# Jet Substructure

## Results in LHC HI experiments

ATHIC2018

Nov. 6 2018

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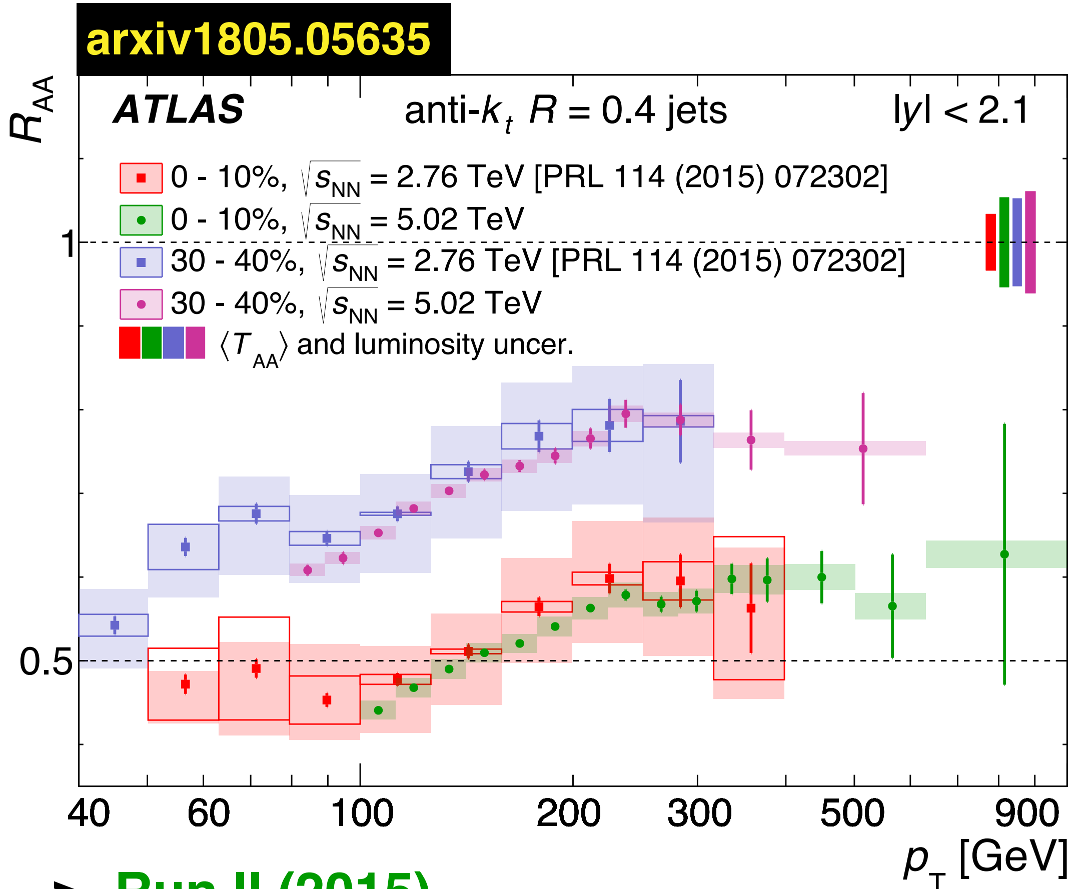
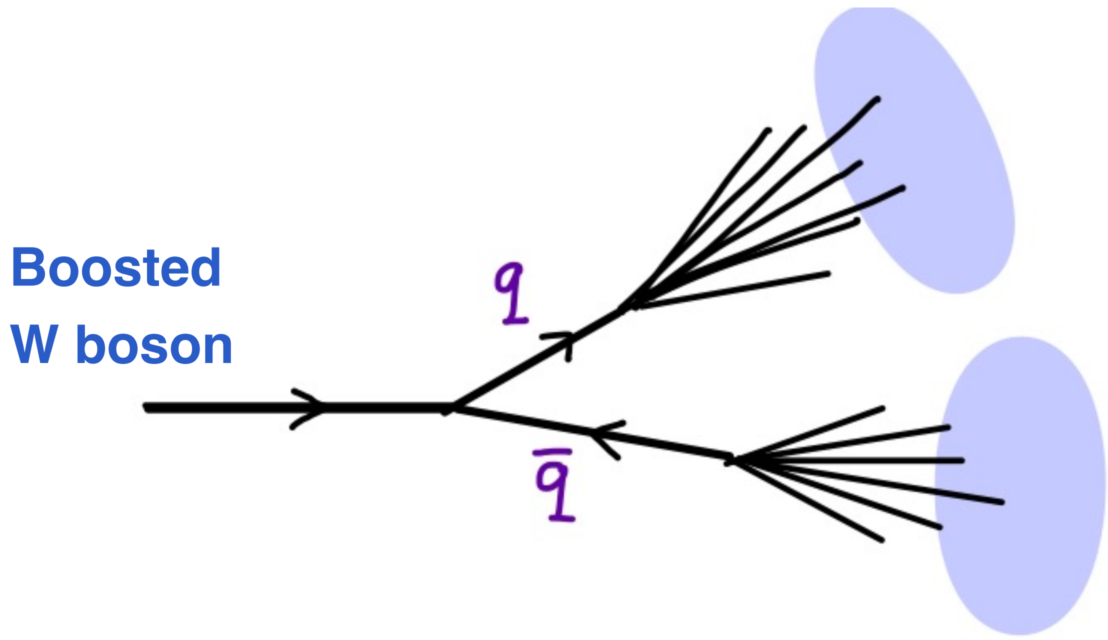
# Evolution of jet results




- **Run I (2011) —> Run II (2015)**
  - Huge improvement in analysis techniques and understanding in detector
  - Statistics of jets increased by factor of O(5)
  - Systematic uncertainties are reduced to 3% level 100 < $p_T$ < 500 GeV/c
  - **Ready to measure something delicate beyond jet energy loss**

# Meanwhile in pp community in early 2010s




Smaller resolution parameter clusters two jets

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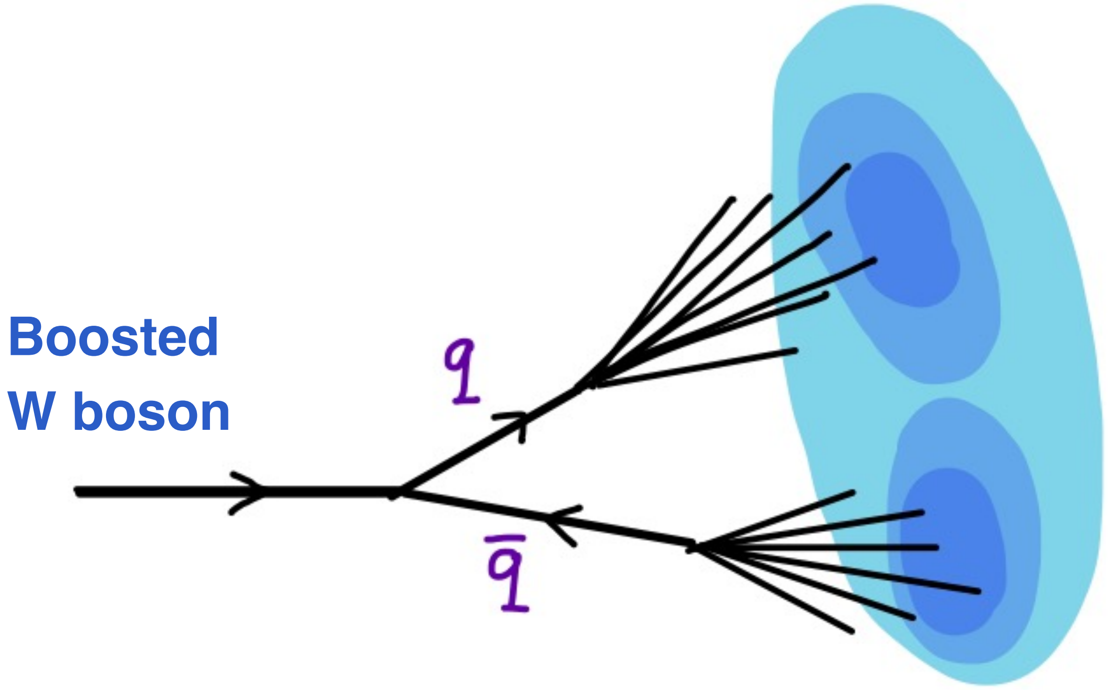



Larger R

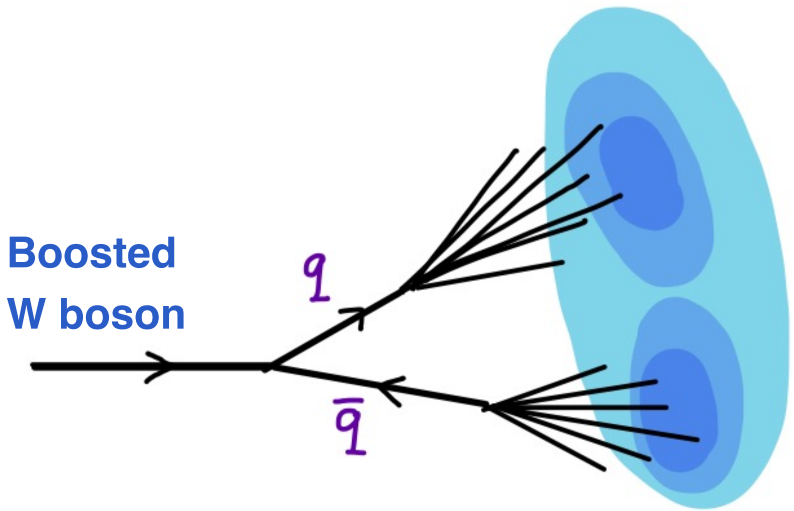
==> **Fat jet** composed of two sub-jets.

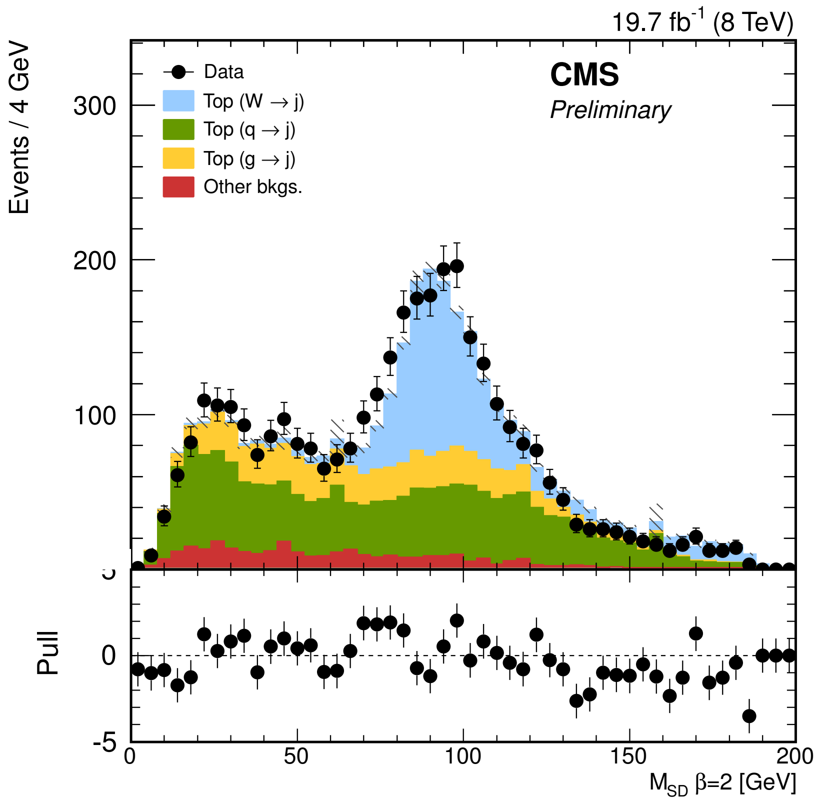
But, the challenge is the high contamination of UE.

