New opportunities of QCD jets for the three-dimensional hadron structure

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第二届强子与重味物理理论与实验联合研讨会　兰州大学　25-29 March 2021

Introduction

One of the most important discoveries in hadron physics over the past decades is the measurements of large spin asymmetries

VOLUME 41, NUMBER 25 PHYSICAL REVIEW LETTERS 18 DECEMBER 1978

Transverse Quark Polarization in Large-p_T Reactions, e^+e^- Jets, and Leptoproduction: A Test of Quantum Chromodynamics

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and

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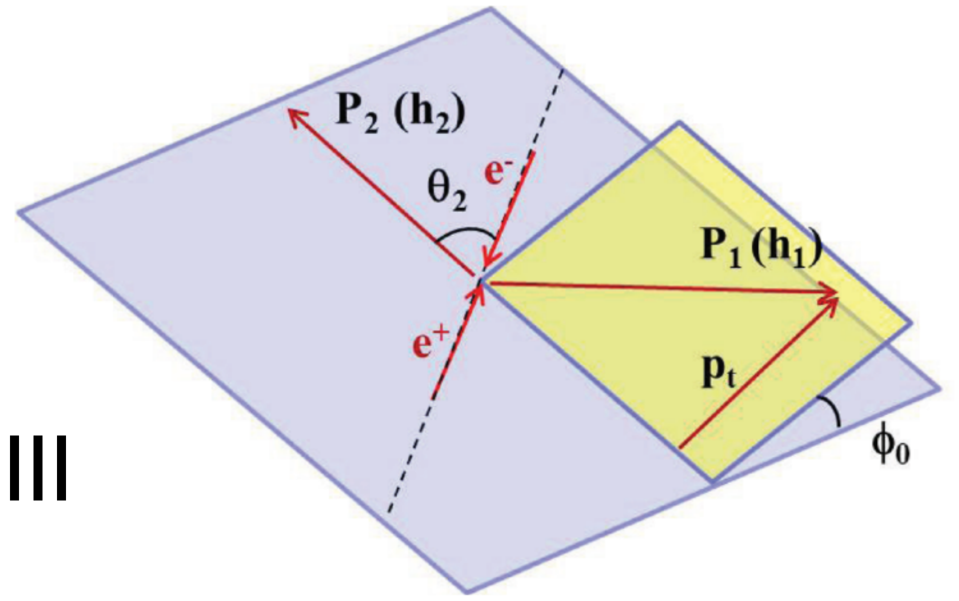
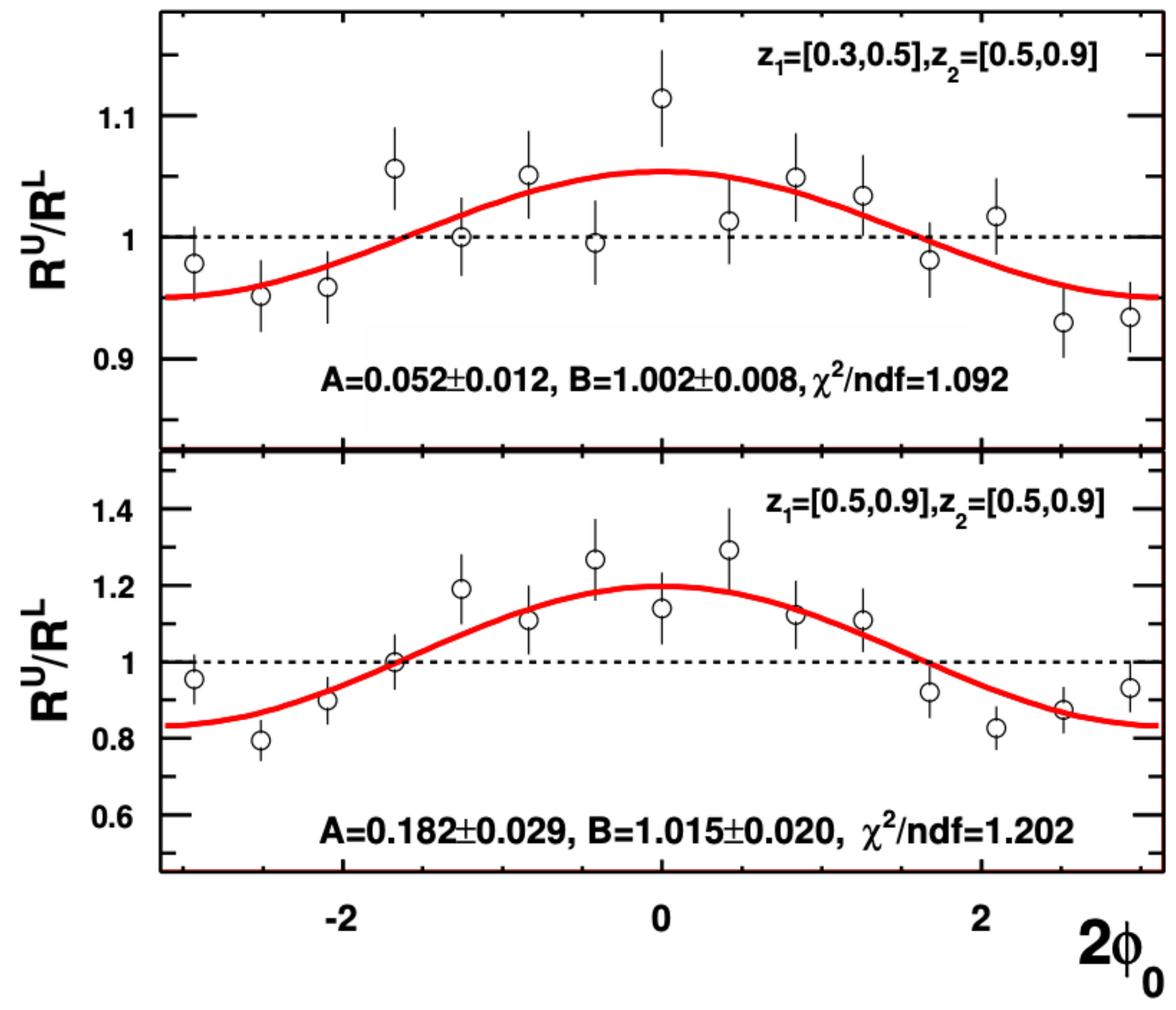
(Received 5 July 1978)

quarks. We discuss how to test the predictions. At least for the cases when P is small, tests should be available soon in large-p_T production [where currently $P(\Lambda) = 25\%$ for $p_T \gtrsim 2$ GeV/c], and e^+e^- reactions. While fragmentation effects could dilute polarizations, they cannot (by parity considerations) induce polarization. Consequently, observation of significant polarizations in the above reactions would contradict either QCD or its applicability.

E.g. Collins asymmetry at BESIII





These experimental measurements can be used to probe the internal structure of hadrons

Future Electron-Ion Colliders

January 9, 2020

- High luminosity

  $10^{33-34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Center-of-mass energy

  $\sqrt{s} = 20 - 140\ \mathrm{GeV}$
- Highly polarized beams
- Electron-proton/nucleus collisions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Department of Energy

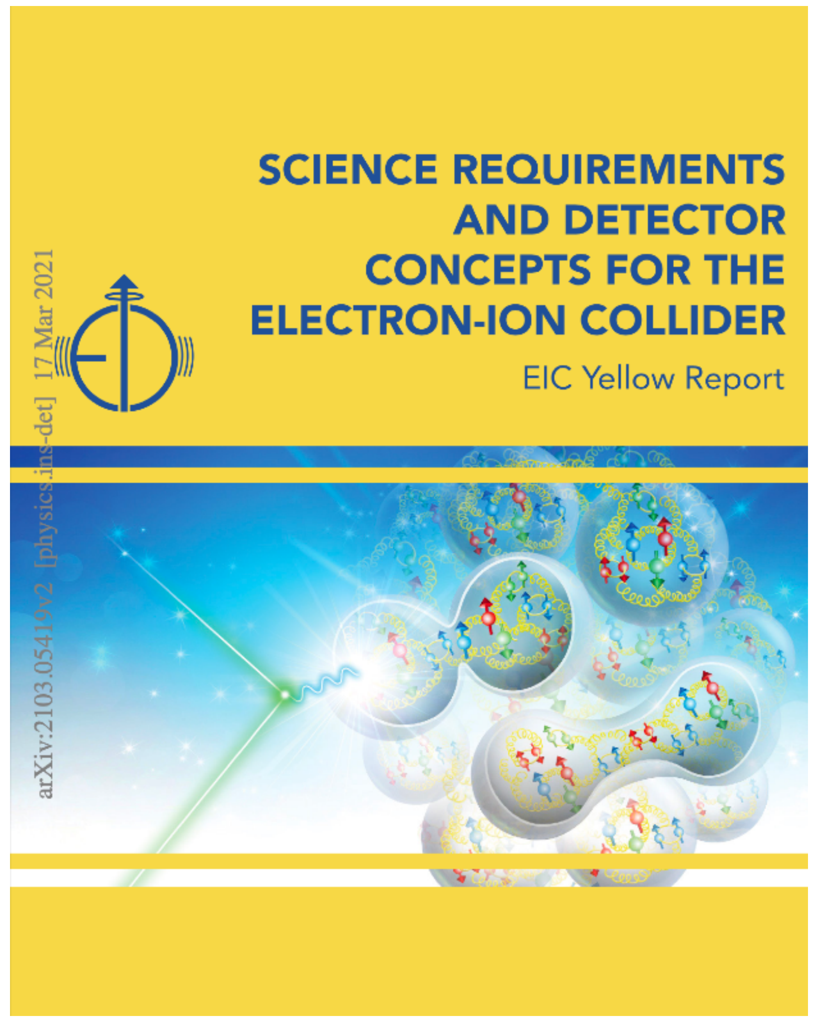
U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

JANUARY 9, 2020

Home » U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

WASHINGTON, D.C. – Today, the **U.S. Department of Energy (DOE)** announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.

The Electron Ion Collider (EIC), to be designed and constructed over ten years at an estimated cost between $1.6 and $2.6 billion, will smash electrons into protons and heavier atomic nuclei in an effort to penetrate the mysteries of the "strong force" that binds the atomic nucleus together.




