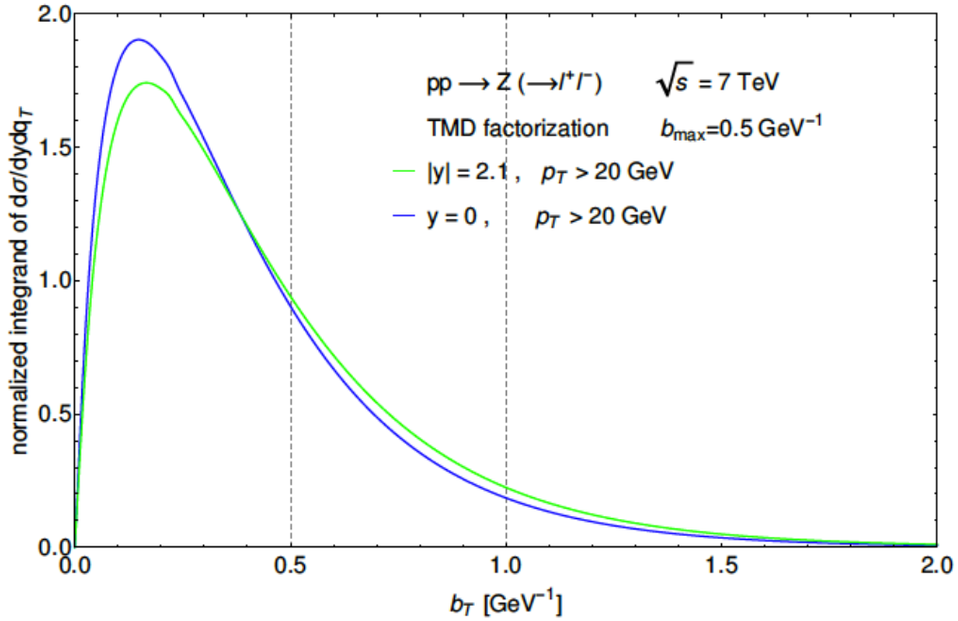
Predictions from TMD Factorization

- **Other than PDFs, effectively, no free parameter:**

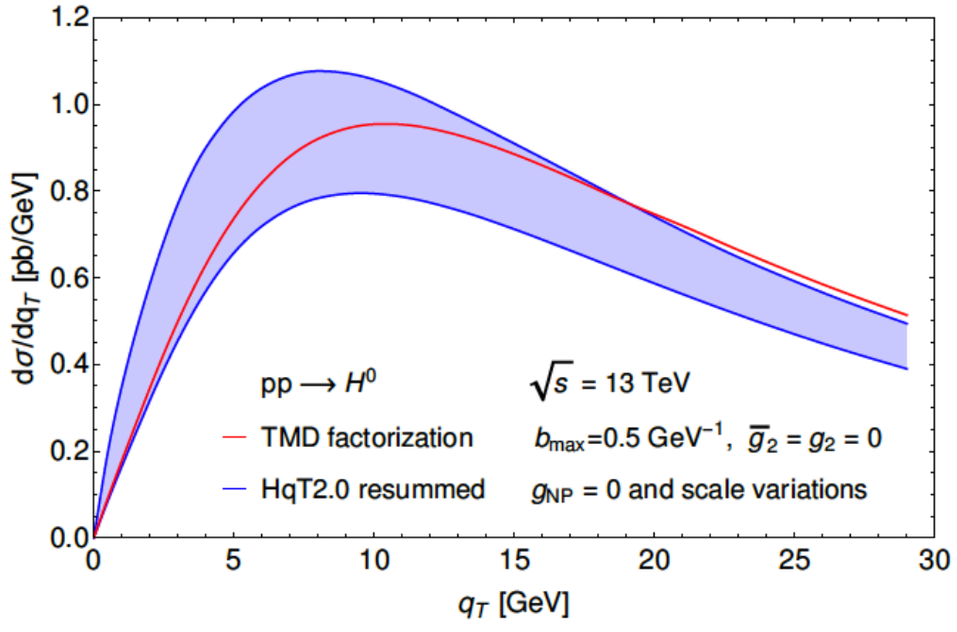
Grewal et al. 2003.07453



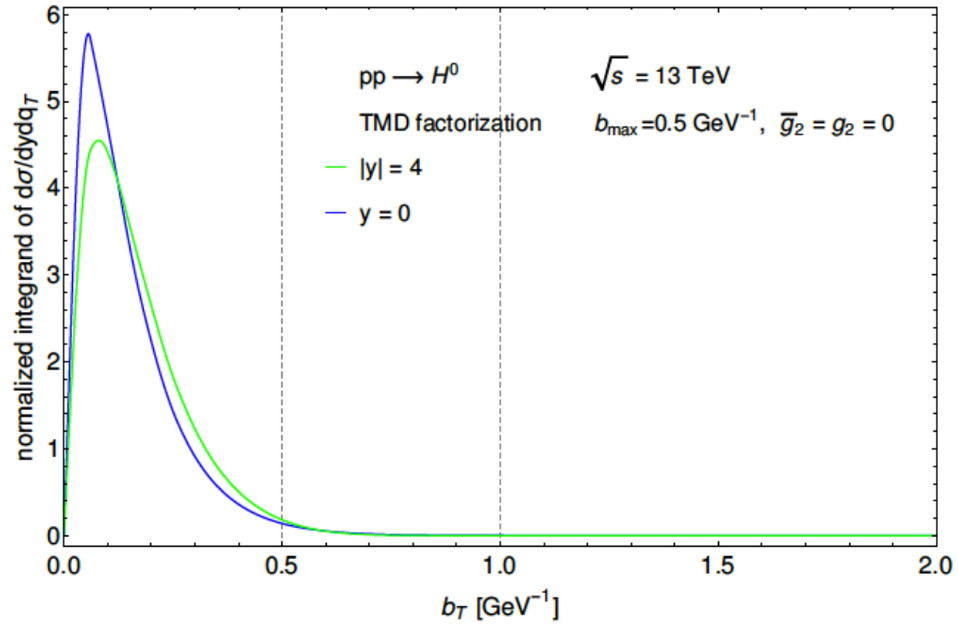
(a)



(b)



(a)



(b)

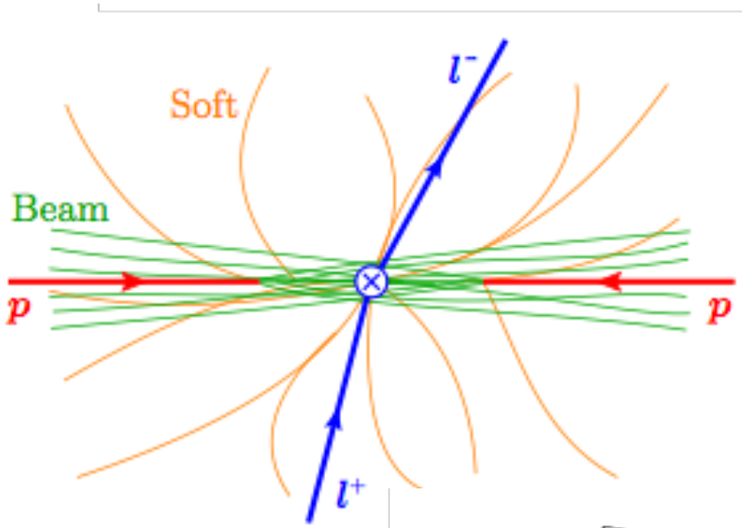
Information on intrinsic confined motion is washed out!

Highlights: Theory – TMD Definitions

- **Definitions:**

$$f_q(x,\vec{b}_T,\mu,\zeta) = \lim_{\epsilon\to 0,\tau\to 0} Z_{\rm uv}(\epsilon,\mu,\zeta) B_q(x,\vec{b}_T,\epsilon,\tau,\zeta)\sqrt{S_q(b_T,\epsilon,\tau)}$$

Universal across (most) schemes!



collinear region — soft region

Scheme dependent

ϵ : regulates UV divergences

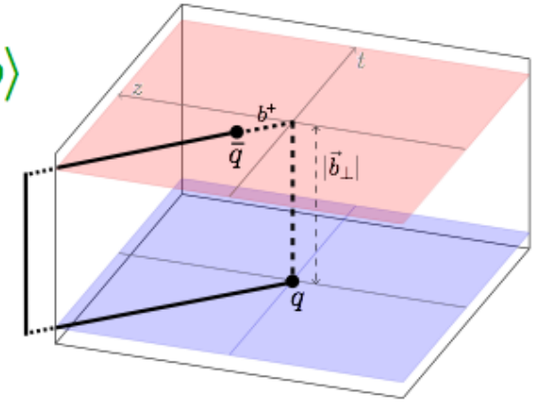
τ : regulates rapidity divergences $\int_0^\infty \frac{dk^+}{k^+}$

- **Wilson lines:**

$B_q = \langle p|O_B|p\rangle$

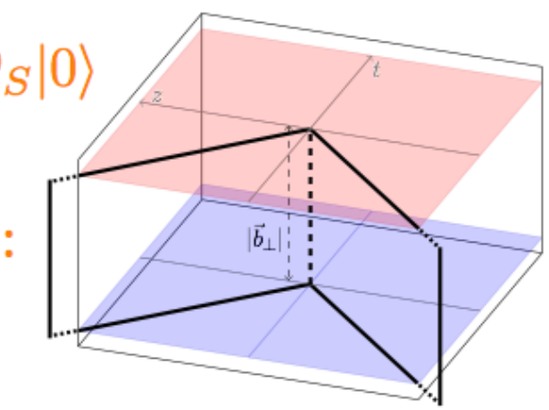
O_B :

staple shaped



$S_q = \langle 0|O_S|0\rangle$

O_S :



Wilson lines have physical implications – encode initial/final state interations

➡ **Sign of Sivers' function is NOT universal:** $f_{1T}^{\perp \rm DIS}(x,k_\perp) = -f_{1T}^{\perp \rm DY}(x,k_\perp)$

- **Schemes – uniqueness?**

TMD Collaboration has compared schemes to extract universal information

Enabled advantages of various schemes to be exploited, … *documented in TMD handbook*

Highlights: Theory – New Observables for TMDs

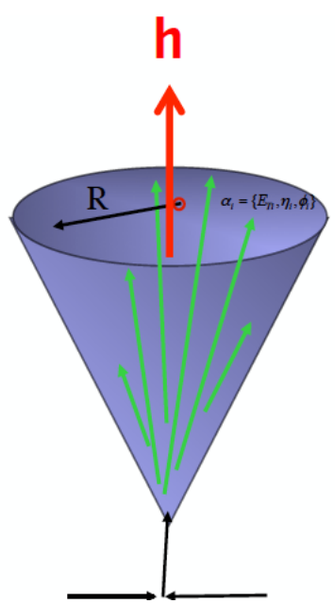
Bain, Makris, Mehen, JHEP 1611, 144 (2016)
Kang, Liu, Ringer, Xing JHEP 1711, 068 (2017)

