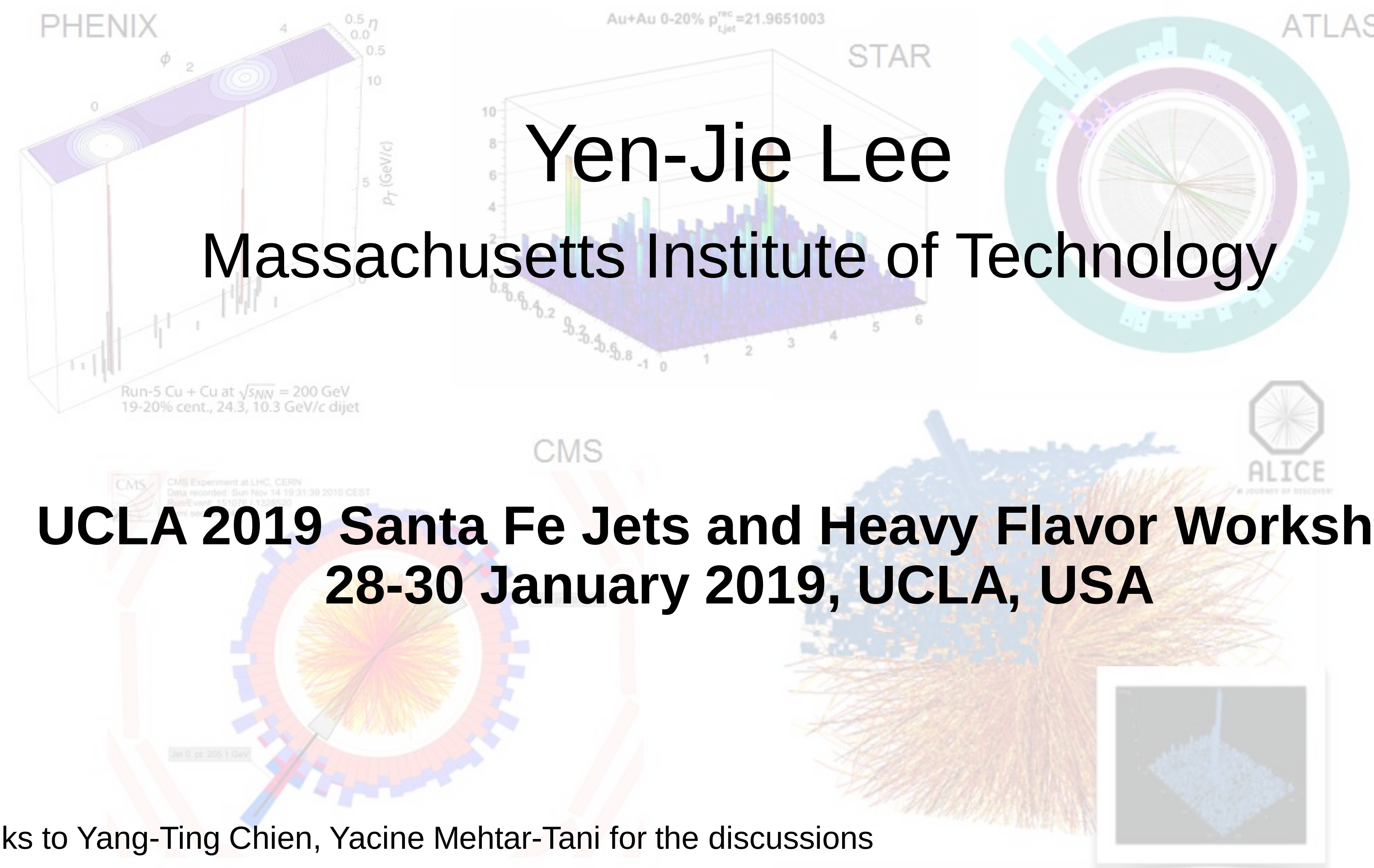
Jet Physics in Heavy Ion Collisions:
Where are we? Where are we going?



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Massachusetts Institute of Technology

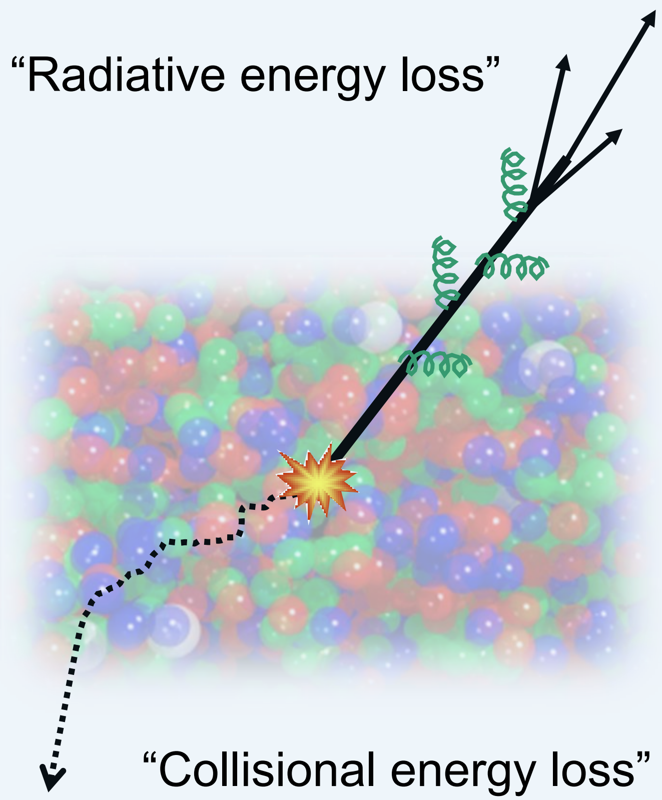
UCLA 2019 Santa Fe Jets and Heavy Flavor Workshop
28-30 January 2019, UCLA, USA

Many thanks to Yang-Ting Chien, Yacine Mehtar-Tani for the discussions

Weak Coupling vs. Strong Coupling Limit

Perturbative QCD
Weak coupling limit

“Radiative energy loss”

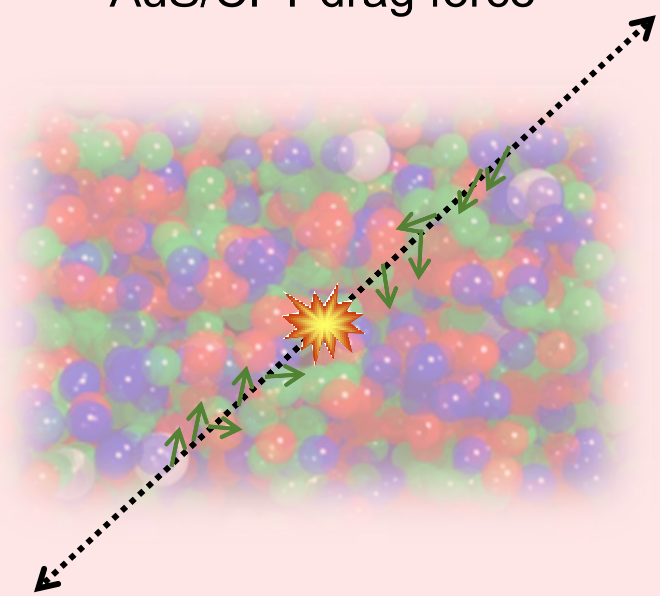


“Collisional energy loss”

Note: both processes happen simultaneously

Holographic calculation
Strong coupling limit

“AdS/CFT drag force”



JETSCAPE

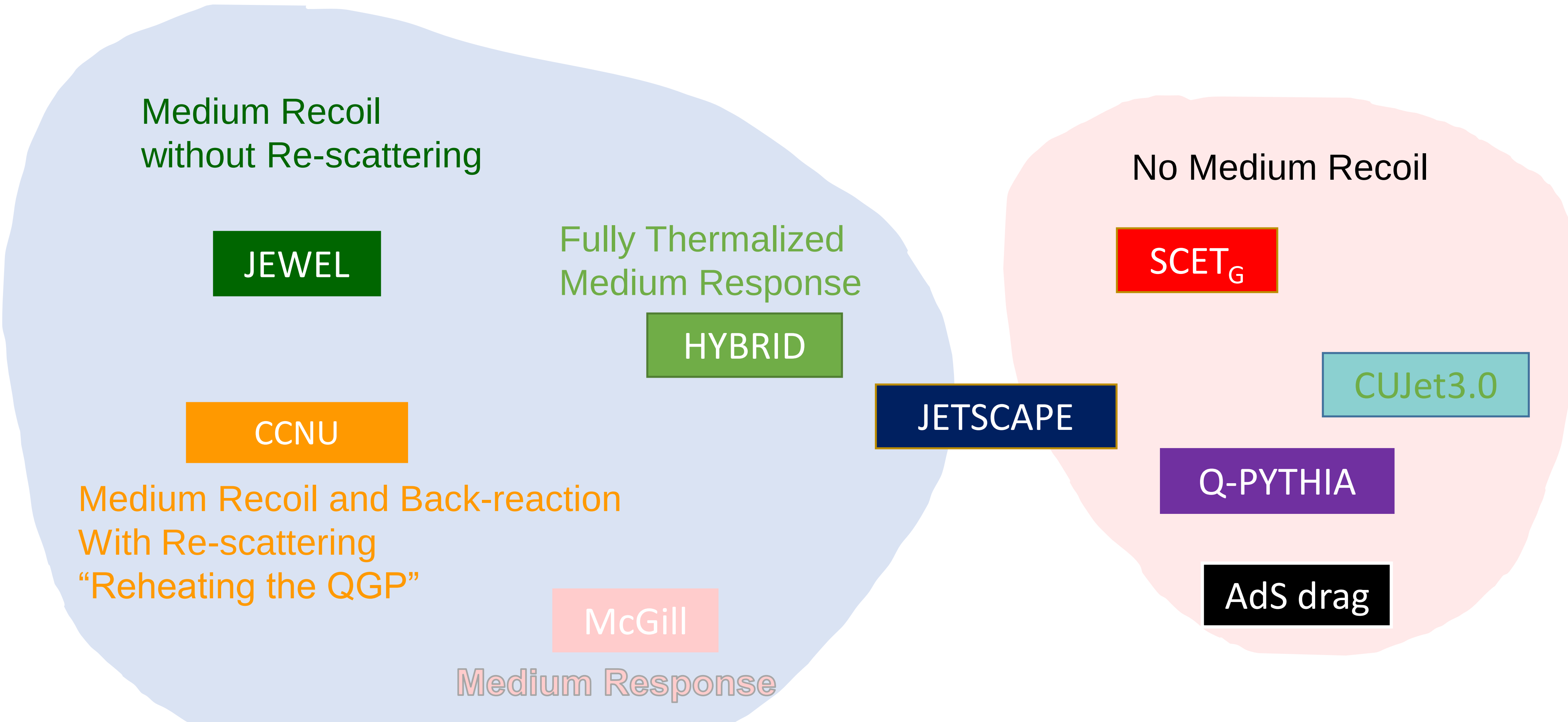
JEWEL | CUJet3.0 | CCNU | Q-PYTHIA | $SCET_G$ | McGill

AdS drag | HYBRID

Jet quenching mechanism (before QGP property extraction)

