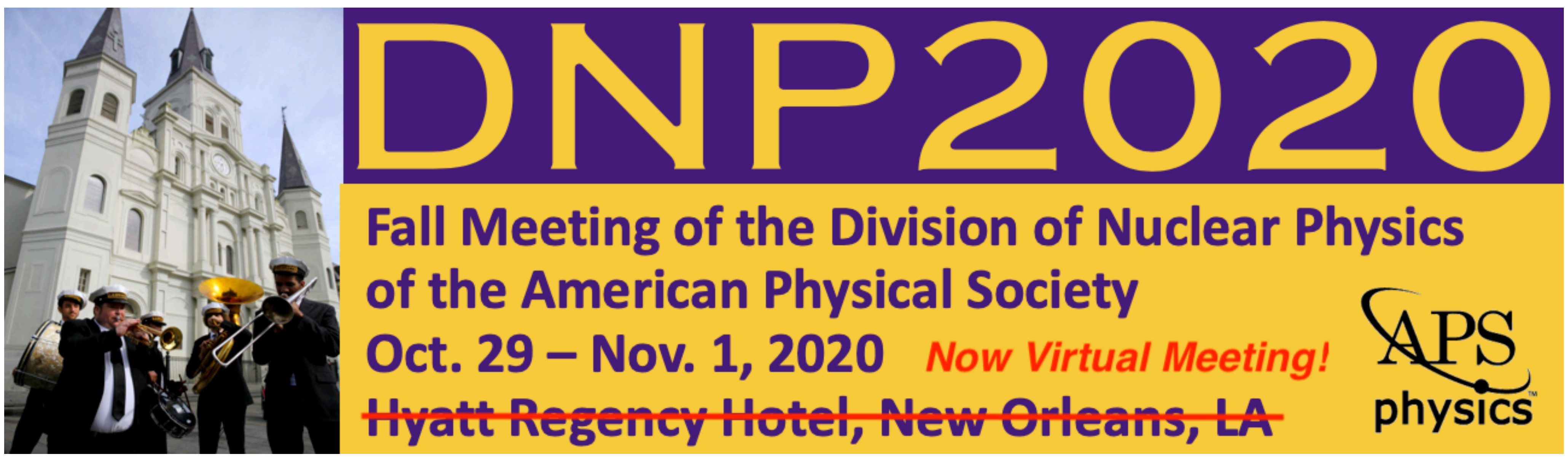
Supported in part by: U.S. DEPARTMENT OF ENERGY | Office of Science — WAYNE STATE UNIVERSITY — STAR

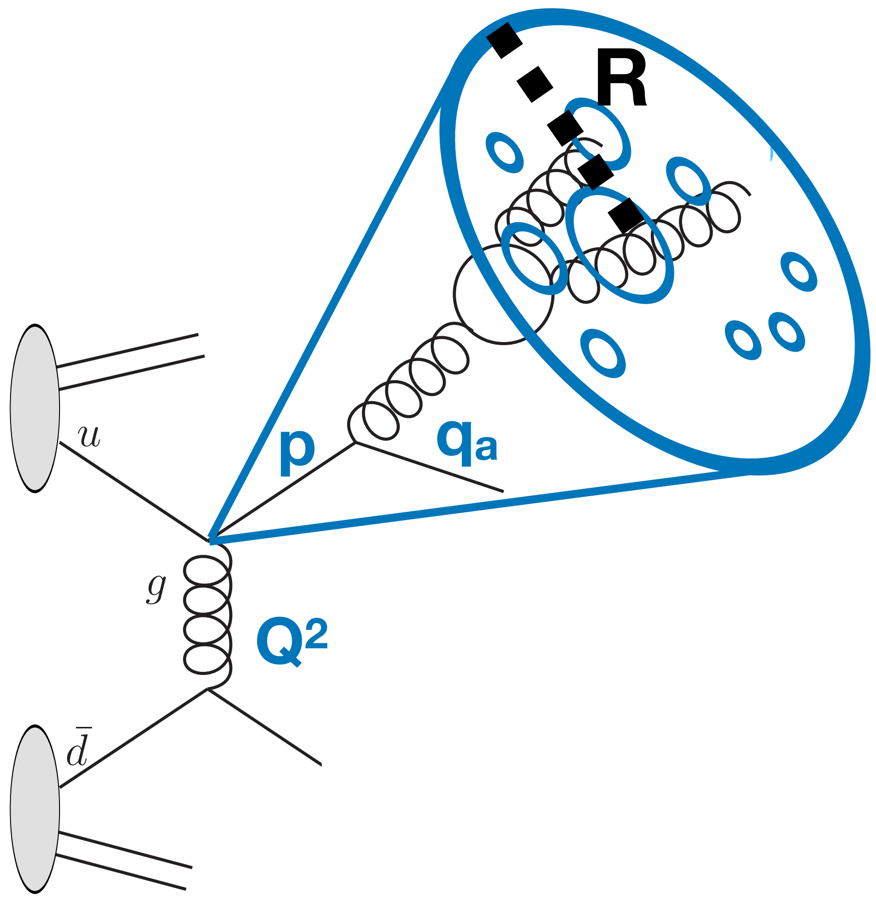
Jet substructure in *p*+*p* and *p*+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV at STAR

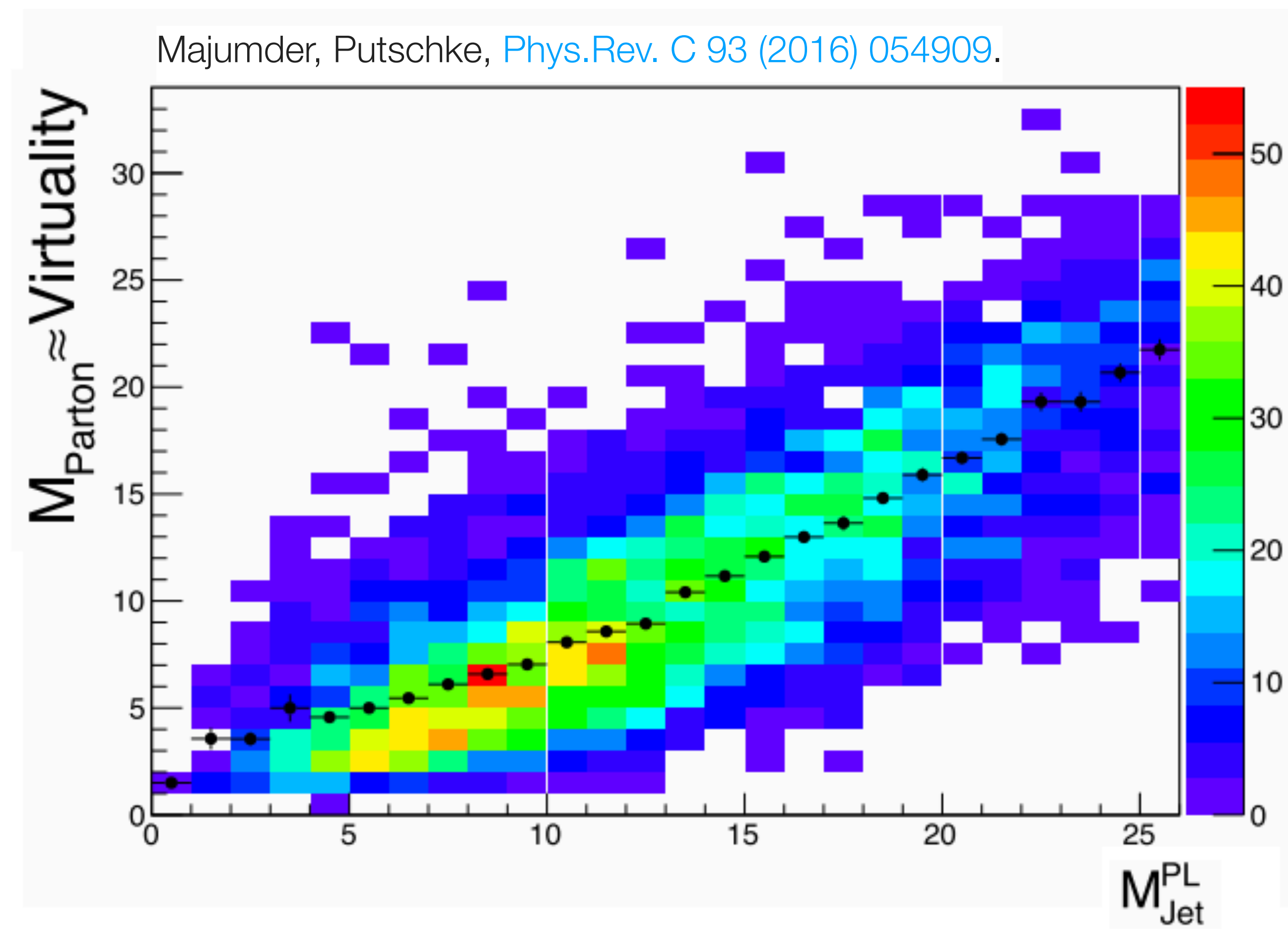


Isaac Mooney (Wayne State University)
for the STAR Collaboration

DNP - New Orleans (virtual)
October 30, 2020

Jet mass





[no hadronization here - would smear correlation]

- ★ ***Partonic mass,*** M_{parton}**:**
  - **Magnitude of 4-momentum - between 0 and scale, *Q***
- ★ ***Reconstructed jet mass,*** $M_{\text{jet}} = \left|\sum_{i \in J} p_i\right| = \sqrt{E^2 - \mathbf{p}^2}$**:**
  - **Magnitude of constituent 4-momentum sum for given *R***

What we measure
[~ initial hard parton virtuality!]

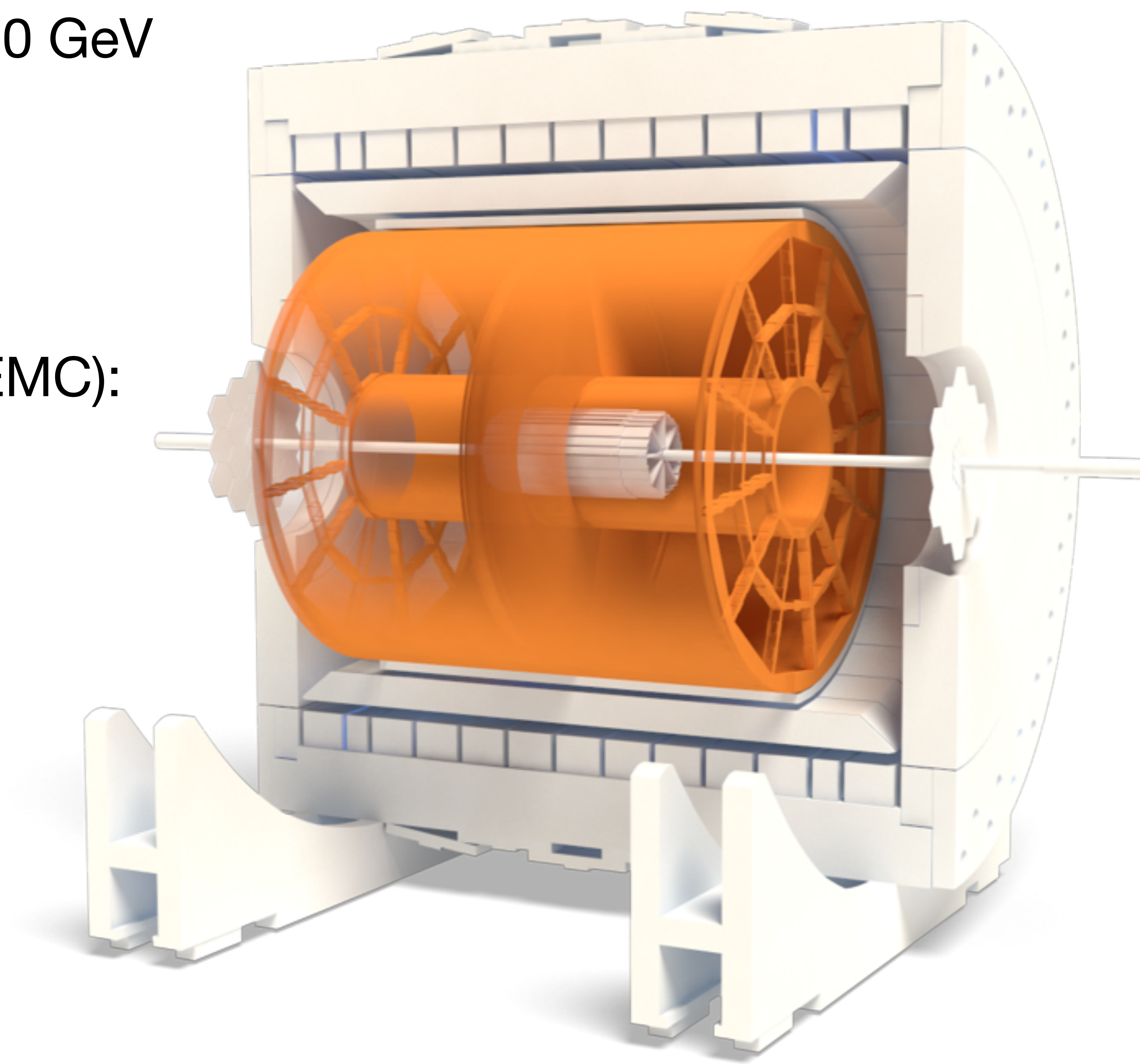
Solenoidal Tracker at RHIC (STAR)

Relativistic Heavy Ion Collider (RHIC) collides p+p, p+Au beams at $\sqrt{s_{NN}}$ = 200 GeV

Time Projection Chamber (TPC): momenta of charged tracks

Barrel Electromagnetic Calorimeter (BEMC): neutral energy deposits
+ provides online trigger
(Jet Patch: $E_T^{patch} > 7.4$ GeV)

Inner Beam-Beam Counter (iBBC): forward detector ($3.4 < |\eta| < 5.0$)
cf. TPC $|\eta| < 1$
east/Au-going side activity used as centrality proxy in p+Au



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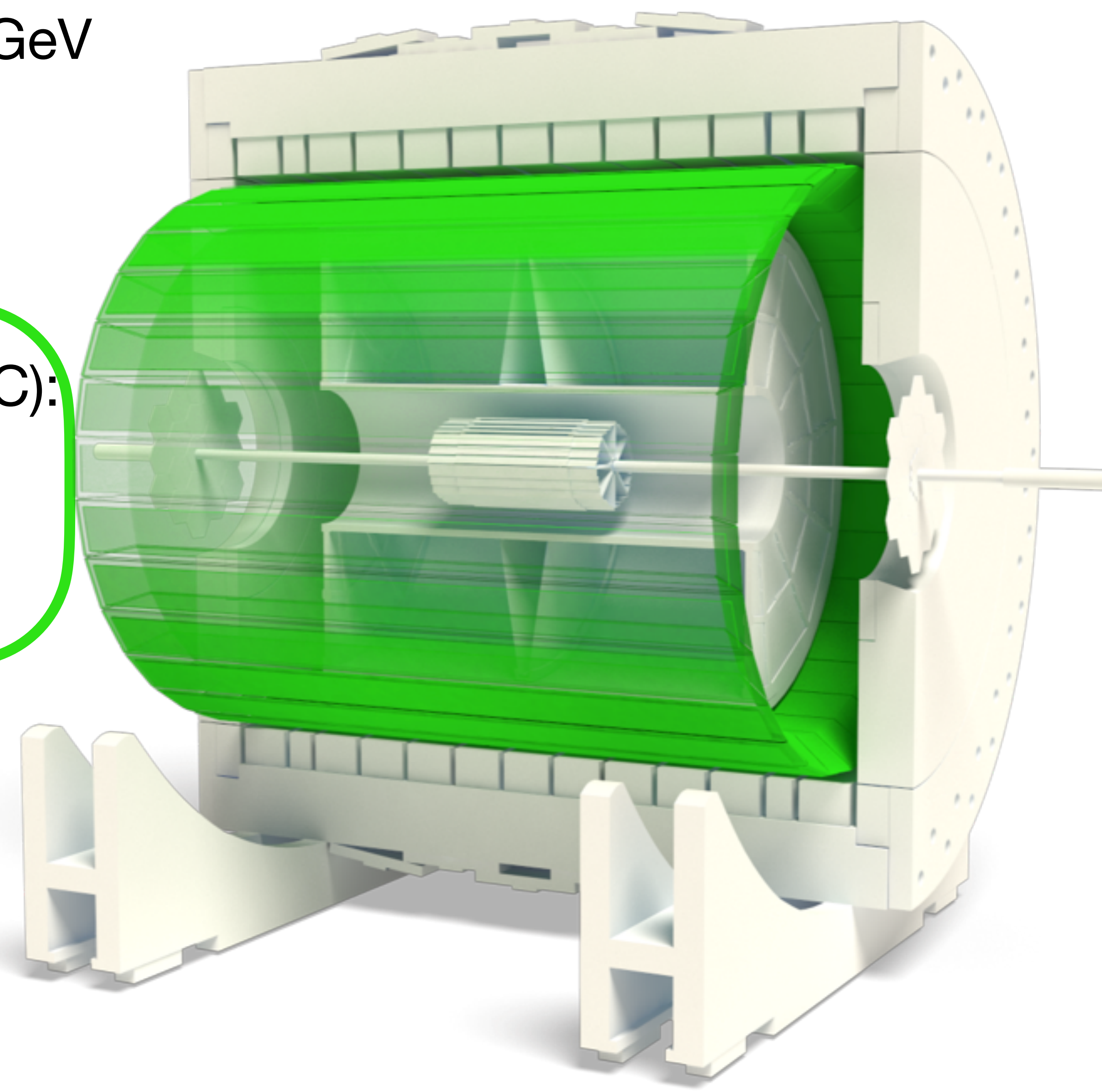

