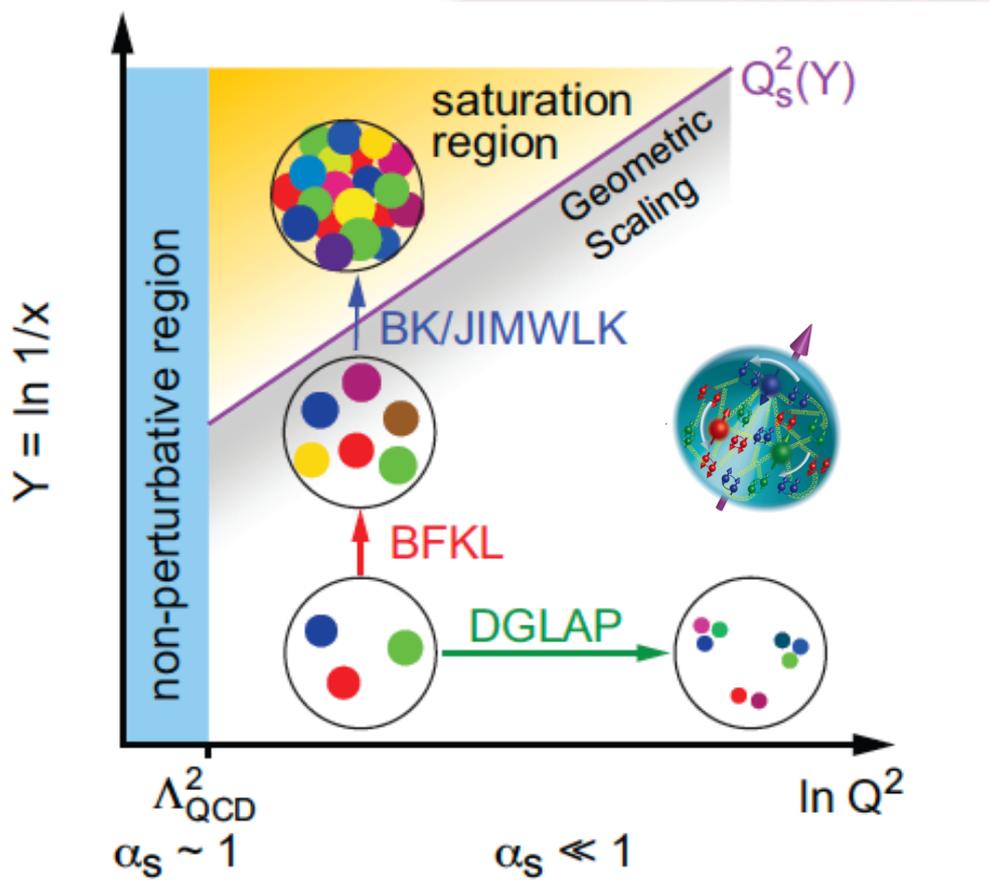


# Hadron Physics



- **Qualitatively**, explain **novel phenomena**
  - **New dynamics**
- **Quantitatively**, describe the exp. data
  - **New structure** → predicting new exp.
- **Precision**, learn the fundamental properties
  - QCD factorization, next-to-leading order corrections, all order resummations

# Proton Spin

## ■ Fundamental property

□ Jaffe-Manohar

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \mathcal{L}_q + \Delta G + \mathcal{L}_g$$

□ Ji-sum rule

$$\frac{1}{2} = J_q + J_g = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

## ■ Emerging phenomena

□ Parity violating, electro-weak interaction, SM

□ (naïve) time-reversal odd Single transverse spin asymmetries

□ Under extreme conditions: small and large x

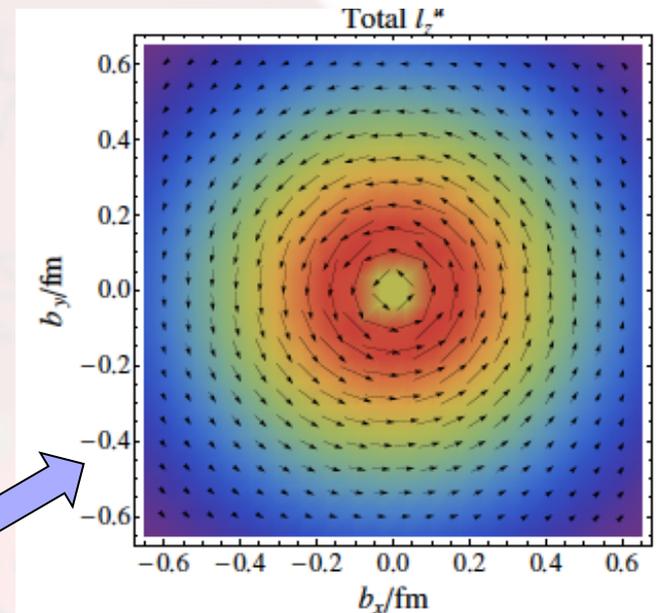
# Parton's orbital motion through the Wigner Distributions

## Phase space distribution:

Projection onto  $p(x)$  to get the momentum (probability) density

## Quark orbital angular momentum

$$L(x) = \int (\vec{b}_\perp \times \vec{k}_\perp) W(x, \vec{b}_\perp, \vec{k}_\perp) d^2\vec{b}_\perp d^2\vec{k}_\perp$$



Gauge link directions  $\rightarrow$  different OAMs (JM or Ji)

- Ji, Xiong, Yuan, PRL, 2012; PRD, 2013
- Lorce, Pasquini, Xiong, Yuan, PRD, 2012
- Lorce-Pasquini 2011
- Hatta 2011

