Probing TMDs with groomed jets

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Dijet decorrelation (lepton colliders)/ jet-lepton decorrelation (DIS)

(In progress: YM, D. G-Reyes, I. Scimemi, V. Vaidya, and L. Zoppi)

TMDs with Jets

Proposed observables:

in-jet fragmentation

- TMDFJF (measurement along the jet axis)

  arXiv:1610.06508 (R. Bain, YM, T. Mehen)

- JTMDFF (measurements along the winner-take-all axis)

  arXiv:1612.04817 (D. Neill, I. Scimemi, W. J. Waalewijn)

  arXiv:1810.12915 (D. Neill, A. Papaefstathiou, W. J. Waalewijn, L. Zoppi)

- siTMDFJF (semi-inclusive)

  arXiv:1705.08443 (Z-B. Kang, X. Liu, F. Ringer, H. Xing)

  arXiv:1707.00913 (Z-B. Kang, A. Prokudin, F. Ringer, F. Yuan)

- gTMDFJF (groomed jets)

  arXiv:1712.07653 (YM, D. Neill, and V. Vaidya)

  arXiv:1807.09805 (YM and V. Vaidya)

jet recoil

- TMDJF

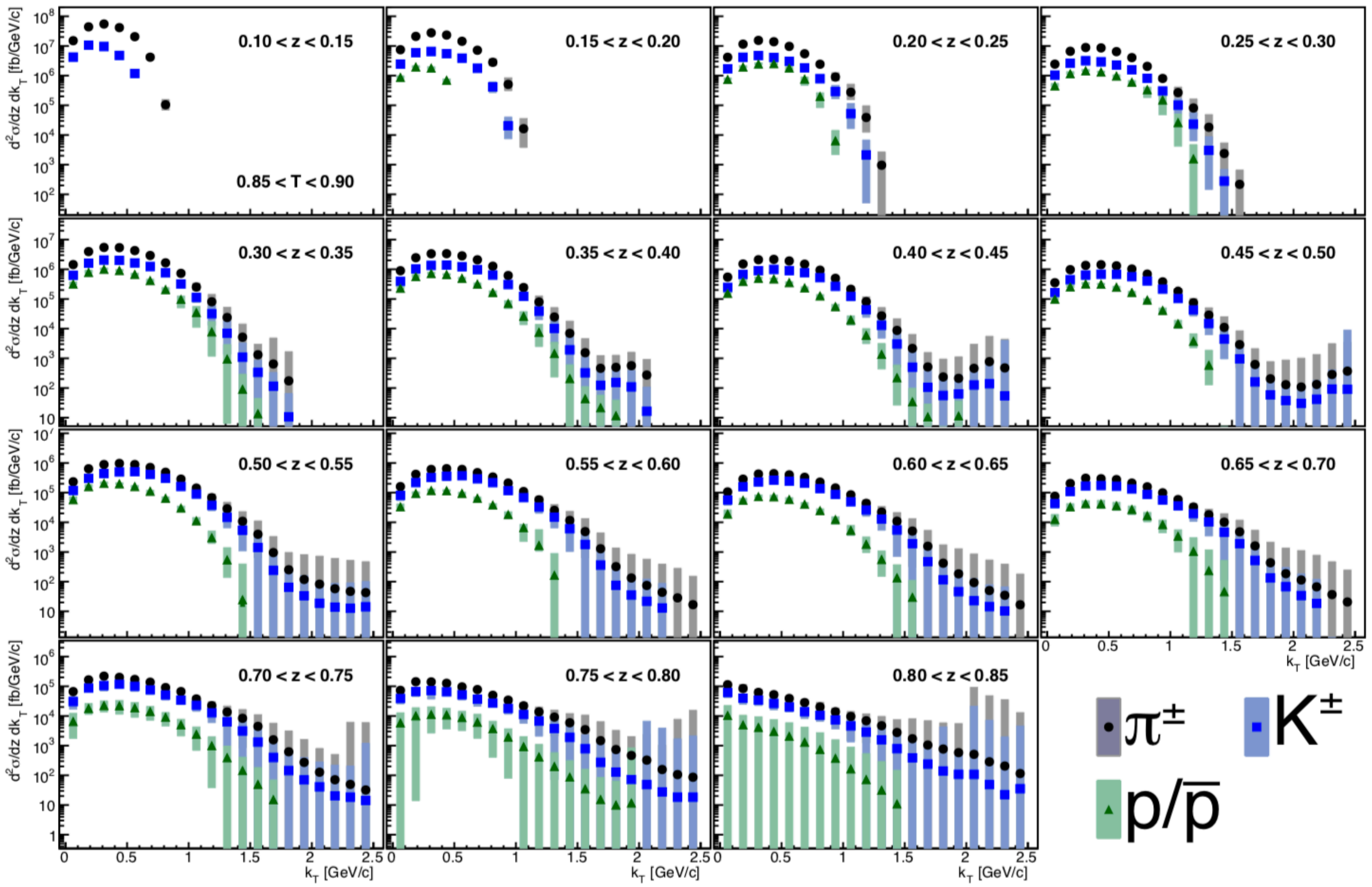
  arXiv:1807.07573 (D. Gutierrez-Reyes, I. Scimemi, W. J. Waalewijn, L. Zoppi)

  arXiv:1812.07549 (M. G.A. Buffing, Z-B. Kang, K. Lee, X. Liu

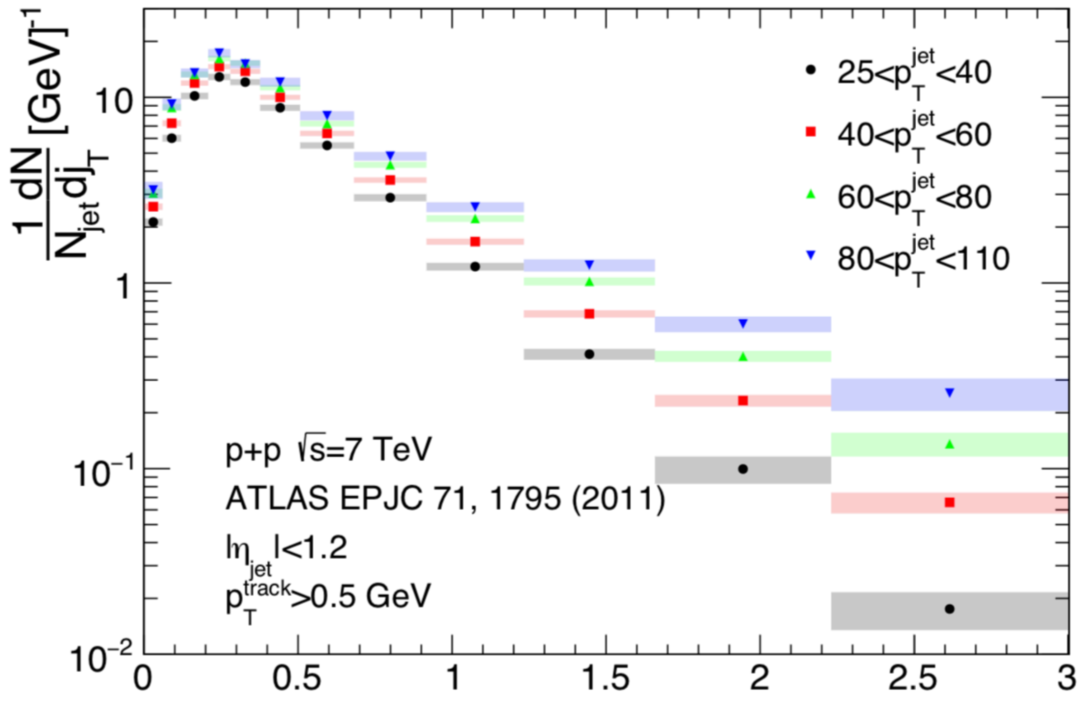
TMDs with Jets

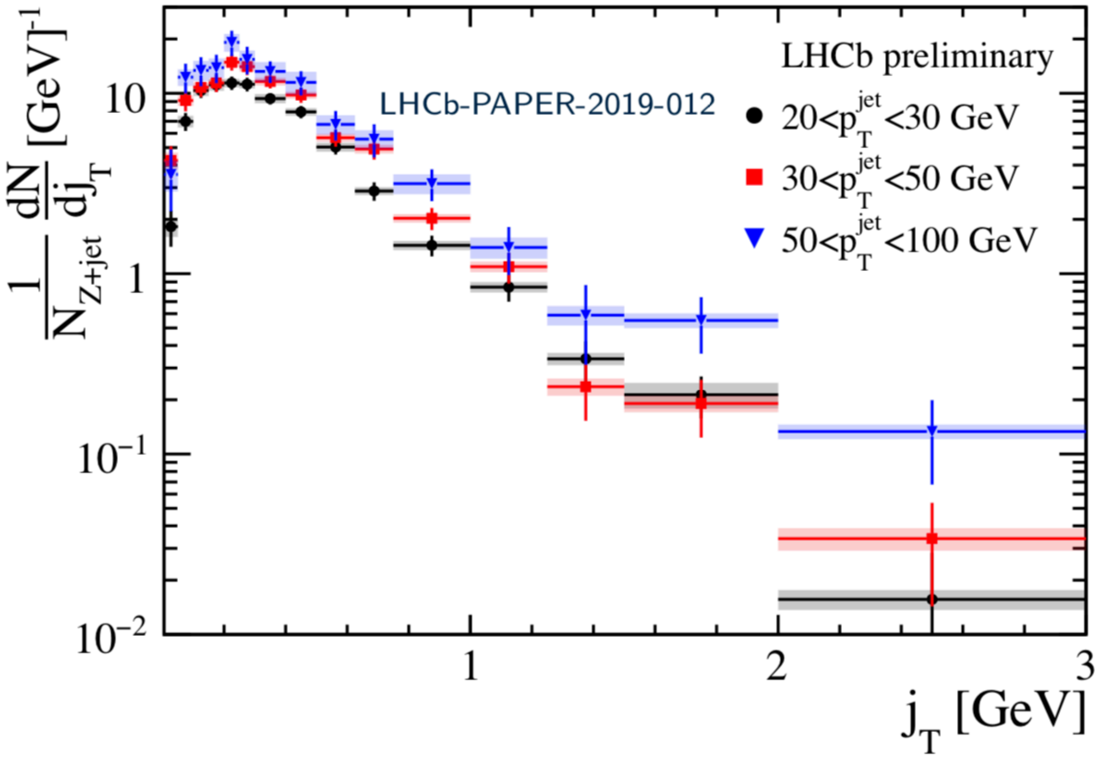
Measured observables:

Belle preliminary (arXiv: 1902.01552)



See also:
arXiv:1708.07080
Phys. Rev. D 97, 032004





TMDs with Jets

Drell-Yan:

$$d\sigma(b) \sim \tilde{S}_2^{\perp}(b;\mu,\nu) \times \tilde{B}_{i/h_1}^{\perp}(b;\mu,\nu) \times \tilde{B}_{j/h_2}^{\perp}(b;\mu,\nu)$$

TMDPDFs: $\tilde{F}_{i/h}(b;\mu,\nu) = \sqrt{\tilde{S}_2^{\perp}(b;\mu,\nu)} \times \tilde{B}_{i/h}^{\perp}(b;\mu,\nu)$

Three dimensional momentum distribution of partons inside the proton.

