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

Jianwei Qiu

Theory Center, Jefferson Lab

Acknowledgement: This talk was prepared with contributed materials from all members of TMD collaboration. Many contributions and references can't be included due the limited space

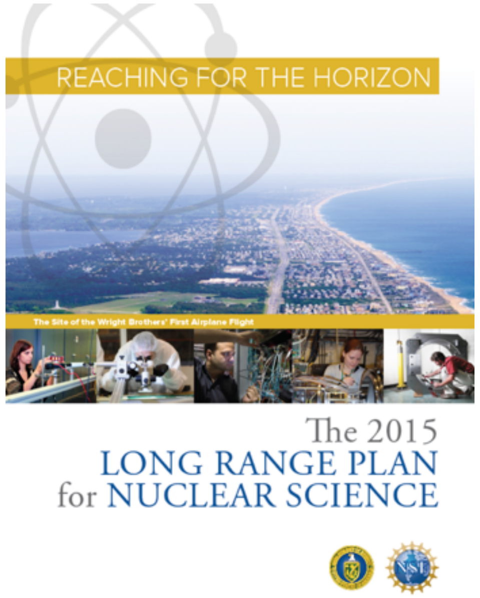
DOE/NSF Nuclear Science Advisory Committee Meeting
Crystal City Marriott, Arlington, Virginia

TMD Collaboration

The last Frontier of the Standard Model - QCD

- **Understanding the structure of hadrons in terms of QCD's quarks and gluons is one of the central goals of modern nuclear physics**

  – 2015 NSAC Long-Range Plan



REACHING FOR THE HORIZON

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

The last Frontier of the Standard Model - QCD

The 2015
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- **Understanding the structure of hadrons in terms of QCD's quarks and gluons is one of the central goals of modern nuclear physics**
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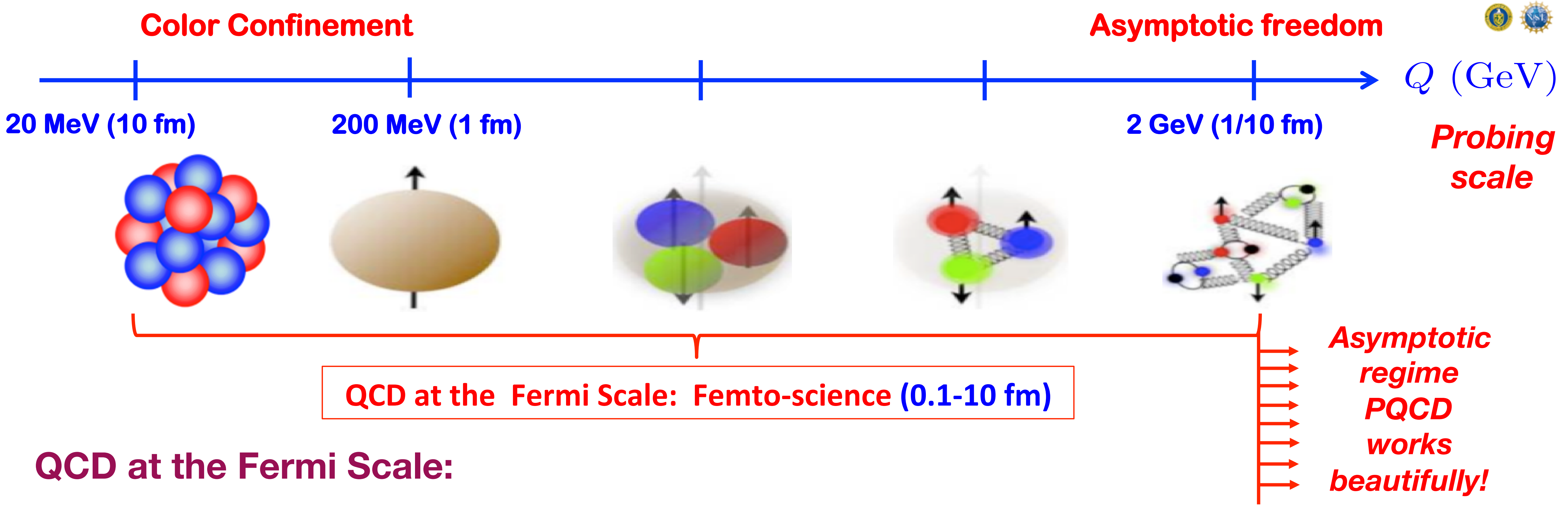
- **The Structure of Hadrons and Nuclei – Emergent properties of QCD**



Color Confinement

Asymptotic freedom

Q (GeV)

20 MeV (10 fm)

200 MeV (1 fm)

2 GeV (1/10 fm)

Probing scale

QCD at the Fermi Scale: Femto-science (0.1-10 fm)

Asymptotic regime PQCD works beautifully!

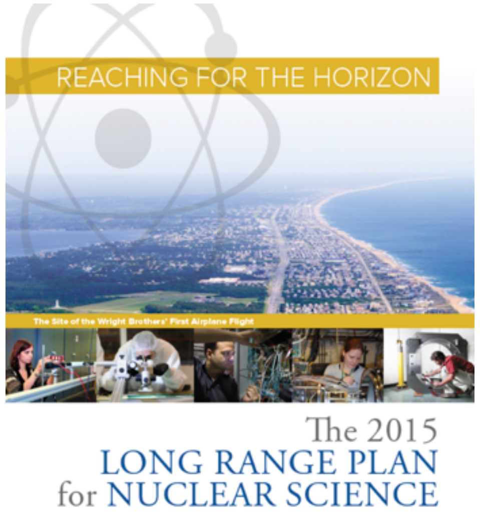
- **QCD at the Fermi Scale:**

  The most interesting, rich, and complex, but mysterious regime of the theory!

  All emergent phenomena depend on the probes and the scale at which we probe them!

  Unprecedented challenge: we do not see any quarks and gluons in isolation!

The last Frontier of the Standard Model - QCD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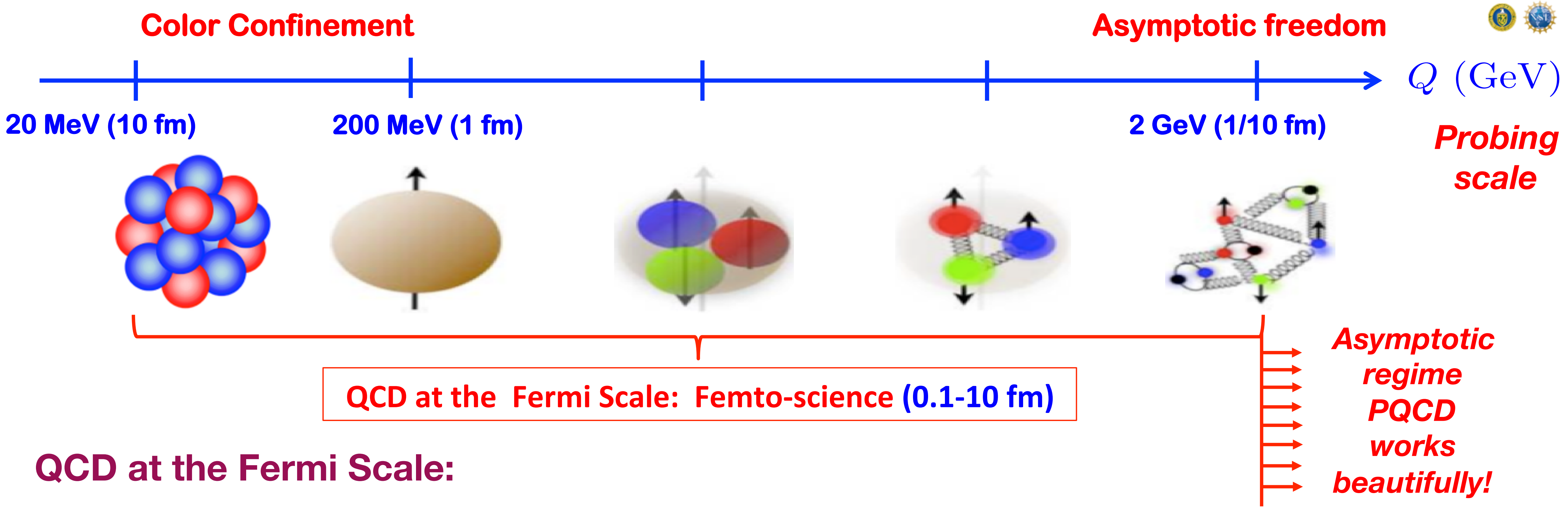


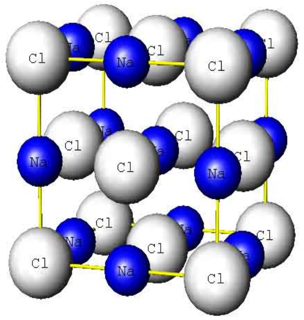
QCD at the Fermi Scale: Femto-science (0.1-10 fm)

- QCD at the Fermi Scale:
  - The most interesting, rich, and complex, but mysterious regime of the theory!
  - All emergent phenomena depend on the probes and the scale at which we probe them!
  - *Unprecedented challenge: we do not see any quarks and gluons in isolation!*
- TMD Collaboration’s mission:
  - Develop reliable and controllable “tools” to match quarks and gluons to observed hadrons
  - Quantify the structure of hadrons in terms of the “particle nature” of quarks and gluons
  - Provide the education and training of younger generation of QCD physicists

Quantify Hadron’s Partonic Structure

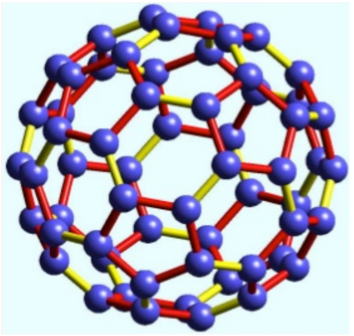
- **Structure – “a still picture”:**

Crystal Structure:



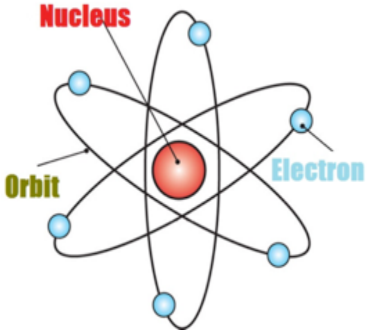
NaCl,
B1 type structure

Nano-material:



Fullerene, C60

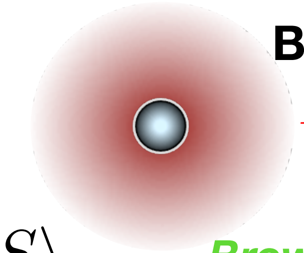
Atomic structure



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”: $\langle P,S|\mathcal{O}(\overline{\psi},\psi,A^\mu)|P,S\rangle$

Quantify Hadron’s Partonic Structure

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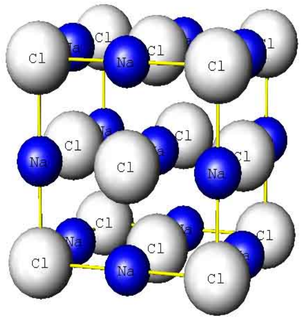

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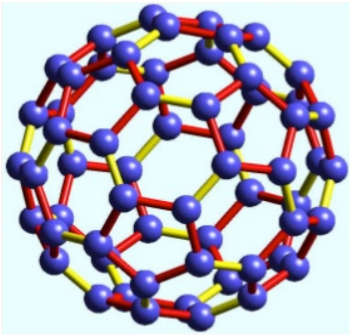

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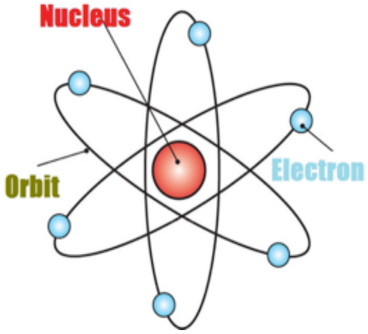

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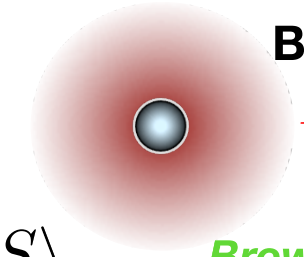
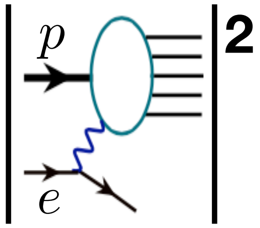


- **Need a probe to “see” quarks and gluons!**

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



Quantify Hadron's Partonic Structure

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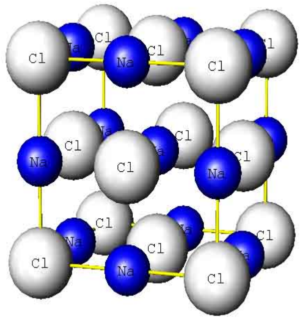

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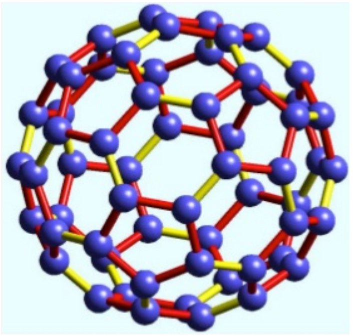

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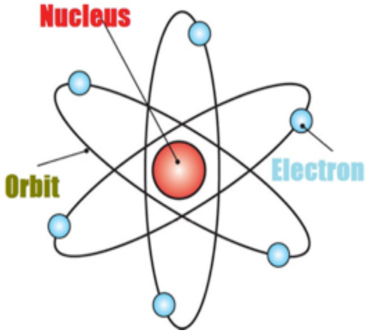

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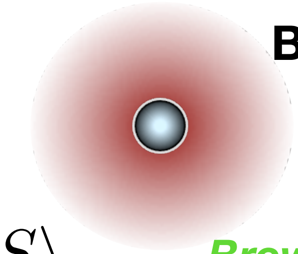

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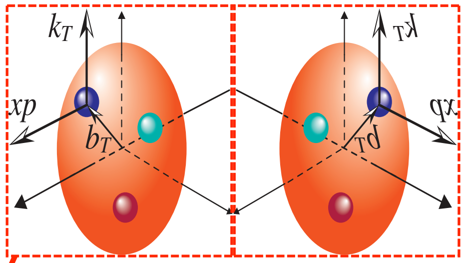
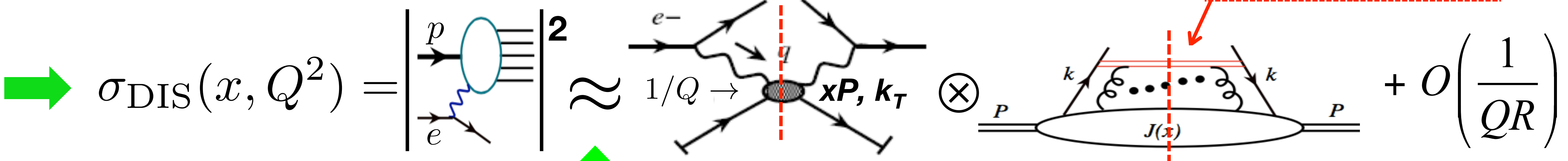




$$\sigma_{\rm DIS}(x,Q^2) = \left|\;\cdots\;\right|^2 \approx 1/Q \to \cdots \otimes \cdots + O\!\left(\frac{1}{QR}\right)$$

Factorization

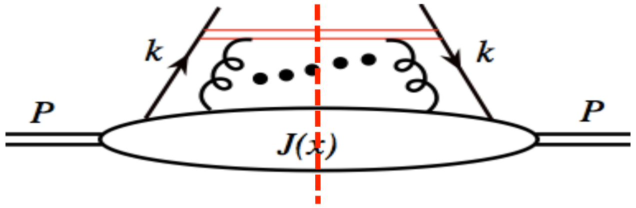
Hard-part Probe

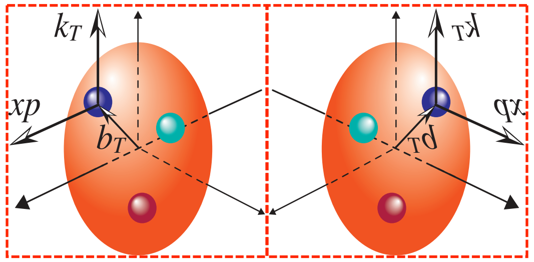
Parton-distribution Structure

Power corrections Approximation

Quantify Hadron's Partonic Structure

- **Parton distribution functions (PDFs):**





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Interpreted as: *Probability density to find a quark with a momentum fraction x*

Quantify Hadron's Partonic Structure

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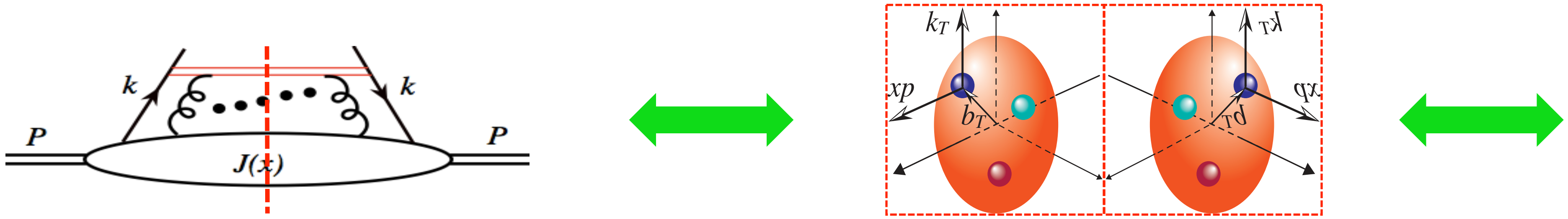

