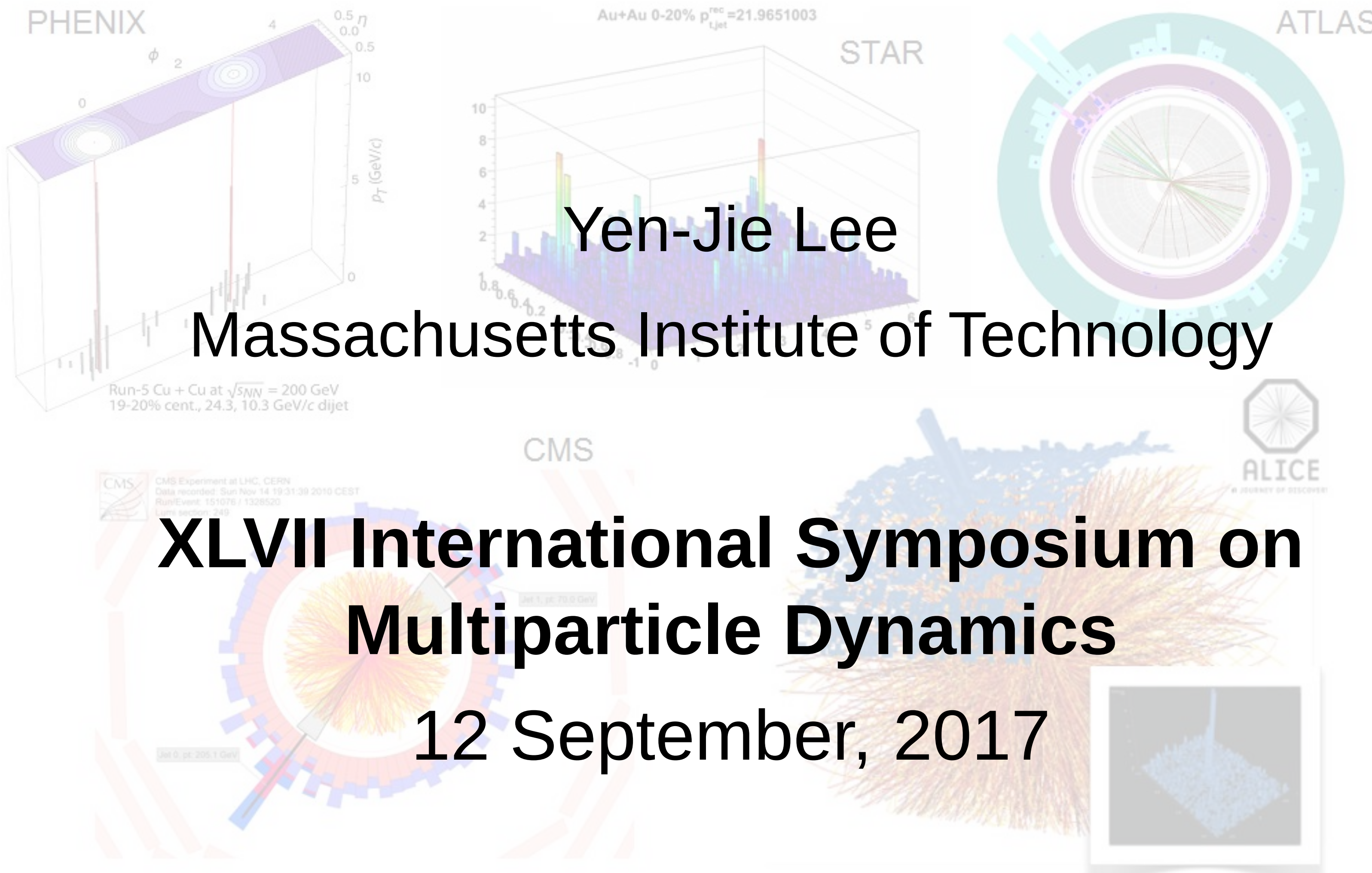
Experimental Results on Jets in Heavy Ion Collisions



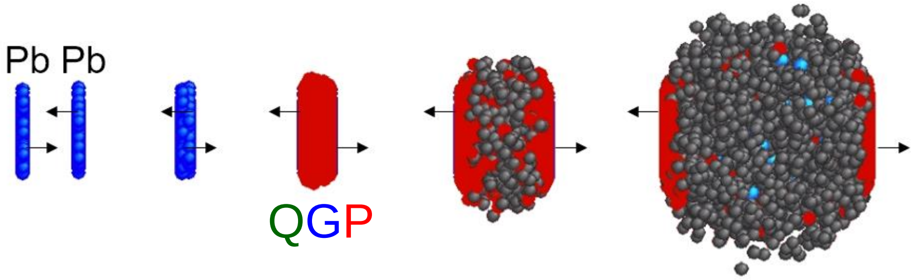
Yen-Jie Lee

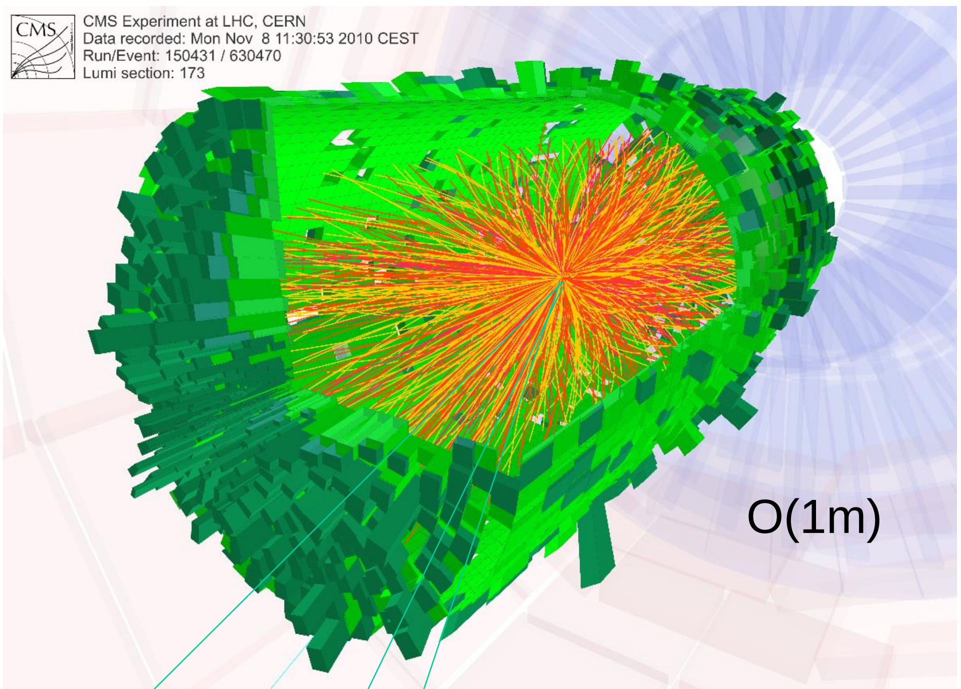
Massachusetts Institute of Technology

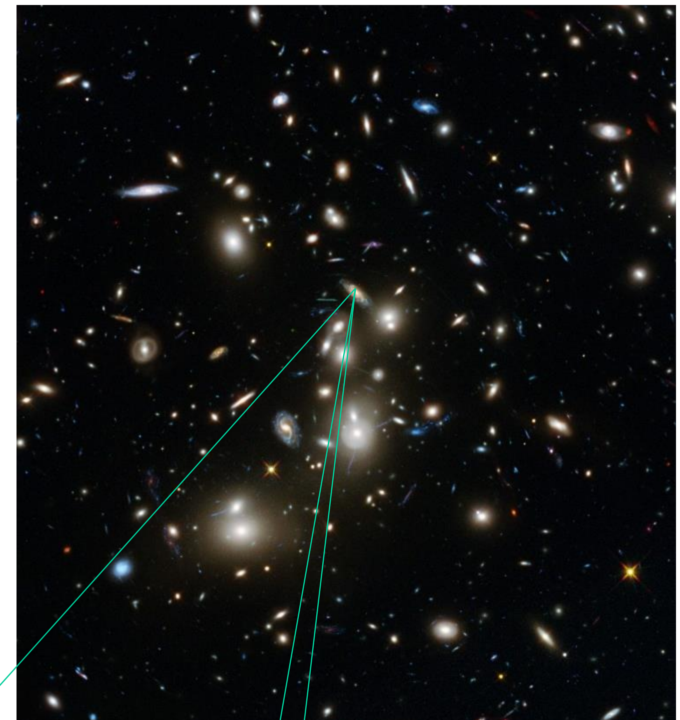
XLVII International Symposium on Multiparticle Dynamics

12 September, 2017

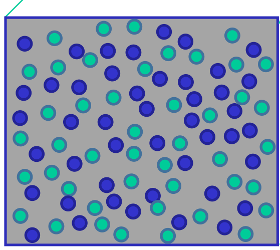
Reconstruct the Quark Gluon Plasma



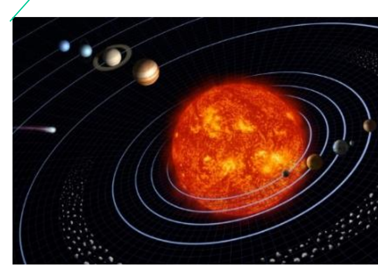




O(10^{27} m)



O(10^{-15} m)



O(10^{13} m)

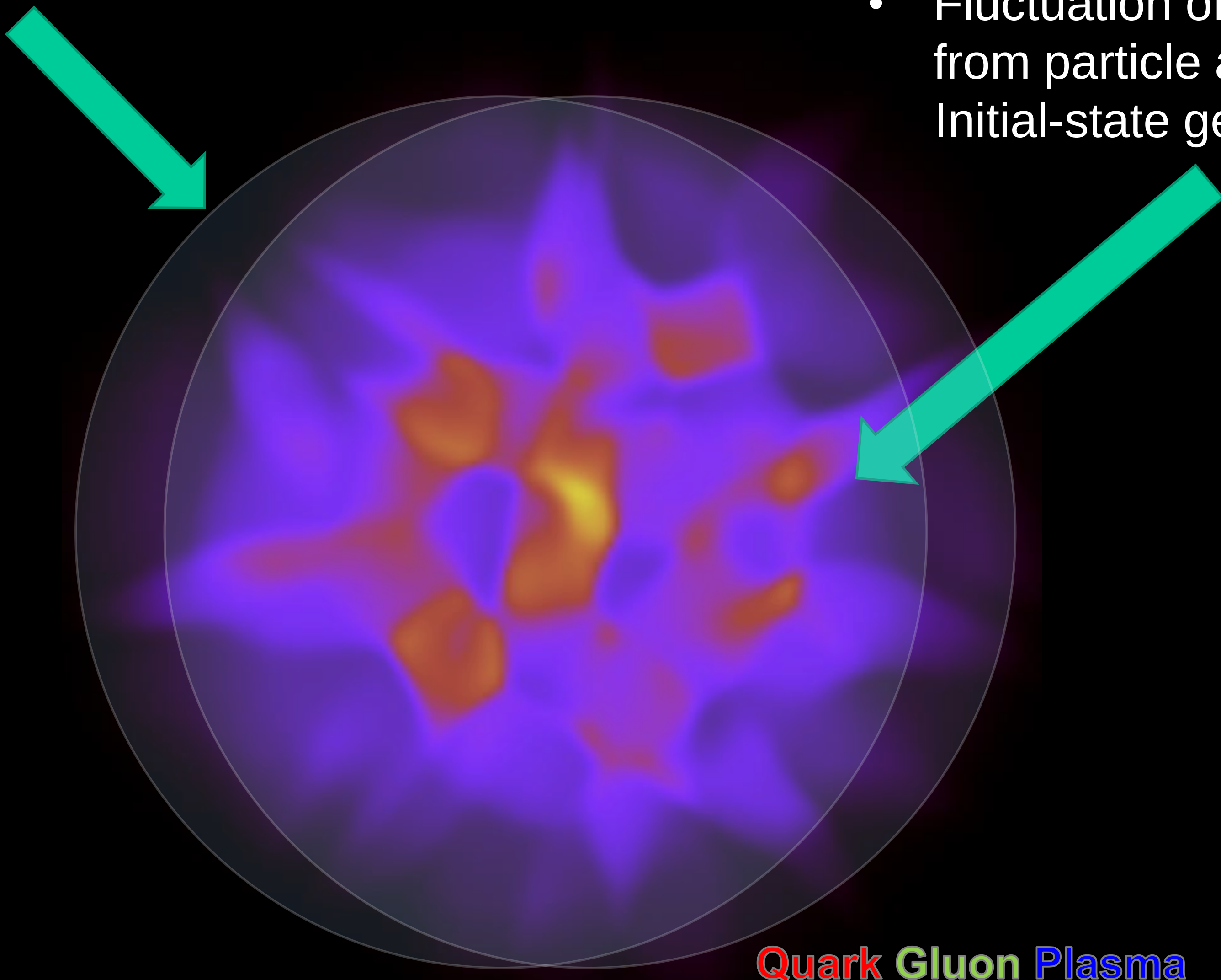
Prepare the Quark Soup

Particle Multiplicity

- Collision impact parameter of the ions
- Energy density of the medium

Azimuthal anisotropy

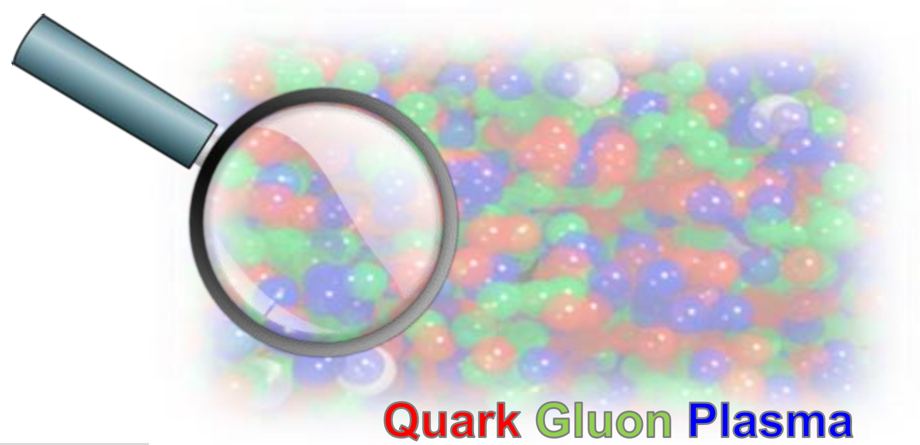
- Early thermalization <1 fm/c
- Shear viscosity
- Fluctuation of v_N coefficients from particle azimuthal correlation: Initial-state geometry fluctuation



Beyond the Analysis of Debris

- How does the strongly interacting medium emerge from an asymptotic free theory (QCD)?

- Can we see quasi particles (quarks and gluons) and medium resonse in the Quark Gluon Plasma?



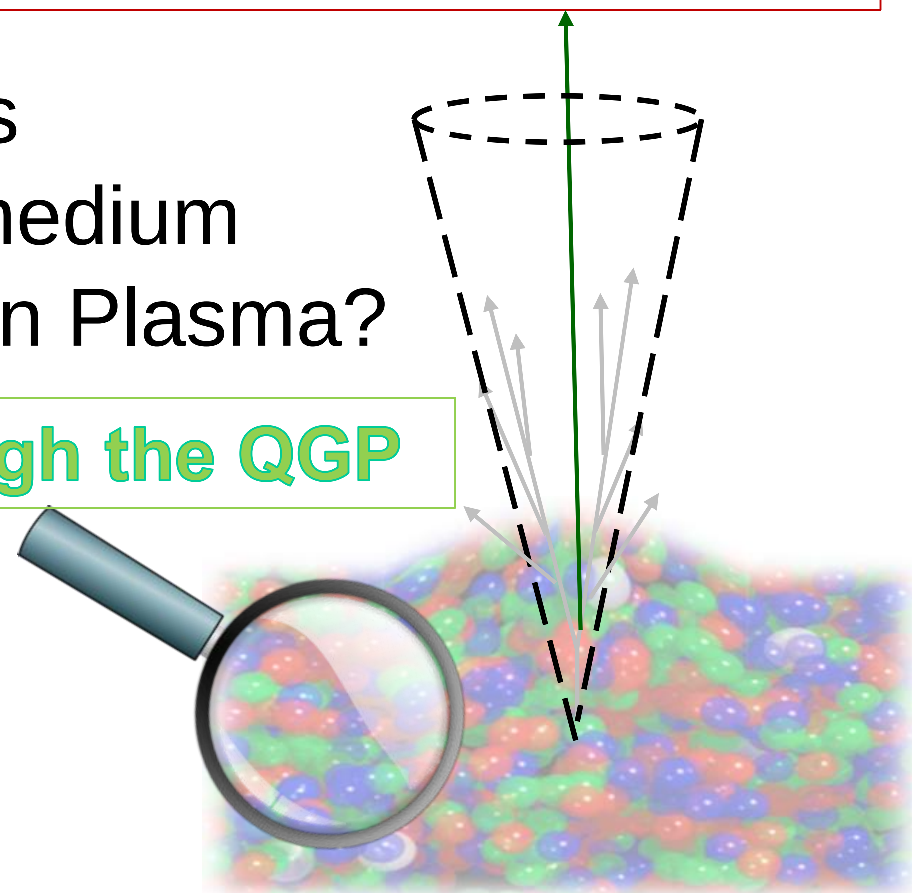
Beyond the Analysis of Debris

- How does the strongly interacting medium emerge from an asymptotic free theory (QCD)?

Start from "un-thermalized" objects and see how they are thermalized in the Quark Soup

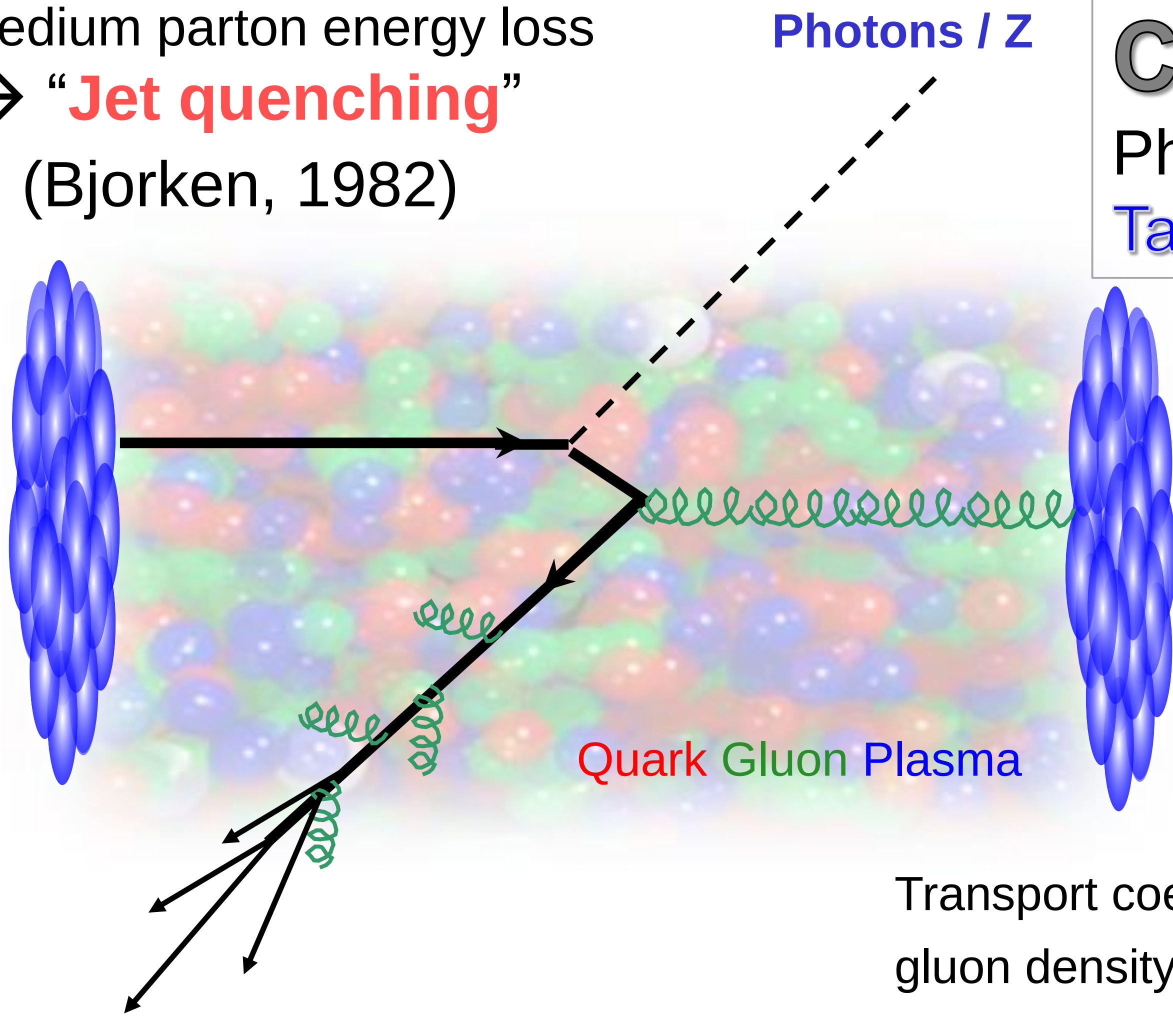
- Can we see quasi particles (quarks and gluons) and medium resonse in the Quark Gluon Plasma?

Shoot colored objects through the QGP



Hard Probes in Heavy Ion Collisions

In medium parton energy loss
→ "**Jet quenching**"
(Bjorken, 1982)



Colorless Probes

Photons, electroweak bosons

Tag the initial state

Transport coefficient $\hat{q}$, stopping power dE/dx, gluon density $\frac{dN_g}{dy}$, temperature T…

Colored Probes:

Jets and hadrons from High energy quarks and gluons

Studies of the medium properties

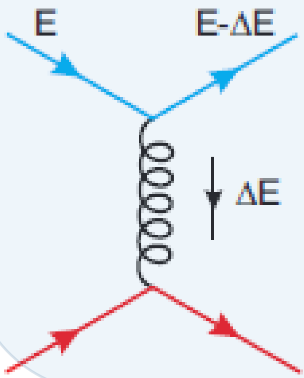
Parton Energy Loss Models

- **The main problem:** we don’t know how to describe the interaction between the hard scattered parton and QGP (a multi-scale problem)

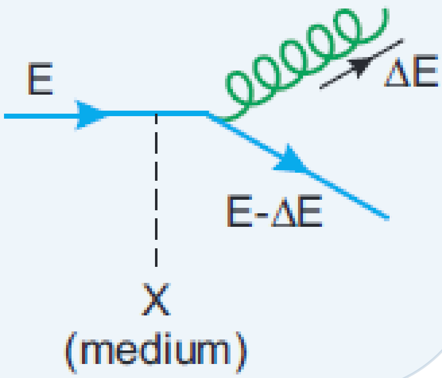
- **Two theoretical approaches:**
(neither of them are the full stories and both of them are effective descriptions in proper regimes)

Perturbative QCD
Weak coupling limit

Collisional
energy loss



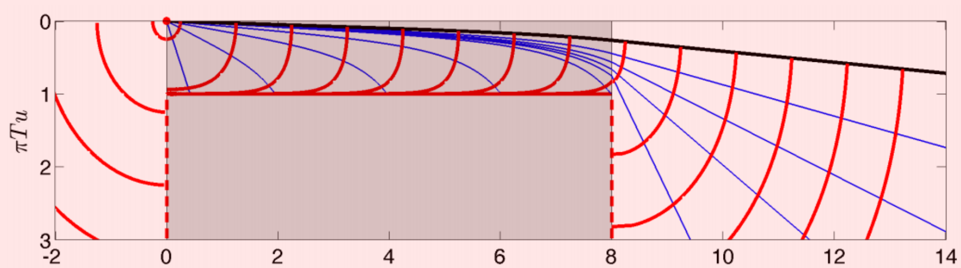
Radiative
energy loss



JEWEL | CUJet3.0 | CCNU | Q-PYTHIA | $SCET_G$ | JETSCAPE

Holographic calculation
Strong coupling limit

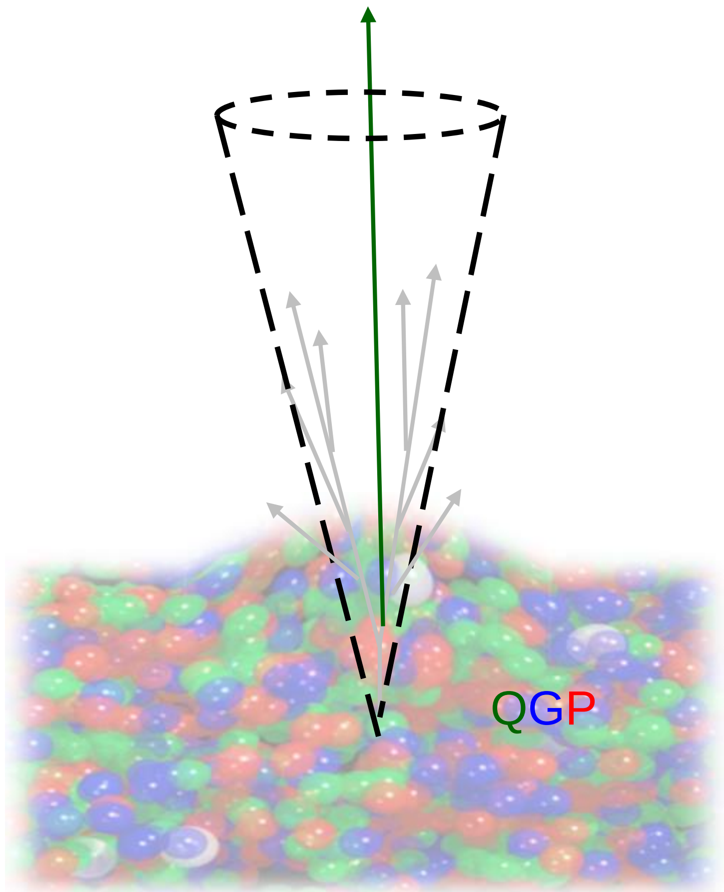
AdS/CFT “drag force”



HYBRID

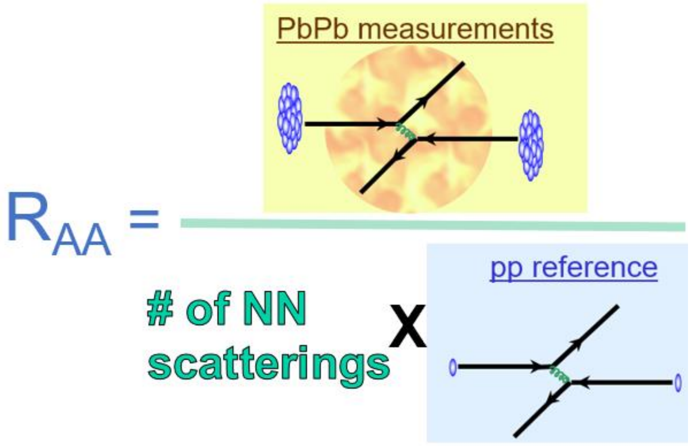
Jet Quenching

What is the mechanism of jet quenching?

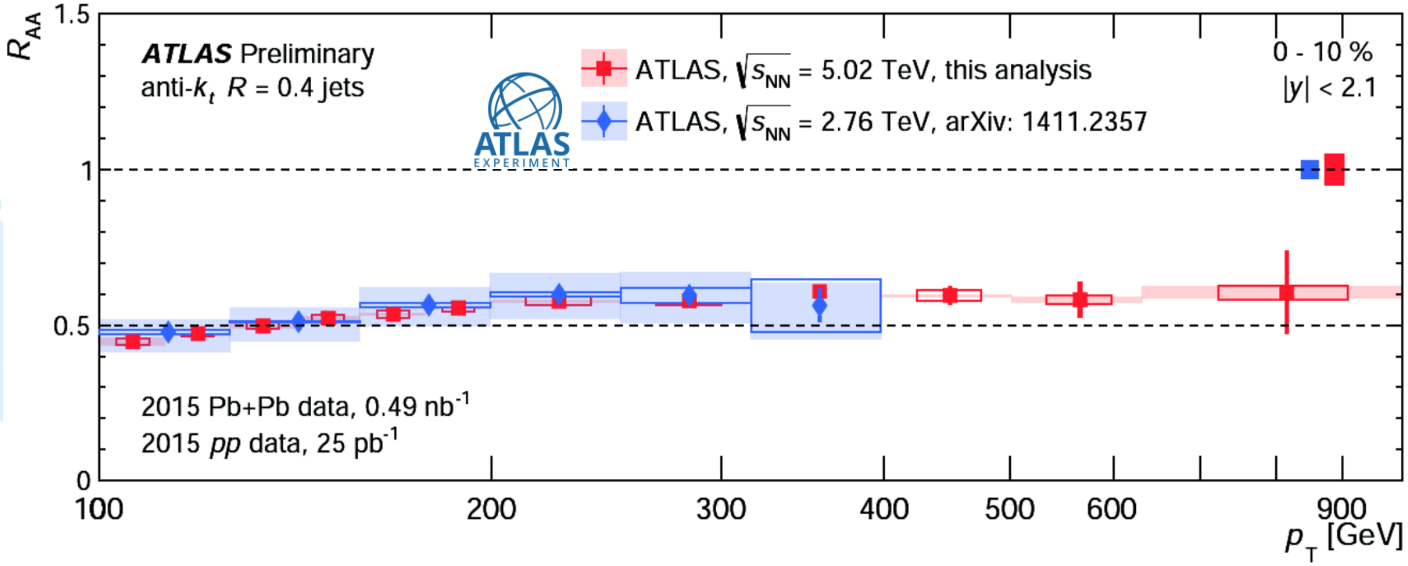


Jet R_{AA} up to p_T ~ 1 TeV

Can we capture all the quenched energy by jet reconstruction?



Anti-k_T R=0.4 Jet R_{AA} in 2.76 and 5.02 TeV

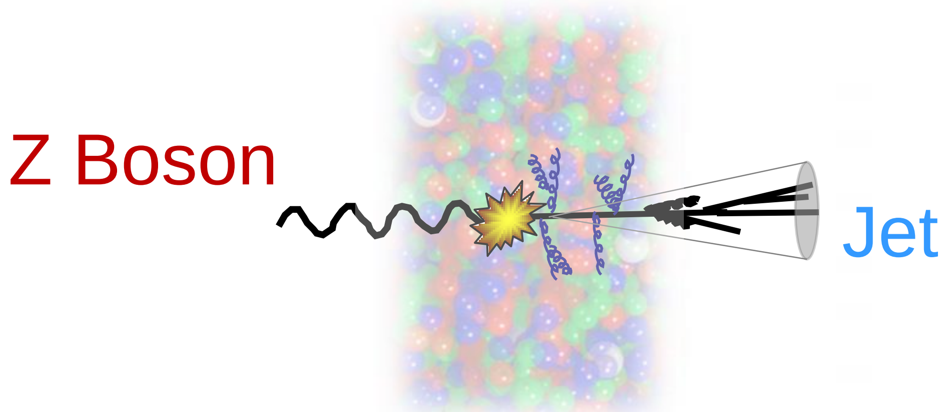


- Jet R_{AA} < 1 : **quenched energy goes out of the jet cone**
  - Similar results from the STAR measurement on the h-jet at RHIC
- Significant jet suppression at high p_T (up to ~ **1 TeV**!)
  - If the suppression is purely due to energy loss

    → Energy transported out of the cone is **O(100) GeV!**

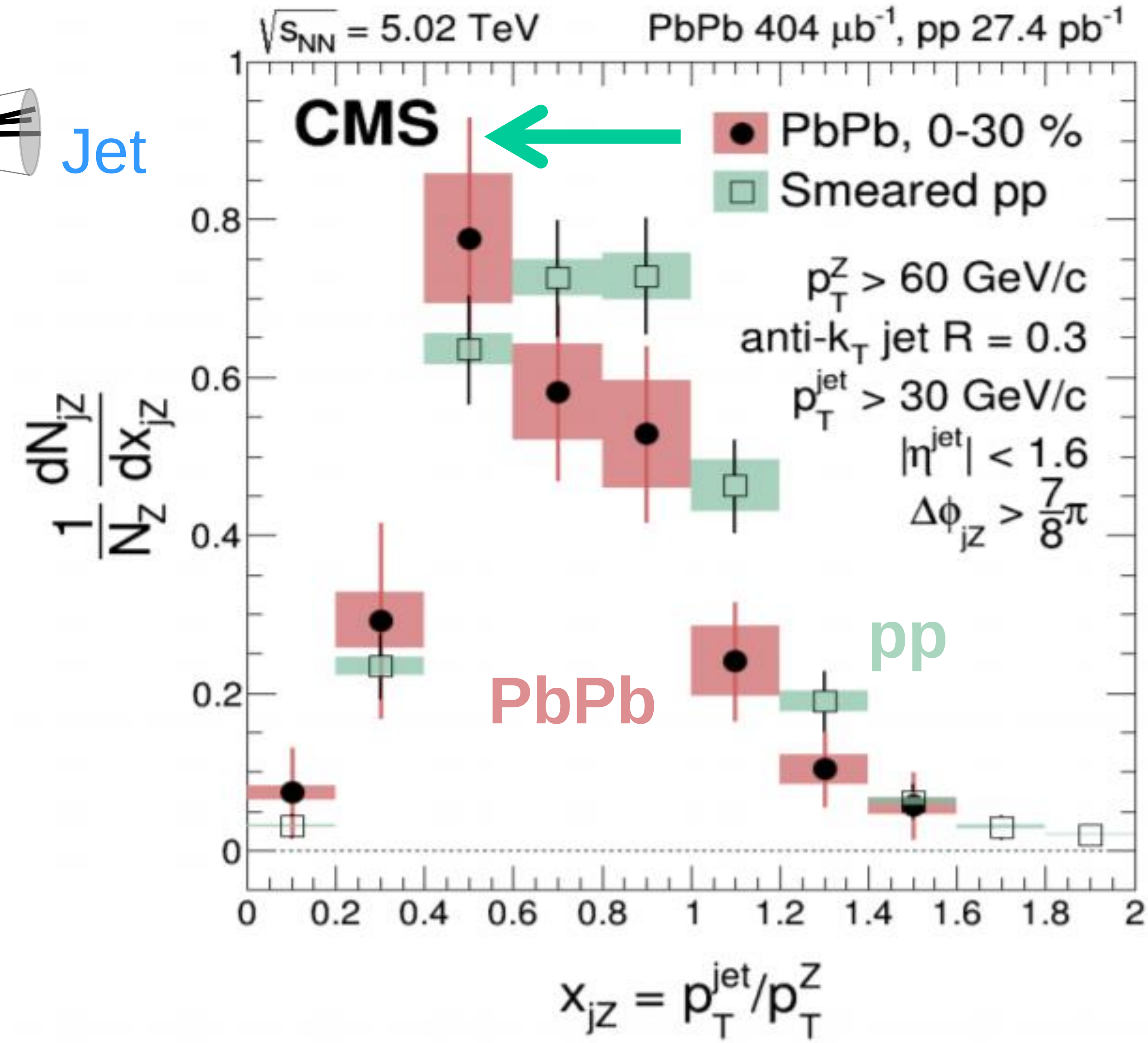
What is the fraction of parton energy going out of the jet cone?

