Understanding wide jet suppression in data through the hybrid strong/weak coupling model

Daniel Pablos

1808.07386

Hard Probes '18
Aix-les-Bains

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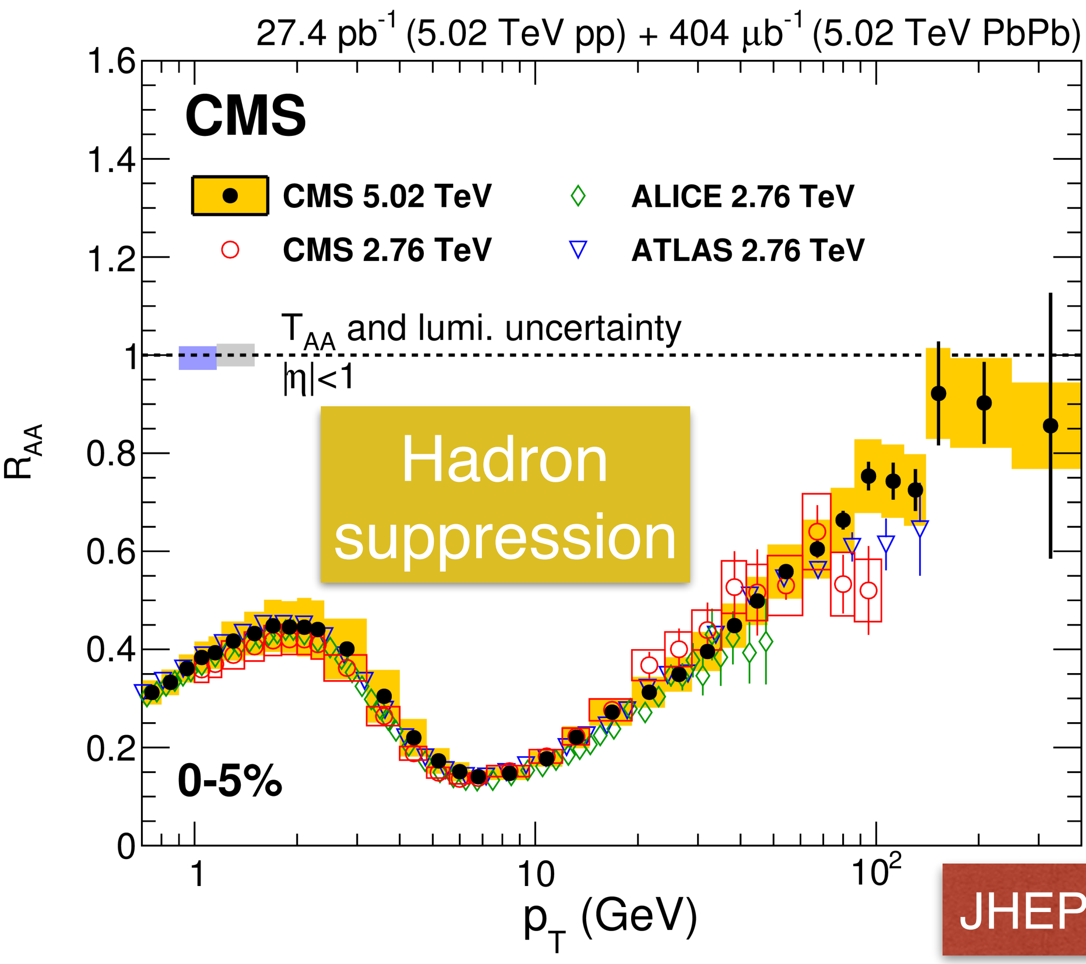
Motivation



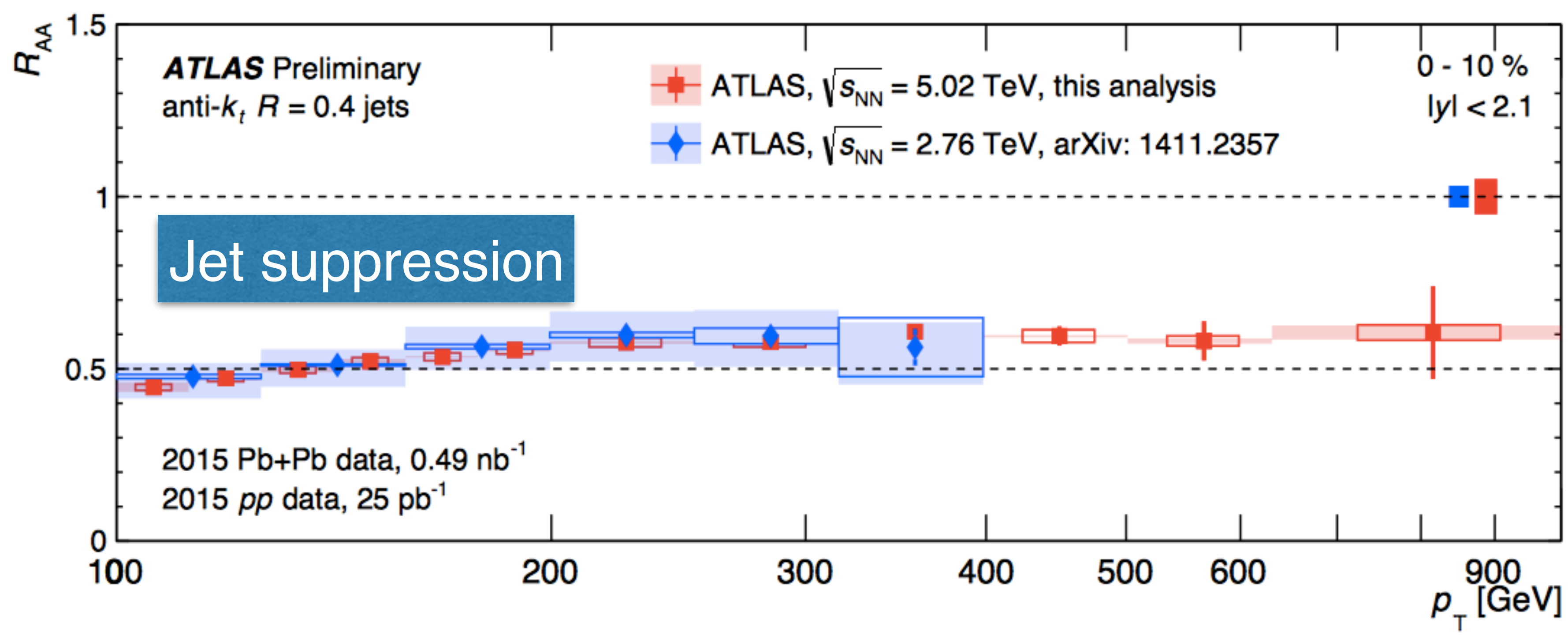
JHEP 1704 (2017) 039

- Want to understand the relative behaviour of jet and hadron suppression:

  notably less suppression for hadrons than jets (at any energy)

  → how to understand this behaviour?

  → dependence on jet radius?

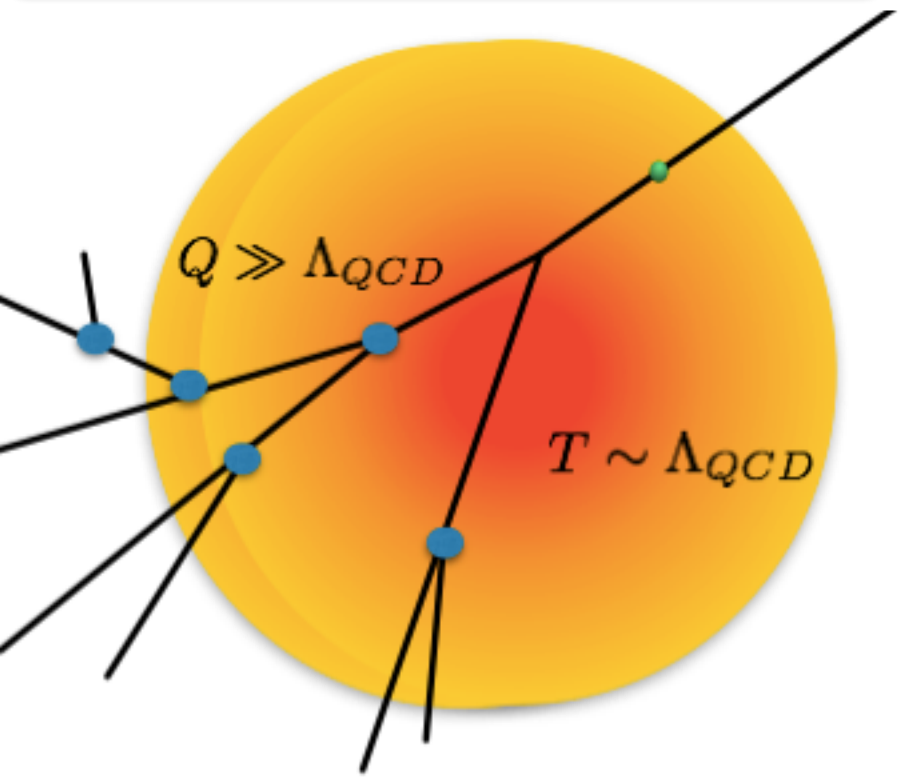


ATLAS, arXiv:1805.05635

- Build a consistent picture by confronting hypothesis to other observables

Hybrid strong/weak coupling approach

Pablos et al. - JHEP '14, '16, '17, '18



High energy jet starts with a high virtuality, much greater than medium scale

→ Parton shower well approximated by vacuum-like splittings (late stages?)

Plasma-jet interaction dominated by temperature scale

→ Use non-perturbative holographic prescription for partonic energy loss

Chesler & Rajagopal - PRD '15, JHEP '16

Energy flowing into hydro modes:

$$\frac{1}{E_{\rm in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x^2_{\rm stop}}\frac{1}{\sqrt{x^2_{\rm stop}-x^2}}$$

$$x_{\rm stop} = \frac{1}{2\kappa_{\rm sc}}\frac{E_{\rm in}^{1/3}}{T^{4/3}}$$

$\mathcal{O}(1)$ free parameter

Estimate the hadronic spectra coming from medium response (assume small perturbation, instantaneous hydrodynamization)

→ Lost jet energy converted into soft particles at large angles (corr. bkgd.)

Constraining the free parameter

PDFs: CTEQ6L1 (pp) & CTEQ6L1+EPS09 (AA)

Jet Production: PYTHIA 8.230 (kinematics) & MC Glauber (trans. position)

Jet Branching: PYTHIA 8.230. Space-time picture through τ_F argument

Hydro Profile: smooth profiles from C. Shen

Energy Loss: apply holographic dE/dx in between splittings

Jet Hadronization: Lund string model from PYTHIA (pp & AA)

Medium Response: Perturbed Cooper-Frye, 4-mom. cons. with Metropolis

χ^2 Goodness of Fit Test

- Find best κ_{sc}

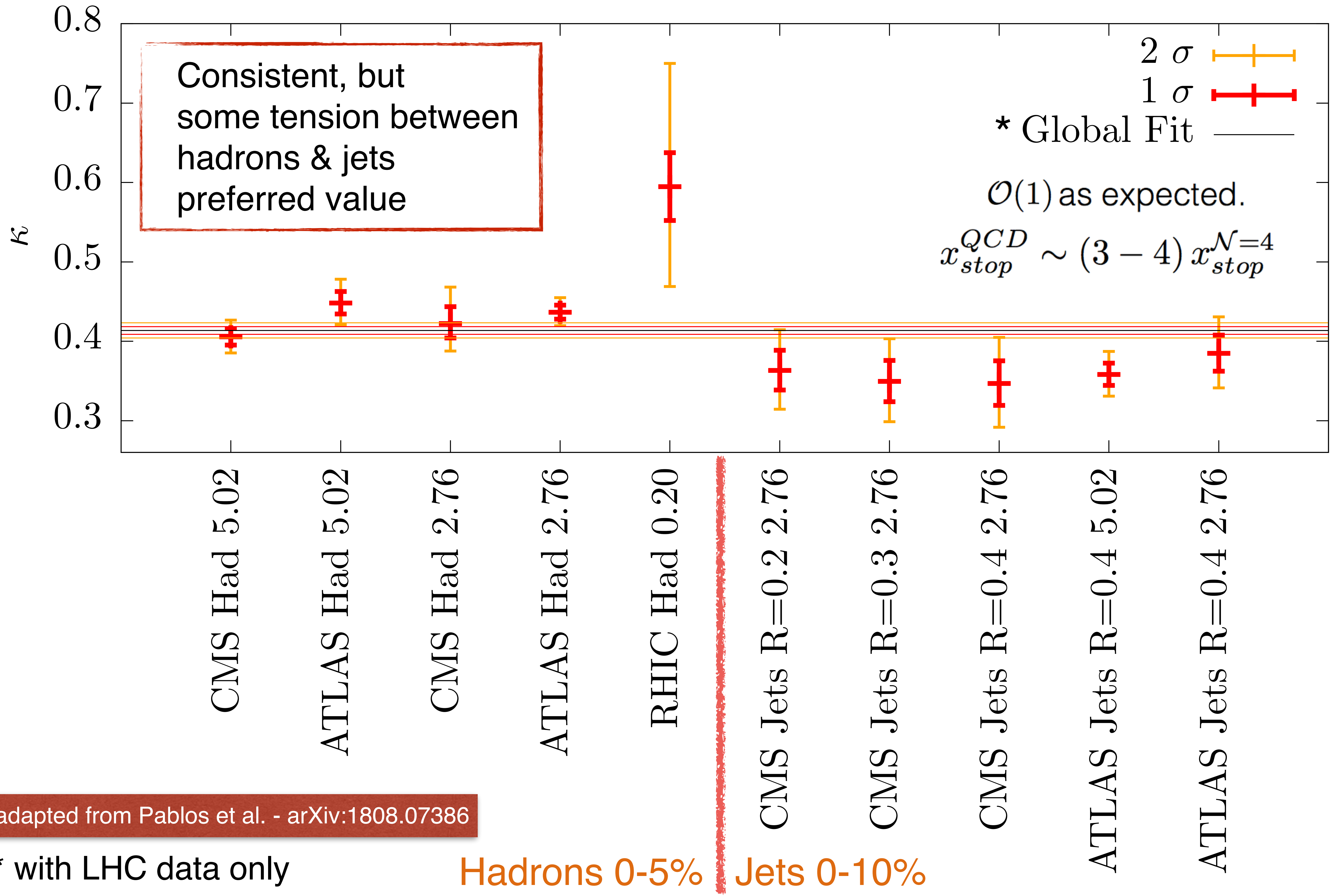
Data
- ATLAS and CMS, jet & hadron ($p_T > 10$ GeV) most central data
- PHENIX, hadron ($p_T > 5$ GeV) most central data

- Consider different error nature (stat., syst. uncorr., syst. corr., norm.)

(following PHENIX PRC 08 arXiv:0801.1665)

Pablos et al. - arXiv:1808.07386

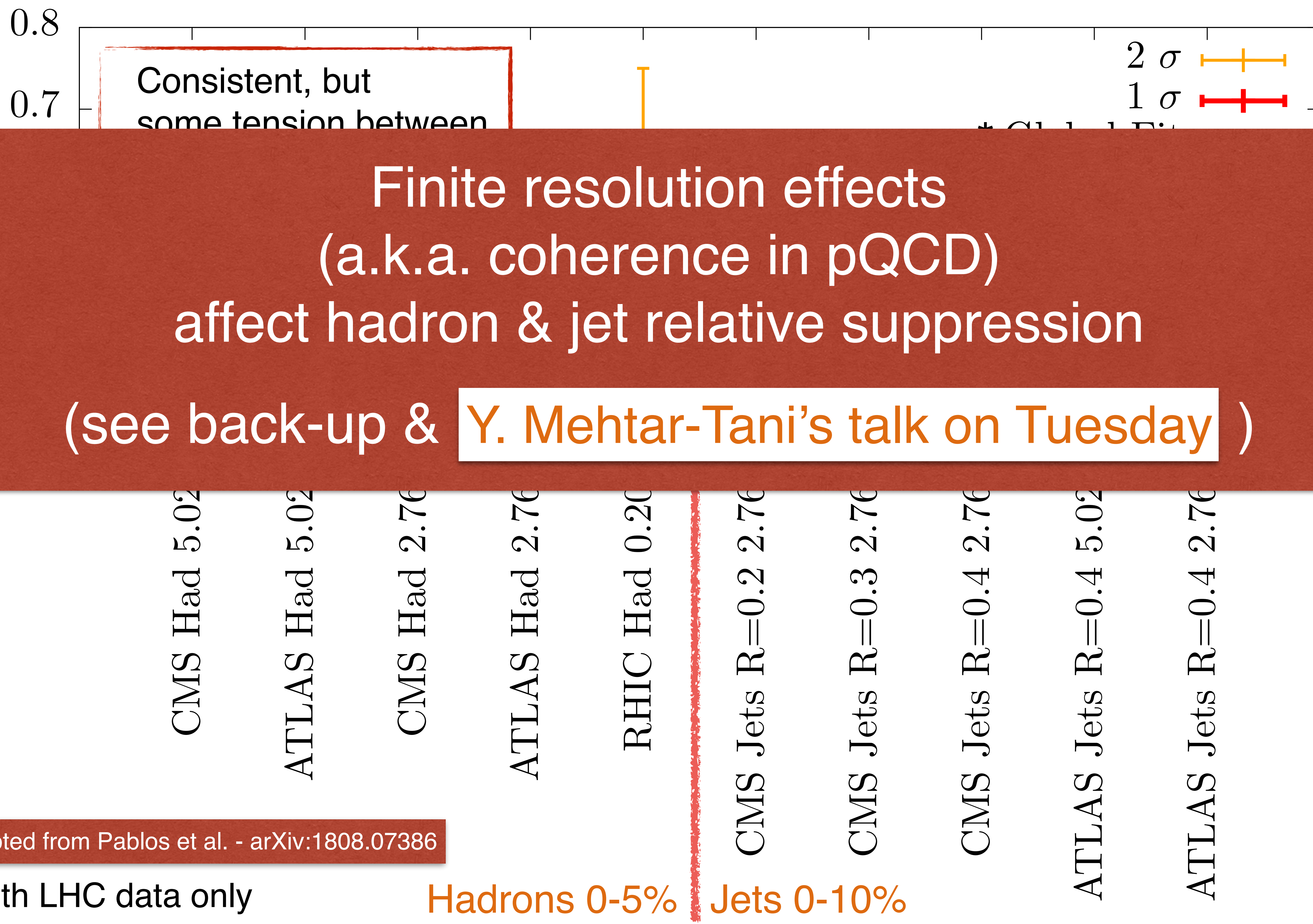
Fit results



adapted from Pablos et al. - arXiv:1808.07386

* with LHC data only

Fit results



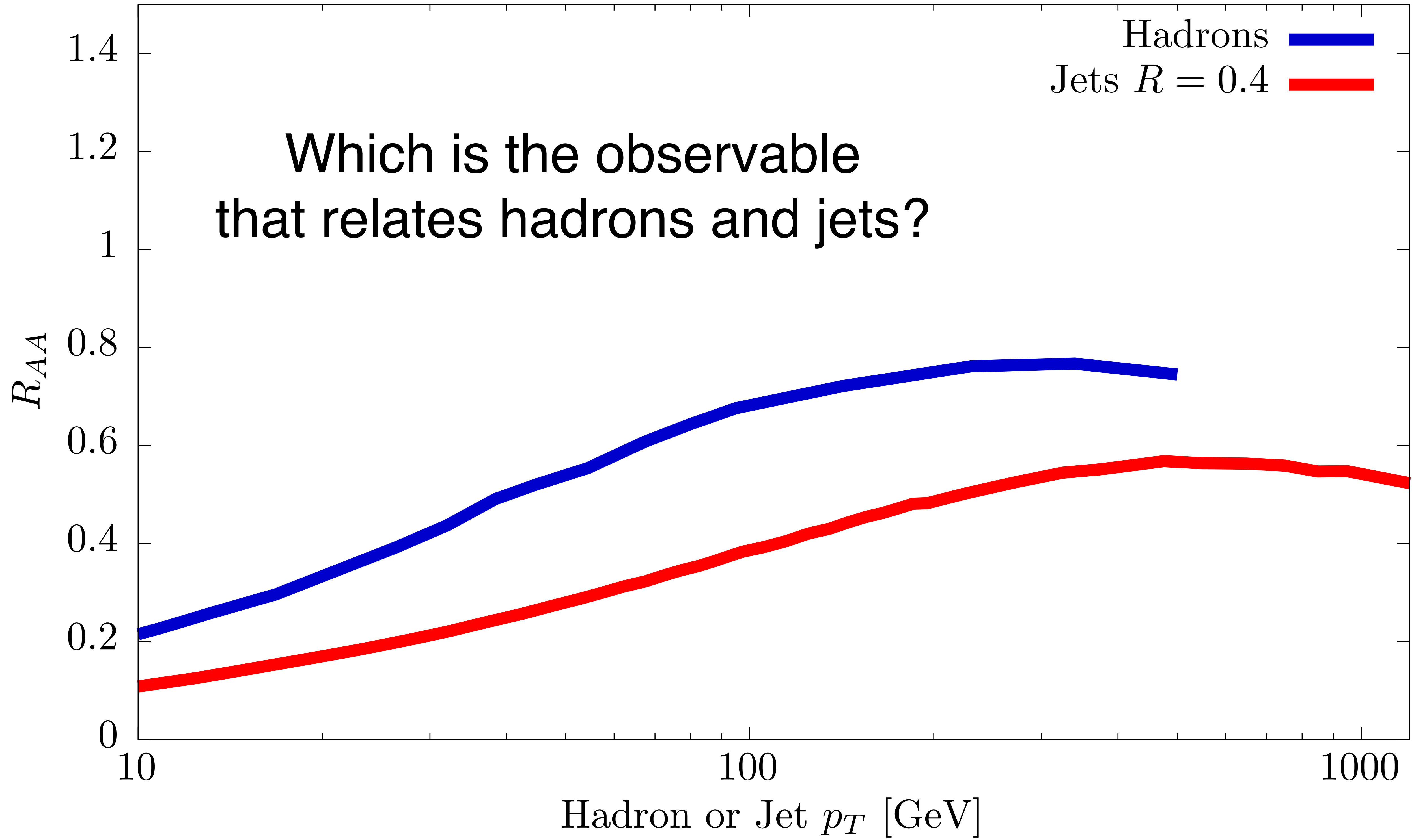
Finite resolution effects
(a.k.a. coherence in pQCD)
affect hadron & jet relative suppression

(see back-up & Y. Mehtar-Tani's talk on Tuesday)

adapted from Pablos et al. - arXiv:1808.07386

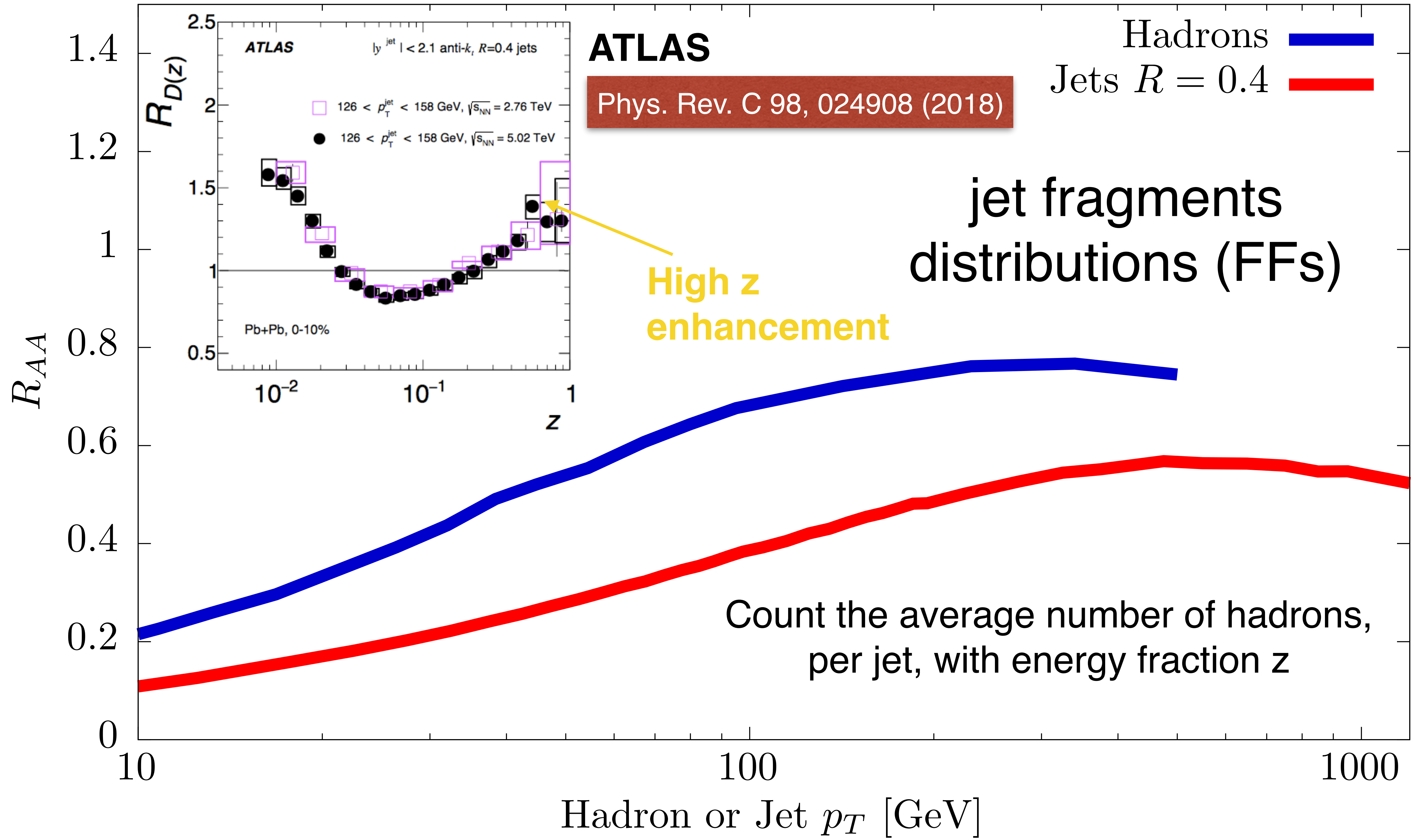
* with LHC data only

Hadron and Jet suppression



Pablos et al. - arXiv:1808.07386

Connection between hadrons and jets



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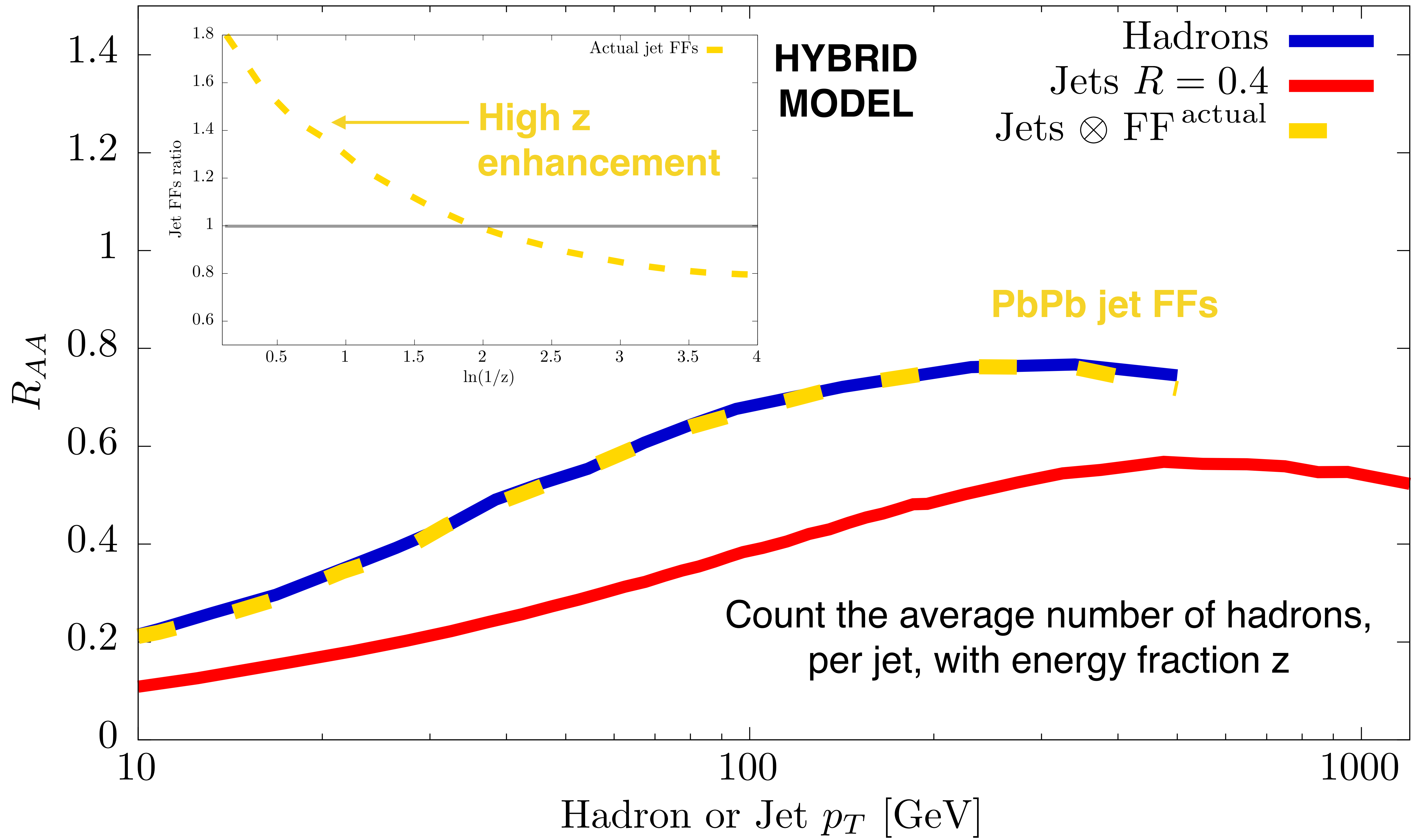

