Determination of TMDs from jet physics

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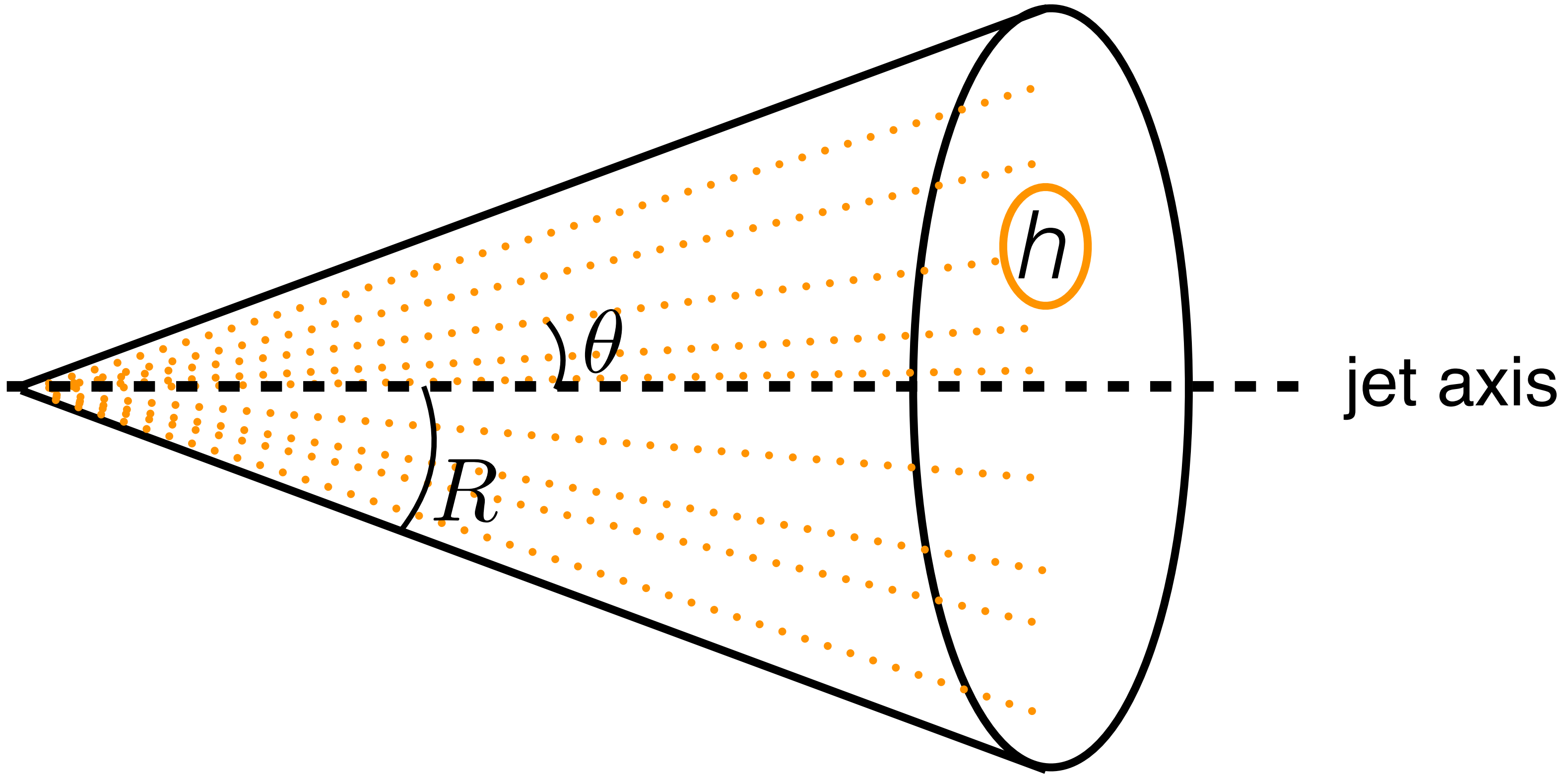
1. Introduction

What? TMD fragmentation



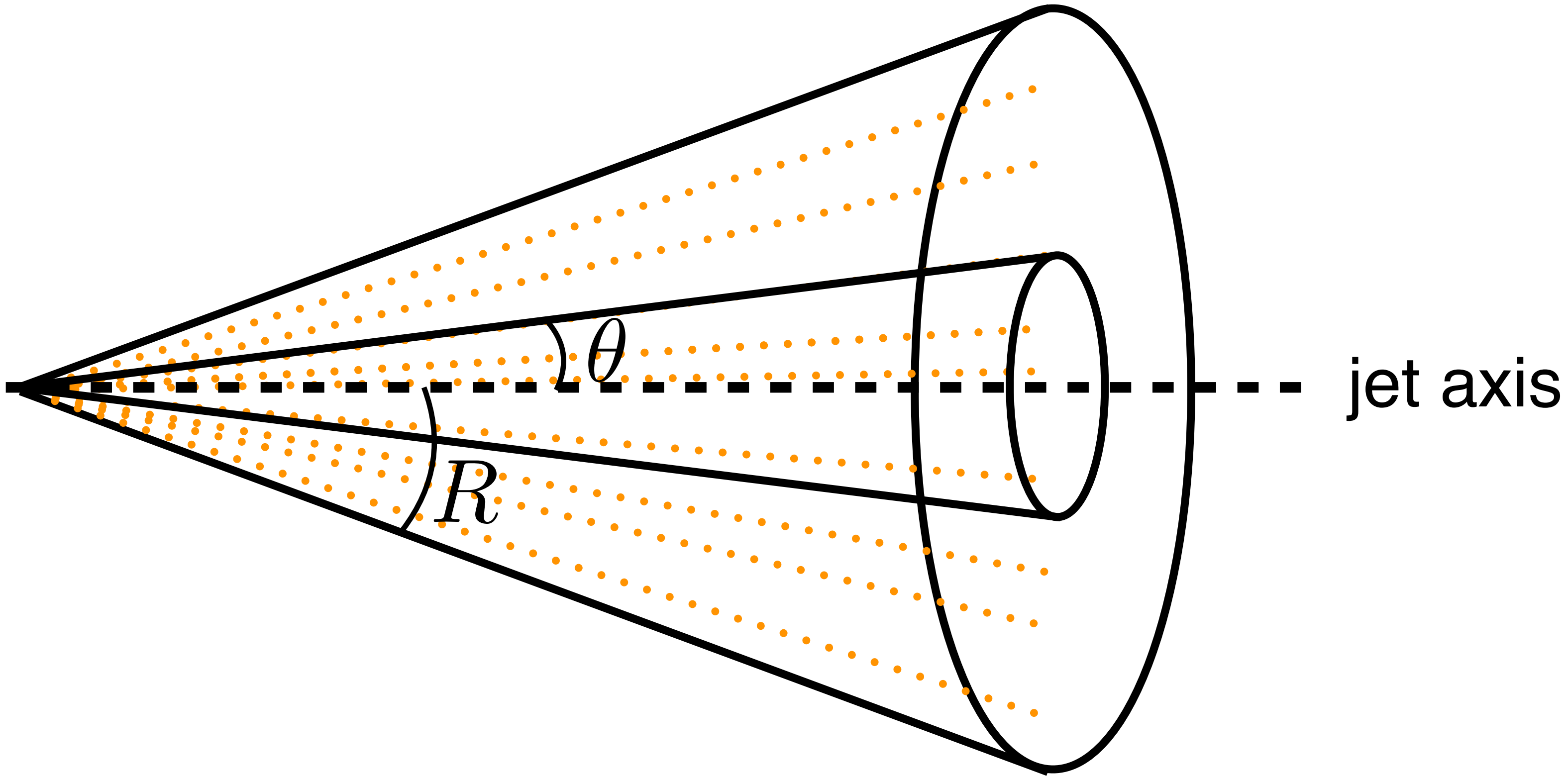
- **TMD fragmentation:** for hadron *h* in jet *J*, measure:

$$z_h = \frac{E_h}{E_J} \qquad \vec{k}_\perp = \frac{\vec{p}_{h\perp}}{z_h}$$

- Transverse momentum is related to angle:

