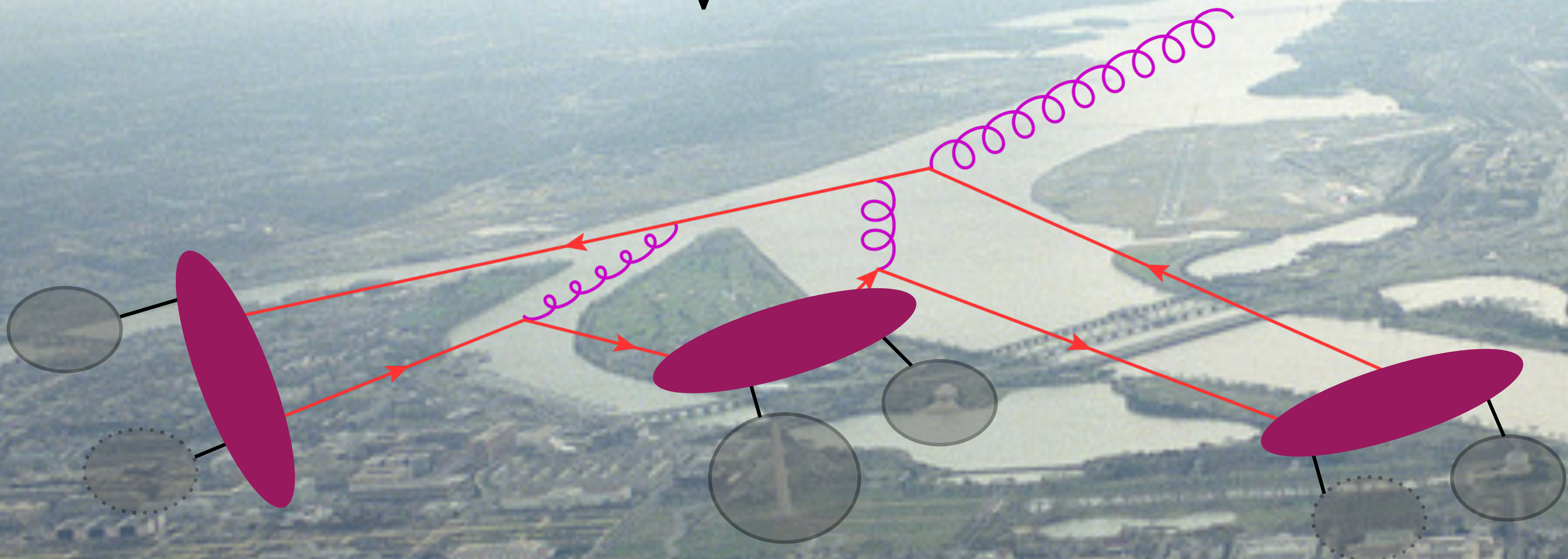
U.S. DEPARTMENT OF ENERGY | Office of Science

WAYNE STATE UNIVERSITY

STAR

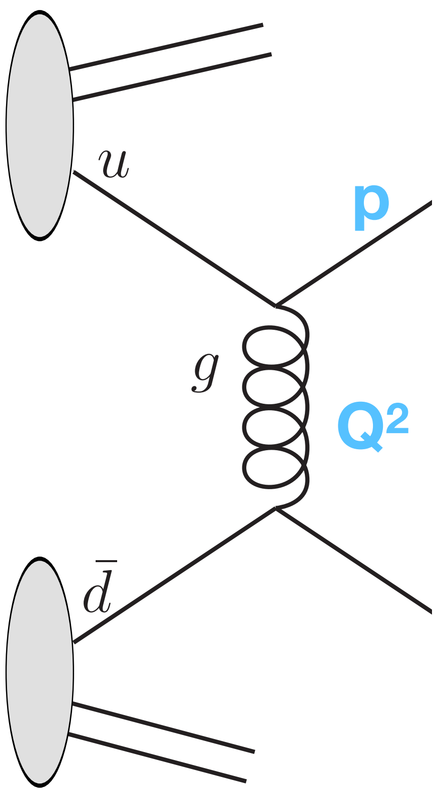
First measurements of the jet mass in p+p collisions at $\sqrt{s}$ = 200 GeV at STAR



Isaac Mooney (Wayne State University)
for the STAR Collaboration

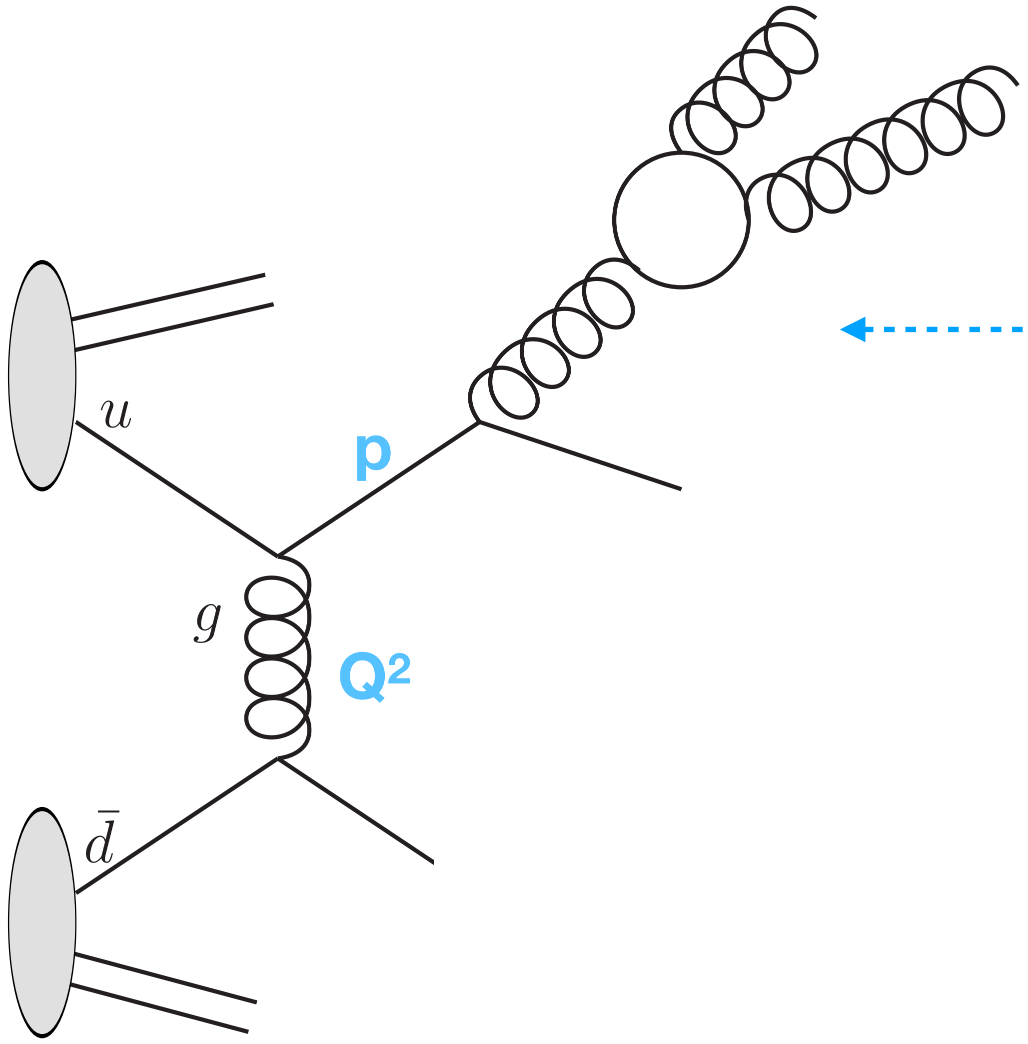
DNP - Crystal City
October 15, 2019

Jets in vacuum



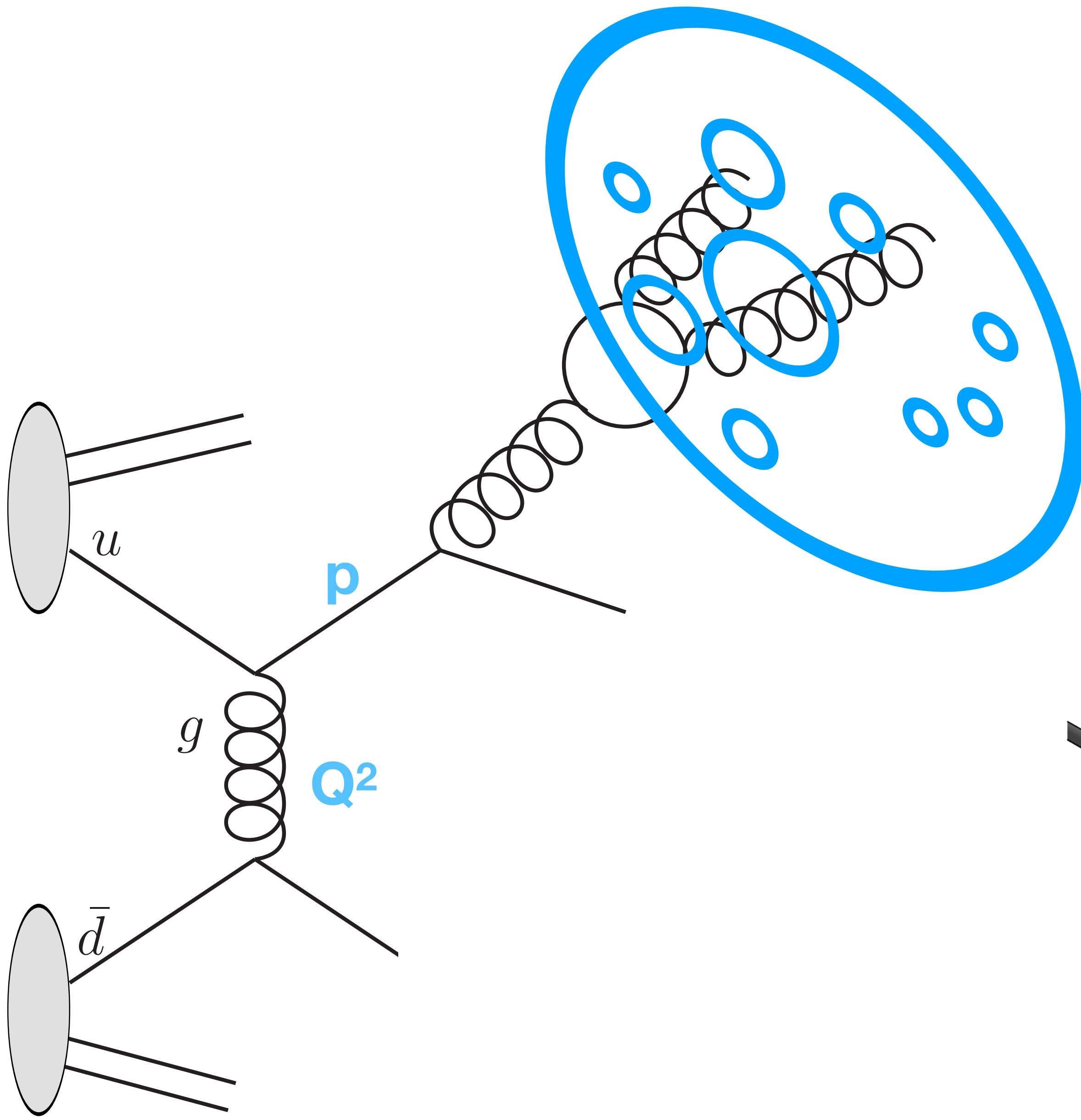
initial hard scatter (large Q^2)

Jets in vacuum



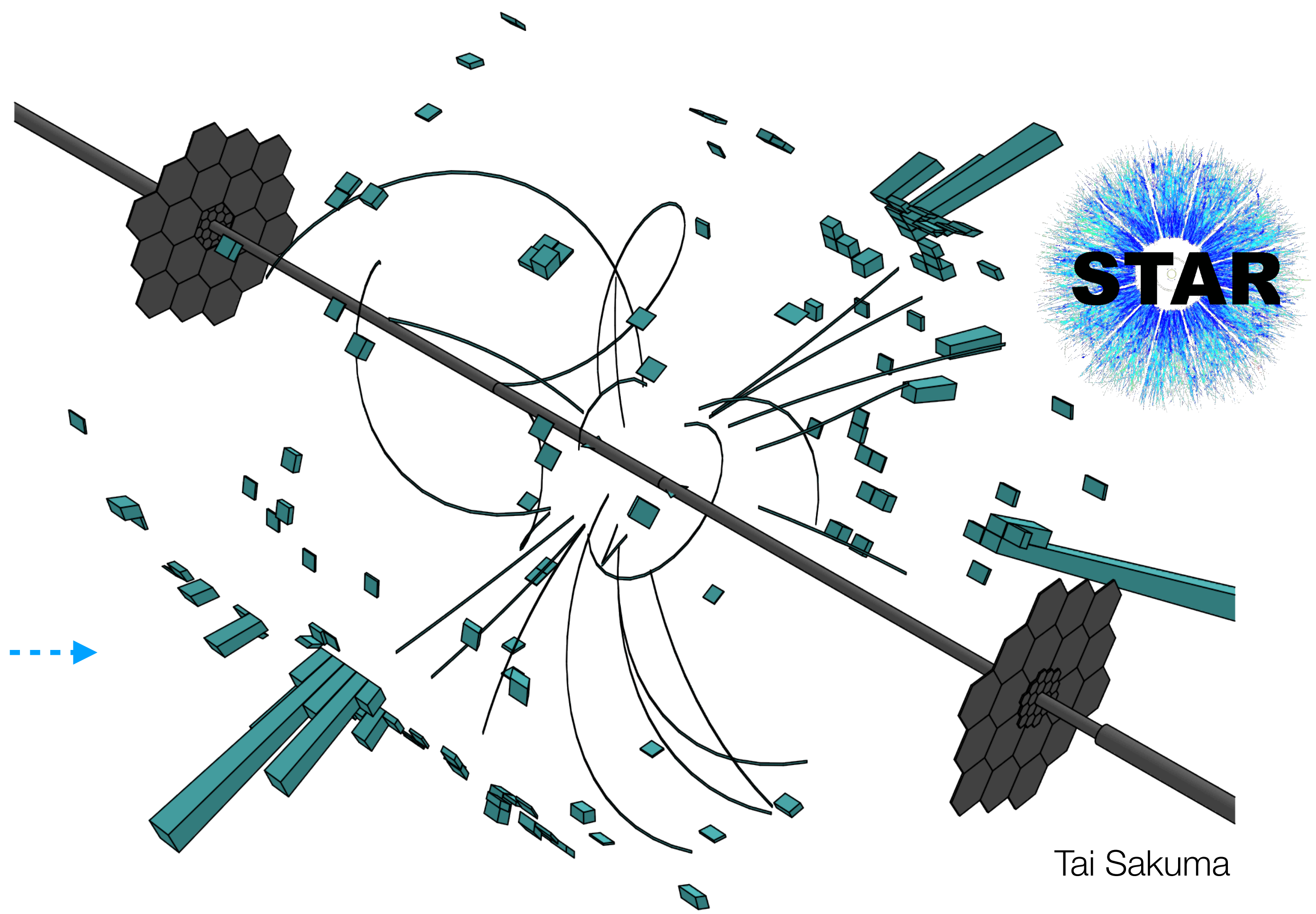
collimated parton shower

Jets in vacuum



Hadronization

Measurement



Tai Sakuma

Jet finding

Need to link hadronic state (*experiment*) to partonic state (*theory*)

Jet finding algorithm does this!

