Heavy flavor jets and their substructure

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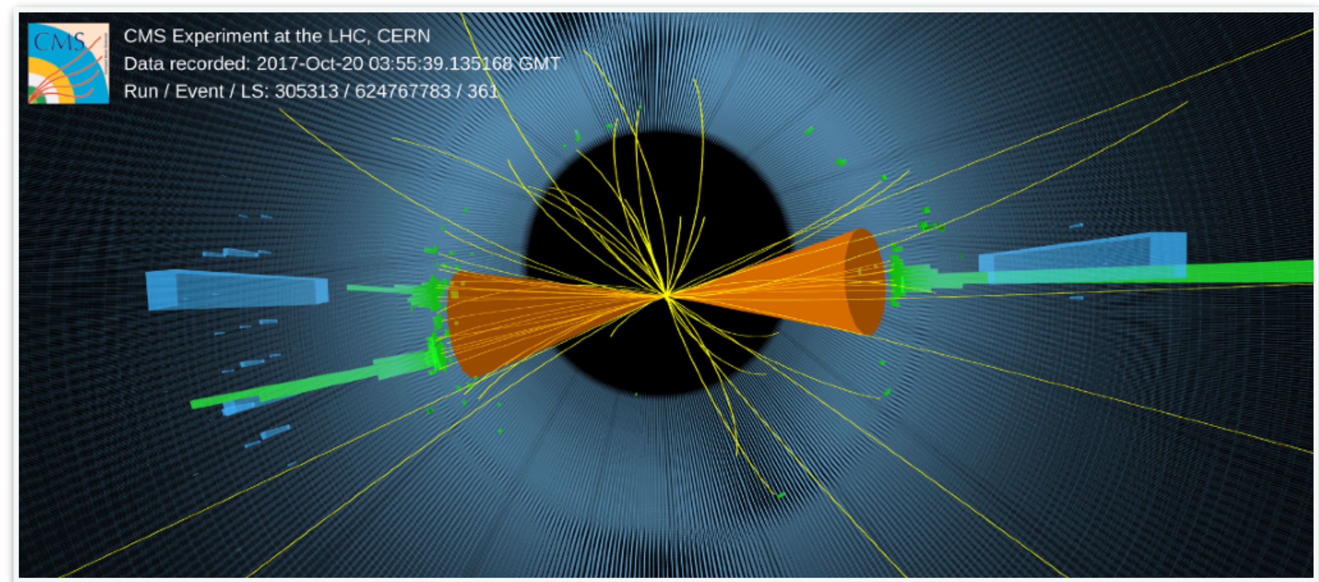
Motivation

Heavy flavor jet production is crucial in both QCD and EW/BSM physics

EW/BSM: b-jet signature is common in many EW/BSM processes, top quark, Higgs …

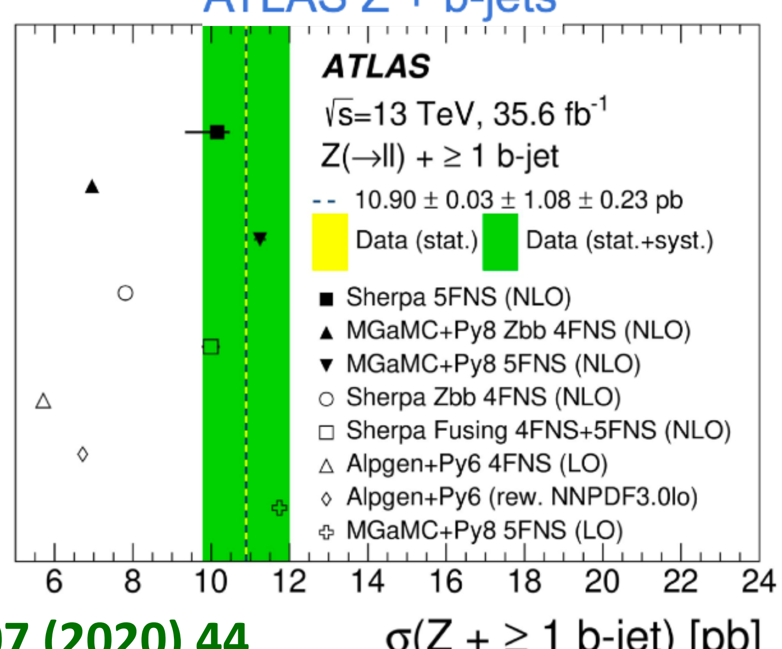
Q: Can you distinguish these two jets?

A: left is a Higgs jet, right is a standard QCD jet; Higgs jet has two prongs inside the jet [b + b-bar jets]



