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WAYNE STATE UNIVERSITY

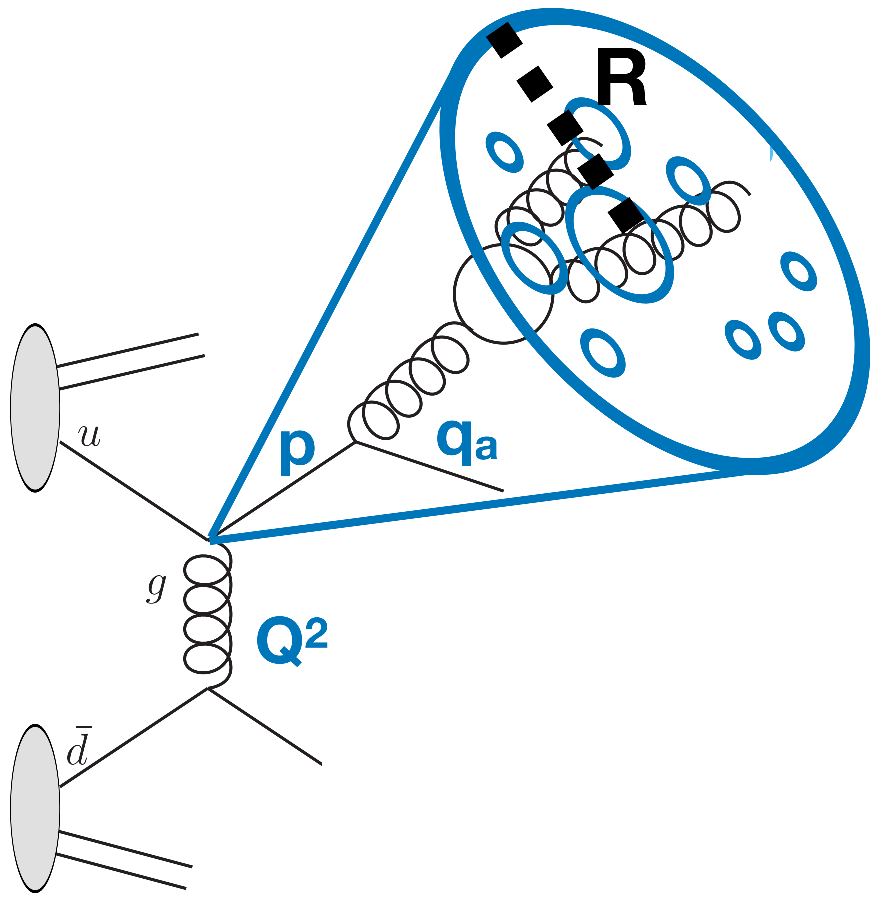
STAR

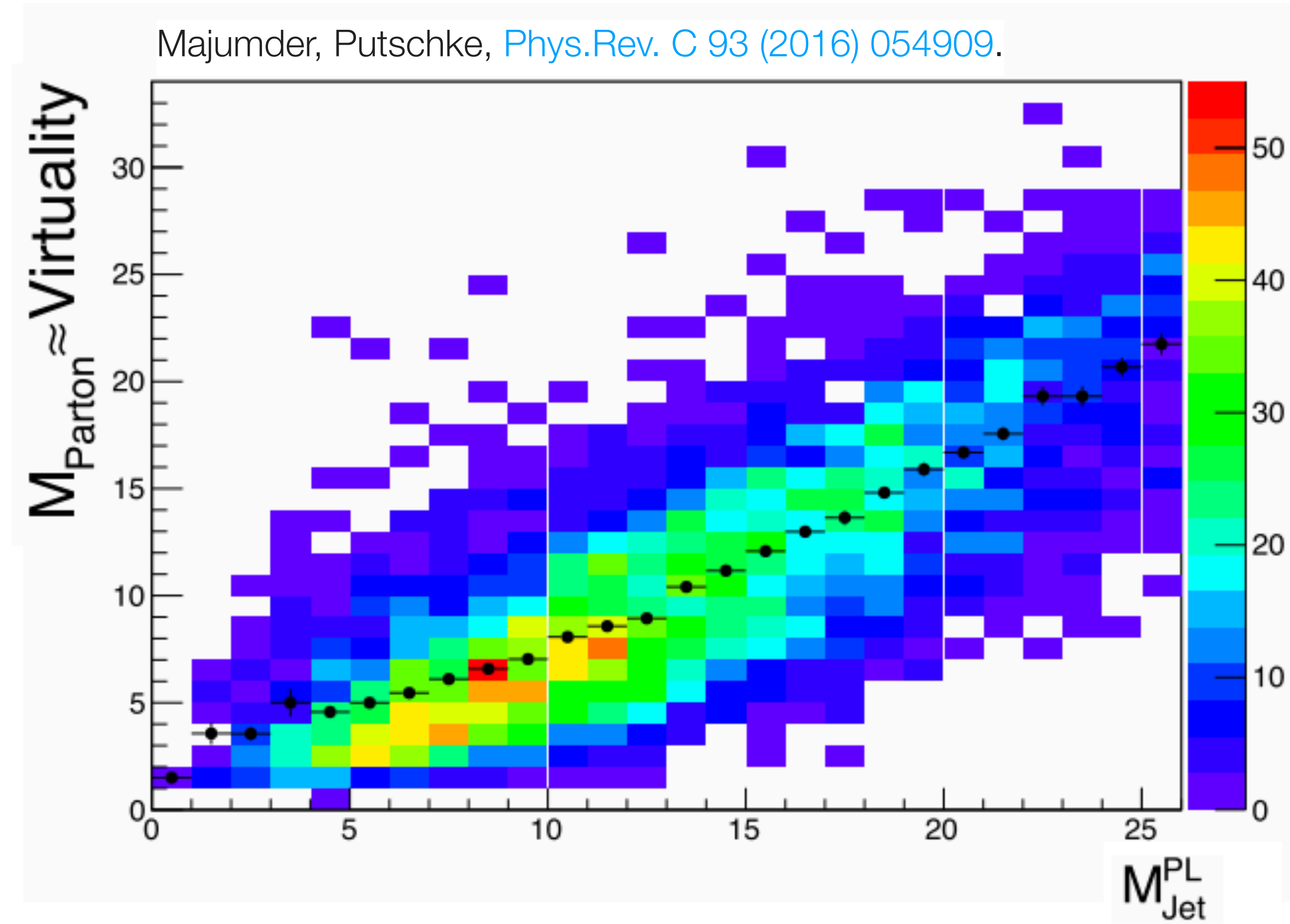
Jet substructure in *p*+*p* and *p*+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 200 GeV at STAR

Isaac Mooney (Wayne State University)
for the STAR Collaboration

10th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions
June 3, 2020

Jet mass





[no hadronization here - would smear correlation]

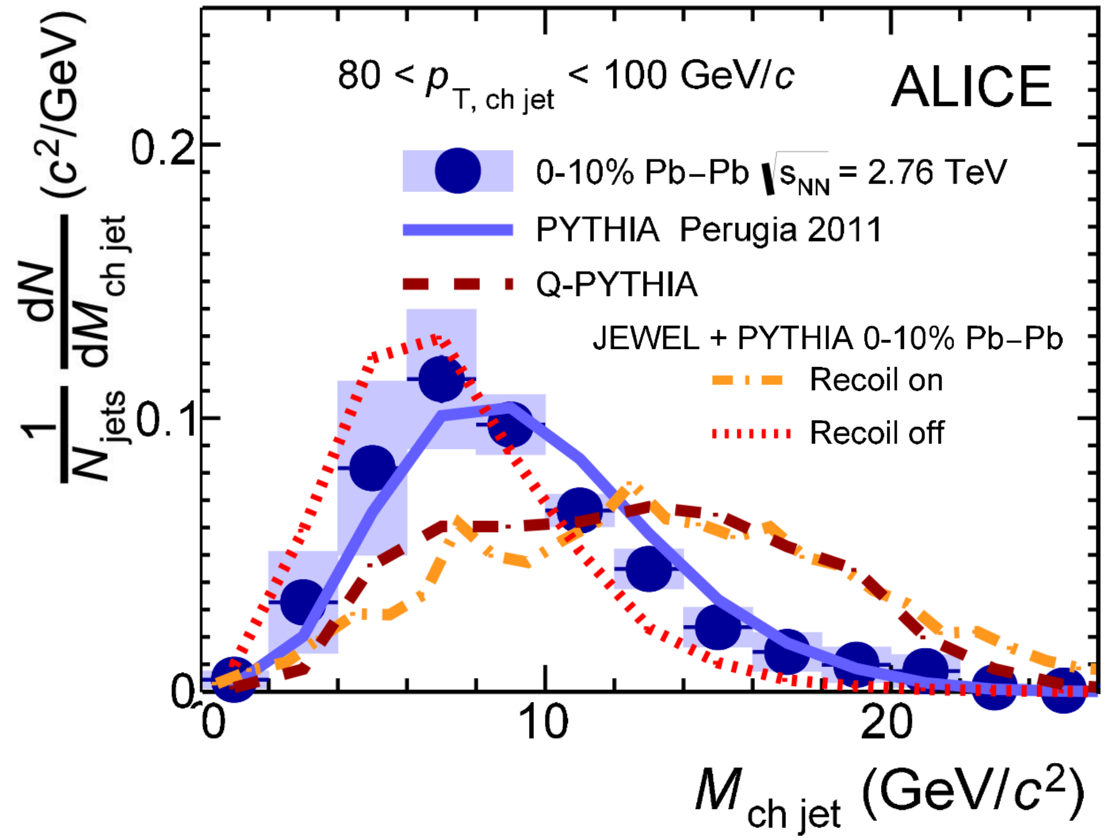
- ★ ***Partonic mass,*** M_{parton}**:**
  - **Magnitude of 4-momentum - between 0 and scale, Q**
- ★ ***Reconstructed jet mass,*** $M_{\text{jet}} = \left|\sum_{i \in J} p_i\right| = \sqrt{E^2 - \mathbf{p}^2}$**:**
  - **Magnitude of constituent 4-momentum sum for given *R***

What we measure
[~ initial hard parton virtuality!]

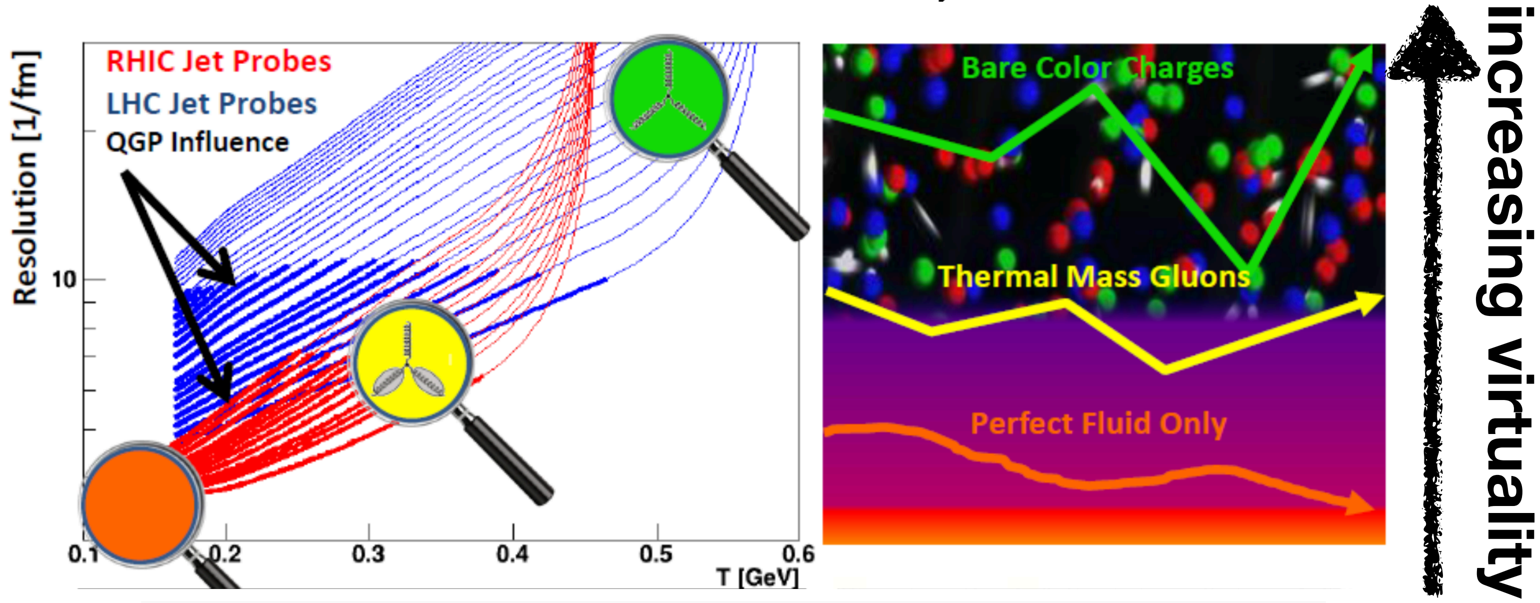
Motivation - heavy ion collisions

- ★ Recent ALICE A+A measurement:
  - ★ Jet mass is sensitive to different implementations of partonic energy loss

ALICE, Phys.Lett. B 776 (2018) 249



- ★ Jet mass ~ virtuality ~ resolution
  - ➡ Jets with **different masses** resolve medium at **different scales**



Reaching for the Horizon: The 2015 Long Range Plan for Nuclear Science

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

STAR

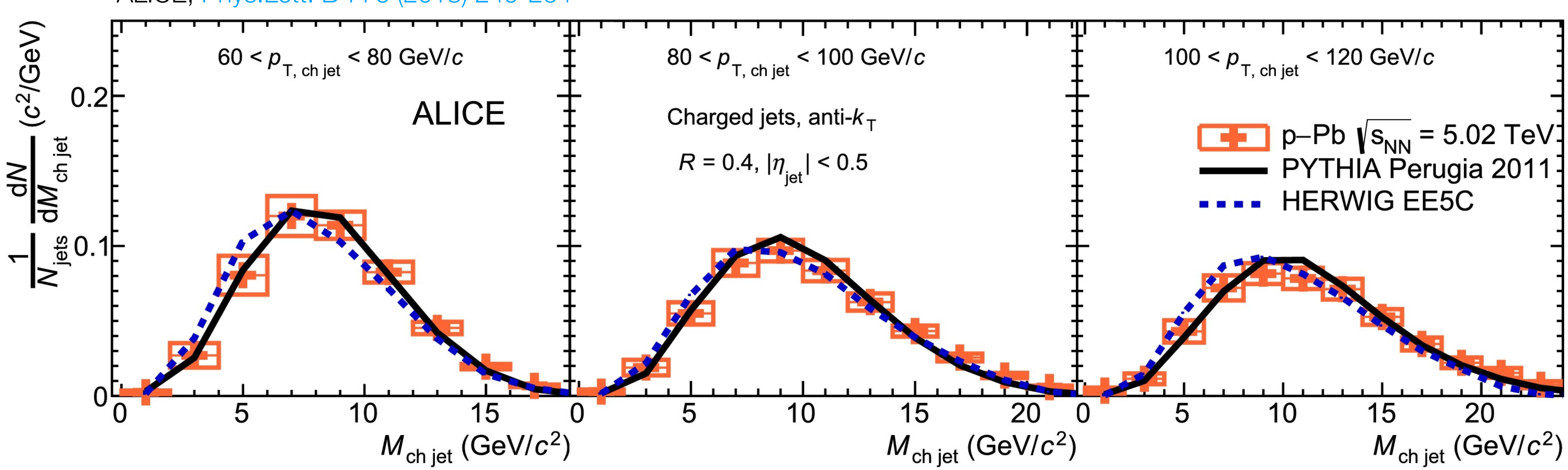
- ★ *p+p* measurements done mostly at LHC[1-7]
  No measurement yet at RHIC!
  → further tune MCs

[1]ATLAS, JHEP 05 (2012) 128
[2]ATLAS, Phys.Rev.Lett. 121 (2018) 092001
[3]ATLAS, tech. rep. ATLAS-CONF-2018-014 (2018)
[4]CDF, Phys.Rev. D 85 (2012) 091101
[5]CMS, JHEP 05 (2013) 090
[6]CMS, Eur.Phys.J. C 77 (2017) 467
[7]CMS, JHEP 10 (2018) 161

- ★ ALICE observes no modification of jet mass in *p*+Pb at 5.02 TeV for $60 < p_{T,jet} < 120$ GeV/*c* w.r.t. PYTHIA, HERWIG

- ★ No measurement yet at RHIC! → modification at RHIC?