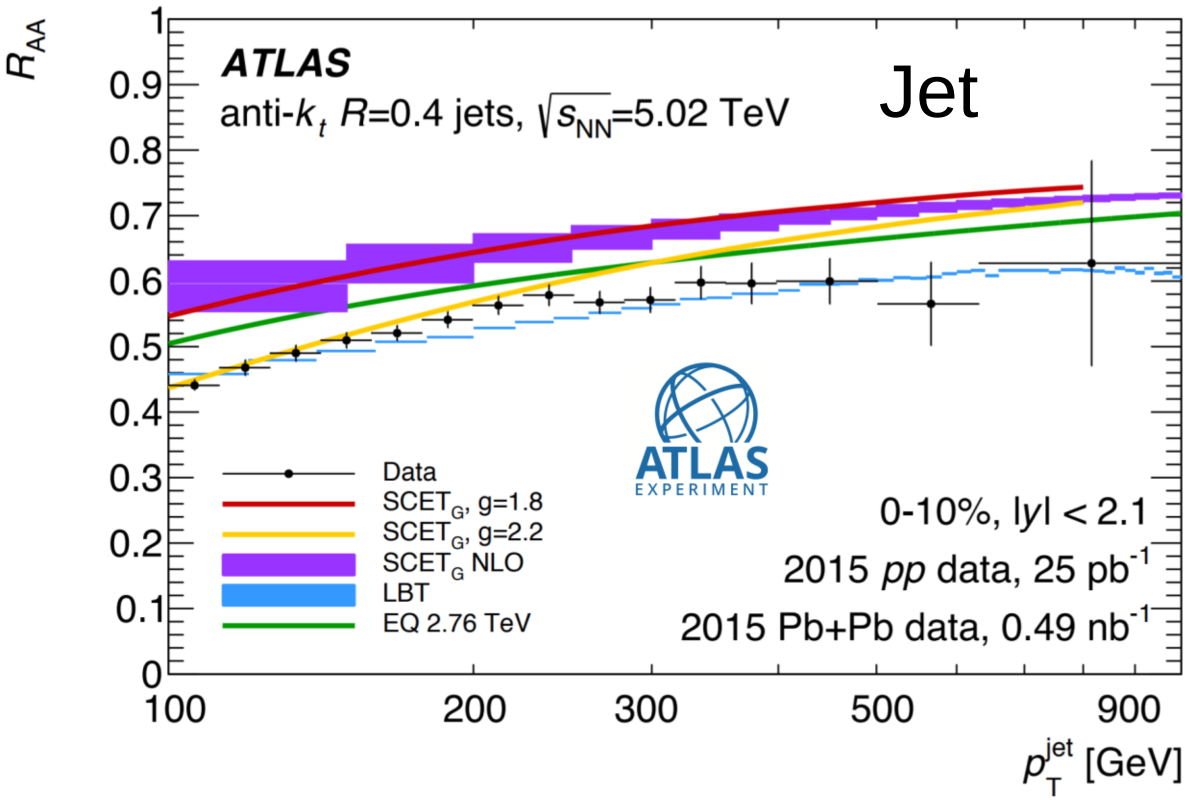
Medium Response

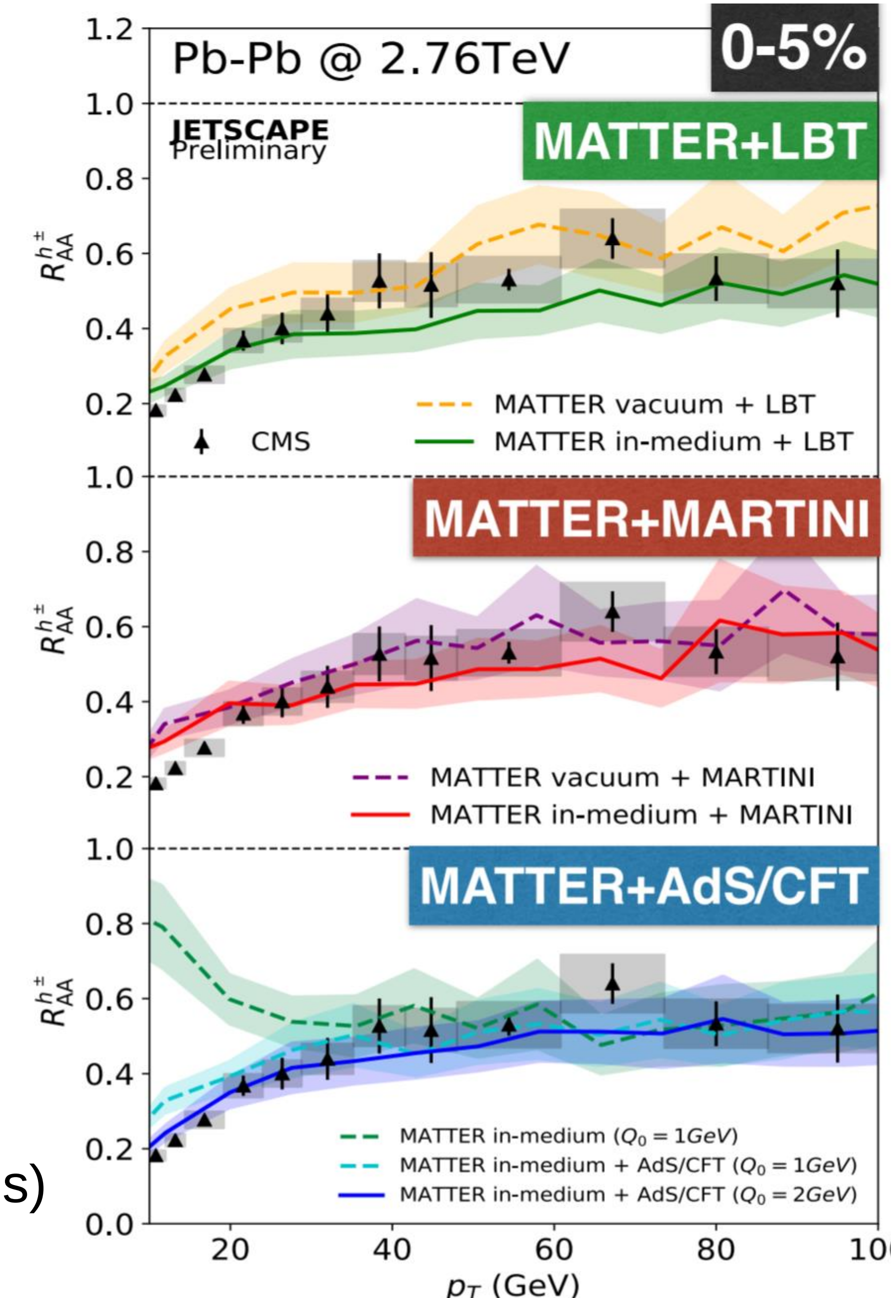
We also don’t know **how much** the medium response (recoil) plays a role in the description of the jet quenching observables
and how to describe it correctly



…and the hadronization of them in QGP

Charged Particle and Jet R_{AA}

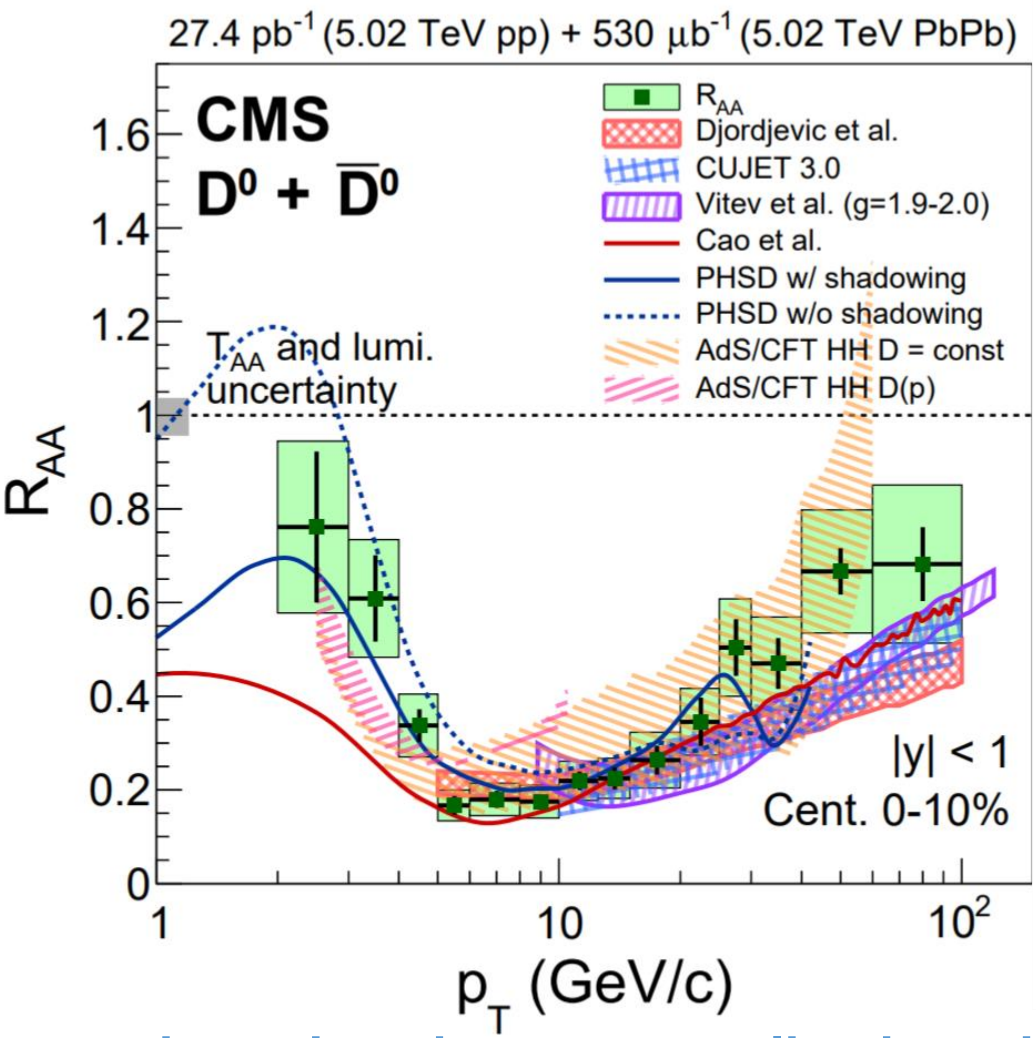


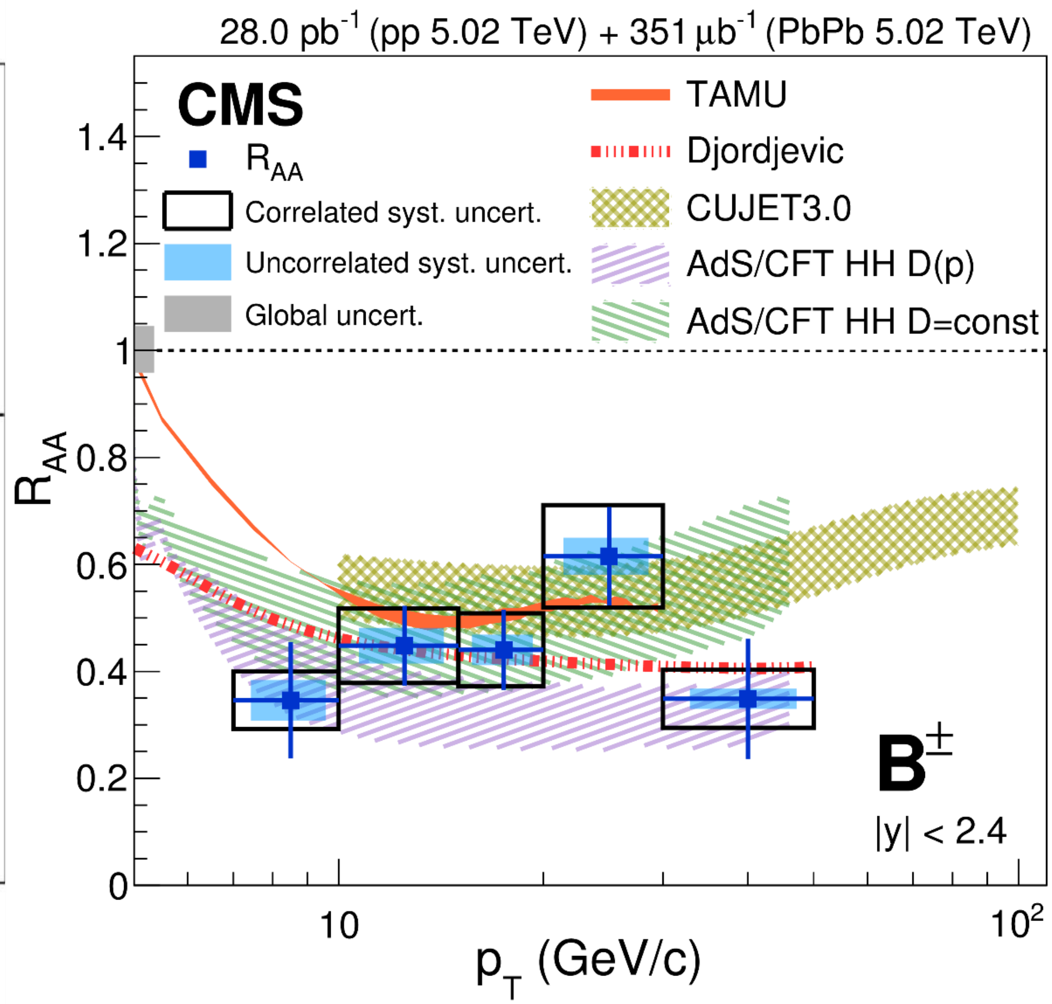


Charged Hadron

Impression: with tuning, models with different underlying physics could fit the data (both strong and weak coupling calculations)

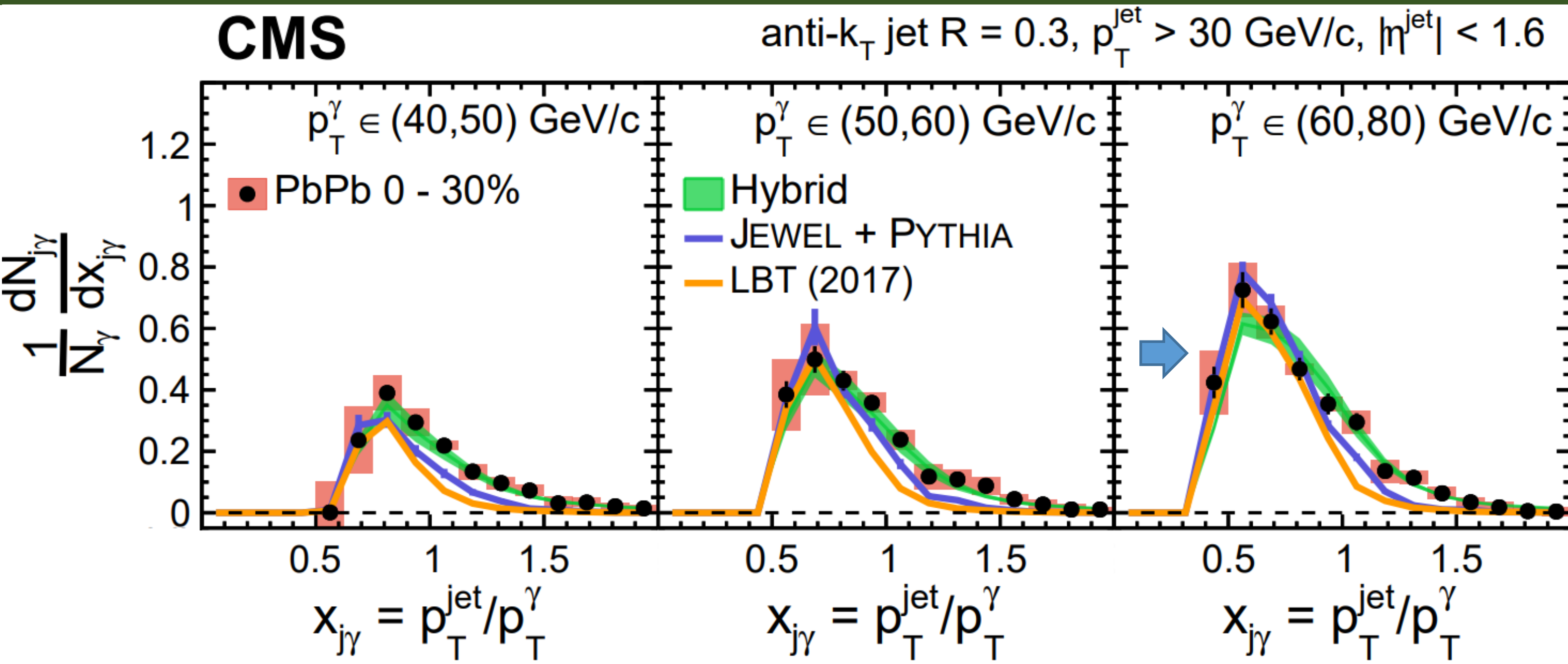
Heavy Flavor Meson R_{AA}





- **Both weak and strong coupling based models** describe the charged hadron, charm and beauty meson R_{AA} data
- Within pQCD world, models with very different level of complexity describe the data
- No significant difference between beauty and inclusive (di-)jet results (not shown, need better accuracy)

