# Studying jet shower modifications in the quark-gluon plasma using the Lund tree (CMS)

Yi Chen (MIT)

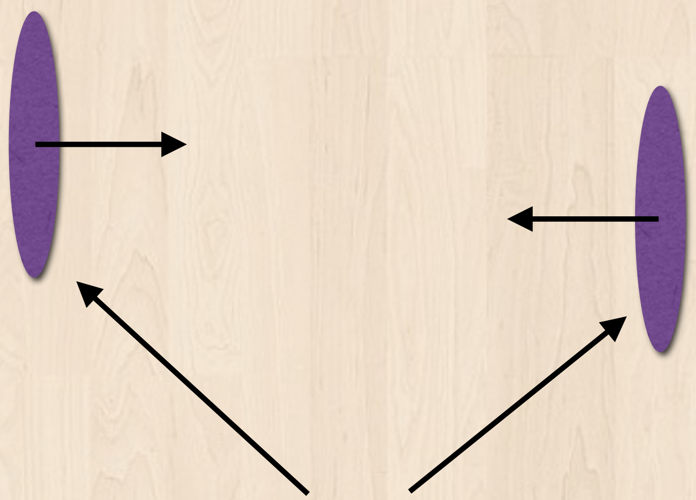
Lund plane workshop, Jul 4, 2023

The MITHIG's work is supported by US DOE-NP

# Jets in QGP

Setting the stage for substructure measurements

# Heavy-ions and the QGP



e.g. Pb/Au/Xe/… ion

Energy up to

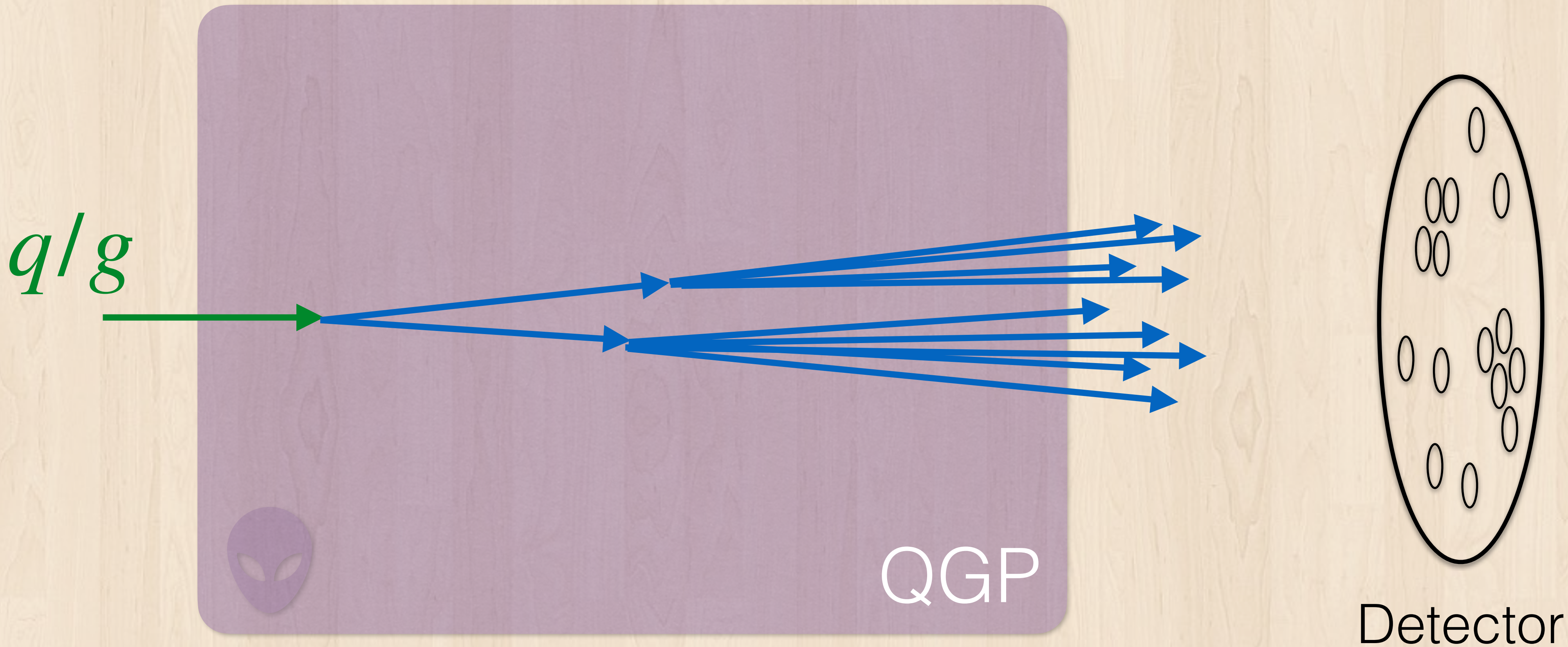
$$\sqrt{s_{NN}} = 5.44 \text{ TeV (XeXe)}$$

$$\sqrt{s_{NN}} = 5.36 \text{ TeV (PbPb)}$$


LHC, CERN, Geneva


RHIC, BNL, New York

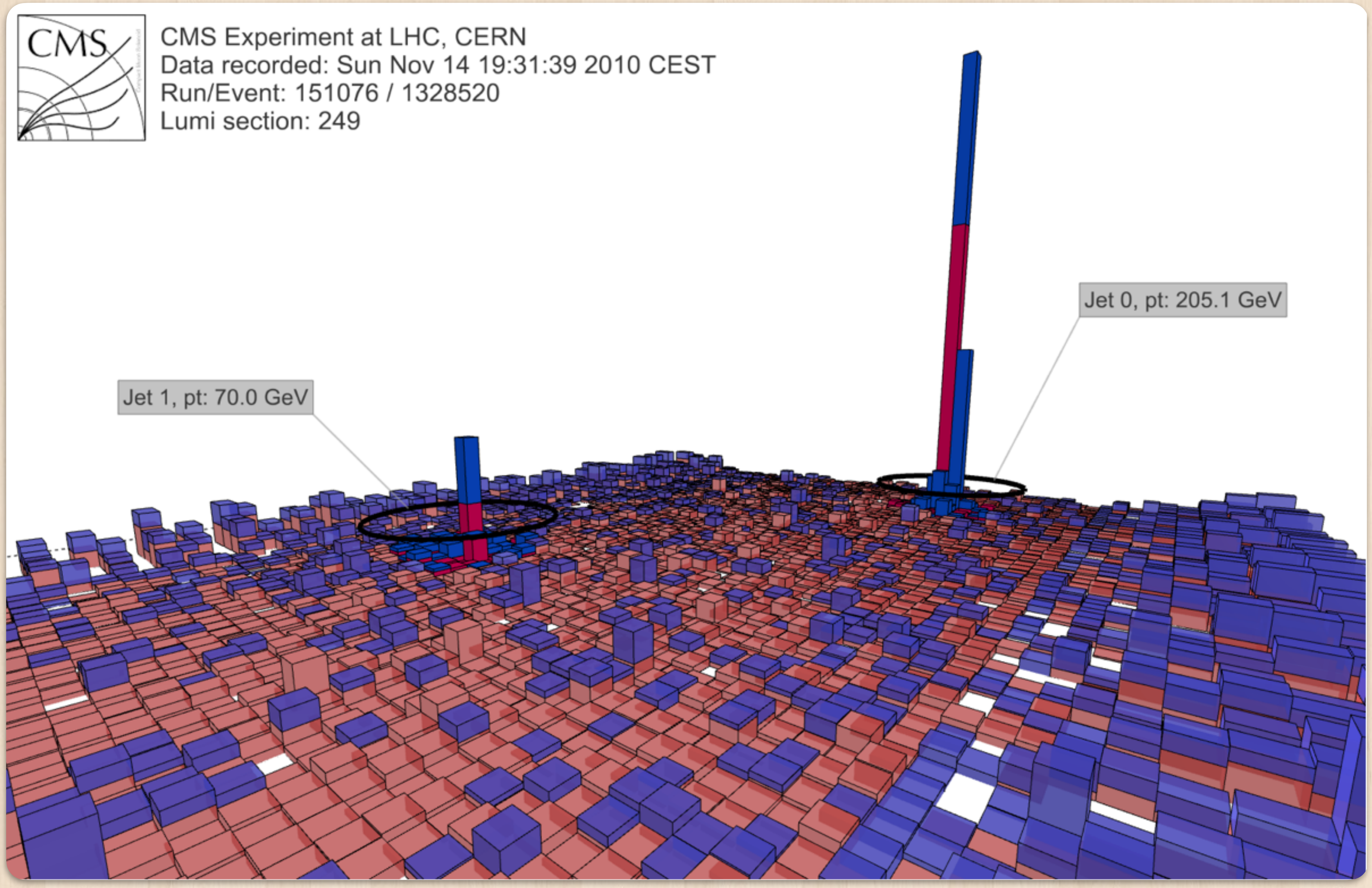
# Jets inside QGP



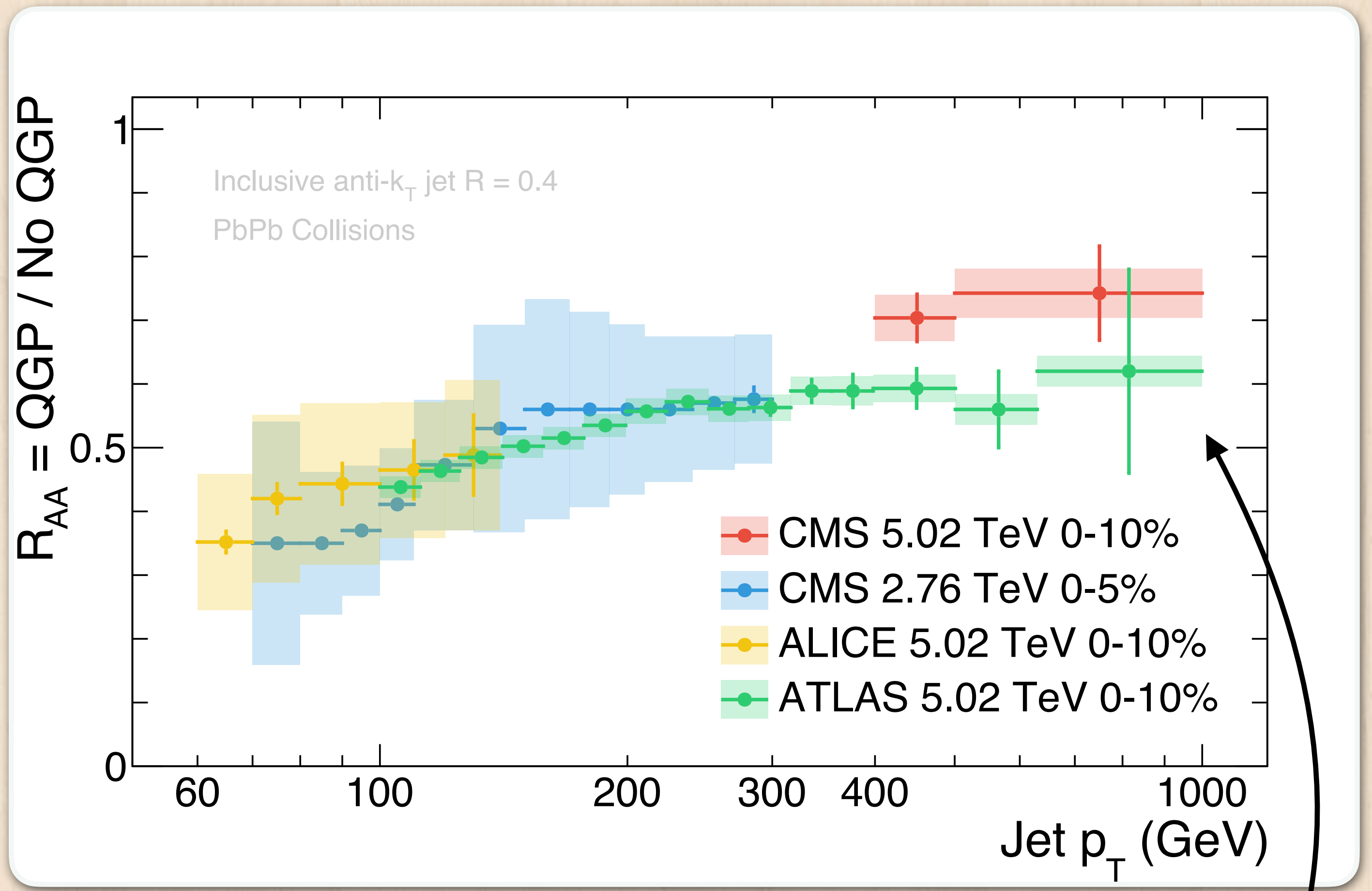

What happens?