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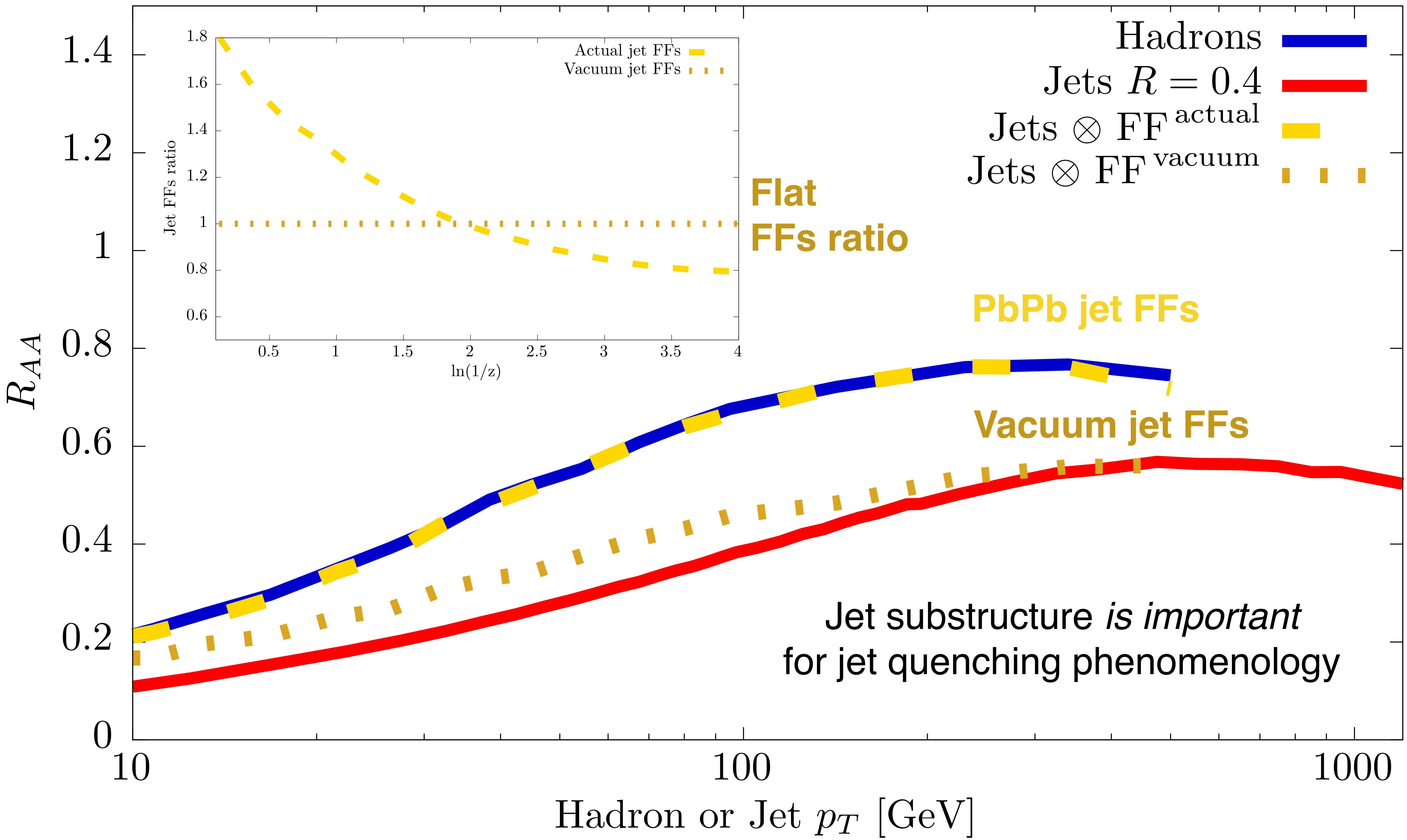


adapted from Pablos et al. - arXiv:1808.07386

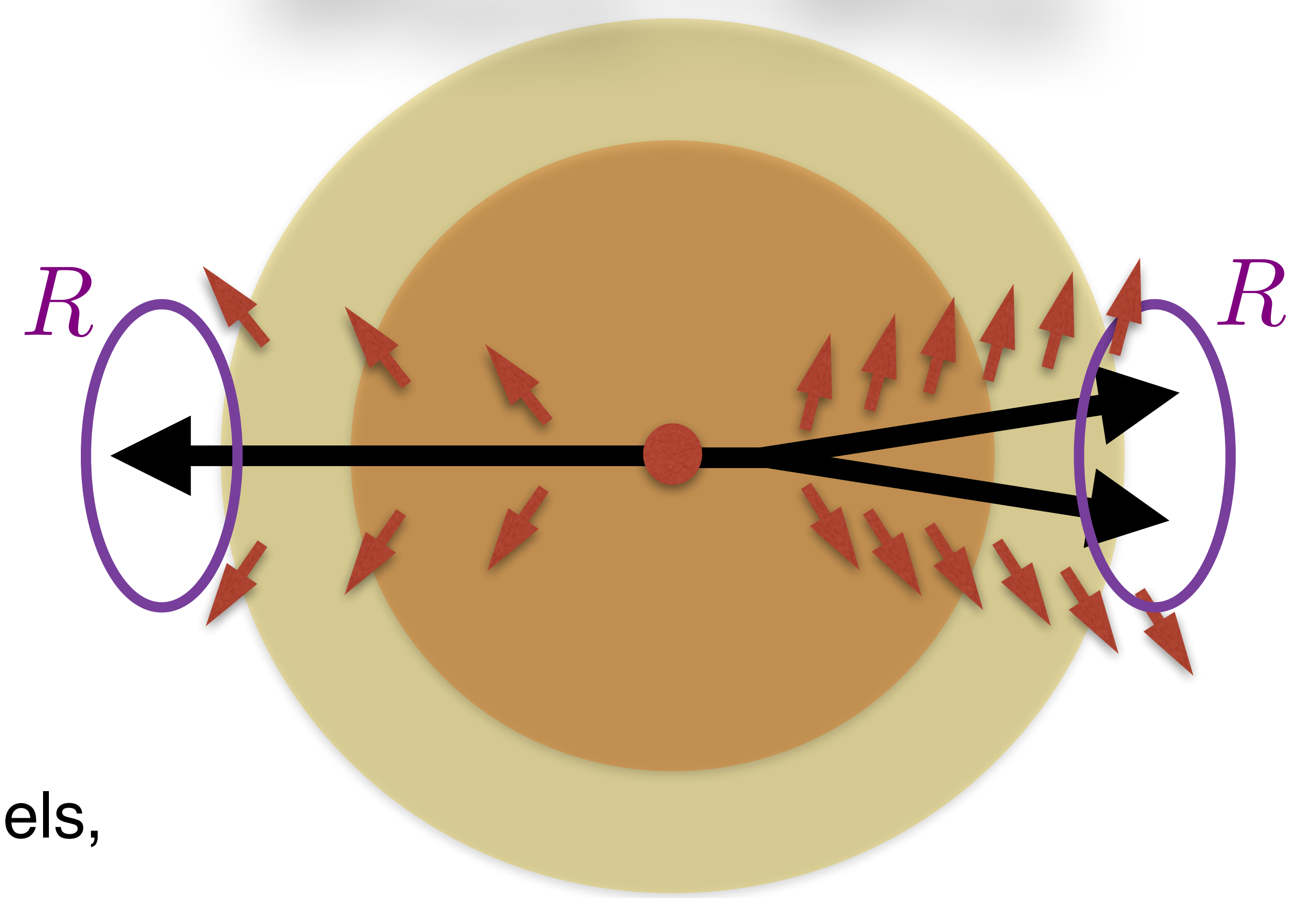
Jet narrowing

Wider, more active jets lose more energy than narrower, hard fragmenting ones

Steeply falling jet spectrum → bias inclusive jet sample to narrower ones, explains high z enhancement

$\Delta E_{\rm narrow} < \Delta E_{\rm wide}$

High p_T hadrons belong to such subsample of narrow jets, which get less quenched, and so $R_{AA}^{had} > R_{AA}^{jet}$



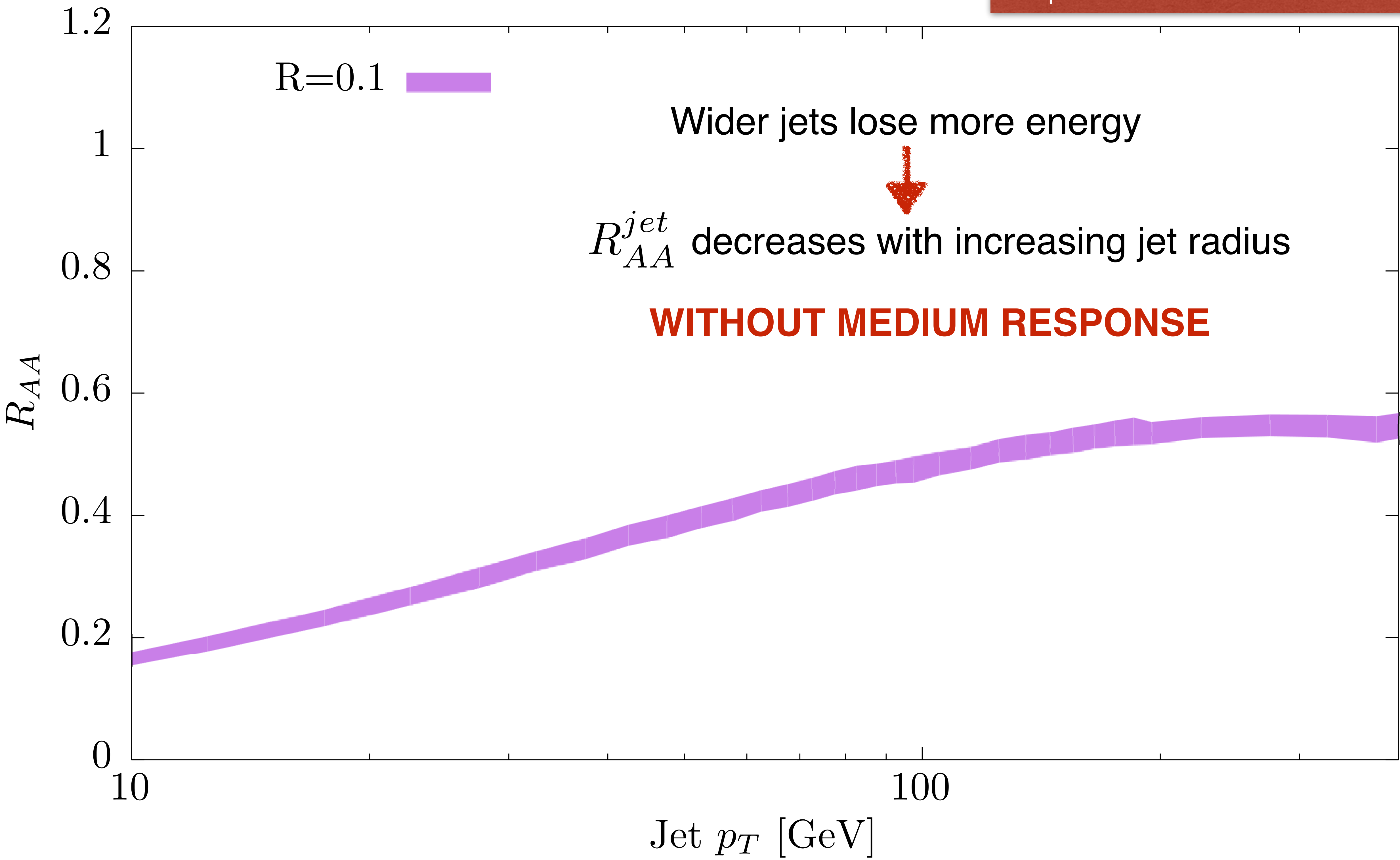
see W. van der Schee's talk on Tuesday

Effect seen in the literature, for different models, on different observables - see for instance:

Brewer et al. - JHEP '18 | Milhano & Zapp - EPJ '16 | Pablos et al. - JHEP '17

R_{AA} vs R

adapted from Pablos et al. - JHEP '16



R_{AA} vs R

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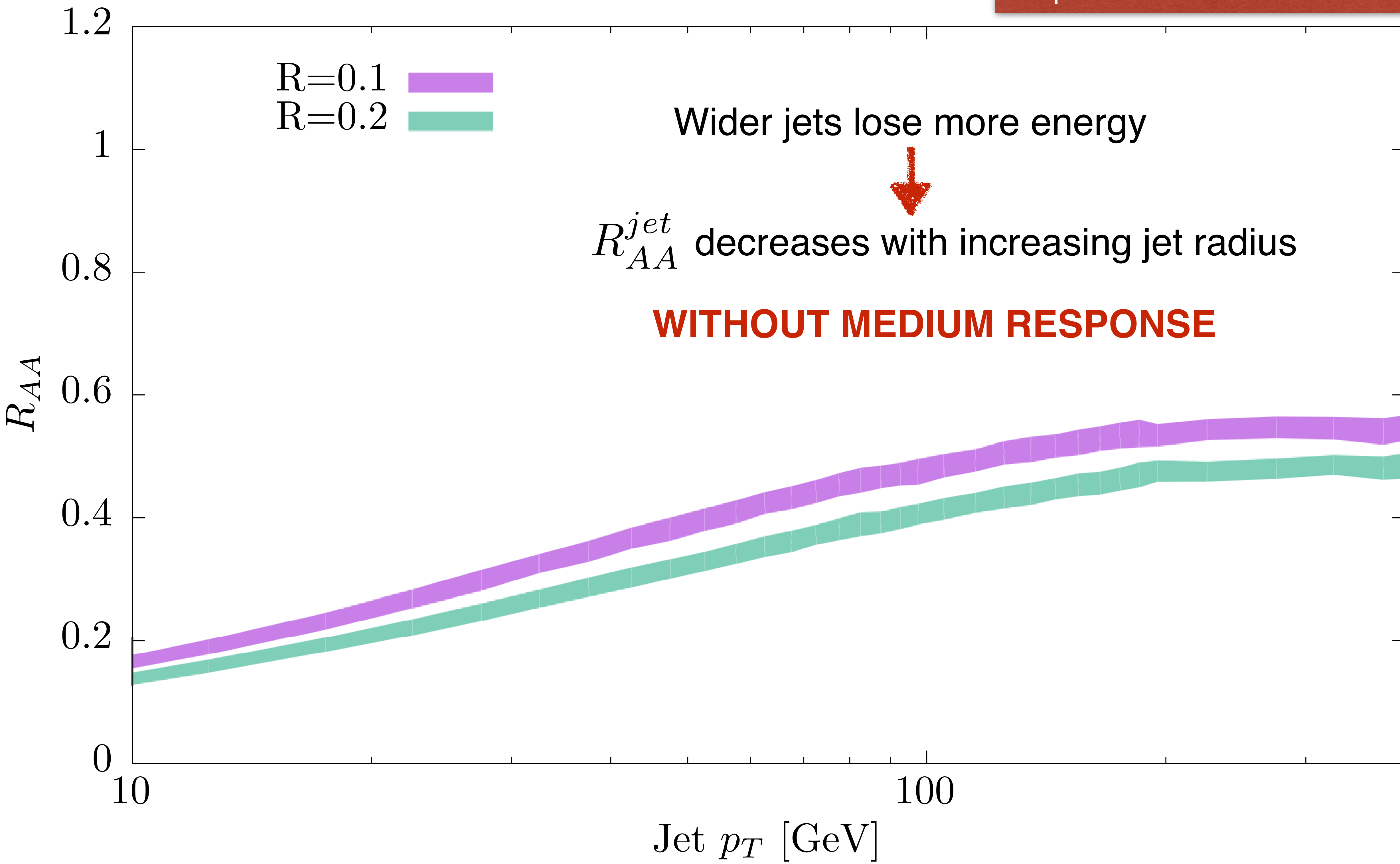

R_{AA} vs R

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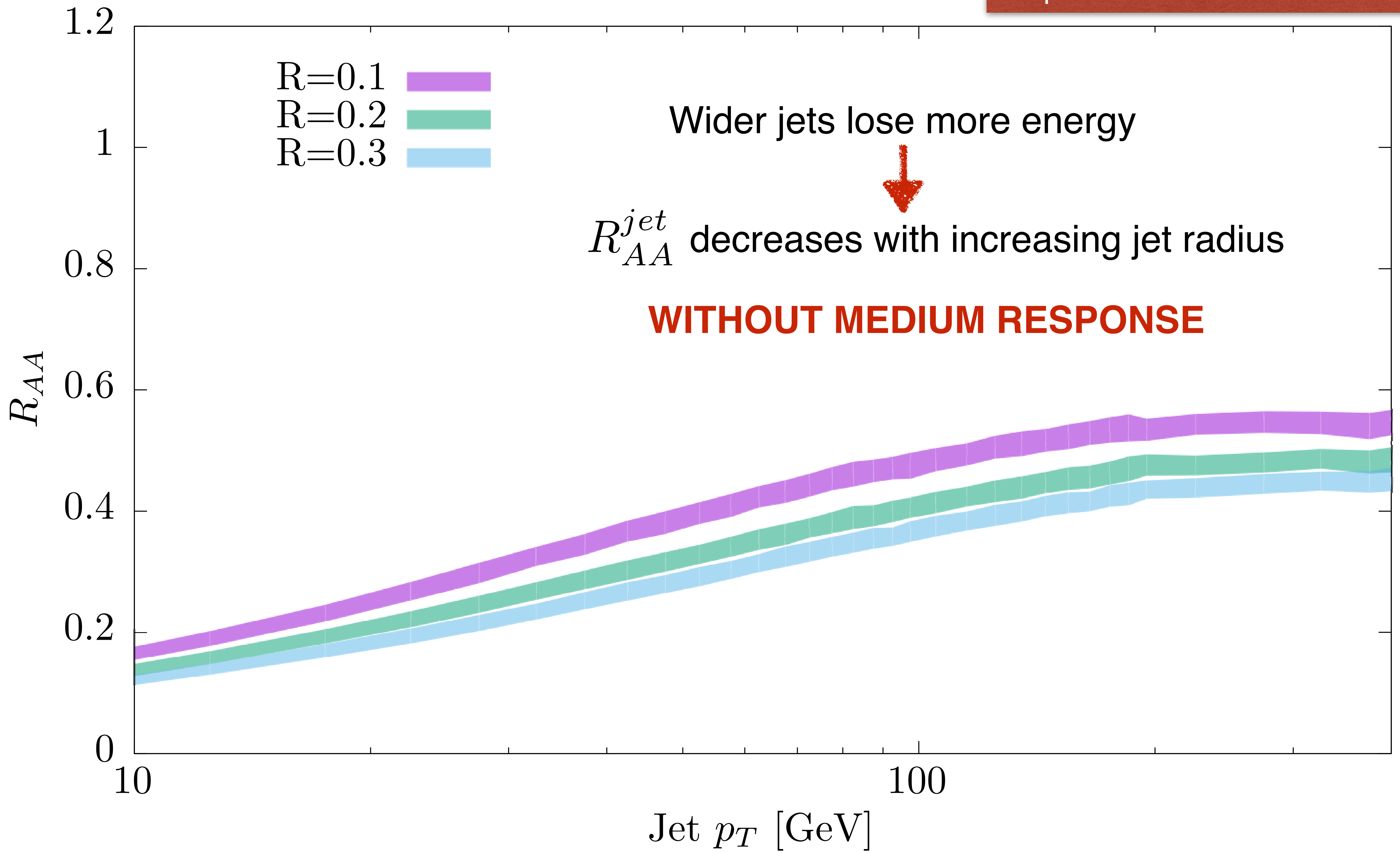

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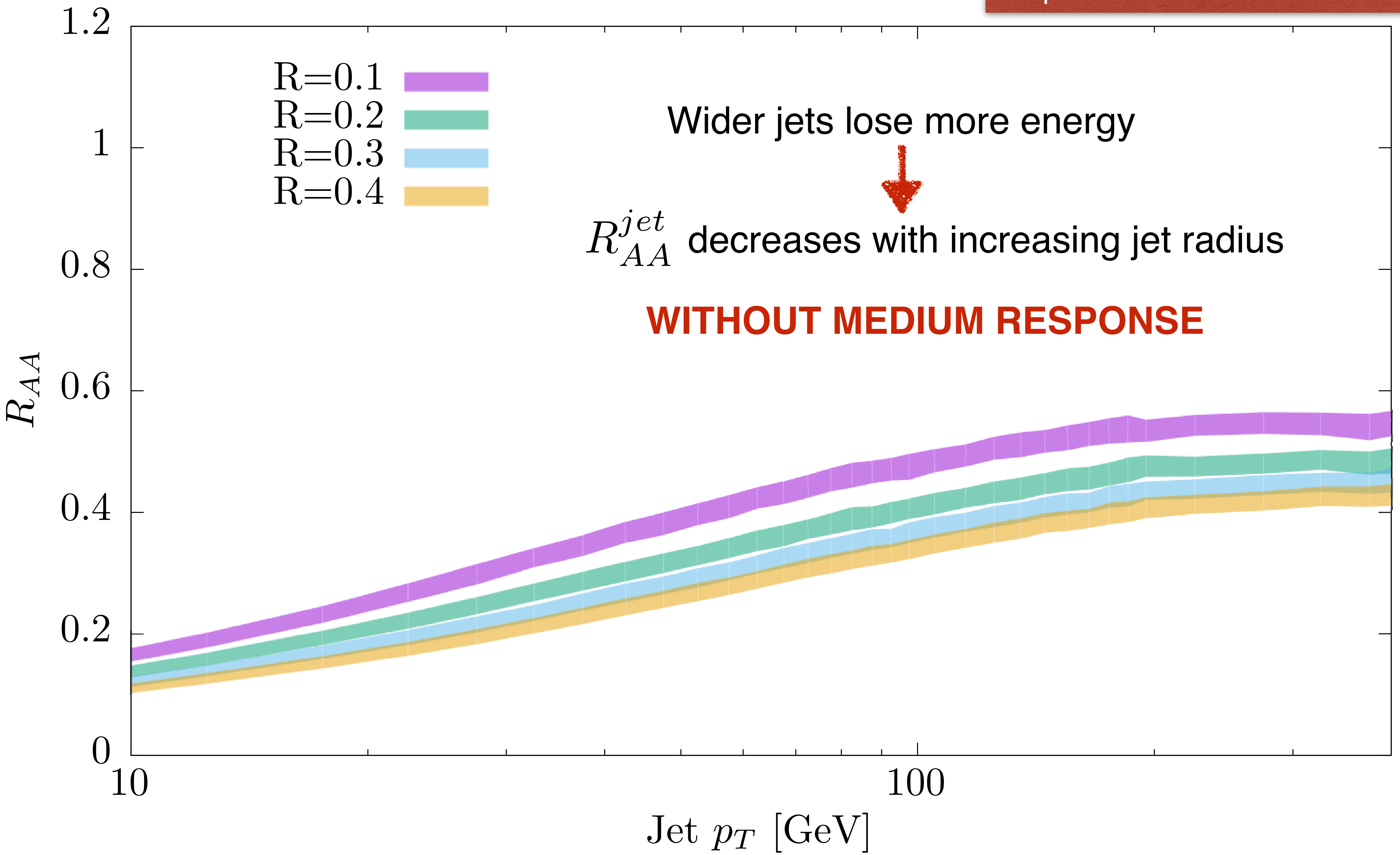

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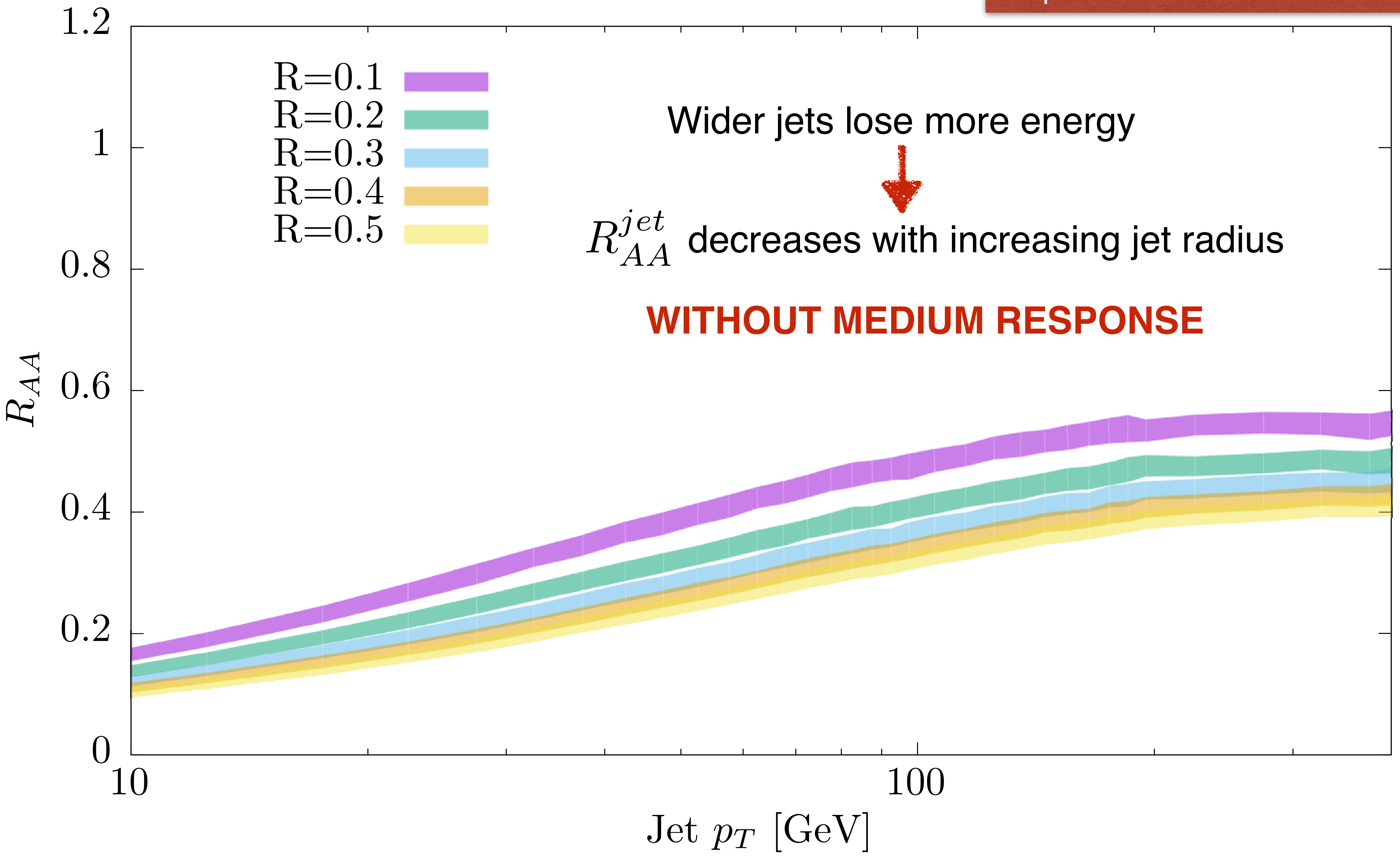