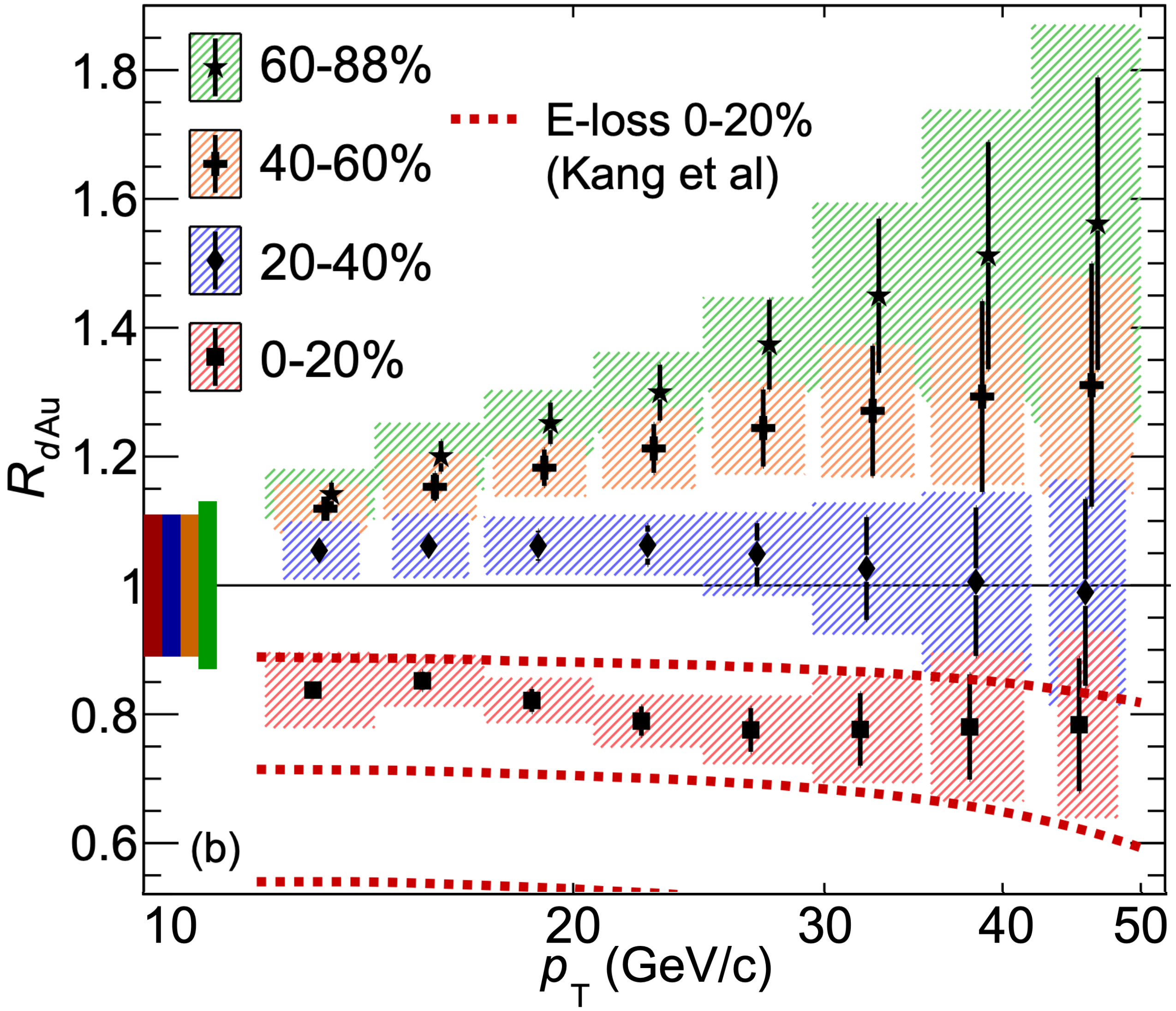
ALICE, Phys.Lett. B 776 (2018) 249-264



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

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



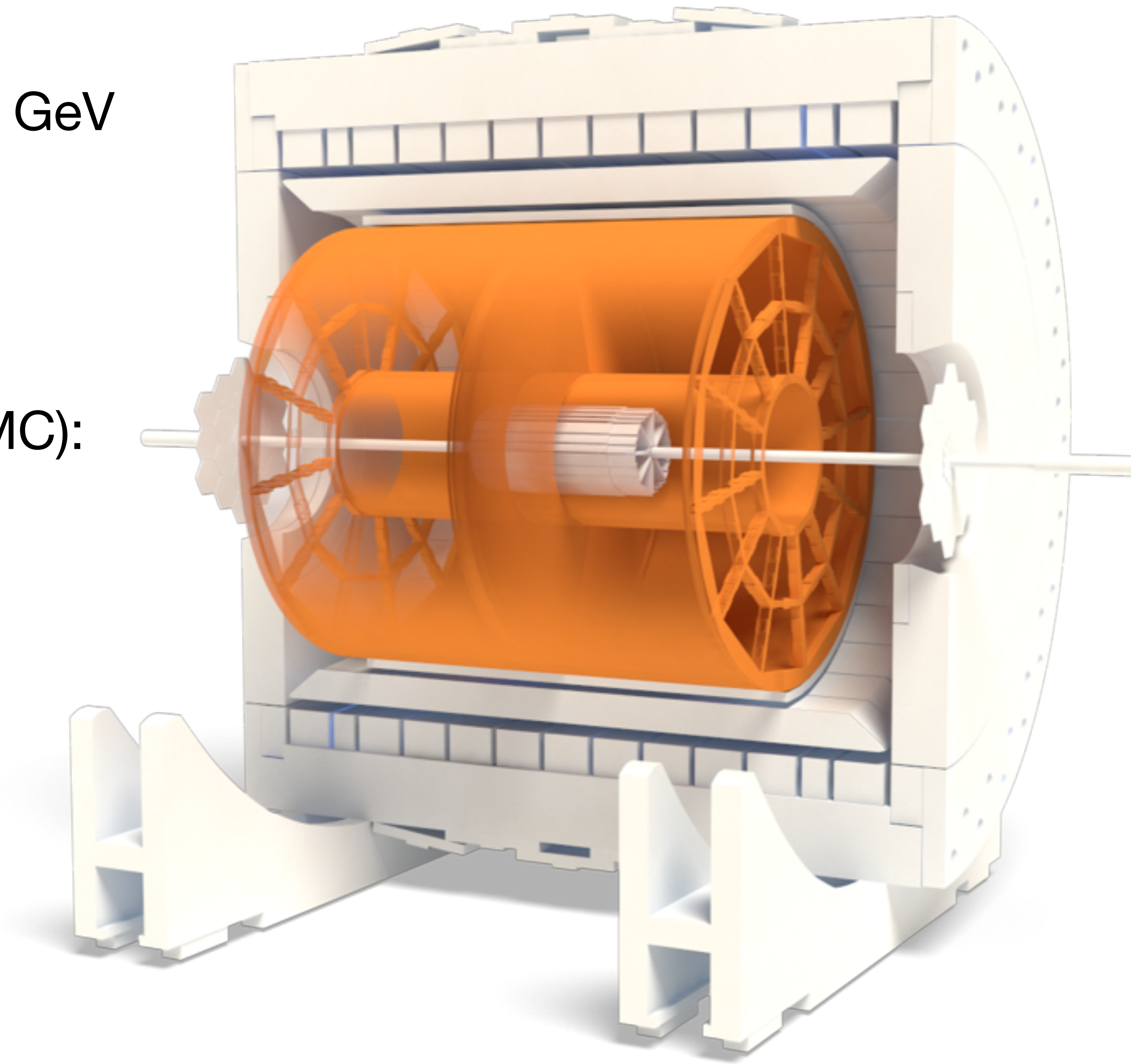
The Solenoidal Tracker at RHIC (STAR)

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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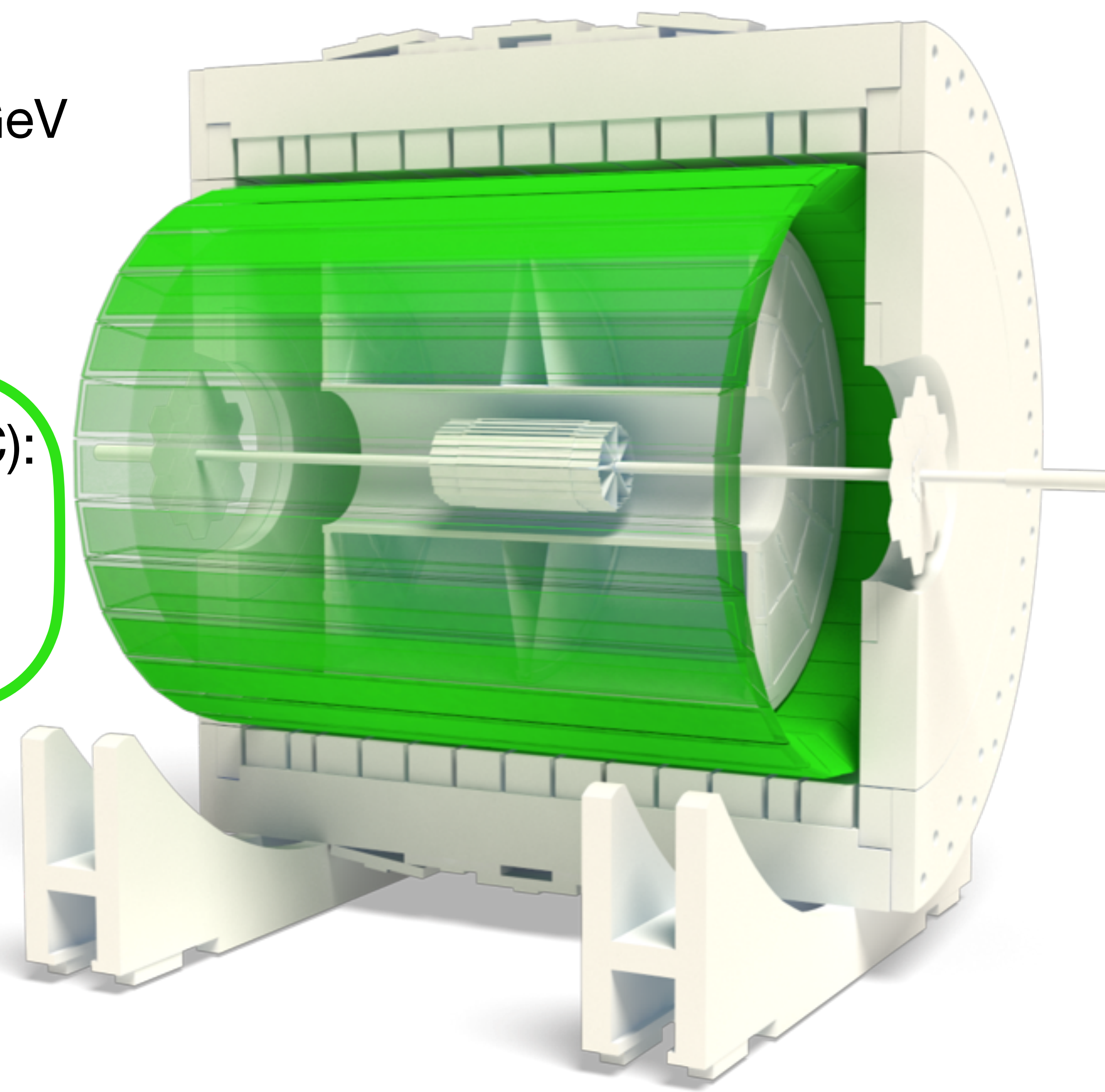

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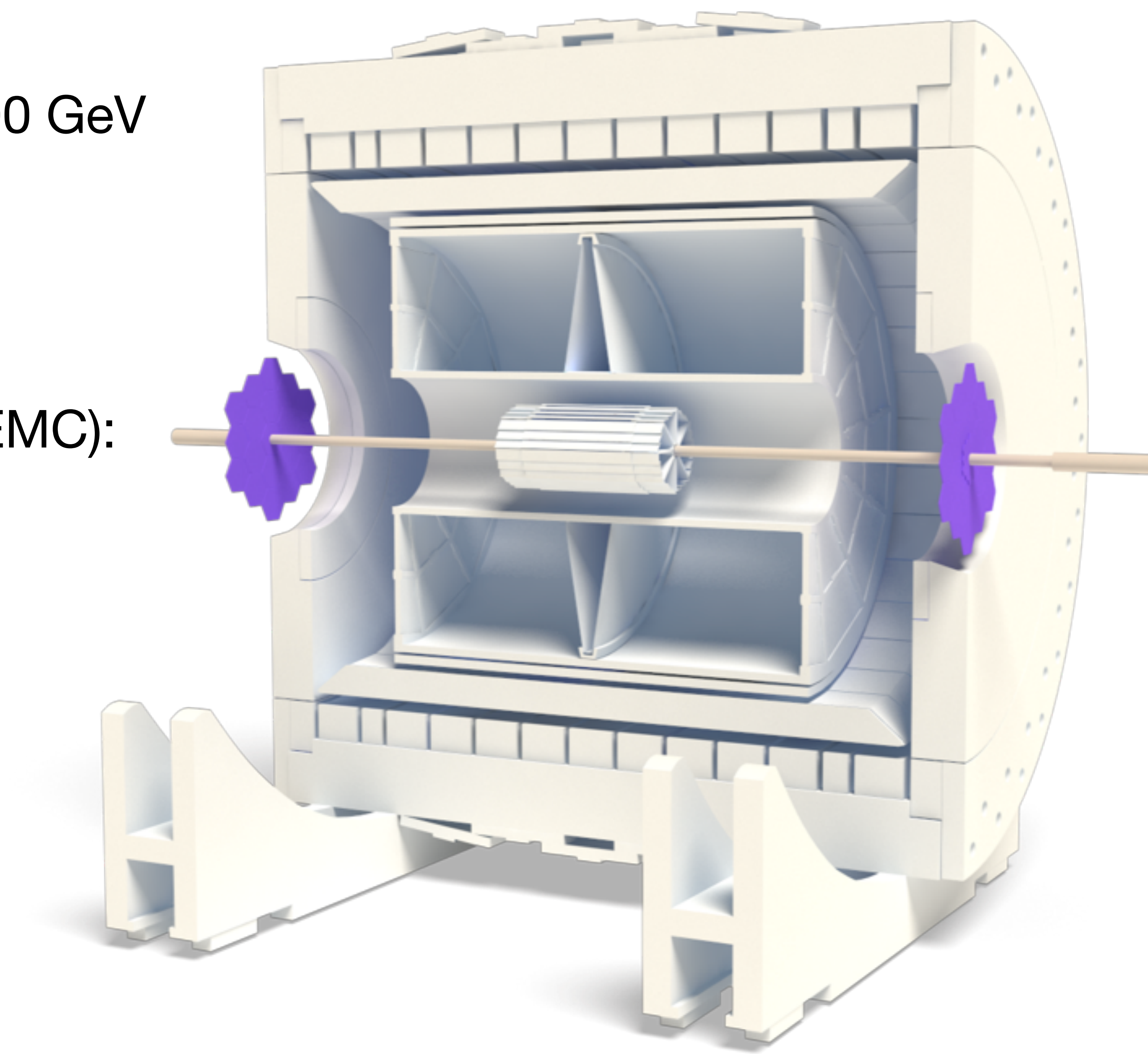
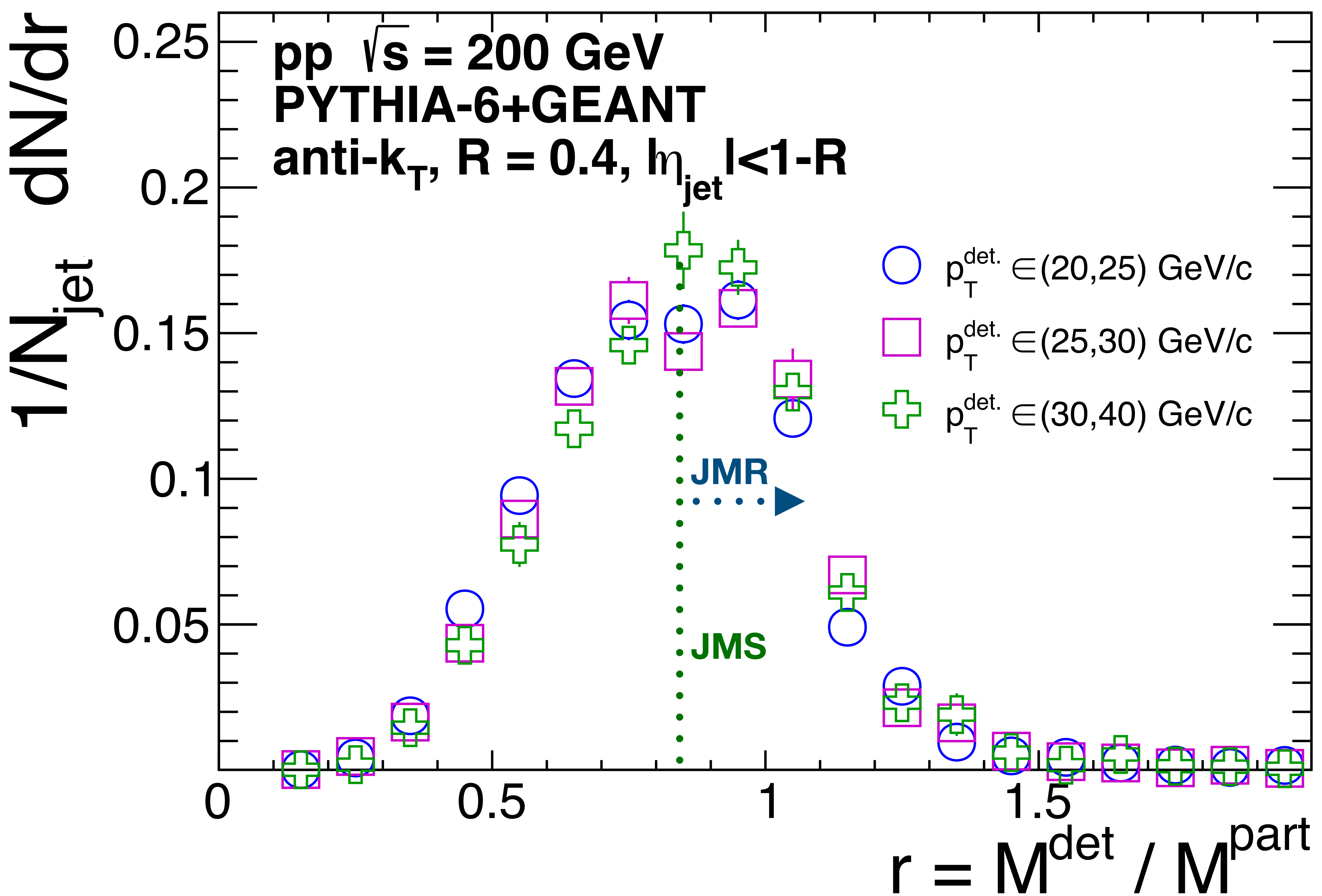
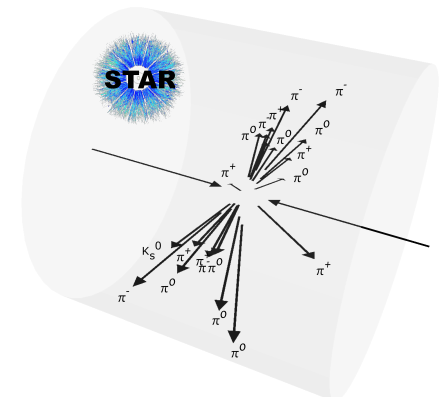


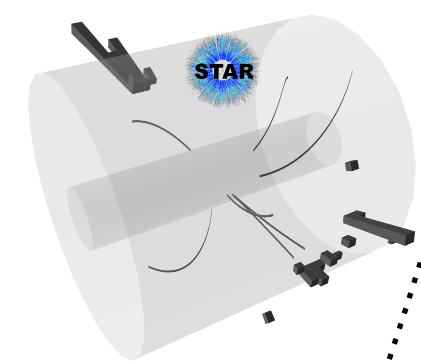
Jet mass resolution





"particle-level":
PYTHIA-6
with RHIC tune

"detector-level":
PYTHIA-6+GEANT-3
with **STAR** detector simulation



Tai Sakuma

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

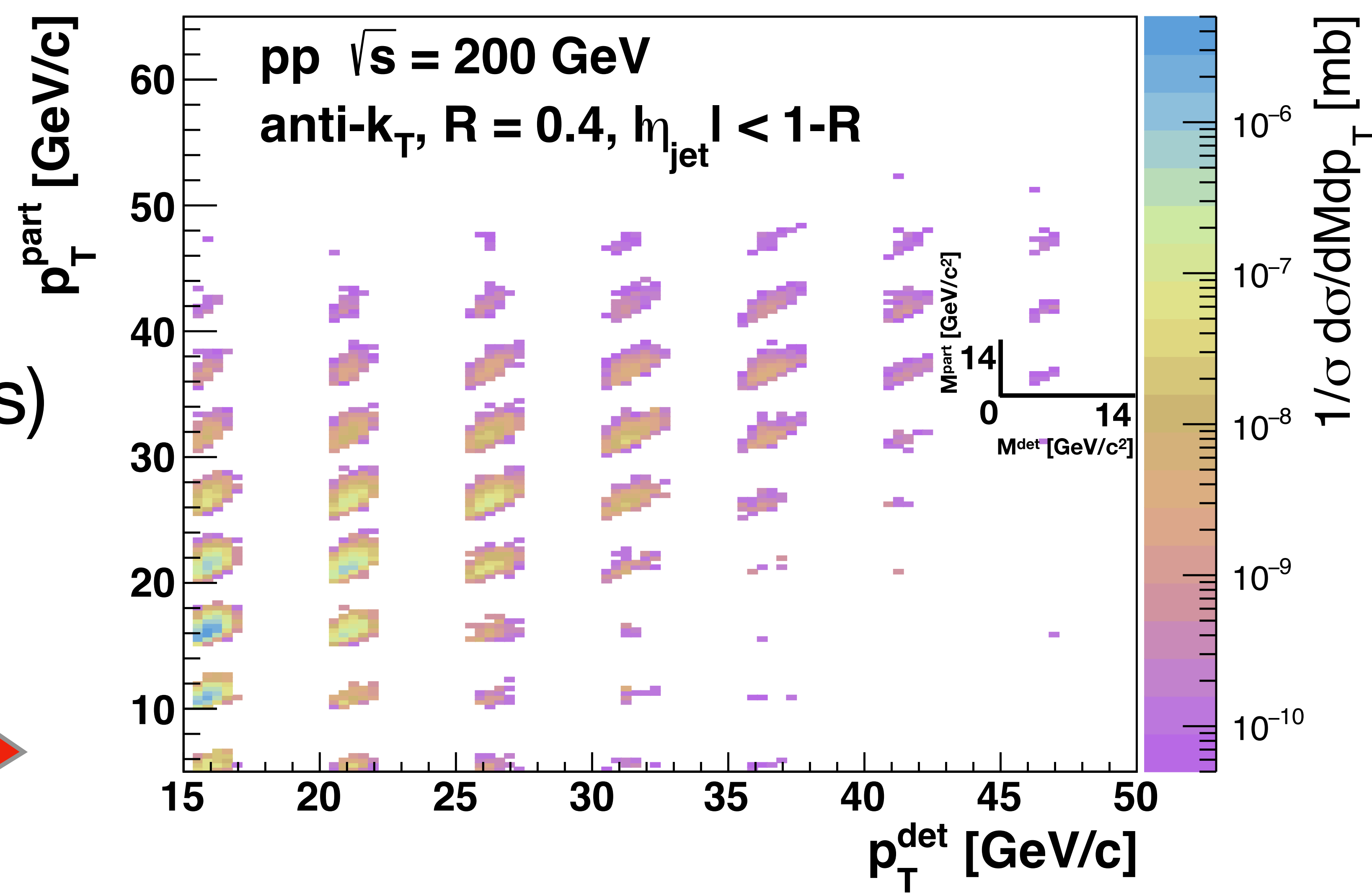
Jet Mass Scale (JMS) shift from unity: mostly from track loss

Jet Mass Resolution (JMR) p_T-independent!

