

Jet Charge with Global Event Shapes at the EIC

Probing Quark Flavor Dynamics

Sonny Mantry

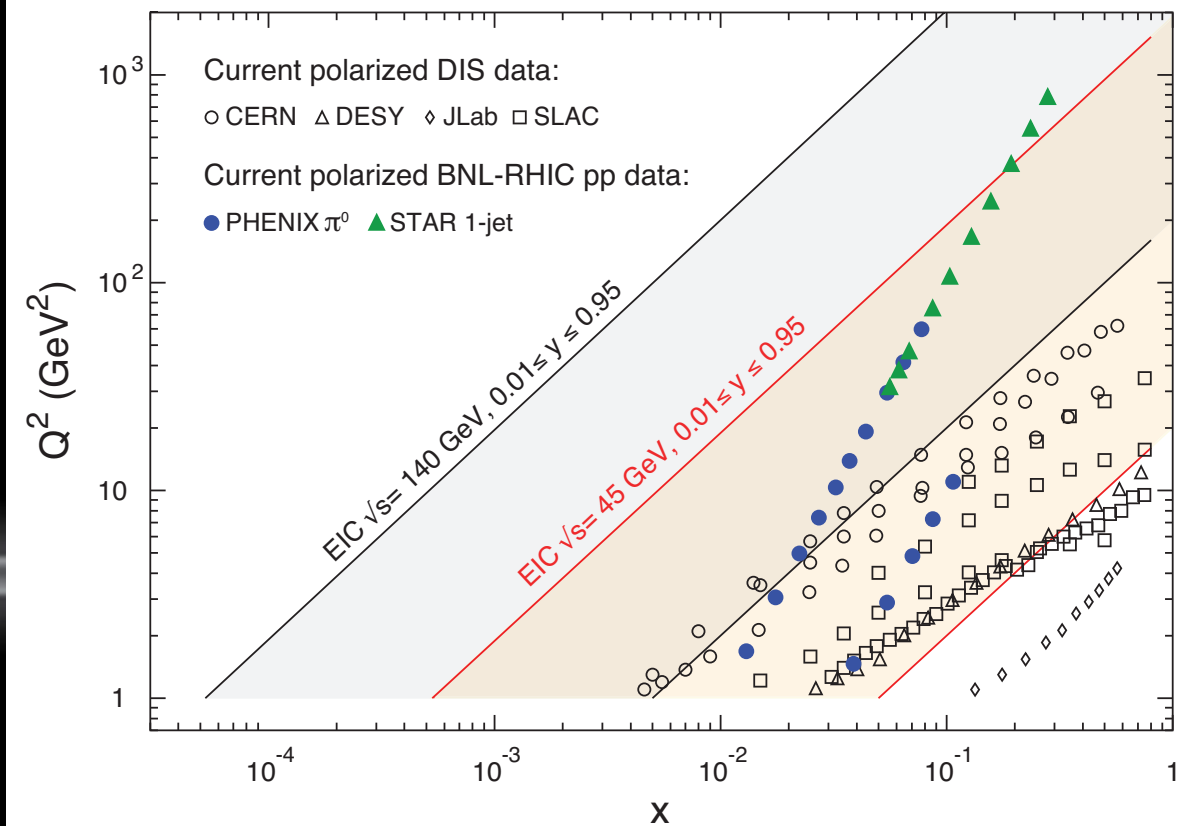
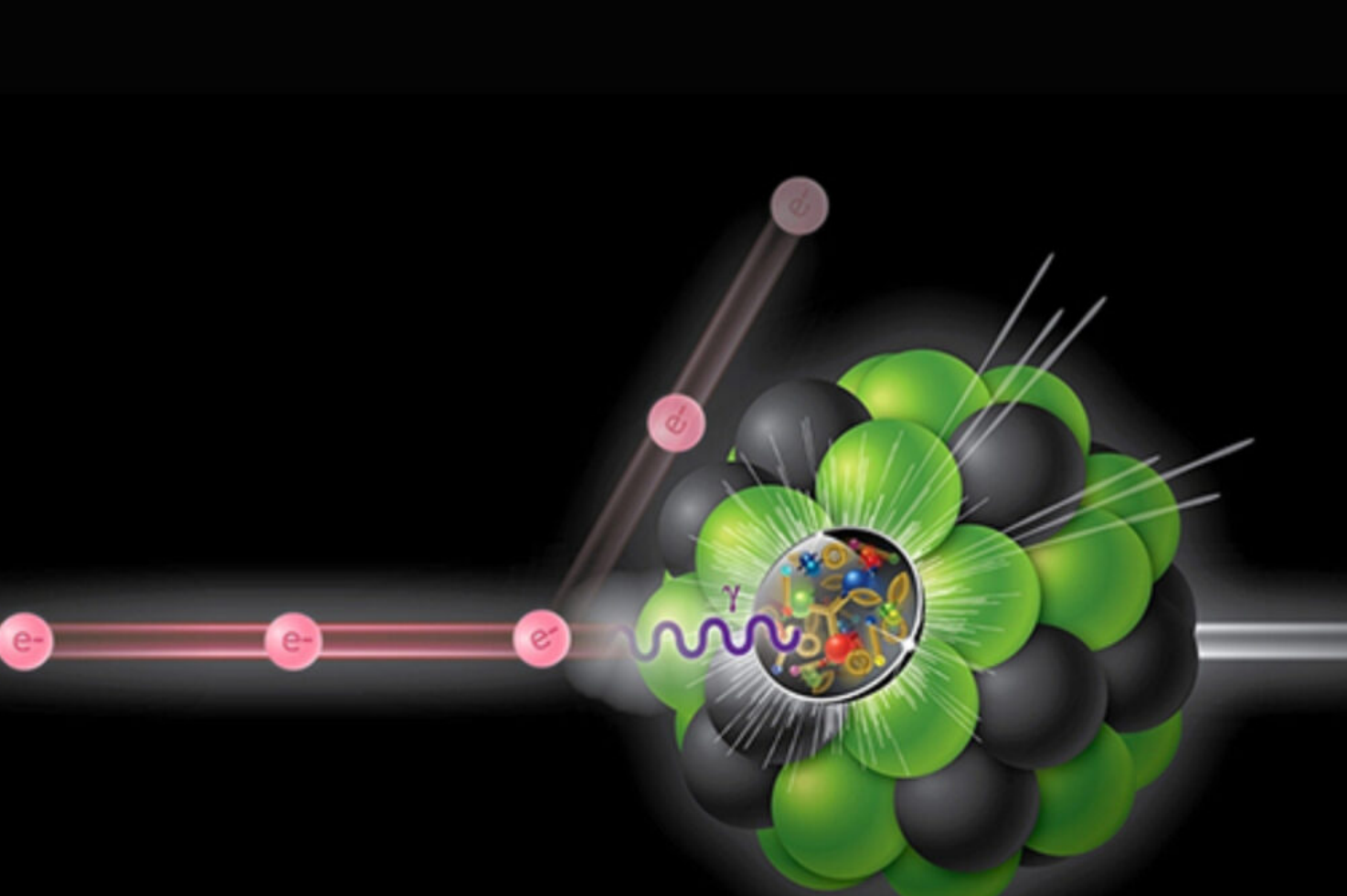
University of North Georgia

HP2026: Satellite Workshop on Jets and Heavy Flavor Physics

June 27th-28th, 2026

In collaboration with Yang-Ting Chien

arXiv:2512.05199, PRD 113 (2026), 114004



- The EIC will serve as a precision probe of hadron structure and hadronization, and will be facilitated by:

high luminosity
wide kinematic range
hermetic detector
polarized beams
variety of nuclear beams



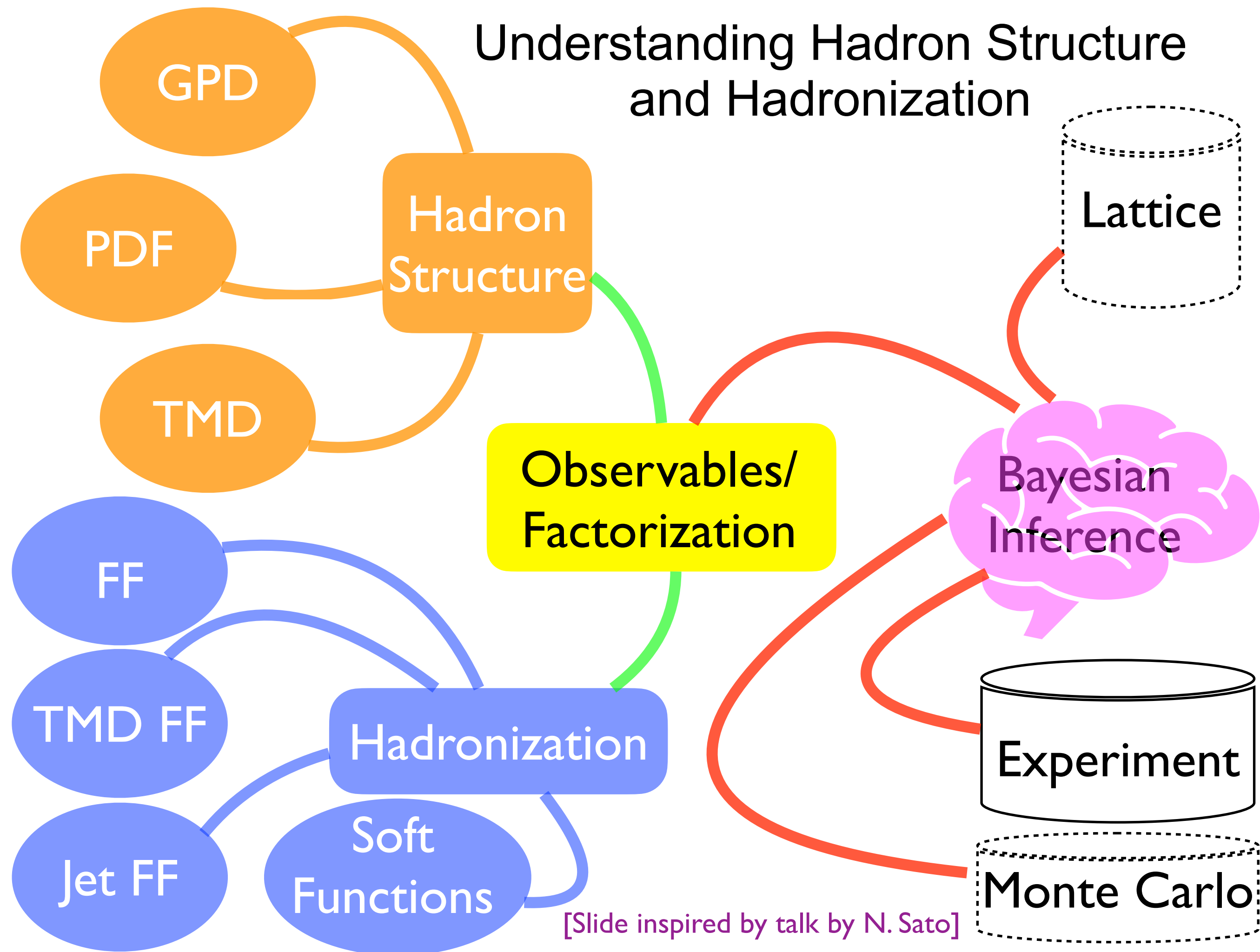
LHC

VS



EIC

Understanding Hadron Structure and Hadronization



Factorization

❖ Fully Inclusive DIS:

$$\sigma(e + p \rightarrow e + X) = H \otimes \text{PDF}$$

❖ Drell-Yan:

$$\sigma(p + p \rightarrow \mu^+ + \mu^- + X) = H \otimes \text{PDF} \otimes \text{PDF}$$

❖ Low q_T Drell-Yan:

$$\sigma(p + p \rightarrow \mu^+ + \mu^- + X) = H \otimes \text{TMD} \otimes \text{TMD}$$

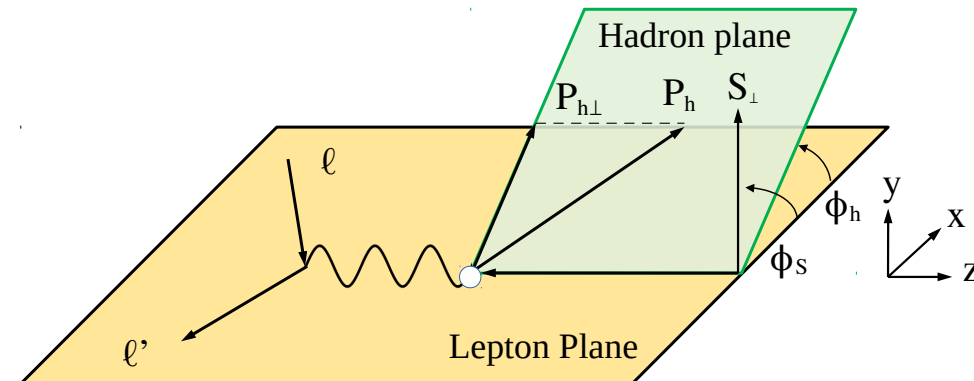
❖ Thrust Global Event Shape:

$$\sigma(e^+ + e^- \rightarrow X) = H \otimes J \otimes J \otimes S$$

- Understanding hadron structure and hadronization requires a wide array of high precision observables that are independent, complementary, and over-constraining.

Disentangling Hadron Structure and Hadronization by Flavor

- Disentangling flavor structure typically requires a flavor tag. For example, Semi-Inclusive DIS (SIDIS):



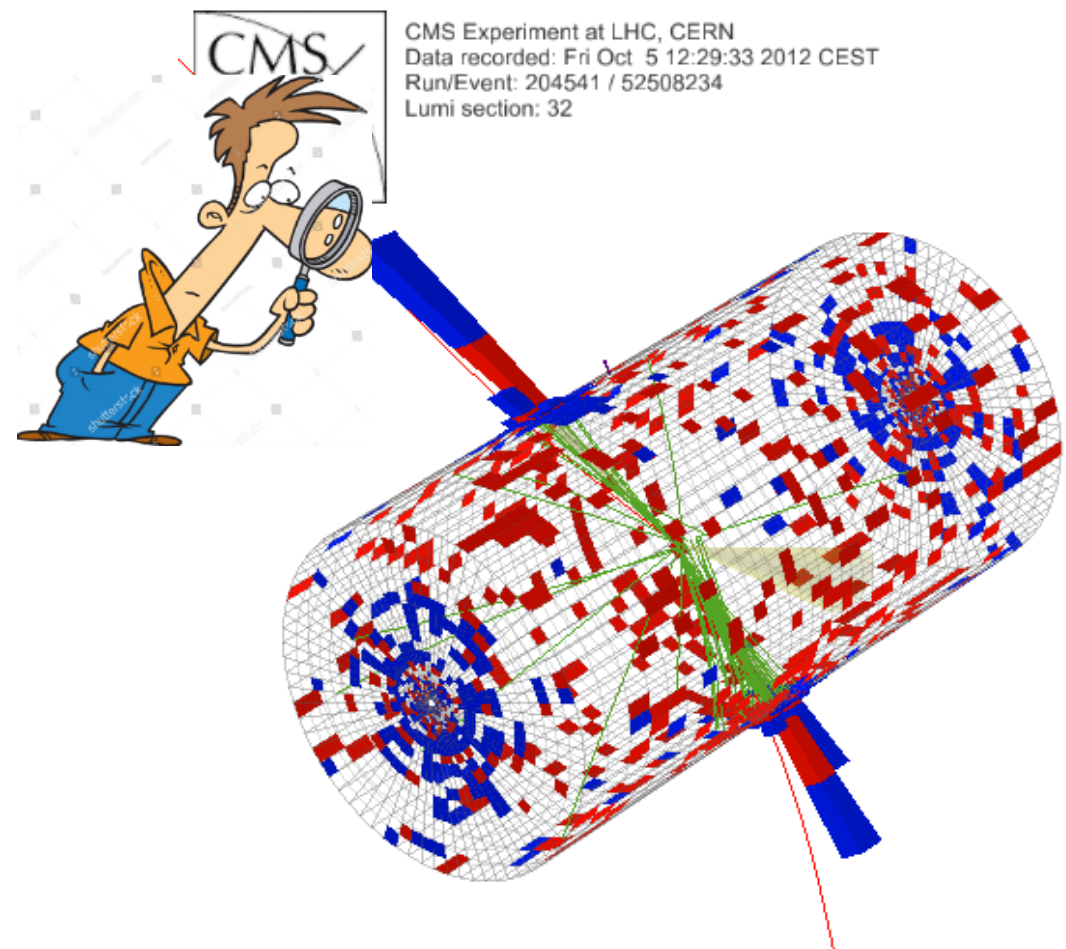
$$\sigma(e + p \rightarrow e + h + X) = H \otimes \text{TMDPDF} \otimes \text{TMDFF}$$

- Final state hadron species used to separate TMDs by flavor.
- However, this requires simultaneously determining TMDPDF and TMDFF.
- Instead tag final state jet which gives universal jet function:

$$\sigma(e + p \rightarrow e + J + X) = H \otimes \text{TMDPDF} \otimes J$$

- How can we tag flavor with jets?

Jet Charge



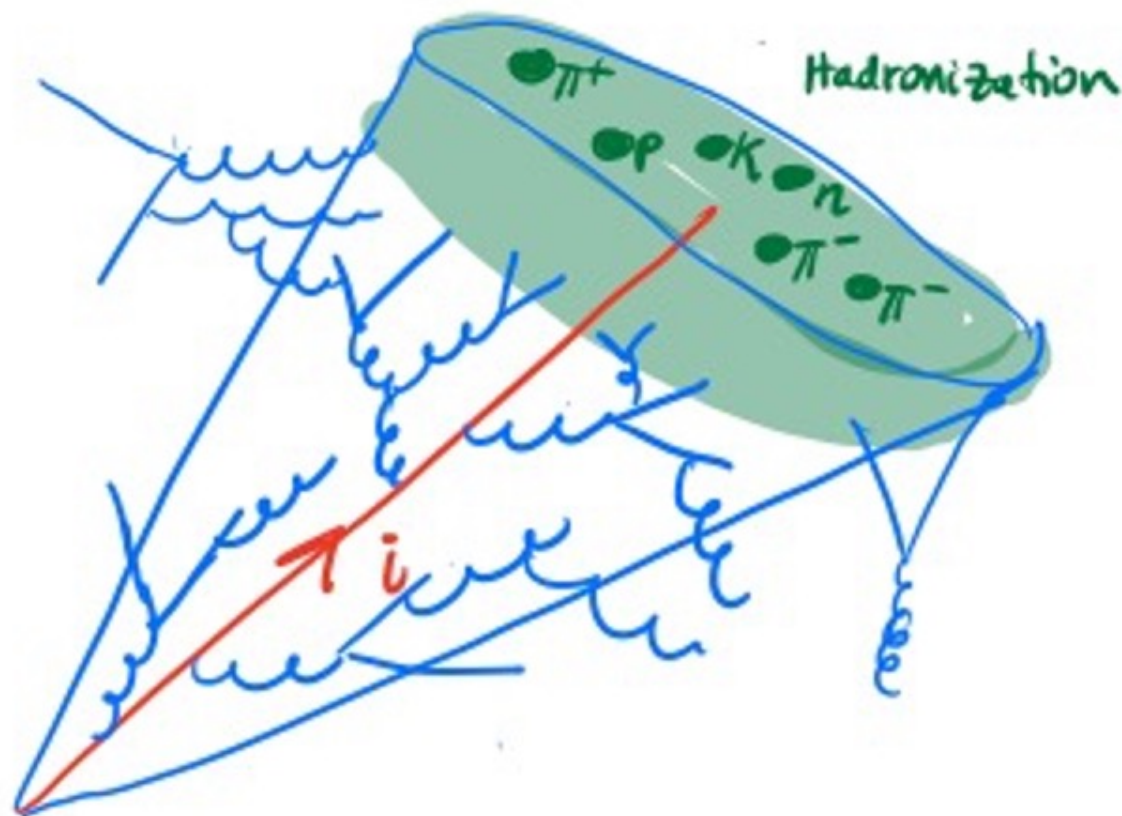
Standard Jet Charge

[Field, Feynman, 1978, Nucl. Phys. B]

[Krohn, Schwartz, Lin, Waalewijn, 2012]

arXiv: 1209.2421 (PRL)

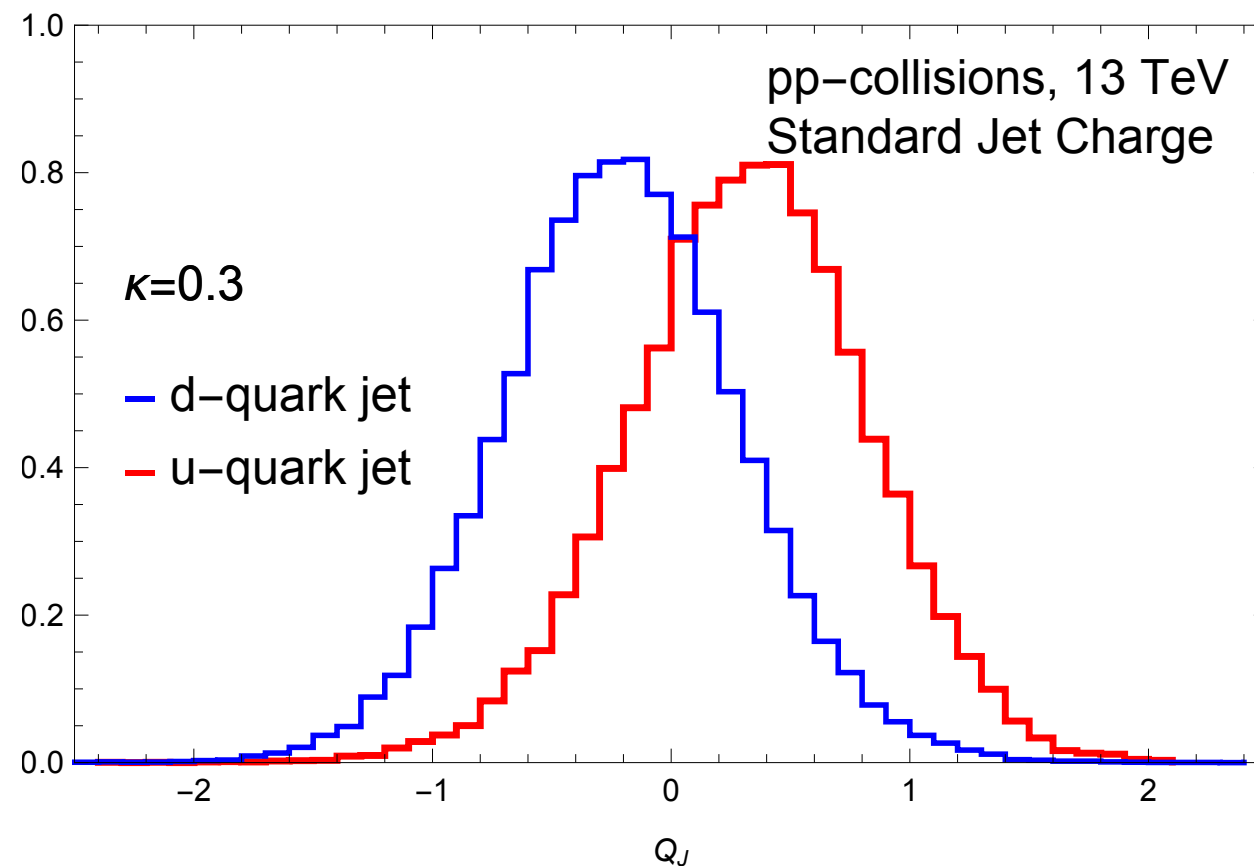
arXiv: 1209.3019 (PRD)