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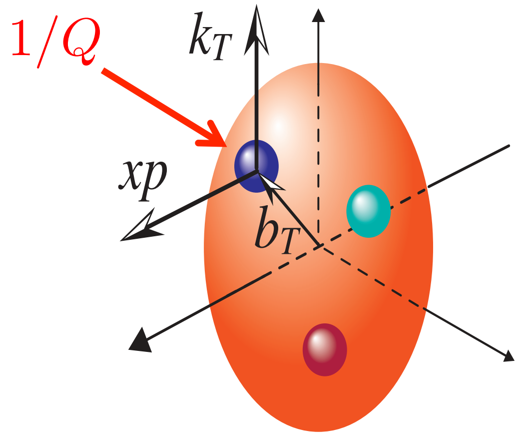
- **3D Confined motion (k_T) and spatial imaging (b_T):**



- More sensitive to how QCD bounds quarks/gluons into a proton
- Fact: b_T ~ fm, k_T ~ 1/fm << Q (> 10^{-1} fm)
- Hard probe pins down particle nature of quarks and gluons
- But, not very sensitive to the detailed structure of hadron ~ fm

➡ *Need new type "Hard Probes" – physical observables with TWO scales!*

- The larger scale to pin down the particle nature of quarks and gluons
- The smaller scale to probe the detailed structure of the hadrons

Quantify Hadron’s Partonic Structure

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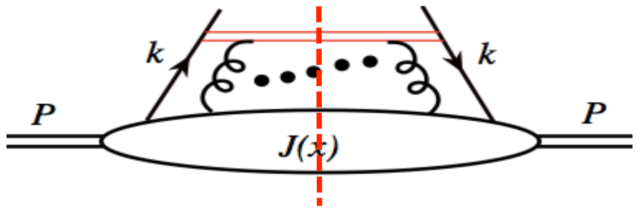

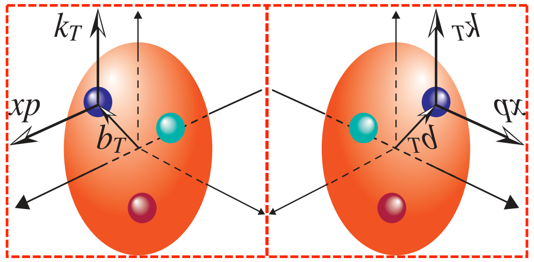

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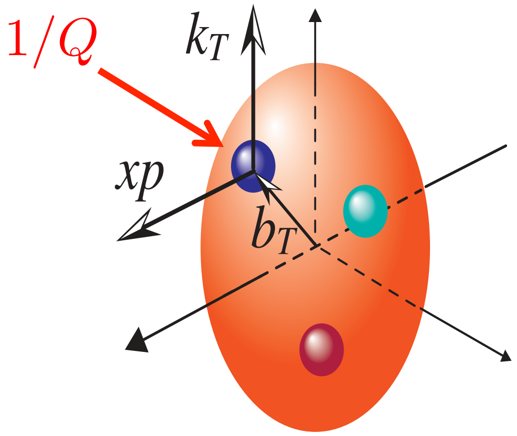

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➡ *Need to identify naturally measurable two-scale observables*

Need to prove or improve “QCD factorization” for new type observables

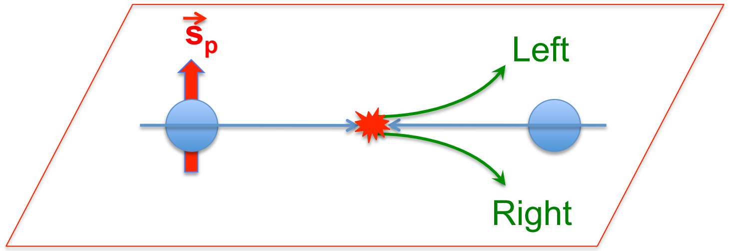
The “Confined Motion” (k_T-dependence) is encoded in the TMDs

➡ **Need for TMD Collaboration**

Challenge: the Sivers Effect

Kane, Pumplin, Repko, PRL, 1978

- **Single Transverse Spin Asymmetry:**



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

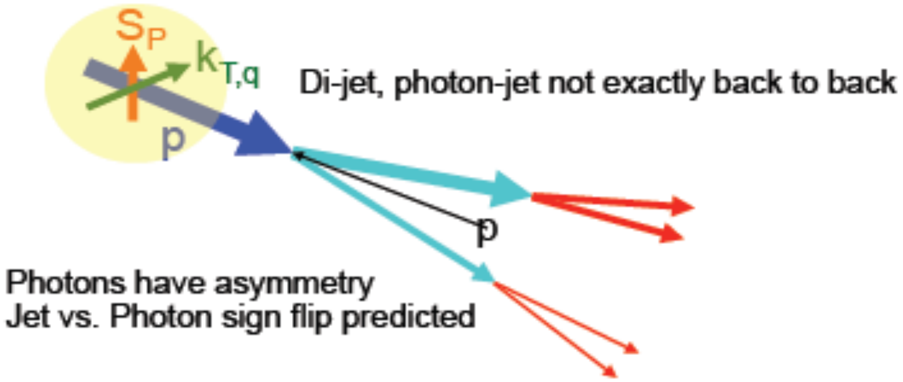
Theory (1978):

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

Experiment (40 yrs)

A_N **As large as 40%**

- **Sivers Effect:** D. Sivers, PRD41 (1990)83



Di-jet, photon-jet not exactly back to back

Photons have asymmetry
Jet vs. Photon sign flip predicted

Quantum Correlation between

- **Spin direction of colliding hadron**
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QCD: Sign Change from SIDIS to Drell-Yan

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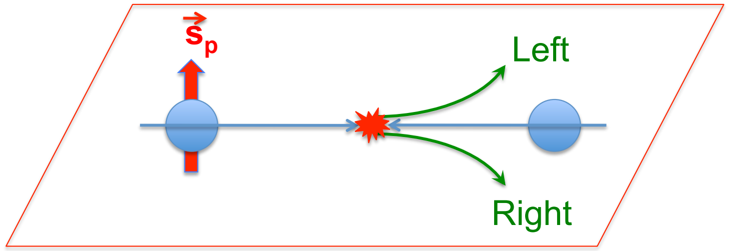

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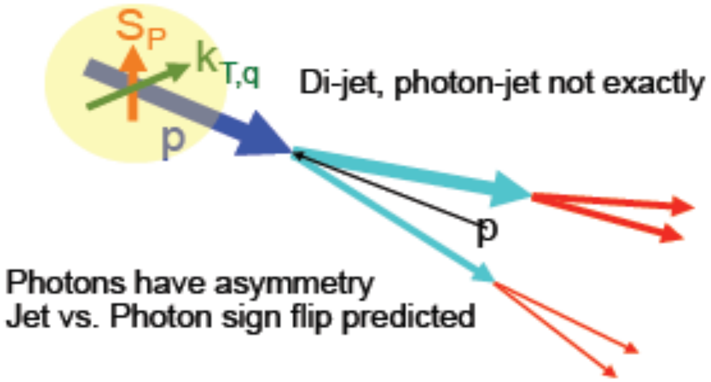

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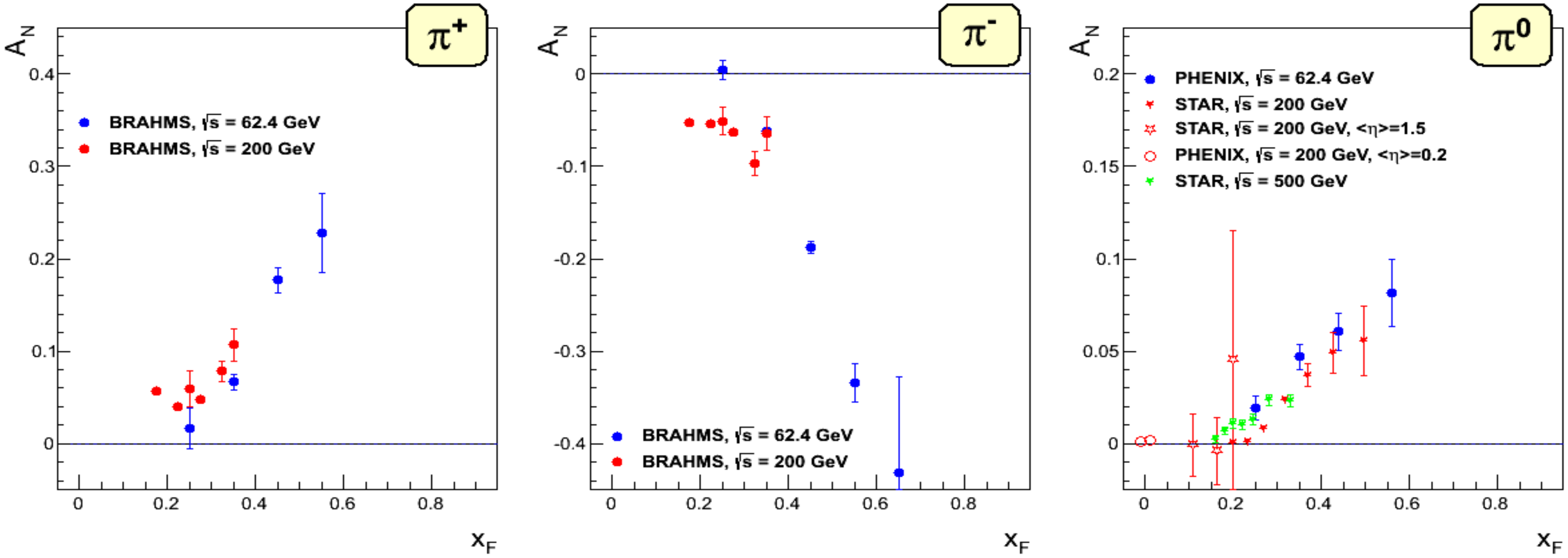
- **Challenge – Asymmetries survives with growing collision energies :**

RHIC spin:

BRAHMS

PHENIX

STAR



TMD Collaboration

Challenge: the Sivers Effect

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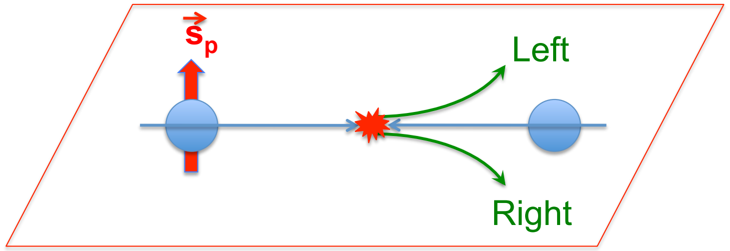

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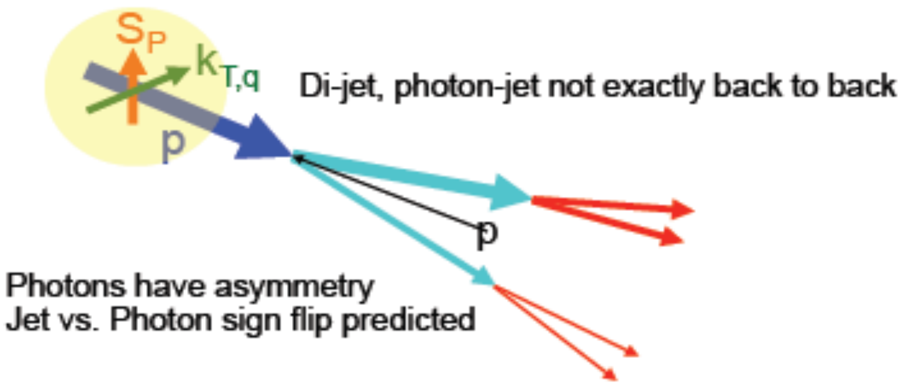

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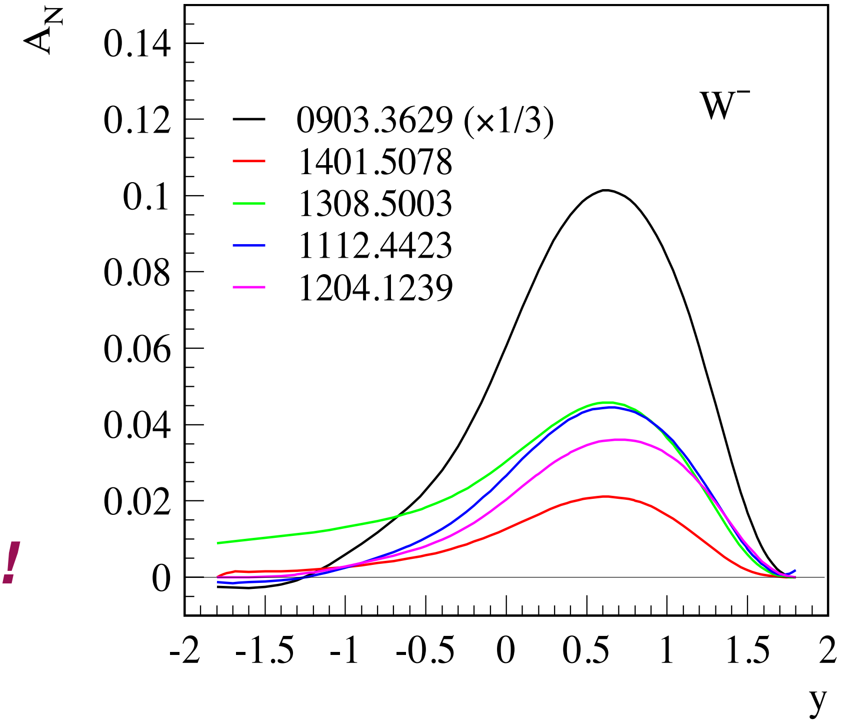
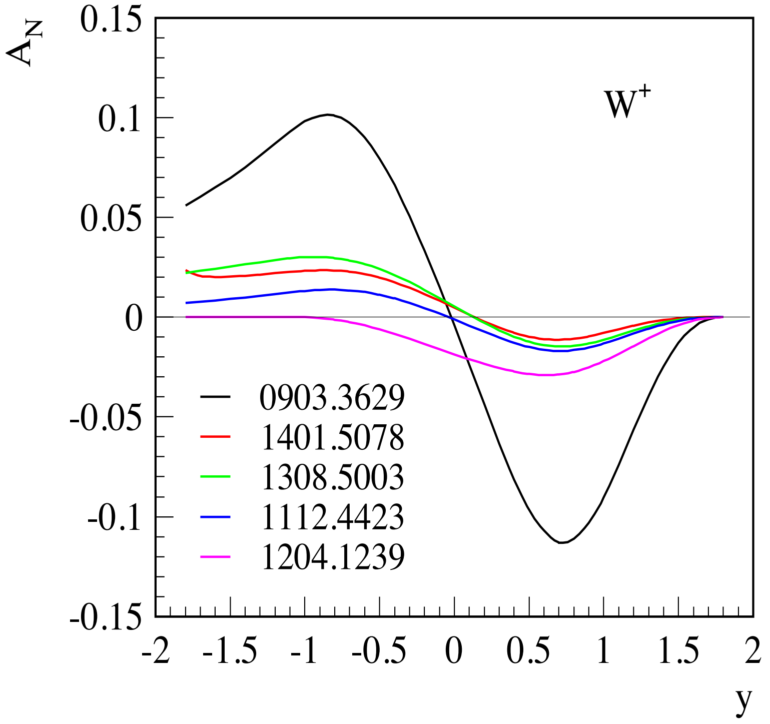
- **Challenge – Phenomenology:**