# Orbital Angular Momentum (OAM) of an electron

Ji-Schafer-Yuan-Zhang-Zhao, PRD2016

- Interesting to find out, up to one-loop

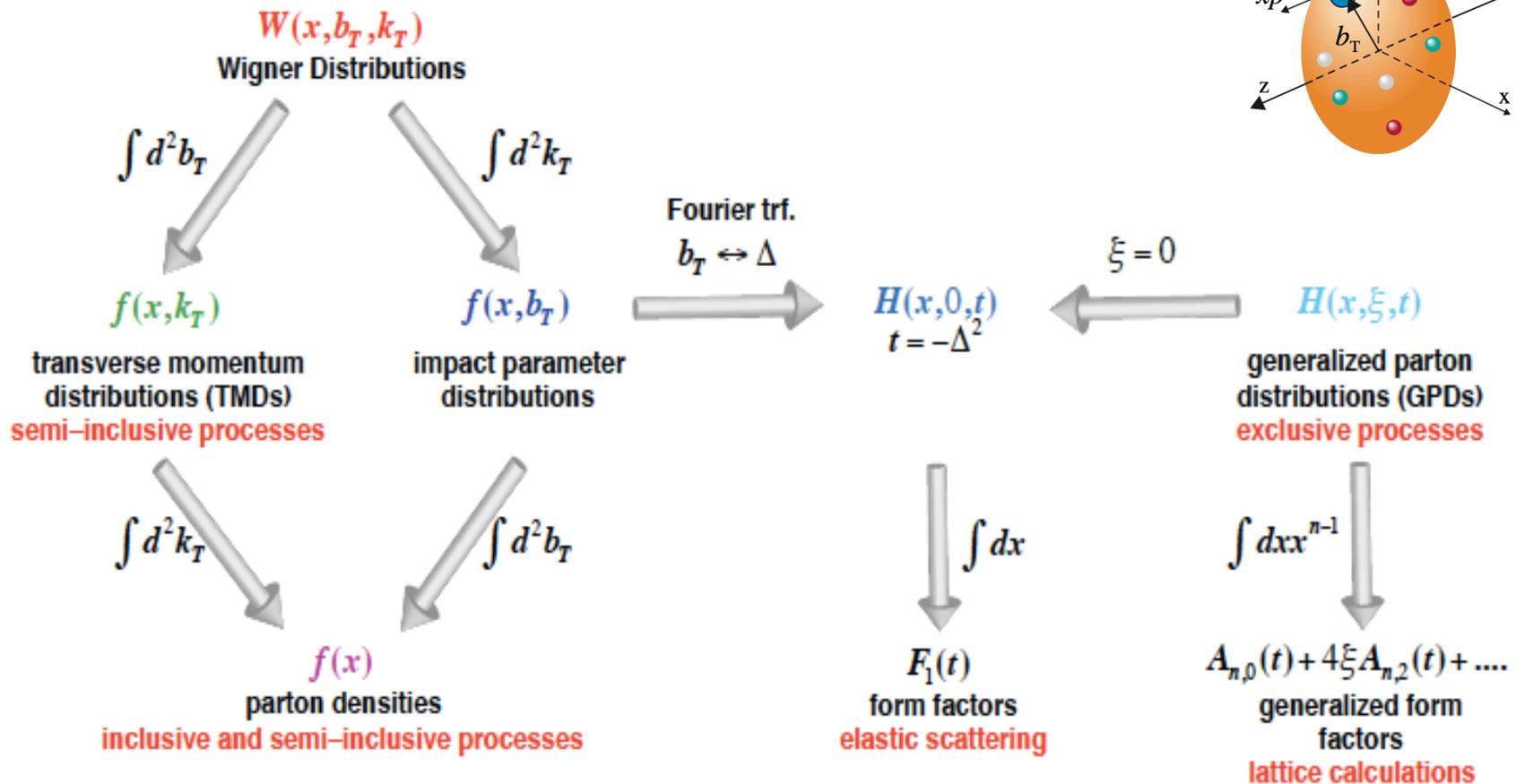
$$\text{OAM}_{\text{Jaffe-Manohar}} = \text{OAM}_{\text{Ji}}$$

- dimension regulation and Pauli-Villars regulation with light-cone wave functions
- likely will change at higher order in QED and QCD
  - Jaffe-Manohar and Ji sum rules are consistent with each other

(earlier works by Burkardt-BC 2009, Liu-Ma 2015)

