Jet charge and one-jettiness at the EIC

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Workshop on PDFs in the EIC era
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In collaboration with Sonny Mantry, work in progress

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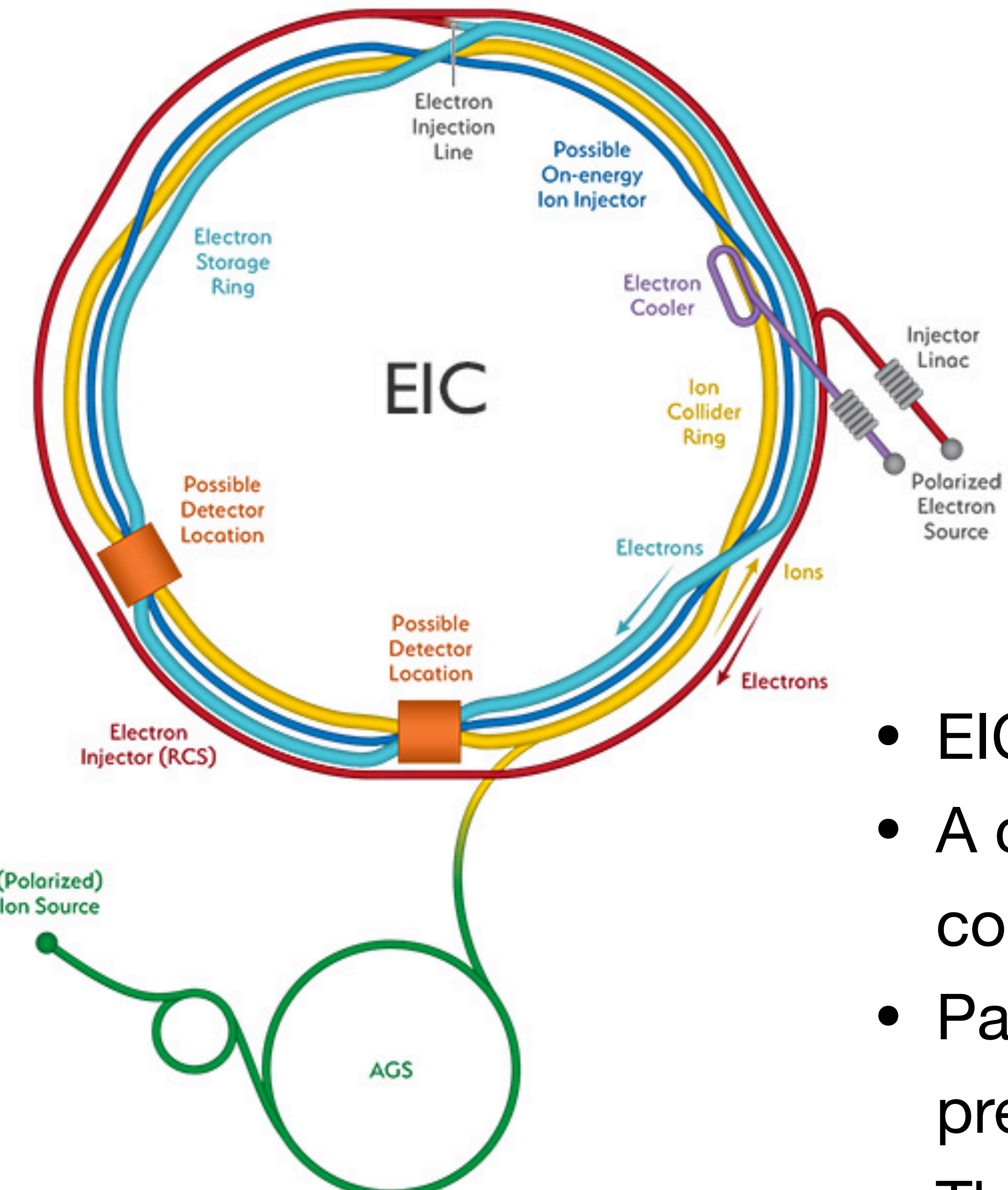
Outline

- Introduction
  - Flavor and energy flows: jet charge and one-jettiness
- Joint jet charge and one-jettiness distribution
  - Parton distribution functions and hadronization
- Phenomenology
- Conclusion

Electron Ion Collider



ePIC

Second detector?

$?   ?

Particle ID
High statistics

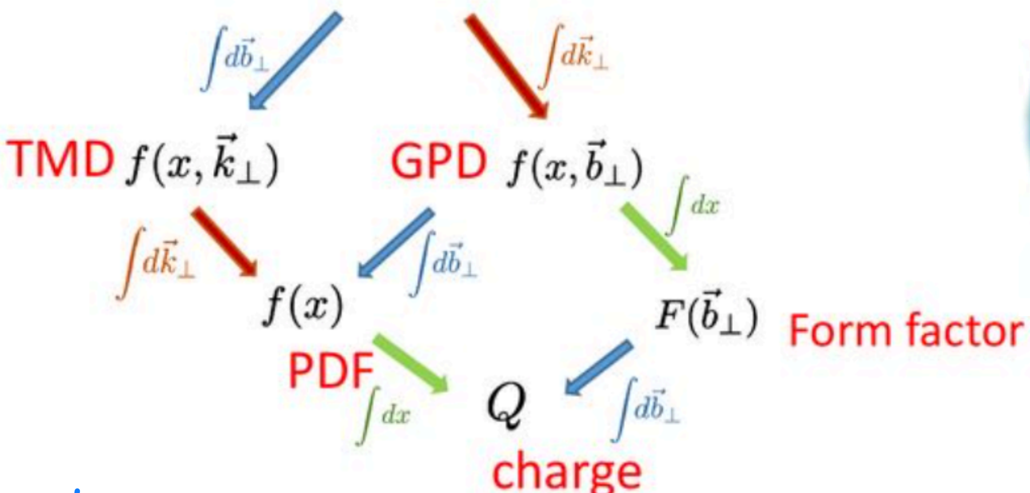
key

- EIC has been making progress toward realization
- A control over spin and polarization d.o.f. allows a complete tagging of partonic quantum numbers
- Particle ID and high statistics are important for precision extraction of proton 3D structure
- The second detector is needed for complementarity, possibly more coverage in the forward region

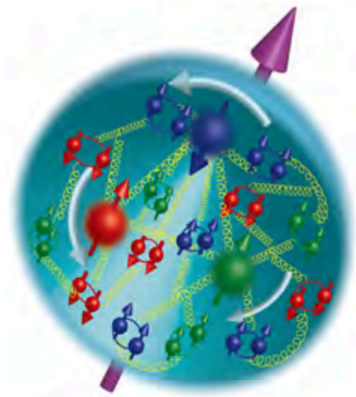
Outstanding questions of strong interaction