Absolute Energy Loss with Z+Jet at 5 TeV

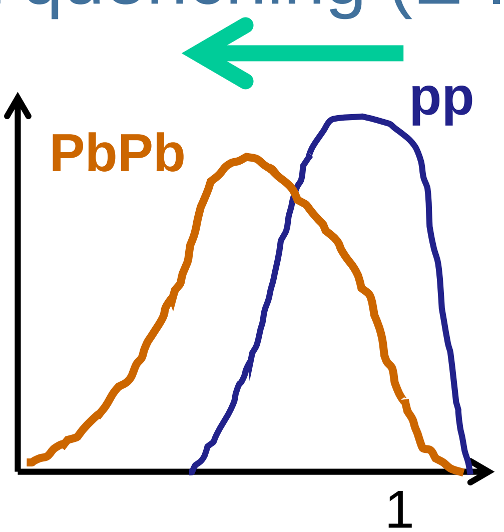


Momentum conservation
in the transverse direction

arXiv 1702.01060
PRL 119, 082301 (2017)



Jet quenching (E-loss)

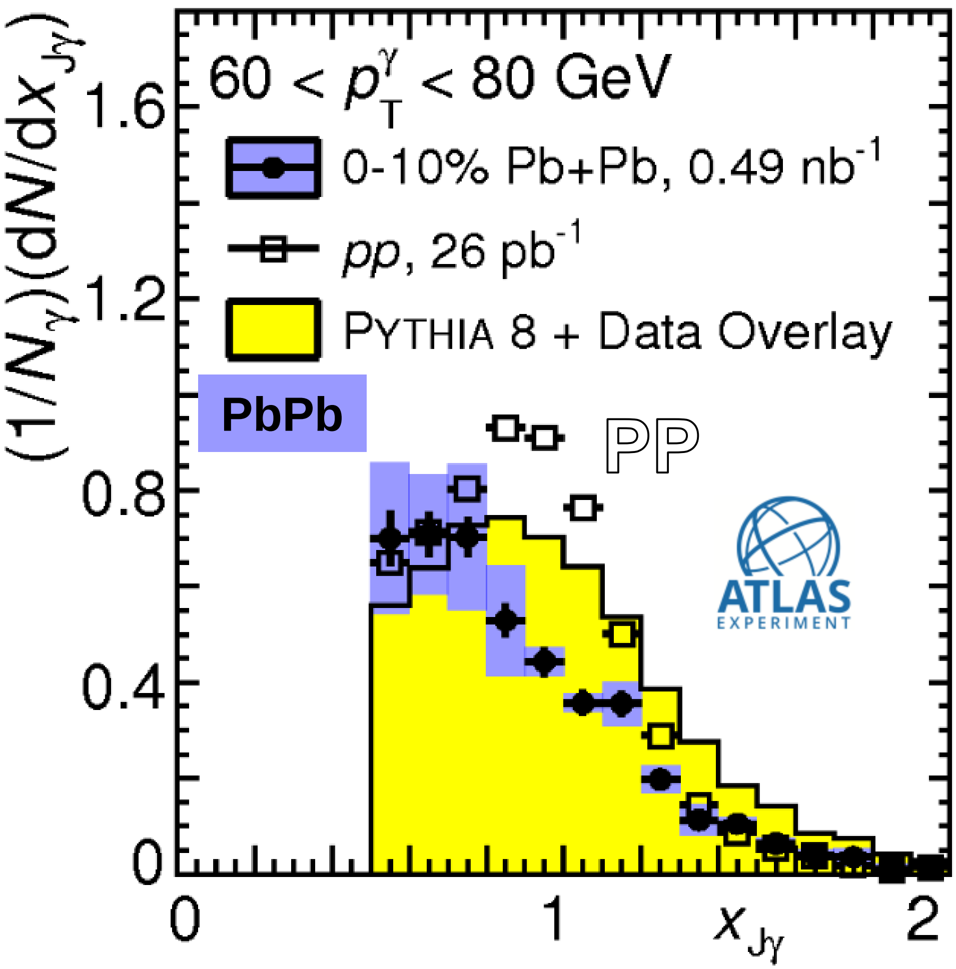


$x = p_T^{Jet} / p_T^{boson}$

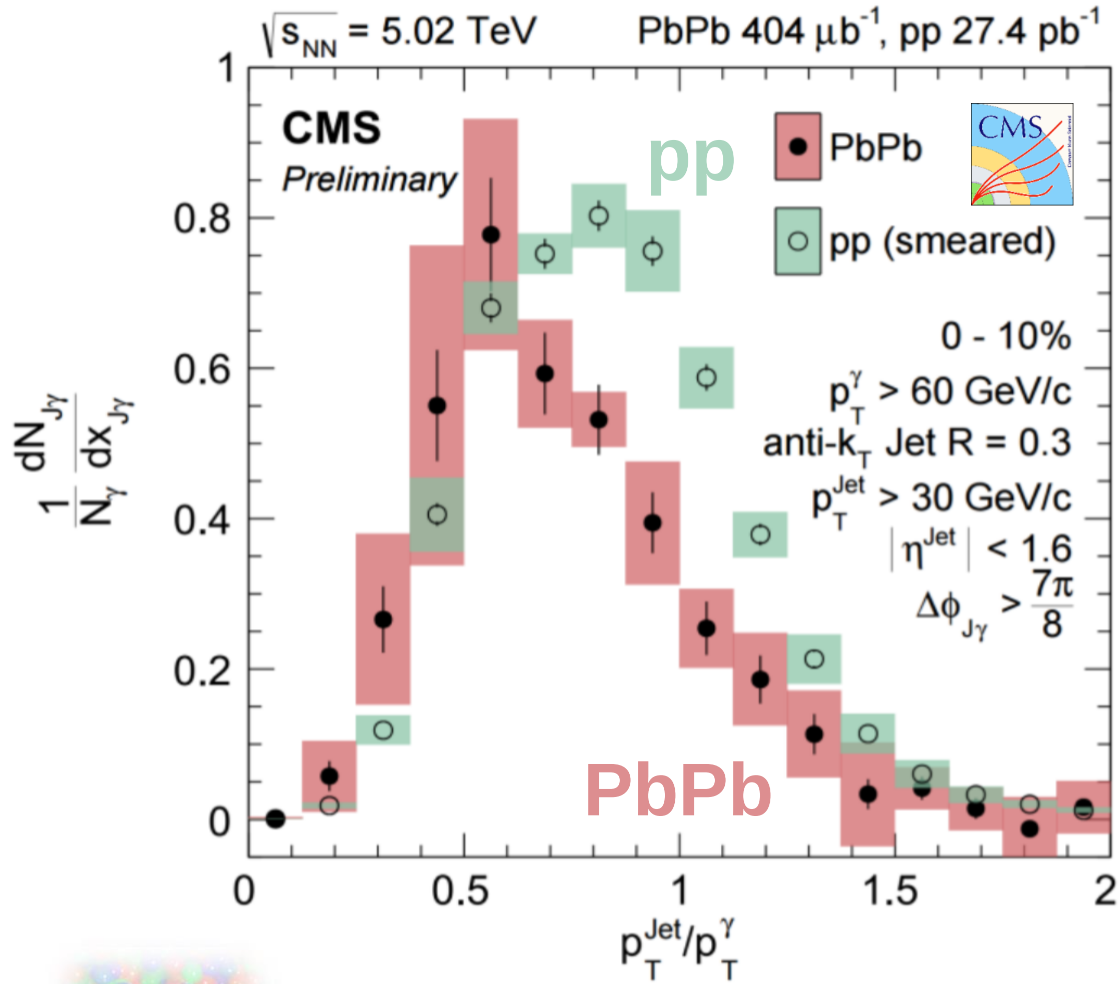
~ 15% of the energy went out of the jet cone (R=0.3)

Absolute Energy Loss with γ+Jet at 5 TeV

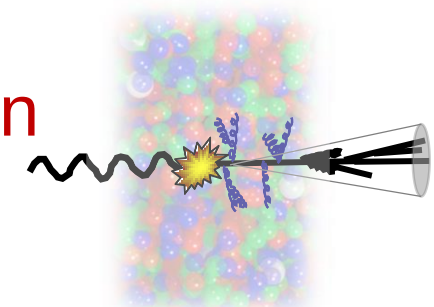
ATLAS-CONF-2016-110



CMS-PAS-HIN-16-002 (2017)

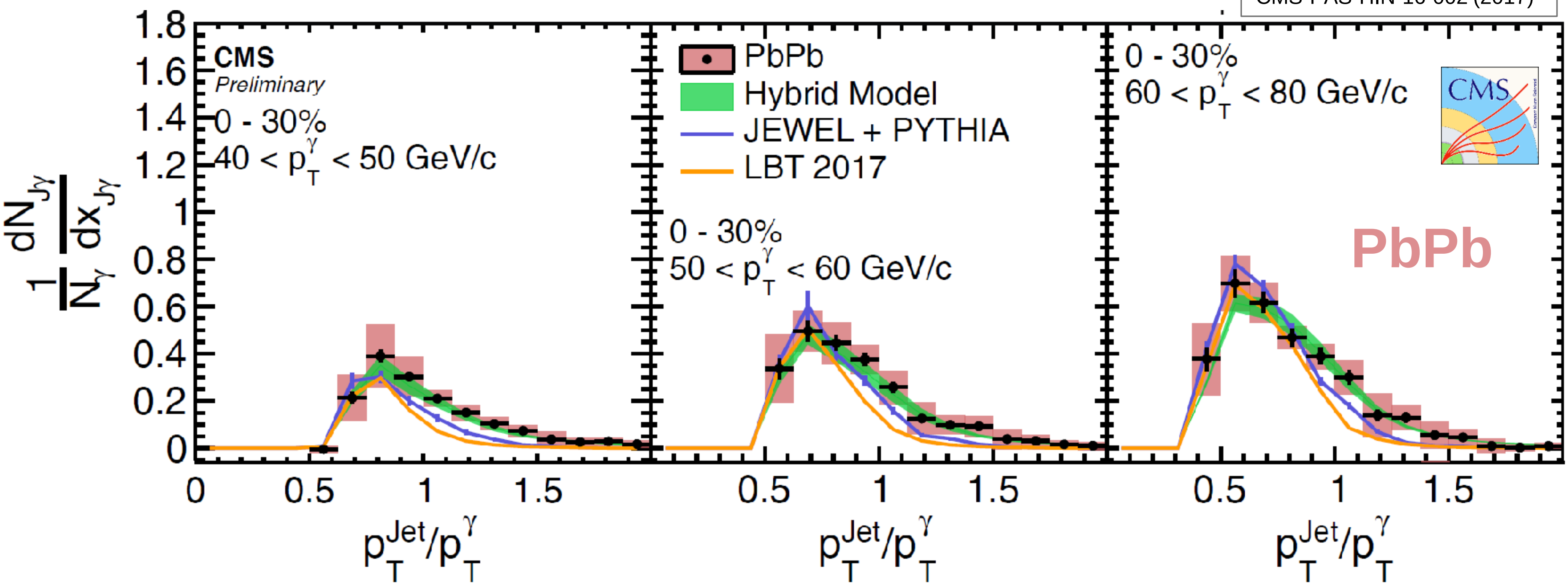


$x_{J\gamma} = p_T^{Jet} / p_T^{\gamma}$



Photon-Jet Data vs. Theoretical Predictions

CMS-PAS-HIN-16-002 (2017)

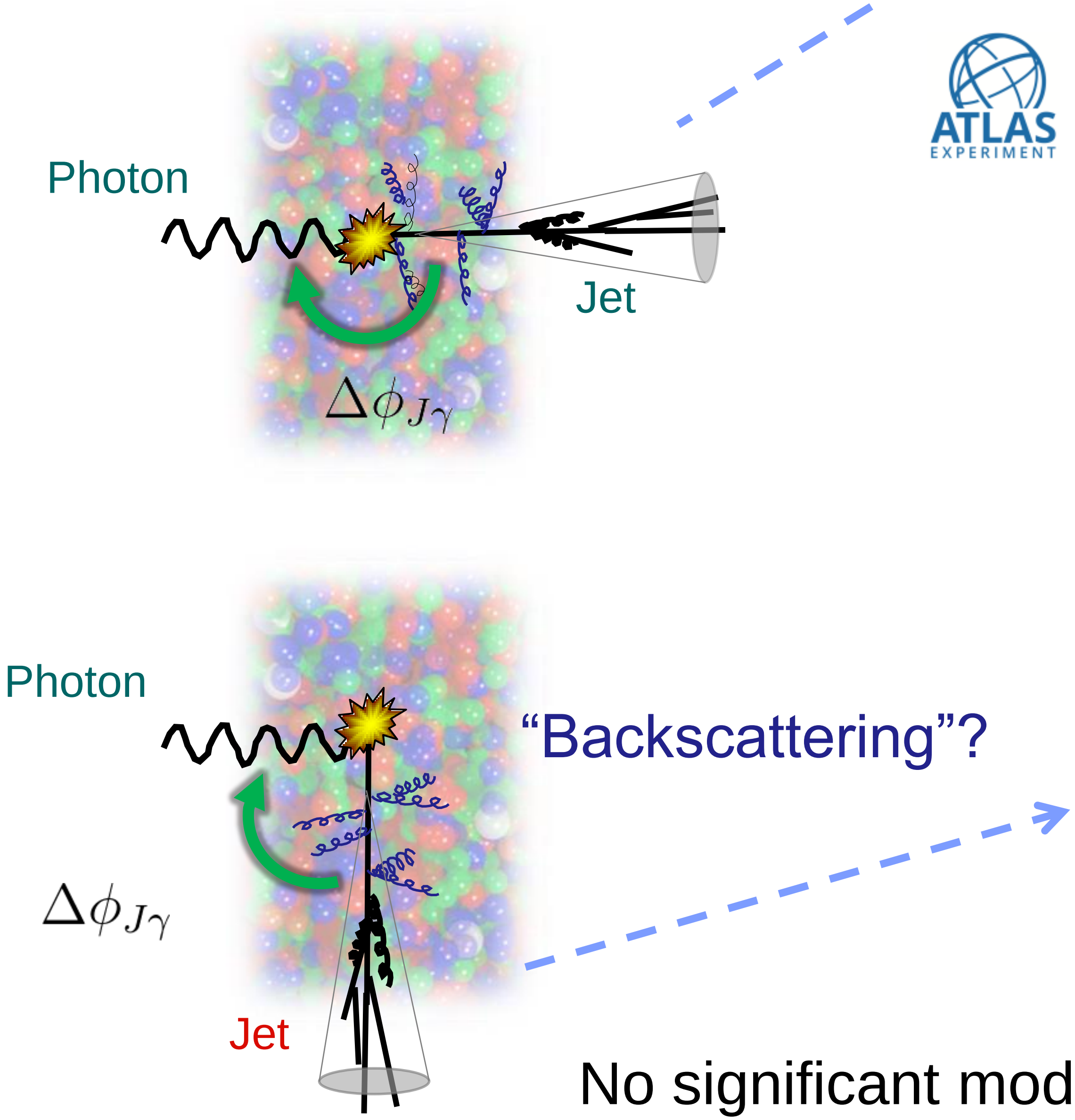


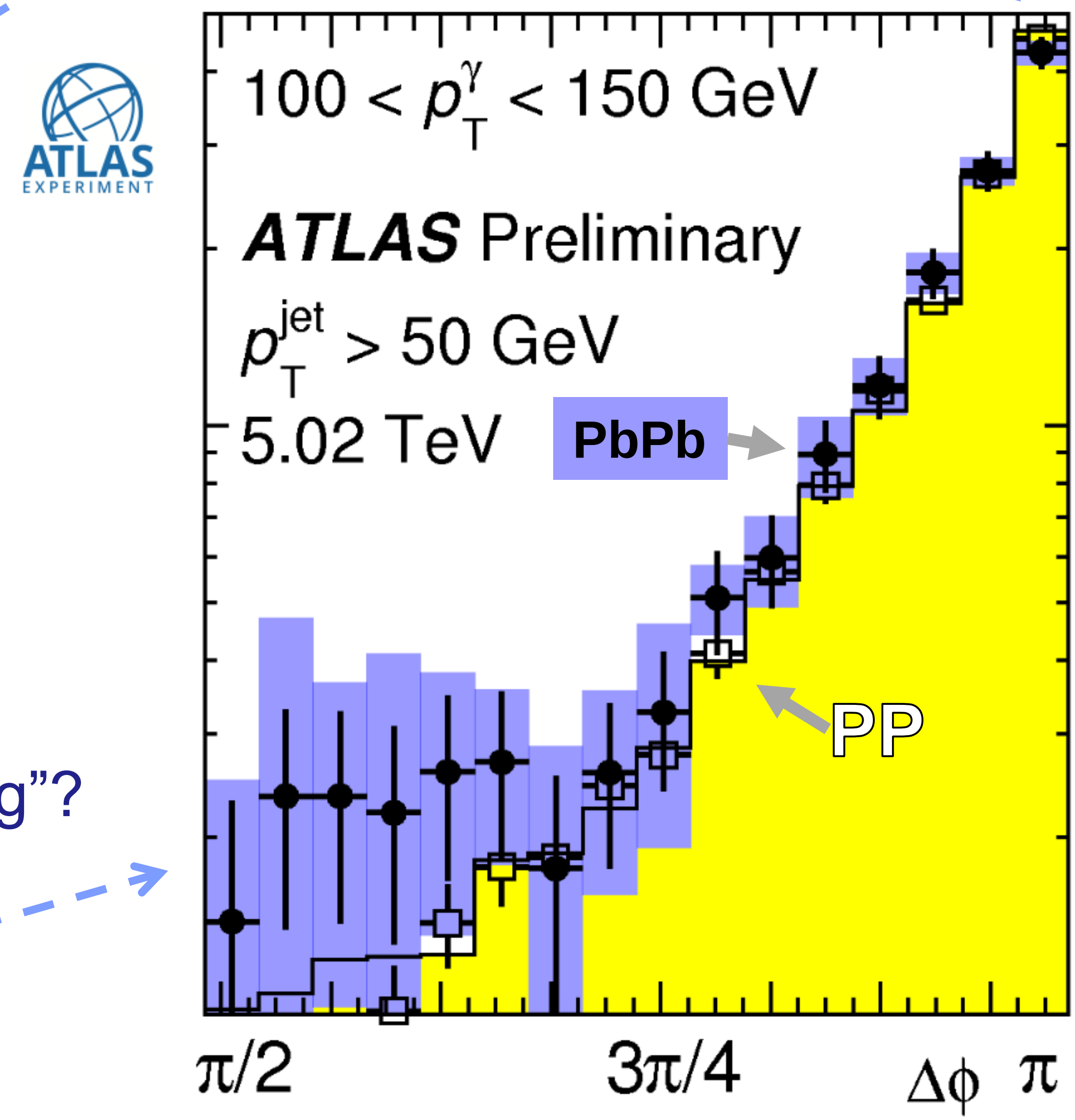
Photon p_T 40-50 GeV/c 50-60 GeV/c 60-80 GeV/c

- JEWEL: pQCD 2 to 2 scattering extrapolated to infrared region + recoil parton
- LBT: pQCD Transport model with medium recoil and thermalization of the quenched energy
- HYBRID Model: PYTHIA8 + AdS/CFT drag force (strong coupling)

Search for Quasi-Particles in the QGP

"QGP Rutherford experiment"



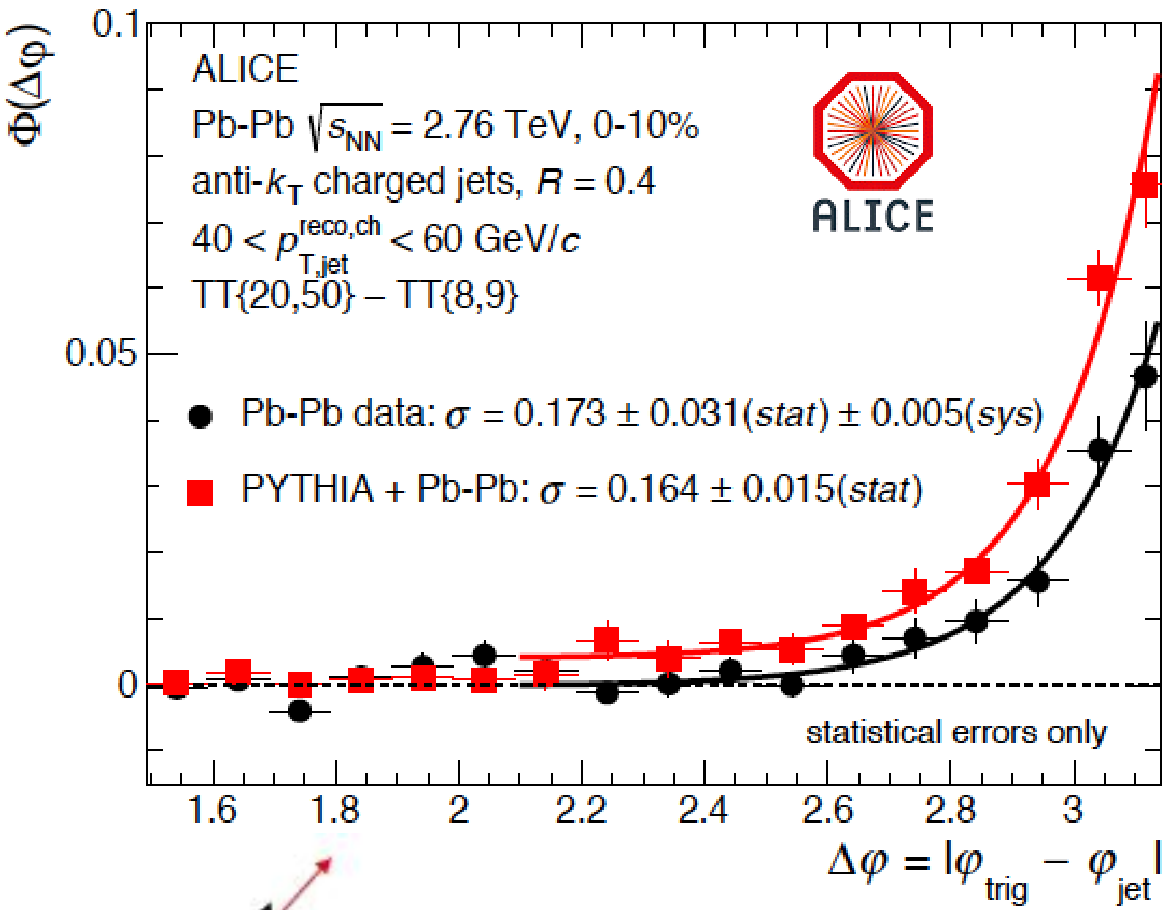


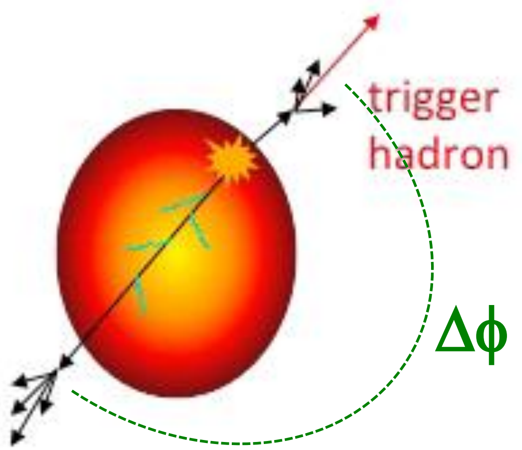
No significant modification

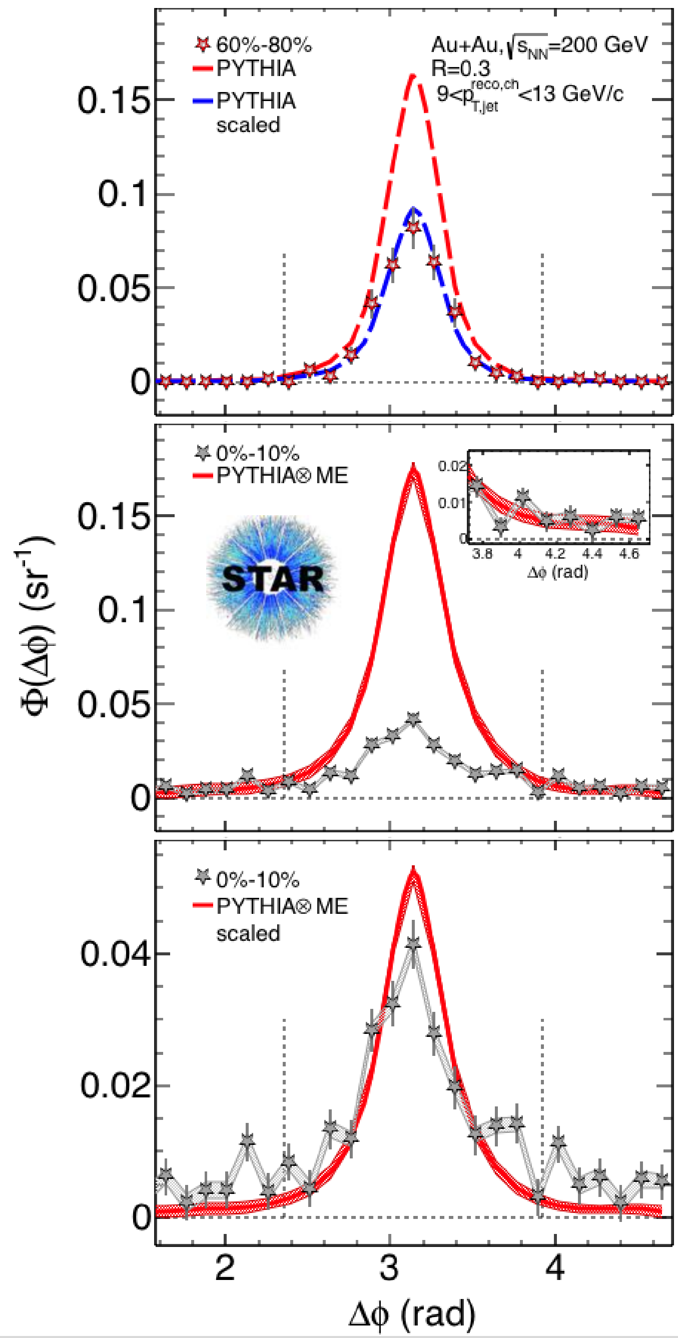
QGP probed looks smooth

ATLAS-CONF-2016-110

Hadron-Jet Angular Correlation



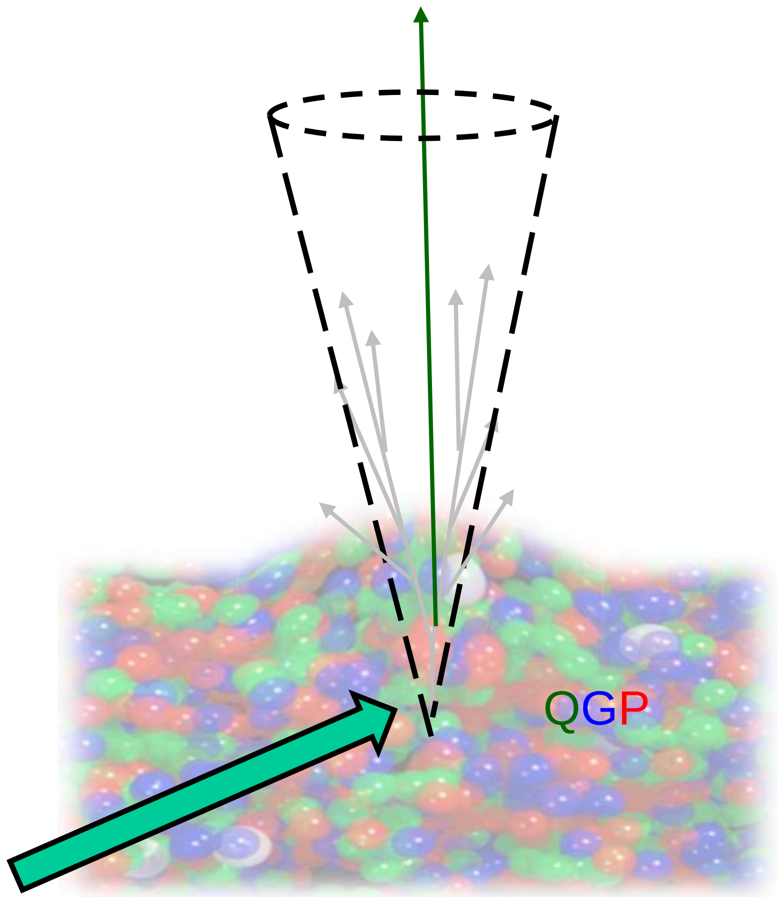




No significant broadening

QGP probed looks **smooth**

Jet Quenching

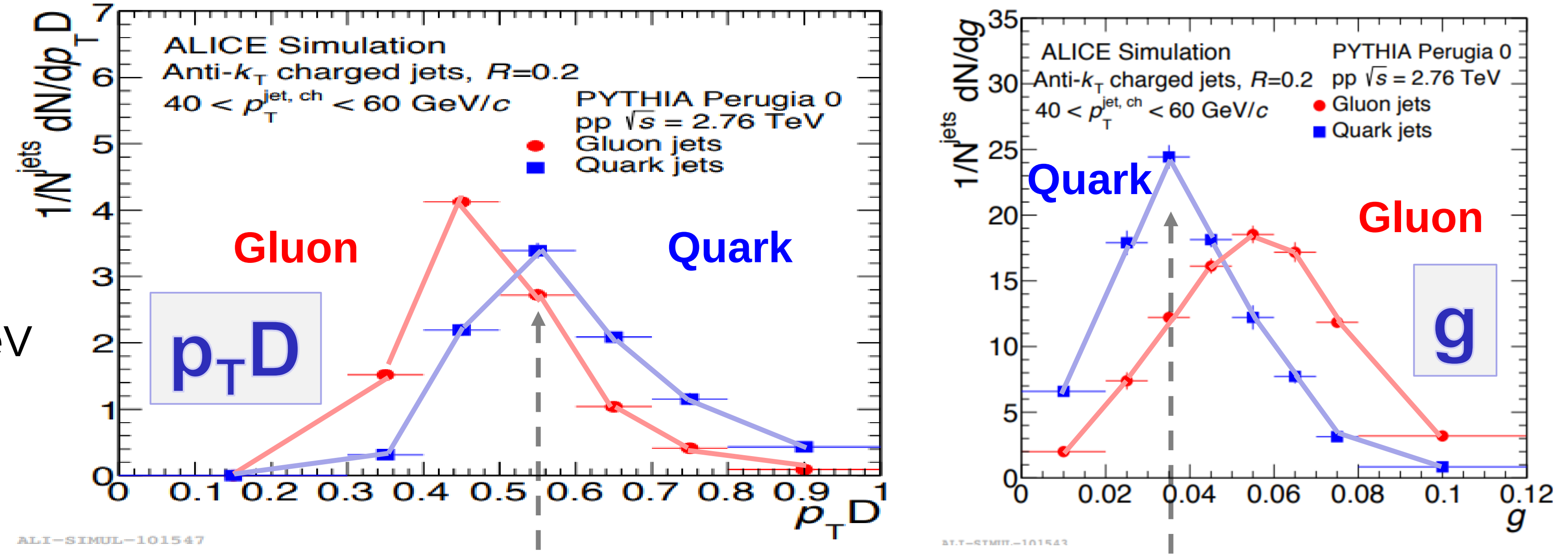


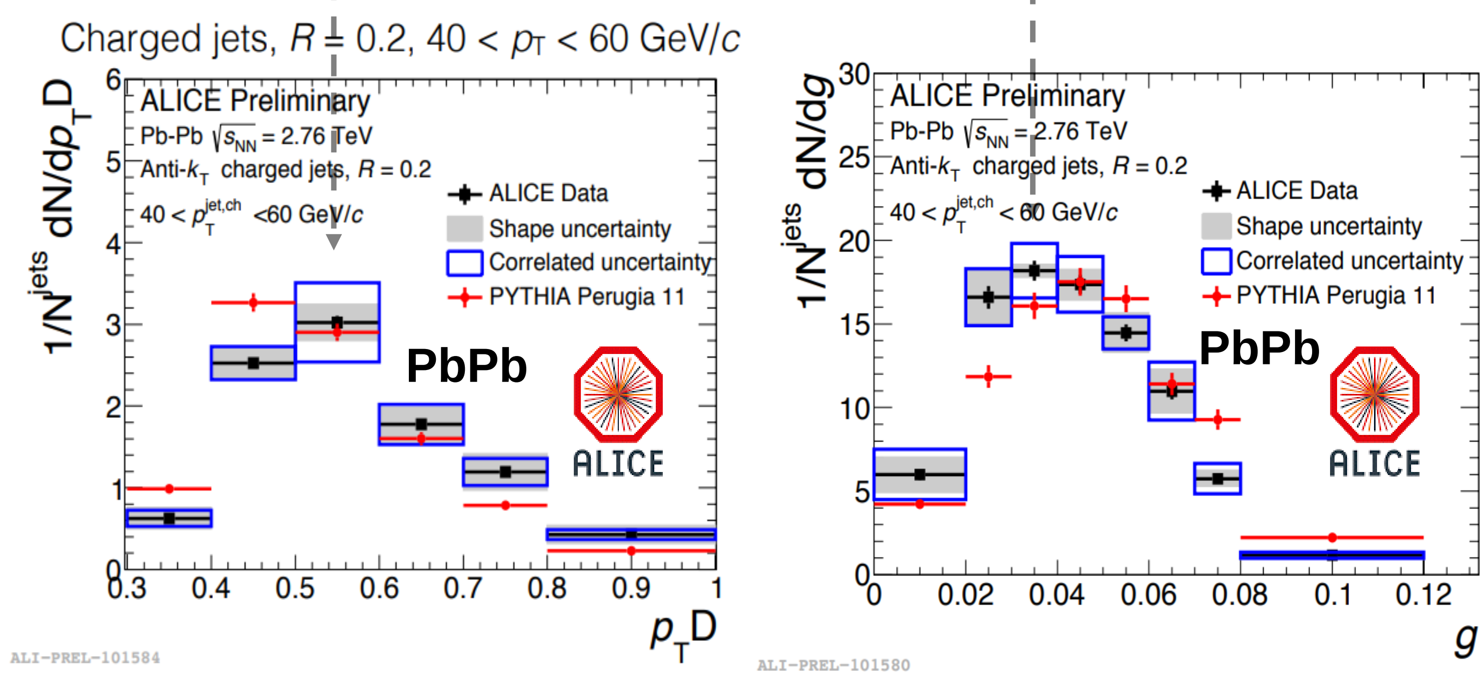
Do gluons lose more energy than the quarks?