QCD: understanding heavy quark effects; mass corrections; flavor schemes …

ATLAS Z + b-jets



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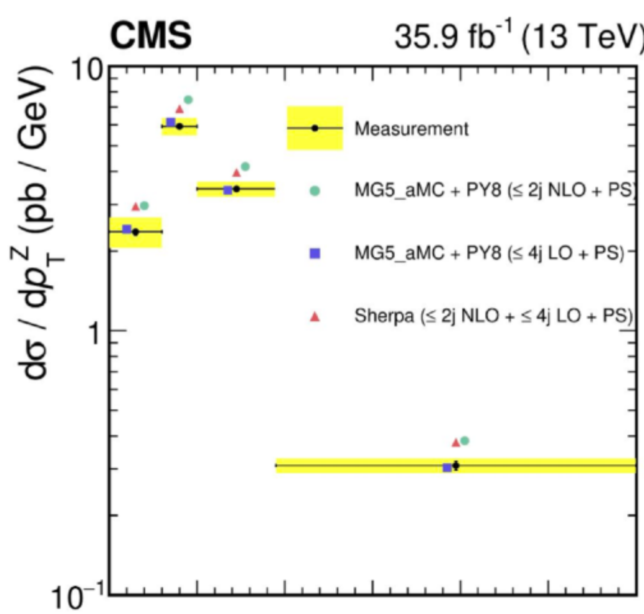
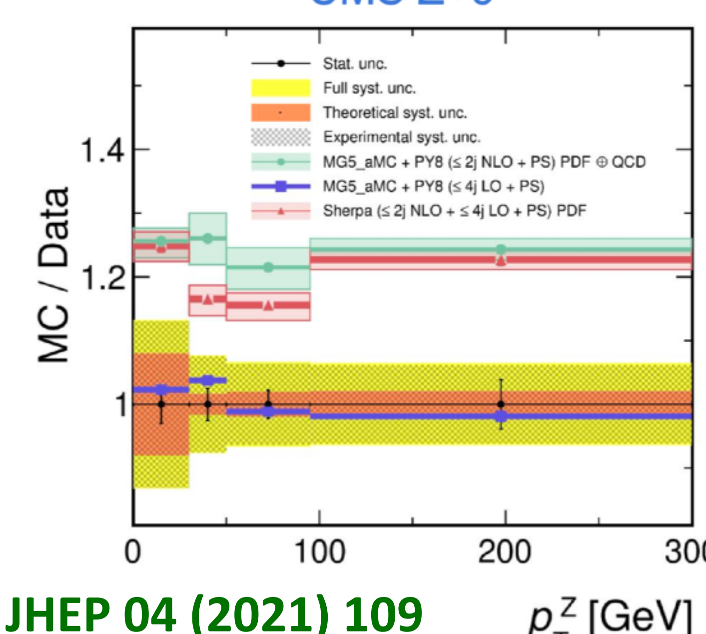


CMS Z+c



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The Electron-Ion Collider

January 9, 2020

- High luminosity

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

  $\sqrt{s} = 20 - 140 \text{ GeV}$
- 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

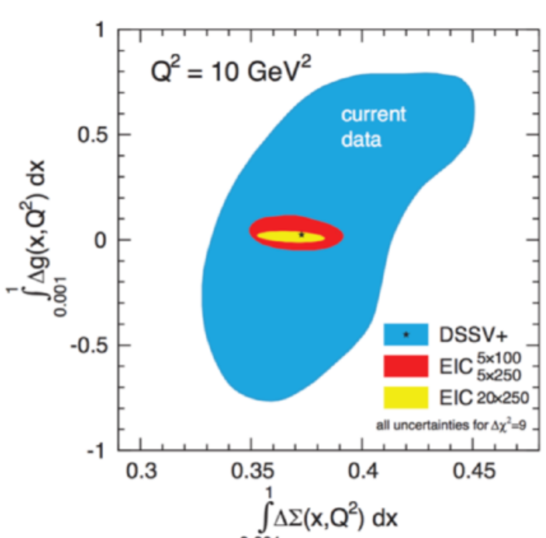
JANUARY 9, 2020

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

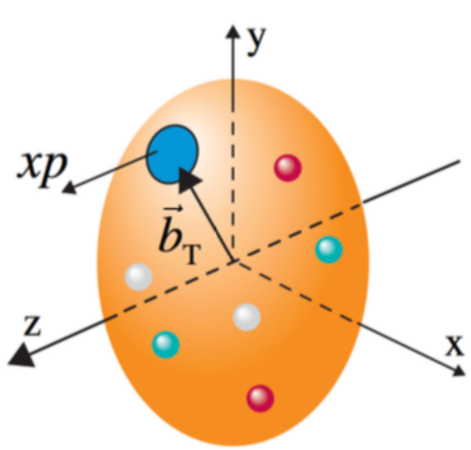
WASHINGTON, D.C. – Today, the **U.S. Department of Energy (DOE)** announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.

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.