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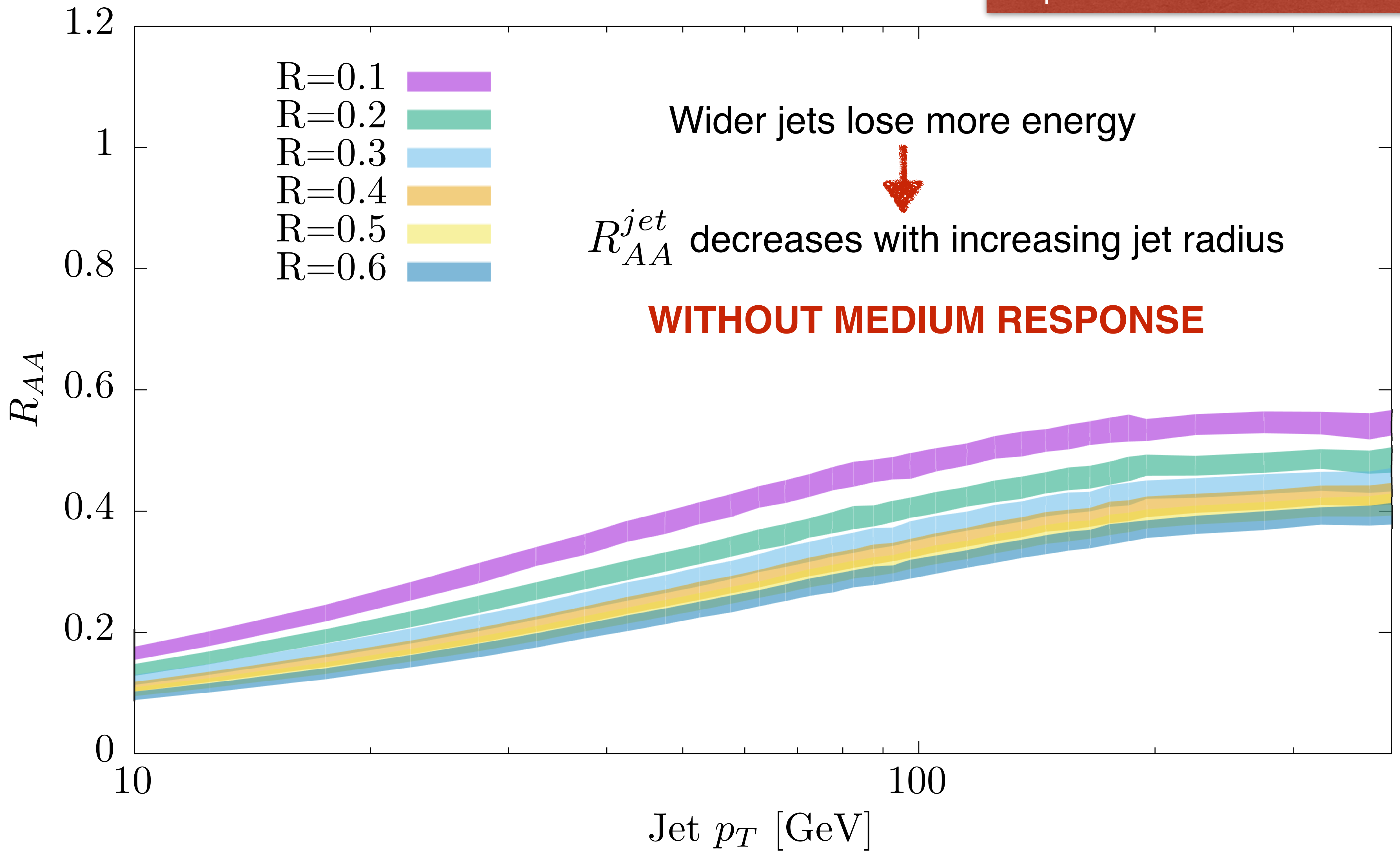

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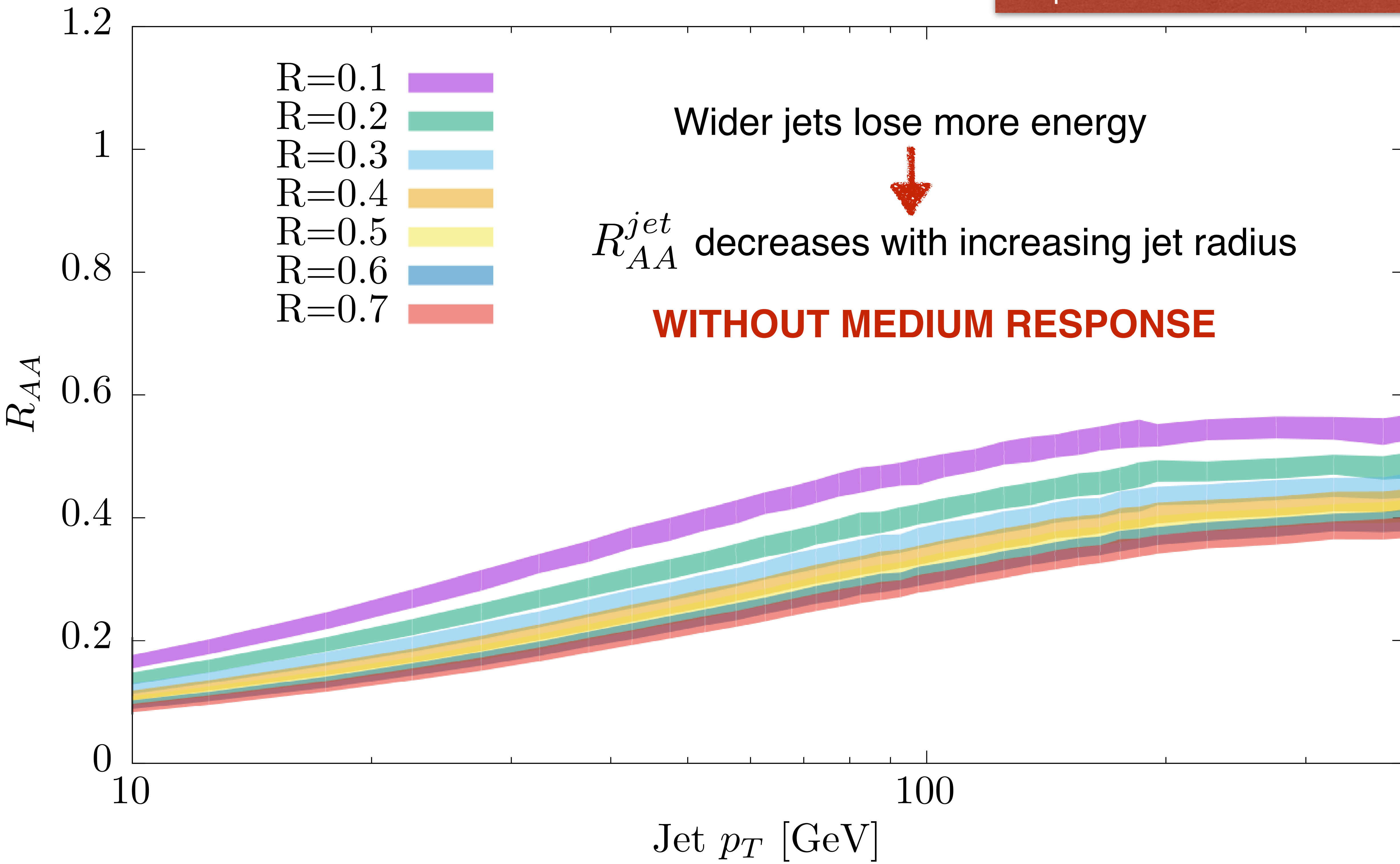

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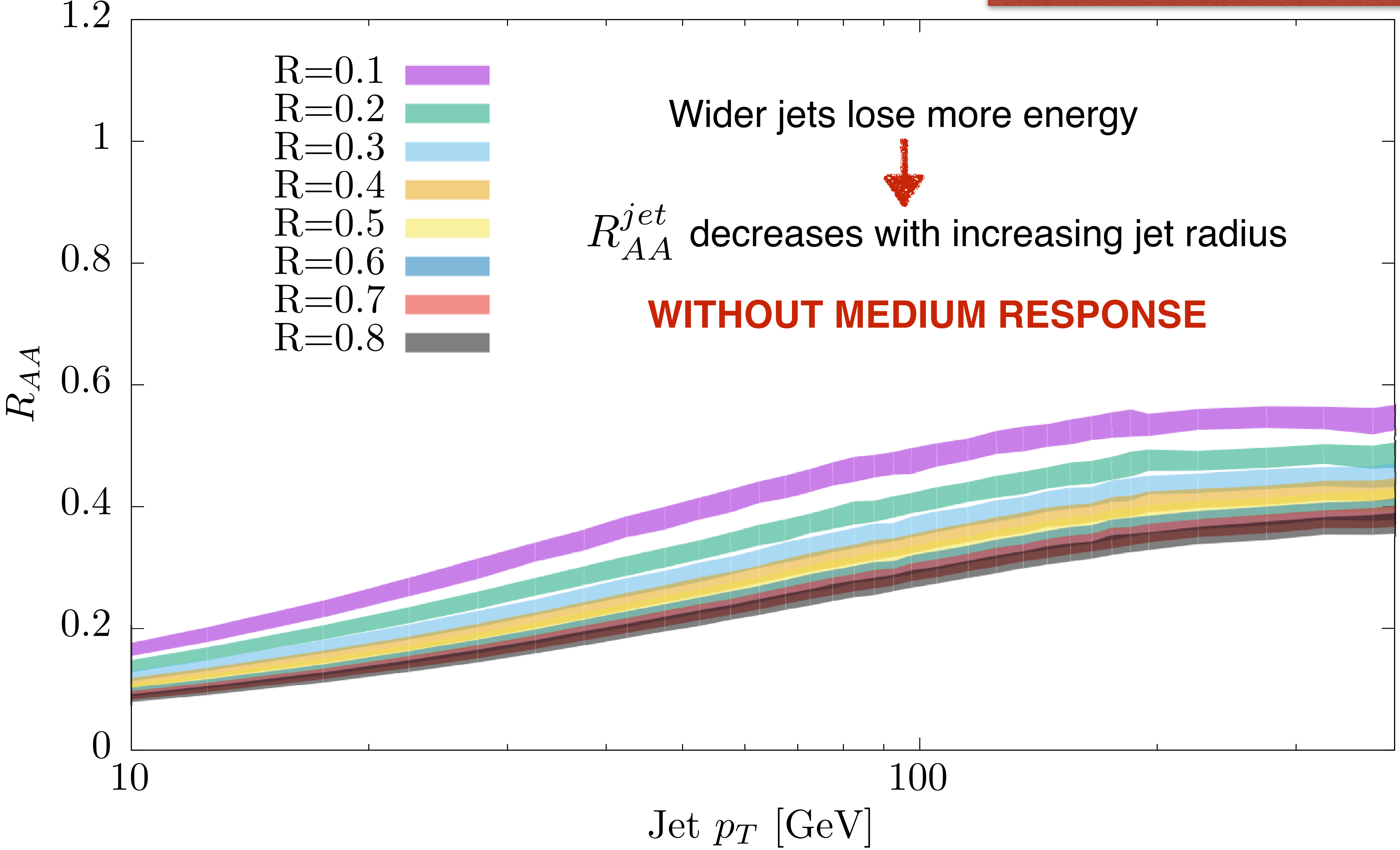

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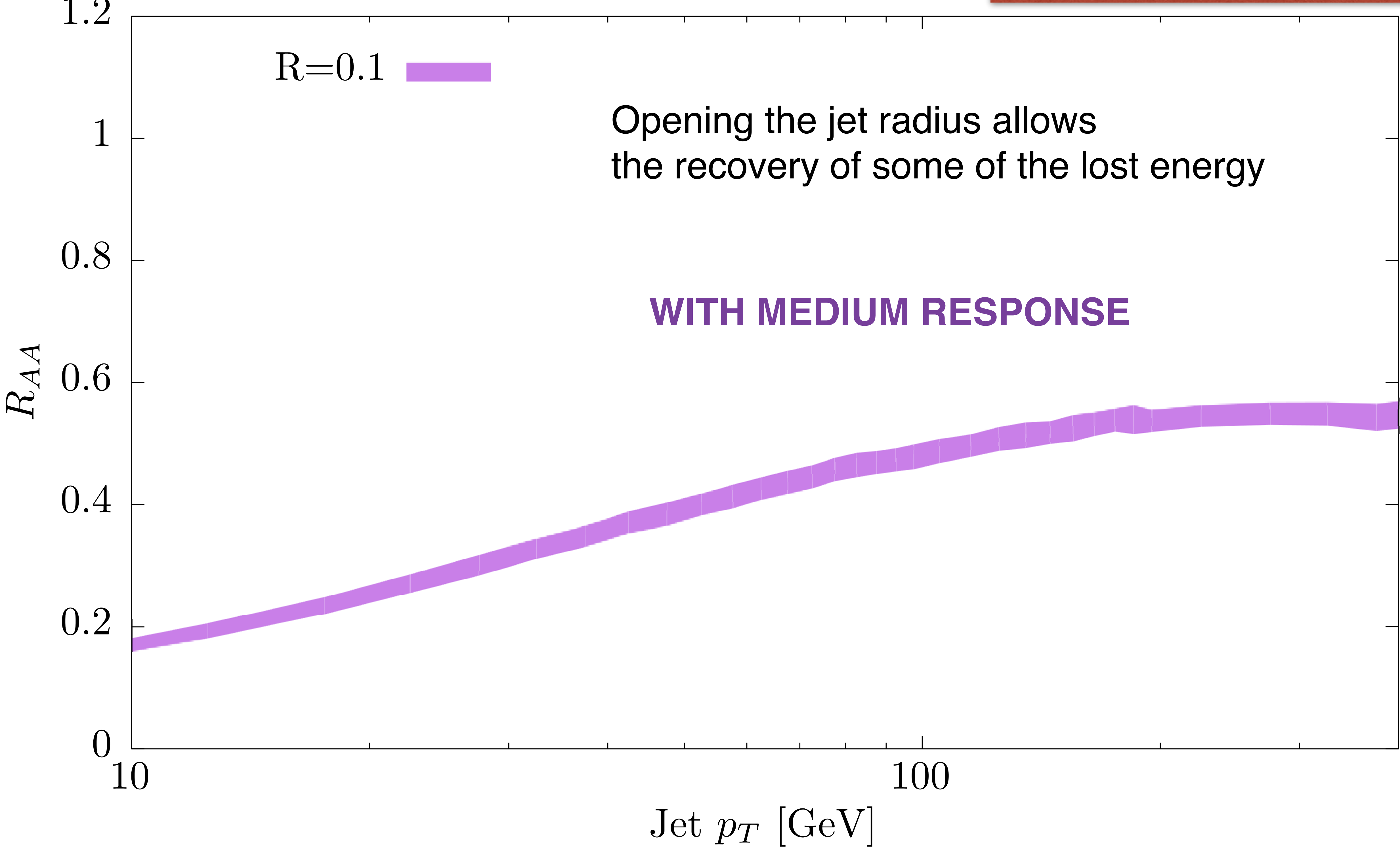

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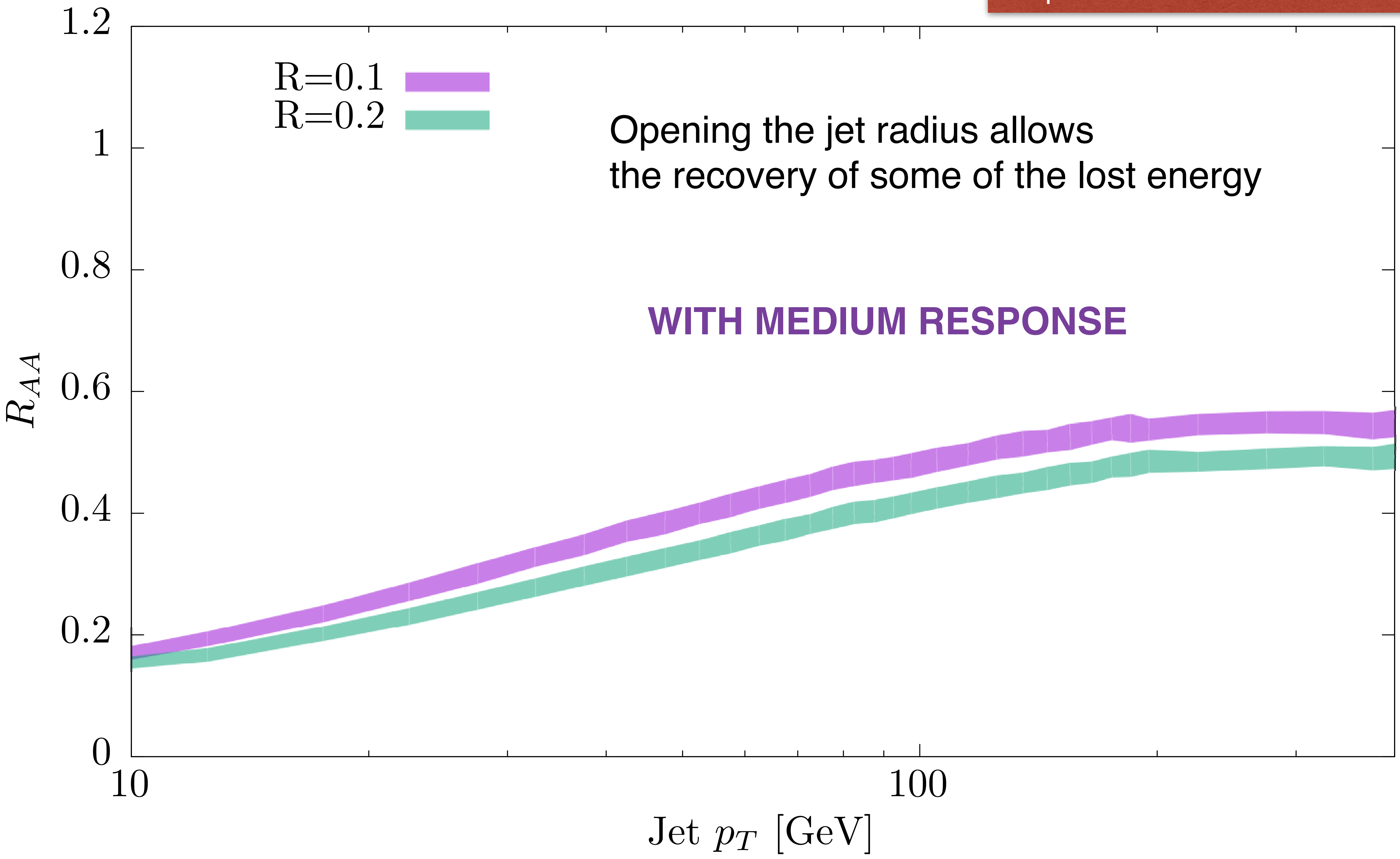
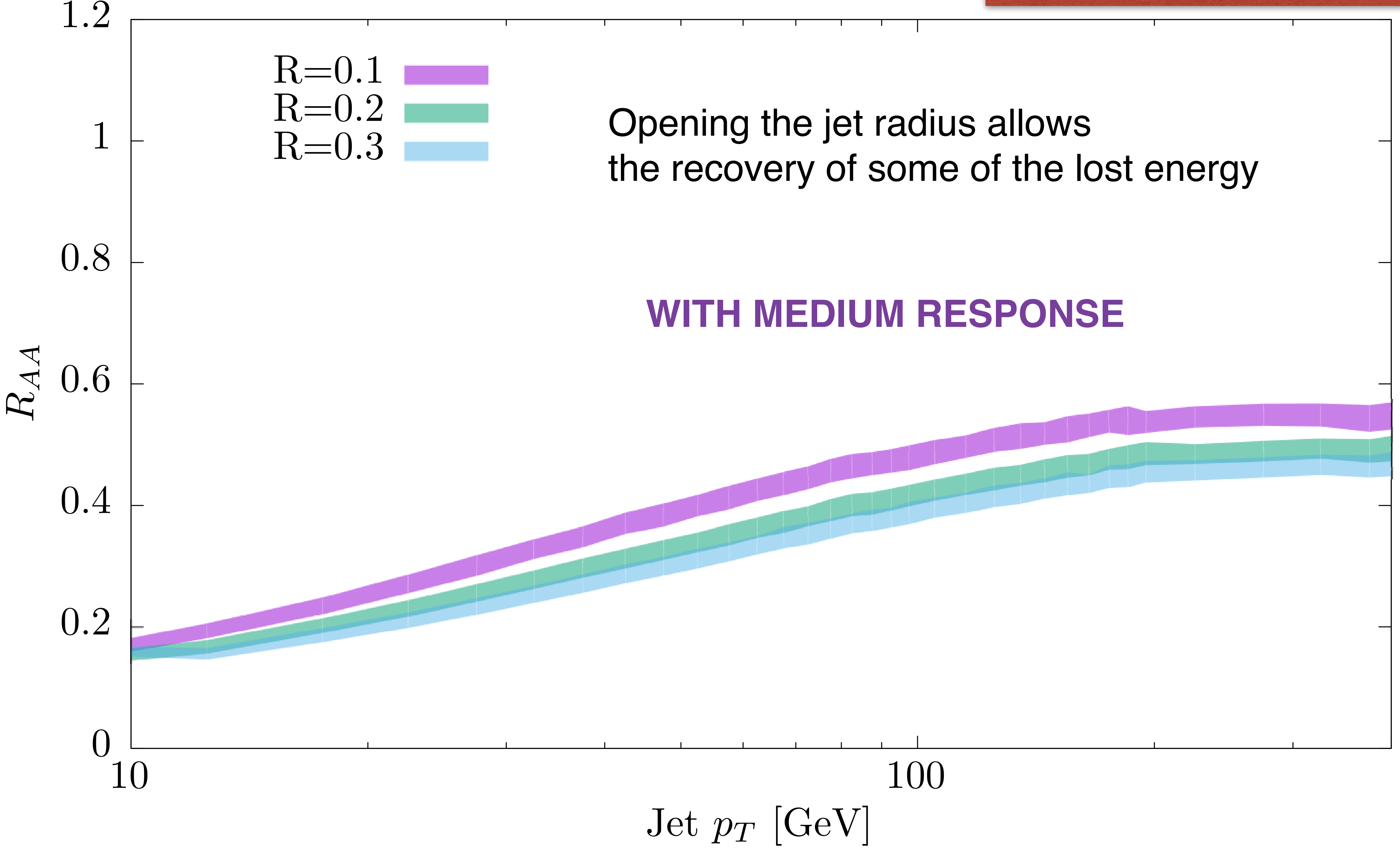


Opening the jet radius allows the recovery of some of the lost energy

R_{AA} vs R

adapted from Pablos et al. - JHEP '16



R_{AA} vs R

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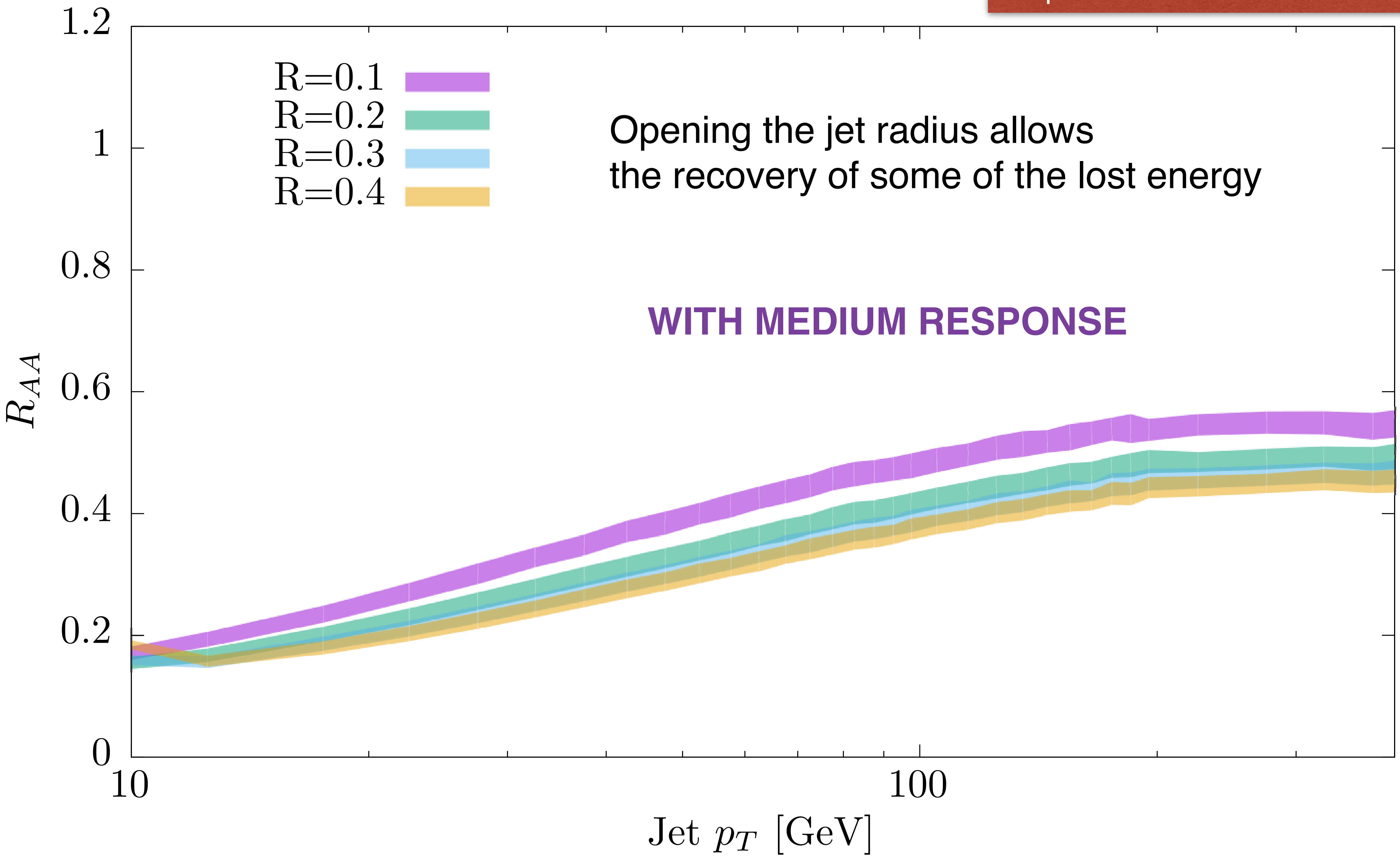

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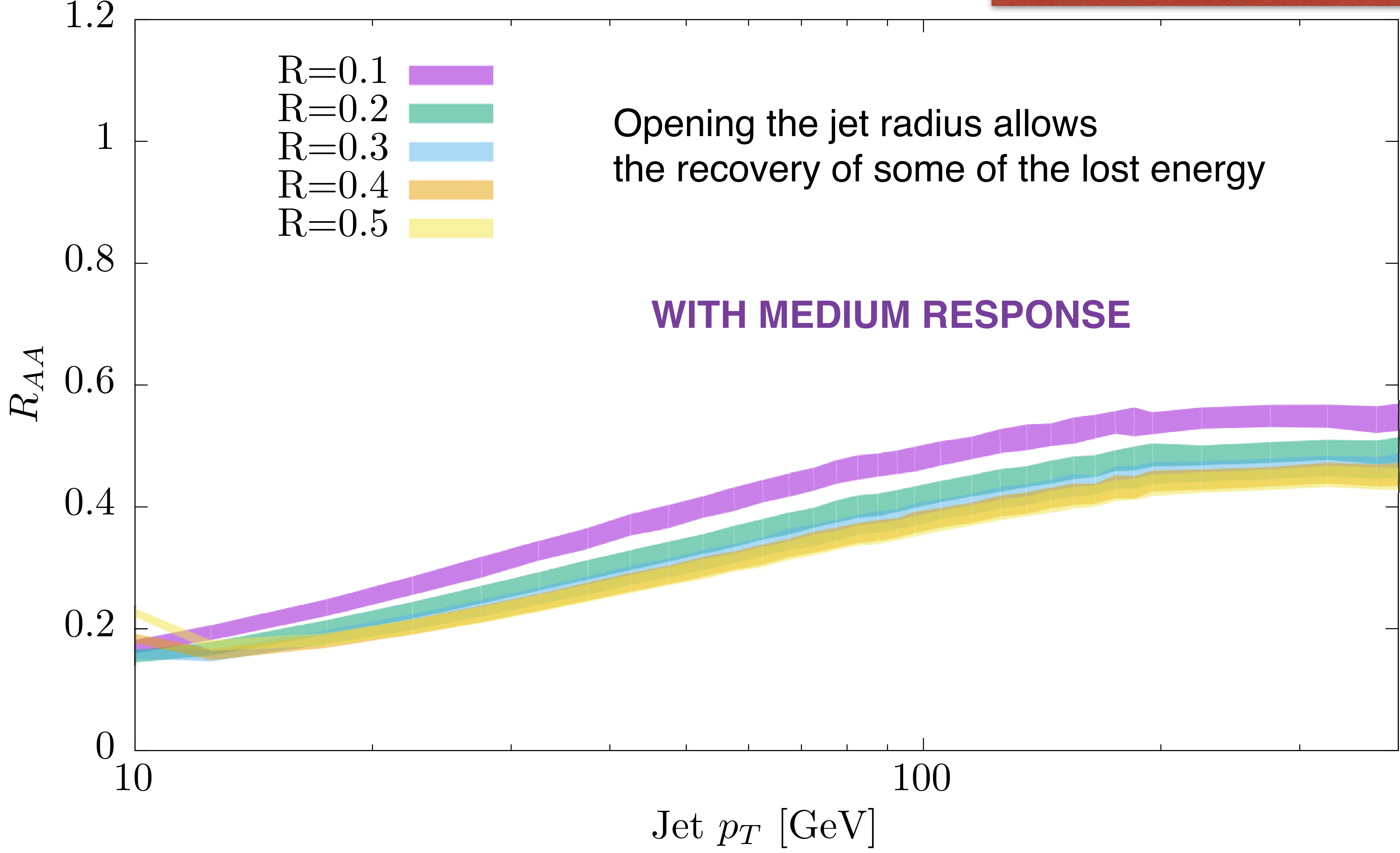

