Sub-jet Structure as a Discriminating Quenching Probe

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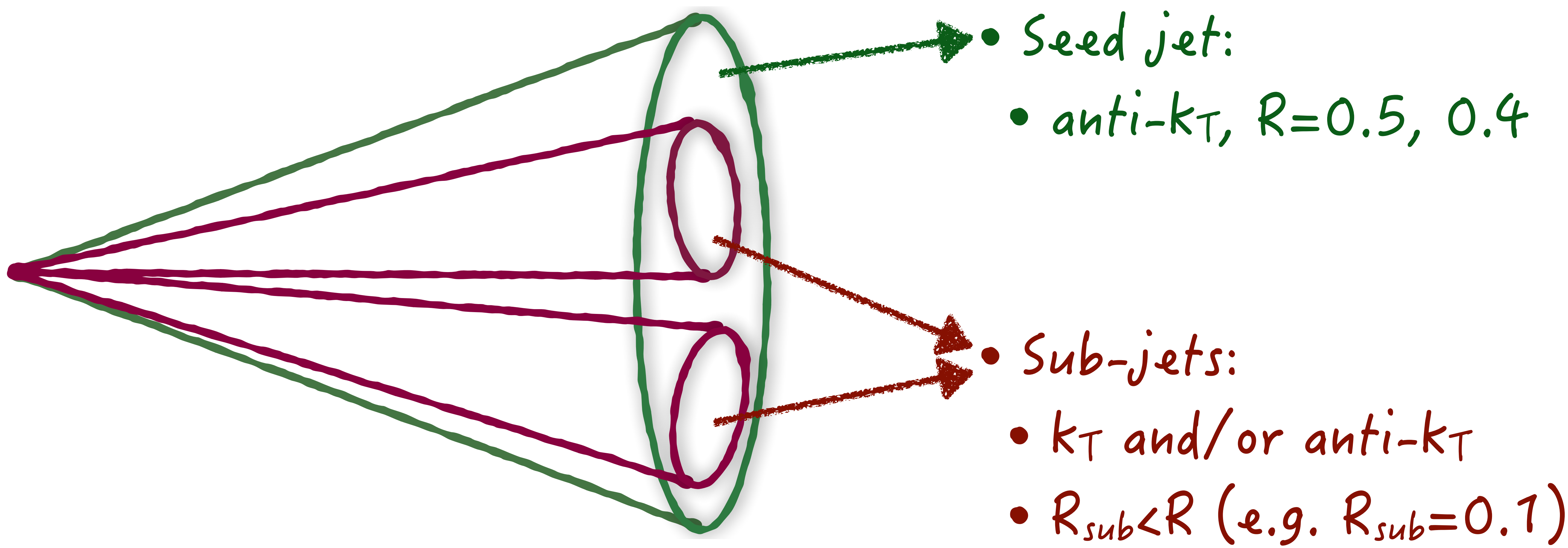
Novel observable for jet quenching

- The problem we want to answer: **define an observable that**
  - Is strongly sensitive to internal jet structure modifications and can differentiate between jet quenching mechanisms
  - Is attractive experimentally
    - Has limited sensitivity to heavy-ion background and its fluctuations
    - Needs no p_{T}/constituent cuts and/or no additional background removal
  - Is attractive theoretically
    - Collinear and IR safe
    - Calculable in theoretical frameworks with little sensitivity to hadronization

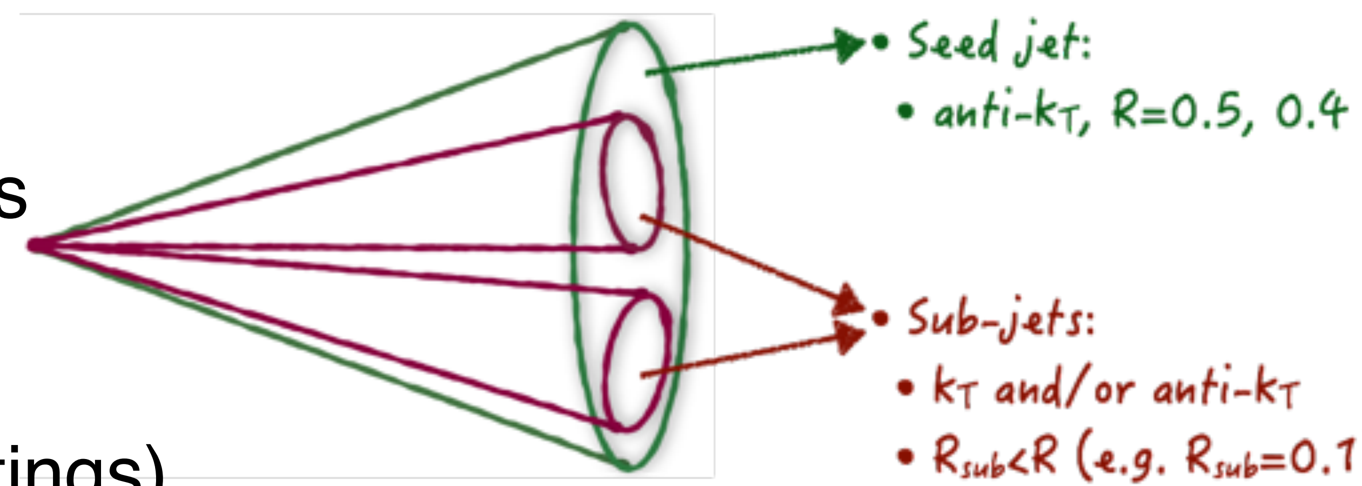
Exploring Jet Structure with Sub-jets



- Sub-jets: re-clustering the constitutes in a jet (possibly a different algorithm)
  - Smaller radius/area — reduces the background fluctuations and pileup
  - Opening the degree of freedom in jets — details of fragmentation with decreased dependency on hadronic DOFs, provides sensitivity to details of the parton radiation/shower

Setup

- Simulation of $\sqrt{s}$ = 2.76 TeV collisions
  - Vacuum: PYTHIA 8, tune 4C
  - Medium: 0-10% Pb–Pb collisions
    - Q-PYTHIA ($\hat{q}$ = 6 GeV^{2}fm^{-1})
    - JEWEL (default HEP forge settings)



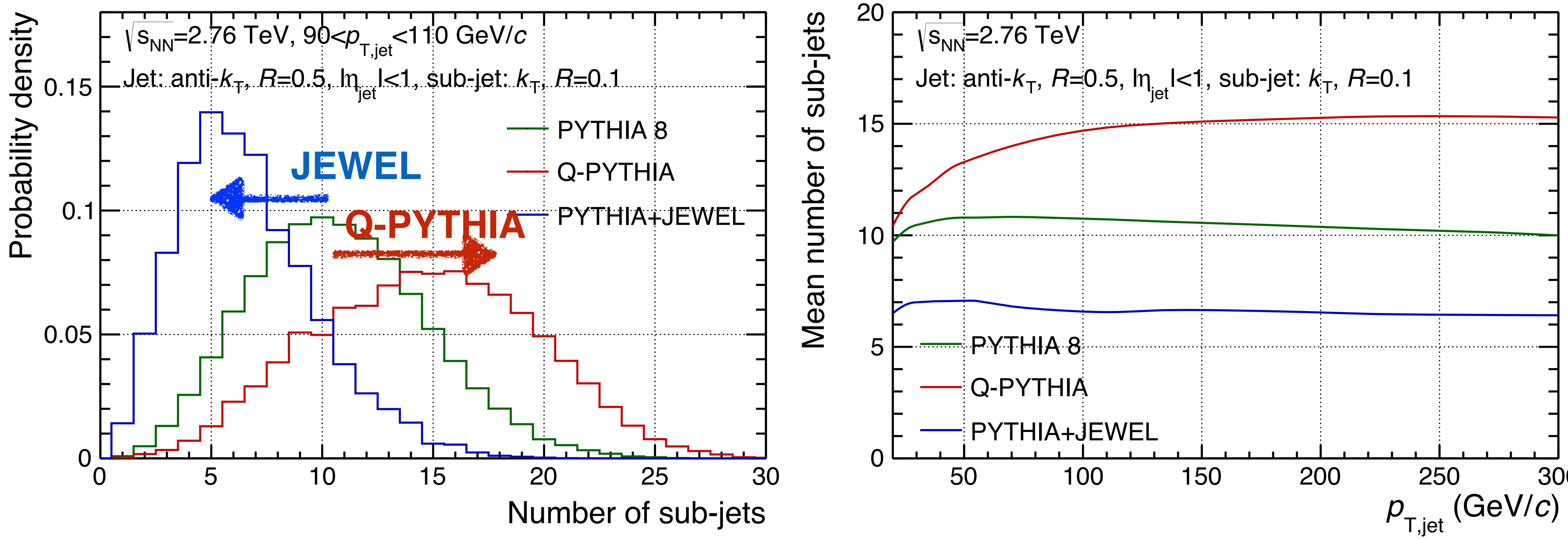
- Jet: anti-k_T, R=0.5 (0.4), sub-jet: k_T, R=0.1

- Q-PYTHIA:
  - medium induced gluon radiation
  - modified vacuum splitting function
  - soft collimated radiation

- JEWEL:
  - radiative+elastic energy loss
  - LPM effect
  - large energy redistribution

1. T. Sjostrand, S. Mrenna, and P. Skands, **PYTHIA 6.4 Physics and Manual**, JHEP 0605 (2006) 026., note PYTHIA 8 used as well
2. Jet reconstruction: M. Cacciari, G. P. Salam, G. Soyez, **FastJet User Manual**, Eur.Phys.J. C72 (2012) 1896.
3. Q-PYTHIA: N. Armesto, L. Cunqueiro and C. A. Salgado, **A Medium-modified implementation of final state radiation**, Eur.Phys.J. C63 (2009) 679-690.
4. JEWEL: K. C. Zapp, F. Krauss and U. Wiedemann, **A perturbative framework for jet quenching**, JHEP 1303 **(2013) 080.**

Subjets within jets…



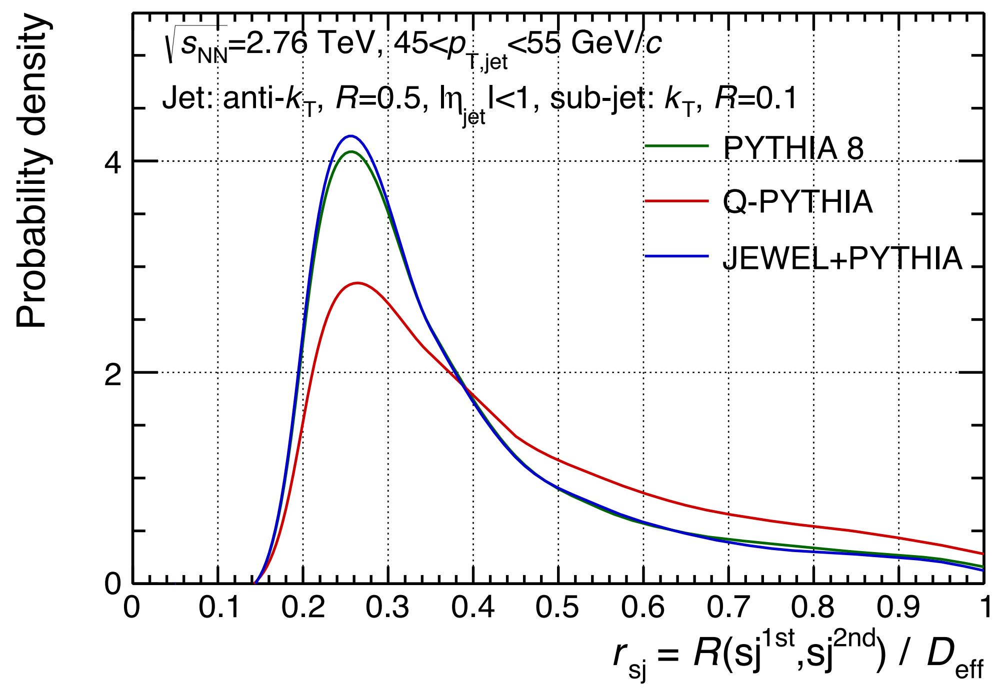
Different multiplicity of sub-jets in the two models

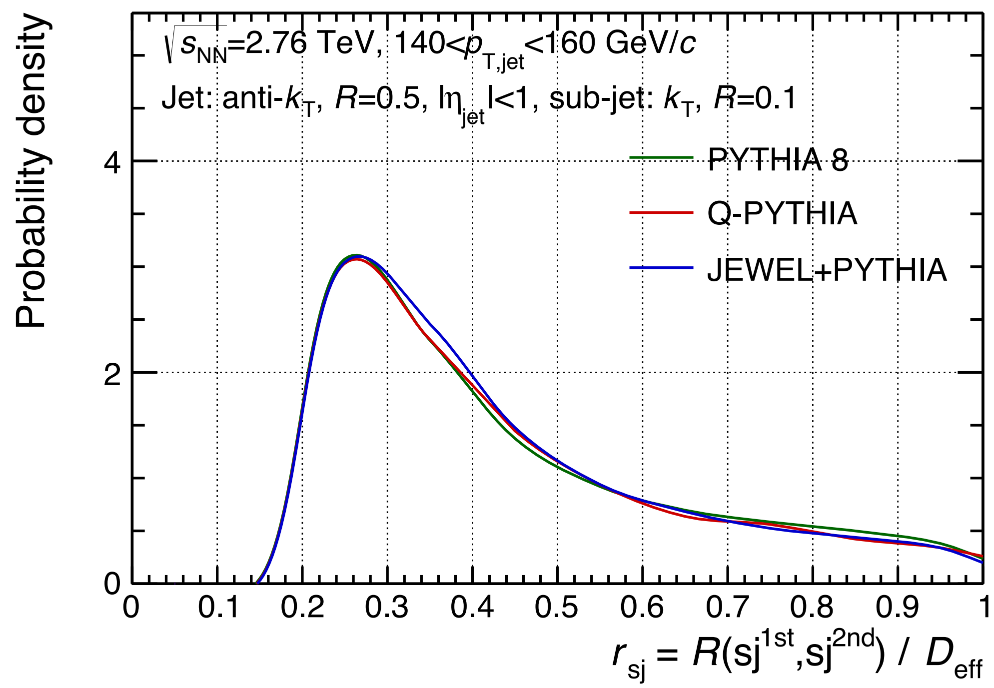
A promising tool for differentiating quenching mechanisms?

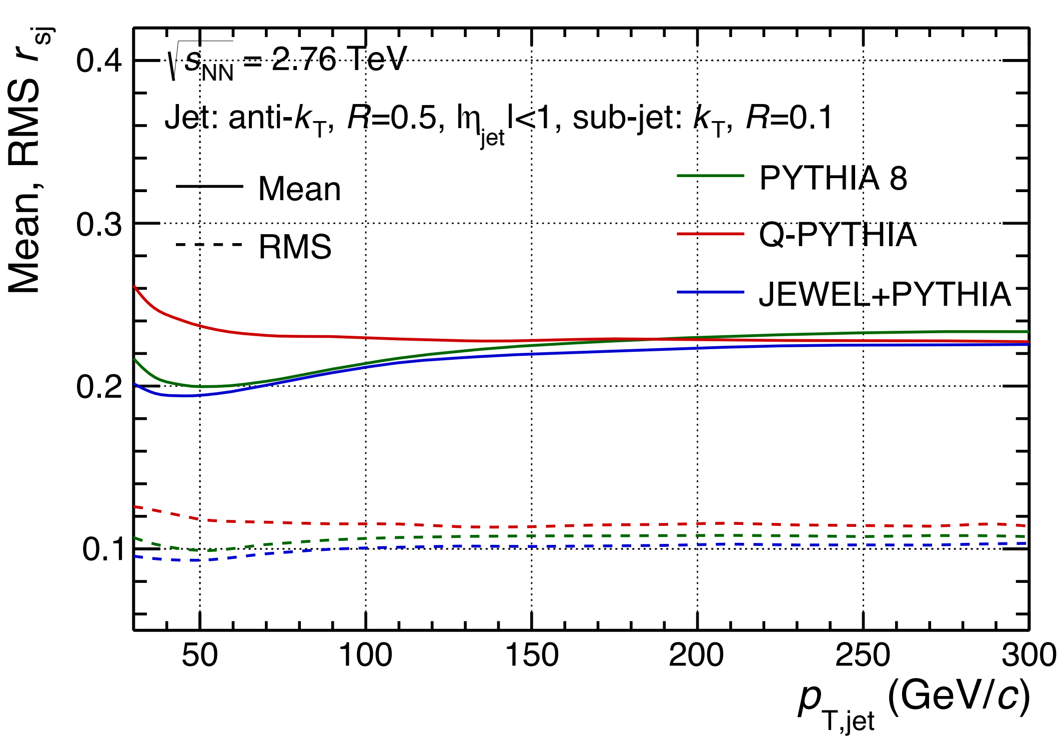
Note: behavior is weakened by the presence of HI background

Some properties of jet substructure - distance

$$r_{\rm sj} = R({\rm sj}^{\rm 1st}, {\rm sj}^{\rm 2nd})/D_{\rm eff}, \ \ D_{\rm eff} = 2\sqrt{A_{\rm jet}/\pi}$$



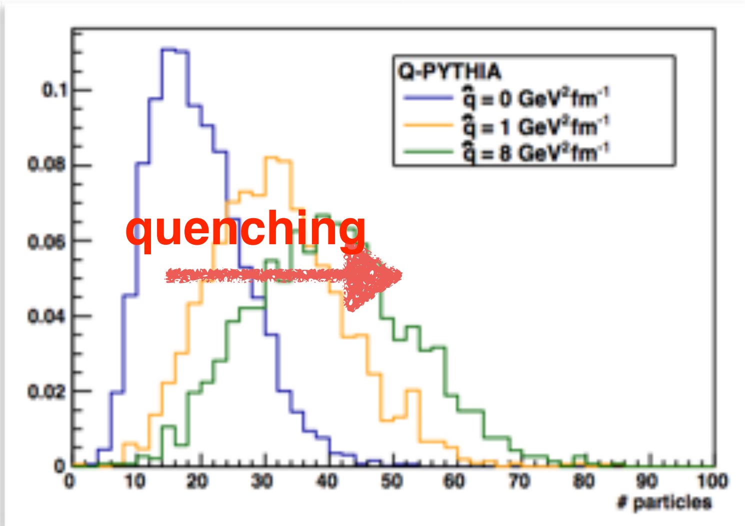


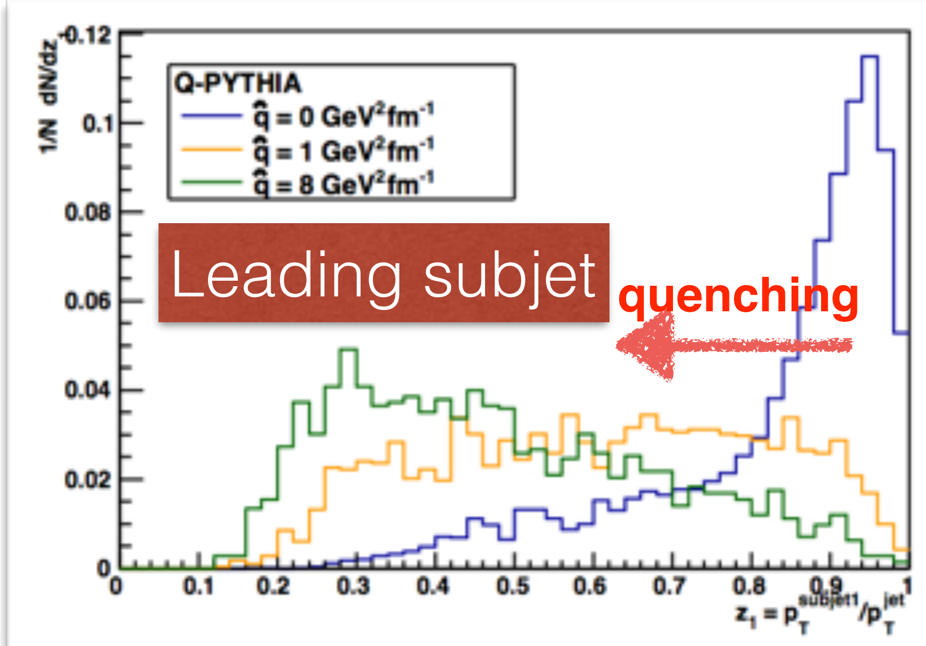


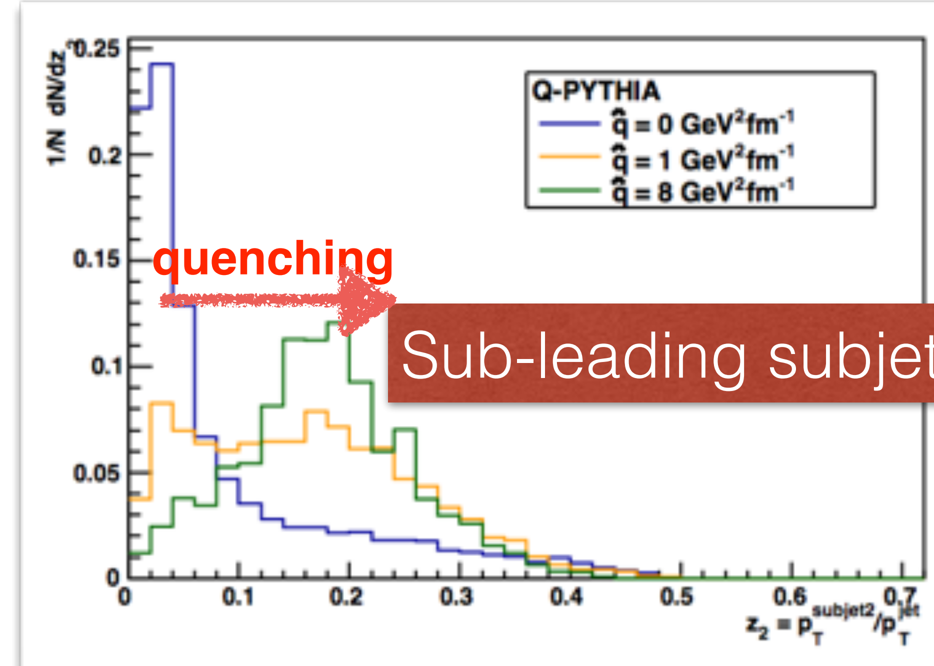
- Distance between the two hardest sub-jets is systematically broader in Q-PYTHIA than in vacuum — opposite feature seen in JEWEL
  - however, it is a small effect and the feature is not robust in heavy-ion background
- At high jet $p_{\rm T}$ — $r_{\rm sj}$ is insensitive to medium effects

