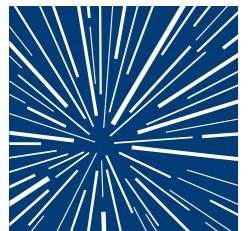


Recent measurements of jets in QCD matter at the LHC

Laura Havener, Yale University
APS GHP Workshop 2019, Denver, Colorado
Wednesday, April 10th, 2019

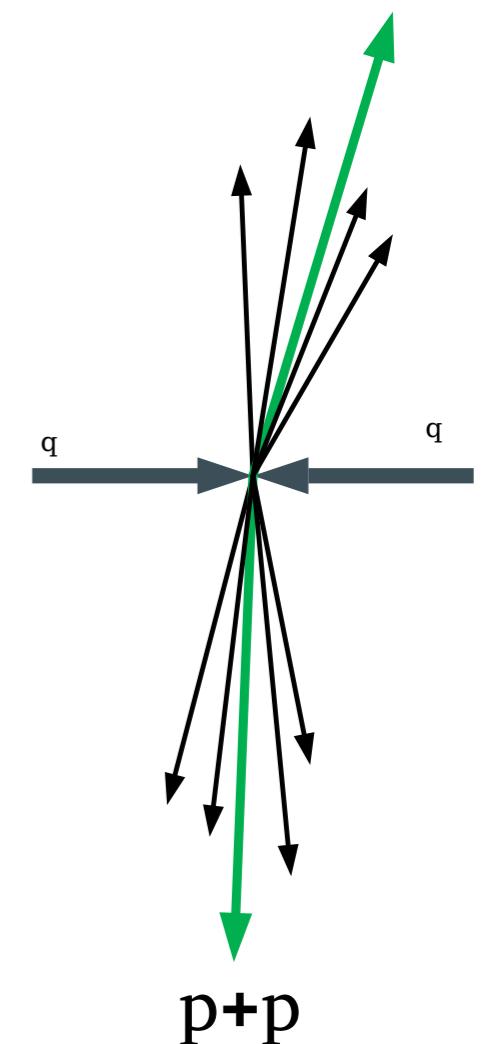


**Wright
Laboratory**

Yale₁

Jets in HI collisions?

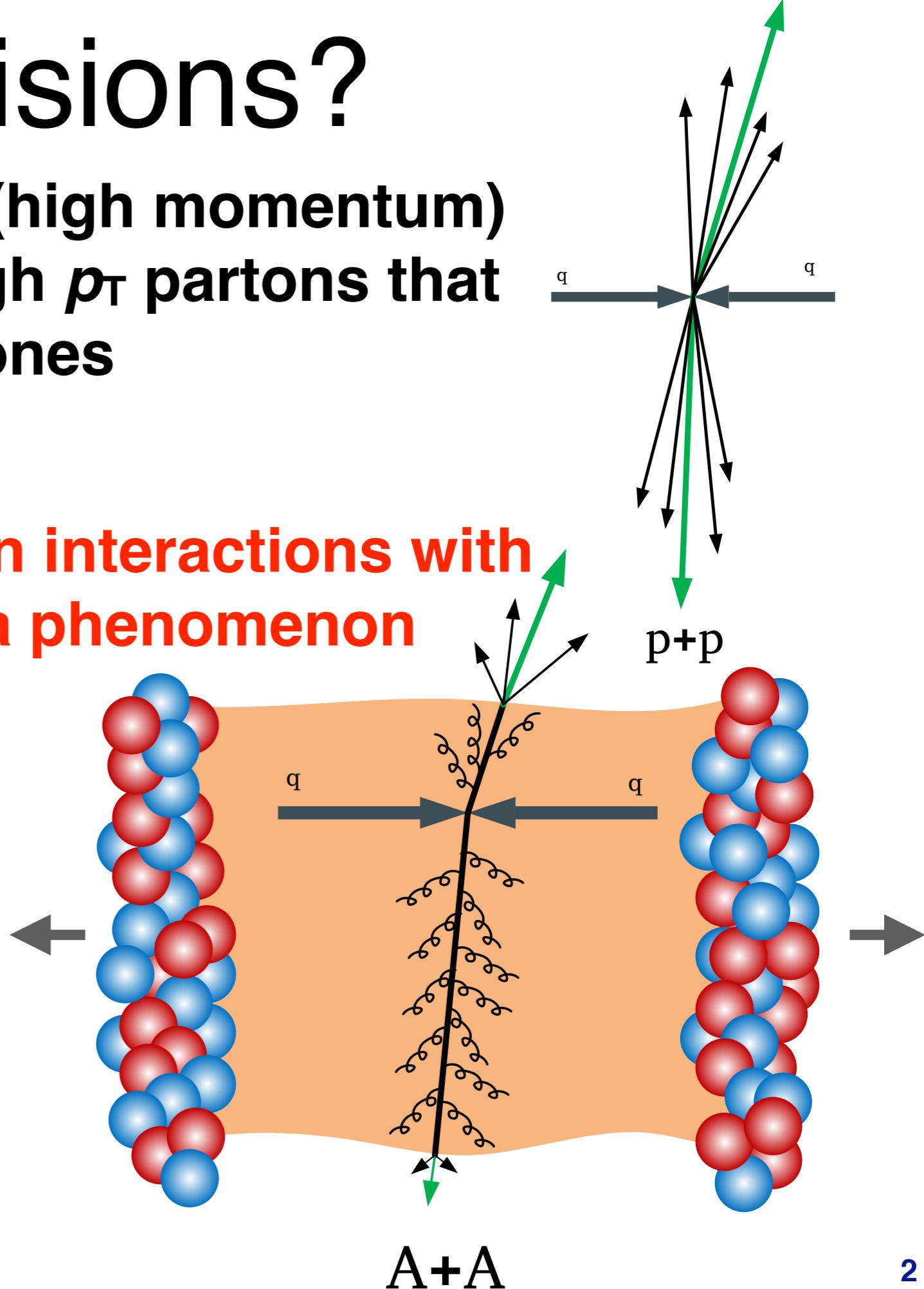
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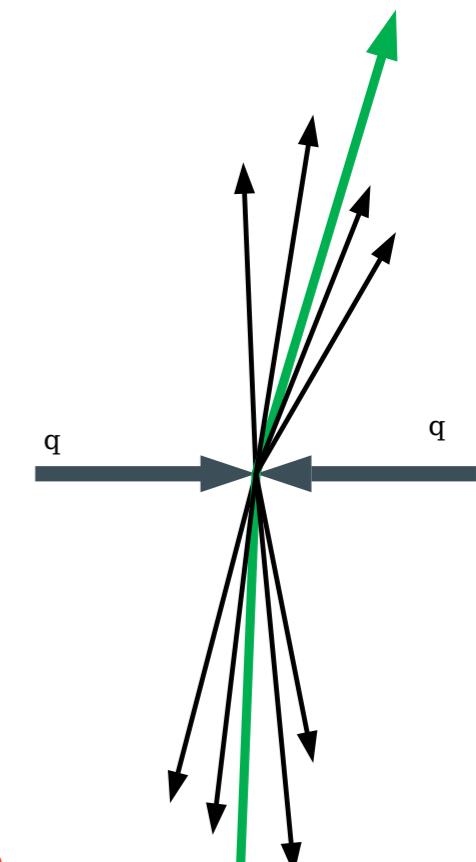
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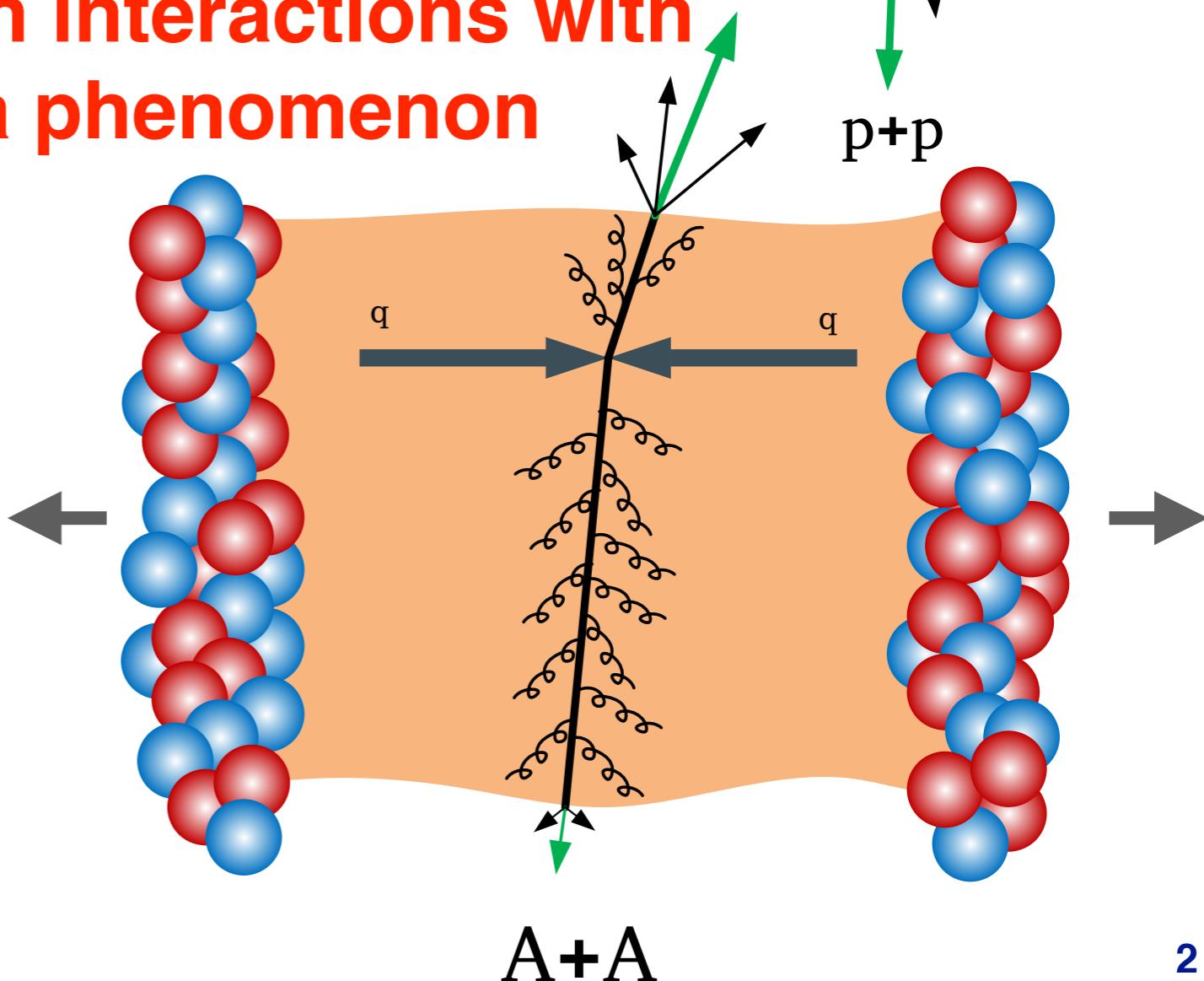
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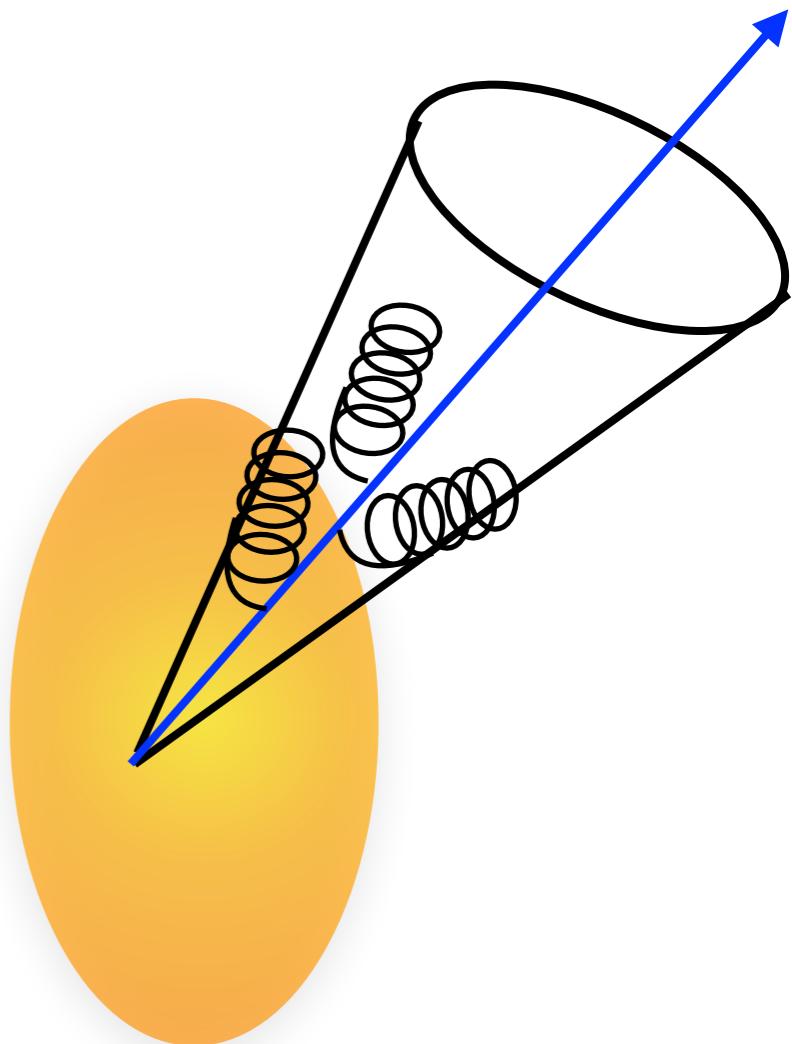
- Produced early in the collision where the initial state is mostly understood



➡ **pp is used as a reference**

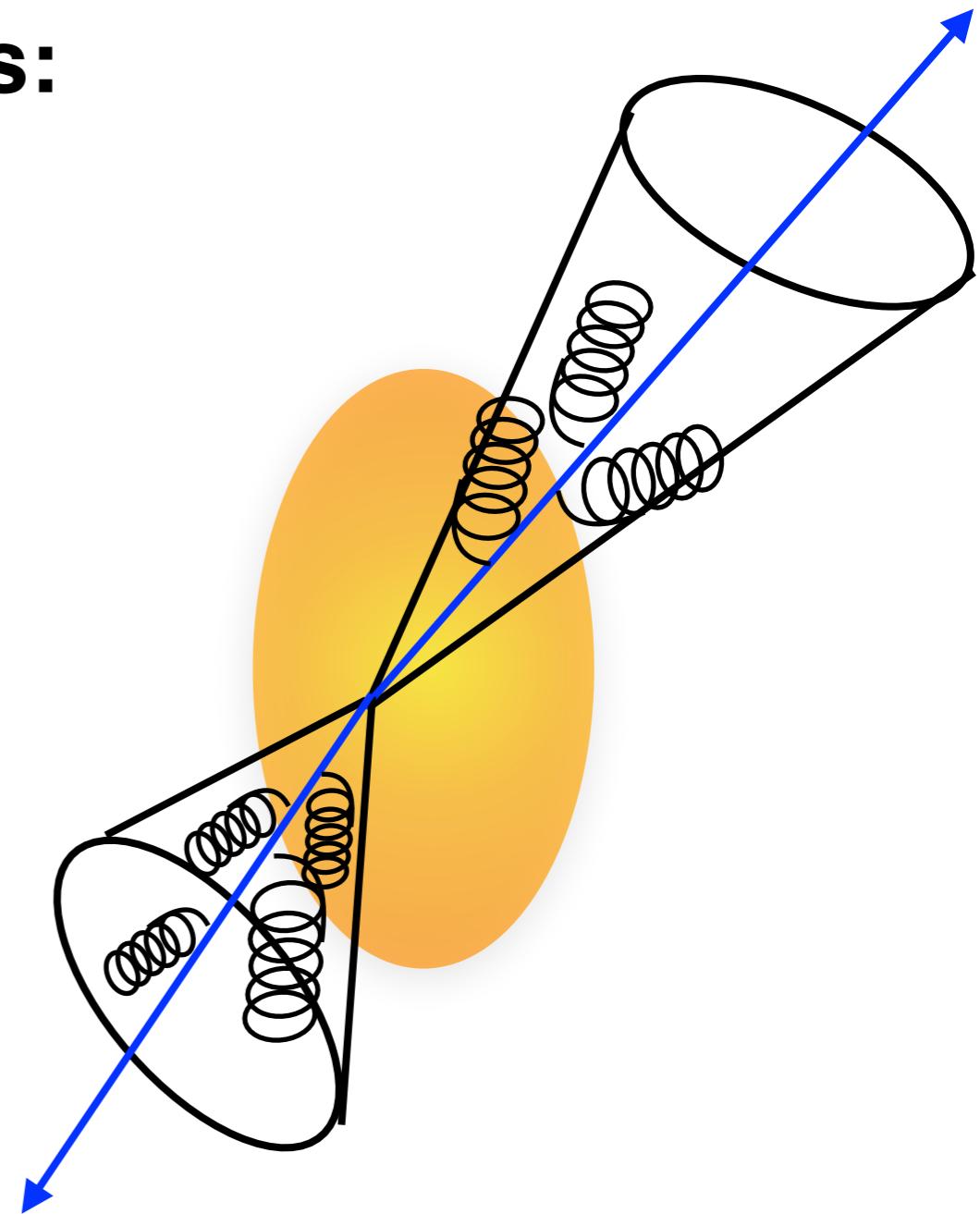
Measuring jet quenching

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 - Inclusive energy loss through the suppression of hard scattering rates of single jets



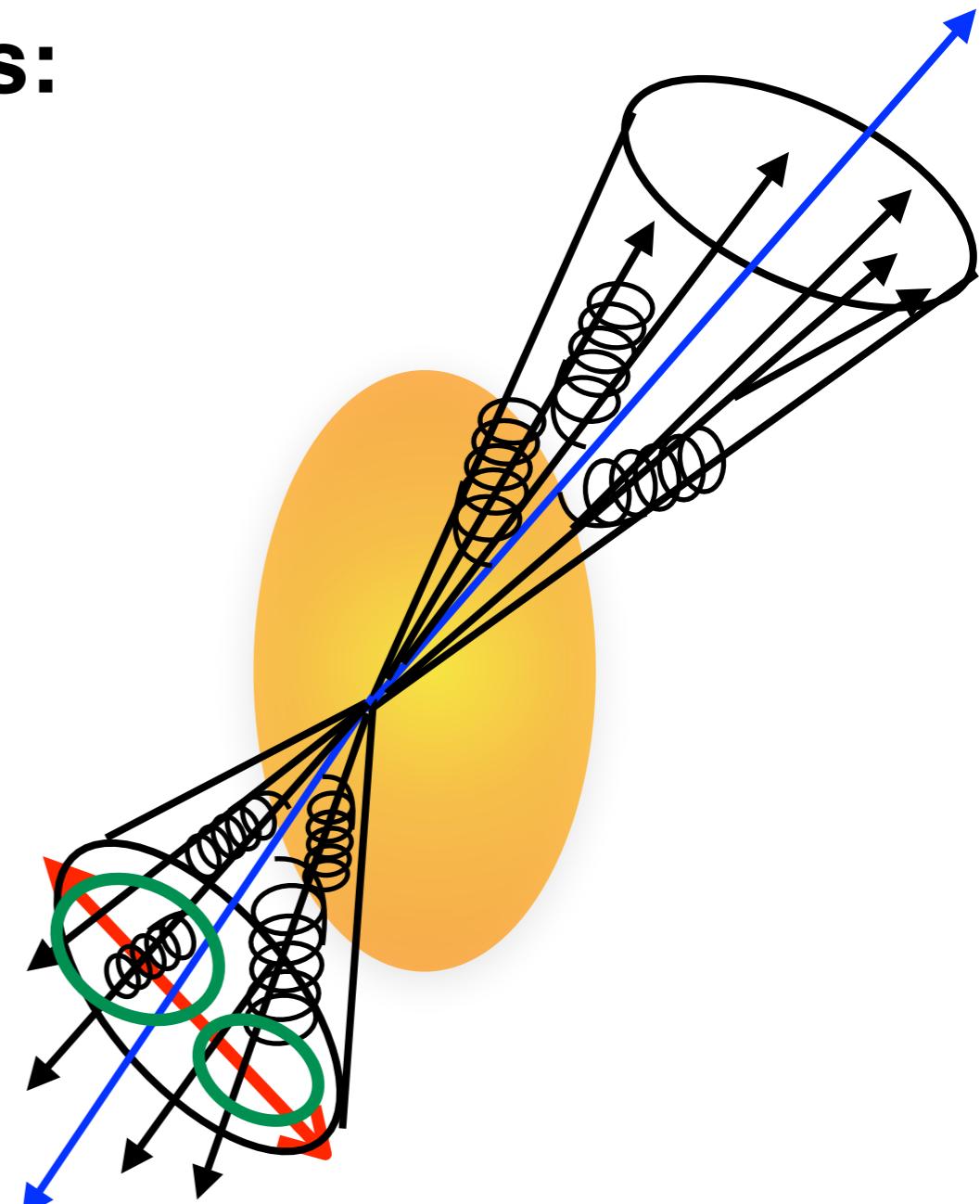
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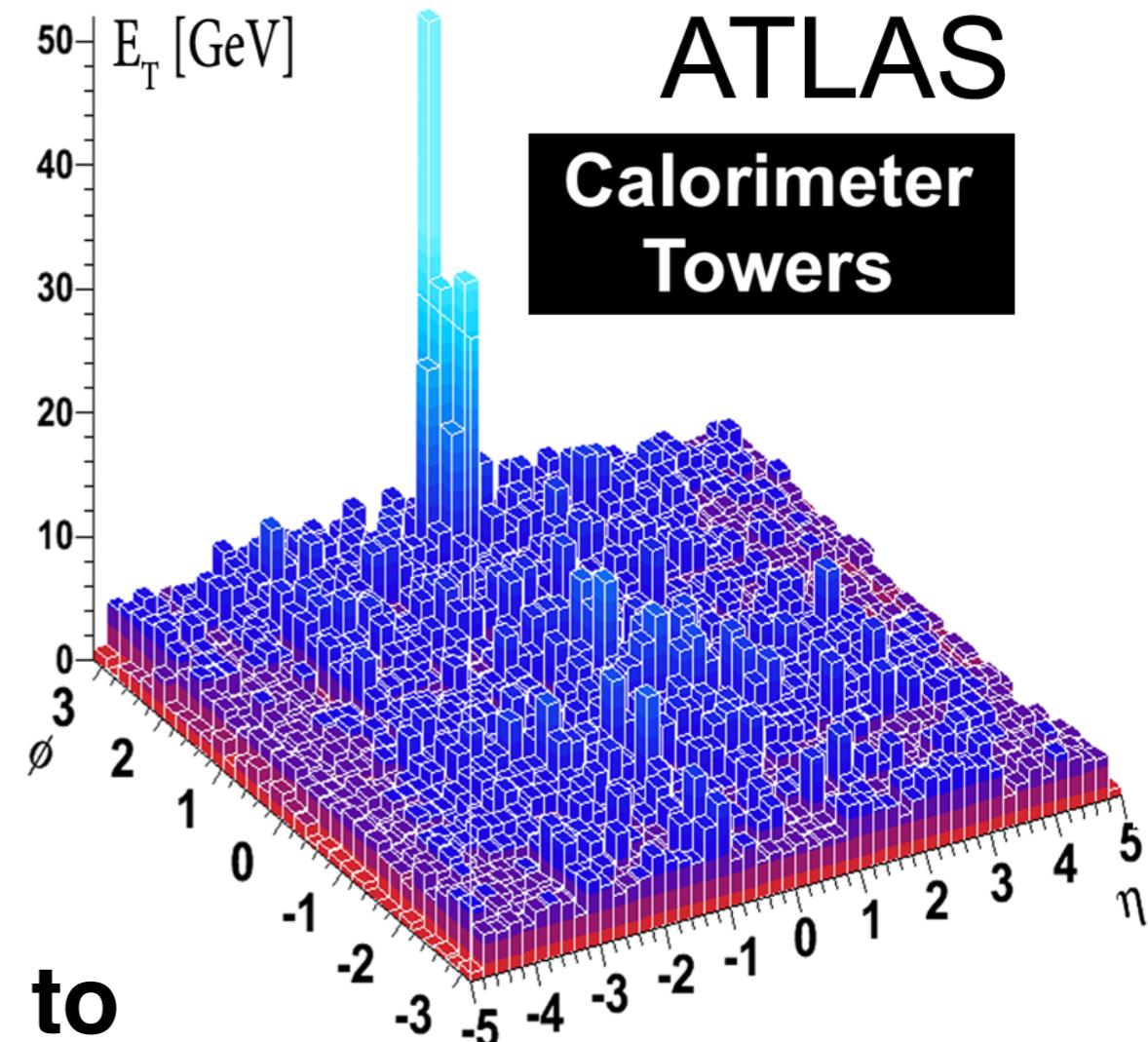
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Jet reconstruction

- Jets are reconstructed using the anti- k_t algorithm for different radii (typically $R=0.4$)
- Heavy ion collisions have a large uncorrelated underlying event (UE).
 - **Contributes background energy inside the jet cone**
 - **Produces “fakes” from upward UE fluctuations**
- Different techniques developed to carefully remove the background and fakes
 - **Constrains how low in p_T jets can be measured and how well measurements can be unfolded for detector effects**



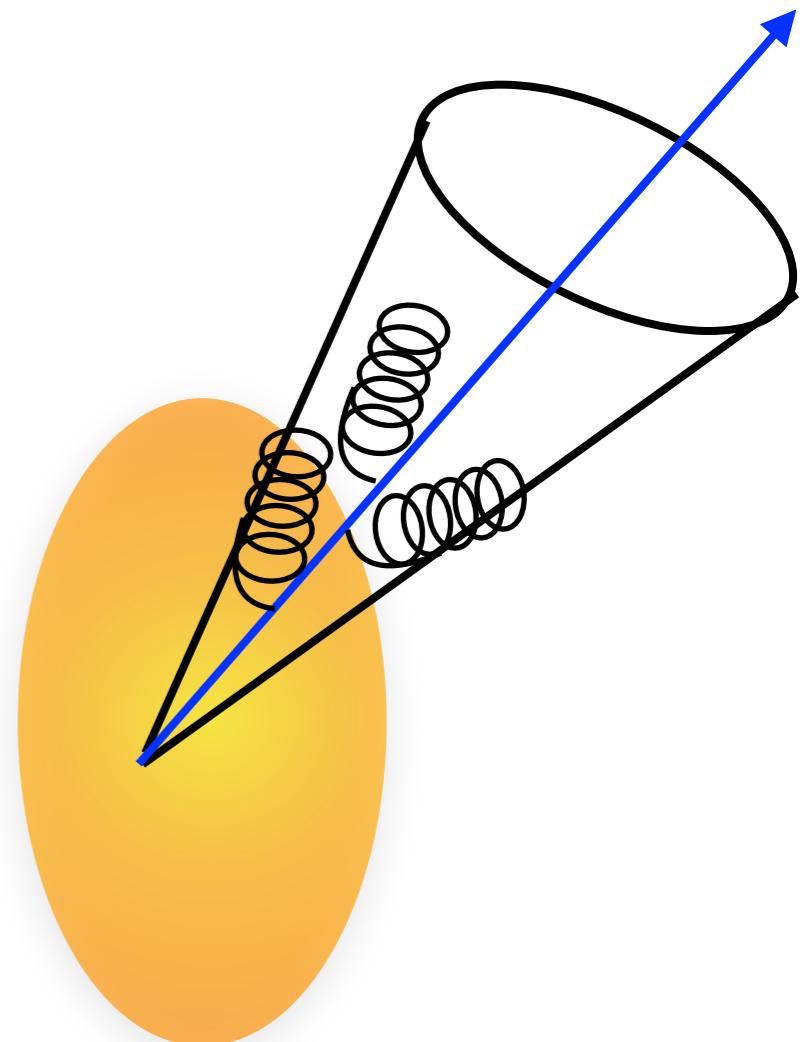
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- Ratio of the jet yield in heavy ion collisions to number of expected jets per event in each centrality class:

$$R_{AA} = \frac{\frac{1}{N_{\text{event}}} \frac{d^2 N_{\text{jet}}^{\text{PbPb}}}{dp_T dy} |_{\text{cent}}}{\langle T_{AA} \rangle_{\text{cent}} \times \frac{d^2 \sigma_{\text{jet}}^{pp}}{dp_T dy}}$$

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Nuclear thickness function

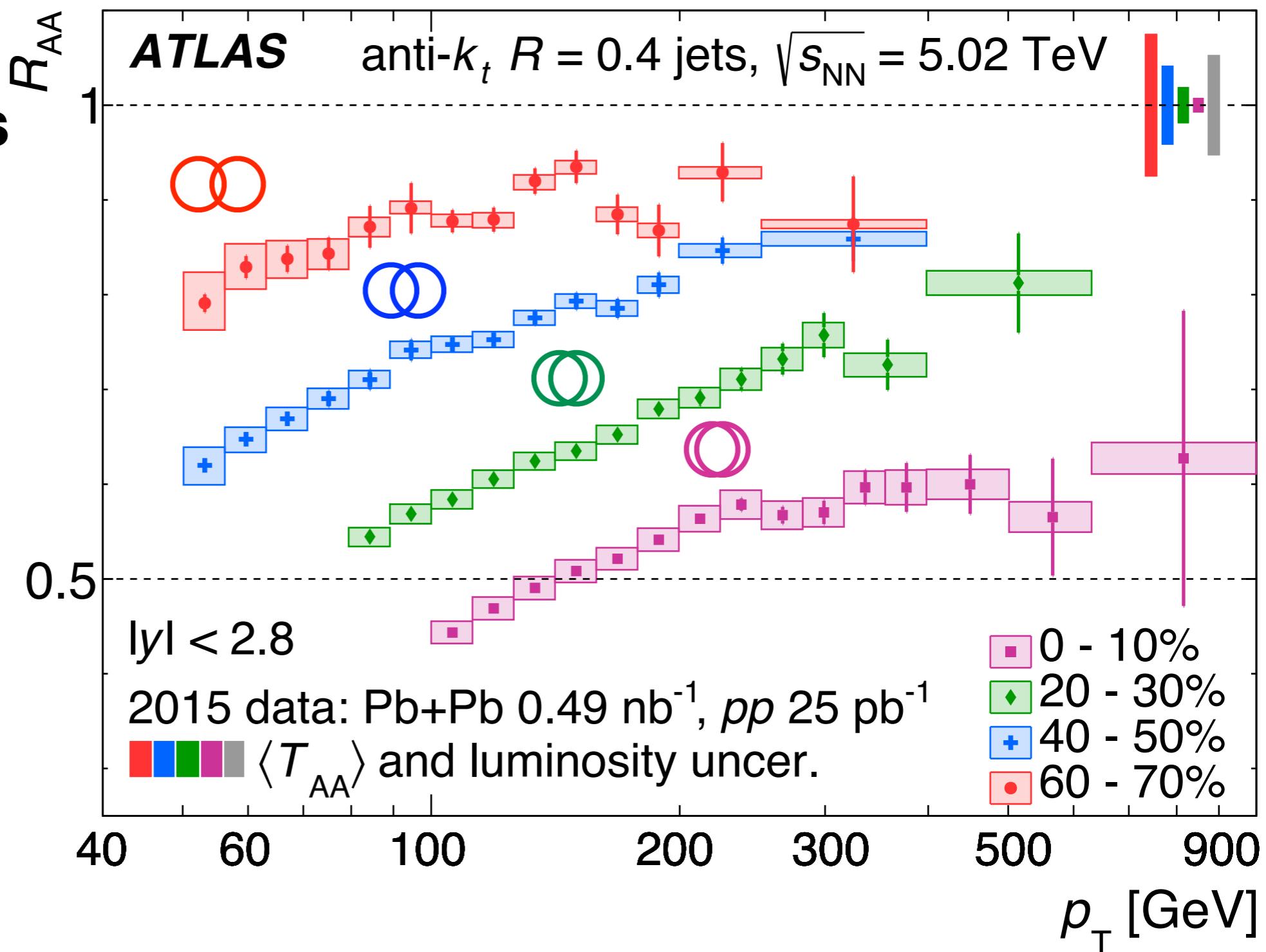
Jet yield measured in heavy ion collisions

Jet cross-section measured in pp collisions

R_{AA} : p_{T} dependence

PLB 790 (2019) 108

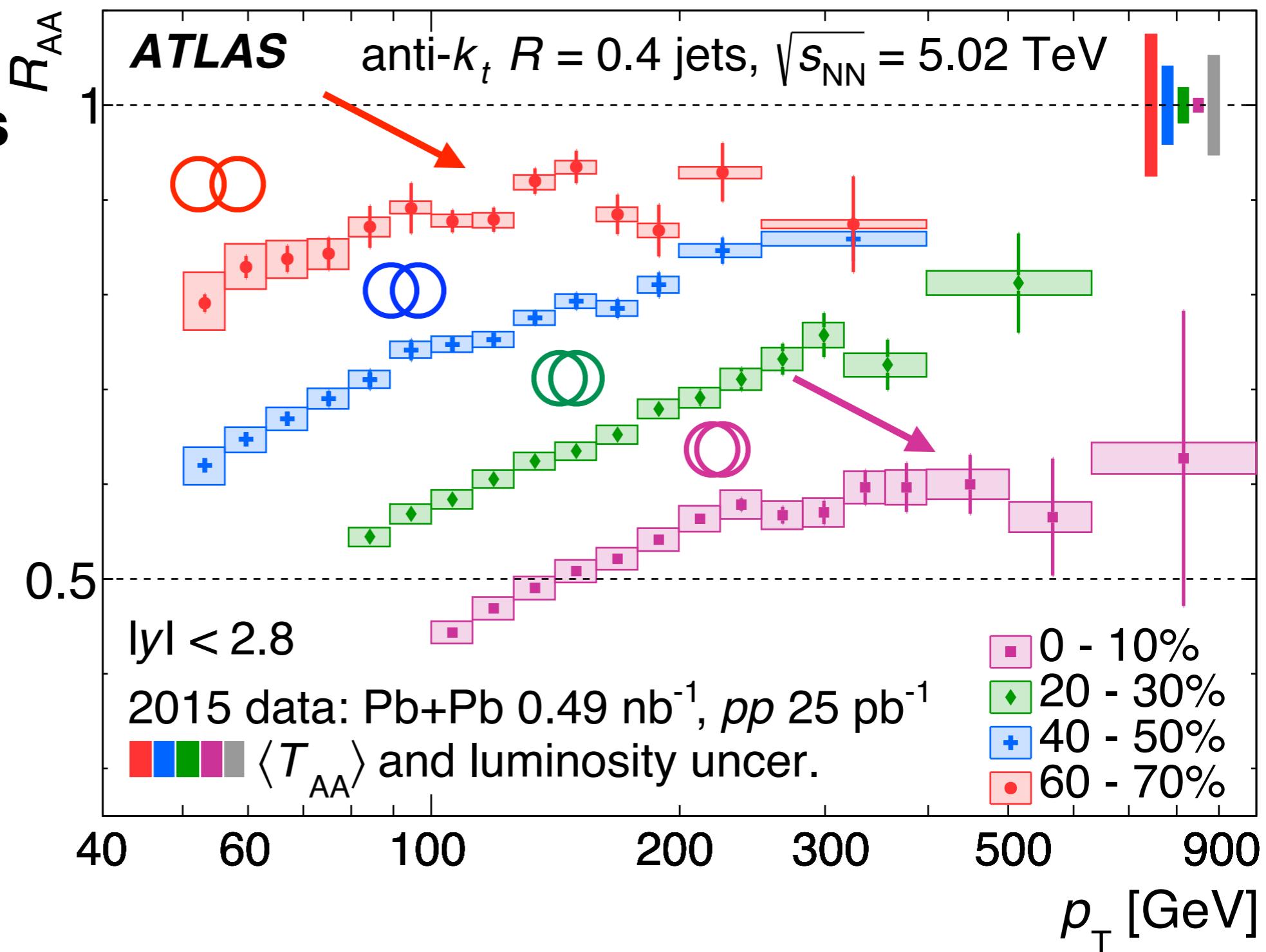
- R_{AA} is < 1 for all centralities



R_{AA} : p_{T} dependence

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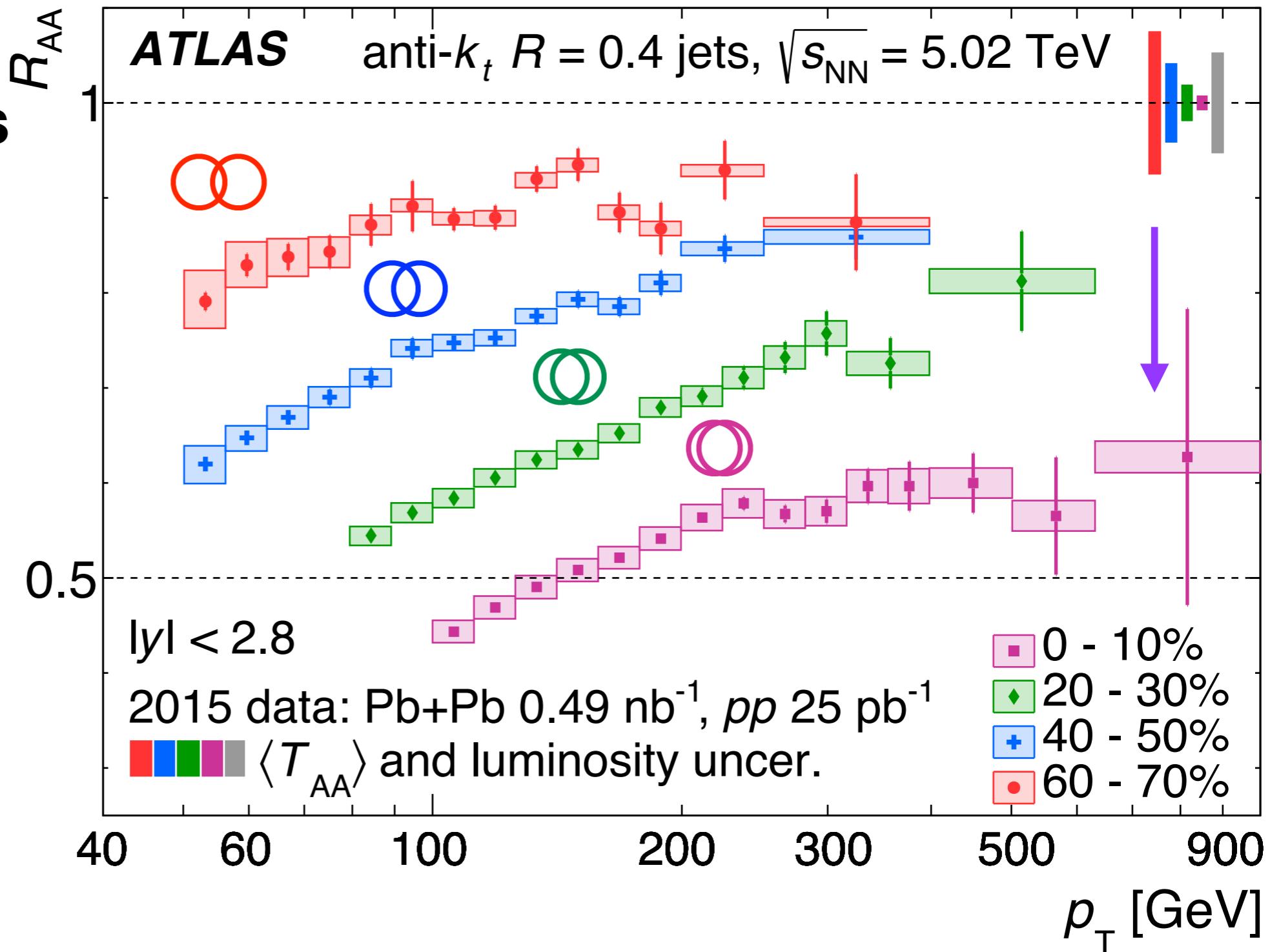
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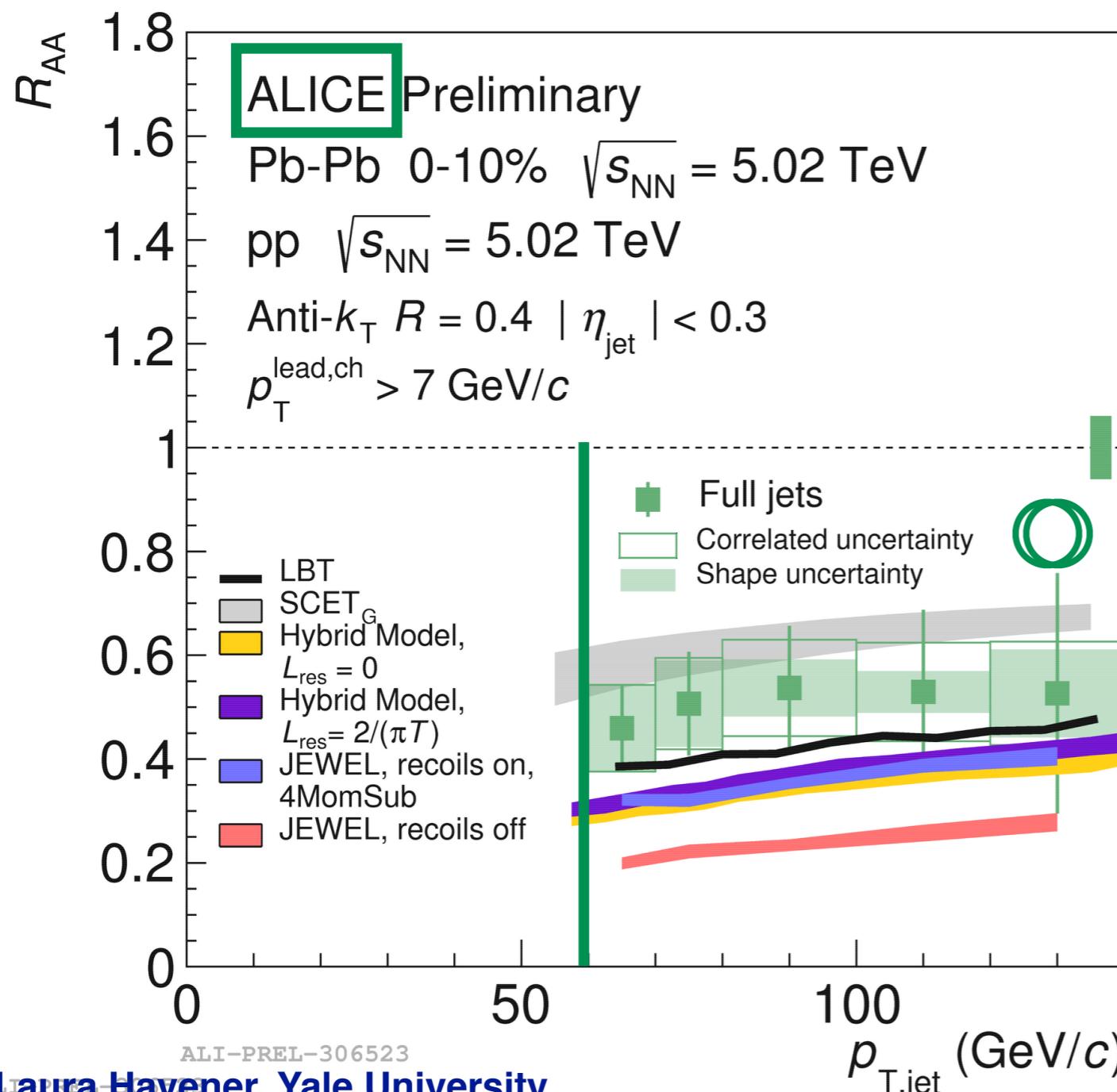
PLB 790 (2019) 108

- R_{AA} is < 1 for all centralities
- R_{AA} is lower in central (~ 0.5) than peripheral (~ 0.9)
- R_{AA} shows suppression up to a TeV!