Key difference to no-QGP case:
**space-time structure** of jet evolution now matters

# Example jets in collisions



# Jets quench





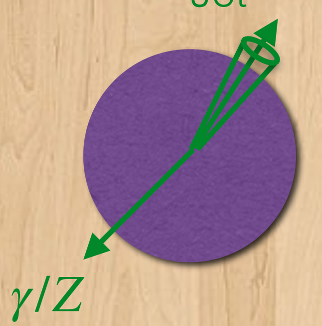
A lot fewer jets

**"Jet quenching"**

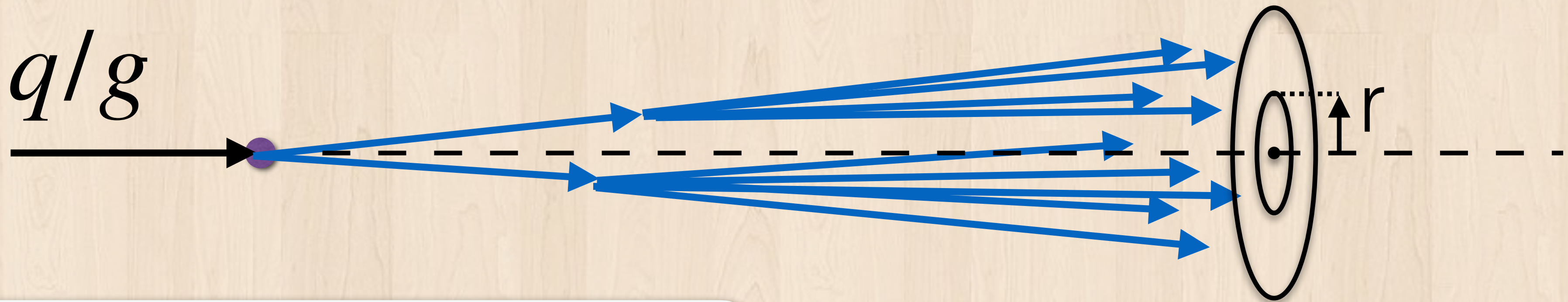
"Nuclear modification factor":

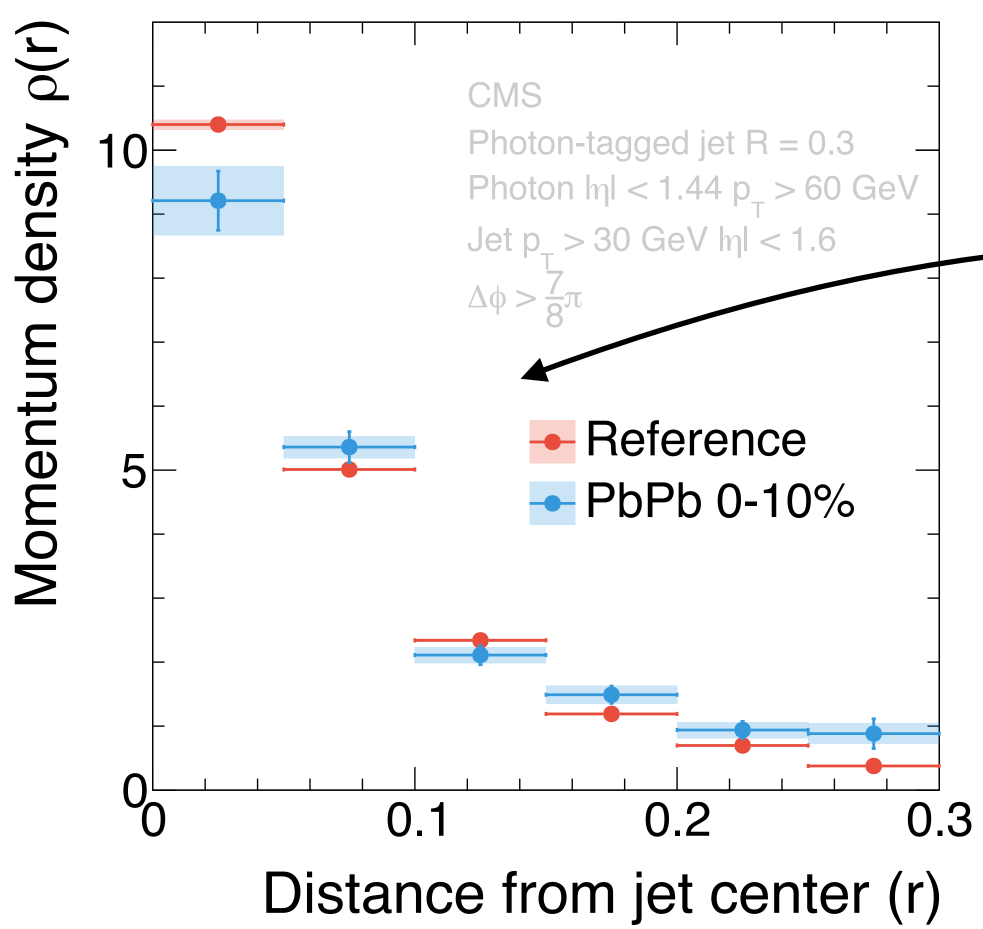
$$\frac{\sigma \text{ with QGP (PbPb)}}{\sigma \text{ without QGP (reference)}} \sim 0.6 - 0.7$$

at 1 TeV




# Radial distribution

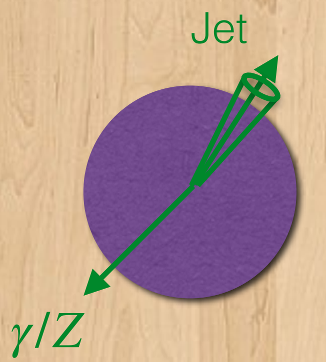


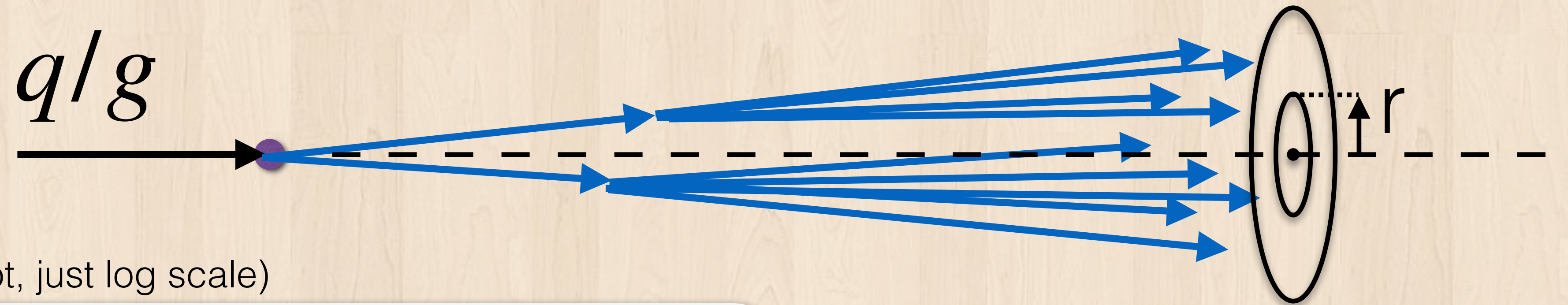

Energy in jets are concentrated in a small area on average

Larger tail observed in jets in PbPb

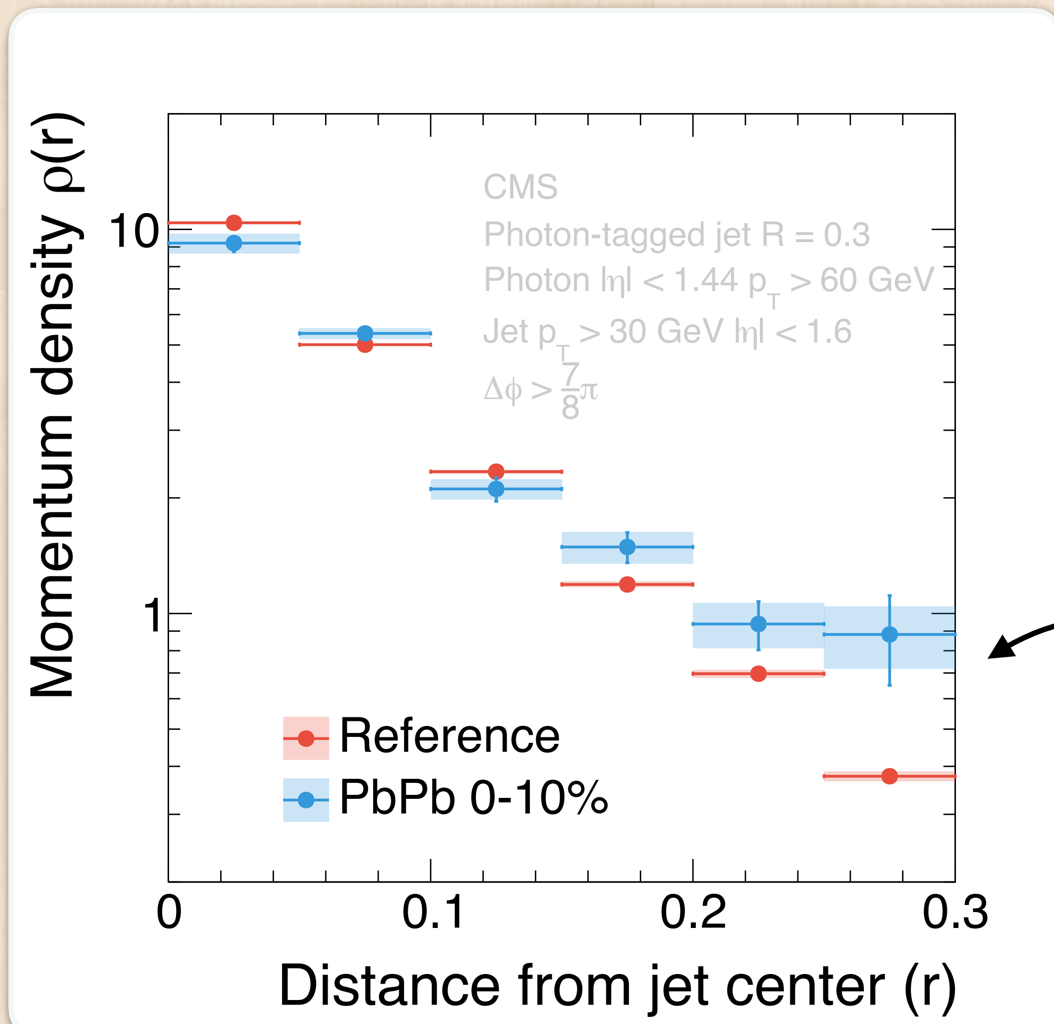
Energy is pushed away




# Radial distribution



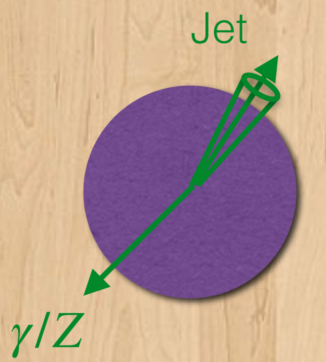

(Same plot, just log scale)



