TMD measurements with jets

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1st EIC Yellow Report Workshop

Temple University, 03/20/20

Berkeley
UNIVERSITY OF CALIFORNIA

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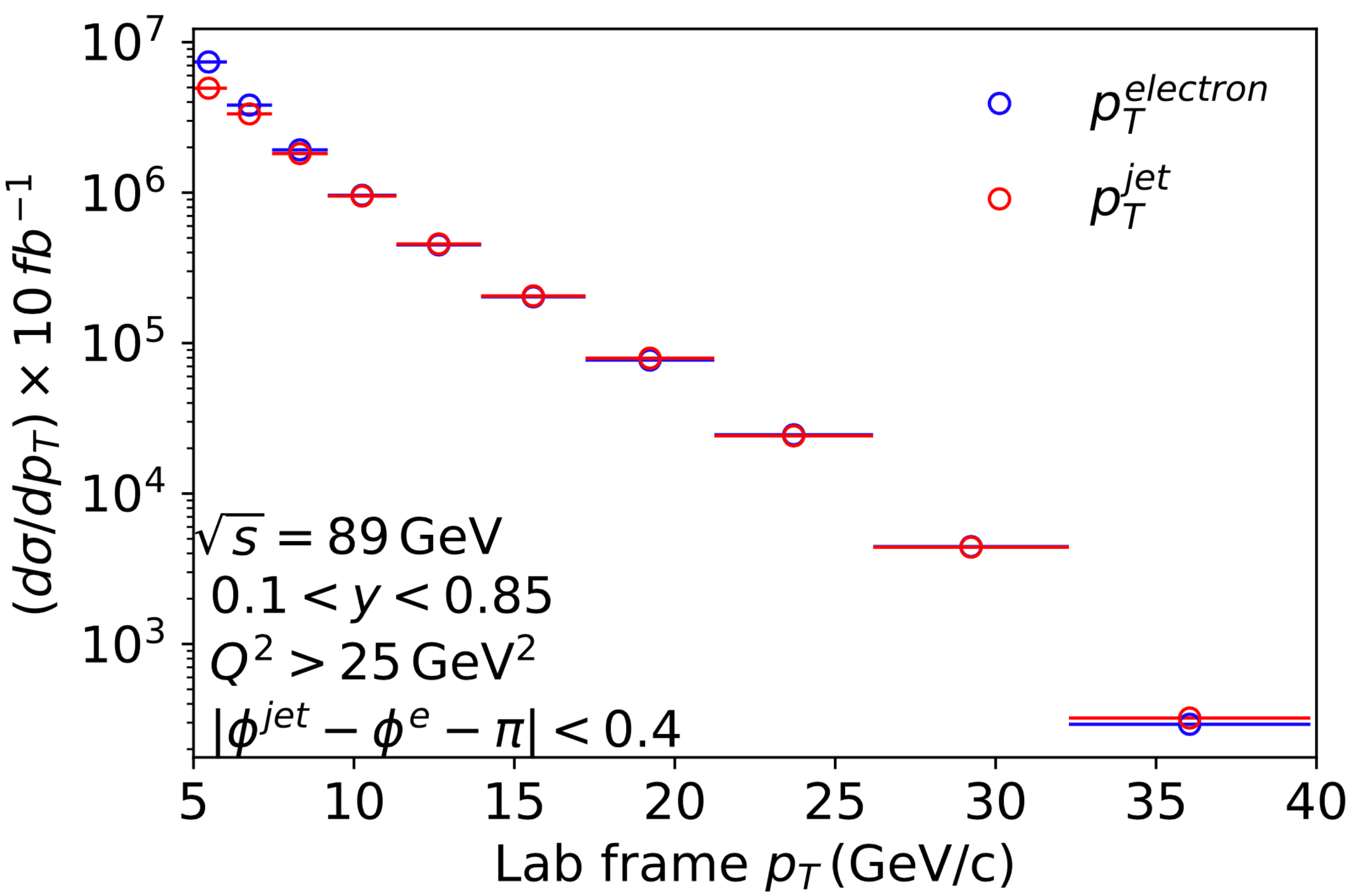
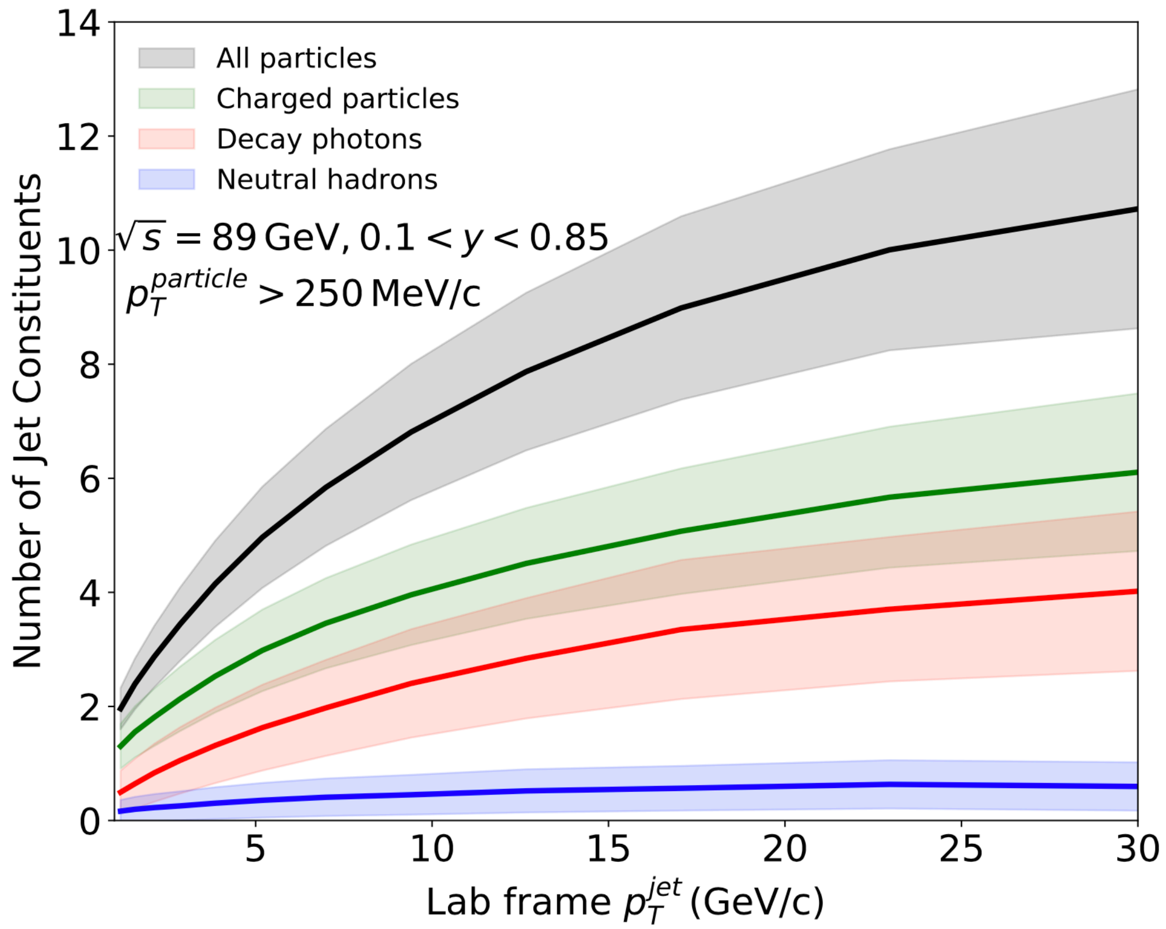
Jets at the Electron-Ion Collider