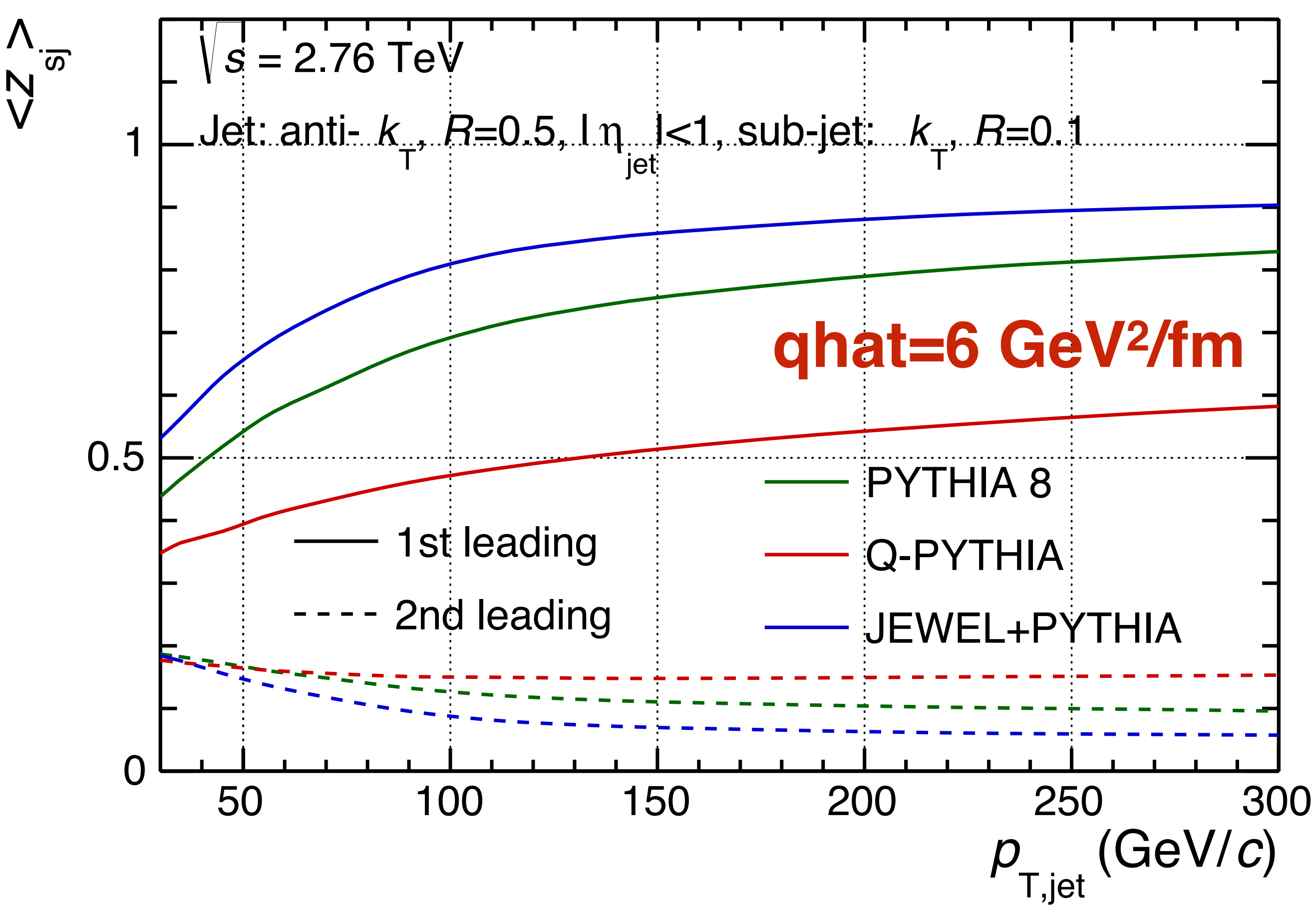
Some properties of jet substructure - p_T fraction

Q-PYTHIA example - sensitivity to quenching









$$z_{\rm sj} = p_{\rm T,sj}/p_{\rm T,jet}$$

- z_{sj} - evolves with jet p_T (slow growth at high-p_T)
  - Useful for disentangling quenching mechanisms
  - CAVEAT: observable strongly susceptible to background (via jet p_T and sub-jet p_T)
  - **Is there a better one?**

Practical observation - robust observable?

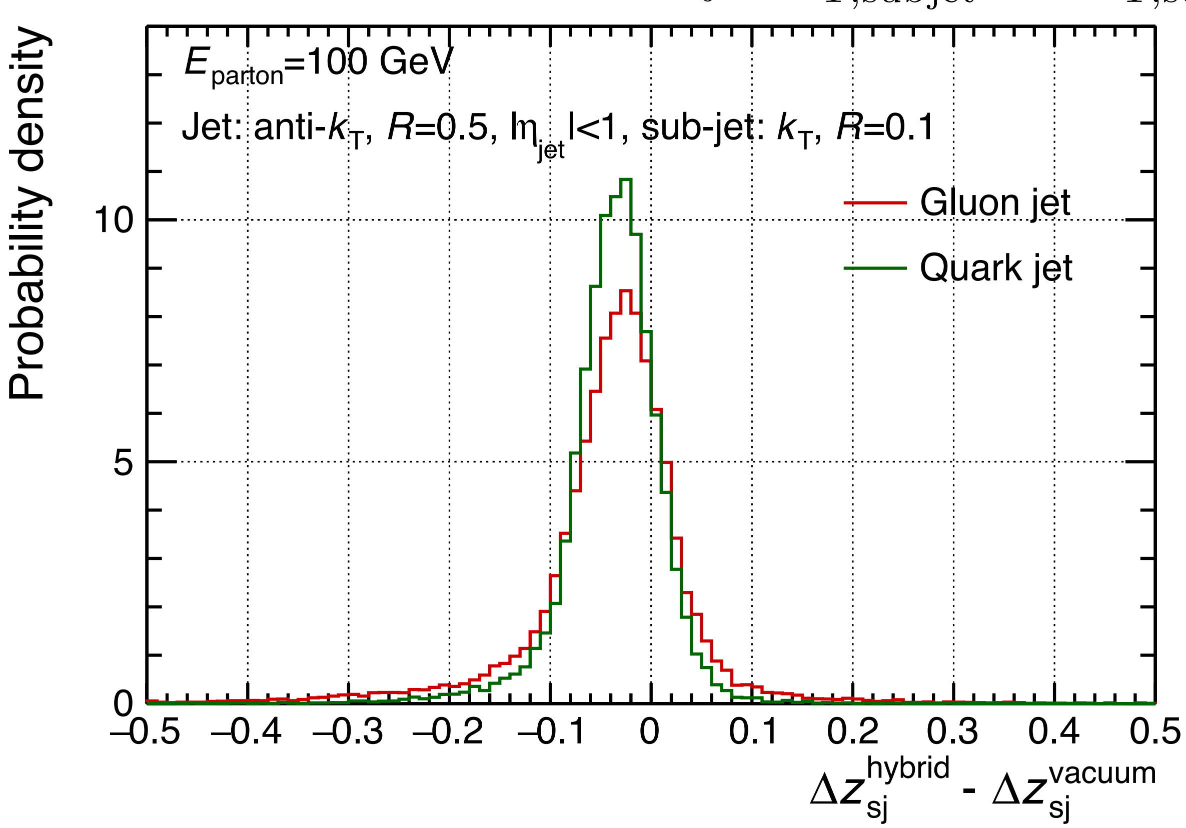
The local background for the two sub-jets
is (to a great extend) similar
=> use the p_T difference between the two leading sub-jets
— In the leading order (FastJet median background subtraction):

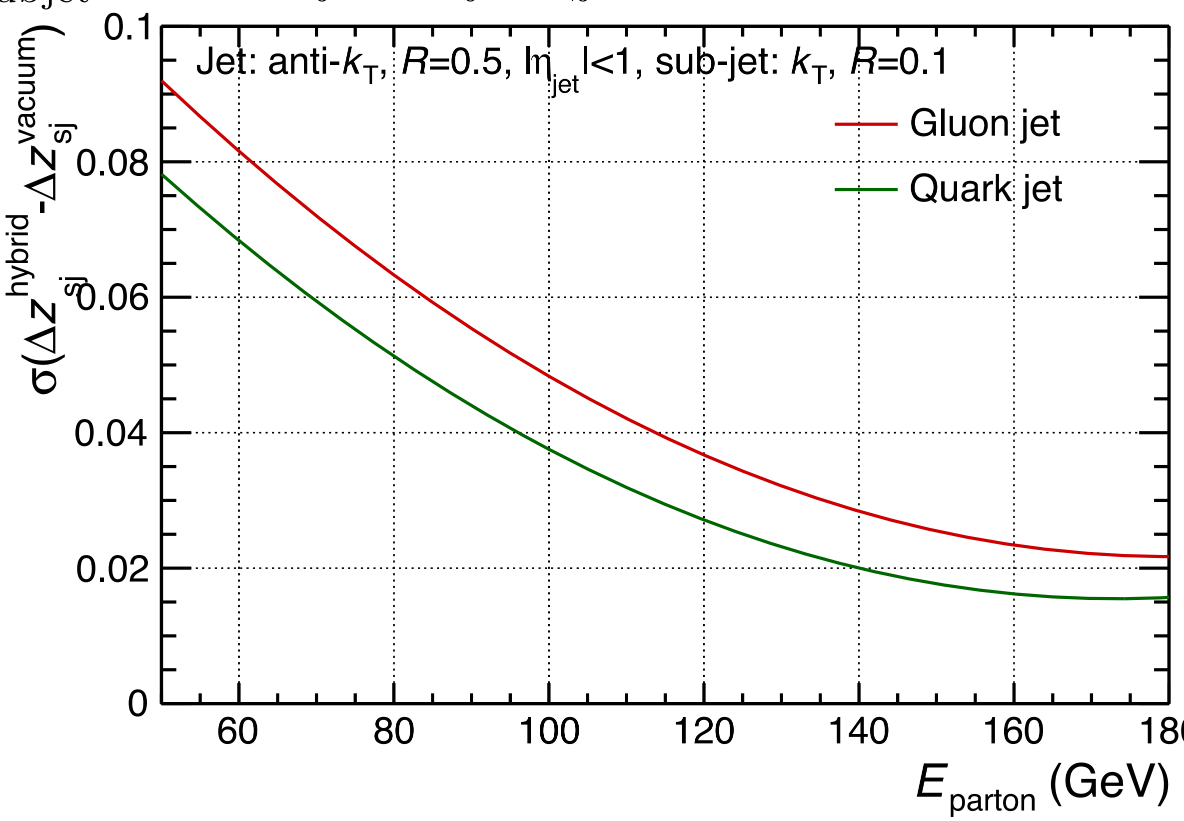
$$\Delta p_T^{sj12} = p_T^{sj1} - \rho^{BG} \times A^{sj1} \pm \delta^{BG}(A^{sj1}) - (p_T^{sj2} - \rho^{BG} \times A^{sj2} \pm \delta^{BG}(A^{sj2}))$$

background terms cancel out for locally uniform background

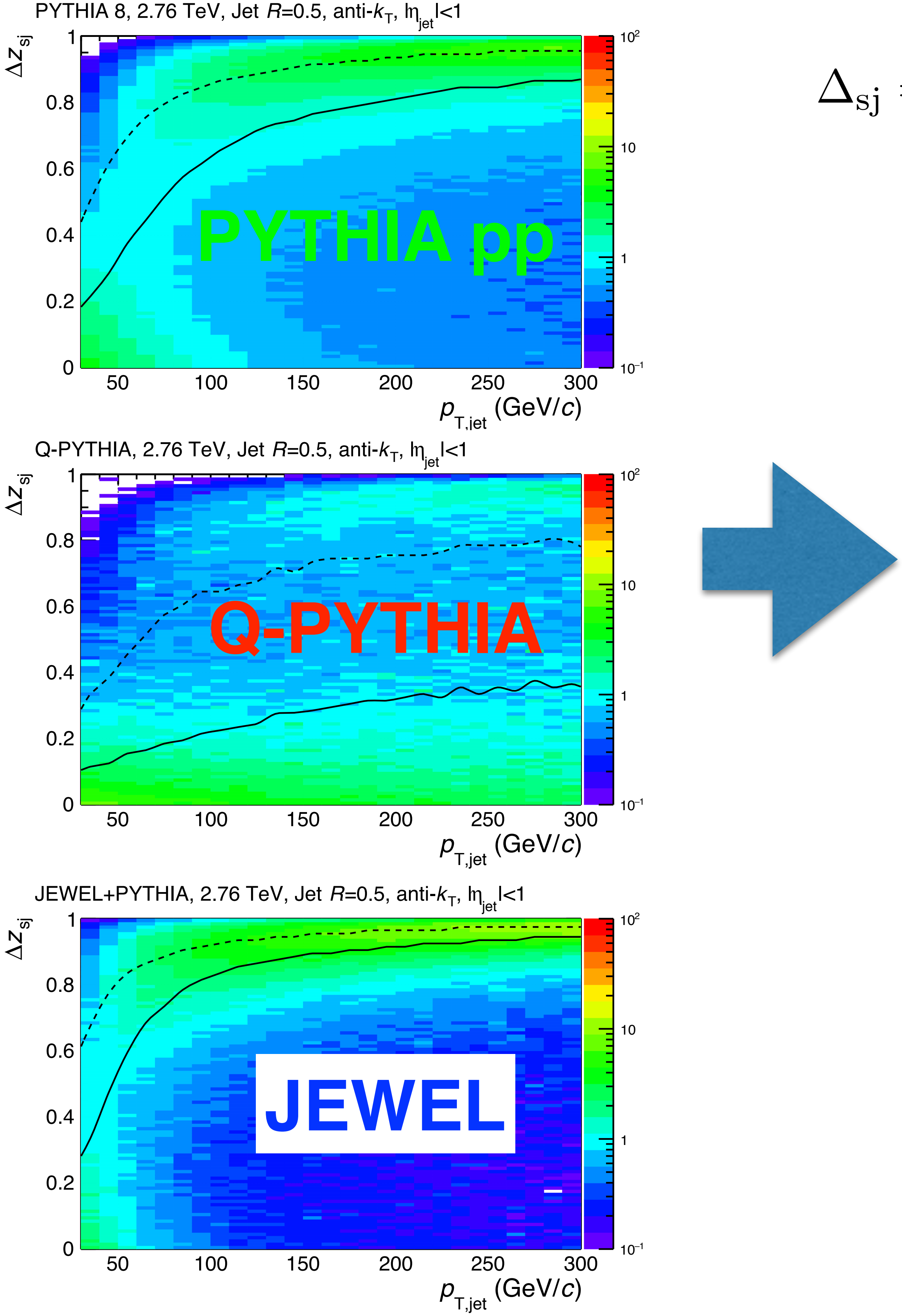
Tests on a realistic LHC heavy-ion background show a promising behavior

$$\Delta_{\mathrm{sj}} = p_{\mathrm{T,subjet}}^{\mathrm{1st\ leading}} - p_{\mathrm{T,subjet}}^{\mathrm{2nd\ leading}}, \quad \Delta z_{\mathrm{sj}} = \Delta_{\mathrm{sj}}/p_{\mathrm{T,jet}}$$

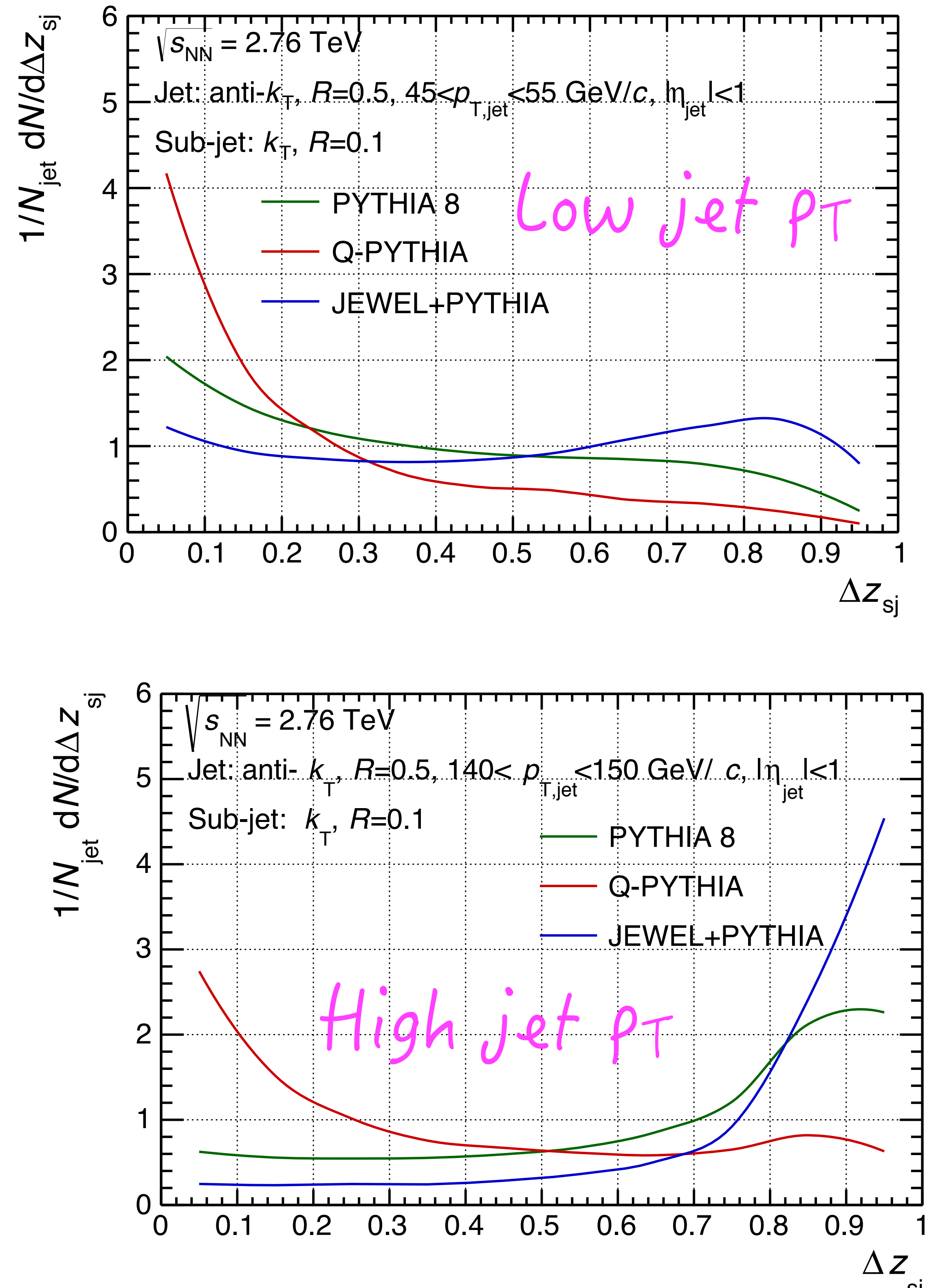




Medium Modified Jet Substructure



$$\Delta_{\rm sj} = p_{\rm T,subjet}^{\rm 1st\ leading} - p_{\rm T,subjet}^{\rm 2nd\ leading}, \quad \Delta z_{\rm sj} = \Delta_{\rm sj}/p_{\rm T,jet}$$