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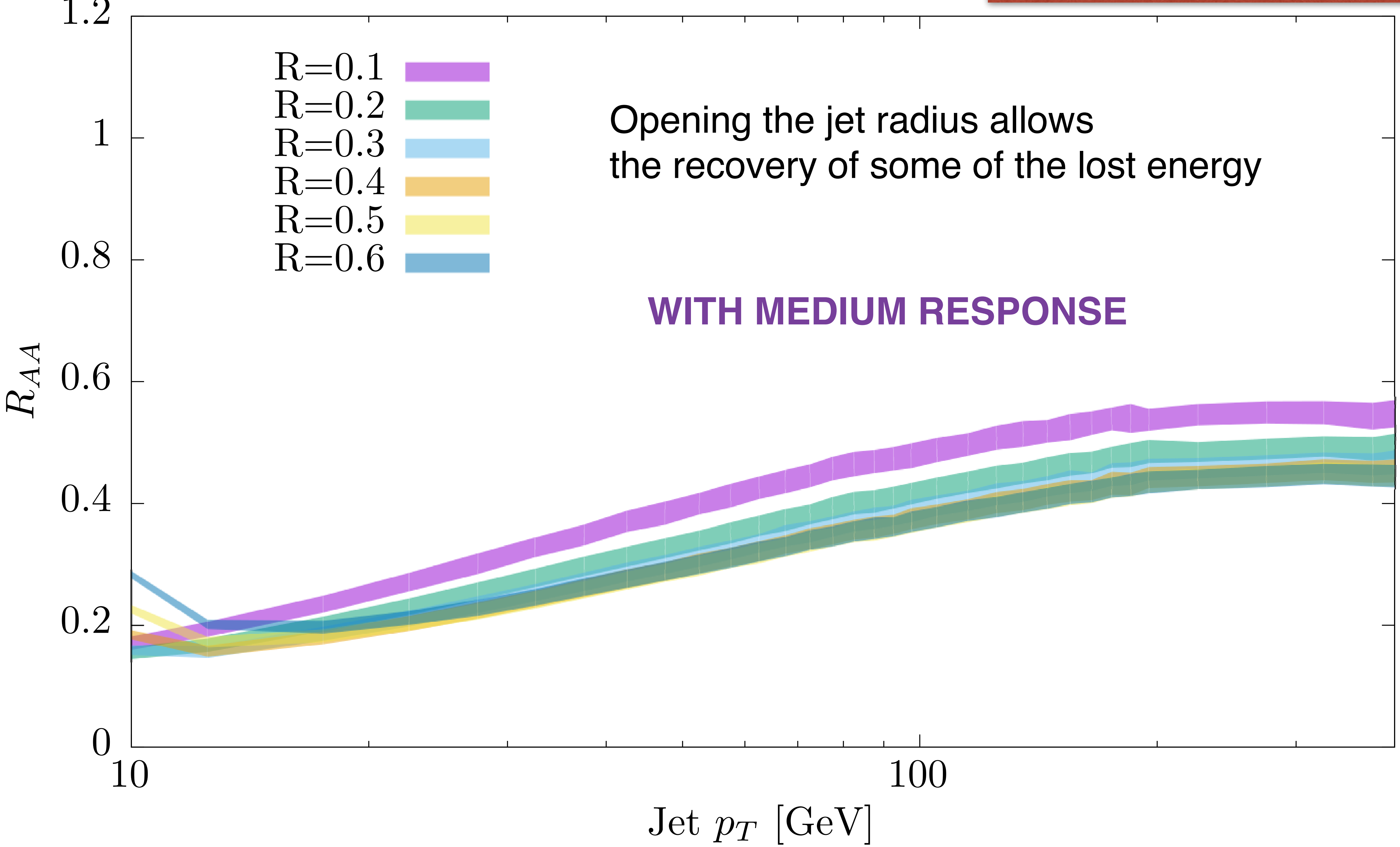

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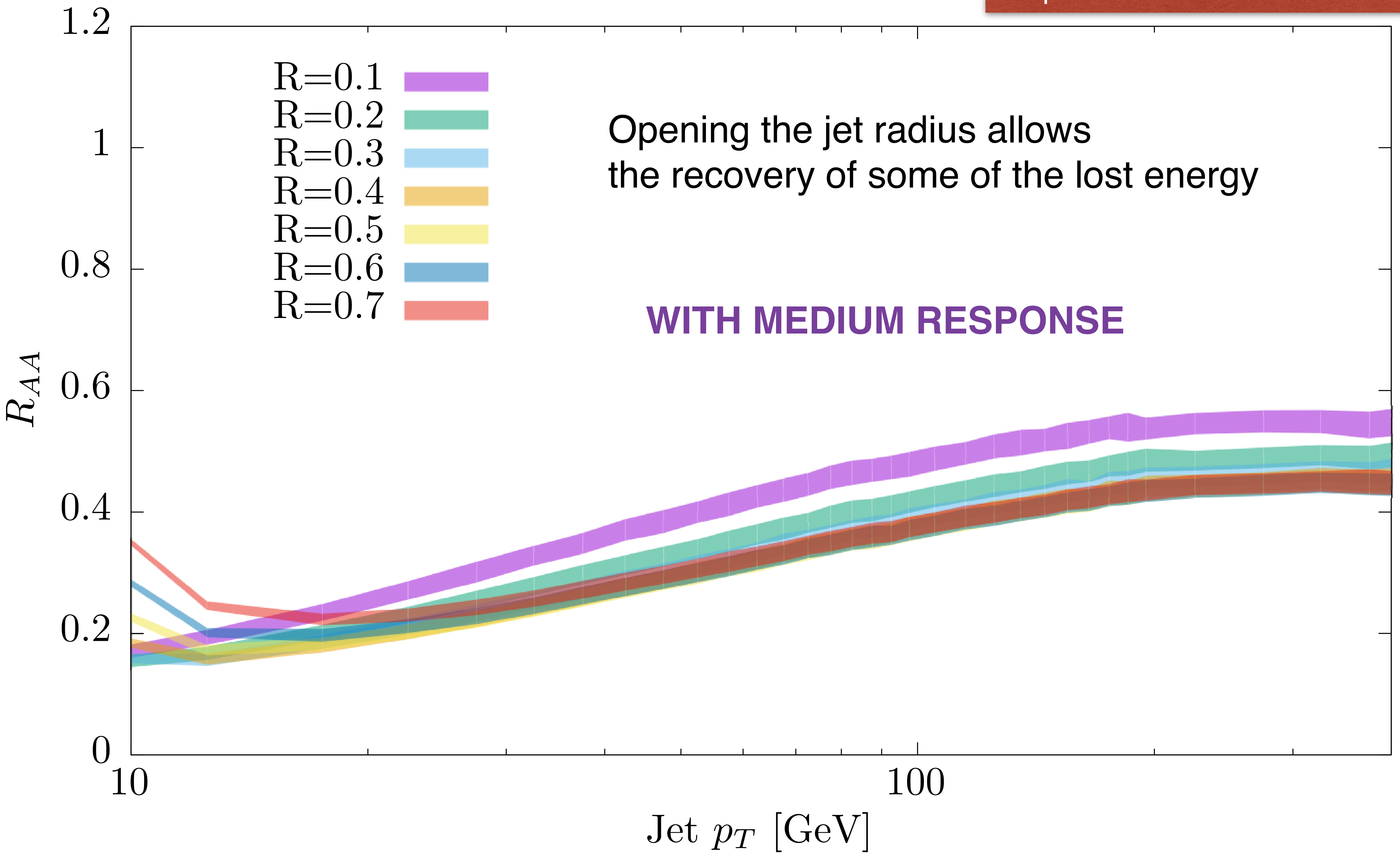

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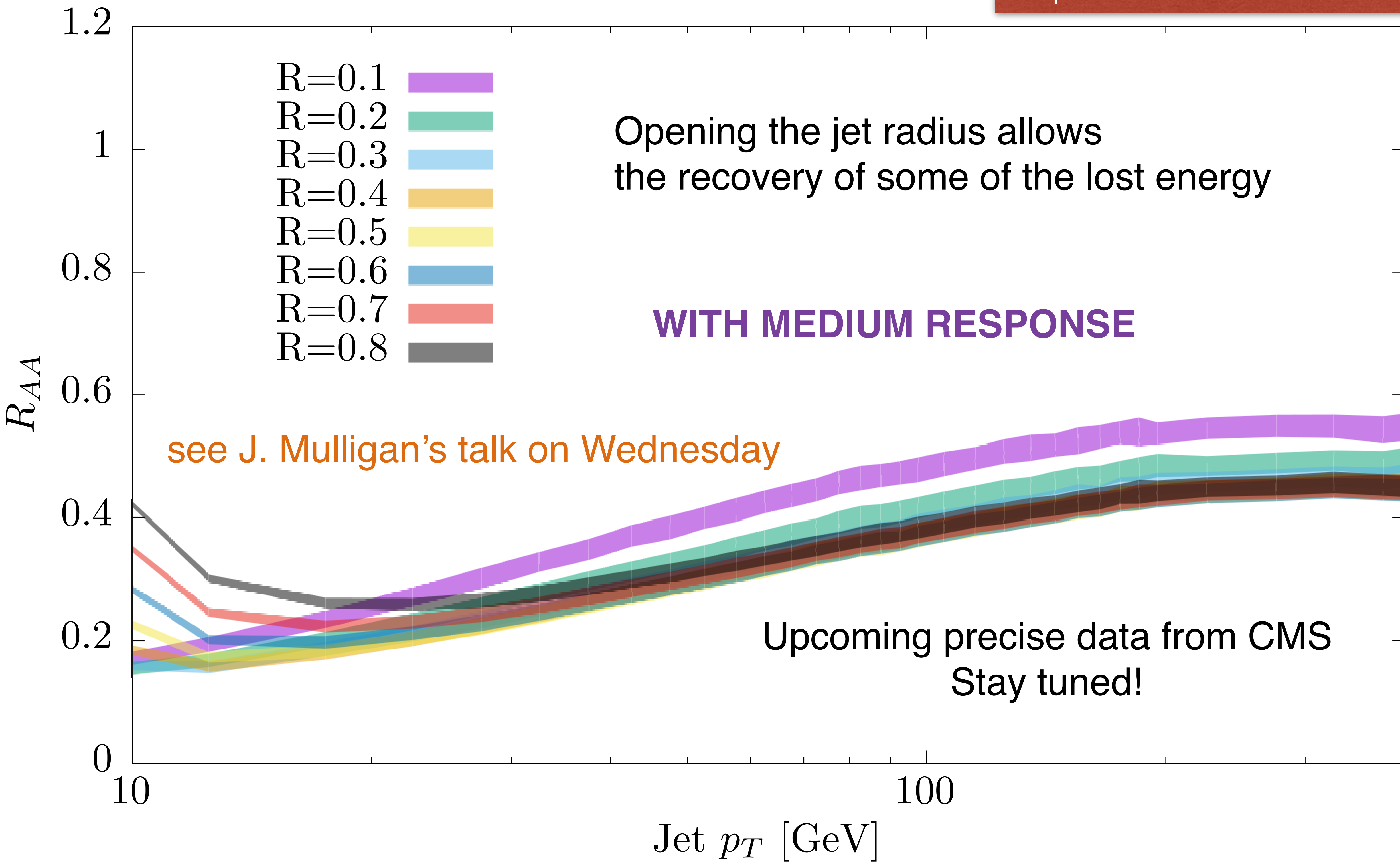


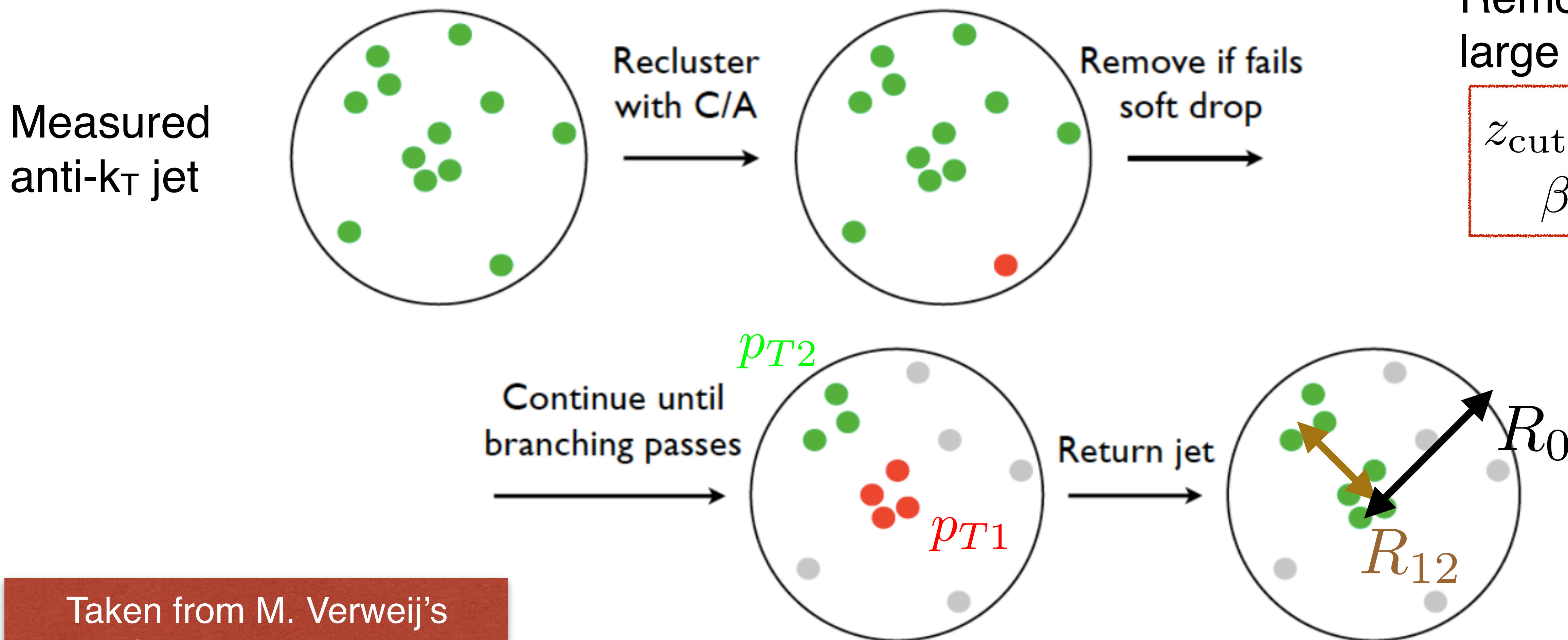
Characteristic behaviour of strong coupling: efficient energy transfer into hydro modes

New substructure observables

Larkoski et al. - JHEP '14, PRD '15

Soft Drop condition: $\frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} > z_{\text{cut}} \left(\frac{R_{12}}{R_0}\right)^{\beta}$

Grooming techniques:



Remove large angle & soft:

$z_{\text{cut}} = 0.1$
$\beta = 0$

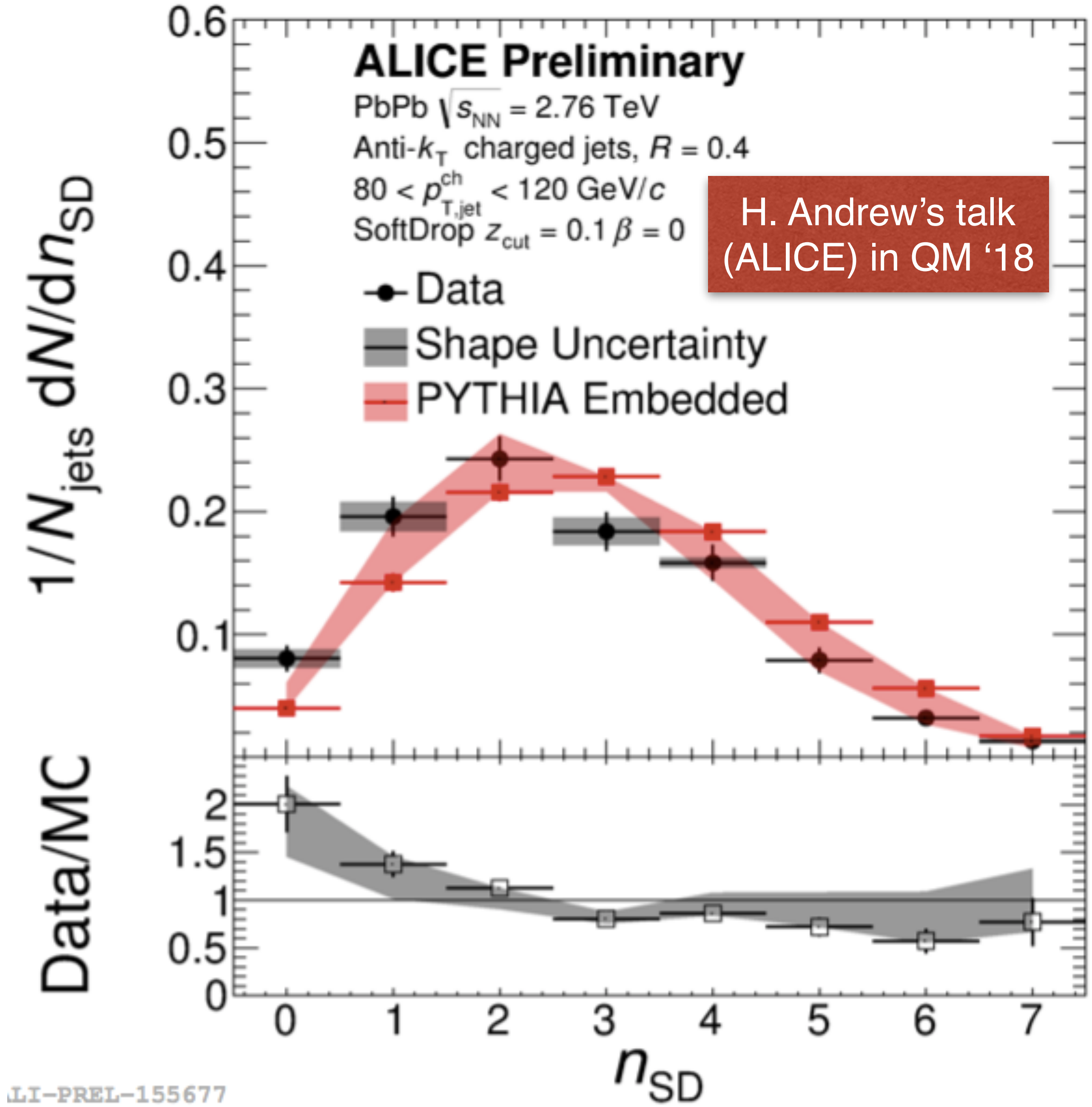
Taken from M. Verweij's slides @ MIT HI workshop '16

Provides momentum balance between the two groomed subjets.

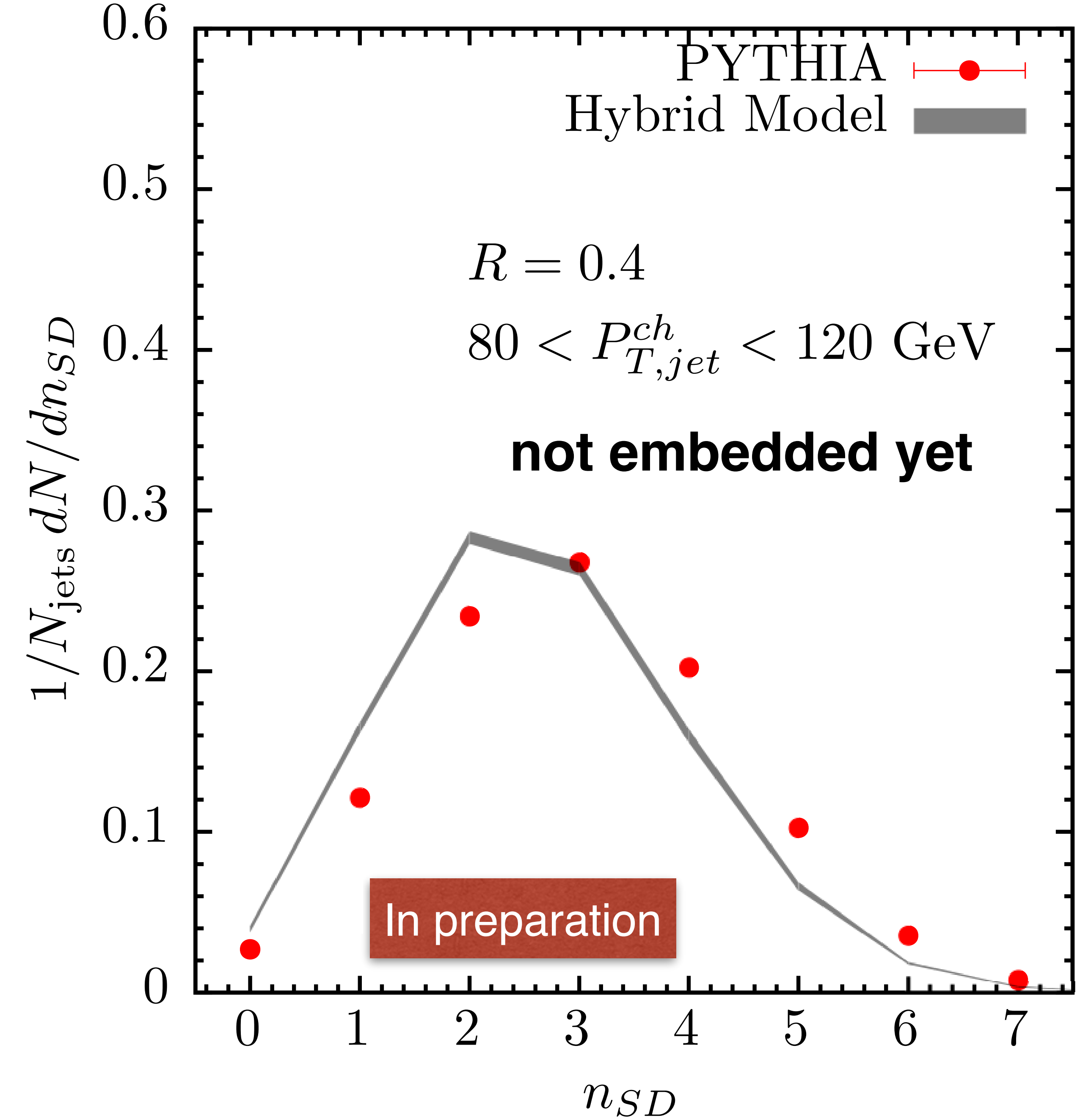
Analytically well understood observable: strongly relates to QCD splitting function.

Recursive Splittings

Count the number of times that the same jet satisfies the Soft Drop condition

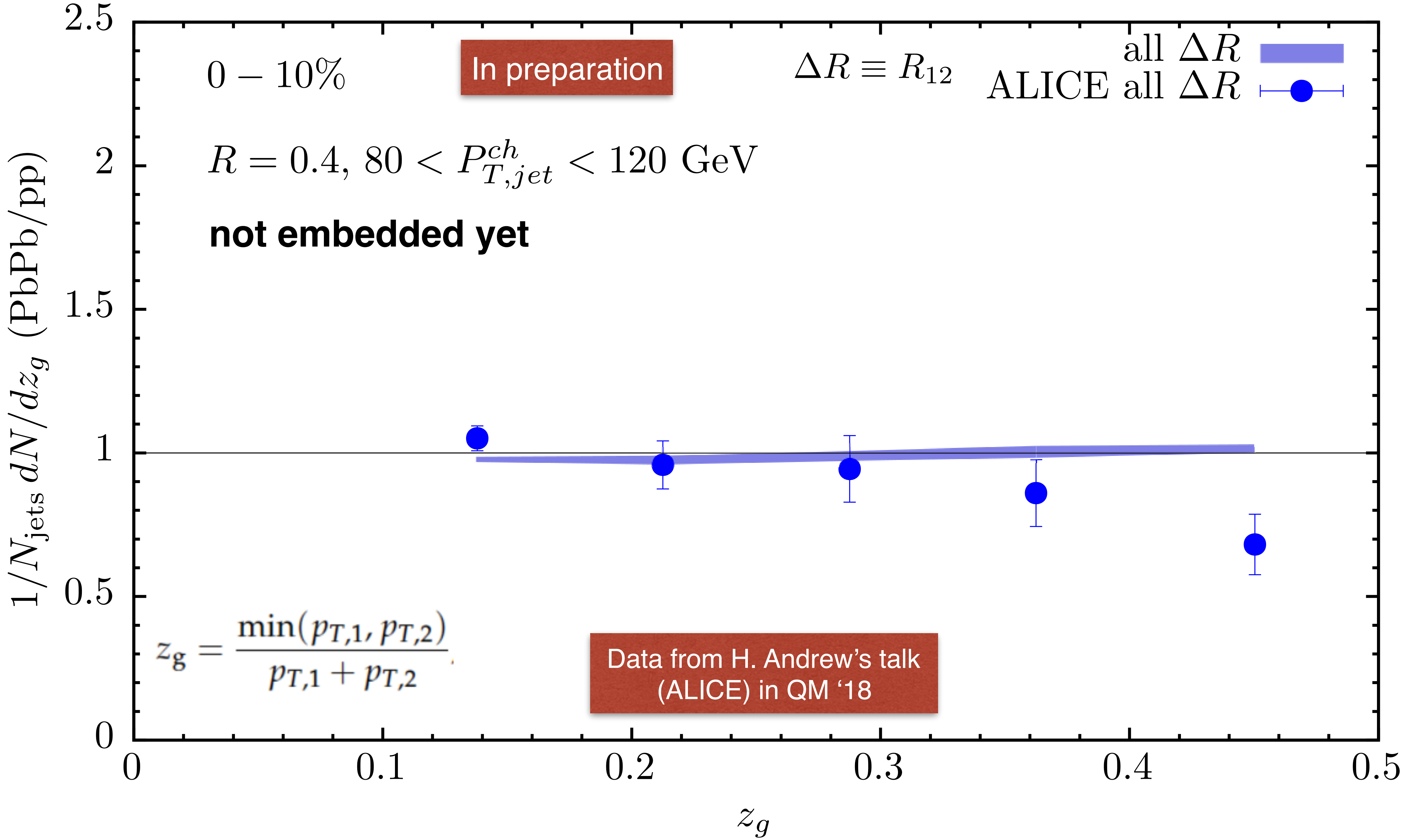


No enhancement in the # splittings passing Soft Drop in medium.



Suppression of wide structures tends to slightly reduce n_{SD}.