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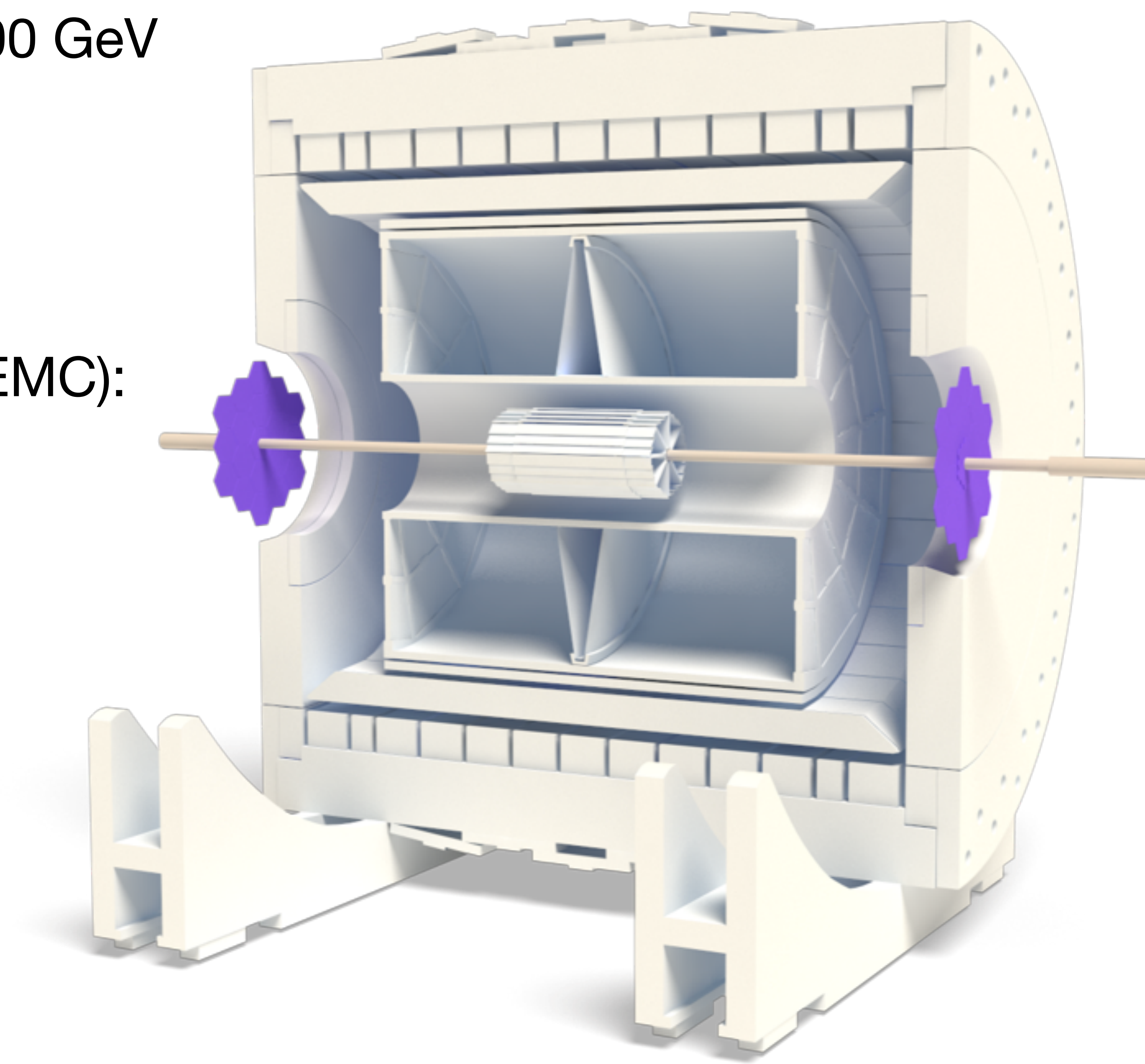
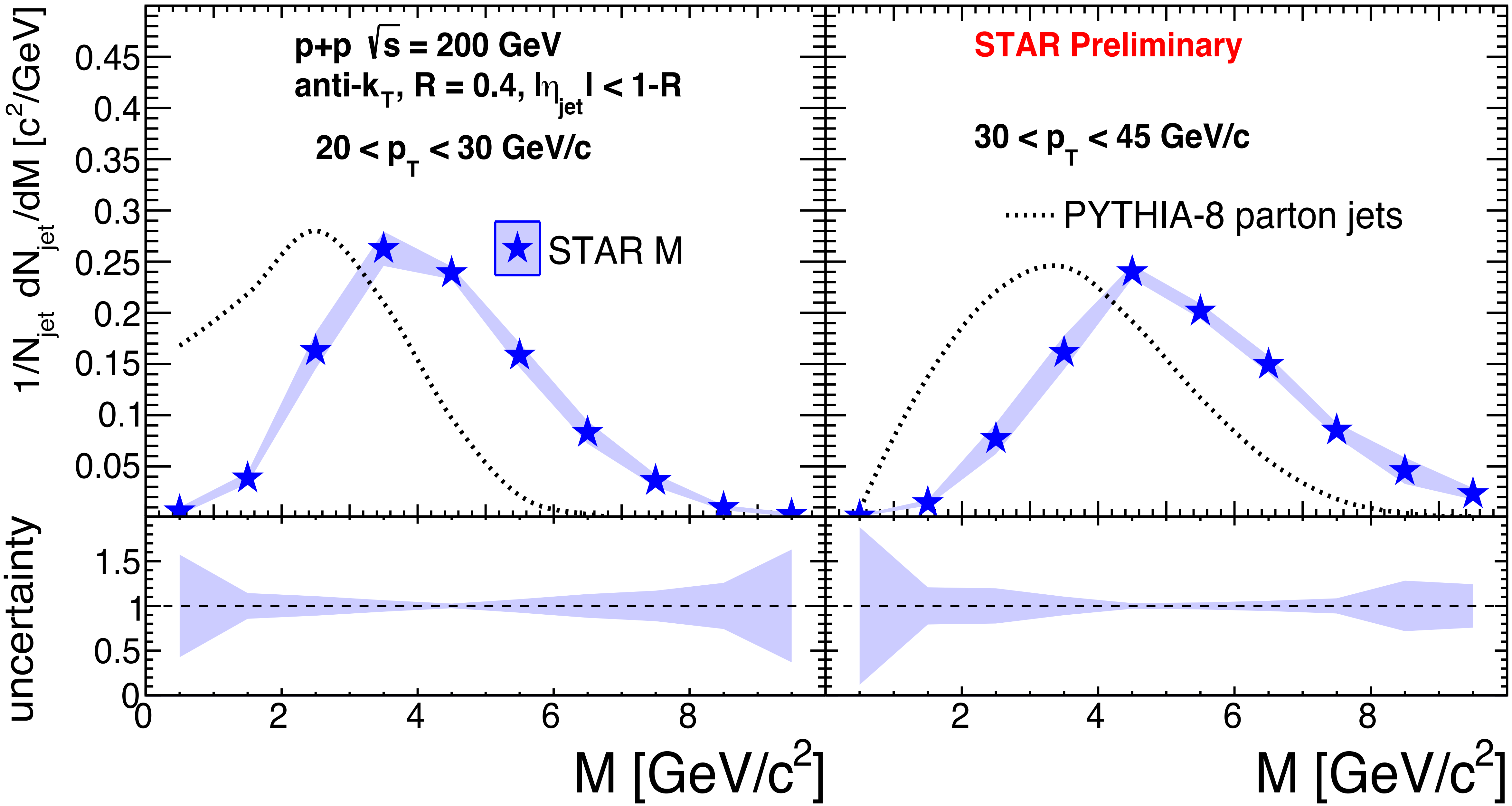
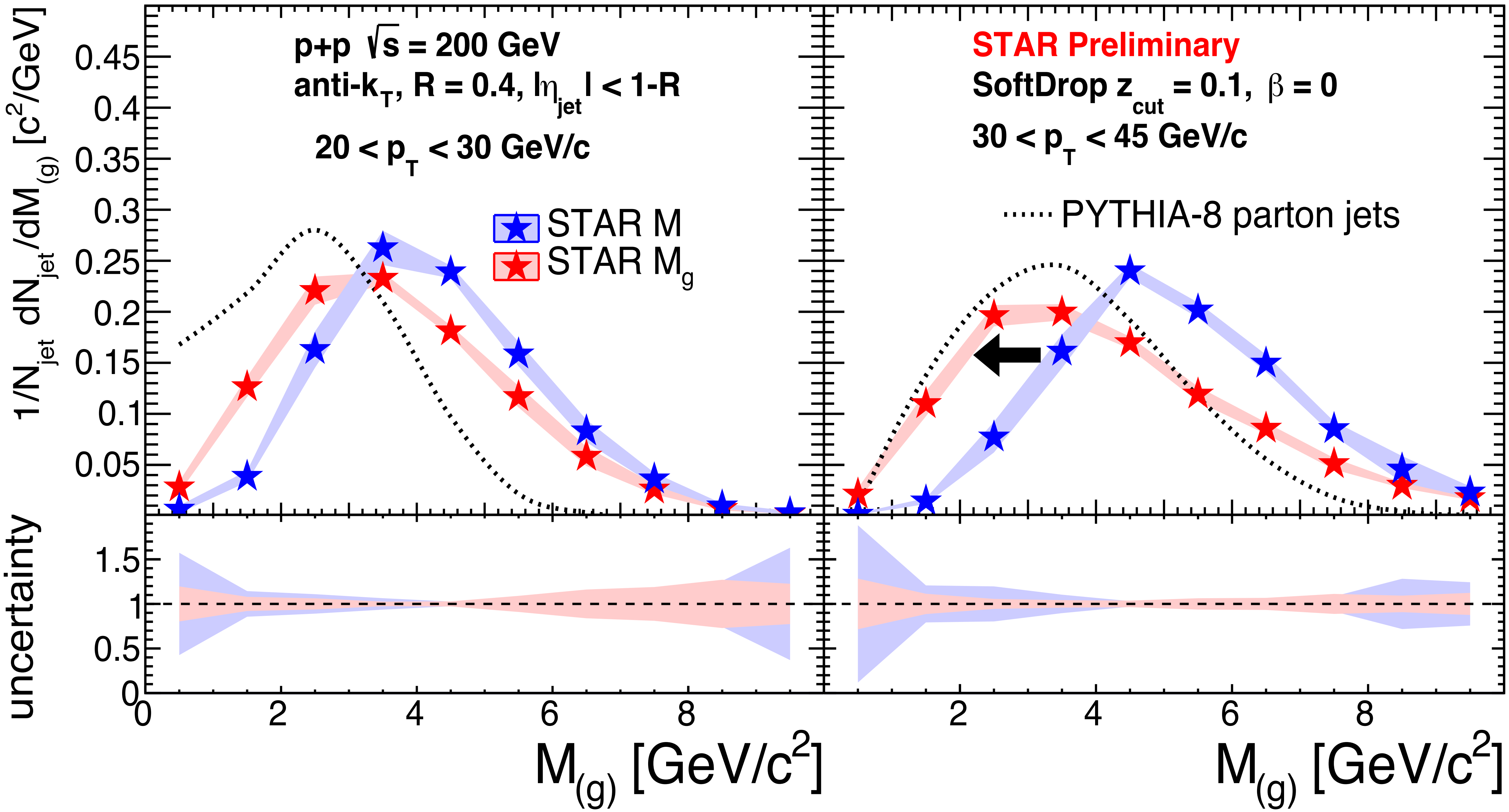


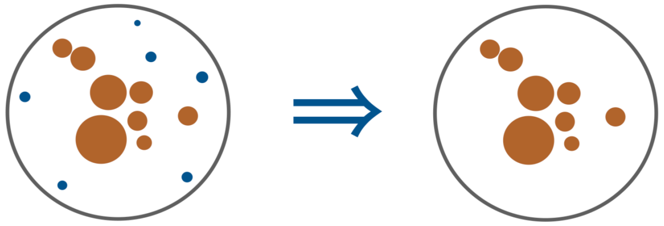
Inclusive jet mass: p+p



Groomed jet mass: $p+p$

Note: p_T panels are *ungroomed* jet p_T

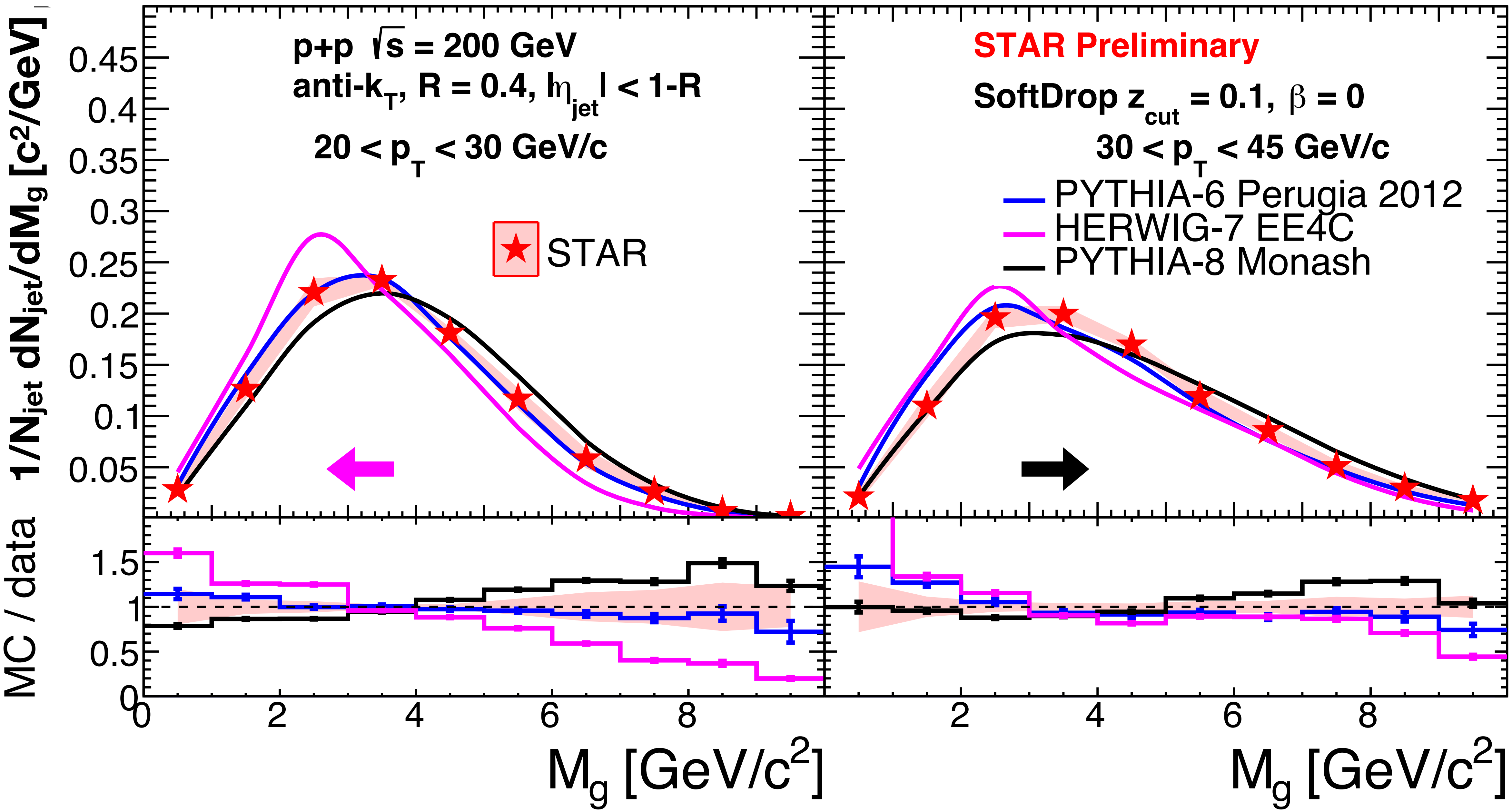




Grooming suppresses non-perturbative effects, decreasing jet mass - in particular, at higher $p_{T,\mathrm{jet}}$

Groomed jet mass: *p+p*

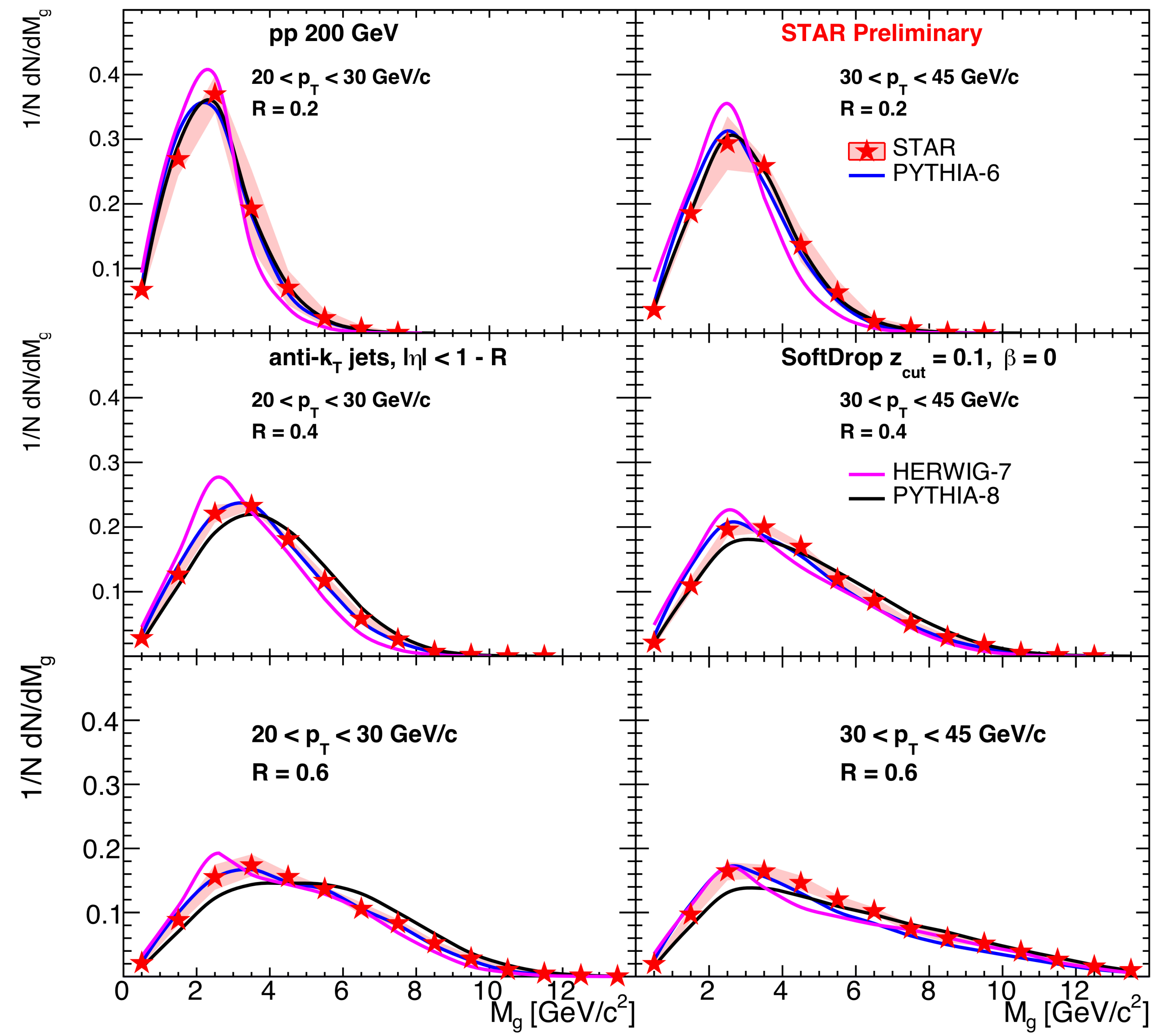
Note: p_T panels are *ungroomed* jet p_T



RHIC-tuned **PYTHIA-6** describes data

HERWIG-7 underpredicts and **PYTHIA-8** overpredicts

M_g evolution with jet R and p_T



Consistent substructure picture, comparing to evolution seen in R_g (see backup) with jet radius, given

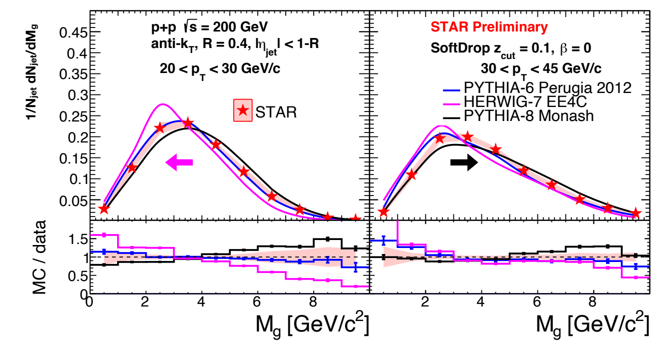
$$M_g \sim z_g R_g^2$$

Consistent with pQCD expectation:

- increased R & p_T
  - → increased phase space for radiation
  - → increased mass

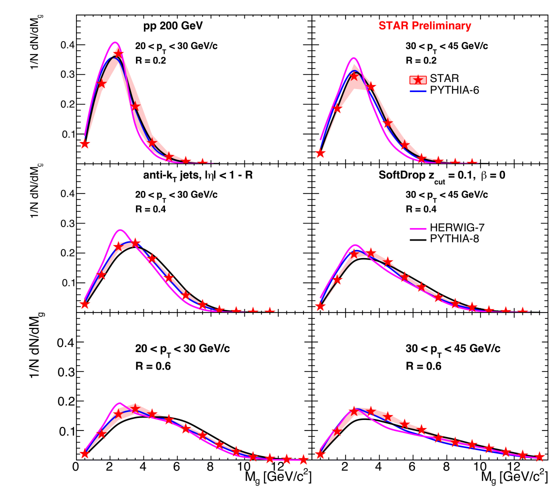
Conclusions - p+p

RHIC-tuned PYTHIA-6:
jet substructure data is well-described



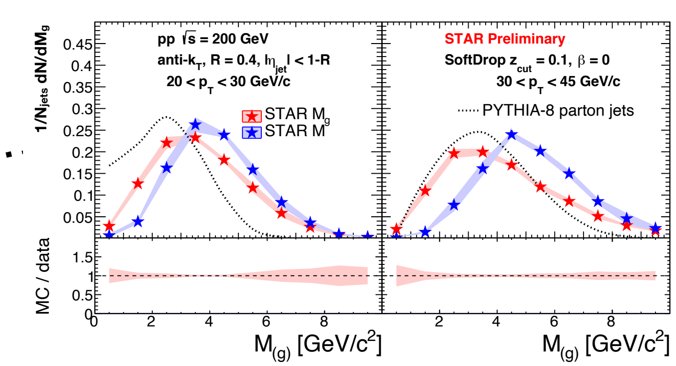
LHC-tuned HERWIG-7, PYTHIA-8:
opportunity for further tuning

First inclusive p+p jet mass measurements at RHIC



Jet mass increases with increased phase space (jet p_T, R), consistent with pQCD expectations

SoftDrop groomed mass is observed to be closer to ungroomed parton level mass; Consistent substructure picture via $M_g \sim z_g R_g^2$



Motivation - *p*+*p*, *p*+Au collisions

- ★ Unexpected PHENIX jet-R_{d+Au} — enhancement for peripheral, suppression for central collisions

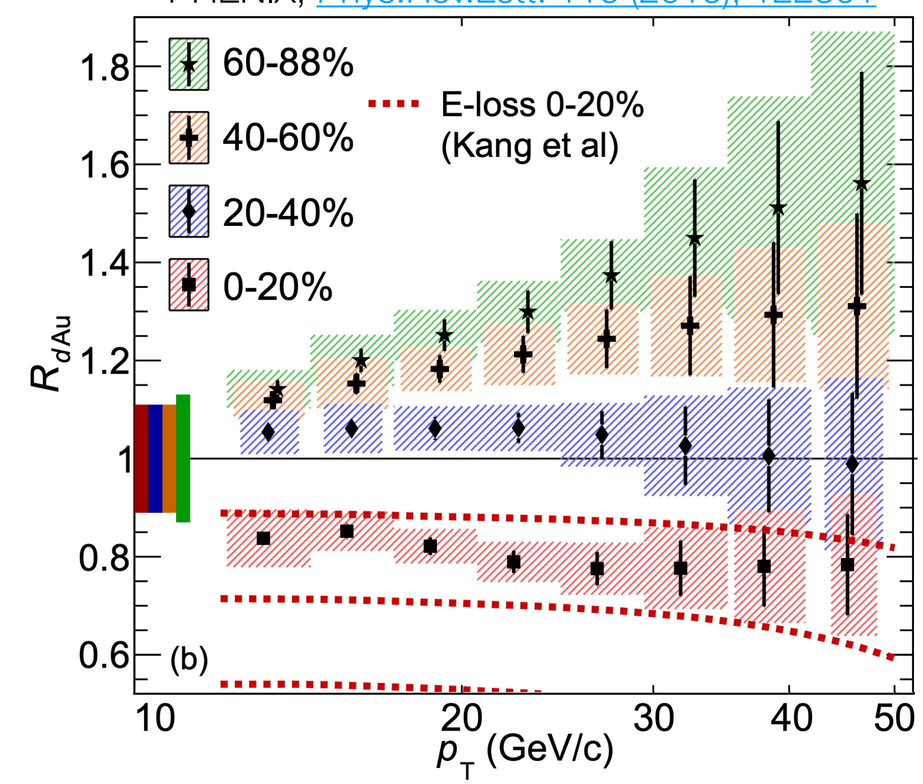
  & STAR semi-inclusive jet yield suppression for high event activity collisions

  - are jets modified at RHIC?