第 43 卷 第 2 期　核　技　术　Vol.43, No.2
2020 年 2 月　NUCLEAR TECHNIQUES　February 2020

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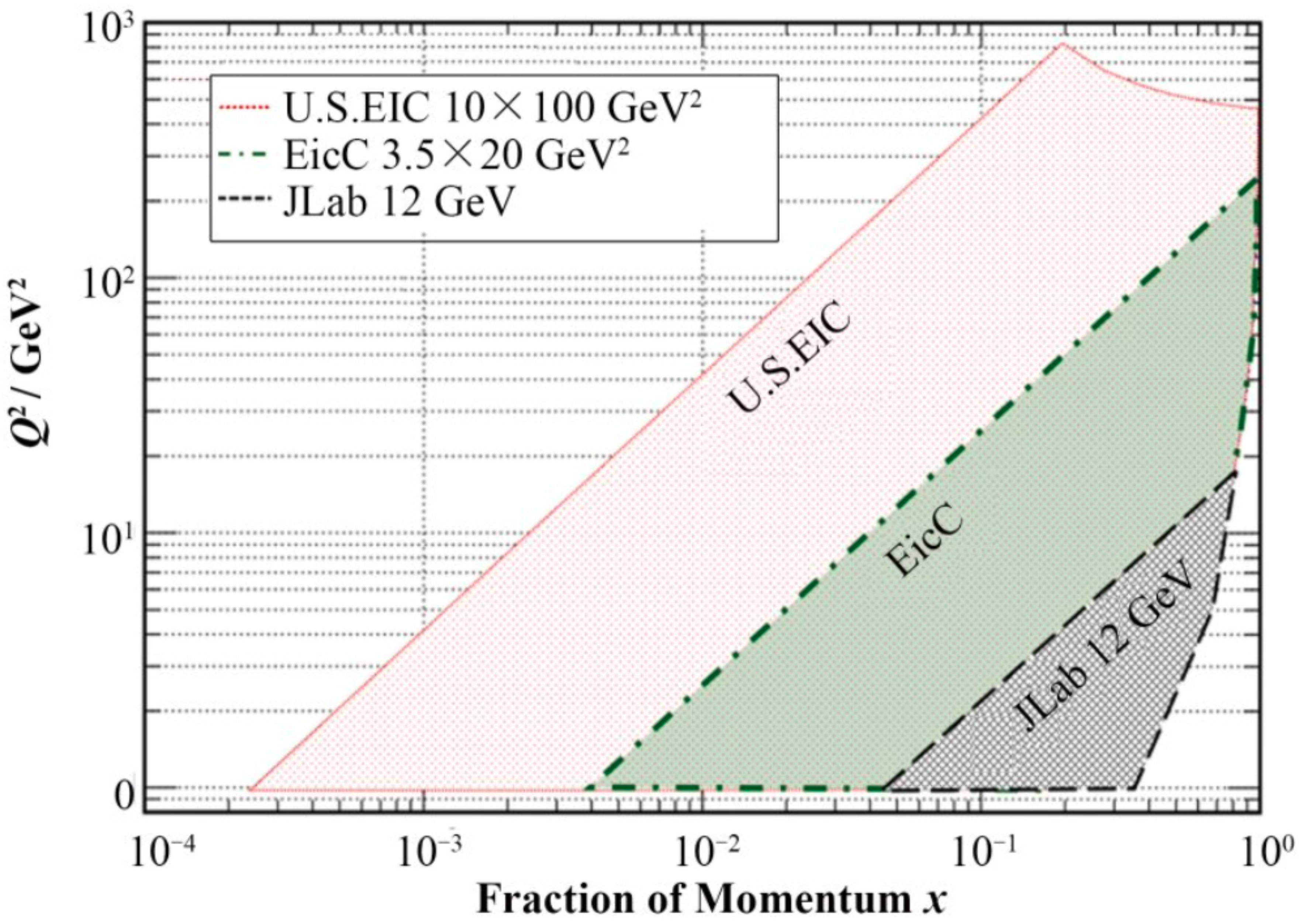
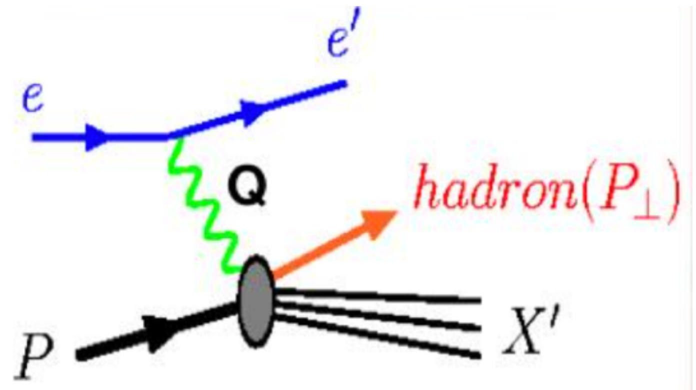
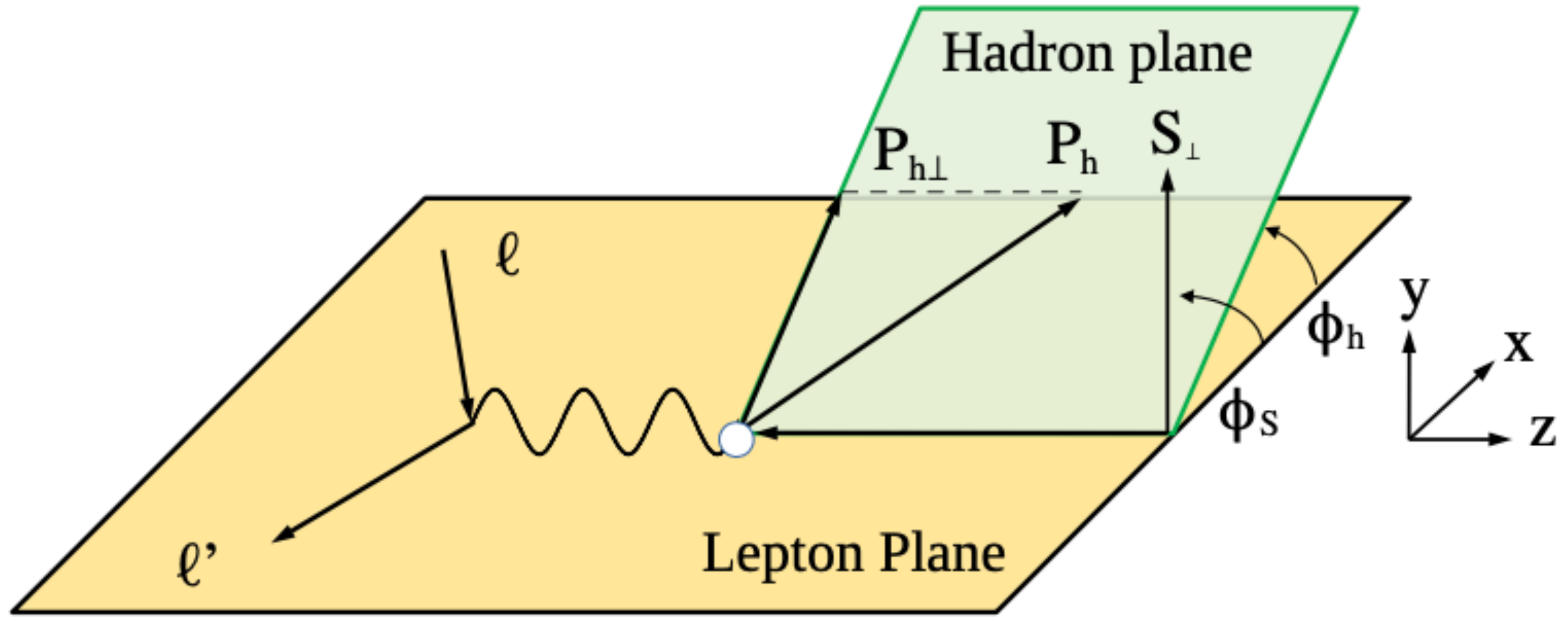


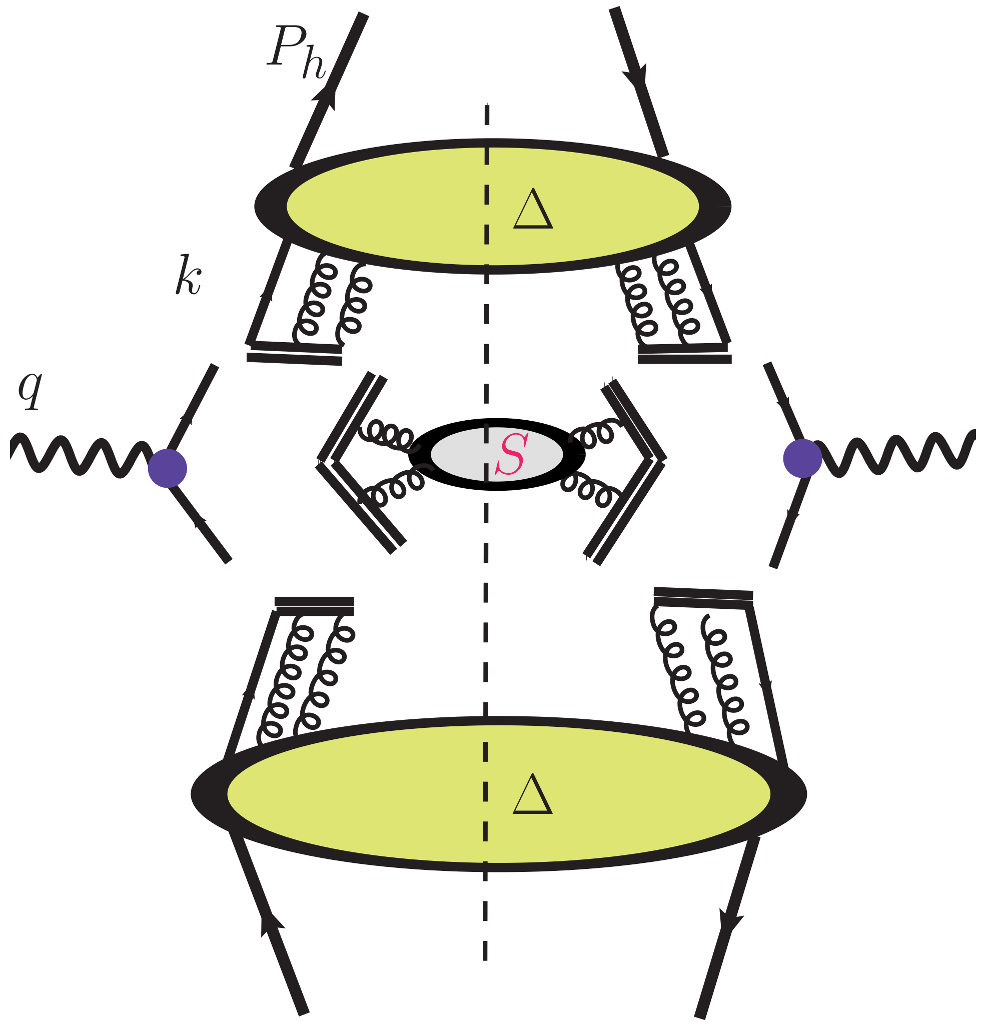
Sivers Formalism in Semi-Inclusive DIS

$$e(\ell) + p\,(P, \mathbf{S}_\perp) \to e\,(\ell') + h\,(P_h) + X$$



TMD factorization theorems have been "well" established





$$W^{\mu\nu} \overset{\text{prelim}}{=} \frac{8\pi^3 z_A z_B}{Q^2} \sum_f \mathrm{Tr}\, k^+_{A,\gamma}\gamma^- H^\nu_f(Q)\, k^-_{B,\gamma}\gamma^+ \overline{H}^\mu_f(Q)$$

$$\times \int \frac{\mathrm{d}^{2-2\epsilon}\boldsymbol{b}_\mathrm{T}}{(2\pi)^{2-2\epsilon}} e^{-i\boldsymbol{q}_{h\mathrm{T}}\cdot\boldsymbol{b}_\mathrm{T}}\, \tilde{S}(b_\mathrm{T}) \tilde{D}_{1,\,H_A/f}(z_A, b_\mathrm{T})\, \tilde{D}_{1,\,H_B/\bar{f}}(z_B, b_\mathrm{T})$$

$$+ \text{polarized terms.}$$

$$\frac{d\sigma}{d\mathcal{PS}} = \sigma_0^{\mathrm{DIS}} \left[F_{UU} + \sin(\phi_h - \phi_s) F_{UT}^{\sin(\phi_h - \phi_s)} \right]$$