Wigner distribution

$$W(x, \vec{k}_\perp, \vec{b}_\perp)$$

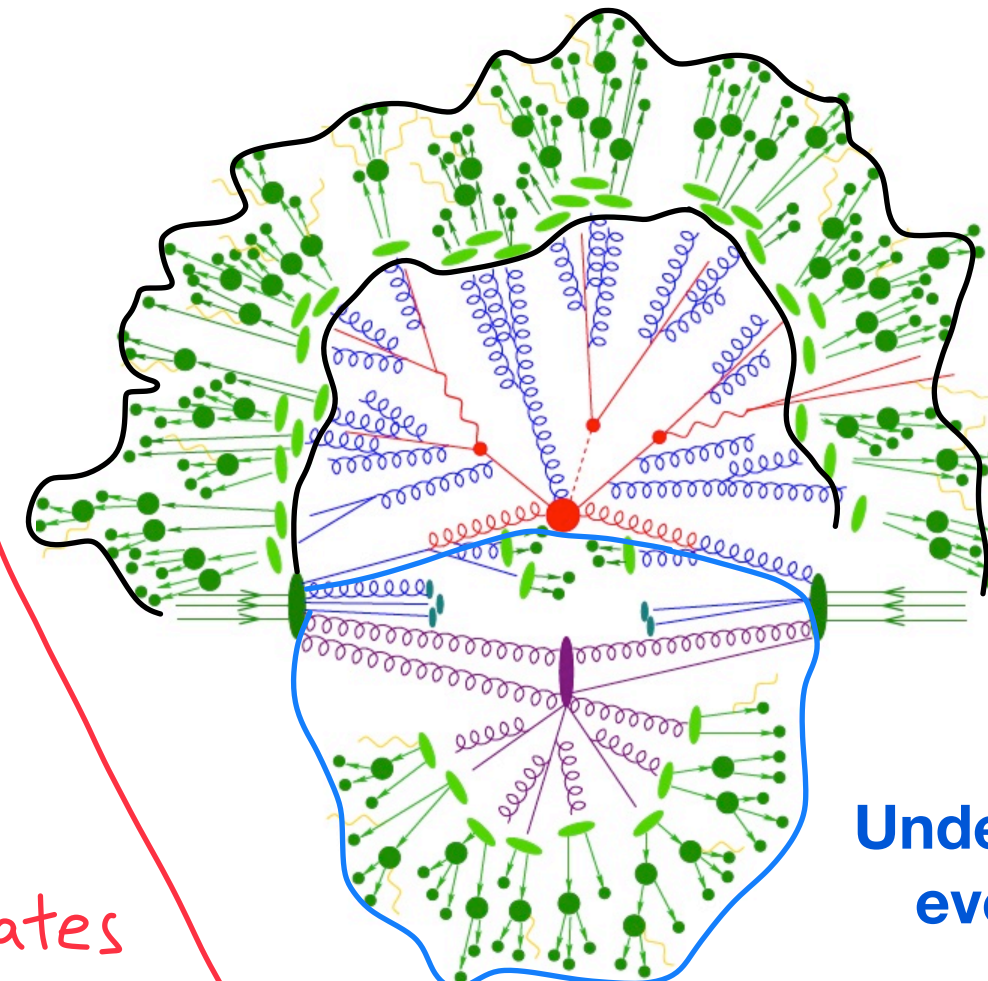


Proton and nuclei 3D structure



Initial states

Hadronization



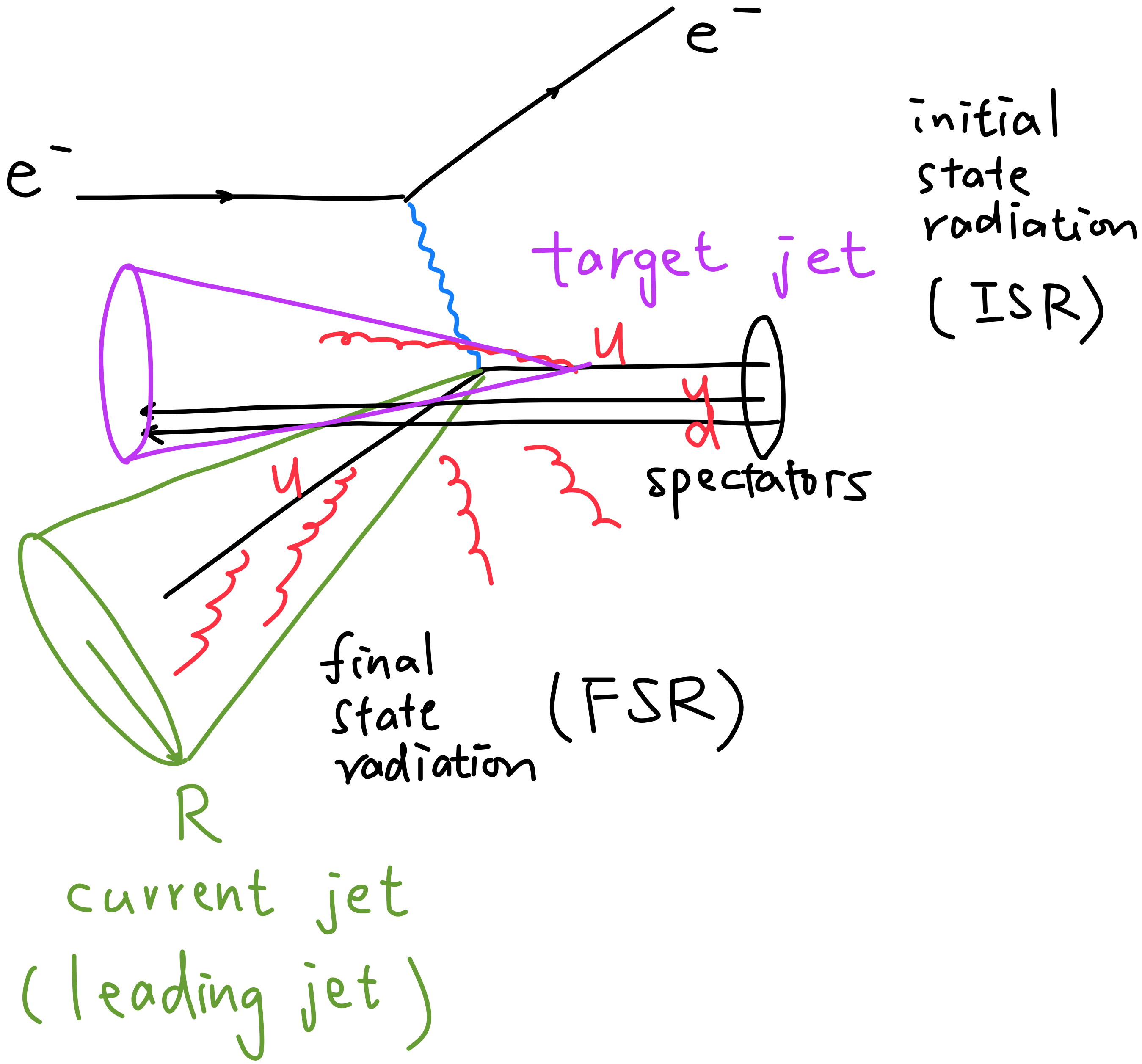
Underlying events

Final states

Interaction of multiple, spectator partons especially at hadron colliders

- Soft and non-perturbative physics is the main subject of study, while perturbative tools remain essential
- At EIC, underlying event contributions are not as prominent as at hadron colliders

Jets production in Deep Inelastic Scattering



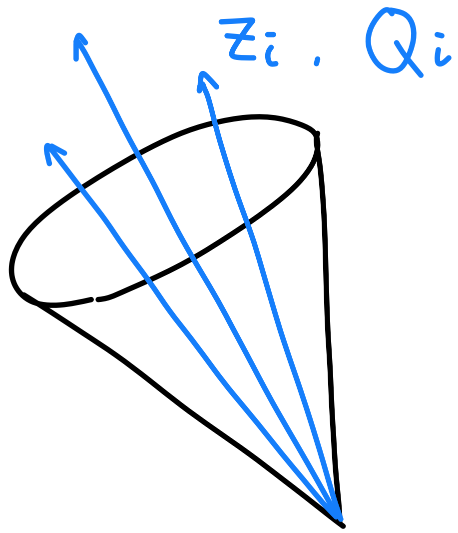
- High momentum transfer in DIS excites energetic partons which turn into jets (FSR)
- Spectators and ISR in the forward region form a target jet (or beam jet)
- Strong correlation between Initial state parton flavor and final state jet flavor
- Strong correlation (or entanglement) between Initial state parton flavor and spectators

Target jet substructure:

Chen, Chien, Esha, Kuo, in preparation

Jet charge

Field and Feynman (1978)
Berge (1981, Fermi lab)
Albanese (1984, EMC)

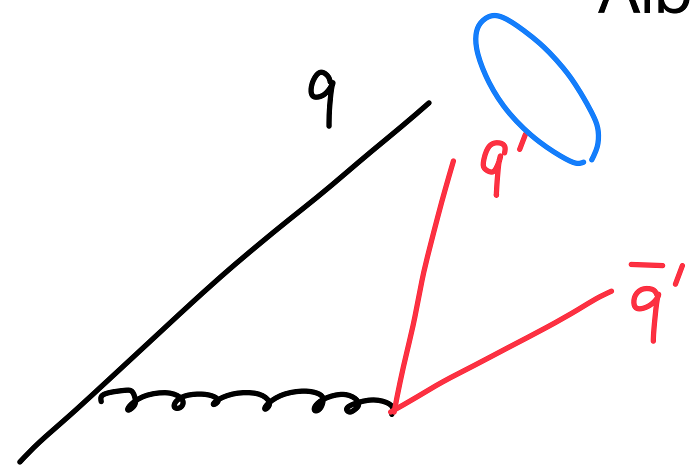


z_i : momentum fraction of i-th jet particle

Q_i : electric charge of i-th jet particle

$$Q_K = \sum_i z_i^K Q_i$$

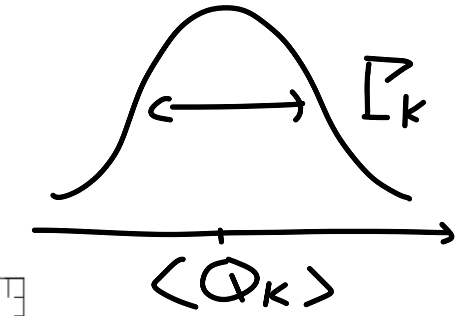
K usually chosen to be positive to weigh more on energetic particles



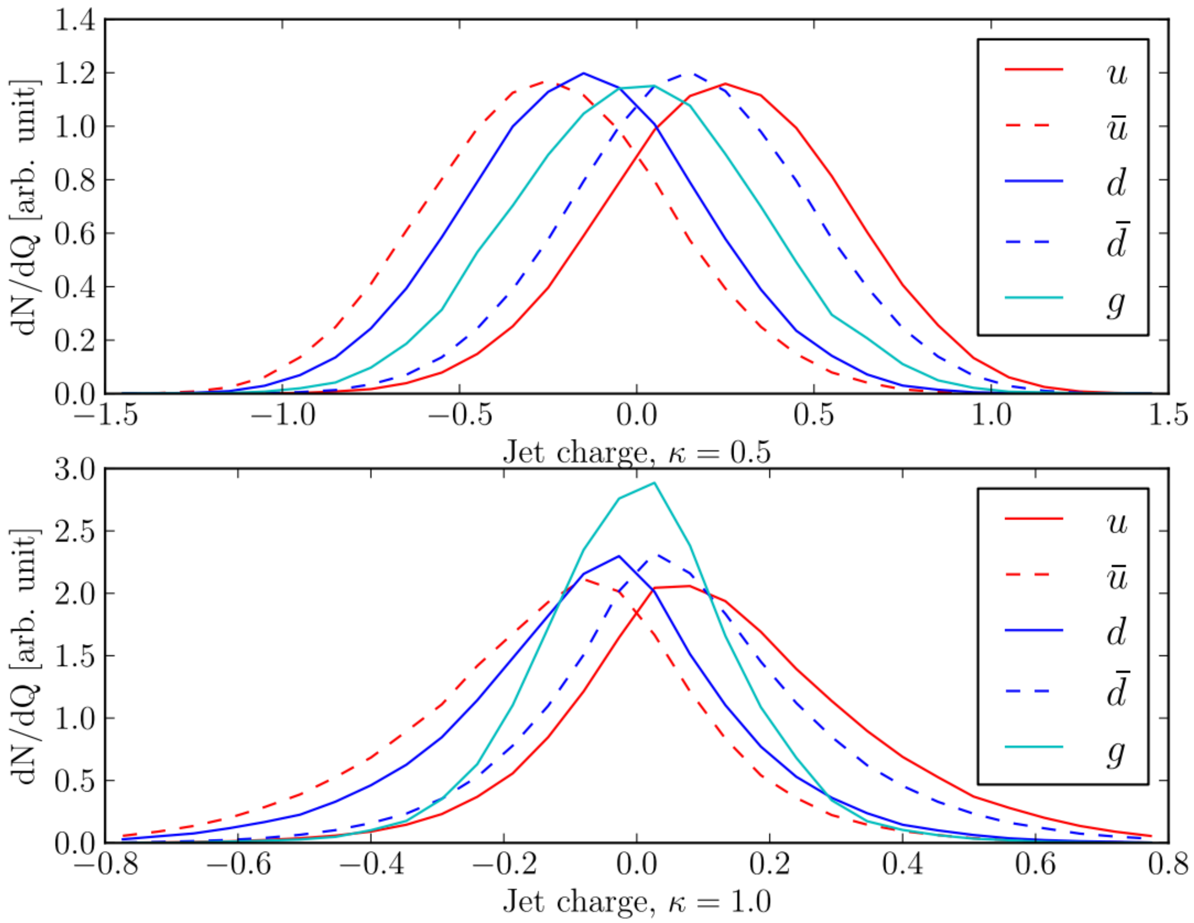
Naive summation of electric charges has large fluctuations due to soft $g \to q' \bar{q}'$ contributions, therefore not useful for connecting to parton origin

