Jet Quenching Measurements at the LHC

Yen-Jie Lee

Massachusetts Institute of Technology

2018 JETSCAPE Winter School and Workshop

Berkeley, California

6 January, 2018

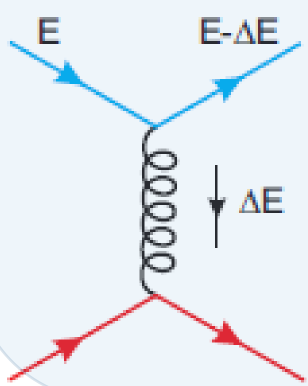
Extraction of the medium properties

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

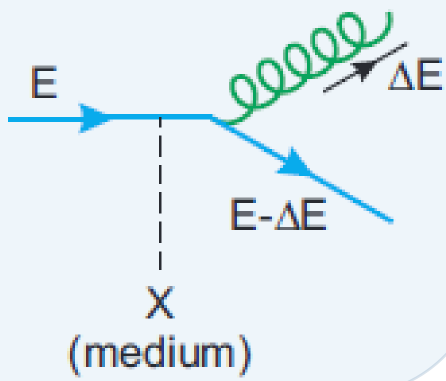
- **Two theoretical approaches:**
  (neither of them are the full stories and both of them are effective descriptions in proper regimes)

Perturbative QCD
Weak coupling limit

Collisional energy loss



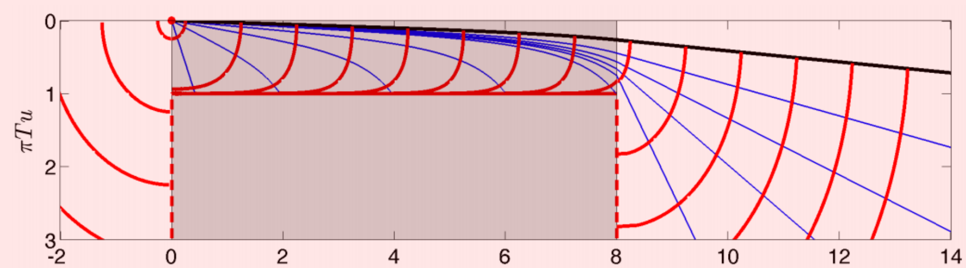
Radiative energy loss



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

Holographic calculation
Strong coupling limit

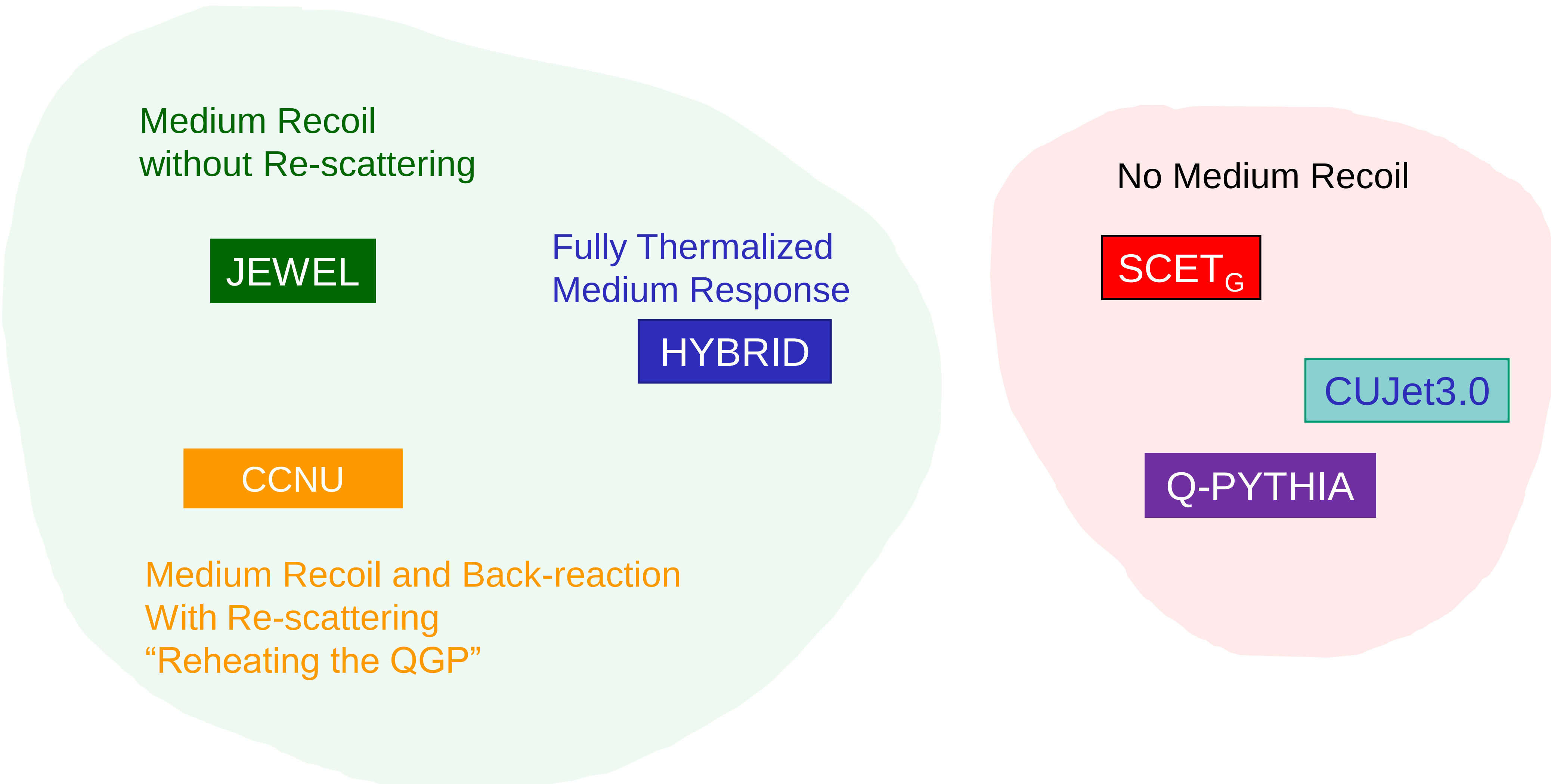
AdS/CFT "drag force"



HYBRID

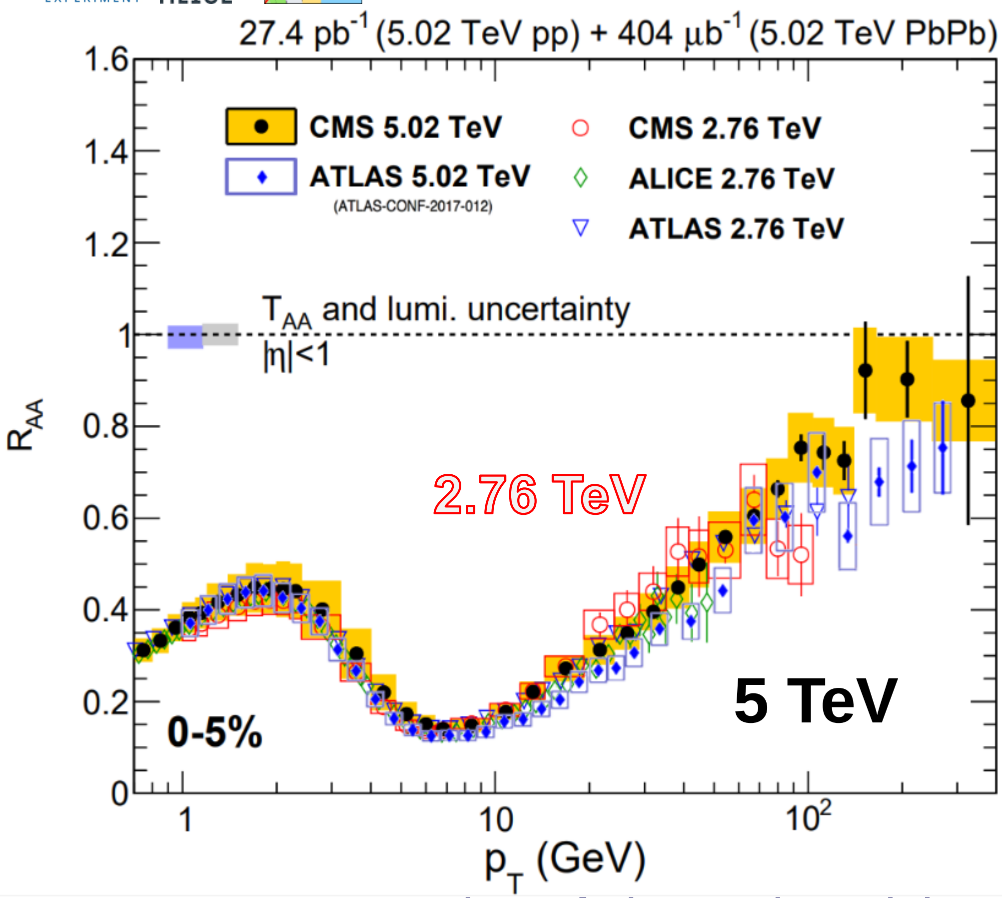
Medium Response

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

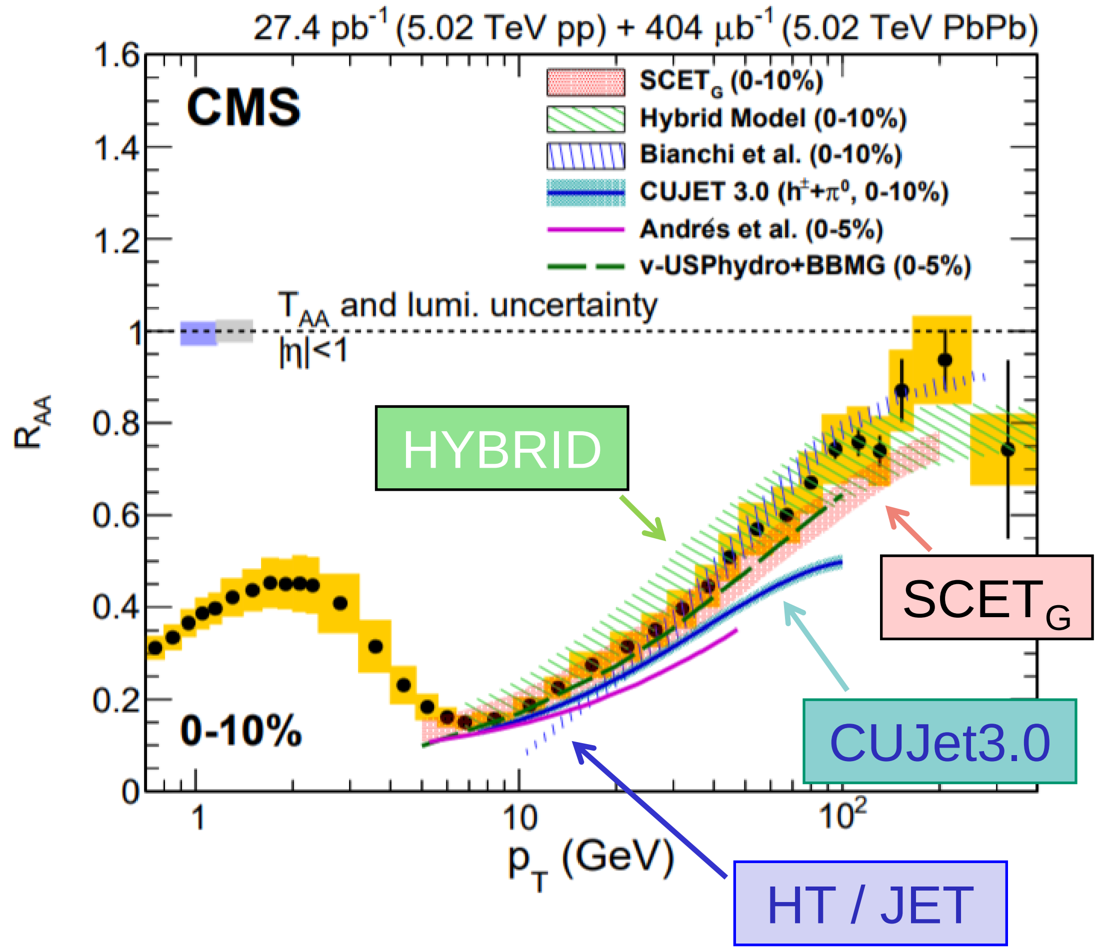


Charged Particle R_{AA}

ATLAS-CONF-2017-012



JHEP 04 (2017) 039

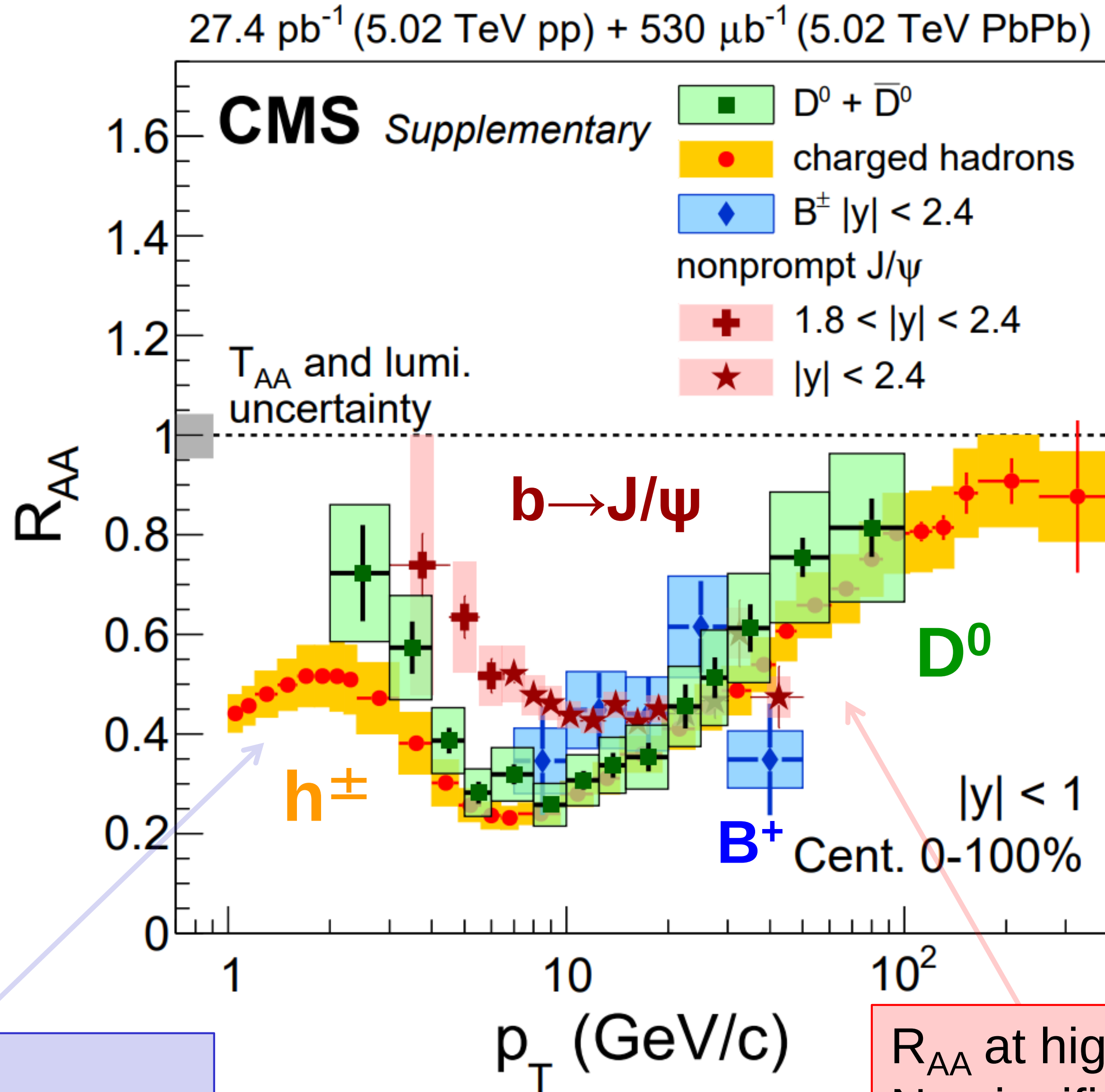


- Strong suppression of charged particles (up to a factor of 6) in PbPb
- Almost no suppression at very high p_T compared to **pp reference** (p_T~400 GeV)
- Similar charged particle R_{AA} in PbPb at **5 TeV** compared to 2.76 TeV

- General trend described by both **pQCD** and **Hybrid** models
- Description of the R_{AA} over the whole p_T range is still challenging

Compilation of Hadron R_{AA}

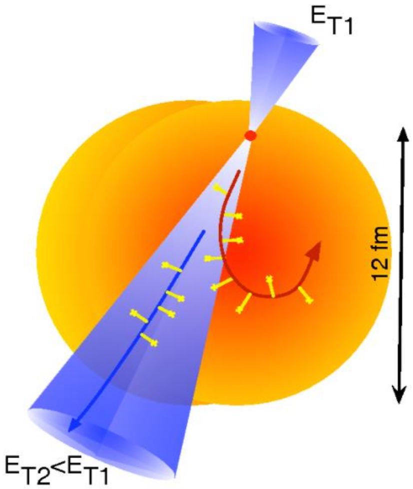
arXiv:1708.04962



R_{AA} at low p_T:
meson flavor dependent
b→J/ψ > D^0 ≥ $h^\pm$

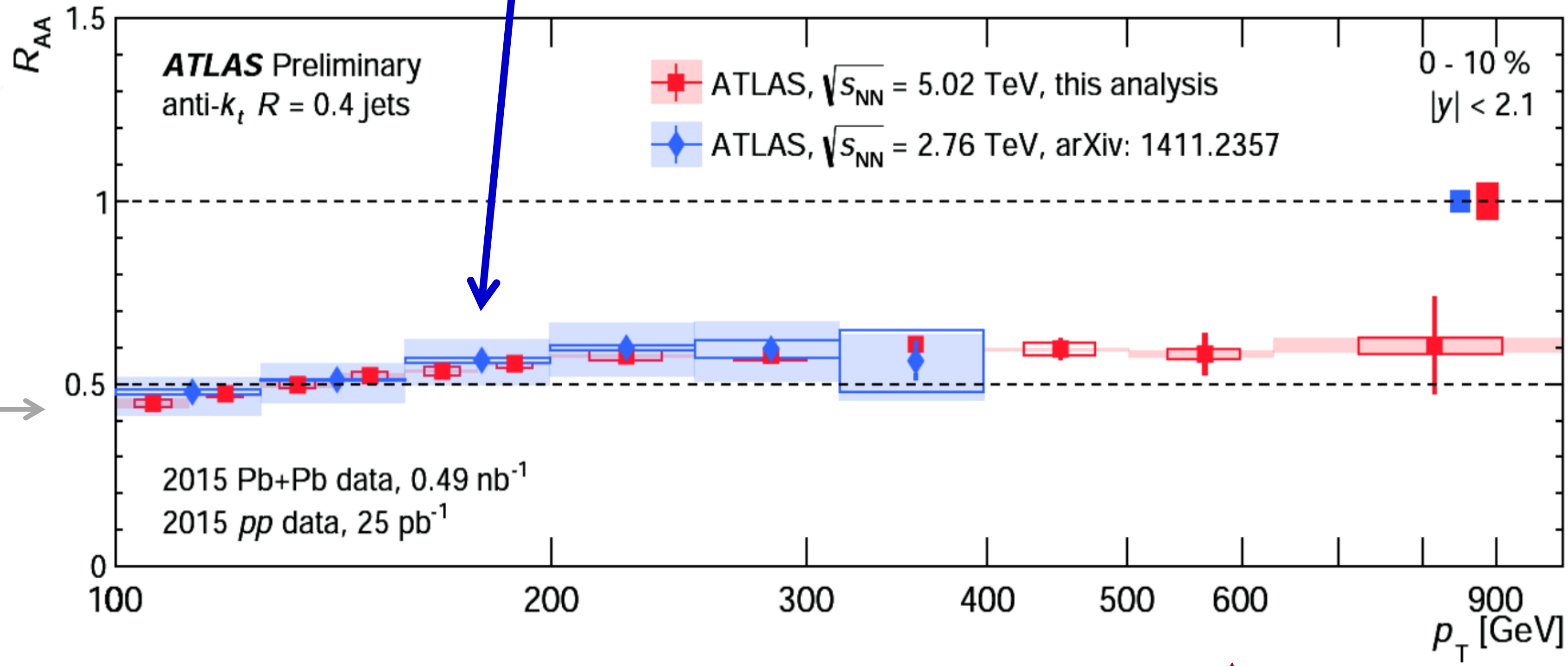
R_{AA} at high p_T:
No significant meson flavor dependence observed yet
B^+ ~ D^0 ~ $h^\pm$

Jet R_{AA} up to p_T ~ 1 TeV in PbPb at 5 TeV



Similar suppression between 2.76 and 5 TeV

Anti-k_T R=0.4 Jet R_{AA}



Fraction of the jet energy out of cone ~ **10%**

Increasing R_{AA} **incompatible** with constant fraction

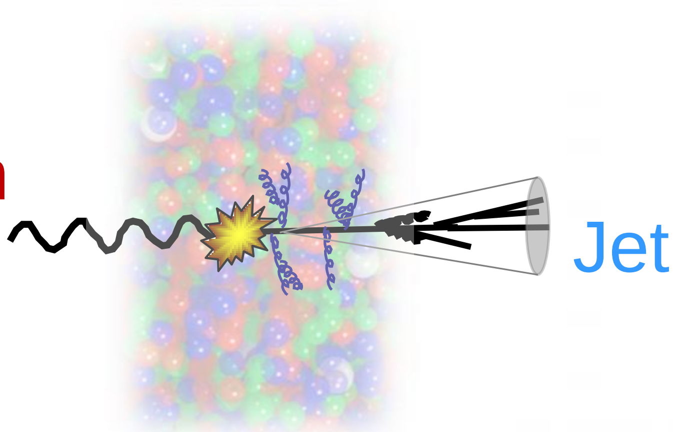
(fraction **decreases** with jet p_T)

arXiv1504.05169 Martin Spousta, Brian Cole

Very high p_T jets are also significantly suppressed

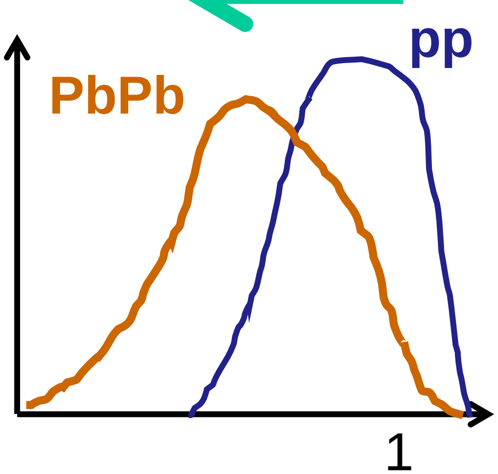
Absolute Energy Loss with Z+Jet at 5 TeV

arXiv 1702.01060
PRL 119, 082301 (2017)

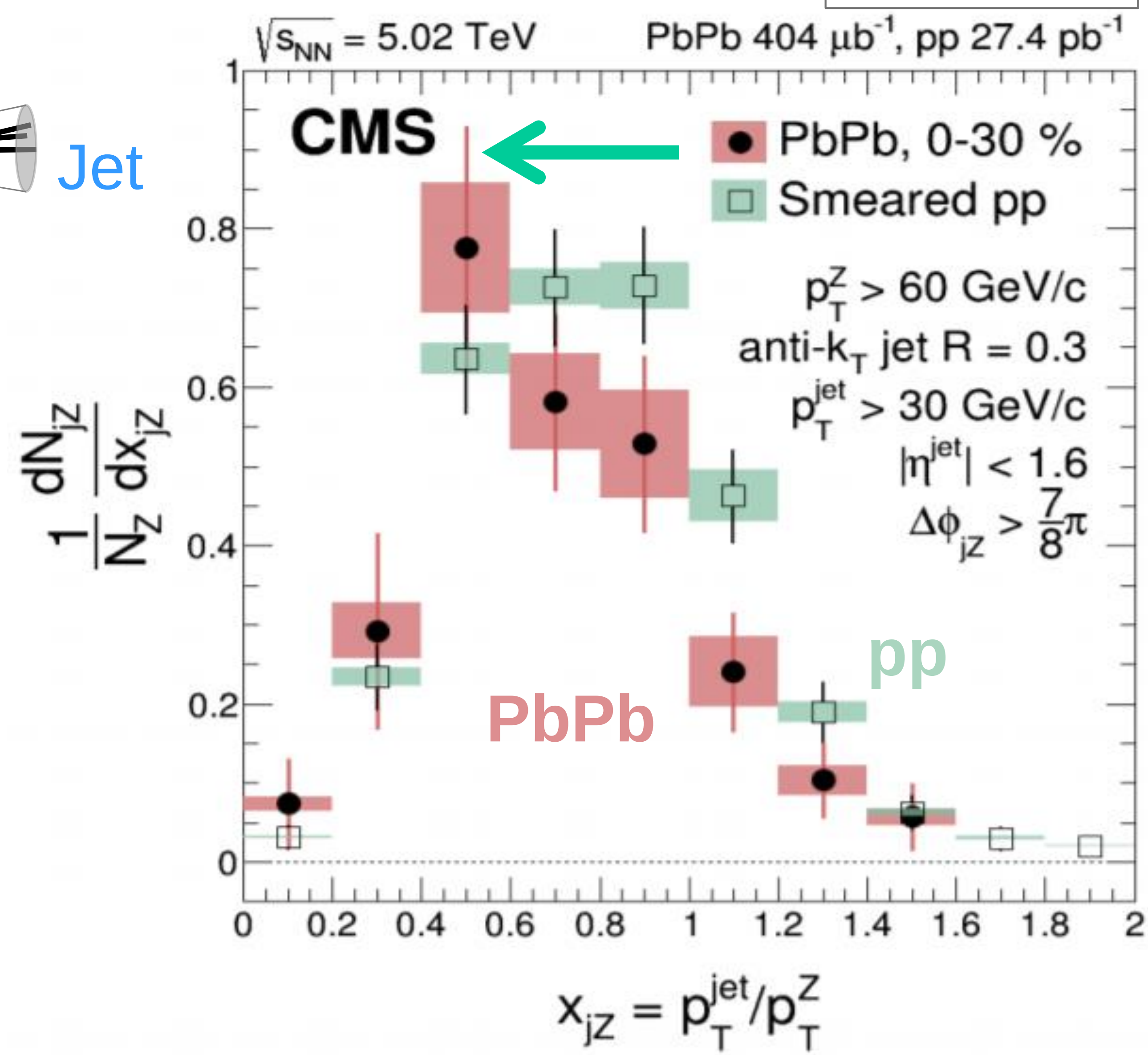


Momentum conservation
in the transverse direction

Jet quenching (E-loss)

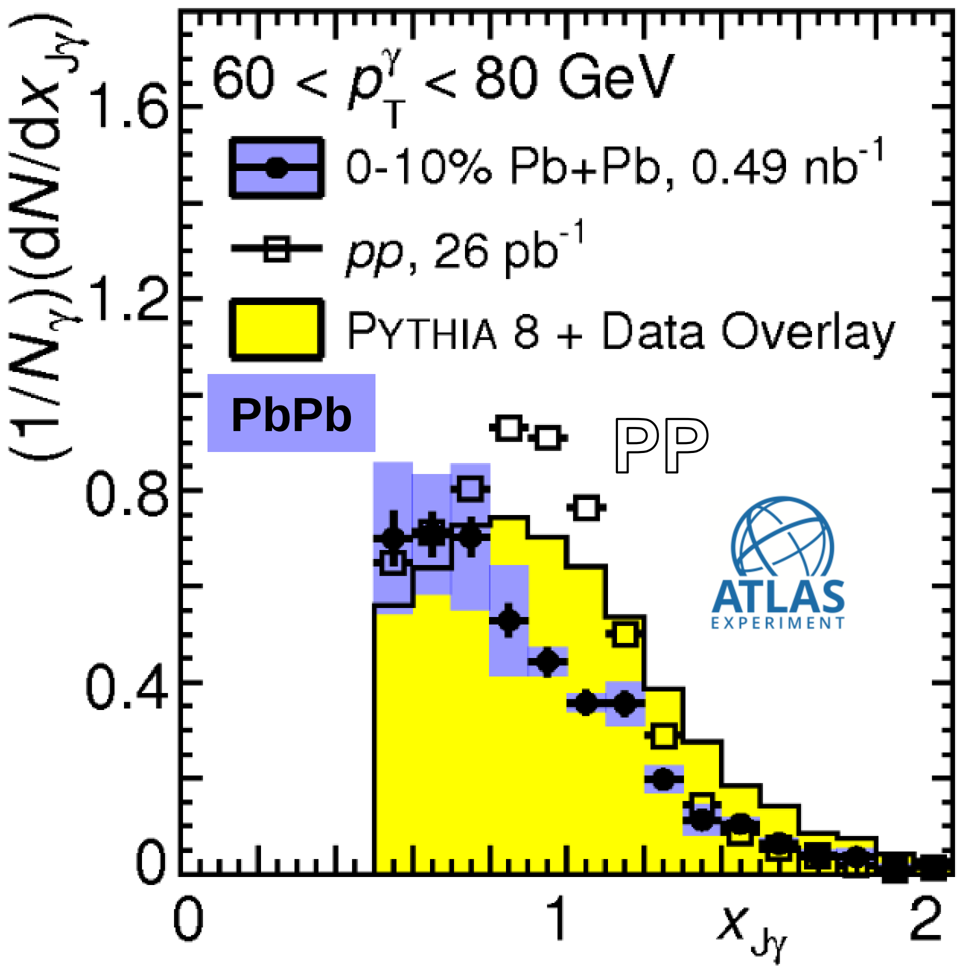


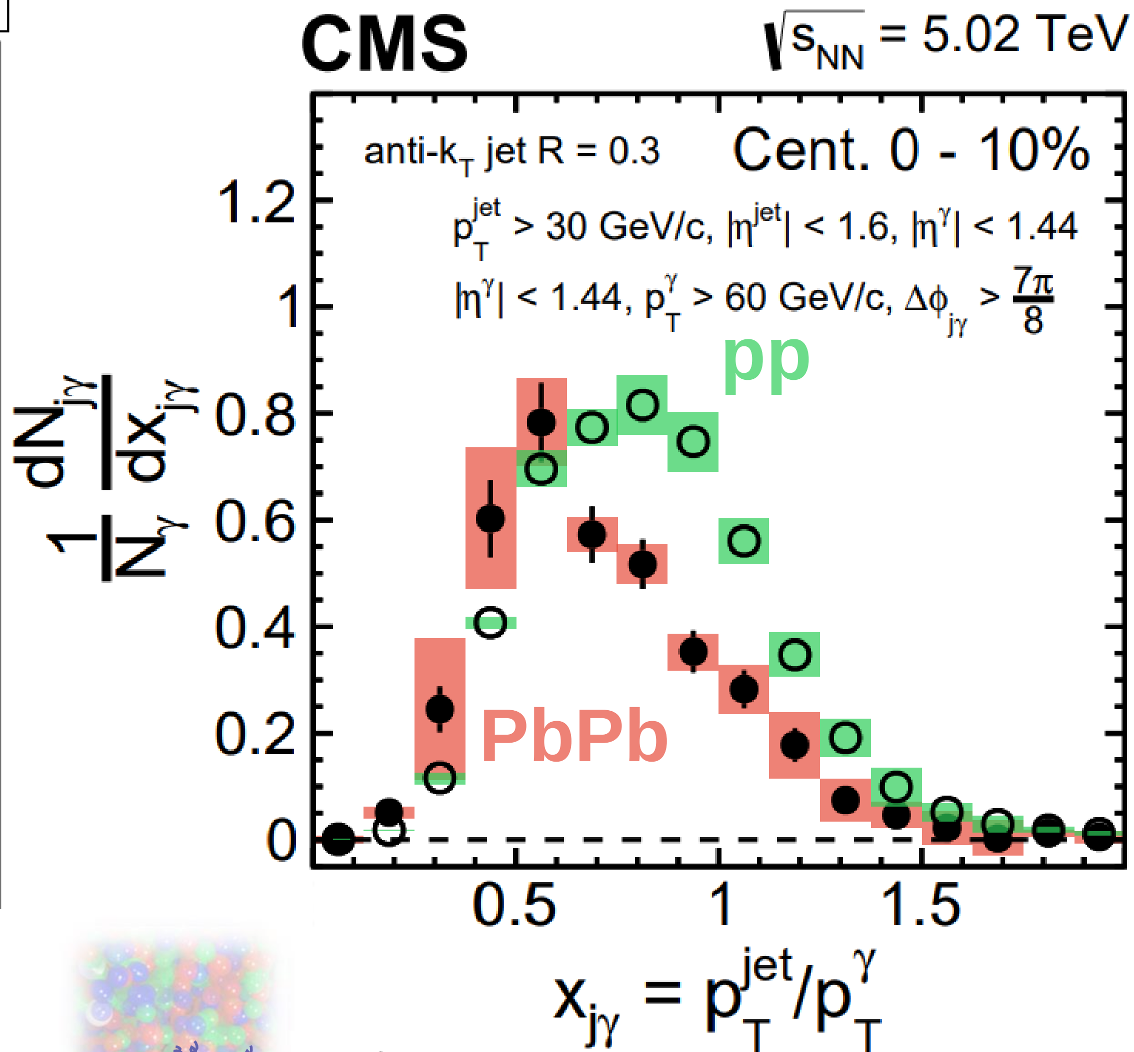
$x = p_T^{Jet} / p_T^{boson}$



Fraction of the jet energy out of cone (R=0.3) **~ 15%±6%**

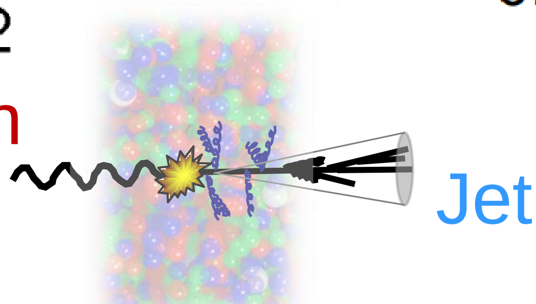
Absolute Energy Loss with γ+Jet at 5 TeV





arXiv: 1711.09738
Submitted to PLB

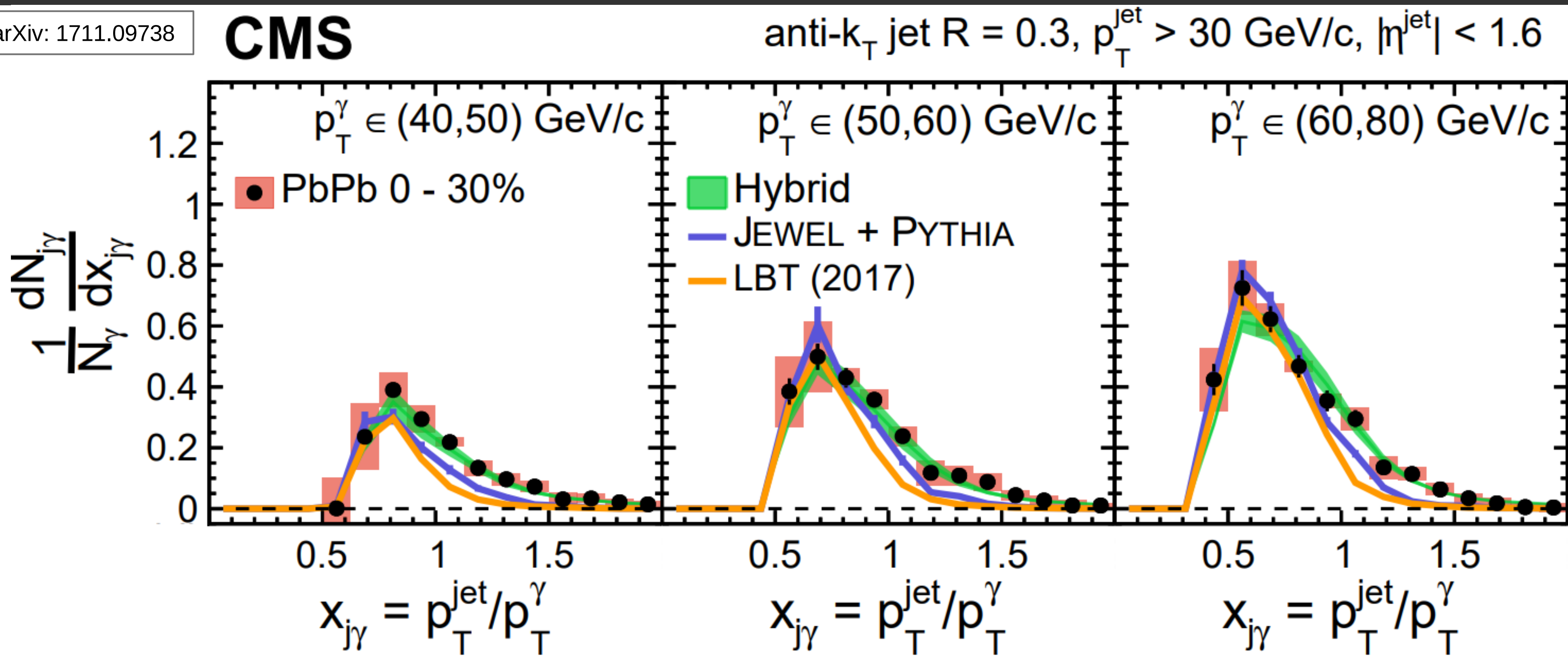
$x_{J\gamma} = p_T^{\ Jet} / p_T^{\ \gamma}$



