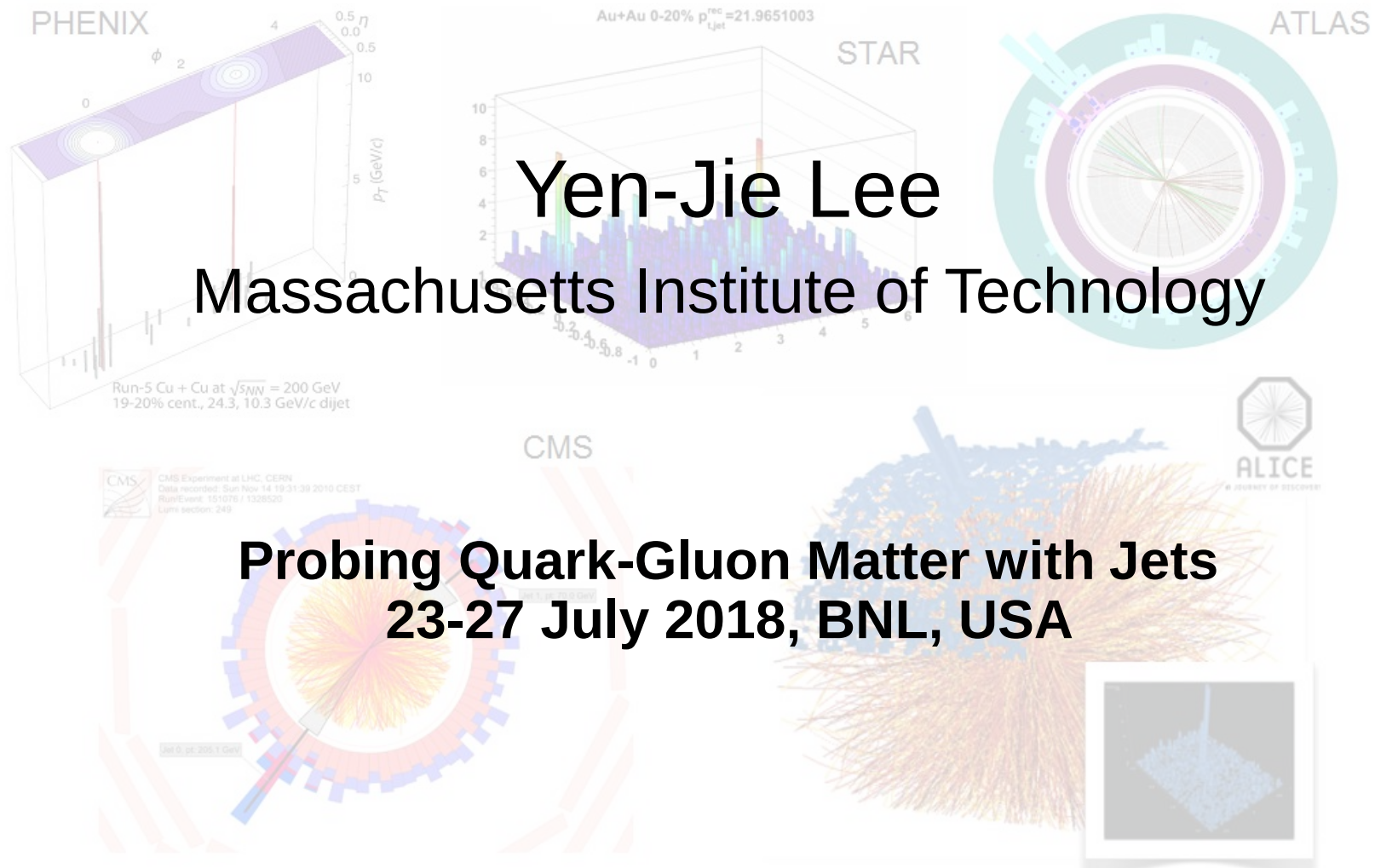


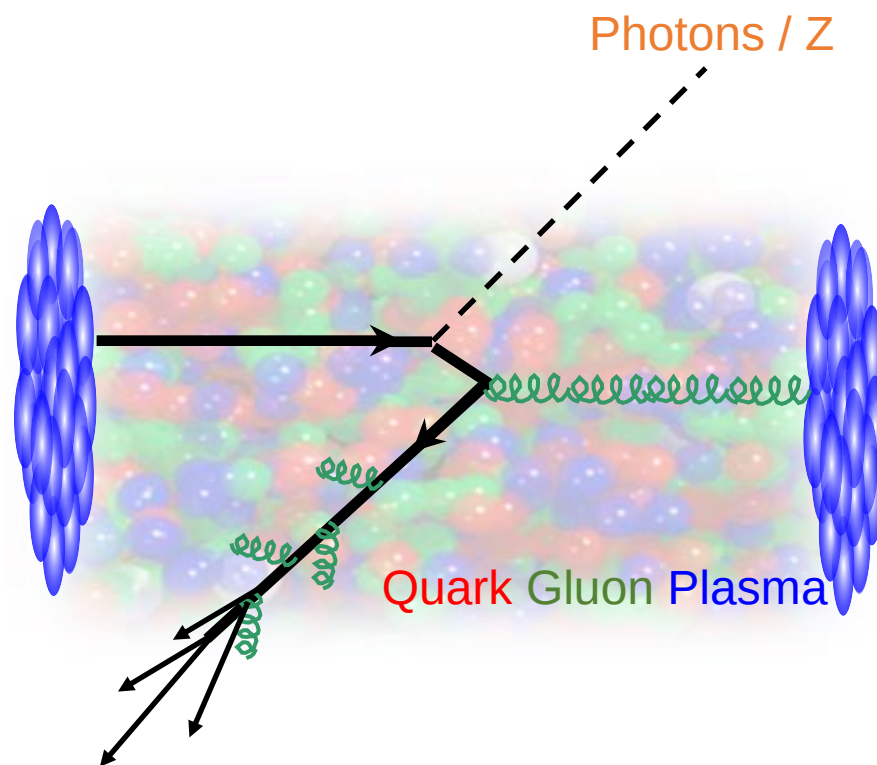
Recent Experimental Results on Jet Quenching



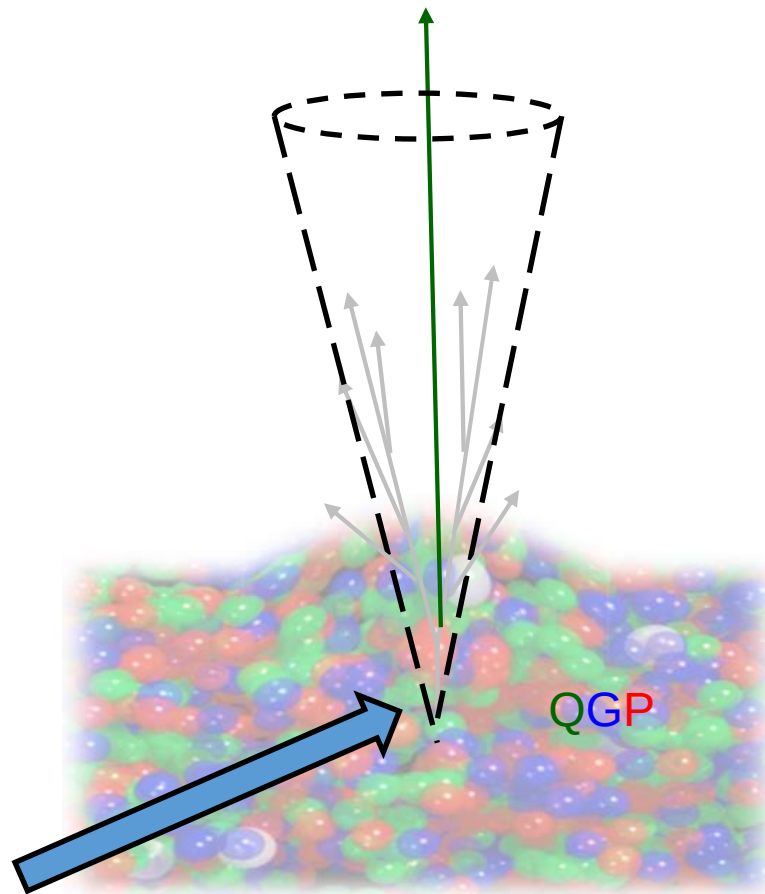
Outline

- Parton Flavor Dependence of Jet Quenching
- Azimuthal Angle Broadening due to QGP
- Medium Response
- Parton Shower Shape Dependence of Jet Quenching
- Jet Quenching in Small System and Peripheral Collisions

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



Heavy Flavor vs. Light Flavor

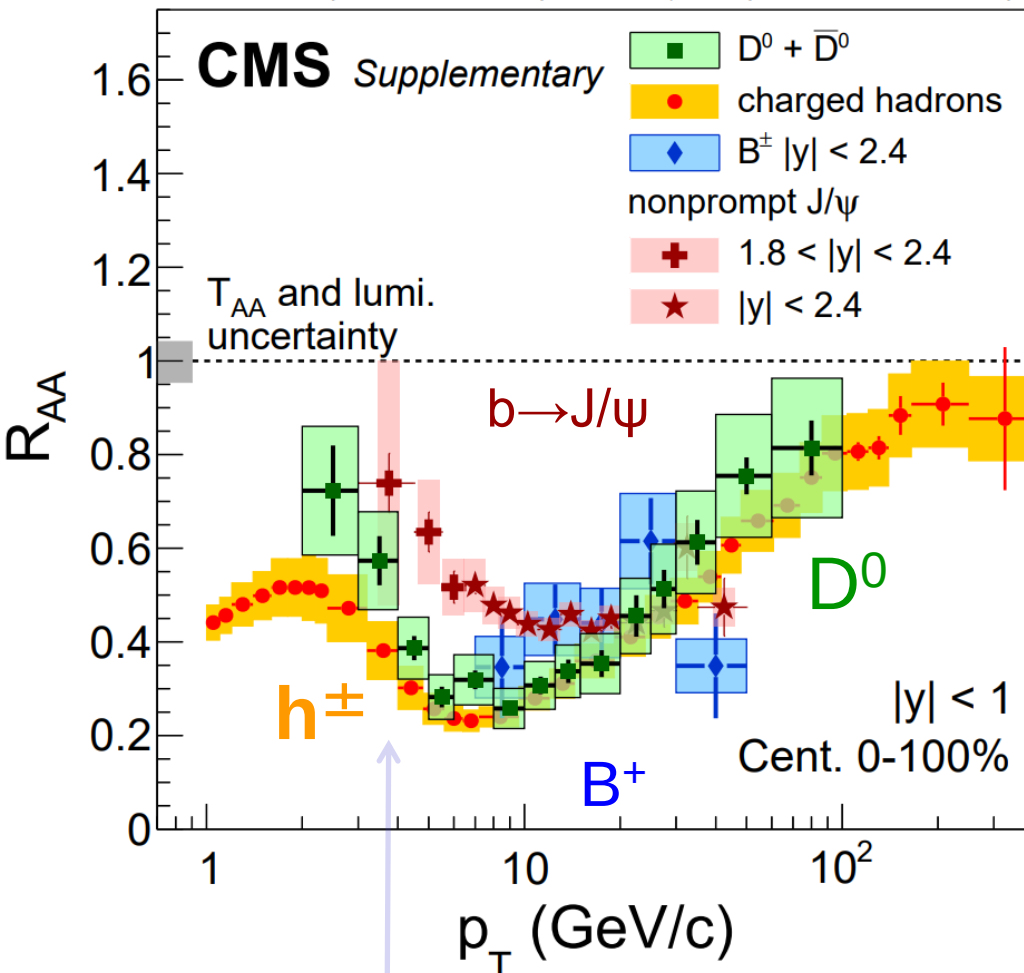


Do we have evidence that heavy quarks lose smaller amount of energy? How about Quarkonia?

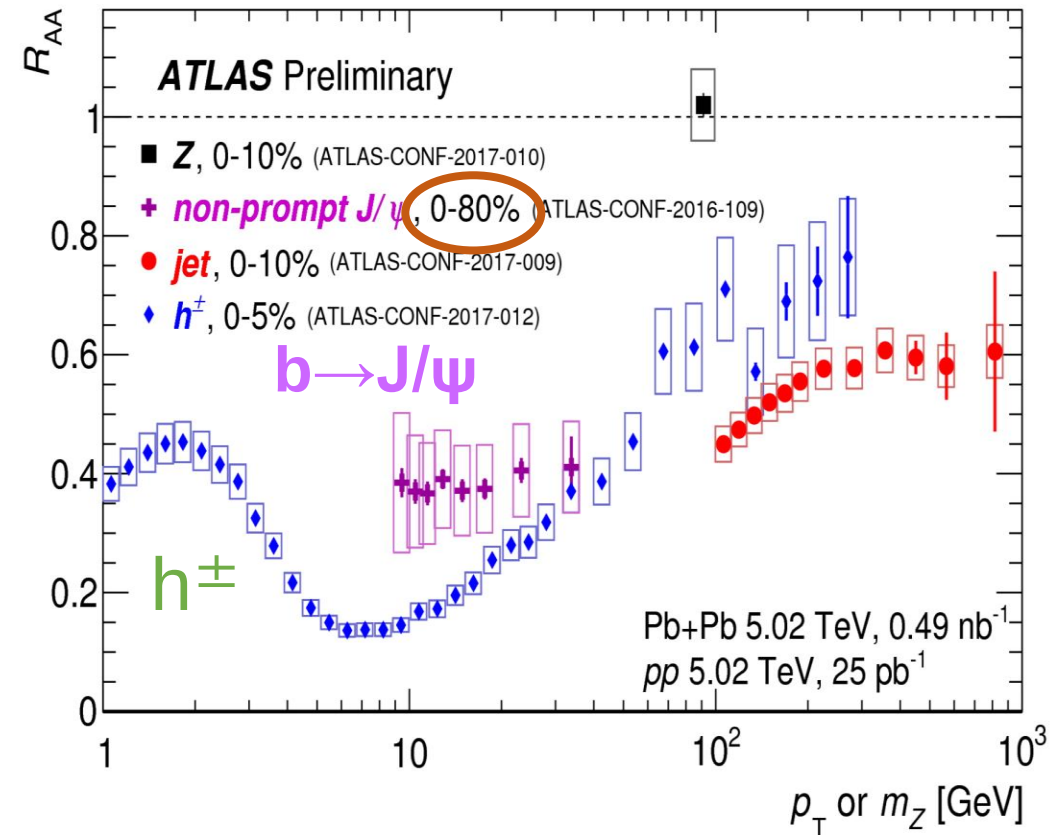
Flavor Dependence of Parton Energy Loss

PbPb 0-100%

27.4 pb⁻¹ (5.02 TeV pp) + 530 μb⁻¹ (5.02 TeV PbPb)

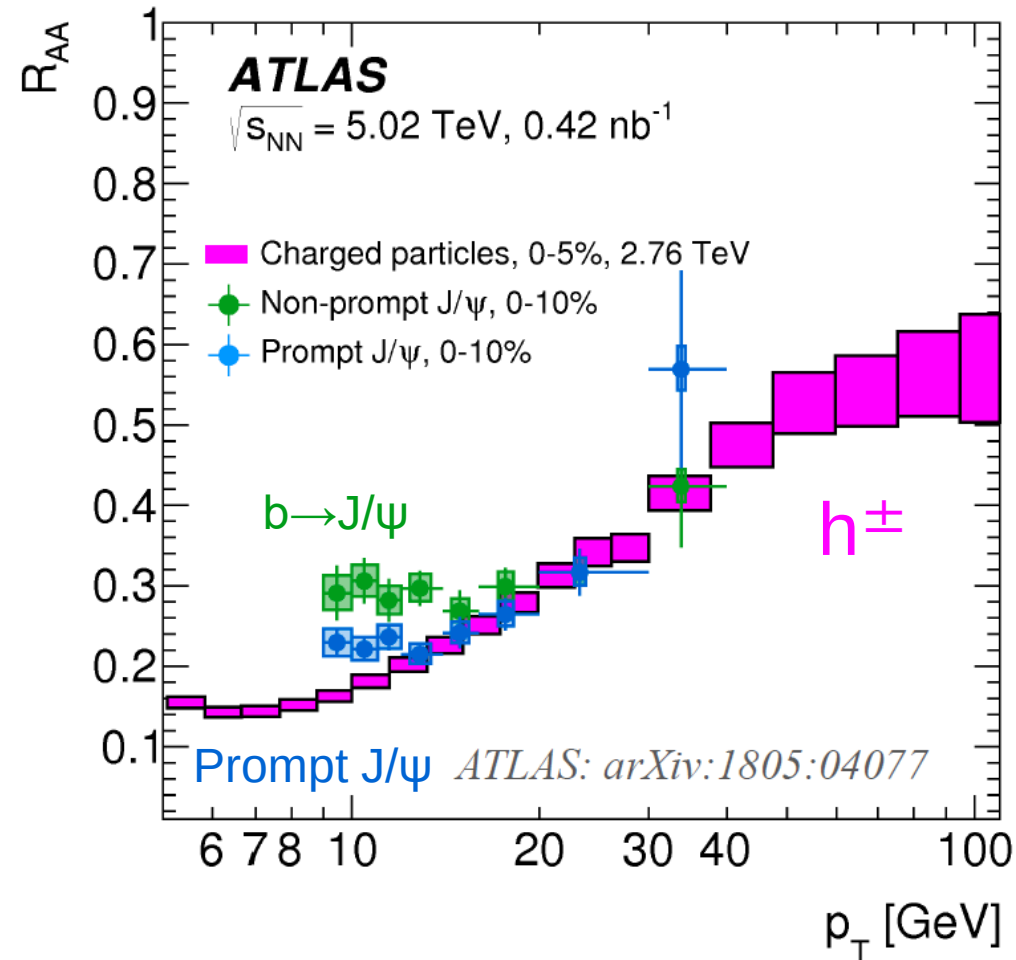
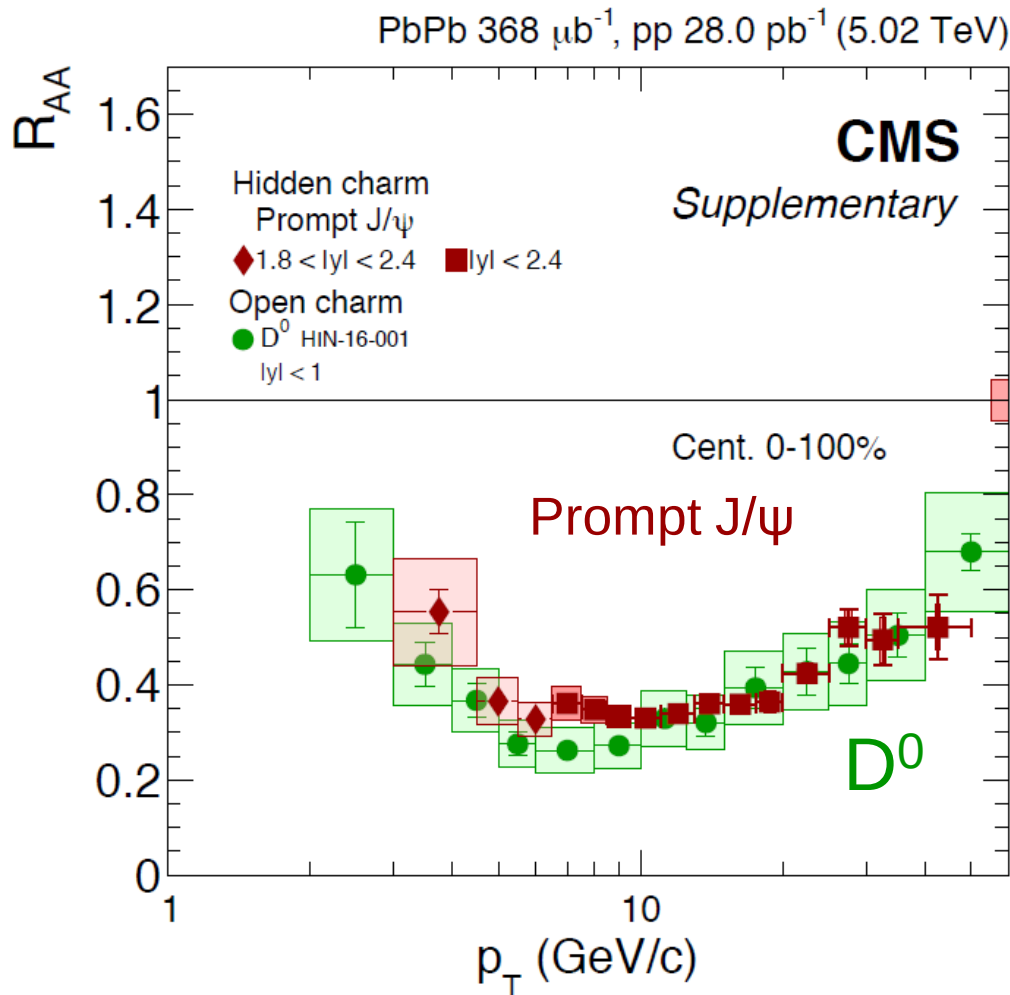


PbPb



- 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

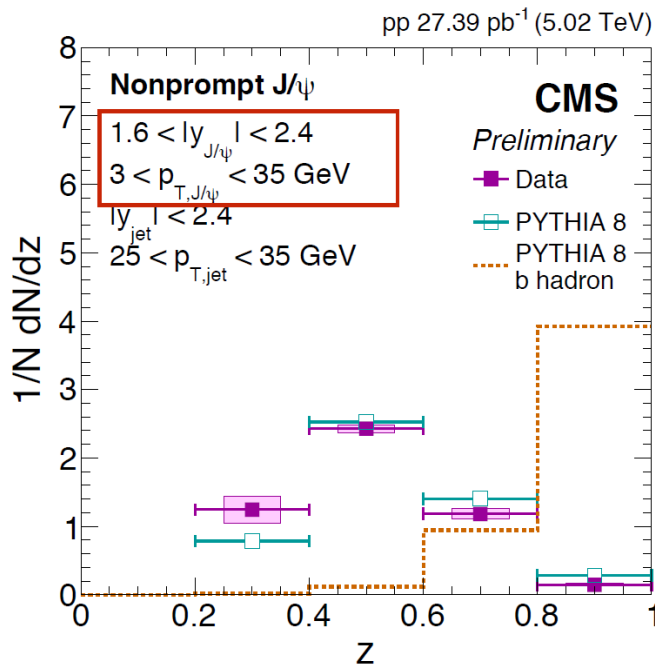
Open vs. Hidden Charm



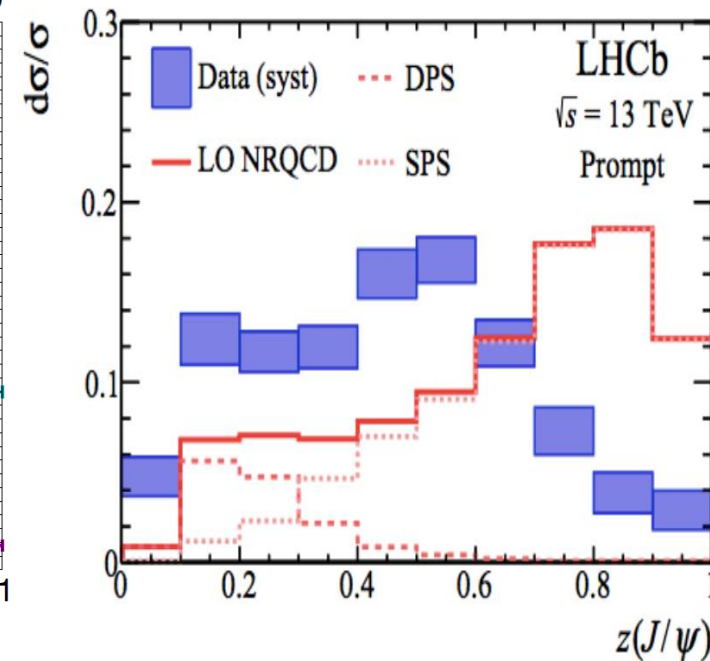
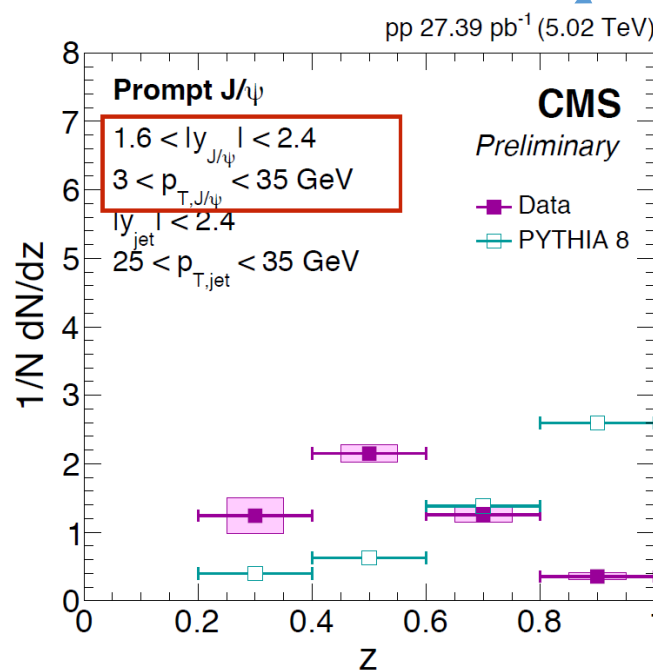
- Similar suppression between open and hidden charm at high p_T
 - $R_{AA} D^0 \sim R_{AA} \text{ Prompt J}/\psi \sim R_{AA} b \rightarrow J/\psi \sim R_{AA} \text{ Charged particles}$
- Why? Is the parton energy loss the dominant effect here?

(Non)Prompt J/ψ Fragmentation Function

$b \rightarrow J/\psi$

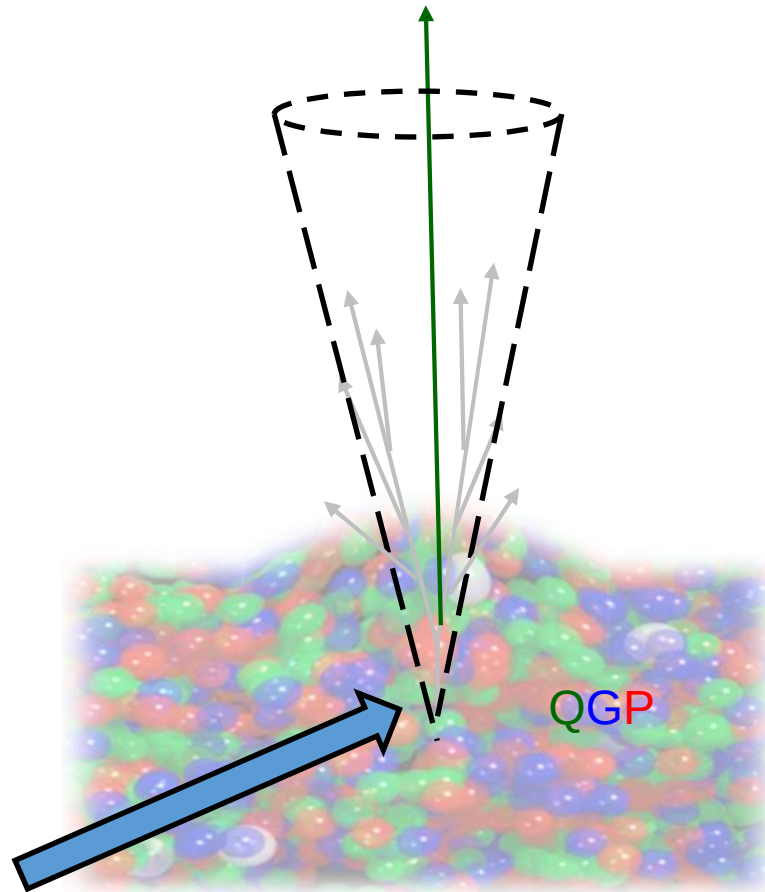


Prompt J/ψ



- PYTHIA8 doesn't describe prompt J/ψ production
- Prompt J/ψ FF data: similar to $b \rightarrow J/\psi$ from fragmentation process
 - Is this process important at low p_T?
 - Connection to the interpretation of prompt J/ψ suppression?

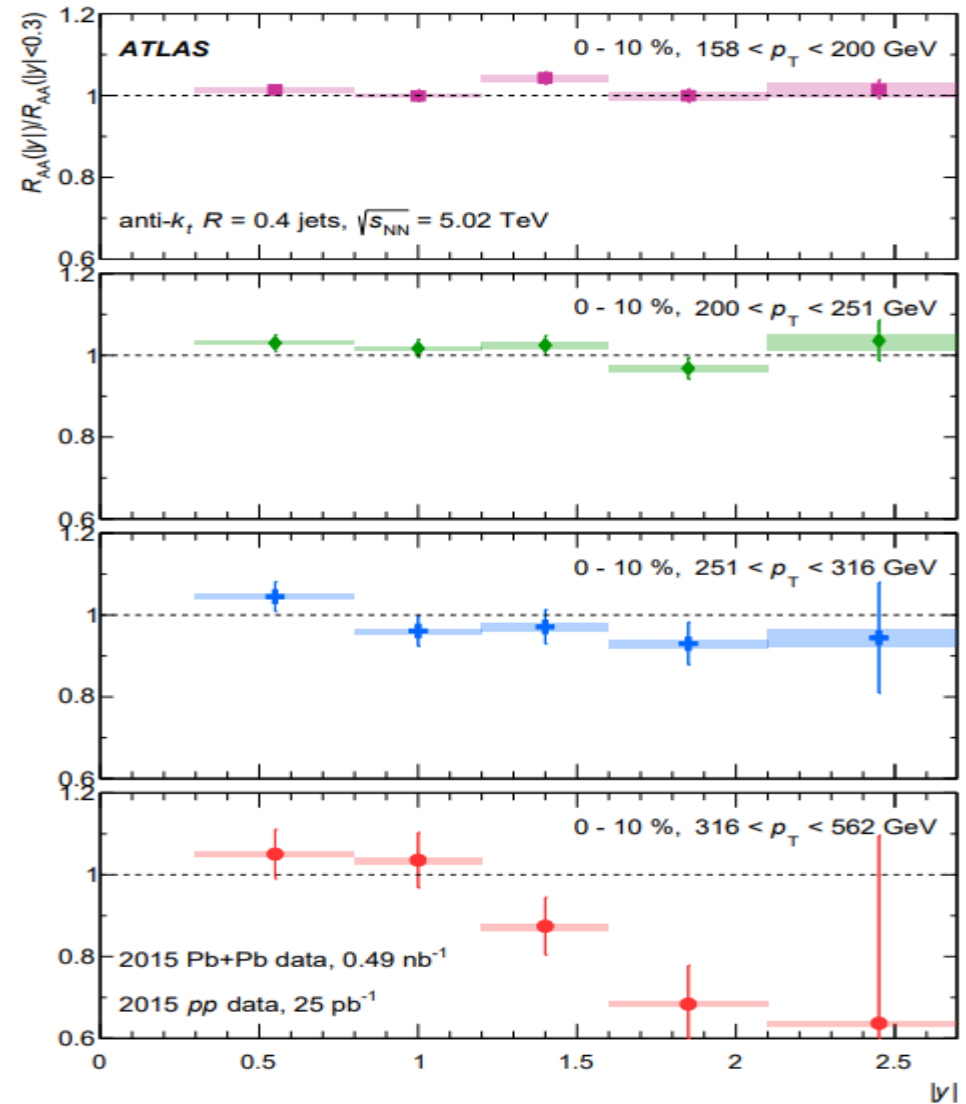
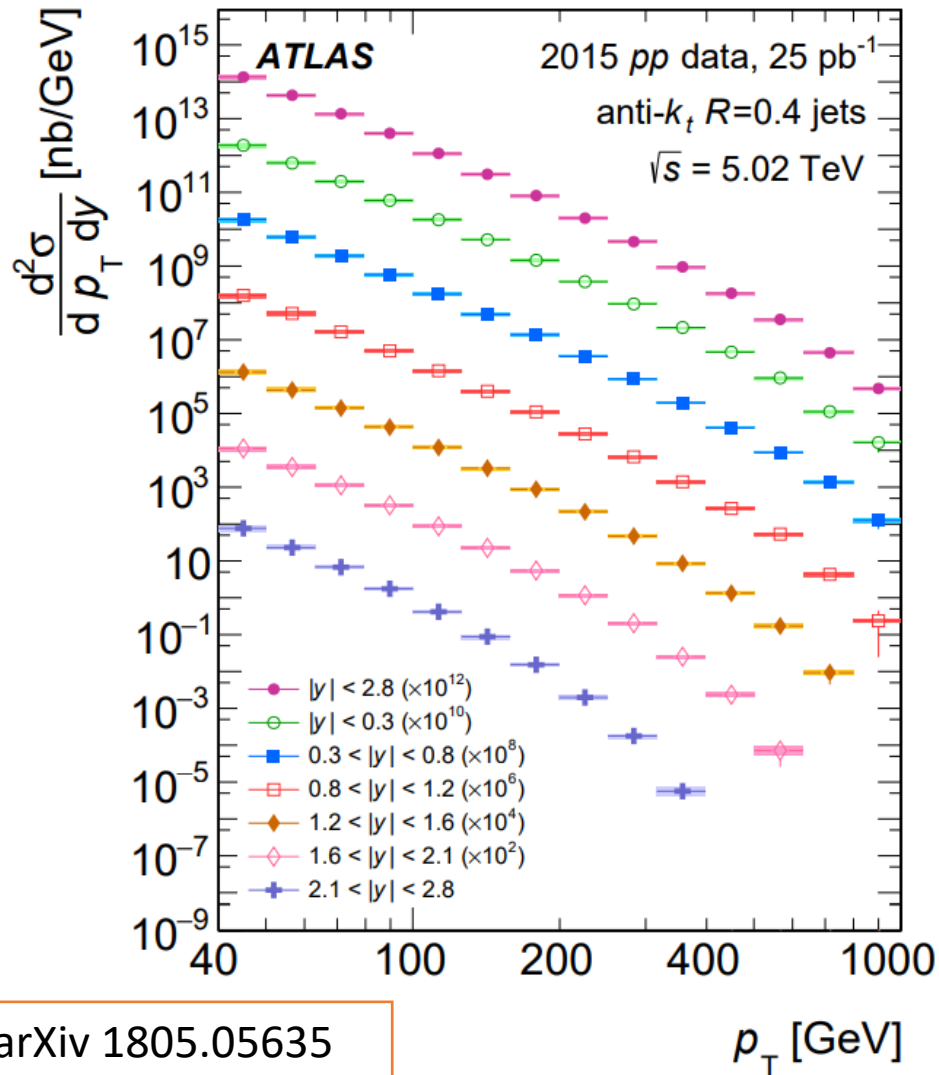
Quark vs. Gluon



Do gluons lose more energy than the quarks?

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

Jet R_{AA} vs. Rapidity



- Larger $|y|$: steeper p_T spectra slope and higher quark fraction
- Flat R_{AA} vs rapidity: **less jet suppression** at larger $|y|$, i.e., quarks lose less energy than gluons.

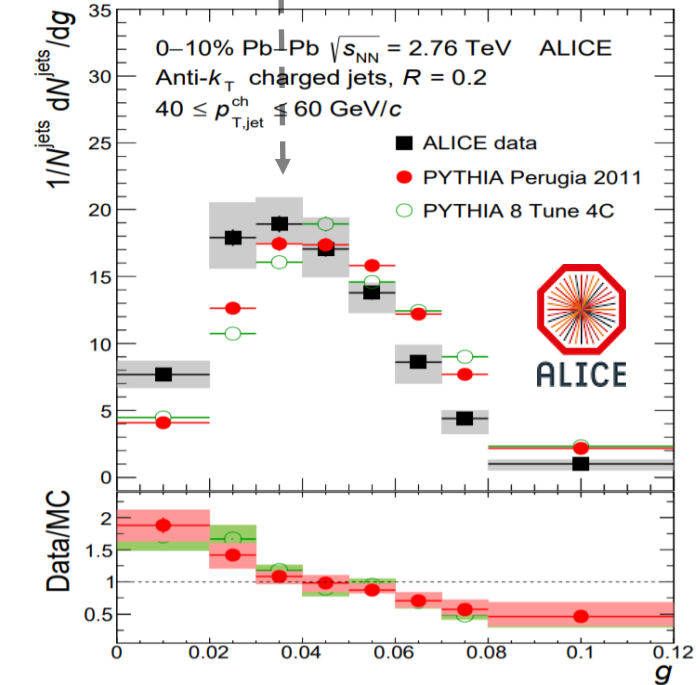
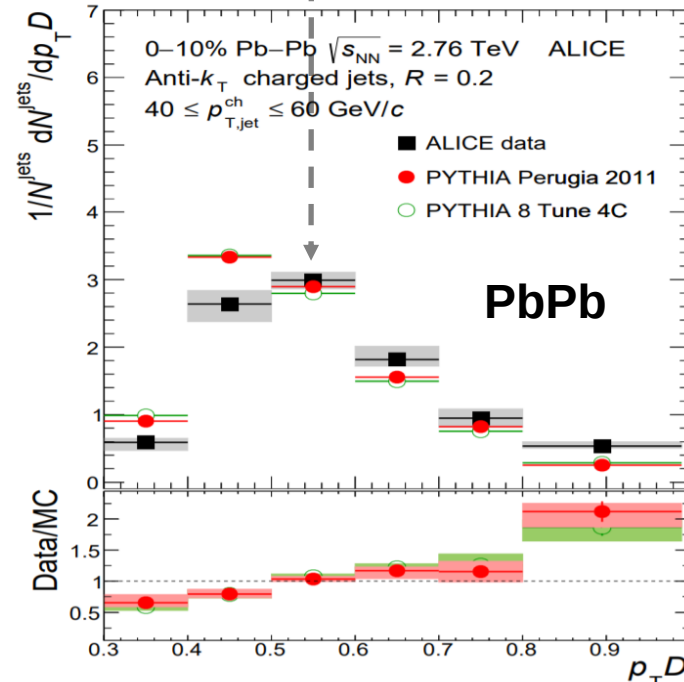
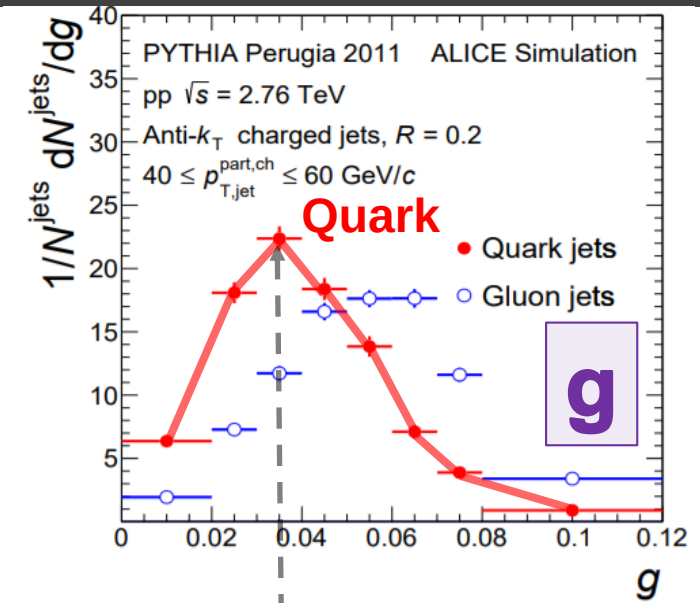
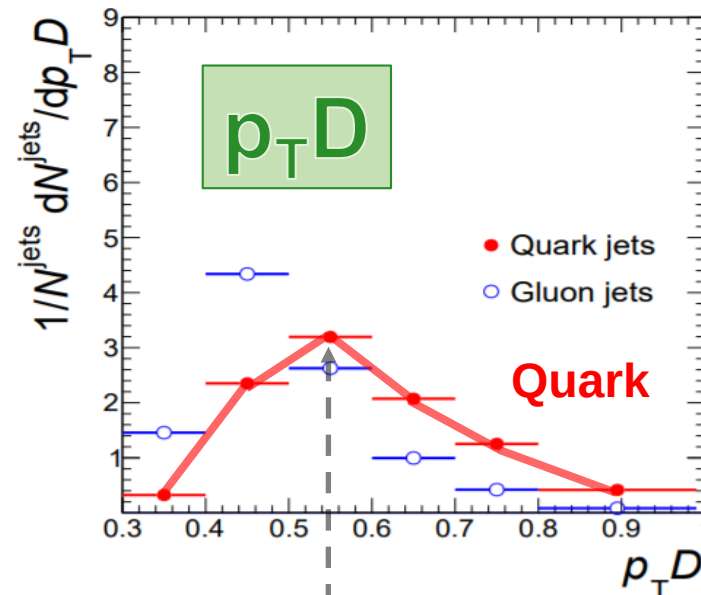
Charged Jet $p_T D$ (Dispersion) and Jet Girth

Anti- k_T $R=0.2$
 $40 < p_{T,jet} < 60$ GeV

arXiv:1807.06854

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

$$g = \sum_{i \in \text{jet}} \frac{p_{T,i}}{p_{T,jet}} |r_i|$$

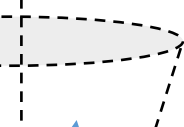


- Charged jets in PbPb are more **Quark-like!** (**Gluon jets** suppressed)

Jet Longitudinal Structure

Jet axis

Δr



Projection to jet axis

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

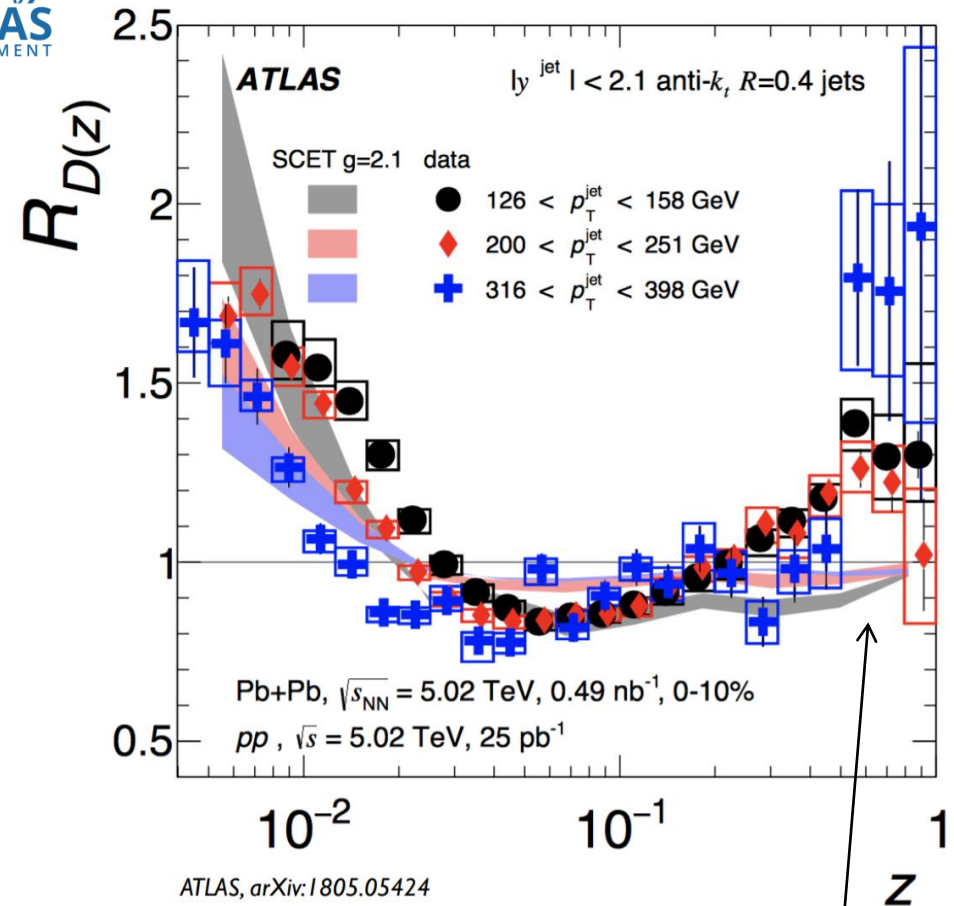
QGP

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



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

ATLAS-CONF-2017-005



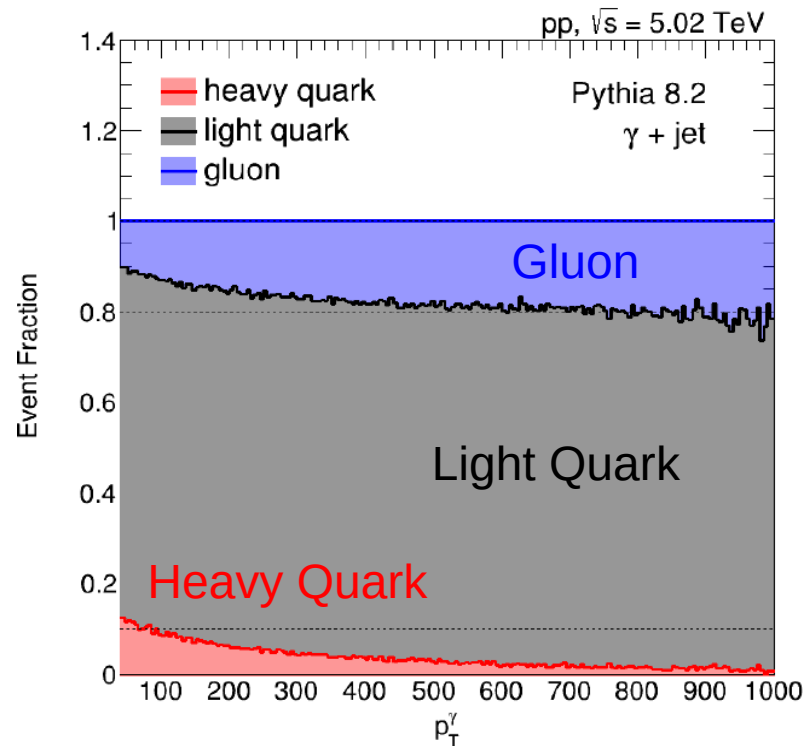
- Fragmentation functions Ratio $R_{D(z)}$ between PbPb and pp collisions at 5 TeV
- Enhancement at large z (high p_T particles in jet): **smaller gluon/quark ratio** in PbPb
- Weak or no dependence on the jet p_T

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

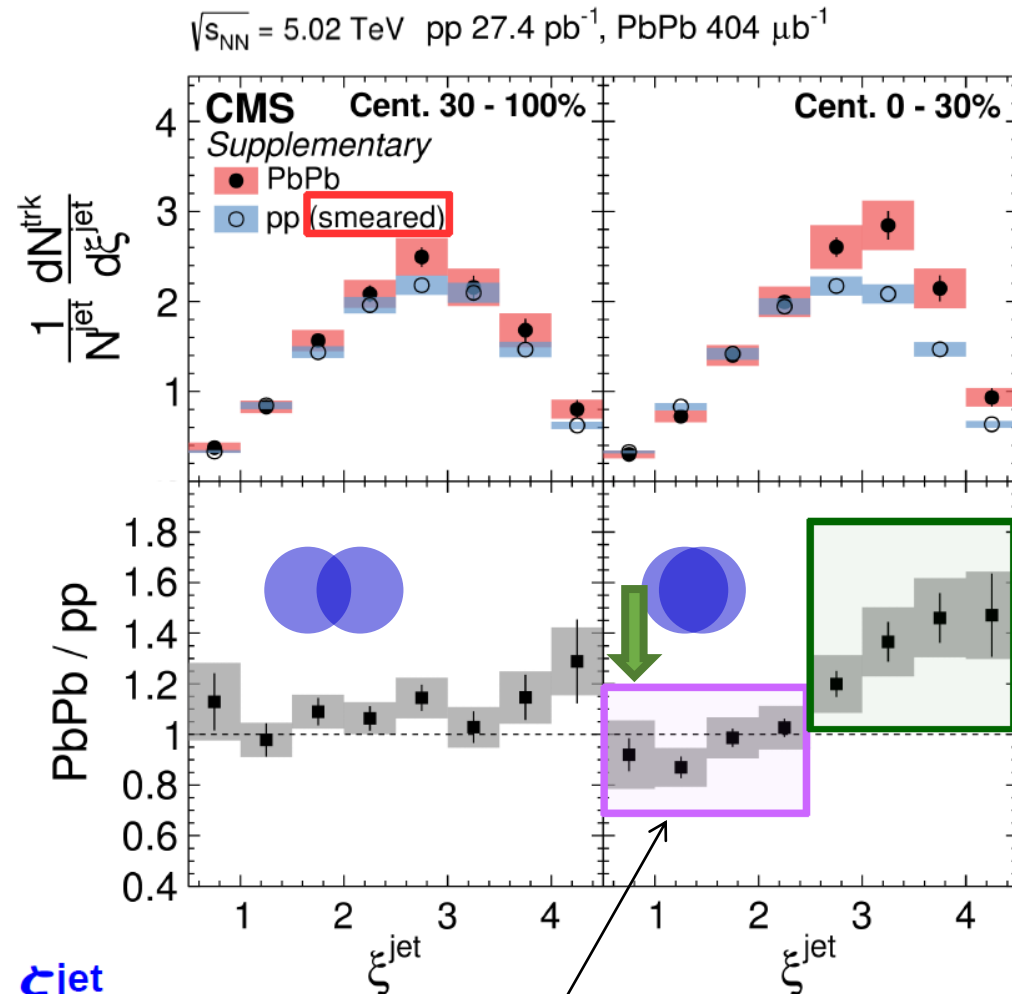
→ If switch to γ -tagged jet (mainly quarks), will this enhancement go away?