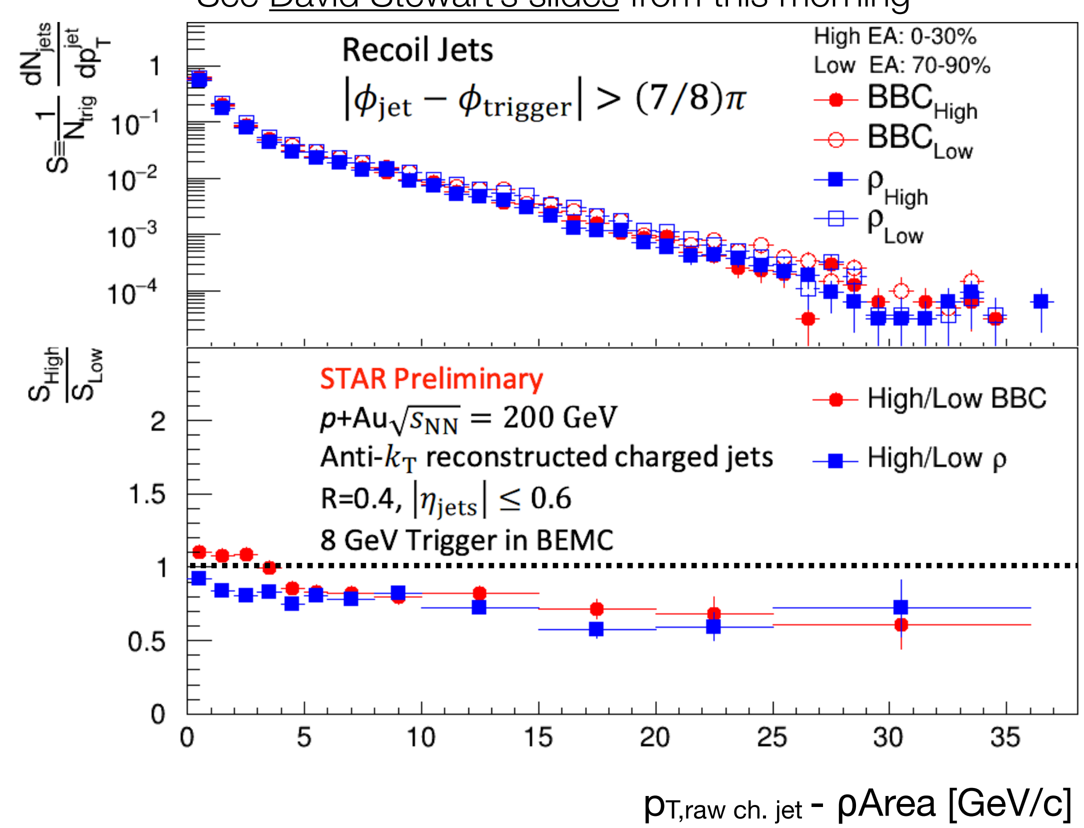
- ★ Jet mass may be sensitive to cold QCD effects, e.g. if initiating parton loses energy traversing the nucleus

- ★ *p*+*p* and *p*+Au serve as vacuum and cold QCD baselines for future STAR Au+Au studies

PHENIX, Phys.Rev.Lett. 116 (2016), 122301



See David Stewart's slides from this morning



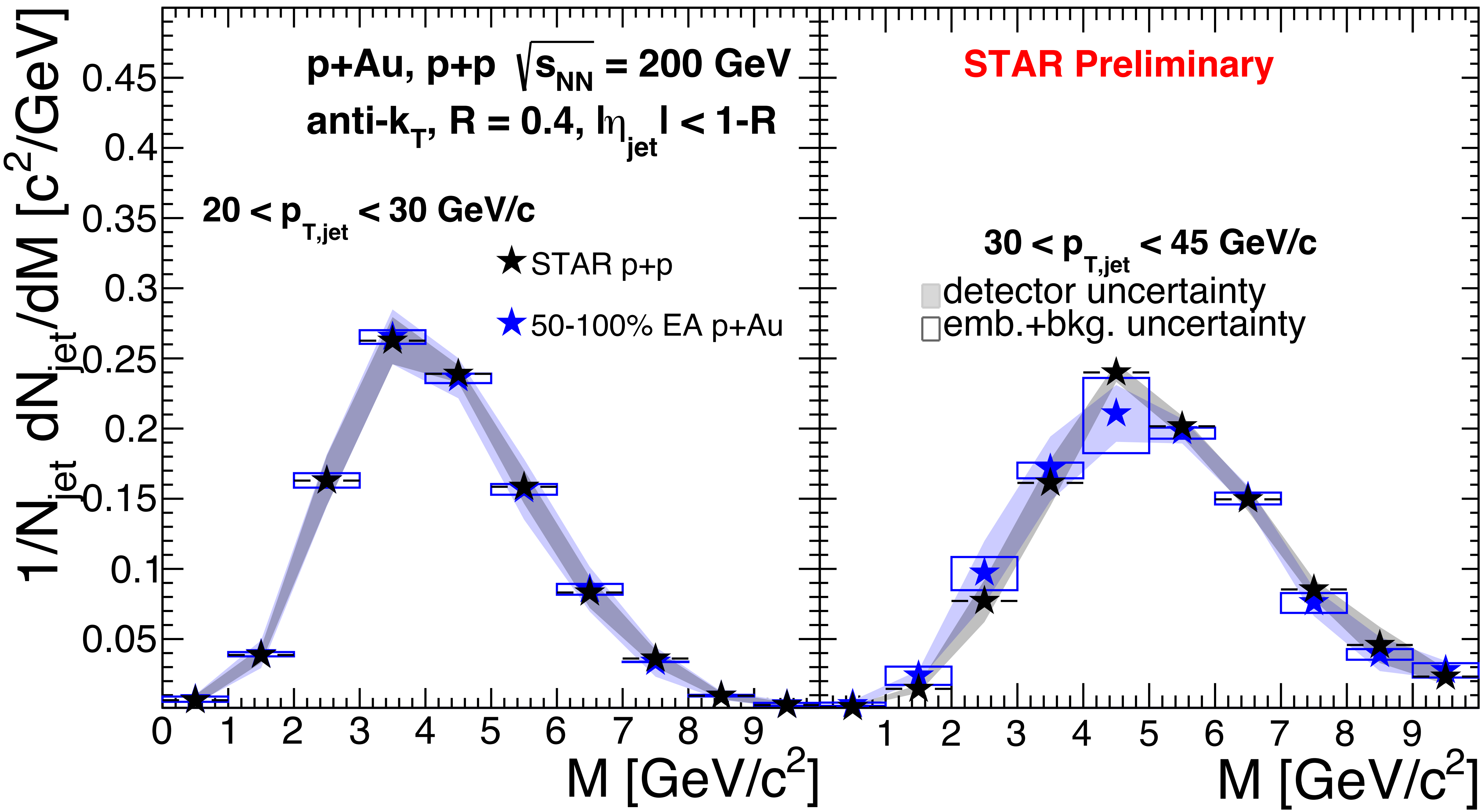
Jet mass in *p*+Au: analysis details

David Stewart, Oct. 30, 11:18 CDT, EB

- ★ Test event activity dependence using the inner BBC on the Au-going (east) side
- ★ Embed PYTHIA+GEANT events into *p*+Au MB background, unfold without event-by-event UE subtraction
- ★ Assess additional systematics due to our embedding procedure and the enhanced background in *p*+Au

Veronica Verkest, Oct. 31, 11:18 CDT, LB

Jet mass: low EA

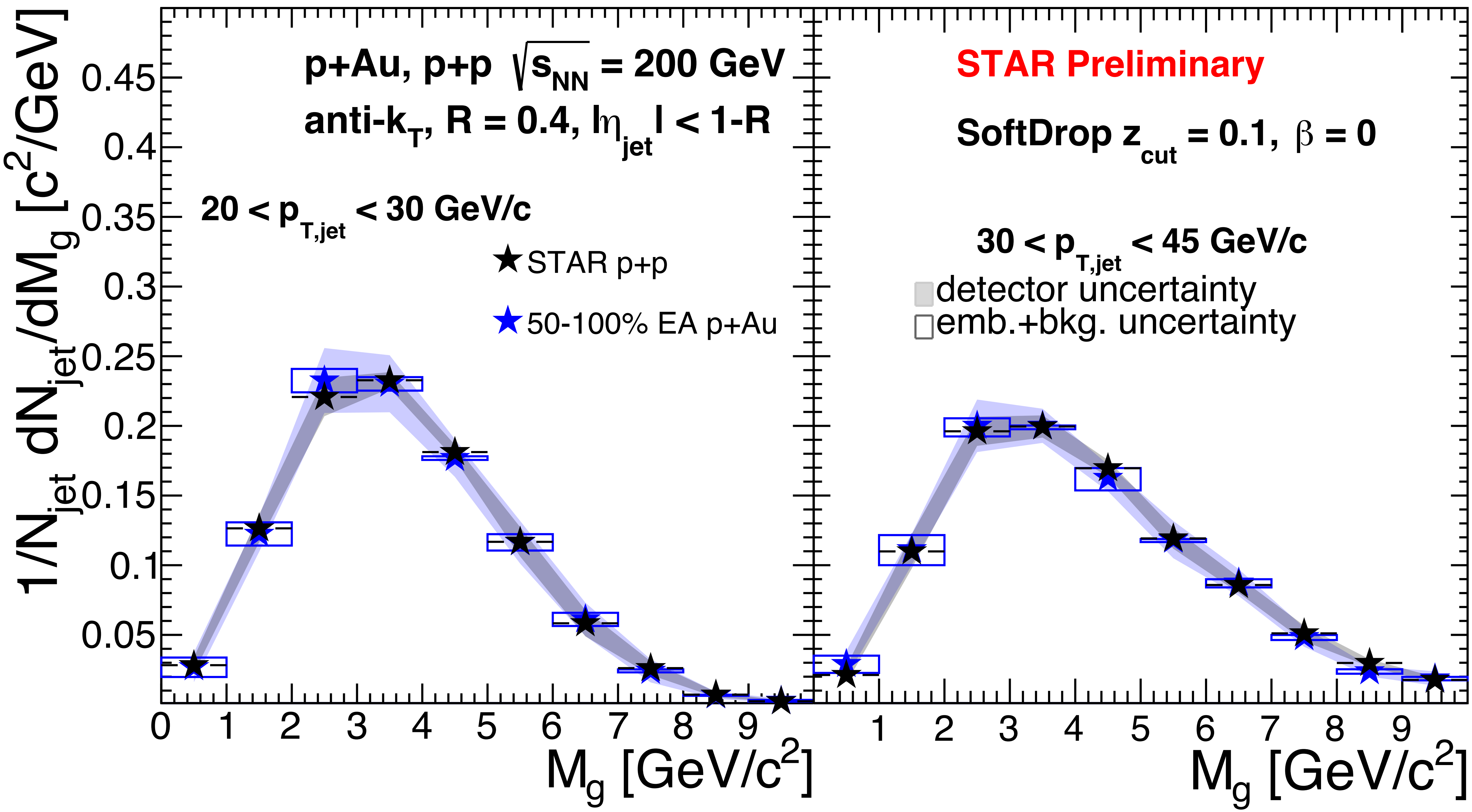


Jet mass results in *p+p* and *p+Au 50-100%* event activity are comparable

p+Au low-EA ~ *p+p* !

Groomed jet mass: low EA

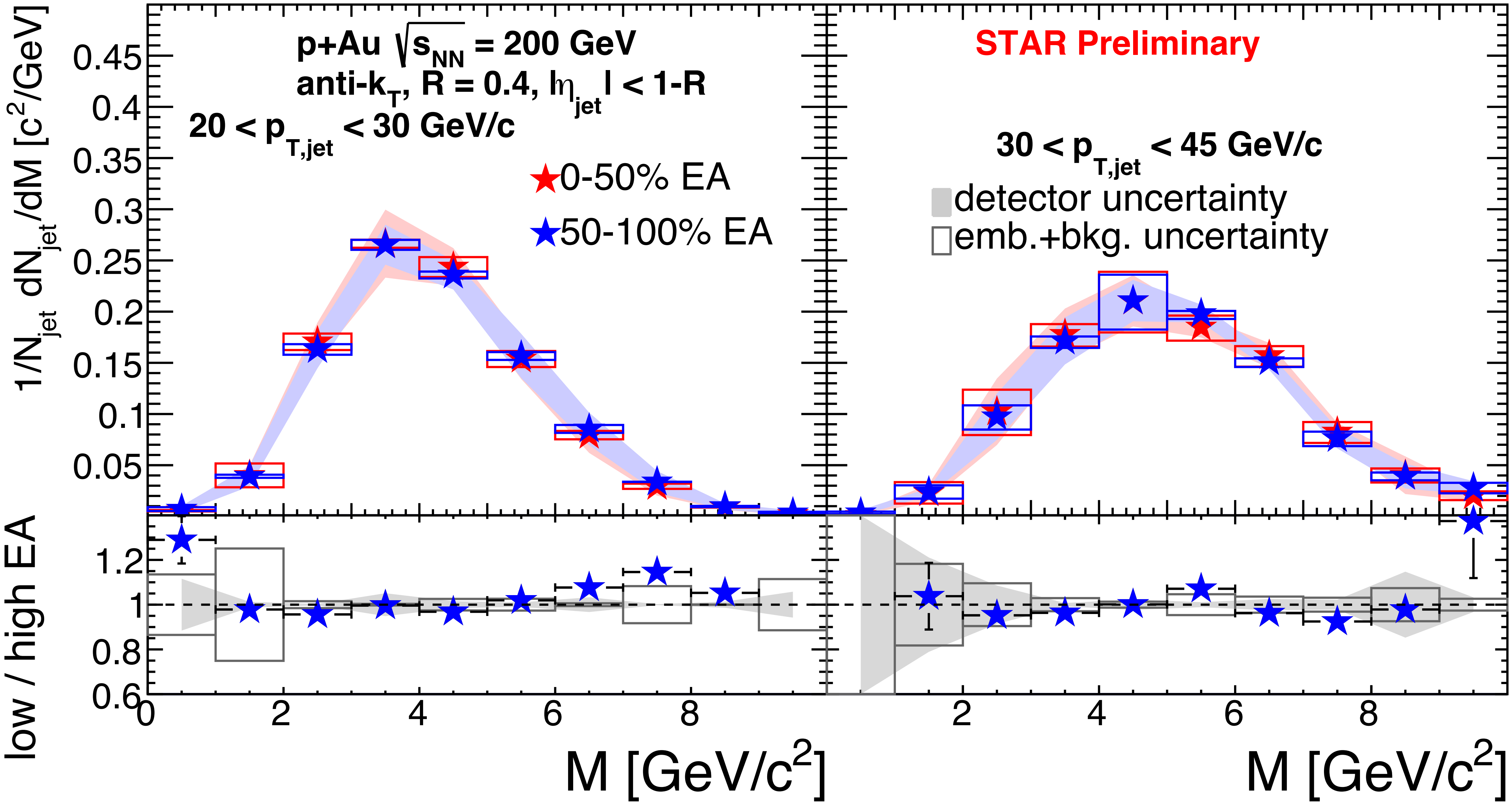
Note: p_T panels are *ungroomed* jet p_T



Groomed jet mass results in *p+p* and *p*+Au 50-100% event activity are comparable

***p*+Au low-EA ~ *p+p* !**

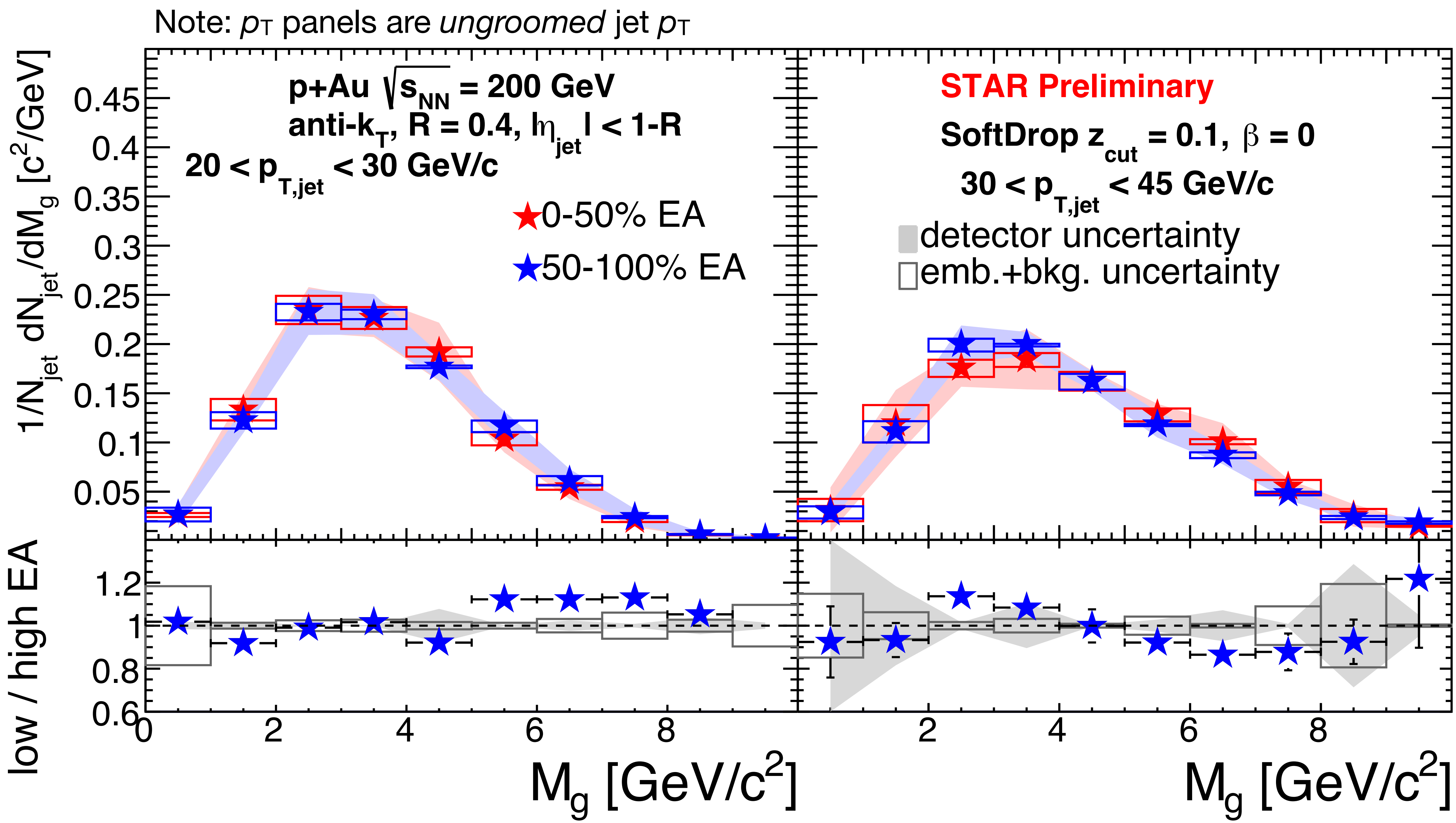
Jet mass: high EA



Low- and high-EA mass ratio is unity within systematic and statistical uncertainties

No significant modification to the jet mass is observed in *p*+Au!