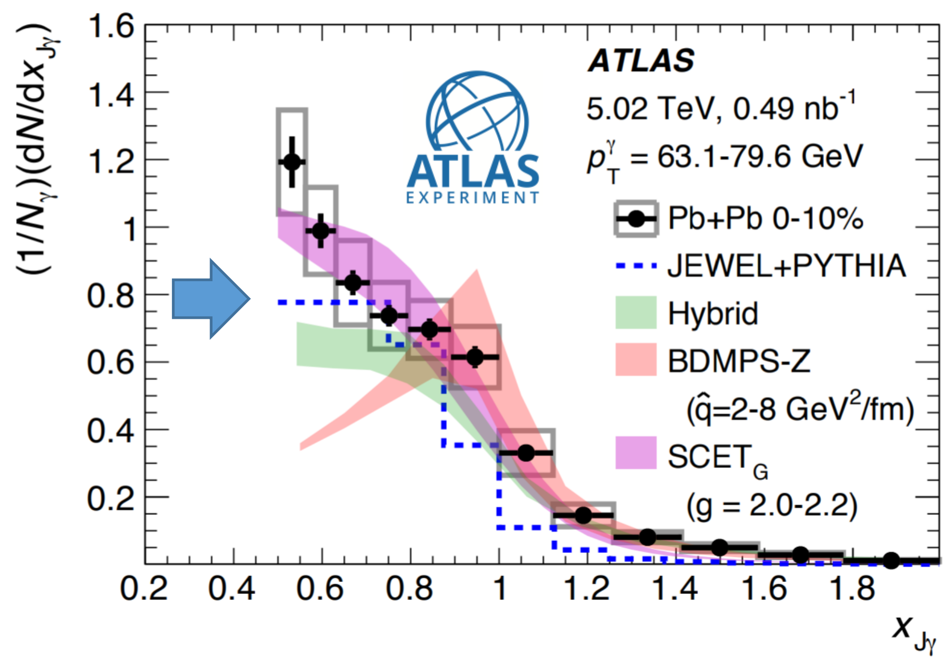
Photon-Jet Momentum Balance



CMS vs. Smeared Theory

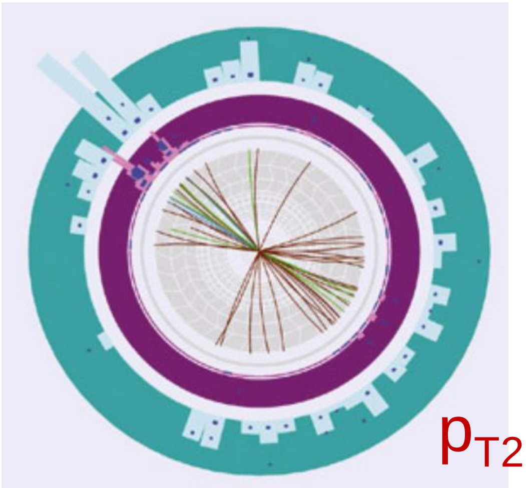
arXiv:1711.09738
Accepted by PLB

Resolution Unfolded ATLAS Data vs. Theory



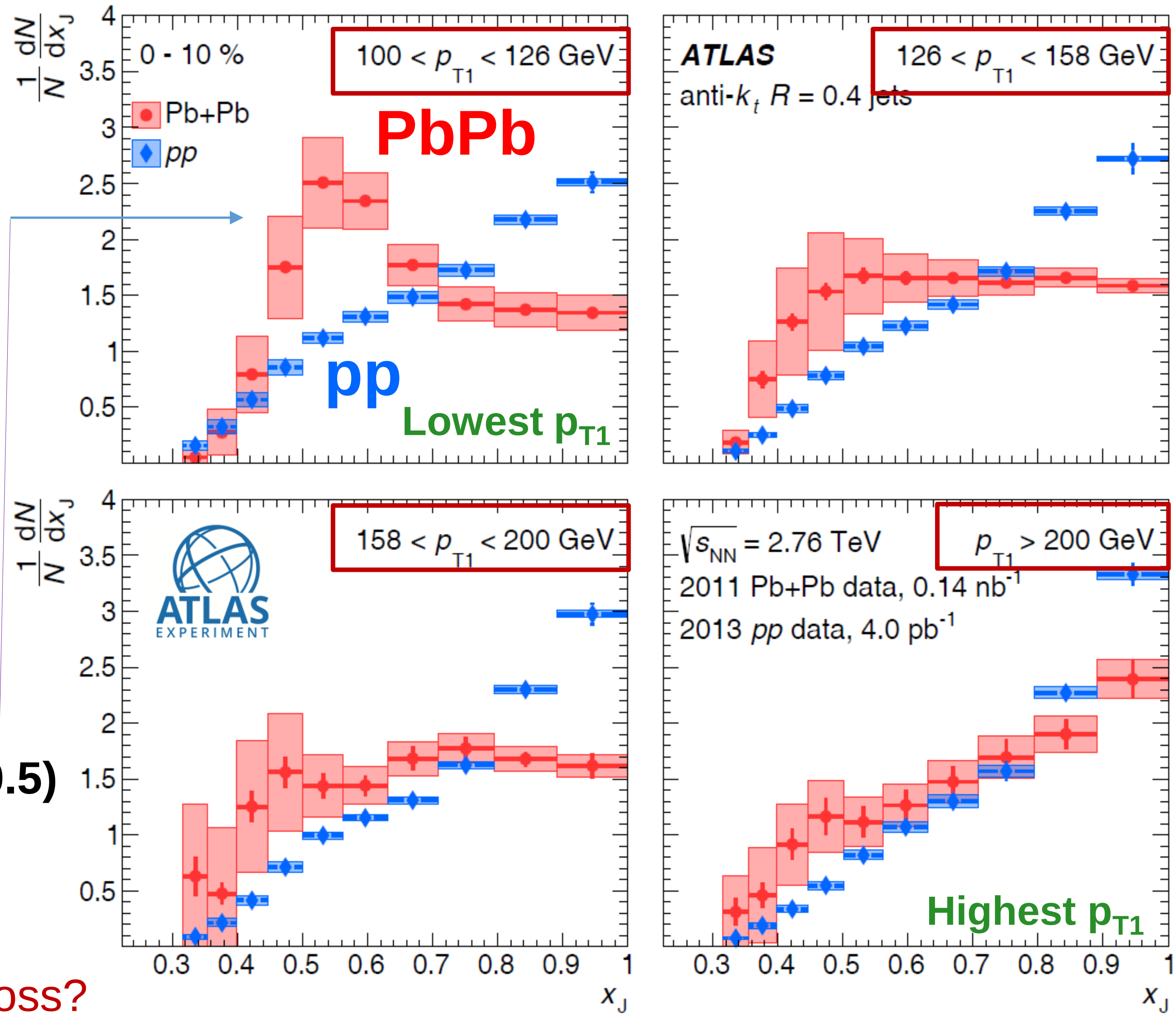
- Different conclusions between CMS and ATLAS at low $x_{j\gamma}$
- **Example**: **HYBRID** (AdS/CFT drag) model describes CMS data almost perfectly; inconsistent with ATLAS preliminary results at lowest **$X_{j\gamma} \sim 0.5$**
- Note the difference in the photon p_T and jet p_T selection between CMS and ATLAS

Dijet Asymmetry in PbPb at 2.76 TeV



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

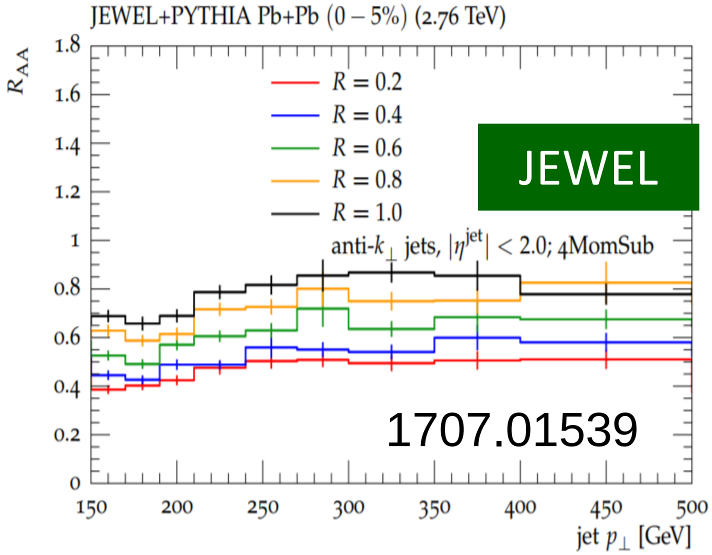
- First unfolded dijet p_T ratio
- **Narrow peak** at low **X_J (~0.5)** visible after jet resolution correction.
  → Small fluctuation of the sub-leading jet energy loss?



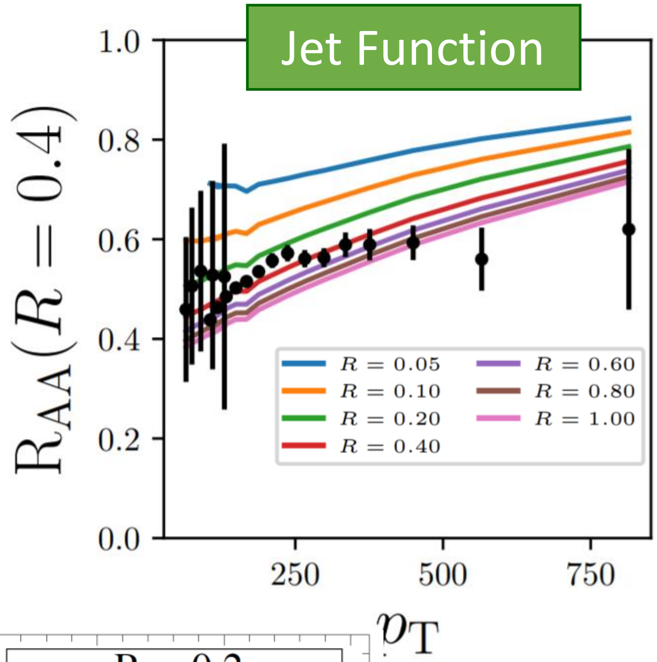
PLB 774 (2017) 379

- **Peak goes away rapidly** as one increase leading jet p_T cut

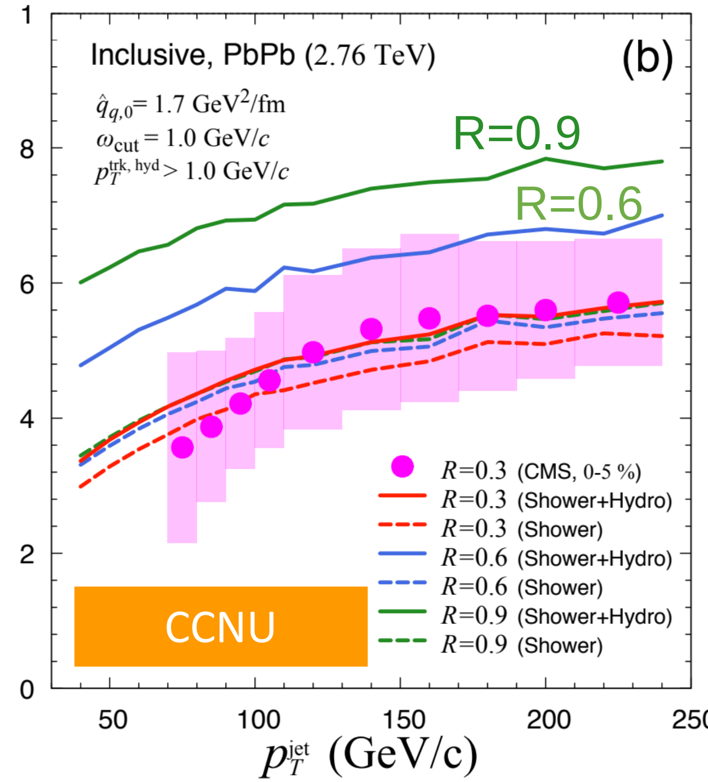
Jet R_{AA} vs. R



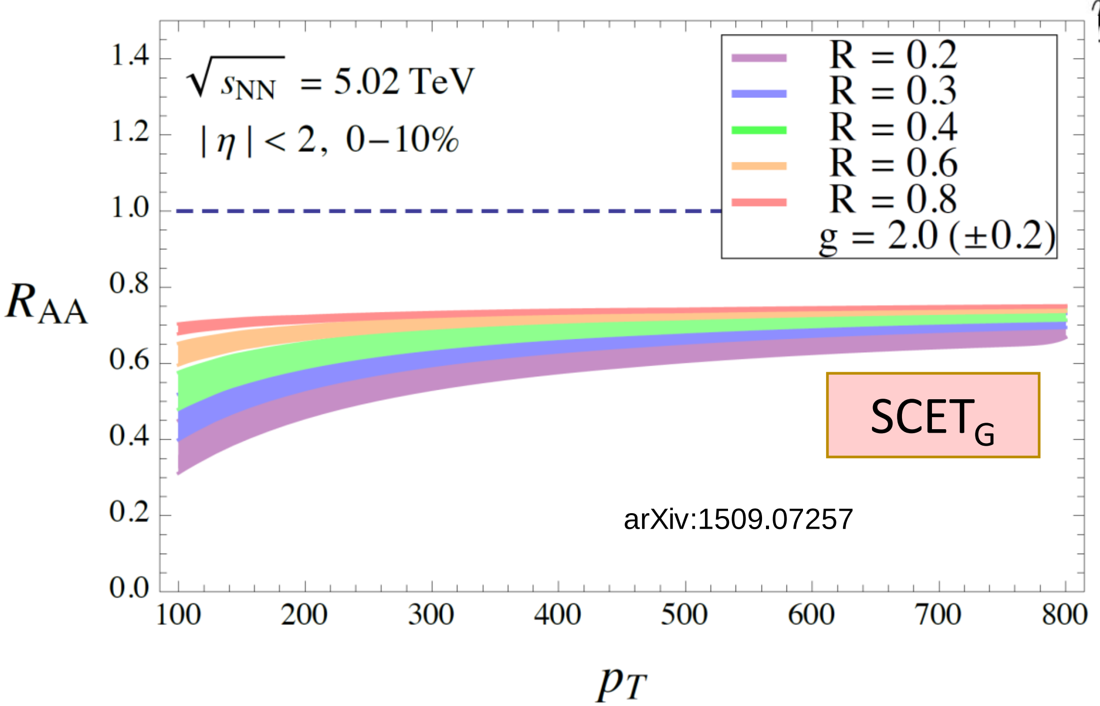
JEWEL+PYTHIA Pb+Pb (0 – 5%) (2.76 TeV)
R_{AA}
$R = 0.2$
$R = 0.4$
$R = 0.6$
$R = 0.8$
$R = 1.0$
JEWEL
anti-$k_\perp$ jets, $|\eta^{jet}| < 2.0$; 4MomSub
1707.01539
jet $p_\perp$ [GeV]



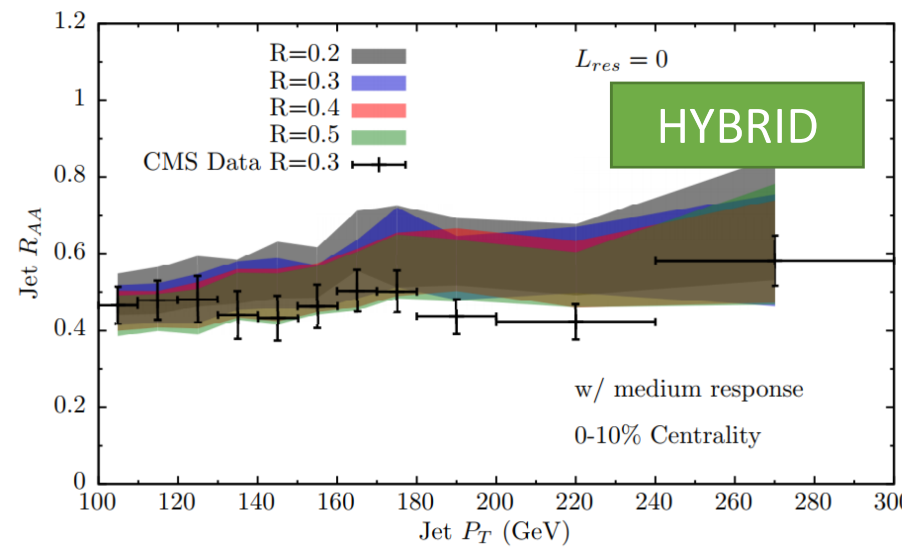
Jet Function
$R_{AA}(R = 0.4)$
$R = 0.05$
$R = 0.10$
$R = 0.20$
$R = 0.40$
$R = 0.60$
$R = 0.80$
$R = 1.00$
p_T



Inclusive, PbPb (2.76 TeV)
(b)
$\hat{q}_{q,0}$= 1.7 GeV^2/fm
ω_{cut} = 1.0 GeV/c
$p_T^{trk, hyd}$ > 1.0 GeV/c
R=0.9
R=0.6
R=0.3 (CMS, 0-5 %)
R=0.3 (Shower+Hydro)
R=0.3 (Shower)
R=0.6 (Shower+Hydro)
R=0.6 (Shower)
R=0.9 (Shower+Hydro)
R=0.9 (Shower)
CCNU
p_T^{jet} (GeV/c)