Arratia, Jacak, FR, Song `19
see also: Aschenauer, Chu, Page `19

Jet transverse momentum p_T



Number of particles in the jet



Jet radius $R = 1.0$

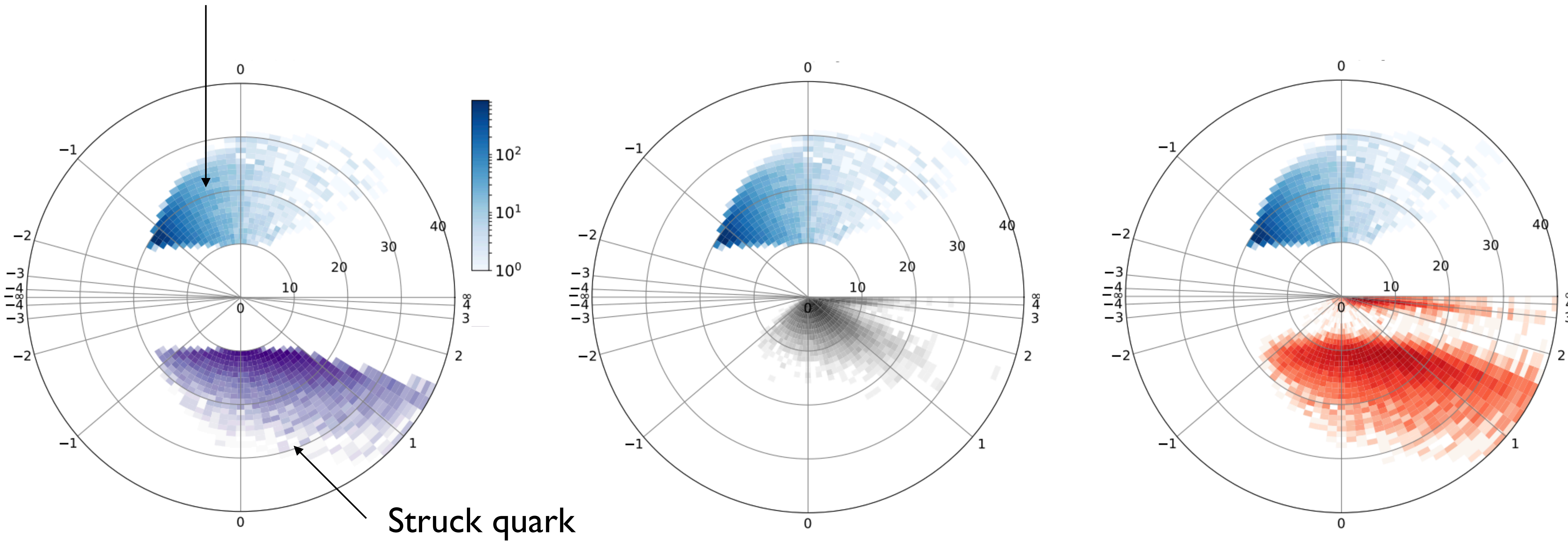
Deep Inelastic Scattering

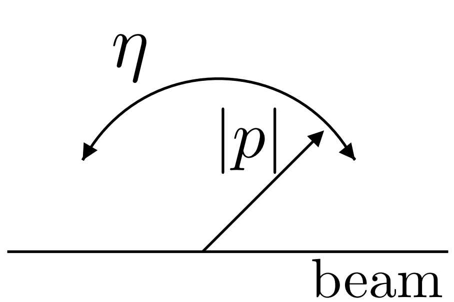
Hadrons and jets at the EIC

$Q^2 > 100\ \mathrm{GeV}^2,\ \sqrt{s} = 89\ \mathrm{GeV}$

$10 < p_T^e < 30\ \mathrm{GeV},\ 0.1 < y < 0.85$

Scattered electron





Arratia, Jacak, FR, Song `19

- Initial and final state shower
- Hadronization

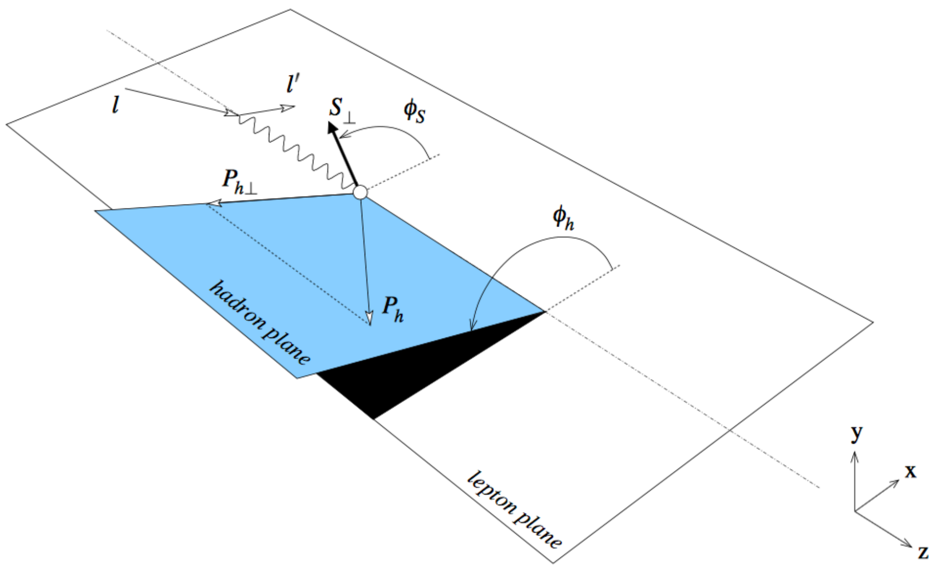
- Initial and final state shower
- Hadronization
- Jet reconstruction

Lab frame, anti-k_T

Measurement of TMDs at the EIC

e.g. Bacchetta, Diehl, Goeke, Metz, Mulders `07

- Semi-Inclusive Deep-Inelastic Scattering
- Measure hadrons with low transverse momentum



$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$$+\ldots$$

⟶ Sensitivity to (polarized) TMD PDFs and FFs

- Complementary processes using jets — universality?
- Study TMD evolution
- Clean environment at the EIC

Outline

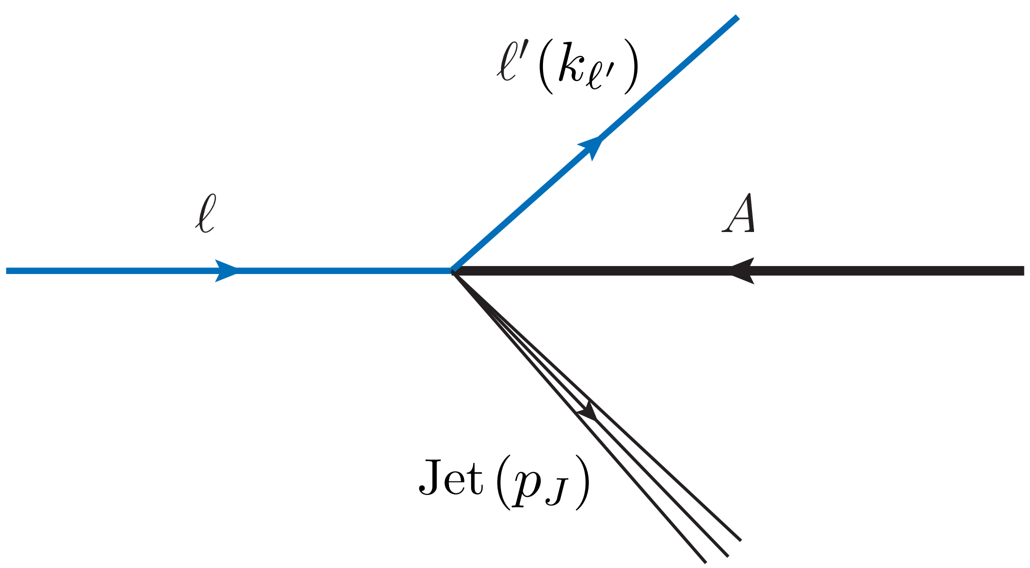
- Introduction
- Jet correlations
- Jet substructure
- Conclusions and outlook

Electron-jet correlations

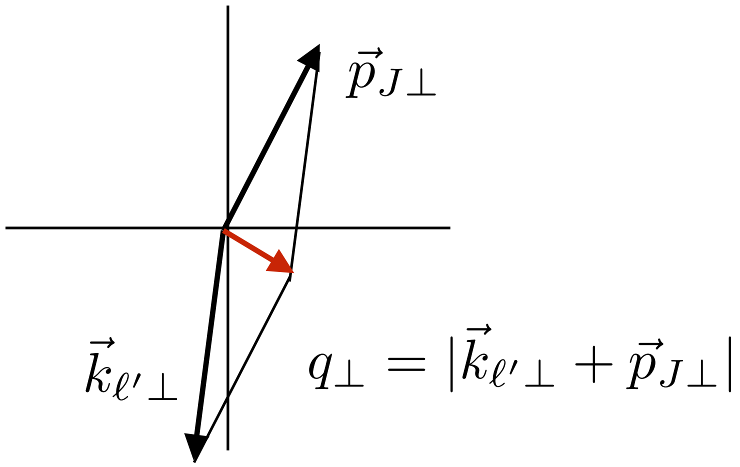
Liu, FR, Vogelsang, Yuan `18

- Require high p_T jet
- Measure imbalance $q_\perp$ between lepton and jet in the lab frame

$$\frac{d\sigma}{d\eta_{\ell'} d^2k_{\perp\ell'} d^2q_\perp}$$



Transverse plane



- Close analogy to proton-proton collisions at RHIC
- No TMD fragmentation
- Test of universality

Boer, Vogelsang `04
Vogelsang, Yuan `05
Bomhof, Mulders, Vogelsang, Yuan `07

Electron-jet correlations

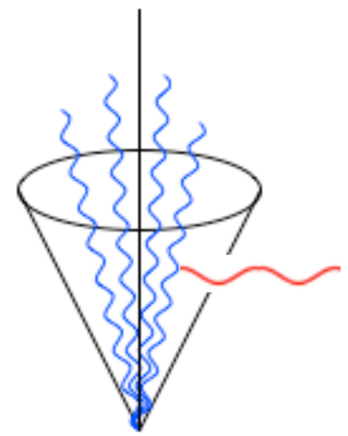
Liu, FR, Vogelsang, Yuan `18

- Factorization

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\eta_{\ell'}\mathrm{d}^2k_{\perp\ell'}\mathrm{d}^2q_\perp} = \sigma_0 \int \frac{\mathrm{d}^2b_\perp}{(2\pi)^2}\mathrm{e}^{iq_\perp\cdot b_\perp}\; xf_q(x,b_\perp,\zeta_c,\mu_F)\,S_J(b_\perp,\mu_F)\,H_{\mathrm{TMD}}(Q,\mu_F)$$

Large radius advantageous $R \sim 1$

- Non-global logarithms $S^{(2)}_{\mathrm{NGL}}(b_\perp) = -C_F\frac{C_A}{2}\left(\frac{\alpha_s}{\pi}\right)^2\frac{\pi^2}{24}\ln^2\left(\frac{k^2_{\ell\perp}b^2_\perp}{c_0^2}\right)$