If Yes: Gluon jet to quark jet ratio will decrease (Gluon jets are more suppressed)

Charged Jet $p_T D$ (Dispersion) and Jet Girth

Anti-k_T R=0.2
40<p_T<60 GeV



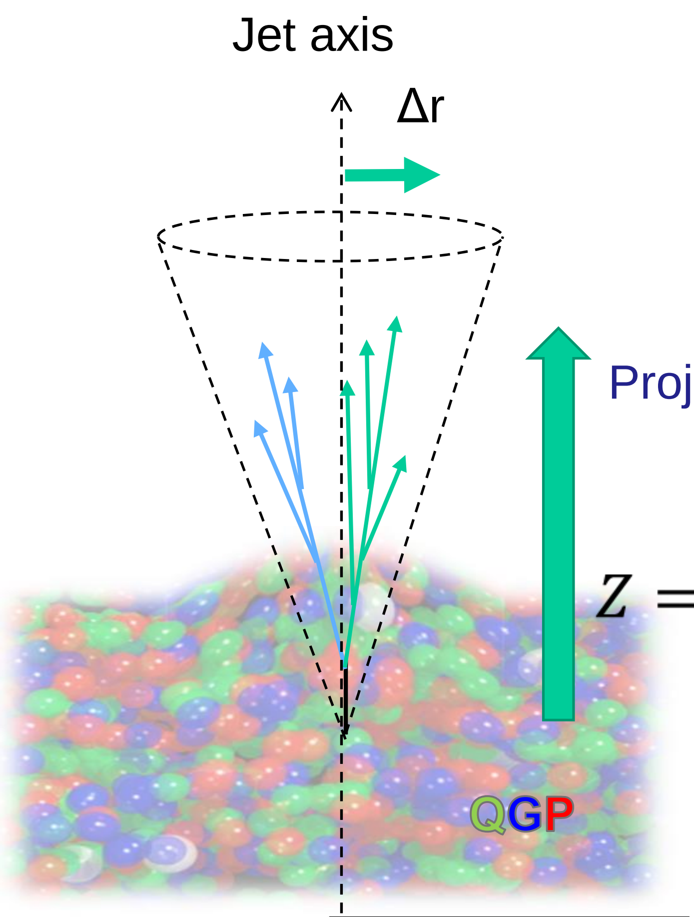


$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

$$g = \sum_{i \in jet} \frac{p_T^i}{p_T^{jet}} |r_i|$$

- Jets in PbPb are more **Quark-like**! (Gluon jets suppressed)

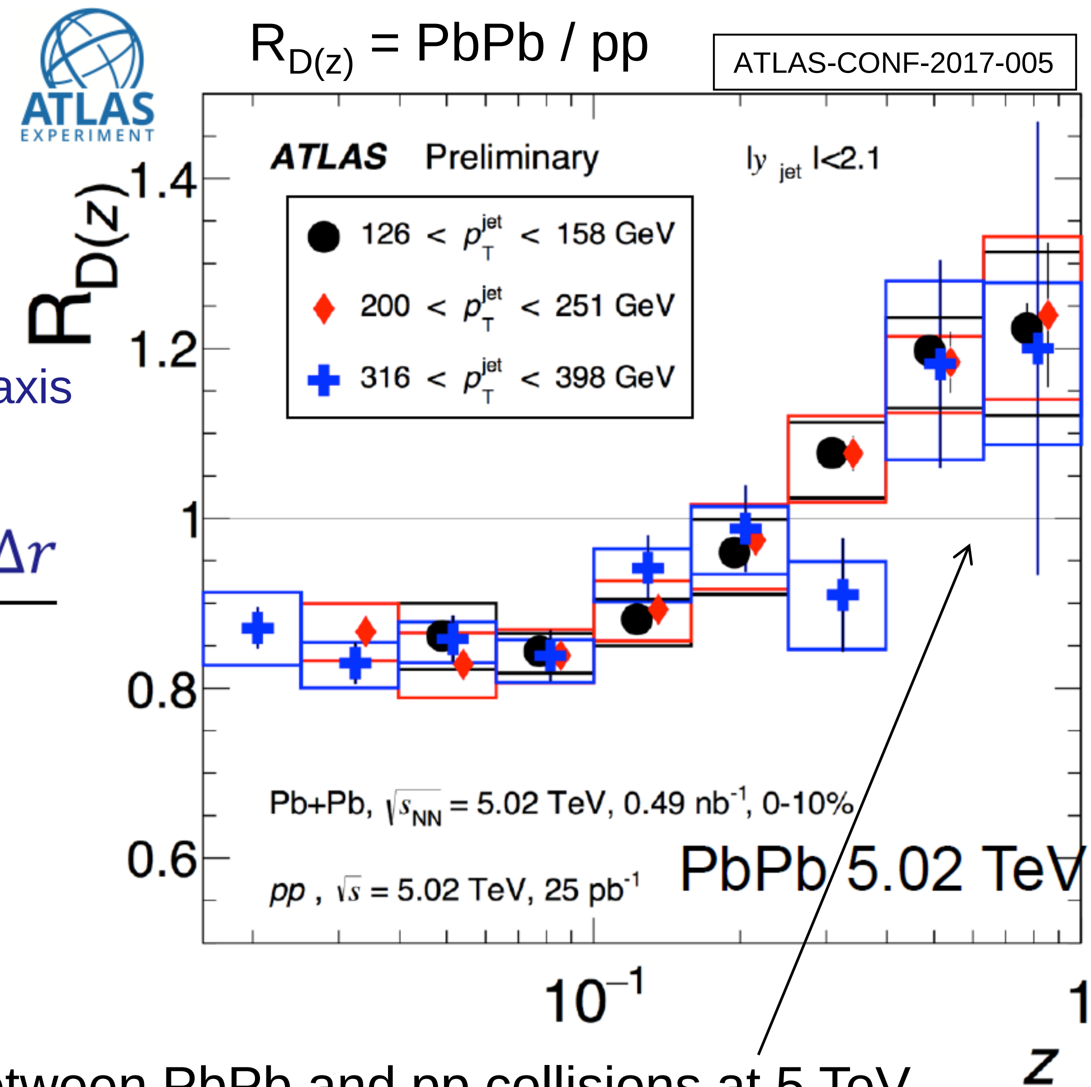
Jet Longitudinal Structure



Projection to jet axis

$$Z = \frac{p_T^{Trk} \cos \Delta r}{p_T^{Jet}}$$

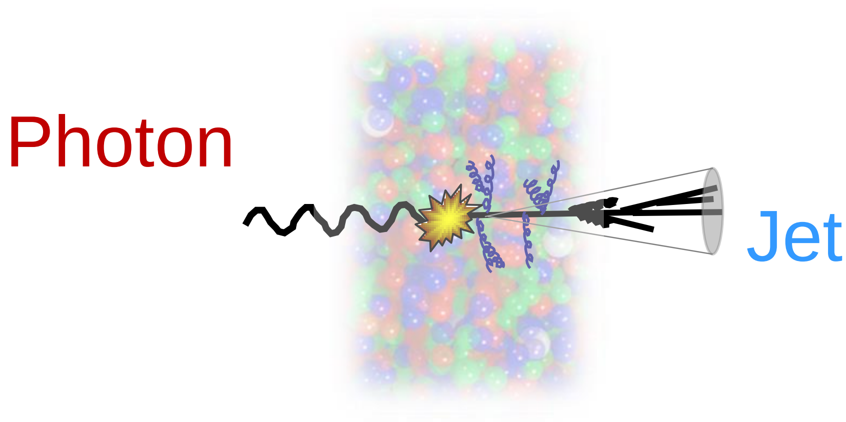
$$\Delta r = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

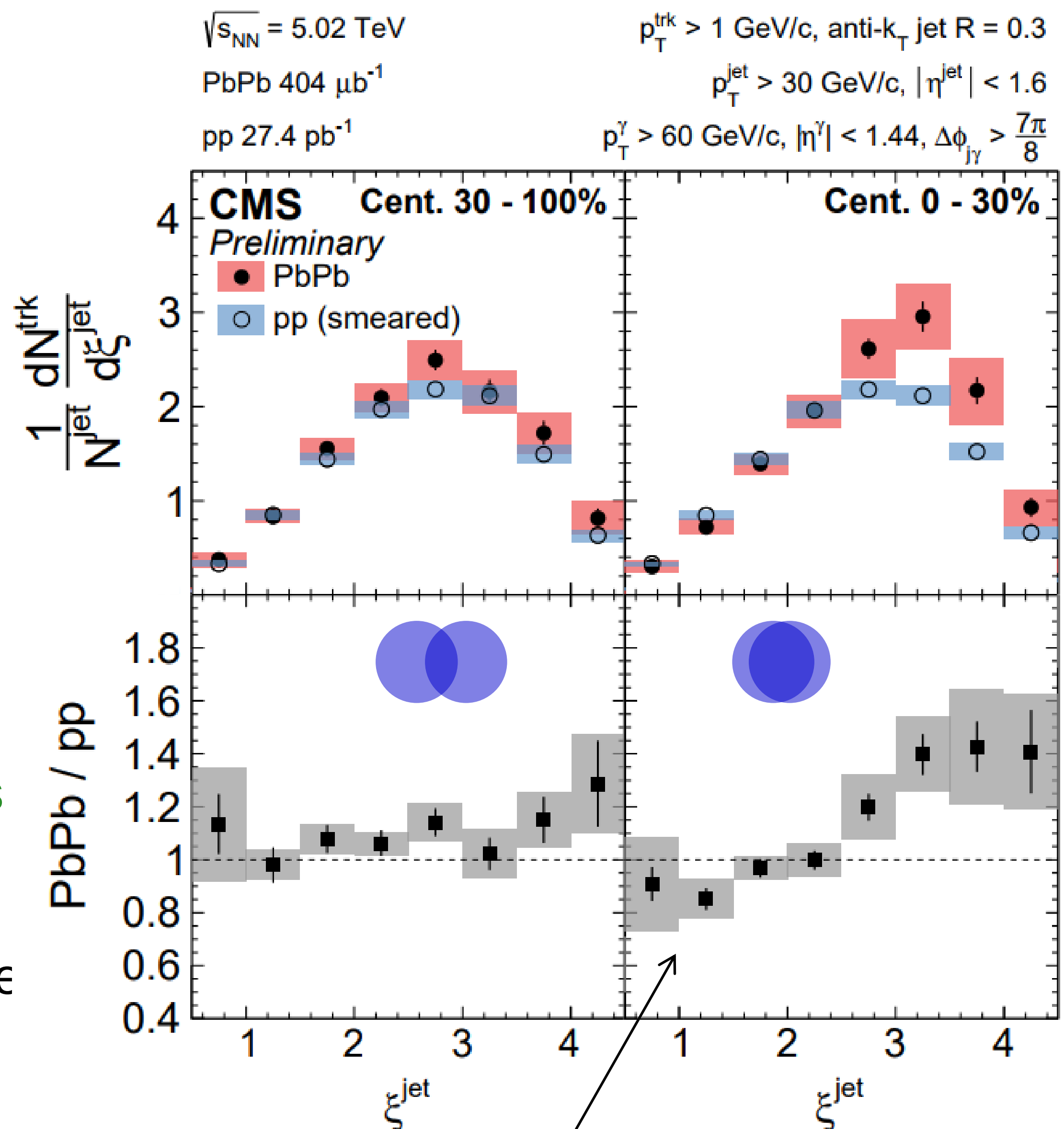


- Fragmentation functions Ratio $R_{D(z)}$ between PbPb and pp collisions at 5 TeV
- Enhancement at large z (high p_T particles in jet): **smaller gluon/quark ratio** in PbPb
- Weak or no dependence on the jet p_T

→ **If switch to γ-tagged jet (mainly quarks), will this enhancement go away?**

Photon-Tagged Fragmentation Function



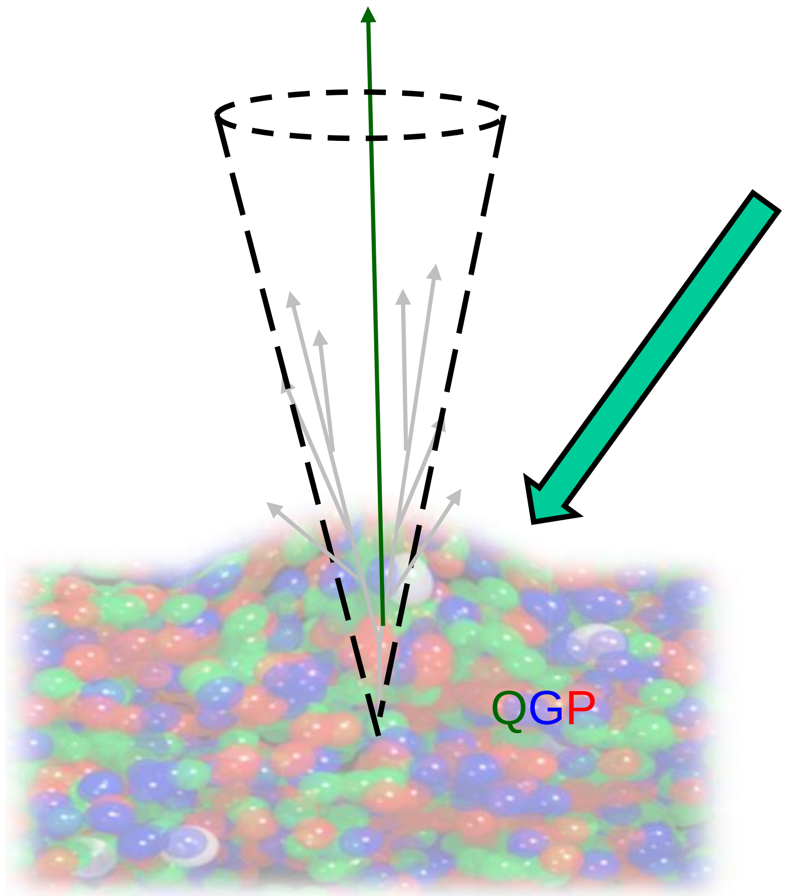


- First γ-tagged fragmentation function!
- Decrease the population of gluon jets: **~70%** of the tagged jets are quark jets
- Significant modification in PbPb with respect to pp reference is observe

- No high z (or small ξ=ln(1/z)) enhancement observed!

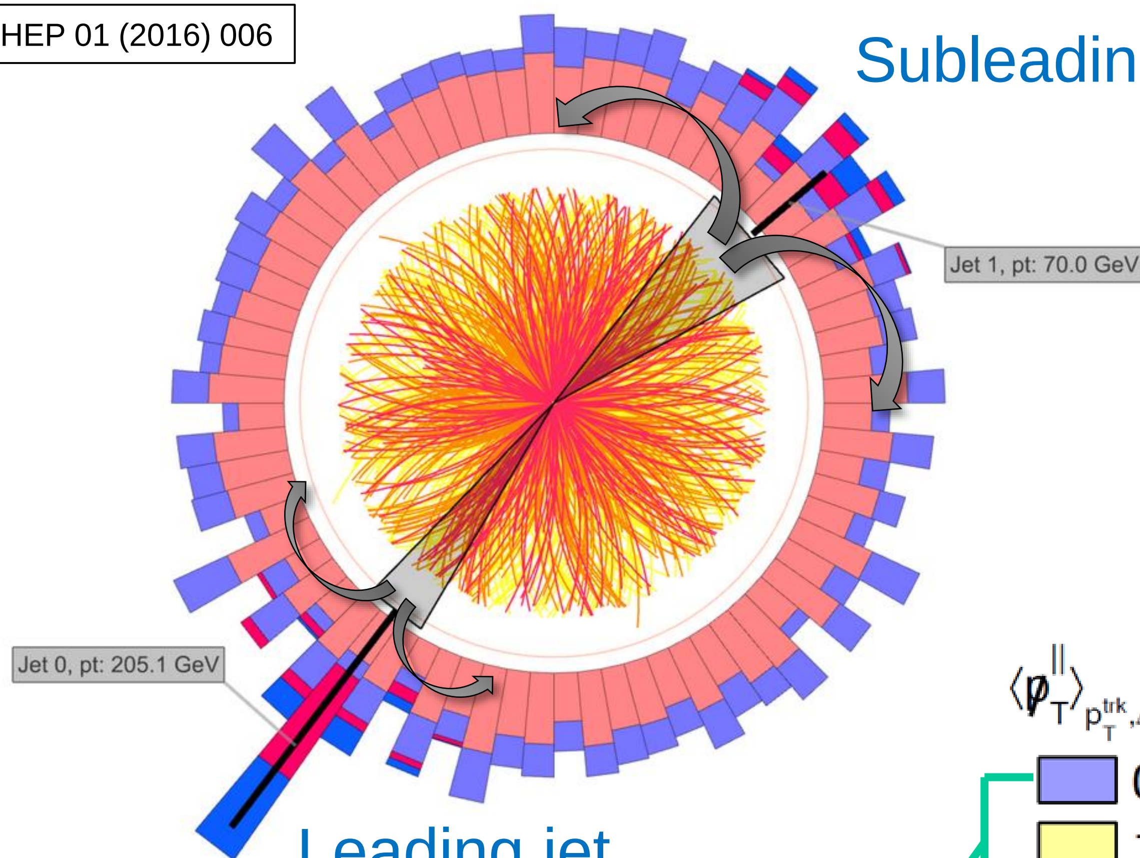
Jet Quenching

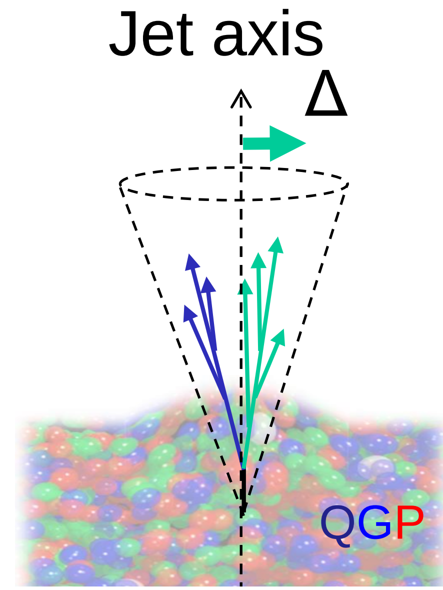
Do we see medium response?



Where does the Quenched Energy Go?

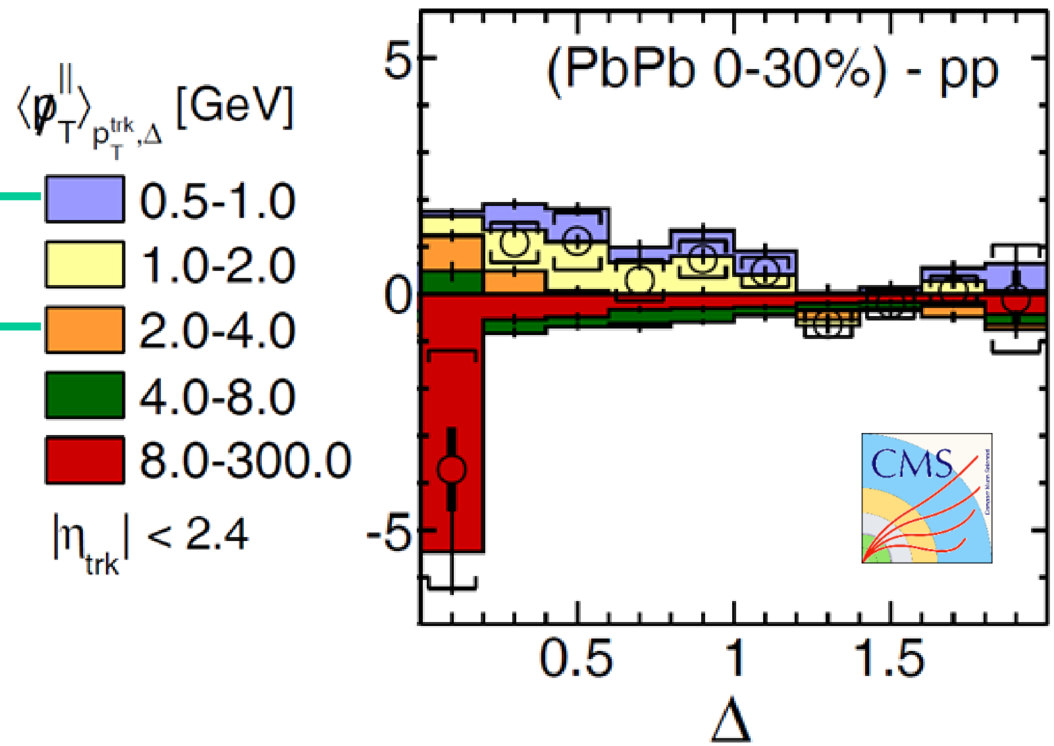
JHEP 01 (2016) 006





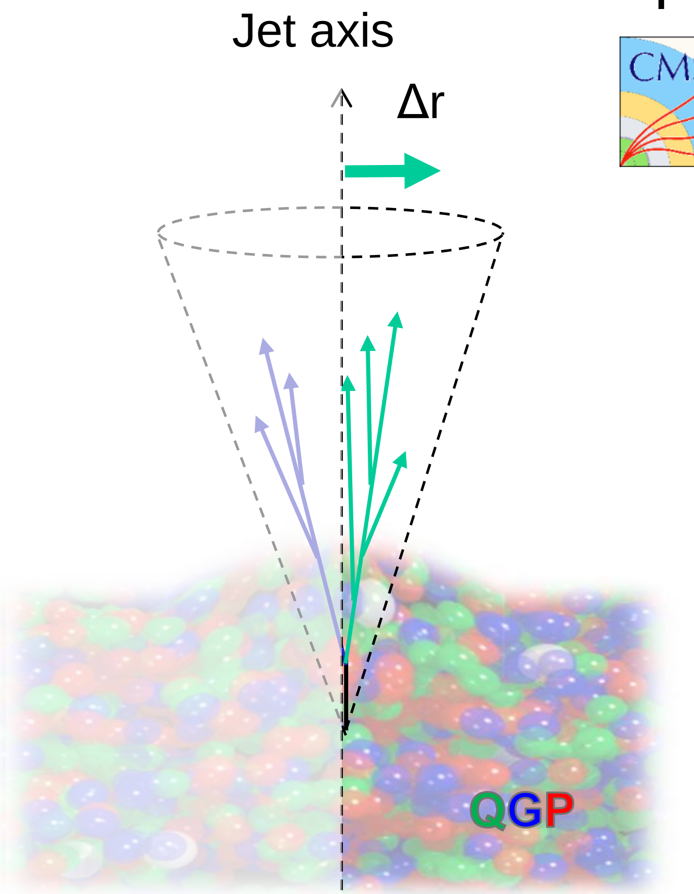
- Quenched energy carried by **low momentum particles!**
- Average momentum of those particles are **higher** than that from medium debris

→ Not Completely Thermalized?

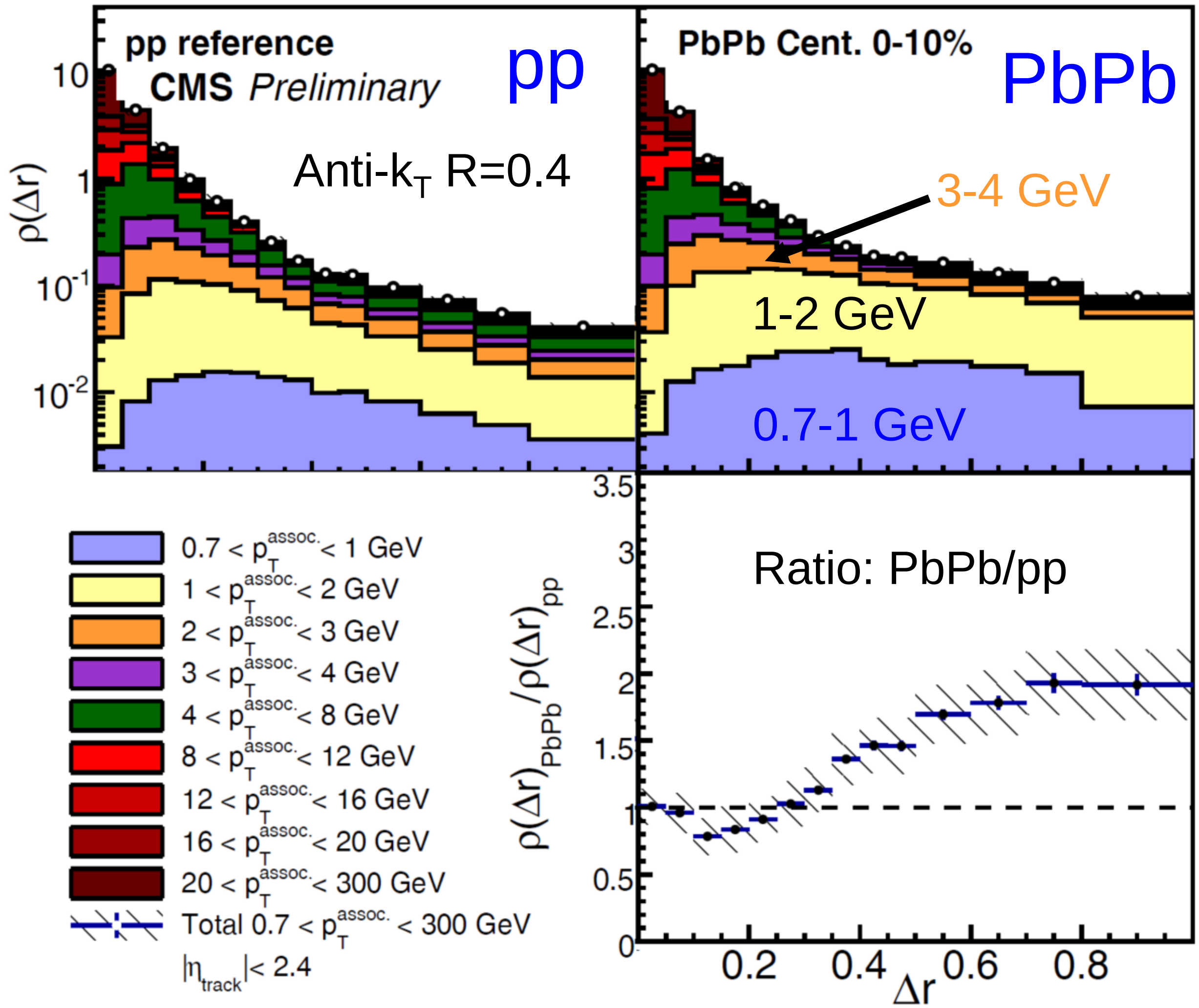


Jet Transverse Structure

Jet shapes in pp and PbPb at 5.02 TeV



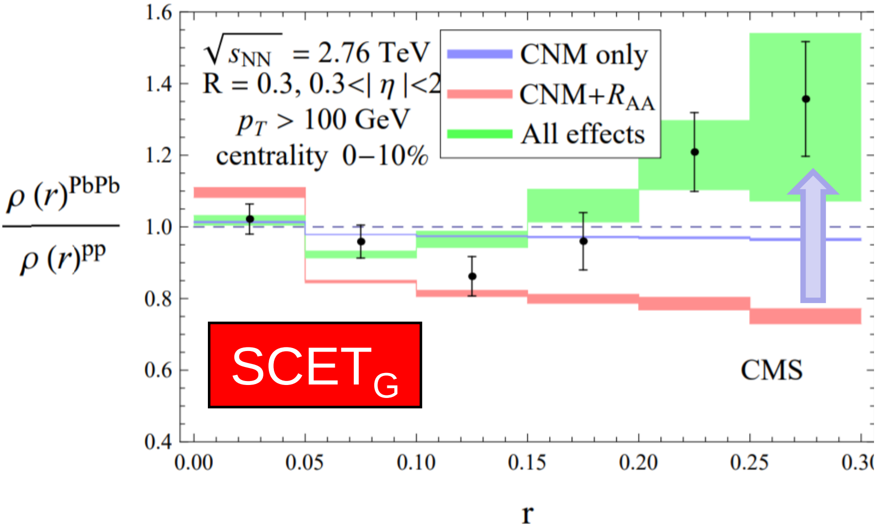
$$\Delta r = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

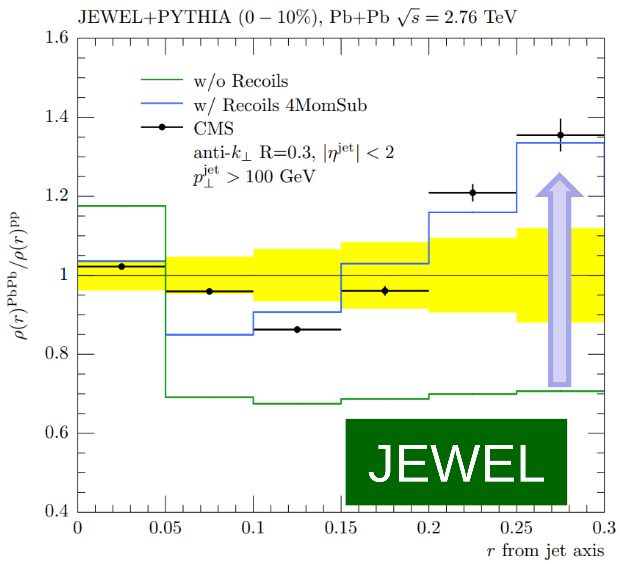


CMS-PAS-HIN-16-020

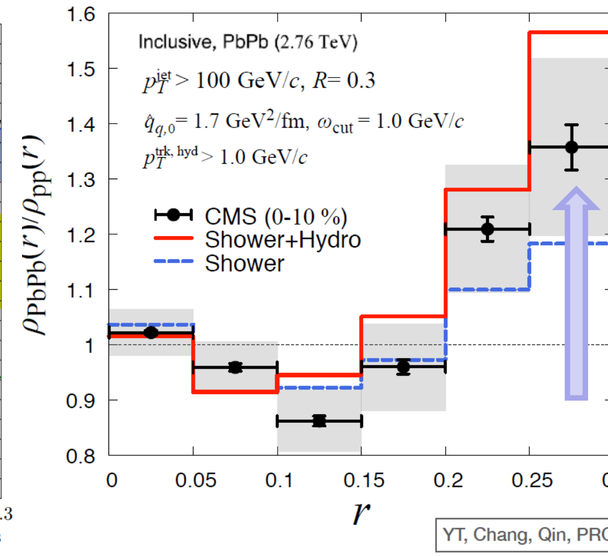
- Jet shapes and fragmentation functions in pp and PbPb collisions at 5 TeV
- Sensitive to the possible **medium response** to hard probes and **induced radiation**

Theoretical Interpretation of the excess





arXiv:1707.01539

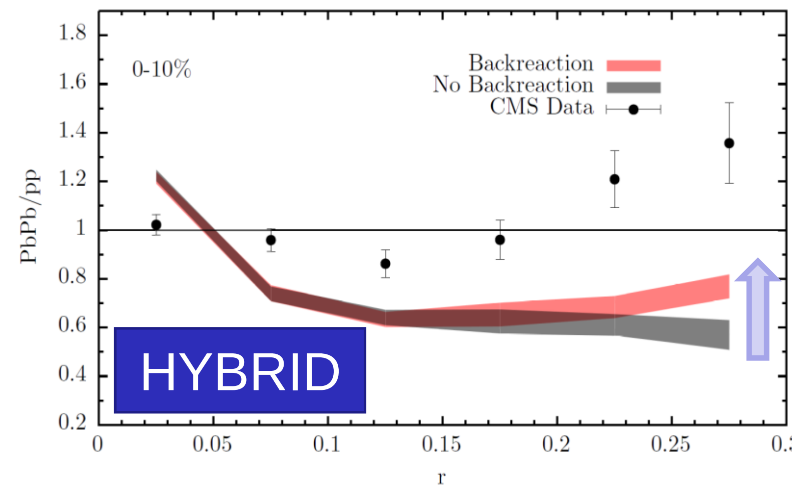


CCNU

arXiv:1701.07951

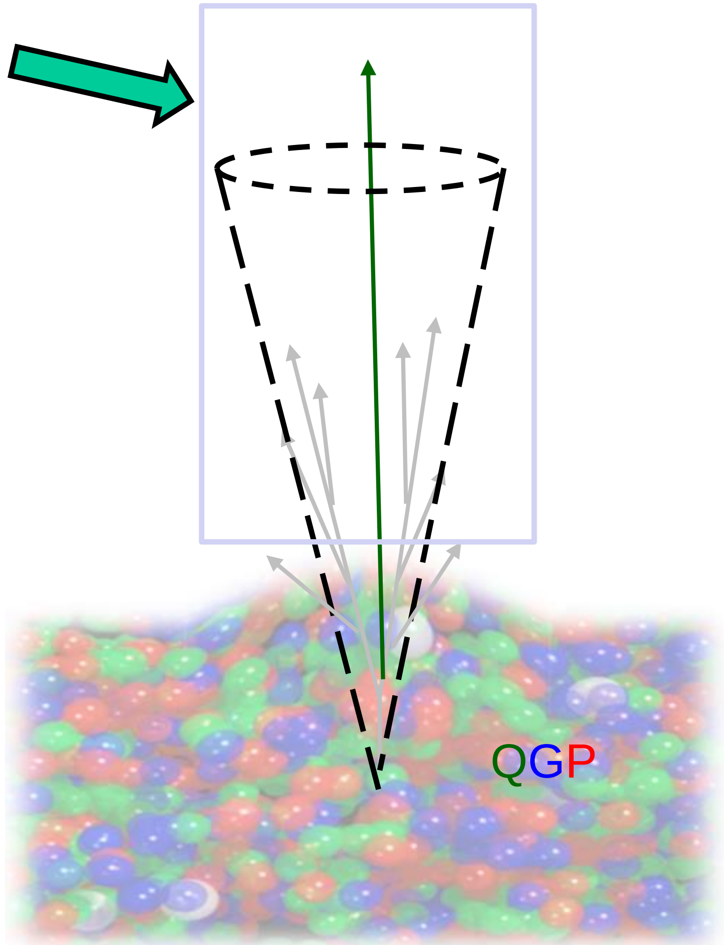
Different explanation of the large angle enhancement in jet shape measurement

- SCET$_G$: Splitting function (large angle radiation)
- JEWEL & JETSCAPE: medium recoil parton
- CCNU: recoil parton + hydro dynamical evolution
- HYBRID: fully thermalized medium response



See talk from Ivan Vitev, Yasuki Tachibana, Abhijit Majumder

Jet Quenching

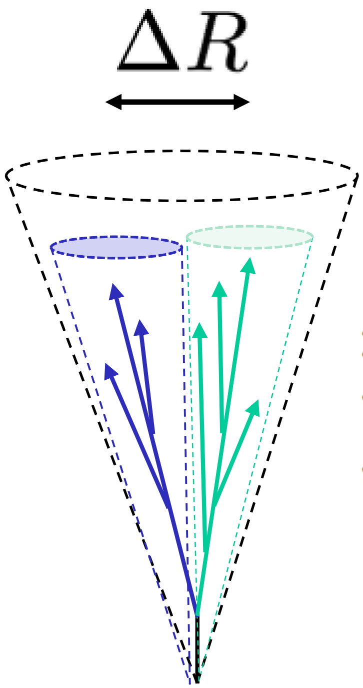


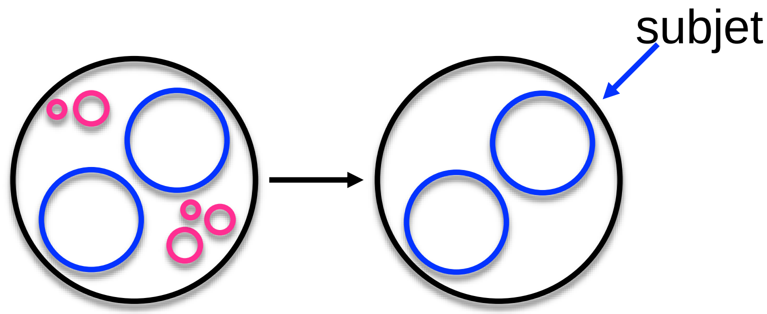
Can we **groom away the soft radiation?** (focus on the hard jet core)
Can jet quenching depends on the structure of parton shower?