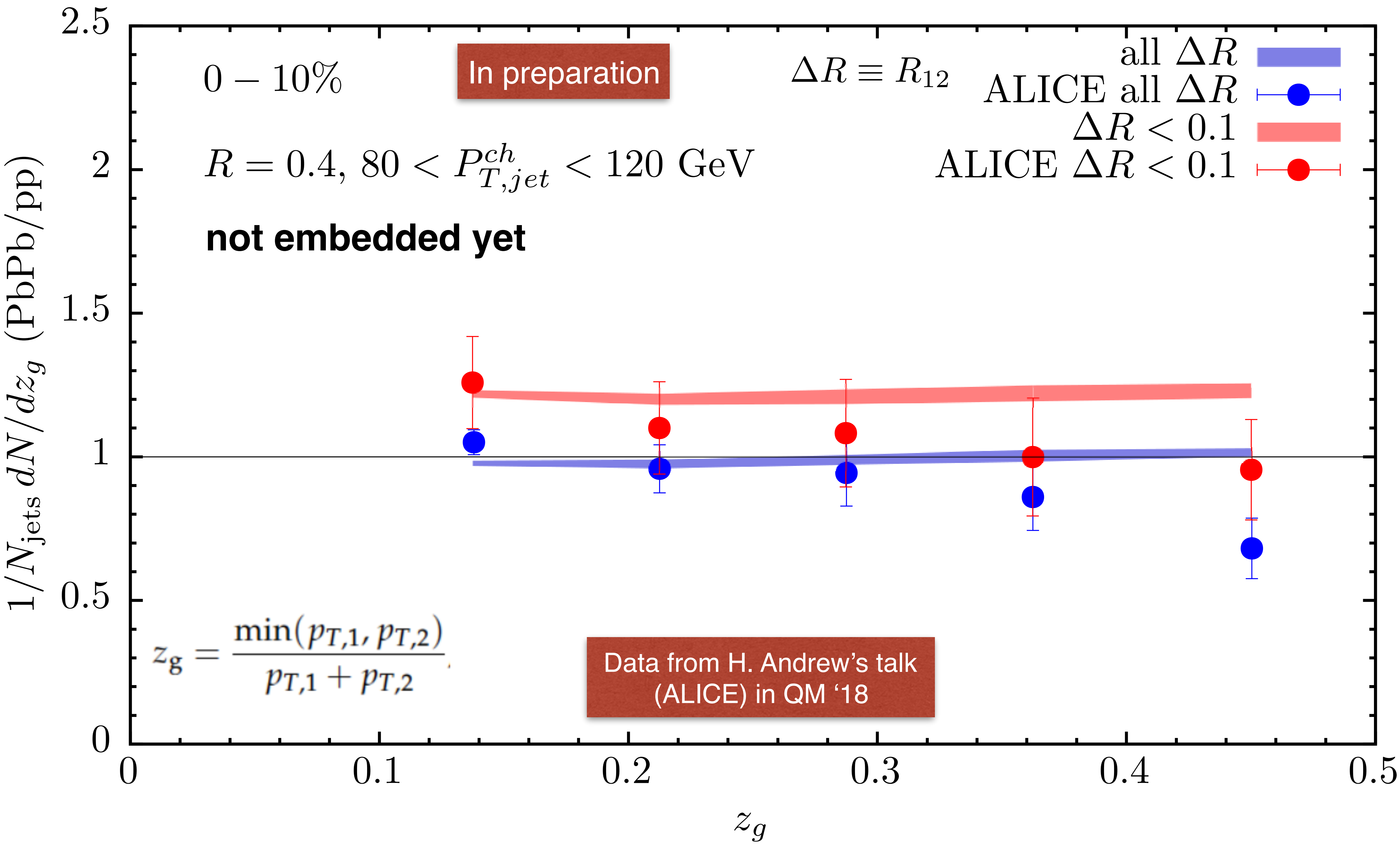
Momentum sharing distribution



Shape of the distribution not modified because our model assumes vacuum-like shower.

Embedding can have non-trivial effect in ratio, since jets in numerator narrower than denominator.

Momentum sharing distribution



Wide structure suppression modifies probability of finding subjet at large angles w.r.t. pp.

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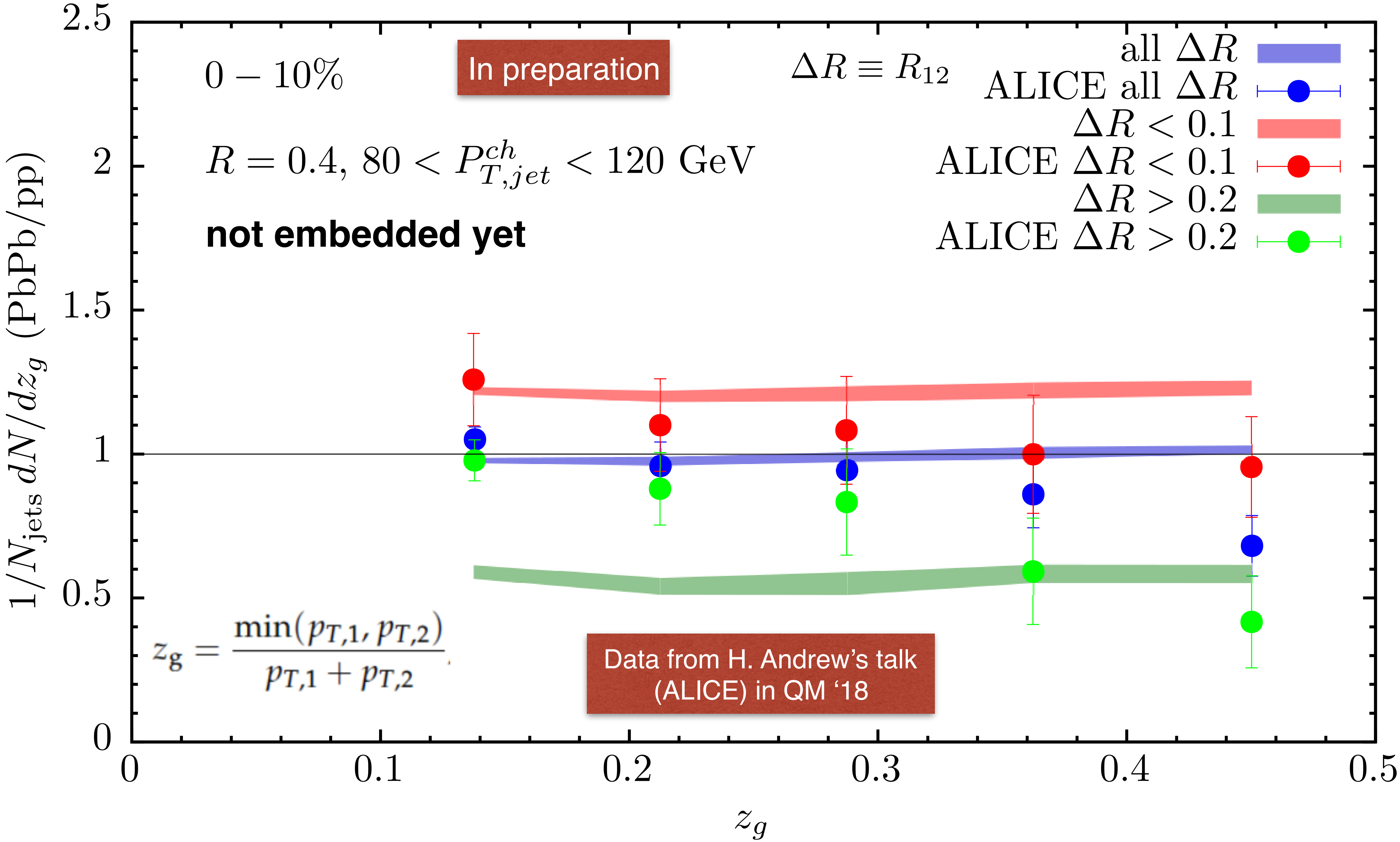
Momentum sharing distribution



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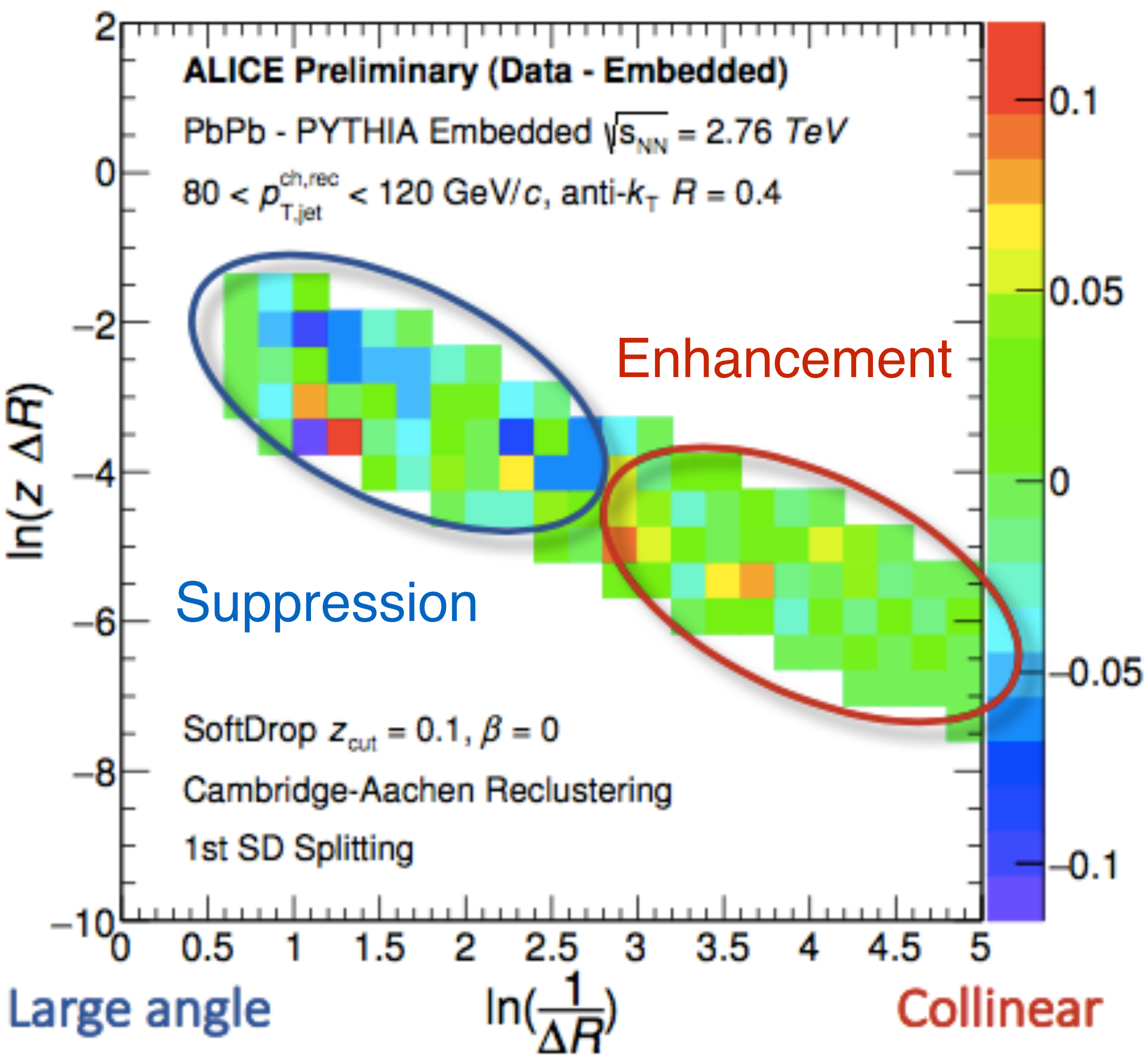
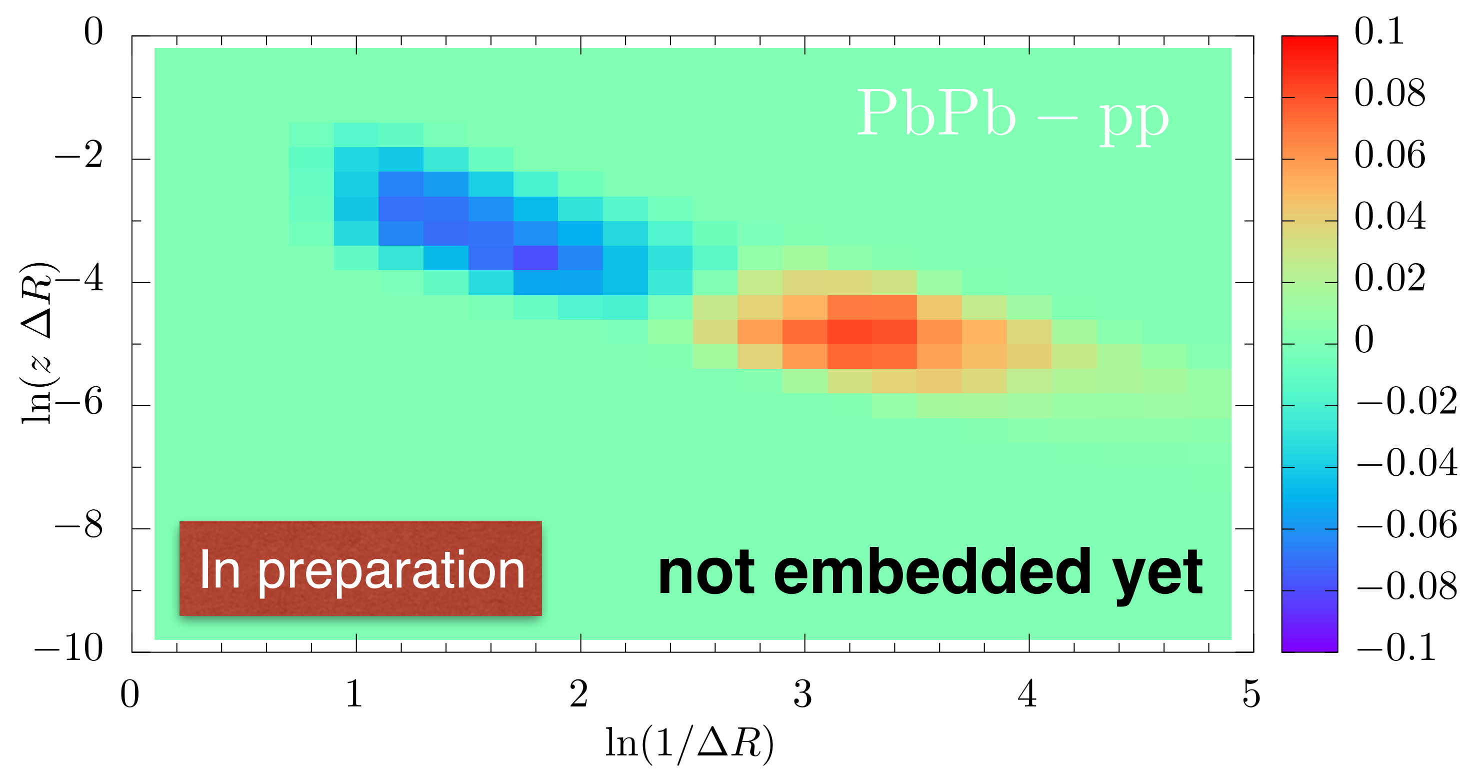
Lund map



H. Andrew's talk (ALICE) in QM '18

Fill a 2D density map by using both momentum balance (z_g) and angular separation (ΔR).



see M. Verweij's talk on Wednesday

A suppression of large angle splittings and enhancement of collinear splittings is observed - consistent with observation in z_g measurement.

In qualitative agreement with the Hybrid Model

Conclusions

- the hybrid model can describe jet and hadron suppression simultaneously!
  - tension between RHIC and LHC results suggesting need for larger coupling at RHIC
- relative hadron vs. jet suppression manifest in high z region of jet FFs AA/pp ratio
  - high z enhancement due to wider jets losing more energy than narrower ones
- jet suppression fairly independent of jet radius due to competing effects
  - jet sample within a larger radius loses more energy, but can recover more lost energy
- new substructure observables are consistent with presented picture
  - # SoftDrop splittings, angular dependence of z_g, Lund map
  - (need to account for bkgd. effects for a fair comparison)

JETSCAPE

v1.0 has been now released! https://github.com/JETSCAPE

Modular simulator of heavy ion collisions

Energy loss modules: MATTER, LBT, MARTINI, AdS/CFT

Will soon feature concurrent Jet+Hydro evolution!

Backup Slides

An *estimate* of finite resolution effects

Mehtar-Tani et al. - PLB '12

Casalderrey & Iancu - JHEP '11

Casalderrey et al. - PLB '13

Weak coupling:

- interplay between antenna angle, formation time and emission wavelength
- medium interactions can destroy antenna color correlations

→ *radiation from the global charge only if system not resolved by QGP*

Strong coupling:

Casalderrey & Ficnar - arXiv:1512.00371

- quark-gluon system emulated by string with kink
- stopping distance modulated by angular separation between endpoint & kink

needs further study!

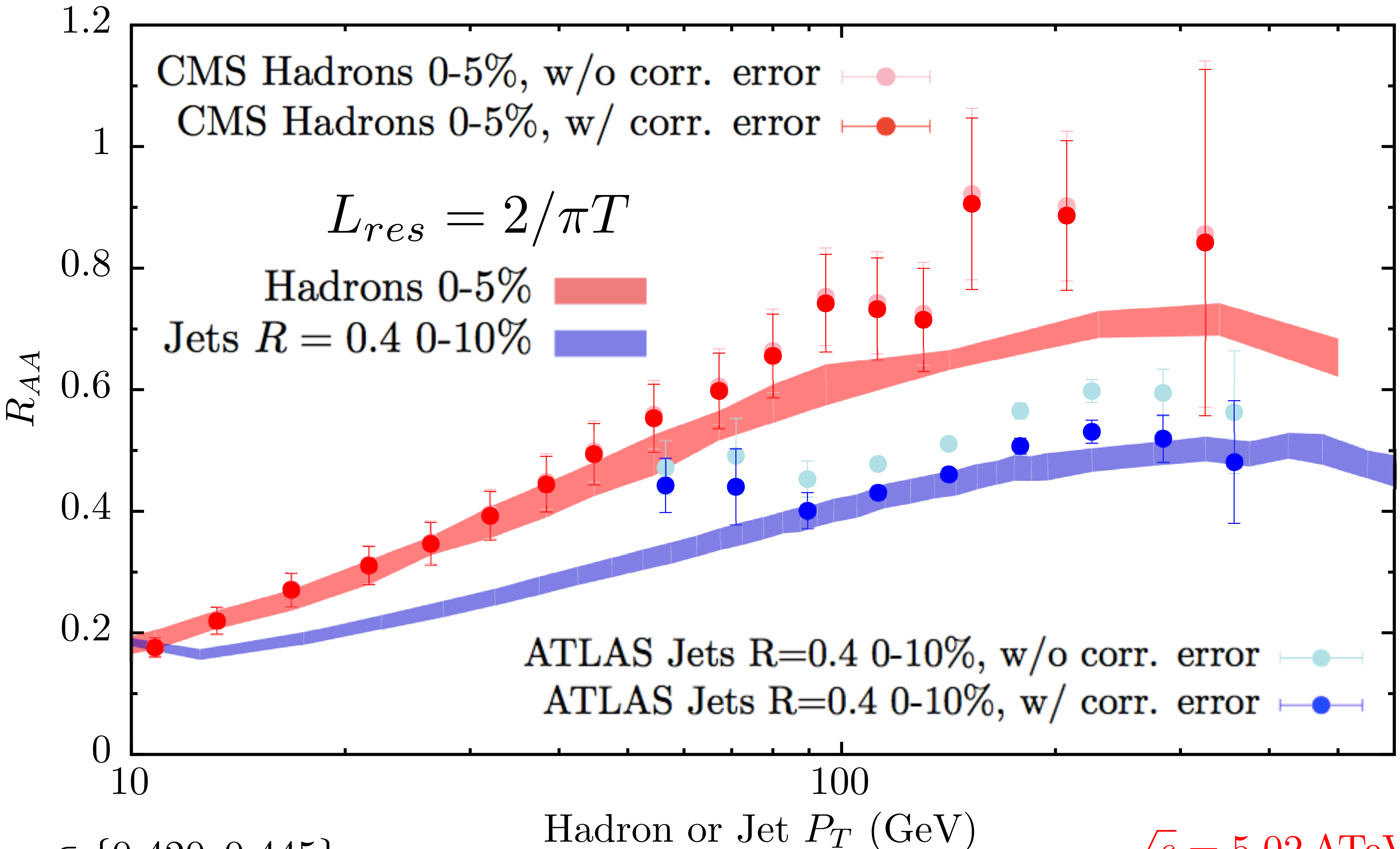
In Hybrid Model:

- unresolved dipoles lose energy as a single effective excitation
- two partons are resolved if their separation is greater than resolution length

Hulcher et al. - JHEP '18

$$L_{\text{res}} \sim \lambda_D$$

Fit results



$\kappa \in \{0.420, 0.445\}$

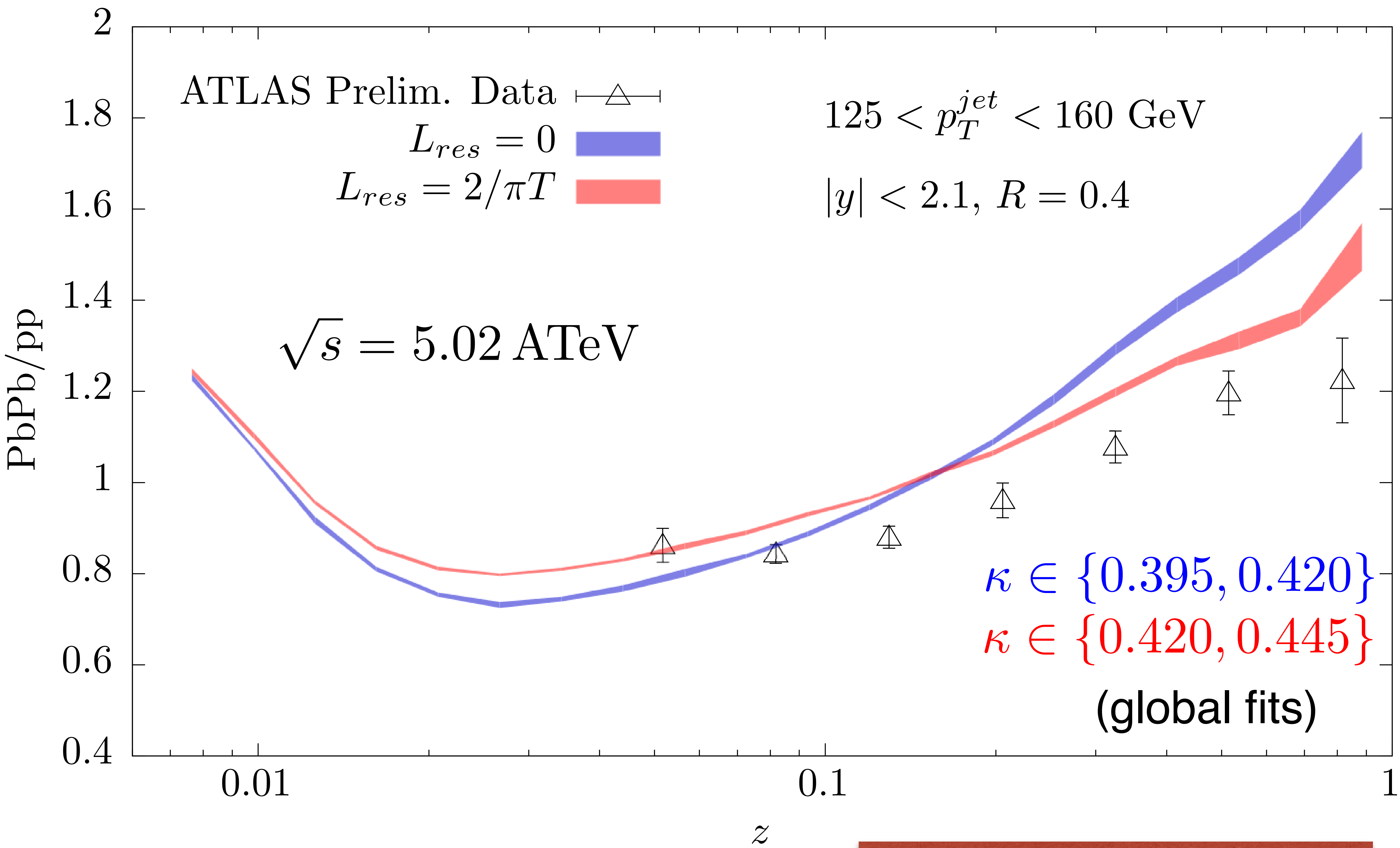
(global fit)

adapted from Pablos et al. - arXiv:1808.07386

$\sqrt{s} = 5.02$ ATeV

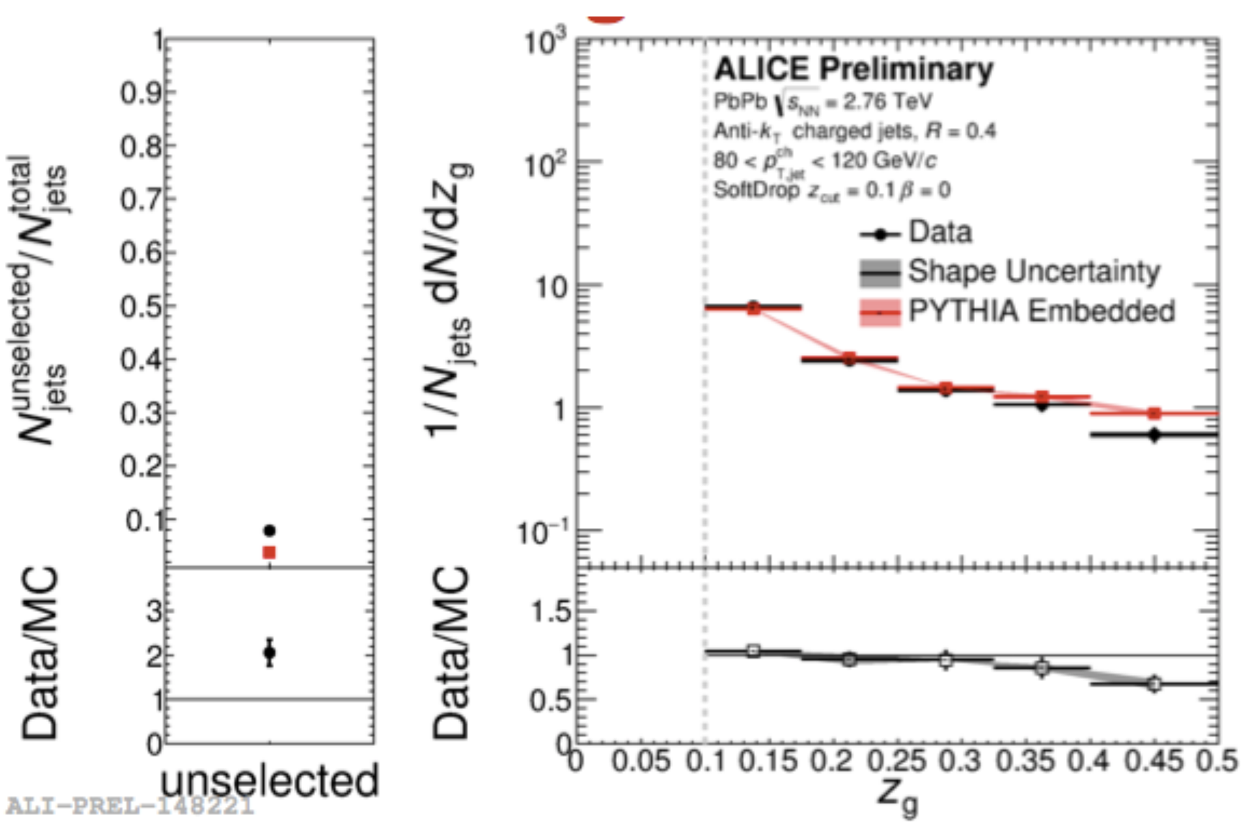
$\sqrt{s} = 2.76$ ATeV

Extracted jet FFs



adapted from Pablos et al. - arXiv:1808.07386

ALICE Preliminary results on z_g

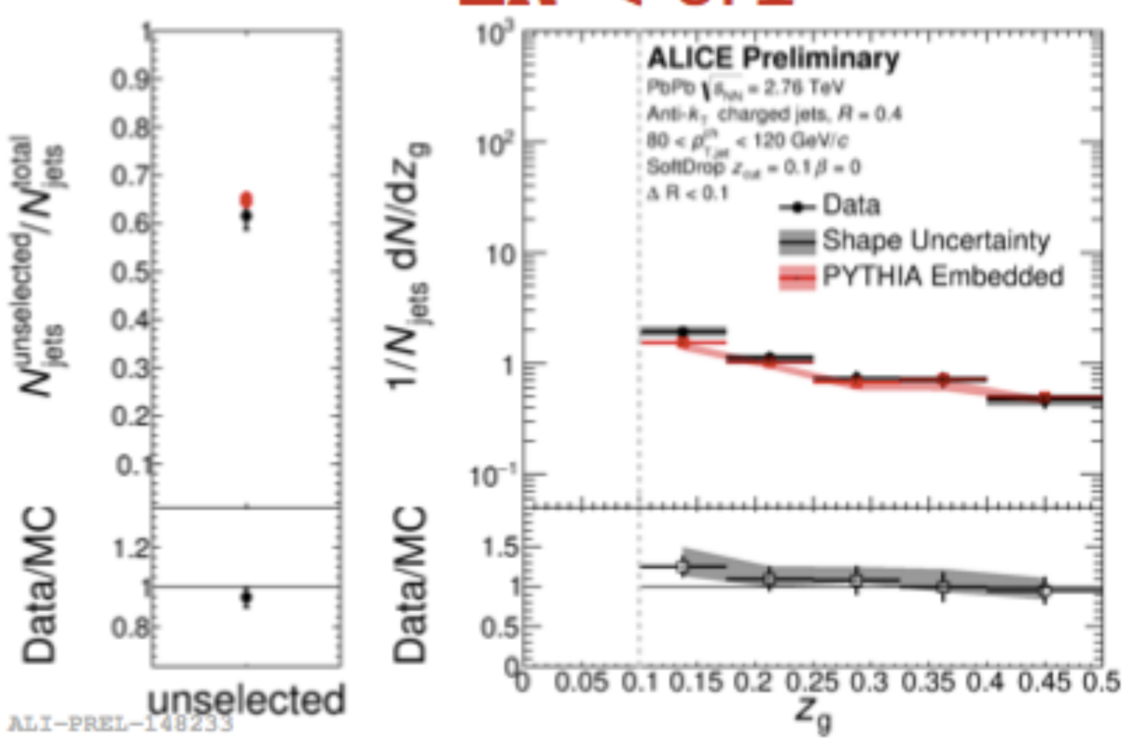


all ΔR

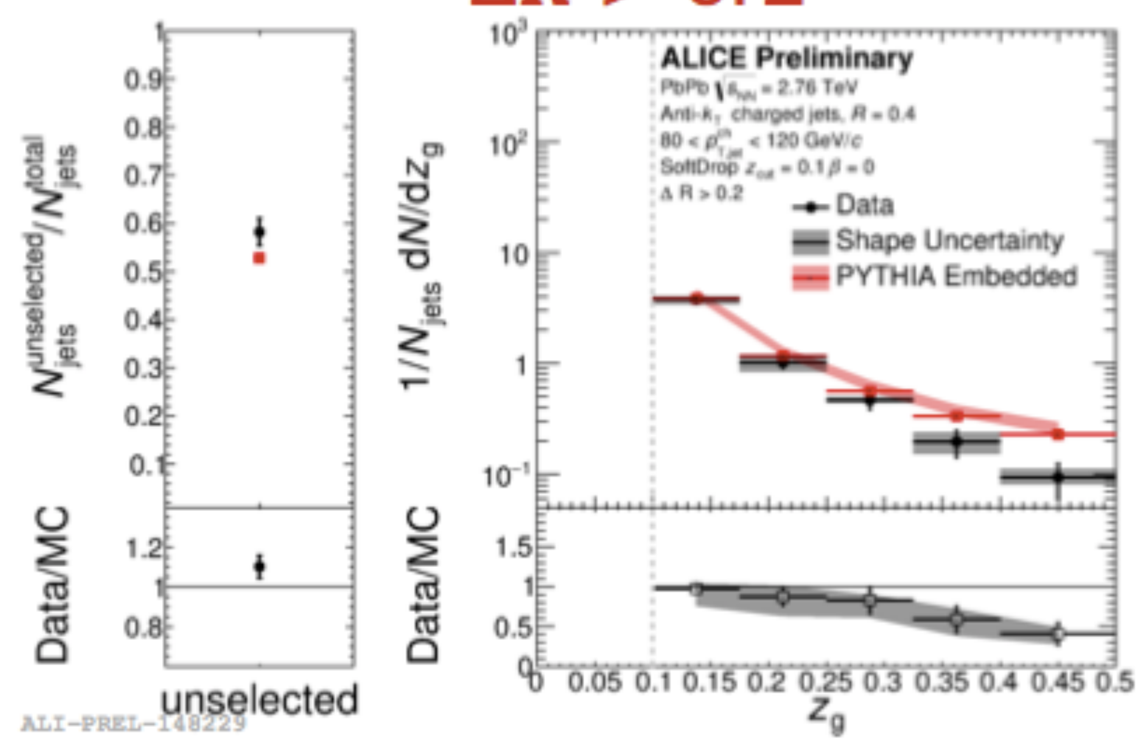
Not unfolded data:
need to smear theory results