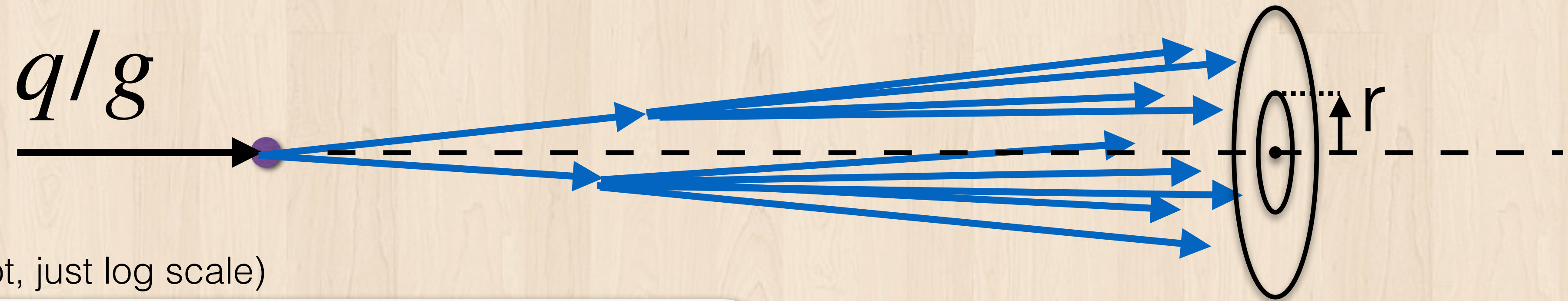

Energy in jets are concentrated in a small area on average

Larger tail observed in jets in PbPb

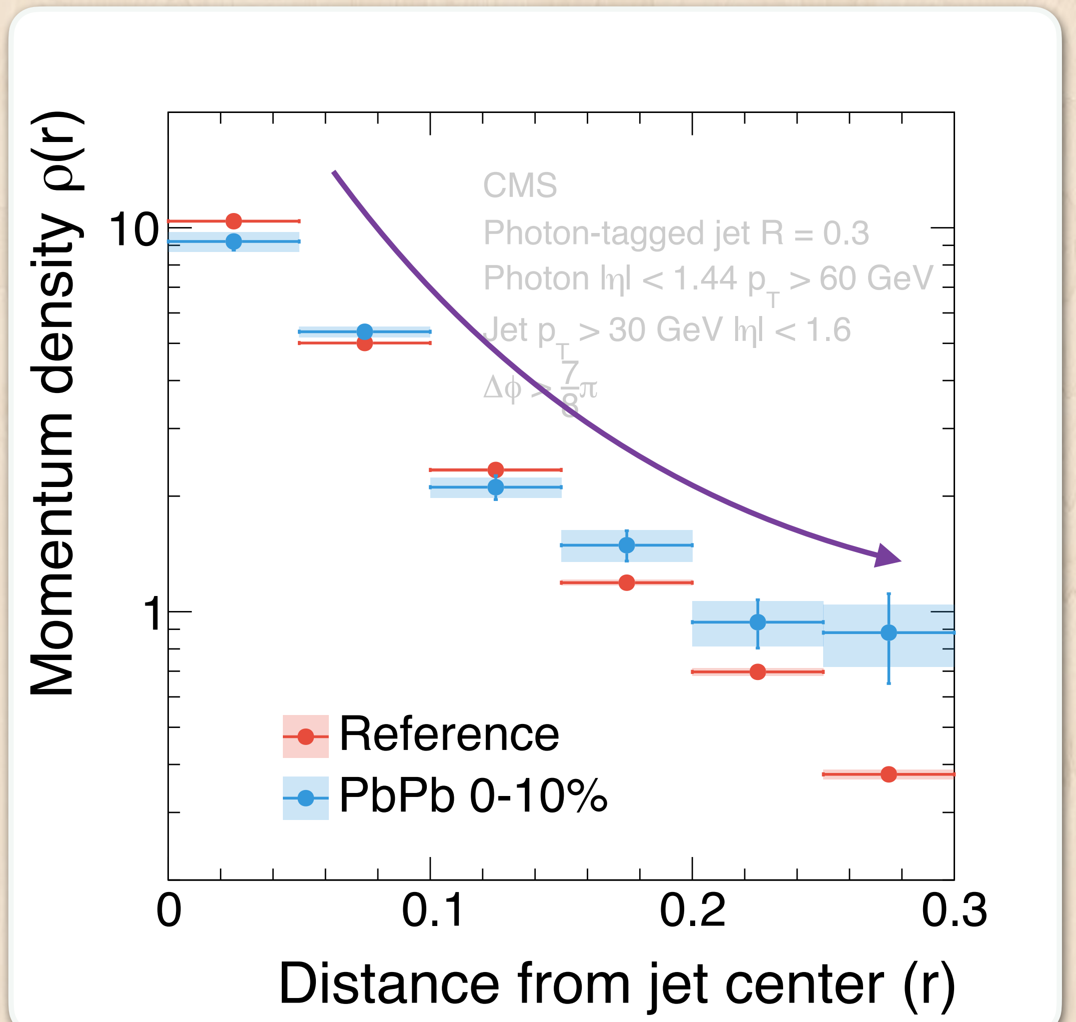
Energy is pushed away




# Radial distribution




(Same plot, just log scale)

