Nucleon Tomography of Transverse Momentum Distributions

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Semi-Inclusive Deep Inelastic Scattering

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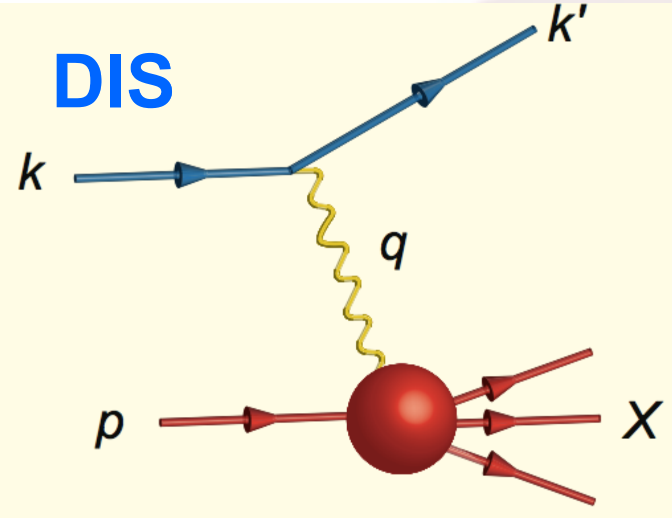
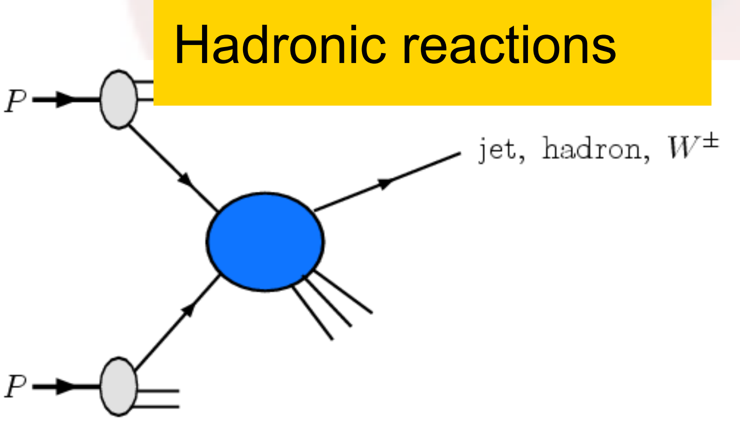
Outline

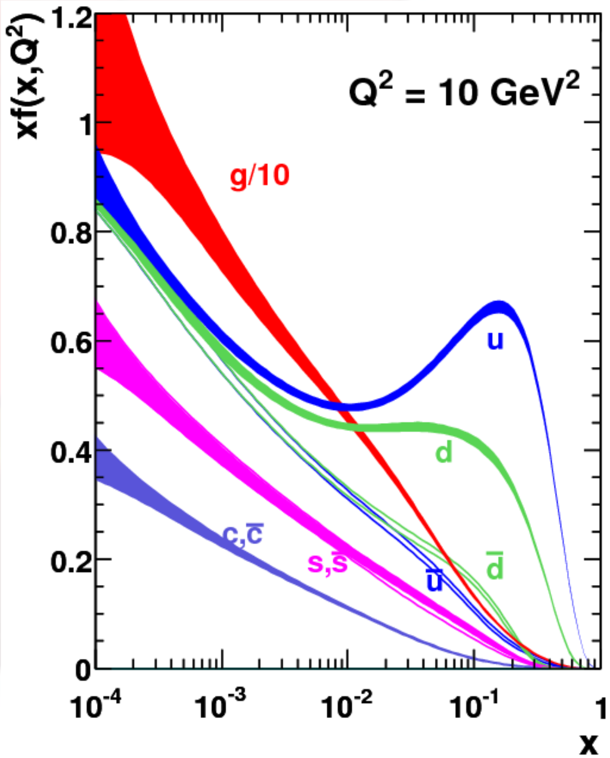
- Basics
  - Definitions, properties, …
- QCD dynamics involved in these processes
  - Universality, factorization, evolutions,…
- Applications
  - Nucleon tensor charge
- TMDs at small-x

Feynman Parton: one-dimension





- Inclusive cross sections probe the momentum (longitudinal) distributions of partons inside nucleon

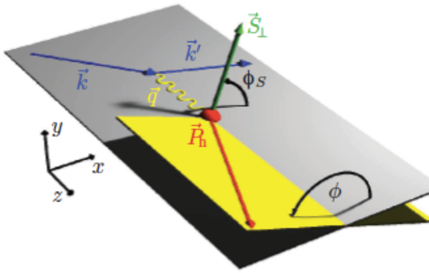


Extension to transverse direction…

- Semi-inclusive measurements (in DIS or Drell-Yan processes)
  - Transverse momentum dependent (TMD) parton distributions
- Deeply Virtual Compton Scattering and Exclusive processes
  - Generalized parton distributions (GPD)

Xiangdong's talk, this afternoon

TMD Parton Distributions



- The definition contains explicitly the gauge links

Collins-Soper 1981,
Collins 2002,
Belitsky-Ji-Yuan 2002

$$f(x,k_\perp) = \frac{1}{2}\int\frac{d\xi^- d^2\xi_\perp}{(2\pi)^3}e^{-i(\xi^- k^+ - \vec{\xi}_\perp\cdot\vec{k}_\perp)}$$
$$\times\langle PS|\overline{\psi}(\xi^-,\xi_\perp)L^\dagger_{\xi_\perp}(\xi^-)\gamma^+ L_0(0)\psi(0)|PS\rangle$$

- QCD factorization has been proved for the hard processes in terms of TMDs
  - Collins-Soper 1981, Ji-Ma-Yuan 2004, Collins 2011

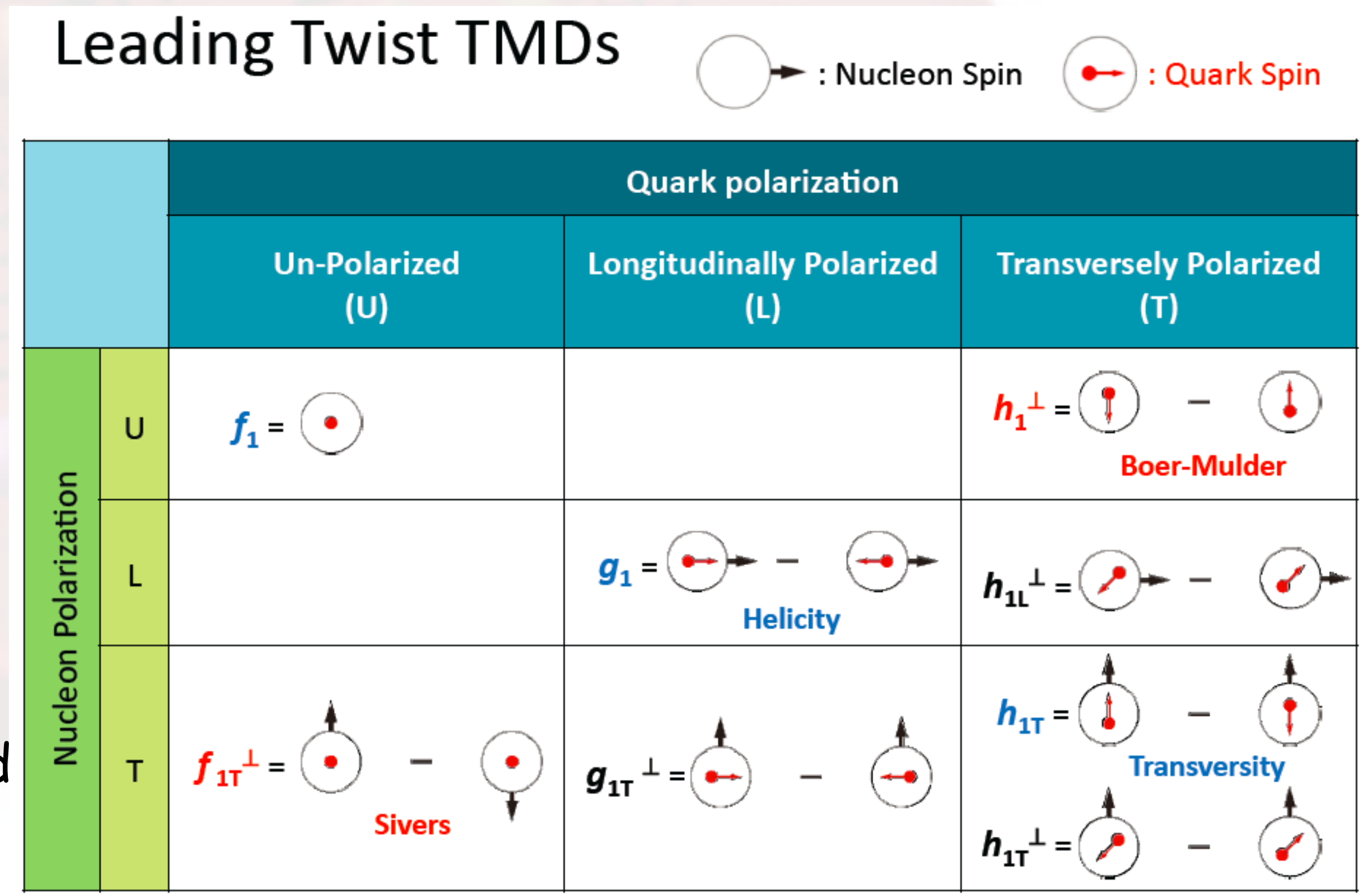
Transverse momentum dependent parton distribution

Straightforward extension

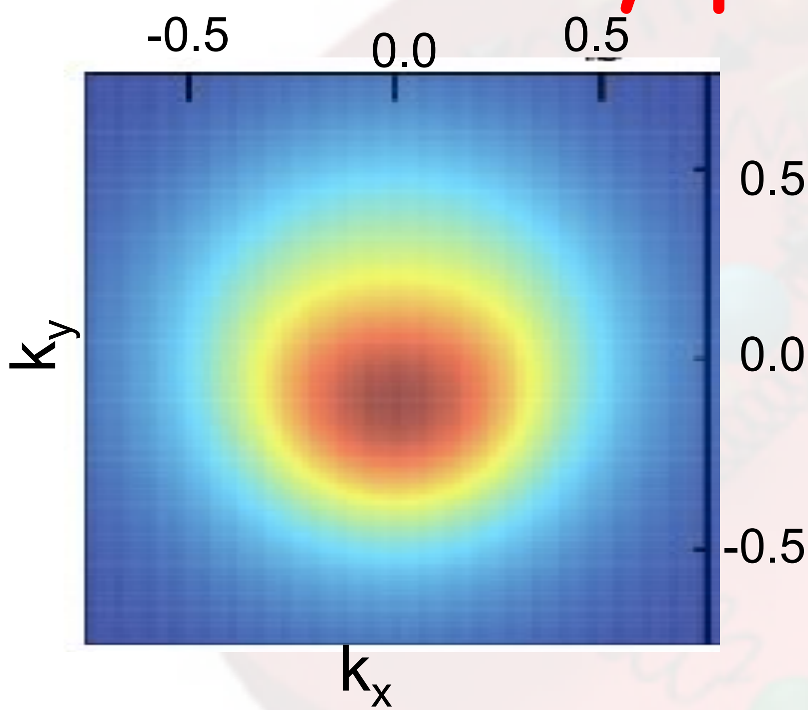
- Spin average, helicity, and transversity distributions