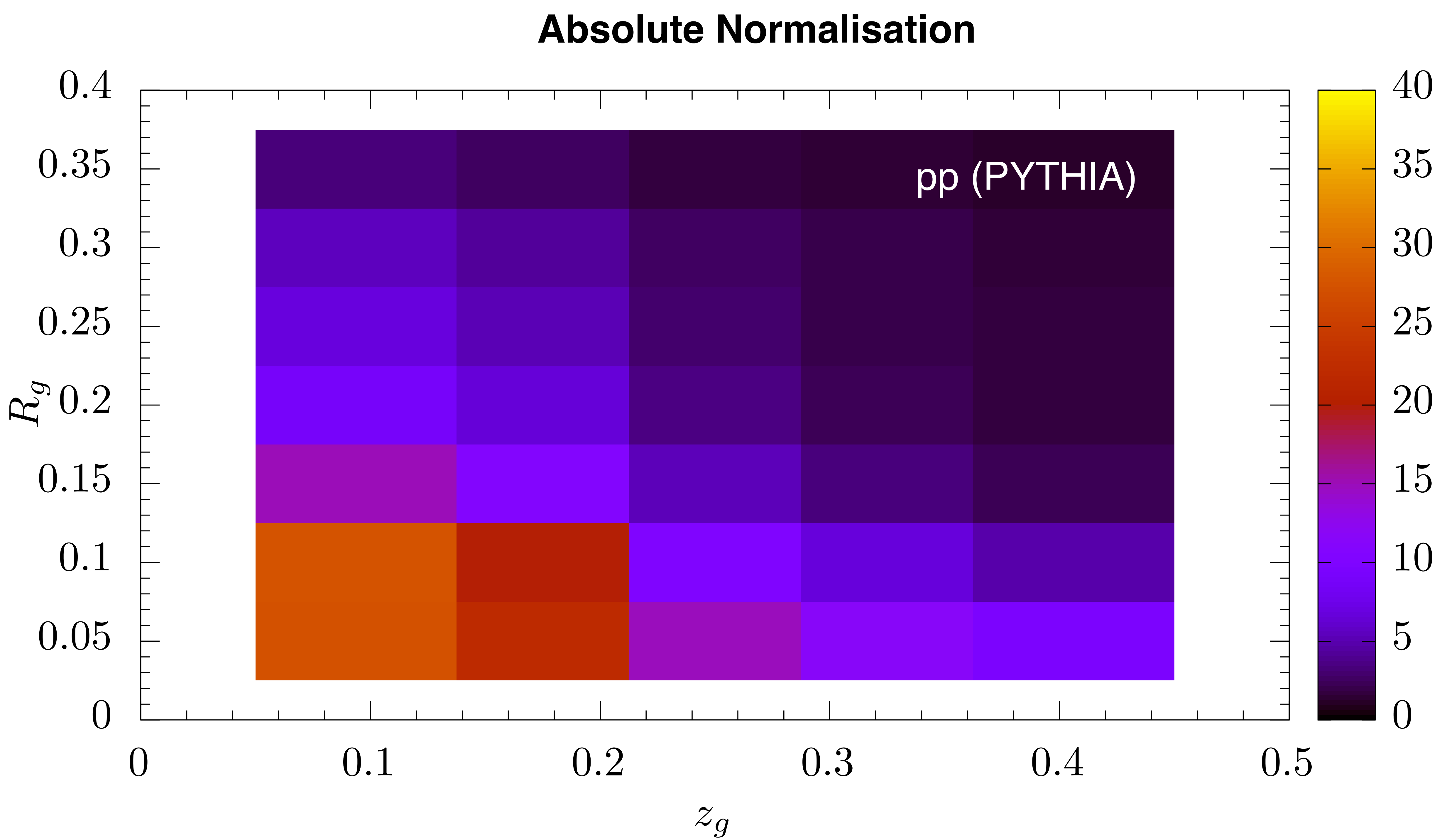
H. Andrew's talk (ALICE) in QM '18

$\Delta R < 0.1$



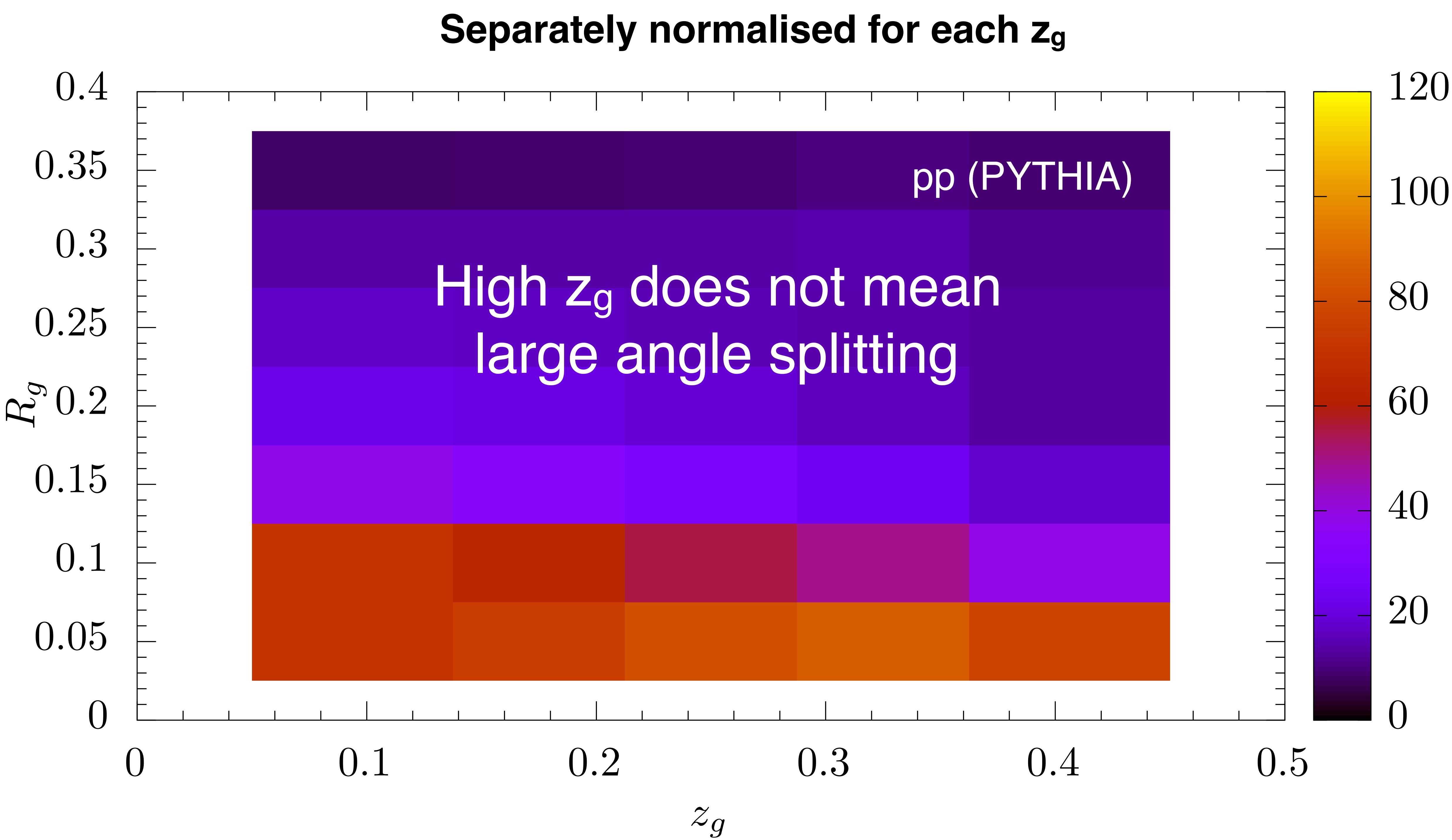
$\Delta R > 0.2$





Correlation between momentum balance & subjet angular separation

Understanding groomed observables



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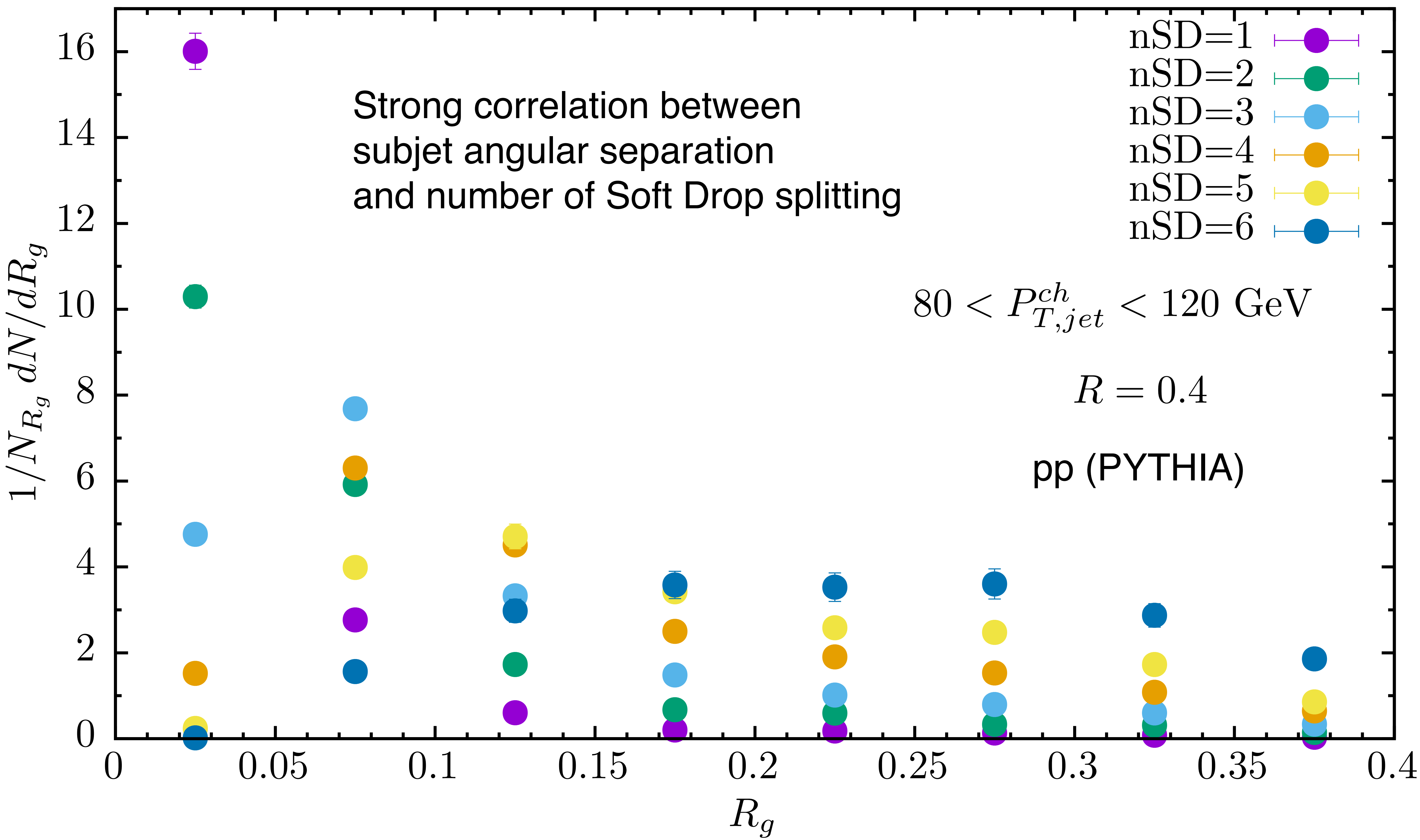
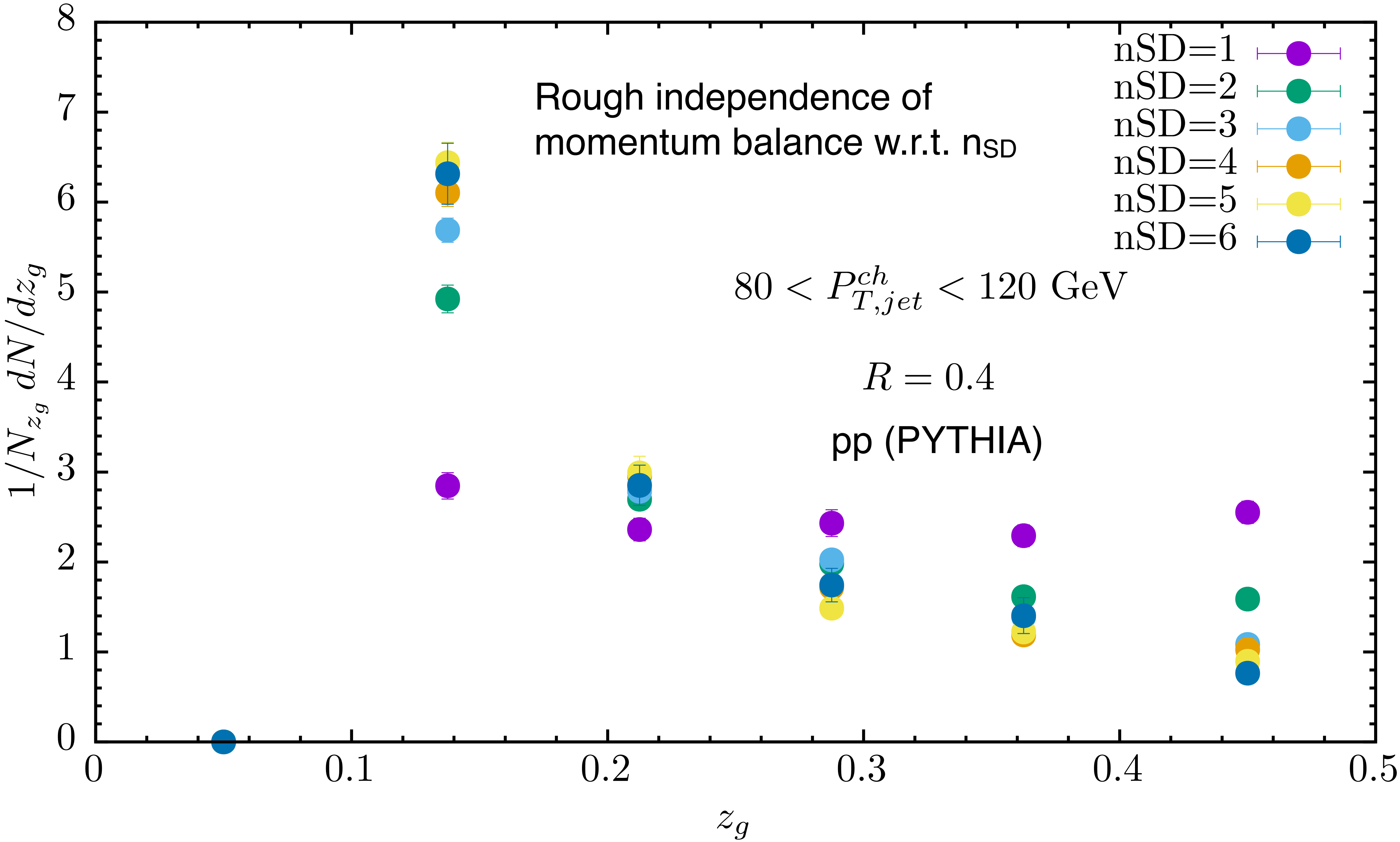


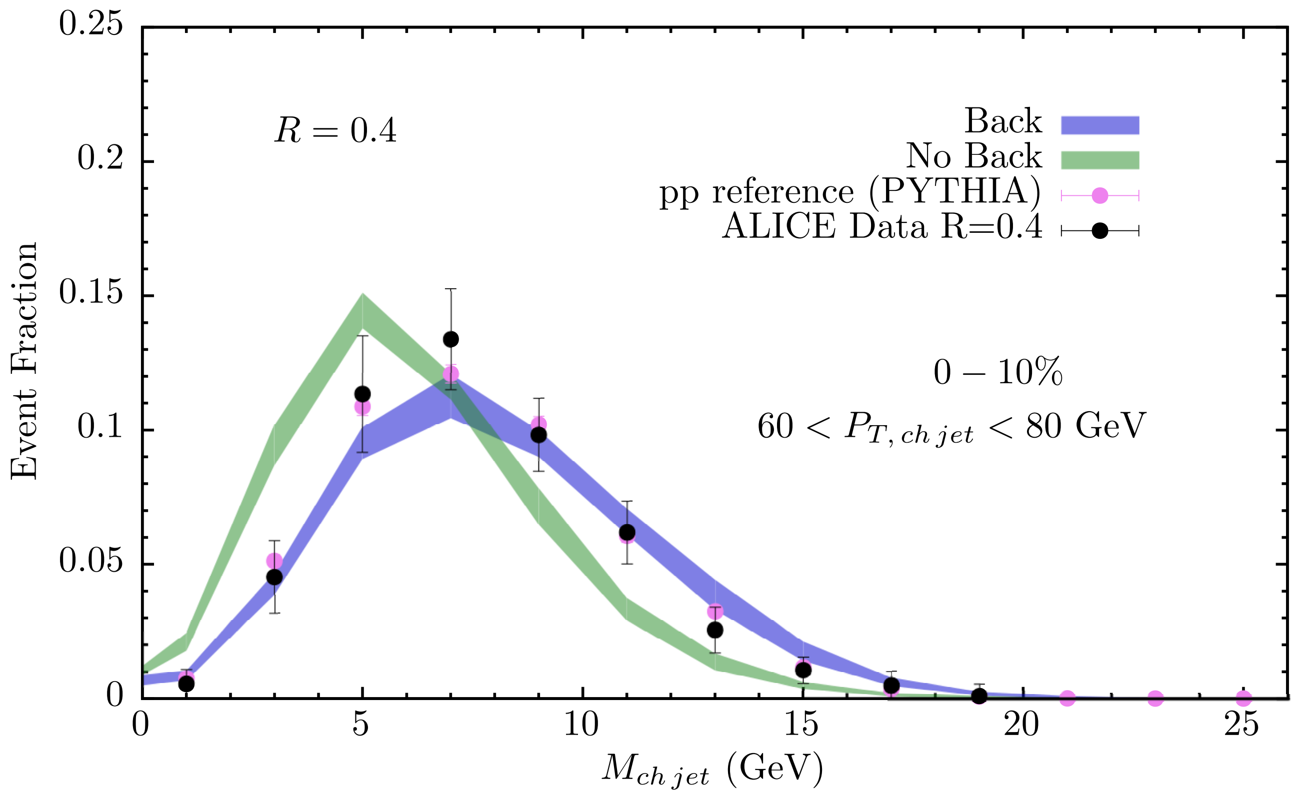
Suppression of wide structures ⟷ Reduction of n_{SD}

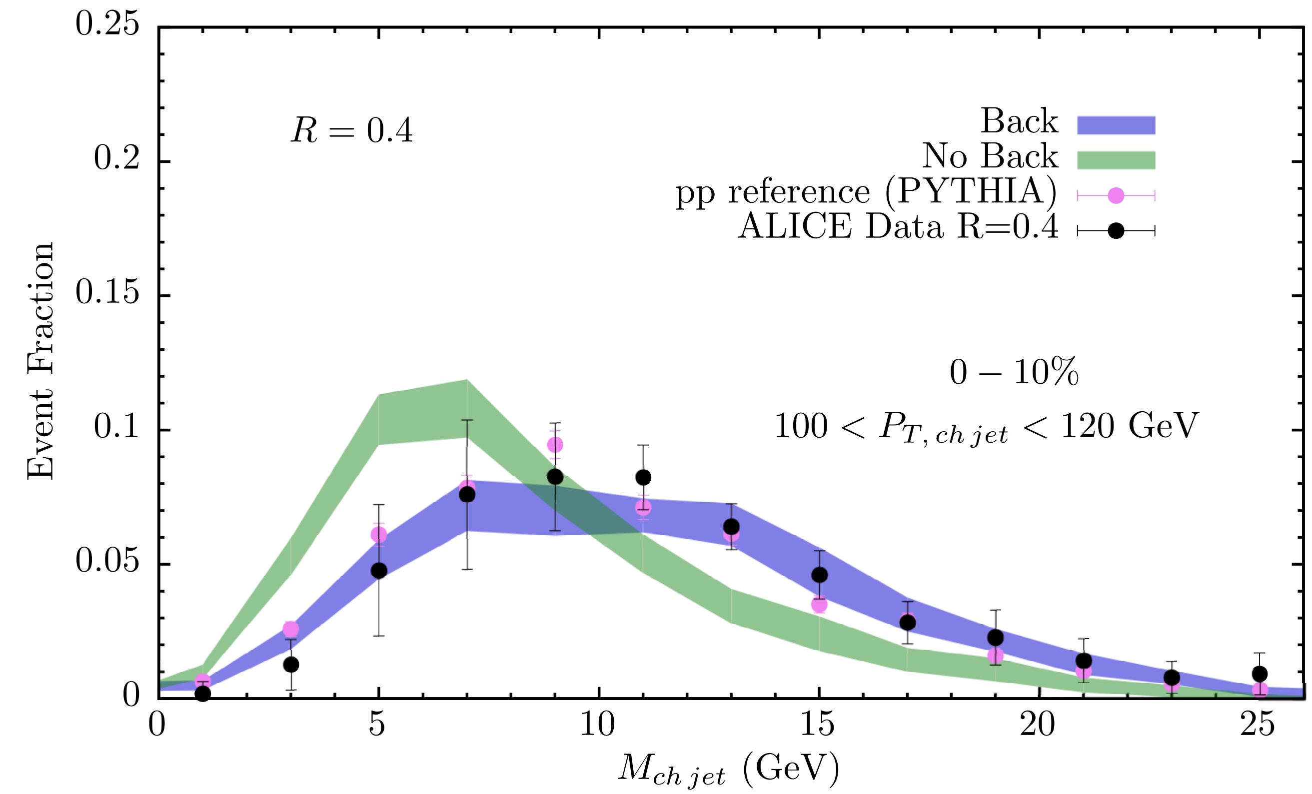
Understanding groomed observables

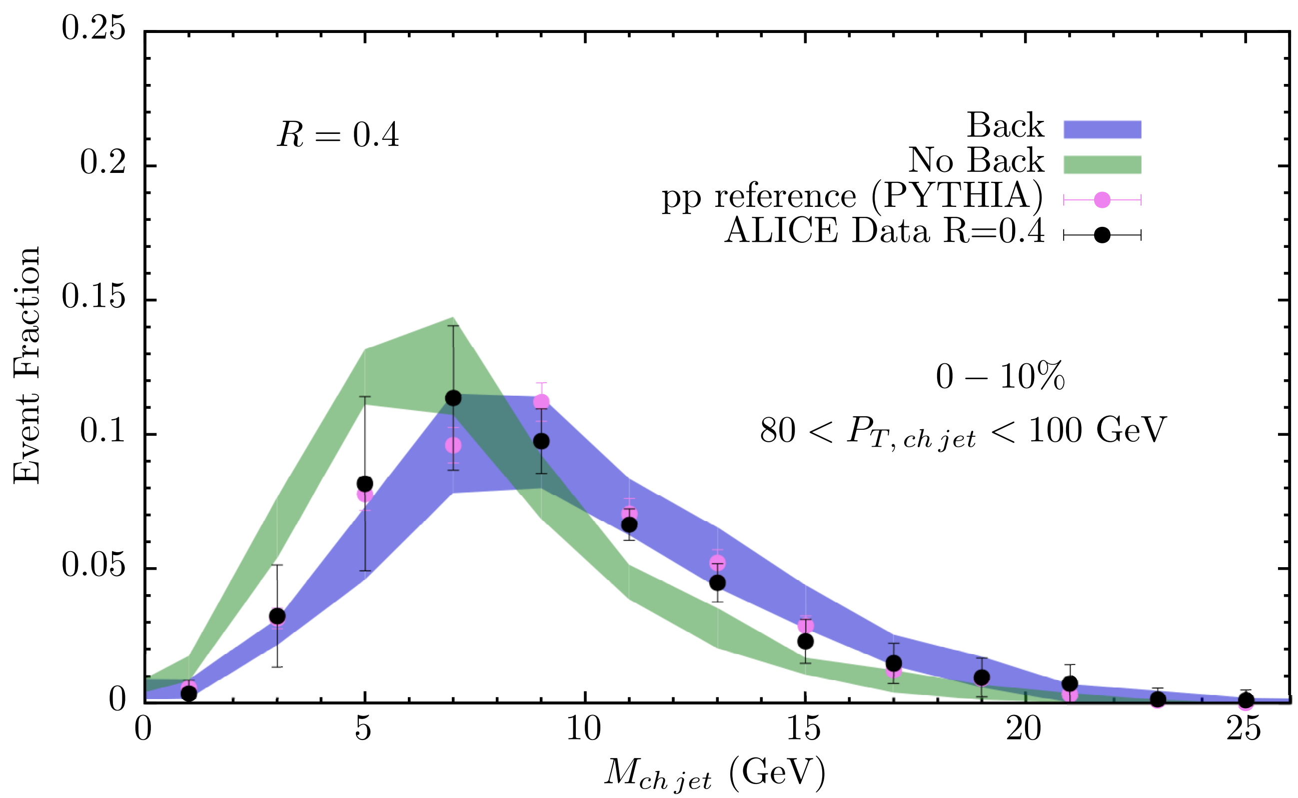


Suppression of wide structures ⟷ Not necessarily modifies z_g

Charged jet mass







$$M = \sqrt{E^2 - p_T^2 - p_z^2}$$

cancellation between two effects

quenching

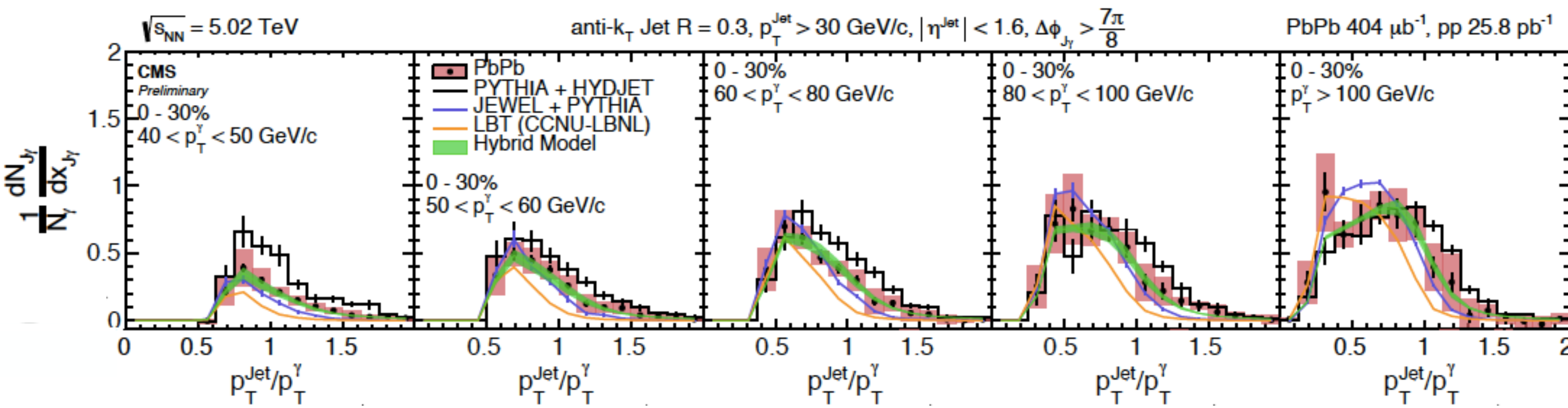
back-reaction

jet narrowing reduces jet mass

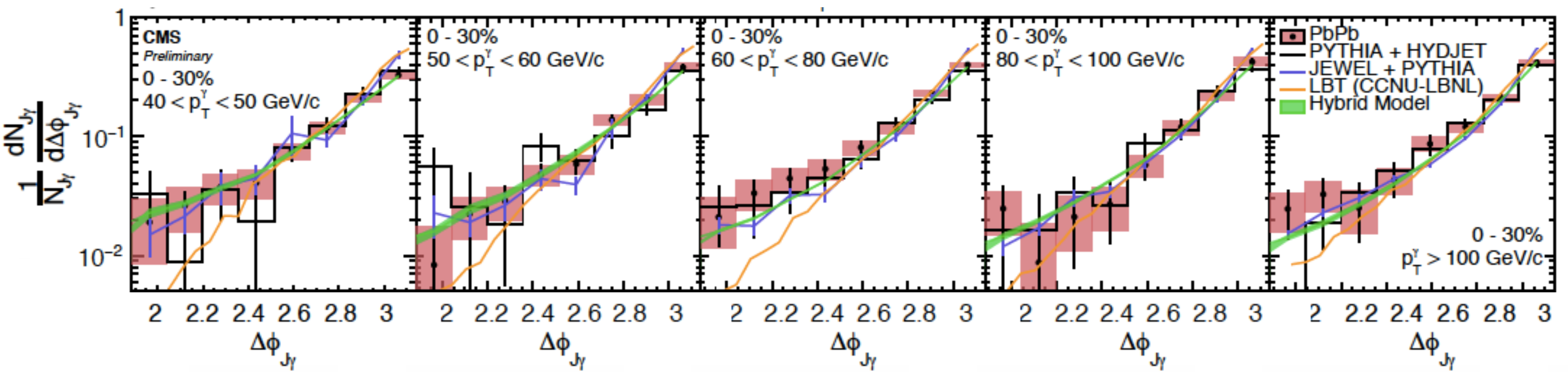
soft particles at edges rapidly increase mass

