Toward precision jet event shape for future Electron-Ion Collider

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3-jet event: discovery of gluon

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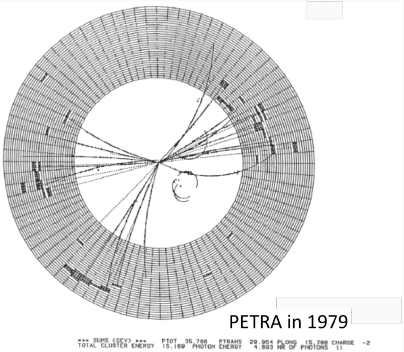
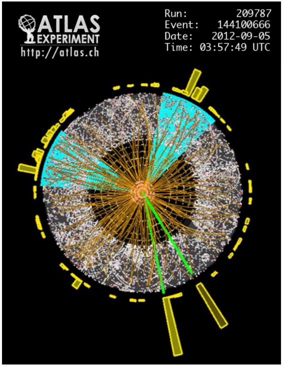
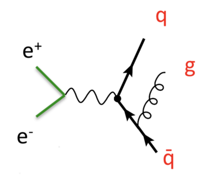
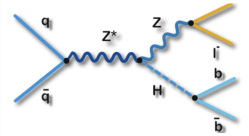




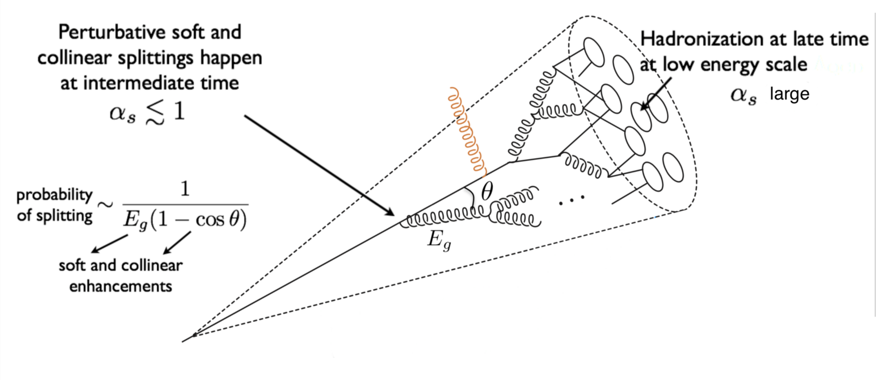




Introduction

Jet production in collider

- Jet?



- Jet contains rich information to probe strong dynamics.

Motivation

Jet production in DIS

$$ep \to 2 - jet$$

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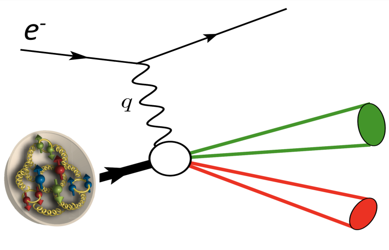
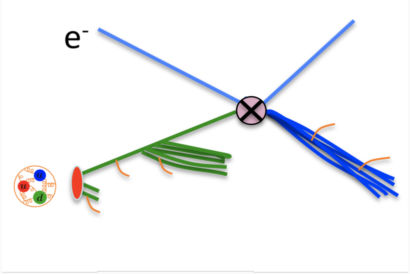




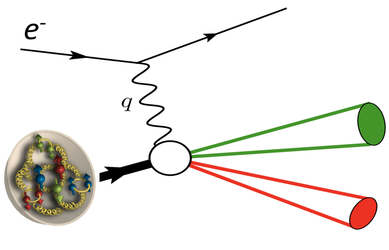
dijet production
in ep collision

- Jet: to investigate short distance phenomenon.
- Beam: created from ISR to investigate internal structure of hadron– PDF, GPD, TMD, Spin structure...

Beam encodes internal structure of incoming proton.

Motivation

Jet production in DIS
$ep \to 2 - jet$



• Jet: to investigate short distance phenomenon.

• Beam: created from ISR to investigate internal structure of hadron– PDF, GPD, TMD, Spin structure...

Precision Jet Physics in DIS:

a new tool to probe strong dynamics

a new level of precision for jets
at the future
Electron-Ion-Collider (EIC)

• **One of early milestones!**

[GPD at EIC: Talk by Paweł Sznajder]

The jet observables are called Event Shapes.

Event Shapes: Jet observables

Several event shapes: Thrust (τ), Angularity (τ_a), Jet Broadening...