SIDIS:

$$d\sigma(b) \sim \tilde{S}_2^{\perp}(b;\mu,\nu) \times \tilde{B}_{i/h_1}^{\perp}(b;\mu,\nu) \times \tilde{\mathcal{D}}_{j/h_2}^{\perp}(b;\mu,\nu)$$

see talk by: Yong Zhao

TMDs with Jets

Drell-Yan:

$$d\sigma(b) \sim \boxed{\tilde{S}_2^{\perp}(b;\mu,\nu)} \times \tilde{B}_{i/h_1}^{\perp}(b;\mu,\nu) \times \tilde{B}_{j/h_2}^{\perp}(b;\mu,\nu)$$

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Three dimensional momentum distribution of partons inside the proton.

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Non-perturbative effects: what is universal?

TMD-FF:

$$\tilde{D}^{\perp}_{i/h}(z_h, b) = \boxed{\sqrt{\tilde{S}^{\perp}_{2}(b)}} \times \boxed{\tilde{\mathcal{D}}^{\perp}_{i/h}(z_h, b)}$$

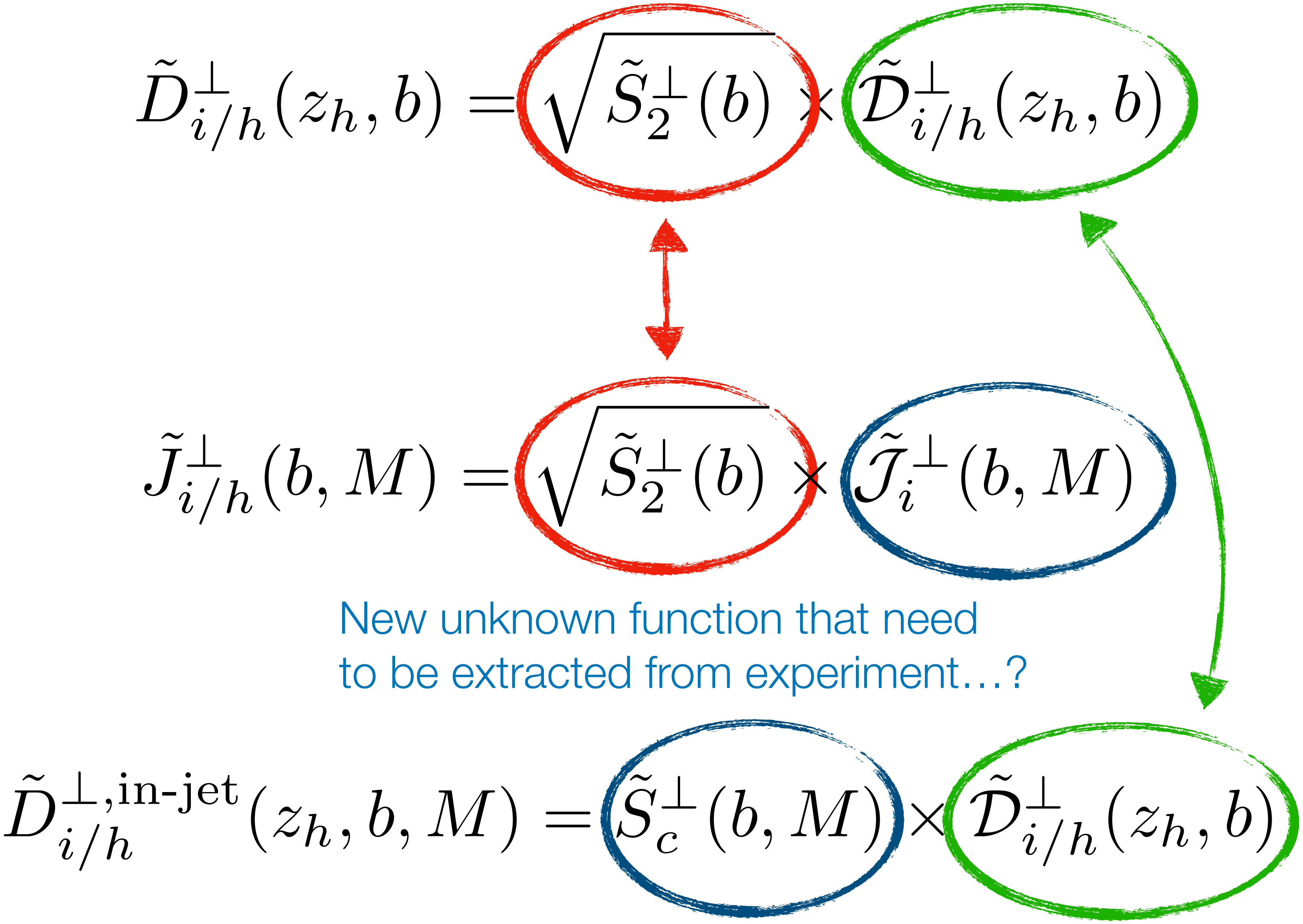
TMD-JF:
(narrow [R<<1] jet,
groomed jet,
WTA analysis)

$$\tilde{J}^{\perp}_{i/h}(b, M) = \boxed{\sqrt{\tilde{S}^{\perp}_{2}(b)}} \times \tilde{\mathcal{J}}^{\perp}_{i}(b, M)$$

in-jet TMD-FF:

$$\tilde{D}^{\perp,\text{in-jet}}_{i/h}(z_h, b, M) = \tilde{S}^{\perp}_{c}(b, M) \times \boxed{\tilde{\mathcal{D}}^{\perp}_{i/h}(z_h, b)}$$

Non-perturbative effects: what is universal?



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$$\tilde{J}^{\perp}_{i/h}(b, M) = \sqrt{\tilde{S}^{\perp}_2(b)} \times \tilde{\mathcal{J}}^{\perp}_{i}(b, M)$$

New unknown function that need to be extracted from experiment…?

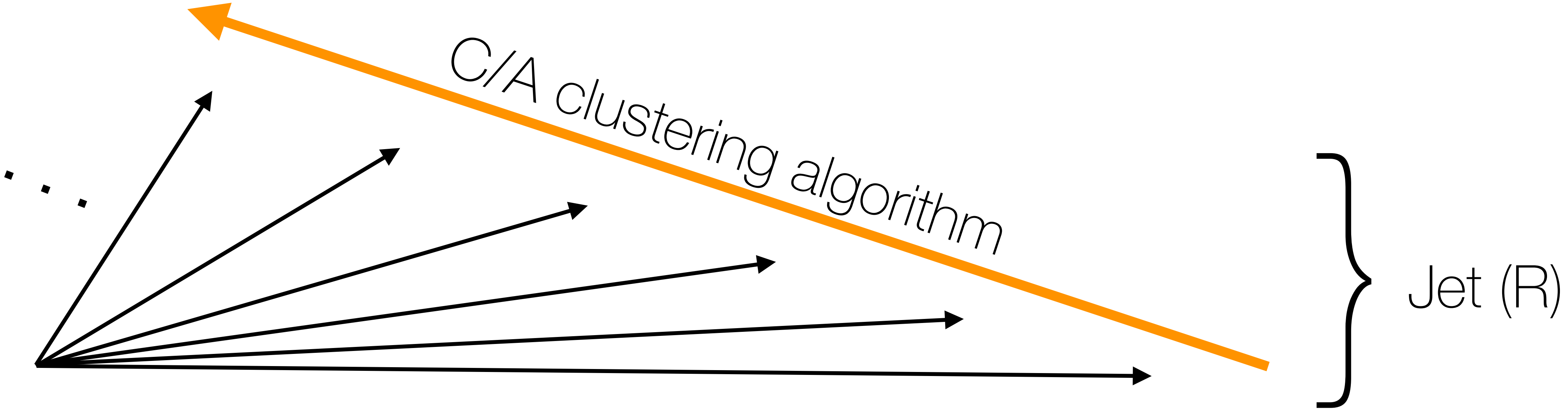
in-jet TMD-FF:

$$\tilde{D}^{\perp,\text{in-jet}}_{i/h}(z_h, b, M) = \tilde{S}^{\perp}_c(b, M) \times \tilde{\mathcal{D}}^{\perp}_{i/h}(z_h, b)$$

In this talk

- Groomed Jets: soft-drop
- Dijet de-correlation in e+e-
  - Hadronization effects - Pythia simulations
  - g-Jet mass cutoff
  - Modes, factorization, and resummation