P_T-spin correlations

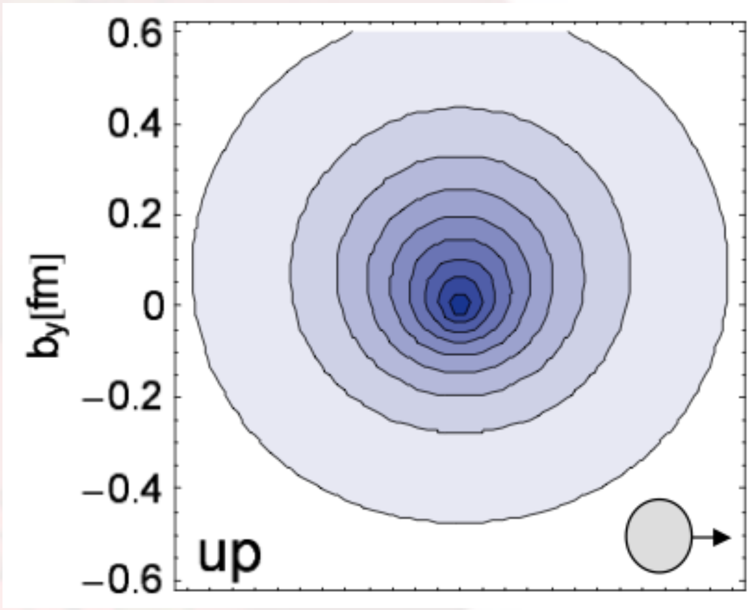
- Nontrivial distributions, $S_T X P_T$
- In quark model, depends on S- and P-wave interference



Deformation when nucleon is transversely polarized



Quark Sivers function fit to the SIDIS Data, Anselmino, et al. 20009

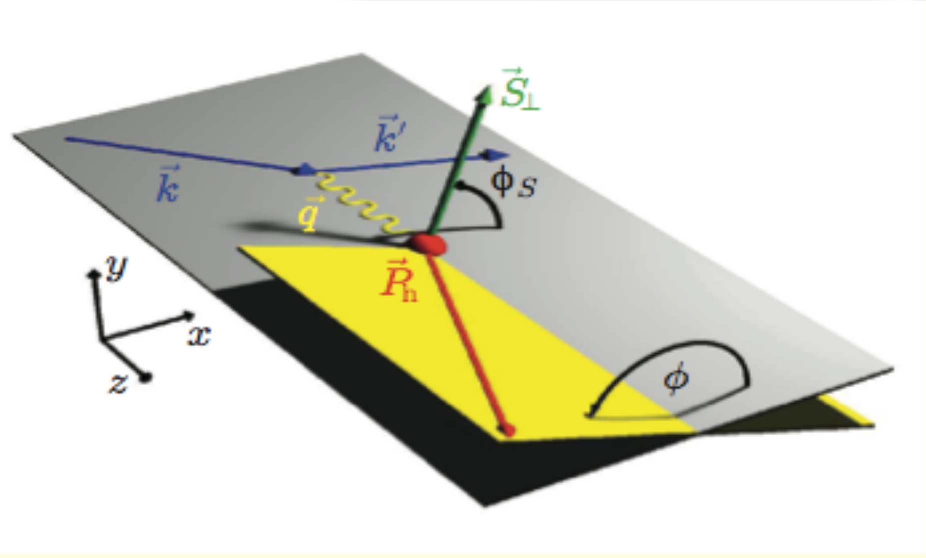


Lattice Calculation of the tran. density of Up quark, QCDSF/UKQCD Coll., 2006

Final State Interactions

Burkardt's picture

Collins and Sivers effects: Semi-inclusive DIS



- Novel Single Spin Asymmetries

Collins: $$A_{UT}^{\sin(\phi+\phi_S)} \propto S_\perp \frac{\sum_{q,\bar{q}} e_q^2 \delta q(x)\, H_1^\perp(z)}{\sum_{q,\bar{q}} e_q^2 q(x)\, D_1(z)}$$

$$z \stackrel{lab}{=} \frac{E_h}{\nu}$$

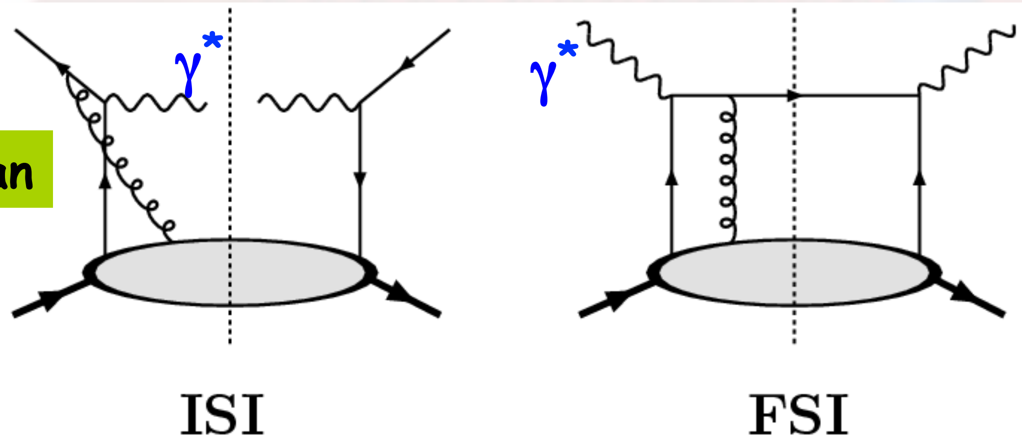
Sivers: $$A_{UT}^{\sin(\phi-\phi_S)} \propto S_\perp \frac{\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp,q}(x) \cdot D_1(z)}{\sum_{q,\bar{q}} e_q^2 q(x)\, D_1(z)}$$

U: unpolarized beam
T: transversely polarized target

Sivers Asymmetries in DIS and Drell-Yan

- Initial state vs. final state interactions

Drell-Yan



DIS

$$\text{Sivers}|_{DY} = -\text{Sivers}|_{DIS}$$

HERMES/ COMPASS/ JLab

- "Universality": QCD prediction

TMD predictions rely on

- Non-perturbative TMDs constrained from experiments
- QCD evolutions, respect to the hard momentum scale Q
  - Strong theory/phenomenological efforts in the last few years
  - lattice calculations may help as well

Collins-Soper-Sterman Resummation

- Large Logs are resummed by solving the energy evolution equation of the TMDs

$$\frac{\partial}{\partial \ln Q} f(k_\perp, Q) = (K(q_\perp, \mu) + G(Q, \mu)) \otimes f(k_\perp, Q)$$

- K and G obey the renormalization group eq.

$$\frac{\partial}{\partial \ln \mu} K = -\gamma_K = \frac{\partial}{\partial \ln \mu} G$$

(Collins-Soper 81, Collins-Soper-Sterman 85)

Solving the evolution equations

$$\widetilde{f}_q^{(sub.)}(x,b,\zeta^2=\rho Q^2;\mu_F=Q) = e^{-S^q_{pert}(Q,b_*)-S^q_{\rm NP}(Q,b)}\widetilde{\mathcal{F}}_q\left(\alpha_s(Q);\rho\right) \times \sum_i C_{q/i}(\mu_b/\mu)\otimes f_i(x,\mu)\ ,$$

Sudakov form factor (perturbative)

Non-perturbative input

- Universal C-function

$$C_{q/q'}(x) = \delta_{qq'}\left[\delta(1-x)+\frac{\alpha_s}{2\pi}C_F(1-x)\right]$$

- Scheme-dept.

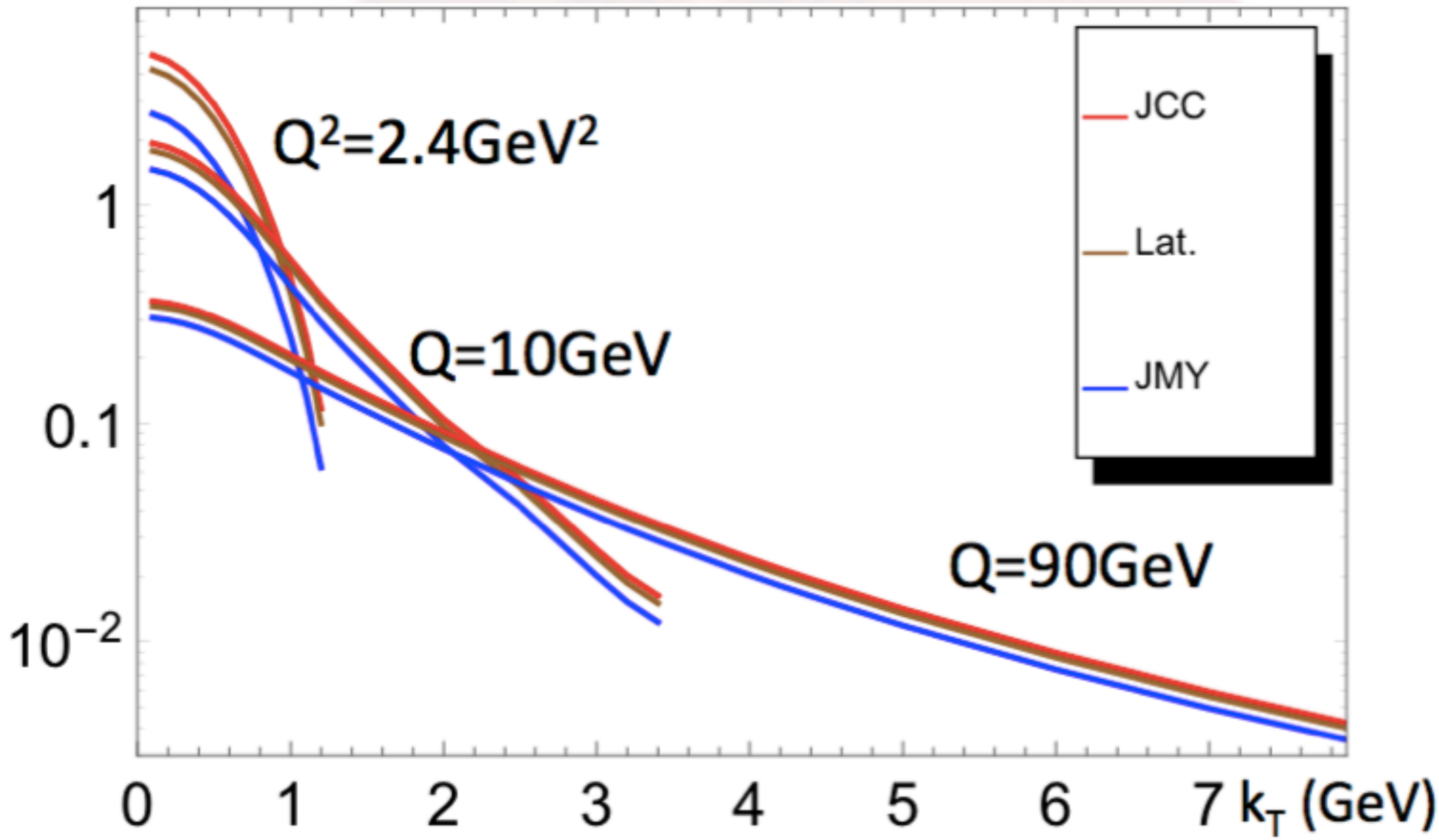
$$\widetilde{\mathcal{F}}_q^{\rm JCC}\left(\alpha_s(Q)\right) = 1+\mathcal{O}(\alpha_s^2)$$

$$\widetilde{\mathcal{F}}_q^{\rm JMY}\left(\alpha_s(Q);\rho\right) = 1+\frac{\alpha_s}{2\pi}C_F\left(\ln\rho-\frac{\ln^2\rho}{2}-\frac{\pi^2}{2}-2\right)$$

$$\widetilde{\mathcal{F}}_q^{\rm Lat.}\left(\alpha_s(Q)\right) = 1+\frac{\alpha_s}{2\pi}C_F\left(-2\right)$$