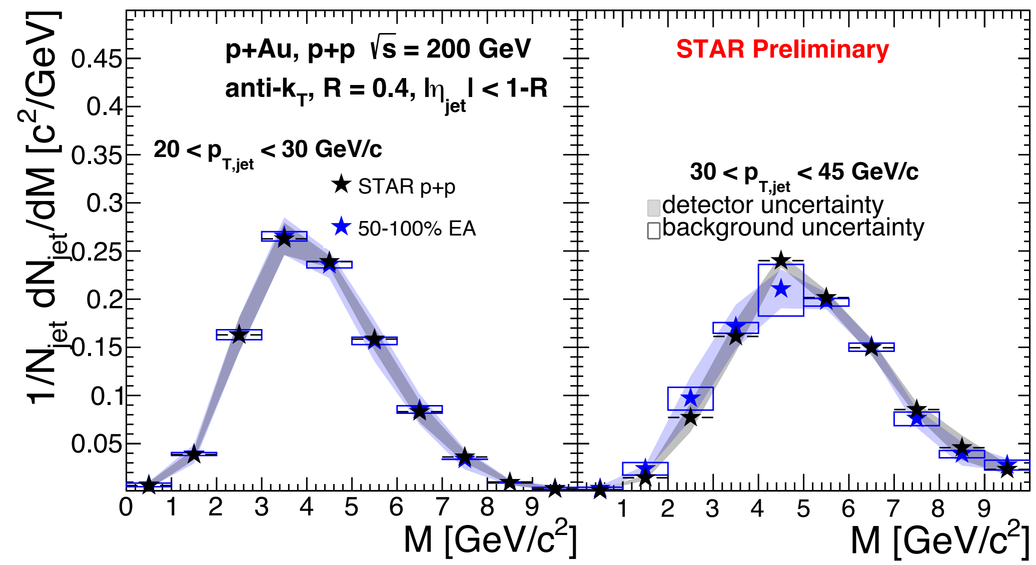
Groomed jet mass: high EA



Low- and high-EA mass ratio is unity within systematic and statistical uncertainties → core of the jets is unmodified

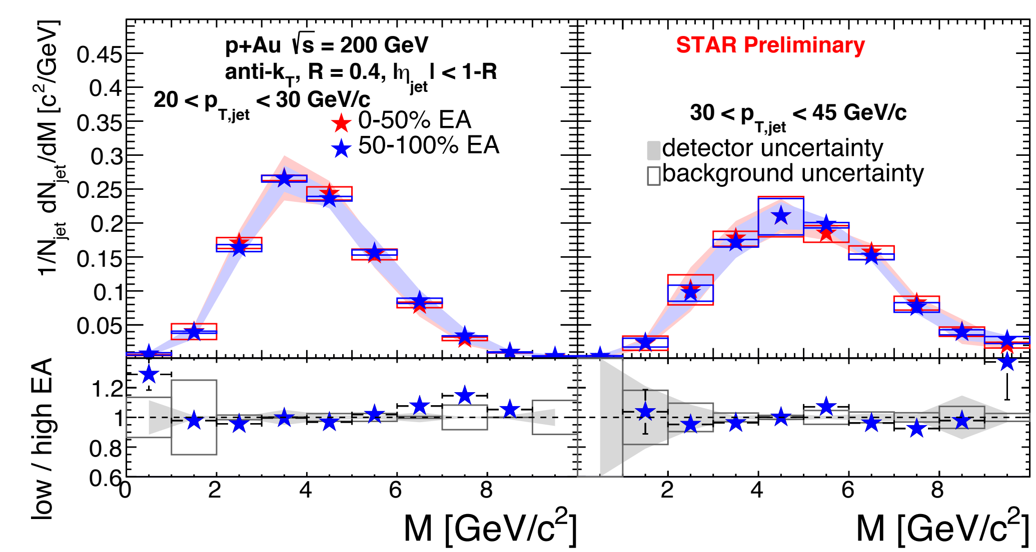
Conclusions - *p*+Au

First inclusive *p*+Au jet mass measurements at RHIC



Overall, we observe no contribution of CNM effects to the jet mass in *p*+Au collisions, suggesting *p*+*p*-like fragmentation, no jet modification

Suggests that activity- (centrality-) dependent modification of jet yields observed by STAR (PHENIX) is not due to CNM effects / jet quenching



Conclusions

First inclusive *p*+*p*, *p*+Au jet mass measurements at RHIC

p+*p*: RHIC-tuned PYTHIA-6: jet substructure data are well described
LHC-tuned HERWIG-7, PYTHIA-8: opportunity for further tuning

p+Au: no contribution of CNM effects to the (groomed) jet mass, suggesting *p*+*p*-like fragmentation

Outlook

z_g, R_g in *p*+Au — are competing modifications canceled in M_g?

Narrow event activity selections to enhance potential CNM effects

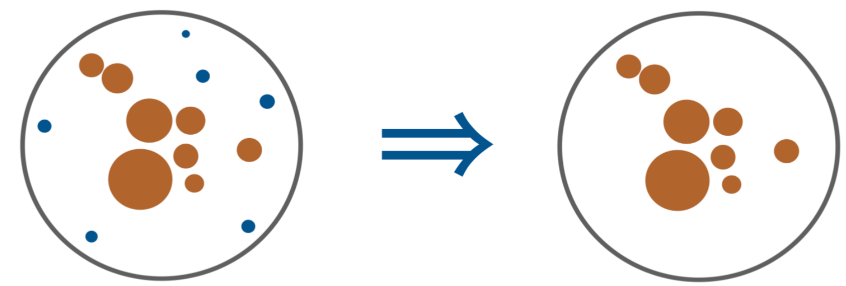
Study jet radius dependence in *p*+Au to compare to *p*+*p*

Au+Au to study hot nuclear matter effects on jet substructure, e.g. jet mass!

Backup

SoftDrop grooming

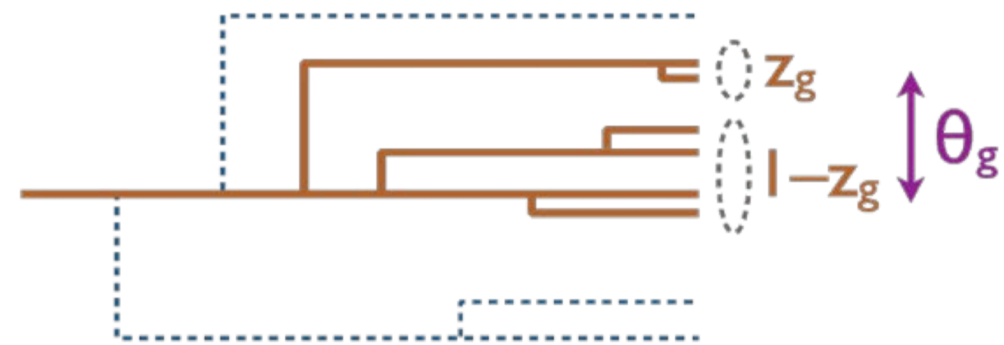
Suppress wide-angle non-perturbative radiation for more direct theory comparison; closer to parton-level



momentum fraction, z_g

angle, R_g

jet mass, M_g



$$z > z_{\rm cut}\,\theta^{\beta}$$

energy threshold

angular exponent

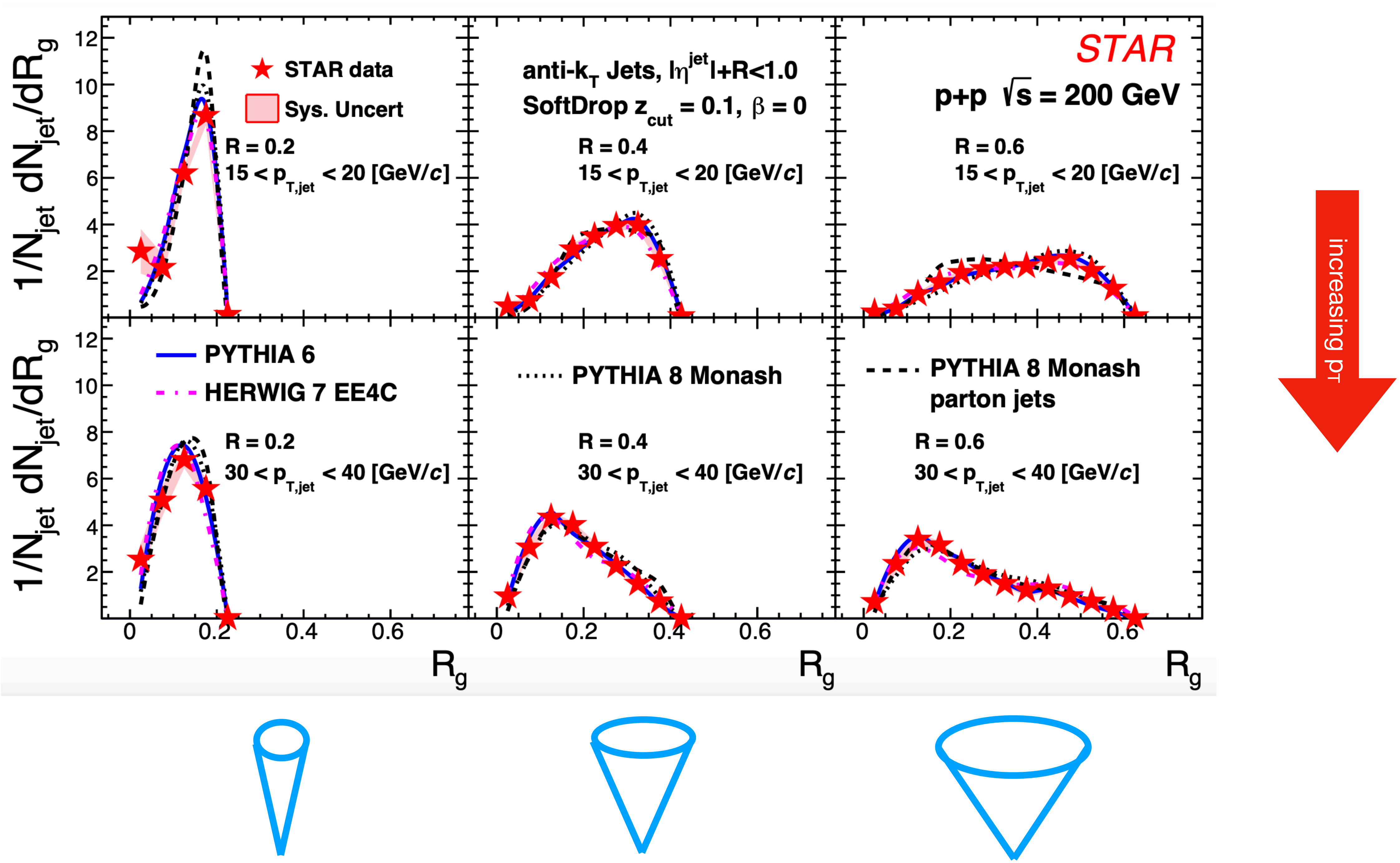
Approach: decluster angular-ordered splitting tree by removing prongs which fail the criterion

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

We consider jets with $z_g > 0.1$ ($\beta = 0$)

Larkoski, Marzani, Soyez, Thaler, JHEP 05 (2014) 146

R_g evolution



Sudakov structure of jet mass

Dominant effect on QCD jet mass:
hard parton radiating gluons

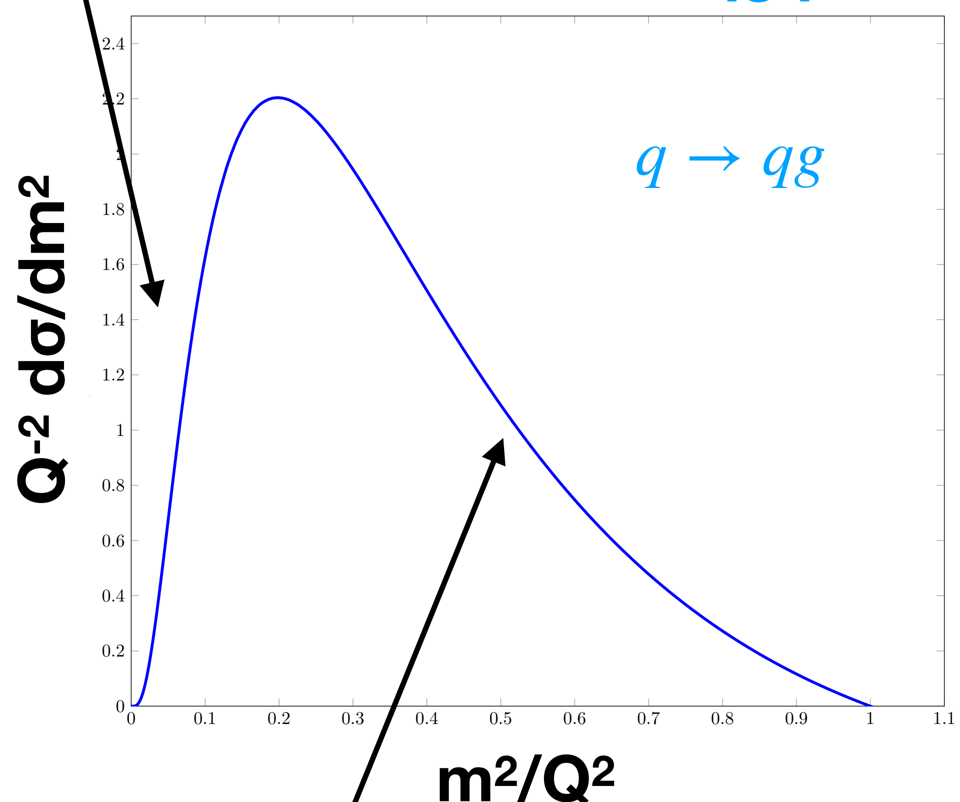
$$\frac{d\sigma}{dm^2} \approx \exp\left(-\frac{\alpha_s}{4\pi} C_F \log^2 \frac{Q^2}{m^2}\right) \frac{1}{m^2} \frac{\alpha_s}{2\pi} C_F \log \frac{Q^2}{m^2}$$

[Cross section for hard quark to produce hardest gluon with pair invariant mass *m*^{2}]

Leading log resummation brings P of perfectly collinear gluon from ∞ (AP splitting functions) to 0

Note: letting $\frac{\alpha_s}{2\pi} C_F = 1$

Invariant mass of qg pair



~ jet mass (compare to e.g. s. 10!)

For a jet, becomes more likely the split results in 2nd jet before about $M/2p_T$.

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"Sudakov factor, Δ(*Q*,*m*)"

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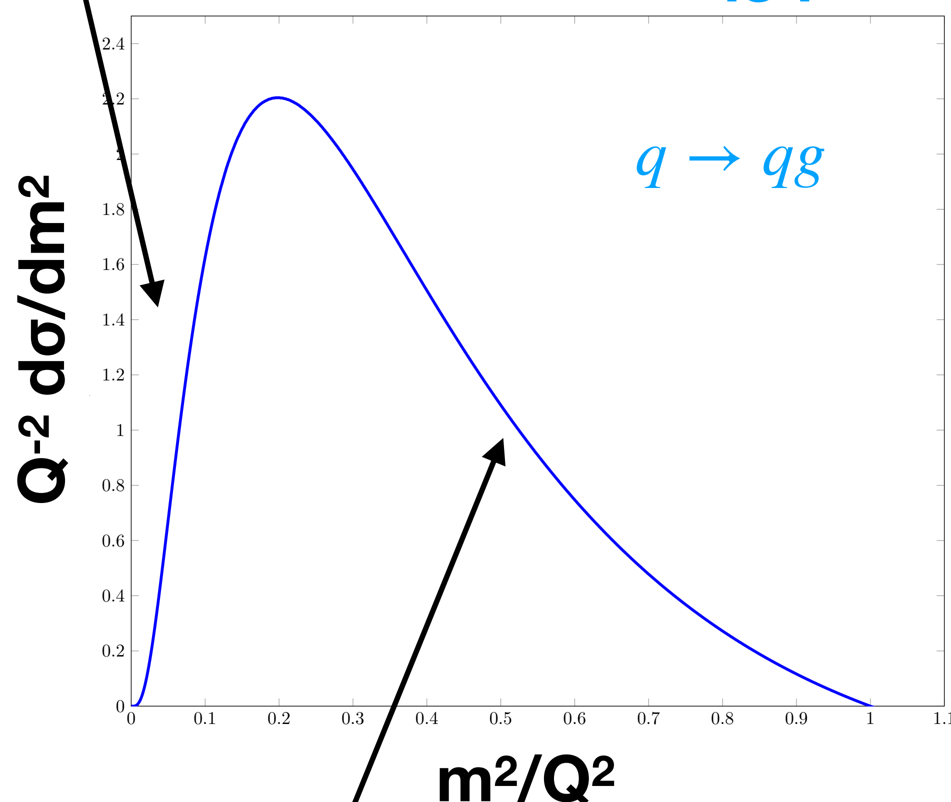


~ jet mass (compare to e.g. s. 10!)

For a jet, becomes more likely the split results in 2nd jet before about $M/2p_T$.

MC tunes

PYTHIA-6.4.28: Perugia 2012 tune."This combination overestimates the inclusive $\pi^{\pm}$ yields by up to 30% for $p_T < 3$ GeV/c, when compared to the previously published STAR measurements at $\sqrt{s}$ = 200 GeV [47,48]. To compensate, a single parameter in the Perugia 2012 PYTHIA tune, PARP(90), was reduced from 0.24 to 0.213. PARP(90) controls the energy dependence of the low-p_T cut-off for the UE generation process."[1]

[1] STAR, Phys.Rev. D 100 (2019), 052005

[2] Skands, Carrazza, Rojo, Eur.Phys.J. C 74 (2014), 3024

[3] Gieseke, Rohr, Siodmok, Eur.Phys.J. C 72 (2012), 2225

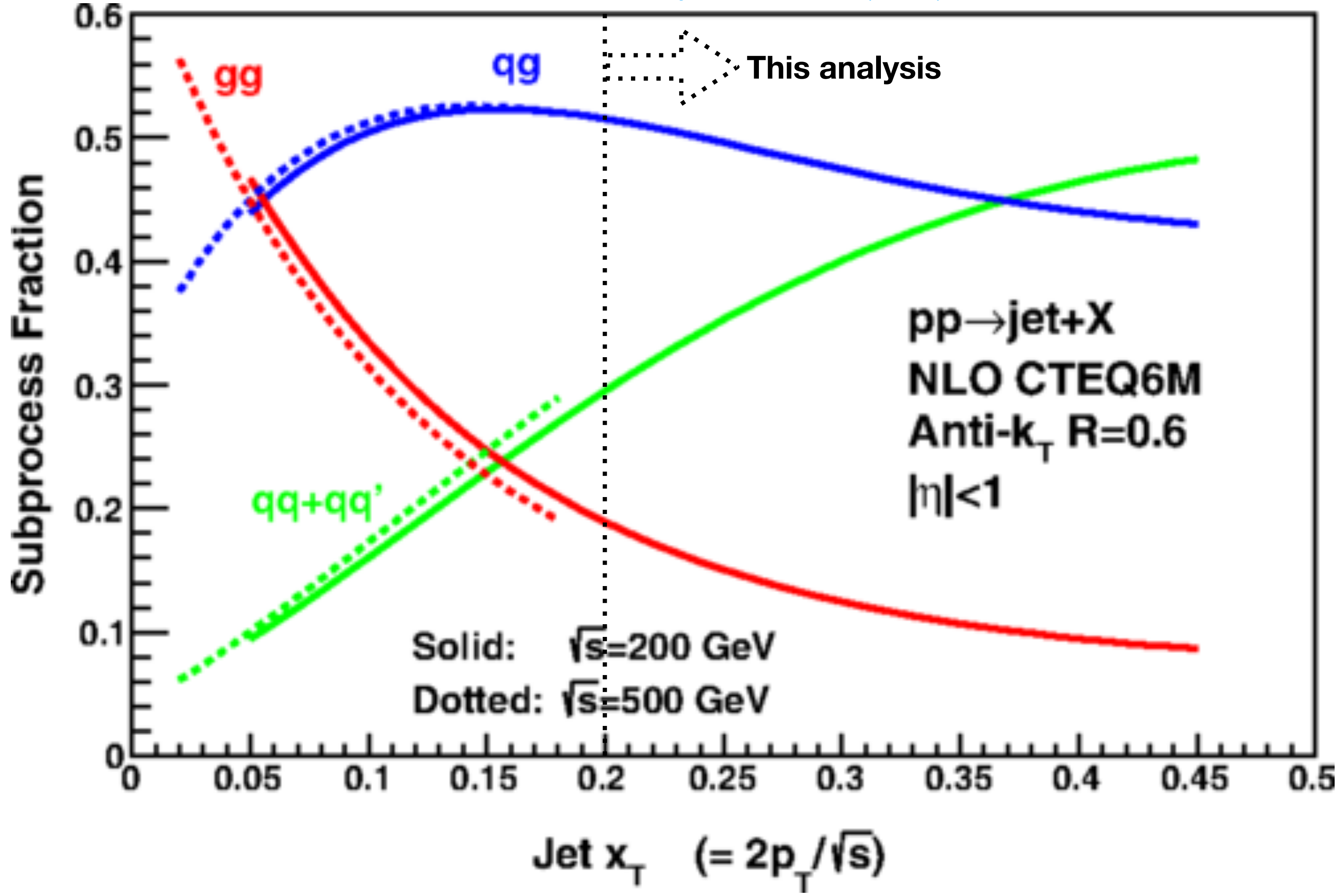
PYTHIA-8.23: Monash tune[2]