Fraction of the jet energy out of cone (R=0.3) **~ 14%±4%**

Photon-Jet Data vs. Theoretical Predictions

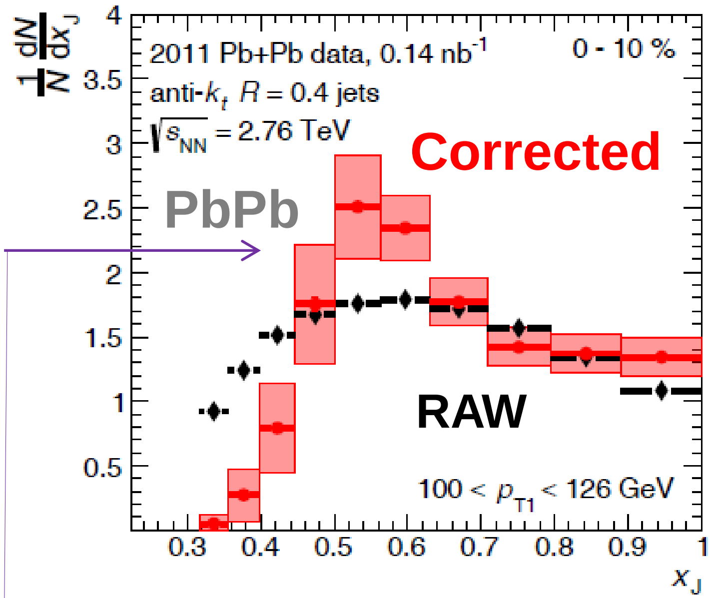
arXiv: 1711.09738



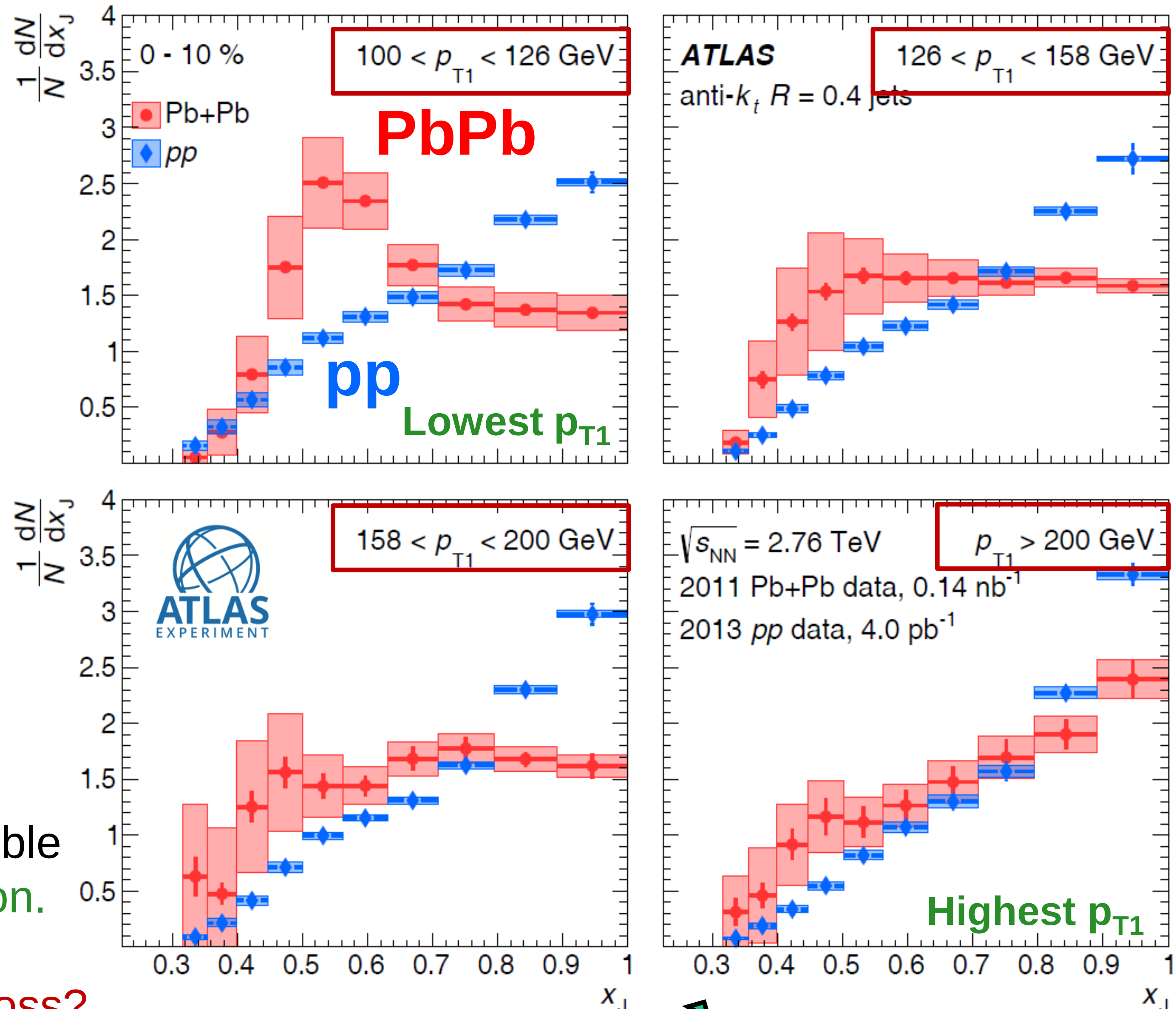
Photon p_T 40-50 GeV/c 50-60 GeV/c 60-80 GeV/c

- **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)

Dijet Asymmetry in PbPb at 2.76 TeV



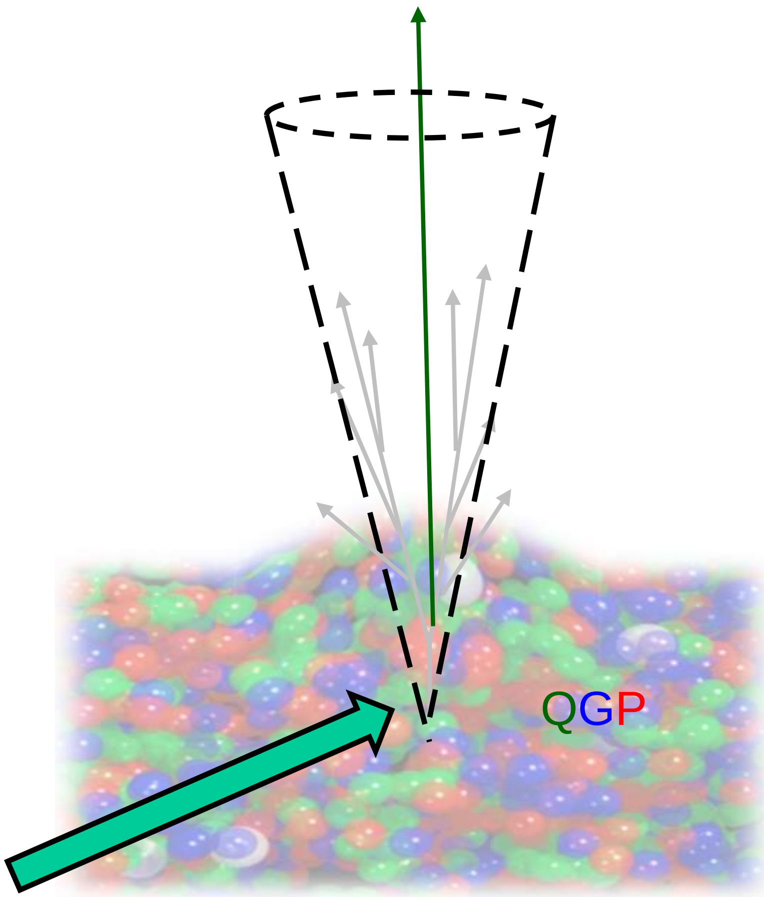
$$x_J = p_{T2} / p_{T1}$$



- First unfolded dijet p_T ratio!
- **Narrow peak** at low X_J visible after jet resolution correction.
  → Small fluctuation of the sub-leading jet energy loss?
- **Peak goes away rapidly** as one increase leading jet p_T cut

See talk by Laura Havener

Quark vs. Gluon

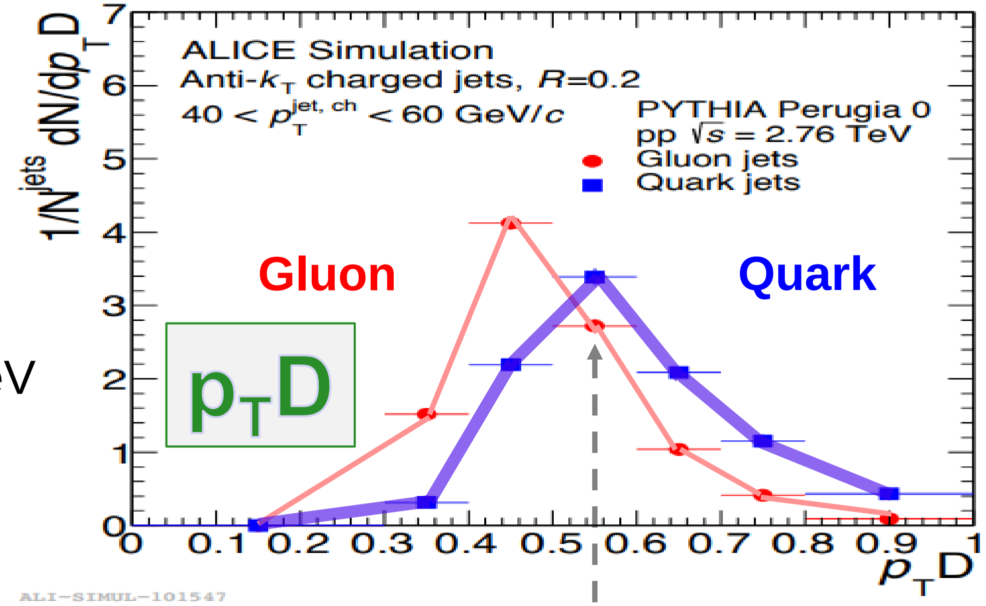


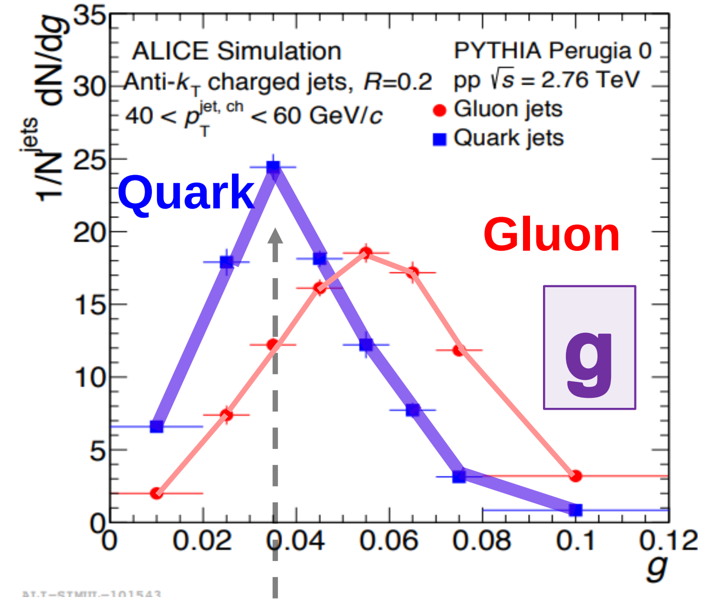
Do gluons lose more energy than the quarks?

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

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

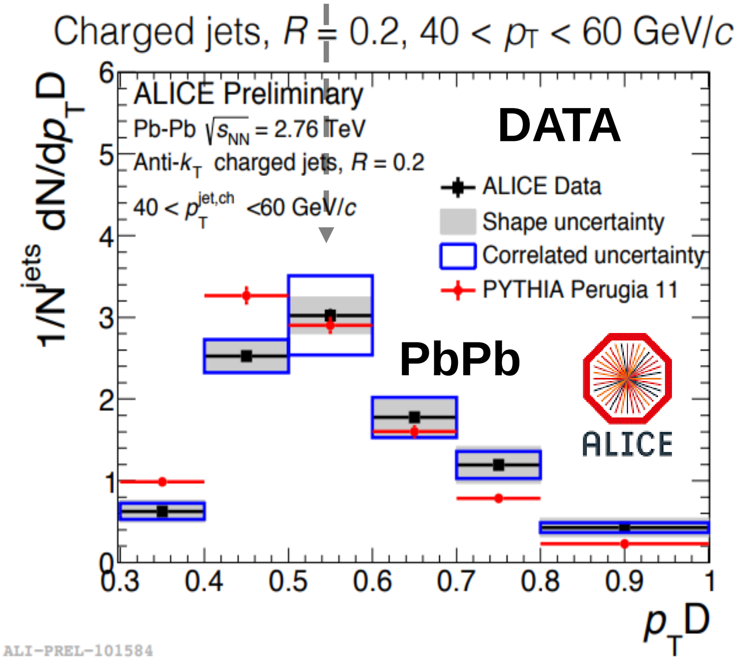
Anti-k_T R=0.2
40<p_T<60 GeV

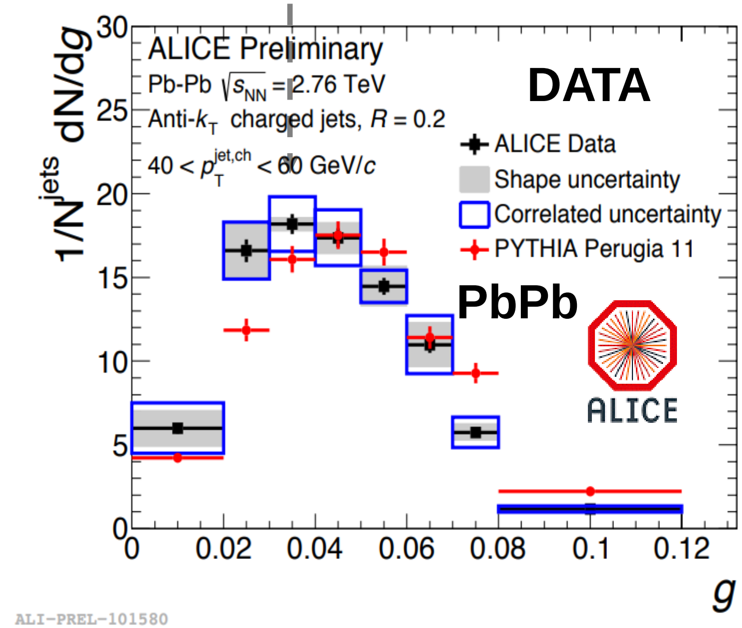




$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$

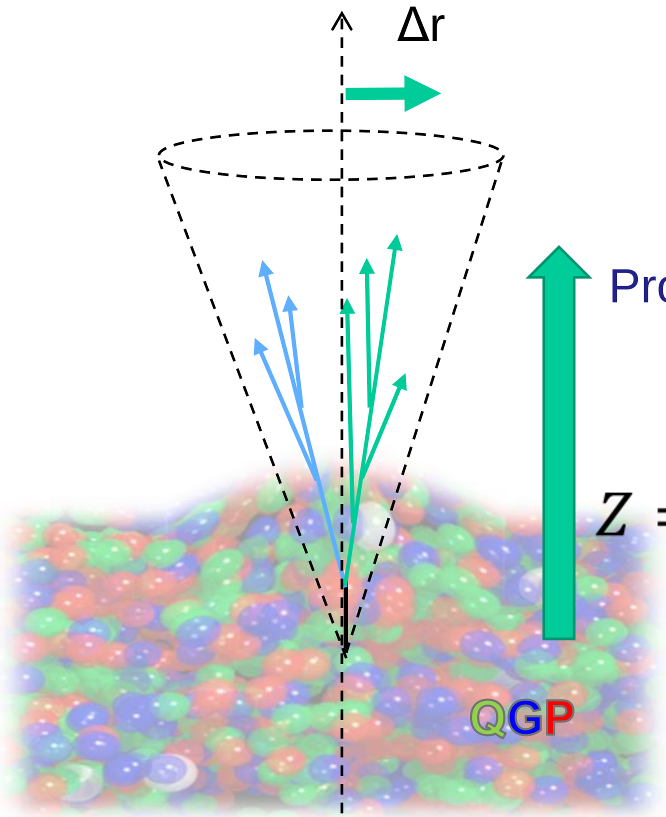
$$g = \sum_{i \in jet} \frac{p_T^i}{p_T^{jet}} |r_i|$$





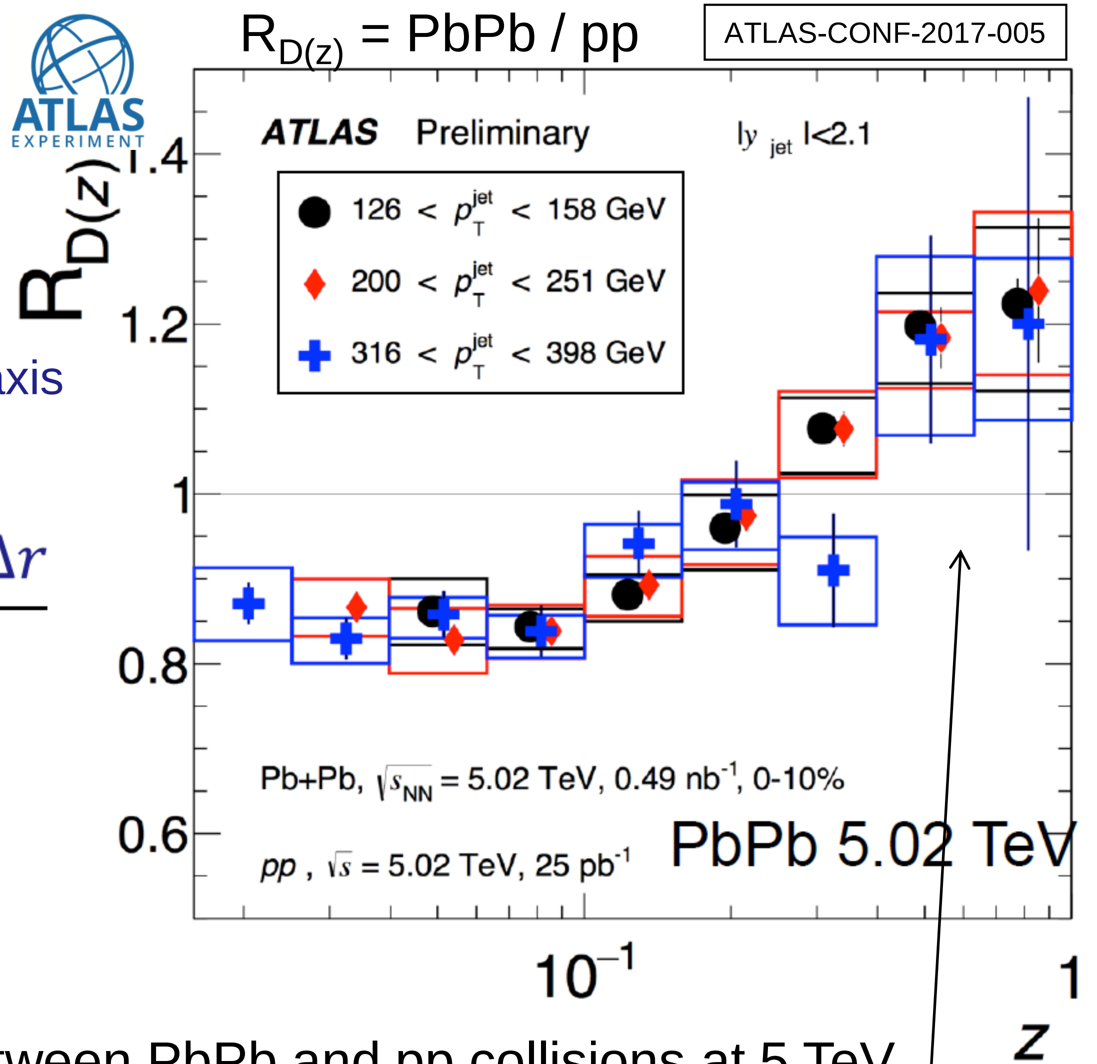
- Charged jets in PbPb are more **Quark-like**! (**Gluon jets** suppressed)

Jet Longitudinal Structure



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

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



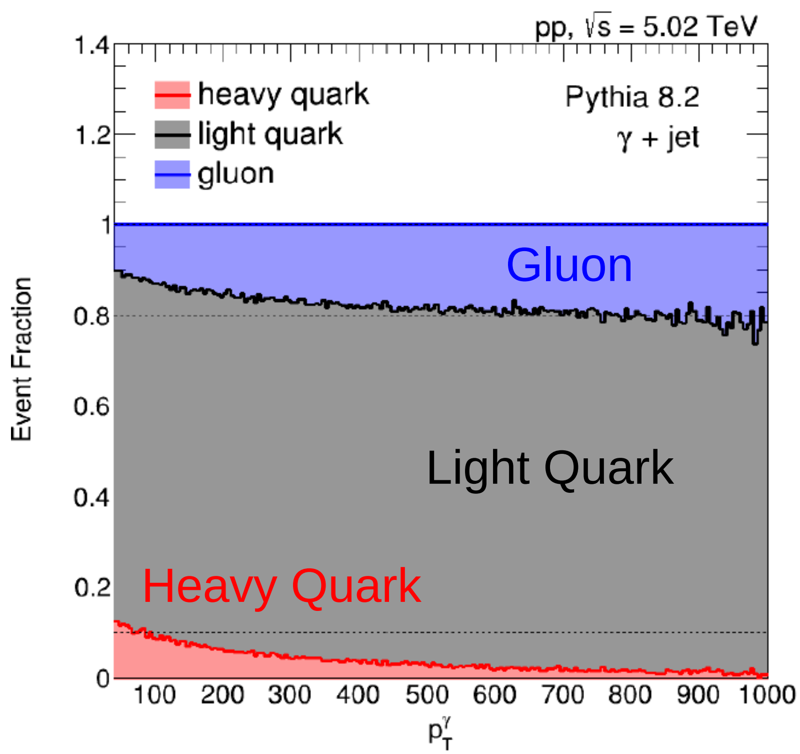
- Fragmentation functions Ratio $R_{D(z)}$ between PbPb and pp collisions at 5 TeV
- Enhancement at large z (high p_T particles in jet): **smaller gluon/quark ratio** in PbPb
- Weak or no dependence on the jet p_T

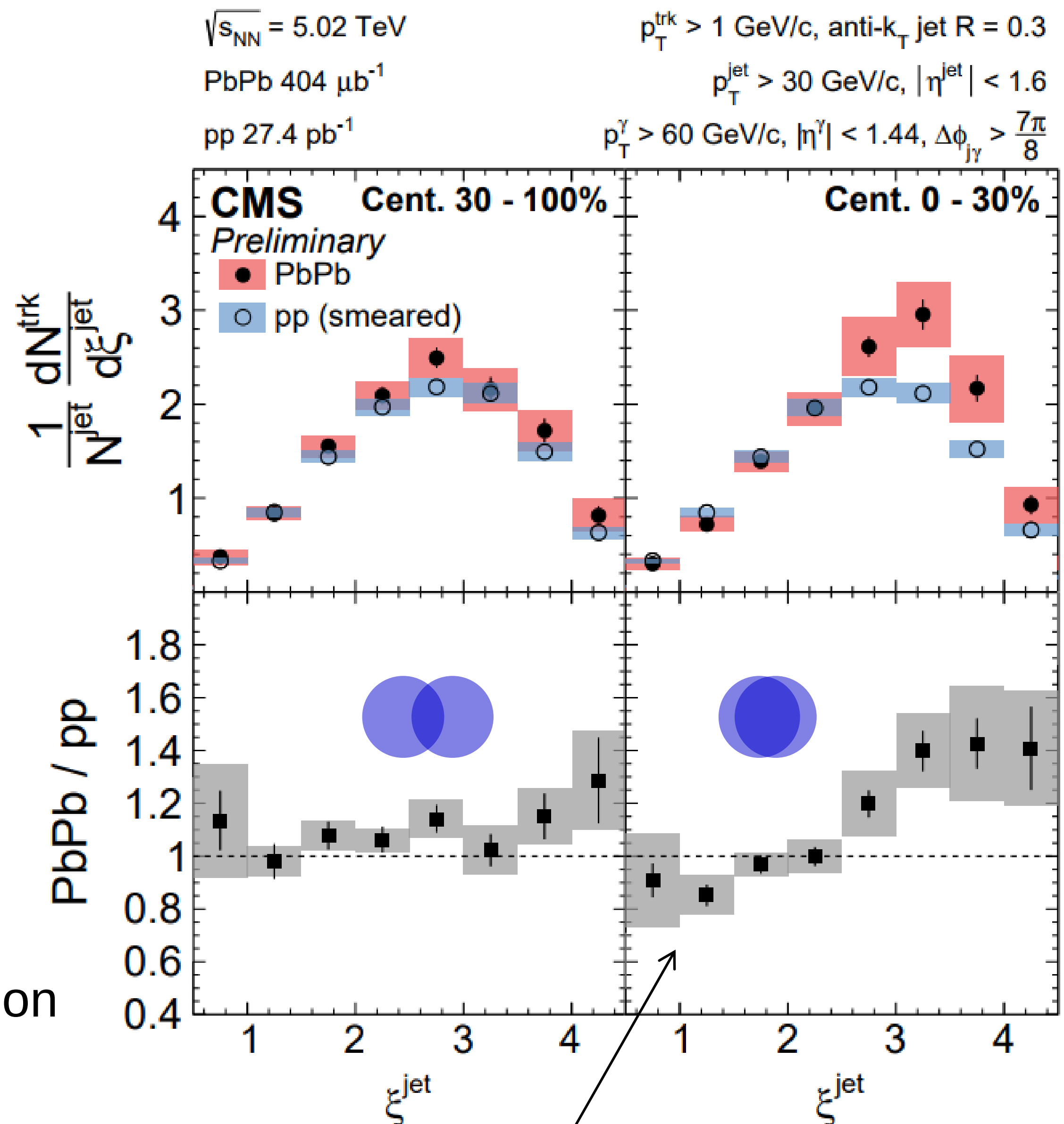
See discussions in Frank Ma, thesis (2013)
arXiv:1504.05169 Martin Spousta, Brian Cole

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

Photon-Tagged Fragmentation Function

From Kaya Tatar





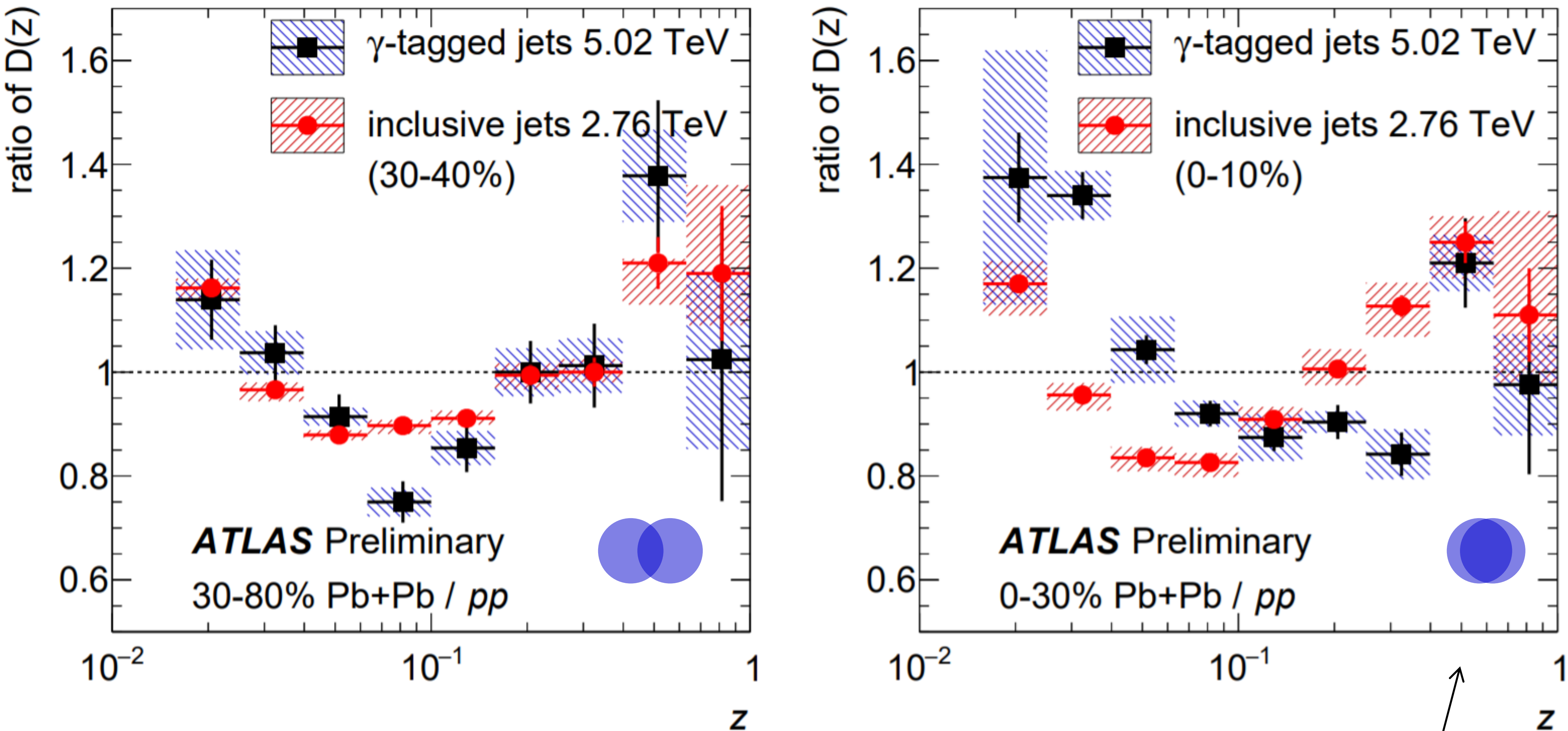
CMS-PAS-HIN-14-014

- Decrease the population of gluon jets: **>70%** of the tagged jets are quark jets
- Observation of modified jet fragmentation function in PbPb with respect to pp

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

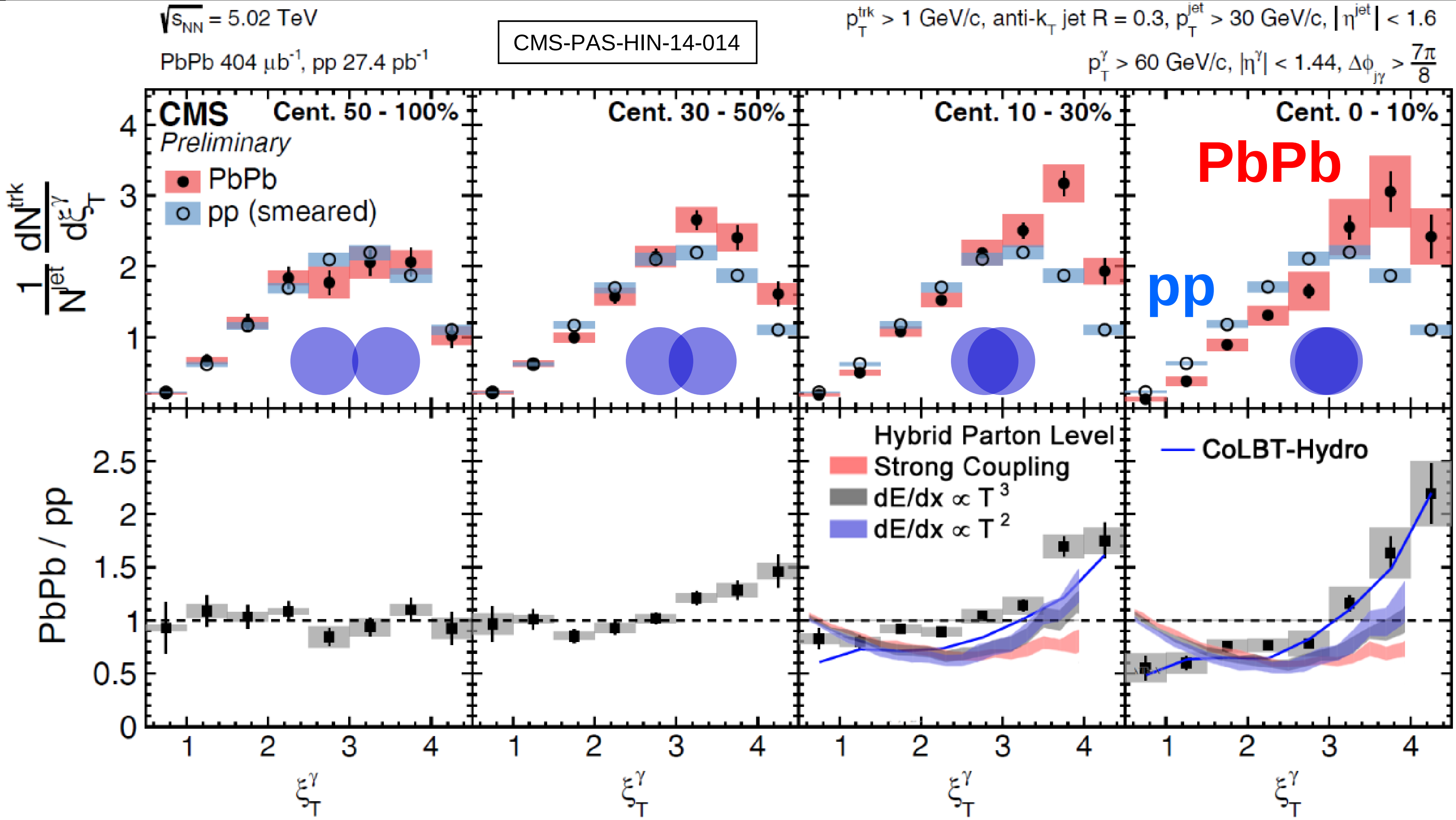
Photon-Tagged Fragmentation Function

ATLAS: Select on jet p_T > ½ Photon p_T



- Strong modification of **photon-tagged jet FF** in both centrality intervals.
- Larger modification in the central collisions than that in **inclusive jets**
- Corrected for jet resolution smearing
- Hint of enhancement in PbPb/pp ratio at the **high z region**

Jet FF with photon p_T as reference



- Almost no modification in 50-100%, significant modification in central events
- Strong modification in central events, compared to **HYBRID** ("Parton level") and **CoLBT**

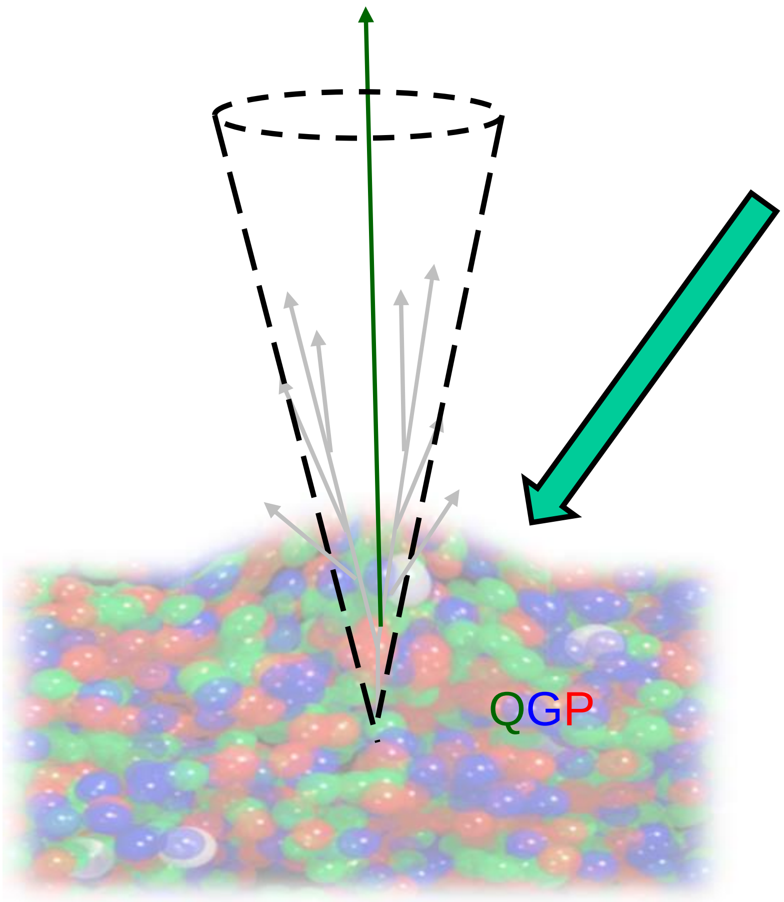
$$\xi_T^\gamma = \ln \frac{-|\mathbf{p}_T^\gamma|^2}{\mathbf{p}_T^{trk} \cdot \mathbf{p}_T^\gamma}$$

HYBRID Parton Level
J. Casalderrey-Solana *et al.*
JHEP 1603 (2016) 053

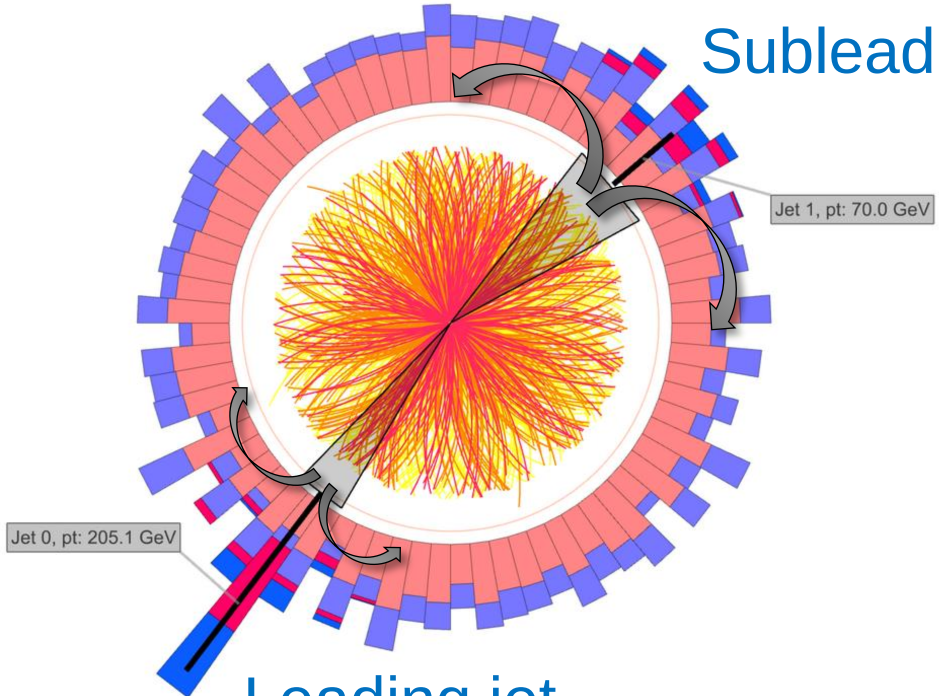
CoLBT-Hydro calculation
W. Chen, S. Cao, T. Luo, L.-G. Pang, X.-N. Wang
arXiv:1704.03648

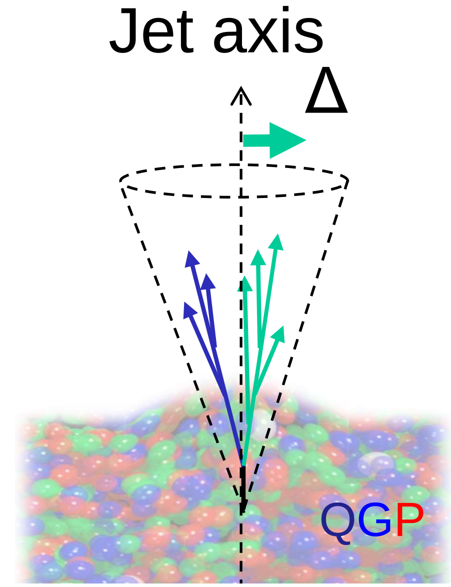
Jet Quenching

Do we see medium response?