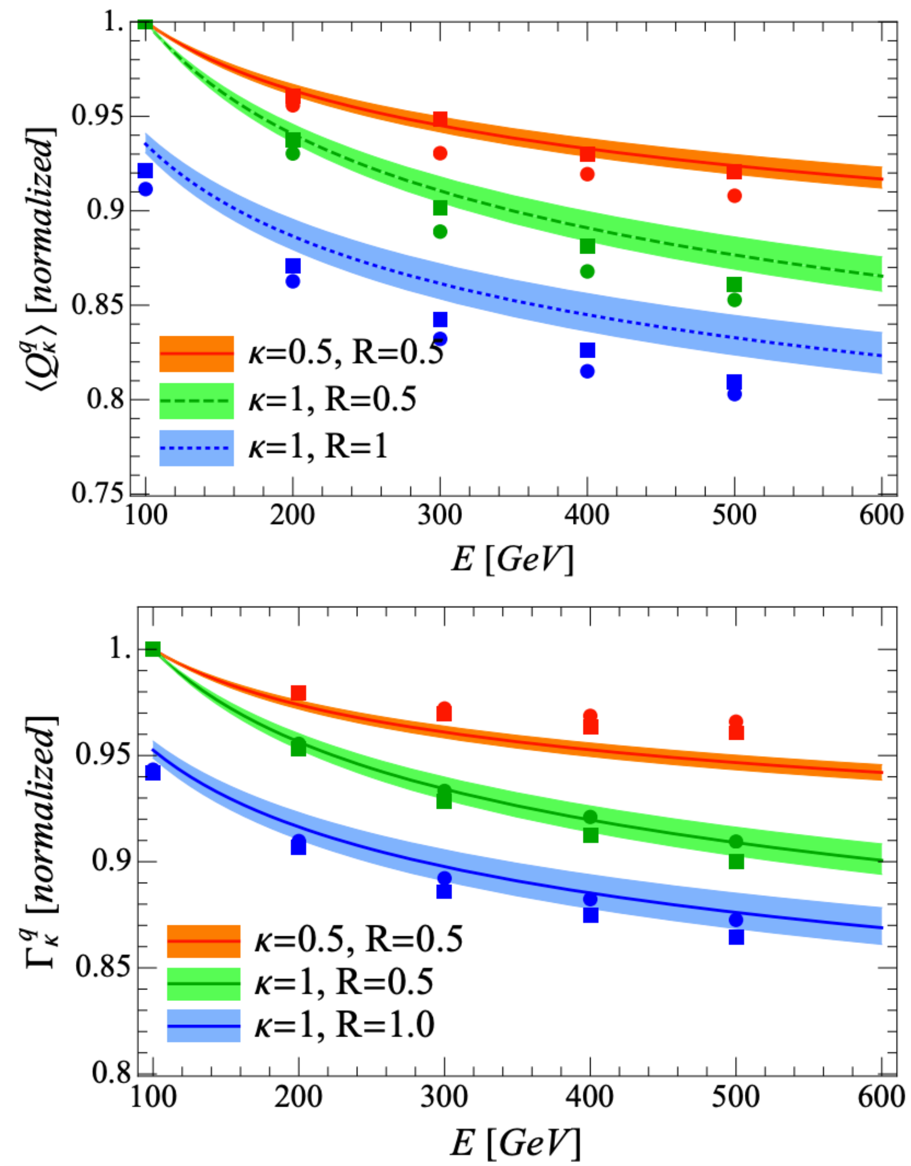
- Jet charge is not infrared and collinear safe and can probe the flavor flow of hadronization

Jet charge



Krohn, Lin, Schwartz, Waalewijn (2012)





$\langle Q_\kappa \rangle$: jet charge average

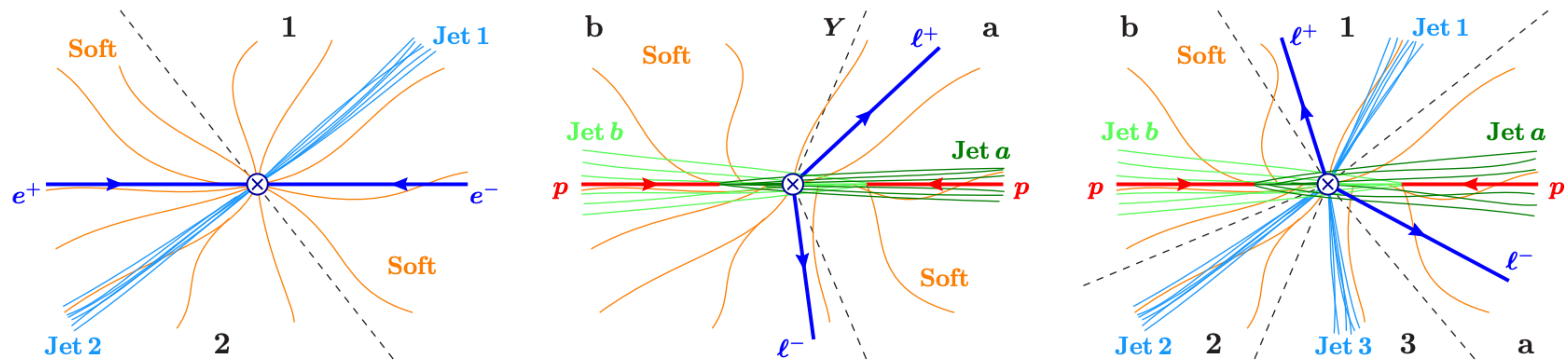
Γ_κ: jet charge width

Jet charge at the LHC is shown to be useful for flavor tagging, which improves discrimination of BSM models

Moments of jet charge distributions are calculated using Soft-Collinear Effective Theory

N-jettiness

Stewart, Tackmann, Waalewijn (2010)

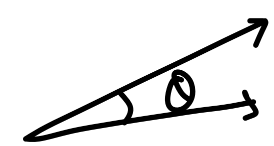


(a) $e^+e^- \to 2$ jets. (b) Isolated Drell-Yan. (c) $pp \to$ leptons plus jets.

$$\tau_N = \sum_k \min_{i:1\to N} \left\{ \frac{2\, q_i \cdot p_k}{Q_i} \right\}$$