Infrared, collinear safe → theory

Recursive clustering

FastJet package provides implementation of k_T family

- we use the standard *anti-k_T* algorithm: IRC safe, insensitive to underlying event, pileup

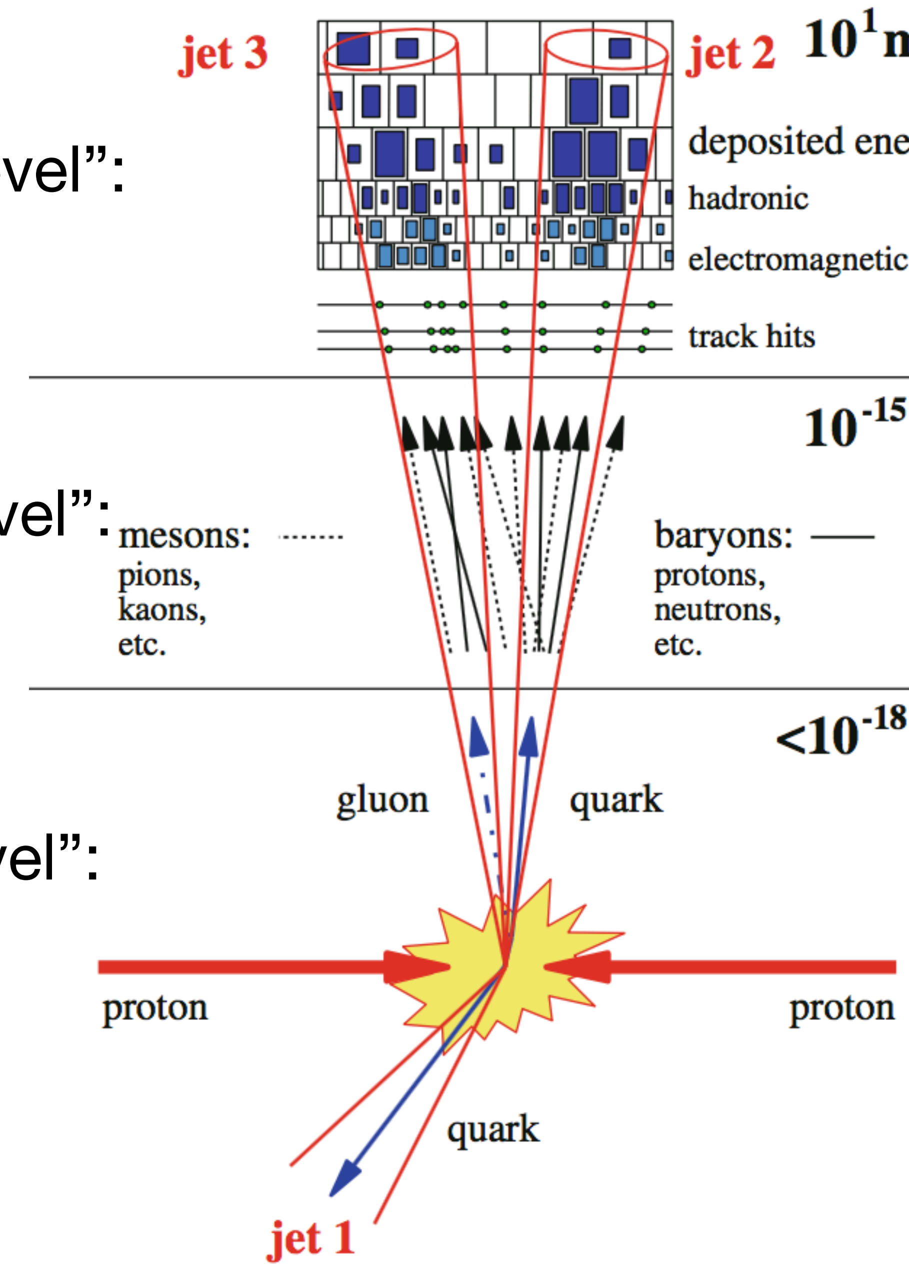
- requires resolution parameter: we use R = 0.4, vary to 0.2, 0.6

"detector-level":

"particle-level":

"parton-level":

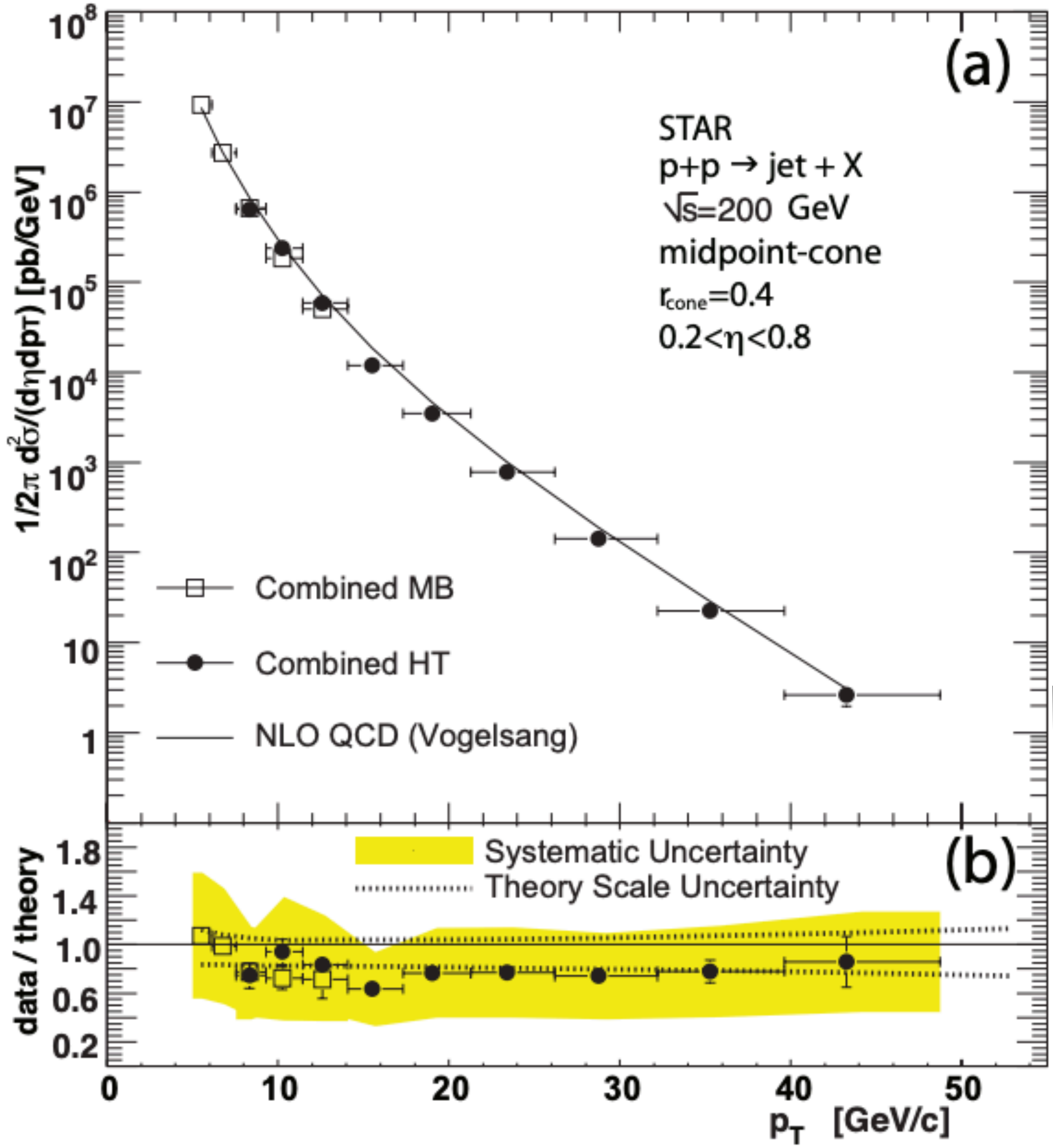
Carli, Rabbertz, Schumann, Studies of Quantum Chromodynamics at the LHC.



Cacciari, Salam, J. High Energ. Phys. 04 (2008) 063
Cacciari, Salam, Soyez, Eur.Phys.J. C 72 (2012) 1896

Jets in pQCD

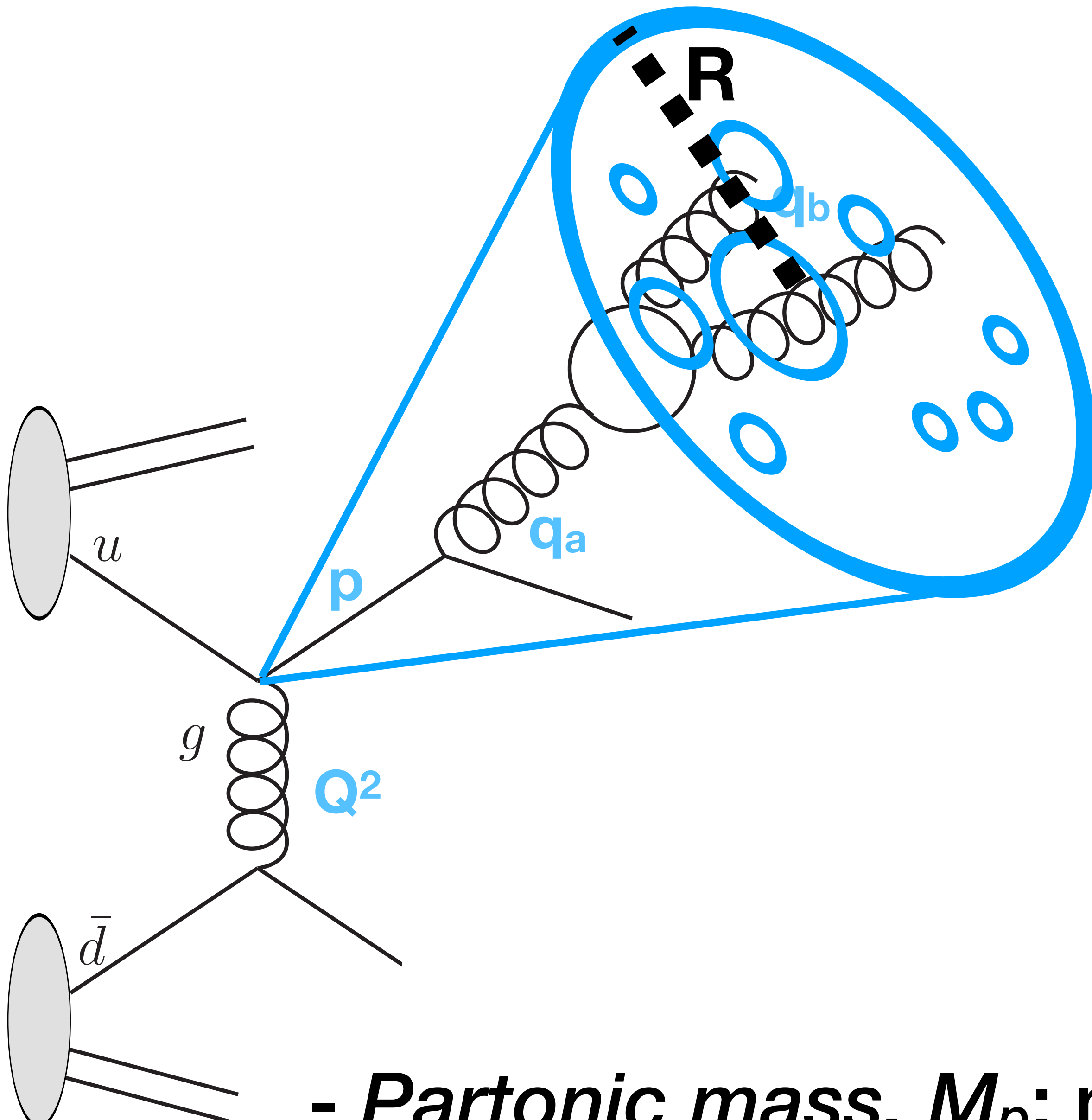
STAR Collaboration, Phys.Rev.Lett. 97 (2006) 252001

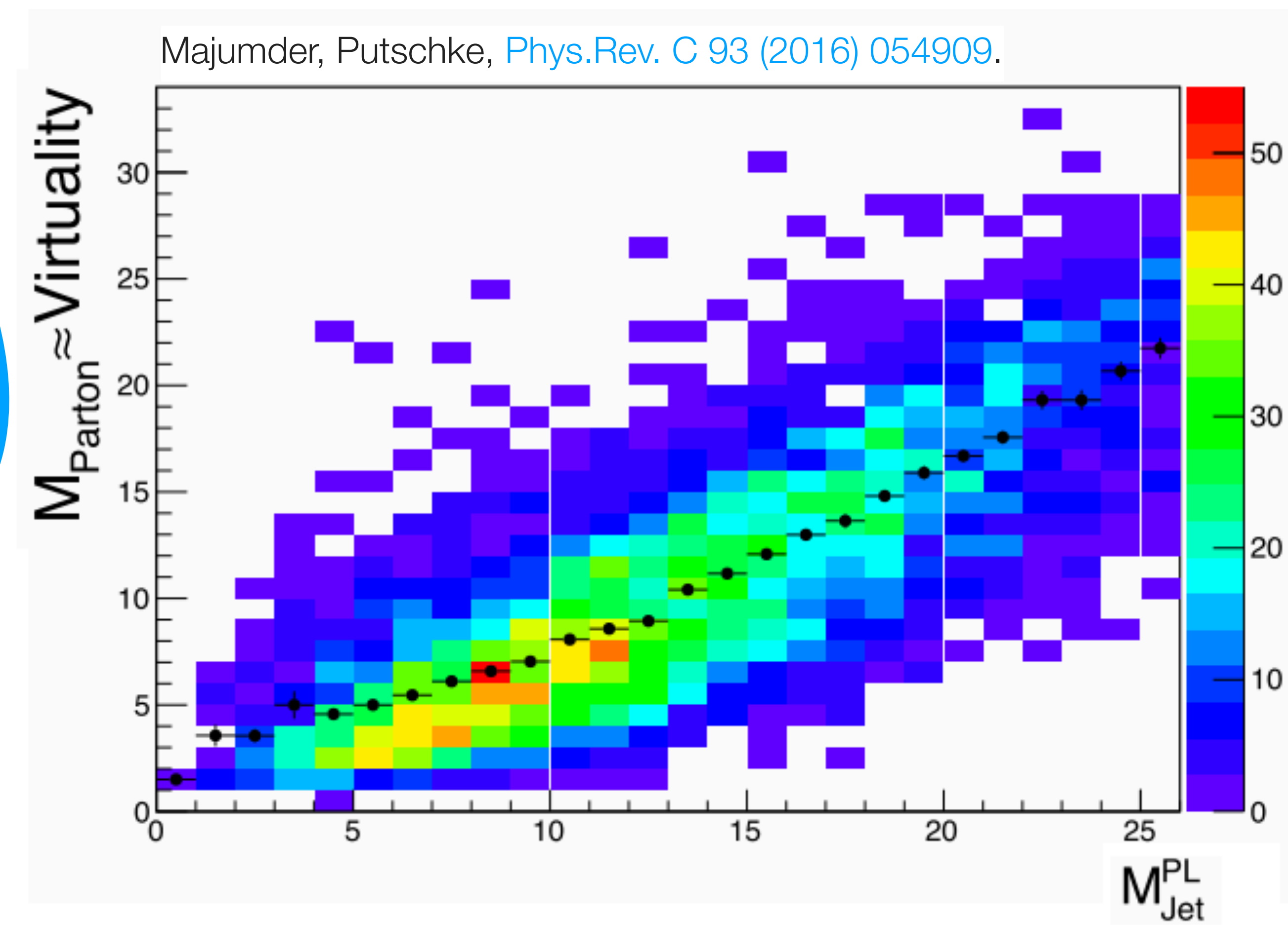


Jet production is calculable in pQCD, over orders of magnitude from RHIC to LHC

But this says little about the *substructure* of the jets

Jet mass





[no hadronization here - would smear correlation]

- *Partonic mass, M_p*: magnitude of 4-momentum - between 0 and scale, Q

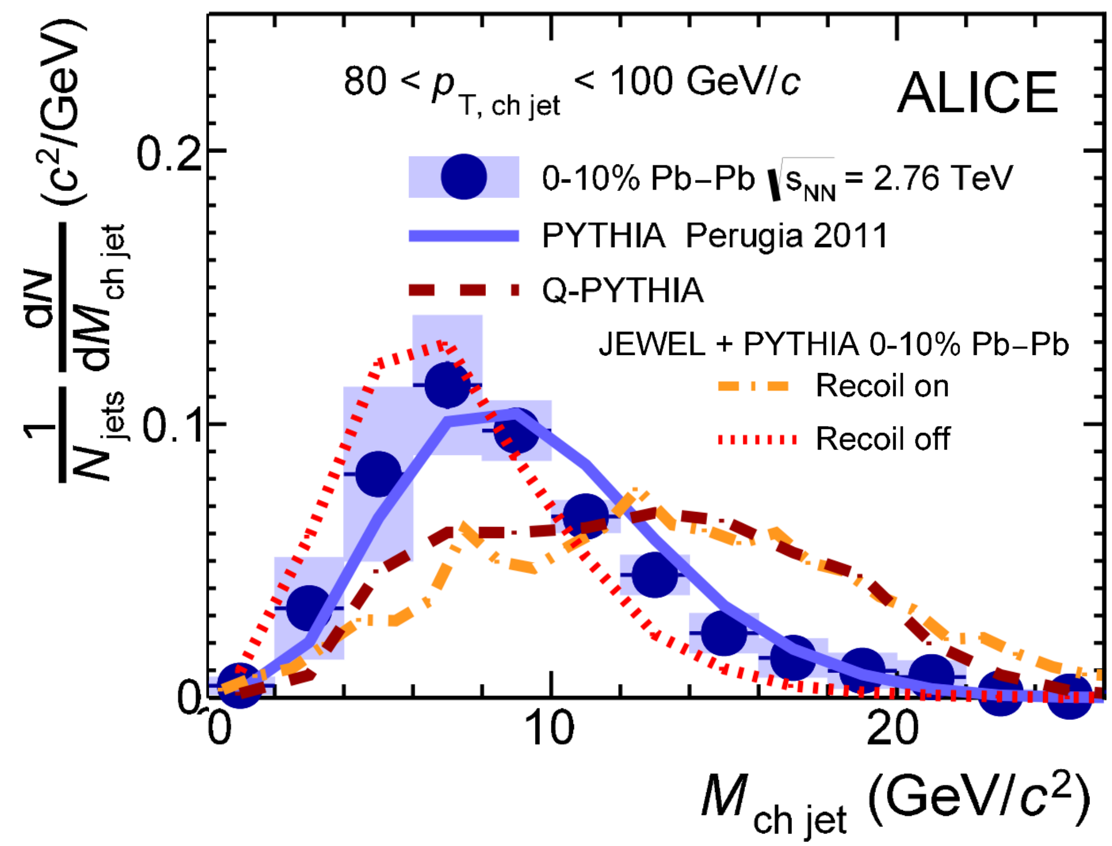
- *Reconstructed jet mass, M*: magnitude of constituent 4-momentum sum for given R

What we measure
[~ initial hard parton virtuality!]