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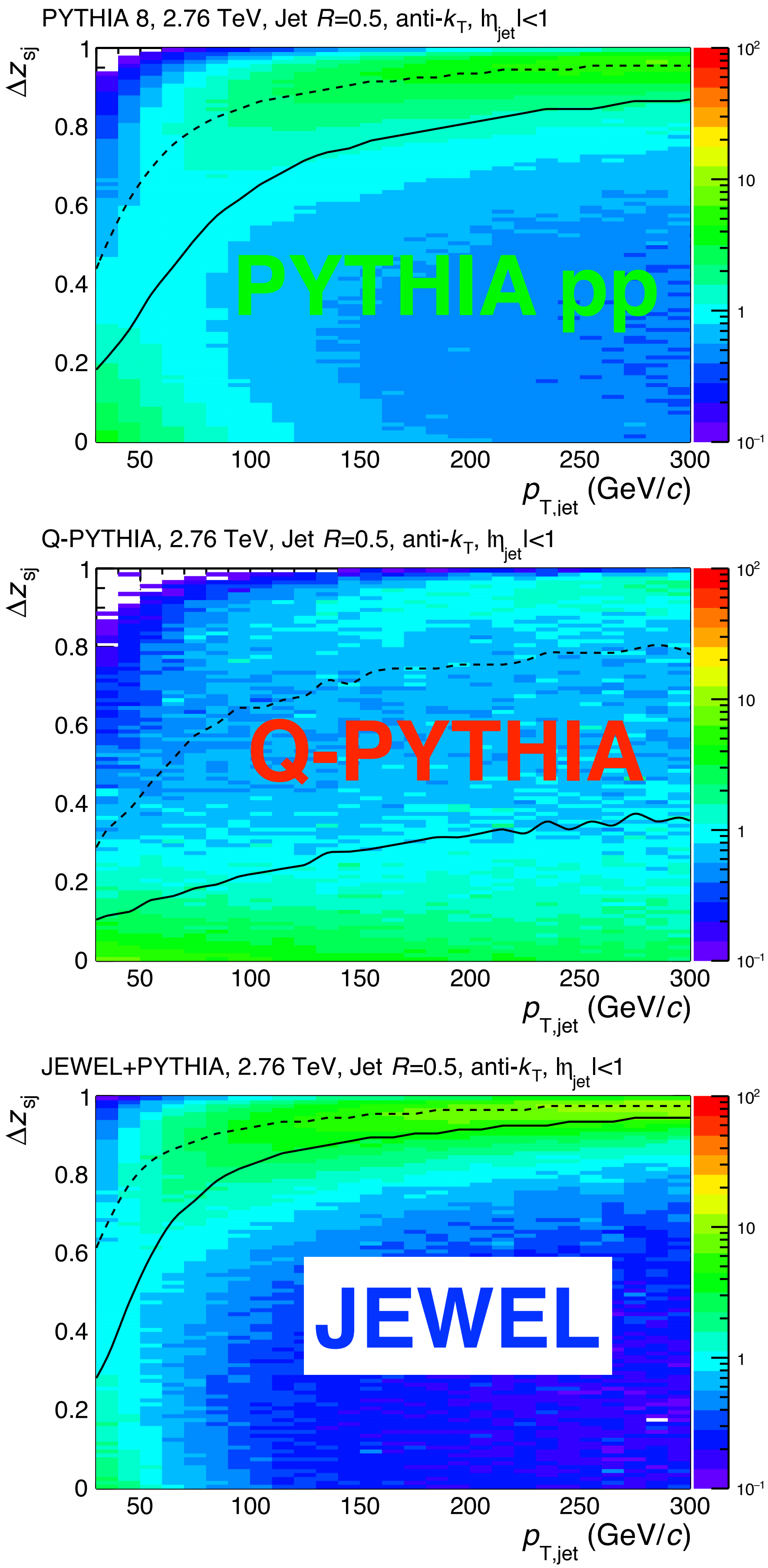
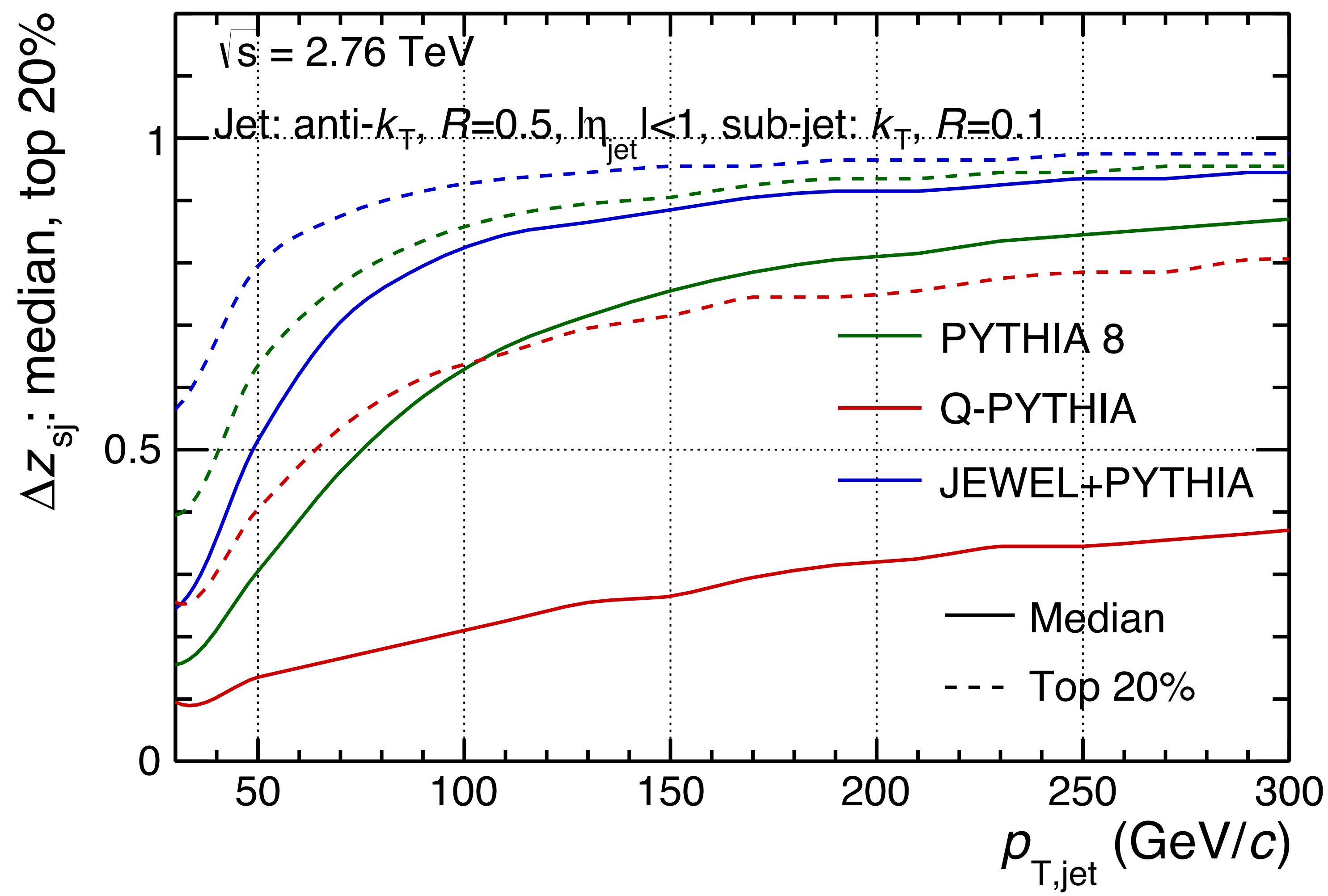


$$\Delta_{\text{sj}} = p_{\text{T,subjet}}^{\text{1st leading}} - p_{\text{T,subjet}}^{\text{2nd leading}}, \quad \Delta z_{\text{sj}} = \Delta_{\text{sj}}/p_{\text{T,jet}}$$



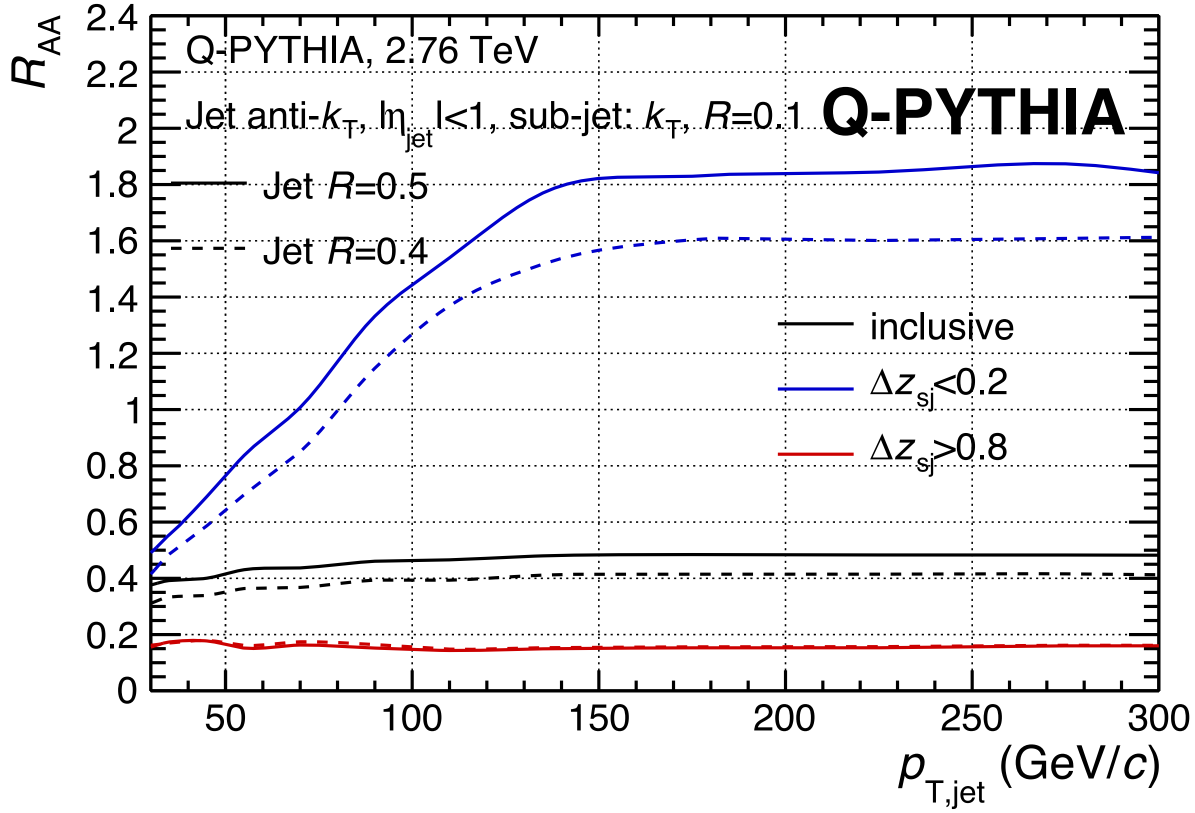
- **Quantiles** of Δz_{sj} evolve with jet p_{T} and are sensitive quenching modeling
- Robust selections is possible

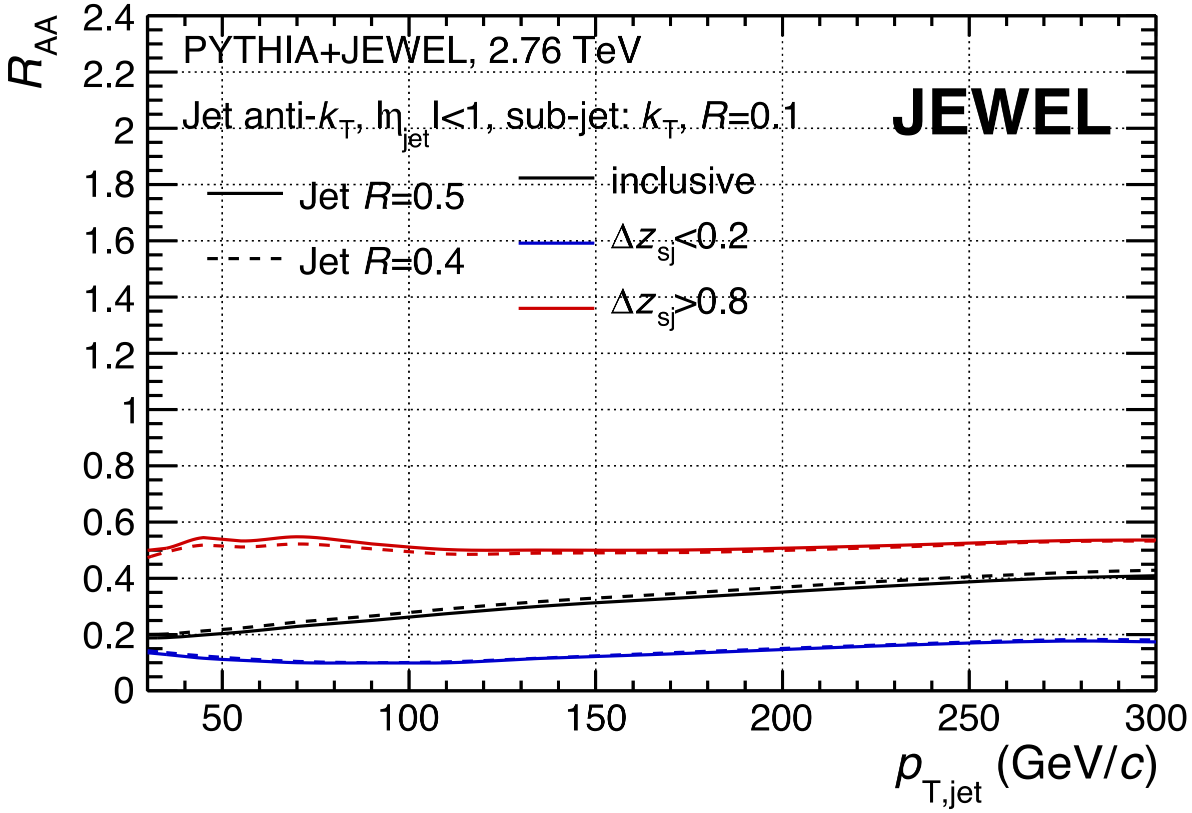
Impact on known observables - examples…

Impact on inclusive observables: Δz_{sj} Triggered Jet R_{AA}

$$R_{AA}(\Delta z_{sj}) = \frac{d\sigma_{medium}/dp_T|_{\Delta z_{sj}}}{d\sigma_{vacuum}/dp_T|_{\Delta z_{sj}}}$$

- R_{AA} reference:
  - Q-PYTHIA — PYTHIA6
  - JEWEL — JEWEL vacuum

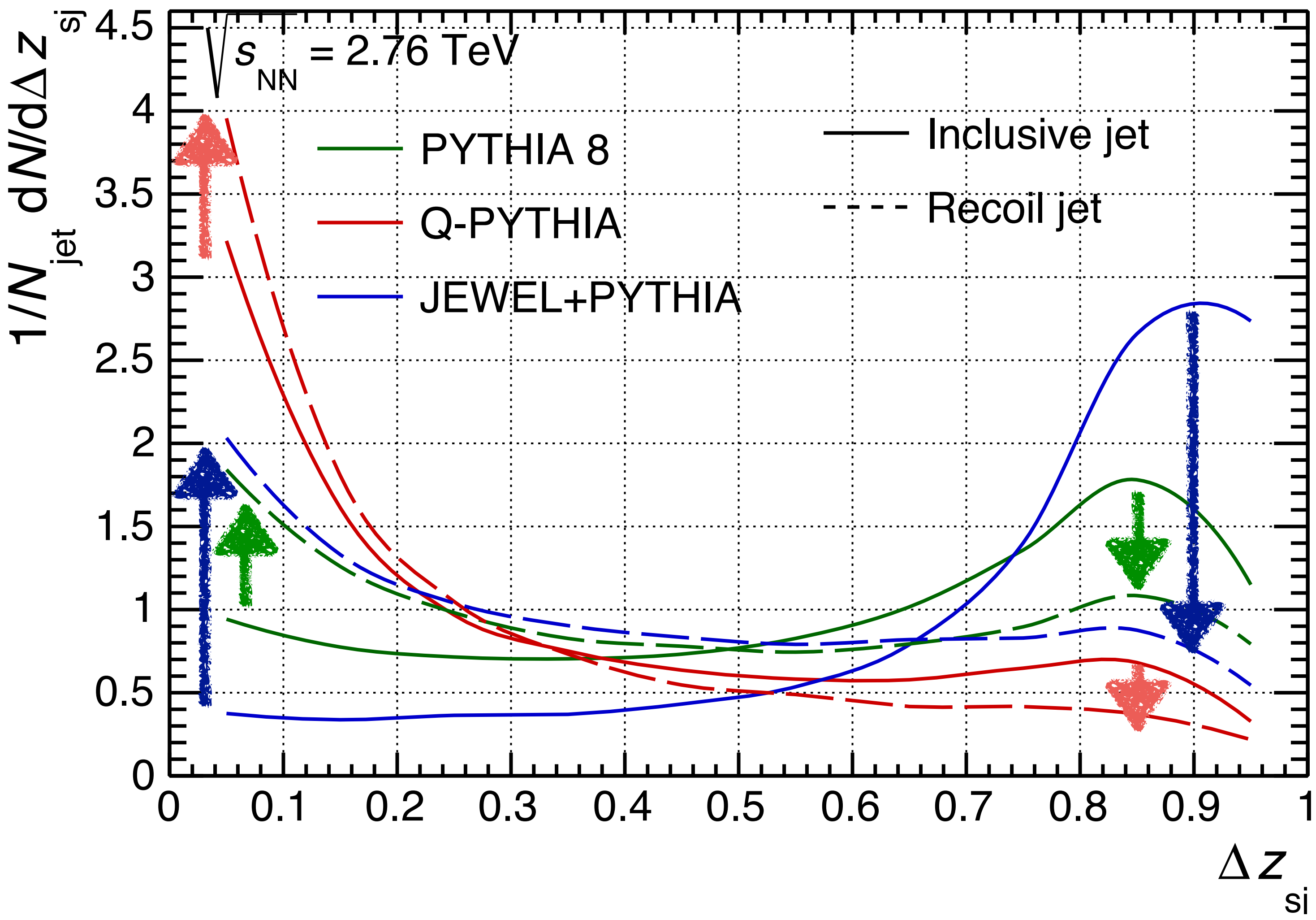




- Jet $R_{AA}(\Delta z_{sj})$ - a simple measurement allowing to study quenching features
  - A jet by jet selection on Δz_{sj} carries little experimental difficulties (both in pp and AA)
- Differences for Δz_{sj} selected jets with respect to inclusive R_{AA}:
  - For large Δz_{sj} : R_{AA} suppressed in Q-PYTHIA but enhanced in JEWEL
    - The opposite behavior for small Δz_{sj}
- Small R-jet dependence only for Q-PYTHIA

Note: These are shown as examples - different selections on sub-jet p_T difference possible - e.g. moments of the distributions etc.)

Coincidences: Jet Trigger - Sub leading Recoil Jet

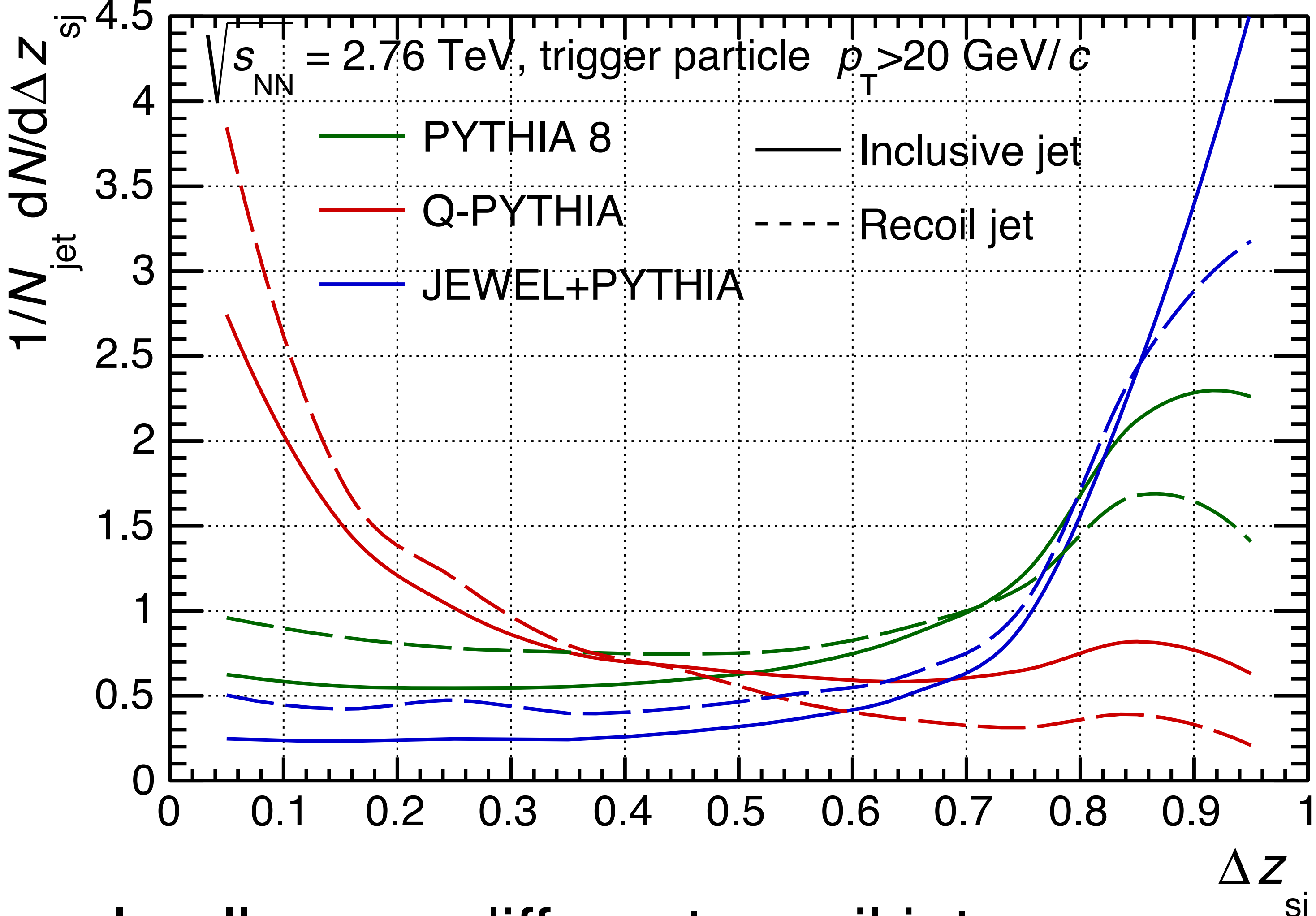


- The Δz_{sj} of the recoil jets
  - Trigger jets — leading jet in $p_T > 80$ GeV/c
  - Recoil jets — sub-leading jet in $p_T > 20$ GeV/c
  - Azimuthal Requirement:
    - ϕ(leading, sub-jet) > $\pi/2$

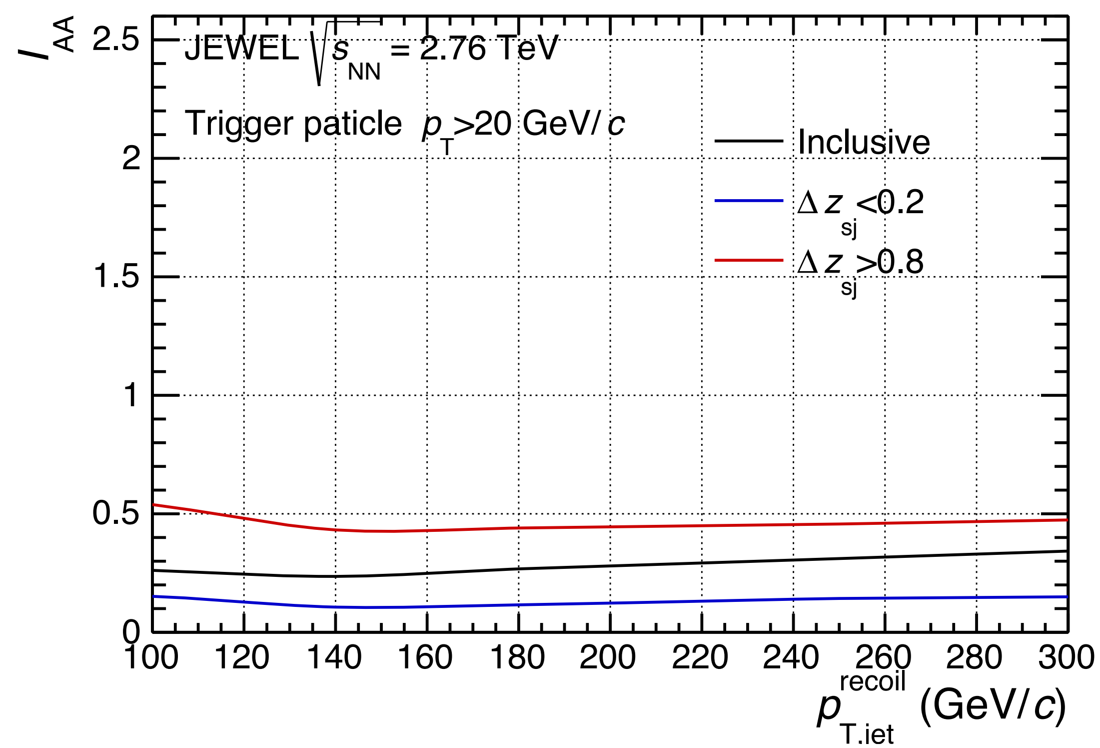
- JEWEL: Strong modifications for sub-leading/recoil jets
  - Similar feature (but quantitatively weaker) seen for “vacuum” di-jets - sign of different fragmentation selection
  - Q-PYTHIA: stronger modification for recoils jets; qualitatively similar as for leading jets