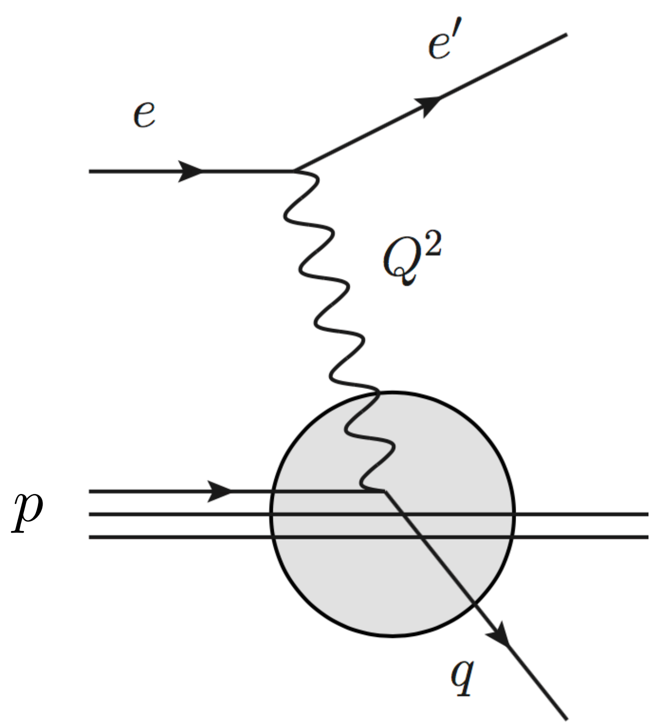


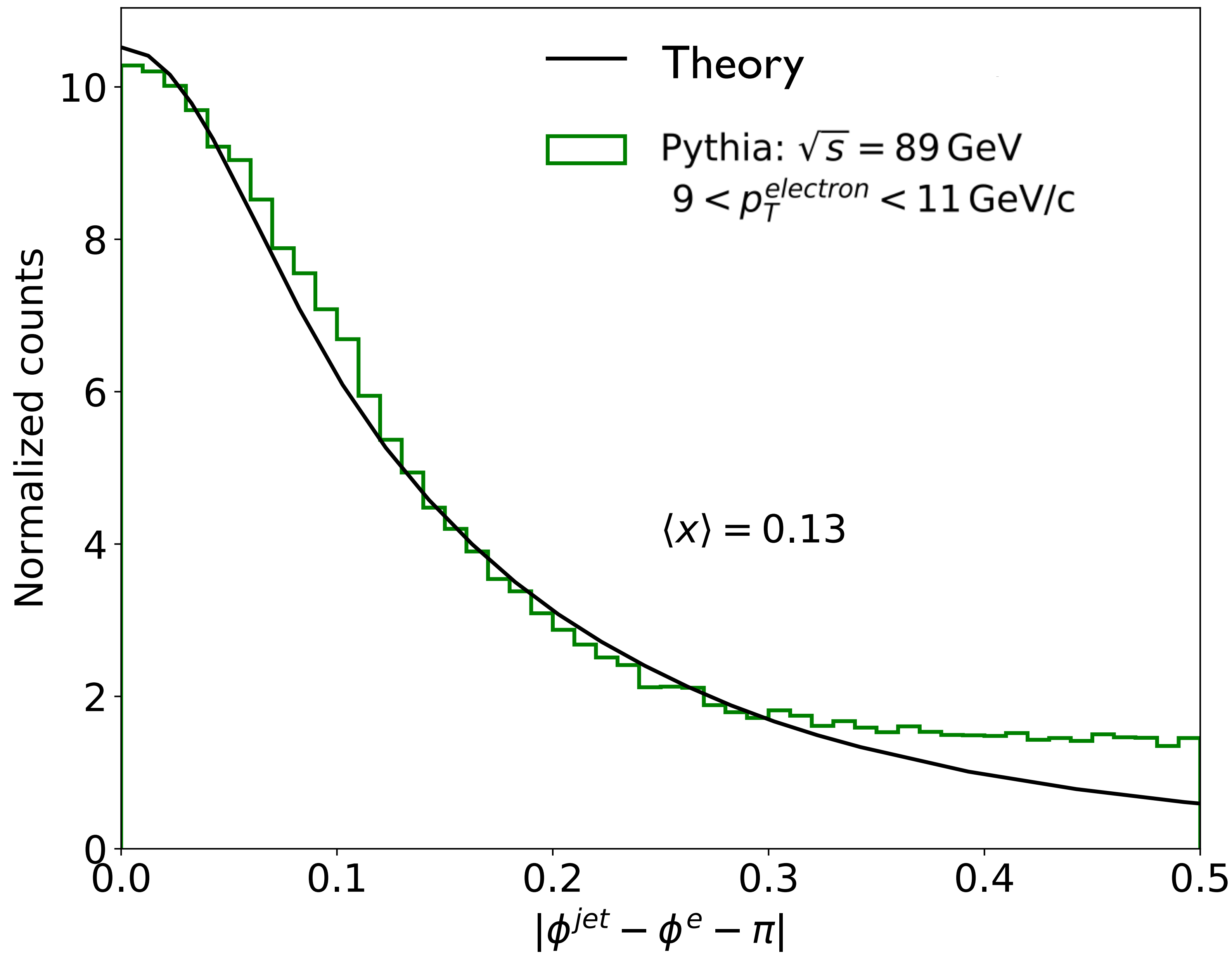
Contributes at NLL, included at leading color, at most a 5% effect

Dasgupta, Salam` 01

Results for the EIC

Liu, FR, Vogelsang, Yuan `18
Arratia, Jacak, FR, Song `19





Comparison to Pythia 8

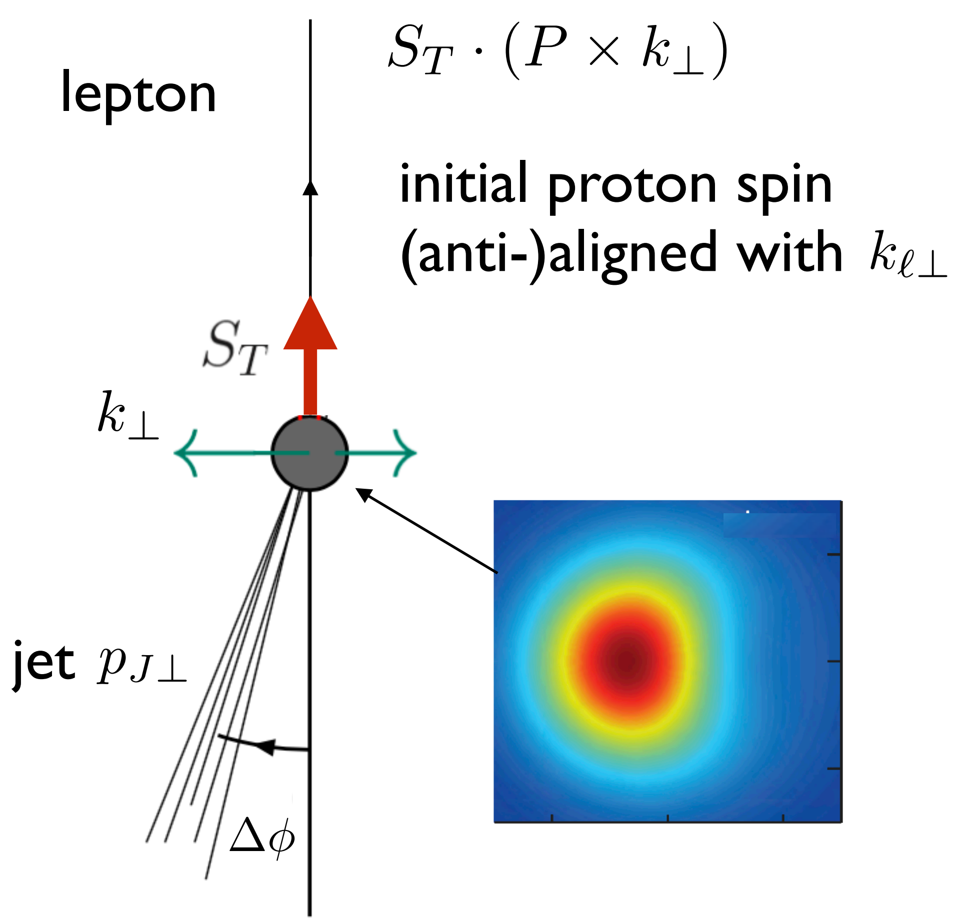
HERA, EIC

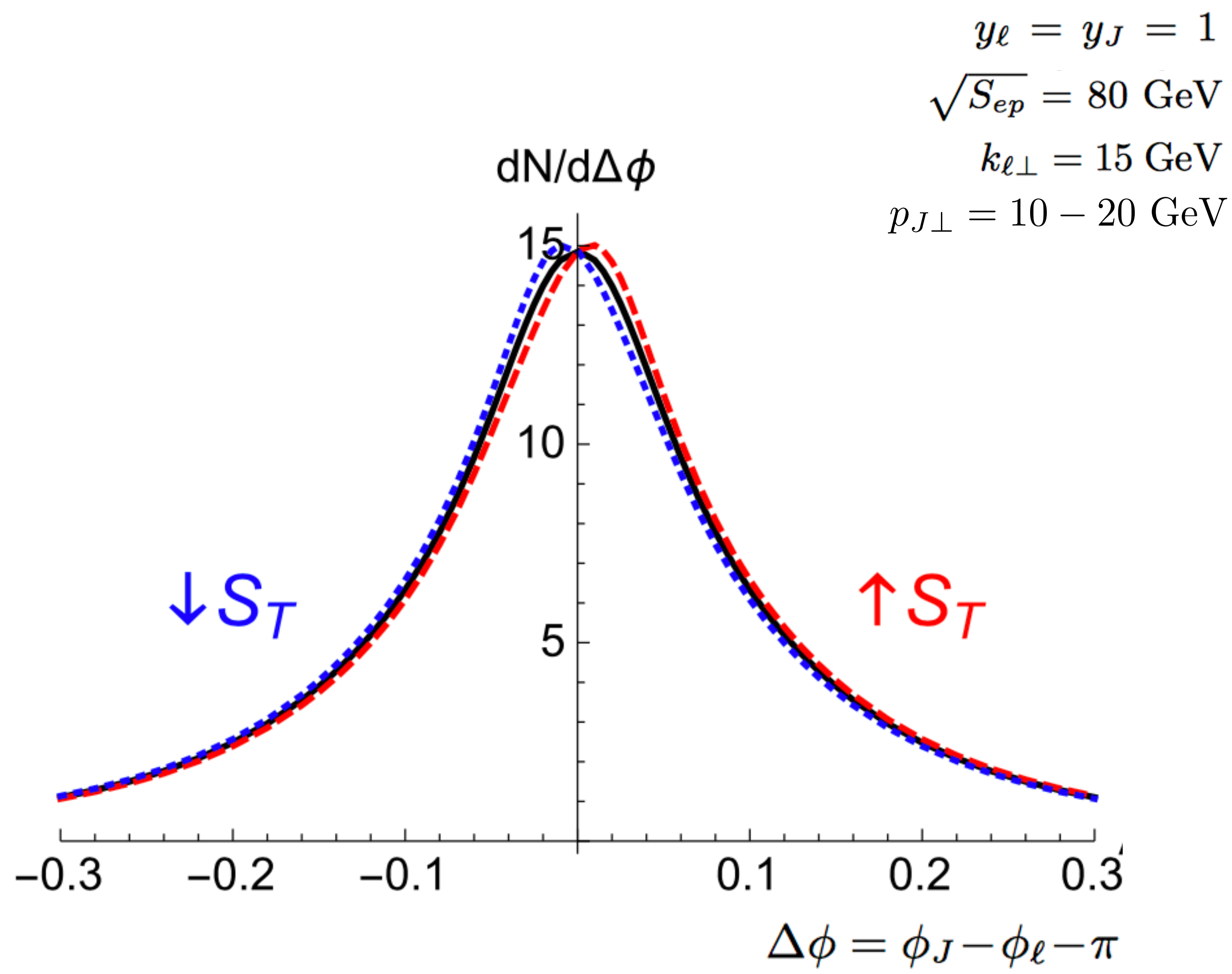
Studies using Pythia 6 see: Aschenauer, Lee, Page, FR `19
See Brian Page's talk

Direct measurement of the Sivers effect

Liu, FR, Vogelsang, Yuan `18

- $H(Q^2, R)\ f_q(q_\perp)\ \otimes_\perp\ S_q(q_\perp, R)$





- Sensitivity to the Sivers TMD PDF *extraction from Sun, Yuan `13*
- Test of universality and factorization breaking effects, see RHIC measurements *STAR, PRL 99 (2007) 142003*