Unfolding

- Correct for finite detector resolution effects
- Correction procedure: Iterative Bayesian from **RooUnfold** (4 iterations)
  - *M* dependent on p_T
    → 2D unfolding
    → 4D response
  - Correct p_T, *M*, and correlation simultaneously

4D jet mass response matrix

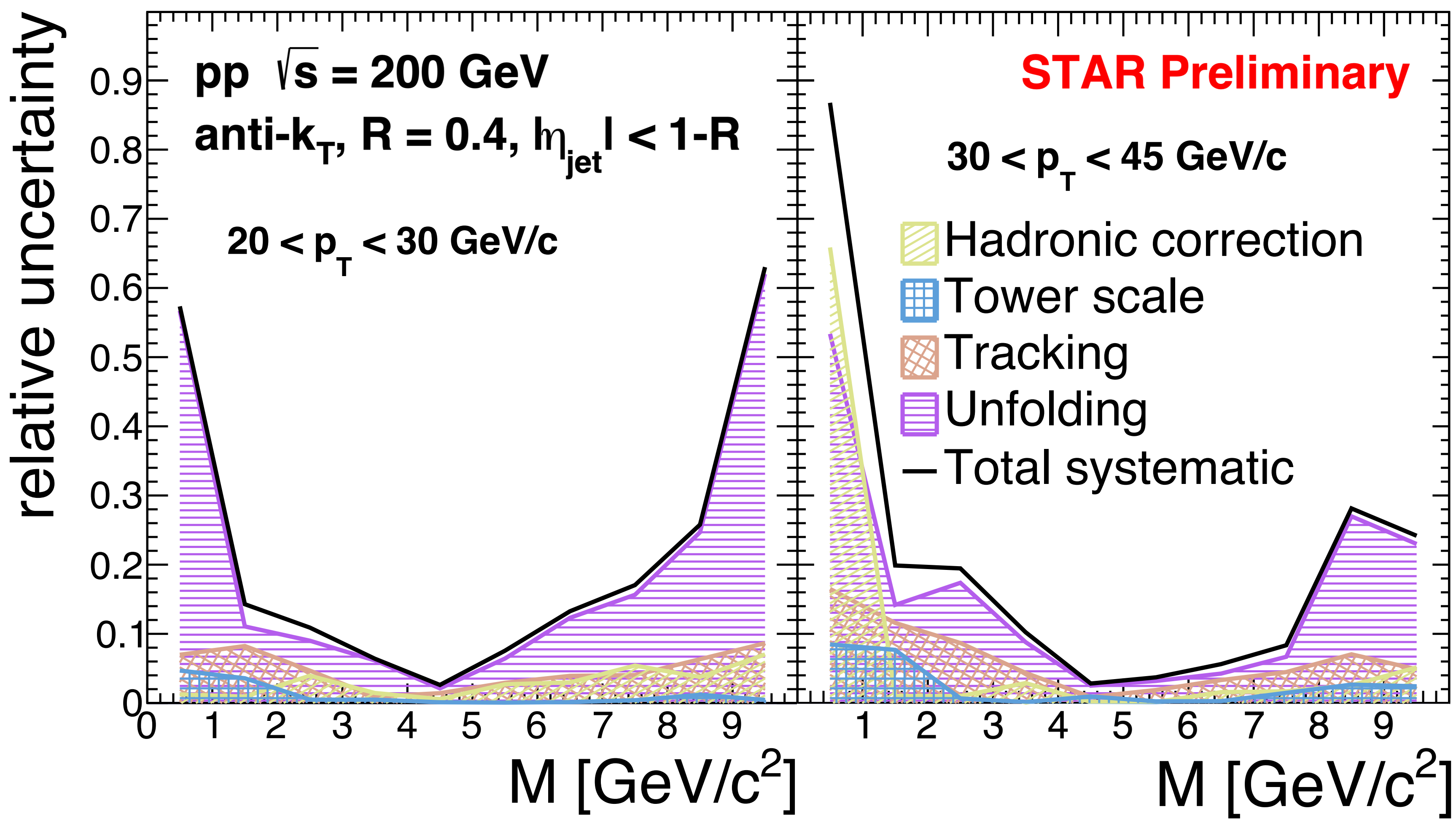


Tim Adye in Proceedings, PHYSTAT 2011, CERN, edited by Prosper and Lyons, CERN-2011-006, pp. 313-318.

Systematic uncertainties

Sources include (decreasing magnitude):

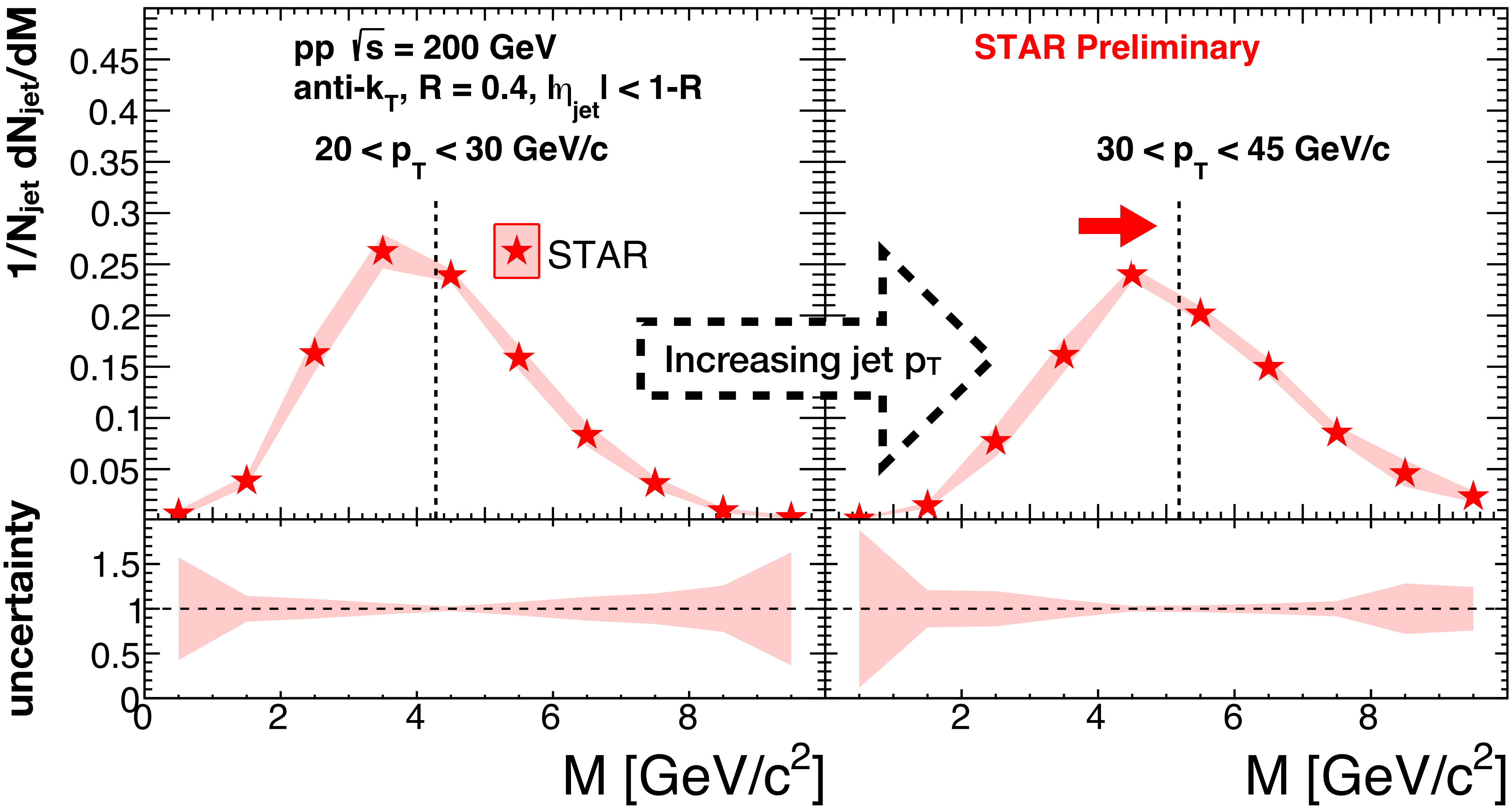
- ★ **Unfolding** (maximum envelope of the following):
  - *Iteration parameter variation*: 2 or 6
  - *Prior variation*: p_T, M spectra varied independently
- ★ **Tracking efficiency** uncertainty of 4%[1]
- ★ **Tower gain** uncertainty of 3.8%[1]
- ★ **Hadronic correction** variation: from nominal 100%[2] to 50%



Total systematic uncertainty is a quadrature sum of the four sources

[1]STAR, Phys.Rev. D 100 (2019) 052005
[2]STAR, Phys.Rev.Lett. 115 (2015) 092002

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

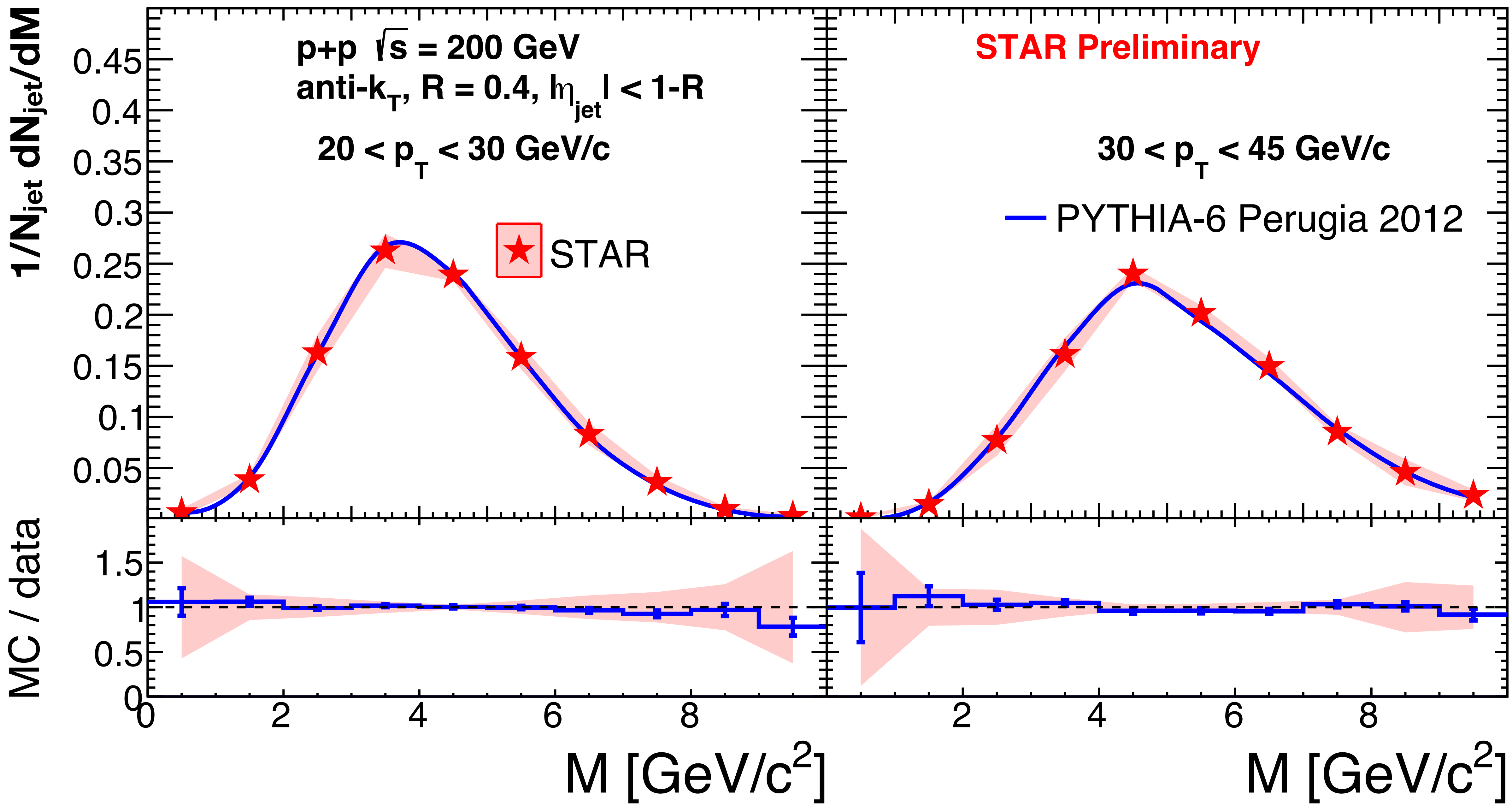


From pQCD, jet p_T increase

→ increased phase space to radiate

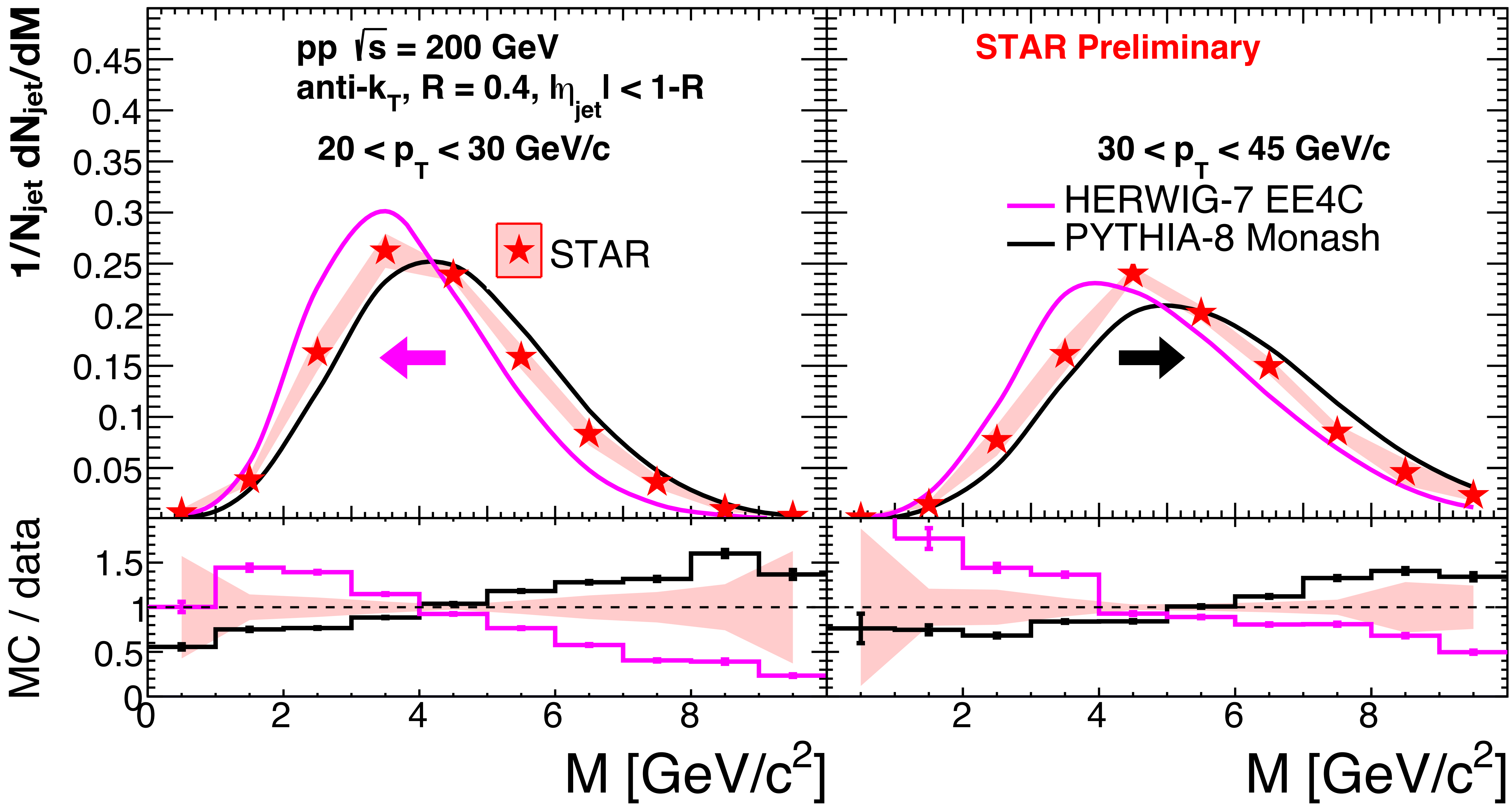
→ increased mass

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



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

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

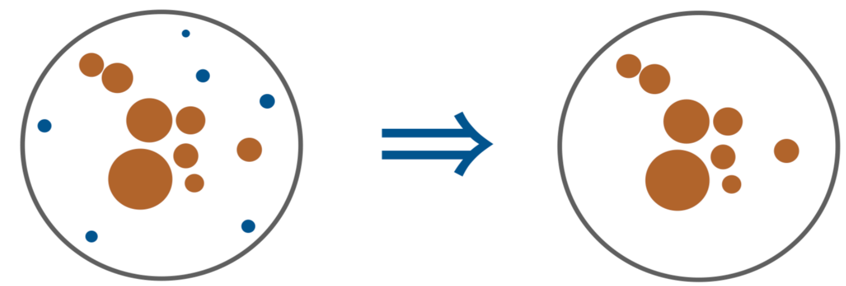


HERWIG-7 underpredicts and **PYTHIA-8** overpredicts

(EE4C) ← LHC → (Monash)

SoftDrop grooming

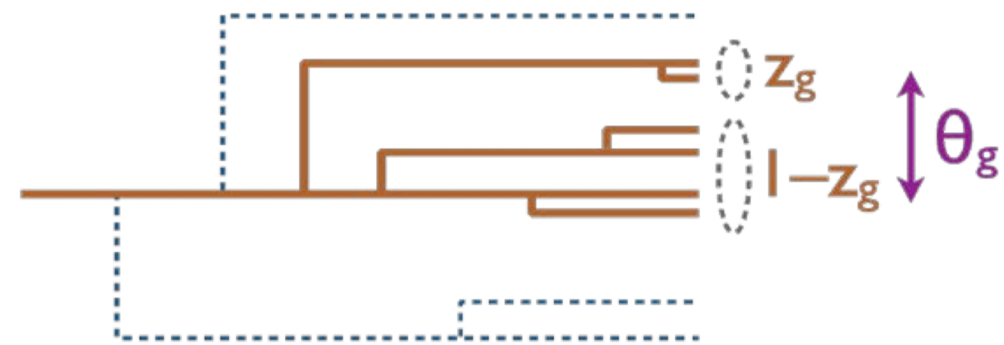
Suppress wide-angle non-perturbative radiation for more direct theory comparison; closer to parton-level