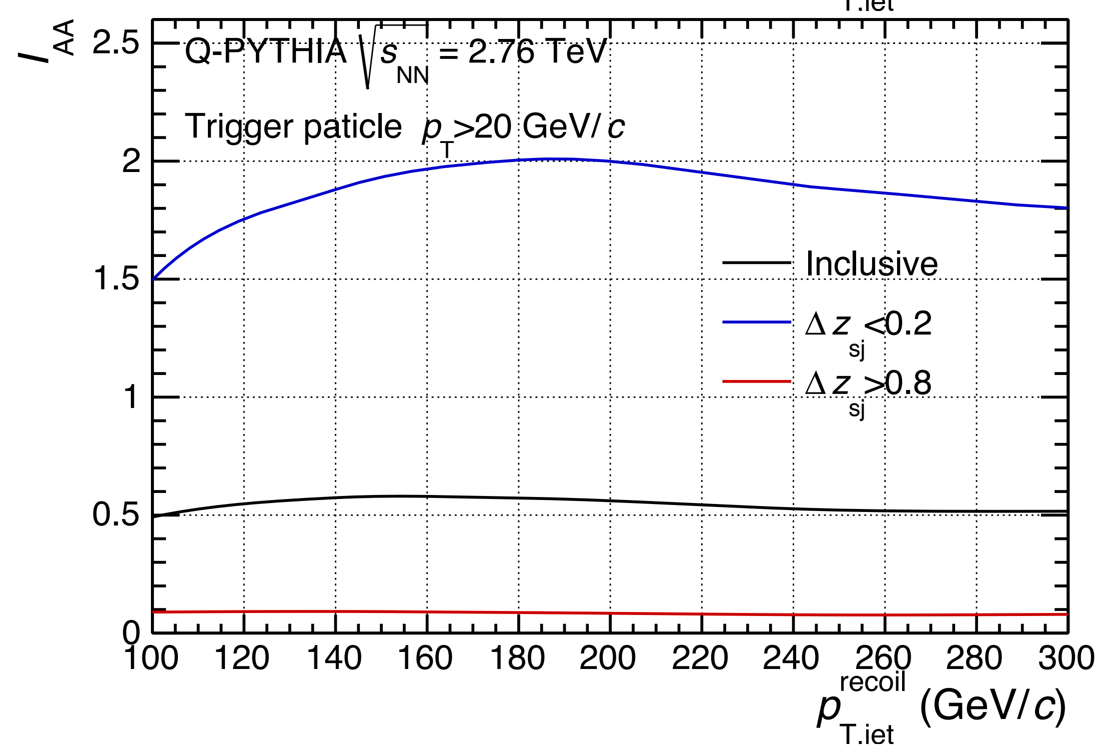
hadron-jet coincidences

Recoil jets: 140 < pT < 160 GeV/c



- The Δz_{sj} of the recoil jets
  - Trigger particle — leading, pT > 20 GeV/c
  - Requirement — ϕ(hadron, recoil-jet)>2/3π





- In all cases different recoil jet fragmentation is selected (trigger hadron selects the hardest jets)
- Weak dependence on jet p_T > 100 GeV/*c*
- As expected inverted I_{AA} for the lowest and highest Δz_{sj}

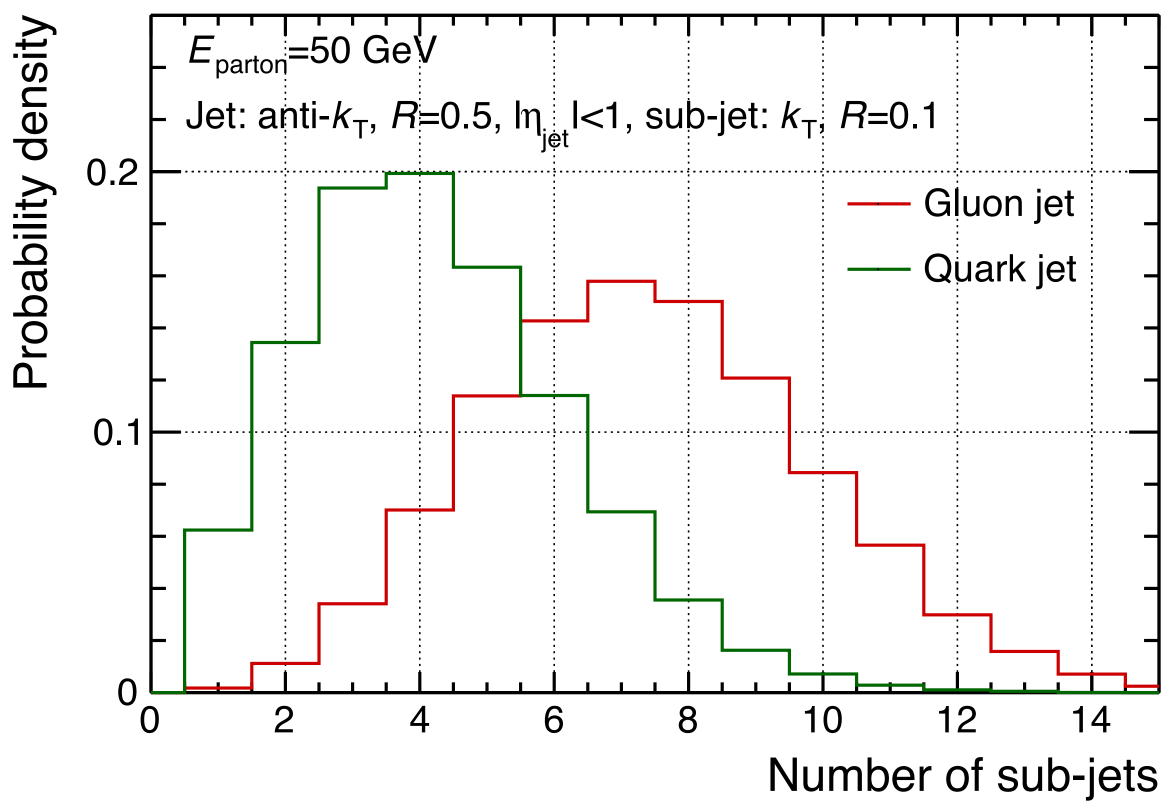
Conclusions and outlook

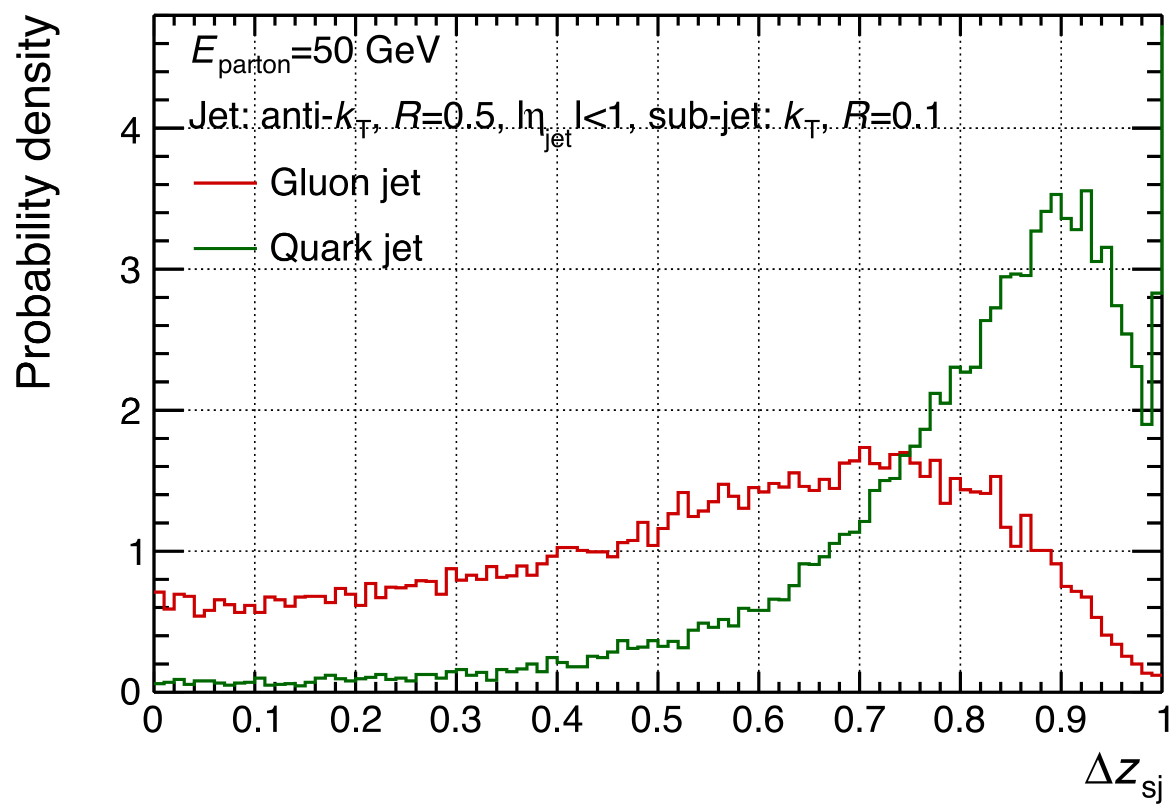
Difference of subjet-p_T:

- Sensitive to quenching mechanism
- Experimentally simple to implement and robust against background
- IR&C safe and calculable in theoretical frameworks

Outlook:

- Using sub-jets and/or Δz_{sj} selections explore
  - Experimental applications! -> measurements rigorously calculable
  - Inclusive and semi-inclusive observables
  - Other jet shape observables
- Study quark and gluon induced fragmentation separately (?)

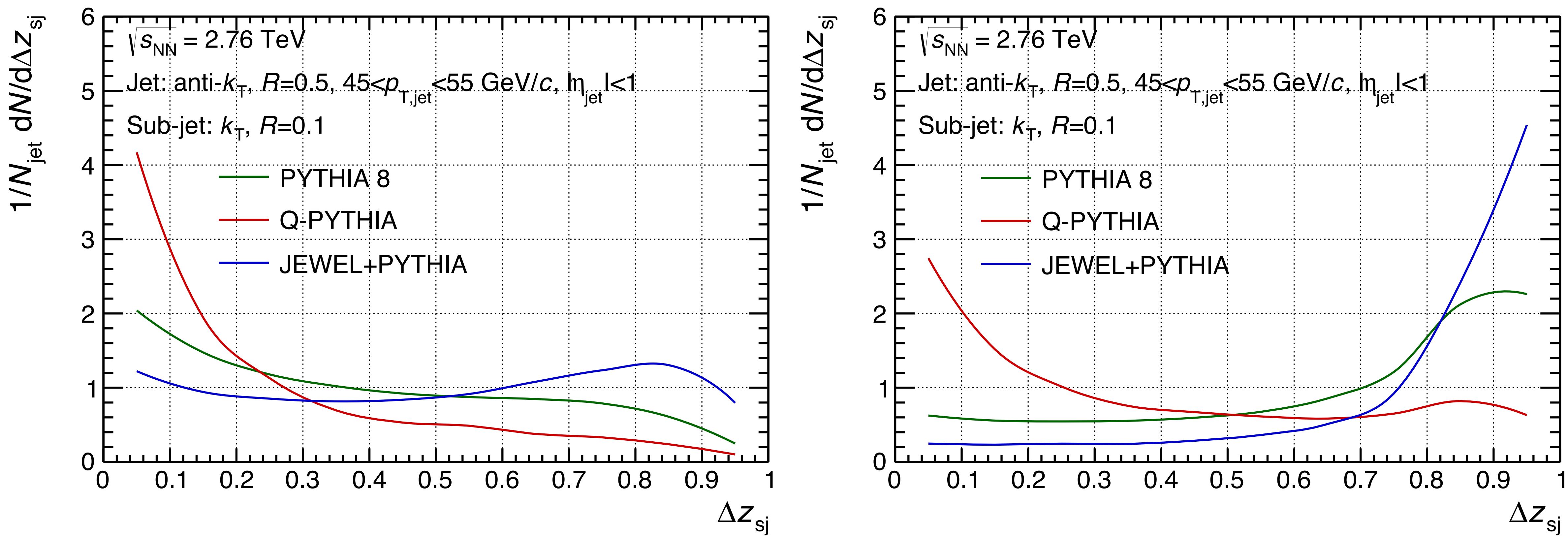




Extra slides

Observation #2

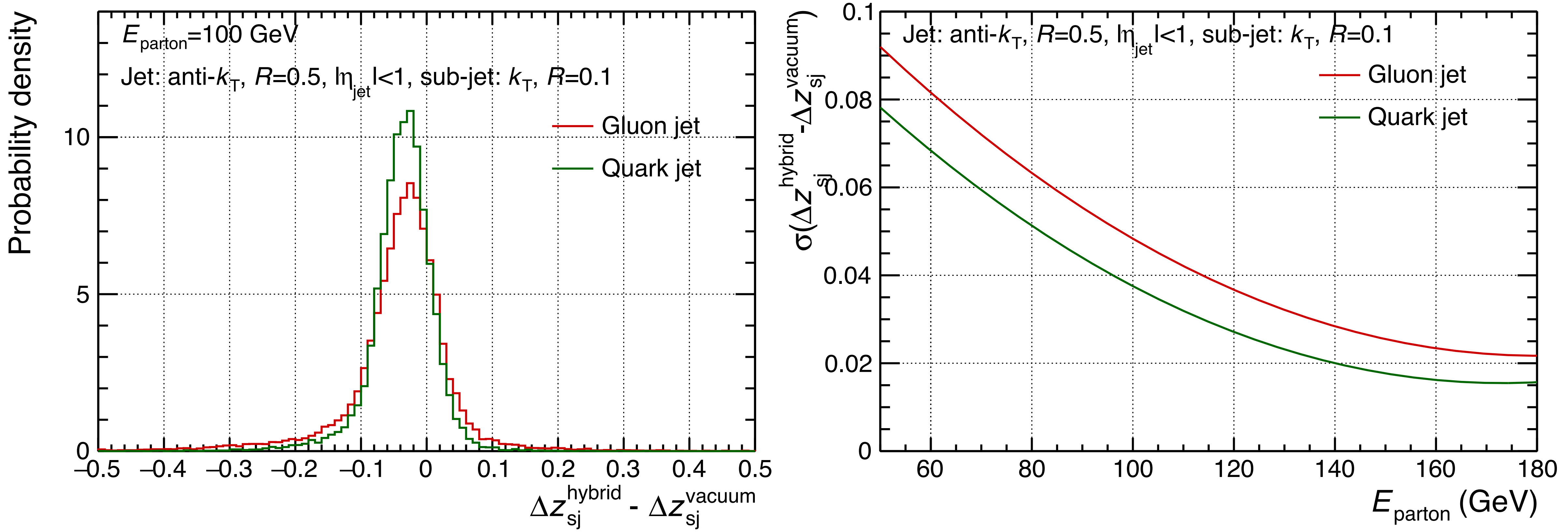
$$\Delta_{\rm sj} = p_{\rm T,subjet}^{\rm 1st\ leading} - p_{\rm T,subjet}^{\rm 2nd\ leading}, \quad \Delta z_{\rm sj} = \Delta_{\rm sj}/p_{\rm T,jet}$$



- Δ_{sj} and/or Δz_{sj} — clean sensitive to jet p_T — opposite behaviors in small and large Δz_{sj}
  - Differences are more visible in higher jet p_T
  - Promising tool of discrimination between models

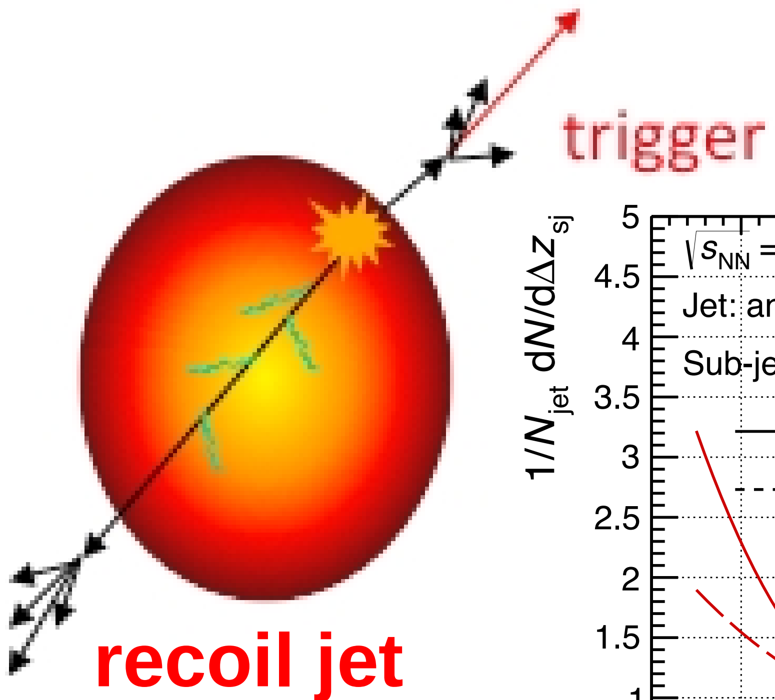
Δz_{sj} — Robust Against HI Background

$$\Delta_{sj} = p_{T,subjet}^{1st\ leading} - p_{T,subjet}^{2nd\ leading}, \quad \Delta z_{sj} = \Delta_{sj}/p_{T,jet}$$

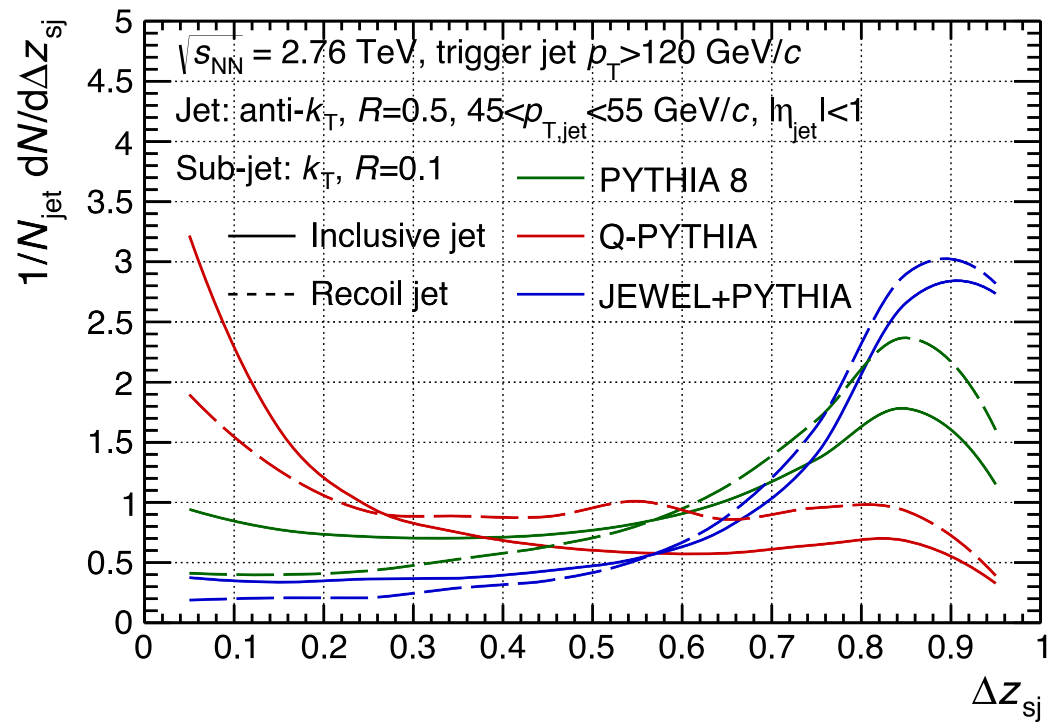


- Inject single energetic gluon and/or quark pairs in PYTHIA — string fragmentation in vacuum
- Hybrid event — embed final state particles in soft background generated according to Boltzmann
- Δz_{sj} — two hardest sub-jets at the same local phase space — robust against the local background fluctuations

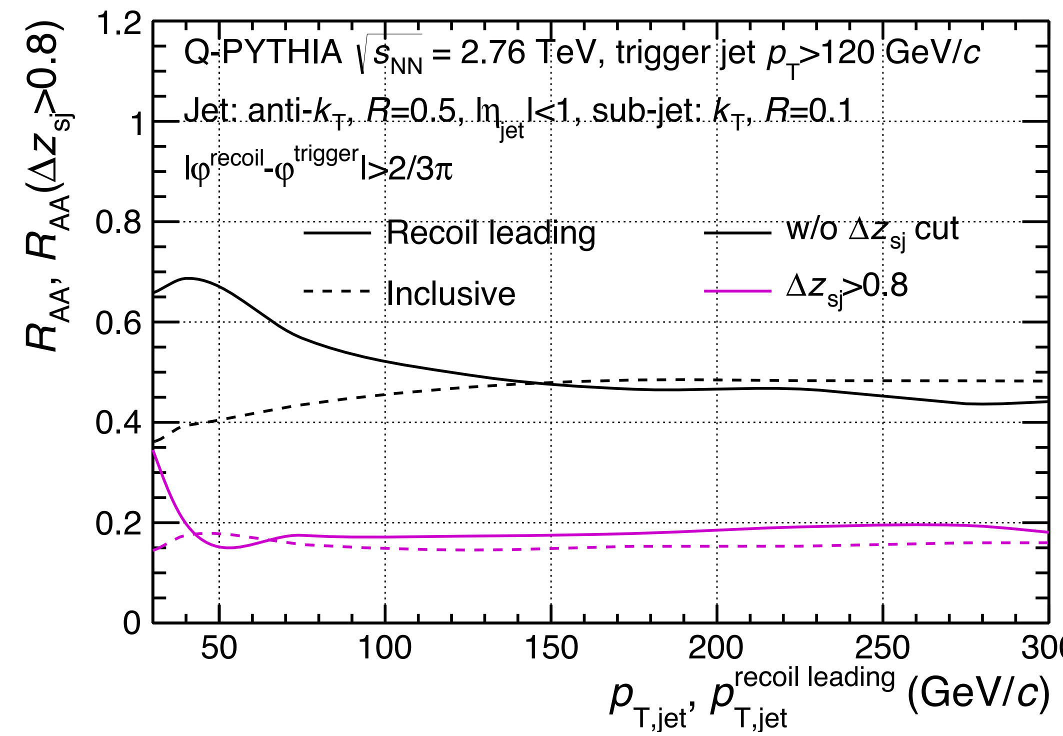
Leading Jet Triggered Recoil Jets



$$|\varphi^{\mathrm{recoil}}_{\mathrm{jet}} - \varphi^{\mathrm{trigger}}| > 2/3\pi$$