==> Need to cut off uncorrelated particles

==> **Jet grooming**

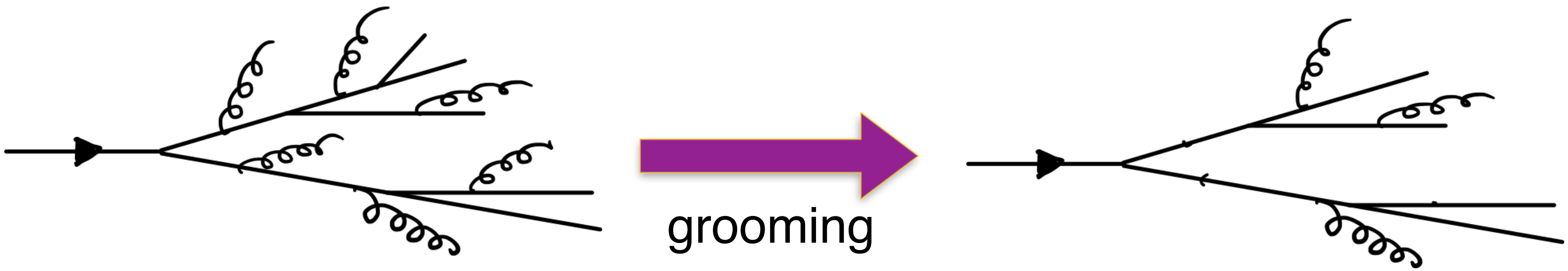
# Meanwhile in pp community in early 2010s

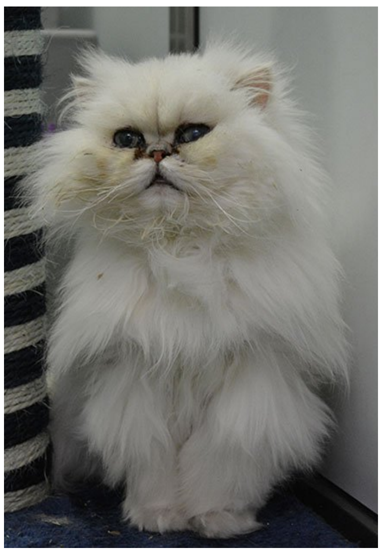



- Development in jet grooming techniques to identify boosted massive particles
  - W/Z jets to enhance the reconstruction of Higgs and BSM particles
  - Typically re-cluster the jet's constituents and cut off soft parts of jet
  - Substructure study necessitates jet grooming techniques

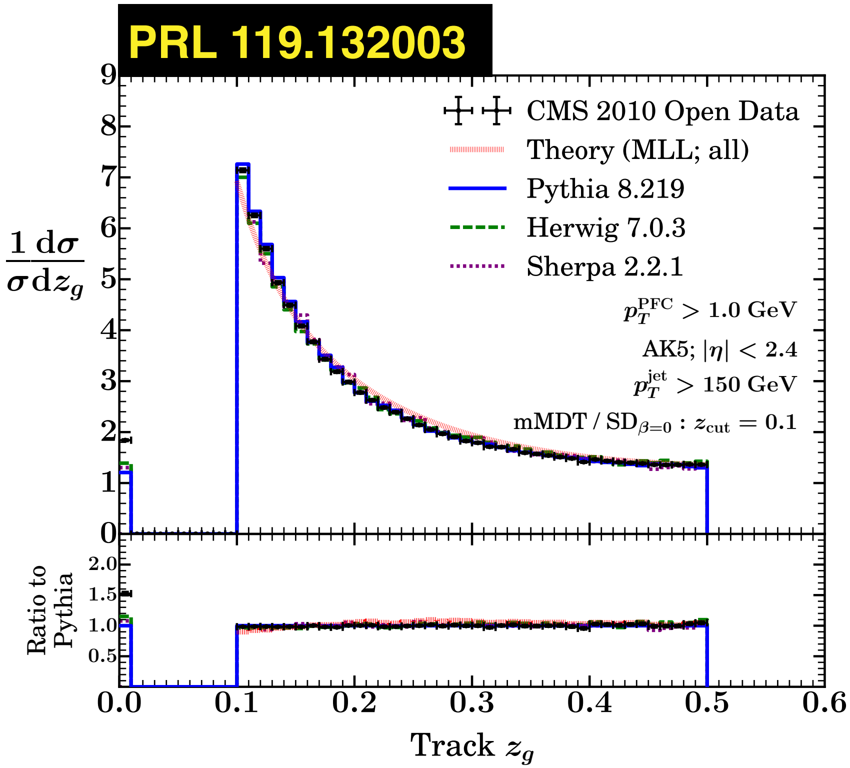
# Jet Grooming is useful for QCD study as well



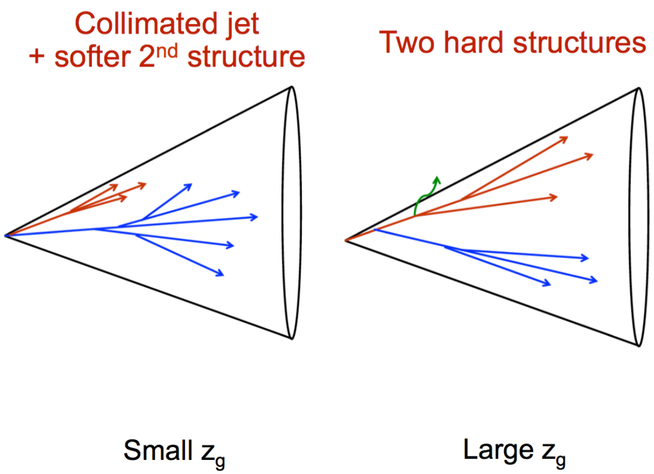



- Jet grooming removes soft divergences, thus converges the experimental result to analytic calculations (e.g. NLLO)
- Many algorithms in market : SoftDrop, Trimming, SoftKill
- Powerful to remove **UE** and **pileup** backgrounds in pp data

# Distribution of SoftDrop $z_g$ in pp data

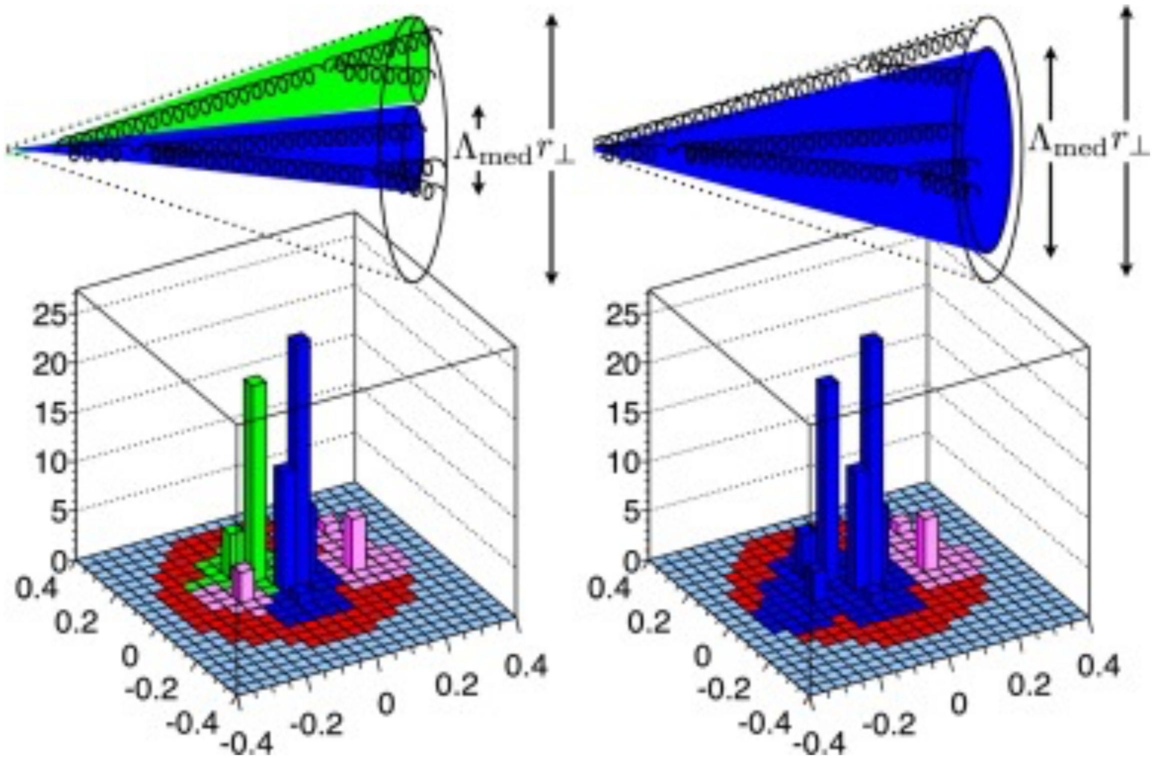



QCD Splitting Function using CMS Open Data




- SoftDrop: Best selling jet algorithm in HI society
  - Larkoski et al (2014)
  - Ends up with two sub-jets which corresponds to the earliest splitting of parton
  - Very robust to several kind of underlying events (Pythia, Herwig, Sherpa, …)

# Why is it interring for heavy ion experiment?

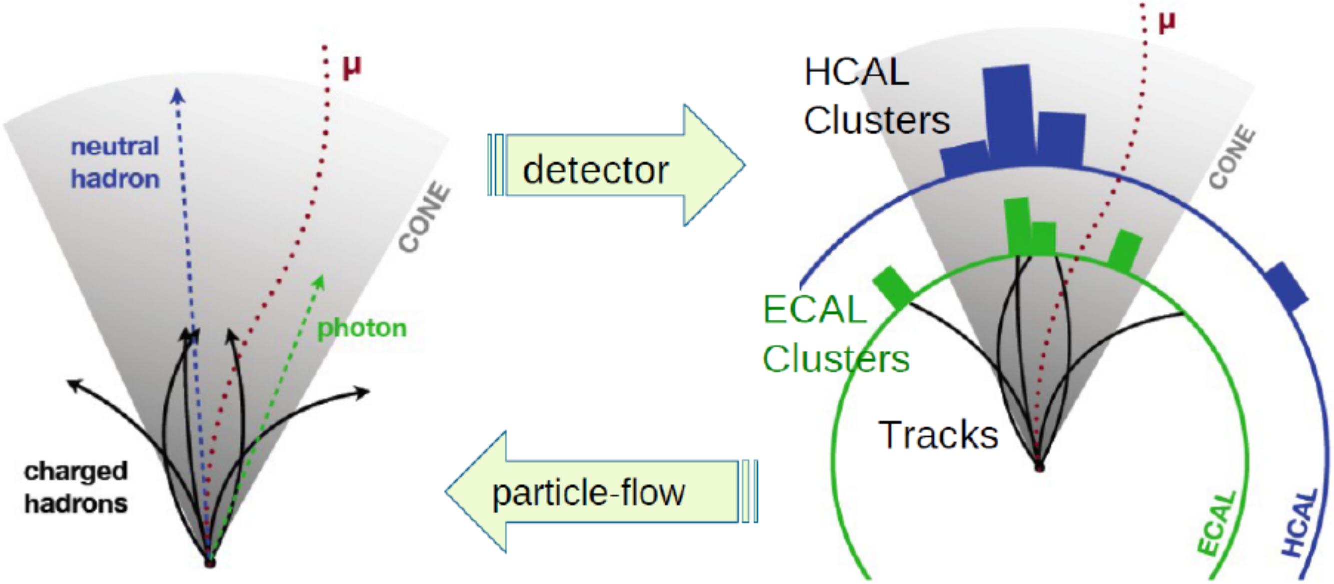



PLB 725 (2013), 357
Casalderre-Solana et al.