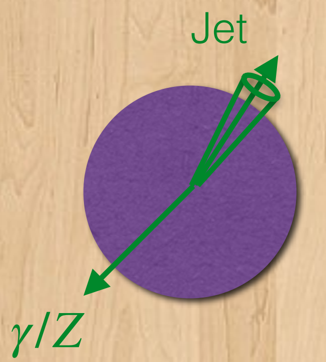



Energy in jets are concentrated in a small area on average

Larger tail observed in jets in PbPb

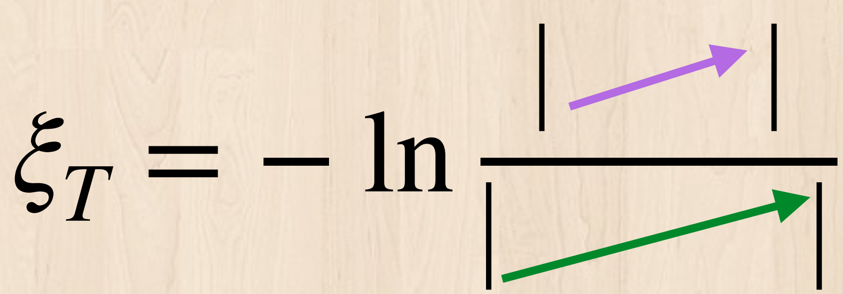
Energy is pushed away

PRL 122 (2019) 152001

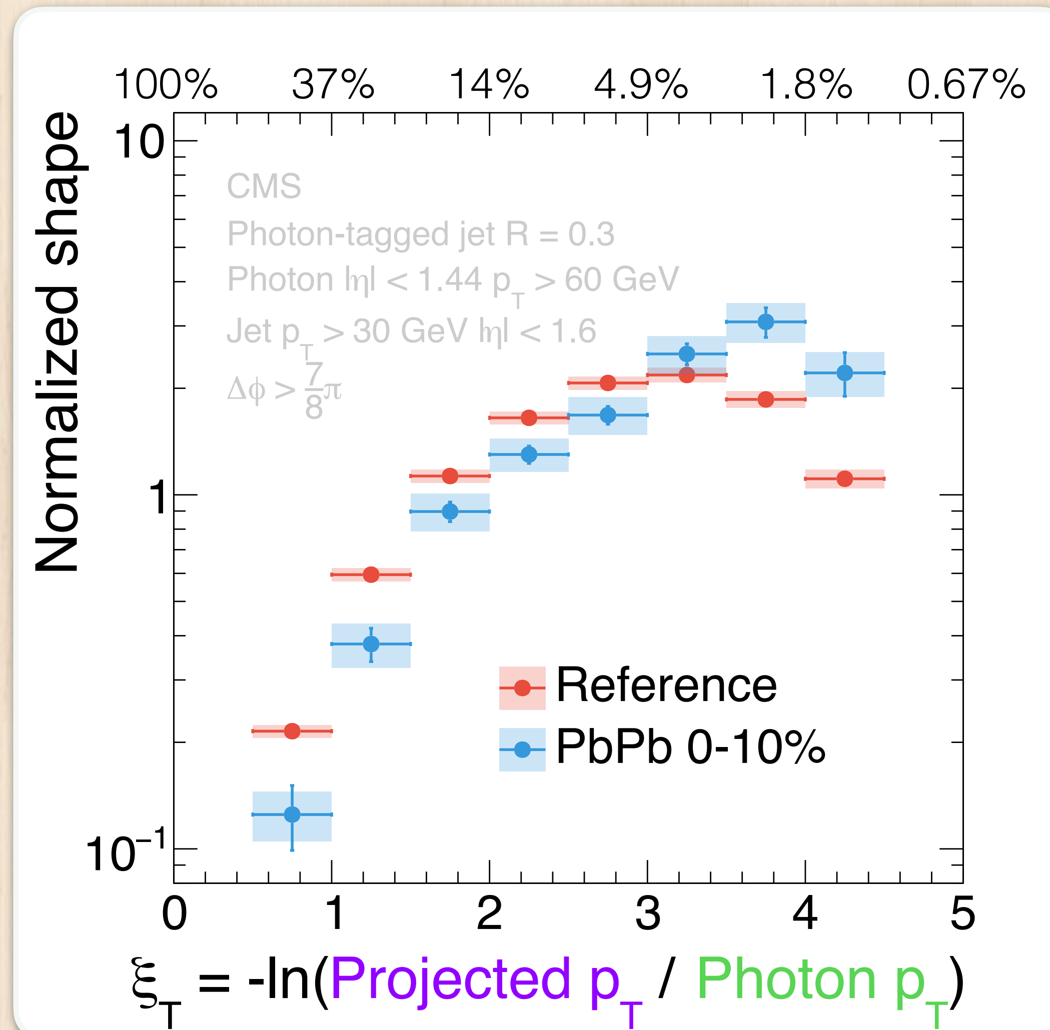



# Particle distribution


Photon $p_T$ ~ initial q/g $p_T$

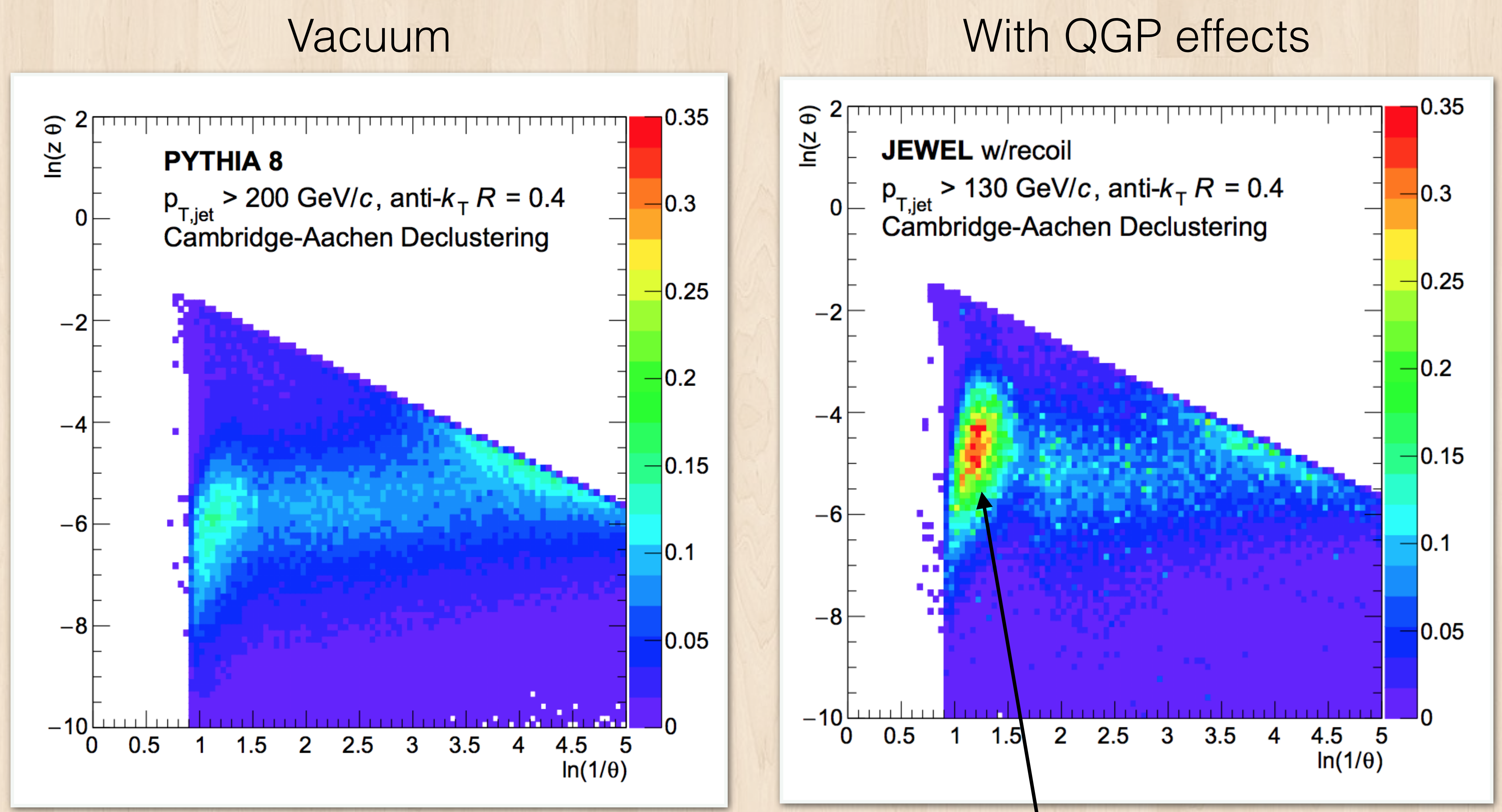



Hard ⟷ Soft




In PbPb we see a lot more soft particles in the jets

# Mapping to (primary) Lund plane




"Hurricane": large angle soft clusters

arXiv:1808.03689

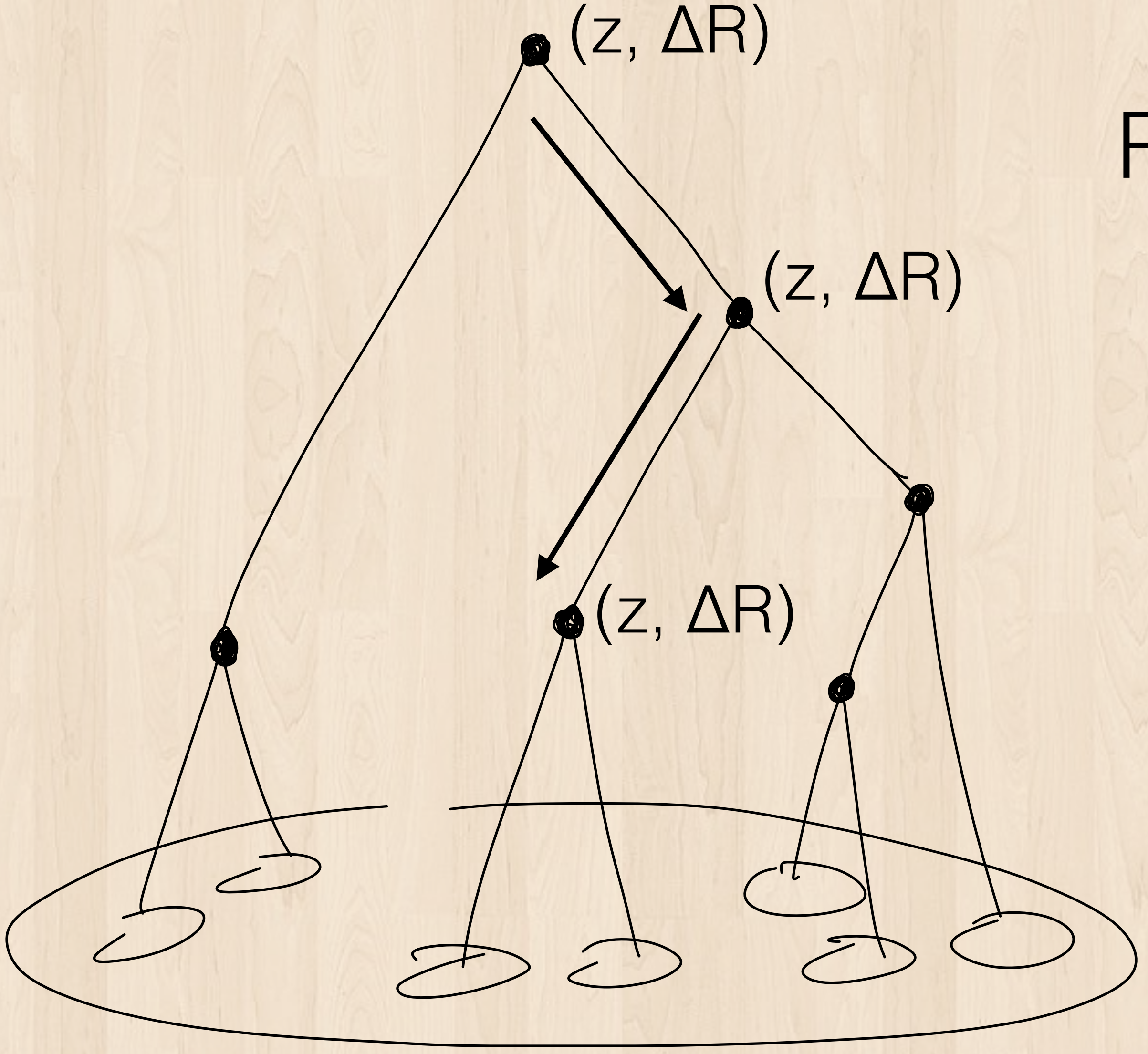
Charge given
by organizers

# (Earlier) measurements by CMS in HI: $z_g$ & $m_g/p_T$

PRL 120, 142302 (2018)
JHEP 10 (2018) 161

Focusing on heavy ion collisions. There are a lot more results in pp

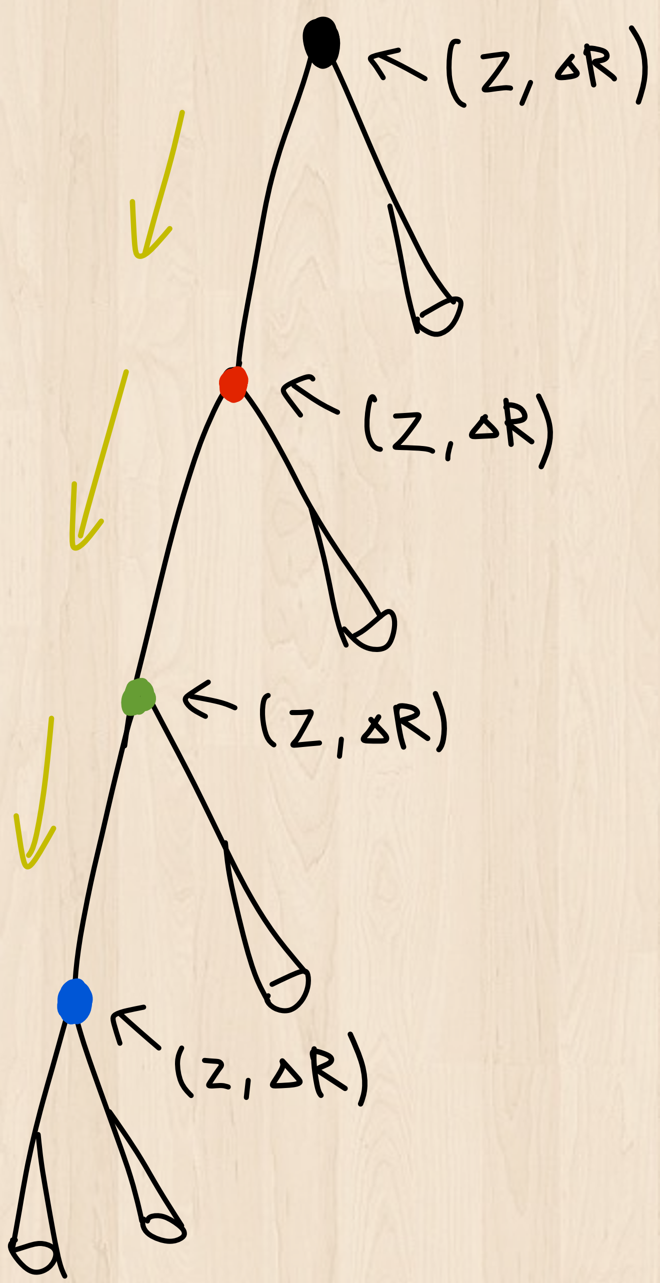
# Recap: Jet declustering



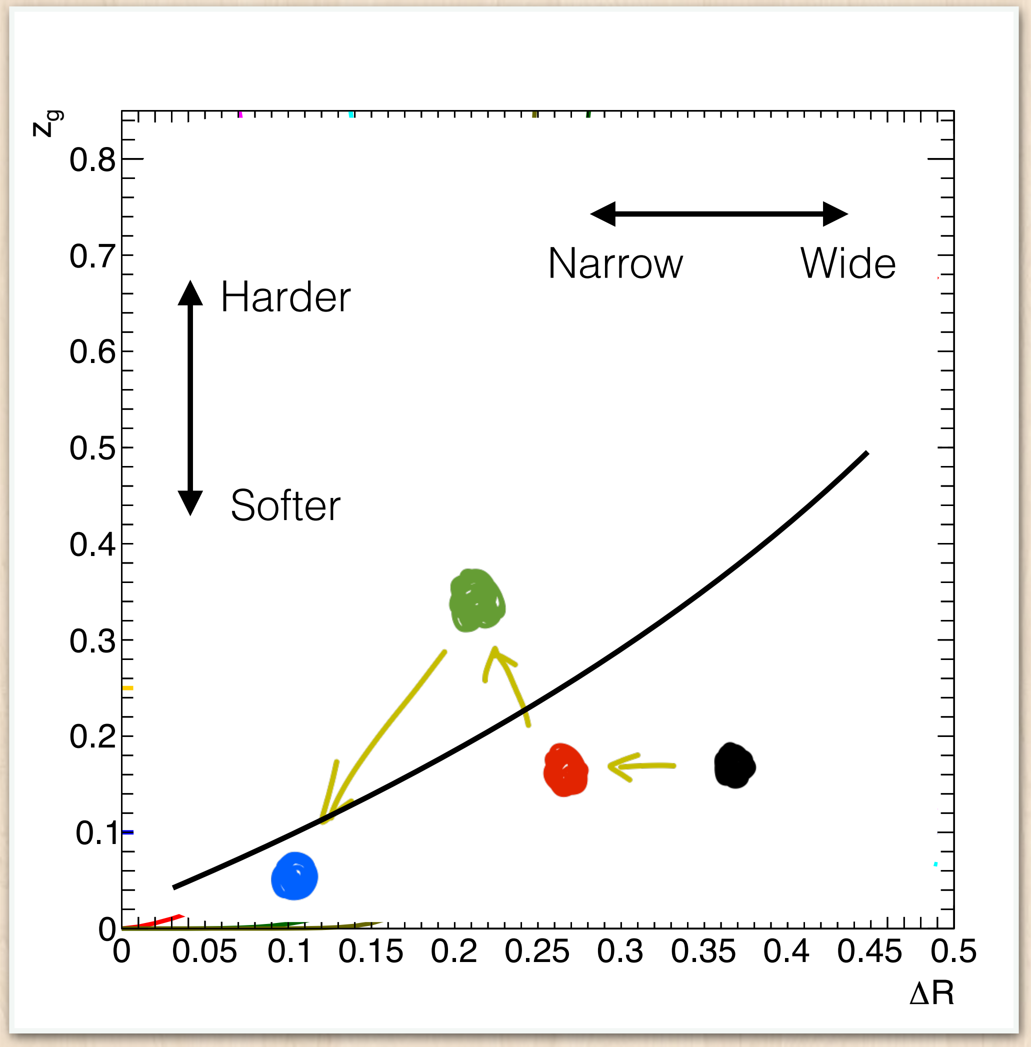

Recluster constituents with recombination algortihms (**C/A**, anti-$k_T$, ...)

We can trace the declustering history and define observables

# Recap: soft drop / mMDT




$$z_g \equiv \frac{p_{T,2}}{p_{T,1} + p_{T,2}} > z_{\text{cut}} \left( \frac{\Delta R}{R_0} \right)^{\beta}$$



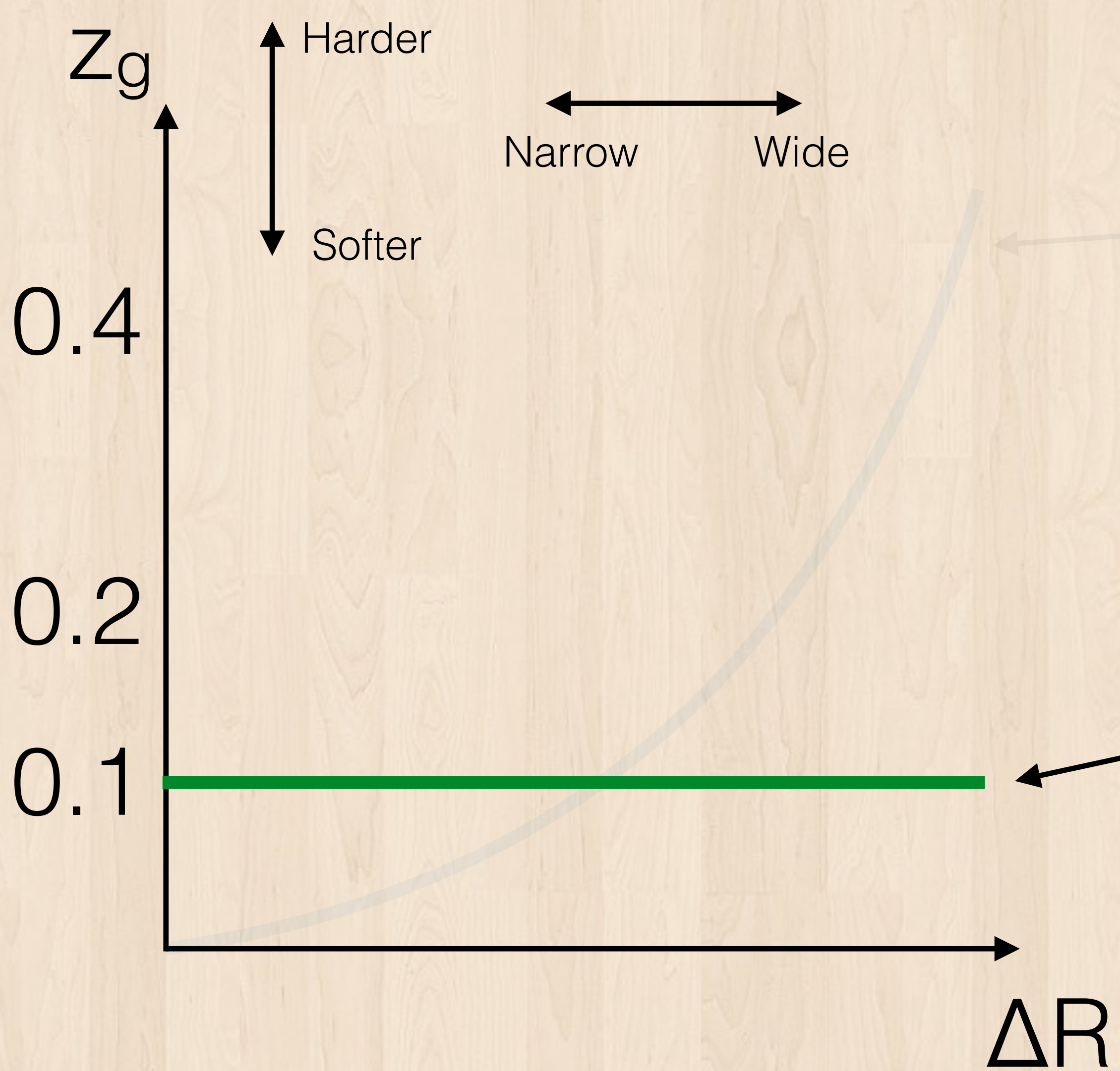

Above line: accepted by grooming

Below line: groomed away

# The grooming setting

$$z_g \equiv \frac{p_{T,2}}{p_{T,1}+p_{T,2}} > z_{\text{cut}} \left(\frac{\Delta R}{R_0}\right)^{\beta}$$