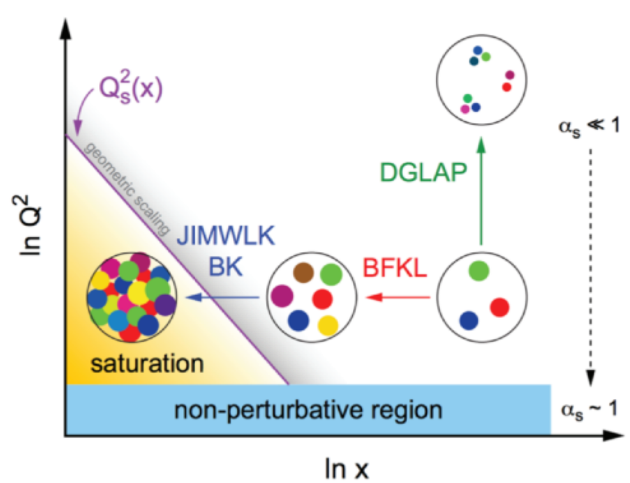
Proton spin



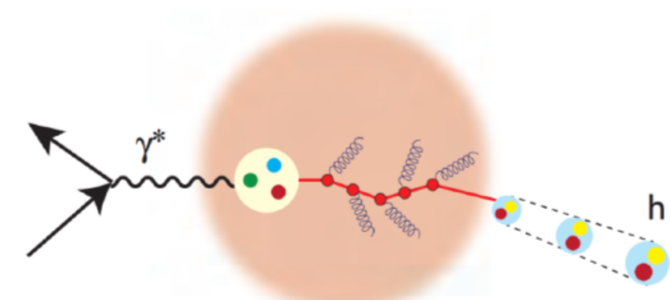
3D nucleon tomography



gluon saturation

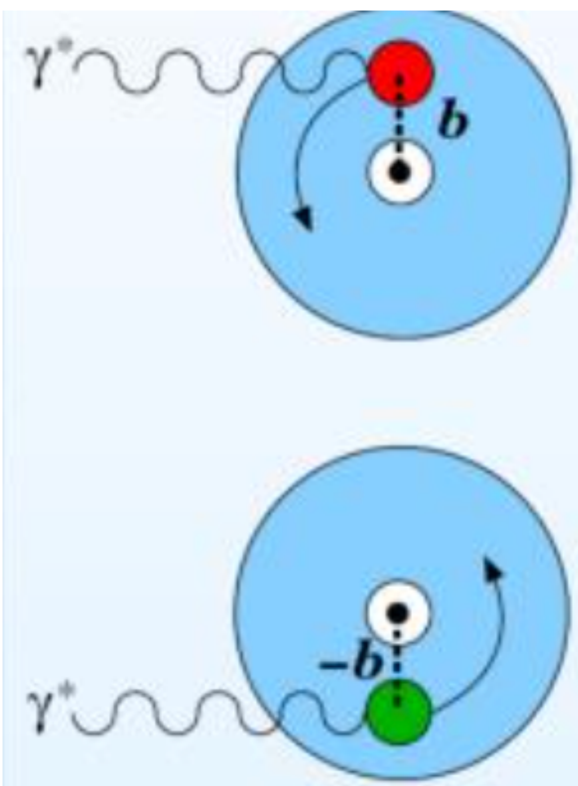


hadronization in the nucleus



3D imaging of the proton

- **Both longitudinal and transverse motion**