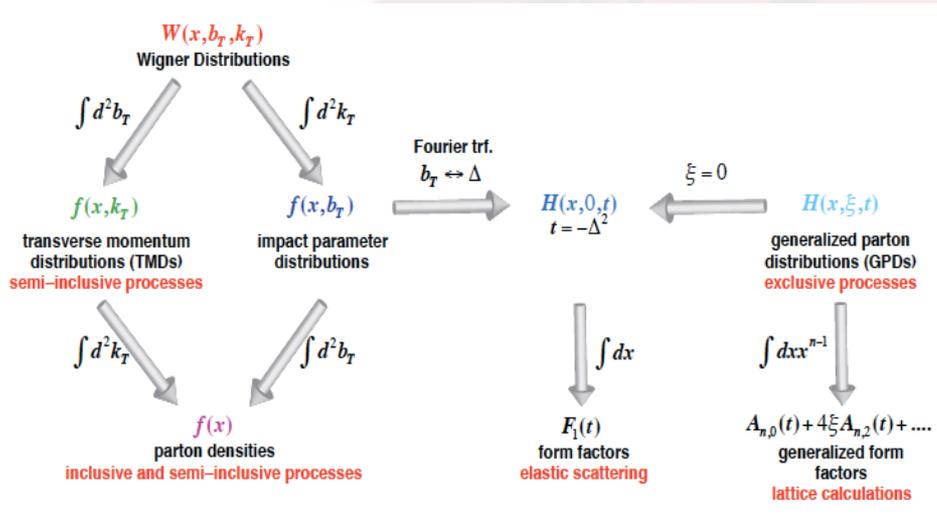
# Grand Jewels of Hadron Physics

## □ Wigner distributions (Belitsky, Ji, Yuan)



# Grand Jewels of Hadron Physics

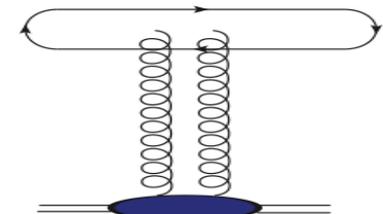
## Wigner distributions (Belitsky, Ji, Yuan)



Small-x

## Dipole scattering amplitudes

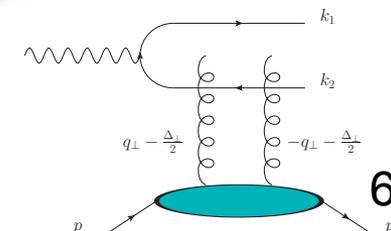
$$\frac{1}{N_c} \left\langle \text{Tr} \left[ U(R_\perp) U^\dagger(R'_\perp) \right] \right\rangle_x$$



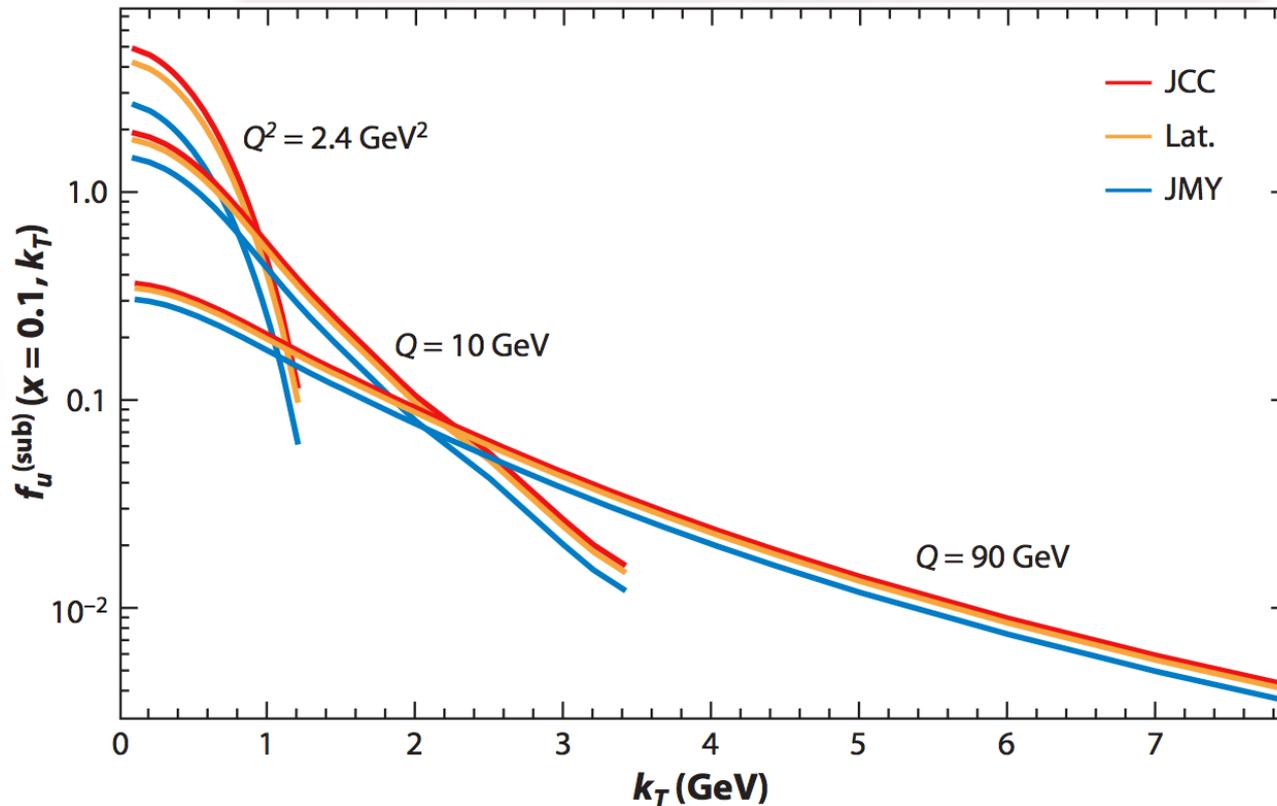
## Hunting the gluon OAM

Hatta-Xiao-Yuan, PRL 2016  
earlier: Mueller, NPB 1999

$$A_{\sin(\phi_\Delta - \phi_q)} = \int d\phi_q d\phi_\Delta \frac{d\sigma_\uparrow - d\sigma_\downarrow}{d\phi_q d\phi_\Delta} \sin(\phi_\Delta - \phi_q)$$