Catani et al, 2000; Prokudin et al, 2015

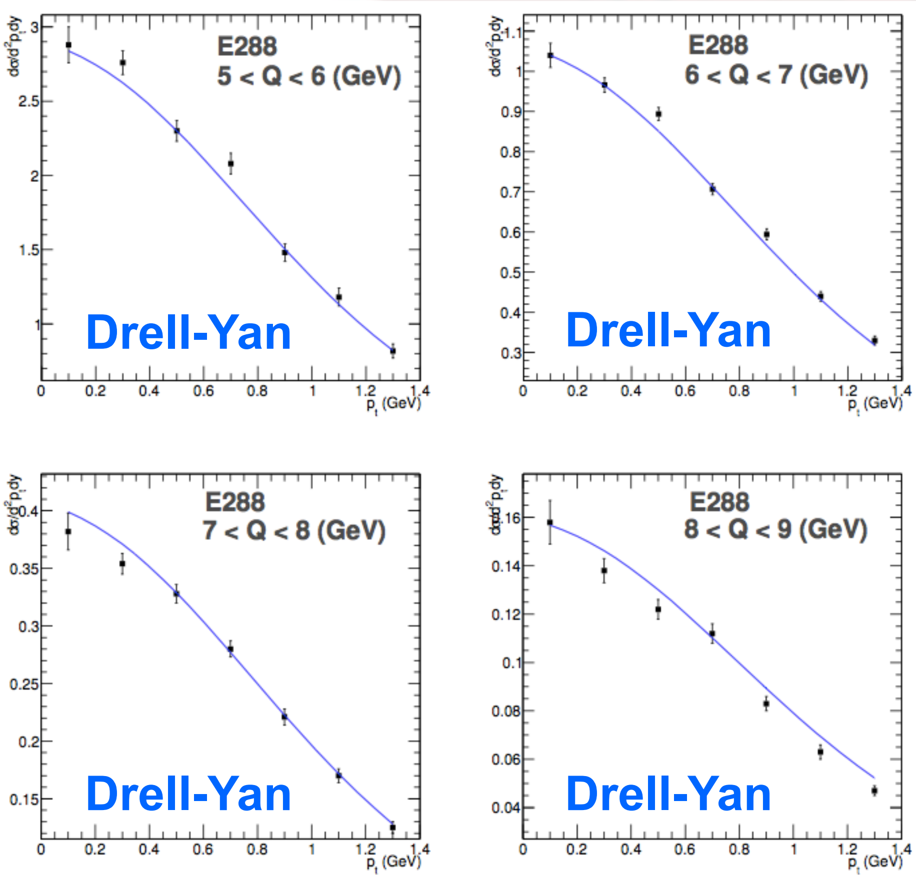
Unpolarized quark distribution

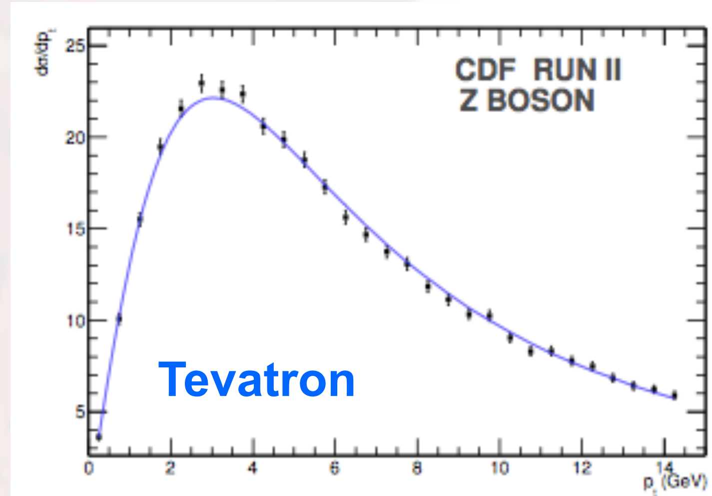


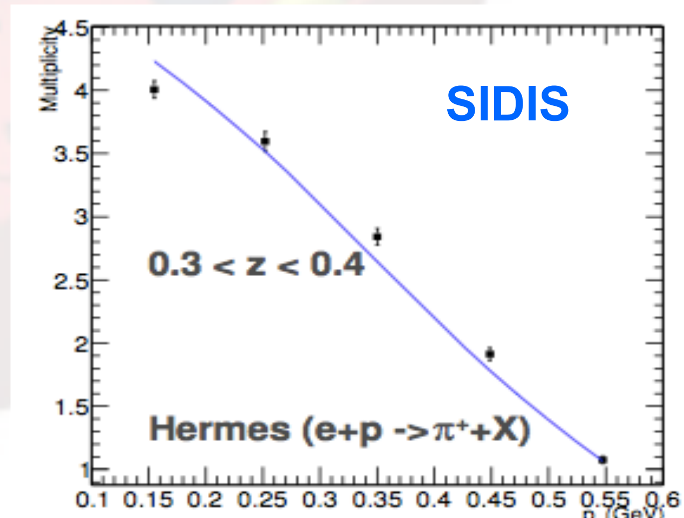
Prokudin-Sun-Yuan, 1505.05588

Describe well the exp. data

Sun-Issacson-Yuan-Yuan, 2014

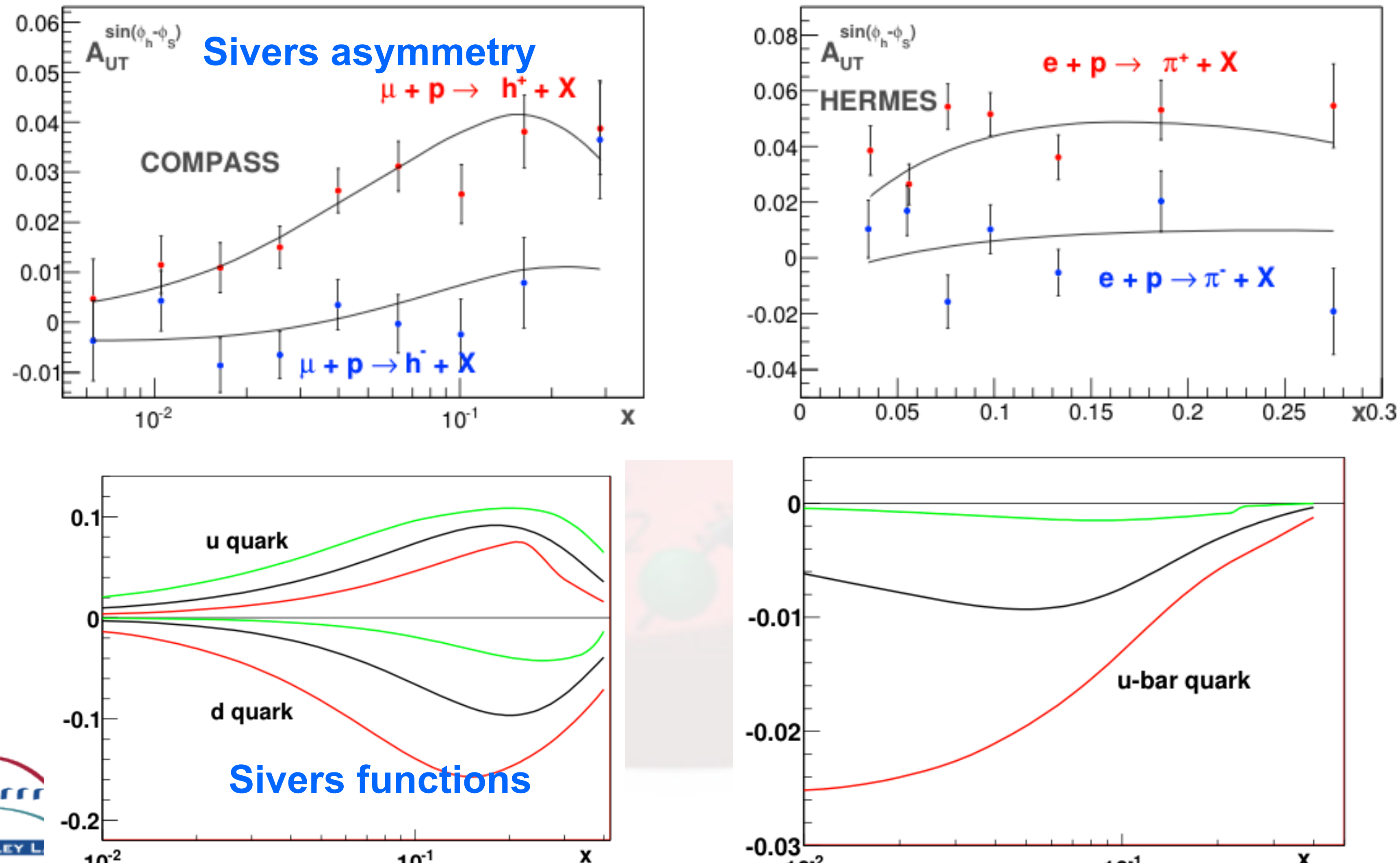






Sivers asymetries in SIDIS with Evolution

Sun, Yuan, PRD 2013
Prokudin-Sun-Yuan, in progress

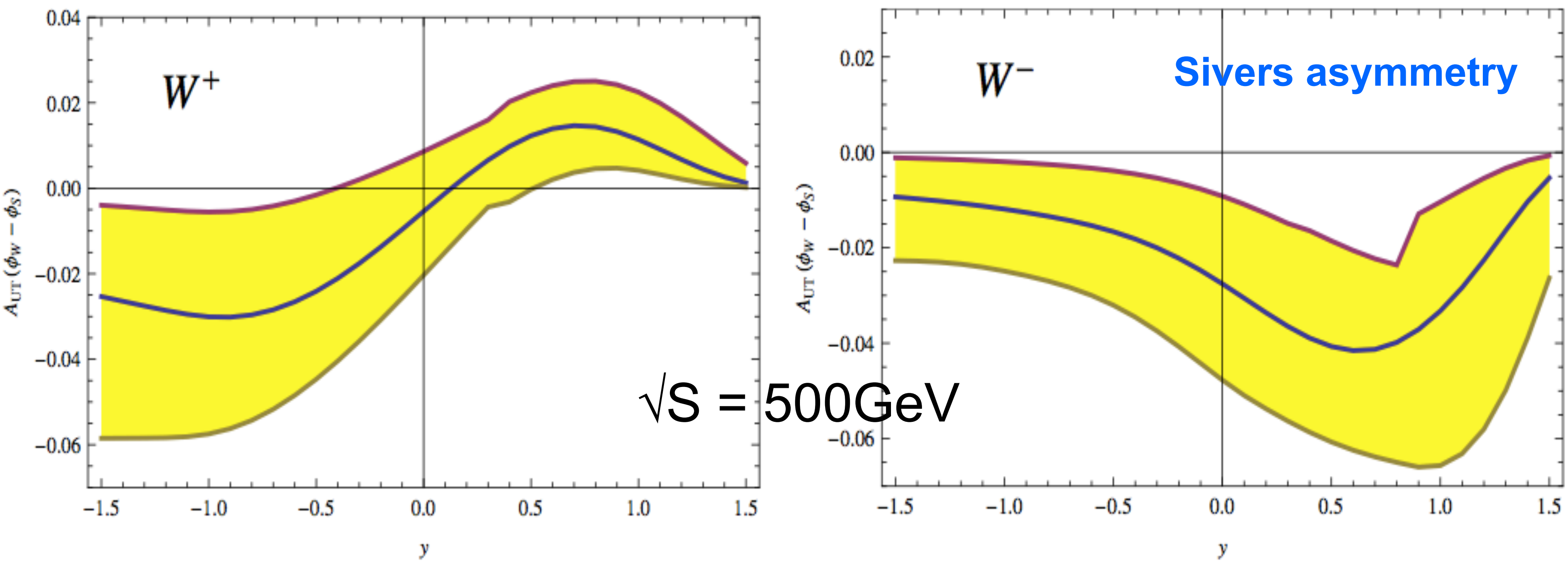


Complementary proposals for Drell-Yan experiments

- COMPASS@CERN
  - Kinematics (x_B) in the same range as existing SIDIS measurements
- SeaQuest@Fermilab
  - Polarized beam (valence) and target (sea)
- RHIC@BNL
  - W-boson, unique flavor dependence
  - Unique on the Q-evolution