Jet R




$z_{cut} = 0.5$, $\beta = 1.5$

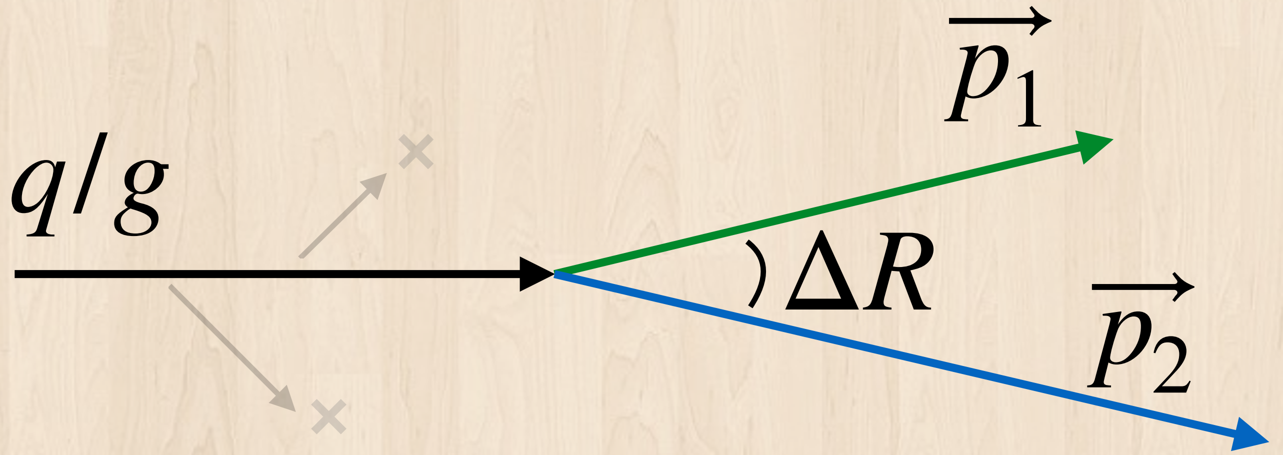
Stronger grooming when subjets are further apart

**$z_{cut} = 0.1$, $\beta = 0$**

Independent of angle

Same overall grooming strength

# $z_g$ and $m_g/p_T$




$$z_g = \frac{\min\left(p_{T,1}, p_{T,2}\right)}{p_{T,1} + p_{T,2}}$$

$$m_g = \sqrt{(E_1 + E_2)^2 - (\overrightarrow{p_1} + \overrightarrow{p_2})^2}$$

Normalize by full jet $p_T$ to reduce dependence on jet spectrum (among other things)

# Analysis in a nutshell

Jets clustered with anti-$k_T$ R = 0.4, particle flow objects, background-subtracted with constituent subtraction

↓

Calibrate back to gen jet $p_T$

↓

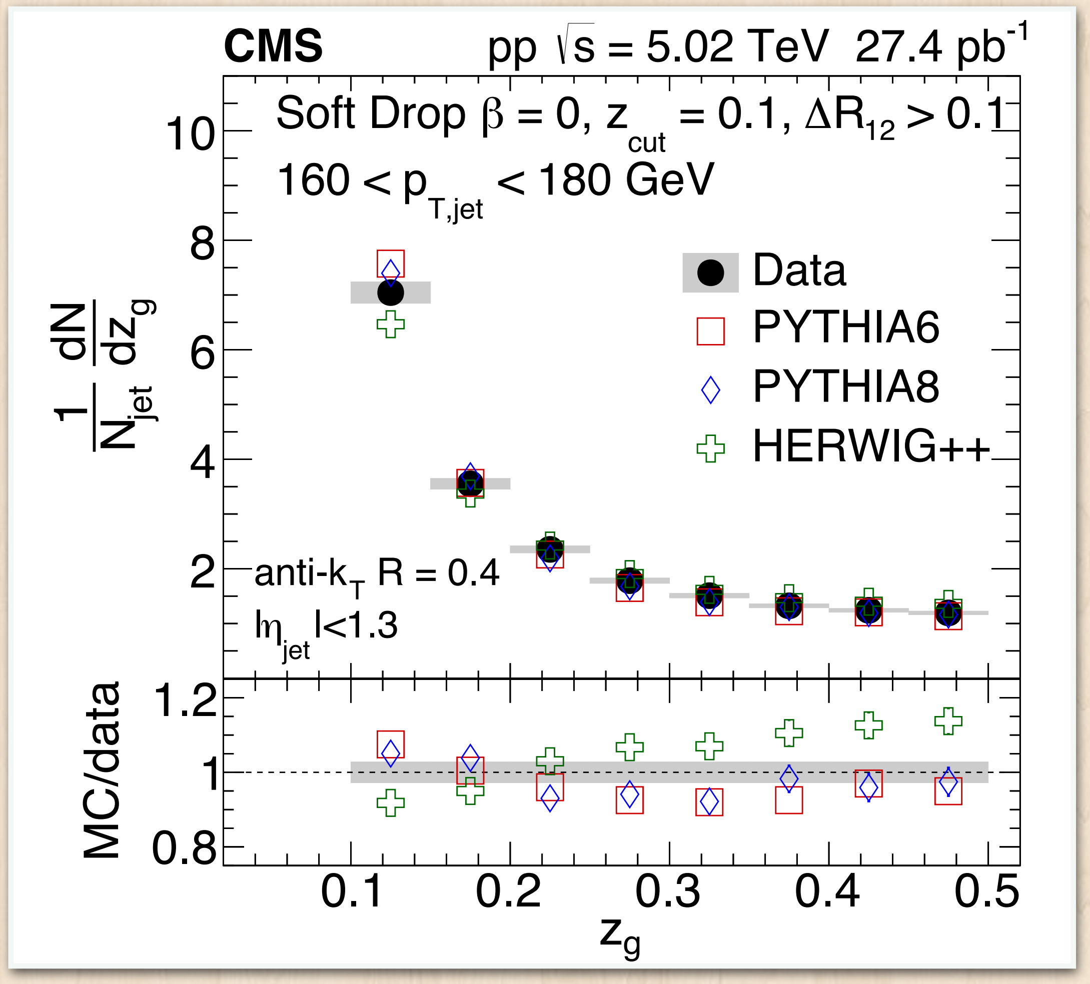
Perform soft drop to identify the splitting of interest

↓

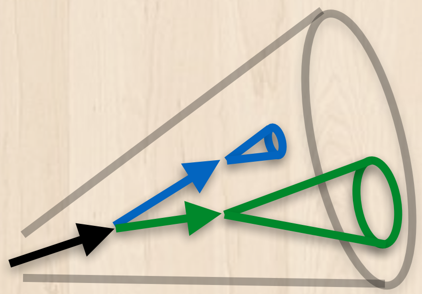
Discard if opening angle $\Delta R < 0.1$
(c.f. CMS hadronic calorimeter cell size 0.087 x 0.087)

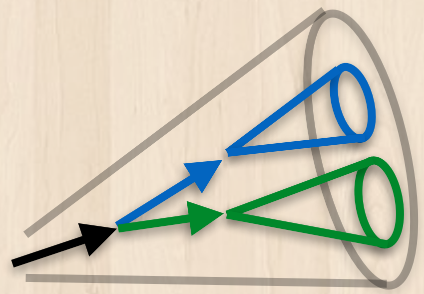
Cuts away low mass region essentially

# Result: pp



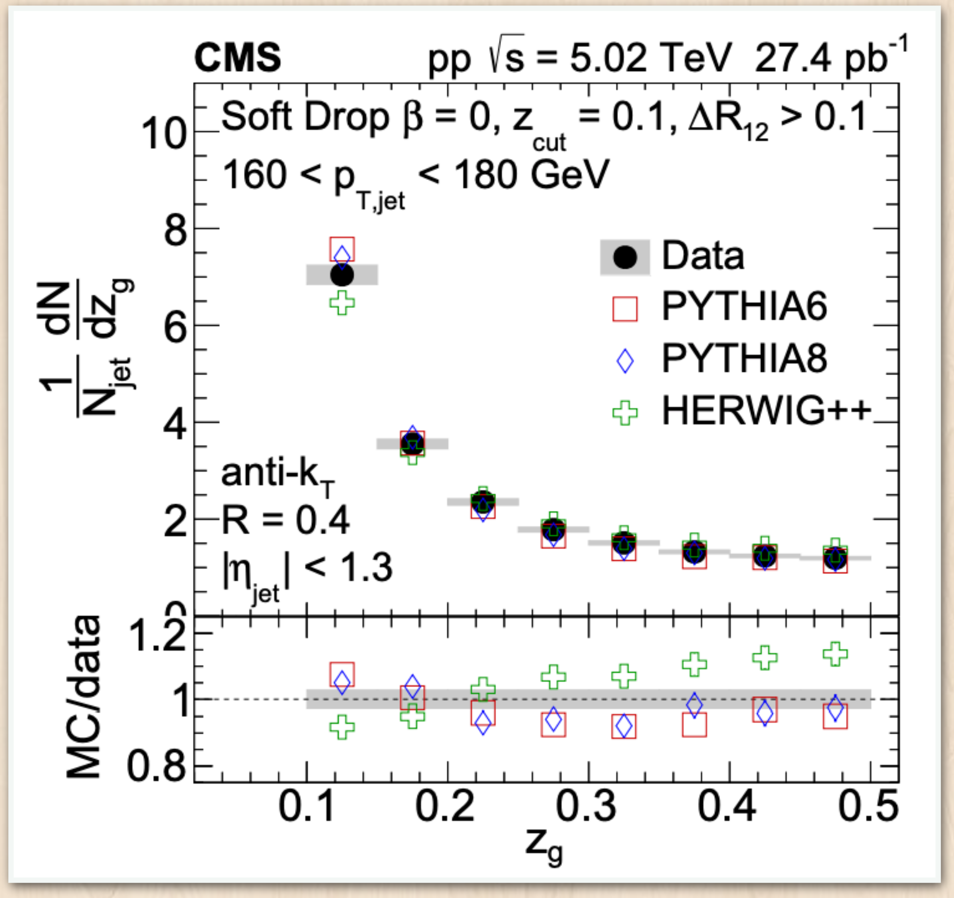

Generally up to 10-20% disagreement by generators

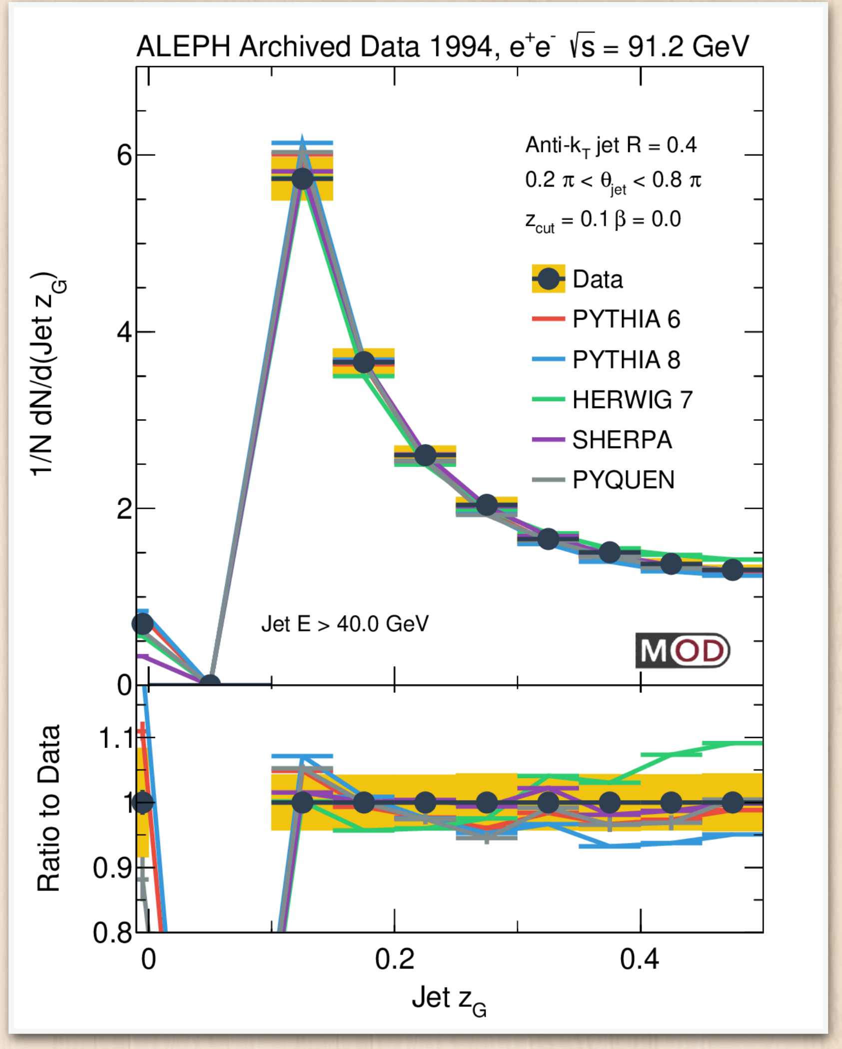




# Comparing to $e^+e^-$

$pp \to \mathrm{jet} + X$




$e^+e^- \to Z \to q\bar{q}$

Similar trend in $e^+e^-$ compared to LHC results

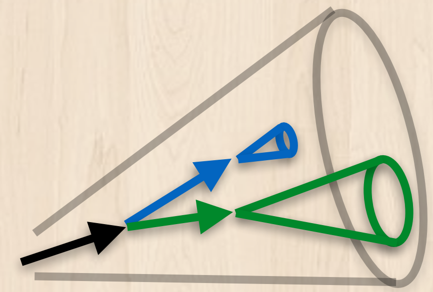
Comparison to **PYTHIA** and **HERWIG** also similar

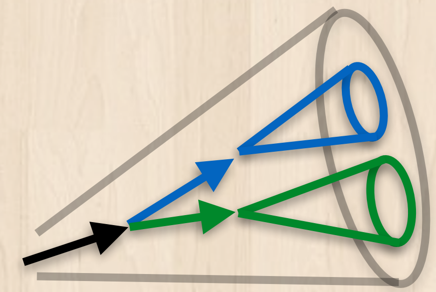
Disagreement in LHC can be improved by $e^+e^-$ input