$$|\vec{k}_\perp| = E_J \sin\theta \approx E_J \theta$$

What? TMD fragmentation and jet shape



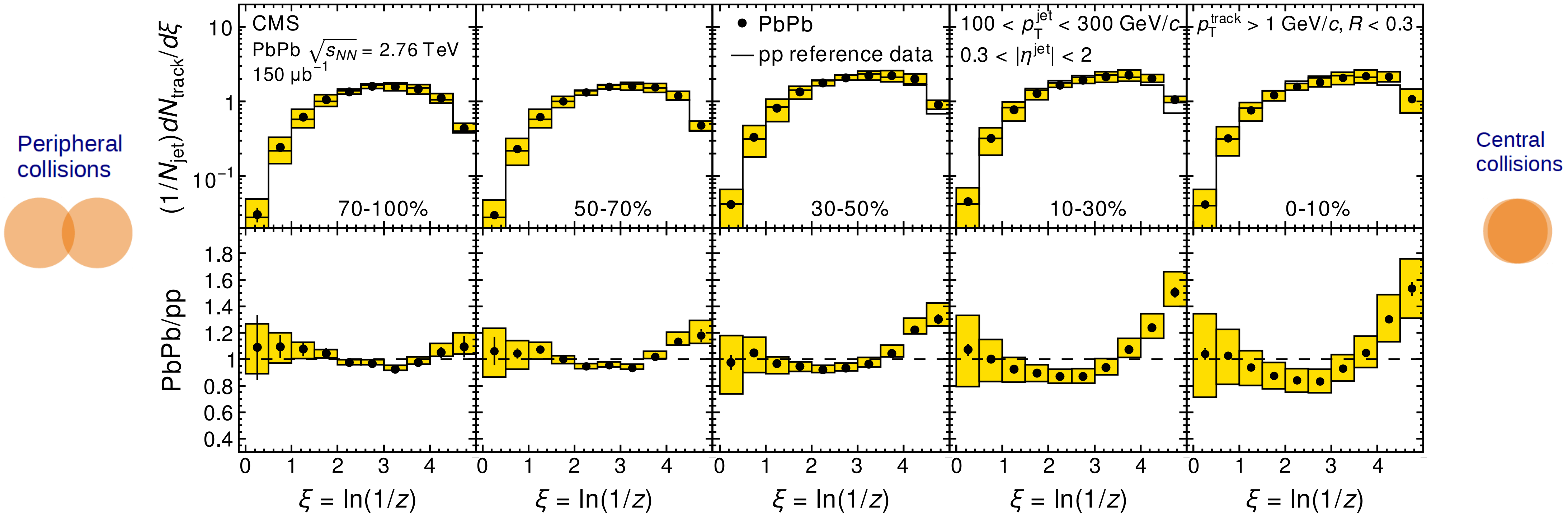
- **Jet shape:** average energy fraction at given angle

$$\frac{1}{E_J}\frac{\mathrm{d}E}{\mathrm{d}\theta} = \frac{1}{\sigma}\sum_h \int \mathrm{d}z_h\, z_h\, \frac{\mathrm{d}\sigma_h}{\mathrm{d}z_h\,\mathrm{d}\theta}$$

- Nonperturbative fragmentation drops out due to sum rule
- Will use e^+e^- (energies, angles), but our results extend to pp

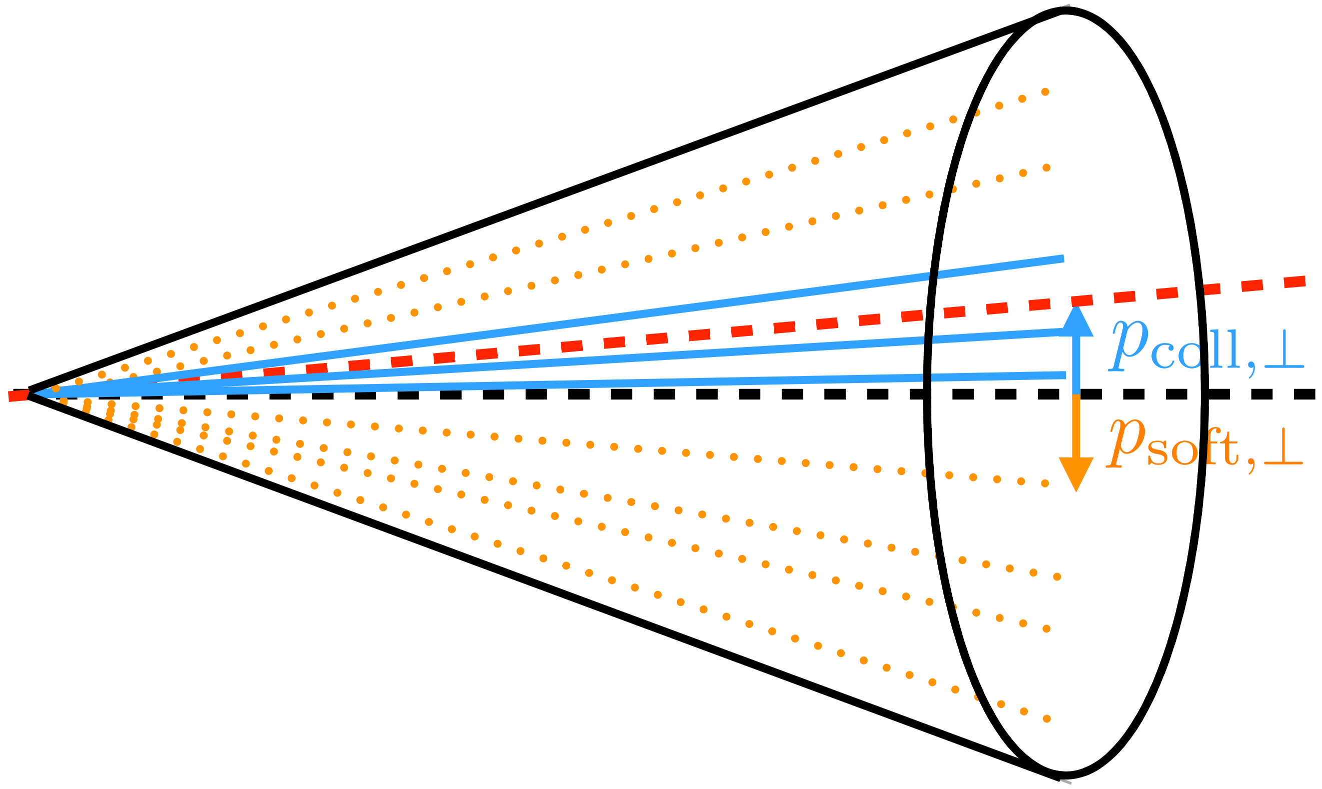
Why? Applications in nuclear and particle physics

- TMD fragmentation: constrain nonpert. physics, study spin
- Probe medium in heavy ion collisions
- Constrain α_s at the LHC using jet shape
- Discriminate quark and gluon-initiated jets



[CMS-HIN-12-013]

How? Recoil-free jet axis



recoil-free axis

standard jet axis

$$p_{\mathrm{coll},\perp} + p_{\mathrm{soft},\perp} = 0$$

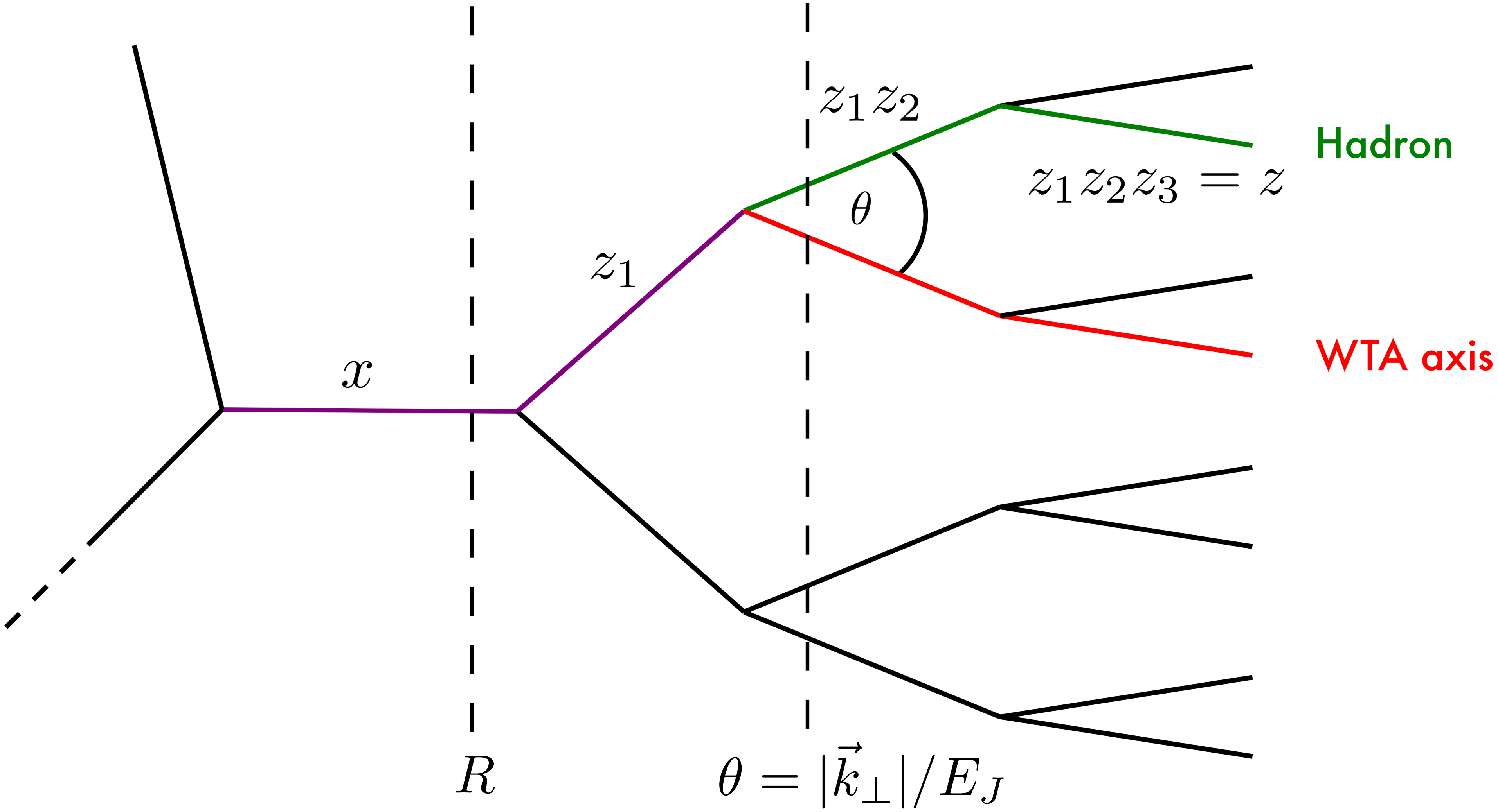
- Standard jet axis sensitive to recoil from soft radiation
- Remove by e.g. using Winner-Take-All clustering in jet algorithm