Event Shapes: Jet observables

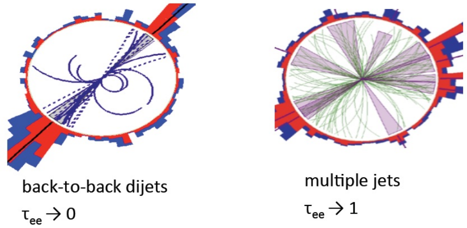
Several event shapes: Thrust (τ), Angularity (τ_a), Jet Broadening...

◂ Thrust (τ) ▸

One of the most precisely measured observables!

$$\tau = \frac{2}{Q} \sum_{i \in \mathcal{X}} |\mathbf{p}_{\perp}^{i}| \, e^{-|\eta_i|}$$

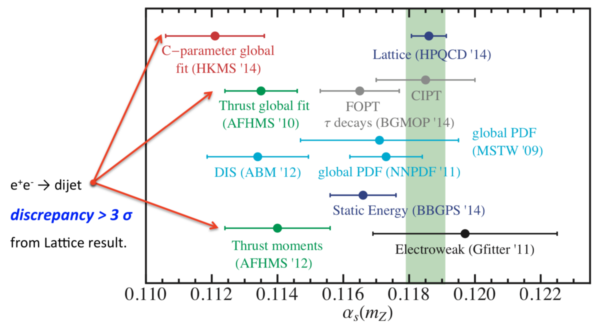
Thrust event shape characterised the geometry of the collision!



- Expt.: LEP, CMS and ATLAS, HERA by the ZEUS and H1

Event Shapes: Determination of strong coupling

▶ Puzzle in strong coupling constant



- Tension between $e^+e^- \to 2-jet$ result and Lattice result!
- Need a new test from an independent experiment!

DIS: ep →dijet !!

Angularity event shapes

future Electron-Ion-Collider

Event Shapes: Angularity

◂ Angularity (τ) ▸

A more general event shapes!

$$\tau_a = \frac{2}{Q} \sum_{i \in \mathcal{X}} \left| \mathbf{p}_\perp^i \right| e^{-|\eta_i|(1-a)}$$

Angularity depends on the continuous parameter a.

$a \to 0$: Thrust

$a \to 1$: Jet Broadening

Event Shapes: Angularity

◂ Angularity (τ) ▸

A more general event shapes!

$$\tau_a = \frac{2}{Q} \sum_{i \in \mathcal{X}} |\mathbf{p}_\perp^i| \, e^{-|\eta_i|(1-a)}$$

Angularity depends on the continuous parameter a.

$a \to 0$: Thrust

$a \to 1$: Jet Broadening

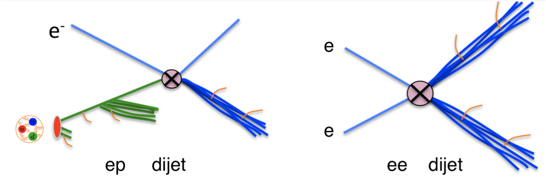
• In terms of the four-vectors q_B along the incident proton beam direction and q_J along the direction of the final state jet we wish to measure

• 1-jettiness axis Choice:

$q_B = xP$

$q_J = \text{Jet axis}$

Breit frame!



Event Shapes: Angularity

Theoretical Prediction:

Accuracy in the theoretical prediction to the event shapes!

Tool:

Soft-collinear effective theory (SCET)

a systematic way to achieve high precision in high-energy scattering

SCET Predictions so far...

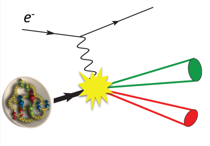
- Thrust : e^+e^- [Becher,Schwartz'08; Stewart,Tackmann,Waalewijn'10]
  pp-collision [Stewart,Tackmann,PRL'10,'11;PRD'13],
  DIS [D. Kang,C. Lee,I. Stewart'13]
  ...
- Angularity: e^+e^- [Hornig,Lee,Ovanesyan'09; Bell,Lee'19]
  DIS [??] Could be important for future EIC!

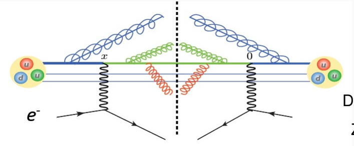
We do...