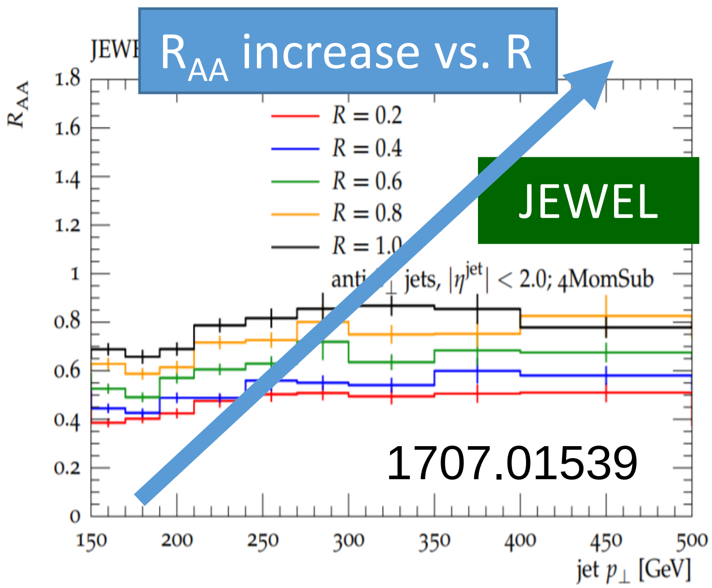


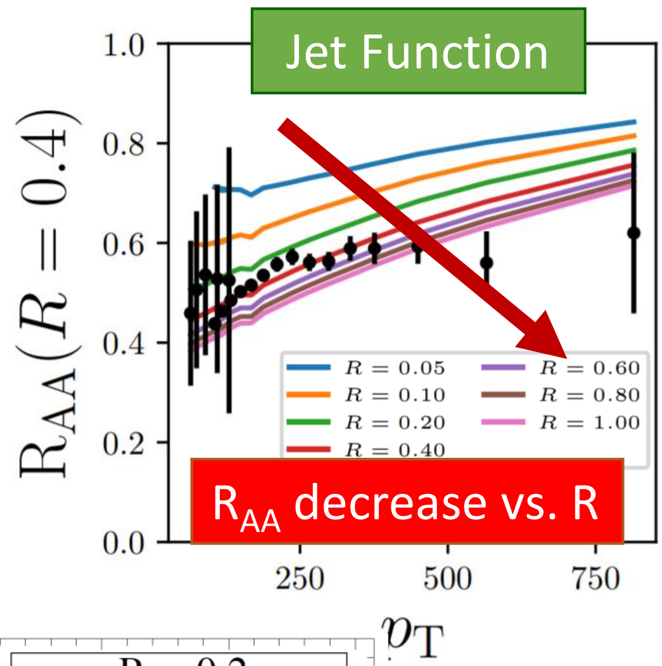
$\sqrt{s_{NN}}$ = 5.02 TeV
$|\eta| < 2,$ 0–10%
R = 0.2
R = 0.3
R = 0.4
R = 0.6
R = 0.8
g = 2.0 (±0.2)
R_{AA}
SCET$_G$
arXiv:1509.07257
p_T

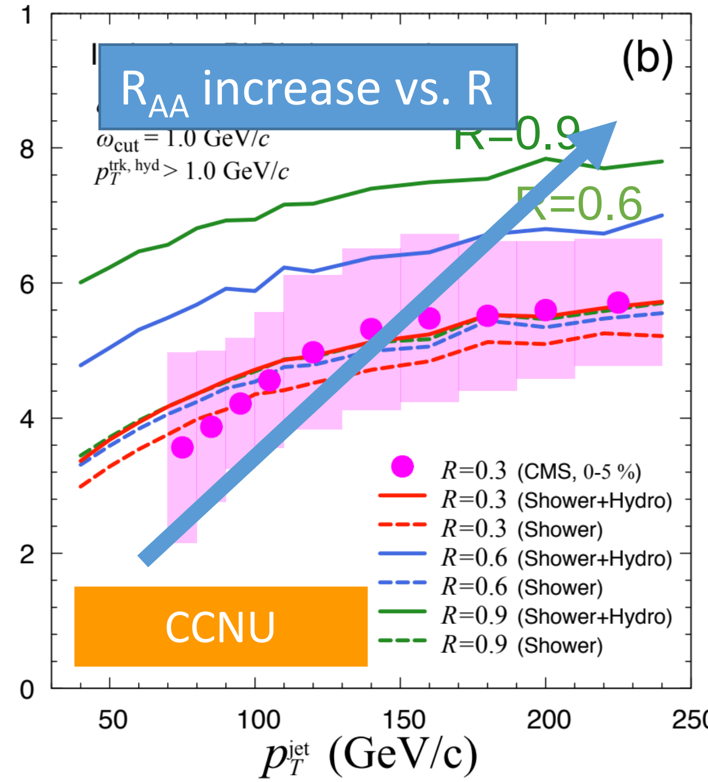


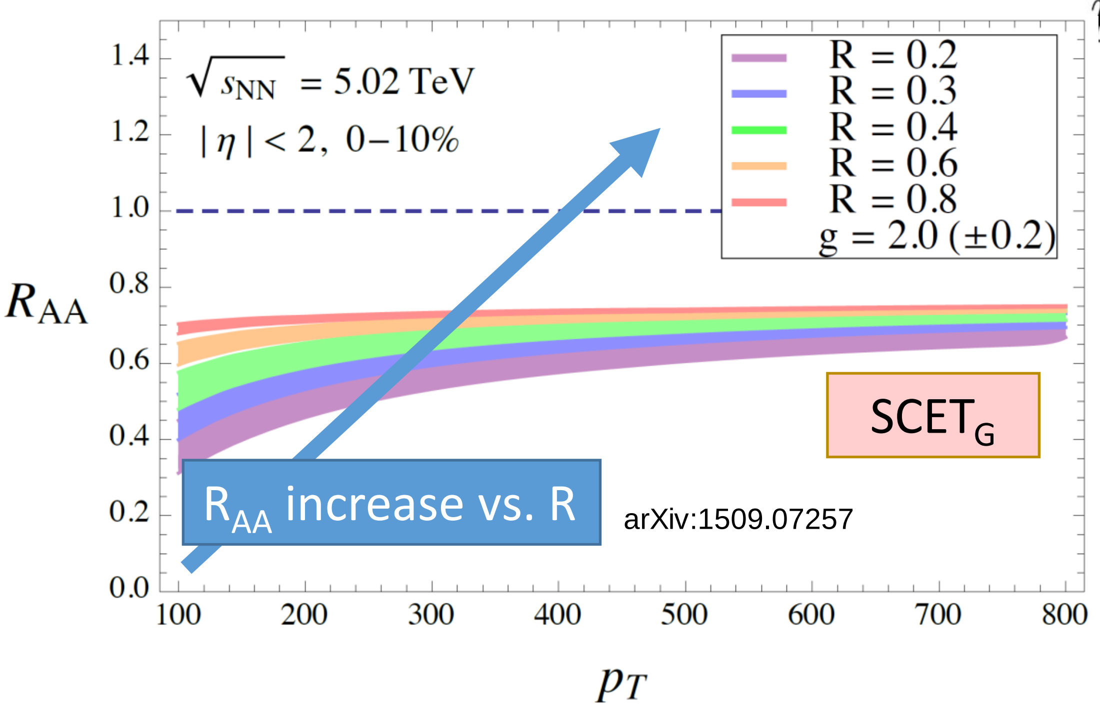
R=0.2
R=0.3
R=0.4
R=0.5
CMS Data R=0.3
$L_{res} = 0$
HYBRID
Jet R_{AA}
w/ medium response
0-10% Centrality
Jet P_T (GeV)

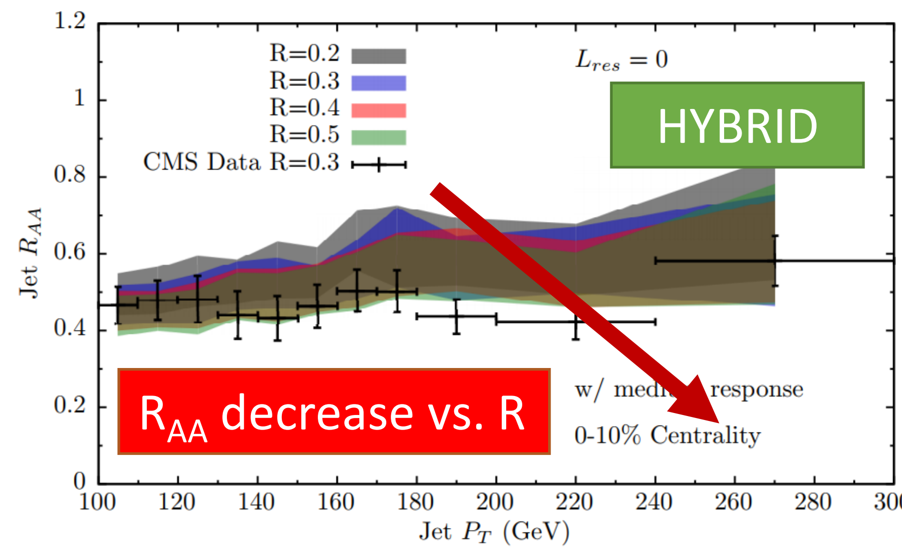
Jet R_{AA} vs. R


R_AA increase vs. R
JEWEL
R = 0.2
R = 0.4
R = 0.6
R = 0.8
R = 1.0
1707.01539
jet p⊥ [GeV]
R_AA


Jet Function
R_AA(R = 0.4)
R = 0.05
R = 0.10
R = 0.20
R = 0.40
R = 0.60
R = 0.80
R = 1.00
R_AA decrease vs. R
p_T


(b)
R_AA increase vs. R
ω_cut = 1.0 GeV/c
R=0.9
R=0.6
R=0.3 (CMS, 0-5 %)
R=0.3 (Shower+Hydro)
R=0.3 (Shower)
R=0.6 (Shower+Hydro)
R=0.6 (Shower)
R=0.9 (Shower+Hydro)
R=0.9 (Shower)
CCNU
p_T^jet (GeV/c)


√s_NN = 5.02 TeV
|η| < 2, 0–10%
R = 0.2
R = 0.3
R = 0.4
R = 0.6
R = 0.8
g = 2.0 (±0.2)
R_AA
SCET_G
R_AA increase vs. R
arXiv:1509.07257
p_T


R=0.2
R=0.3
R=0.4
R=0.5
CMS Data R=0.3
L_res = 0
HYBRID
Jet R_AA
R_AA decrease vs. R
0-10% Centrality
Jet P_T (GeV)

Spectra-based Observables

- Both strong and weak coupling models describe the charged particle and jet R_{AA} data
- Accumulation of very low p_T jets in ATLAS unfolded data: ATLAS dijet X_J ~0.5 peak in unfolded results: no model could describe it currently. (Also shown as enhancement in ATLAS photon-jet $X_{J\gamma}$~0.5) Words from CMS and ALICE?

Possible future direction:

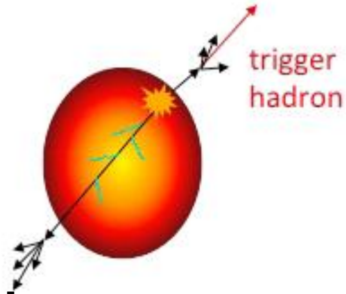
- **Raise our standard of "data-model" agreement:** p-value and global fit on multiple dataset
- Treat these observables as baseline data for model parameter extraction and predict other jet substructure (fluctuation) observables
- Comprehensive measurements on the R dependence of jet R_{AA}, $X_{j\gamma}$ and h-jet I_{AA} up to large R (with LHC experiments, STAR and sPHENIX)

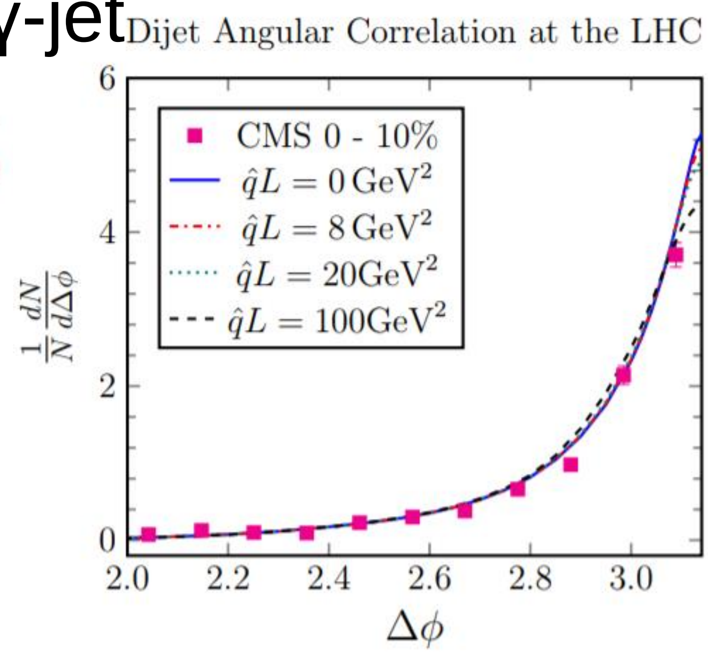
QGP Rutherford Exp: back scattering

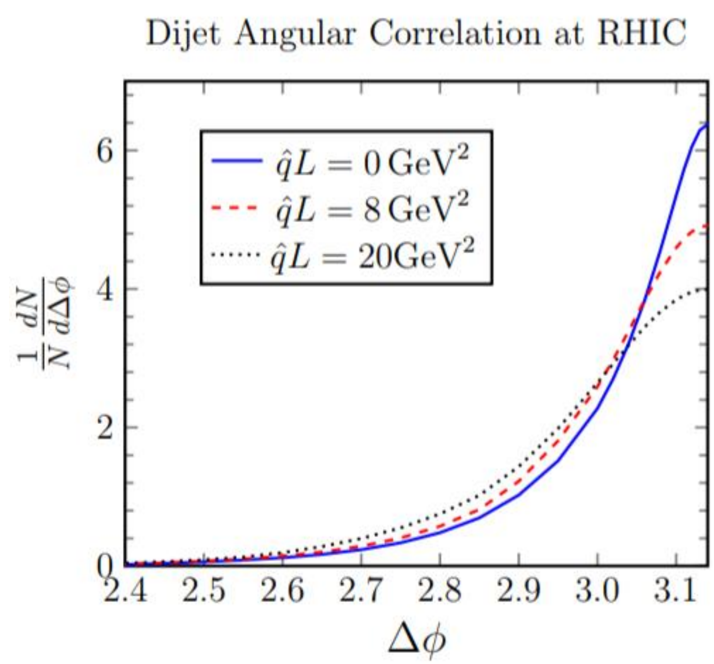
- No significant modification in h-jet and γ-jet

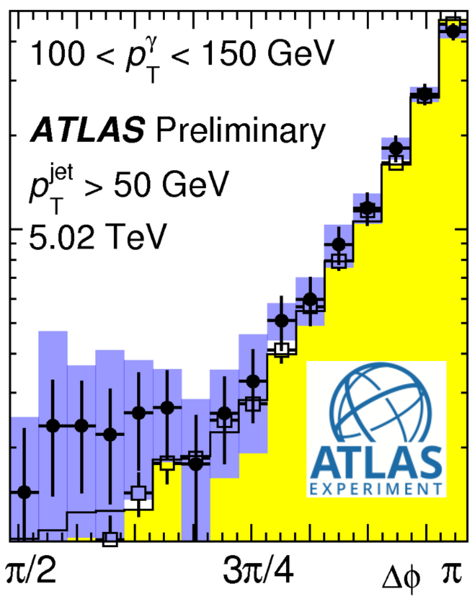
Possible future direction:

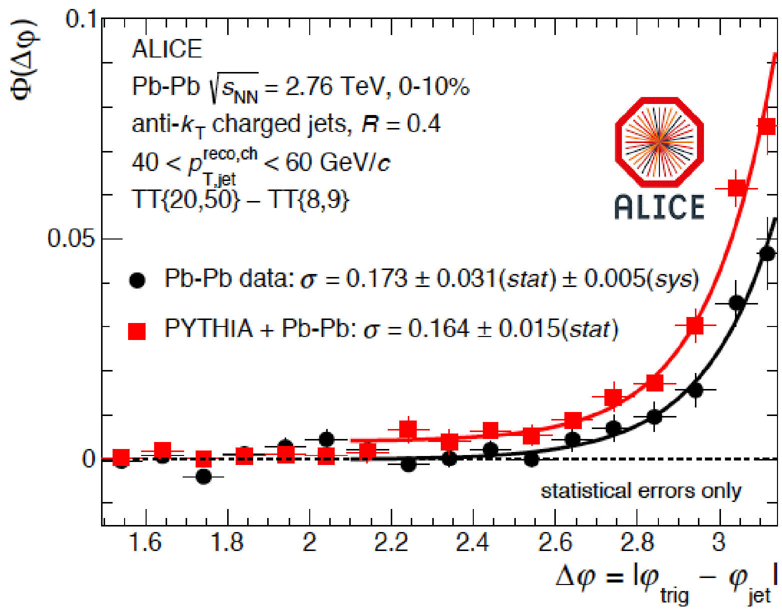
- Need next level of accuracy and resolution at small ΔΦ and high statistics at large ΔΦ at LHC
- More promising at RHIC energy where the correlation is less affected by initial state radiation (STAR and sPHENIX)



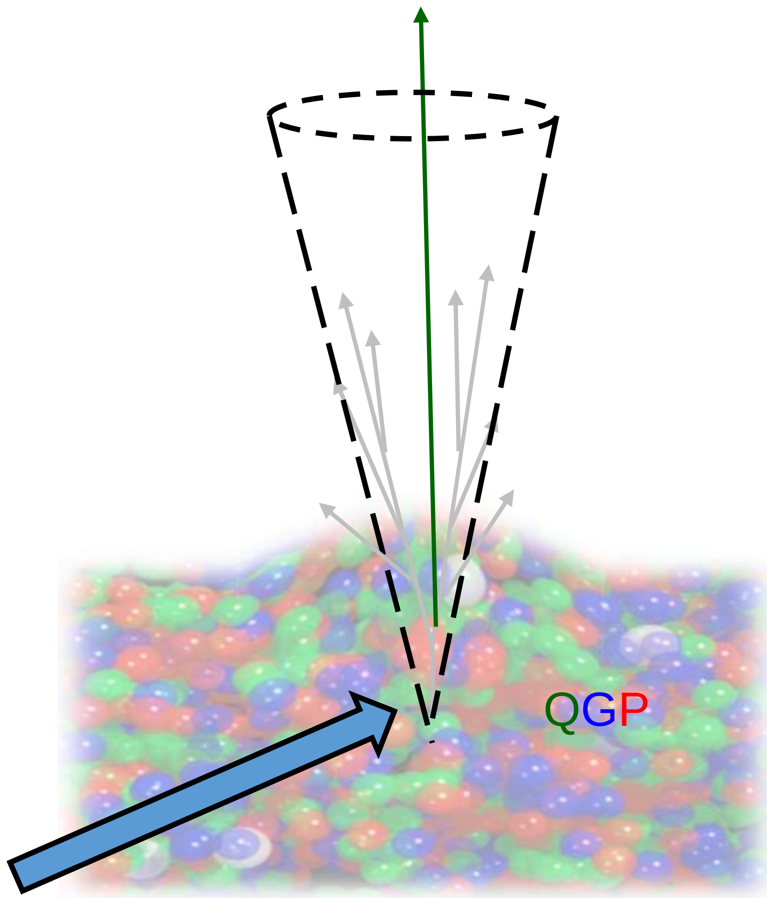








Flavor Dependence of Parton Energy Loss



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

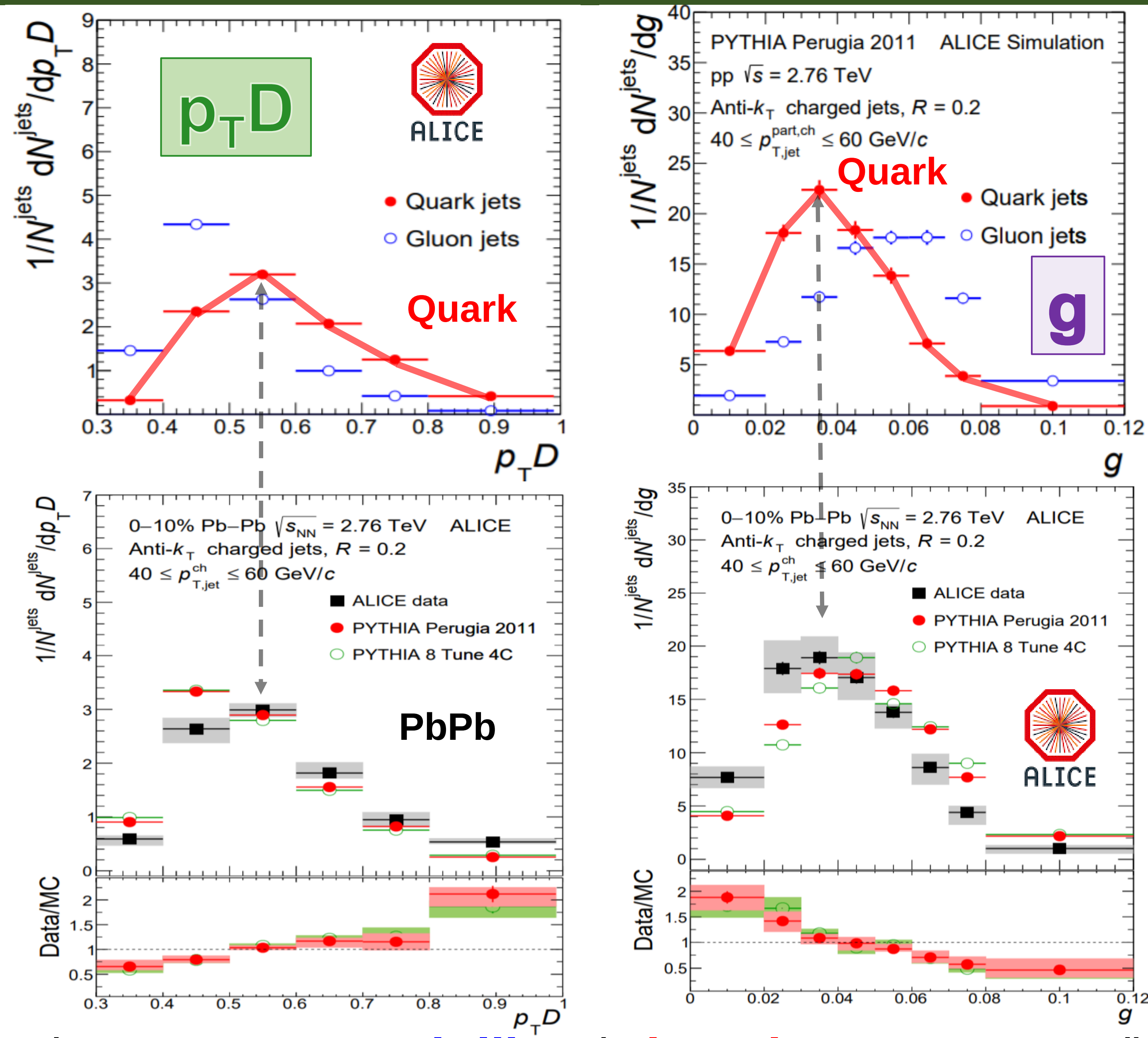
arXiv:1807.06854
Submitted to JHEP

ALICE Simulation

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

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

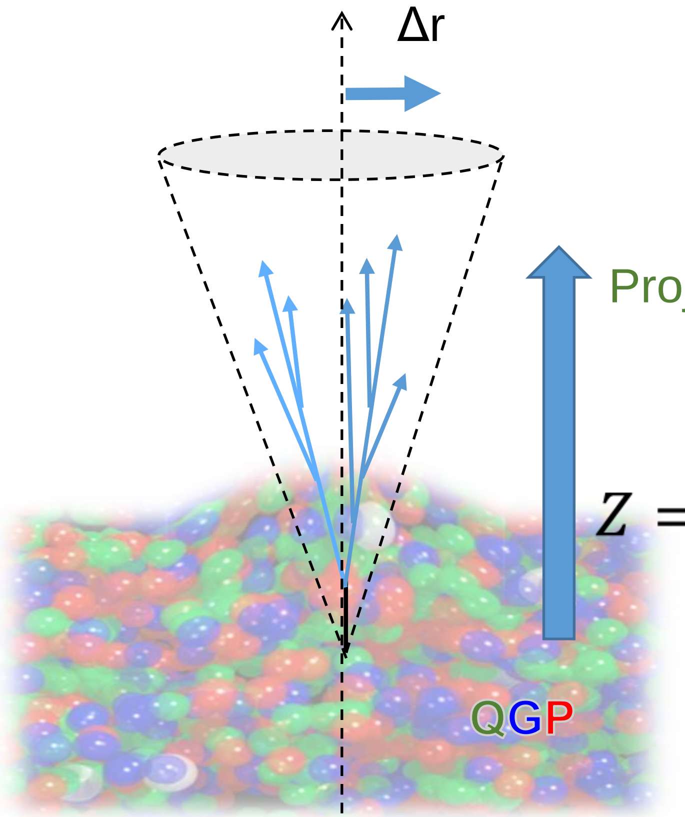
ALICE Data



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

Jet Longitudinal Structure

Jet axis



Projection to jet axis

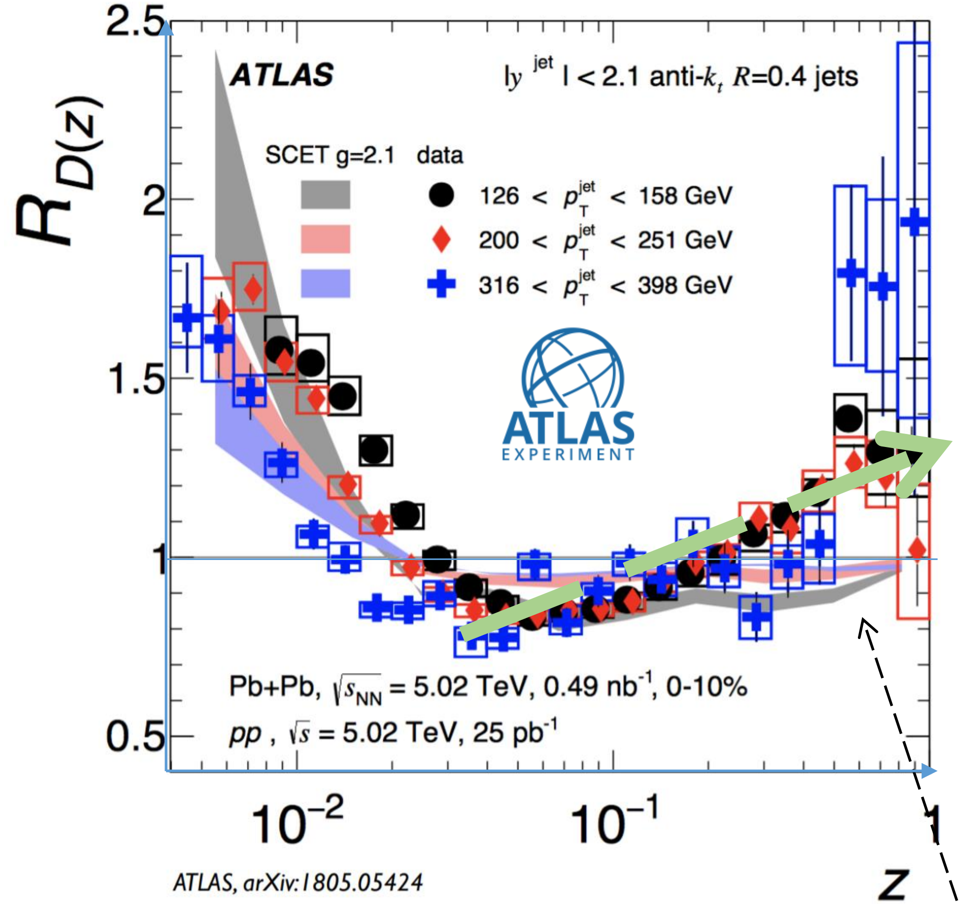
$$Z = \frac{p_T^{Trk} \cos \Delta r}{p_T^{Jet}}$$

$\xi = \ln(1/z)$

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

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

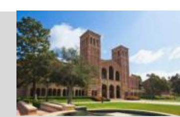
ATLAS-CONF-2017-005



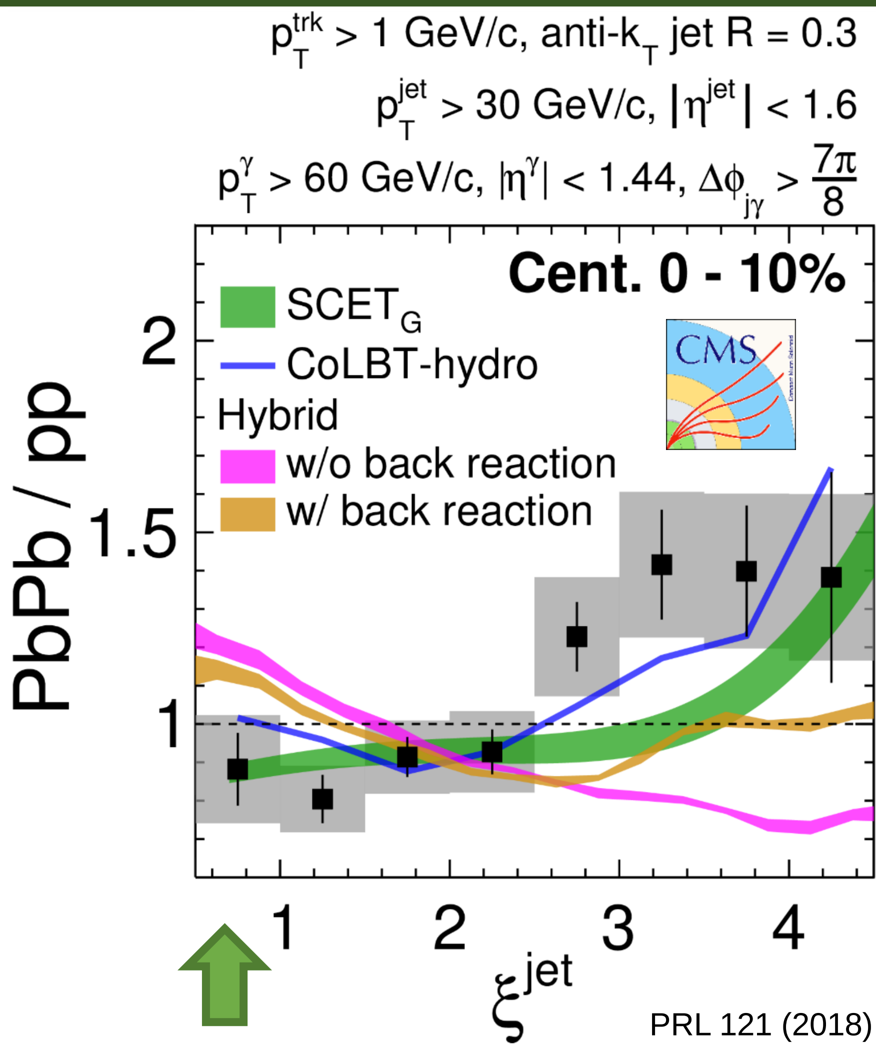
- Enhancement at low p_T (low Z) and depletion at intermediate Z
- Enhancement at large z (high p_T particles in jet): **smaller gluon/quark ratio** in PbPb
- High Z region: Weak or no dependence on the jet p_T

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?