Where does the Quenched Energy Go?

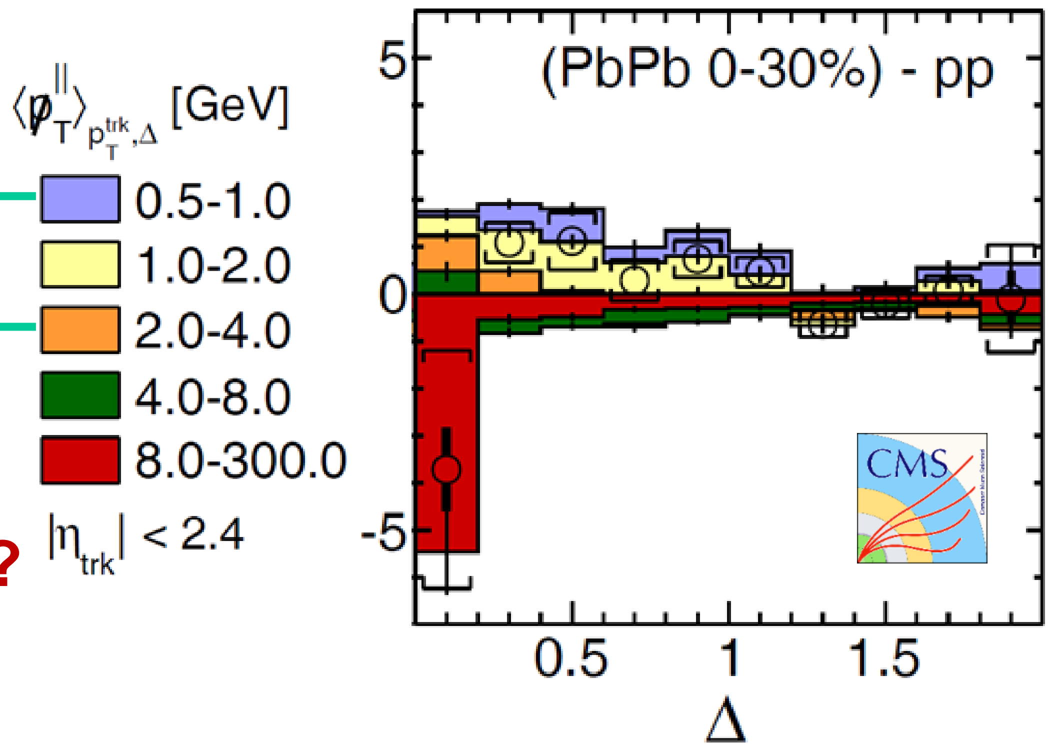




JHEP 01 (2016) 006

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

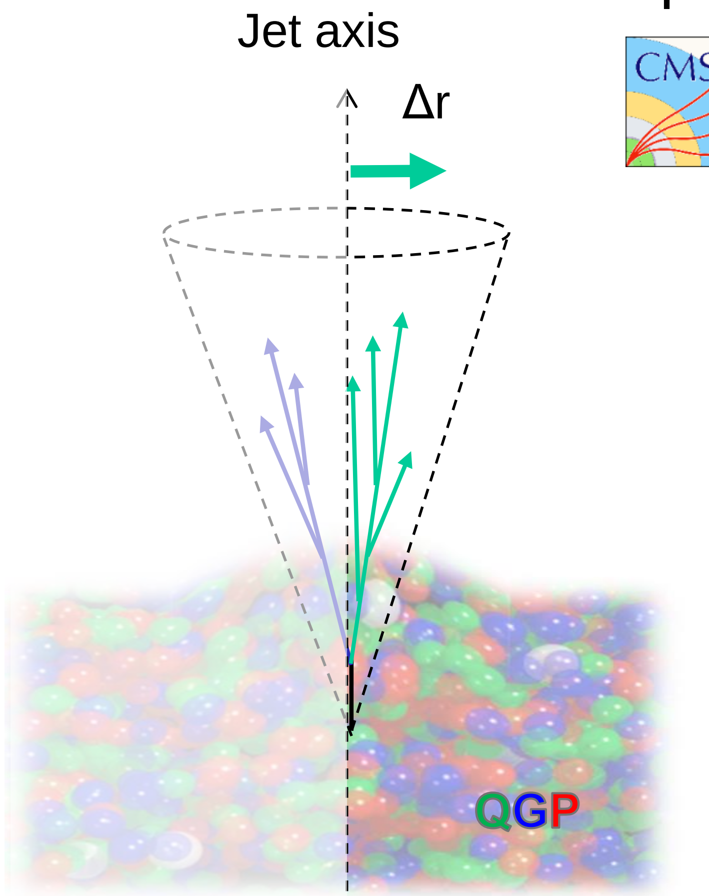
→ **Not Completely Thermalized?**



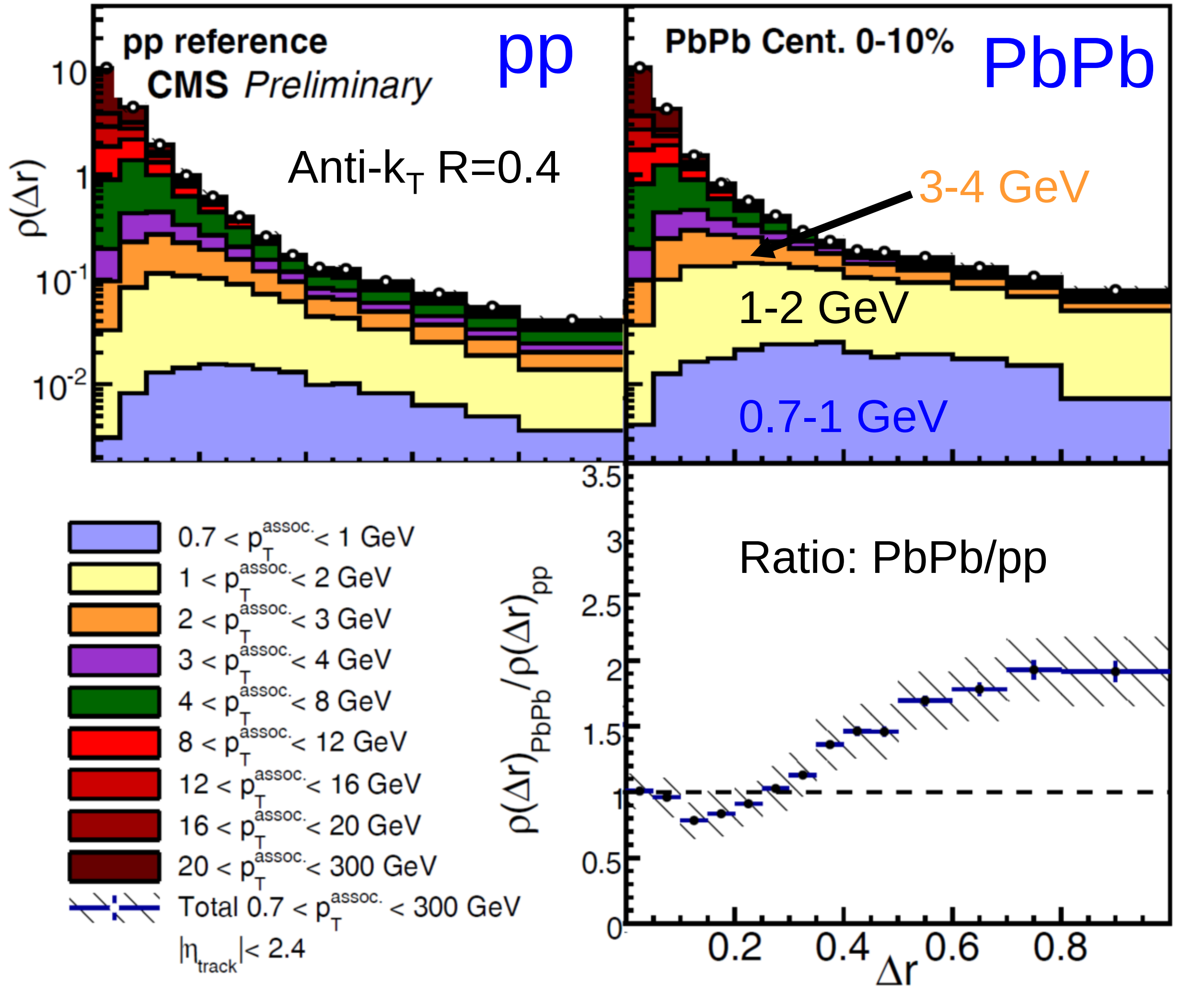
For instance the discussion in JHEP 1703 (2017) 135 from J. Casalderrey-Solana *et al.*

Jet Transverse Structure

Jet shapes in pp and PbPb at 5.02 TeV



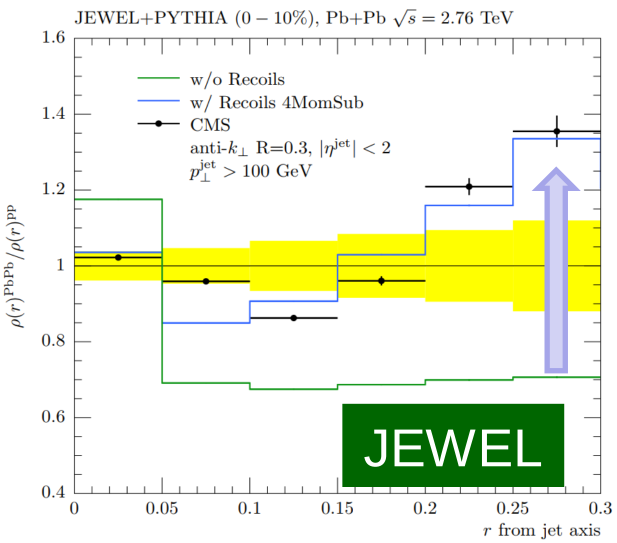
$$\Delta r = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$



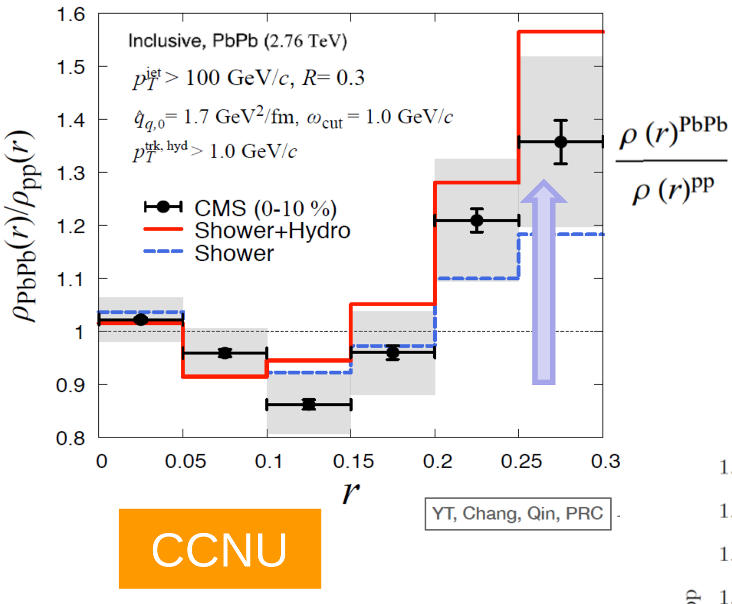
CMS-PAS-HIN-16-020

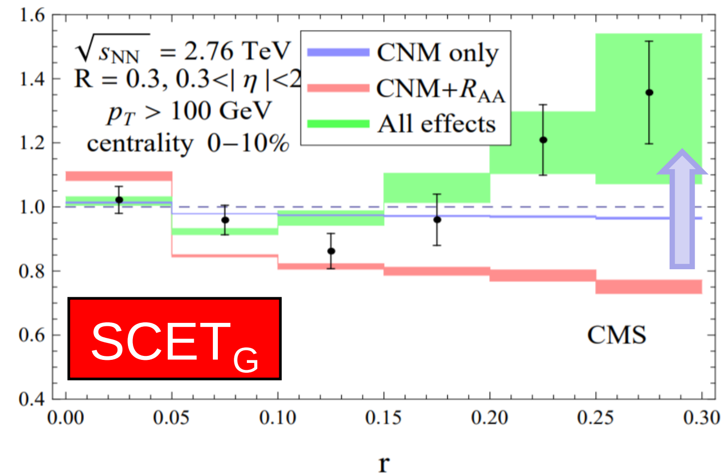
- Jet shapes and fragmentation functions in pp and PbPb collisions at 5 TeV
- Sensitive to the possible **medium response** to hard probes and **induced radiation**

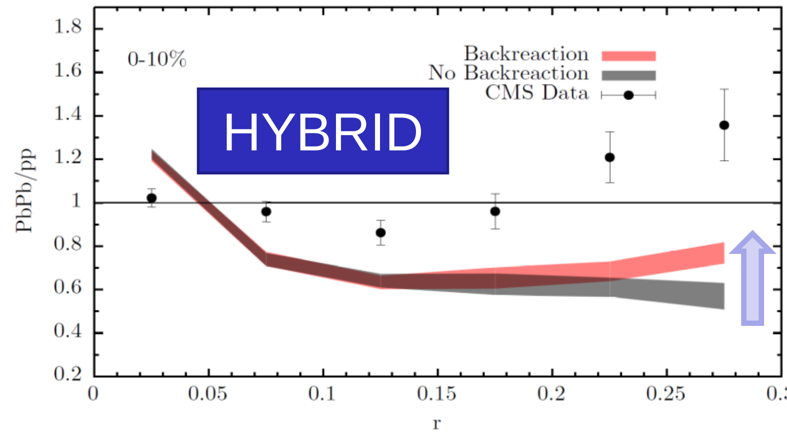
Theoretical Interpretation of the Excess



arXiv:1707.01539



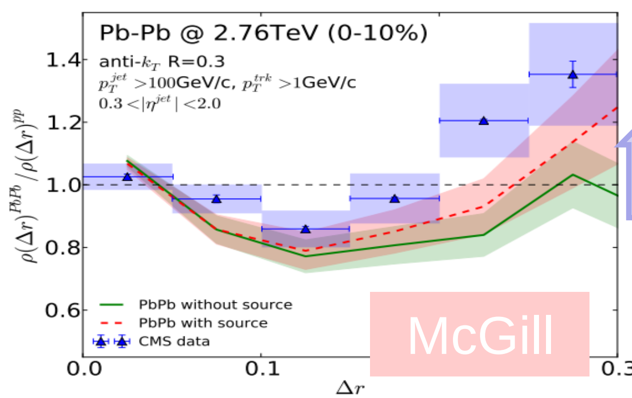




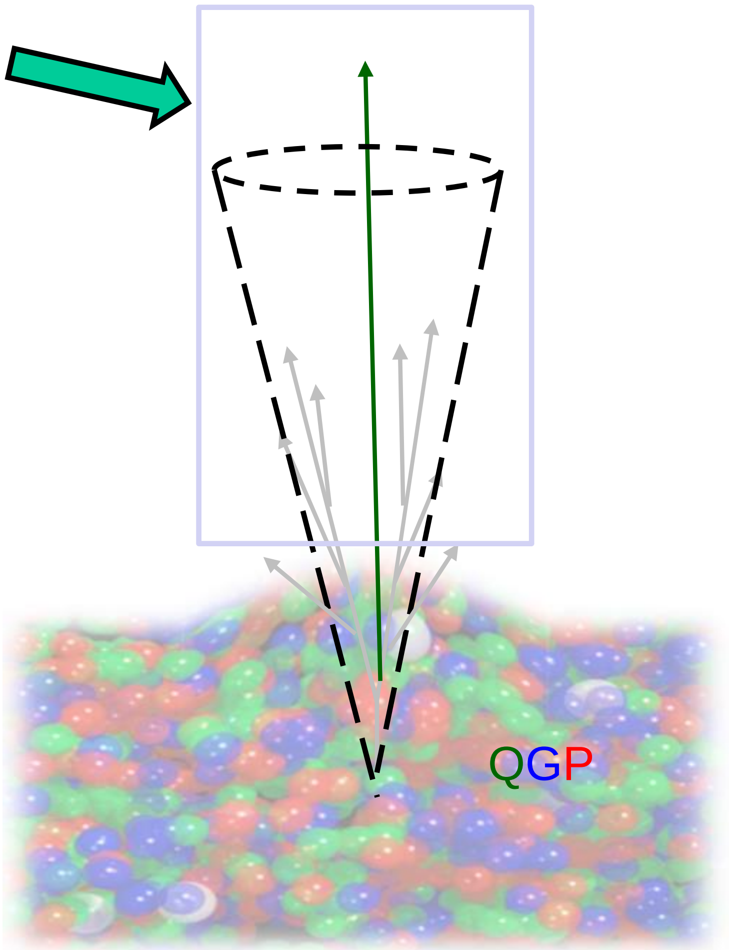
Different explanation of the large angle enhancement in jet shape measurement

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

(See Sangyong's talk)



Focus on the hardest substructure

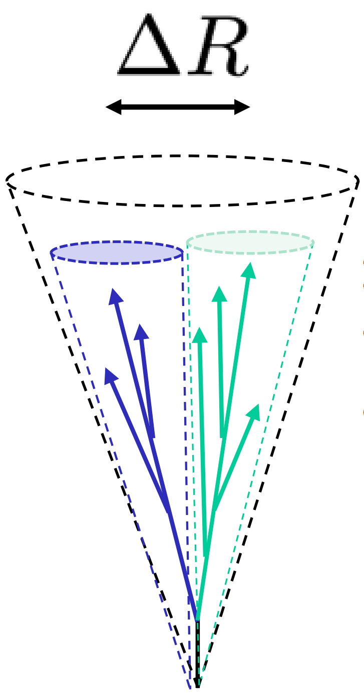


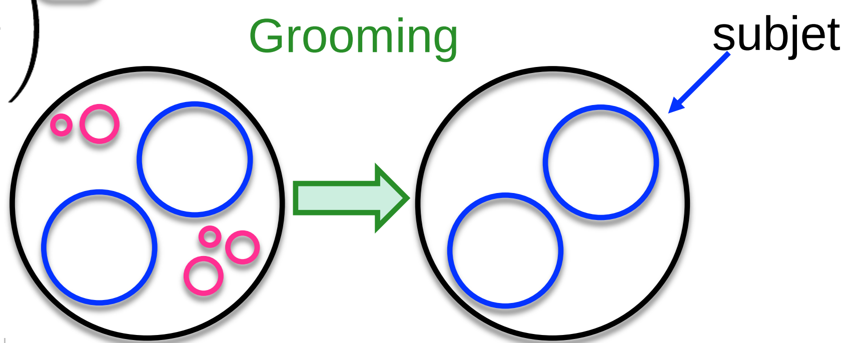
Does the magnitude of quenching depend on the structure of parton shower?
One could **remove the soft radiation** (isolate the hard jet core)

Groomed Jet Substructure with Soft Drop

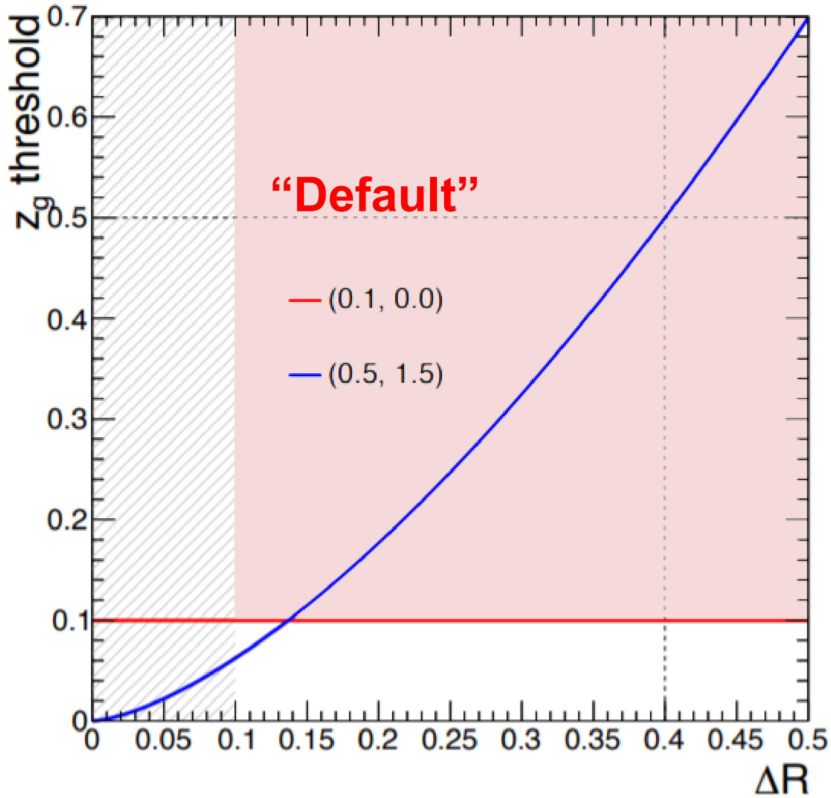
CMS: used two grooming settings with ΔR>0.1 cut

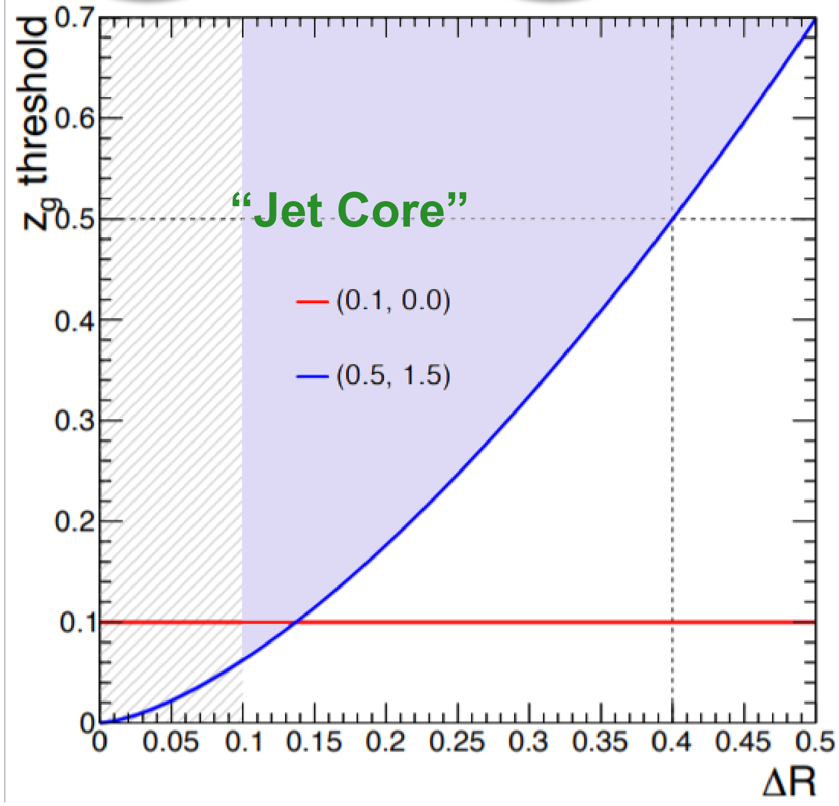
$$z_g \equiv \frac{\min(p_1, p_2)}{p_1 + p_2} > z_{\text{cut}} \left(\frac{\Delta R}{R_0} \right)^{\beta}$$





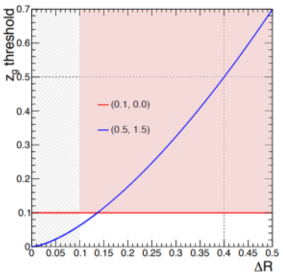
Soft Drop:
JHEP 1405 (2014) 146



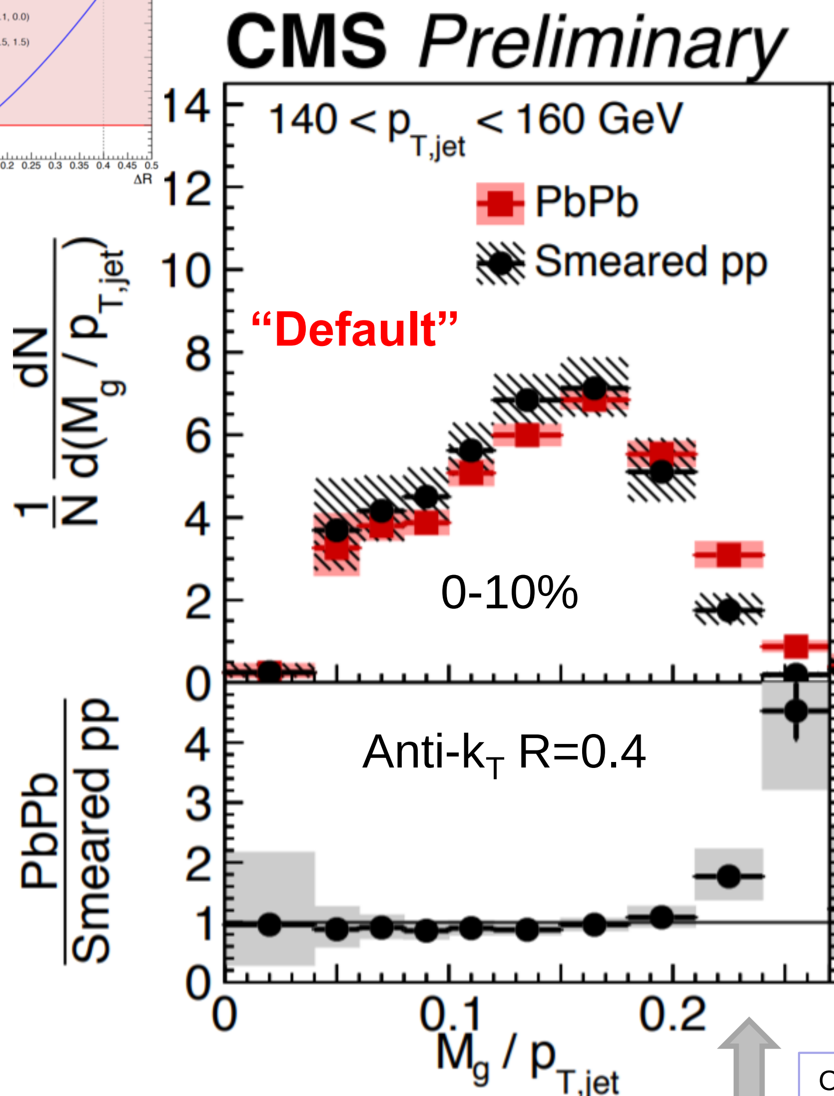


Phase diagram
from Yi Chen

Groomed Jet Mass

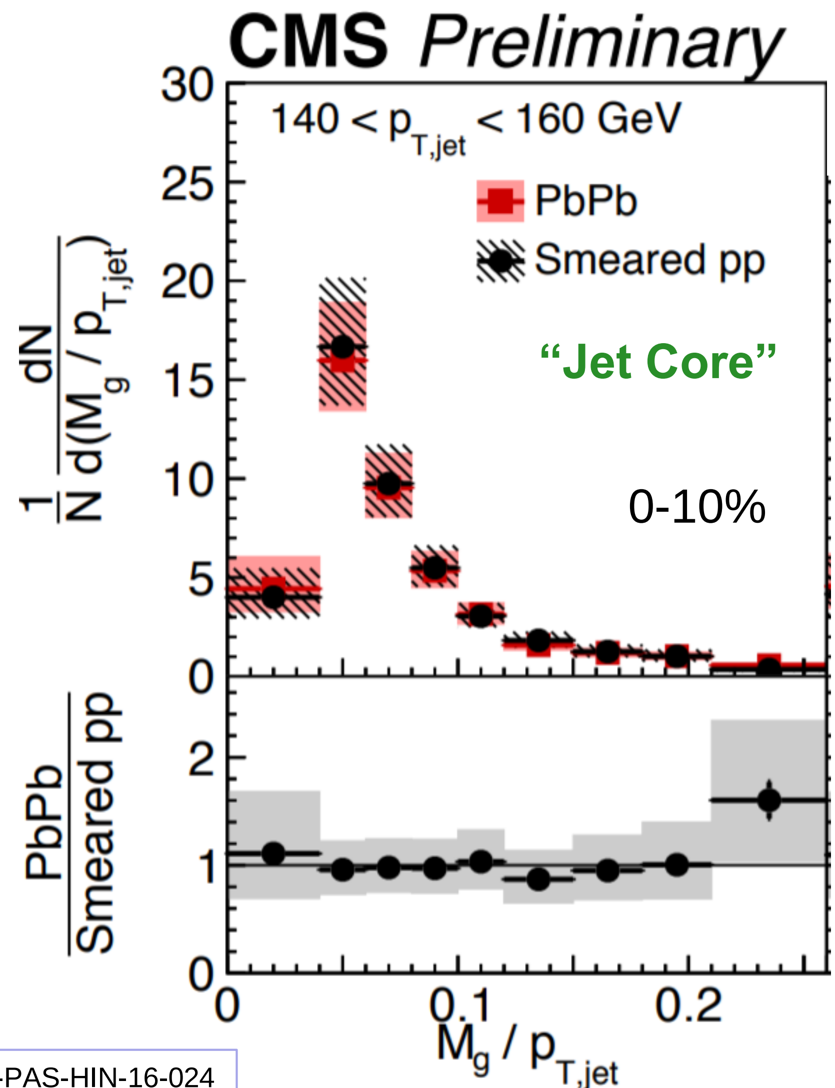


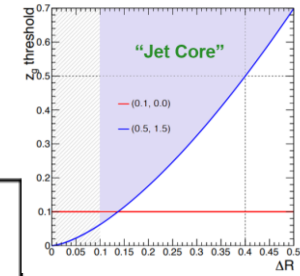
$(z_{cut},\beta) = (0.1,0.0)$ $\Delta R>0.1$



CMS-PAS-HIN-16-024

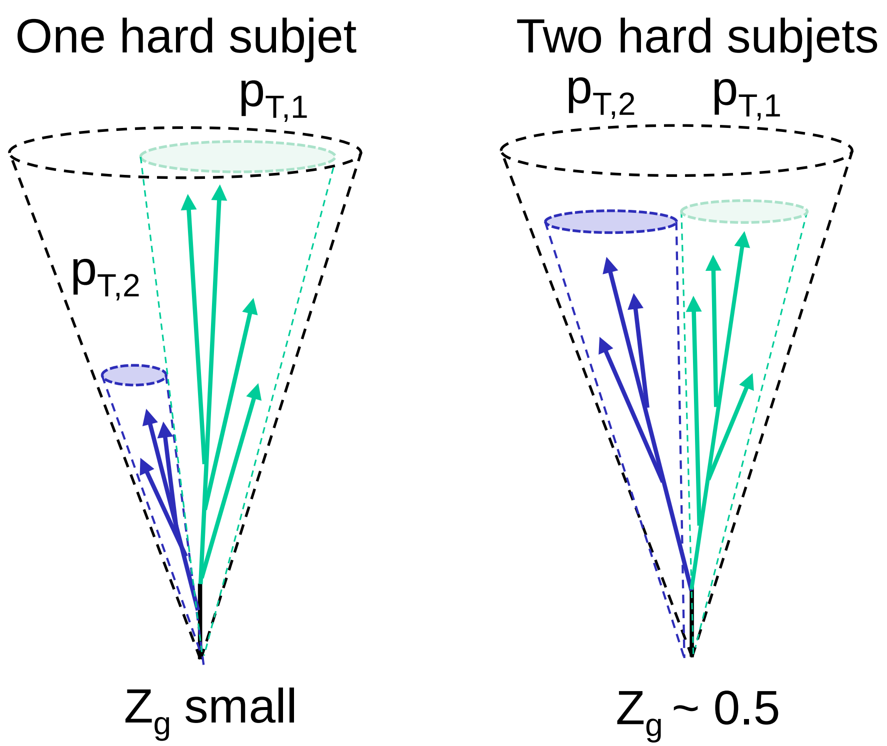
$(z_{cut},\beta) = (0.5,1.5)$ $\Delta R>0.1$