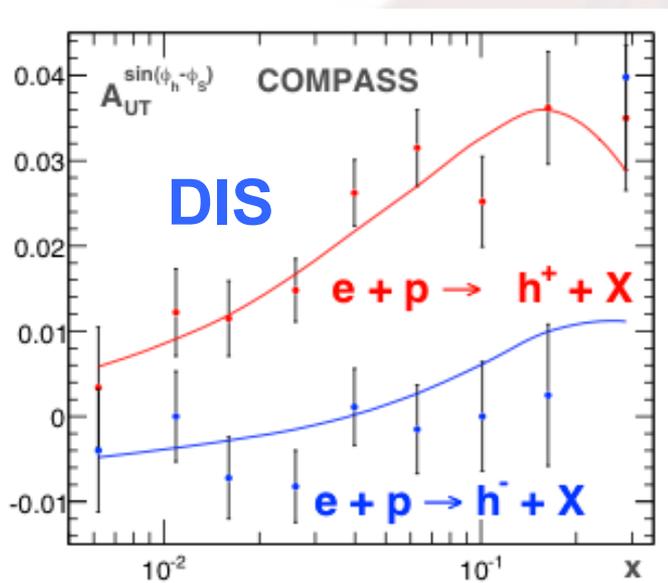
# Scale dependence of Transverse momentum distributions (TMDs)



Grosse-Perdekamp, Yuan, Ann. Rev. 2015  
Prokudin, Sun, Yuan, 2015

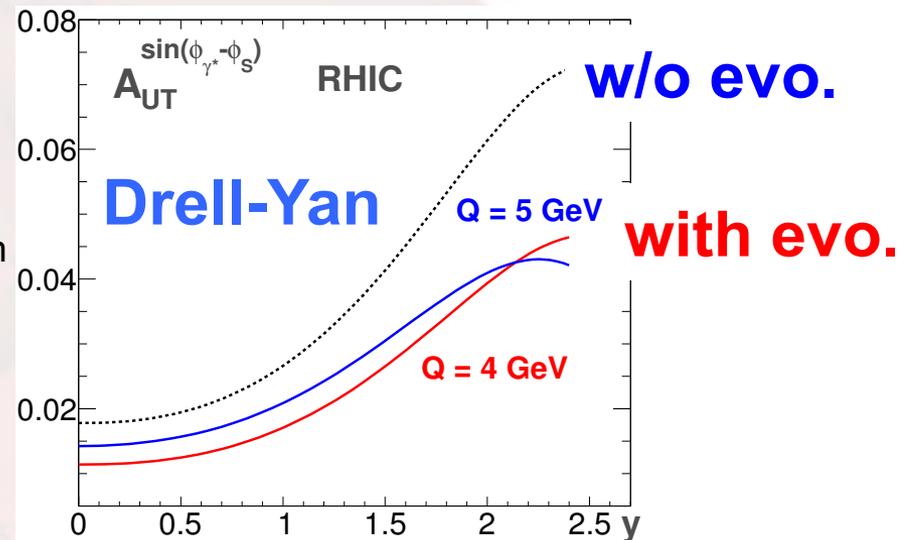
# Transverse spin asymmetries: QCD evolution plays crucial role

Sun, Yuan, PRD 2013



DIS,  $Q^2 \sim 4 \text{ GeV}^2$

QCD evolution

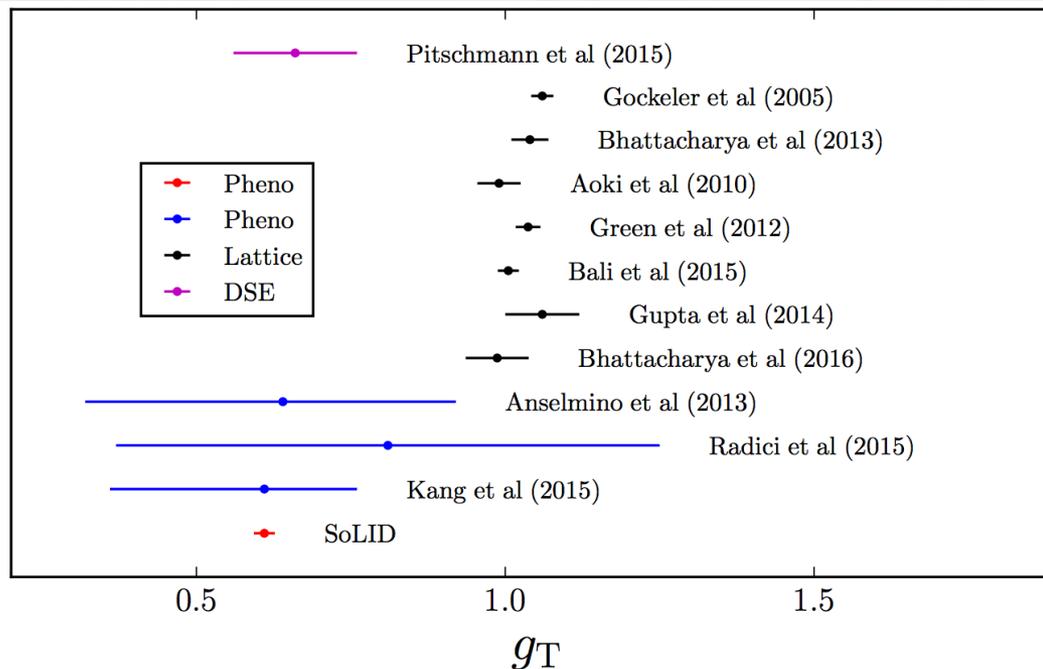


RHIC,  $E_{c.m.} = 200 \text{ GeV}$

- First analysis for both **polarized** and **unpolarized** cross sections with consistent evolution effects for DIS and Drell-Yan processes