$$E_r = E_1 + E_2$$

$$\hat{n}_r = \begin{cases} \hat{n}_1 & \text{if } E_1 > E_2 \\ \hat{n}_2 & \text{if } E_2 > E_1 \end{cases}$$

[Salam; Bertolini, Chan, Thaler]

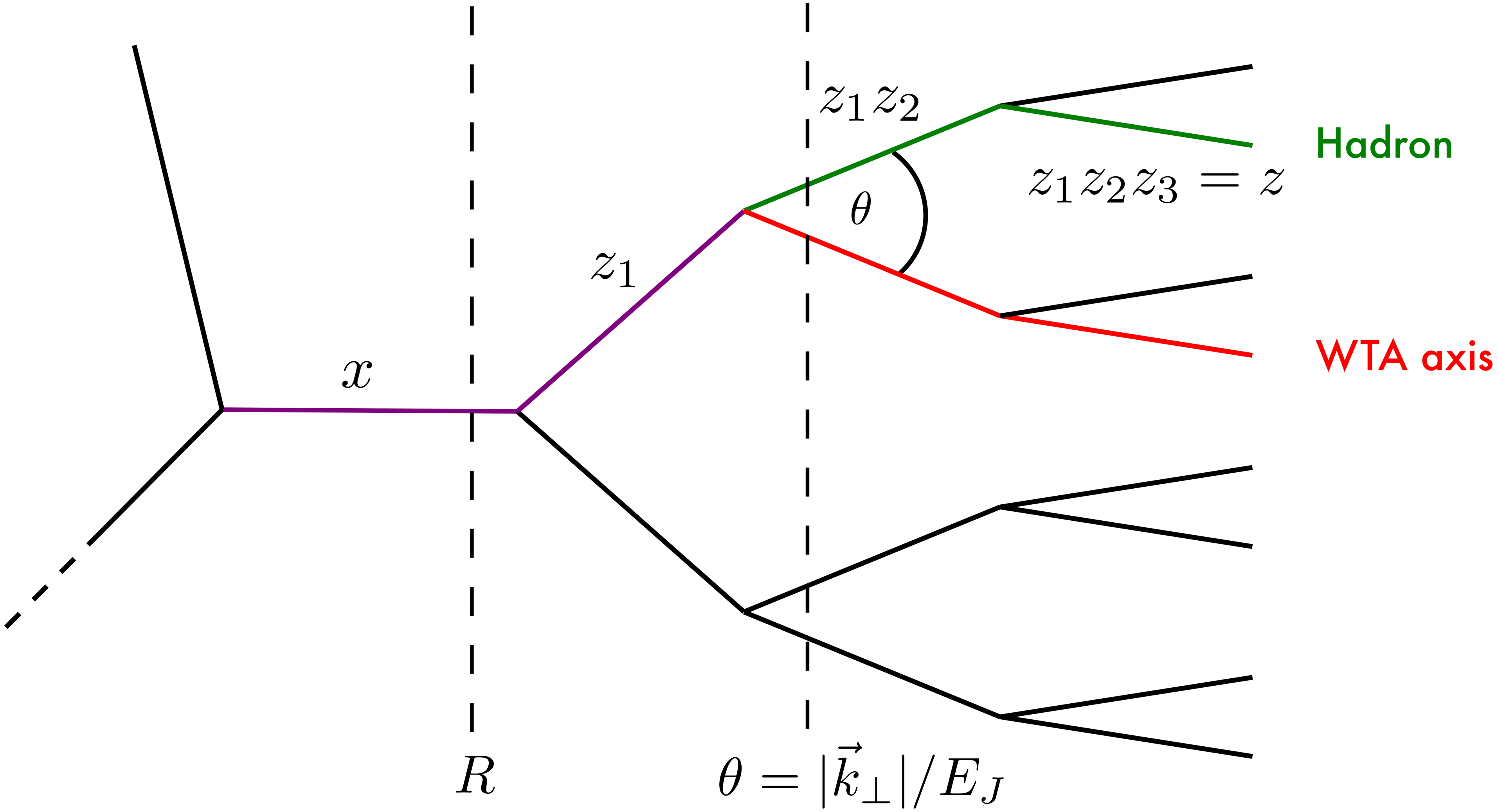
Calculating with Winner-Take-All axis



- Strong angular ordering (LL) → parton shower = clustering tree
- Splitting with angle $\alpha > R$ produces separate jets, DGLAP evolution of $x = 2E_J/Q$

[Dasgupta, Dreyer, Salam, Soyez; Kang, Ringer, Vitev; Dai, Kim, Leibovich]

Calculating with Winner-Take-All axis



- $R > \alpha > \theta$: WTA axis & hadron follow most energetic branch, **modified** DGLAP evolution of z [Neill, Scimemi, WW]
- $\theta > \alpha$: WTA axis and hadron have split, DGLAP evolution of z

Modified evolution leads to power law

- Modified evolution from $\mu = E_J R$ to $|\vec{k}_\perp|$

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu} D_{i\to h}(\vec{k}_\perp, z_h, \mu) = \sum_j \int \frac{\mathrm{d}z}{z}\, \theta\Big(z - \frac{1}{2}\Big) P_{ji}(z,\mu) D_{j\to h}\Big(\vec{k}_\perp, \frac{z_h}{z}, \mu\Big)$$

- TMDs match onto fragmentation functions at $\mu = |\vec{k}_\perp|$ which satisfy regular DGLAP evolution

- Leading $|\vec{k}_\perp|$ dependence follows from evolution kernels *U* (Mellin space, ignoring mixing)

$$\frac{\mathrm{d}}{\mathrm{d}|\vec{k}_\perp|} \tilde{U}(ER, |\vec{k}_\perp|)\, U(|\vec{k}_\perp|, \mu_0) \sim \frac{\mathrm{d}}{\mathrm{d}|\vec{k}_\perp|} \exp\bigg(\tilde{P} \ln \frac{ER}{|\vec{k}_\perp|} + P \ln \frac{|\vec{k}_\perp|}{\mu_0}\bigg)$$

$$\sim |\vec{k}_\perp|^{-1+P-\tilde{P}}$$

- Power law instead of Sudakov double logarithms

Pros and cons of Winner-Take-All axis

Because WTA axis is insensitive to soft radiation:

✓Robust: good for noisy environments (heavy ion)

✓Universal: not sensitive to radiation at/outside jet boundary

✓Theoretically clean → extend to higher orders (extract α_s?)