Photon-Tagged Fragmentation Function

From Kaya Tatar (MIT)

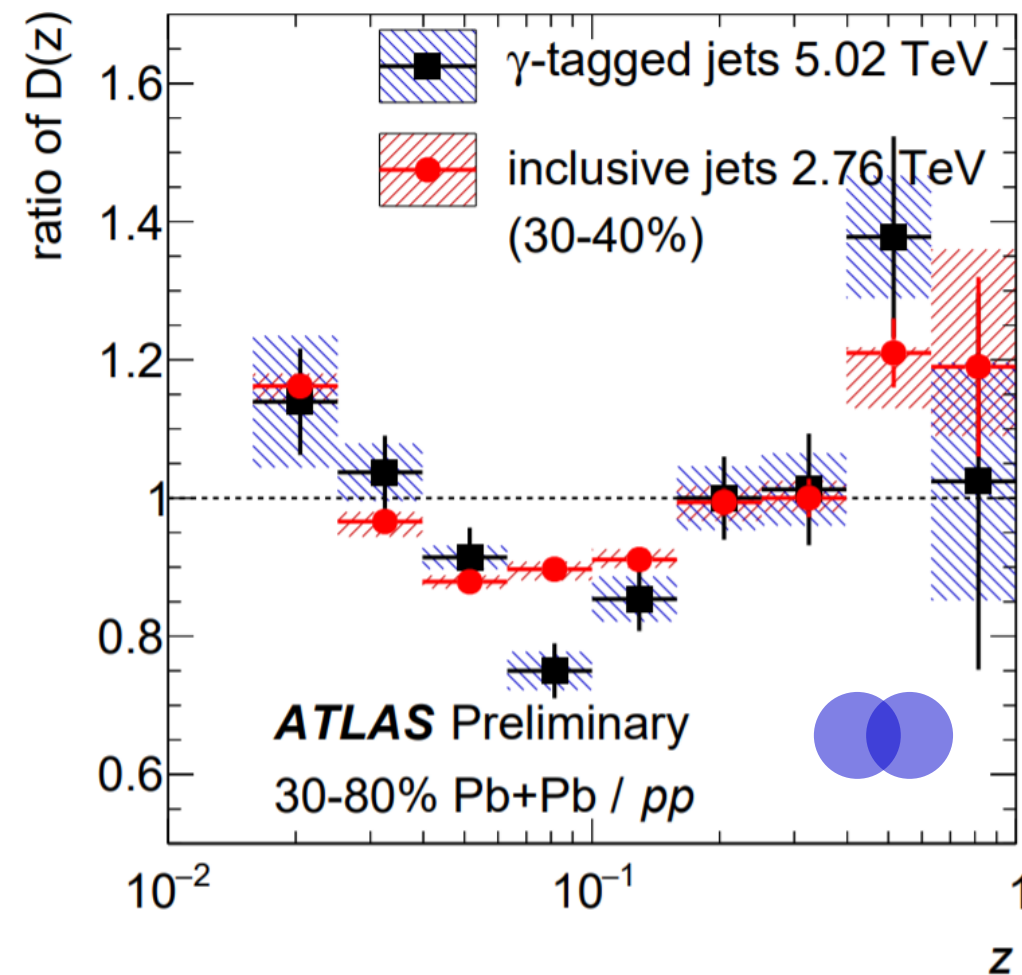


- Decrease the population of **gluon jets**:
>70% of the tagged jets are quark jets
- Observation of modified jet fragmentation function in **PbPb** with respect to **pp**
 - No significant high z (or small $\xi = \ln(1/z)$) enhancement observed
 - CMS only measured down to $\xi \geq 0.5$ (or $z \leq 0.7$)
 - It would be good to have high p_T associated jet version of this analysis

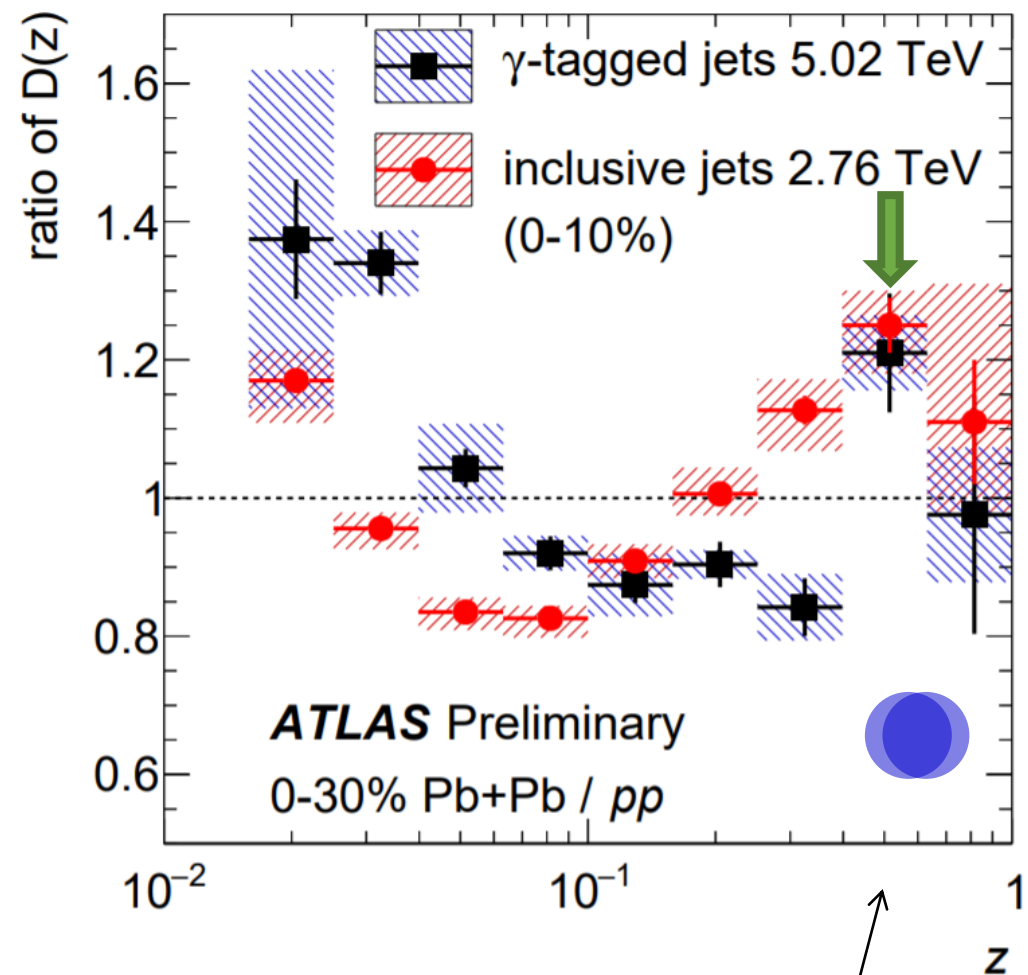


Photon-Tagged Fragmentation Function

ATLAS: Select on jet $p_T > \frac{1}{2}$ Photon p_T



photon p_T : 79.6-125 GeV
jet p_T : 63.1-144 GeV



- 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?**

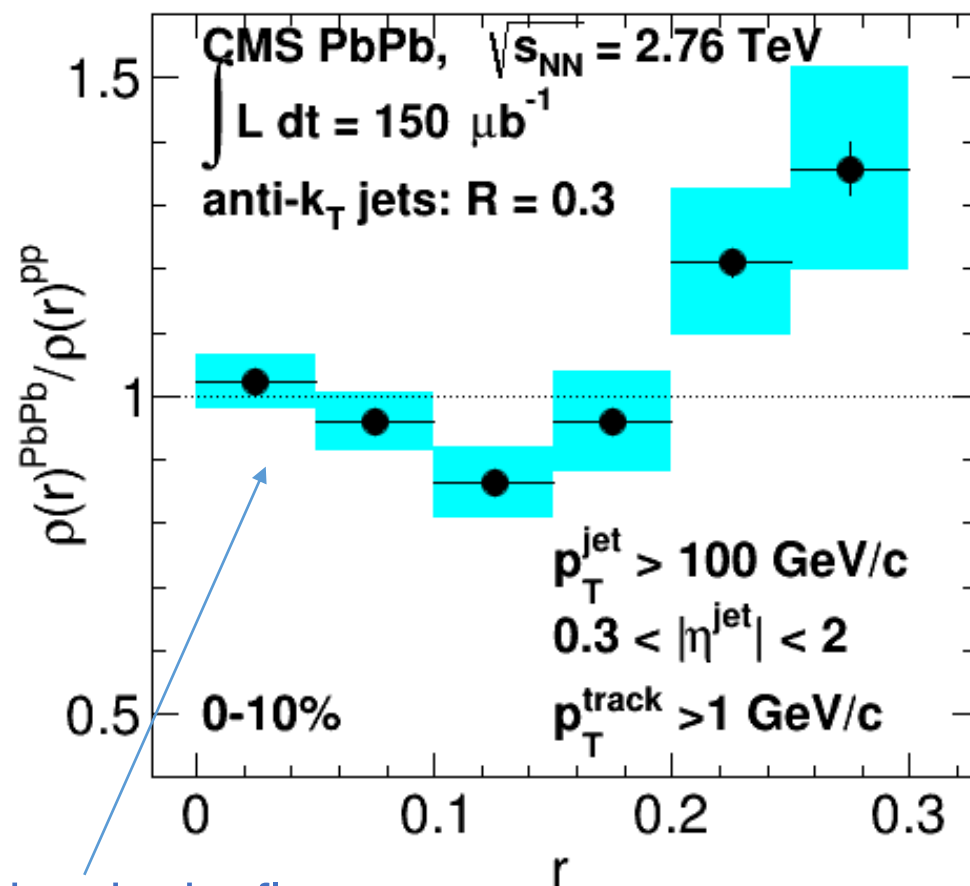
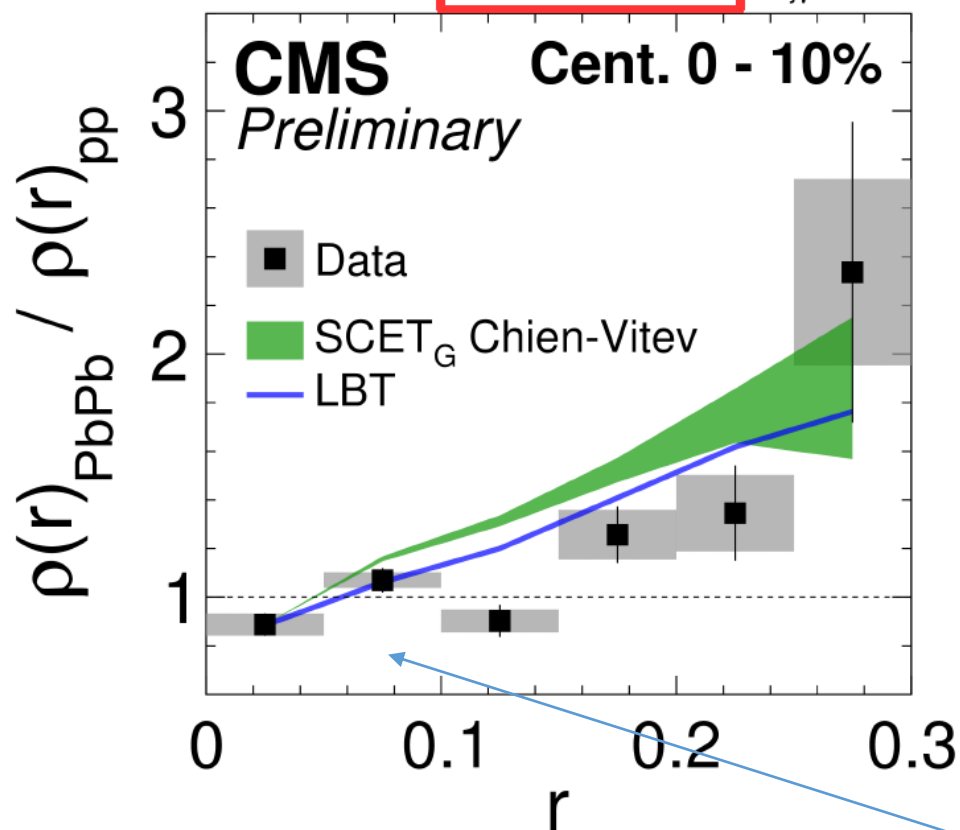
Inclusive Jet Shape

Photon-tagged Jet shape **PbPb / pp**

Inclusive Jet shape **PbPb / pp**



$\sqrt{s_{NN}} = 5.02 \text{ TeV}$ $p_T^\gamma > 60 \text{ GeV/c}$
 PbPb $404 \mu\text{b}^{-1}$ anti- k_T jet $R = 0.3$
 pp 27.4 pb^{-1} $p_T^{\text{jet}} > 30 \text{ GeV/c}, \Delta\phi_{j\gamma} > \frac{7\pi}{8}$



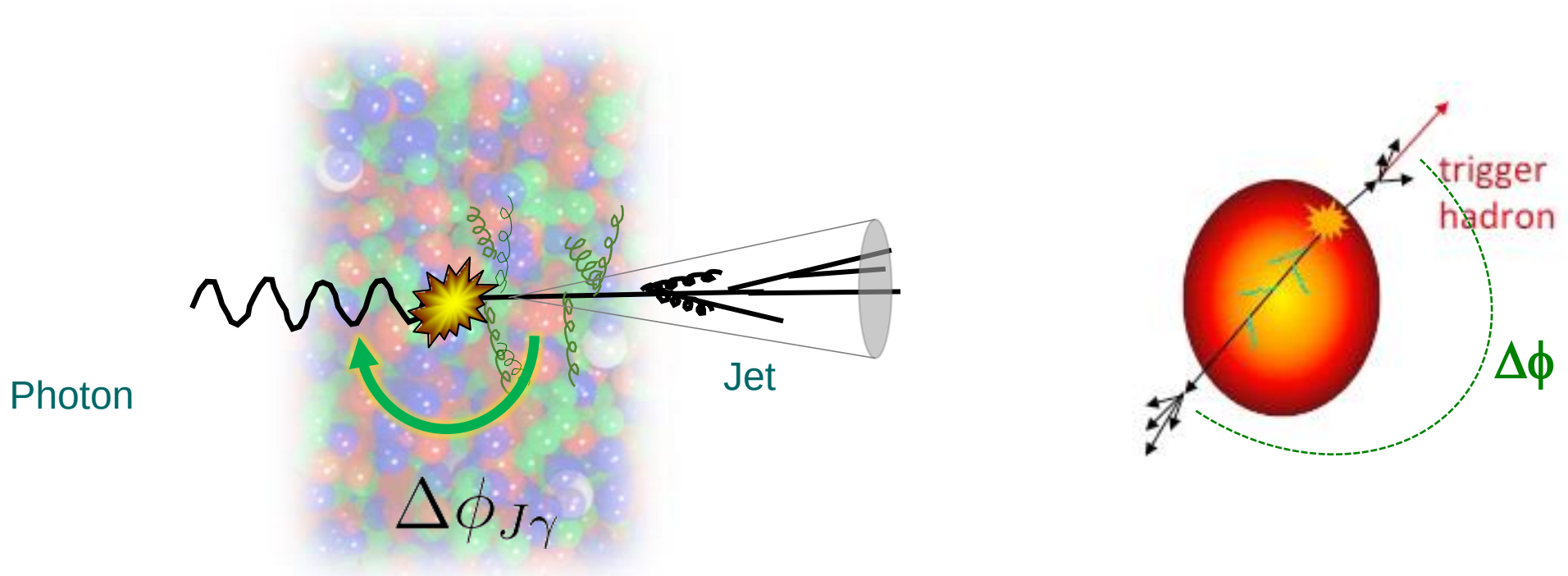
$$\rho(\Delta r) = \frac{1}{\delta r} \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{\sum_{\text{tracks} \in (r_a, r_b)} p_T^{\text{trk}}}{\sum_{\text{tracks}} p_T^{\text{trk}}}$$

- Varying the jet flavor
- Due to the lower jet p_T in photon-tagged jet and changed quark vs. gluon ratio
- Would be nice to measure high p_T tagged jet

Flavor Dependence of Parton Energy Loss

- Heavy quarks lose less energy than the light flavor:
 - Established in LHC data though model comparisons
- Quark vs. gluon energy loss:
 - Collected hints from various jet substructure observables, ATLAS jet and charged particle R_{AA} measurements vs. η
 - Indication of Gluon $E_{\text{loss}} > \text{Quark } E_{\text{loss}}$
- Quarkonia production and suppression similar to open charm:
 - Eloss + Fragmentation process

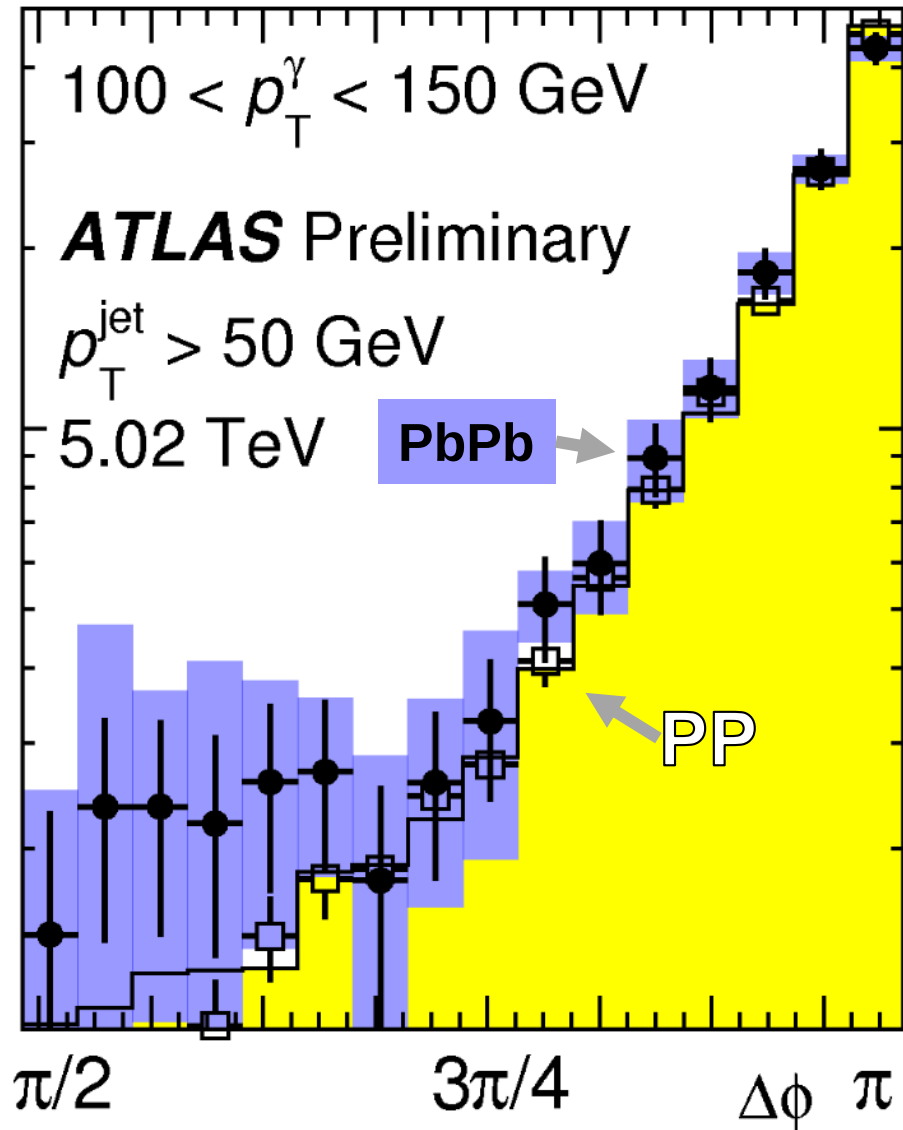
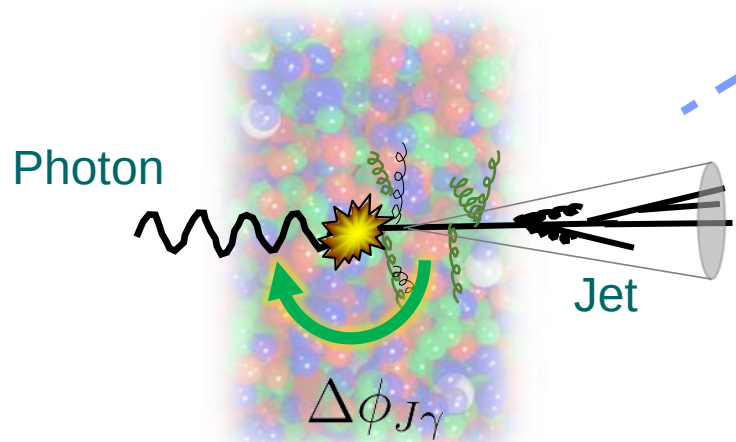
Photon-Jet and h-Jet Azimuthal Angle



Search for the $\Delta\phi$ broadening

Search for Quasi-Particles in the QGP

“QGP Rutherford experiment”

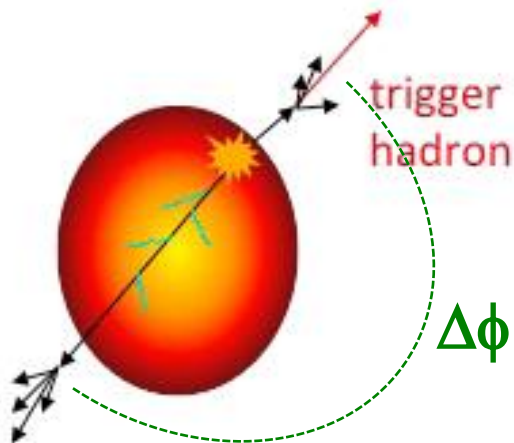
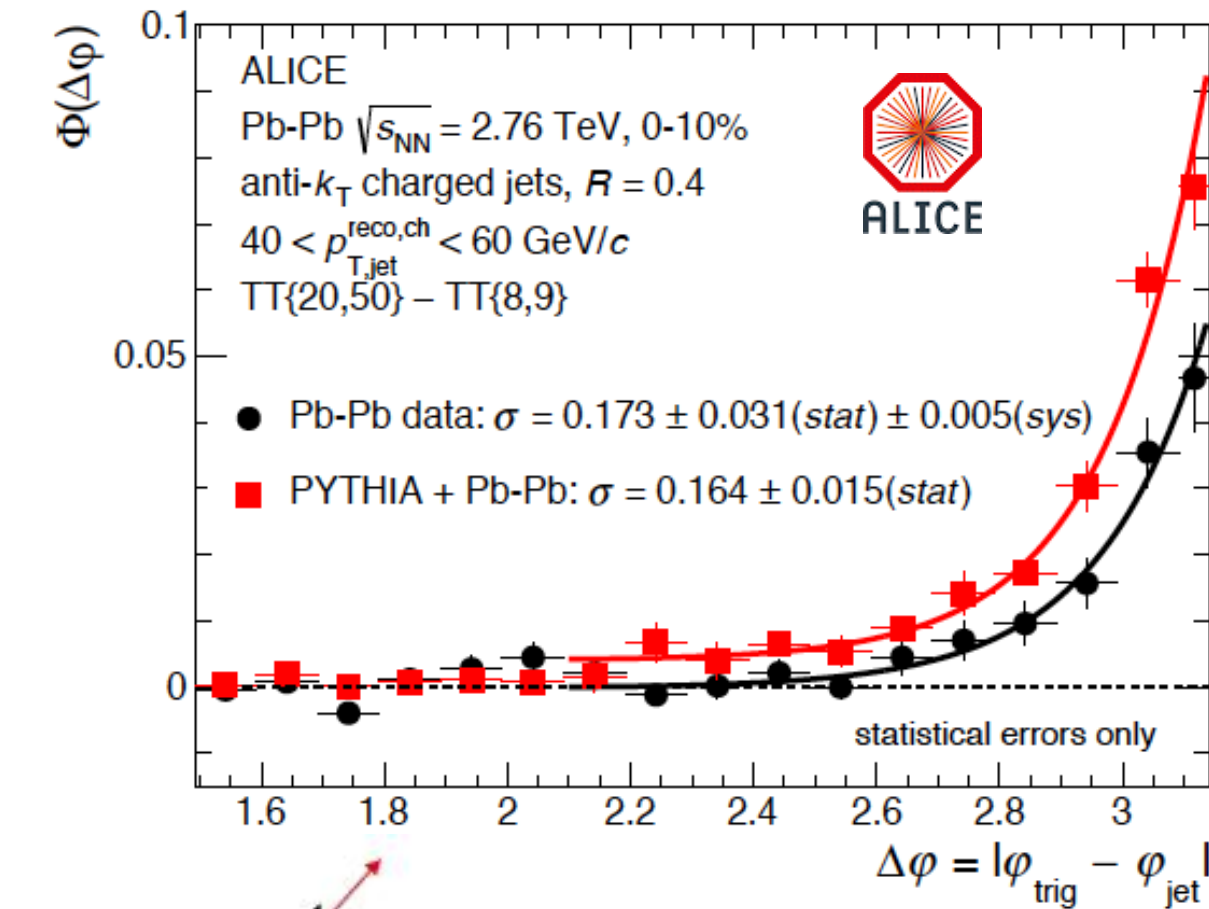


“Backscattering”?

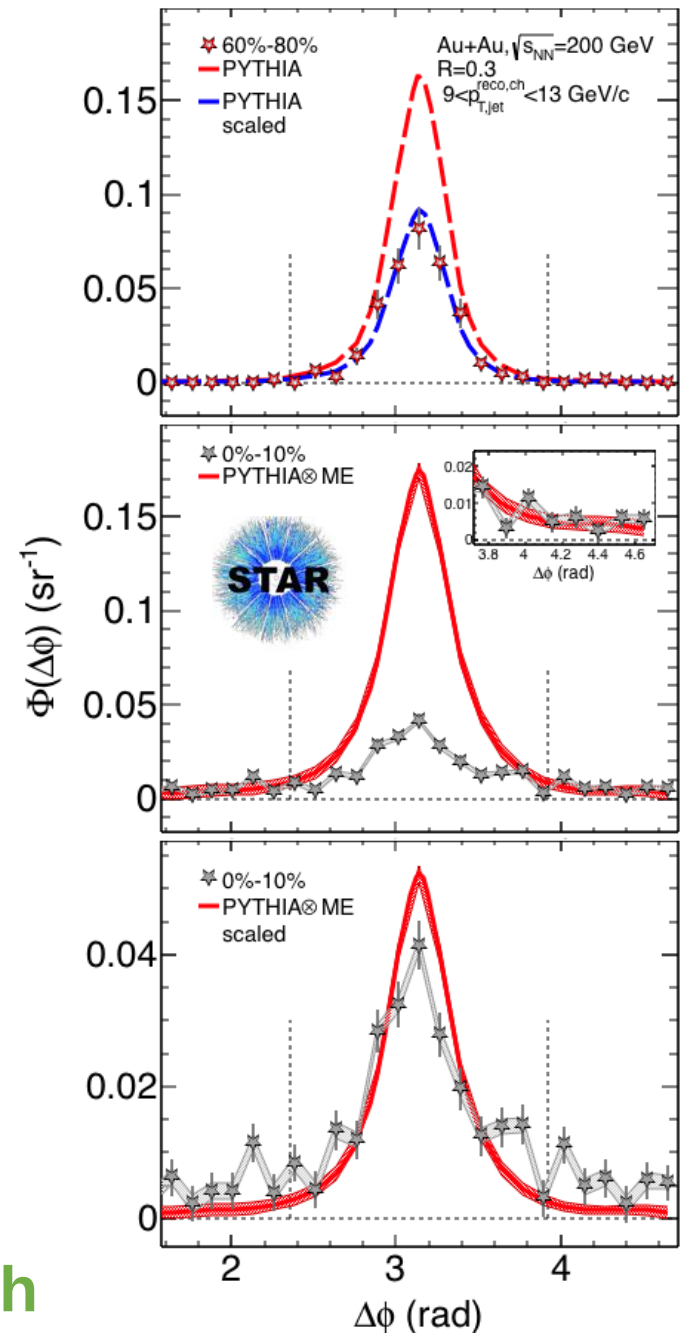
The Quark Soup probed is very smooth!

ATLAS-CONF-2016-110

Hadron-Jet Angular Correlation



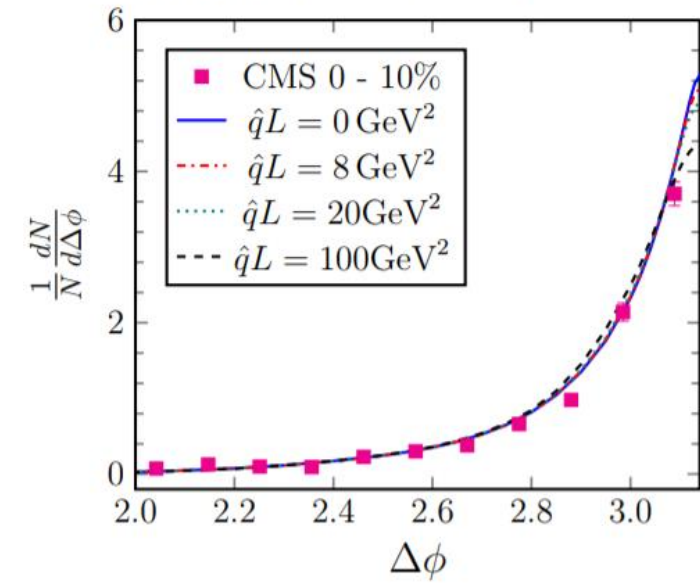
No significant broadening
QGP probed looks **smooth**



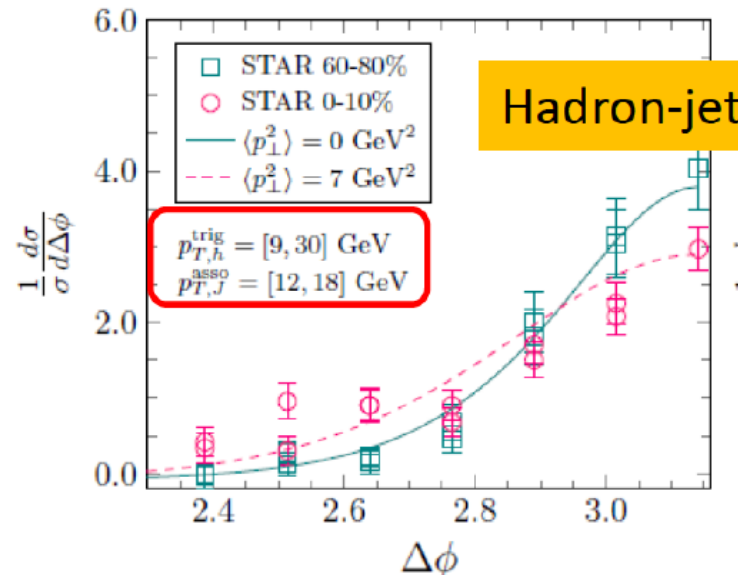
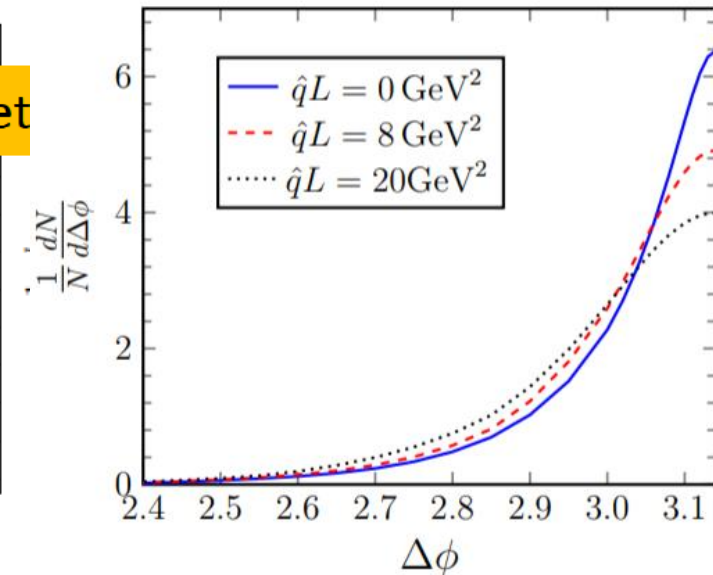
X-Jet and Dijet Azimuthal Angle Correlation

- No significant modification so far with full / charged jets
 - Need next level of accuracy and resolution unfolding at $\Delta\Phi \sim \pi$ region and go to lower p_T at LHC
 - More promising at RHIC energy where the correlations are less affected by initial state radiation

Dijet Angular Correlation at the LHC



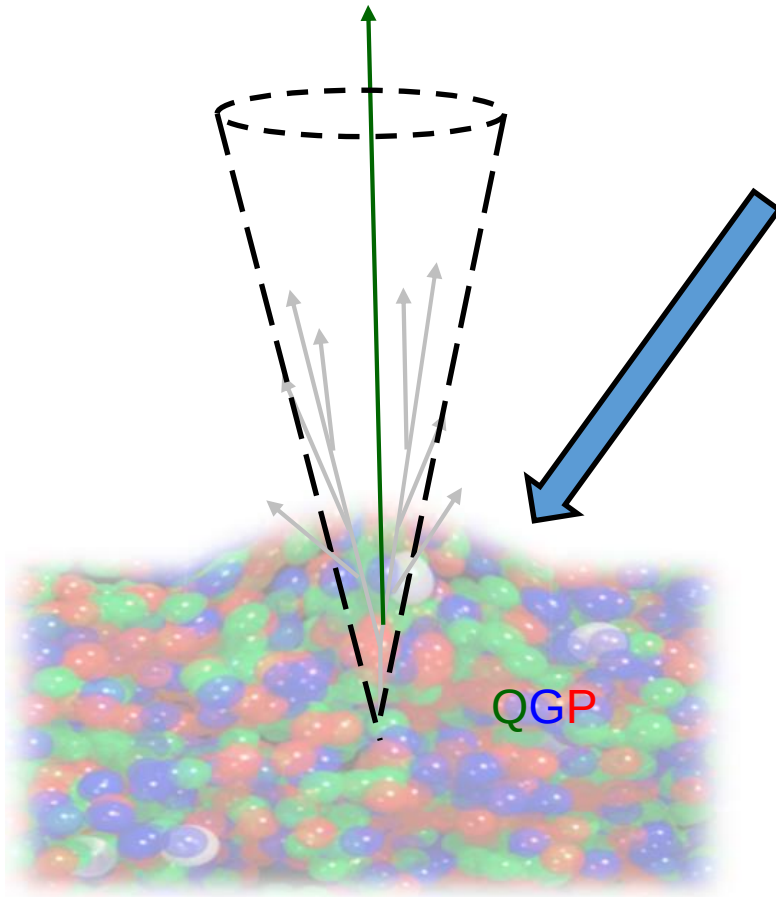
Dijet Angular Correlation at RHIC



On the other hand, we do see broadening in jet-hadron correlation at the LHC

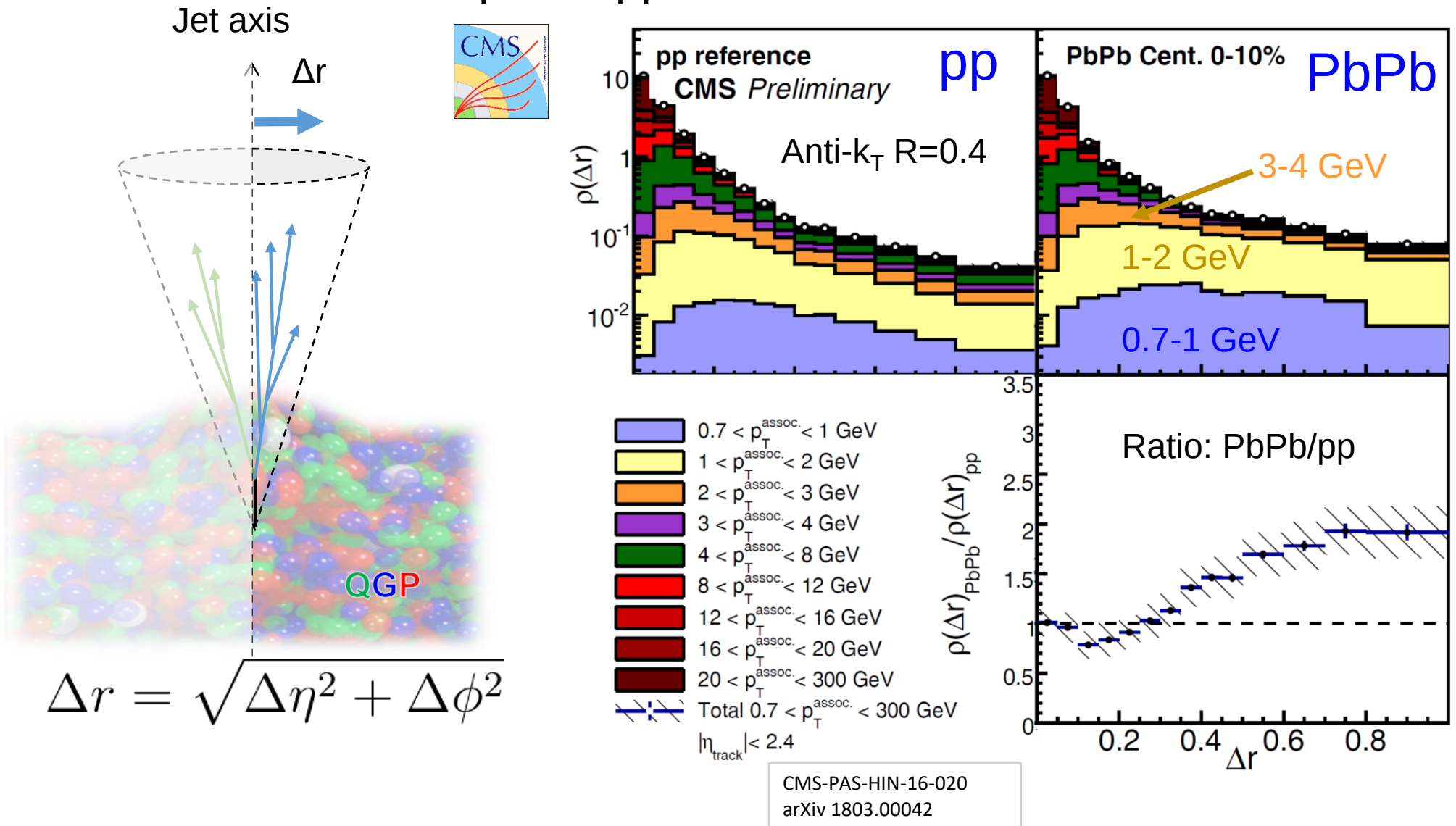
Jet Quenching

Do we see medium response?



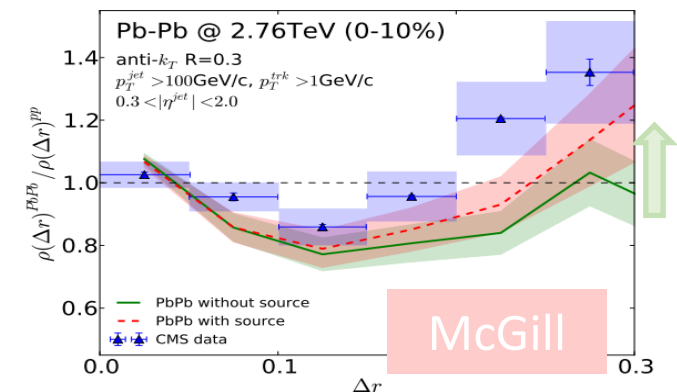
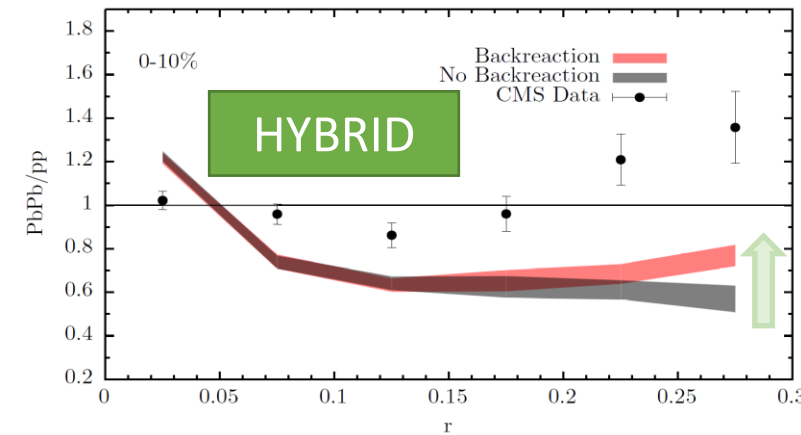
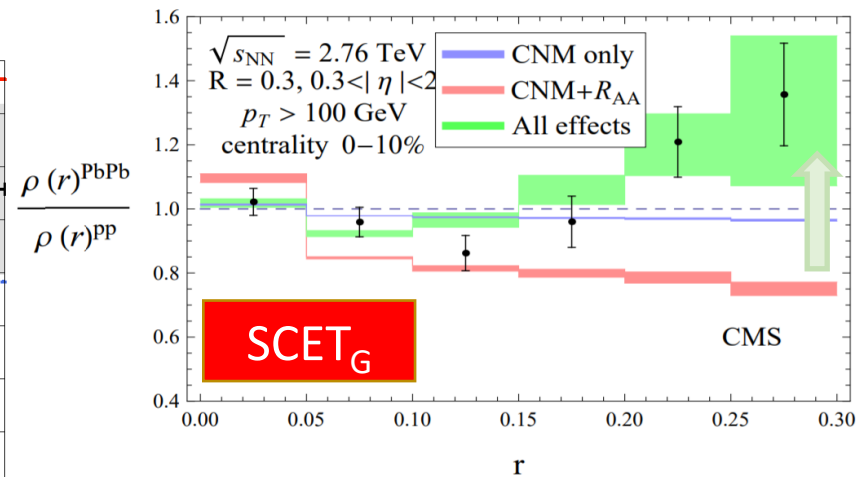
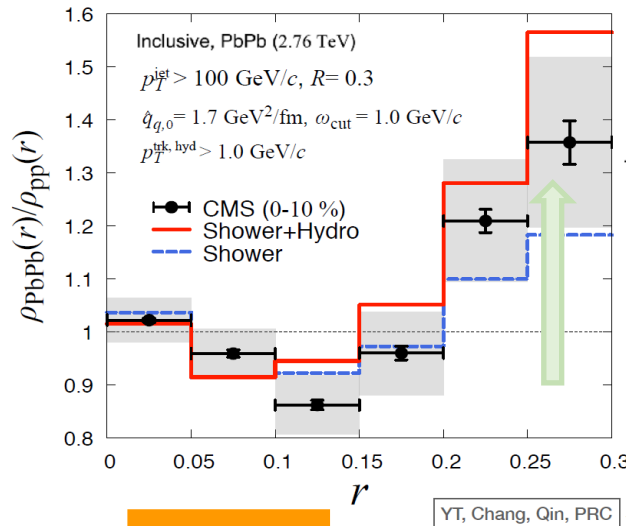
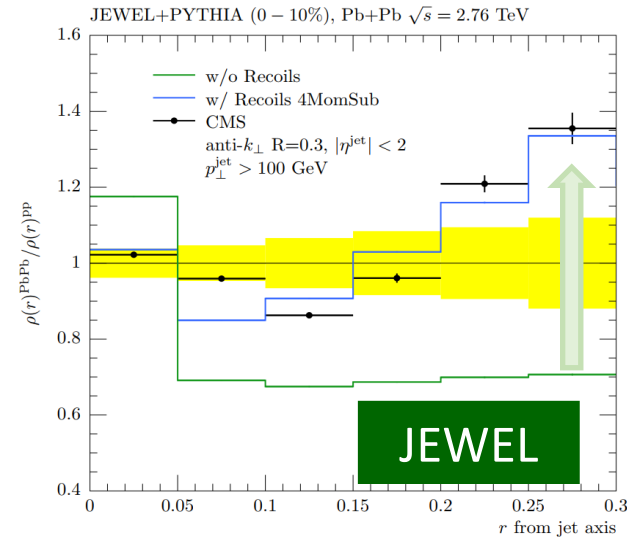
Jet Transverse Structure

Jet shapes in pp and PbPb at 5.02 TeV



- 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

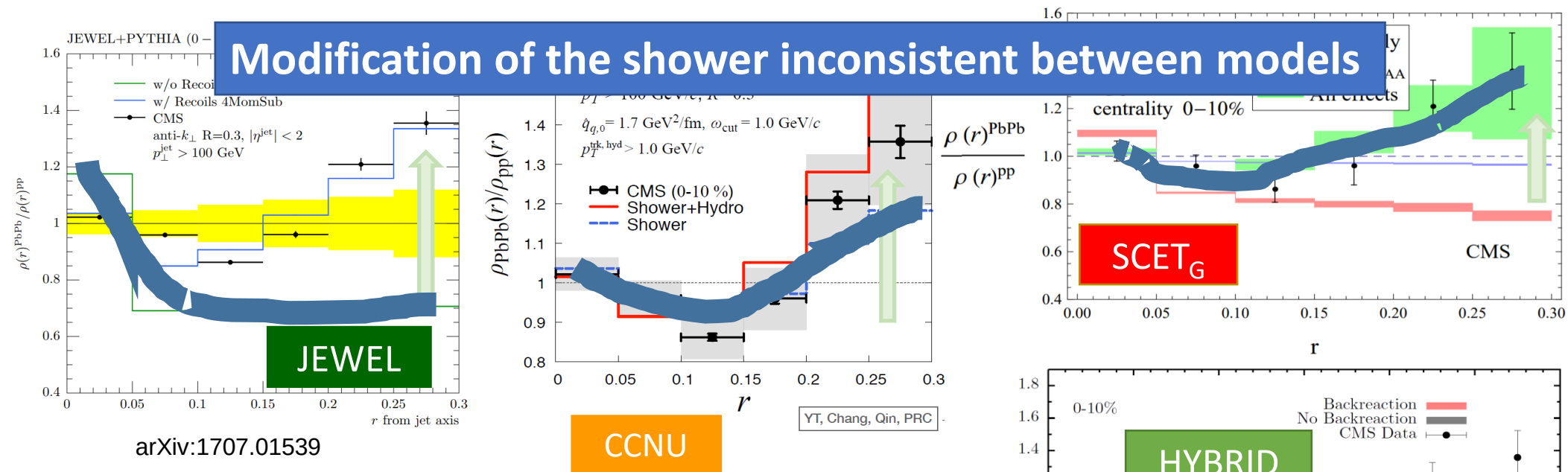


Different explanation of the large angle enhancement in jet shape measurement

- **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

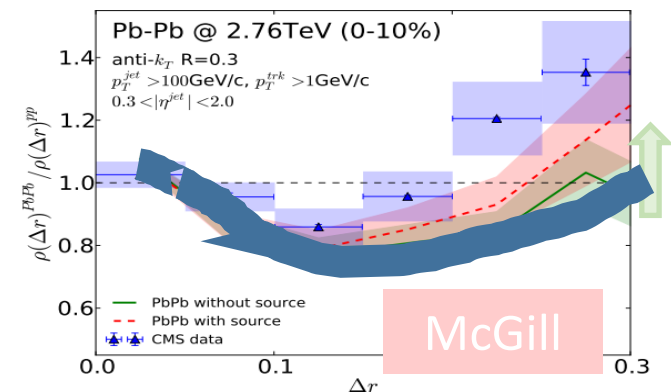
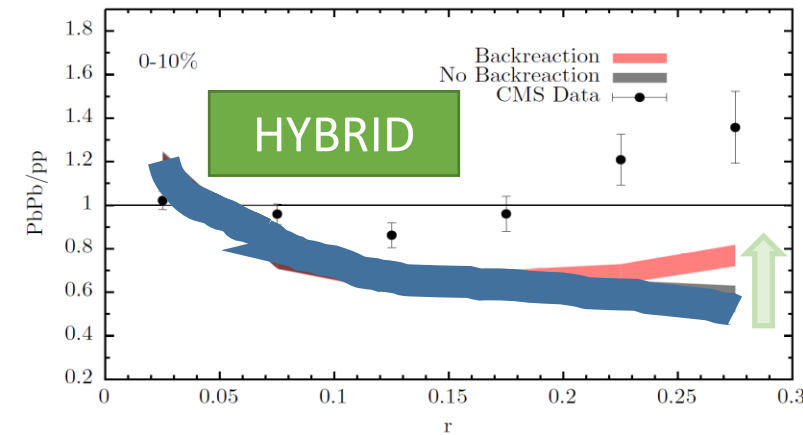
Theoretical Interpretation of the Excess

Modification of the shower inconsistent between models



Different explanation of the large angle enhancement in jet shape measurement

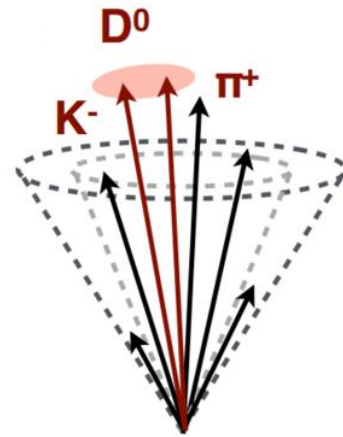
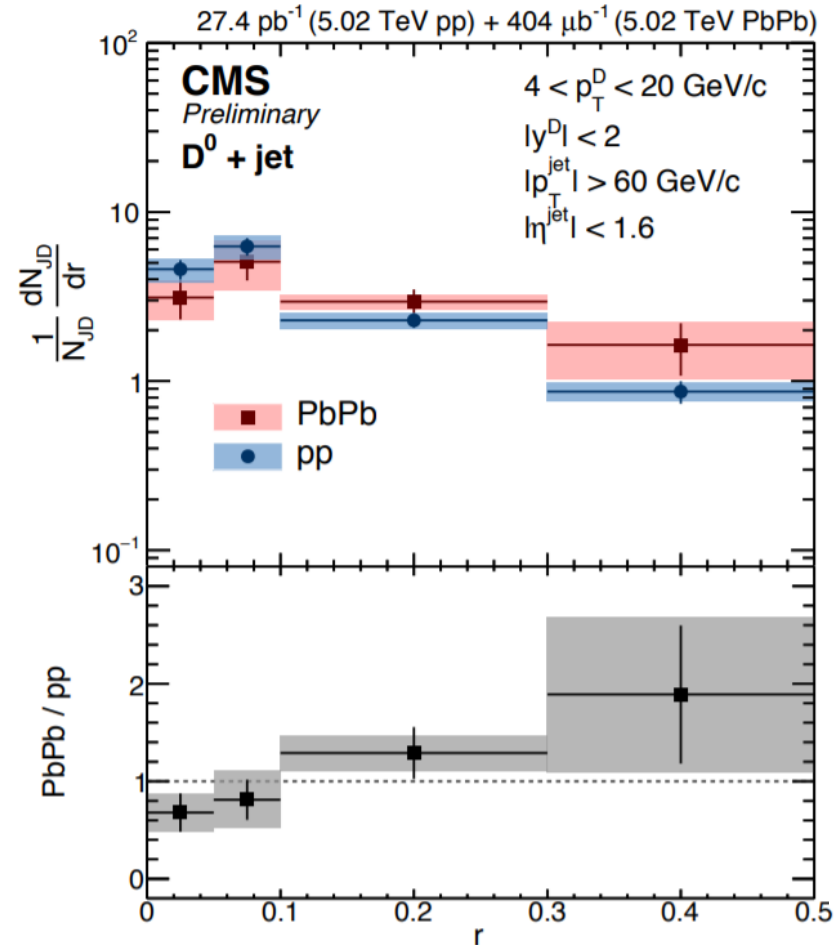
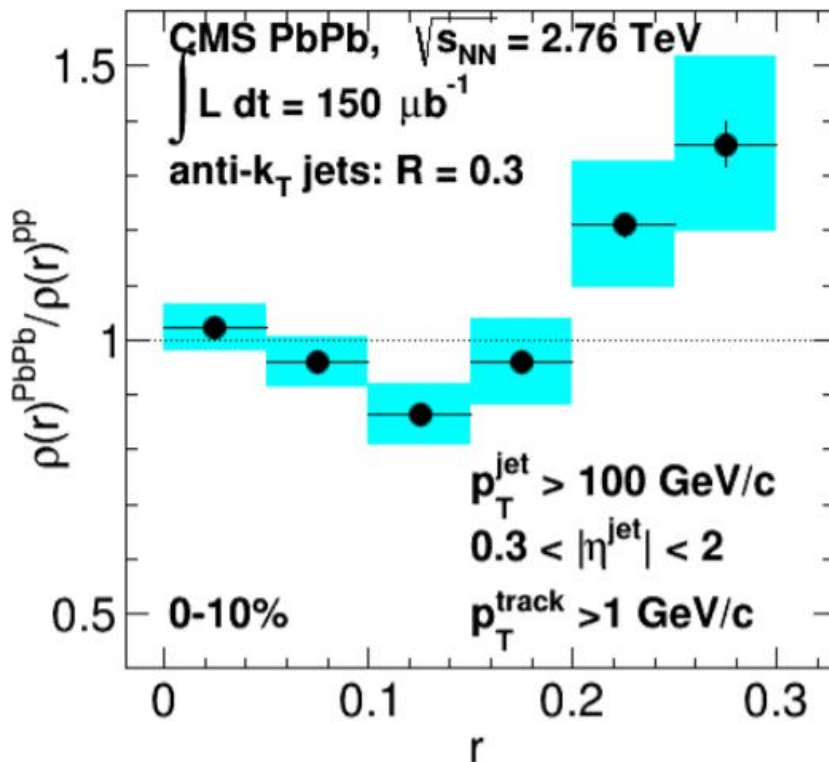
- **SCET_G**: Splitting function (large angle radiation)
- **JEWEL & JETSCAPE**: medium recoil parton
- **CCNU**: recoil parton + hydro dynamical evolution
- **HYBRID**: fully thermalized medium response
- **McGill**: medium response + shower



How do we make more progress?