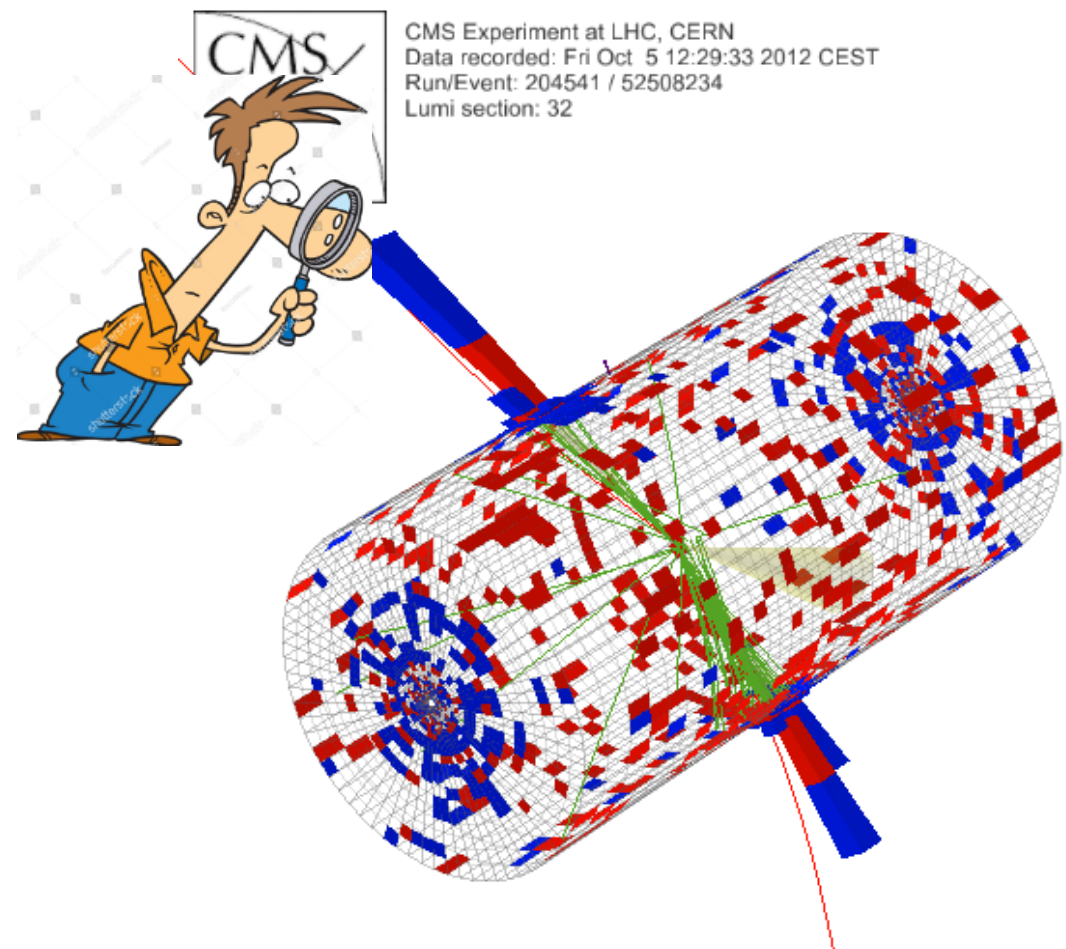
$$z_h = \frac{p_{T_h}}{P_{J_T}}$$

$$Q_\kappa = \sum_{h \in \text{jet}} z_h^\kappa Q_h, \quad \kappa > 0$$

Discriminating between u-Quark and d-Quark Jets



$$Q_{\kappa} = \sum_{h \in \text{jet}} z_h^{\kappa} Q_h$$

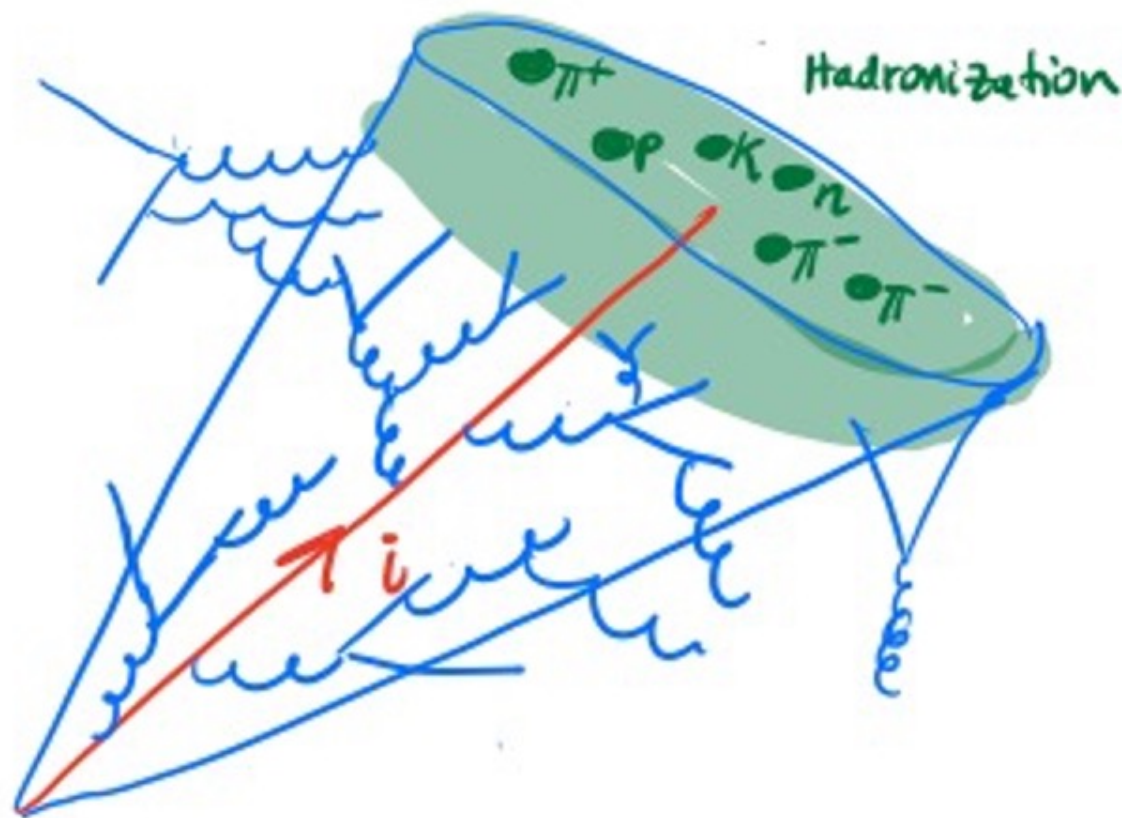


Dynamic Jet Charge

[Kang, Liu, SM, Spraker, Wilson, 2021]

arXiv: 2101.04304 (PRD)

Dynamic Jet Charge

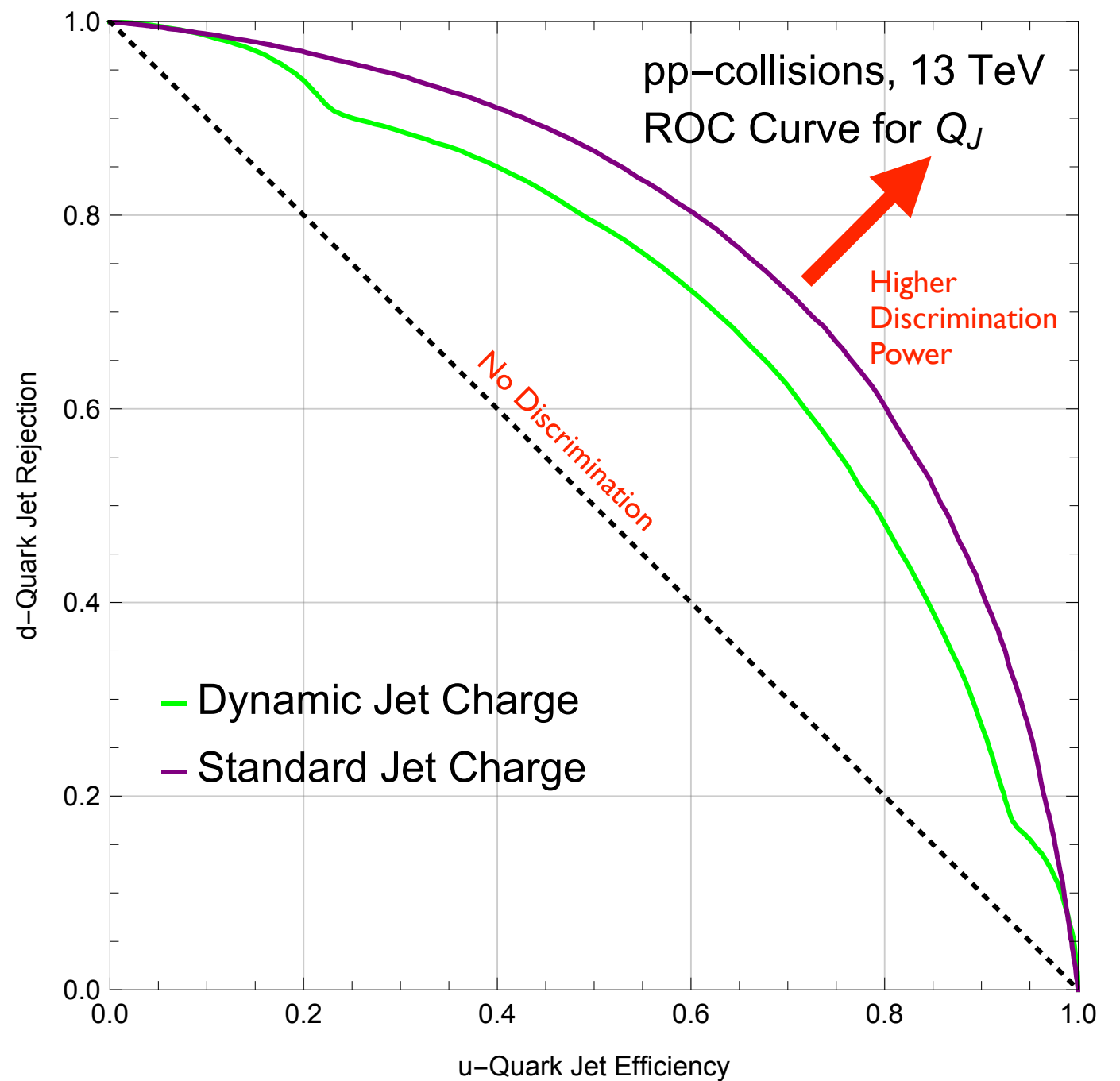
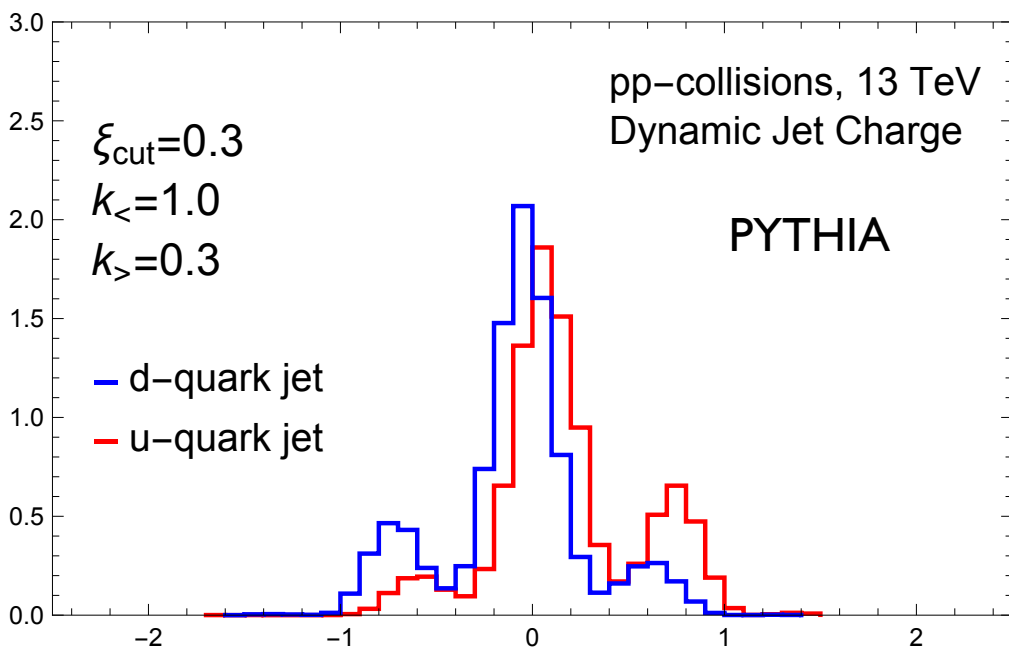
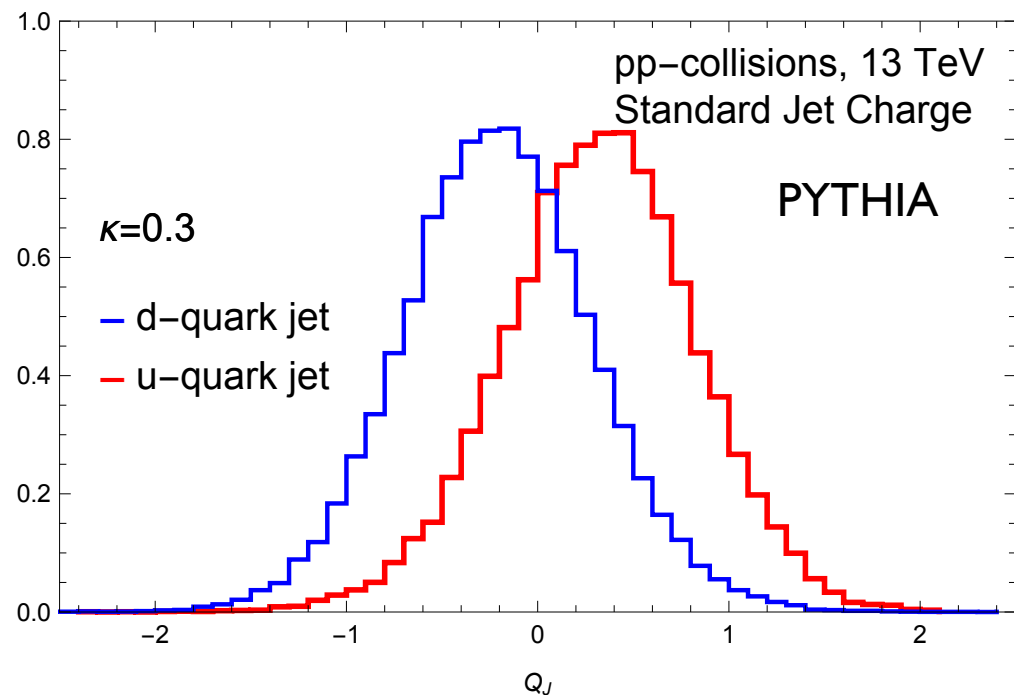


$$\kappa(z_h) = \begin{cases} k_<, & z_h < \xi_{\text{cut}} \\ k_>, & z_h \geq \xi_{\text{cut}} \end{cases}$$

$$Q_K^{\text{dyn.}} = \sum_{h \in \text{jet}} z_h^{\kappa(z_h)} Q_h$$

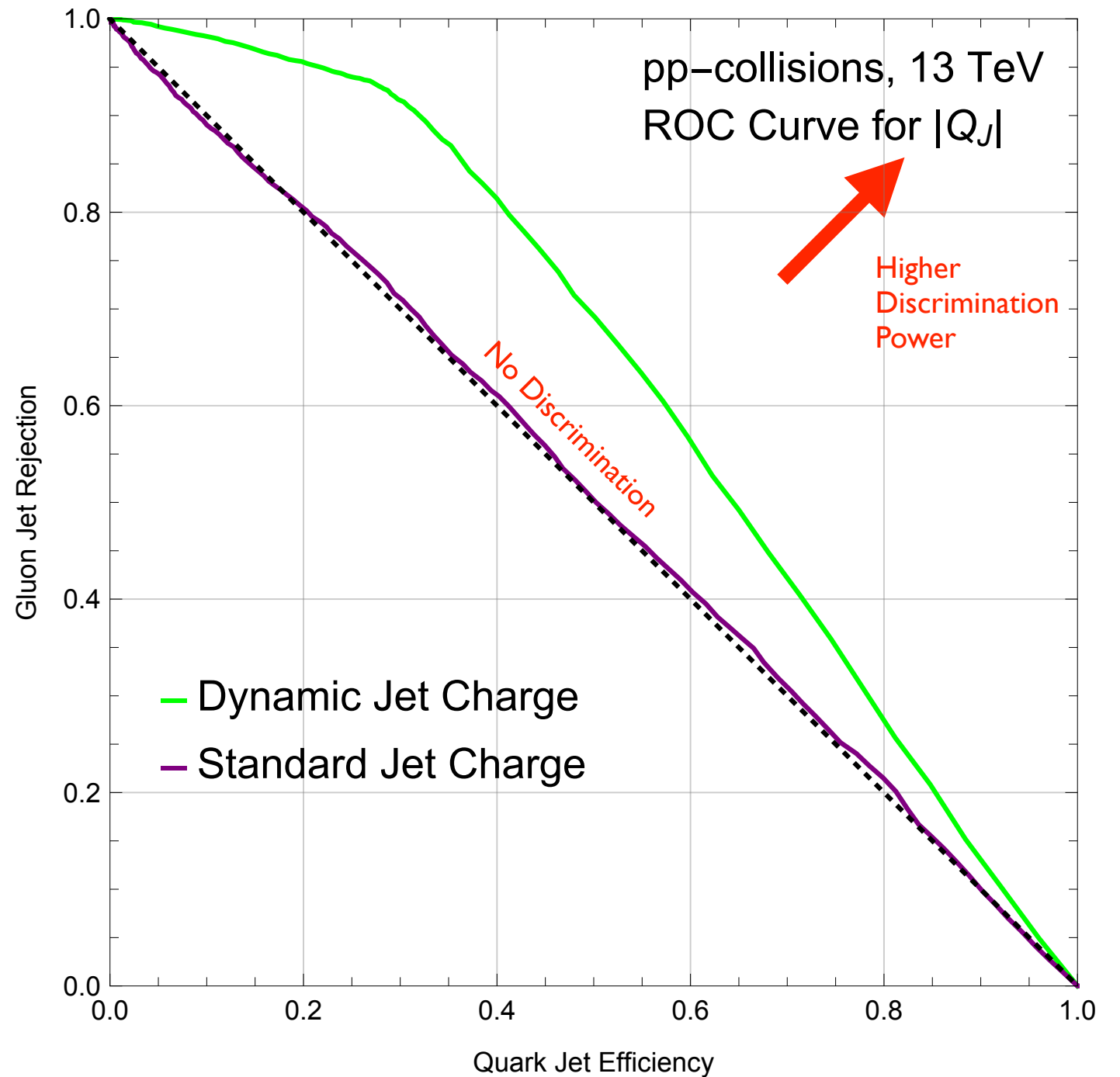
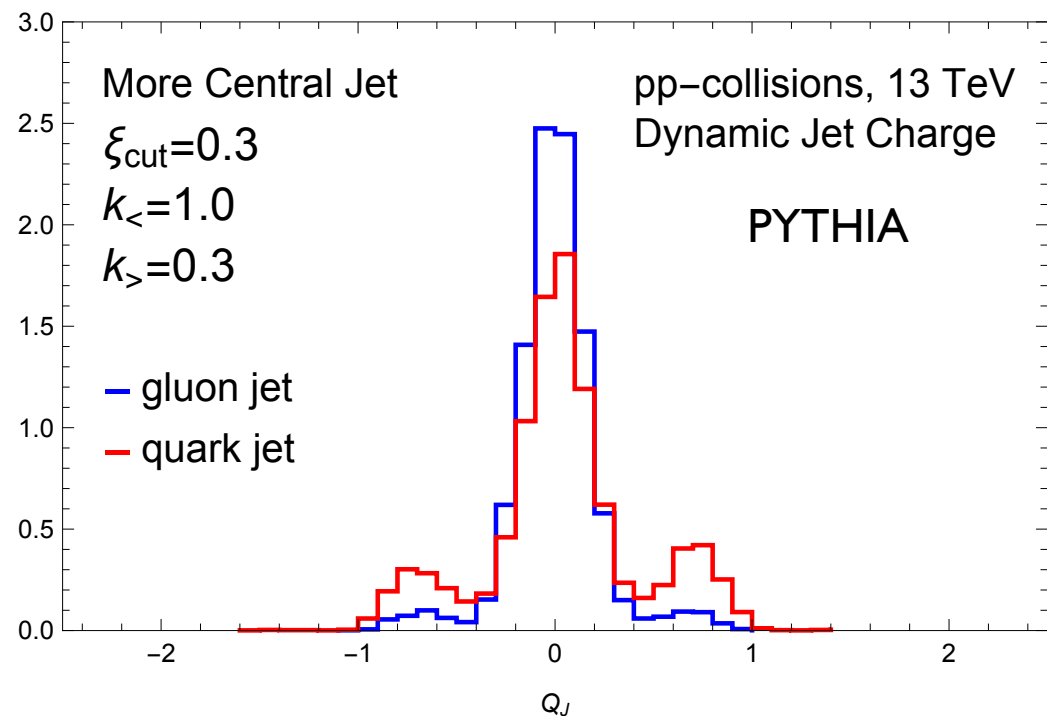
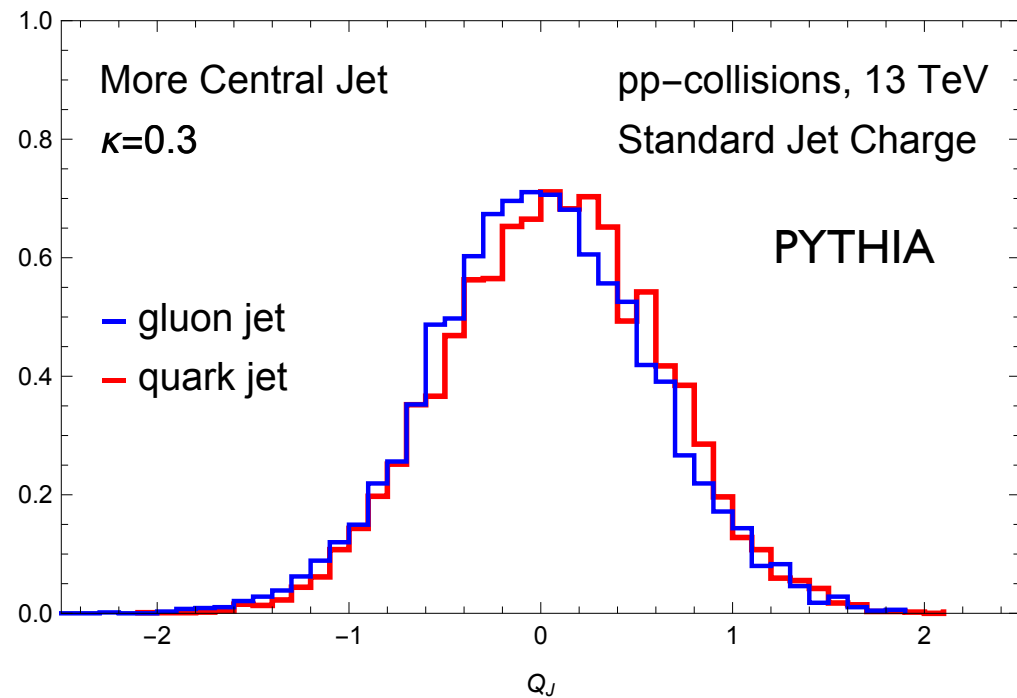
- Constant parameter κ to a dynamic function of jet constituent properties

Discriminating between u-Quark and d-Quark Jets



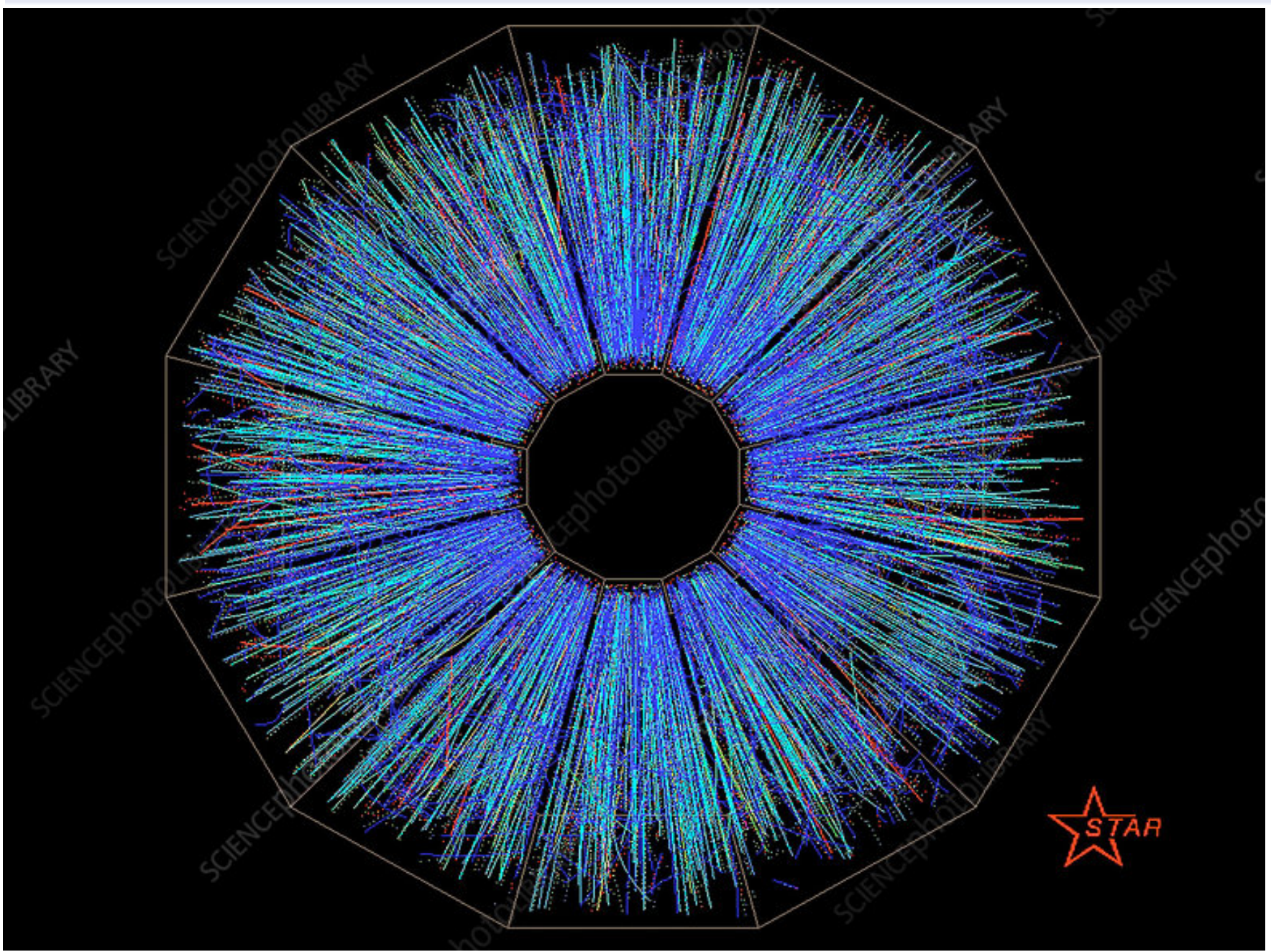
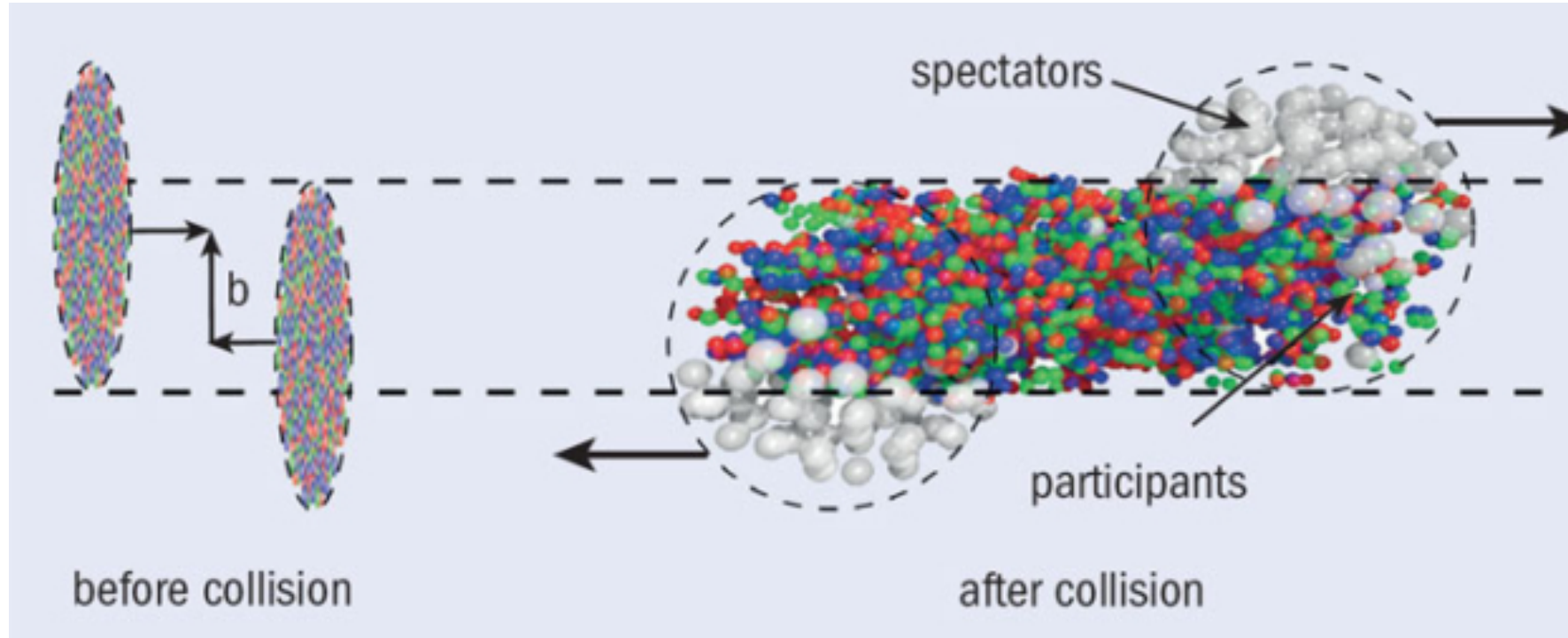
- Standard jet charge has higher discrimination power between u-quark and d-quark jets in pp collisions