Predictions for A_N
of W-production at RHIC

Huge difference!
Role of non-perturbative physics

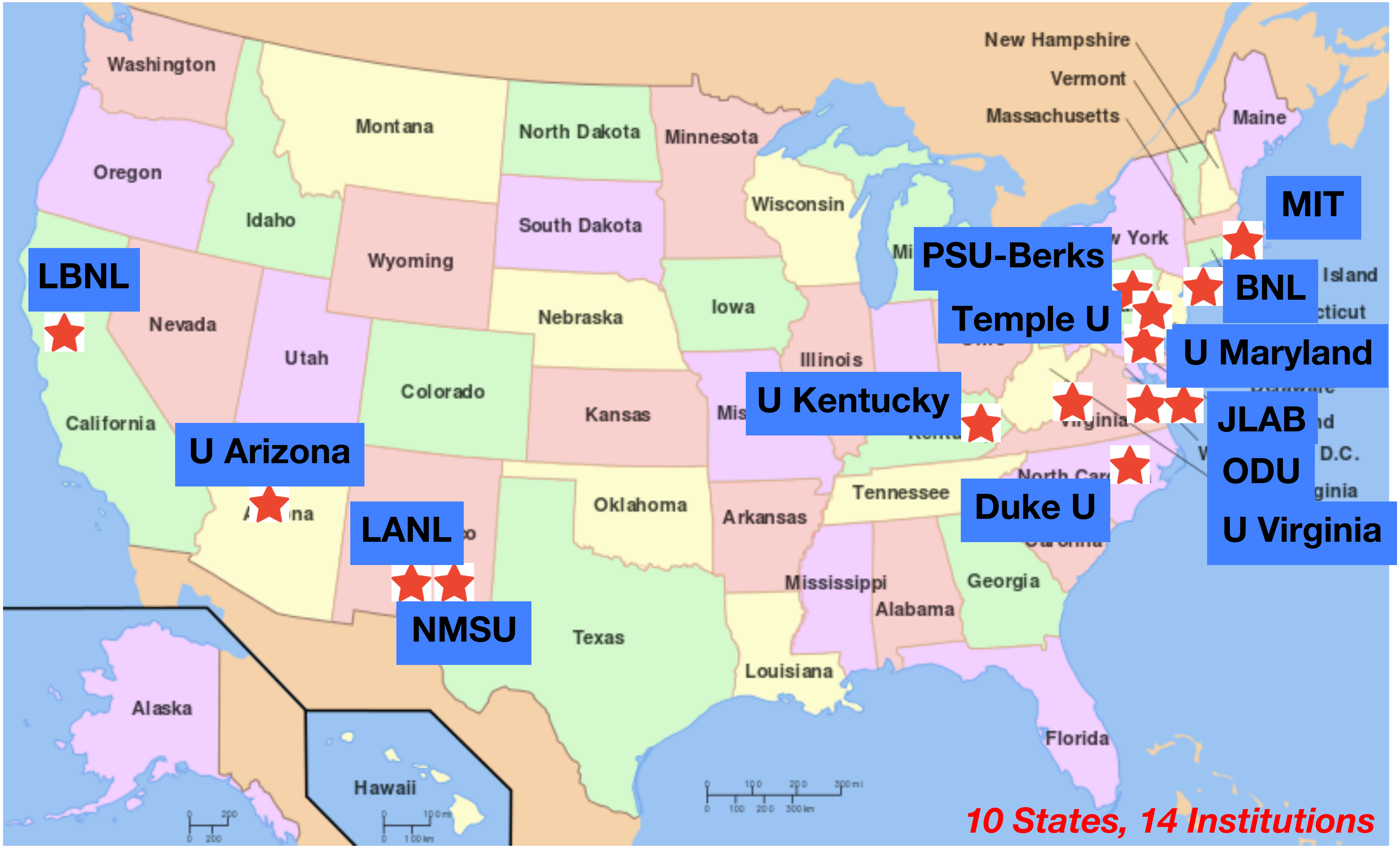
Need for TMD Collaboration!





TMD Collaboration

The Team - TMD Topical Collaboration



10 States, 14 Institutions

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)

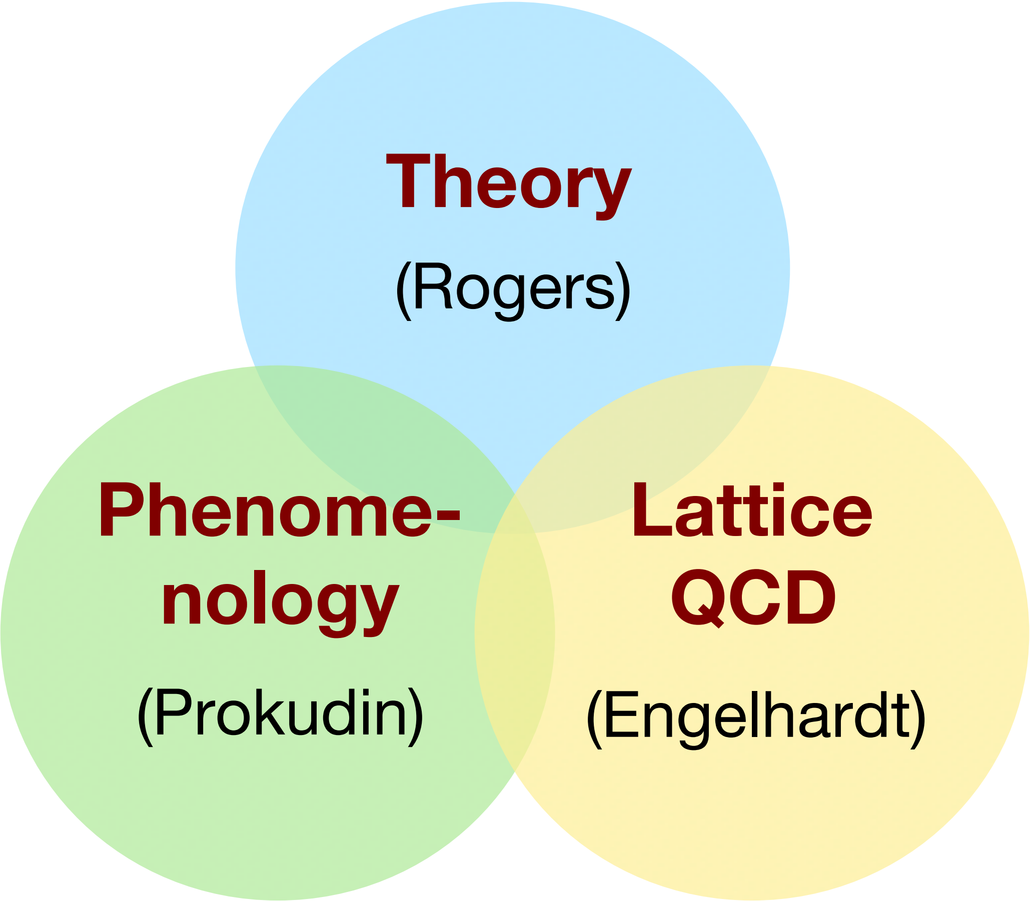
4 National Labs, 10 Universities

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 Method, Service, Productivity

- **Coherent three-pronged approach:**



Theory

– Strengthen the theoretical foundation of TMD physics;

- Scrutinize the definition,
- Broaden our knowledge on the role and 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
- Explore the nature of parton orbital angular momentum

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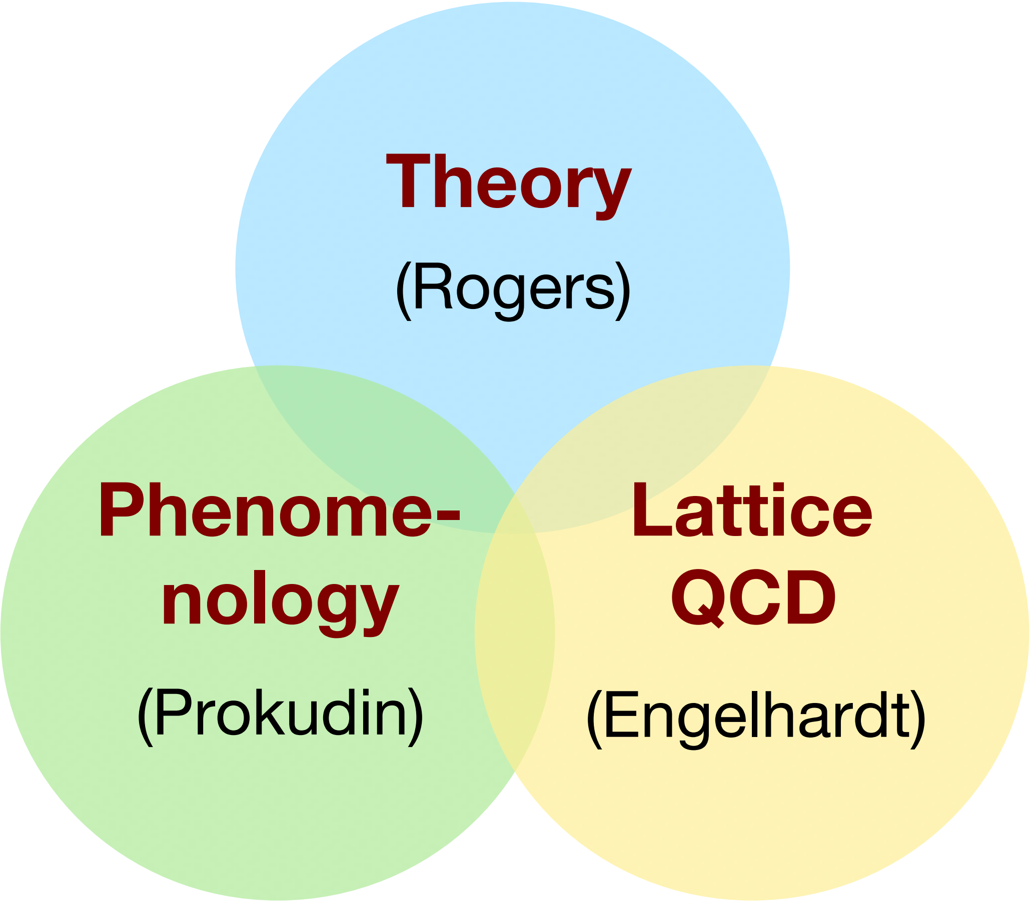

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- **Service to the community and productivity:**

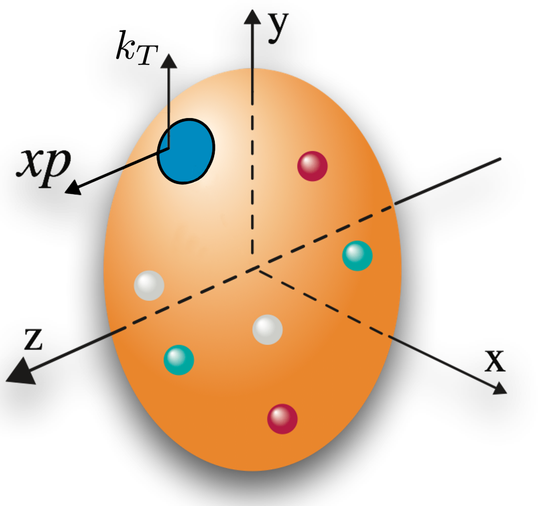
Provide compelling research, training and career opportunities for young nuclear theorists

– 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



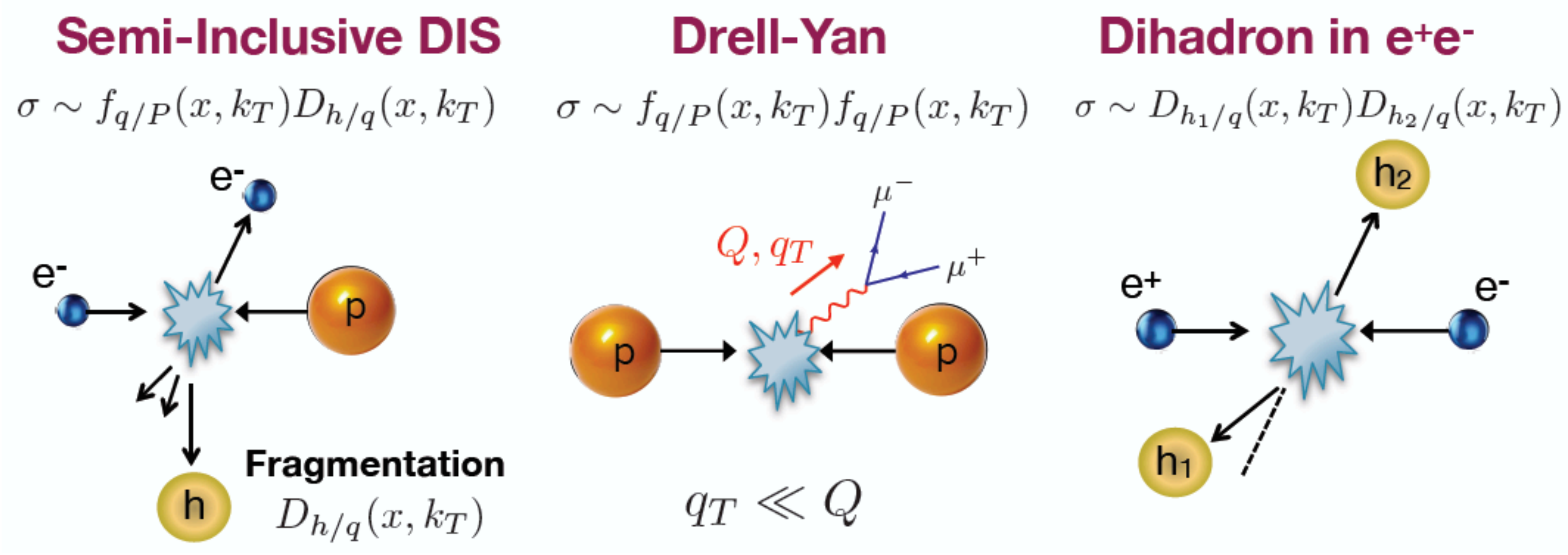
- **From PDFs to TMDs:**

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

longitudinal

longitudinal & Transverse

- **Classical two-scale observables:**



Semi-Inclusive DIS

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

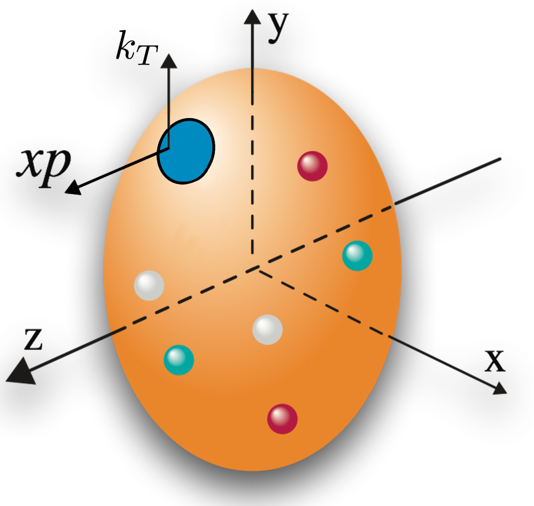
Drell-Yan

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

Dihadron in e^+e^-

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

TMDs from Two-Scale Observables



- **From PDFs to TMDs:**

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

longitudinal → longitudinal & Transverse

- **Classical two-scale observables:**

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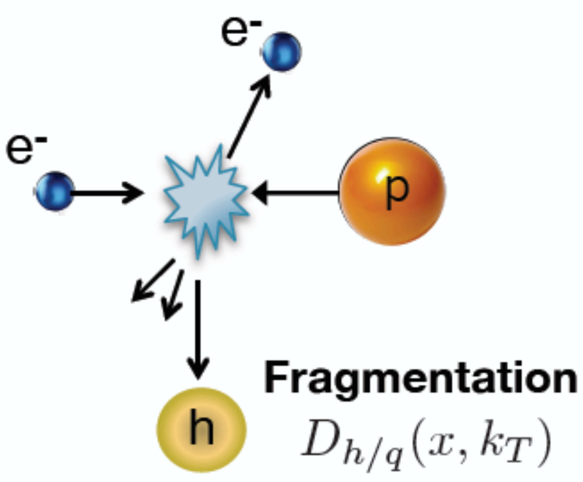
$\sigma \sim f_{q/P}(x, k_T) D_{h/q}(x, k_T)$

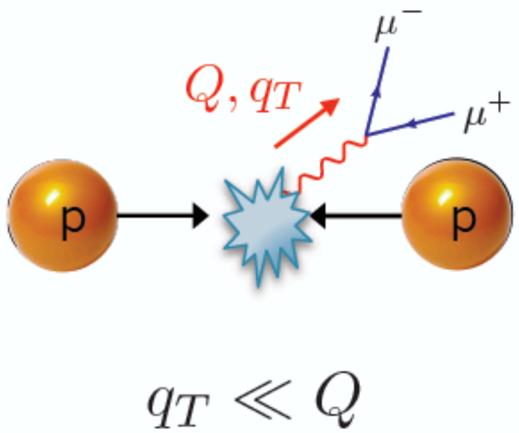


Fragmentation

$D_{h/q}(x, k_T)$

Drell-Yan

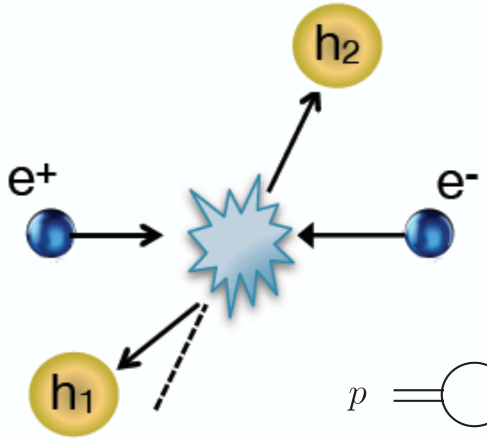
$\sigma \sim f_{q/P}(x, k_T) f_{q/P}(x, k_T)$