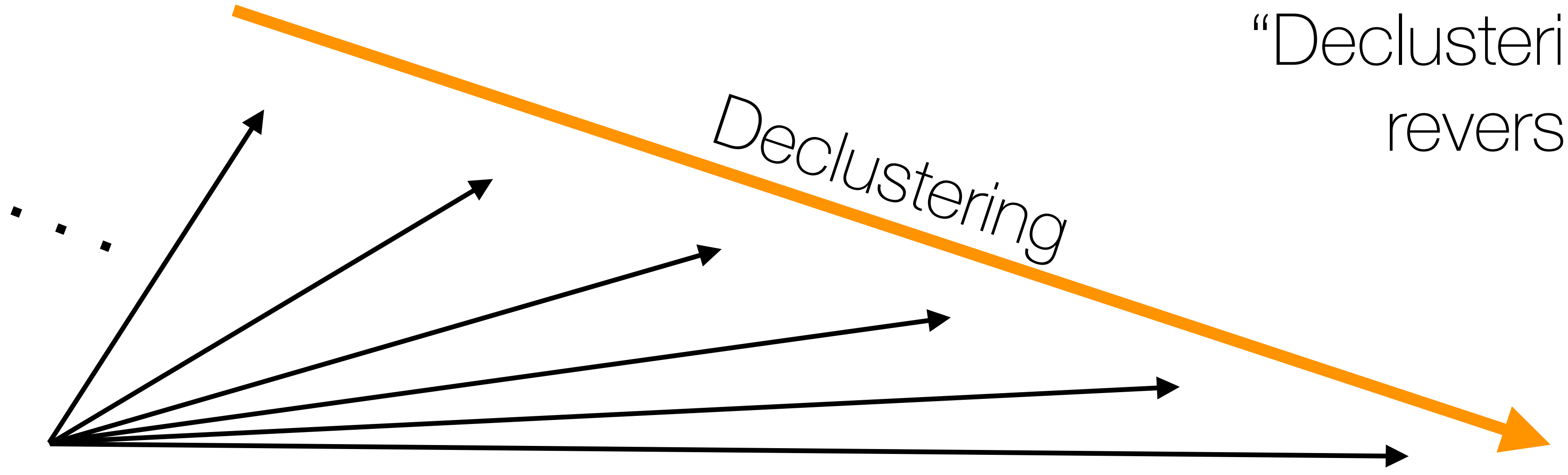
Grooming algorithm: soft-drop



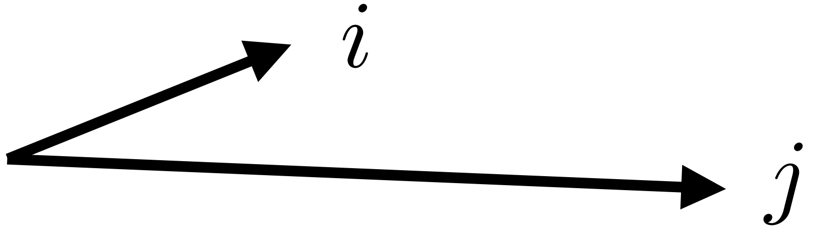
- The algorithm is imposed **only** on the jet constituents
- Record clustering history in each step
- Particles closer in angle get clustered first

For details on soft-drop see: **arXiv:1402.2657** A. J. Larkoski, S. Marzani, G. Soyez, and J. Thaler

Grooming algorithm: soft-drop



“Declustering” with the reverse order:



$$\frac{\min\{E_i, E_j\}}{E_i + E_j} > z_{\mathrm{cut}} \left(\frac{\theta_{ij}}{R}\right)^{\beta}$$

In this talk: $\beta = 0$

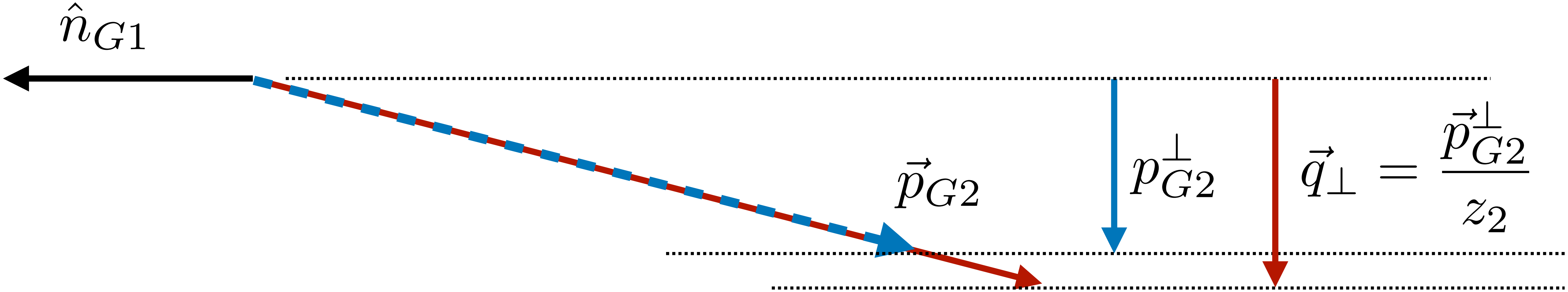
True
Stop. Remaining particles consist groomed jet

False
Drop the softer of the two branchings

Dijet de-correlation (work in progress)

jet + jet
jet + hadron (out)

$$Q \gg Q z_{cut} \gg q_\perp, \quad R \sim 1$$

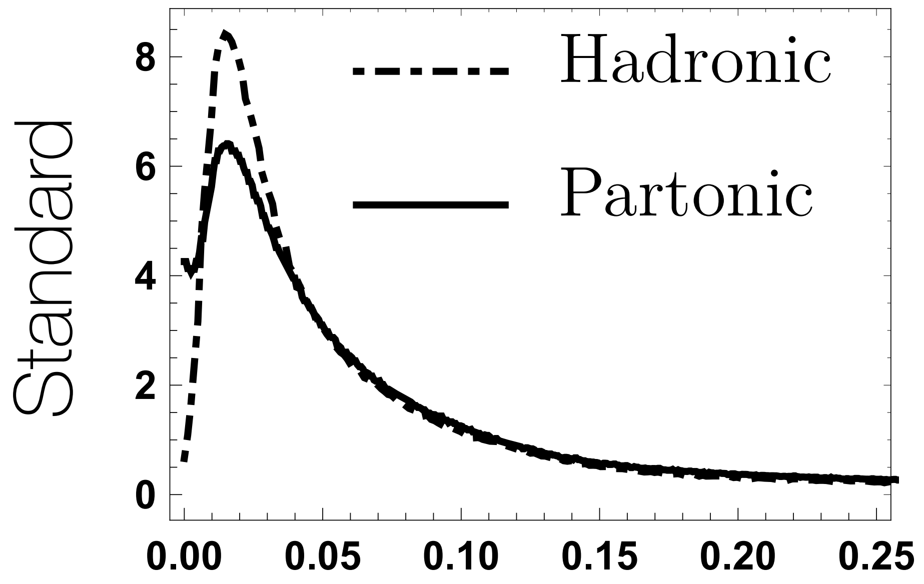


$$\theta = \frac{2q_\perp}{Q} \qquad z_i = \frac{2E_{Gi}}{Q}$$

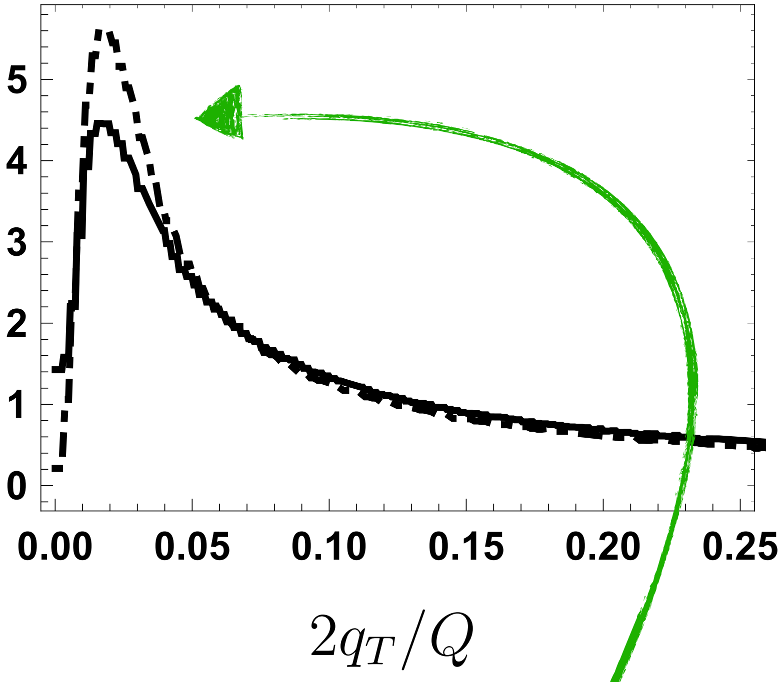
Simulations (Pythia 8)

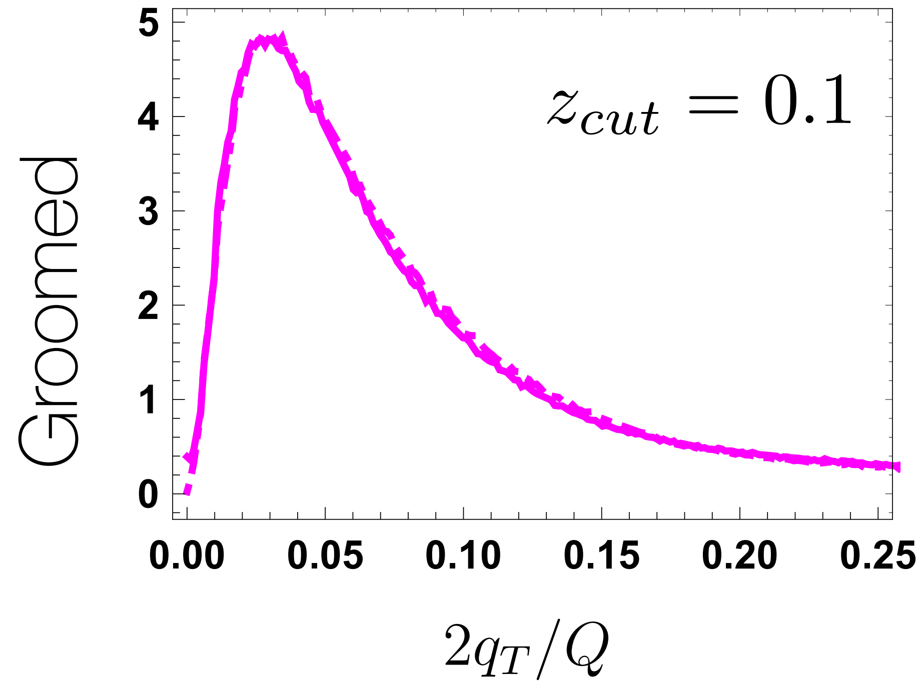
Groomed Jet Axis (GJA) - Hadronization Effects