The price you pay:

x Jet axis is not along jet momentum

- Nonperturbative collinear physics important near axis

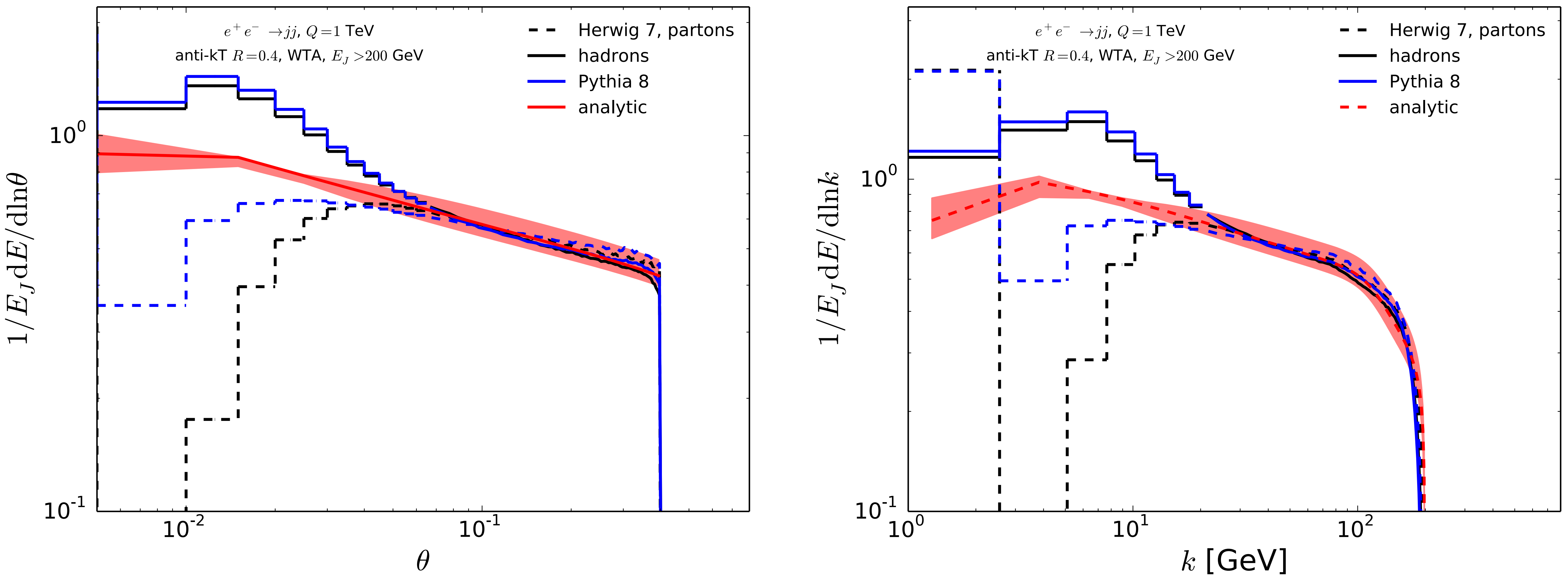
Another possibility:

- Grooming [Makris, Neill, Vaidya]

2. Preliminary Results

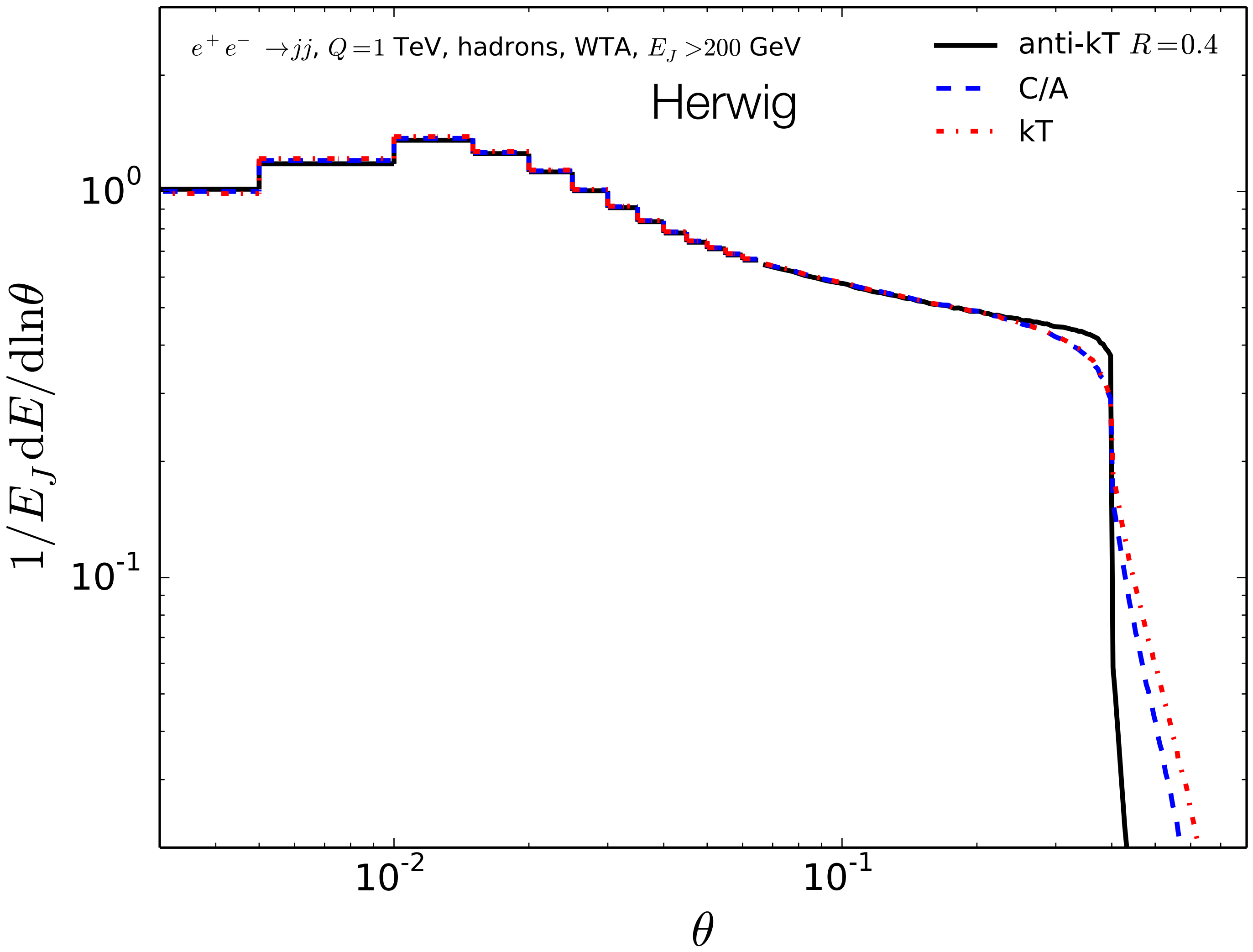
With D. Neill, A. Papaefstathiou, L. Zoppi

Jet shape



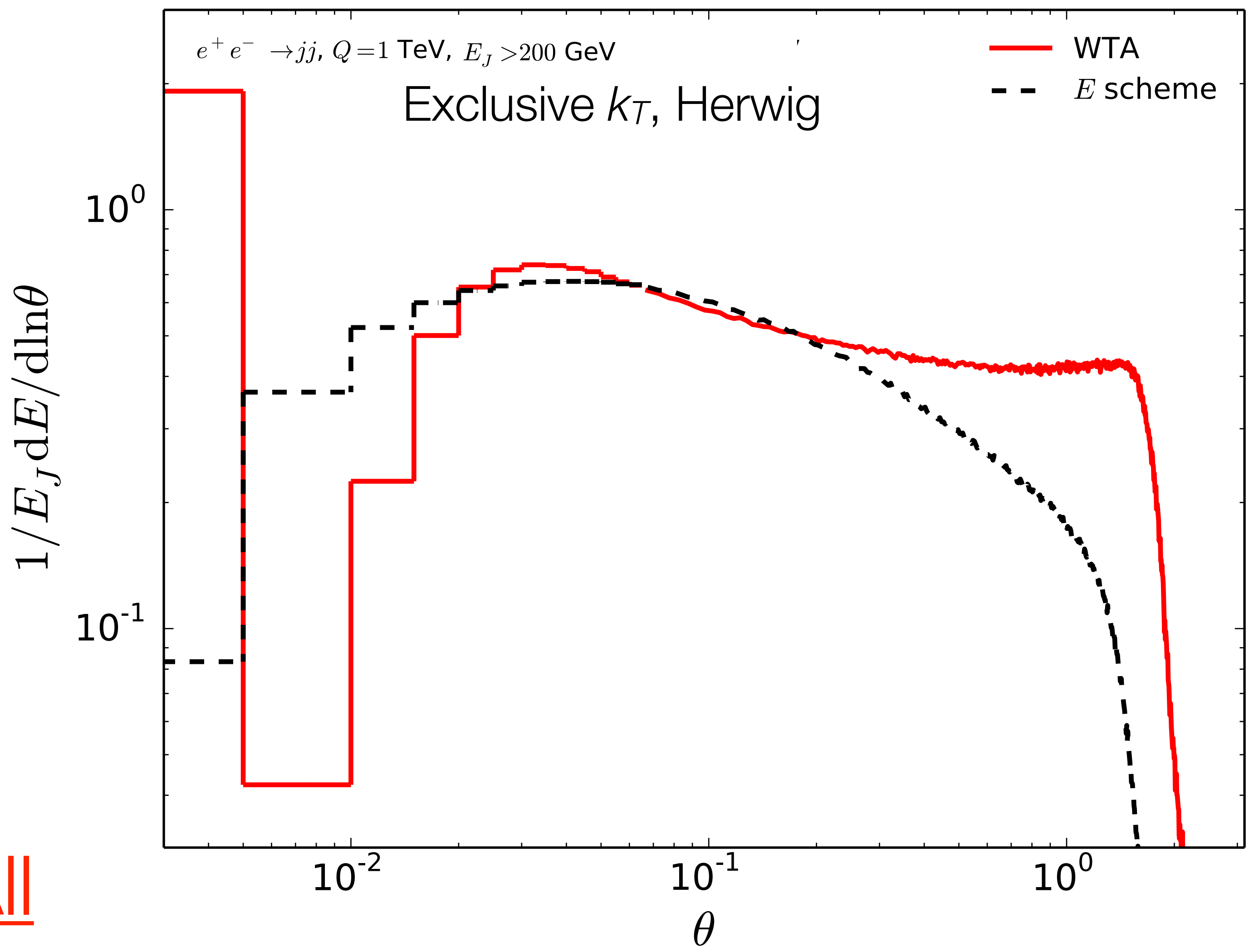
- Power law behavior
- Turn off for $k = |\vec{k}_\perp|$ smoothed by jet energy distribution
- Substantial collinear nonperturbative effects (fills “dead cone”)