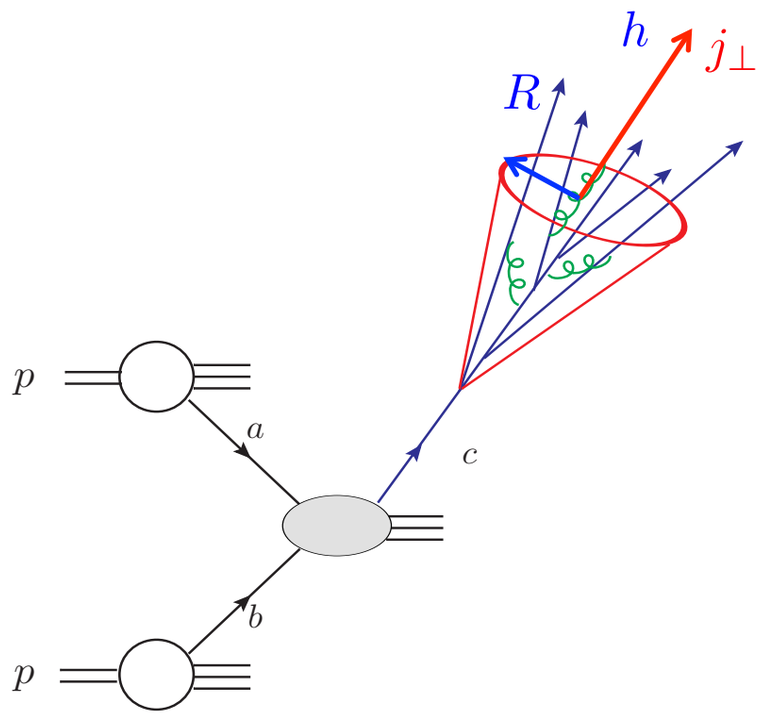
- **TMD fragmentation within measured jets:**
  - **Classic observables (SIDIS, DY, ee) involve two TMD distributions**
  - **Measurement within a jet enables us to probe a single TMD frag. function**

$$\frac{d\sigma}{dp_T d\eta dz_h d^2 j_\perp} \propto \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab\to c} \otimes \mathcal{G}_c^h(z, z_h, \omega_J R, j_\perp, \mu)$$

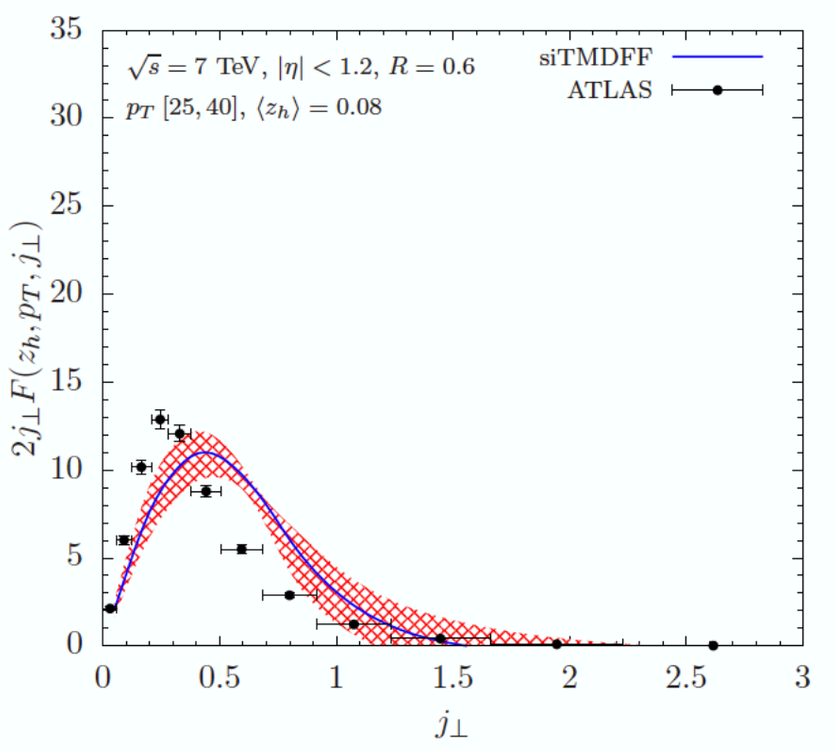
$$\mathcal{G}_c^h(z, z_h, p_T R, j_\perp, \mu) = \mathcal{C}_{c\to i}(z, \mu_J = p_T R, \mu)\, D_{h/i}(z_h, j_\perp, \mu_J)$$

fragmenting jet function — **TMD fragmentation function**





- **Sum large logs with DGLAP and TMD evolution**
- **Important observable for measurements at EIC**

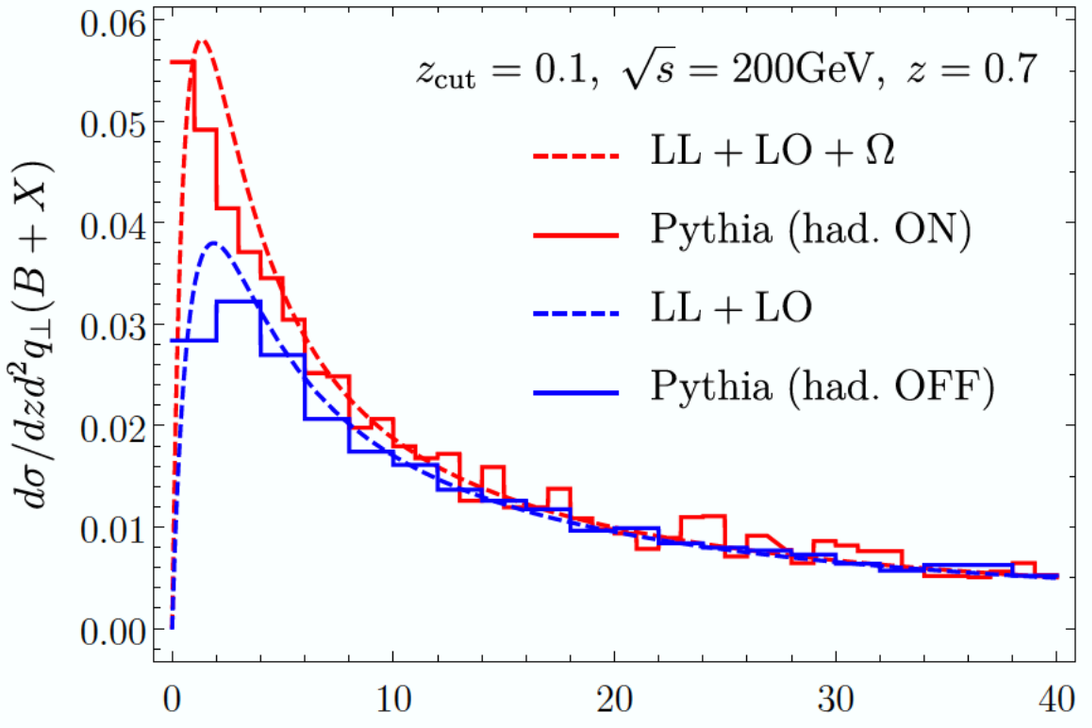


Highlights: Theory – New Observables for TMDs

- **Heavy meson TMDs in a Jet:**

  Makris, Vaidya, JHEP 1810, 019 (2018)

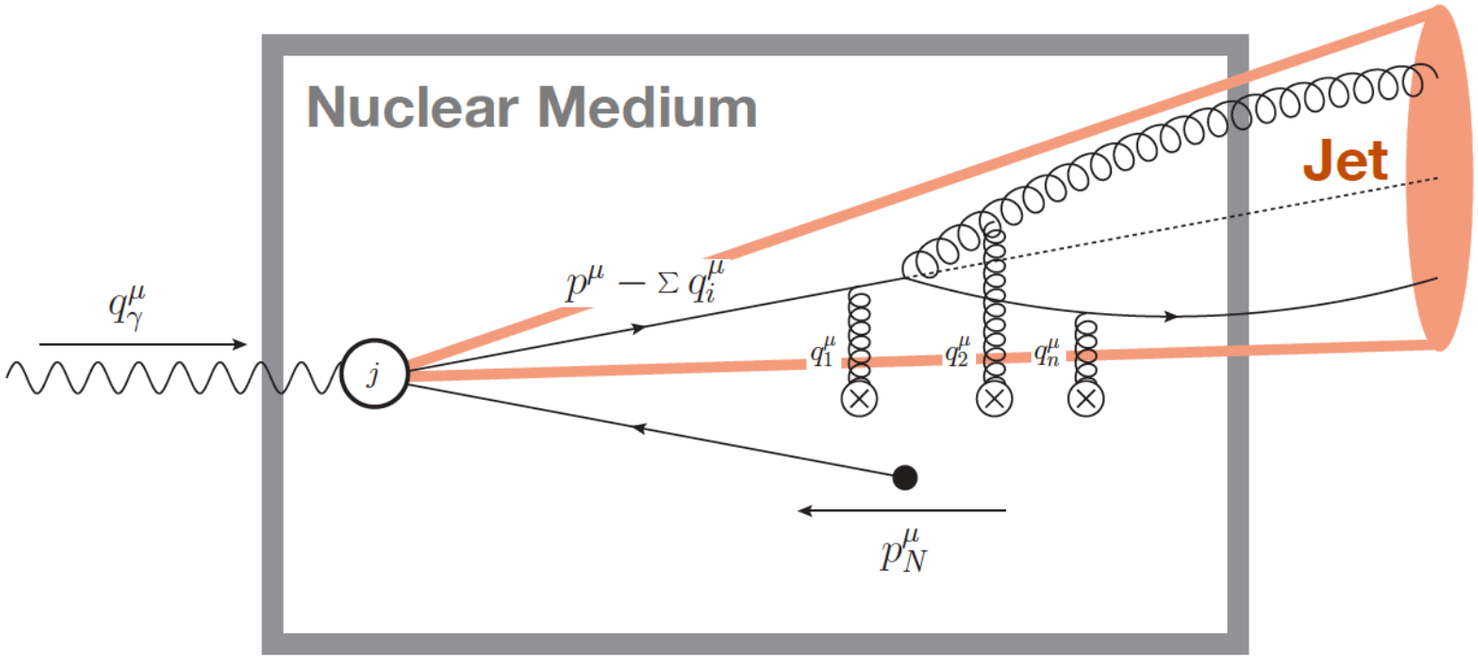
  - Measure TMD fragmentation function with a heavy quark
  - Interesting for probing hadronization in both proton and heavy-ion collisions



- **TMDs in nuclei:**

  Sievert, Vitev, Phys.Rev. D98, 094010 (2018)

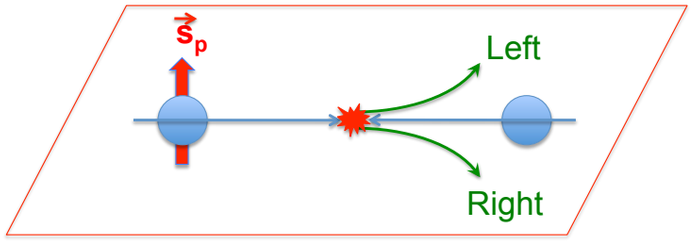
  - Formalism developed to carry out calculations with any number of interactions with the nuclear medium
  - Can be applied to calculate medium effects for EIC