JHEP 06 (2022) 008

# What we see in PbPb

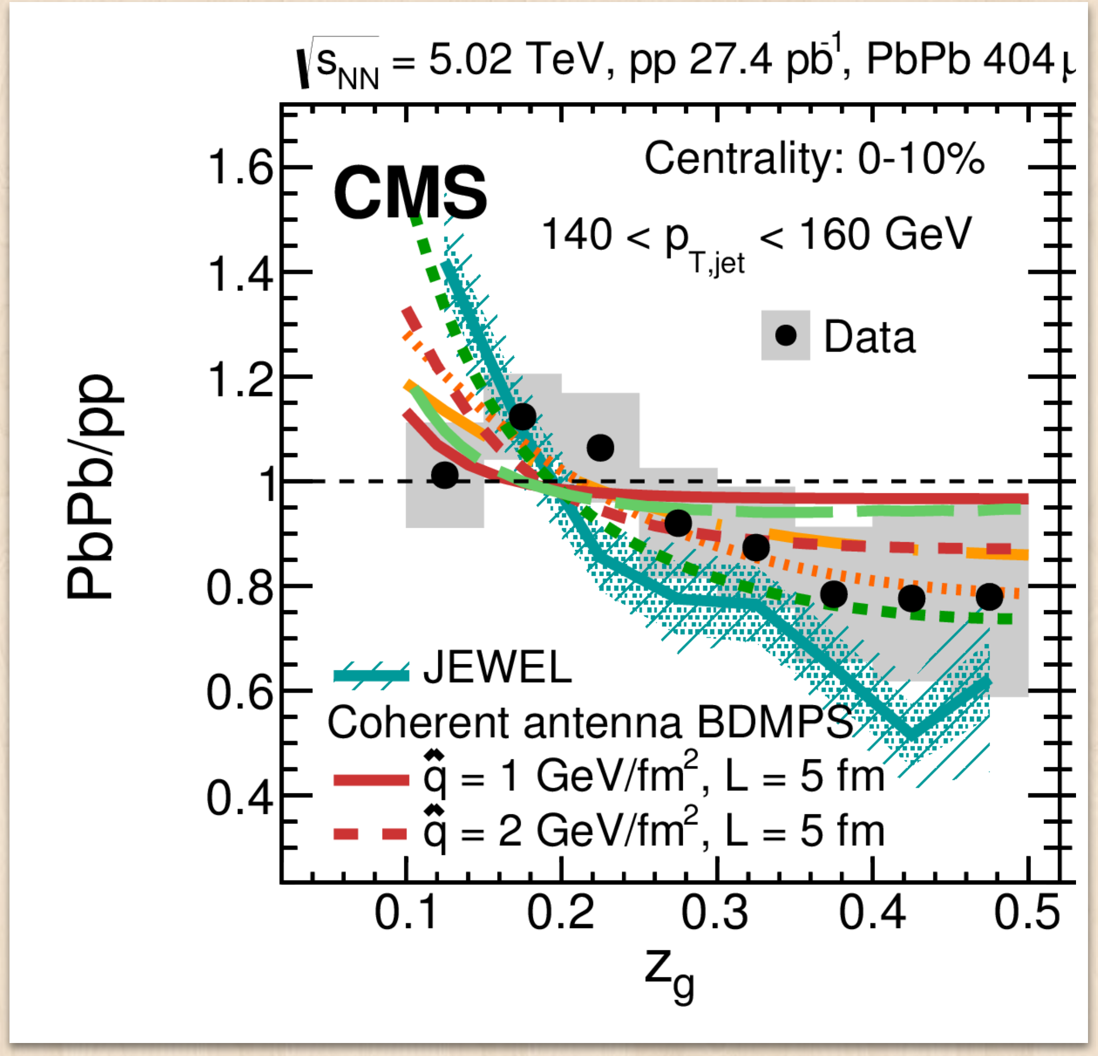




Distribution is steeper in PbPb

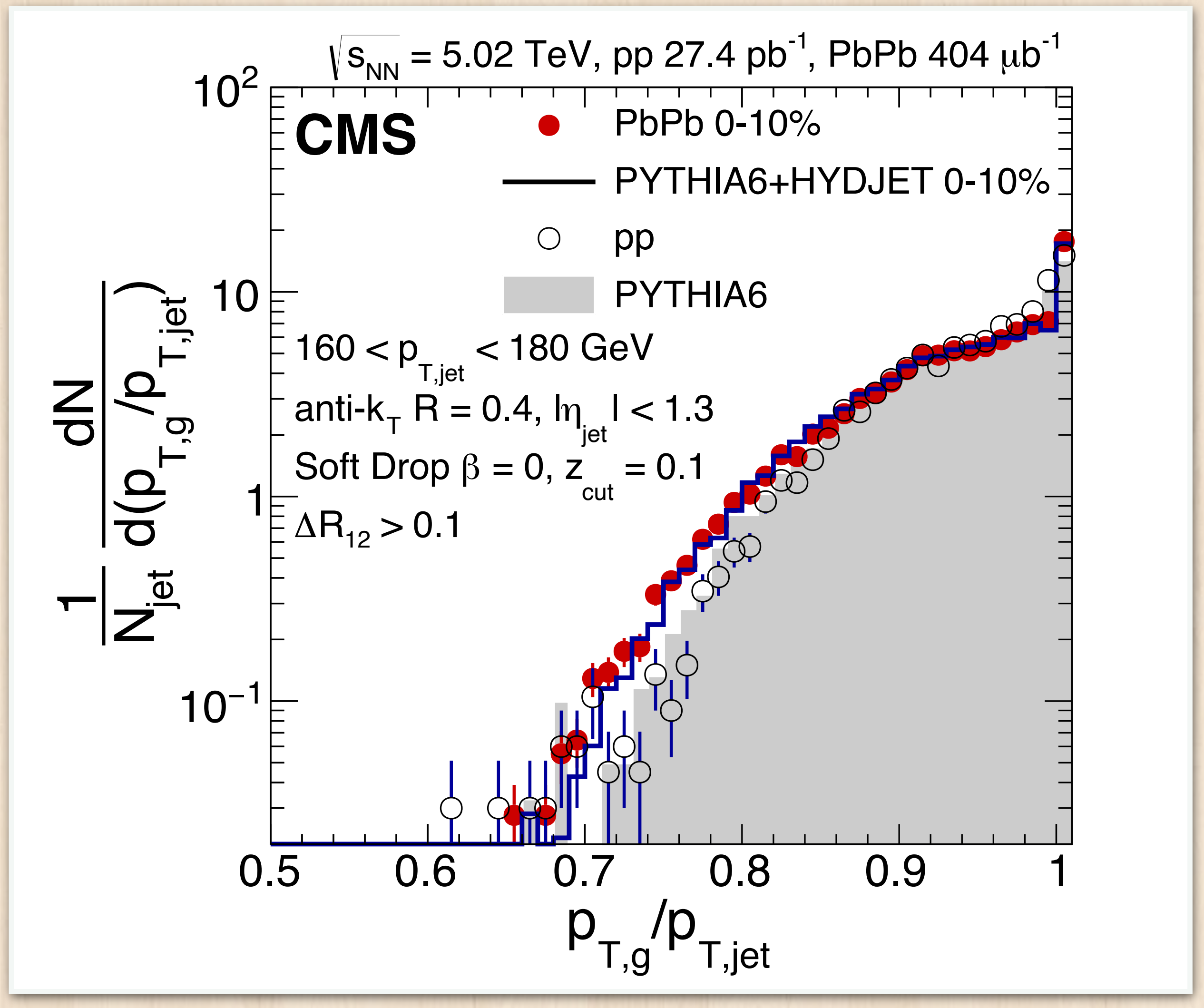
More imbalanced configurations

One possibility: subjet formed from pushed out energy




Qualitatively reproduced by calculations/generators

# Groomed away energy




How much $p_T$ is left after grooming

Larger amount of energy groomed away in PbPb

Mostly reproduced by MC generator

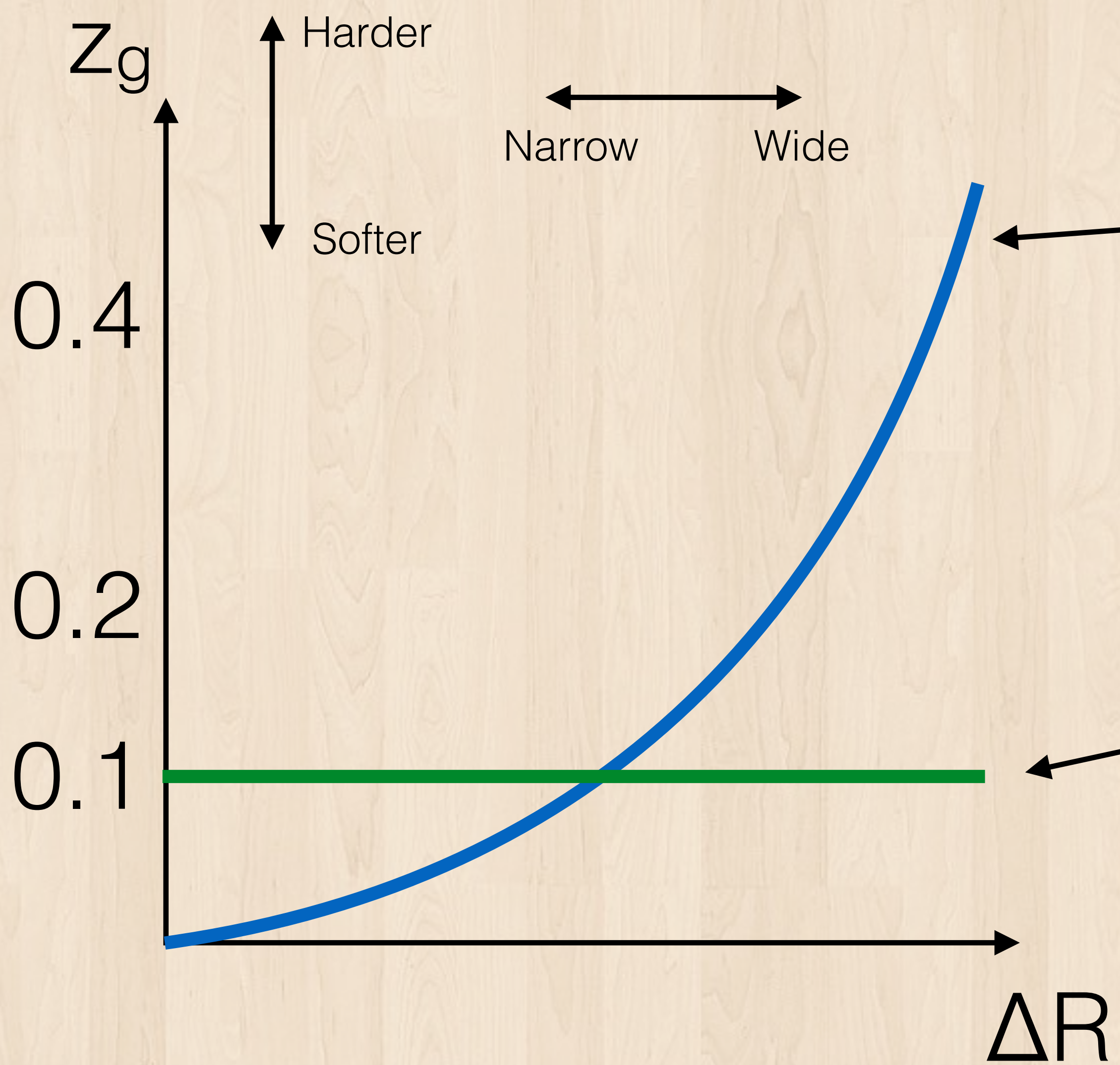
More differential look would be useful

c.f. collinear drop

# The second grooming setting

$$z_g \equiv \frac{p_{T,2}}{p_{T,1} + p_{T,2}} > z_{\text{cut}} \left( \frac{\Delta R}{R_0} \right)^{\beta}$$