Predictions at RHIC

Sun, Yuan, PRD 2013

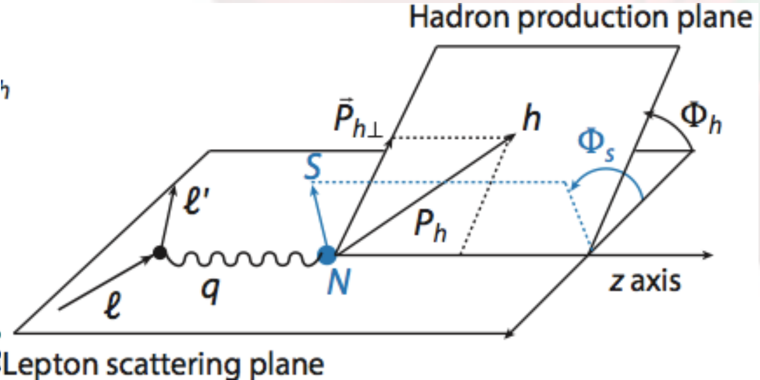


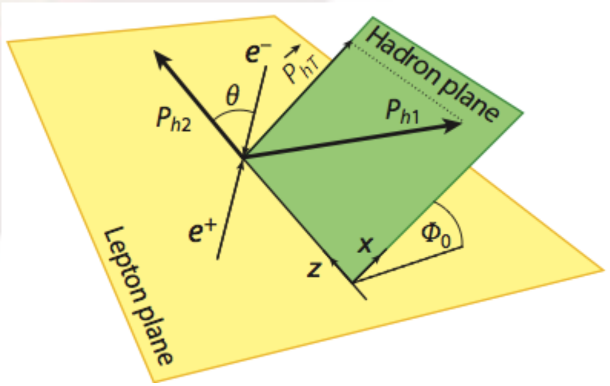
Additional theory uncertainties: x-dependence of the TMDs comes from a fit to fixed target Drell-Yan and w/z production at Tevatron by Nadolsky et al.

Transversity and Collins FF

Kang-**Prokudin-Sun**-Yuan 2014

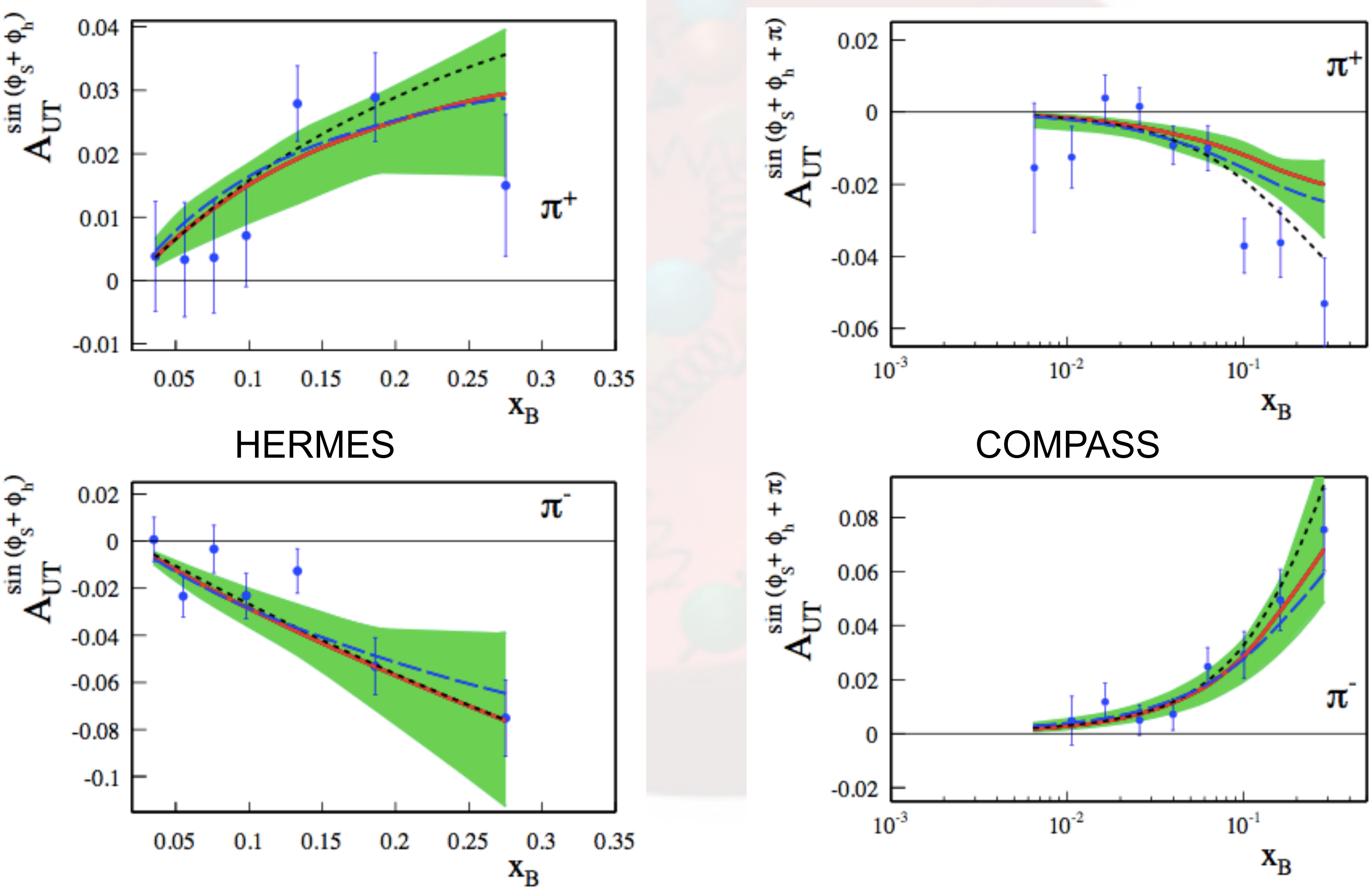
- First comprehensive analysis with TMD evolution at next-to-leading logarithm
- Consistent treatment of both unpolarized and polarized cross sections
- Nucleon tensor charge determined with much theoretical improvement