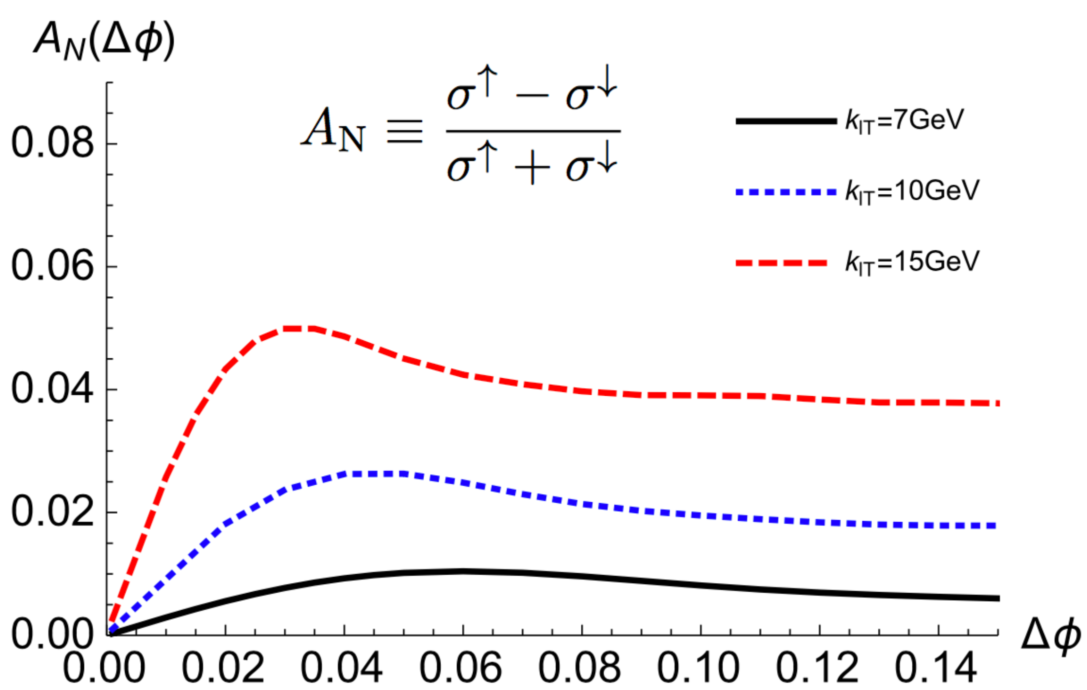
Direct measurement of the Sivers effect

Liu, FR, Vogelsang, Yuan `18

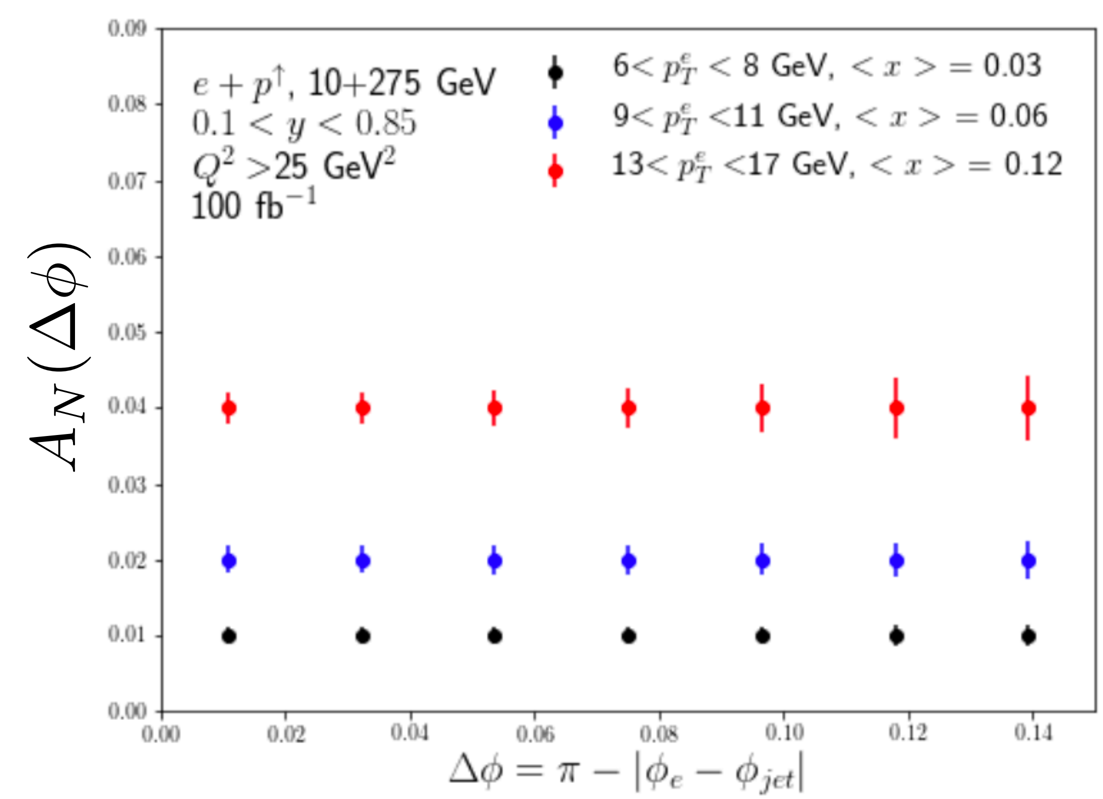
- TMD factorization

$$H(Q^2, R)\ f_q(q_\perp)\ \otimes_\perp S_q(q_\perp, R)$$

Asymmetry



EIC projections



see Miguel Arratia's talk

- Sensitivity to the Sivers TMD PDF *extraction from Sun, Yuan `13*
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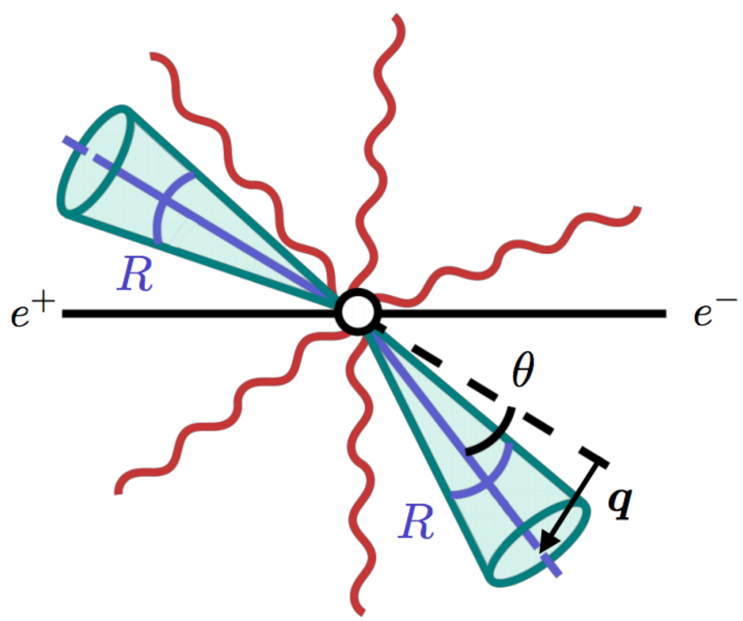
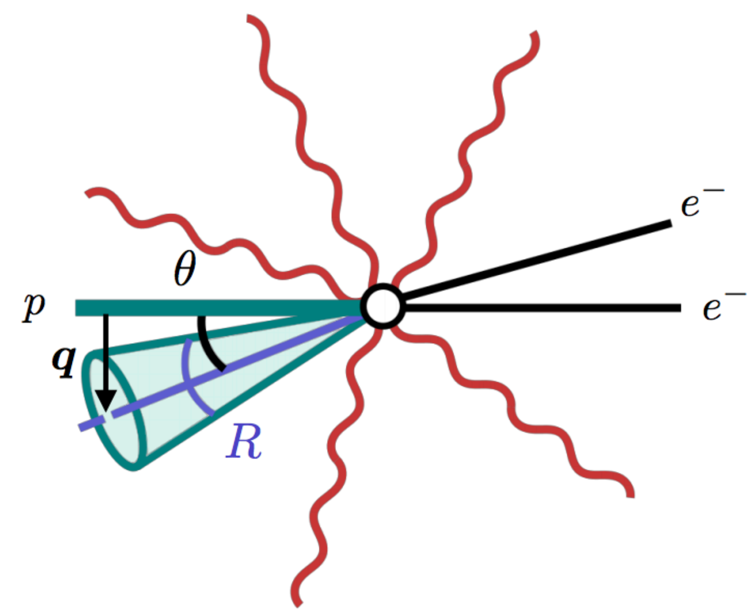
Proton-jet correlations

Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi `18, `19
Gutierrez-Reyes, Makris, Vaidya, Scimemi, Zoppi `20

- Semi-Inclusive Deep Inelastic Scattering
- Breit frame
- Initial and final state TMD factorization





- Soft function with back-to-back Wilson lines
- TMD fragmentation function $\longrightarrow$ perturbative TMD jet functions. Close connection to e^+e^-
- Winner-take-all jets, different jet radii

Proton-jet correlations

Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi `18, `19
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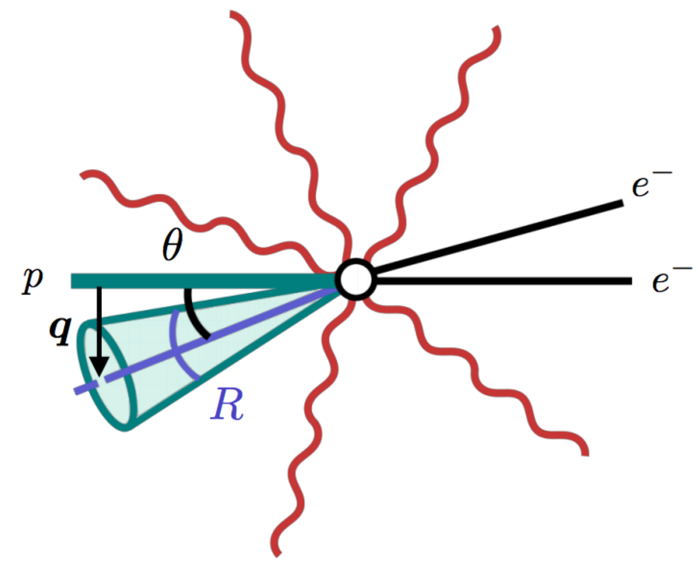
- Semi-Inclusive Deep Inelastic Scattering
- Breit frame
- Initial and final state TMD factorization

$$\frac{\mathrm{d}\sigma_{ep\to eJX}}{\mathrm{d}Q^2\,\mathrm{d}x\,\mathrm{d}z\,\mathrm{d}\boldsymbol{q}} = \sum_q \sigma_{0,q}^{\mathrm{DIS}}(x,Q^2)\,H_{\mathrm{DIS}}(Q^2,\mu)\int\frac{\mathrm{d}\boldsymbol{b}}{(2\pi)^2}\,e^{-\mathrm{i}\boldsymbol{b}\cdot\boldsymbol{q}}F_q(x,\boldsymbol{b},\mu,\zeta)\,J_q\Big(z,\boldsymbol{b},\frac{Q\mathcal{R}}{2},\mu,\zeta\Big)$$

$$\boldsymbol{q} = \frac{\boldsymbol{P}_J}{z} + \boldsymbol{q}_{\mathrm{in}} \qquad z = 2E_J/Q$$