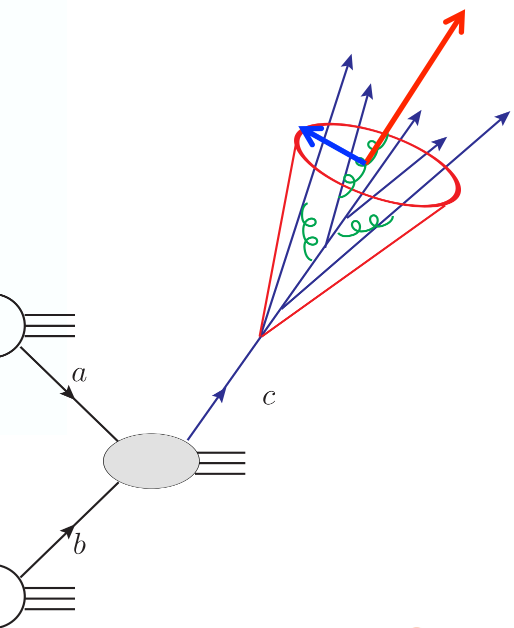


$q_T \ll Q$

Dihadron in e⁺e⁻

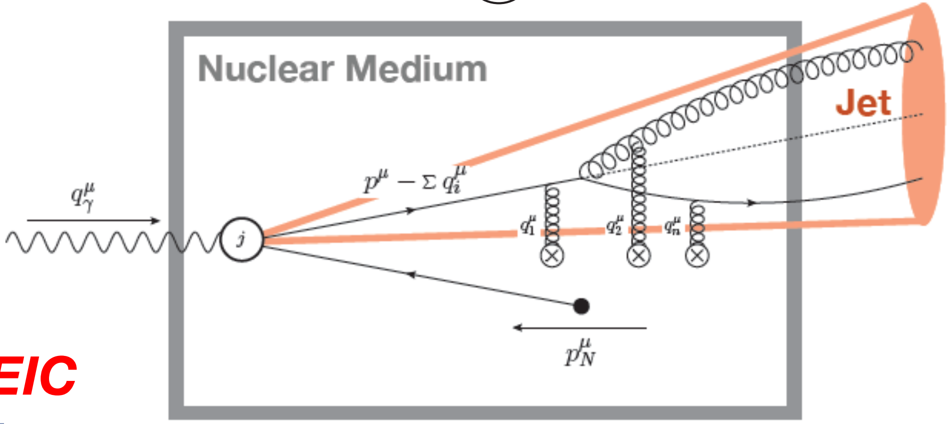
$\sigma \sim D_{h_1/q}(x, k_T) D_{h_2/q}(x, k_T)$





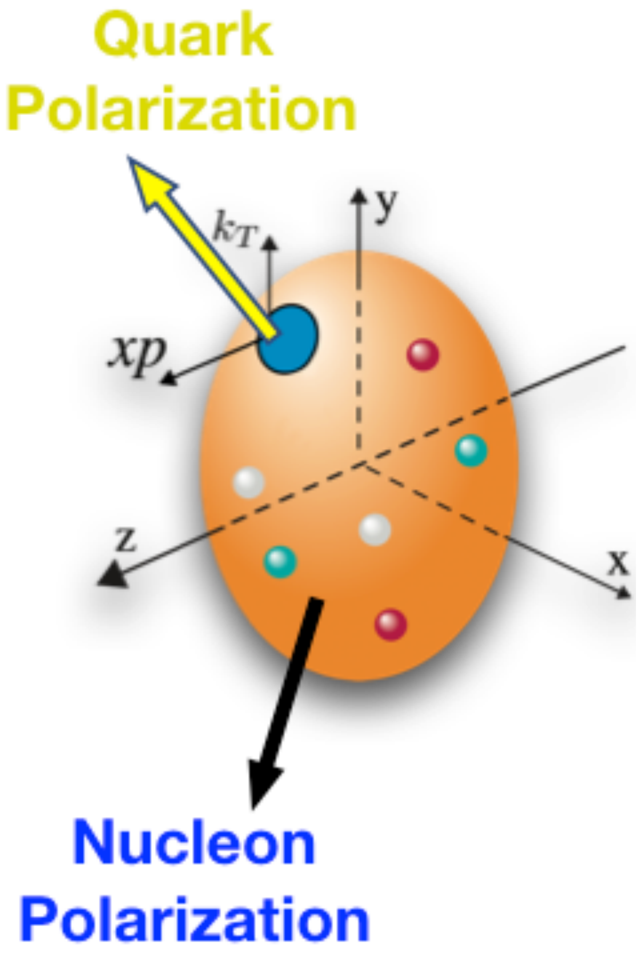
- **Newly identified two-scale observables:**

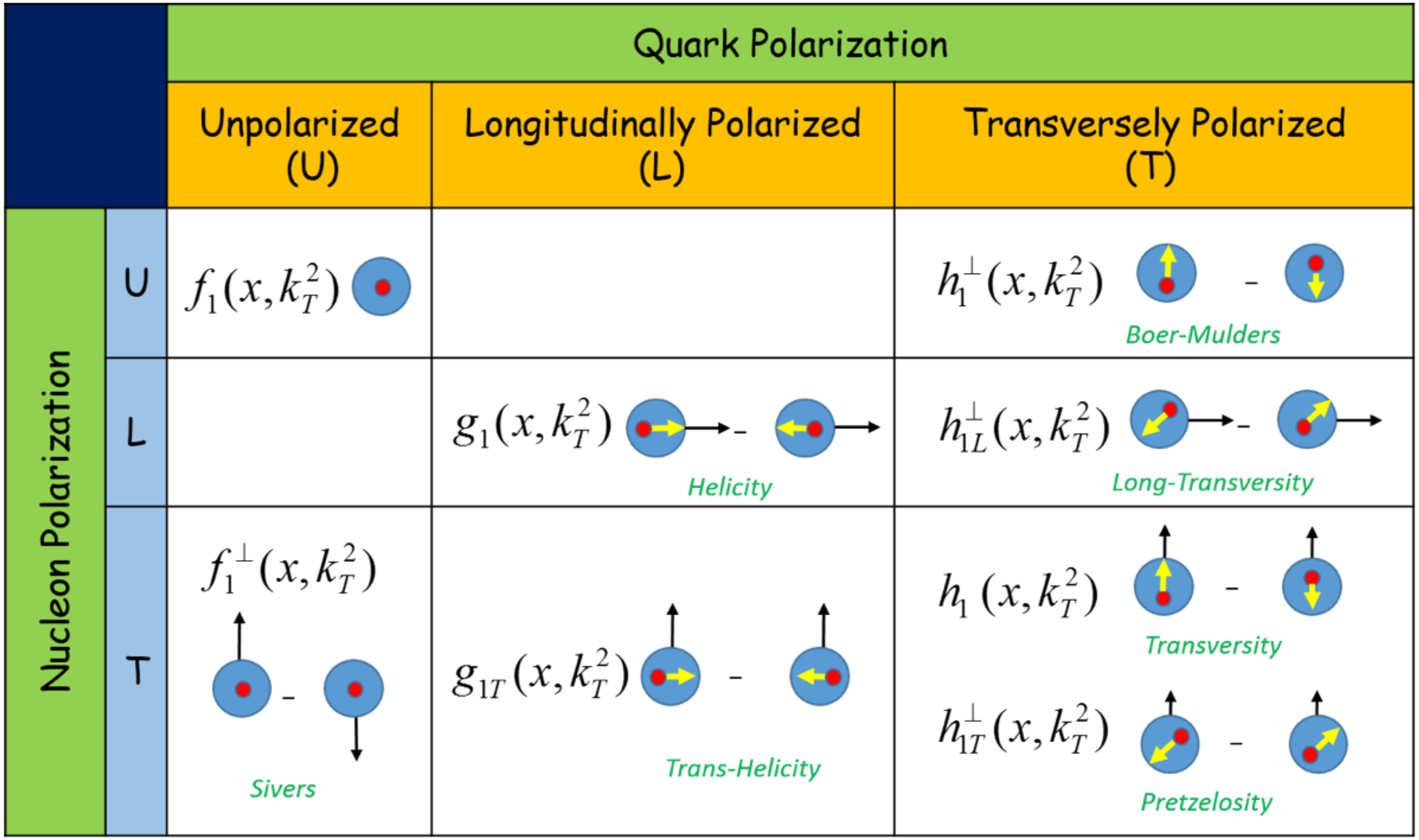
  - TMDs within Measured Jets - Light Hadrons
  - TMDs with Groomed Jets
  - TMDs within Measured Jets - Heavy Hadrons
  - TMDs in Nuclei and at small x
  - TMDs with Quarkonia
  - …



Particularly relevant for EIC

TMDs with Polarization





		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	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*

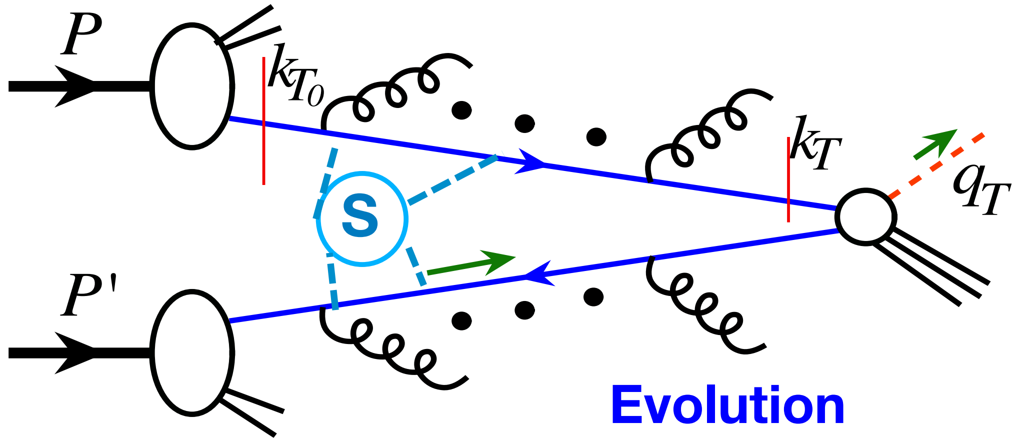
Analogous tables for:

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

Highlights: Theory – TMD Factorization

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

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

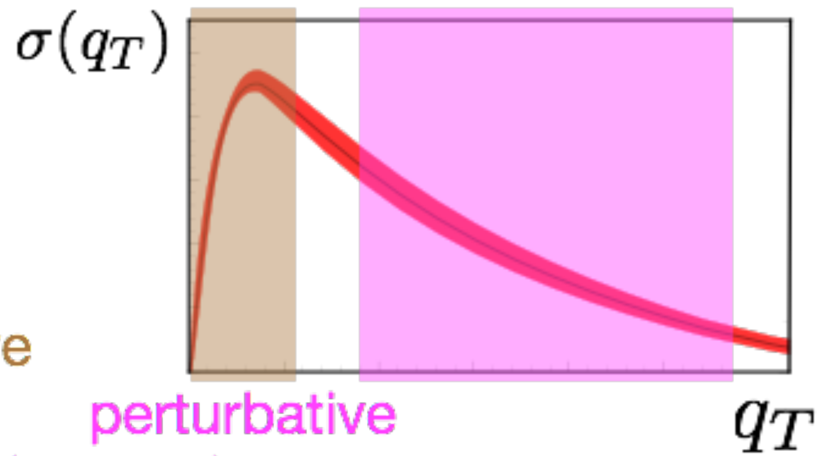


$$\sigma(q_T) = H(Q,\mu) \int d^2\vec{b}_T \, e^{i\vec{q}_T\cdot\vec{b}_T} \, f_q(x_a,\vec{b}_T,\mu,\zeta_a) \, f_q(x_b,\vec{b}_T,\mu,\zeta_b) + \mathcal{O}\left(\frac{q_T^2}{Q^2}\right)$$

$\updownarrow$ **FT**

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

Hard virtual corrections



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

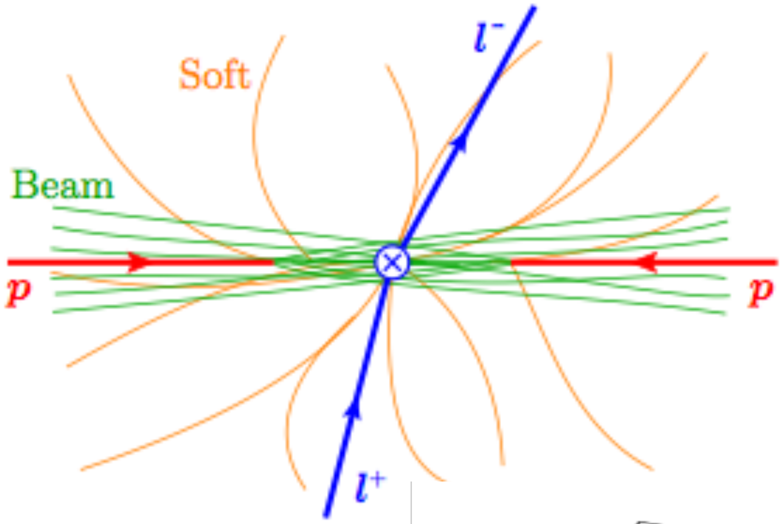
Highlights: Theory – TMD Definitions

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

- **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

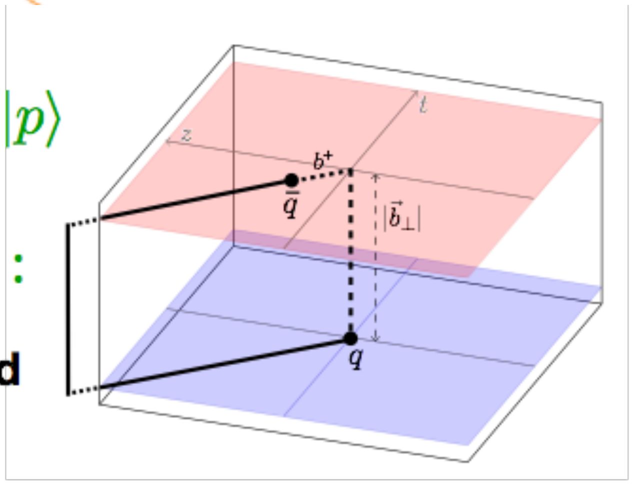
τ : regulates rapidity divergences $\int_0^\infty \frac{dk^+}{k^+}$

- **Wilson lines:**

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

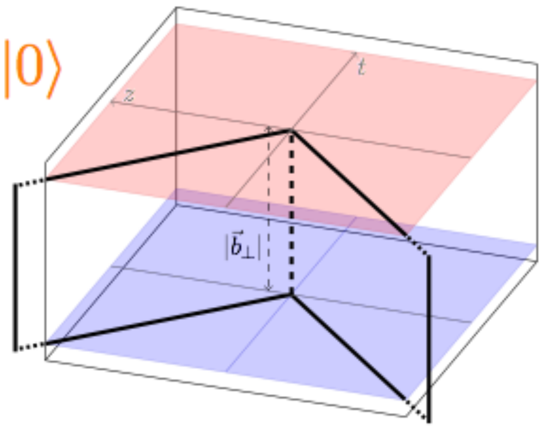
O_B :

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

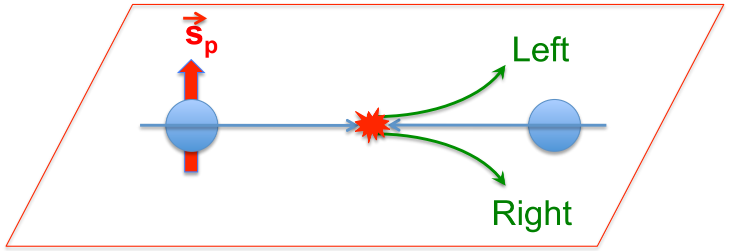
- **Schemes – uniqueness?**

TMD Collaboration has compared schemes to extract universal information

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

Highlights: Phenomenology – Extraction of TMDs

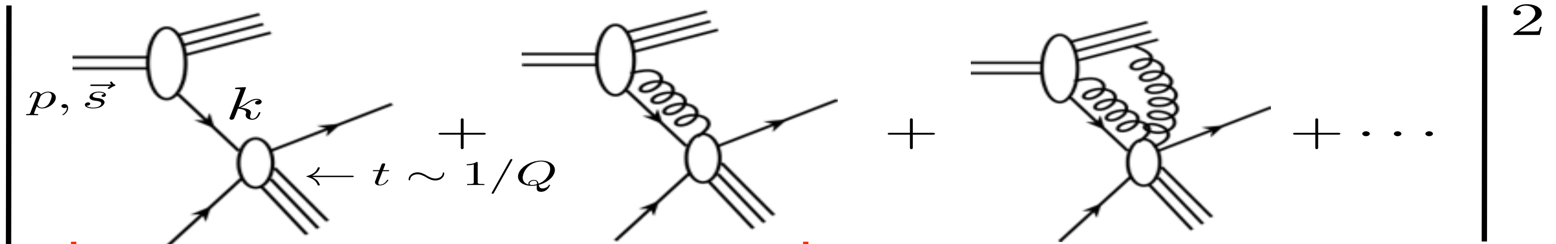
- **Single Transverse Spin asymmetry:**



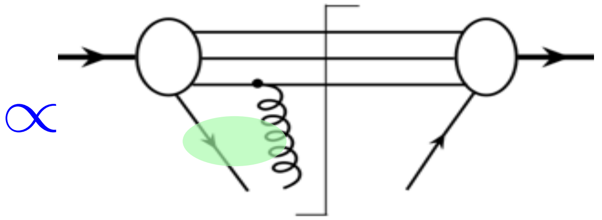
$$A_N \equiv \frac{\Delta\sigma(\ell,\vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell,\vec{s})-\sigma(\ell,-\vec{s})}{\sigma(\ell,\vec{s})+\sigma(\ell,-\vec{s})}$$