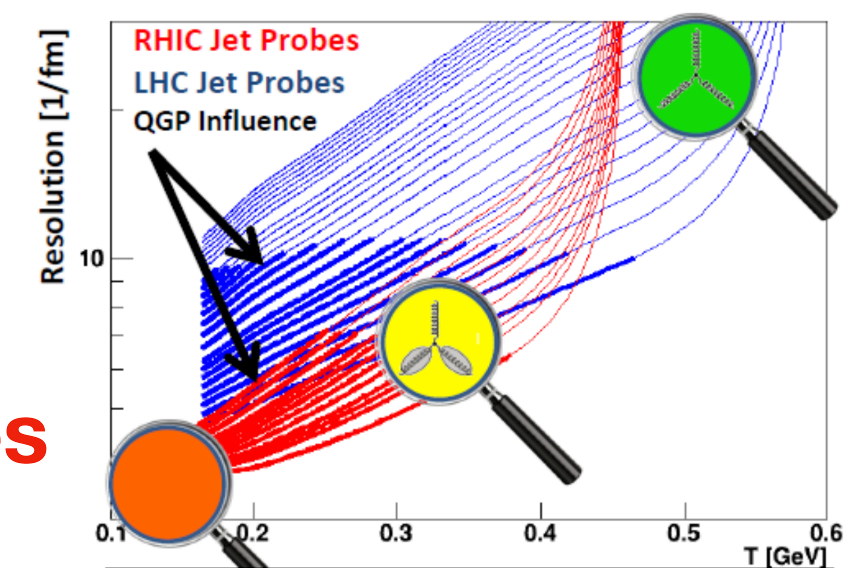
Motivation - Heavy Ion Collisions

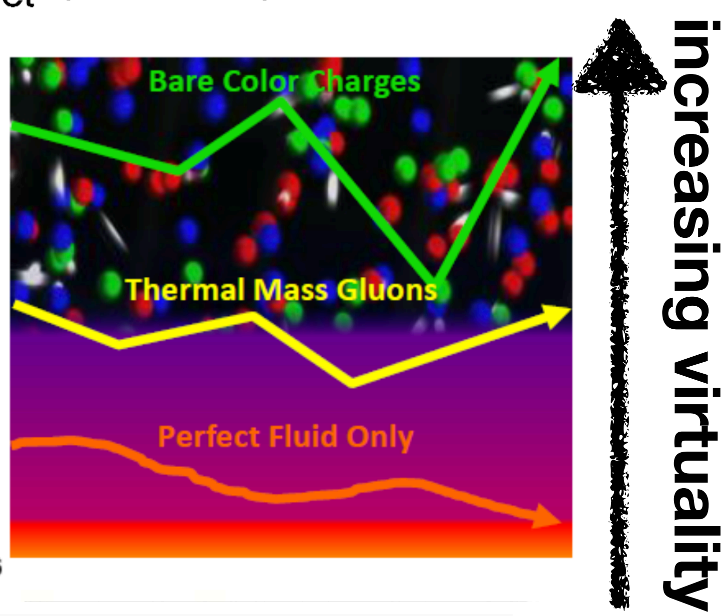
Recent ALICE AA measurement: mass is sensitive to differing implementations of partonic energy loss

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



jet mass ~ virtuality ~ resolution → jets with different masses resolve medium at different scales





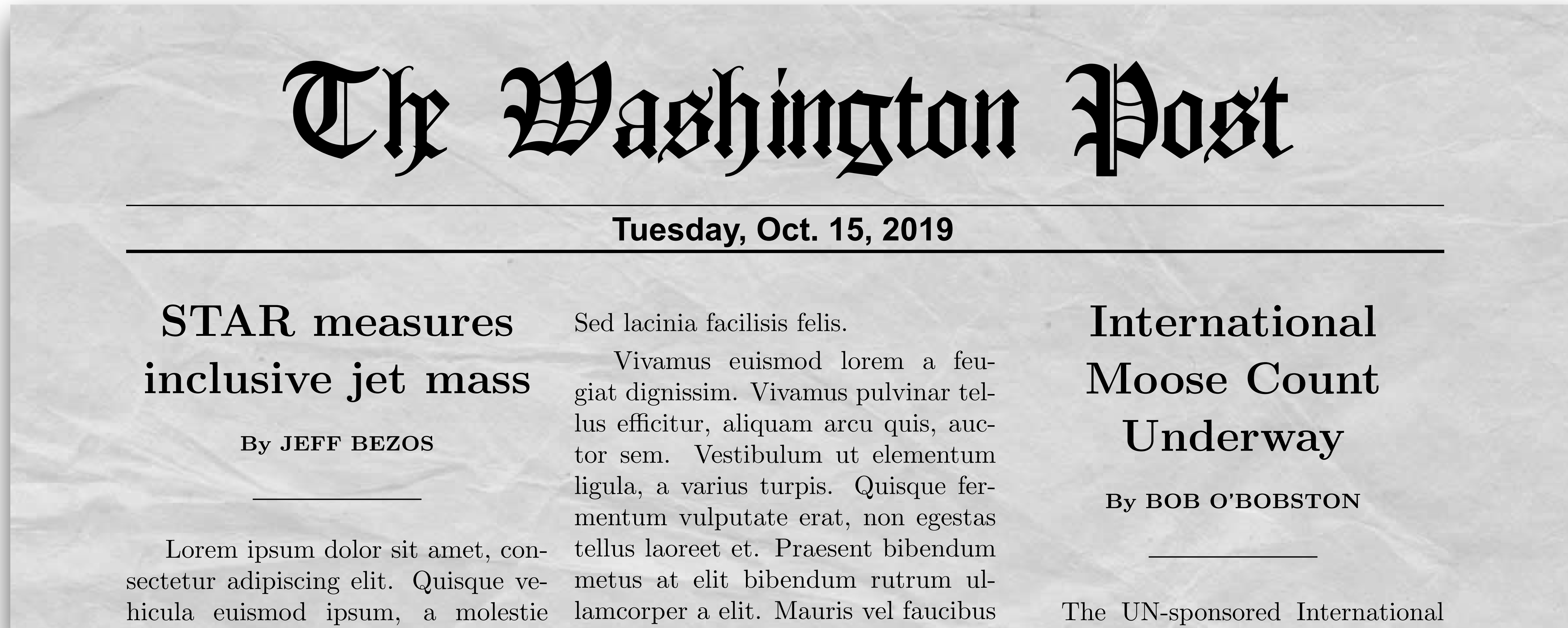
Reaching for the Horizon: The 2015 Long Range Plan for Nuclear Science

Motivation - pp Collisions

Measurements done at LHC[1-7]
No measurement yet at RHIC!
→ further tune MCs

Baseline for future AA studies

[1]ATLAS, J. High Energ. Phys. 05 (2012) 128
[2]ATLAS, Phys.Rev.Lett. 121 (2018) no.9, 092001
[3]ATLAS, tech. rep. ATLAS-CONF-2018-014 (2018)
[4]CDF, Phys.Rev. D 85 (2012) 091101
[5]CMS, J. High Energ. Phys. 05 (2013) 090
[6]CMS, Eur.Phys.J. C 77 (2017) no.7, 467
[7]CMS, J. High Energ. Phys. 10 (2018) 161


The Washington Post

Tuesday, Oct. 15, 2019

STAR measures inclusive jet mass

By JEFF BEZOS

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Sed lacinia facilisis felis.

Vivamus euismod lorem a feugiat dignissim. Vivamus pulvinar tellus efficitur, aliquam arcu quis, auctor sem. Vestibulum ut elementum ligula, a varius turpis. Quisque fermentum vulputate erat, non egestas tellus laoreet et. Praesent bibendum metus at elit bibendum rutrum ullamcorper a elit. Mauris vel faucibus

International Moose Count Underway

By BOB O'BOBSTON

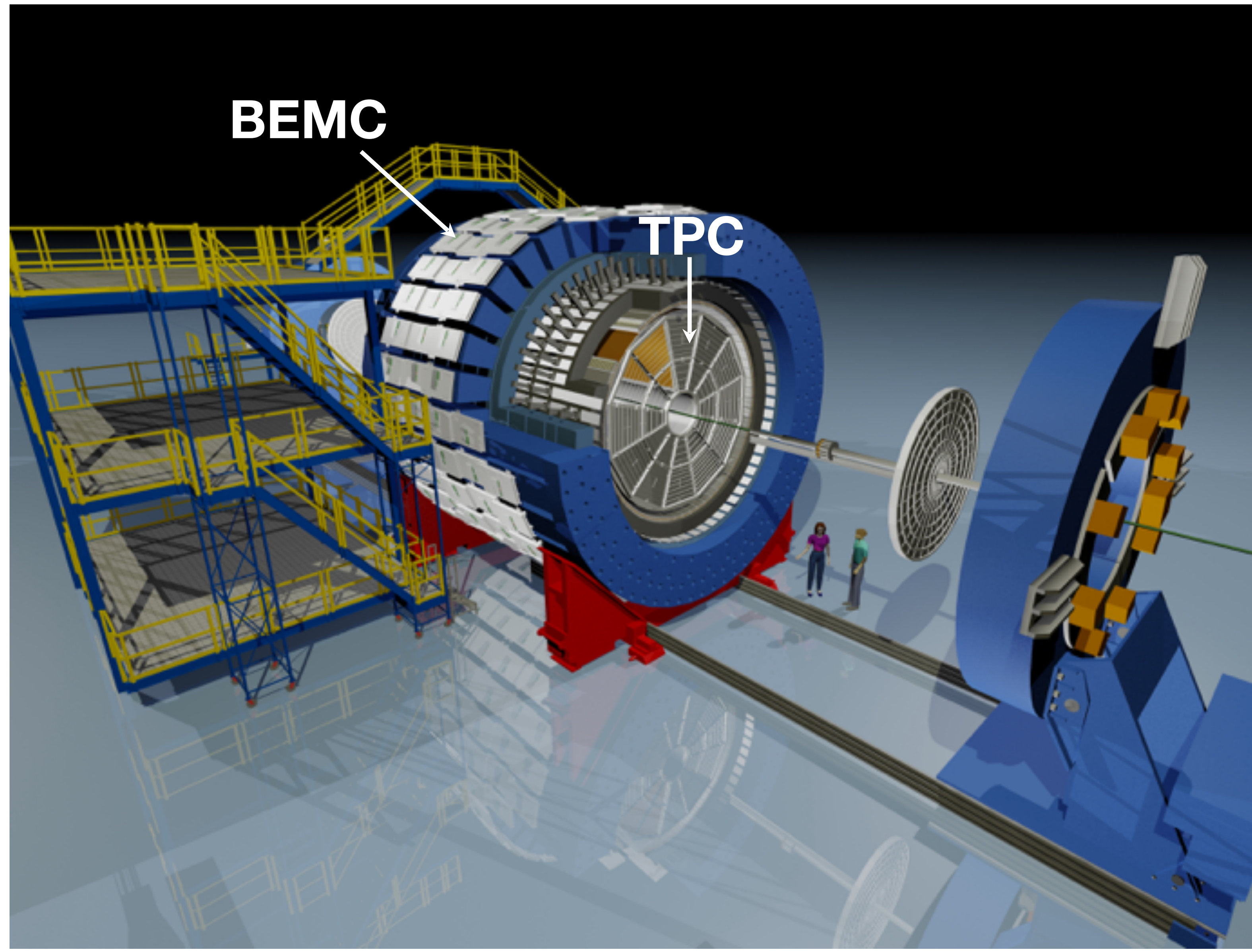
The UN-sponsored International

The Solenoidal Tracker at RHIC (STAR)

Relativistic Heavy Ion Collider (RHIC) collides pp beams at $\sqrt{s}$ = 200 GeV

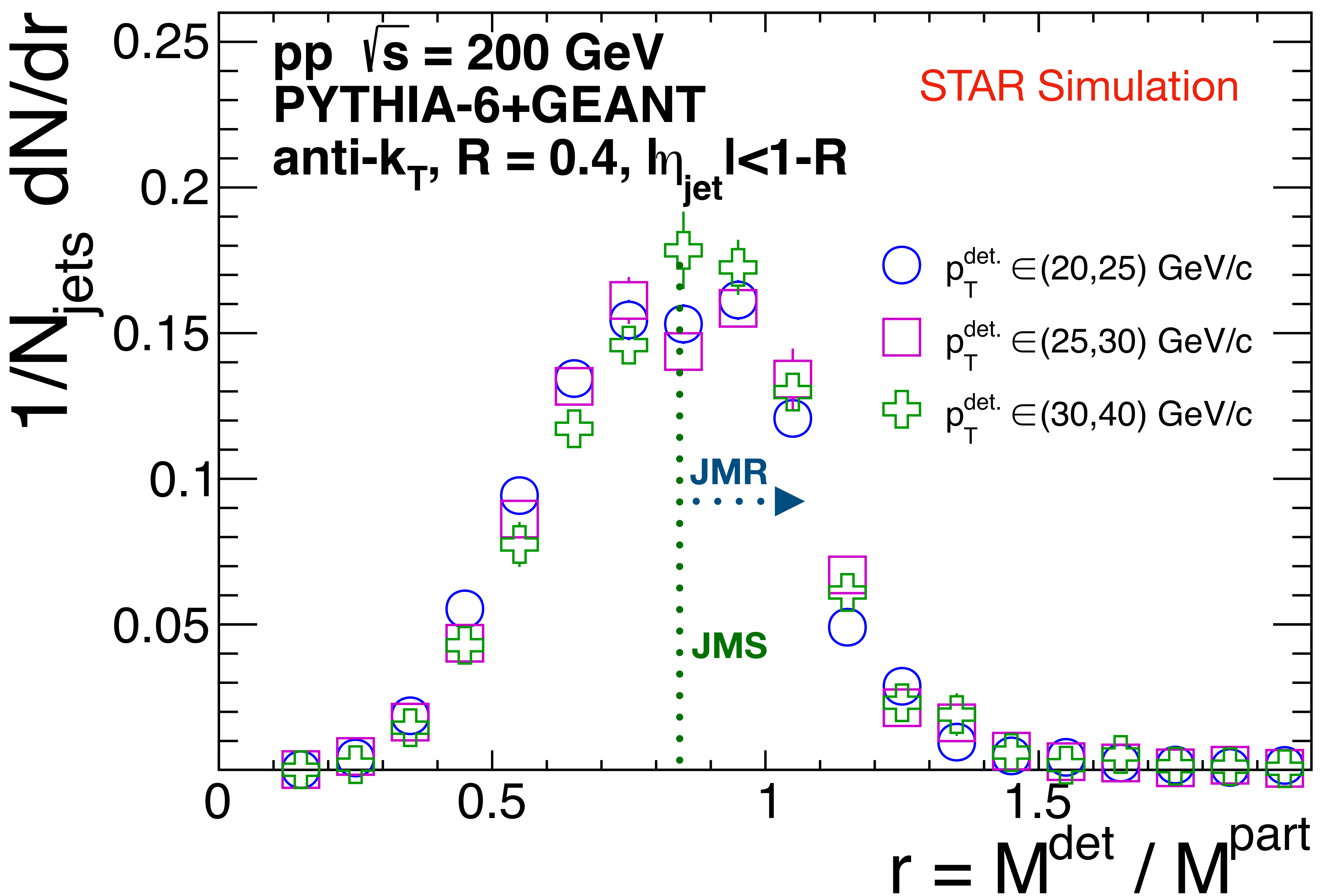
Time projection chamber, (TPC): momenta of **charged** tracks

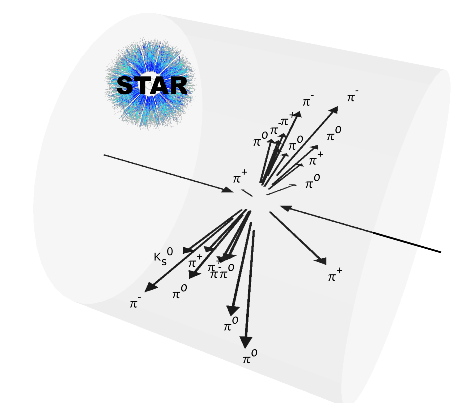
Barrel electromagnetic calorimeter, (BEMC): **neutral** energy deposits
+ used as online trigger
(Jet Patch: in 1.0x1.0 area in η-ϕ sum of E_T > 7.4 GeV)



→ Capable of measuring *charged & neutral* energy in a jet

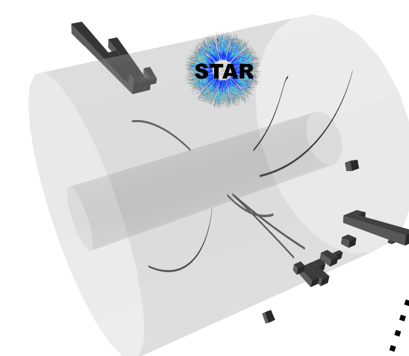
Jet mass resolution





“particle-level”:
PYTHIA-6
with RHIC tune

“detector-level”:
PYTHIA-6+GEANT-3
with STAR detector simulation



Tai Sakuma

STAR Collaboration, Phys.Rev. D 100 (2019) no.5, 052005

Jet Mass Scale shift from unity: mostly from track loss

Jet Mass Resolution p_T-independent! Helps the unfolding

Unfolding

Correct for detector effects encompassed by response matrix *R* with *D* = *RP* (*D* = detector-level, *P* = particle-level). Matrix inversion to obtain *P*.

Procedure: Iterative Bayesian from **RooUnfold**.