HERWIG-7: LHC-UE-EE-4-CTEQ6L1 underlying event tune[3]

Note: relatively stable particles are left undecayed until interaction with the detector material in the GEANT-3 simulation. These "stable" particles include $\pi^0, \pi^{\pm}, \eta, K^+, K^0_S, K^0_L, \Sigma^{\pm}, \bar{\Sigma}^{\pm}, \Lambda, \bar{\Lambda}, \Xi^-, \bar{\Xi}^+, \Omega^-, \bar{\Omega}^+$

Quark and gluon fractions

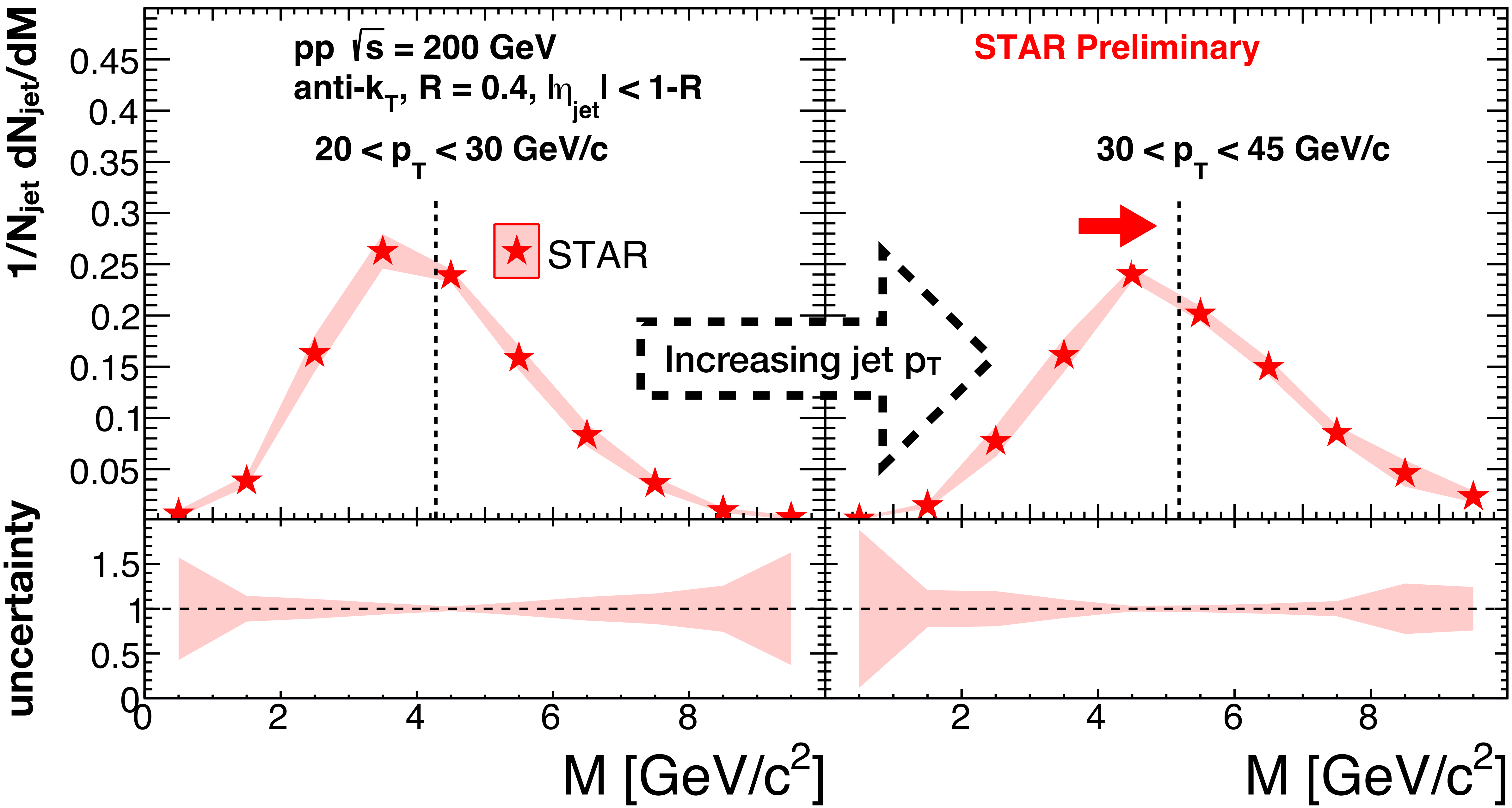
STAR, Phys.Rev. D 100 (2019), 052005



Gluon jets have larger mass than quark jets ($C_A/C_F = 9/4$)

Majority of jets are quark-initiated in this kinematic regime

Jet mass as a function of $p_{T,\text{jet}}$

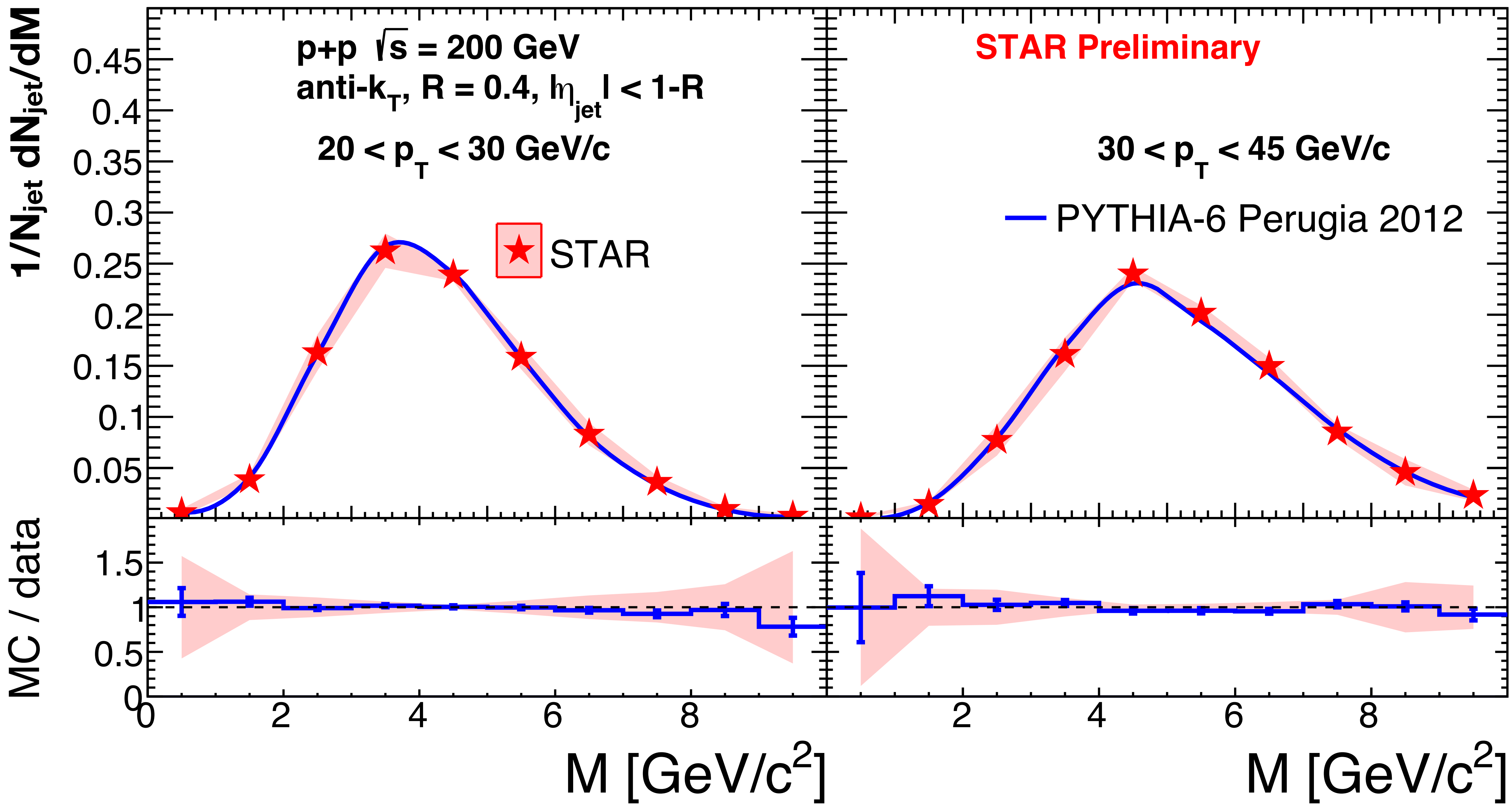


From pQCD, jet p_T increase

→ increased phase space to radiate

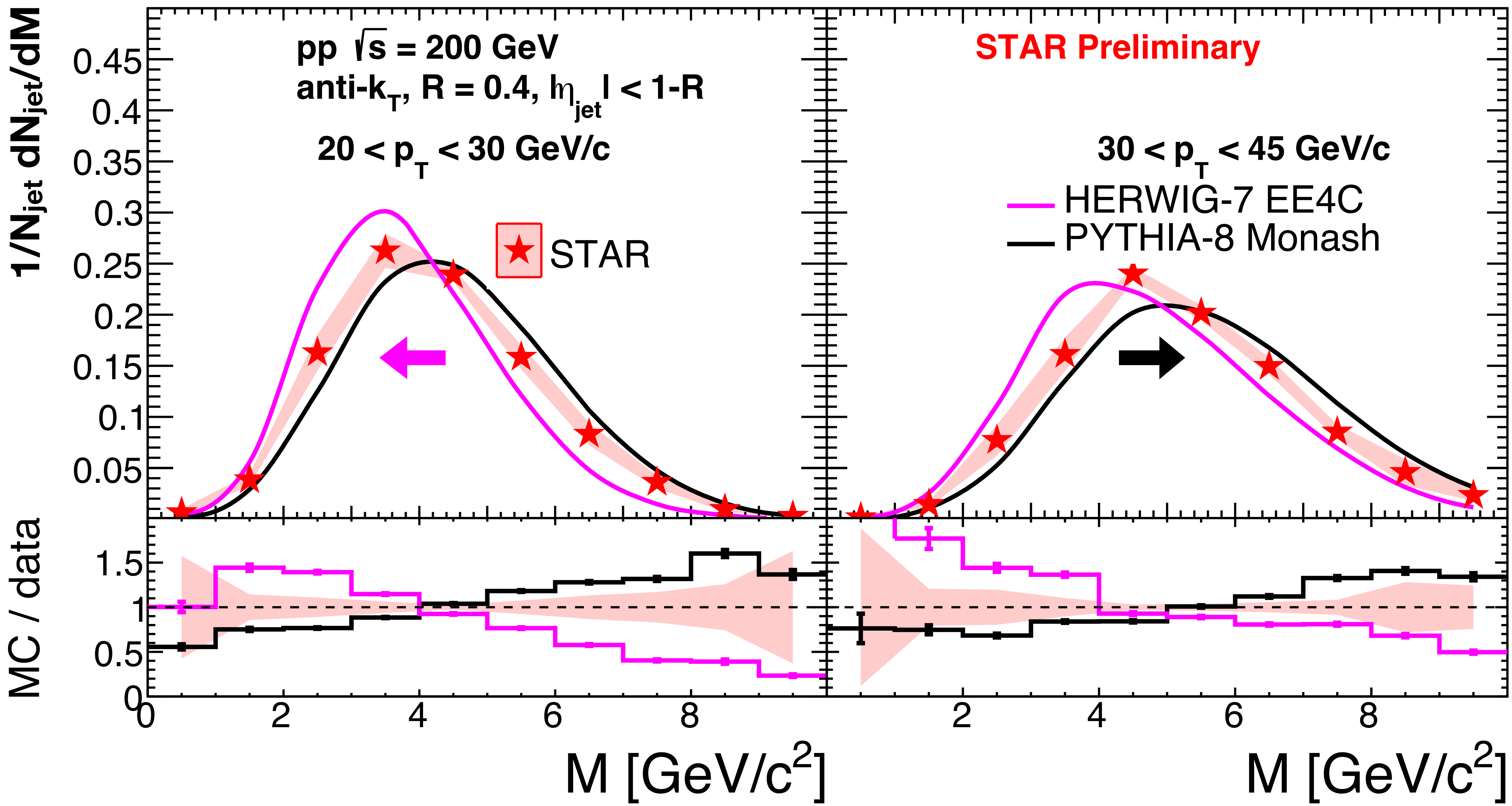
→ increased mass

Jet mass as a function of $p_{T,jet}$



RHIC-tuned **PYTHIA-6** describes data

Jet mass as a function of $p_{T,jet}$

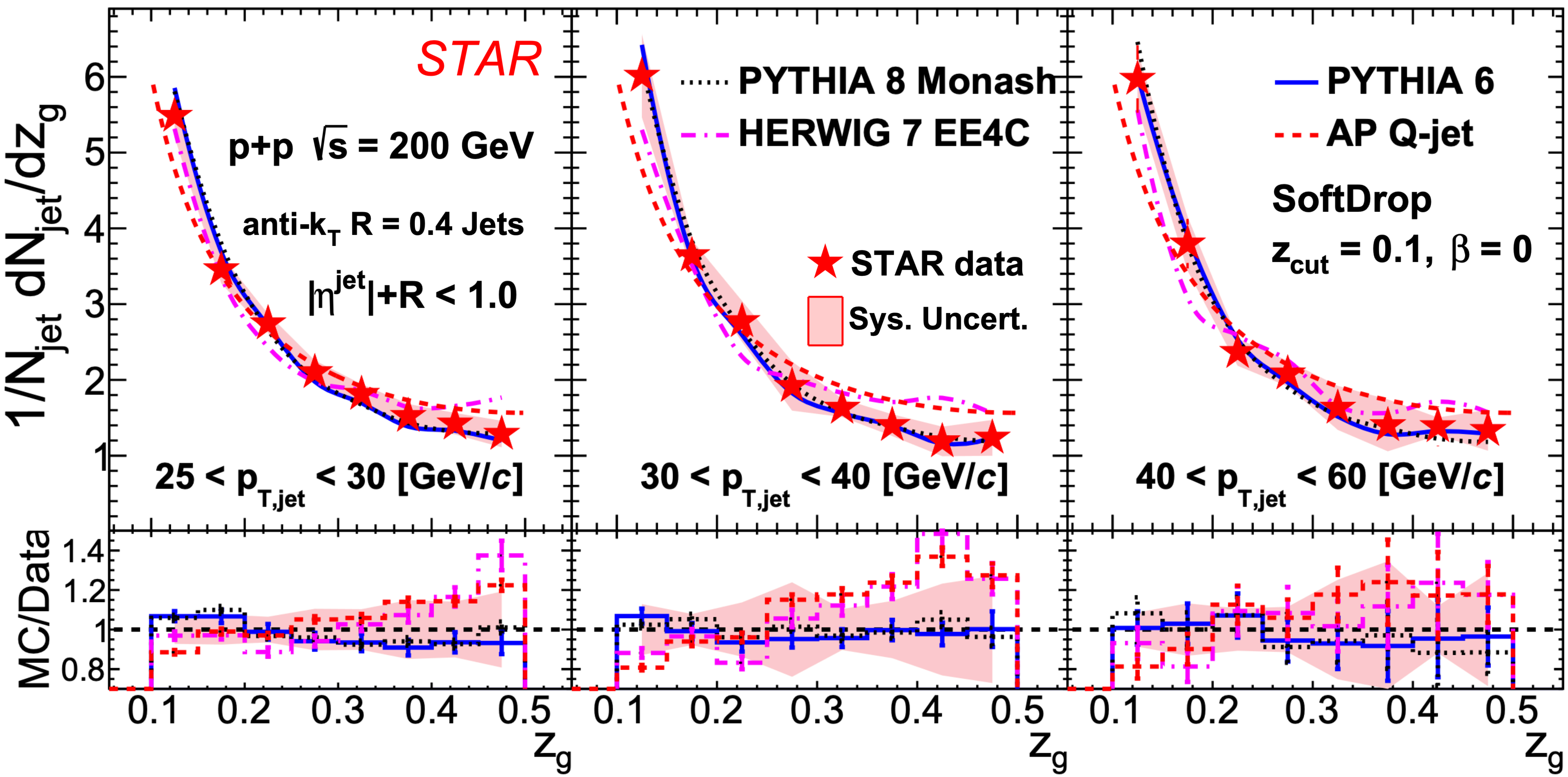


HERWIG-7 underpredicts and **PYTHIA-8** overpredicts

(EE4C) ← LHC → (Monash)

Groomed momentum fraction

Note: p_T panels are *ungroomed* jet p_T — arXiv:2003.02114 (accepted to PLB)

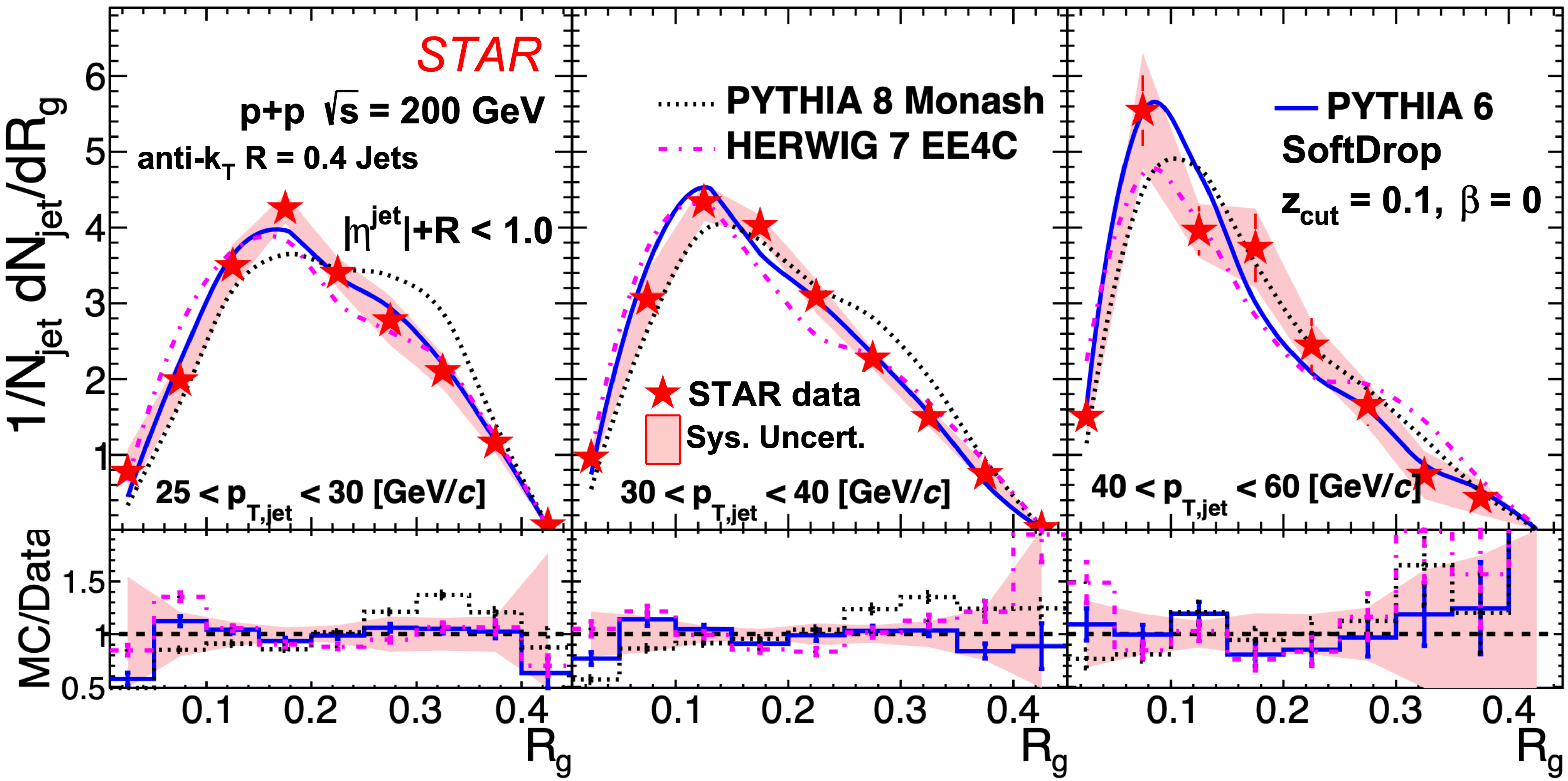


- ★ Recover the universal 1/*z* behavior starting from p_T ~ 25 GeV/*c*
- ★ **PYTHIA-6** and **PYTHIA-8** describe data
- ★ **HERWIG-7** predicts harder splitting