- **Large Lorentz boost in longitudinal direction, but not in transverse momentum**
- **Correlation between nucleon spin with parton(quark, gluon) orbital angular momentum**



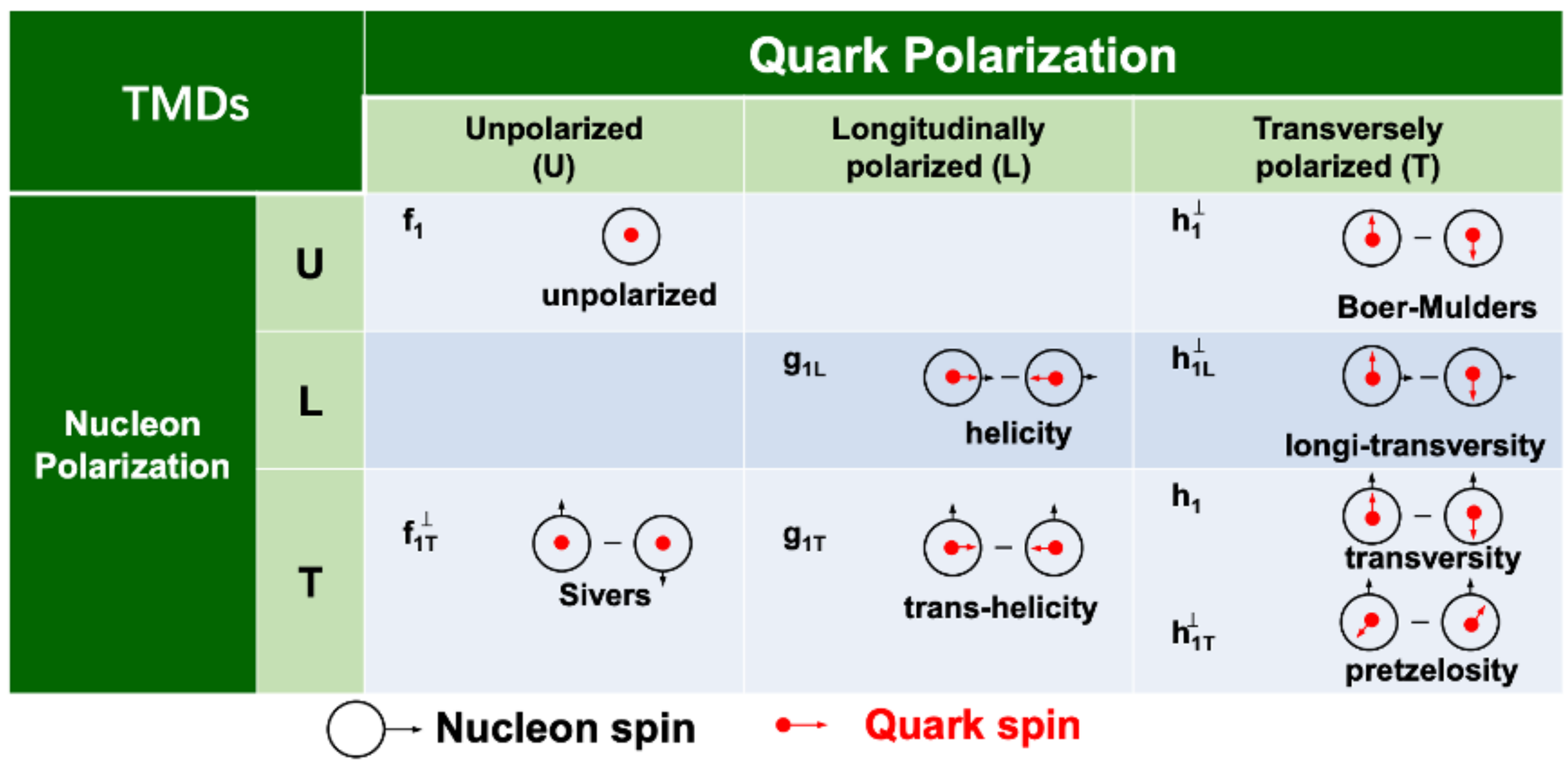
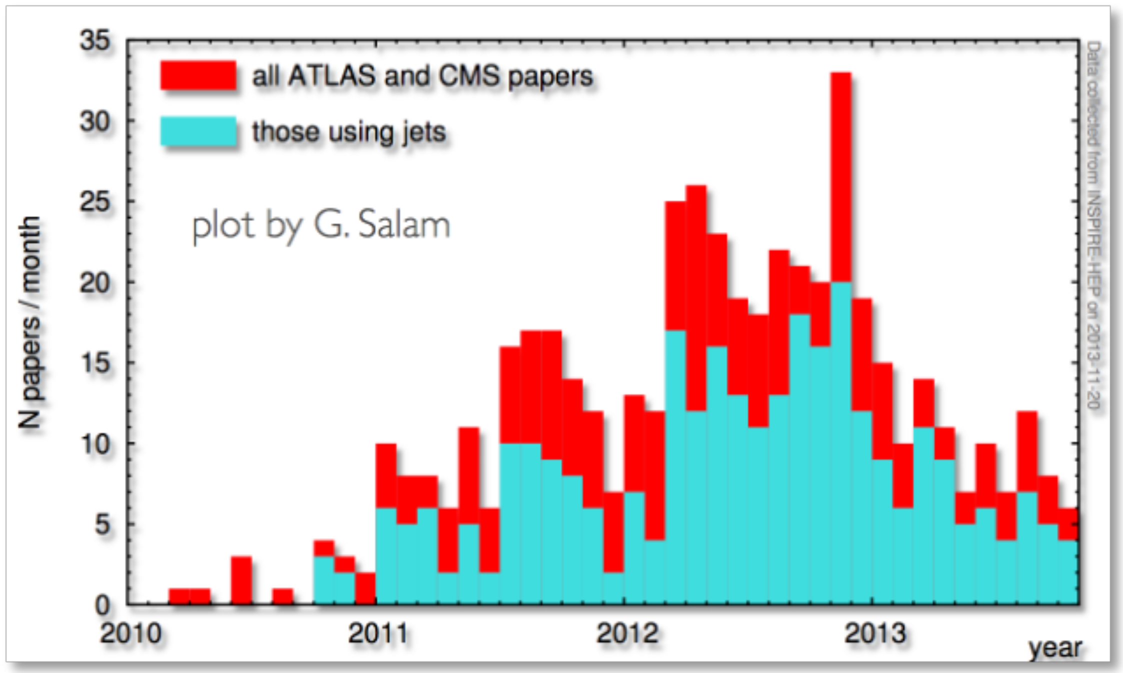
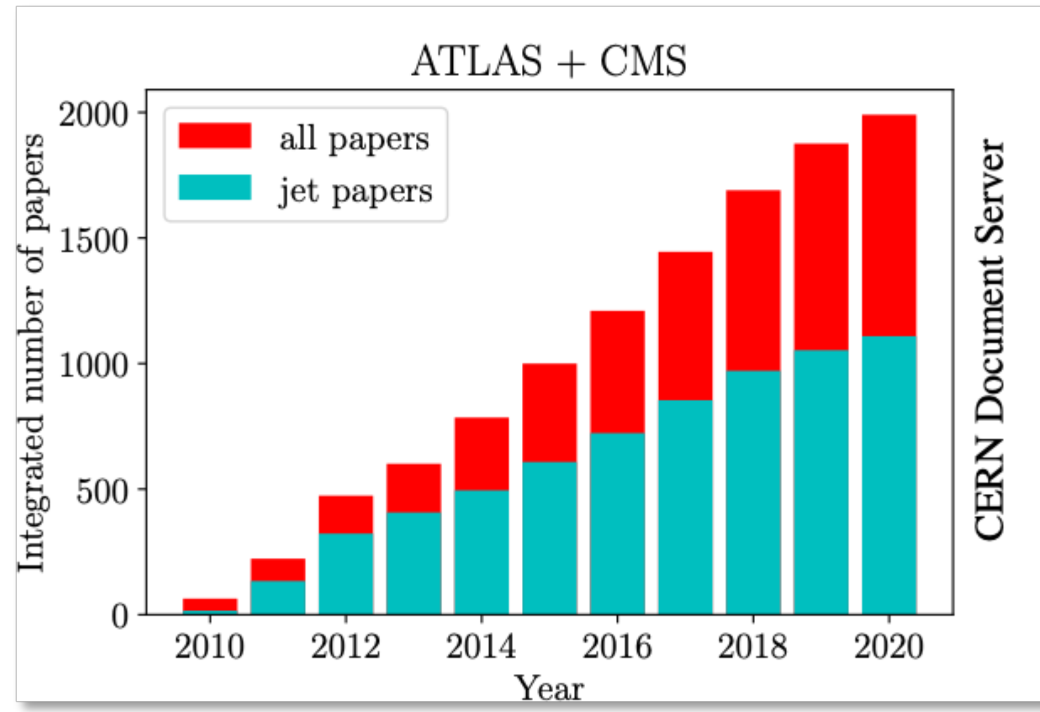