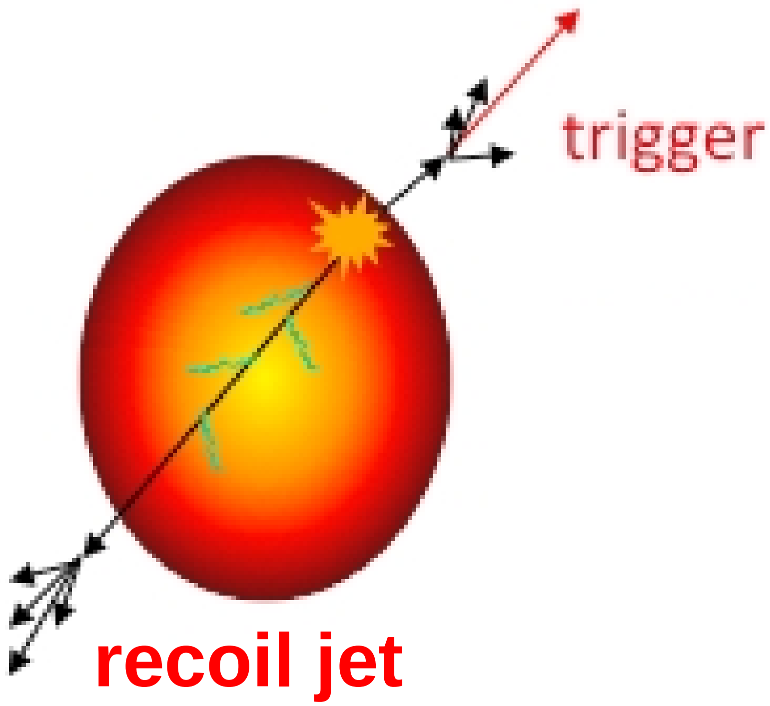


- Trigger jet: leading jet in p_T>120 GeV/c
- Recoil jet: sub-leading jet in p_T>50 GeV/c



- Leading jet triggered recoil sub-leading jets
  - Sensitive to medium modification
  - Tag the path length dependence of medium effect
- Recoil sub-leading jet R_{AA} in Δz_{sj}>0.8 — significant from the sub-leading jets w/o Δz_{sj} cut, consistent with inclusive jets in p_T>50 GeV/c

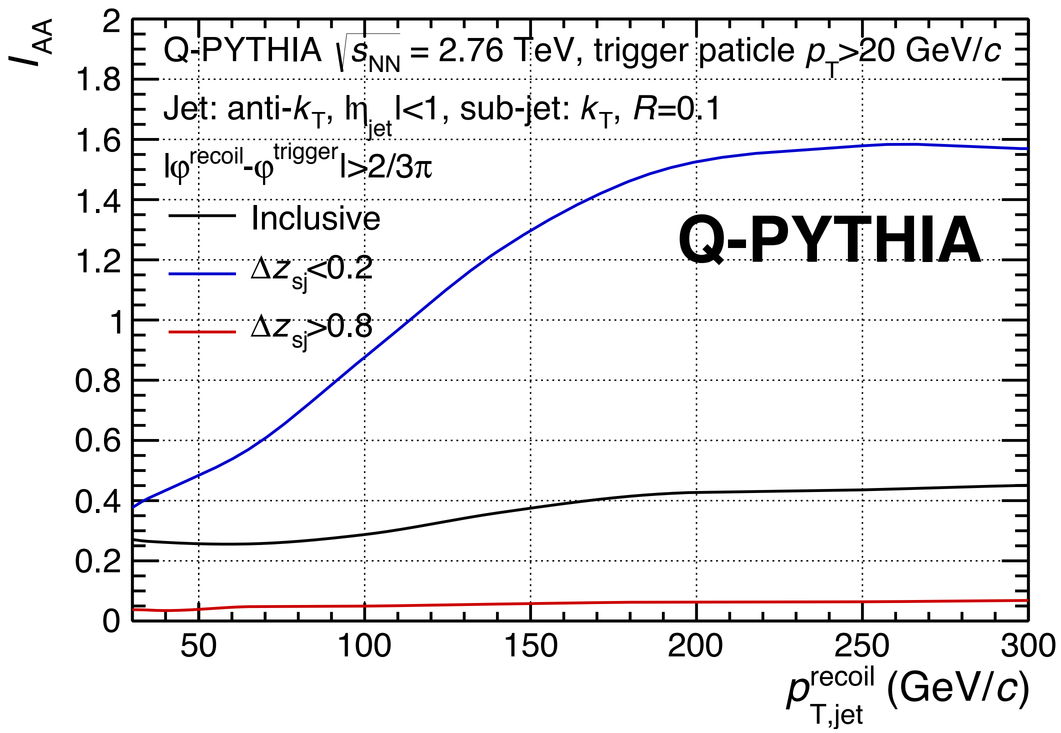
Δz_{sj} Triggered Recoil Jet I_{AA}

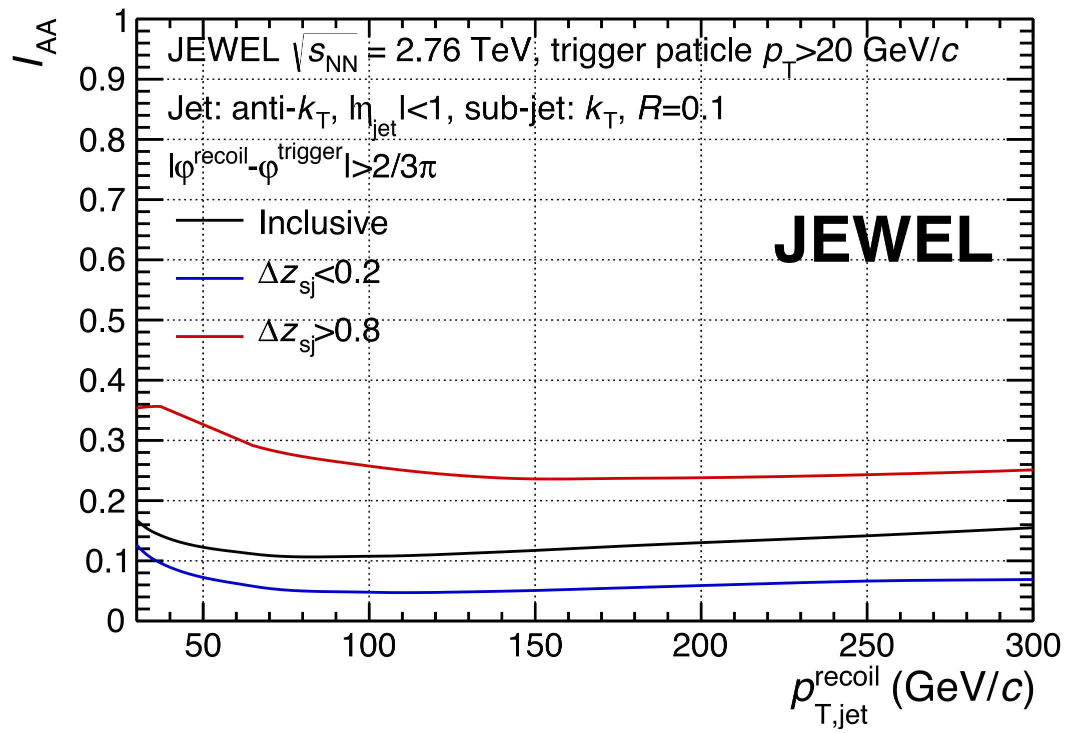


- Trigger: leading particle in p_T>10 GeV/c
- Recoil jet: away side associate jets

$$I_{\rm AA}(\Delta z_{\rm sj}\ {\rm cut}) = \frac{1/N^{\rm trg}_{\rm AA}{\rm d}N_{\rm AA}/{\rm d}p_{\rm T}|_{\Delta z_{\rm sj}\ {\rm cut}}}{1/N^{\rm trg}_{\rm pp}{\rm d}N_{\rm pp}/{\rm d}p_{\rm T}|_{\Delta z_{\rm sj}\ {\rm cut}}}$$

$$|\varphi^{\rm recoil}_{\rm jet} - \varphi^{\rm trigger}| > 2/3\pi$$

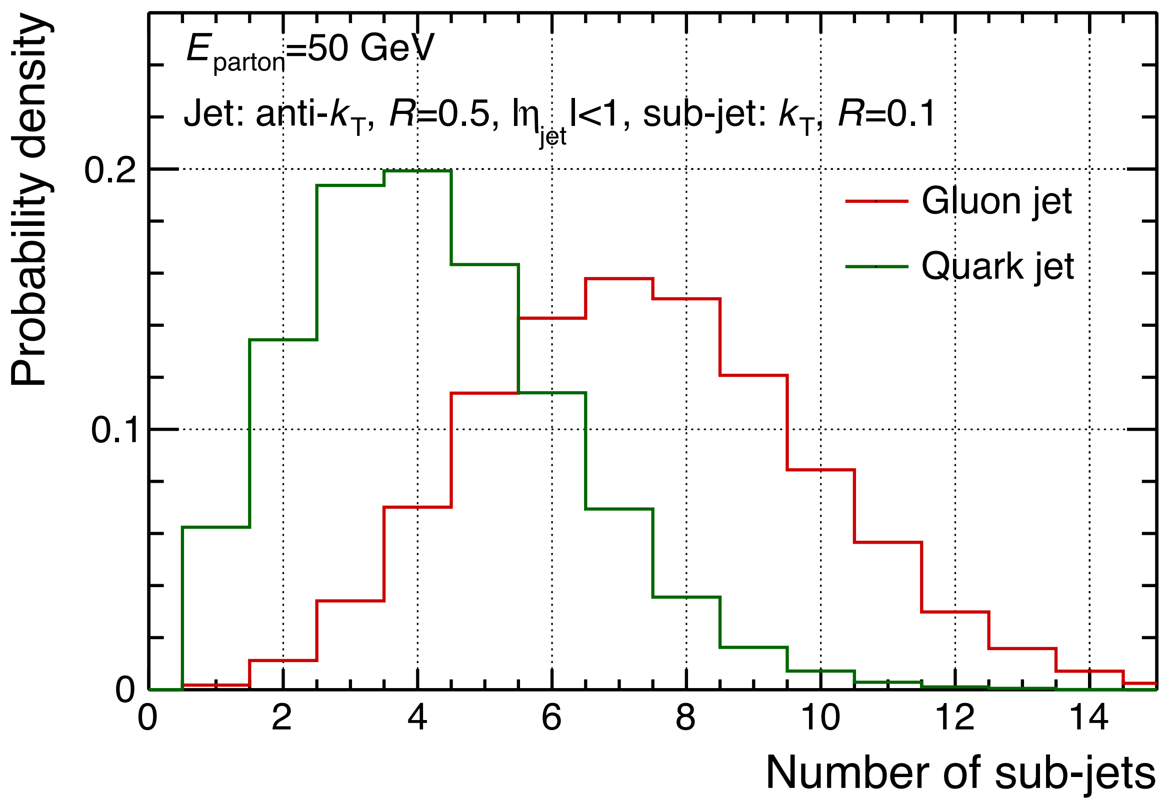




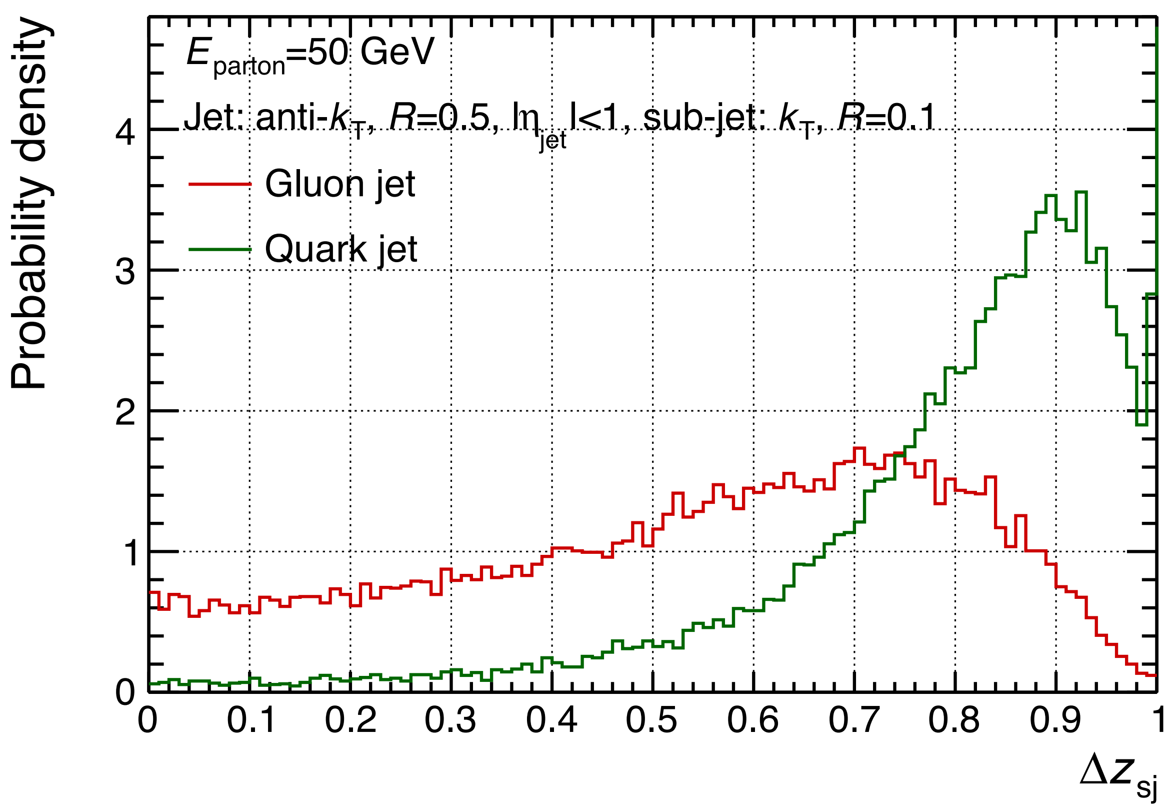
- Δz_{sj} triggered jet I_{AA} — very clean signal to distinguish quenching modelings
  - Independent on jet R — Insensitive to large angular (soft) radiation

Conclusion and Outlook

- Sub-jet structure, Δz_{sj}, robust against background fluctuations
- Δz_{sj} triggered jet R_{AA}, I_{AA} — clean sensitive to quenching modelings, insensitive to (soft) large angular energy redistribution



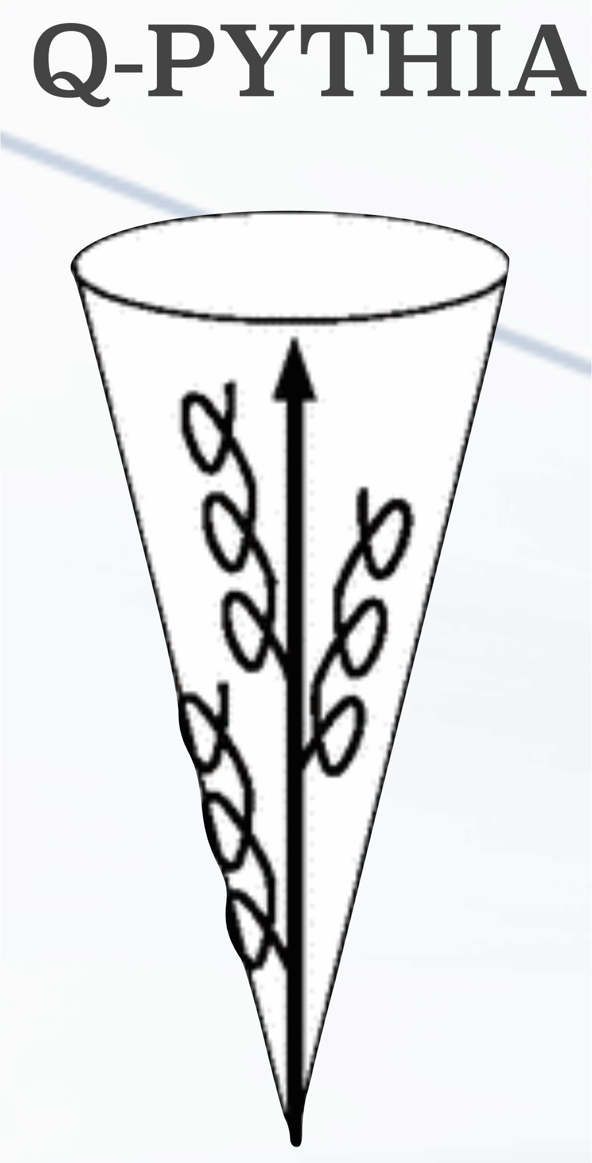
- Outlook
  - Distinguish quenched and unquenched jet samples or constrain the quenching "strength"
  - Opportunity to differentiate gluon jets and quark jets, light flavor jets and have flavor jets (?)

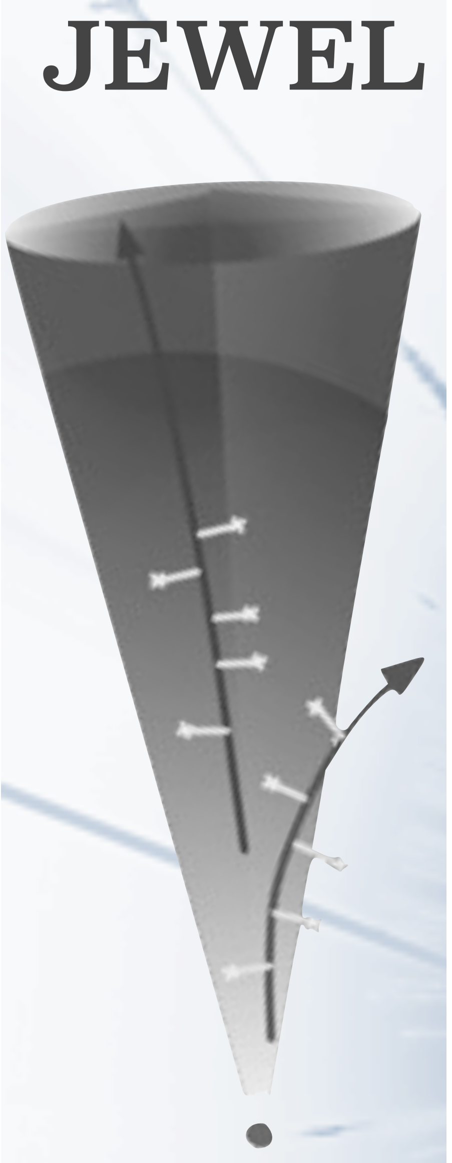


Backup

Quenching Models

- Vacuum jets — PYTHIA
- Medium modified jets:
  - Q-PYTHIA: radiation energy loss of BDMPS-Z type — modification of parton splitting function in vacuum
  - JEWEL: contains both of elastic and radiative energy loss — implemented the Landau-Pomeranchuck-Migdal effect