Jet algorithm



- Jet algorithm dependence is small and only shows up close to jet boundary $\theta = R$

Winner-Take-All vs. standard axis



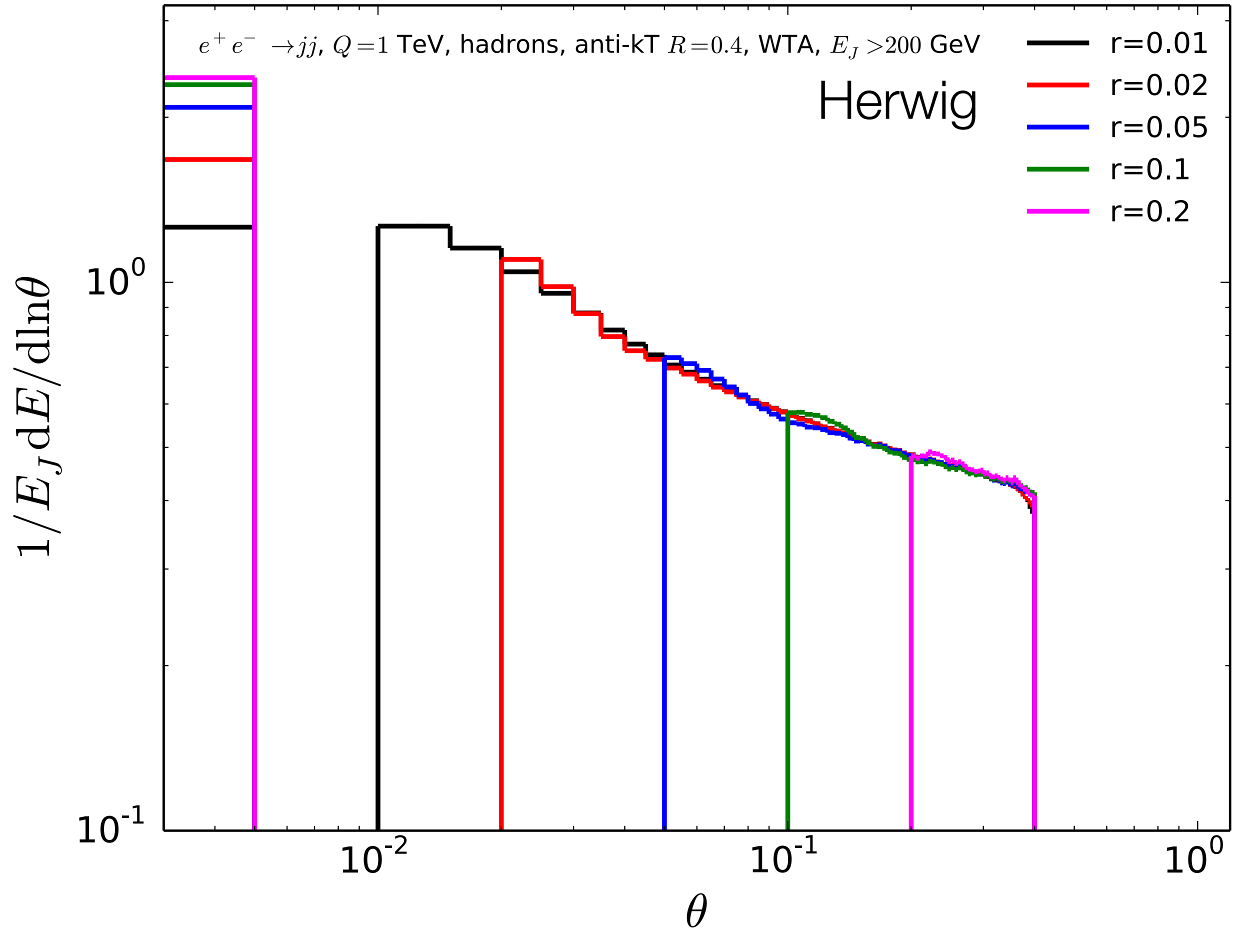
Winner-Take-All

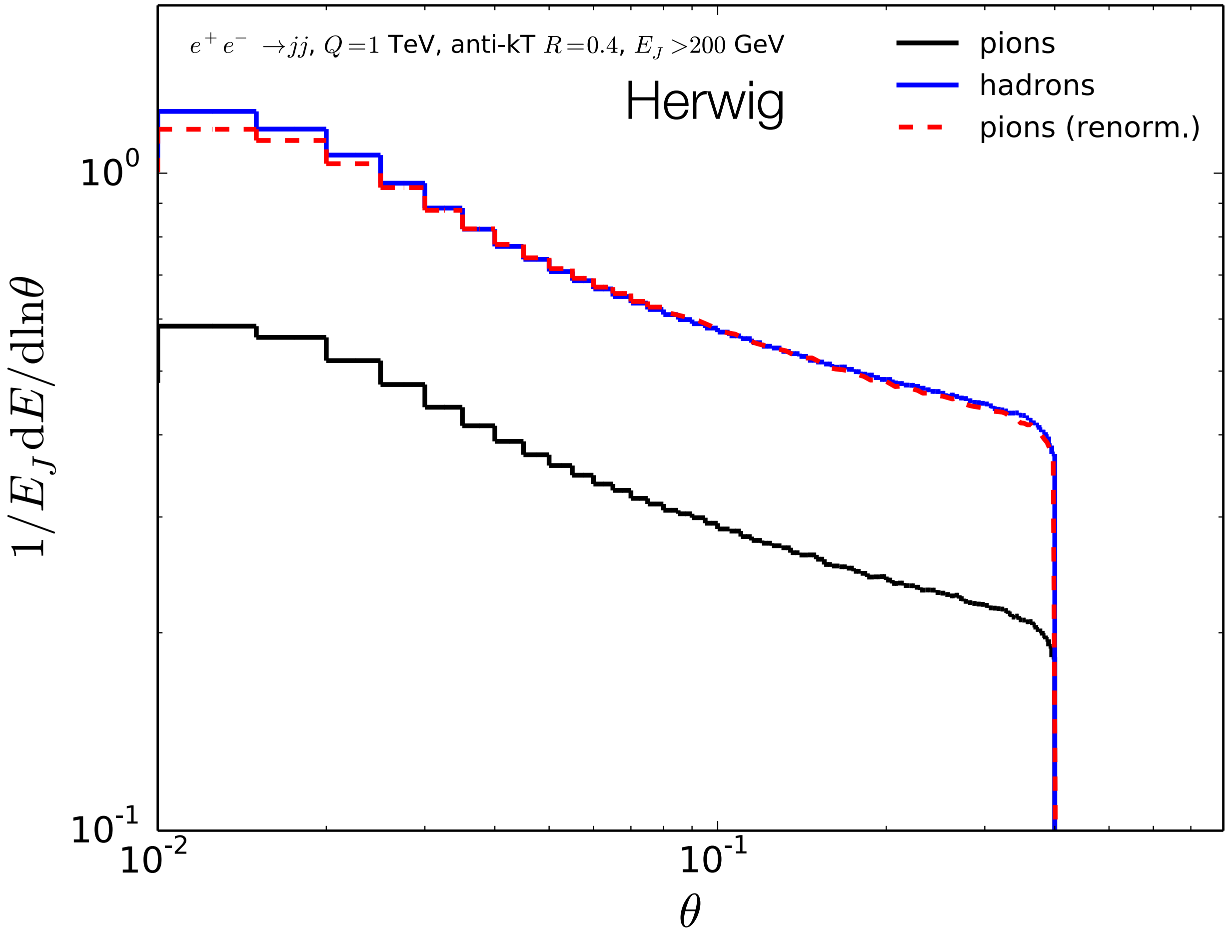
- (Approximate) power law
- Constant energy at large θ
- Large nonpert. effects

standard axis

- Sudakov double logarithms
- Jet axis repositions itself
- Smoothed by soft fluctuations