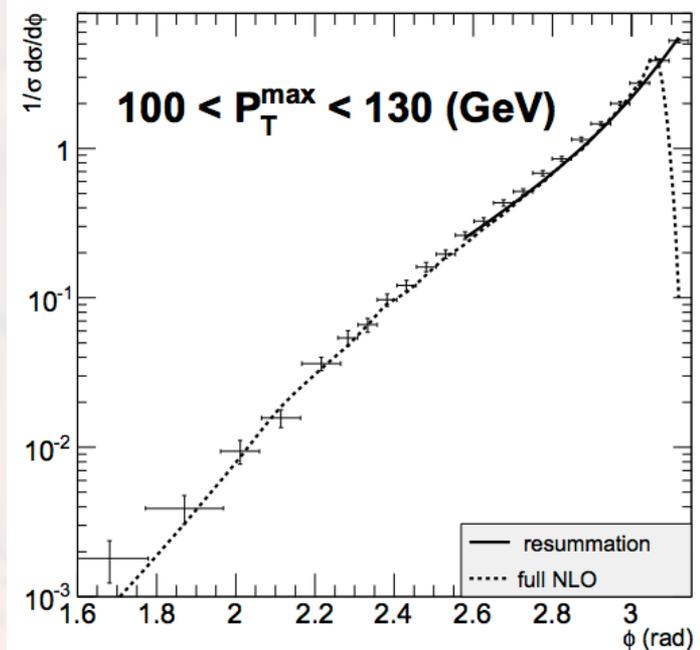
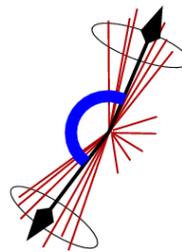
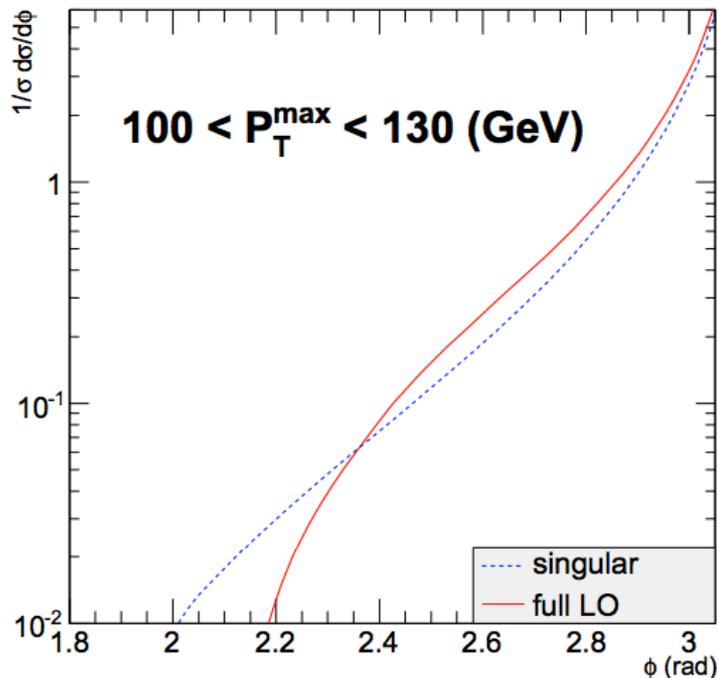
# Transversity and Nucleon Tensor Charge

- First comprehensive analysis with TMD evolution at next-to-leading logarithm
- Consistent treatment of both unpolarized and polarized cross sections



Kang-Prokudin-Sun-Yuan, PRD 2015;  
Ye, et al, 1609.02449

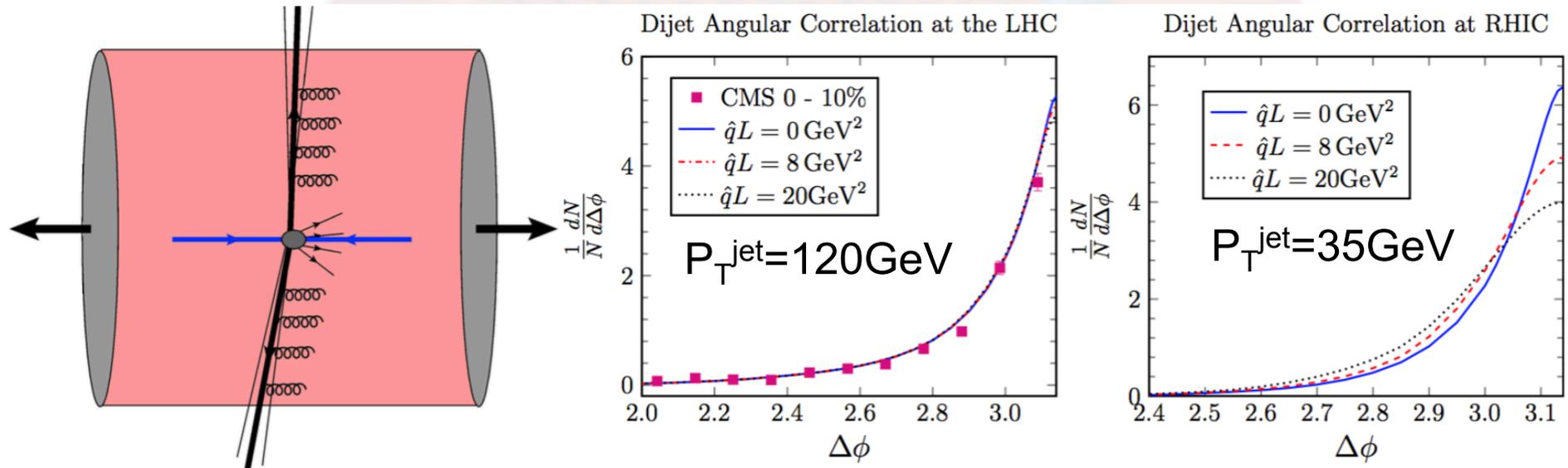
# Applications in Jet Productions (or with Higgs) at Colliders