$R = 1., \quad Q = 100 \text{ GeV}$



$R = 0.5, \quad Q = 100 \text{ GeV}$

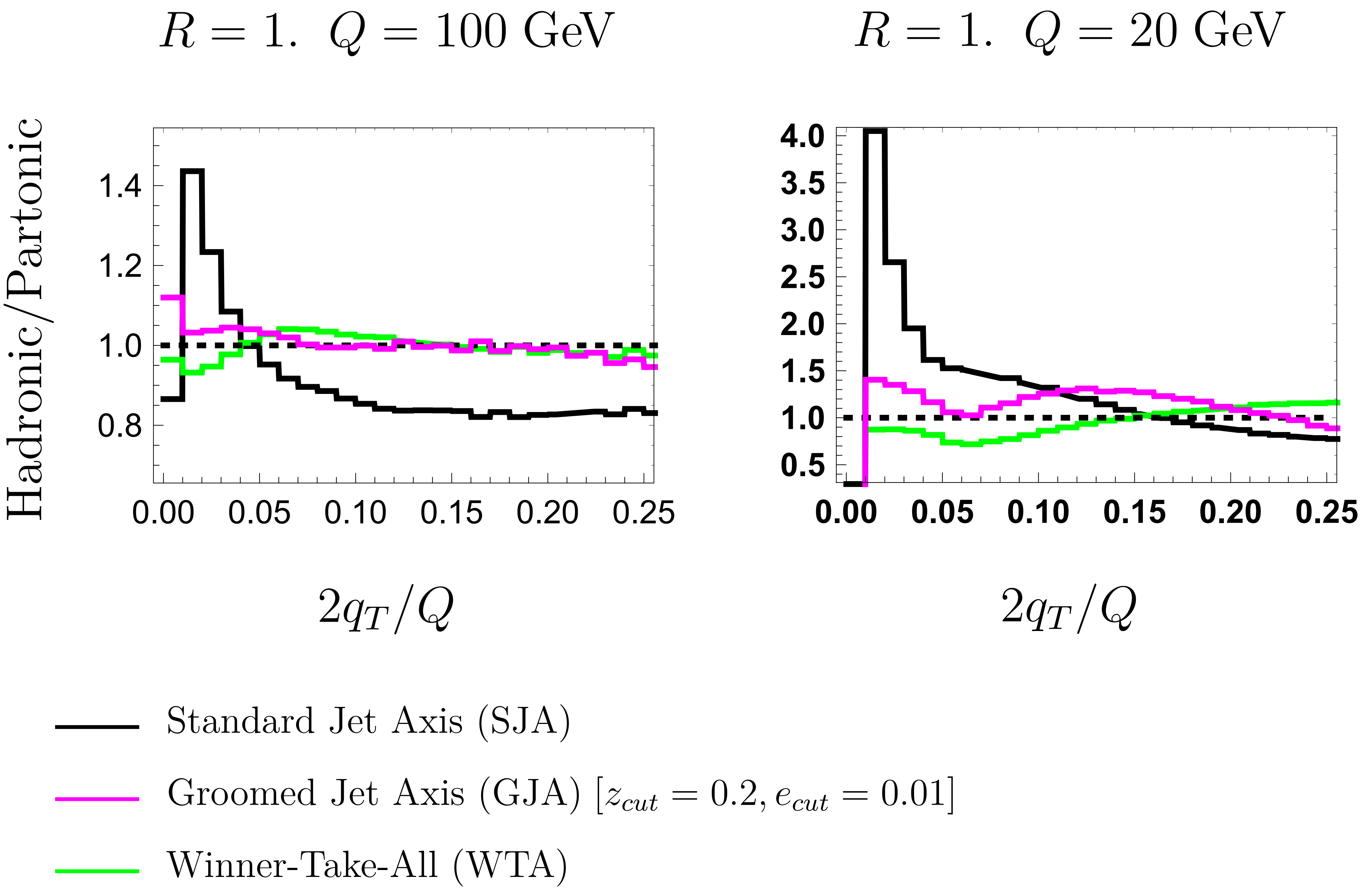




Small hadronization effects
(up to normalization)

Smaller jet radius does NOT fix the problem

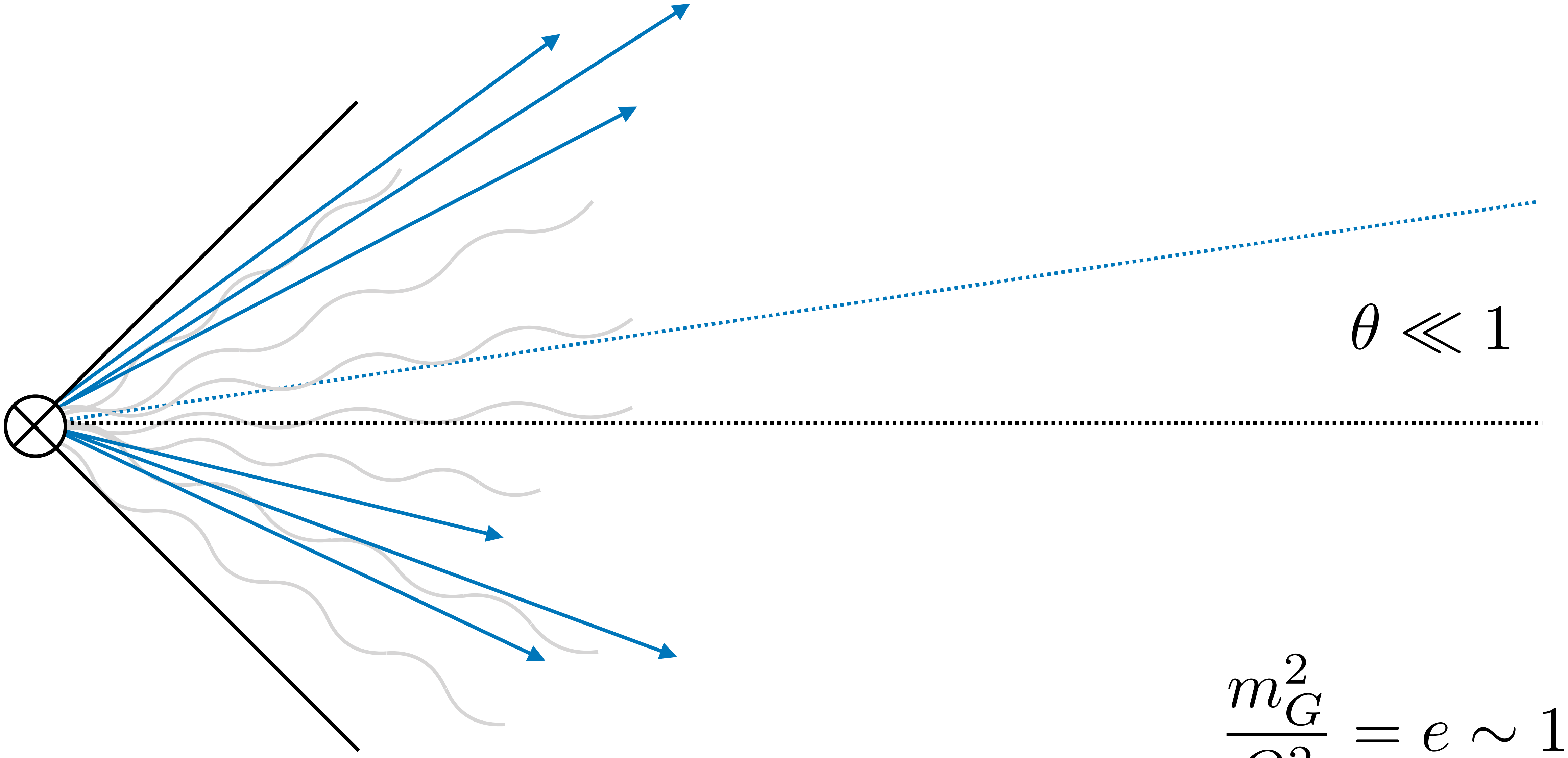
Groomed Jet Axis (GJA) - Hadronization Effects



The jet mass cutoff

The jet mass cutoff

Improve our observable by imposing groomed jet mass cutoff. This will eliminate hard splittings which could induce boundary effects.

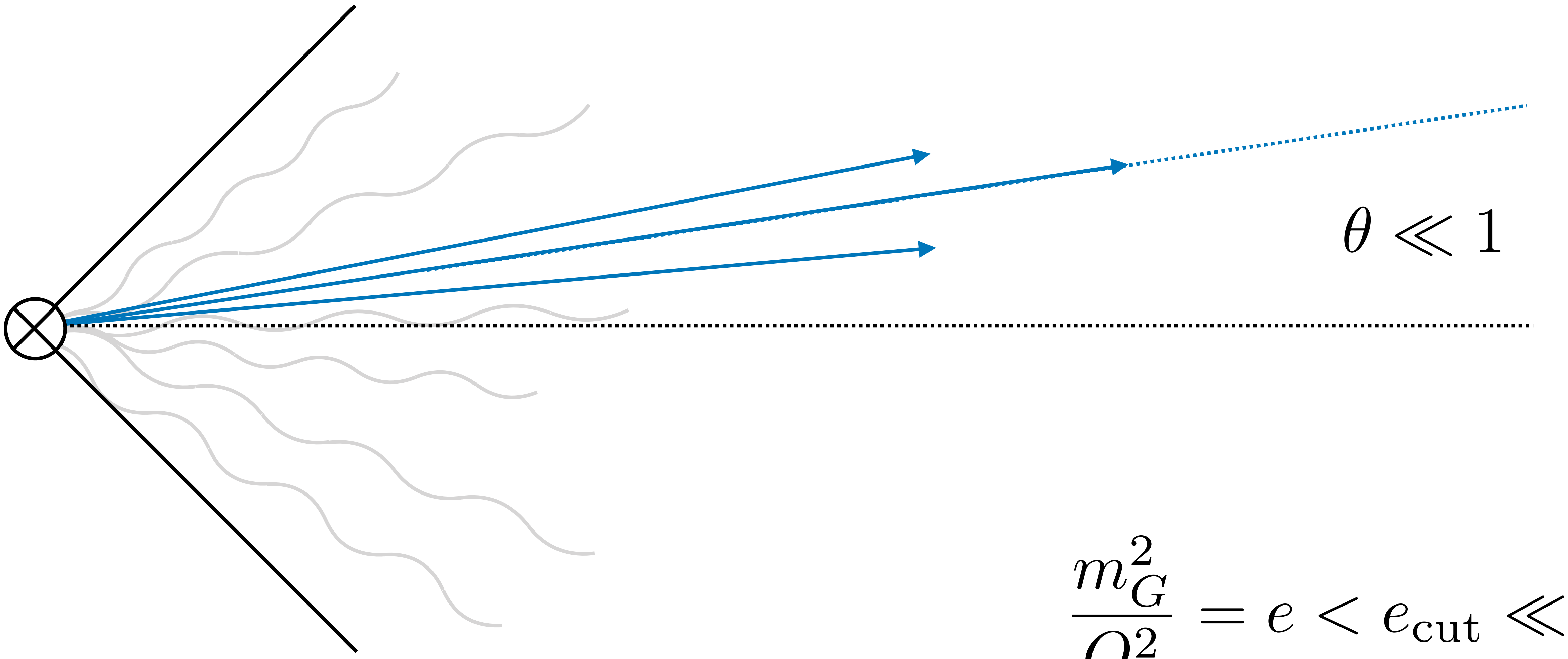


$$\theta \ll 1$$

$$\frac{m_G^2}{Q^2} = e \sim 1$$

The jet mass cutoff

Improve our observable by imposing groomed jet mass cutoff. This will eliminate hard splittings which could induce boundary effects.