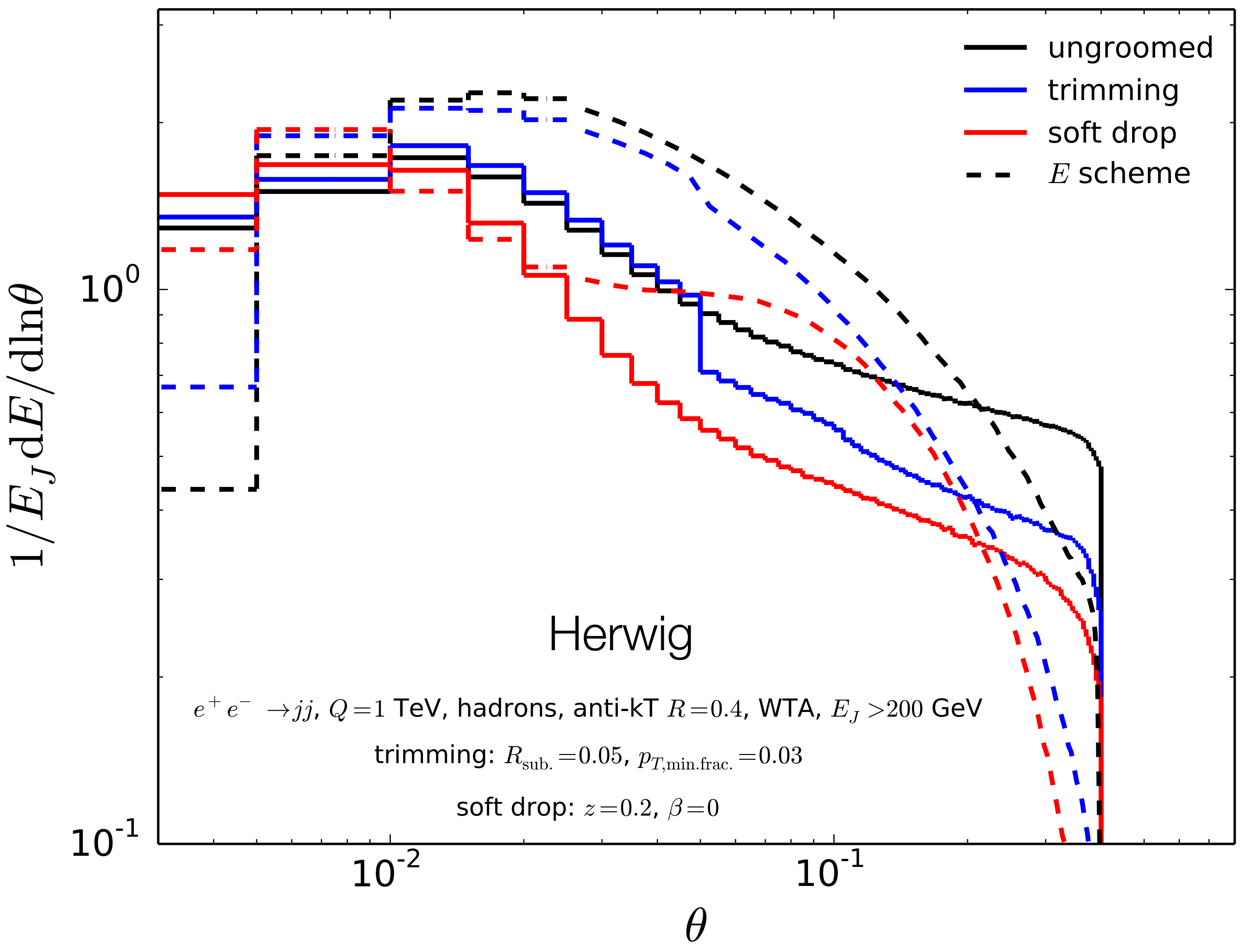
Angular resolution is not intrinsic limitation





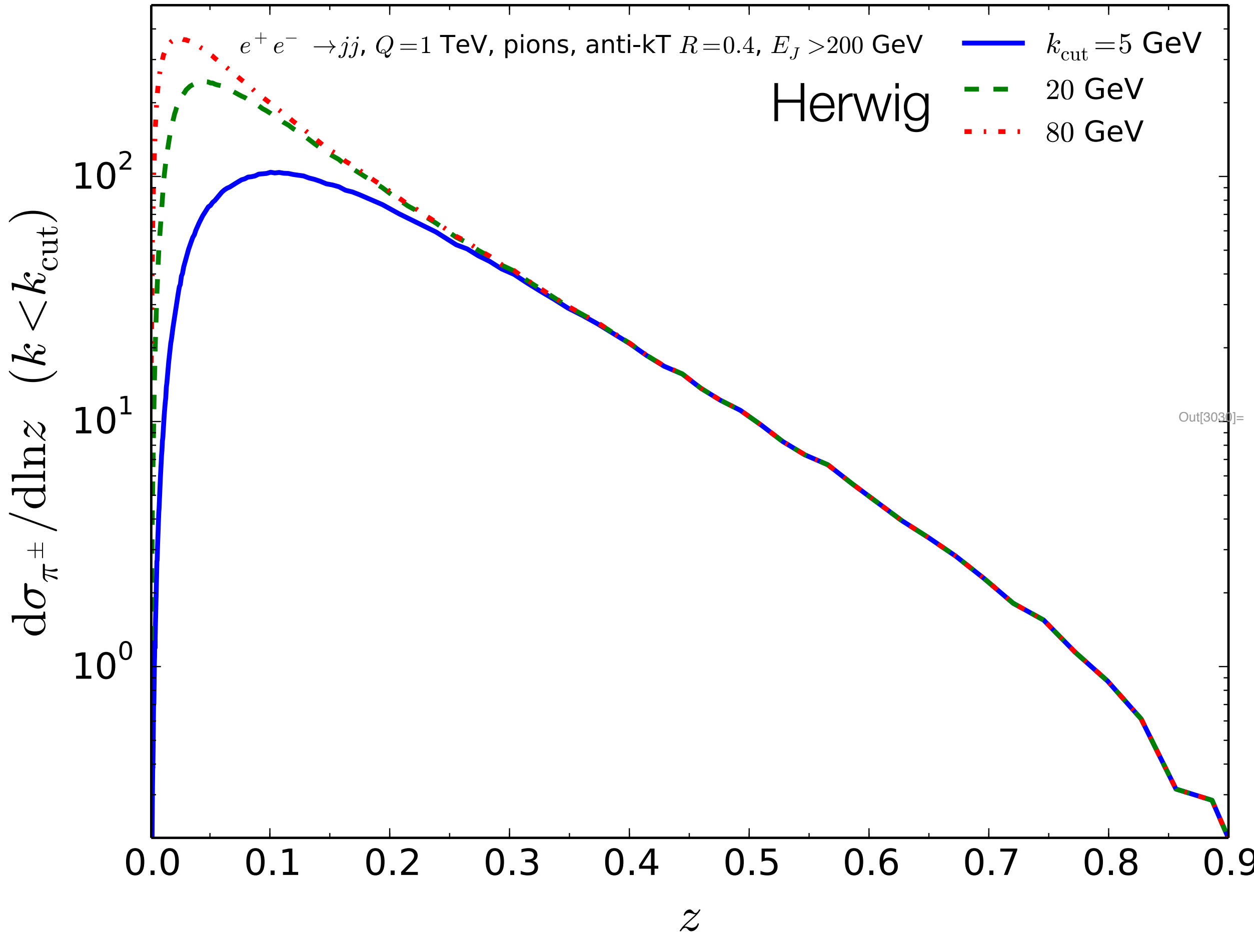
- Jet shape on subjets of radius r gives same distribution if $\theta \gtrsim r$
- Jet shape on charged pions gives almost same shape (Nonpert. input: energy fraction of quarks and gluons to $\pi^\pm$)