- In the *antenna radiation picture*, the resolution scale of gluon emitter is determined by the medium properties
- If medium can resolve splitting of sub-jets, the medium-induced radiation comes from two emitters
  - Expect suppression of jet yield to depend on the splitting pattern

# Challenge in heavy ion experiment

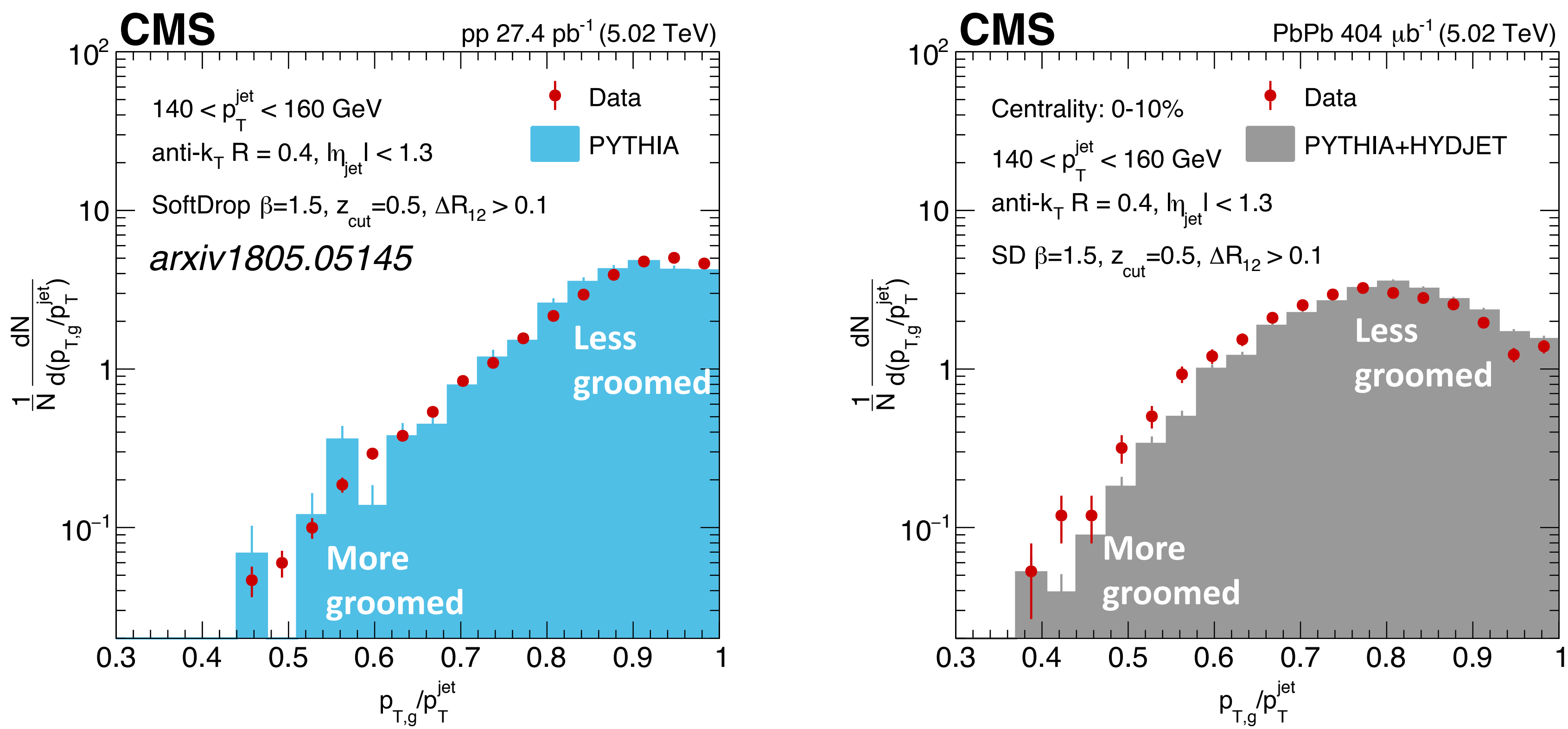
- Large UE background
  - Should subtract up to 150 GeV for a R=0.4 cone
  - Particle-level subtraction is necessary instead of cone-integrated one
  - **Constituent subtraction** algorithm can solve this problem
- Reclustering in Softdrop requires high spatial resolution of constituents
  - ParticleFlow (CMS)
  - Tracks (ALICE)




ParticleFlow algorithm in CMS

# SoftDrop performance in CMS framework

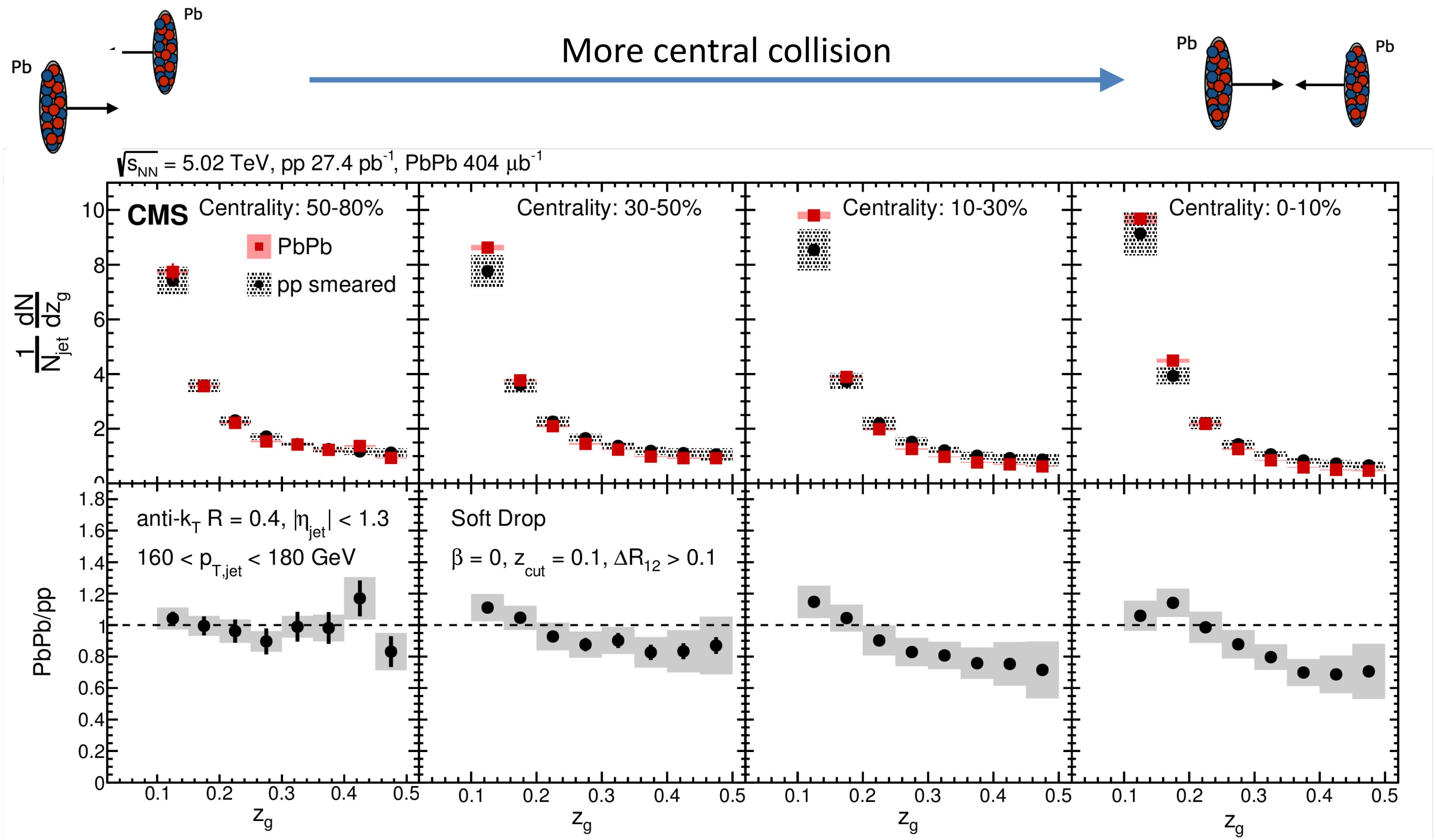
Distribution of $z_g$ in MC and data




**pp data vs MC** | **PbPb data vs MC**

- For PbPb case, the peak is shifted and smeared by resolution, but the simulation reproduces the data well

# Jet splitting function in PbPb vs pp (CMS)




The subjet pairs became more **imbalanced** in central PbPb collisions.
Does QGP give evert suppression depending on the splitting pattern?

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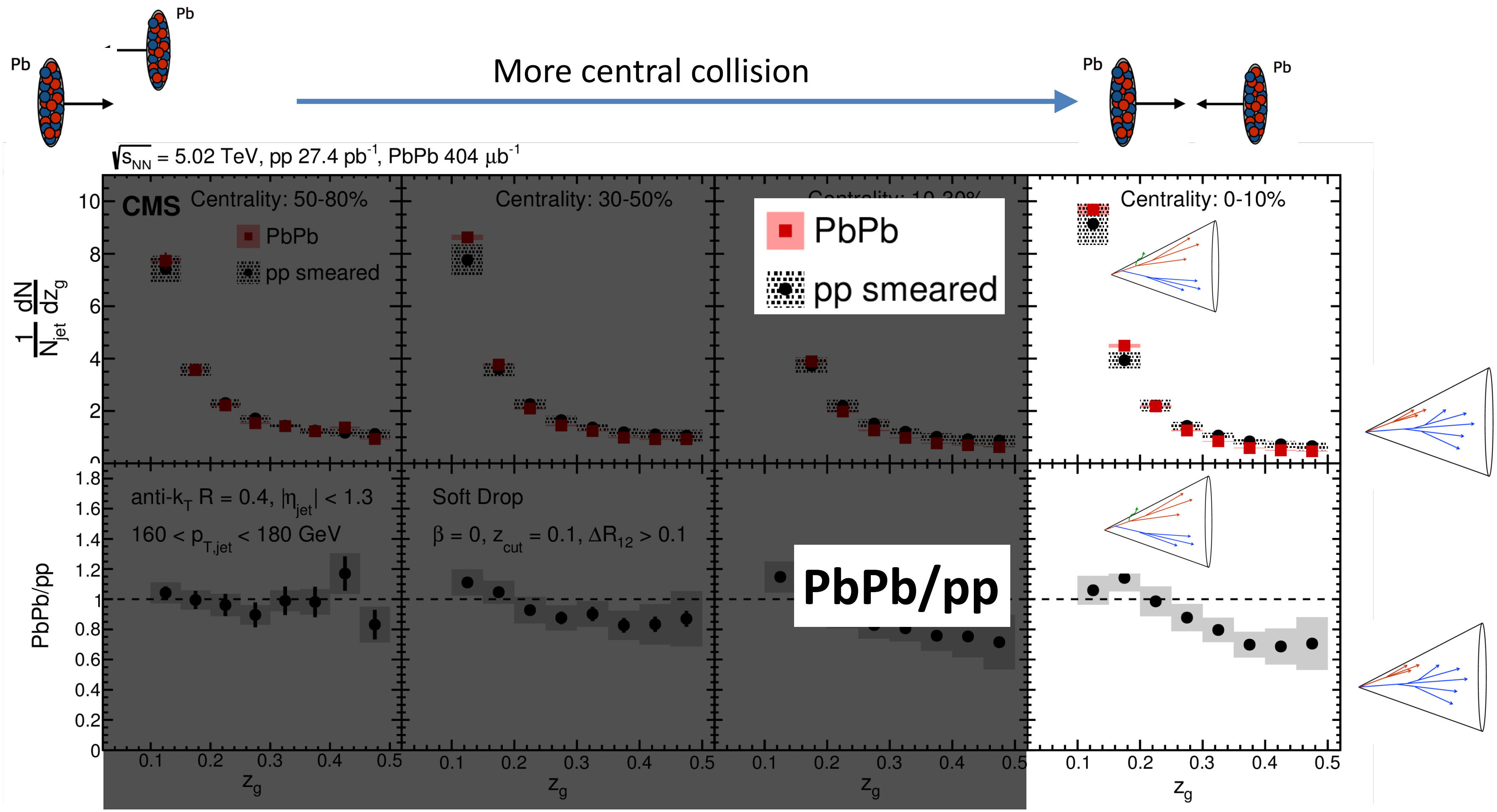