- **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,**

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

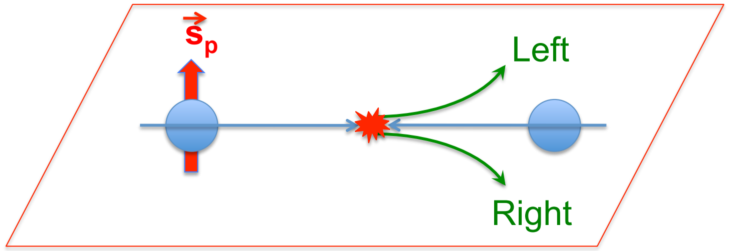


$\sigma(s)-\sigma(-s)$ ➡ **Quantum interference** ➡ $T^{(3)}(x,x) \propto$



Highlights: Phenomenology – Extraction of TMDs

- **Single Transverse Spin asymmetry:**



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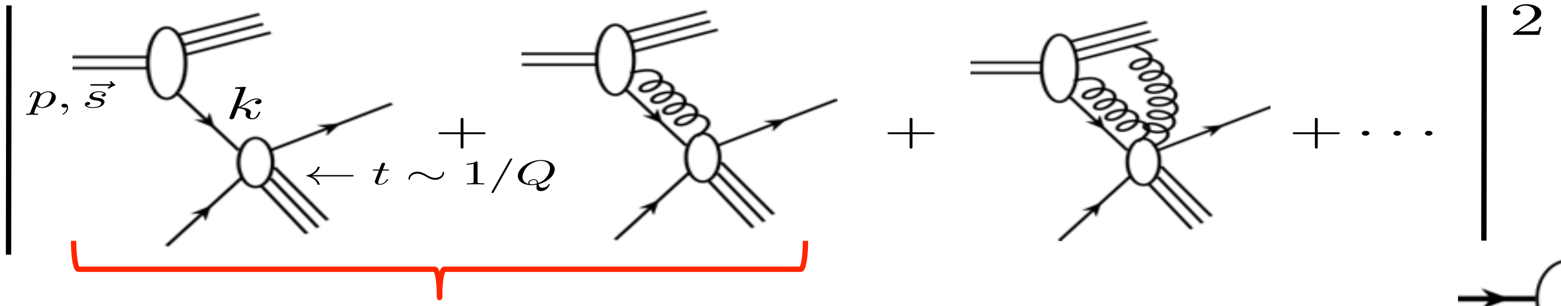

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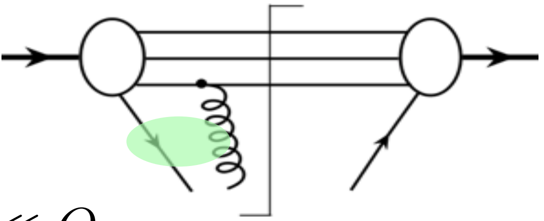
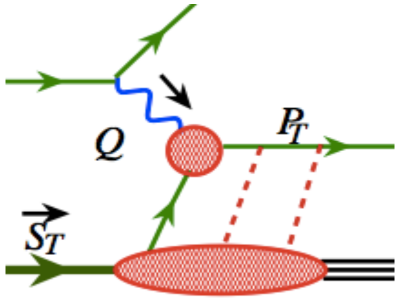
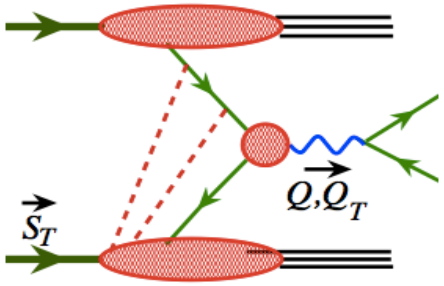


- **Two-scale observables: SIDIS, W-production at RHIC, …** $\Lambda_{\rm QCD} \sim q_T \ll Q$
  - ✧ **QCD TMD factorization is the relevant theory tool,** $k_T \sim q_T \ll Q$
  - ✧ **Asymmetry is generated by parton's asymmetric transverse motion, …**



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:

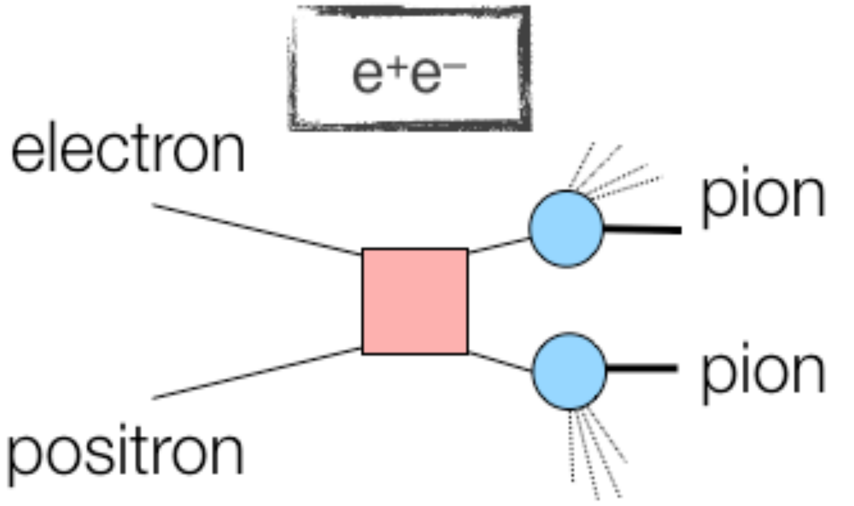
LQCD, Data

Highlights: Phenomenology – Extraction of TMDs

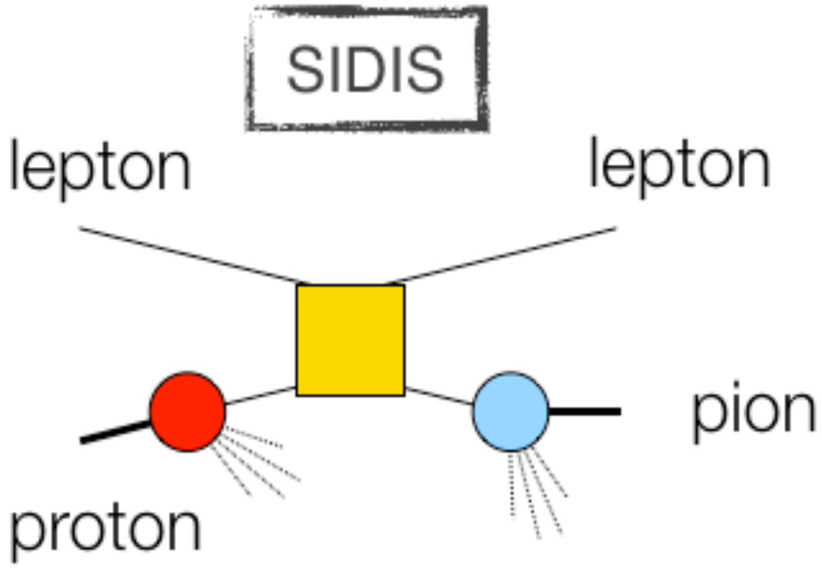
- **TMD universal global fit 2020:**

arXiv:2002.08384

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

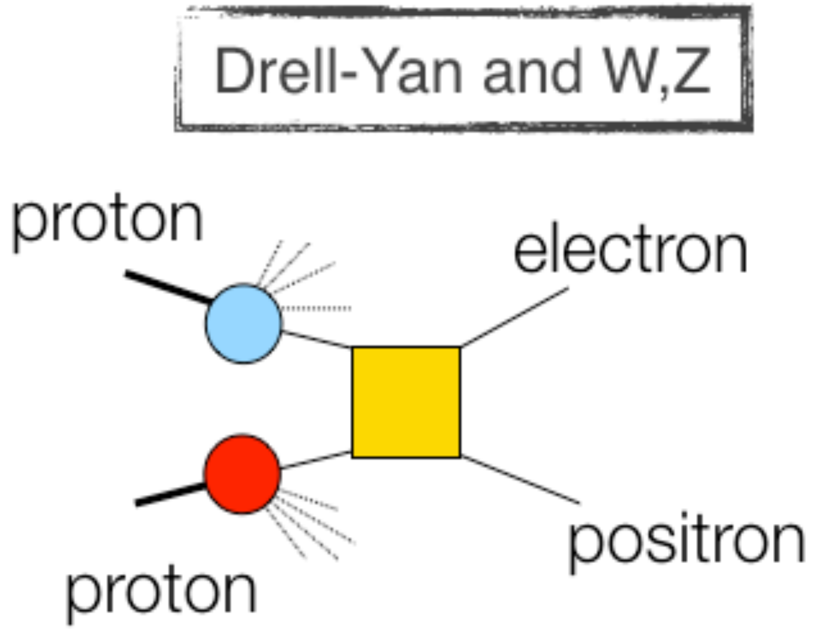


Collins asymmetries
BELLE, BaBar, BESIII data

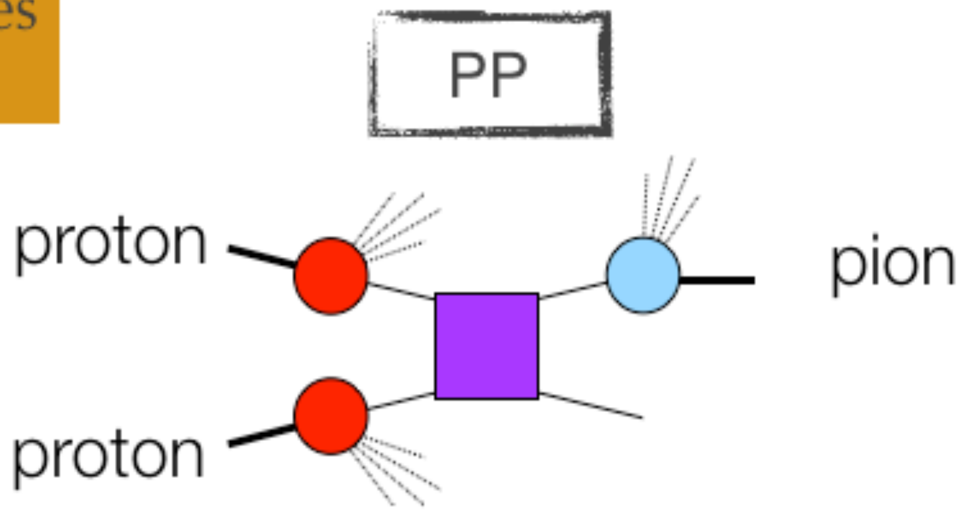


Sivers, Collins asymmetries
COMPASS, HERMES, JLab data

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



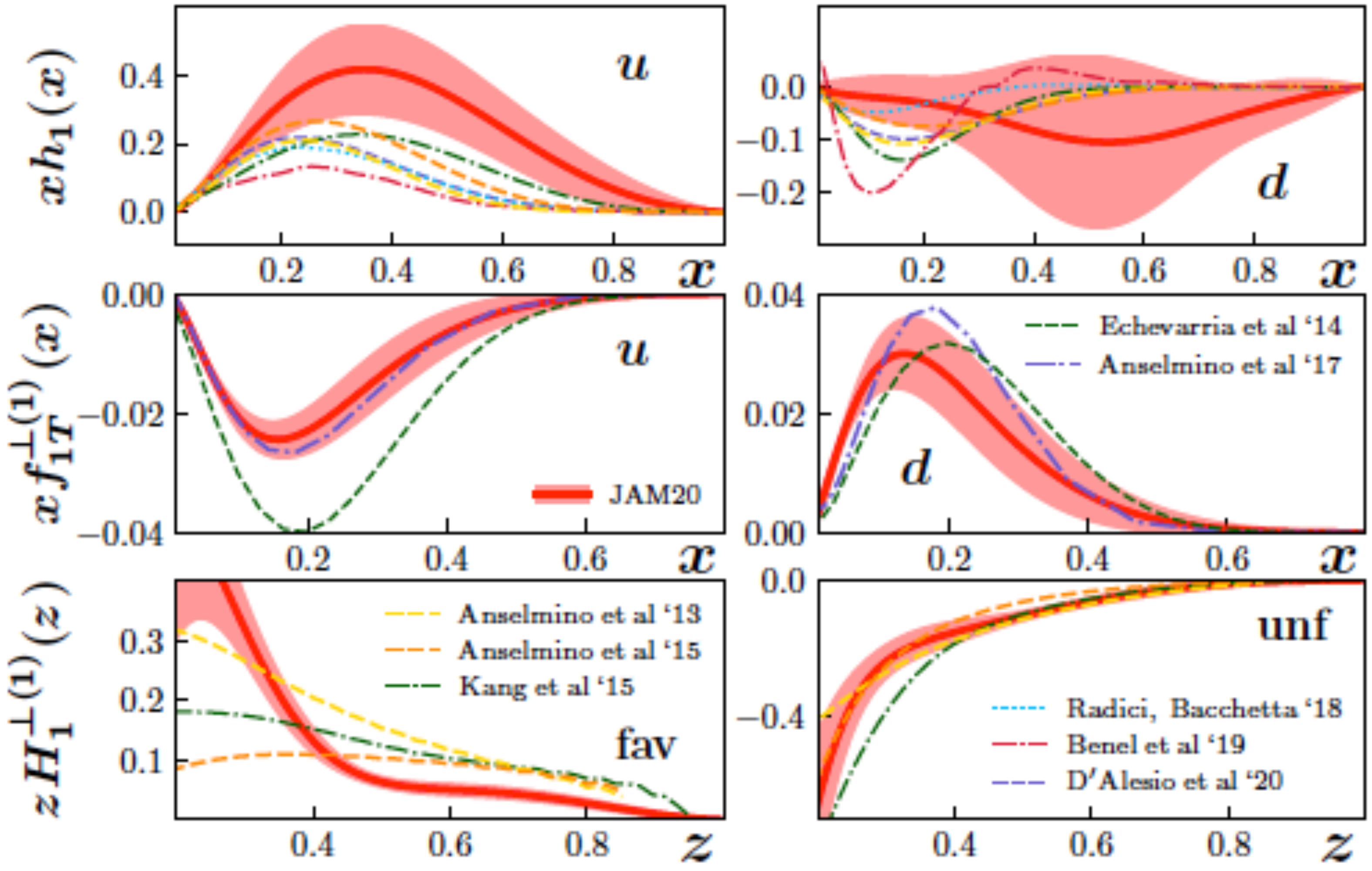
A_N asymmetry
STAR, PHENIX, BRAHMS data

Highlights: Phenomenology – Extraction of TMDs

- **Data and the fits:**

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

- **Extracted non-perturbative functions:**



Transversity distribution:

$$h_1(x)\propto \text{F.T.}\ \langle P,s_T|\overline{\psi}(0)\gamma^+\gamma_\perp\psi(z)|P,s_T\rangle$$