Jet R



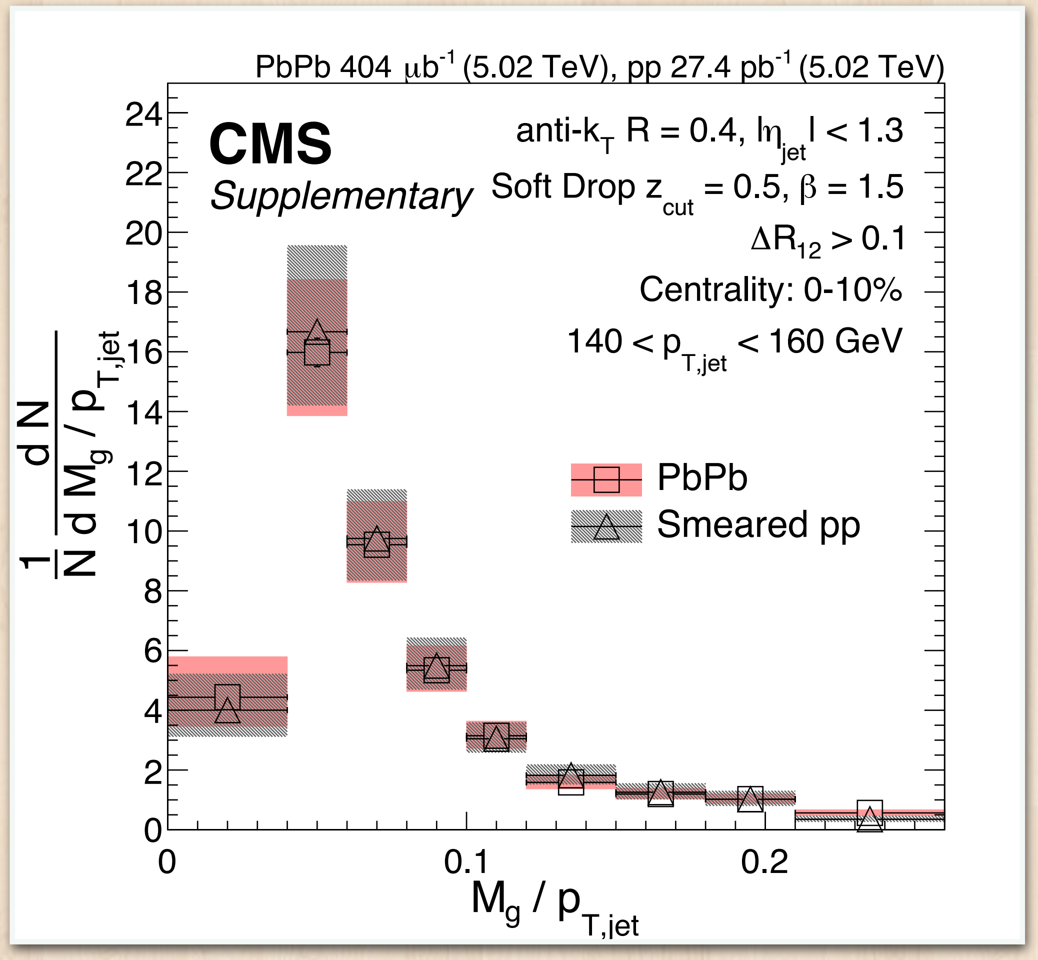

**$z_{cut}$ = 0.5, β = 1.5**

Stronger grooming when subjets are further apart

**$z_{cut}$ = 0.1, β = 0**

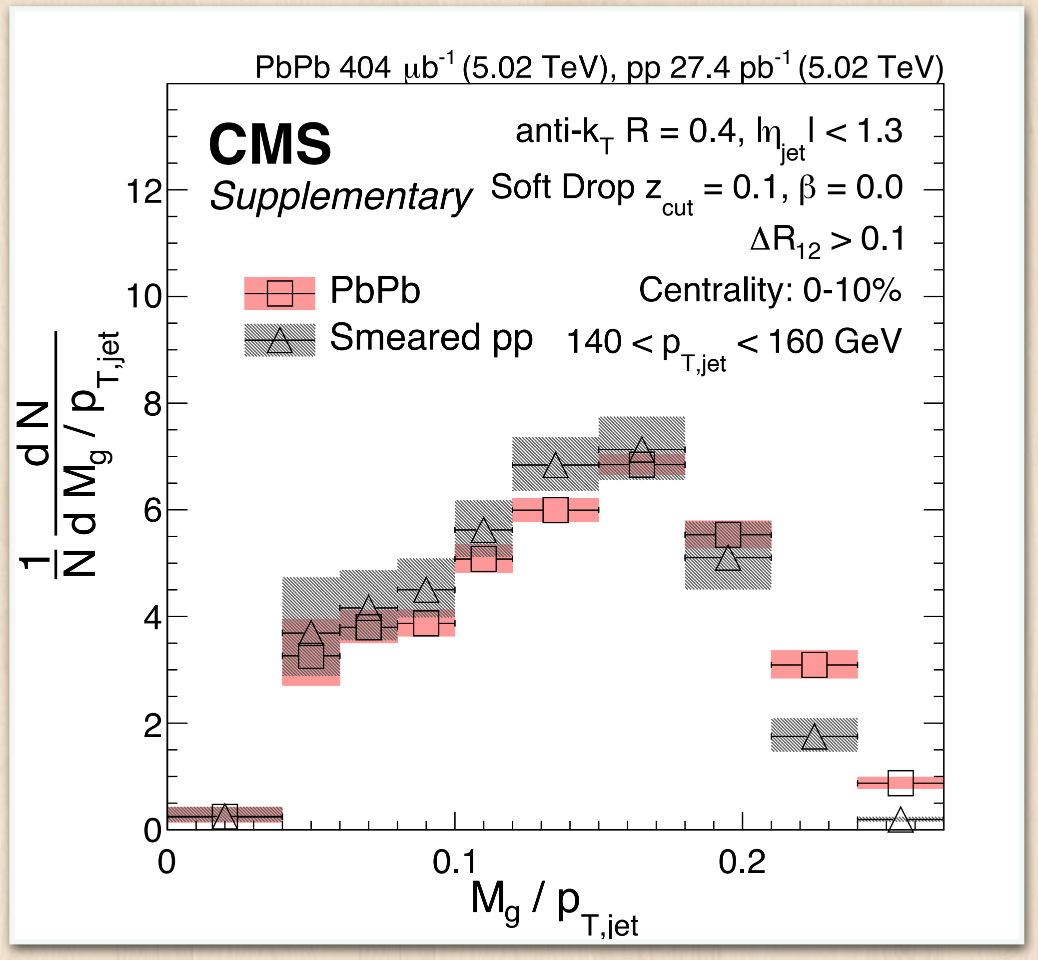
Independent of angle
Same overall grooming strength

# Groomed jet mass




**($z_{cut}$, β) = (0.5, 1.5)**

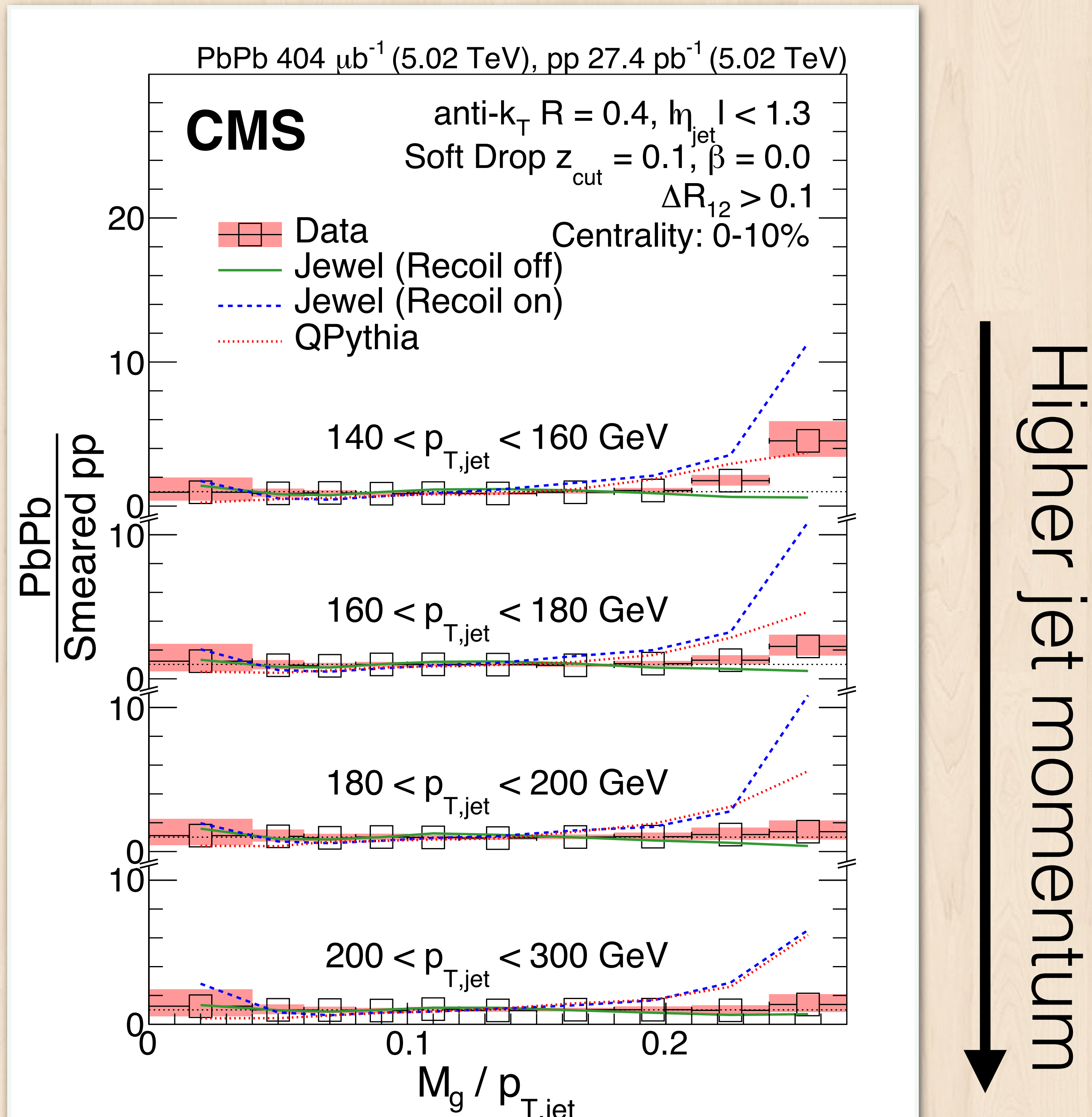
Stronger grooming at large angles
=> nothing