M dependent on p_T → 2D unfolding → 4D response

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

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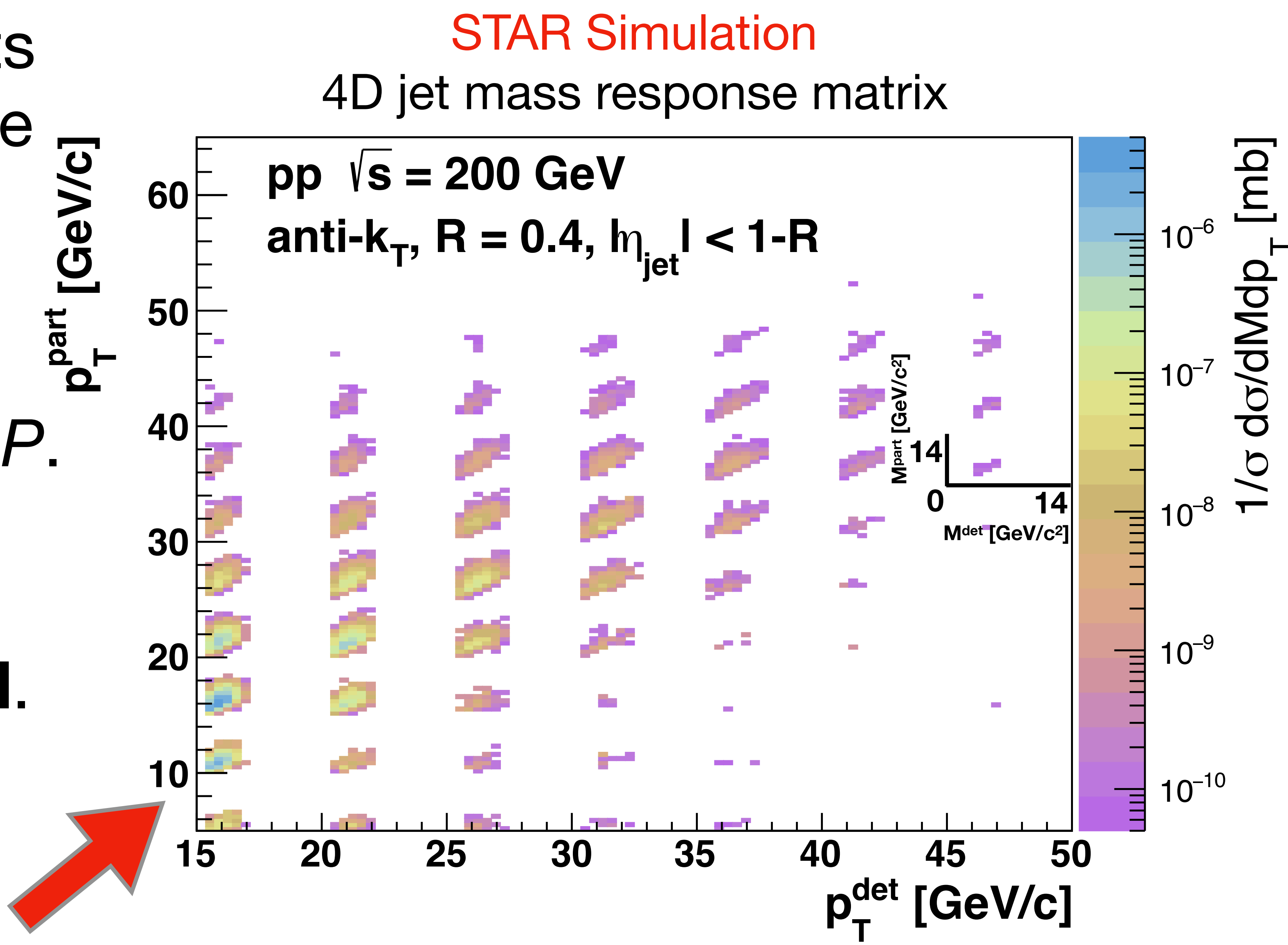
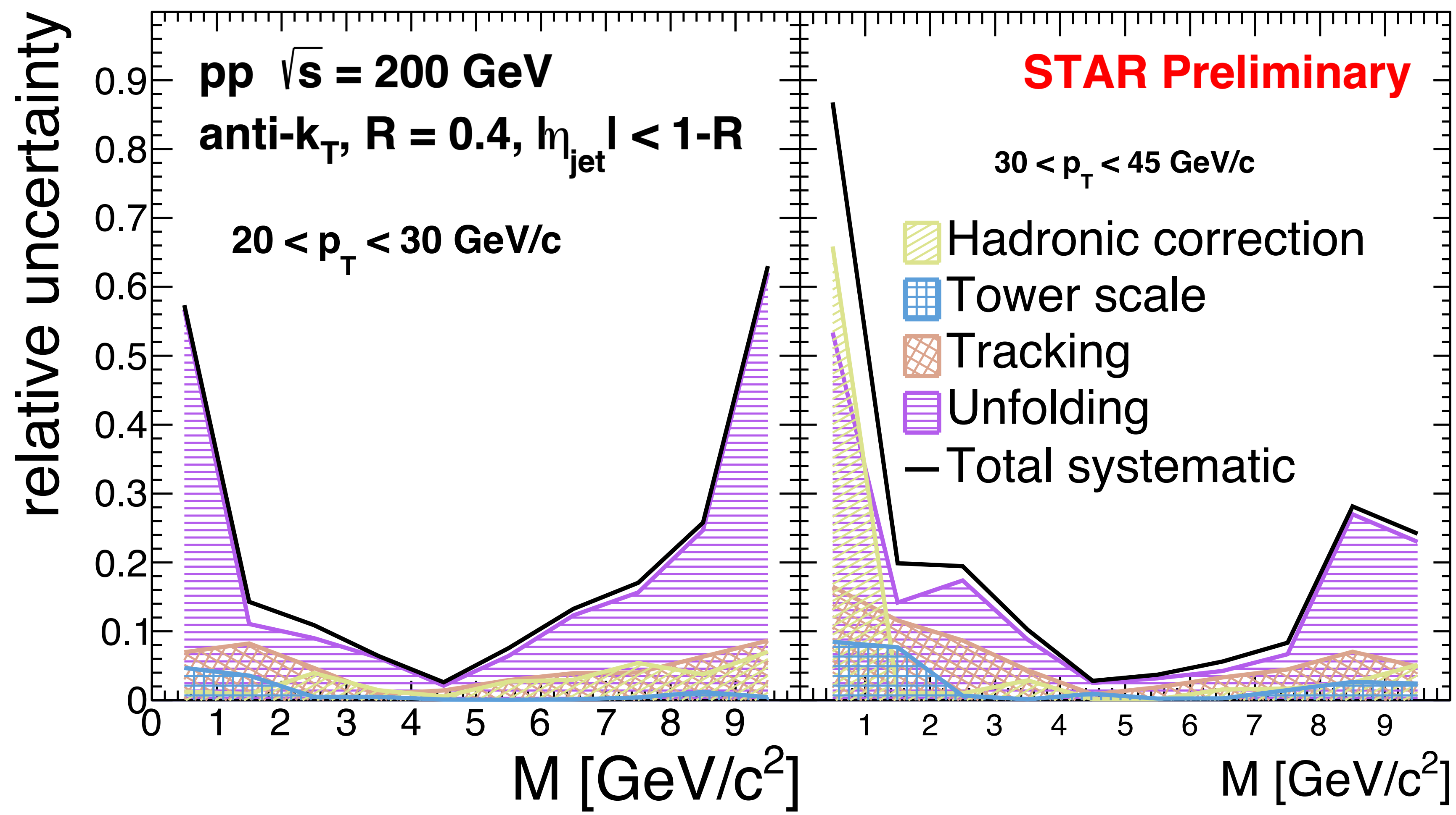


Tim Adye in Proceedings, PHYSTAT 2011, CERN, edited by Prosper and Lyons, CERN-2011-006, pp. 313-318.

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]
- **Hadronic correction** variation: from nominal 100%[2] to 50%
- **Tower gain** uncertainty of (+)3.8%[1]

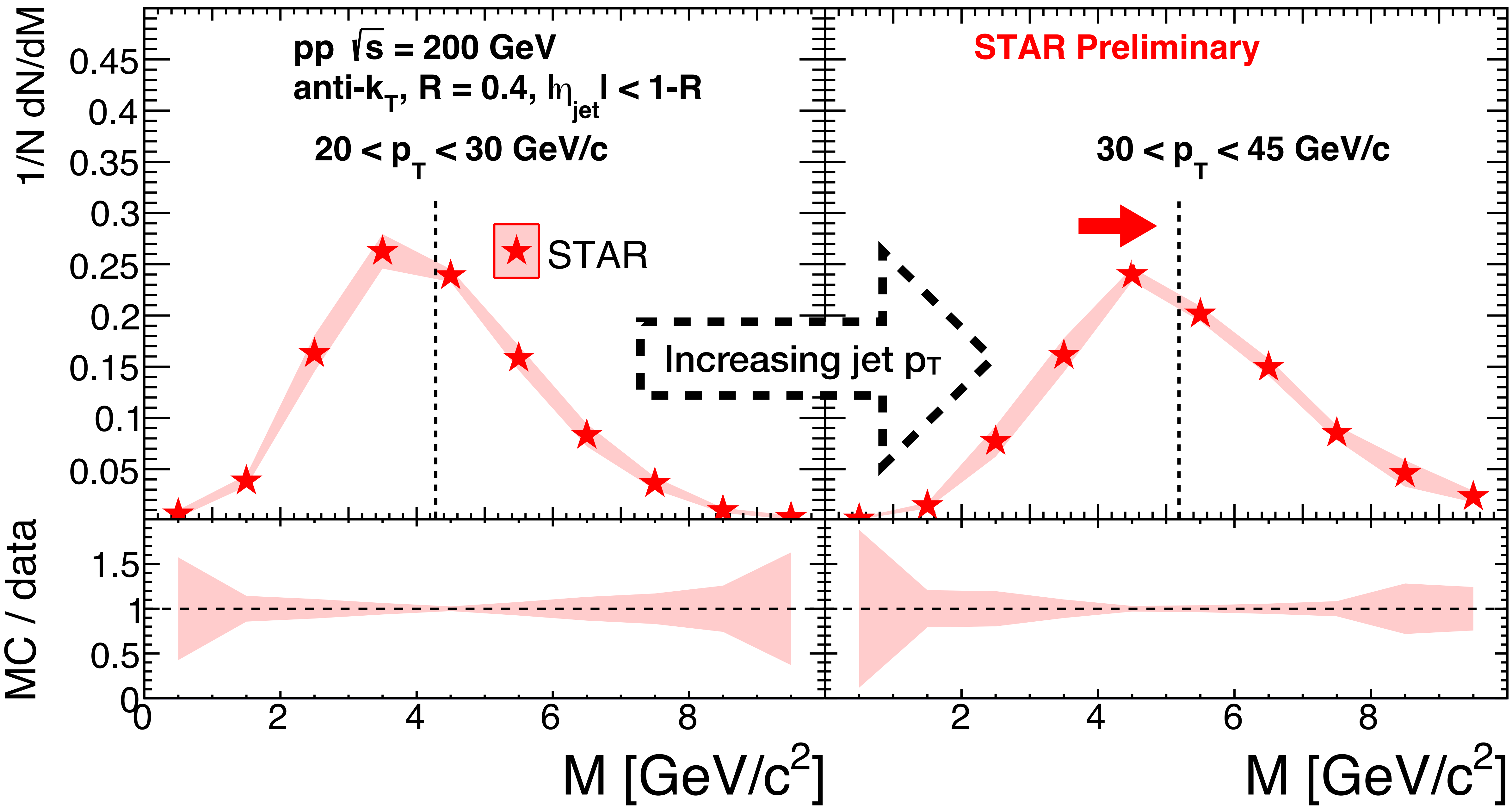


Total systematic uncertainty is a quadrature sum of the four sources

[1]STAR Collaboration, Phys.Rev. D 100 (2019) no.5, 052005

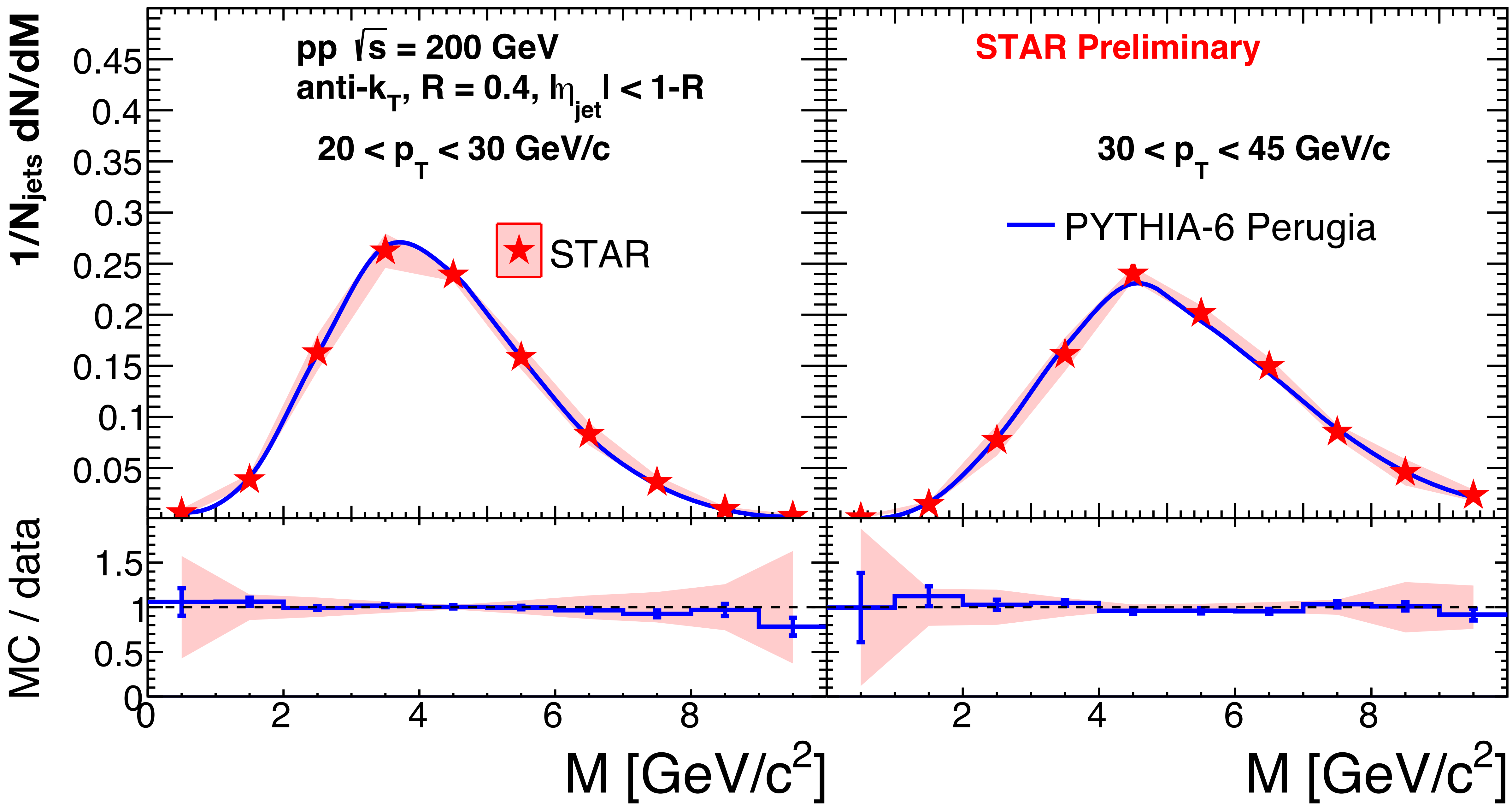
[2]STAR Collaboration, Phys.Rev.Lett. 115 (2015) no.9, 092002

p_T scan



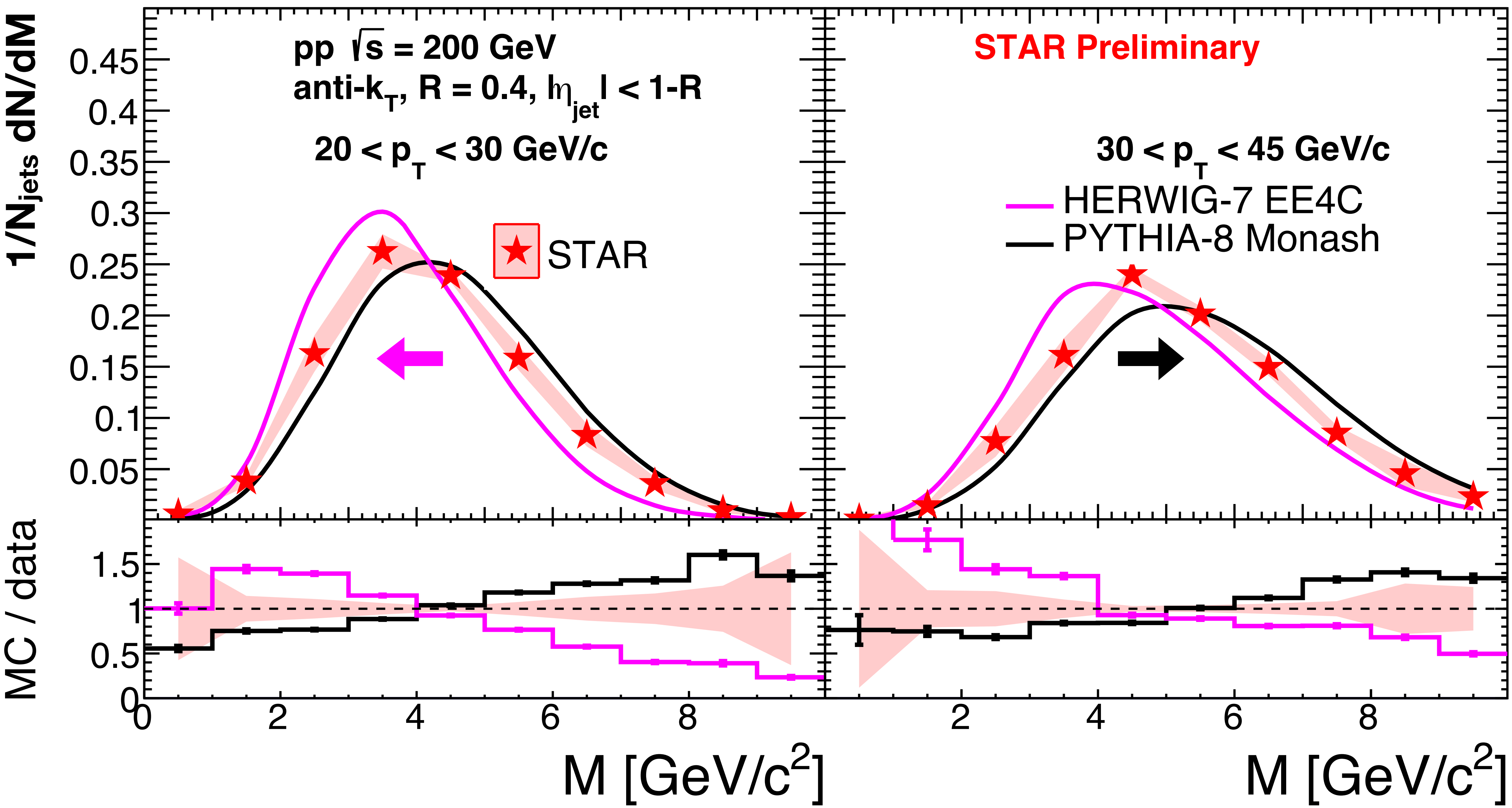
From pQCD, jet p_T increase → increased phase space to radiate → increased mass