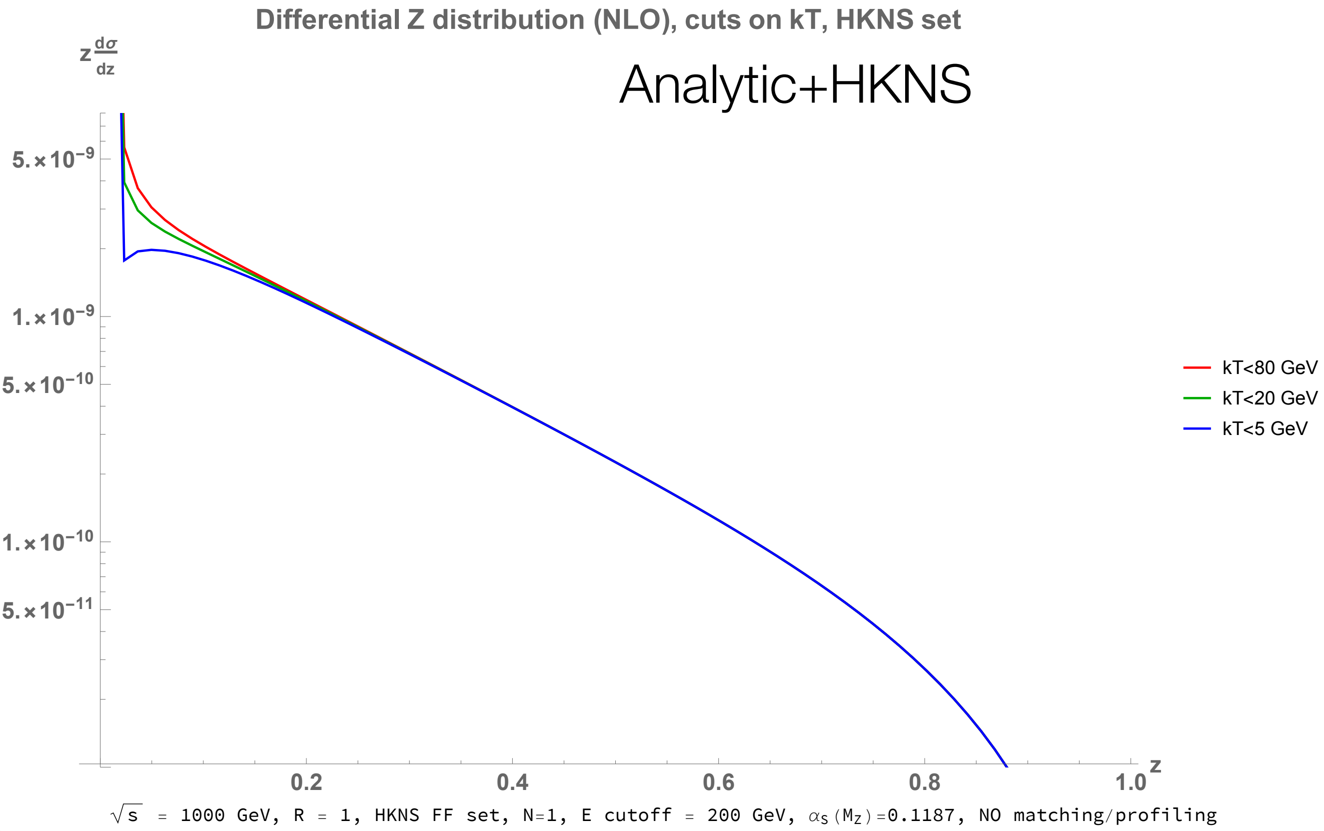
Grooming



- Trimming: no effect for $\theta < R_{\text{sub}}$, reduced norm. for $\theta > R_{\text{sub}}$
- Aggressive soft drop sculpts result for standard axis (*E* scheme)

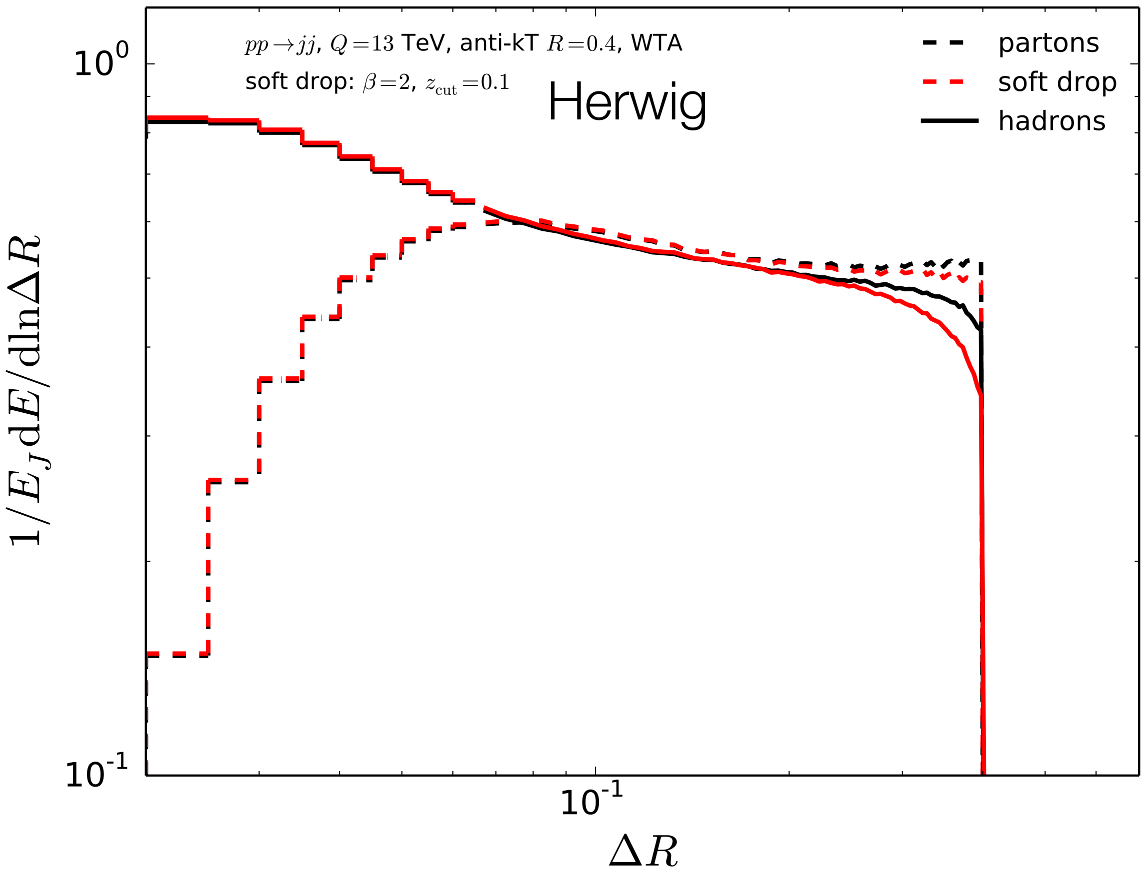
TMD fragmentation

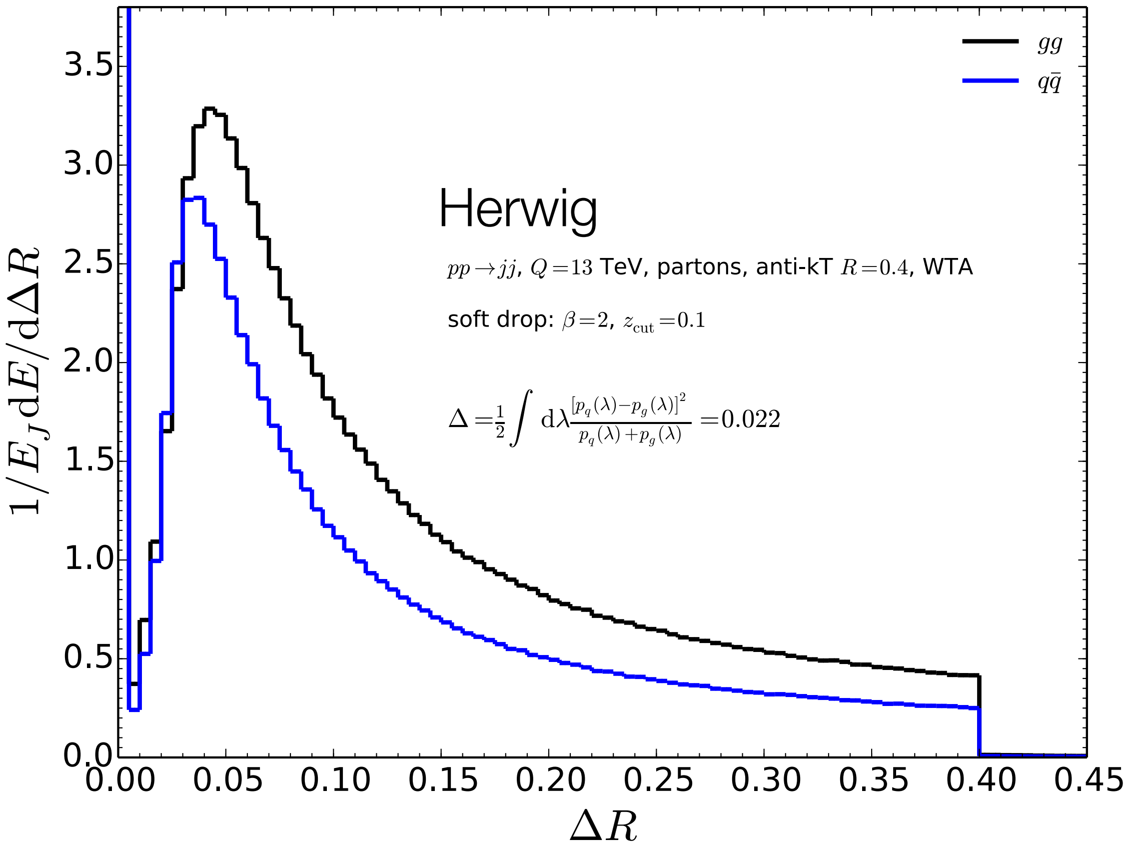




- Effect of cut on transverse momentum mostly at small z
- Difference with analytic calculations due to different fragmentation functions