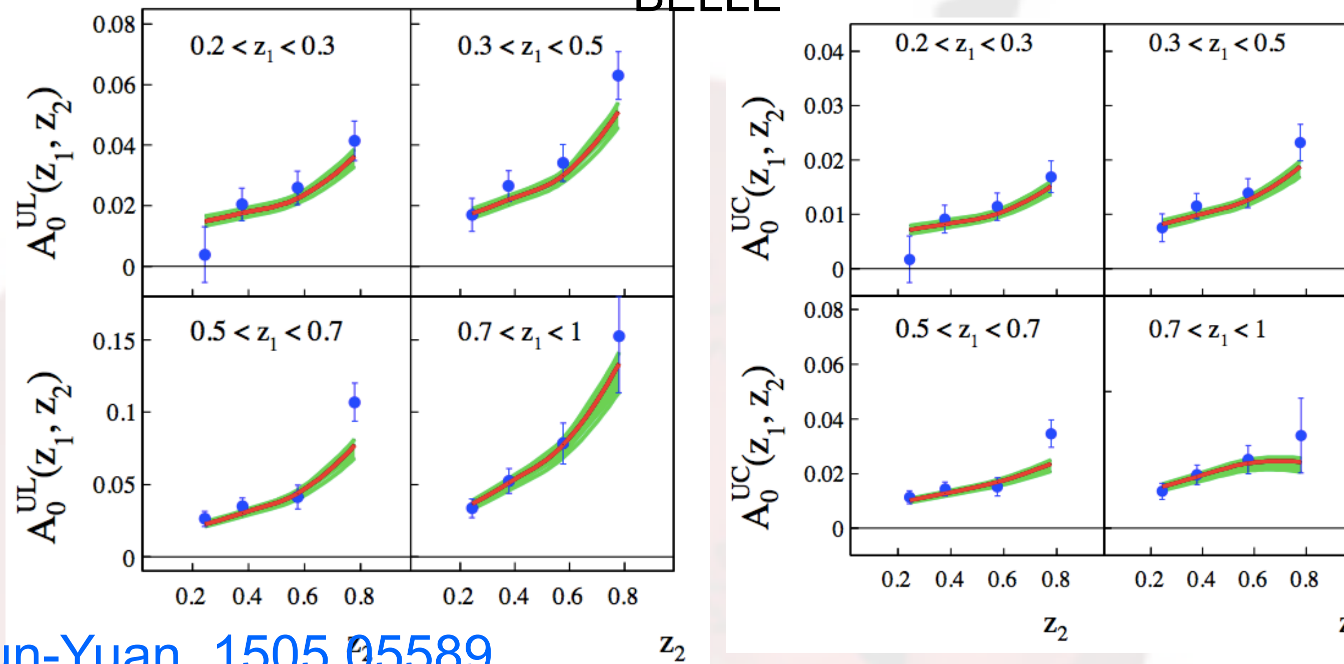
Fit to SIDIS

Kang-Prokudin-Sun-Yuan, 1505.05589



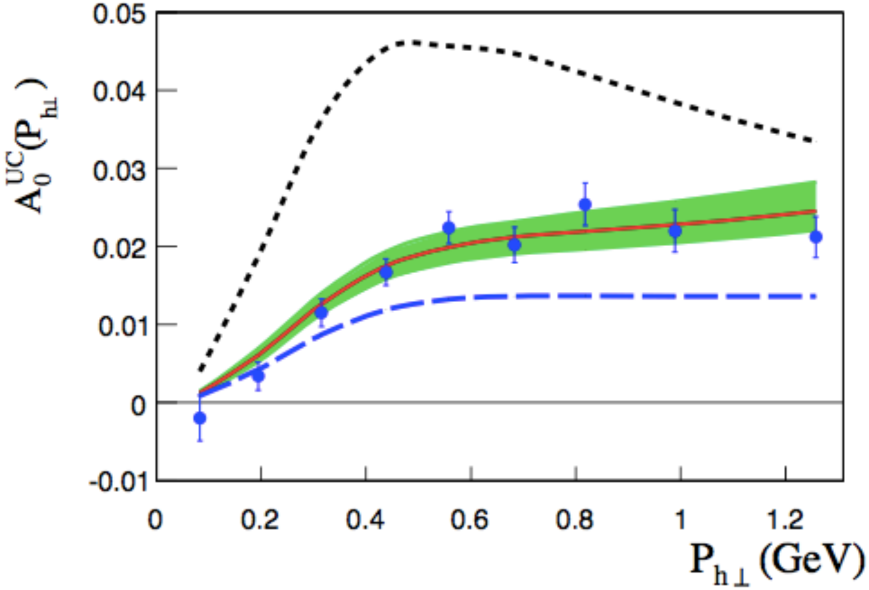
e^+e^-

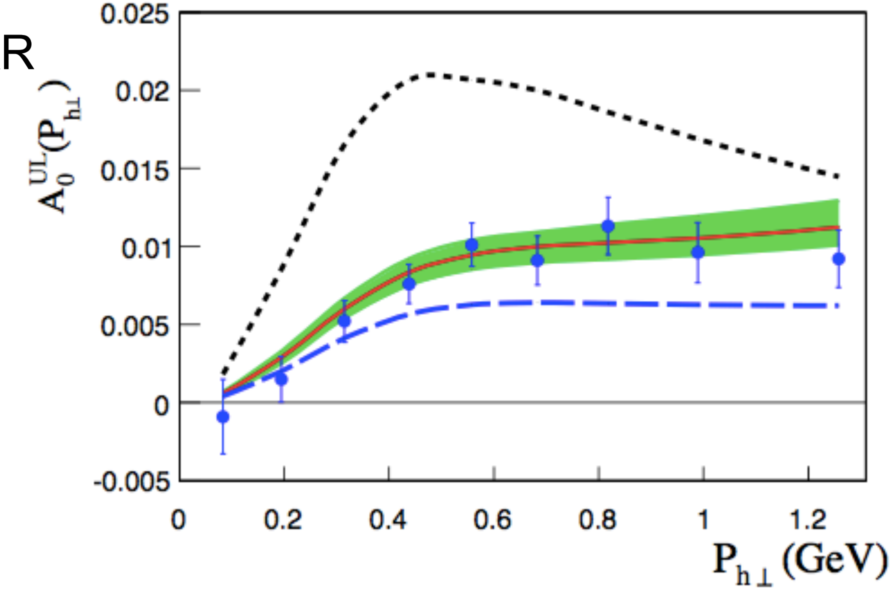
BELLE



Kang-Prokudin-Sun-Yuan, 1505.05589

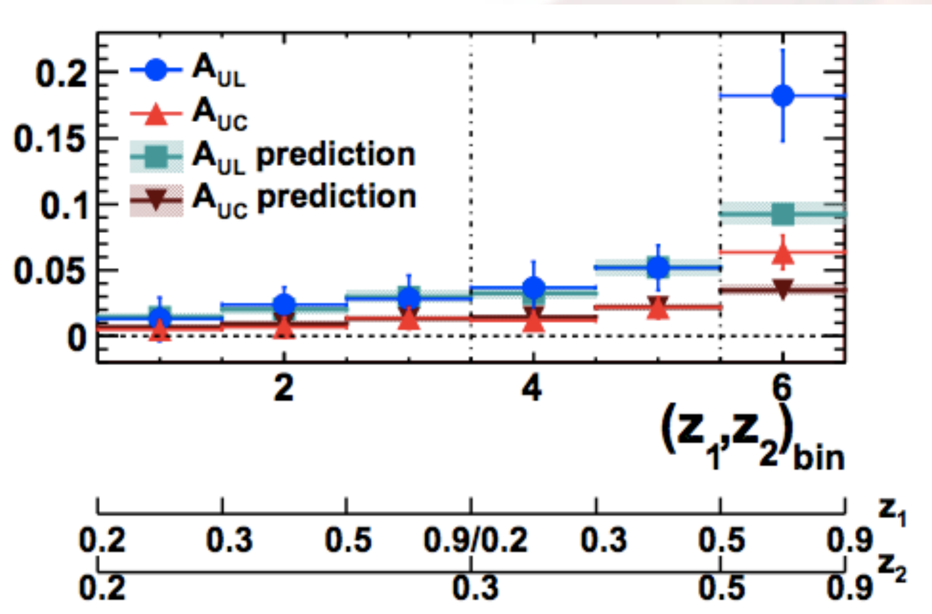
BABAR

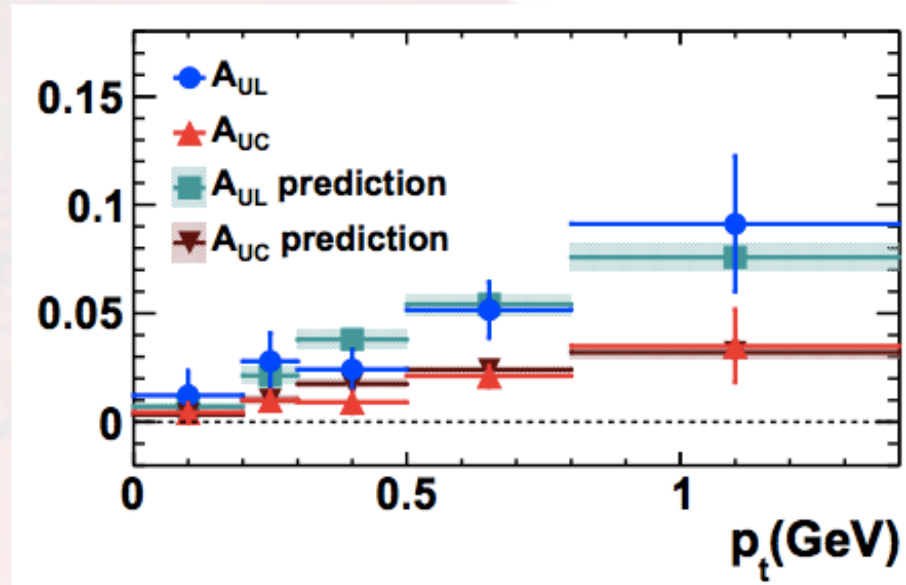




BESIII @ BEPCII (Q=3.65GeV)

1507.06824



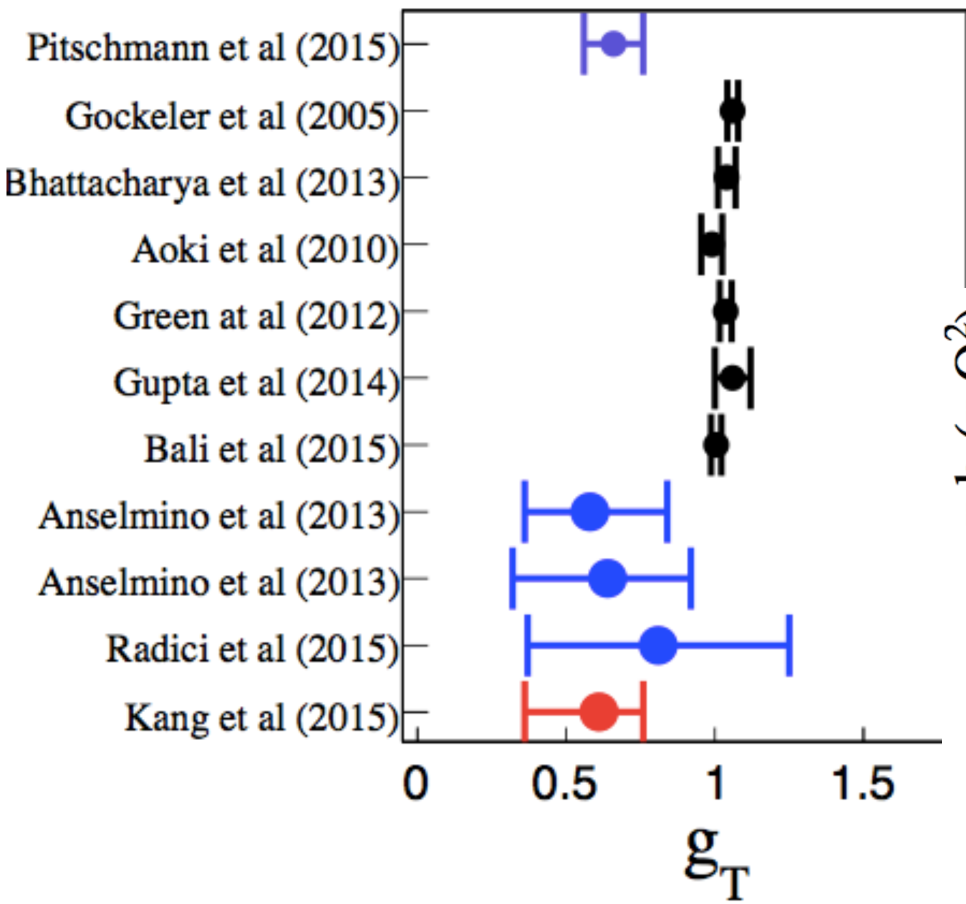


*Data not in the fit

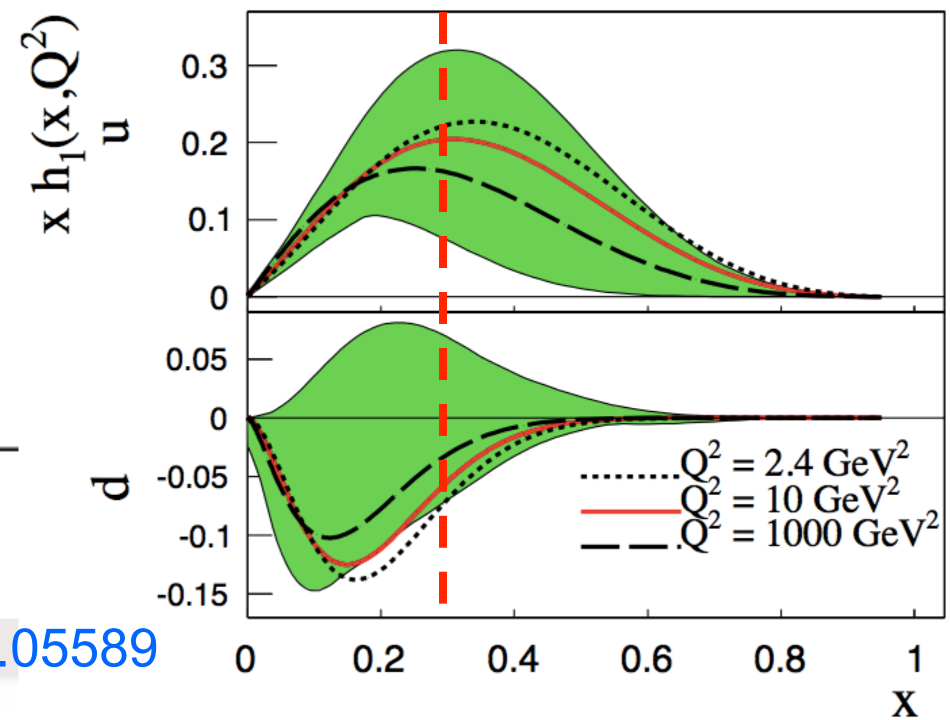
Energy is between DIS and previous e+e- annihilation exp.

Explore the QCD evolution!!