Figure 2.5: The leading-twist quark TMD distributions.

Jets are most common at the LHC

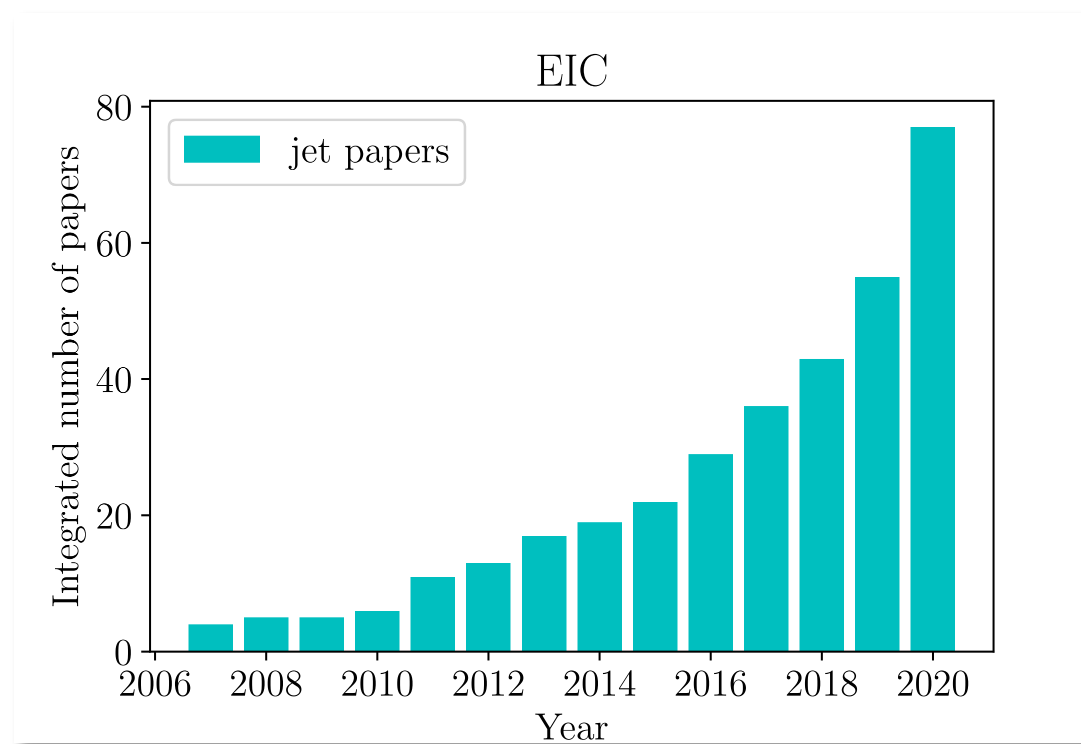
At the LHC, 70% of ATLAS & CMS papers use jets in their analysis





Active study at the EIC

EIC jet papers grow exponentially



Gluon Sivers function (GSF)

- **Gauge link dependent gluon Transverse-momentum-dependent PDFs**

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

- **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

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

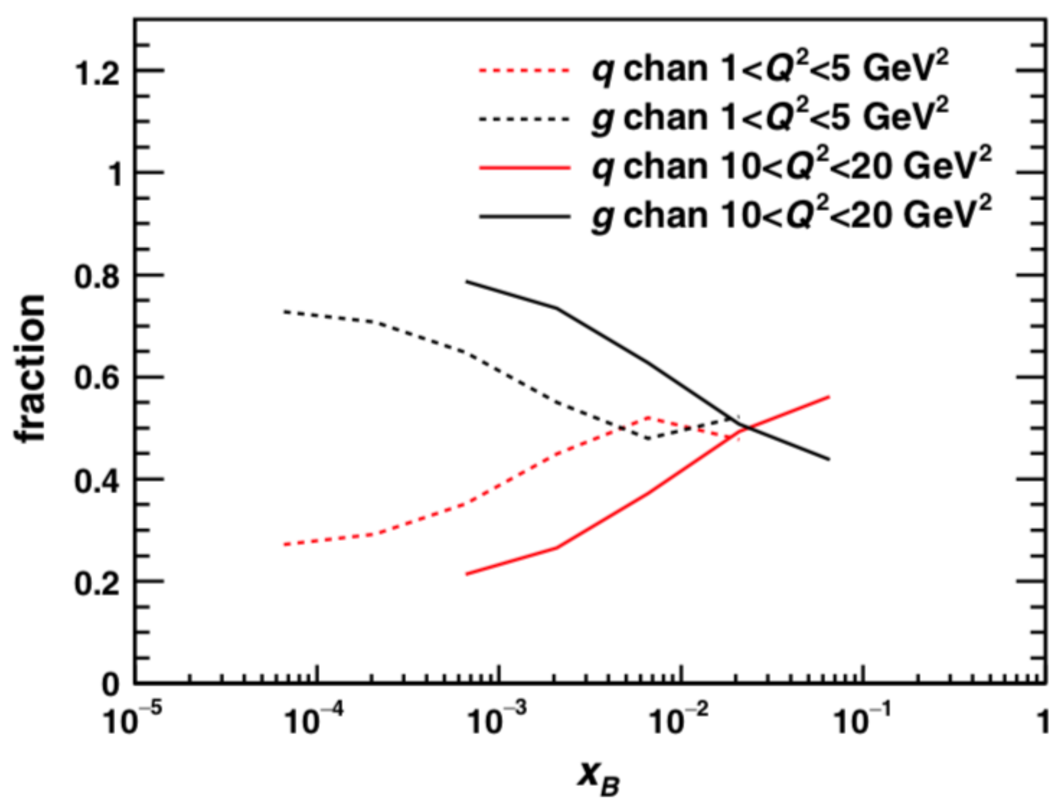
$$f_{1T}^{\perp g[e\,p^\uparrow \to e'\,Q\bar{Q}\,X]}(x,p_T^2) = -f_{1T}^{\perp g[p^\uparrow\,p \to \gamma\,\gamma\,X]}(x,p_T^2)$$