LHC, quark vs. gluon

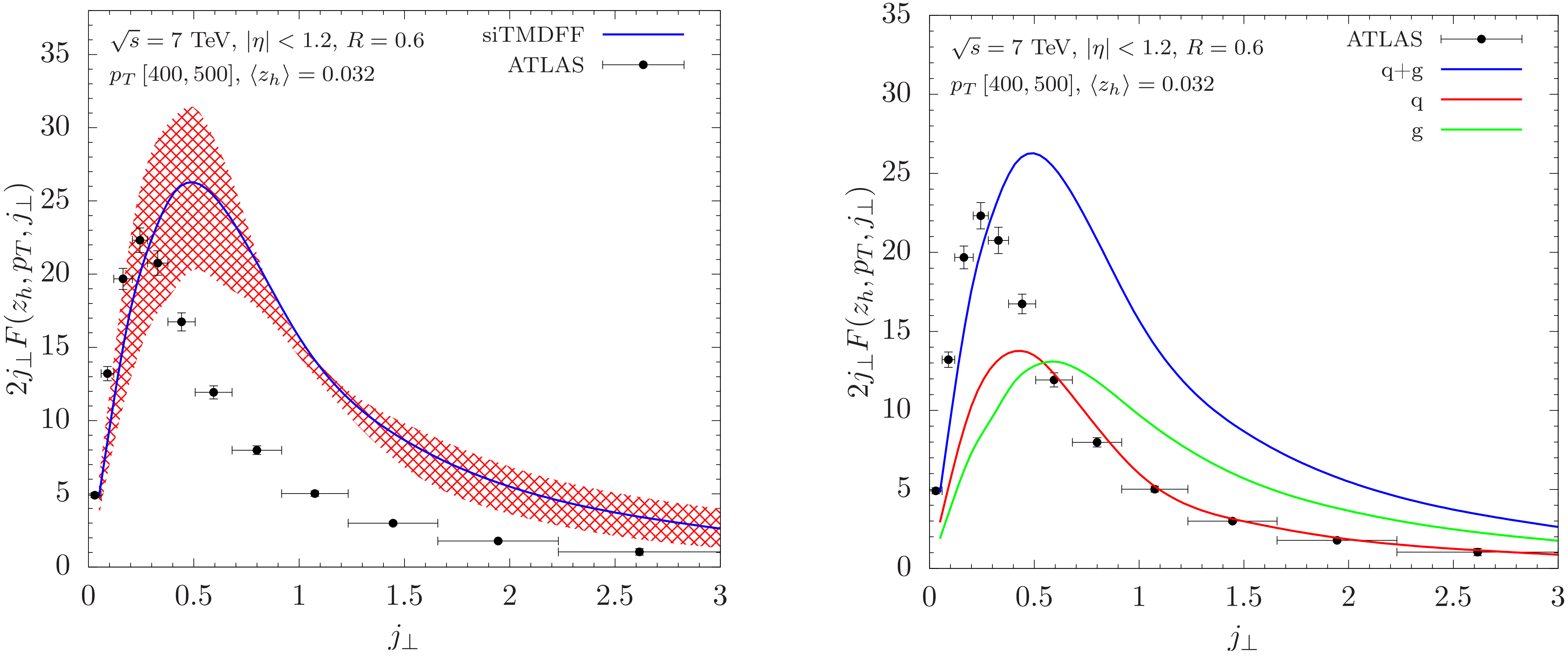




- pp has similar power law, but more contamination
  Soft drop mostly effects boundary
- Limited use as quark/gluon discriminant

3. Related Work

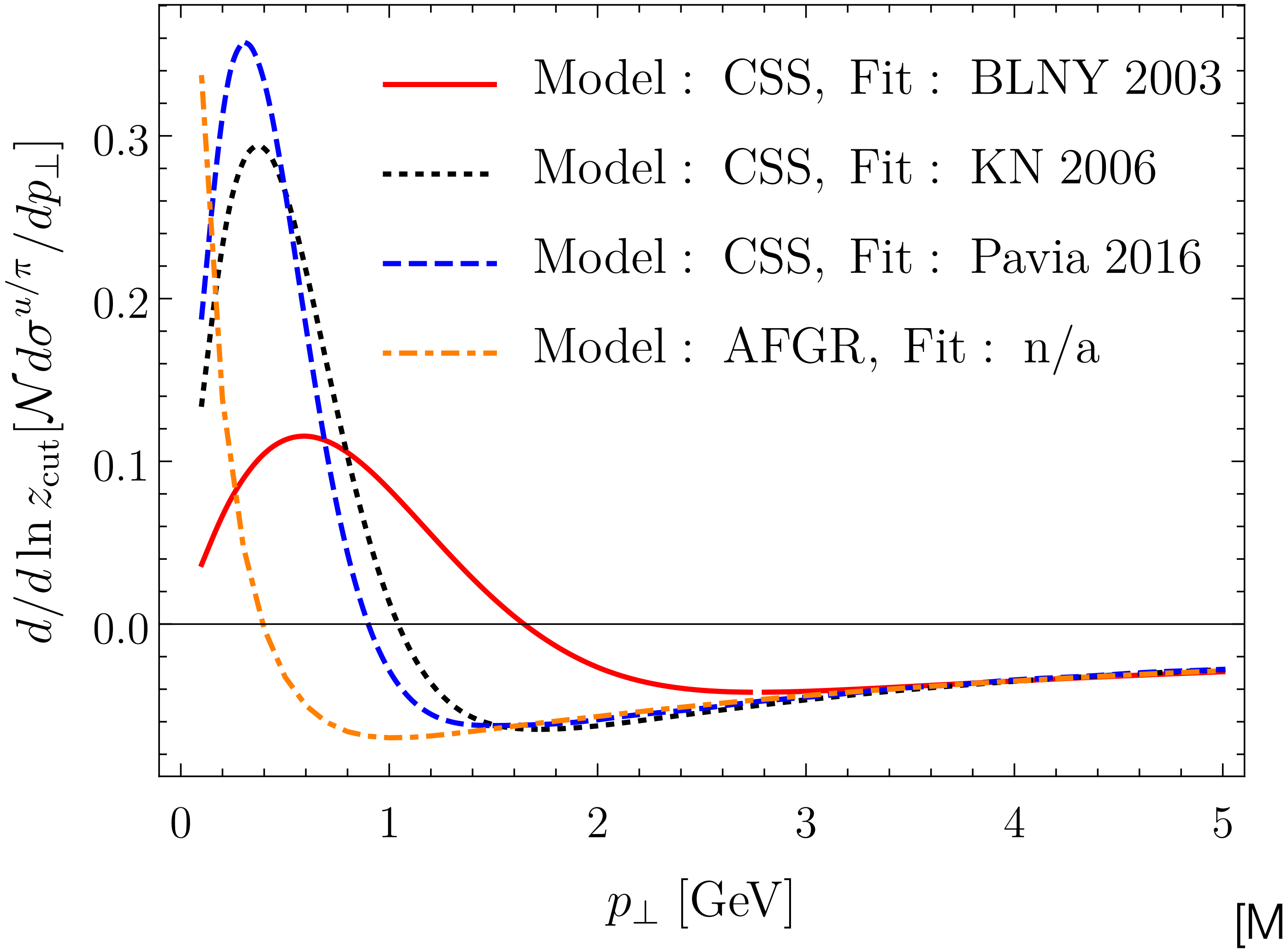
TMD fragmentation with standard jet axis



[Kang, Liu, Ringer, Xing]

- Described by same TMD fragmentation functions as in SIDIS
- Nonperturbative Sudakov has large uncertainties → opportunity to constrain them if other soft physics under control

TMD fragmentation with modified mass drop



[Makris, Neill, Vaidya]

- Grooming reduces soft sensitivity and remove non-global logs
- Dependence on grooming parameter $z_{\rm cut}$ can be used to constrain nonperturbative model

Conclusions

- Jets provide a new avenue to study TMDs
- Jet shape and TMD fragmentation with winner-takes-all axis:
  - Robust and process independent measurement
  - Theoretically clean
  - Power law instead of Sudakov
  - New window on nonperturbative physics
- Potential applications from nuclear to particle physics

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Thank you!