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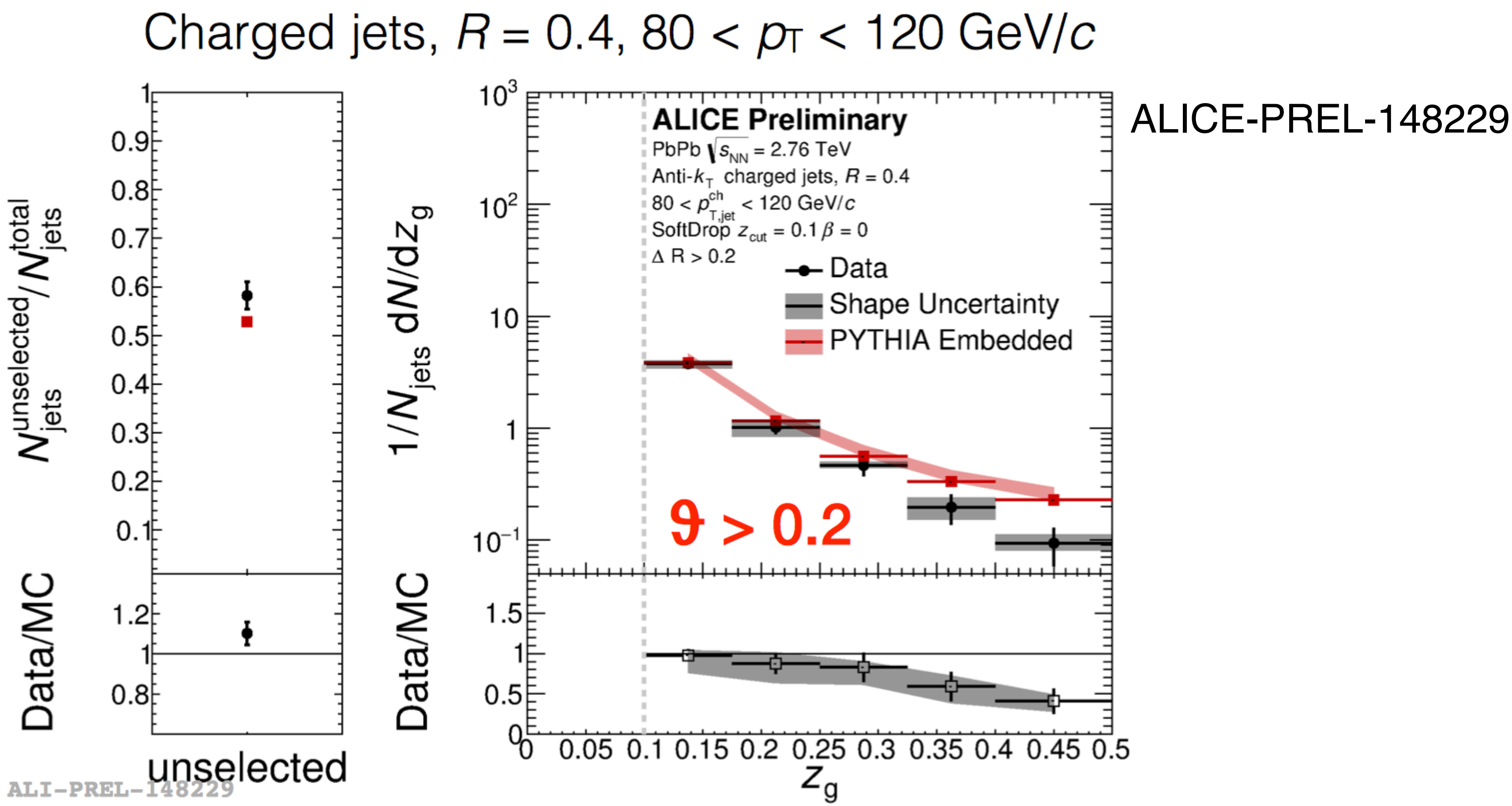
Does QGP give evert suppression depending on the splitting pattern?

# Same measurement in ALICE




- Measured charged jets at 2.76 TeV and compared with PYTHIA reference
- Qualitatively same conclusion with CMS

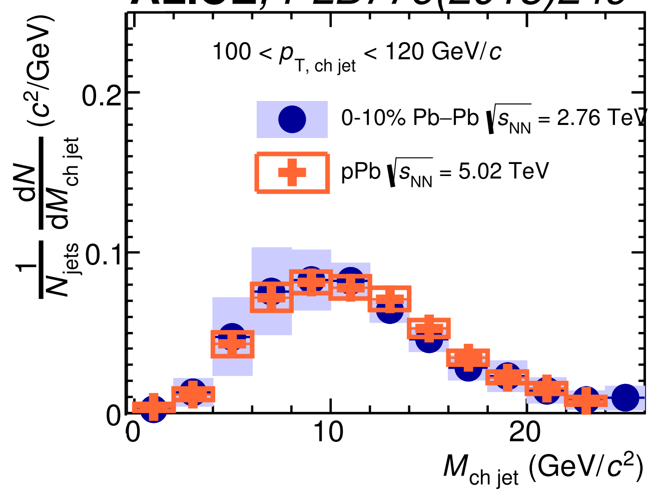
# Measurement of jet mass

- Jet mass was measured by ALICE (2.76 TeV) and CMS (5.02 TeV) in per-jet normalization —> Focus on the modification on jet shape

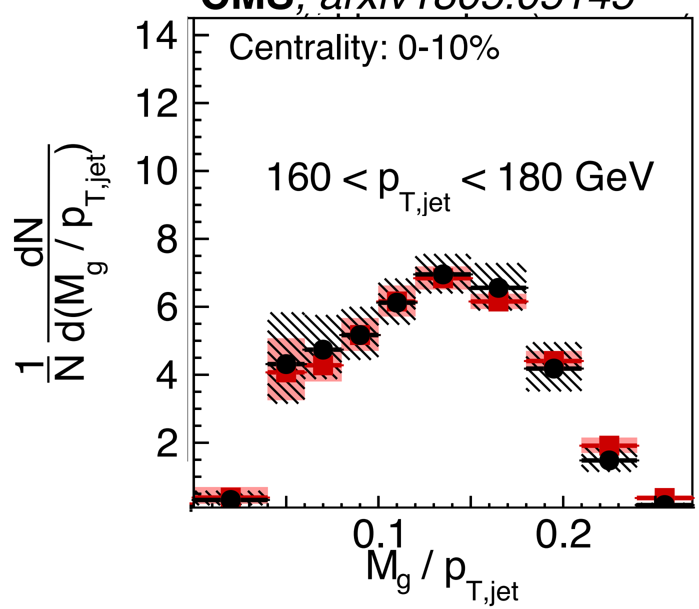
- However, jet mass and energy loss mutually affect
  - **$R_{AA}$ vs $m/p_T$** measures "*modification of jet mass by quenching*"
  - **$R_{AA}$ vs $p_T$ in $p_T$ bins** measures "*mass dependence of jet energy loss by medium*"

- ATLAS measured **jet $R_{AA}$ as a function of $p_T$ and $m/p_T$**

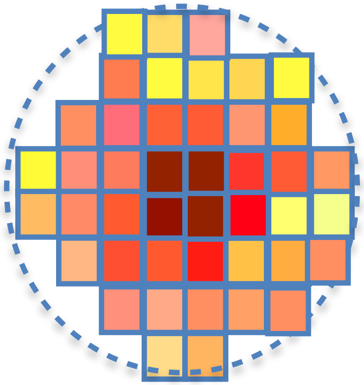
**ALICE**, *PLB776(2018)249*




**CMS**, *arxiv1805.05145*



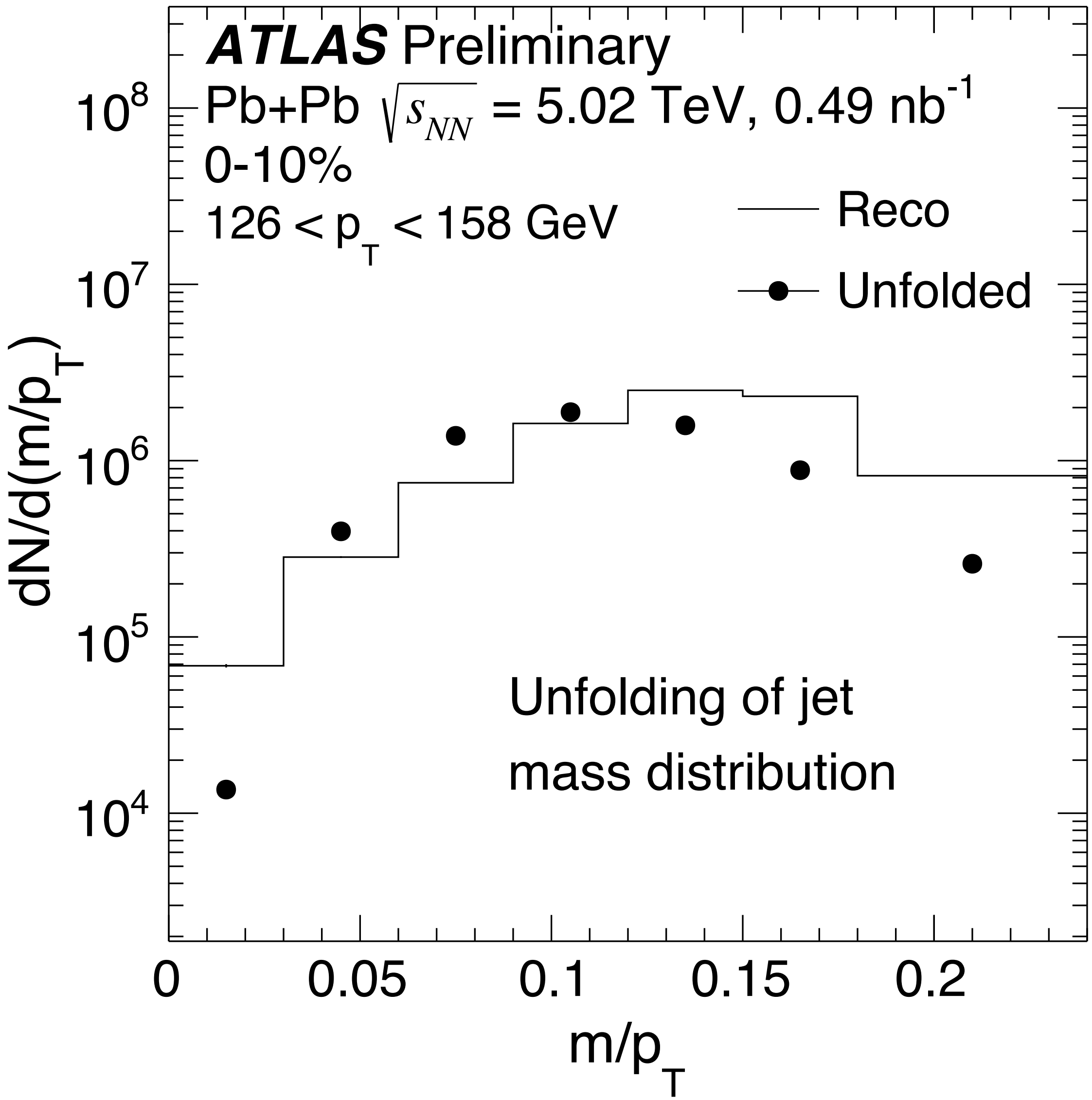
# Reconstruction of jet mass in ATLAS at 5.02 TeV