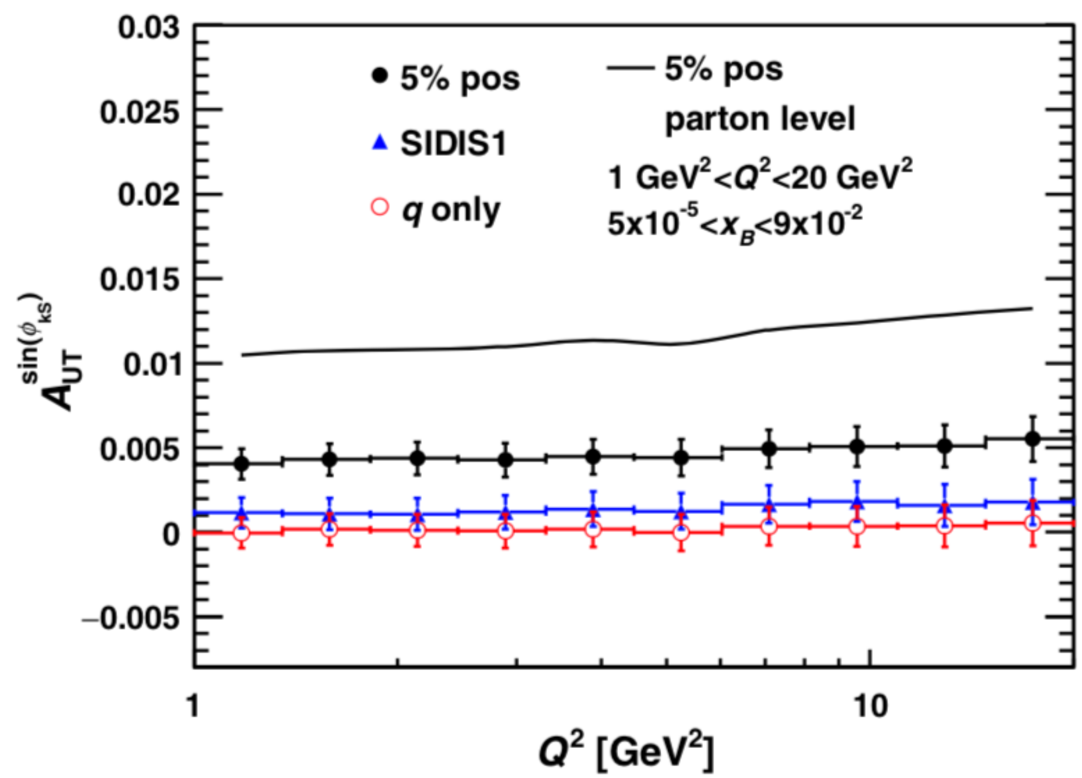
GSF and spin asymmetry in di-jet at the EIC

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: $\gamma^* q \to qg \qquad \gamma^* g \to q\bar{q}$



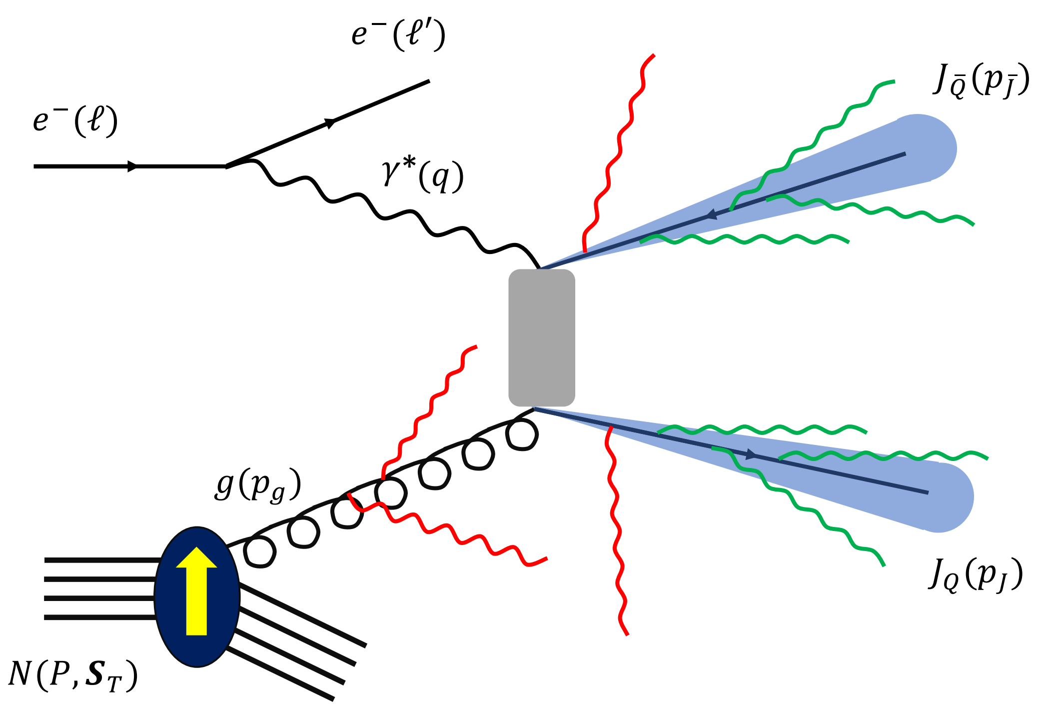


- **to distinguish different TMDs**
  - **jet charge tagging “different quark TMDs”** (Kang, Liu, Mantry, **DYS** ’20 PRL)
  - **Heavy-flavor tagging, where q-channel starts to contribute beyond the LO** (Kang, Reiten, **DYS**, Terry ’21 JHEP)

TMD factorization for heavy-flavor dijet production in DIS

(Kang, Reiten, **DYS**, Terry '21 JHEP)

$$e(\ell) + N(P, \boldsymbol{S}_T) \to e(\ell') + J_Q(p_J) + J_{\bar{Q}}(p_{\bar{J}}) + X$$



In the Breit frame, the dijet imbalance is defined as $\boldsymbol{q}_T = \boldsymbol{p}_{JT} + \boldsymbol{p}_{\bar{J}T}$

$$q_T R \ll q_T \lesssim m_Q \lesssim p_T R \ll p_T$$

R: Jet radius; m_Q: heavy quark mass

Construction of the theory formalism

- **Multiple scales in the problem**
- **Rely on effective field theory: SCET + Jet Effective Theory** (Becher, Neubert, Rothen, **DYS** '16 PRL, …)

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**

Heavy quark mass corrections in the evolution equation

Anomalous dimension for the HF quark jet function: see also (Kim '20)