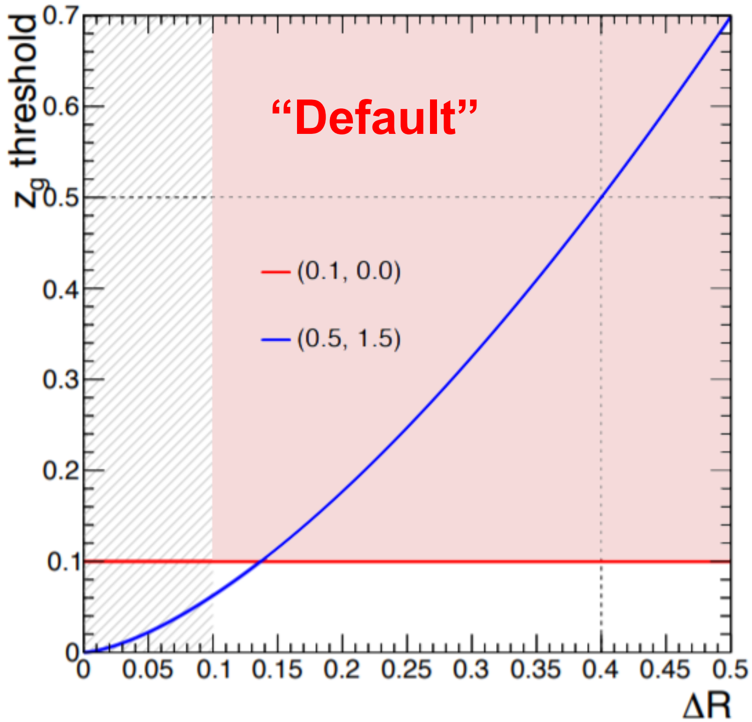
Groomed Jet Substructure with Soft Drop

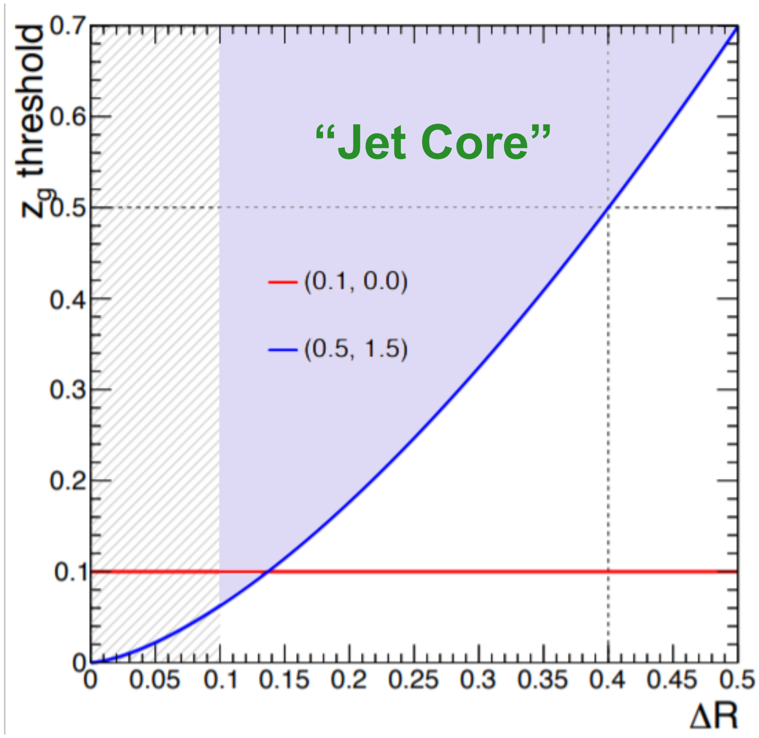
CMS: used two grooming settings with ΔR>0.1 cut

$$z_g \equiv \frac{\min(p_1, p_2)}{p_1 + p_2} > z_{\rm cut} \left(\frac{\Delta R}{R_0}\right)^{\beta}$$





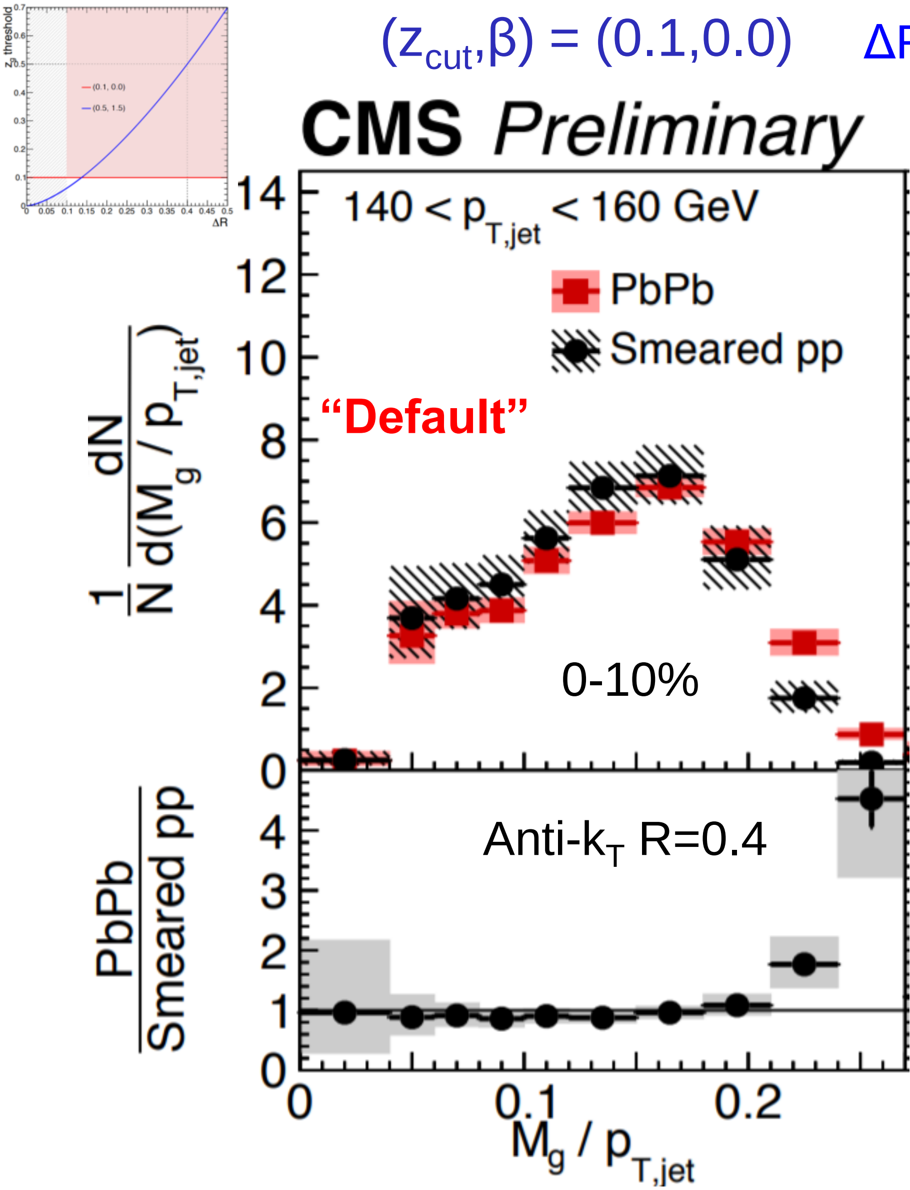




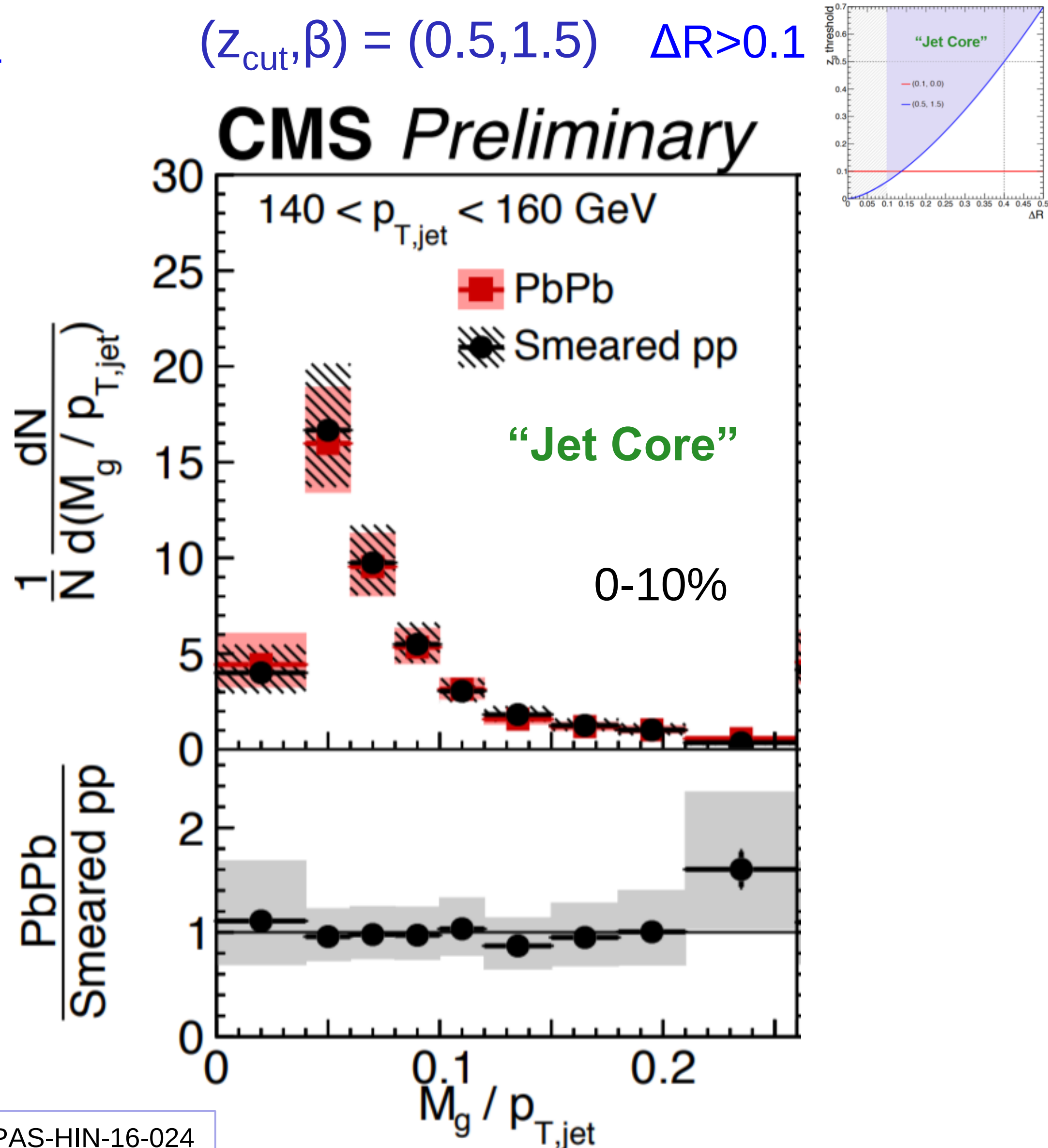
From Yi Chen

Groomed Jet Mass

$(z_{cut},\beta) = (0.1,0.0)$ $\Delta R>0.1$



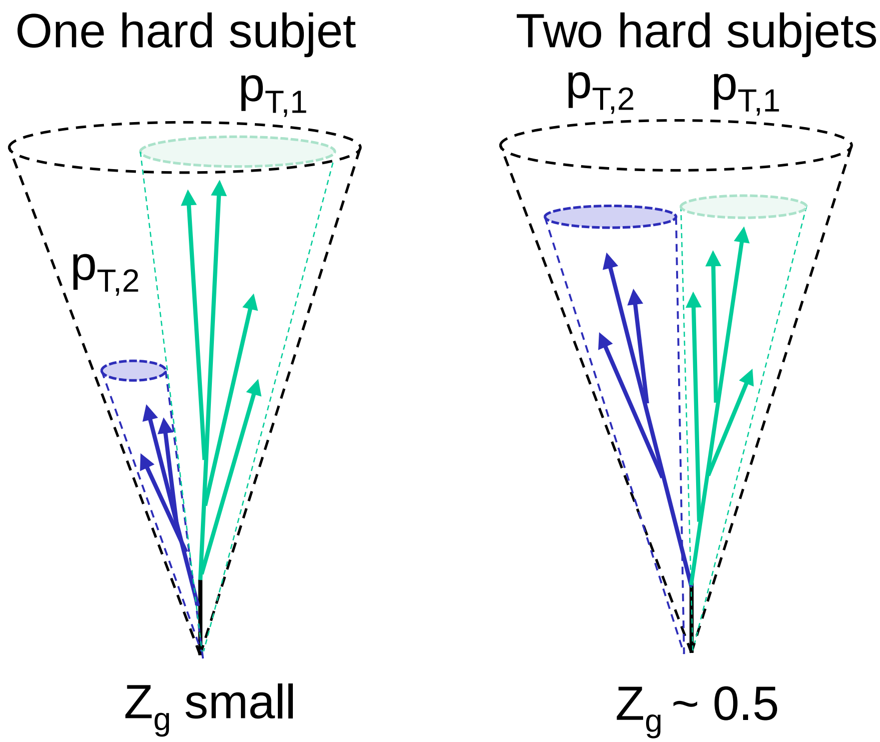
$(z_{cut},\beta) = (0.5,1.5)$ $\Delta R>0.1$



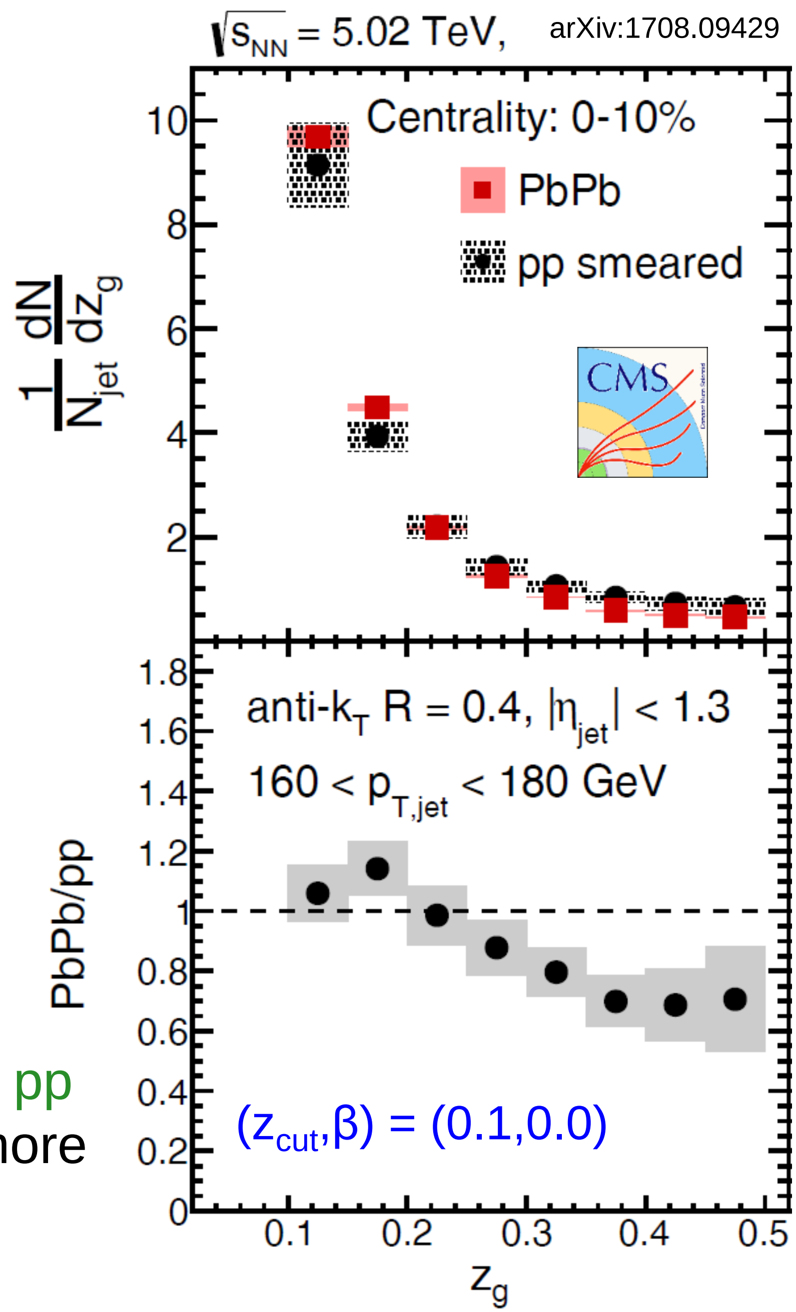
CMS-PAS-HIN-16-024

- Enhancement of large mass when looking at a less aggressive grooming setting
- Results with a "more aggressive grooming"
- No significant modification of the "jet core"

Momentum Sharing of Subjets



$$Z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$

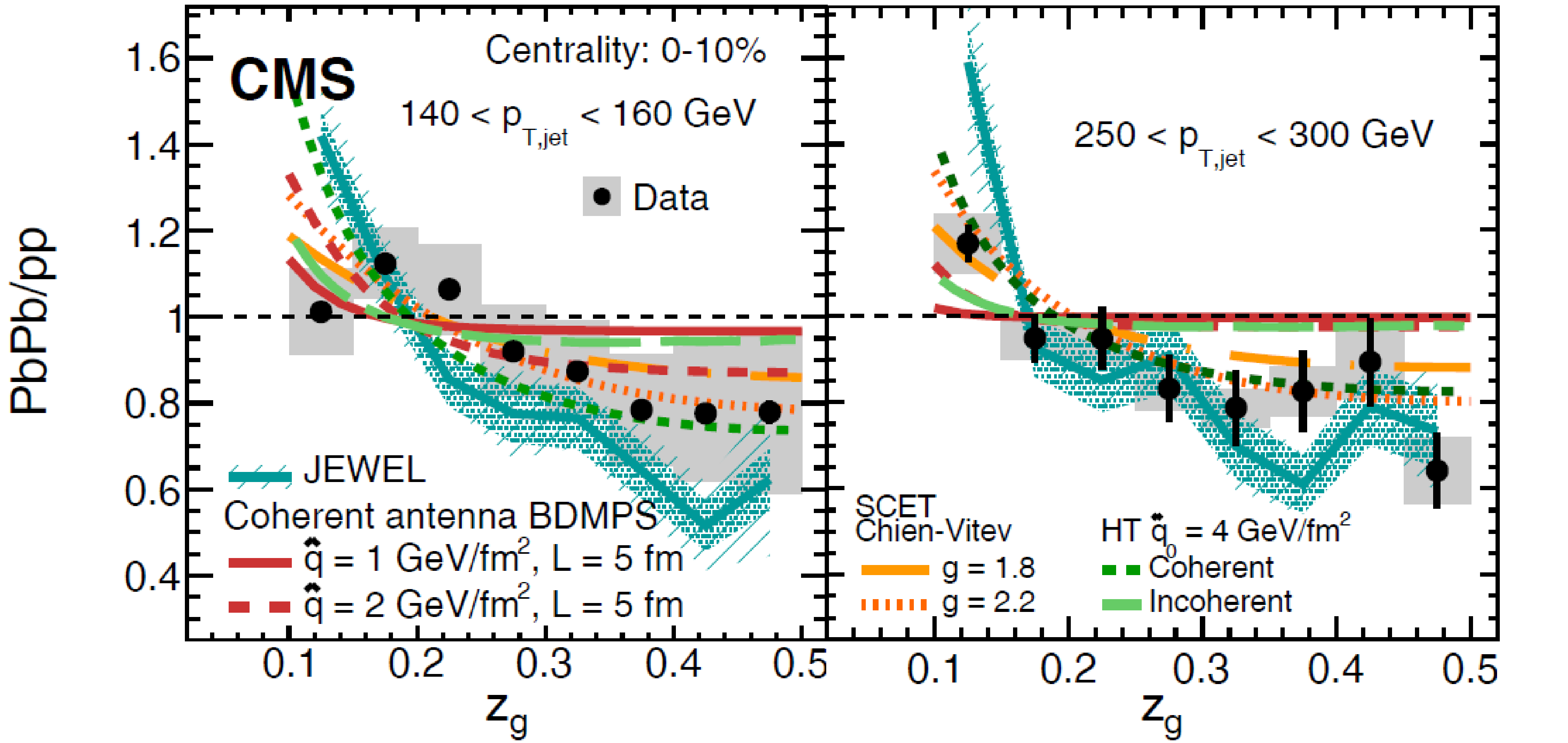


- Quark and gluon Z_g distributions are very similar in pp
- Jets with two hard subjets (large Z_g) **"relatively"** more suppressed than jets with a single core (small Z_g)

(Or small Z_g is enhanced)

CMS Groomed Jet Splitting Function

arXiv:1708.09429



- **JEWEL**: enhancement of low Z_g jets (due to **medium recoil**)
- **SCET$_G$**: modification due to medium induced splitting function
- **HT** & **Coherent antenna BDMPS**: Data prefer coherent energy loss
- **Measurement of r_g and groomed R_{AA} would help to separate models**

Summary

- Consistent picture of energy flow with respect to jet at LHC from ALICE, ATLAS and CMS
  - Modification of jet shapes and fragmentation function
  - Jet substructure become more quark-like
  - Quenched energy out of the cone (R>0.5) carried by low p_T particle

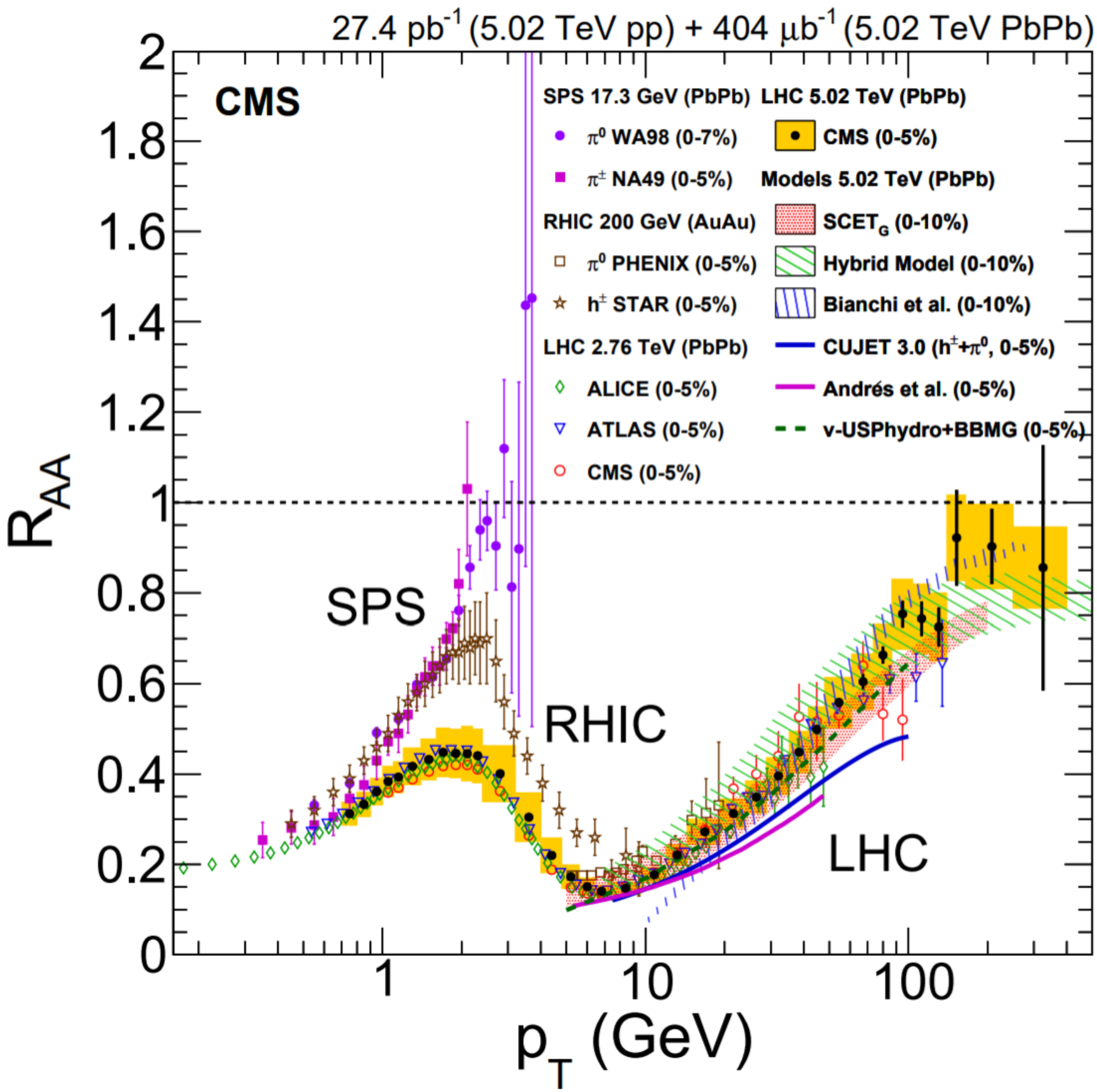
- Hint of medium response from LHC data
  - Different interpretations from theory groups

- Situation at RHIC is not as clear as at LHC
  - Opportunity for STAR and sPHENIX

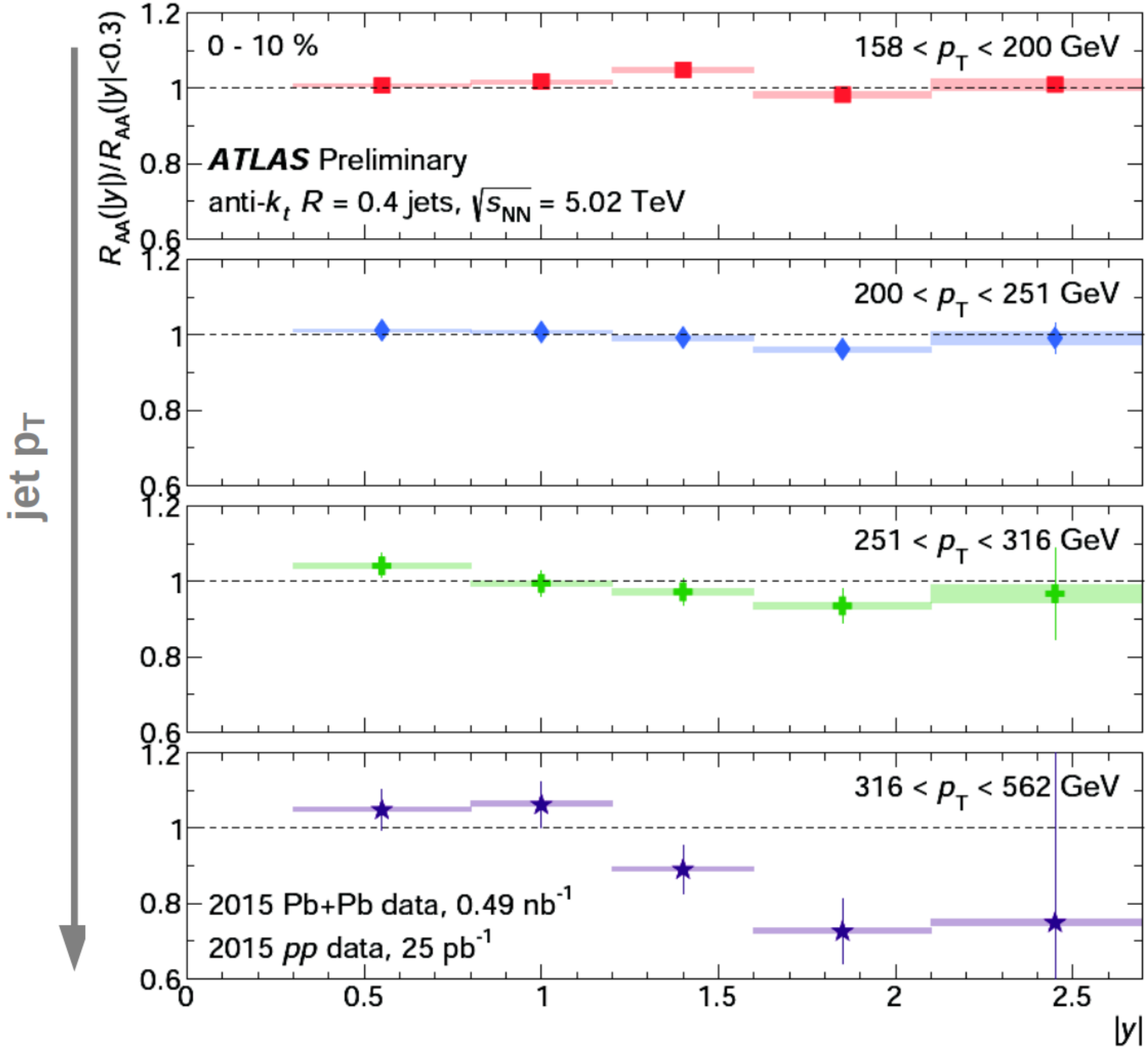
- "Parton shower shape dependence" of jet quenching:
  - Groomed jet substructure: a power tool for the highly differential studies of jet quenching

Backup slides

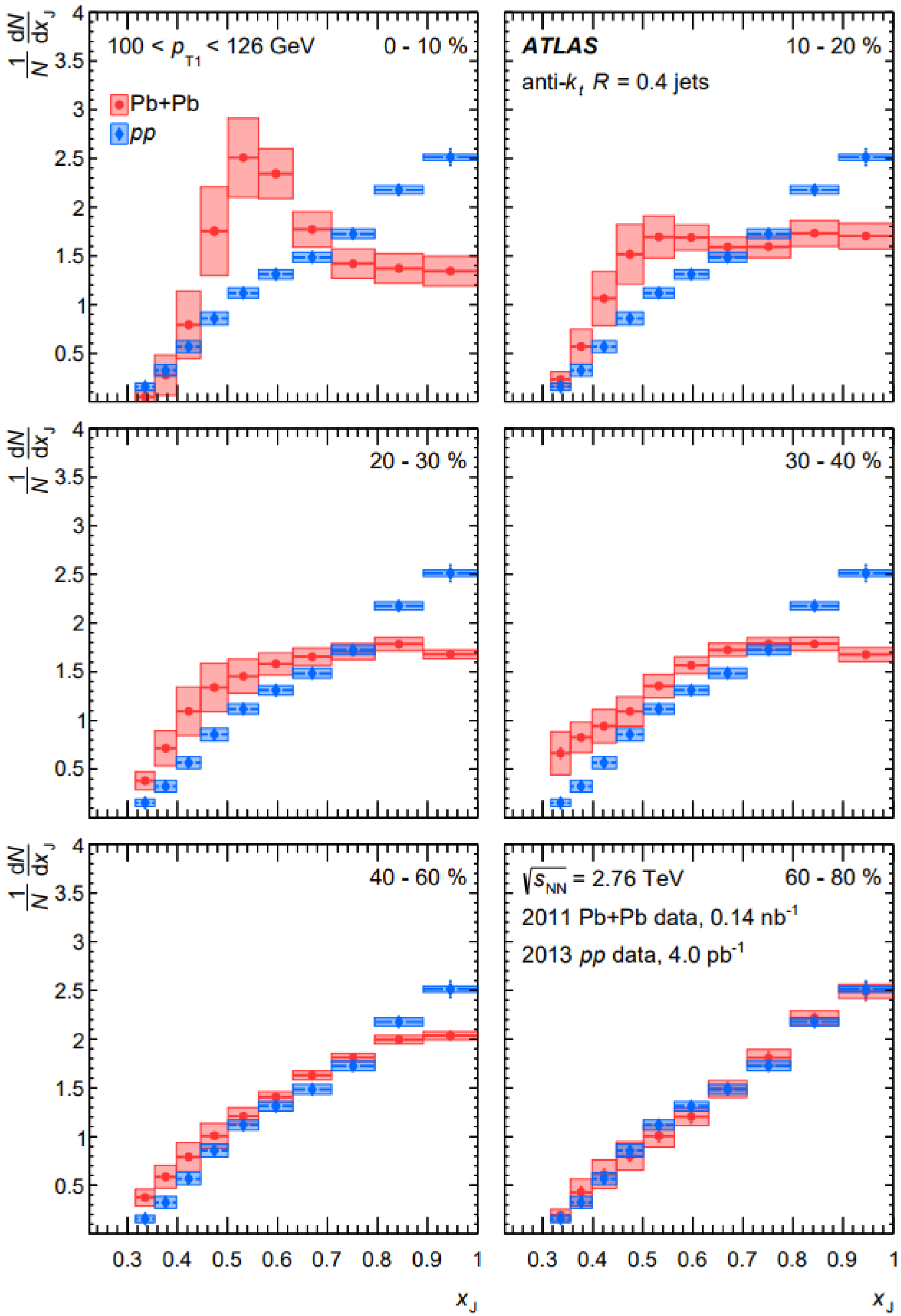
Compilation of the charged hadron R_{AA}



Jet R_{AA} vs. rapidity



Dijet asymmetry

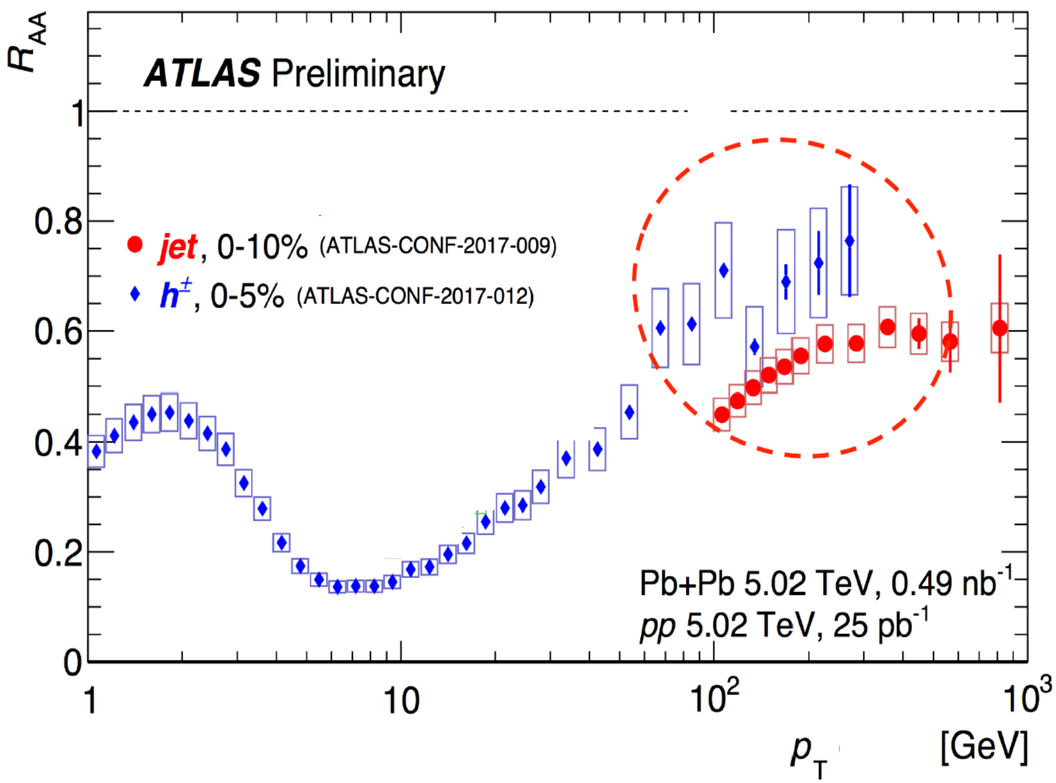


- Progress on the 2-D unfolding from ATLAS
- Hint of peak structure in the low pT bin observed at the threshold

Jet Longitudinal Structure

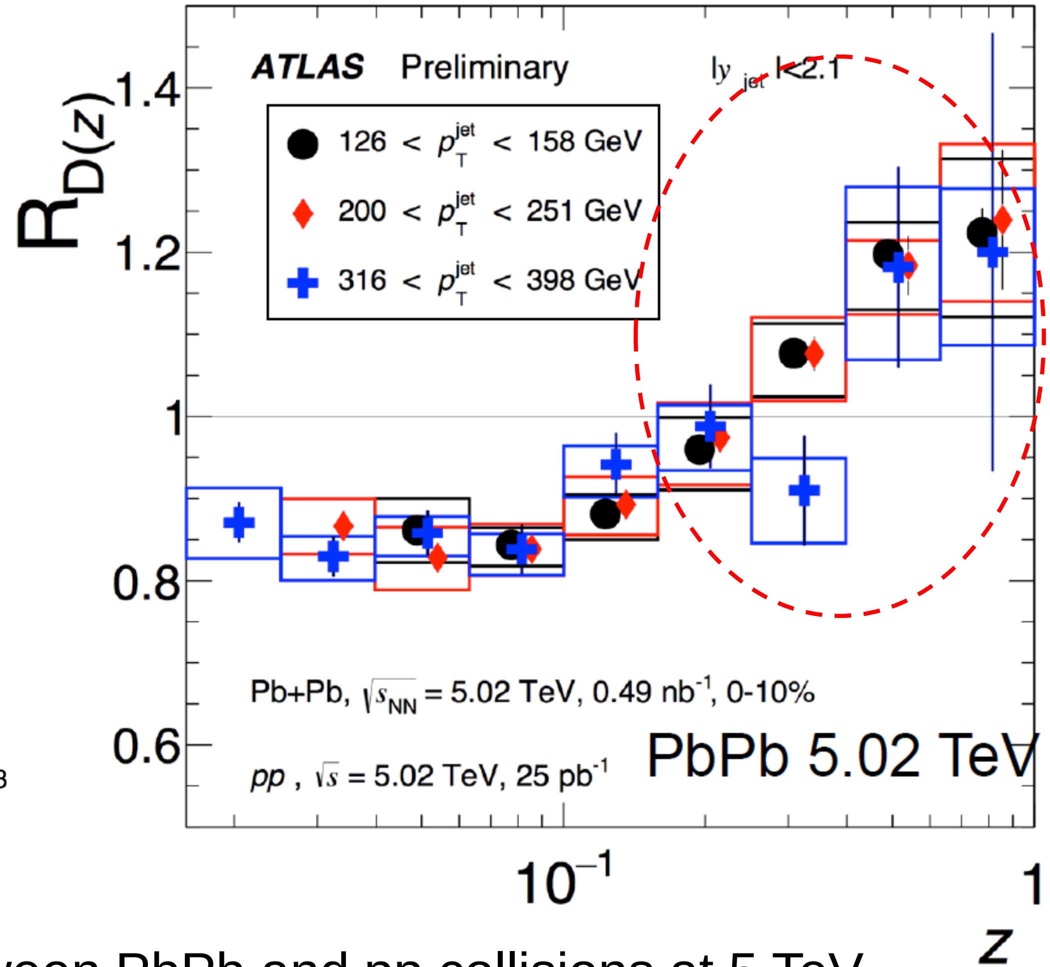
Charged hadron R_{AA}

Jet R_{AA}



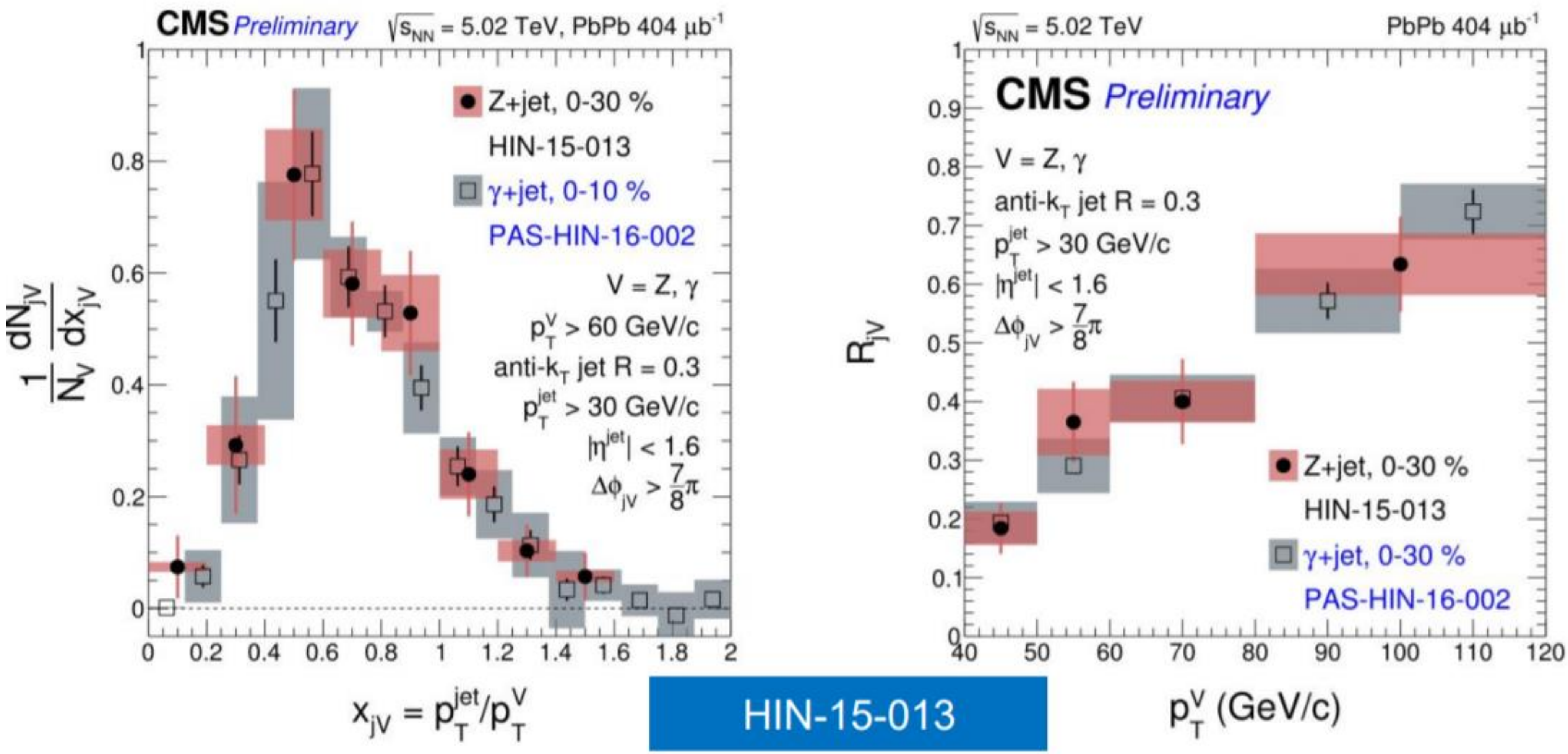
$R_{D(z)}$ = PbPb / pp

ATLAS-CONF-2017-005



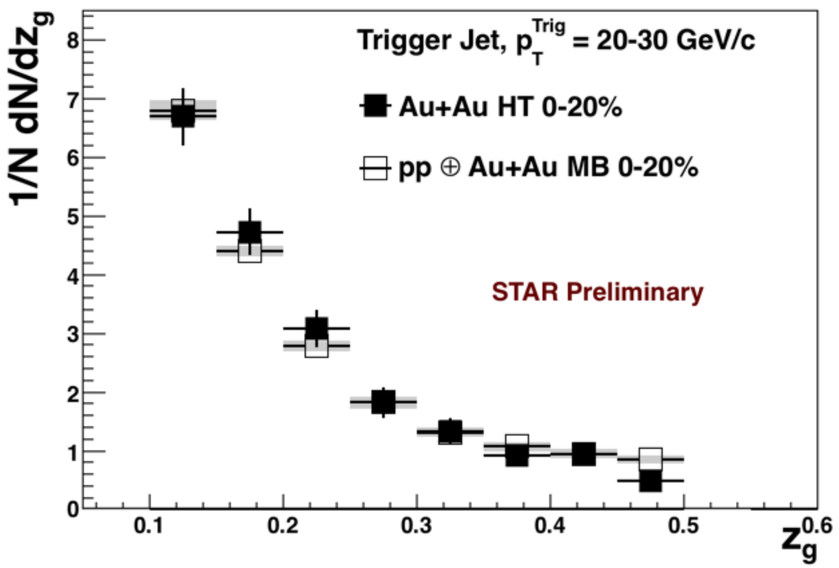
- Fragmentation functions Ratio $R_{D(z)}$ between PbPb and pp collisions at 5 TeV
- Enhancement at large z: consistent with **smaller gluon/quark ratio** in PbPb data
- Modified fragmentation could be the reason why high p_T charged hadron R_{AA} > jet R_{AA}