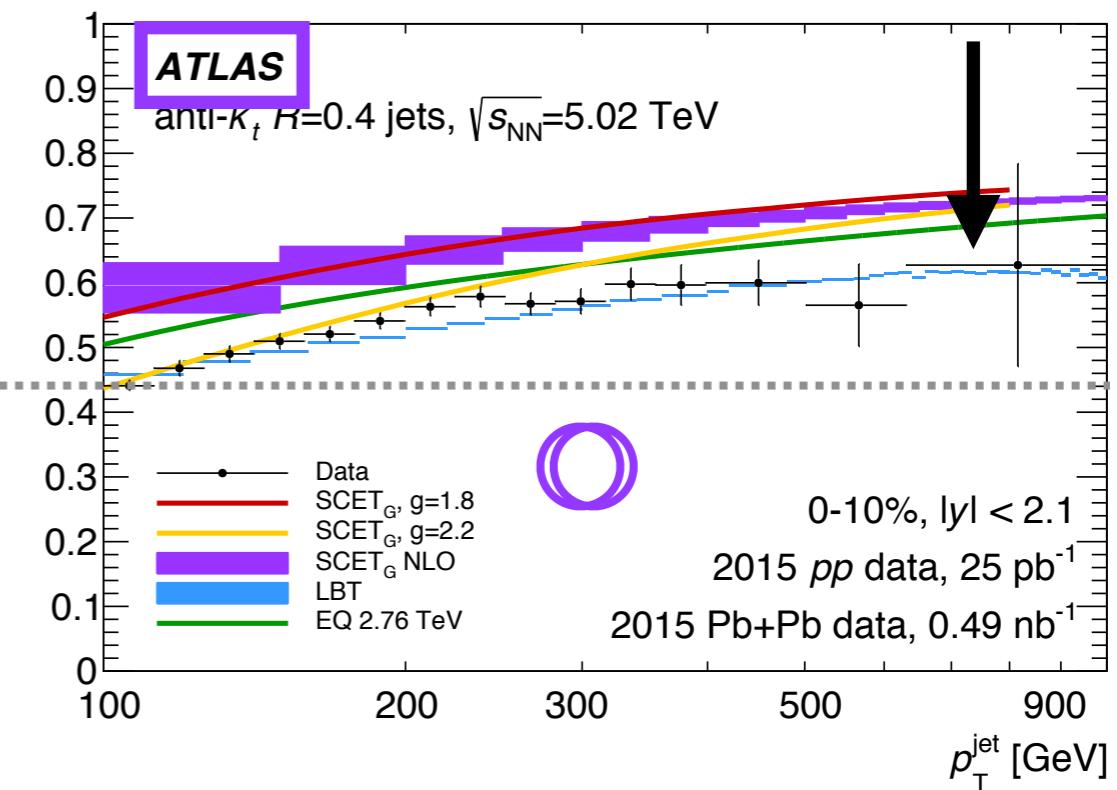
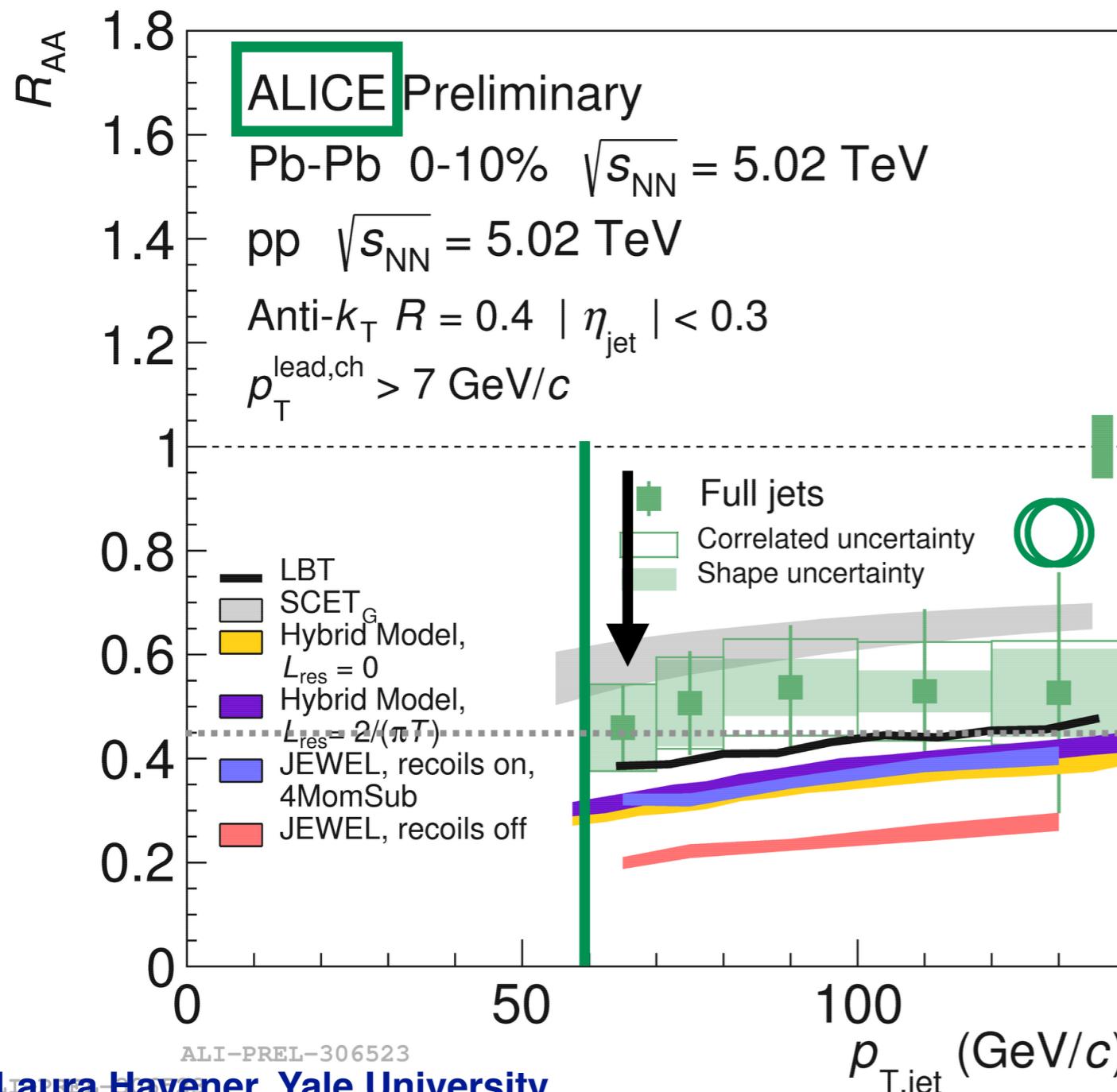
Jet suppression

- ALICE measures jets down to 60 GeV for R=0.4 jets



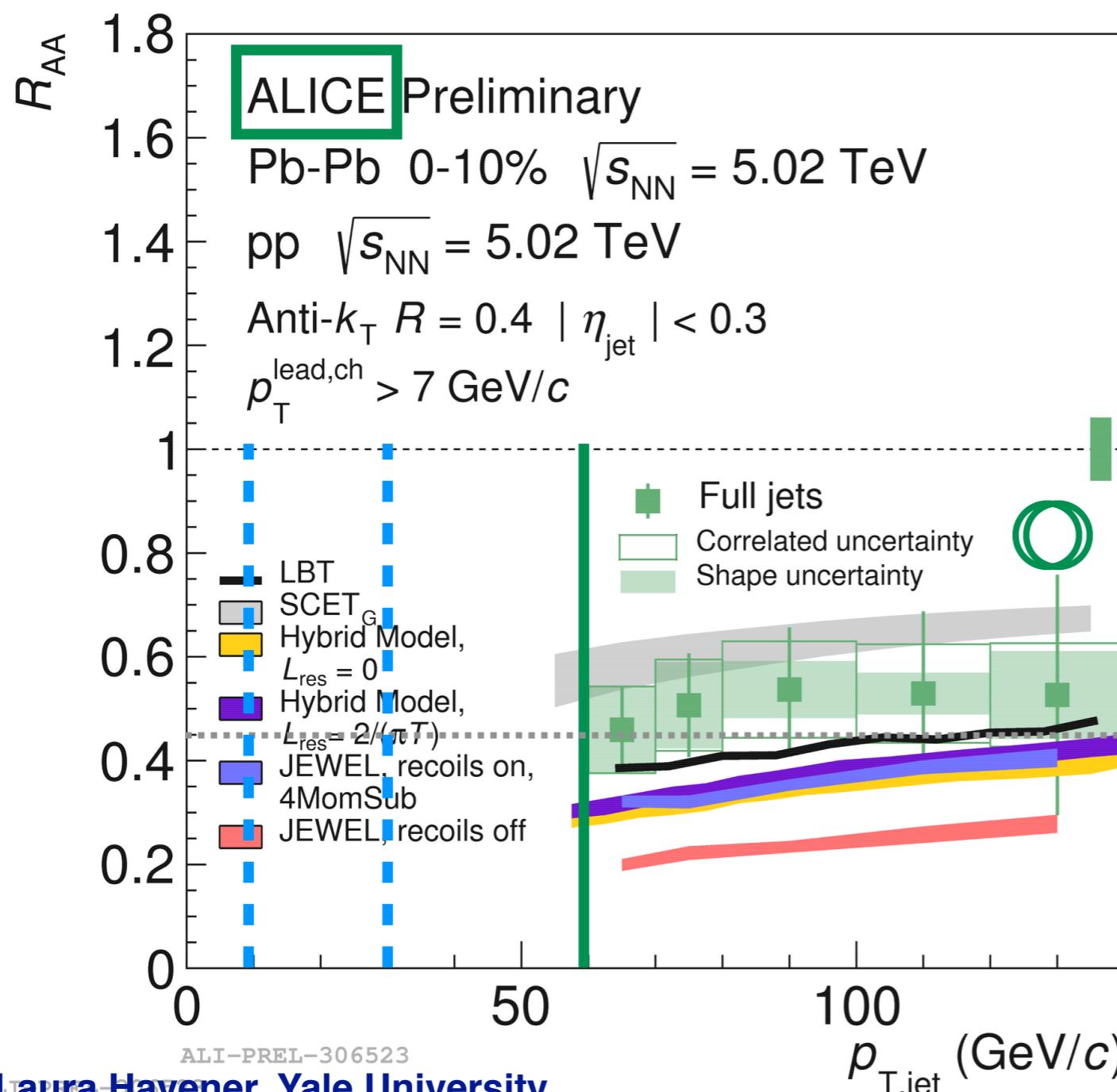
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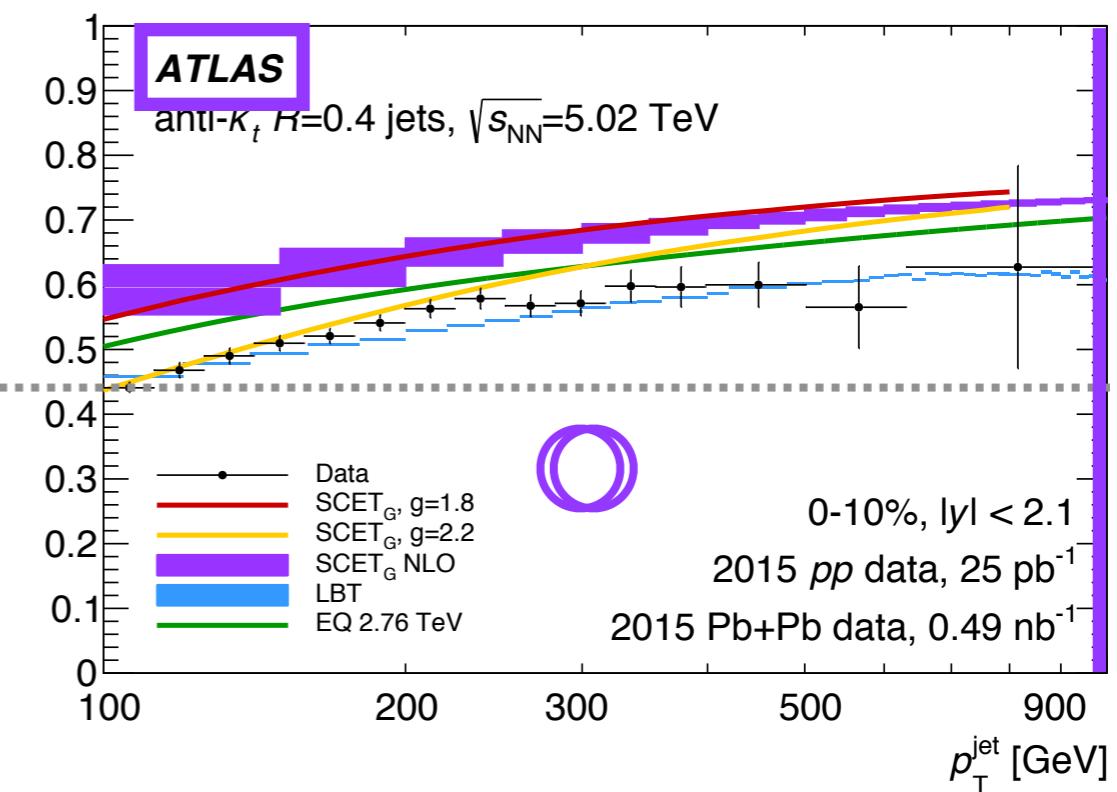


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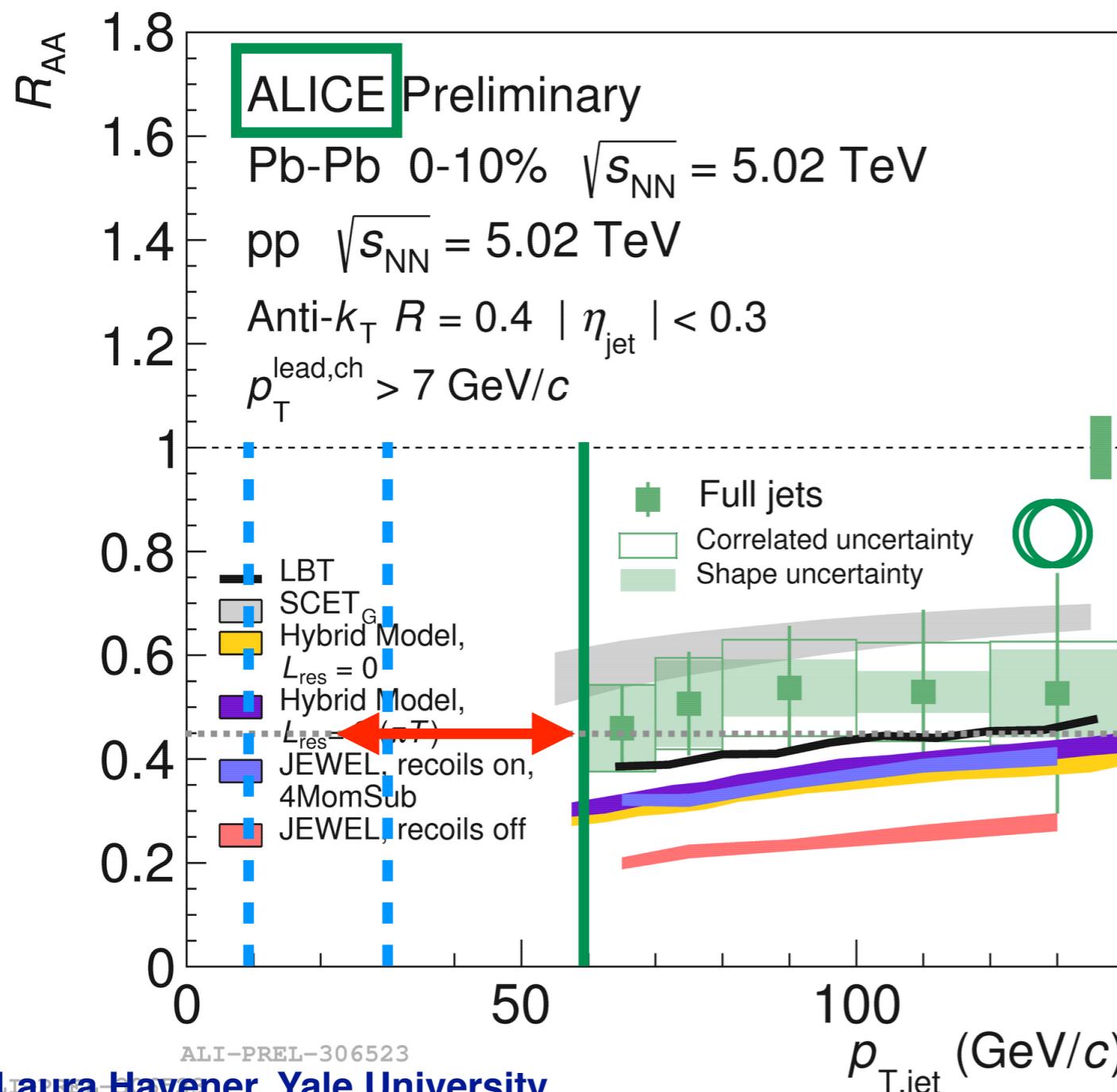


**ALICE (60-140 GeV)
 bridges gap between
 RHIC (~10-30 GeV)
 and ATLAS LHC
 (100 GeV - 1 TeV)**

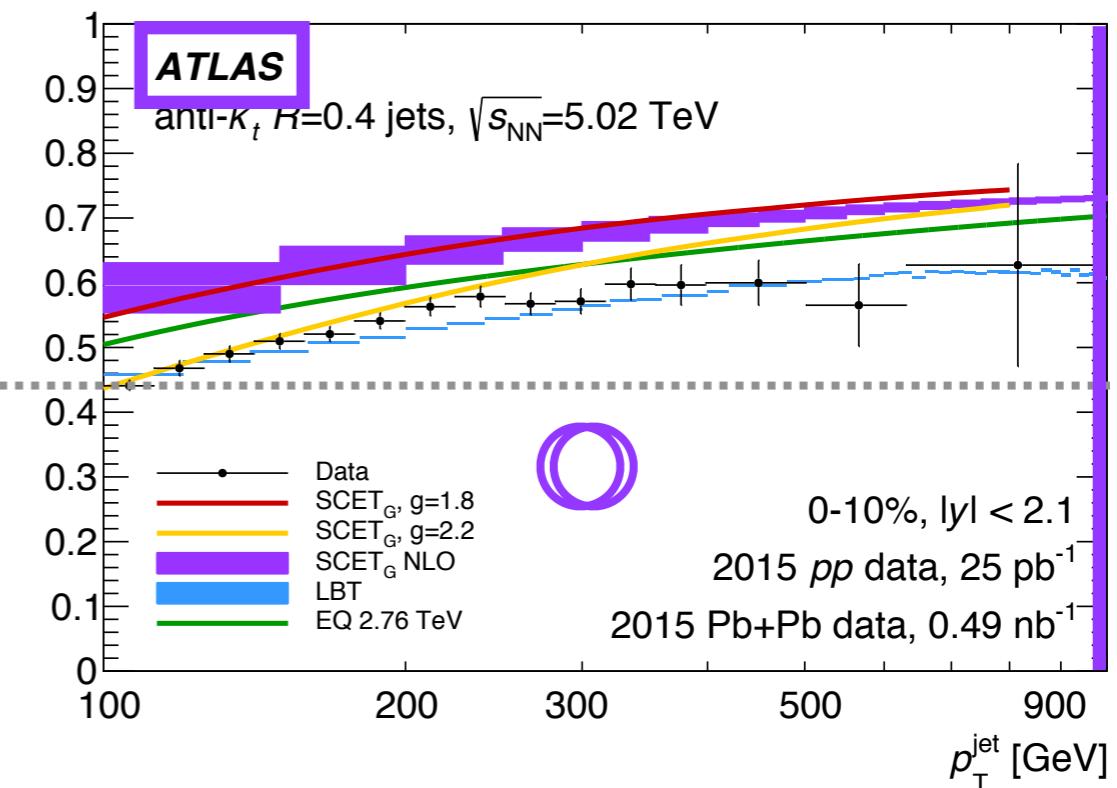


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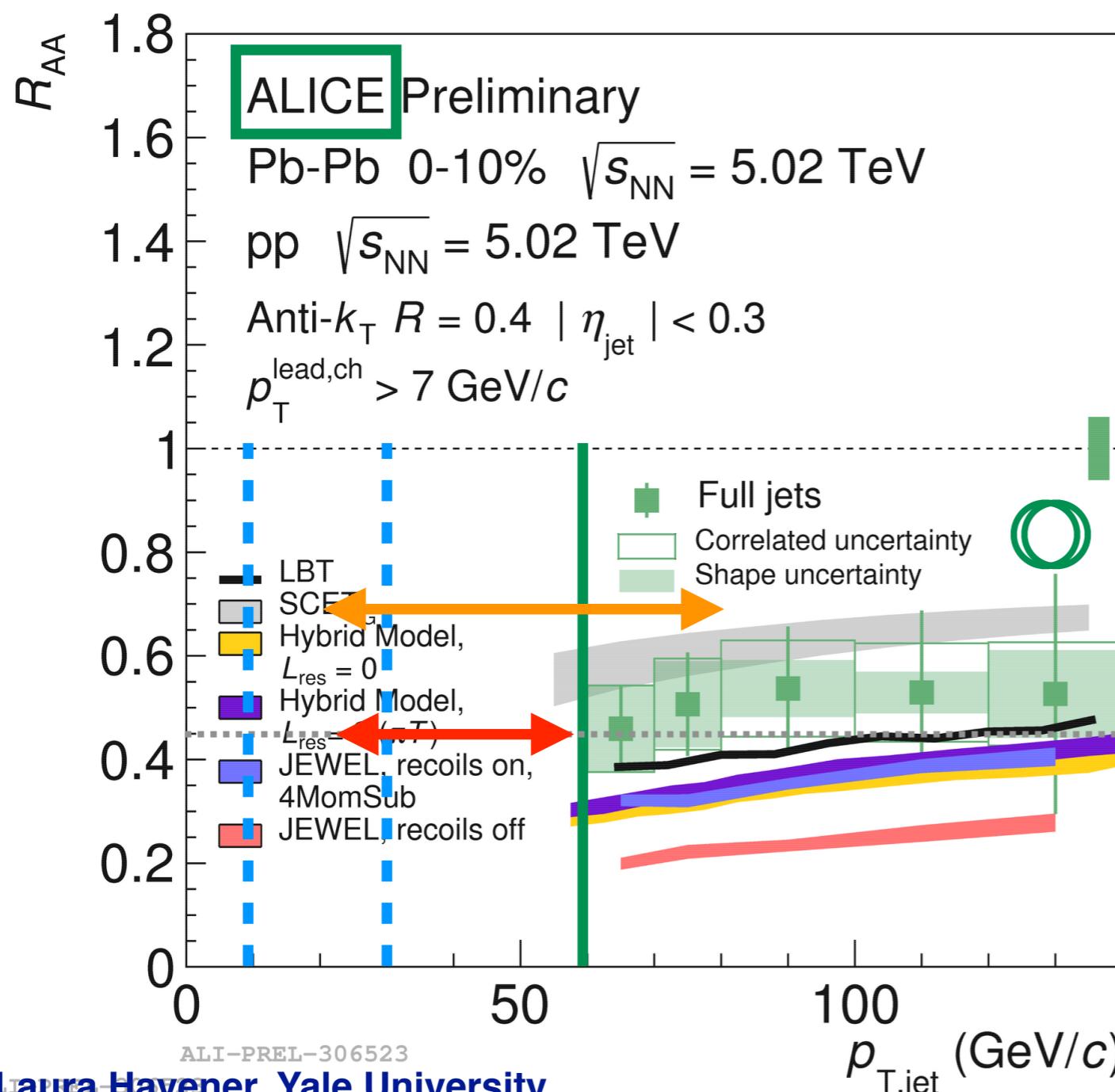


*Better background
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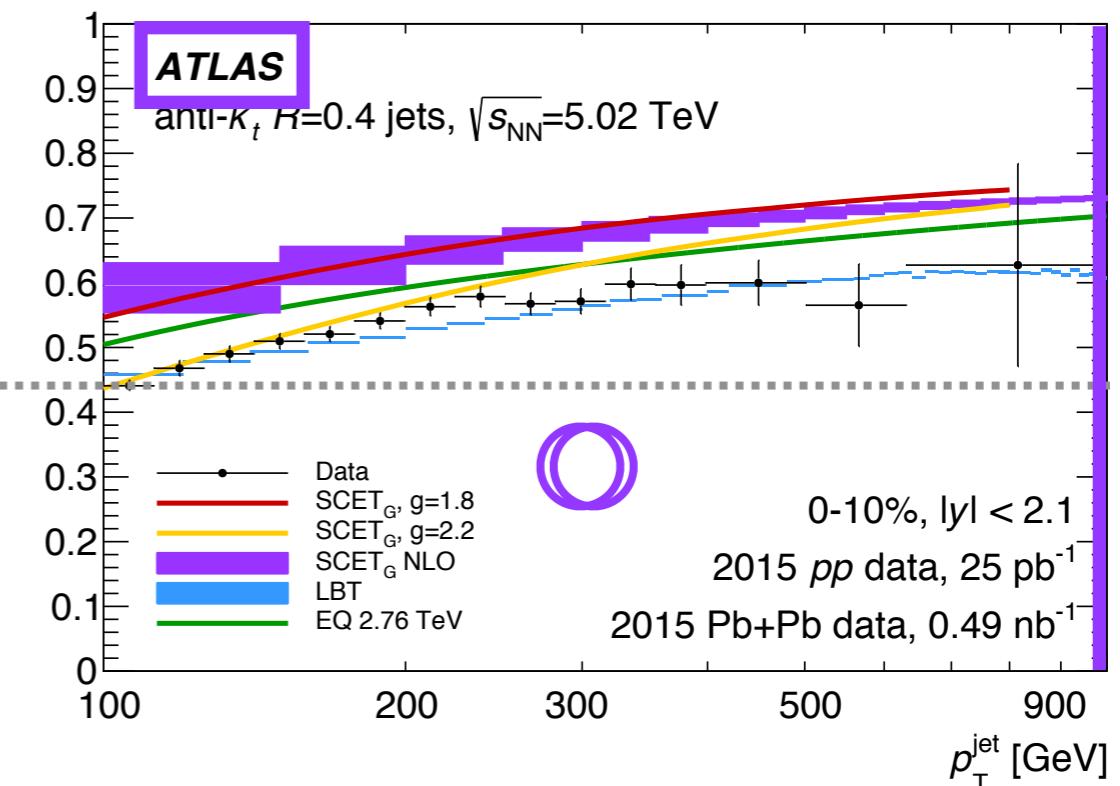


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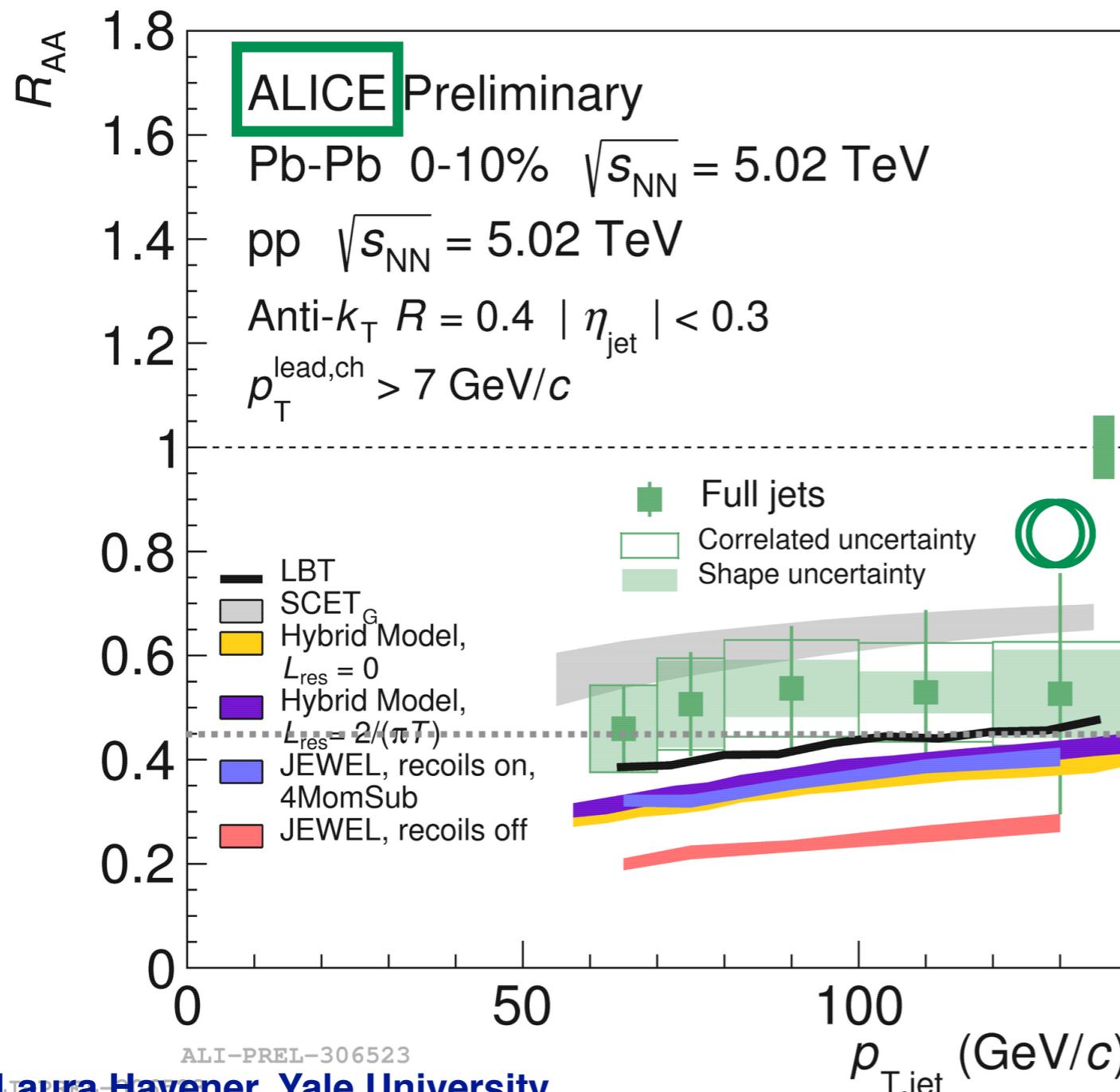


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sPHENIX

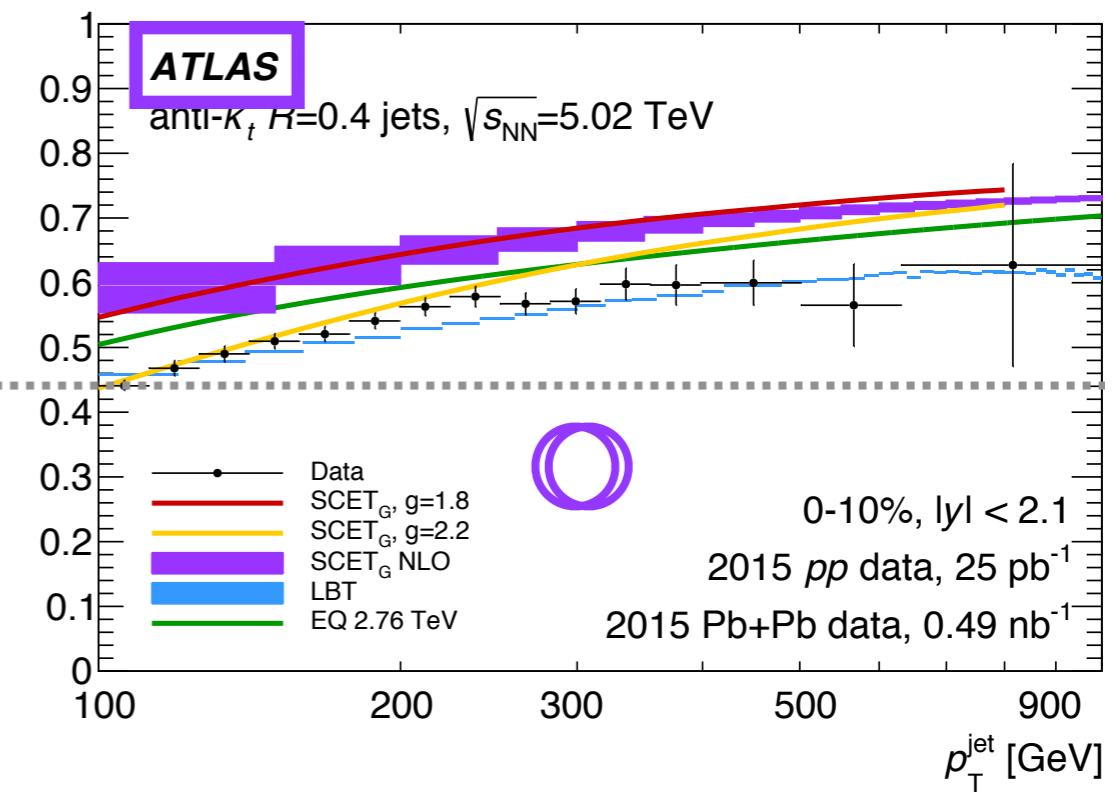


Theoretical models

- Both ALICE and ATLAS results compared to various theoretical models of jet quenching
 - Most describe the data fairly well



Need more detailed information about the jets to distinguish between models



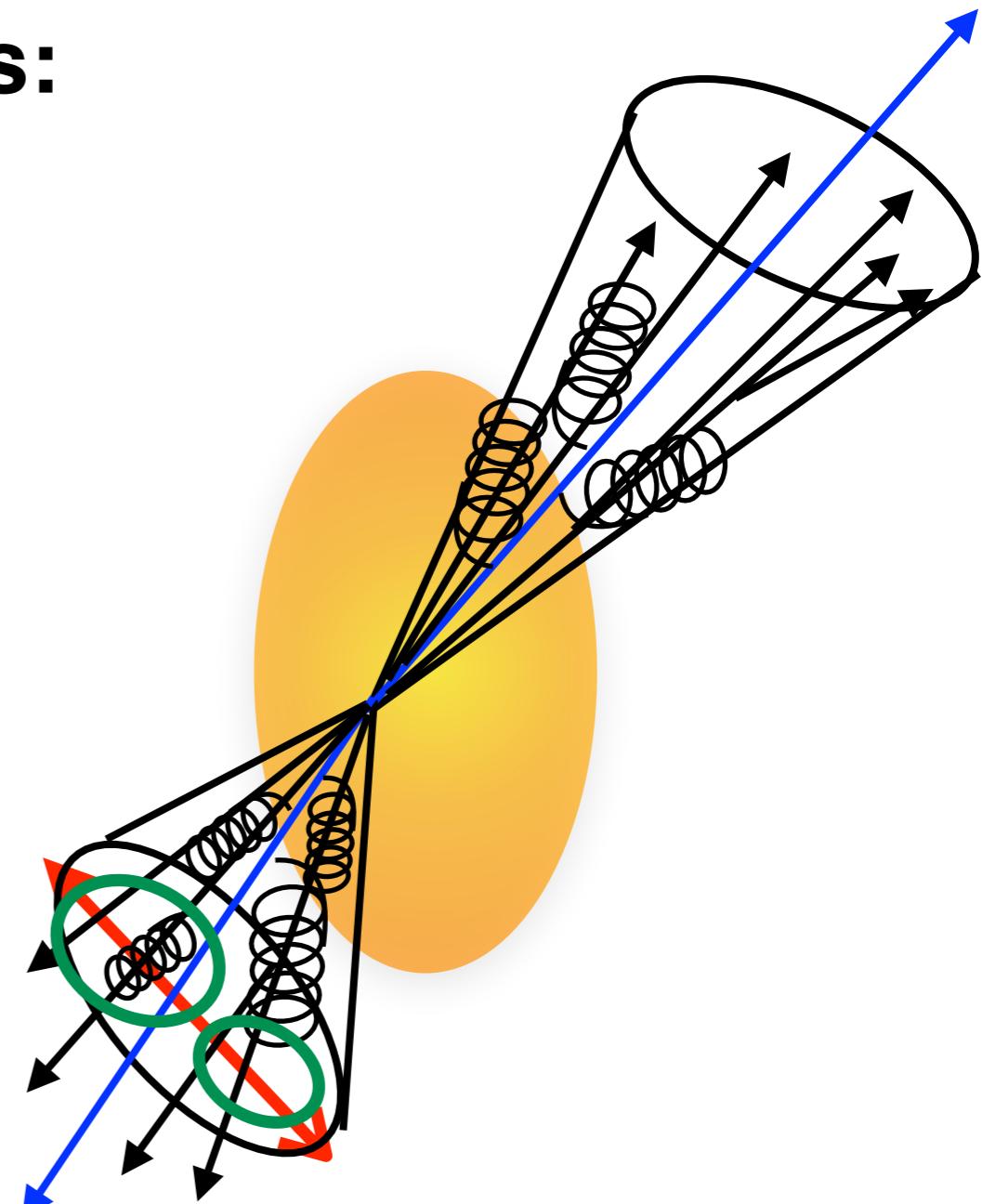
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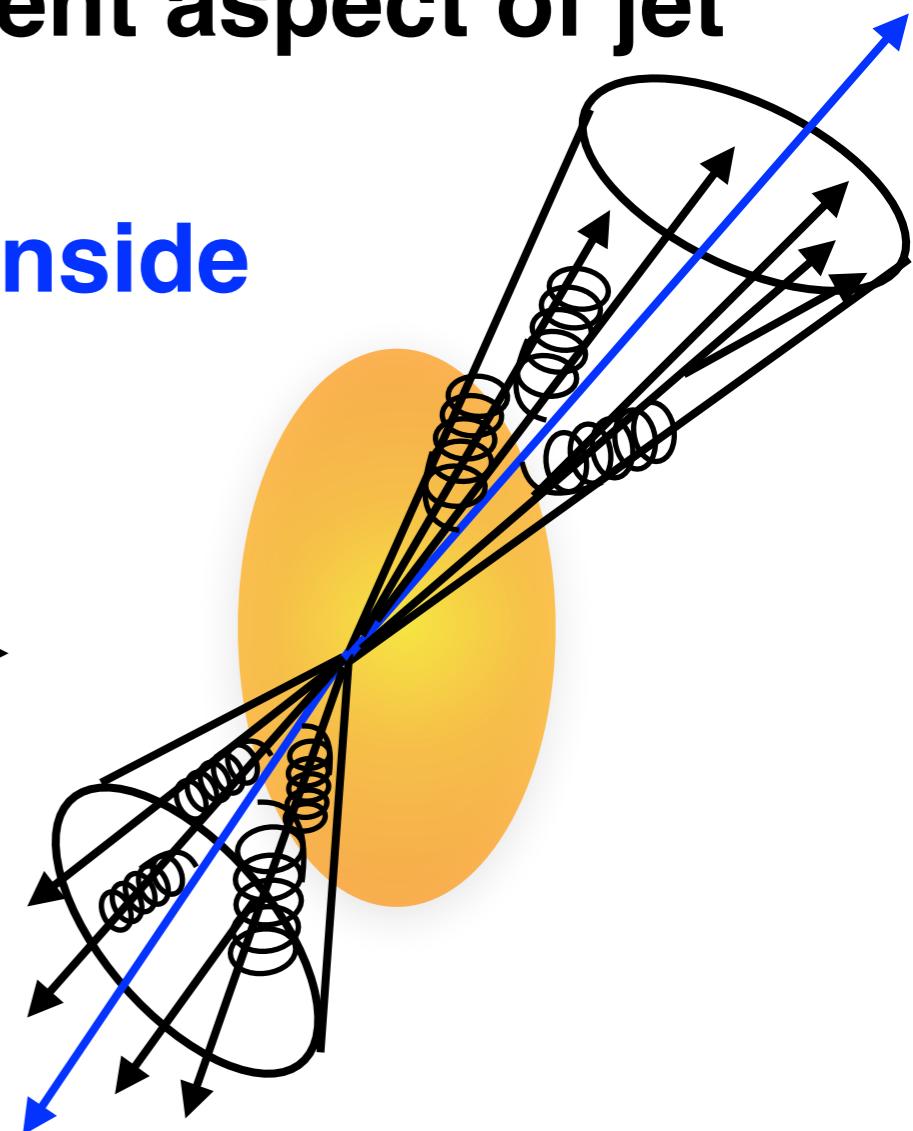
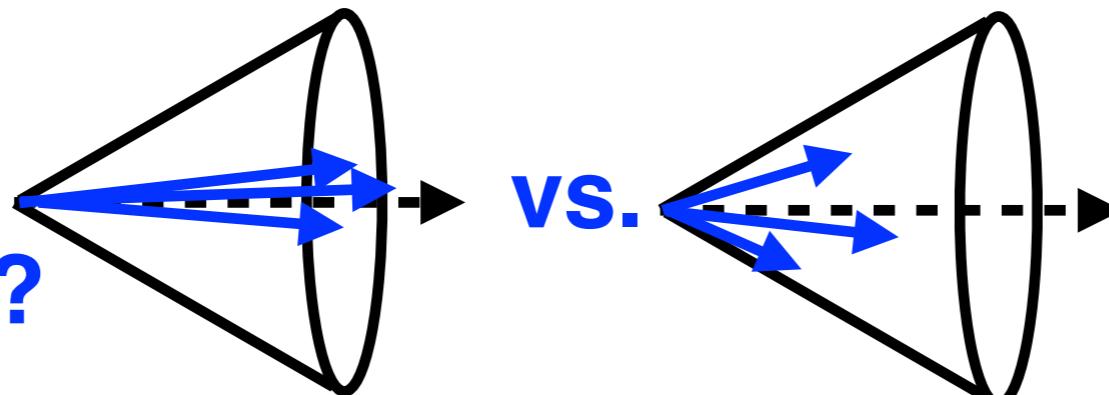