Discriminating between Quark and Gluon Jets

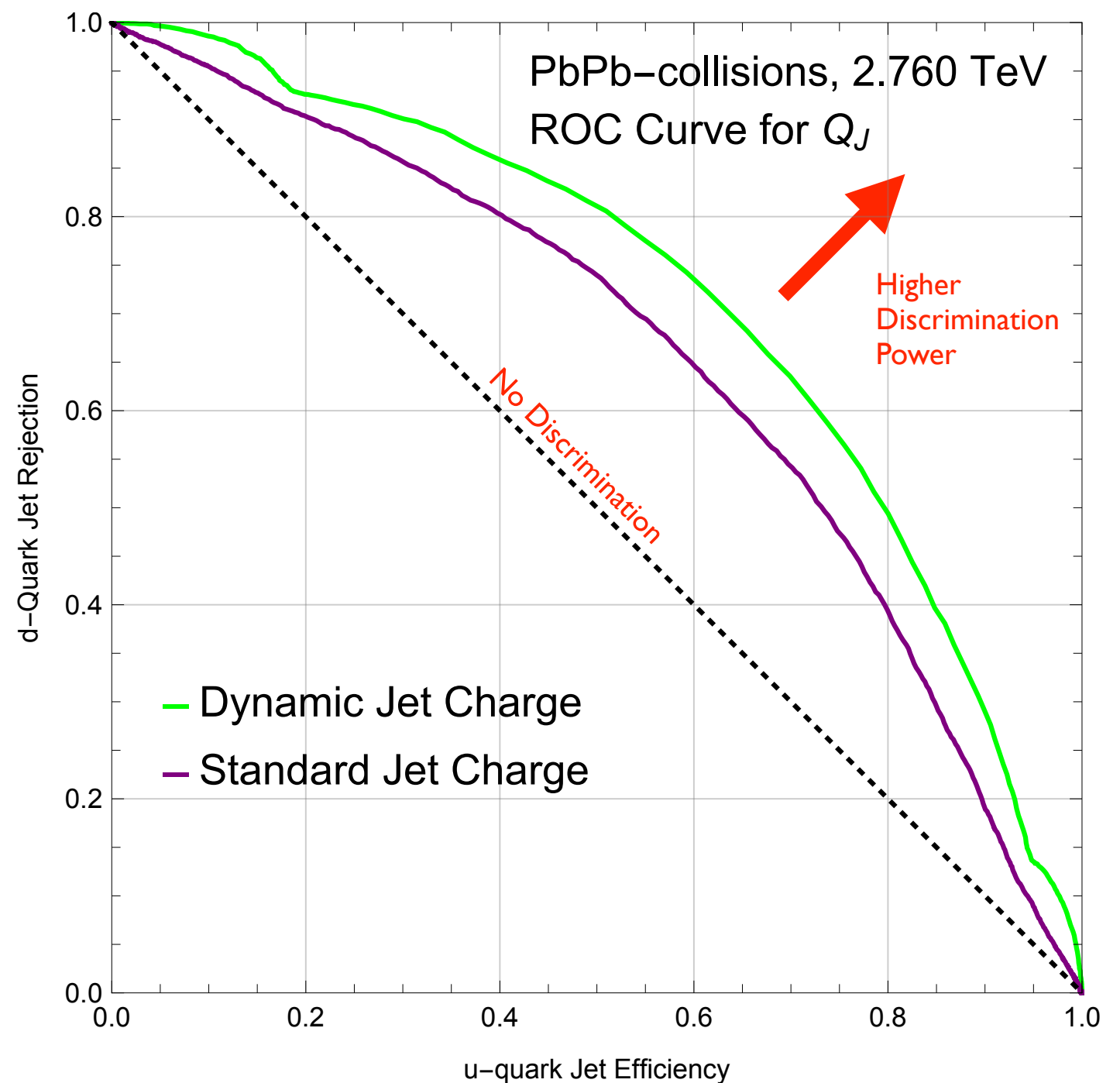
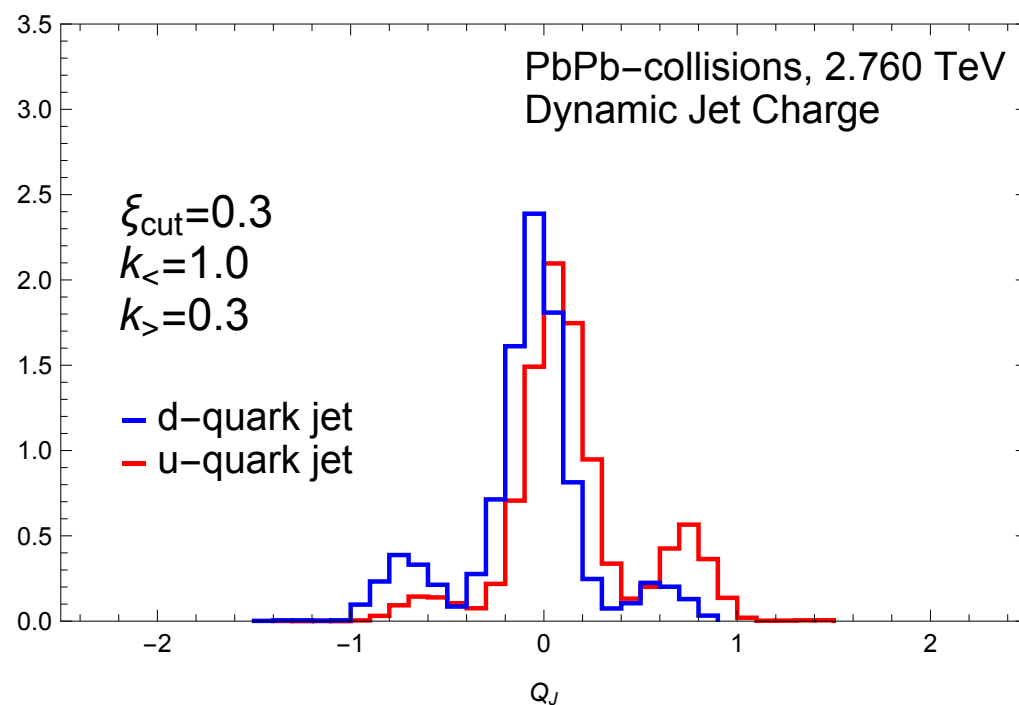
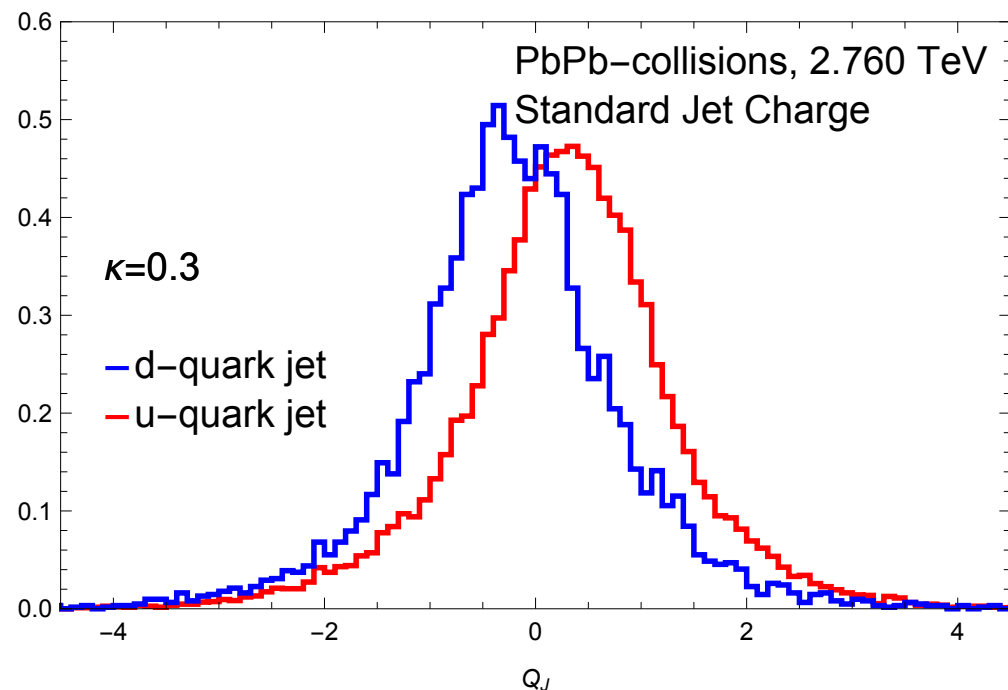


- Dynamic jet charge has higher discrimination power between quark and gluon jets in pp collisions

Heavy Ion Collisions



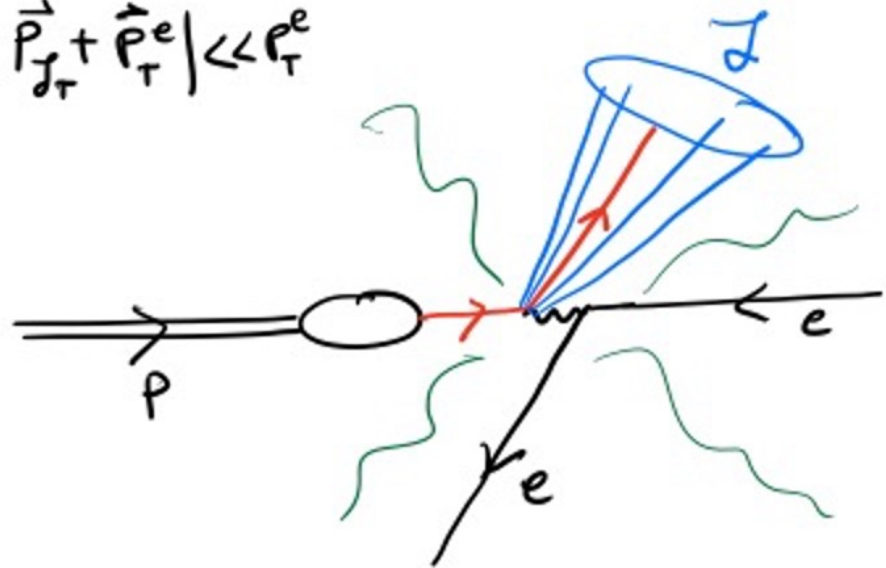
Discriminating between u- and d-Quark Jets in Heavy Ion Collisions



- Dynamic jet charge has higher discrimination power between u-quark and d-quark jets in heavy ion collisions

Small q_T Distribution to Probe TMDs

$$q_T = |\vec{p}_{jT} + \vec{p}_T^e| \ll p_T^e$$

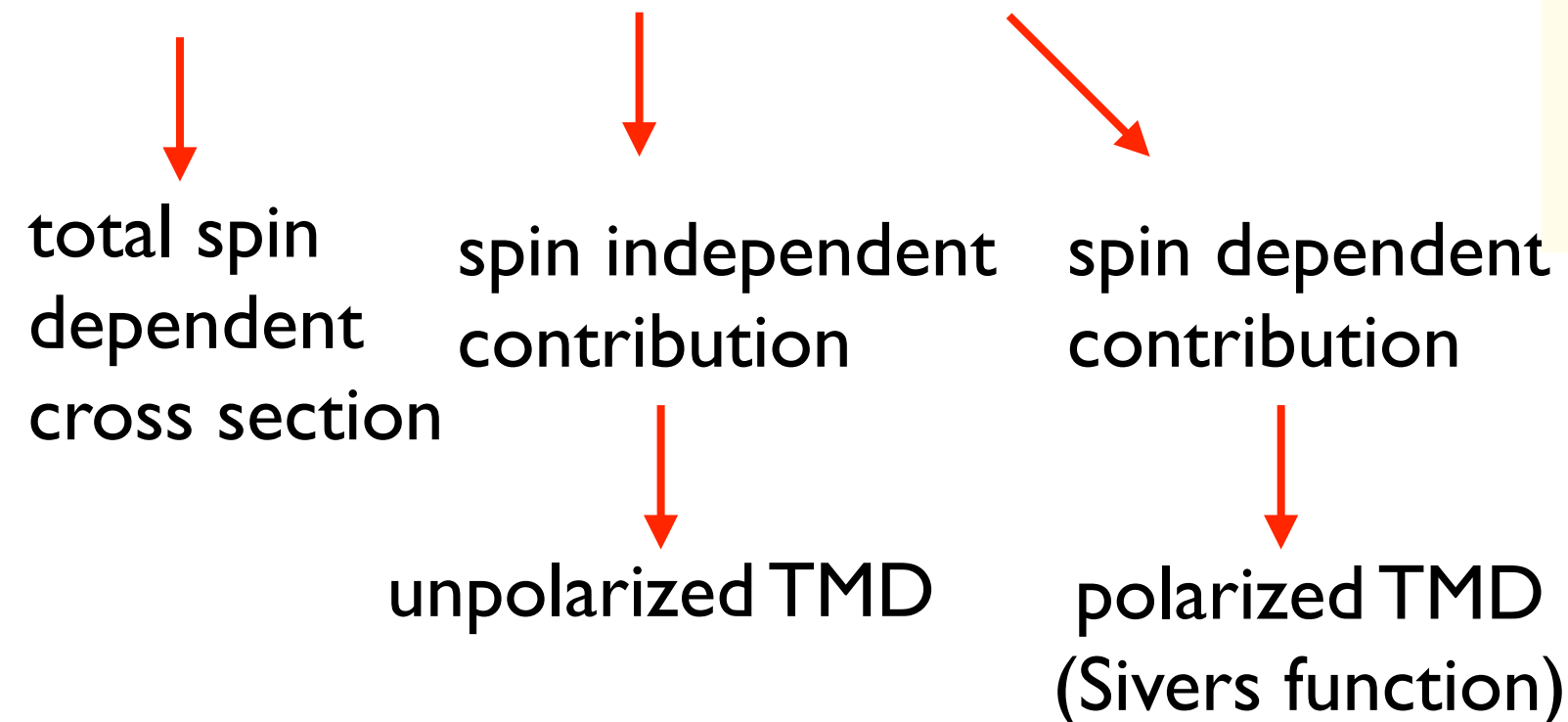


$$e + p \rightarrow e + \text{jet} + X$$

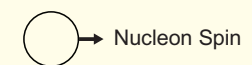
$$q_T = |\vec{p}_T^e + \vec{p}_{jT}| \ll p_T^e \sim p_T$$

- Cross section:

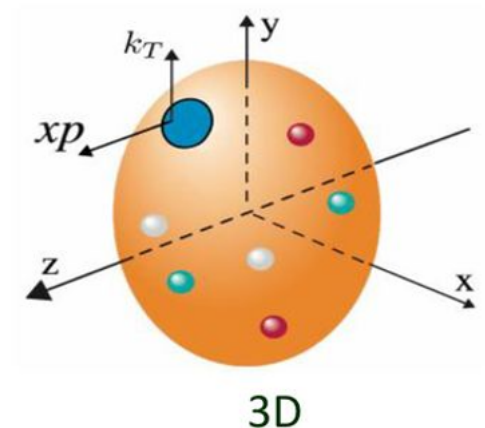
$$d\sigma(S_\perp) = d\sigma_{UU} + d\sigma_{UT}(S_\perp)$$



Leading Twist TMDs



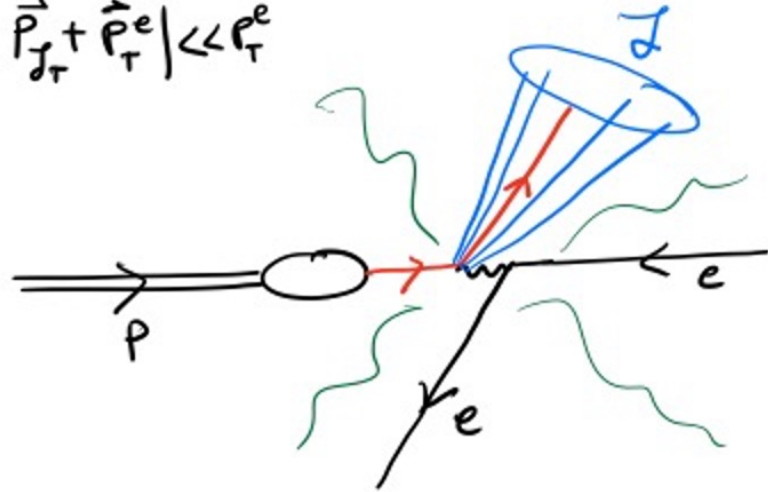
		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$		$h_1^\perp =$ — Boer-Mulders
	L		$g_{1L} =$ — Helicity	$h_{1L}^\perp =$ — Transversity
	T	$f_{1T}^\perp =$ — Sivers	$g_{1T}^\perp =$ — Helicity	$h_1 =$ — Transversity $h_{1T}^\perp =$ — Transversity



Factorization for Small q_T Distribution: Unpolarized TMD

[Liu, Ringer, Vogelsang, Yuan, 2020]

$$q_T = |\vec{p}_T^e + \vec{p}_T^e| \ll p_T^e$$



$$e + p \rightarrow e + \text{jet} + X$$

$$q_T = |\vec{p}_T^e + \vec{p}_T^e| \ll p_T^e \sim p_T$$

$$d\sigma(S_\perp) = d\sigma_{UU} + d\sigma_{UT}(S_\perp)$$

- Unpolarized TMD Factorization:

$$\frac{d^5\sigma_{UU}^i}{dy_e d^2p_T^e d^2q_T} = \sigma_0 e_i^2 \int \frac{d^2b_T}{(2\pi)^2} e^{iq_T \cdot b_T} \tilde{W}_i$$

$$\tilde{W}_i = \tilde{f}_i(x, b_T, \mu) S_J(b_T, R, \mu) H(Q, \mu) \mathcal{J}_i(p_T R, \mu)$$

Unpolarized TMD

soft function

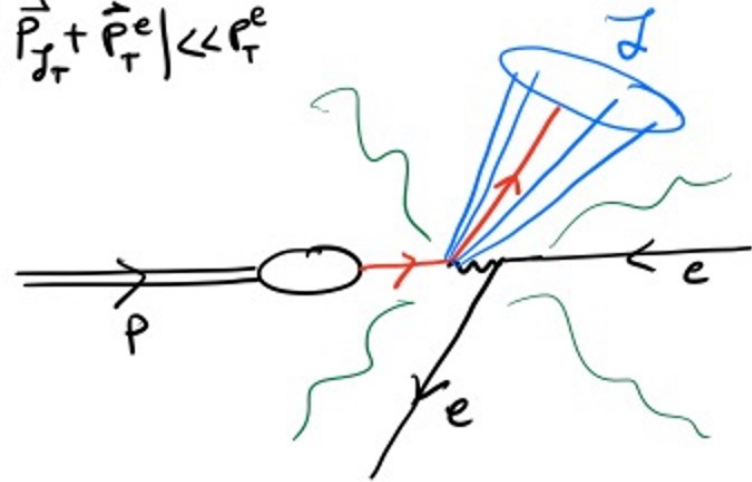
hard function

jet function

Factorization for Small q_T Distribution: Polarized TMD (Sivers Function)

[Liu, Ringer, Vogelsang, Yuan, 2020]

$$q_T = |\vec{p}_T^e + \vec{p}_T^e| \ll p_T^e$$



$$e + p \rightarrow e + \text{jet} + X$$

$$q_T = |\vec{p}_T^e + \vec{p}_T^e| \ll p_T^e \sim p_T$$

$$d\sigma(S_\perp) = d\sigma_{UU} + d\sigma_{UT}(S_\perp)$$

- Polarized TMD Factorization:

$$\frac{d^5\sigma_{UT}^i(S_\perp)}{dy_e d^2p_T^e d^2q_T} = e_i^2 \sigma_0 \epsilon_{\alpha\beta} S_\perp^\alpha \int \frac{d^2b_T}{(2\pi)^2} e^{iq_T \cdot b_T} \tilde{W}_{T,i}^\beta$$

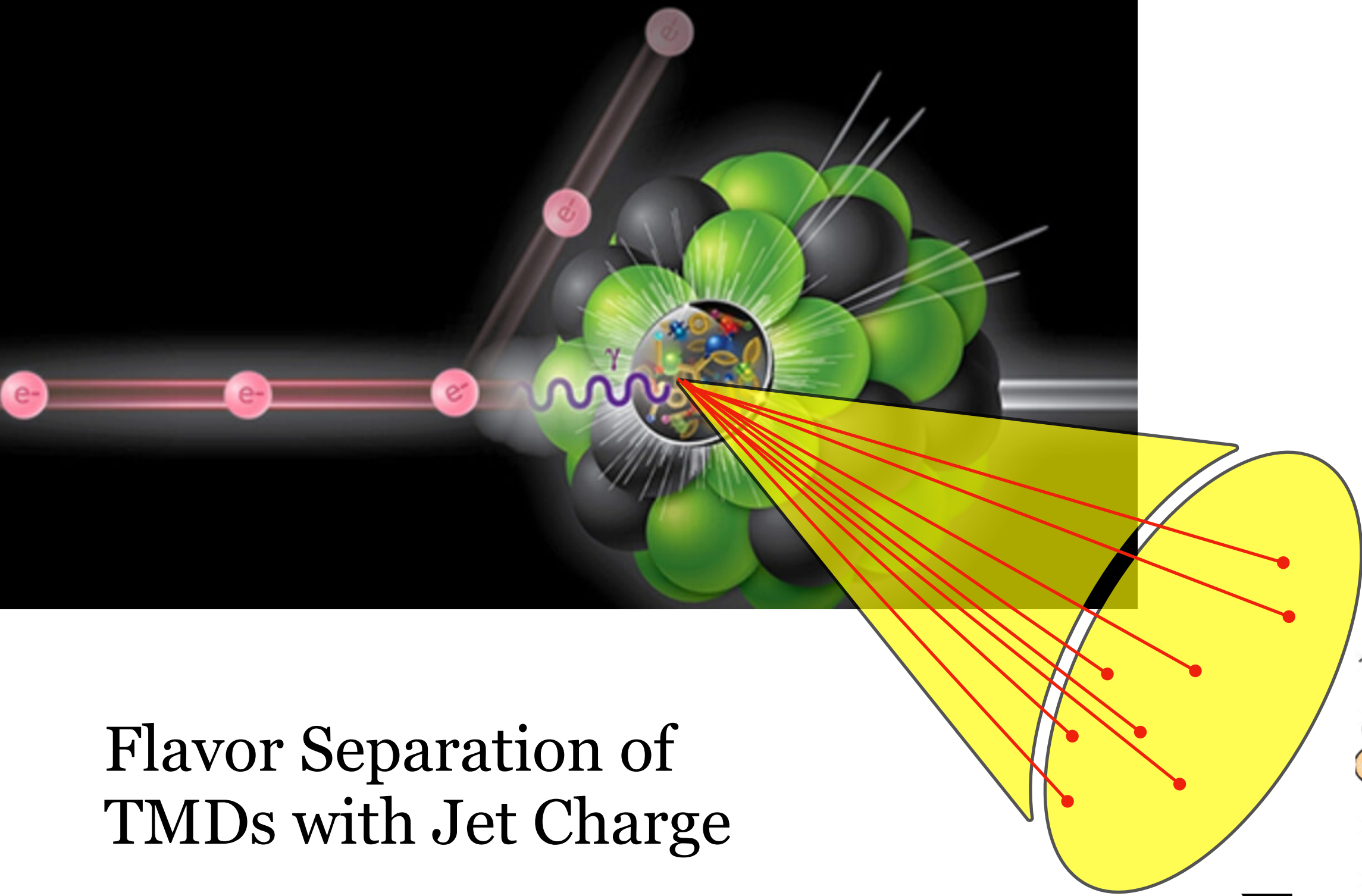
$$\tilde{W}_{T,i}^\beta = \tilde{f}_{1T,i}^{\perp,\beta}(x, b_T, \mu) S_J(b_T, R, \mu) H(Q, \mu) \mathcal{J}_i(p_T R, \mu)$$

polarized TMD
(Sivers Function)

soft function

hard function

jet function



Flavor Separation of TMDs with Jet Charge

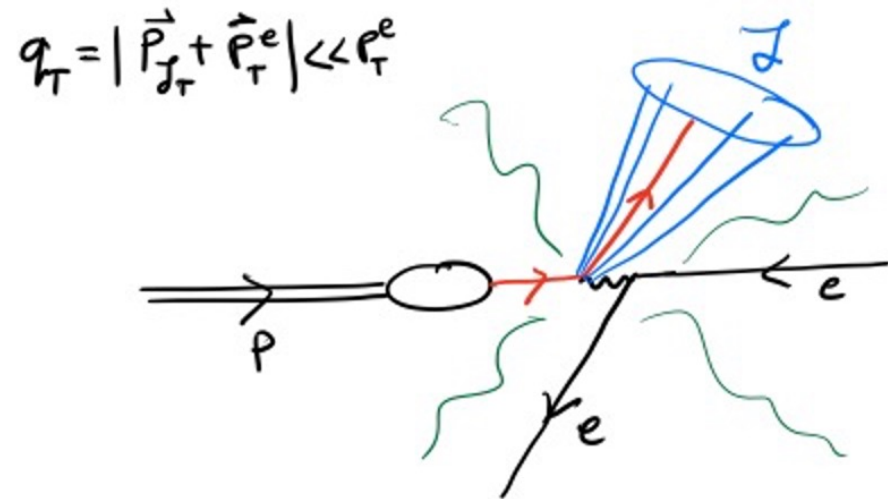
[Kang, Liu, SM, Shao]

arXiv: 2008.00655 (PRL 2020)

$$Q_{\kappa} = \sum_{h \in \text{jet}} z_h^{\kappa} Q_h$$



Flavor Separation of with Jet Charge: Unpolarized TMDs



$$e + p \rightarrow e + \text{jet} + X$$

$$q_T = |\vec{p}_T^e + \vec{p}_T| \ll p_T^e \sim p_T$$

$$d\sigma(S_\perp) = d\sigma_{UU} + d\sigma_{UT}(S_\perp)$$

- Unpolarized TMD Factorization:

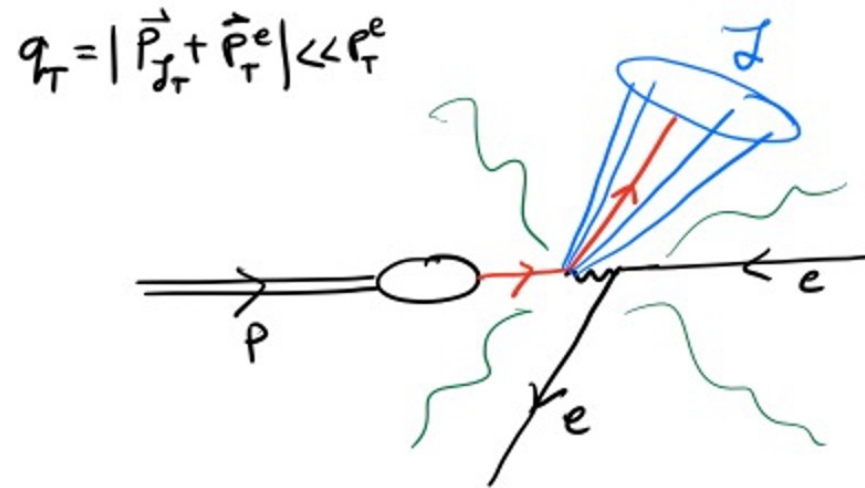
$$\frac{d^5\sigma_{UU}^i}{dy_e d^2p_T^e d^2q_T} = \sigma_0 e_i^2 \int \frac{d^2b_T}{(2\pi)^2} e^{iq_T \cdot b_T} \tilde{W}_i$$

$$\tilde{W}_i = \tilde{f}_i(x, b_T, \mu) S_J(b_T, R, \mu) H(Q, \mu) \mathcal{J}_i(p_T R, \mu)$$

Jet charge
measurement

$$\mathcal{G}_i(Q_\kappa, p_T R, \mu)$$

Flavor Separation of with Jet Charge: Polarized TMDs (Sivers Function)



$$e + p \rightarrow e + \text{jet} + X$$

$$q_T = |\vec{p}_T^e + \vec{p}_T| \ll p_T^e \sim p_T$$

$$d\sigma(S_\perp) = d\sigma_{UU} + d\sigma_{UT}(S_\perp)$$

- Polarized TMD Factorization:

$$\frac{d^5\sigma_{UT}^i(S_\perp)}{dy_e d^2p_T^e d^2q_T} = e_i^2 \sigma_0 \epsilon_{\alpha\beta} S_\perp^\alpha \int \frac{d^2b_T}{(2\pi)^2} e^{iq_T \cdot b_T} \tilde{W}_{T,i}^\beta$$

$$\tilde{W}_{T,i}^\beta = \tilde{f}_{1T,i}^{\perp,\beta}(x, b_T, \mu) S_J(b_T, R, \mu) H(Q, \mu) \mathcal{J}_i(p_T R, \mu)$$

Jet charge
measurement

$$\mathcal{G}_i(Q_\kappa, p_T R, \mu)$$

Separate Small q_T Distribution by Jet Charge Bin: Unpolarized TMDs

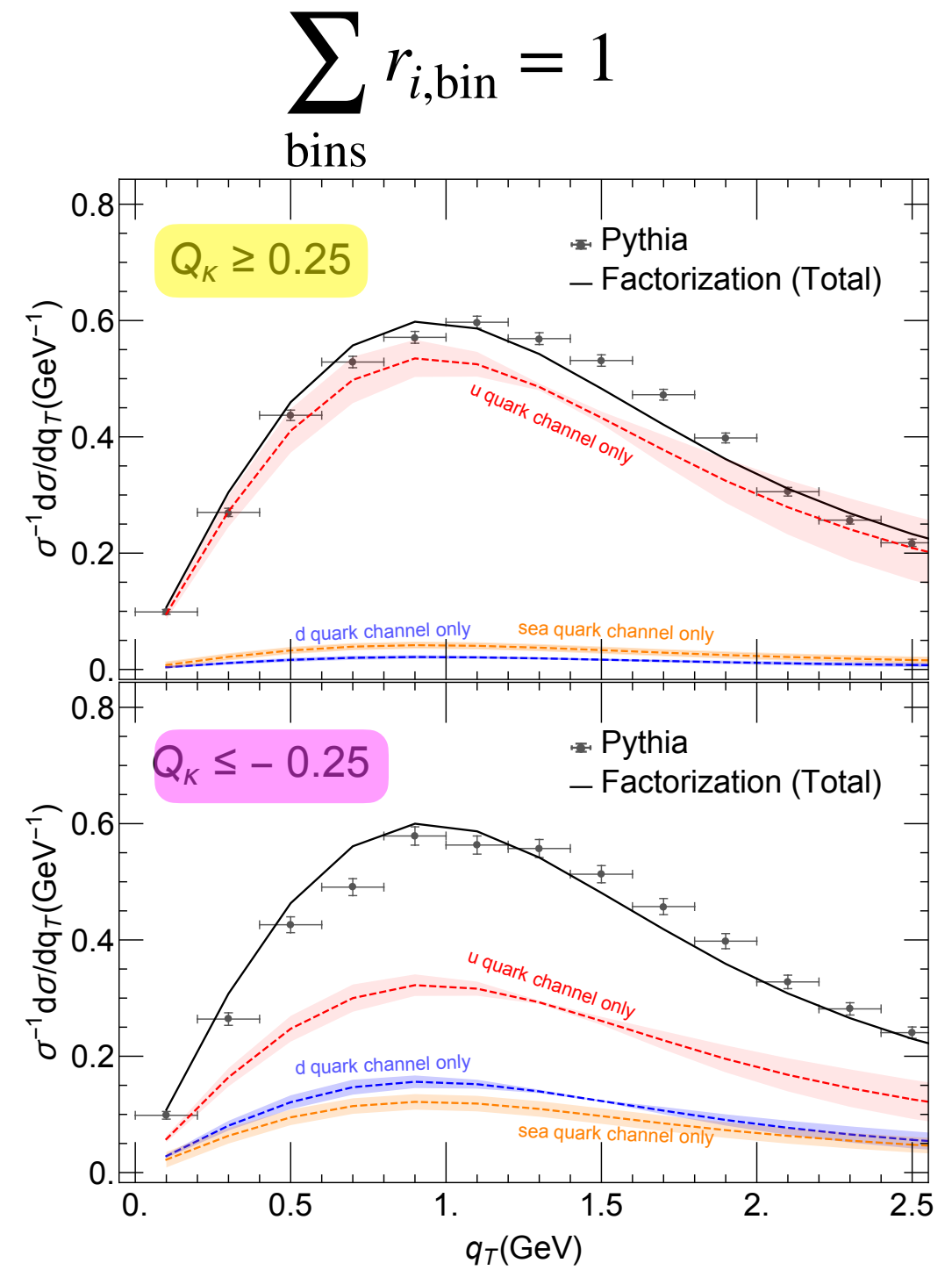
- Fraction of i -quark jets in a given jet charge bin:

$$r_{i,\text{bin}} = \int_{Q_\kappa \in \text{bin}} dQ_\kappa \frac{\mathcal{G}_i(Q_\kappa, p_T R, \mu)}{\mathcal{J}_i(p_T R, \mu)}, \quad \sum_{\text{bins}} r_{i,\text{bin}} = 1$$

$Q_\kappa = \sum_{h \in \text{jet}} z_h^\kappa Q_h$		u	$\bar{u}$	d	$\bar{d}$	s	$\bar{s}$
$h \in \{\pi^+, \pi^-\}$	$r_{i,+}$	0.52	0.17	0.15	0.53	0.30	0.34
	$r_{i,-}$	0.15	0.49	0.52	0.15	0.36	0.32
	$r_{i,0}$	0.33	0.35	0.33	0.32	0.35	0.34

- Fraction of i -quark jets in a given jet charge bin:

$$\frac{d^5 \sigma_{UU, \text{bin}}}{dy_e d^2 p_T^e d^2 q_T} = \sum_{i=u,d,\dots} r_{i,\text{bin}} \frac{d^5 \sigma_{UU}^i}{dy_e d^2 p_T^e d^2 q_T}$$



Separate Siverson Asymmetry Small q_T Distribution by Jet Charge Bin: Unpolarized TMDs

$$d\sigma(S_{\perp}) = d\sigma_{UU} + d\sigma_{UT}(S_{\perp})$$

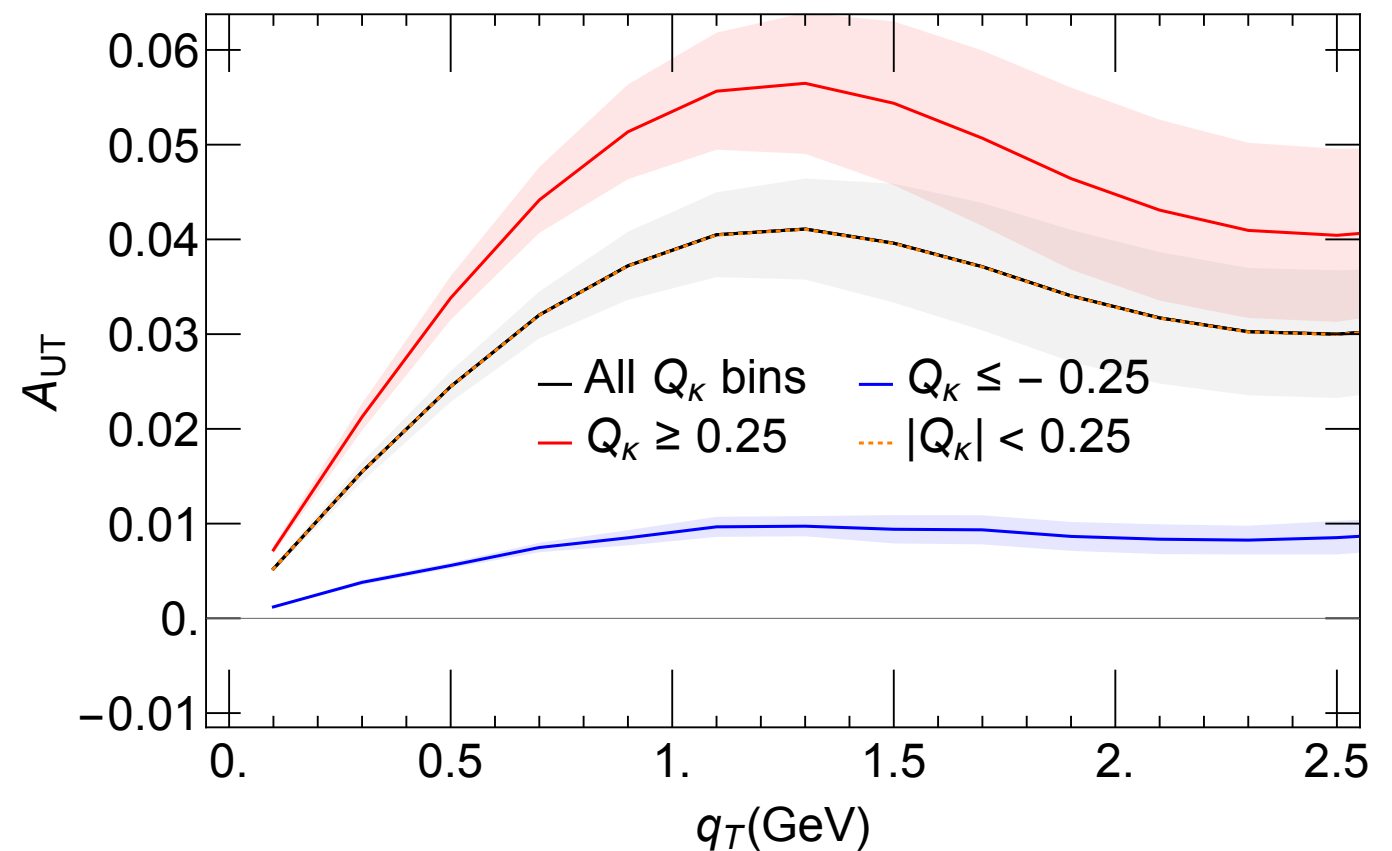
- Jet charge binned cross sections:

$$\frac{d^5\sigma_{UU, \text{bin}}}{dy_e d^2p_T^e d^2q_T} = \sum_{i=u,d,\dots} r_{i,\text{bin}} \frac{d^5\sigma_{UU}^i}{dy_e d^2p_T^e d^2q_T}$$

$$\frac{d^5\sigma_{UT, \text{bin}}(S_{\perp})}{dy_e d^2p_T^e d^2q_T} = \sum_{i=u,d,\dots} r_{i,\text{bin}} \frac{d^5\sigma_{UT}^i(S_{\perp})}{dy_e d^2p_T^e d^2q_T}$$

- Siverson asymmetry:

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



Separate Siverson Asymmetry Small q_T Distribution by Jet Charge Bin: Unpolarized TMDs

$$d\sigma(S_{\perp}) = d\sigma_{UU} + d\sigma_{UT}(S_{\perp})$$

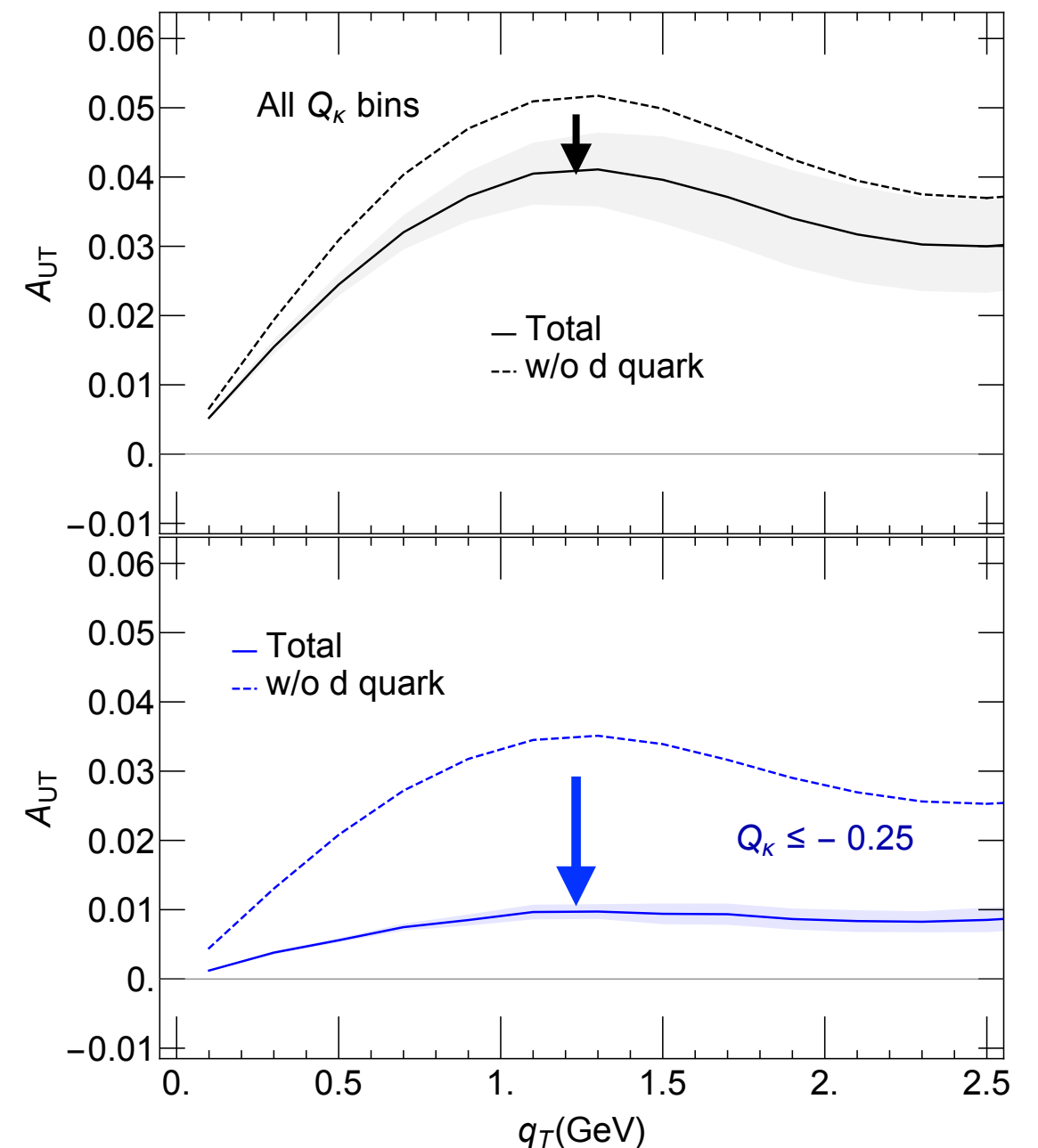
- Jet charge binned cross sections:

$$\frac{d^5\sigma_{UU, \text{bin}}}{dy_e d^2p_T^e d^2q_T} = \sum_{i=u,d,\dots} r_{i,\text{bin}} \frac{d^5\sigma_{UU}^i}{dy_e d^2p_T^e d^2q_T}$$

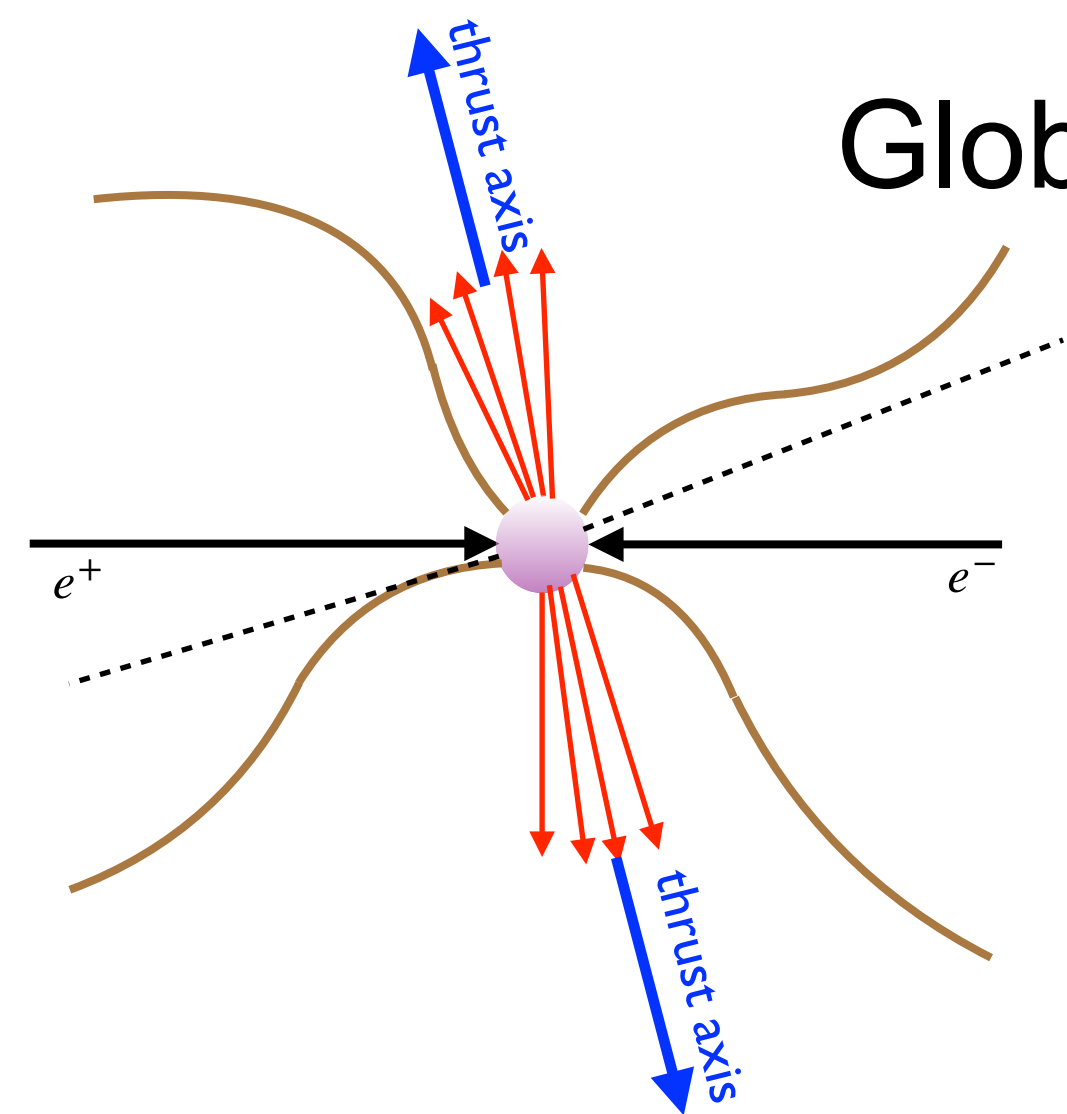
$$\frac{d^5\sigma_{UT, \text{bin}}(S_{\perp})}{dy_e d^2p_T^e d^2q_T} = \sum_{i=u,d,\dots} r_{i,\text{bin}} \frac{d^5\sigma_{UT}^i(S_{\perp})}{dy_e d^2p_T^e d^2q_T}$$

- Sivers asymmetry:

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

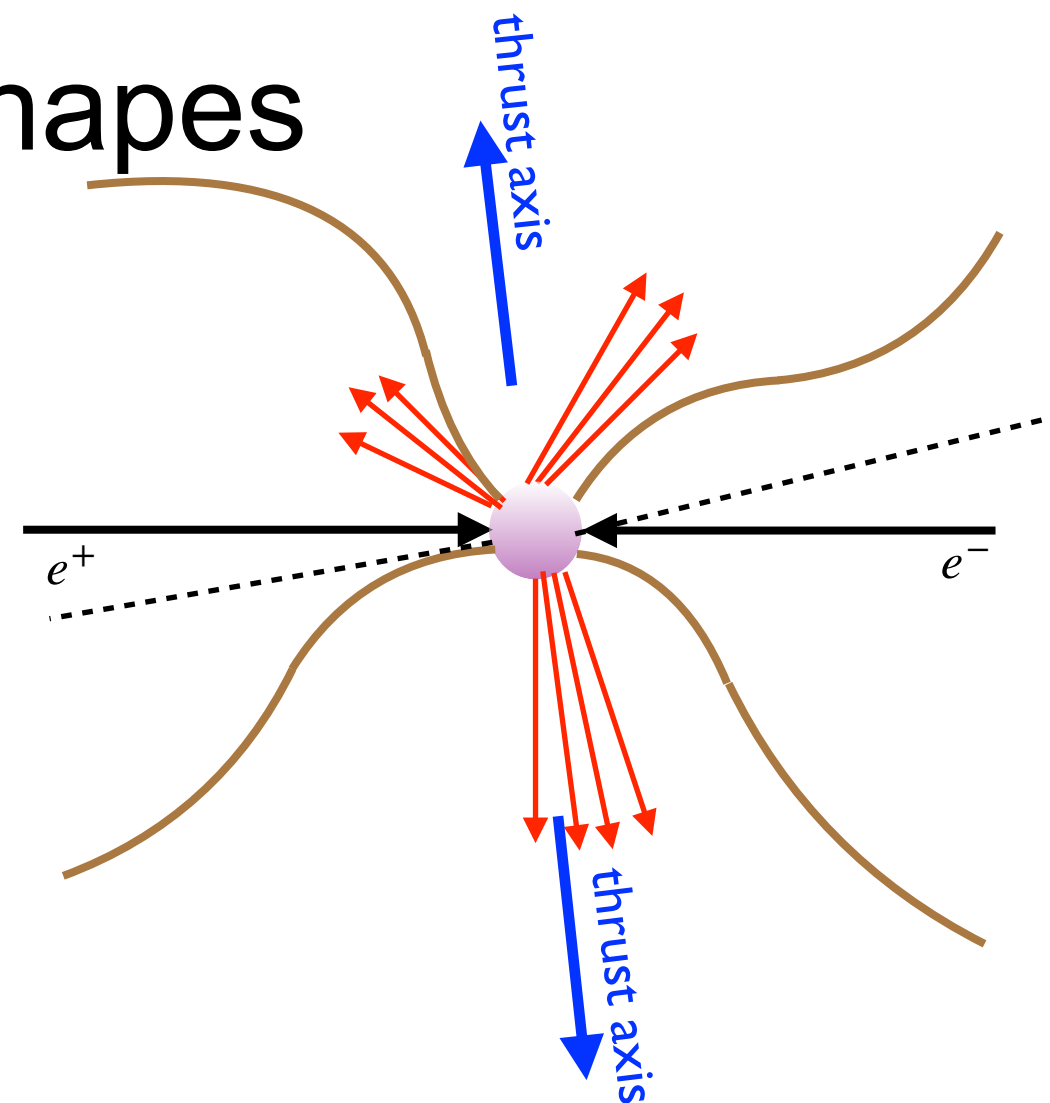


Global Event Shapes



$$\tau = 1 - T \ll 1$$

(Dijet configuration)



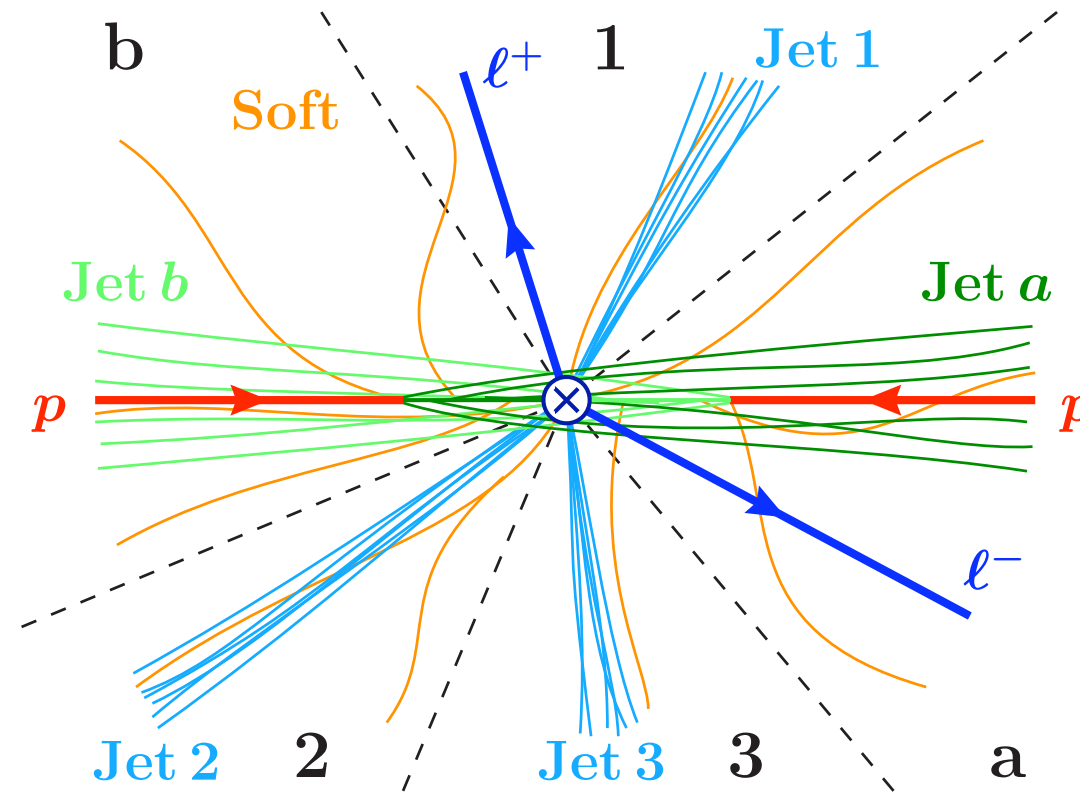
$$\tau = 1 - T \sim 1$$

(multijet configuration)

- Global event shapes quantify the pattern and geometry of energy flow in the final state.
- Many examples of global events shapes:
 - thrust
 - broadening
 - C-parameter
 - angularities
 - N-jettiness
- Simpler than tagging hadrons or jet algorithms. Can be computed to high accuracy. Provides high precision tests of QCD and powerful probes of hadronization.