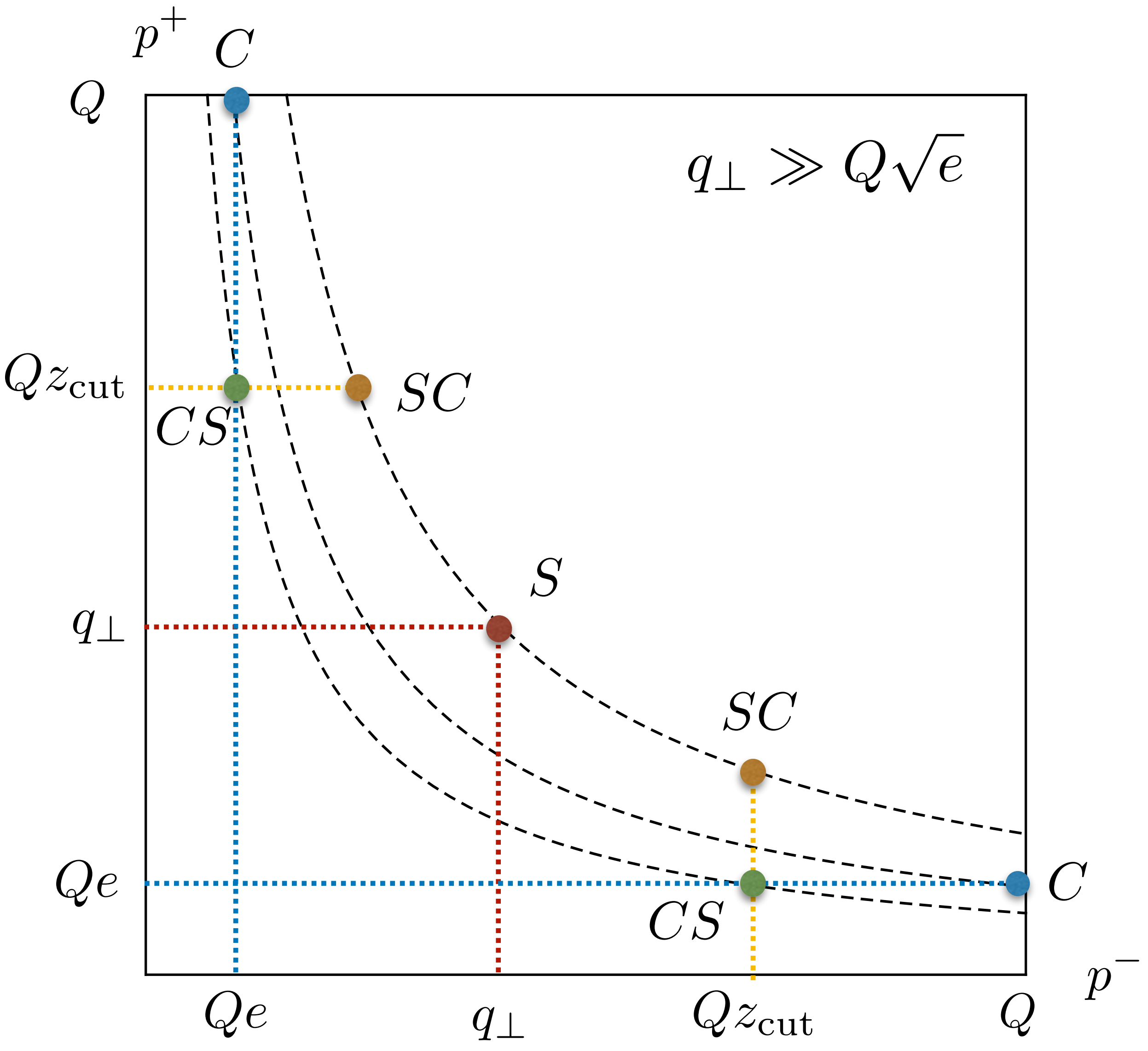
$\theta \ll 1$

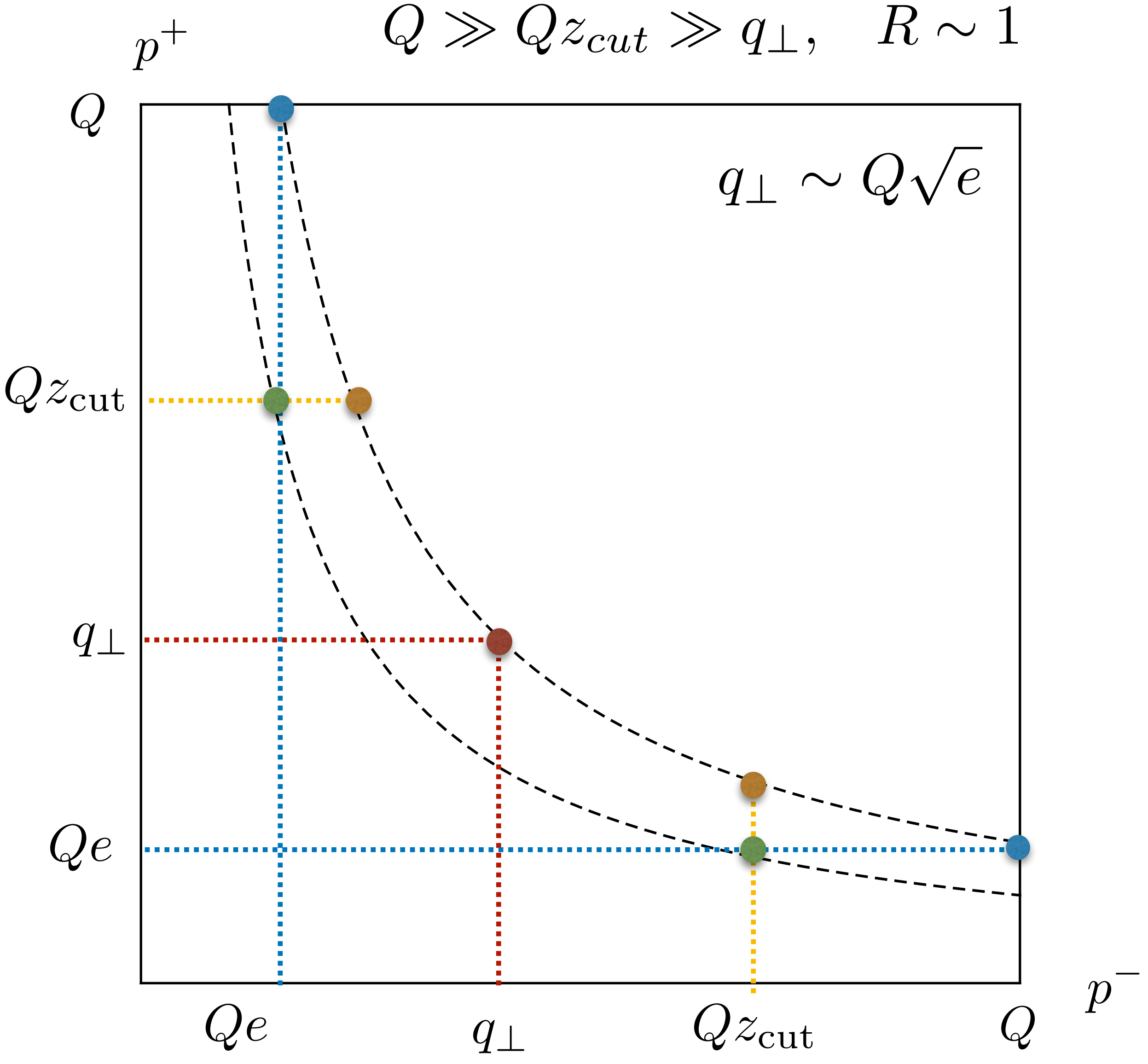
$$\frac{m_G^2}{Q^2} = e < e_{\text{cut}} \ll 1$$

Modes-Factorization-Resummation

Modes

$$Q \gg Qz_{cut} \gg q_\perp, \quad R \sim 1$$





Factorization

$$Q \gg Q z_{\rm cut} \gg q_\perp \sim Q\sqrt{e_{\rm cut}}$$

electron-positron annihilation

jet + jet:

TMD jet function

$$\frac{d\sigma}{d^2\vec{q}_\perp} = H_2^{ij}(Q;\mu) \times S_2^\perp(\mu,\nu) \otimes \mathcal{J}_i^\perp(e_{\rm cut}, Q, z_{\rm cut};\mu,\nu) \otimes \mathcal{J}_j^\perp(e_{\rm cut}, Q, z_{\rm cut};\mu,\nu)$$

Universal soft function
same for Drell-Yan

jet + hadron (out):

$$\frac{d\sigma}{d^2\vec{q}_\perp} = H_2^{ij}(Q;\mu) \times S_2^\perp(\mu,\nu) \otimes \mathcal{J}_i^\perp(e_{\rm cut}, Q, z_{\rm cut};\mu,\nu) \otimes \mathcal{D}_{j\to h}^\perp(Q;\mu,\nu)$$

Un-subtracted
TMDFF

TMD jet function re-factorization

$$\mathcal{J}_j^{\perp}(e_{\rm cut}, Q, z_{\rm cut}; \mu, \nu) = \int_0^{e_{\rm cut}} de\; \mathcal{J}_j^{\perp}(e, Q, z_{\rm cut}; \mu, \nu)$$

$$q_\perp \sim Q\sqrt{e} \Big/ q_\perp \gg Q\sqrt{e}$$

soft-collinear: $p_{sc}^\mu \sim Q z_{\rm cut}(\lambda_{sc}^2, 1, \lambda_{sc}),\ \lambda_{sc} = q_\perp/(Q z_{\rm cut})$

collinear: $p_c^\mu \sim Q(\lambda_c^2, 1, \lambda_c),\ \lambda_c = \sqrt{e}$

collinear-soft: $p_{cs}^\mu \sim Q z_{\rm cut}(\lambda_{cs}^2, 1, \lambda_{cs}),\ \lambda_{cs} = \sqrt{e/z_{\rm cut}}$

$$\mathcal{J}_i^{\perp}(e, Q, z_{\rm cut}; \mu, \nu) = S_{sc,i}^{\perp}(Q z_{\rm cut}; \mu, \nu) \times \int de'\; S_{cs,i}(e - e', Q z_{\rm cut}; \mu) J_i(e', Q; \mu)$$