- Illustration of tower constituents in a R =0.4 jet

- A jet includes up to 50 constituent towers

$$m = \sqrt{(\sum_i E_i^{subt'd})^2 - |\sum_i \vec{p}_i^{subt'd}|^2}$$



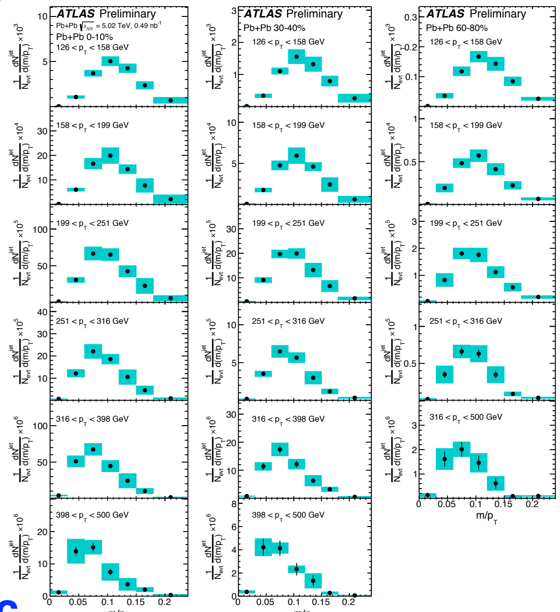
# ATLAS jet mass results

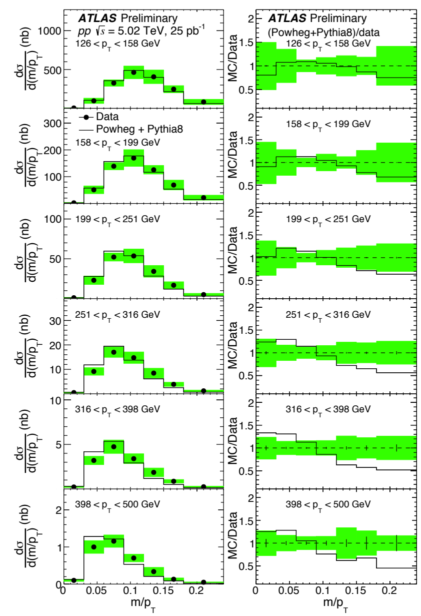
**ATLAS-CONF-2018-014**

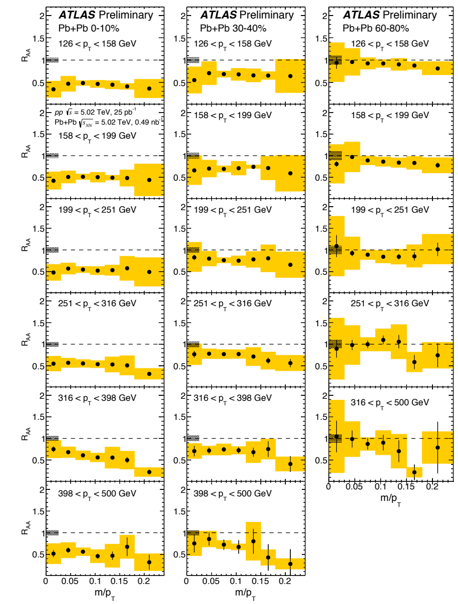
**126 GeV/c**

**Jet $p_T$**

**500 GeV/c**



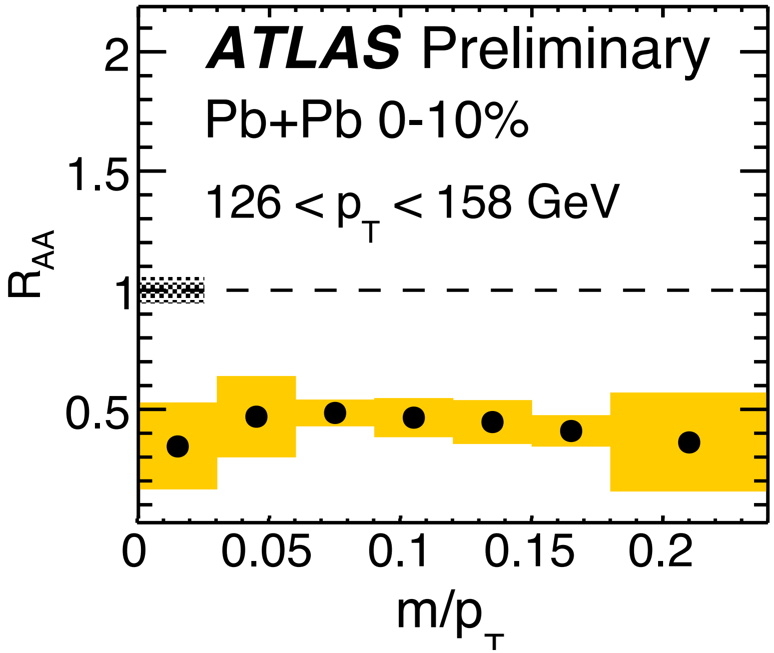




Jet mass spectra in PbPb at 5.02

Jet mass spectra in pp

**Jet $R_{AA}$ vs $m/p_T$ in different $p_T$ bins**

# Mass dependence of jet $R_{AA}$




- $R_{AA}$ is flat as a function of $m/p_T$ within systematic uncertainties.
- Uncertainty is large for low mass region due to the finite granularity of calorimeter tower



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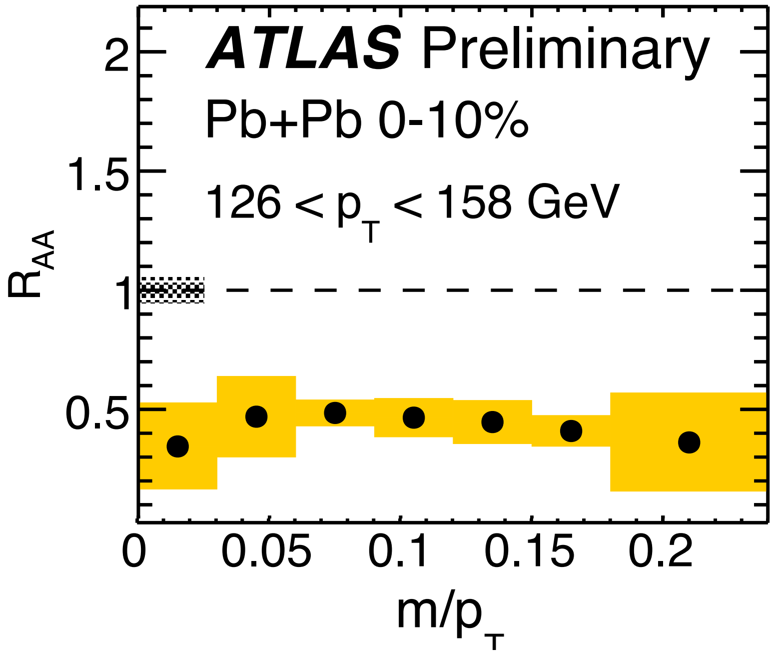
# Mass dependence of jet $R_{AA}$

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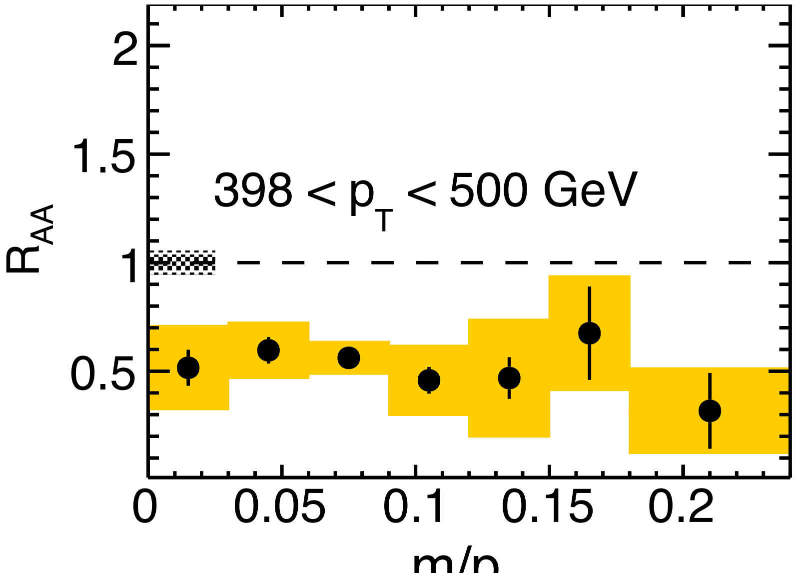


- Same observation for all $p_T$ bins



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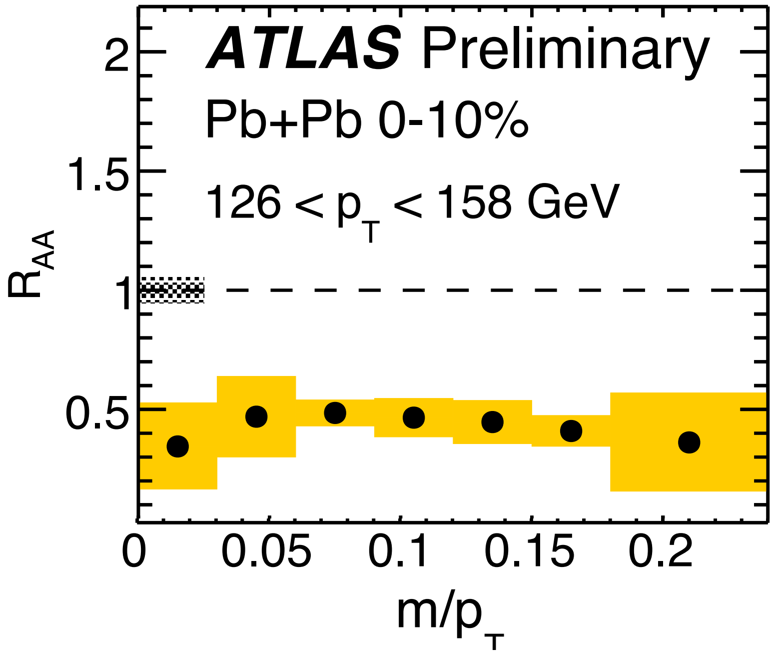