q_i: a set of N reference, lightlike 4-vectors

Q_i: high energy scale of the energy flow i

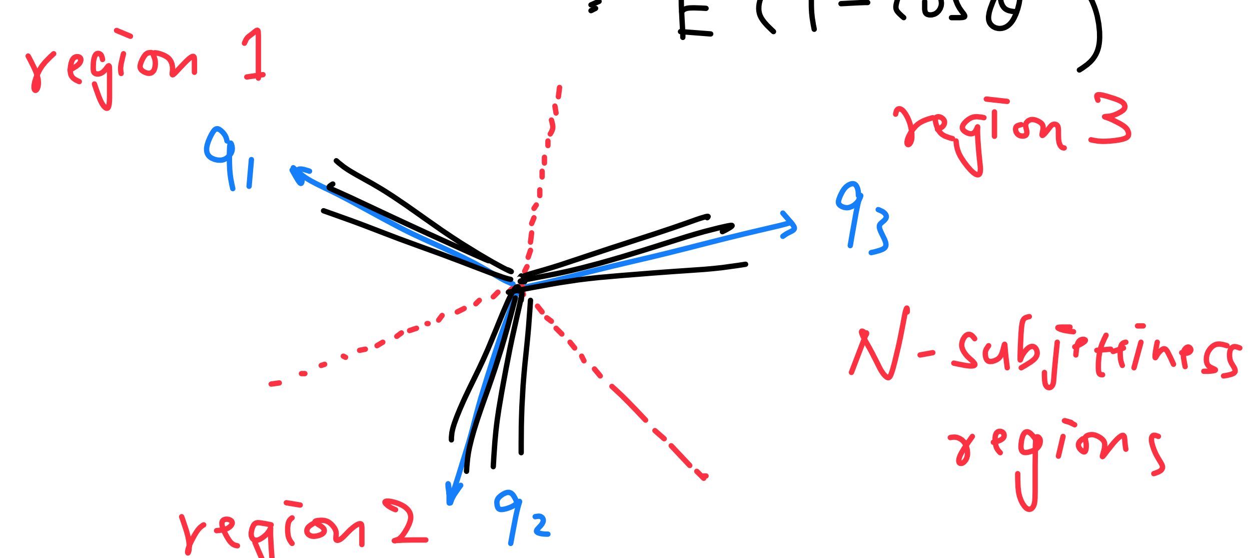


$q_i = (1, \hat{n}_i)$

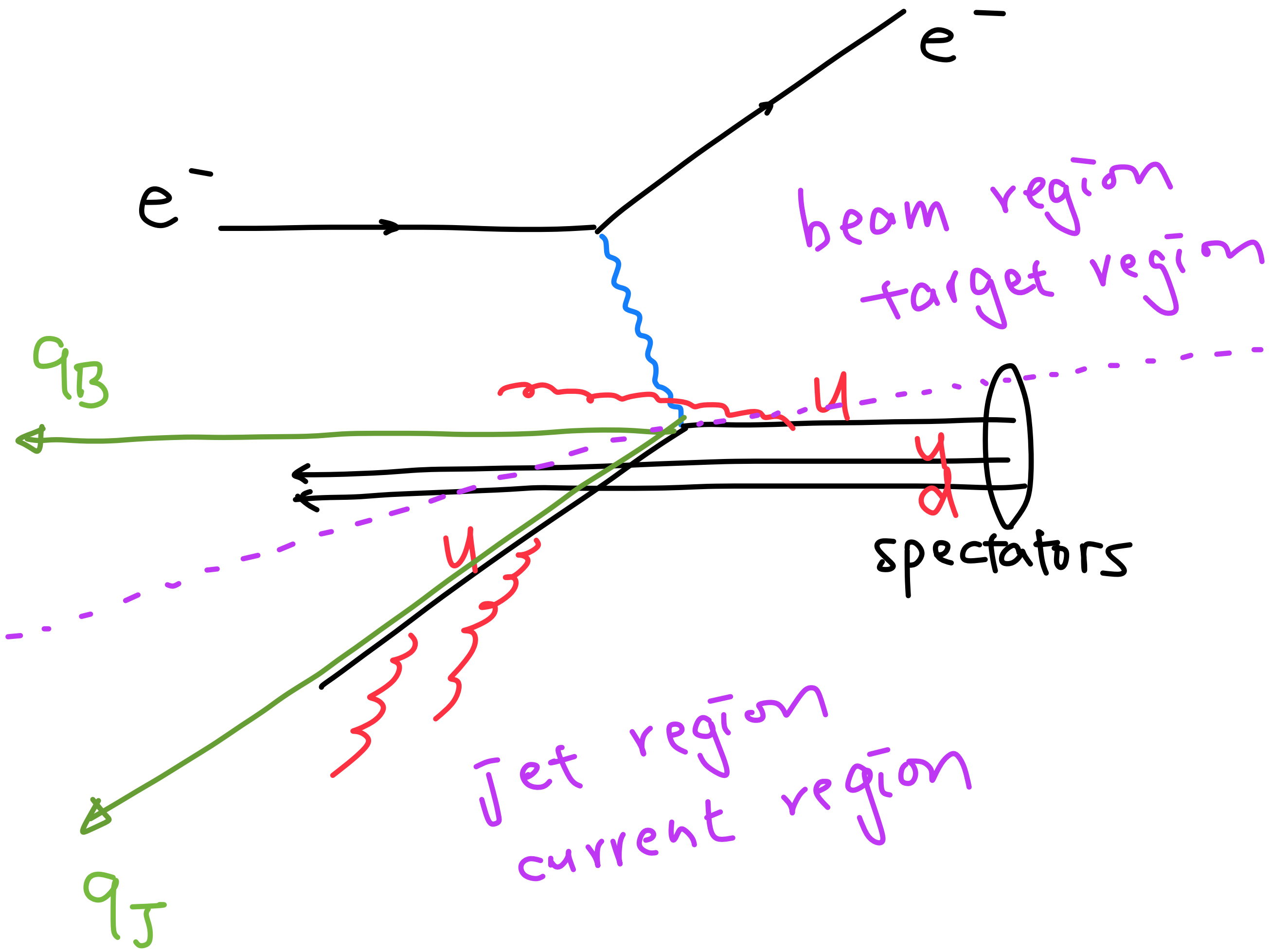
$p_k \sim E(1, \hat{n}_k)$

$q_i \cdot p_k = E(1 - \hat{n}_i \cdot \hat{n}_k)$

$= E(1 - \cos\theta)$



One-jettiness for EIC



$$\tau_1 = \sum_k \min\left\{ \frac{2\, q_B \cdot p_k}{Q_B}, \frac{2\, q_J \cdot p_k}{Q_J} \right\}$$

In the context of EIC, in the region of large x and large Q^2, i.e. the picture of "leading order parton deflection" is accurate, 1-jettiness (the "1" excludes the beam in the naming ...) captures the event topology

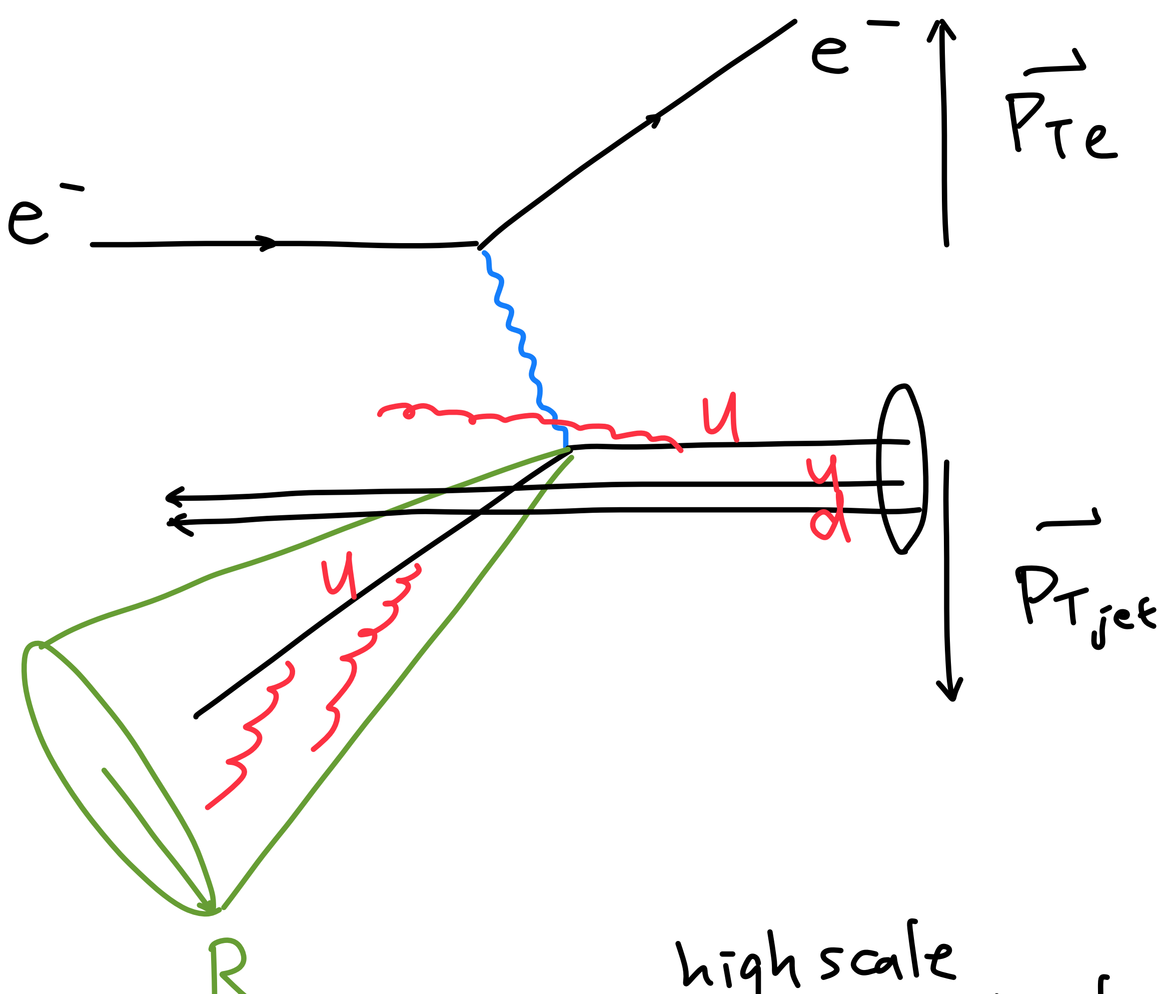
we use SCET

- τ_1 is IRC safe so can be calculated order-by-order using pQCD
- τ_1 does not depend on jet algorithm (no artificial boundary) and is global event shape that allows high accuracy calculation

Flavor separation and TMD physics

Liu, Ringer, Vogelsang, Yuan (2020)

Kang, Liu, Mantry, Shao (2020)



$$\frac{d\sigma^i_{UU}}{d^2 q_T} = \sigma_0 \, e_i^2 \int \frac{d^2 b_T}{(2\pi)^2} e^{i q_T \cdot b_T} \widetilde{W}_i$$

$$\widehat{W}_i = f_i(x, b_T) \, S_J(b_T, R) \, H \, J_i(p_T R)$$

TMD function — soft factor — hard function — jet fn. (b_T indep.)

$$\frac{d\sigma^i_{UU}}{d^2 q_T \, dQ_K} : \quad J_i(p_T R) \rightarrow \mathcal{G}_i(Q_K, p_T R)$$

high scale — high scale

$$q_T = \left| \vec{P}_{Te} + \vec{P}_{T_{jet}} \right|$$

mostly cancel

For $\frac{d\sigma^i_{UT}}{d^2 q_T}$: $f_i(x, b_T) \rightarrow \epsilon_{\alpha\beta} S_\perp^\alpha f_{1T,i}^{\perp\beta}$

Sivers fn.

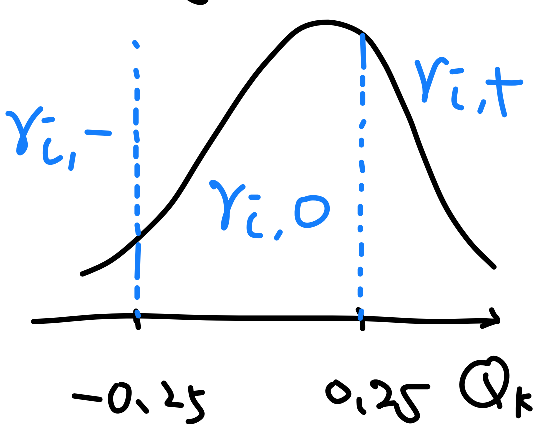
Flavor separation and TMD physics

Kang, Liu, Mantry, Shao (2020)