Groomed jet radius

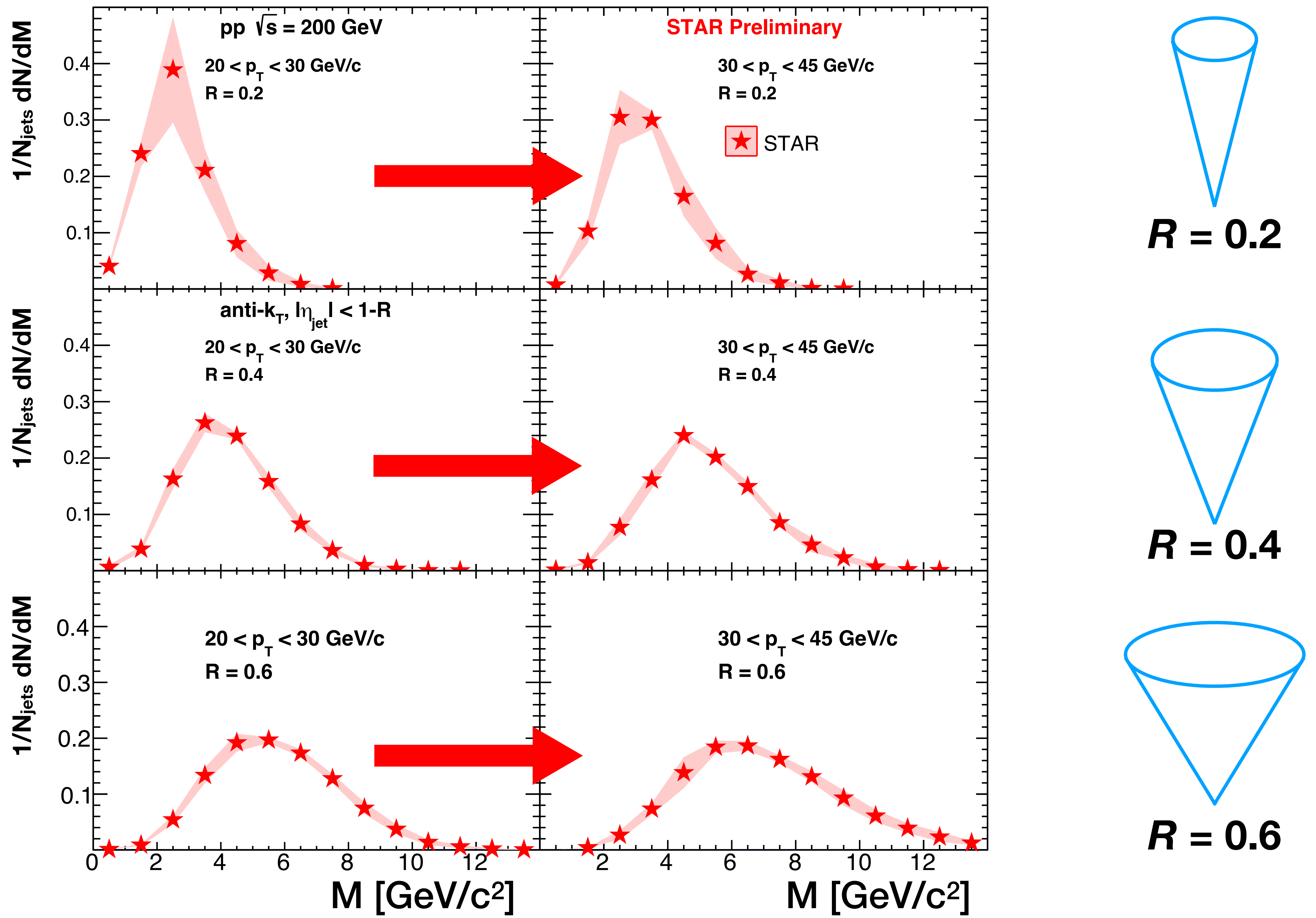
Note: p_T panels are *ungroomed* jet p_T

arXiv:2003.02114 (accepted to PLB)



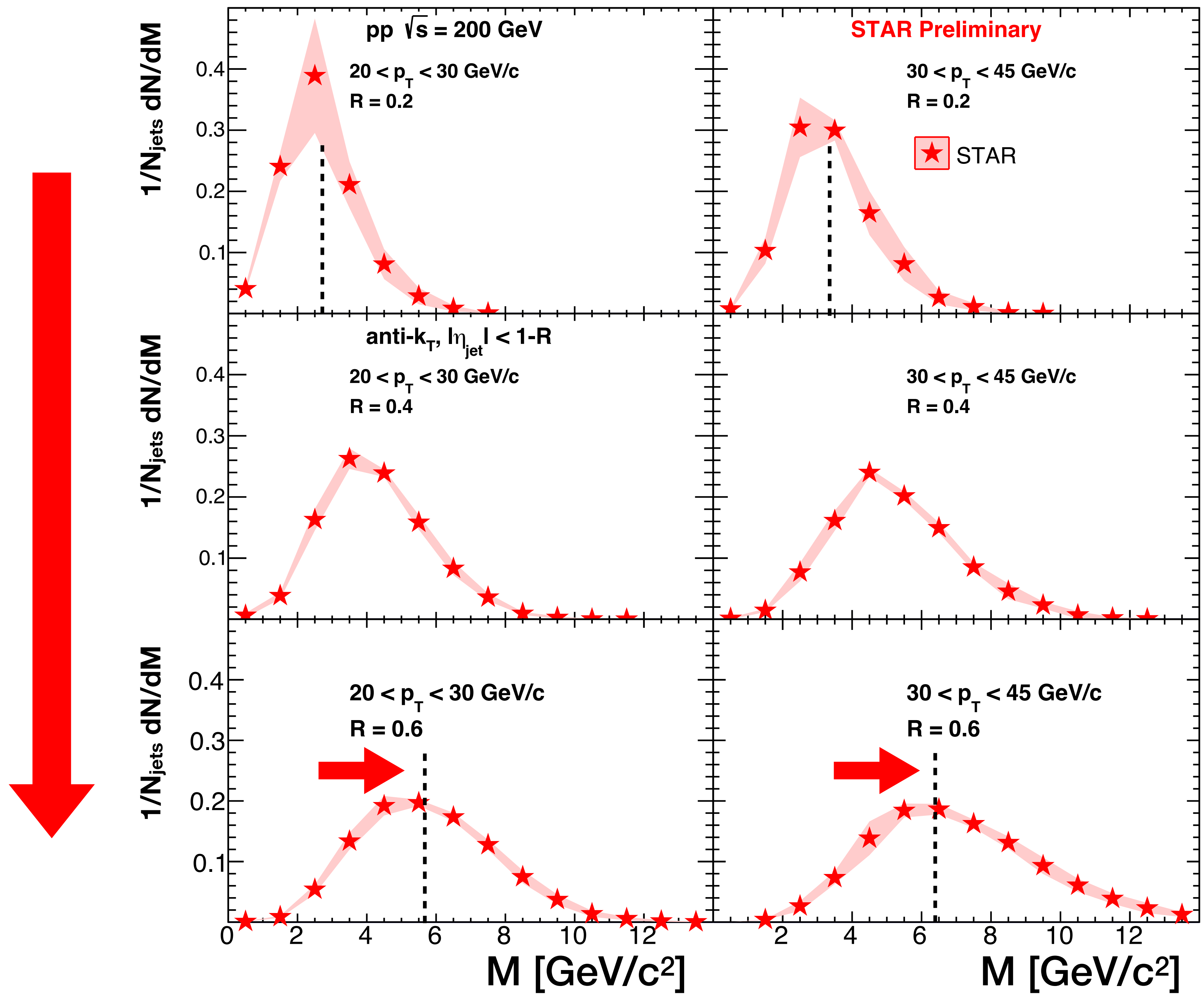
- ★ R_g reflects momentum-dependent narrowing of jet structure
- ★ **PYTHIA-6** describes data
- ★ **PYTHIA-8** predicts larger groomed jet angular scale