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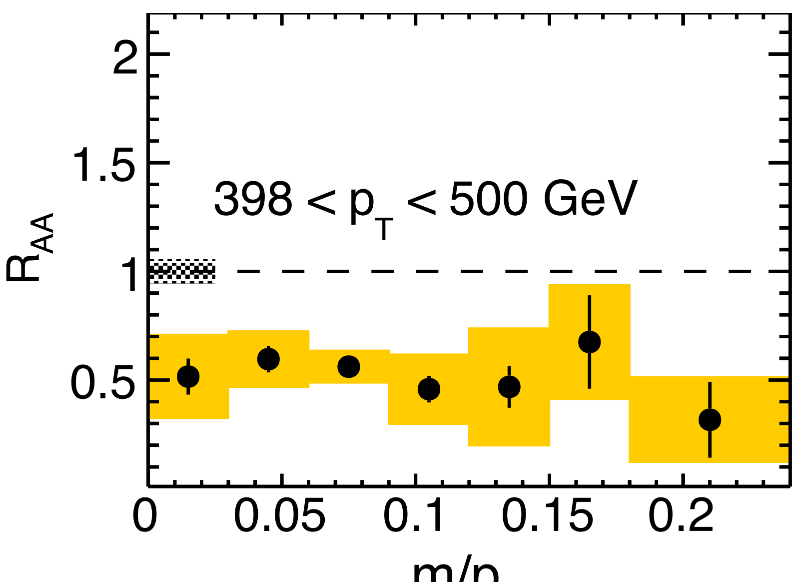


- Jet mass in the most peripheral bin is consistent with pp data


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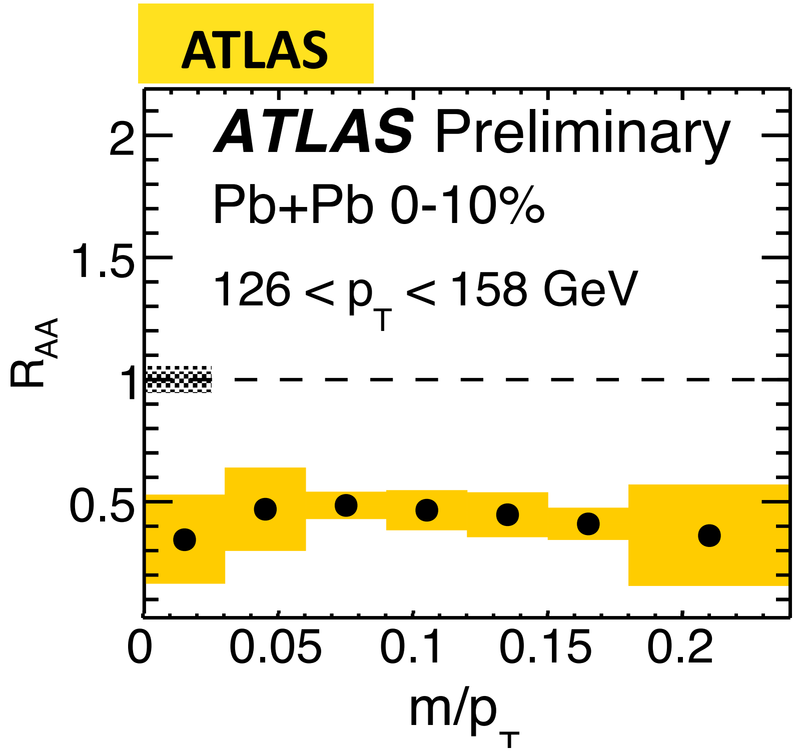
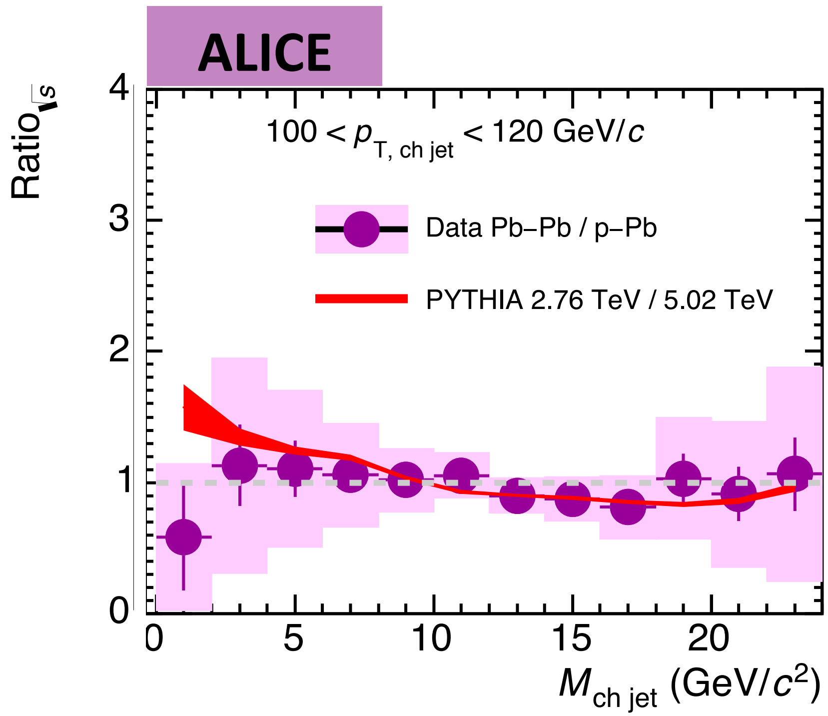
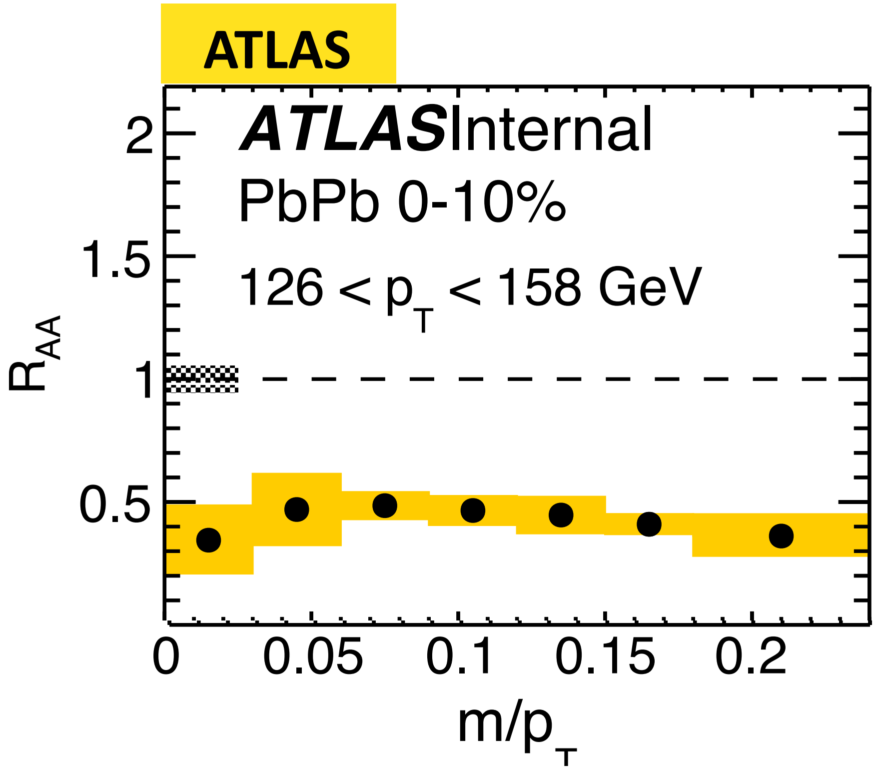
# Comparison of ATLAS, ALICE and CMS results

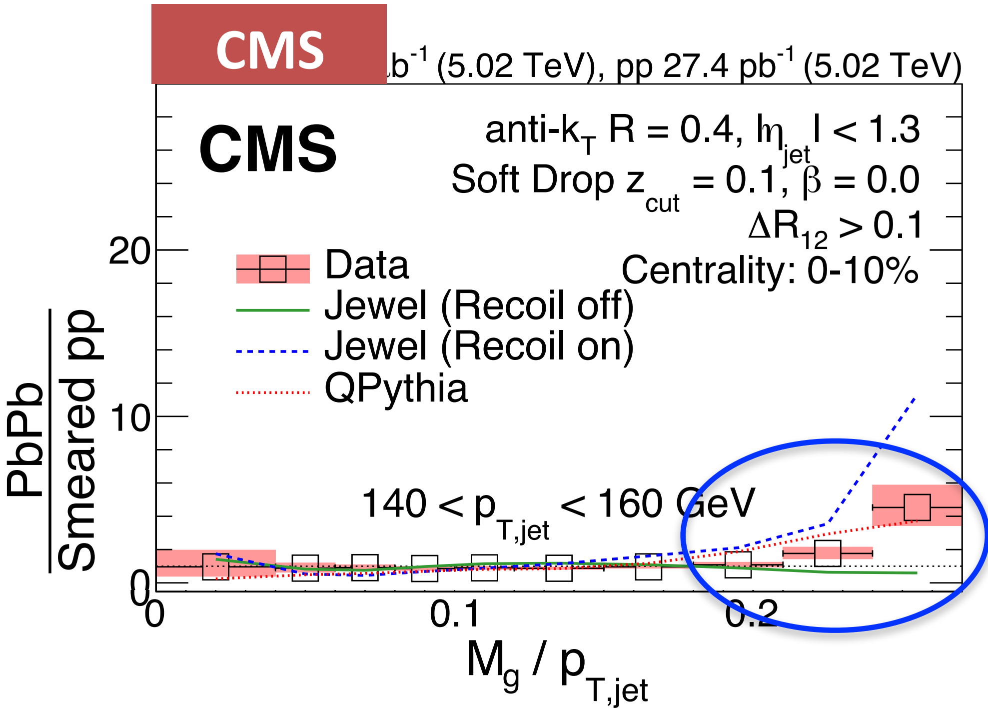



- ALICE measured jet mass in PbPb@2.76TeV and pPb@5.02TeV for reference
- Two results were consistent within uncertainty.
- Subtle discrepancy was attributed to the different collision energy using PYTHIA

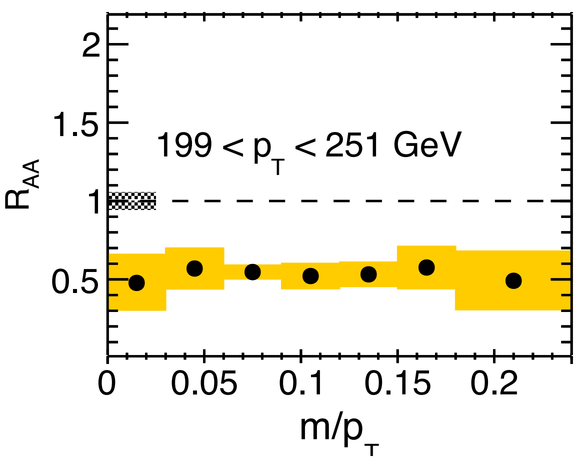
# Comparison of ATLAS, ALICE and CMS results