Jet substructure variables

- Different variables get probe a different aspect of jet structure modification

→ **Distribution of charged particles inside the jet (fragmentation functions)**

**Distribution
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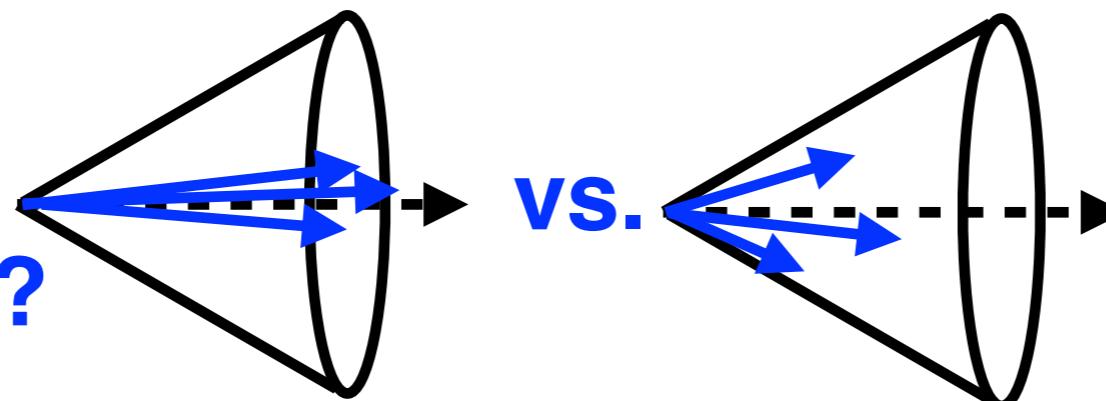


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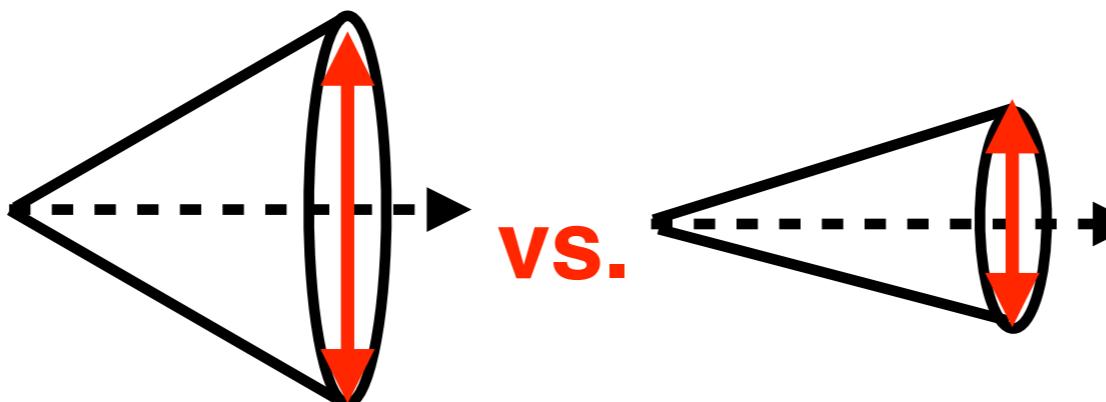
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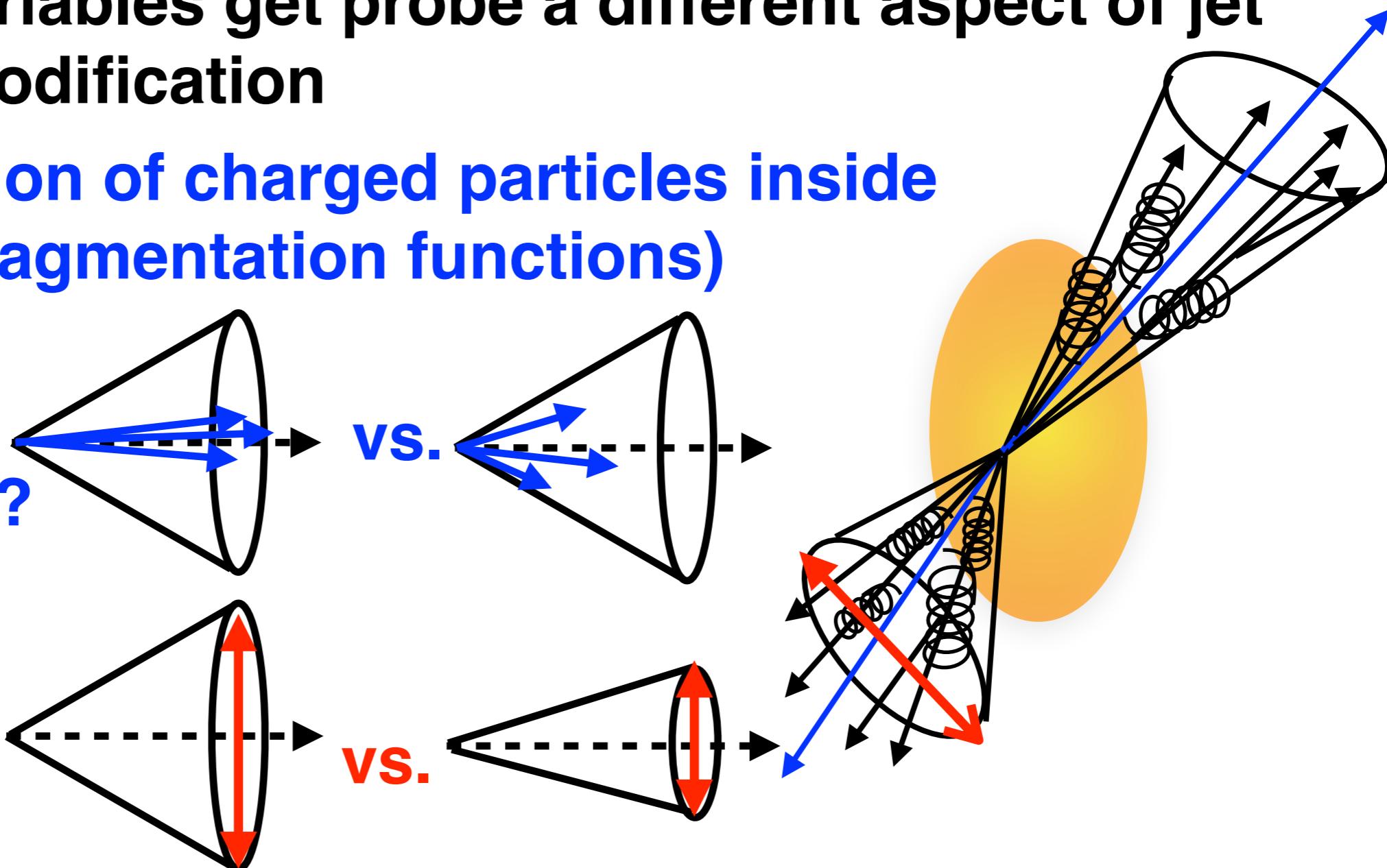


vs.

Jet mass
How wide are the jets?



vs.

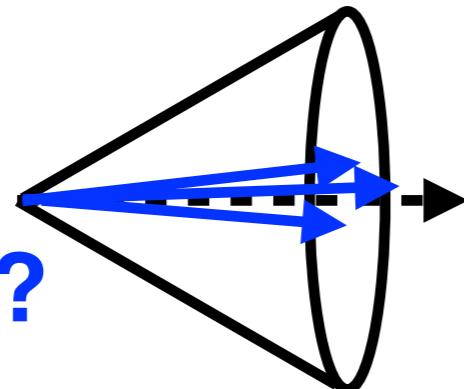


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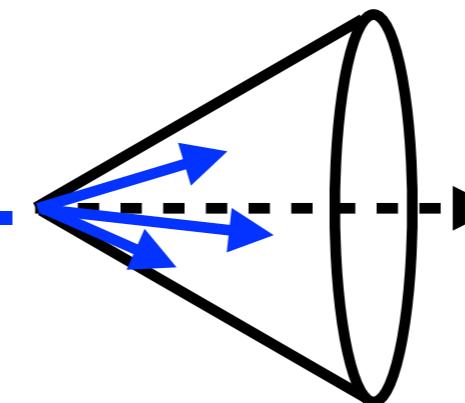
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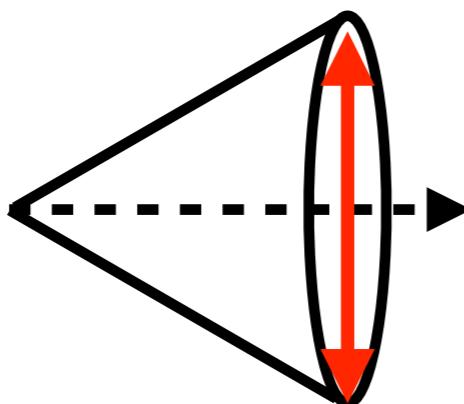


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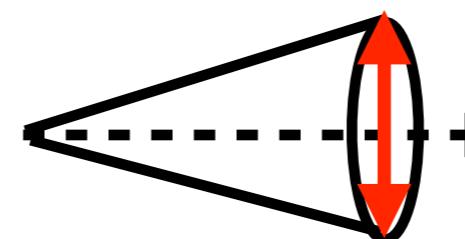


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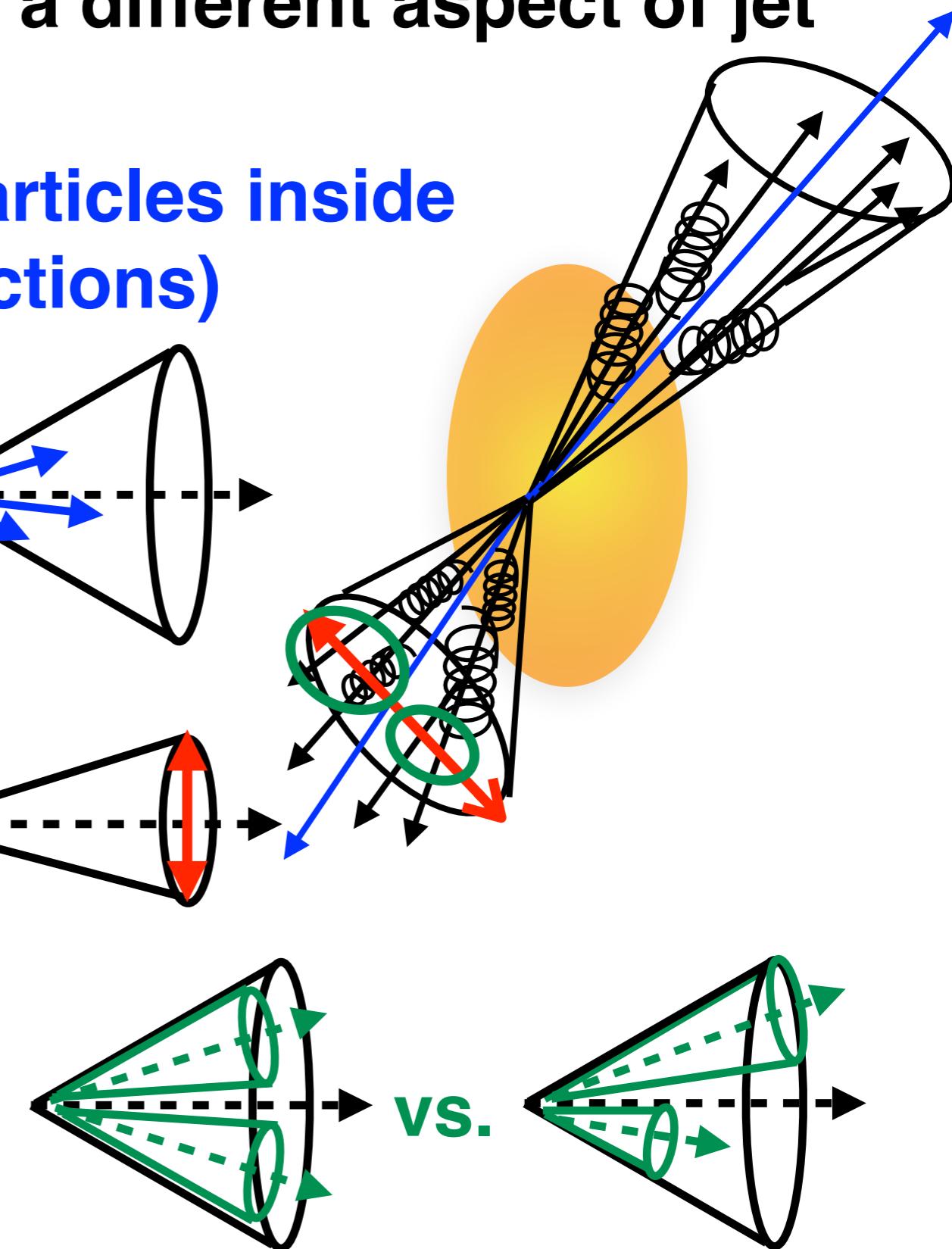


vs.



→ Subjets

How symmetric is the jet splitting?

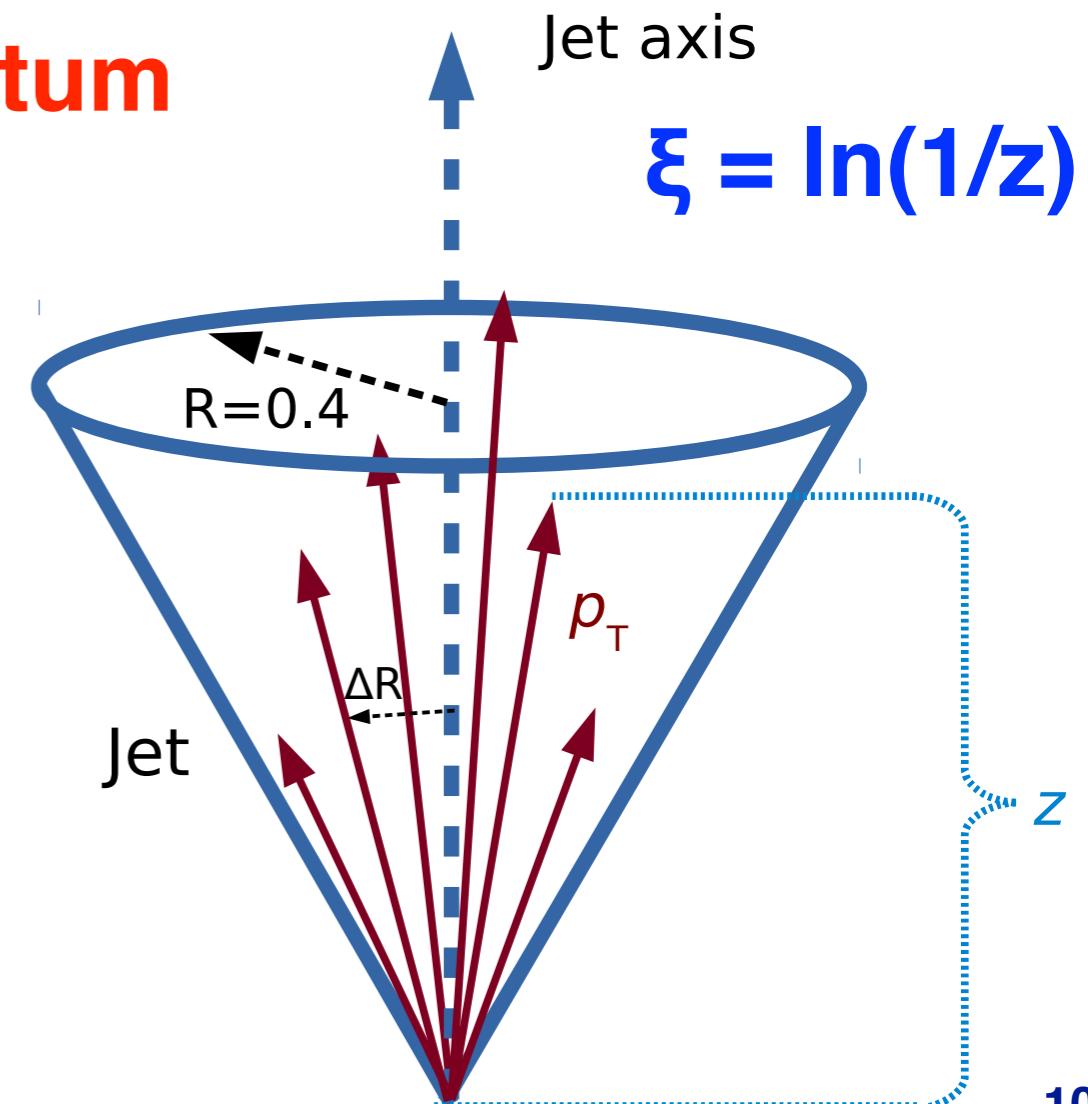


Internal structure: FFs

- Fragmentation functions measure how the particles within the jet are distributed by looking at number of charged particles in jets (N_{ch})

→ z measures of the fraction of the track momentum in the jet momentum

$$D(z) = \frac{1}{N_{jet}} \frac{dN_{ch}}{dz}$$
$$z = \frac{p_T \cos \Delta R}{p_T^{\text{jet}}}$$



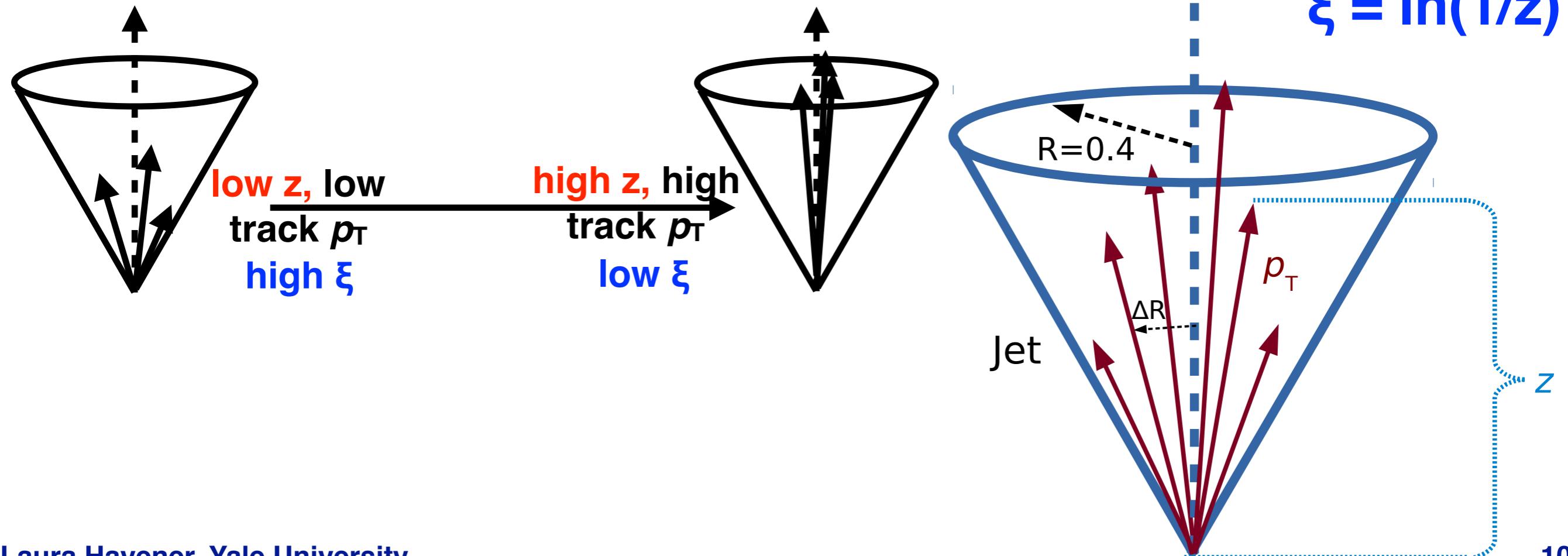
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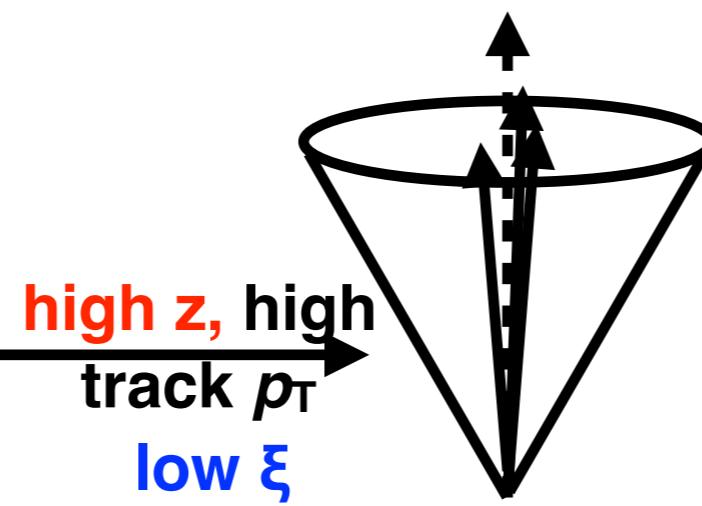
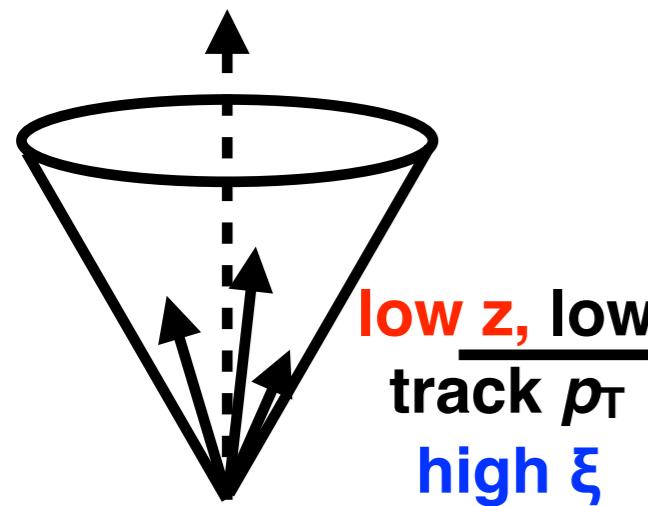
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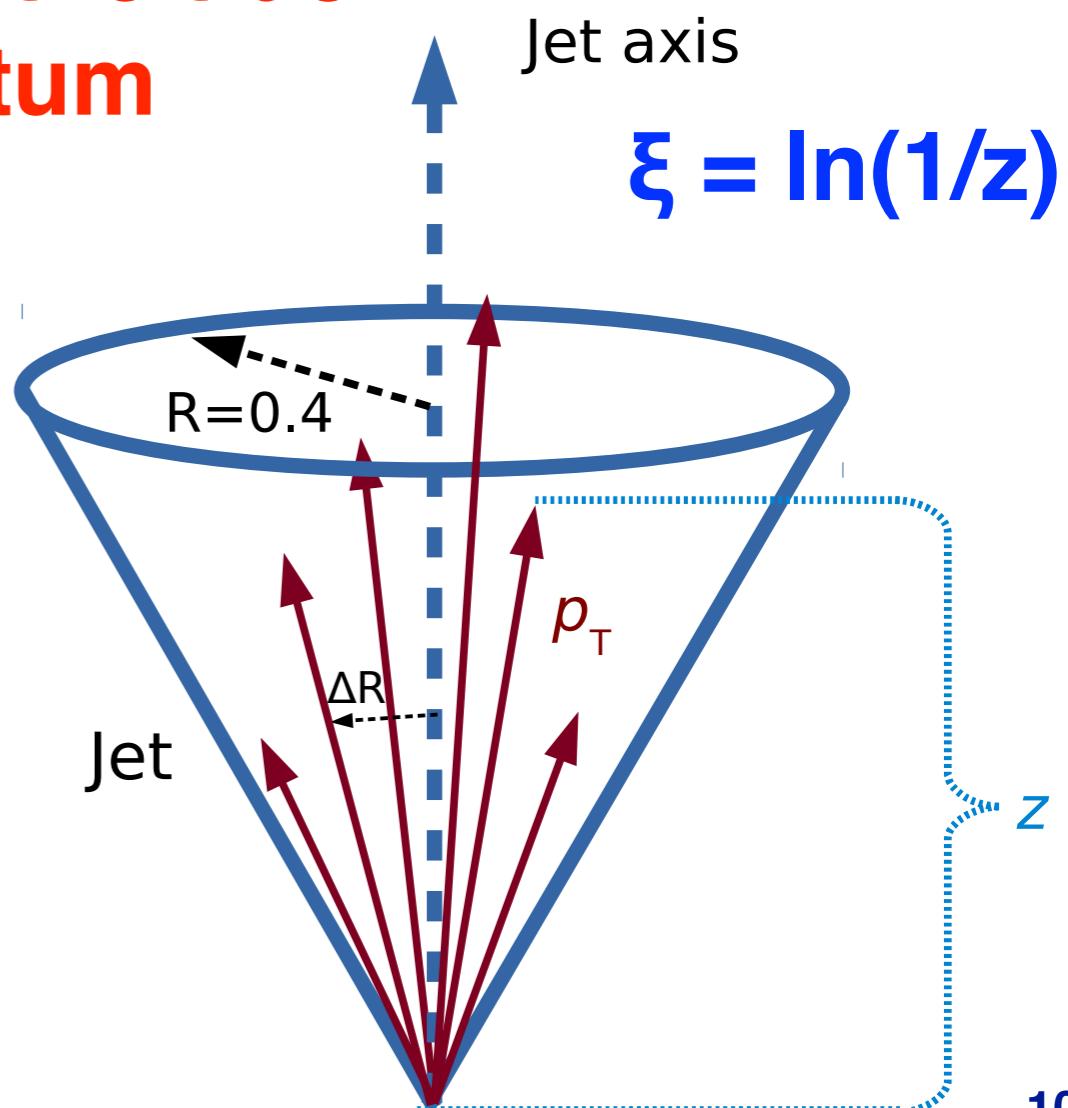


- FF ratio in Pb+Pb to pp needed to see modification.

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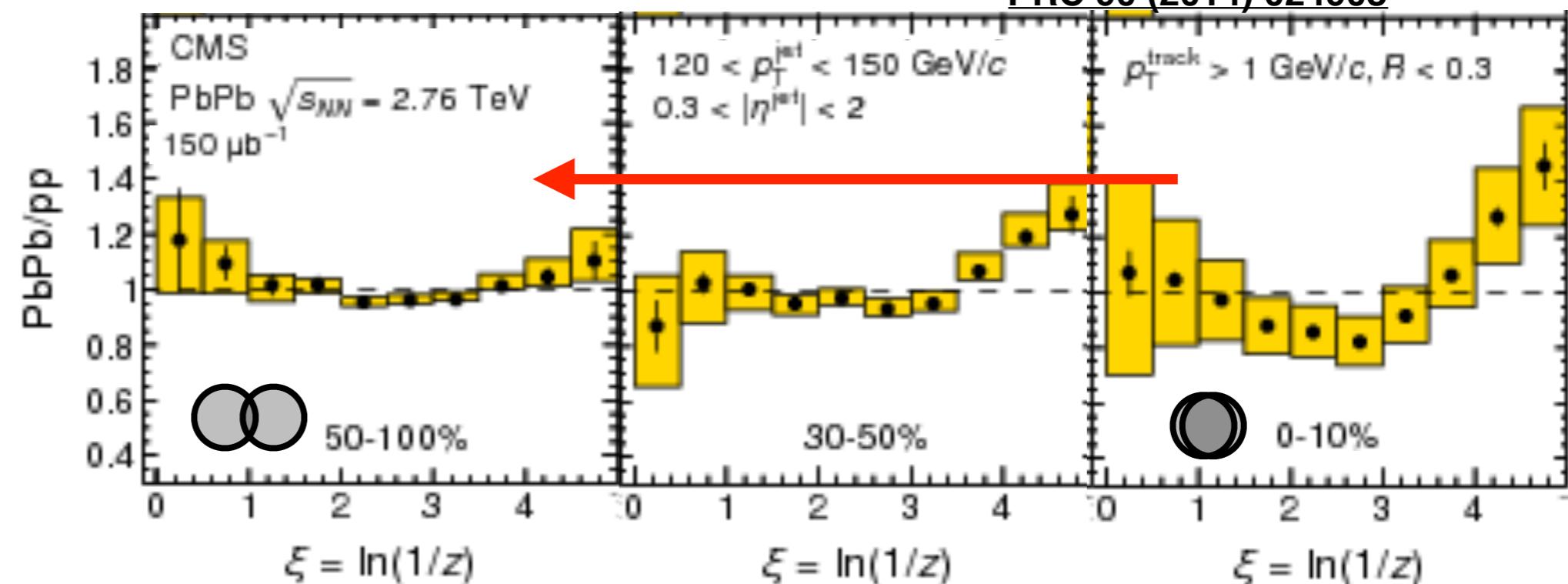


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PRC 90 (2014) 024908

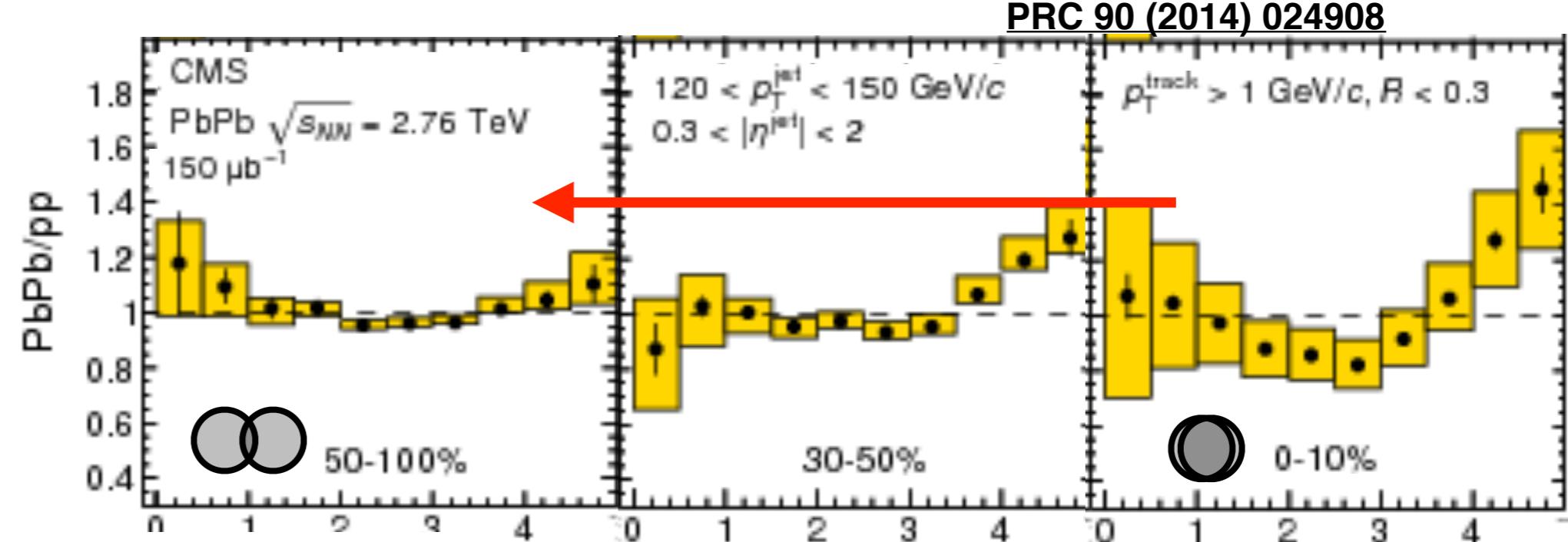
- Jets are modified in central collisions and not in peripheral



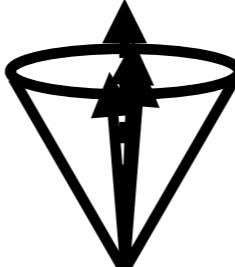
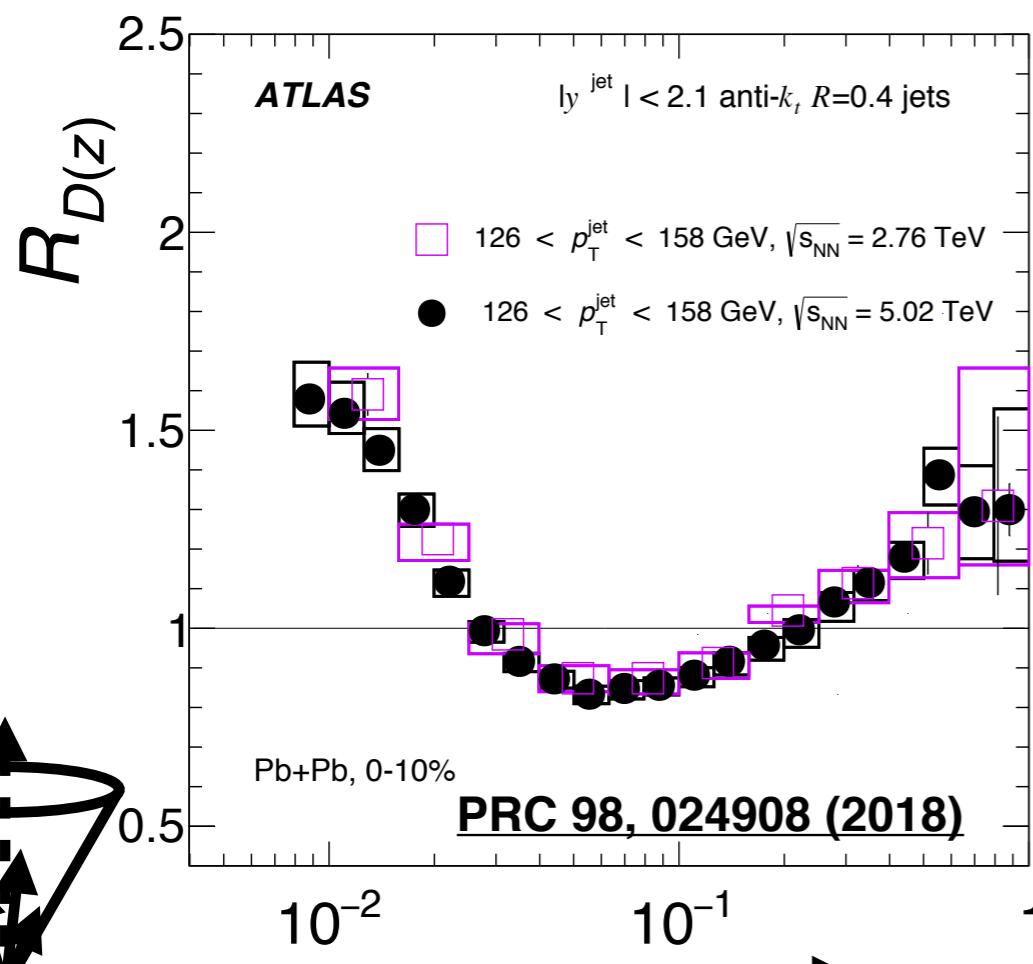
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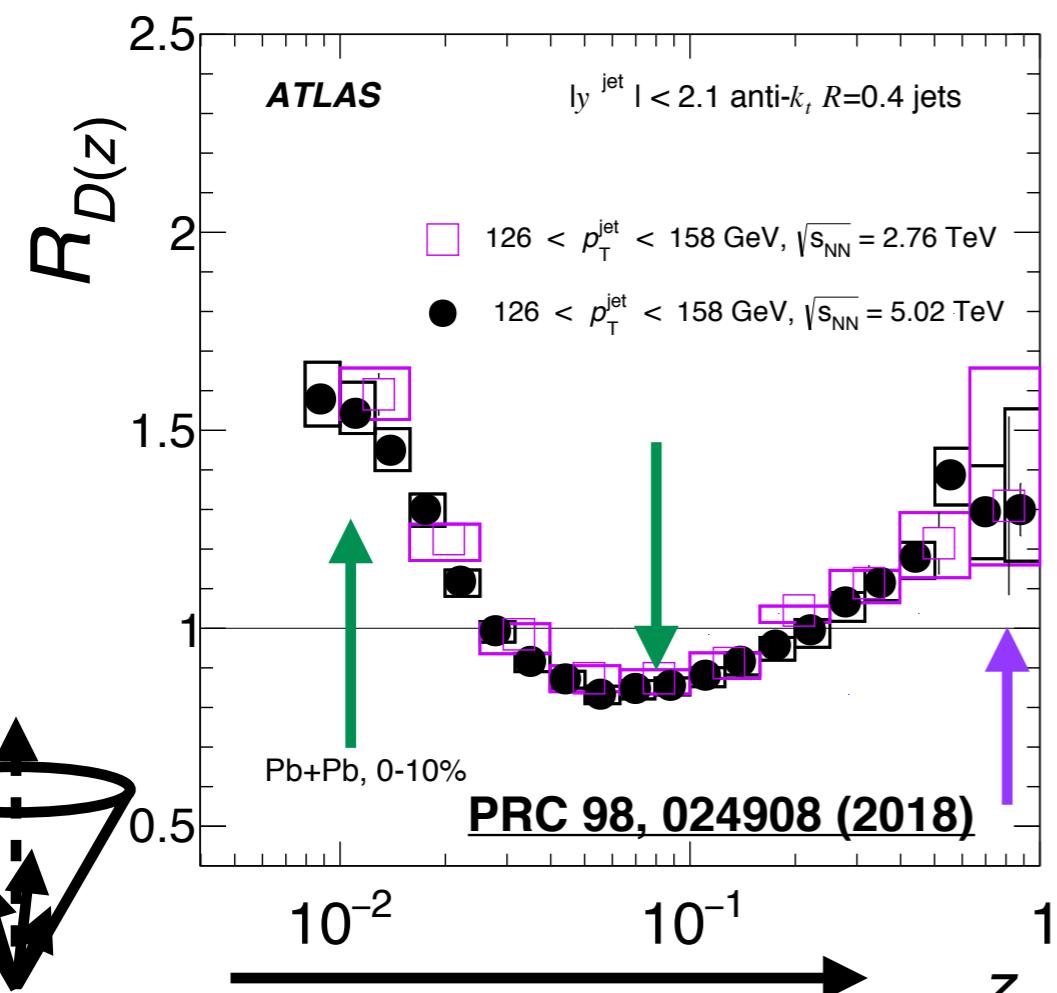
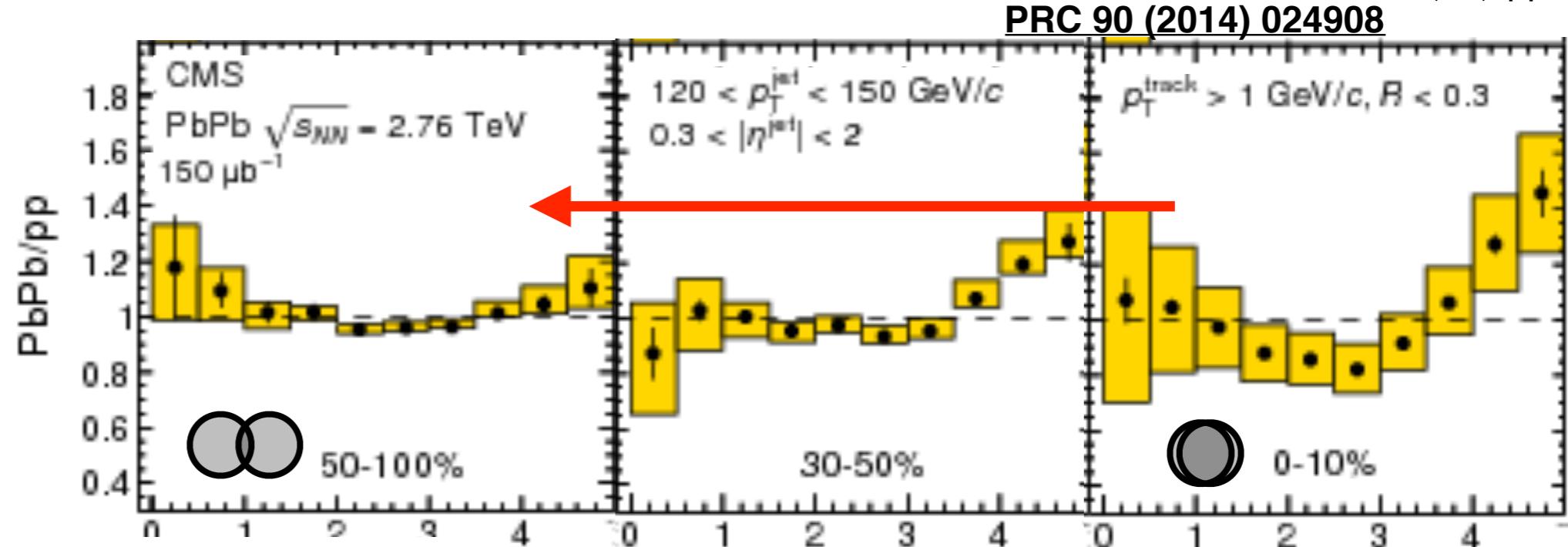
- Detailed modification shape probes different types of jets



Internal structure: FFs

$$R_{D(z)} = \frac{D(z)_{\text{PbPb}}}{D(z)_{\text{pp}}}$$

- Jets are modified in central collisions and not in peripheral



- Detailed modification shape probes different types of jets
 - Low z enhancement and intermediate z suppression from energy transfer to soft particles around jet
 - Enhancement at high z