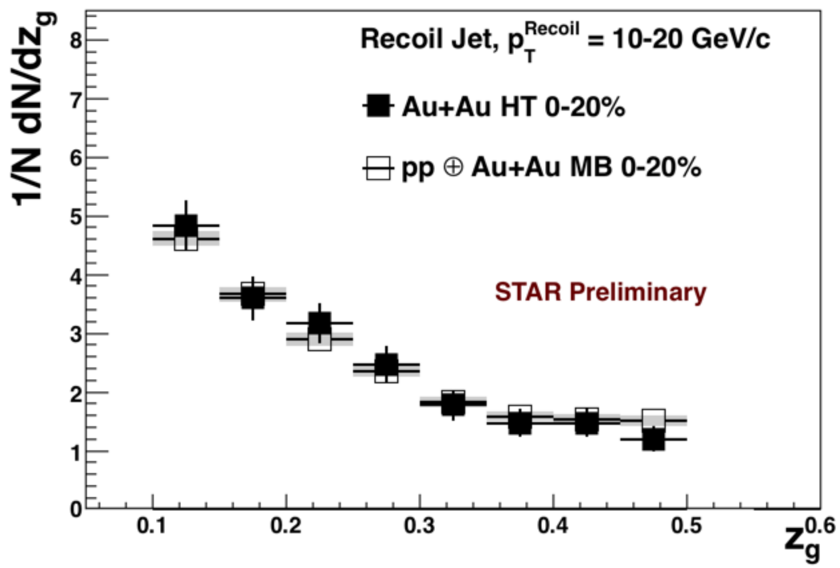
Comparison between Z-Jet and Photon-Jet



STAR Jet Splitting function

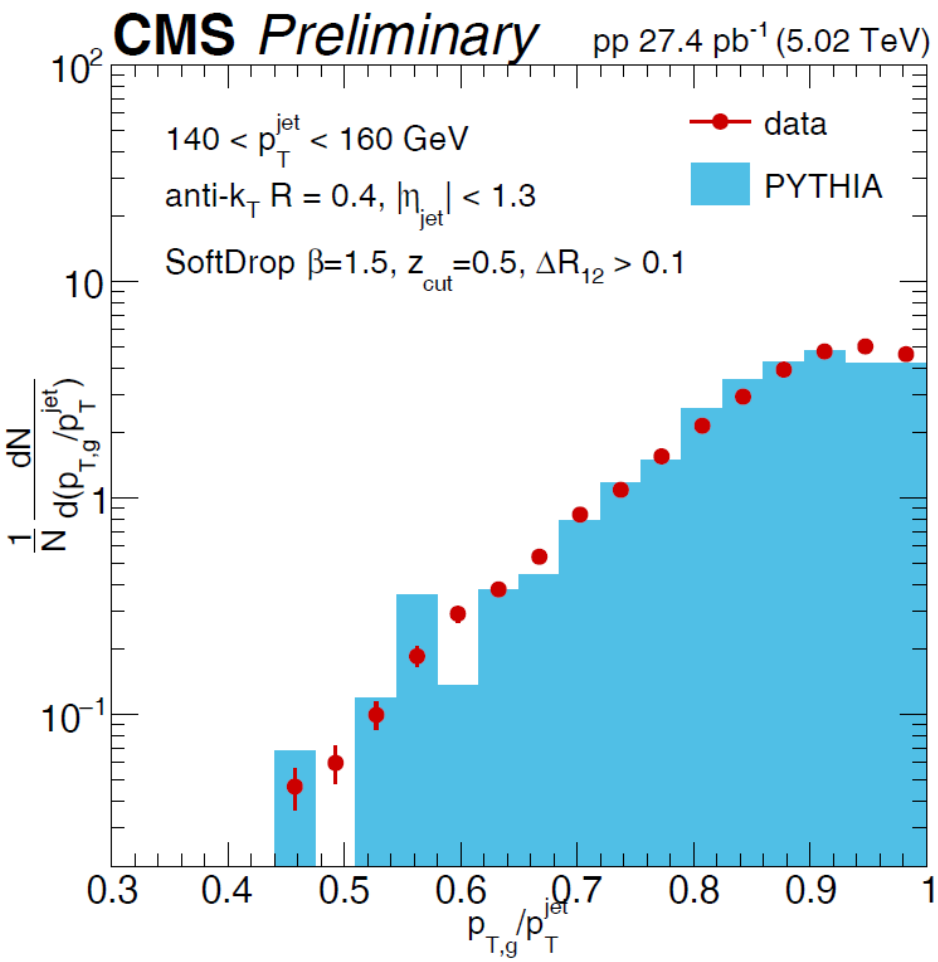
$p_T^{Trig,Recoil}$: **Calculated with $p_{T,cut}$>2 GeV/c**
z_g: **Measured on matched jets with $p_{T,cut}$>0.2 GeV/c**

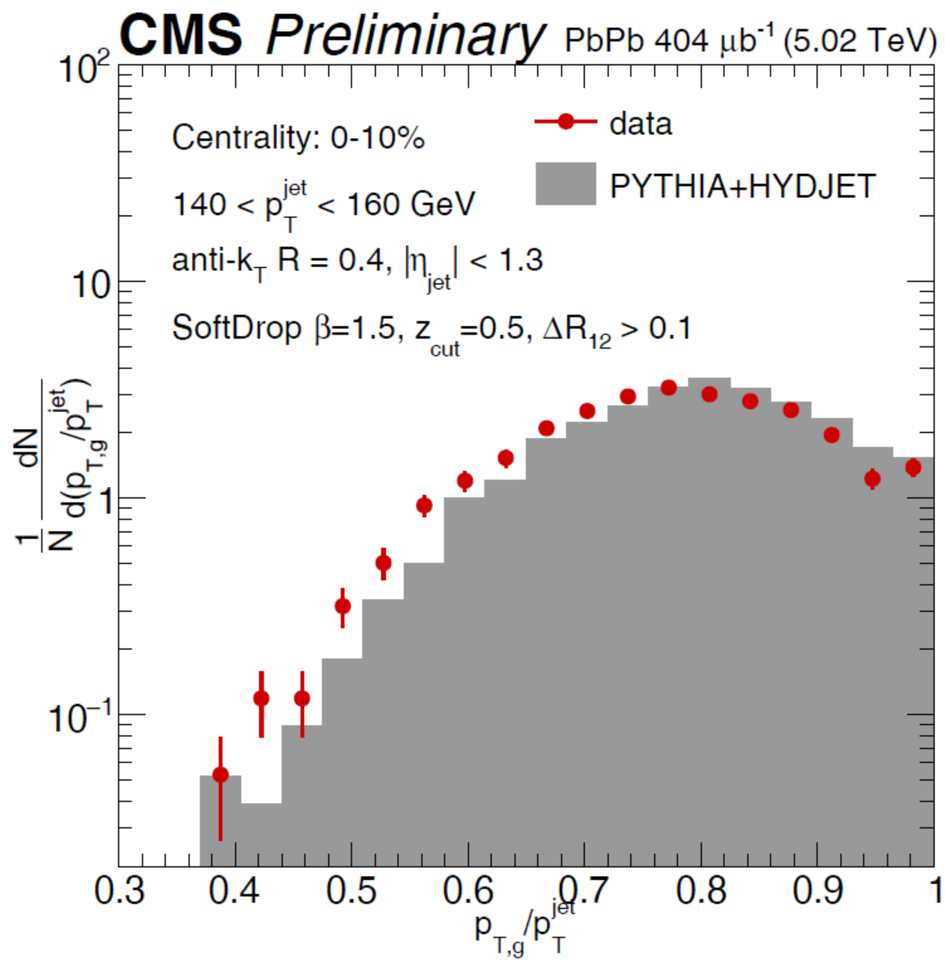




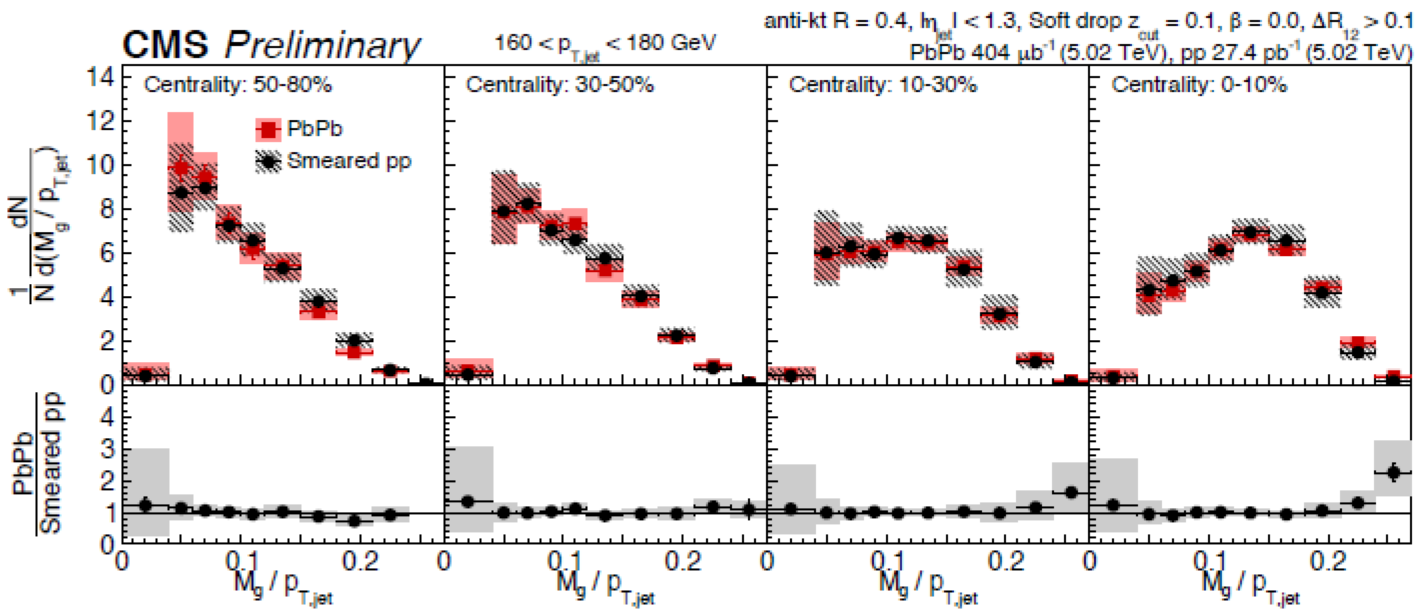
- Direct comparison to embedded p+p – no unfolding
- Selected di-jets with hard cores:
  No significant modification of the splitting function in Au+Au observed with z_g

Groomed jet p_T fraction

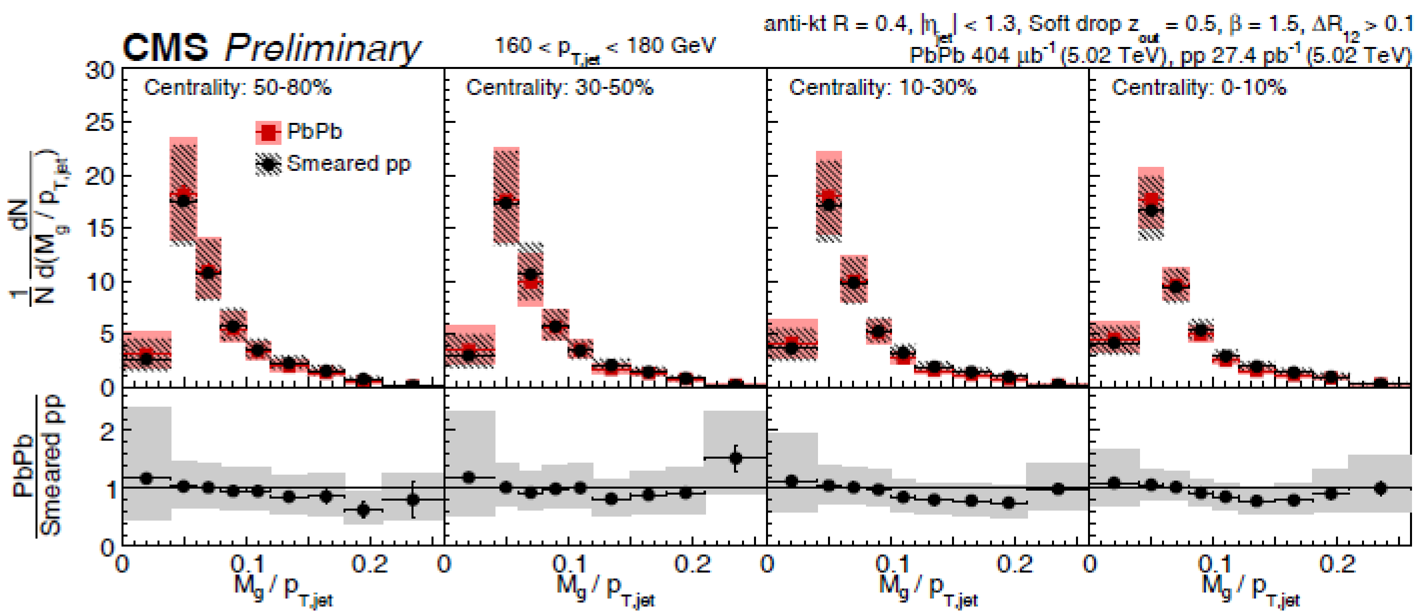




CMS Jet Mass

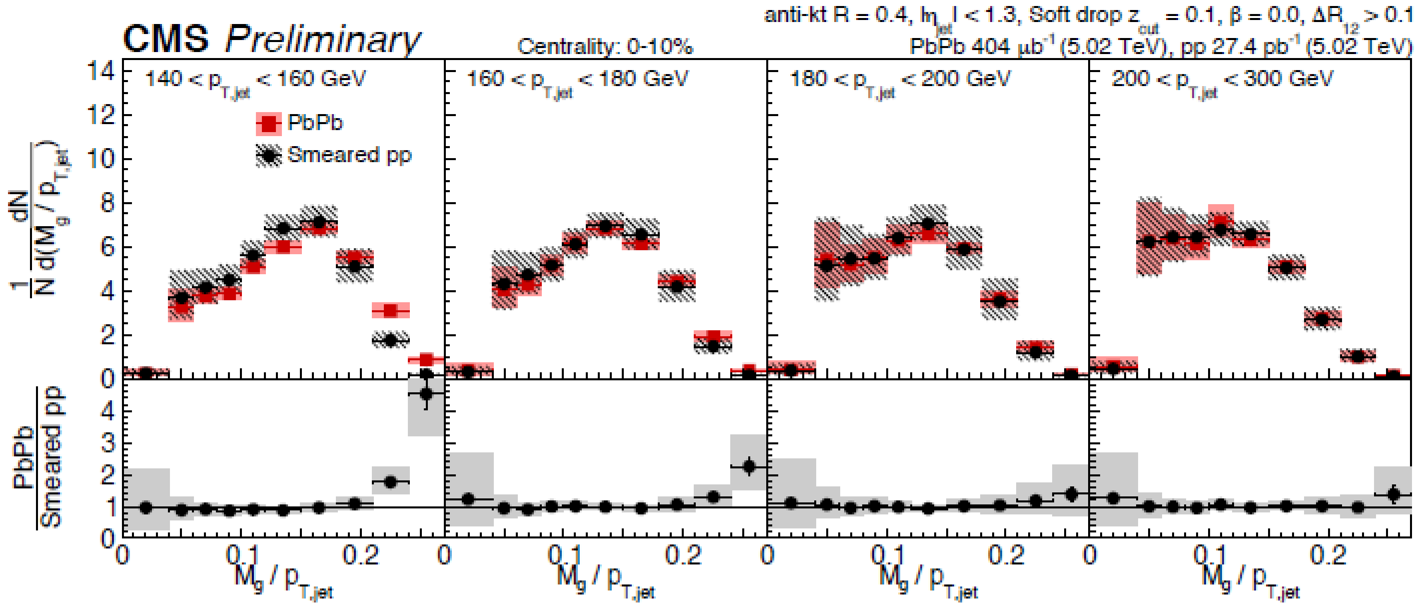


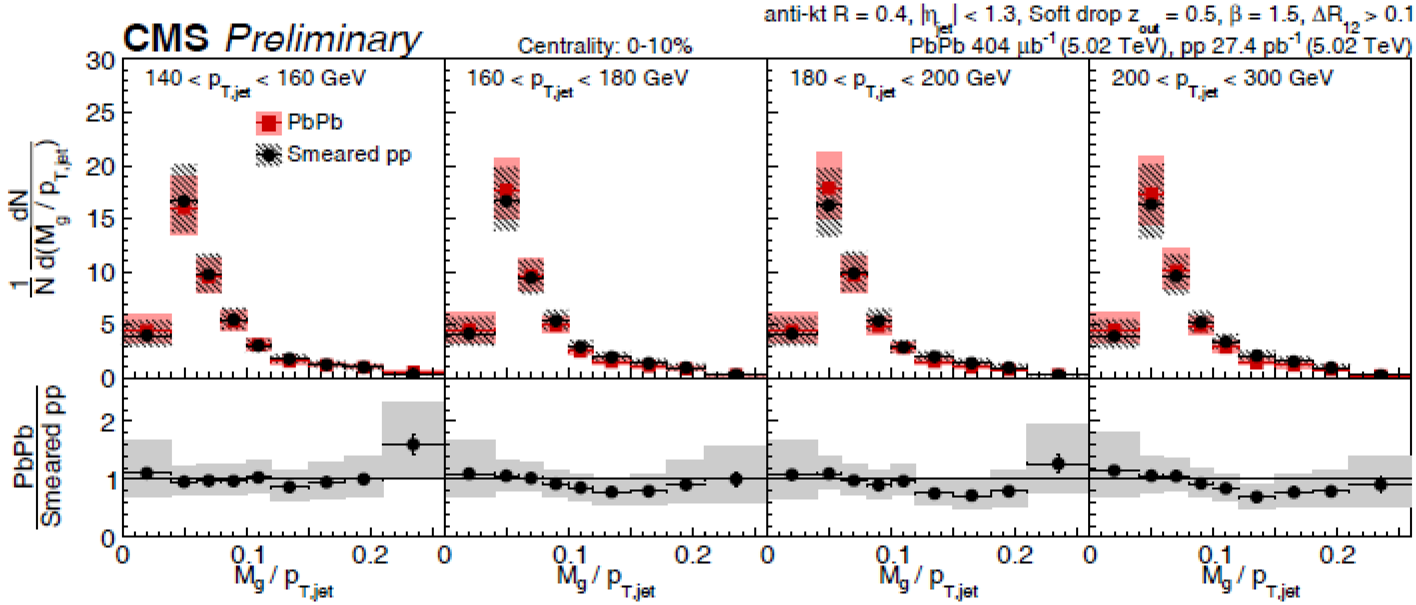
CMS Preliminary
160 < $p_{T,jet}$ < 180 GeV
anti-kt R = 0.4, $|\eta_{jet}|$ < 1.3, Soft drop z_{cut} = 0.1, β = 0.0, ΔR_{12} > 0.1
PbPb 404 μb^{-1} (5.02 TeV), pp 27.4 pb^{-1} (5.02 TeV)
Centrality: 50-80%
Centrality: 30-50%
Centrality: 10-30%
Centrality: 0-10%
PbPb
Smeared pp
$\frac{1}{N}\frac{dN}{d(M_g / p_{T,jet})}$
$\frac{PbPb}{Smeared\ pp}$
$M_g / p_{T,jet}$



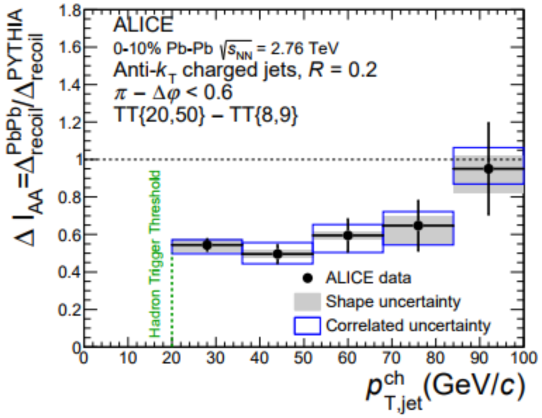
CMS Preliminary
160 < $p_{T,jet}$ < 180 GeV
anti-kt R = 0.4, $|\eta_{jet}|$ < 1.3, Soft drop z_{cut} = 0.5, β = 1.5, ΔR_{12} > 0.1
PbPb 404 μb^{-1} (5.02 TeV), pp 27.4 pb^{-1} (5.02 TeV)
Centrality: 50-80%
Centrality: 30-50%
Centrality: 10-30%
Centrality: 0-10%
PbPb
Smeared pp
$\frac{1}{N}\frac{dN}{d(M_g / p_{T,jet})}$
$\frac{PbPb}{Smeared\ pp}$
$M_g / p_{T,jet}$

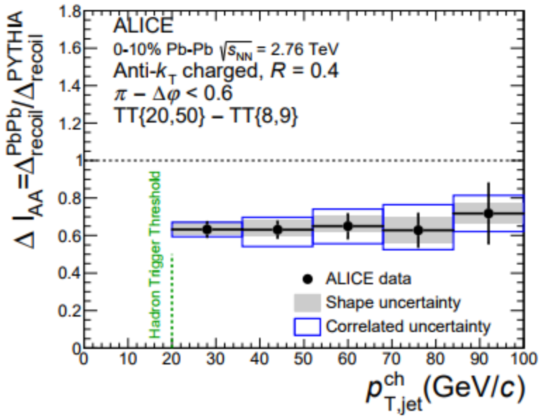
CMS Jet Mass vs. Jet energy

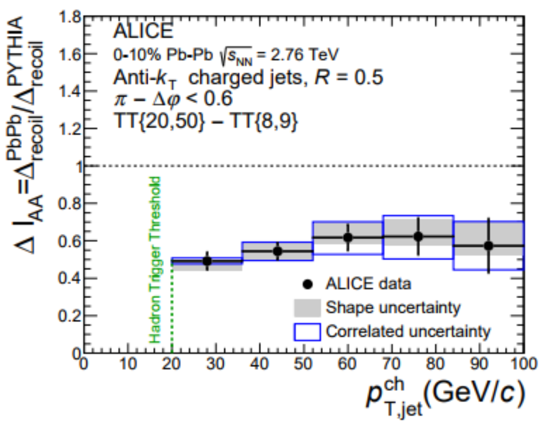


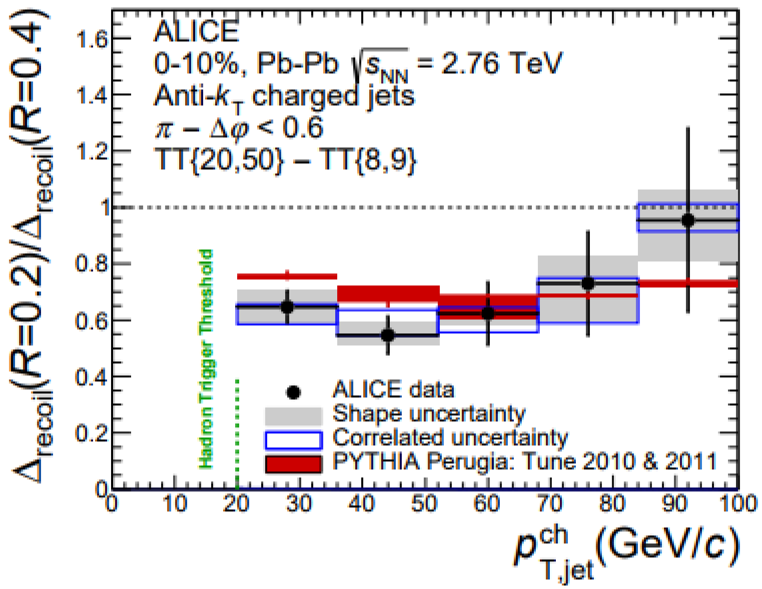


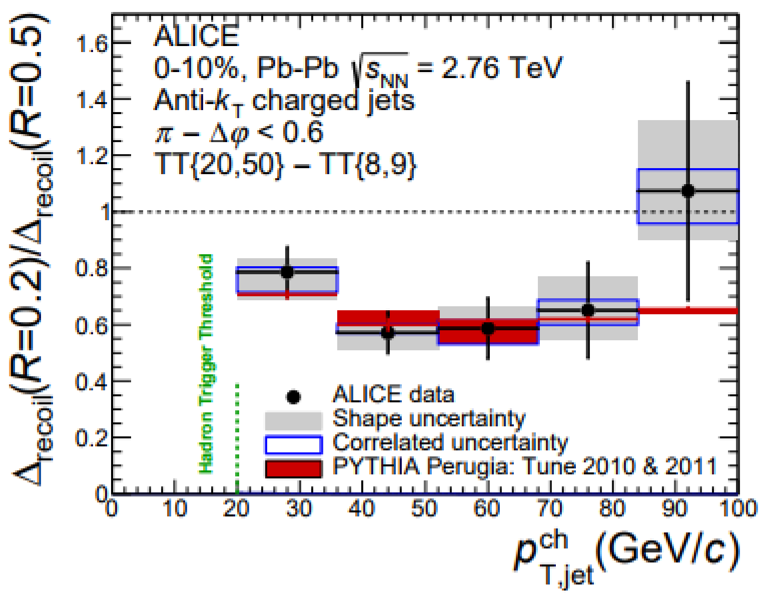
ALICE Hadron-Jet









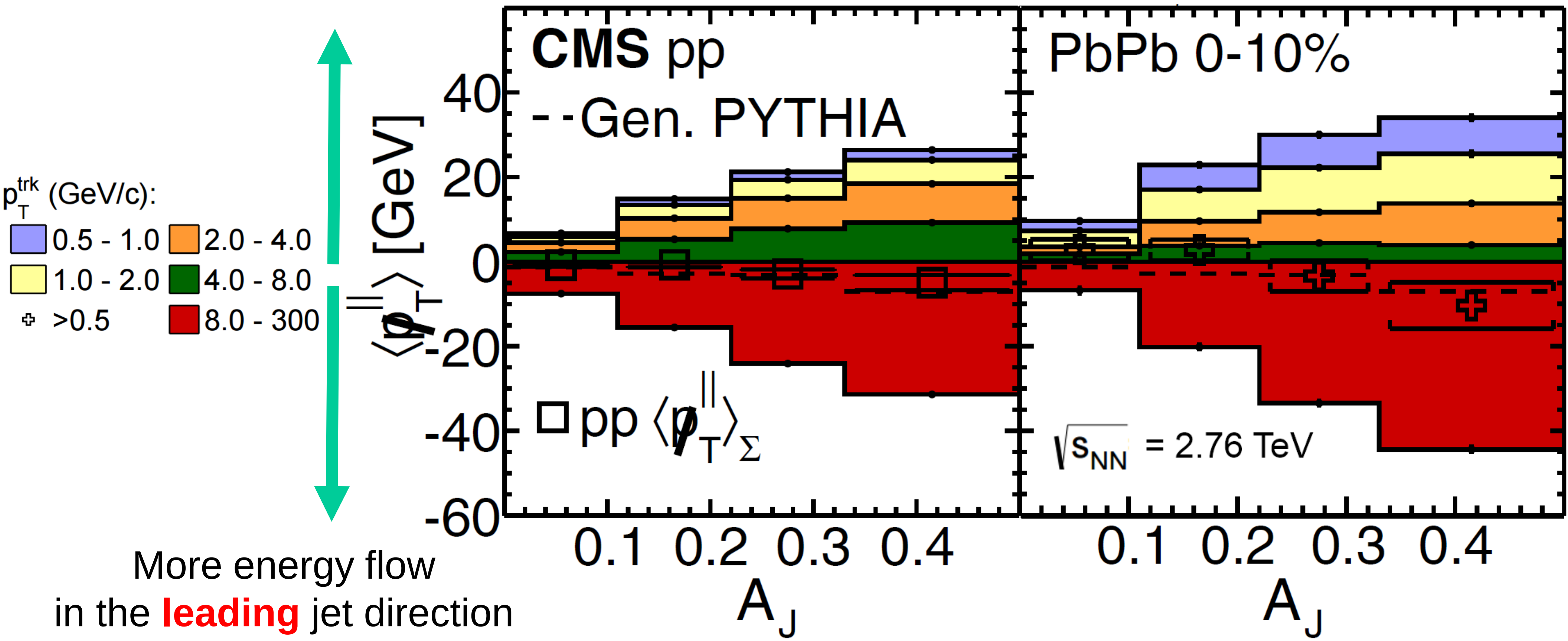


No **sizable** modification of jet shape

Missing $p_T^{||}$ vs. A_J

More energy flow in the **subleading** jet direction

PP **0-10% PbPb**



More energy flow in the **leading** jet direction

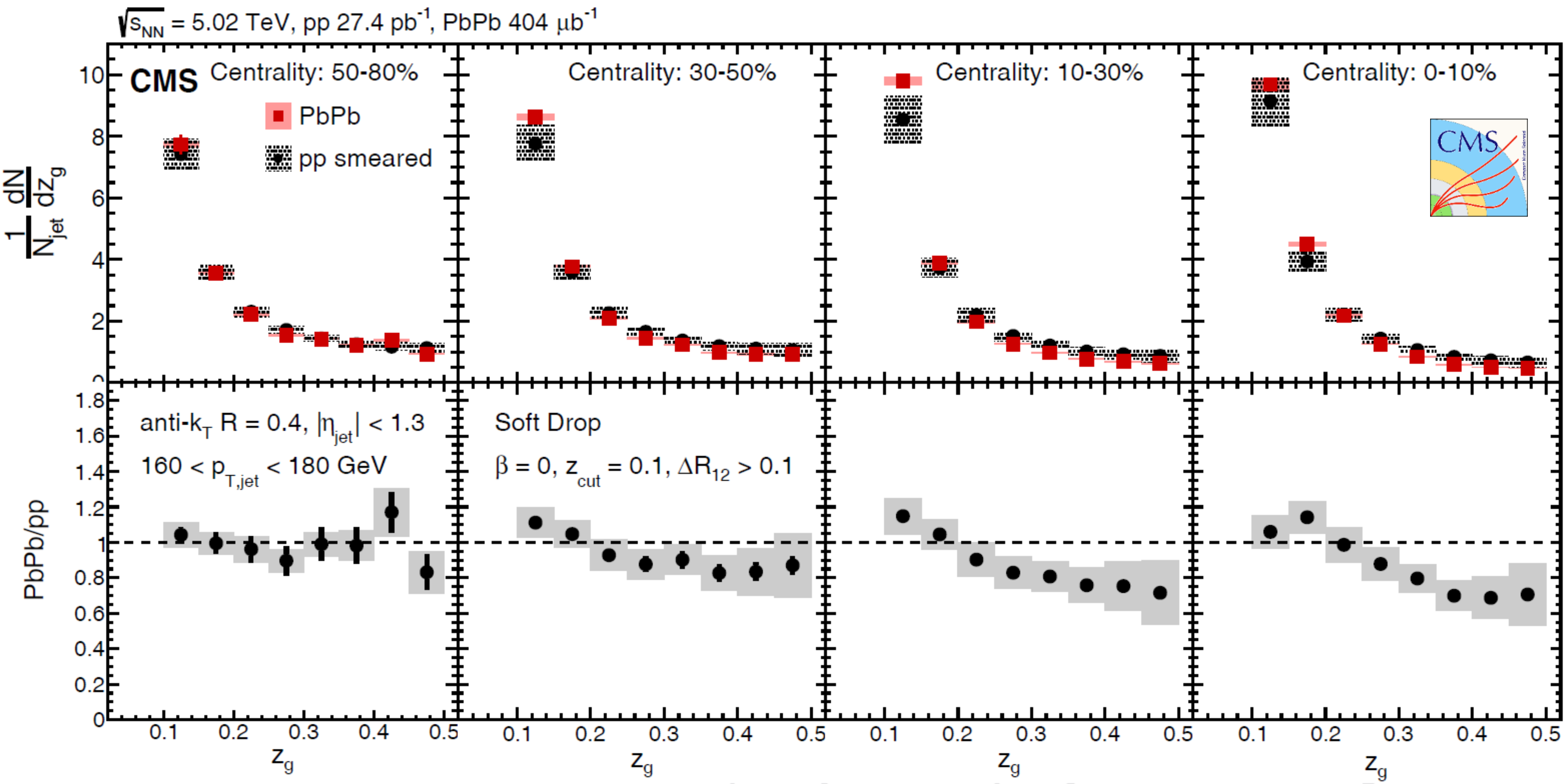
Missing p_T from high p_T particles increases as a function of A_J