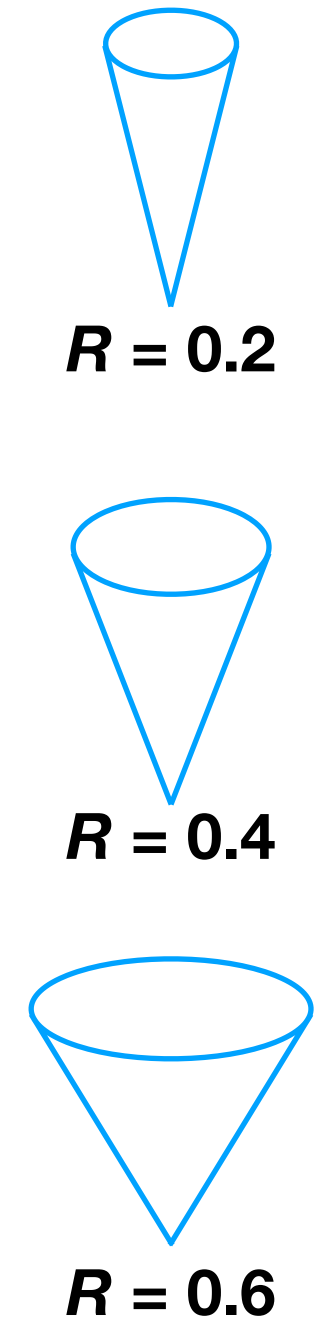
Jet mass as a function of *R*



From pQCD, jet p_T increase → increased phase space to radiate → increased mass

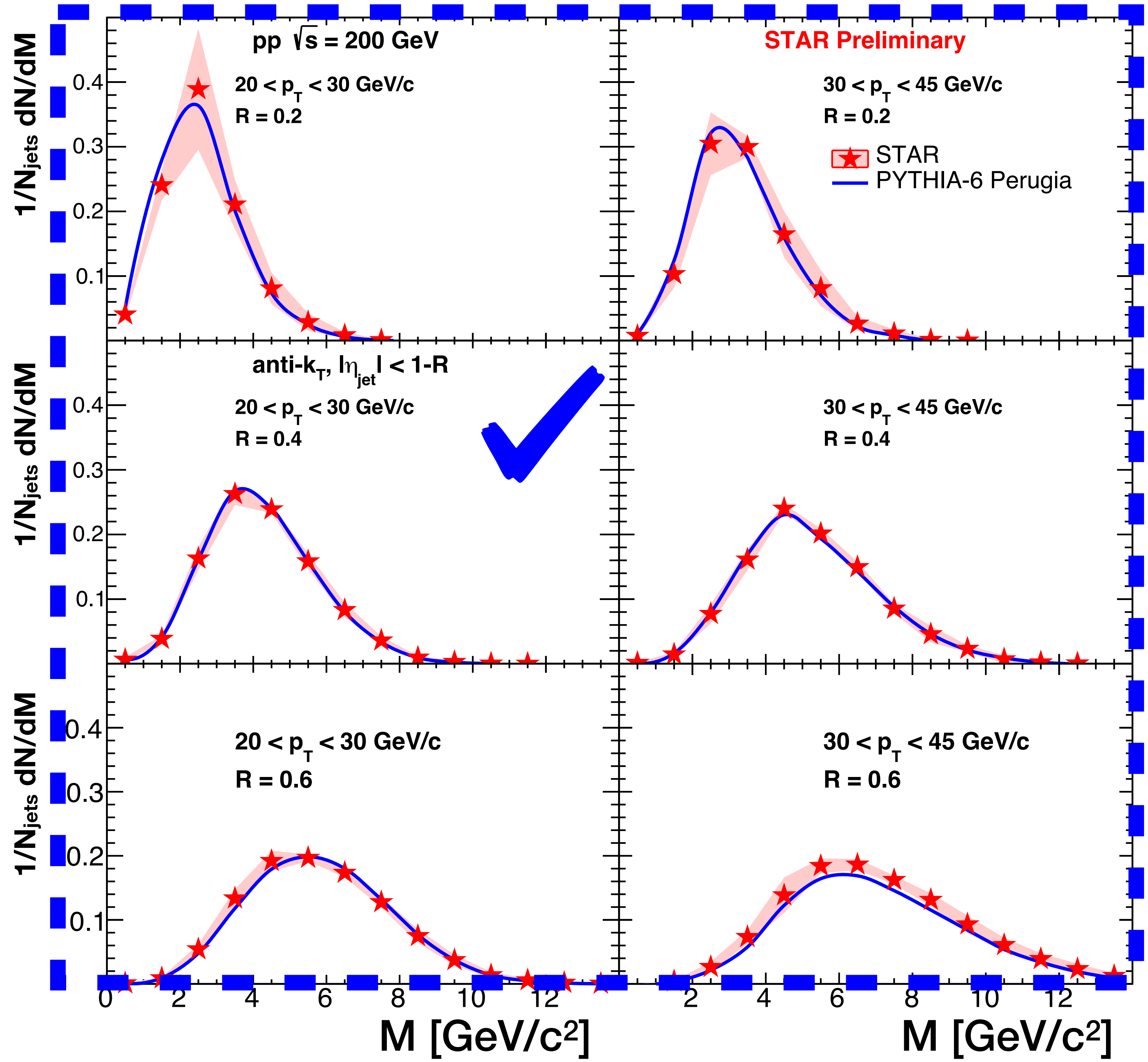
Jet mass as a function of *R*

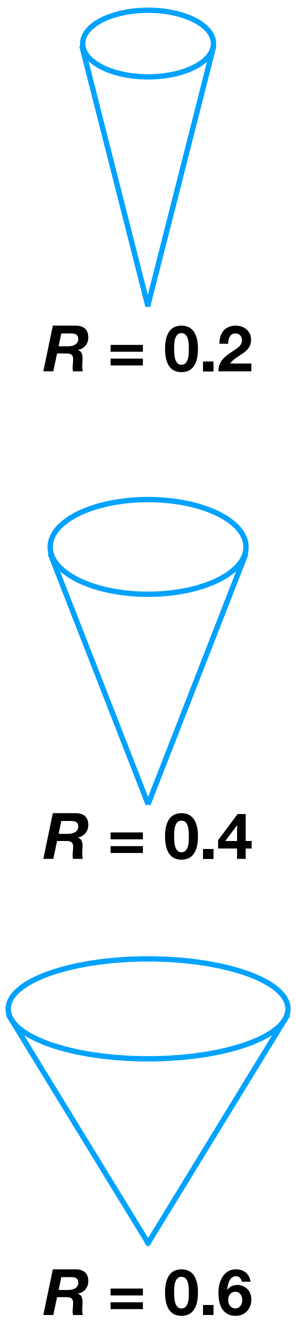




As radius increases, jets encompass more wide-angle radiation → increased mass

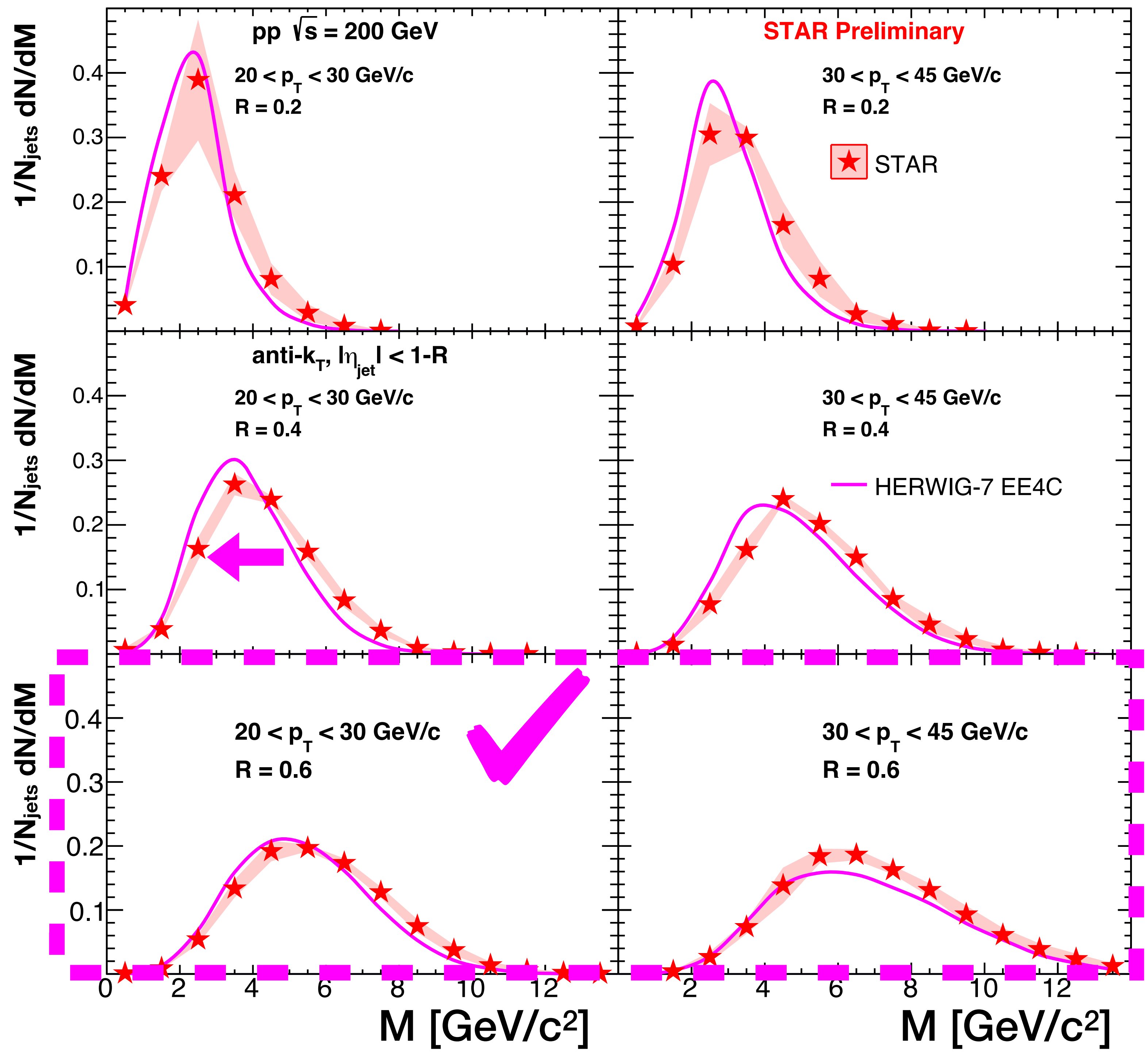
Jet mass as a function of *R*

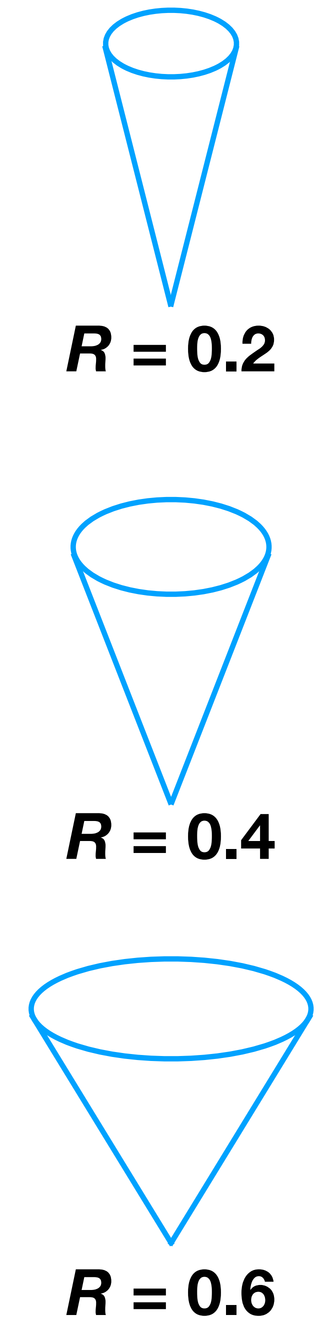




RHIC-tuned **PYTHIA-6** describes data

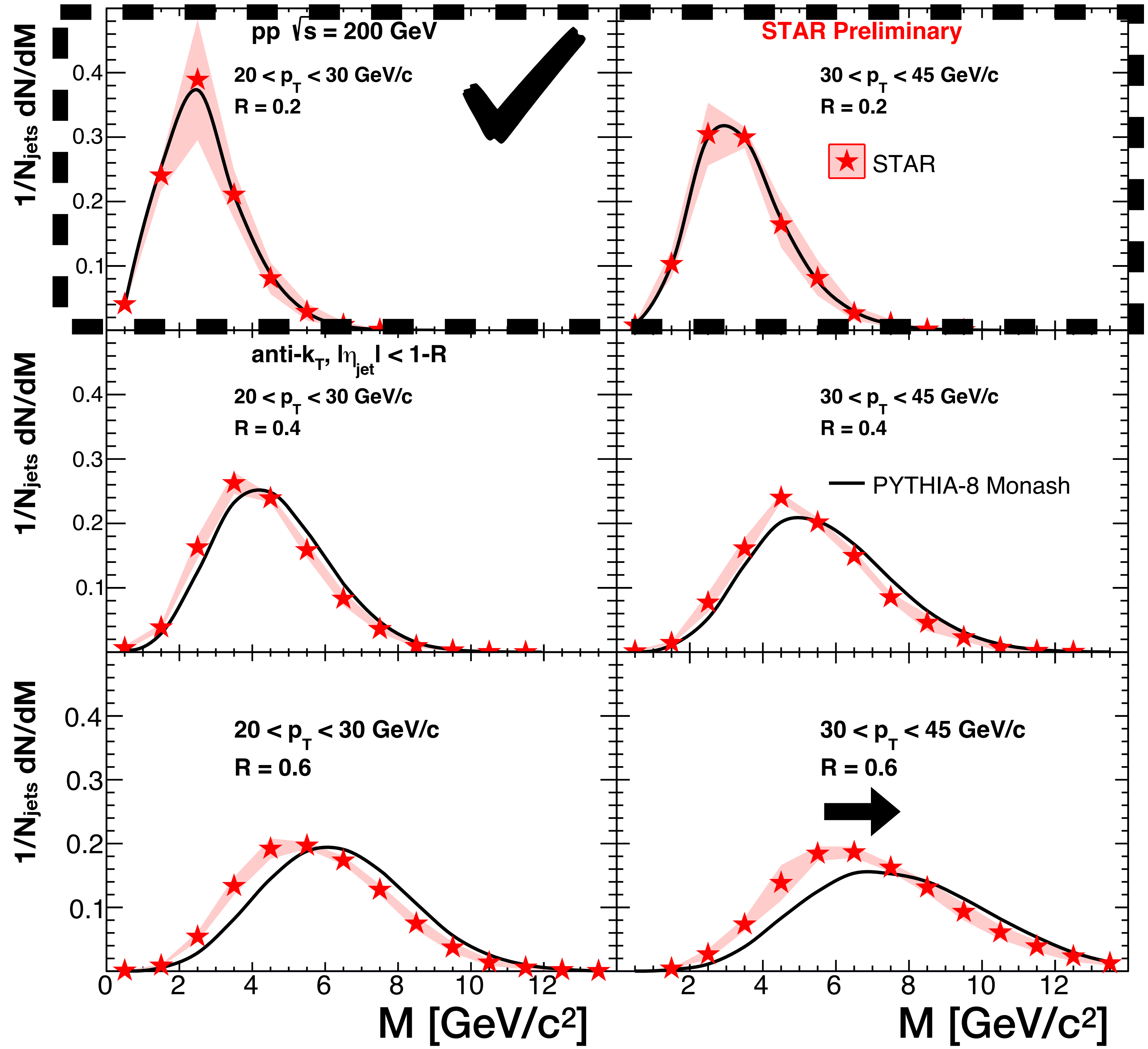
Jet mass as a function of *R*

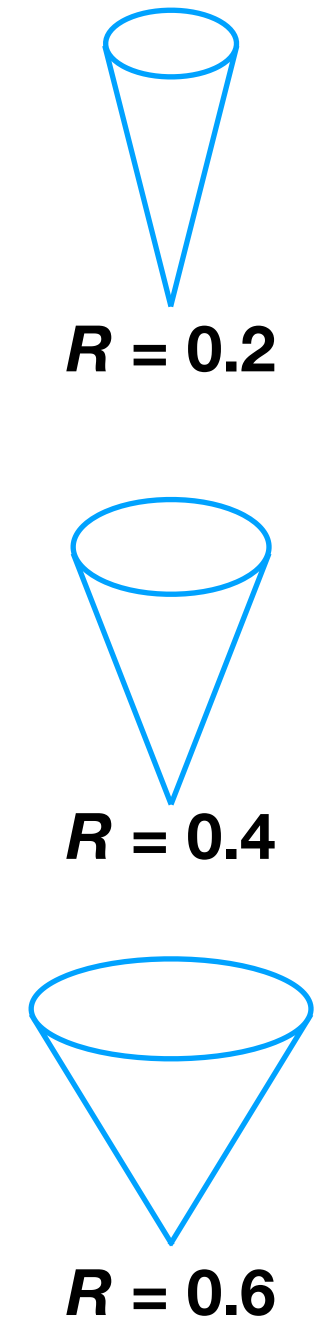




HERWIG-7 under-predicts for small *R*,
better agreement with data by *R* = 0.6

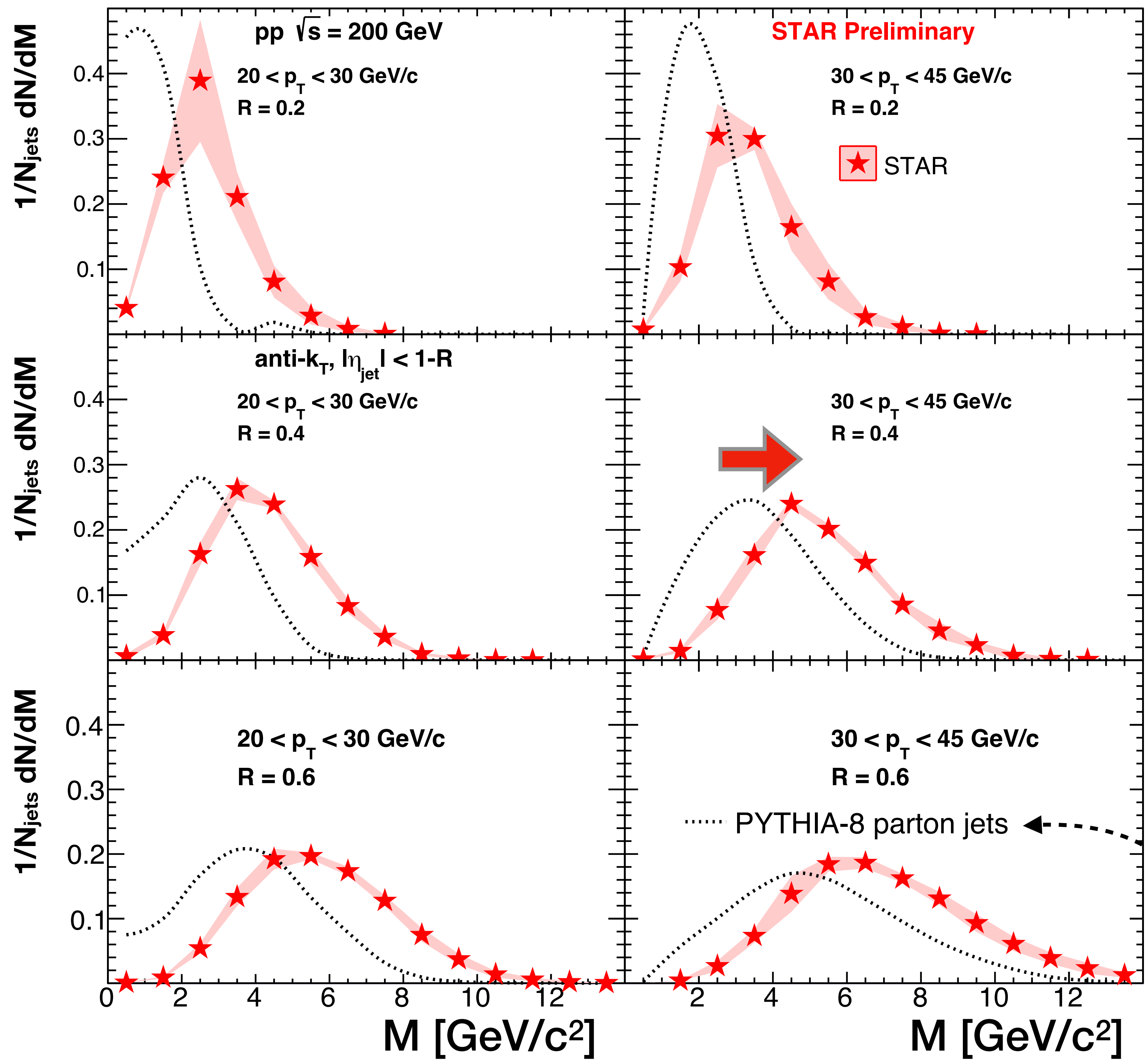
Jet mass as a function of *R*

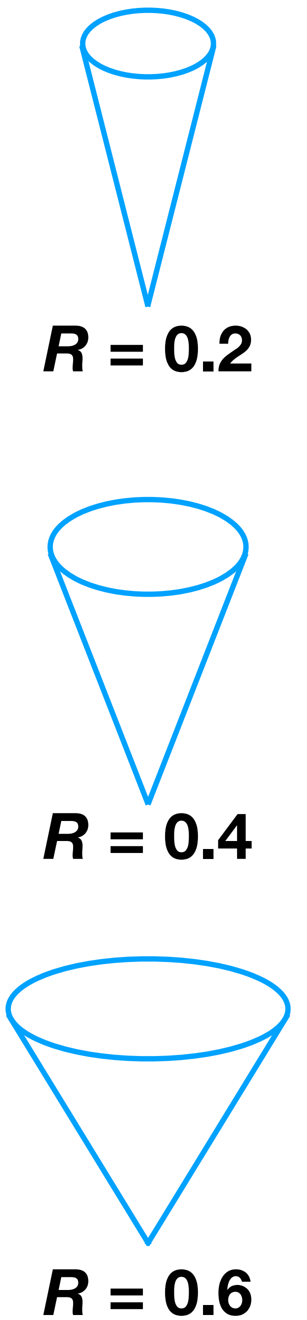




PYTHIA-8 is consistent with data for *R* = 0.2, over-predicts more as radius increases

Jet mass as a function of *R*



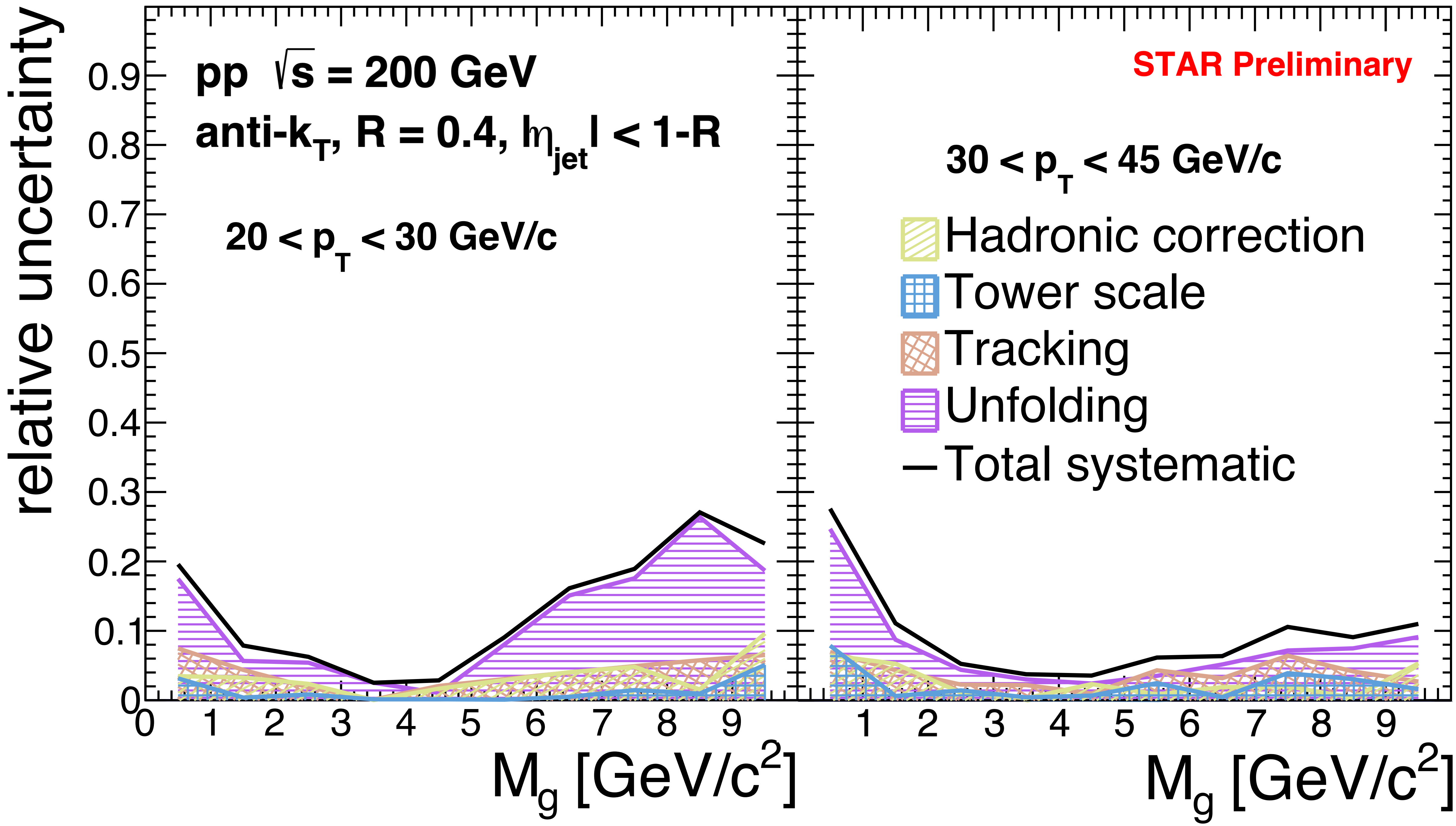


(Jets from PYTHIA events with hadronization = off)

Non-perturbative effects increase the mass

Groomed jet mass systematics

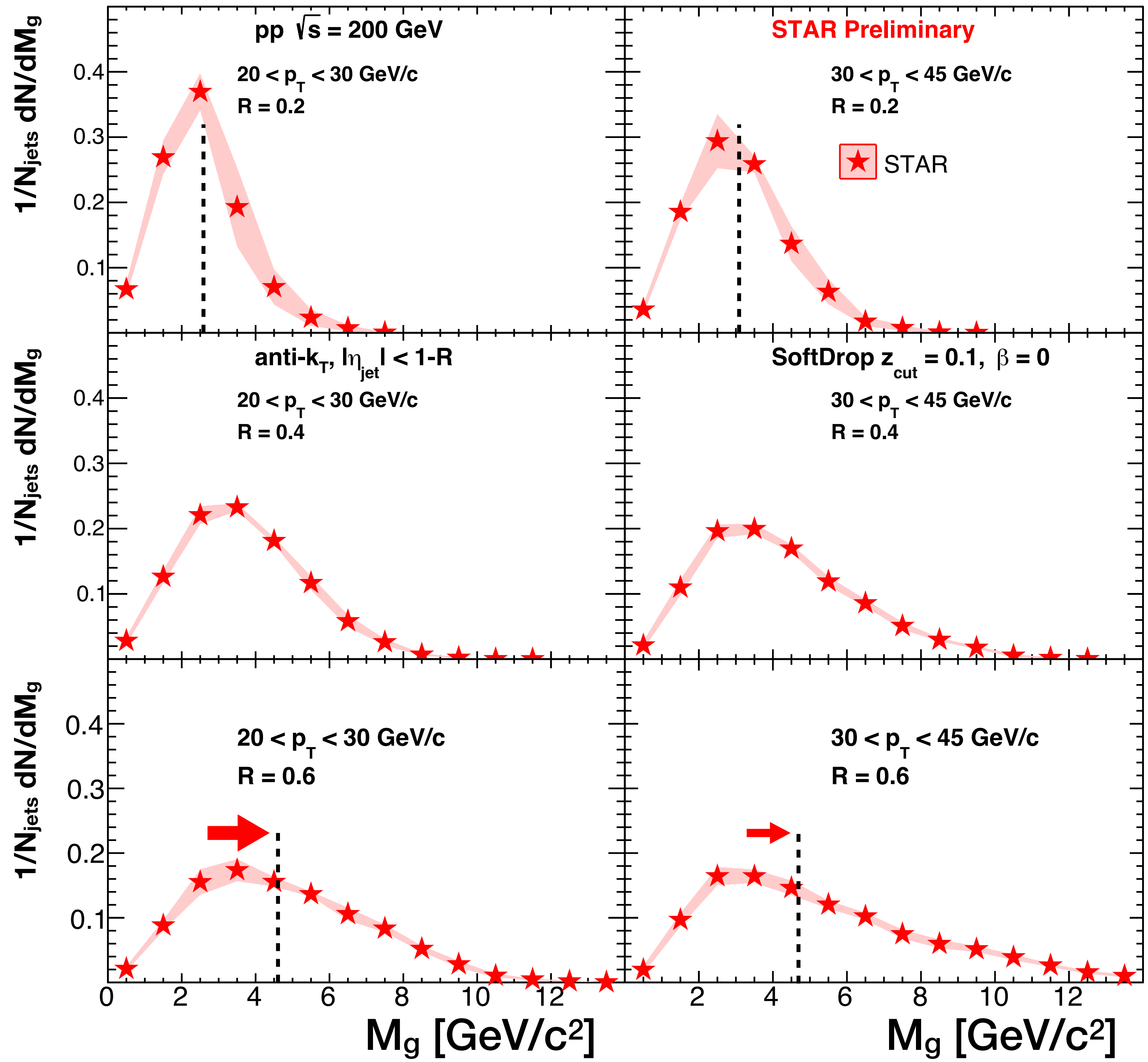
Note: p_T panels are *ungroomed* jet p_T