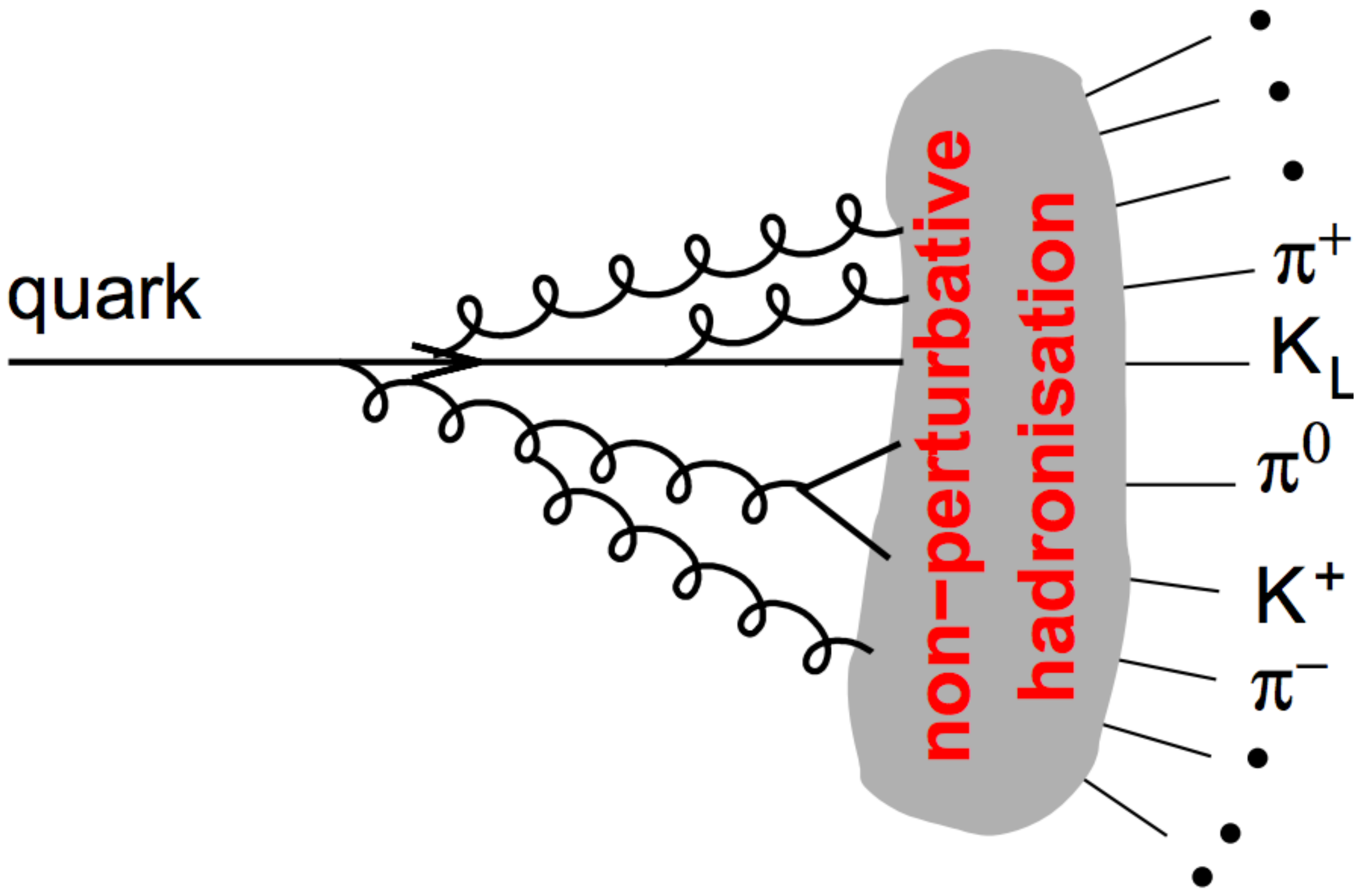
Collins-Soper-Sterman, Ji-Ma-Yuan, Soft-Collinear Effective Theory ……

Power corrections see A. P. Chen & J.P. Ma '16; Ebert *et.al.* '18 ……

Lattice QCD results on the TMD soft function An Qi Zhang et.al. '20 PRL

Parton (quark or gluon) fragmentation and hadronization

High-energy partons lead to collimated bunches of hadrons



From short to long distances in quantum field theory

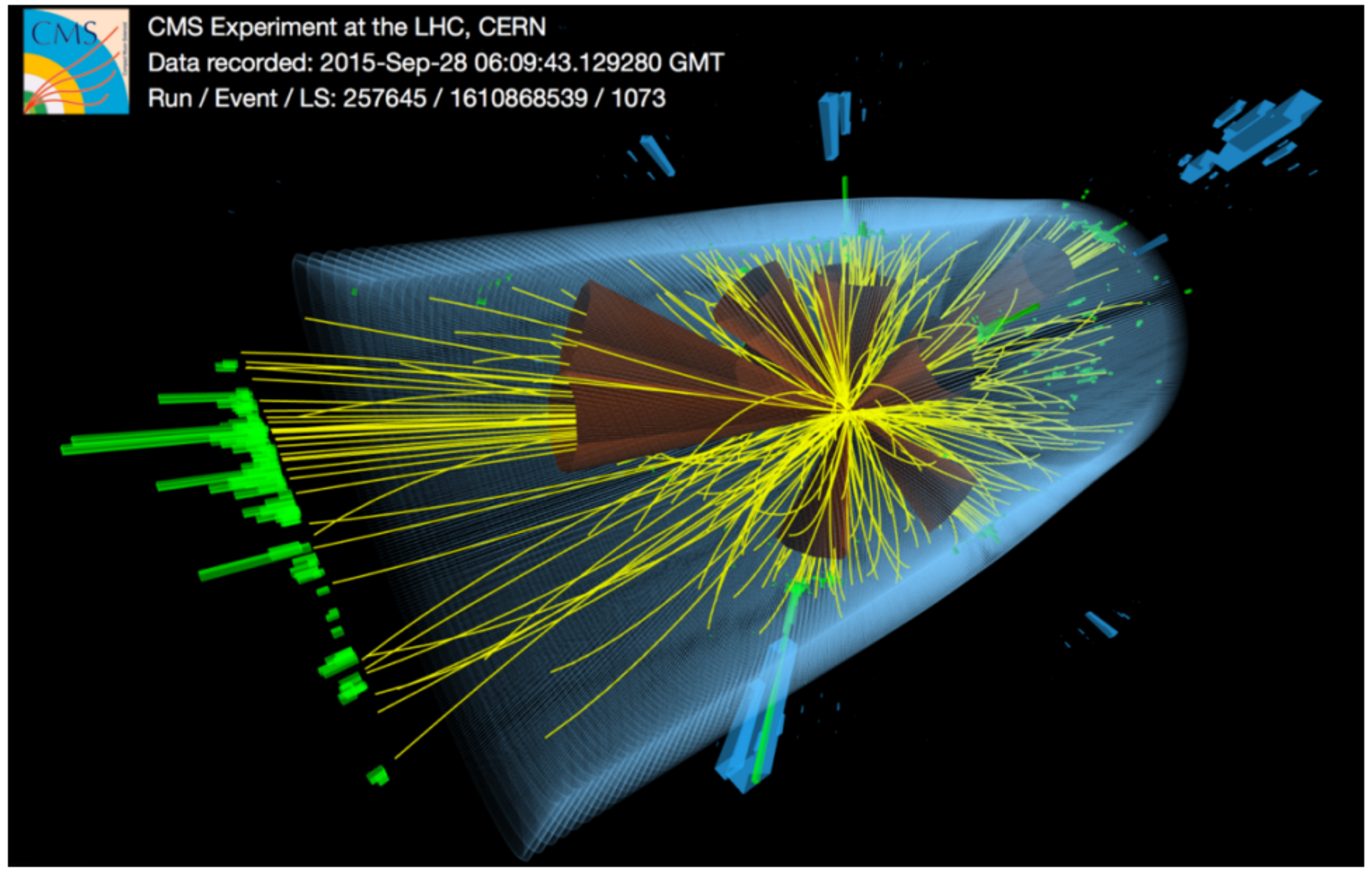
$$J\,(\text{ scale } \mu_2) \sim J\,(\text{scale}\,\mu_1)\exp\left[\int_{\mu_1}^{\mu_2}\frac{d\mu'}{\mu'}\int dx P\left(x,\alpha_s\left(\mu'\right)\right)\right]$$

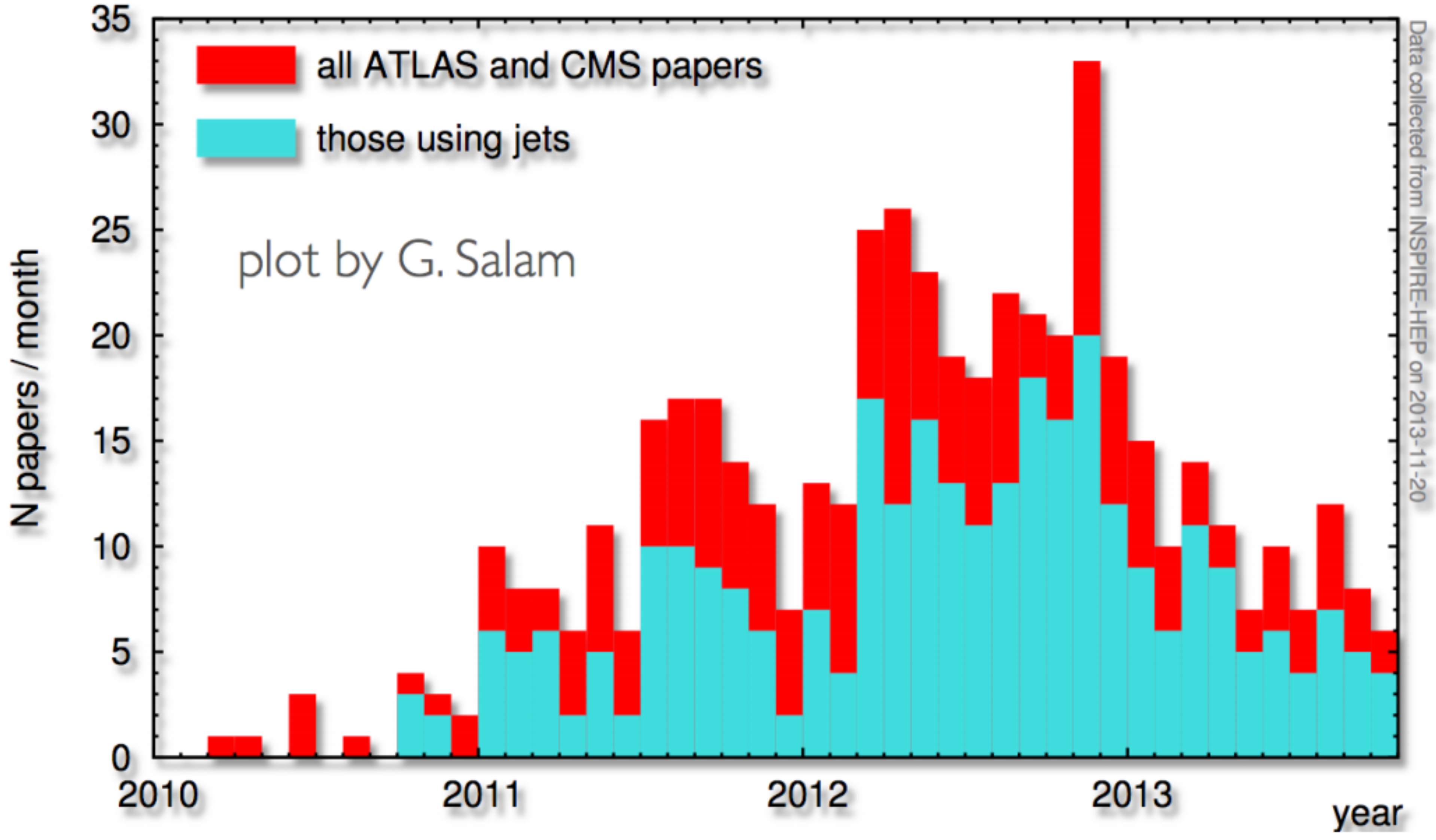
TMD resummation Sun, Yuan, Yuan `14,`15 PRL
Jet Effective theory Becher, Neubert, Rothen, DYS, '16 PRL
Threshold resummation Liu, Moch, Ringer '17 PRL
Energy-energy correlation Gao, Li, Moult, Zhu, '19 PRL
……