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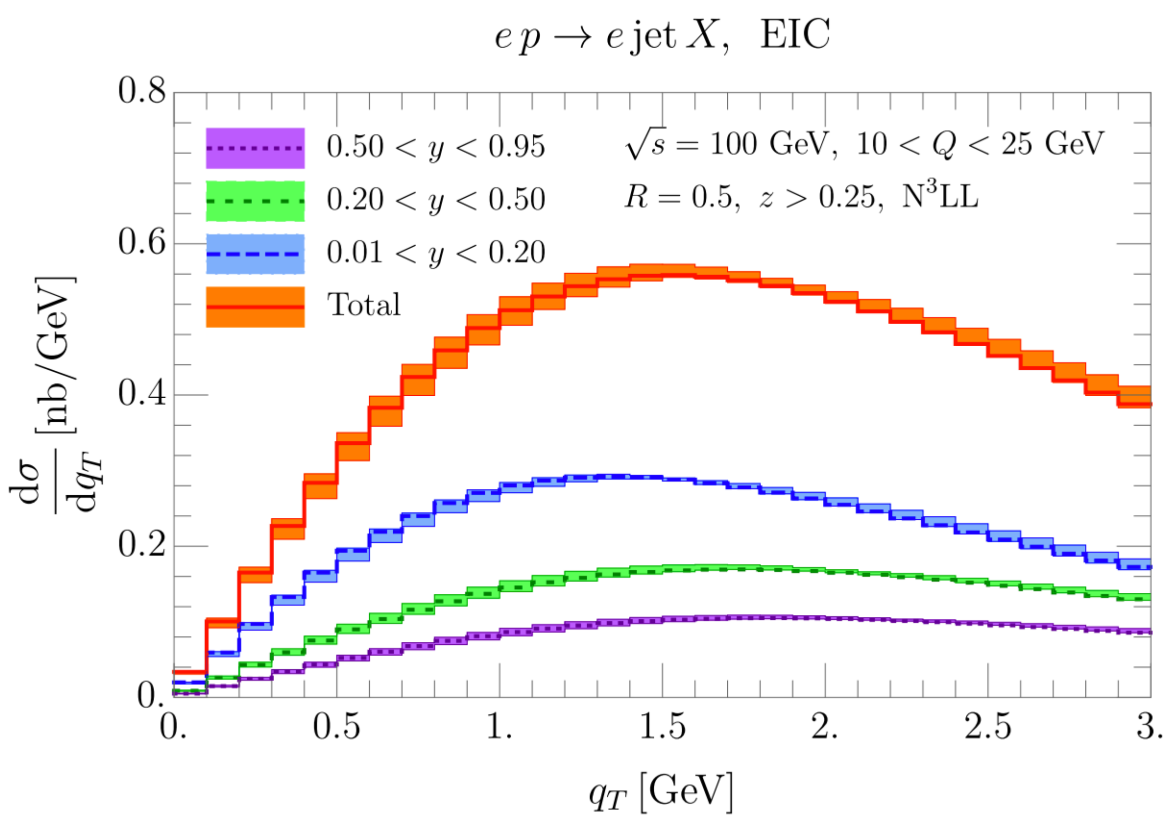
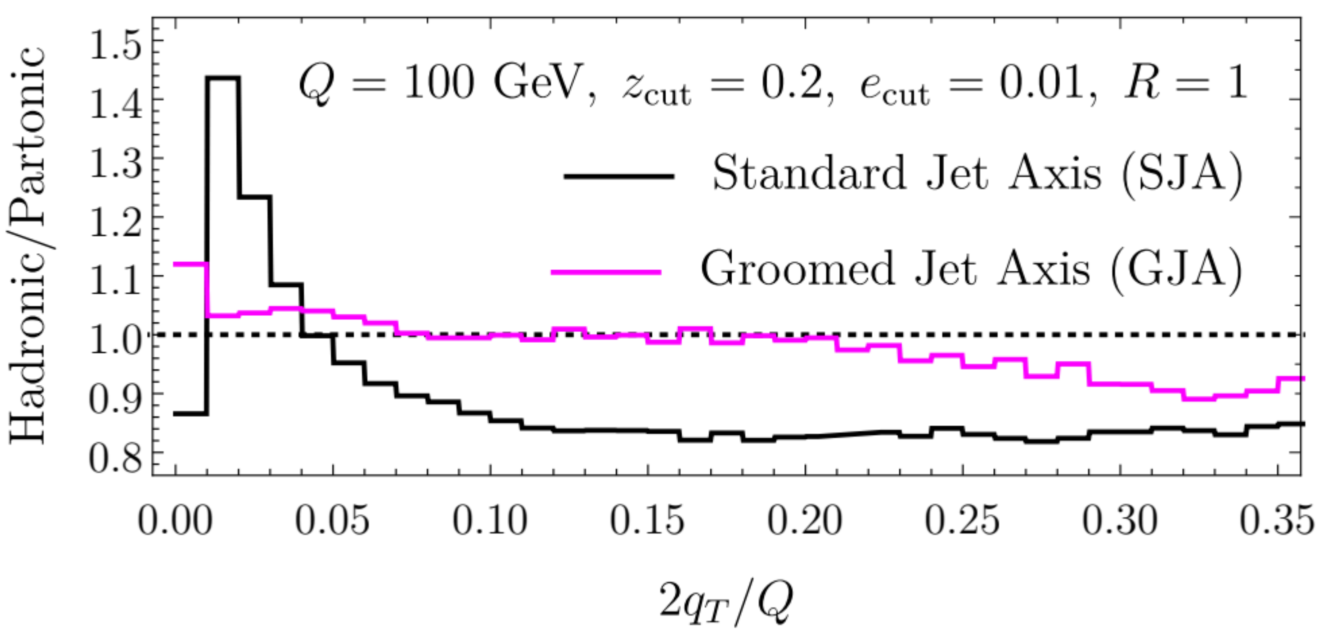
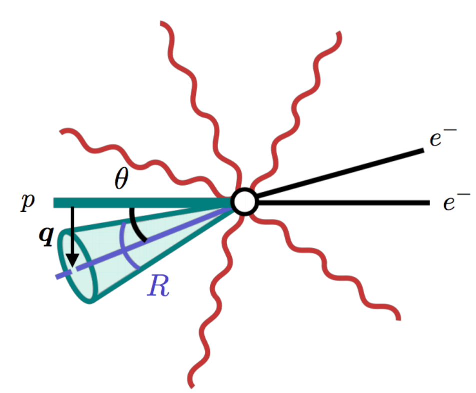


WTA-axis



Soft drop groomed jet axis



- Reduction of hadronization effects
- Mitigate effect of non-global logarithms

Outline

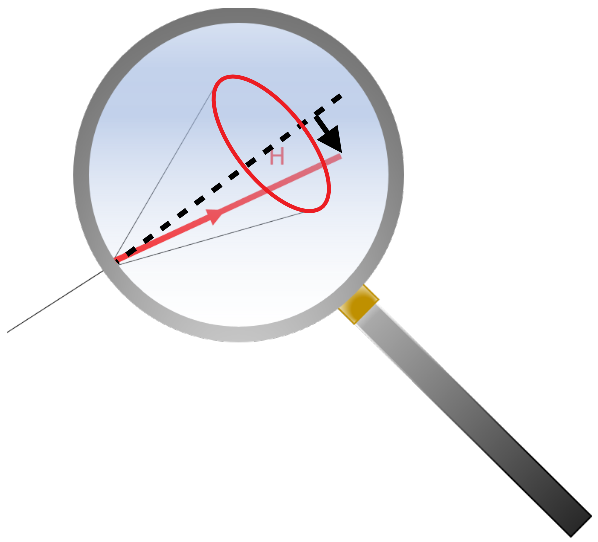
- Introduction
- Jet correlations
- Jet substructure
- Conclusions and outlook

TMD in-jet distributions

see also Yiannis Makris' talk

The hadron distribution inside jets p_T, η

- Measure additional two variables:
  - Longitudinal momentum fraction $z_h = p_T^h / p_T$
  - Relative transverse momentum wrt. to a predetermined axis $\boldsymbol{j}_\perp$



$$F\left(z_h, \boldsymbol{j}_\perp; \eta, p_T, R\right) = \frac{d\sigma^{pp\to(\text{jet}+h)X}}{dp_T d\eta dz_h d^2 j_\perp} \bigg/ \frac{d\sigma^{pp\to\text{ jet } X}}{dp_T d\eta}$$

1. Collinear factorization

$$\frac{d\sigma^{pp\to(\text{jet}+h)X}}{dp_T d\eta dz_h d^2 \boldsymbol{j}_\perp} = \sum_{a,b,c} f_a\left(x_a, \mu\right) \otimes f_b\left(x_b, \mu\right) \otimes H_{ab}^c\left(x_a, x_b, \eta, p_T/z, \mu\right) \otimes \boxed{\mathcal{G}_c^h\left(z, z_h, \boldsymbol{j}_\perp, p_T R, \mu\right)} + \mathcal{O}(R^2)$$

2. Refactorization …

- EIC — Switch out hard functions

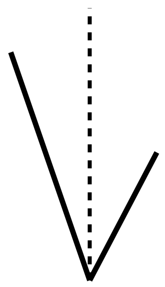
Different TMD in-jet distributions

- Overview: The choice of the jet axis

Standard jet axis

Bain, Makris, Mehen `16
Kang, Liu, FR, Xing `17
Kang, Lee, Terry, Xing `19

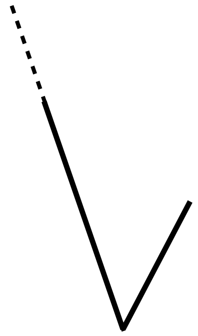
TMD factorization



Recoil free axis
e.g. Winner-take-all

Neill, Scimemi, Waalewijn `17
Neill, Papaefstathiou, Waalewijn, Zoppi `18

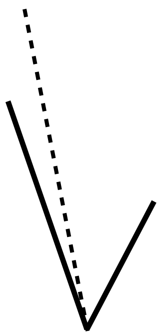
Collinear factorization



Groomed jet axis

Makris, Neill, Vaidya `17

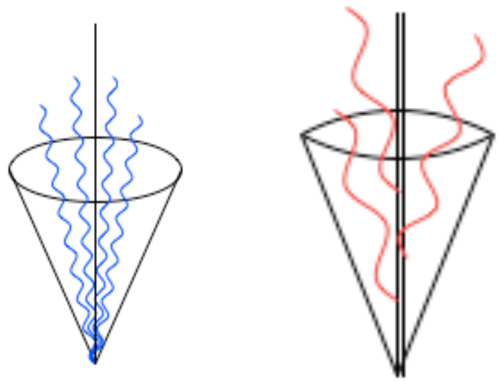
TMD factorization



In-jet TMD distributions

Bain, Makris, Mehen `16
Kang, Liu, FR, Xing `17

$$\mathcal{G}_c^h(z, z_h, p_T R, \boldsymbol{j}_\perp, \mu) = \mathcal{H}_{c\to i}(z, p_T R, \mu) \int d^2\boldsymbol{k}_\perp d^2\boldsymbol{\lambda}_\perp \delta^2\left(z_h\boldsymbol{\lambda}_\perp + \boldsymbol{k}_\perp - \boldsymbol{j}_\perp\right)$$
$$\times\, D_{h/i}(z_h, \boldsymbol{k}_\perp, \mu, \nu) S_i(\boldsymbol{\lambda}_\perp, \mu, \nu R)$$