Jet Longitudinal Structure

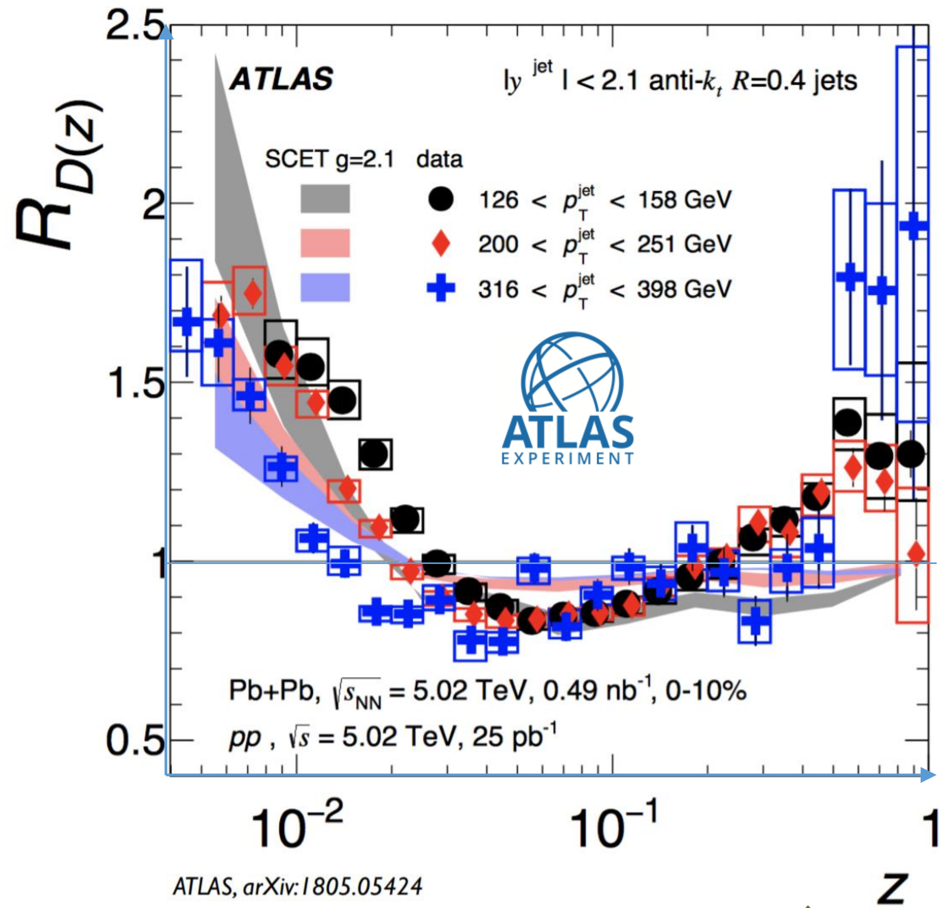


PRL 121 (2018) 242301

High p_T particle (Low ξ)

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

ATLAS-CONF-2017-005



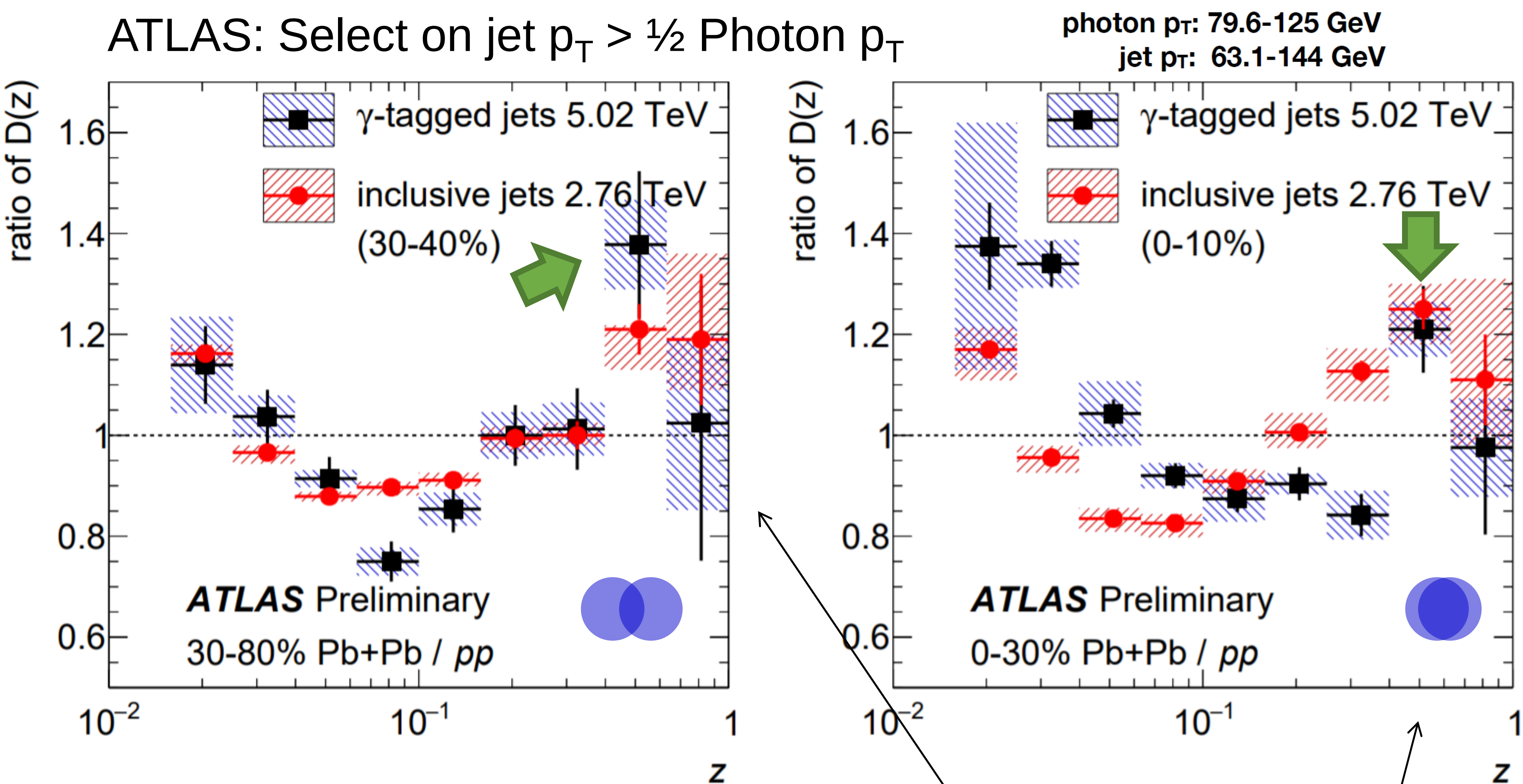
$\xi = \ln(1/z)$

High p_T particle (High Z)

→ **If switch to γ-tagged jet (mainly quarks), will this enhancement go away?**
Seems to be the case from CMS data (caveat: jet p_T also changed)

Photon-Tagged Fragmentation Function

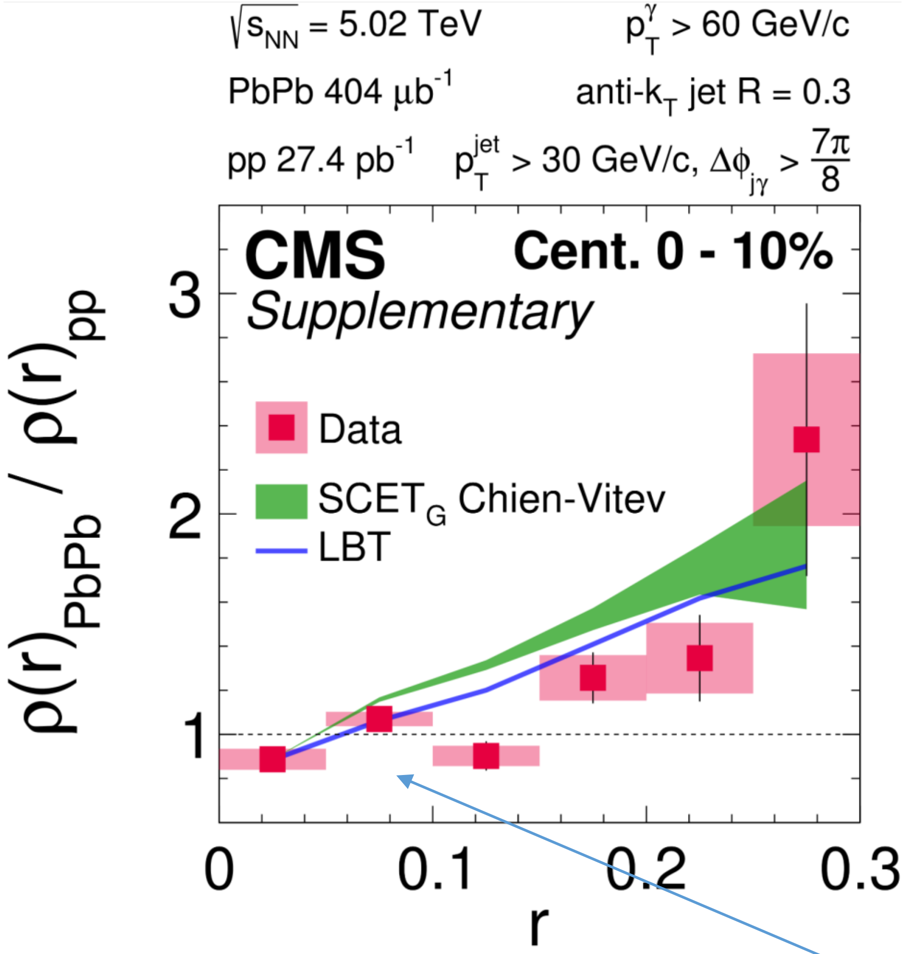
ATLAS: Select on jet p_T > ½ Photon p_T



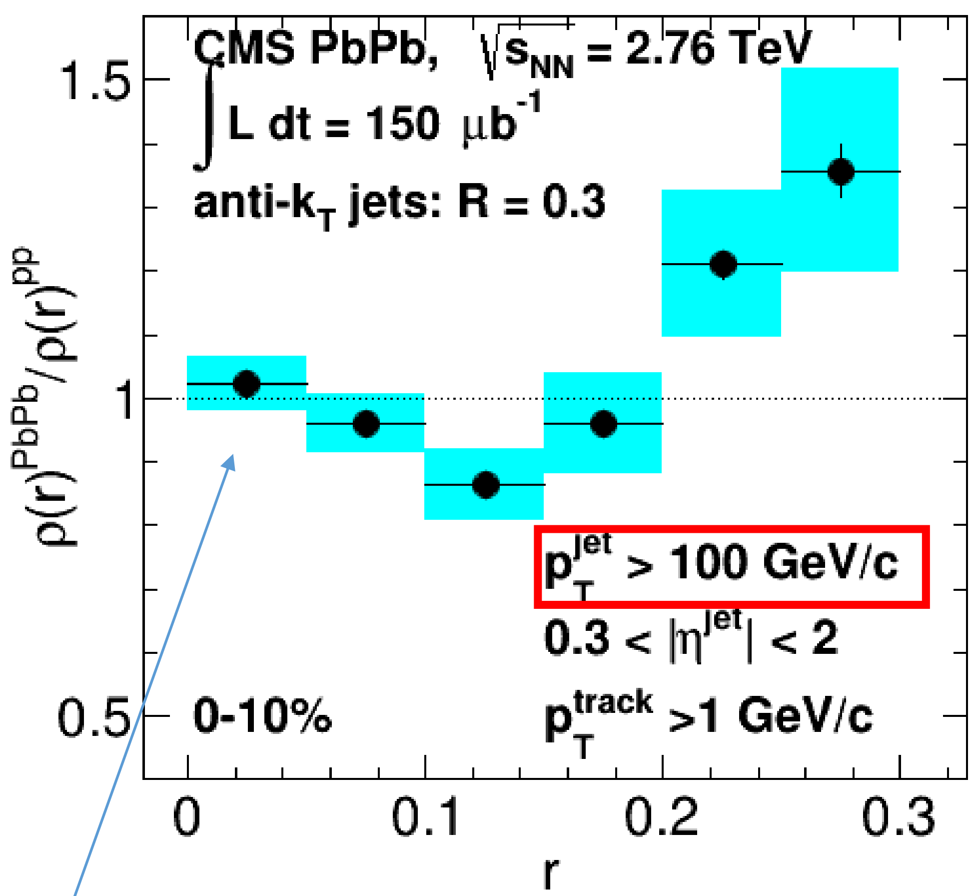
- Different picture from ATLAS (jet hardening at large z region)
- Significant of **photon-tagged jet FF** in both centrality intervals.
- Corrected for jet resolution smearing
- Hint of enhancement in PbPb/pp ratio at the **high z region?**

Photon-Tagged Jet and Inclusive Jet Shape

Photon-tagged (Quark Enriched)



Inclusive (Quark + Gluon)