N-Jettiness Global Event Shape

[Stewart, Tackmann, Waalewijn]
[PRL 2020]



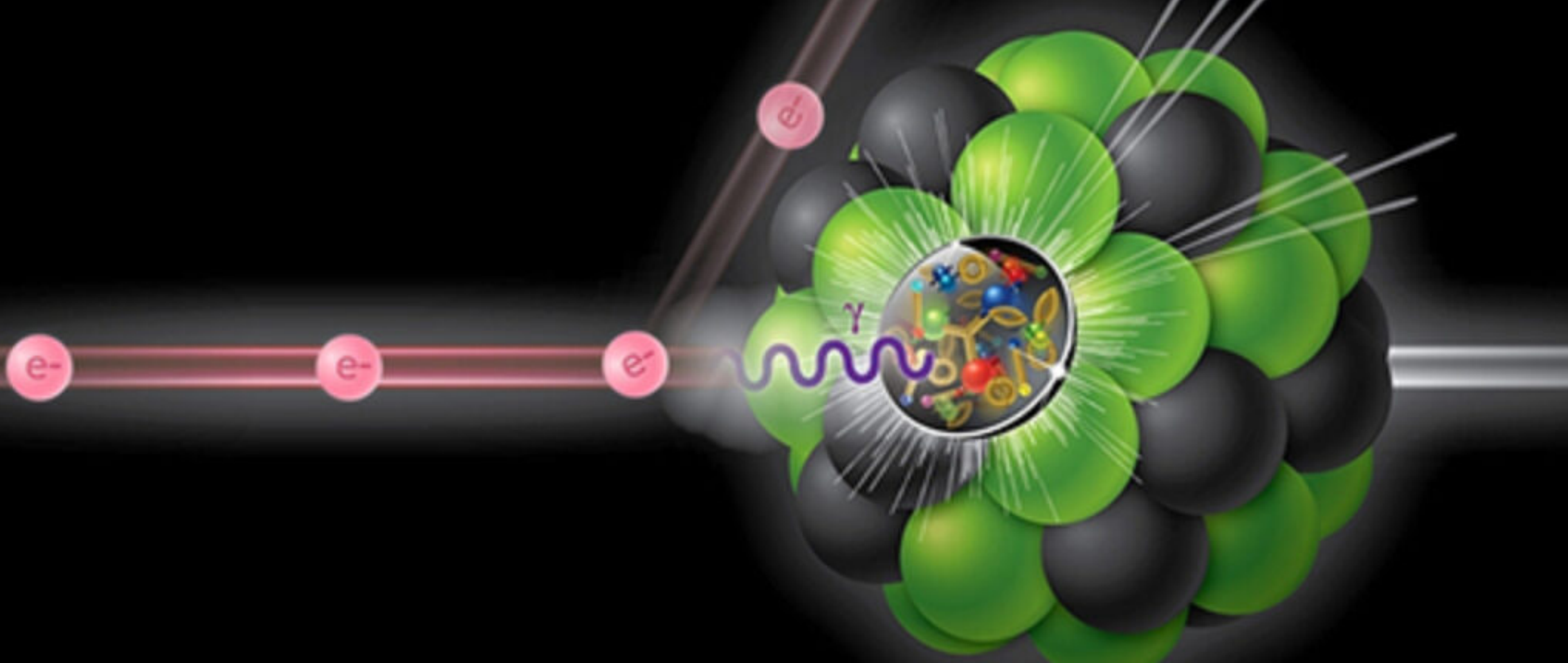
(c) $pp \rightarrow$ leptons plus jets.

- N-jettiness allows for an event-shape based analysis of multi-jet events (generalization of Thrust)

$$\tau_N = \sum_k \min_i \left\{ \frac{2q_i \cdot p_k}{Q_i} \right\}$$

- Limit of N narrow jets is given by (Jet Veto)

$$\tau_N \rightarrow 0$$

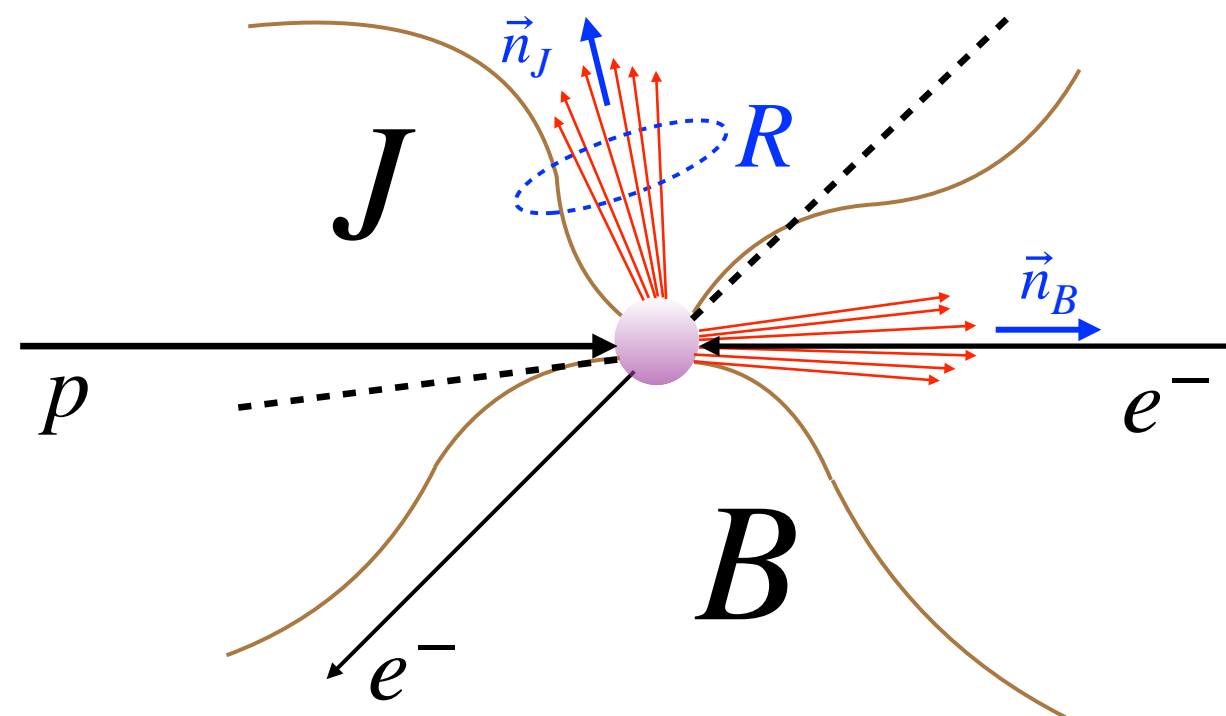


1-Jettiness in Deep Inelastic Scattering

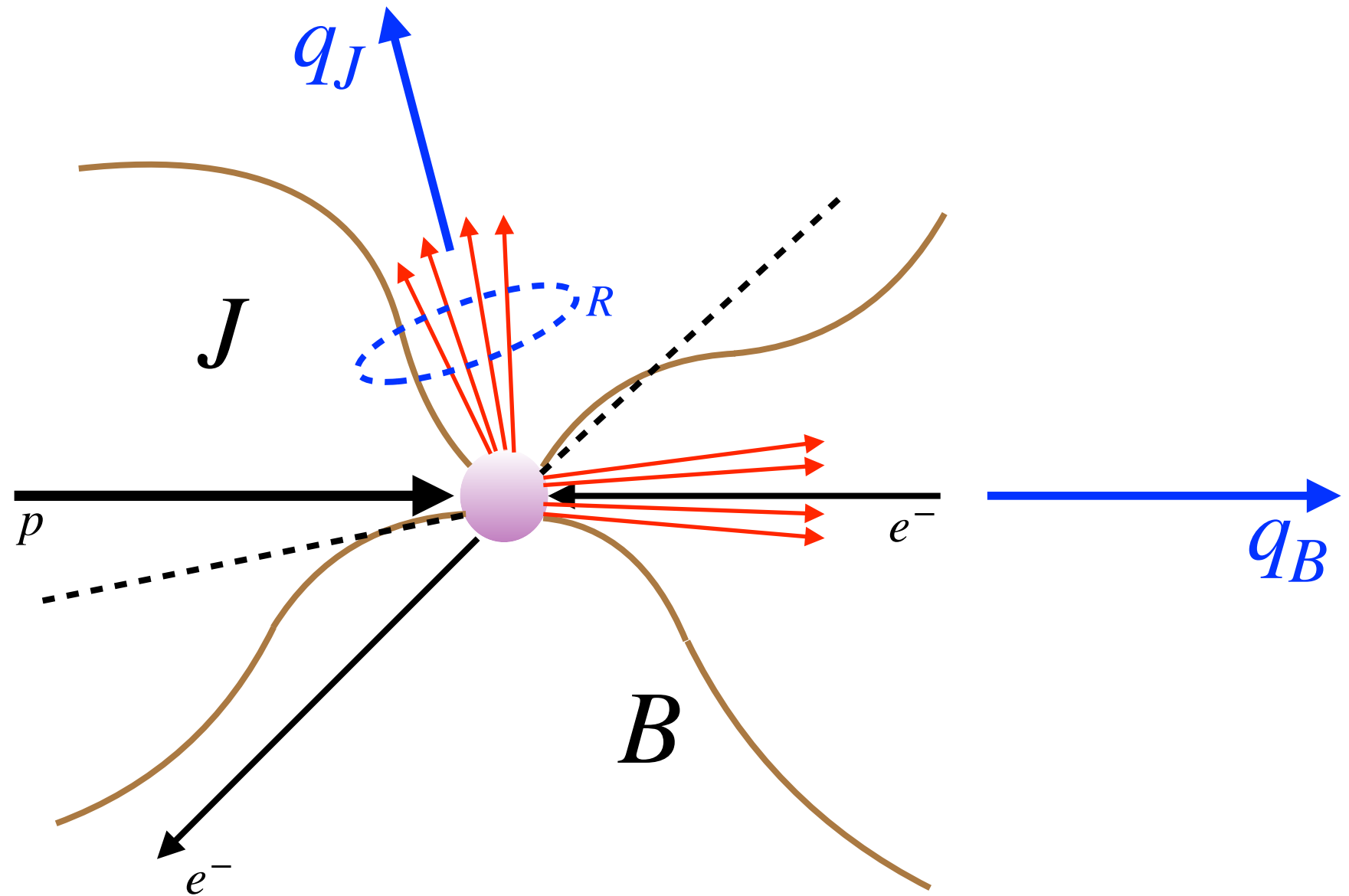
[Z. Kang, SM, Qiu PRD 2012]

[Z. Kang, Liu, SM, Qiu PRD 2013]

[D. Kang, Lee, Stewart PRD 2013]



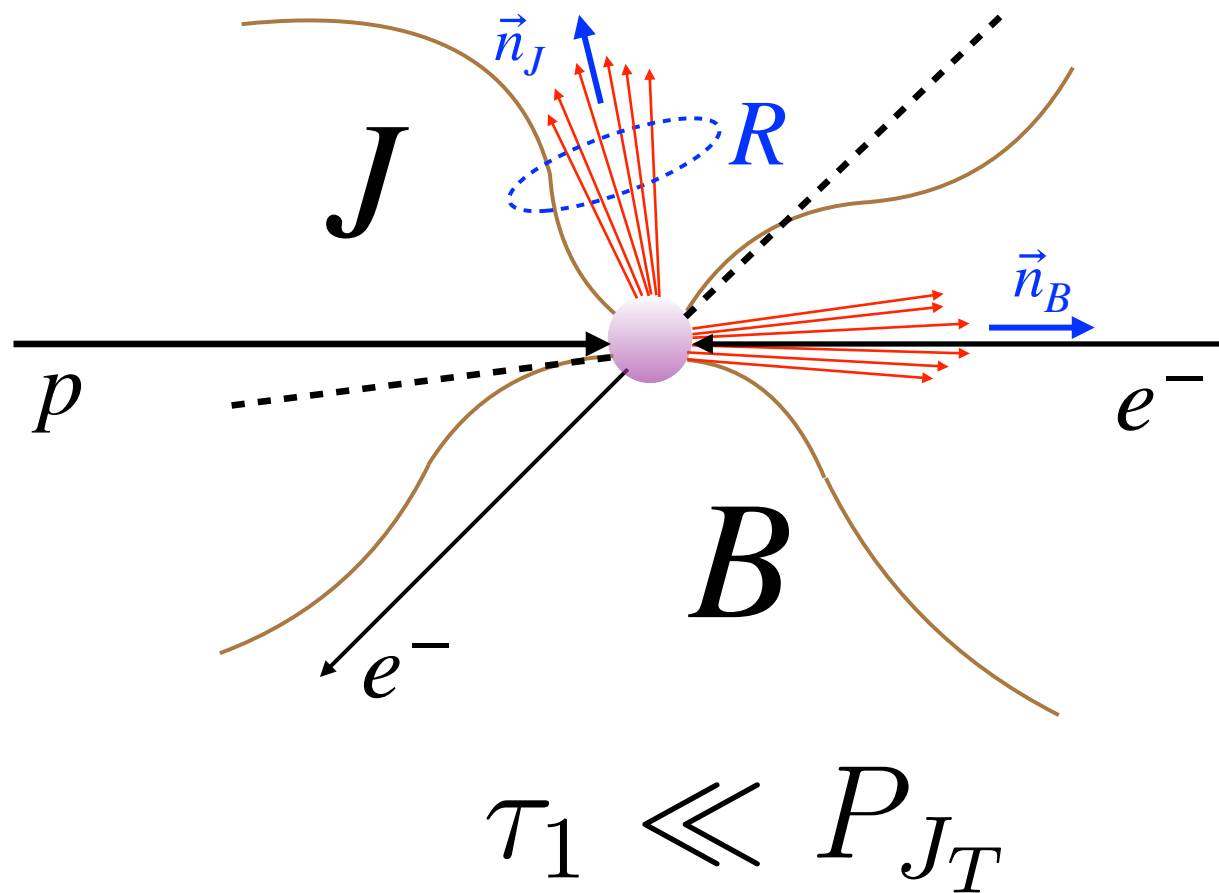
1-Jettiness Global Event Shape



- 1-Jettiness definition:

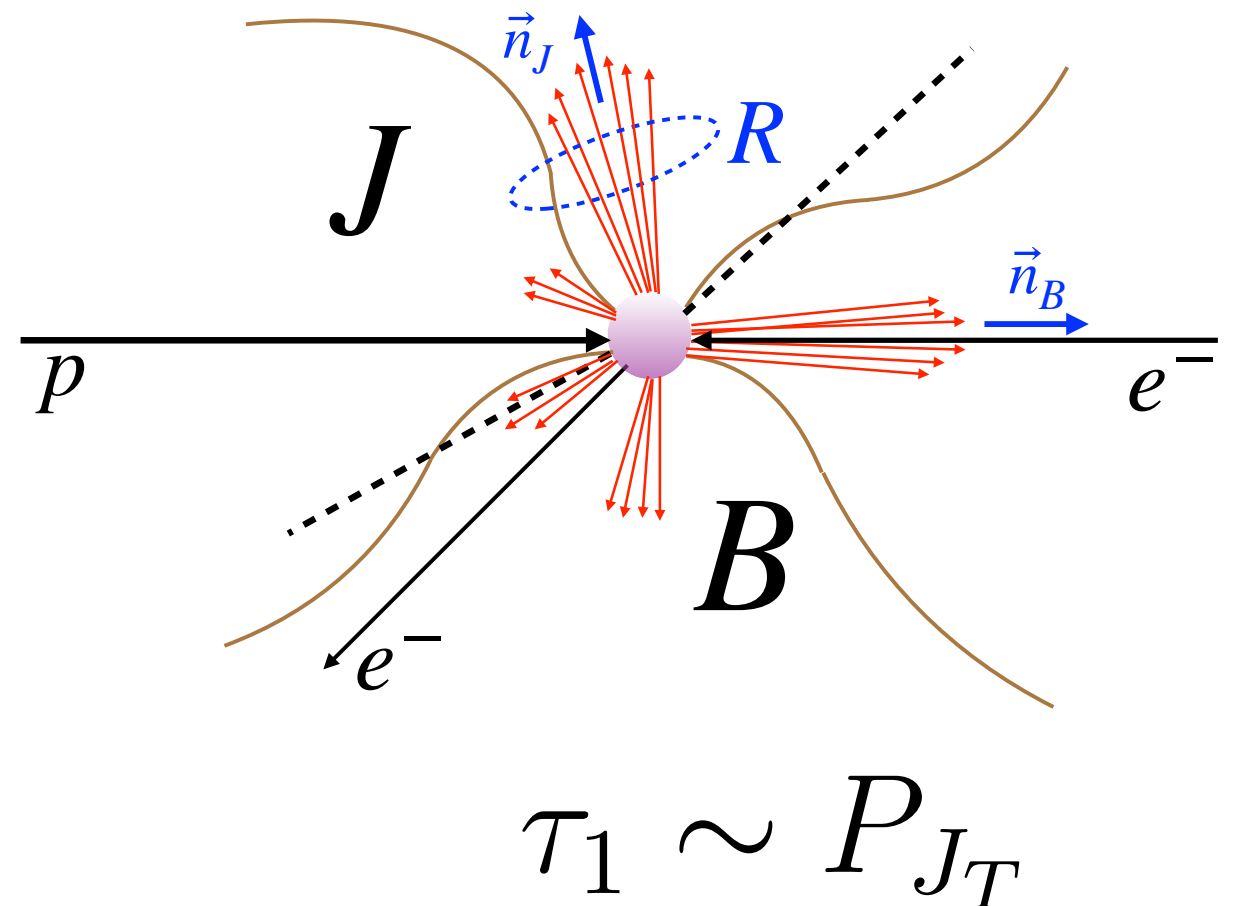
$$\tau_1 = \sum_k \min \left\{ \frac{2q_B \cdot p_k}{Q_B}, \frac{2q_J \cdot p_k}{Q_J} \right\}$$

1-Jettiness Global Event Shape



- 1-Jettiness definition:

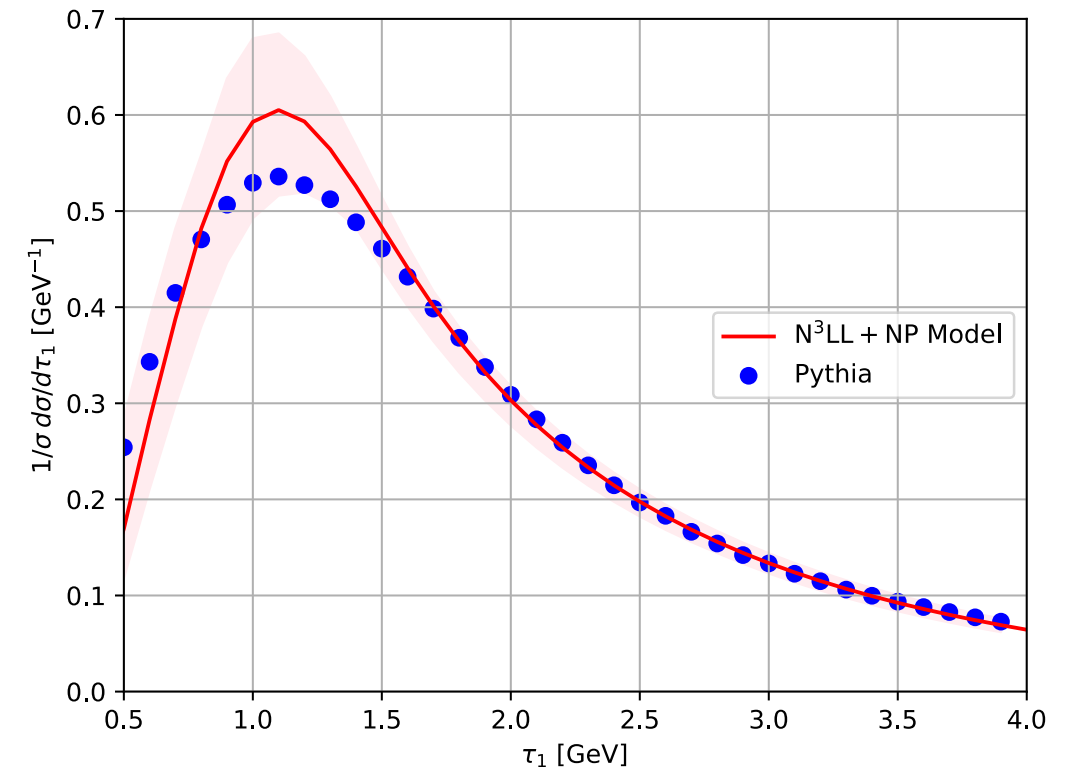
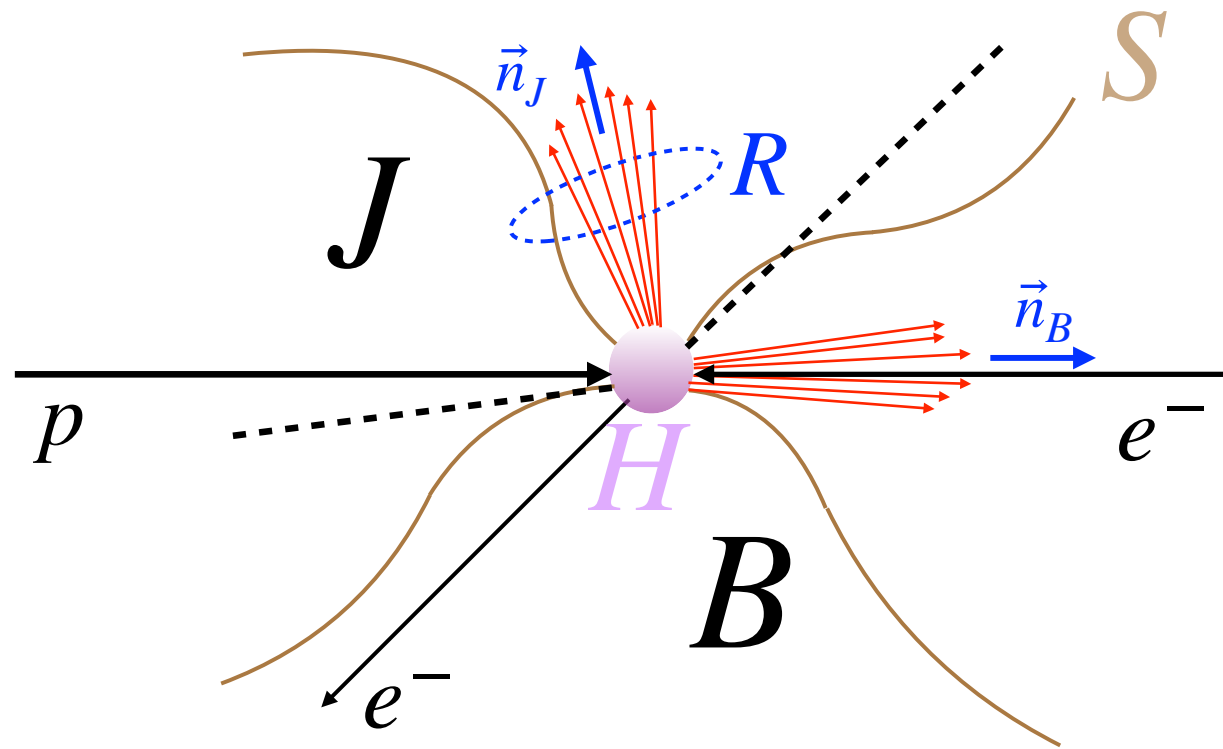
$$\tau_1 = \sum_k \min \left\{ \frac{2q_B \cdot p_k}{Q_B}, \frac{2q_J \cdot p_k}{Q_J} \right\}$$