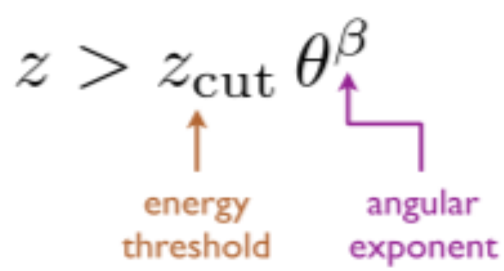


momentum fraction, z_g

angle, R_g

jet mass, M_g





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

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

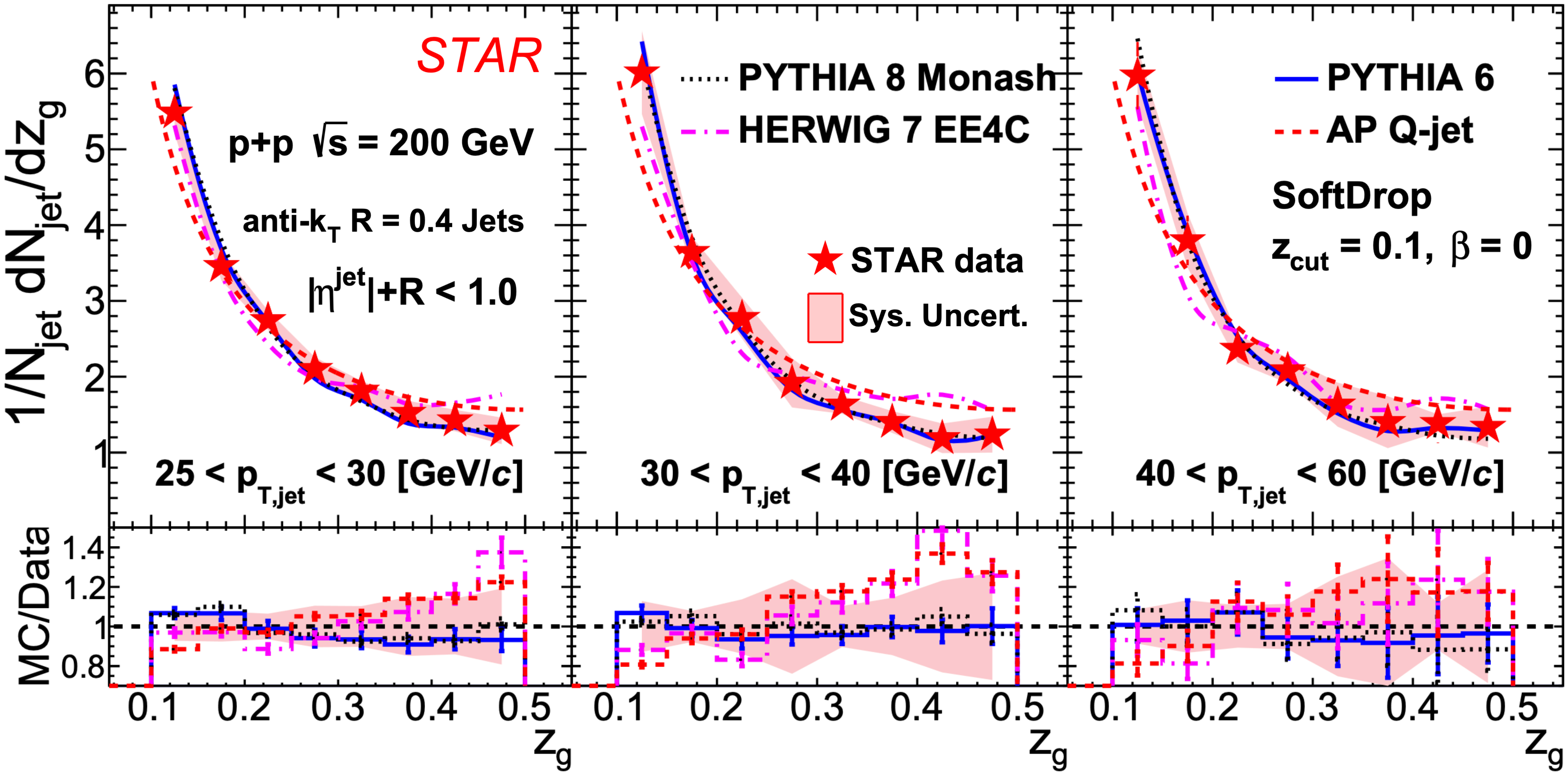
We consider jets with $z_g > 0.1$ ($\beta = 0$)

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

Groomed momentum fraction

Note: p_T panels are *ungroomed* jet p_T

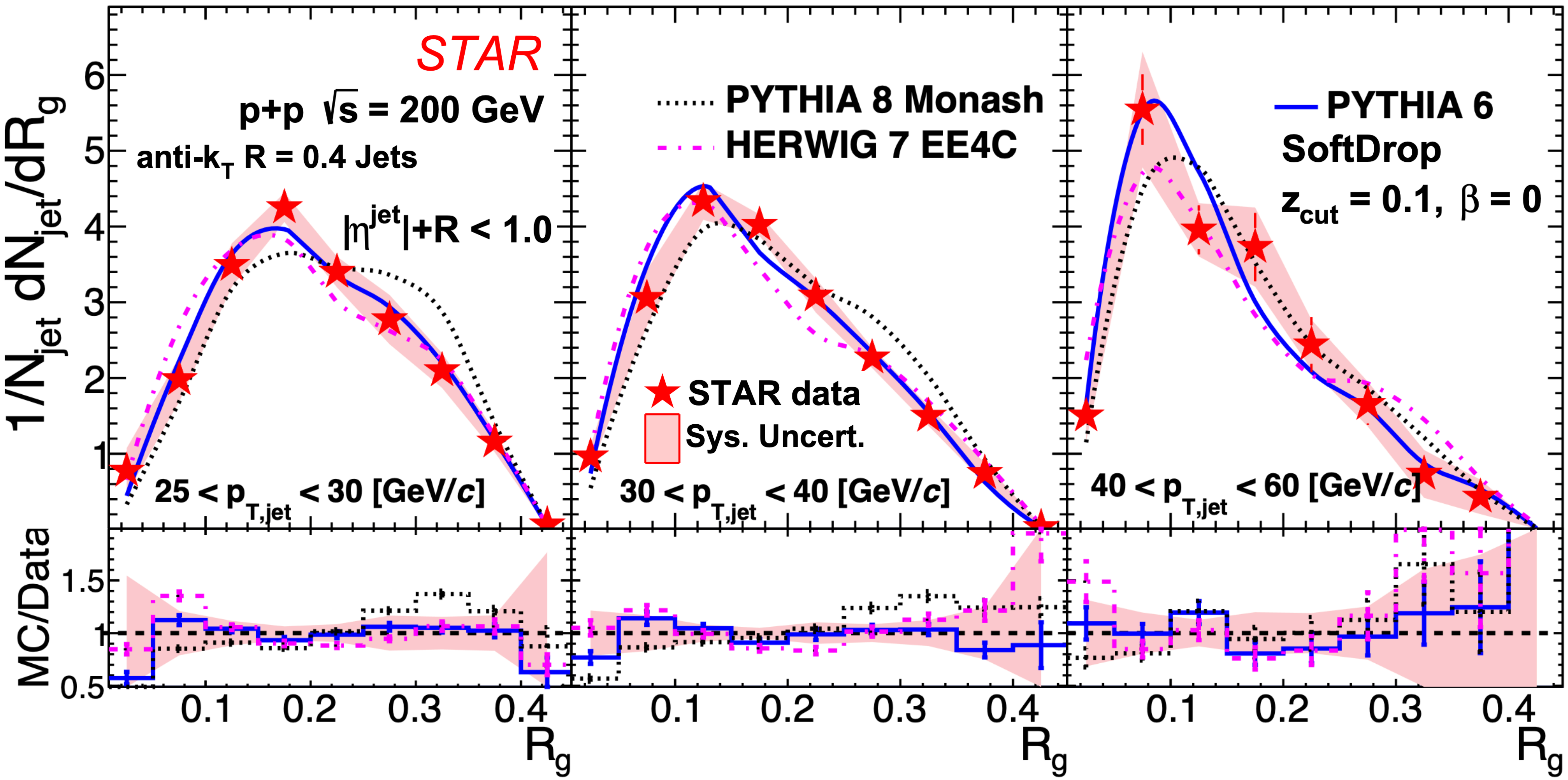
arXiv:2003.02114



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

Groomed jet radius

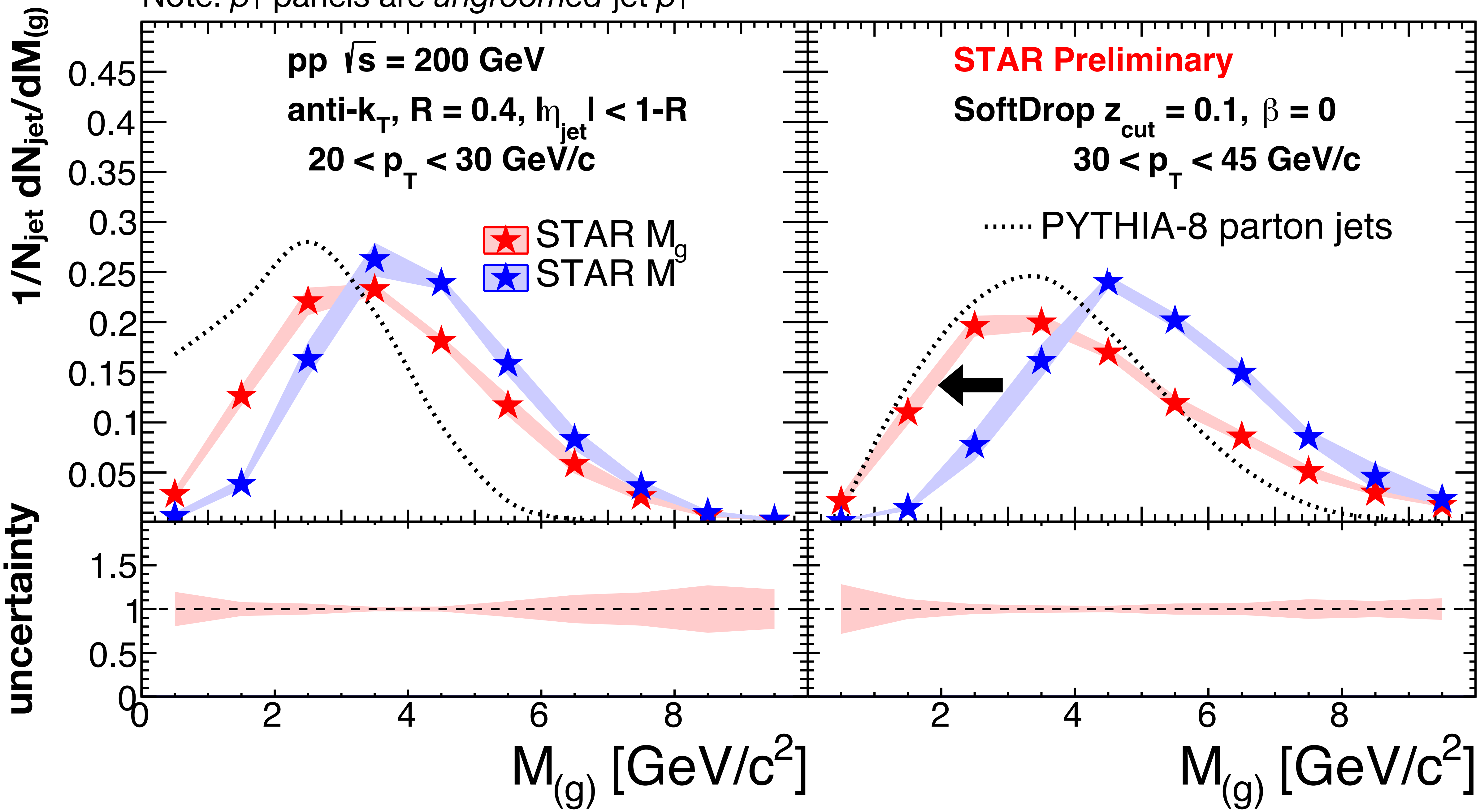
Note: p_T panels are *ungroomed* jet p_T arXiv:2003.02114



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

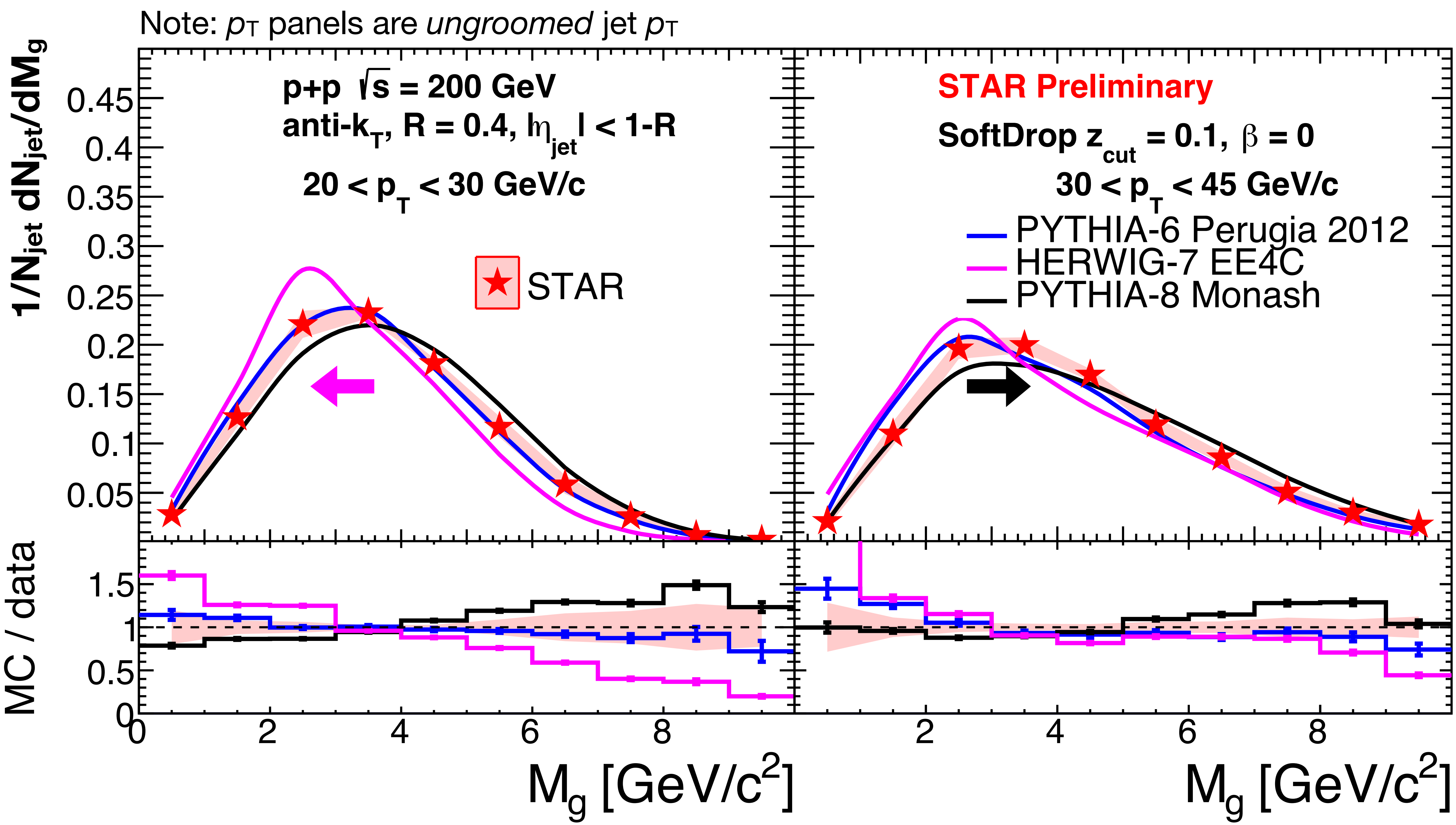
Groomed jet mass

Note: p_T panels are *ungroomed* jet p_T



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

Groomed jet mass

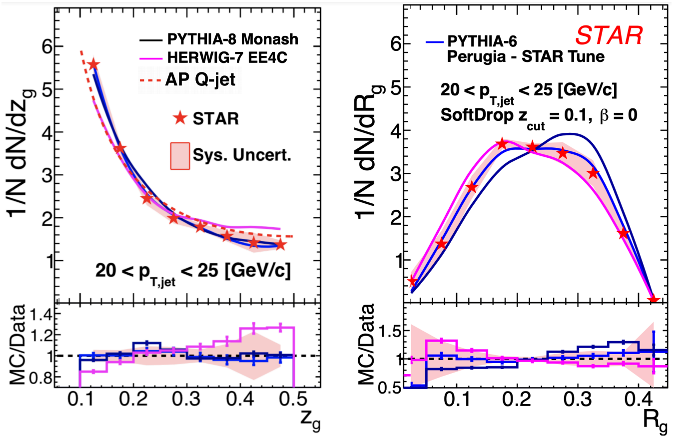


RHIC-tuned **PYTHIA-6** describes data

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

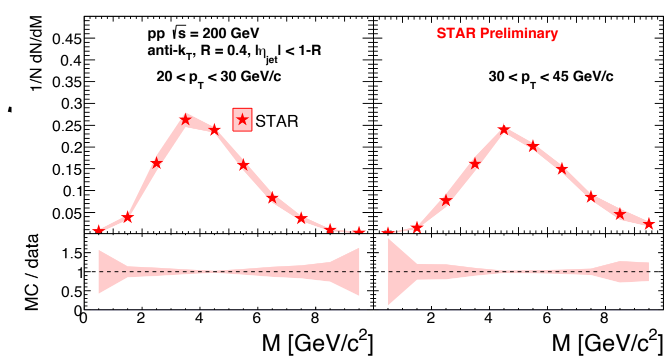
Conclusions - p+p

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



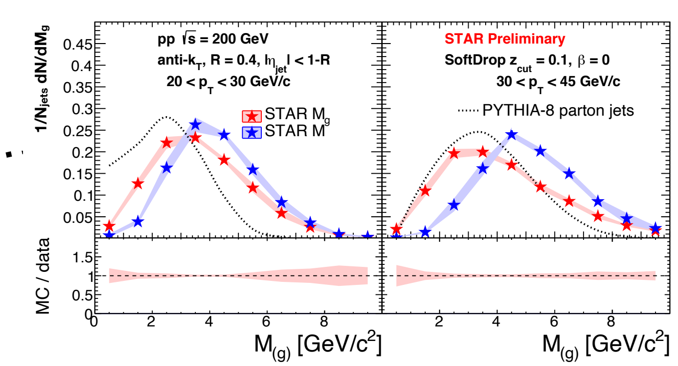
LHC-tuned HERWIG-7, PYTHIA-8:
opportunity for further tuning

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



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

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



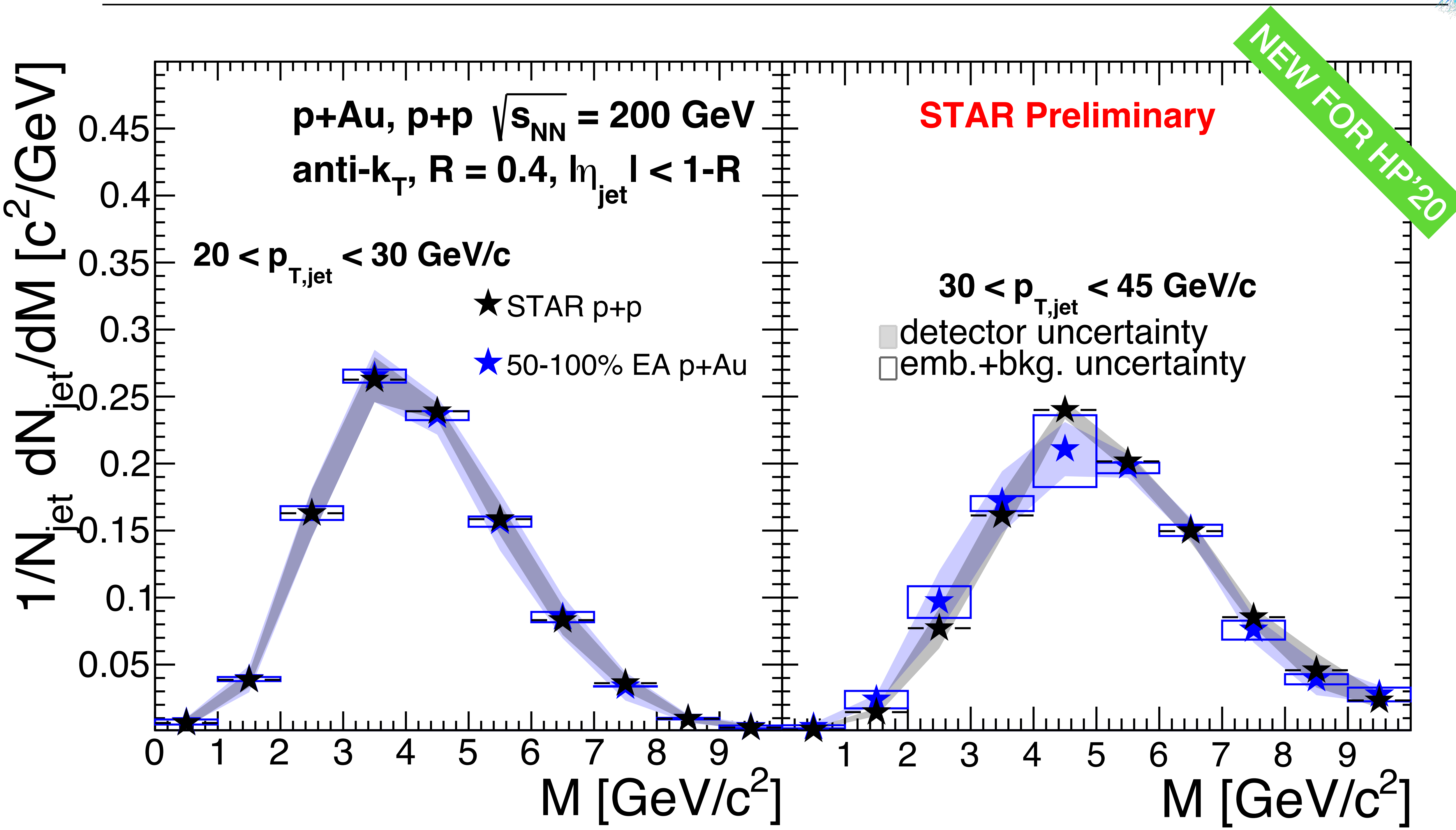
Jet mass in *p*+Au: analysis details

- Test event activity dependence using the inner BBC on the Au-going (east) side — see Dave's talk [link TBD]