Jet mass

- Jet mass is reconstructed from summing the energy and p_T of constituents inside of jets
- Ratio m/p_T (like the opening angle θ) which is easier to unfold and has a weaker dependence on p_T

$$m = \sqrt{(\sum_{i \in J} E_i)^2 - (\sum_{i \in J} \vec{p}_i)^2}$$

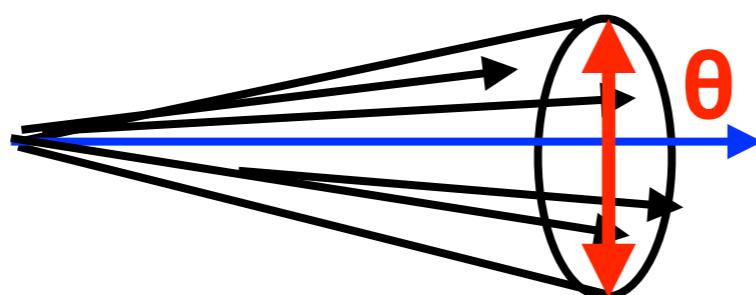
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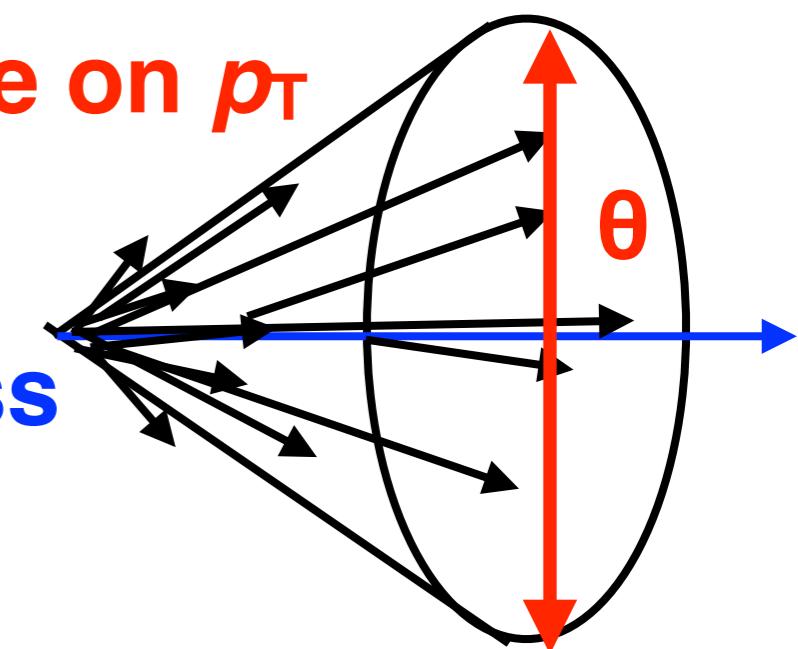
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narrow jets:
lower mass
and m/p_T



wide jets:
higher mass
and m/p_T



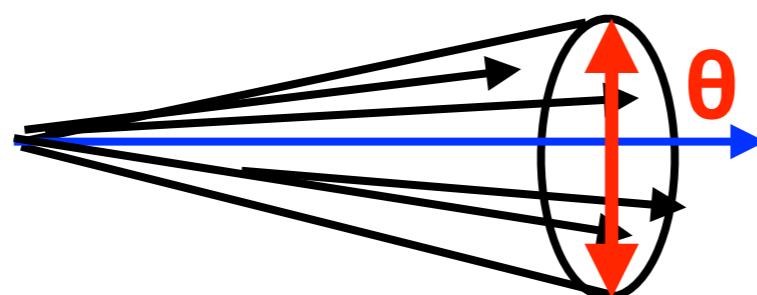
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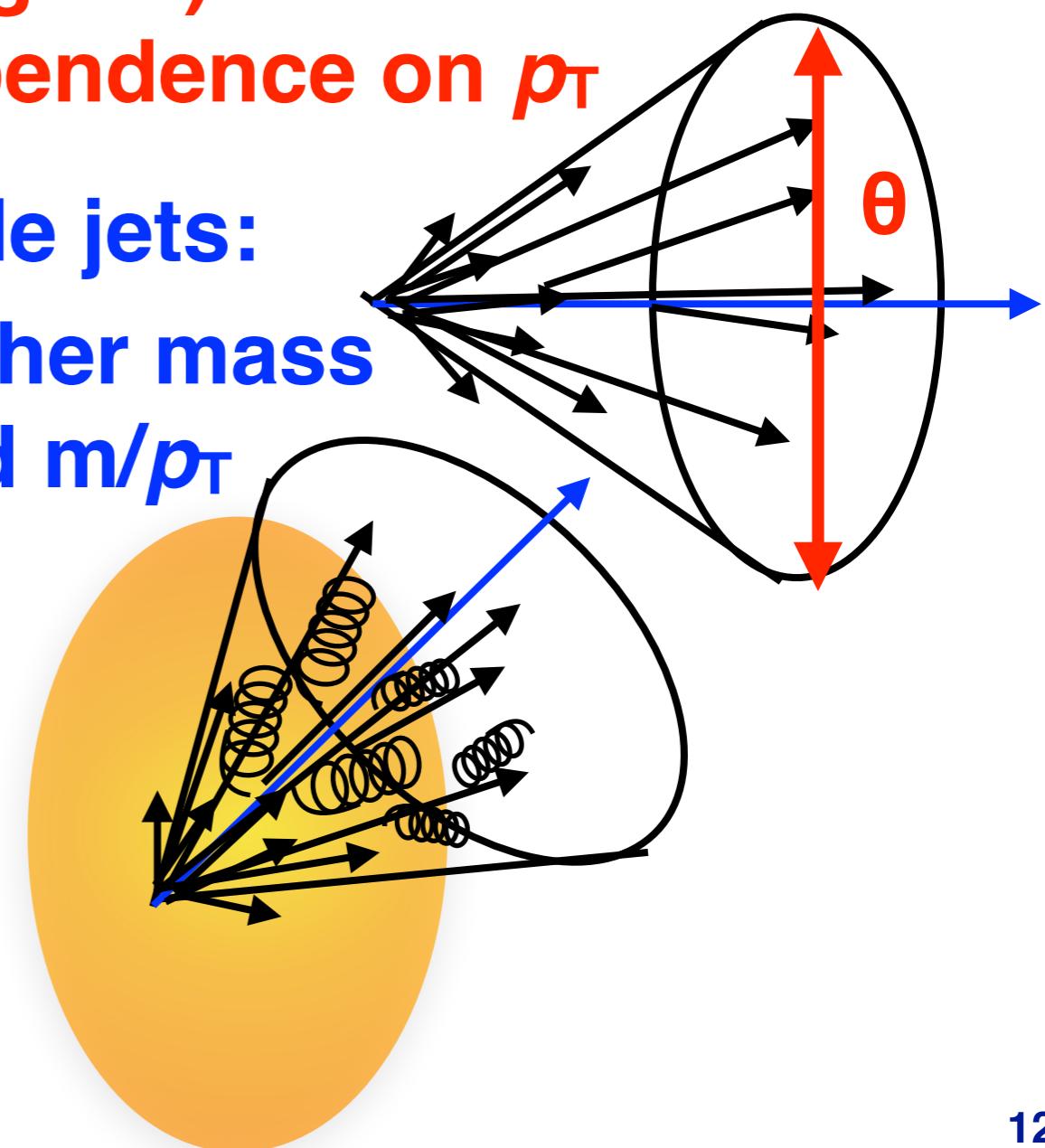
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- In medium:
 - Jet widens \rightarrow larger mass

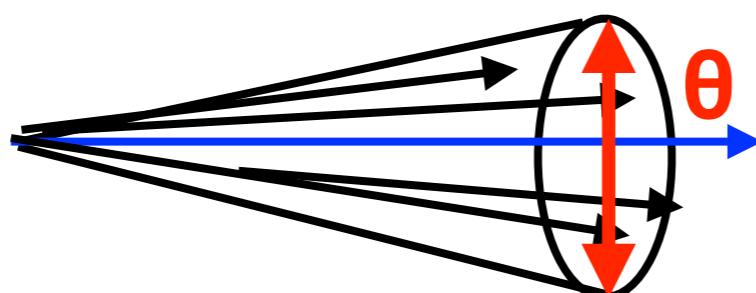
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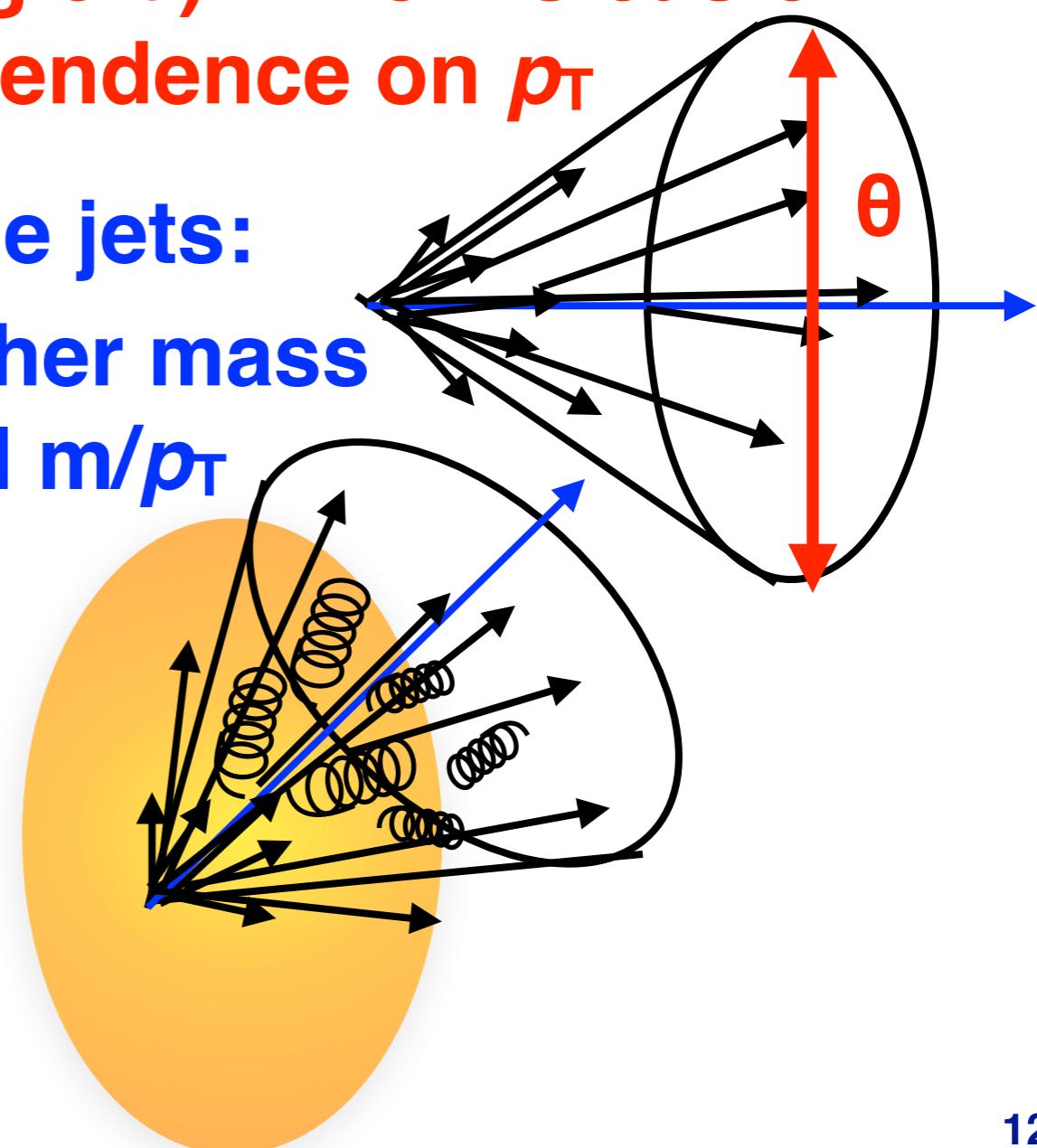
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wide jets:
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- In medium:
 - Jet widens \rightarrow larger mass
 - Jet widens too much and energy moves outside of jet cone \rightarrow smaller mass

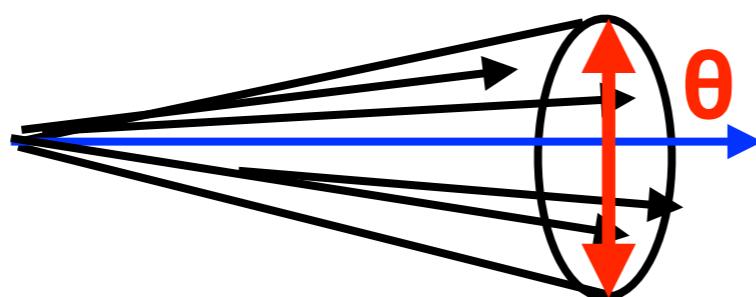
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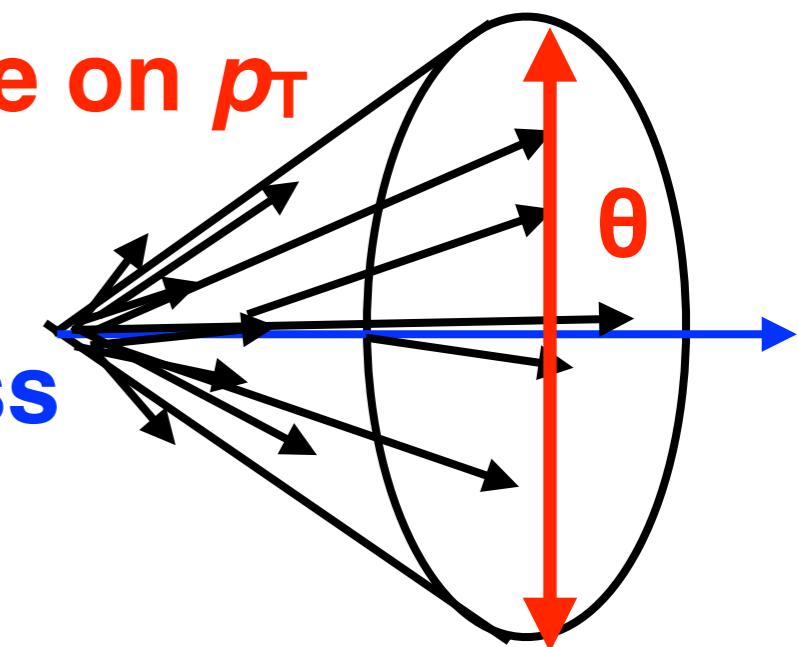
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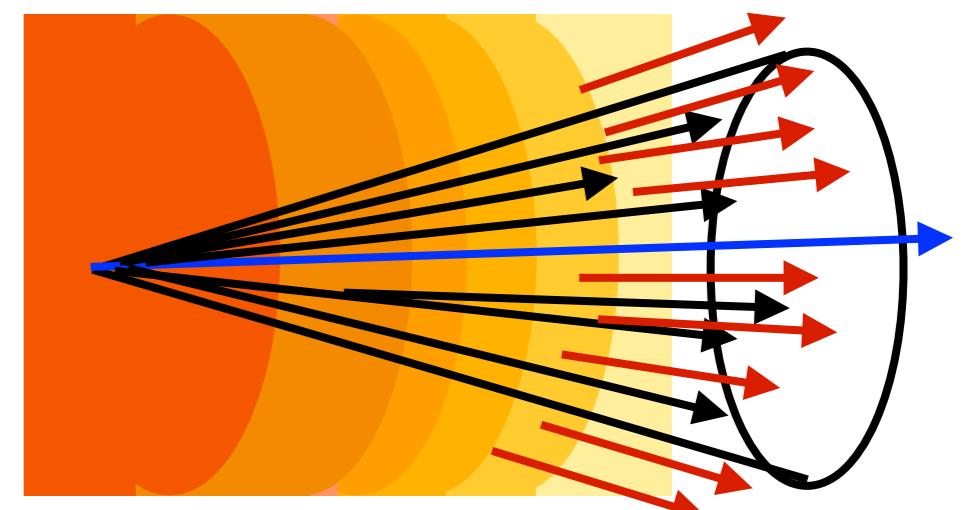


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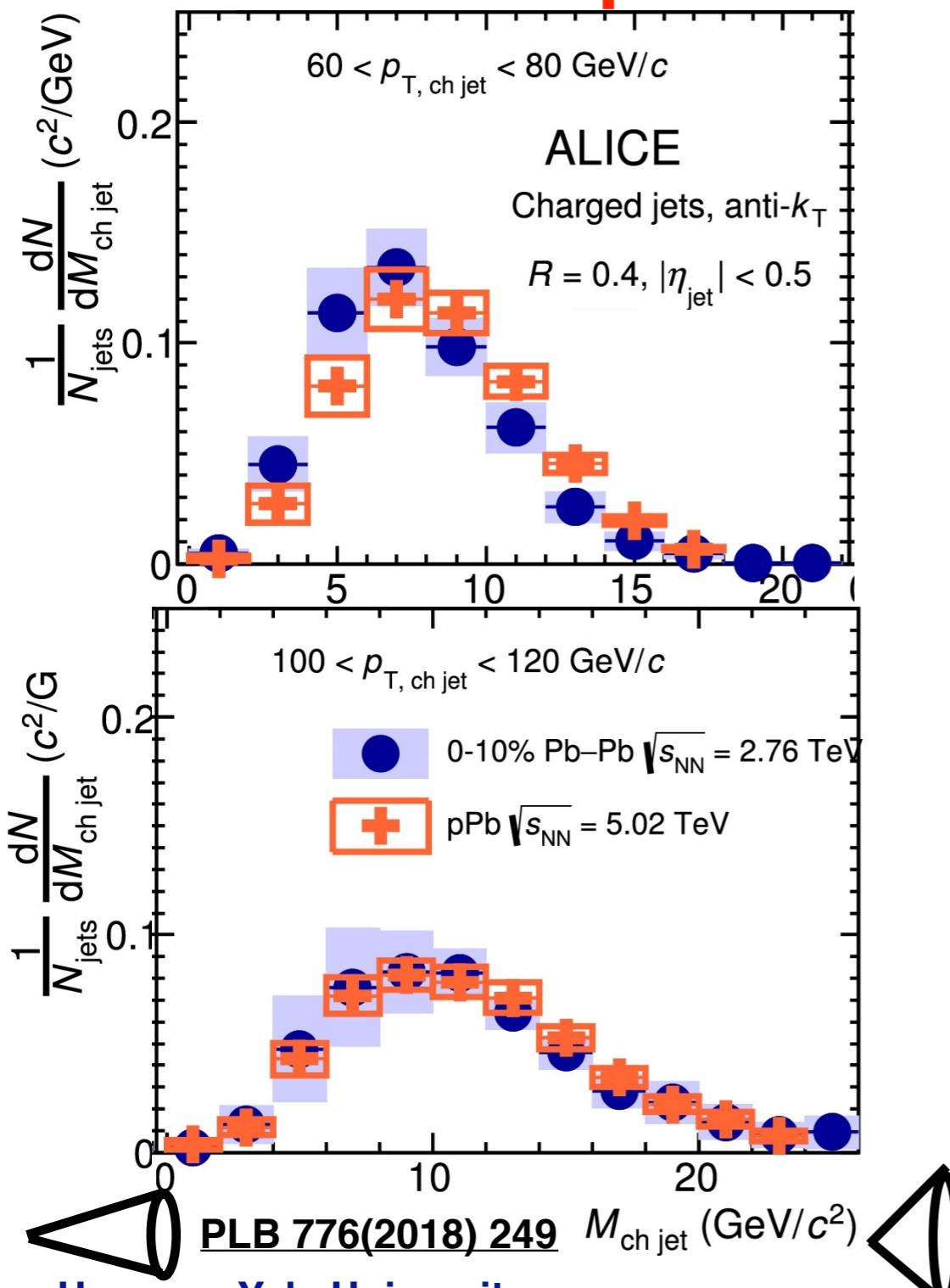
- In medium:

- Medium responds to jet and recoils, causing a wake that pushes soft particles back inside the jet -> increases mass

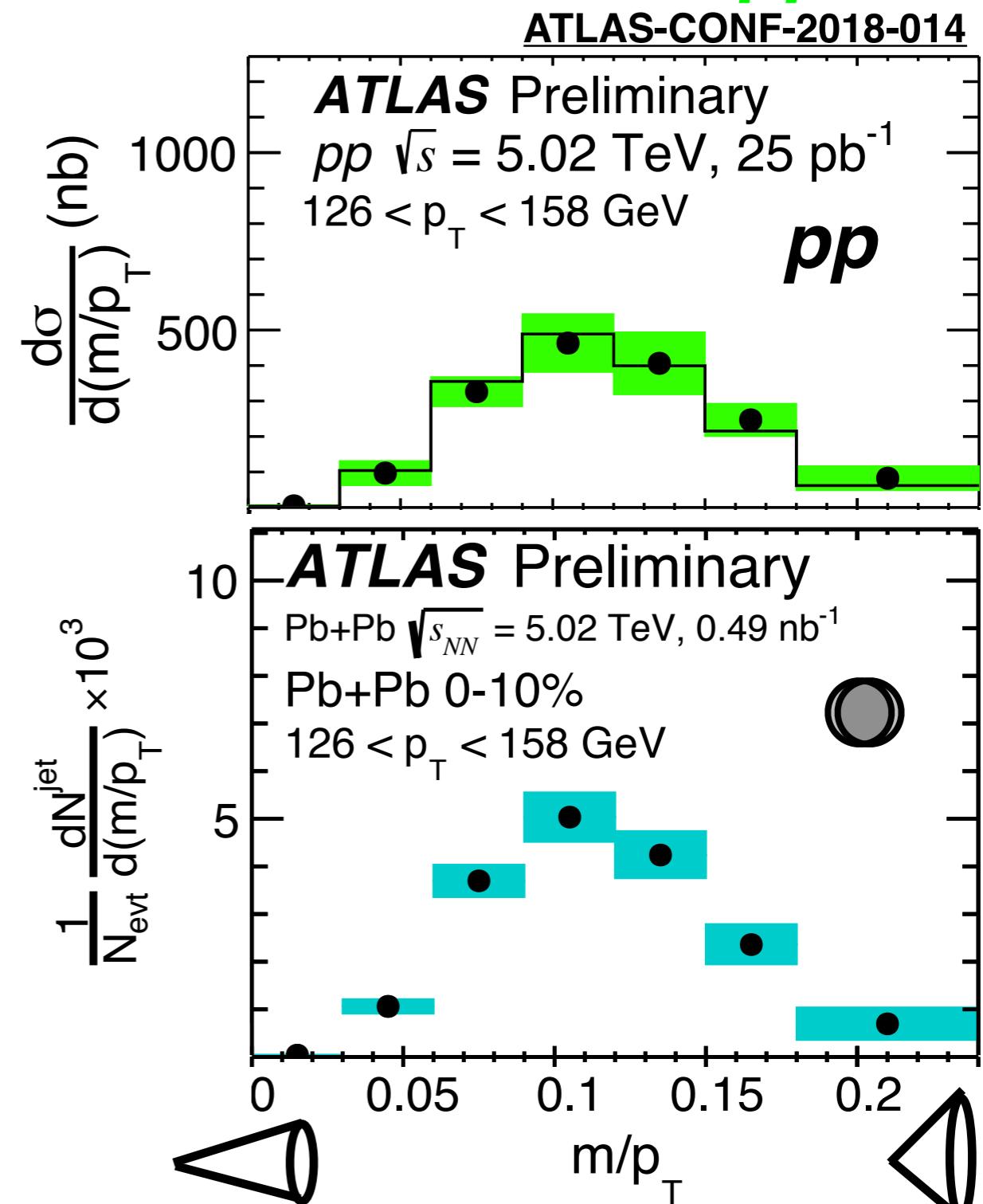


Jet mass

ALICE jet mass in Pb+Pb and p+Pb

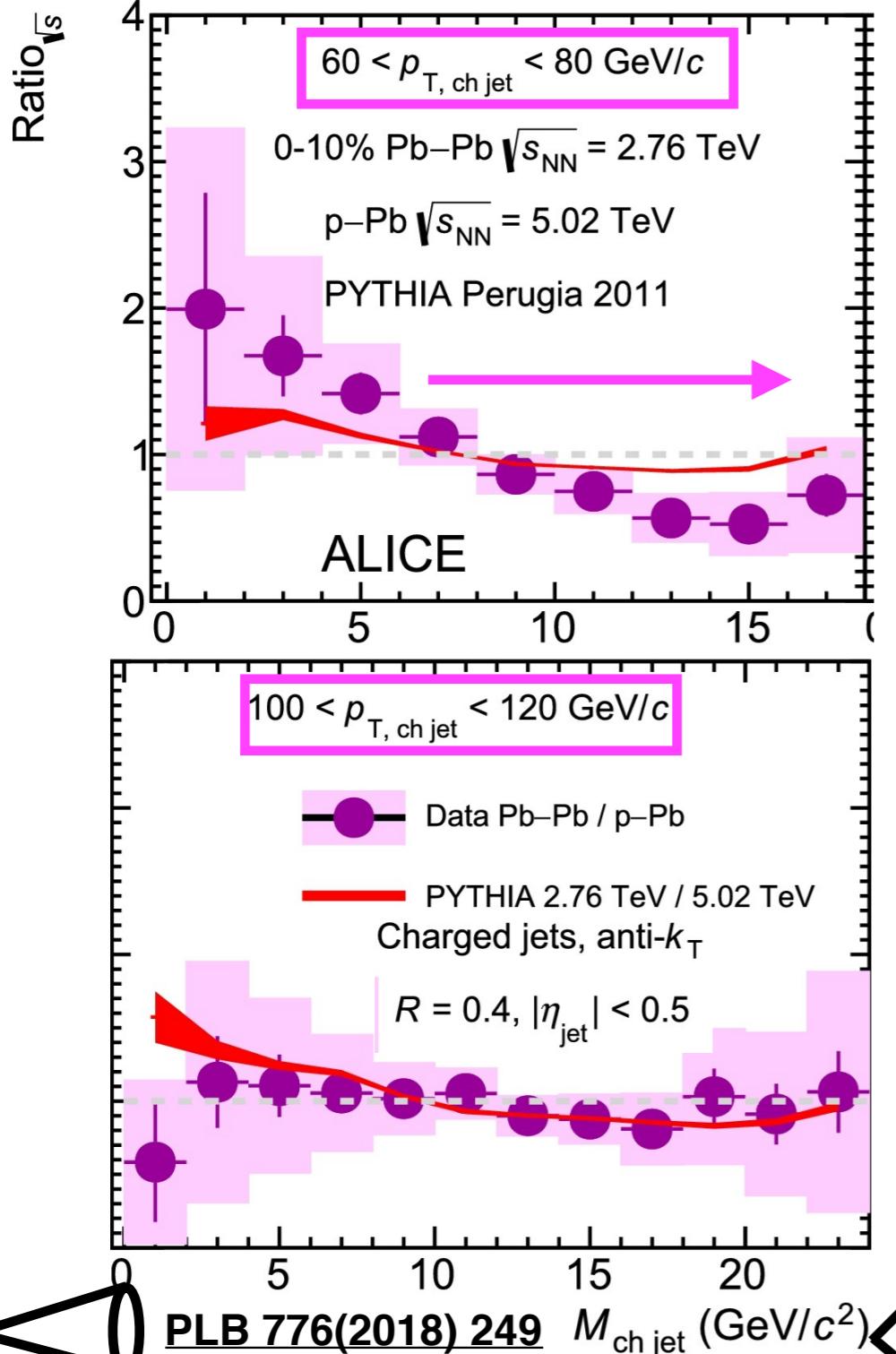


ATLAS m/p_T in Pb+Pb and pp

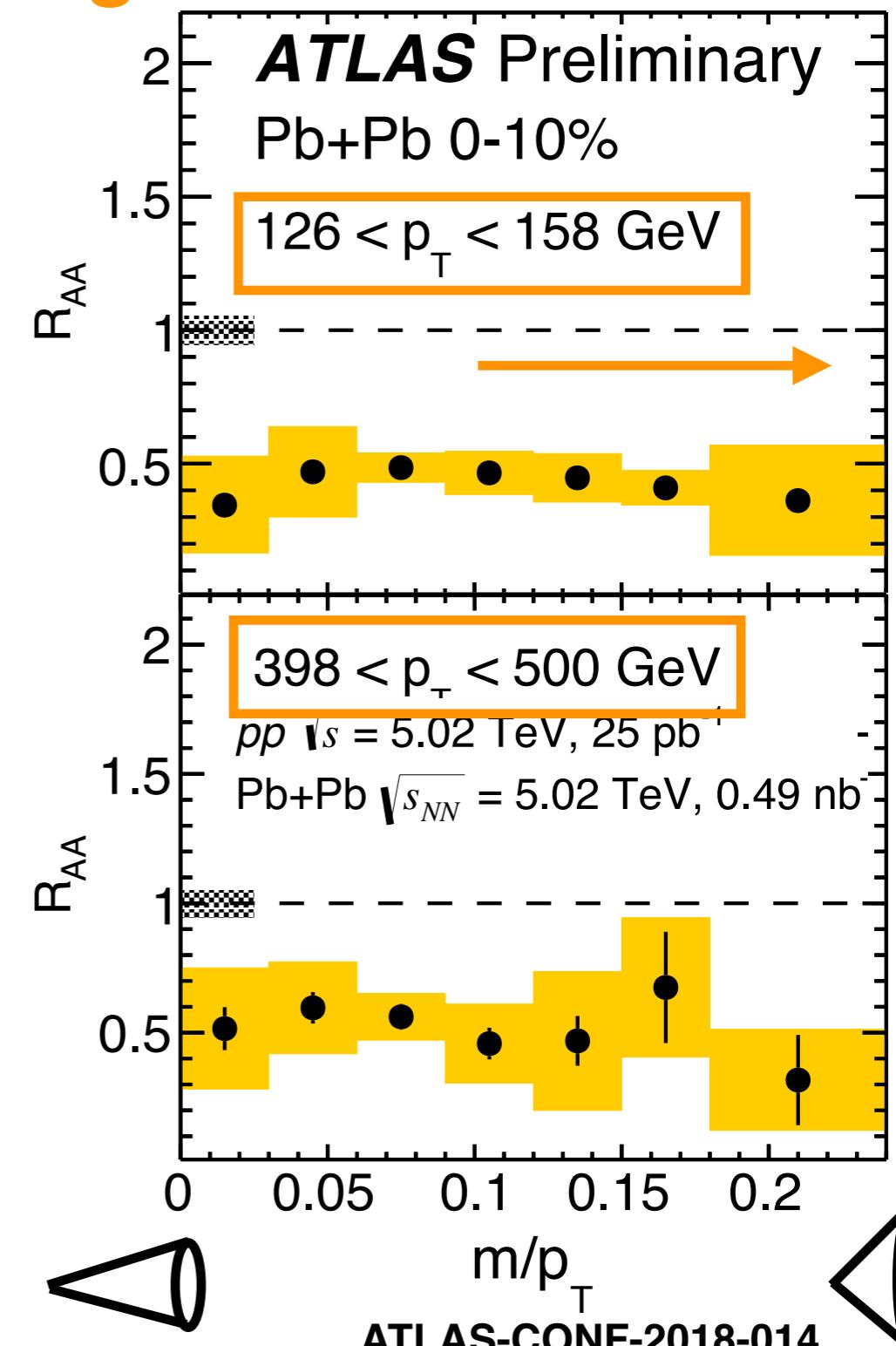


Jet mass: ratio

ALICE m_{jet} : no significant modification to Pb+Pb

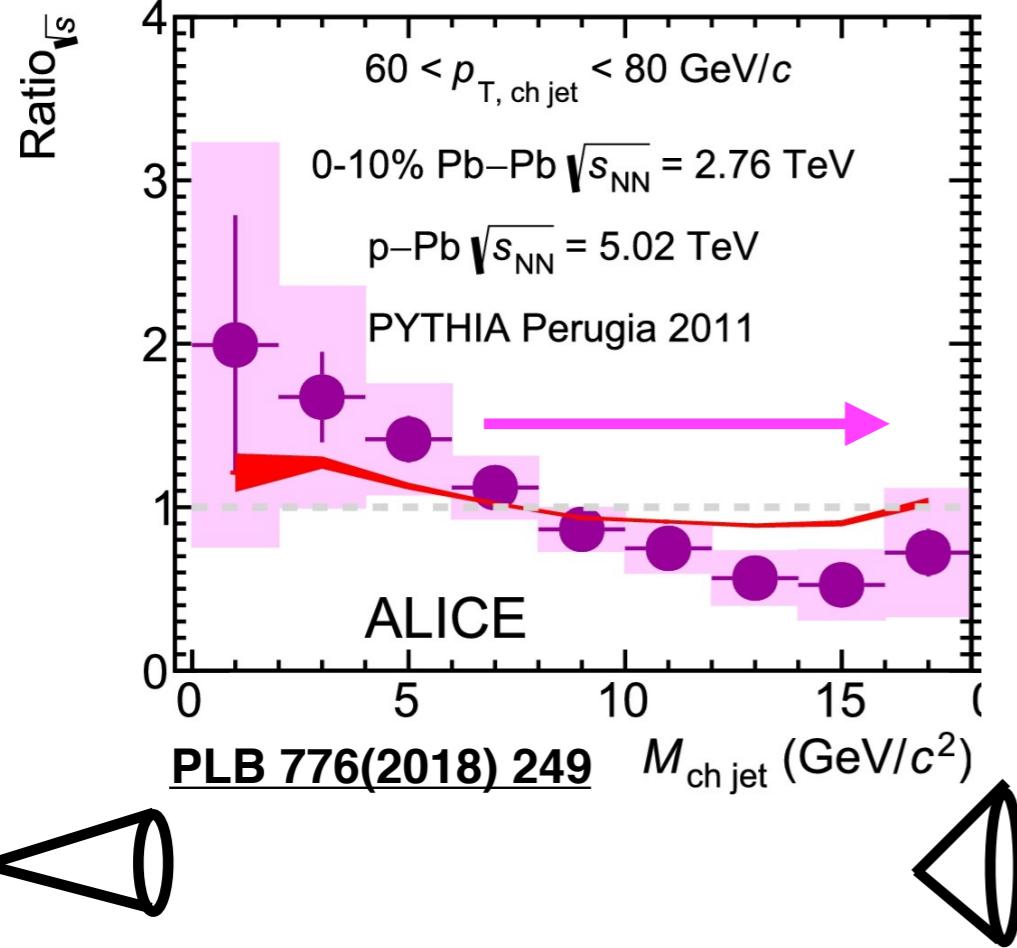


ATLAS R_{AA} vs. m/p_{T} : no significant modification

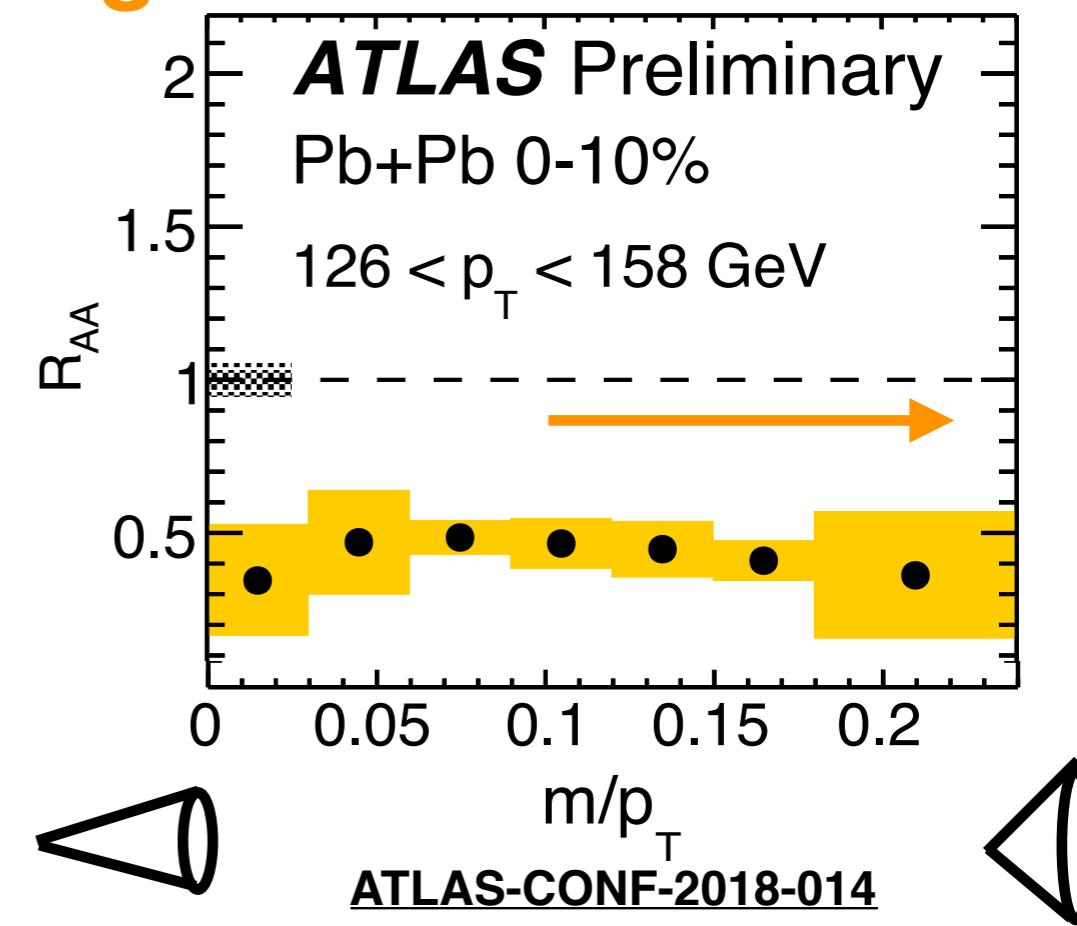


Jet mass: ratio

ALICE m_{jet} : no significant modification to Pb+Pb



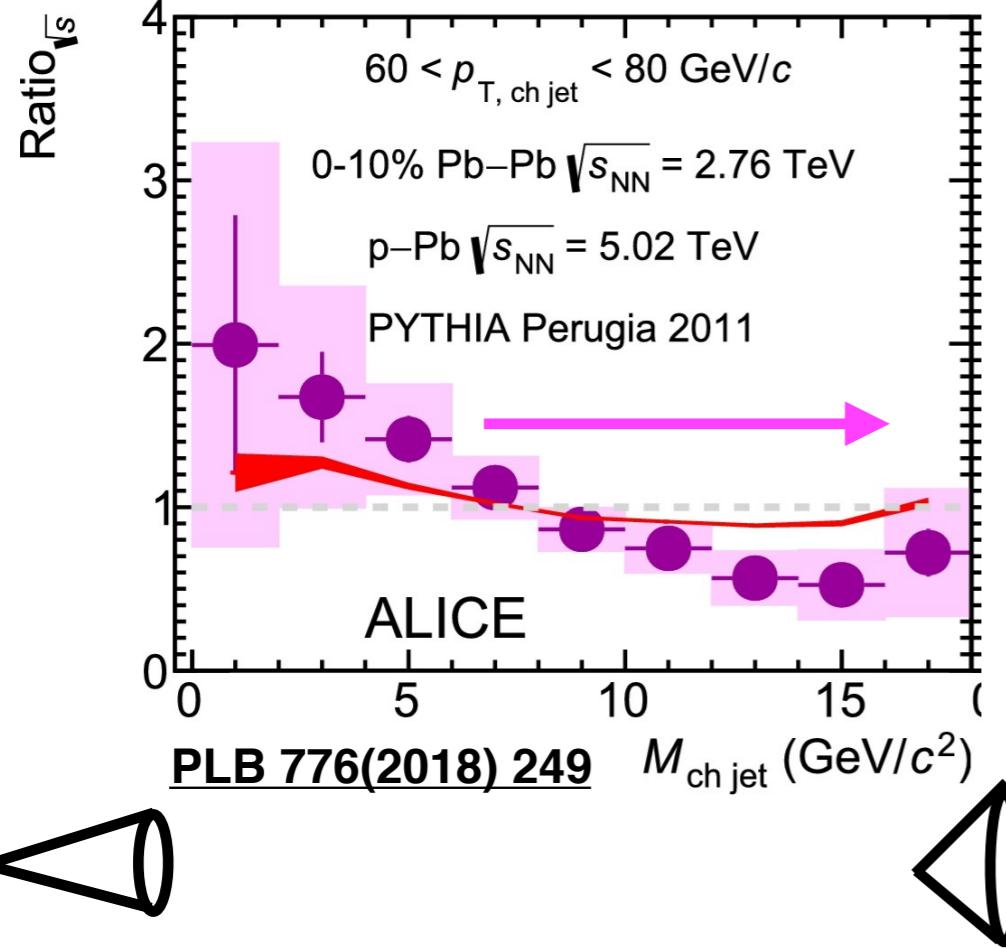
ATLAS R_{AA} vs. m/p_{T} : no significant modification



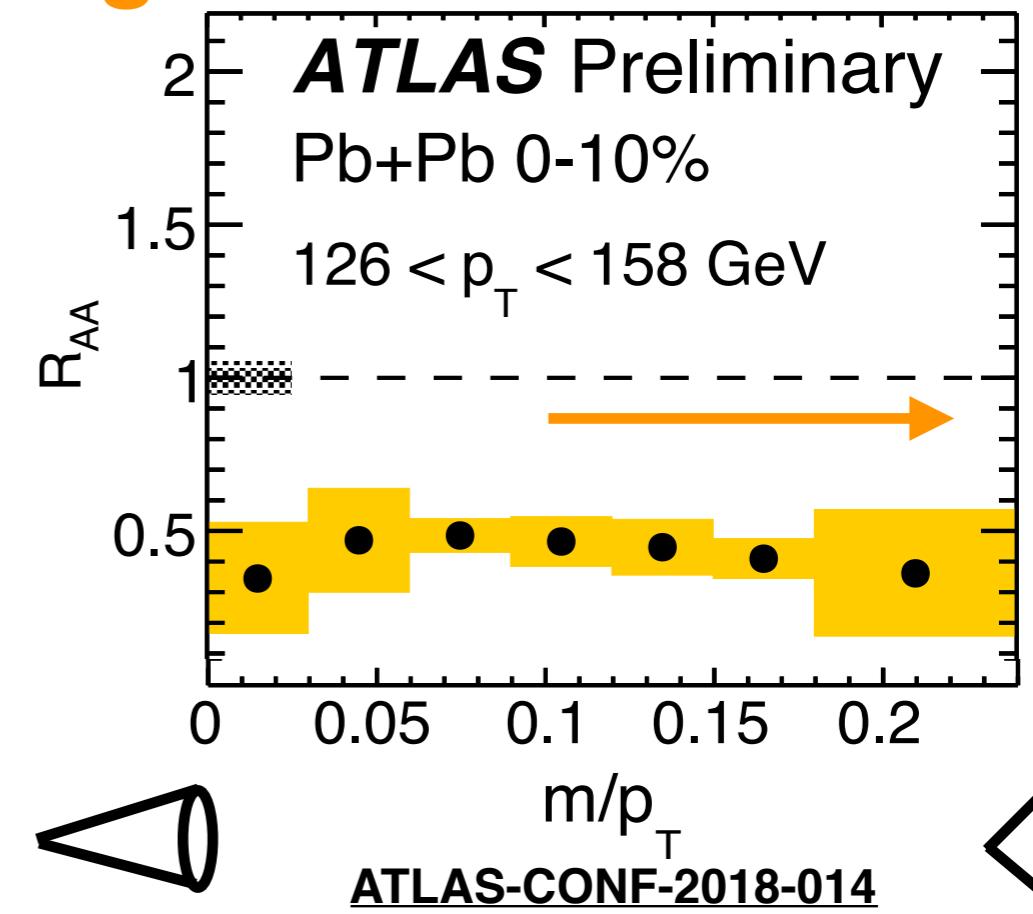
Suggests coherence?

Jet mass: ratio

ALICE m_{jet} : no significant modification to Pb+Pb



ATLAS R_{AA} vs. m/p_{T} : no significant modification



Suggests coherence?