Jets are not the same as partons

Jets inherit quantum property of partons

Jets at the LHC

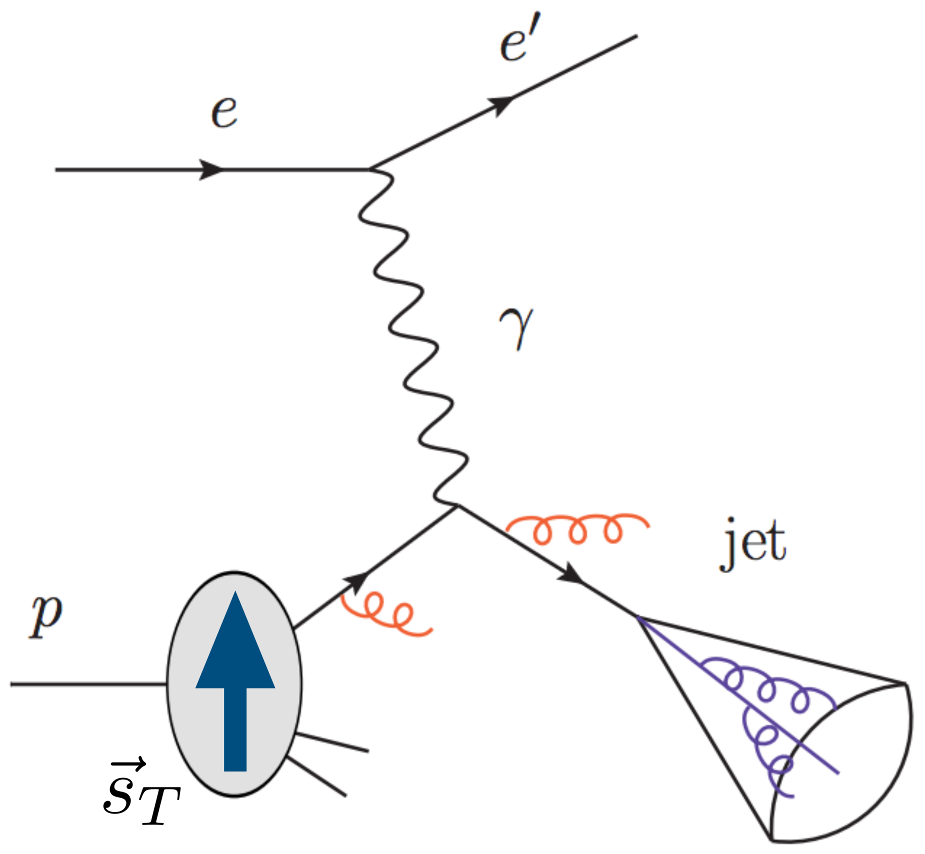


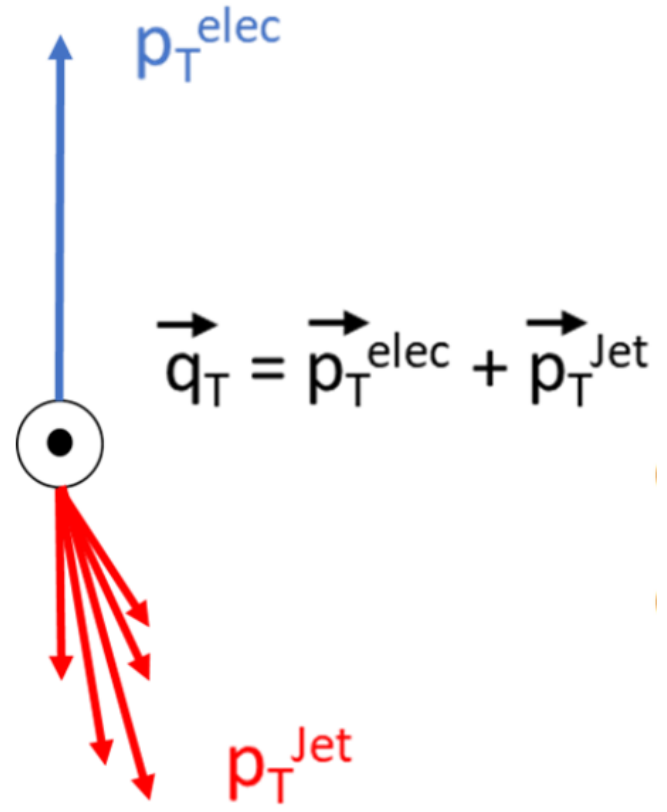


- **Jets are produced copiously at the LHC**
- **At the LHC, 60 - 70 % of ATLAS & CMS papers use jets in their analysis!**

QCD jets and 3D proton imaging at the EIC

Liu, Ringer, Vogelsang, Yuan ’19 PRL, ……

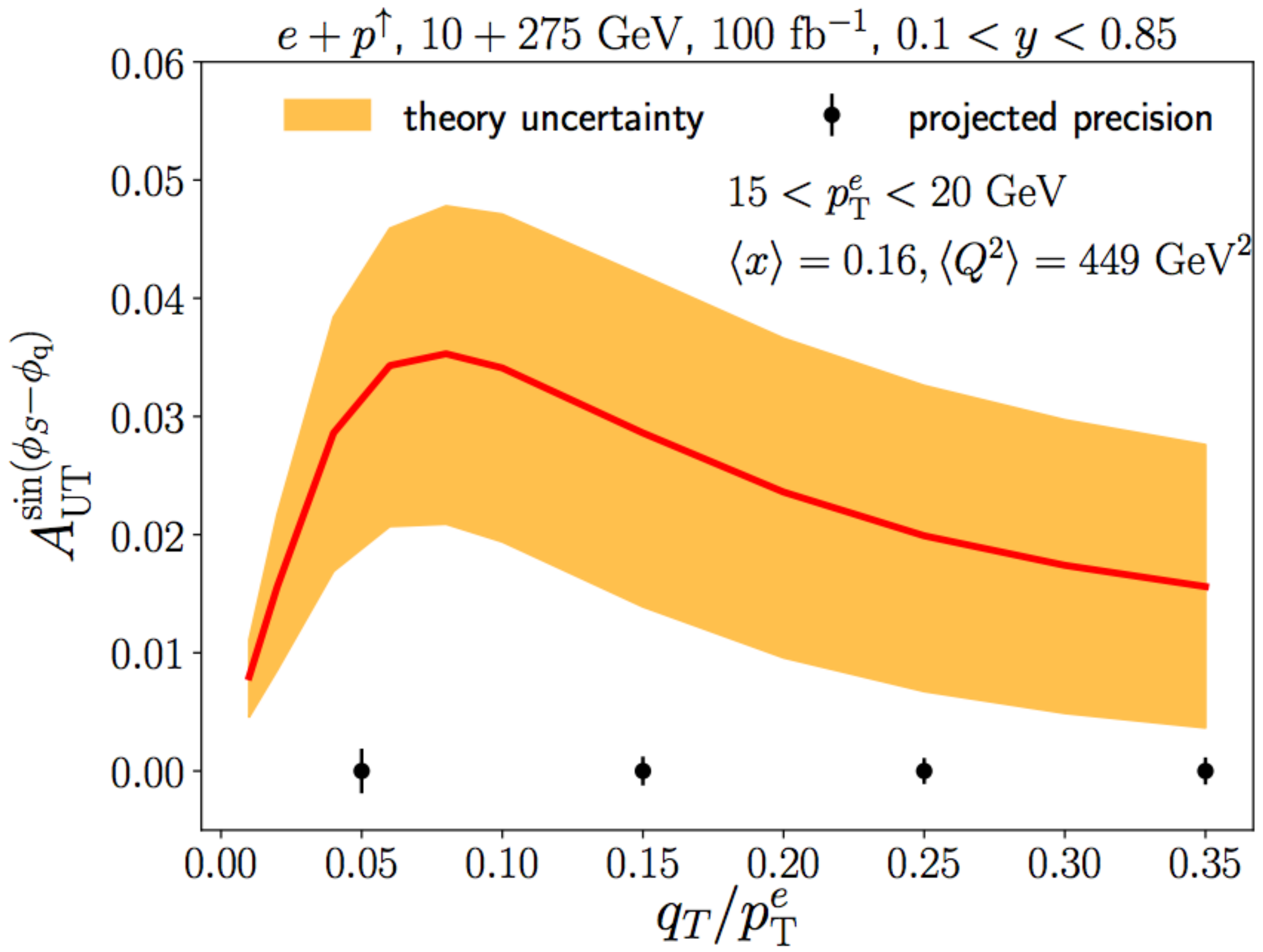




Spin-dependent cross section:

$$\frac{d\sigma(\vec{s}_T)}{d\mathcal{PS}} = F_{UU} + \sin(\phi_s - \phi_q) F_{UT}^{\sin(\phi_s-\phi_q)}$$

quark TMDs: $f_q(x, k_T)$ $\quad \frac{1}{M}\epsilon_{\alpha\beta}\, s_T^\alpha\, k_T^\beta\, f_{1T}^{\perp q}(x, k_T)$

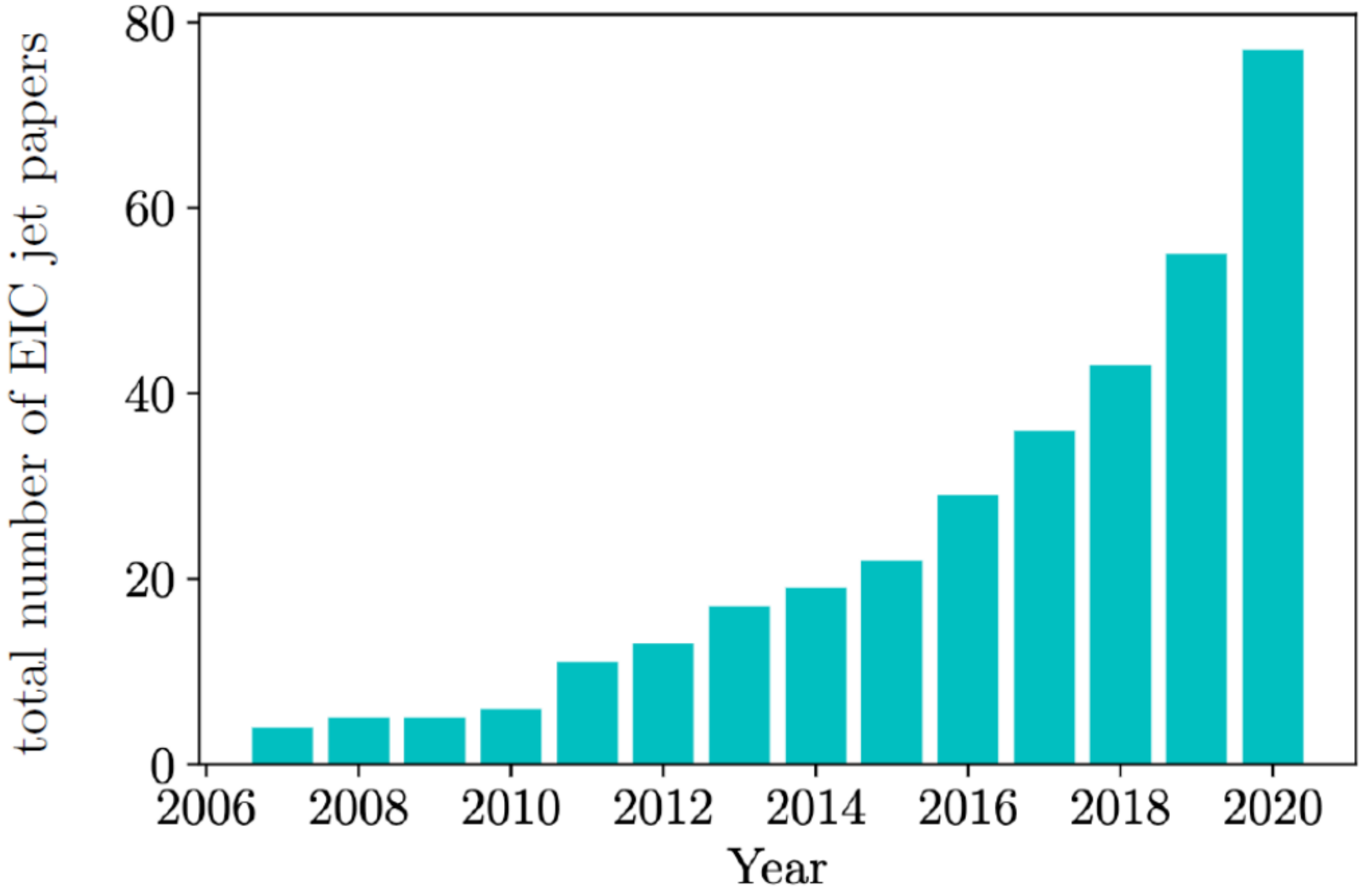


Arratia, Kang, Prokudin, Ringer ‘19

- Jets are complementary to standard SIDIS extractions of TMDs
- Jet measurements allow independent constraints on TMD PDFs and FFs from a single measurement
- Azimuthal correlation between jet and lepton sensitive to TMD PDFs
- Precision measurement on the spin asymmetry, need precision theory calculation

Jets at the EIC

- low $p_{T,J}$
- smaller jet multiplicity
- less contamination from underlying events and pileups



Different environment compared with the LHC

new opportunities and new challenges!!!