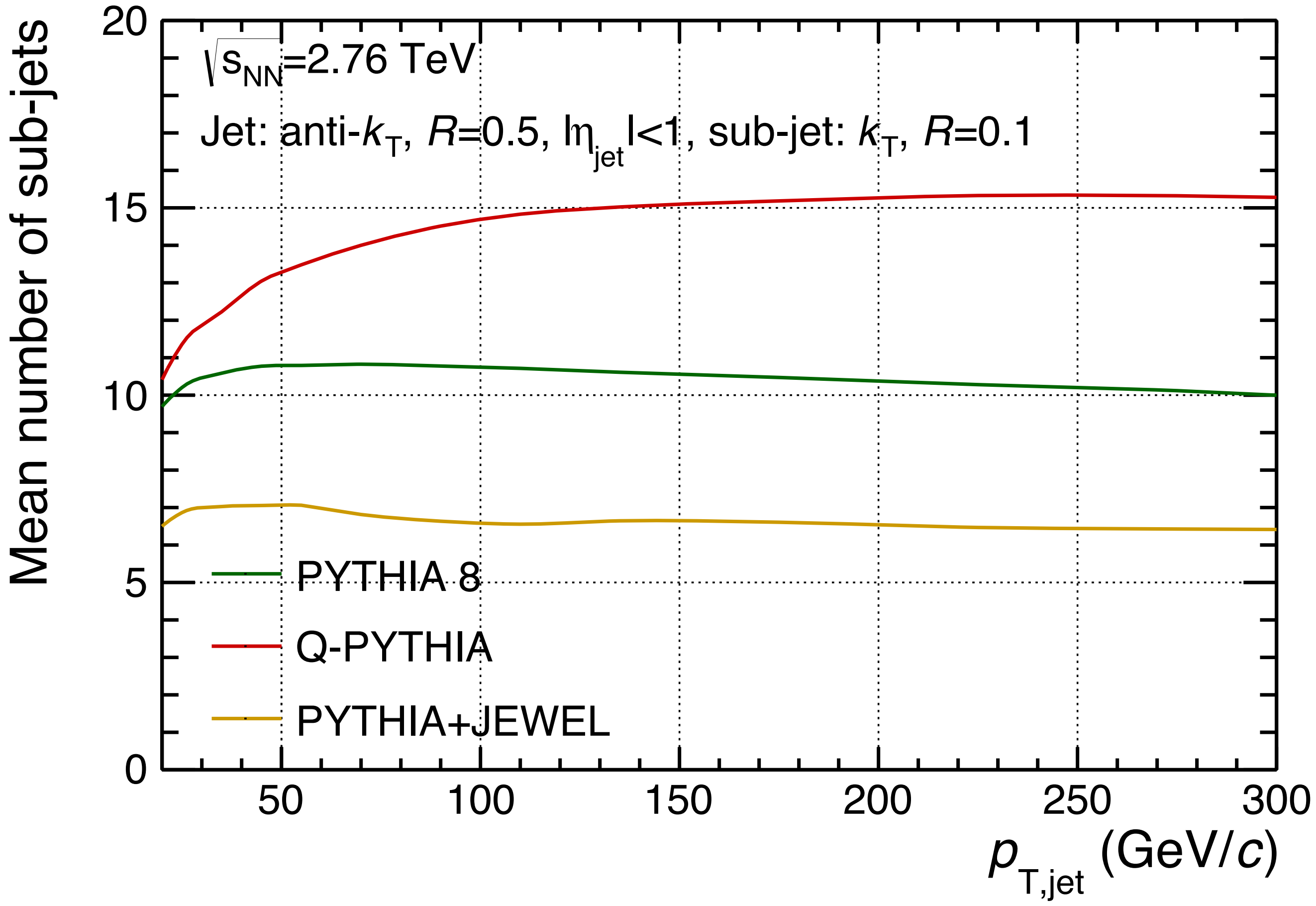


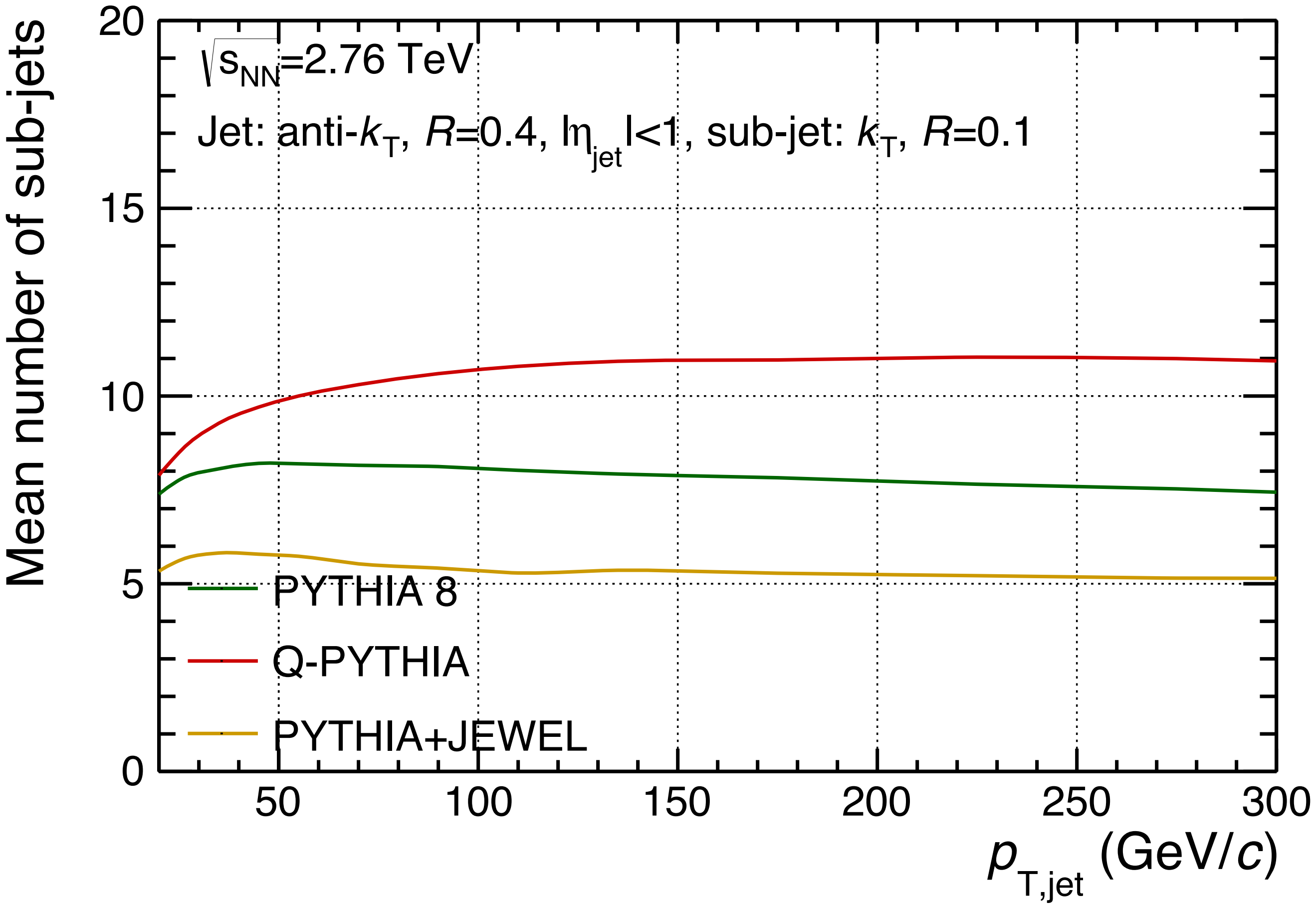


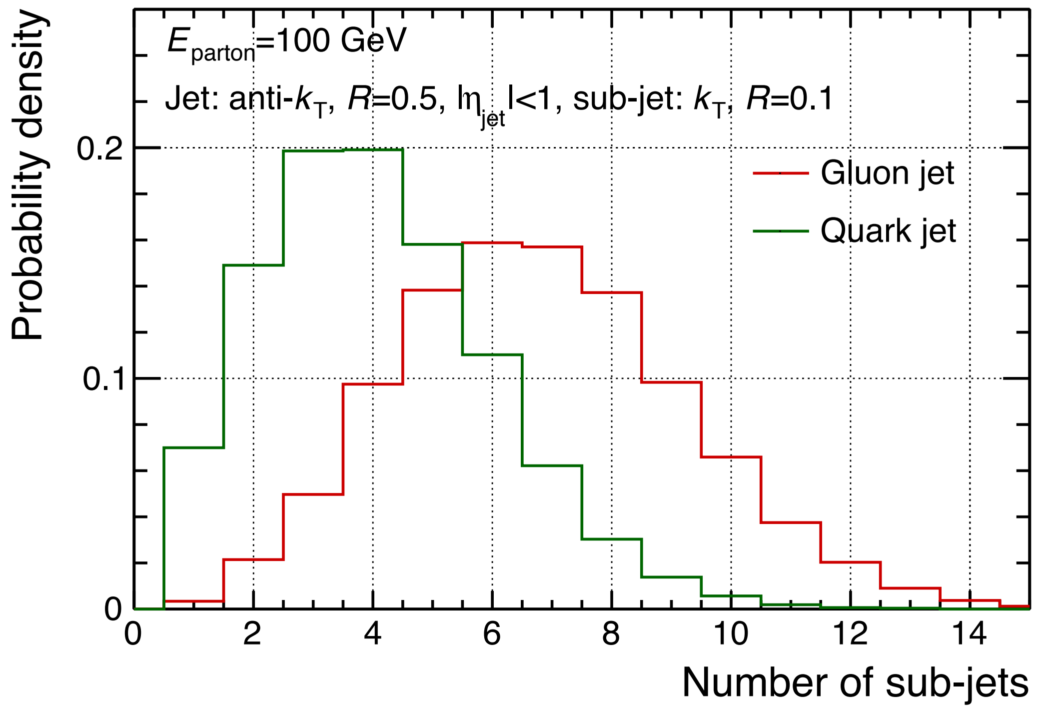
N. Armesto, L. Cunqueiro and C. A. Salgado, Q-PYTHIA: A Medium-modified implementation of final state radiation, Eur. Phys. J. C63 (2009) 679

K. C. Zapp, F. Krauss and U. Wiedemann, A perturbative framework for jet quenching, JHEP 1303 (2013) 080.

Number of Sub-jets

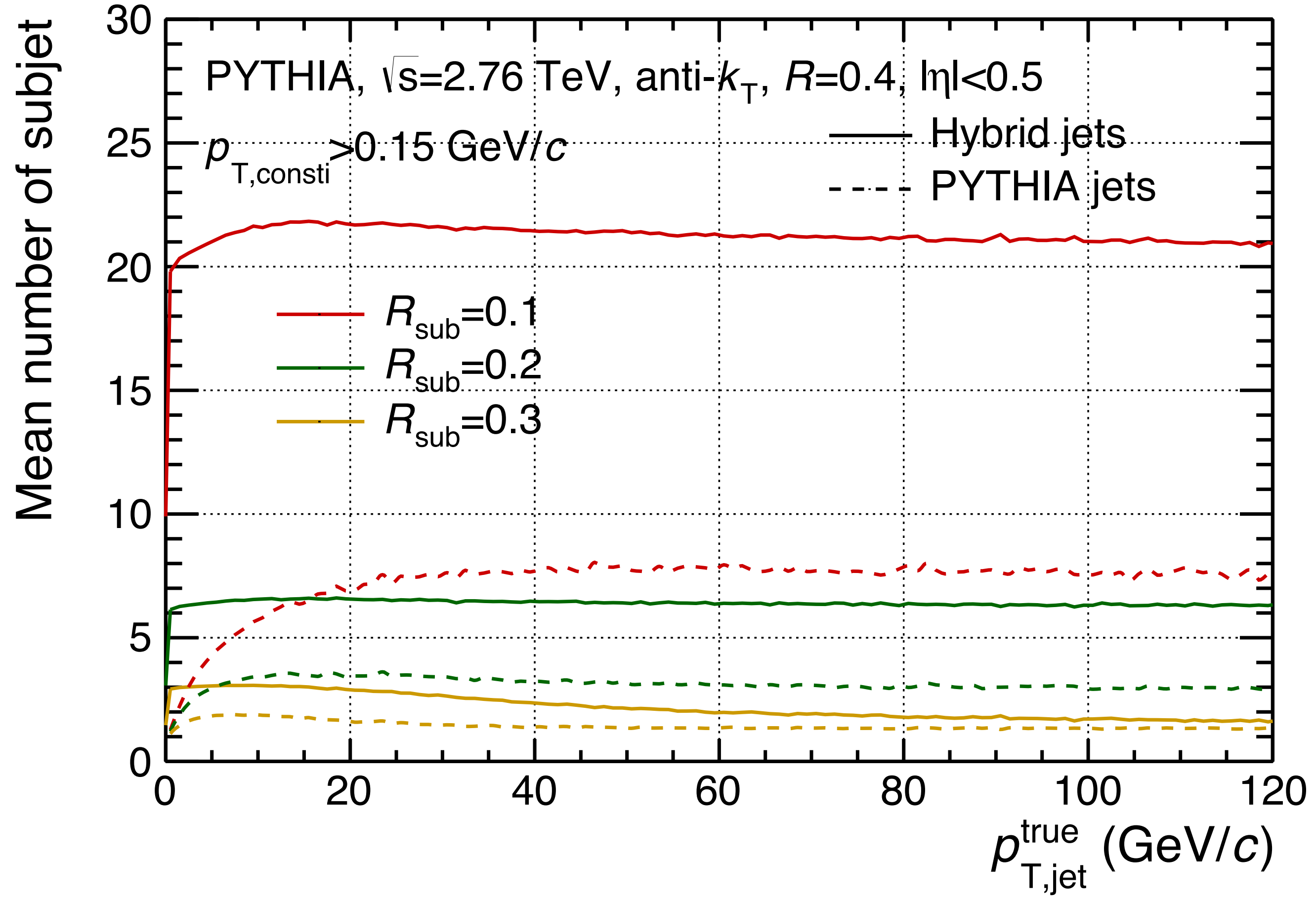


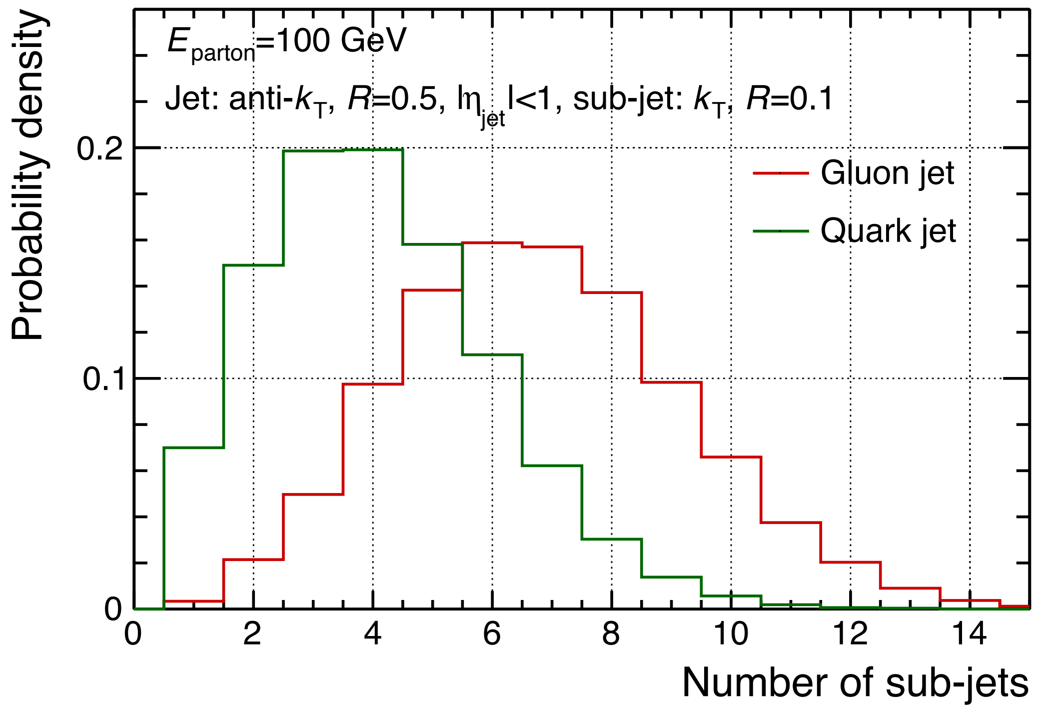




- Number of sub-jets
  - Sensitive to quenching mechanisms
  - Promising tool to distinguish quark jets and gluon jets

Number of Sub-jets





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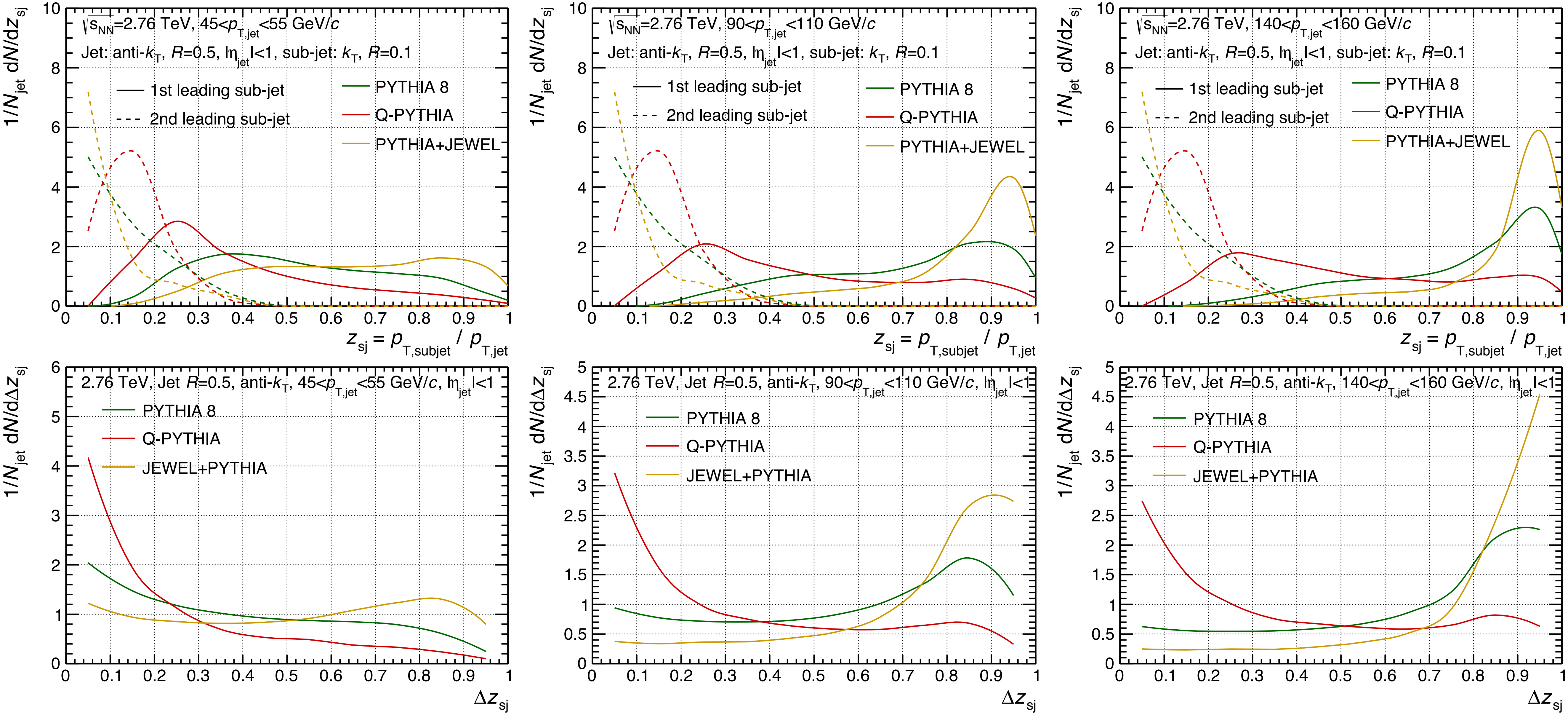
Medium Modified Jet Substructure

$$\Delta_{\rm sj} = p_{\rm T,subjet}^{\rm 1st\ leading} - p_{\rm T,subjet}^{\rm 2nd\ leading}, \quad \Delta z_{\rm sj} = \Delta_{\rm sj}/p_{\rm T,jet}$$



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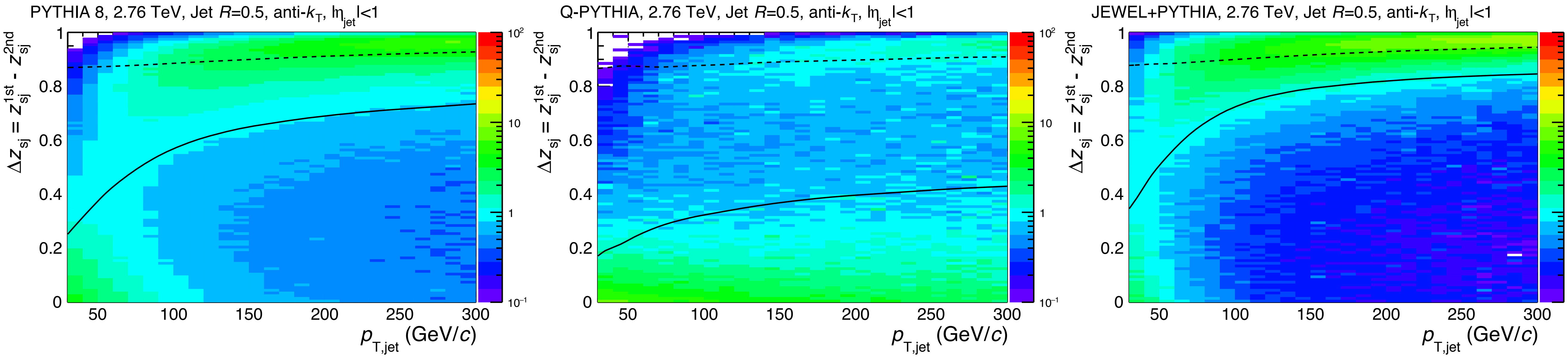
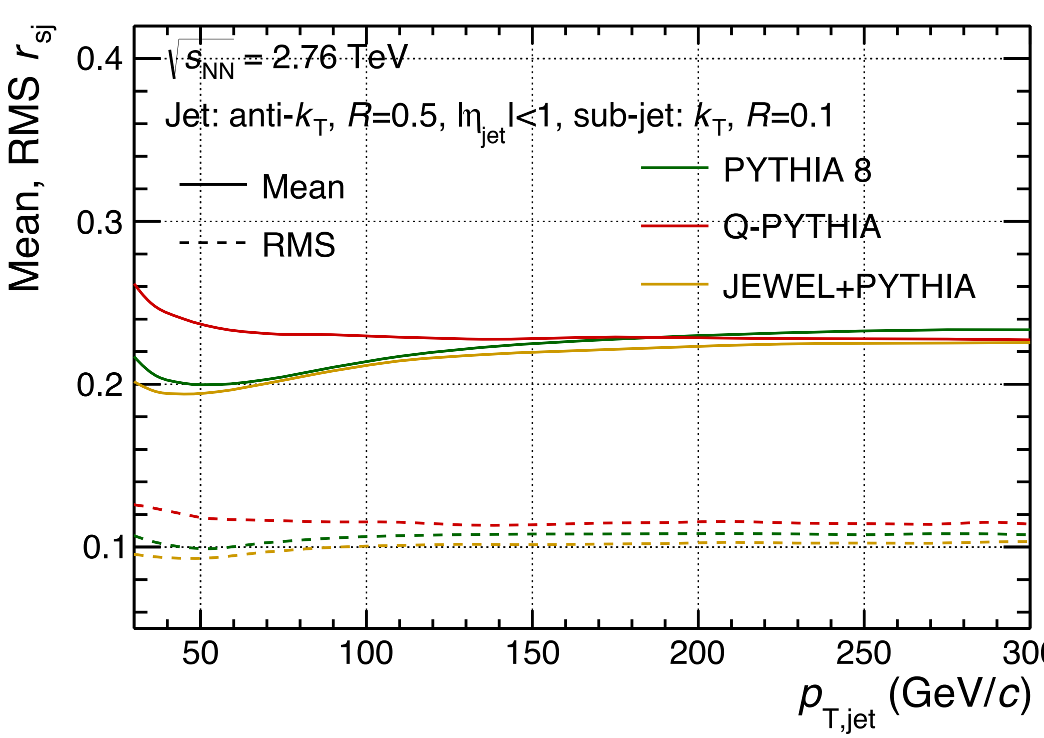