TMD jet function re-factorization

$$\mathcal{J}_j^{\perp}(e_{\text{cut}}, Q, z_{\text{cut}}; \mu, \nu) = \int_0^{e_{\text{cut}}} de\, \mathcal{J}_j^{\perp}(e, Q, z_{\text{cut}}; \mu, \nu)$$

$q_\perp \sim Q\sqrt{e}$ / $q_\perp \gg Q\sqrt{e}$

soft-collinear: $p_{sc}^{\mu} \sim Q z_{\text{cut}}(\lambda_{sc}^2, 1, \lambda_{sc}),\ \lambda_{sc} = q_\perp/(Q z_{\text{cut}})$

collinear: $p_c^{\mu} \sim Q(\lambda_c^2, 1, \lambda_c),\ \lambda_c = \sqrt{e}$

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$$\mathcal{J}_i^{\perp}(e, Q, z_{\text{cut}}; \mu, \nu) = S_{sc,i}^{\perp}(Q z_{\text{cut}}; \mu, \nu) \times \int de'\, S_{cs,i}(e - e', Q z_{\text{cut}}; \mu) J_i(e', Q; \mu)$$

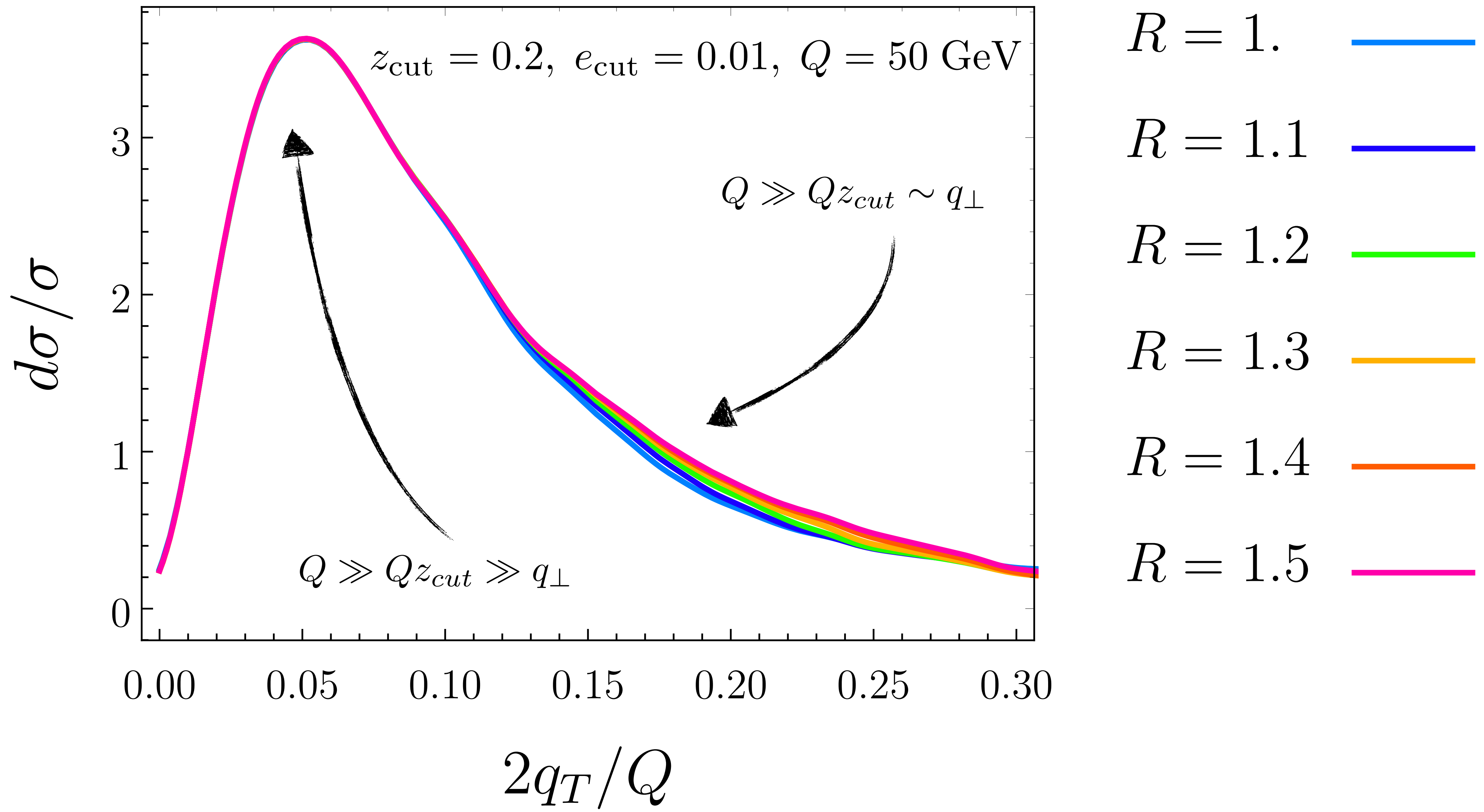
- The e_cut dependence can only change the normalization of the TMD spectrum and the change can be predicted analytically.

- No jet radius dependence

Jet radius dependence

Direction of the groomed jet axis insensitive to jet Radius (for R ~ 1):

In contrast to the SJA where the shift is greater as we approach the “large R” limit.



TMD evolution

Rapidity divergences in global soft and soft-collinear using:
J.-Y. Chiu, A. Jain, D. Neill and I. Z. Rothstein **arXiv:1202.0814**

$$\tilde{F}^{\perp}(b;\mu,\zeta) \equiv \sqrt{\tilde{S}_2^{\perp}(\mu,\nu_s)}\;\tilde{S}_{sc}^{\perp}(Qz_{\mathrm{cut}};\mu,\nu_{sc}) \qquad \nu_s = \sqrt{\zeta} \qquad \nu_{sc} = Qz_{\mathrm{cut}}$$

$$\mu^2 \frac{d}{d\mu^2}\tilde{F}^{\perp}(b;\mu,\zeta) = \frac{1}{2}\gamma_F(\mu,\zeta)\tilde{F}^{\perp}(b;\mu,\zeta)\ ,$$

$$\zeta\frac{d}{d\zeta}\tilde{F}^{\perp}(b;\mu,\zeta) = -\mathcal{D}(\mu)\tilde{F}^{\perp}(b;\mu,\zeta)$$

One loop results:

$$\tilde{F}^{\perp}(b;\mu,\zeta) = 1 + \frac{\alpha_s(\mu)C_i}{2\pi}\Big\{2\ln\Big(\frac{\mu_E}{\mu}\Big)\ln\Big(\frac{\zeta}{\mu^2}\Big) - 2\ln^2\Big(\frac{\mu_E}{\mu}\Big) - \frac{\pi^2}{12} + \mathcal{O}(\alpha_s^2)\Big\}$$

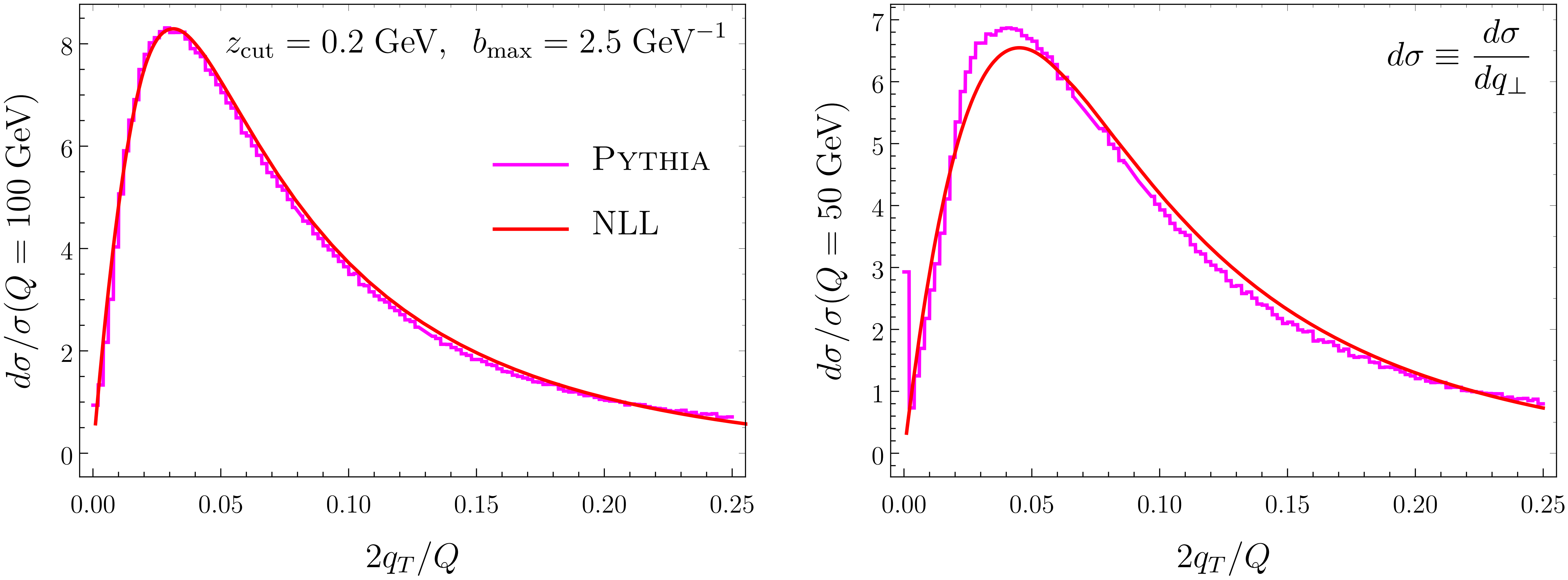
Perturbative @NLL vs Pythia **Had. OFF**

$$\mu(b_*) = \frac{C_0}{b_*}$$

$$b_* = \frac{b}{\sqrt{1+(b/b_{\max})^2}}$$

Consistency check (effect of power corrections) against Pythia simulations.

NLL cross section in **good agreement** with partonic shower of MC.