- 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 (see Veronica's poster [link TBD])

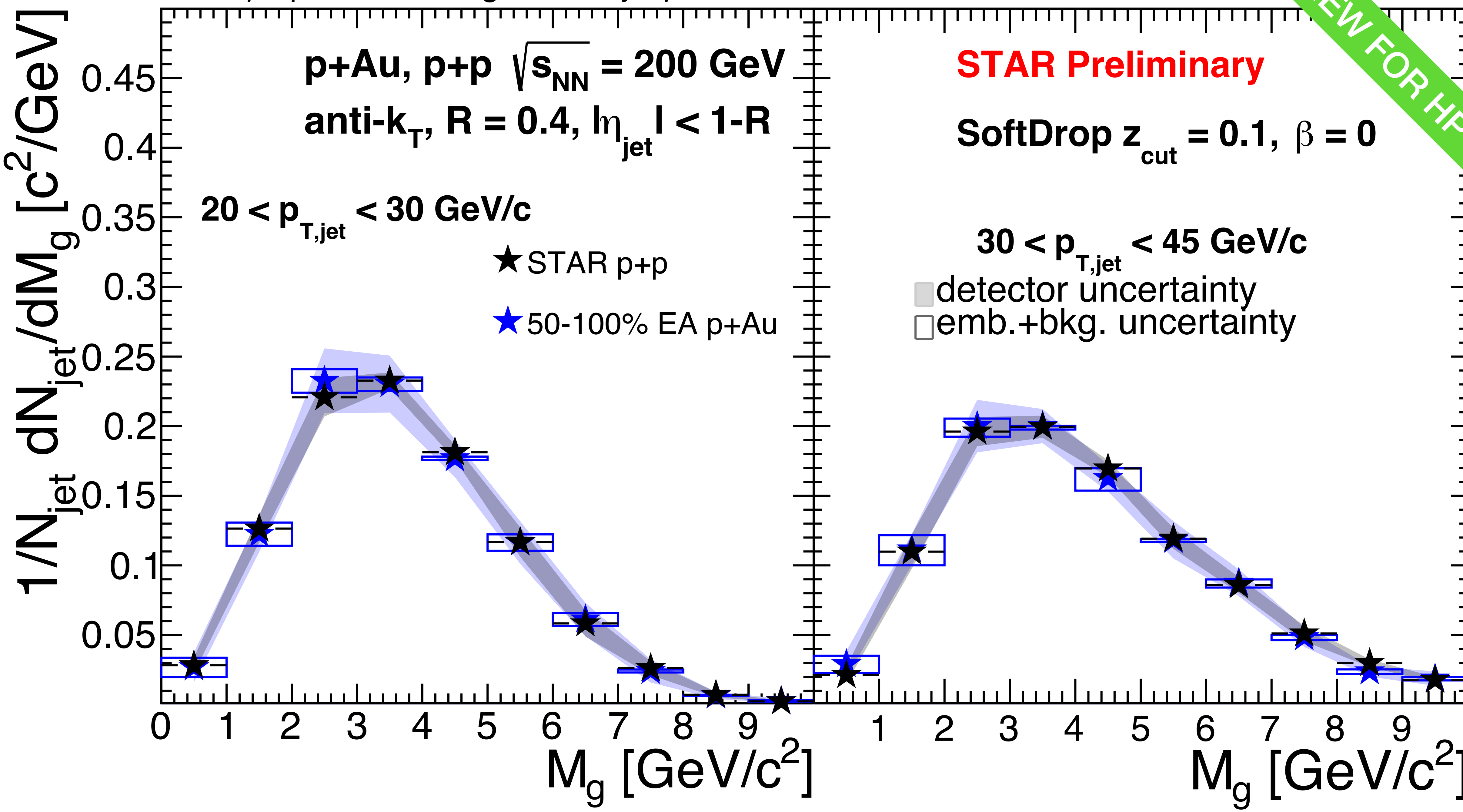
Jet mass: low EA



p+*p* and *p*+Au 50-100% event activity are comparable (low-EA *p*+Au is *p*+*p*-like as expected)

Groomed jet mass: low EA

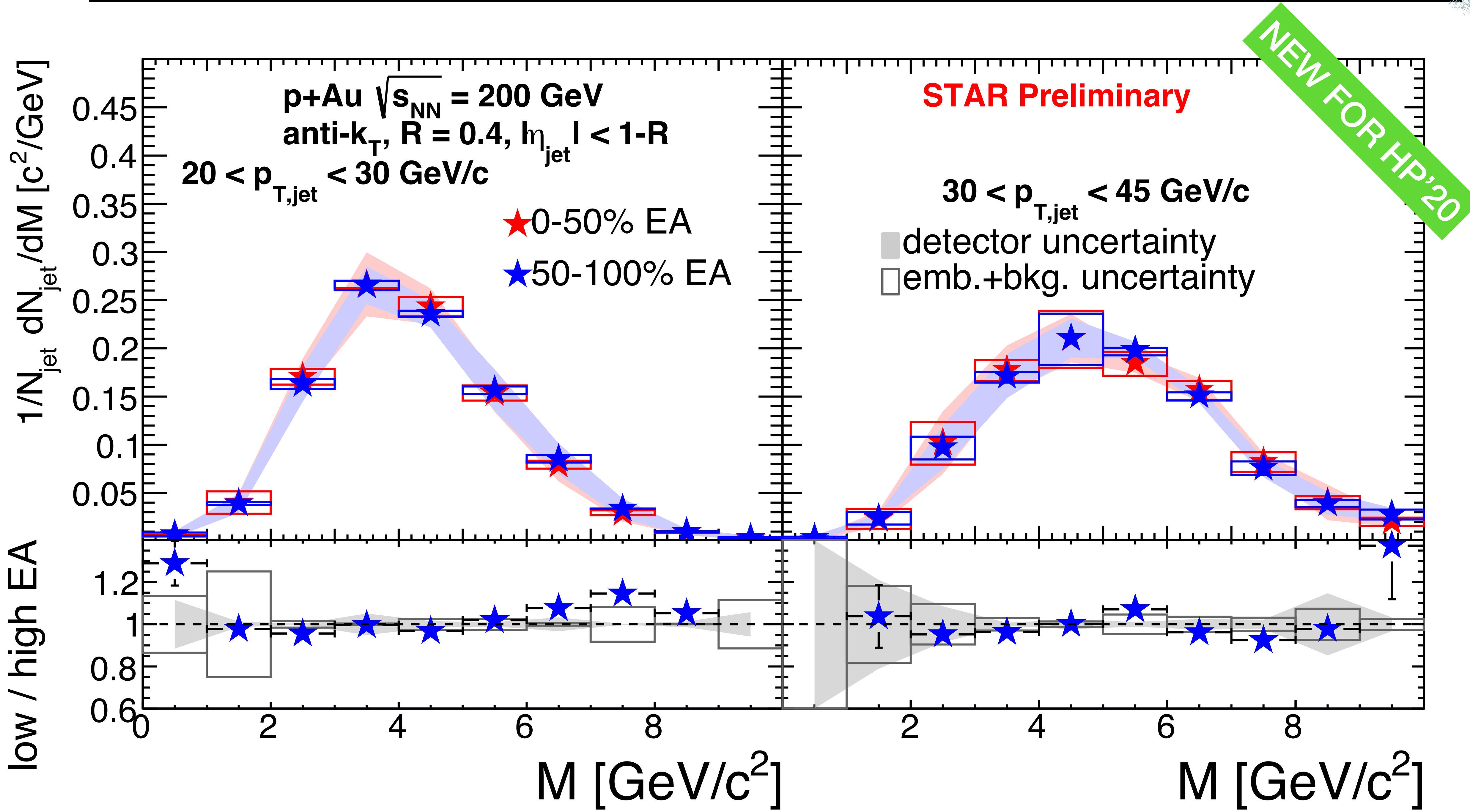
Note: p_T panels are *ungroomed* jet p_T



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

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

Jet mass: high EA

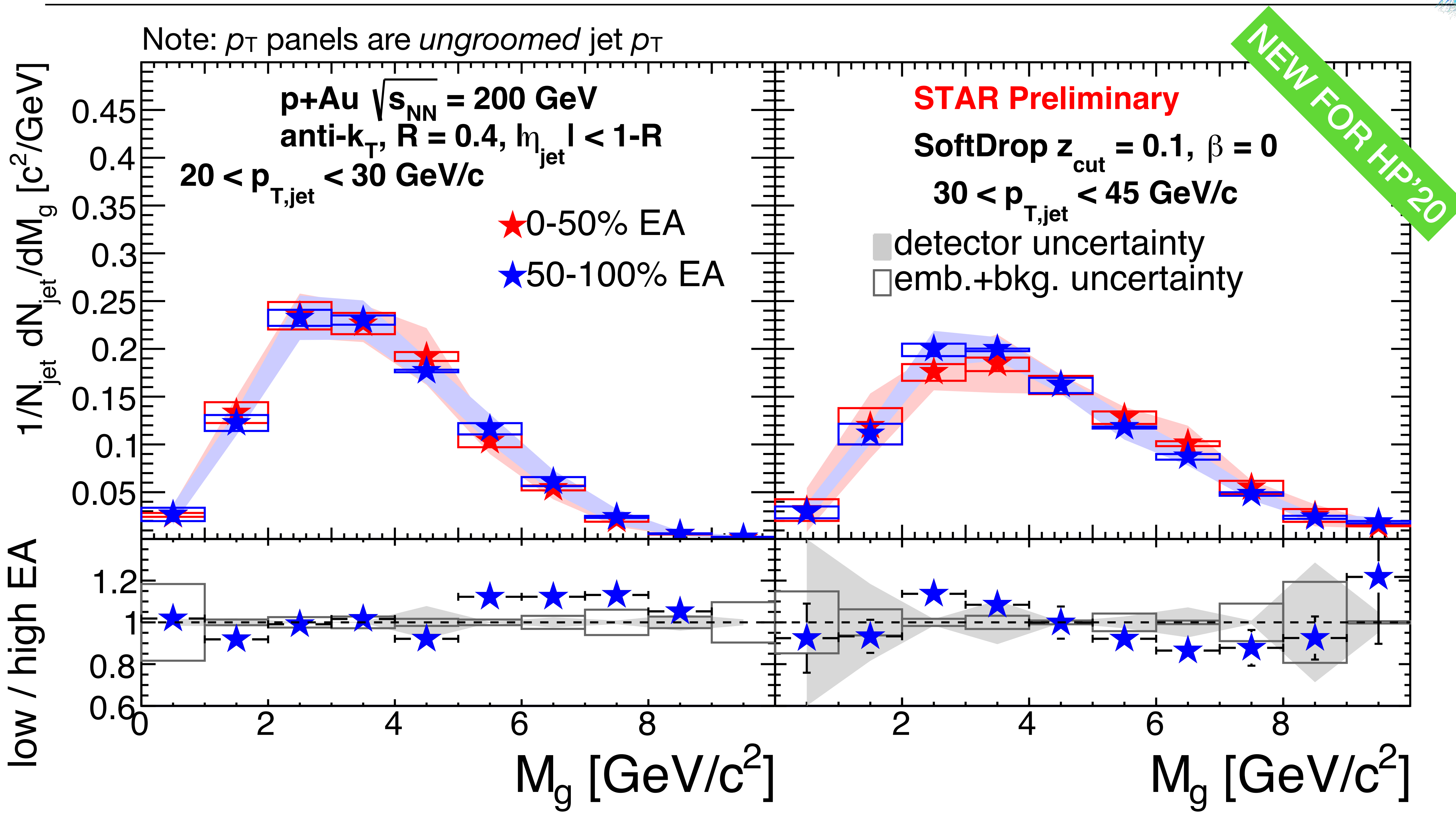


Low- and high-EA mass ratio is unity within systematic and statistical uncertainties

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

Groomed jet mass: high EA

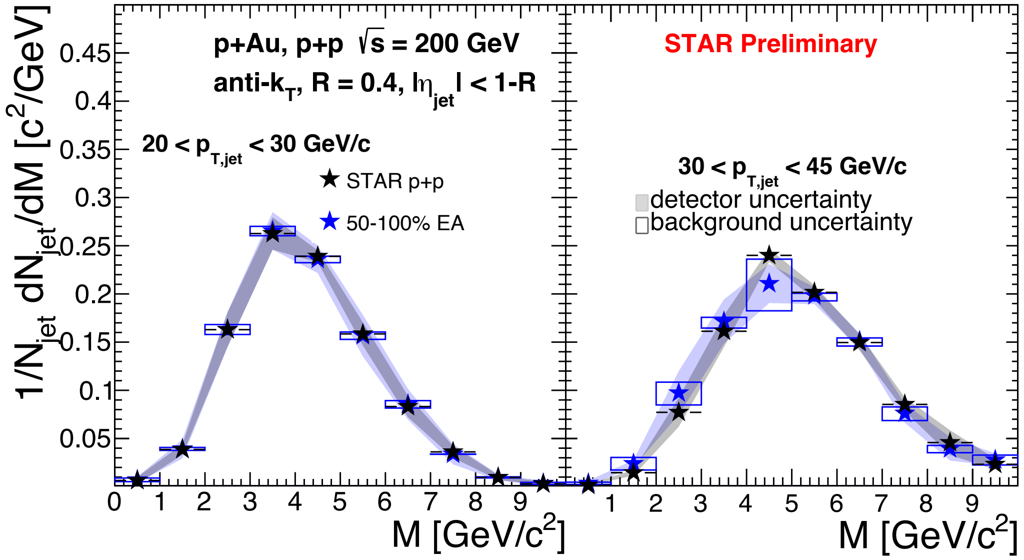
Note: p_T panels are *ungroomed* jet p_T



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

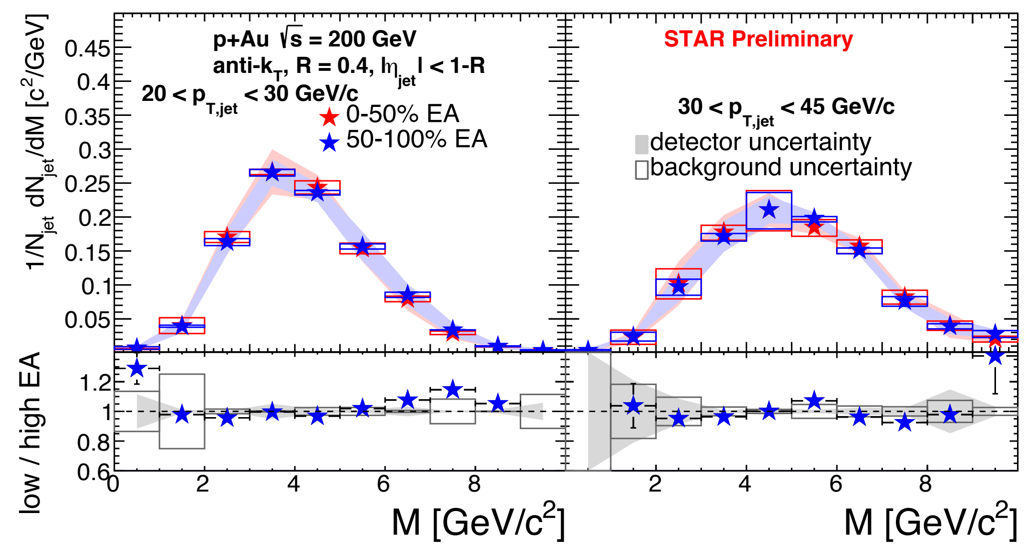
Conclusions - *p*+Au

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 centrality-dependent modification of jet yields observed by PHENIX is not due to modification of the internal structure of jets themselves.



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

Sudakov structure of jet mass

Dominant effect on QCD jet mass:
hard parton radiating gluons →

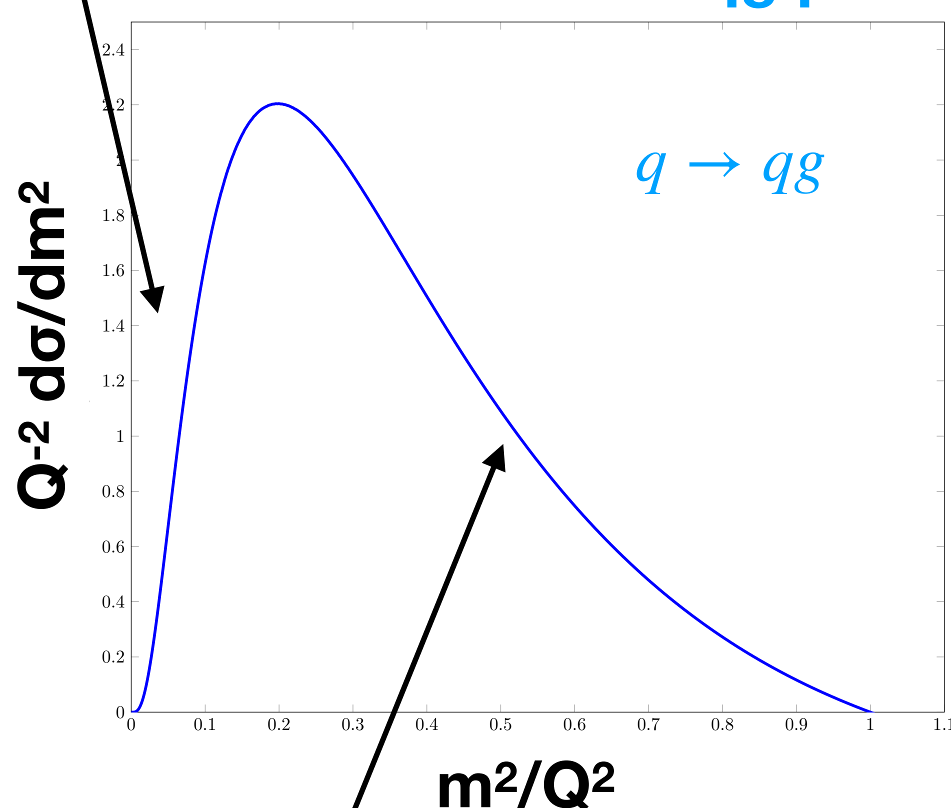
$$\frac{d\sigma}{dm^2} \approx \exp\left(-\frac{\alpha_s}{4\pi} C_F \log^2 \frac{Q^2}{m^2}\right) \frac{1}{m^2} \frac{\alpha_s}{2\pi} C_F \log \frac{Q^2}{m^2}$$

[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 $M/2p_T$.