Highlights: Phenomenology – Sivers Effect

- **Single Transverse Spin Asymmetry:**

Kane, Pumplin, Repko, PRL, 1978



$$A_N \equiv \frac{\Delta\sigma(\ell,\vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell,\vec{s}) - \sigma(\ell,-\vec{s})}{\sigma(\ell,\vec{s}) + \sigma(\ell,-\vec{s})}$$

Theory (1978):

$$A_N \propto \alpha_s \frac{m_q}{p_T} \to 0$$

Experiment (40 yrs)

A_N **As large as 40%**

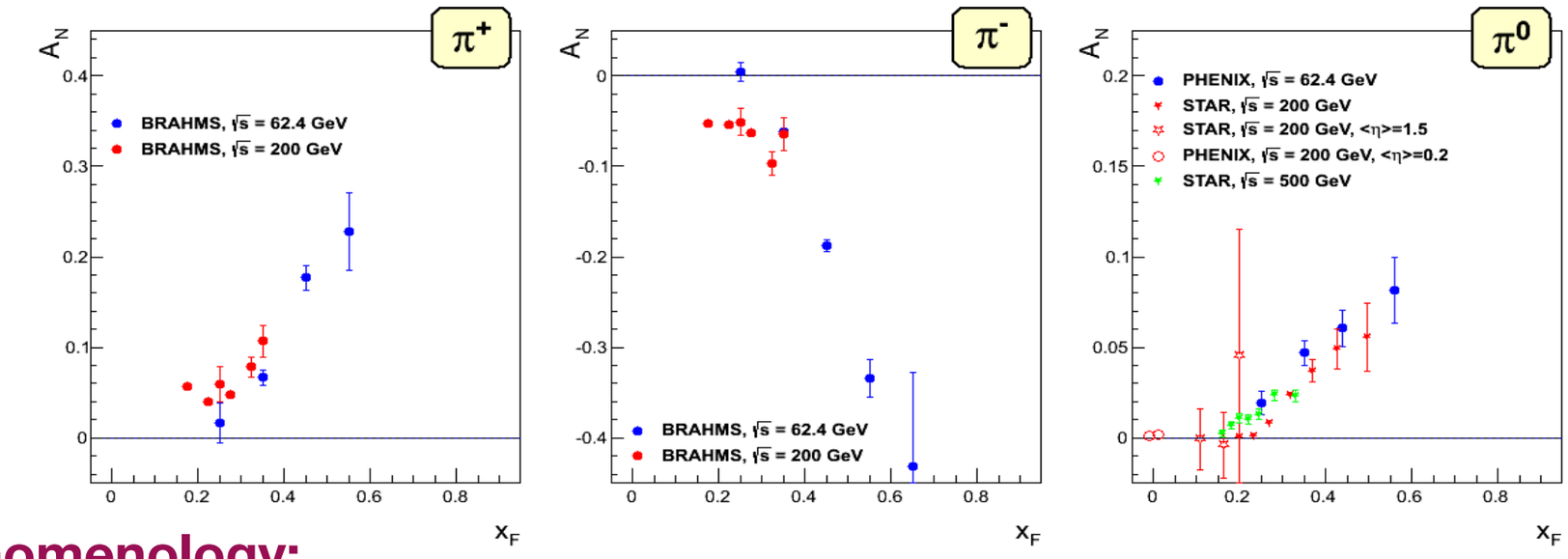
- **Single-scale – Asymmetries survives with growing collision energies :**

RHIC spin:

BRAHMS

PHENIX

STAR

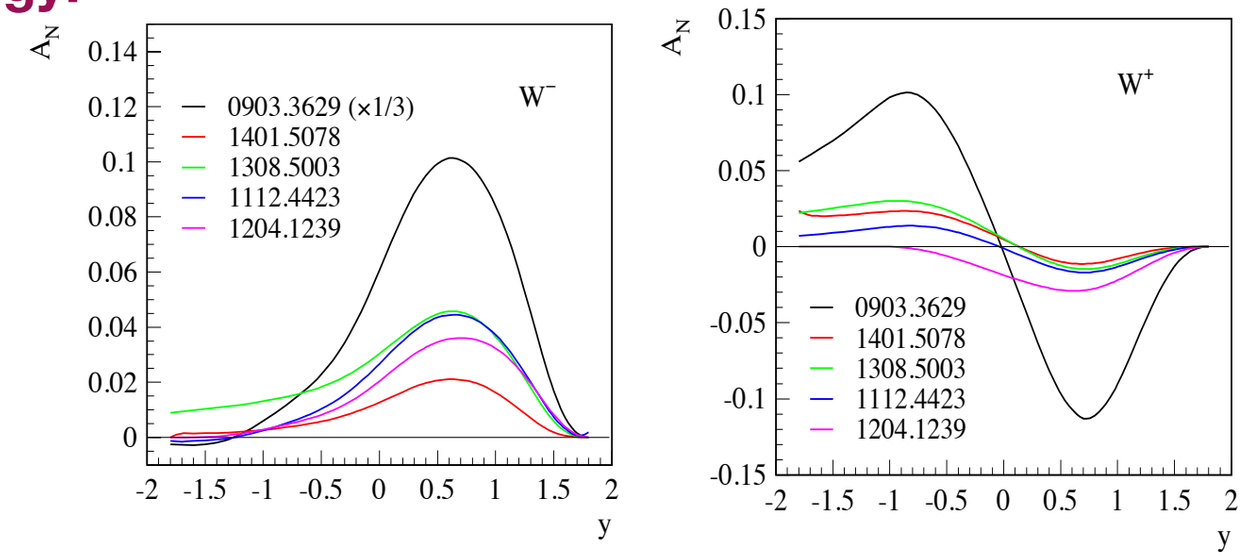


- **Challenge - Phenomenology:**

Predictions for A_N of W-production at RHIC

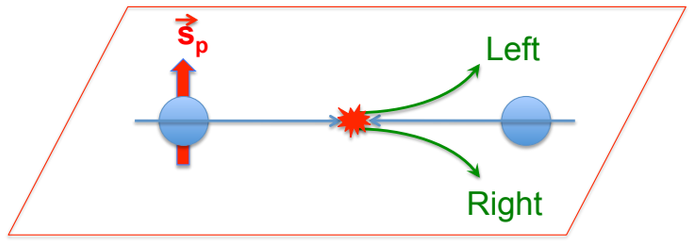
Huge difference!

Role of non-perturbative physics



Highlights: Phenomenology – Sivers Effect

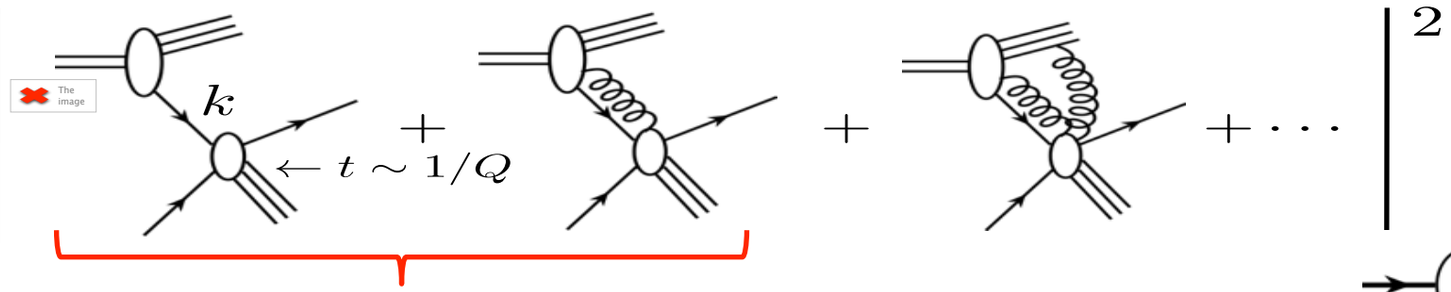
- **Single Transverse Spin asymmetry:**



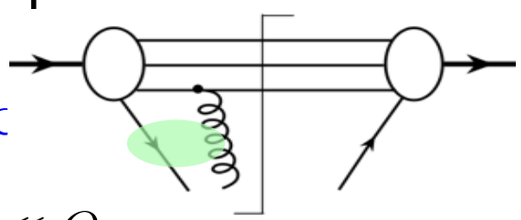
$$A_N \equiv \frac{\Delta\sigma(\ell,\vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell,\vec{s})-\sigma(\ell,-\vec{s})}{\sigma(\ell,\vec{s})+\sigma(\ell,-\vec{s})}$$

- **Single hard scale:** $p_T \gg \Lambda_{\rm QCD}$ **or** $q_T \sim Q \gg \Lambda_{\rm QCD}$, **…**
  - ✧ **QCD Collinear factorization is the relevant theory tool,** $k_T \ll p_T$ **, integrated**
  - ✧ **Asymmetry is generated by QCD quantum interference,**

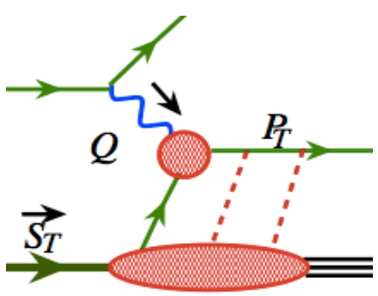
$$\sigma(Q,\vec{s}) \propto \left| \quad + \quad + \quad + \cdots \right|^2$$



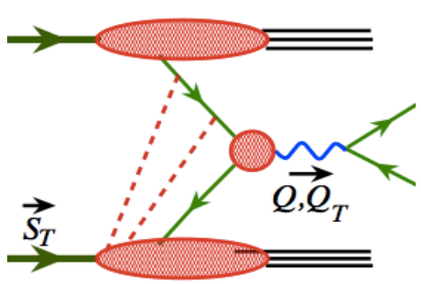
$$\sigma(s)-\sigma(-s) \Rightarrow \textbf{Quantum interference} \Rightarrow T^{(3)}(x,x) \propto$$



- **Two-scale observables: SIDIS, W-production at RHIC, …** $\Lambda_{\rm QCD} \sim q_T \ll Q$
  - ✧ **QCD TMD factorization is the relevant theory tool,** $k_T \sim q_T \ll Q$
  - ✧ **Asymmetry is generated by parton's asymmetric transverse motion, …**



SIDIS: Q>>P_T



DY: Q>>Q_T

QCD prediction:

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

Verification:

LQCD, Data

Highlights: Phenomenology – Extraction of TMDs

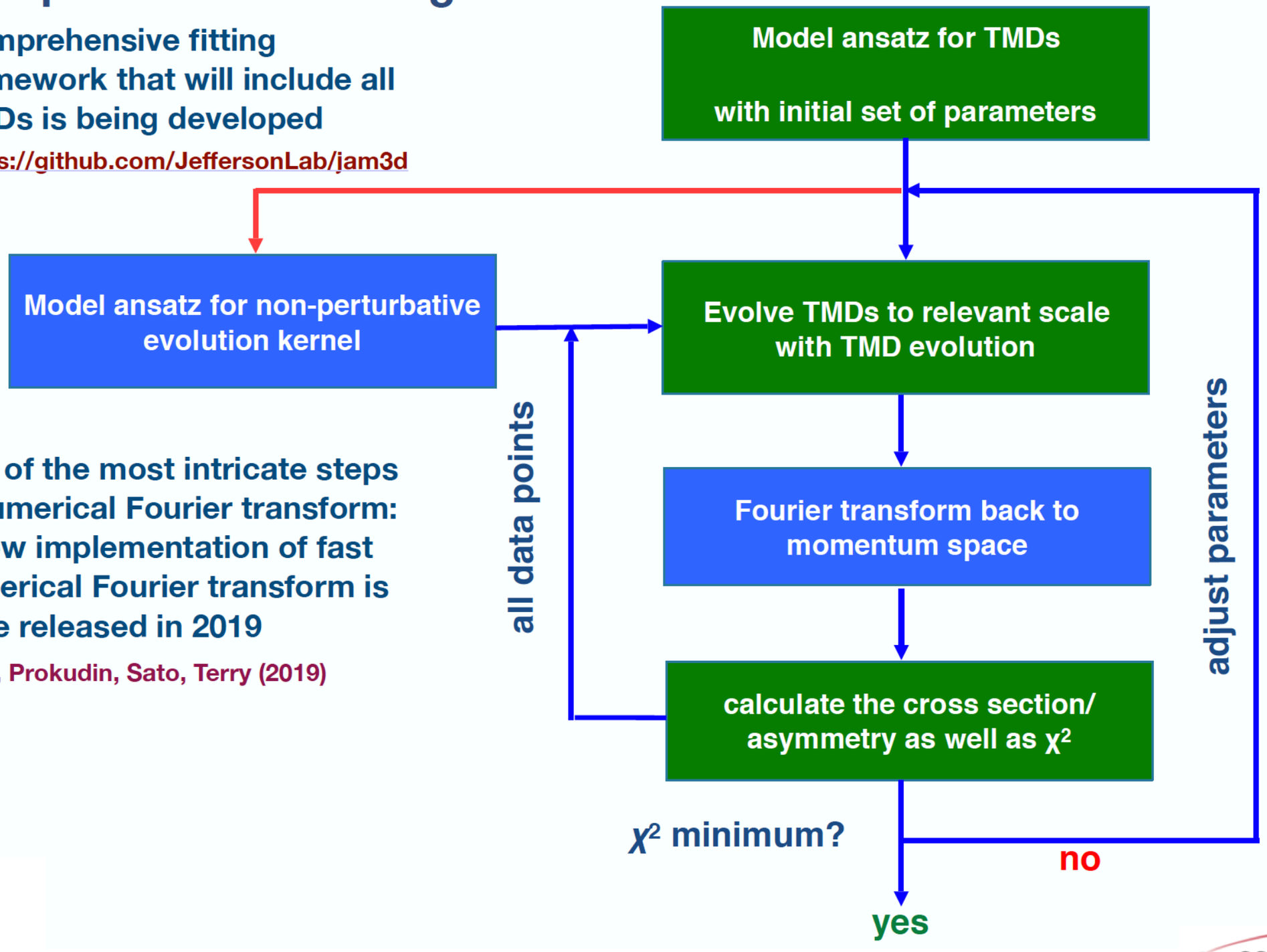
- **Performing a TMD global analysis represents a numerical computational challenge**

Comprehensive fitting framework that will include all TMDs is being developed

https://github.com/JeffersonLab/jam3d

One of the most intricate steps is numerical Fourier transform: A new implementation of fast numerical Fourier transform is to be released in 2019

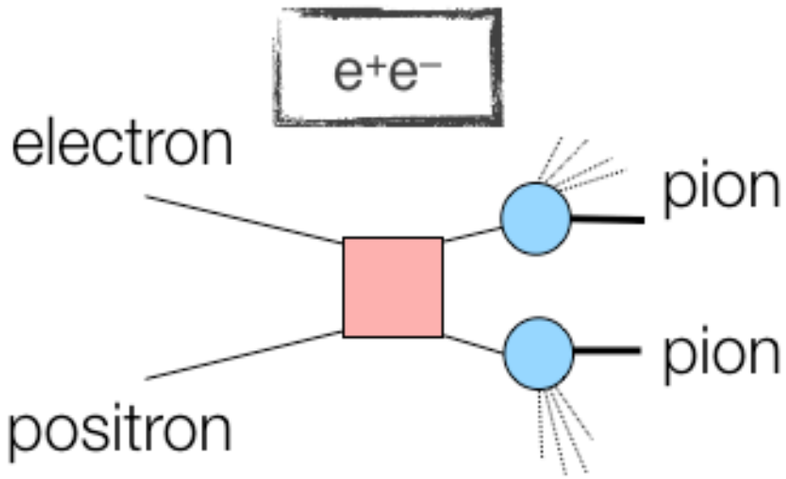
Kang, Prokudin, Sato, Terry (2019)



Highlights: Phenomenology – Extraction of TMDs

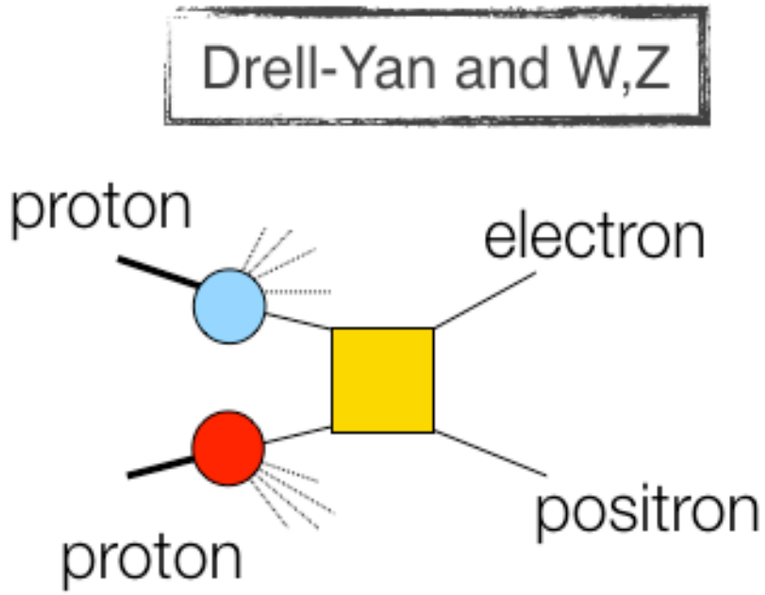
- **TMD universal global fit 2020:** arXiv:2002.08384

Cammarota, Gamberg, Kang, Miller, Pitonyak, Prokudin, Rogers, Sato (2020)

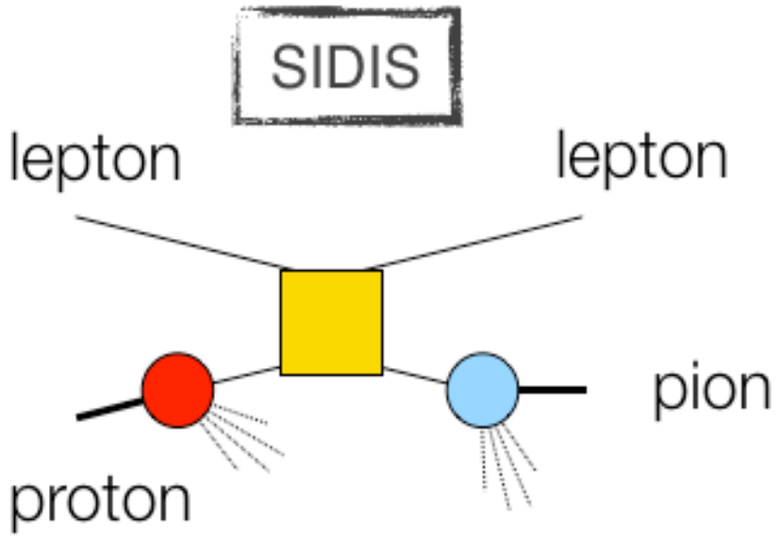


Collins asymmetries
BELLE, BaBar, BESIII data

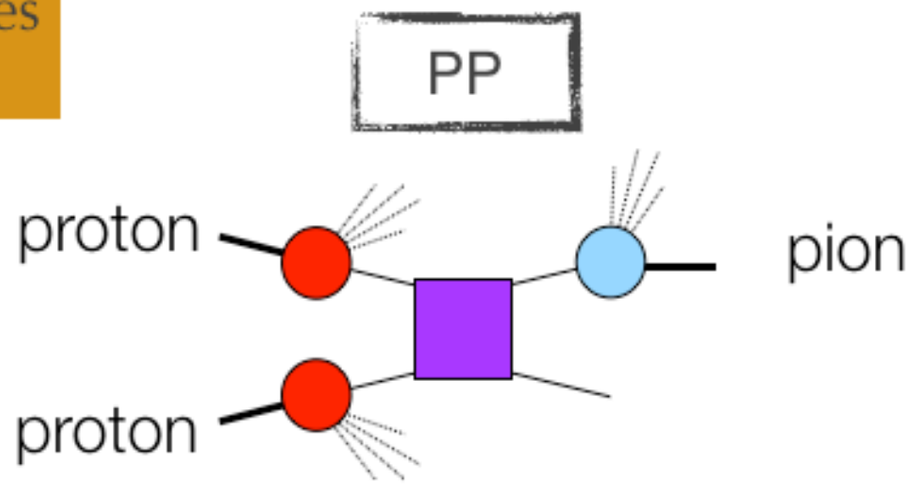
To demonstrate the common origin of SSAs in various processes, we will combine all available data and extract a universal set of non perturbative functions that describes all of them