In preparation

Jet suppression: Photon-Jet events

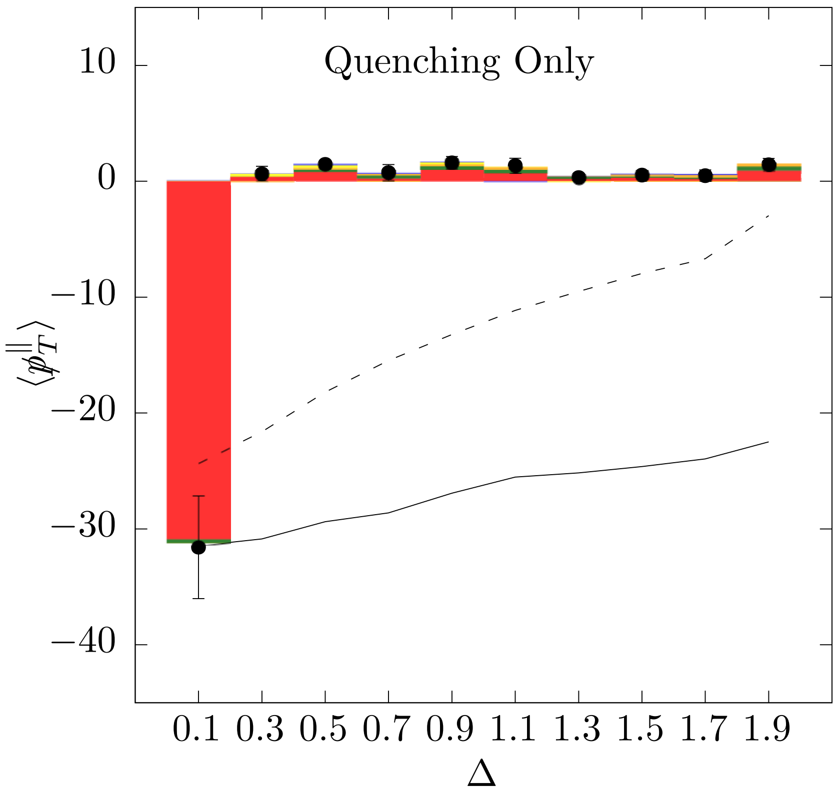


Core features of the model have been validated by e.g. photon-jet observables predictions

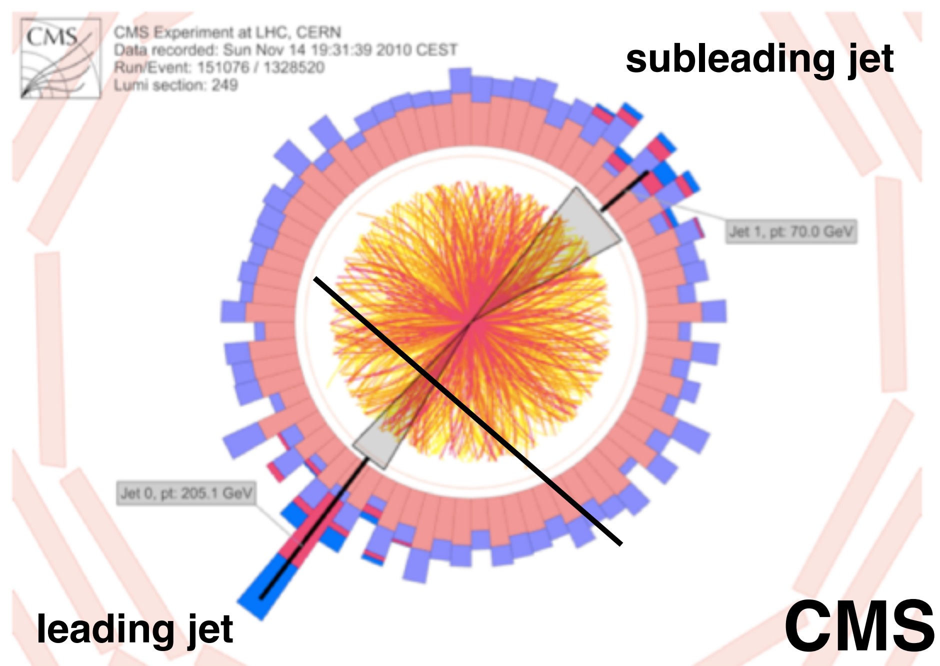


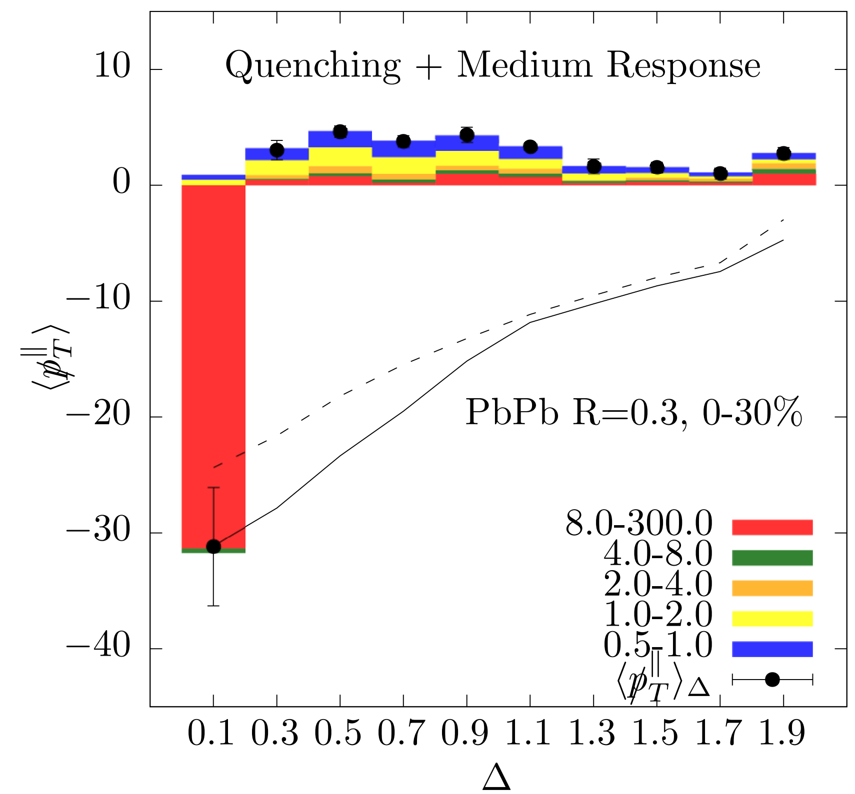
No strong evidence so far of hard point-like scatterers

Where does lost energy go to?



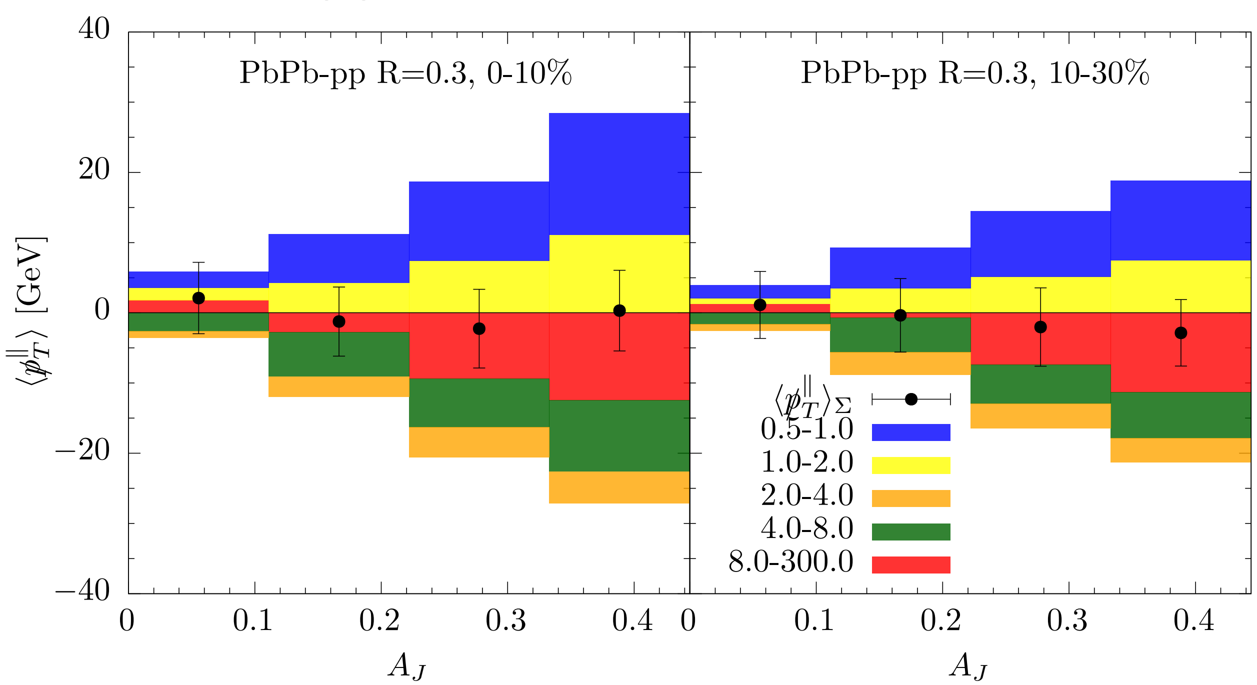
'missing-pt' observables

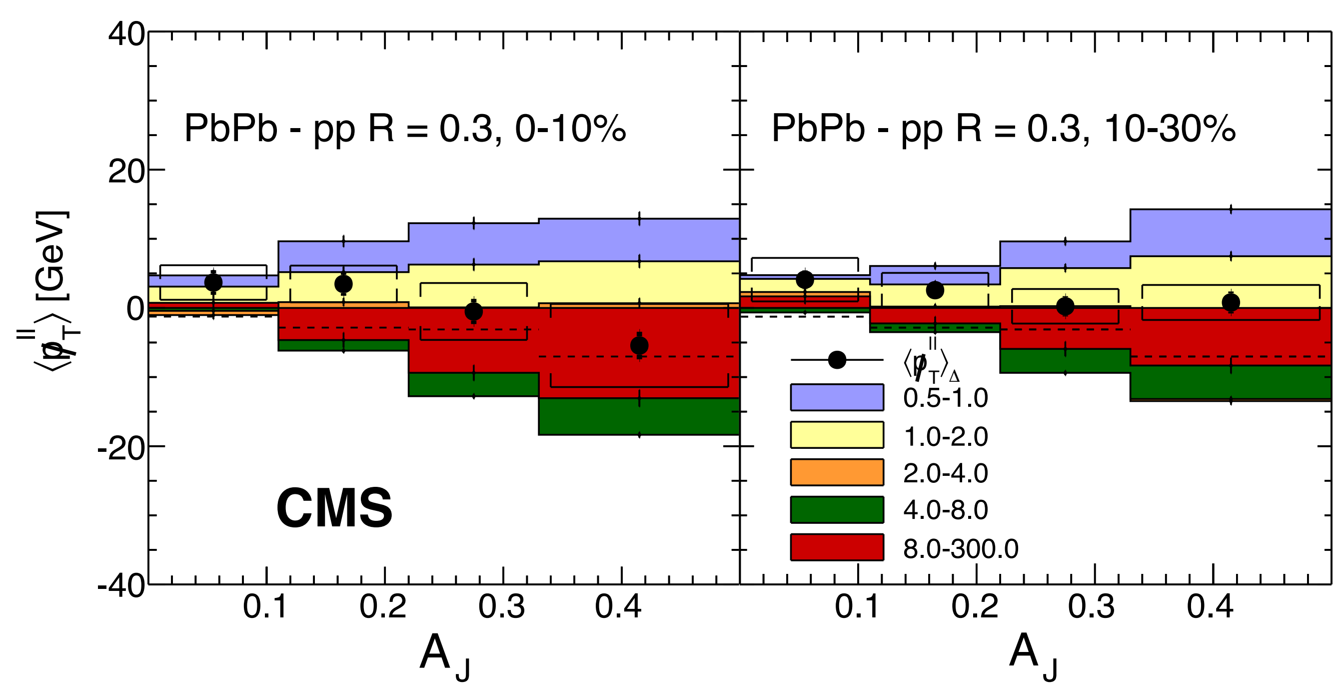




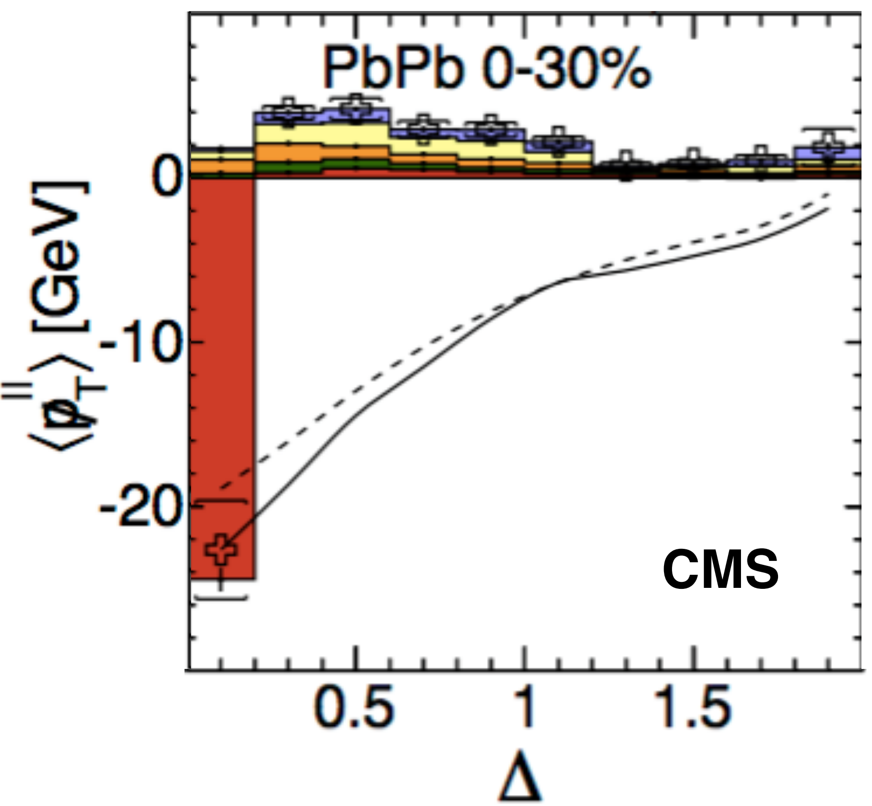
energy is recovered at large angles in the form of soft particles

data suggests that implementation of back-reaction might mistreat semi-hard particles

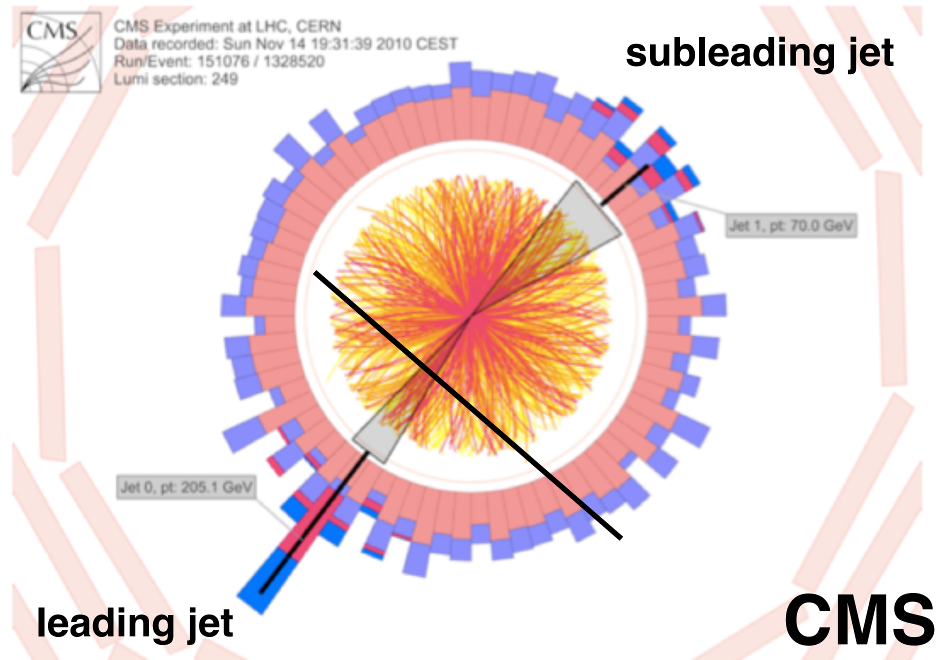


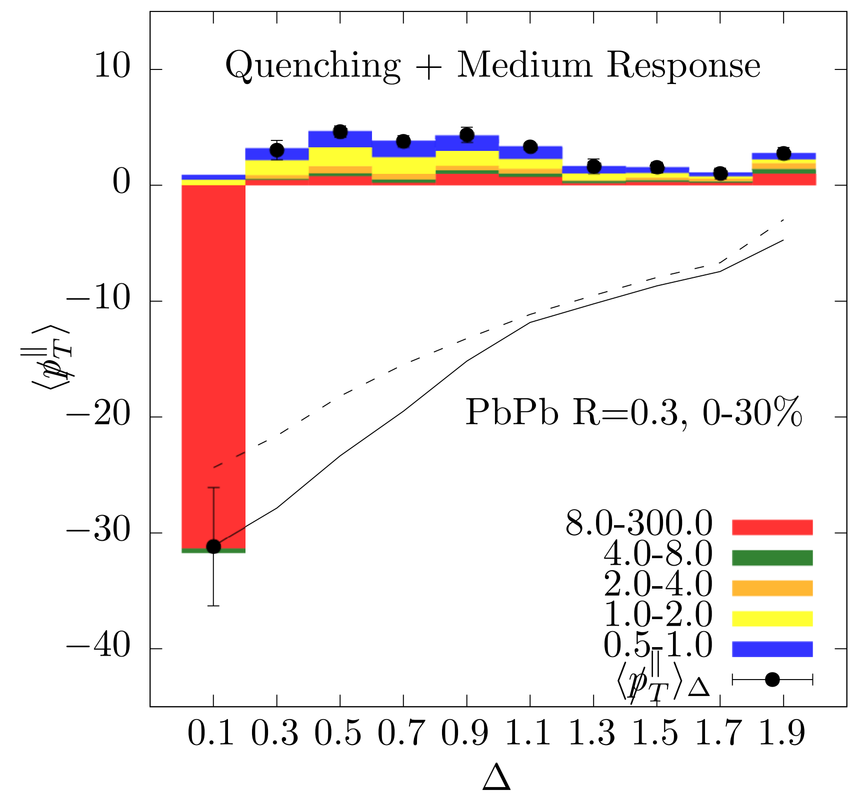


Where does lost energy go to?



‘missing-pt’ observables





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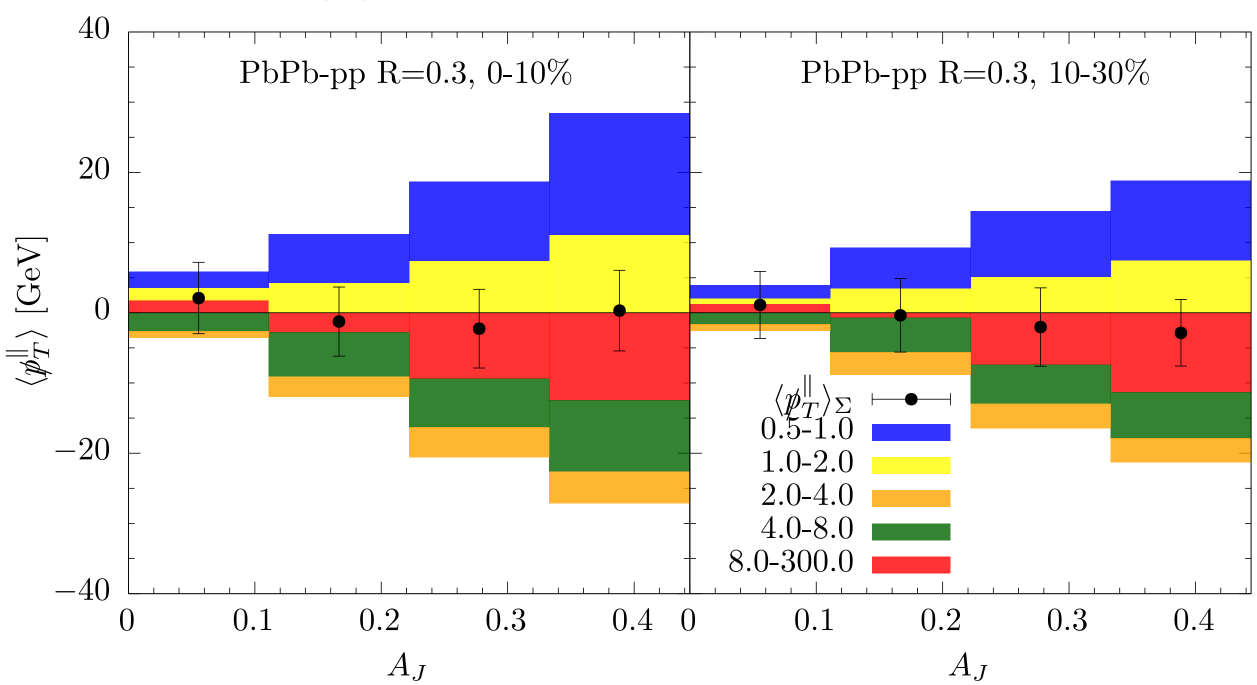
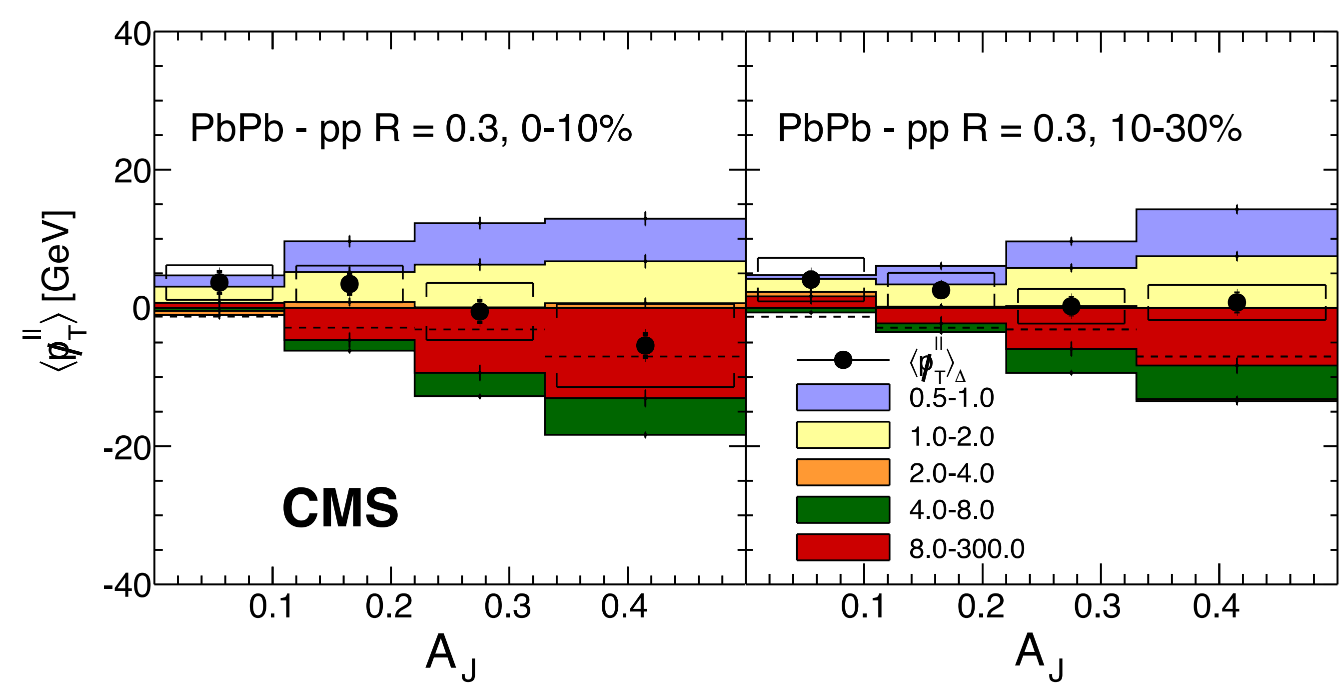
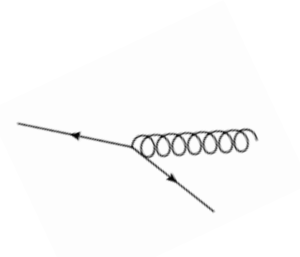