Gluon Sivers function (GSF)

- **Gauge link dependent gluon TMDs**

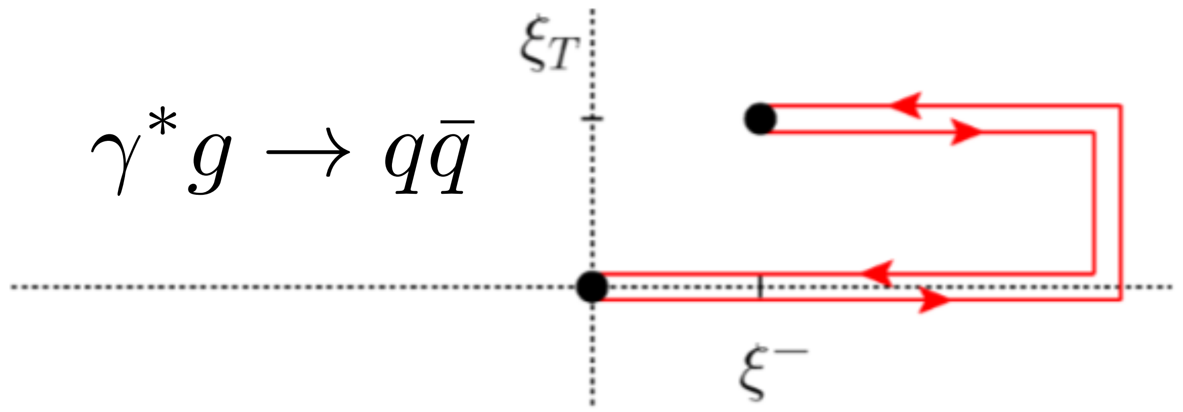
$$\Gamma^{[U,U']\mu\nu}(x,p_T;n) = \int \frac{d\xi\cdot P d^2\xi_T}{(2\pi)^3} e^{ip\cdot\xi}\langle P,S|F^{n\mu}(0)\,U_{[0,\xi]}F^{n\nu}(\xi)U'_{[\xi,0]}|P,S\rangle\Big|_{\rm LF}$$

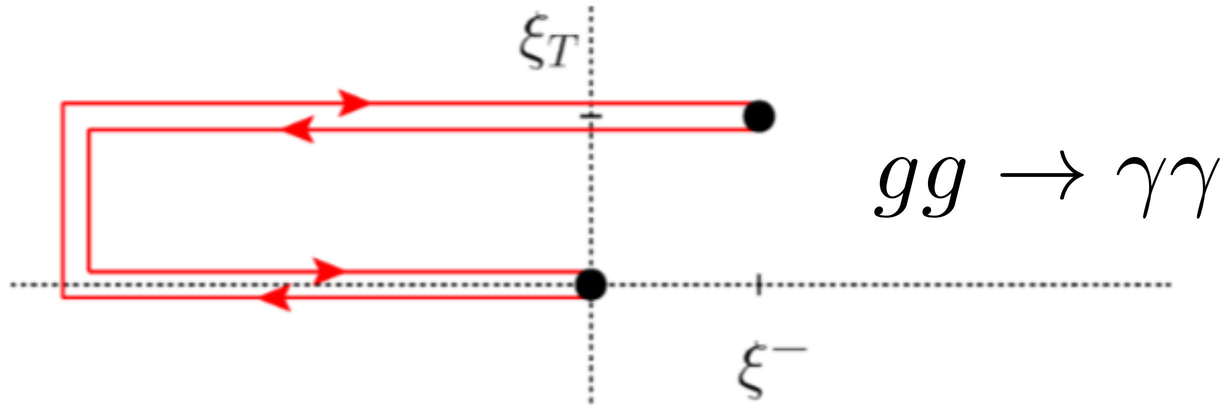
- **GSF: T-odd object; two gauge links; process dependence more involved**
- **For any process GSF can be expressed in terms of two functions:** (Buffing, Mukherjee, Mulders'13)

$$f_{1T}^{\perp g[U]}\left(x,\mathbf{k}_\perp^2\right) = \sum_{c=1}^{2} C_{G,c}^{[U]} f_{1T}^{\perp g(Ac)}\left(x,\mathbf{k}_\perp^2\right)$$

calculable for each channel

- **f-type, C-even** $f_{1T}^{\perp g(f)}$
- **d-type, C-odd** $f_{1T}^{\perp g(d)}$





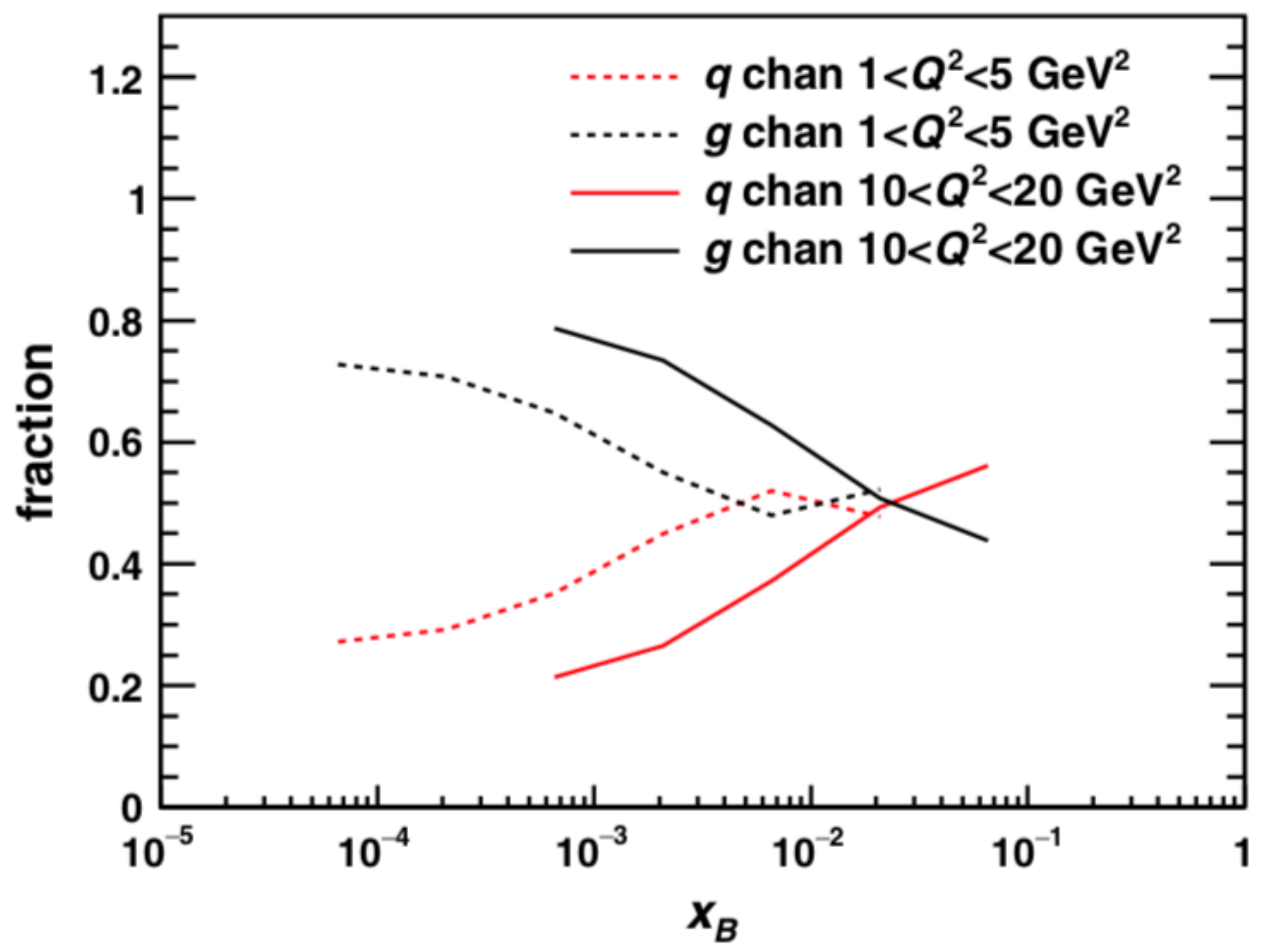
$$f_{1T}^{\perp g[e\,p^\uparrow\to e'\,Q\bar{Q}\,X]}(x,p_T^2) = -f_{1T}^{\perp g[p^\uparrow\,p\to\gamma\,\gamma\,X]}(x,p_T^2)$$

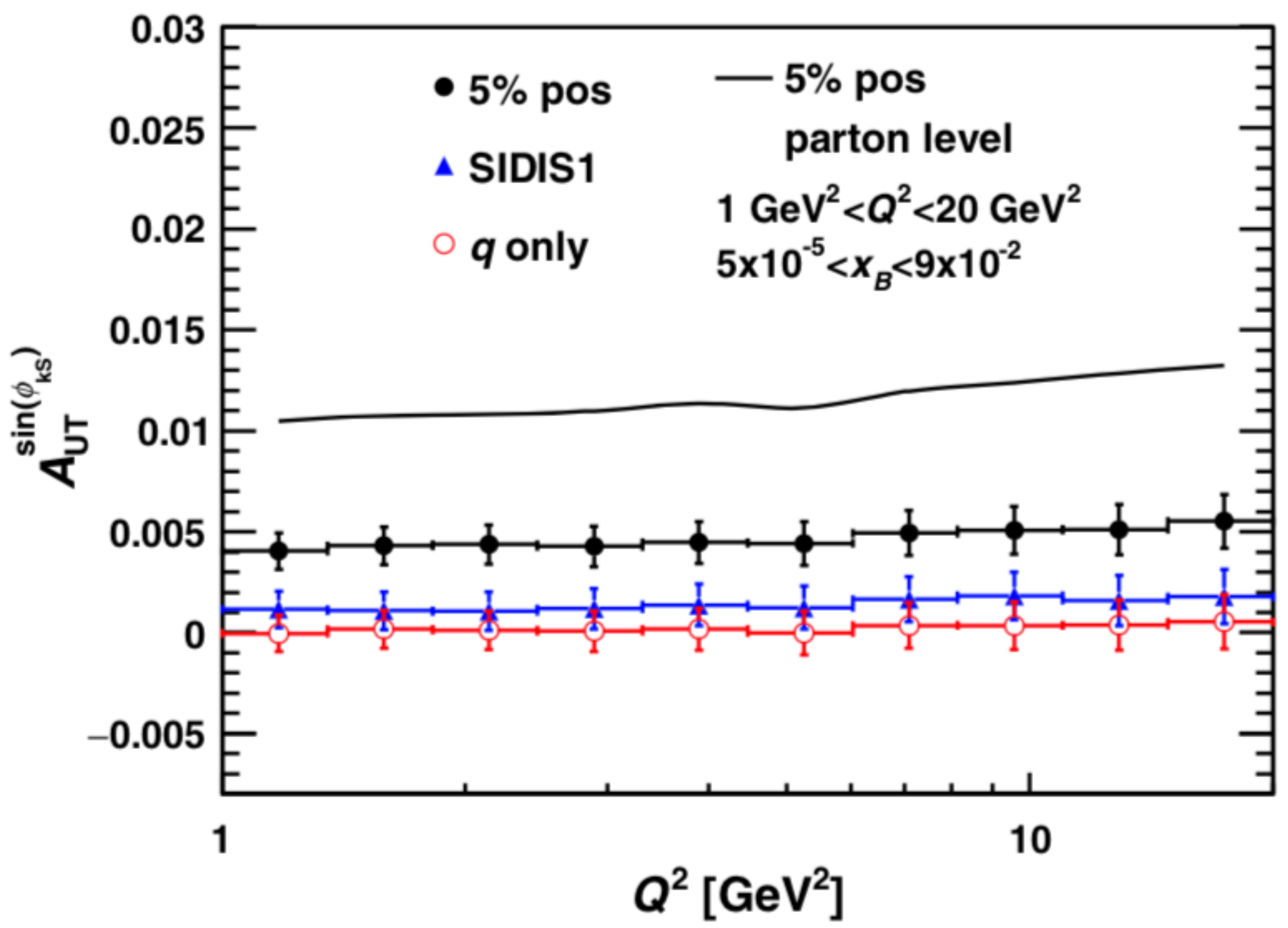
Gluon Sivers function and spin asymmetry in di-jet