Sivers' function

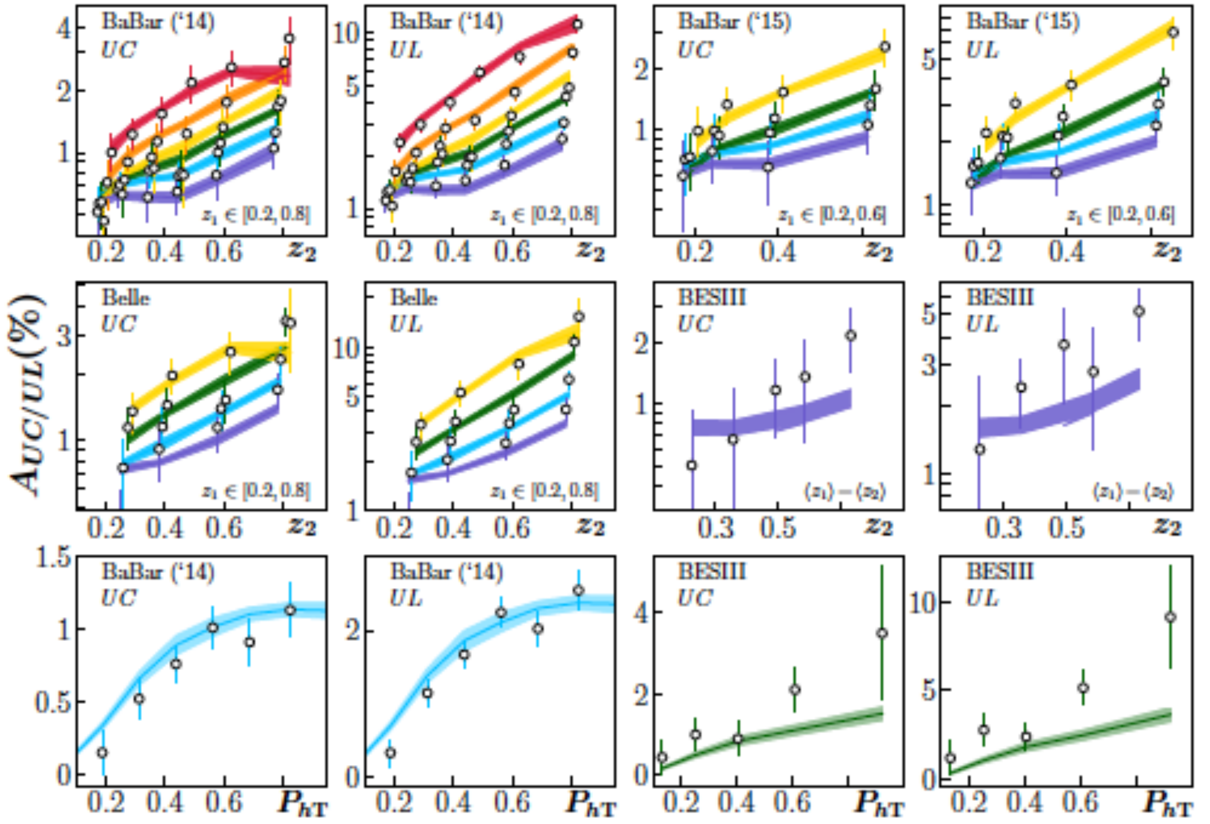
$$f^{\perp}_{1T}(x)$$

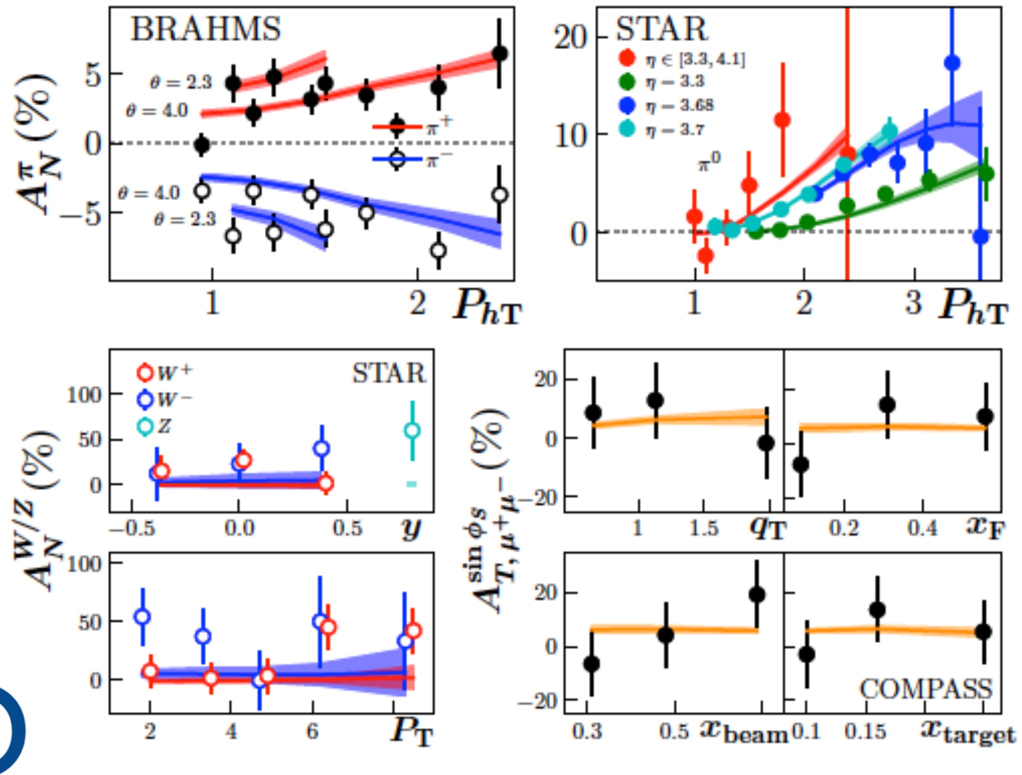
Collin's fragmentation function:

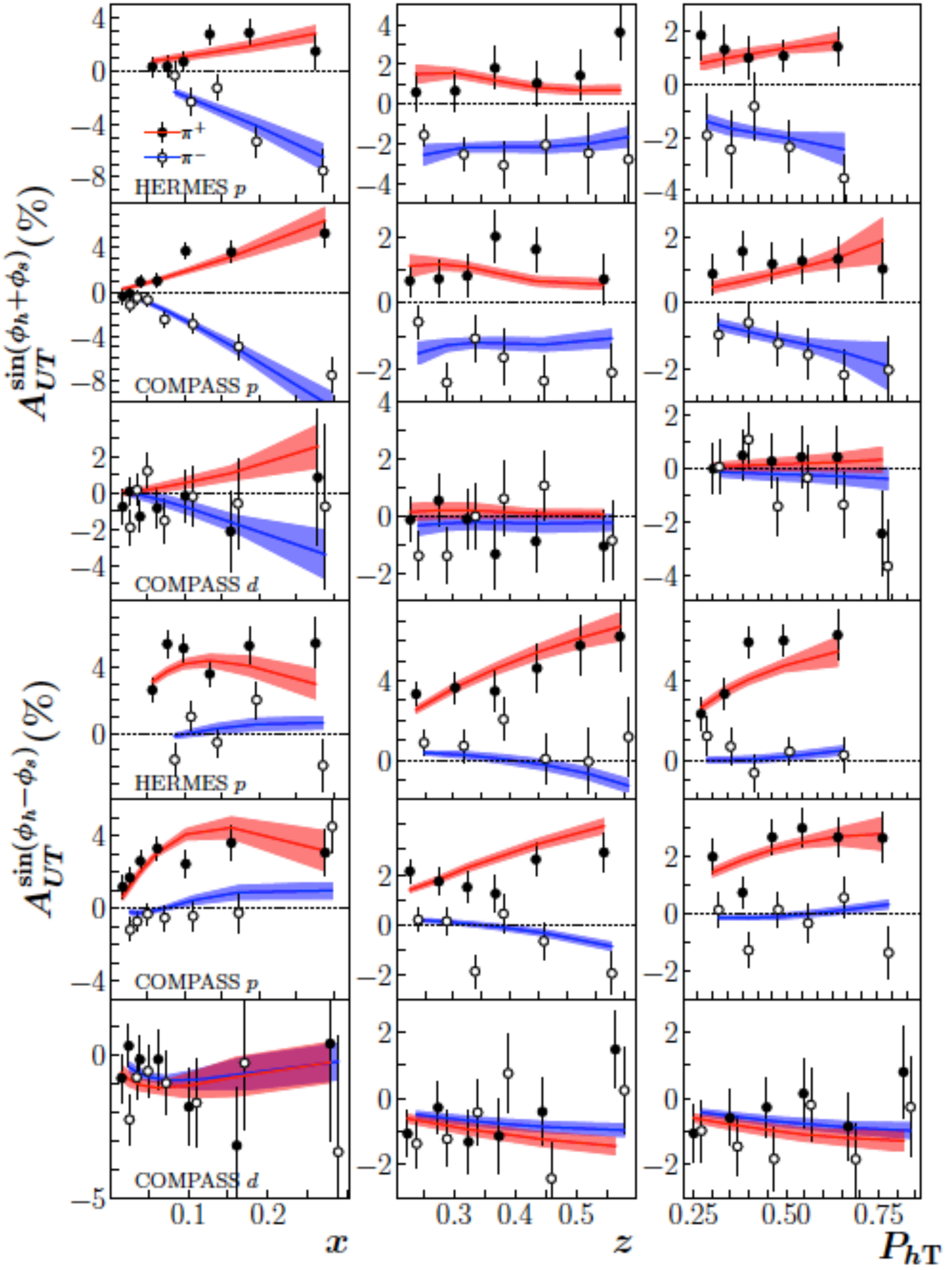
$$H_1^{\perp(1)}(z)$$

Highlights: Phenomenology – Extraction of TMDs

- **Quality of the fit:**





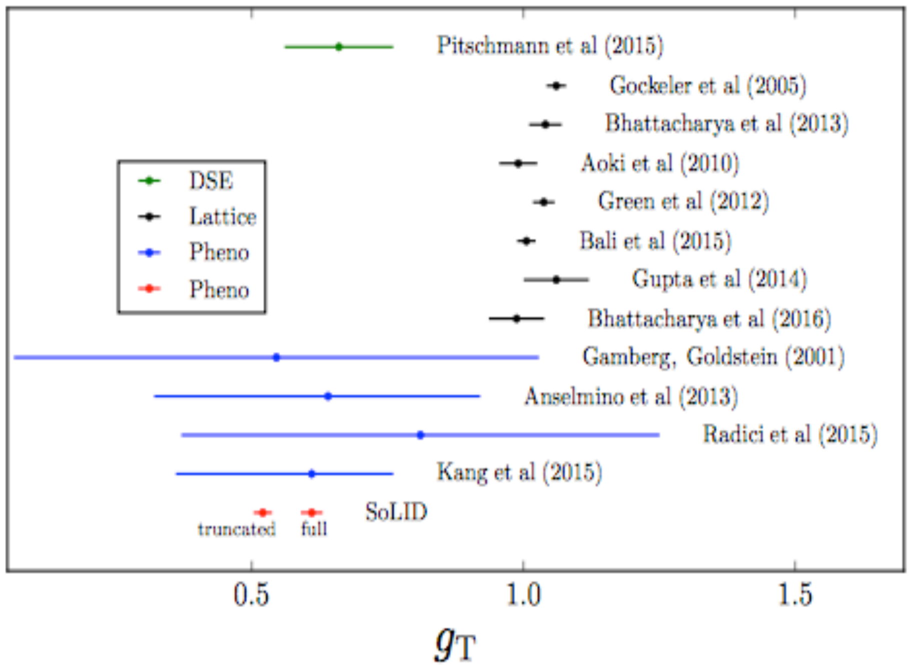


Highlights: Phenomenology – Extraction of TMDs

- **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?



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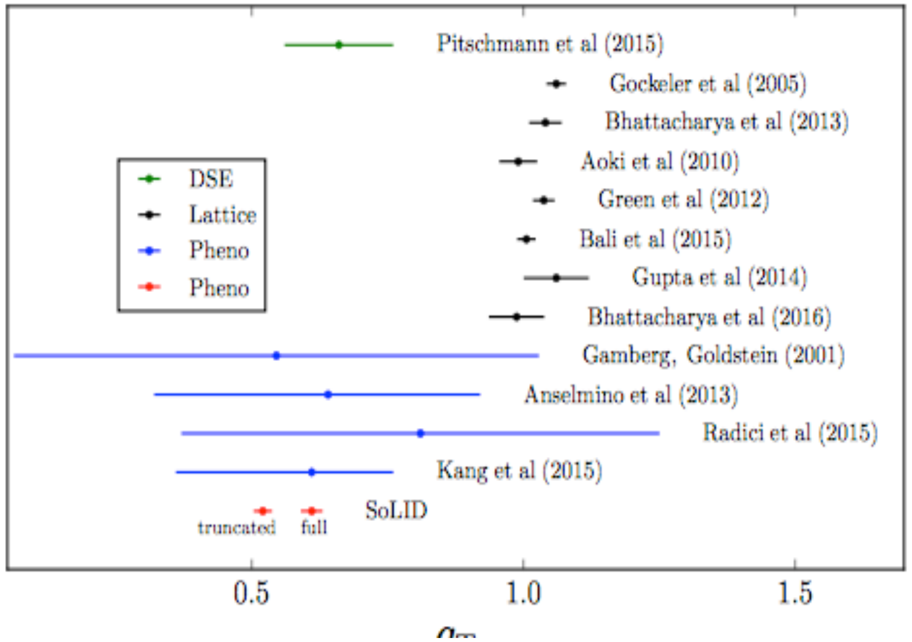
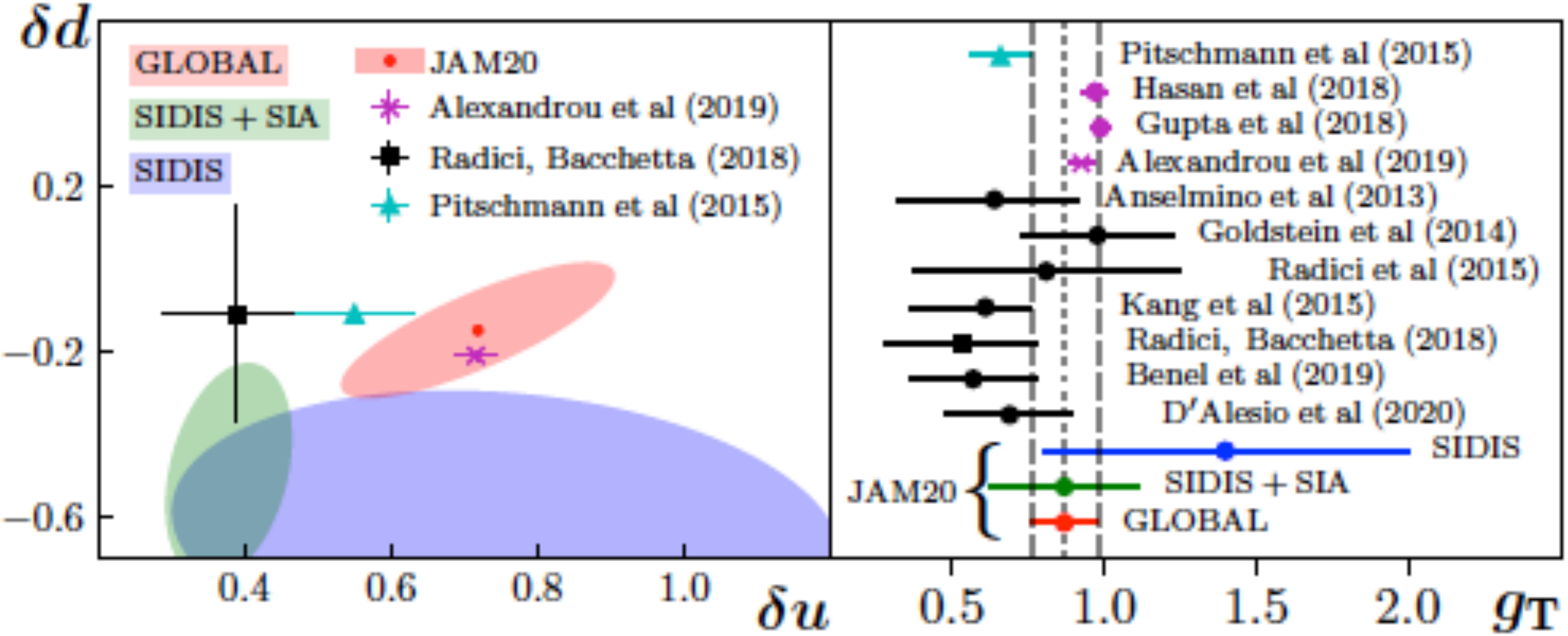


- **Immediate Impact of the global fits:**

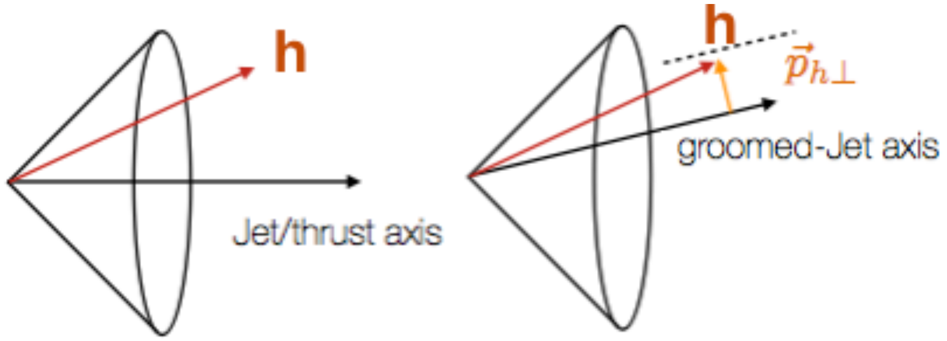


Global fitted results are now consistent with LQCD calculations!