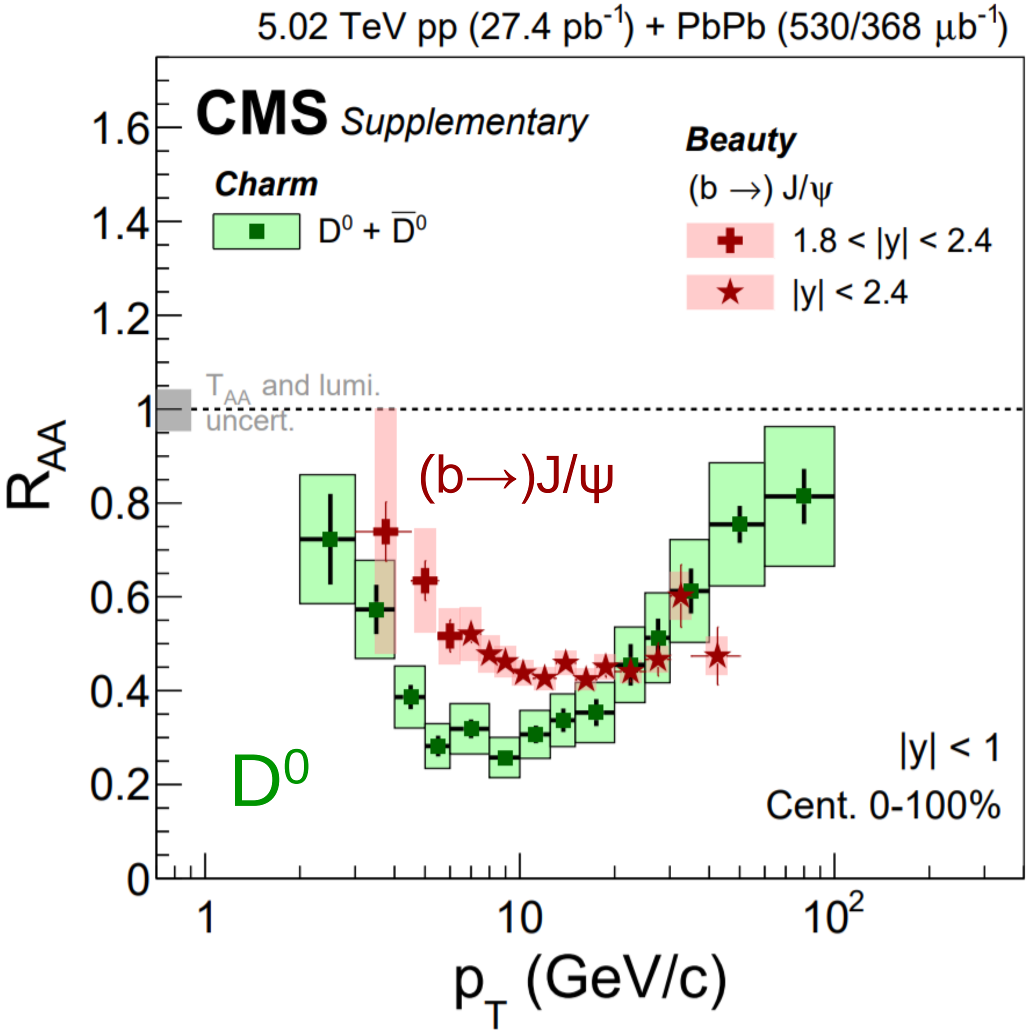


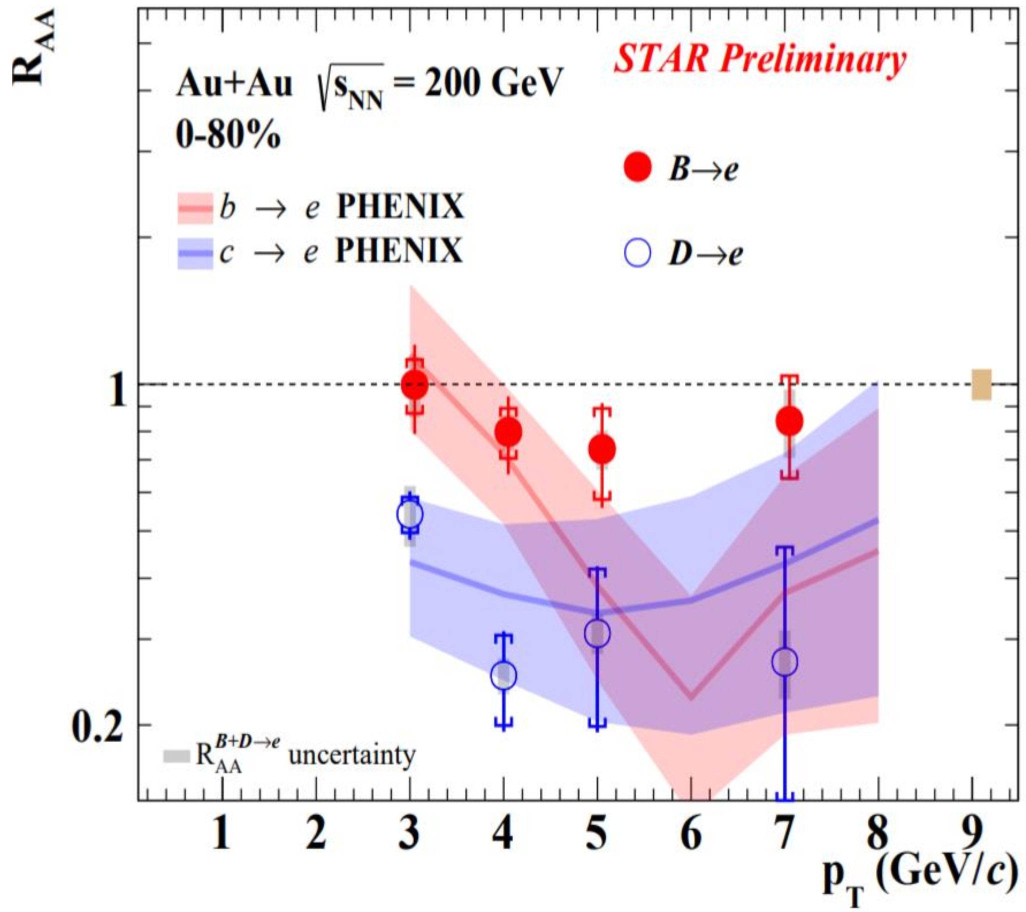
CMS-HIN-18-006
arXiv:1809.08602

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

- Difference at small r due to the lower jet p_T in photon-tagged jet and larger quark jet fraction
- Photon tagged jet in PbPb are **wider** than pp ref
- Need to measure higher p_T photon-tagged jet

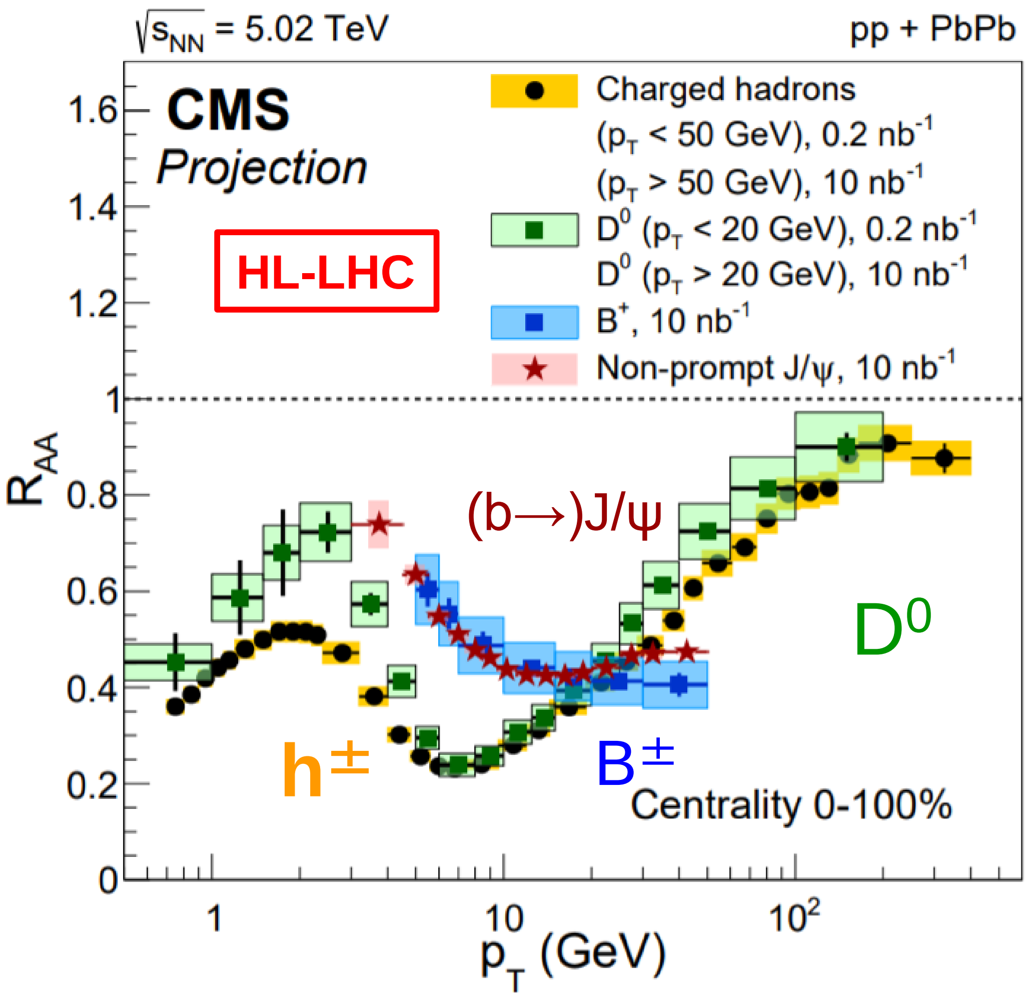
Beauty vs. Charm hadrons

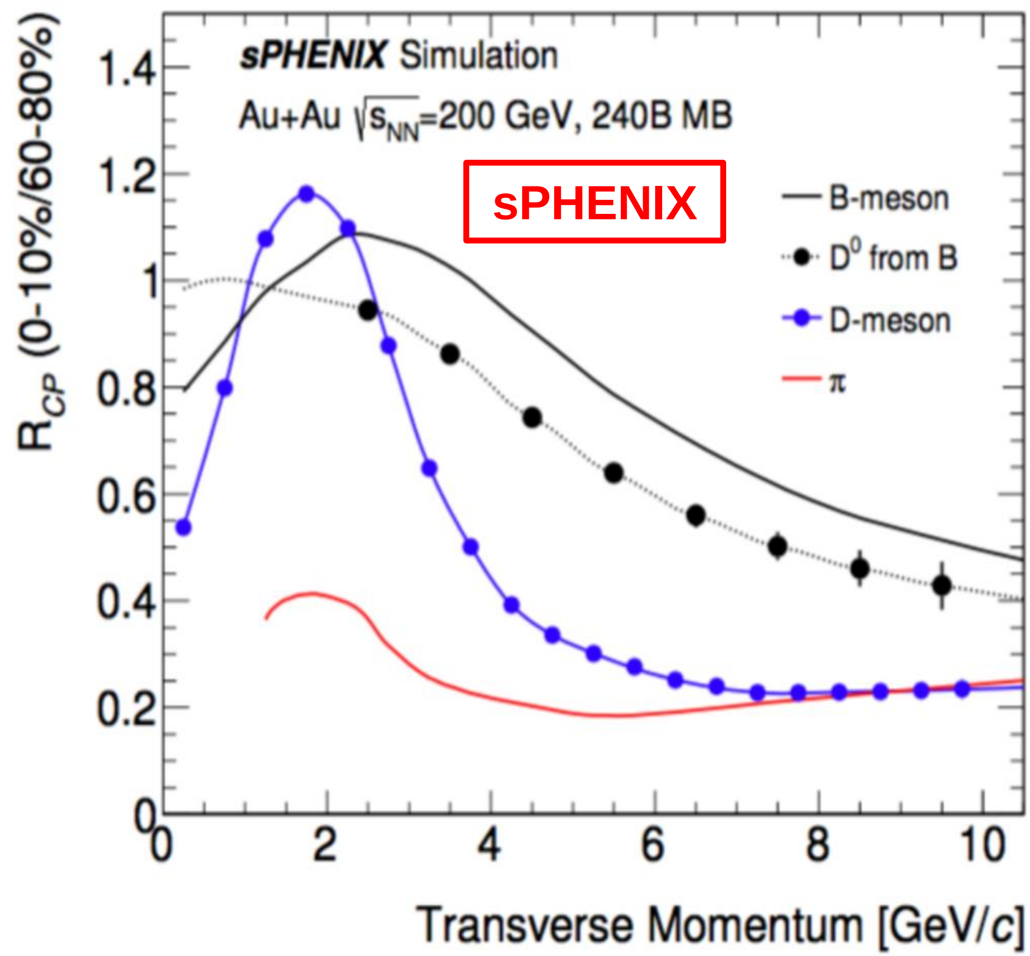




- Mass effect observed in LHC data though various fully / partially reconstructed decay channels
- Indication of mass effect from STAR and PHENIX data at RHIC

Heavy Flavor vs. Light Flavor





- Expect significantly better accuracy with HL-LHC data and future sPHENIX data

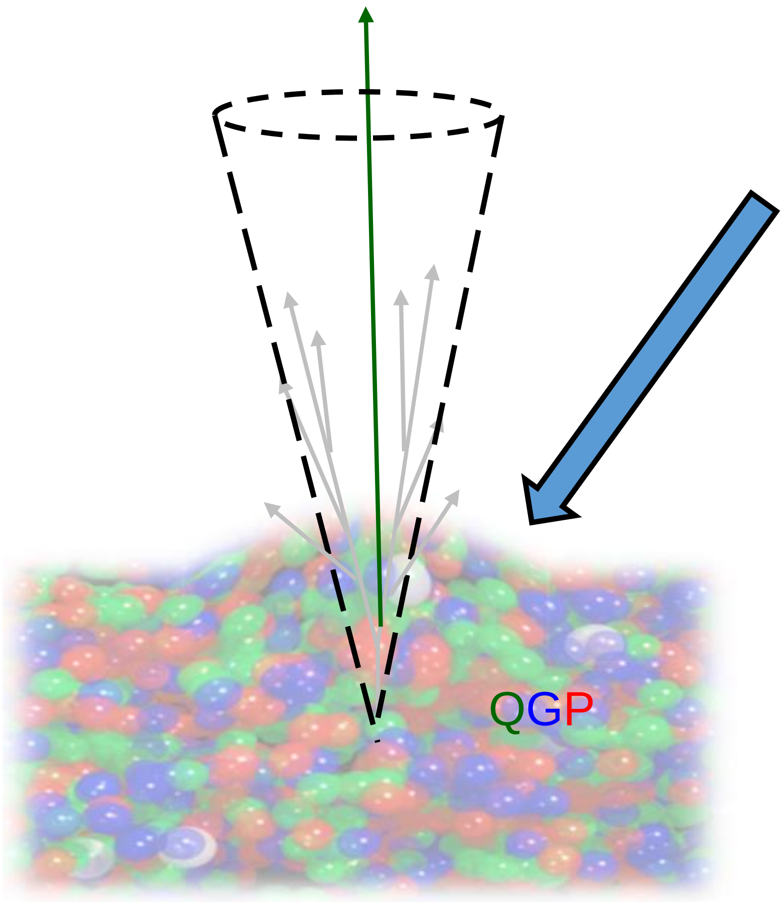
Flavor Dependence of Jet Energy Loss

- Heavy quarks lose less energy than the light flavor: Established in LHC data though model comparisons
  - Quarkonia production and suppression similar to open charm: fragmentation process (not shown)
- Overall narrowing (hardening) of the inclusive ‘jet core’ in AA collision
- Larger gluon jet suppression than quark: collected hints from various jet substructure observables + ATLAS jet and charged particle R_{AA} measurements vs. η

Possible future direction:

- High precision photon-tagged jet shape and FF (LHC+sPHENIX)
- High precision HF-jet measurements down to low p_T (LHC+sPHENIX)
- Q vs. g: Employ unsupervised ML technique: jet topic separation
- A comprehensive HF program at HL-LHC experiments (ALICE upgrade) and at RHIC (sPHENIX)
- Underlying mechanism of HF energy loss: go beyond HF spectra and HF-soft correlation (v_N):
  DDbar, Jet-D and γ-D correlation, HF jet FF and shape

Quenched Energy out of the Jet Cone



Do we see medium response?