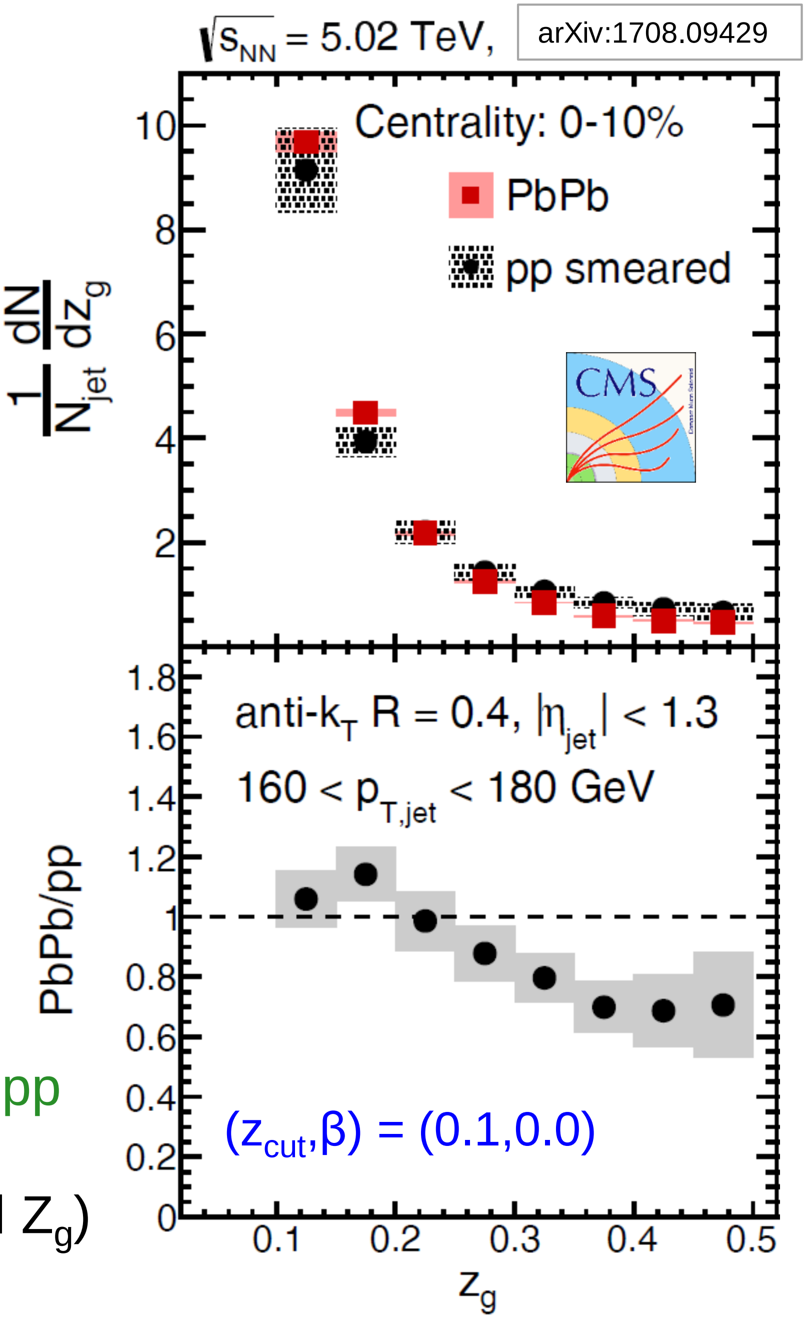


- Enhancement of large mass when looking at a less aggressive grooming setting
- Results with a "more aggressive grooming"
- No significant modification of the "jet core"

Momentum Sharing of Subjets



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

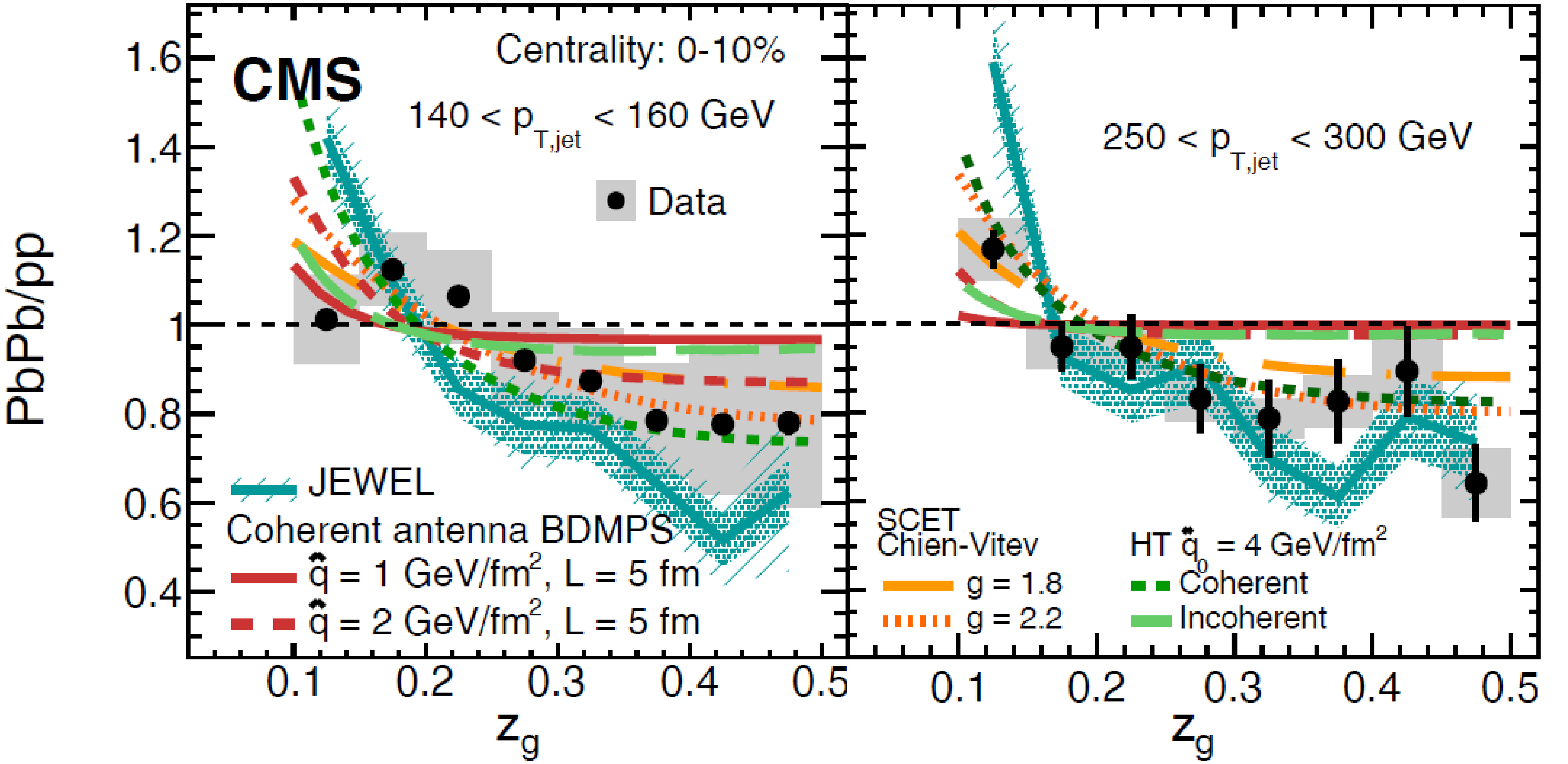


- Quark and gluon Z_g distributions are very similar in pp
- Jets with **two hard subjets** (large Z_g) **"relatively"** more suppressed than jets with a single core (small Z_g)

(Or small Z_g is enhanced)

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

- **Energy flow with respect to jet** at the LHC
  - Unprecedented wide p_T reach with high statistics data
  - Modification of jet shapes and fragmentation function
  - 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

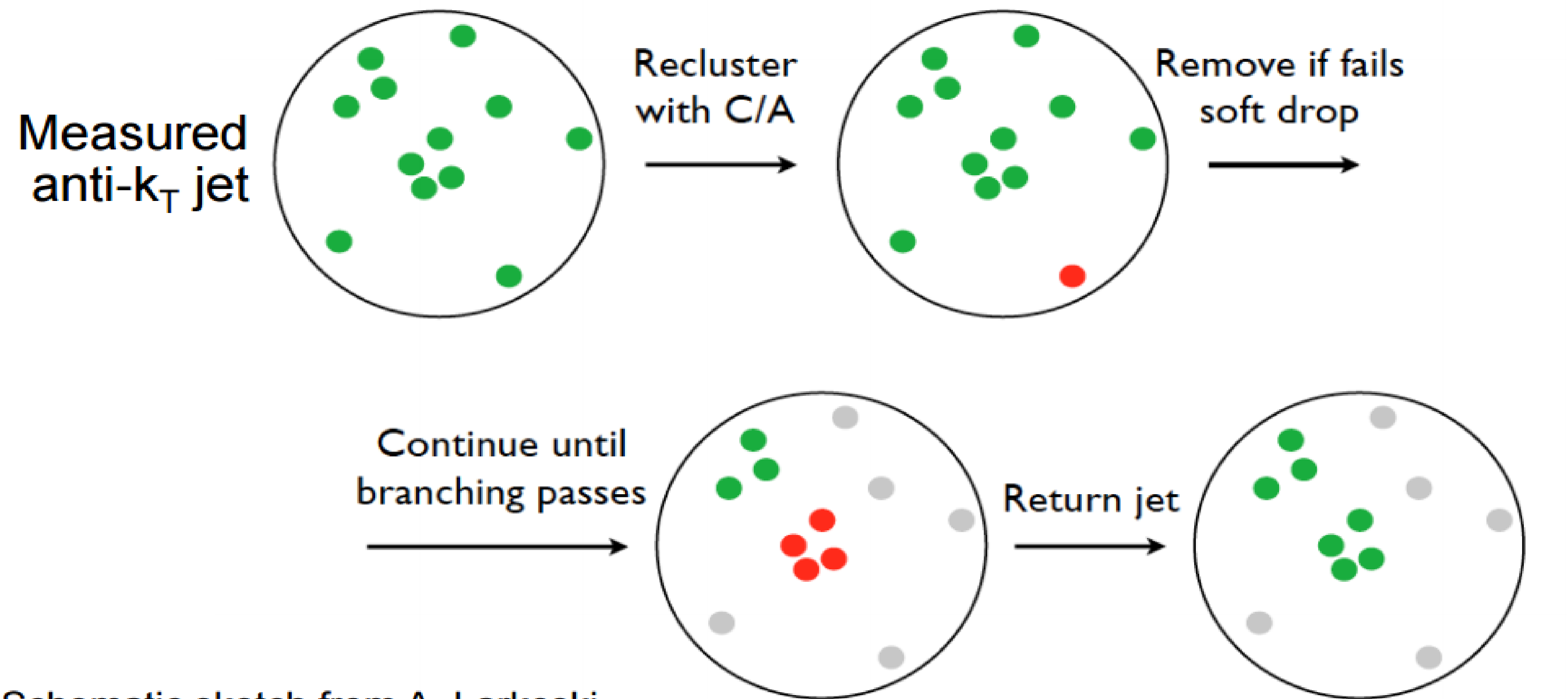
- **Observation of parton flavor dependence of jet quenching:**
  - R_{AA} depends on meson flavor (light vs. charm vs. beauty) at low p_T
  - (Ungroomed) jet substructure become more quark-like in PbPb collisions: Gluons lose more energy than quarks

- **"Parton shower shape dependence" of jet quenching:**
  - Fate of jets with different shower history
  - Jet substructure: one could create observables with different sensitivity to medium response
  - Groomed jet substructure as a power tool for the highly differential studies of jet quenching: isolate the most sensitive phase space to medium property

Backup slides

3. Groomed Jets

Jet grooming removes soft divergences and uncorrelated background
Common technique in HEP
This analysis is the first one using jet grooming in heavy ion collisions



Schematic sketch from A. Larkoski
LPC Workshop JetMET Jan. 2014

Soft drop condition in this analysis

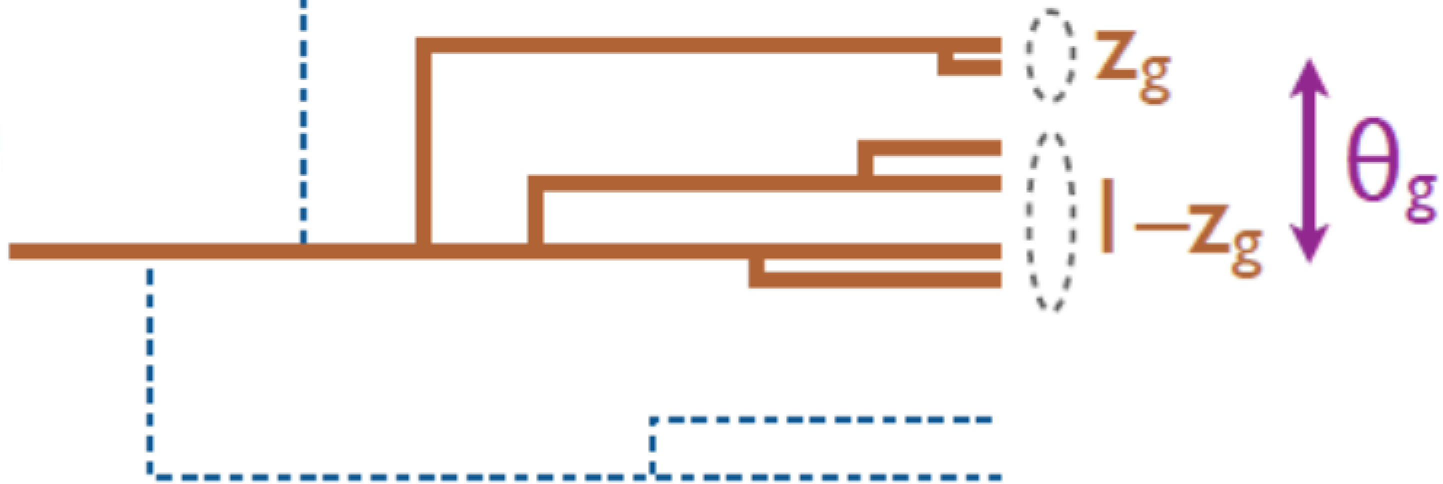
$$\frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > 0.1$$

Andrew Larkoski, Jesse Thaler (CTP)
JHEP 1405 (2014) 1465

Jet grooming with Soft Drop

Anti-k_T jet is re-clustered with Cambridge/Aachen (CA)
Then decluster the angular-ordered CA tree
Drop soft branches

$$z_g = \frac{p_{T2}}{p_{T1} + p_{T2}}$$

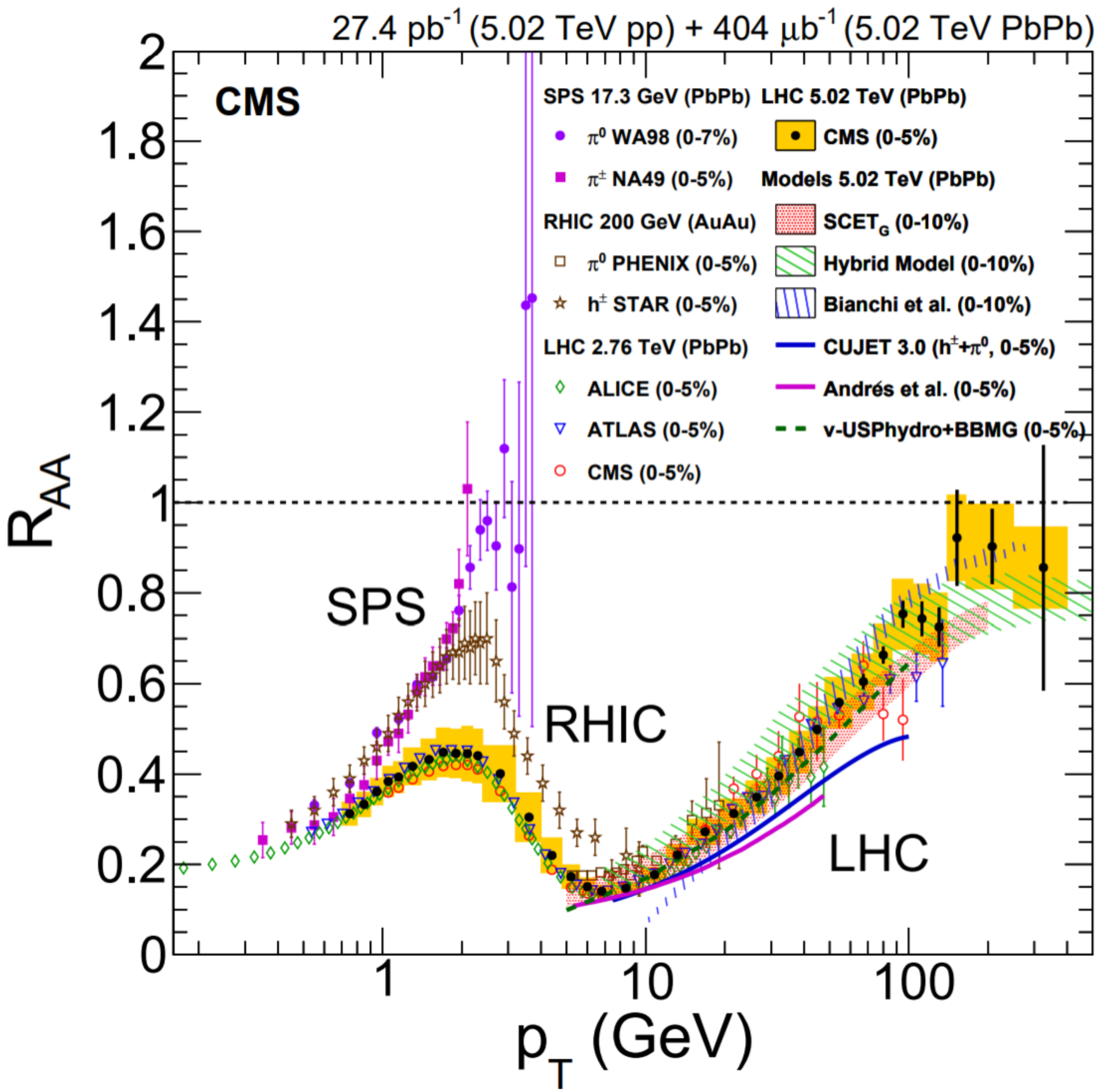


To minimize the smearing effect from PbPb underlying event, $\Delta R_{12} > 0.1$ is applied

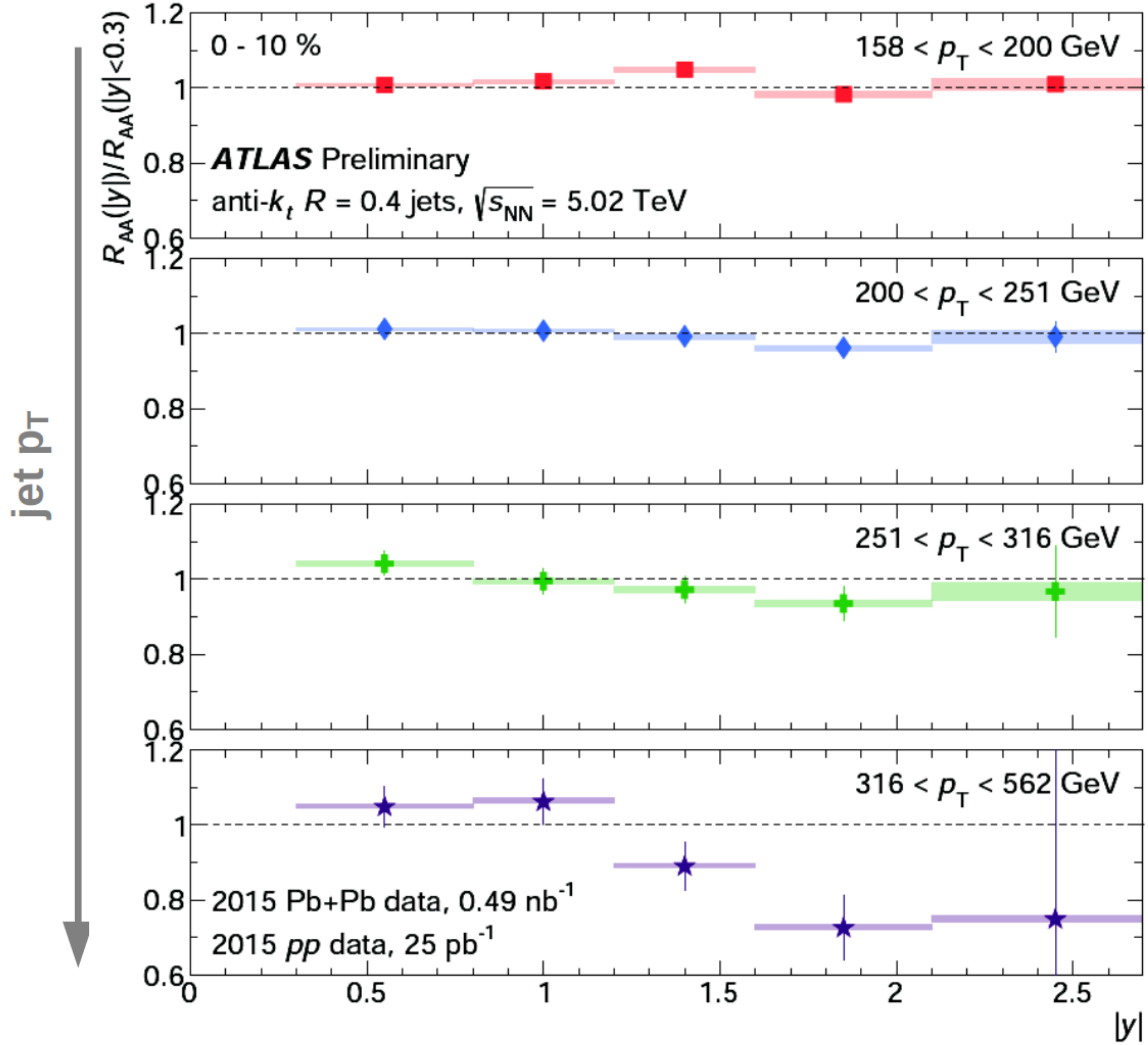
Measurement of **momentum sharing** between leading and subleading subjets

Andrew Larkoski, Jesse Thaler (CTP)
JHEP 1405 (2014) 1465

Compilation of the charged hadron R_{AA}



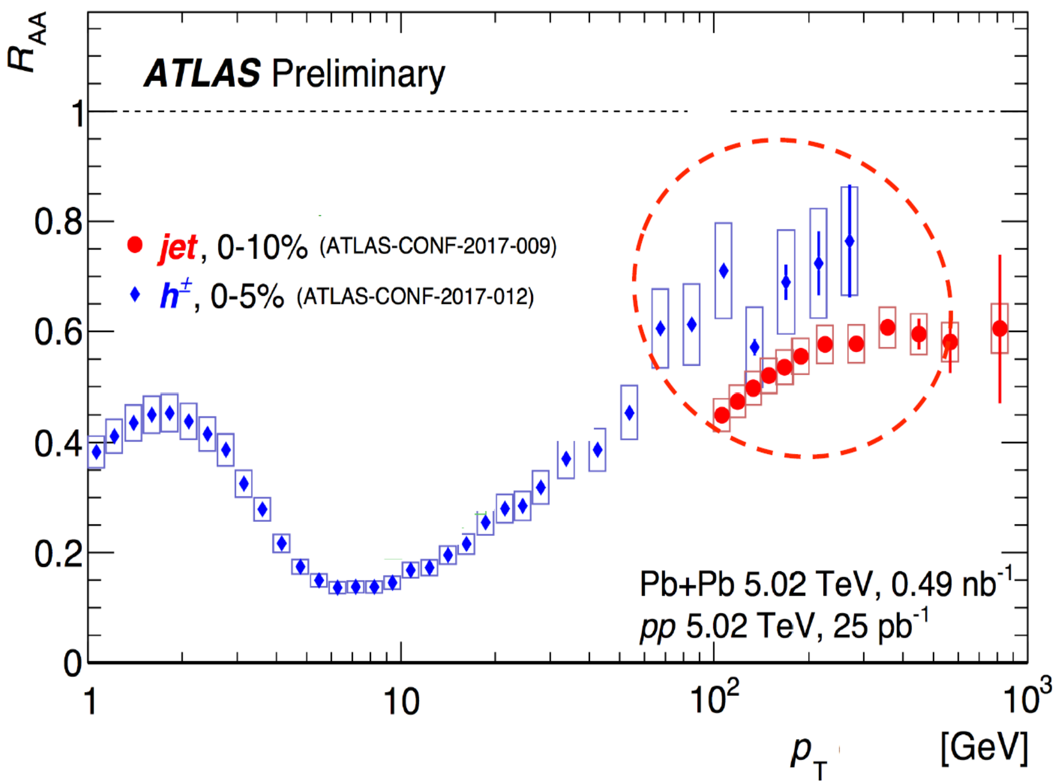
Jet R_{AA} vs. rapidity



Jet Longitudinal Structure

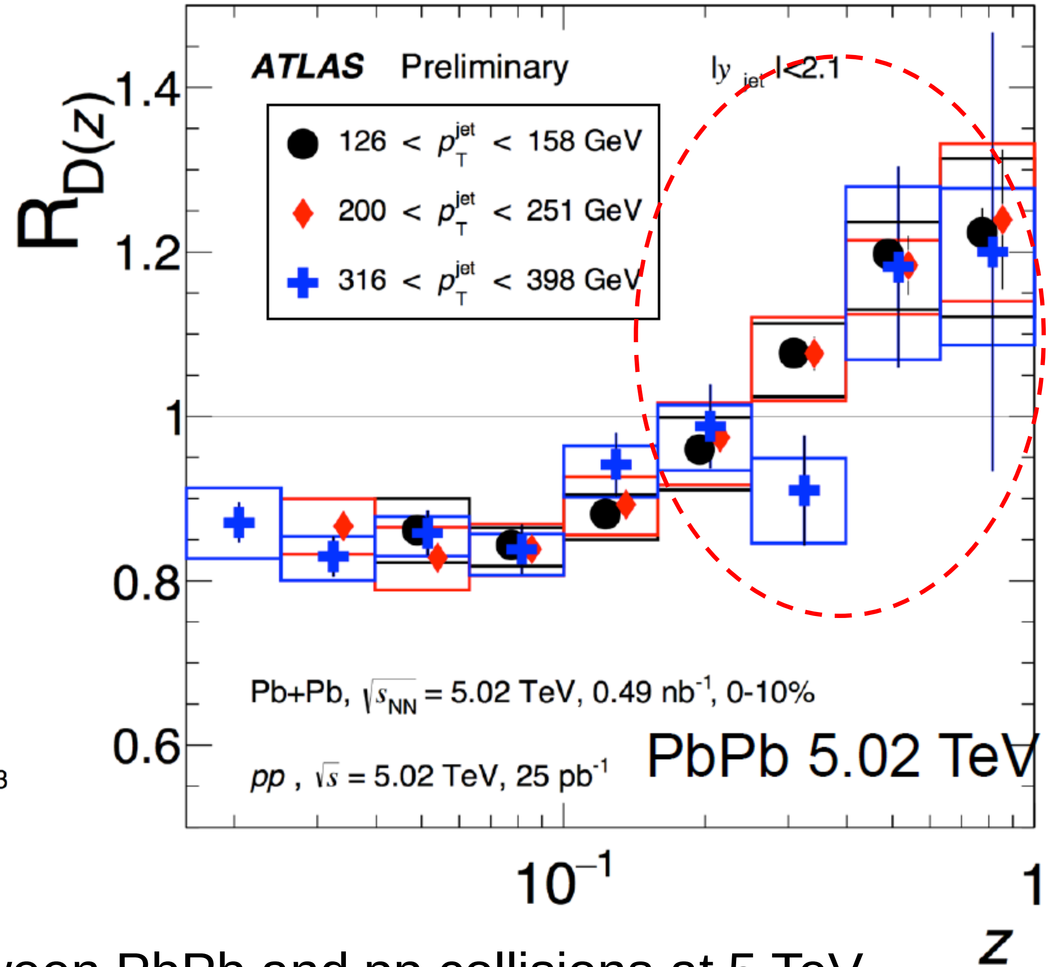
Charged hadron R_{AA}

Jet R_{AA}



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

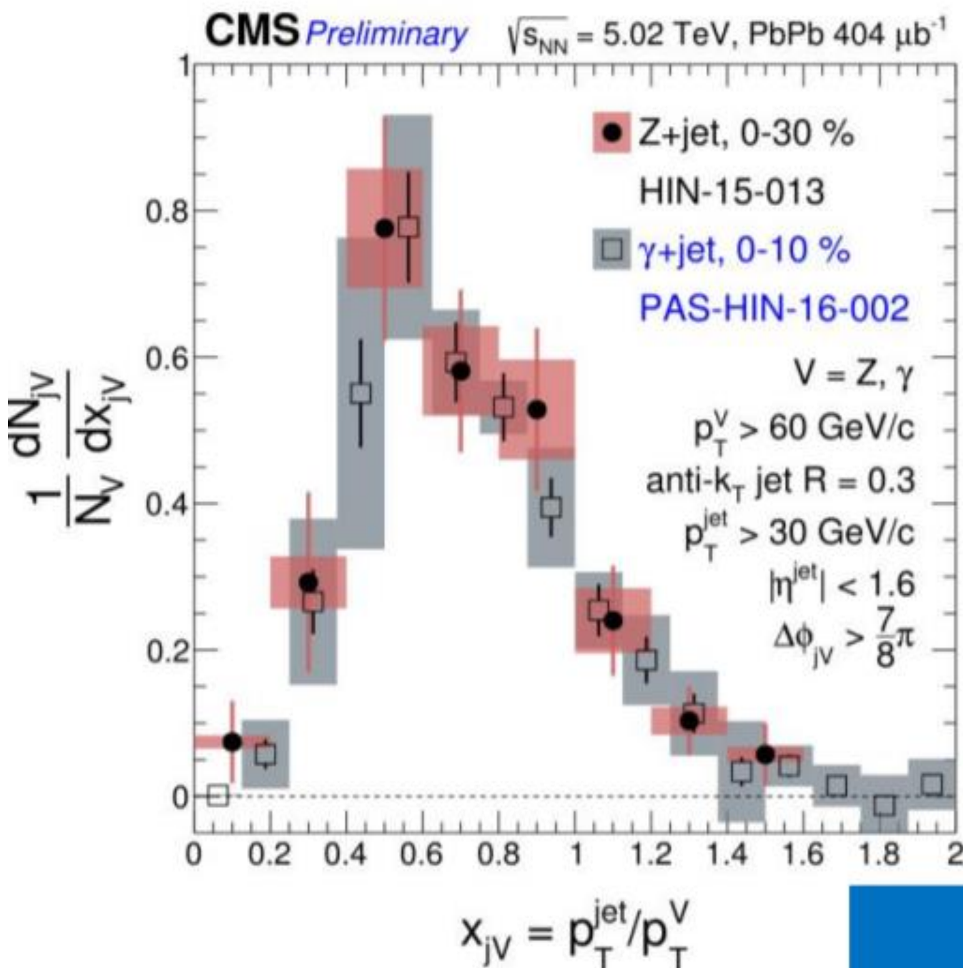
ATLAS-CONF-2017-005



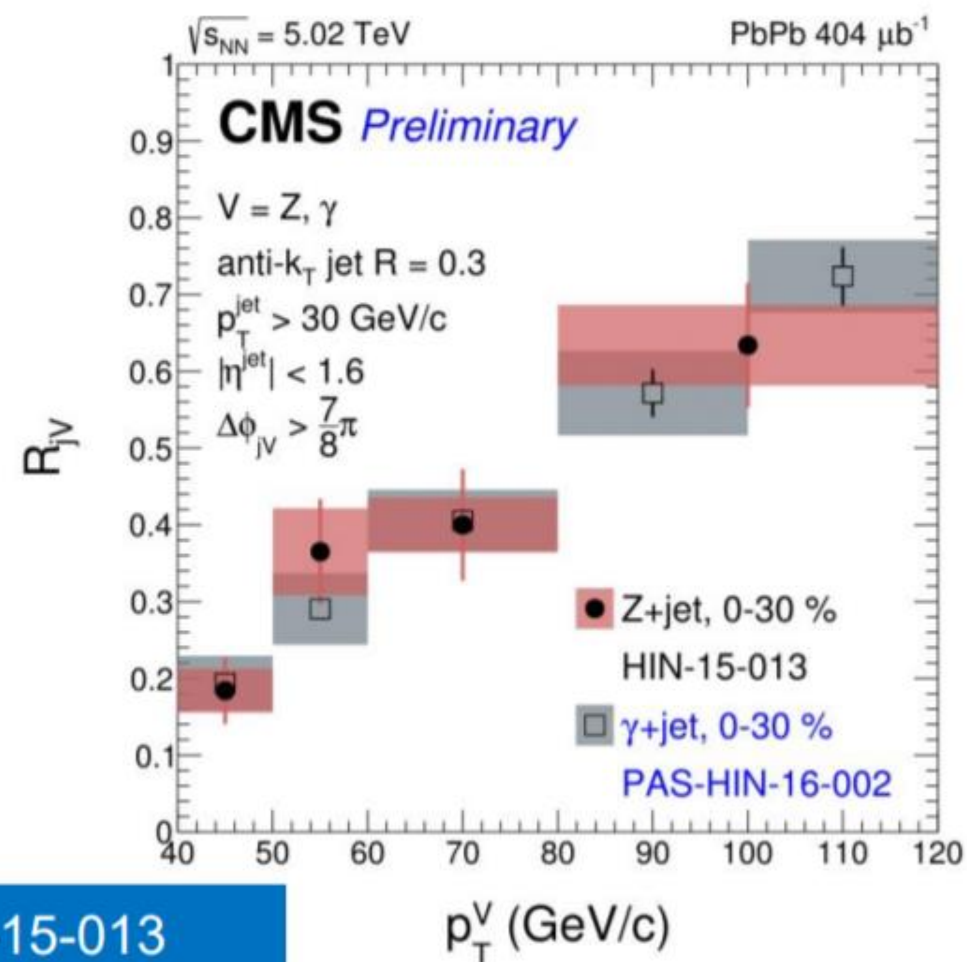
- Fragmentation functions Ratio $R_{D(z)}$ between PbPb and pp collisions at 5 TeV
- Enhancement at large z: consistent with **smaller gluon/quark ratio** in PbPb data
- Modified fragmentation could be the reason why