(1) Look into the Excess

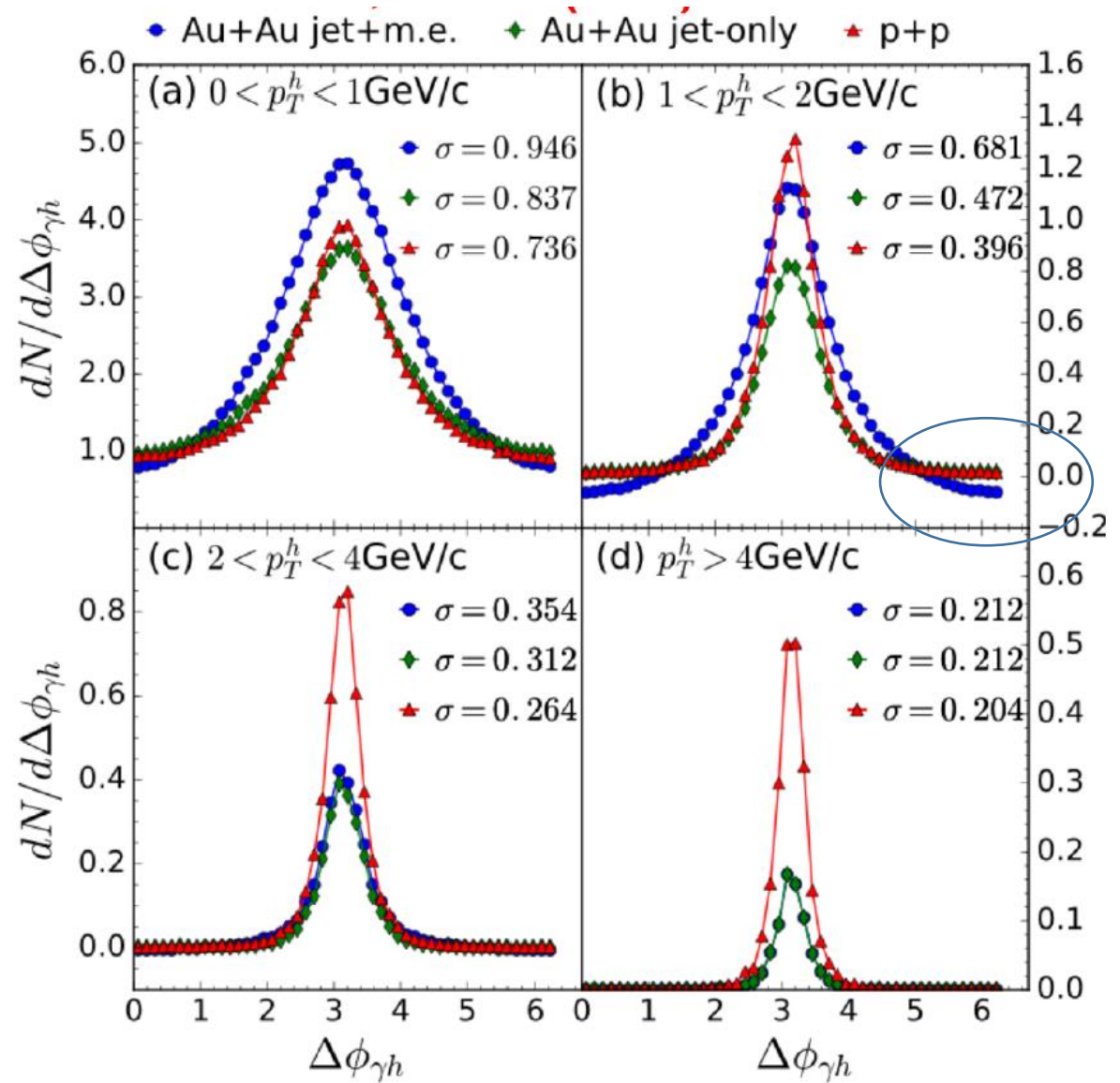
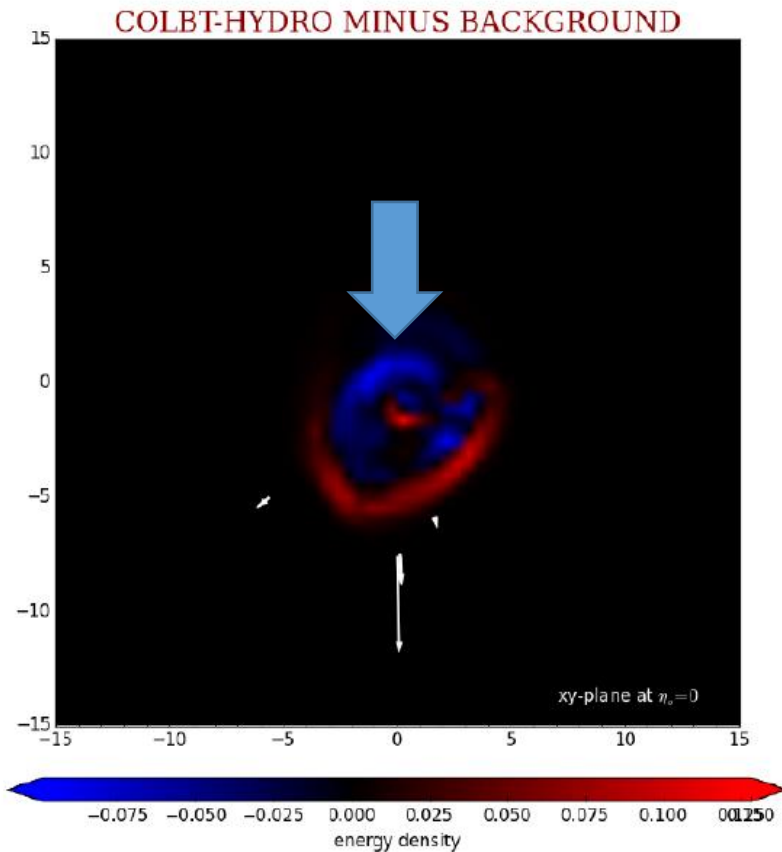
Phys. Lett. B 730 (2014) 243



Jing Wang (MIT)

- One possibility is to look at the particle composition which carry the large angle radiation: can ALICE do the measurement?
- An attempt to check the mass dependence with Jet-D correlation

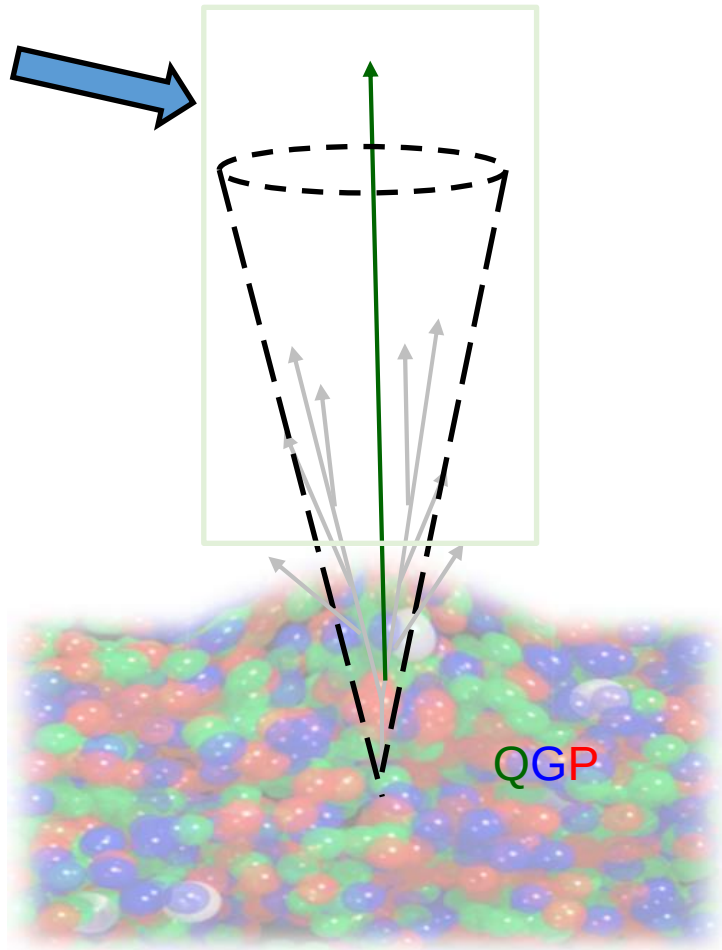
(2) To Measure the Depletion



Measure the near-side associated yield with photon-jet and Z-jet

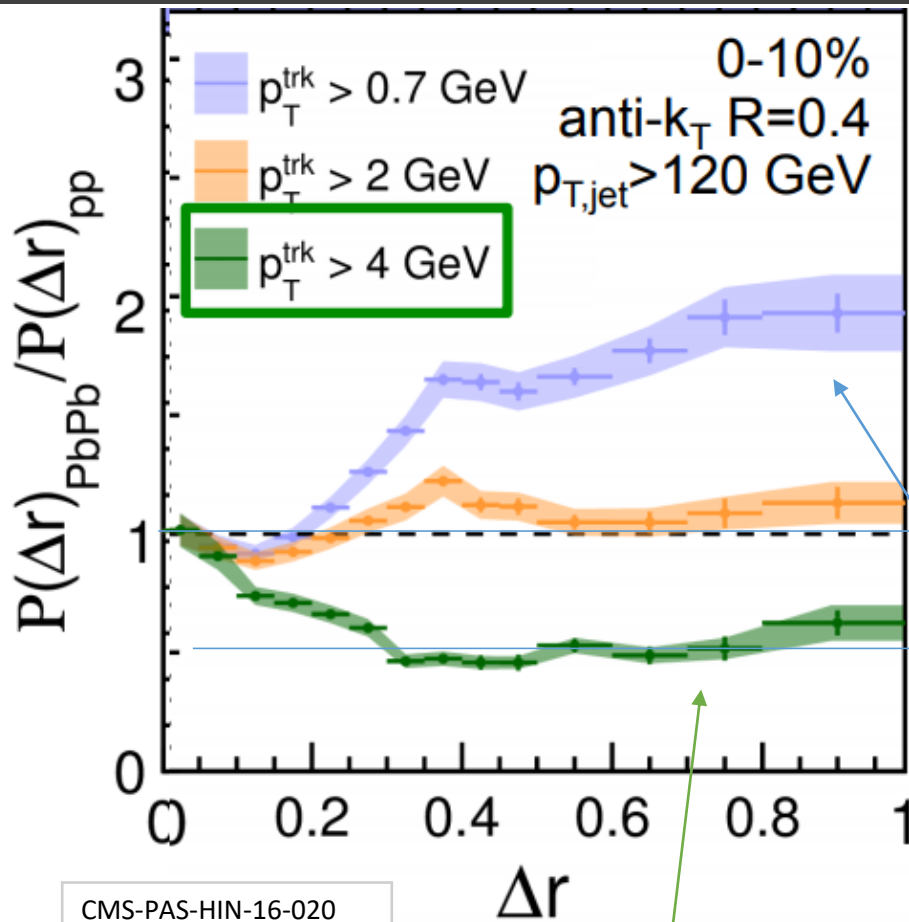
Tan Luo, Xin-Nian Wang

(3) 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)

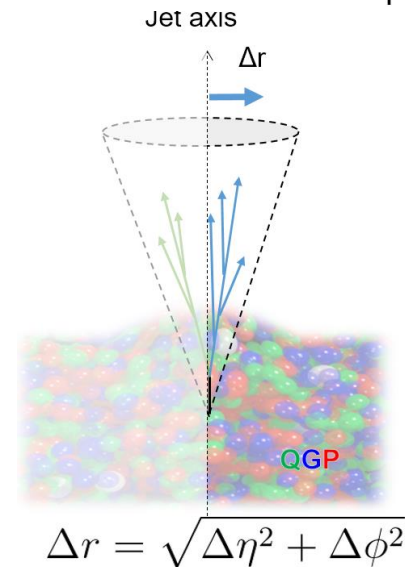
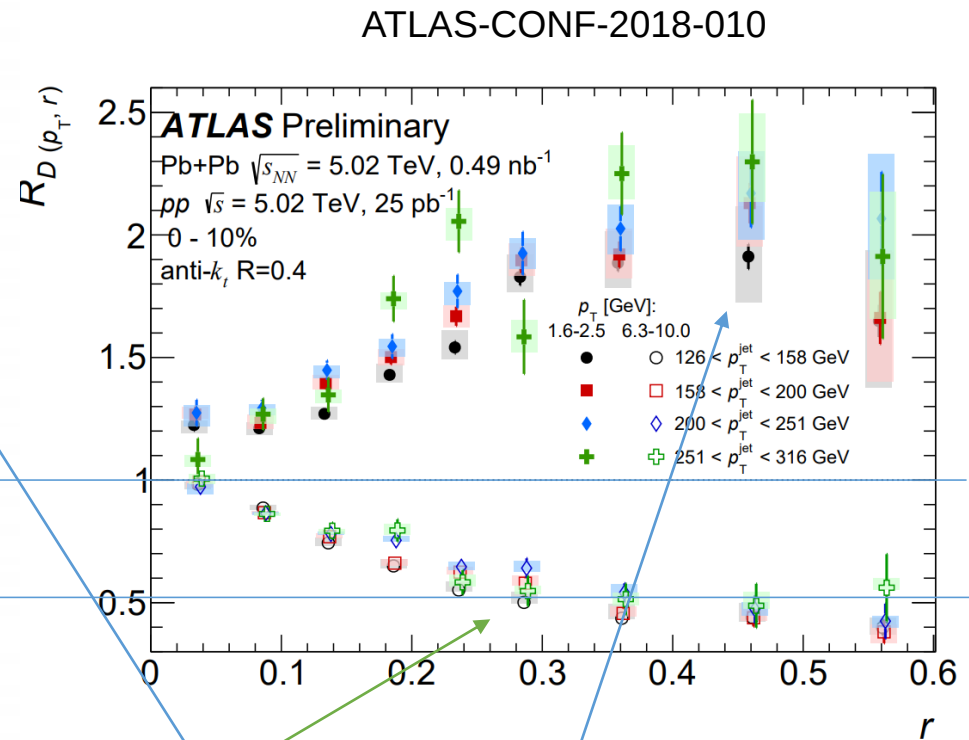
Charged Hadron Based Method



CMS-PAS-HIN-16-020
 arXiv 1803.00042

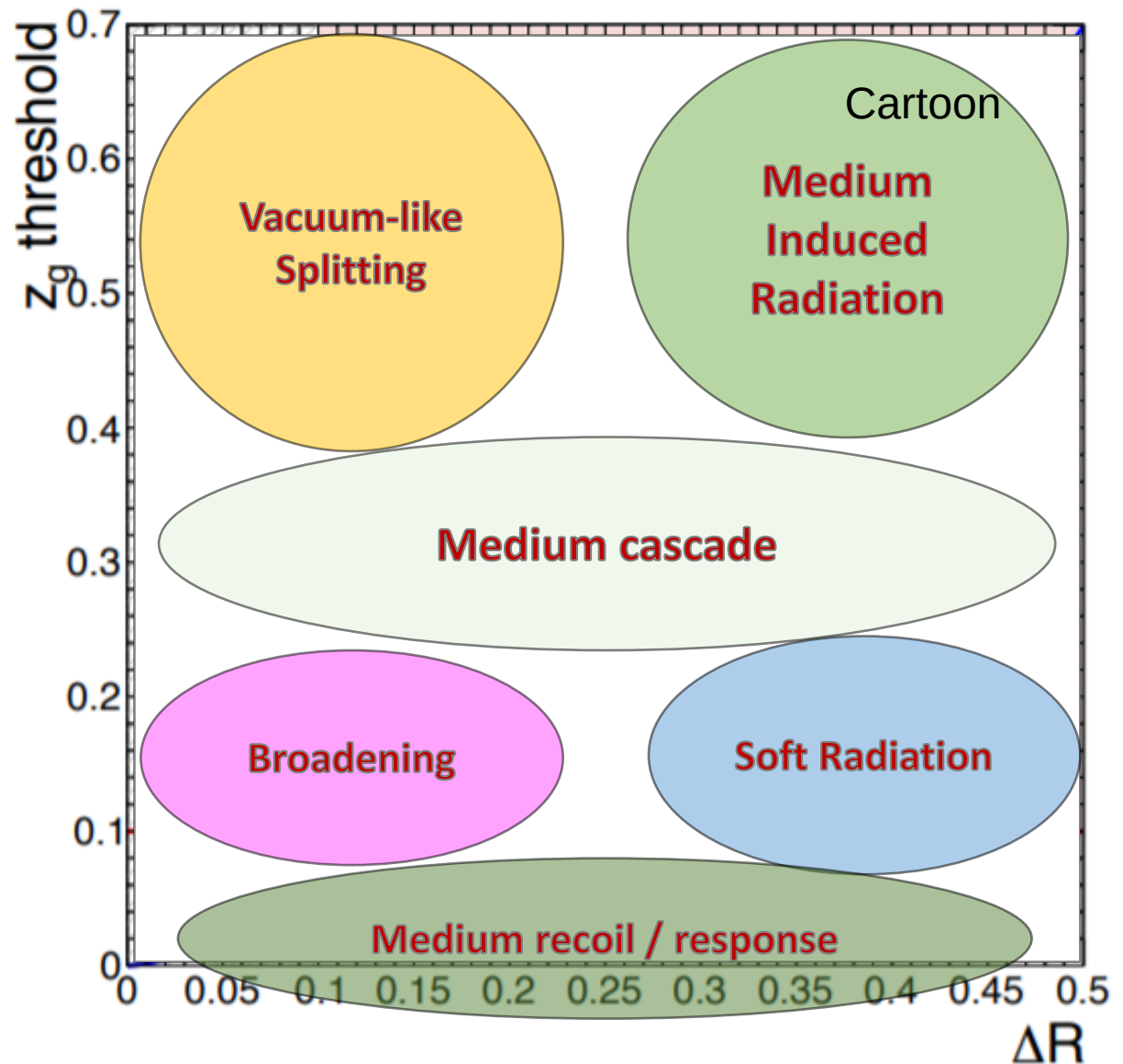
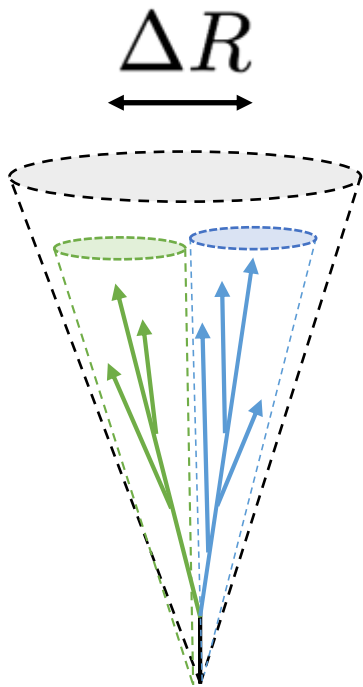
Depletion of high p_T tracks at large Δr

Enhancement of low p_T tracks at large Δr



Z_g vs. ΔR Phase Space

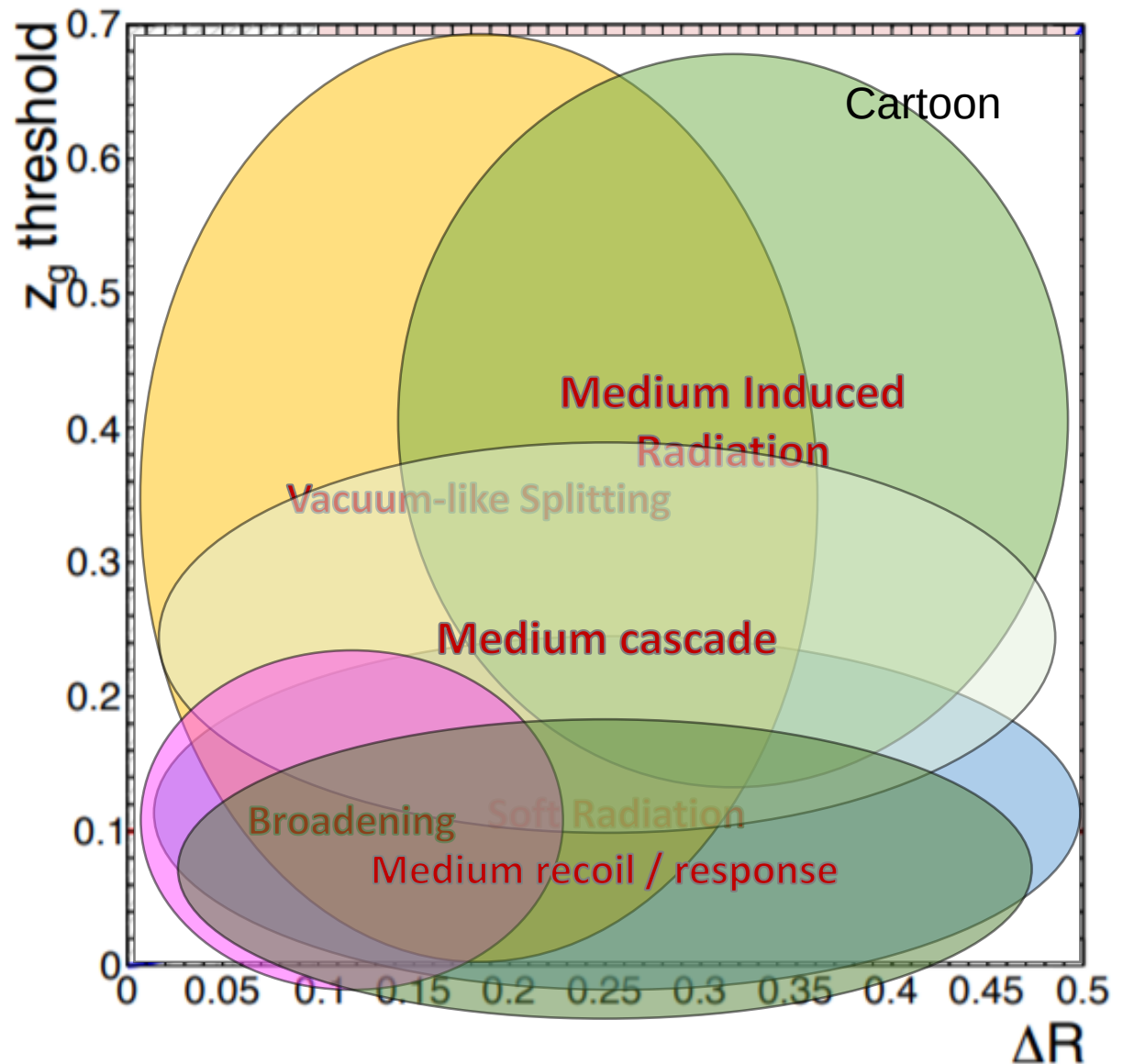
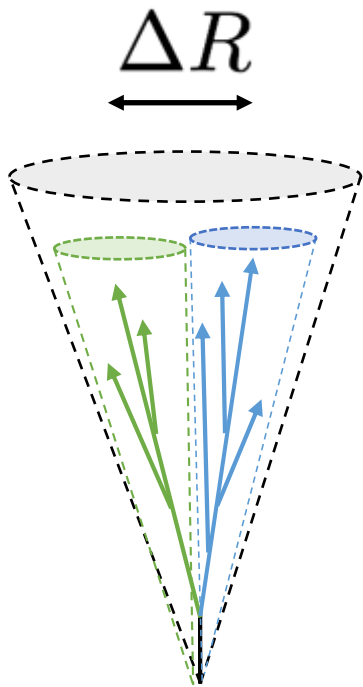
$$Z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$



Ideal world, different phase space correspond to different physics

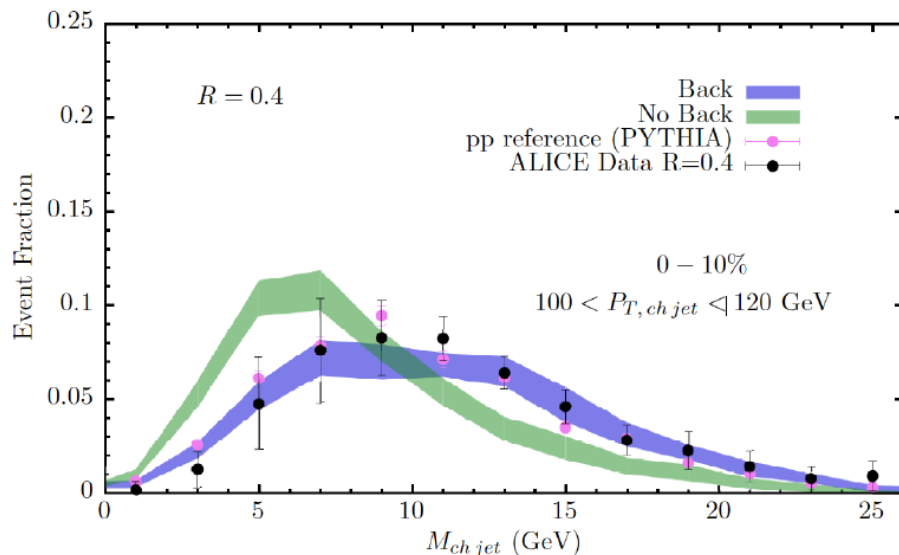
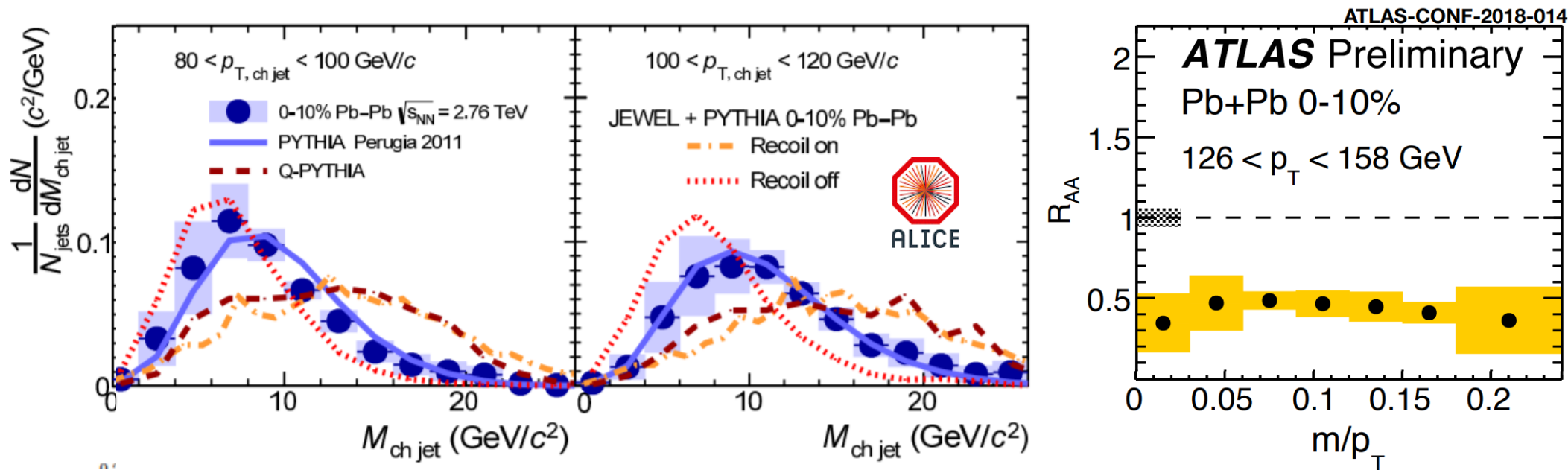
Z_g vs. ΔR Phase Space

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



- The reality may be much more complicated than that
- The excitement: One could construct different observables which are sensitive to different part of the phase space and provide stress test on models

“Ungroomed” jet mass

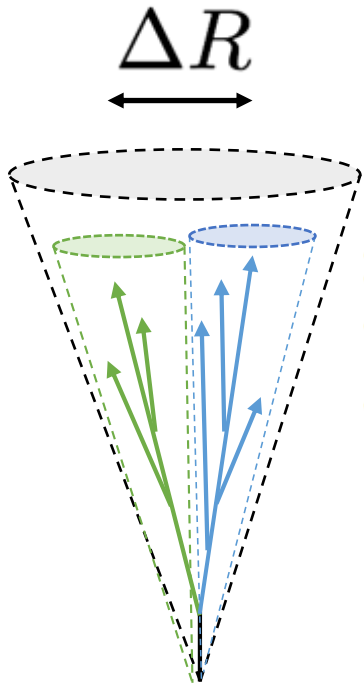


- No modification of the distribution is observed in **ALICE** and **ATLAS** data with respect to pp reference
- Cancelling effects from medium modifications of the shower and medium response

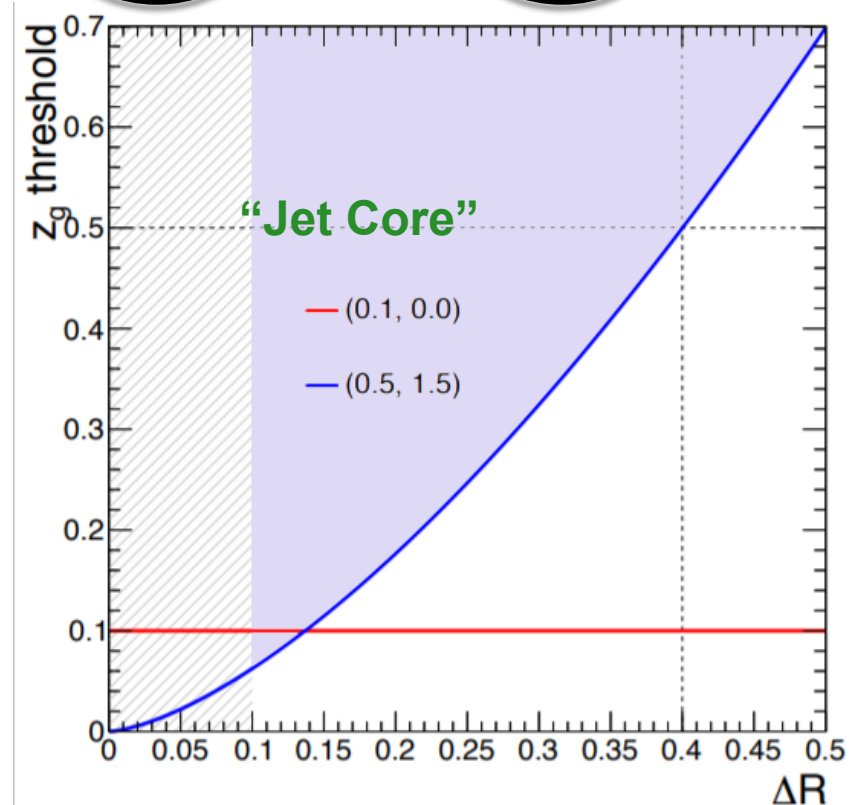
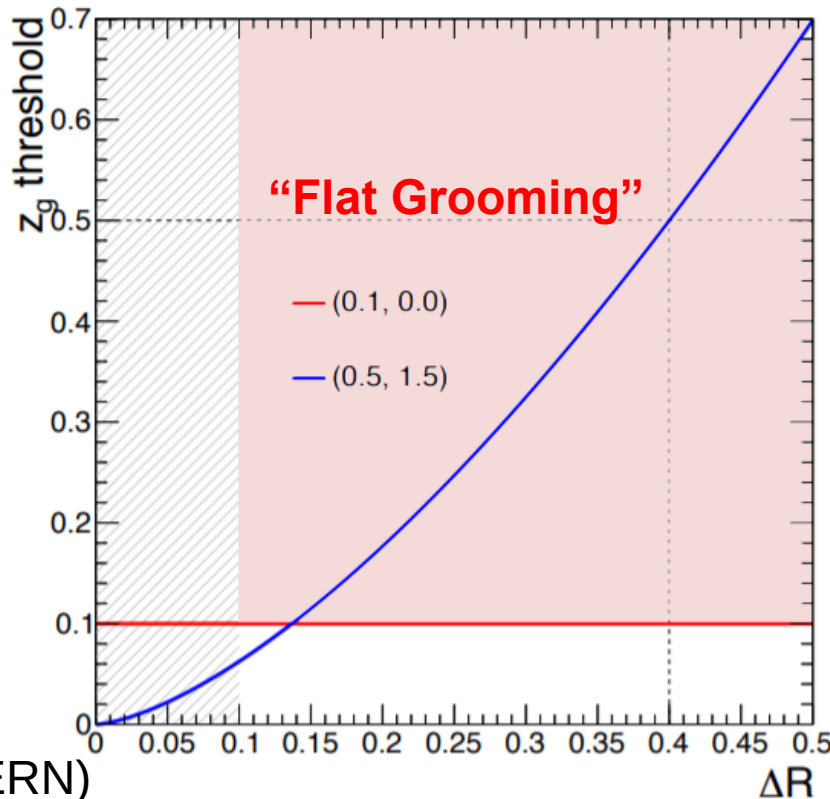
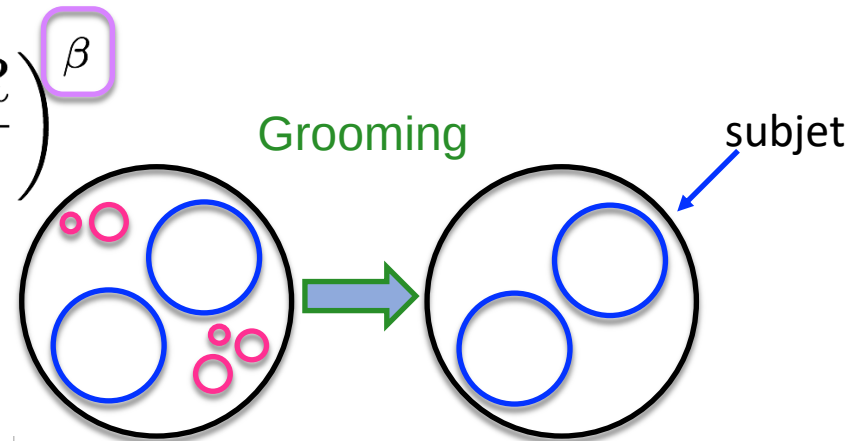
Groomed Jet Substructure with Soft Drop

- CMS: used two grooming settings with $\Delta R > 0.1$ 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

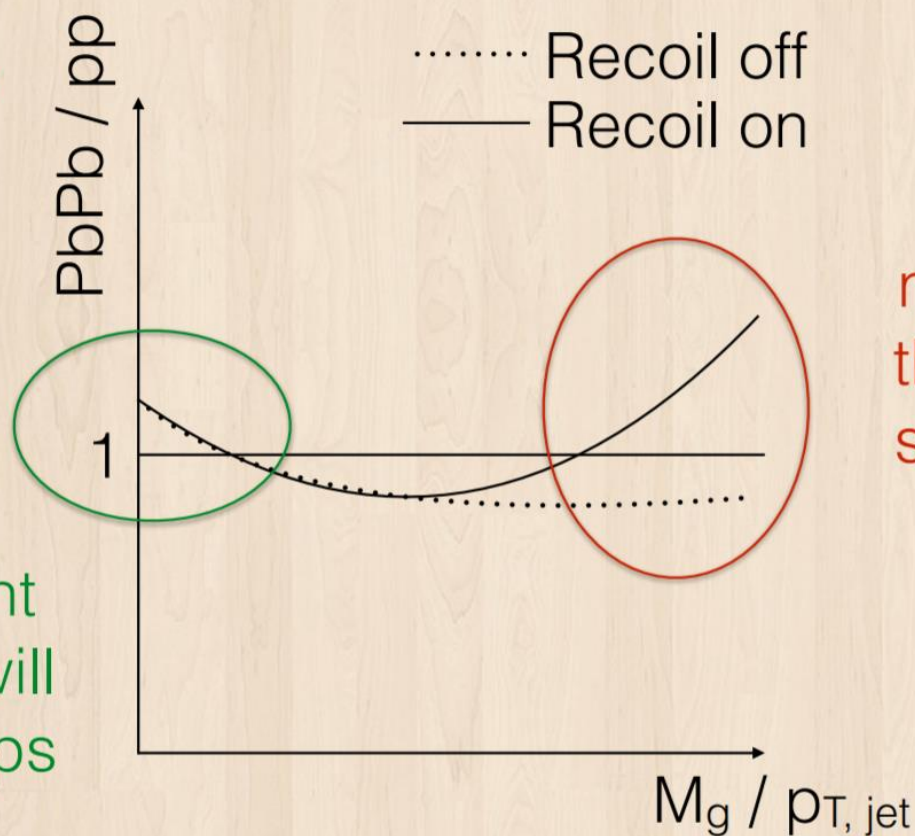


Phase diagram
from Yi Chen (CERN)

Groomed Jet Mass

Partons lose energy
— bulk moves to
smaller mass
compared to
ungroomed jet P_T

If there is large amount
of broadening, mass will
increase and ratio drops



The rise in large
mass tail is due to
the recoil particles
scattered at larger
angles

From Yi Chen (CERN)

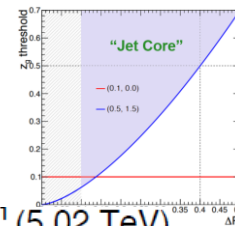
Groomed Jet Mass

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

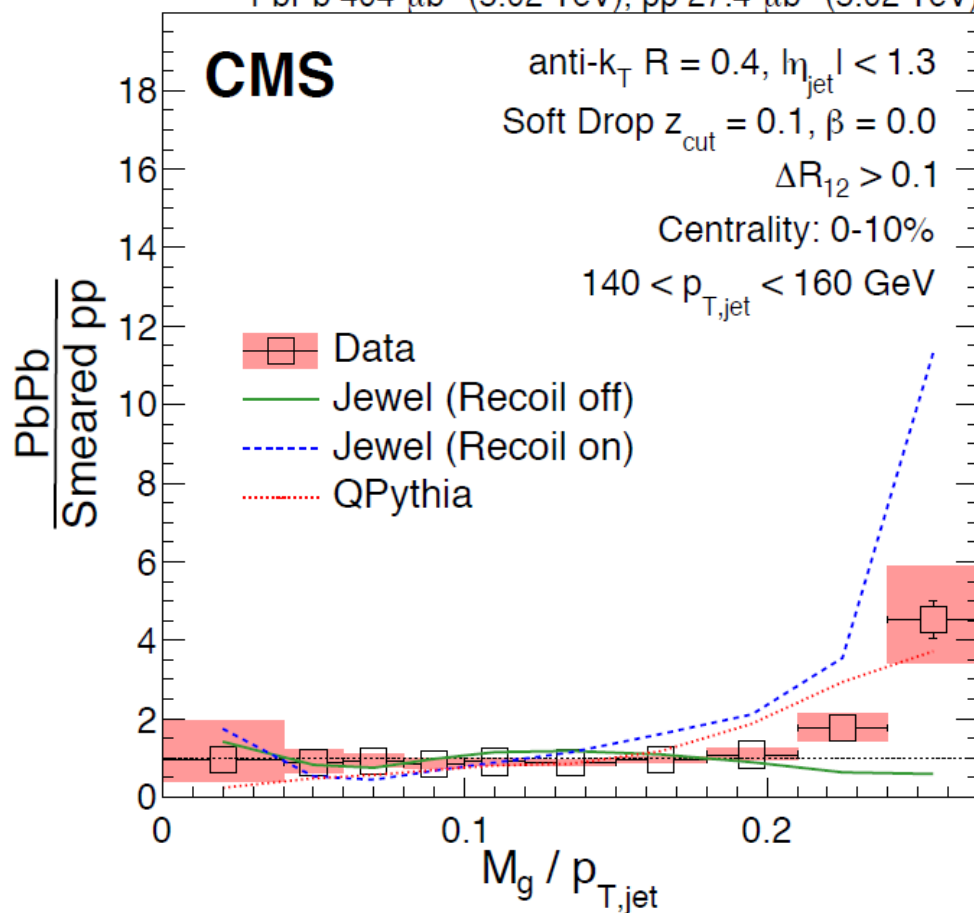
“Flat Grooming”

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

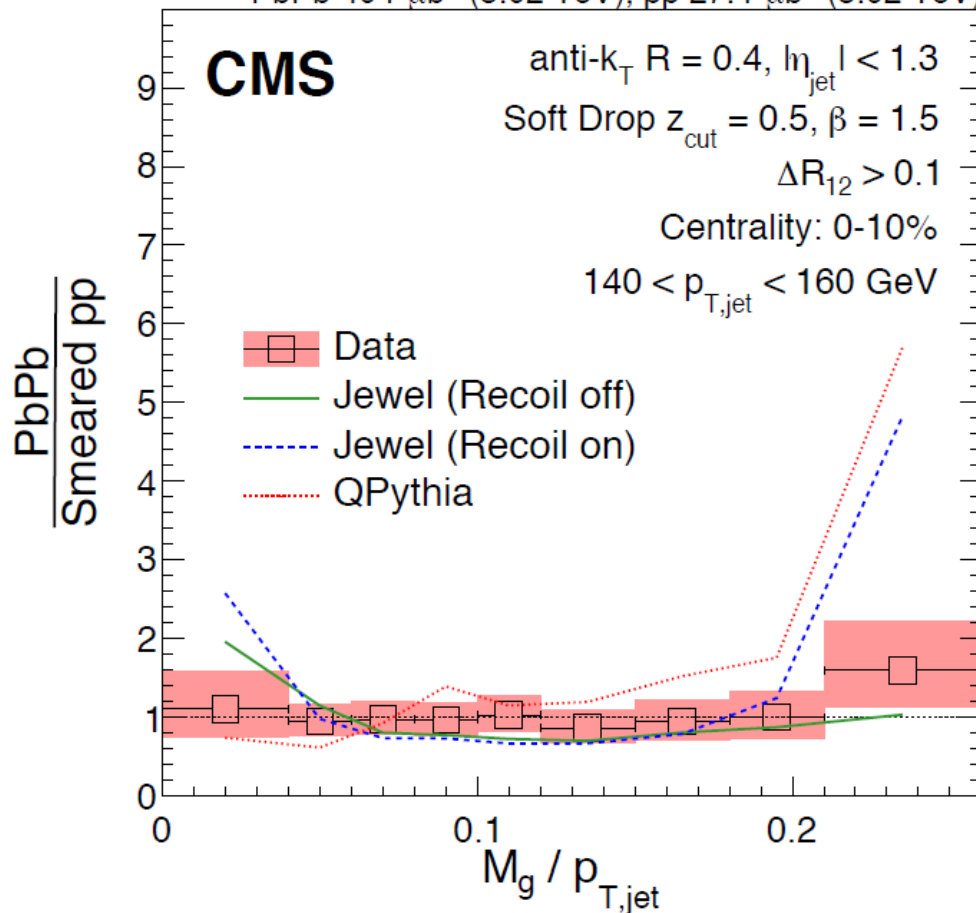
“Jet Core”