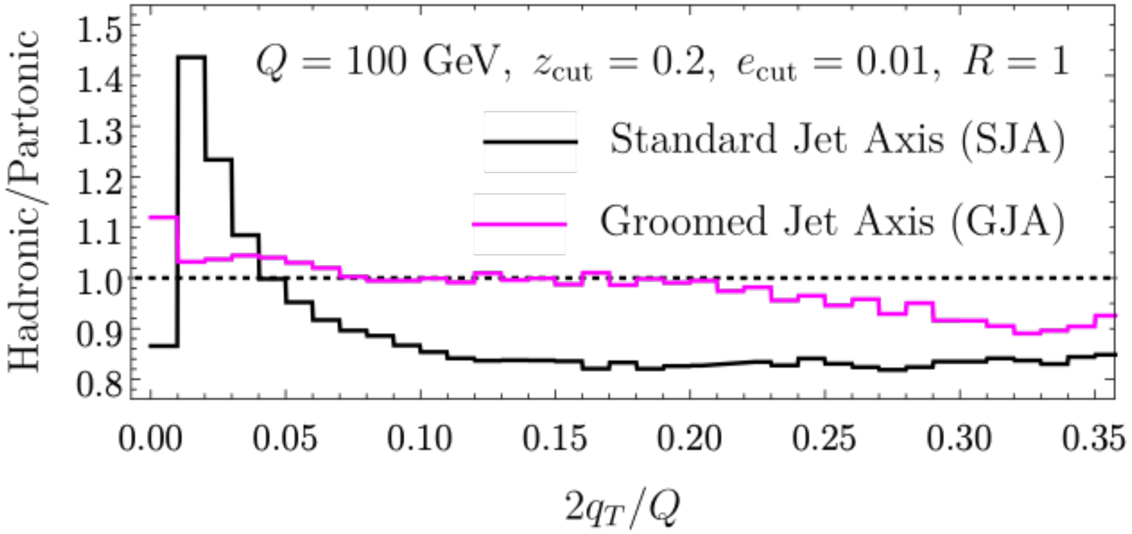
Highlights: Phenomenology – Extraction of TMDs

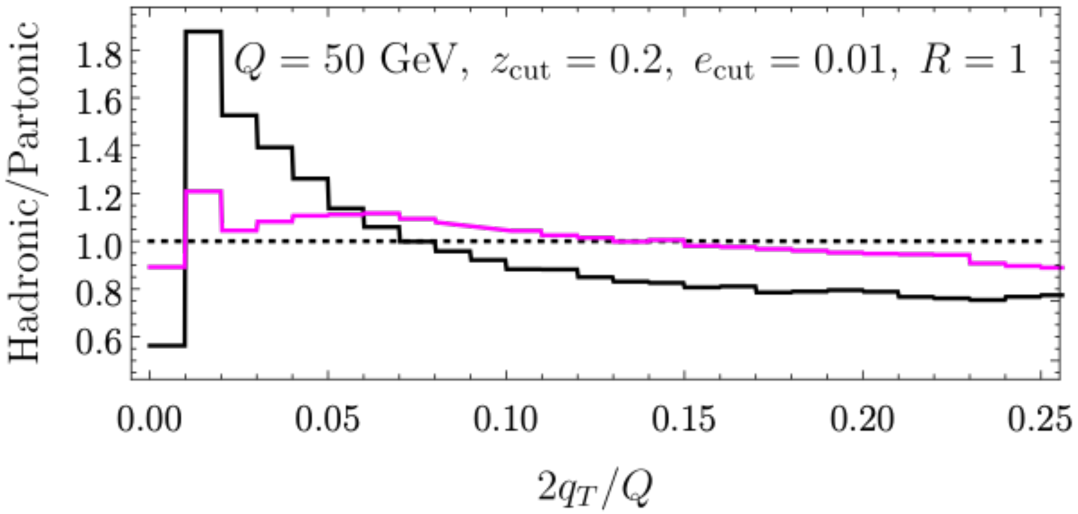
- **Improved TMD phenomenology with groomed jets:**

Groomed jet removes soft radiation



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





Highlights: Phenomenology – Extraction of TMDs

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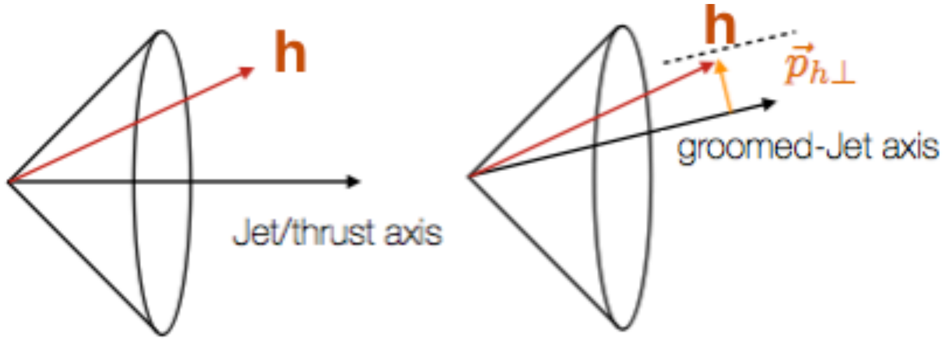

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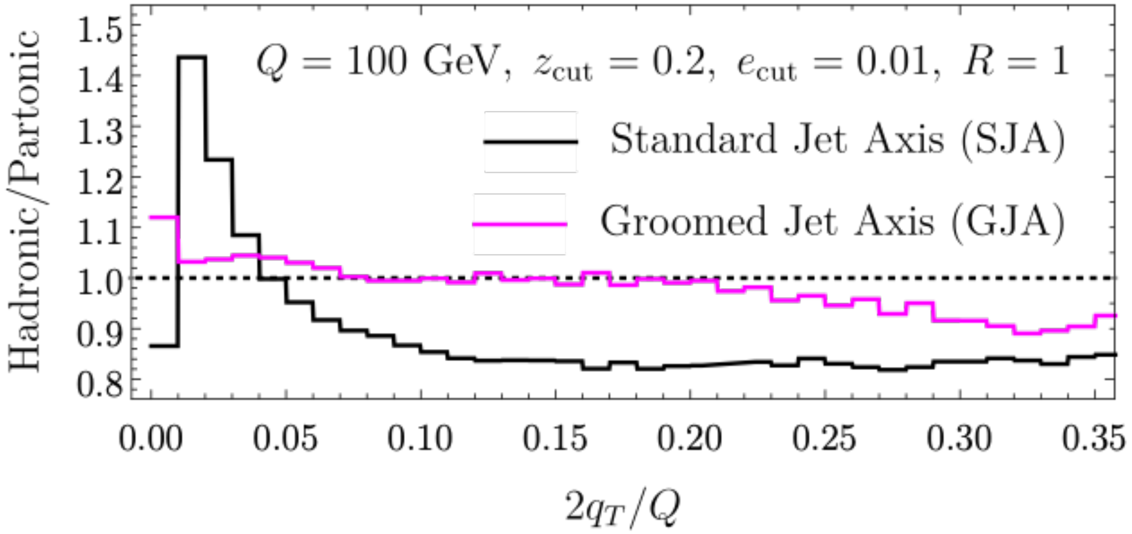
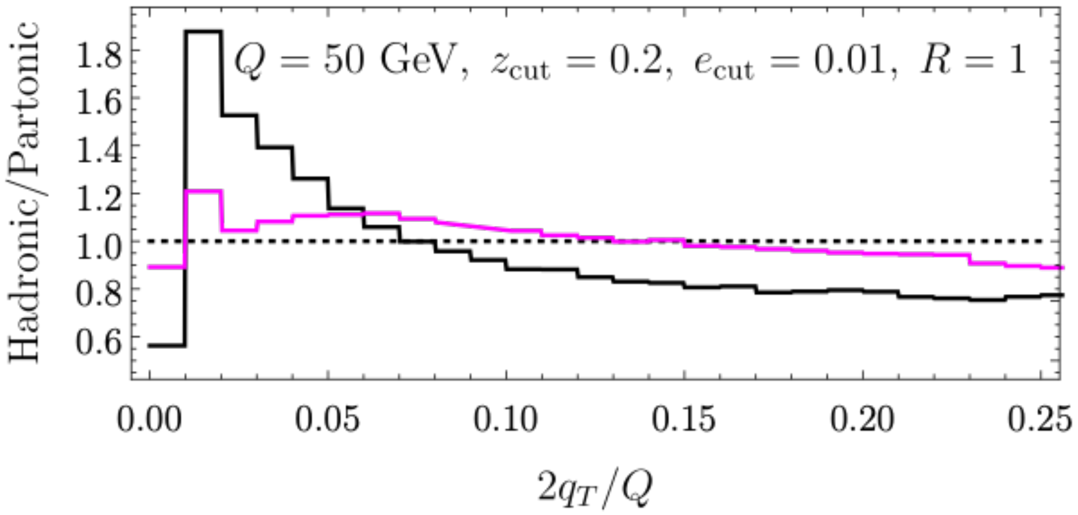
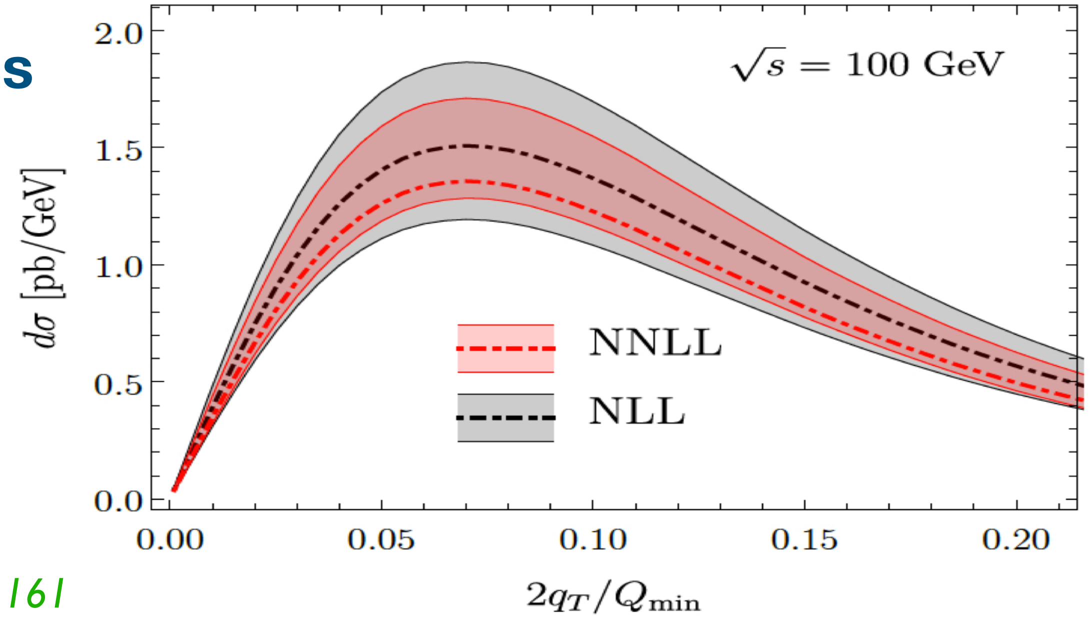




Better controlled calculation of TMDs

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



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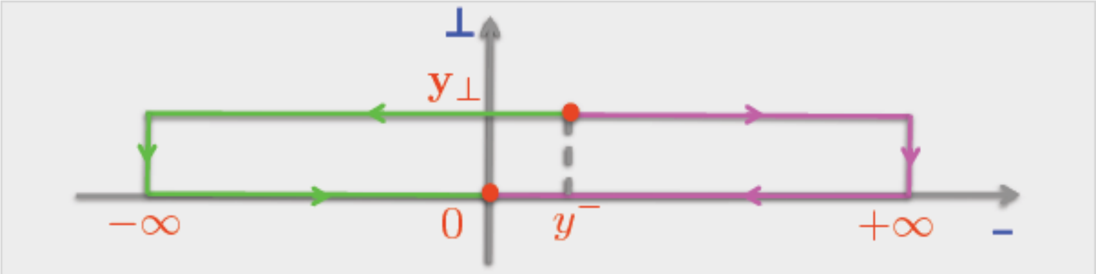
TMD Collaboration

Highlights: LQCD meets Phenomenology

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

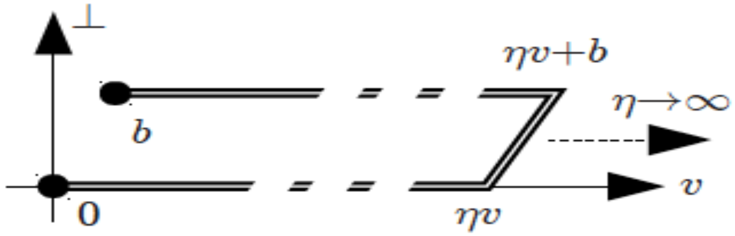


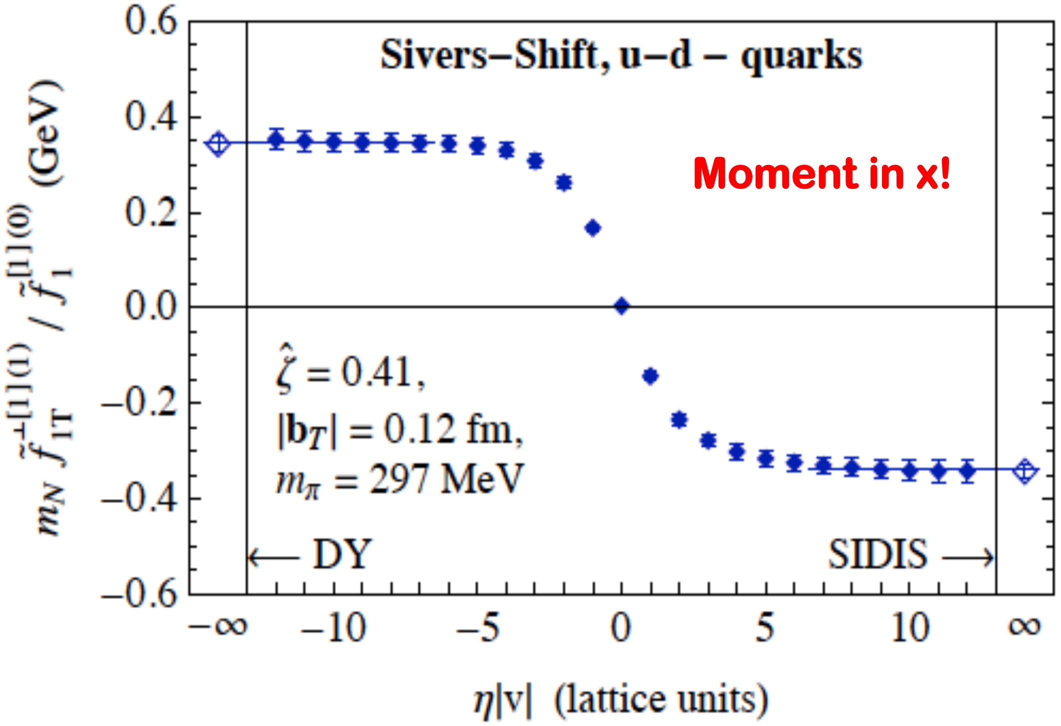
$$f_{1T}^{\perp \text{DIS}}(x, k_\perp) = -f_{1T}^{\perp \text{DY}}(x, k_\perp)$$

Consequence different gauge links – sign of the phase

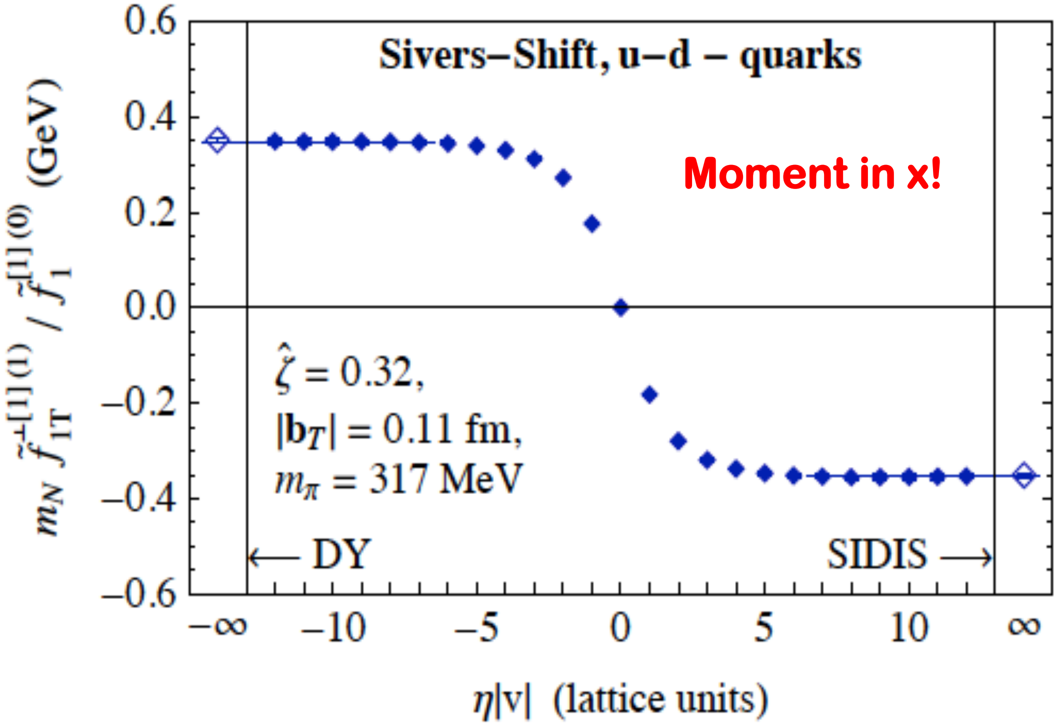
- **Normalized Sivers moment at a given b_T - LQCD:**

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





Moment in x!



Moment in x!