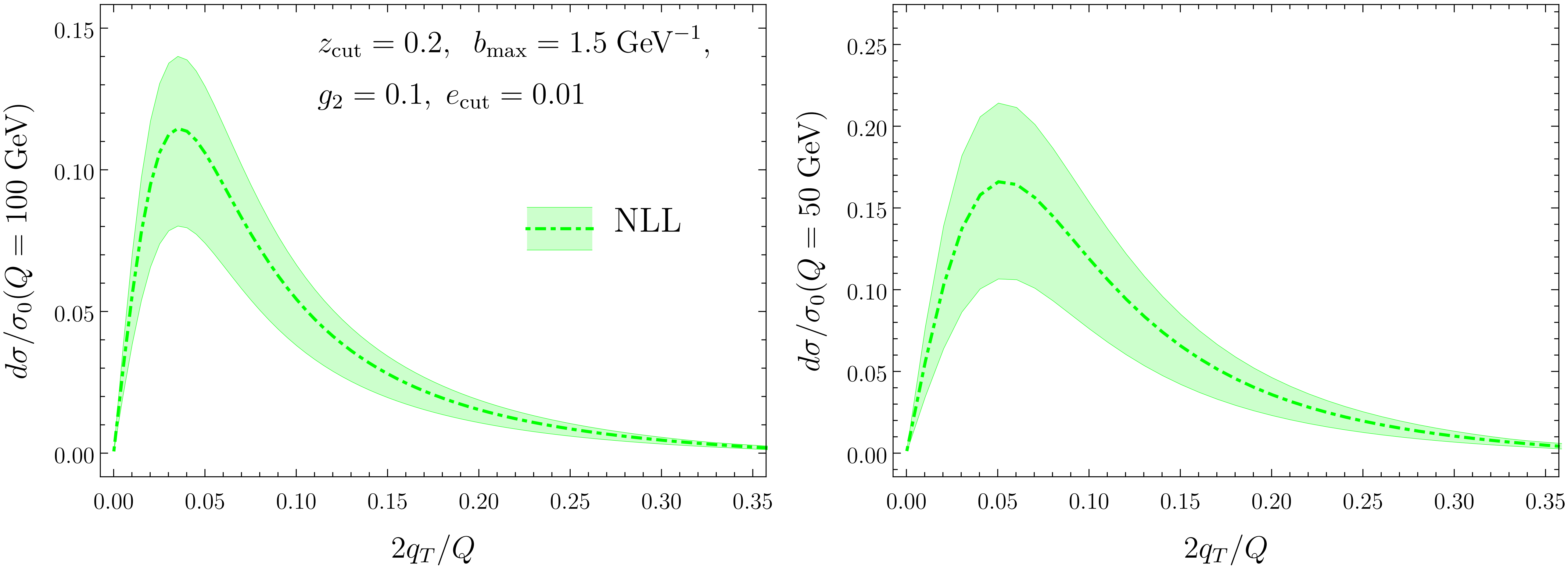


Perturbative @NLL scale variation

Theoretical uncertainties estimated by varying canonical scales by factor 1/2 and 2.

Envelope of virtuality added in quadrature with envelope from rapidity variation.

Can we do better?



Resummation in b-space @ NNLL

$$\mu^2 \frac{d}{d\mu^2}\tilde{F}^{\perp}(b;\mu,\zeta) = \frac{1}{2}\gamma_F(\mu,\zeta)\tilde{F}^{\perp}(b;\mu,\zeta)\ ,$$

We only need to figure the non-cusp part.
Use consistency of factorization

$$\gamma_F(\mu,\zeta = Qz_{\mathrm{cut}}) = \gamma_S(\mu)$$

N(2)LL from arXiv:1603.09338

$$\zeta \frac{d}{d\zeta}\tilde{F}^{\perp}(b;\mu,\zeta) = -\mathcal{D}(\mu)\tilde{F}^{\perp}(b;\mu,\zeta)$$

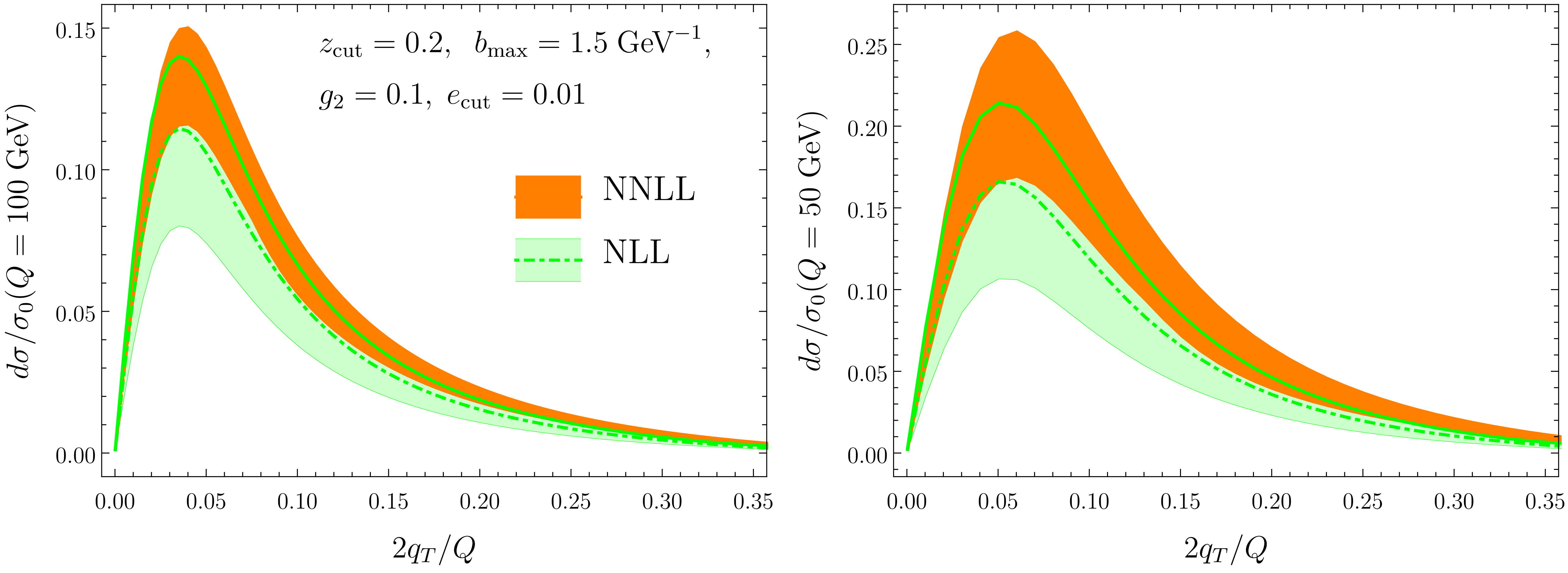
Universal

Scale variation: NNLL vs NLL

For jet energies < 25 GeV, the theoretical uncertainty is relatively large for NNLL.

Work in progress:

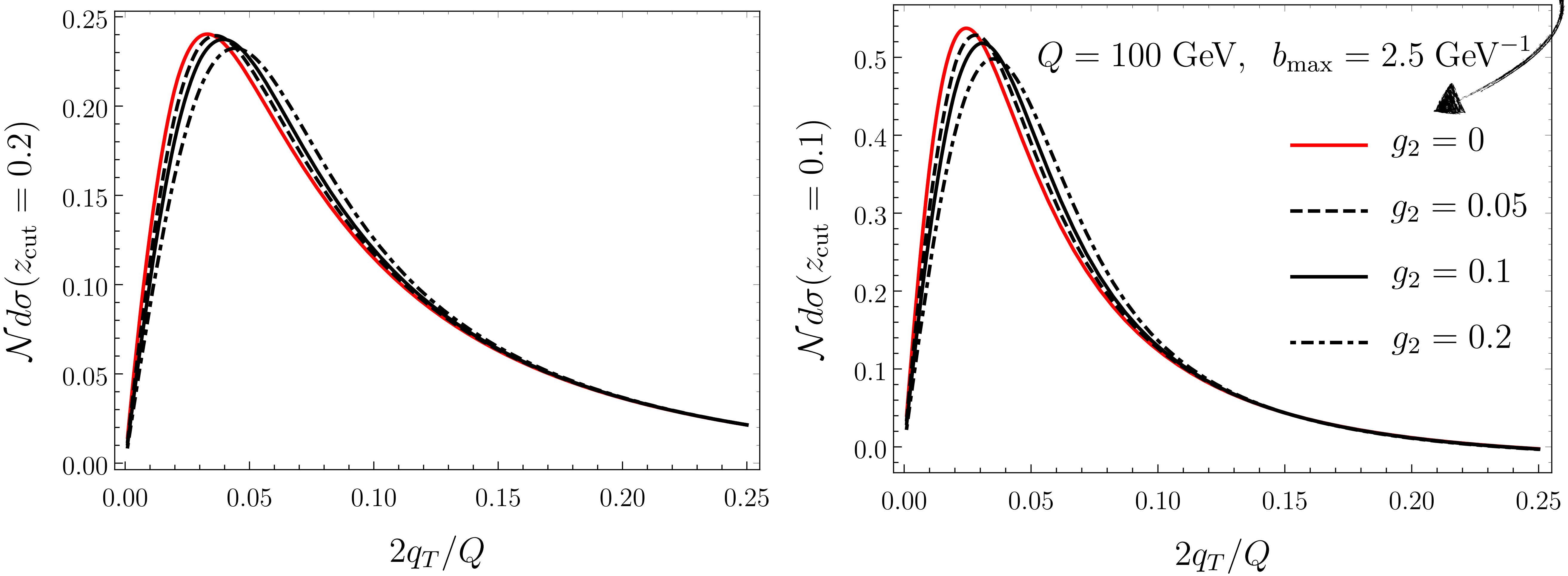
- Implement other resummation schemes, e.g. zeta-prescription.
- Cross section for DIS.



Non-perturbative effects: rapidity AD

$$\mathcal{D} \to \mathcal{D} + g_K(b, b_{\max}) \qquad g_K(b; b_{\max}) = \frac{1}{2} g_2(b_{\max}) b^2$$

Non-perturbative model for rapidity anomalous dimension



Summary

- Groomed jet axis much more stable during hadronization, independent of jet radius (R ~ 1) or jet algorithms. Factorization involves universal soft function.

- Additional measurement needs to be imposed to avoid boundary effects (Not necessary for Winner-Take-All, see arXiv:1807.07573).

- All ingredients for NNLL resummation are available.