PbPb 404 μb^{-1} (5.02 TeV), pp 27.4 μb^{-1} (5.02 TeV)



PbPb 404 μb^{-1} (5.02 TeV), pp 27.4 μb^{-1} (5.02 TeV)

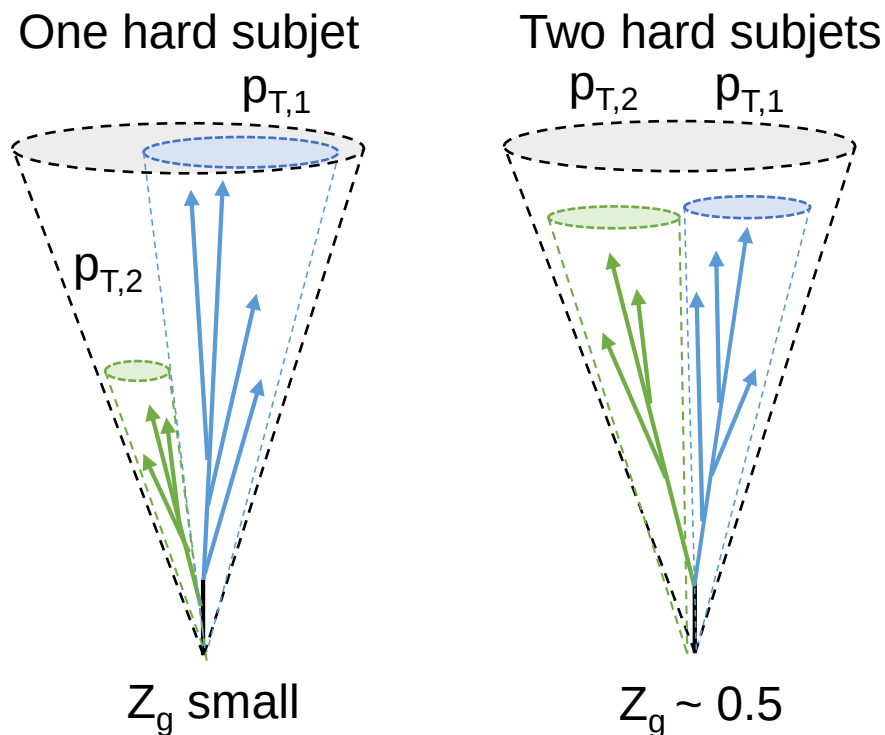


CMS-HIN-16-024

- Enhancement of large mass when looking at a less aggressive grooming setting

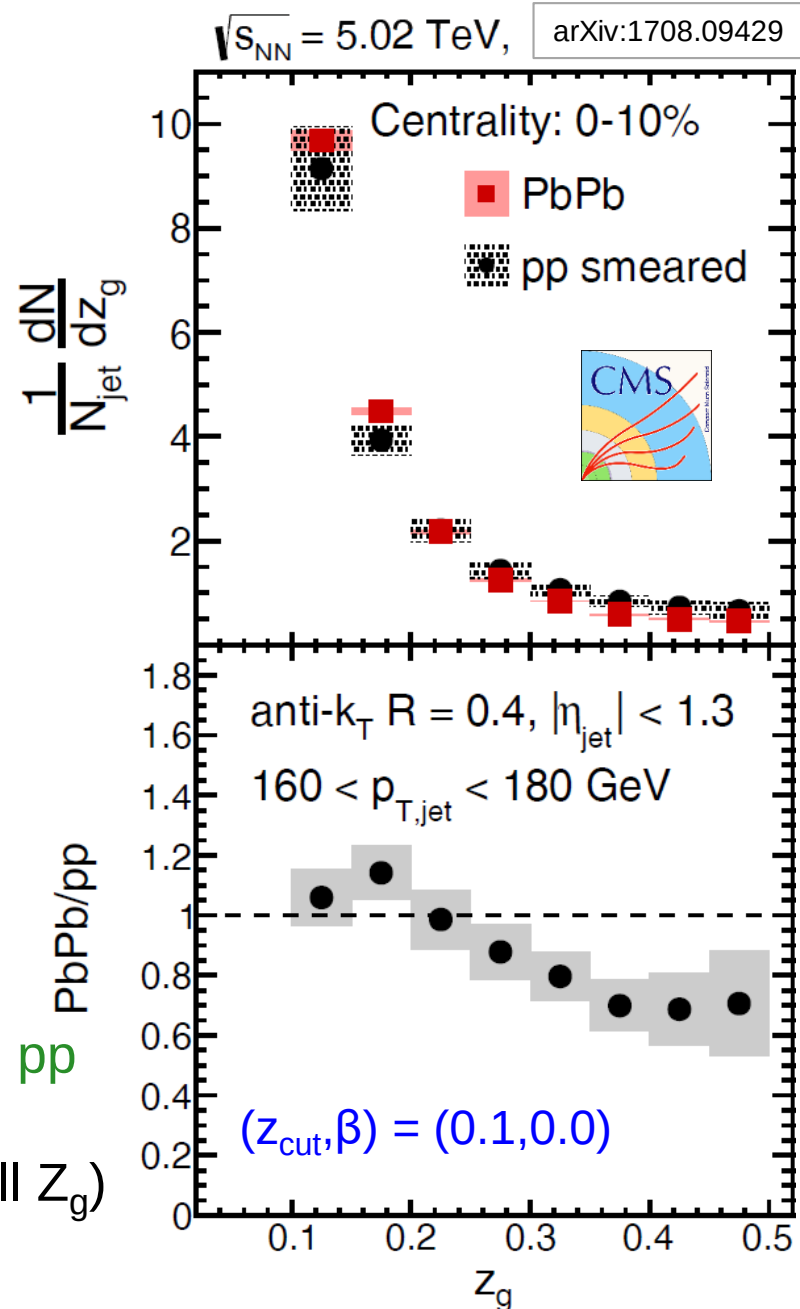
- Results with a “more aggressive grooming”
- Smaller or no significant modification of the “jet core”

Momentum Sharing of Subjets



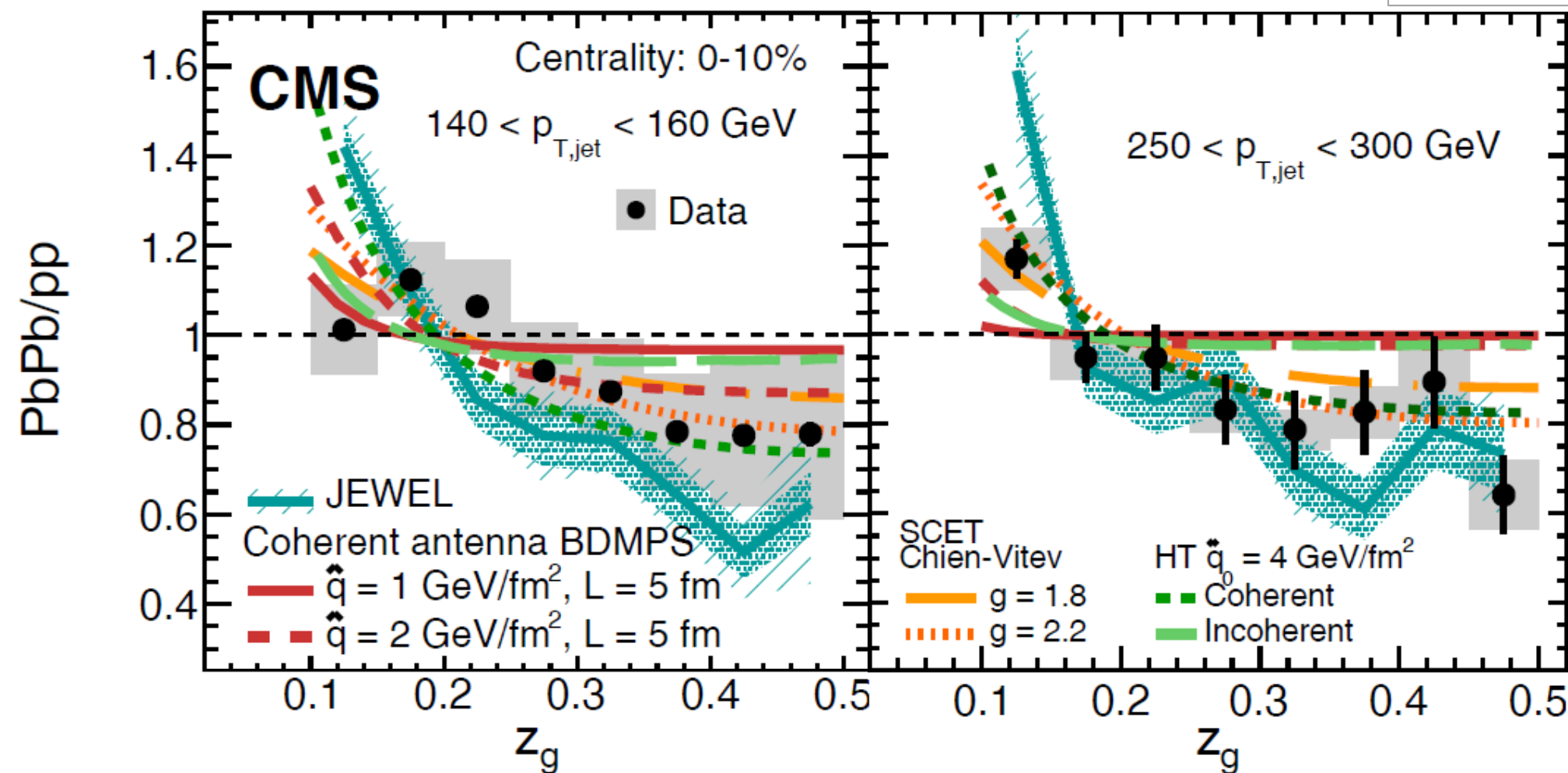
$$Z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$

- 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)



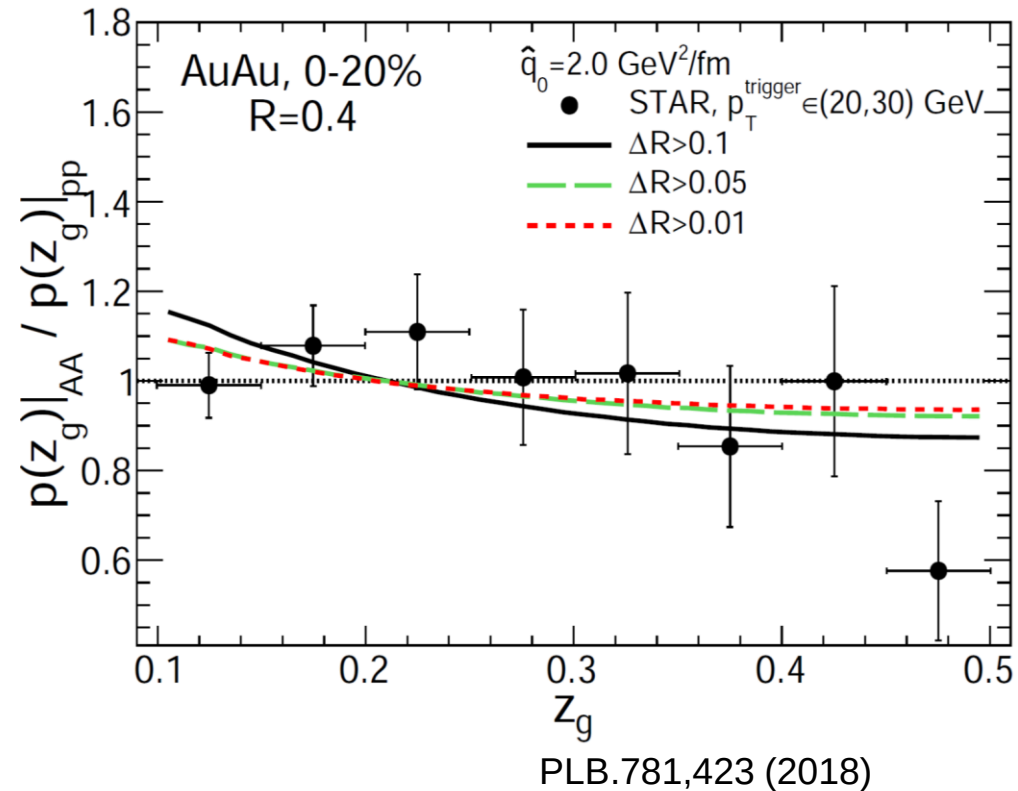
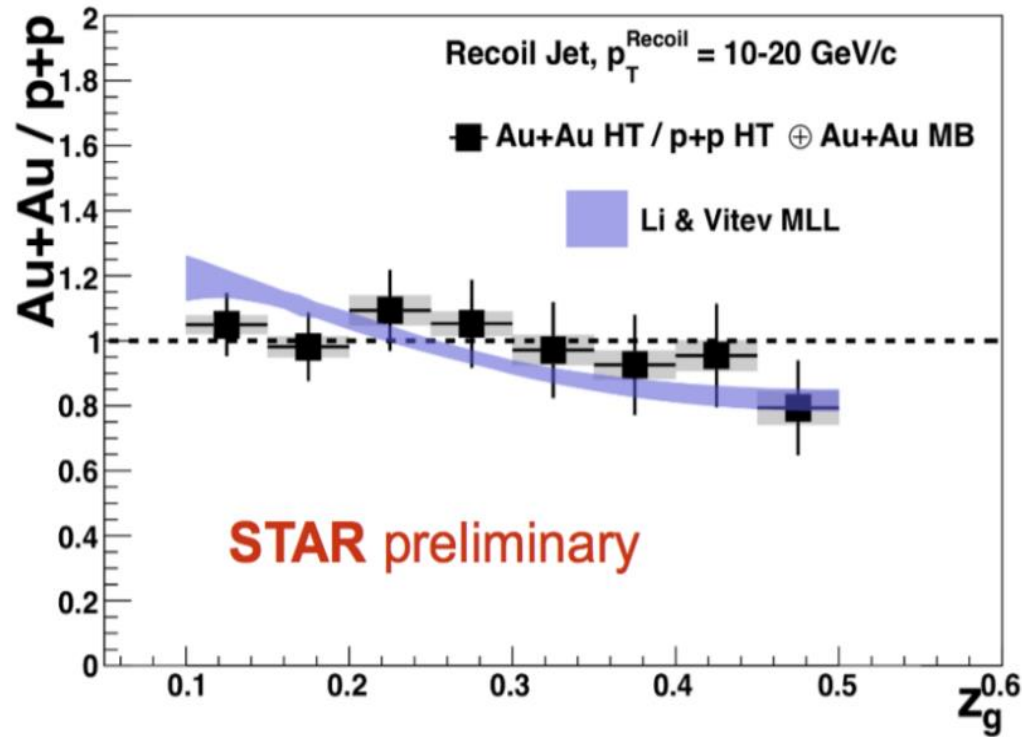
Momentum Sharing of Subjets

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**

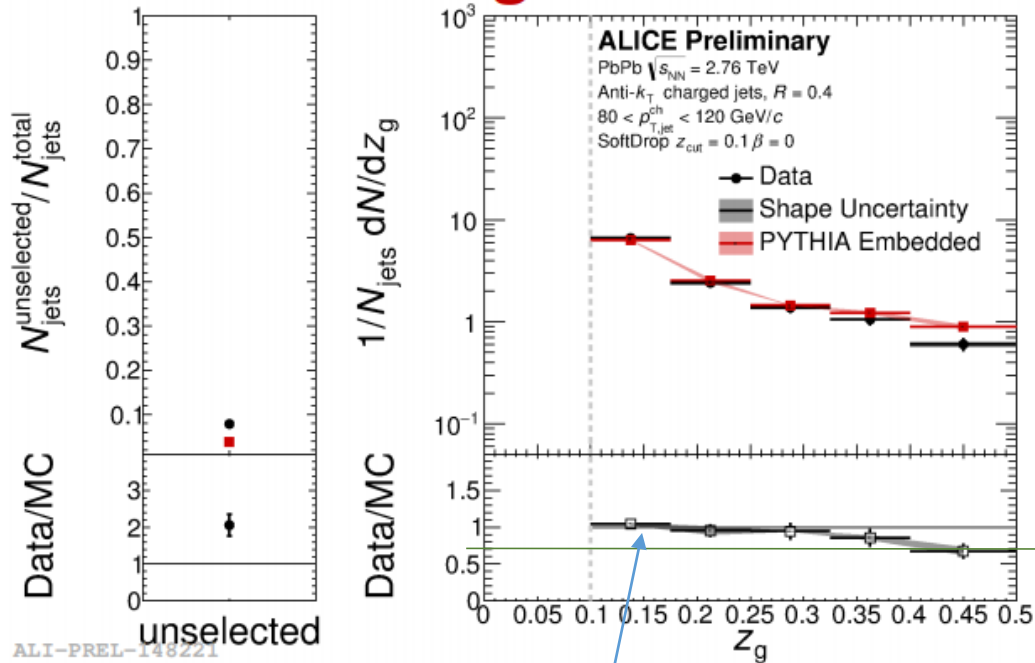
Groomed Momentum Sharing of Subjets



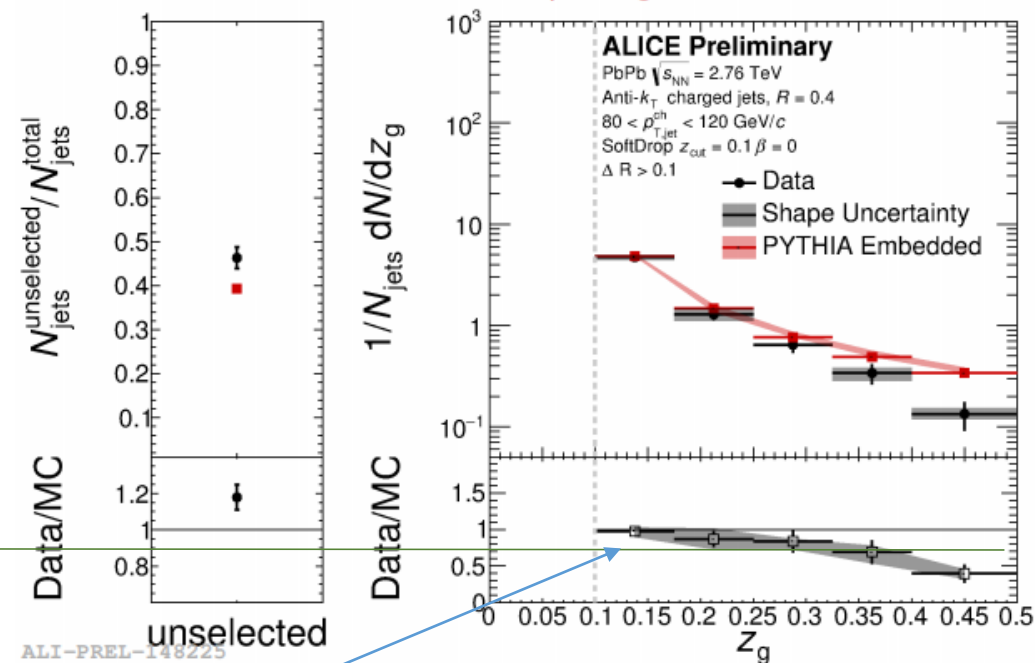
- No significant or small modification of subjet momentum sharing
- Not necessary a contradiction to the CMS result due to the difference in the grooming (no ΔR cut in STAR measurement) and collision energy

Effect of ΔR selection

No angular cutoff

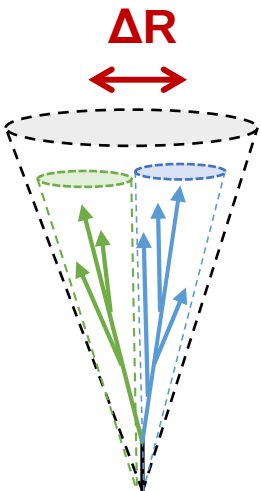


$\Delta R > 0.1$



Normalized by total number of jets

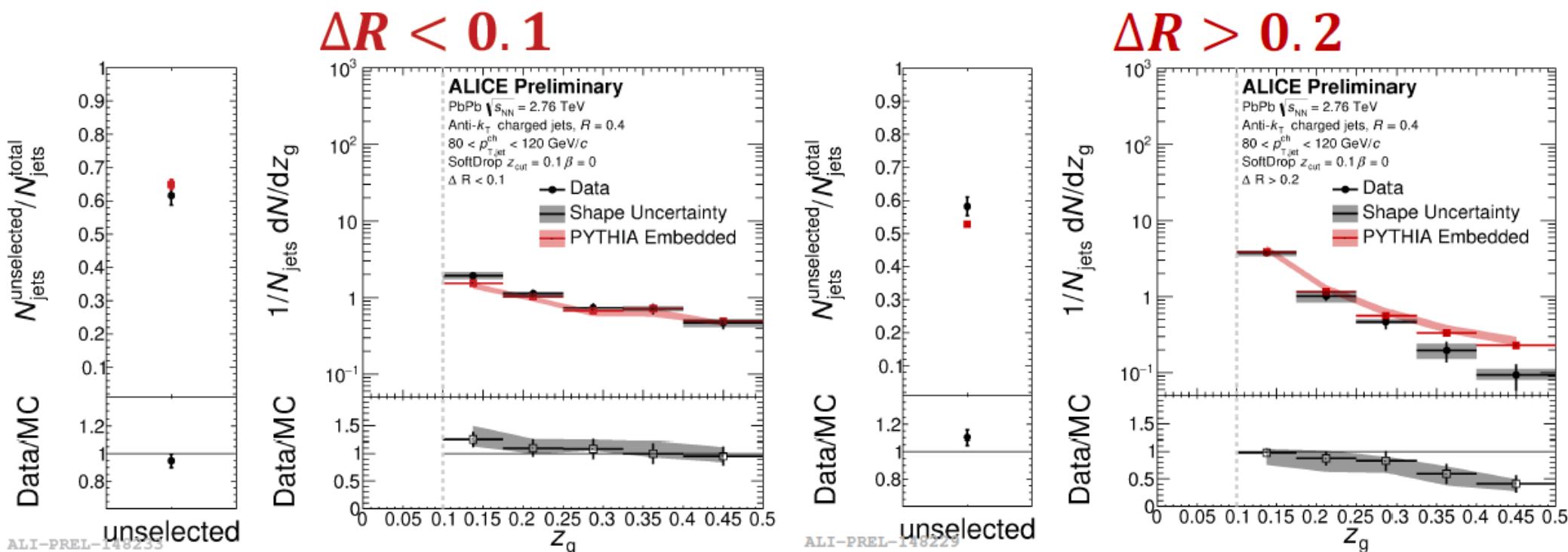
Unselected = Untagged (SD) + cut by ΔR cut



- No enhancement of low Z_g jets, different from JEWEL prediction
Too high correlation between medium recoil and jet in JEWEL?
(hints also seen in jet mass and Z_g measurements)
- ΔR cut increase the suppression of large Z_g jets

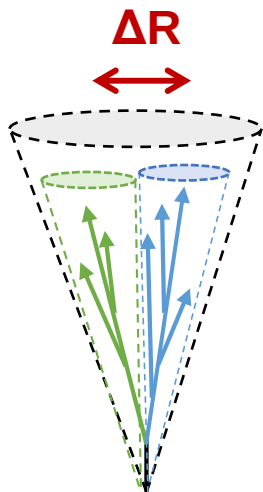
Harry Andrews (QM2018)

Collimated jets vs. Large Opening Angle



Normalized by total number of jets

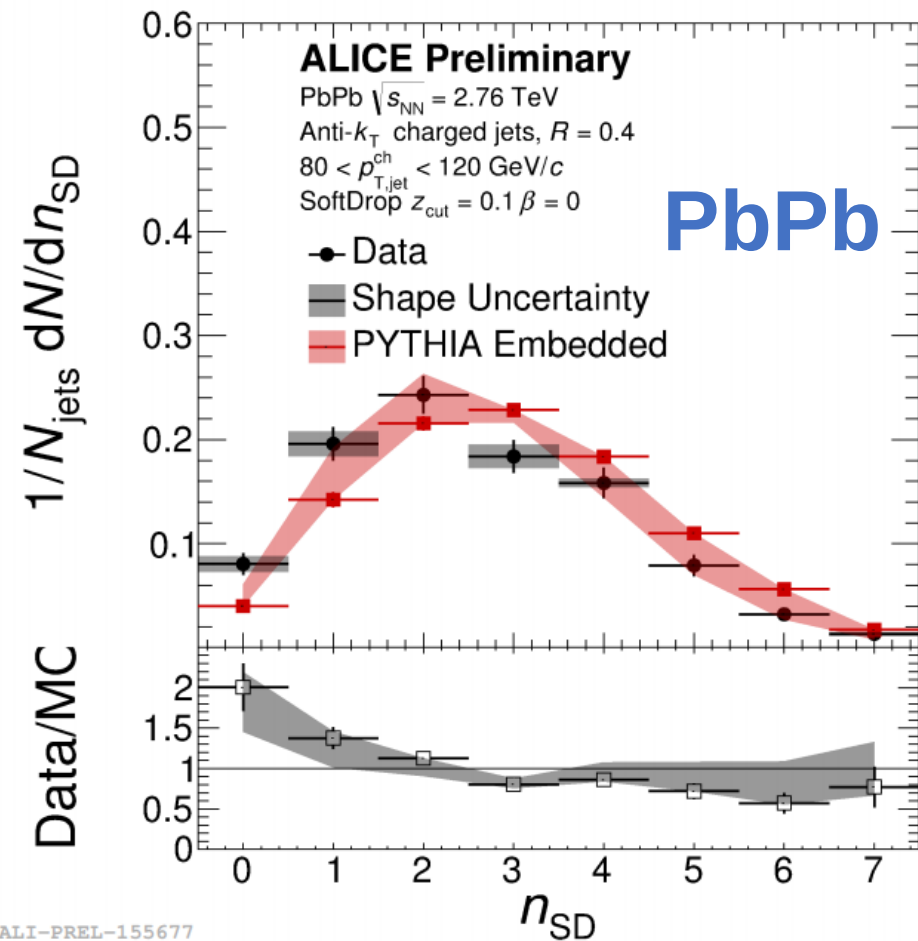
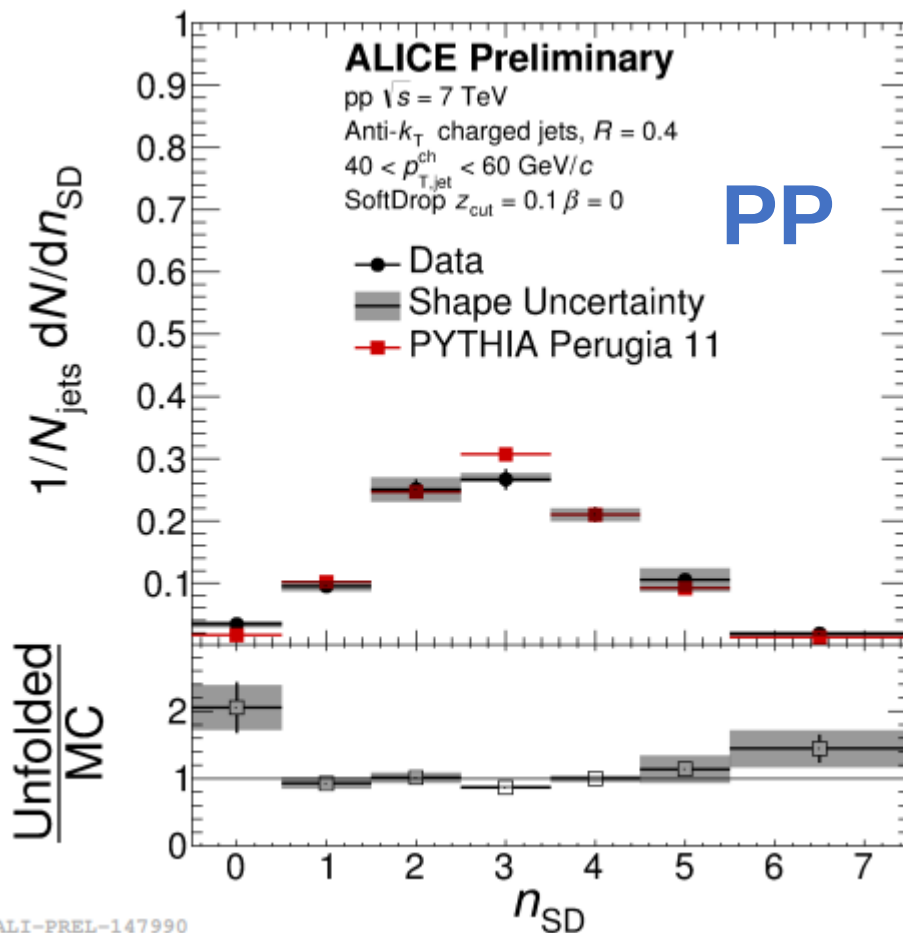
Unselected = Untagged (SD) + cut by ΔR cut



- Small or no modification of “collimated jets” (small ΔR between subjets)
- Larger ΔR cut ($\Delta R > 0.2$ large opening angle between subjets): Significant suppression at large Z_g

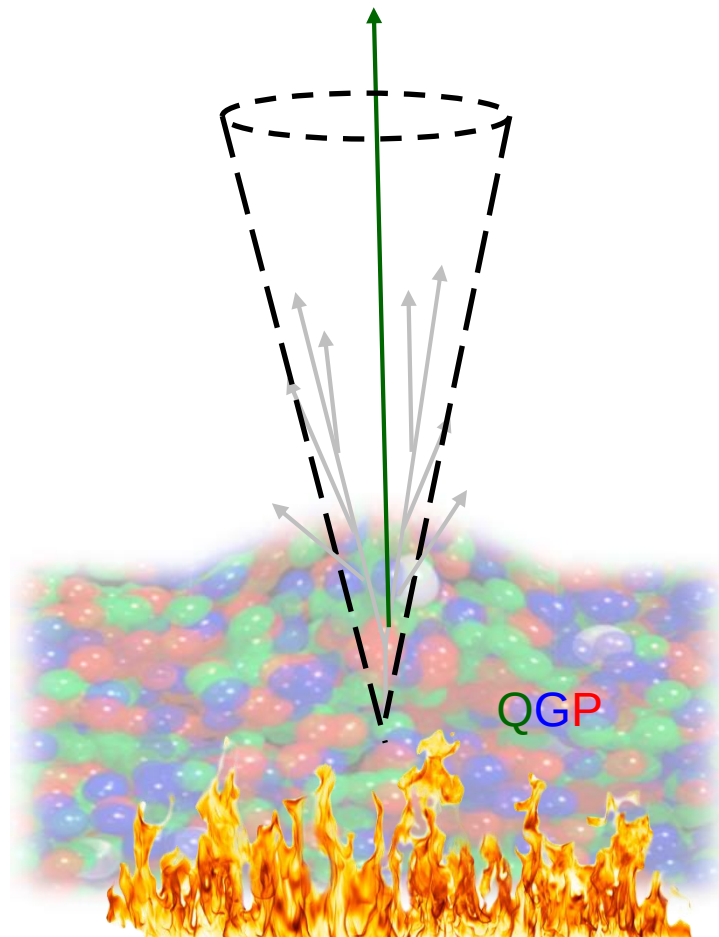
Harry Andrews (QM2018)

Recursive Splittings

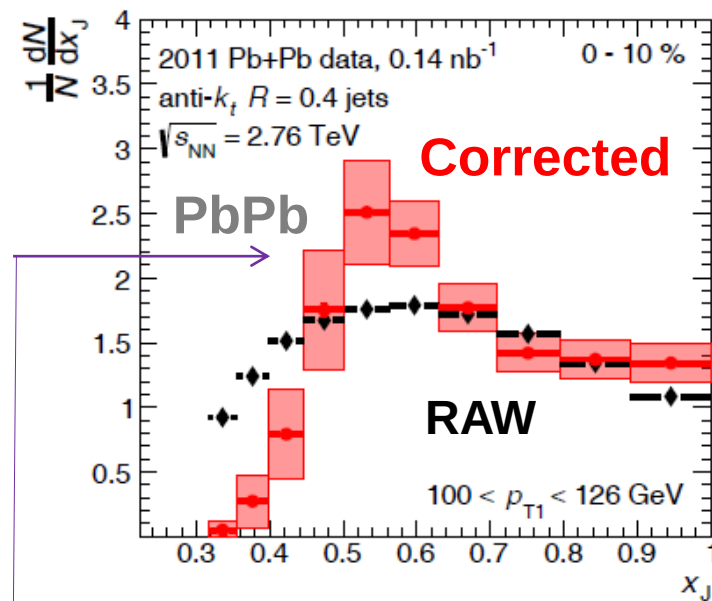


- No enhancement in the number of splitting passing Soft Drop in PbPb compared to pp

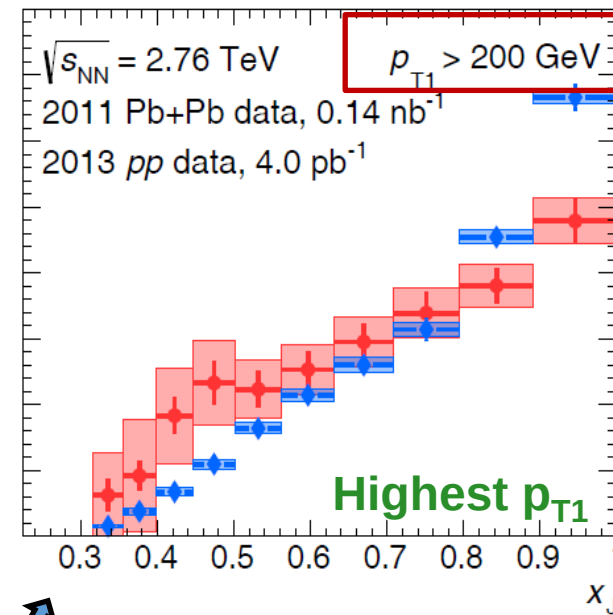
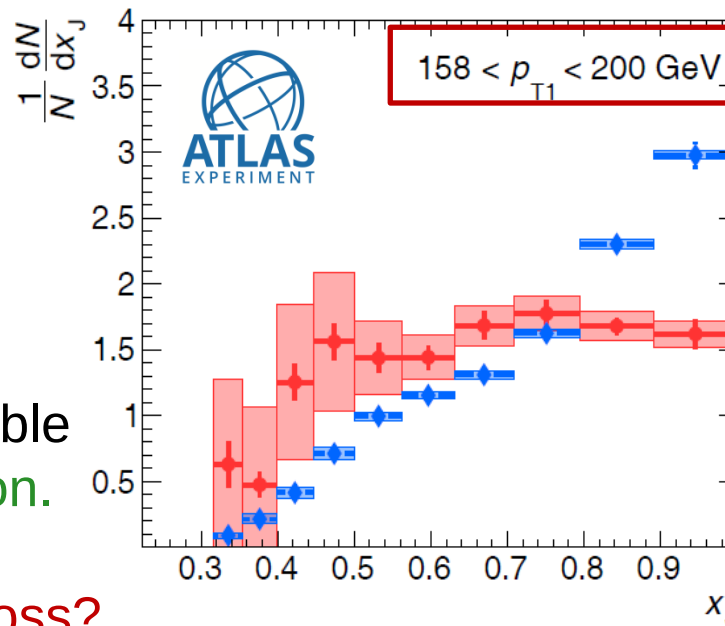
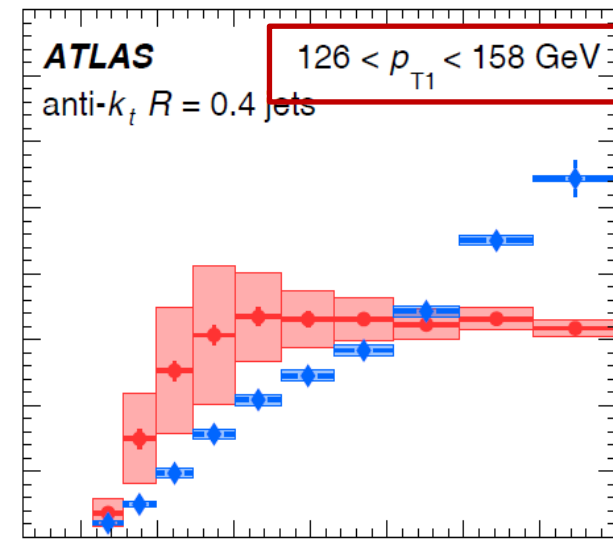
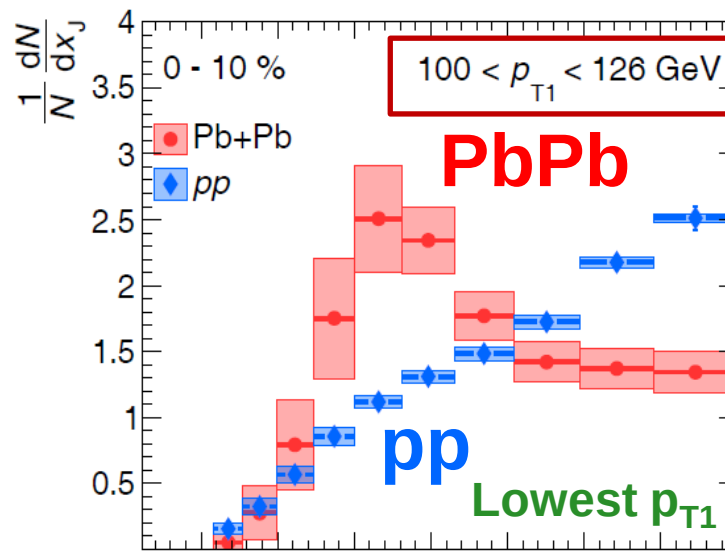
Burning Experimental Issues



Dijet Asymmetry in PbPb at 2.76 TeV



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



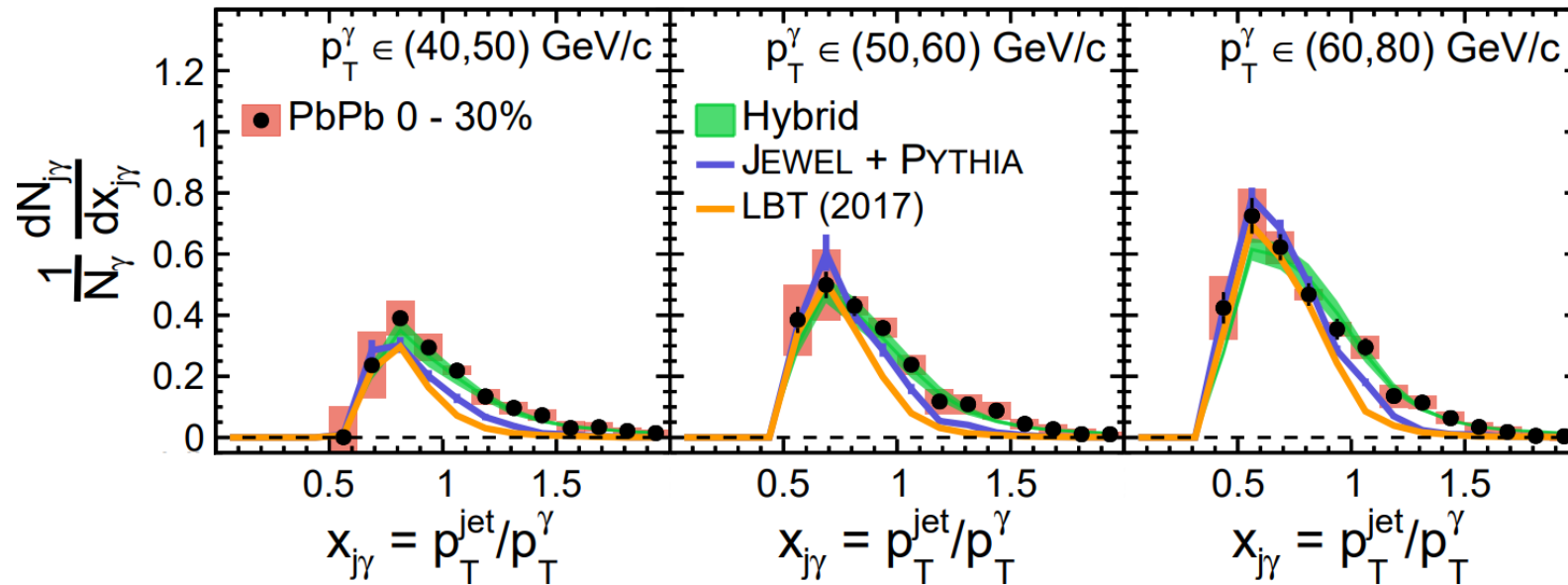
Origin of the peak??

- 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

Photon-Jet Asymmetry

CMS

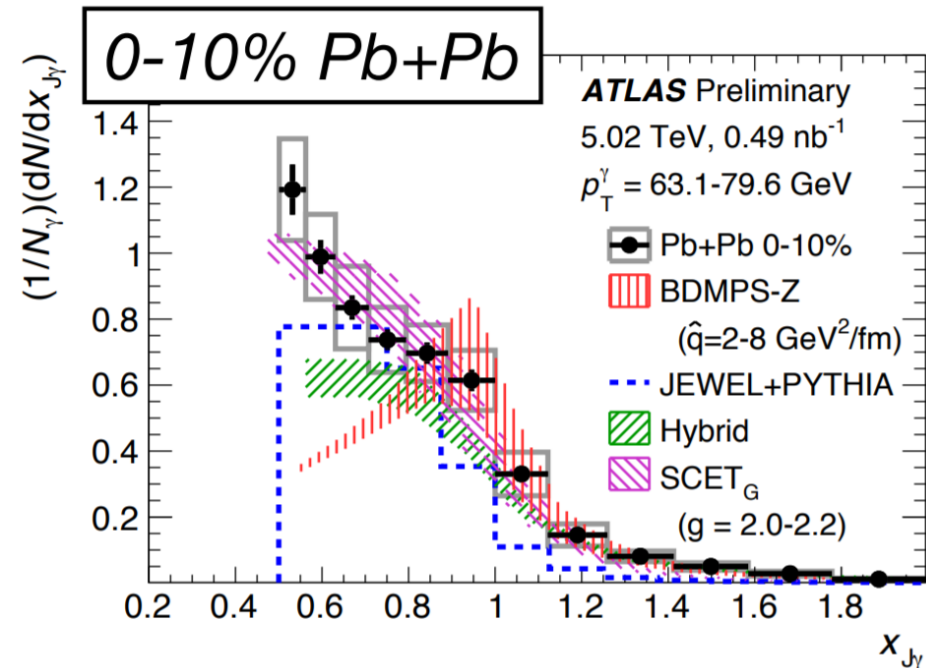
anti- k_T jet $R = 0.3$, $p_T^{\text{jet}} > 30$ GeV/c, $|\eta^{\text{jet}}| < 1.6$



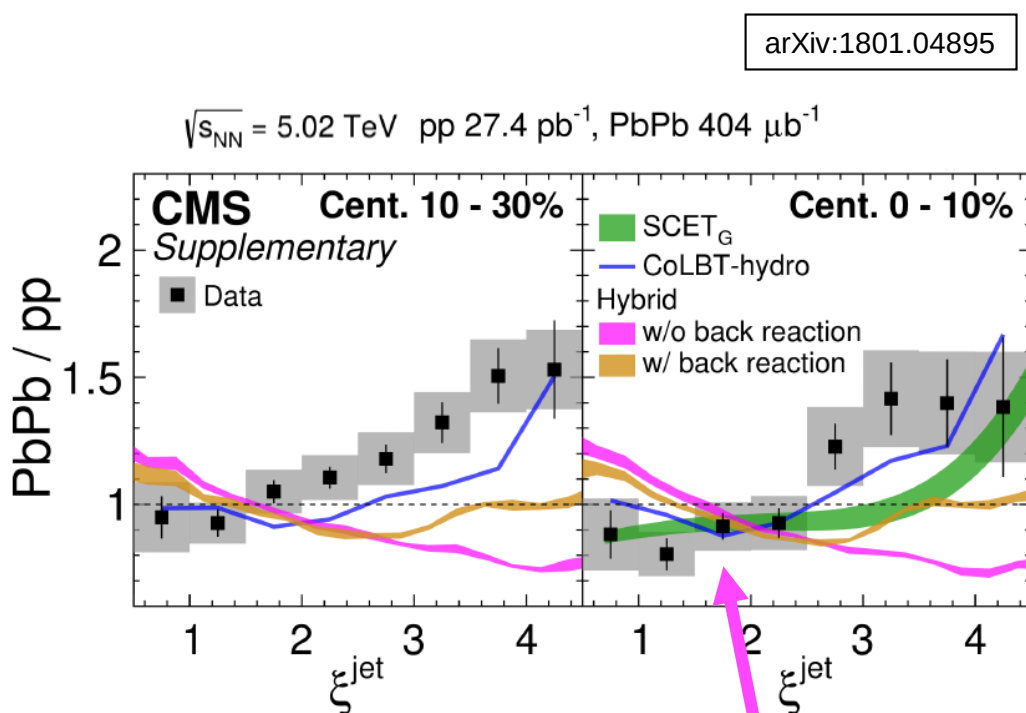
Theory smeared

Data Unfolded

- Different conclusions on model comparisons between CMS and ATLAS at low $x_{j\gamma}$
- Example: **HYBRID** model describes CMS data almost perfectly; inconsistent with ATLAS data at low $x_{j\gamma}$
- Note the difference in the photon p_T and jet p_T selection

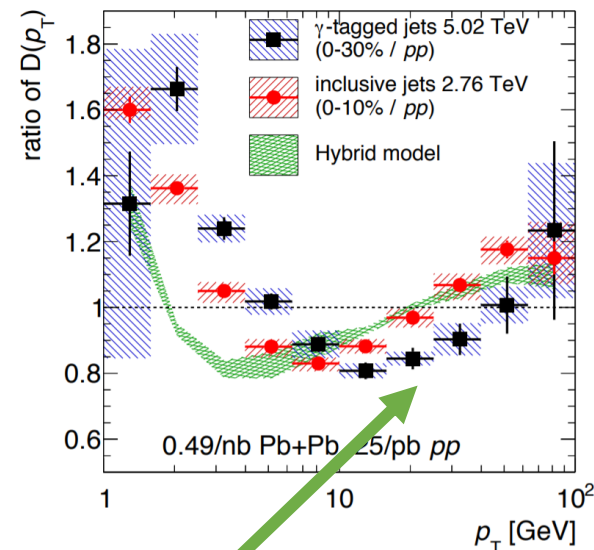


Jet FF with photon p_T as reference

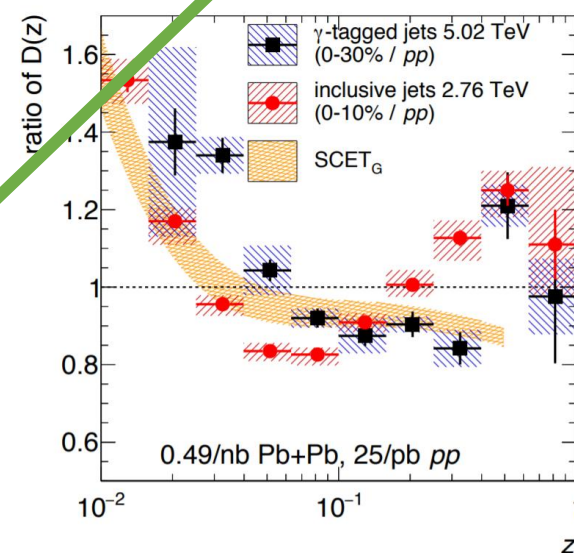


Let's focus on the high p_T part of the spectra:

- Different slope between **HYBRID model** and the CMS data (vs ξ)
- Similar slope (but an offset) between **HYBRID** and ATLAS data (vs p_T)