Sudakov structure of jet mass

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"Sudakov factor, Δ(Q,m)"

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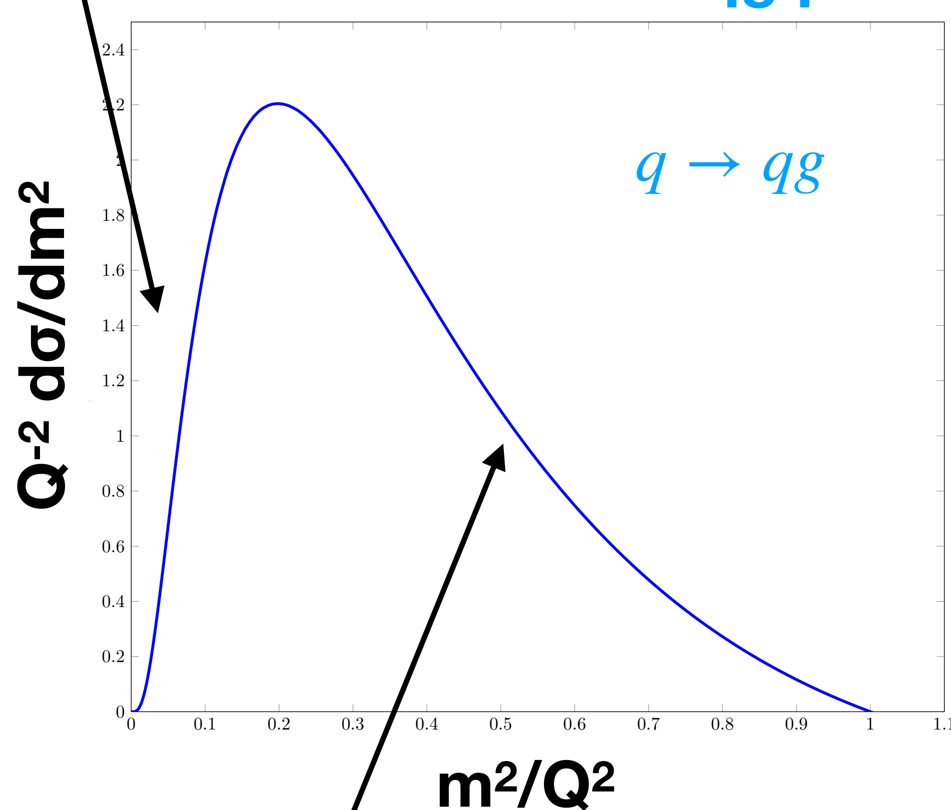
Invariant mass of qg pair



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

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

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]

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 $\pi^0, \pi^{\pm}, \eta, K^+, K_S^0, K_L^0, \Sigma^{\pm}, \bar{\Sigma}^{\pm}, \Lambda, \bar{\Lambda}, \Xi^-, \bar{\Xi}^+, \Omega^-, \bar{\Omega}^+$

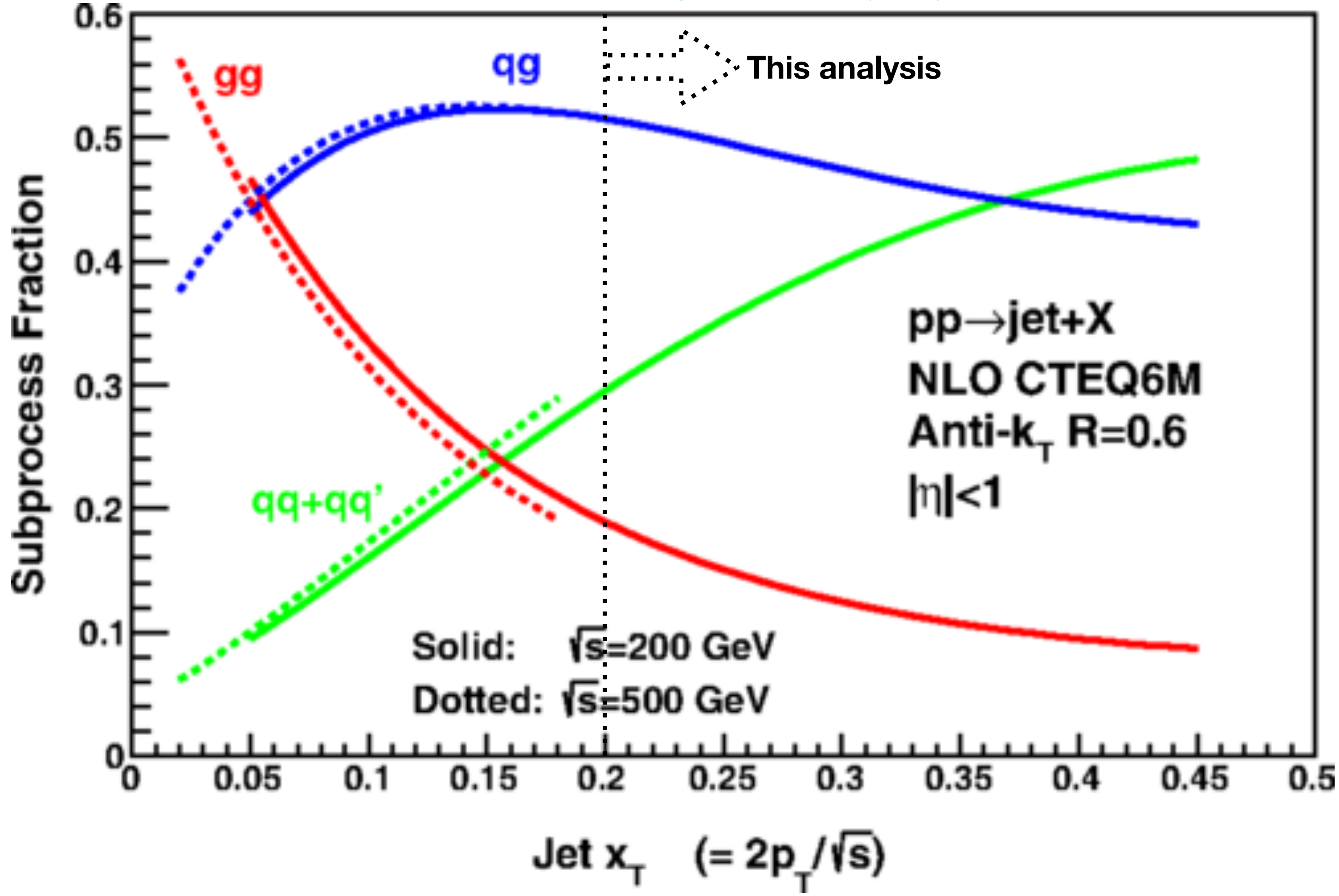
[1] STAR, Phys.Rev. D 100 (2019), 052005

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

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

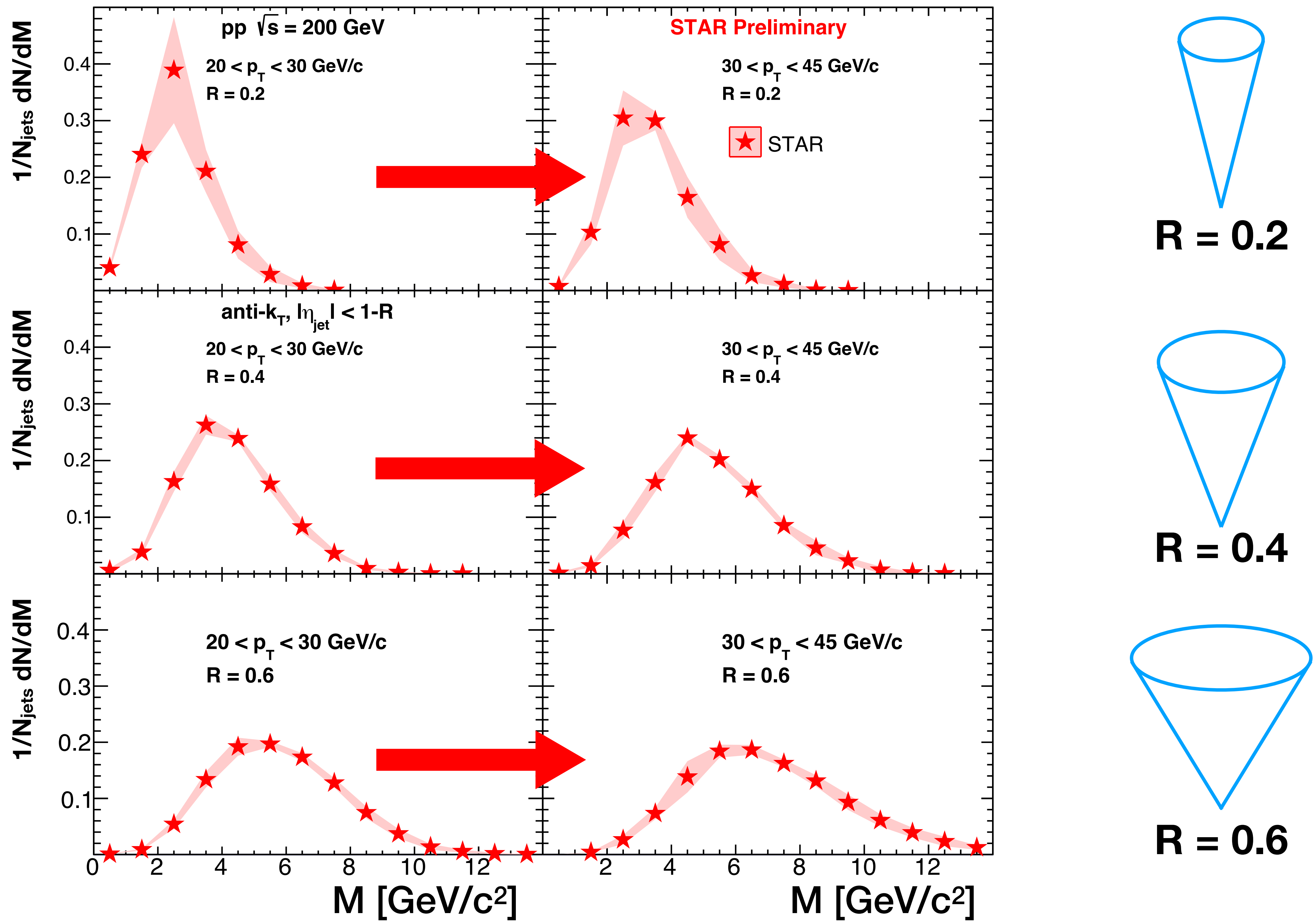
Quark and gluon fractions

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



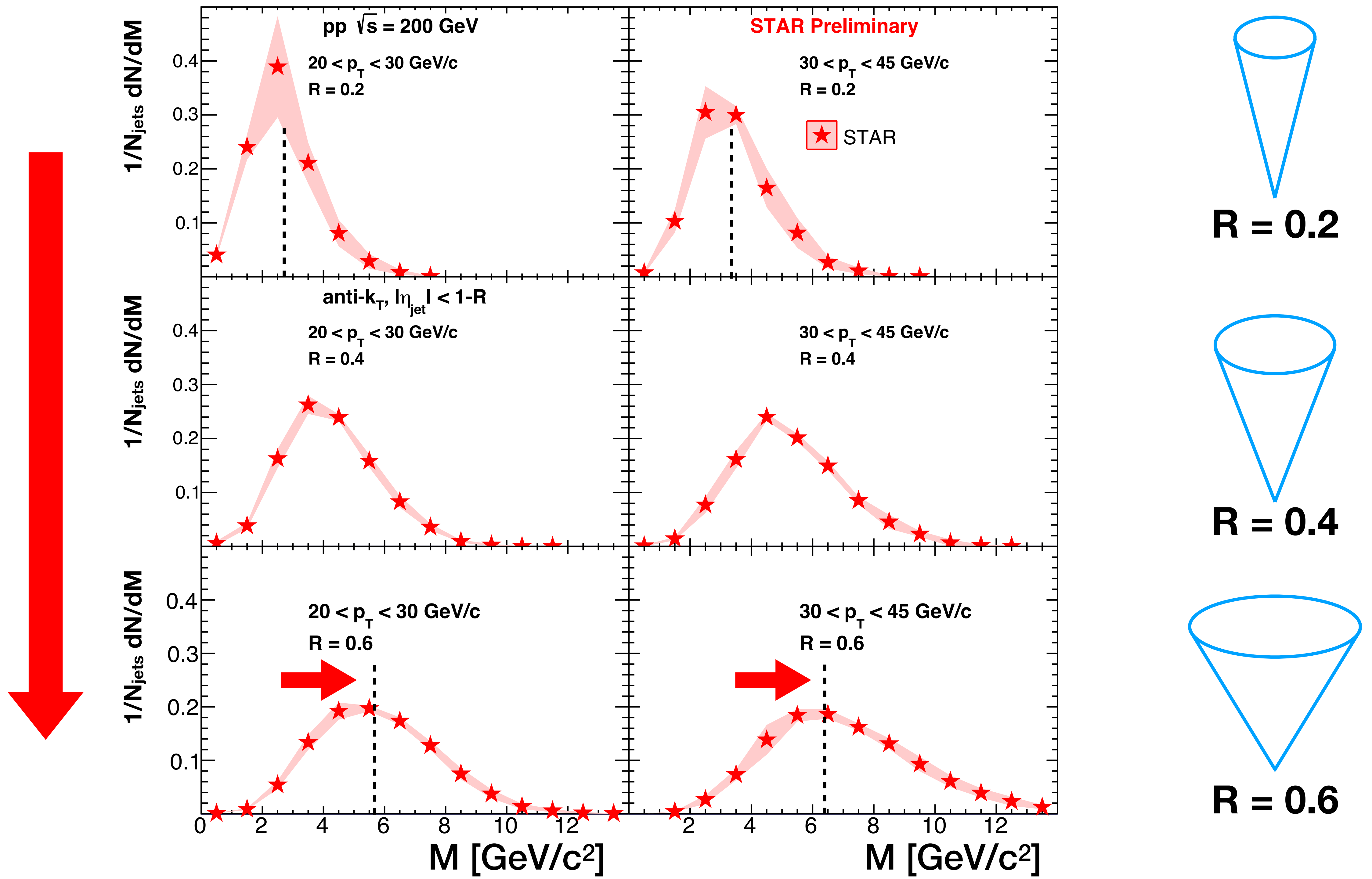
Gluon jets have larger mass than quark jets ($C_A/C_F = 9/4$)
Majority of jets are quark-initiated in this kinematic regime

Jet mass as a function of *R*



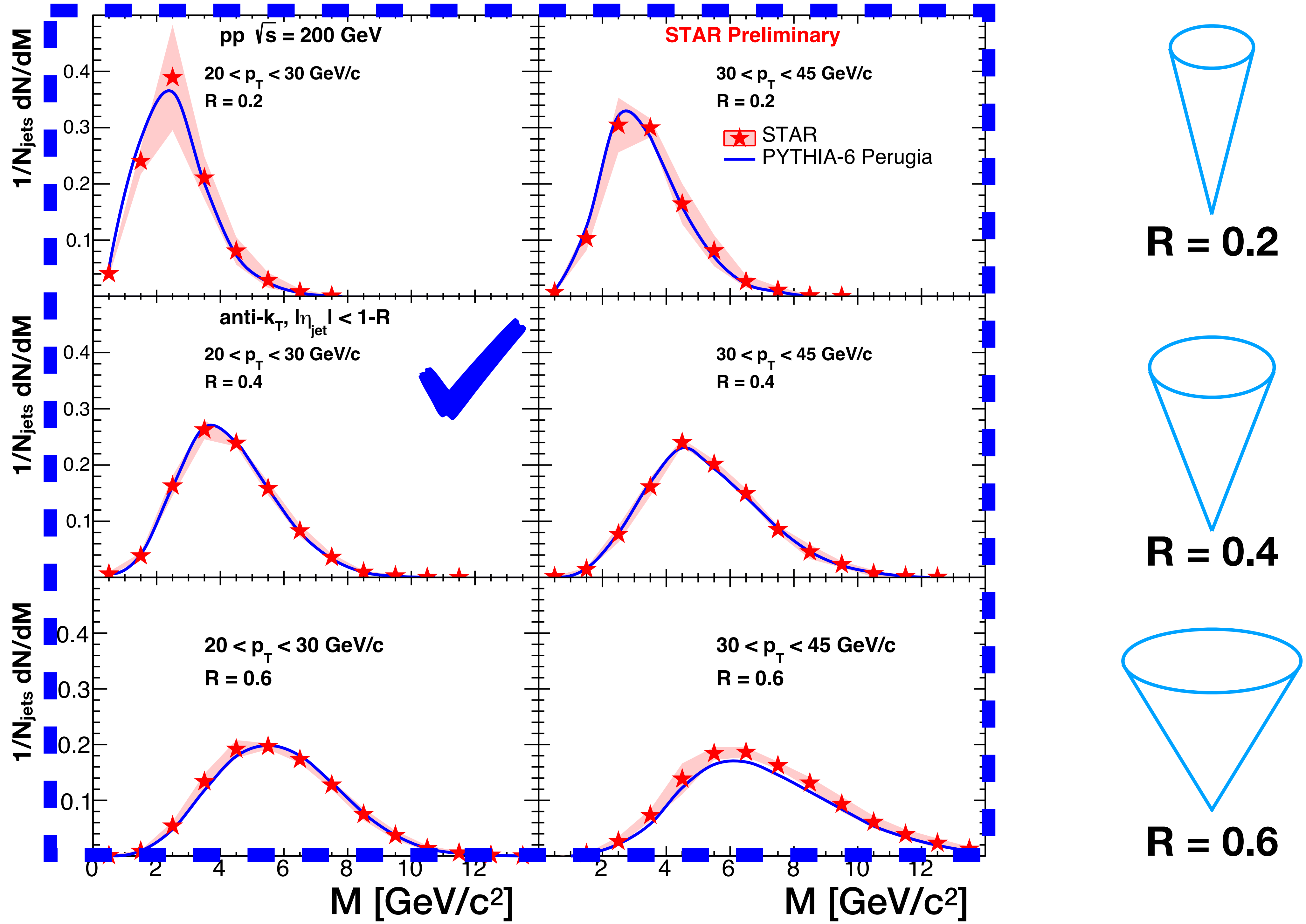
From pQCD, jet p_T increase → increased phase space to radiate → increased mass