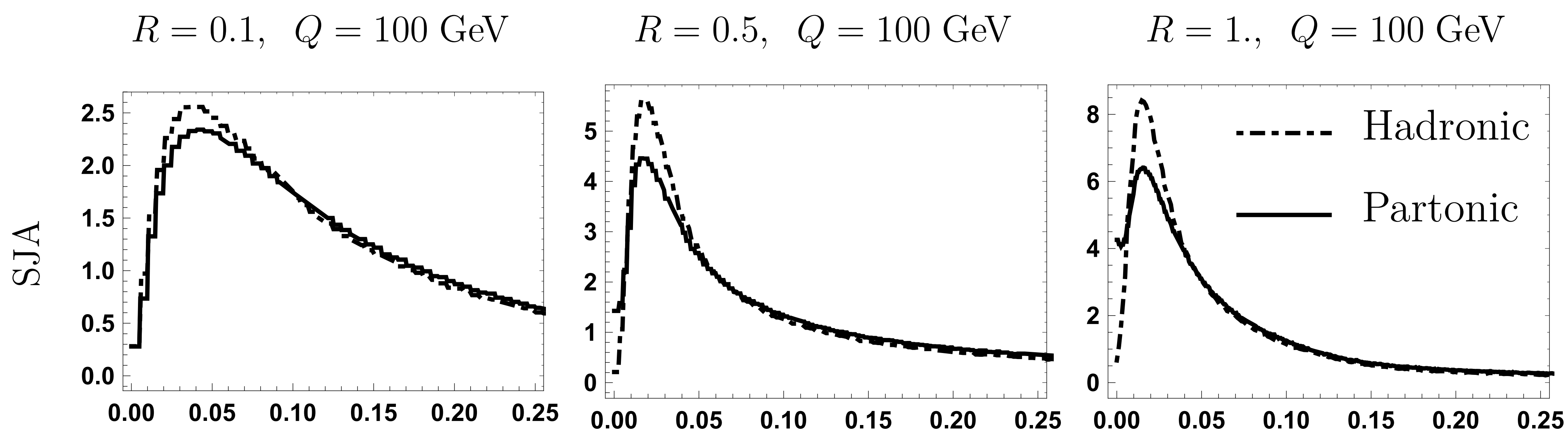
- In progress: Groomed jets in DIS give access to TMDPDFs with minimum additional input.

- In progress: zeta-prescription using the arTiMiDe package.

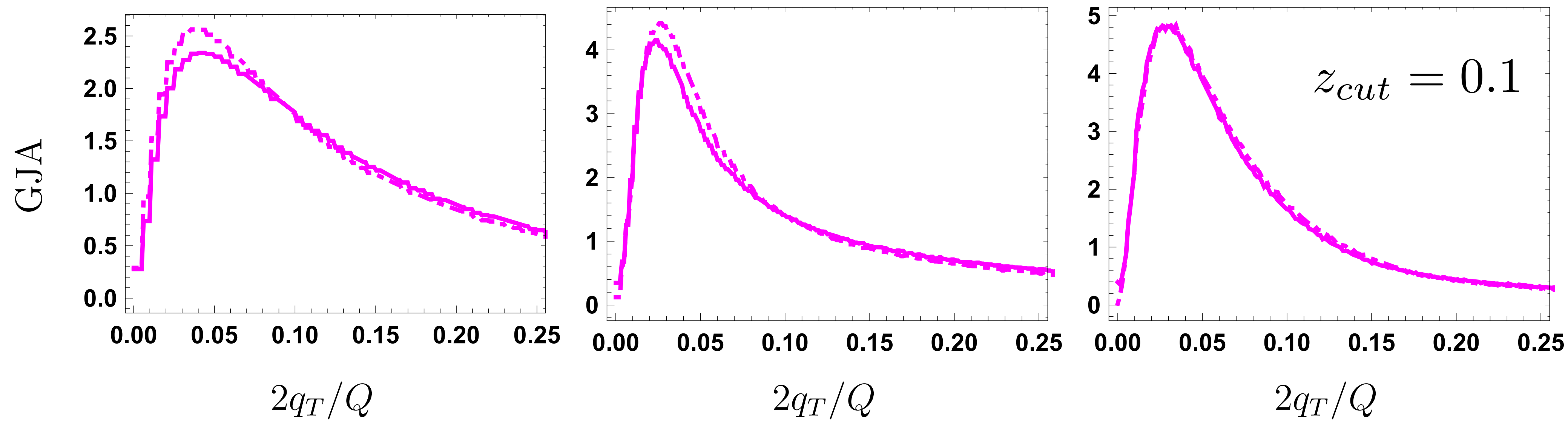
- We need to understand non-perturbative effects.

Additional slides

Groomed Jet Axis (GJA) - Hadronization Effects



$\ln(QR/q_\perp)$

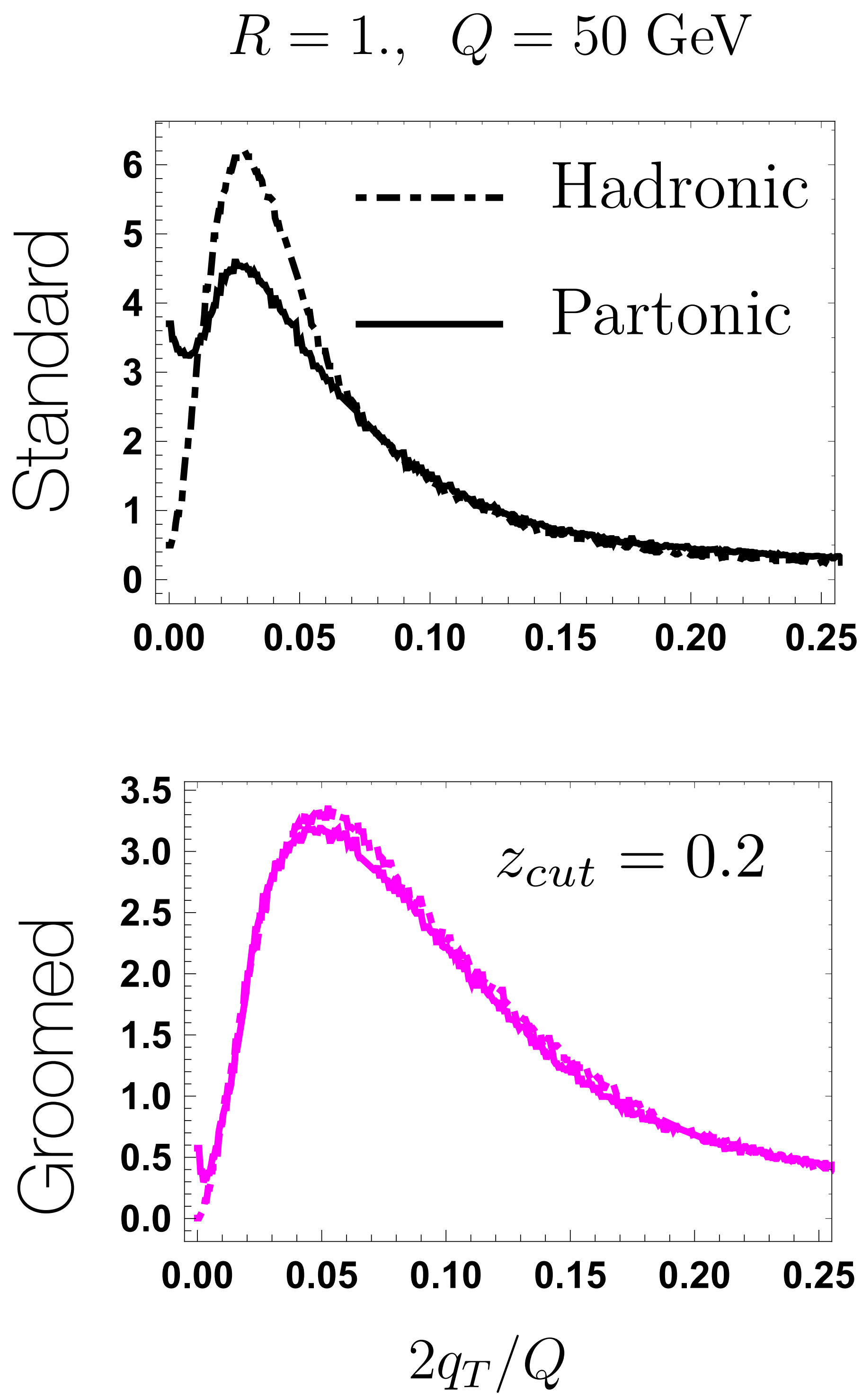


$\ln(QR/q_\perp)$

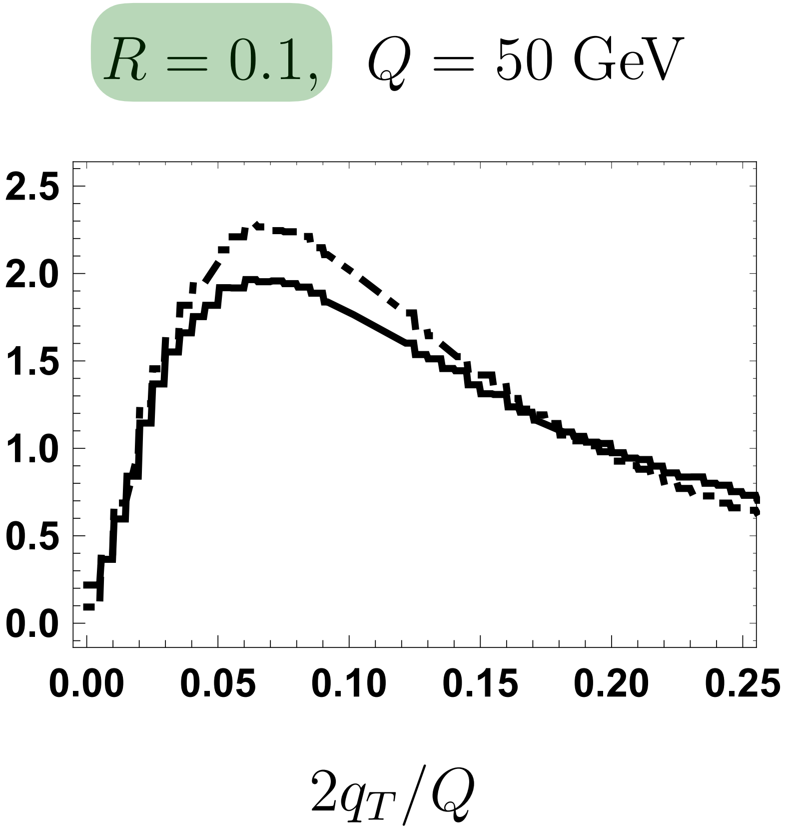
?

$\ln(Qz_{cut}/q_\perp)$

Groomed Jet Axis (GJA) - Hadronization Effects



$R = 1.,\quad Q = 50\ \text{GeV}$



$R = 0.1,\quad Q = 50\ \text{GeV}$

The jet mass cutoff

~ **80%** of the cross section is captured with e_cut < 0.01

$$\frac{m_G^2}{Q^2} = e < e_{\mathrm{cut}} \ll 1$$