Investigation of angularity in DIS in the frame-work of soft-collinear effective theory (SCET) tools and to push the frontier of the precision jet physics in the future Electron-Ion Collider (EIC)

DIS factorization and Beam function at NNLL

DIS process: $e\ P \to 2\mathrm{Jets}$





D.Kang,Lee,Stewart'2013

Z.Kang,Mantry,Qiu'2012

$$\text{SCET facto.} \quad \sigma_{eP} \quad = \quad Hard \times Beam \otimes Jet \otimes Soft$$

- Beam is produced due to the initial state radiation (ISR) and can be used to study internal structure of proton!

$$\text{Beam func.} \quad B(\tau_a, x, \mu) \quad = \quad \text{pdf} \otimes \left[\delta_{qj}\delta(\tau_a) + \tilde{\mathcal{I}}^{(1)}_{qj} + \mathcal{O}(\alpha_s^2) + ...\right]$$

$$NP \qquad LO \qquad NLO \qquad NNLO$$

- Angularity Jet and soft function is presented at NNLL accuracy [Bell,Horning,Lee'2018]

Angularity beam function at NLO is presented for the first time!

Fixed order Beam function at NLO

$$\text{Beam func.} \quad B(\tau_a, x, \mu) \quad = \quad \text{pdf} \otimes \left[\delta_{qj}\delta(\tau_a) + \tilde{\mathcal{I}}_{qj}^{(1)} + \mathcal{O}(\alpha_s^2) + ...\right]$$

$NP \qquad LO \qquad NLO \qquad NNLO$

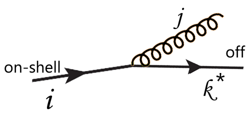
Angularity beam function at NLO is presented for the first time!

$$\tilde{\mathcal{I}}_{qj}^{(1)} = \frac{\alpha_s}{4\pi}\left[\left(j_B \kappa_B \frac{\Gamma_0}{2} L_B^2 + \gamma_0^B L_B\right) 1 + 4C_{qj} P_{qj}(z) L_B + c_1^{qj}(z)\right]$$

$$L_B(\tau_a) = \log\left[\frac{Q}{\mu_B}(\tau_a e^{-\gamma_E})^{1/j_B}\right]$$

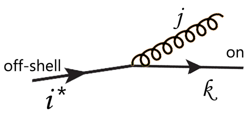
Beam Func. and Fragmentation Func.

Beam at NLO: $i \to k^* j$



Crossing Symmetry!

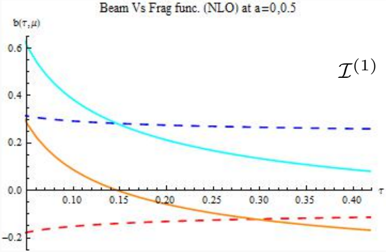
Fragmentation at NLO: $i^* \to kj$



Splitting Function: [M.Ritzmann,W.J.Waalewijn,PRD90(2014)]

$$P_{i\to k^* j}(2pi.pj, x) \equiv (-1)^{\Delta_f} P_{k*\to ij}(-2pi.pj, 1/x)$$

- Change comes only from the two-particle phase-space and effectively change in sign of the $\log(x)$ term in the matching co-efficient $\mathcal{I}^{(1)}$.



$$\mathcal{I}^{(1)} \sim \ldots - \frac{\alpha_s C_F}{2\pi} \frac{2(1-a)}{2-a} \frac{1+x^2}{1-x} \log x$$

Beam match. Coeffi.: $a = 0$

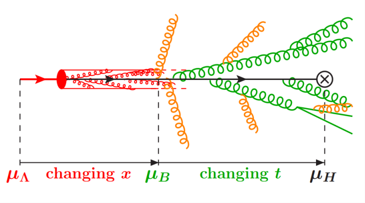
Beam match. Coeffi.: $a = 0.5$

FF match. Coeffi.: $a = 0$

FF match. Coeffi.: $a = 0.5$

- Difference decreases with the increase of angularity parameter a.