  high p_T charged hadron R_{AA} > jet R_{AA}

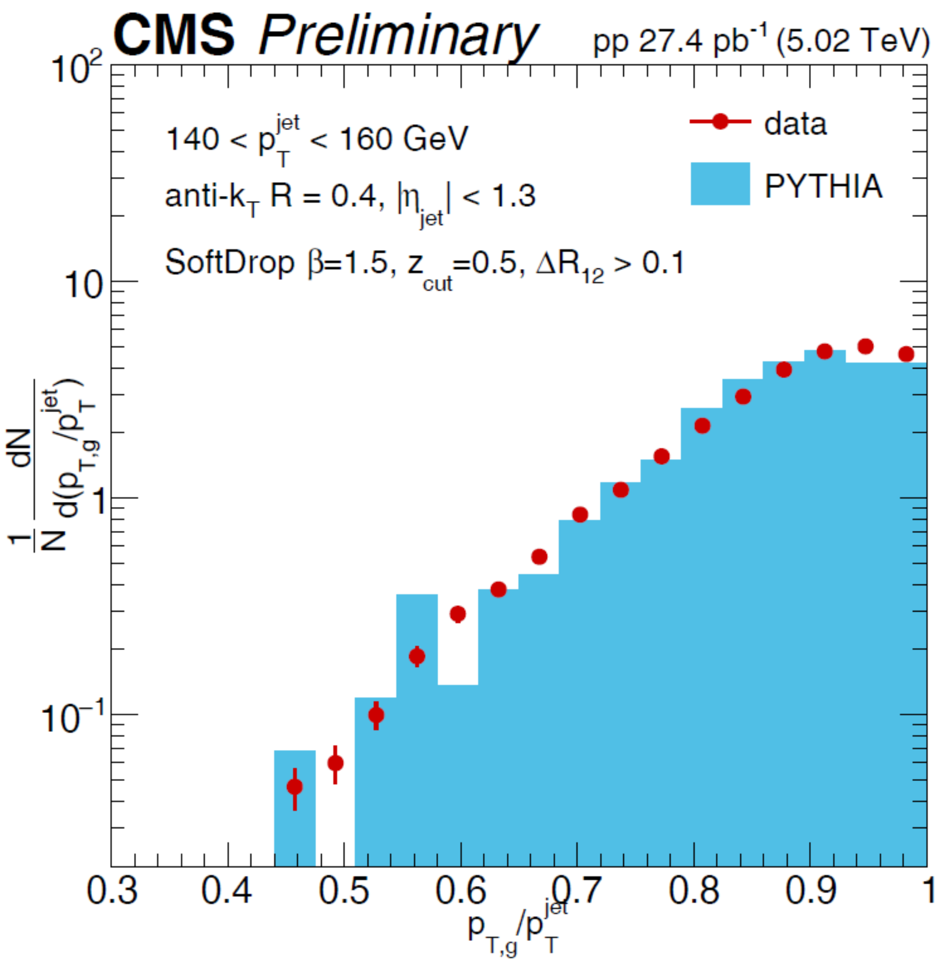
Comparison between Z-Jet and Photon-Jet

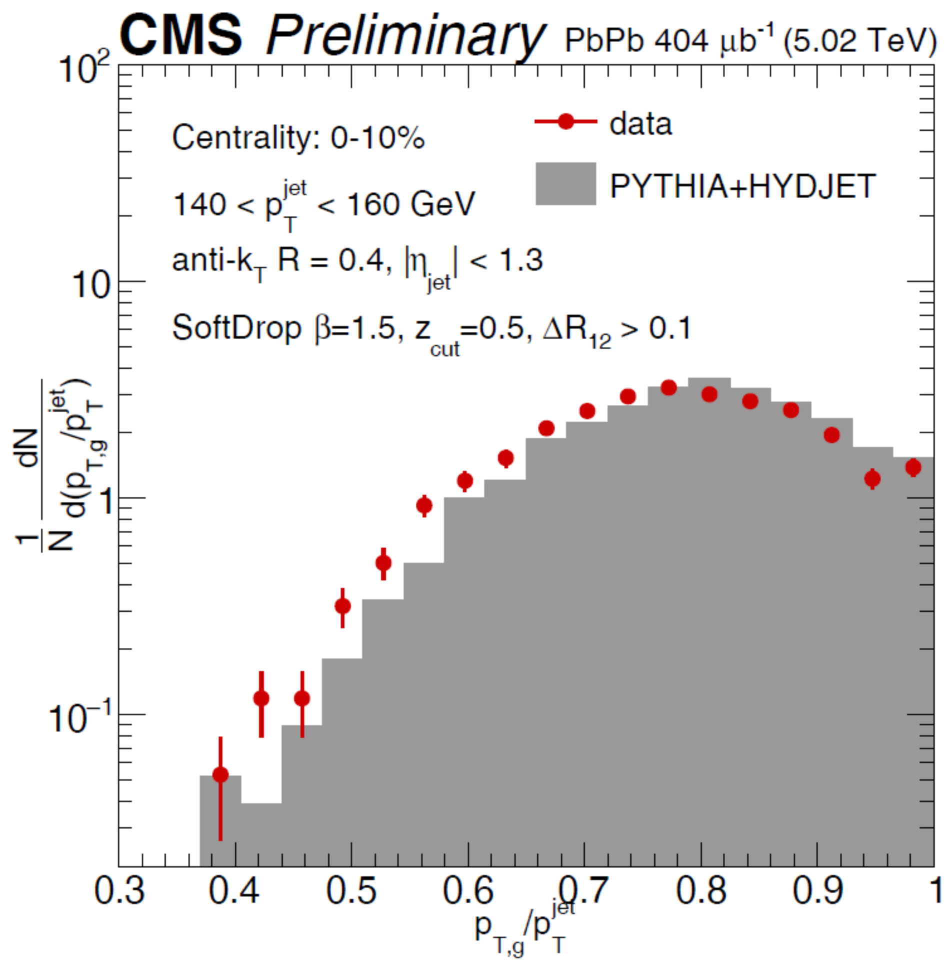


HIN-15-013

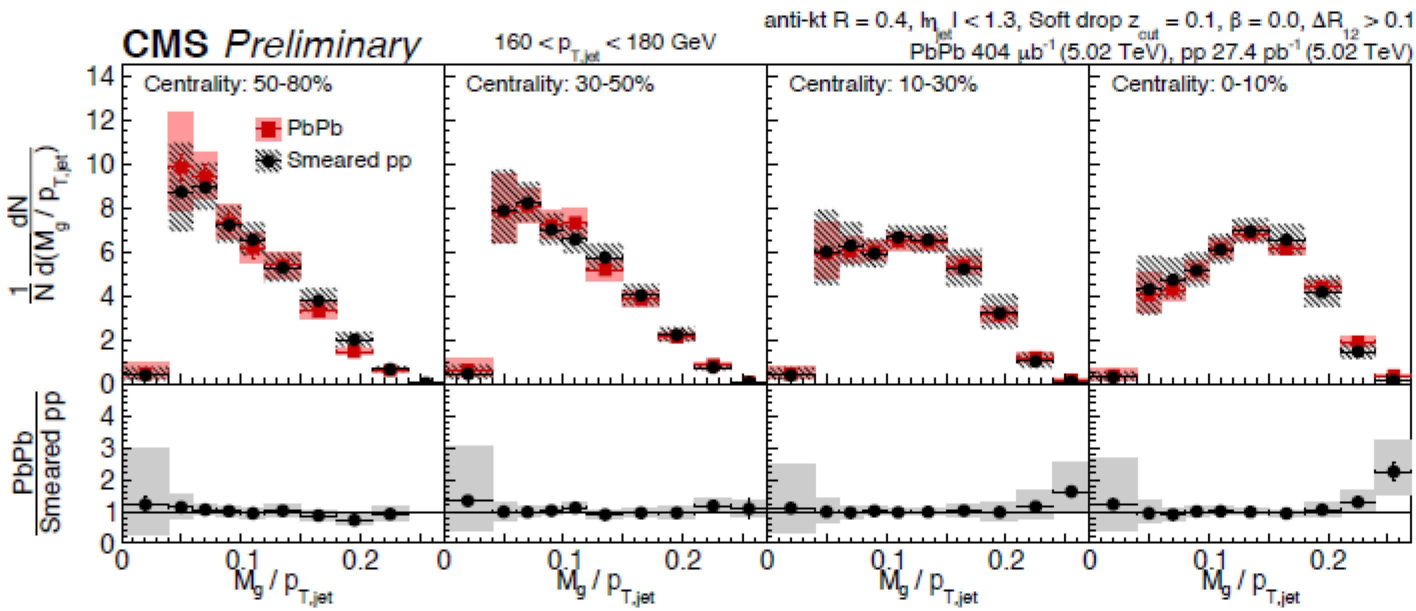


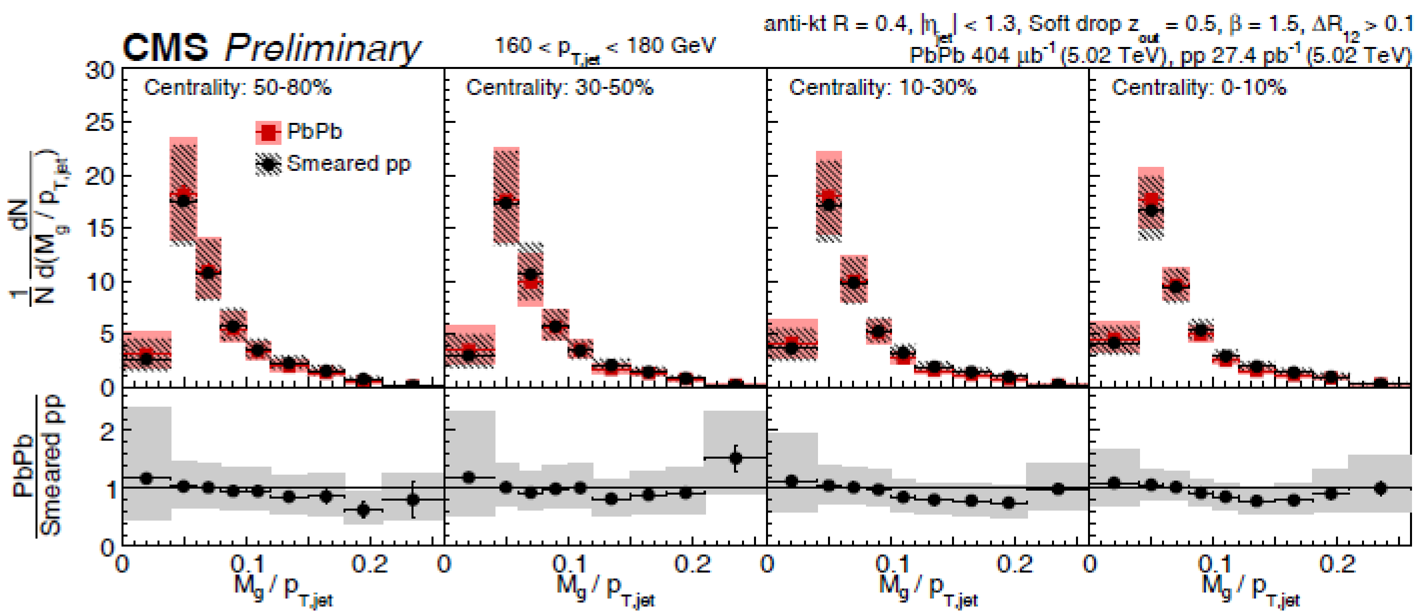
Groomed jet p_T fraction



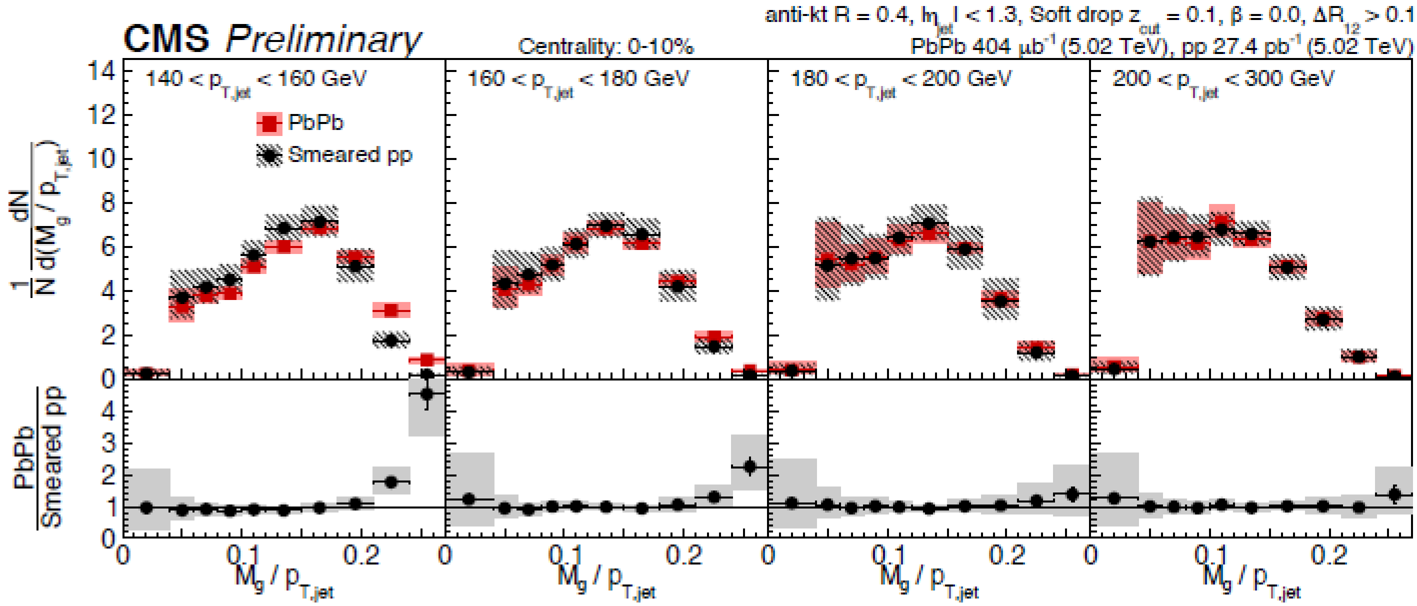


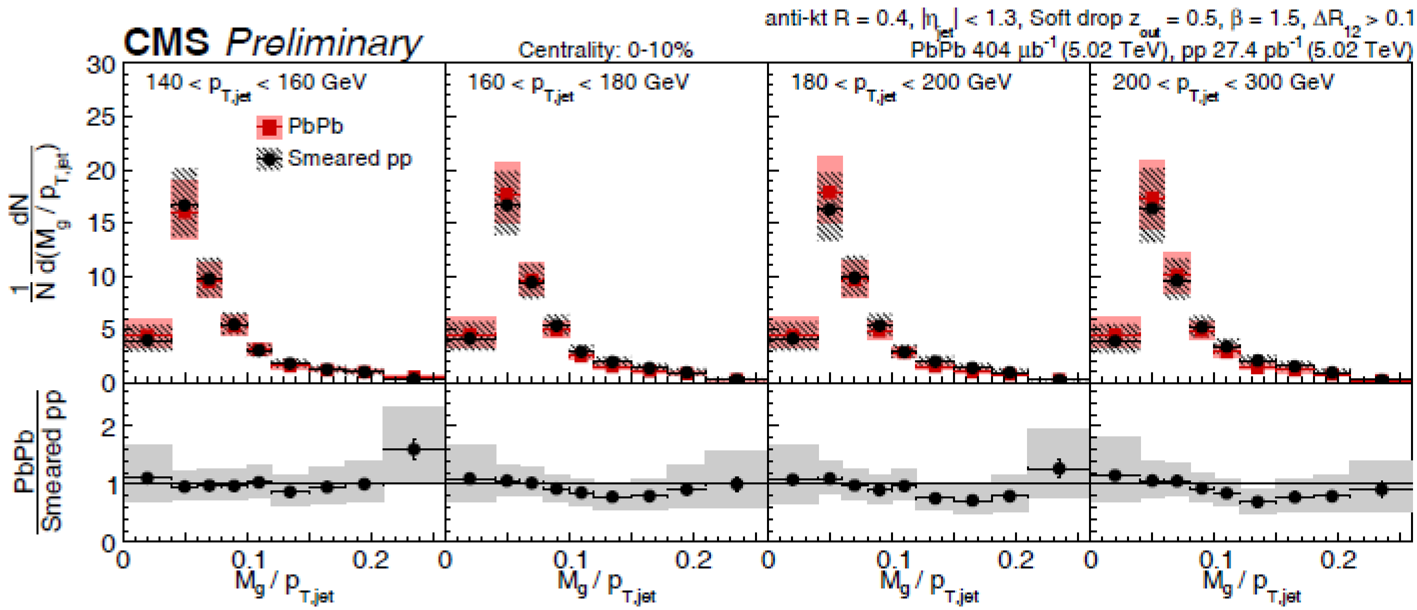
CMS Jet Mass


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
$\frac{1}{N}\frac{dN}{d(M_g / p_{T,jet})}$
$\frac{PbPb}{Smeared\ pp}$
$M_g / p_{T,jet}$

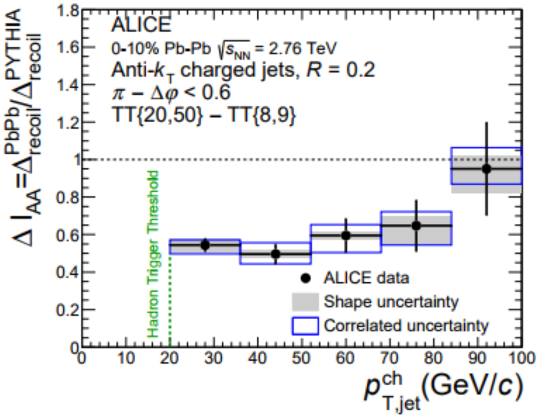

CMS Preliminary
160 < $p_{T,jet}$ < 180 GeV
anti-kt R = 0.4, $|\eta_{jet}|$ < 1.3, Soft drop z_{cut} = 0.5, β = 1.5, ΔR_{12} > 0.1
PbPb 404 μb^{-1} (5.02 TeV), pp 27.4 pb^{-1} (5.02 TeV)
Centrality: 50-80%
Centrality: 30-50%
Centrality: 10-30%
Centrality: 0-10%
PbPb
Smeared pp
$\frac{1}{N}\frac{dN}{d(M_g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

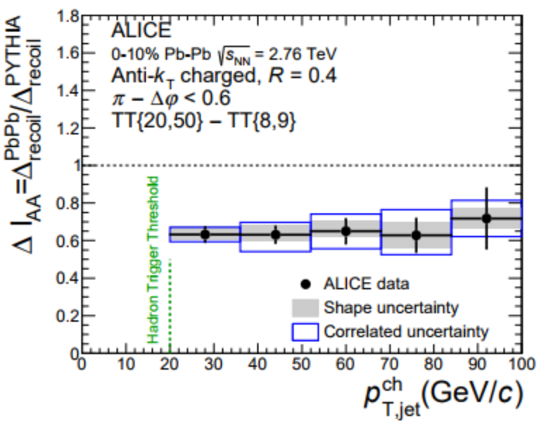
CMS Jet Mass vs. Jet energy

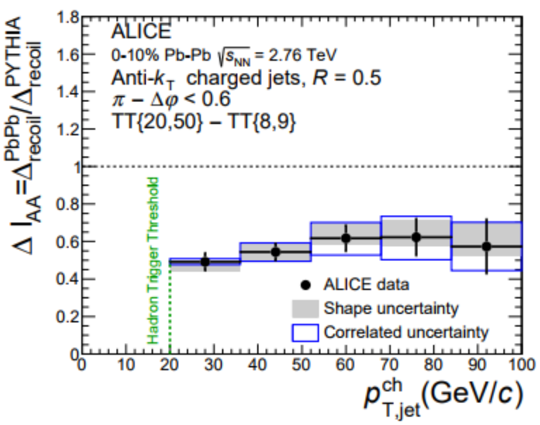


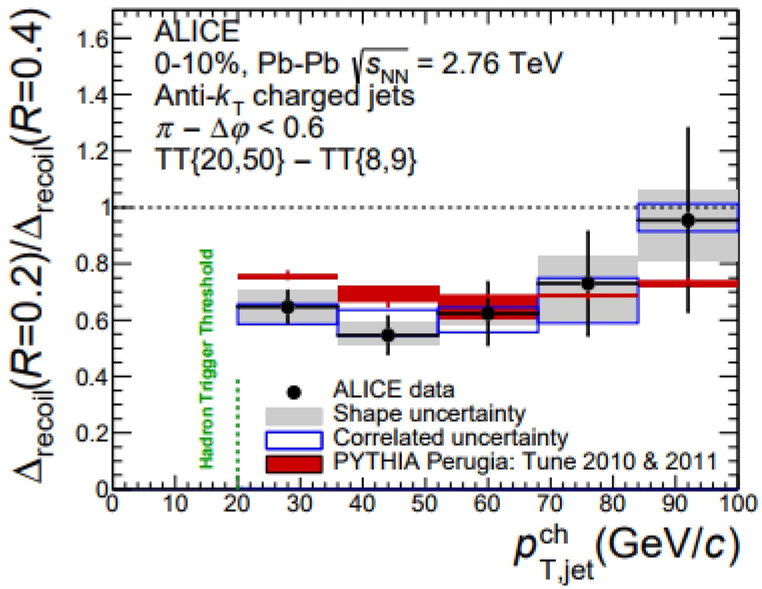


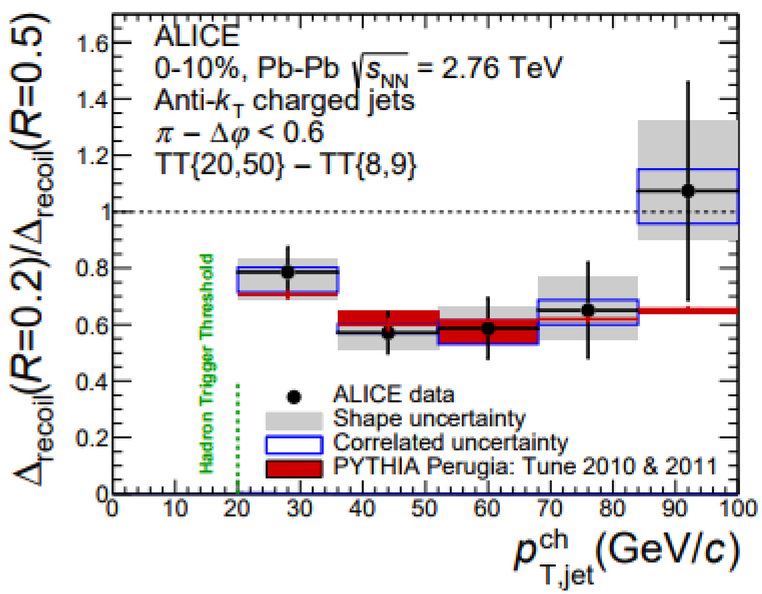
ALICE Hadron-Jet









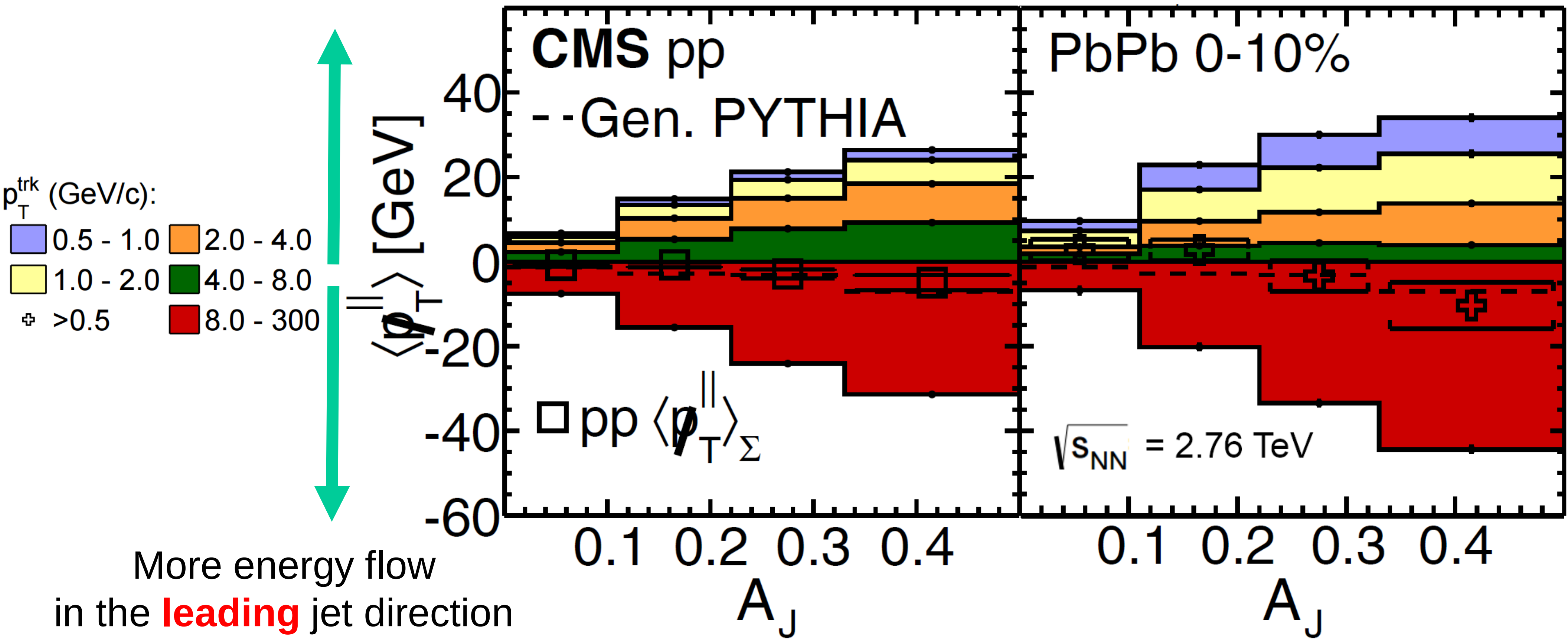


No **sizable** modification of jet shape

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

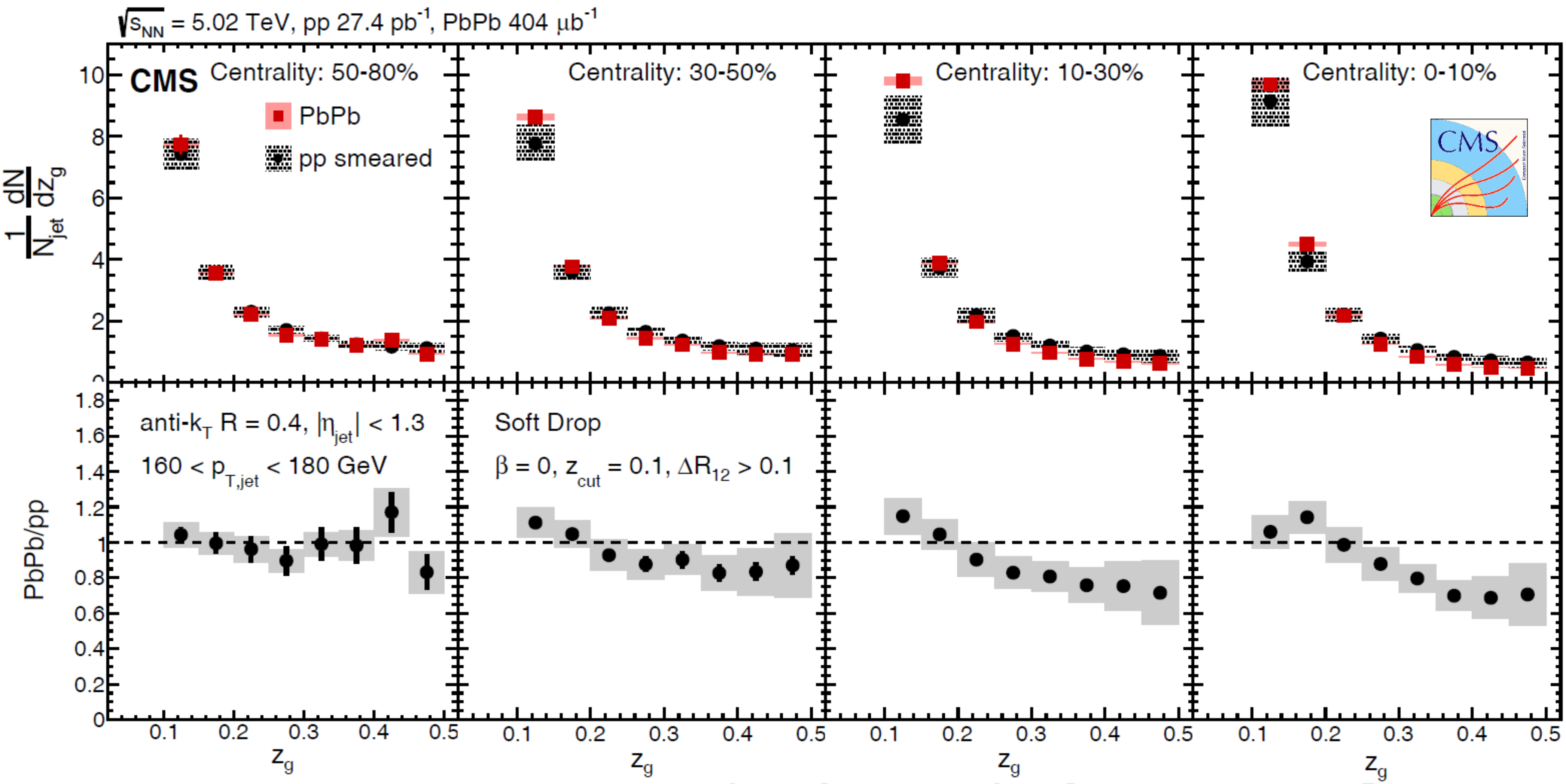
Missing p_T from high p_T particles increases as a function of A_J

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

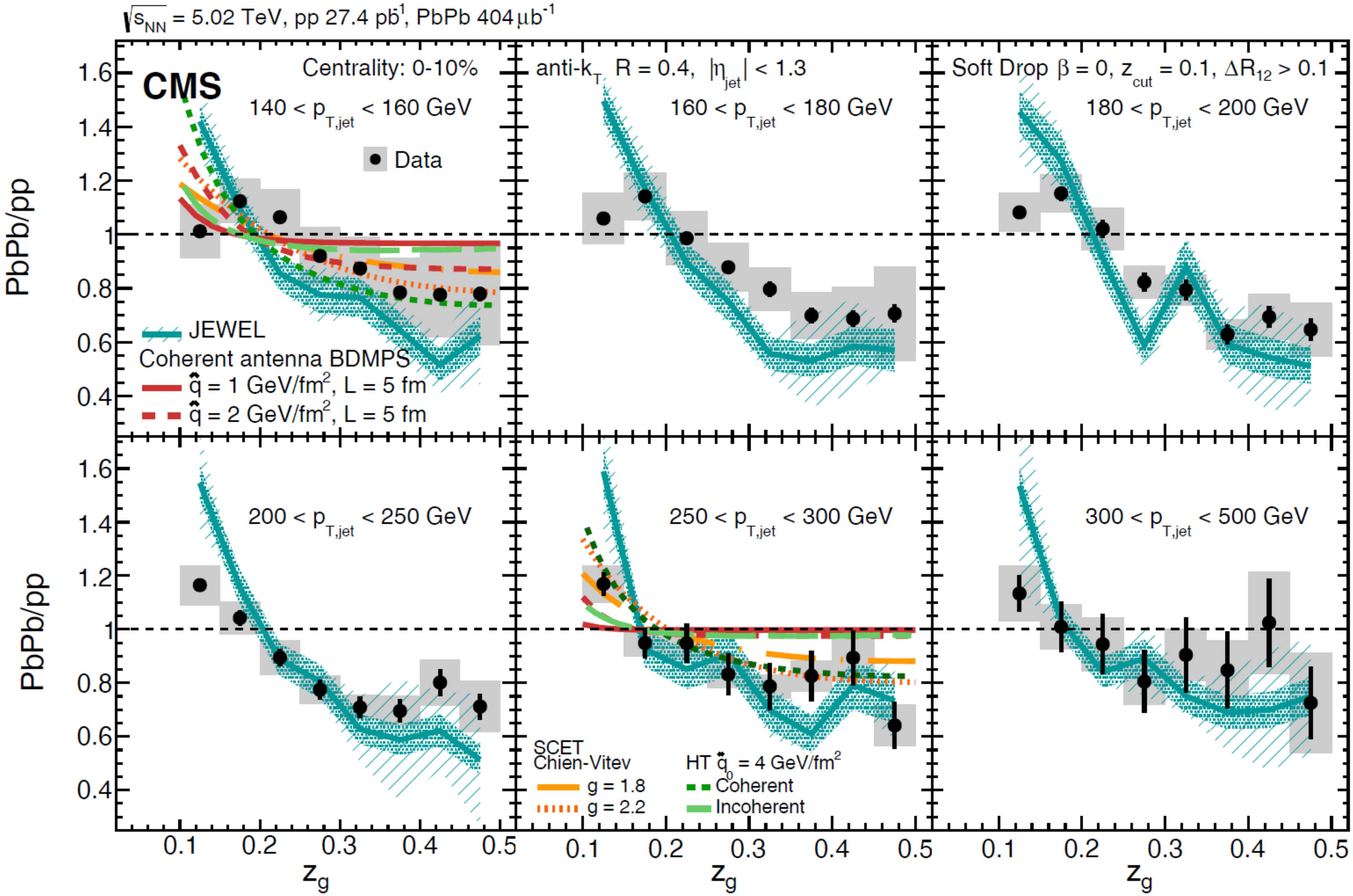
JHEP 1601 (2016) 006

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

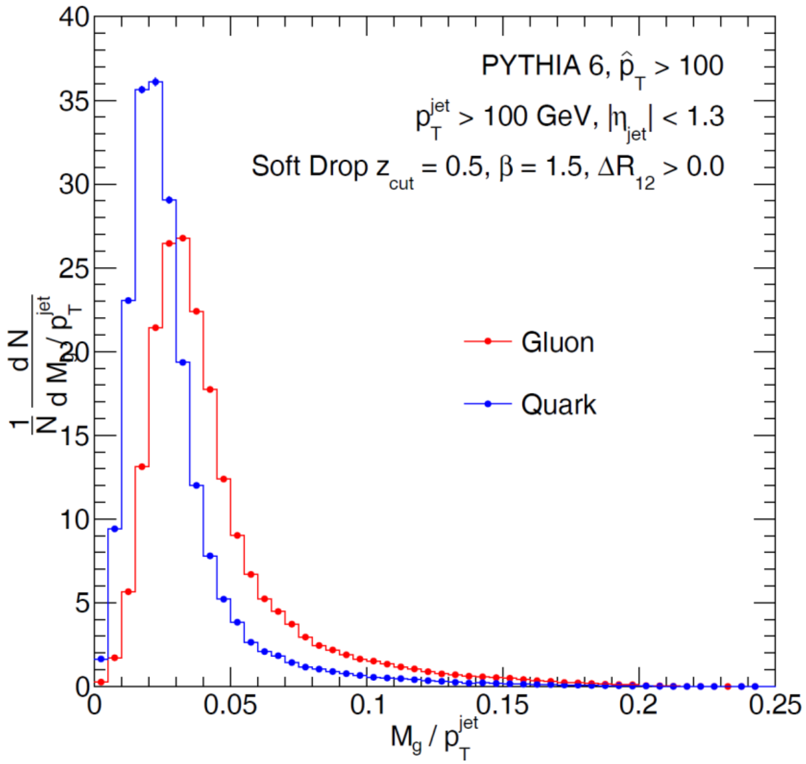
CMS Groomed Jet Splitting Function

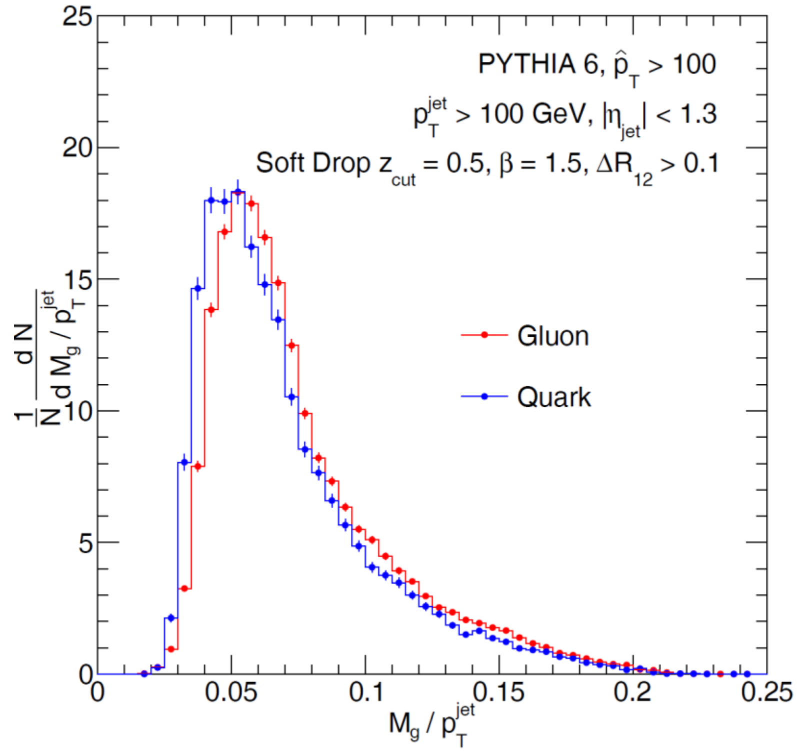


CMS Groomed Jet Splitting Function

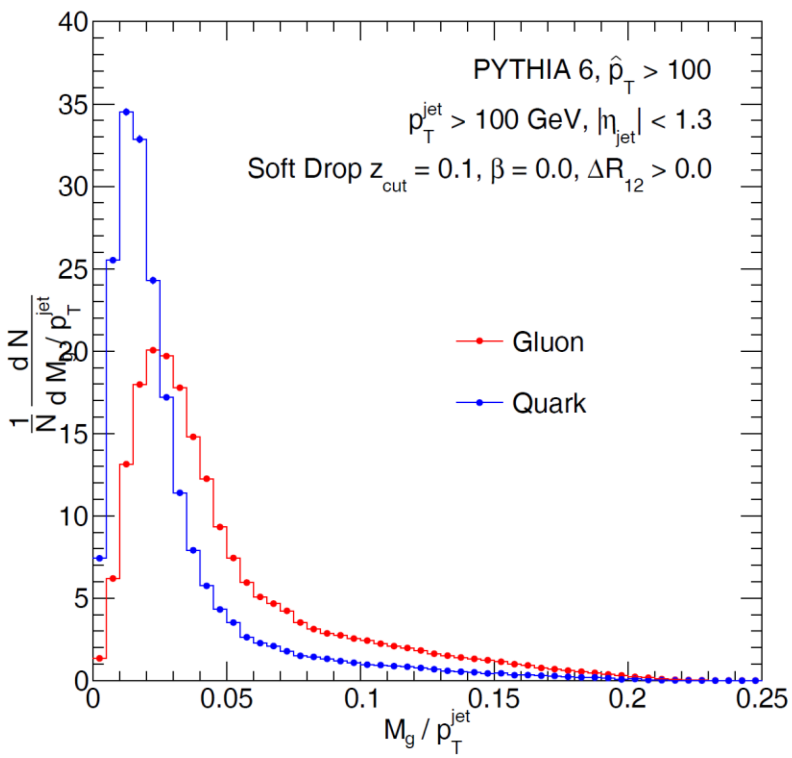


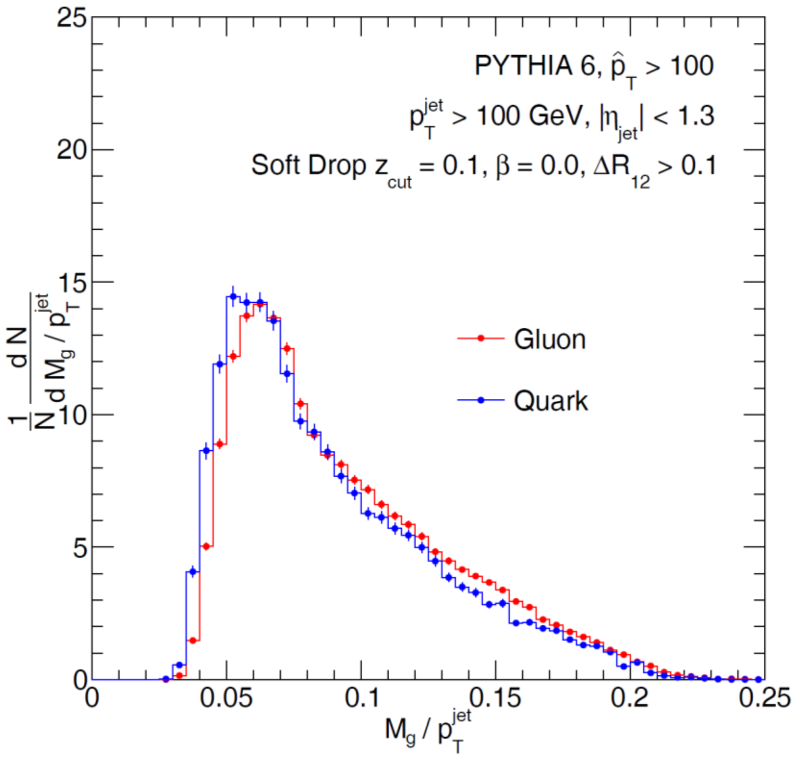
Groomed Jet Mass (Q vs G)