At the EIC , accessing of GSF via high-p_T dihadron, open di-charm, di-D-meson and dijet has been investigated using PYTHIA and reweighing methods in Zheng, Aschenauer, Lee, Xiao, Yin ’18

- **They find that dijet process is the most promising channel**

At the LO di-jet production in DIS involves two processes: $\gamma^* q \to qg \qquad \gamma^* g \to q\bar{q}$

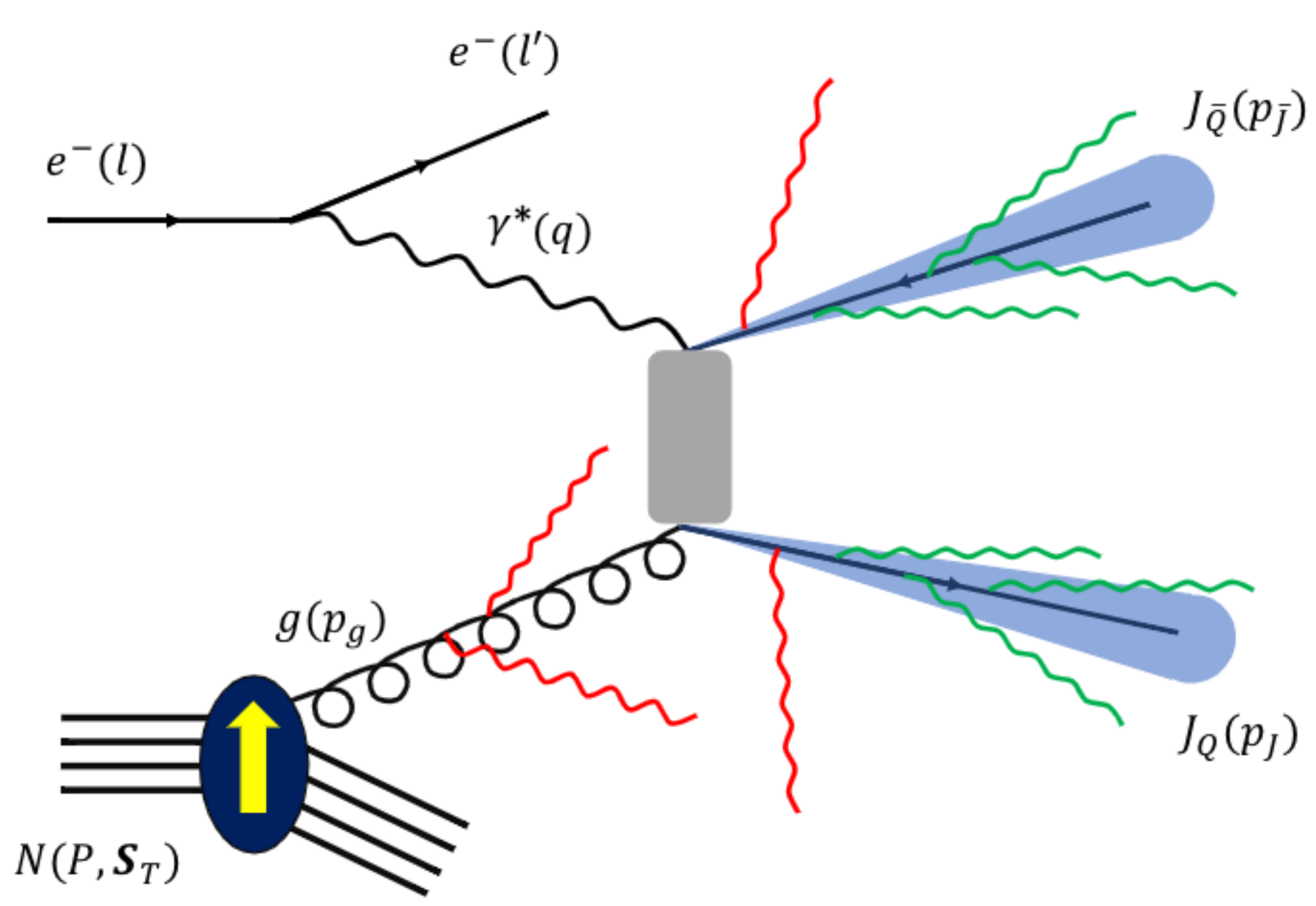


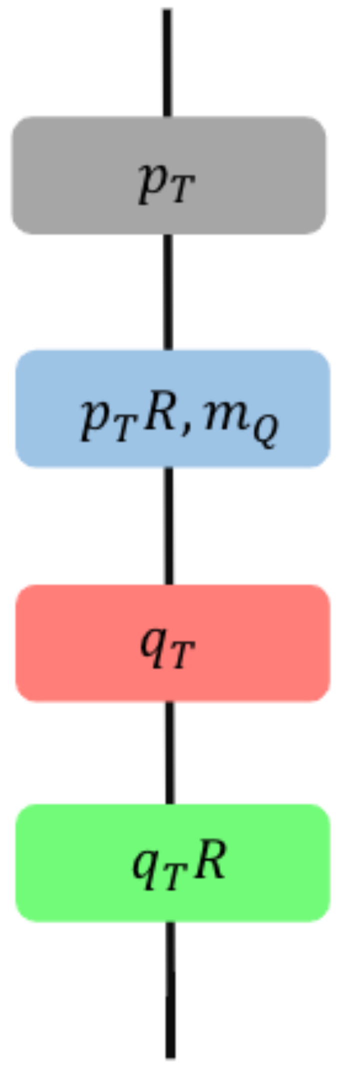


- **to distinguish different TMDs “Jets inherit quantum property of partons”**
  - **Jet substructure (e.g. jet charge “different quark TMDs”** Kang, Liu, Mantry, DYS ’20 PRL**)**
  - **Heavy-flavor (HF) dijet processes, where q-channel starts to contribute beyond the LO** (Kang, Reiten, DYS, Terry `20)

TMD factorization for heavy-flavor dijet production in DIS

(Kang, Reiten, DYS, Terry ’20)





$q_T \ll p_T$

$m_Q \lesssim p_T R \ll p_T$

the factorized form of the spin-independent cross section

$$d\sigma^{UU} \sim H(Q, p_T) J_Q(p_T R, m_Q) J_{\bar{Q}}(p_T R, m_Q) S(\boldsymbol{\lambda}_T) f_g(\boldsymbol{k}_T) S^c_Q(\boldsymbol{l}_{QT}) S^c_{\bar{Q}}(\boldsymbol{l}_{\bar{Q}T}) \delta^{(2)}(\boldsymbol{k}_T + \boldsymbol{\lambda}_T + \boldsymbol{l}_{QT} + \boldsymbol{l}_{\bar{Q}T} - \boldsymbol{q}_T)$$

- **Hard and soft functions are the same as light-jet cases, since $p_T \gg m_Q$**
- **Jet and collinear-soft functions are new, which receive finite quark mass correction**