Resummation from evolution



-Stewart et. al. PRD81(2010)

Evolution Equation for beam function

$$\mu \frac{d}{d\mu} B(\nu,\mu) = \gamma_G(\mu)\, B(\nu,\mu) \quad ; \qquad \text{similar to} J, S, H$$

$$\text{Solution}: \; B(\nu,\mu) = B(\nu,\mu_B)\, e^{K_B(\mu_B,\mu)+j_B \eta_B(\mu_B,\mu) L_B} \,,$$

- Jet and beam functions are defined by same collinear operator: $\gamma_J(\mu) = \gamma_B(\mu)$

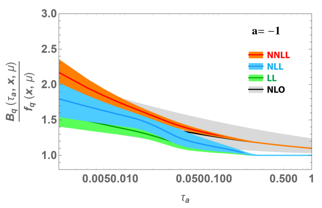
$$K_B(\mu_B,\mu) = L_B \sum_{k=1}^{\infty} (\alpha_s L_B)^k + \sum_{k=1}^{\infty} (\alpha_s L_B)^k + \ldots$$

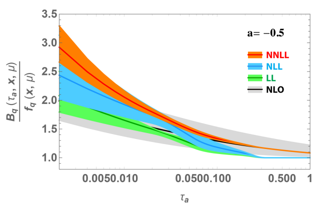
LL $\qquad NLL$

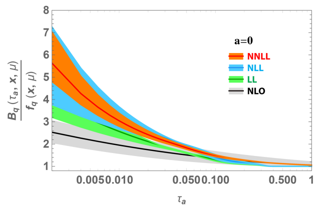
$$L_B = \ln(\mu/\mu_B)$$

- Resummation of large logs provides better perturbative convergence.

Beam function result at NNLL

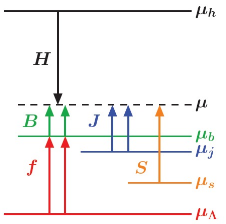






Differential Cross-Section

$$\sigma_{eP} = Hard \times Beam \otimes Jet \otimes Soft$$



Evolved form

$$\sigma(x, Q^2, \tau_a, \mu) \quad = \quad \sigma_0(x, Q^2)\left(\frac{Q}{\mu_H}\right)^{\eta_H(\mu,\mu_H)} e^{\kappa(\mu_H,\mu_J,\mu_B,\mu_S,\mu)}$$

$$\times\left(\left(\frac{Q}{\mu_J}\right)^{2-a}\tau_a e^{-\gamma_E}\right)^{\eta_J(\mu,\mu_J)}\left(\left(\frac{Q}{\mu_B}\right)^{2-a}\tau_a e^{-\gamma_E}\right)^{\eta_B(\mu,\mu_B)}\left(\frac{Q^2}{\mu_S}\tau_a e^{-\gamma_E}\right)^{2\eta_S(\mu,\mu_S)}$$

$$\times\tilde{j}_q\left(\partial_\Omega + \log\left(\frac{Q^{2-a}}{\mu_J^{2-a}}\tau_a e^{-\gamma_E}\right), \mu_J\right)\tilde{s}\left(\frac{1}{Q_R}\left(\partial_\Omega + \log(\frac{Q}{\mu_S}\tau_a e^{-\gamma_E})\right), \mu_S\right)$$

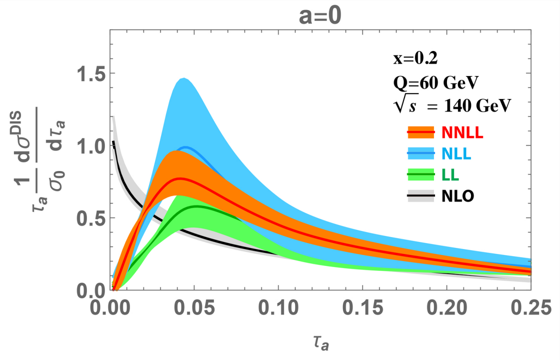
$$\times\Bigg[H_q(y, Q^2, \mu_H)\tilde{b}_q\left(\partial_\Omega + \log\left(\frac{Q^{2-a}}{\mu_B^{2-a}}\tau_a e^{-\gamma_E}\right), x, \mu_B\right)$$

$$+H_{\bar{q}}(y, Q^2, \mu_H)\tilde{b}_{\bar{q}}\left(\partial_\Omega + \log\left(\frac{Q^{2-a}}{\mu_B^{2-a}}\tau_a e^{-\gamma_E}\right), x, \mu_B\right)\Bigg]\frac{1}{\tau_a\Gamma(\Omega)}$$

Cross-section at NNLL

Prediction to EIC: NNLL resummation accuracy for angularity in $ep \to\ 2 - jets$