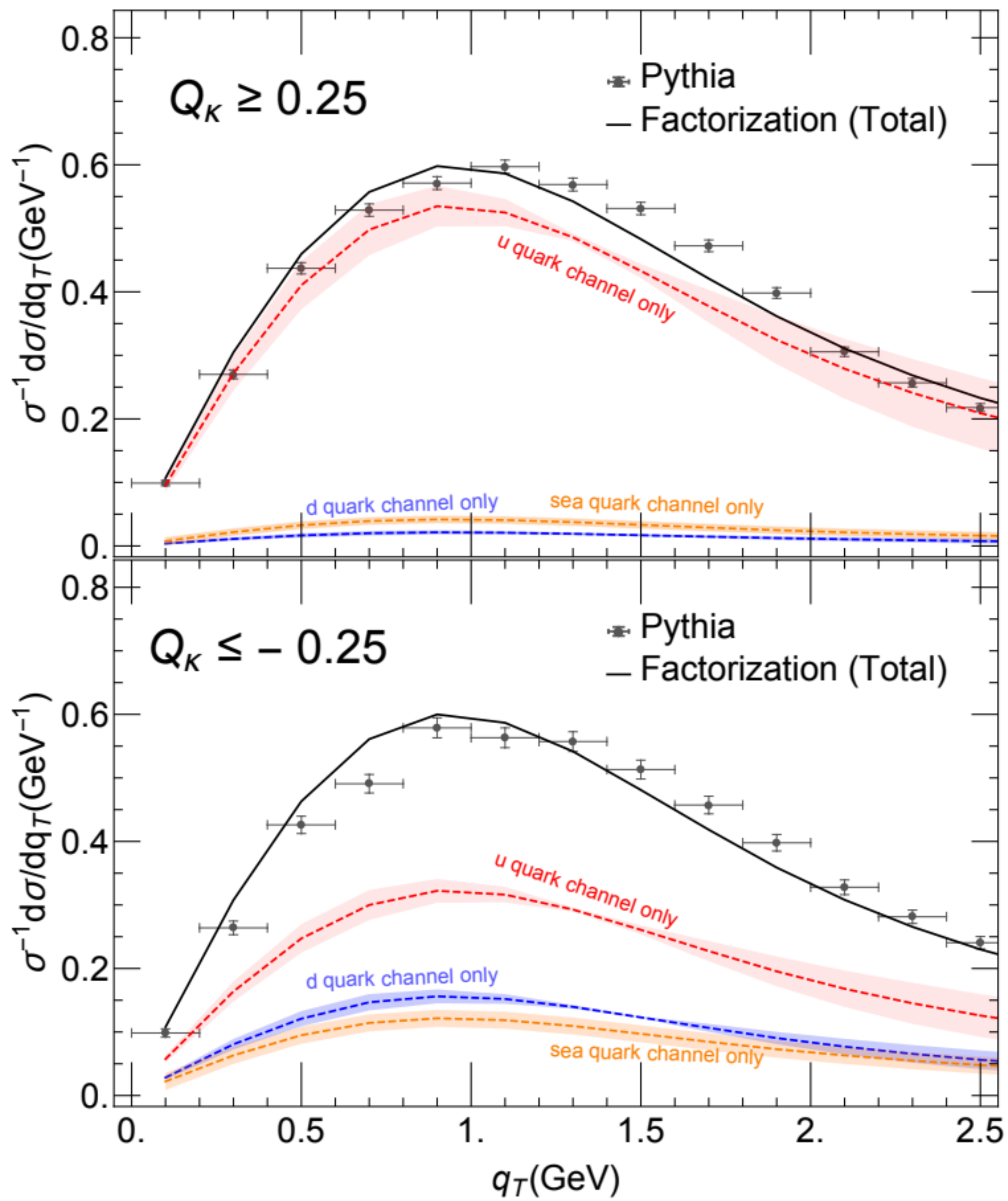
- Most of the cross section comes from the u-quark contributions (not surprising)
- Binning Q_K enhance sensitivity to different quark flavors

$$r_{i,\mathrm{bin}} = \int_{Q_K \in \mathrm{bin}} dQ_K \, \frac{g_i(Q_K, p_T R)}{J_i(p_T R)}$$

$$\int g_i(Q_K, p_T R)\, dQ_K = J_i(p_T R)$$



	u	$\bar{u}$	d	$\bar{d}$	s	$\bar{s}$
$r_{i,+}$	0.62	0.18	0.13	0.50	0.19	0.52
$r_{i,-}$	0.08	0.50	0.48	0.13	0.43	0.13
$r_{i,0}$	0.30	0.32	0.39	0.37	0.38	0.35



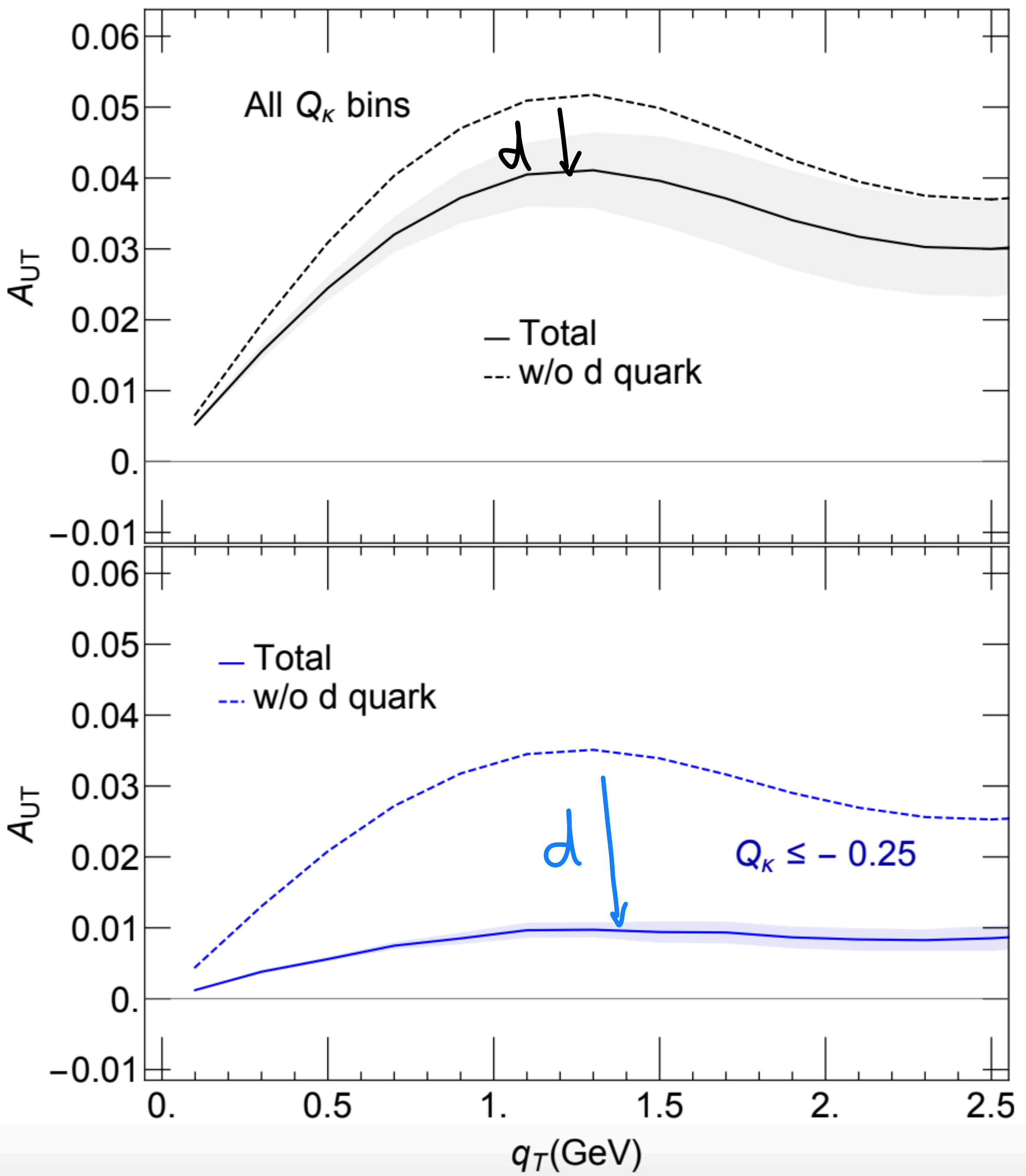
Flavor separation and TMD physics

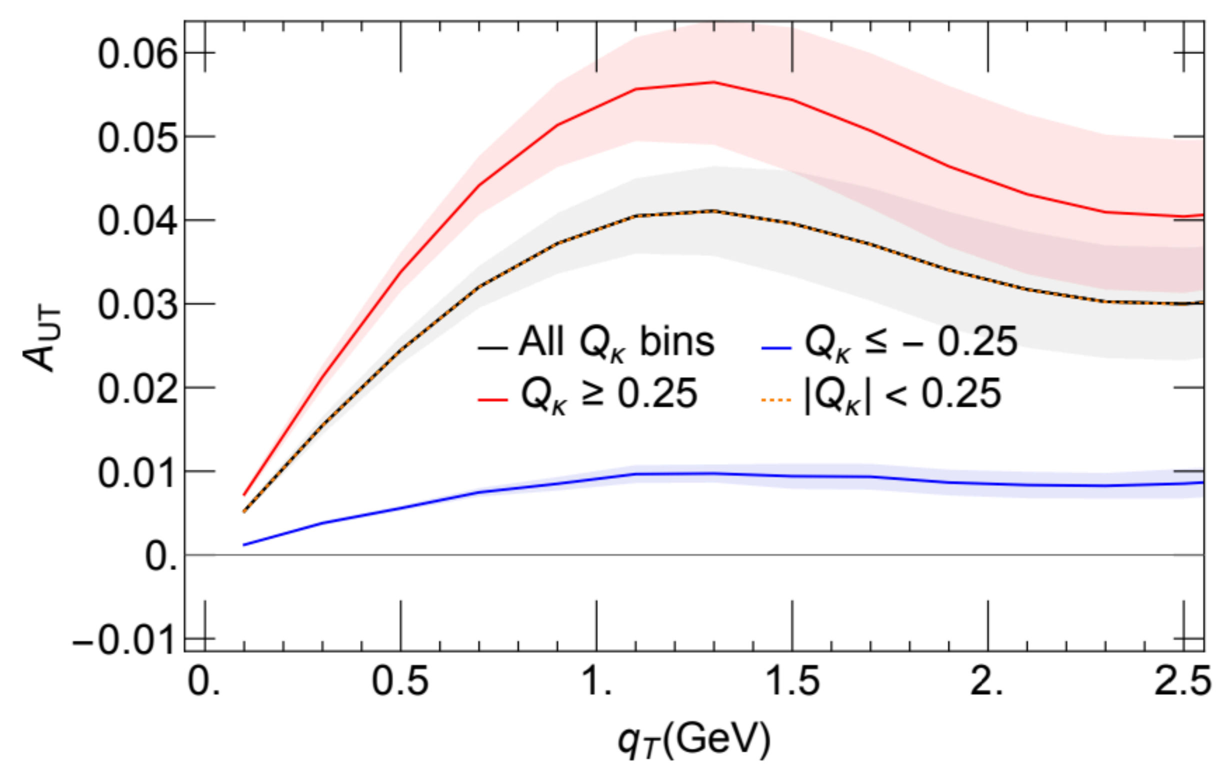
Kang, Liu, Mantry, Shao (2020)

$$A_{UT} = \frac{d\sigma(S_\perp^\uparrow) - d\sigma(S_\perp^\downarrow)}{d\sigma(S_\perp^\uparrow) + d\sigma(S_\perp^\downarrow)}$$