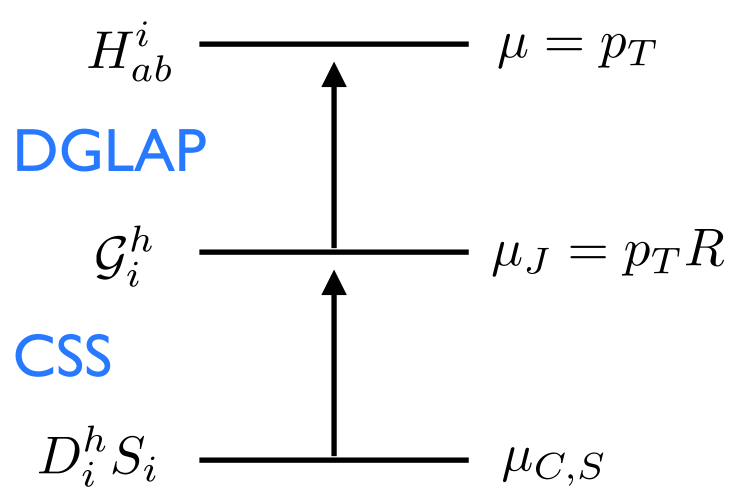


- TMD evaluated at the jet scale

$$\hat{\mathcal{D}}_{h/i}(z_h, \boldsymbol{j}_\perp; \mu_J) = \frac{1}{z_h^2}\int \frac{b\,db}{2\pi} J_0(j_\perp b/z) C_{j\leftarrow i} \otimes D_{h/j}(z_h, \mu_{b_*}) e^{-S^i_{\rm pert}(b_*,\mu_J) - S^i_{\rm NP}(b,\mu_J)}$$

At NLL usual TMD Sudakov *Collins, Soper, Sterman `85*

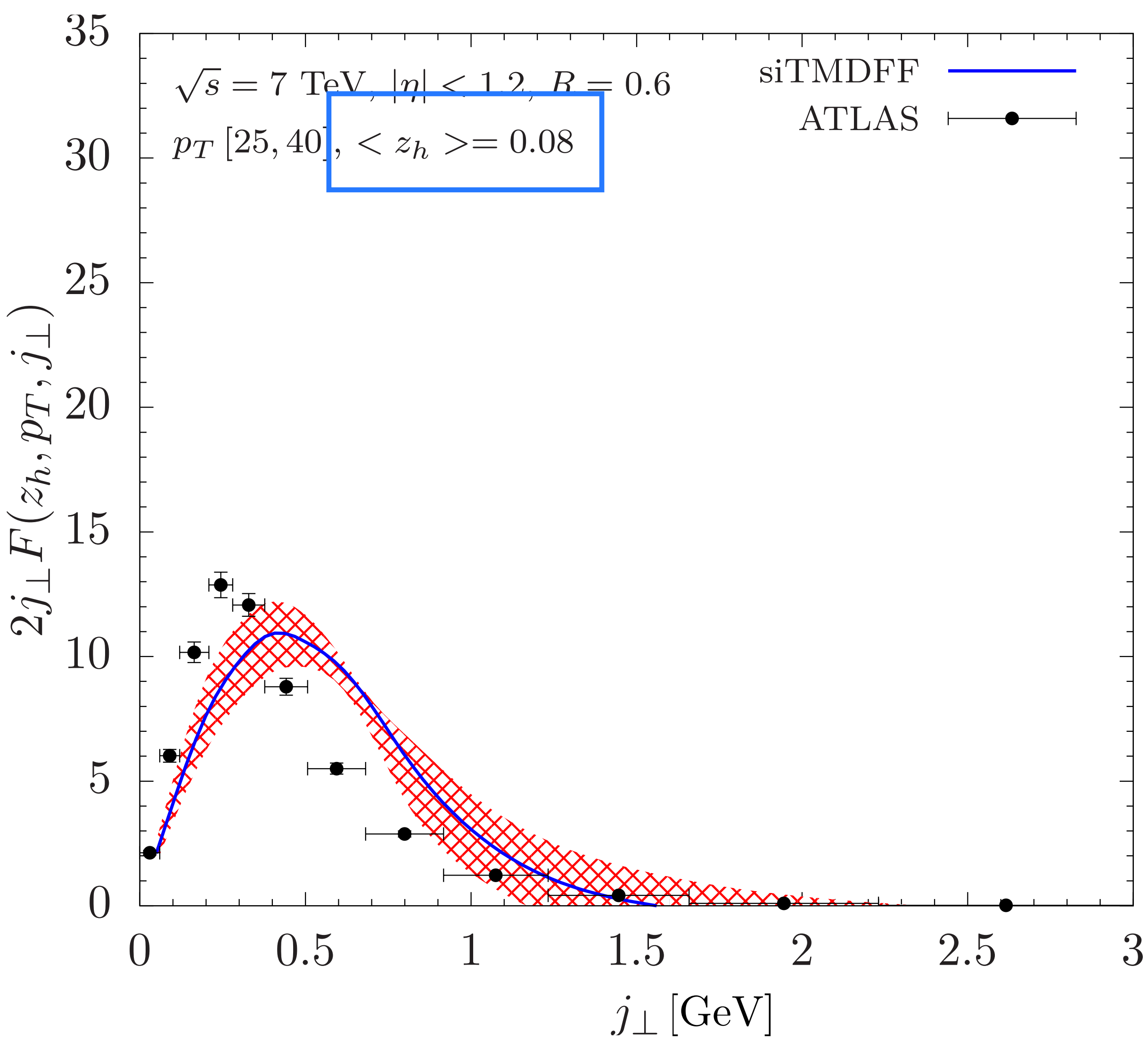
RG evolution



- Non-perturbative input from *Sun, Isaacson, Yuan, Yuan `14*

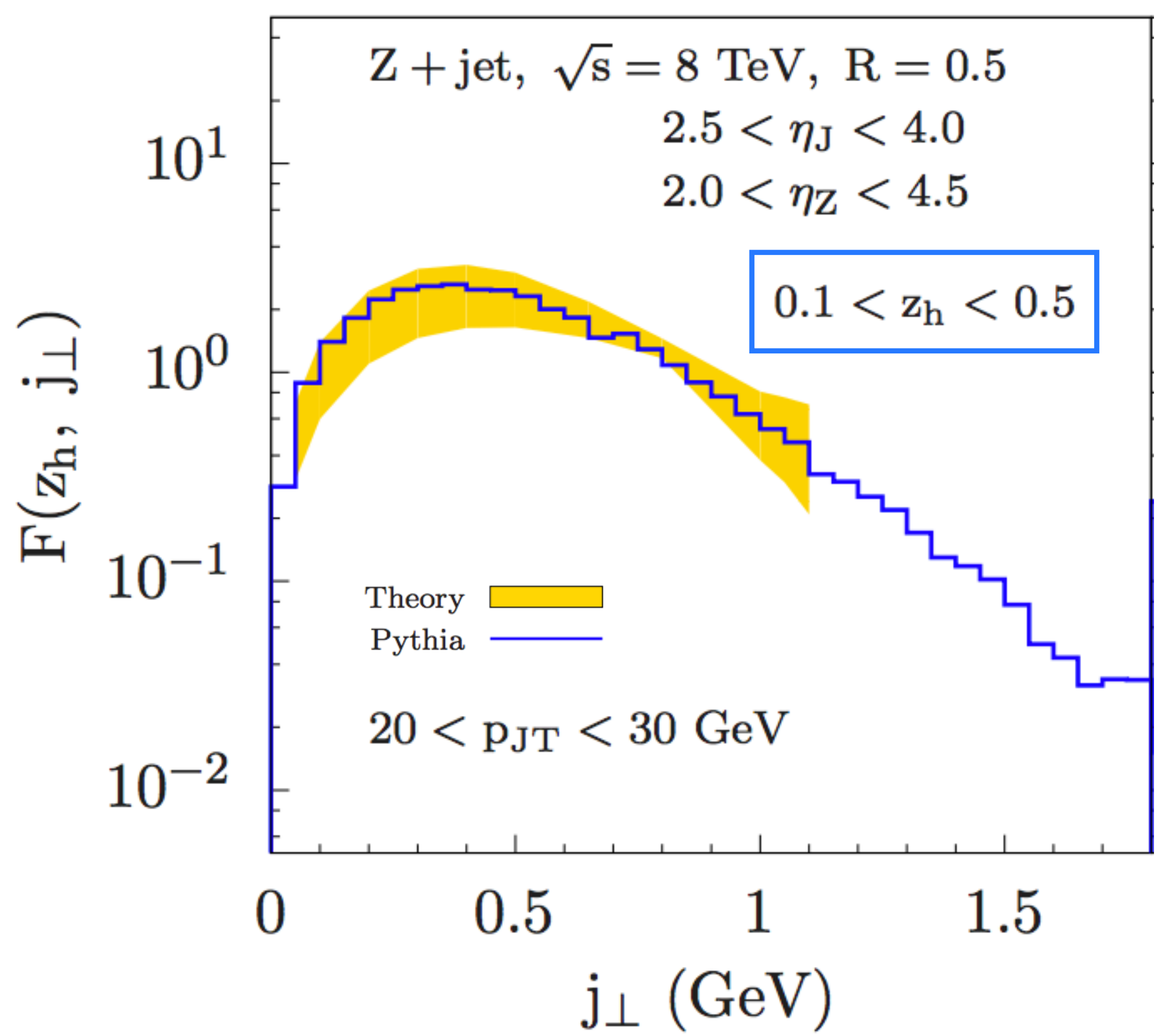
The TMD hadron-in-jet distribution

Inclusive jets, comparison to ATLAS data



Kang, Liu, FR, Xing `17

Z tagged jets, comparison to Pythia



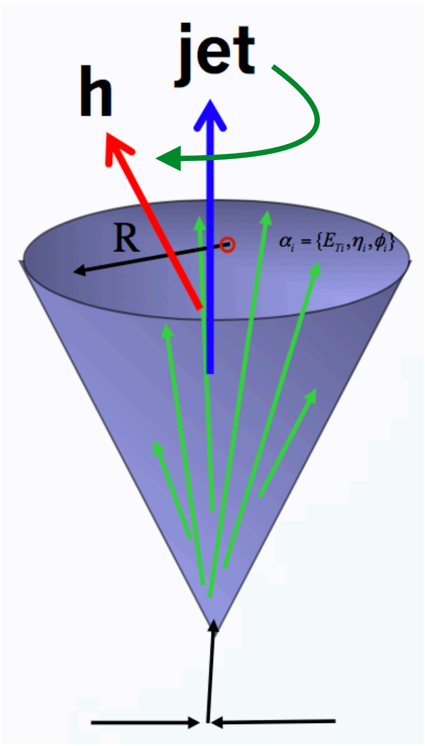
Kang, Lee, Terry, Xing `19

Including spin effects

- Transversely polarized pp collisions

$$p^{\uparrow}(P_A, S_T, \phi_S) + p(P_B) \to \mathrm{jet}(\eta, p_T)\, h(z_h, j_\perp, \phi_H) + X$$