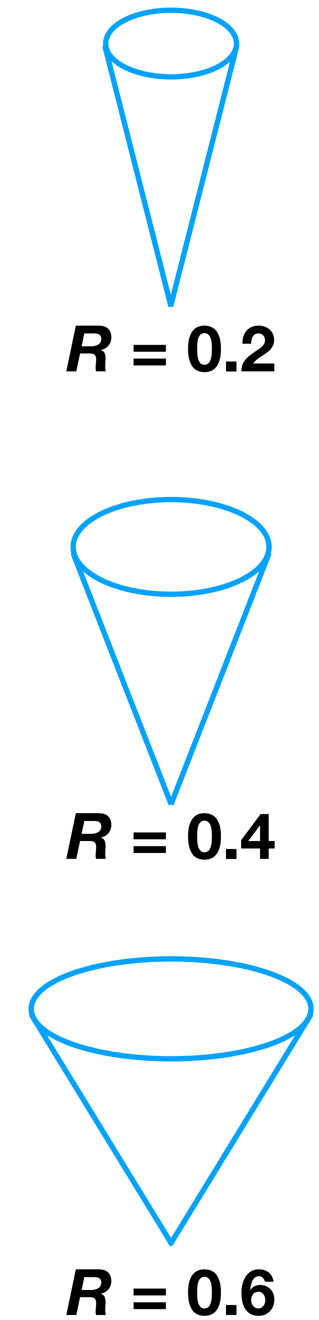


Systematic uncertainties are reduced from ungroomed case

M_g as a function of *R*

Note: p_T panels are *ungroomed* jet p_T

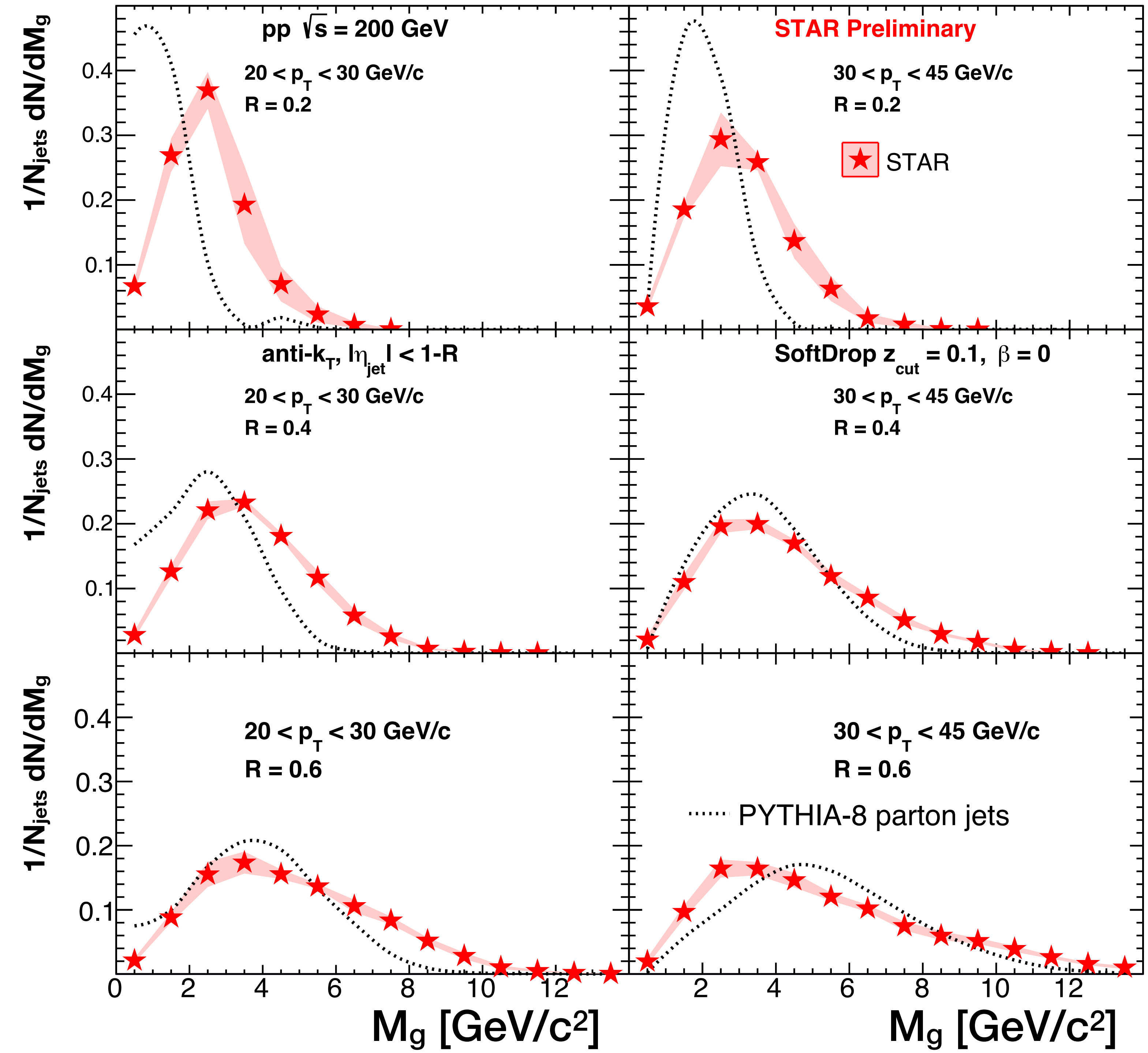


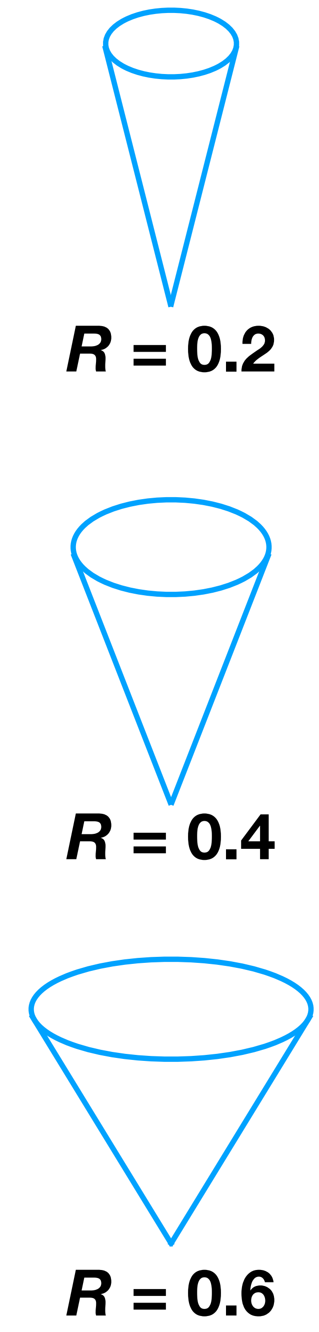


Groomed mean mass less sensitive to radius / p_T variation

M_g as a function of *R*

Note: p_T panels are *ungroomed* jet p_T

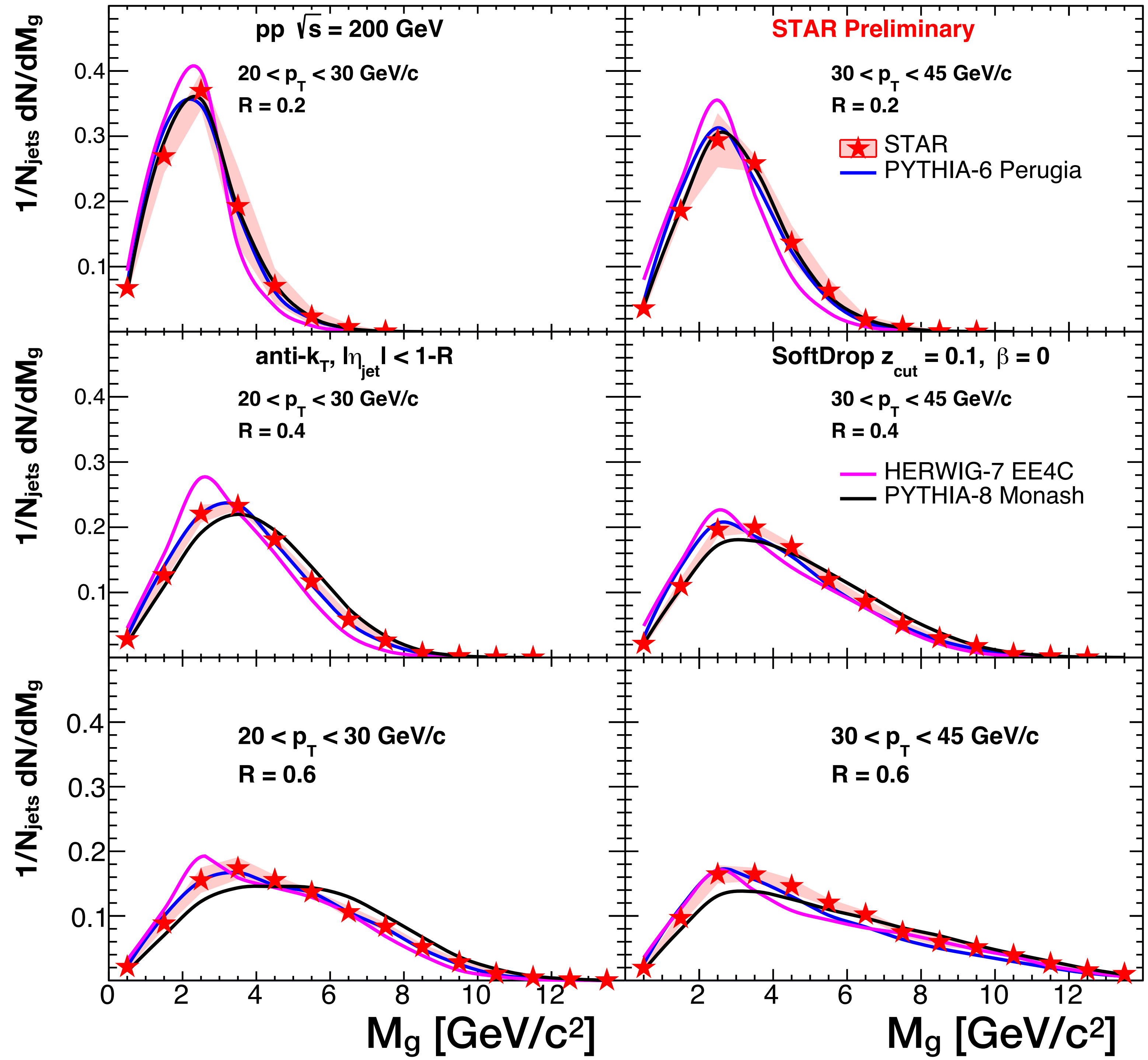


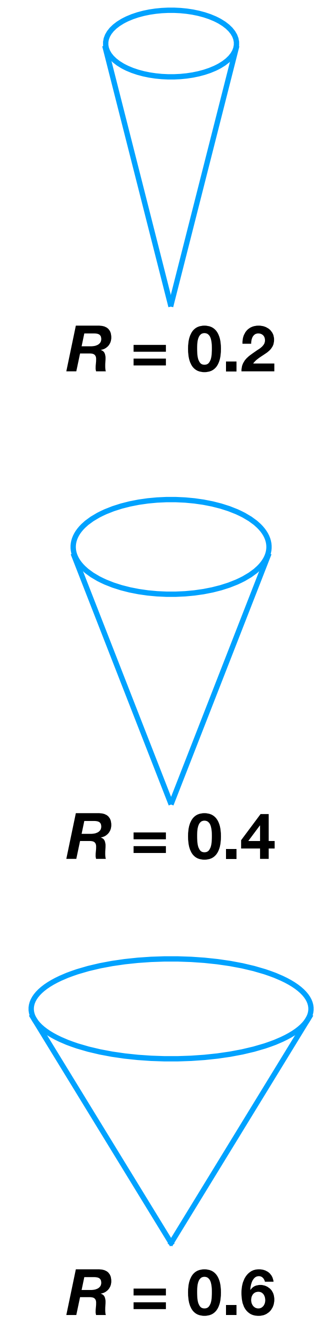


Non-perturbative effects suppressed, in particular, at higher radii!

M_g as a function of R

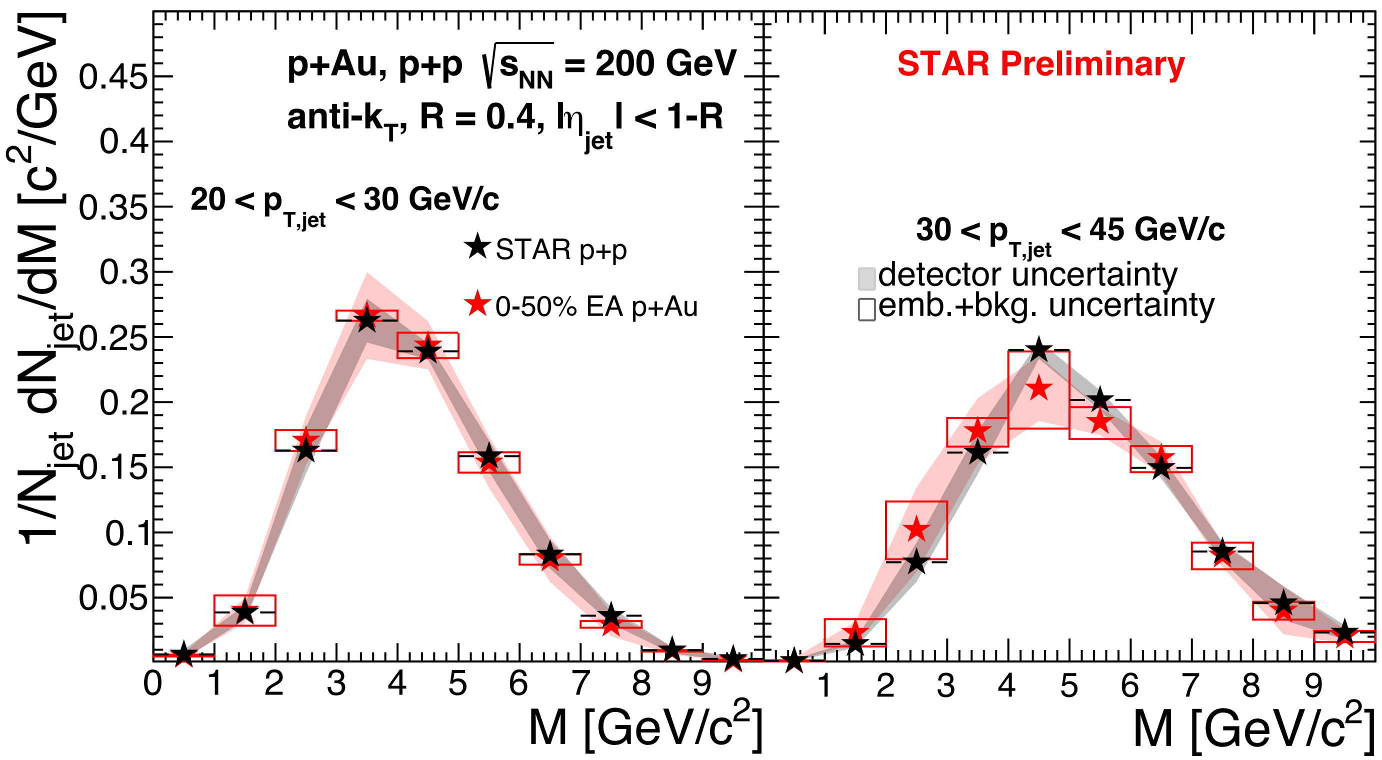
Note: p_T panels are *ungroomed* jet p_T



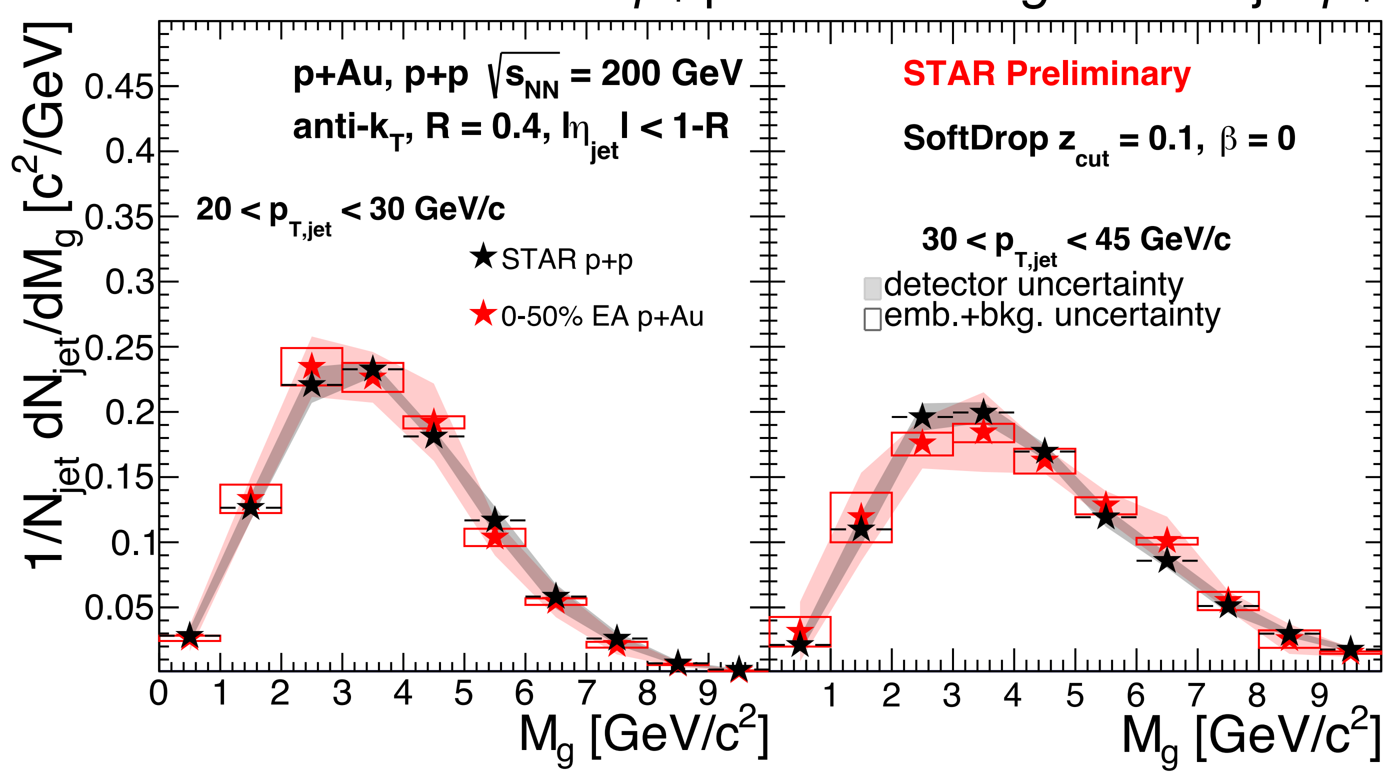


RHIC-tuned **PYTHIA-6** ~ data; **HERWIG-7**, **PYTHIA-8** same trends but better description

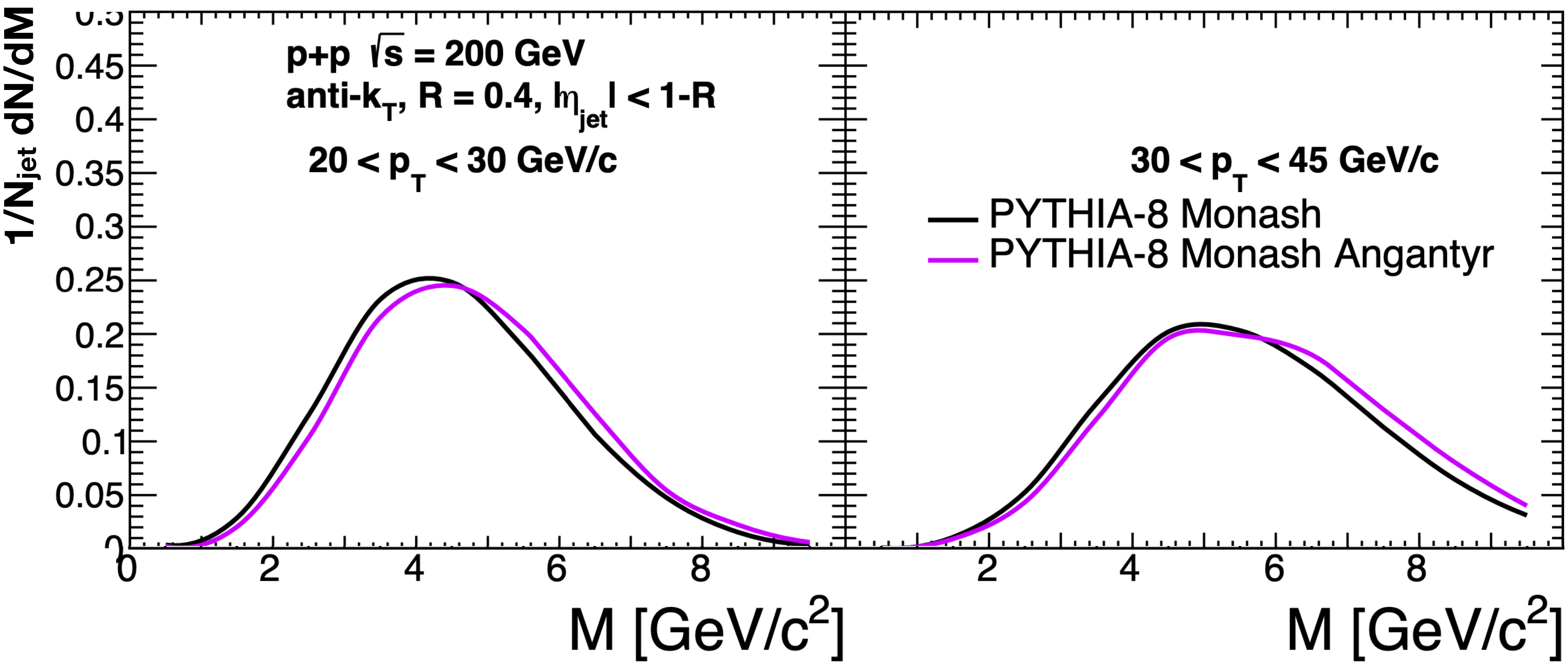
Comparing high-EA p+Au to p+p



Note: p_T panels are *ungroomed* jet p_T



PYTHIA-8 Angantyr (heavy ions)



PYTHIA-8.219 *p+p* and PYTHIA-8.219 *p*+Au (Angantyr) use the same tune (Monash)
Weak decays turned off to be consistent with the PYTHIA-6 used in the measurement

PartonLevel:MPI = on
PartonLevel:ISR = on
PartonLevel:FSR = on
HadronLevel:Hadronize = on