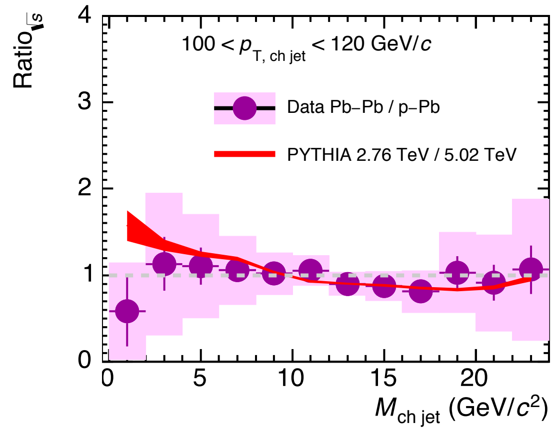


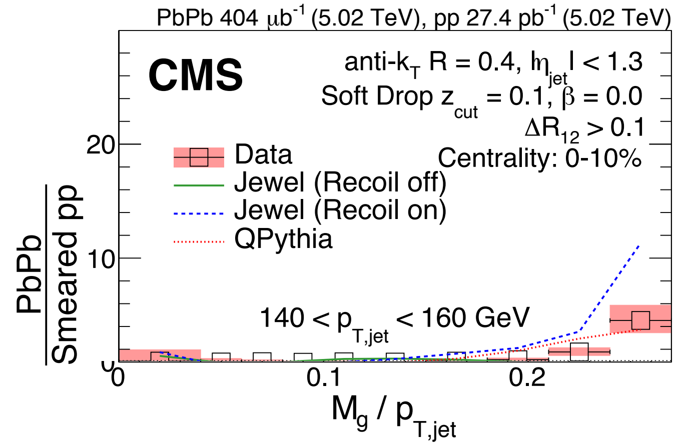




- Enhancement of large $m/p_T$ yield in CMS was not observed in ATLAS and ALICE result
- Jewel can reproduce the high mass rise when the recoil is on
- Then why was such a pattern not shown in other experiments?

# **Banna** vs **Blueberry** vs **Strawberry**




**ATLAS**

- *Ungroomed mass*
- Fully unfolded
- pp for ref.

**ALICE**

- *Ungroomed mass*
- Fully unfolded
- ***pPb for ref. (different energy)***

**CMS**

- ***SoftDrop mass***
- ***Smeared pp***
- pp for ref.

- Three experiments are using different measurement configuration
- Which one could be the reason of different results?

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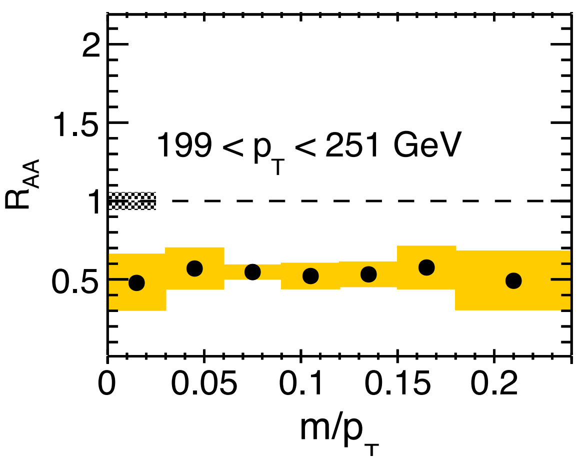


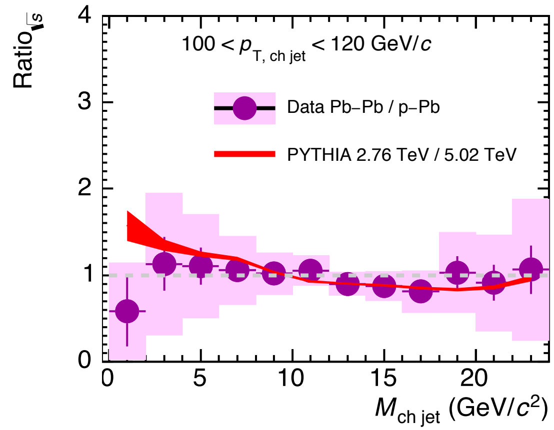


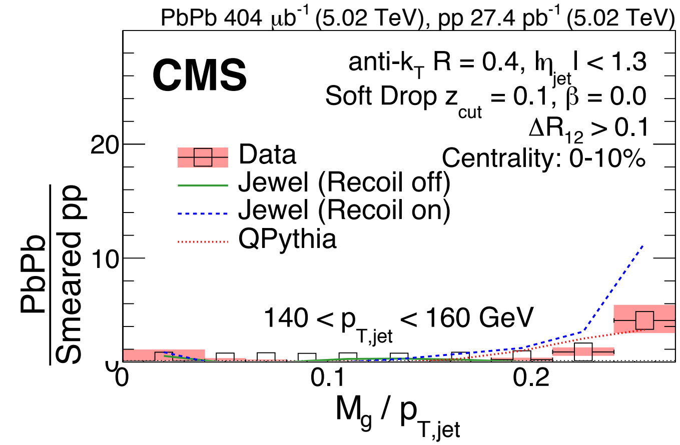


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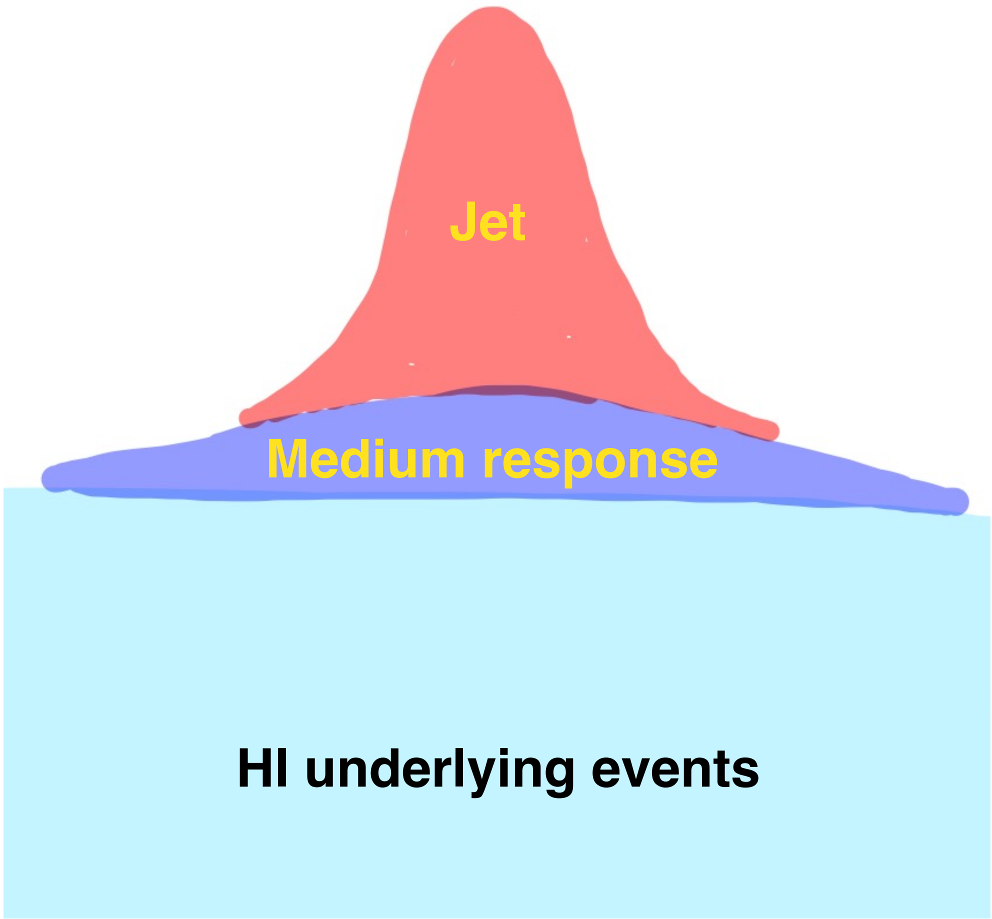
# Medium response



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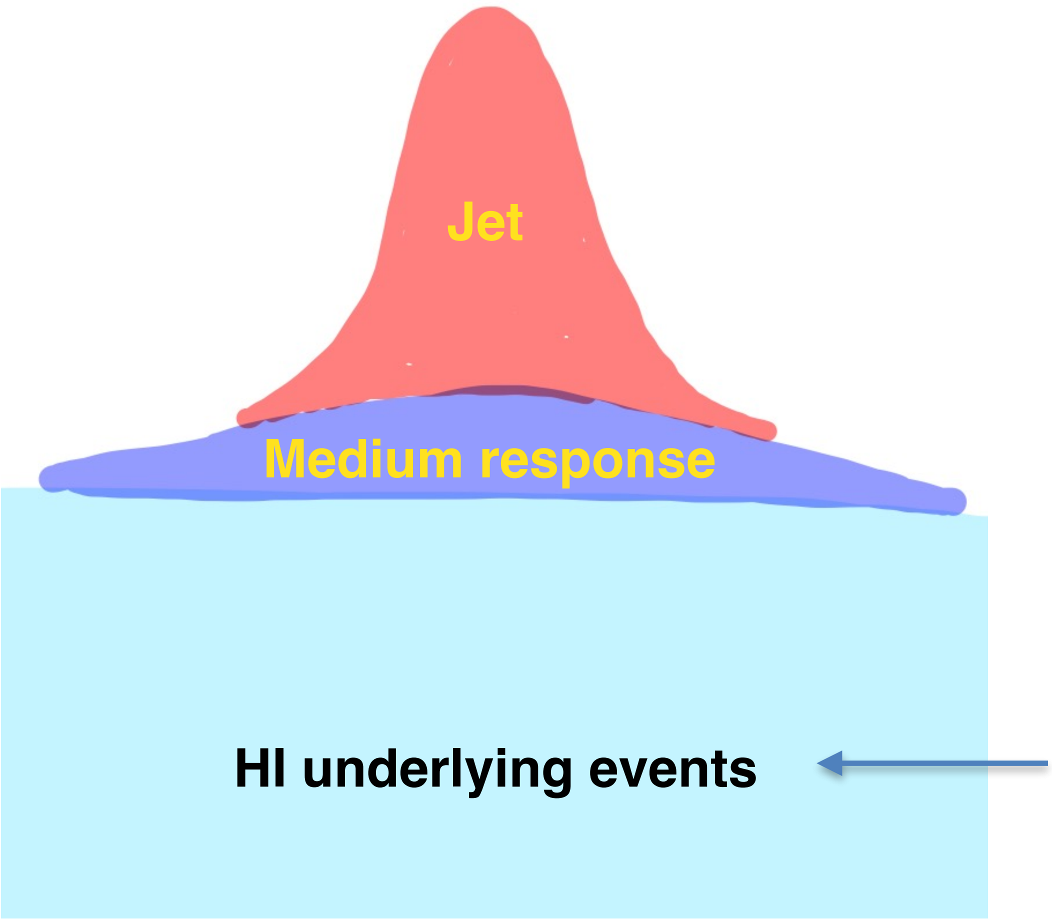


Can be removed by event-by-event subtraction methods (e.g. constituent subtraction)