Nucleon tensor charge



We don't know large-x region
12 GeV JLab

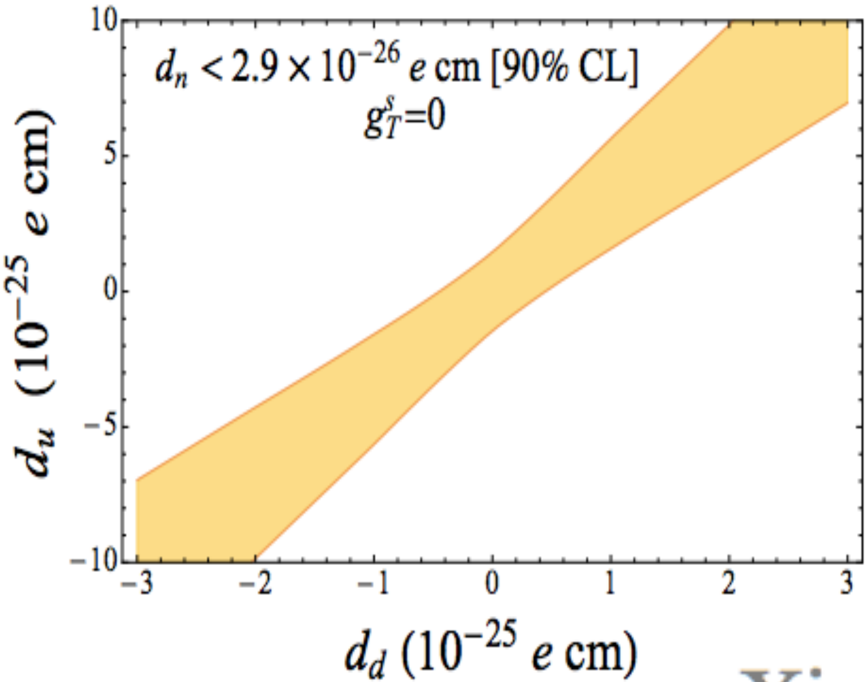


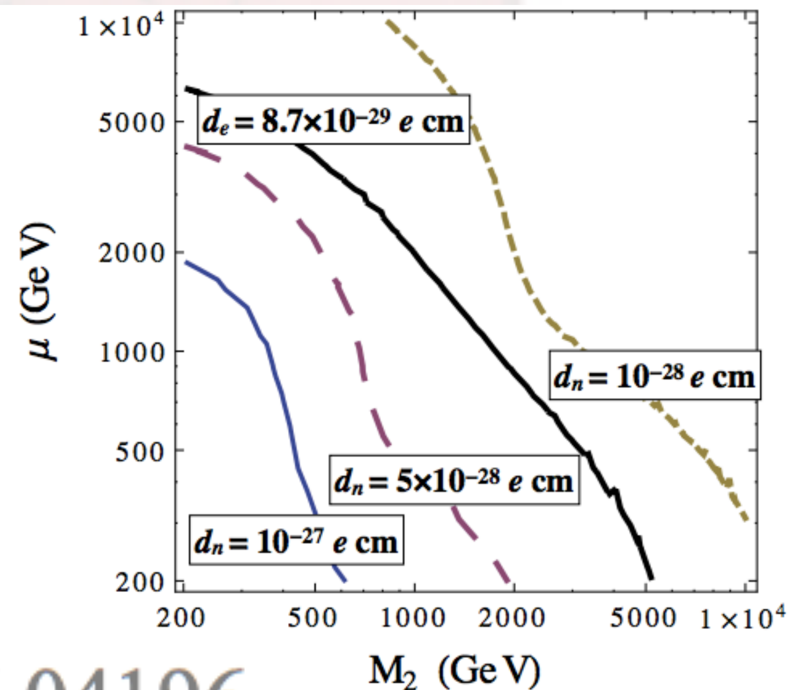
Kang-Prokudin-Sun-Yuan, 1505.05589

Implication for neutron EDM and new physics search

Neutron Electric Dipole Moment and Tensor Charges from Lattice QCD

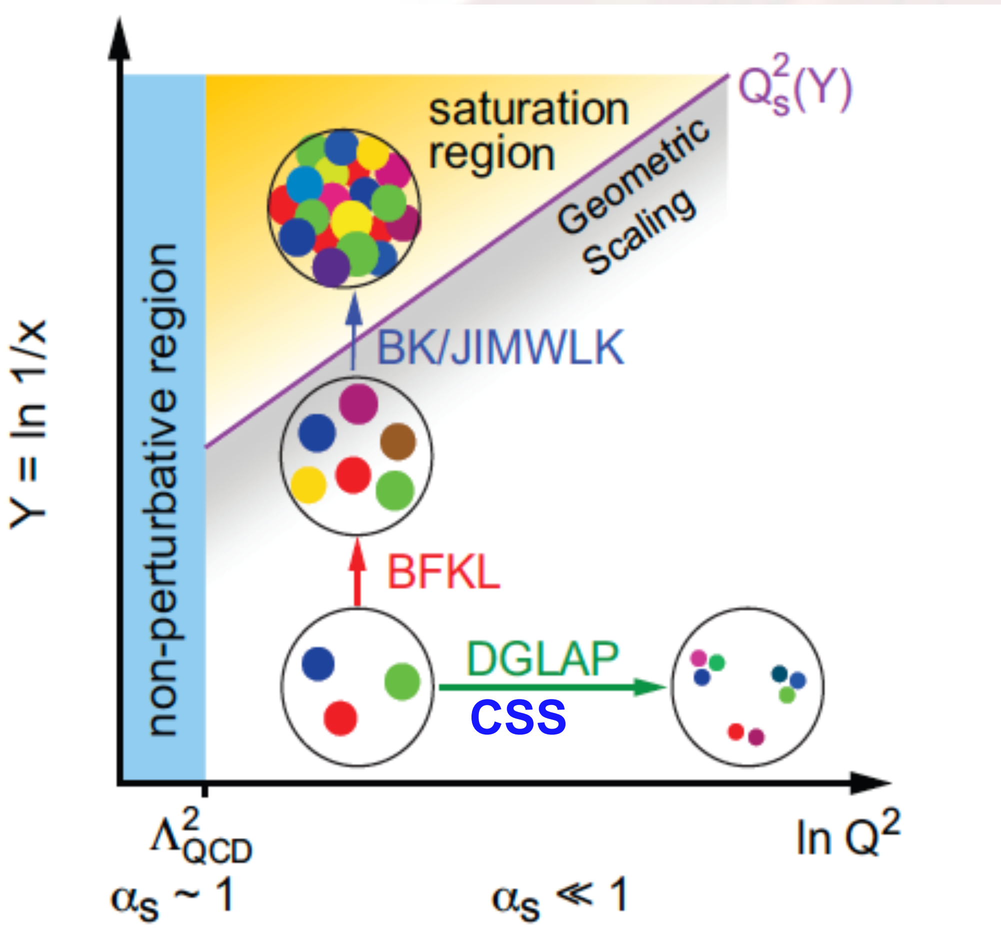
Tanmoy Bhattacharya,[1,*] Vincenzo Cirigliano,[1,†] Rajan Gupta,[1,‡] Huey-Wen Lin,[2,§] and Boram Yoon[1,¶]

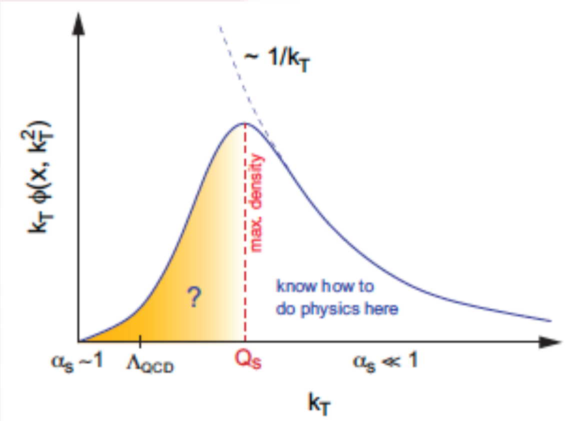




arXiv:1506.04196

TMDs at small-x





- Hard processes probe the kt-dependent gluon distributions directly
- Saturation phenomena manifest in the observables
  - Marquet, 2007
  - Dominguiz-Marquet-Xiao-Yuan, 2010

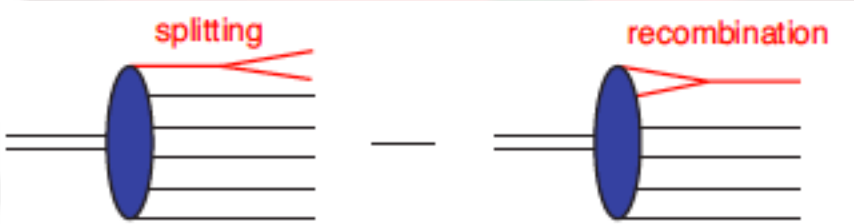
Non-linear term at high density

- Balitsky-Fadin-Lipatov-Kuraev, 1977-78

$$\frac{\partial N(x, r_T)}{\partial \ln(1/x)} = \alpha_s K_{\text{BFKL}} \otimes N(x, r_T)$$

- Balitsky-Kovchegov: Non-linear term, 98

$$\frac{\partial N(x, r_T)}{\partial \ln(1/x)} = \alpha_s K_{\text{BFKL}} \otimes N(x, r_T) - \alpha_s [N(x, r_T)]^2.$$