- 1-Jettiness jet momentum:

$$P_J^\mu = \sum_k p_k^\mu \theta \left(\frac{2q_B \cdot p_k}{Q_B} - \frac{2q_J \cdot p_k}{Q_J} \right)$$

1-Jettiness: Factorization



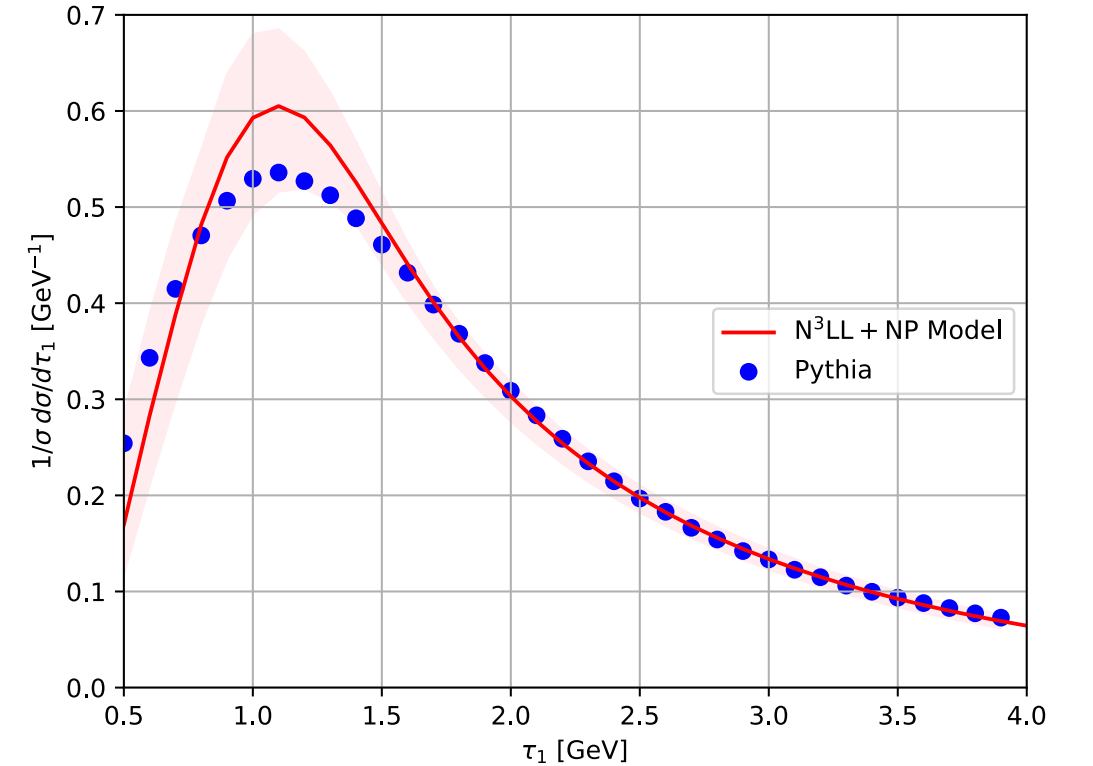
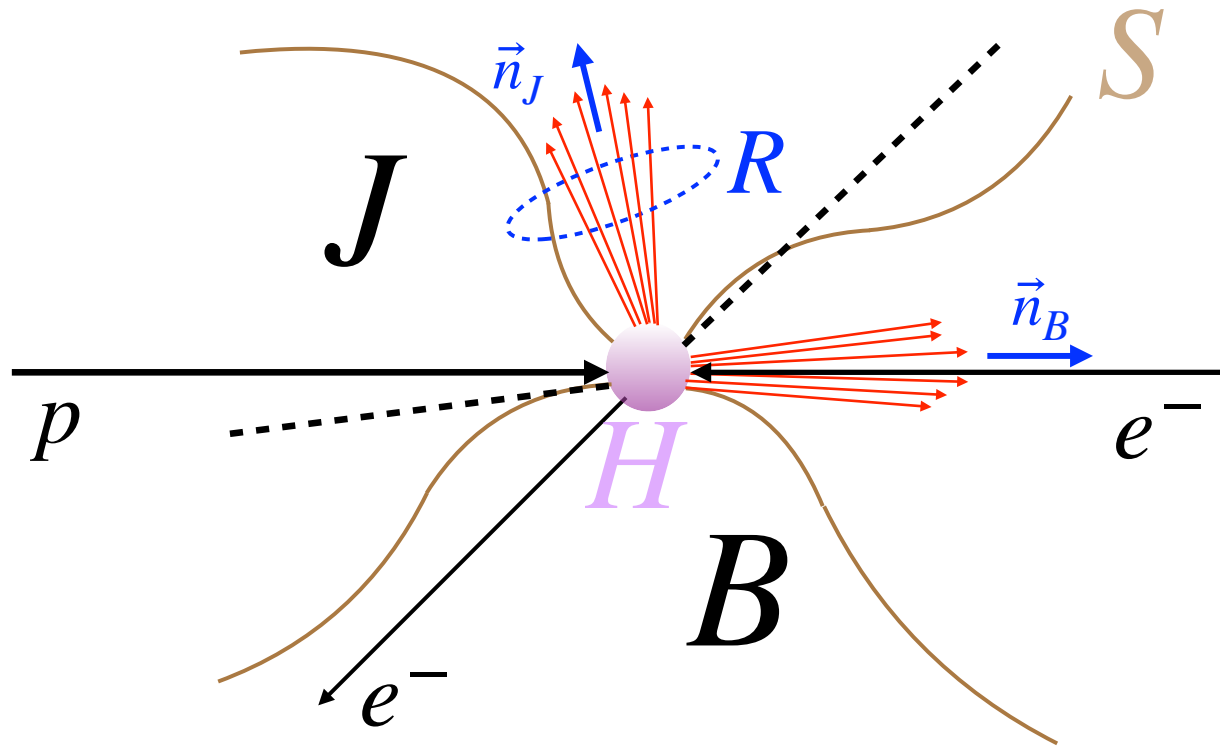
- Results known at $N^3\text{LL} + \mathcal{O}(\alpha_s^2)$:
[Cao, Kang, Liu, SM]
arXiv: 2008.00655 (PRD 2024)

- 1-Jettiness factorization formula:

$$d\sigma_{\text{resum}} [\tau_1, P_{J_T}, y_J] \sim H \otimes B \otimes J \otimes S$$

$$B \sim \mathcal{I} \otimes f$$

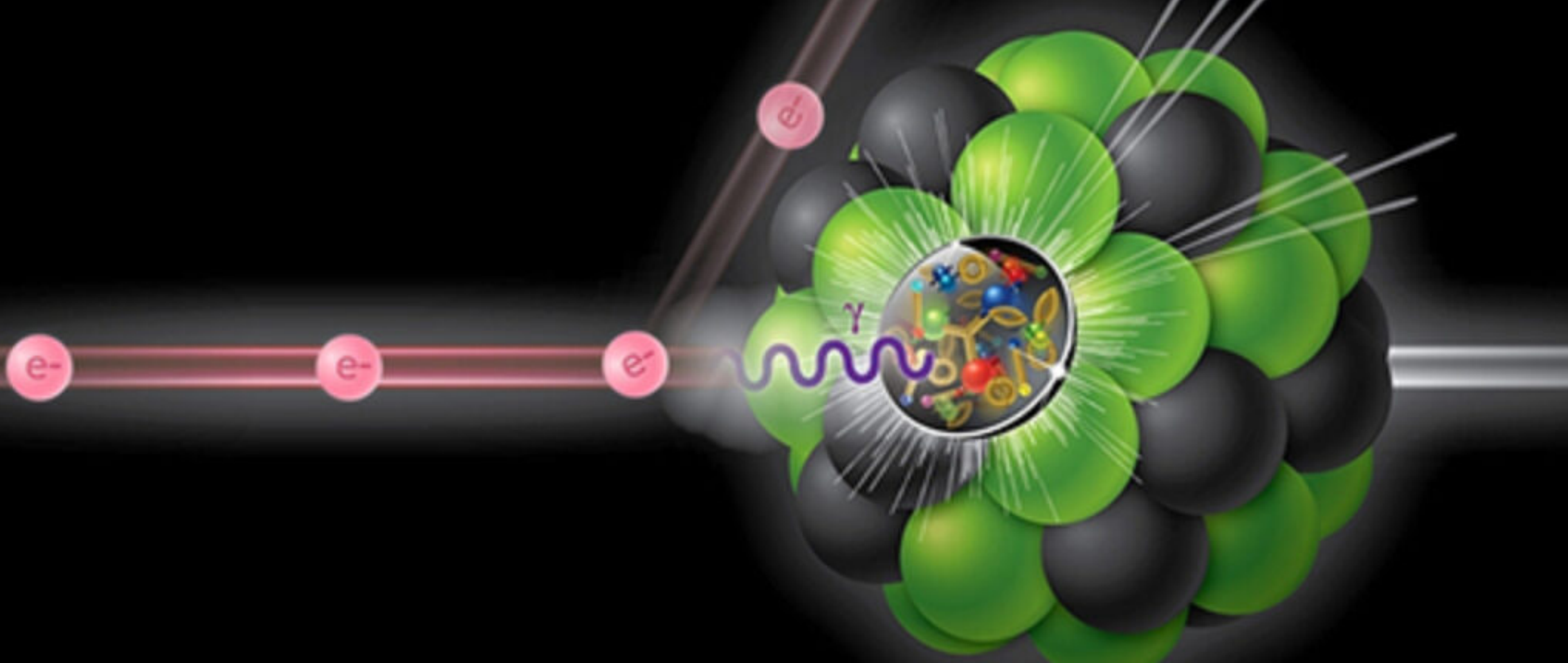
1-Jettiness: Factorization



- 1-Jettiness factorization formula:

$$\begin{aligned}
 d\sigma_{\text{resum}}[\tau_1, P_{J_T}, y_J] &= \sigma_0 H(\xi, \mu; \mu_H) \\
 &\times \int ds_J \int dt_a \mathcal{S}\left(\tau_1 - \frac{t_a}{Q_a} - \frac{s_J}{Q_J}, \mu; \mu_S\right) \\
 &\times \left[\sum_{q_i} L_{q_i} J^{q_i}(s_J, \mu; \mu_J) B_{q_i}(x_*, t_a, \mu; \mu_B) \right. \\
 &\left. + \sum_{\bar{q}_i} L_{\bar{q}_i} J^{\bar{q}_i}(s_J, \mu; \mu_J) B_{\bar{q}_i}(x_*, t_a, \mu; \mu_B) \right],
 \end{aligned}$$

$$B^q(x, t_a, \mu; \mu_B) = \int_x^1 \frac{dz}{z} \mathcal{I}^{qi}\left(\frac{x}{z}, t_a, \mu; \mu_B\right) f_{i/A}(z, \mu_B)$$

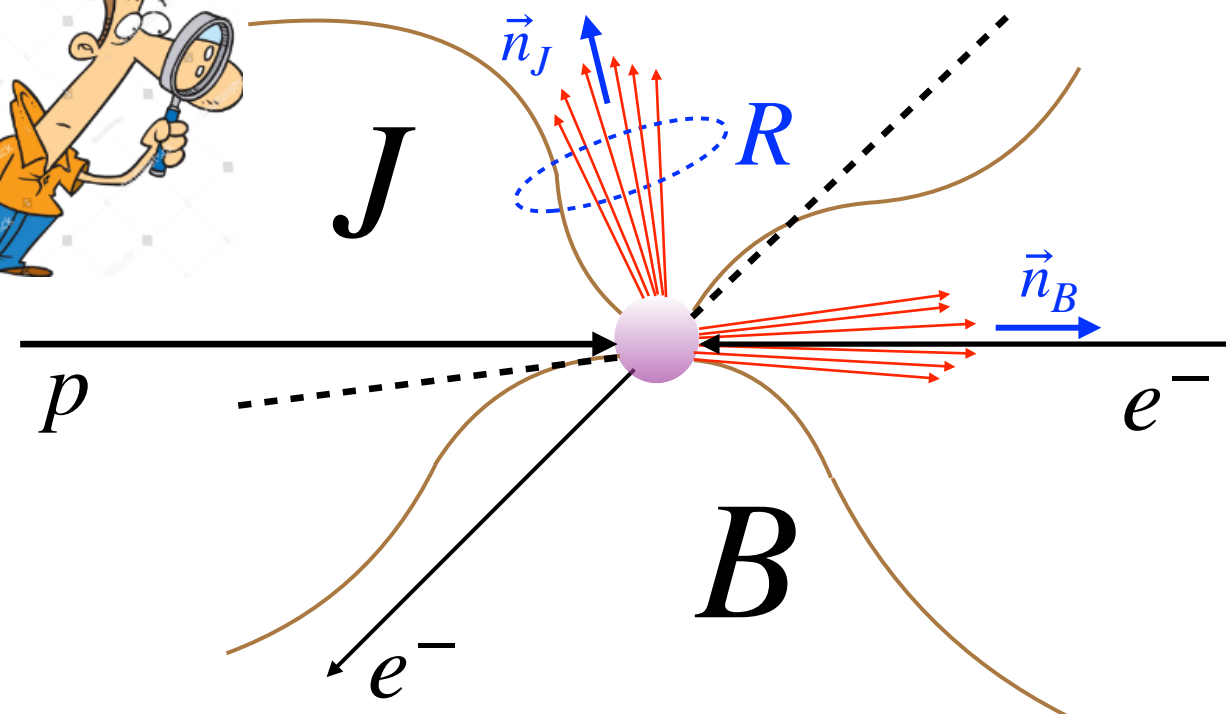


Jet Charge Measurement with 1-Jettiness

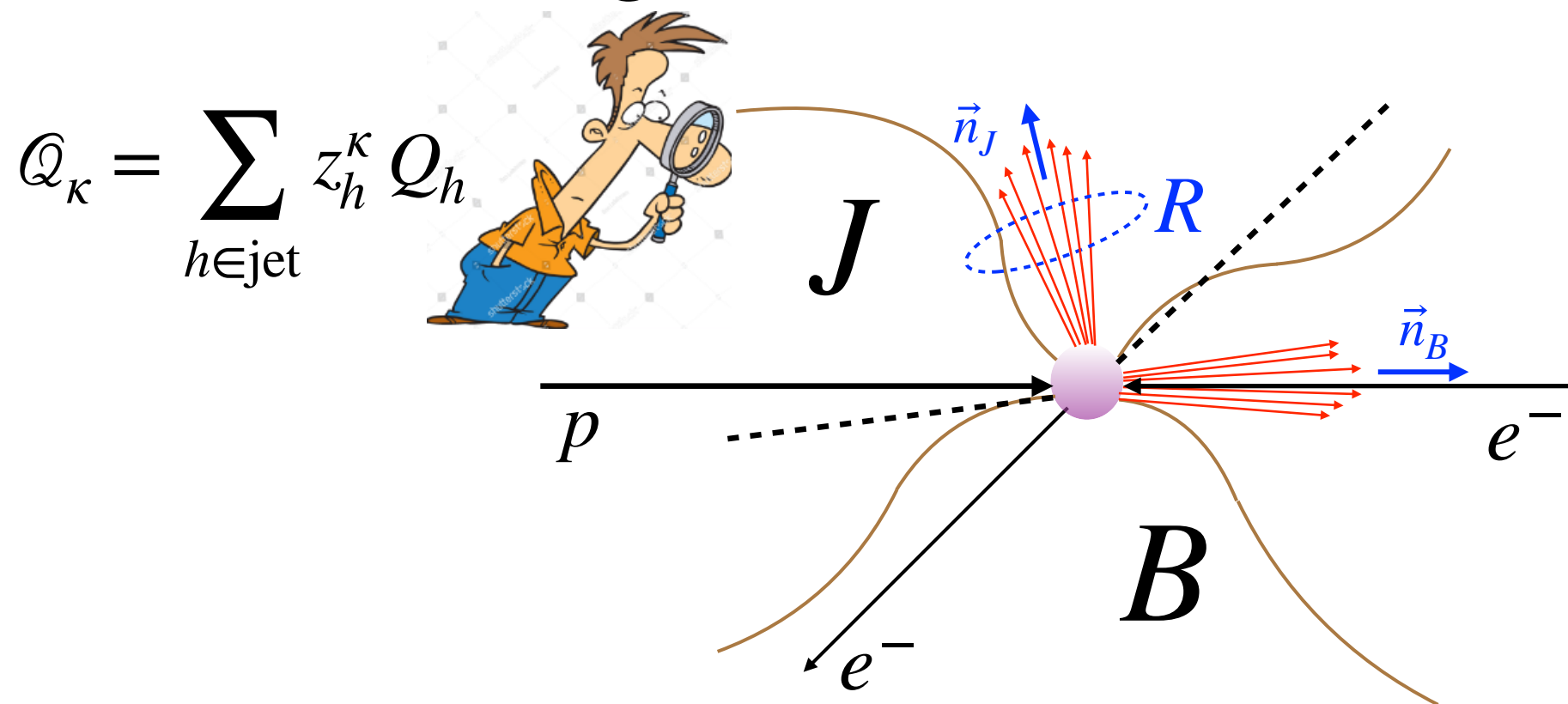
[Chien, SM]

arXiv: 2512.05199 (PRD 2026)

$$Q_\kappa = \sum_{h \in \text{jet}} z_h^\kappa Q_h$$



Jet Charge Measurement with 1-Jettiness



- Factorization formula:

$$d\sigma_{\text{resum}} [\tau_1, P_{J_T}, y_J] \sim H \otimes B \otimes J \otimes S$$

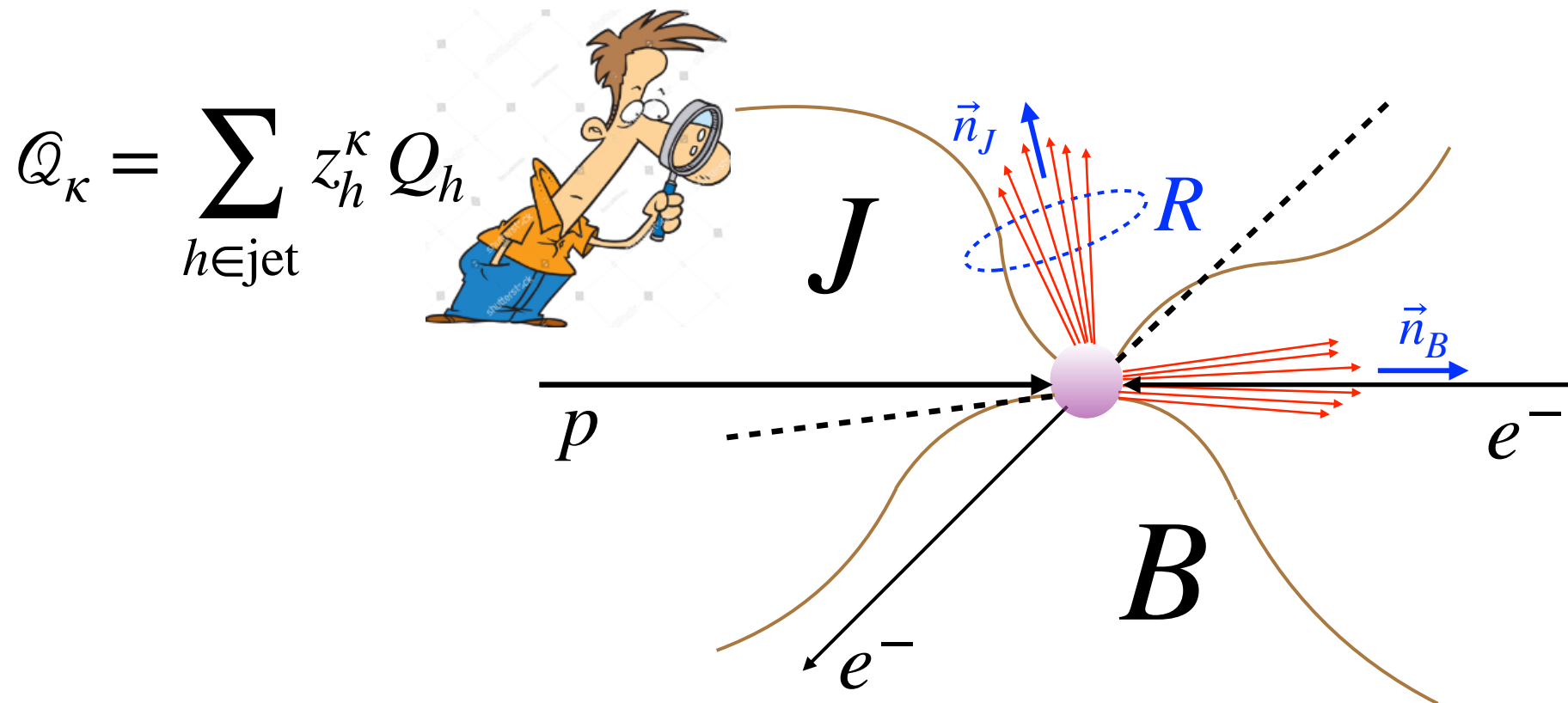
$$B \sim \mathcal{I} \otimes f,$$

“charged jet function”

$$\mathcal{G}(\mathcal{Q}, s)$$

describes evolution of single quark to a jet with charge $\mathcal{Q}$ and jet mass squared s

Jet Charge Measurement with 1-Jettiness



- Factorization formula:

$$\begin{aligned}
 d\sigma_{\text{resum}}[Q, \tau_1, P_{JT}, y_J] &= \sigma_0 H(\xi, \mu; \mu_H) \\
 &\times \int ds_J \int dt_a \mathcal{S}\left(\tau_1 - \frac{t_a}{Q_a} - \frac{s_J}{Q_J}, \mu; \mu_S\right) \\
 &\times \left[\sum_{q_i} L_{q_i} \mathcal{G}^{q_i}(Q, s_J, \mu; \mu_J) B_{q_i}(x_*, t_a, \mu; \mu_B) \right. \\
 &\left. + \sum_{\bar{q}_i} L_{\bar{q}_i} \mathcal{G}^{\bar{q}_i}(Q, s_J, \mu; \mu_J) B_{\bar{q}_i}(x_*, t_a, \mu; \mu_B) \right]
 \end{aligned}$$

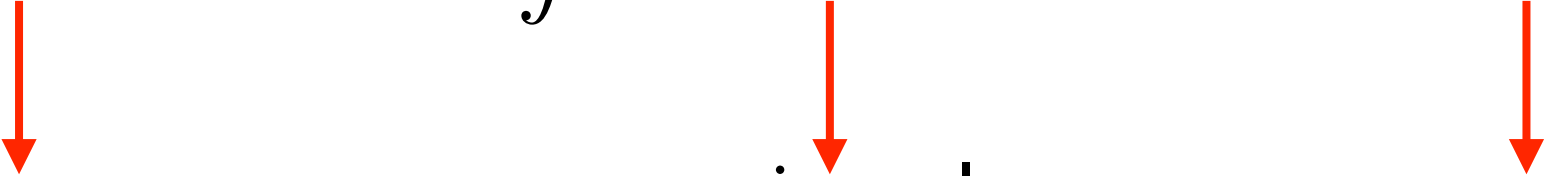


“charged jet function”

- Charged jet function is convoluted with soft function since both contribute to the “jet region mass” which in turn contributes to 1-Jettiness