Single spin asymmetry

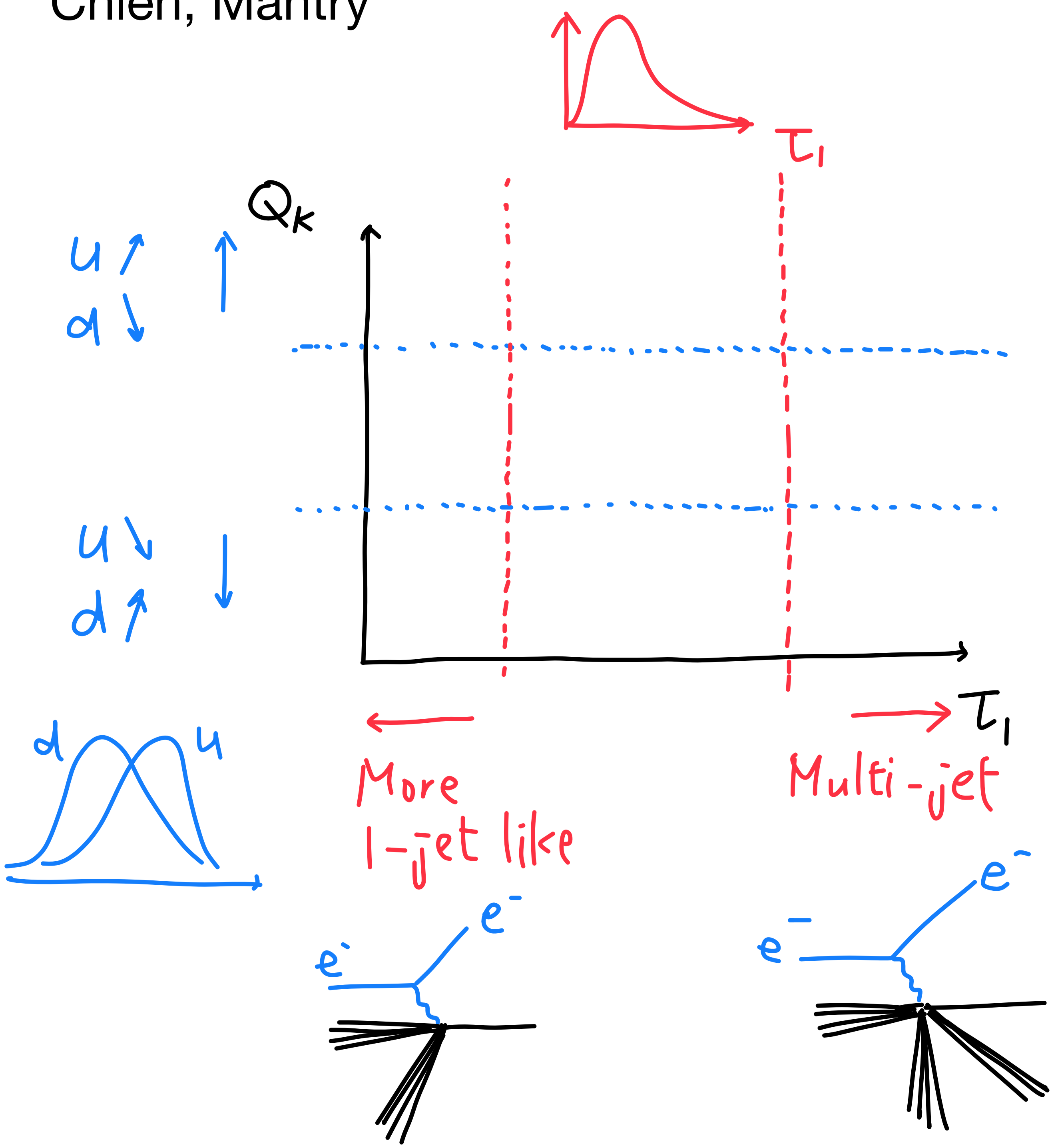
- u-quark and d-quark contributions cancel
- Binning Q_K can enhance single spin asymmetry





Joint jet charge and one-jettiness

Chien, Mantry



- Combine the utility and advantage of jet charge for flavor separation and τ_1 for precision QCD studies (q_T can not, yet)
- τ_1 sensitive to both the beam and jet contributions, allowing us to constrain the energy flow along the jet

→ Allow us to study the final state hadronization

(not just because τ_1 contains hadronization corrections)

Factorization

$$\frac{d\sigma}{d\tau_1} = \sigma_0 H \int ds \int dt \int du \, \underbrace{J(s)}_{\text{jet fn.}} \Big[\sum_{q_i} L_{q_i} \underbrace{B_{q_i}(t, x_*)}_{\text{beam fn.}} + \sum_{\bar{q}_i} L_{\bar{q}_i} \underbrace{B_{\bar{q}_i}(t, x_*)} \Big] \underbrace{S(u)}_{\text{soft fn}} \, \delta\left(\tau_1 - \frac{s}{Q_J} - \frac{t}{Q_B} - u\right)$$

$$x_* = \frac{e^{y_J} p_{TJ}}{\sqrt{s} - e^{-y_J} p_{TJ}}$$

$$B_i(t, x) = \sum_j \int_x^1 \frac{dz}{z} L_{ij}\left(\frac{x}{z}, t\right) \underbrace{f_j(z)}_{\text{collinear PDF}}$$

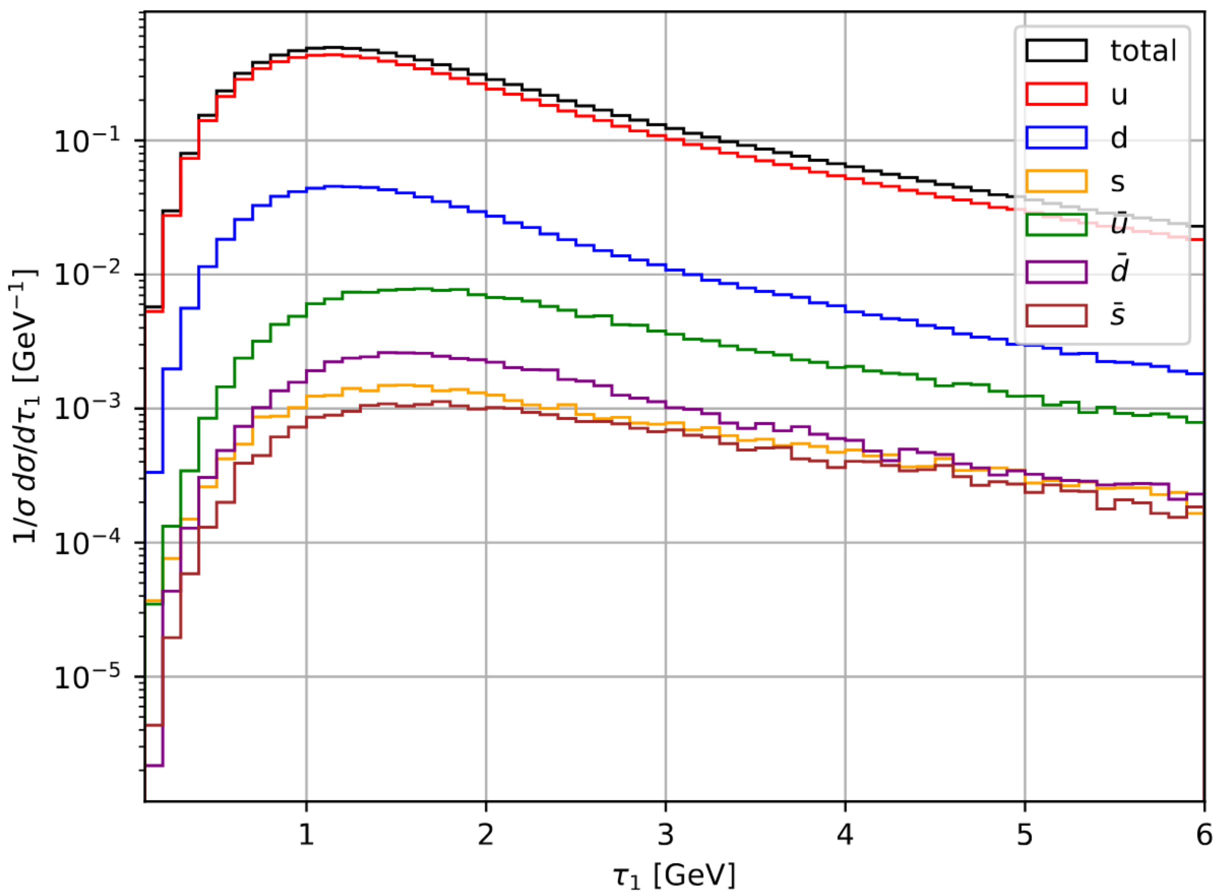
$$\frac{d\sigma}{d\tau_1 \, dQ_K} = \sigma_0 H \int ds \int dt \int du \, \underbrace{J(Q_K, s)} \Big[\sum_{q_i} L_{q_i} B_{q_i} + \sum_{\bar{q}_i} L_{\bar{q}_i} B_{\bar{q}_i} \Big] S(u) \, \delta(\cdots)$$