p_T scan



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

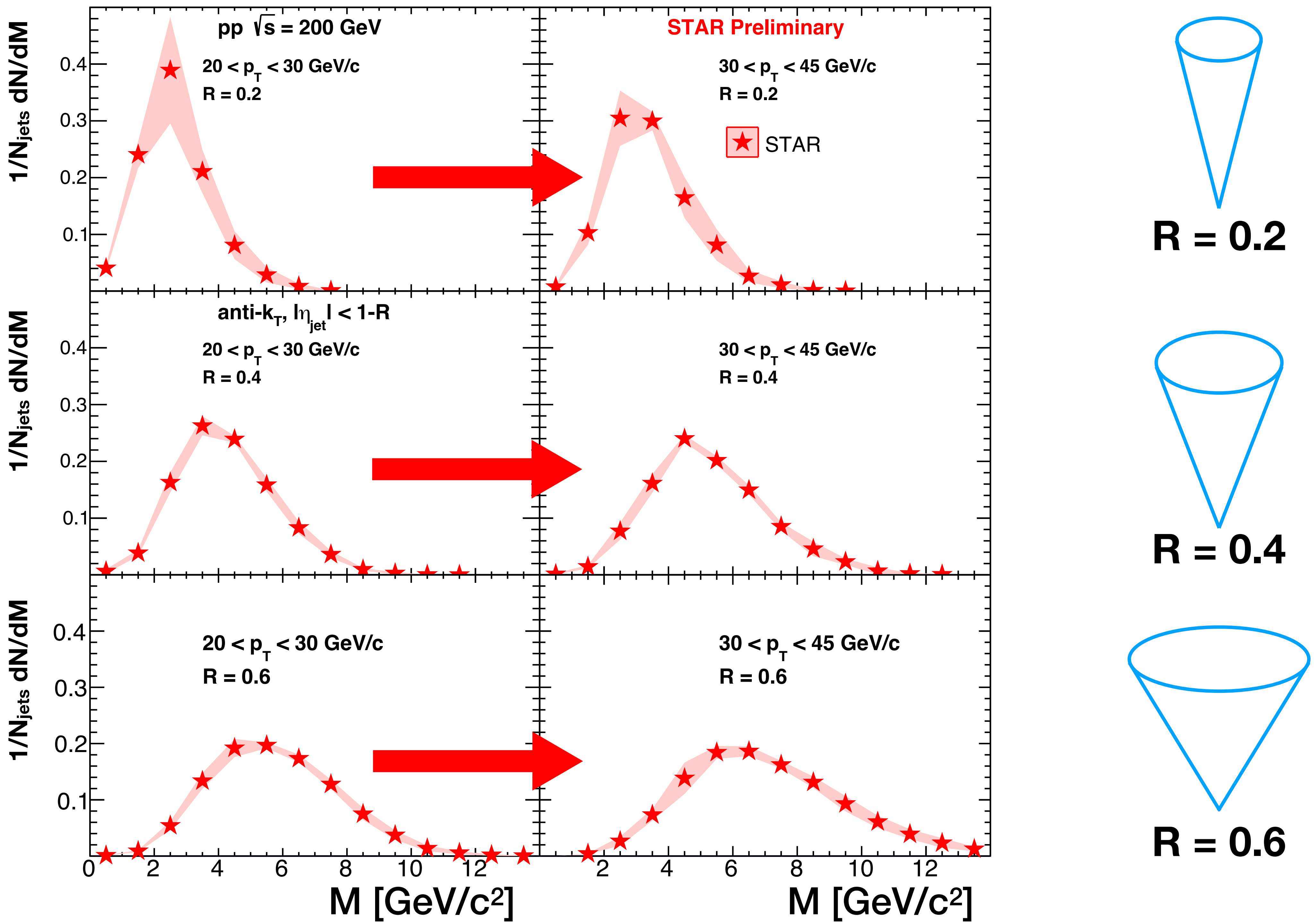
p_T scan



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

(EE4C) (Monash)

Radial scan



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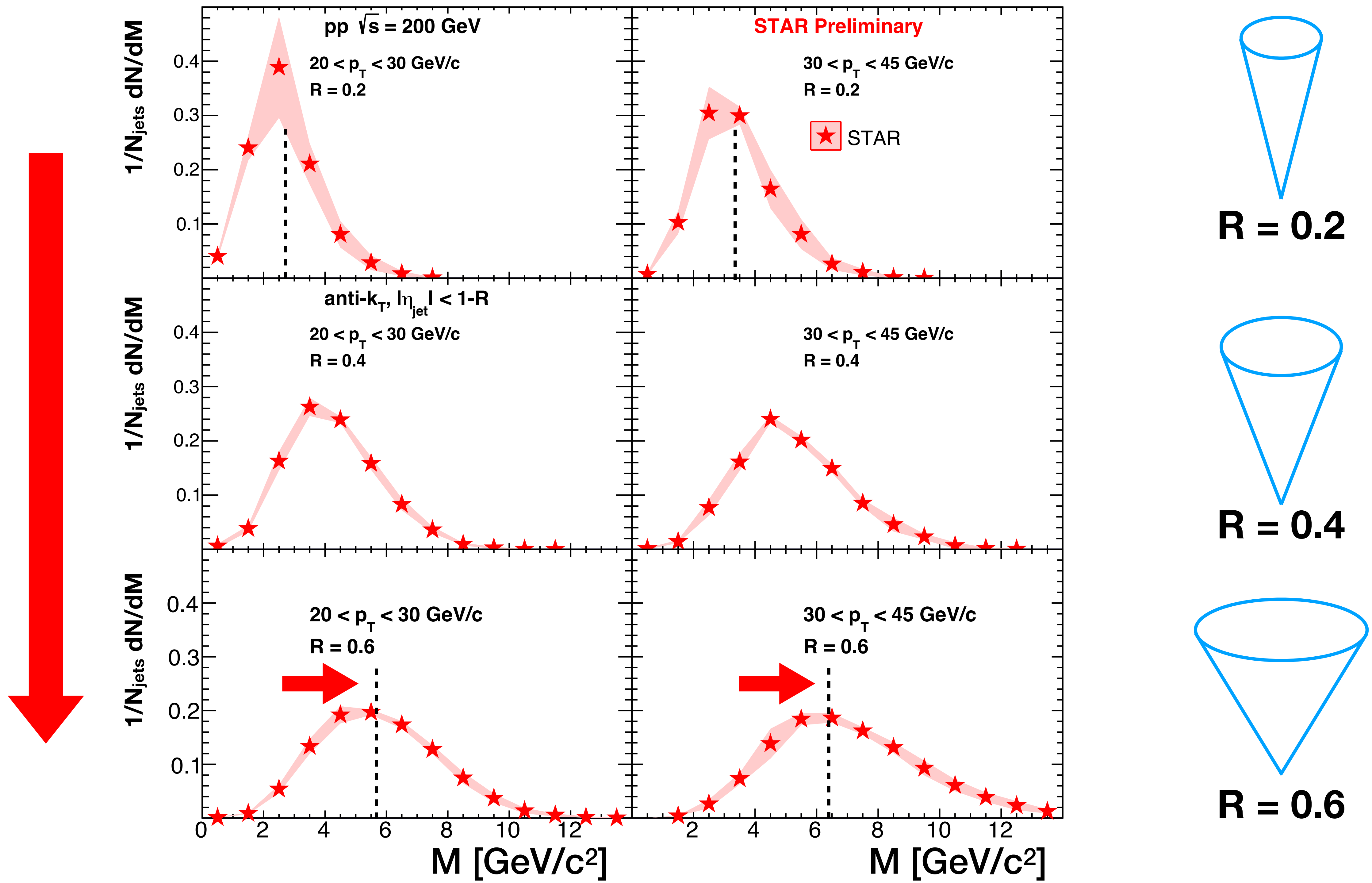
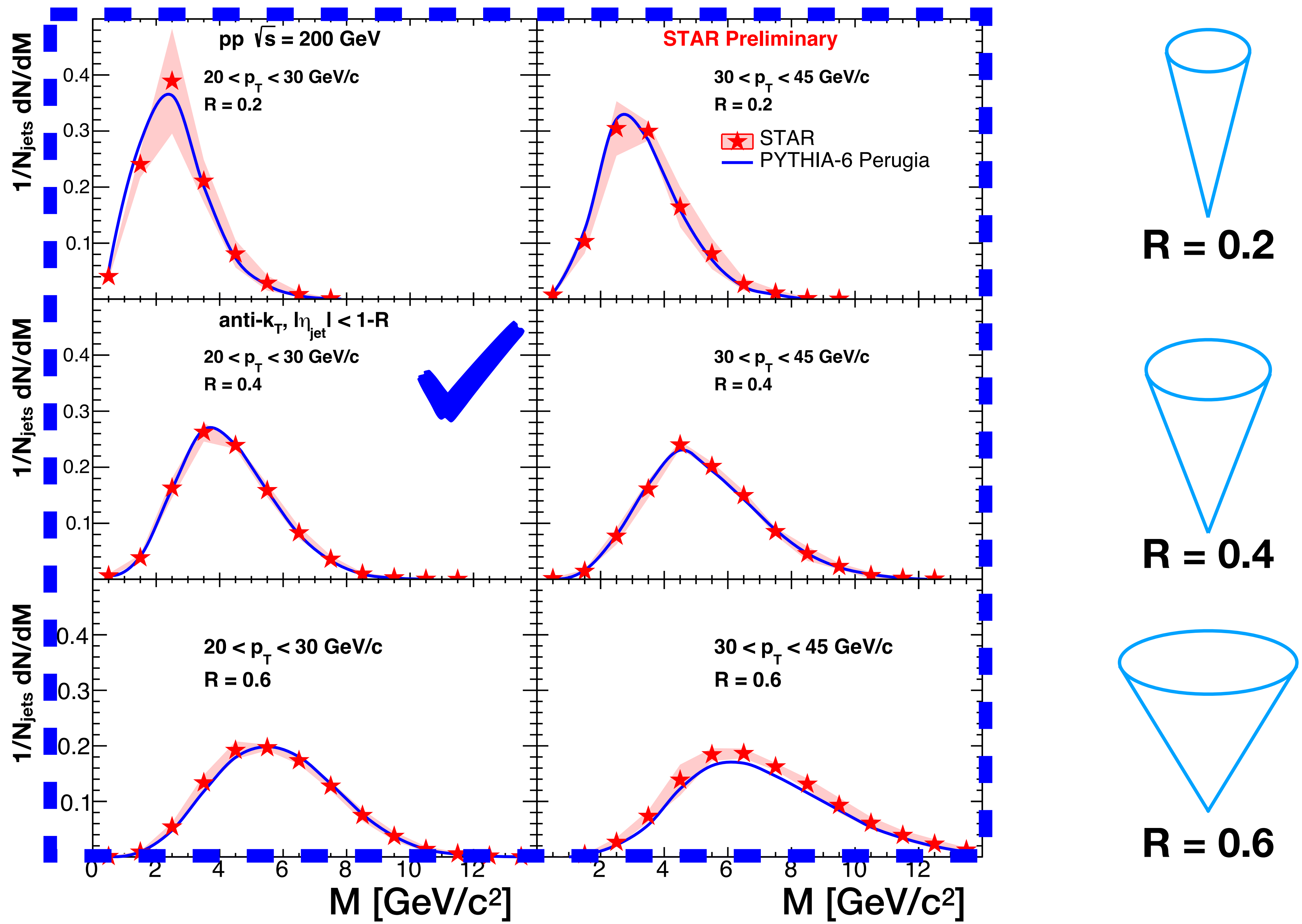


As radius increases, jets encompass more wide-angle radiation → increased mass

Radial scan



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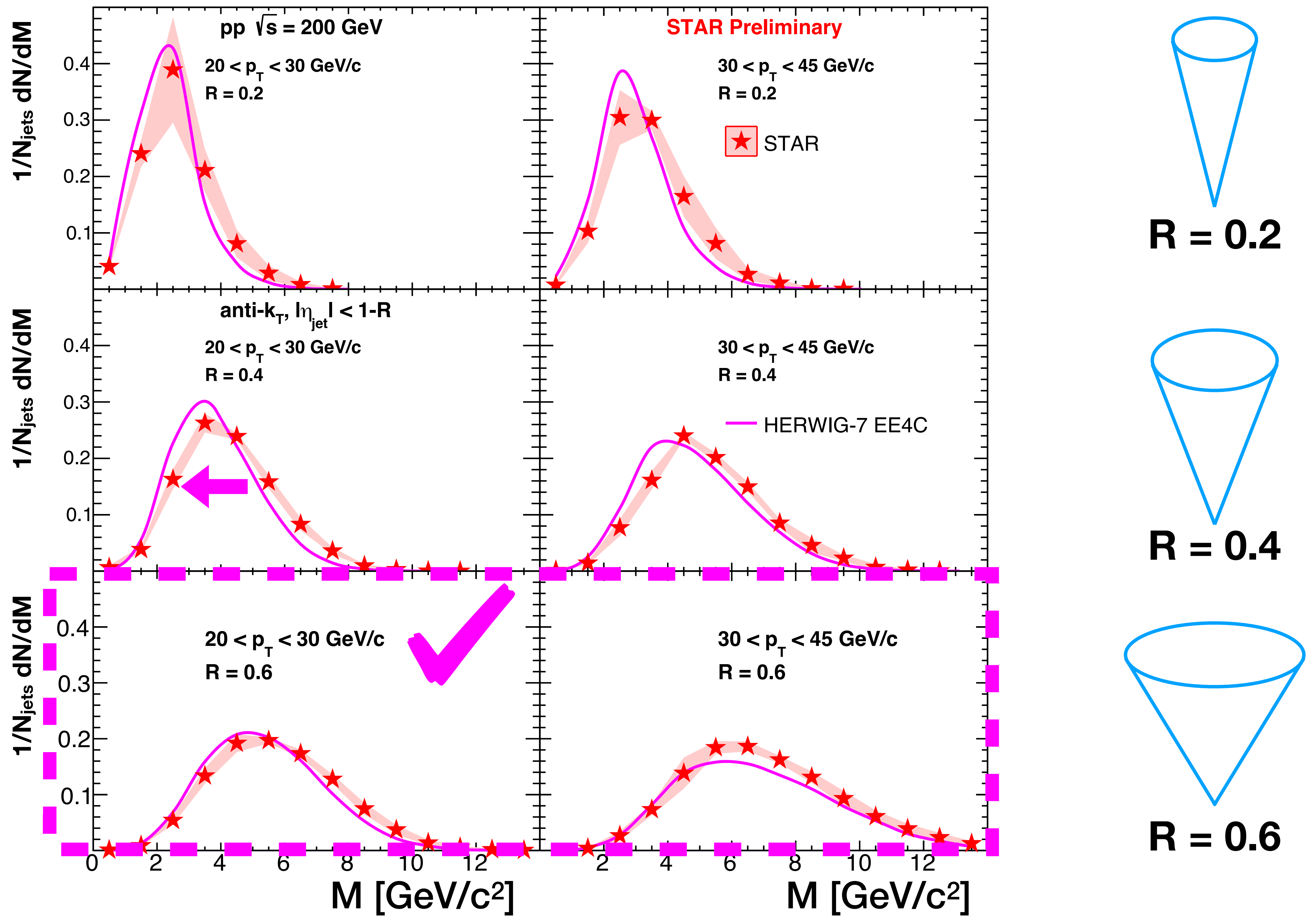
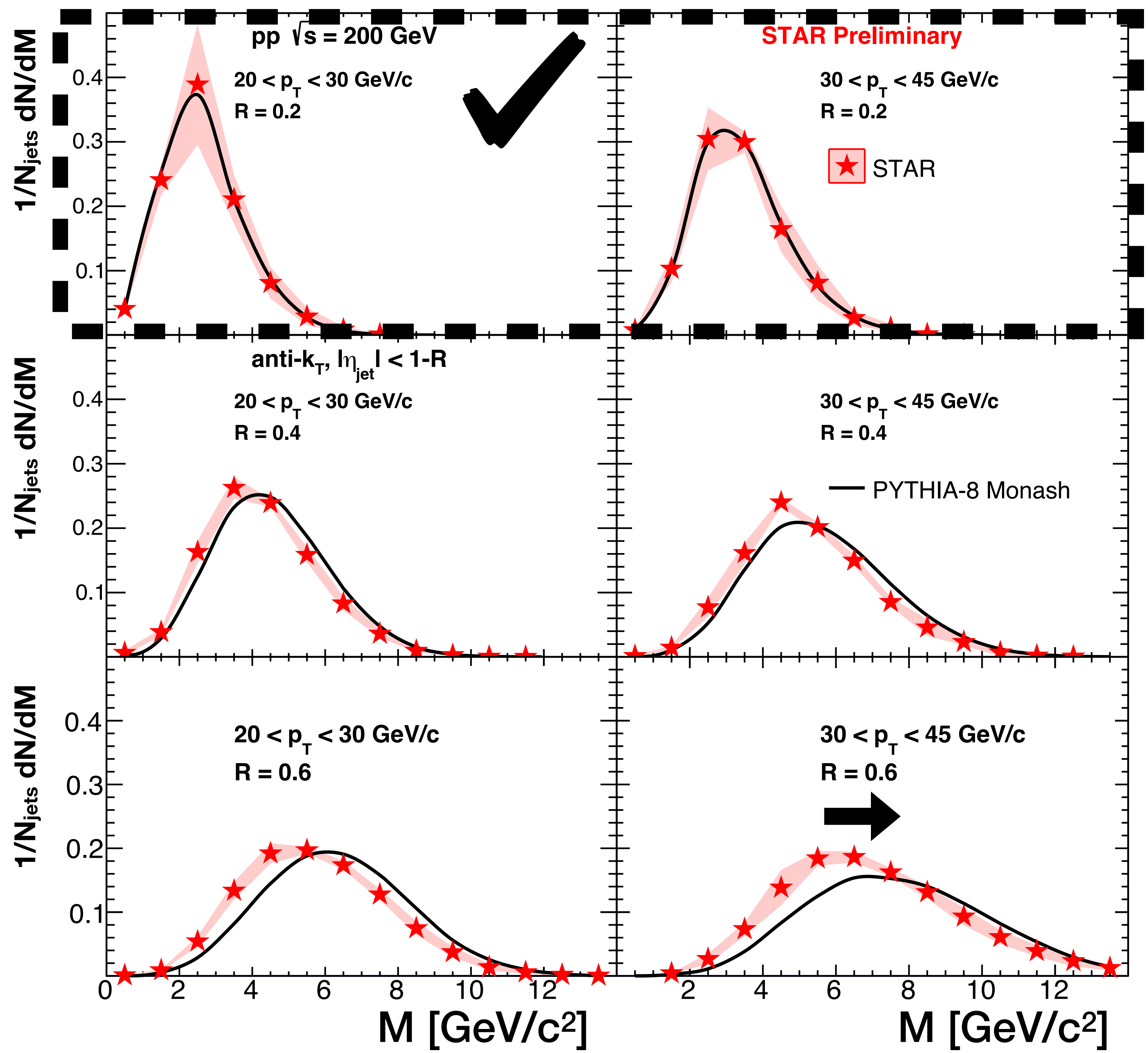
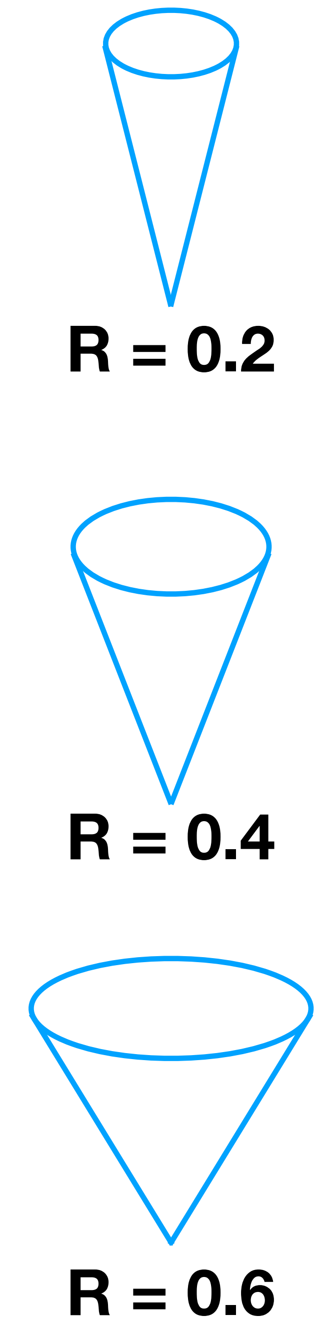