Charged Jet Function

$$\mathcal{G}^q(\mathcal{Q}, s, \mu) = \int ds' R^q(\mathcal{Q}, s - s') J^q(s', \mu)$$



charged jet function universal non-perturbative function standard jet function

- Must recover standard jet function when integrated over all possible jet charge values (no jet charge measurement):

$$\int d\mathcal{Q} \mathcal{G}^q(\mathcal{Q}, s_J, \mu) = J^q(s_J, \mu)$$

- Implies normalization condition:

$$\int d\mathcal{Q} R^q(\mathcal{Q}, s) = \delta(s)$$

Universality of Charged Jet Function

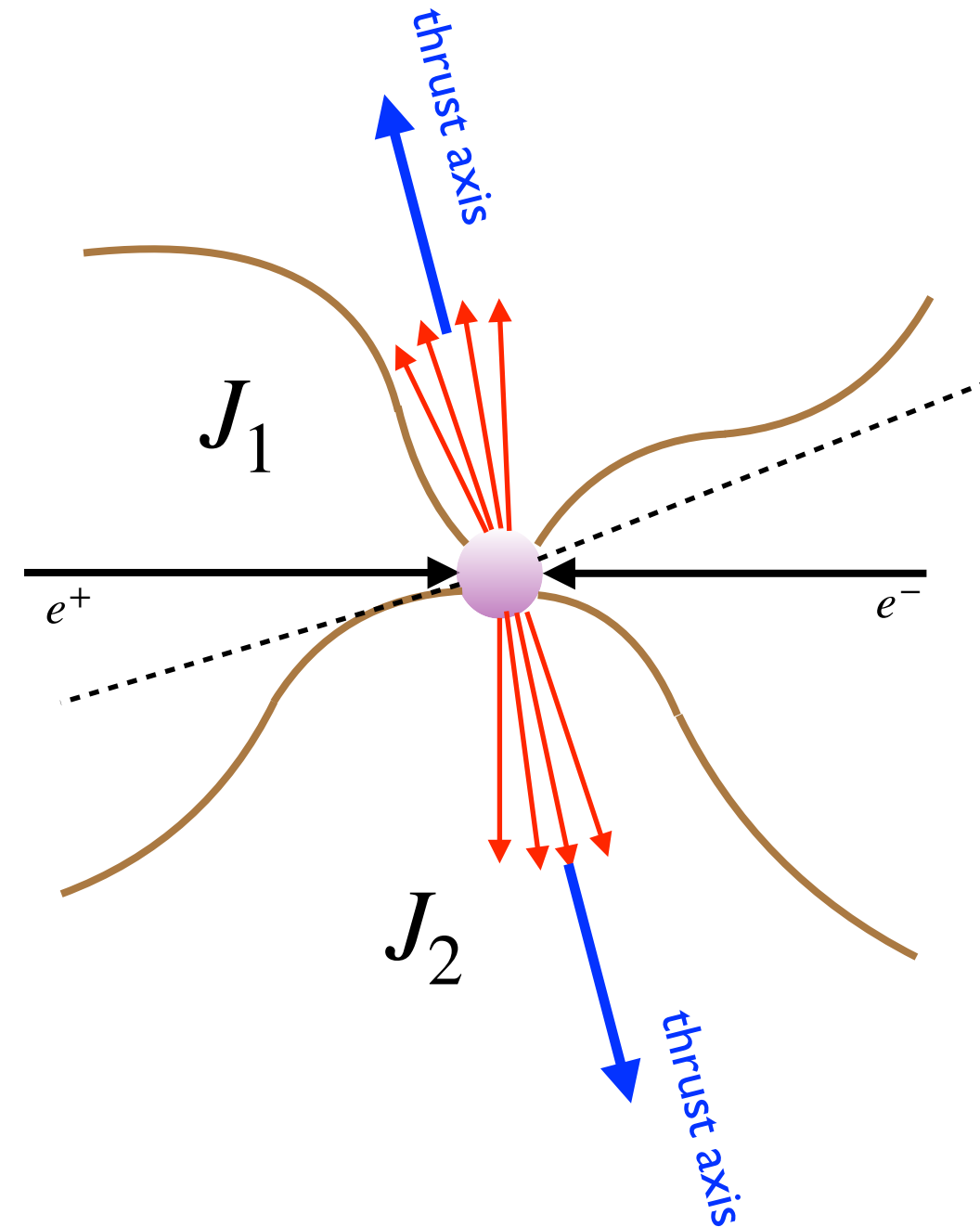
- Universal charged jet function can be extracted from global event shapes at e^+e^- colliders
- Factorization for thrust or 2-jettiness:

$$\frac{d\sigma_{\text{resum}}}{d\tau_2} \sim H \otimes J_1 \otimes J_2 \otimes S$$

measure hemisphere
jet charge

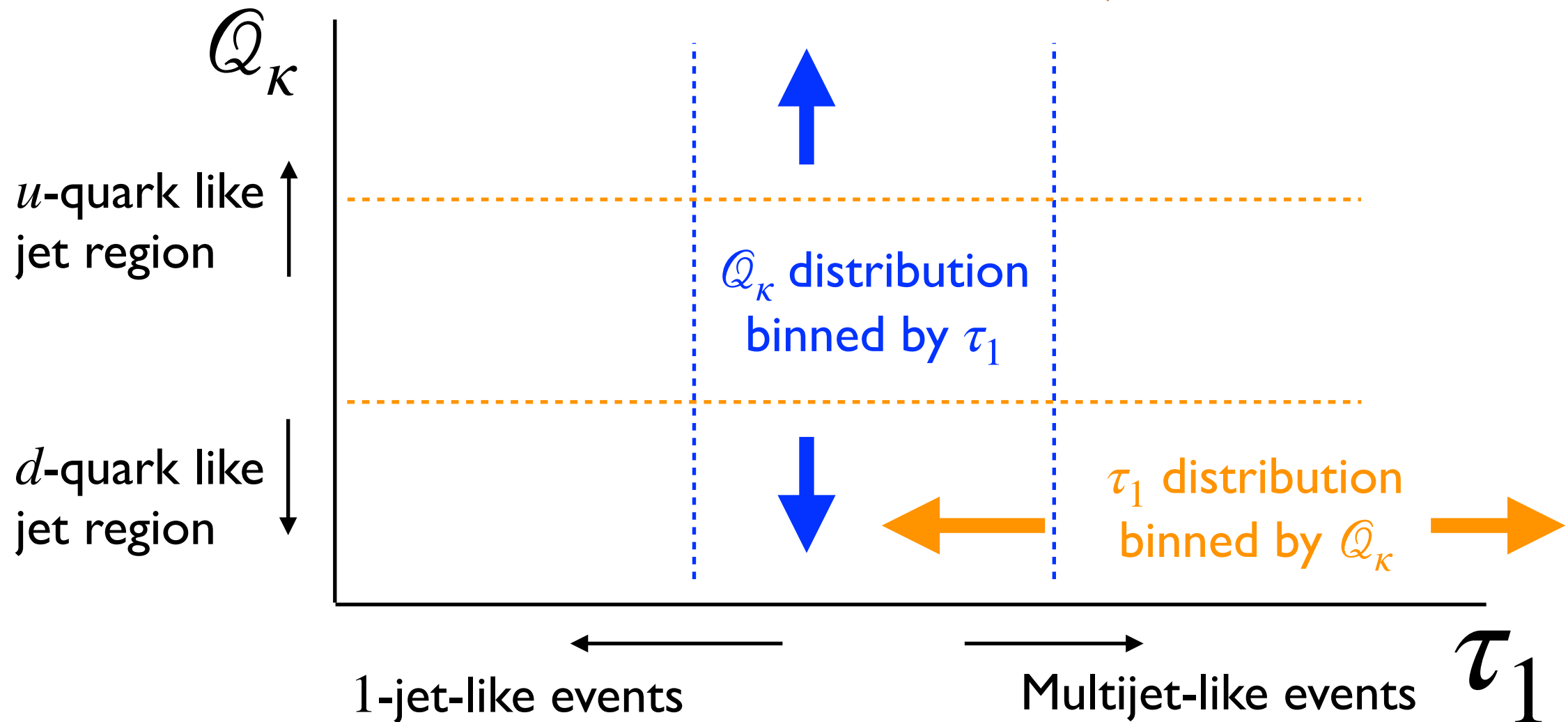
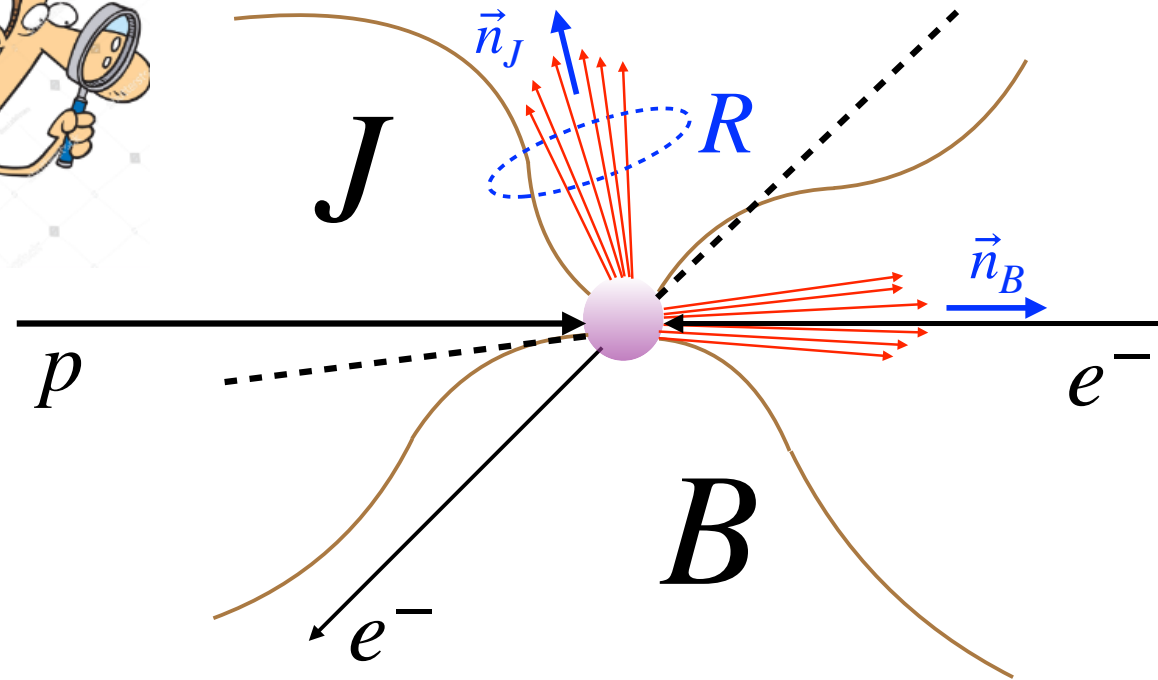
$$\frac{d\sigma_{\text{resum}}}{d\tau_2 dQ} \sim H \otimes \mathcal{G}_1 \otimes J_2 \otimes S$$

same universal charged jet
function as for DIS 1-jettiness



Simultaneously Tracking Charge and Energy Flow

$$Q_\kappa = \sum_{h \in \text{jet}} z_h^\kappa Q_h$$



Probing Hadron Structure and Hadronization

τ_1 distribution
binned by Q_κ

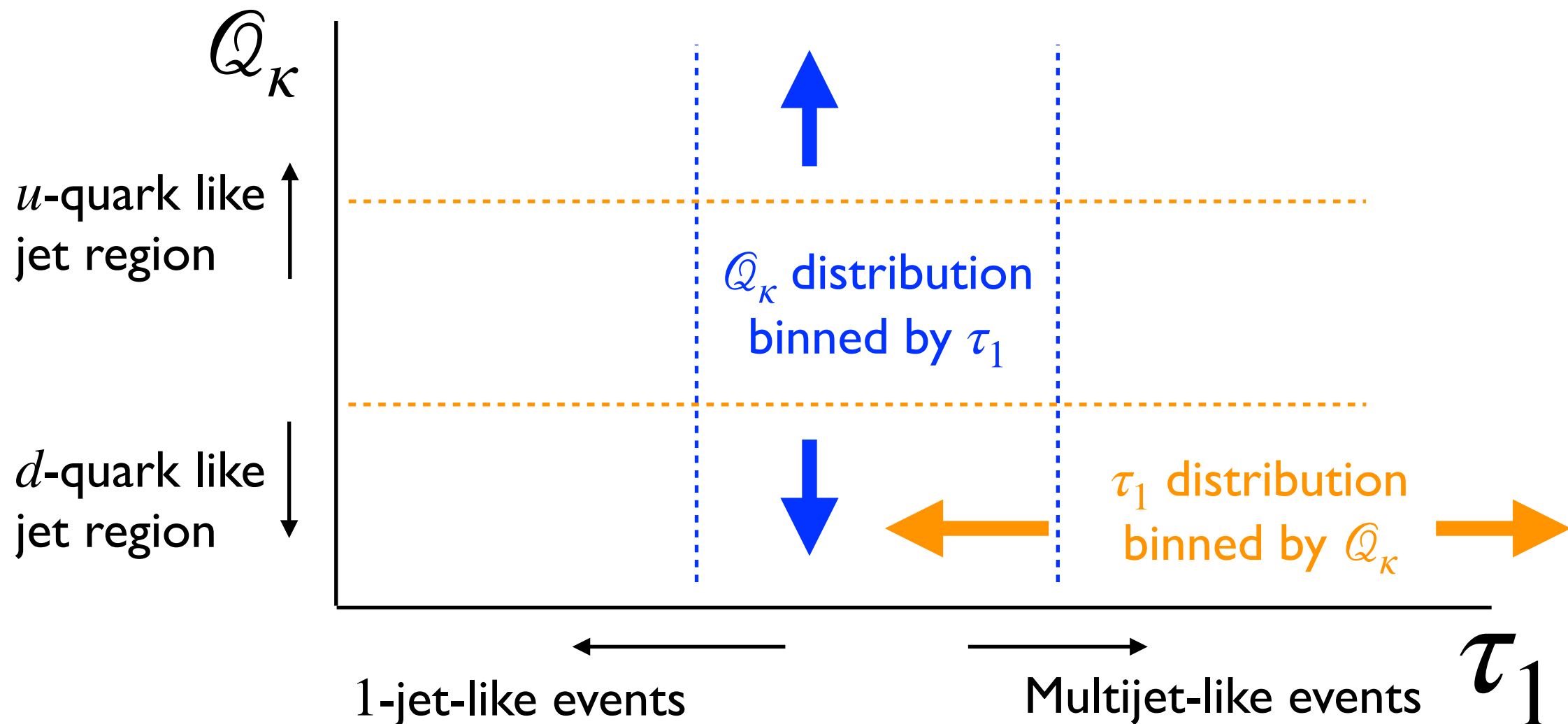


flavor probe of
hadron structure

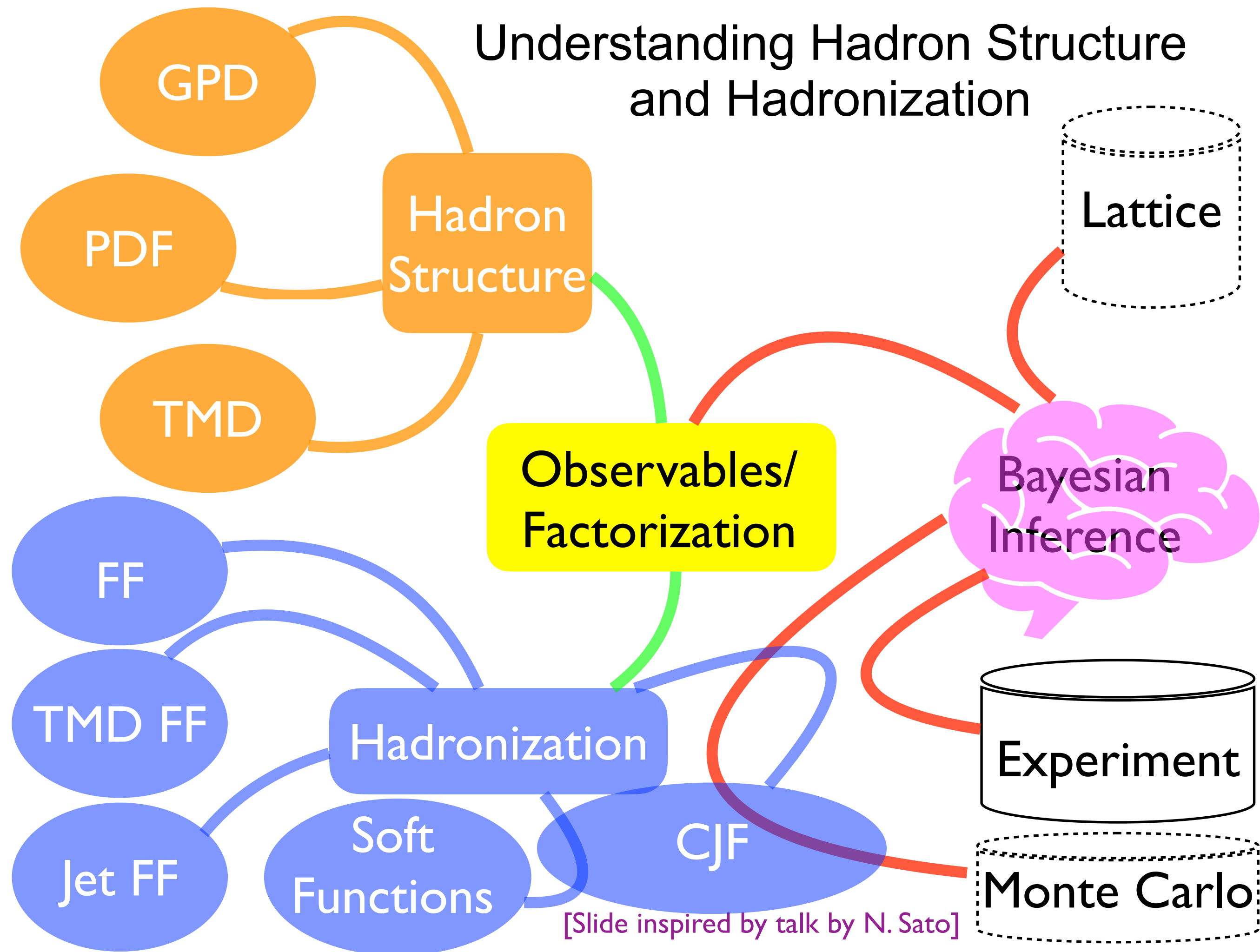
Q_κ distribution
binned by τ_1



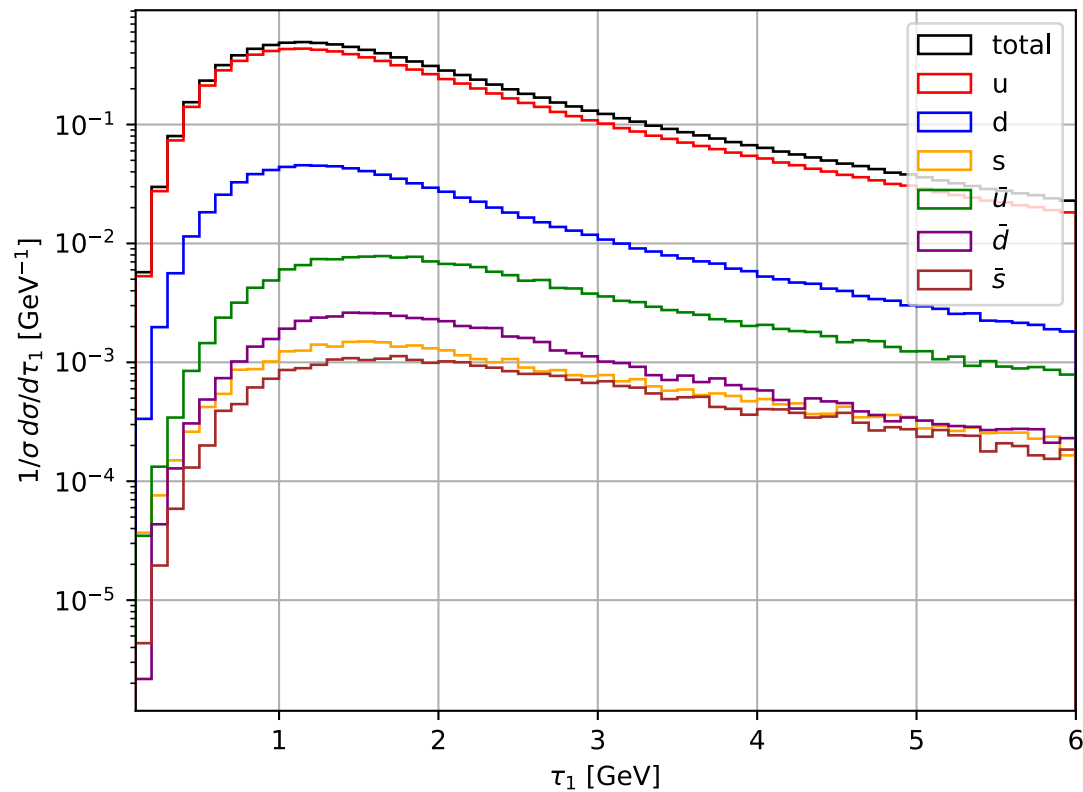
flavor probe of
hadronization



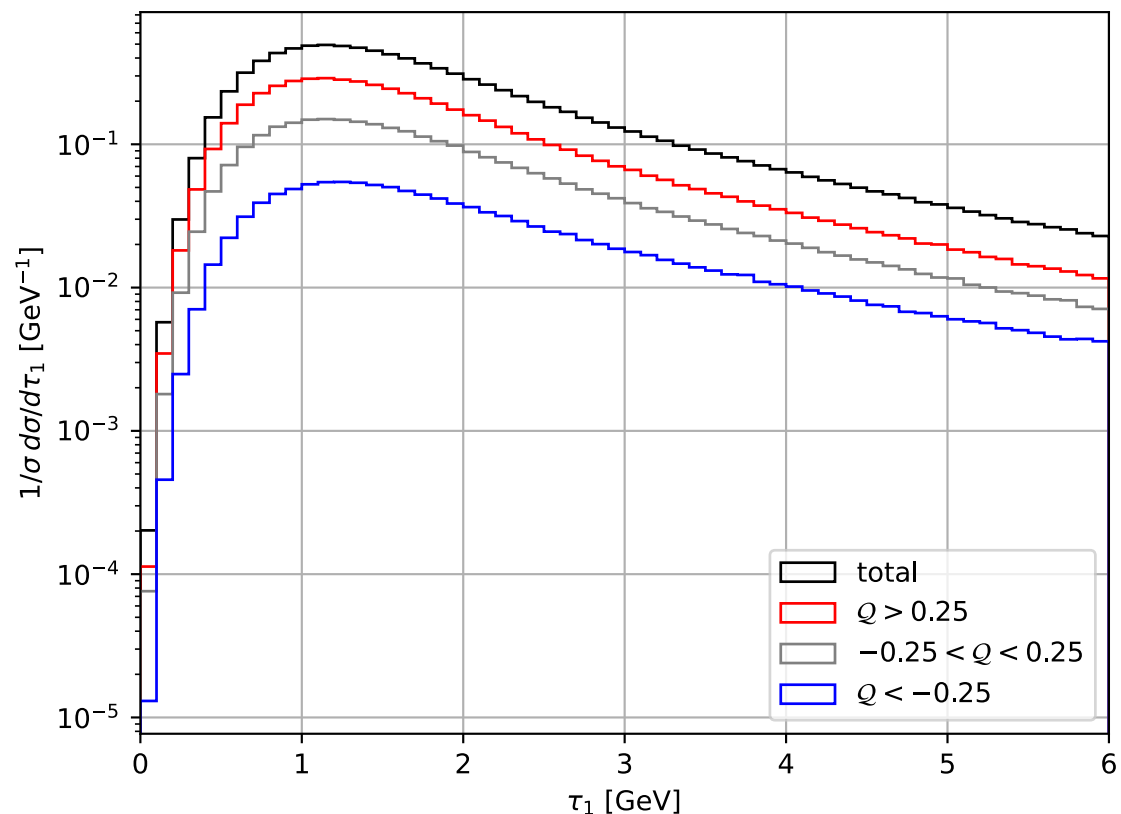
Understanding Hadron Structure and Hadronization



1-Jettiness Spectrum: Pythia Simulations



- Contributions to the 1-Jettiness spectrum from different quark flavors.
- Spectrum is dominated by the u -quark



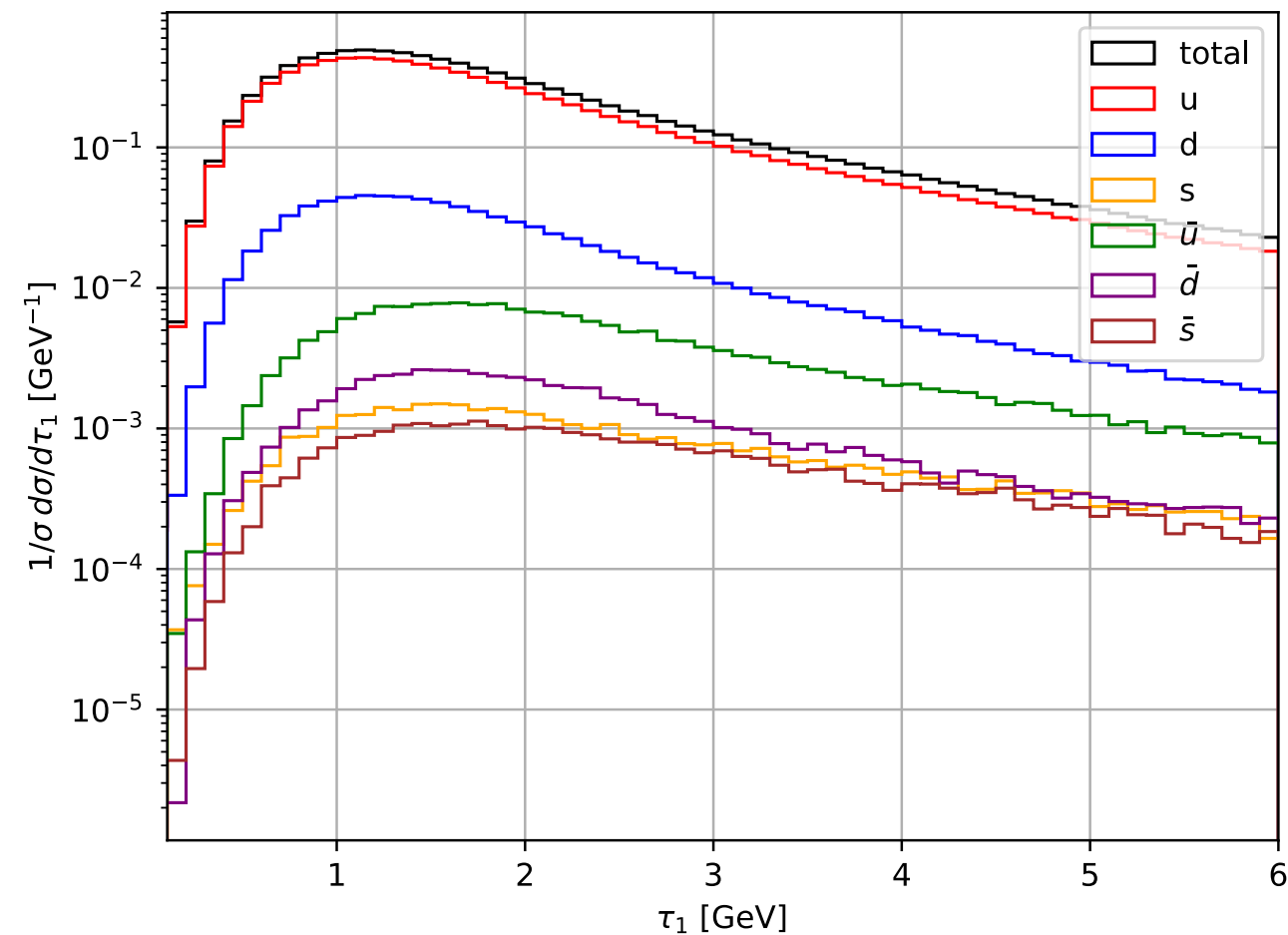
- 1-jettiness spectrum separated by jet charge bins:

$$+ : Q > 0.25$$

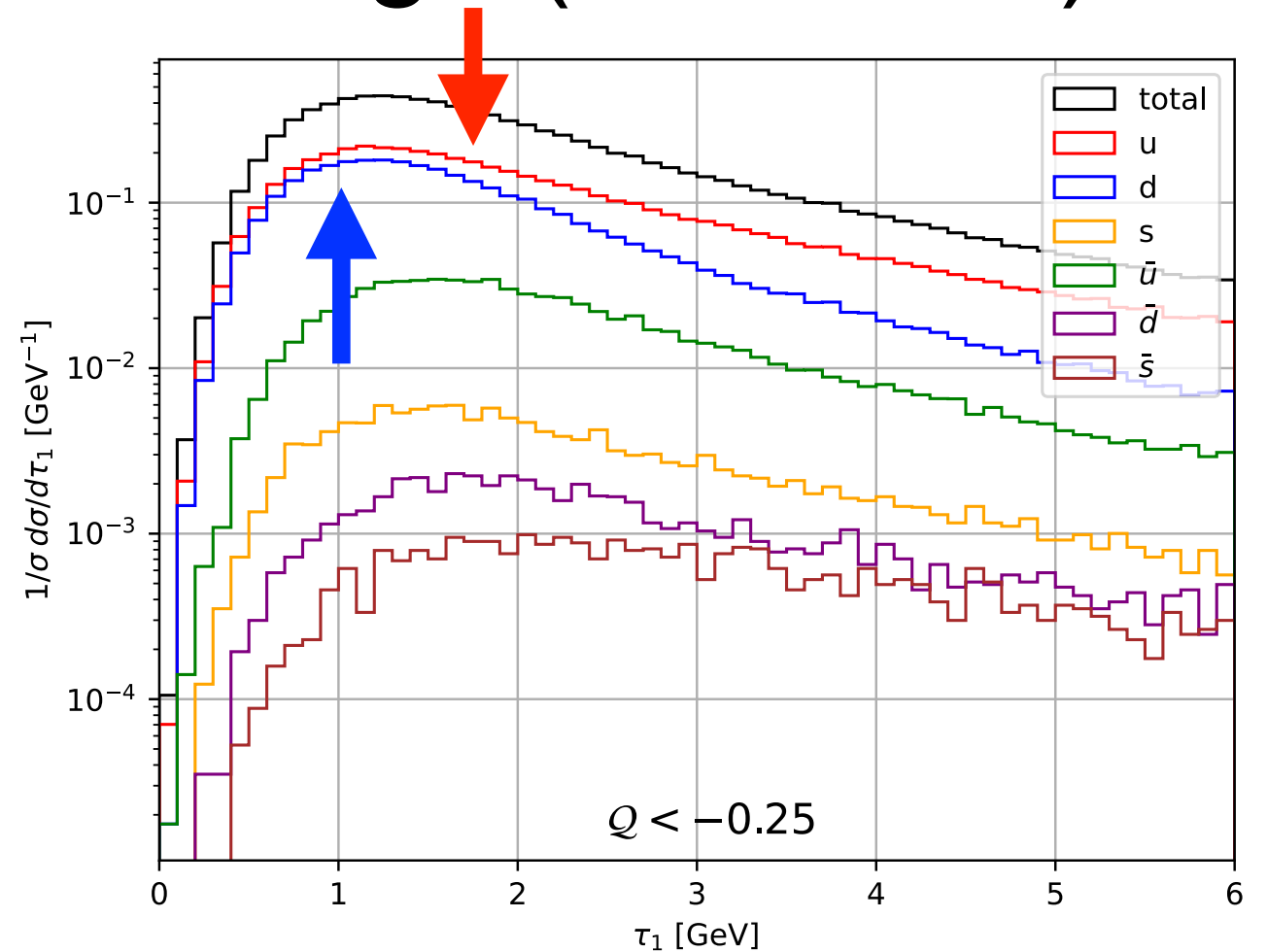
$$0 : -0.25 < Q < 0.25$$

$$- : Q < -0.25$$

1-Jettiness: Negative Jet Charge (Standard) Bin



no jet charge
measurement



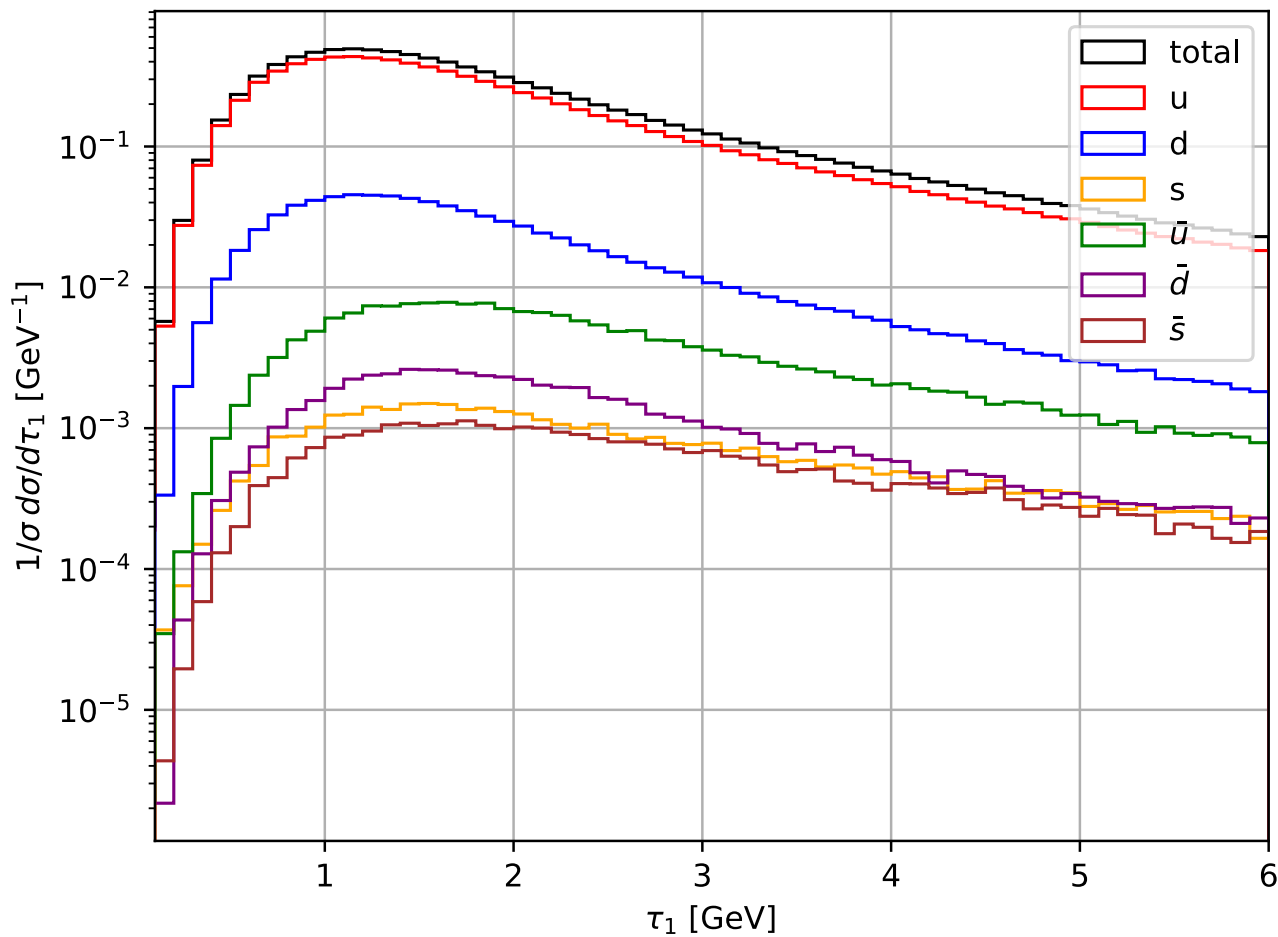
restricted to negative
jet charge bin:

$$Q < -0.25$$

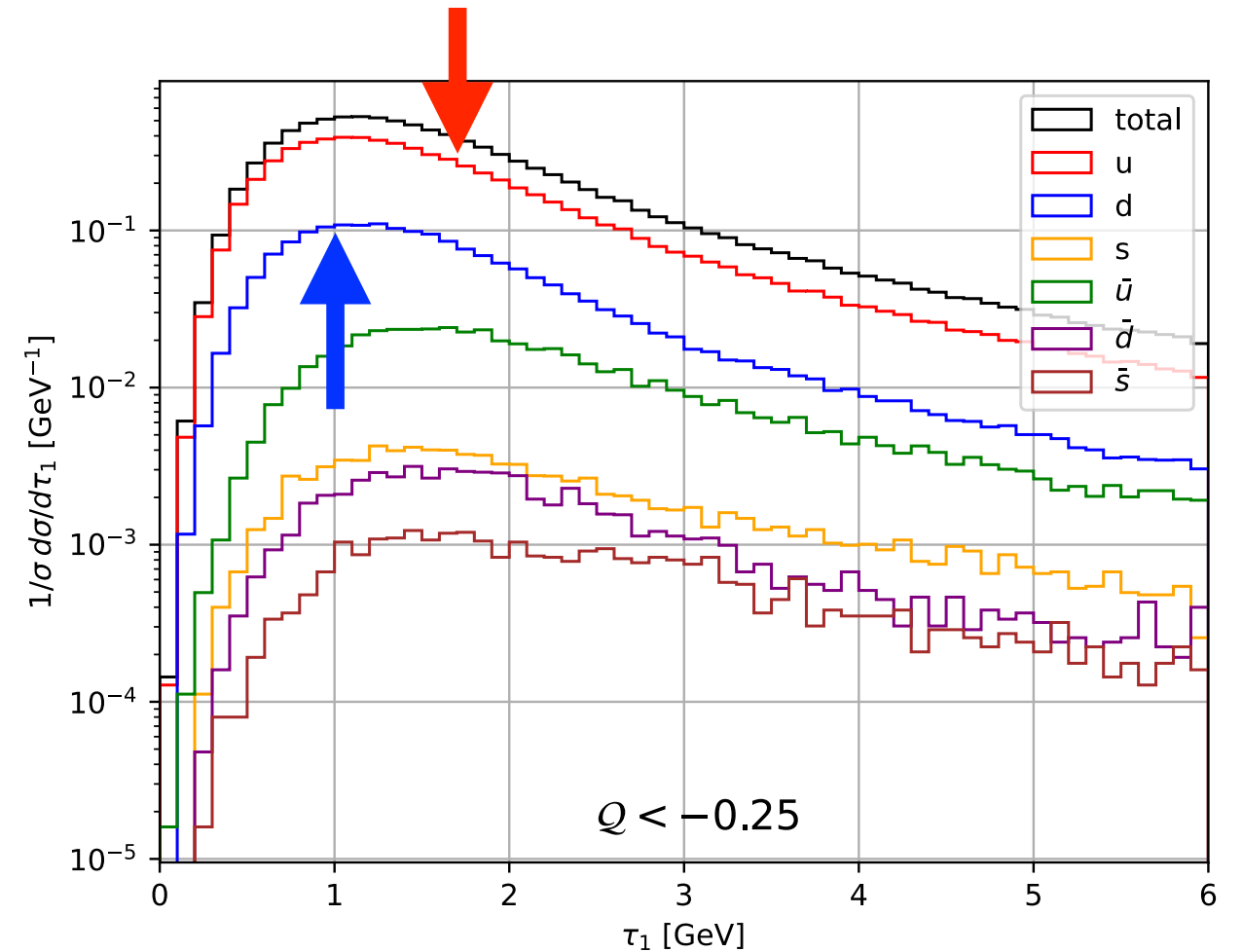
Enhanced sensitivity
to d -quark PDF

- Jet charge binned 1-Jettiness can disentangle PDFs by flavor.

1-Jettiness: Negative Jet Charge (Dynamic) Bin



no jet charge
measurement



restricted to negative
jet charge bin: $Q < -0.25$

- Jet charge binned 1-Jettiness can disentangle PDFs by flavor.

1-Jettiness and Jet Charge as a Probe of Helicity PDFs

- 1-Jettiness distributions of the longitudinal proton spin asymmetry can probe helicity PDFs:

$$d\Delta\sigma_{\text{resum}} [\tau_1, P_{J_T}, y_J] \sim \Delta H \otimes \Delta B \otimes J \otimes \mathcal{S}$$



$$\Delta B \sim \Delta \mathcal{I} \otimes \Delta f$$



helicity PDF

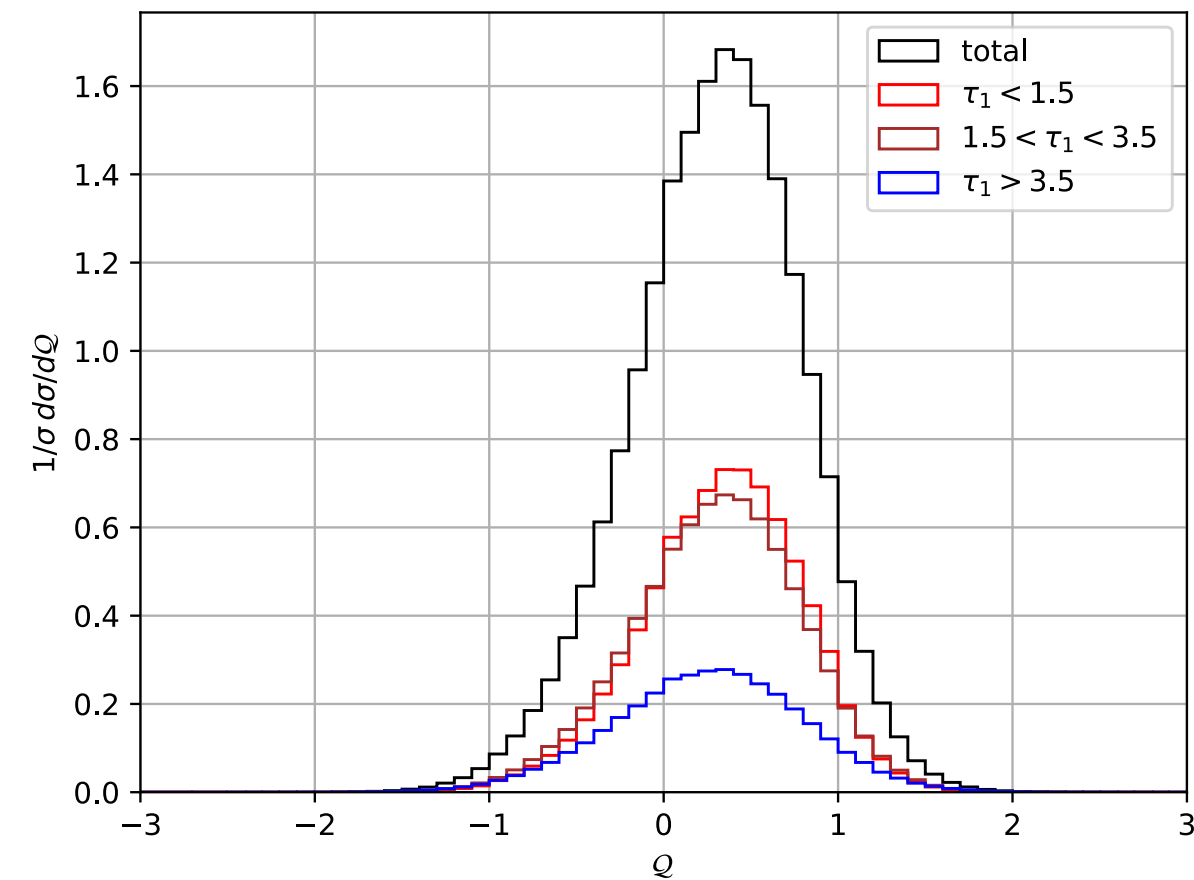
- 1-Jettiness combined with jet charge can be used to disentangle helicity PDFs by flavor:

$$d\Delta\sigma_{\text{resum}} [\tau_1, P_{J_T}, y_J] \sim \Delta H \otimes \Delta B \otimes J \otimes \mathcal{S}$$

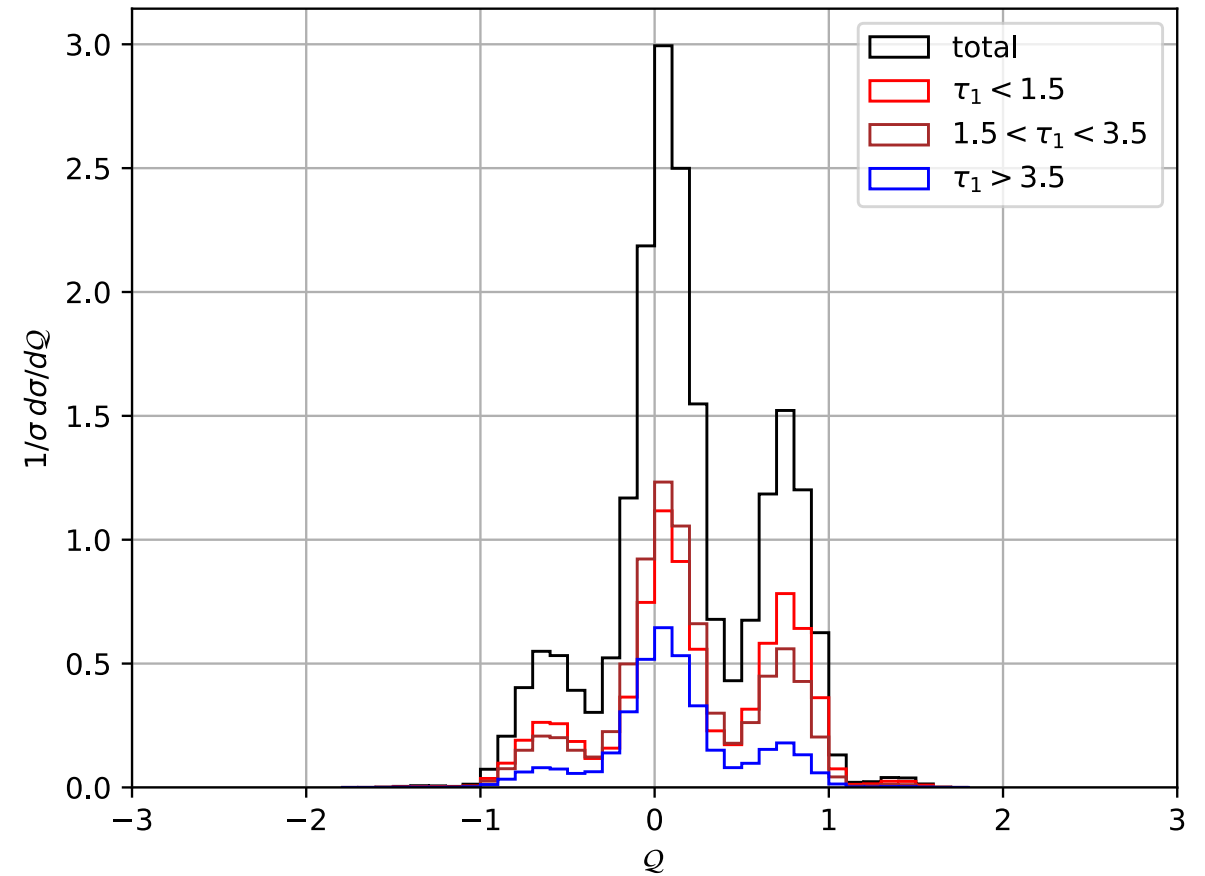


$$d\Delta\sigma_{\text{resum}} [\mathcal{Q}, \tau_1, P_{J_T}, y_J] \sim \Delta H \otimes \Delta B \otimes \mathcal{G} \otimes \mathcal{S}$$

Jet Charge Distribution Binned by 1-Jettiness



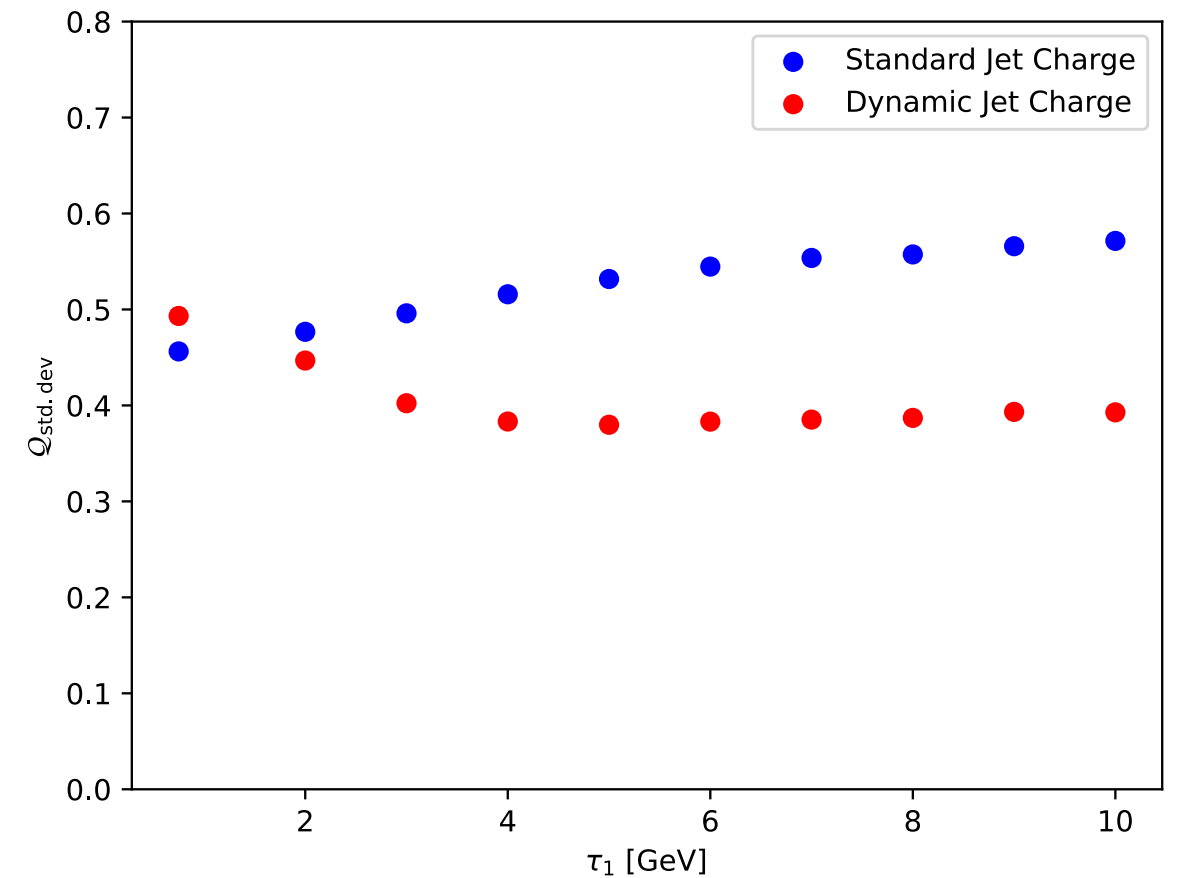
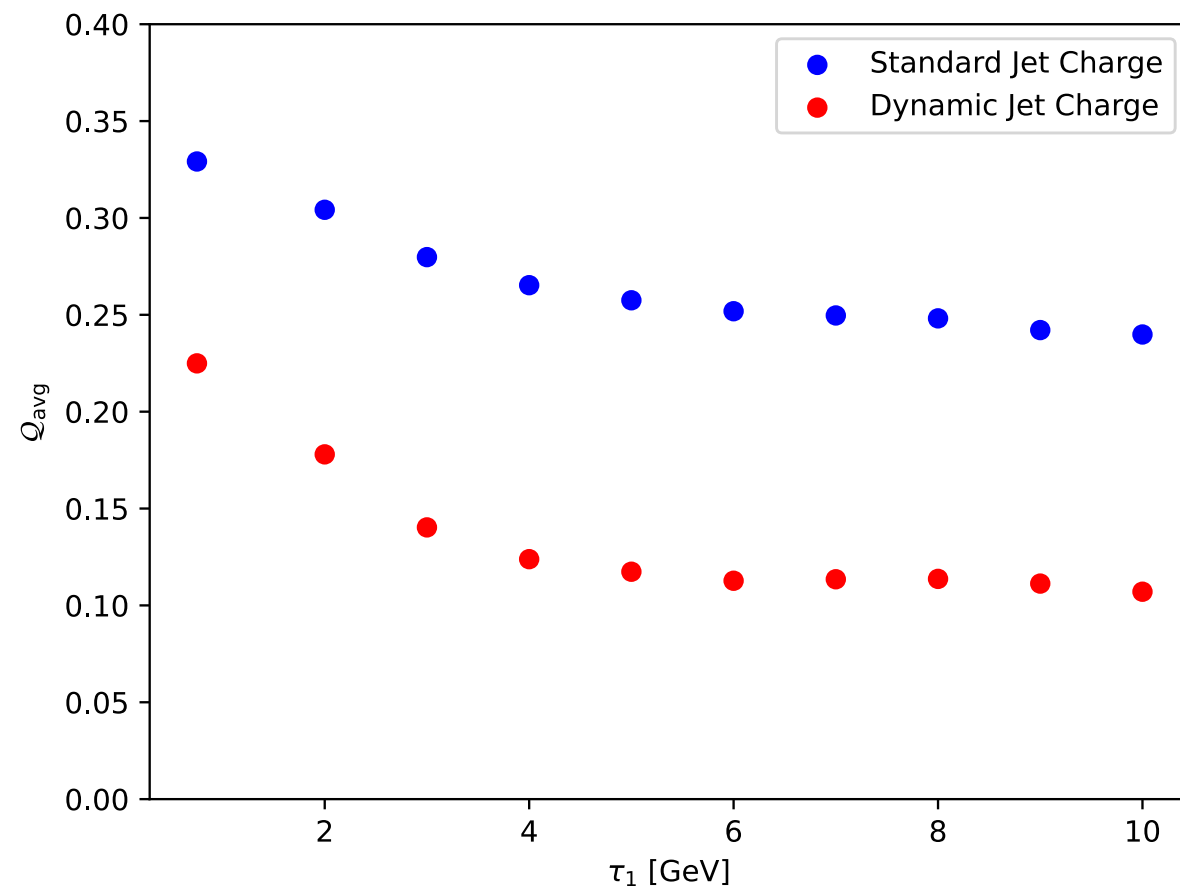
Standard jet charge
distribution binned
by 1-Jettiness



Dynamic jet charge
distribution binned
by 1-Jettiness

- Correlations of jet charge and 1-Jettiness (energy flow) can constrain flavor dynamics in hadronization.

Correlation of Jet Charge with 1-Jettiness



- Correlations of jet charge and 1-Jettiness (energy flow) can constrain flavor dynamics in hadronization.

Conclusions

- Jet based observables provide powerful and complementary probes of hadron structure and hadronization.
- Combining jet observables with jet charge measurements allow for disentangling hadron structure and hadronization by quark flavor.
- We have now also combined jet charge measurements with jet-based global event shapes into a unified factorization framework that will allow high precision studies of the quark flavor dynamics of hadron structure and hadronization at the EIC.