Sivers asymmetries
COMPASS, STAR data



Sivers, Collins asymmetries
COMPASS, HERMES, JLab data



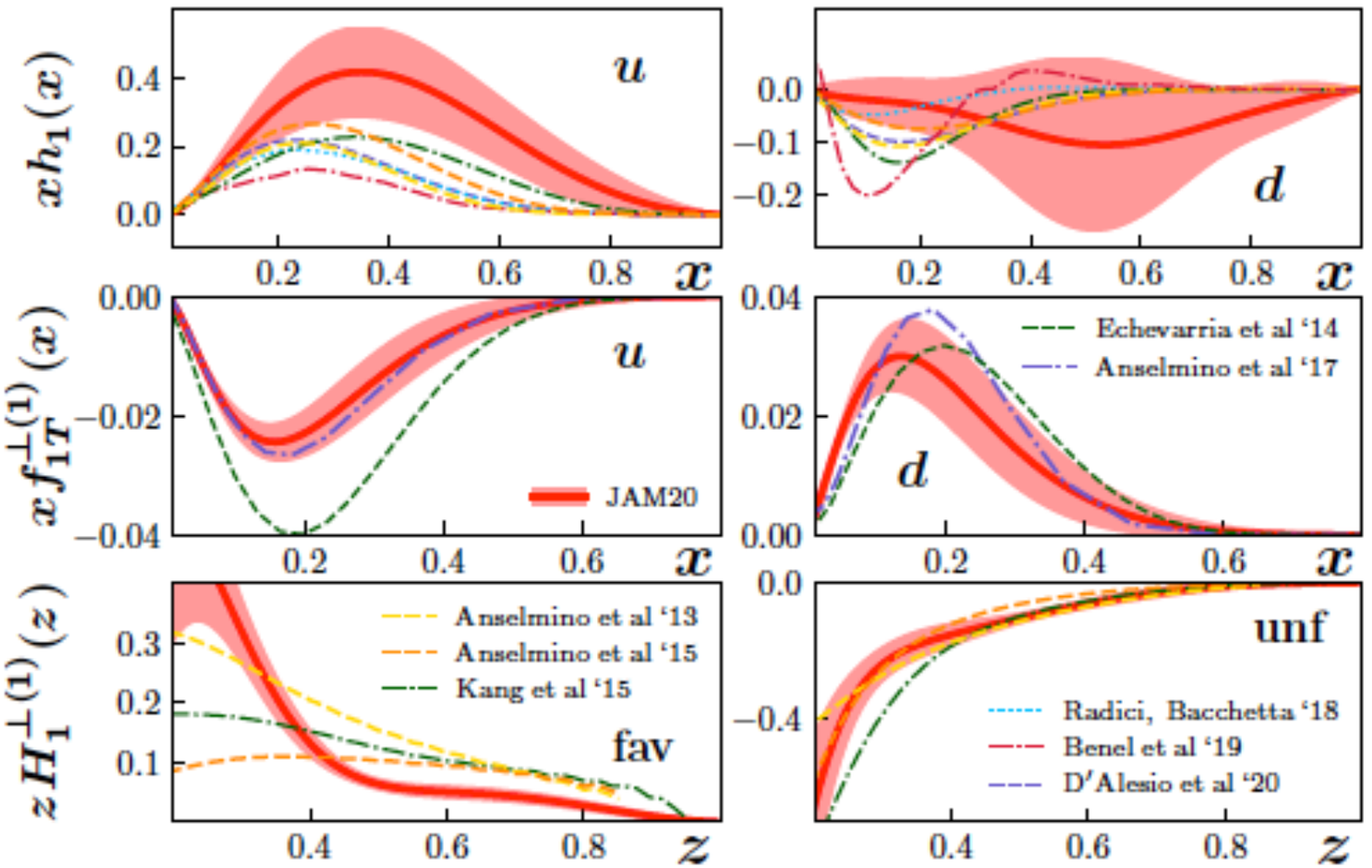
A_N asymmetry
STAR, PHENIX, BRAHMS data

Highlights: Phenomenology – Extraction of TMDs

- **Data and the fits:**

Observable	Reactions	Non-Perturbative Function(s)	$\chi^2/N_{\rm pts.}$	Exp. Refs.
$A_{\rm SIDIS}^{\rm Siv}$	$e+(p,d)^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$	$f_{1T}^\perp(x,k_T^2)$	$150.0/126=1.19$	[67, 68, 70]
$A_{\rm SIDIS}^{\rm Col}$	$e+(p,d)^\uparrow \to e+(\pi^+,\pi^-,\pi^0)+X$	$h_1(x,k_T^2), H_1^\perp(z,z^2p_\perp^2)$	$111.3/126=0.88$	[68, 70, 73]
$A_{\rm SIA}^{\rm Col}$	$e^+ + e^- \to \pi^+\pi^-(UC,UL)+X$	$H_1^\perp(z,z^2p_\perp^2)$	$154.5/176=0.88$	[76–79]
$A_{\rm DY}^{\rm Siv}$	$\pi^- + p^\uparrow \to \mu^+\mu^- + X$	$f_{1T}^\perp(x,k_T^2)$	$5.96/12=0.50$	[75]
$A_{\rm DY}^{\rm Siv}$	$p^\uparrow + p \to (W^+,W^-,Z)+X$	$f_{1T}^\perp(x,k_T^2)$	$31.8/17=1.87$	[74]
A_N^h	$p^\uparrow + p \to (\pi^+,\pi^-,\pi^0)+X$	$h_1(x), F_{FT}(x,x)=\frac{1}{\pi}f_{1T}^{\perp(1)}(x), H_1^{\perp(1)}(z)$	$66.5/60=1.11$	[7, 9, 10, 13]

- **Extracted non-perturbative functions:**



Transversity distribution:

$$h_1(x) \propto \text{F.T.}$$

The image cannot be displayed. Your computer may not have enough memory to open the image, or the image may have been corrupted. Restart your computer, and then open the file again. If the red x still appears, you may have to delete the image and then insert it again.

Sivers' function

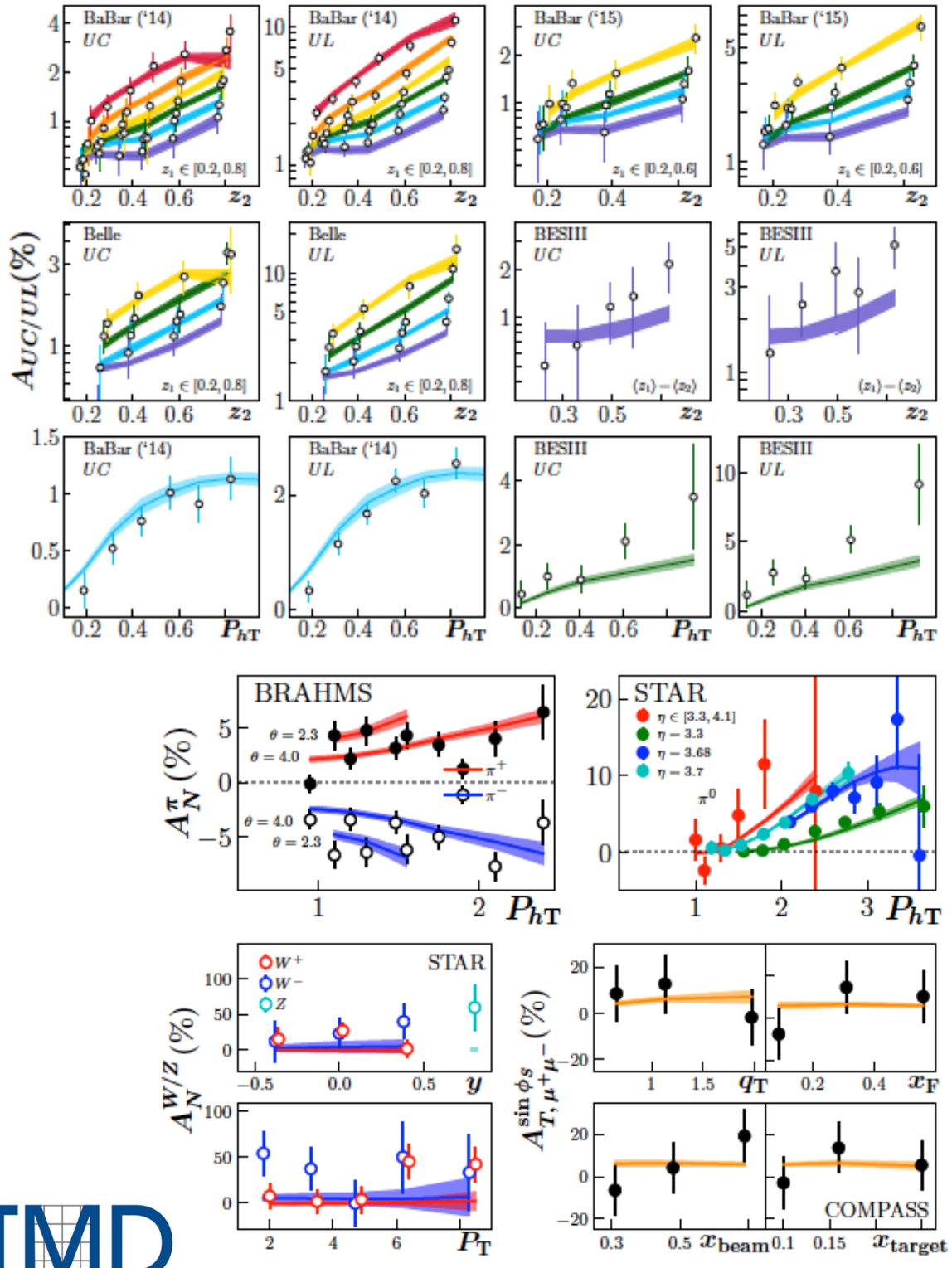
$$f_{1T}^\perp(x)$$

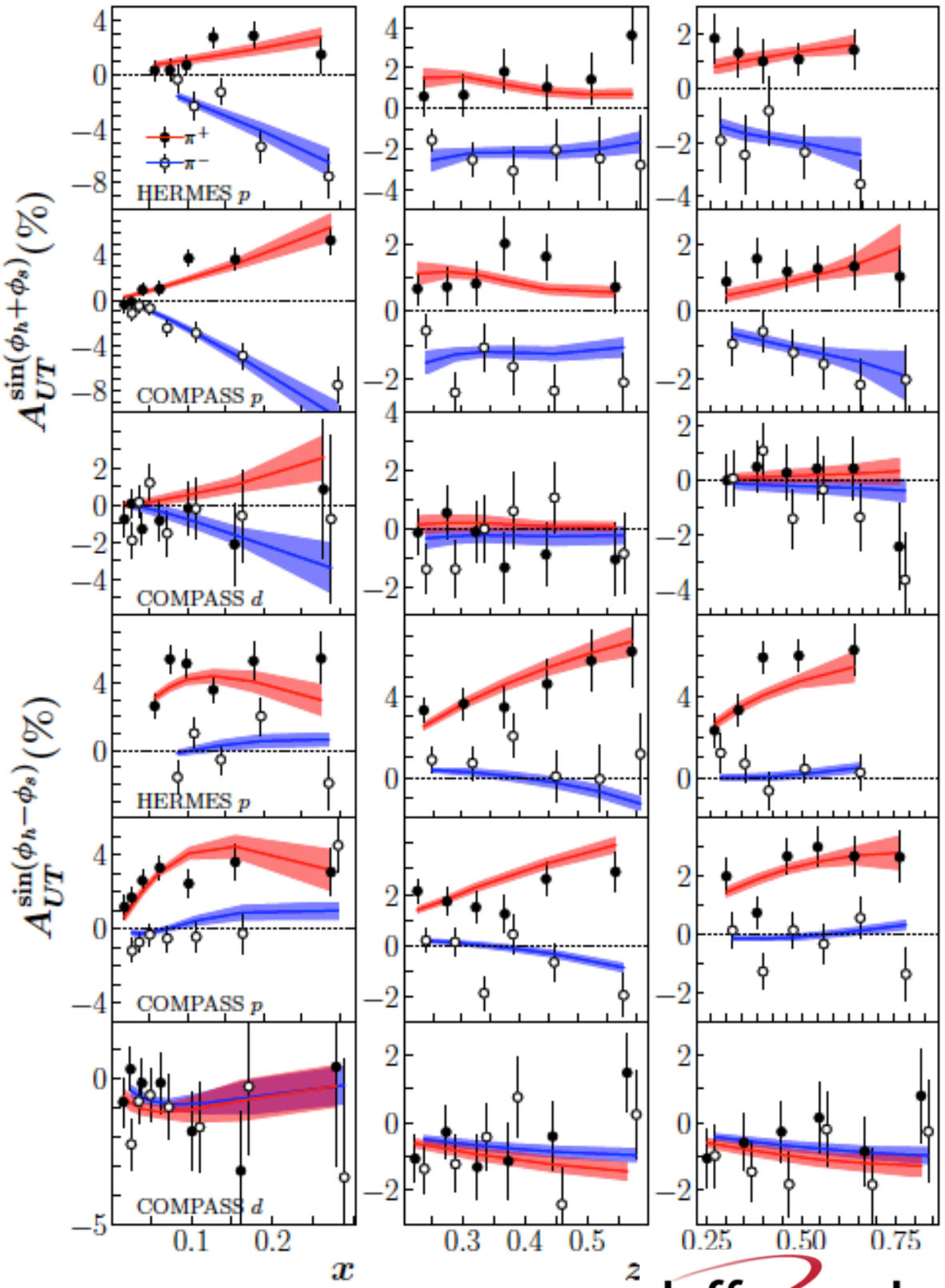
Collin's fragmentation function:

$$H_1^{\perp(1)}(z)$$

Highlights: Phenomenology – Extraction of TMDs

- **Quality of the fit:**



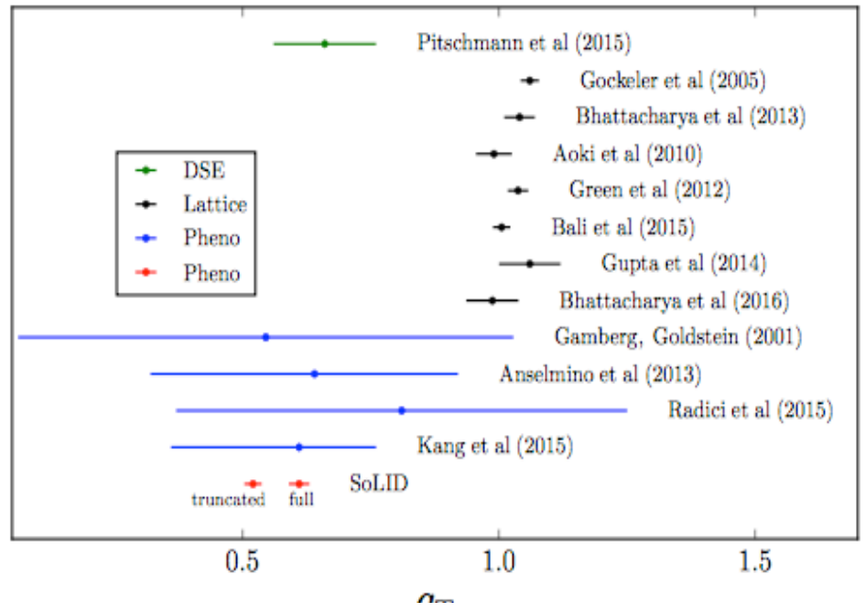


Highlights: Phenomenology – Extraction of TMDs

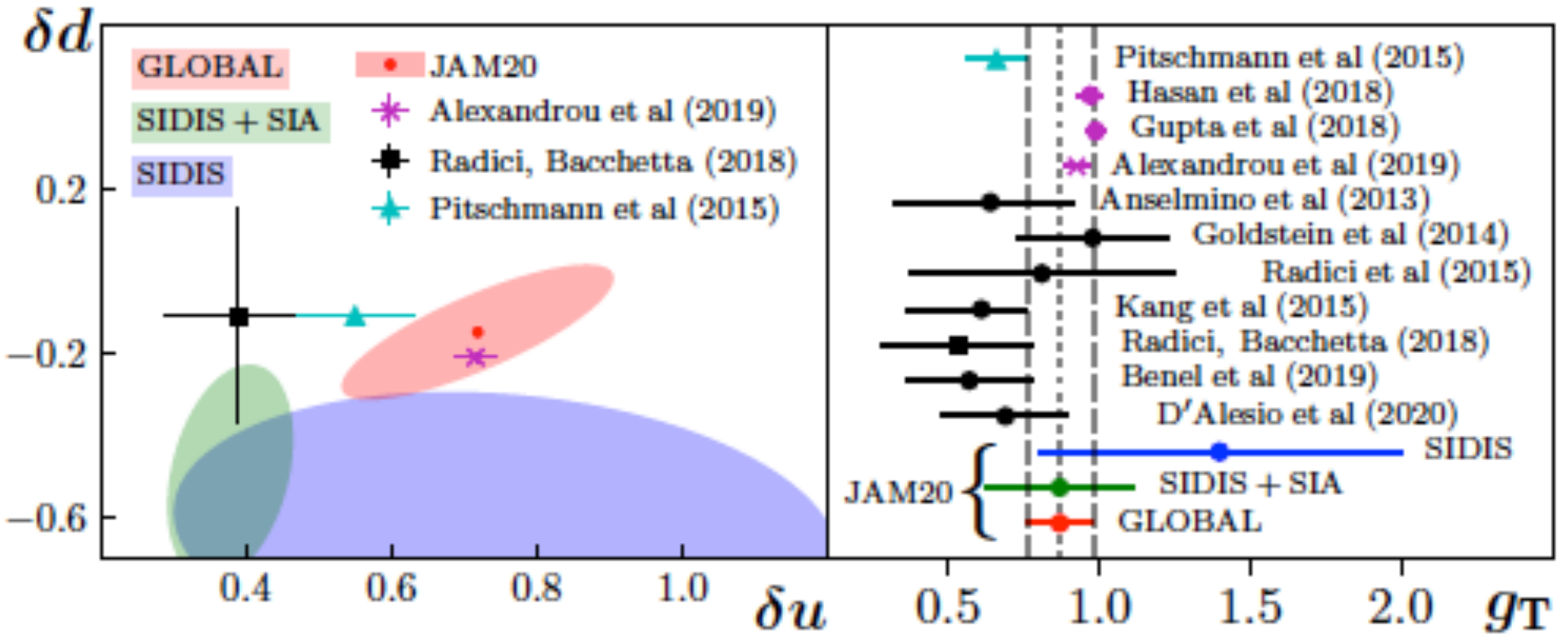
- **Puzzle on the Tensor Charge:**

$$\delta q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)]dx$$

Lattice QCD calculated values consistently *differ* from those extracted from phenomenological fits?



- **Immediate Impact of the global fits:**

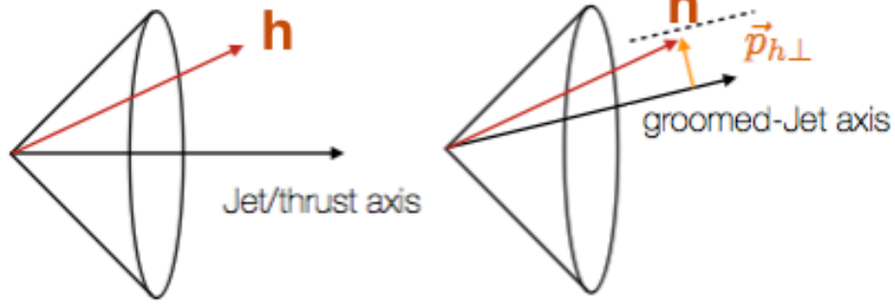


Global fitted results are now consistent with LQCD calculations!

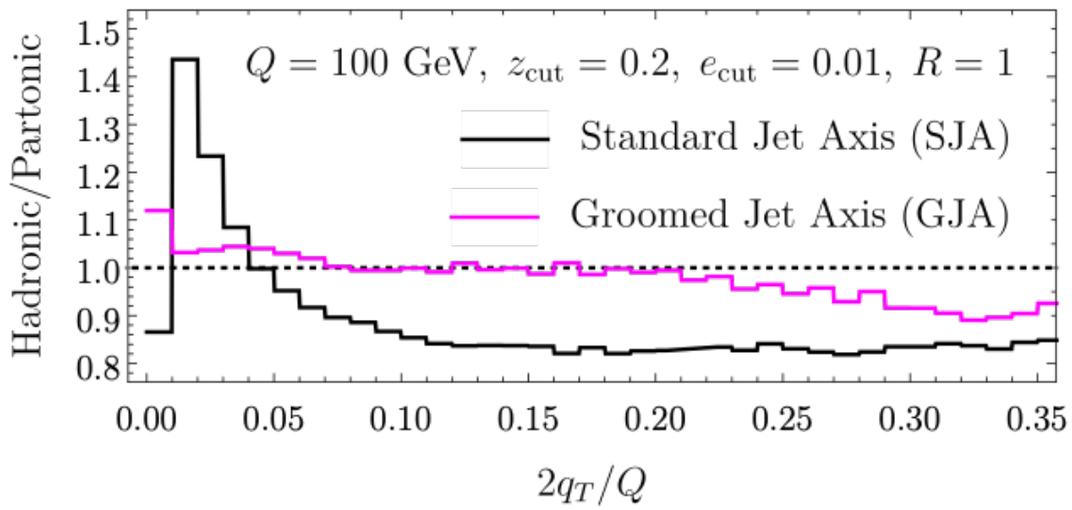
Highlights: Phenomenology – Extraction of TMDs

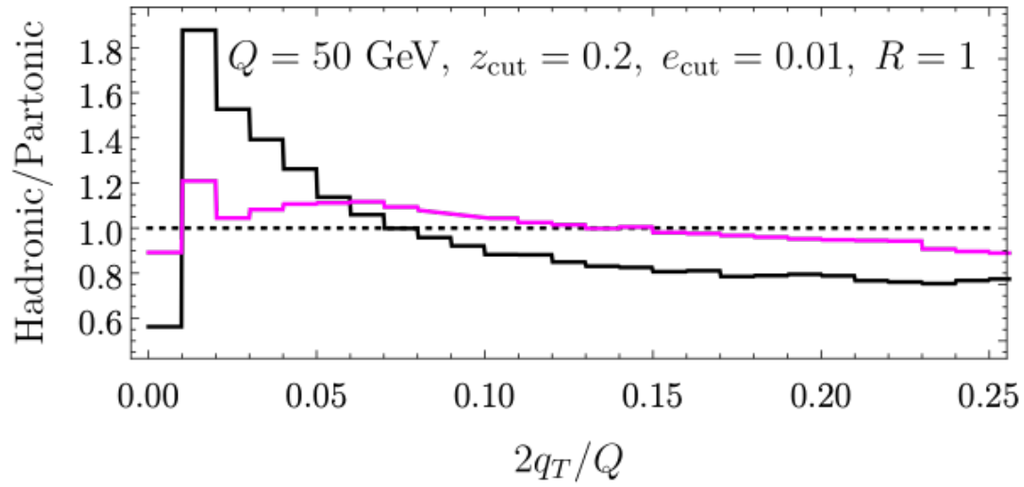
- **Improved TMD phenomenology with groomed jets:**