HERWIG-7 under-predicts for small R, better agreement with data by R = 0.6

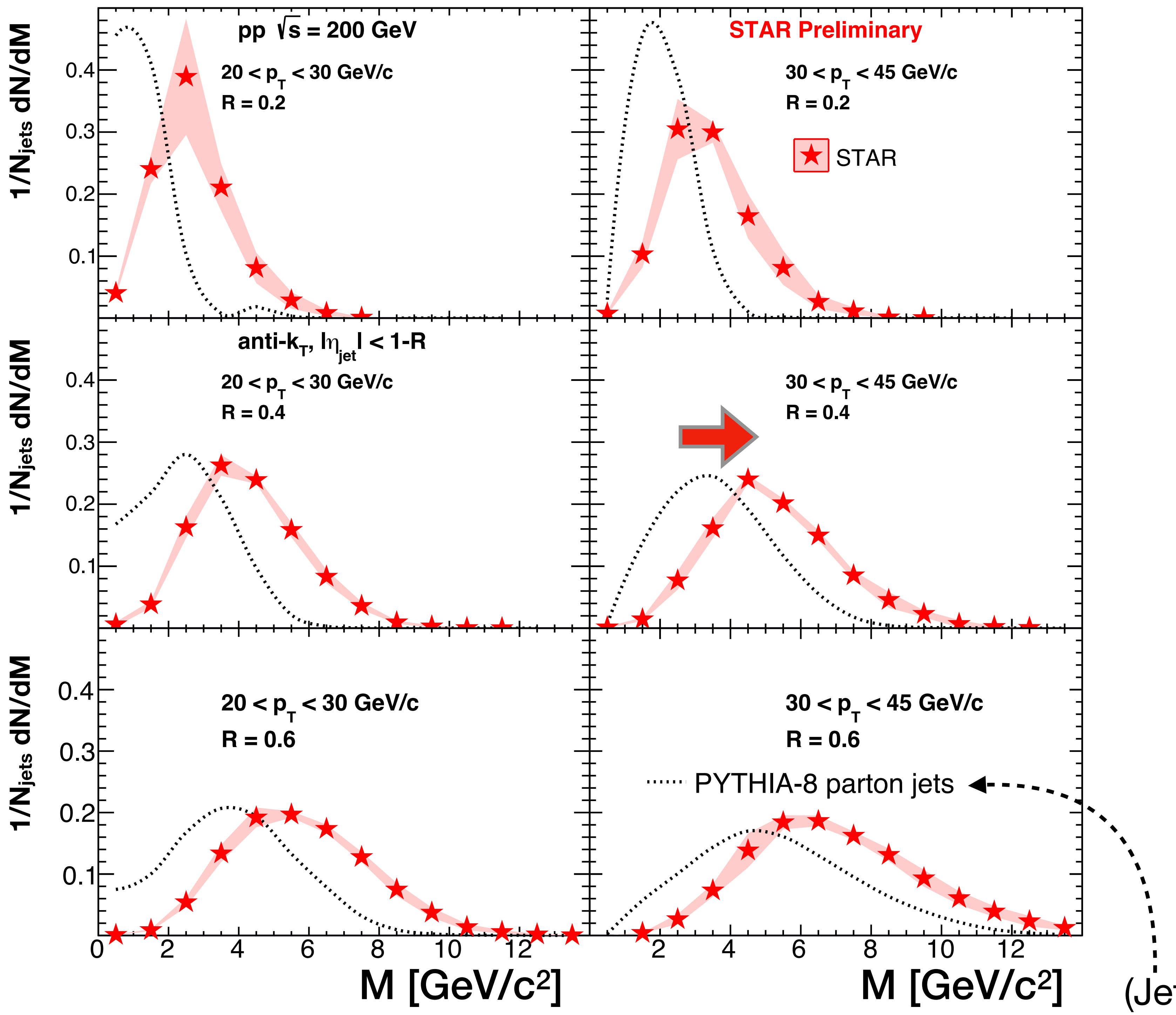
Radial scan

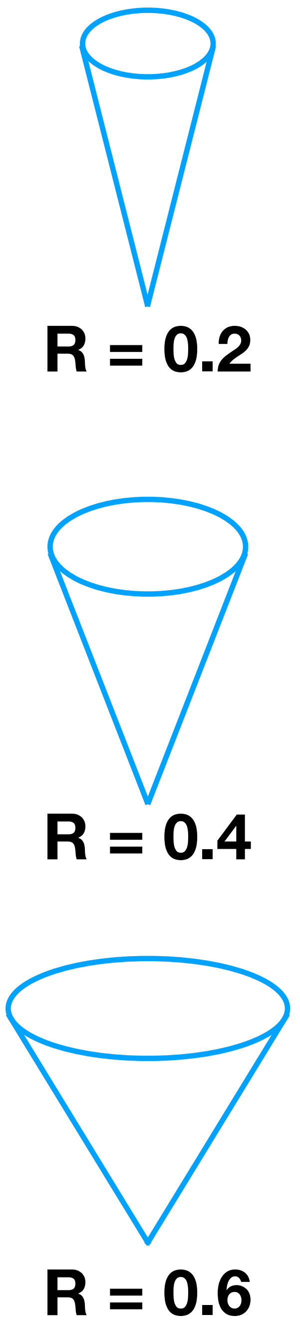




PYTHIA-8 is consistent with data for R = 0.2, over-predicts more as radius increases

Radial scan



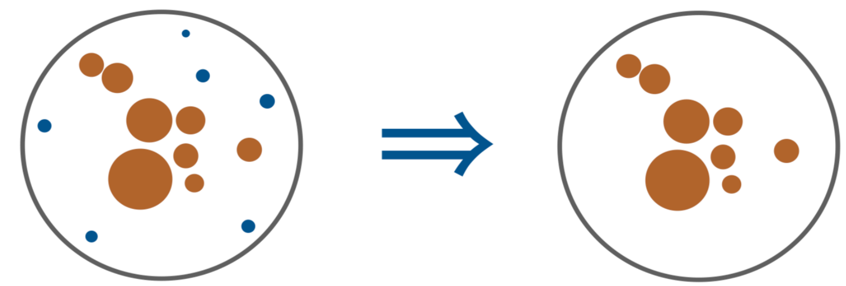


(Jets from PYTHIA events with hadronization = off)

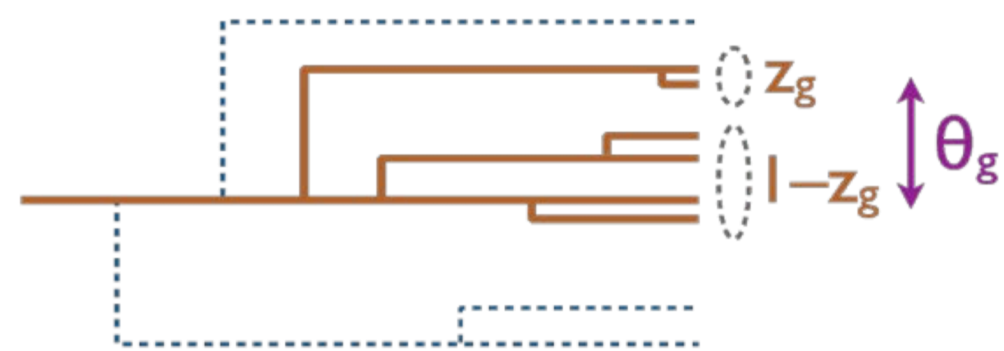
Non-perturbative effects increase the mass

SoftDrop grooming

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



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



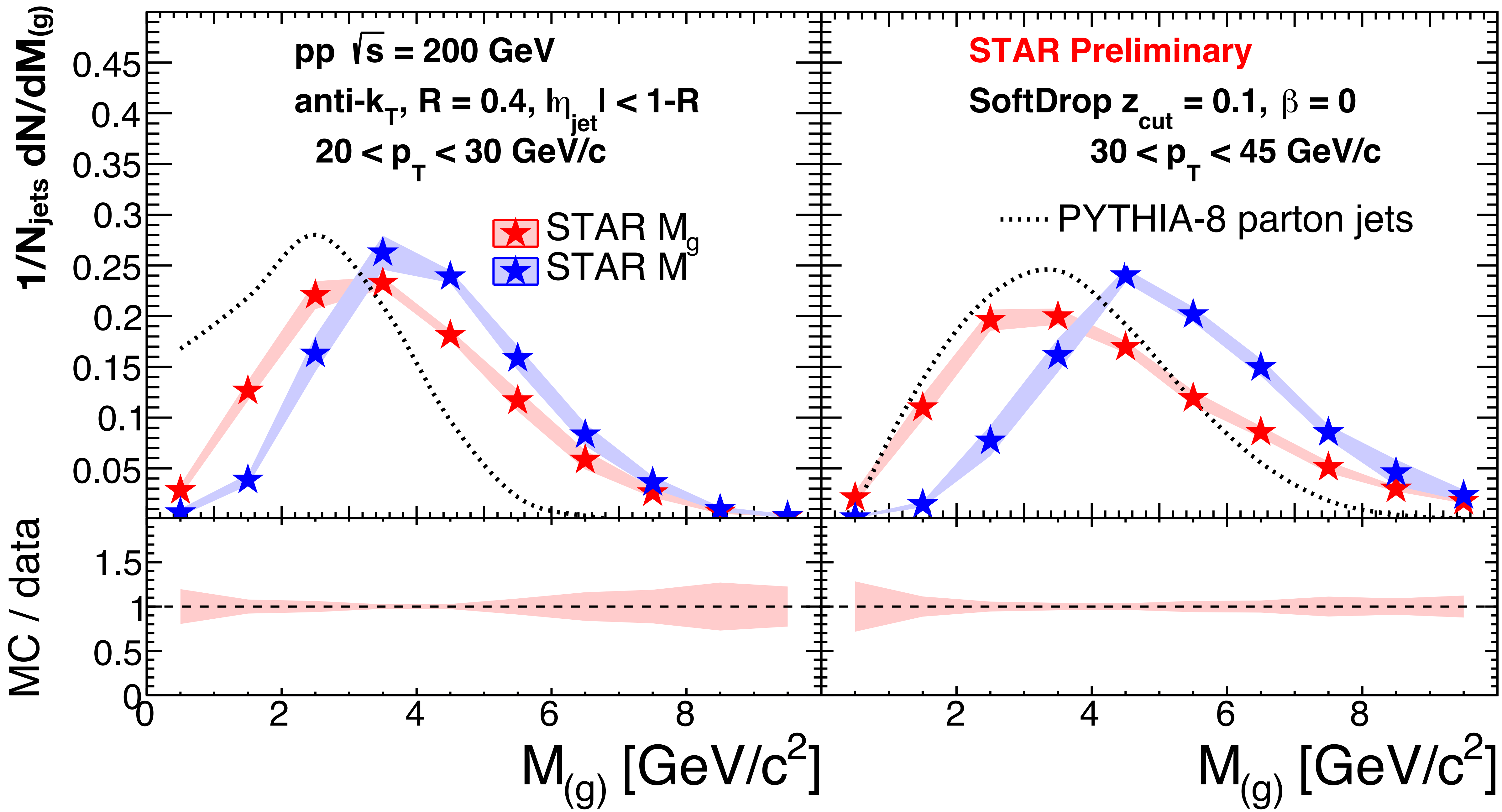
$$z > z_{\text{cut}}\, \theta^{\beta}$$

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

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

Groomed mass

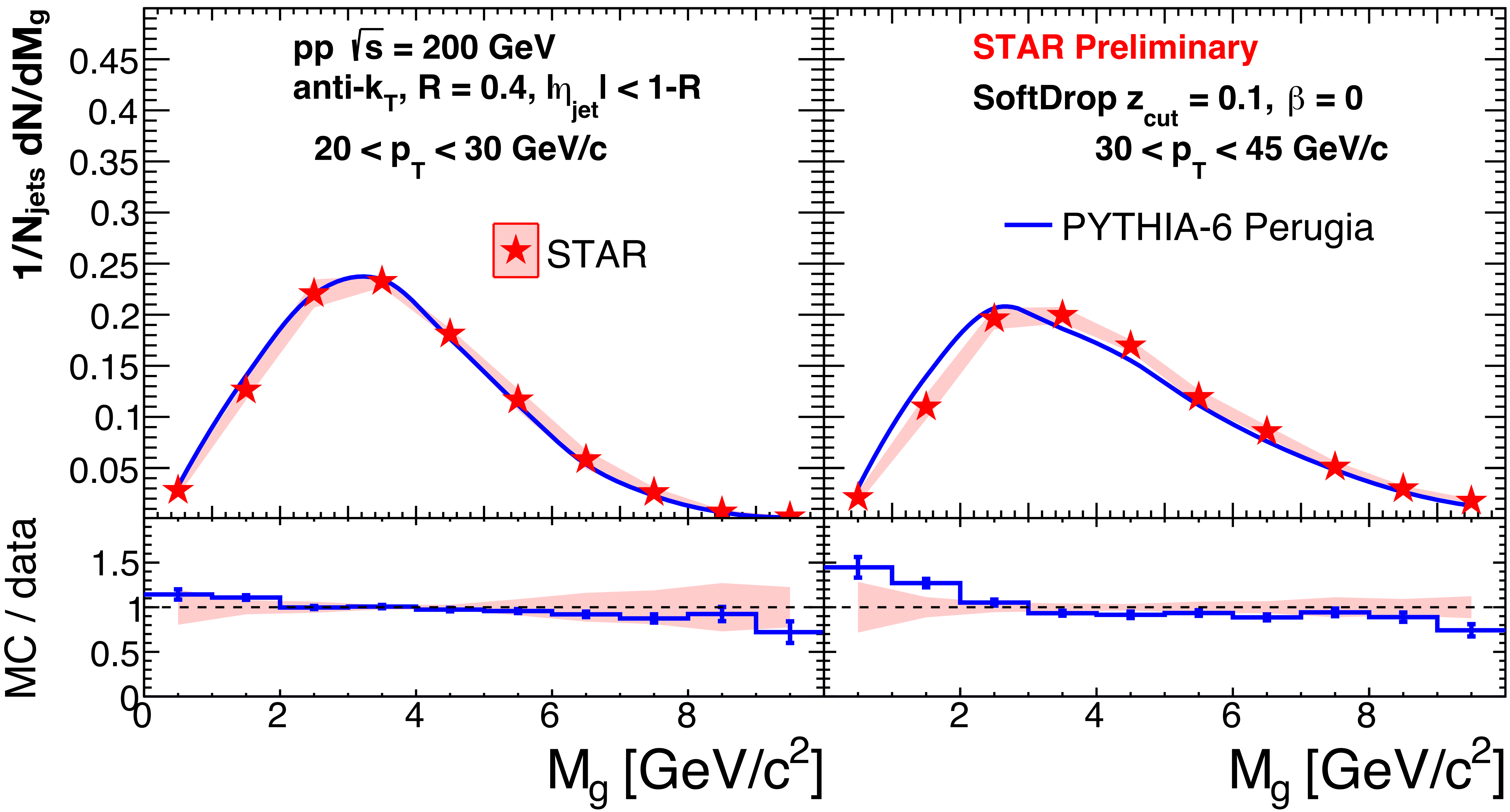
Note: p_T panels are *ungroomed* jet p_T