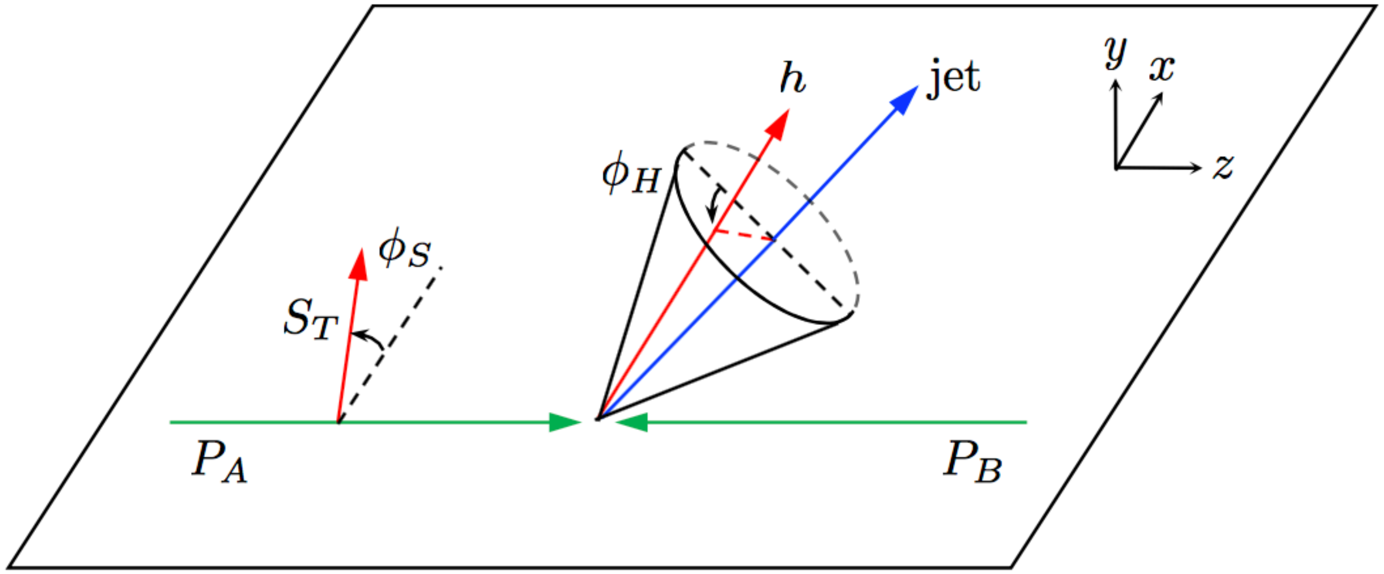
$$\frac{\mathrm{d}\sigma^{pp\to(\mathrm{jet}+h)X}}{\mathrm{d}p_T\mathrm{d}\eta\mathrm{d}z_h\mathrm{d}^2\boldsymbol{j}_\perp} = F_{UU} + \sin(\phi_S - \phi_H) F_{UT}^{\sin(\phi_S-\phi_H)}$$



  - Collinear transversity
  - Collins TMDFF

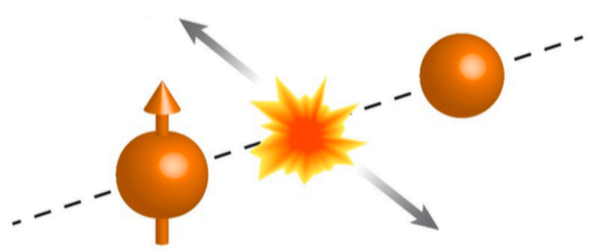
Spin asymmetry

$$A_{UT}^{\sin(\phi_S-\phi_H)}(z_h, j_\perp; \eta, p_T) = \frac{F_{UT}^{\sin(\phi_S-\phi_H)}}{F_{UU}}$$

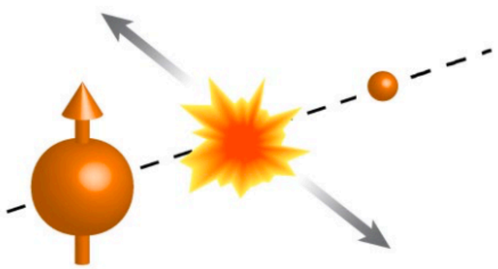


Yuan `08
Kang, Prokudin, FR, Yuan `17
see also: D'Alesio, Murgia, Pisano `11, `17