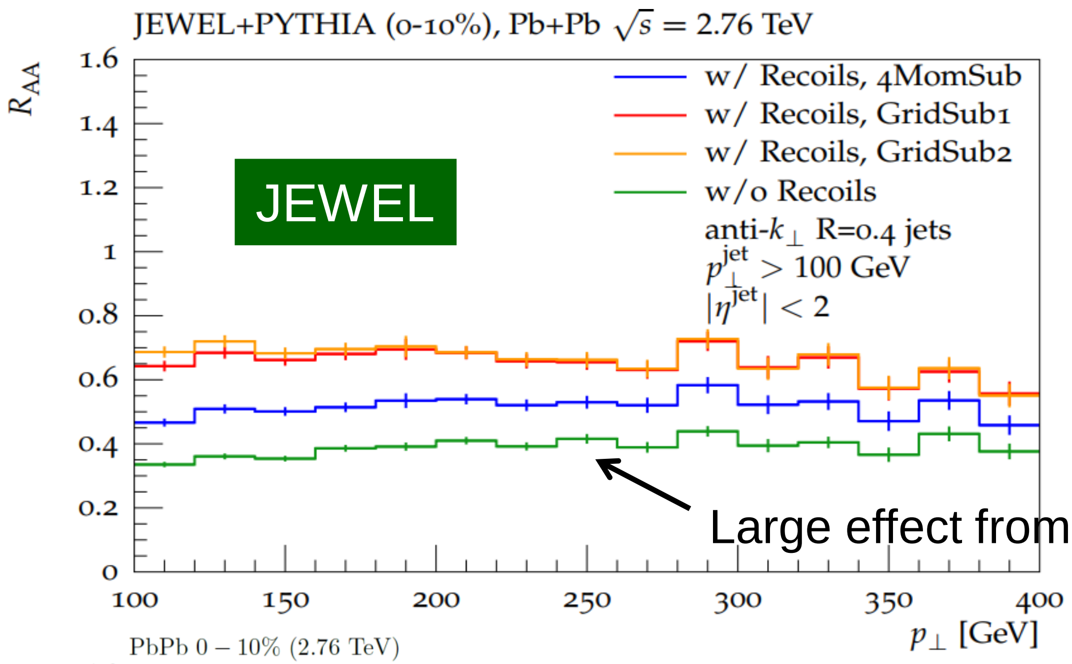


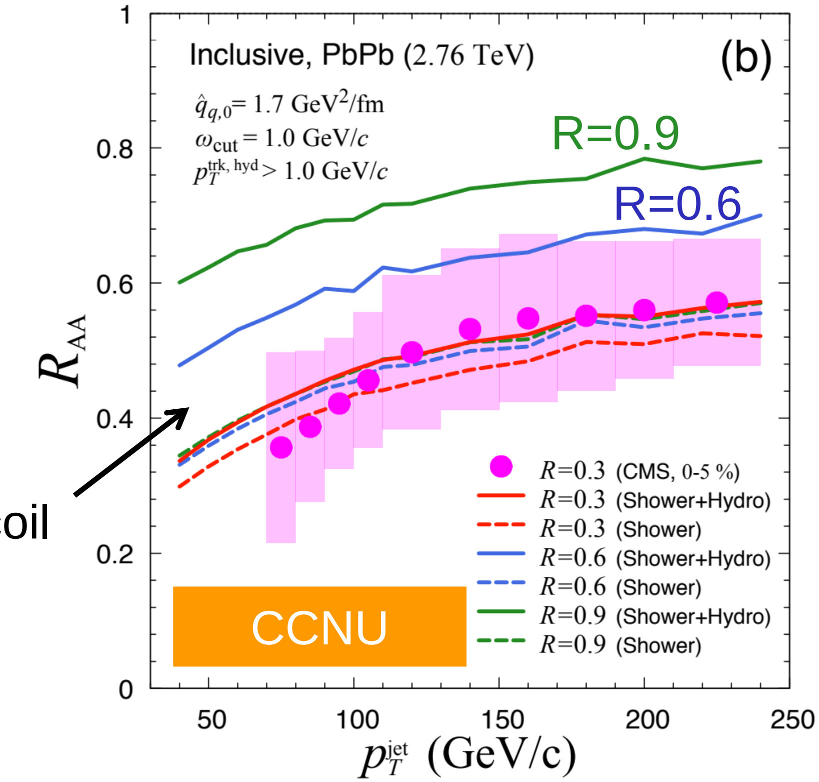
Groomed Jet Mass (Q vs G)



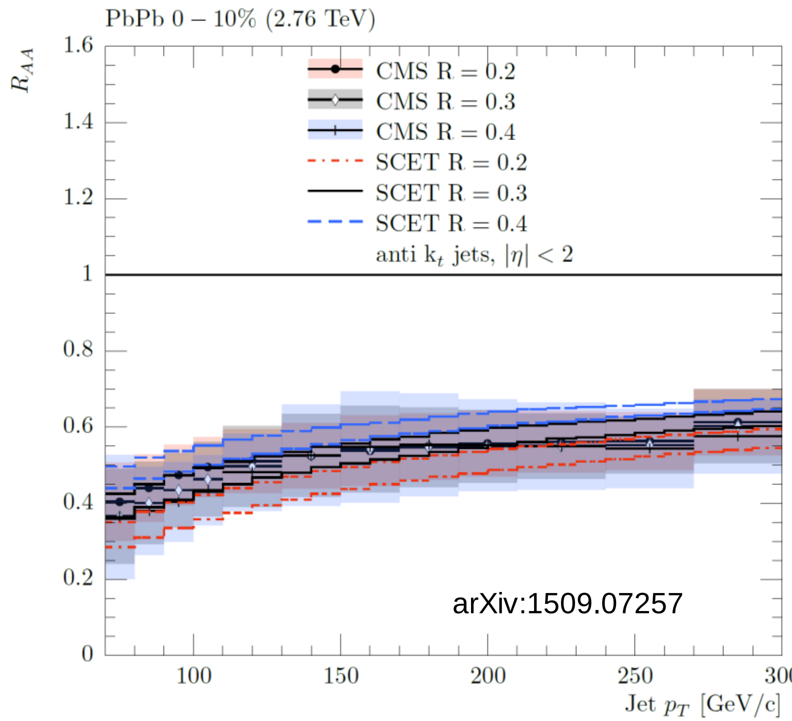


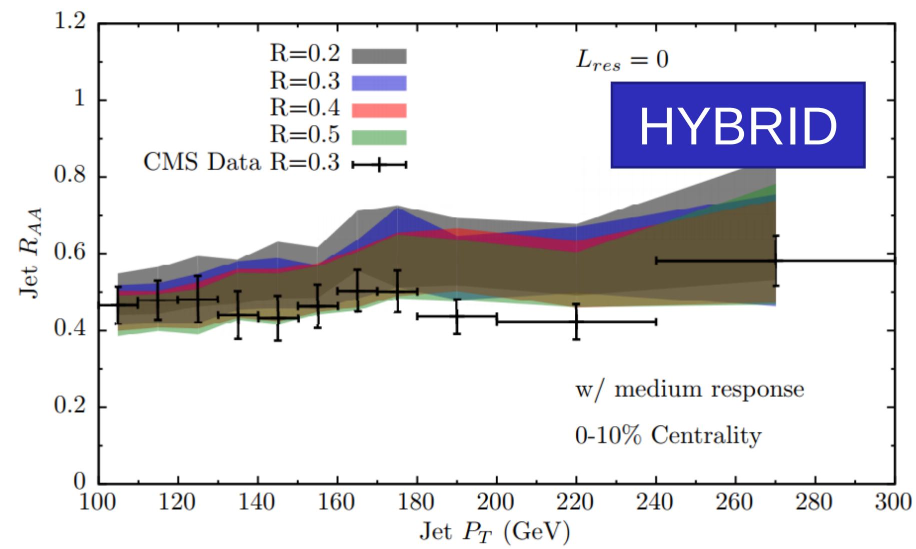
Jet R_{AA} vs. Theory



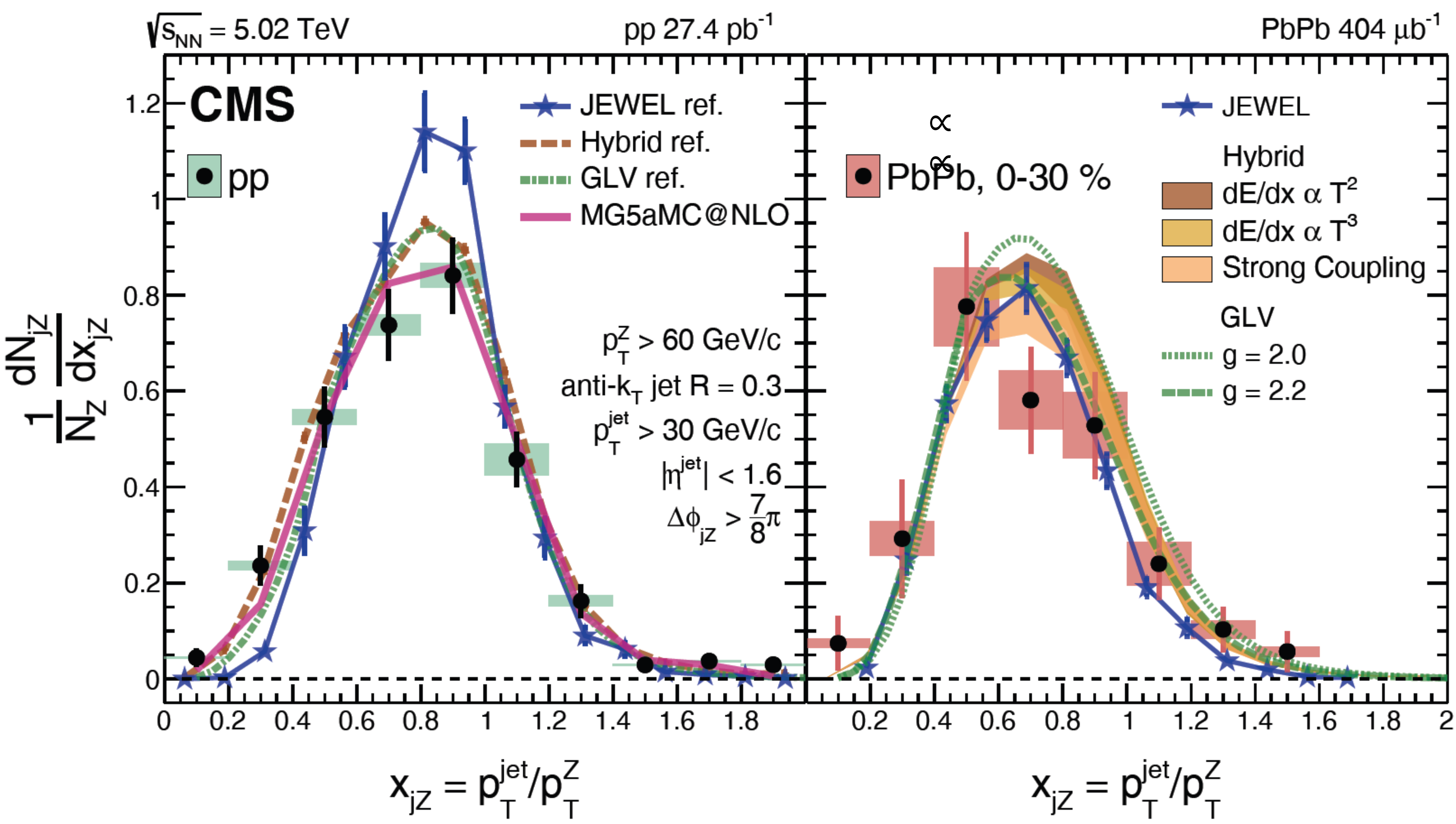


Large effect from recoil



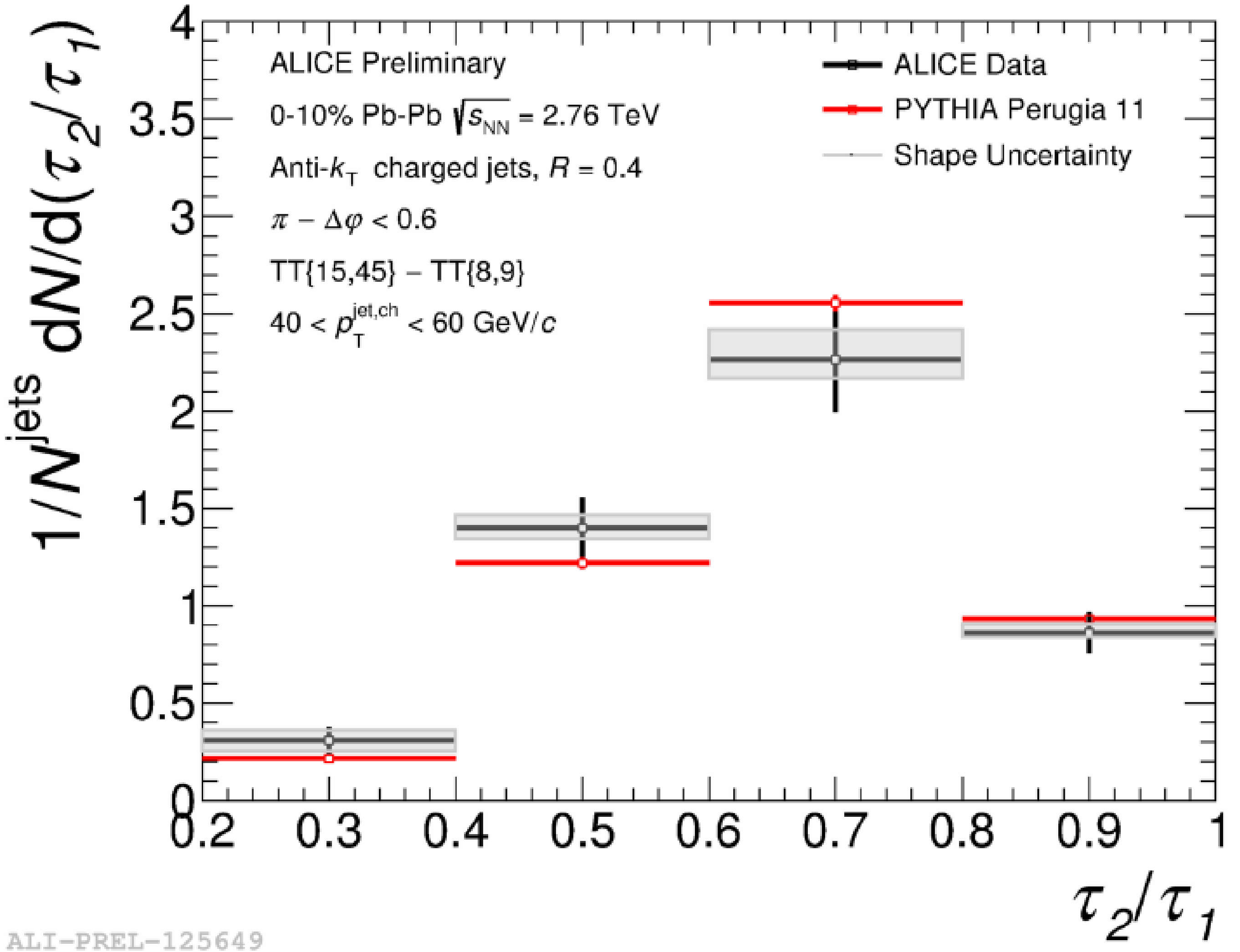


Z-Jet vs calculations



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

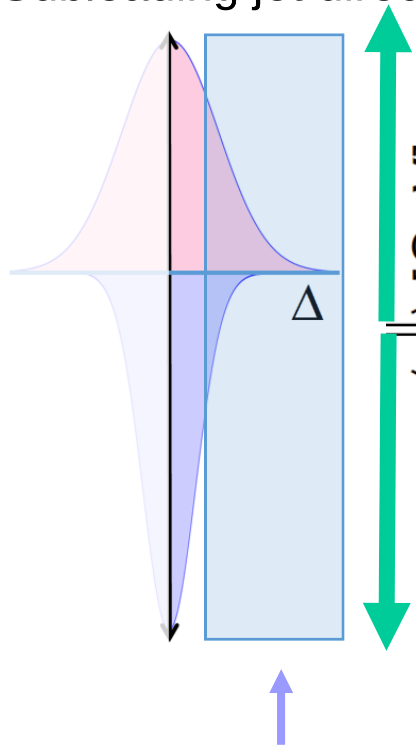
N-Subjettiness in PbPb at 2.76 TeV



- 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

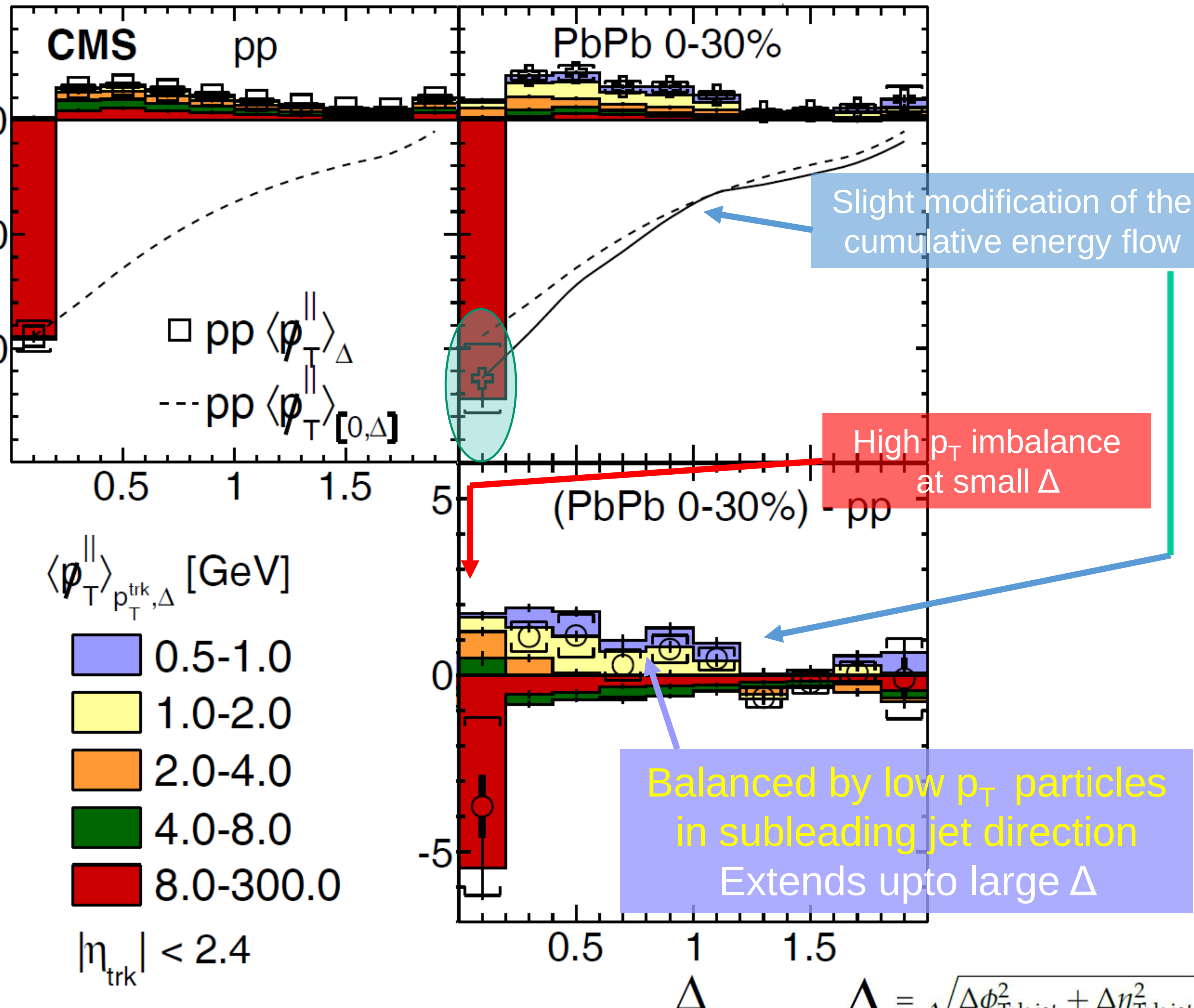


Leading jet direction

$p_{T,1}>120$, $p_{T,2}>50$ GeV/c
$|\eta_1|,|\eta_2|<0.50$, $\Delta\phi_{1,2}>5\pi/6$
anti-k_T Calo R=0.3

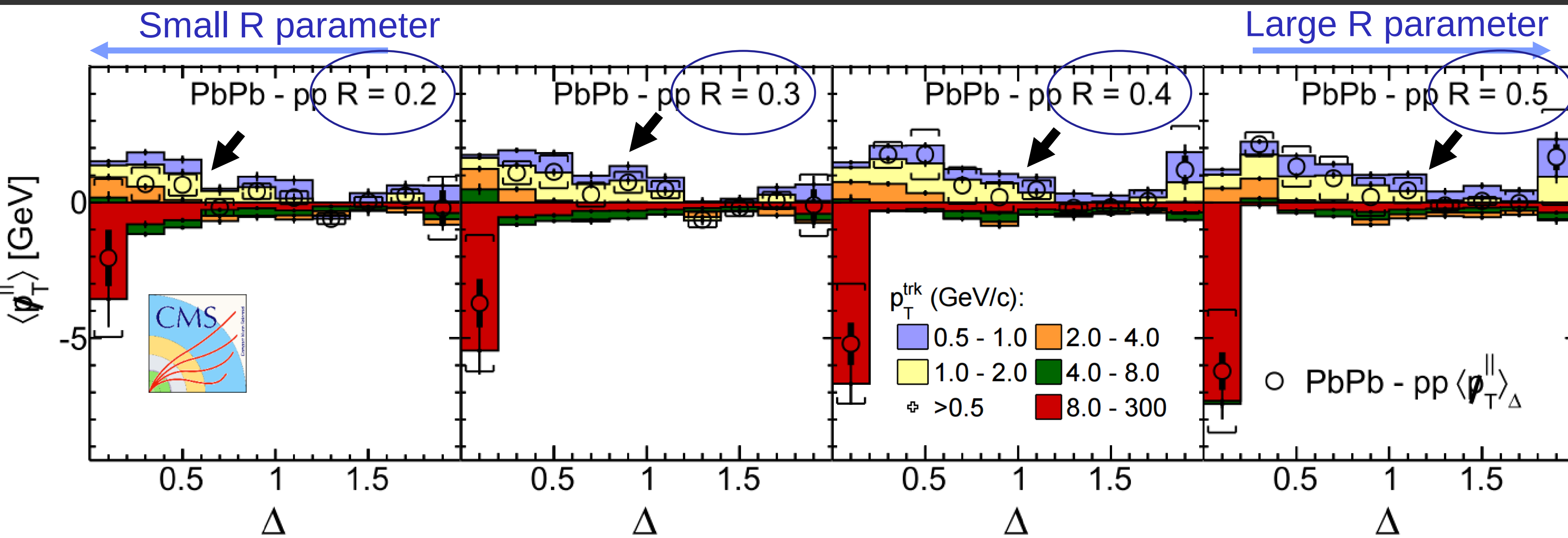
Inclusive A_J

JHEP 1601 (2016) 006

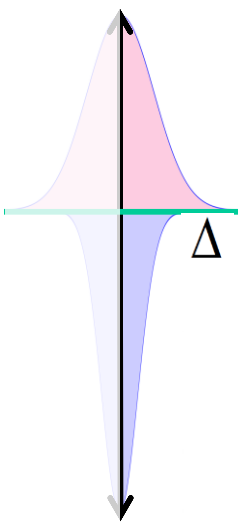


$$\Delta = \sqrt{\Delta\phi^2_{\mathrm{Trk,jet}} + \Delta\eta^2_{\mathrm{Trk,jet}}}$$

"Shooting Jets with Different Width" through the Medium



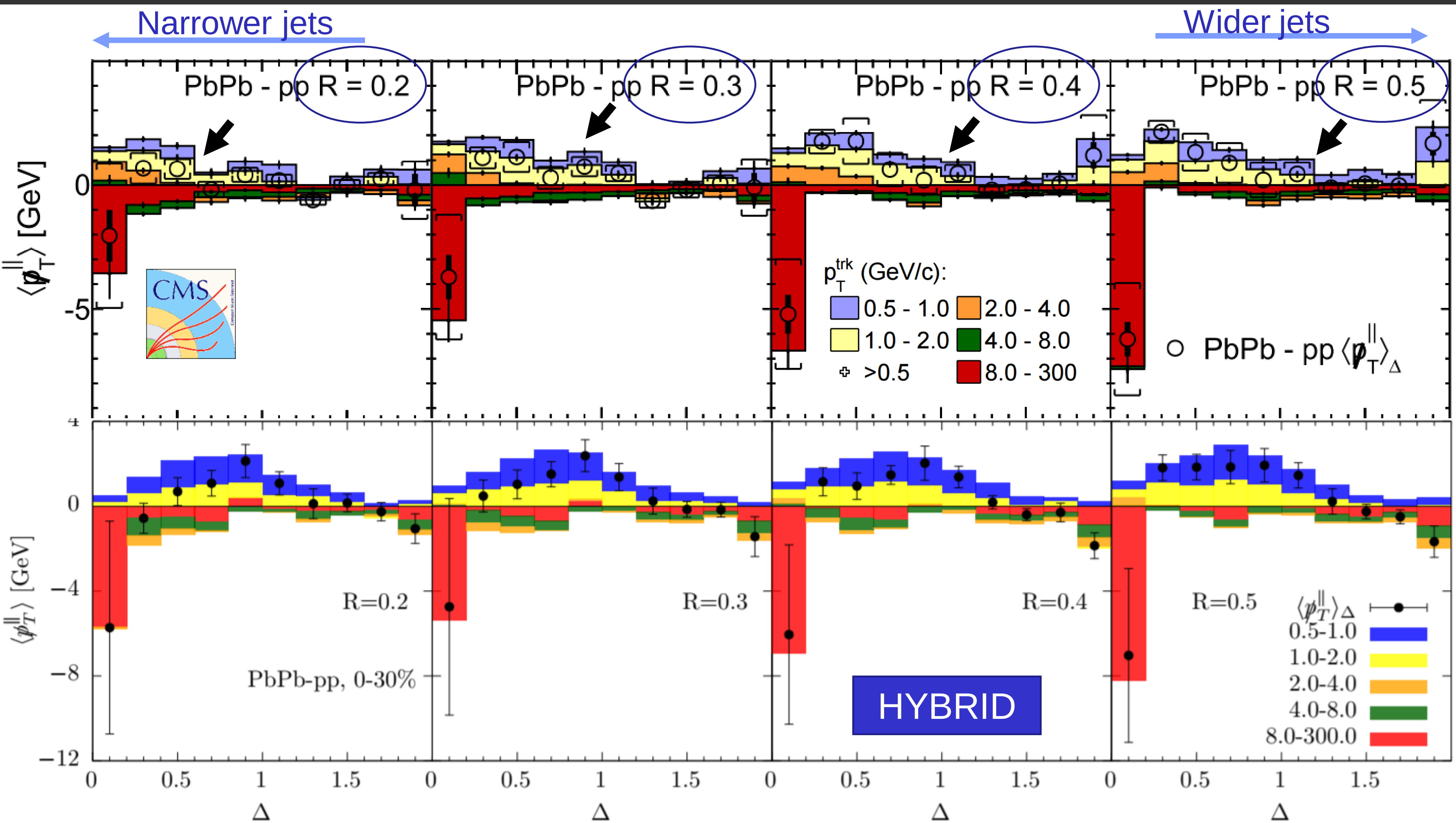
JHEP 1601 (2016) 006



- 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**

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

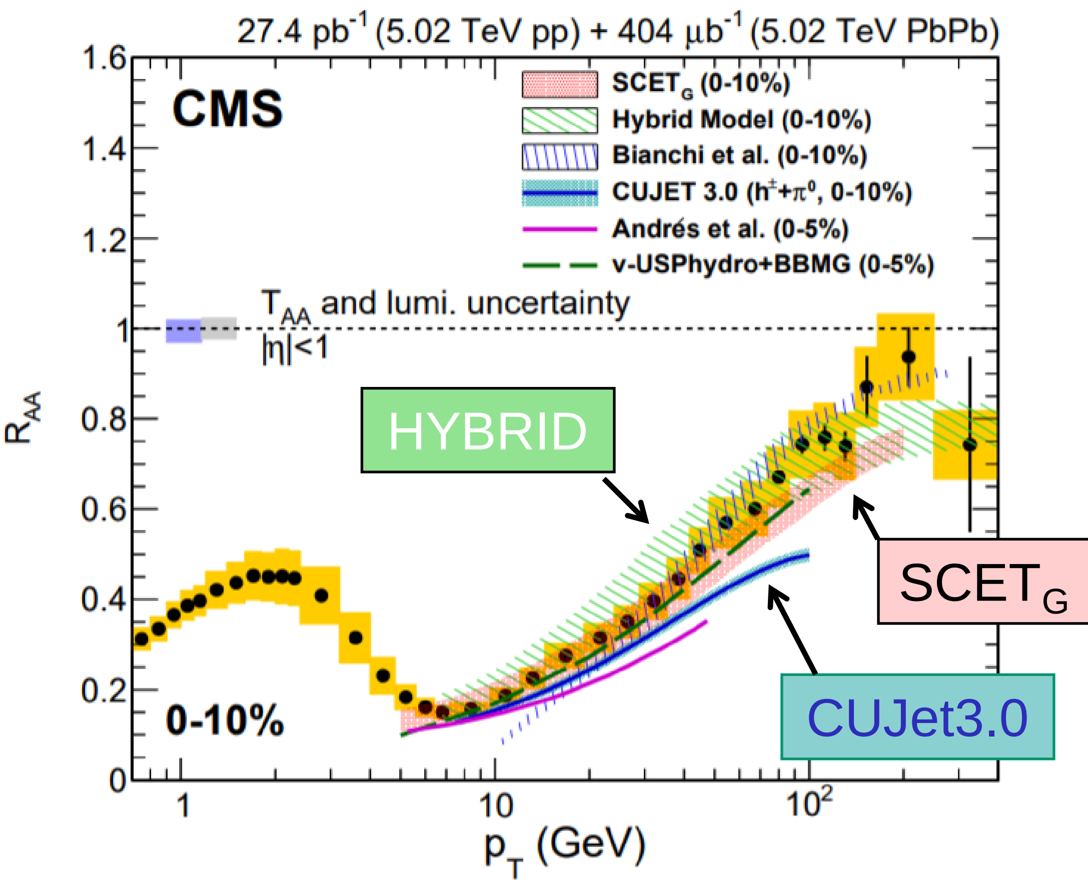
"Shooting Jets with Different Width" through the Medium



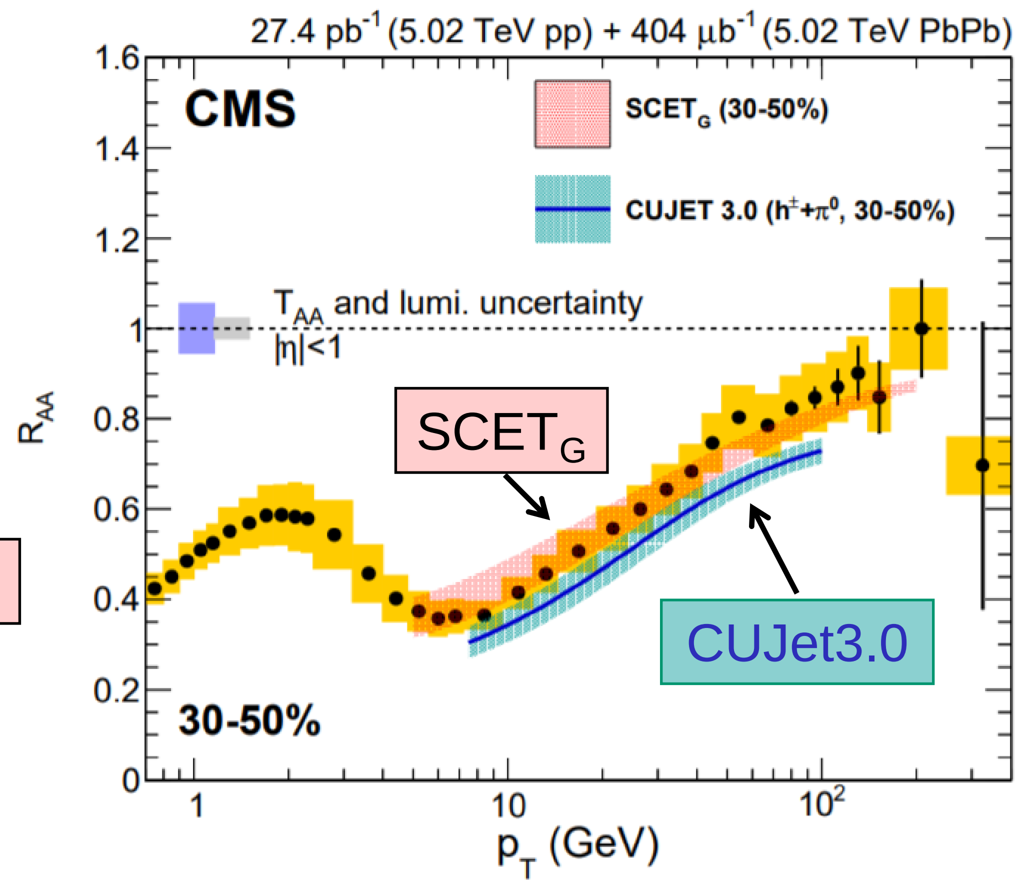
- Medium response from HYBRID is farer away from the jet axis.
- Shower not completely thermalized?
- Where are the calculations from JEWEL, CCNU, QPYTHIA and $SCET_G$?