Grooming suppresses non-perturbative effects - in particular, at higher p_T

Groomed mass

Note: p_T panels are *ungroomed* jet p_T



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

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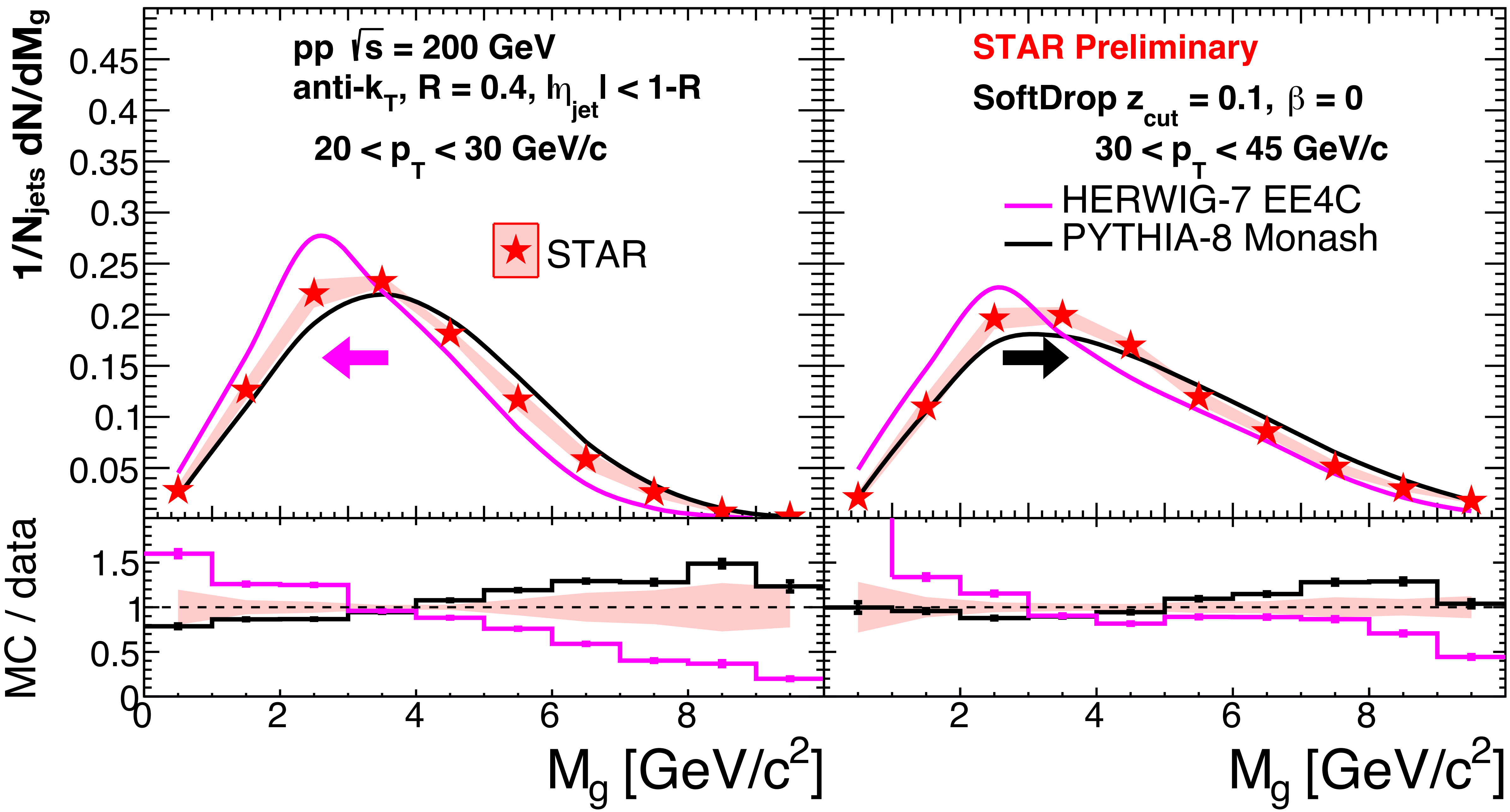

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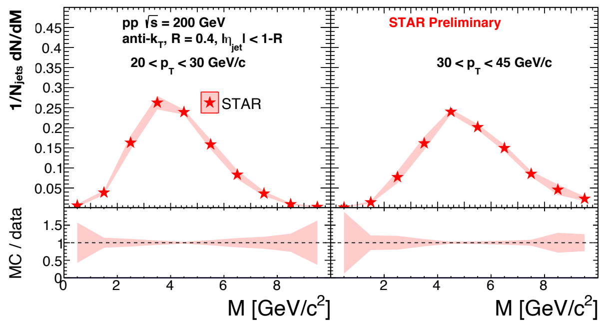
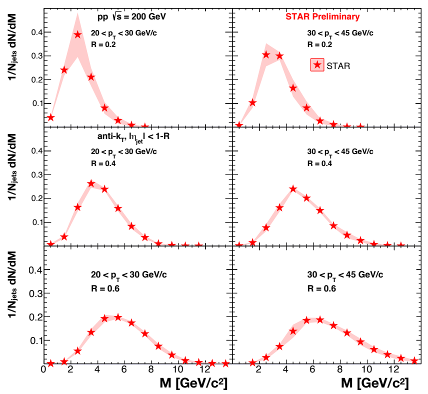
Conclusions

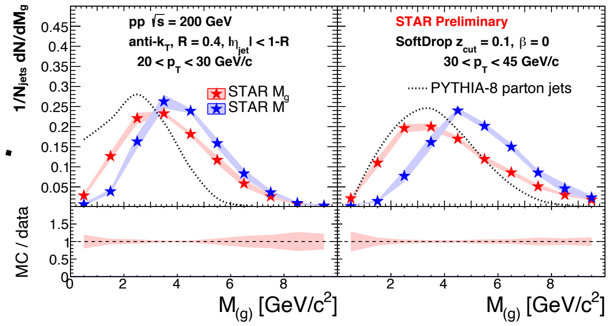
First inclusive jet mass measurements at RHIC



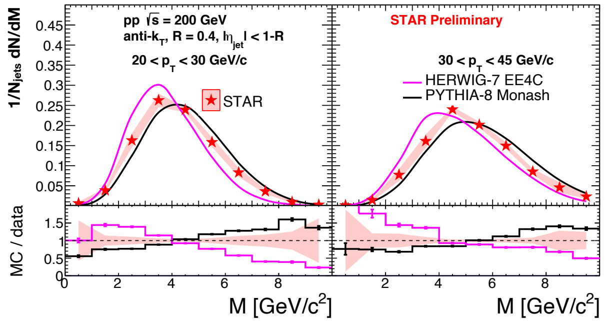
Jet mass increases with increased phase space (jet p_T) and inclusion of more wide-angle soft radiation (jet R), consistent with pQCD expectation



SoftDrop groomed mass is observed to be closer to ungroomed parton level mass



RHIC-tuned MC: data is well-described
LHC-tuned MC: opportunity for further tuning



Next steps: pAu & AuAu, to study cold & hot nuclear matter effects!

Backup

Sudakov structure of jet mass

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

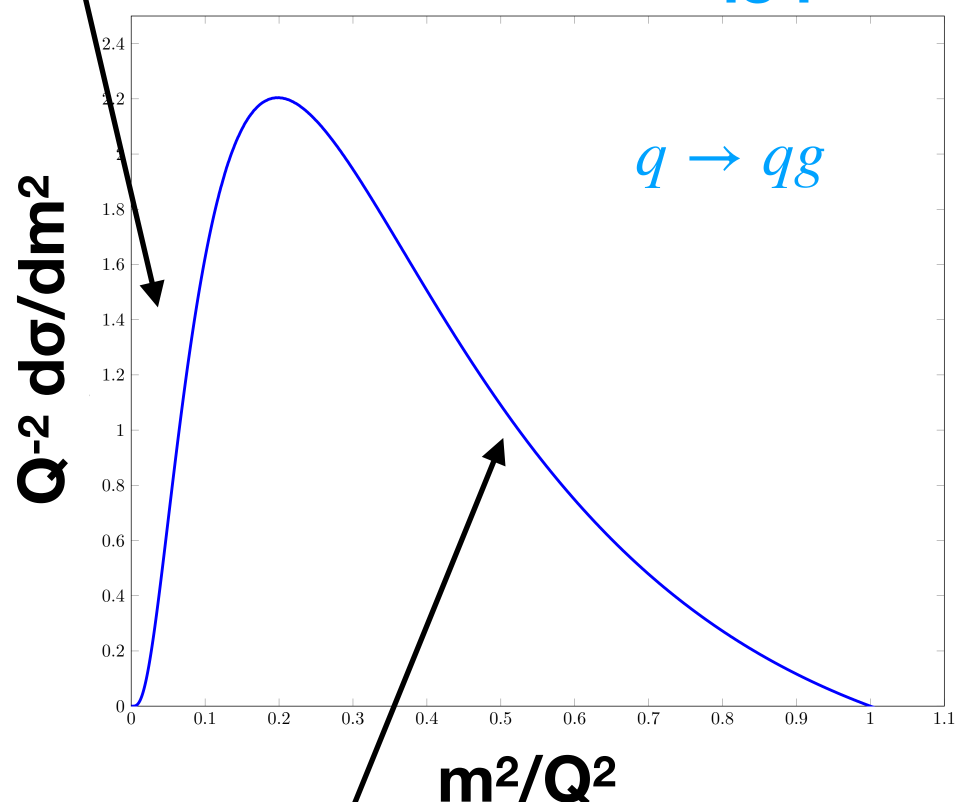
$$\frac{d\sigma}{dm^2} \approx \exp\left(-\frac{\alpha_s}{4\pi} C_F \log^2 \frac{Q^2}{m^2}\right) \frac{1}{m^2} \frac{\alpha_s}{2\pi} C_F \log \frac{Q^2}{m^2}$$

[Cross section for hard quark to produce hardest gluon with pair invariant mass m²]

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. 12!)

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

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Dominant effect on QCD jet mass:
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"Sudakov factor, Δ(Q,m)"

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

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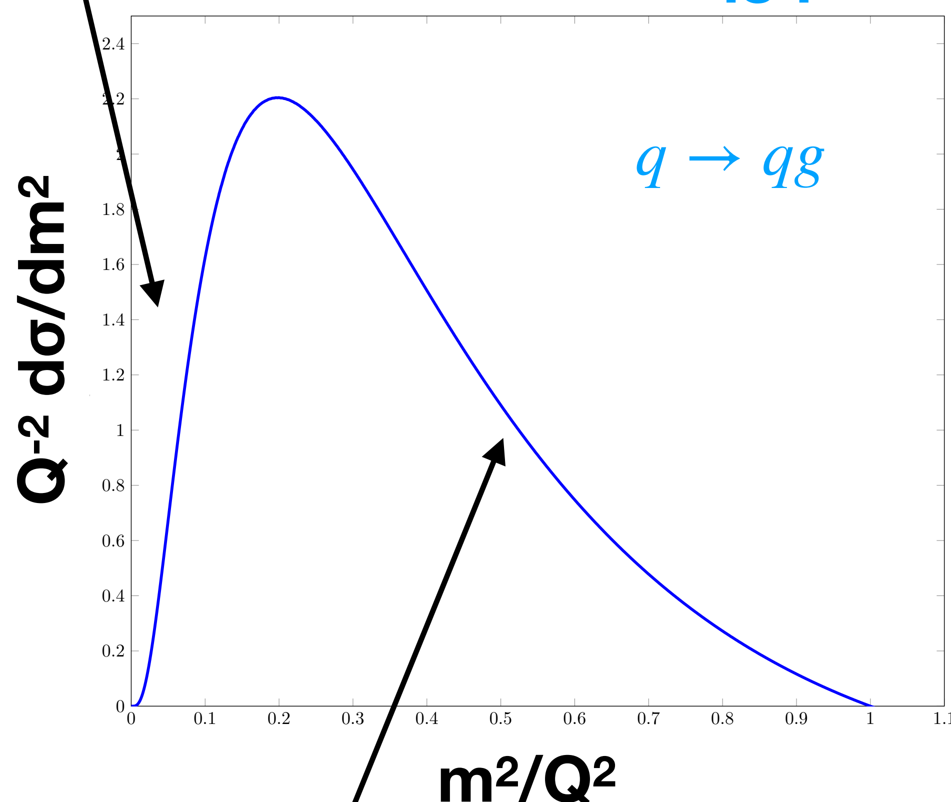
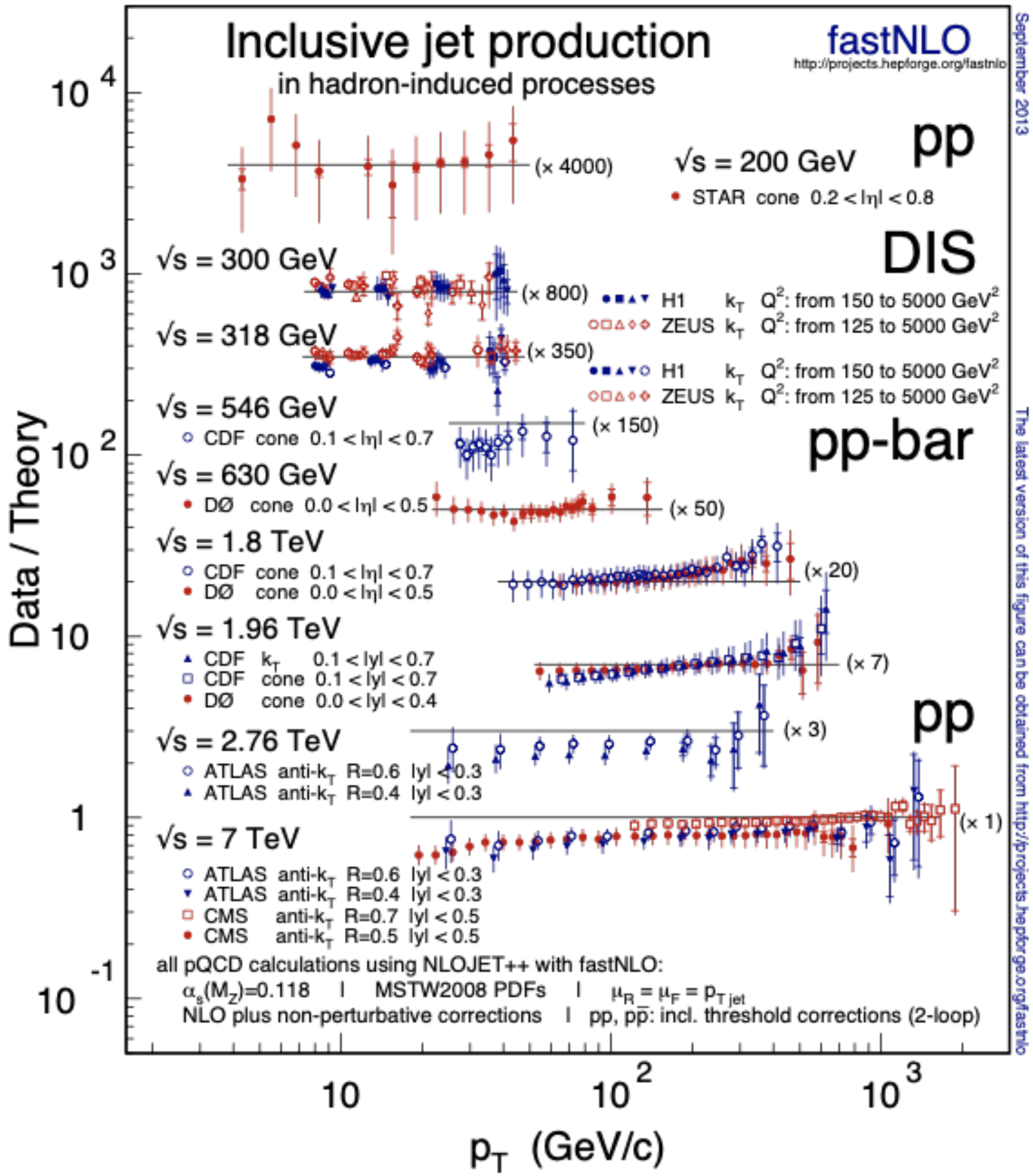
Invariant mass of qg pair



~ jet mass (compare to e.g. s. 12!)

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

Jet production at NLO



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]

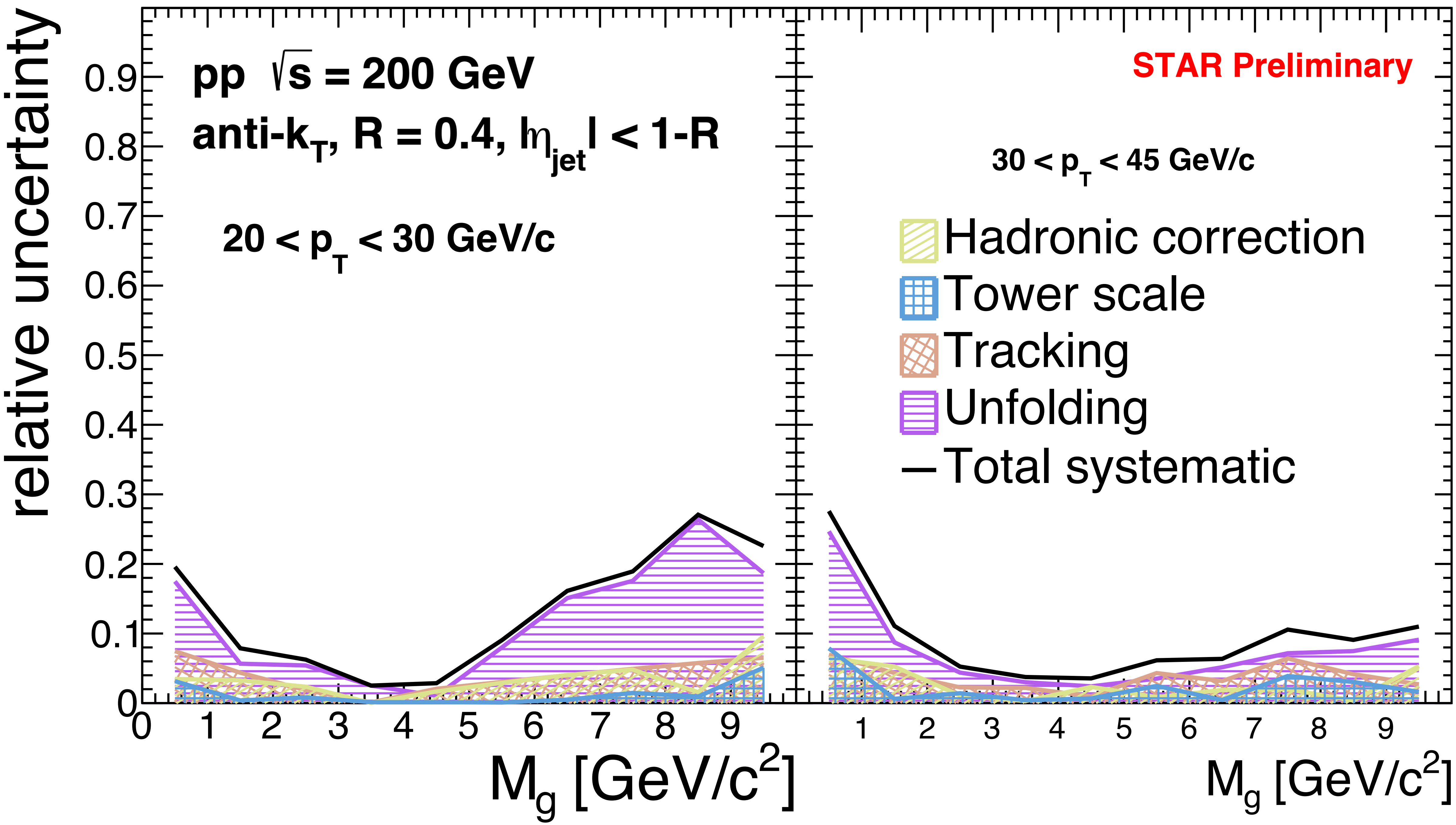
Note: relatively stable particles are left undecayed until interaction with the detector material in the GEANT-3 simulation. These “stable” particles include $\pi^0, \pi^{\pm}, \eta, K^+, K^0_S, K^0_L, \Sigma^{\pm}, \bar{\Sigma}^{\pm}, \Lambda, \bar{\Lambda}, \Xi^-, \bar{\Xi}^+, \Omega^-, \bar{\Omega}^+$