Numerical results

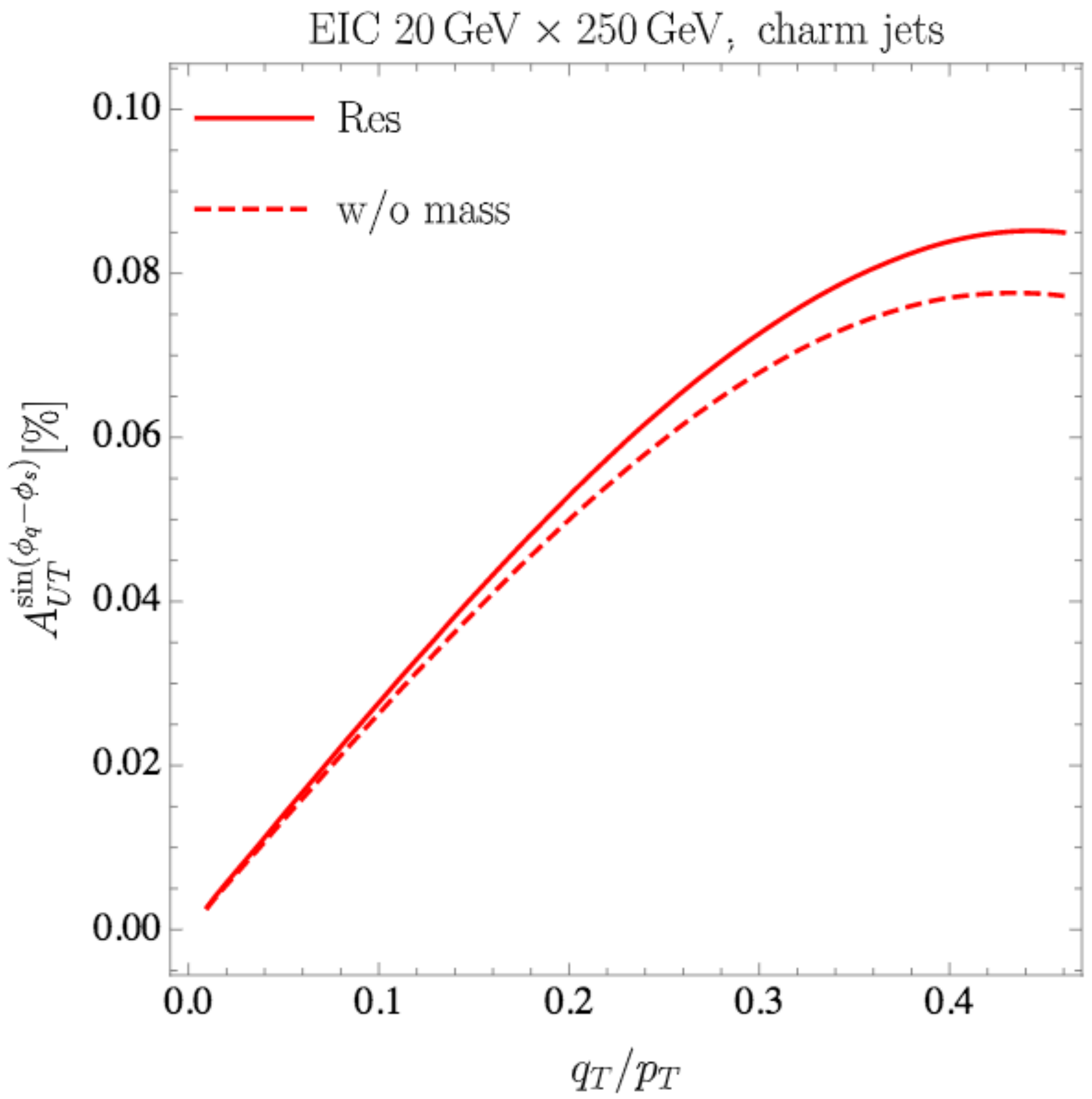
Anti-k$_T$, R=0.6

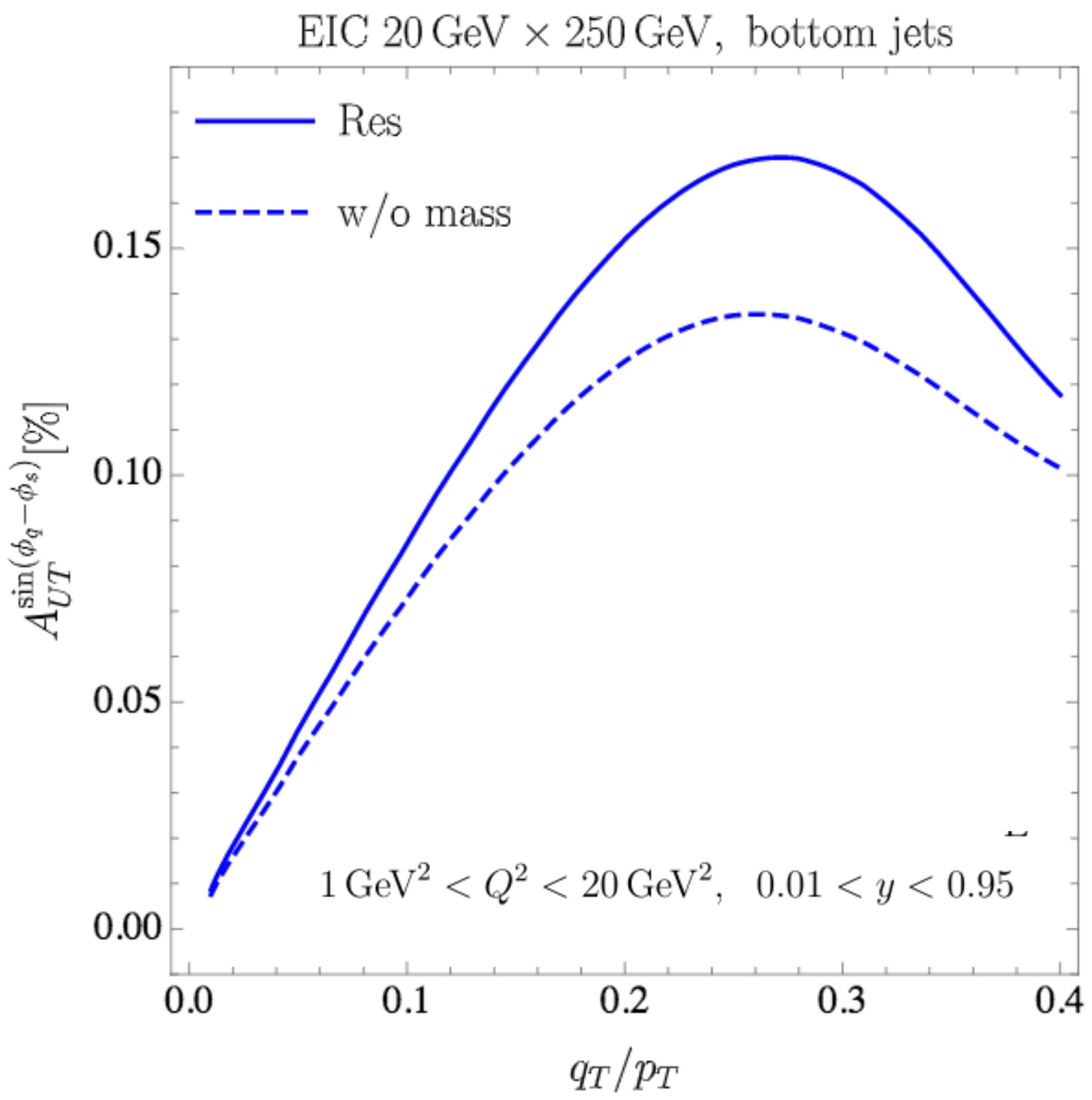
c-jets: $5\,\text{GeV} < p_T < 10\,\text{GeV}, \quad |\eta_J| < 4.5,$

b-jets: $10\,\text{GeV} < p_T < 15\,\text{GeV}, \quad |\eta_J| < 4.5,$

$$d\sigma(\boldsymbol{S}_T) = d\sigma^{UU} + \sin(\phi_q - \phi_s) d\sigma^{UT}$$

$$A_{UT}^{\sin(\phi_q-\phi_s)} = \frac{d\sigma^{UT}}{d\sigma^{UU}}$$



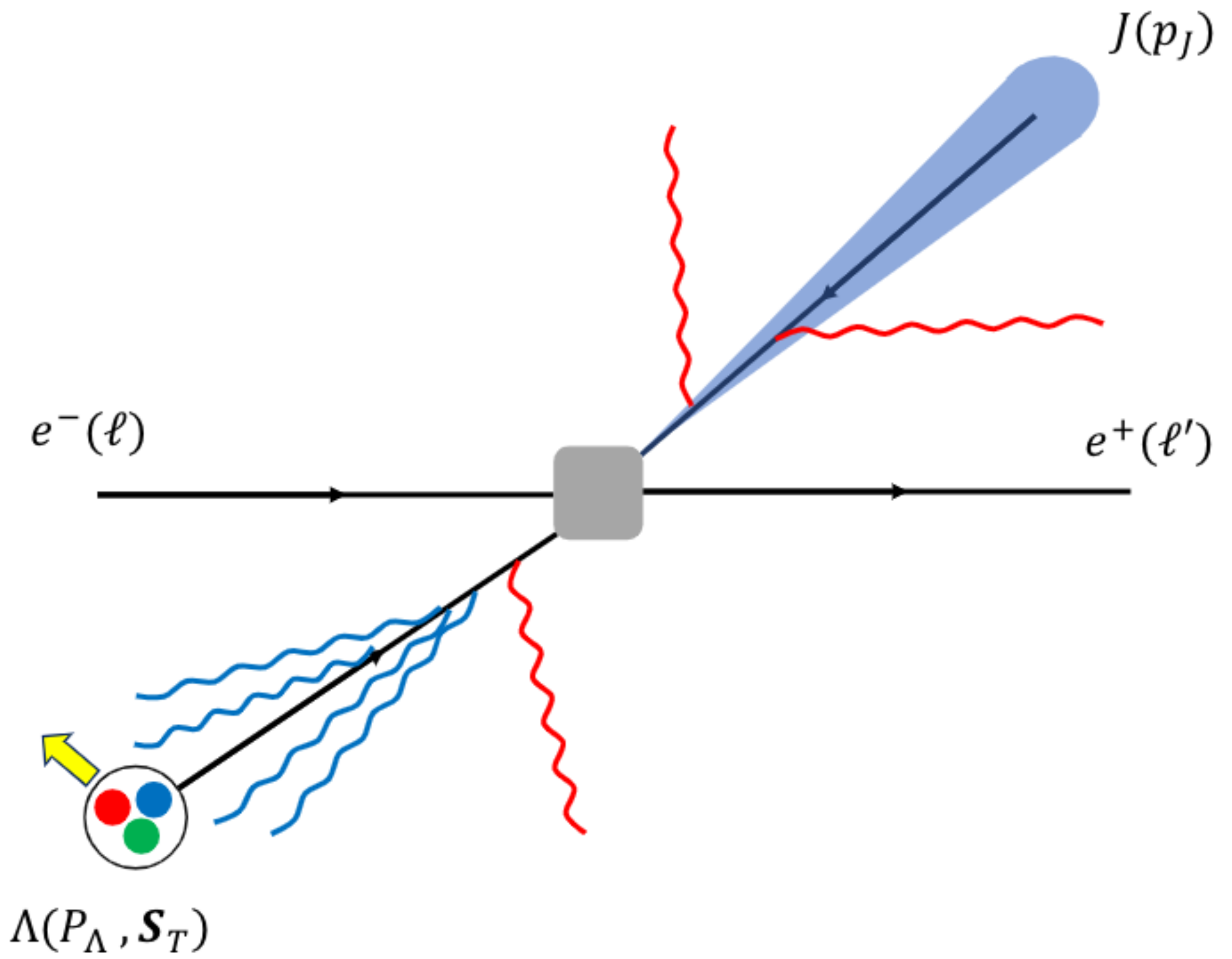


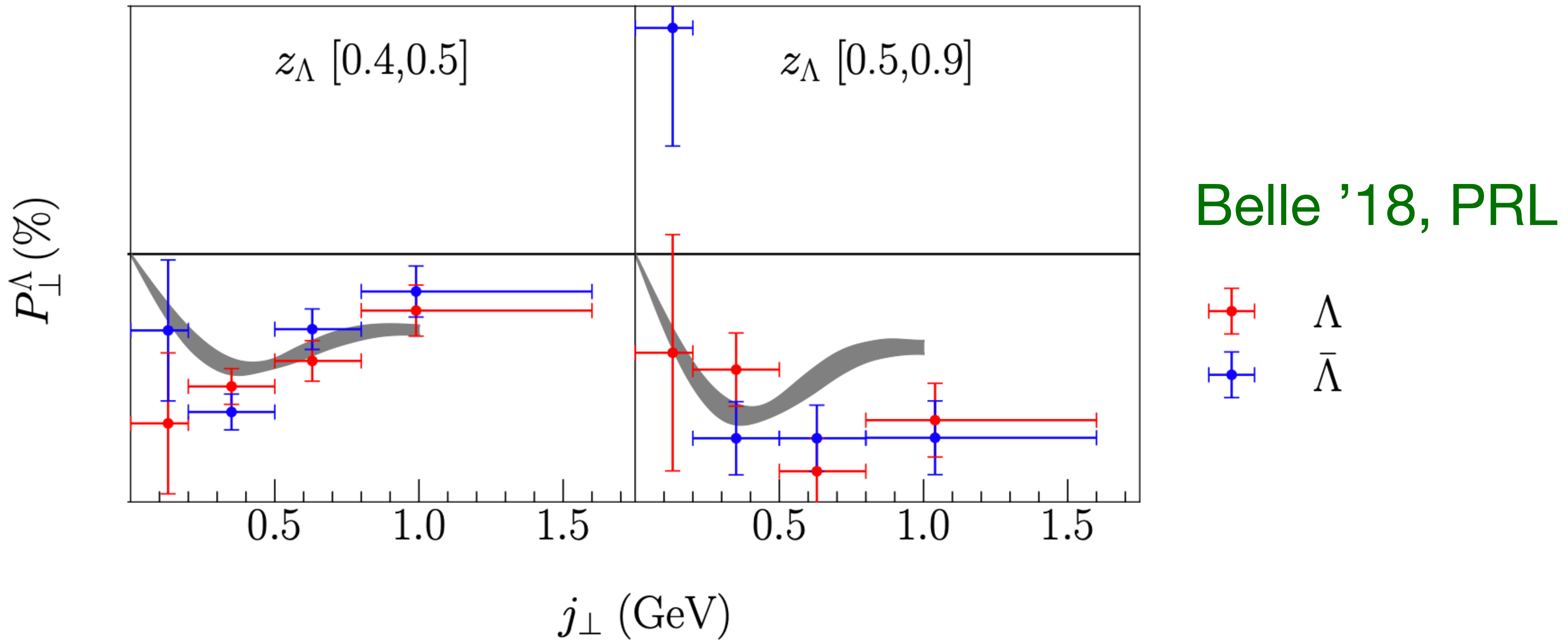
Mass effects can give sizable corrections to the predicted asymmetry