**($z_{cut}$, β) = (0.1, 0.0)**

Flat grooming regardless of angle
=> some hint of larger mass

# As a function of jet $p_T$

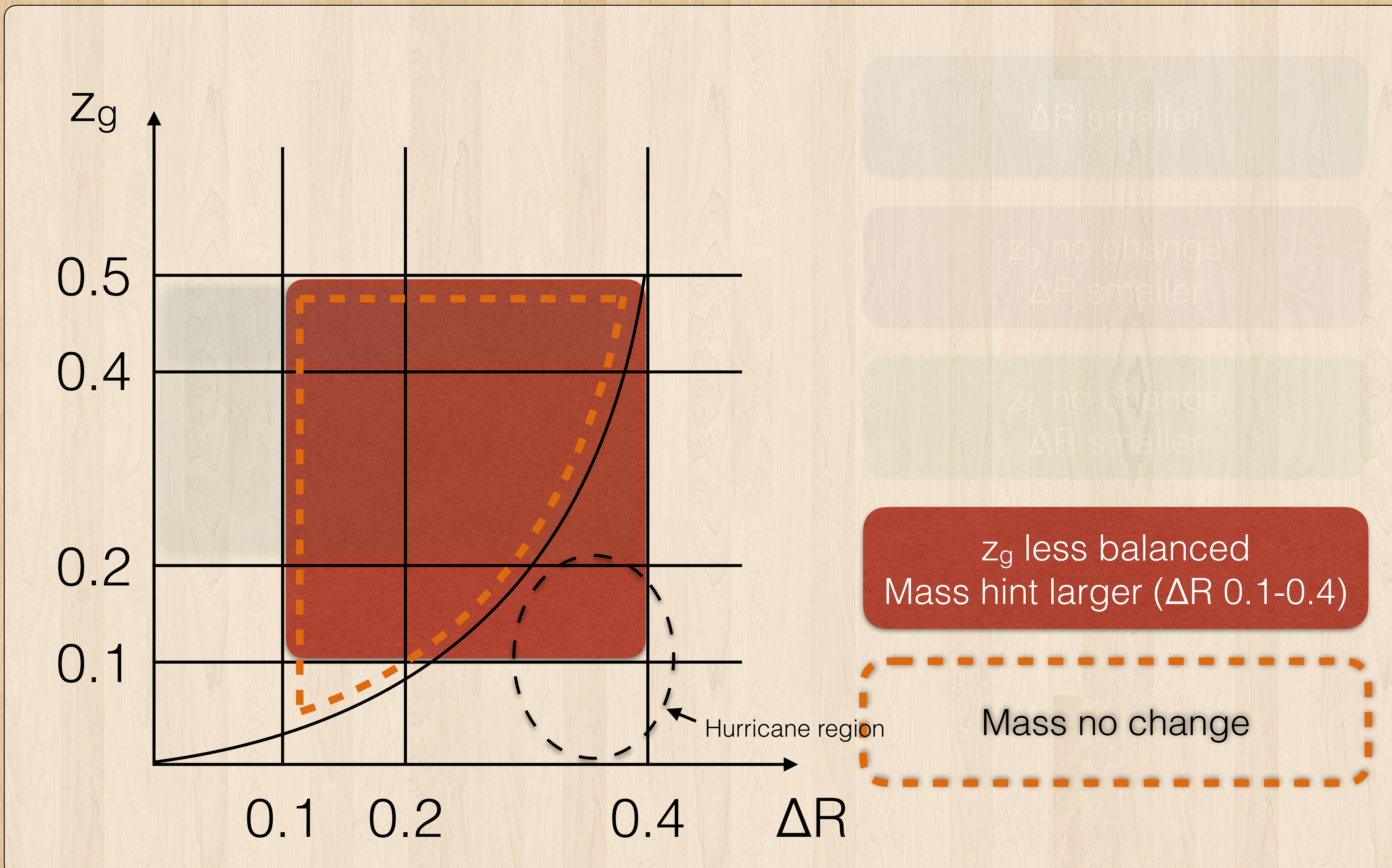



Effect becomes progressively smaller with high $p_T$

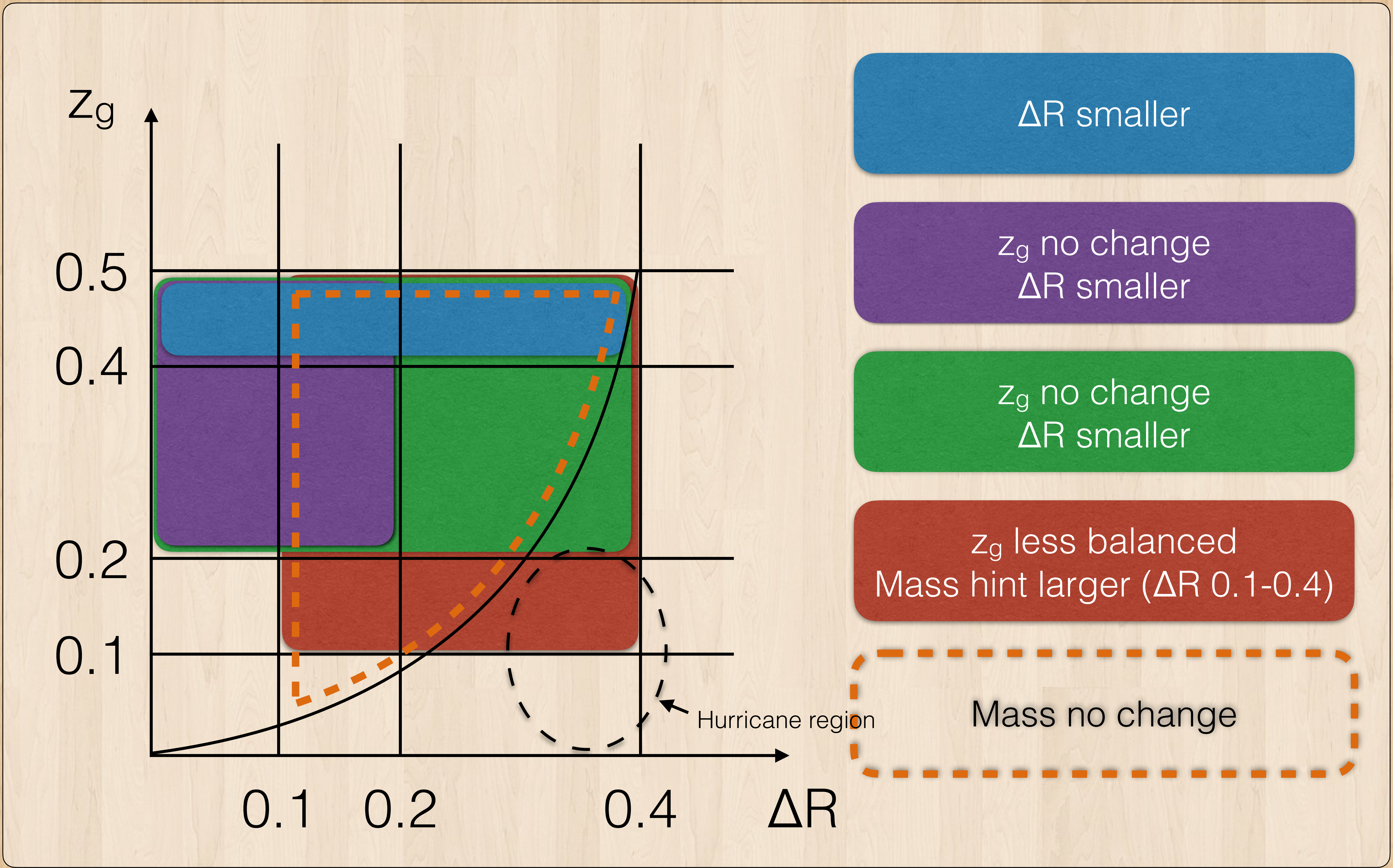
Interplay between QGP scale and jet scale?

# Putting Into Context

# Putting them together

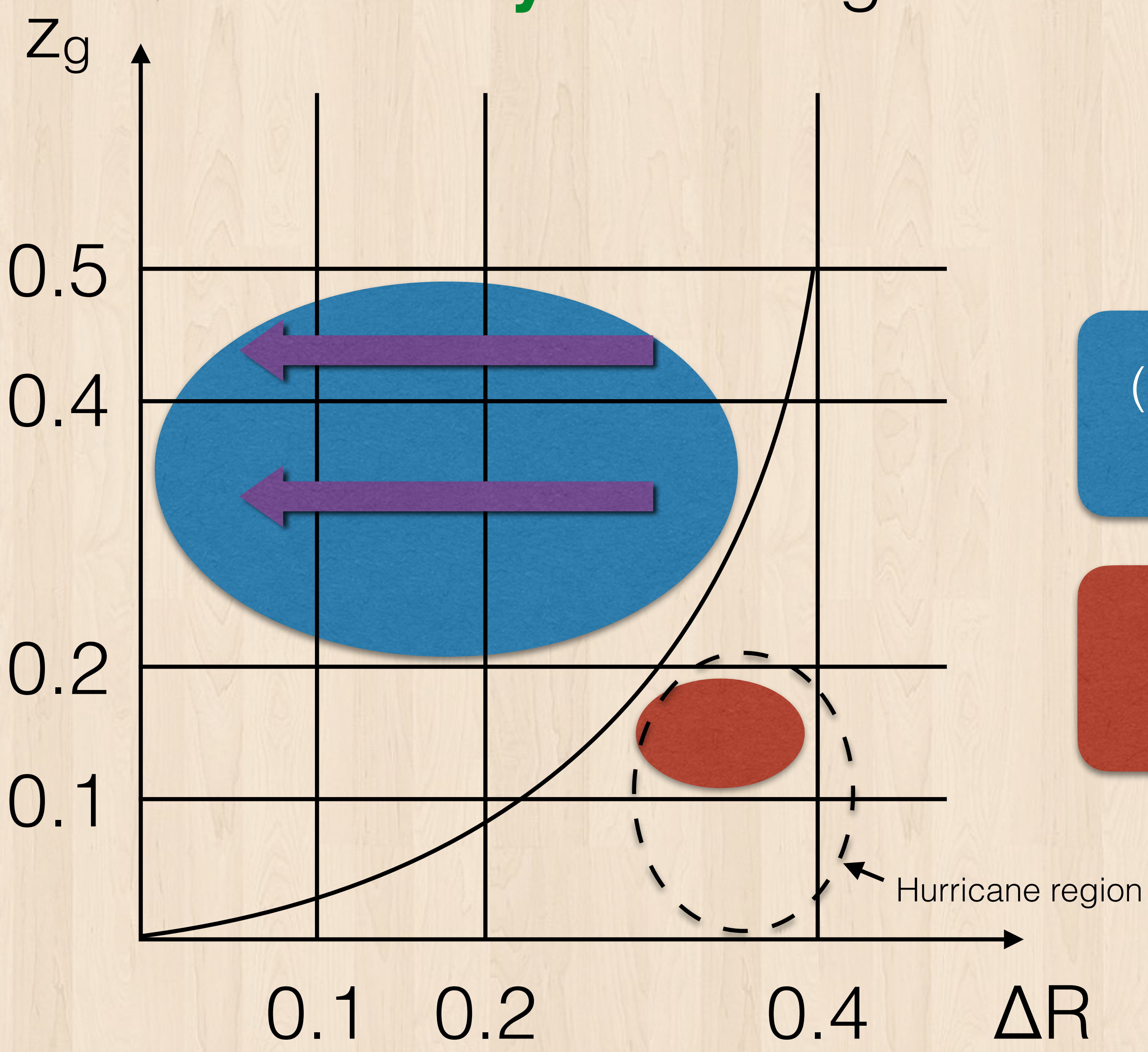


# Adding also other experiments*



# Putting them together

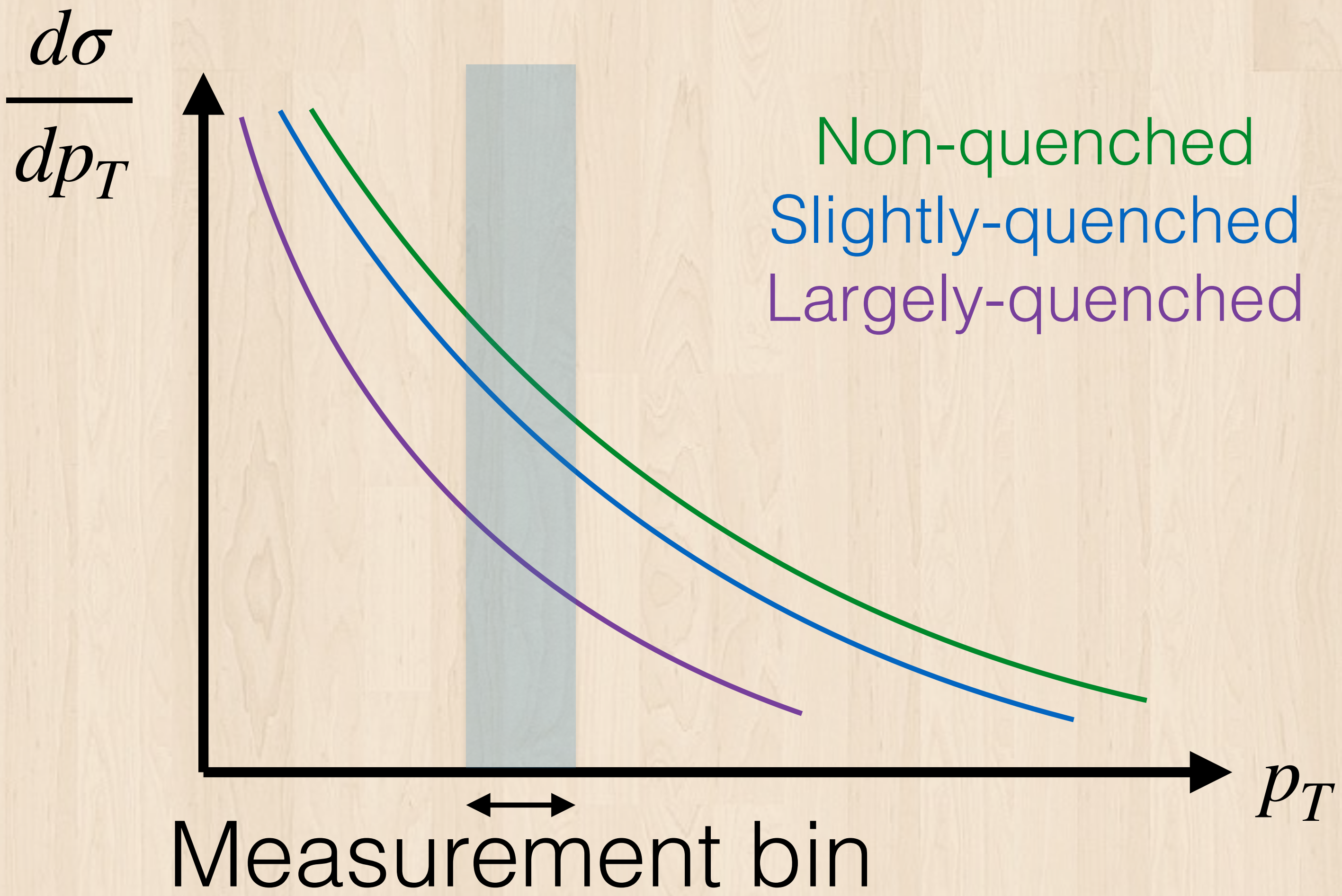
**Qualitatively** some regions stand out (from 1D)




(Inclusive) jets seem to be more collimated

Large angle soft stuff
=> $z_g$, mass

# Selection bias in jets

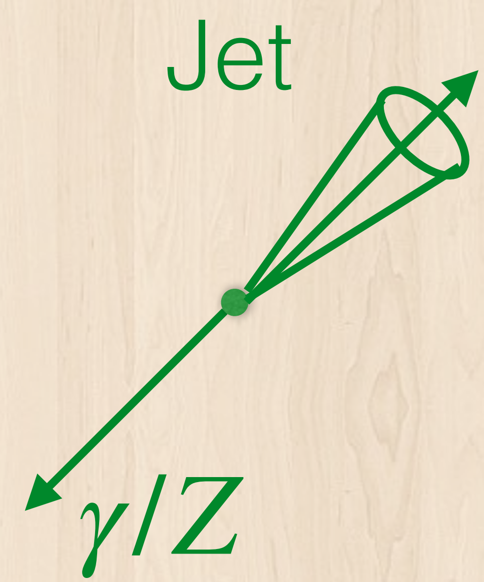



Jet measurements always mix different quenchiness

Makes interpretation less straightforward!

# Reducing bias: one possibility


Inclusive jets
Need high enough energy cut for many reasons (triggers, etc)




Tagged jet — allows a tag of initial energy, and also lower jet energy cut

# Concluding Remarks

# Concluding remarks

- Lund-plane-based observables are powerful tools to look inside jets in heavy-ion environment
- Isolate interesting regions of phase space for further studies
- Good synergy comparing different collision systems
- Important to gain a handle on selection bias effects for a fuller picture

# Backup Slides Ahead