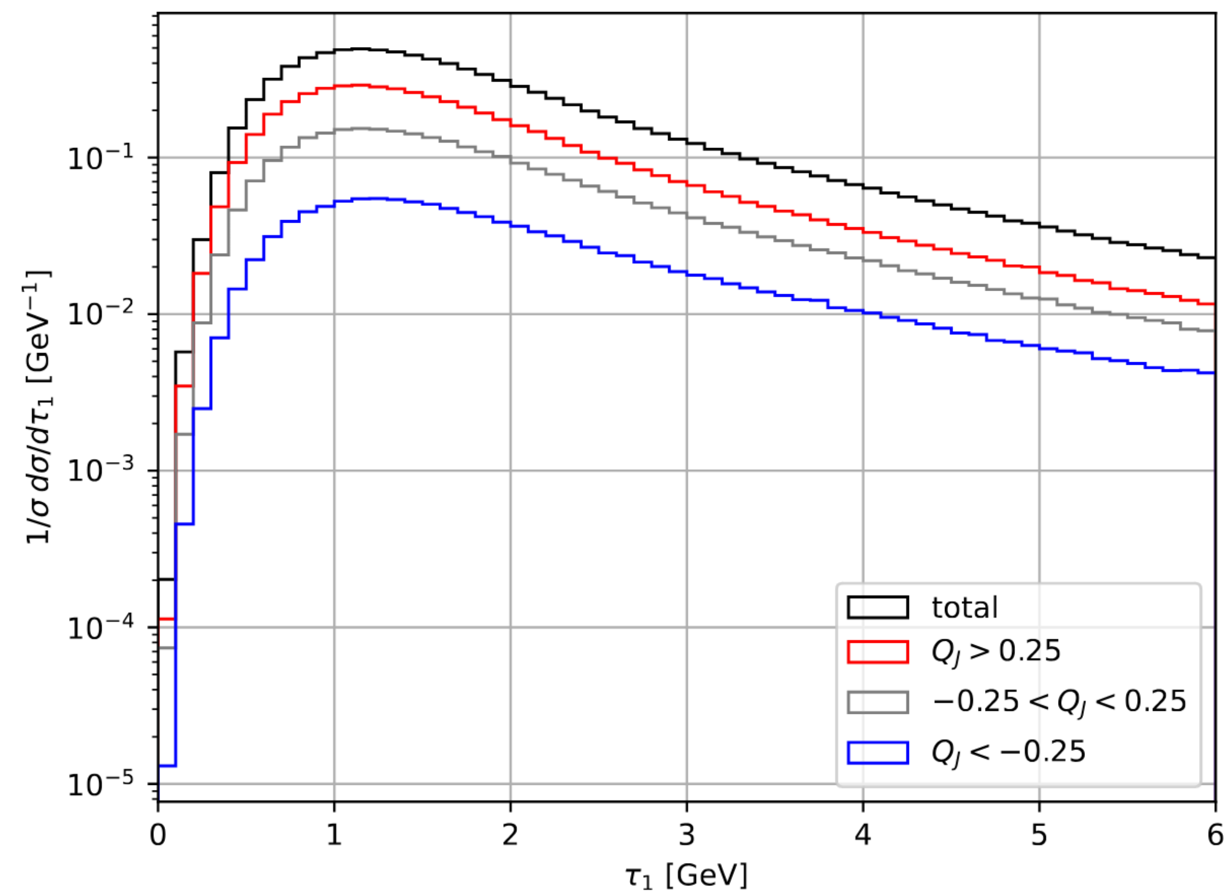
$$\boxed{\frac{J(Q_K, s)}{J(s)}} \; J(s)$$

$$\boxed{r_{i,\mathrm{bin}}(s) = \int_{Q_K \in \mathrm{bin}} dQ_K \, \frac{J(Q_K, s)}{J(s)}}$$

In most s regions the dependence is mild (except small s)

Flavor separation



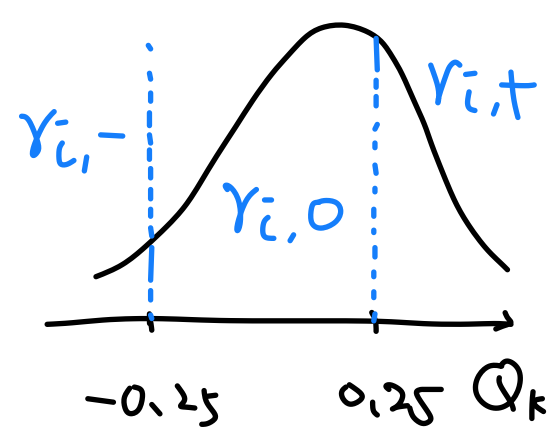


- Cross section dominated by u-quark (therefore large Q_K bin) contributions

$\sqrt{s}$ = 90 GeV

$pT_{jet} \in [20, 30]$ GeV

$y_J \in [-2.5, 2.5]$



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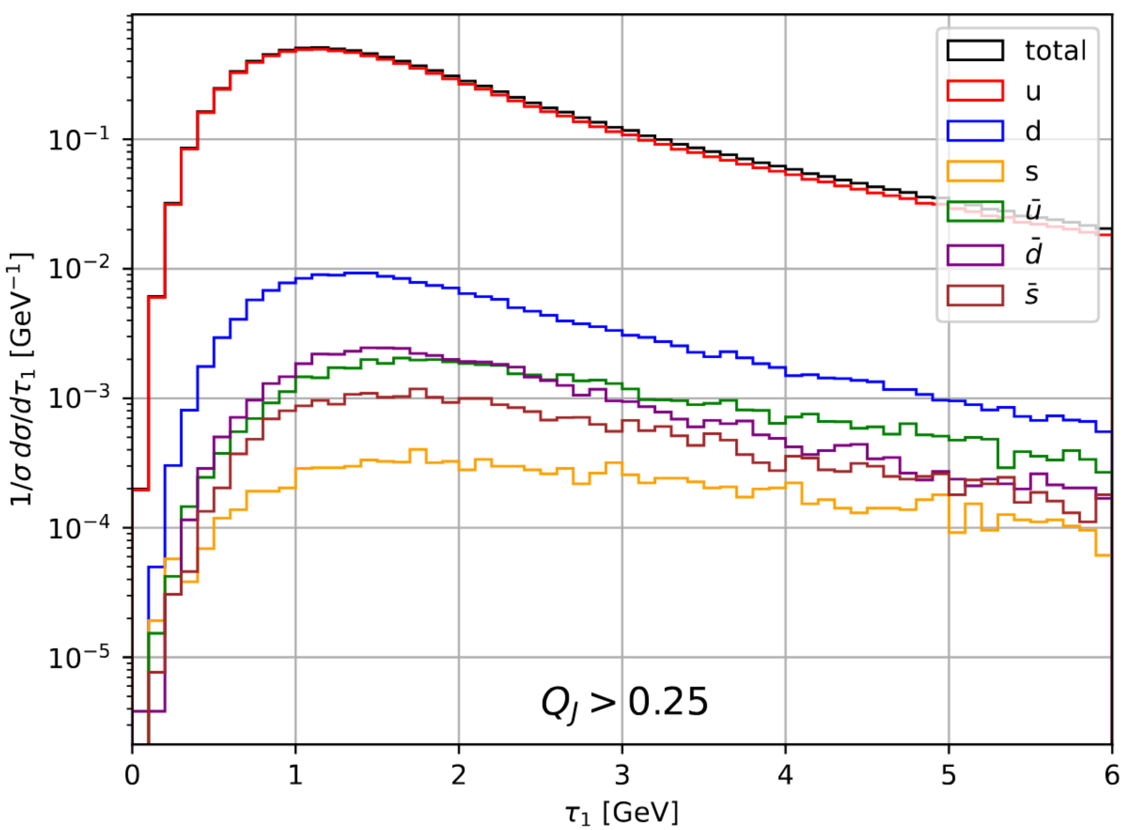
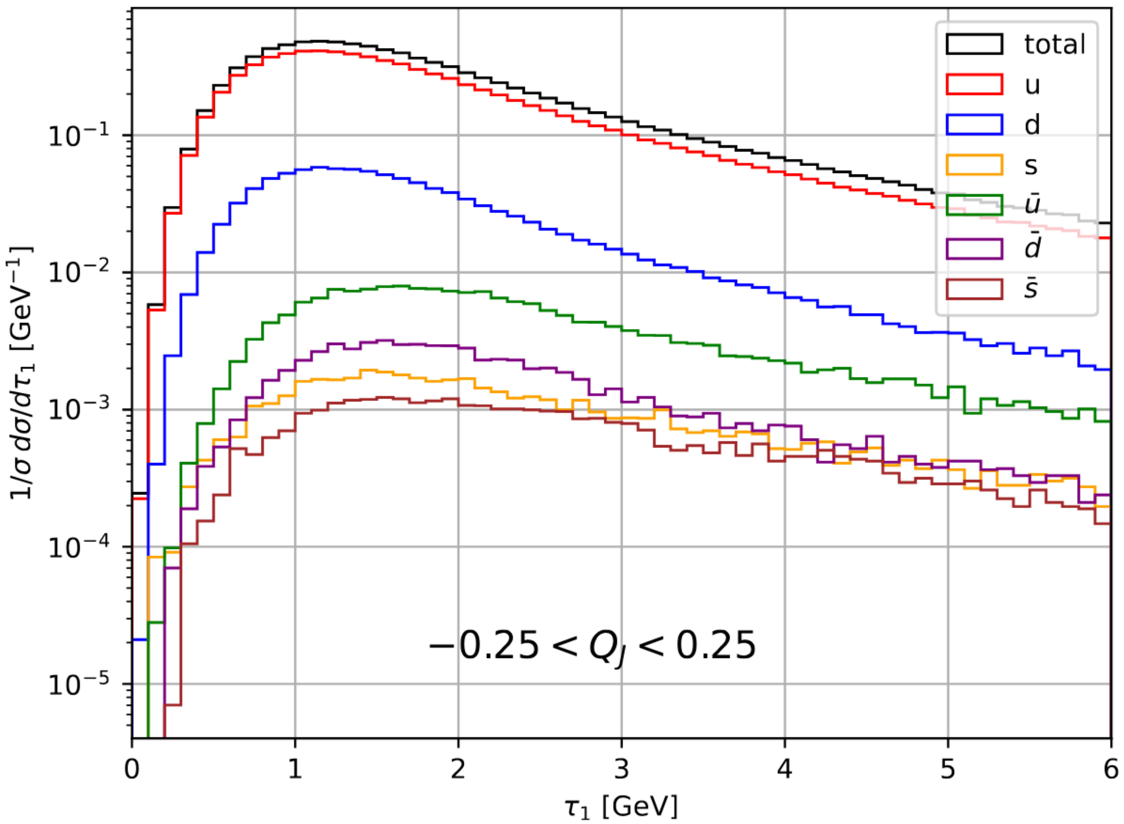
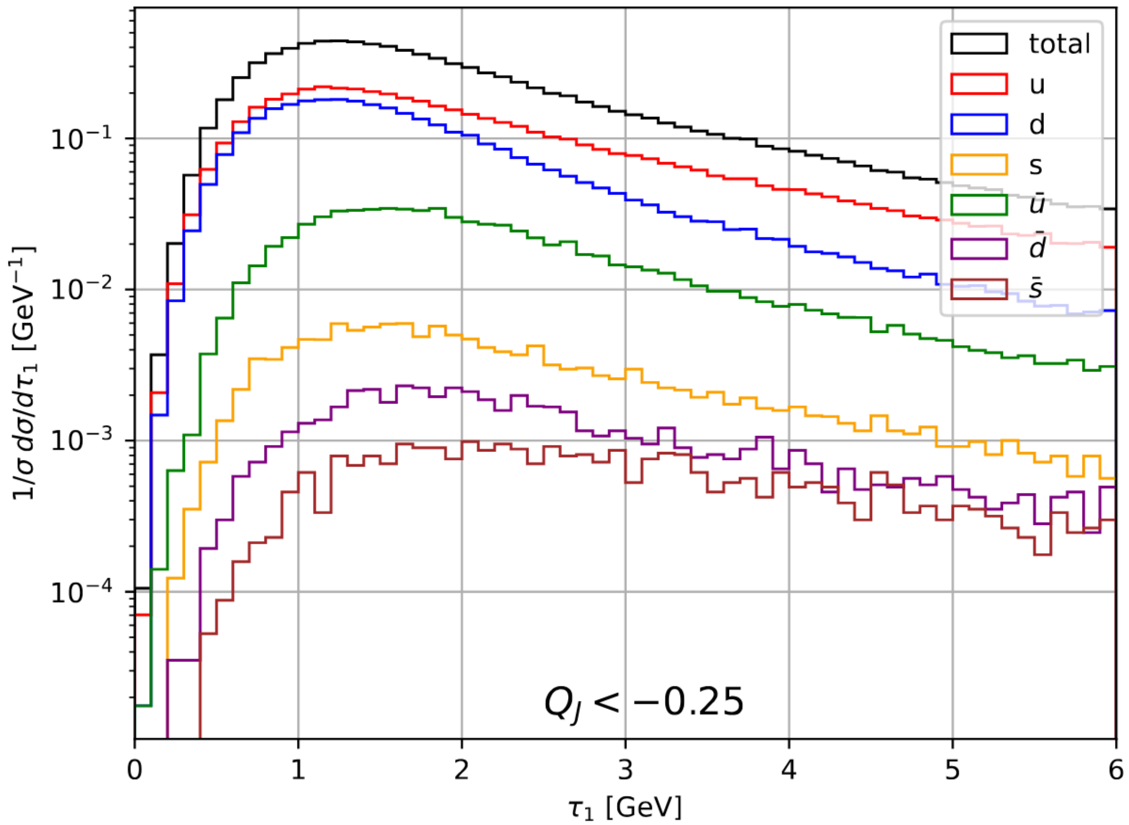
Flavor separation