Jets and transverse Lambda polarization

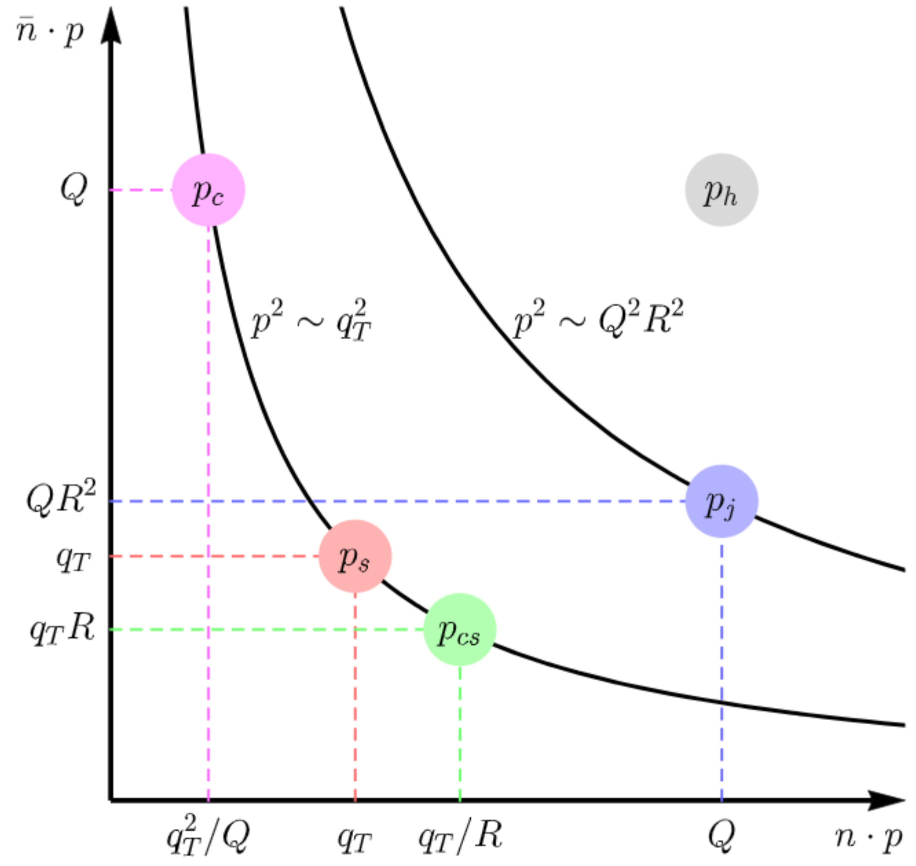
(Becher, Rahn, DYS '17; Kang, DYS, Zhao '20; Gamberg, Kang, DYS, Terry, Zhao '21, in progress)

$$e^-(\ell) + e^+(\ell') \to J(p_J) + \Lambda(P_\Lambda, \boldsymbol{S}_T) + X$$

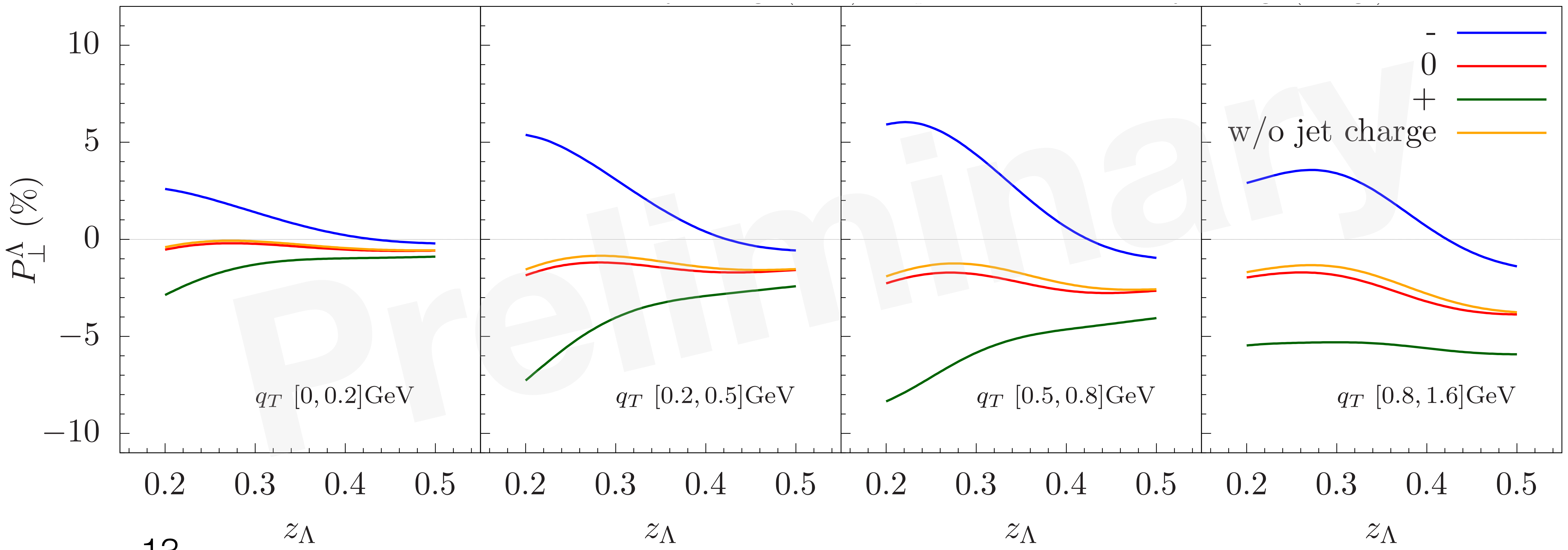




- hard: $p_h \sim Q(1,1,1)$,
- soft: $p_s \sim q_T(1,1,1)$,
- collinear: $p_c \sim (q_T^2/Q, Q, q_T)$,
- jet: $p_j \sim Q(1, R^2, R)$,
- collinear-soft: $p_{cs} \sim q_T/R(1, R^2, R)$,



Polarization w/ jet charge



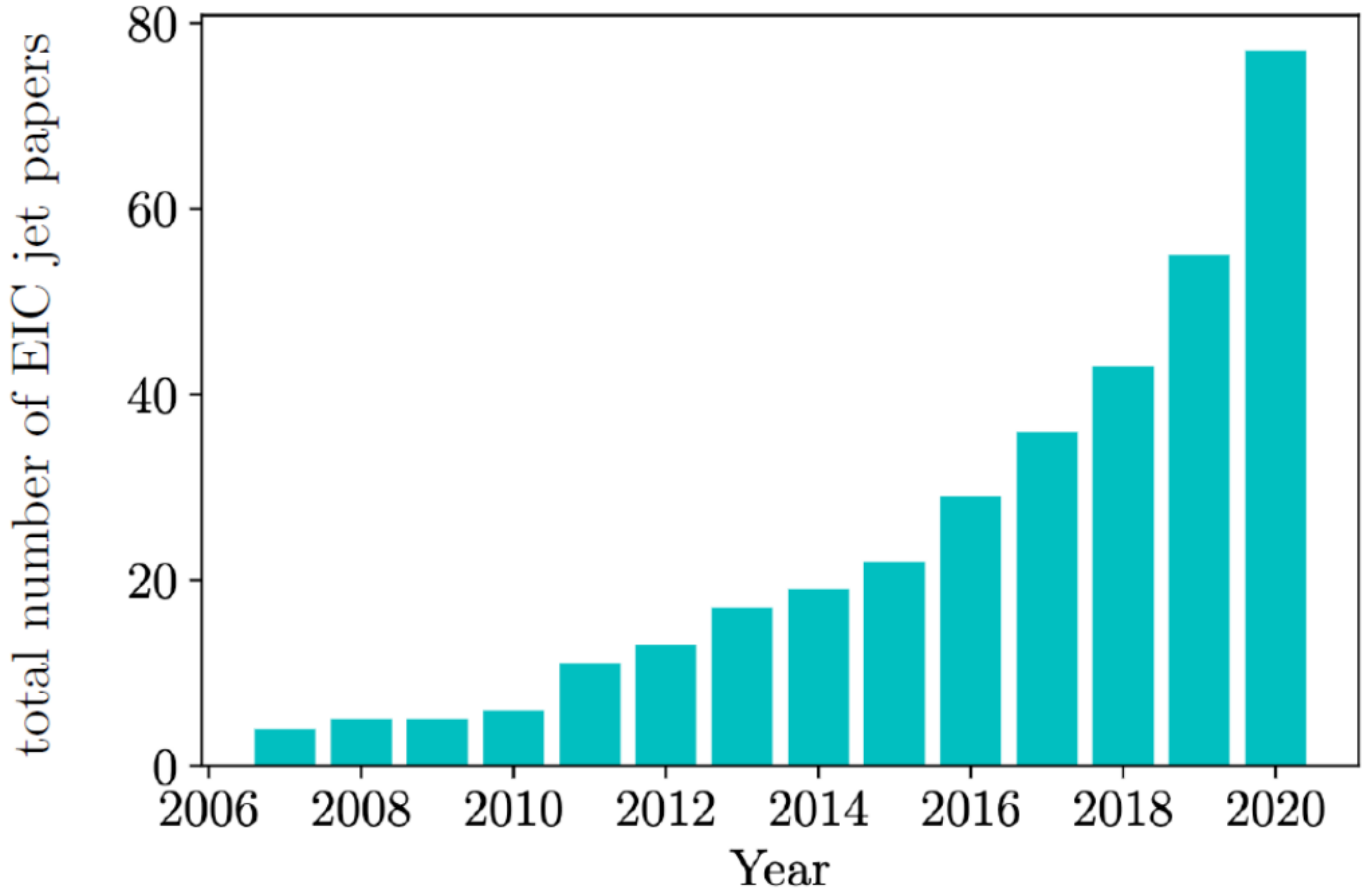
Summary

- Jets and jet substructures offer new opportunity to understand hadron inner structures
- Spin asymmetry can be measured at the future EIC very precisely.
- Two examples:
  - Heavy flavor dijet production at the EIC -> gluon Sivers function
  - Hyperon and jet production at the Belle -> quark polarizing fragmentation function
  - We develop the TMD factorization formalism for both processes; Include QCD evolution from Q to $q_T \gtrsim \Lambda_{QCD}$
  - Our predictions are consistent with Belle data; Verify the universality of polarizing fragmentation function
  - Use jet charge to separate different flavors of PFFs at the Belle

展望

理论精确预言

新型喷注观测量的构造



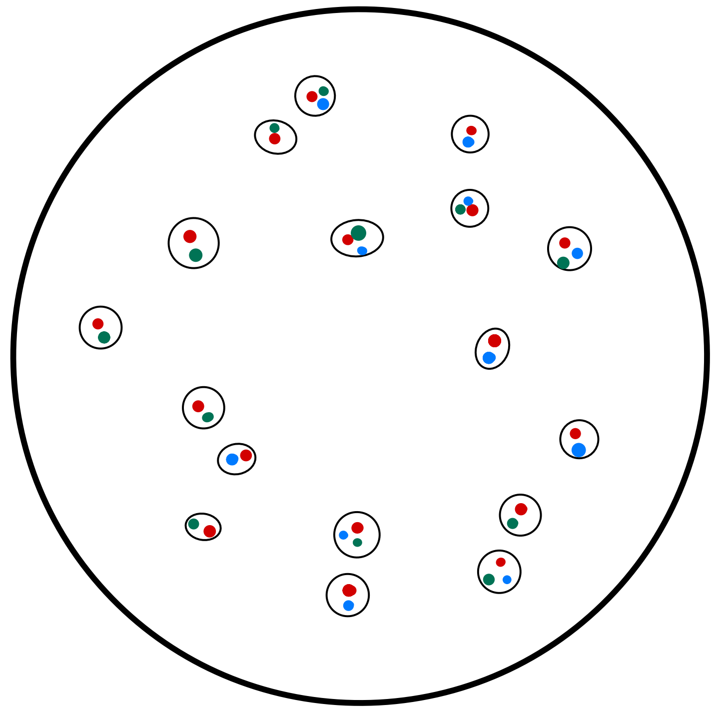
Thank you

Flavor separation and the jet electric charge

A PARAMETRIZATION OF THE PROPERTIES OF QUARK JETS *

R.D. FIELD and R.P. FEYNMAN
California Institute of Technology, Pasadena, California 91125, USA

Received 11 October 1977



Definition:

$$Q_\kappa = \sum_i \left(\frac{p_{i,T}}{p_J}\right)^\kappa Q_i$$