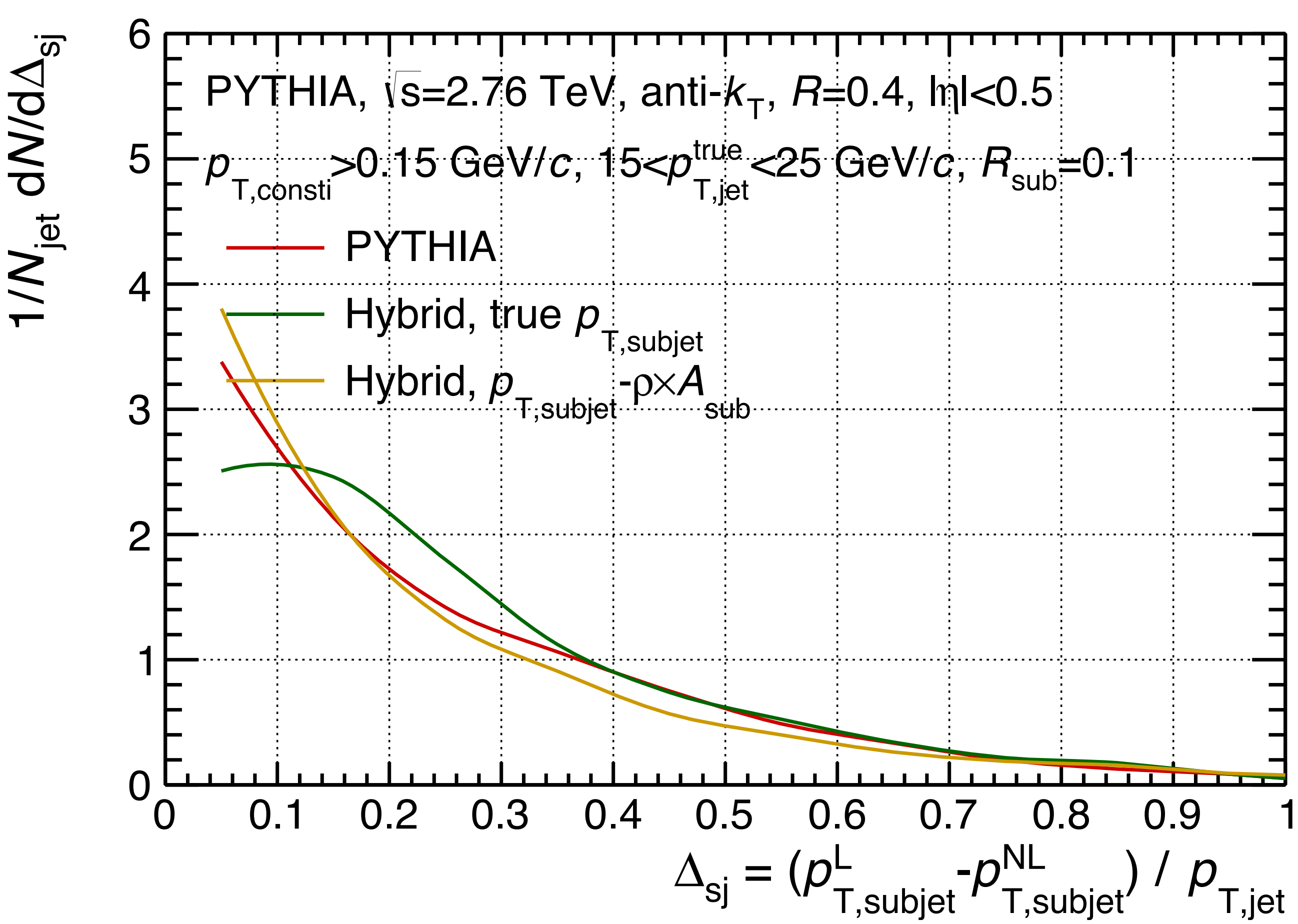


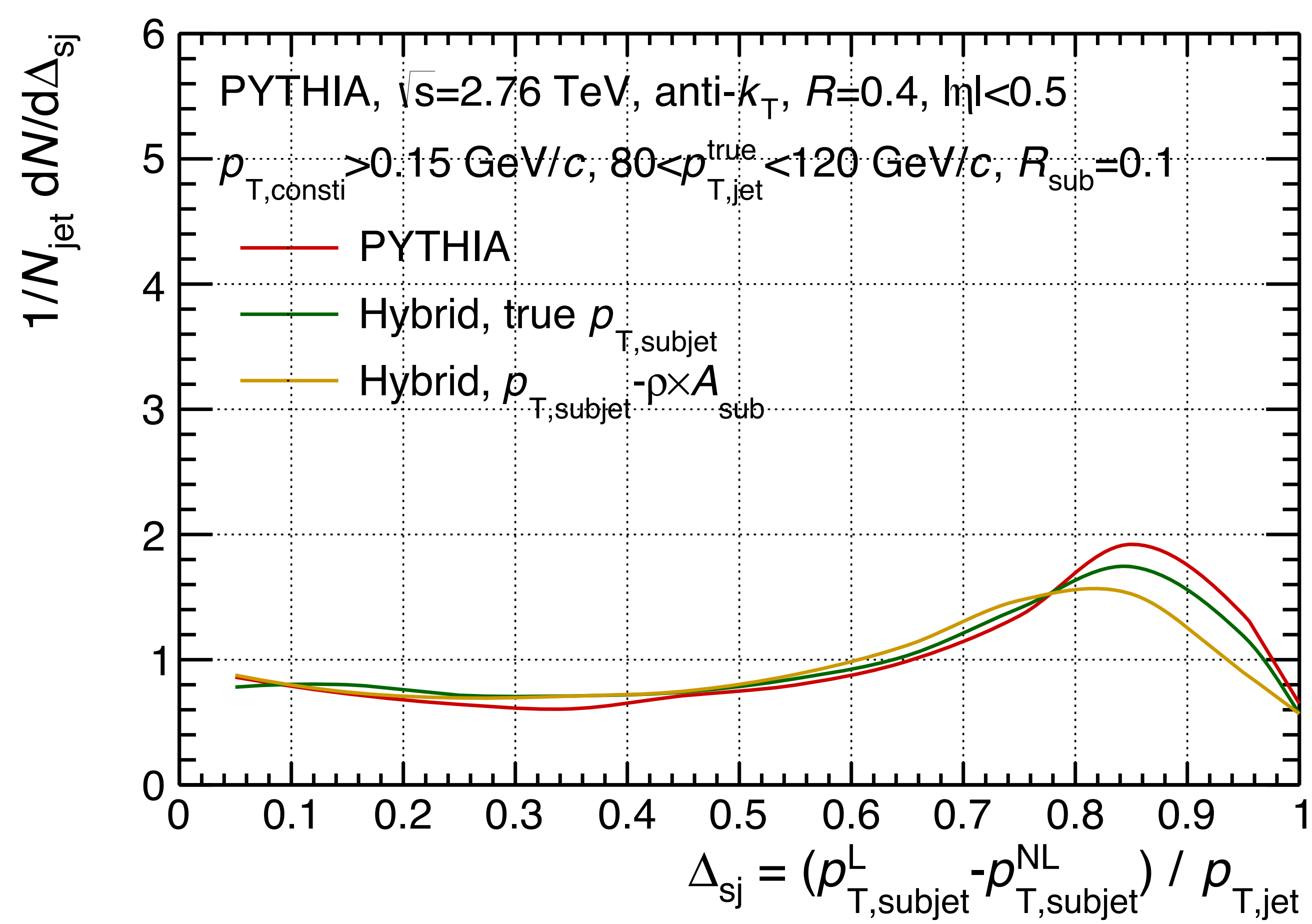
- Mean value of $\Delta z_{\rm sj}$ clean evolves with jet $p_{\rm T}$ and sensitive to to quenching modeling
- Strong power of discrimination between models
- In $\Delta z_{\rm sj}$>0.8, mean value insensitive to quenching models — similar response to jet $p_{\rm T}$ between models

Δ_{sj} and Δz_{sj} Distributions

$$\Delta_{\rm sj} = p_{\rm T,subjet}^{\rm 1st\ leading} - p_{\rm T,subjet}^{\rm 2nd\ leading}, \quad \Delta z_{\rm sj} = \Delta_{\rm sj}/p_{\rm T,jet}$$

- Δ_{sj} and Δz_{sj} — (partly) cancels out the background fluctuations on $p_{T,subjet}$
- Sensitive to the details of modeling — the energy carried by 1st leading subjets

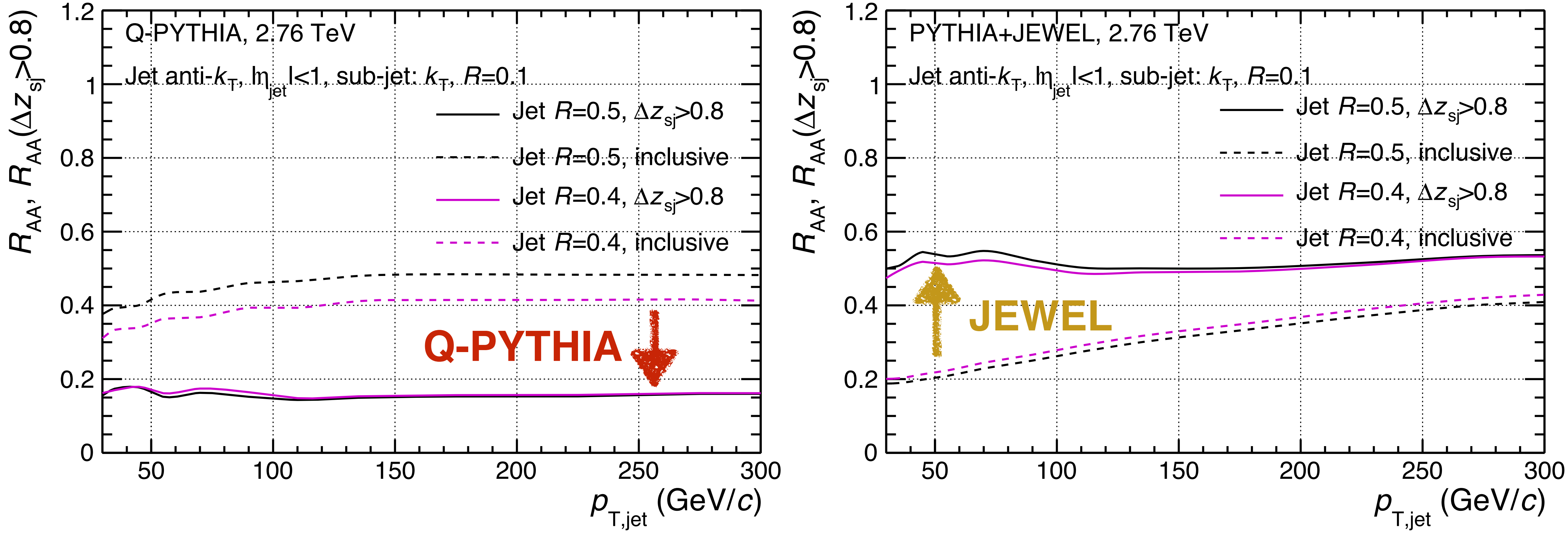




Δz_{sj} Triggered Jet R_{AA}

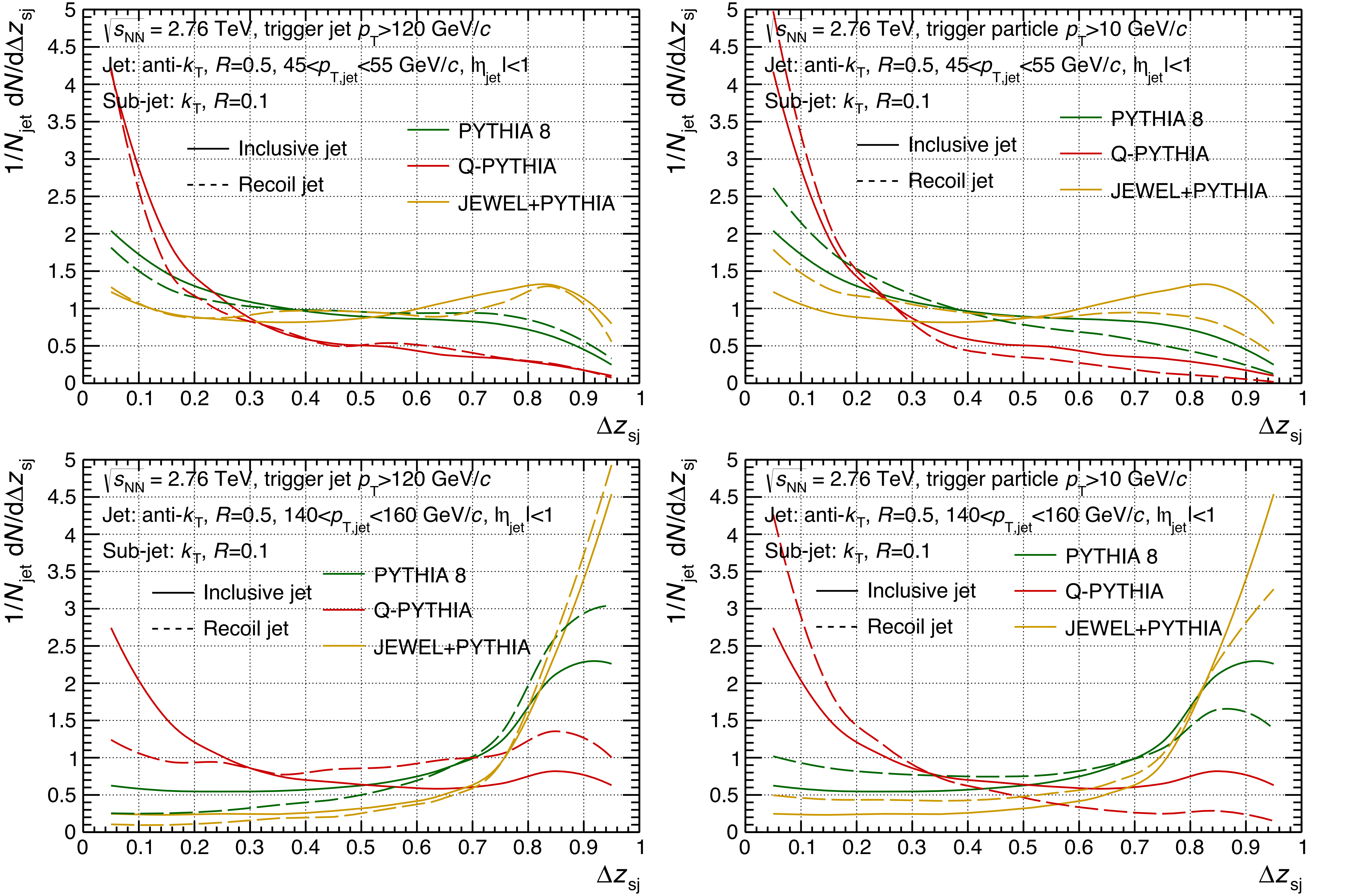
$$R_{AA}(\Delta z_{sj} > 0.8) = \frac{1}{< N_{coll} >} \frac{d\sigma_{AA}/dp_T|_{\Delta z_{sj}>0.8}}{d\sigma_{pp}/dp_T|_{\Delta z_{sj}>0.8}}$$

- R_{AA} reference:
  - Q-PYTHIA — PYTHIA6
  - JEWEL — JEWEL vacuum

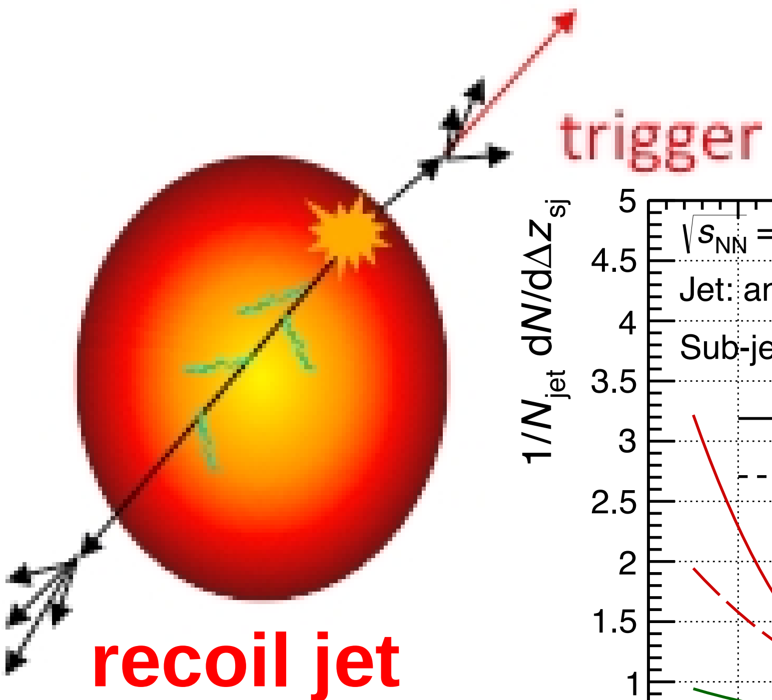


- Δz_{sj} triggered jet R_{AA} is strongly suppressed in Q-PYTHIA and clean enhanced JEWEL w. r. t. the inclusive — very clean signal to distinguish quenching modelings
- Triggered R_{AA} uncorrelated with jet R — insensitive to large angular (soft) radiation

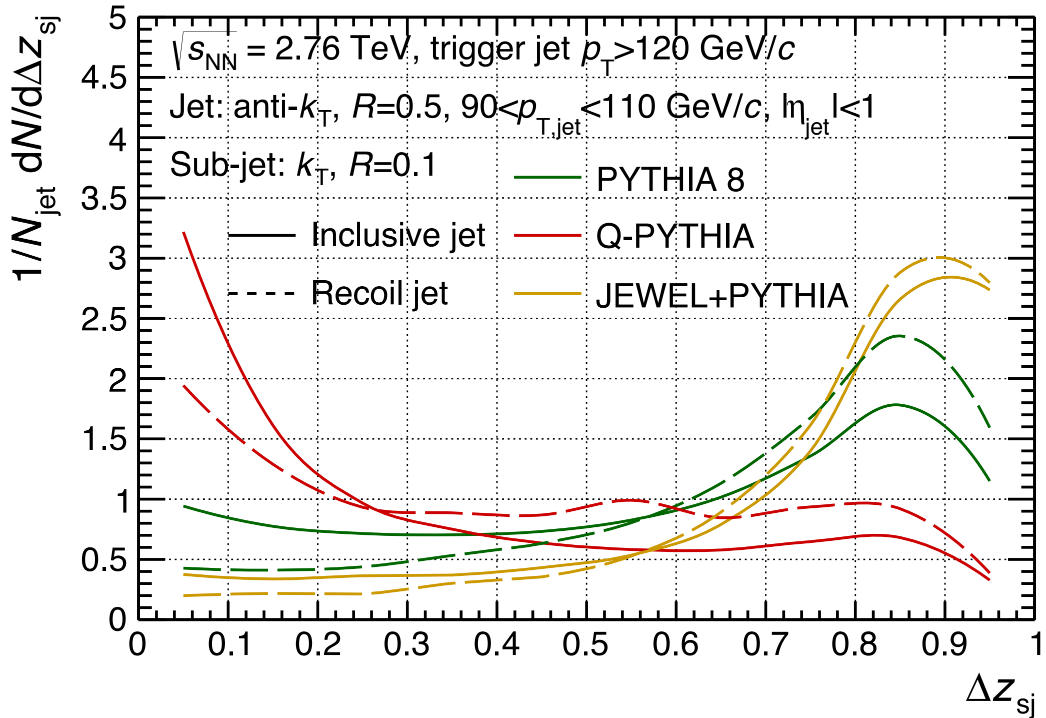
Leading Particle/Jet Triggered Jets



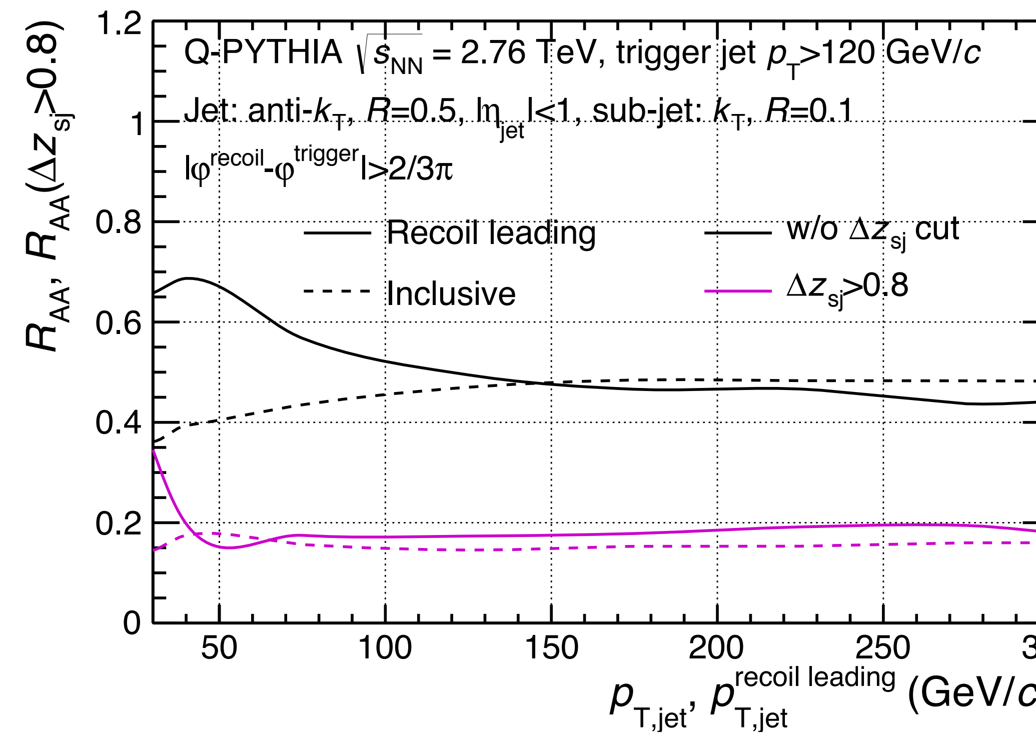
Leading Jet Triggered Recoil Jets



$$\left|\varphi_{\rm jet}^{\rm recoil} - \varphi^{\rm trigger}\right| > 2/3\pi$$

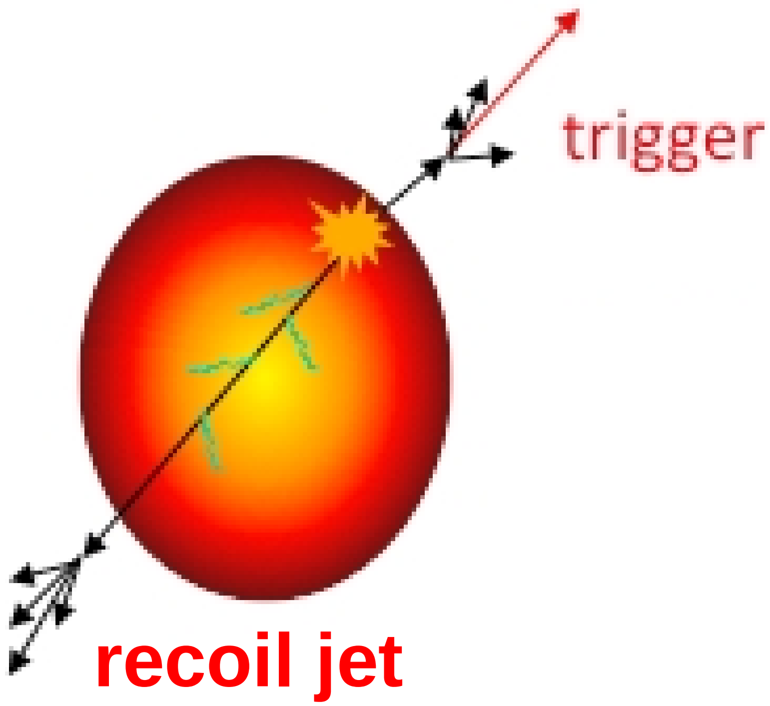


- Trigger jet: leading jet in p_T>120 GeV/c
- Recoil jet: sub-leading jet in away side