Groomed jet removes soft radiation



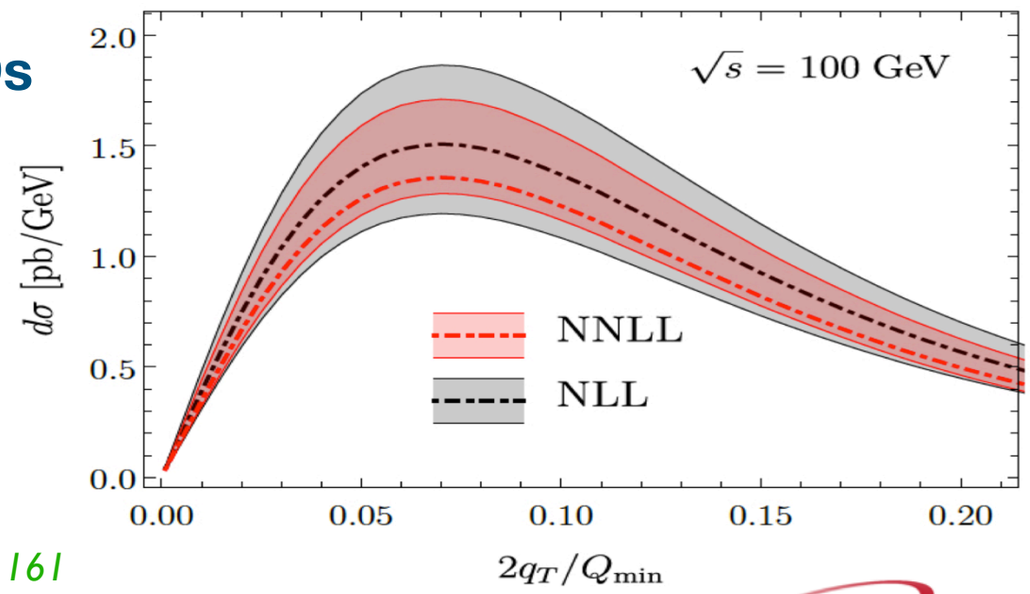
Jet grooming reduces sensitivity to hadronization, soft contamination, underlying event effects





Better controlled calculation of TMDs

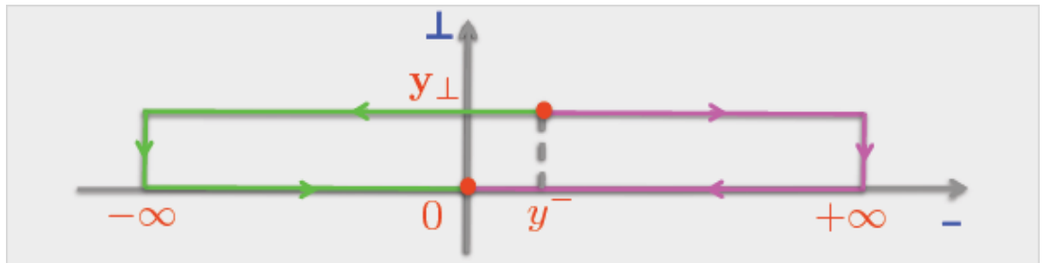
e.g. Precise resummed TMD spectra for groomed jets in DIS at the EIC energy



JHEP ***08*** *(2019) 161*

Highlights: LQCD meets Phenomenology

- **Sign change of Sivers function from LQCD:**

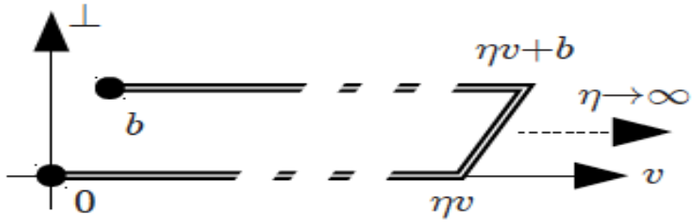


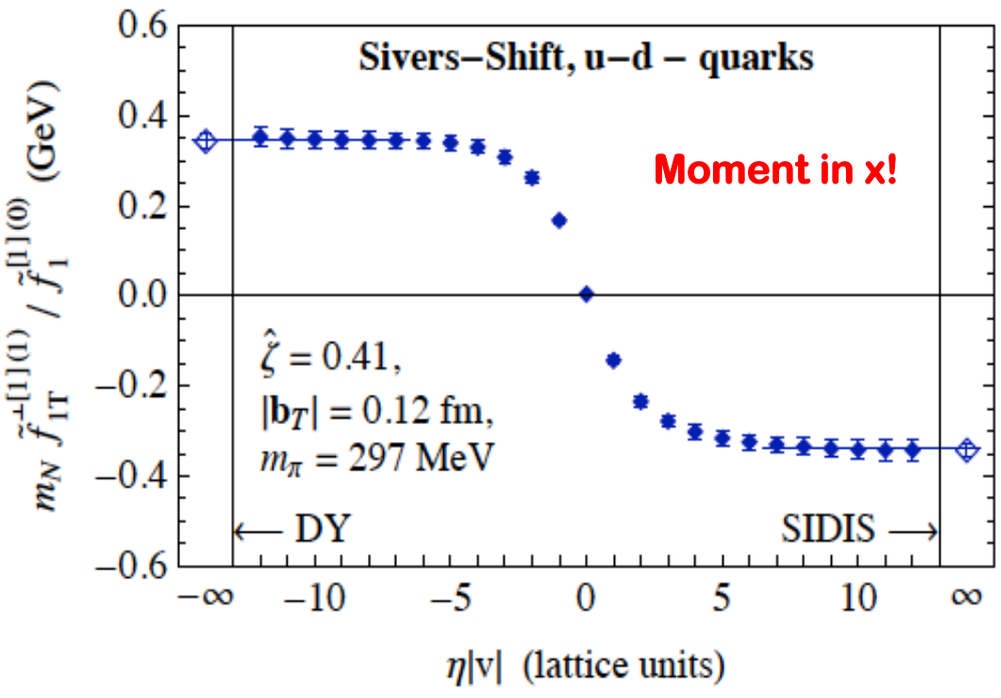
$$f_{1T}^{\perp \mathrm{DIS}}(x, k_\perp) = -f_{1T}^{\perp \mathrm{DY}}(x, k_\perp)$$

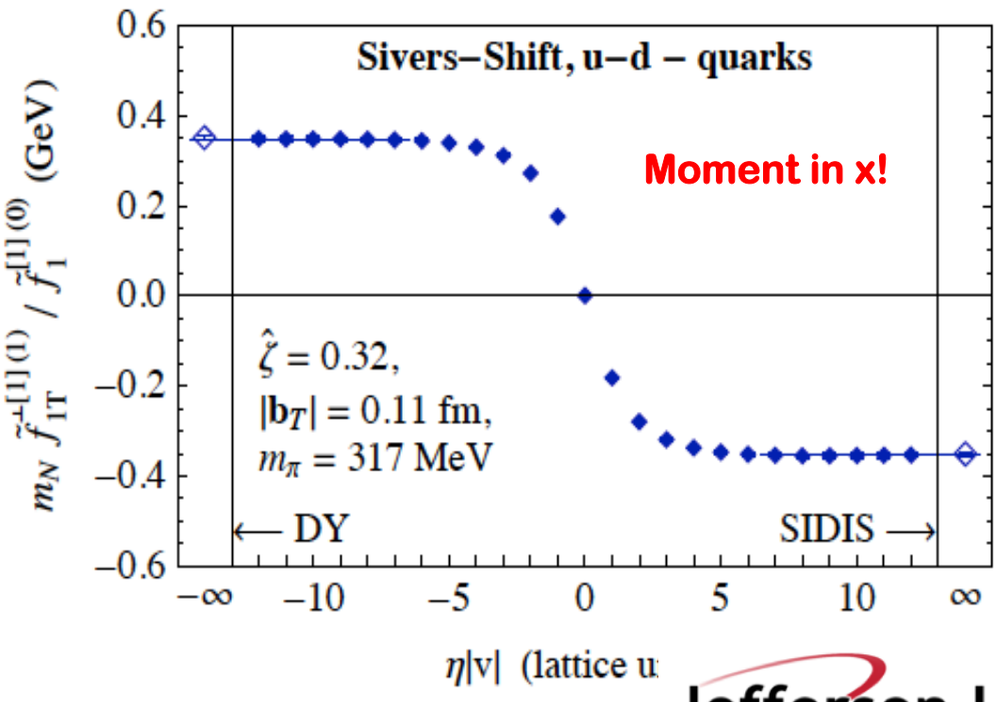
Consequence different gauge links – sign of the phase

- **Normalized Sivers moment at a given b_T - LQCD:**

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







Highlights: LQCD meets Theory

- **Operators for PDFs and TMDs live on the light-cone – Minkowski time**

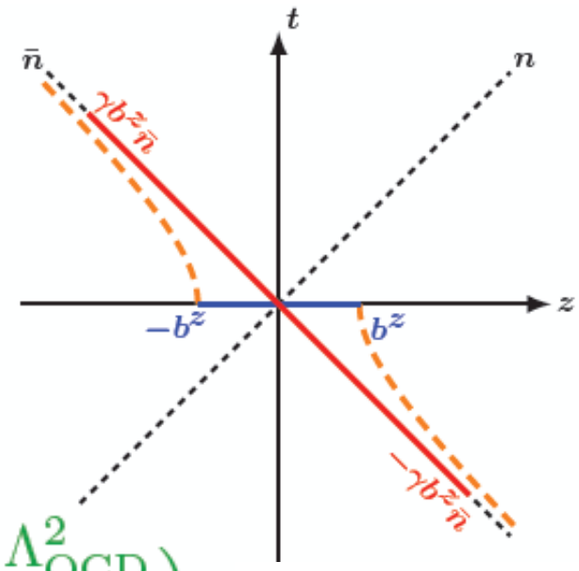
  Cannot be calculated directly in LQCD – Euclidean path integral ! $n_E^2 = 0 \;\Rightarrow\; n_E^\mu = 0$

- **Quasi-PDFs and TMDs: Operators live at a fixed time, $t_M = 0$**

  Share the same collinear physics as PDFs and TMDS

  Boost to the proton state ⟺ **Boost to the operators**

  "LaMET" **take** $P^z \gg \Lambda_{\rm QCD}$ **Ji, PRL 2013**



- **Perturbative matching:**

$$\tilde{f}_i(x, P^z, \tilde{\mu}) = \int_{-1}^{1} \frac{dy}{|y|}\, C_{ij}\Big(\frac{x}{y}, \frac{\tilde{\mu}}{P^z}, \frac{\mu}{yP^z}\Big) f_j(y,\mu) + \mathcal{O}\Big(\frac{M^2}{P_z^2}, \frac{\Lambda_{\rm QCD}^2}{x^2 P_z^2}\Big)$$

simulation & renormalization on lattice

Perturbative matching coefficient

PDF

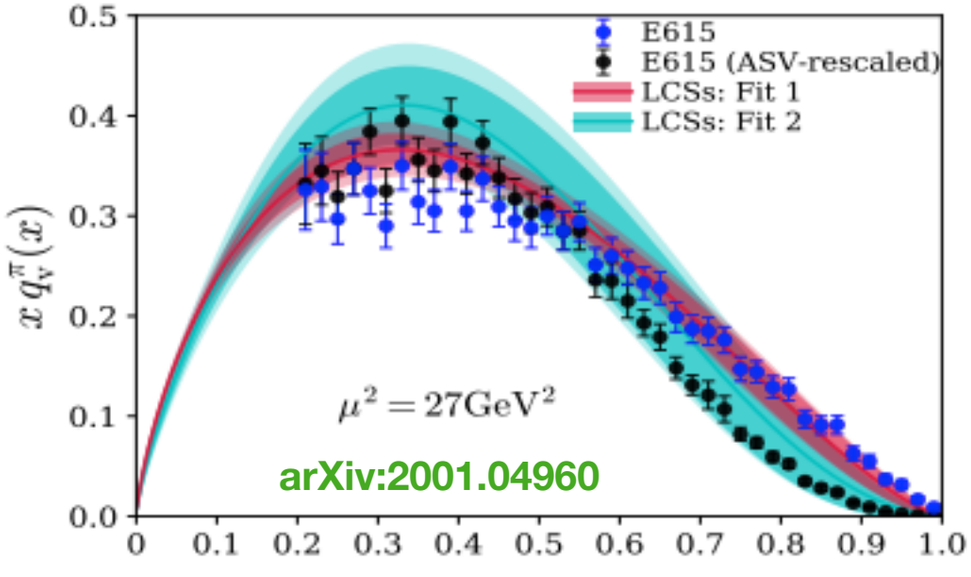
Power corrections

- **"Doing" experiments on the lattice:**

$$\sigma_n(\omega, \xi^2, P^2) = \langle P | T\{\mathcal{O}_n(\xi)\} | P \rangle$$

with $\omega \equiv P\cdot\xi,\ \xi^2 \neq 0,\ \text{and}\ \xi_0 = 0;$

if calculable in lattice QCD with precision, factorizable to PDFs, TMDs, …



Highlights: LQCD meets Theory

- **Quasi-TMDs:**

Phys. Rev. D99 (2019) 034505
arXiv:1910.11415, arXiv:1911.03840

$$\tilde{f}_q(x,\vec{b}_T,\mu,P^z) = \int \frac{db^z}{2\pi}\, e^{ib^z(xP^z)} \lim_{\substack{a\to 0\\ L\to\infty}} \tilde{Z}'_q(b^z,\mu,\tilde{\mu})\tilde{Z}^q_{\rm uv}(b^z,\tilde{\mu},a)\,\tilde{B}_q(b^z,\vec{b}_T,a,L,P^z)\tilde{\Delta}^q_S(b_T,a,L)$$