In pp ⟶ Balanced by 2-8 GeV/c particles

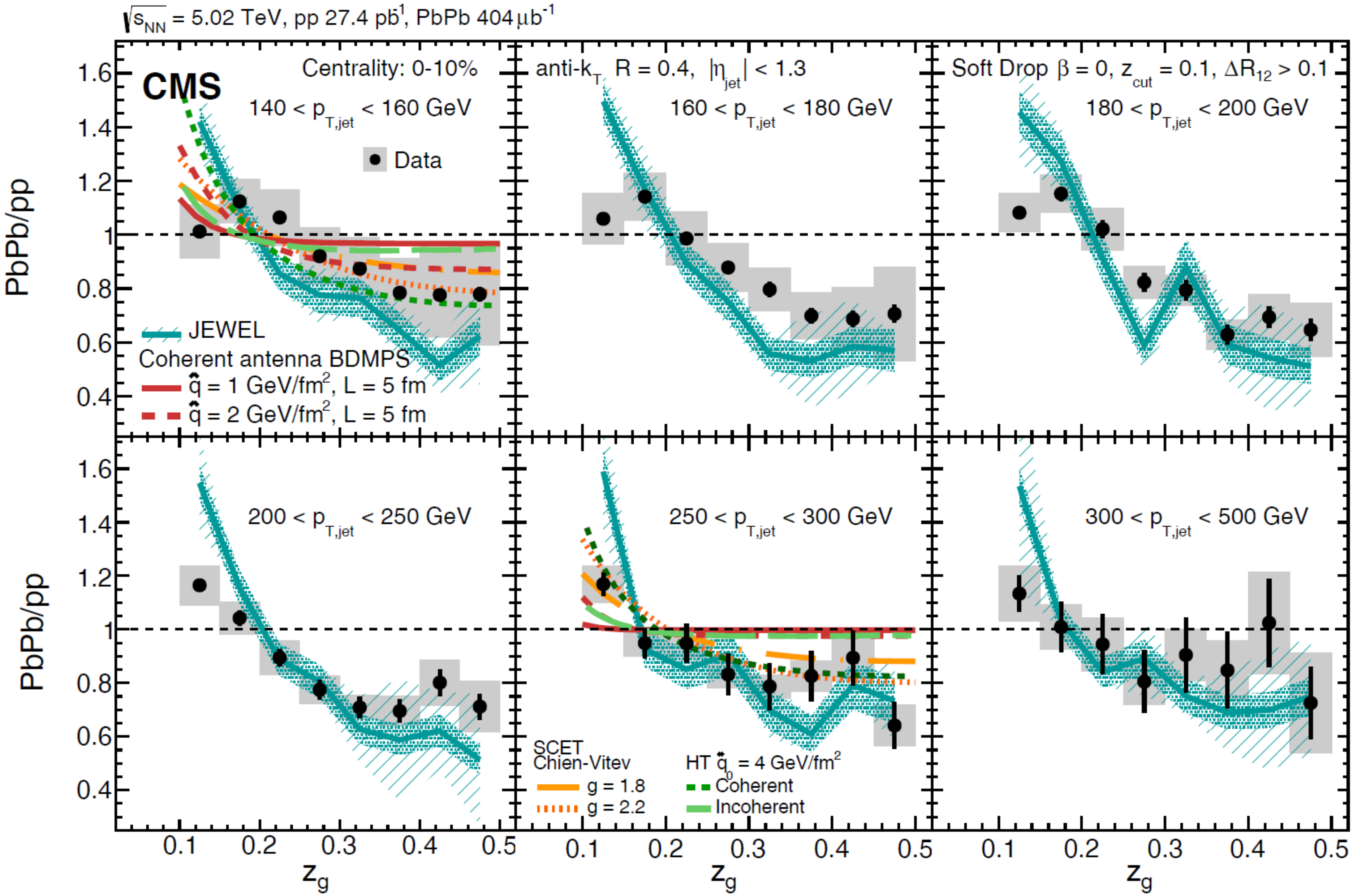
JHEP 1601 (2016) 006

In 0-10% PbPb ⟶ Balanced by particles with p_T < 4 GeV/c

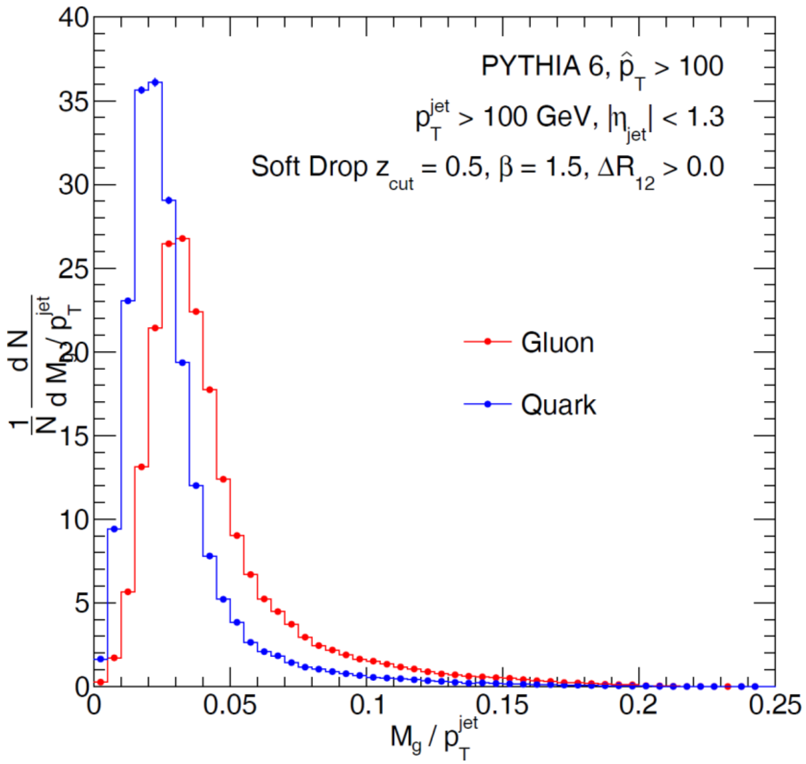
CMS Groomed Jet Splitting Function

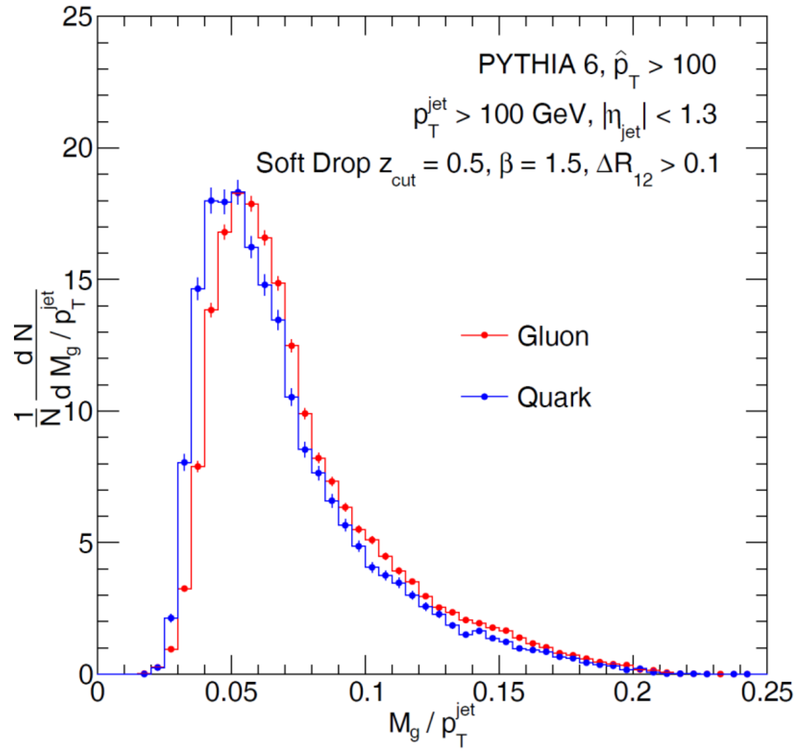


CMS Groomed Jet Splitting Function



Groomed Jet Mass (Q vs G)





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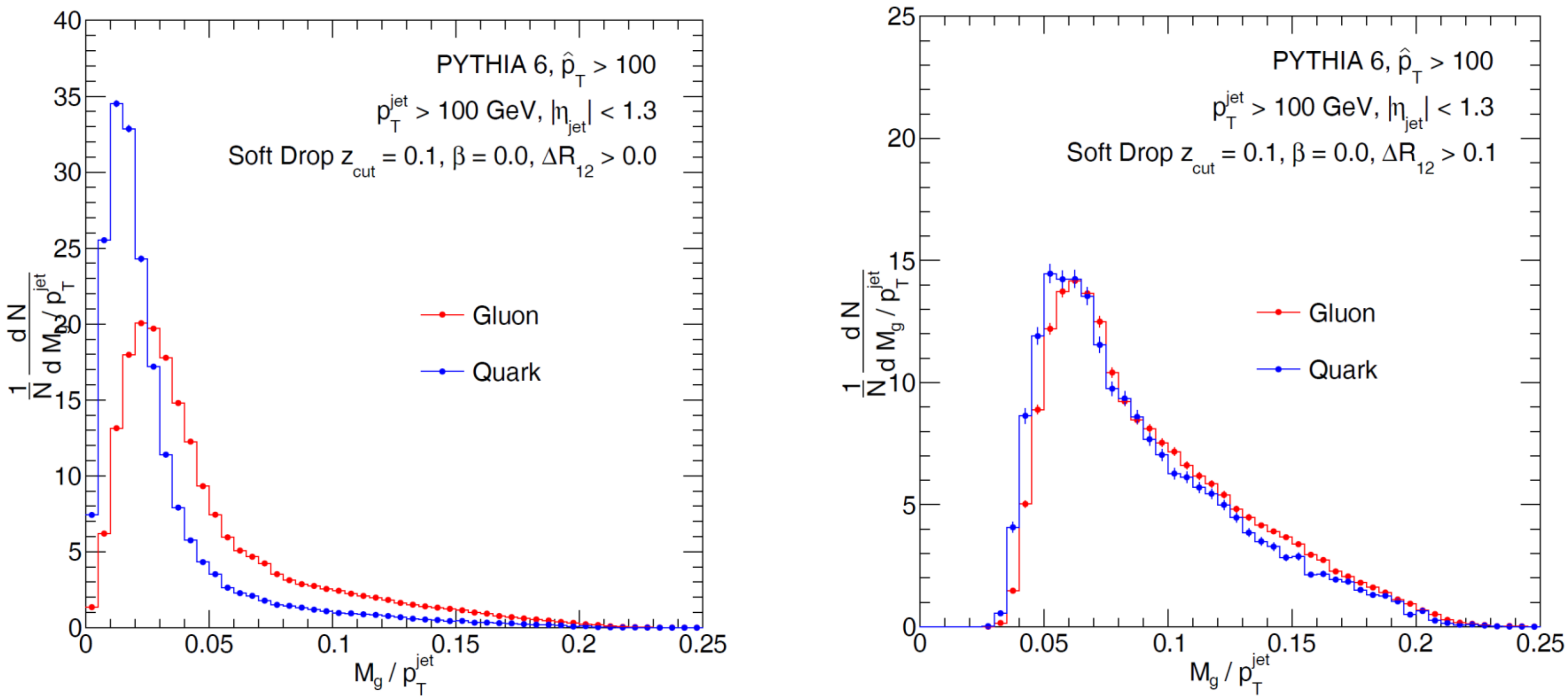
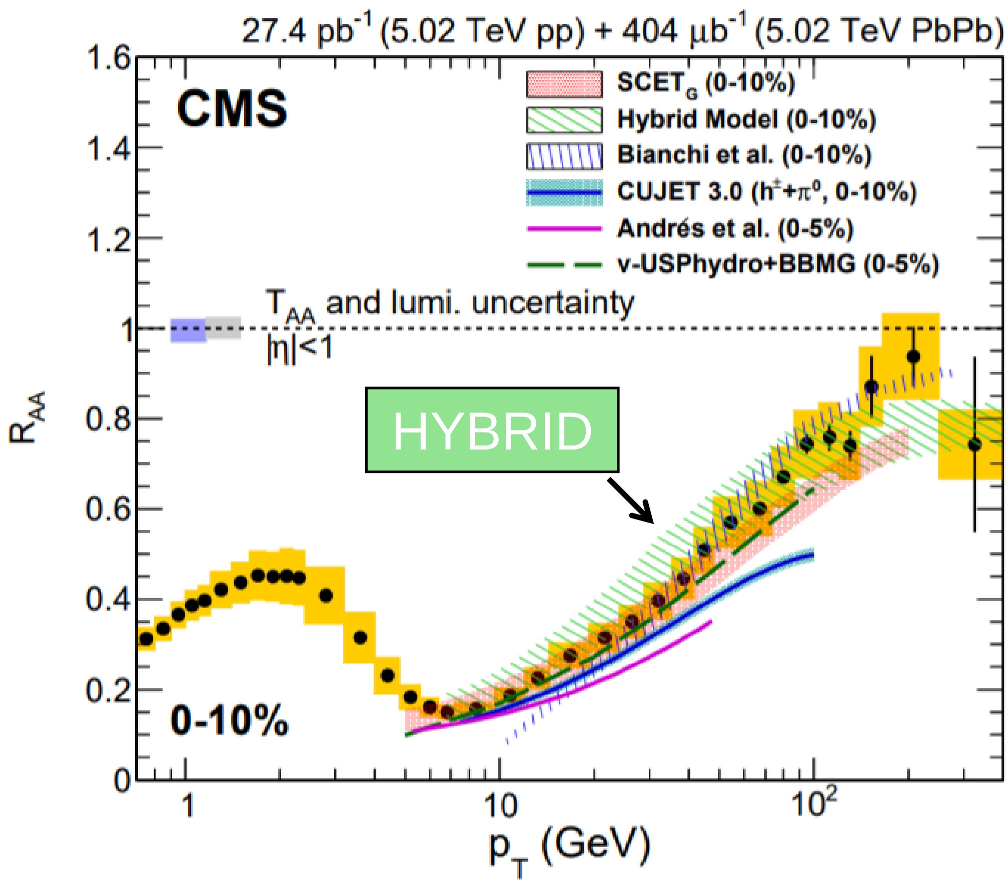
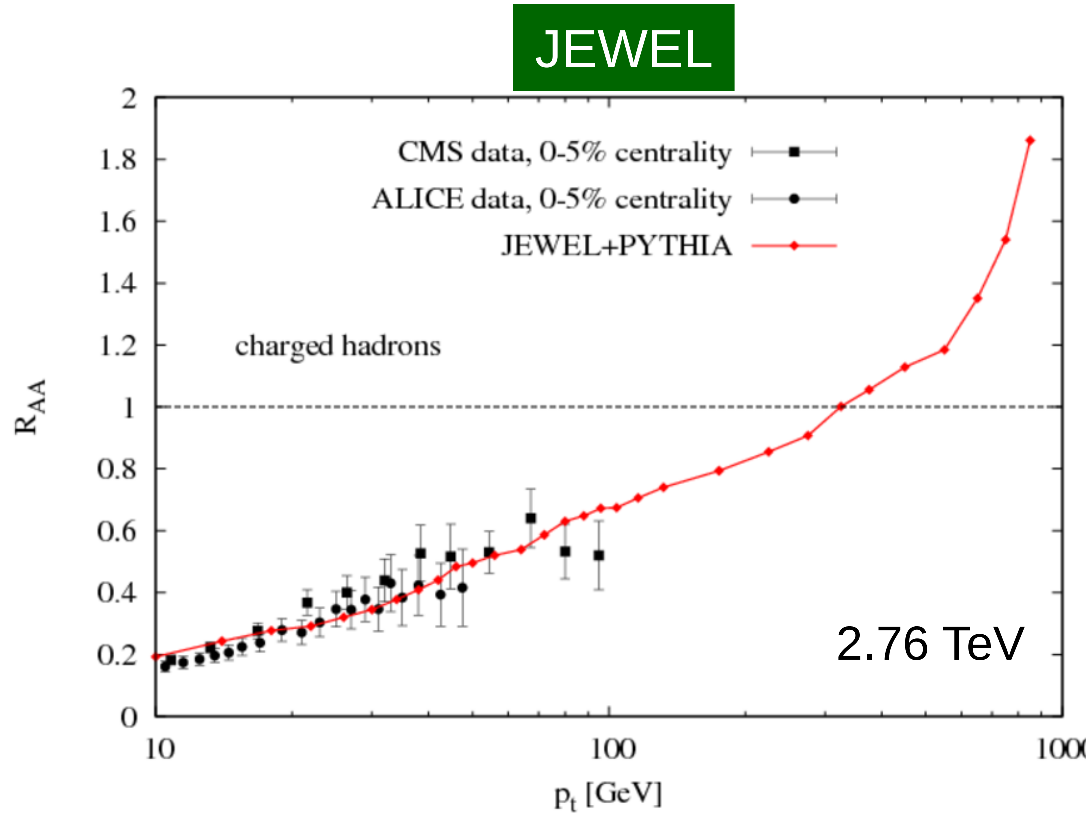


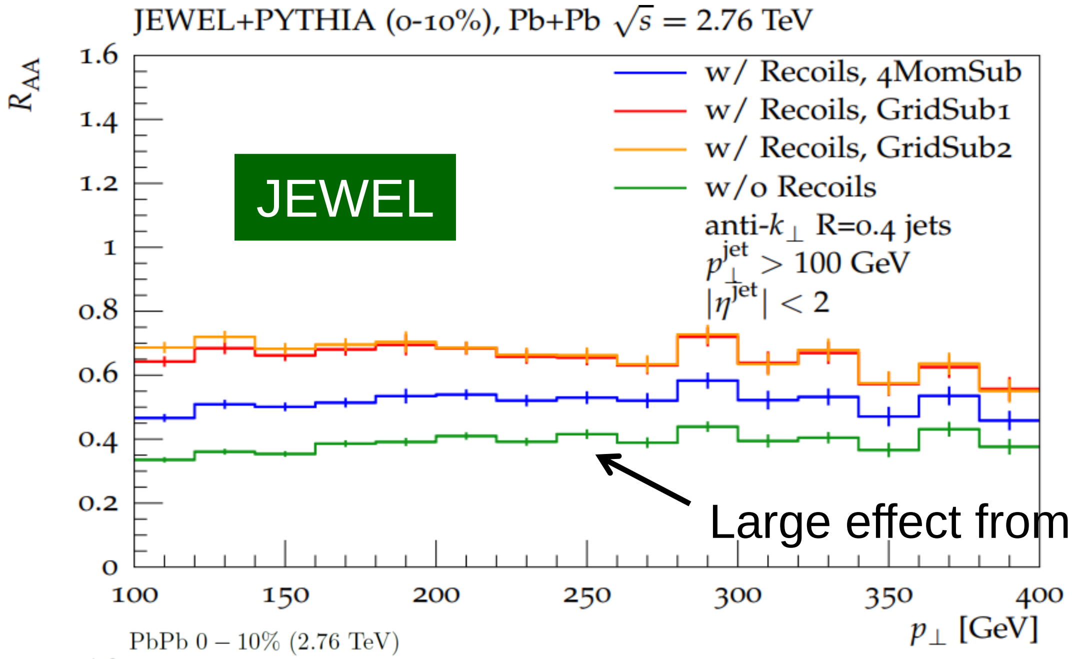
Charged Particle R_{AA} vs. Theoretical Models

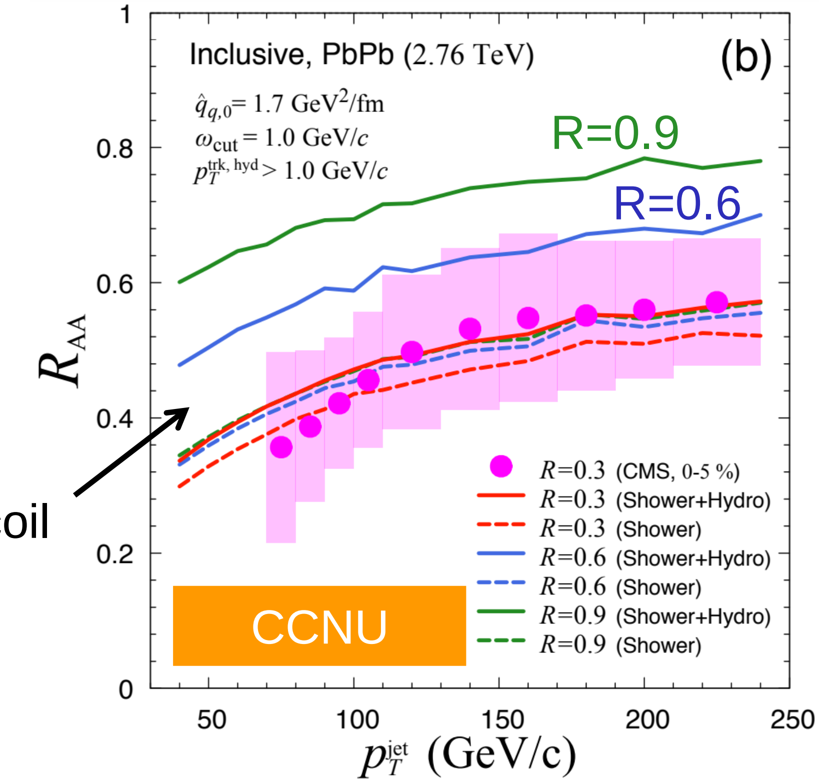




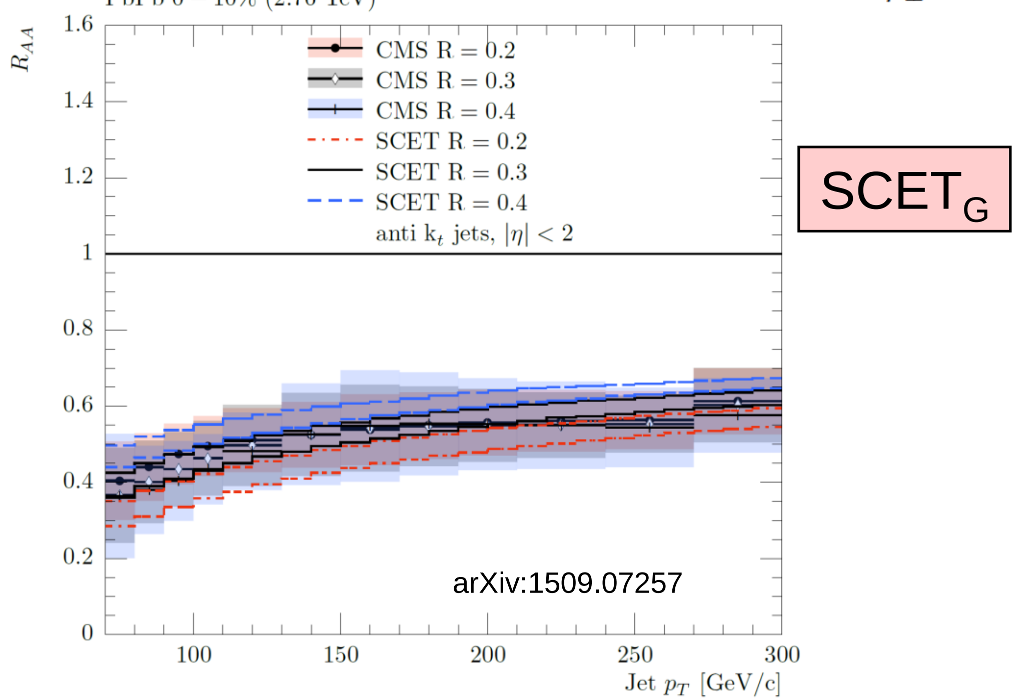
- General trend described by pQCD based and Hybrid models
- A full description of the R_{AA} is still challenging for some models

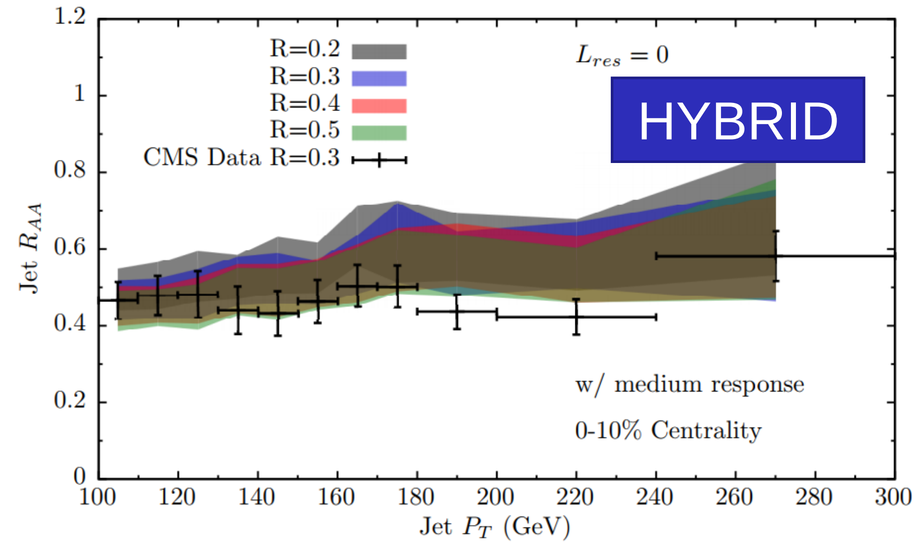
Jet R_{AA} vs. Theory



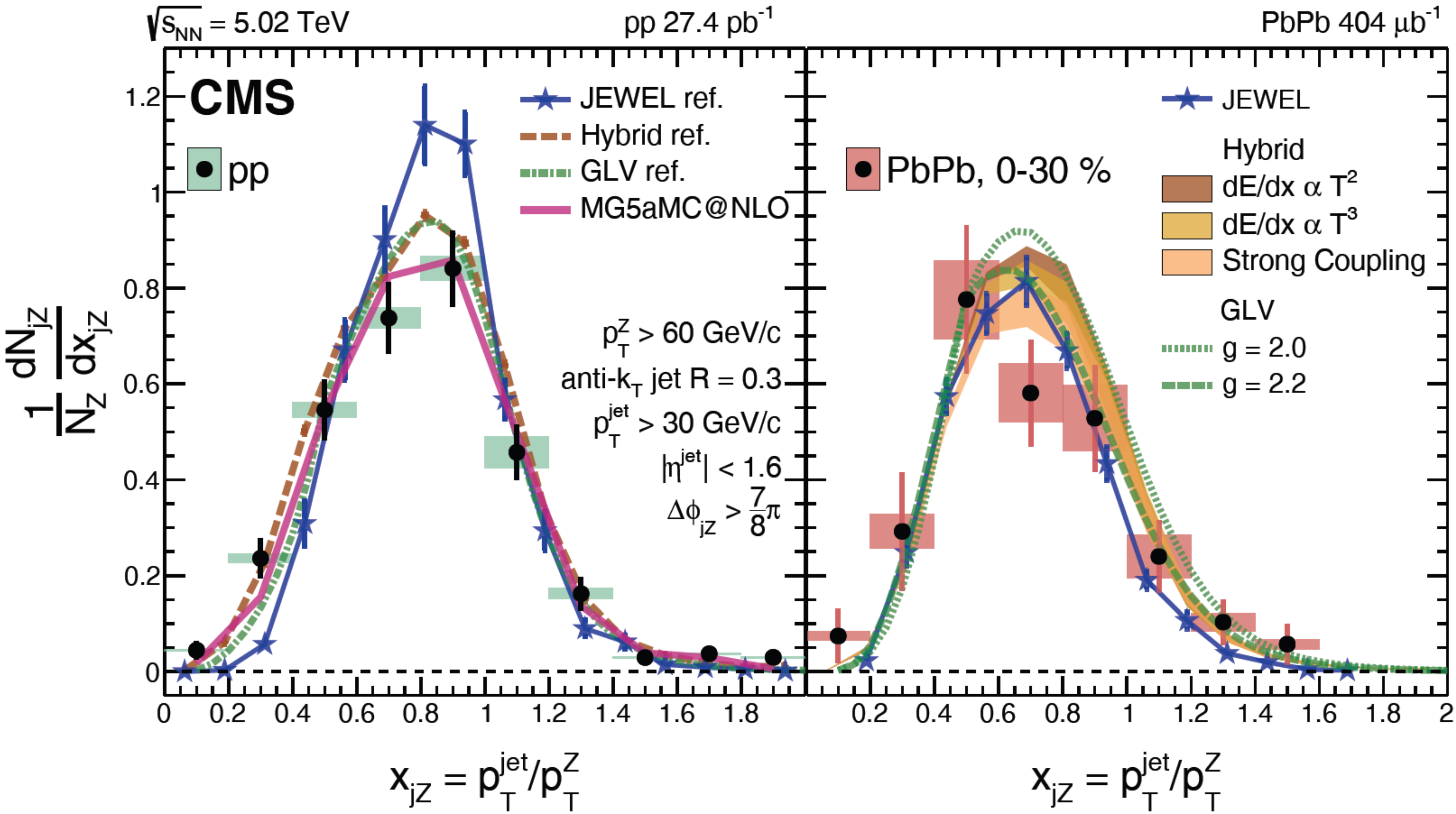


Large effect from recoil



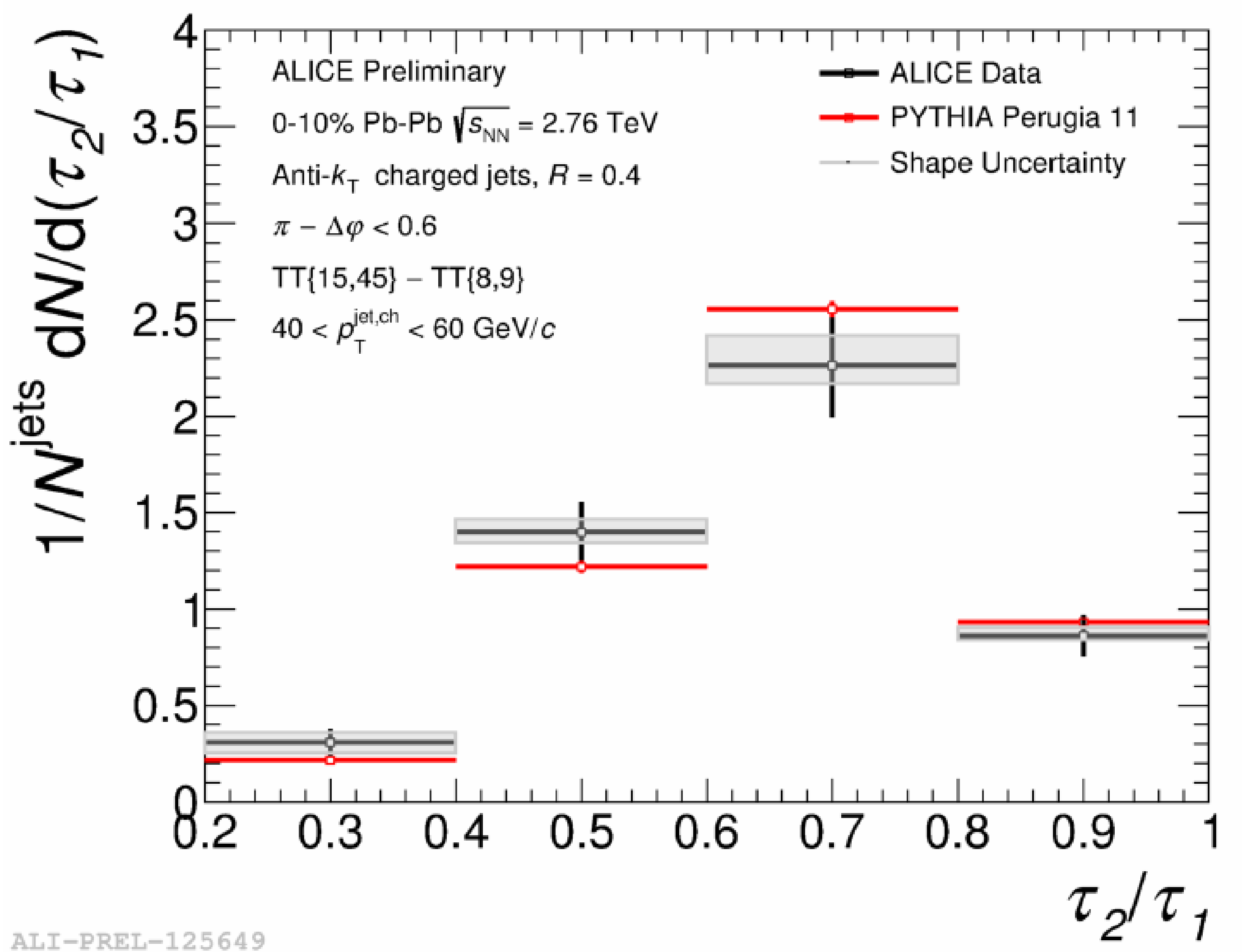


Z-Jet vs calculations



- Important to have correct pp baseline
- Reasonable agreement between data and theory curves from JEWEL, HYBRID and GLV

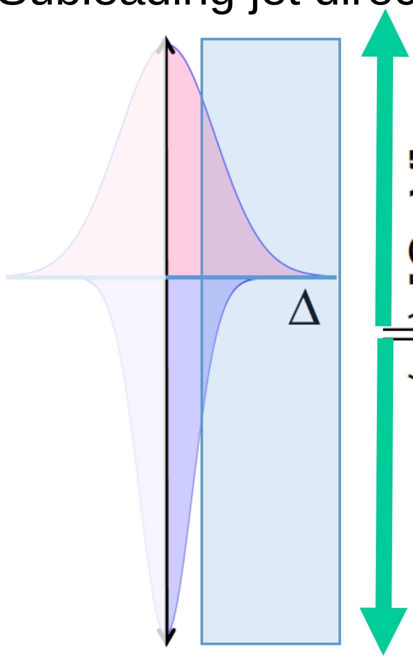
N-Subjettiness in PbPb at 2.76 TeV



- Small τ_2/τ_1 related to leading parton splitting into 2 resolvable partons
- Medium modification could shift τ_2/τ_1 to higher values
- No significant difference between **PbPb data** and PYTHIA within the uncertainties
- Could JEWEL, HYBRID, CCNU and $SCET_G$ reproduce this data?