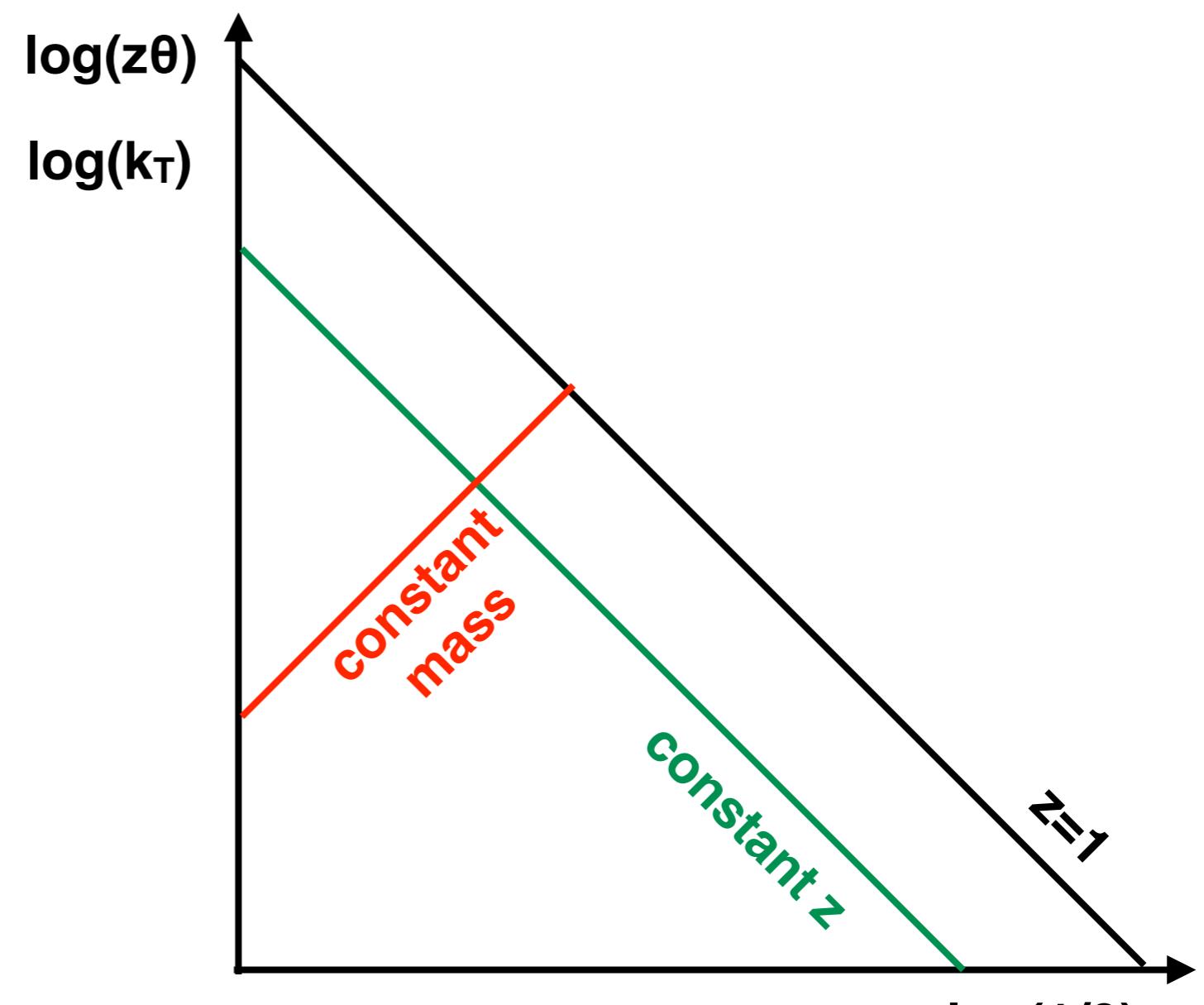
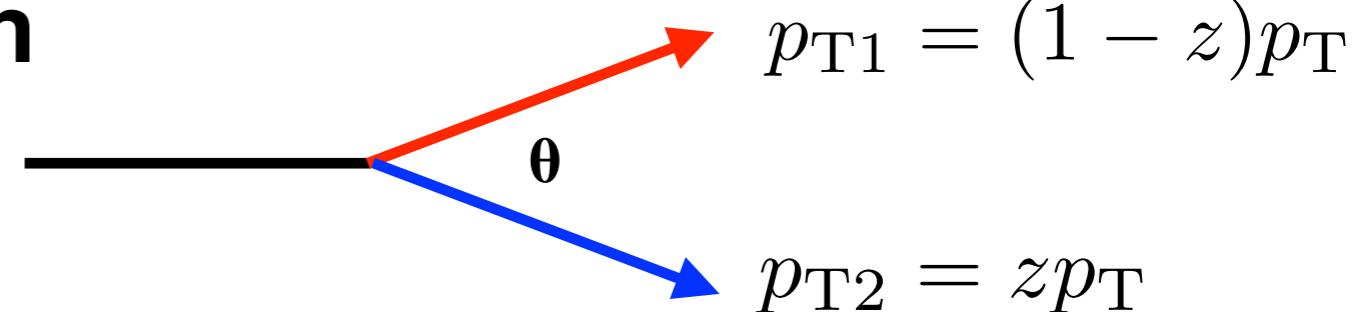
- The medium recoil increases the jet mass

Competing effects?

- k_{T} broadening outside jet cone decreases mass

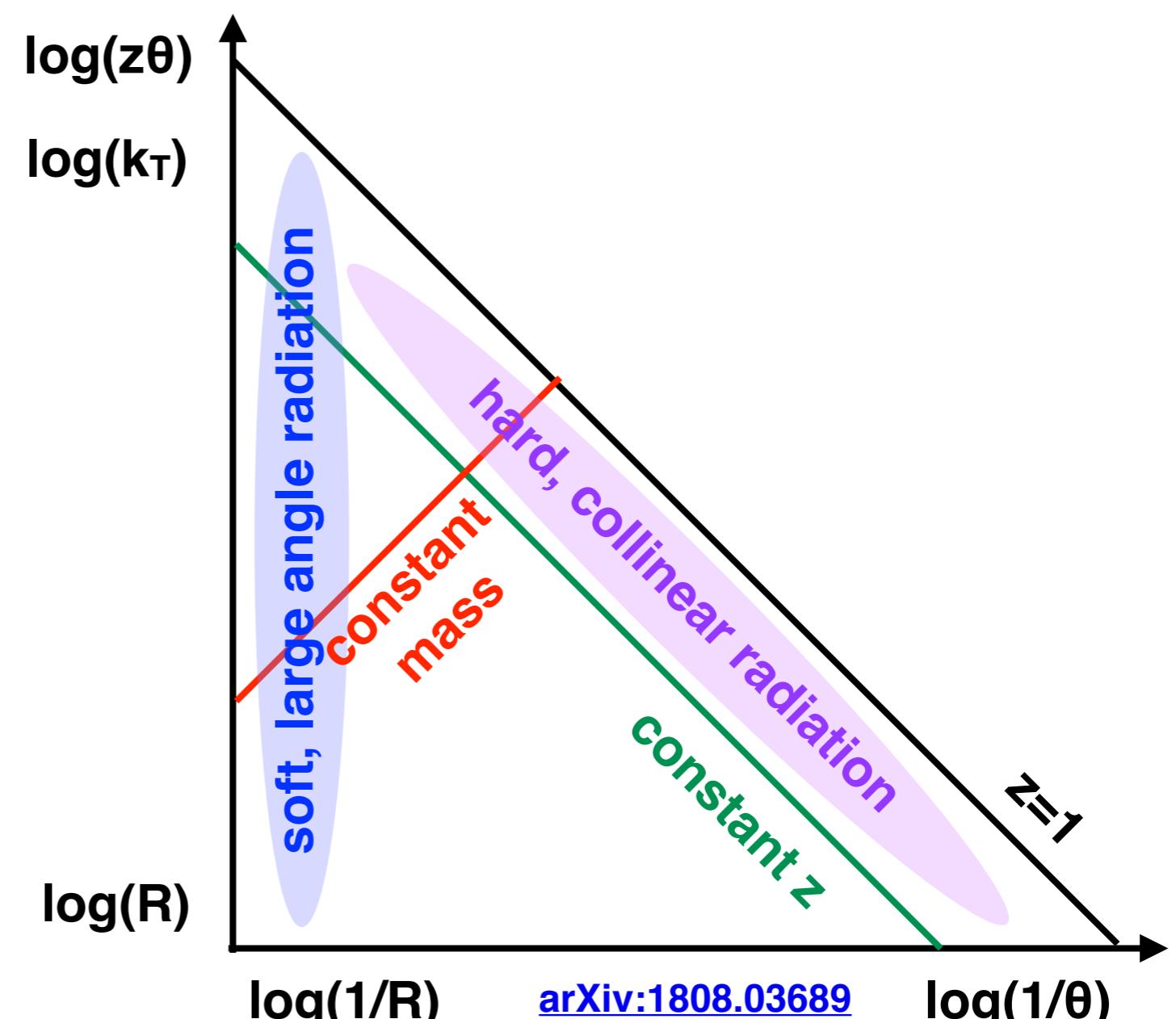
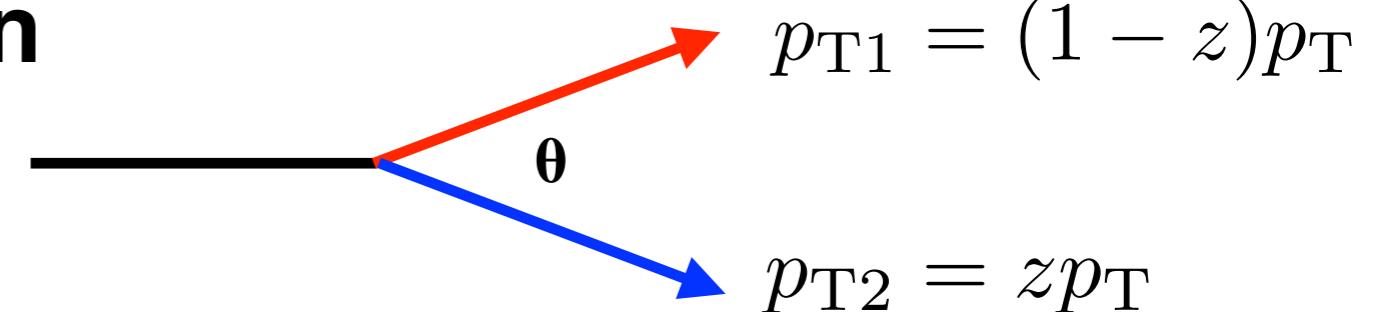
Jet splitting

- Shared momentum fraction and angle between two subjets in parton shower
- Lund Diagram: phase space of jet splitting



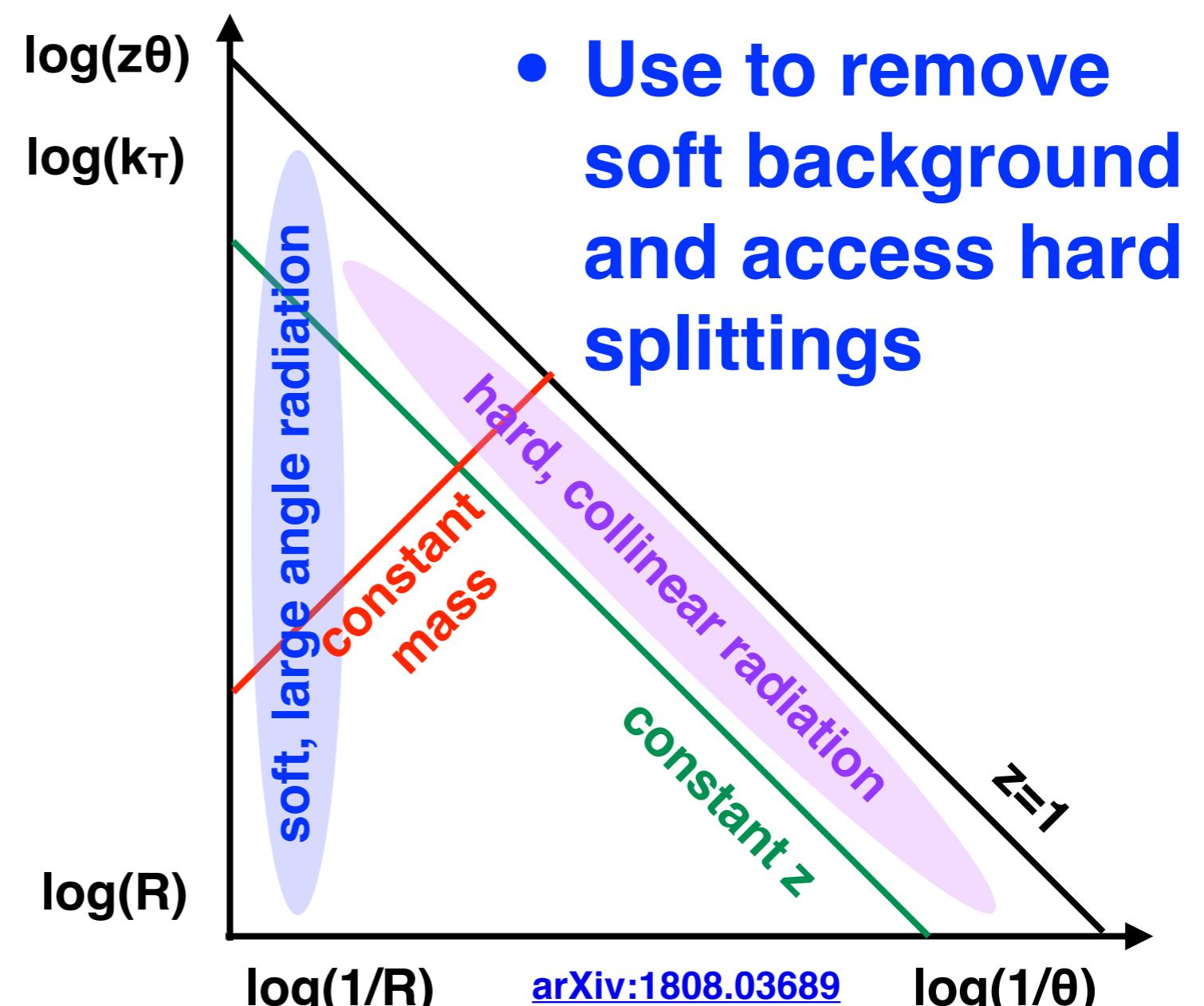
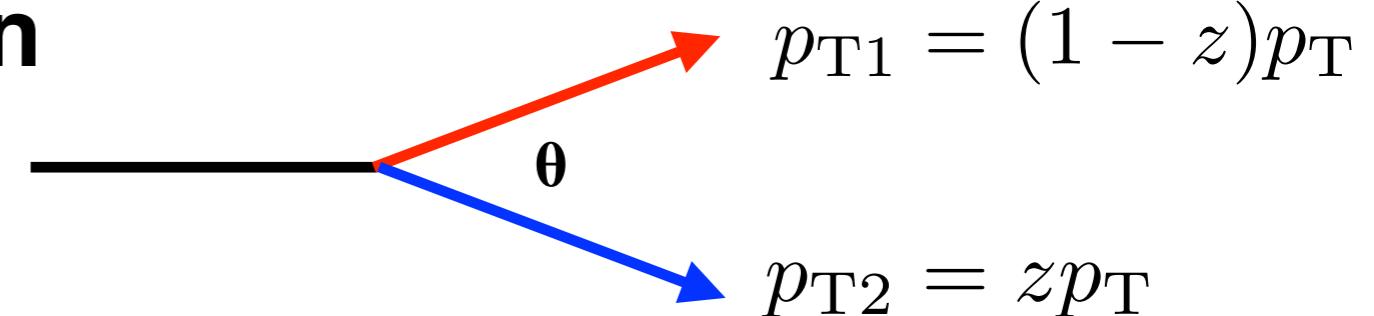
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- Shared momentum fraction and angle between two subjets in parton shower
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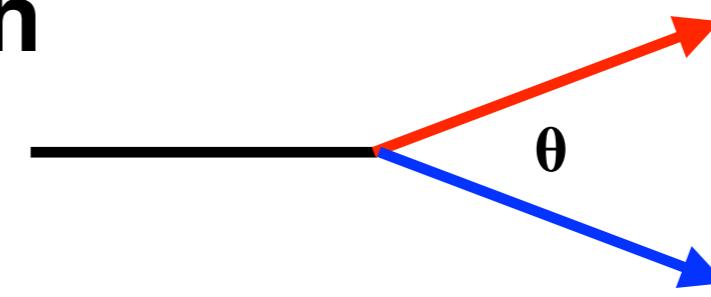
Jet splitting

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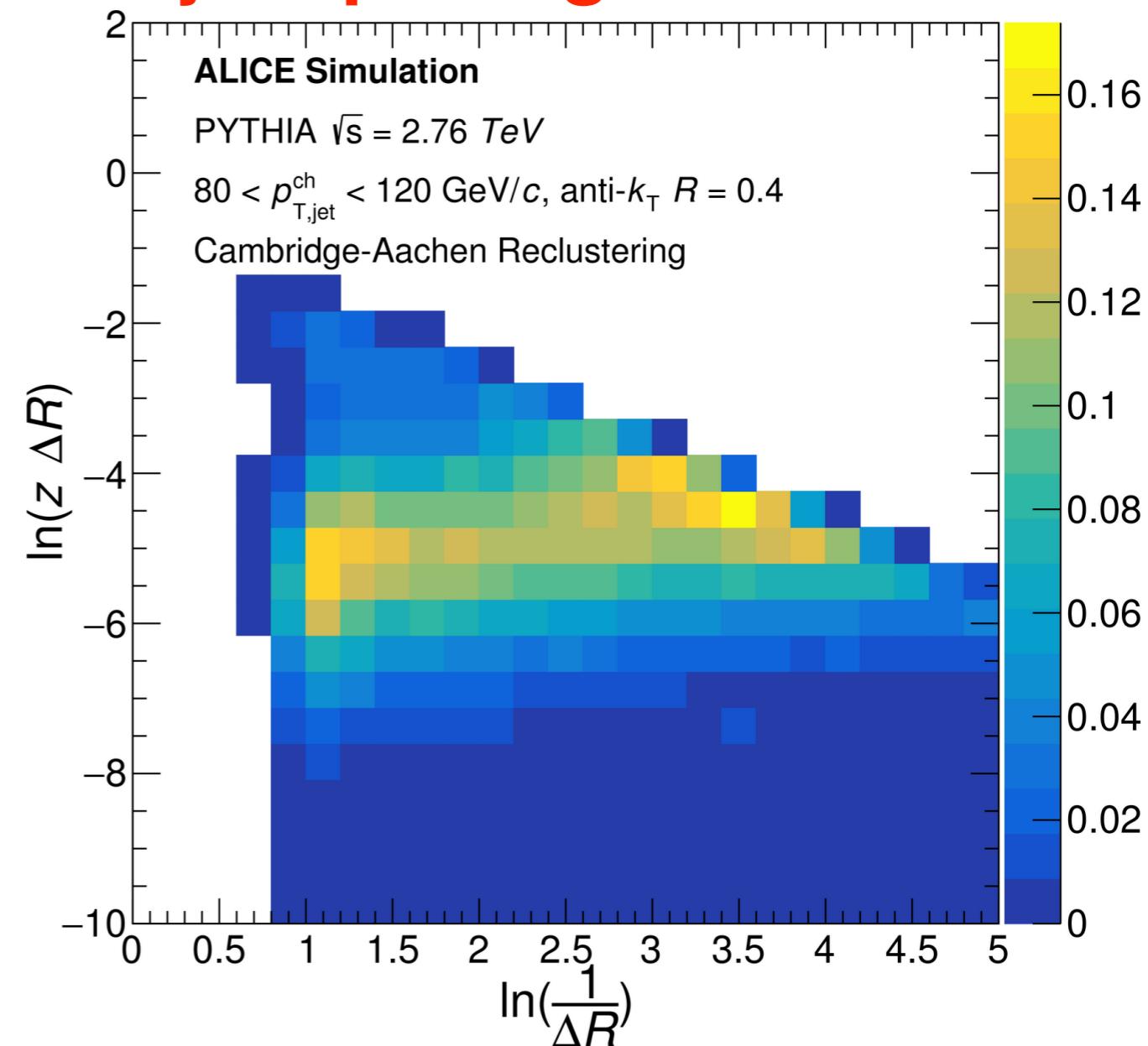
Jet splitting

- Shared momentum fraction and angle between two subjets in parton shower

$$\begin{array}{l} p_{T1} = (1 - z)p_T \\ \theta \\ p_{T2} = zp_T \end{array}$$


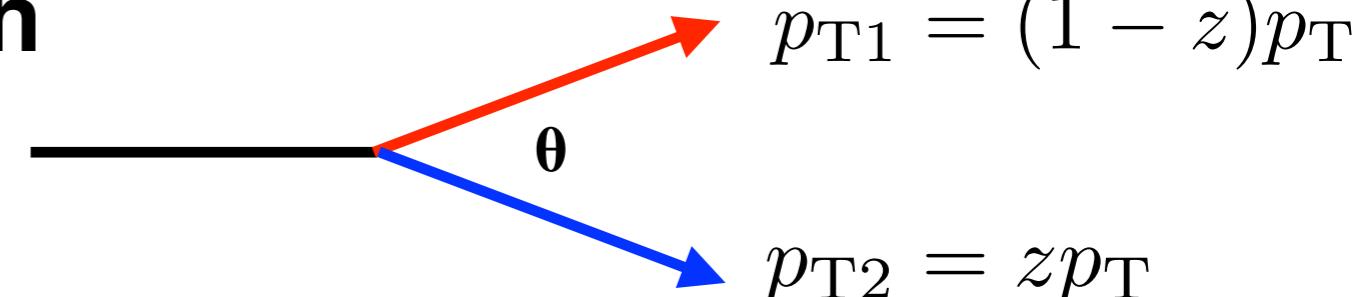
- Lund Diagram: phase space of jet splitting

- Recluster jets with Cambridge/Aachen* to enforce angular ordering and fill Lund diagram with splittings



Jet splitting

- Shared momentum fraction and angle between two subjets in parton shower

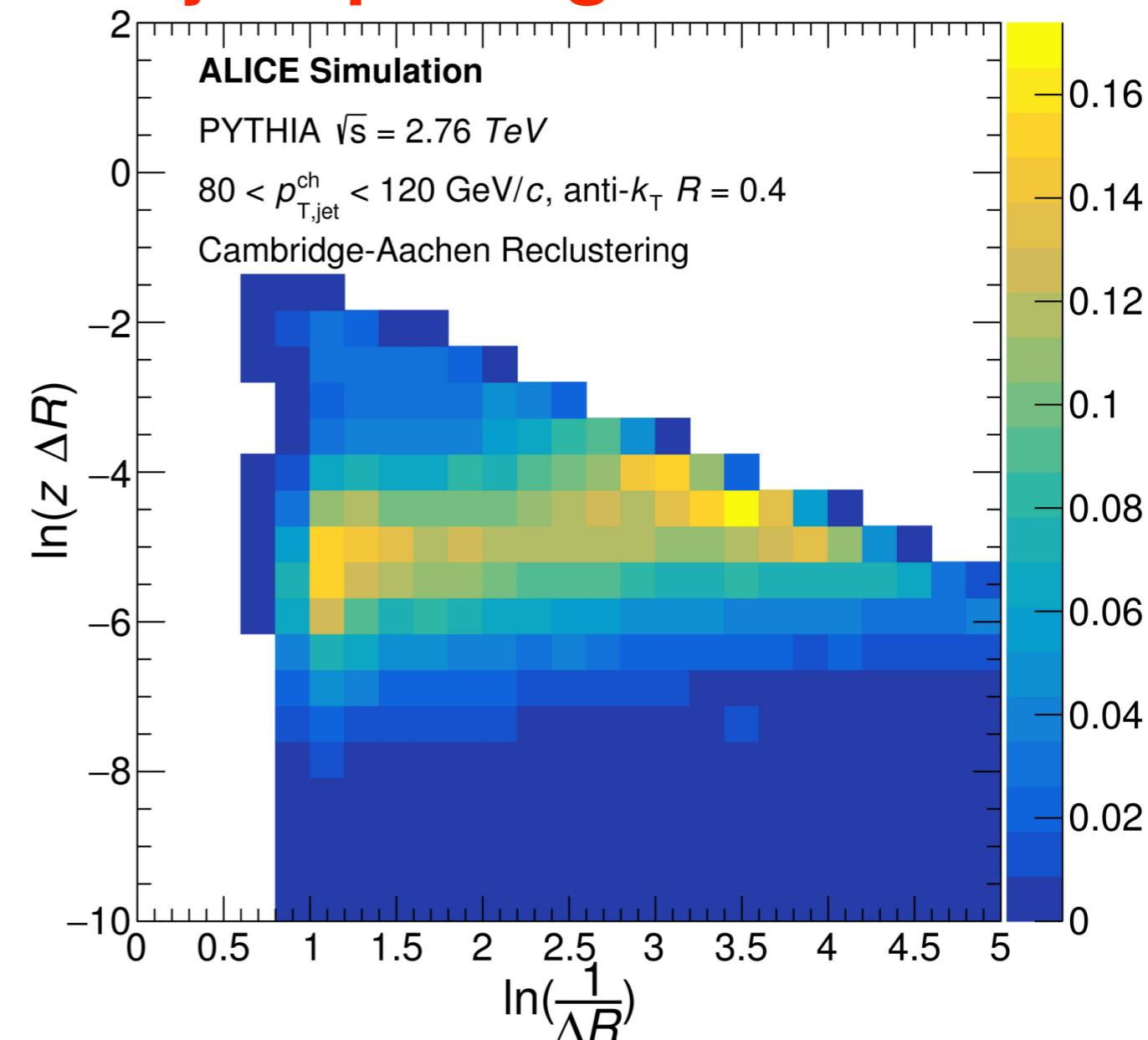


- Lund Diagram: phase space of jet splitting

- Recluster jets with Cambridge/Aachen* to enforce angular ordering and fill Lund diagram with splittings

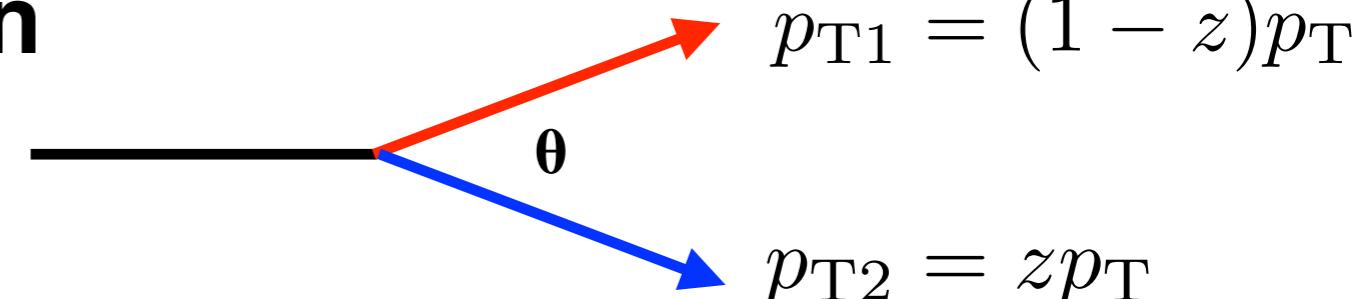
- Soft drop grooming to access hard splitting

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



Jet splitting

- Shared momentum fraction and angle between two subjets in parton shower

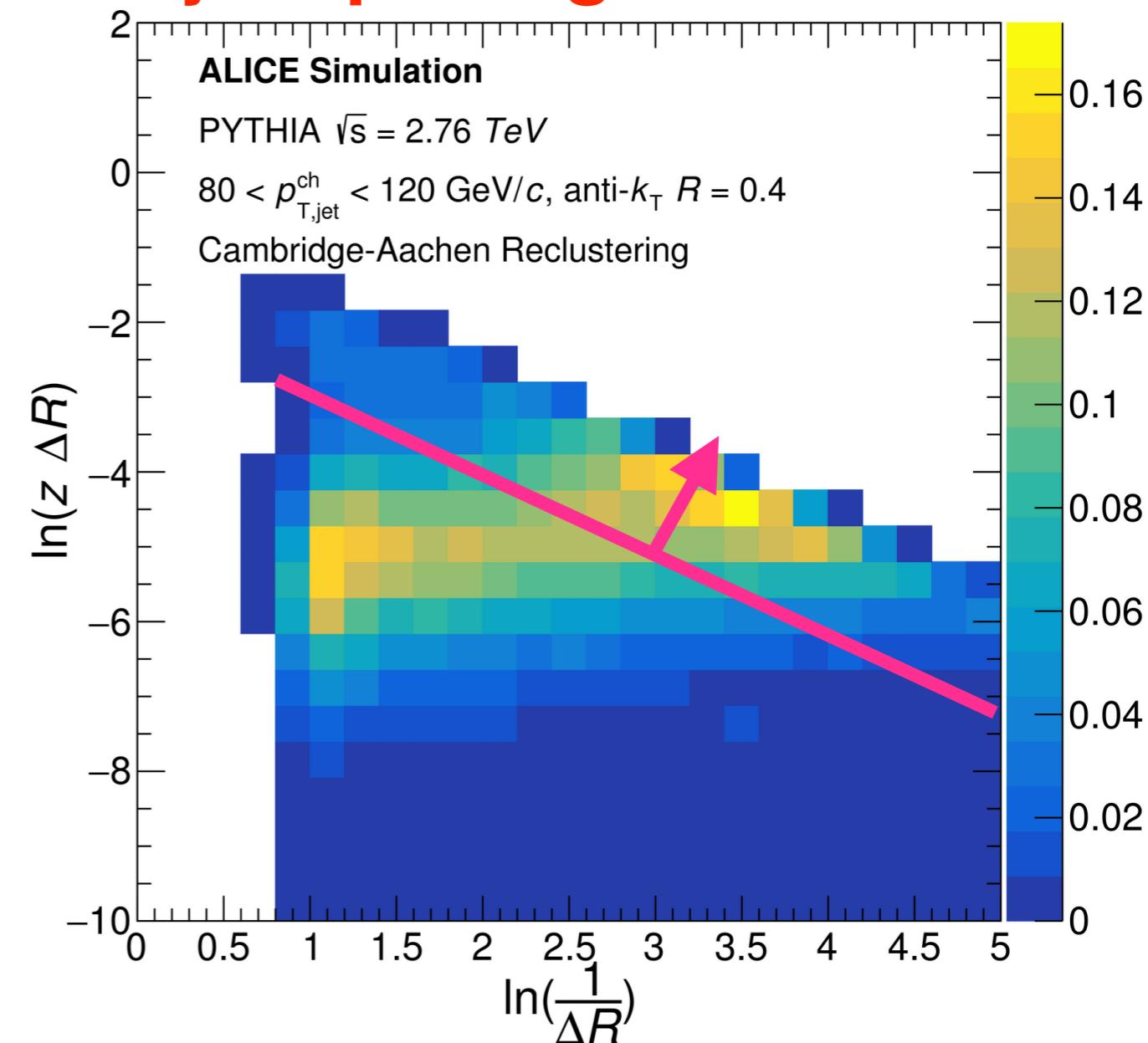


- Lund Diagram: phase space of jet splitting

- Recluster jets with Cambridge/Aachen* to enforce angular ordering and fill Lund diagram with splittings

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

- Default condition: $z_{\text{cut}} = 0.1$
- $\beta = 0$

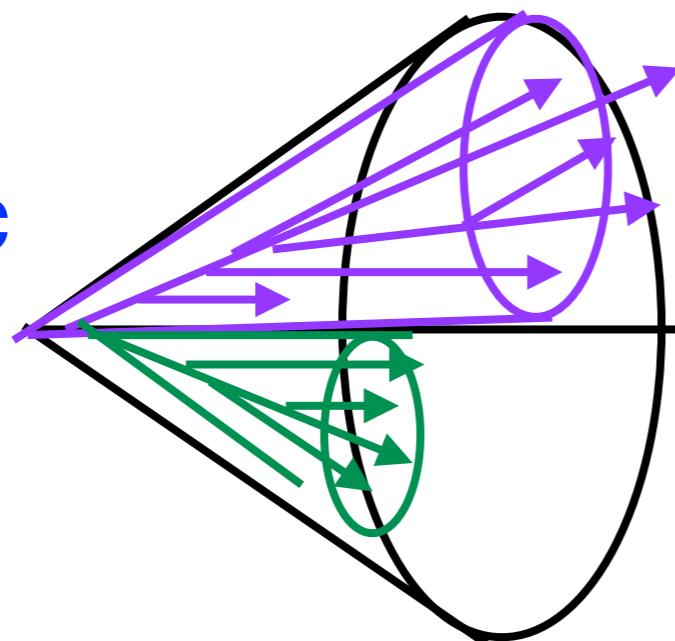


Jet splitting

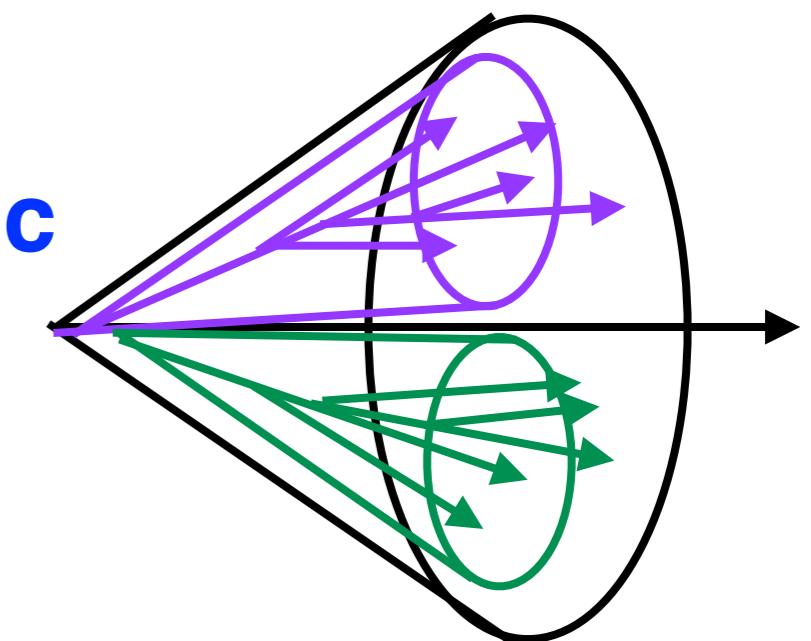
- Shared momentum fraction between two hardest subjets in parton shower

$$z_g = \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}}$$

**asymmetric
splitting:
low z_g**



**symmetric
splitting:
high z_g**

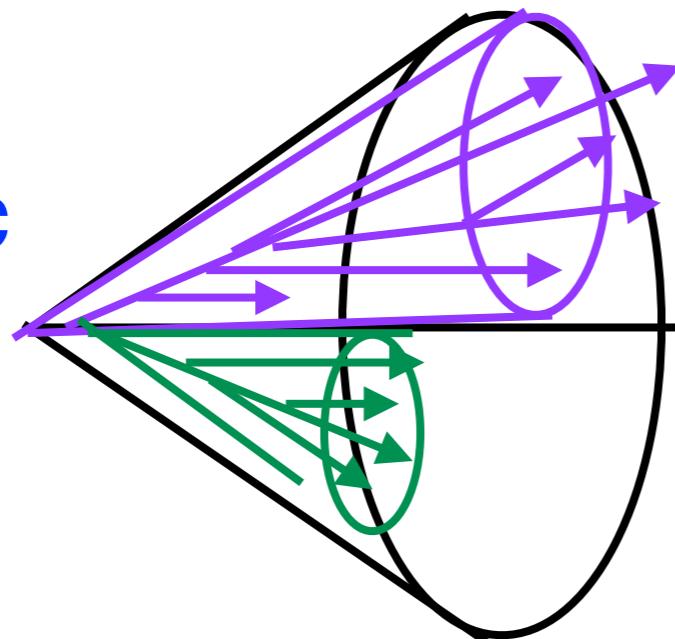


Jet splitting

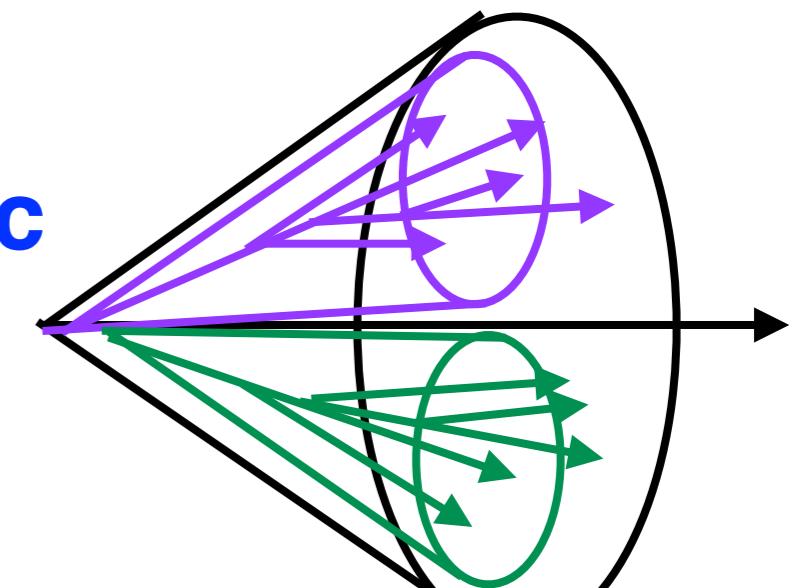
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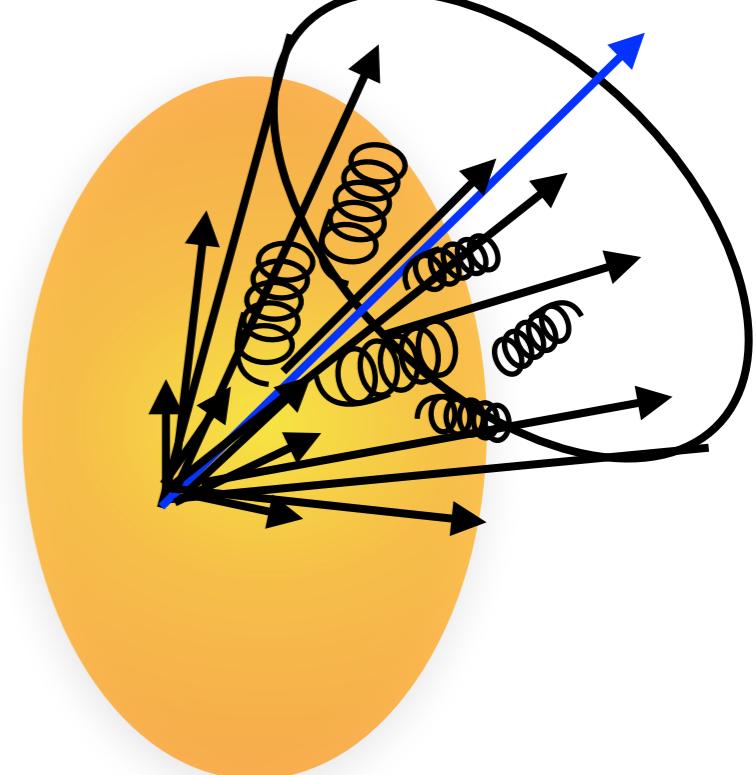
**asymmetric
splitting:**
low z_g