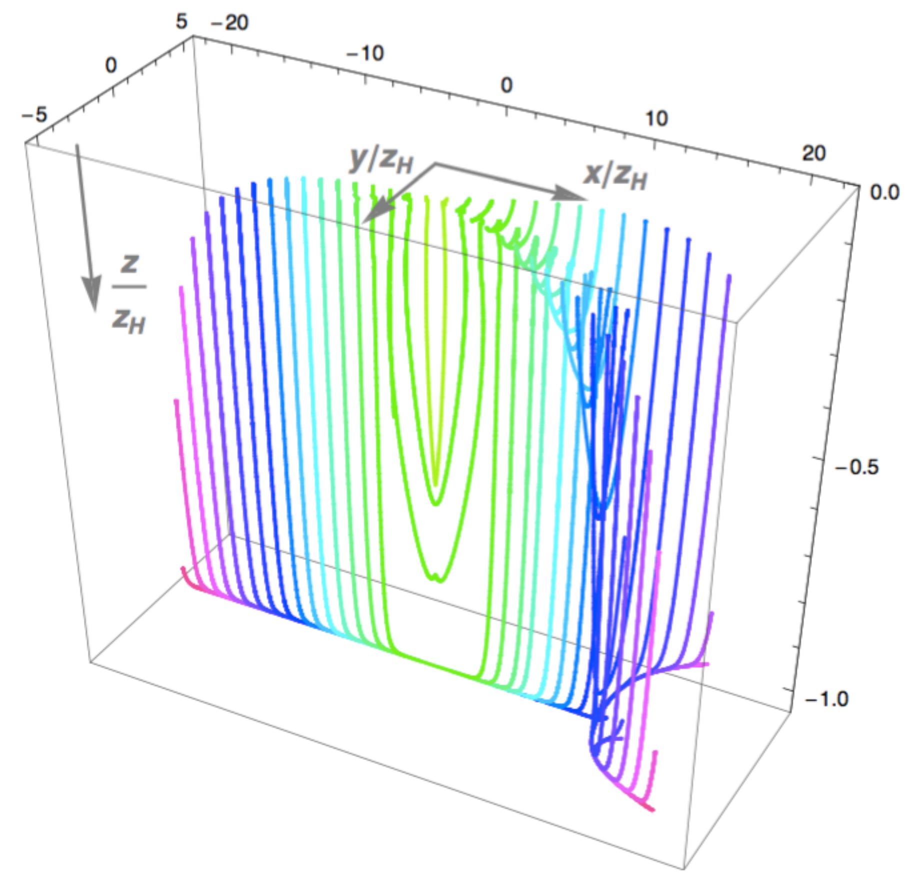


Finite resolution effects @ strong coupling

Casalderrey & Ficnar - arXiv:1512.00371

holographic description of 3-jet events

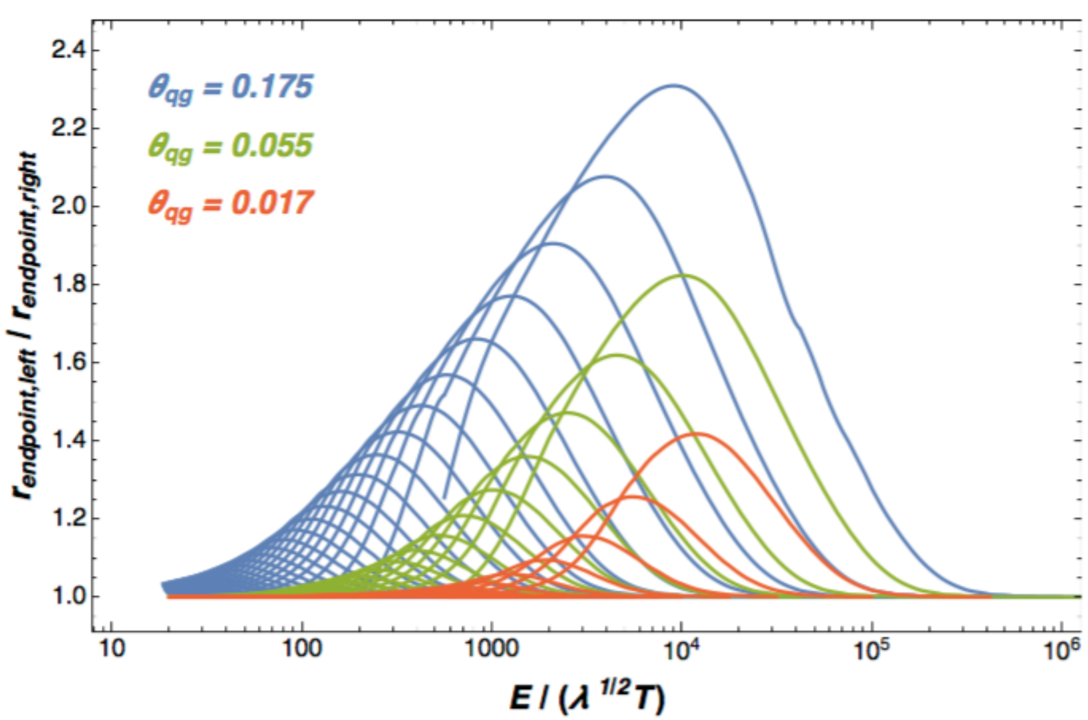




smallest angular separation between two jets that the medium can resolve?

assign a transverse structure to the string such that a quark-gluon system is emulated

study the stopping distances as a function of opening angle and energy

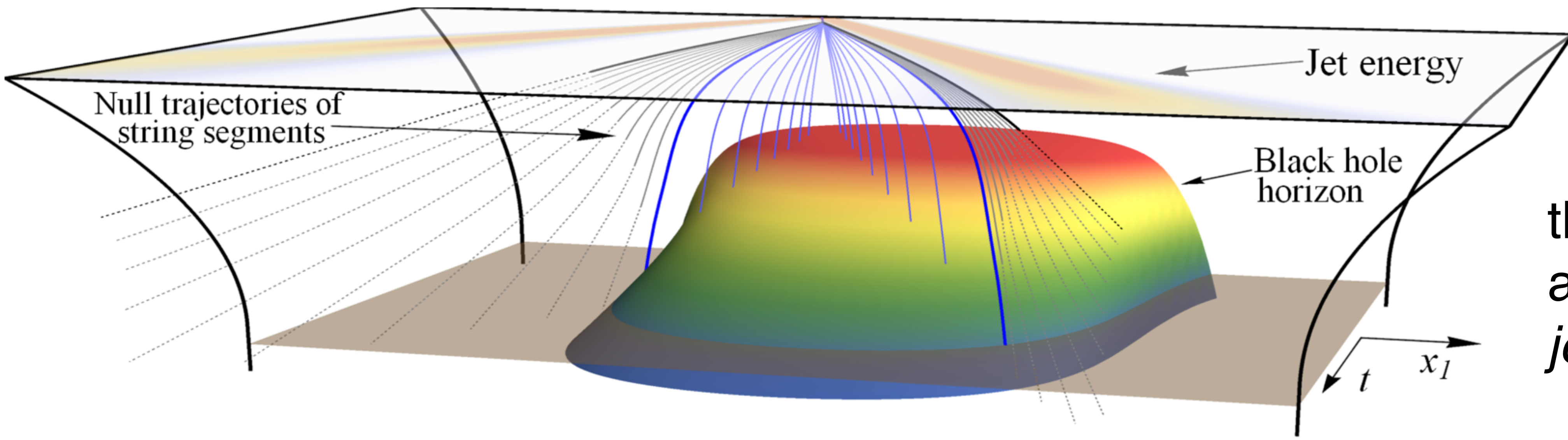


$$\theta_{\rm res} = \frac{2^{4/3}}{\pi}\frac{\Gamma(3/4)^2}{\Gamma(5/4)^2}\left(\frac{E}{\sqrt{\lambda}T}\right)^{-2/3}$$

different scaling than pQCD in a dense plasma

$$\theta_{\rm res}^{\rm pQCD} \propto E^{-3/4}$$

Holographic quenching with pure strings

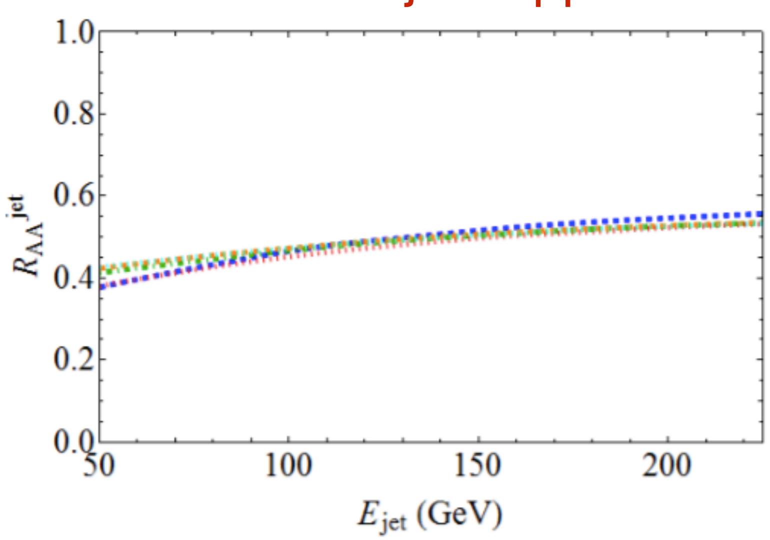


the *string* is treated as a model for the *jet as a whole*

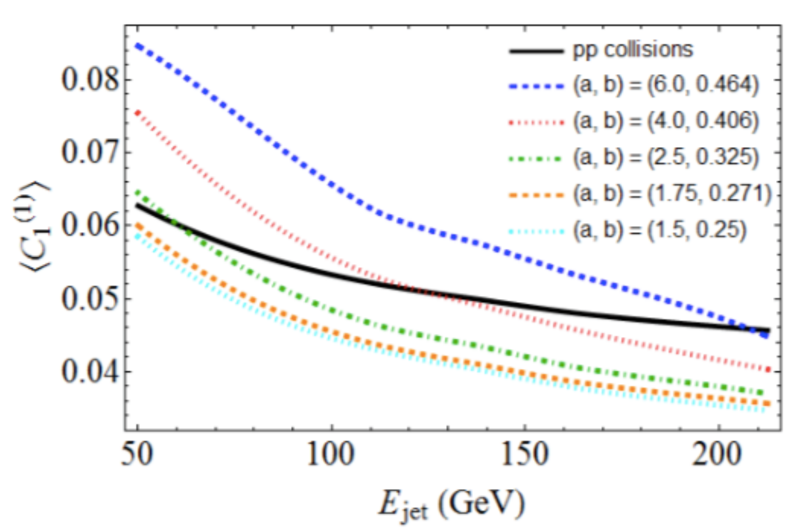
Rajagopal et al. - PRL '16

- consider *ensemble* of jets by choosing initial distributions of energy & angle from pQCD
- competing effects: each individual jet widens, while wider jets lose more energy

for the same jet suppression



different final angle dist.



$$C_1^{(\alpha)} \equiv \sum_{i,j} z_i z_j \left(\frac{|\theta_{ij}|}{R} \right)^{\alpha}$$

measures jet angle in pQCD

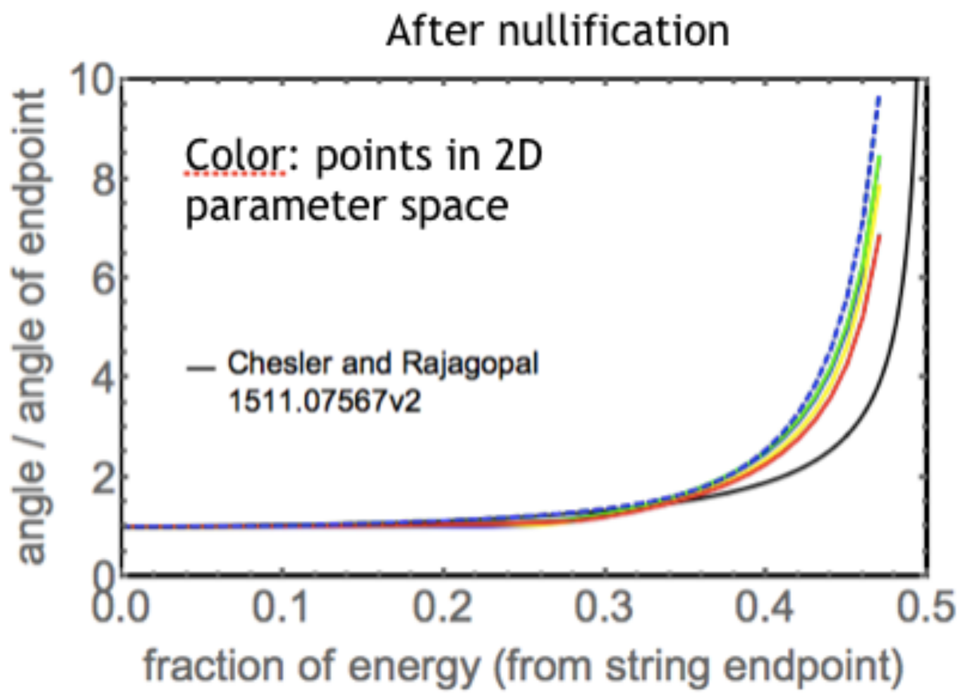
$$C_1^{(1)} = a\,\sigma_0$$

$$T_{\mathrm{SYM}} = b\,T_{\mathrm{QCD}}$$

effect also observed in pQCD

Milhano & Zapp - EPJ '16

Holographic quenching with pure strings

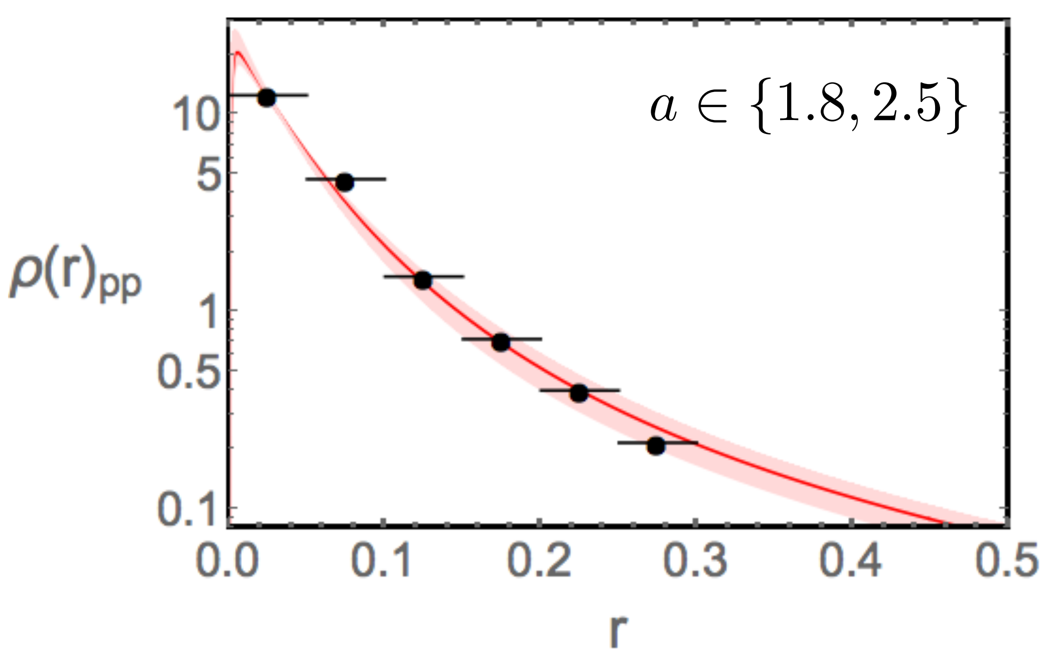


- determine string energy density by considering different initial profiles evolved within *full string dynamics*

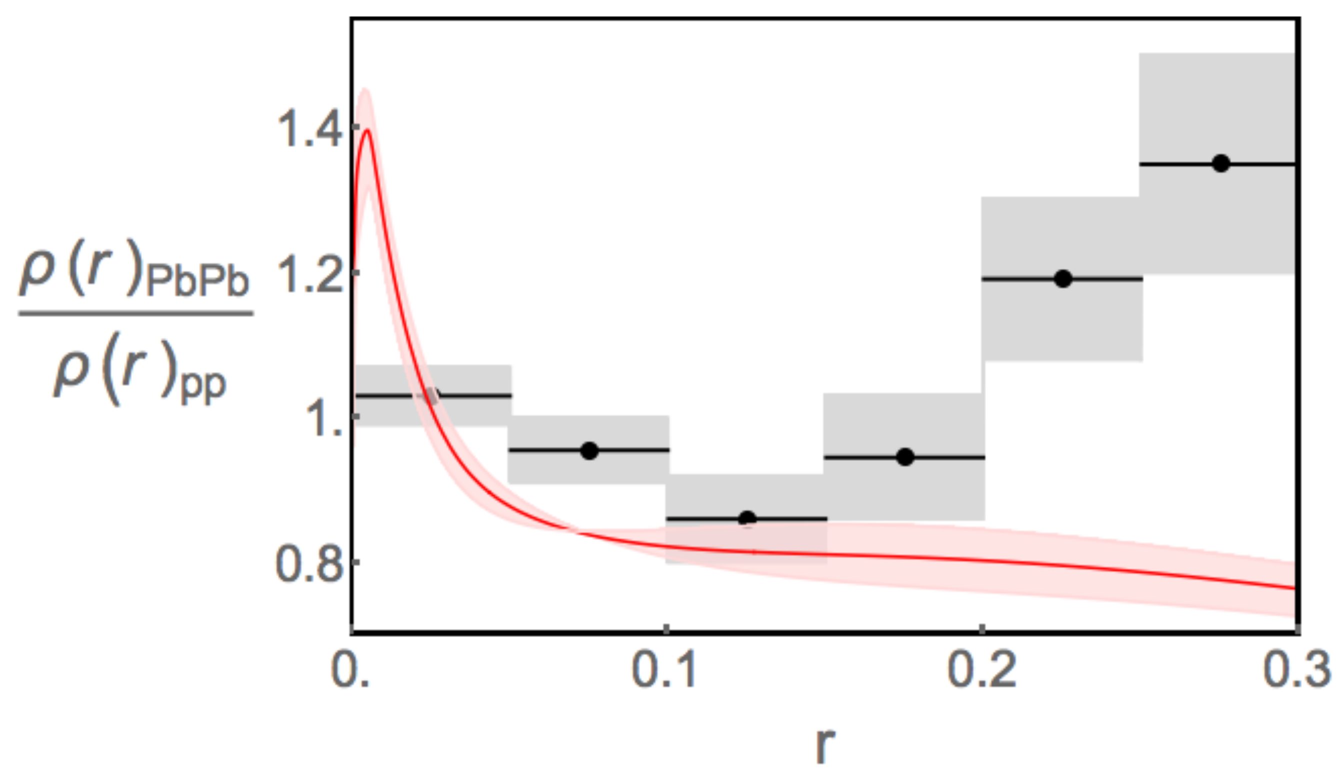
as the string nullifies, different initial choices tend to converge

Brewer et al. - JHEP '18

- use pp jet shapes to determine angle distribution

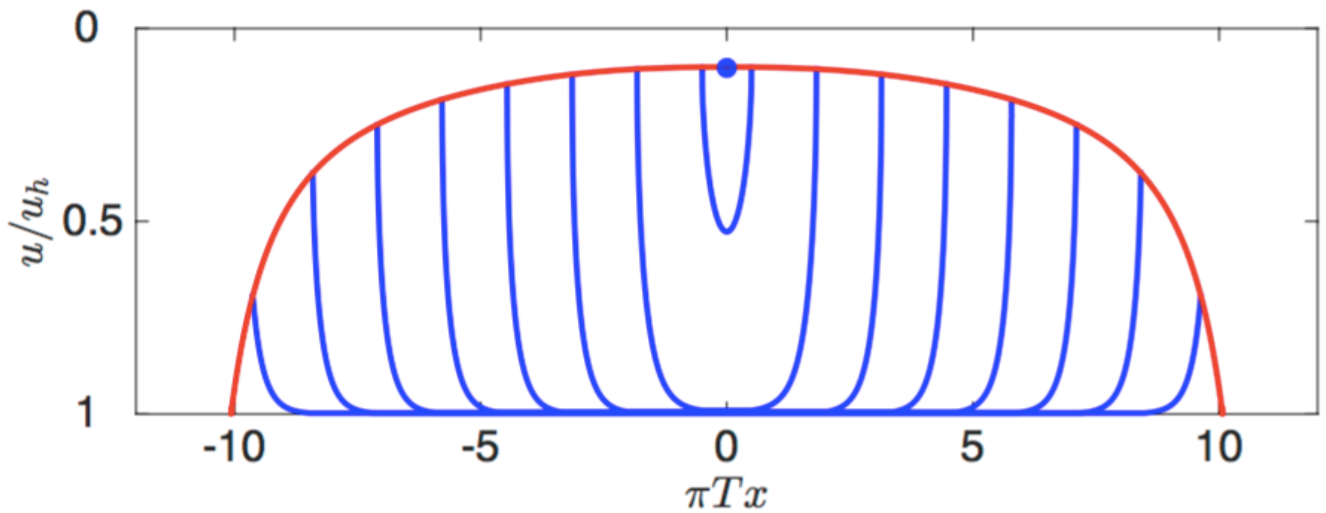


- nuclear jet shape modification *captures core dynamics* - lacks contribution from medium response

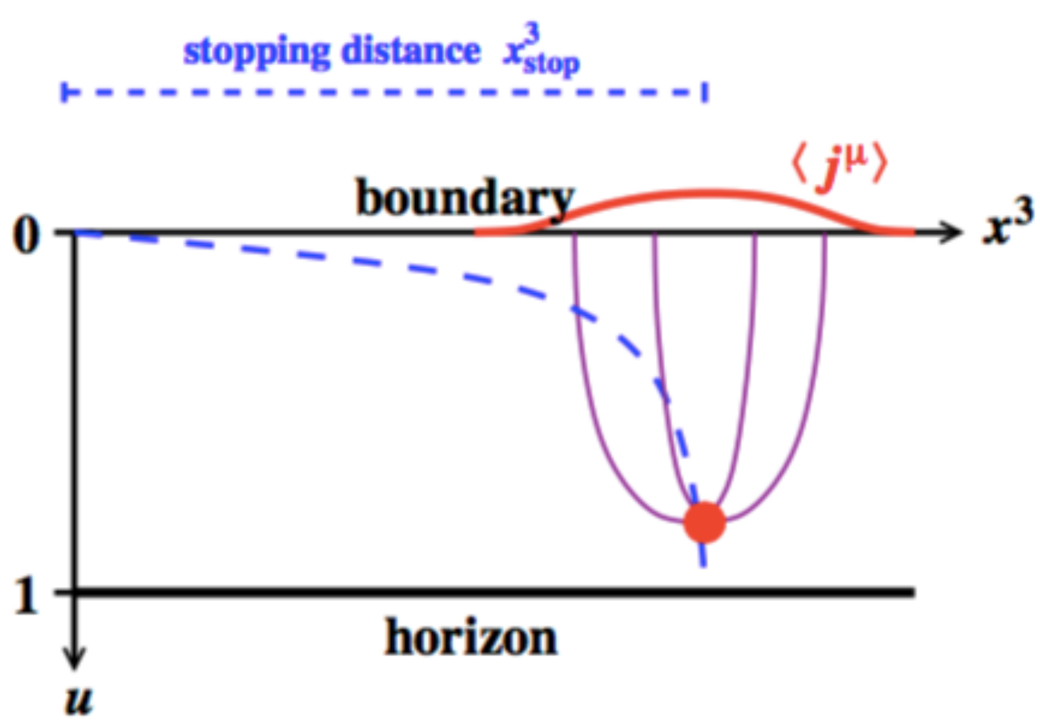


light quark endpoint can fall unimpeded towards the black brane

$$z_q \to 0$$



Chesler et al. '09



Arnold & Vaman '11

semiclassical string description

$$\kappa_{\rm sc} = 1.05\,\lambda^{1/6}$$

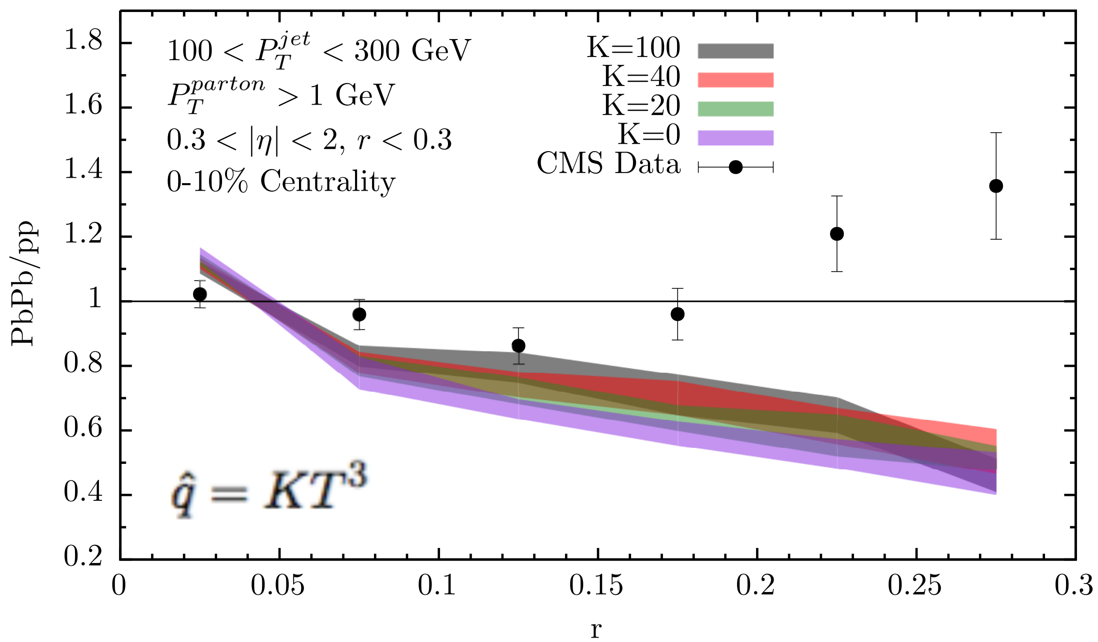
$$x_{\rm stop} = \frac{1}{2\,\kappa_{\rm sc}} \frac{E_{\rm in}^{1/3}}{T^{4/3}}$$

robust result at strong coupling

$$\kappa_{sc} \propto \lambda^0$$

external boosted U(1) fields

Intra-jet broadening



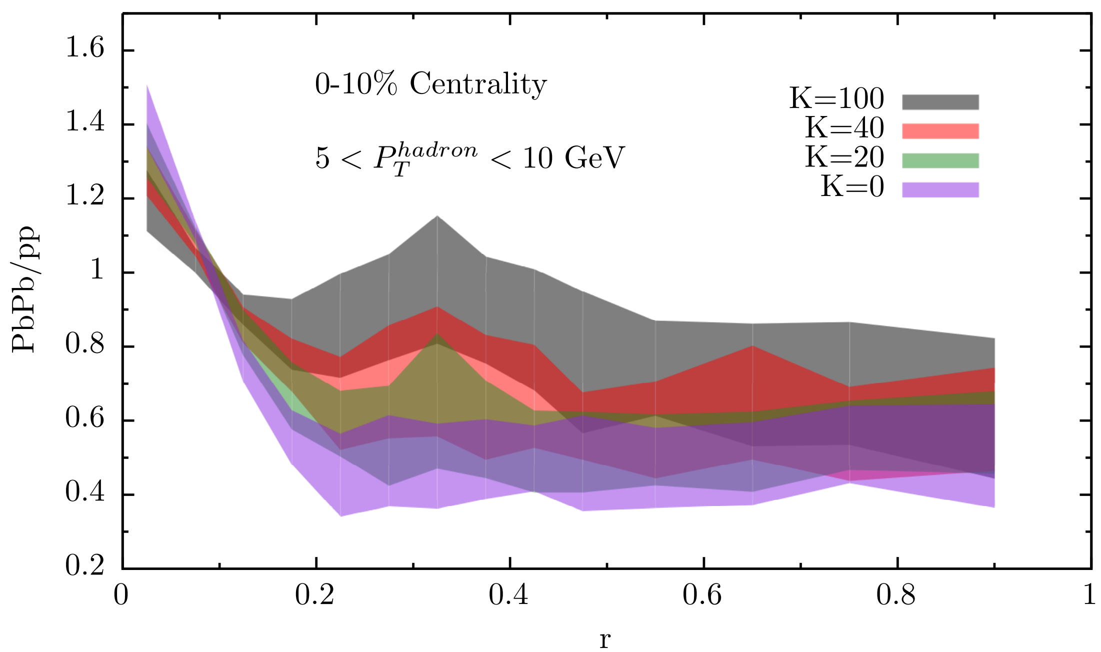
Inclusive jets - all tracks

strong quenching suppresses the effect of broadening

$Q\uparrow, \theta\uparrow, \tau_f\downarrow$ early wide fragments quenched

$Q\downarrow, \theta\downarrow, \tau_f\uparrow$ late narrow fragments survive

selection bias towards narrower jets,
merely a jet axis deflection



Subleading jets - semi-hard tracks

kinematical limits chosen such that:

- no effect from background (soft tracks)
- intra-jet activity above average (hard tracks)

deviations from such Gaussian broadening

hard momentum transfers from QGP quasiparticles