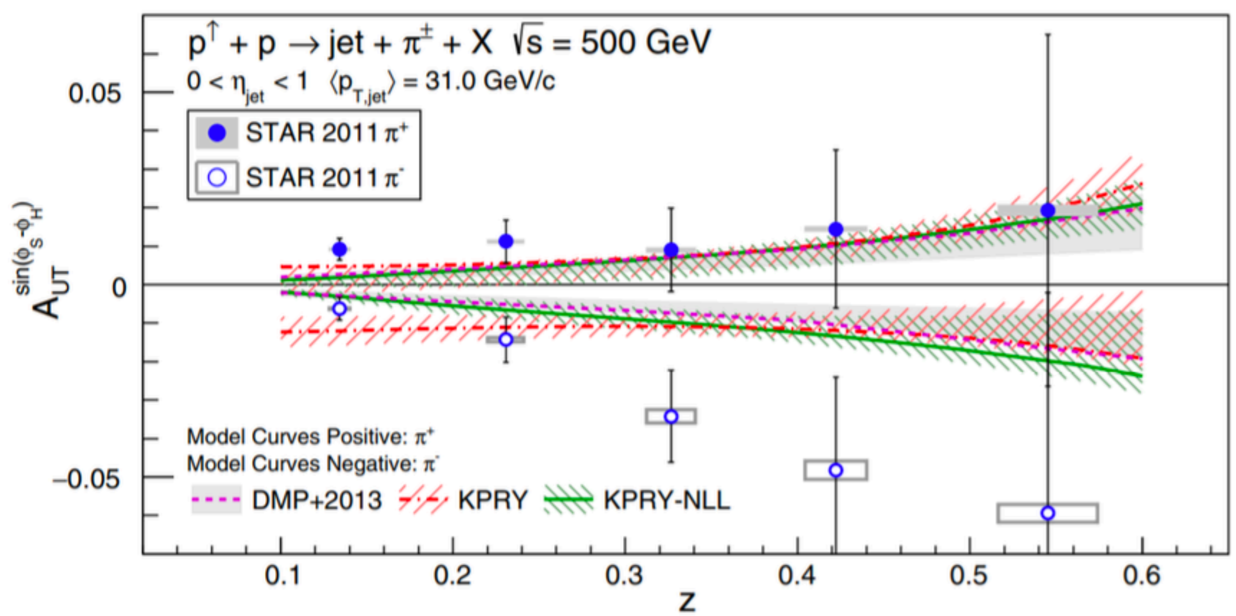
Transversity and Collins fragmentation

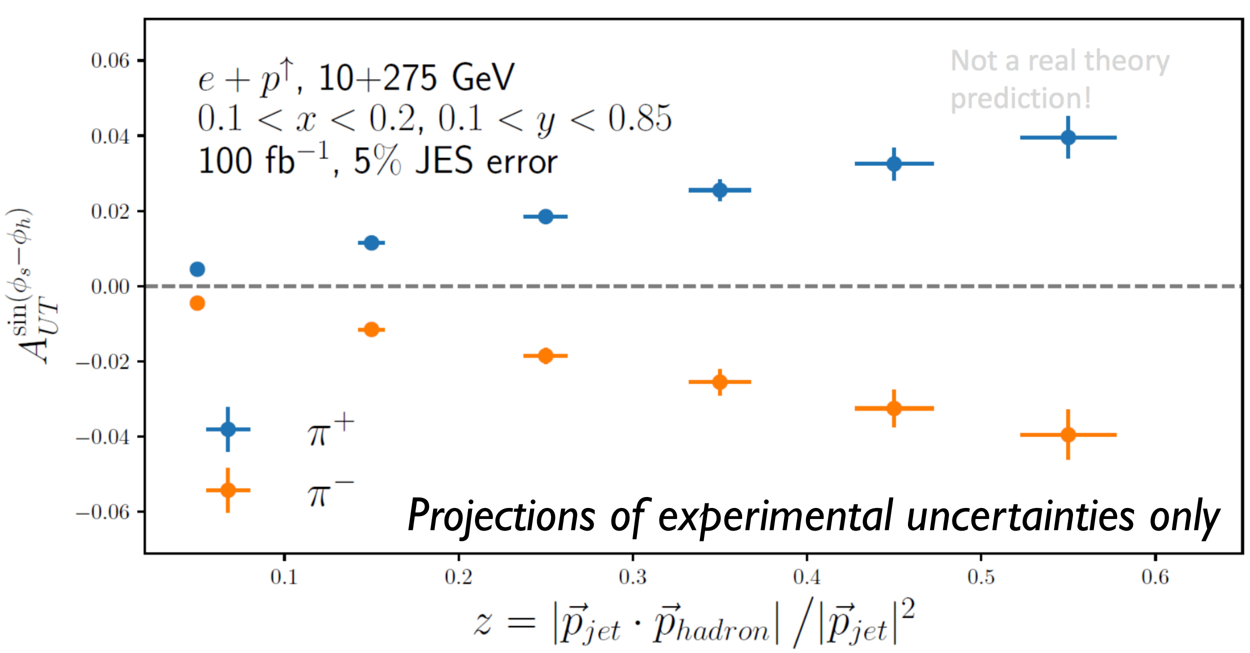


RHIC



EIC



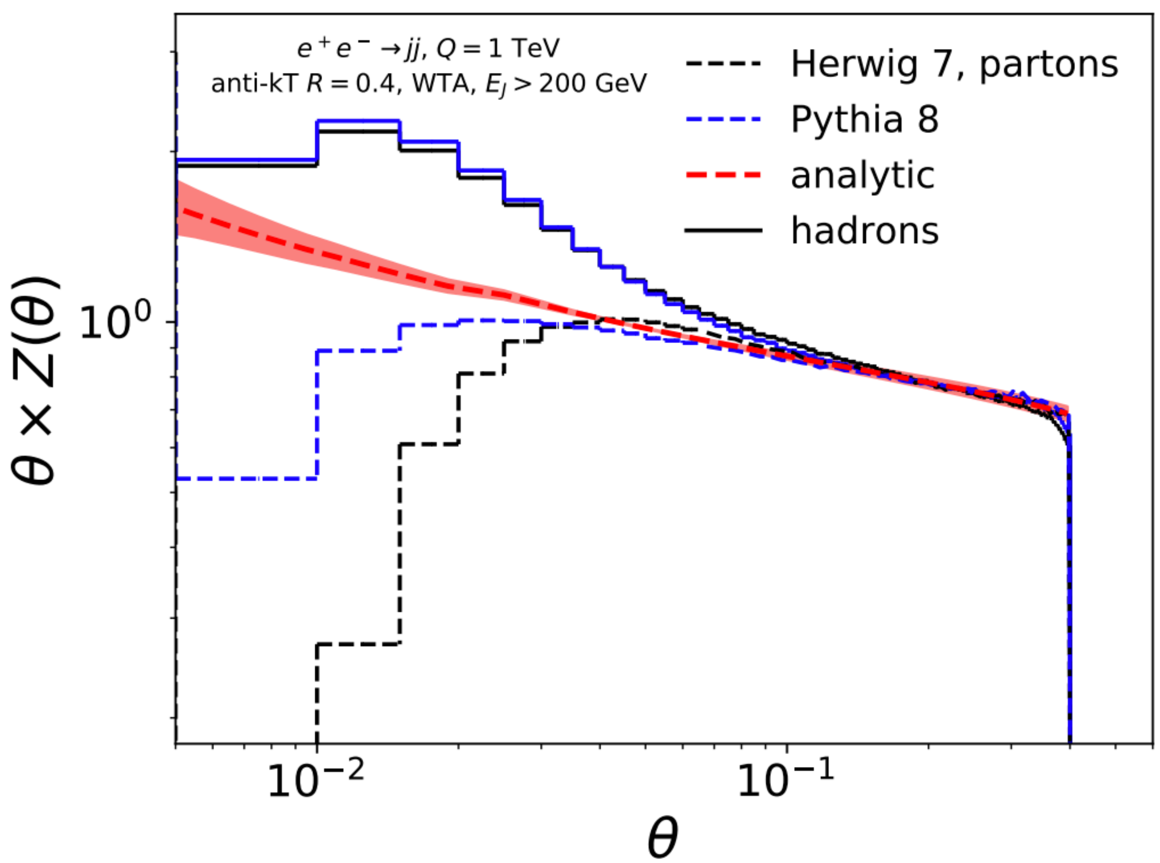


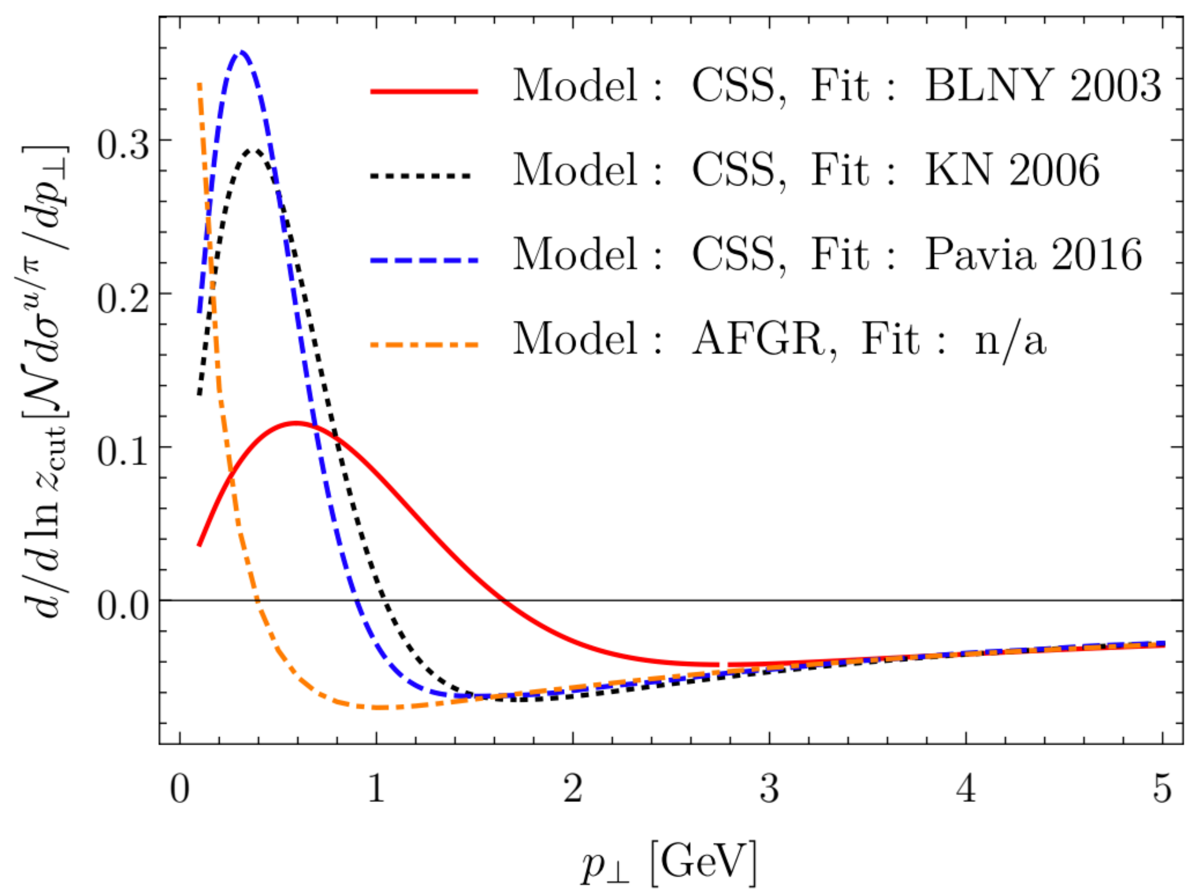
Kang, Prokudin, FR, Yuan `17
STAR, PRD 97 032004 (2018)

see Miguel Arratia's talk

The WTA axis and groomed jets

$\theta = j_\perp / p_T$





Nonperturbative effects very important at small angles, $j_\perp$

Constraints on the nonperturbative part of the rapidity anomalous dimension

Neill, Scimemi, Waalewijn `17
Neill, Papaefstathiou, Waalewijn, Zoppi `18

Makris, Neill, Vaidya `17

Angles between jet axes

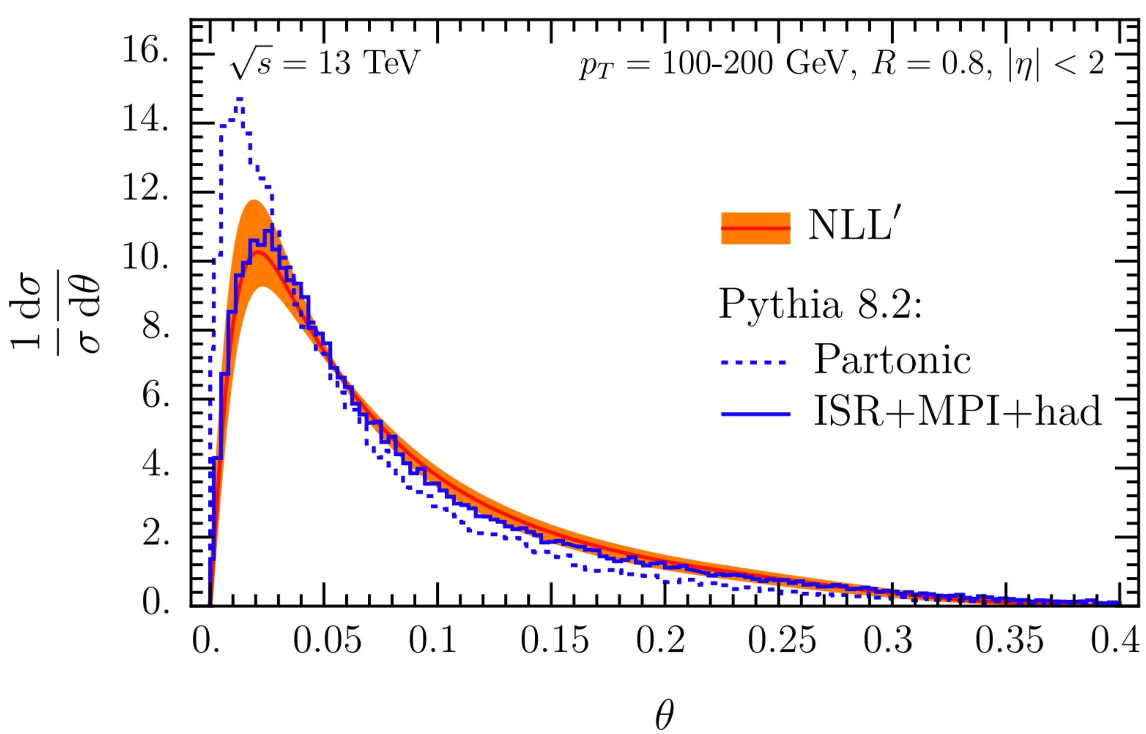
Cal, Neill, FR, Waalewijn `19
see also: Makris, Neill, Vaidya `18

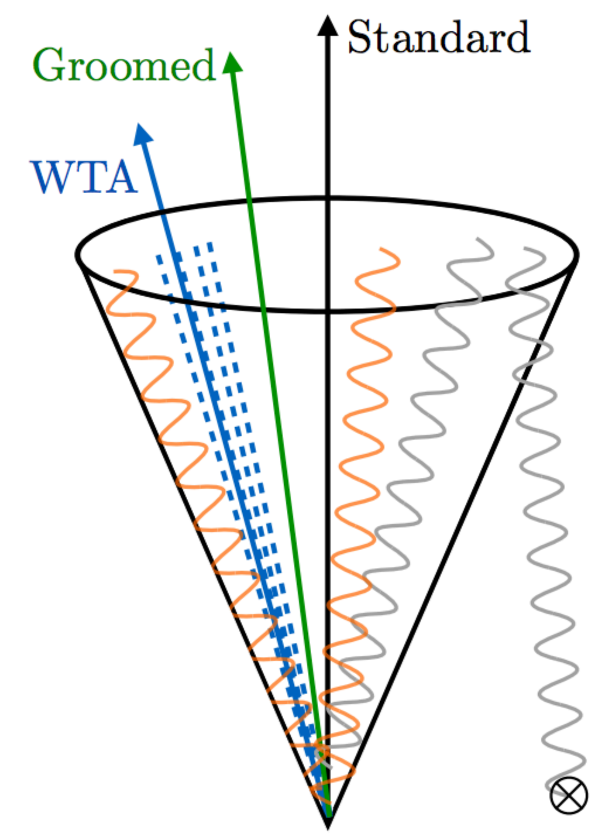
- IRC safe observables
- Probe of TMD evolution

$$\exp(-g_K \ln(\mu/\mu_0)) \quad \textbf{e.g.} \quad \exp\left[-g_K(b_\perp, b_*)\frac{1}{1+\beta}\ln\frac{z_{\rm cut}p_T R}{\mu_b}\right]$$

Nonperturbative part of the rapidity anomalous dimension

- Ideal observable at low energies such as the EIC





Soft drop parameters $z_{\rm cut}, \beta$

Outline

- Introduction
- Jet correlations
- Jet substructure
- Conclusions and outlook

Overview

Jet correlations

Lepton-jet, Lab frame	Proton-jet, Breit frame	Di-jet, Breit frame
IS-TMD	IS&FS-TMD	IS-TMD
ST, WTA, GR	ST, WTA, GR	ST, WTA, GR

Jet substructure

Hadron-ST, GR axes	Hadron-WTA axis	Jet axes-ST, WTA, GR or Jet shape
FS-TMD		FS-TMD

IS-Initial state, FS-Final state

TMD-Rapidity evolution, ST-Standard, WTA-Winner-take-all, GR-Soft drop groomed jet axis

Other choices of the jet axes possible

Conclusions

- Recent significant progress of TMD-jet observables
- Important observables at the EIC
- Jet substructure and jet correlations
- Non-global logarithms
- Include in fits
- EIC detector requirements