- Sun, C.P. Yuan, F. Yuan, PRL14, PRD15, PRL15, PLB16
  - Fixed order pQCD divergent at back-to-back
  - All order Sudakov resummation for the colored final states
  - Next-to-leading logarithm depends on jet size ( $R$ )

# New and direct way to measure $q\hat{t}$

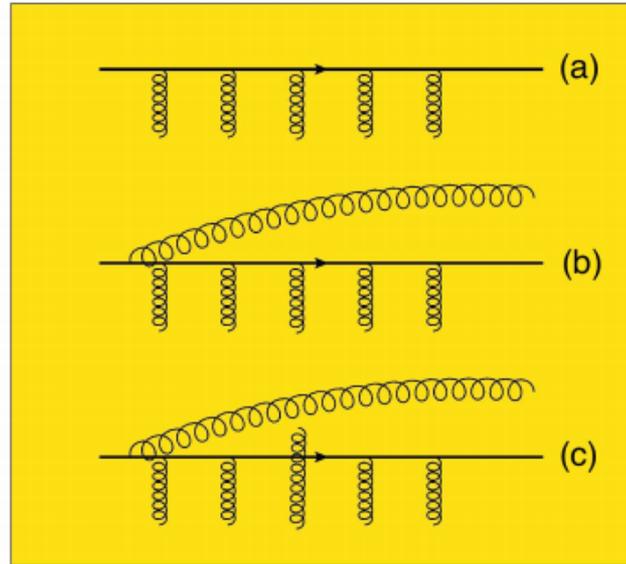
- Dijet azimuthal angular correlation in heavy ion collisions



Mueller-Wu-Xiao-Yuan,  
1604.04250;1608.07339

- Phenomenological relevance at RHIC/LHC
- Different physics are well separated

# Theory Advances: TMD and Medium-induced radiations



- Medium  $P_T$  broadening ( $q_{\text{hat}}$ ) vs **Sudakov (TMD)**
  - Mueller-Wu-Xiao-Yuan, [1604.04250](#); [1608.07339](#)
- BFKL (BK) vs **Sudakov (TMD)**
  - Mueller-Xiao-Yuan, [PRL 2013](#), [PRD 2013](#)
  - Mueller-Szymanowski-Wallon-Xiao-Yuan, [JHEP2016](#)

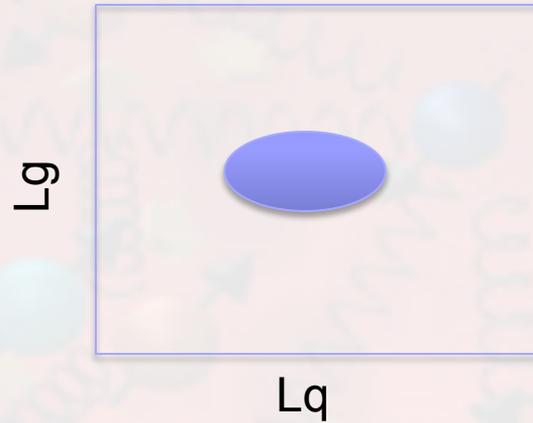
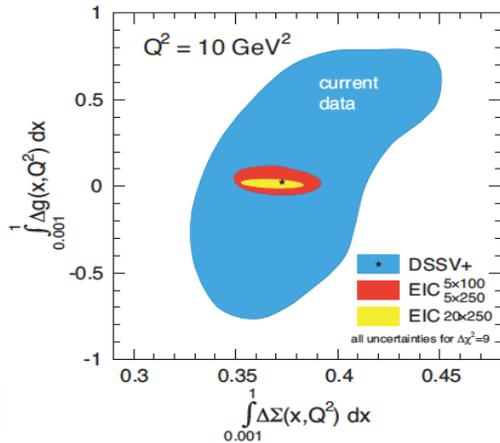
# Looking Forward

LDRD support for EIC theory (Gyulassy, Wang, Yuan, postdoc)

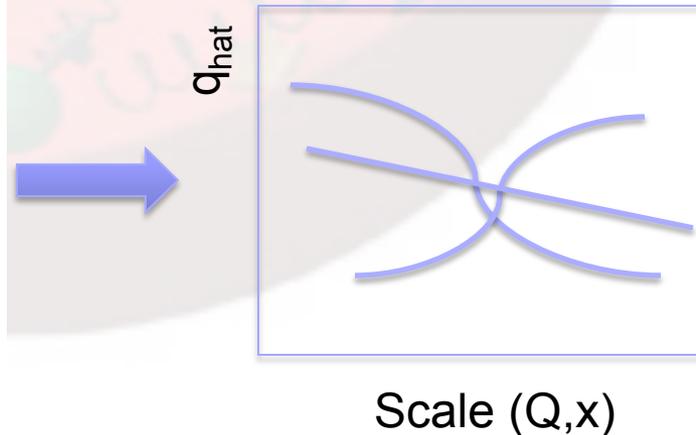
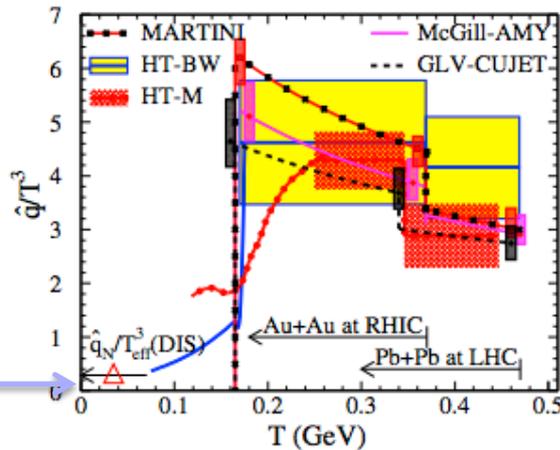
- Identify processes in Deep Inelastic Scattering (diffractive DIS) to probe the **gluon tomography** and **Orbital Angular Momentum** at the EIC
  - Perform simulations to see the sensitivity to constrain the gluon OAM
- Study the QCD factorization property for hadron/**Jet** production in DIS of eA/ep
  - Solid foundation for the physical observables and compare to Heavy Ion Collisions