Charged Particle R_{AA} vs. Theoretical Models

0-10%



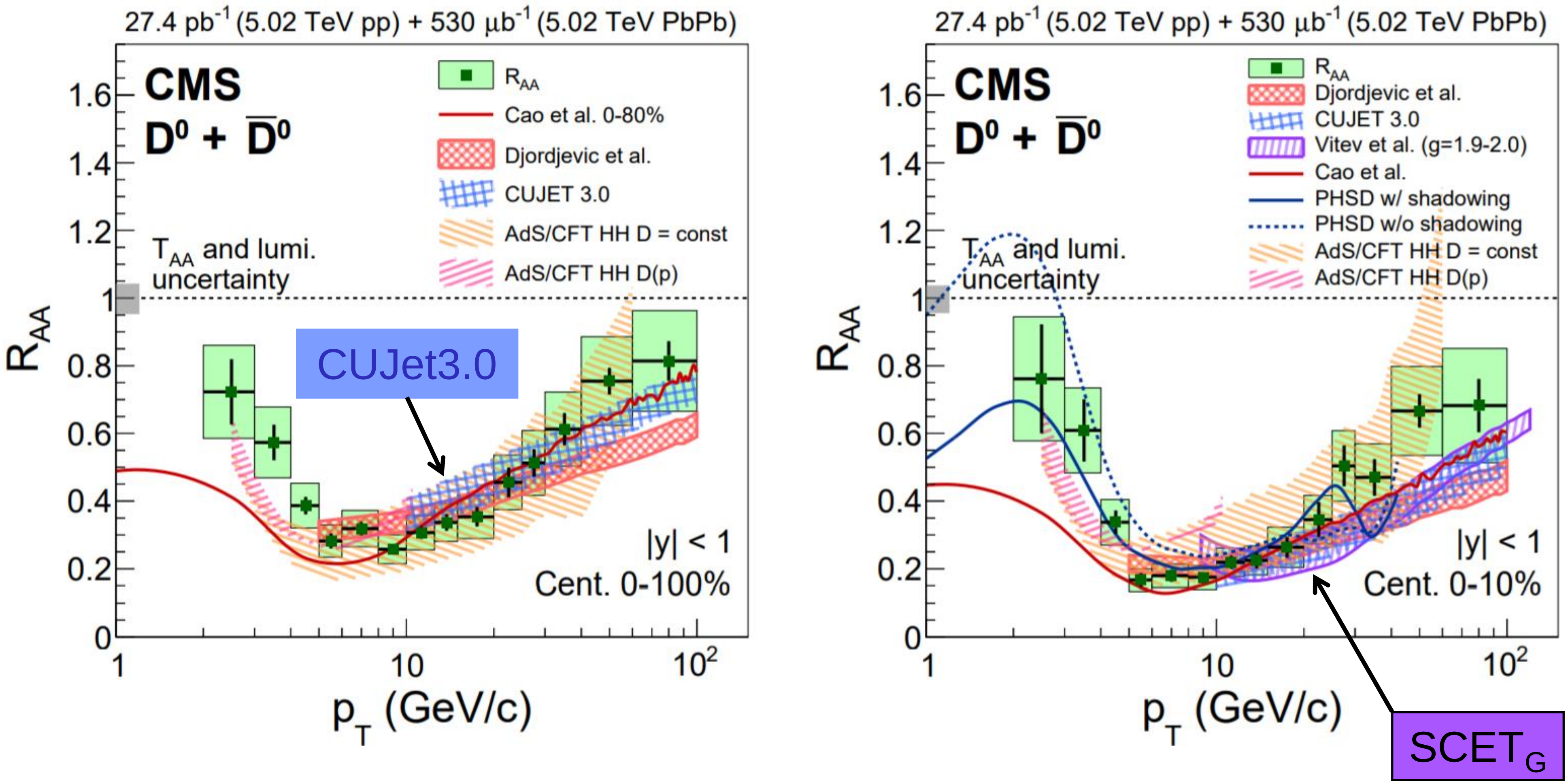
30-50%



- 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

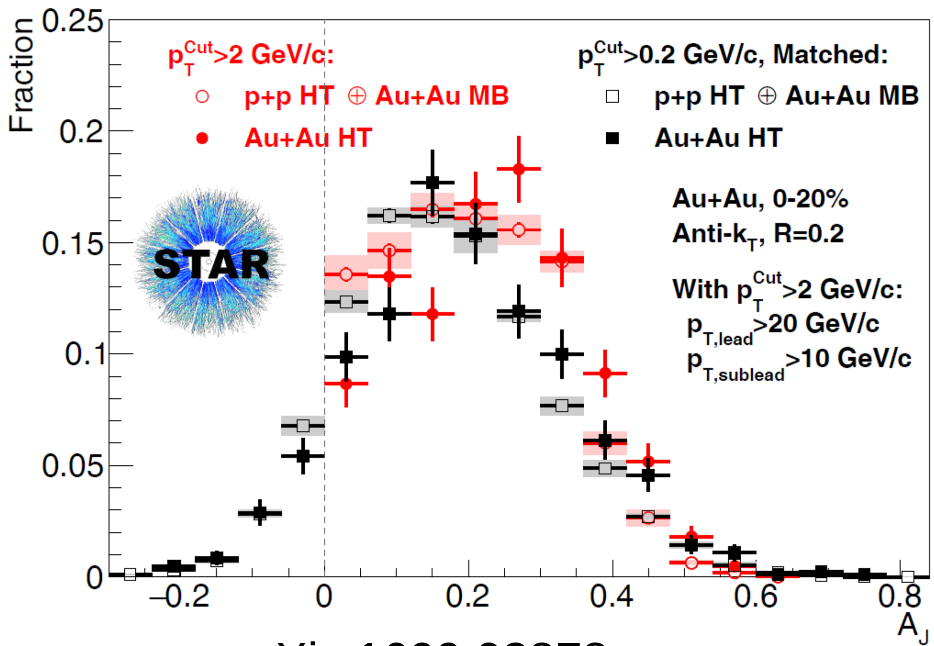
arXiv:1708.04962



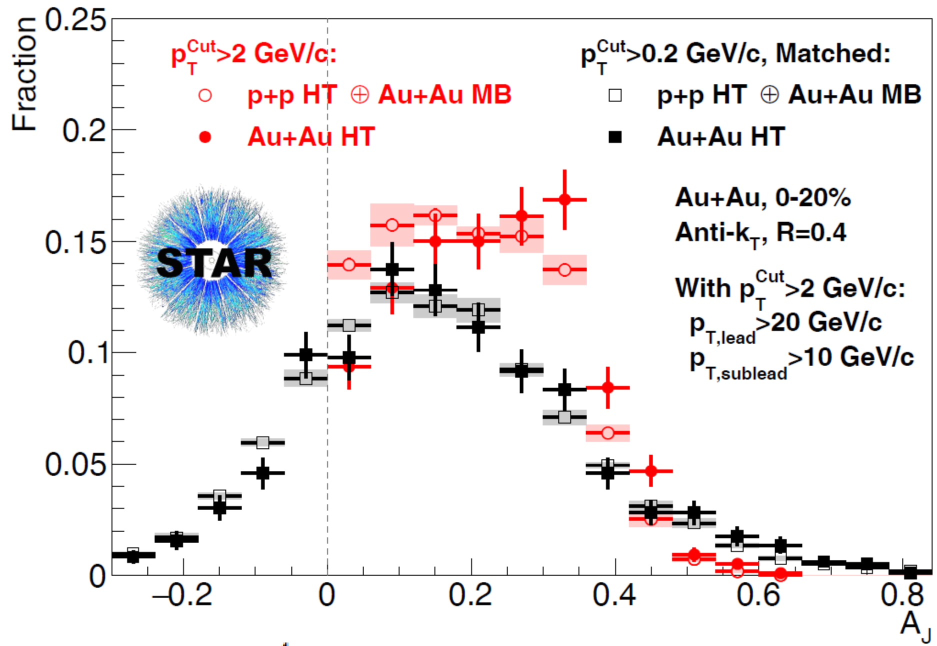
- At high D^0 p_T: Trend captured by pQCD and AdS/CFT based models
- Reasonable description of the data could be achieved
- Details doesn't work perfectly, especially the slope of the D^0 R_{AA} vs. p_T

Dijet Transverse Momentum Correlation

R=0.2

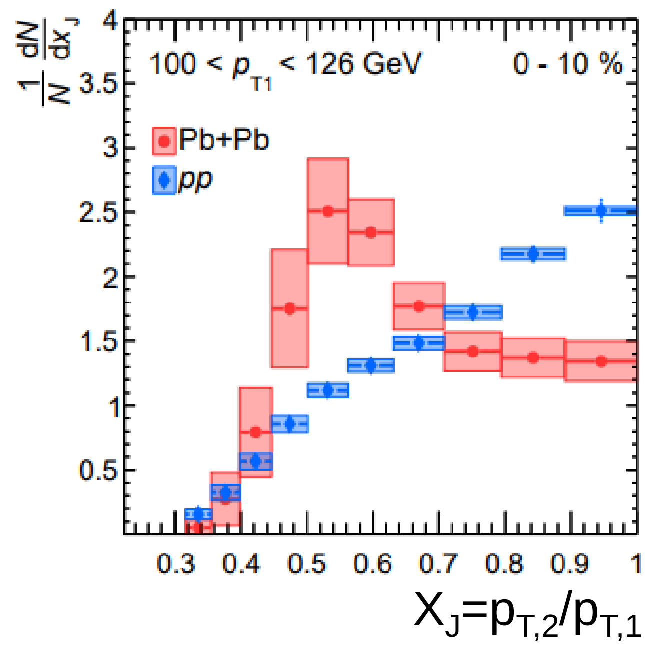


R=0.4

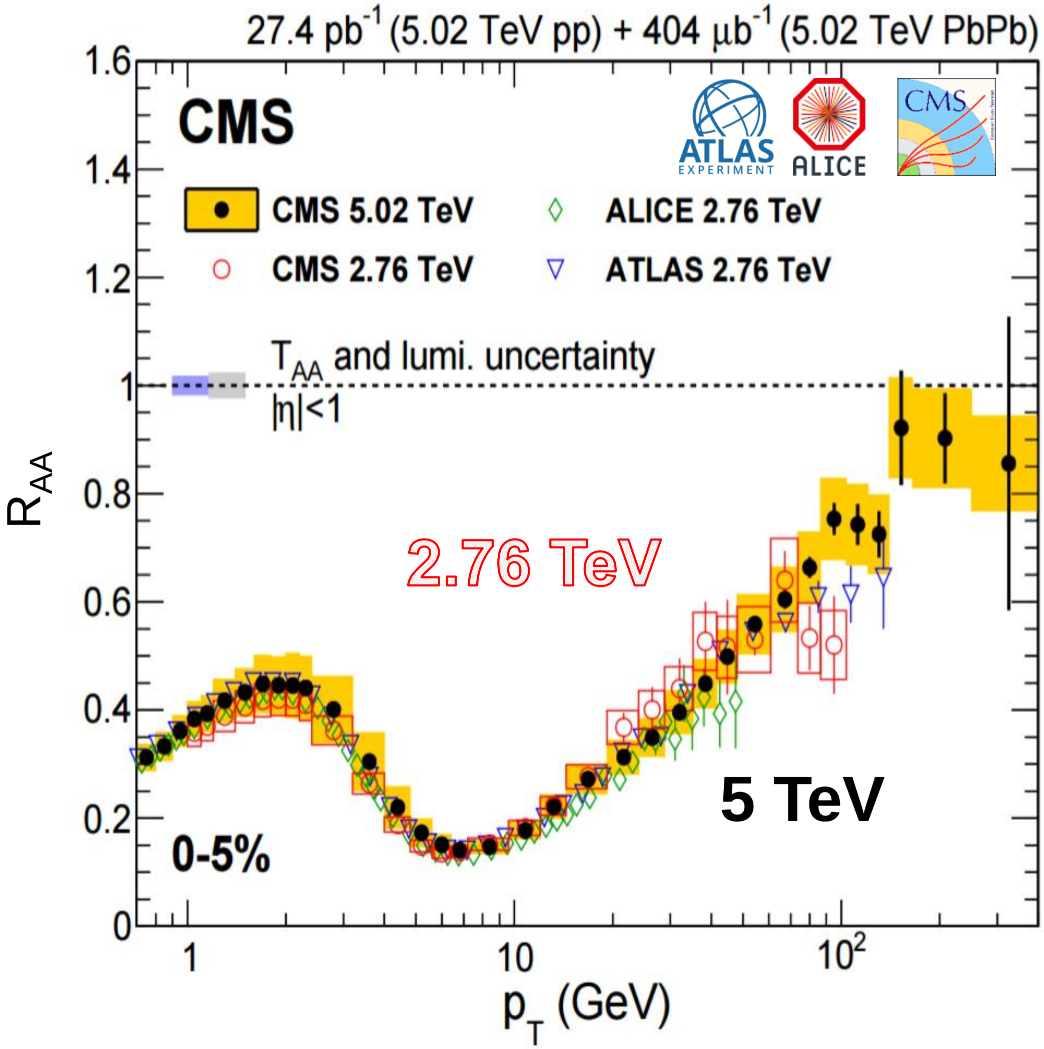


arXiv:1609.03878

- **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?

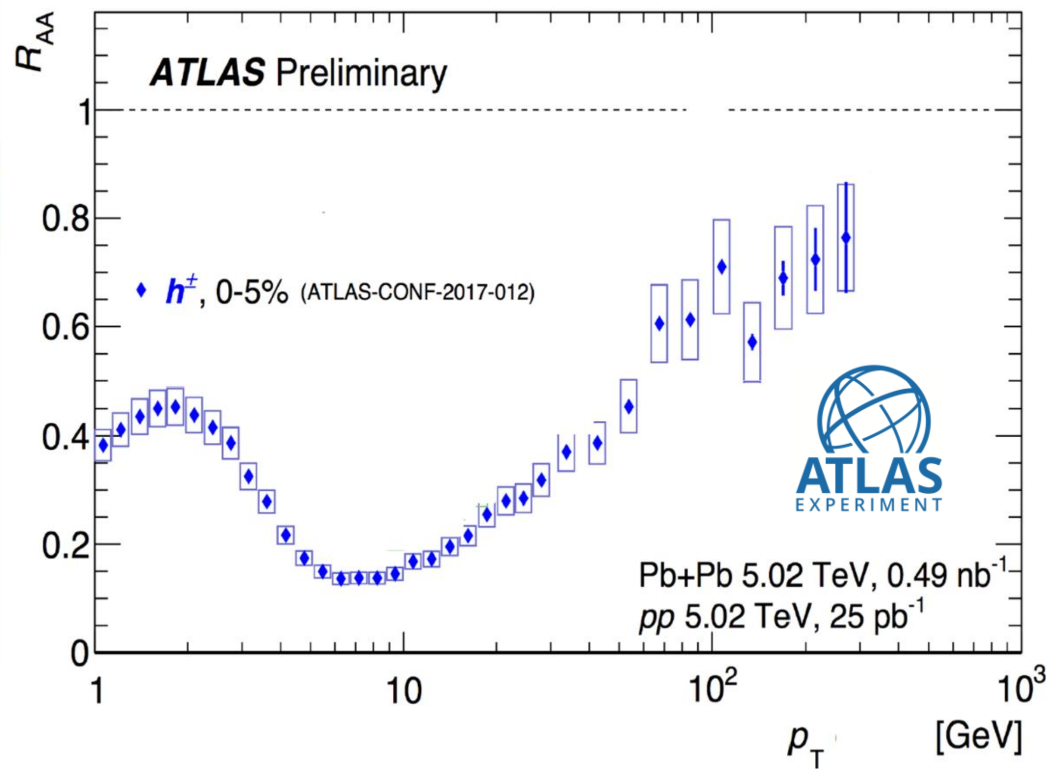


Jet Quenching with Inclusive Charged Particles



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!

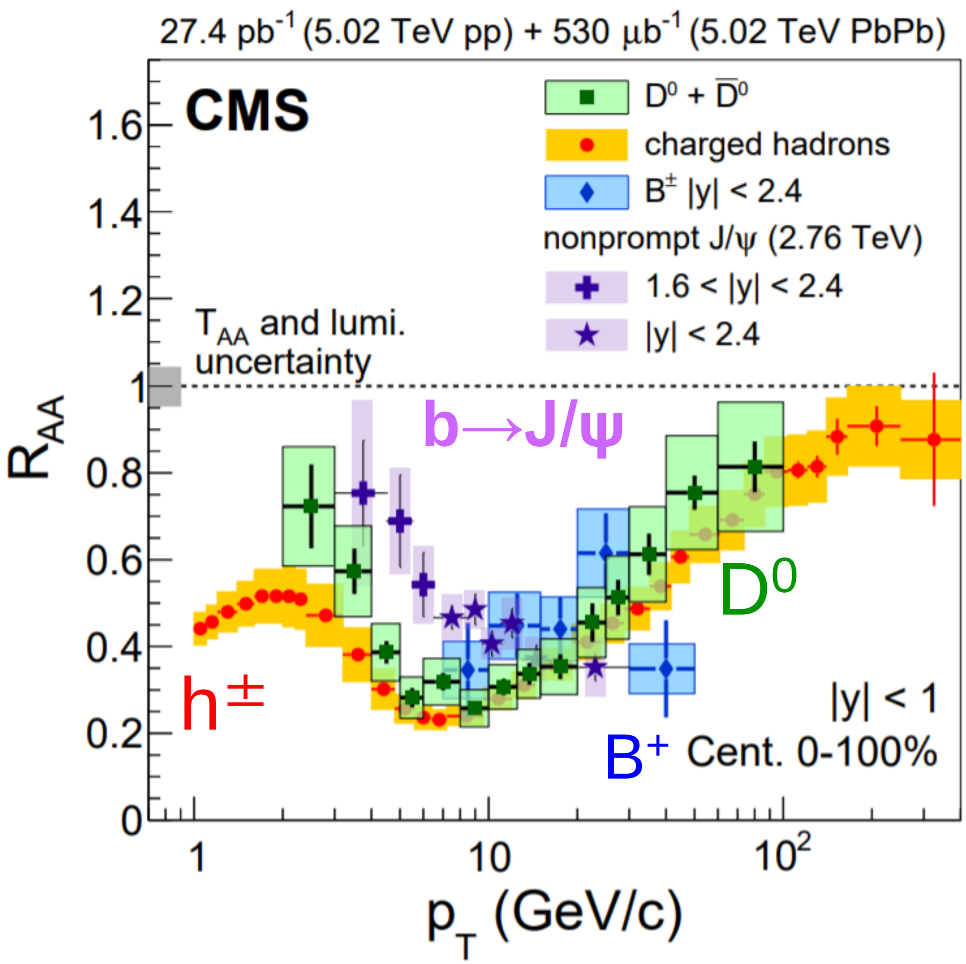
JHEP 04 (2017) 039

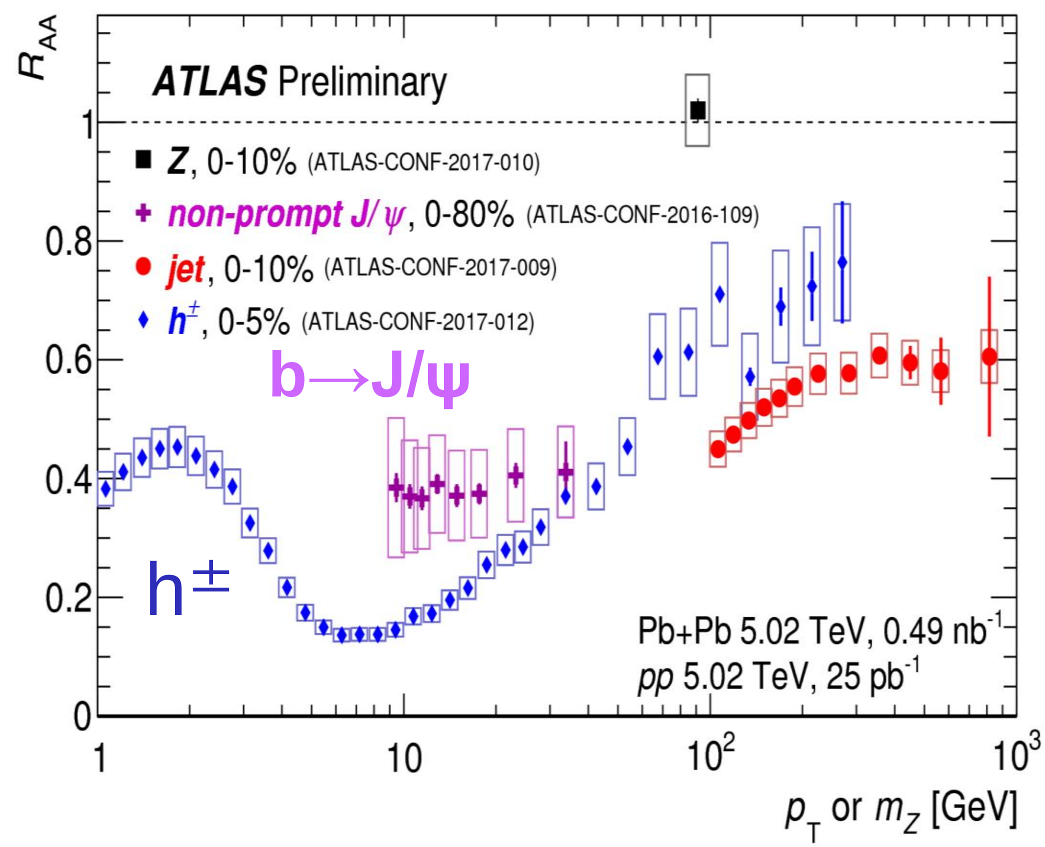
- Similar Charged particle R_{AA} in PbPb at **5 TeV** compared to 2.76 TeV
- Good agreement between ATLAS, CMS and ALICE measurements

ATLAS-CONF-2017-012

Flavor Dependence of Parton Energy Loss

arXiv:1708.04962



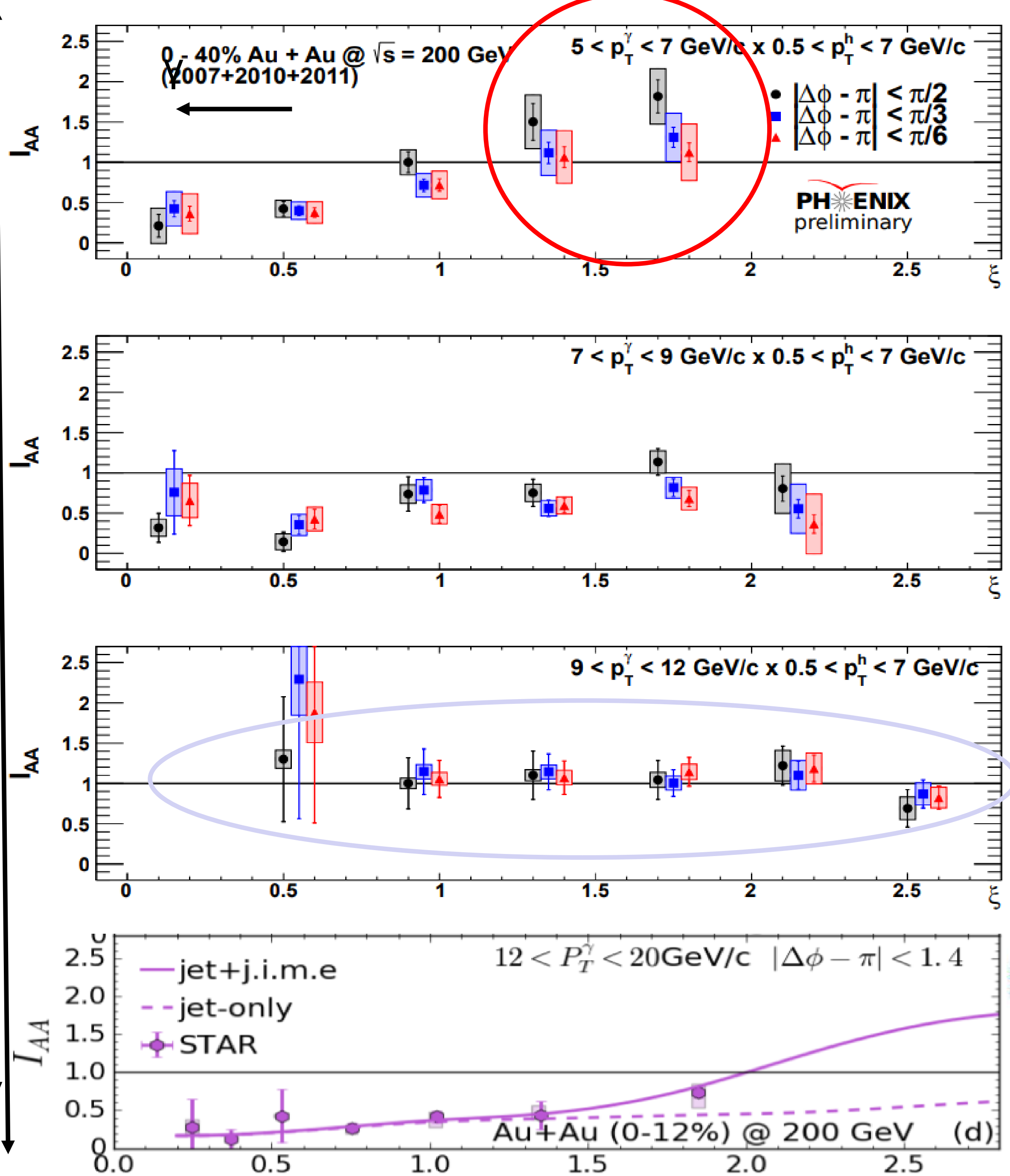


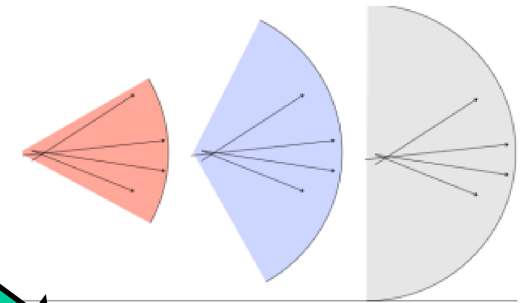
- R_{AA} is meson flavor dependent at low hadron p_T
- Disappearance of the effect at high hadron p_T
- Results are consistent with the expectation from models with parton flavor dependent energy loss

PHENIX Photon-Hadron Correlation

Low p_T Photon 5-7 GeV

High p_T Photon 12-20 GeV





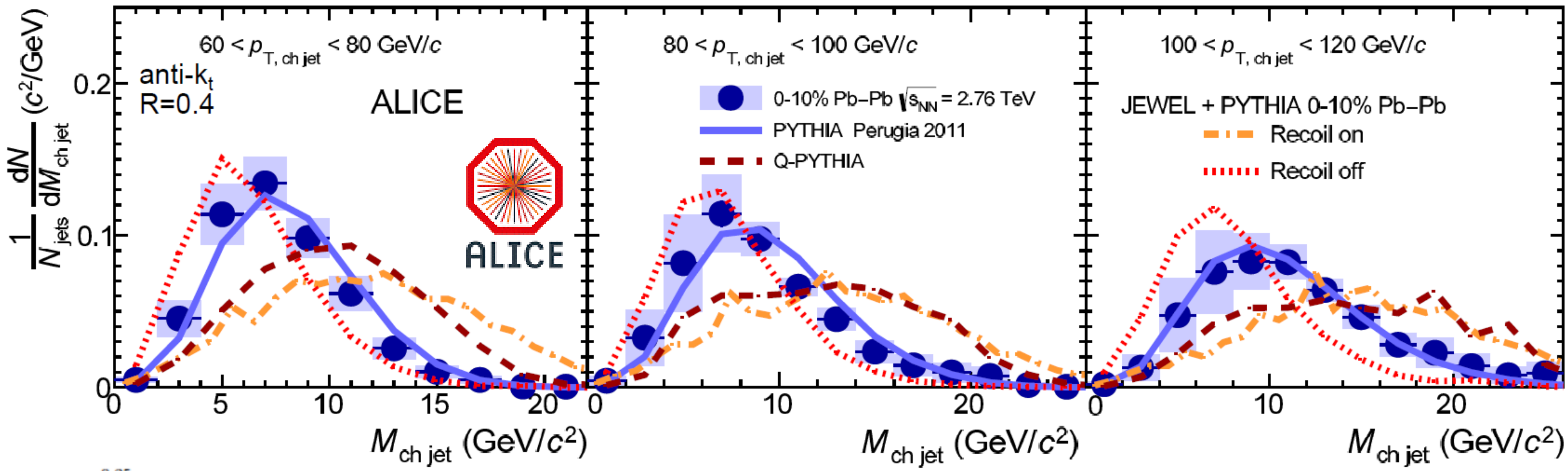
Indication of wide angle radiation carried by soft particle. Significant modification of jet FF

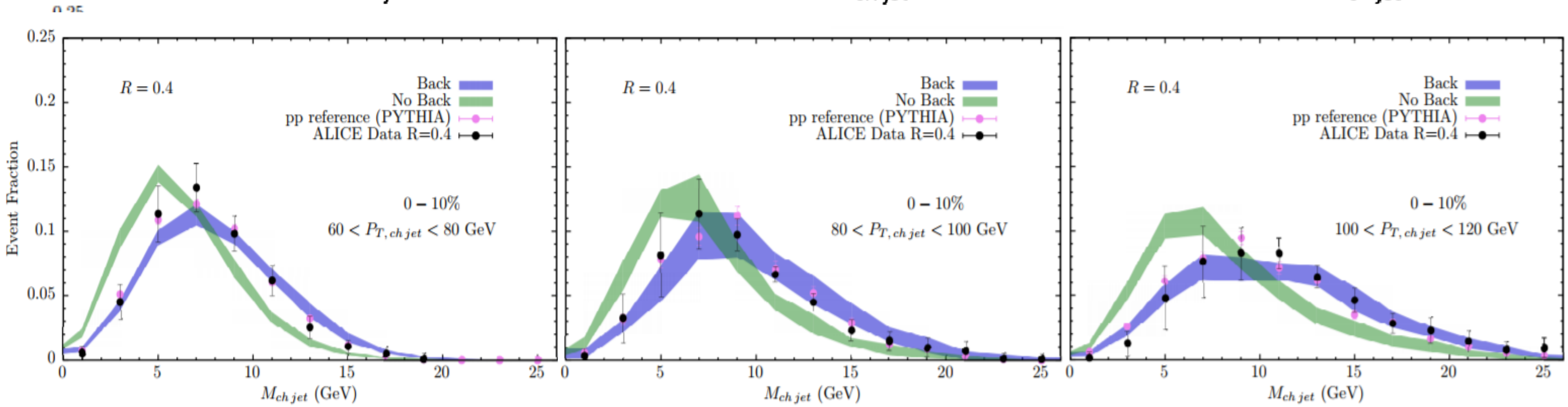
Something in between

No modification of jet fragmentation (?)

Significant modification of jet FF

ALICE Charged Jet Mass

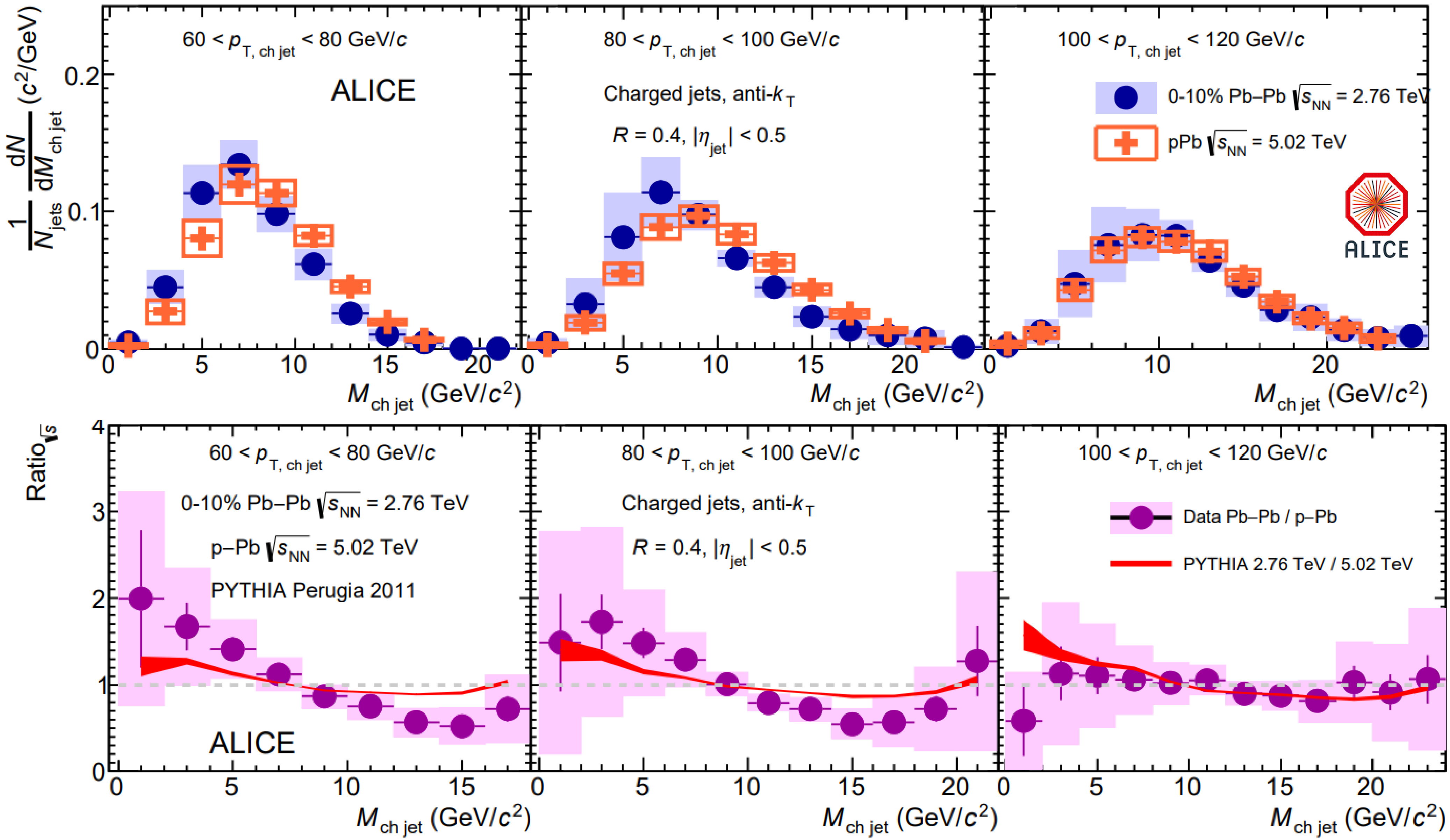




- Data sit between **JEWEL** recoil on and off
- HYBRID need medium recoil to describe the ALICE data

HYBRID

Charged Jet Mass in pPb and PbPb

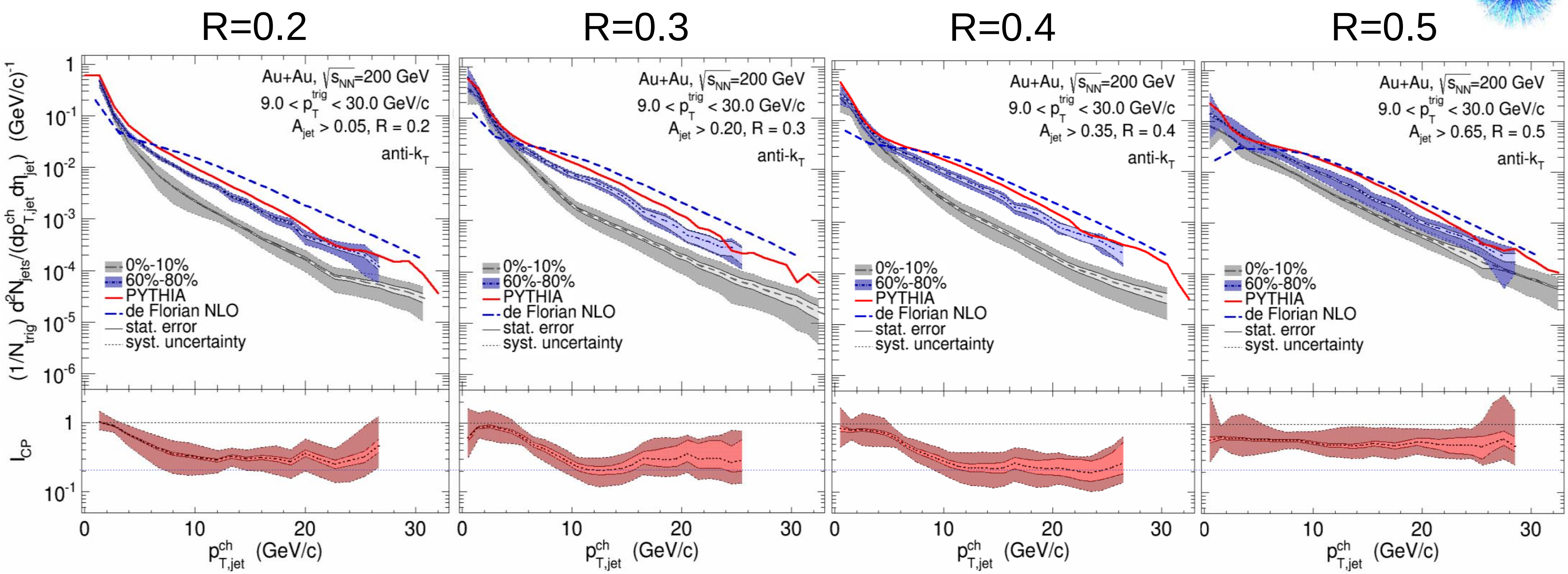


Hint of smaller charged jet mass in PbPb (more quark like) with respect to reference