Jet mass as a function of *R*



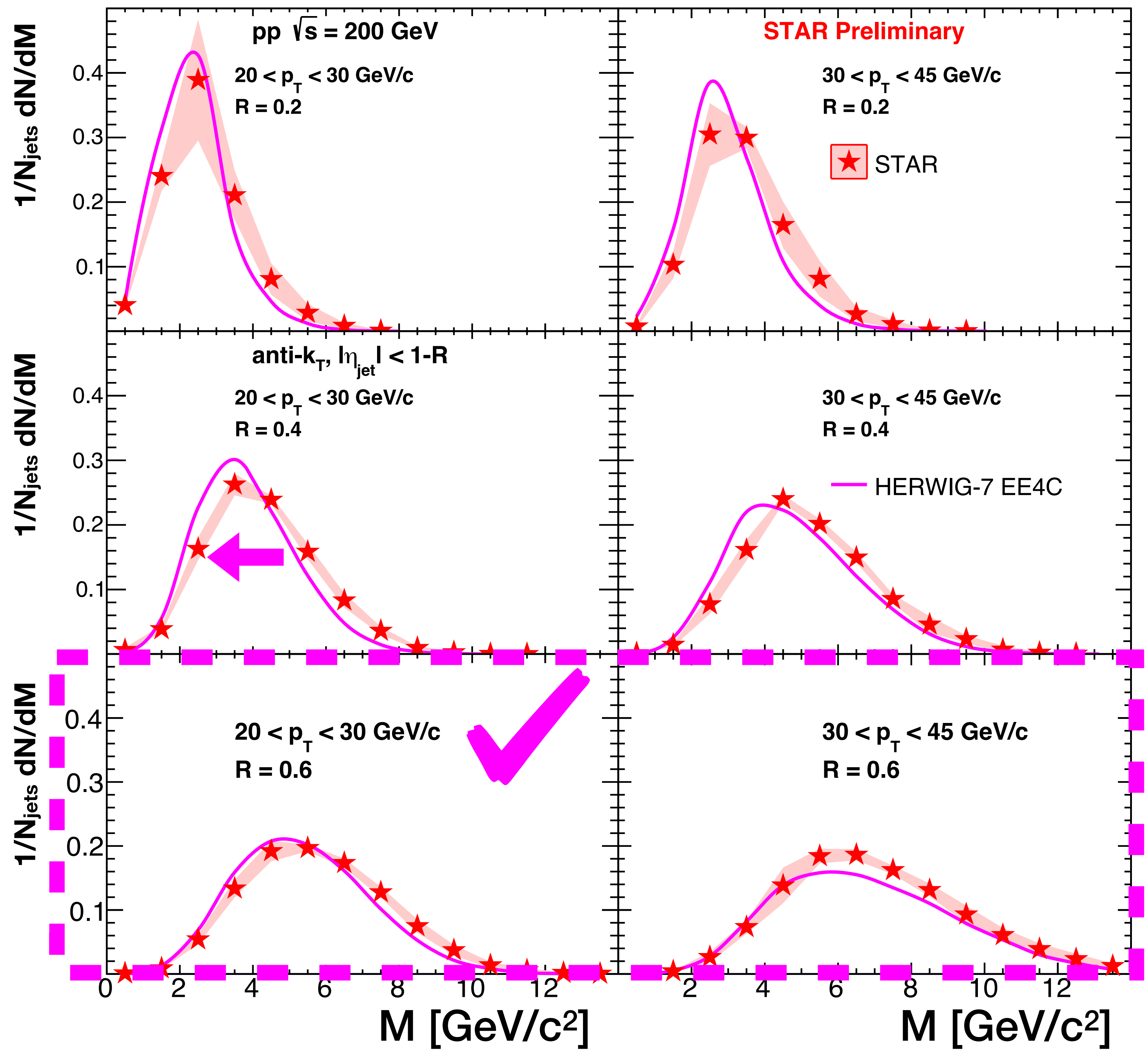
As radius increases, jets encompass more wide-angle radiation → increased mass

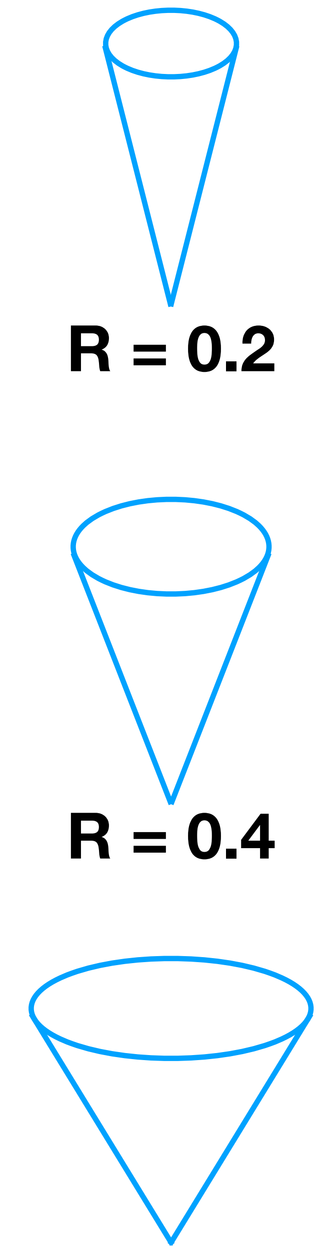
Jet mass as a function of *R*



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

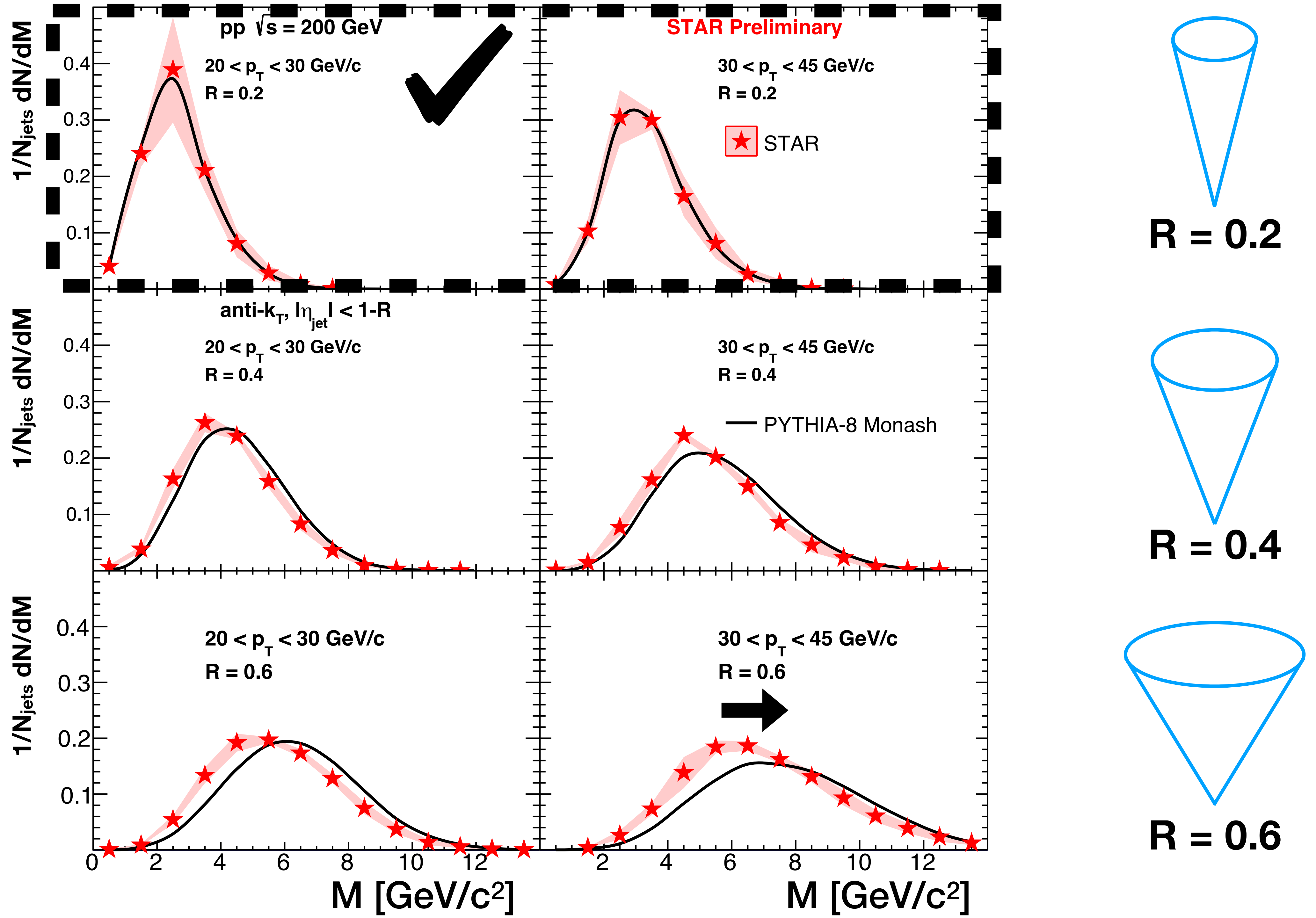
Jet mass as a function of R





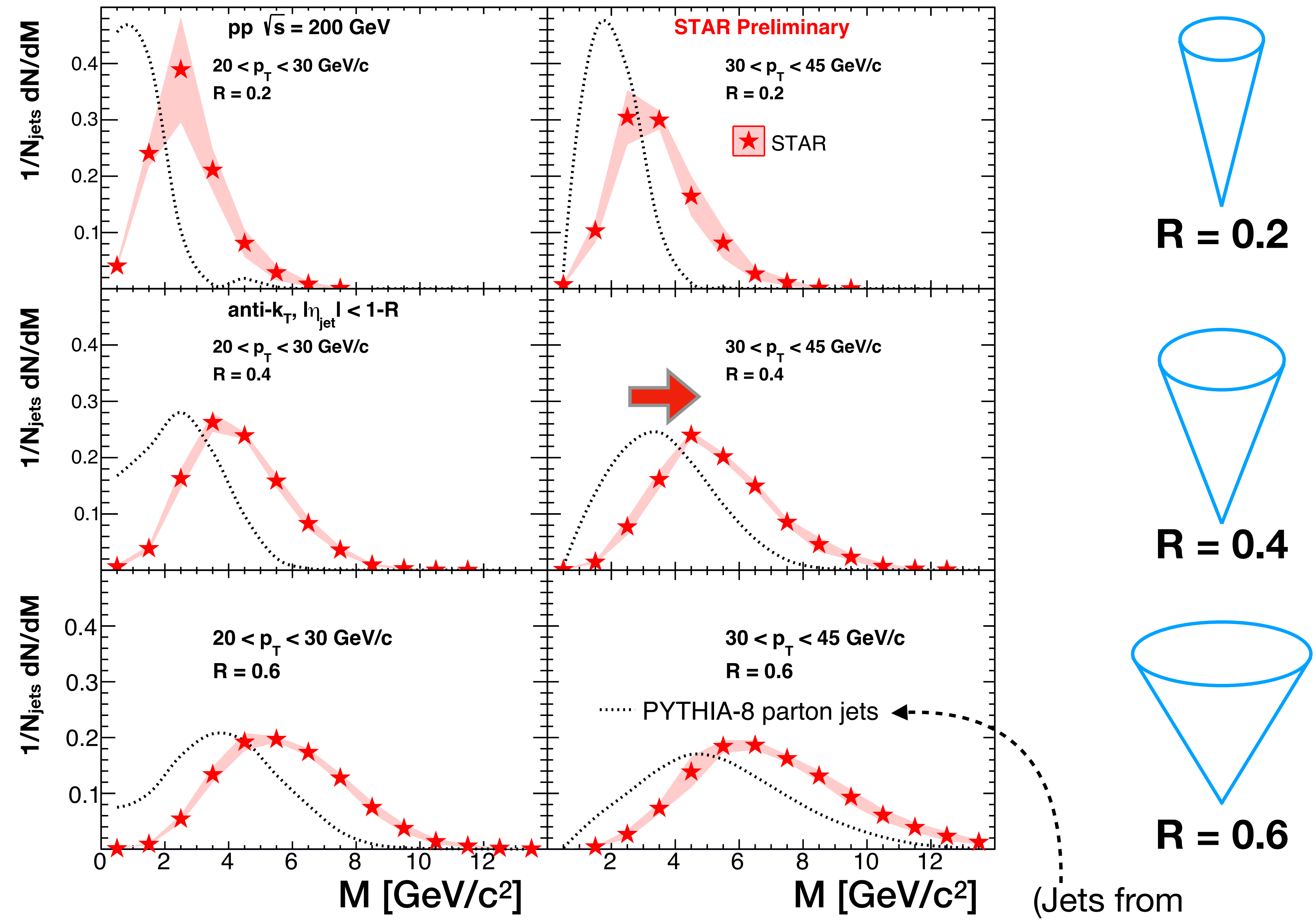
HERWIG-7 under-predicts for small R, better agreement with data by R = 0.6

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*

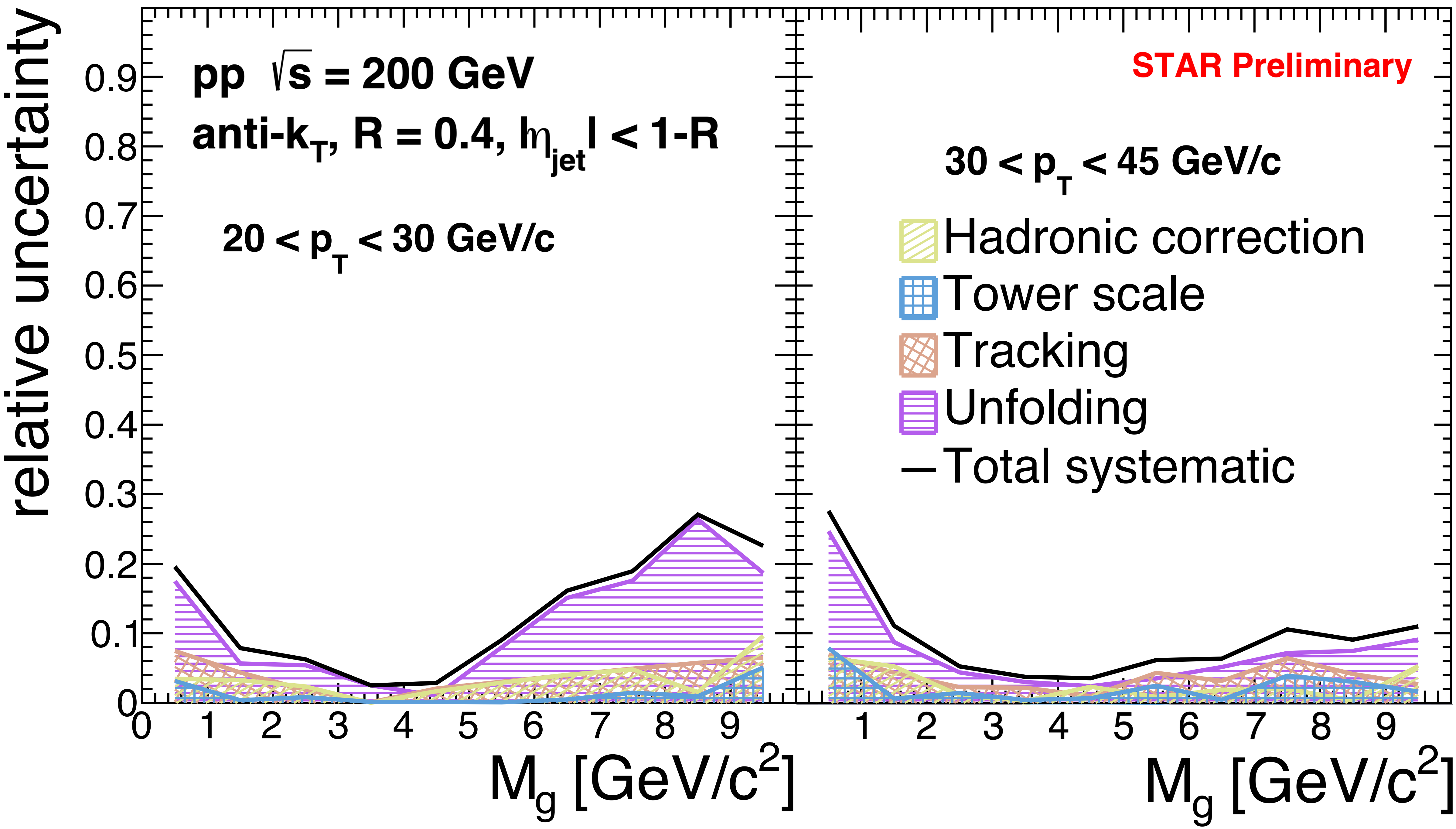


(Jets from PYTHIA events with hadronization = off)

Non-perturbative effects increase the mass

Groomed jet mass systematics

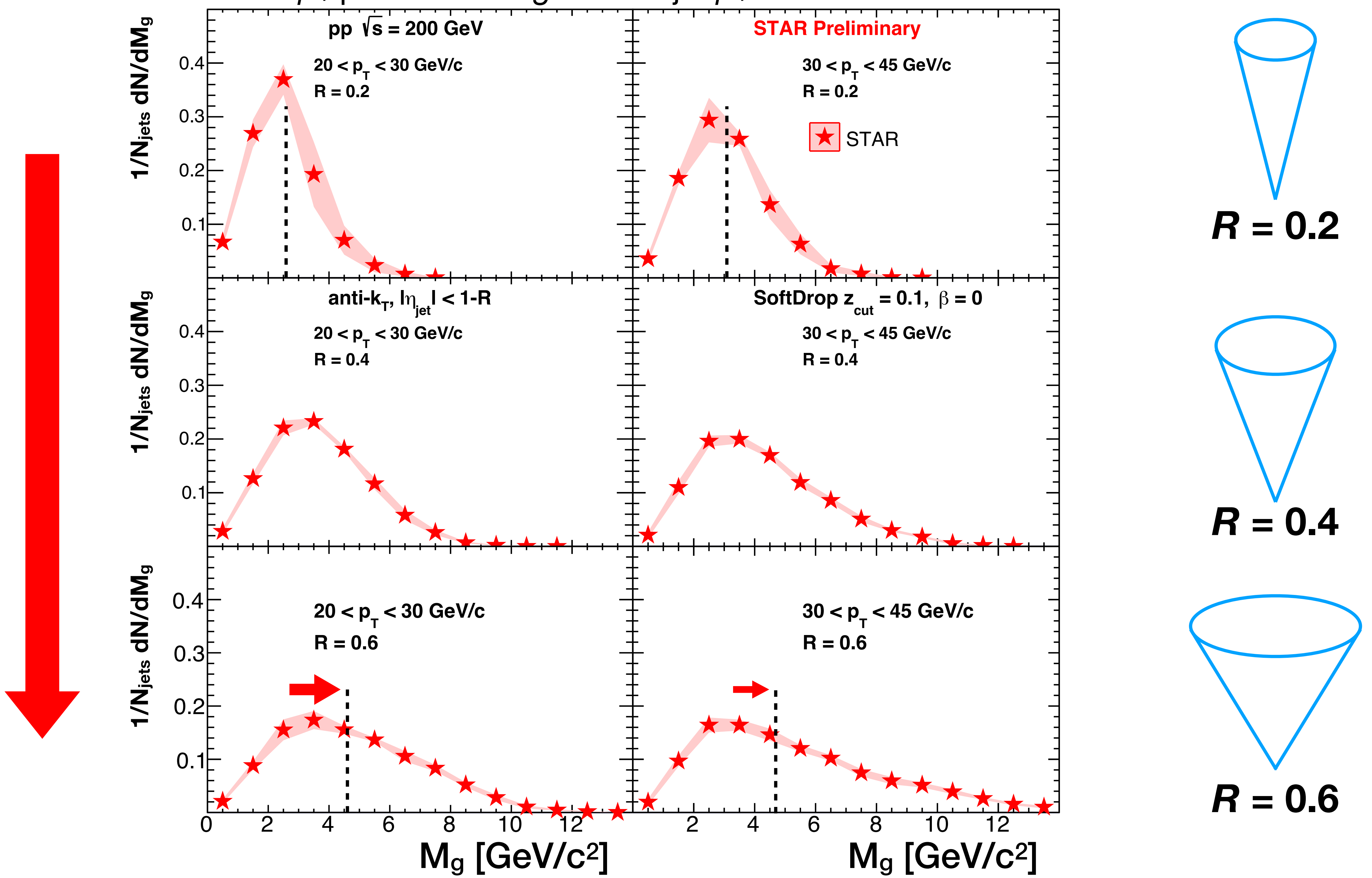
Note: p_T panels are *ungroomed* jet p_T