Missing $p_T^{||}$ vs. Δ

Subleading jet direction



Leading jet direction

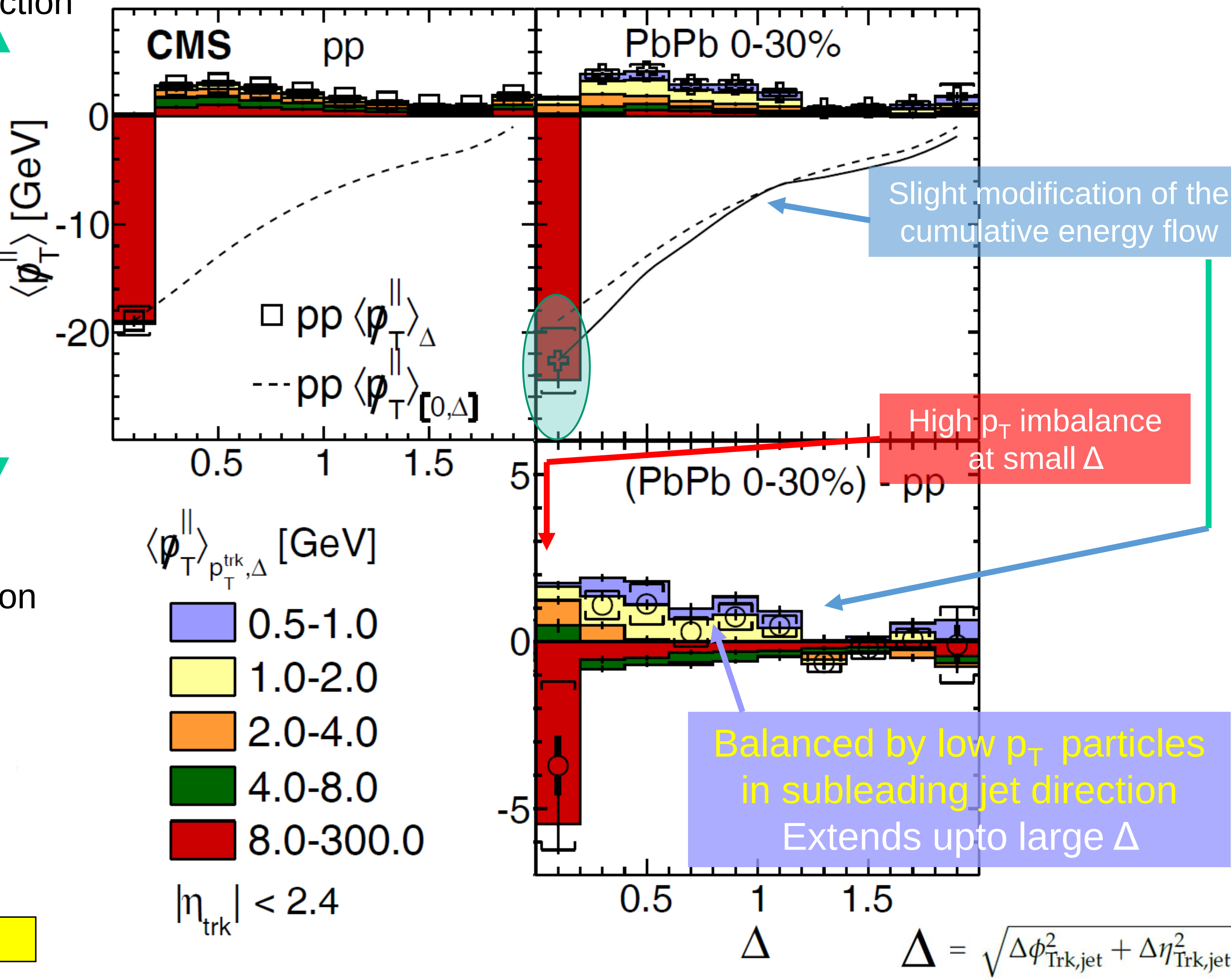
$p_{T,1}$>120, $p_{T,2}$>50 GeV/c

$|\eta_1|,|\eta_2|$<0.50, $\Delta\phi_{1,2}$>5π/6

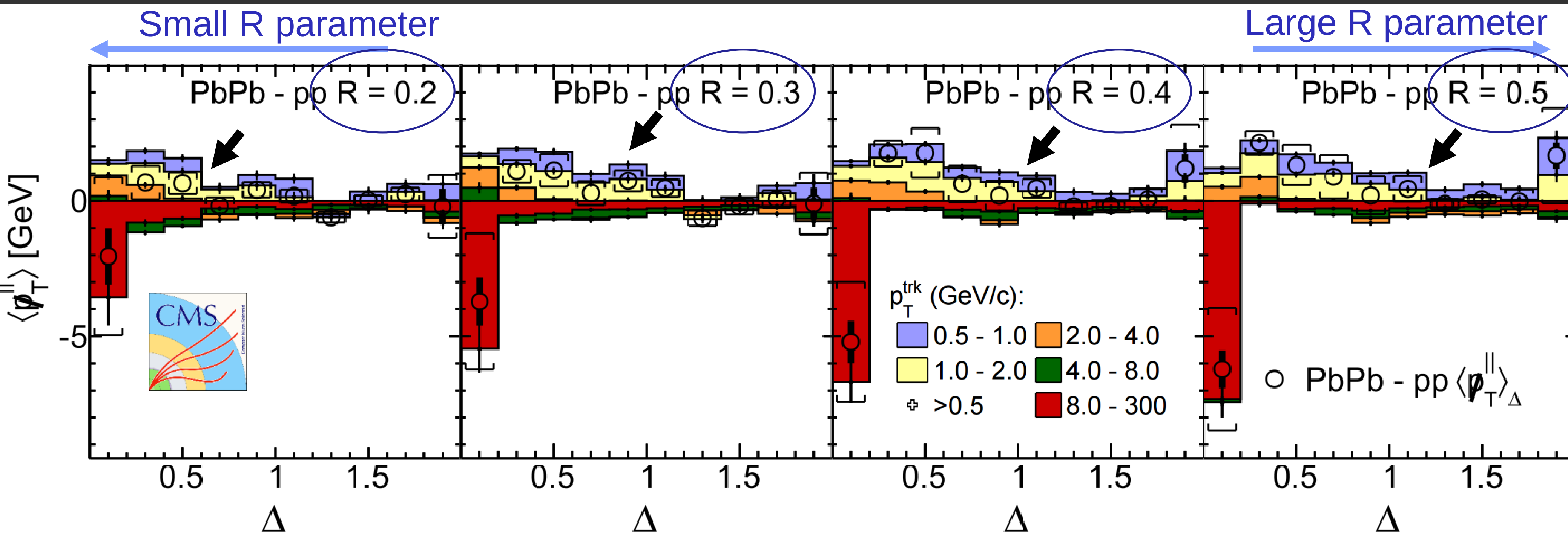
anti-k_T Calo R=0.3

Inclusive A_J

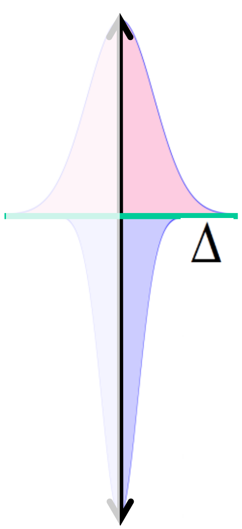
JHEP 1601 (2016) 006



"Shooting Jets with Different Width" through the Medium



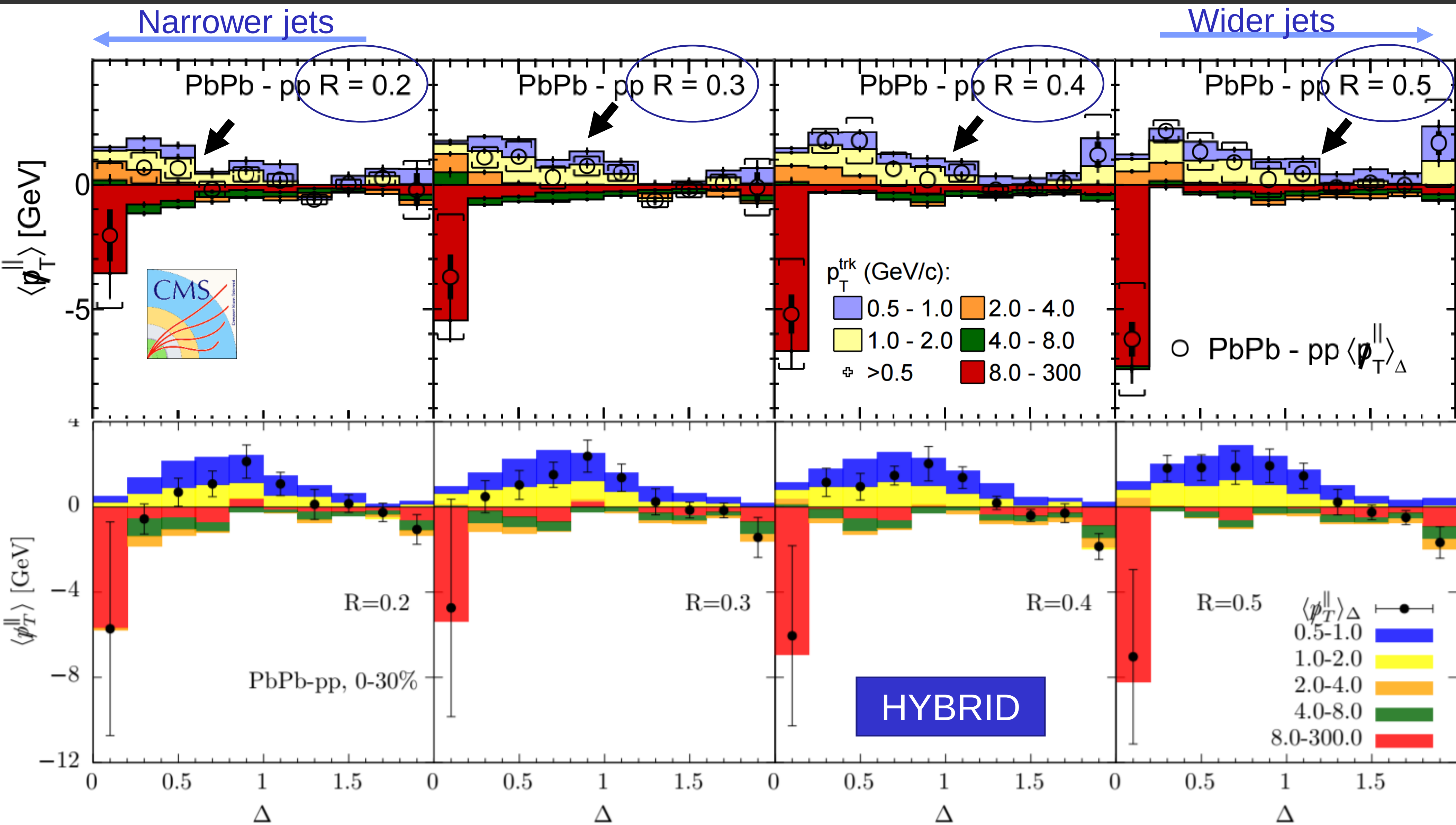
JHEP 1601 (2016) 006



- Quenched energy distribution depends on the R parameter used in the Anti-k_T algorithm
- Hint of narrower leading jet (or wider subleading jet) in PbPb collisions.
- Soft particles extends to larger Δ in dijet events reconstructed with larger R parameter

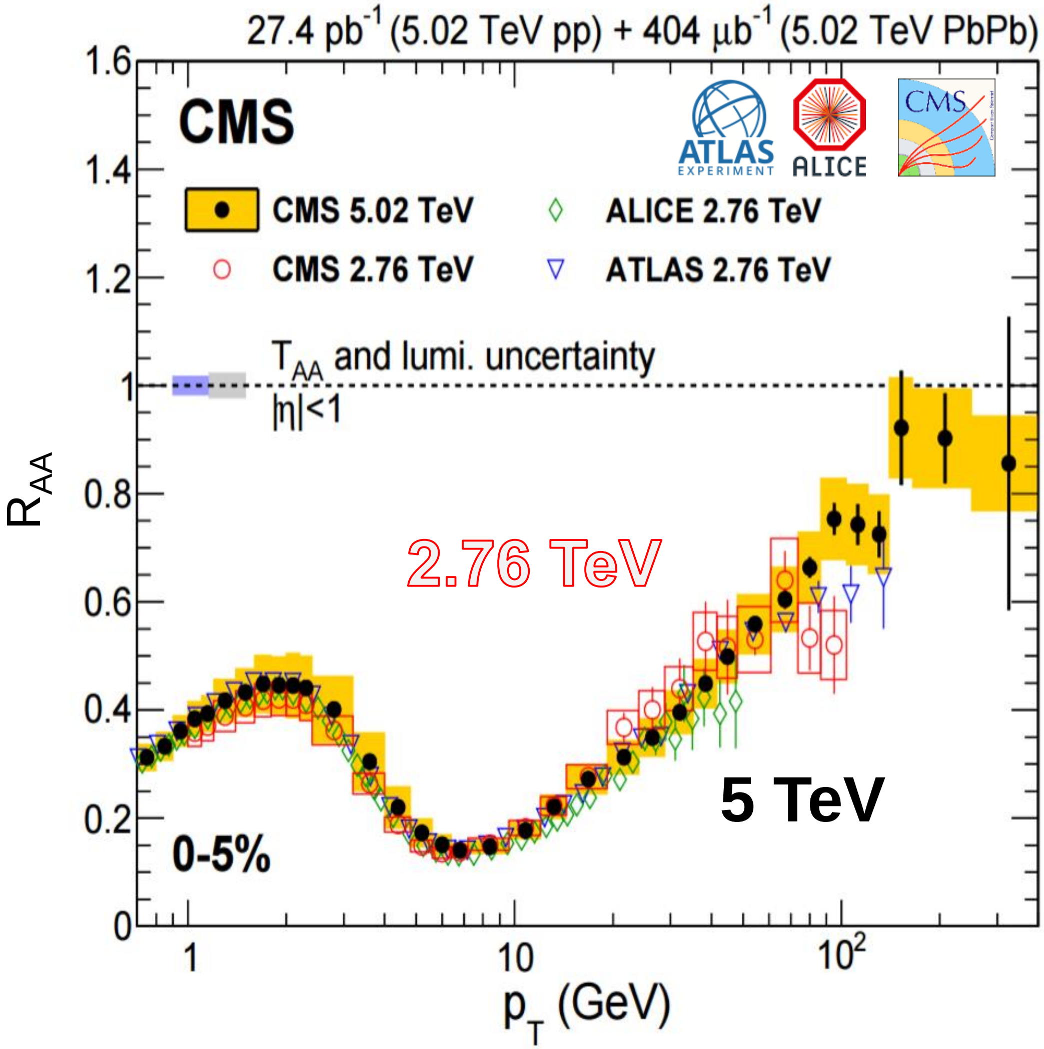
$$\Delta = \sqrt{\Delta\phi^2_{\mathrm{Trk,jet}} + \Delta\eta^2_{\mathrm{Trk,jet}}}$$

"Shooting Jets with Different Width" through the Medium



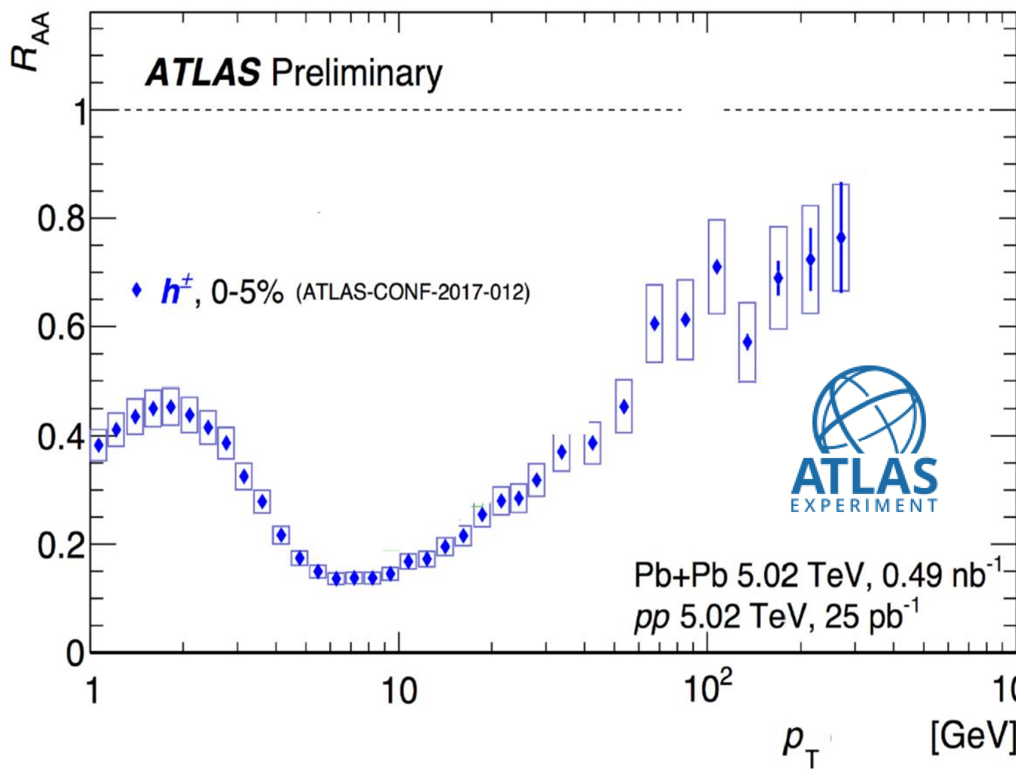
- Medium response from HYBRID is farer away from the jet axis.
- Shower not completely thermalized?
- Where are the calculations from JEWEL, CCNU, QPYTHIA and $SCET_G$?

Jet Quenching with Inclusive Charged Particles



Charged particle R_{AA}

- Strong suppression of charged particles (up to a factor of 6) in PbPb compared to pp



- Almost no suppression at very high p_T compared to **pp reference**
- **Charged particle R_{AA}** measured up to p_T = 400 GeV for the first time!

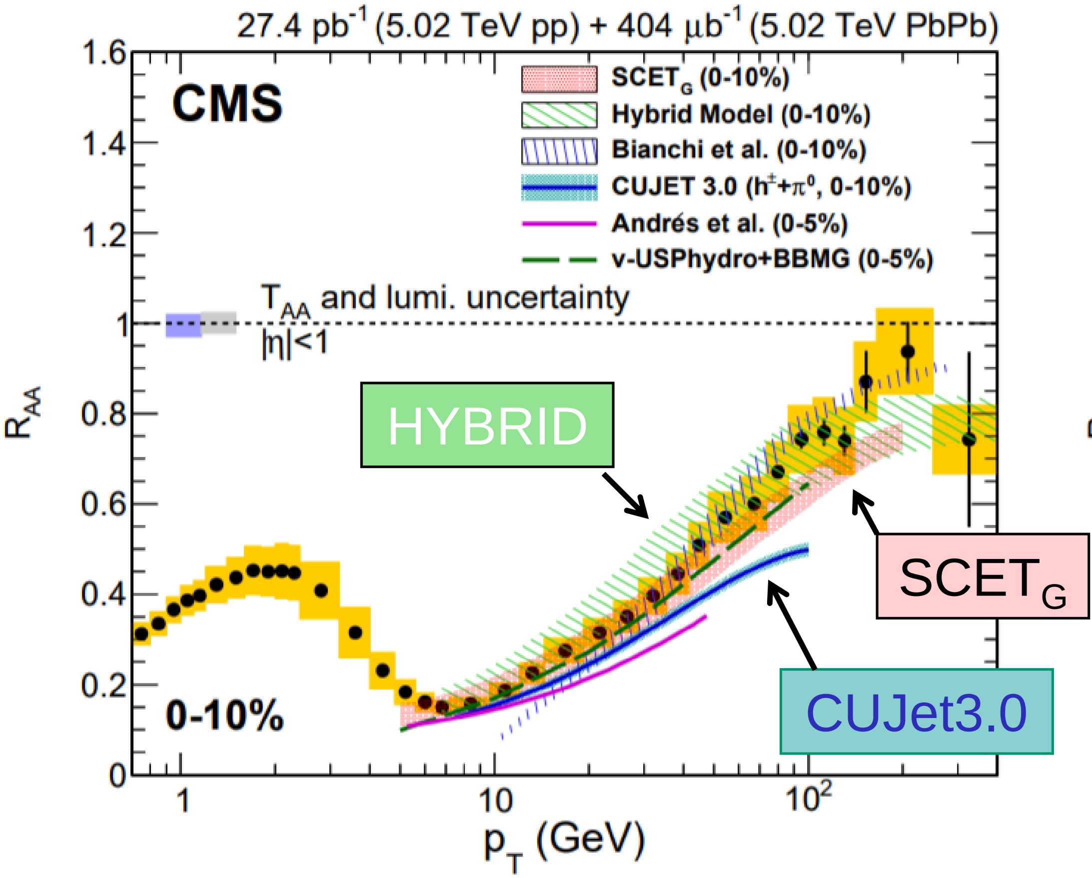
JHEP 04 (2017) 039

- Similar Charged particle R_{AA} in PbPb at **5 TeV** compared to 2.76 TeV
- Good agreement between ATLAS, CMS and ALICE measurements

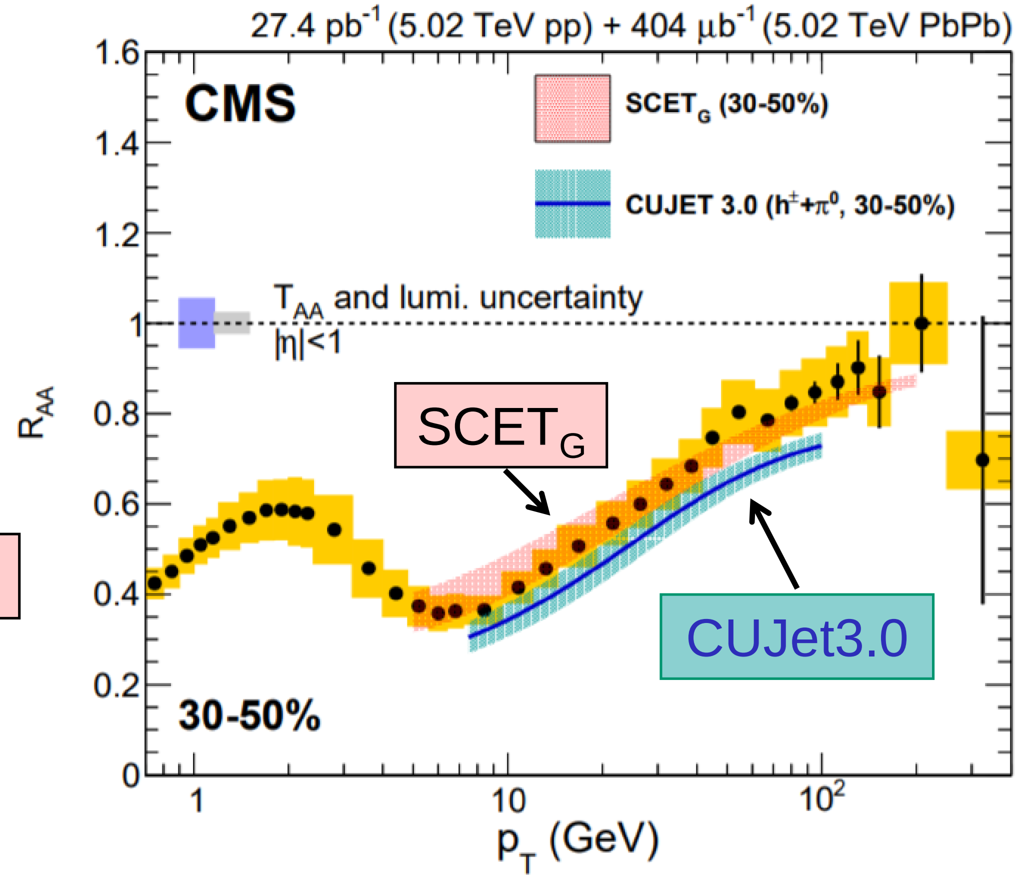
ATLAS-CONF-2017-012

Charged Particle R_{AA} vs. Theoretical Models

0-10%



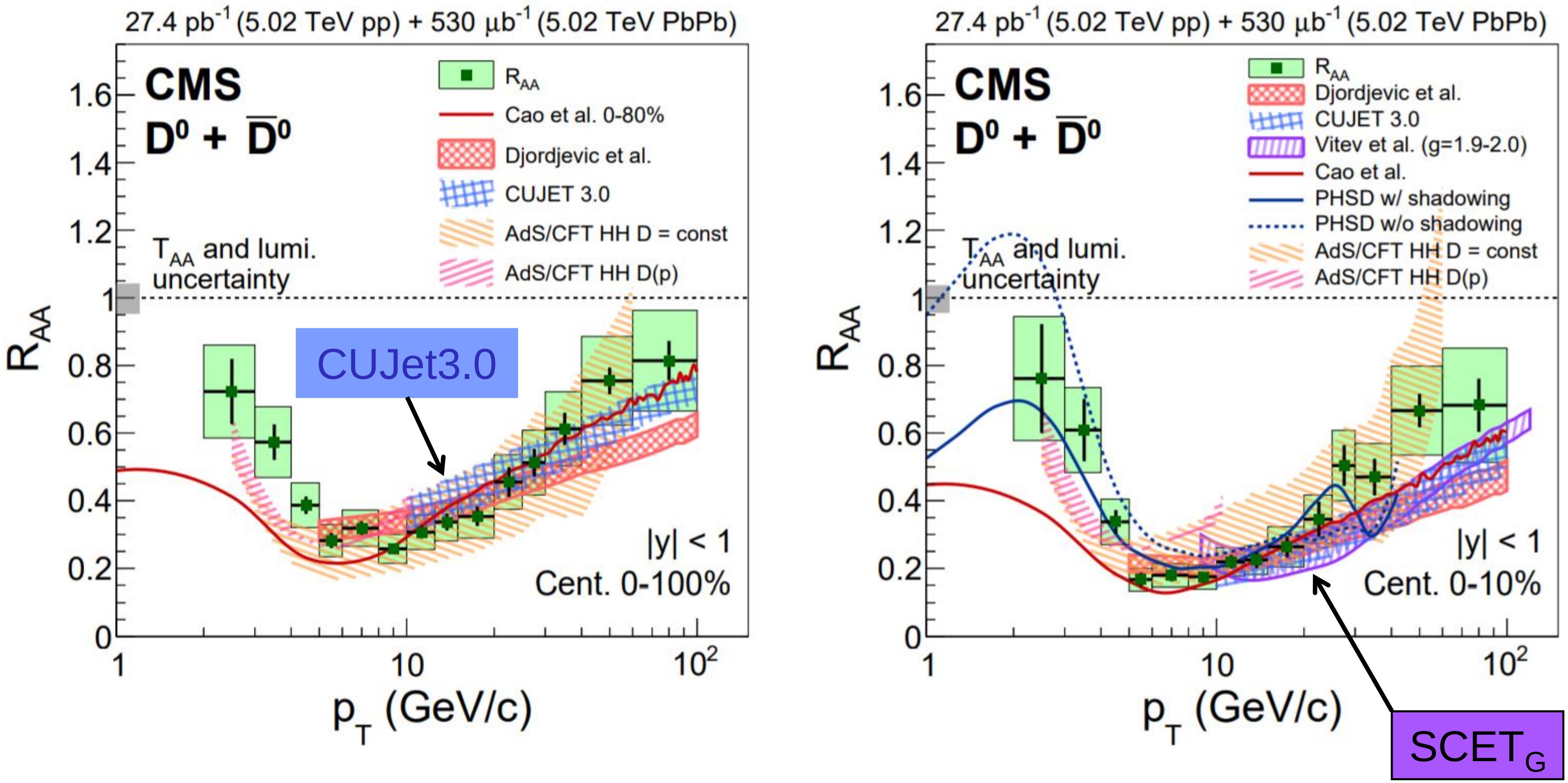
30-50%



- General trend described by pQCD based and Hybrid models
- A full description of the R_{AA} is still challenging for some models

Description of the D^0 Meson Data

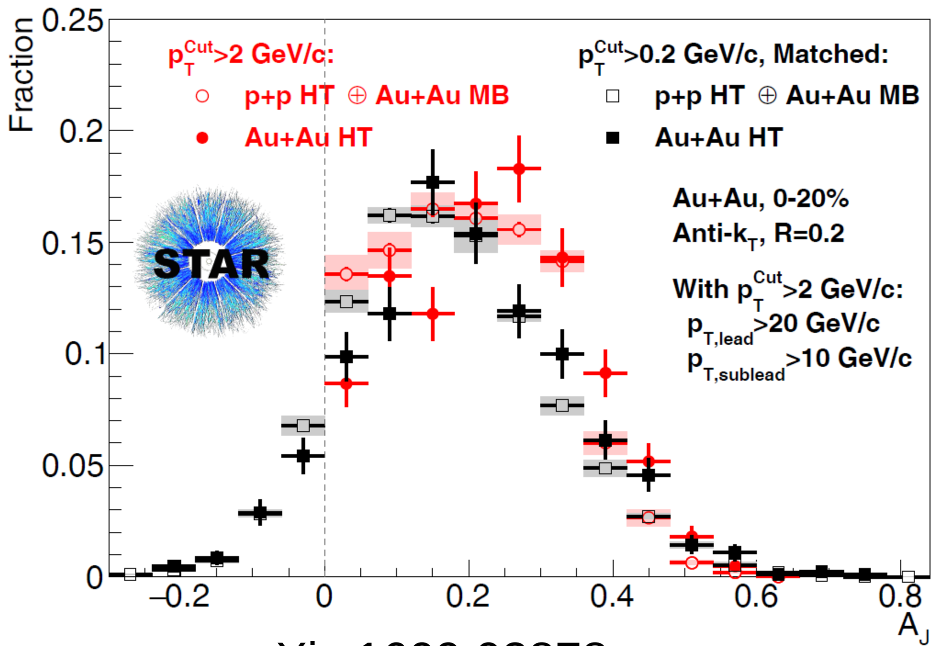
arXiv:1708.04962



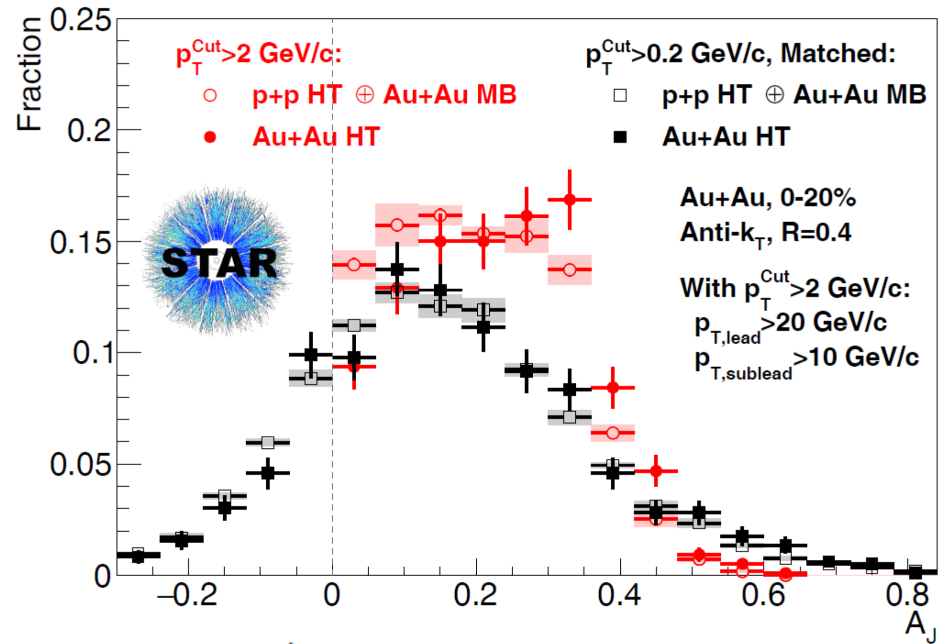
- At high D^0 p_T: Trend captured by pQCD and AdS/CFT based models
- Reasonable description of the data could be achieved
- Details doesn't work perfectly, especially the slope of the D^0 R_{AA} vs. p_T

Dijet Transverse Momentum Correlation

R=0.2

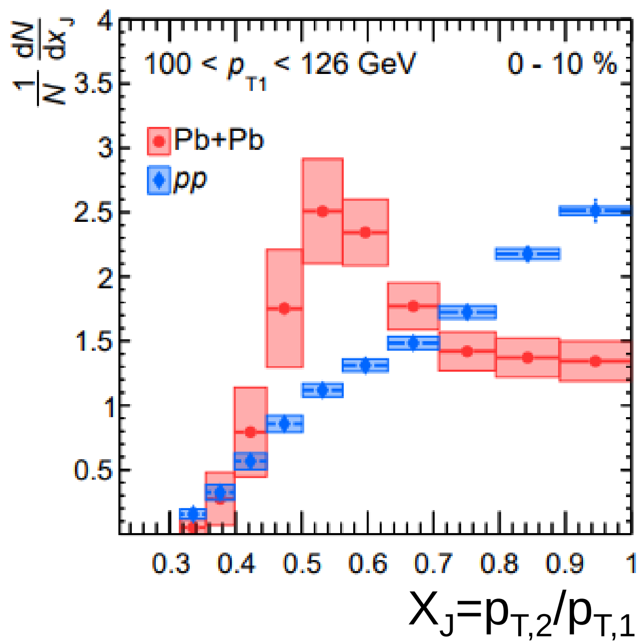


R=0.4



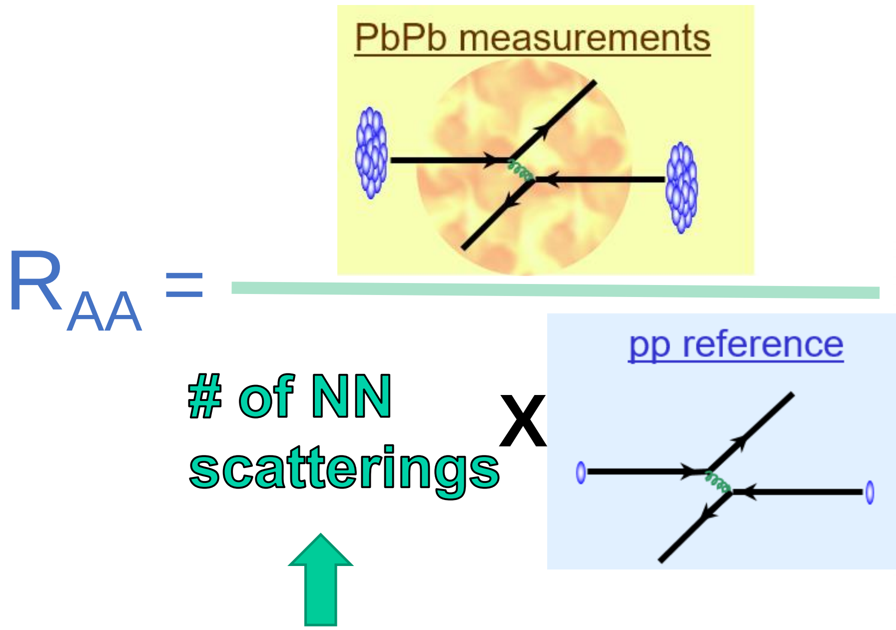
arXiv:1609.03878

- **STAR**: Di-jet pairs seeded with “hard core”
  - No significant energy flow out of the jet cone R~0.4 in this subset of dijets
- **ATLAS**: inclusive dijet (resolution unfolded)
  - Peak at ~ 0.5
  - Check from CMS?