PLB 776 (2018) 249-264

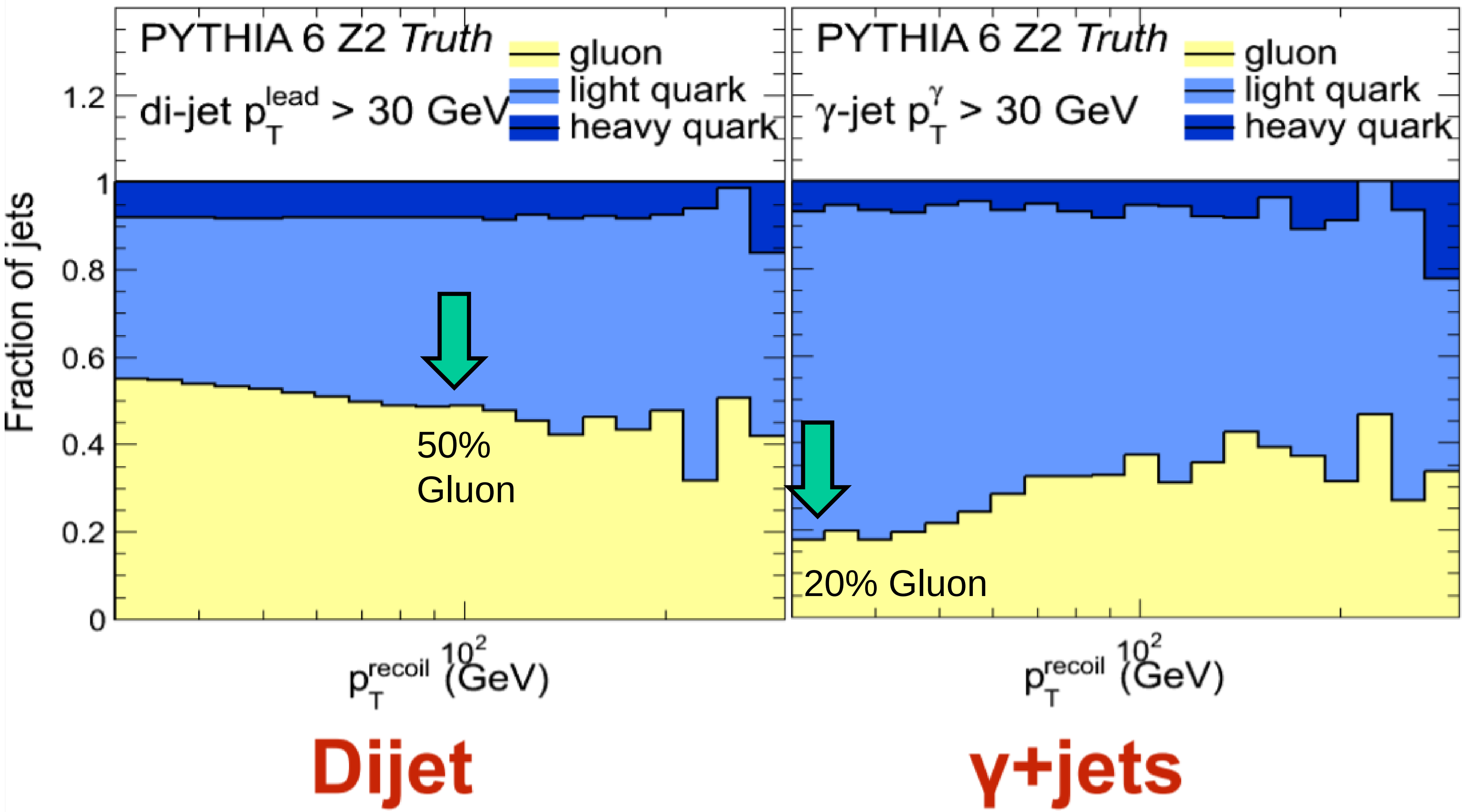
STAR Hadron-Jet Correlation

arXiv:1702.01108



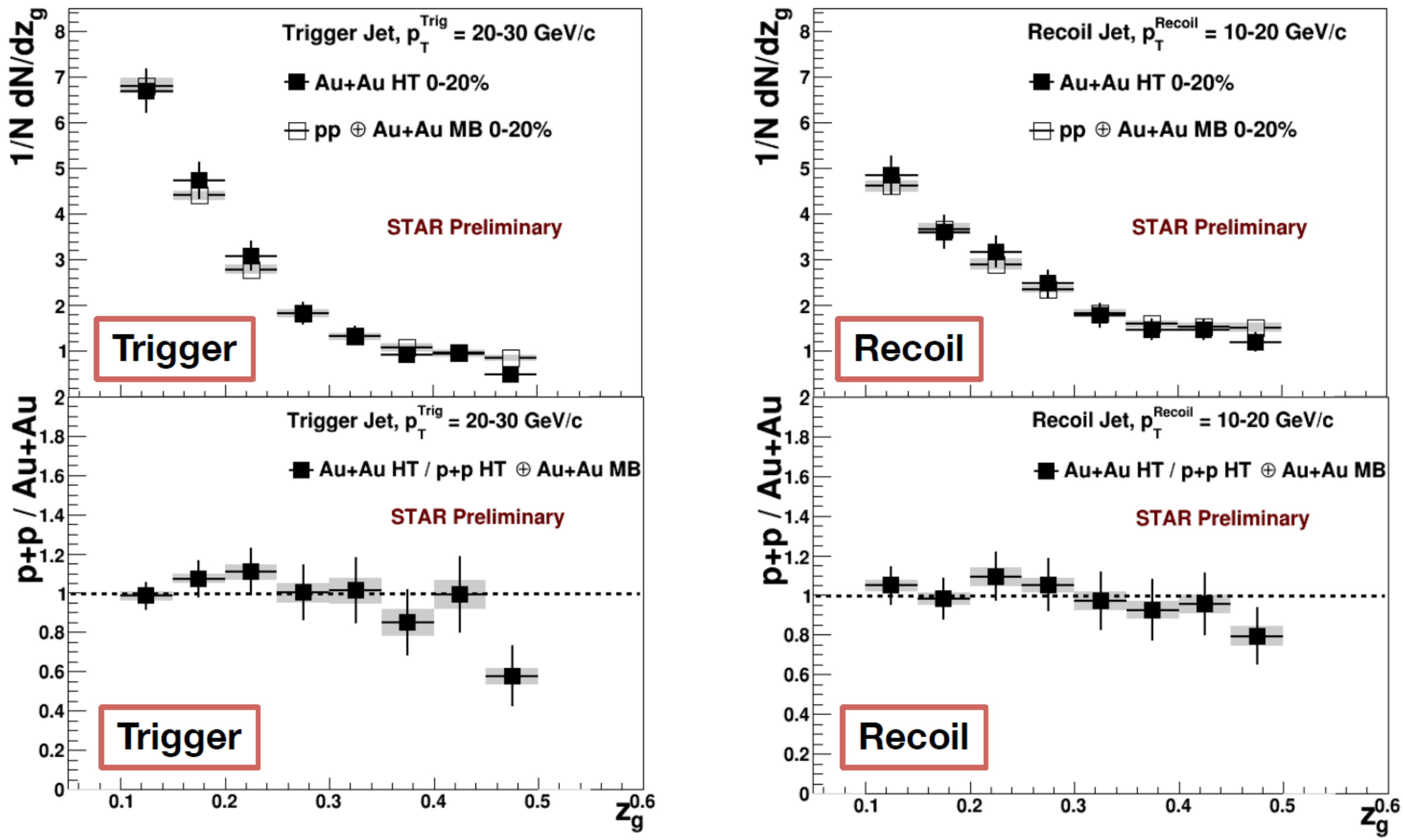
- R=0.2-0.4
  - I_{CP} significantly lower than unity; significant out-of-cone Eloss
- R=0.5 I_{CP} **>** R=0.2 I_{CP}
  - indication of the recovery of the quenched energy

Jet Flavor Composition in Dijet and γ-Jet



From Doga Gulhan

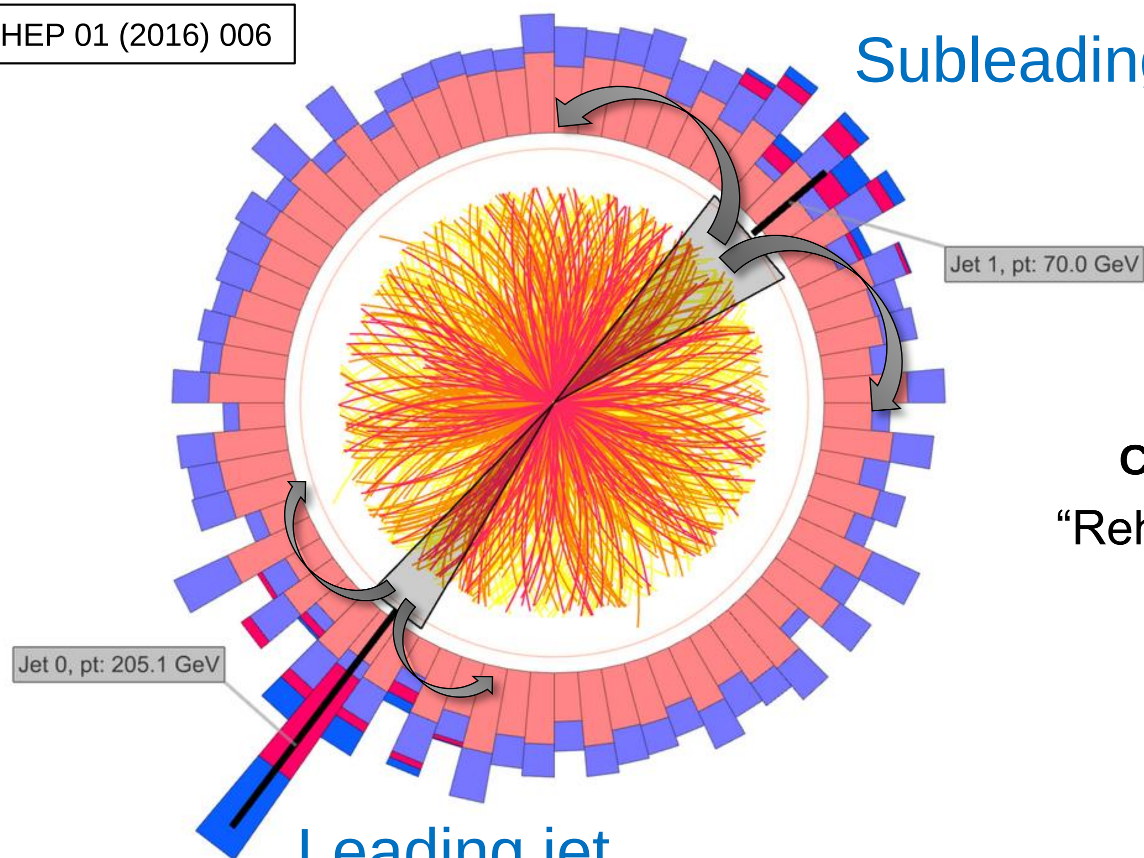
STAR Splitting Function

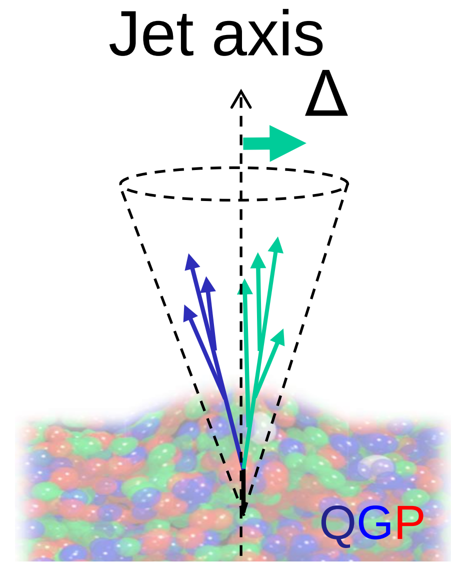


- STAR: Di-jet pairs seeded with “hard core”
- No significant modification in this subset of dijet

Quenched Energy out of the Jet Cone

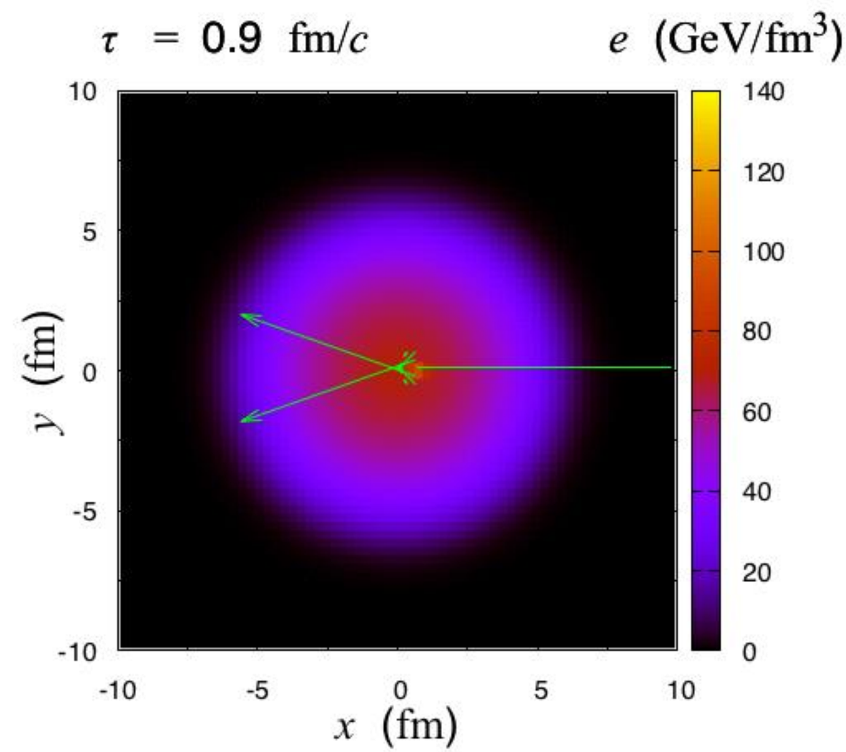
JHEP 01 (2016) 006





CCNU Model

"Reheating" the QGP

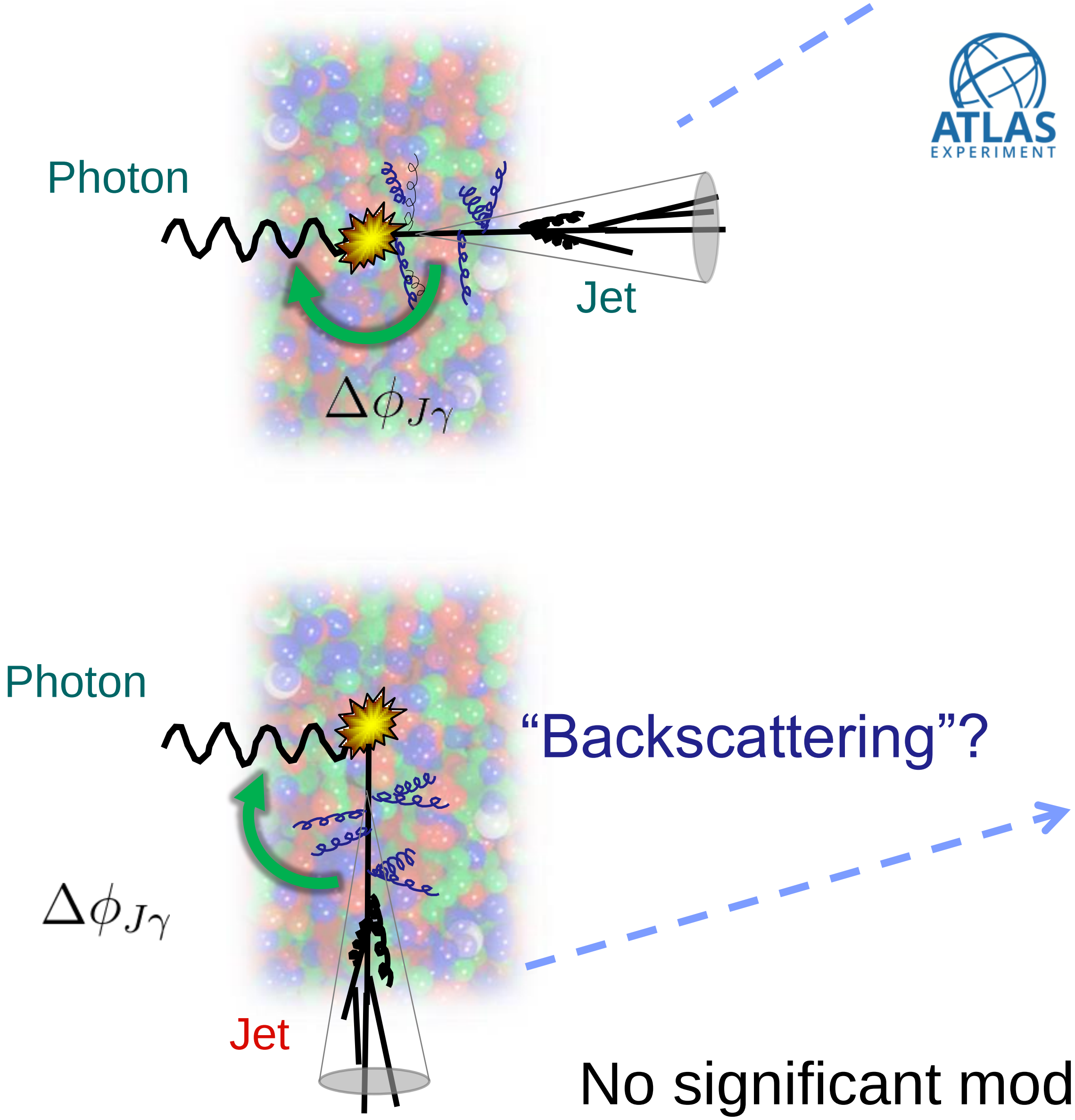


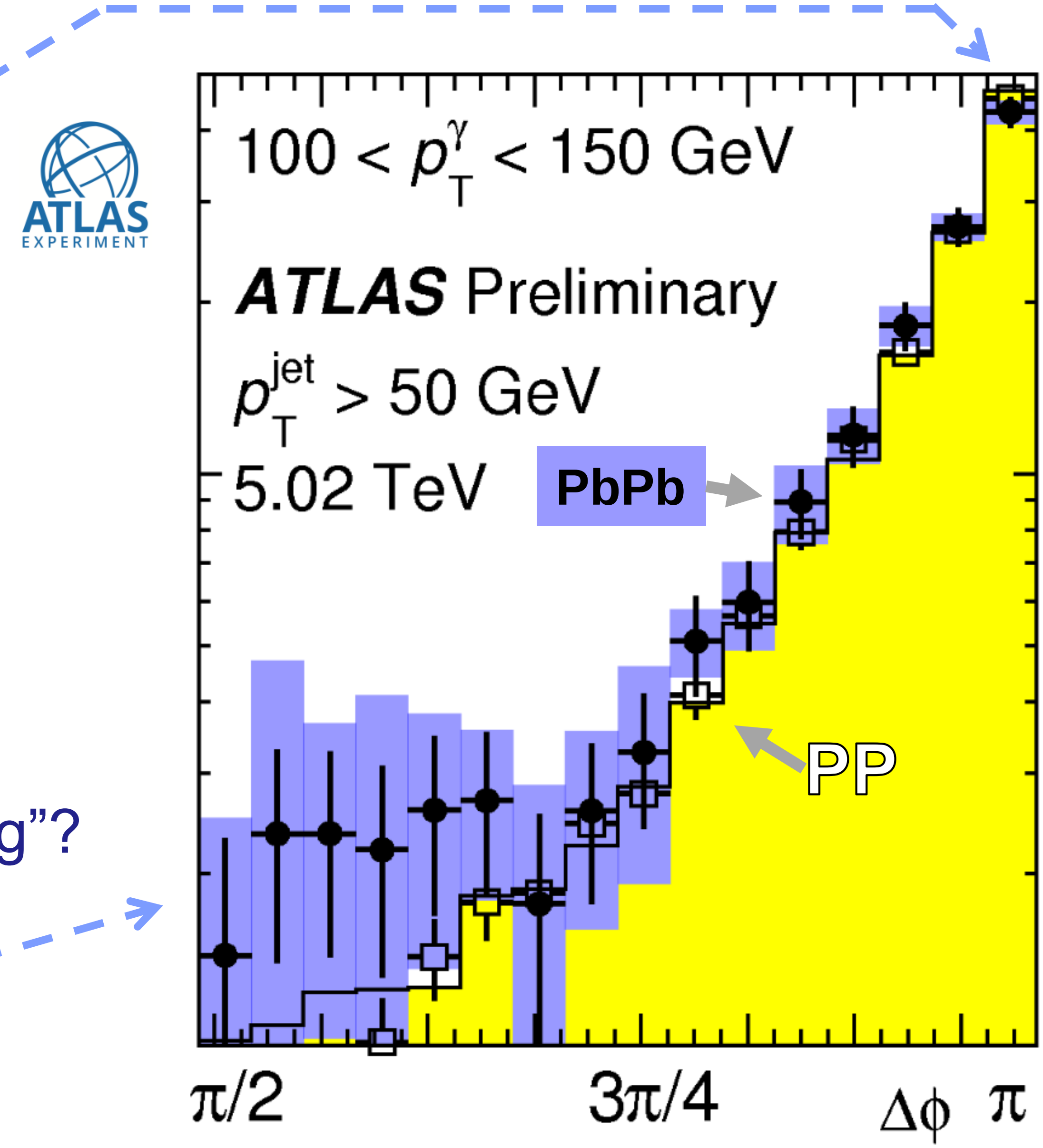
- Quenched energy carried by **low momentum particles!**
- Average momentum of those particles are **higher** than that from medium debris

→ Not Completely Thermalized?

Search for Quasi-Particles in the QGP

“QGP Rutherford experiment”



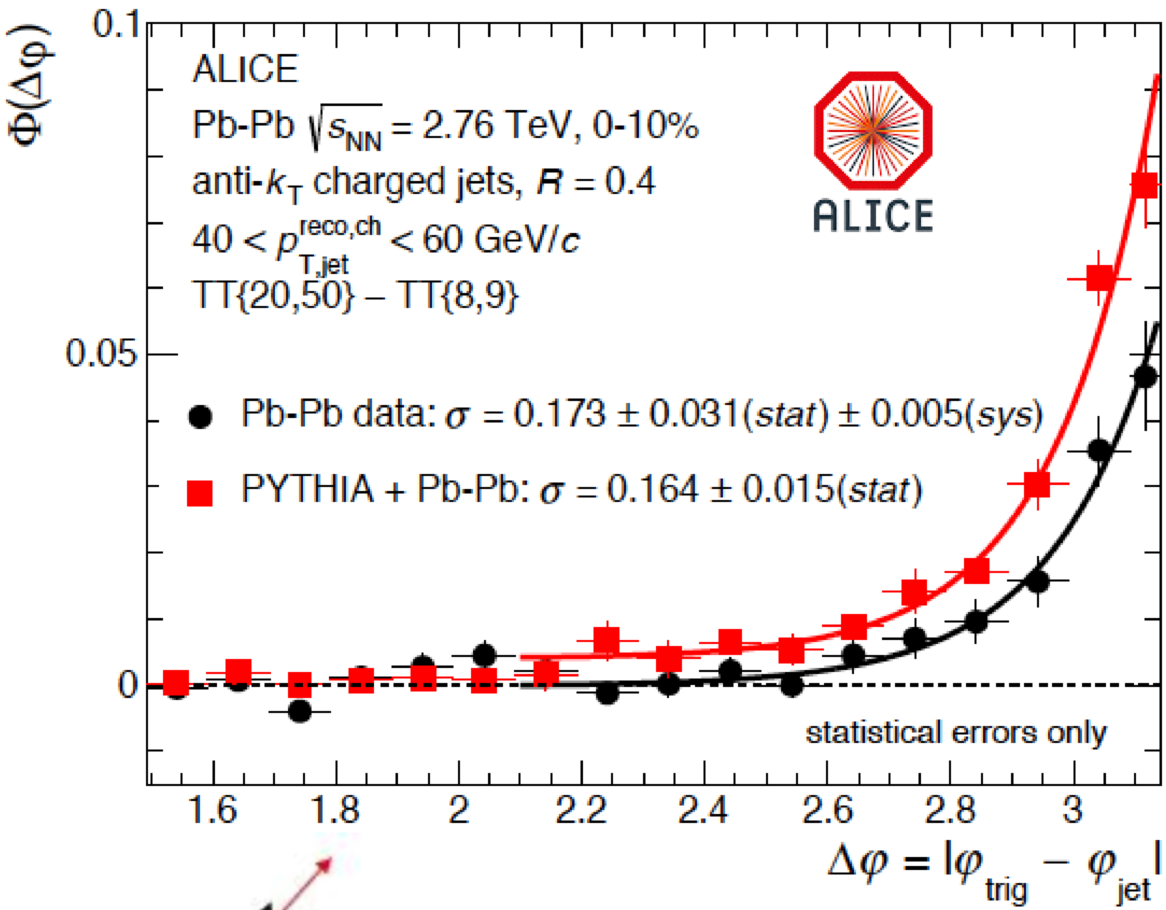


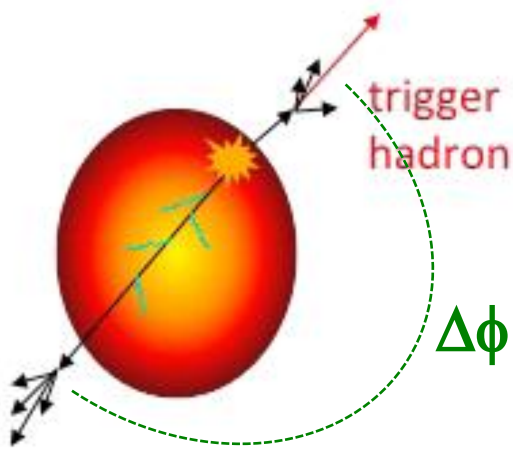
No significant modification

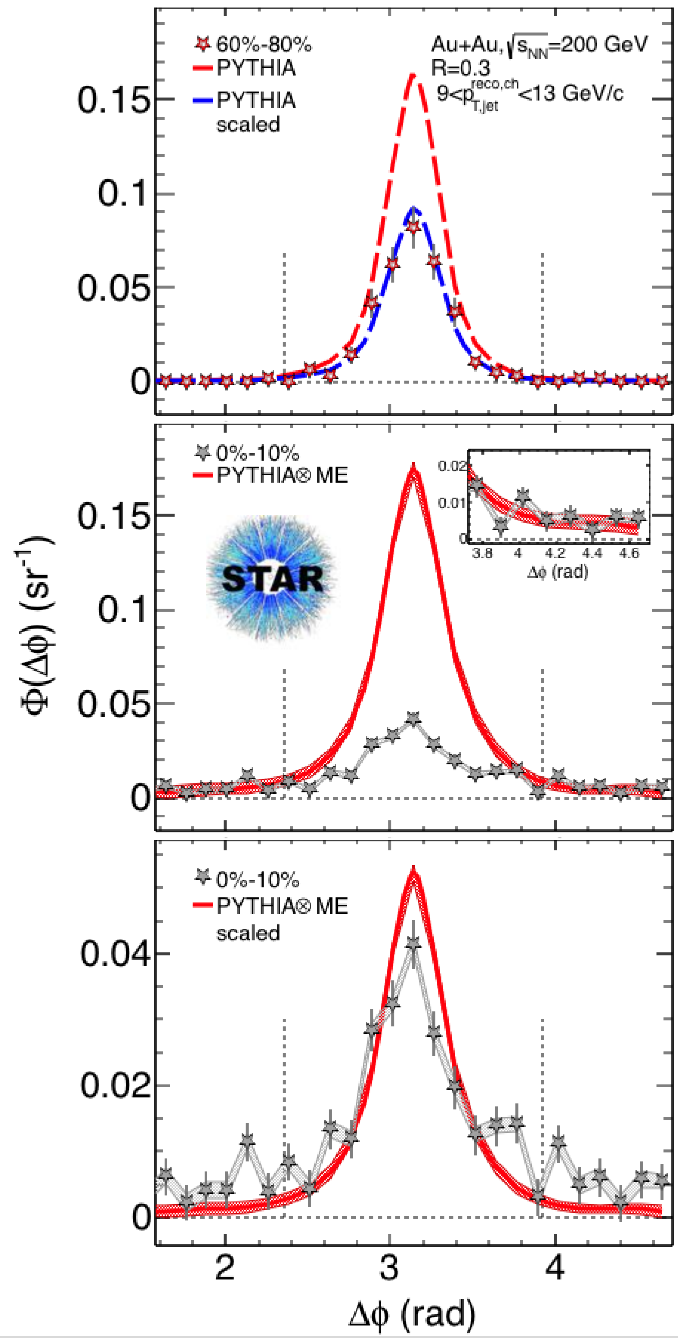
QGP probed looks smooth

ATLAS-CONF-2016-110

Hadron-Jet Angular Correlation



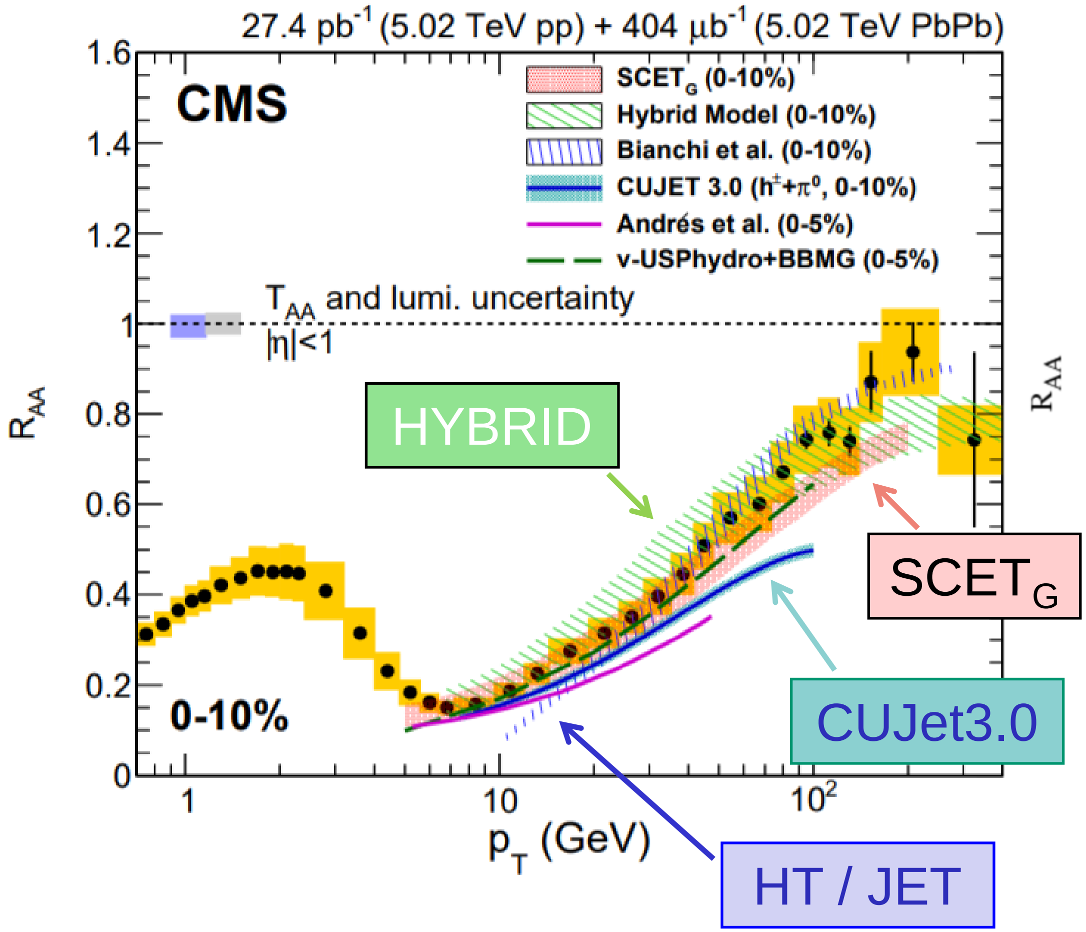


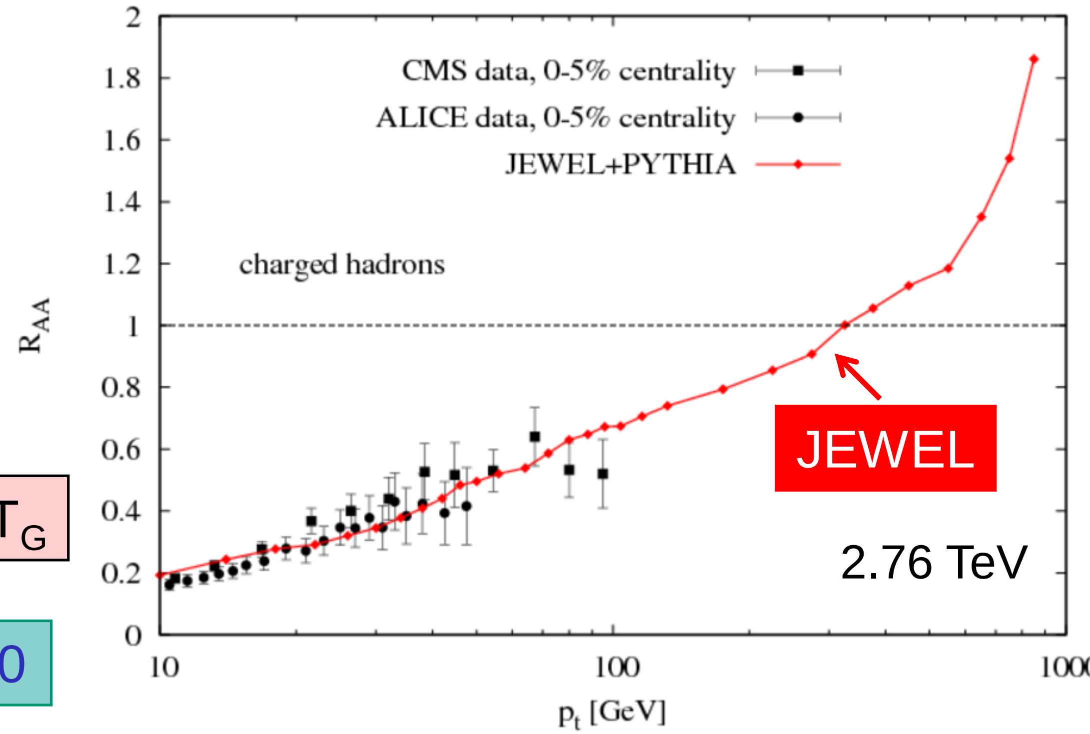


No significant broadening

QGP probed looks **smooth**

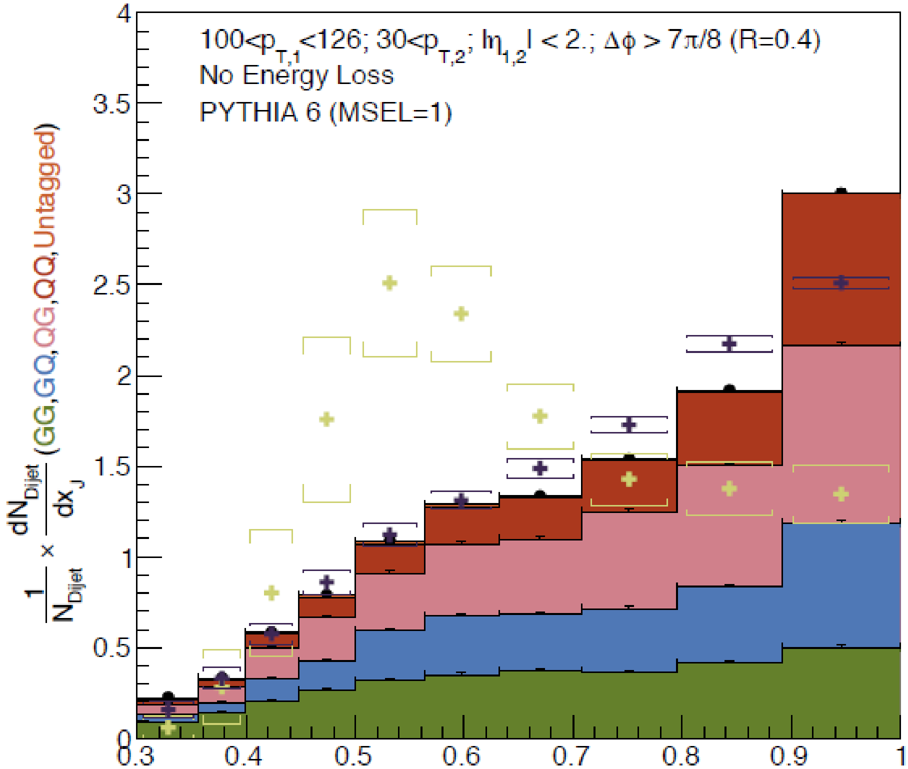
Charged Particle R_{AA} vs. Theoretical Models



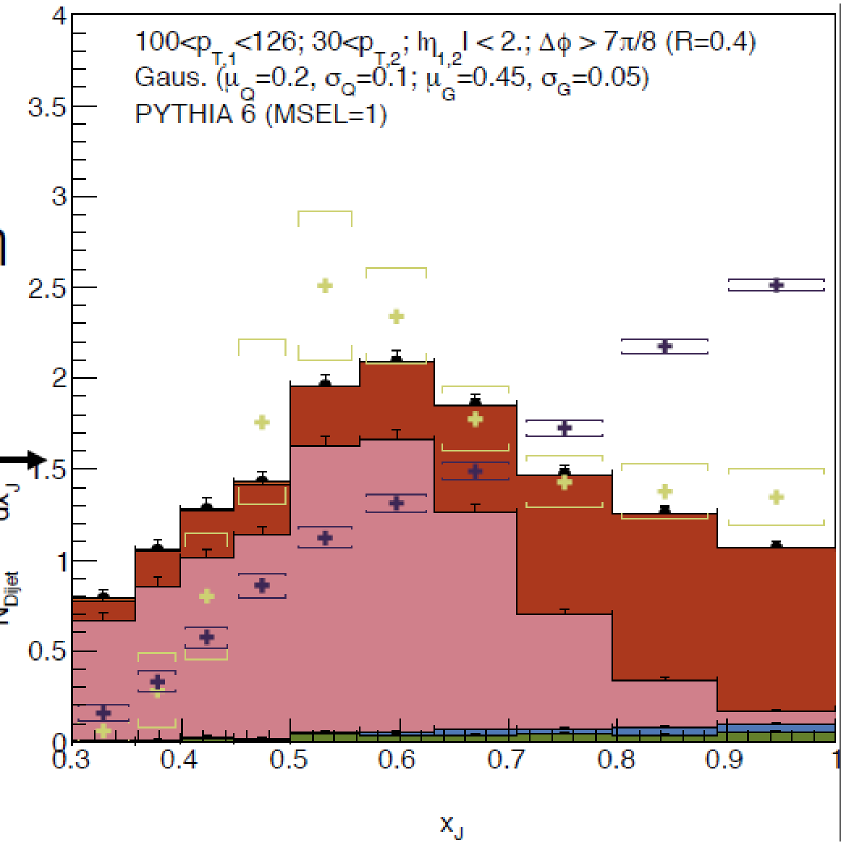


- High p_T: General trend described by both pQCD and Hybrid models
- Description of the R_{AA} over the whole p_T range is still challenging

Reproduce ATLAS X_J



Add Gaussian Energy Loss



From Chris McGinn