ATLAS



SCET_G

Z.-B. Kang, F. Ringer, I. Vitev *et al.*
JHEP 11 (2016) 155

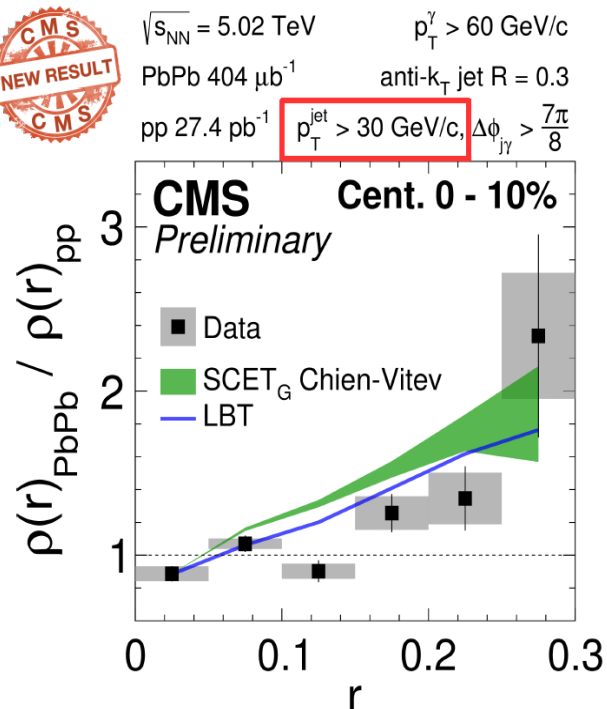
HYBRID

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

CoLBT-Hydro calculation

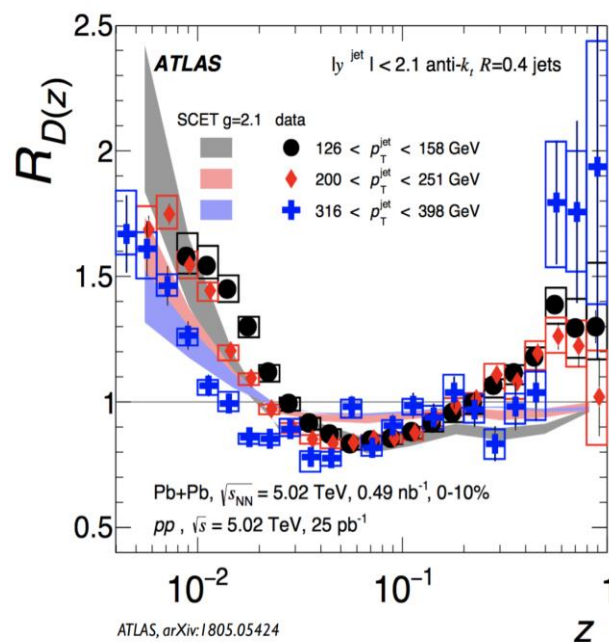
W. Chen, S. Cao, T. Luo, L.-G. Pang, X.-N. Wang
arXiv:1704.03648

Jet Shape and FF



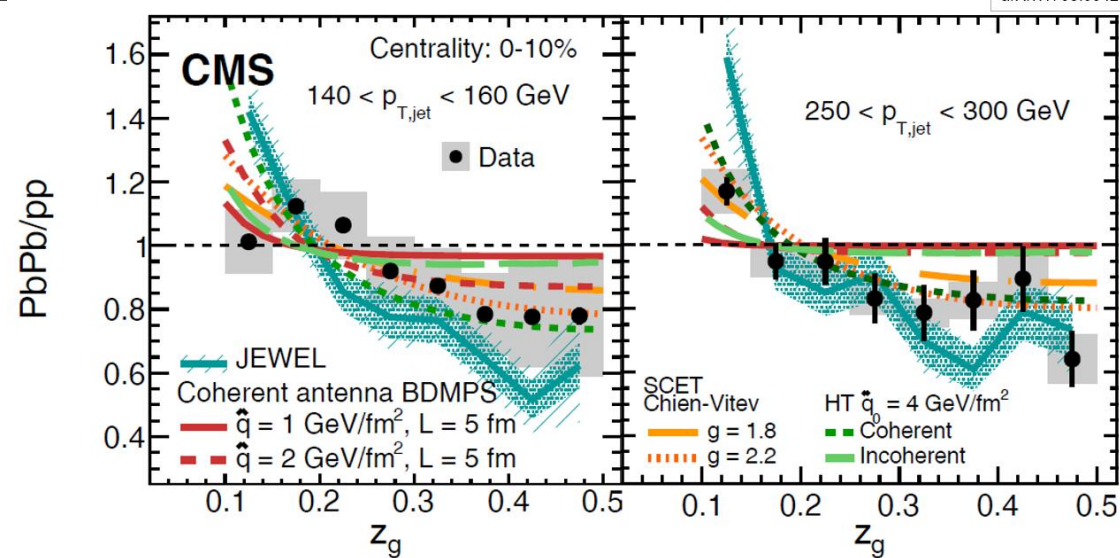
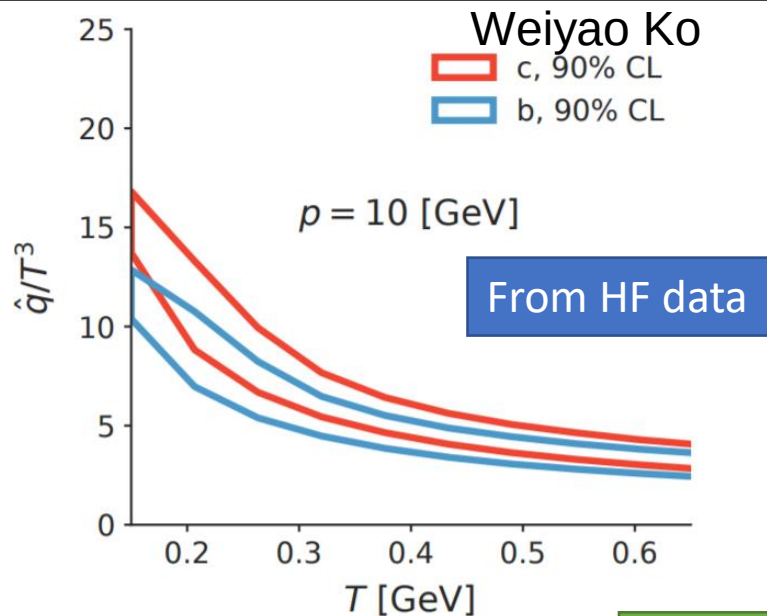
Need an ATLAS version of jet shape

Need a CMS version of jet FF for inclusive jet



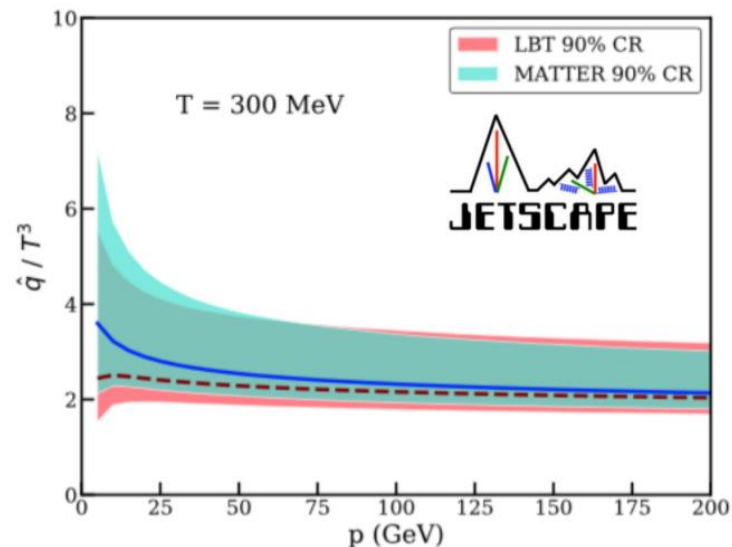
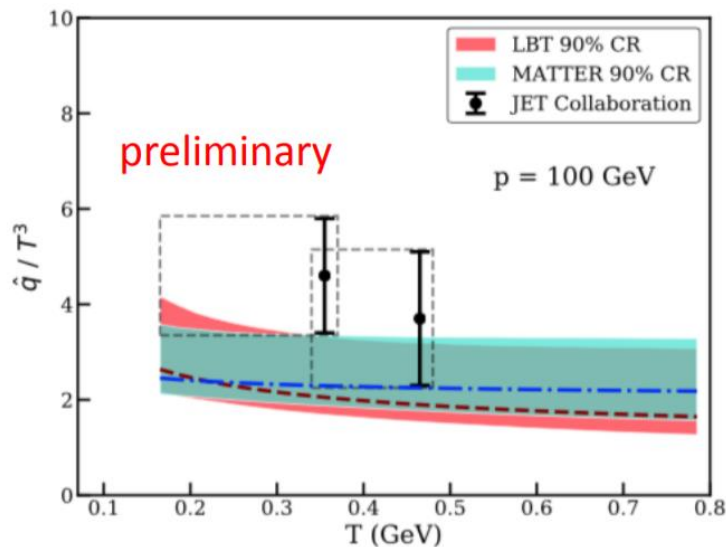
Can we measure them at RHIC?

Extraction of the Medium Properties



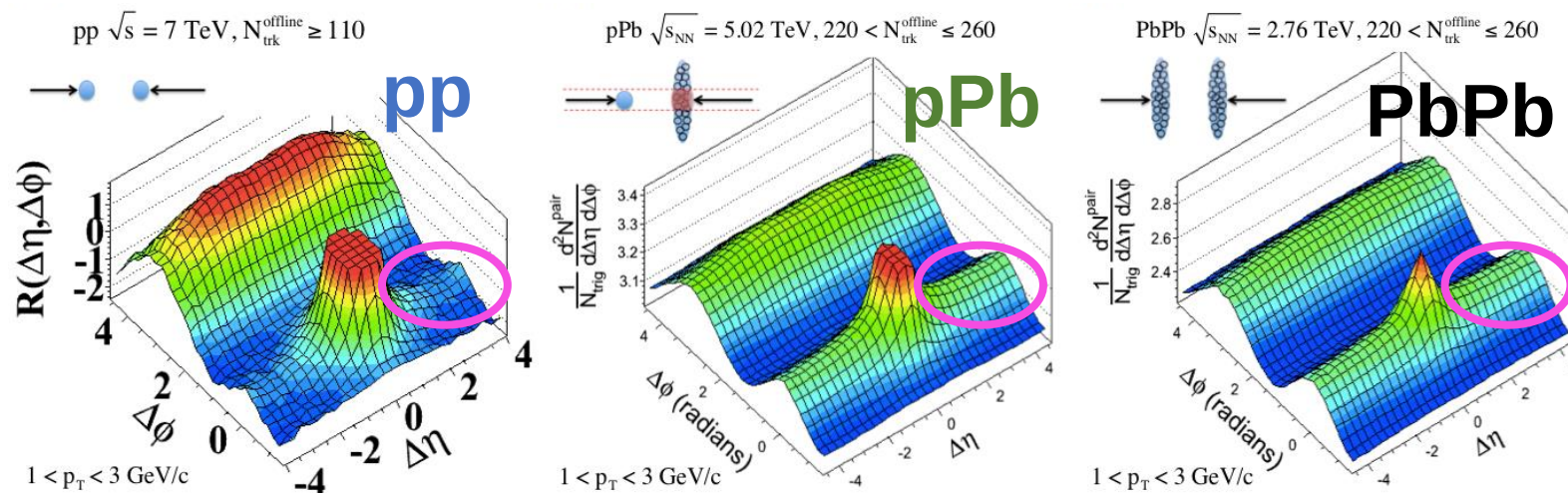
From charged hadron data

From jet substructure data



One could only gain confidence if we get consistent results from various observables

Jet Quenching in Small System

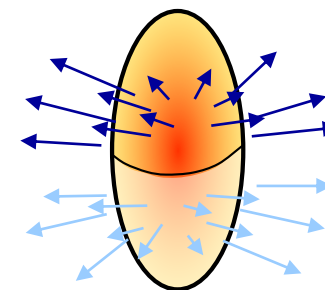
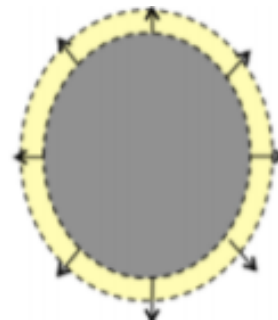
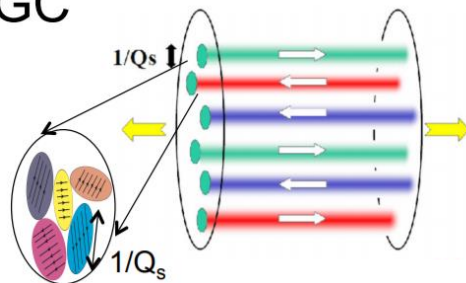


Initial State Correlation

Escape Mechanism

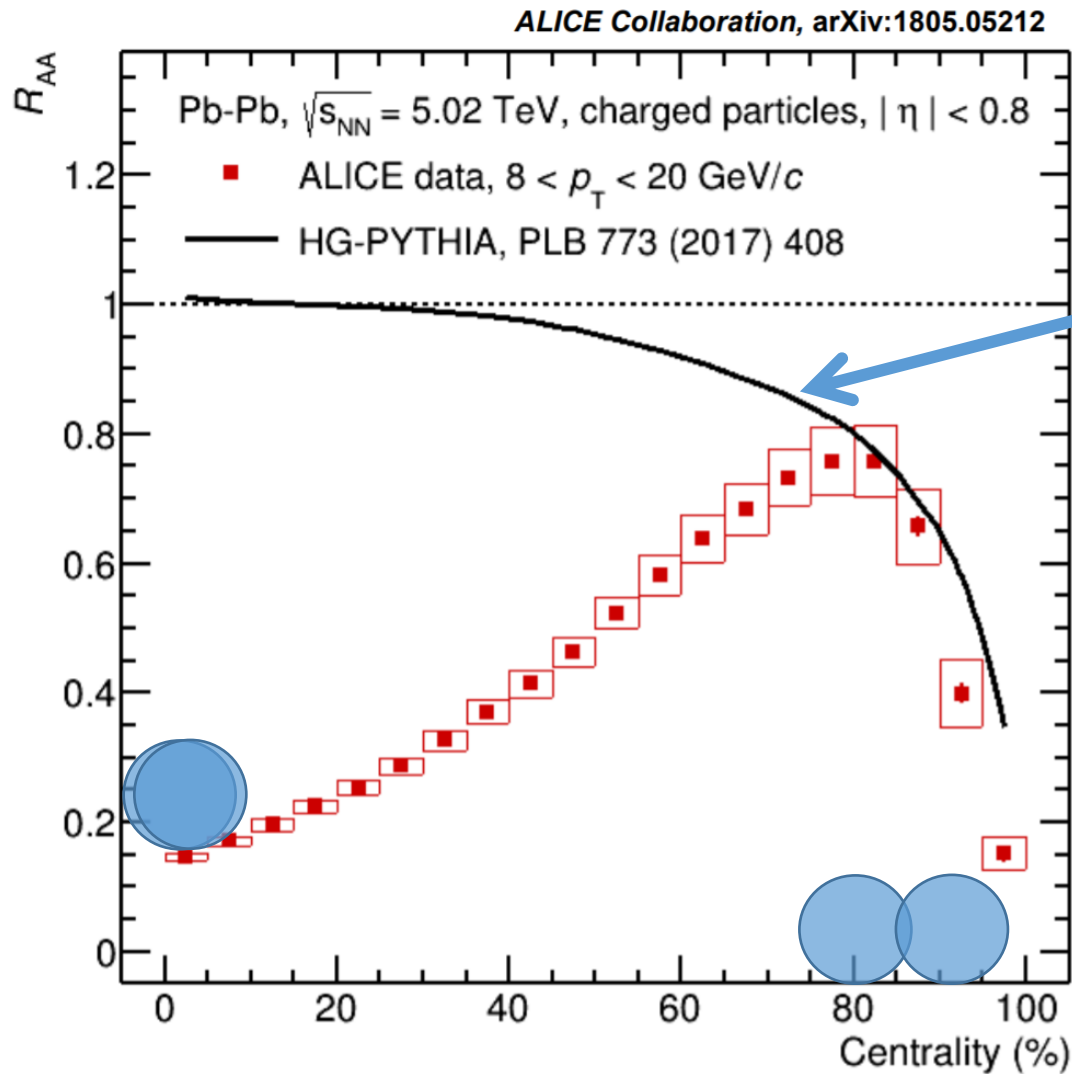
QGP Formation

CGC



- Collective behavior is observed in small systems
- Have we detected jet quenching in small system?
- Connection to suppression in peripheral AA collisions?

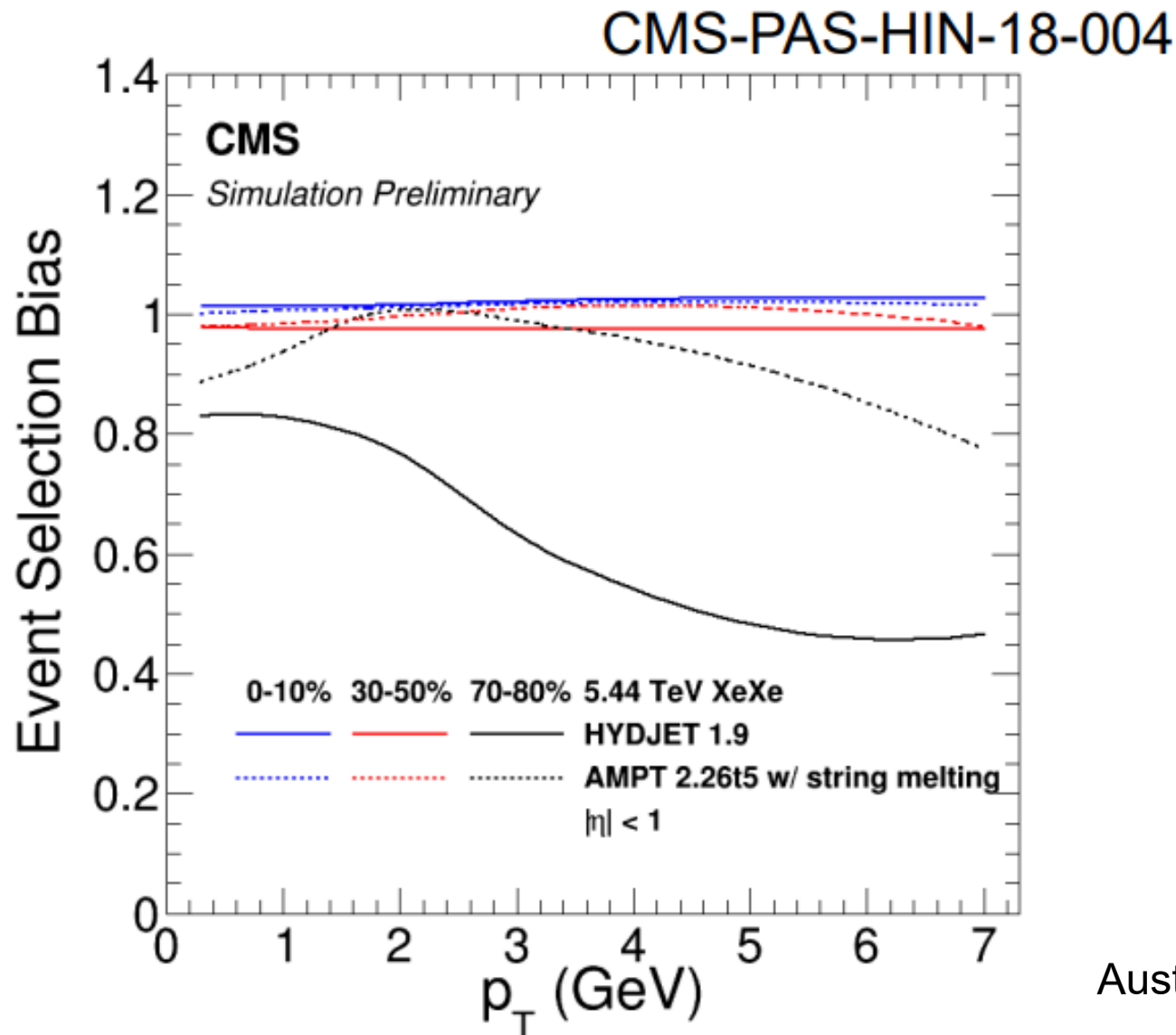
Centrality Selection Bias



Incoherent superposition of many PYTHIA events (nucleon-nucleon collision) according to the # of multi-parton interaction in HIJING generator

- Selection bias plays a very important role in peripheral events
- Very important input to the interpretation of the peripheral data
- Amount of bias: can be process dependent

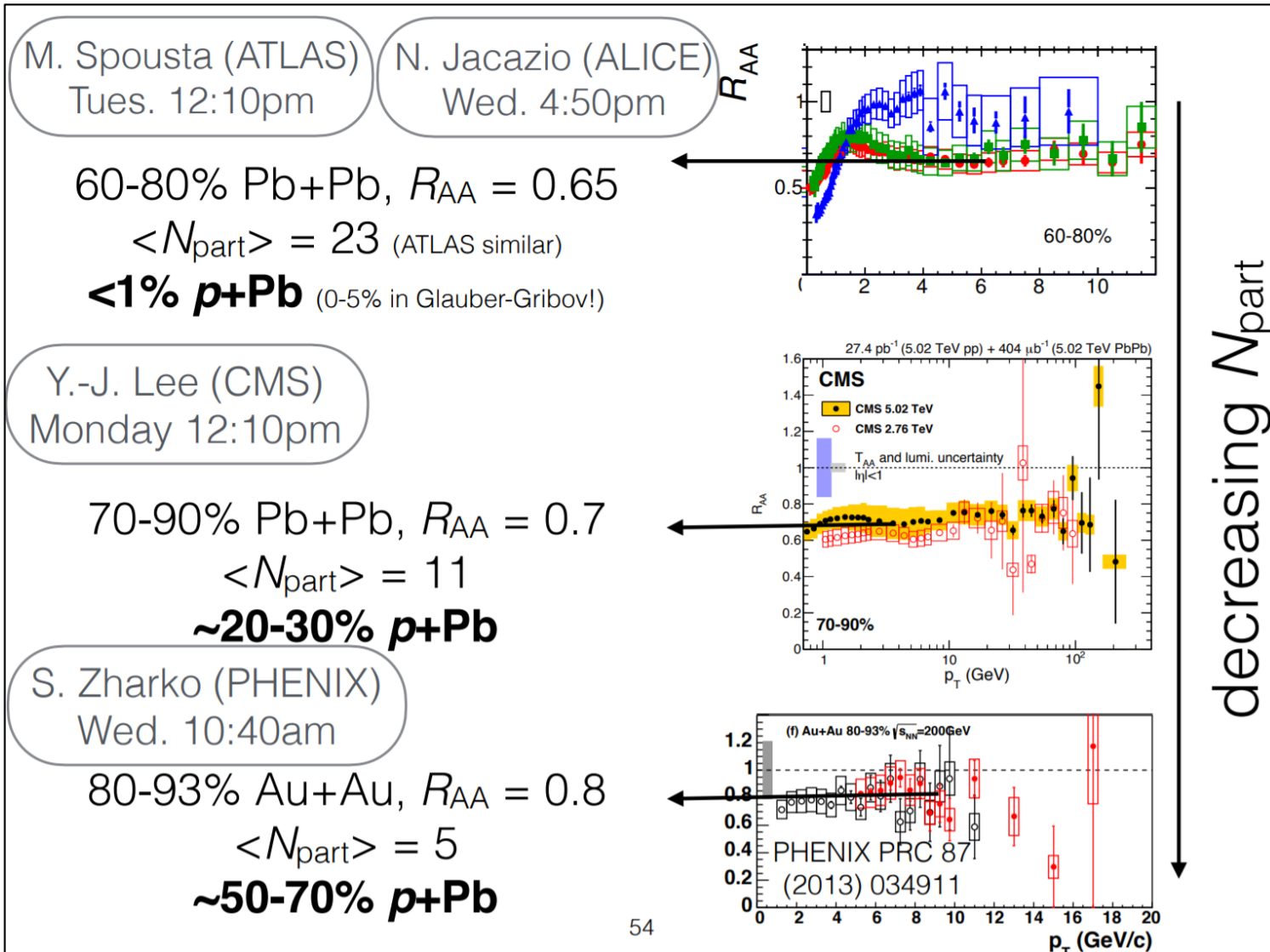
Selection Bias



Austin Baty (QM'18)

- Size of the selection bias is model dependent (and process dependent!)
- i.e., this problem can not be resolved by using Z boson production as normalization

R_{AA} in peripheral events



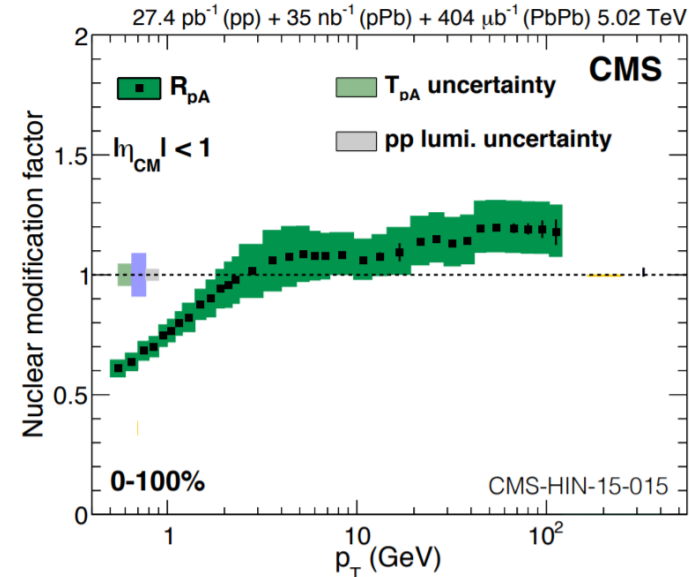
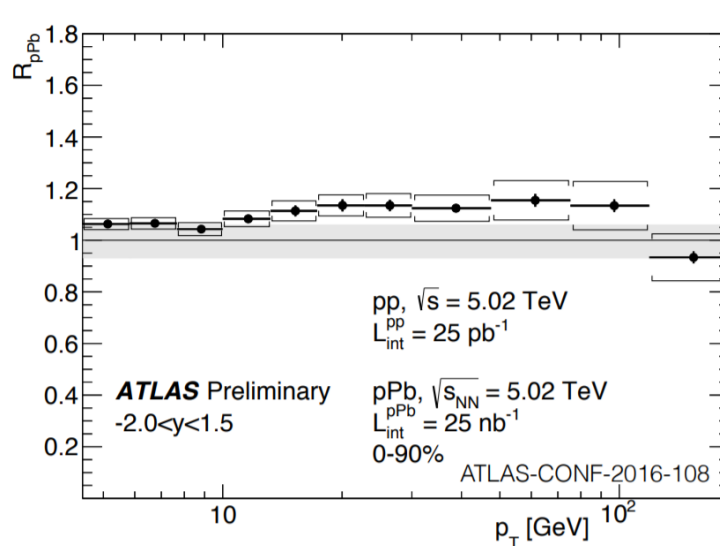
From Dennis Perepelisa QM'17

With ALICE data analysis (also CMS generator studies) shown in QM'18

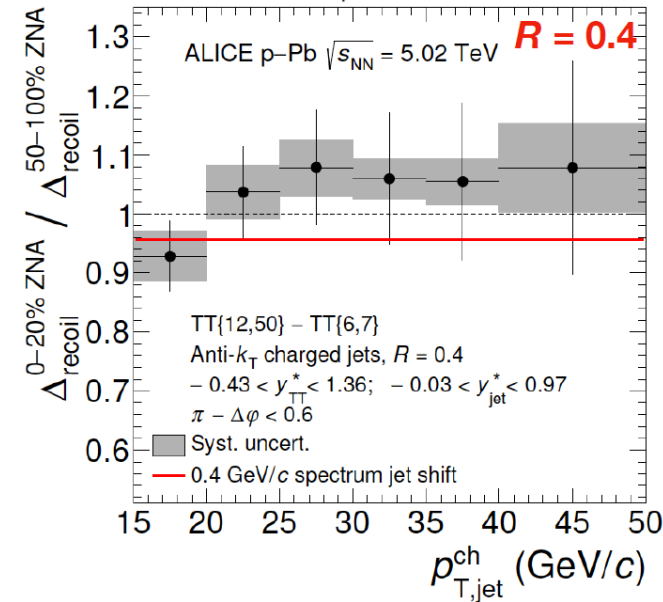
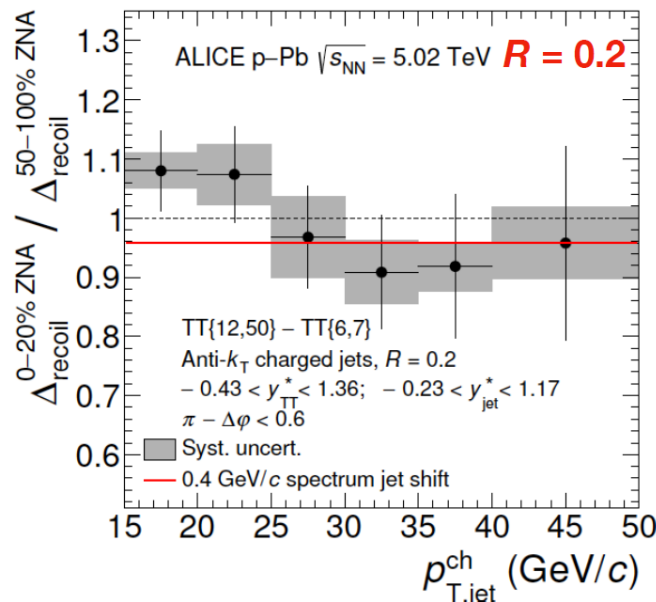
Models which interpreted these data as cold nuclear effects are wrong

pPb collisions

R_{AA}

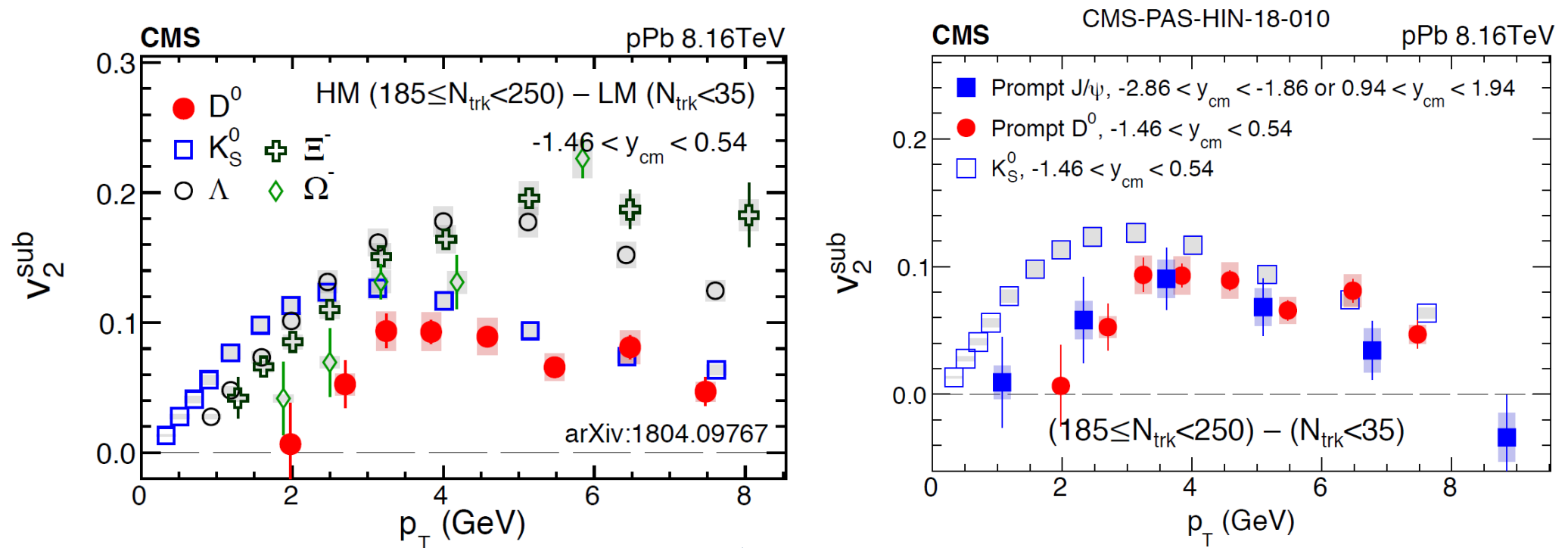


Δ_{recoil}



- Also Charged Particle Q_{pPb} from ALICE and CMS dijet
- No suppression observed in pPb collisions from those observables

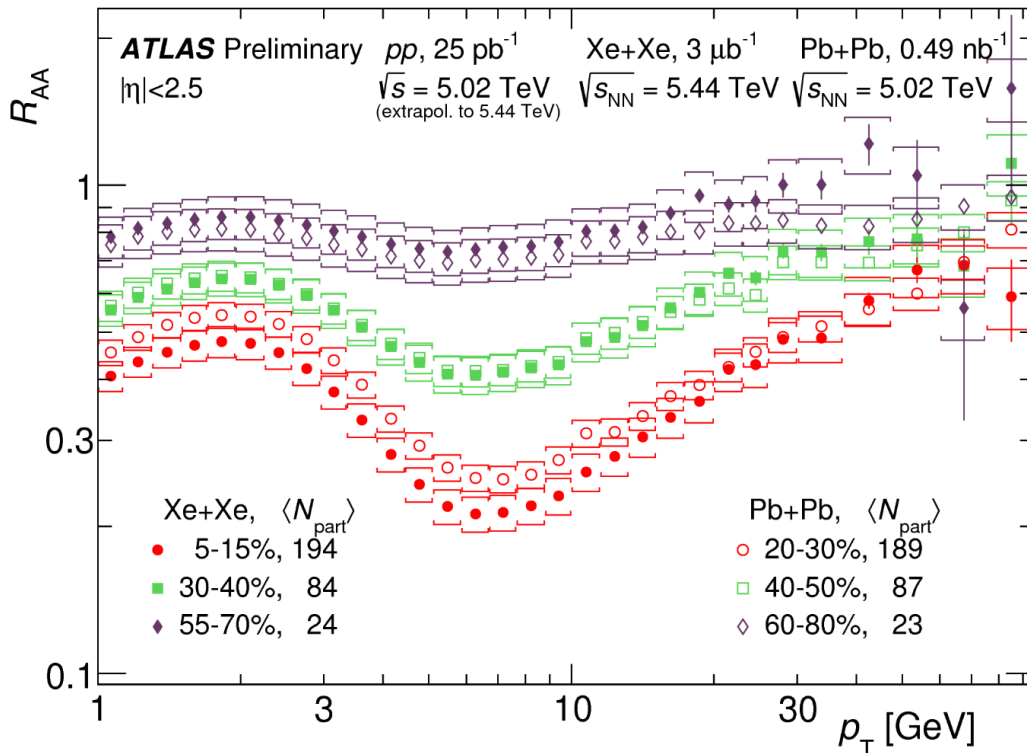
D^0 and Prompt J/ψ v_2 in pPb



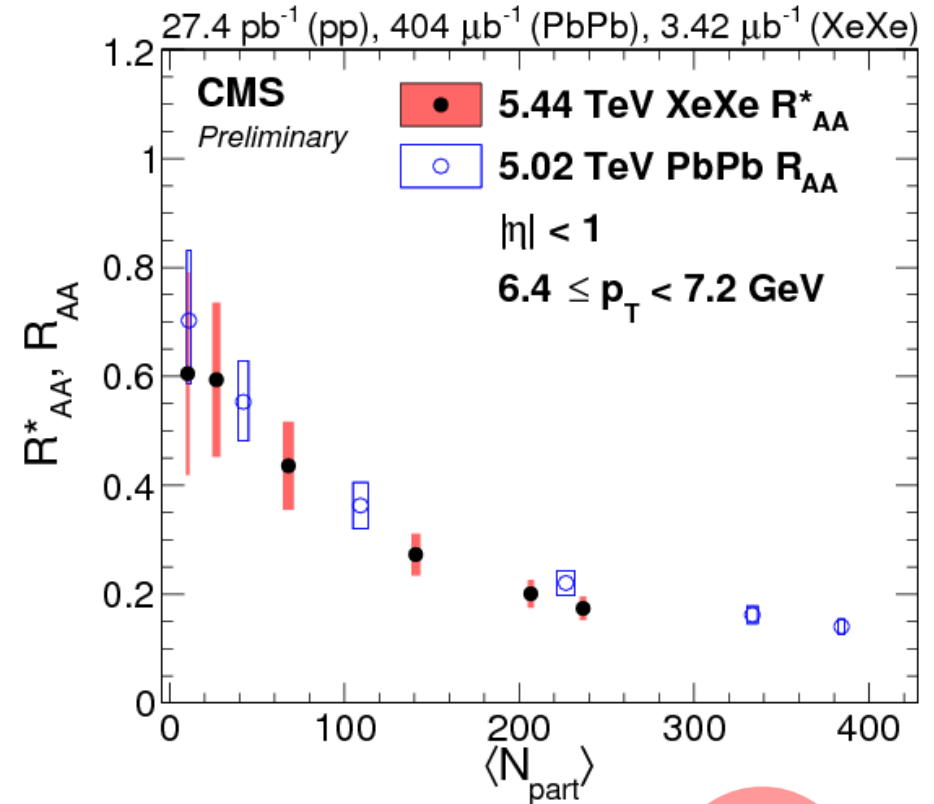
- Sizable v_2 signal at high p_T in various identified hadrons
- Also shown by ATLAS from inclusive charged particle v_2
- Is this an indication that CGC and/or Escape Mechanism could be the dominant source in pPb?

System Size Dependence

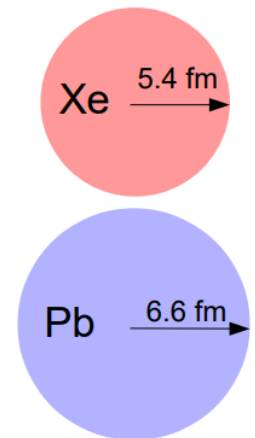
ATLAS-CONF-2018-007



CMS-PAS-HIN-18-004



- High p_T charged particles are strongly suppressed in XeXe collisions
- Approximate scaling with N_{part}
- Future measurements in even smaller systems like OO, ArAr and KrKr could be of interest

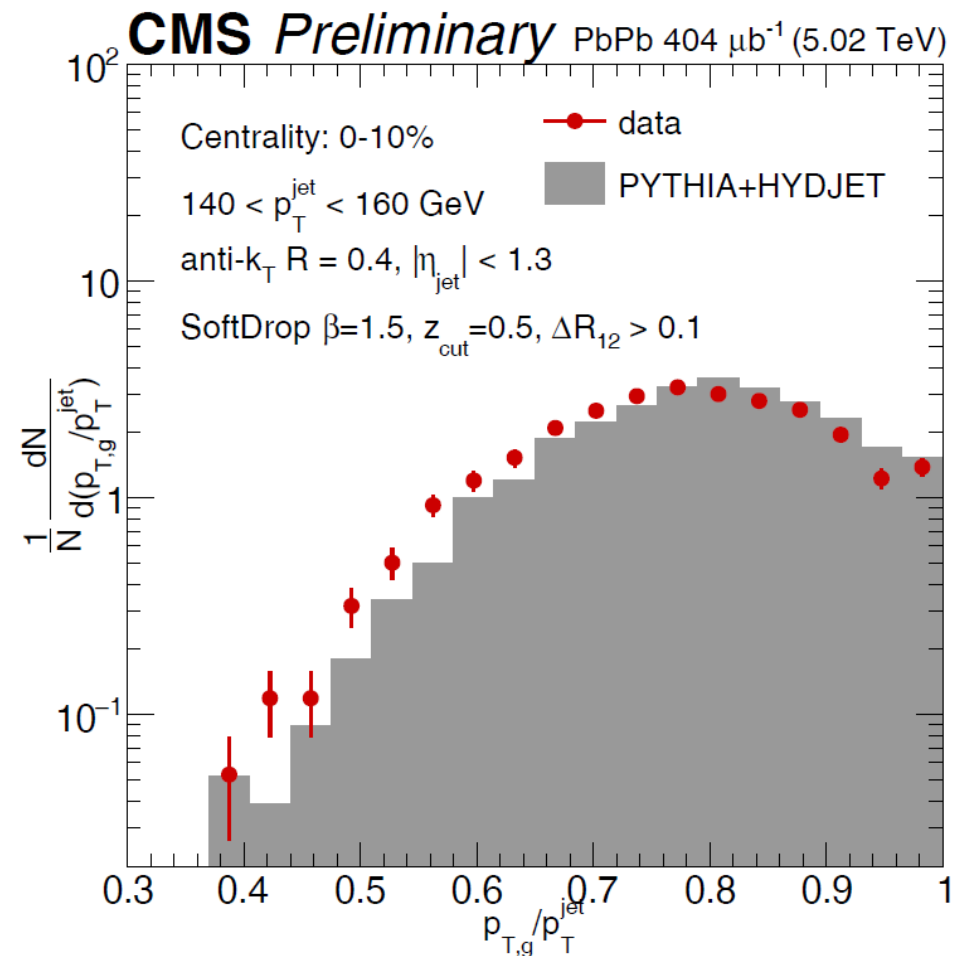
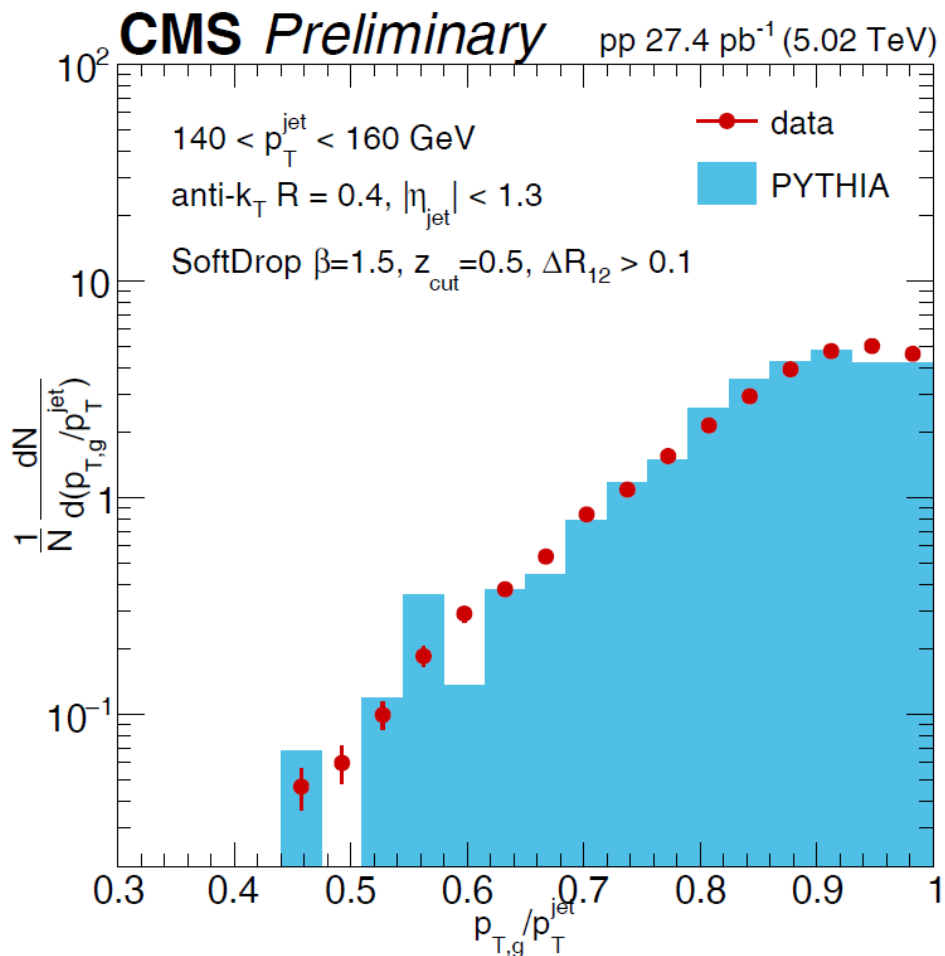


Summary

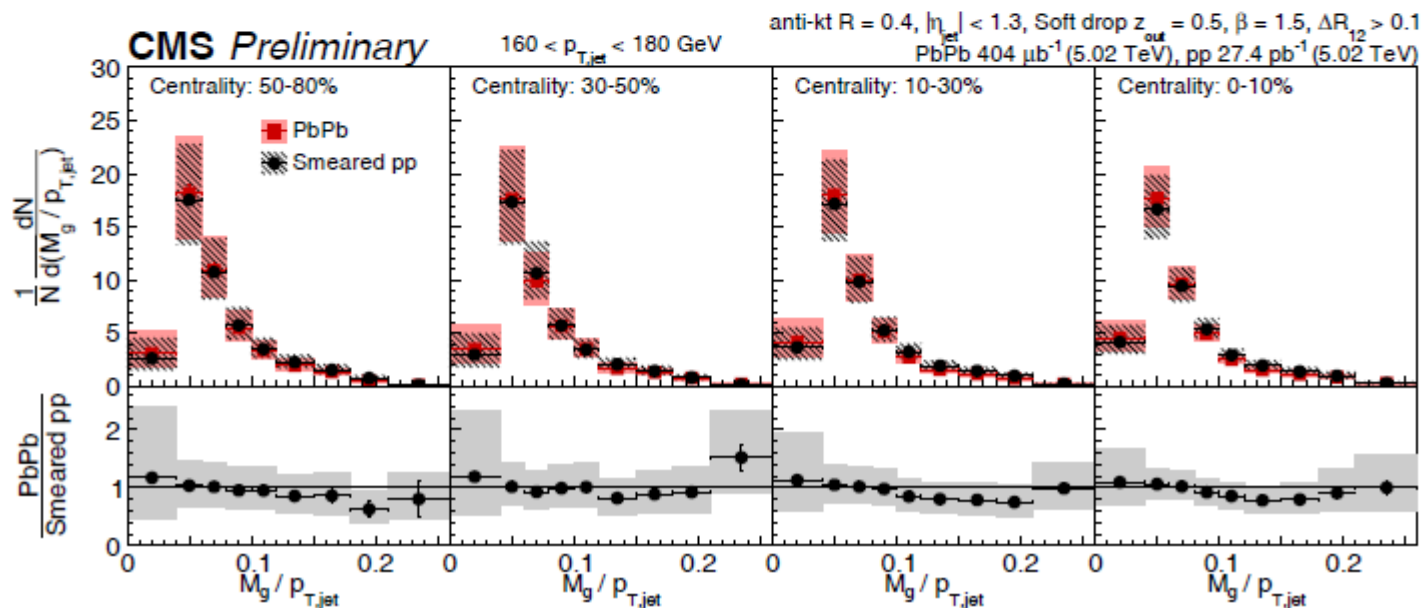
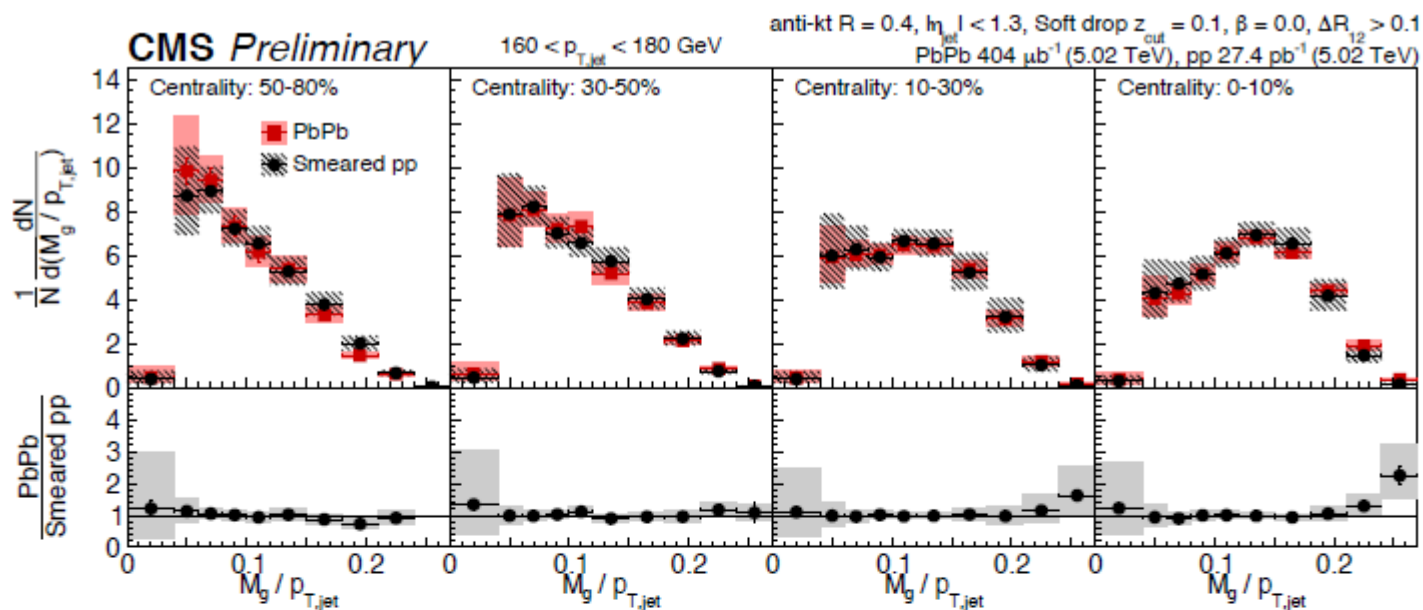
- **Energy flow with respect to jet**
 - Unprecedented wide p_T reach with high statistics data
 - Modification of jet shapes and fragmentation function
 - Narrowing of the jet core in inclusive jet with respect to pp reference
 - Possible differences between CMS and ATLAS need to be resolved
- **Hint 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**
 - Toward the understanding of jet quenching as a function of the jet substructure
- **Jet Quenching in small system**
 - No significant evidence yet
 - Could be relevant for the interpretation of large systems