**symmetric
splitting:**
high z_g



- In medium:
 - **Coherence: jet loses energy as a whole**

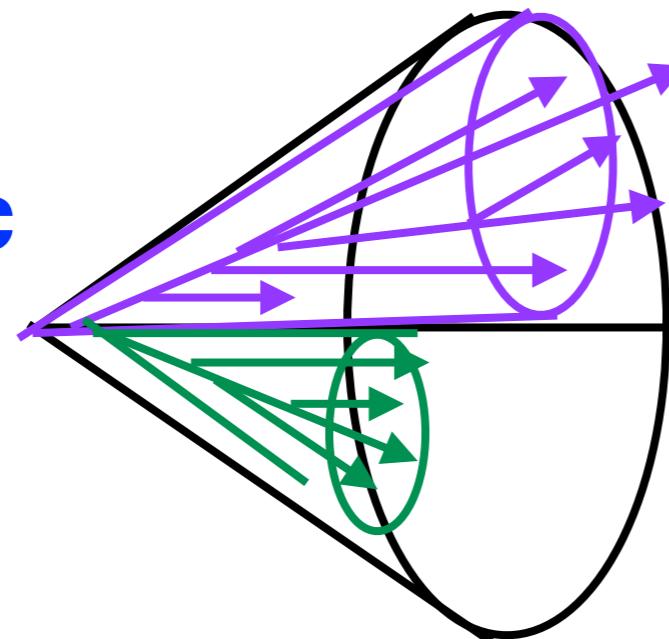


Jet splitting

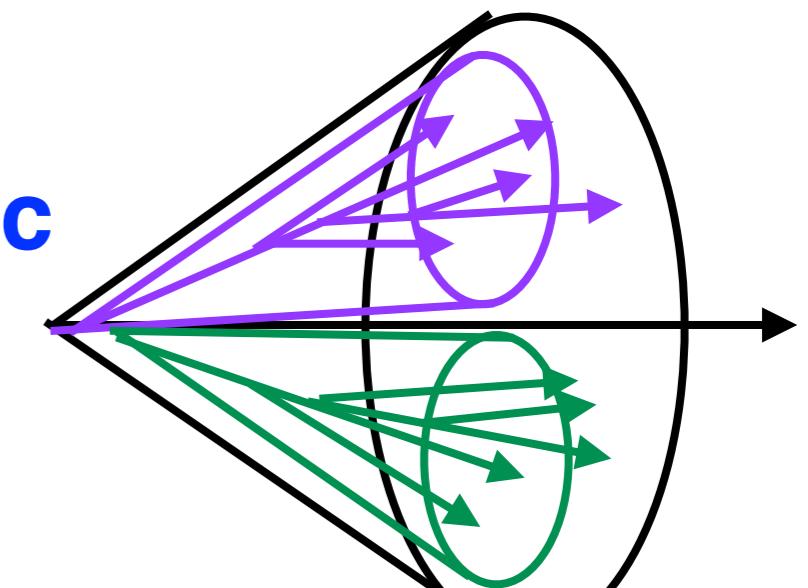
- Shared momentum fraction between two hardest subjets in parton shower

$$z_g = \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}}$$

**asymmetric
splitting:**
low z_g

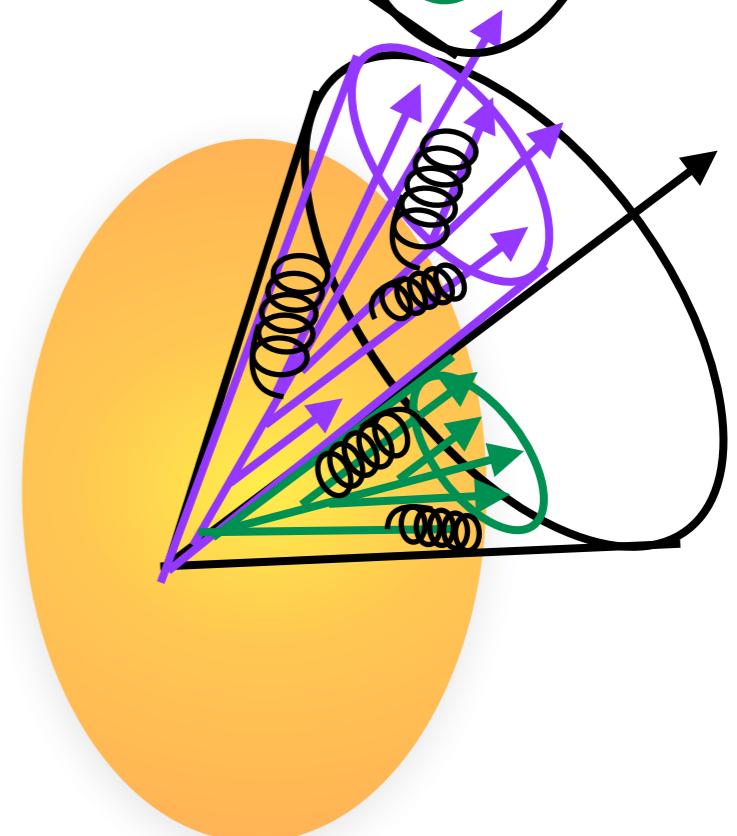


**symmetric
splitting:**
high z_g



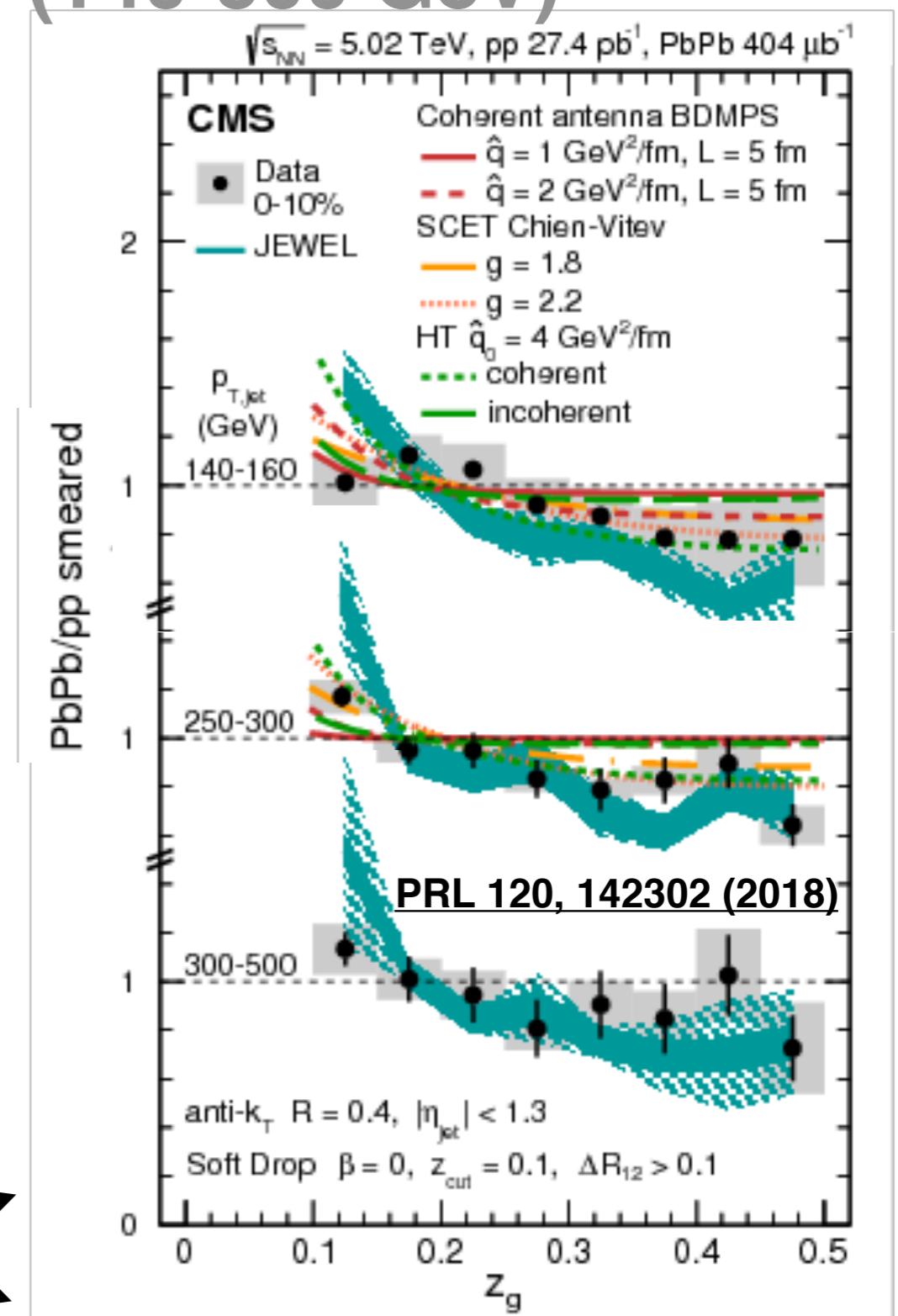
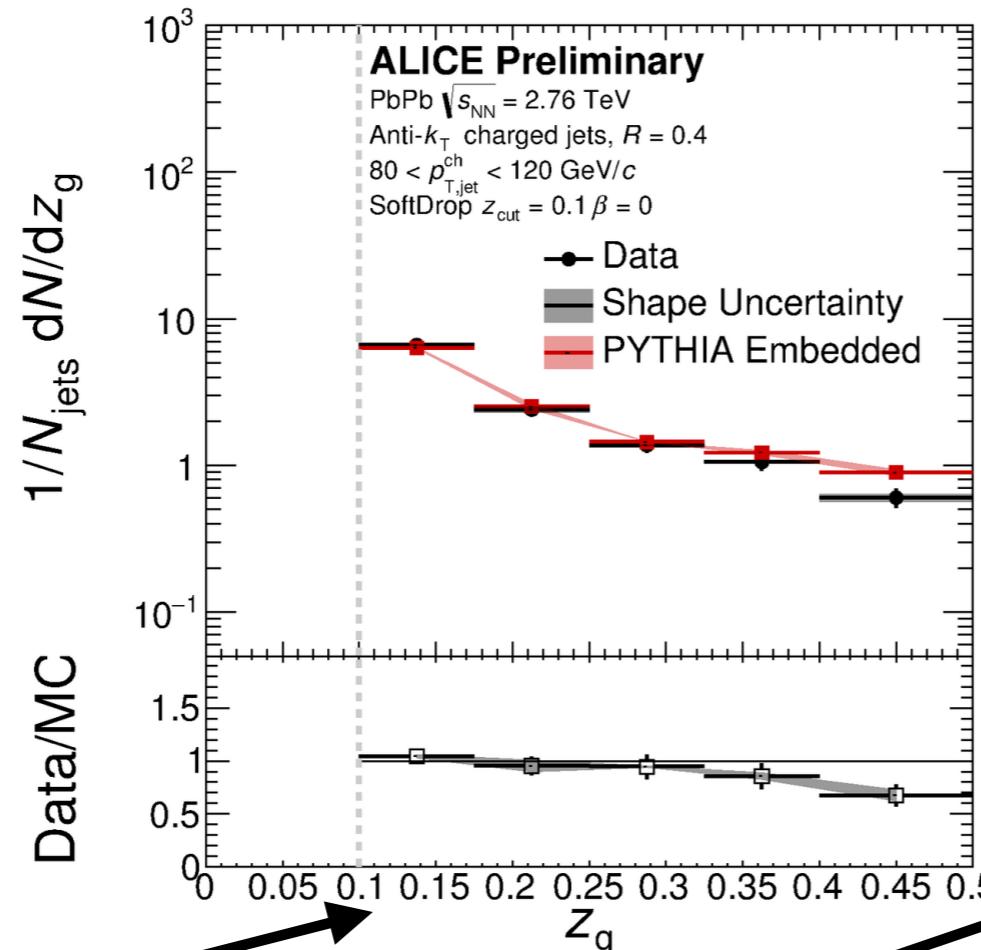
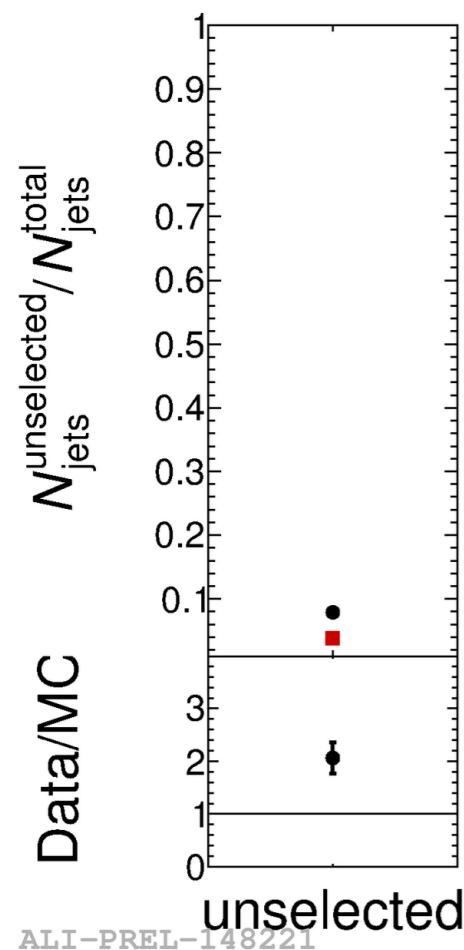
- In medium:

- **Coherence:** jet loses energy as a whole
- **Decoherence:** medium resolves the subjets resulting in a stronger asymmetric e-loss and a suppression of split jets



Jet splitting: Z_g ratio

- Compare between Pb+Pb and pp collisions (or MC) in **ALICE (80-120 GeV)** and **CMS (140-500 GeV)**



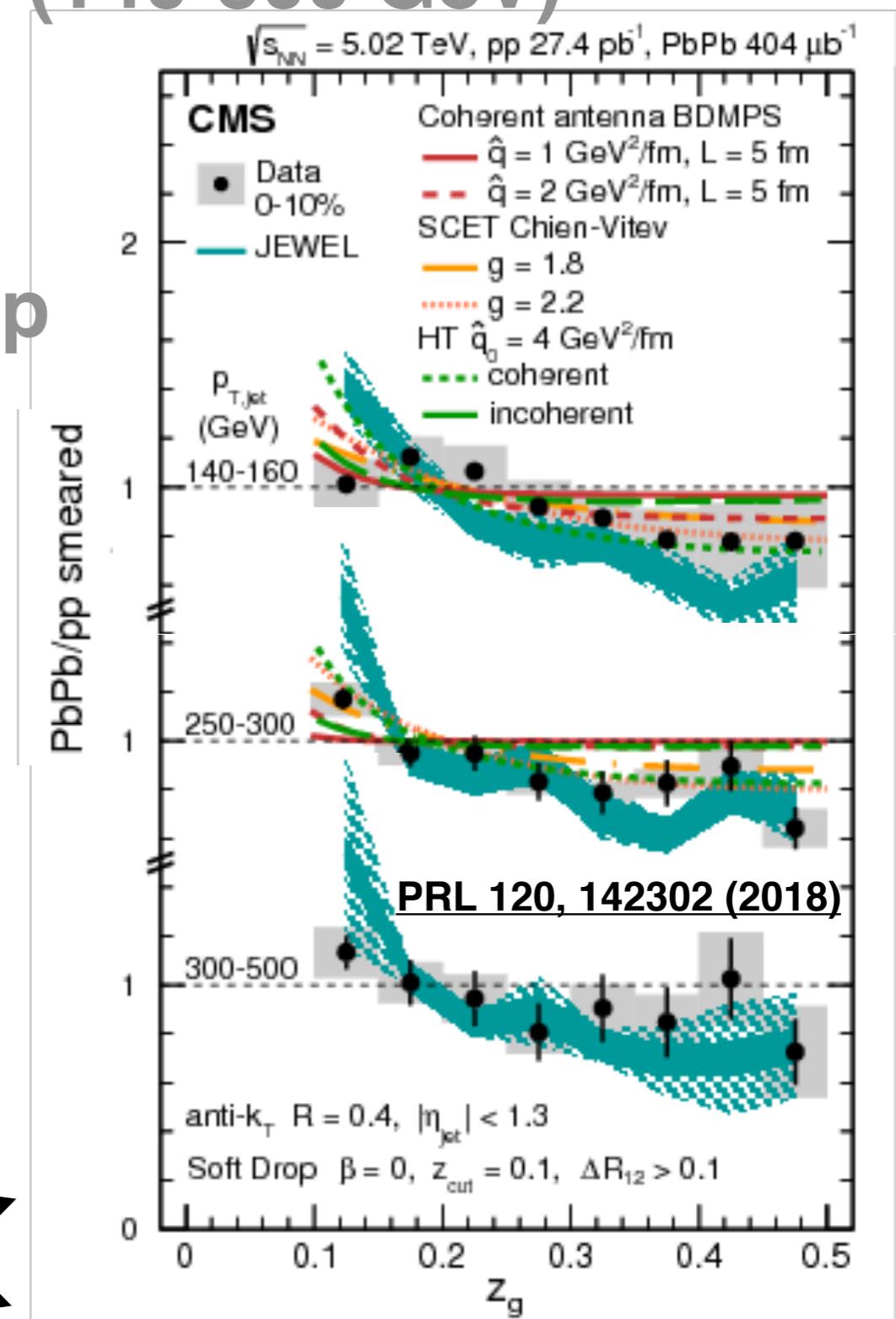
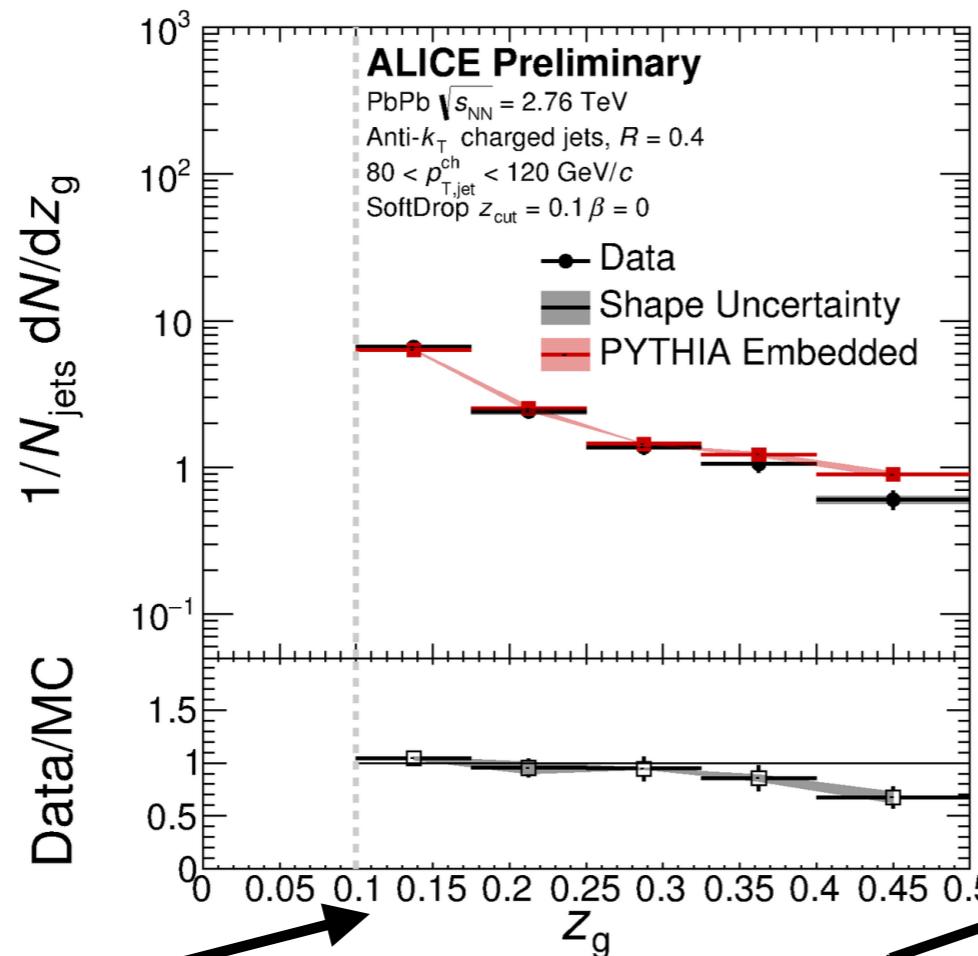
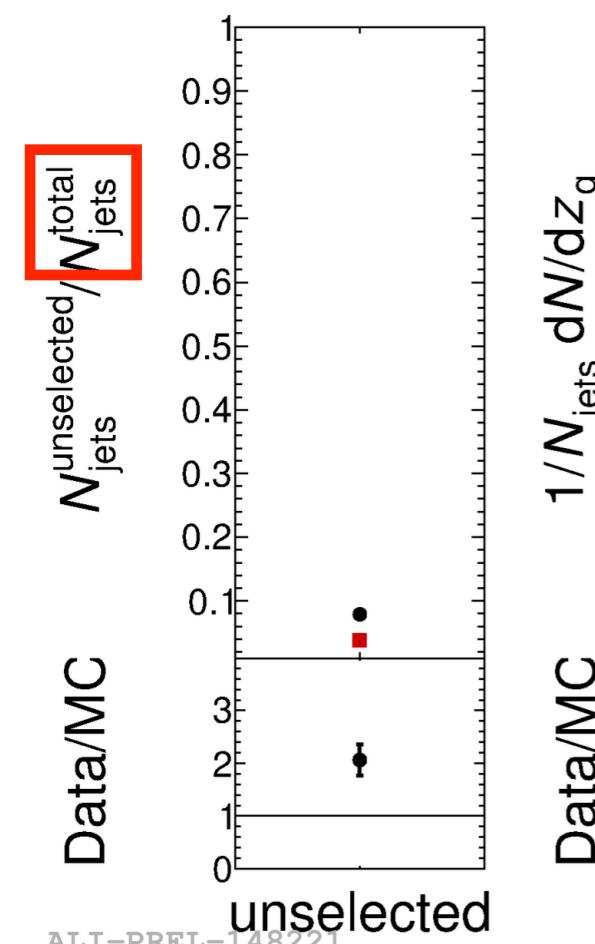
Jet splitting: Z_g ratio

- Compare between Pb+Pb and pp collisions (or MC) in **ALICE (80-120 GeV)** and CMS (140-500 GeV)

► *Normalization different*

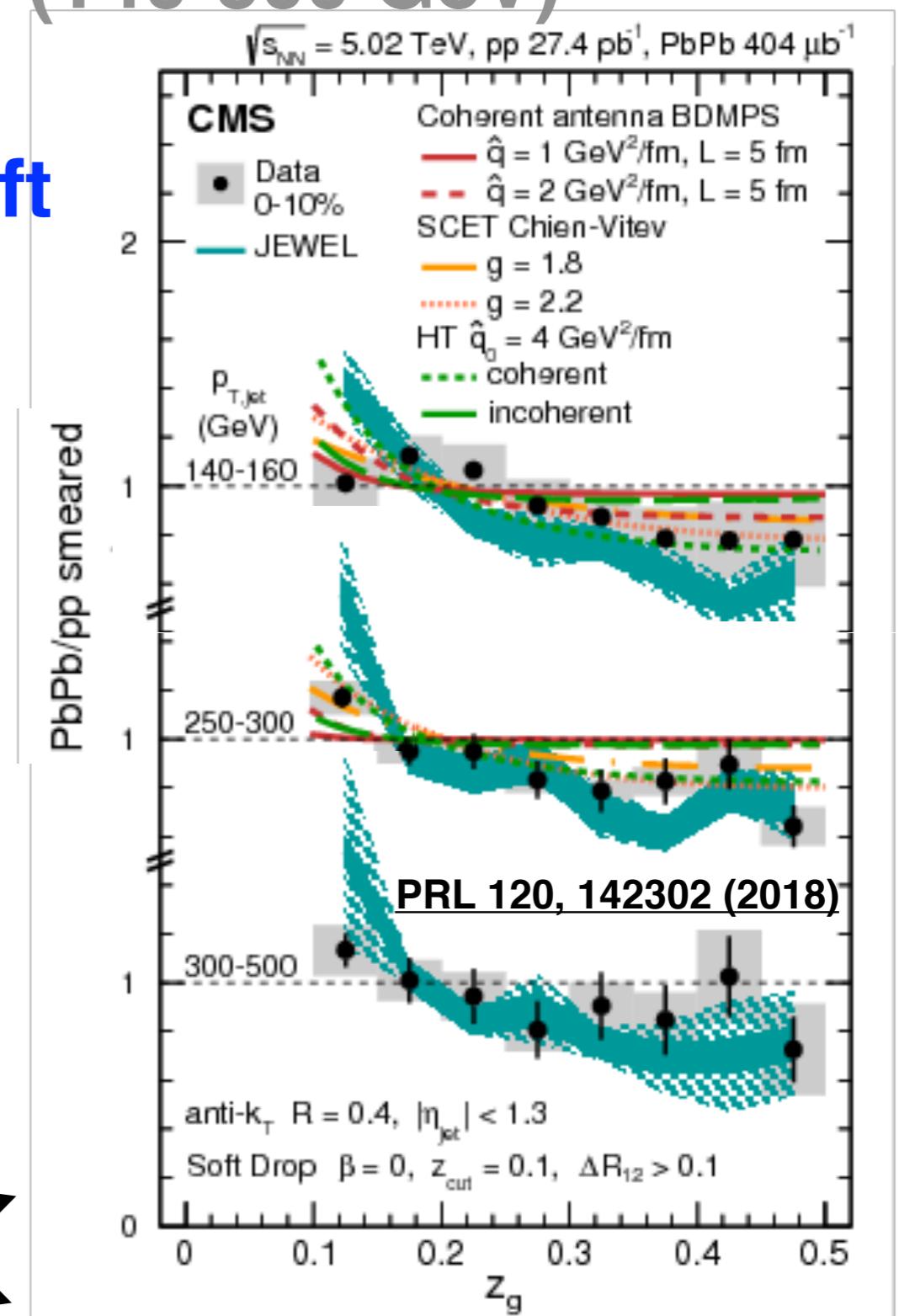
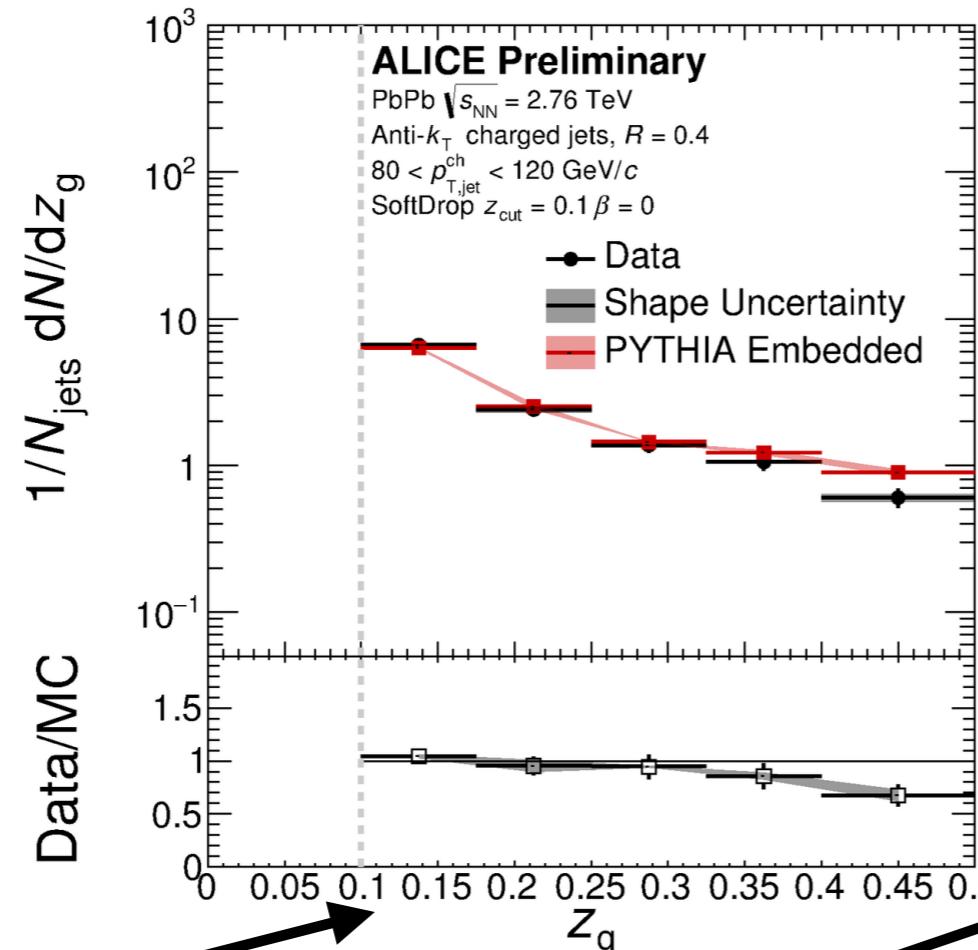
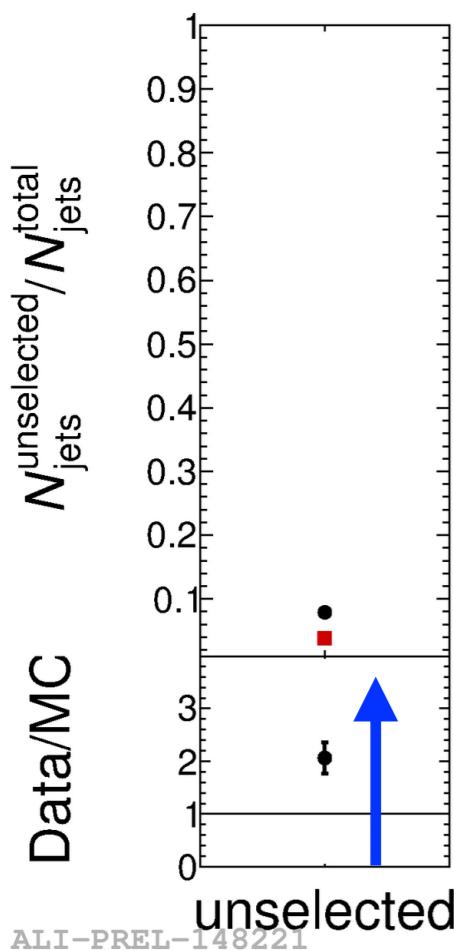
ALICE: all jets in p_T bin

CMS: all jets that pass soft drop



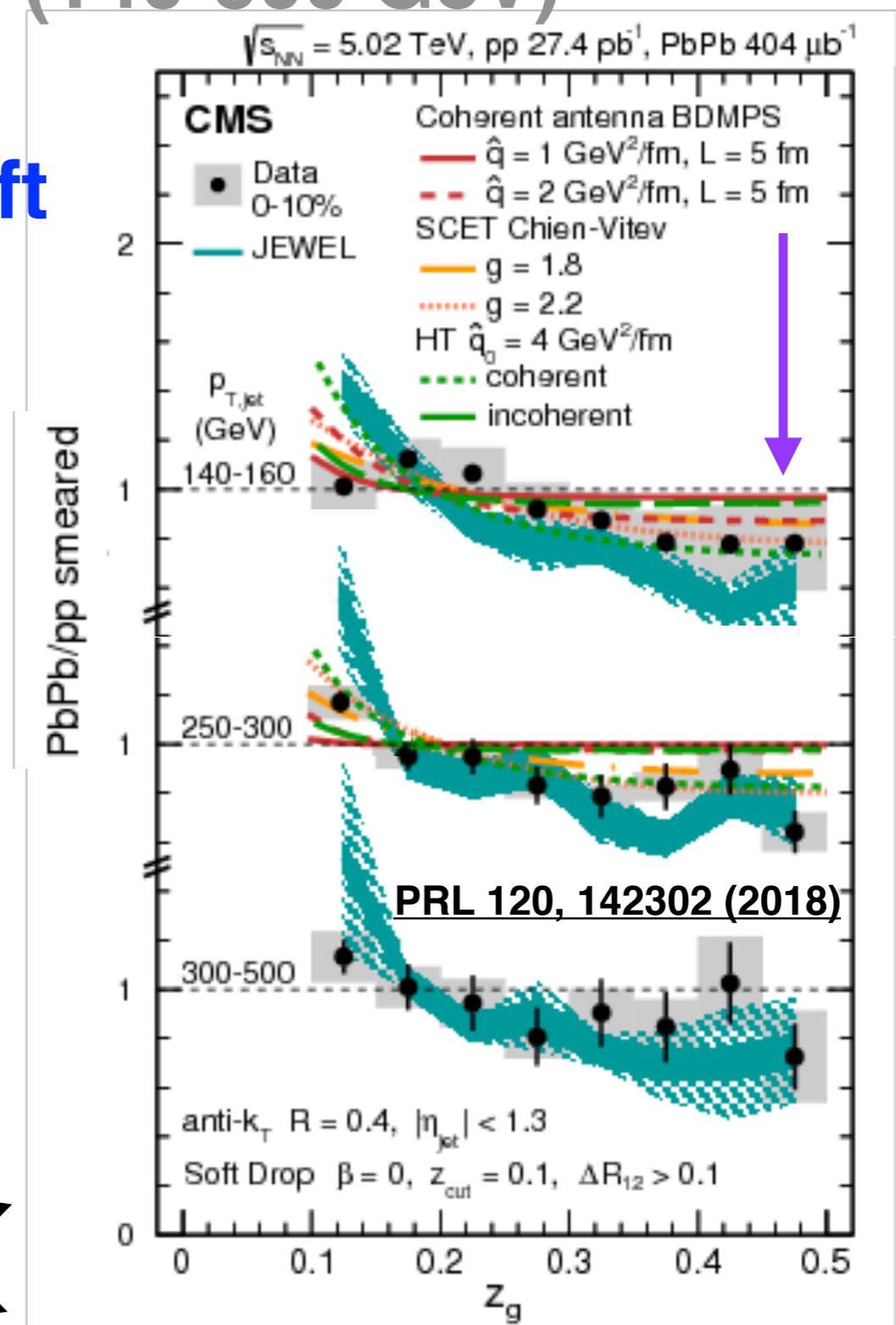
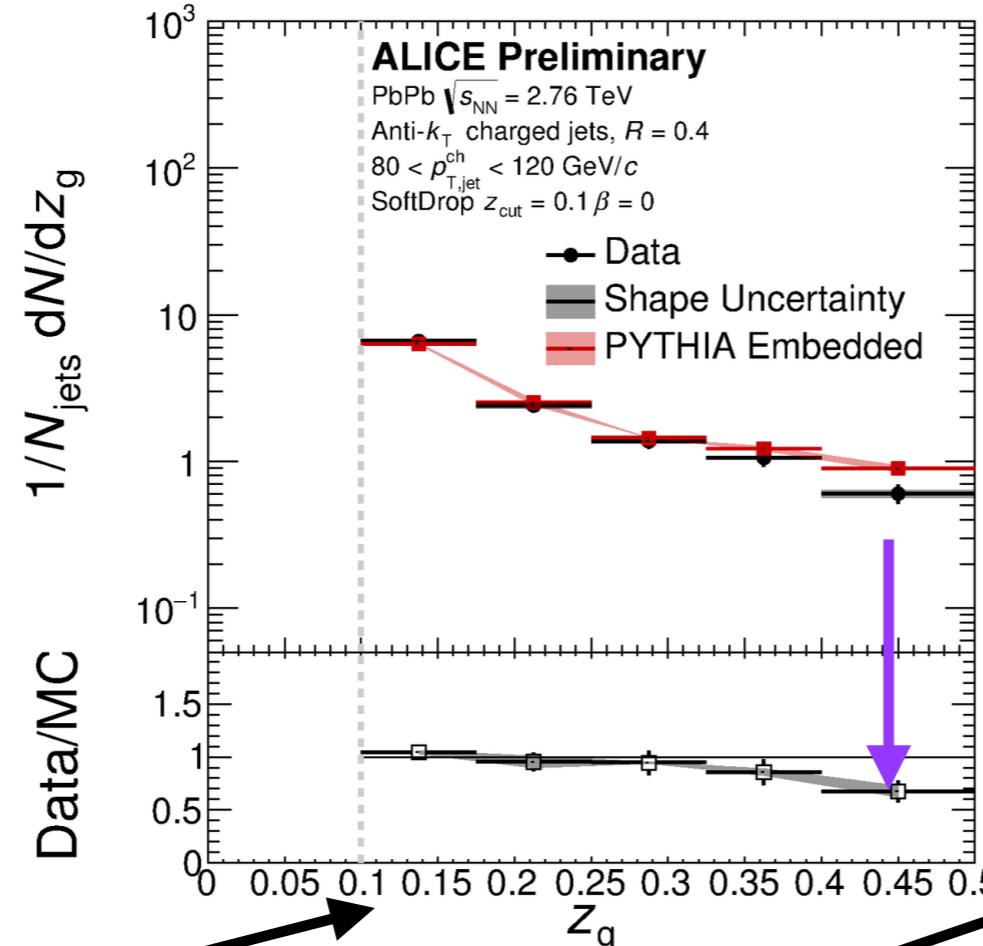
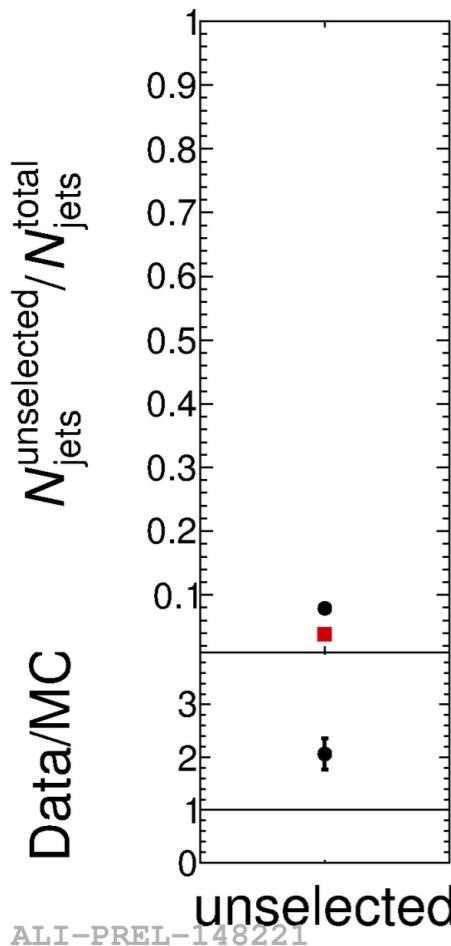
Jet splitting: Z_g ratio

- Compare between Pb+Pb and pp collisions (or MC) in **ALICE (80-120 GeV)** and CMS (140-500 GeV)
 - **Normalization different**
- **Enhancement of jets that fail soft drop (2-prong jets suppressed)**



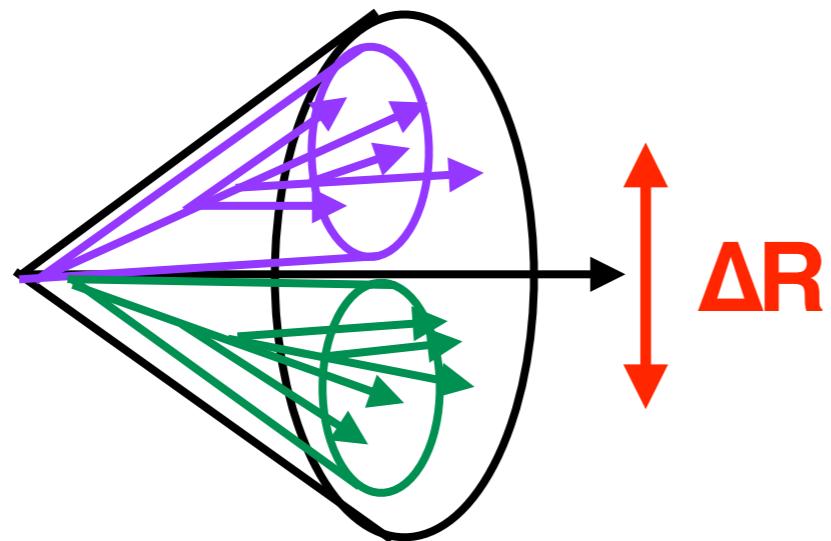
Jet splitting: z_g ratio

- Compare between Pb+Pb and pp collisions (or MC) in **ALICE (80-120 GeV)** and CMS (140-500 GeV)
 - **Normalization different**
- **Enhancement of jets that fail soft drop (2-prong jets suppressed)**
- **Both show high z_g suppression**