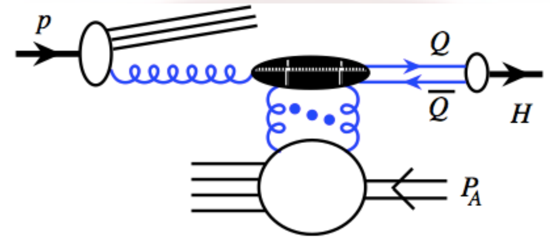


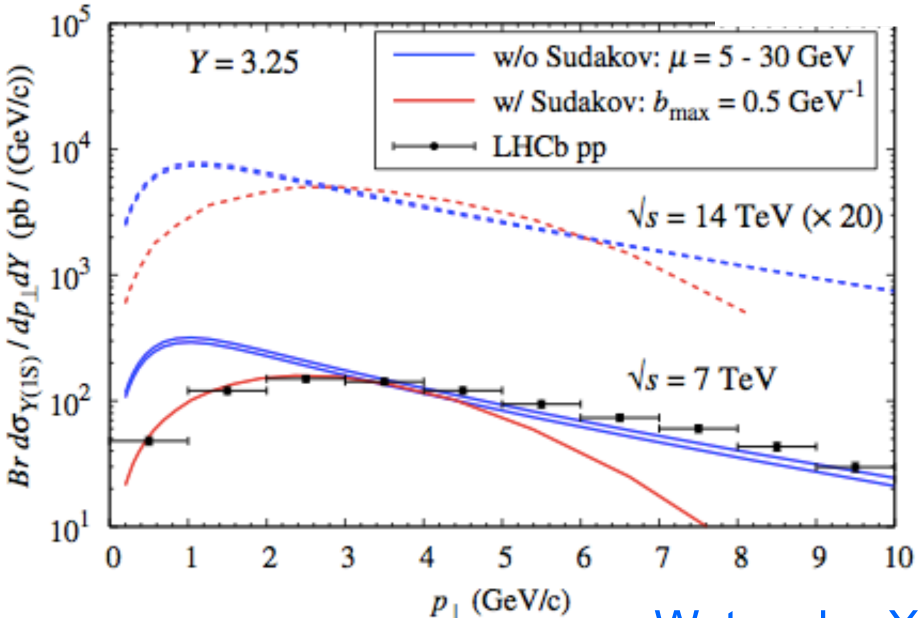
Therefore

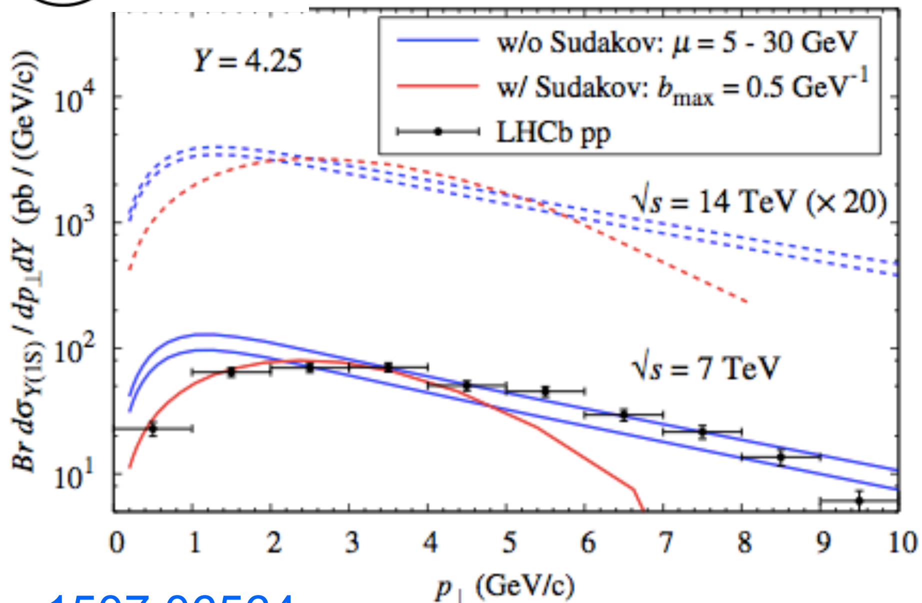
- x-dependence of the TMDs at small-x, in principle, can be calculated from the QCD evolution (BK-JIMWLK)
- How about Q^2
  - It has been shown that the Sudakov double log resummation (which controls Q-evolution) can be performed consistently in the small-x formalism

Mueller, Xiao, Yuan, PRL110,082301 (2013); Phys.Rev. D88 (2013) 114010
Kovchegov-Sievert, 1505.01176
Balitsky-Tarasov,,1505.02151

Upsilon Production: BFKL(BK) & Sudakov





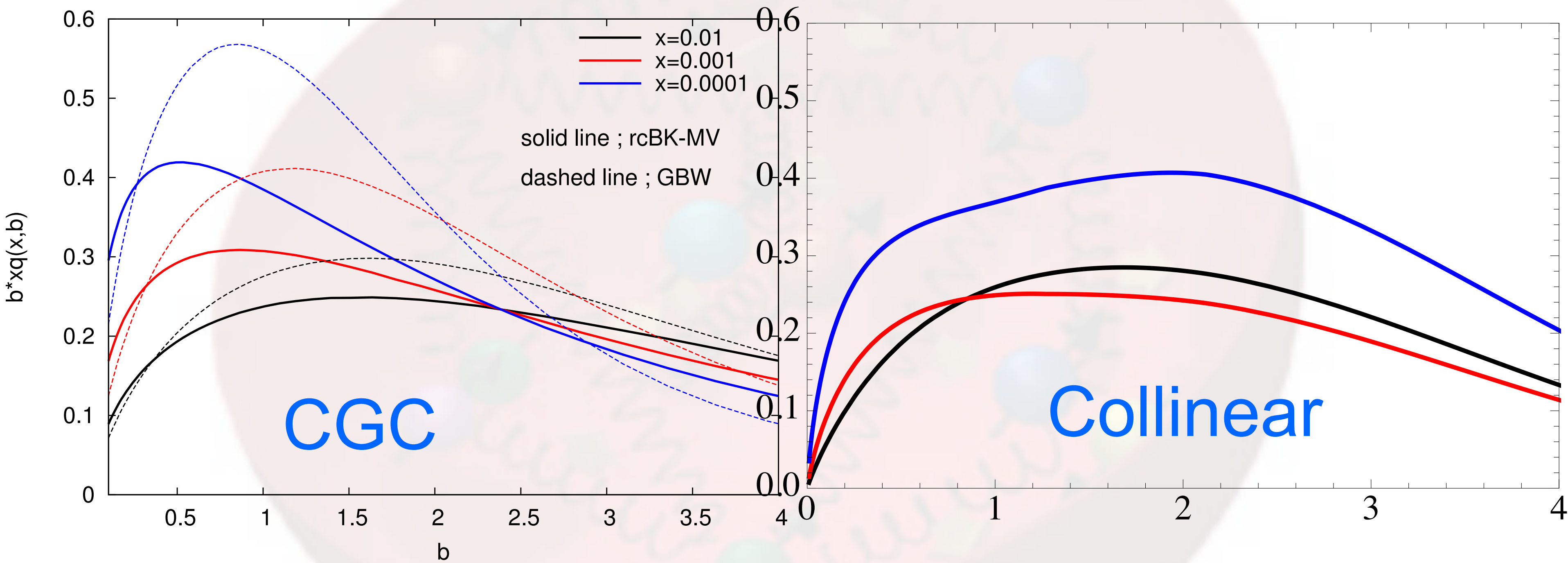


Watanabe-Xiao, 1507.06564

collinear + Sudakov:
Berger-Qiu-Wang, hep-ph/0404158
Sun-Yuan-Yuan, 1210.3432

CGC:
Fujii-Watanabe, 1304.2221; Qiu-Sun-Xiao-Yuan, 1310.2230; Kang-Ma-Venugopalan, 1309.7337; Ma-Rajugopalan,1408.4075; Duclouse-Lappi-Mantysaari,1503.02789

Merging Framework: Spin and Small-x communities



- Realistic comparison will shed light on the TMD quarks at small-x (work in progress)

Summary: What we have learned

- Unpolarized TMDs from, mainly, Drell-Yan, W/Z boson productions, partially from SIDIS processes
- Indications of polarized quark distributions (Sivers and cousins), from low energy SIDIS (HERMES, COMPASS, Jlab)

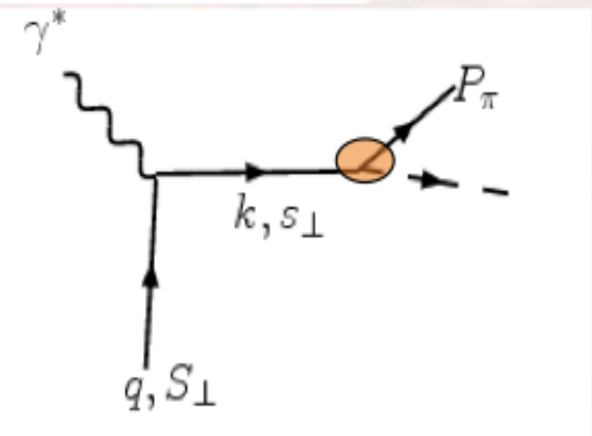
What we are missing

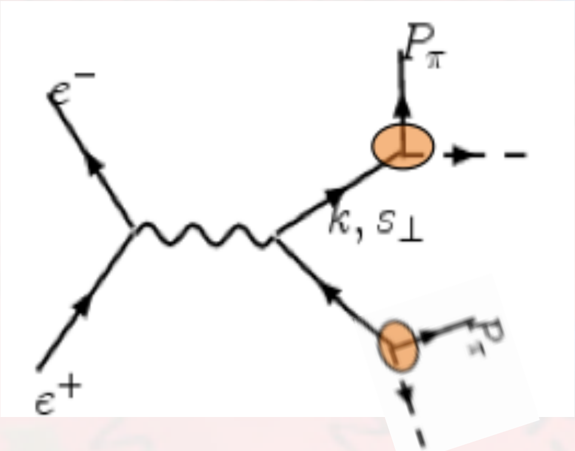
- Precision and detailed mapping of polarized quark/gluon distribution
  - Universality/evolution more evident
- Spin correlation in momentum and coordinate space/tomography
- Systematics at small-x
- Jlab 12 and EIC are essential to answer these questions

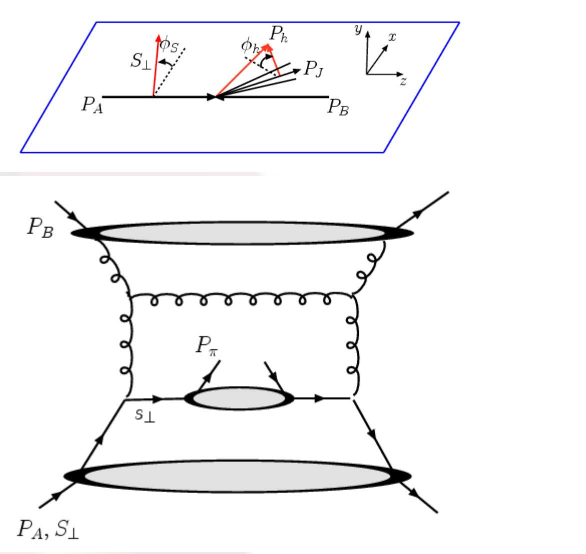
All the talks yesterday!!