Backup slides

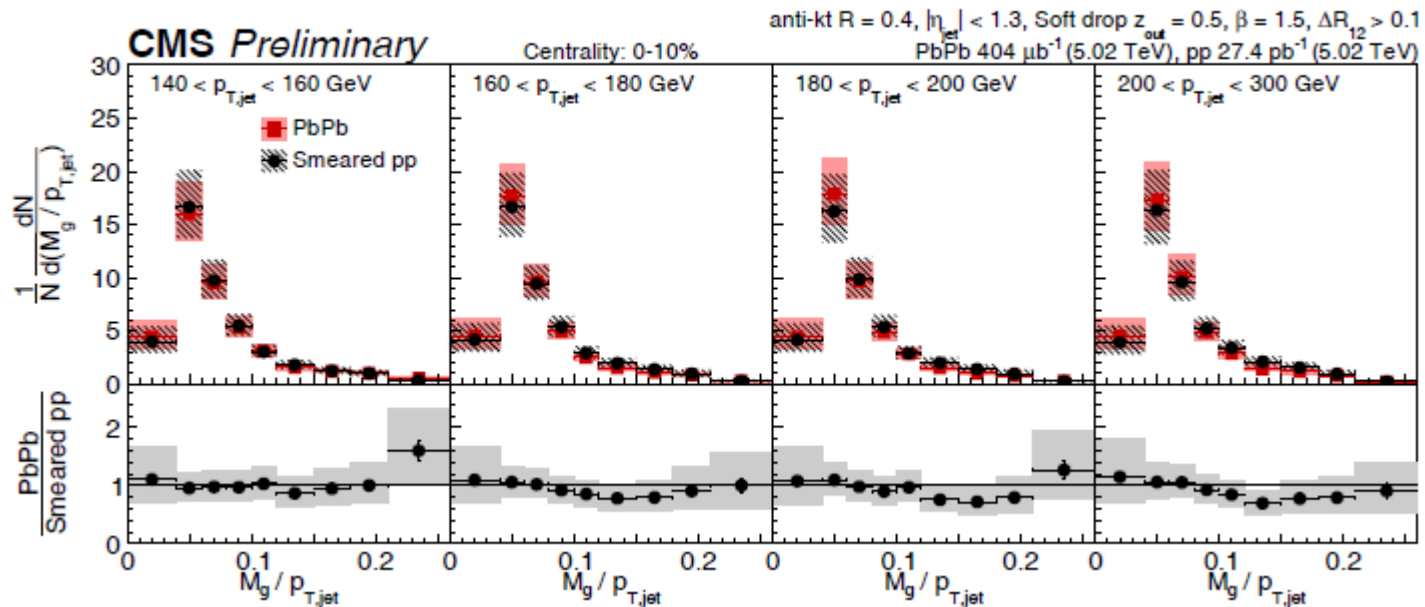
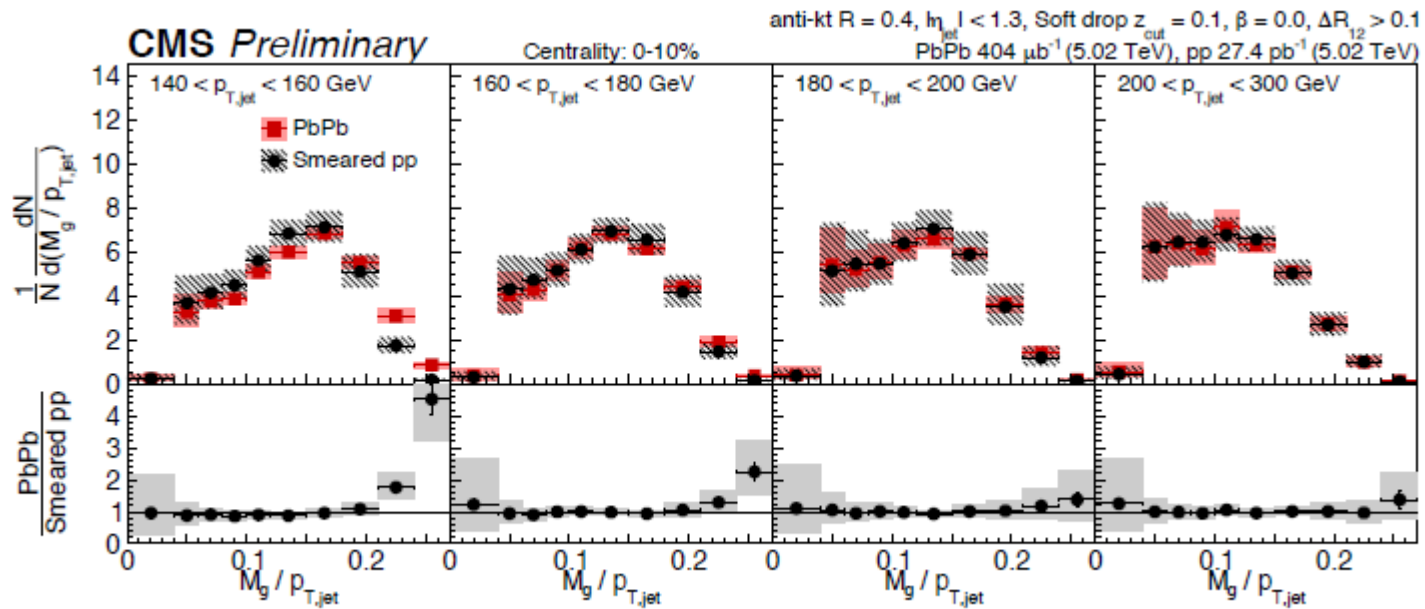
Groomed jet p_T fraction



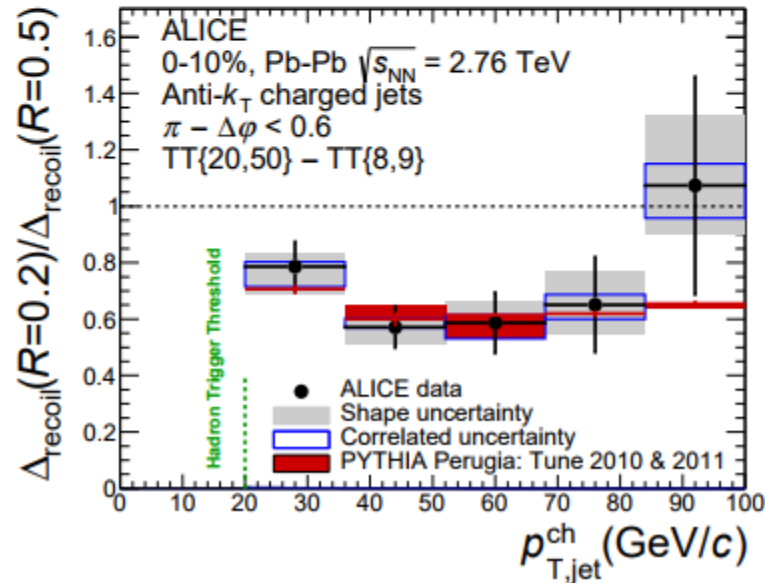
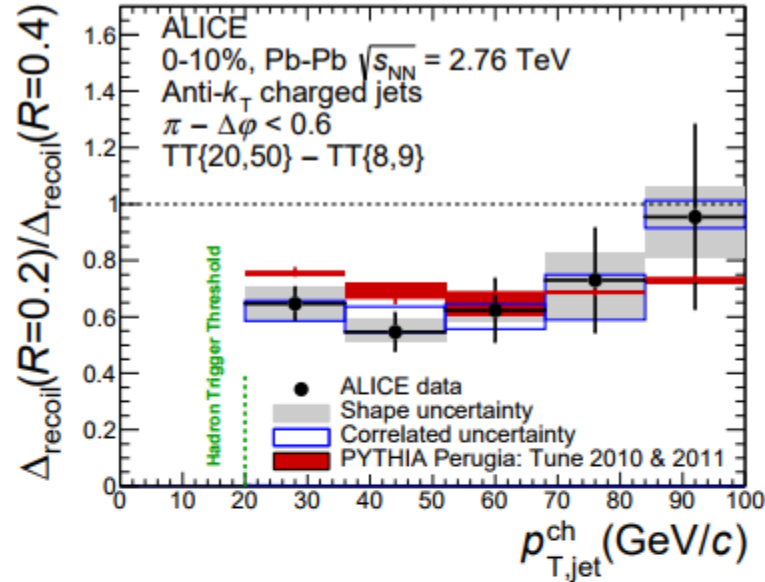
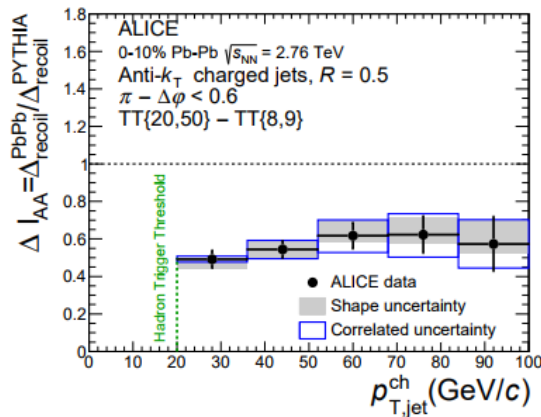
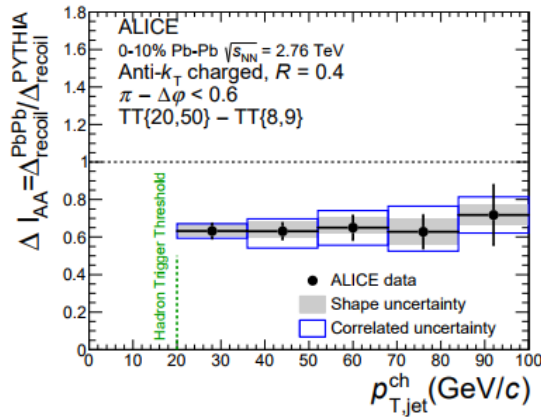
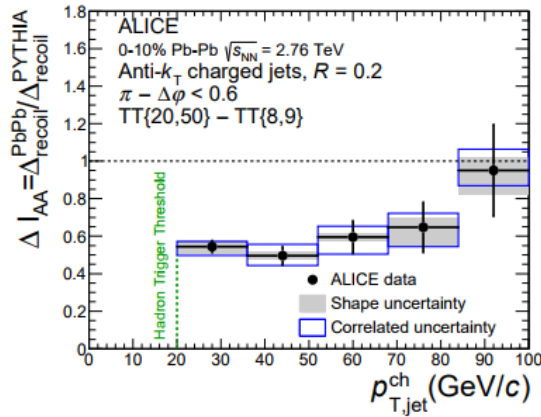
CMS Jet Mass



CMS Jet Mass vs. Jet energy

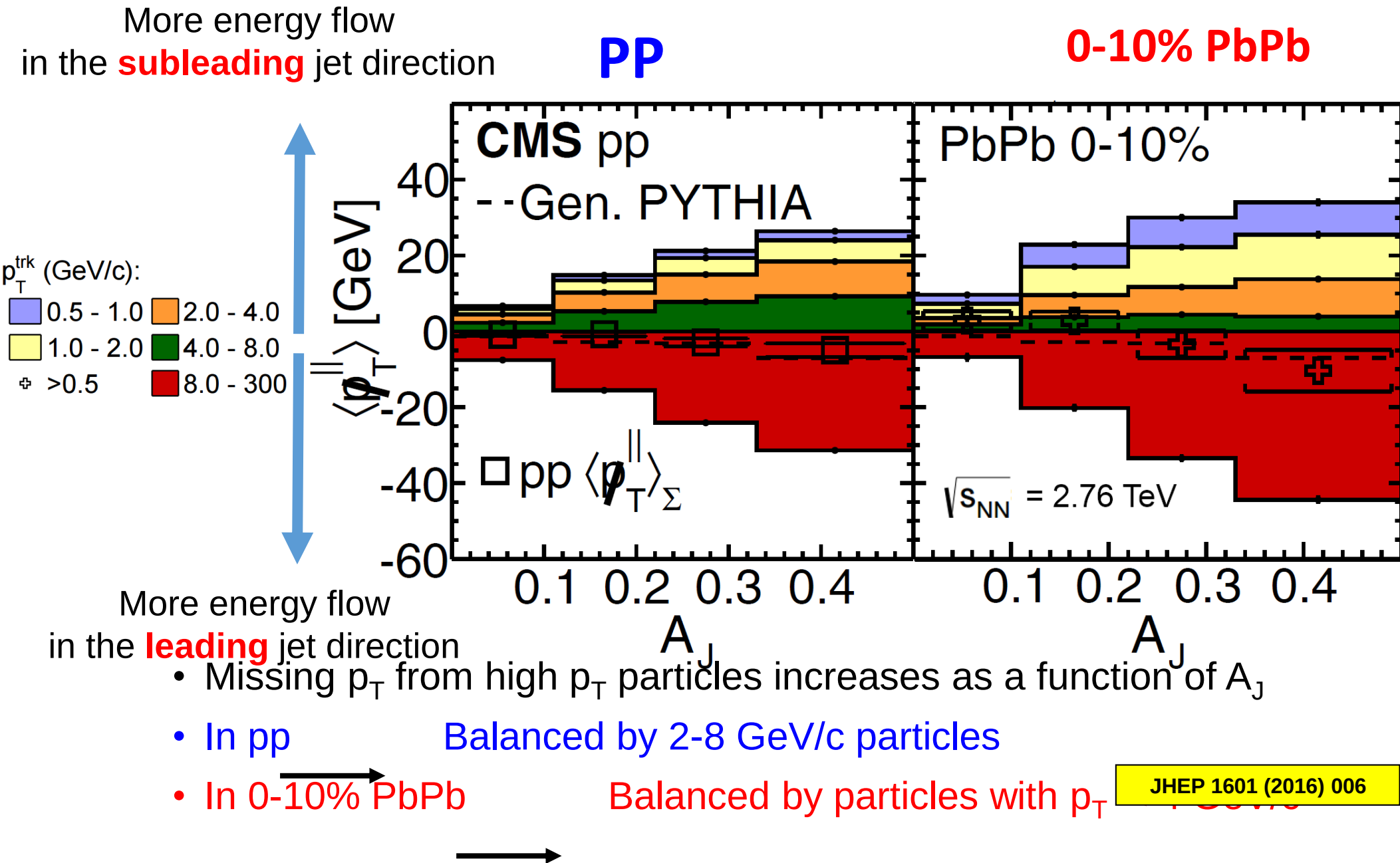


ALICE Hadron-Jet

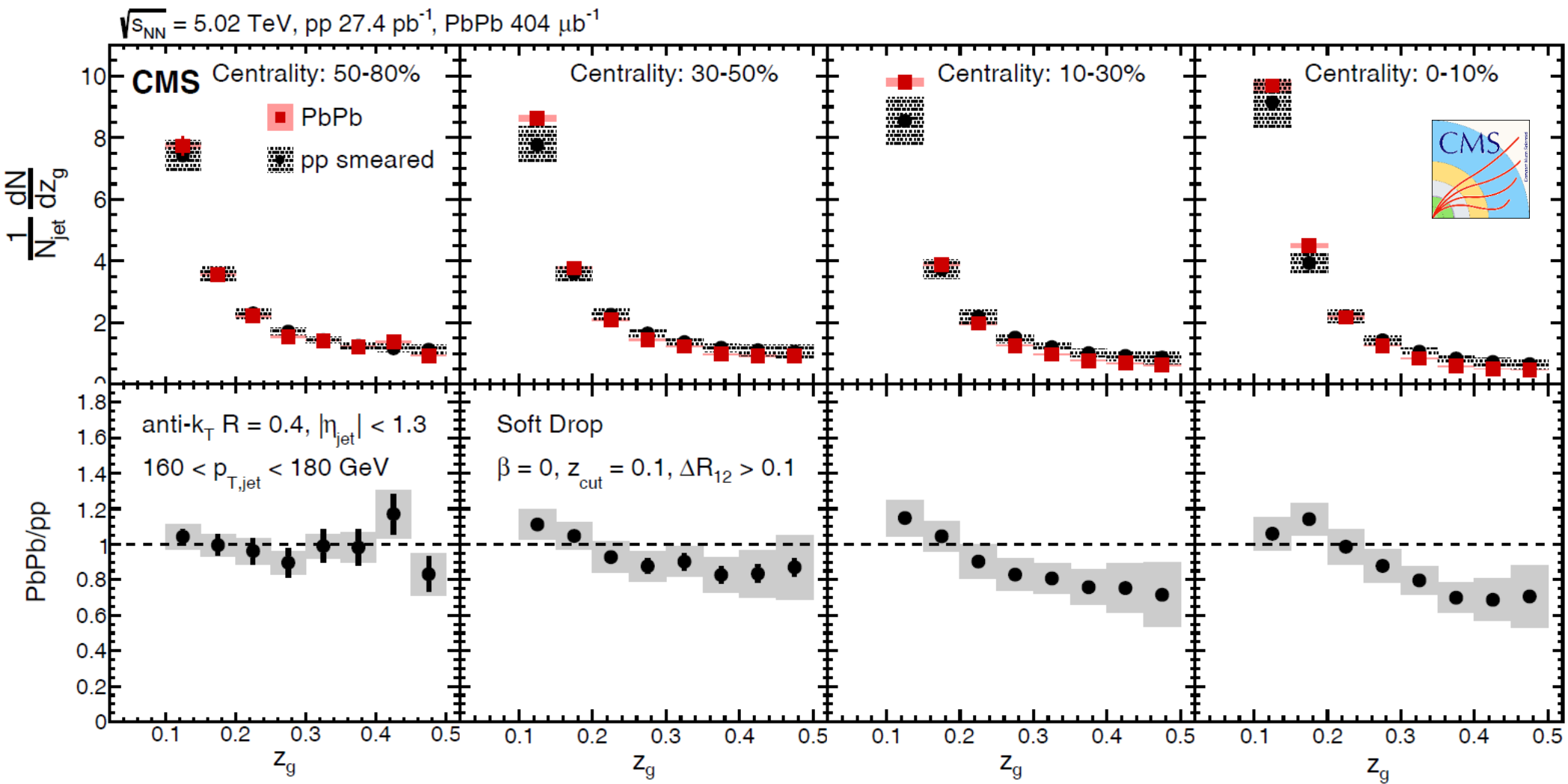


No **sizable** modification of jet shape

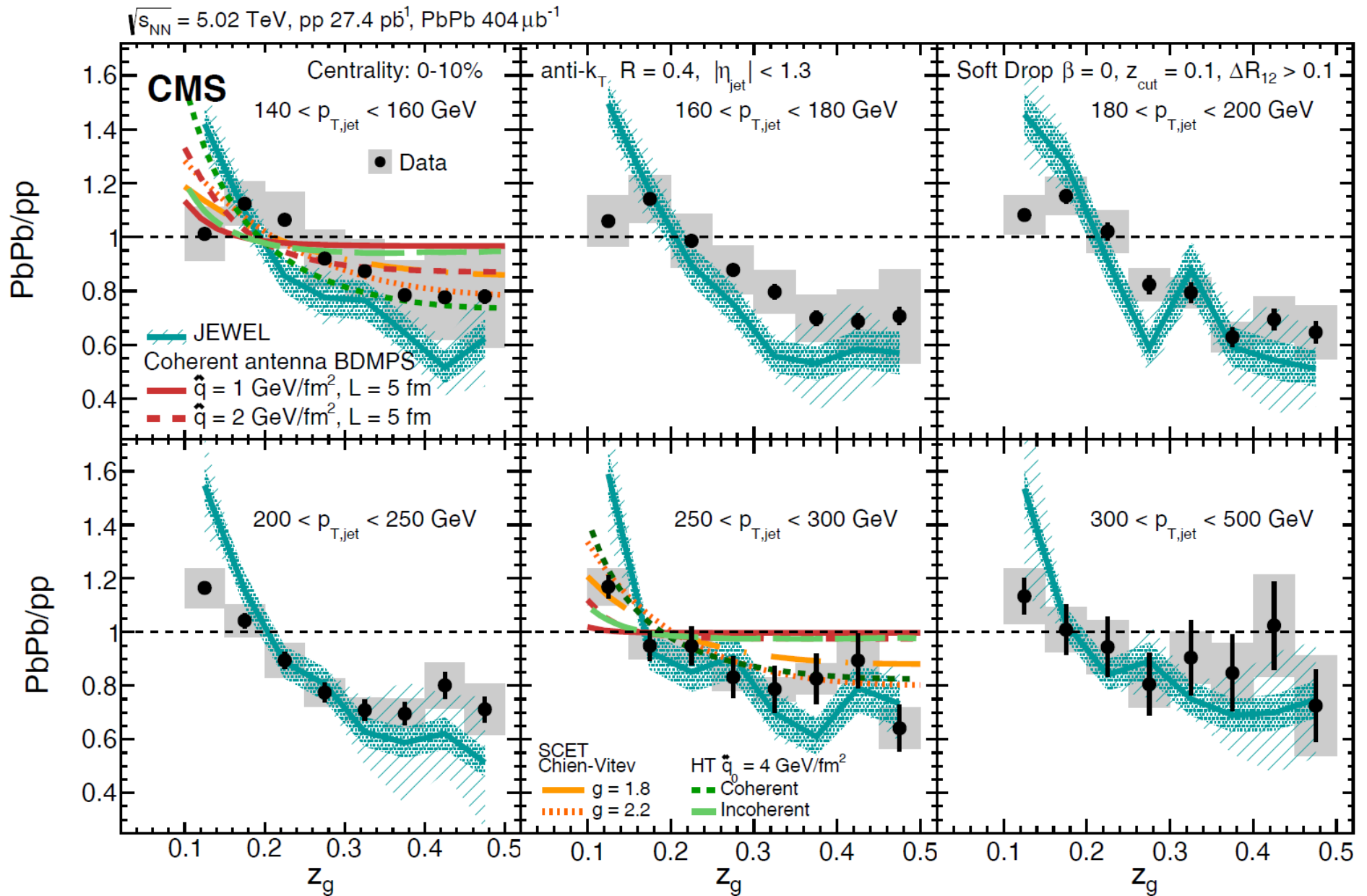
Missing $p_T^{\parallel}$ vs. A_J



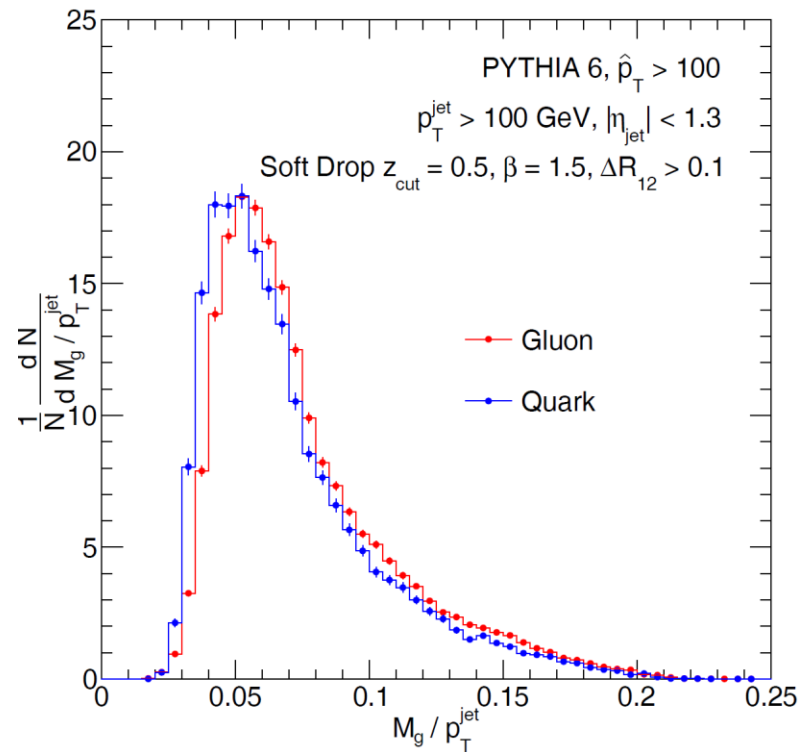
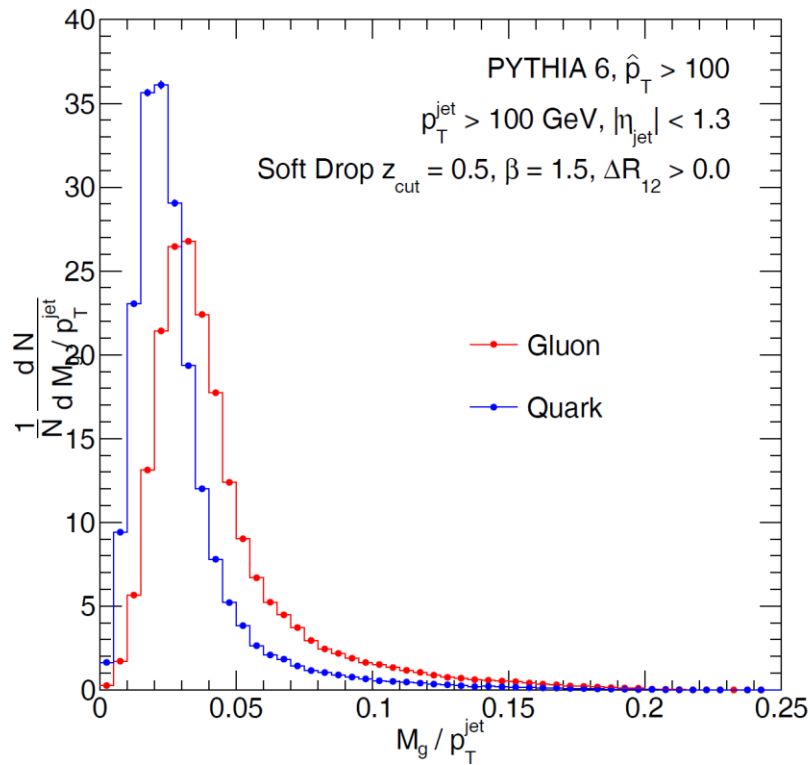
CMS Groomed Jet Splitting Function



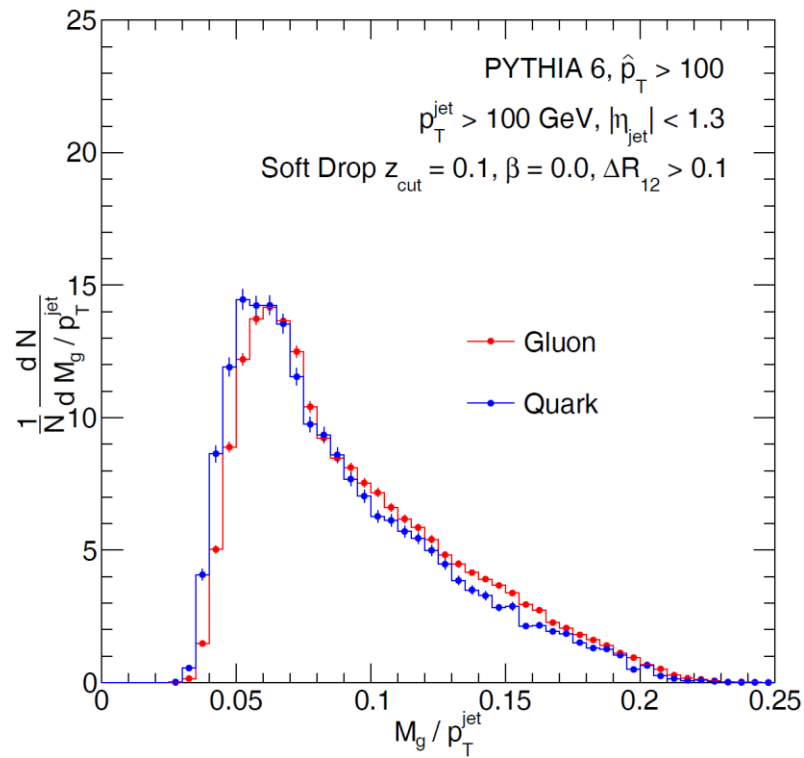
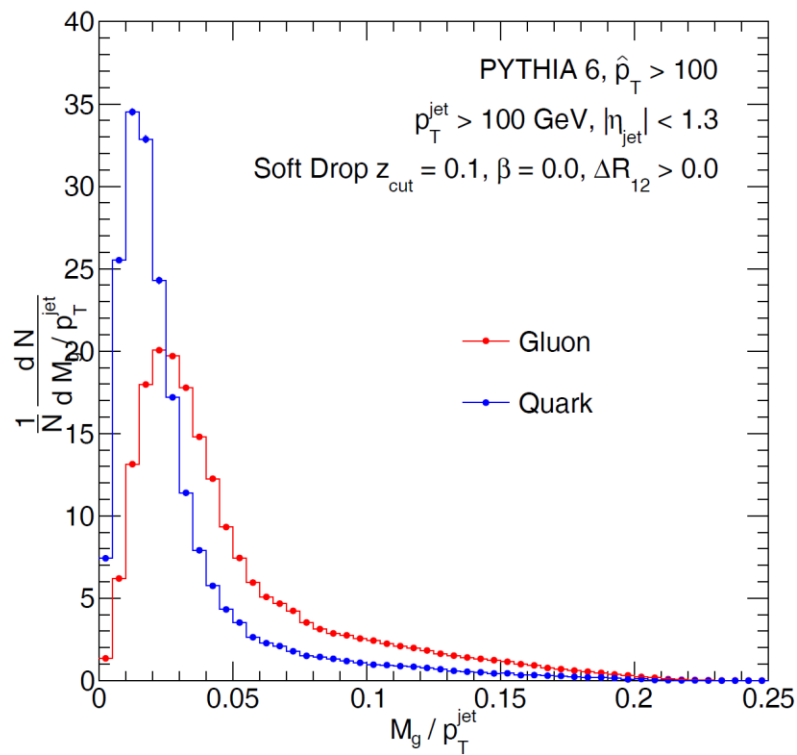
CMS Groomed Jet Splitting Function



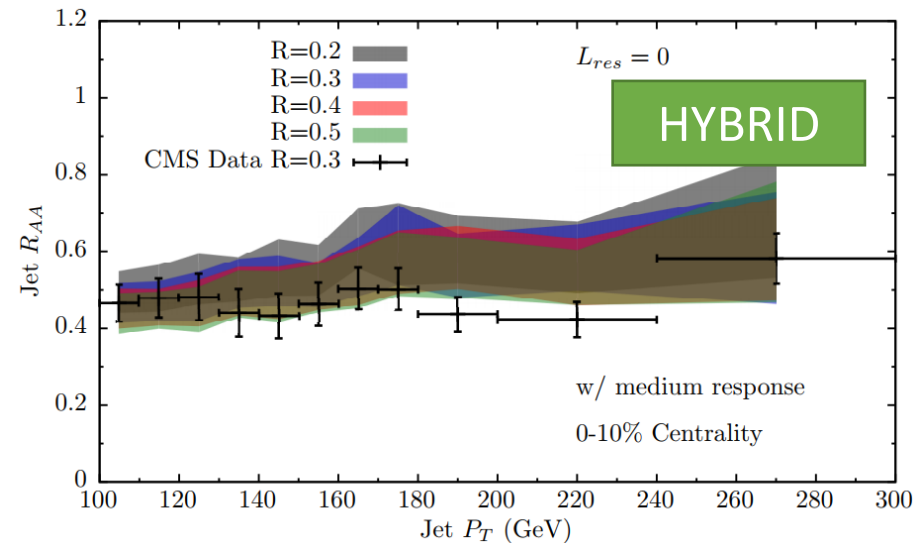
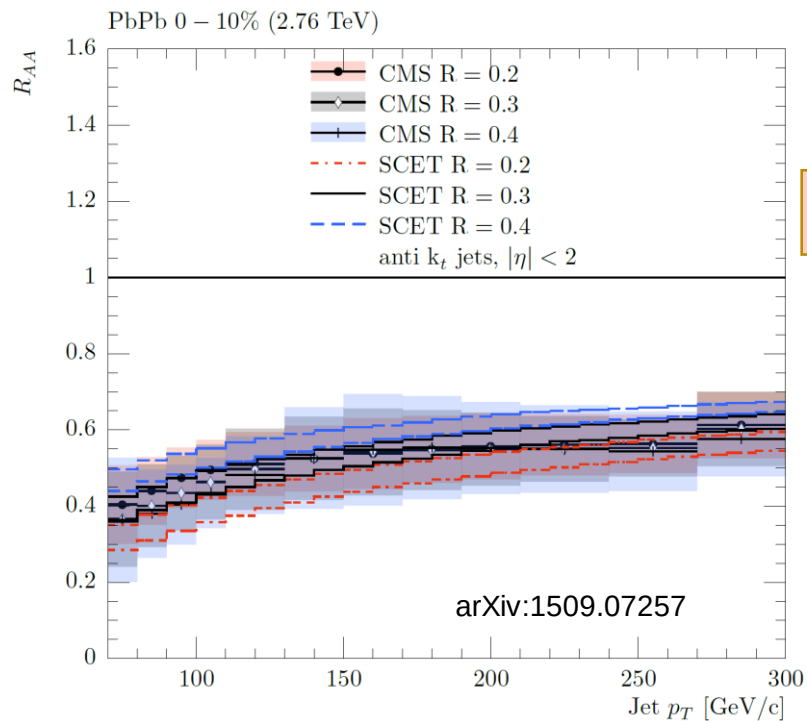
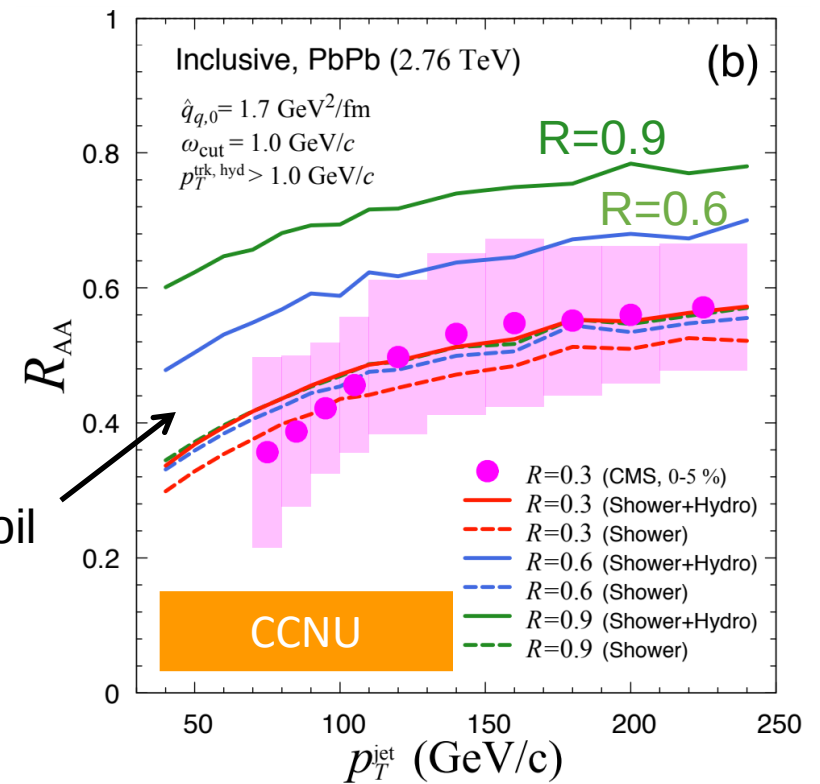
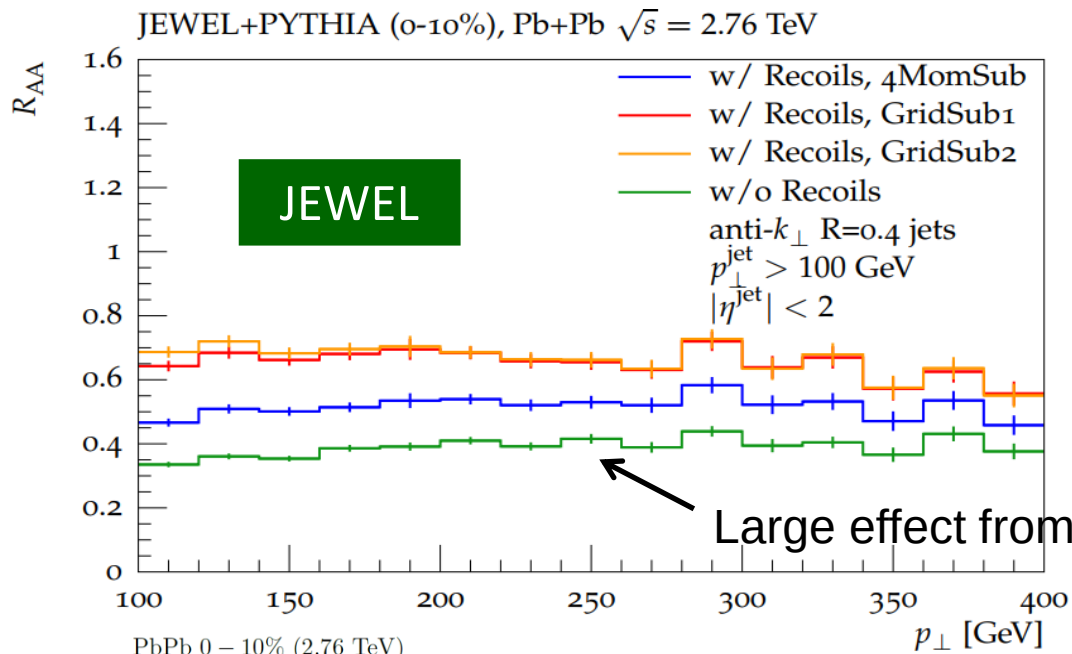
Groomed Jet Mass (Q vs G)



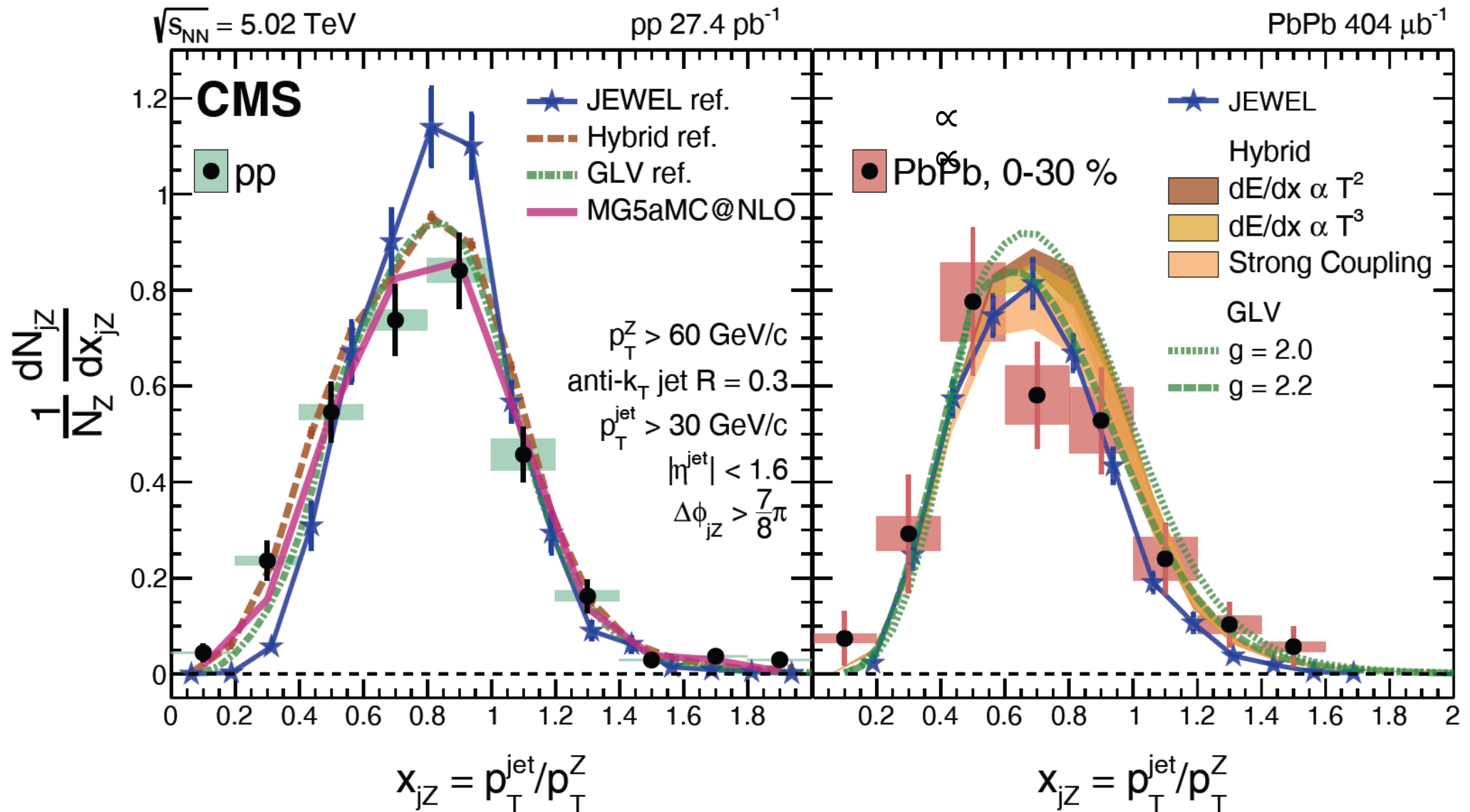
Groomed Jet Mass (Q vs G)



Jet R_{AA} vs. Theory

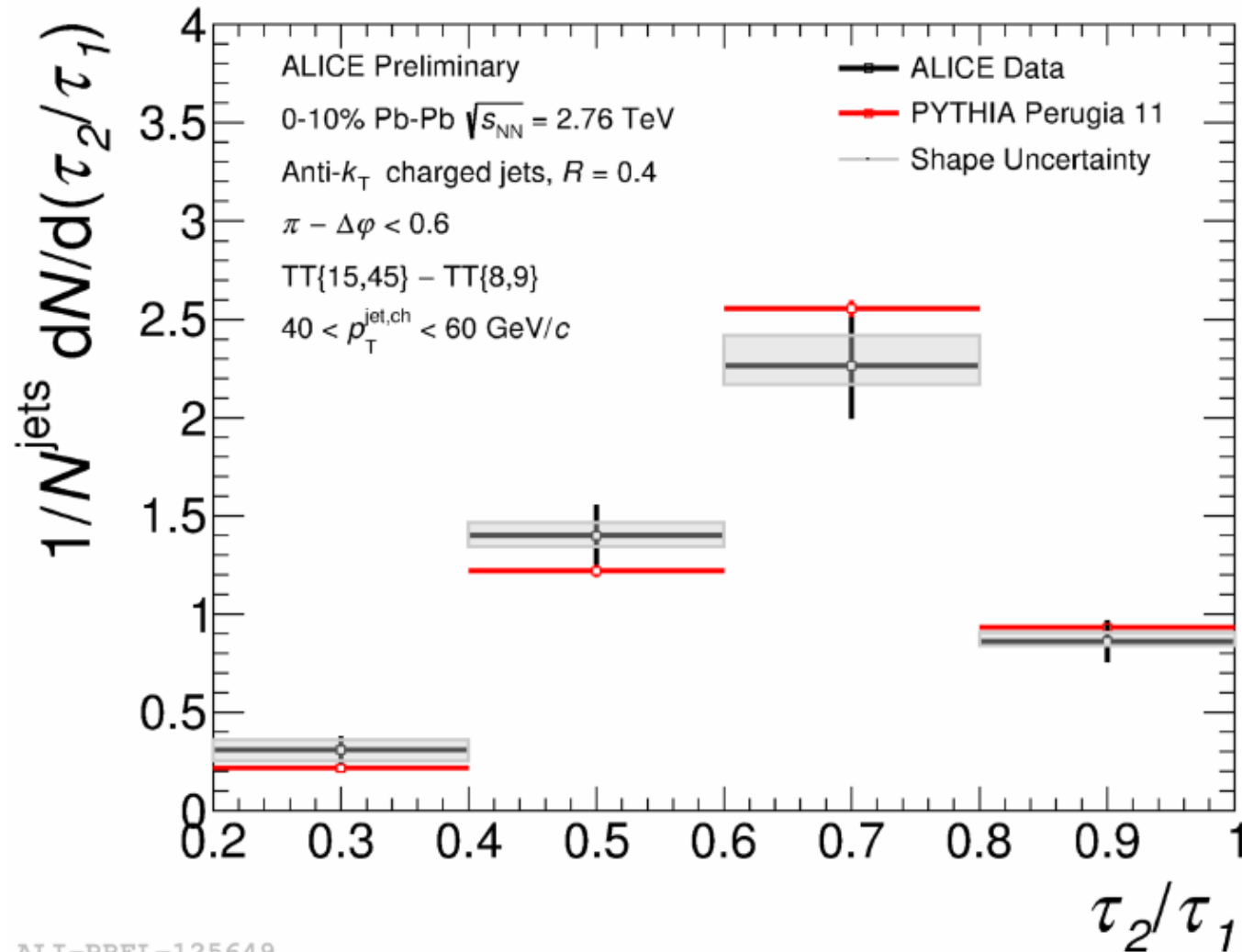


Z-Jet vs calculations



- 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

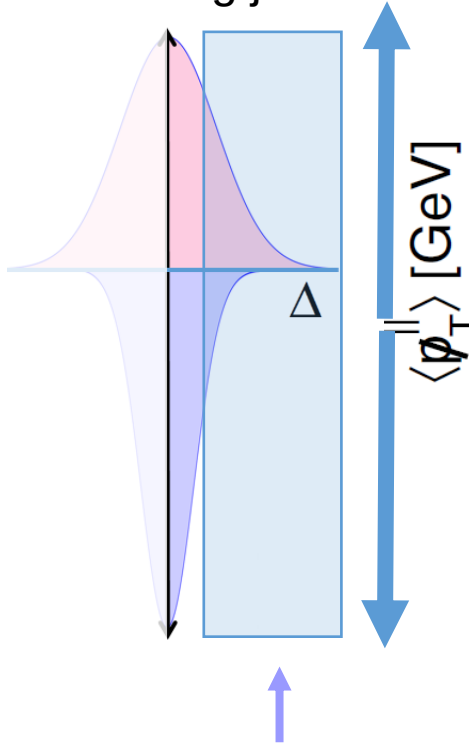


ALI-PREL-125649

- 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 $p_T^\parallel$ vs. Δ

Subleading jet direction

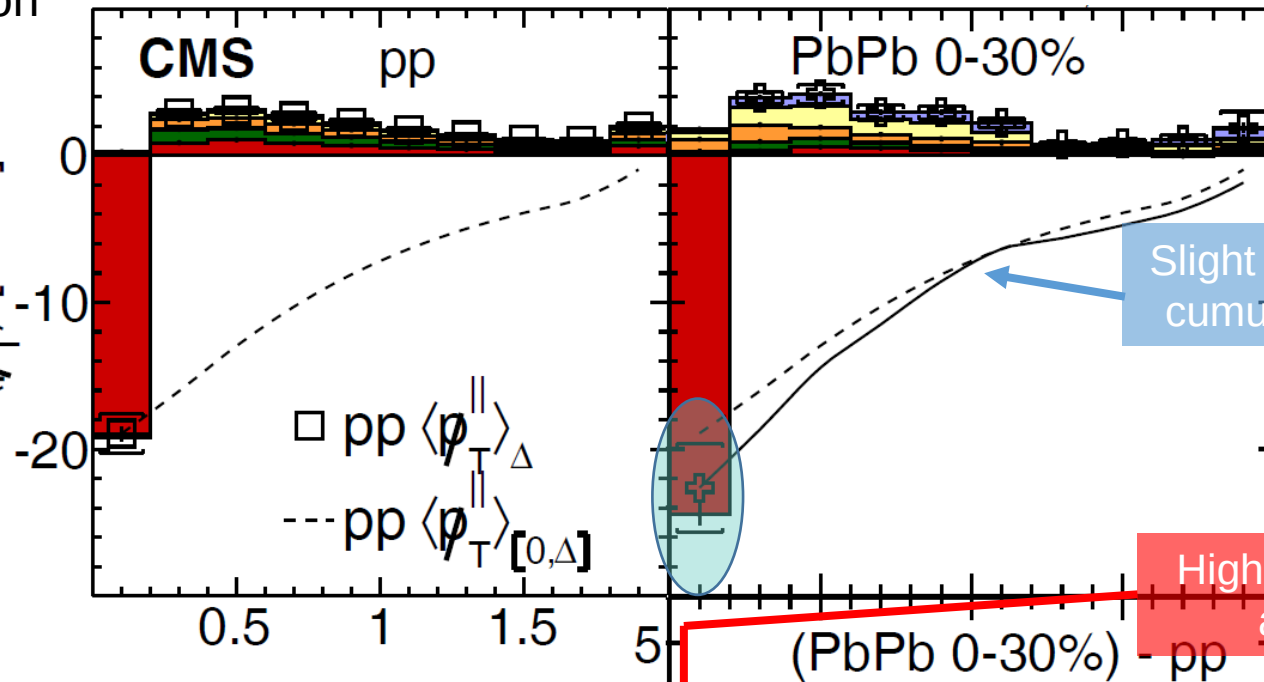


Leading jet direction

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

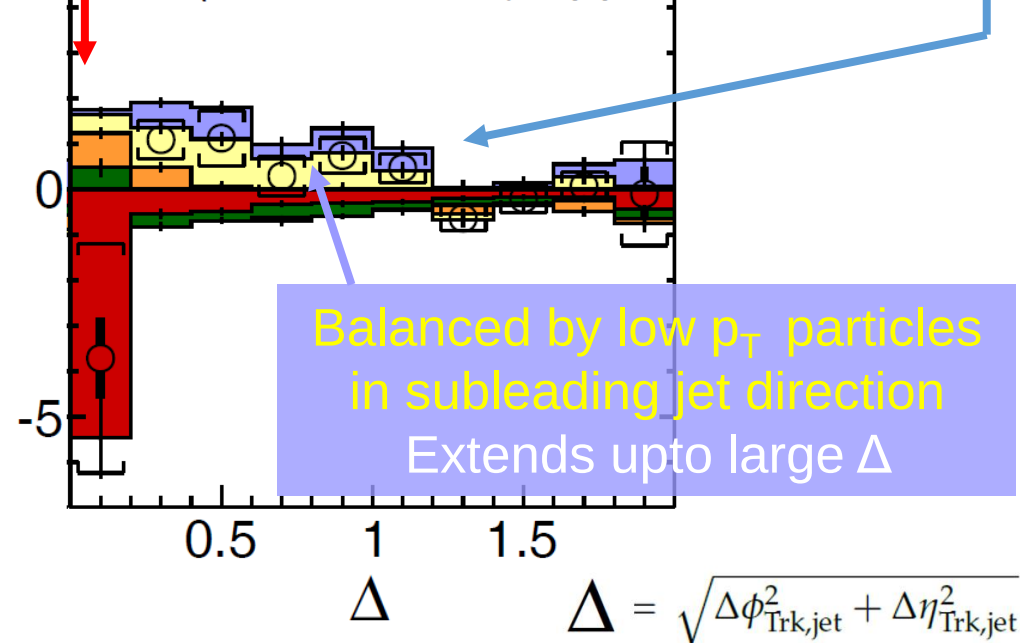
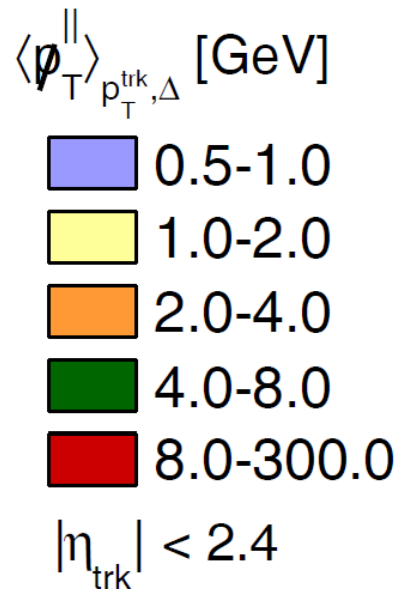
Inclusive A_J