Systematic uncertainties are reduced from ungroomed case

Groomed jet mass as a function of *R*

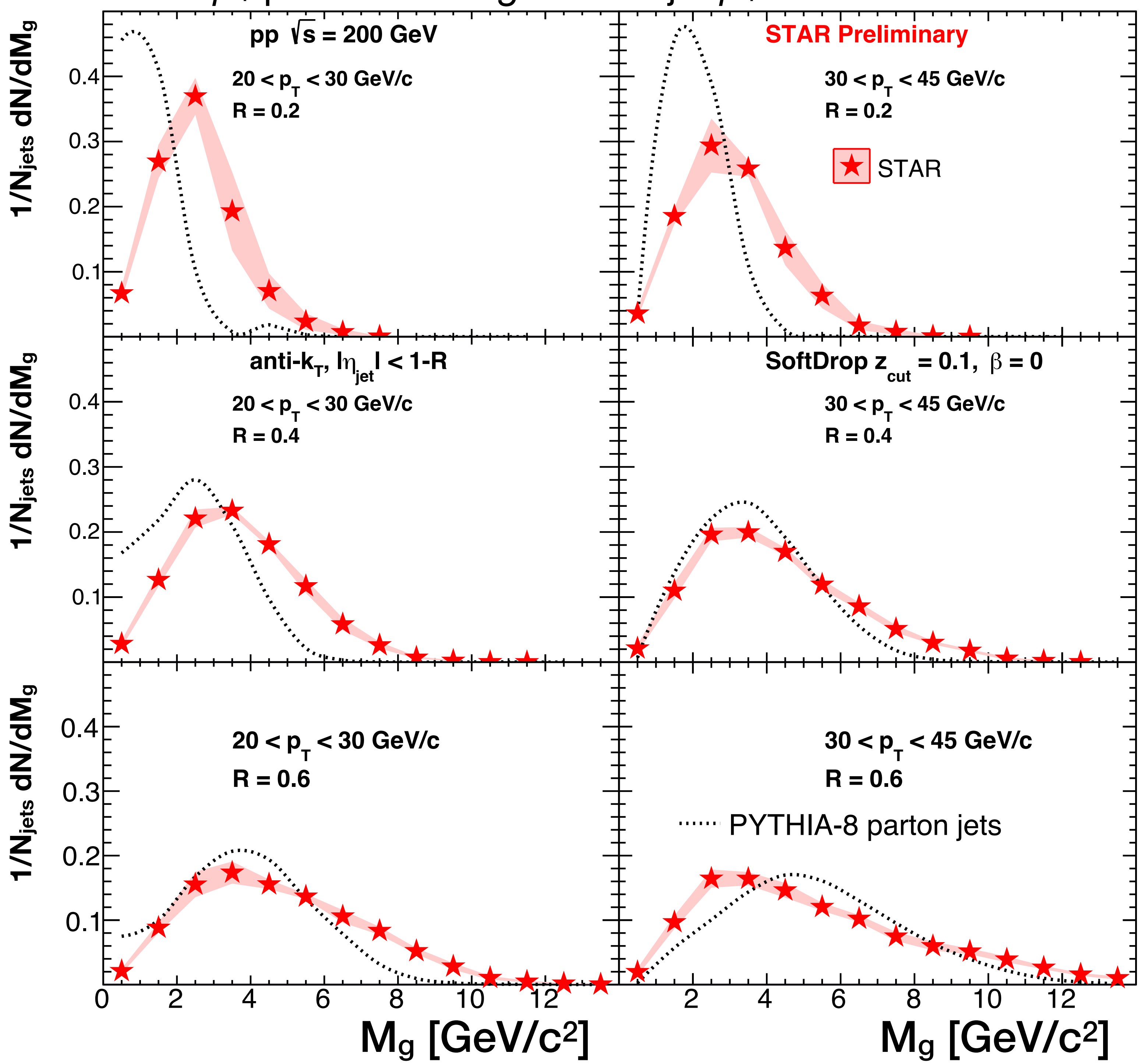
Note: p_T panels are *ungroomed* jet p_T

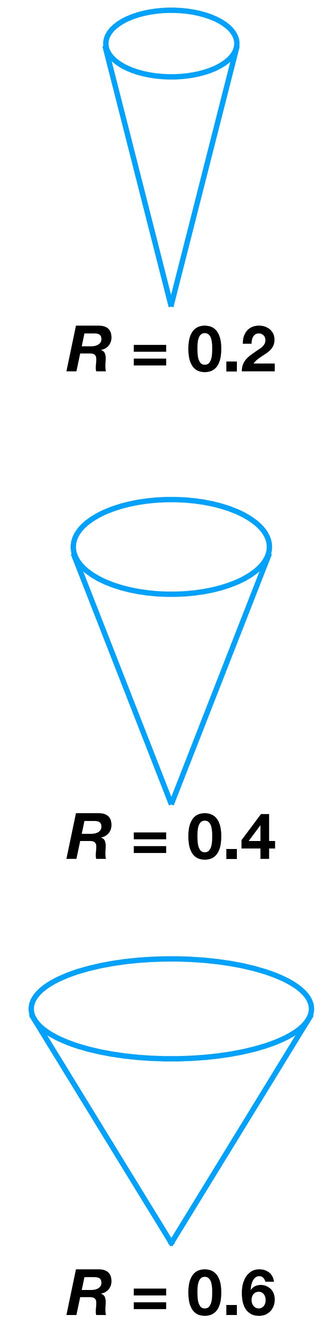


Groomed mean mass less sensitive to radius / p_T variation

Groomed jet mass as a function of *R*

Note: p_T panels are *ungroomed* jet p_T

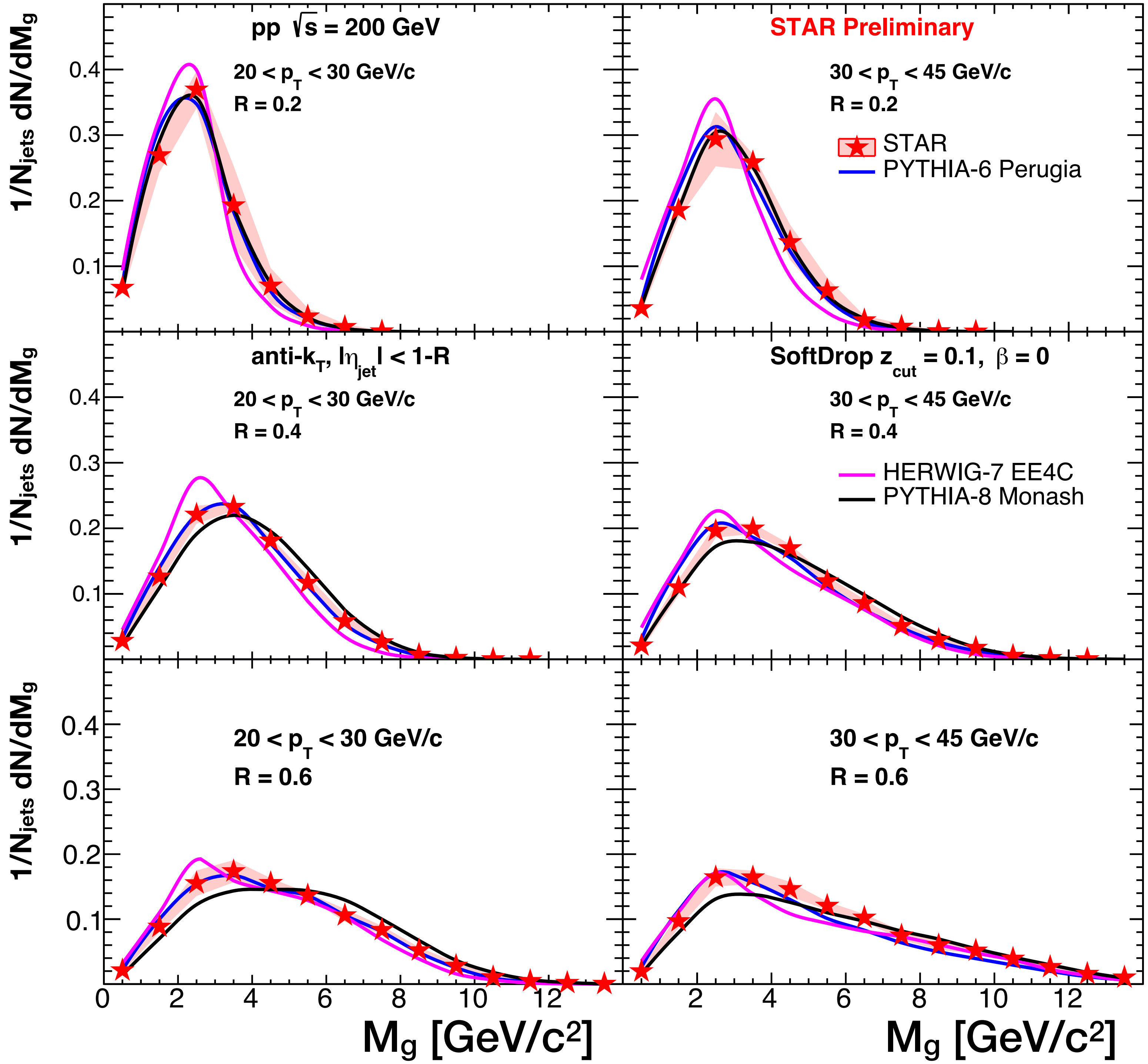


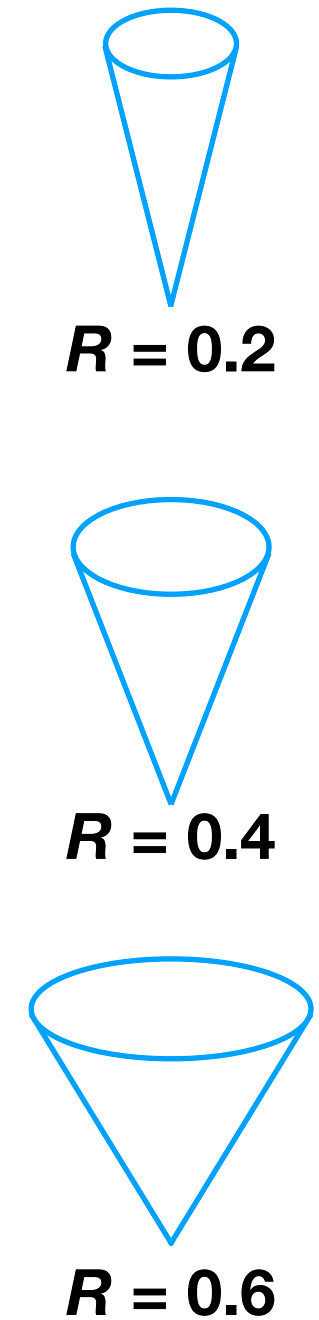


Non-perturbative effects suppressed, in particular, at higher radii!

Groomed jet mass as a function of *R*

Note: p_T panels are *ungroomed* jet p_T

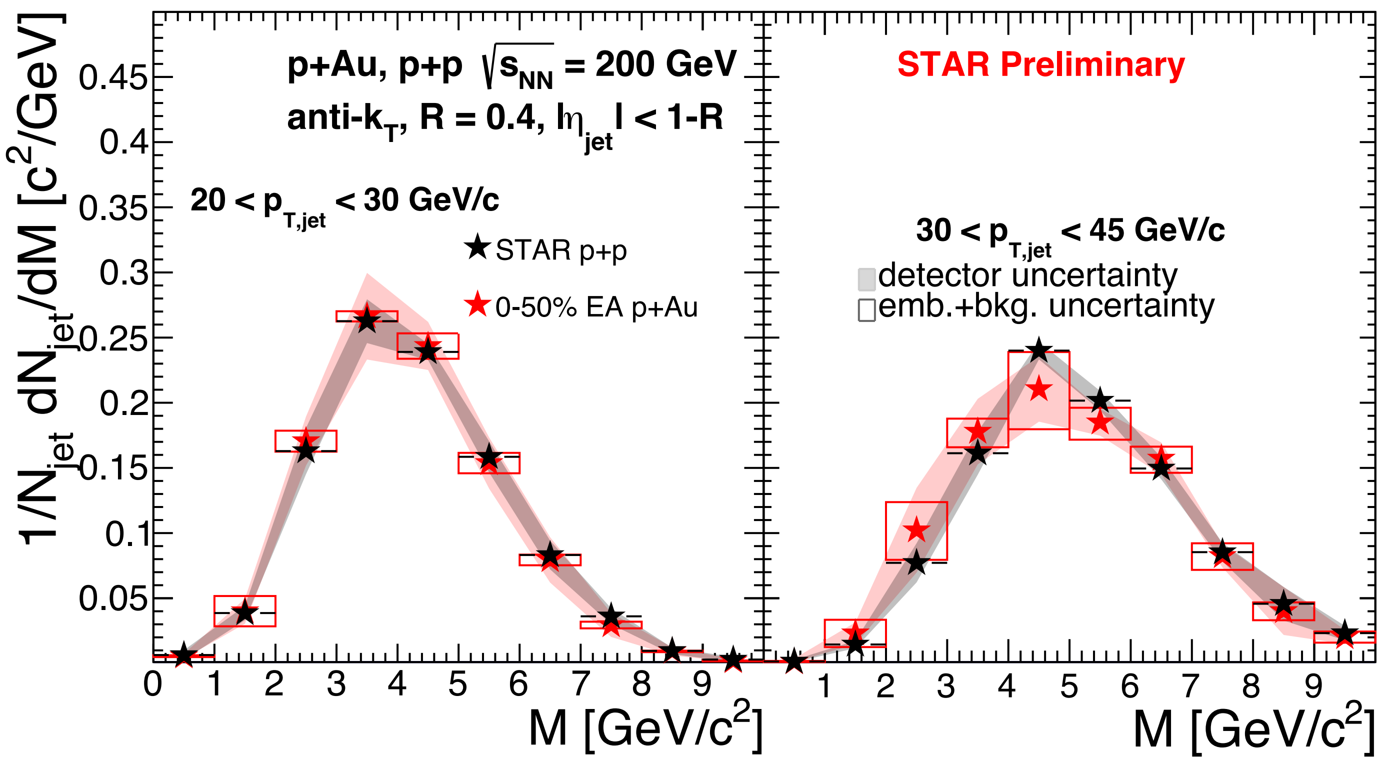




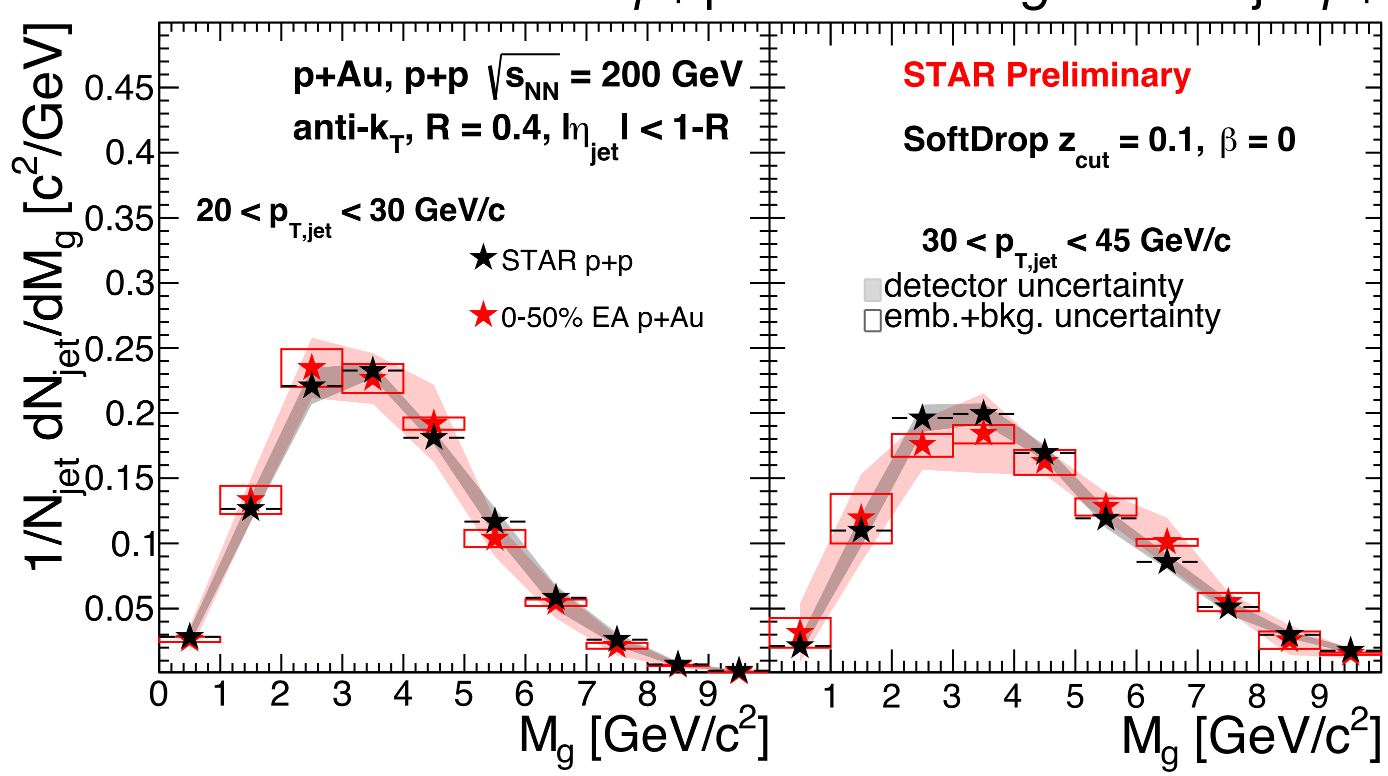
RHIC-tuned **PYTHIA-6** describes data

HERWIG-7 and **PYTHIA-8** same trends but better description

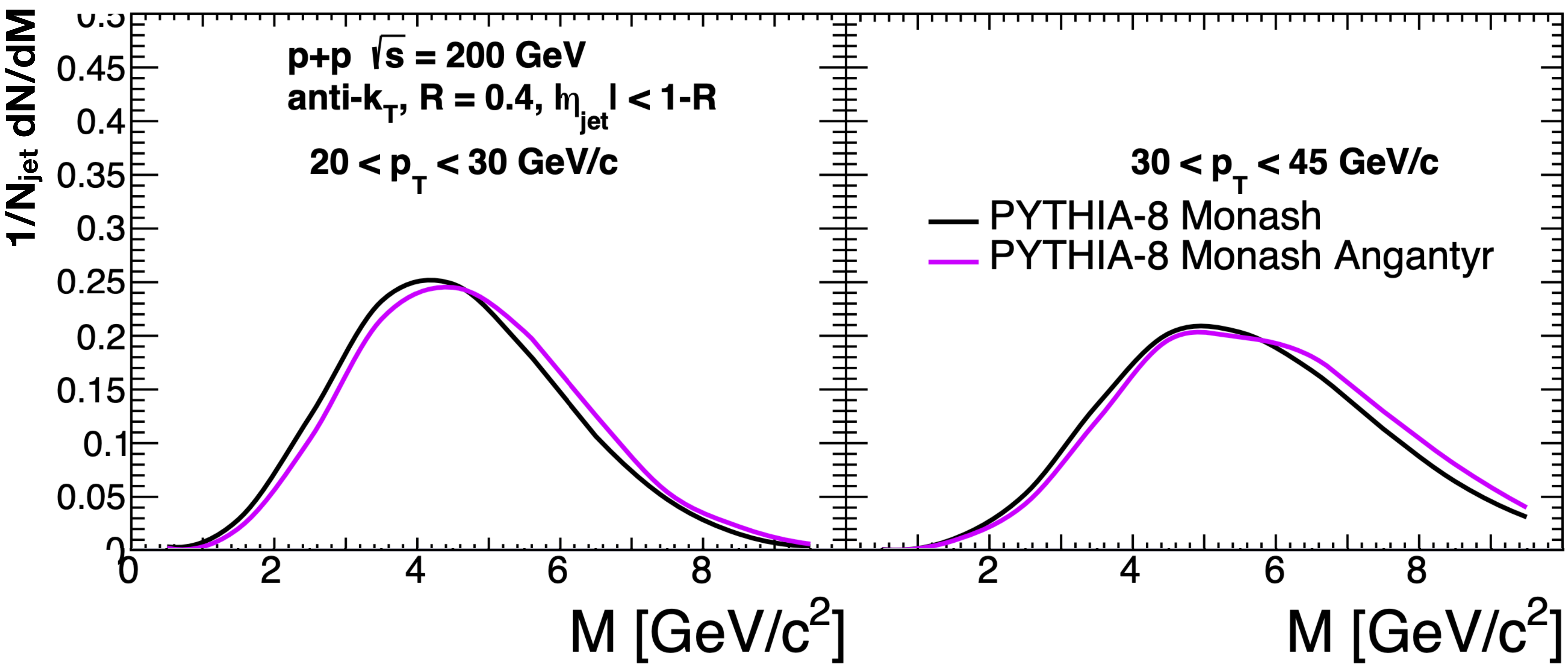
Comparing high-EA p+Au to p+p



Note: p_T panels are *ungroomed* jet p_T



PYTHIA-8 Angantyr (heavy ions)



PYTHIA-8 p+p and PYTHIA-8 p+Au (Angantyr) use the same tune (Monash)

TBD: list other parameters