Highlights: LQCD meets Theory

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

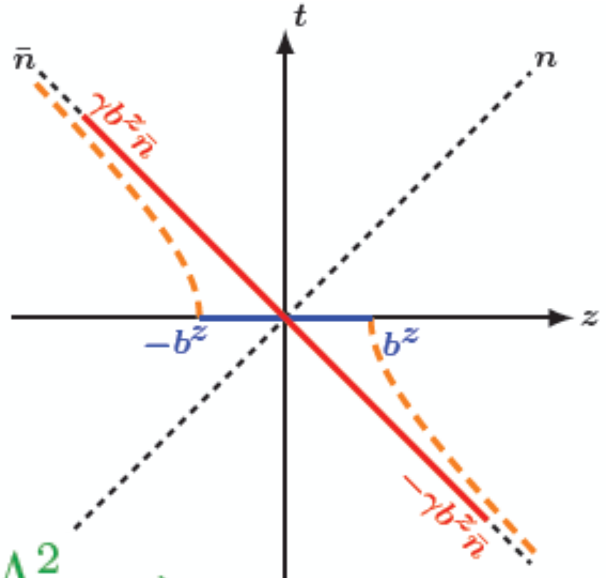
  Cannot be calculated directly in LQCD – Euclidean path integral ! $n_E^2 = 0 \;\Rightarrow\; n_E^\mu = 0$

- **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:**

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

simulation & renormalization on lattice

Perturbative matching coefficient

PDF

Power corrections

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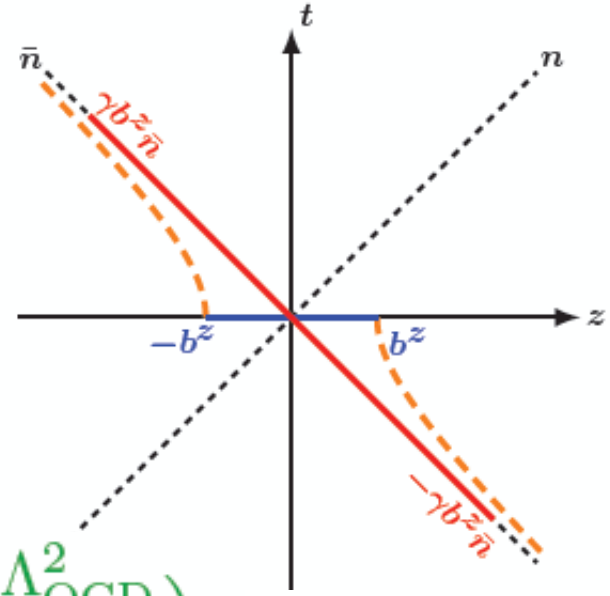

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simulation & renormalization on lattice

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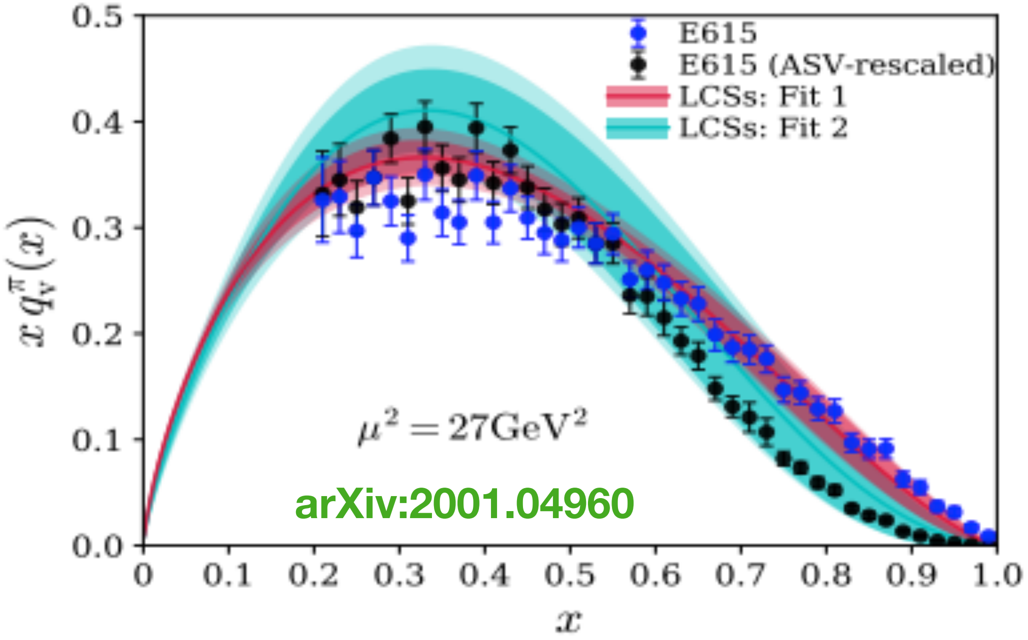
Power corrections

- **"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, …



arXiv:2001.04960

Highlights: LQCD meets Theory

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

- **Quasi-TMDs:**

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

  - $\tilde{Z}^q_{\rm uv}$ 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

Highlights: LQCD meets Theory

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Quasi-TMD

Collins-Soper Kernel

TMD

$$\begin{aligned}\gamma^q_\zeta(\mu,b_T) &= \frac{1}{\ln(P^z_1/P^z_2)}\ln\frac{C^{\rm TMD}(\mu,xP^z_2)\;\tilde f_q(x,\vec b_T,\mu,P^z_1)}{C^{\rm TMD}(\mu,xP^z_1)\;\tilde f_q(x,\vec b_T,\mu,P^z_2)}\\ &= \frac{1}{\ln(P^z_1/P^z_2)}\ln\frac{C^{\rm TMD}(\mu,xP^z_2)\int db^z\, e^{ib^z xP^z_1}\,\tilde Z'_q\,\tilde Z^q_{\rm uv}\,\tilde B_q(b^z,\vec b_T,a,L,P^z_1)}{C^{\rm TMD}(\mu,xP^z_1)\int db^z\, e^{ib^z xP^z_2}\,\tilde Z'_q\,\tilde Z^q_{\rm uv}\,\tilde B_q(b^z,\vec b_T,a,L,P^z_2)}\end{aligned}$$

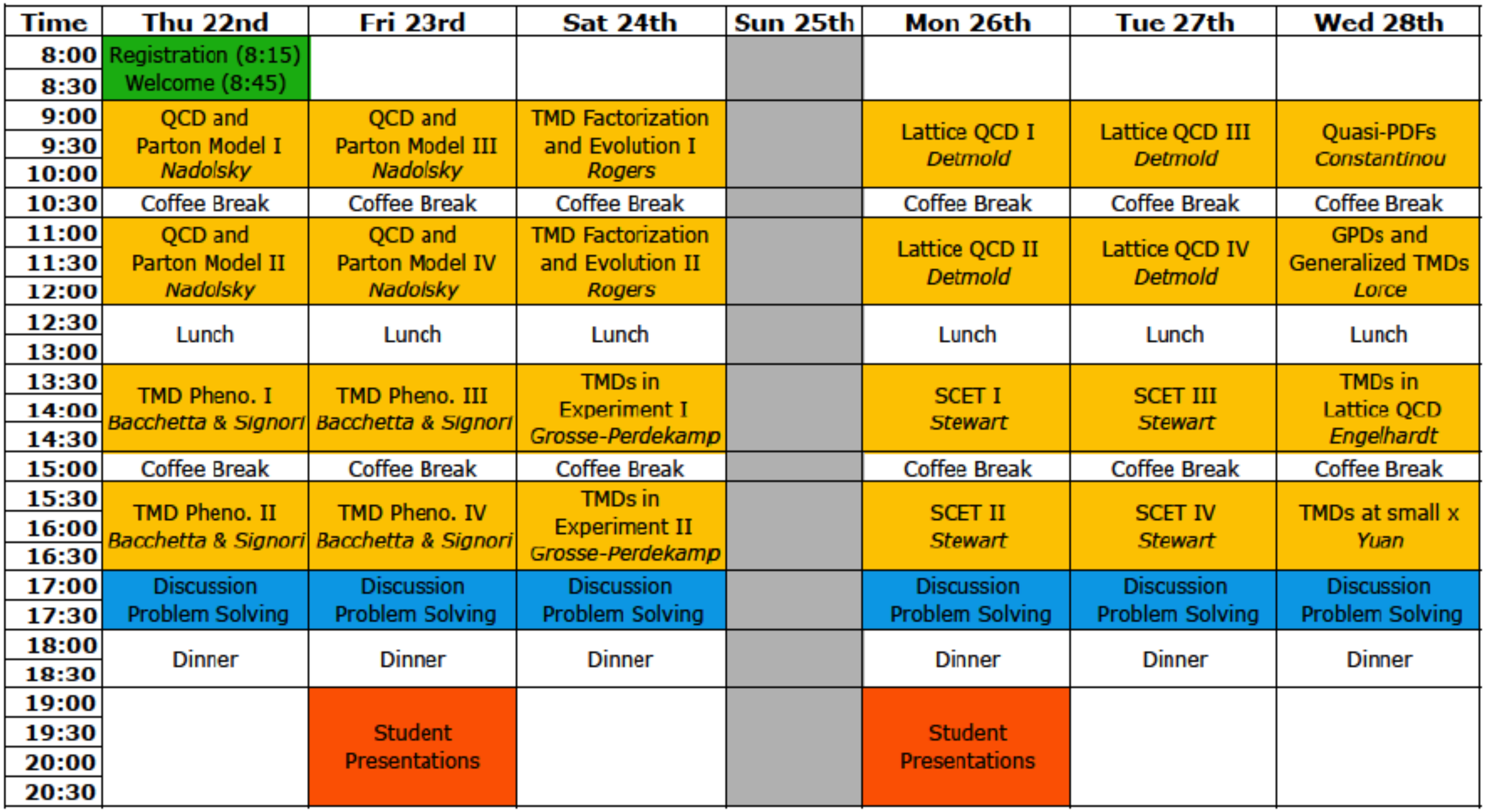
quasi-Beam fns.

- **needs** $\tilde B_q$, $\tilde Z^q_{\rm uv}$, $\tilde Z'_q$, $C^{\rm TMD}$ → ***Universal QCD function from LQCD!***
- **LHS independent of** $P^z_1, P^z_2, x,$ **<u>hadron state</u>, 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 8:30	Registration (8:15) Welcome (8:45)						
9:00 9:30 10:00	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*
10:30	Coffee Break	Coffee Break	Coffee Break		Coffee Break	Coffee Break	Coffee Break
11:00 11:30 12:00	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*
12:30 13:00	Lunch	Lunch	Lunch		Lunch	Lunch	Lunch
13:30 14:00 14:30	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*
15:00	Coffee Break	Coffee Break	Coffee Break		Coffee Break	Coffee Break	Coffee Break
15:30 16:00 16:30	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*
17:00 17:30	Discussion Problem Solving	Discussion Problem Solving	Discussion Problem Solving		Discussion Problem Solving	Discussion Problem Solving	Discussion Problem Solving
18:00 18:30	Dinner	Dinner	Dinner		Dinner	Dinner	Dinner
19:00 19:30 20:00 20:30		Student Presentations			Student Presentations		

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

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

Service to the Community

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

Service to the Community

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

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.

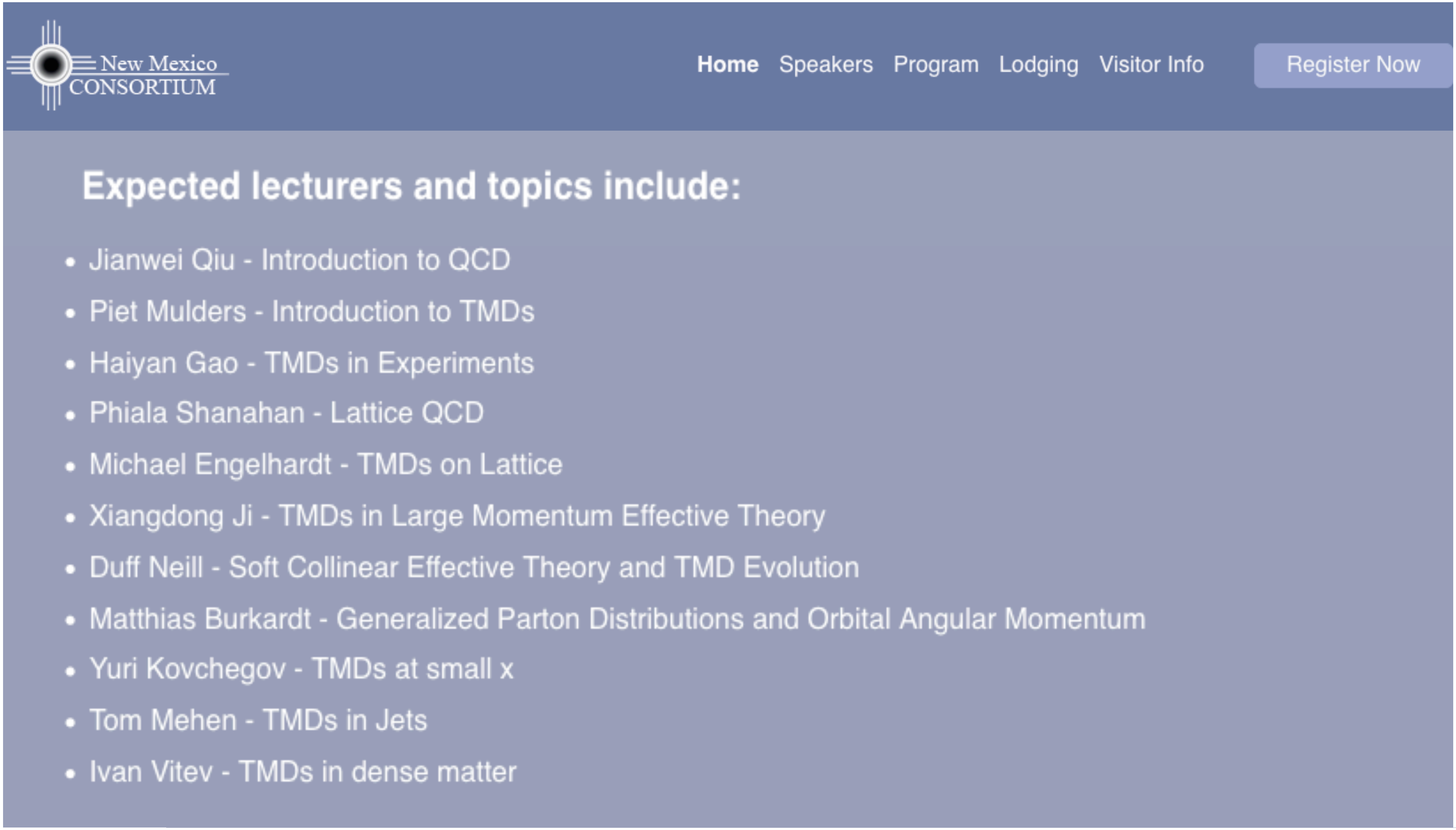
We invite PhD students and early postdocs doing their research in QCD, collider physics, and hadron structure, broadly related to the physics of transverse momentum dependent distributions to tackle such open problems as 3-D hadron structure, proton spin, and properties of strongly interacting matter.

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**



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

TMD Collaboration

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

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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!

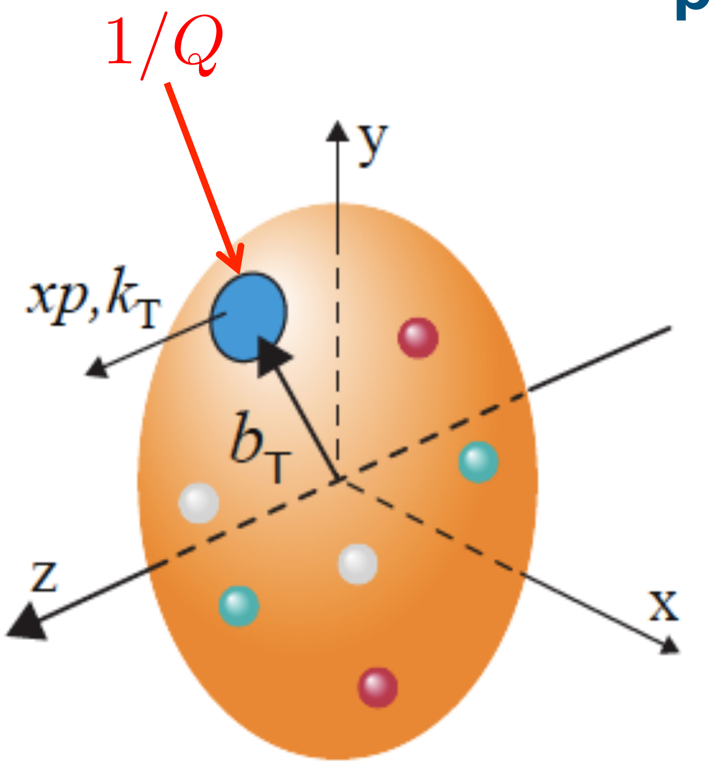
Without the network of Topical Collaboration, and DOE support, this would not happen!

Thank you!

Overarching TMD Questions

What are the 2D confined transverse motion of quarks and gluons inside a colliding proton?

How to identify universal proton structure properties from measured k_T-dependence?



How does the confined motion change along with probing x, Q^2?

Can we extract QCD color force responsible for the confined motion?

How is the motion correlated with macroscopic proton properties, as well as microscopic parton properties, such as the spin?