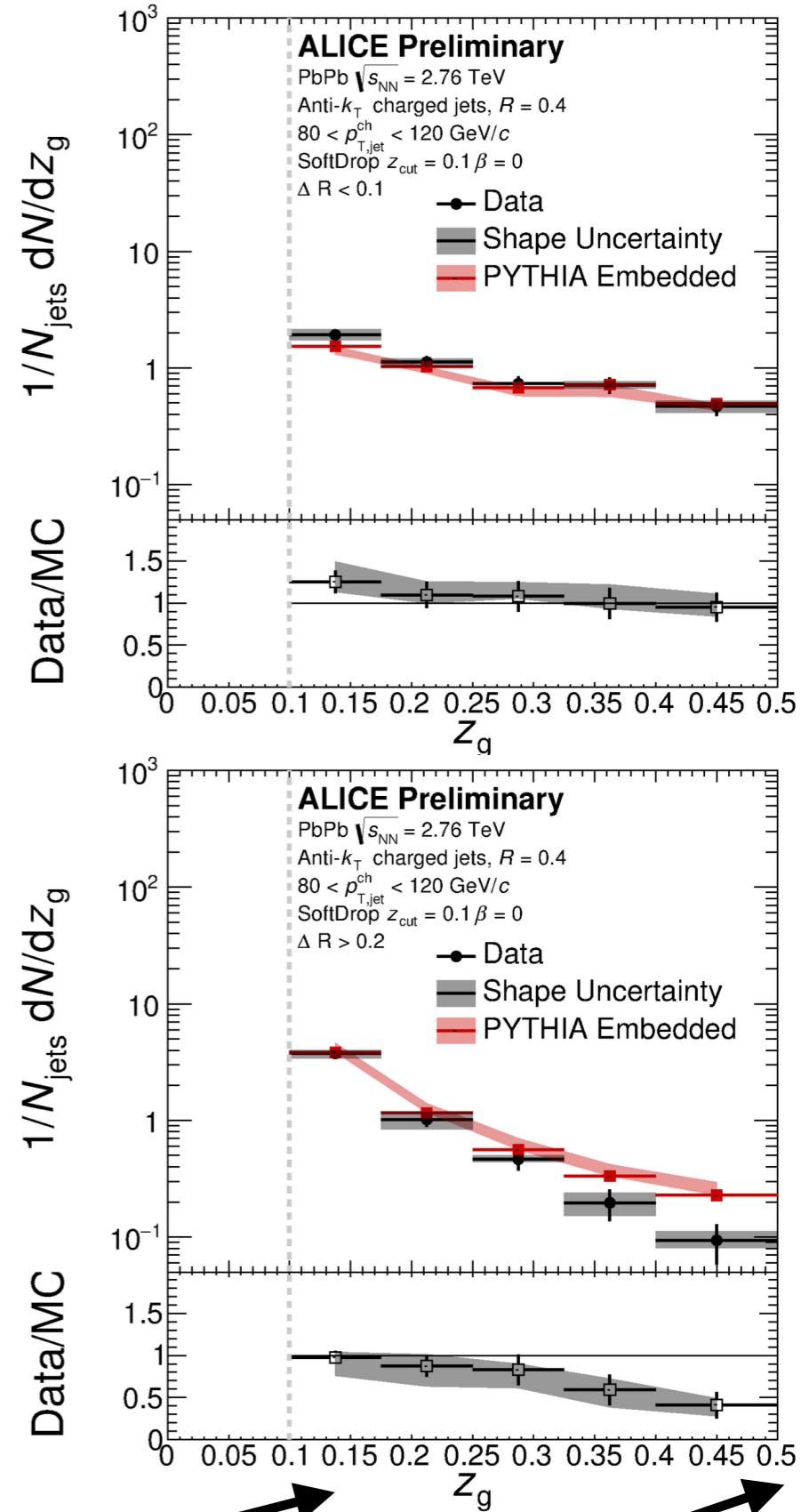
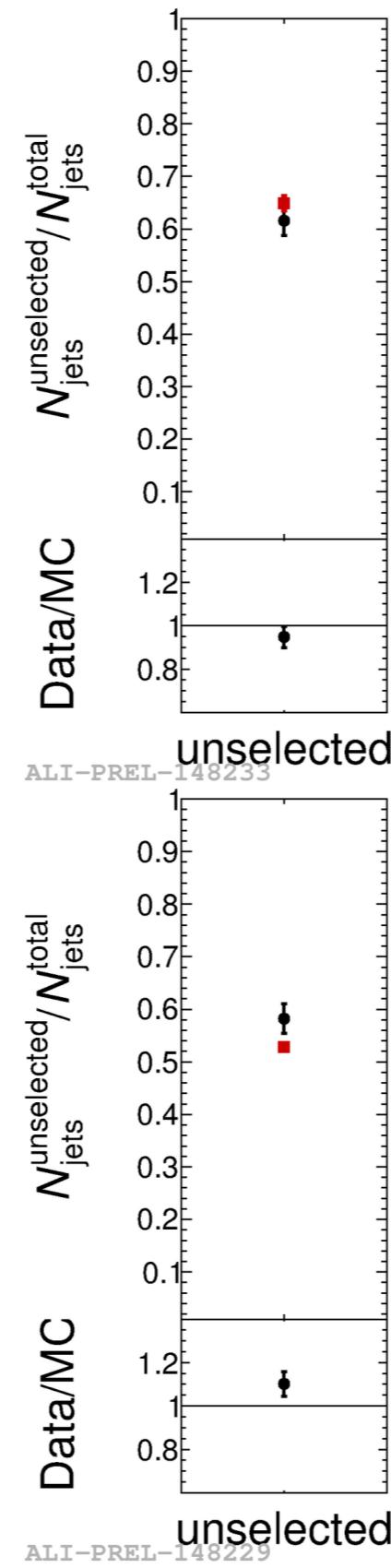
Jet splitting: open angle

collimated
 $\Delta R < 0.1$



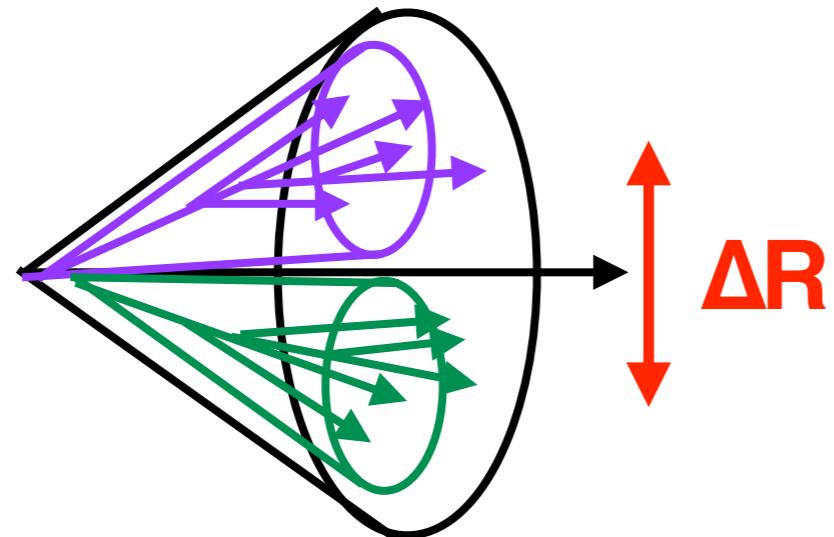
wide angle
 $\Delta R > 0.2$

unselected = untagged SD + cut by ΔR



Jet splitting: open angle

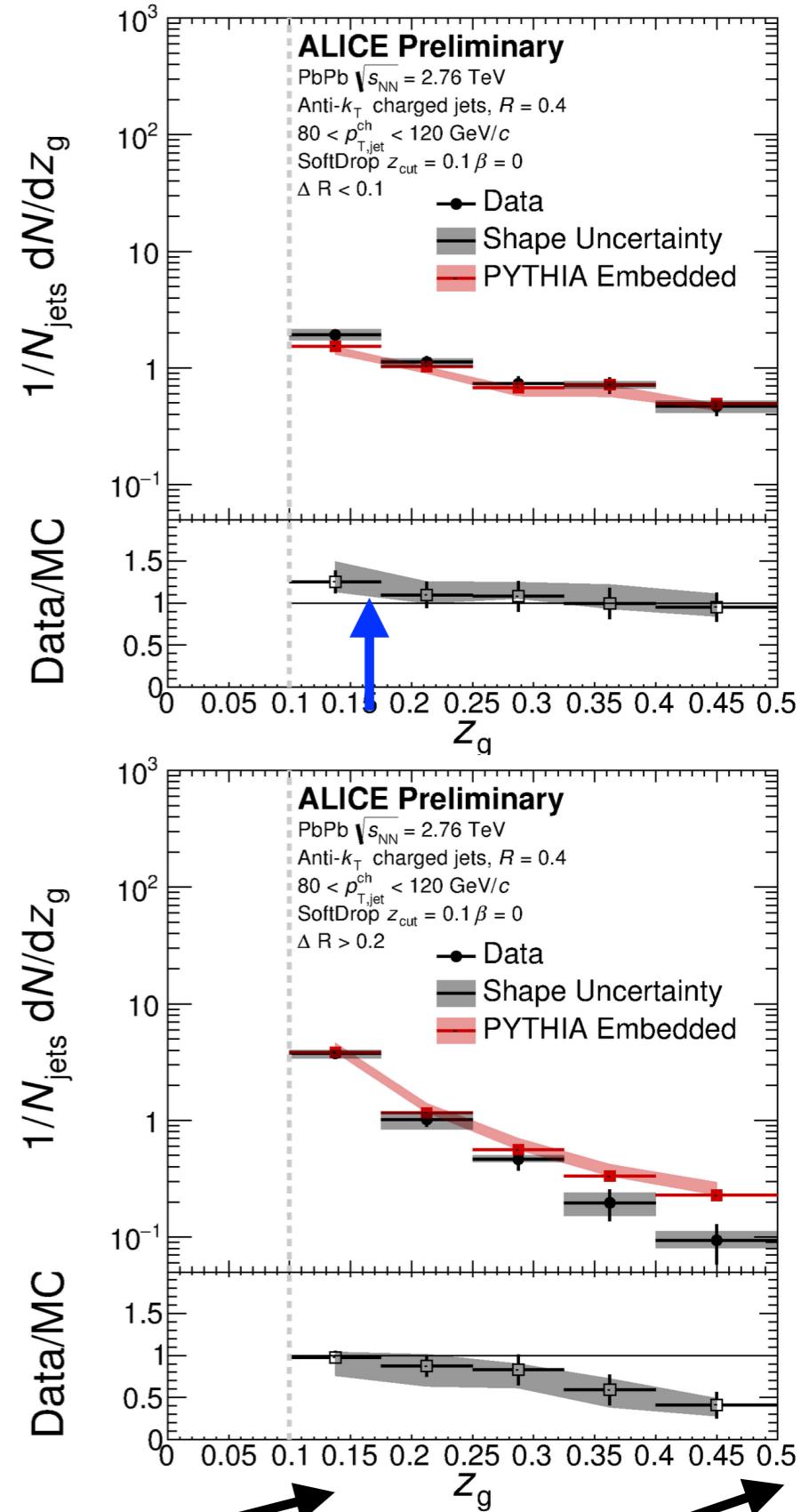
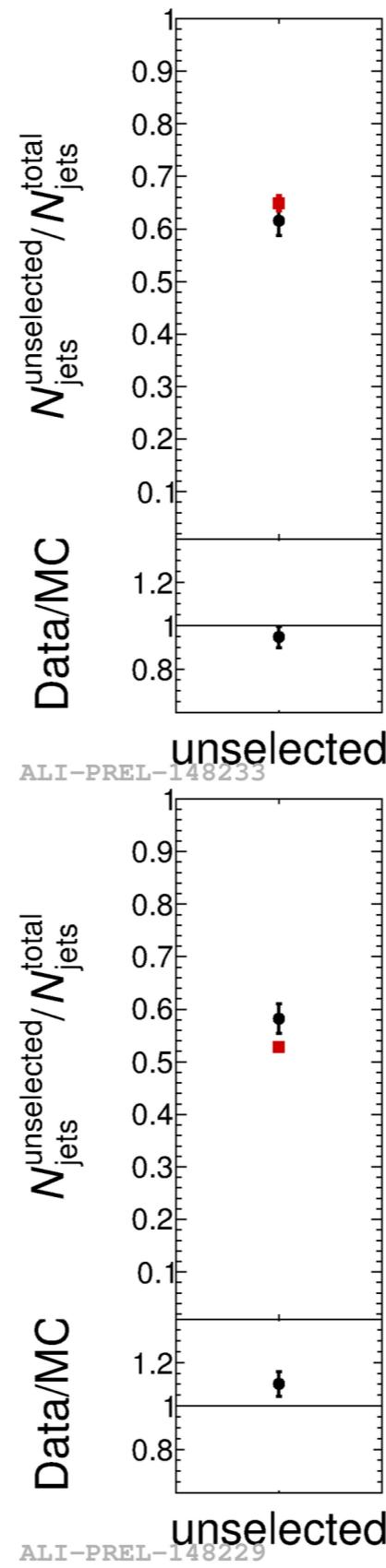
- Small or no modification to collimated jets



collimated
 $\Delta R < 0.1$

wide angle
 $\Delta R > 0.2$

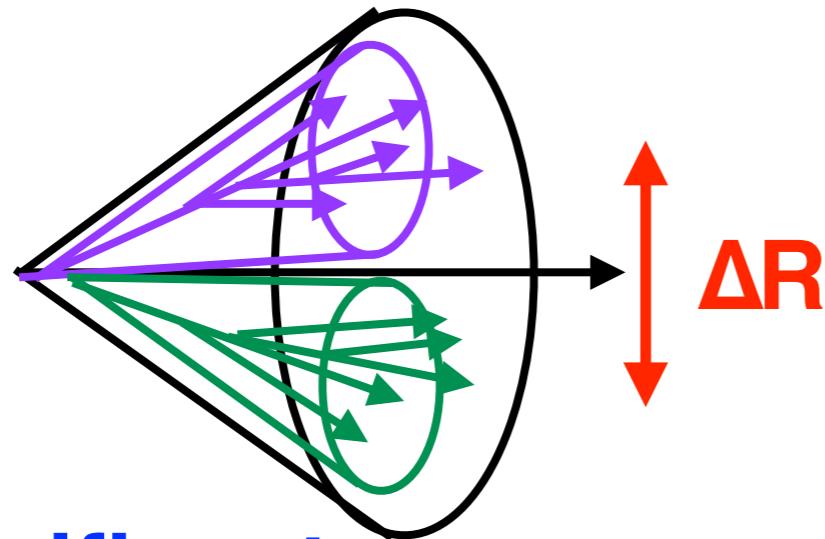
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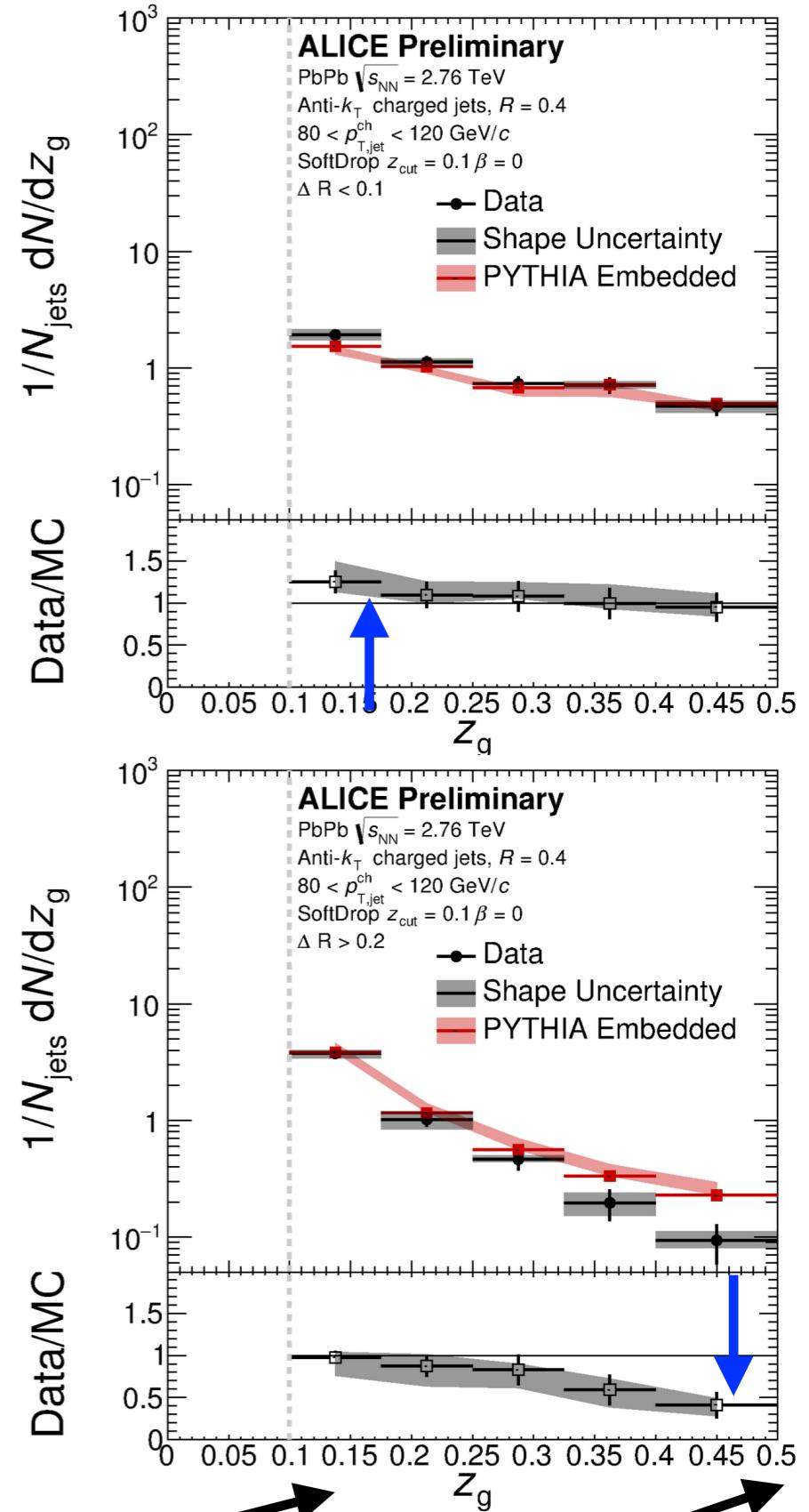
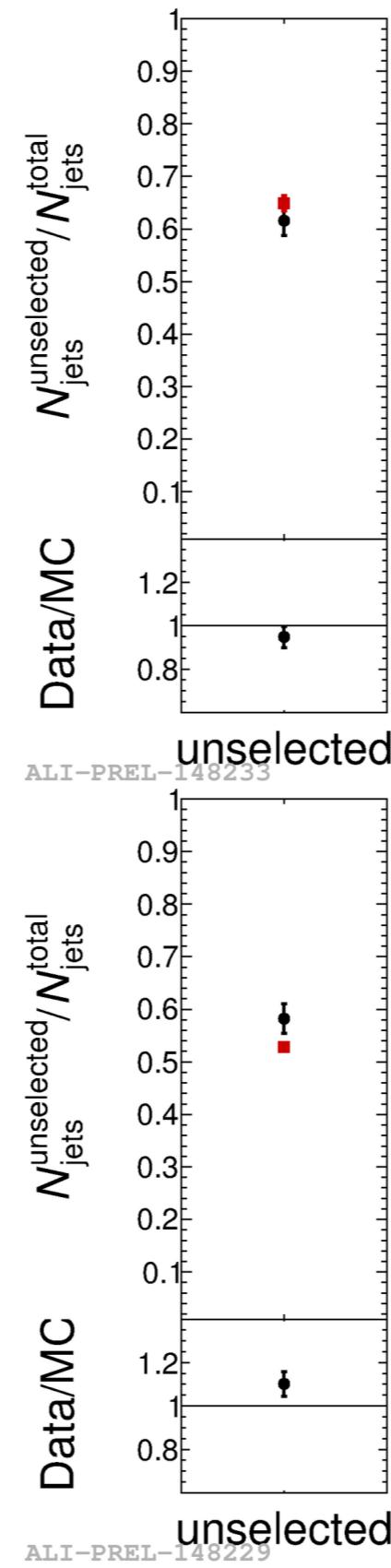
Jet splitting: open angle

collimated
 $\Delta R < 0.1$

- Small or no modification to collimated jets

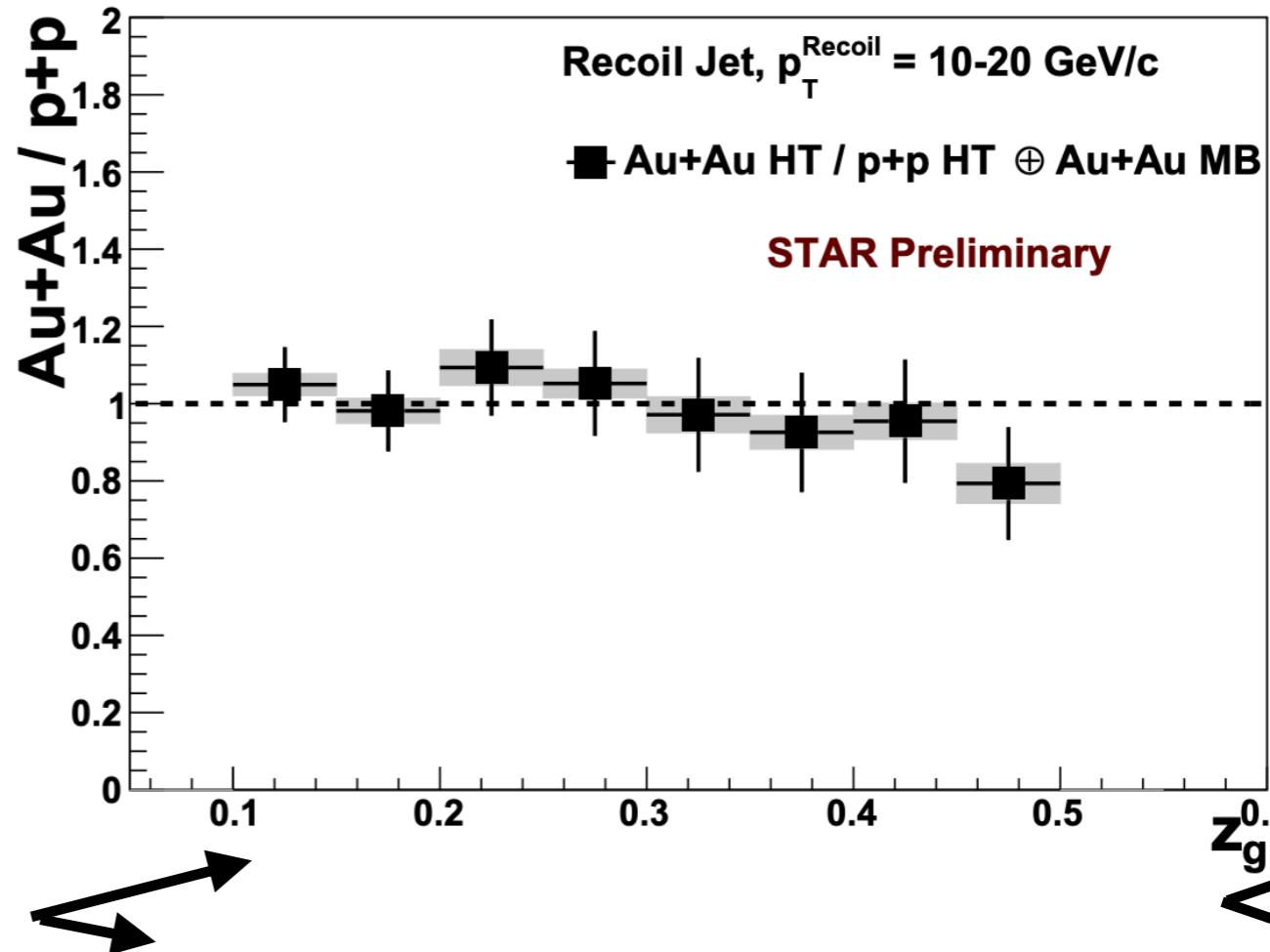
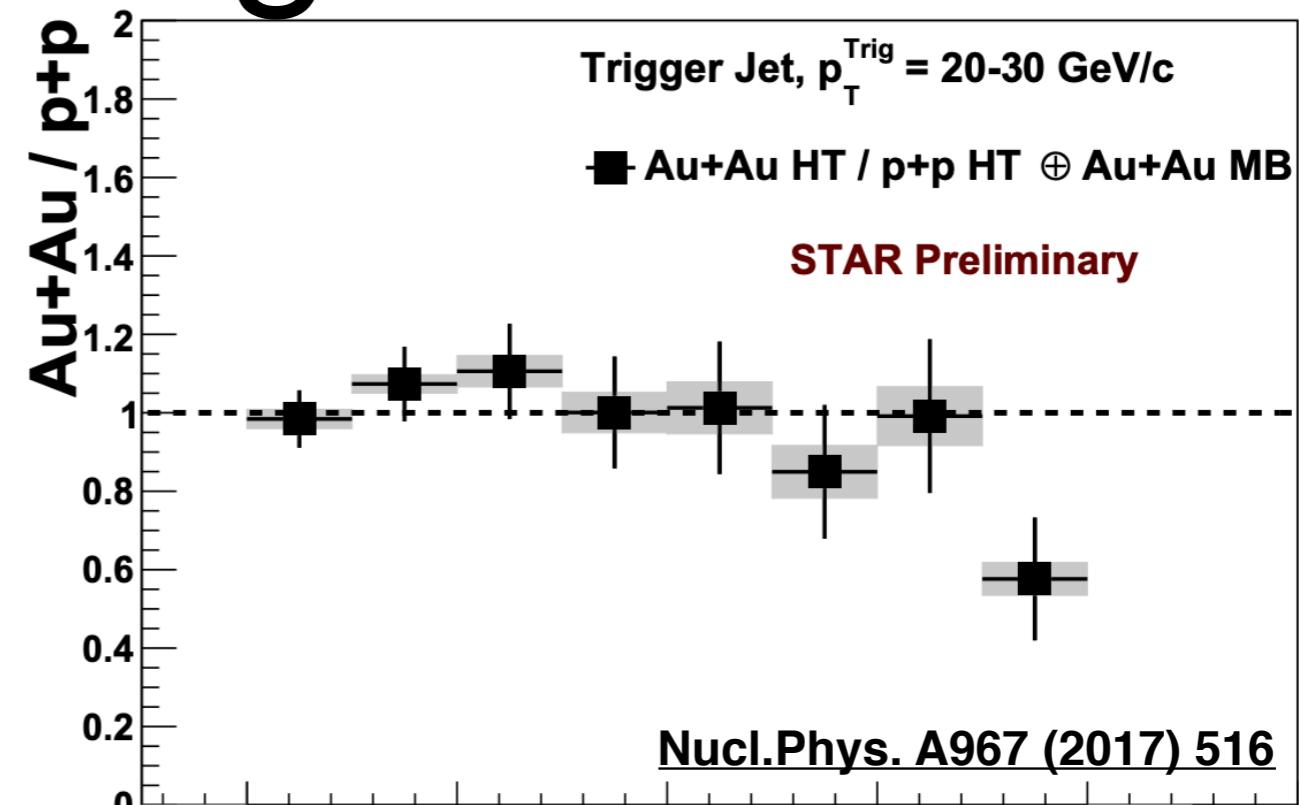


- More significant suppression of symmetric splittings for wide jets
- wide angle
 $\Delta R > 0.2$



Jet splitting: RHIC

- STAR shows little or no modification of z_g
- Not necessarily in contradiction with ALICE and CMS because they probe different formation times



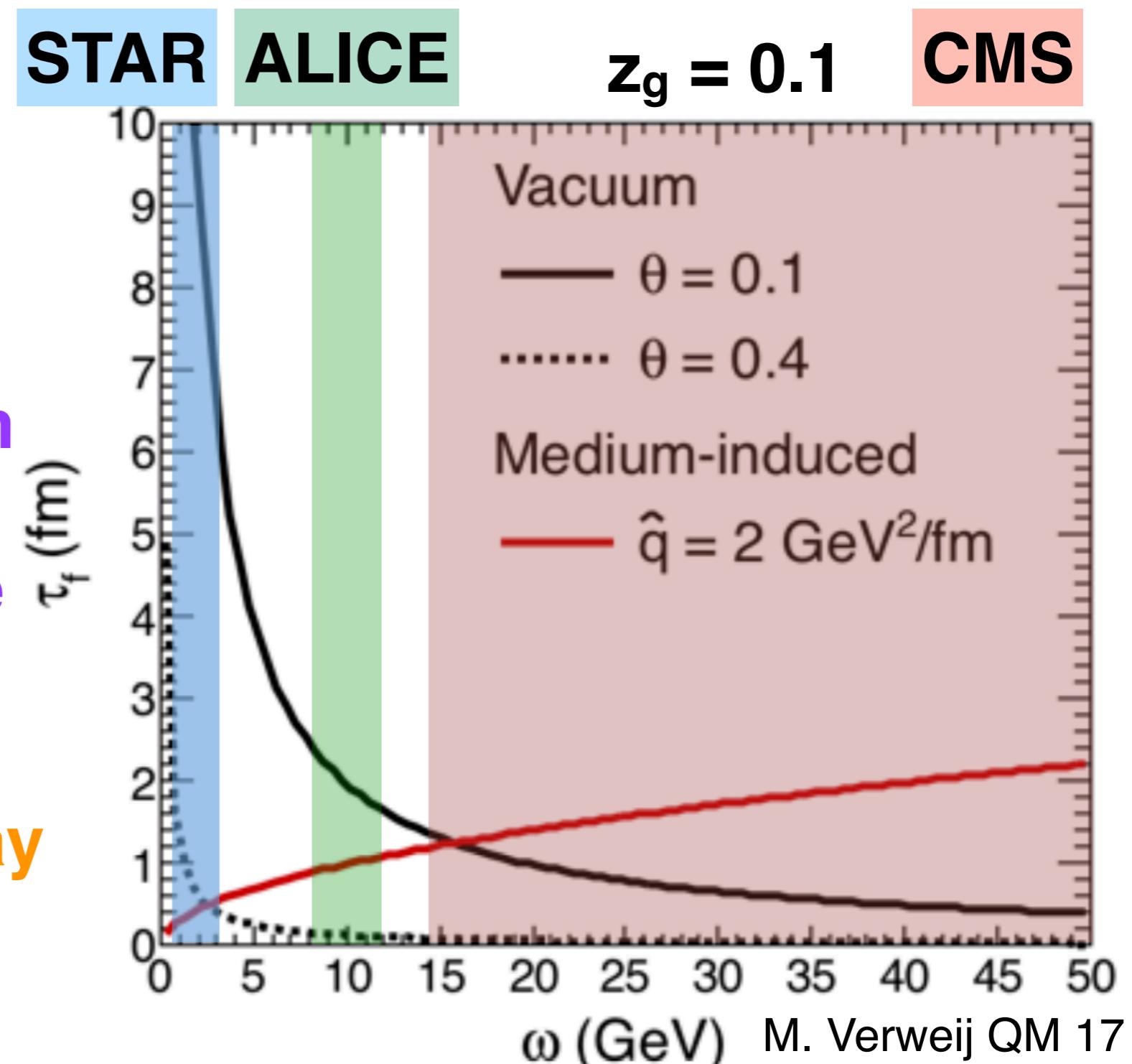
Jet splitting: RHIC vs. LHC

- Formation time for gluons in vacuum or medium

$$t_f^{\text{vac}} = \frac{1}{\theta^2 \omega} \quad t_f^{\text{med}} = \sqrt{\frac{\omega}{\hat{q}}}$$

- Wider splittings form earlier in a vacuum so more likely to see the medium

- Low energy gluons emitted later and may not see medium (STAR vs. LHC)



- Not necessarily in contradiction with ALICE and CMS because they probe different formation times

Conclusion and Outlook

- Jet suppression is seen for a wide range of jet momentum at the LHC
- Many measurements of the modification of the structure of jets in the medium
 - ➡ Fragmentation functions show a strong modification
 - ➡ Jet mass shows no modification
 - ➡ Jet splitting shows a suppression of symmetric splittings
 - ➡ Measurements in the high statistics 2018 Pb+Pb run at the LHC allow more detailed substructure studies
 - ➡ New tools continuously being developed
- Taking the jet measurements at the LHC and RHIC together helps us get the full picture of jets in QGP
 - ➡ Examples: different jet p_T scales and formation times

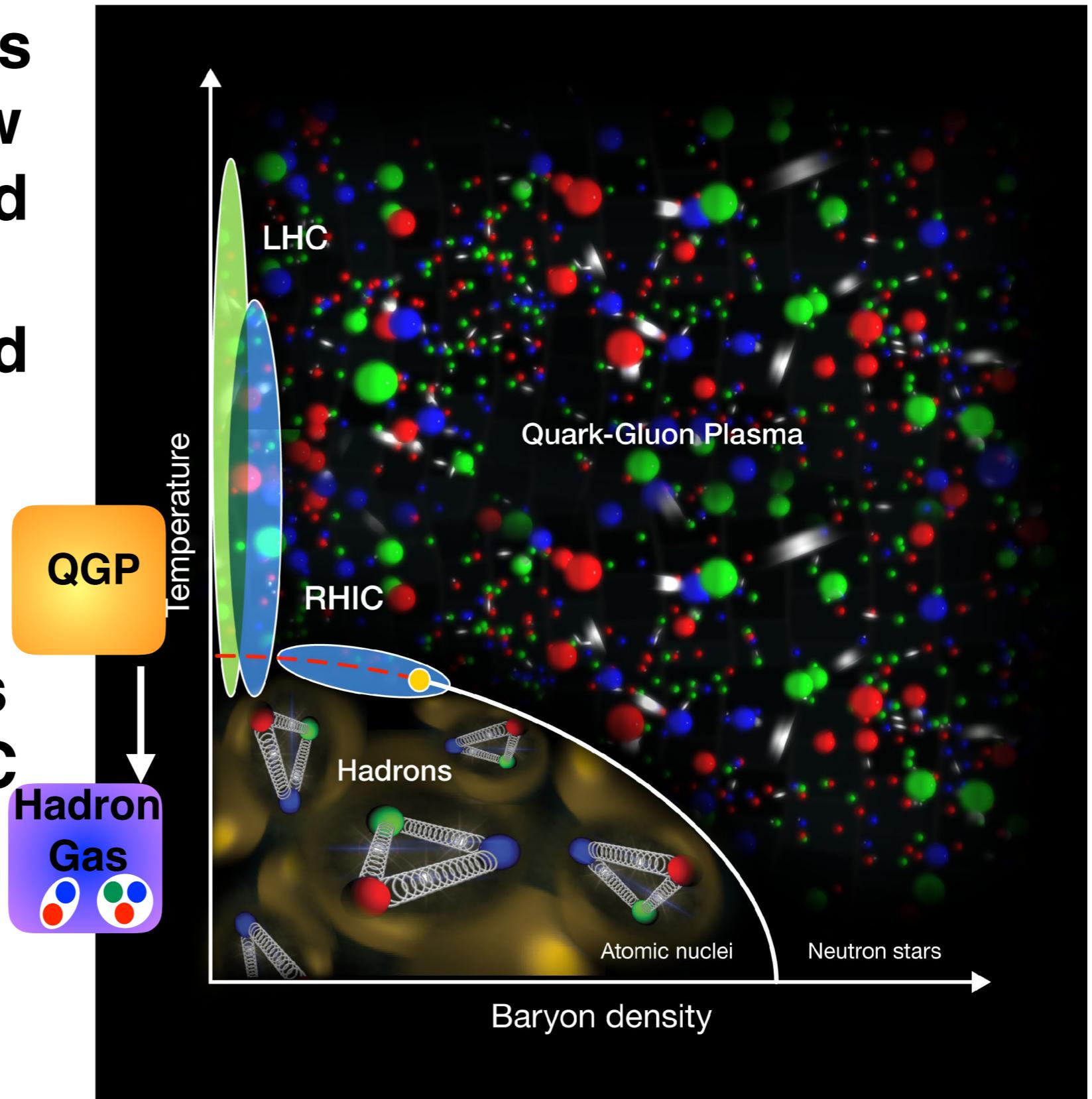
Backup

Heavy ion collisions

- At high temperatures and pressures a new state of matter called quark-gluon plasma (QGP) can be formed

► where the quarks and gluons are deconfined

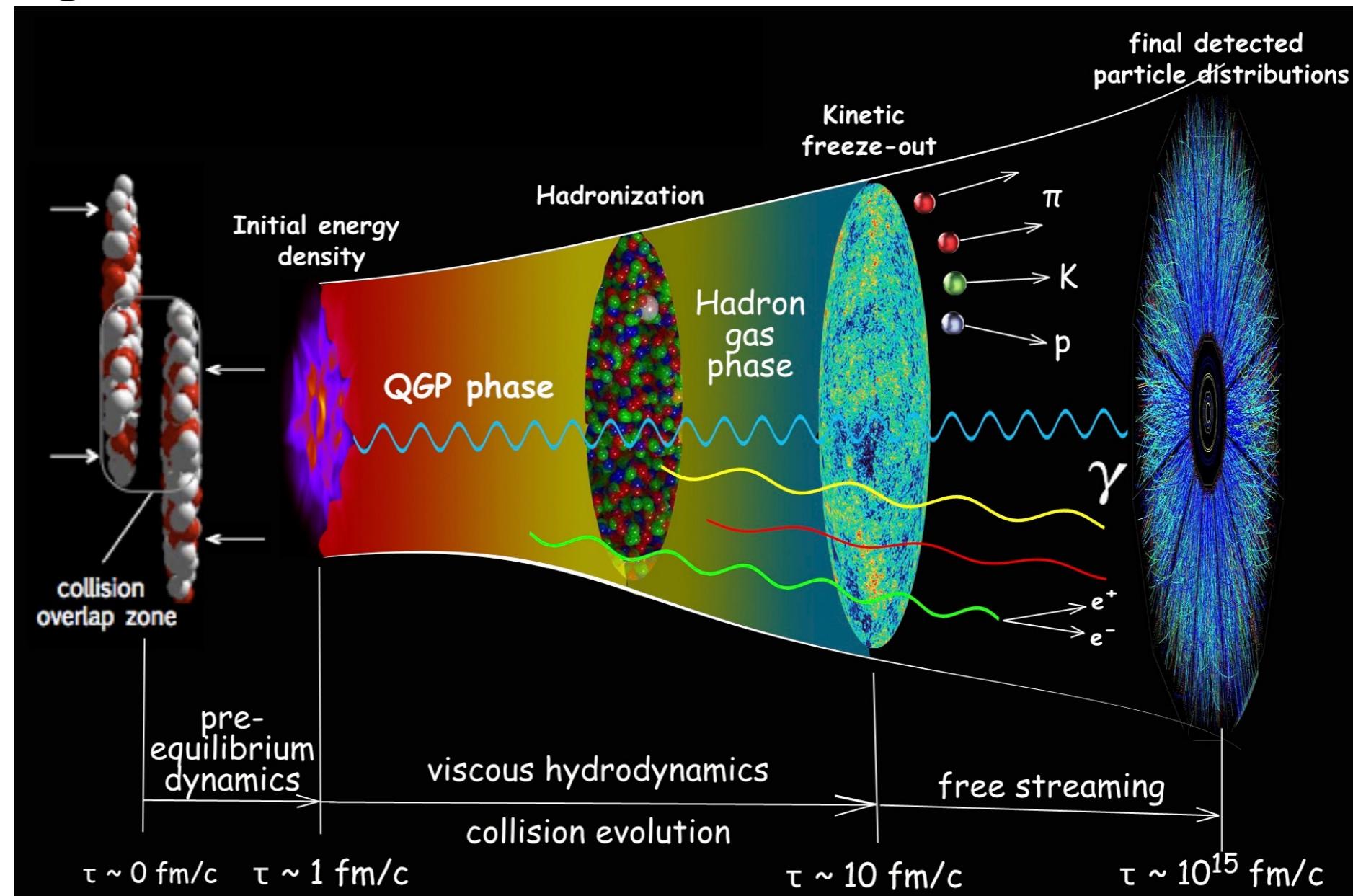
- Heavy ion collisions at RHIC and the LHC produce energy densities that allow the transition to the QGP to occur



Heavy ion collisions

- Collide heavy ions at very high energies
- Brief phase of QGP that quickly hadronizes
- Becomes final state particles

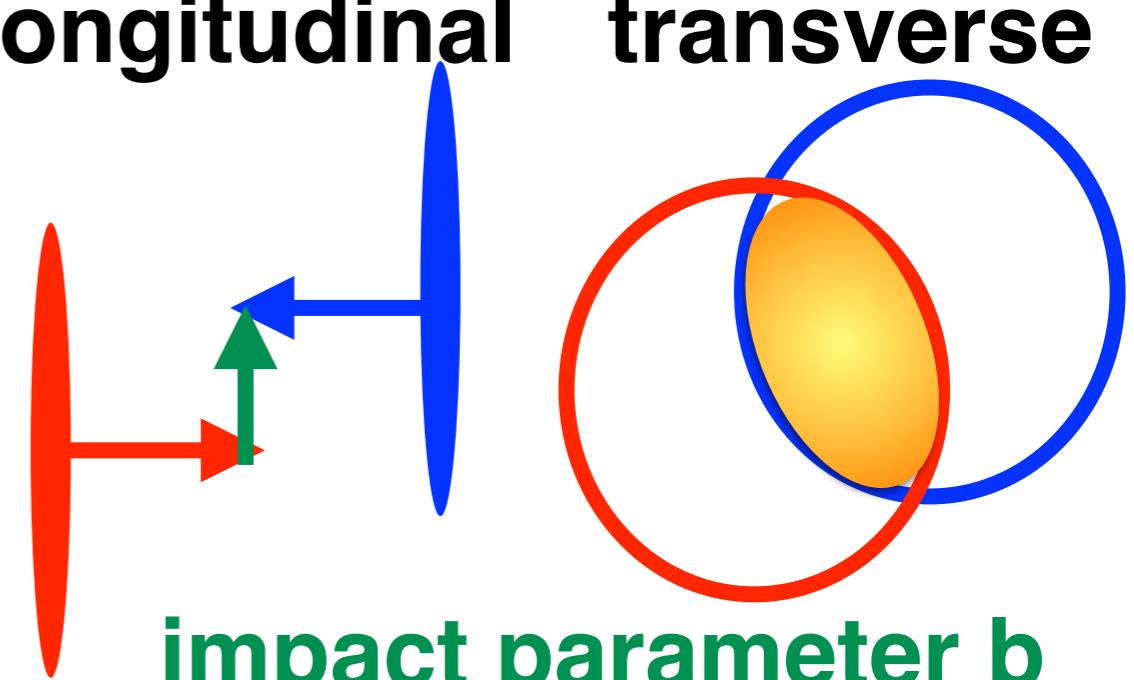
Image by Chun Shen



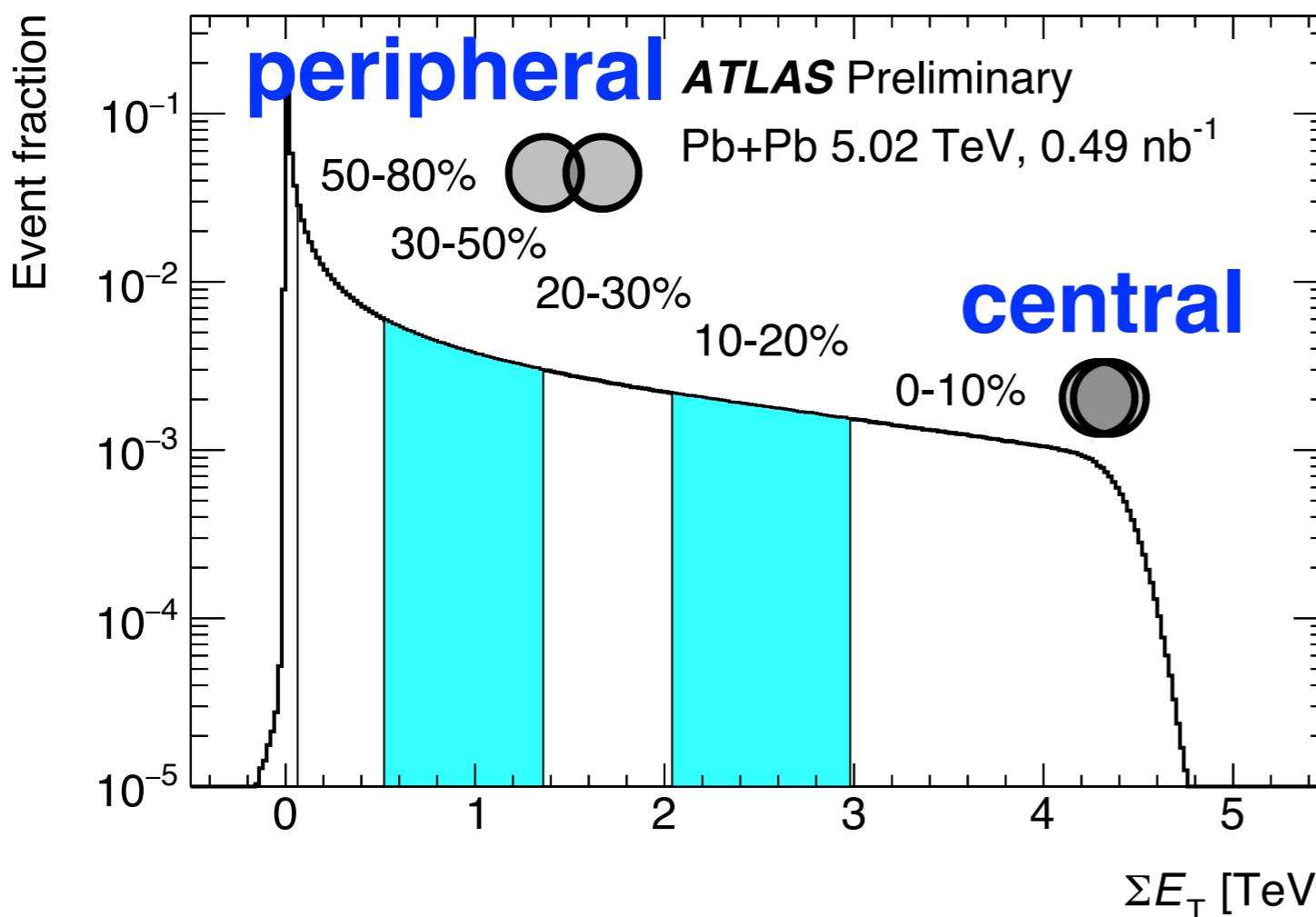
- Collective expansion of the strongly-coupled system is described by viscous hydrodynamics
 - Low shear viscosity (η/s) makes a nearly perfect fluid
 - Very opaque allows for large parton energy loss