- Leading jet triggered recoil sub-leading jets
  - Sensitive to medium modification
  - Tag the path length dependence of medium effect
- Recoil sub-leading jet R_{AA} in Δz_{sj}>0.8 — significant from the sub-leading jets w/o Δz_{sj} cut, consistent with inclusive jets in p_T>50 GeV/c

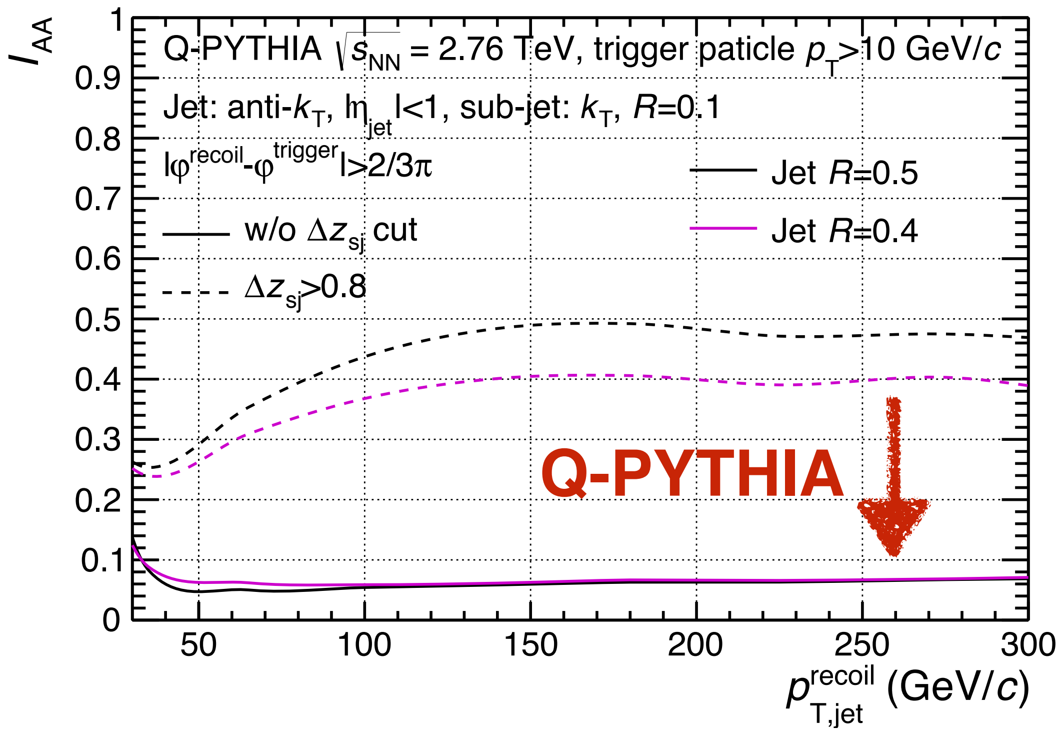
Δz_{sj} Triggered Recoil Jet I_{AA}

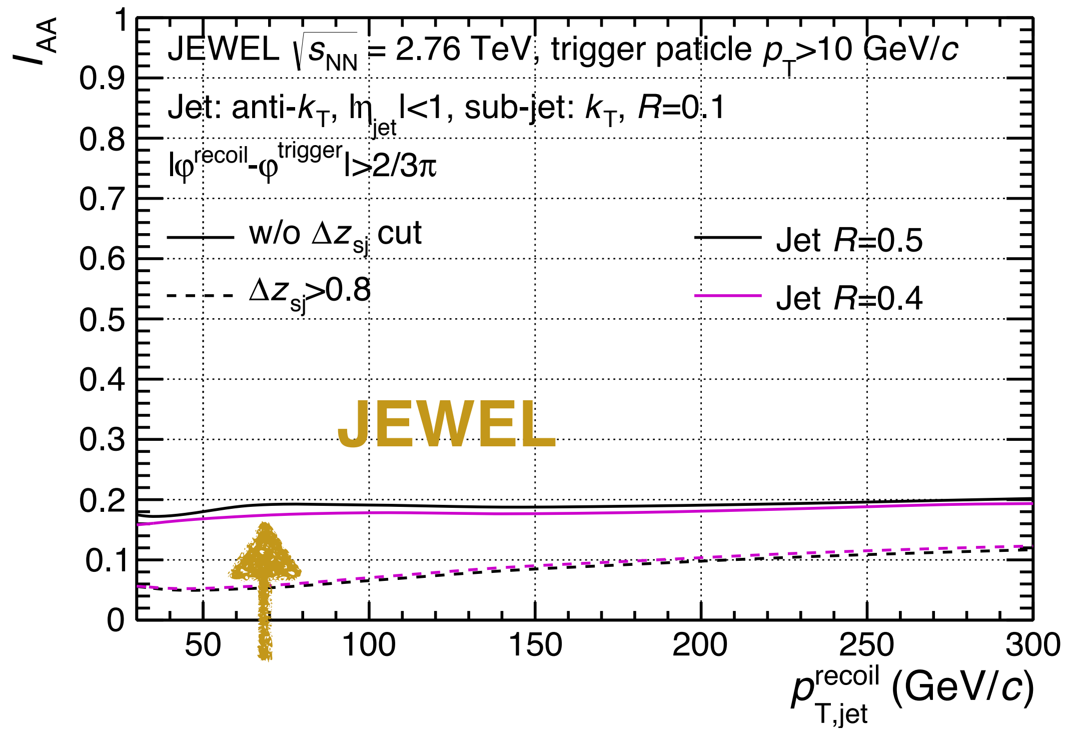


- Trigger: leading particle in p_T>10 GeV/c
- Recoil jet: away side associate jets

$$I_{\rm AA}(\Delta z_{\rm sj}\ {\rm cut}) = \frac{1/N^{\rm trg}_{\rm AA}{\rm d}N_{\rm AA}/{\rm d}p_{\rm T}|_{\Delta z_{\rm sj}\ {\rm cut}}}{1/N^{\rm trg}_{\rm pp}{\rm d}N_{\rm pp}/{\rm d}p_{\rm T}|_{\Delta z_{\rm sj}\ {\rm cut}}}$$

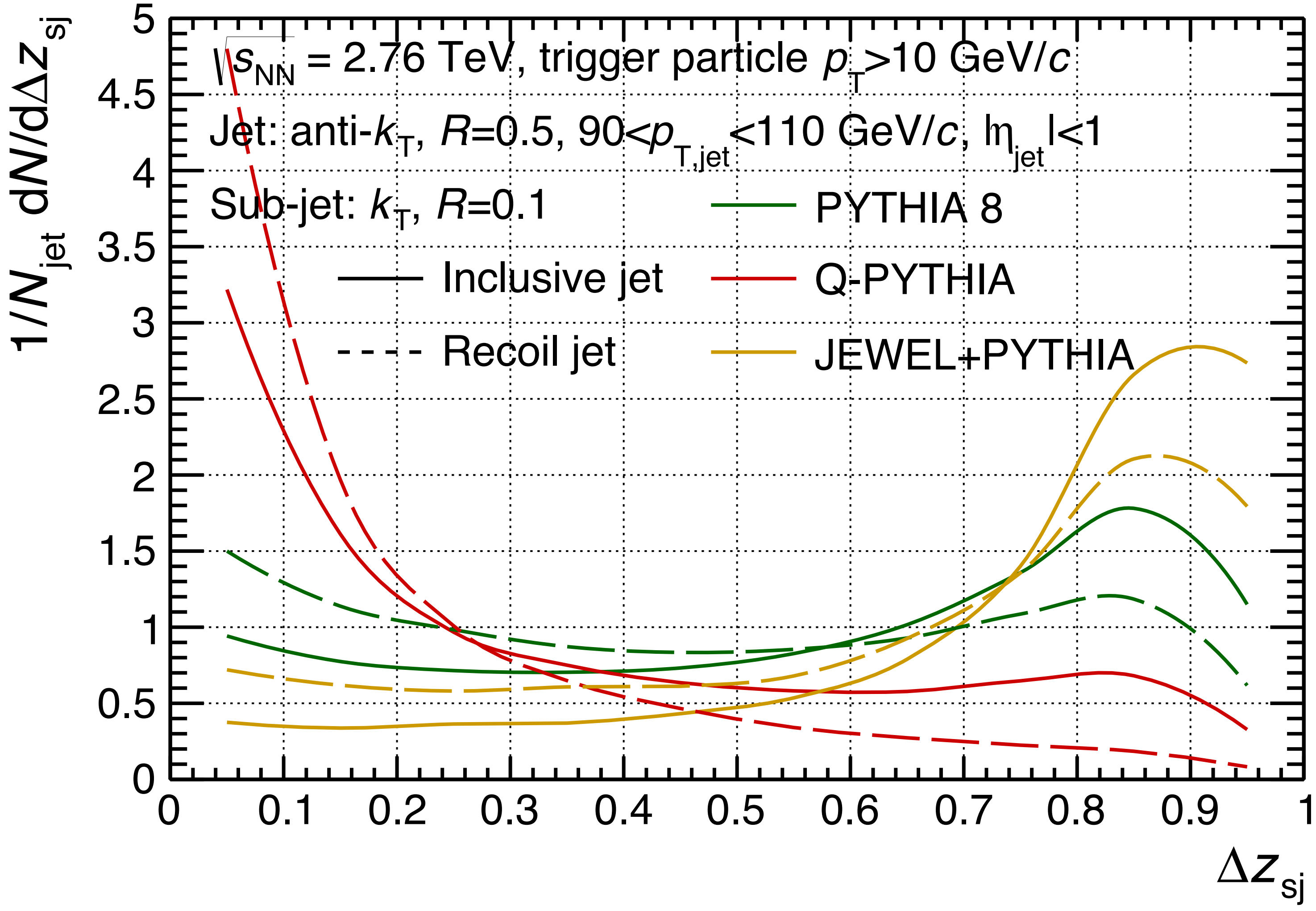
$$|\varphi^{\rm recoil}_{\rm jet} - \varphi^{\rm trigger}| > 2/3\pi$$



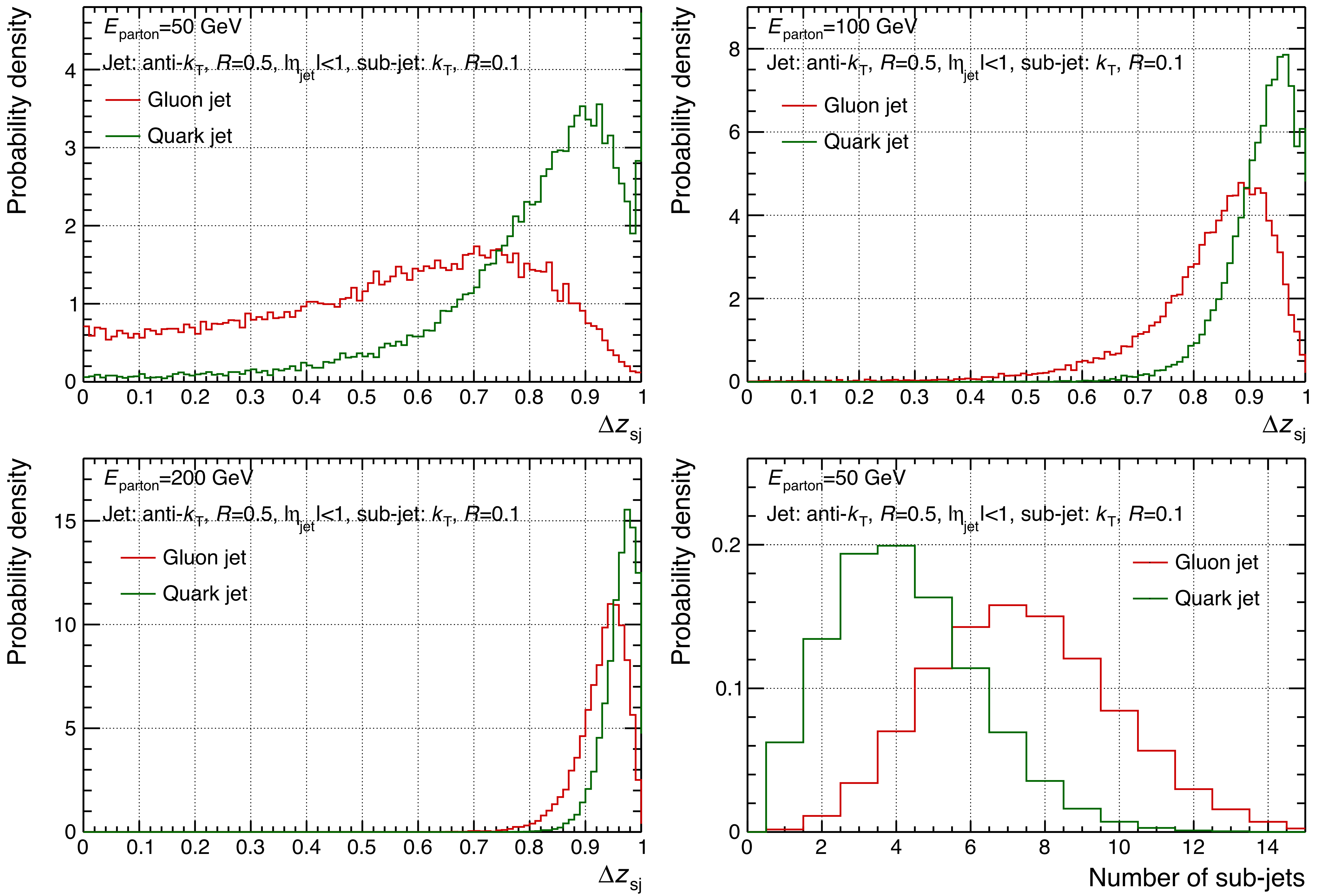


- Δz_{sj} triggered jet I_{AA} — very clean signal to distinguish quenching modelings
  - Independent on jet R — Insensitive to large angular (soft) radiation

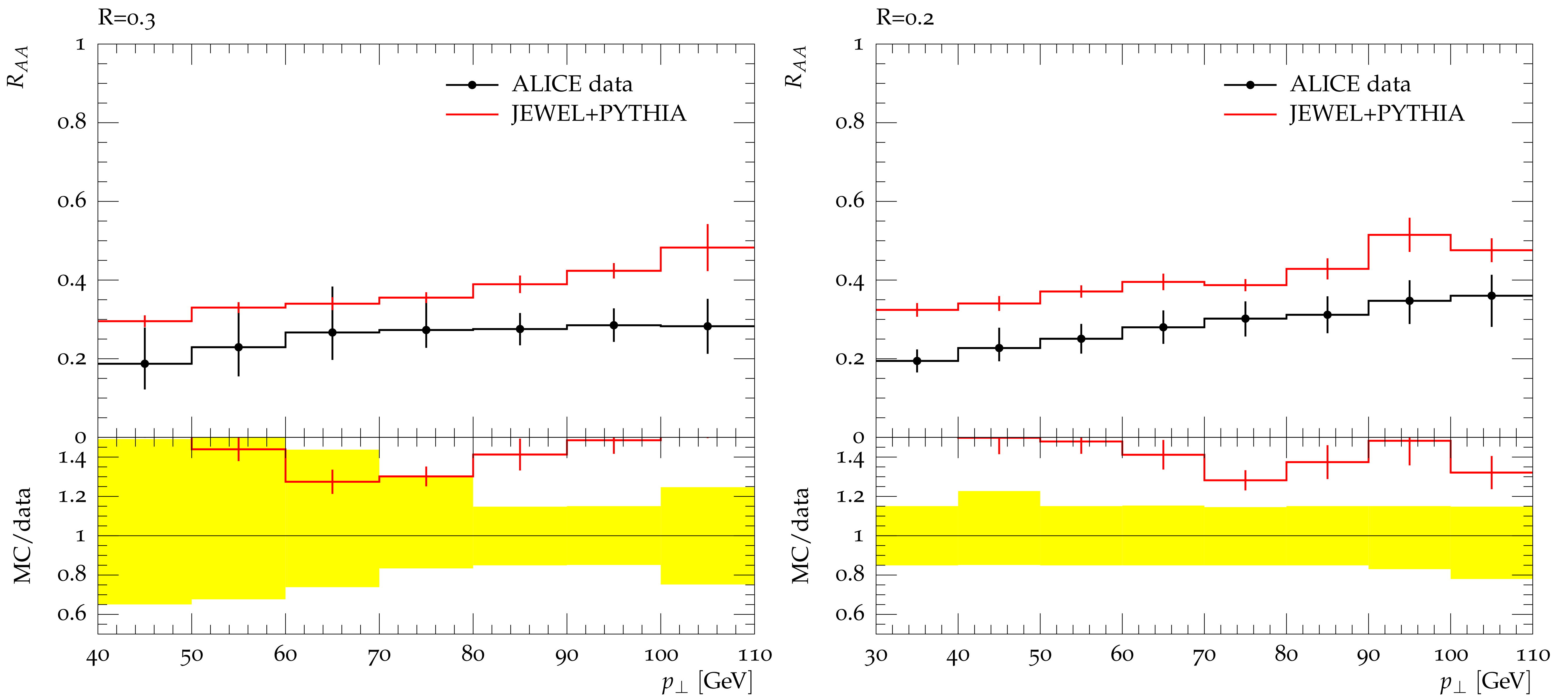
Δz_{sj} Triggered Recoil Jet I_{AA}



Quark vs. Gluon Jets

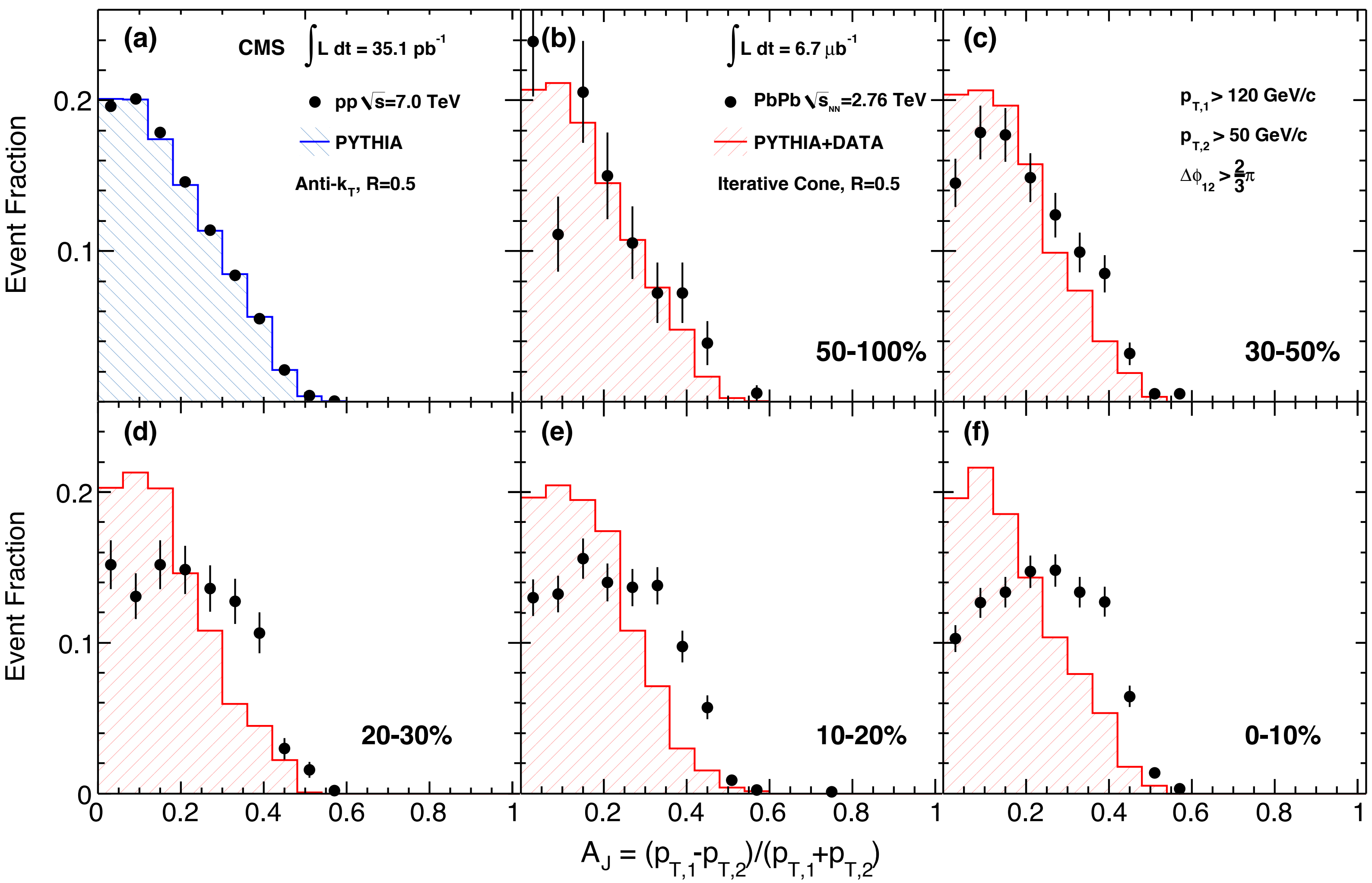


JEWEL+PYTHIA



Eur. Phys. J. C74 (2014) 2, 2762

CMS Di-jet



Phys.Rev. C84 (2011) 024906