[1] STAR Collaboration, Phys.Rev. D 100 (2019) no.5, 052005

[2] Skands, Carrazza, Rojo, Eur.Phys.J. C 74 (2014) no.8, 3024

[3] Gieseke, Rohr, Siodmok, Eur.Phys.J. C 72 (2012) no.11, 2225

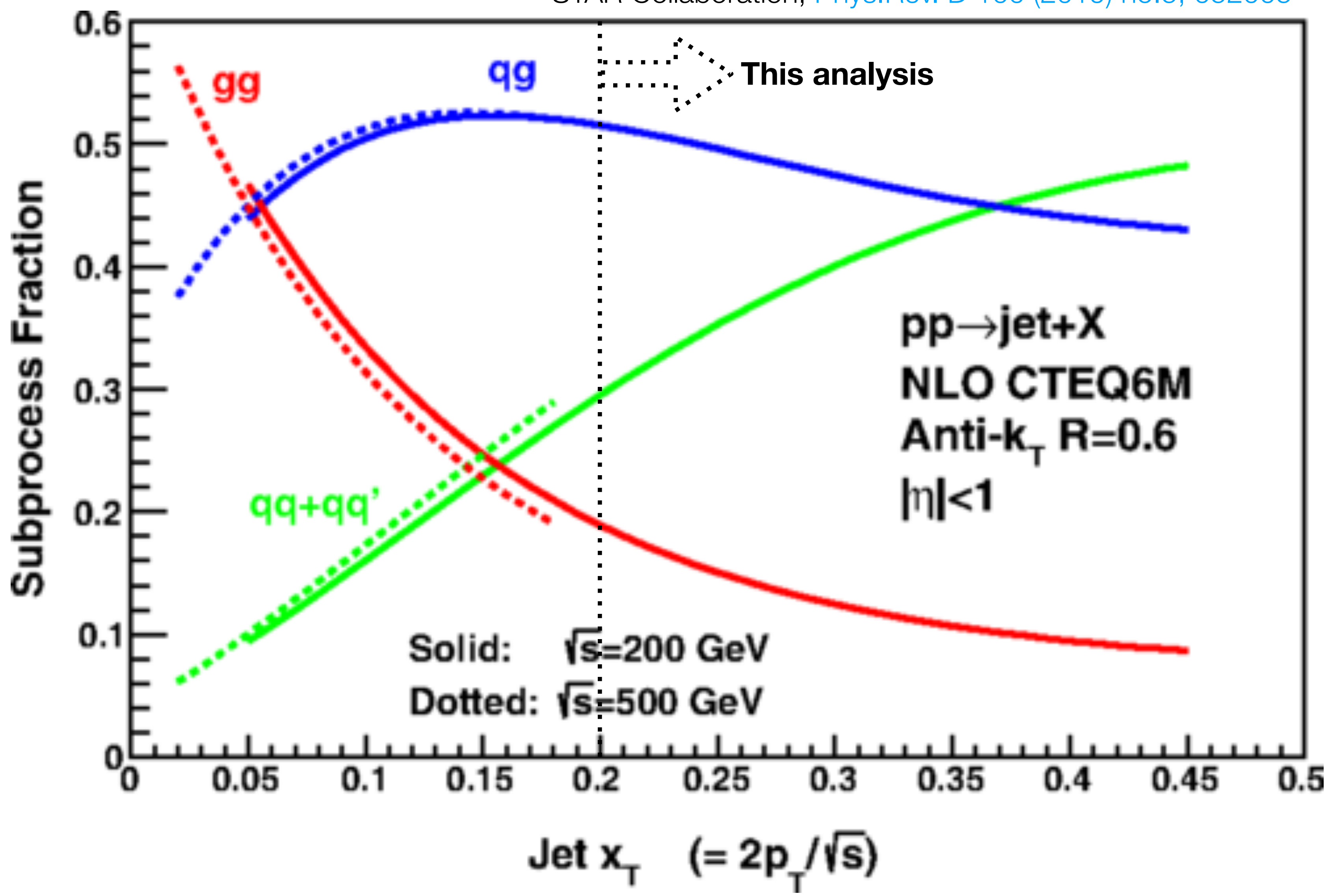
Groomed systematics



Systematic uncertainties are reduced from ungroomed case

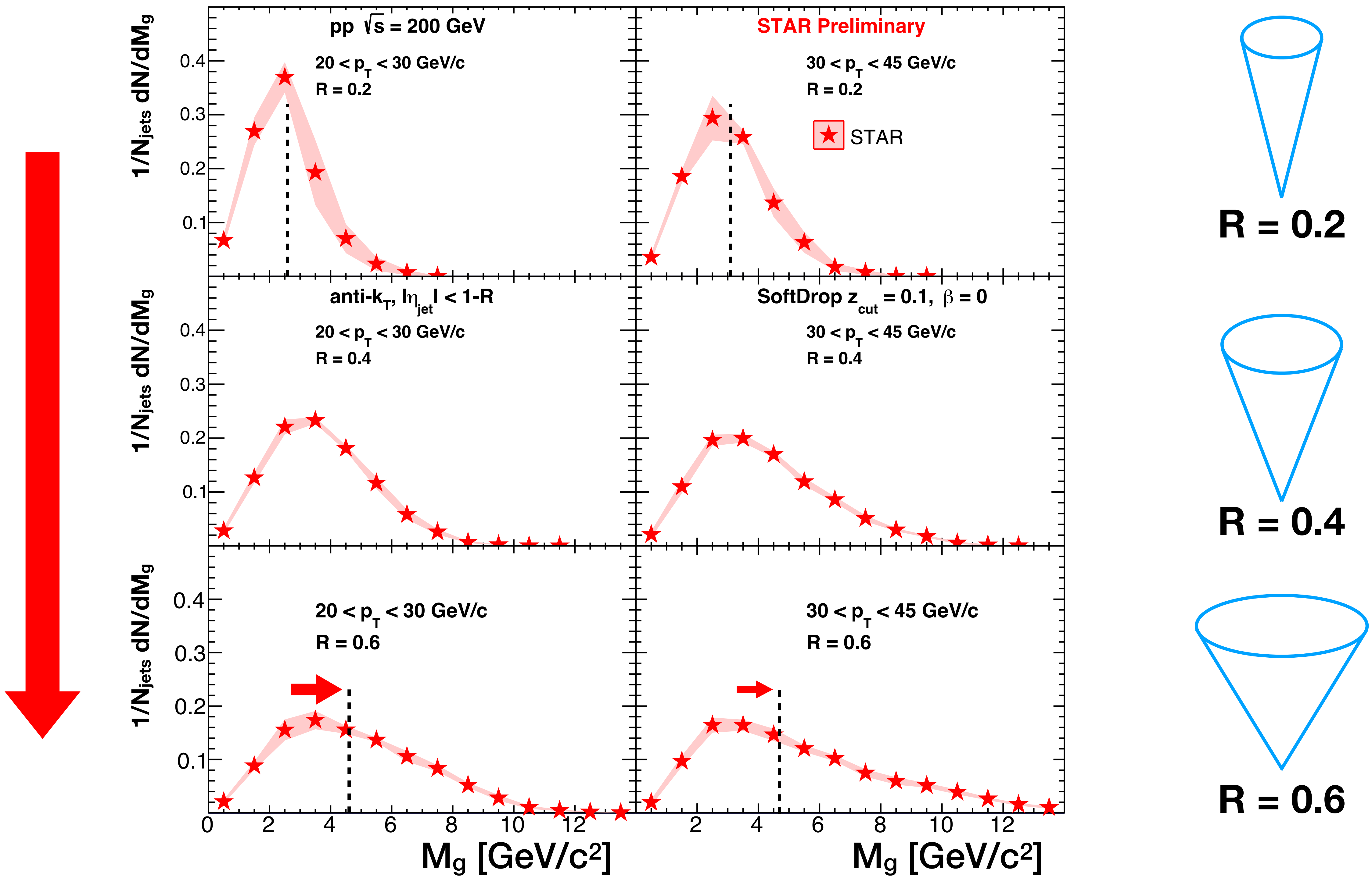
Quark and gluon fractions

STAR Collaboration, Phys.Rev. D 100 (2019) no.5, 052005



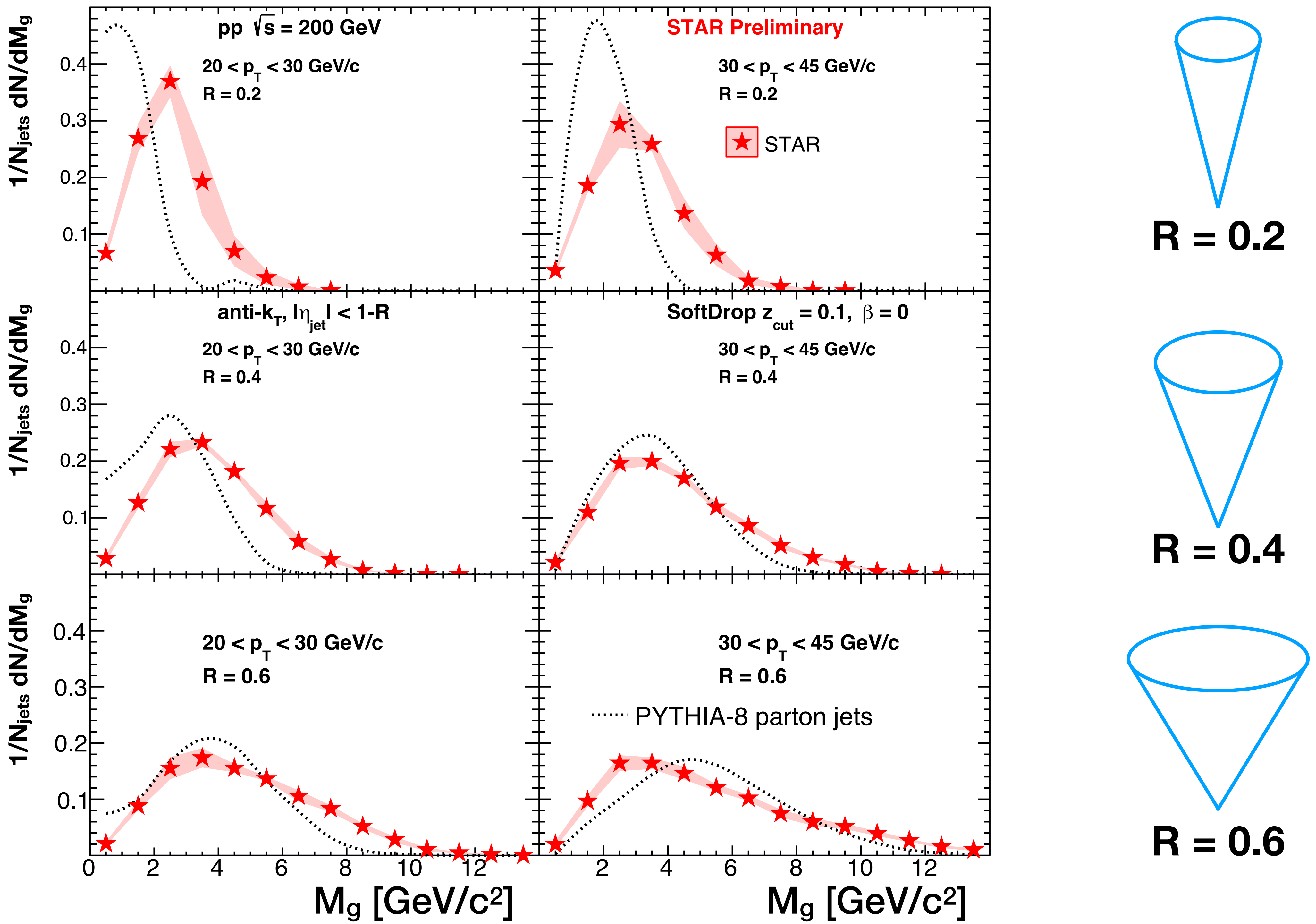
Gluon jets have larger mass than quark jets ($C_A/C_F = 9/4$)
Majority of jets are quark-initiated in this kinematic regime

Groomed radial scan



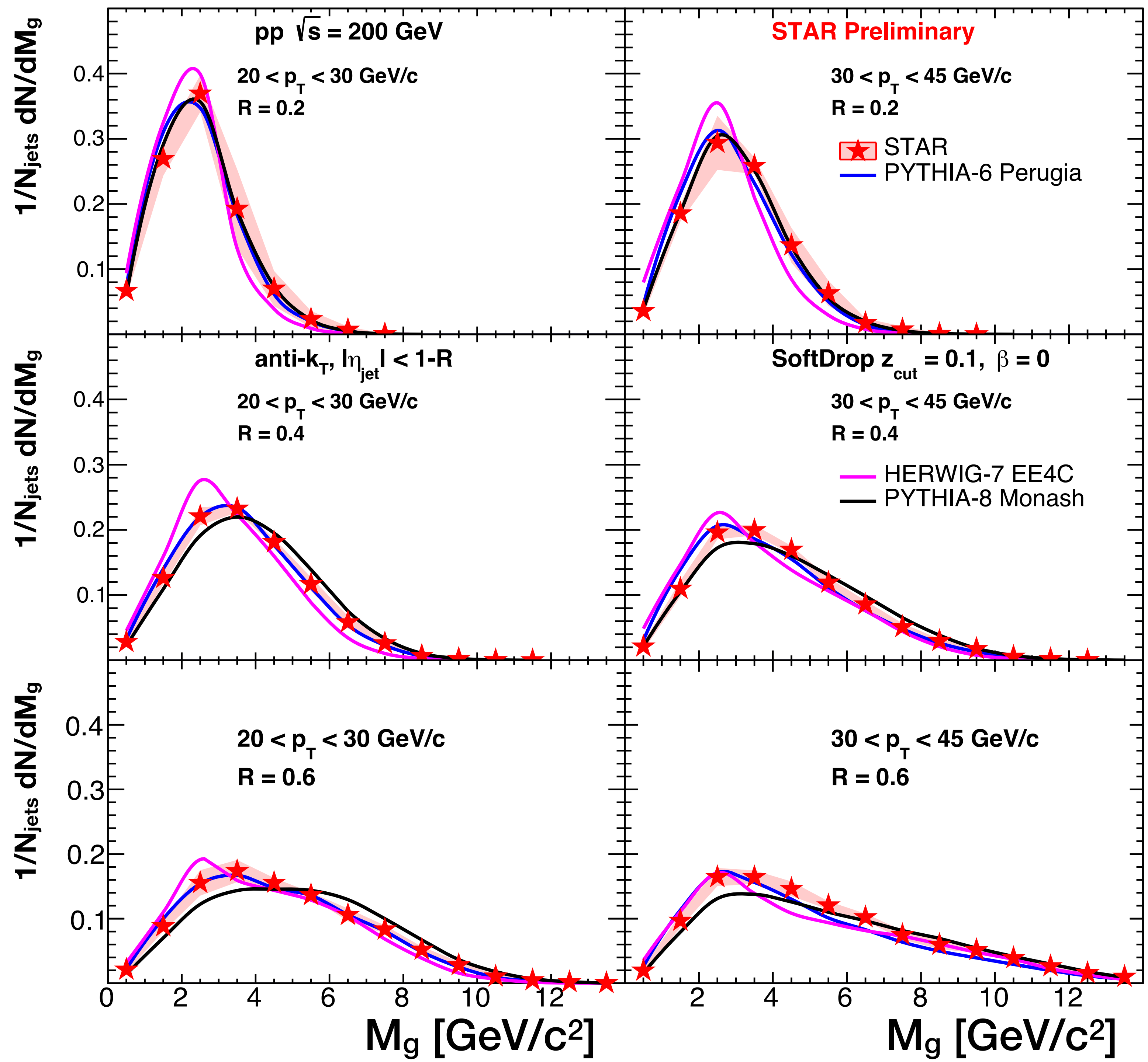
Groomed mean mass less sensitive to radius / p_T variation

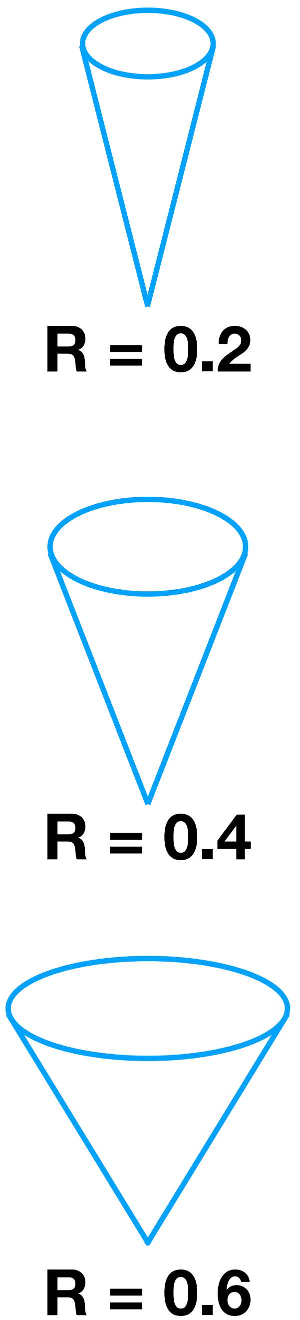
Groomed radial scan



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

Groomed radial scan





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

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