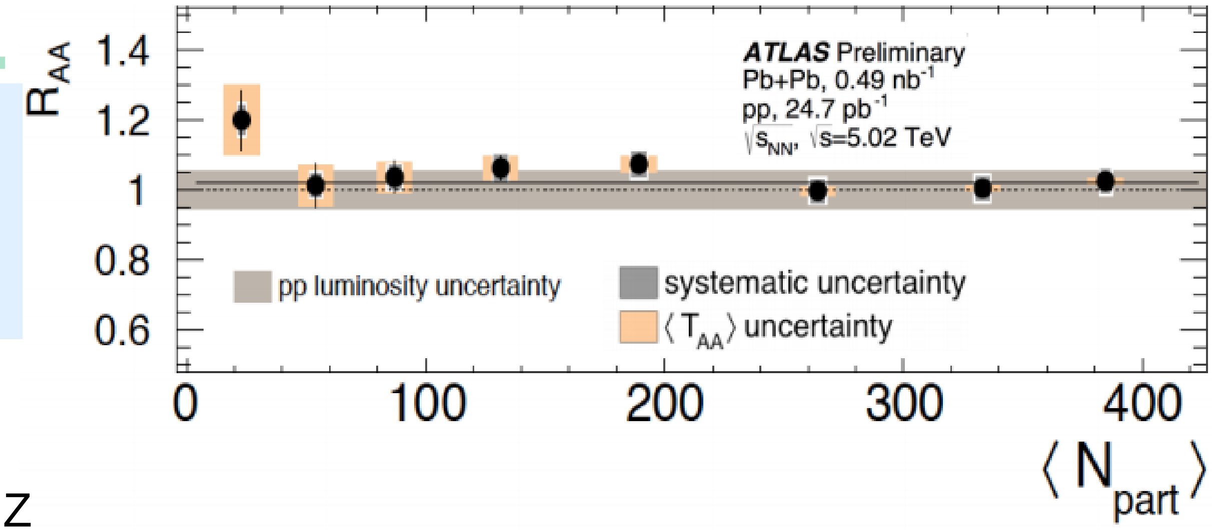


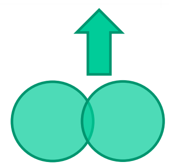
Nuclear Modification Factors (R_{AA})

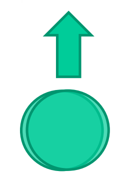
ATLAS-CONF-2017-010



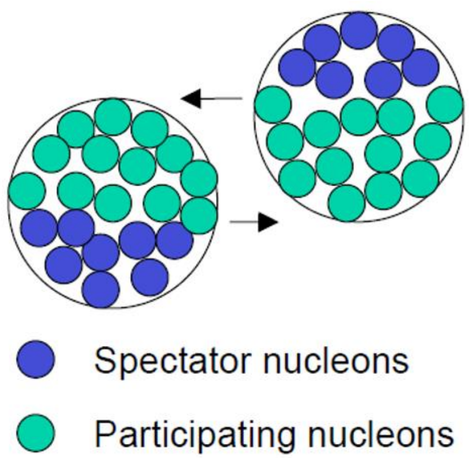
Z boson R_{AA} (PbPb at 5 TeV)





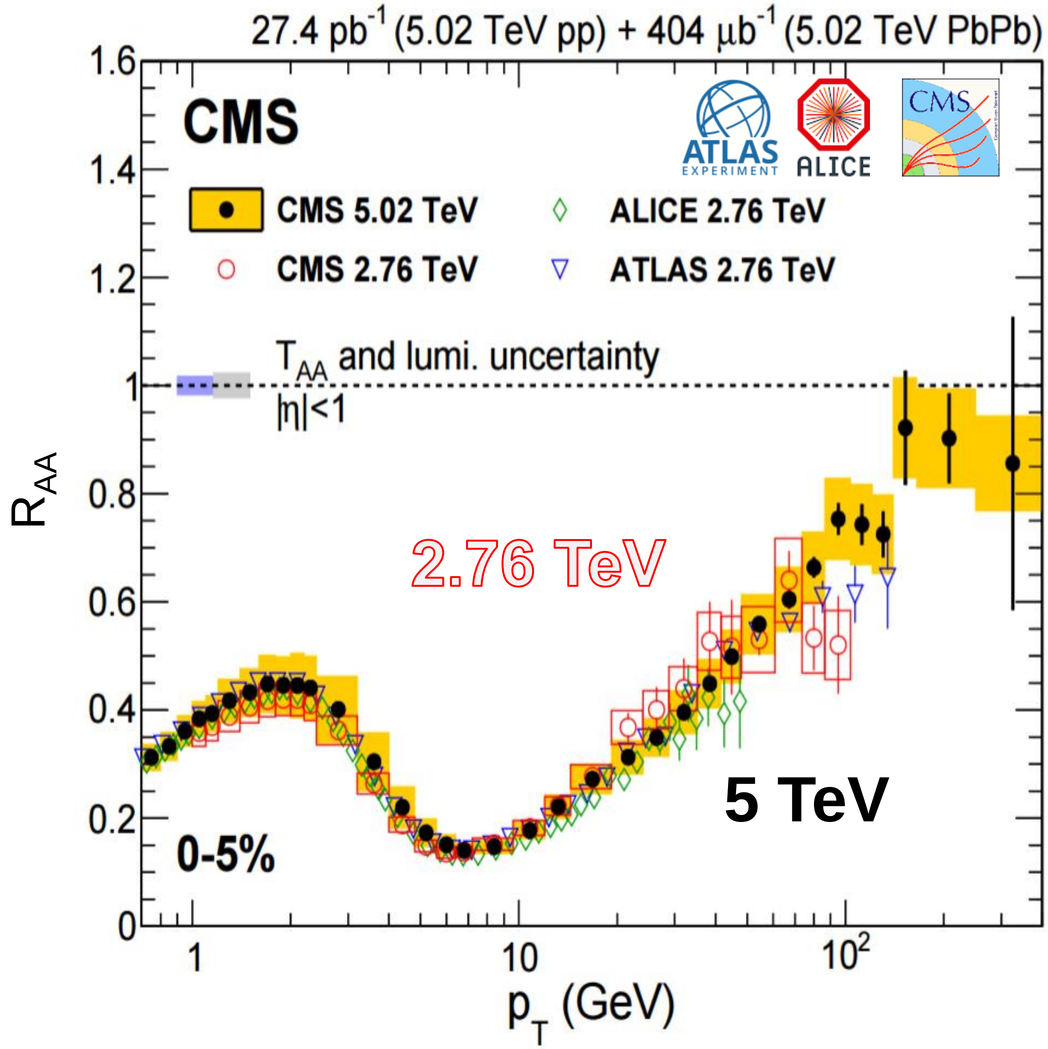


- From a Glauber model calculation
- Validated by isolated photon, W and Z production studies (R_{AA}~ 1)



No significant modification of colorless probes in PbPb collisions

Jet Quenching with Inclusive Charged Particles



Charged particle R_{AA}

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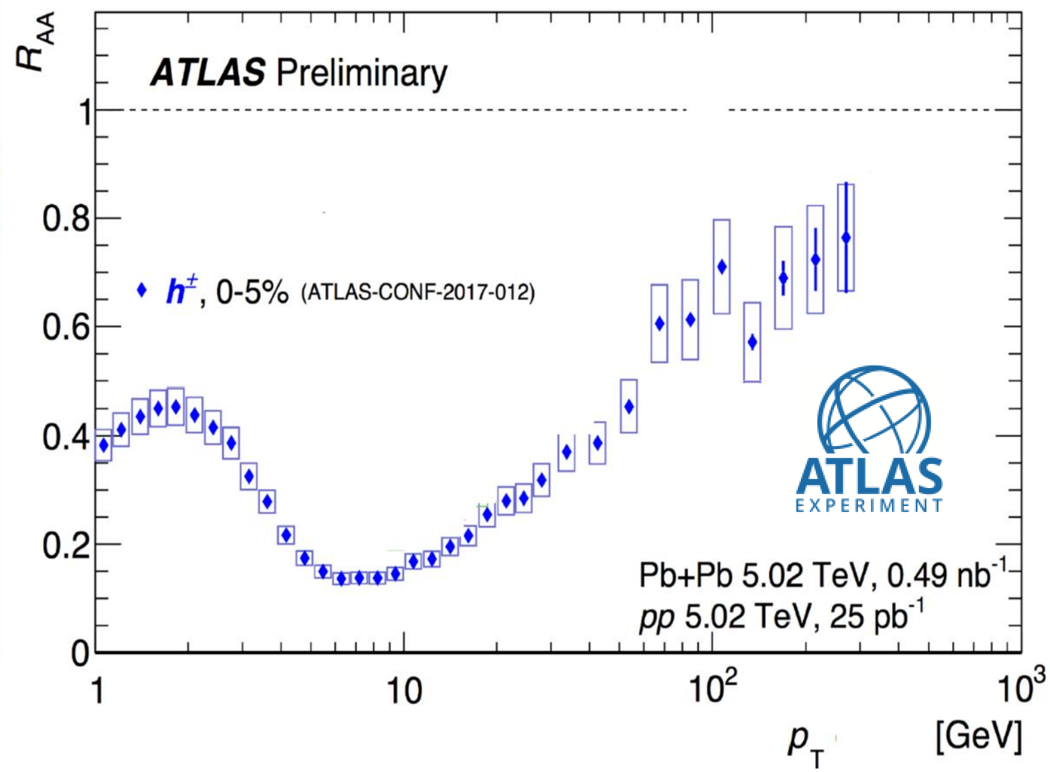

- Almost no suppression at very high p_T compared to **pp reference**
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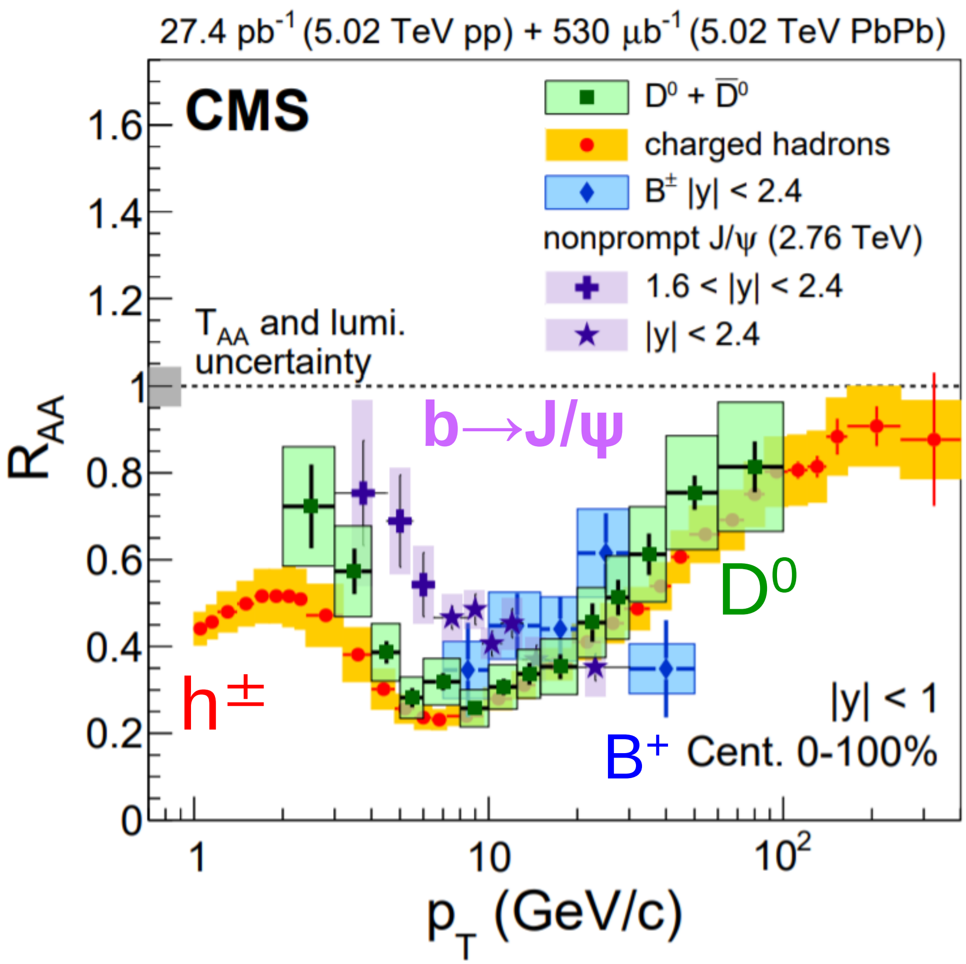
JHEP 04 (2017) 039

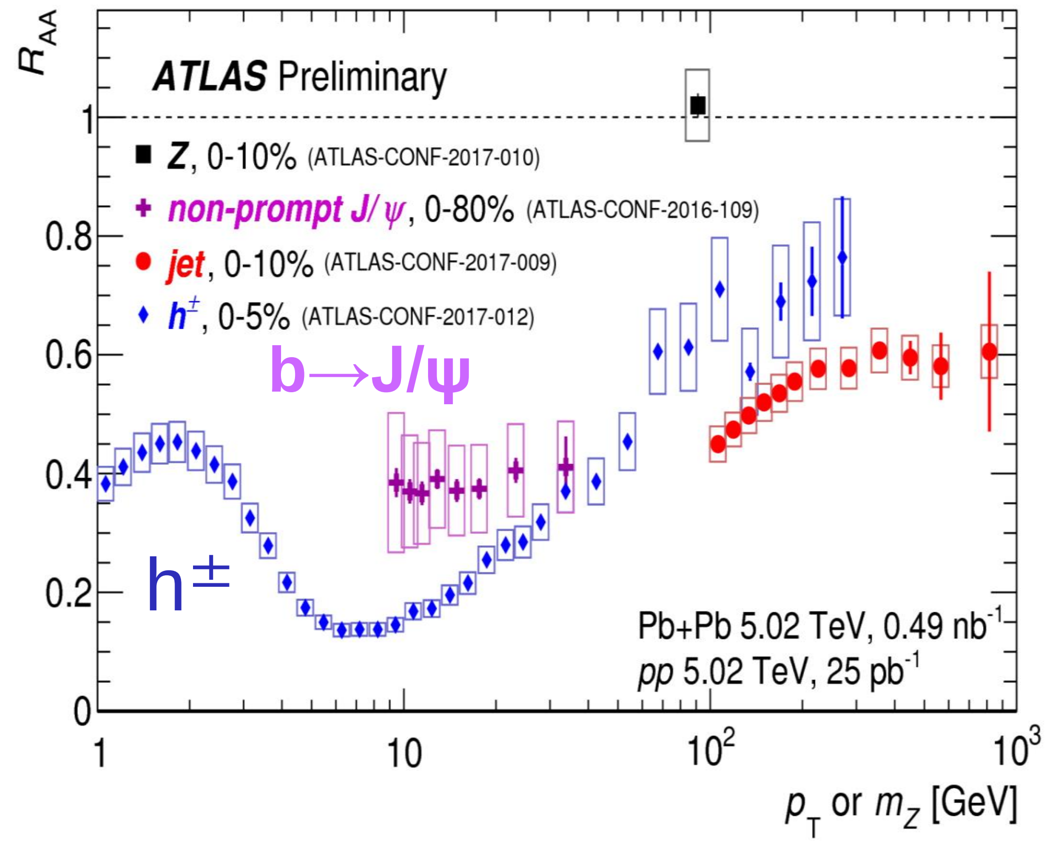
- Similar Charged particle R_{AA} in PbPb at **5 TeV** compared to 2.76 TeV
- Good agreement between ATLAS, CMS and ALICE measurements

ATLAS-CONF-2017-012

Flavor Dependence of Parton Energy Loss

arXiv:1708.04962

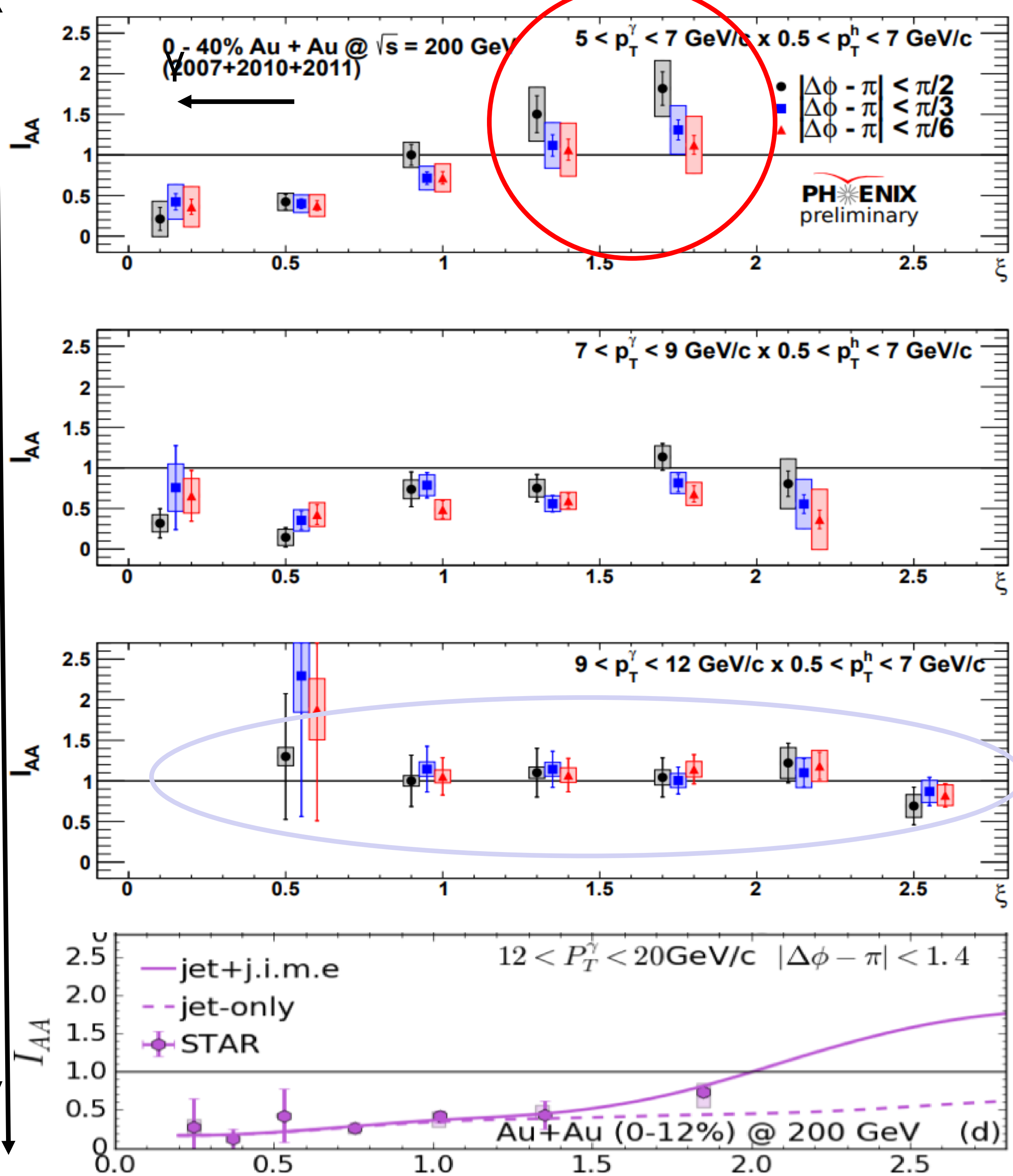


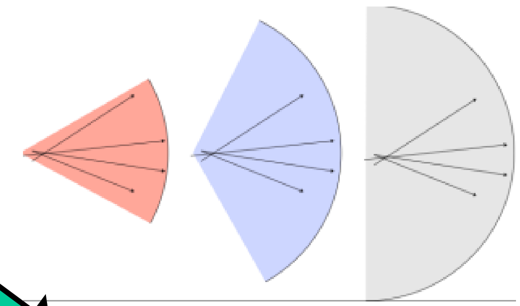


- R_{AA} is meson flavor dependent at low hadron p_T
- Disappearance of the effect at high hadron p_T
- Results are consistent with the expectation from models with parton flavor dependent energy loss

PHENIX Photon-Hadron Correlation

Low p_T Photon 5-7 GeV





Indication of wide angle radiation carried by soft particle. Significant modification of jet FF

Something in between

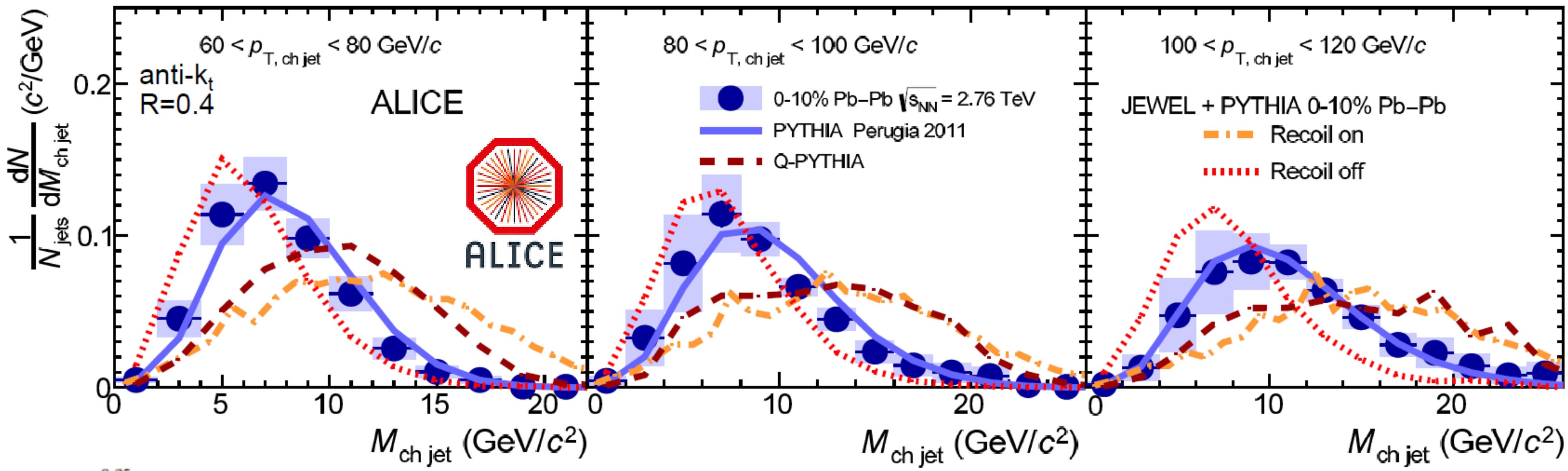
No modification of jet fragmentation (?)

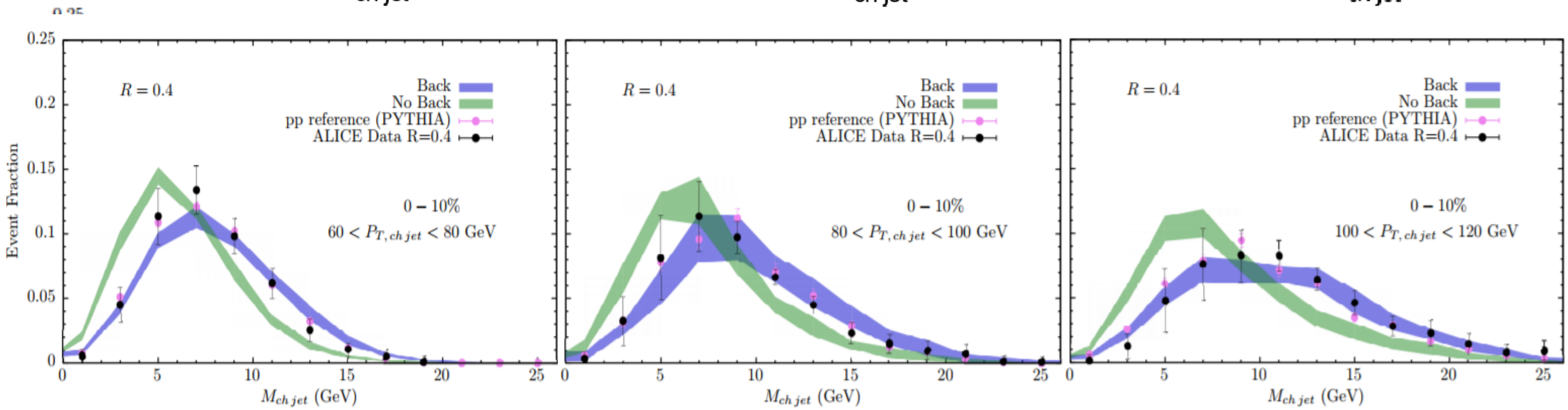
Significant modification of jet FF

High p_T Photon 12-20 GeV

Plot from Wei Chen

ALICE Charged Jet Mass



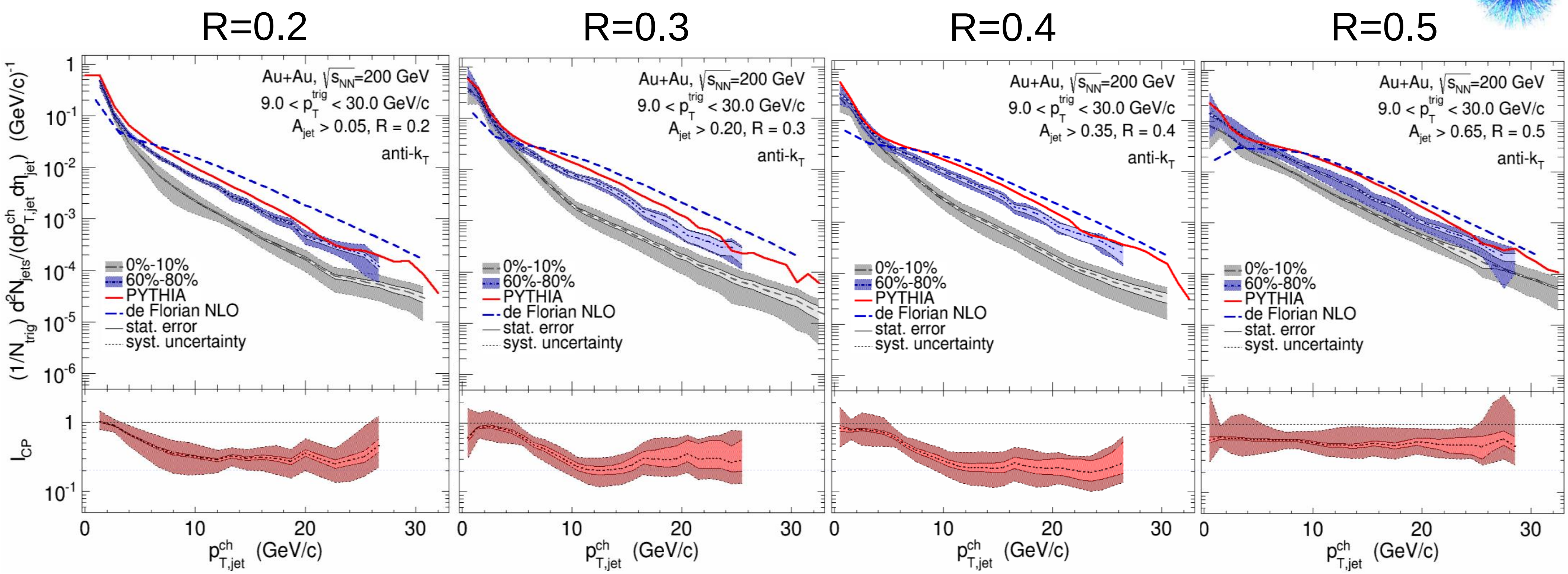


- Data sit between **JEWEL** recoil on and off
- HYBRID need medium recoil to describe the ALICE data

HYBRID

STAR Hadron-Jet Correlation

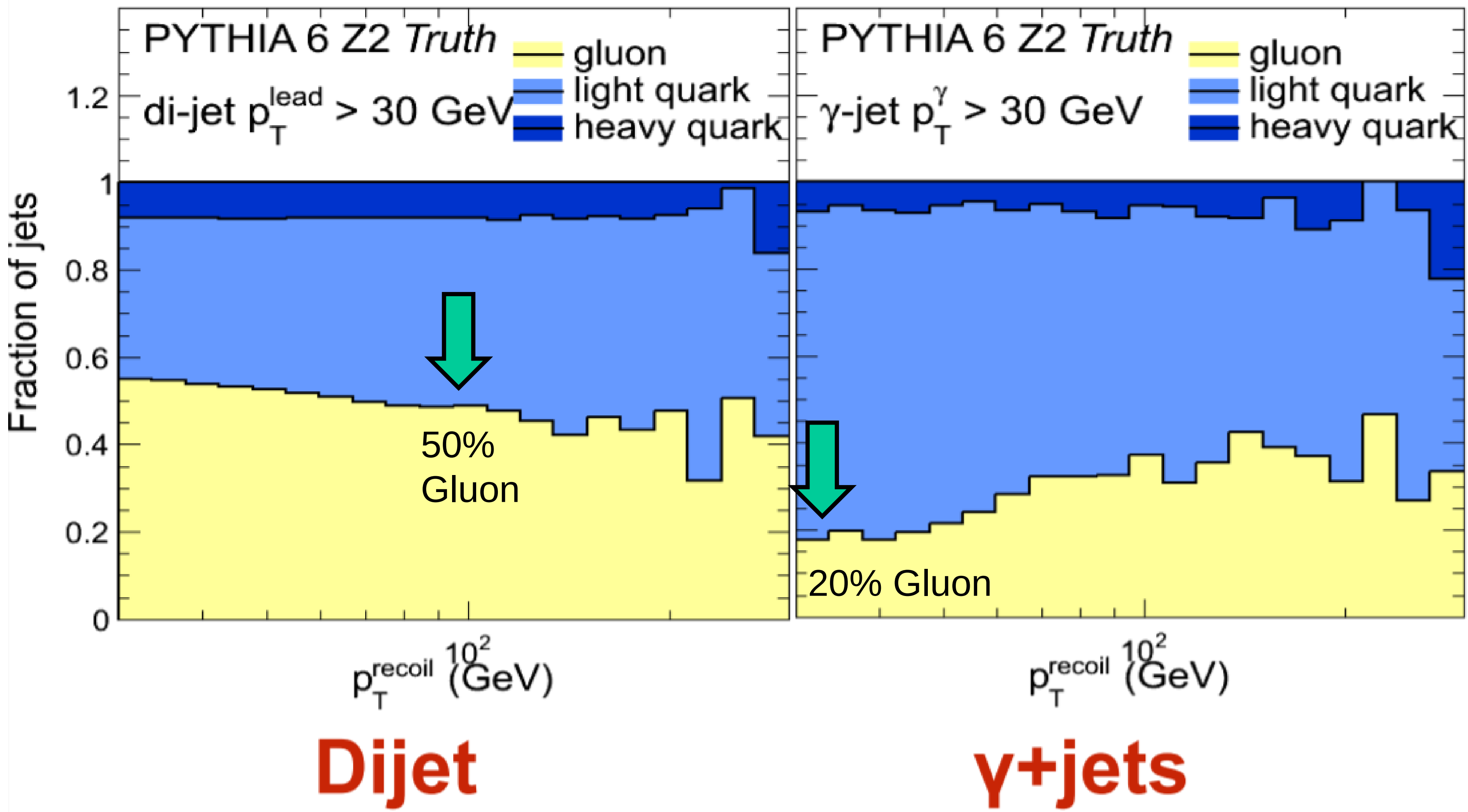
arXiv:1702.01108



- R=0.2-0.4
  - I_{CP} significantly lower than unity; significant out-of-cone Eloss

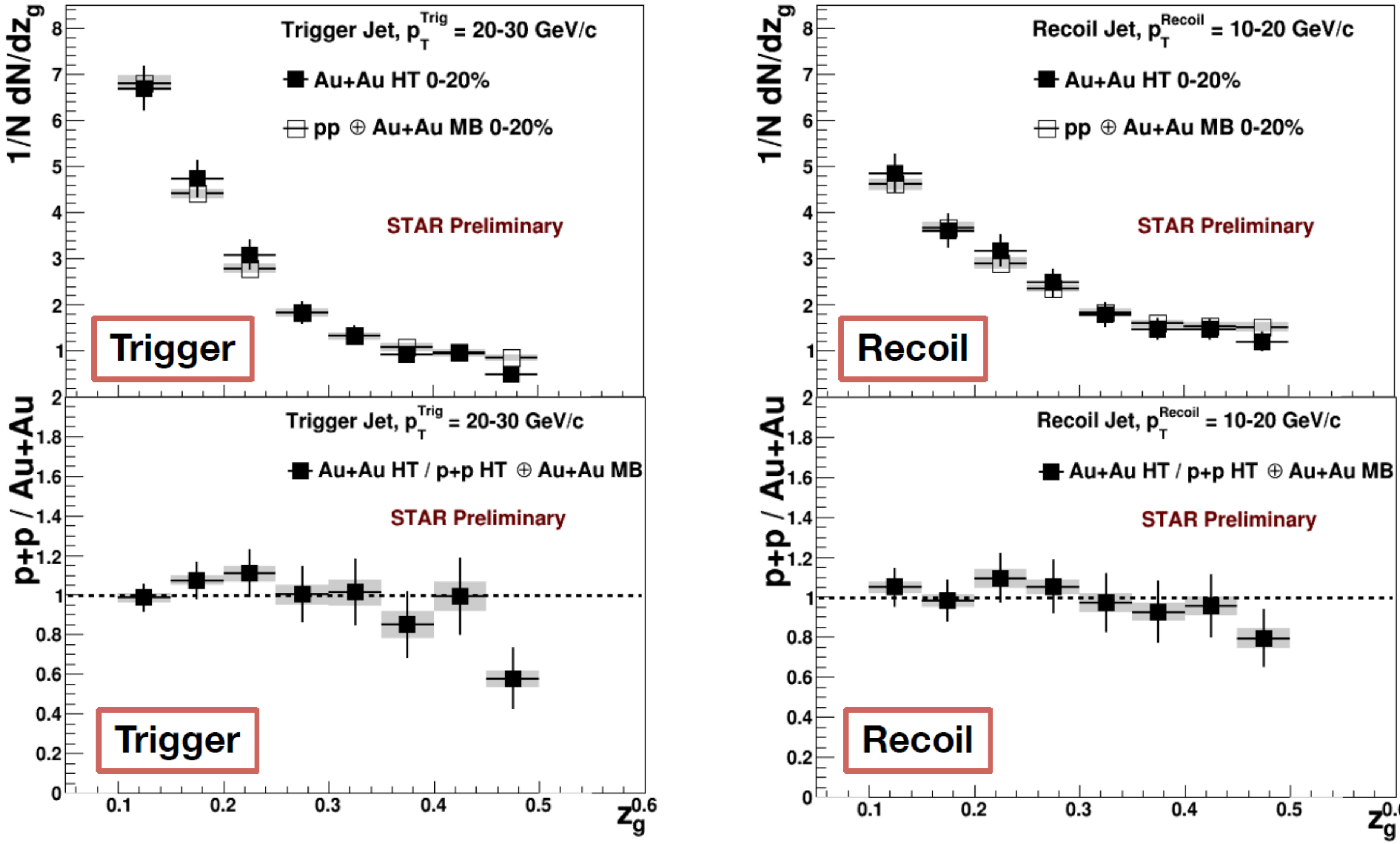
- R=0.5 I_{CP} **>** R=0.2 I_{CP}
  - indication of the recovery of the quenched energy

Jet Flavor Composition in Dijet and γ-Jet



From Doga Gulhan

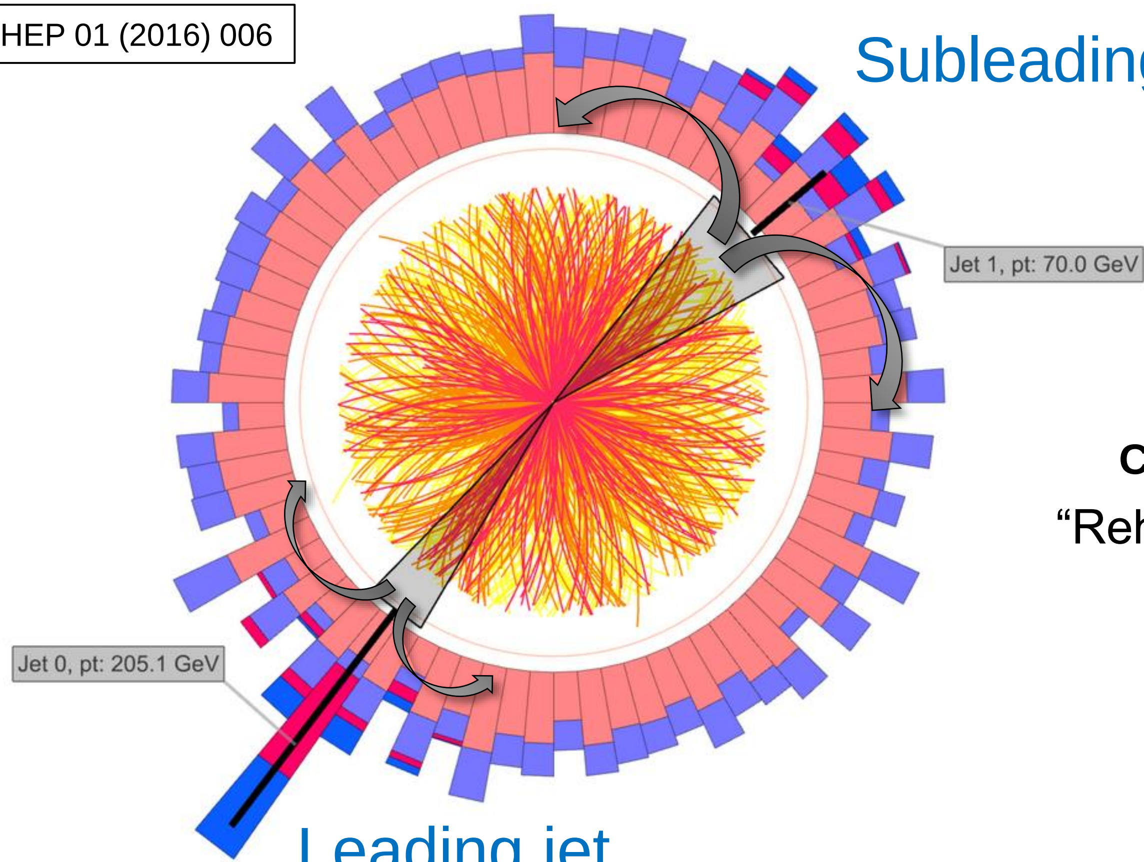
STAR Splitting Function

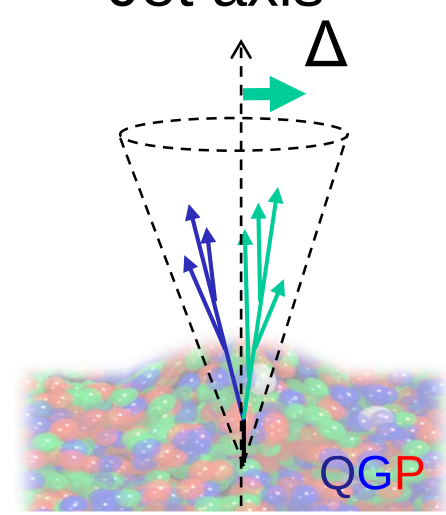


- STAR: Di-jet pairs seeded with "hard core"
- No significant modification in this subset of dijet

Quenched Energy out of the Jet Cone

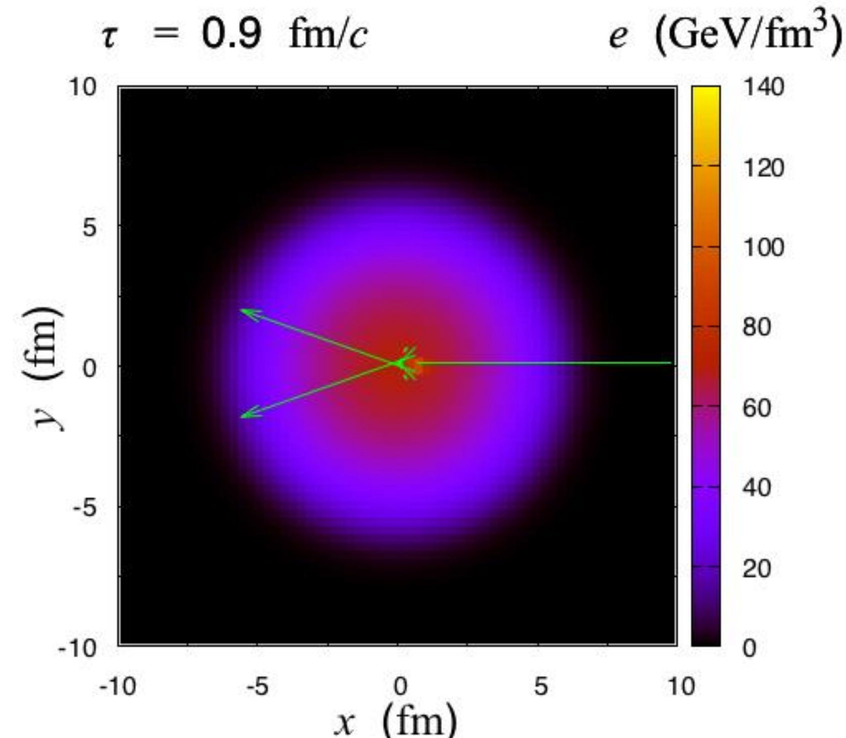
JHEP 01 (2016) 006





CCNU Model

"Reheating" the QGP



See talk from Yasuki Tachibana

- Quenched energy carried by **low momentum particles!**
- Average momentum of those particles are **higher** than that from medium debris
  → Not Completely Thermalized?

Medium Response

We also don't know **how much** the medium response (recoil) plays a role in the description of the jet quenching observables and how to describe it correctly