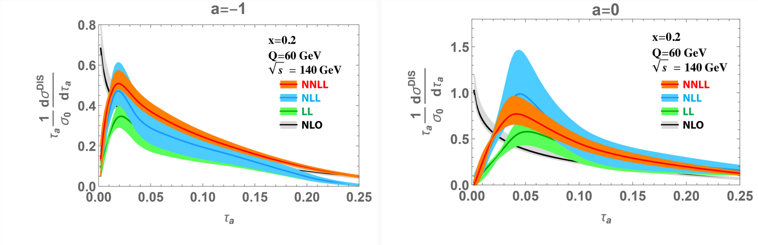
EIC $\sqrt{s} = 140 GeV, 0.01 \leq y \leq 0.95$



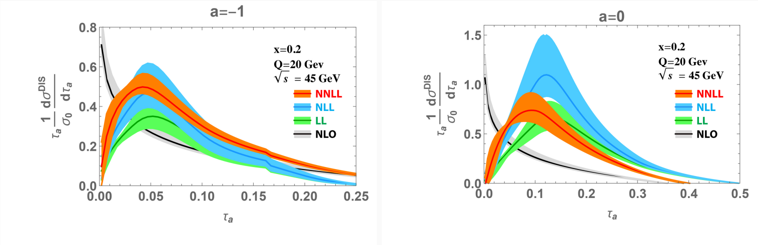
- Low angularity region: Log singularity at NLO
- Tail region: Resummation gives convergence from LL to NNLL.
- Far-tail region: Need full QCD.

Cross-section dependency on a

EIC $\sqrt{s} = 140$ GeV



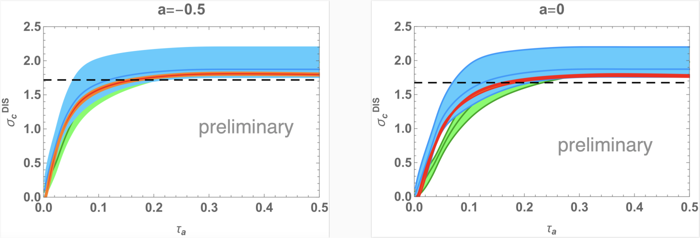
EIC $\sqrt{s} = 45$ GeV



- Peak shifts towards right for larger value of angularity parameter a.

Cumulant

$$\sigma_c(x, Q^2, \tau_a) = \frac{1}{\sigma_0} \int_0^{\tau_a} d\tau_a' \frac{d\sigma}{dx dQ^2 d\tau_a'} .$$



- Deviation of NNLL prediction from the total cross-section (at $\mathcal{O}(\alpha_s)$) at large angularity is due to the non singular term that not considered.
- Non-singular contribution decreases with the decreasing angularity parameter a.

Summary & Future direction

▶ We define DIS angularity event shape, τ_a^{DIS} , for the axis aligned to the jet axis and present angularity beam function at NNLL accuracy.

▶ We present precision prediction to differential cross-section and cumulant for the future EIC kinematics which could be early prediction to future Electron-Ion-Collider.

[In collaboration with: Daekyoung Kang, IMP, Fudan University]

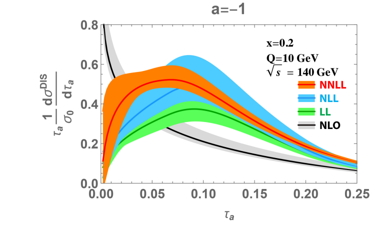
Towards the precision measurement for electron proton scattering (DIS)

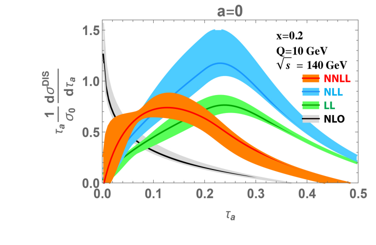
"And miles to go before I sleep"

Thank you!

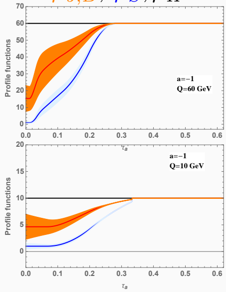
Cross-section dependency on a

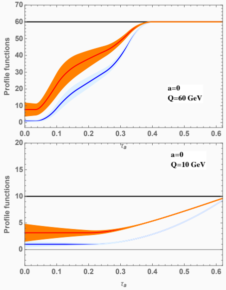
Low $Q = 10$ GeV





Profile function: $\mu_{J,B}$, μ_S, μ_H





- Choice of other scale profile functions may improve tail region for low Q.

Profile Function