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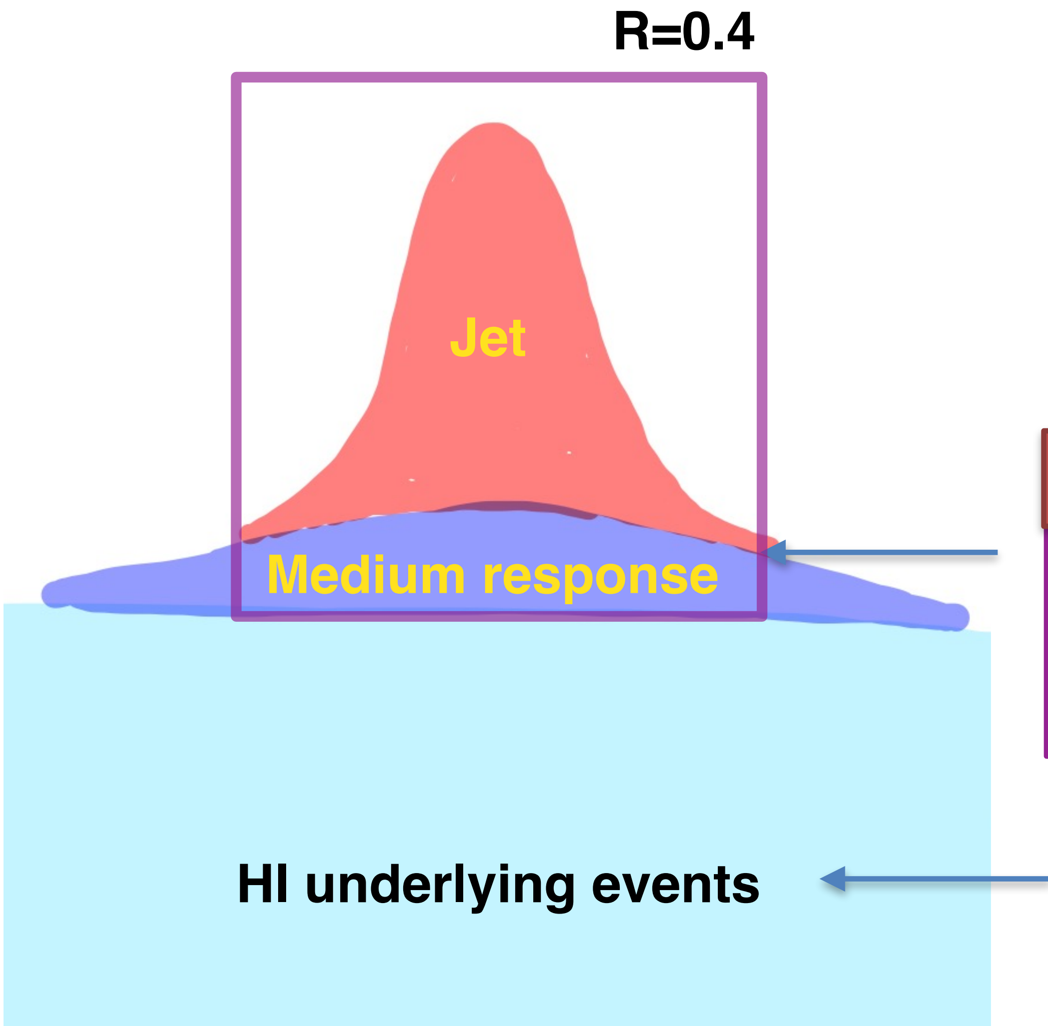


**inclusive jet mass**

- Jet mass includes the medium response
- ATLAS and ALICE

Can be removed by event-by-event subtraction methods (e.g. constituent subtraction)

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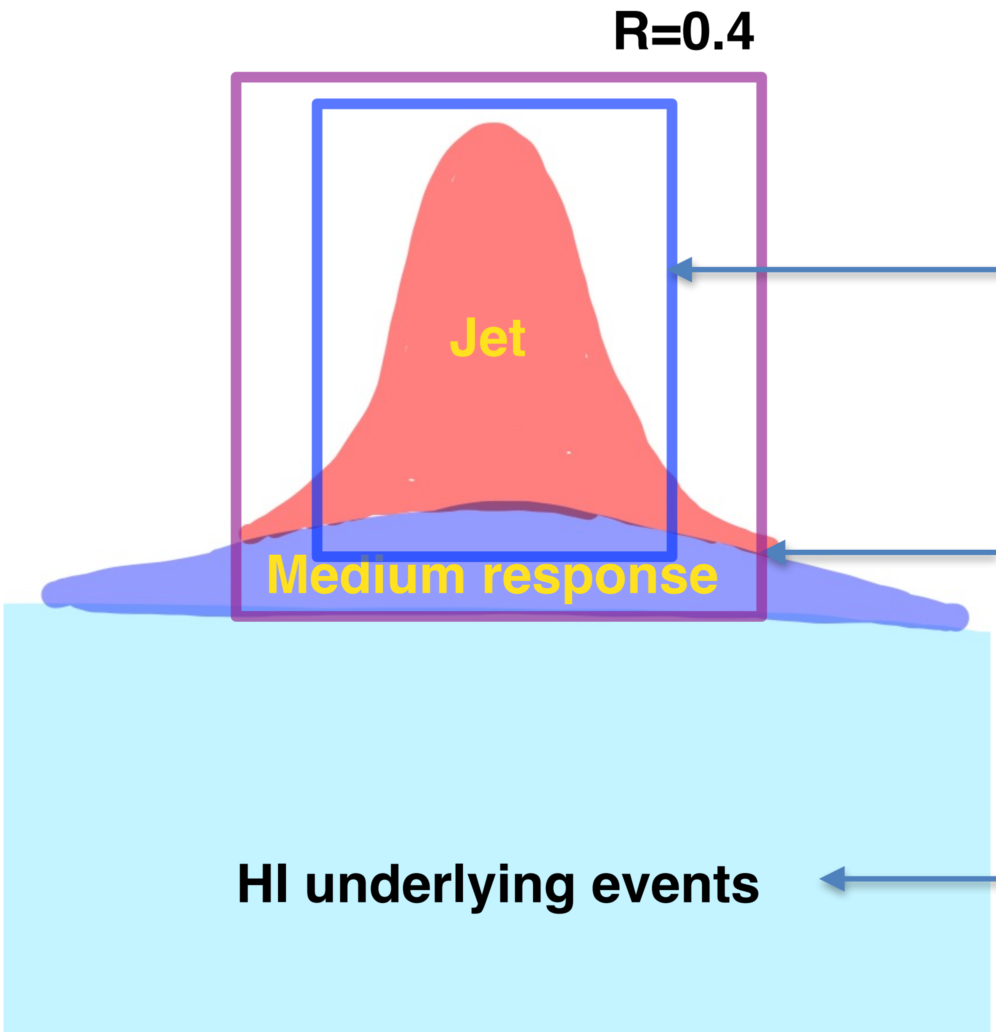



**Groomed jet**

- Softdrop selects the core area of a jet, thus the medium response partially contribute
- CMS

**inclusive jet mass**

- Jet mass includes the medium response
- ATLAS and ALICE

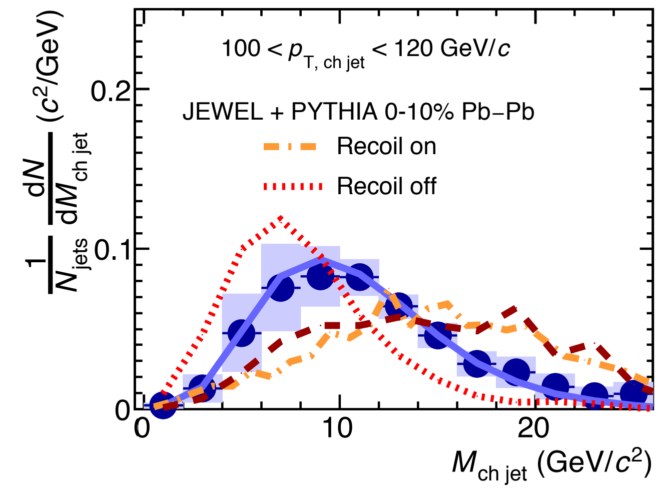
Can be removed by event-by-event subtraction methods (e.g. constituent subtraction)

The shape of medium response must be fully understood to converge the discrepancy between the groomed result and ungroomed one.

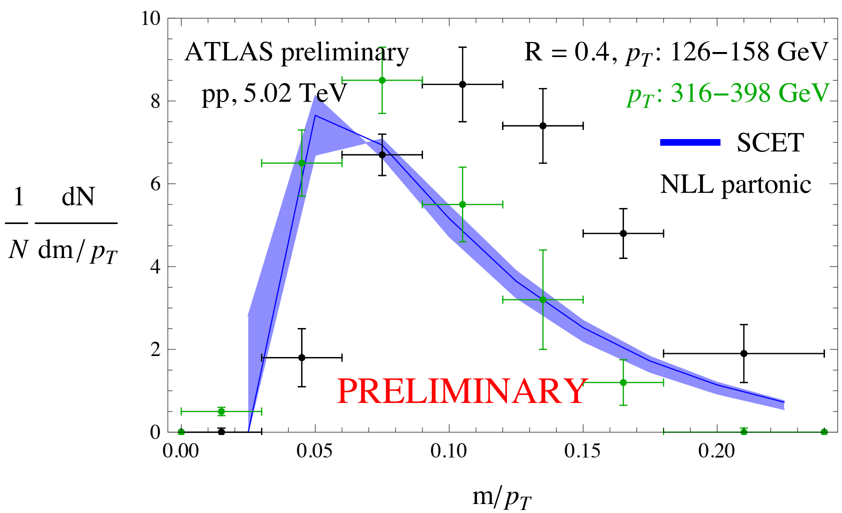
# Model calculation for jet mass

- Many models reflects the two competing effects for mass distribution
  (a) Loss of mass by quenching
  (b) Gain of mass by medium response

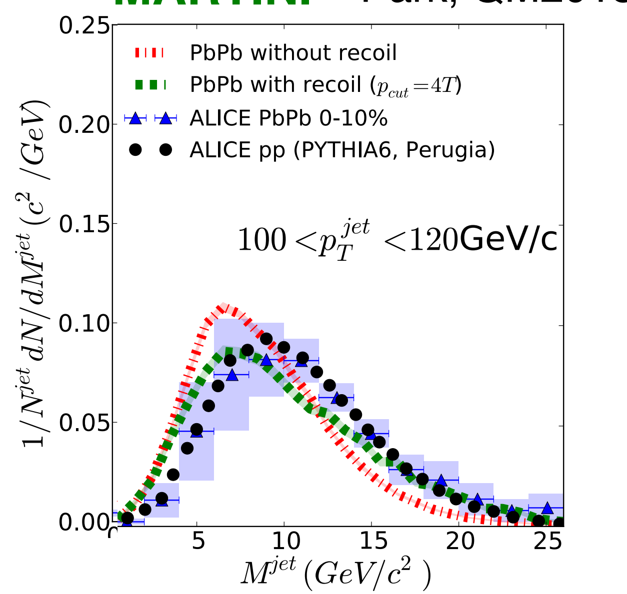
**JEWEL** *PLB776(2018)249*




**SCET** Chien, HardProbes2018




**MARTINI** Park, QM2018



# Summary

- A modification of jet splitting function was observed, which indicates that the medium can resolve the early splitting of jet in heavy ion collision
- No significant modification found in the ungroomed jet mass distribution but when it was groomed, high mass region was enhanced
- Such a discrepancy may provide the input to understand the medium recoil