Centrality

- Nucleon flux increases with increasing centrality (or decreasing b)
 - Define “centrality classes” as events with similar degrees of overlap



impact parameter b



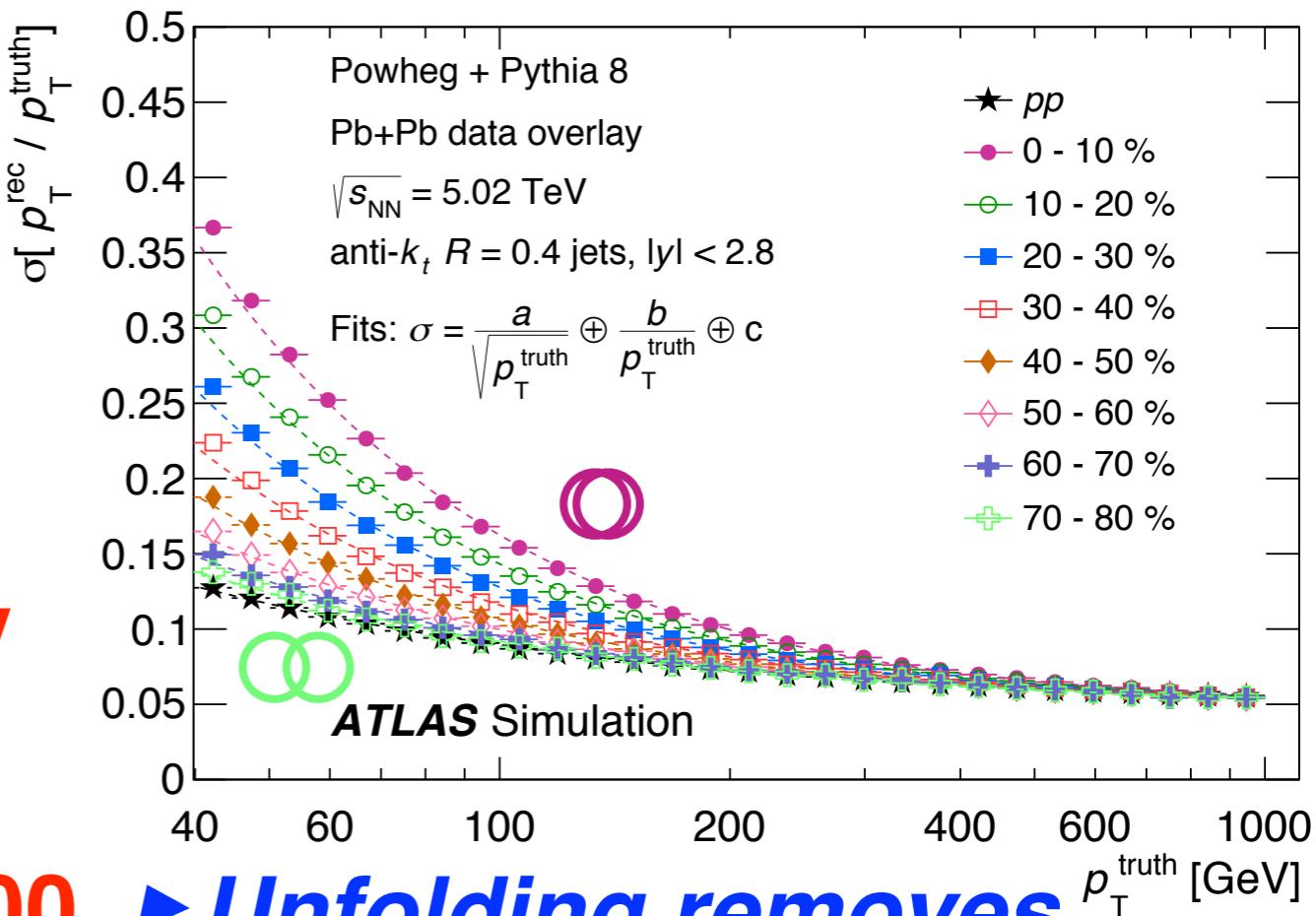
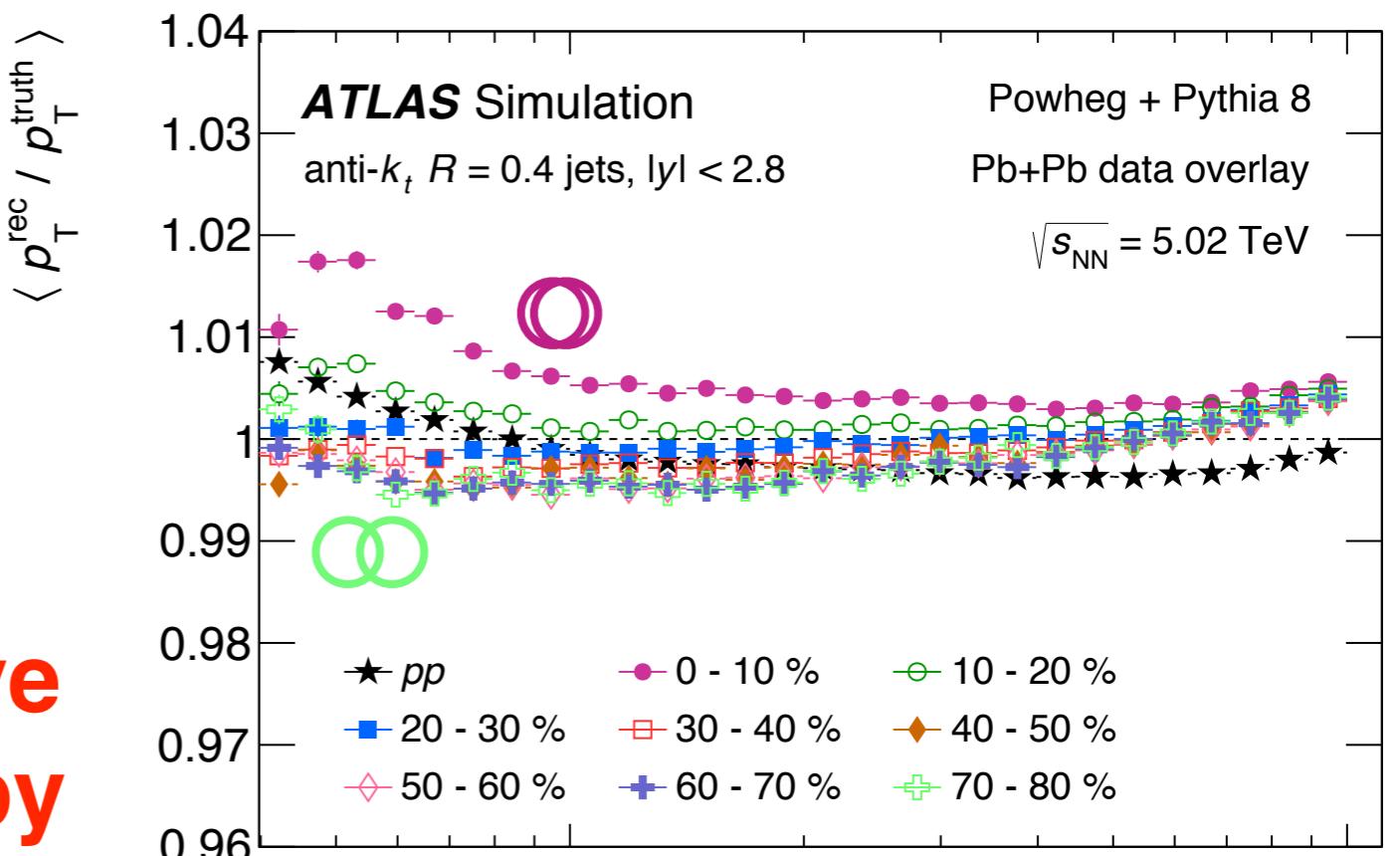
In experiment the total particle production is used

In ATLAS FCal E_T is strongly correlated with event activity

Partition distribution into percentiles

Performance

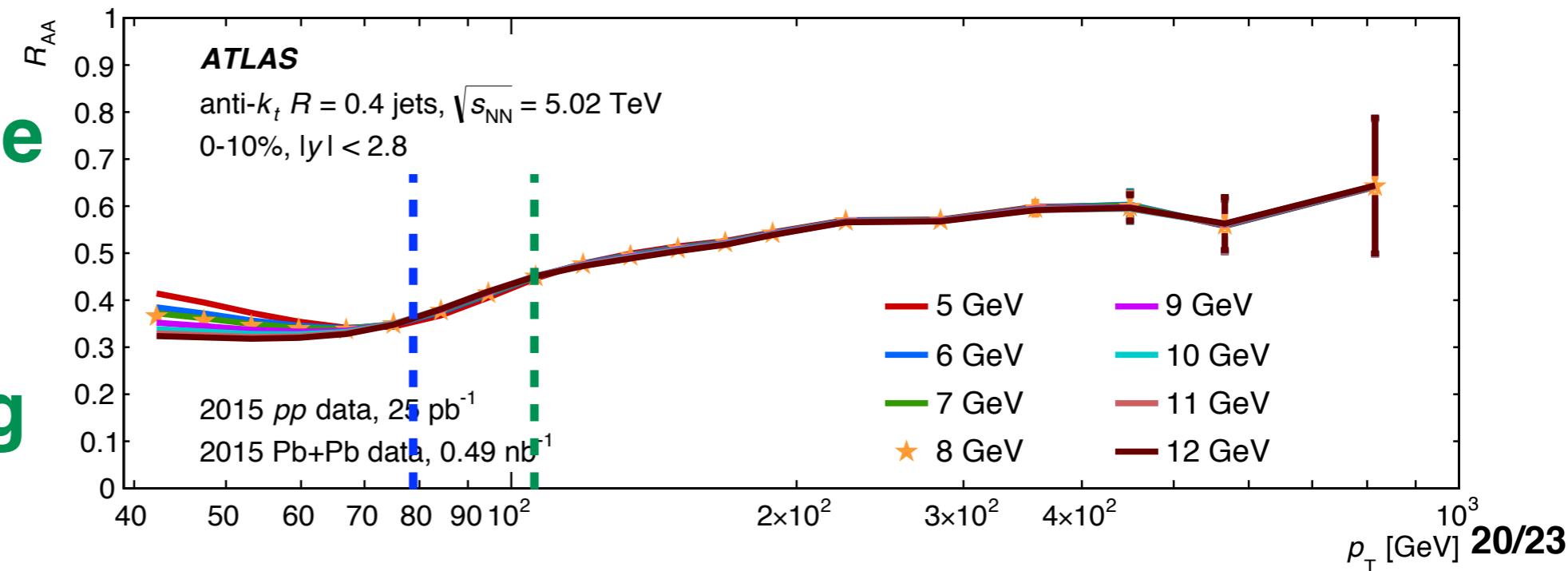
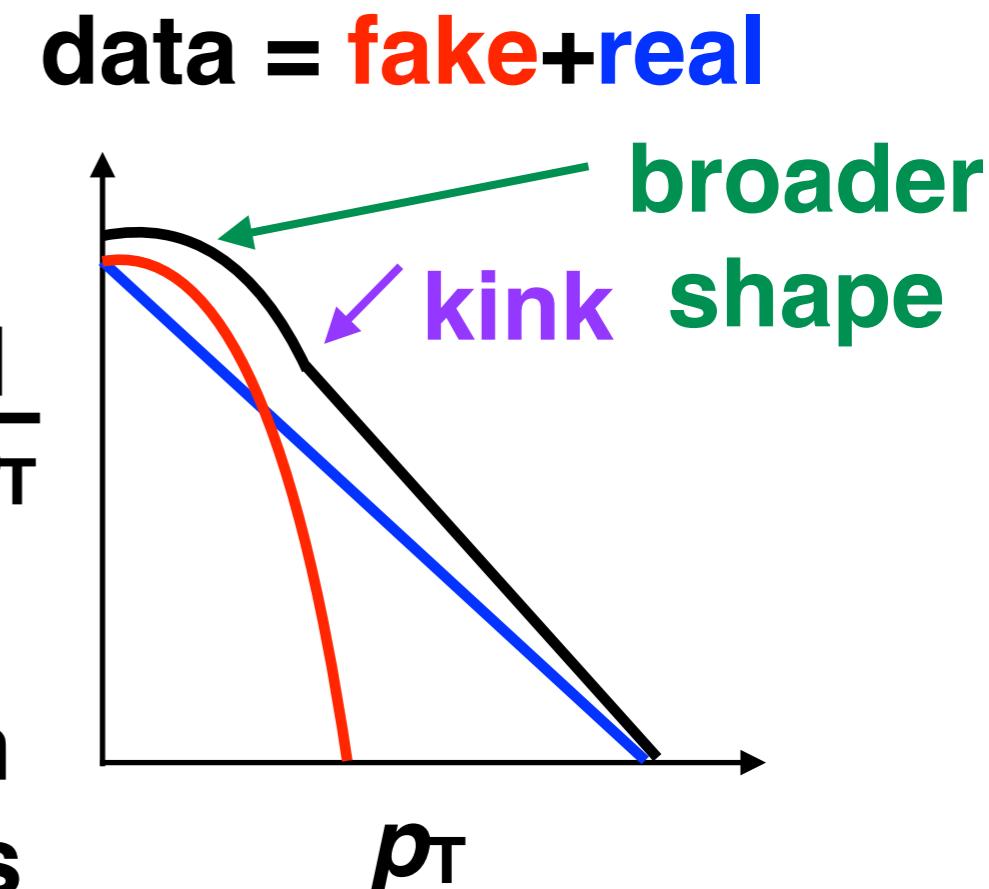
- Large uncorrelated underlying event (UE) that varies with η , Φ and event
 - Subtracted with iterative procedure modulated by harmonic flow
- MC jets are embedded into real Pb+Pb data and reconstructed in the same way as data
 - JES is ~1% above 100 GeV for 0-10%
 - JER in 0-10% is ~16% at 100 GeV and decreases to ~6%.



► *Unfolding removes remaining JES/JER*

Fakes

- **Fake, or “UE jets”, are jets that are reconstructed from upward fluctuations due the UE**
- **Removed before unfolding**
- **R_{AA} fake rejection:** look at different $\sum p_T^{\text{trk}}$ cuts for charged tracks with $p_T^{\text{trk}} > 4 \text{ GeV}$ within $\Delta R < 0.4$ of jets
- **Fakes mostly contribute below $\sim 75 \text{ GeV}$ in 0-10%**
- **Above this see little change so use $\sum p_T^{\text{trk}} > 8 \text{ GeV}$ as the rejection**
- **Determines the measurement kinematic cut after unfolding to be 100 GeV**



Model comparisons

- Lorentz Boltzmann Transport (LBT) model:
 - MC model of parton propagation
 - Elastic and inelastic e-loss
 - UE estimate from hydrodynamics with medium recoil and recoil propagation [Y. He, T. Luo, X.-N. Wang and Y. Zhu](#)
- Soft Collinear Effective Field Theory (SCETg):
 - EFT for soft and collinear particles
 - Jets and their interactions with the medium are mediated by a Glauber gluon exchange
 - Modifications are made to the splitting functions
 - No medium recoil [Y.-T. Chien, A. Emerman, Z.-B. Kang, G. Ovanesyan and I. Vitev](#)
- Effective Quenching (EQ) model:
 - two downward shifts in p_T , larger for gluons than quarks [B. Cole and M. Spousta](#)

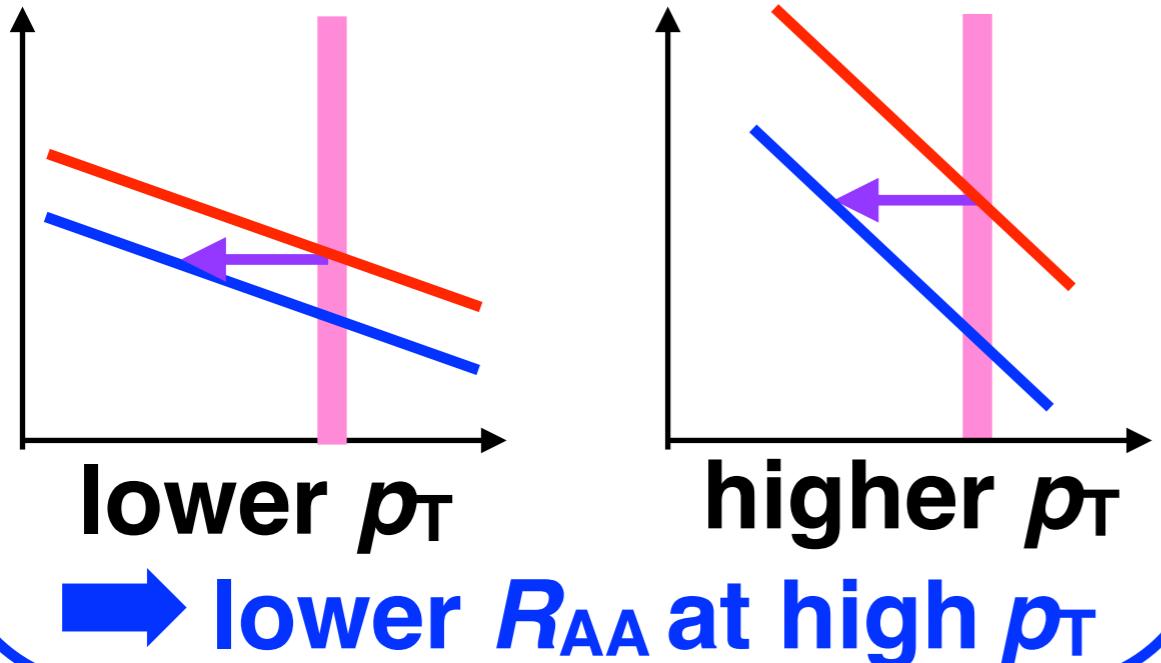
Model comparisons

- Effective Quenching (EQ) model:

→ fractional energy loss decreases with p_T

→ p_T dependence to the power-law distribution

Spectra steeper with increasing p_T for the same amount of energy loss



$$S = \Delta p_T^{\text{jet}} = s' \left(\frac{p_T^{\text{jet}}}{p_T^0} \right)^a$$

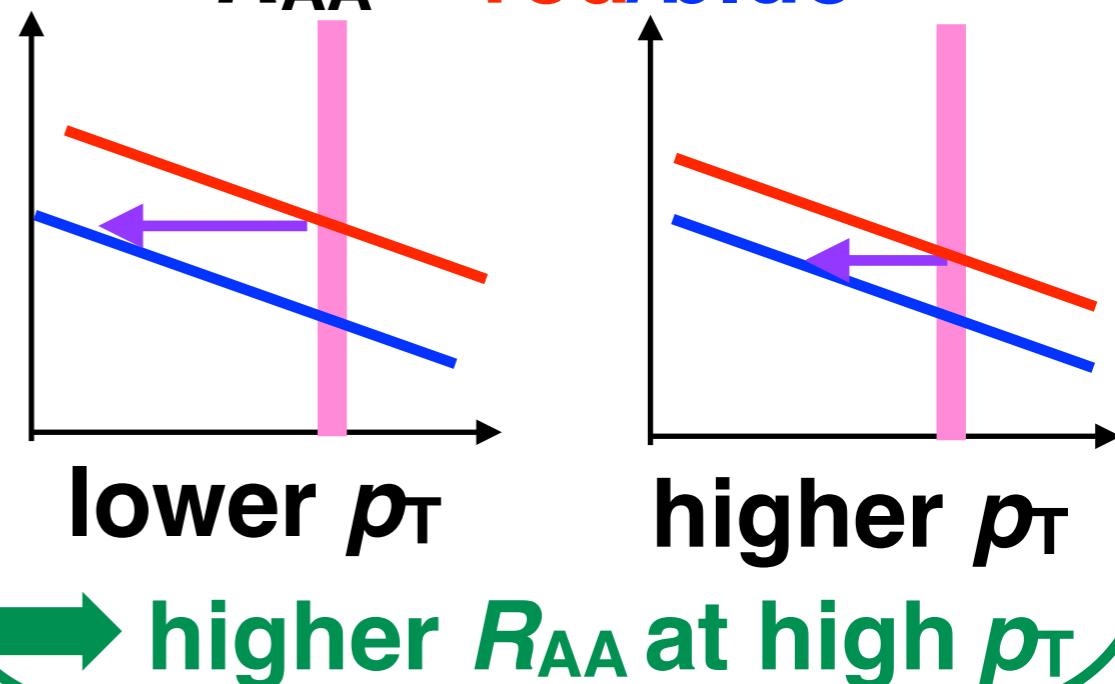
$a < 1$

$$\frac{dN}{dp_T^{\text{jet}}} \propto (p_T^{\text{jet}})^{-n}$$

$n \propto \ln p_T^{\text{jet}}$

Amount of energy loss smaller at high p_T

$R_{AA} \sim \text{red/blue}$



Internal structure

- Fragmentation functions are a measure of how charged particles are distributed inside a jet

$$D(z) = \frac{1}{N_{\text{jet}}} \frac{dN_{ch}}{dz} \quad z = \frac{p_T \cos \Delta R}{p_T^{\text{jet}}}$$

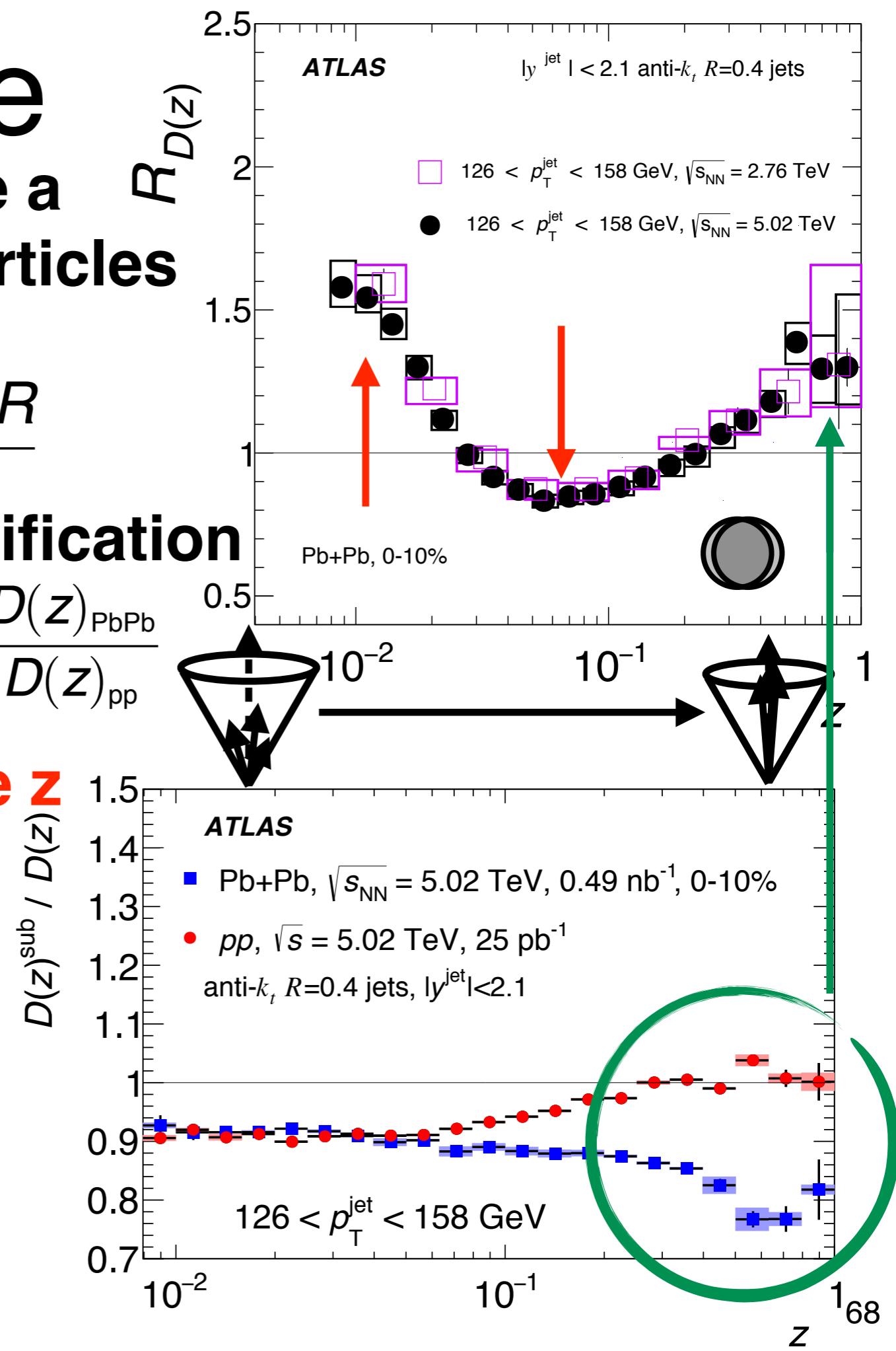
- Ratio of FF used to see modification of jet structure

$$R_{D(z)} = \frac{D(z)_{\text{PbPb}}}{D(z)_{\text{pp}}}$$

- Enhancement at low z and suppression at intermediate z
- Enhancement at high z

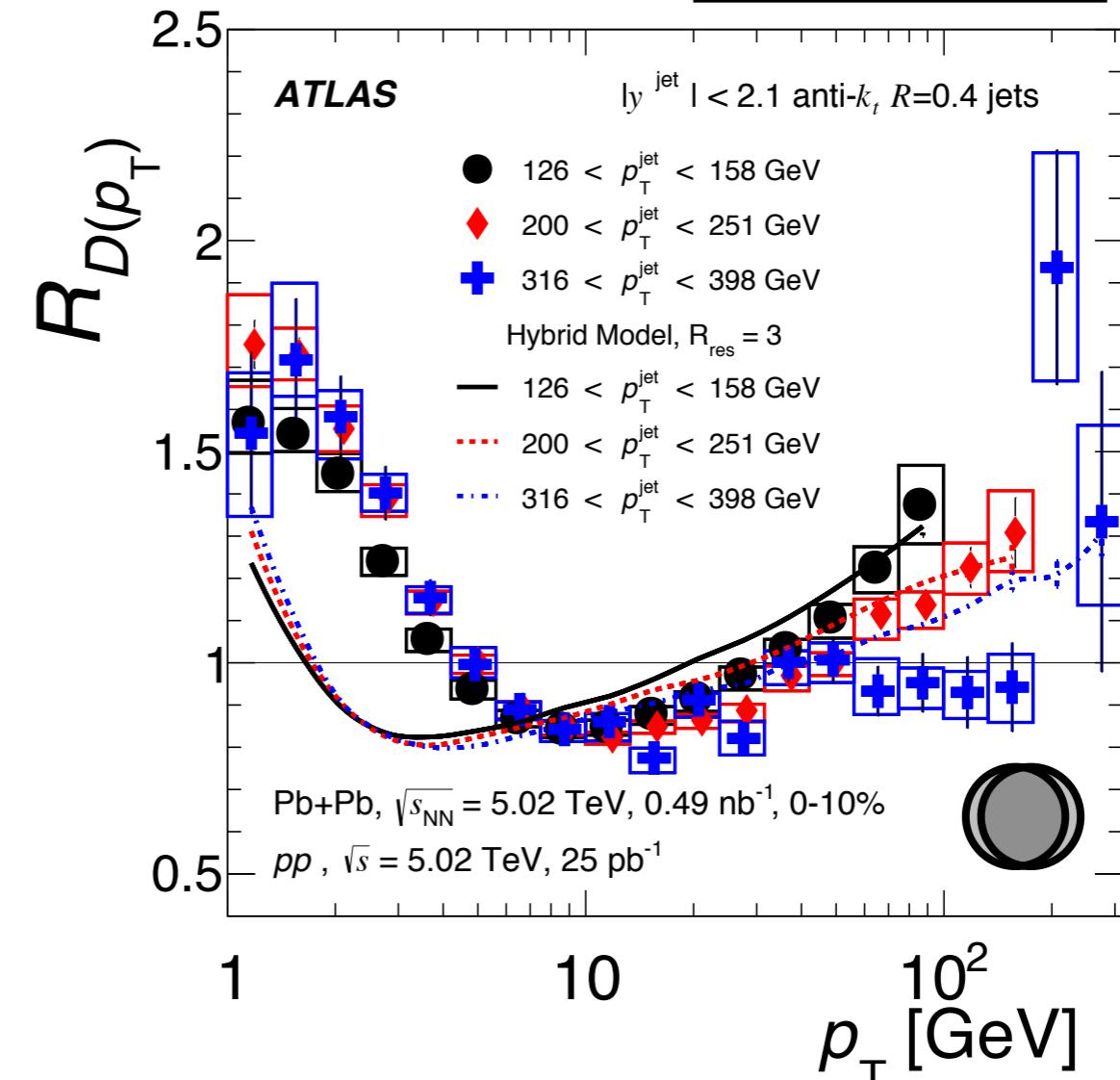
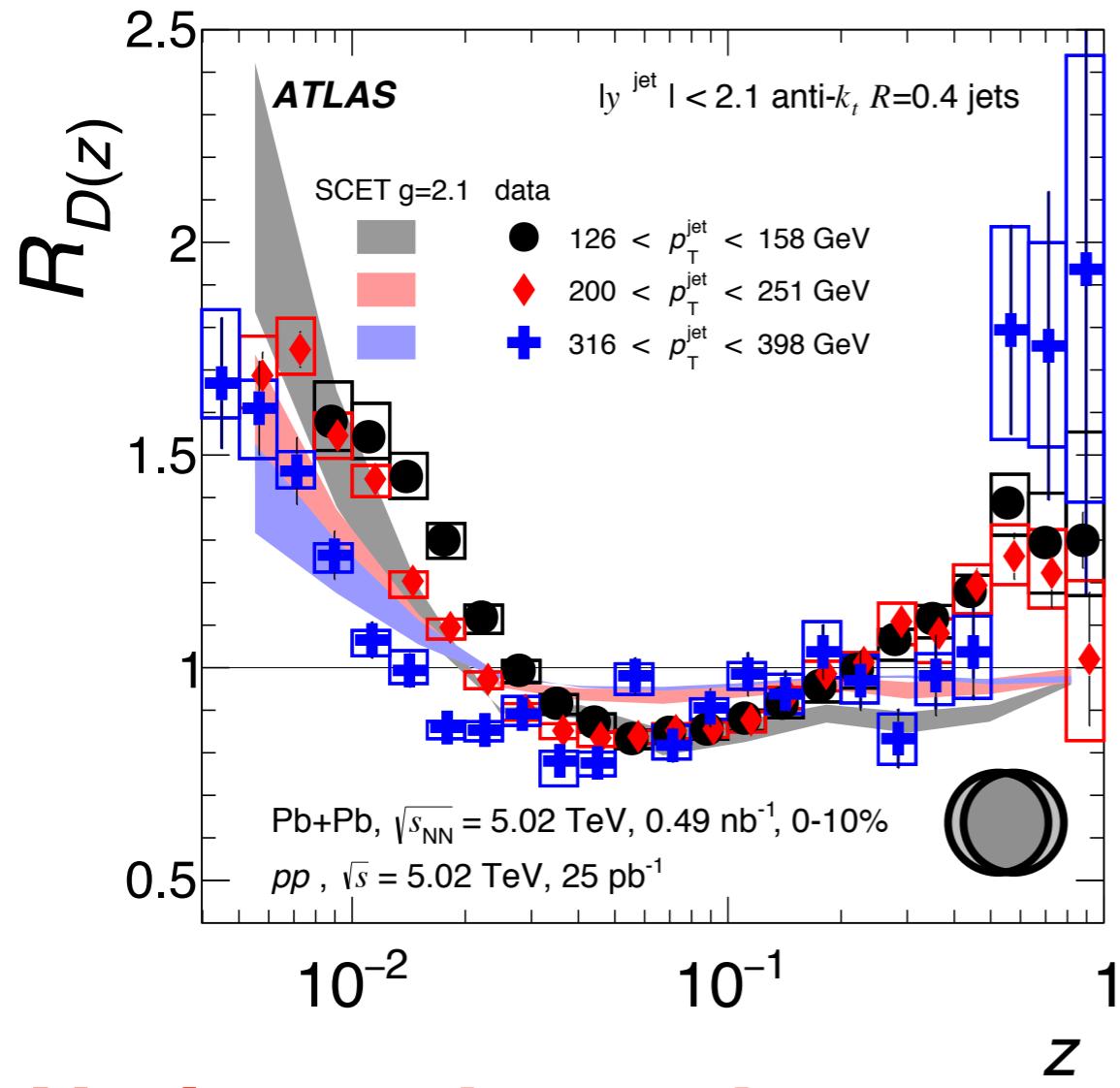
- 2D unfolding in z and jet p_T

- Unfolding increases Pb+Pb FF and decreases pp FF at high z , resulting in the enhancement at high z



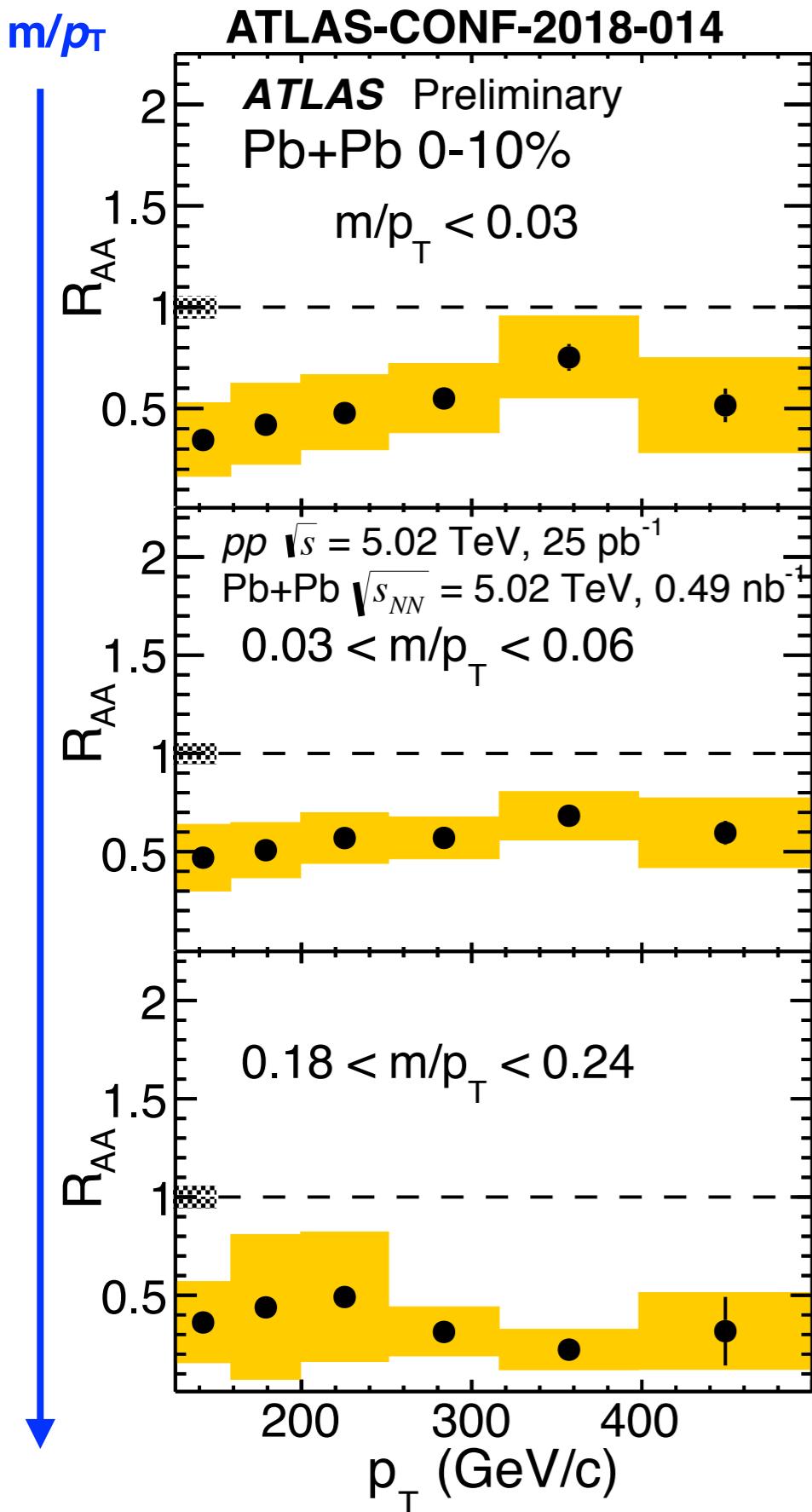
Internal structure: p_T dep.

[arXiv:1805.05424](https://arxiv.org/abs/1805.05424)

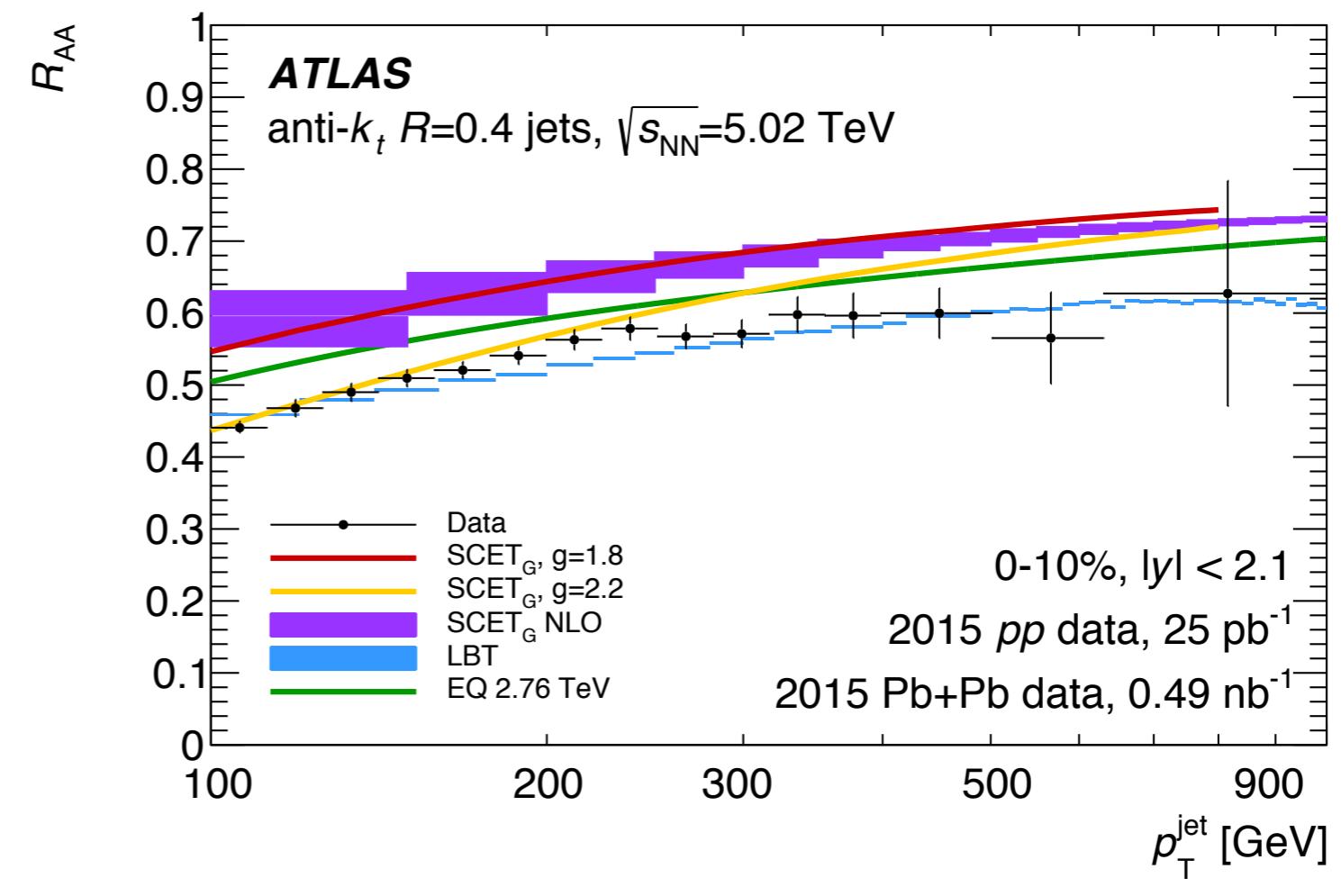


- No jet p_T dependence at high z
- Less enhancement for high jet p_T at low z
- Described by model
- Jet p_T dependence shows more low p_T tracks at high p_T
 - response of medium to jets?
- Model describes jet p_T dependence at high track p_T

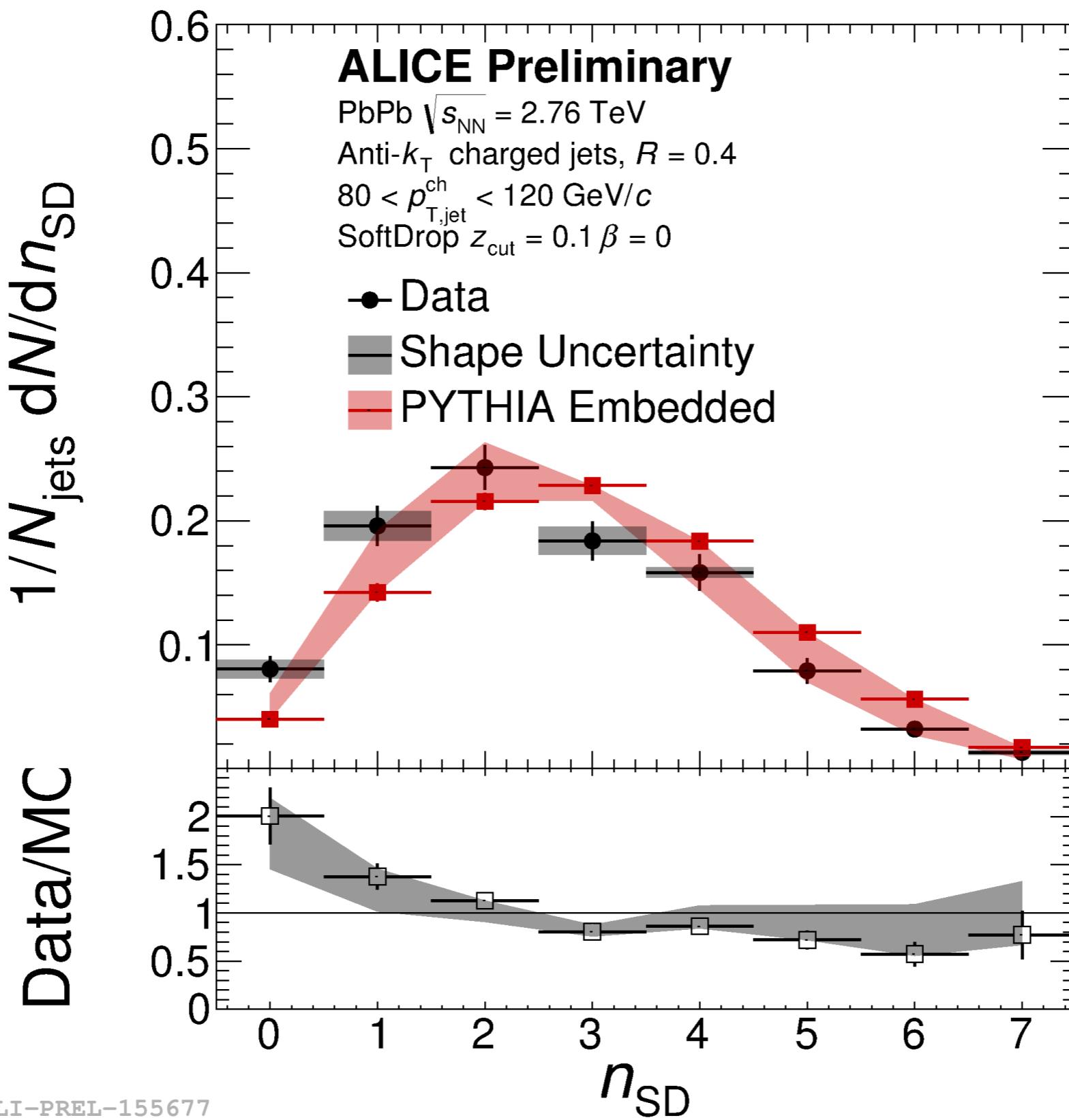
Jet mass: ratio



- ATLAS R_{AA} vs. p_T : no significant modification
- R_{AA} is consistent with inclusive R_{AA} for all m/p_T



ALICE nSD



ALICE response matrixes