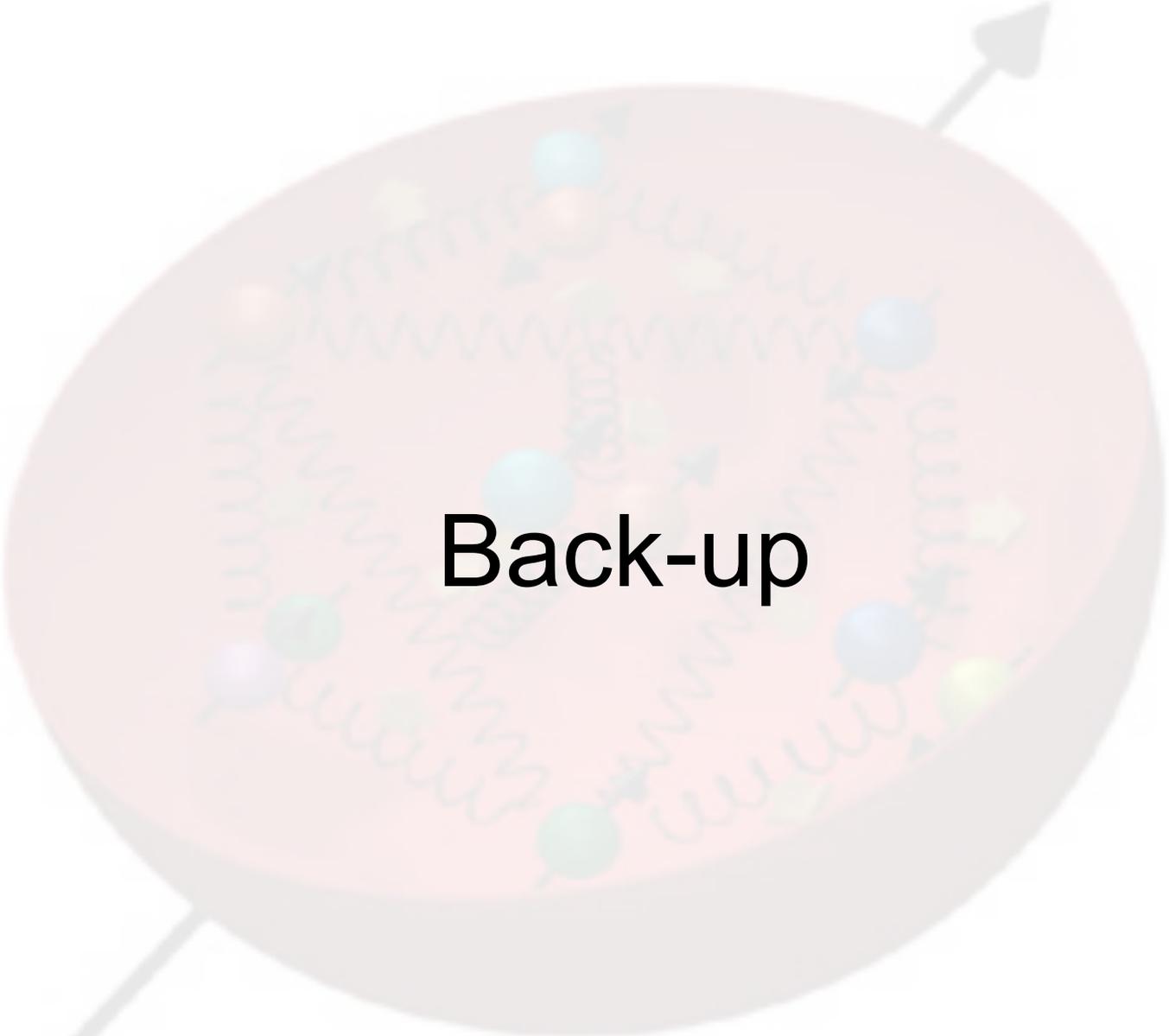
# Goal: EIC-White Paper in 2020?

- EIC is going to solve the proton spin puzzle



- Jet quenching in cold nuclei matter

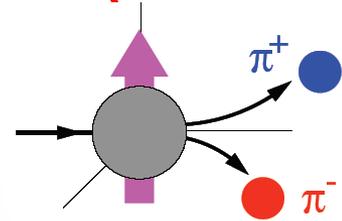




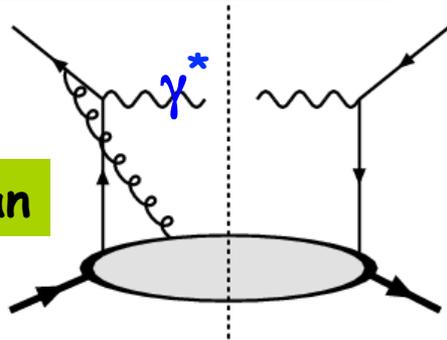
Back-up

# Single Transverse Spin Asymmetries (TMD Observables)

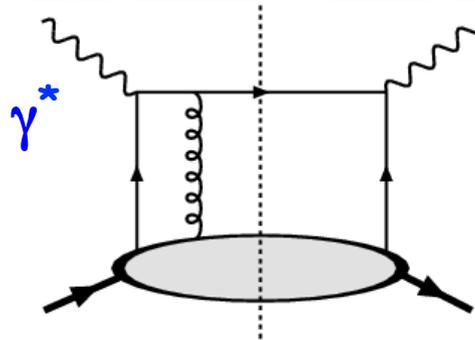
- Nontrivial prediction from QCD: Initial state vs. final state interactions