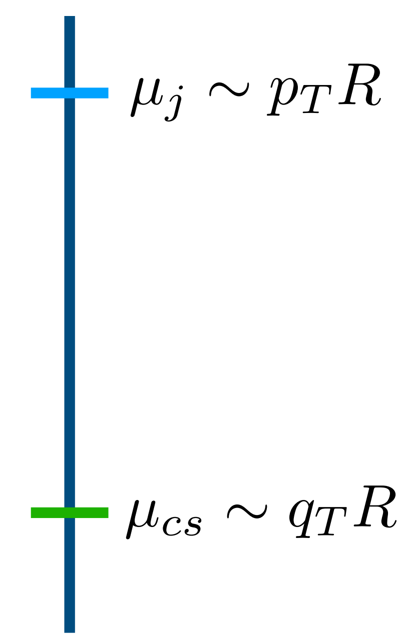
$$\Gamma^{jQ}(\alpha_s) = -C_F \gamma^{\text{cusp}}(\alpha_s) \ln \frac{m_Q^2 + p_T^2 R^2}{\mu^2} + \gamma^{jQ}(\alpha_s) \qquad \gamma_0^{jQ} = 2C_F \left(3 - \frac{2m_Q^2}{m_Q^2 + p_T^2 R^2}\right)$$

Anomalous dimension for the HF collinear-soft function

$$\Gamma^{csQ}(\alpha_s) = C_F \gamma^{\text{cusp}}(\alpha_s) \ln \frac{R^2 \mu_b^2}{\mu^2} + \gamma^{csQ}(\alpha_s) \qquad \gamma_0^{csQ} = -4C_F \left[2\ln\left[-2i\cos(\phi_b - \phi_J)\right] - \frac{m_Q^2}{m_Q^2 + p_T^2 R^2} - \ln \frac{m_Q^2 + p_T^2 R^2}{p_T^2 R^2}\right]$$

Heavy-quark mass dependence cancels out in

$$\Gamma^{jQ} + \Gamma^{csQ} = \Gamma^{jq} + \Gamma^{csq}$$



Heavy quark mass will contribute the RG evolution between jet and collinear-sot function

different from the case for the inclusive HF quark jet production Dai, Kim, Leibovich '18

Spin dependent cross section

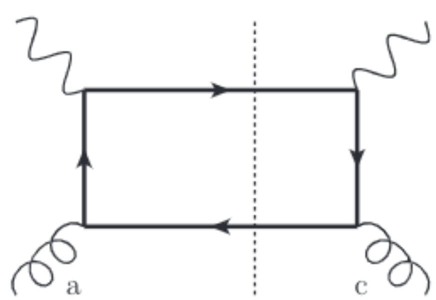
- **Resummation formula:**

$$\frac{d\sigma^{UT}(\boldsymbol{S}_T)}{dQ^2 dy d^2\boldsymbol{q}_T dy_J d^2\boldsymbol{p}_T} = \sin(\phi_q - \phi_s)\, H(Q, p_T, y_J, \mu_h) \int_0^\infty \frac{b^2 db}{4\pi} J_1(b\, q_T) f_{1T,g/p}^{\perp}(x_g, \mu_{b*})$$
$$\times \exp\left[-\int_{\mu_{b*}}^{\mu_h} \frac{d\mu}{\mu} \Gamma^h(\alpha_s) - 2\int_{\mu_{b*}}^{\mu_j} \frac{d\mu}{\mu} \Gamma^j(\alpha_s) - 2\int_{\mu_{b_*}}^{\mu_{cs}} \frac{d\mu}{\mu} \Gamma^{cs}(\alpha_s) \right]$$
$$\times \exp\left[-S_{\rm NP}^{\perp}(b, Q_0, n\cdot p_g) \right]$$

- **Polarized hard function: For the polarized process, we must consider the attachment of an additional gluon from gauge link in GSF**

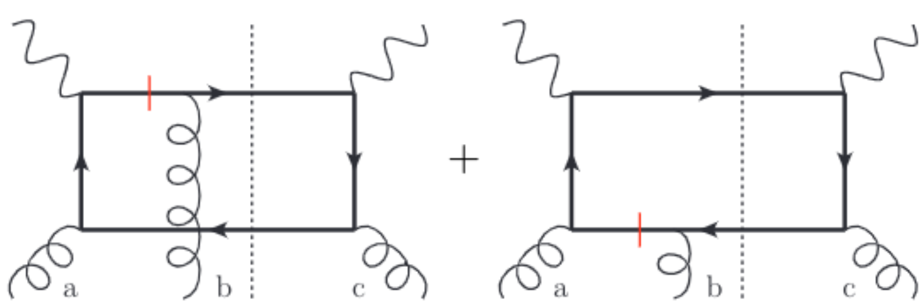
Qiu, Vogelsange, Yuan '07;
Kang, Lee, **DYS**, Terry, '20 JHEP …

unpolarized:



$$= C_u\, \delta^{ac}\, h^{(0)}(Q, p_T, y_J, \mu)$$

polarized:



$$= (C_1 + C_2)\left(-i f^{abc}\right) h^{(0)}(Q, p_T, y_J, \mu)$$

polarized and unpolarized hard functions are the same $C_1 + C_2 = C_u$

f-type gluon Sivers function

Numerical results

Anti-k$_T$, R=0.6

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

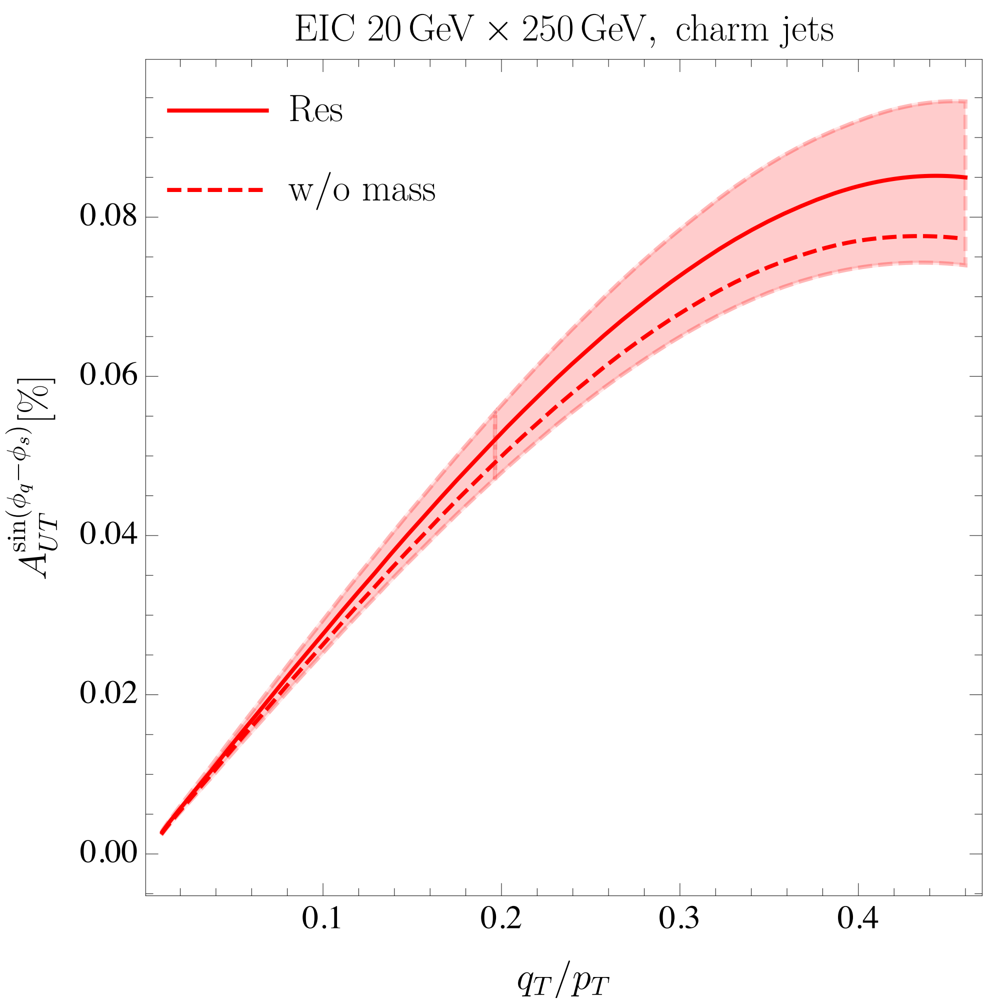
b-jets: $10\,\text{GeV} < p_T < 15\,\text{GeV}, \quad |\eta_J| < 4.5,$

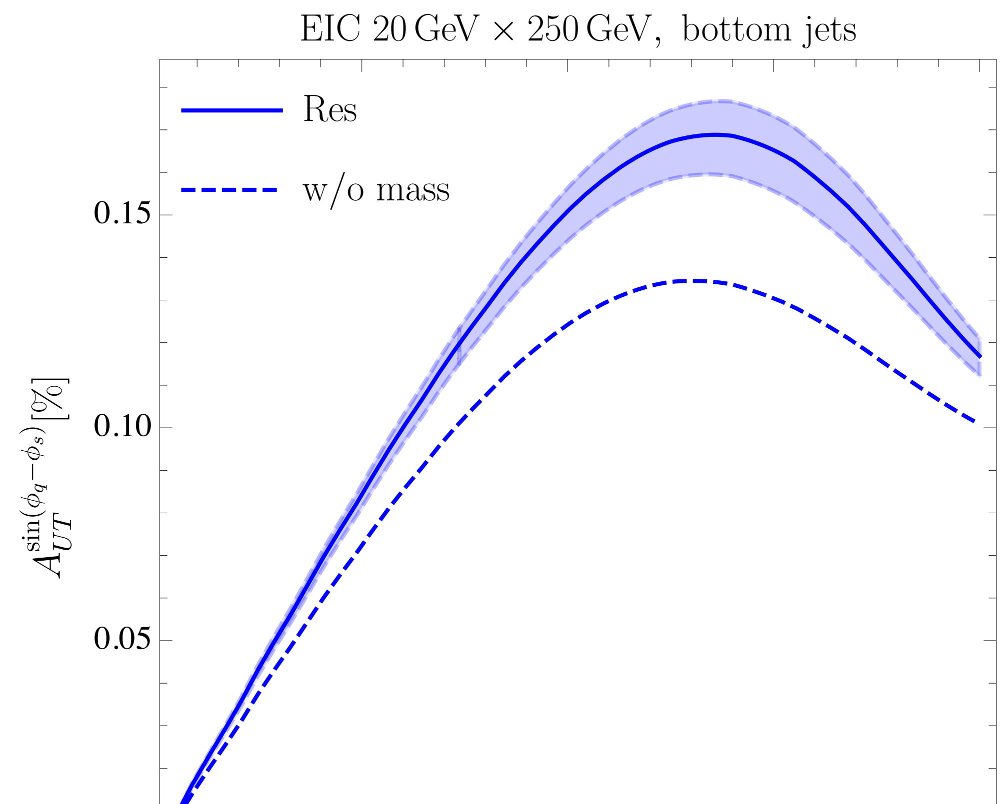
$$d\sigma(\boldsymbol{S}_T) = d\sigma^{UU} + \sin(\phi_q - \phi_s) d\sigma^{UT}$$

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

GSF: SIDIS1 set

D'Alesio, Murgia, Pisano '15





(Kang, Reiten, **DYS**, Terry '21 JHEP)

Heavy quark mass can give sizable corrections to the predicted asymmetry

Summary

- **Heavy flavor jets offer new opportunity to understand nucleon inner structures**
- **We develop the TMD factorization formalism for heavy flavor dijet production in electron polarized proton collisions.**
  - **Theory tools: EFT of QCD in collinear and soft limit (e.g. SCET)**
- **Flavor tagging provides a novel probe of flavor structure in the nucleon spin program**
  - **It enhances the sensitivity of spin asymmetries to gluon, which opens new avenues of exploration for the nucleon spin program**
- **The application of our theory framework at the LHC&RIHC is in progress**

Thank you