  - $\tilde{Z}^q_{\rm uv}$ **multiplicative, and removes linear** b^z/a **divergence**
  - $\tilde{Z}'_q$ **converts lattice friendly scheme (**$\tilde{\mu}$**) to** $\overline{\rm MS}$ **(**μ**)**

- **Collins-Soper Kernel from LQCD:**

$$\tilde{f}_q(x,\vec{b}_T,\mu,P^z) = C^{\rm TMD}(\mu,xP^z)\; g^S_q(b_T,\mu)\exp\left[\frac{1}{2}\gamma^q_\zeta(\mu,b_T)\ln\frac{(2xP^z)^2}{\zeta}\right] f_q(x,\vec{b}_T,\mu,\zeta)$$

Quasi-TMD — **Collins-Soper Kernel** — **TMD**

$$\gamma^q_\zeta(\mu,b_T) = \frac{1}{\ln(P_1^z/P_2^z)}\ln\frac{C^{\rm TMD}(\mu,xP_2^z)\;\tilde{f}_q(x,\vec{b}_T,\mu,P_1^z)}{C^{\rm TMD}(\mu,xP_1^z)\;\tilde{f}_q(x,\vec{b}_T,\mu,P_2^z)}$$

quasi-Beam fns.

$$= \frac{1}{\ln(P_1^z/P_2^z)}\ln\frac{C^{\rm TMD}(\mu,xP_2^z)\int db^z e^{ib^z xP_1^z}\tilde{Z}'_q\,\tilde{Z}^q_{\rm uv}\,\tilde{B}_q(b^z,\vec{b}_T,a,L,P_1^z)}{C^{\rm TMD}(\mu,xP_1^z)\int db^z e^{ib^z xP_2^z}\tilde{Z}'_q\,\tilde{Z}^q_{\rm uv}\,\tilde{B}_q(b^z,\vec{b}_T,a,L,P_2^z)}$$

- **needs** $\tilde{B}_q$, $\tilde{Z}^q_{\rm uv}$, $\tilde{Z}'_q$, $C^{\rm TMD}$ → ***Universal QCD function from LQCD!***
- **LHS independent of** $P_1^z, P_2^z, x,$ **hadron state, spin**
- **can setup** $\tilde{Z}^q_{\rm uv}$ **to remove power law divergences**

Service to the Community

- **The 1st TMD Summer School – June 22 – 28, 2017**
  Provide advanced training to students and young postdocs on QCD and TMD Physics

Time	Thu 22nd	Fri 23rd	Sat 24th	Sun 25th	Mon 26th	Tue 27th	Wed 28th
8:00	Registration (8:15) Welcome (8:45)						
8:30							
9:00	QCD and Parton Model I *Nadolsky*	QCD and Parton Model III *Nadolsky*	TMD Factorization and Evolution I *Rogers*		Lattice QCD I *Detmold*	Lattice QCD III *Detmold*	Quasi-PDFs *Constantinou*
9:30							
10:00							
10:30	Coffee Break	Coffee Break	Coffee Break		Coffee Break	Coffee Break	Coffee Break
11:00	QCD and Parton Model II *Nadolsky*	QCD and Parton Model IV *Nadolsky*	TMD Factorization and Evolution II *Rogers*		Lattice QCD II *Detmold*	Lattice QCD IV *Detmold*	GPDs and Generalized TMDs *Lorce*
11:30							
12:00							
12:30	Lunch	Lunch	Lunch		Lunch	Lunch	Lunch
13:00							
13:30	TMD Pheno. I *Bacchetta & Signori*	TMD Pheno. III *Bacchetta & Signori*	TMDs in Experiment I *Grosse-Perdekamp*		SCET I *Stewart*	SCET III *Stewart*	TMDs in Lattice QCD *Engelhardt*
14:00							
14:30							
15:00	Coffee Break	Coffee Break	Coffee Break		Coffee Break	Coffee Break	Coffee Break
15:30	TMD Pheno. II *Bacchetta & Signori*	TMD Pheno. IV *Bacchetta & Signori*	TMDs in Experiment II *Grosse-Perdekamp*		SCET II *Stewart*	SCET IV *Stewart*	TMDs at small x *Yuan*
16:00							
16:30							
17:00	Discussion Problem Solving	Discussion Problem Solving	Discussion Problem Solving		Discussion Problem Solving	Discussion Problem Solving	Discussion Problem Solving
17:30							
18:00	Dinner	Dinner	Dinner		Dinner	Dinner	Dinner
18:30							
19:00		Student Presentations			Student Presentations		
19:30							
20:00							
20:30							

- 10 Lecturers (TMD + non-TMD Lecturers)
- Problem solving sessions
- Student presentations

- 30 students
- From 16 institutions
- Limited by funding
- Active in TMD

Service to the Community

- **TMD Summer School – June 22 – 28, 2017**

Service to the Community

- **The 2nd TMD Summer School – June 22-27, 2020**

New Mexico CONSORTIUM

Home Speakers Program Lodging Visitor Info Register Now

TMD Collaboration

2020 TMD Summer School

June 22 - 27, 2020

Hilton Santa Fe Historic Plaza Hotel

Santa Fe, New Mexico

We are pleased to announce the 2020 TMD Summer School, to be held in beautiful Santa Fe, New Mexico, June 22-27, 2020.

The School is sponsored by the TMD Collaboration (The DOE Topical Collaboration for the Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD), and is the 2nd edition of the TMD School held in 2017 at Temple University.

We invite PhD students and early postdocs doing their research in QCD, collider physics, and hadron structure, broadly related to the physics of transverse momentum dependent distributions to tackle such open problems as 3-D hadron structure, proton spin, and properties of strongly interacting matter.

Working knowledge of quantum field theory is a prerequisite to maximally benefit from the School. We expect to be able to host about 30 students.

We anticipate the TMD Collaboration will be able to support lodging expenses for all students. (Travel to Santa Fe will need to be covered by the student's home institution.) Lodging and lectures will both be at the Hilton Santa Fe Historic Plaza Hotel. Our funding will pay for Summer School participants to be lodged in shared, double rooms at the Hilton. (Those requiring single rooms can inquire about alternate arrangements, with the home institution or the student responsible for the extra cost.)

Service to the Community

- **The 2nd TMD Summer School – June 22-27, 2020**

New Mexico CONSORTIUM

Home Speakers Program Lodging Visitor Info Register Now

Expected lecturers and topics include:

- Jianwei Qiu - Introduction to QCD
- Piet Mulders - Introduction to TMDs
- Haiyan Gao - TMDs in Experiments
- Phiala Shanahan - Lattice QCD
- Michael Engelhardt - TMDs on Lattice
- Xiangdong Ji - TMDs in Large Momentum Effective Theory
- Duff Neill - Soft Collinear Effective Theory and TMD Evolution
- Matthias Burkardt - Generalized Parton Distributions and Orbital Angular Momentum
- Yuri Kovchegov - TMDs at small x
- Tom Mehen - TMDs in Jets
- Ivan Vitev - TMDs in dense matter

Service to the Community

- **Handbook of TMDs:**
  - Fast growth of TMD community – wide range of approaches to TMD physics
  - Need to unify the language and terminologies, summarize technologies for TMDs
  - To survey the state of experimental data for TMDs, and future opportunities
  - Comprehensive resource for students and young postdocs entering the field
- **Table of Contents (Collaboration meeting at Duke):**
  - Introduction– *J.-W. Qiu, M. Burkardt, S. Fleming*
  - Fundamentals of QCD and pQCD – *J.-W. Qiu, M. Burkardt, S. Fleming*
  - Definition of TMDs – *I.W. Stewart, T. Rogers*
  - Factorization – *T. Rogers, I.W. Stewart, J.-W. Qiu*
  - Evolution – *L. Gamberg, T. Mehen, C. Lee*
  - Phenomenology – *A. Prokudin, A. Metz, D. Pitnoyak*
  - Generalized TMDs – *A. Metz, M. Schlegel, F. Yuan*
  - Small x TMDs – *F. Yuan, R. Venugopalan*
  - Models for TMDs – *M. Burkardt, P. Schweitzer, A. Metz*
  - Orbital Angular Momentum – *S. Liuti, M. Burkardt*
  - Jet Fragmentation – *T. Mehen, Z.-B. Kang, I. Vitev*
  - Lattice QCD for TMDs – *W. Detmold, M. Constantinou, M. Engelhardt, K.-F. Liu, Y.-B. Yang, Y. Zhao*
- **Timeline:**
  - Complete draft by April 24th, 2020 – ready for TMD Summer School – "text book"
  - Finalize and publish after the School

Summary

- **We established an organized, coherent and interactive scientific collaboration/network**
  - Focusing on QCD and hadron physics, in particular, the physics of TMDs
  - Pulling together expertise in theory, phenomenology, and lattice QCD
  - Forming a unique multi-institution and three-pronged scientific effort
  - Enabling a paradigm shift in our approach taking on projects impossible by single PI
- **With DOE and leveraged support, we help to strengthen the TMD effort in the U.S.**
  - Two bridged faculty positions were created for QCD and hadron structure
  - 8 postdocs + 4 graduate and several undergraduate students work on TMD physics
- **We made major achievements impacting physics programs at JLab, RHIC, future EIC, …**
  - Well on track to achieve all proposed milestones
- **We have done important service to the NP community by training young researchers**
  - Organized a very successful summer school, will organize another one this year
  - Providing theory support to experimental program
  - Producing the handbook of TMDs physics – very important to the community

Our collaboration has provided a very positive impact to the community of QCD and structure of hadron and nuclei – many people would like to join our activities!

Without the network of Topical Collaboration, and DOE support, this would not happen!

Thank you!