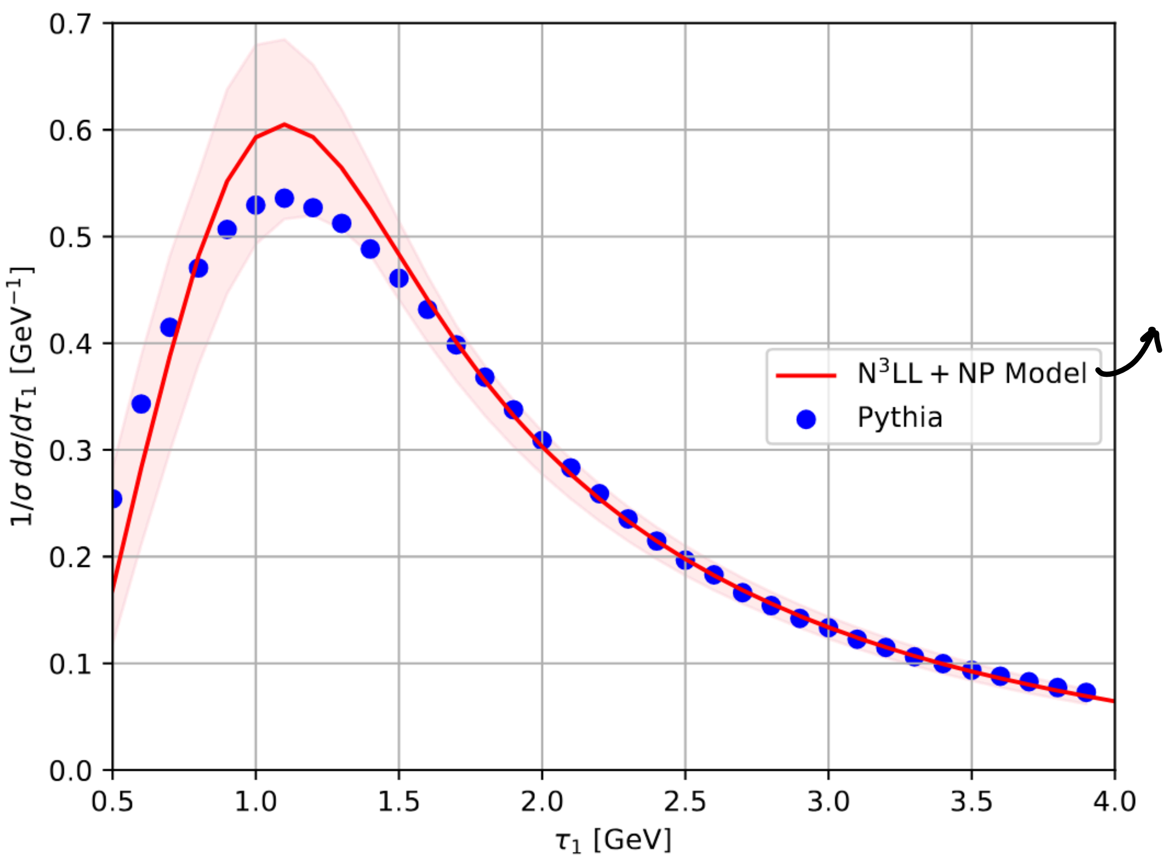


- Going into negative Q_k bin, u-quark and d-quark contributions start to become more comparable
- Noticeable difference between u & d τ_1 distributions





Resummed one-jettiness distribution



within the soft fn convolution with a shape fn.

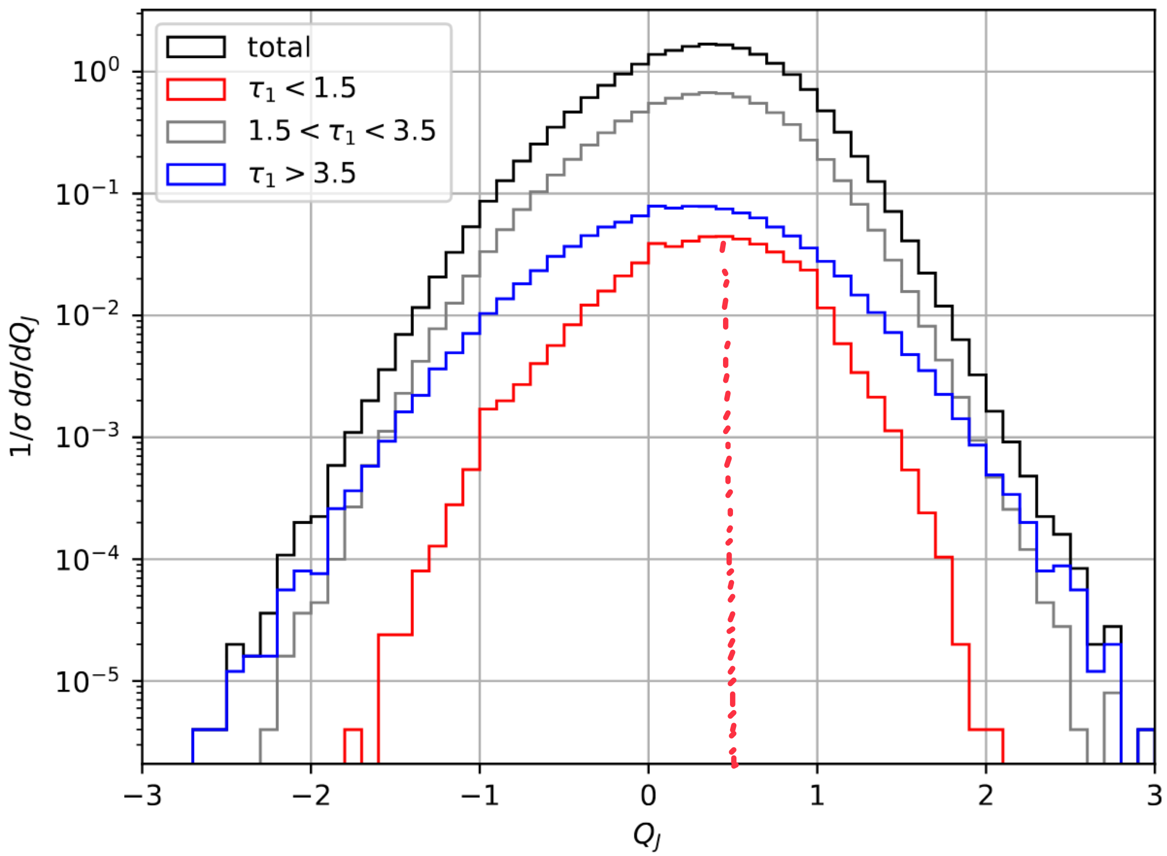
$\sqrt{s} = 90$ GeV

$pT_{jet} \in [20, 30]$ GeV

$y_J \in [-2.5, 2.5]$

- Surprising "agreement" between high accuracy analytic calculation with Monte Carlo simulations
- Higher order effect not significant at EIC kinematics ??
- Q_K binned τ_1 distribution work in progress

Jet charge with restricted energy flow



- Significant dependence of Q_K on τ_1 observed in pheno studies, analytic understanding work in progress

- In the $\tau_1 \to 0$ limit, will the collimated hadrons maximally expose the underlying parton?

Conclusions

- PDF global analysis is required to constrain a mixture of PDF contributions
- Jet charge is useful for enhancing sensitivity to different flavor contributions
- Precision studies of global event shapes such as one-jettiness is possible
- Jet charge and one-jettiness correlation can help PDF flavor separation and isolating intrinsic hadronization properties

arXiv > hep-ph > arXiv:2305.14572

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High Energy Physics – Phenomenology

[Submitted on 23 May 2023]

The case for an EIC Theory Alliance: Theoretical Challenges of the EIC

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