JHEP 1601 (2016) 006



Slight modification of the cumulative energy flow

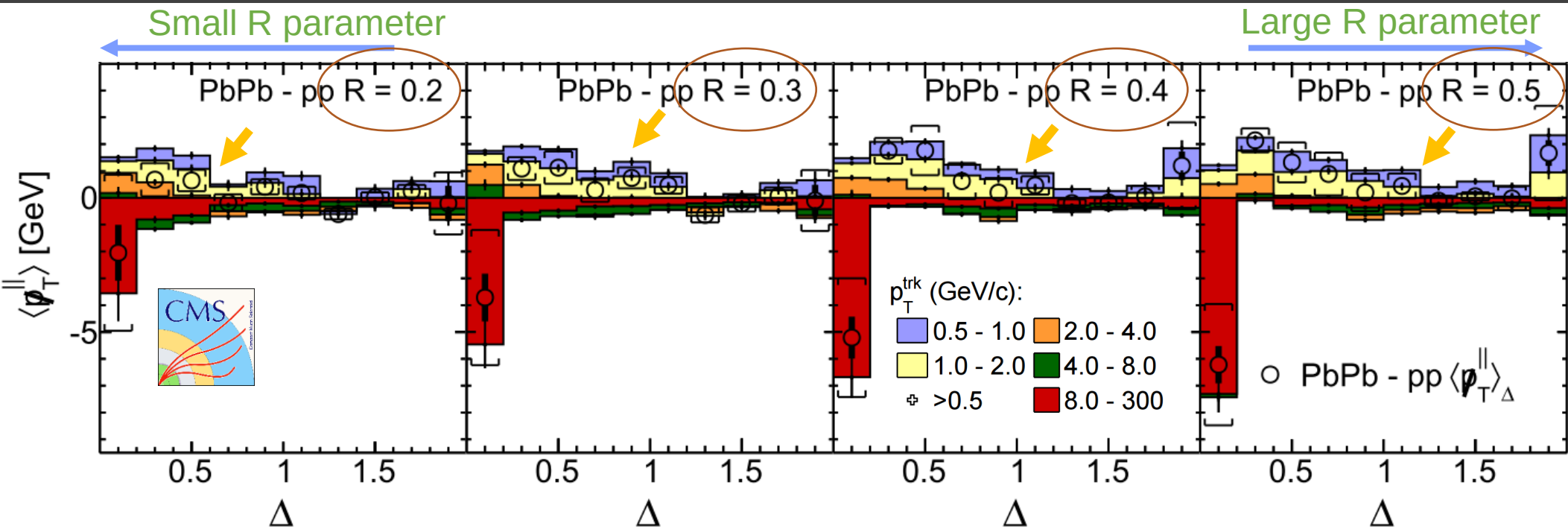
High p_T imbalance at small Δ



Balanced by low p_T particles in subleading jet direction
 Extends upto large Δ

$$\Delta = \sqrt{\Delta\phi_{Trk,jet}^2 + \Delta\eta_{Trk,jet}^2}$$

Shooting Jets with Different Width” through the Medium

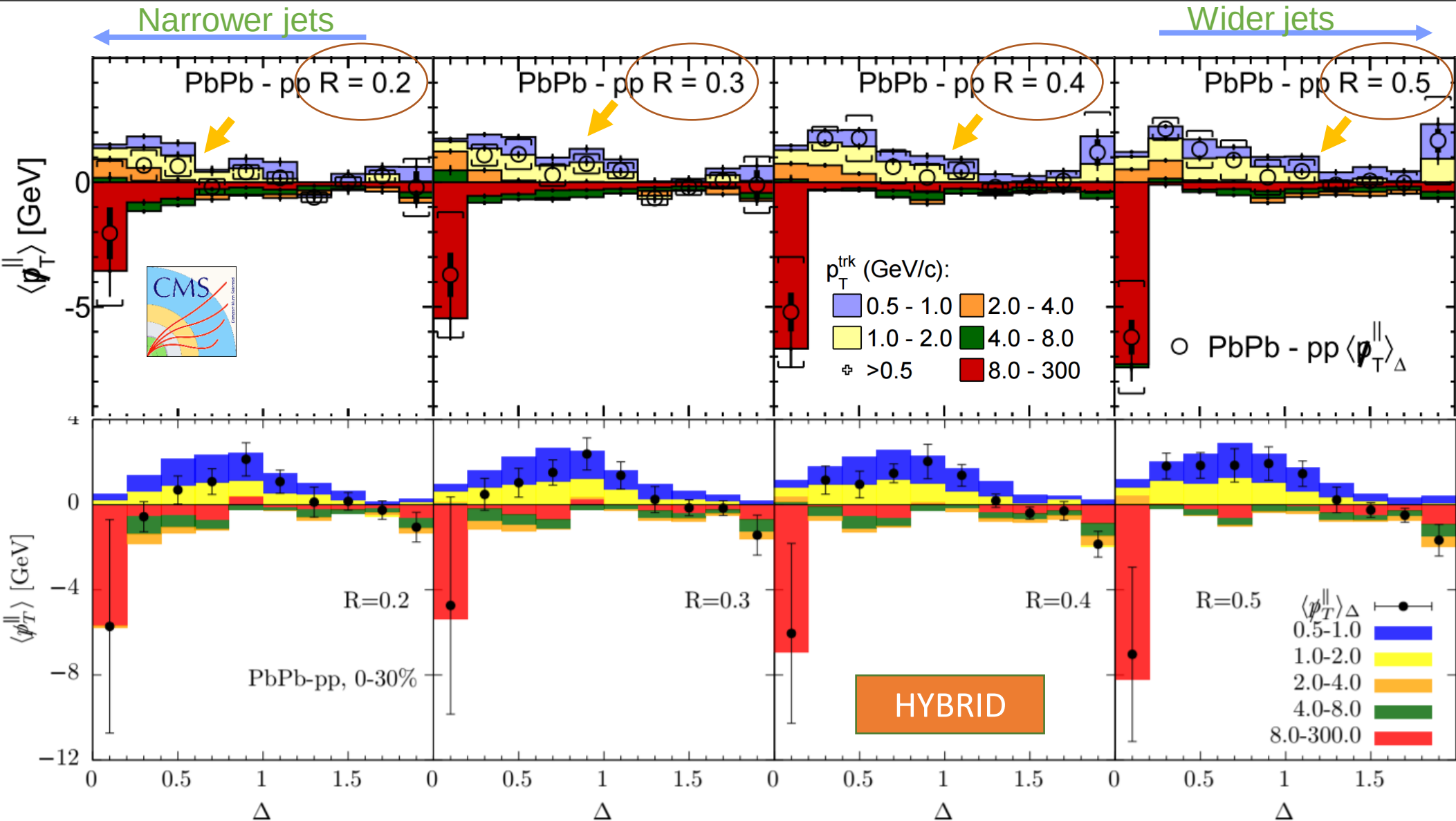


JHEP 1601 (2016) 006

- 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**

$$\Delta = \sqrt{\Delta\phi_{\text{Trk,jet}}^2 + \Delta\eta_{\text{Trk,jet}}^2}$$

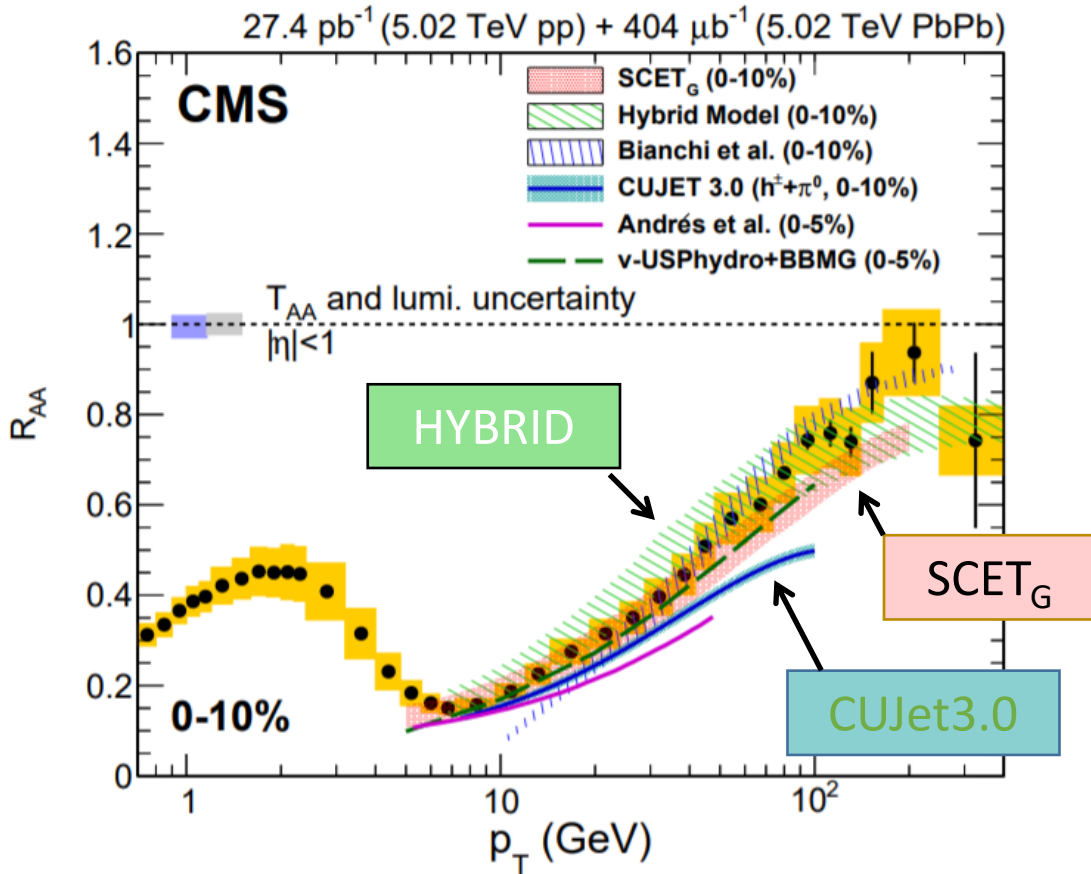
“Shooting Jets with Different Width” through the Medium



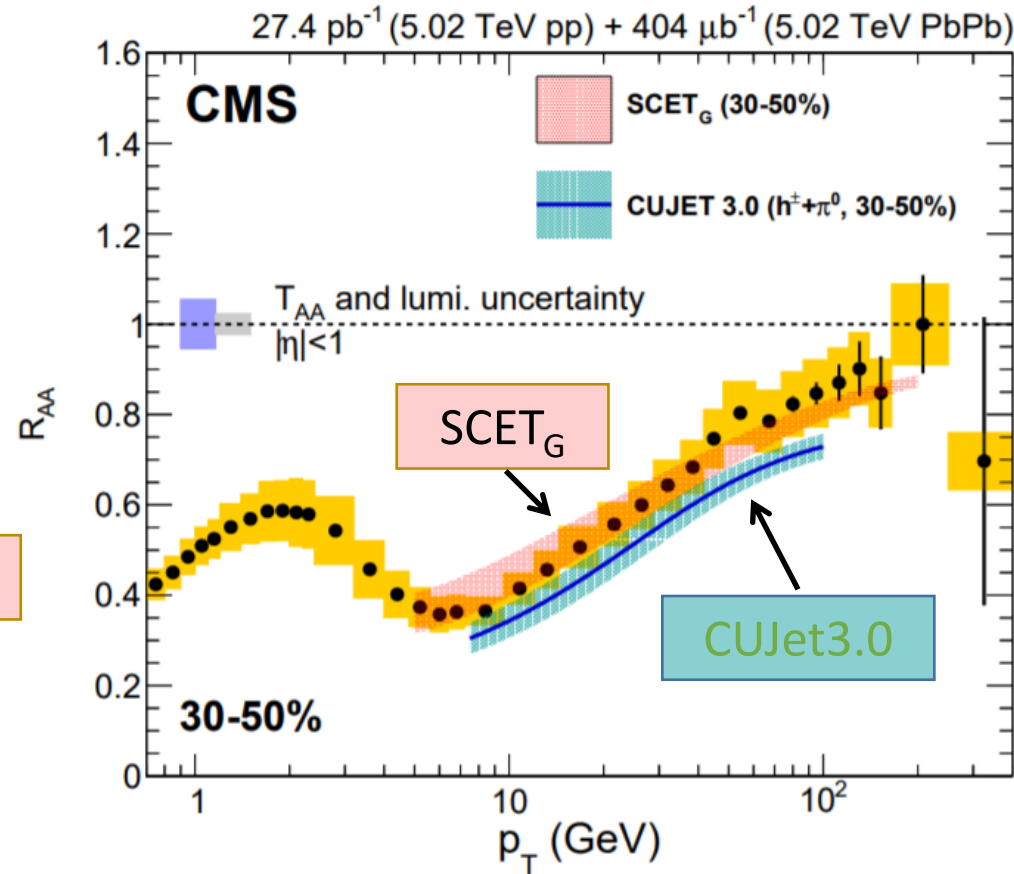
- Medium response from **HYBRID** is farer away from the jet axis.
- Shower not completely thermalized?
- Where are the calculations from **JEWEL**, **CCNU**, QPYTHIA and SCET_G?

Charged Particle R_{AA} Vs. Theoretical Models

0-10%



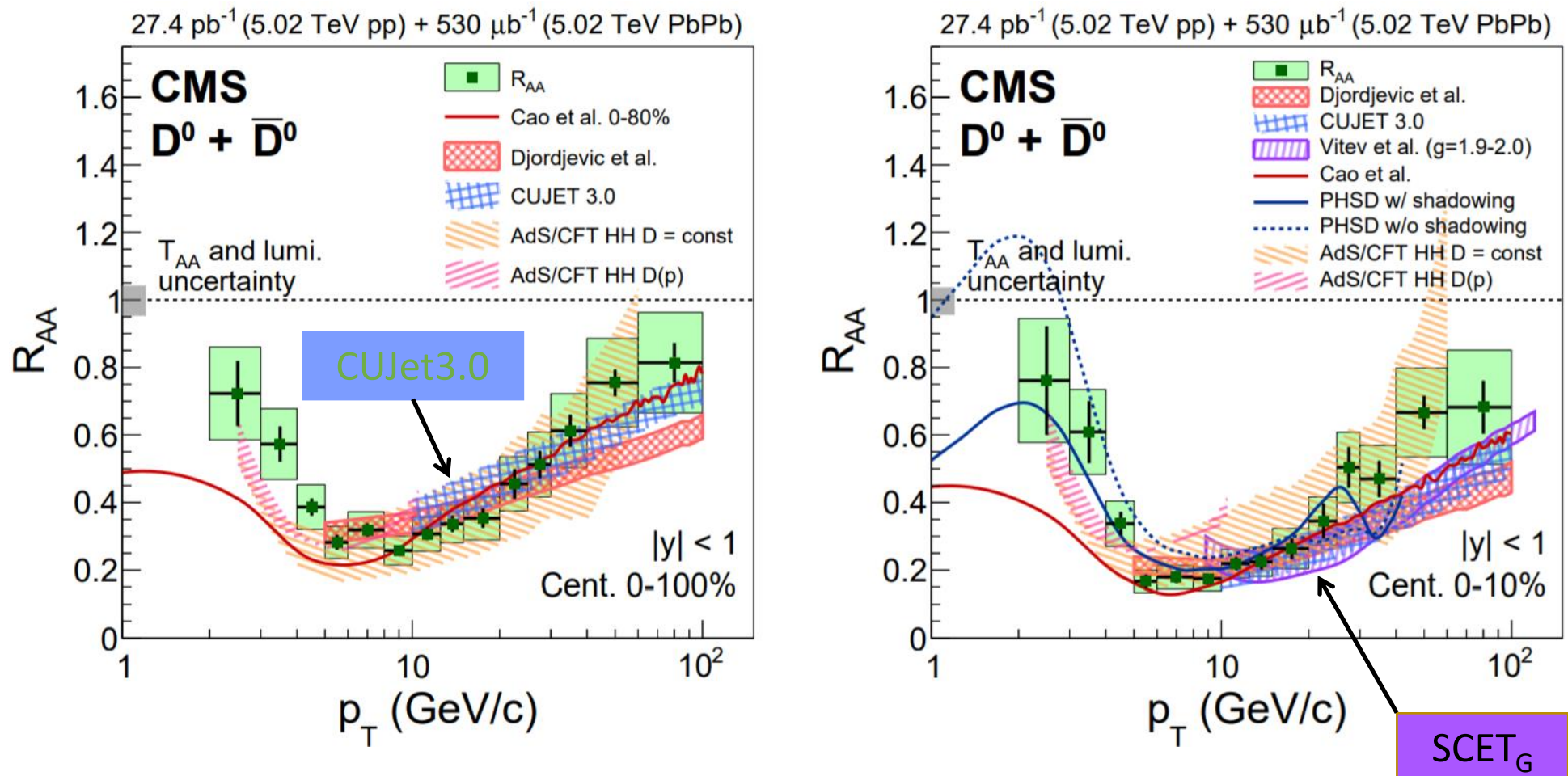
30-50%



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

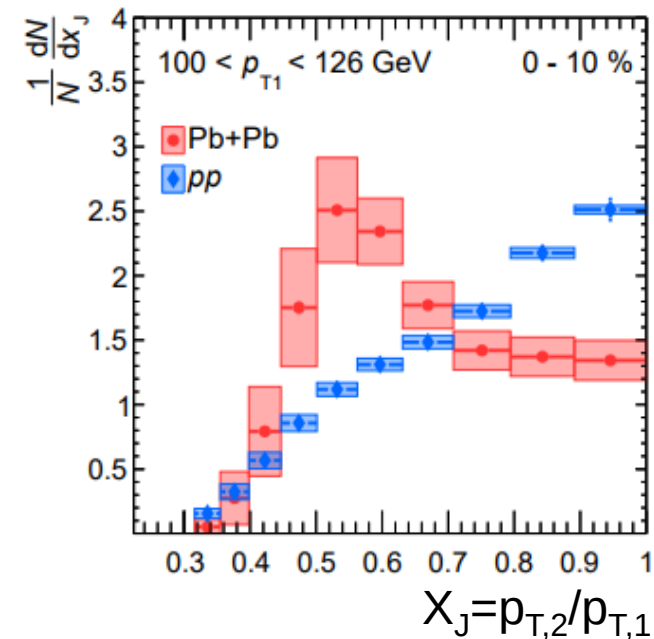
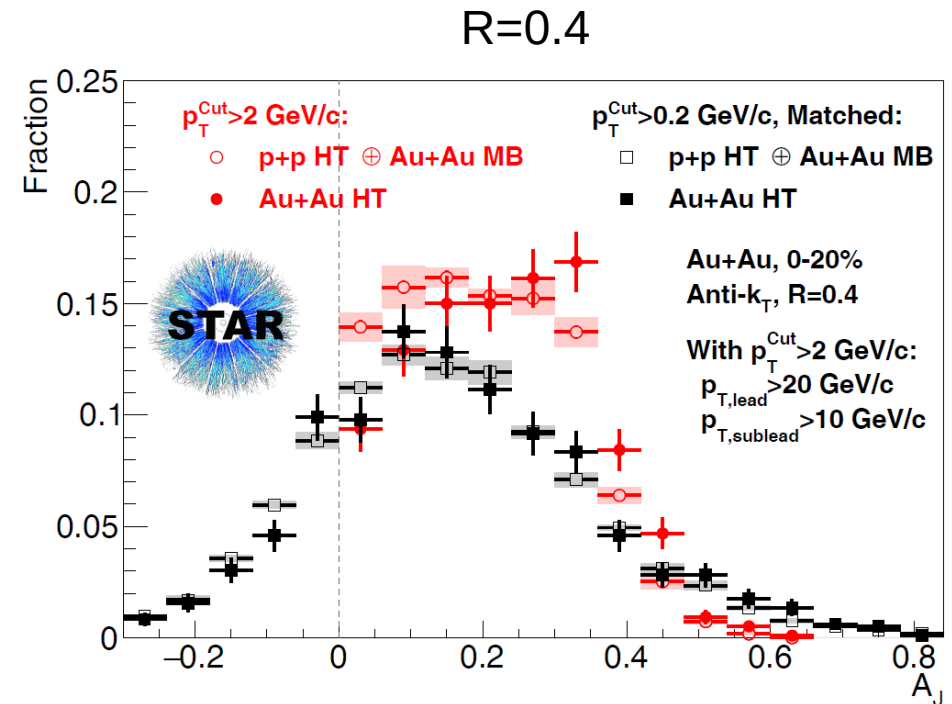
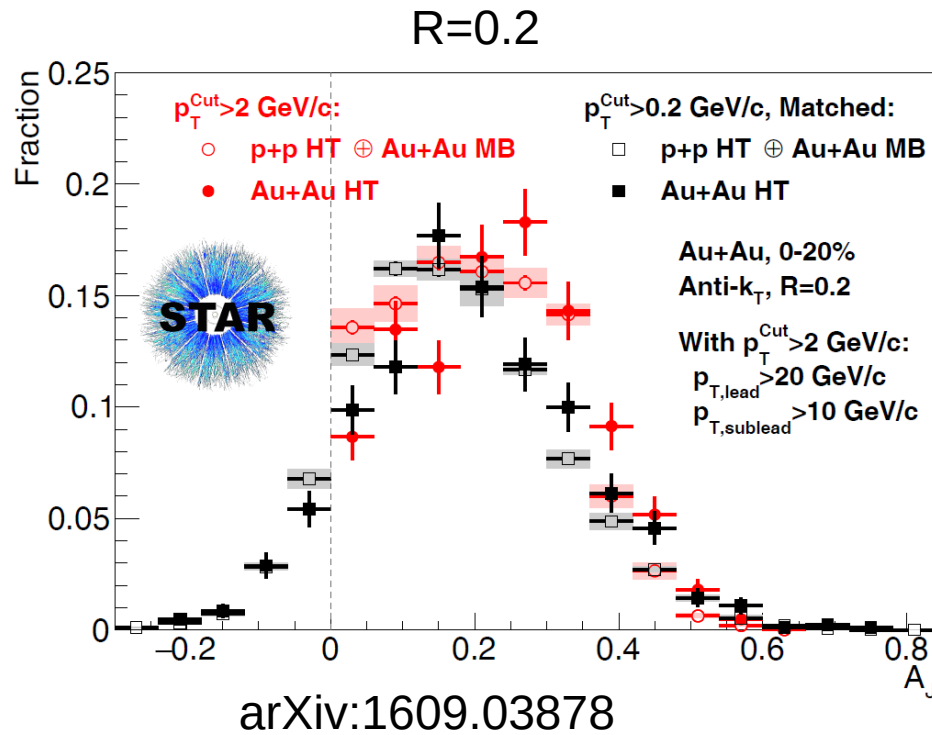
Description of the D^0 Meson Data

arXiv:1708.04962



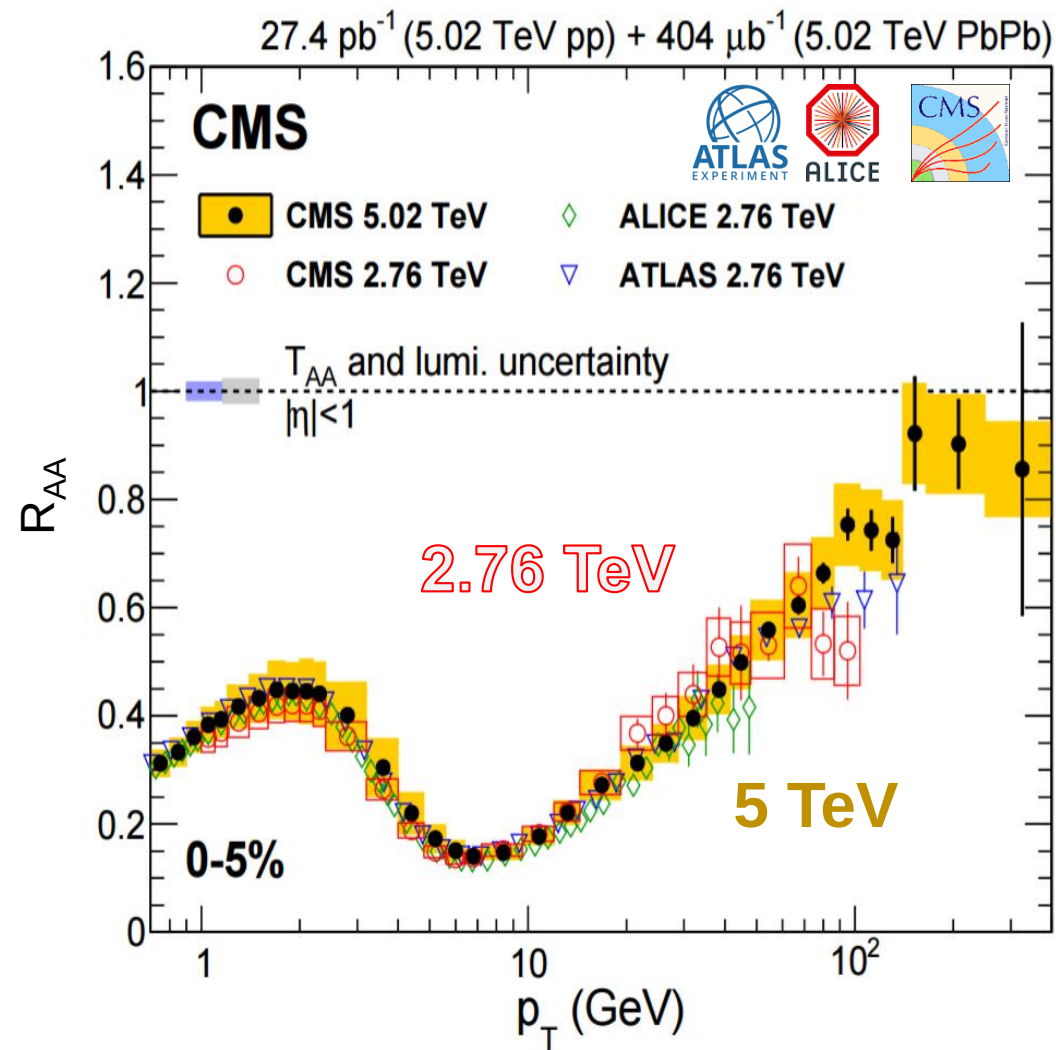
- At high D^0 p_T : Trend captured by pQCD and AdS/CFT based models
- Reasonable description of the data could be achieved
- Details doesn't work perfectly, especially the slope of the D^0 R_{AA} vs. p_T

Dijet Transverse Momentum Correlation



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

Jet Quenching with Inclusive Charged Particles

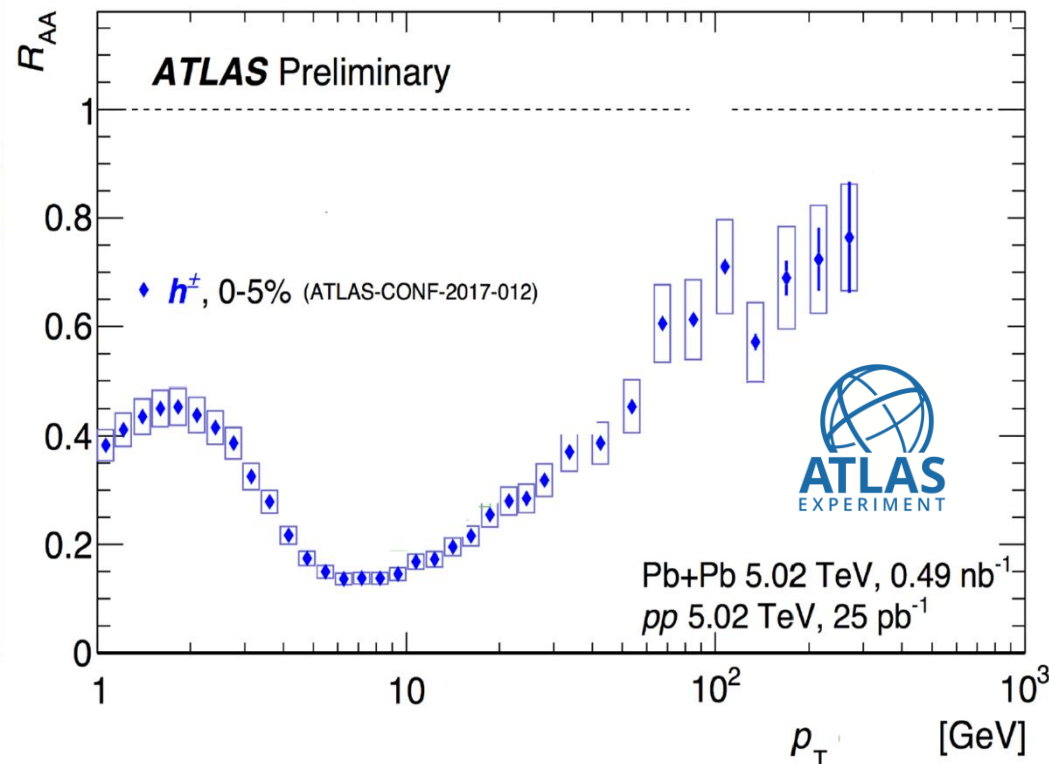


- Almost no suppression at very high p_T compared to **pp reference**
- **Charged particle R_{AA}** measured up to $p_T = 400$ GeV for the first time!

JHEP 04 (2017) 039

Charged particle R_{AA}

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

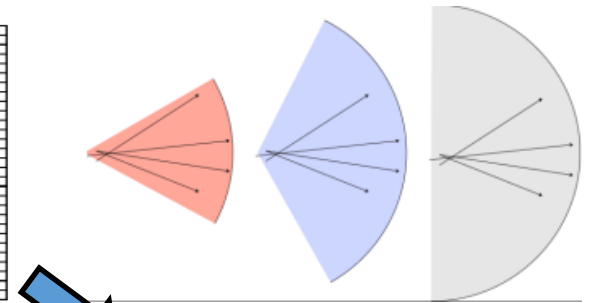
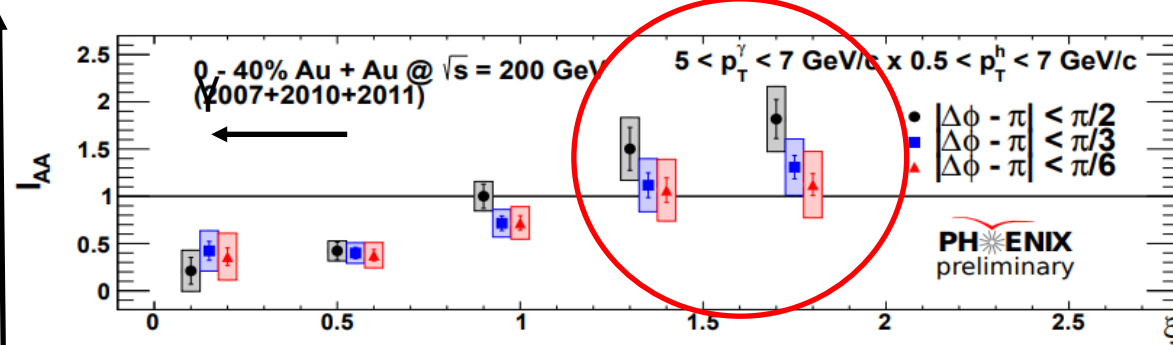


- Similar Charged particle R_{AA} in PbPb at **5 TeV** compared to **2.76 TeV**
- Good agreement between ATLAS, CMS and ALICE measurements

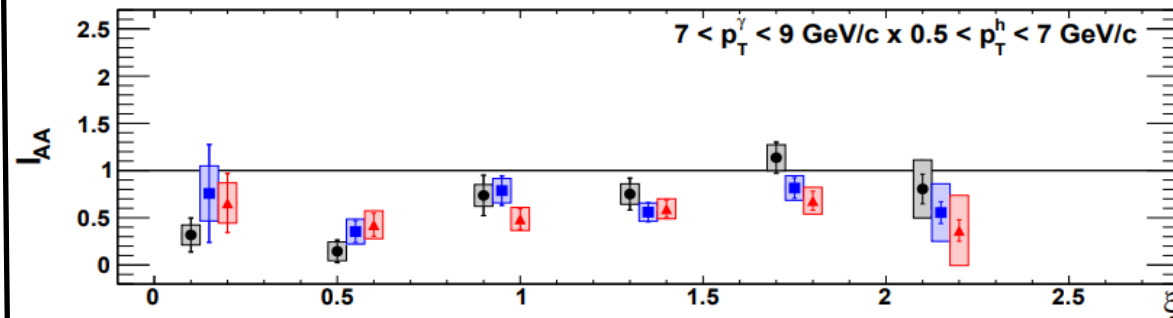
ATLAS-CONF-2017-012

PHENIX Photon-Hadron Correlation

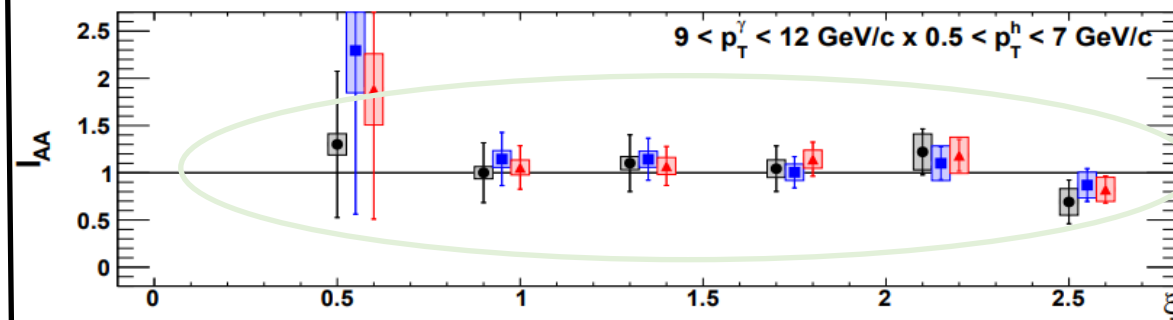
Low p_T
Photon
5-7 GeV



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

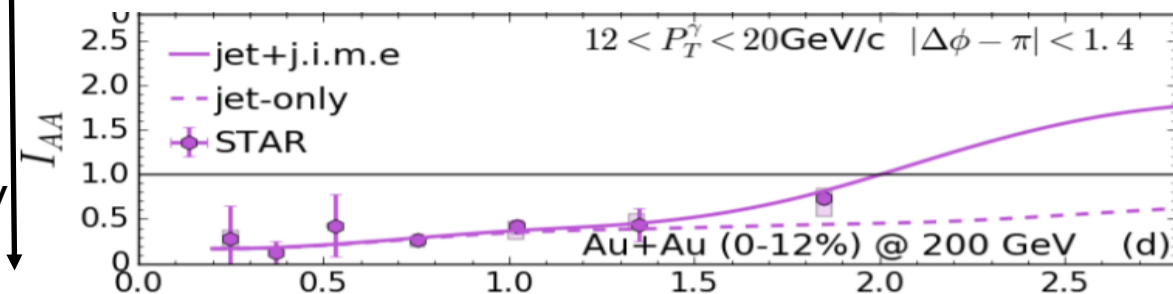


Something in between



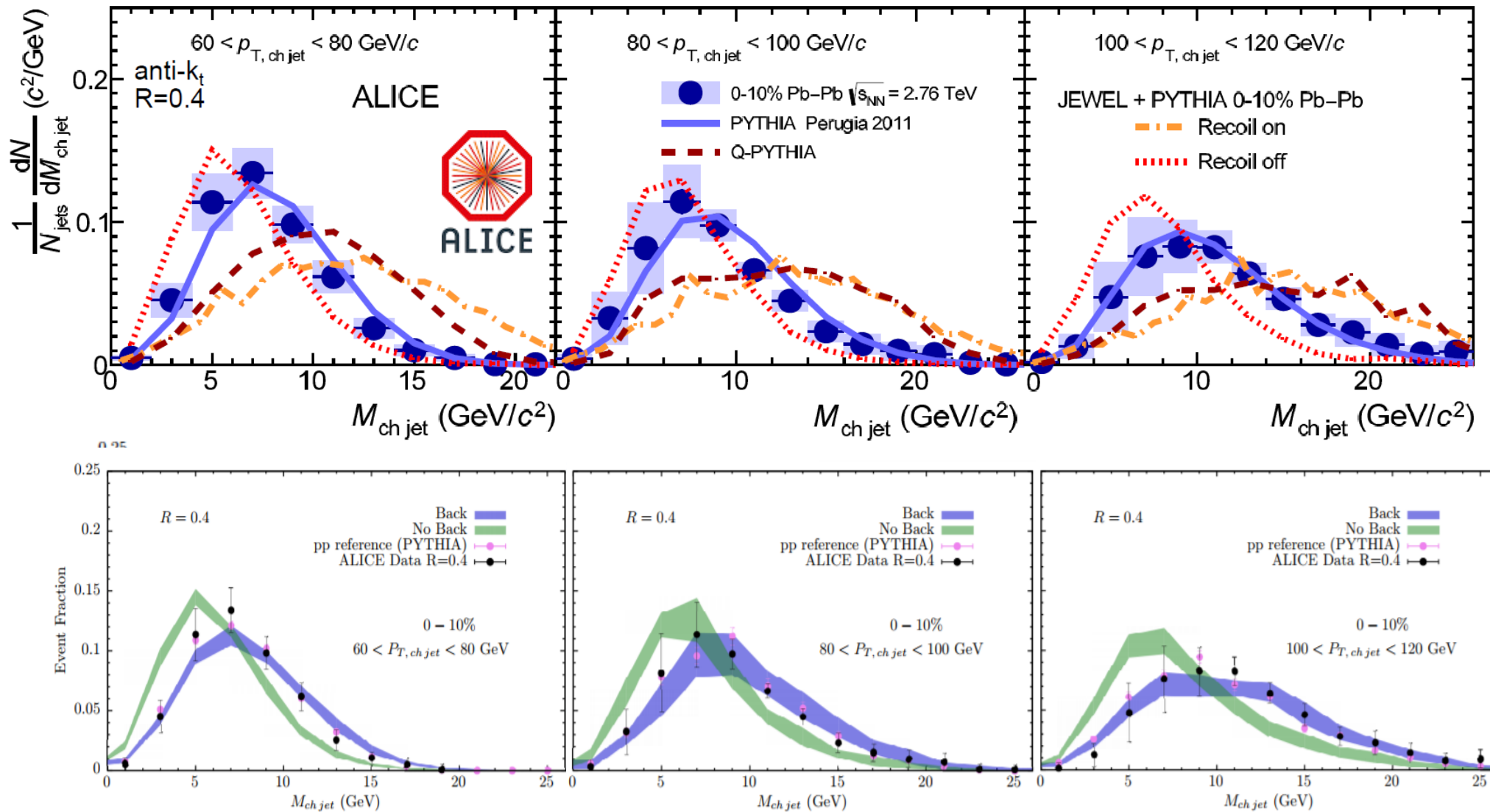
No modification of jet fragmentation (?)