Drell-Yan



ISI



FSI

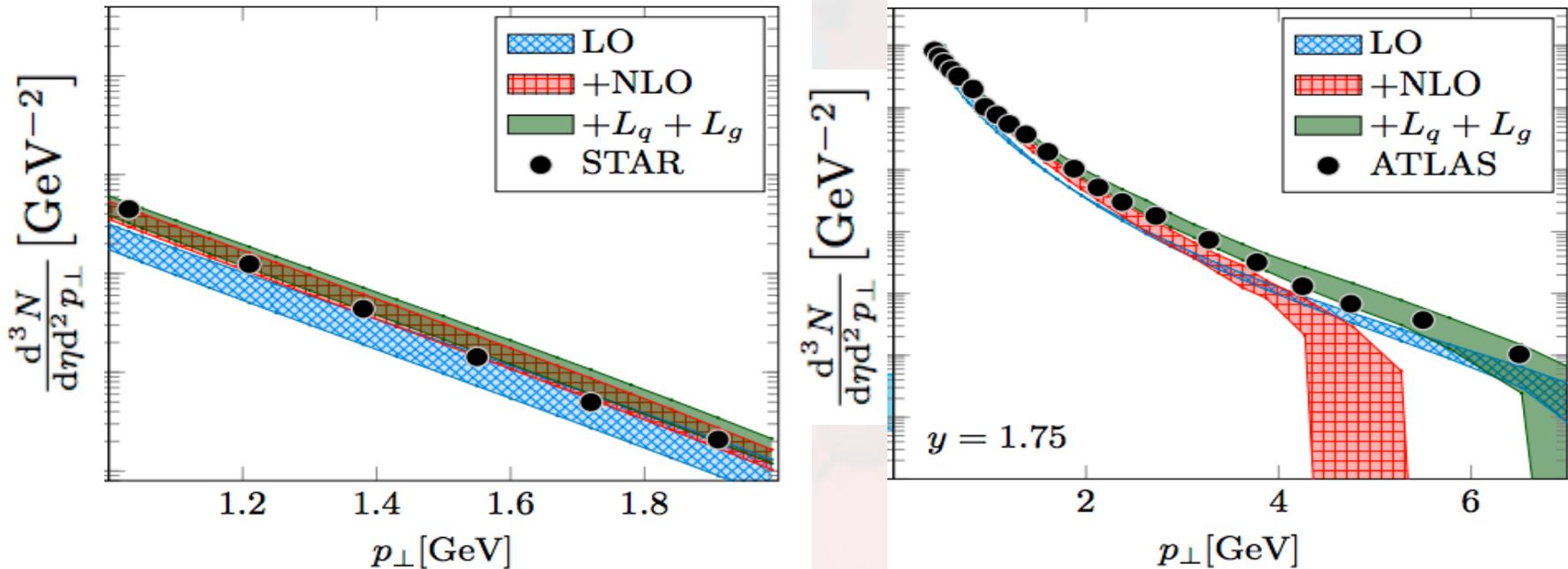
DIS

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

SSAs have been observed in DIS:  $Q^2 \sim 3\text{GeV}^2$   
 Drell-Yan:  $Q^2 \sim 20\text{GeV}^2$

Brodsky, Hwang, Schmidt 02  
 Collins, 02;  
 Ji, Yuan, 02;  
 Belitsky, Ji, Yuan, 02

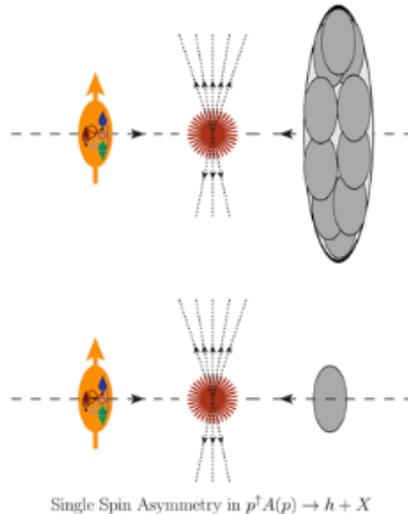
# Achieve precision for small-x physics



Forward hadron production in pA collisions at RHIC and LHC  
(based on the first NLO calculation, Chirilli-Xiao-Yuan, PRL12, PRD12)

- Match to the collinear calculations
  - Stasto-Xiao-Yuan-Zaslavsky PRD 2014
- Implement kinematic constraints
  - Watanabe-Xiao-Yuan-Zaslavsky PRD 2015

# When small-x meets spin: Single spin asymmetry in forward pA collisions



## EDITORS' SUGGESTION

### Single spin asymmetry in forward pA collisions

Using a certain hybrid approach, the authors computed the transverse single-spin asymmetry (SSA) in proton/nucleus collisions in the forward region. One of the most important results they found is that the SSA is independent of the mass number  $A$  of the target nucleus, which can be tested experimentally at the Relativistic Heavy Ion Collider (RHIC).

Yoshitaka Hatta, Bo-Wen Xiao, Shinsuke Yoshida, and Feng Yuan

[Phys. Rev. D \*\*94\*\*, 054013 \(2016\)](#)