BACK-UP

Universality of the Collins Fragmentation







ep--> e Pi X

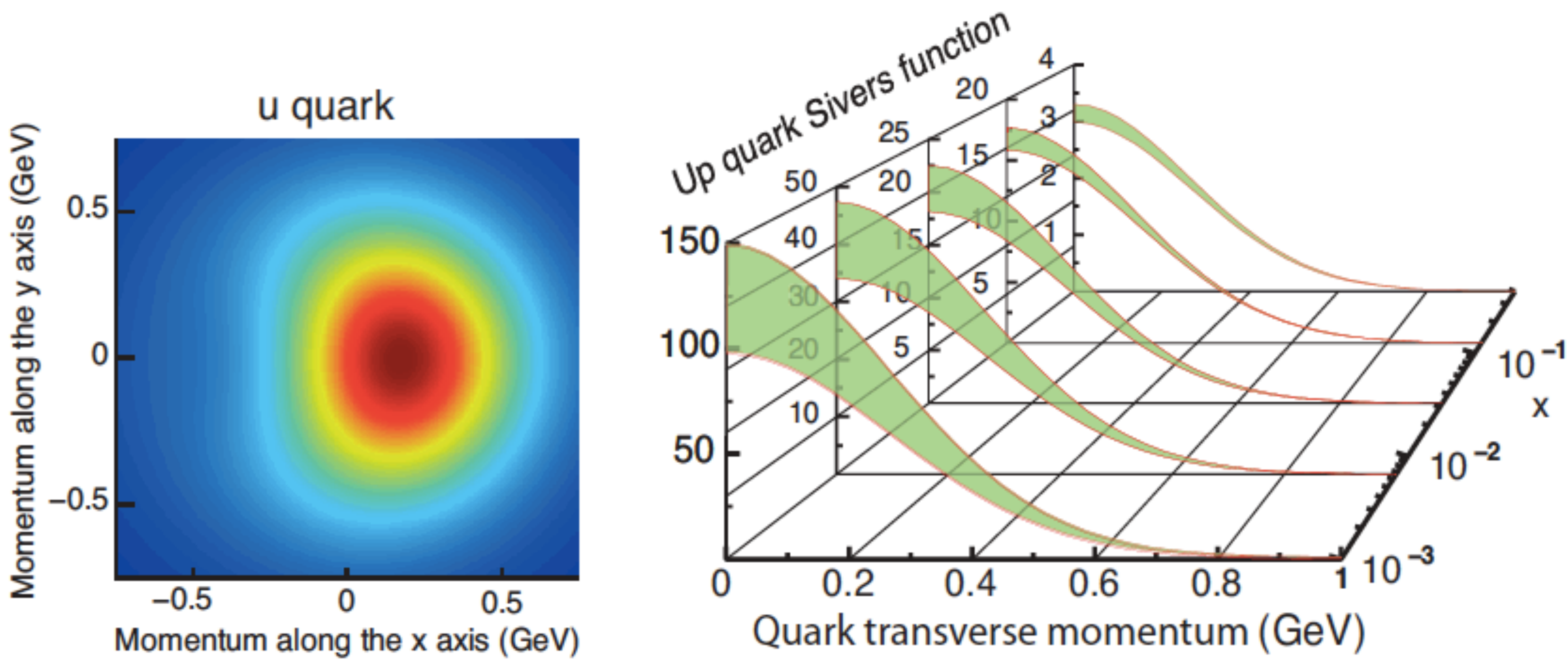
e^+e^---> Pi Pi X

pp--> jet(->Pi) X

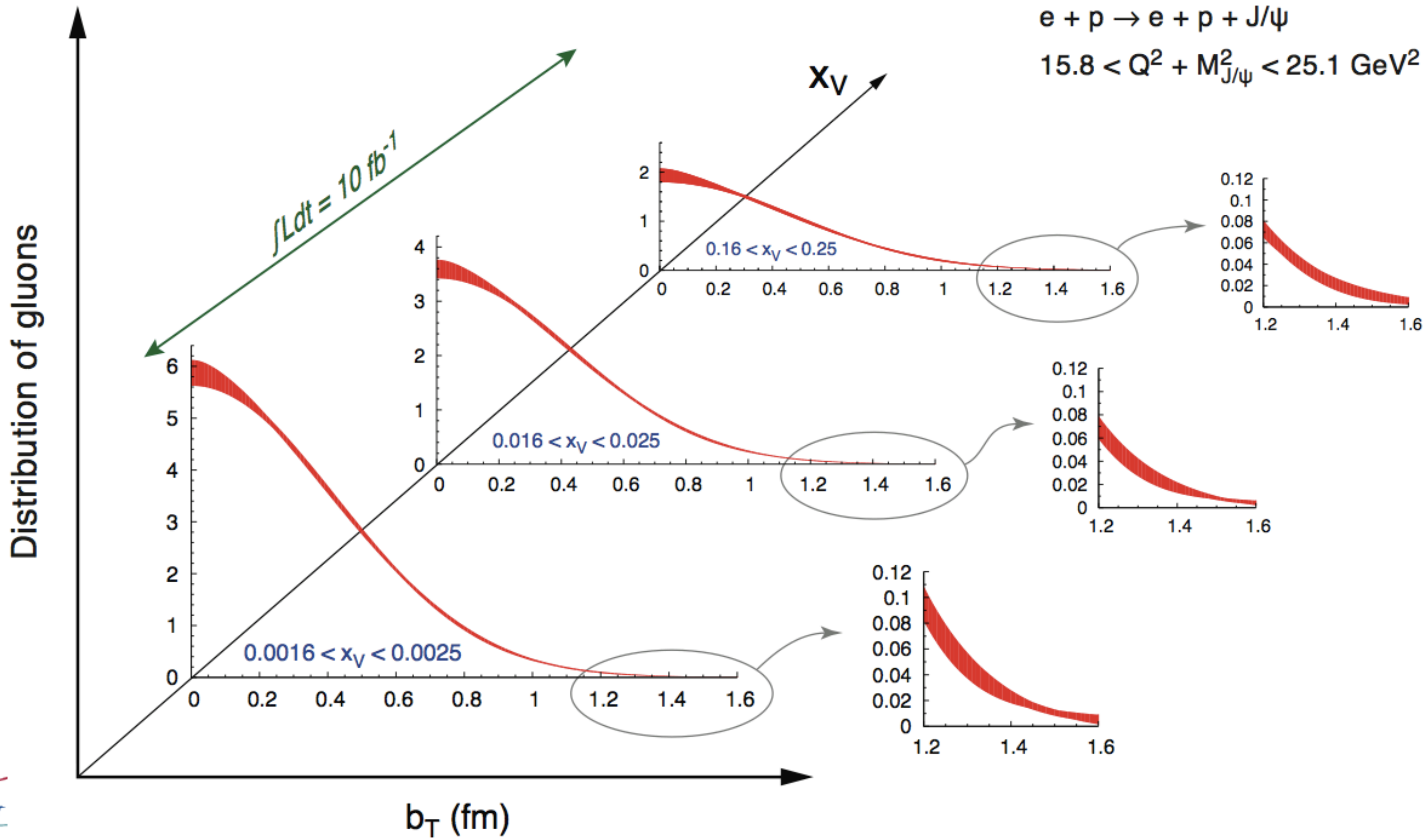
Metz 02, Collins-Metz 02,
Yuan 07,
Gamberg-Mukherjee-Mulders 08,10
Meissner-Metz 0812.3783
Yuan-Zhou, 0903.4680

Exps: BELLE, HERMES, RHIC

Kt-dependence

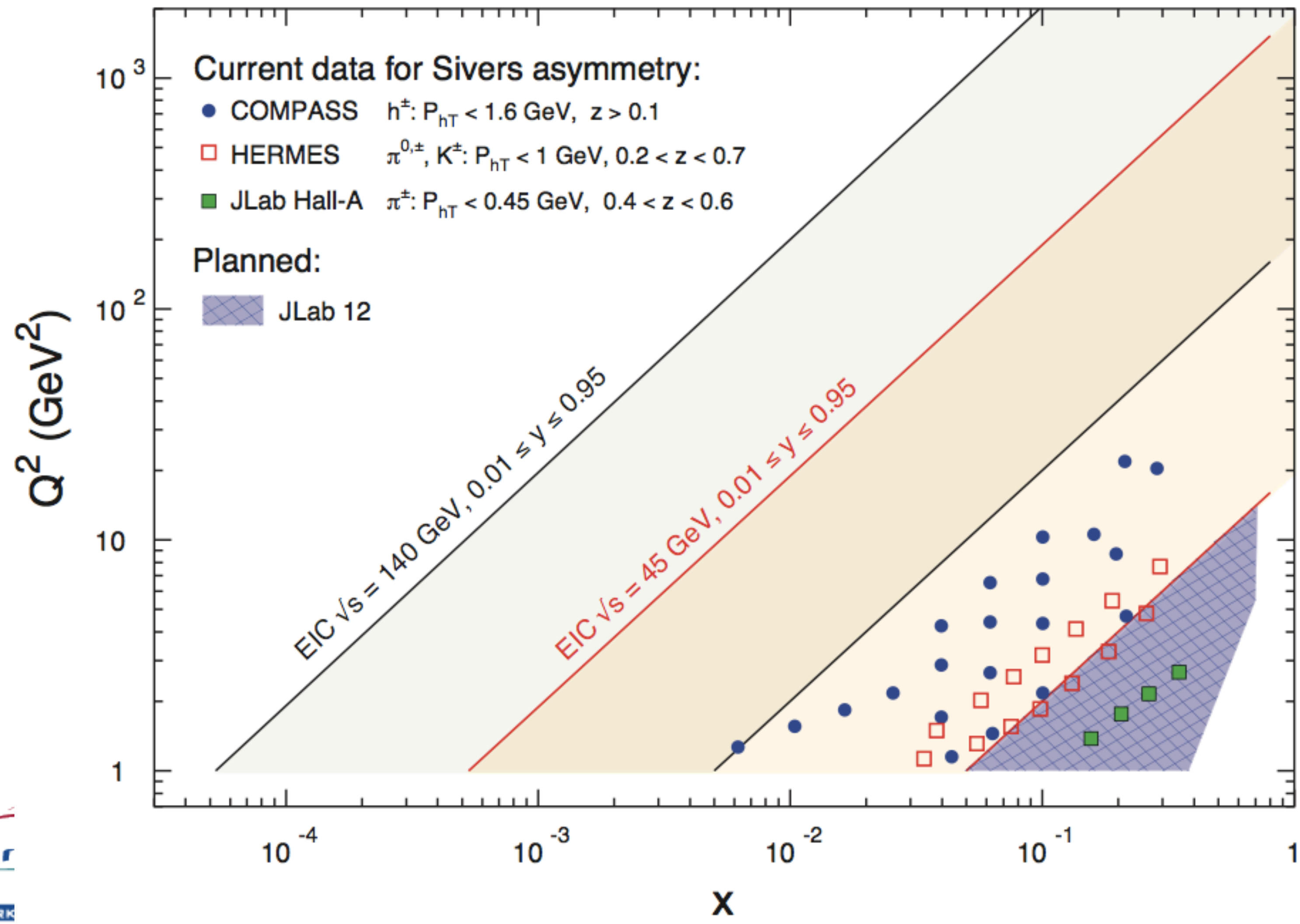


Tomography



e + p → e + p + J/ψ
15.8 < Q² + M²_J/ψ < 25.1 GeV²
x_V
∫Ldt = 10 fb⁻¹
Distribution of gluons
b_T (fm)
0.0016 < x_V < 0.0025
0.016 < x_V < 0.025
0.16 < x_V < 0.25

EIC kinematics



Computational access

- Lattice calculations of the parton distributions (as functions of x) become possible by a recent proposal

$$q(x,\mu^2,P^z) = \int \frac{dz}{4\pi} e^{izk^z} \langle P|\overline{\psi}(z)\gamma^z \times \exp\left(-ig\int_0^z dz' A^z(z')\right)\psi(0)|P\rangle$$

Ji, PRL110 (2013) 262002

TMDs on lattice

Ji-Sun-Xiong-Yuan, PRD 2015

$$q(x_z, k_\perp; P_z) = \frac{1}{2}\int \frac{d^3z}{(2\pi)^3} e^{ik\cdot z} \langle PS|\overline{\psi}(0)\mathcal{L}^\dagger_{n_z(0,-\infty)}\gamma^z\mathcal{L}_{n_z(z,-\infty)}\psi(z)|PS\rangle \times \sqrt{\frac{S^{n_x,n_y}(b_\perp)}{S^{n_x,n_z}(b_\perp)S^{n_z,n_y}(b_\perp)}} ,$$

- Nontrivial soft factor subtraction is essential to achieve the factorization
  - All unwanted divergences cancelled out
- Calculable on lattice
  - shall be extended to small-x

TMD factorization in quasi-pdfs

- For example, for Drell-Yan lepton pair production

$$W(Q,b_\perp) = q^{sub.}(x_z,b_\perp)\overline{q}^{sub.}(x'_z,b_\perp)H(Q,\mu)$$
$$= q^{unsub.}(x_z,b_\perp)\overline{q}^{unsub.}(x'_z,b_\perp)H(Q,\mu)S(b_\perp,\mu)$$

Lattice calculation
Quasi-pdfs

Soft factor

$$\sqrt{\frac{S^{n_x,n_y}(b_\perp)}{S^{n_x,n_z}(b_\perp)S^{n_z,n_y}(b_\perp)}}$$