High p_T
Photon
12-20 GeV



Significant modification of jet FF

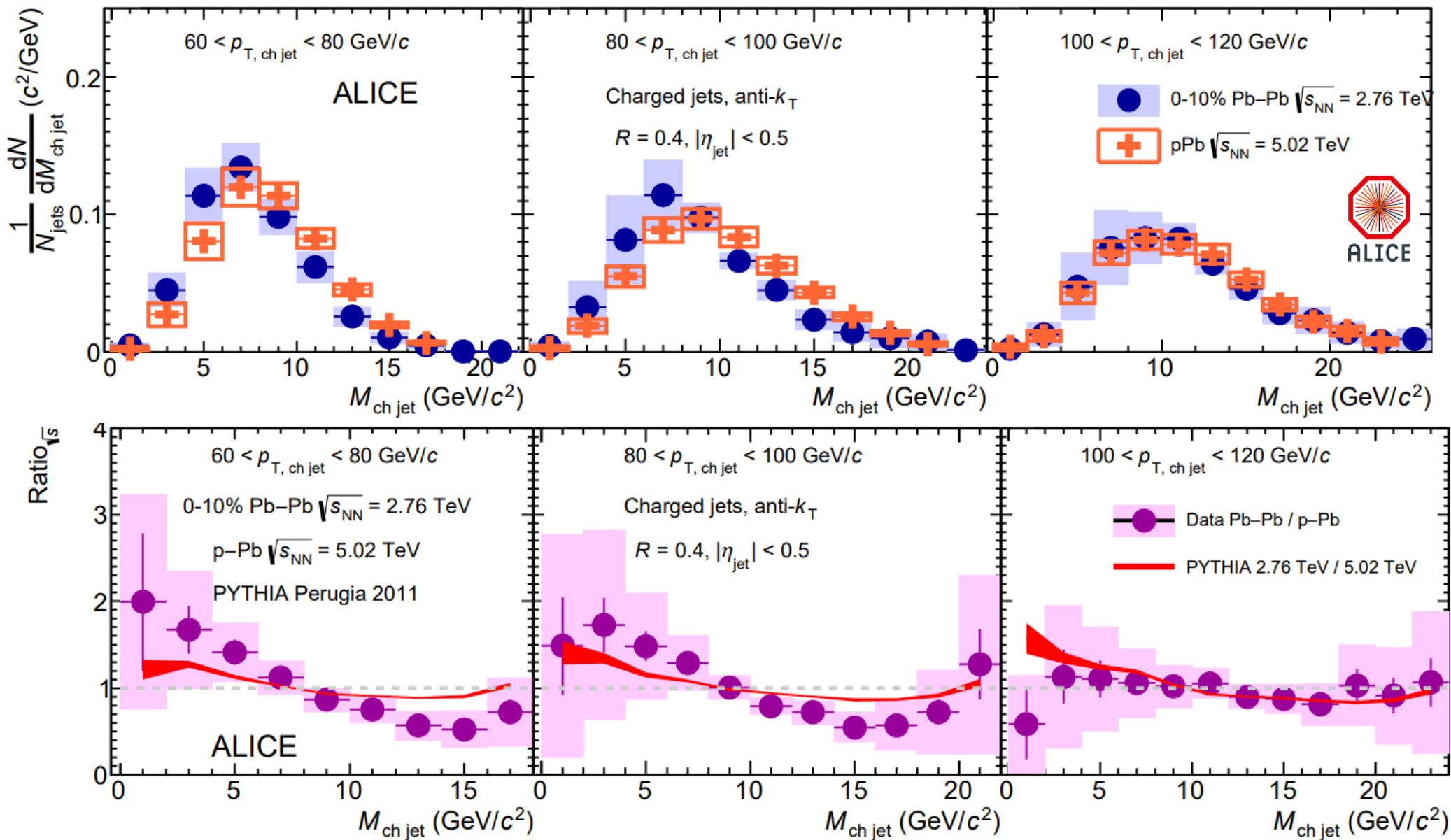
ALICE Charged Jet Mass



- 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

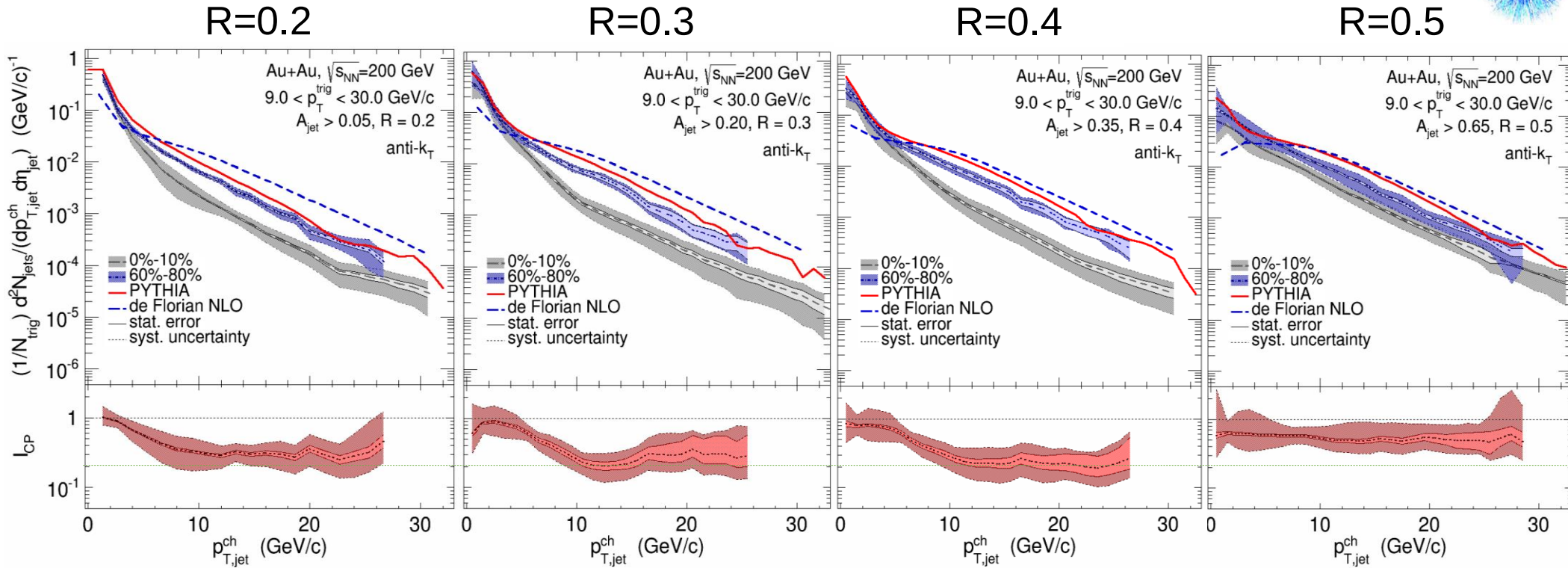


Hint of smaller charged jet mass in PbPb (more quark like)
with respect to reference

PLB 776 (2018) 249-264

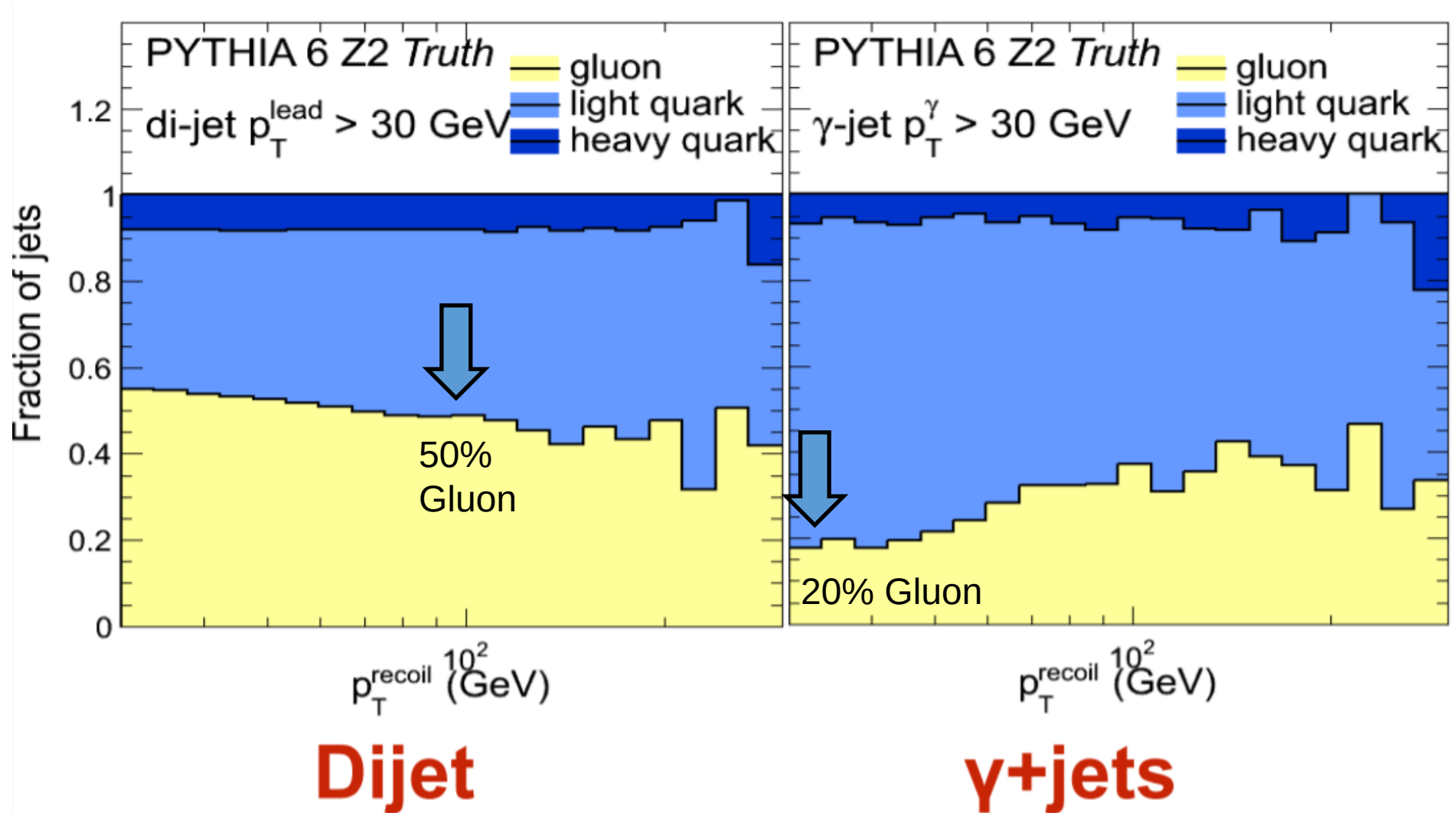
STAR Hadron-Jet Correlation

arXiv:1702.01108



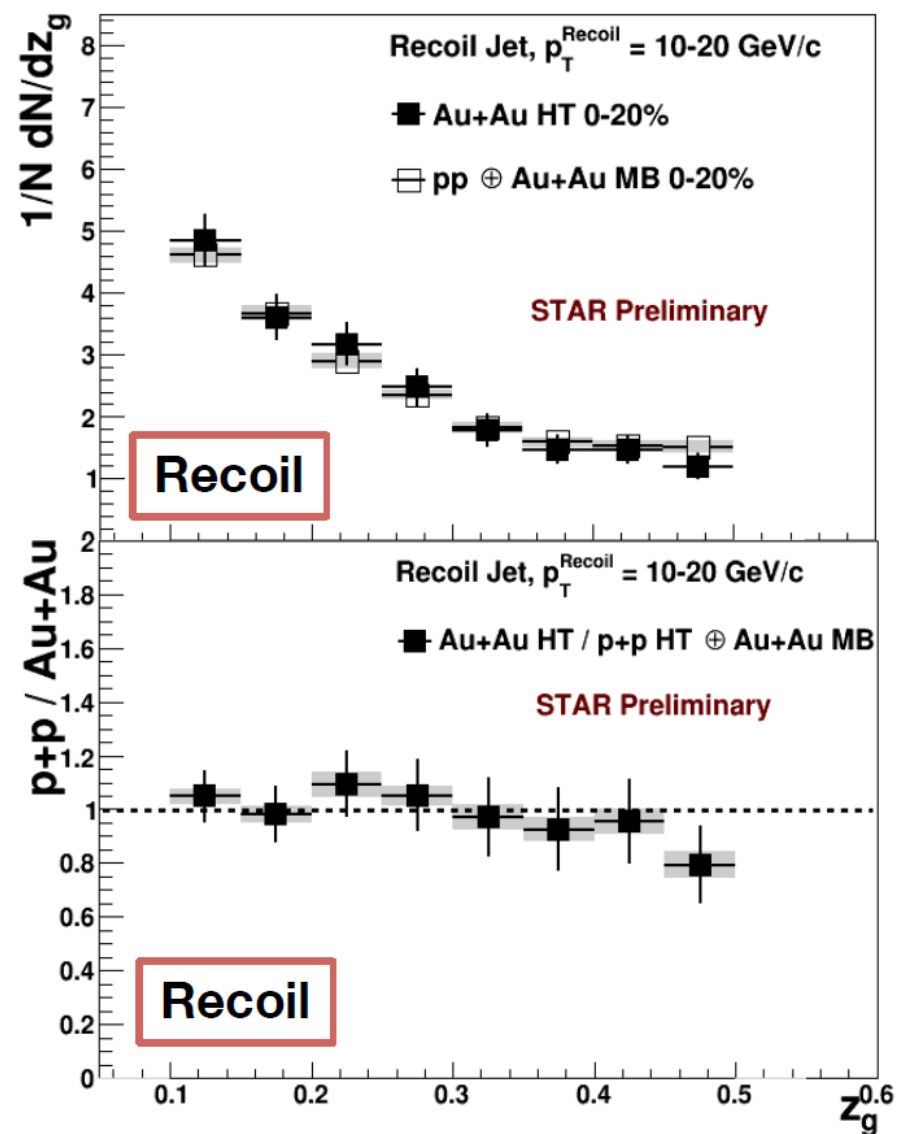
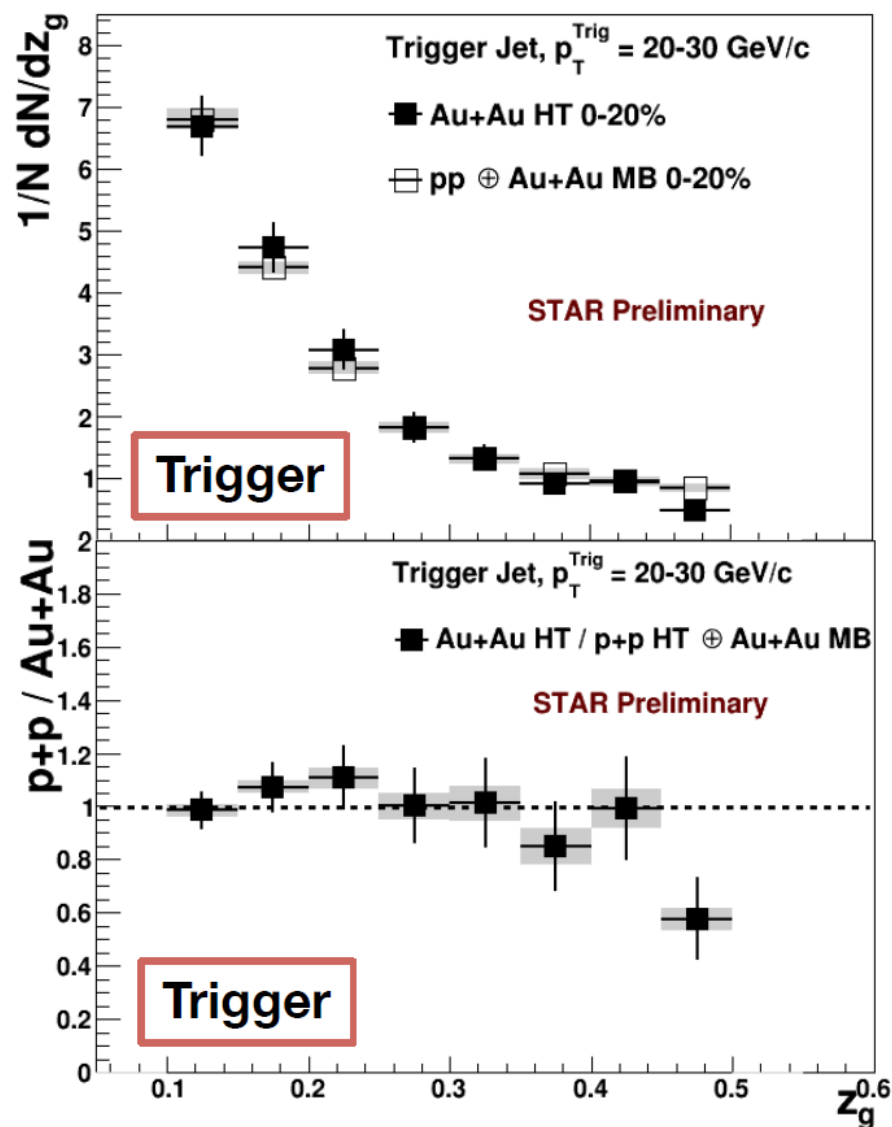
- $R=0.2-0.4$
 - I_{CP} significantly lower than unity; significant out-of-cone Eloss
- $R=0.5$ $I_{\text{CP}} > R=0.2$ I_{CP}
 - indication of the recovery of the quenched energy

Jet Flavor Composition In Dijet and γ -Jet



From Doga Gulhan

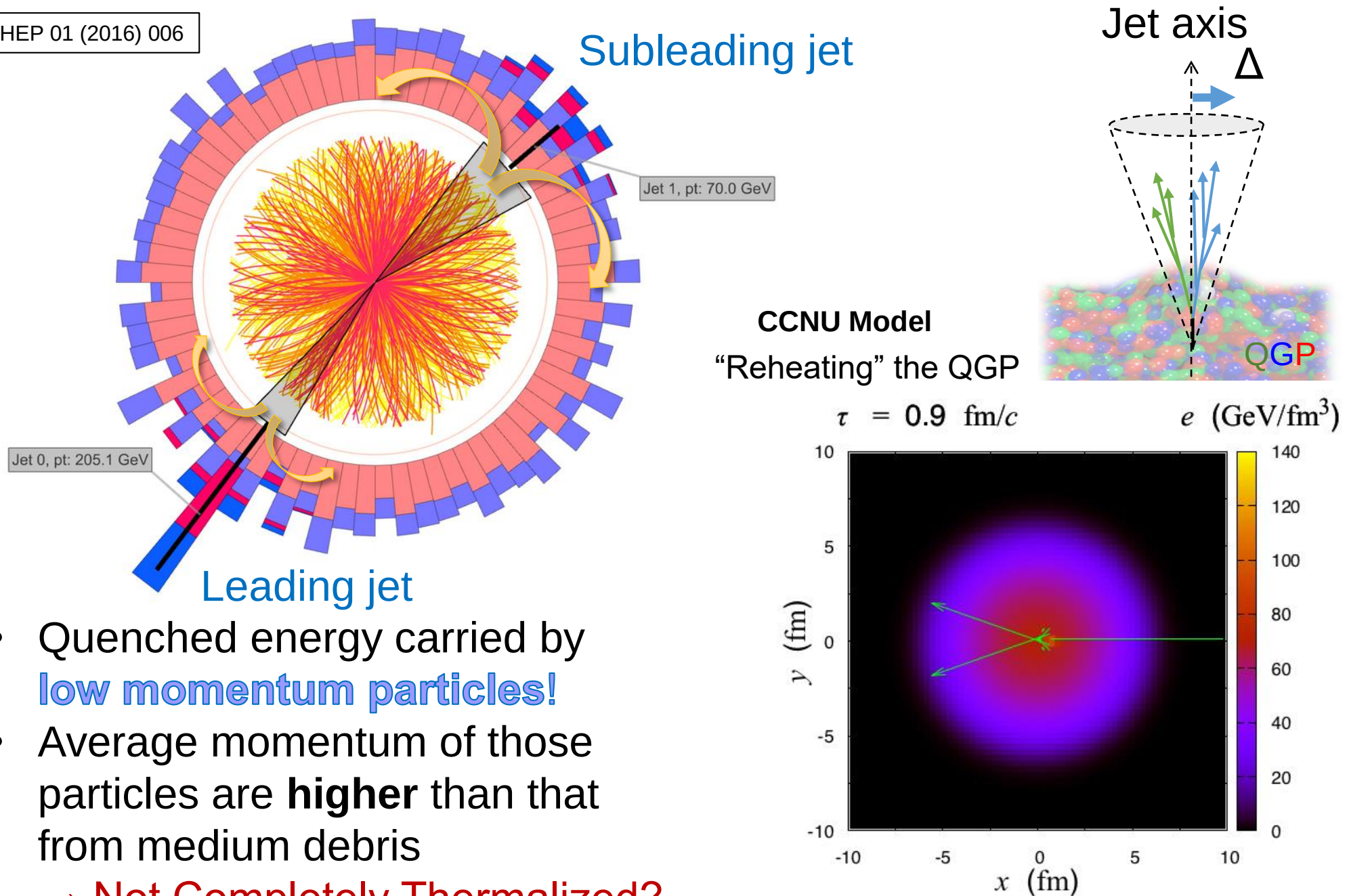
STAR Splitting Function



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

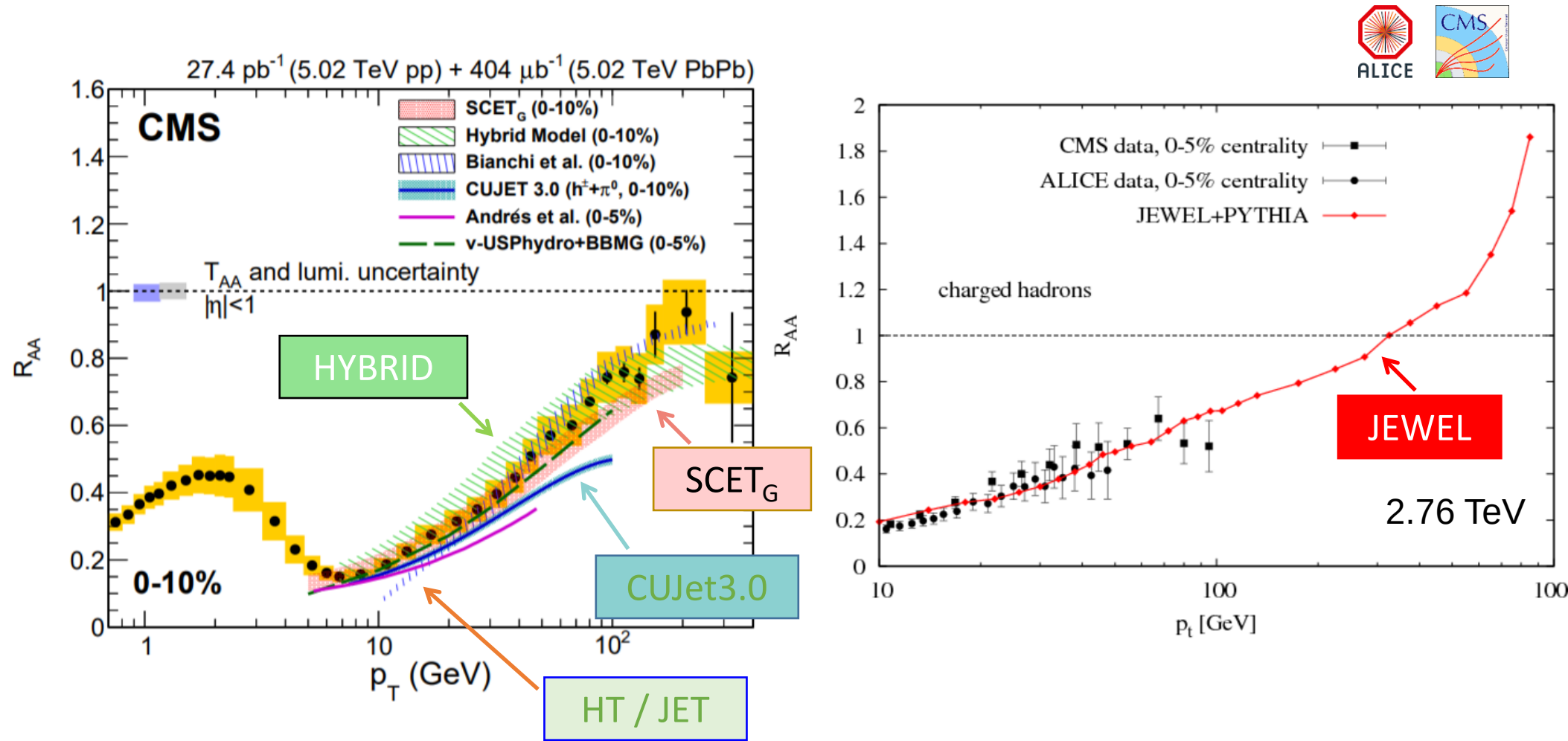
Quenched Energy out of the Jet Cone

JHEP 01 (2016) 006



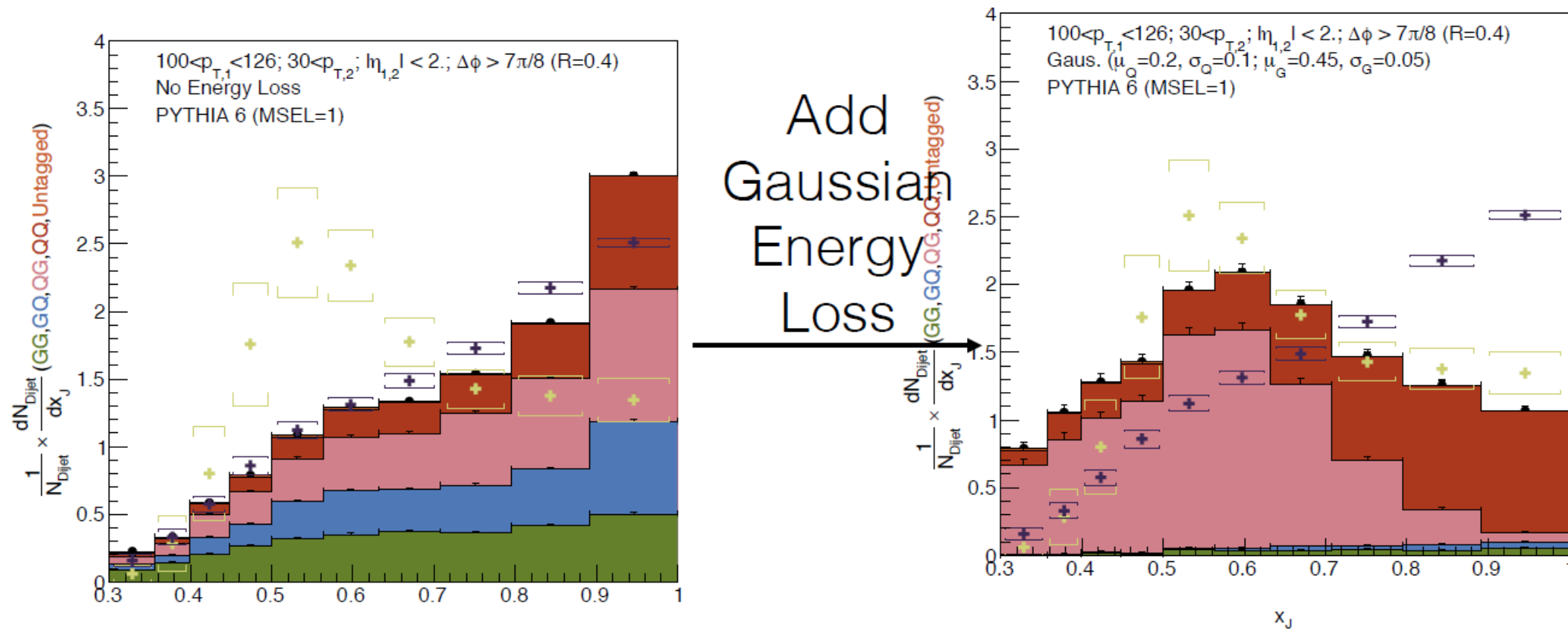
- Quenched energy carried by **low momentum particles!**
 - Average momentum of those particles are **higher** than that from medium debris
- **Not Completely Thermalized?**

Charged Particle R_{AA} vs. Theoretical Models



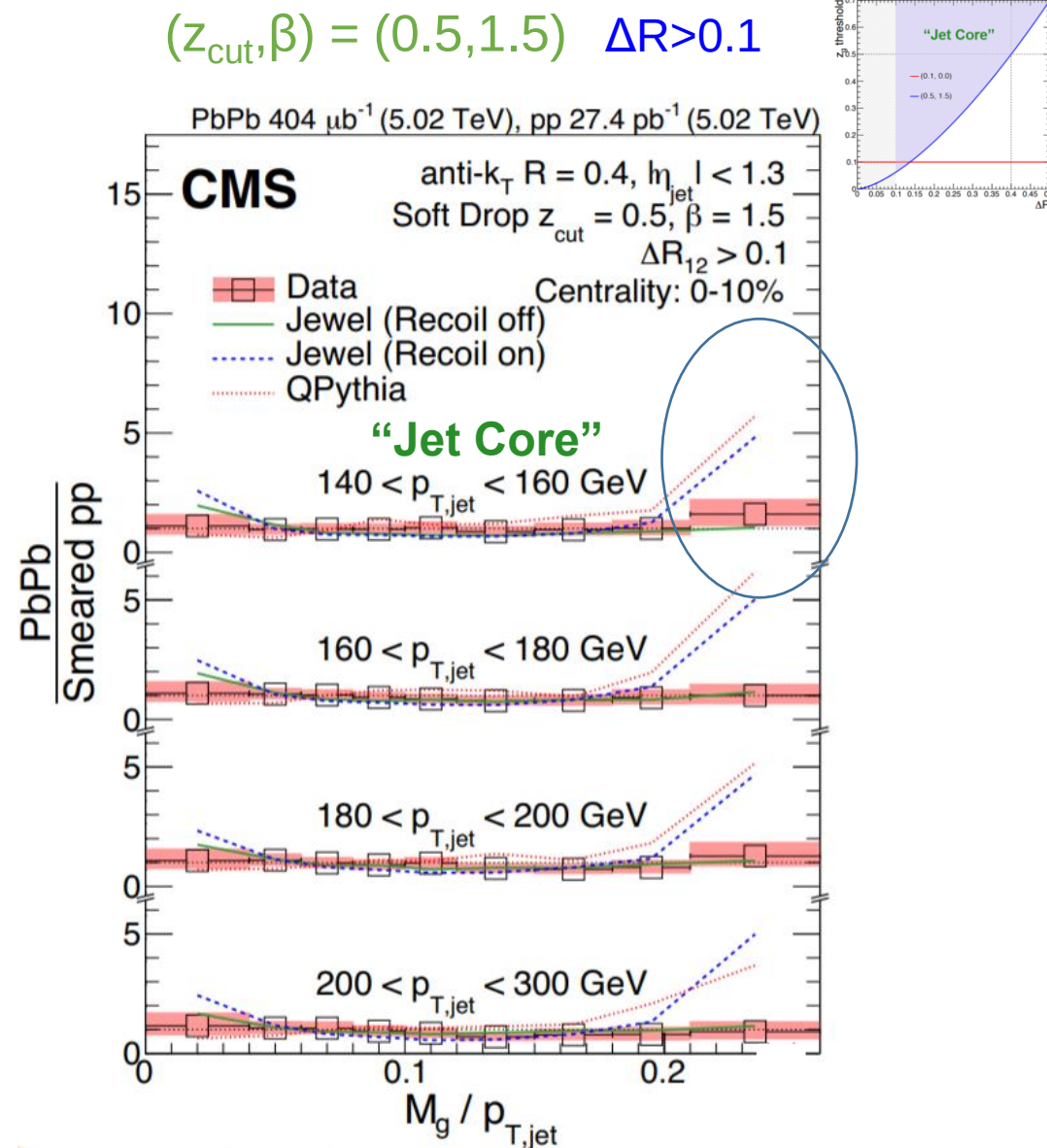
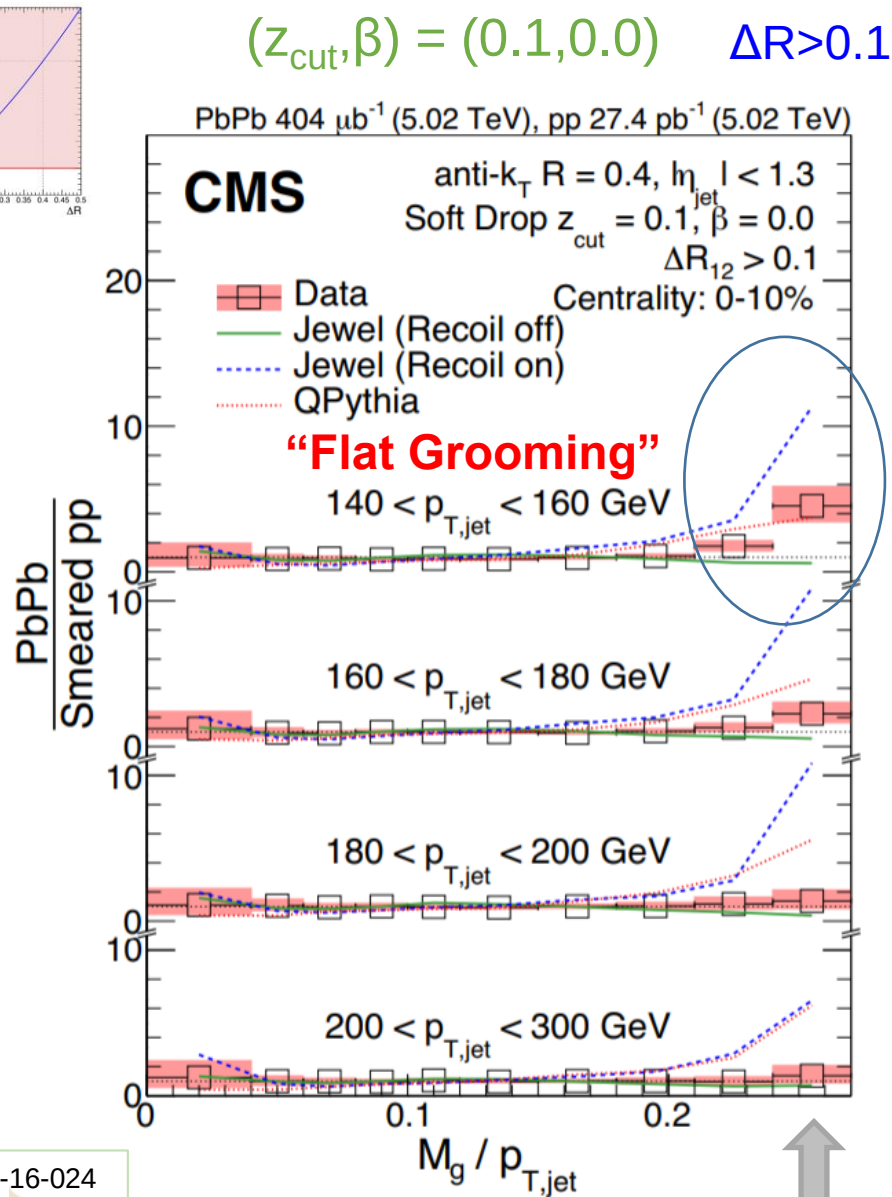
- High p_T : General trend described by both pQCD and Hybrid models
- Description of the R_{AA} over the whole p_T range is still challenging

Reproduce ATLAS X_J



From Chris McGinn

Groomed Jet Mass



CMS-HIN-16-024

- Enhancement of large mass when looking at a less aggressive grooming setting

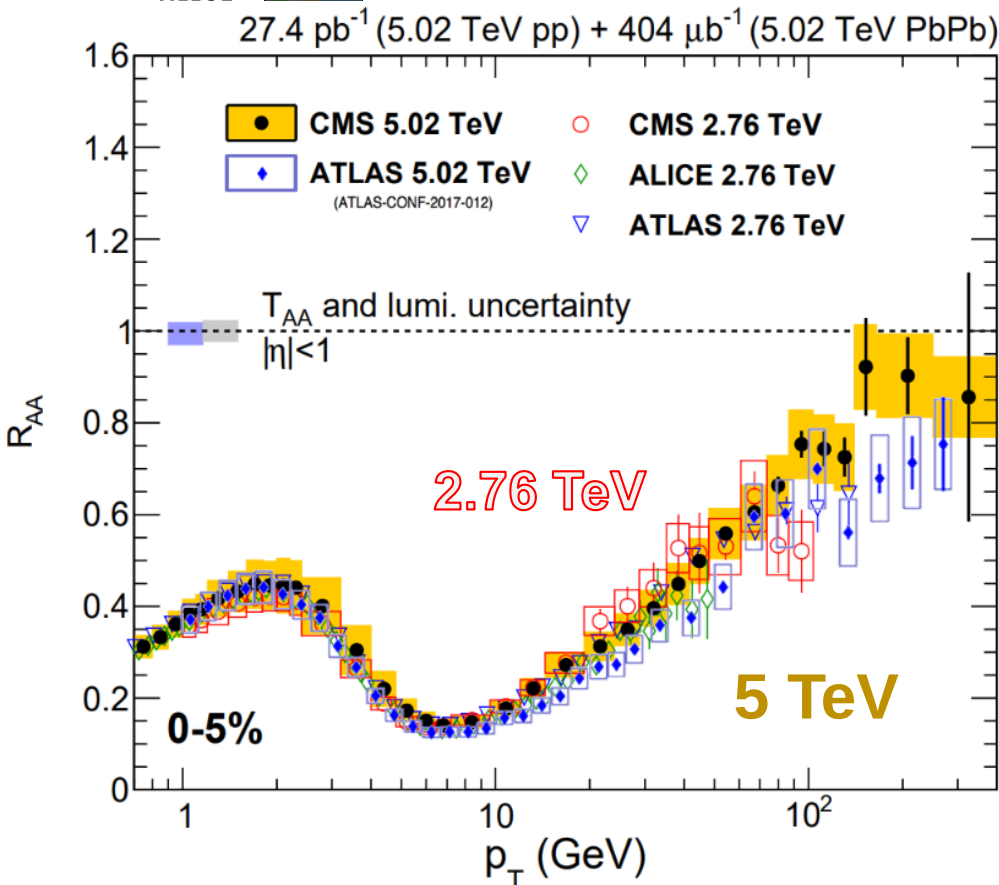
- Results with a “more aggressive grooming”
- No significant modification of the “jet core”

Charged Particle R_{AA}

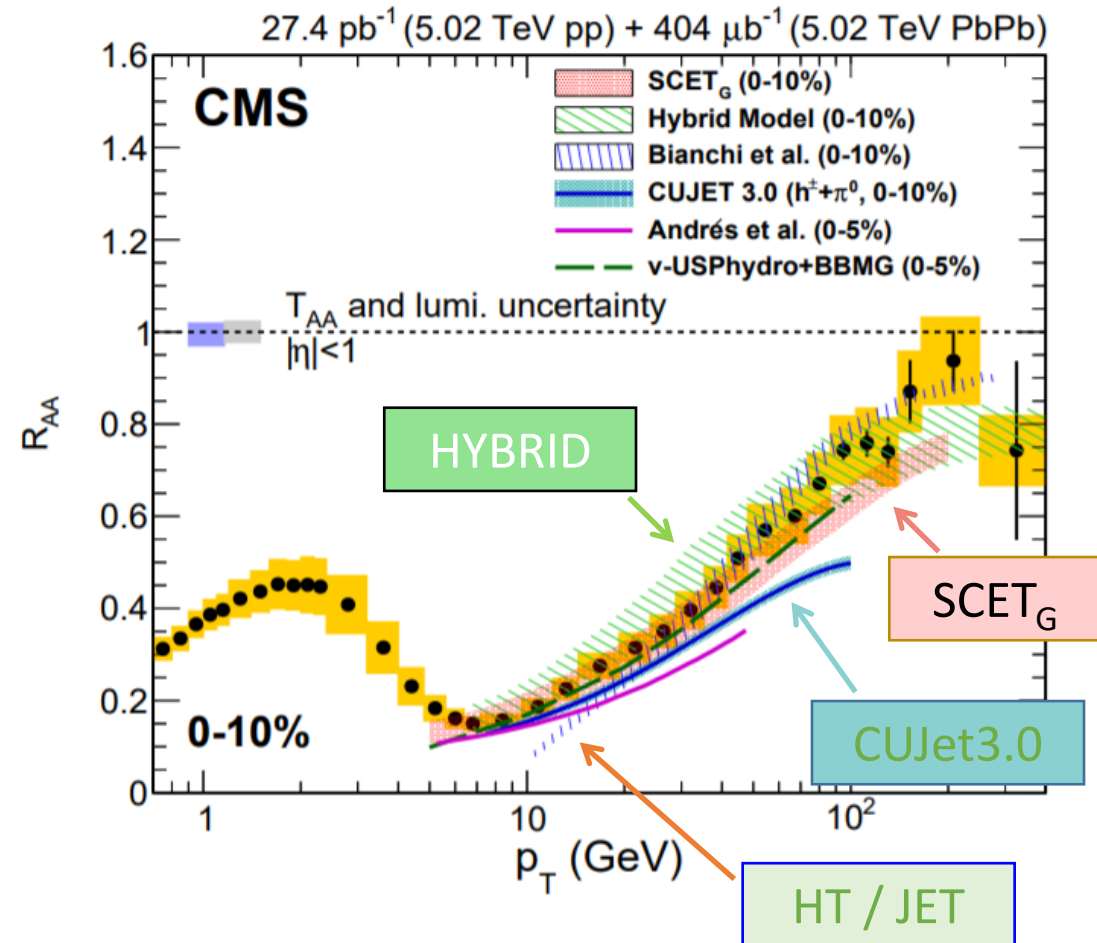


ATLAS-CONF-2017-012

JHEP 04 (2017) 039



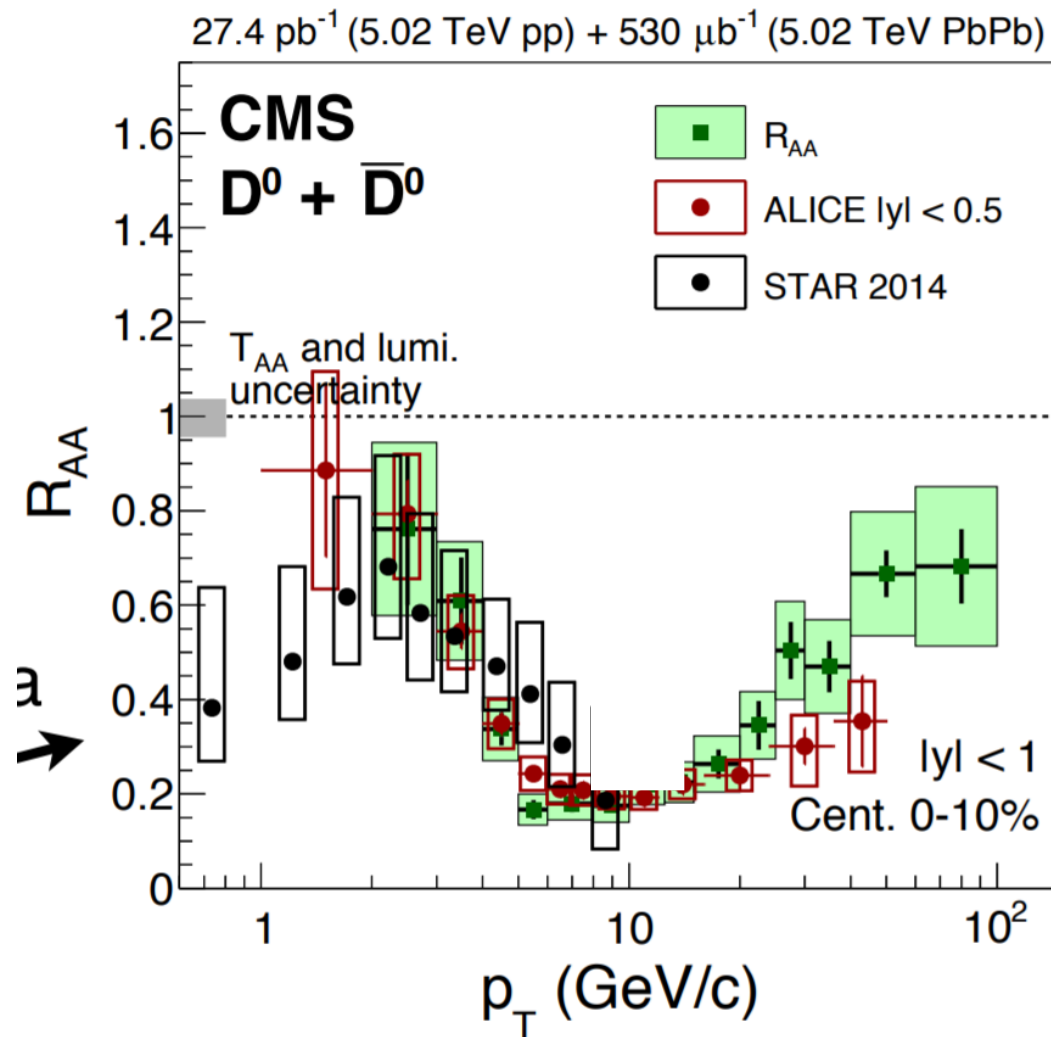
- Strong suppression of charged particles (up to a factor of 6) in PbPb
- Almost no suppression at very high p_T compared to **pp reference** ($p_T \sim 400$ GeV)
- Similar charged particle R_{AA} in PbPb at **5 TeV** compared to **2.76 TeV**



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

Prompt D^0 R_{AA} in PbPb at 5.02 TeV

PbPb 0-10%



Compilation
from Jing Wang (MIT)

- D^0 production is strongly suppressed
- Strongest suppression around D^0 $p_T = 5-8$ GeV

Background Subtraction Techniques

- Statistical subtraction
 - ALICE mixed event subtraction
 - STAR mixed event subtraction
- Event-by-event
 - STAR: hard-core jet ID + subtraction
 - CMS iterative pile-up subtraction
 - CMS constituent subtraction (+ flow modulation)
 - ATLAS iterative subtraction
 - ...
- Can theorists understand / use them?
- Introduced in Christine Nattrass's talk

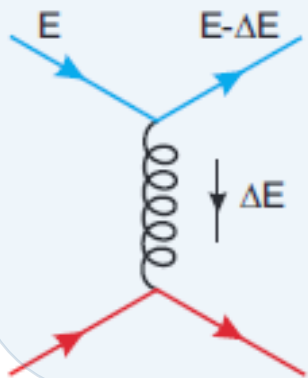


Extraction of the medium properties

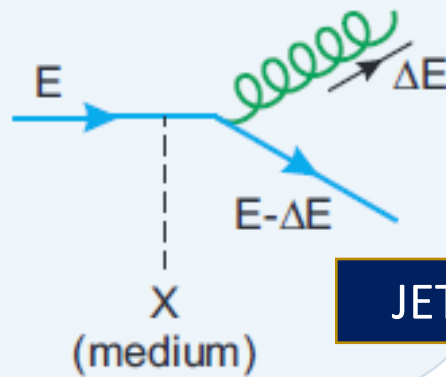
- **The main difficulty:** we don't know how to describe the interaction between the hard scattered parton and QGP (a multi-scale problem)
- **Two theoretical approaches:**
(neither of them are the full stories and both of them are effective descriptions in proper regimes)

Perturbative QCD
Weak coupling limit

Collisional
energy loss



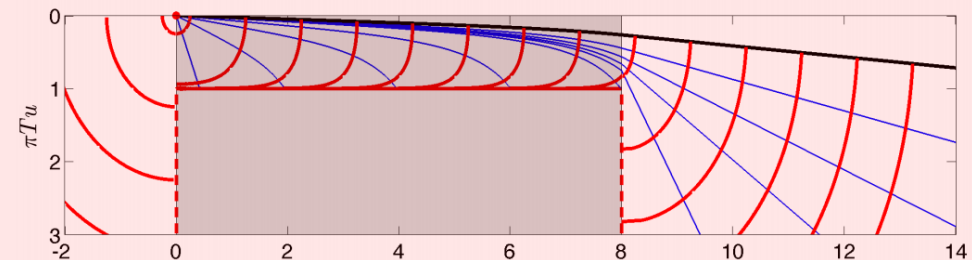
Radiative
energy loss



JETSCAPE

Holographic calculation
Strong coupling limit

AdS/CFT “drag force”



JEWEL

CUJet3.0

CCNU

HYBRID

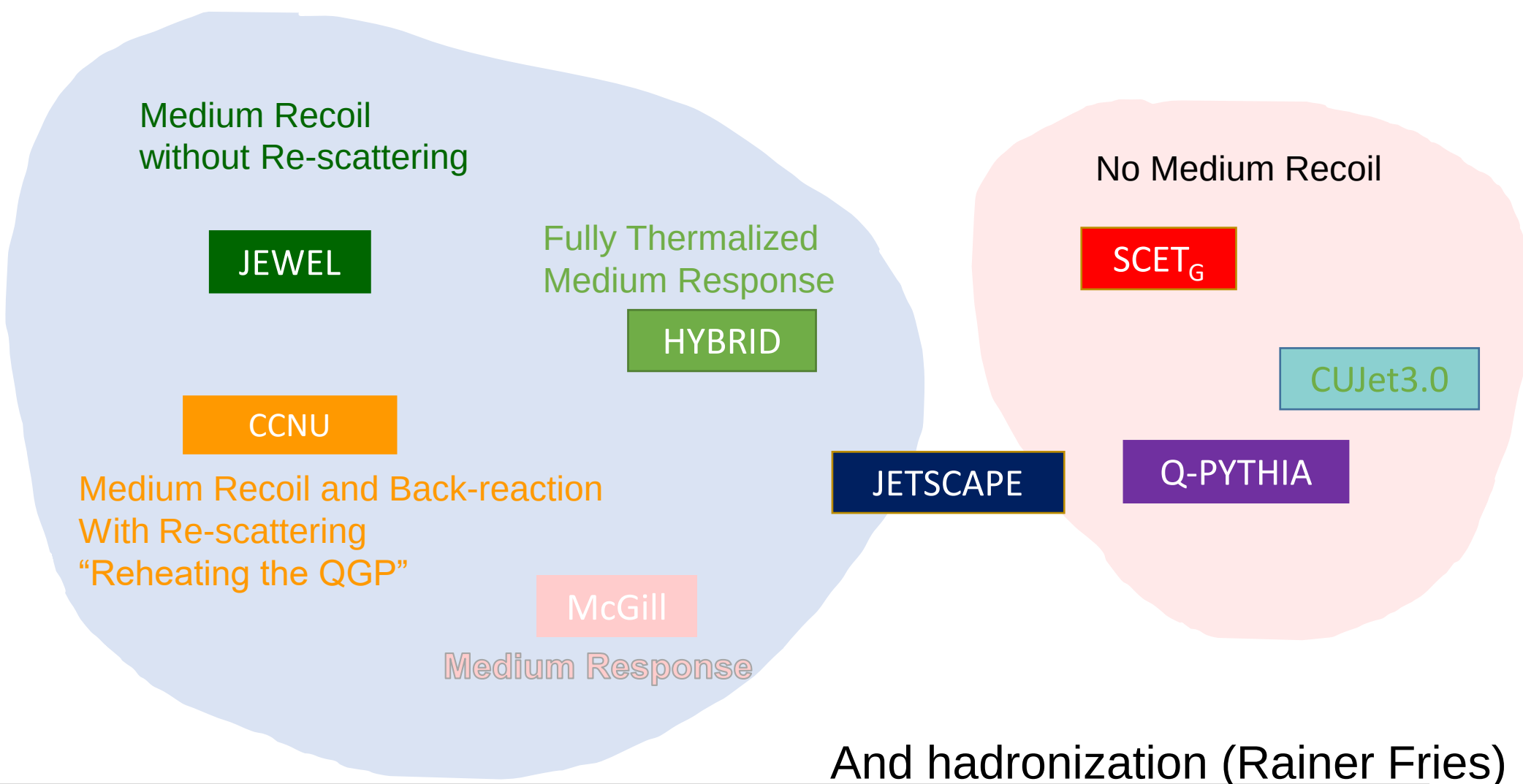
Q-PYTHIA

SCET_G

McGill

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



And hadronization (Rainer Fries)

TABLE I: $\langle N_{\text{coll}} \rangle$ and $\langle v_2 \rangle$ of all final partons from normal (first number in each column) and azimuth-randomized AMPT (Debye σ) and MPC (isotropic σ) results (second number). The d +Au impact parameter is $b = 0$ fm.

	AMPT d +Au		AMPT Au+Au ($b = 7.3$ fm)						MPC Au+Au ($b = 8$ fm)					
σ	3 mb		3 mb	20 mb	40 mb	60 mb			5.5 mb	20 mb	40 mb	60 mb		
$\langle N_{\text{coll}} \rangle$	1.2	1.4	4.6 5.8	13 22	17 32	20 39	4.7	5.4	17	23	35	52	53	83
$\langle v_2 \rangle$	2.7%	2.5%	3.9% 2.7%	5.9% 2.7%	6.0% 2.3%	5.7% 2.0%	5.5%	3.5%	8.6%	3.5%	9.8%	3.0%	10%	2.6%
$\langle v_2 \rangle_{\text{Rndm}} / \langle v_2 \rangle$	93%		69%	46%	38%	34%	64%	41%	31%	26%				

Arxiv 1502.05572

	pPb ($b = 0$ fm)			AuAu ($b = 6.6$ -8.1 fm)			PbPb ($b = 8$ fm)		
Quark flavor	u,d	s	c	u,d	s	c	u,d	s	c
$\langle N_{\text{coll}} \rangle$	2.02	2.54	4.23	4.58	5.45	8.68	9.82	11.14	15.48
$\langle v_2 \rangle_{\text{Random}}$	2.39%	1.89%	1.21%	2.93%	2.27%	0.85%	3.21%	2.23%	0.67%
$\langle v_2 \rangle_{\text{Normal}}$	3.28%	3.20%	2.14%	4.47%	4.78%	3.89%	7.56%	8.42%	7.92%
$\langle v_2 \rangle_{\text{Random}} / \langle v_2 \rangle_{\text{Normal}}$	73%	59%	57%	66%	47%	22%	43%	27%	8.5%

TABLE I: $\langle N_{\text{coll}} \rangle$, $\langle v_2 \rangle_{\text{Random}}$, $\langle v_2 \rangle_{\text{Normal}}$ and the ratio of $\langle v_2 \rangle$ from ϕ -randomized AMPT over that from normal AMPT for final partons of different flavors within $|\eta| < 1$ in three collision systems.

Arxiv 1804.02681