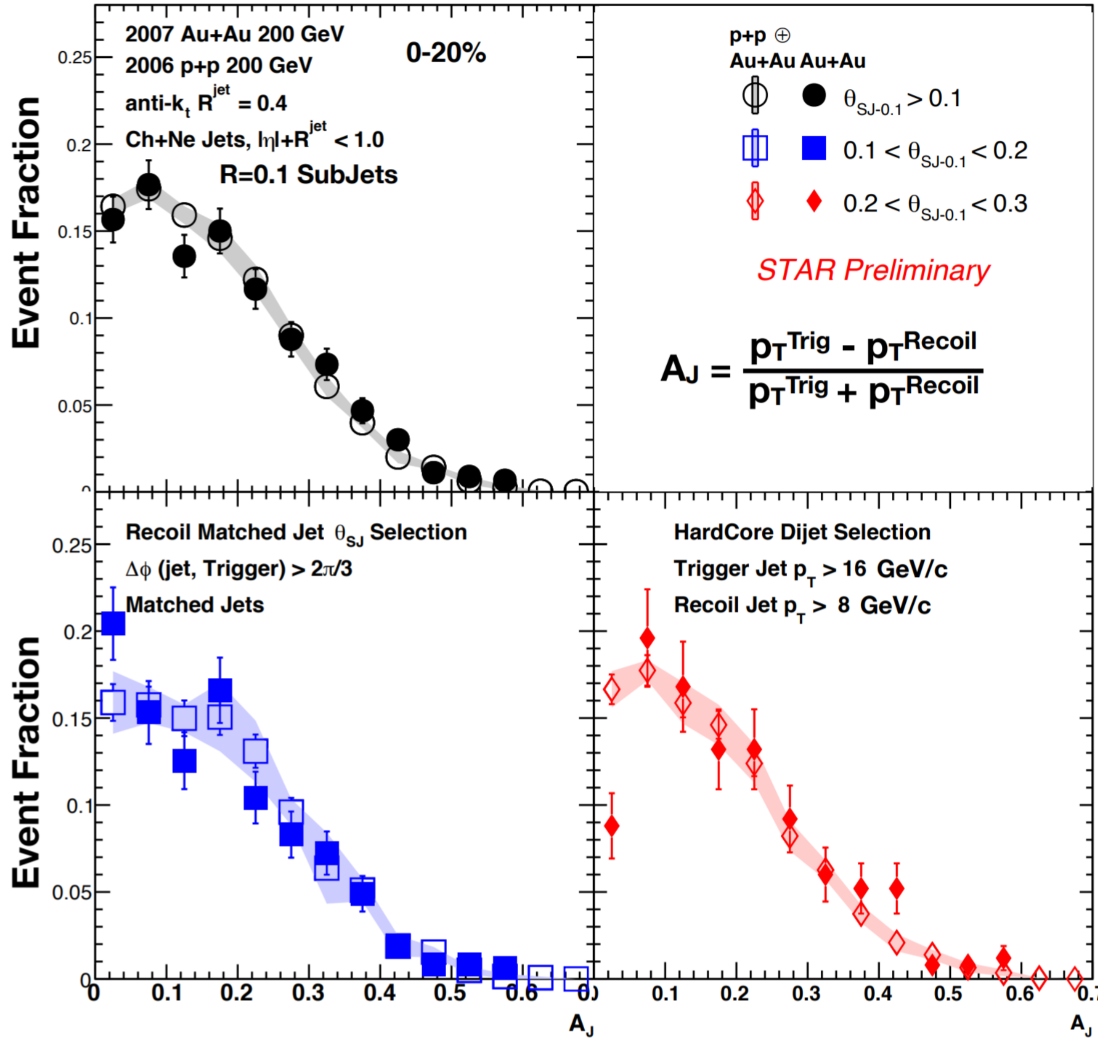
Quenched Energy Flow at RHIC

Slide shown by RKE, HP 2018

Matched A_J

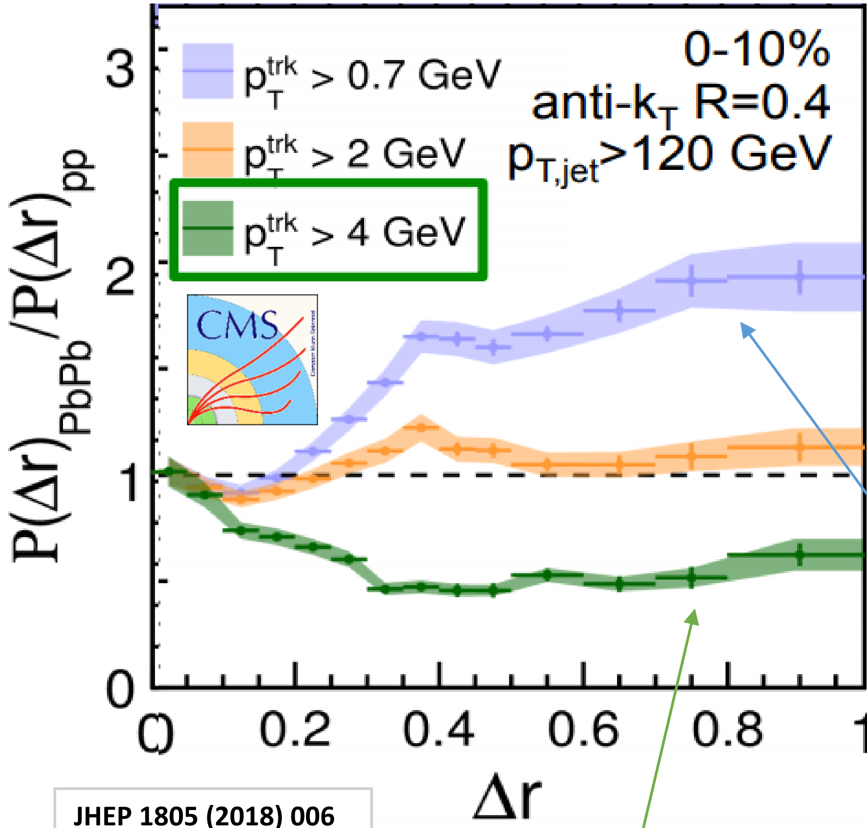
$p_T^{const} > 0.2$ GeV/c

Matched jets of different θ_{SJ} selections are balanced at RHIC



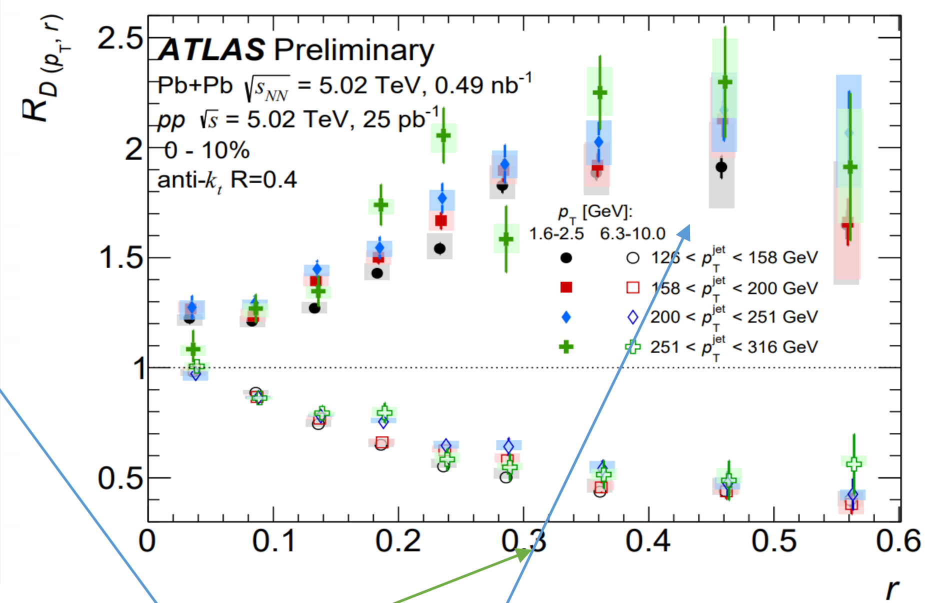
- STAR high tower triggered A_J : lost energy recovered within R=0.4
- On the other hand, STAR h-Jet and PHENIX γ-hadron correlations (not shown): the quenched energy goes to large angle

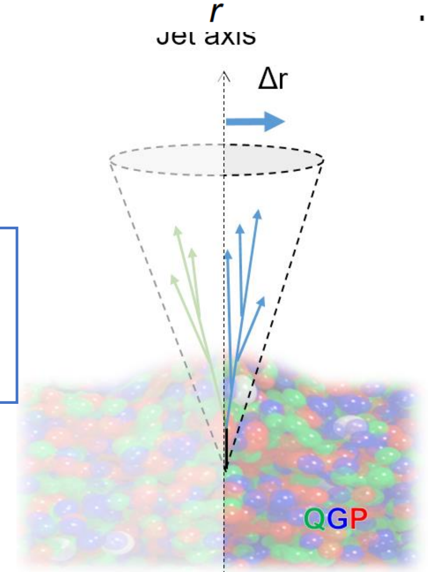
Excess in Jet-Hadron Correlation



JHEP 1805 (2018) 006

ATLAS-CONF-2018-010





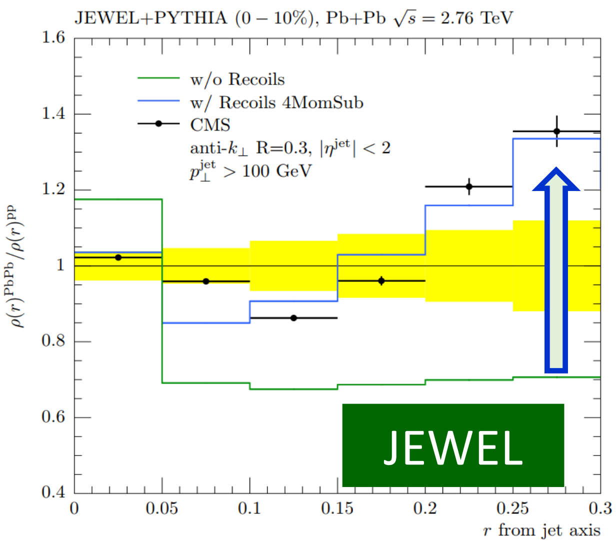
$$\Delta r = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

Depletion of high p_T charged particles at large Δr

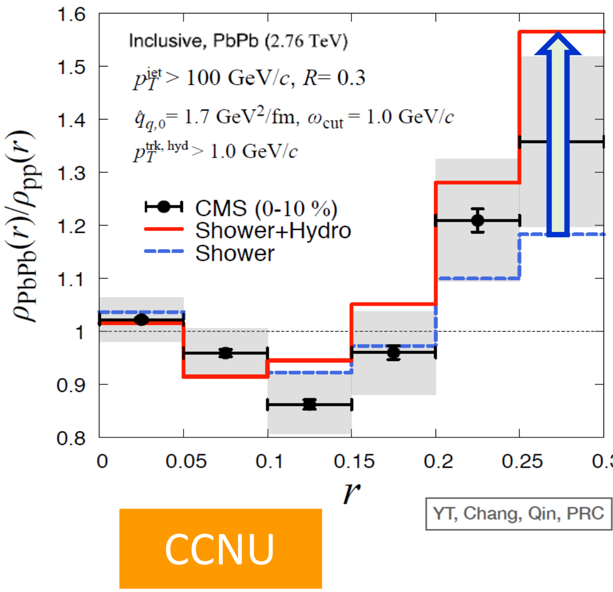
Enhancement of low p_T charged particles at large Δr

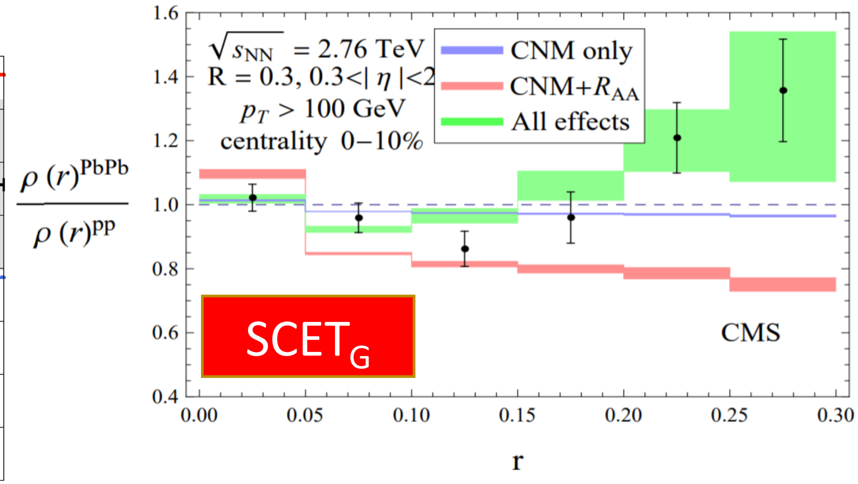
Interpretations of the low p_T enhancement at large ΔR include **medium response**, **medium induce radiation / splitting**, and **vacuum-like emissions out of the medium** (Edmond Iancu QM'18)

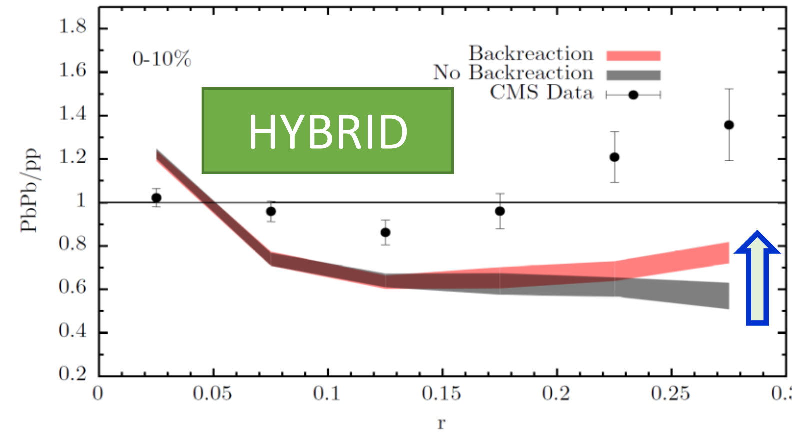
Theoretical Interpretation of the Excess

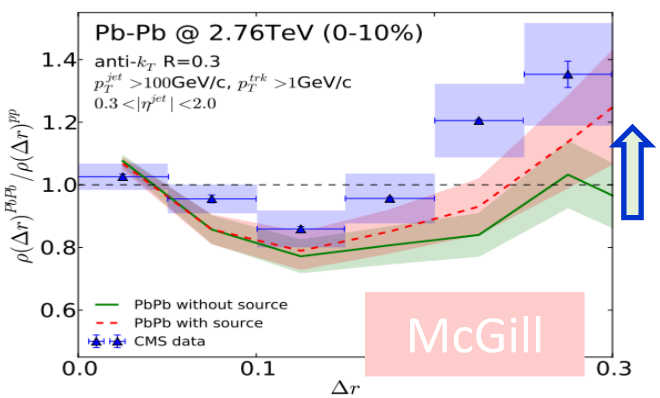


arXiv:1707.01539



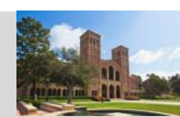






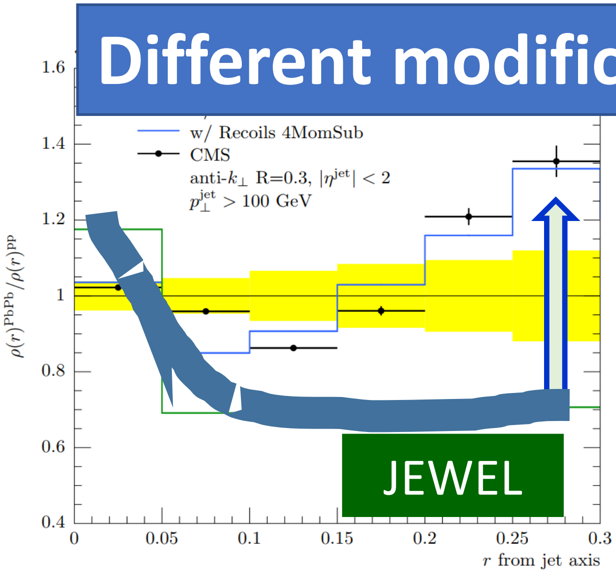
Different explanations of the large angle enhancement in jet shape measurement

- 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

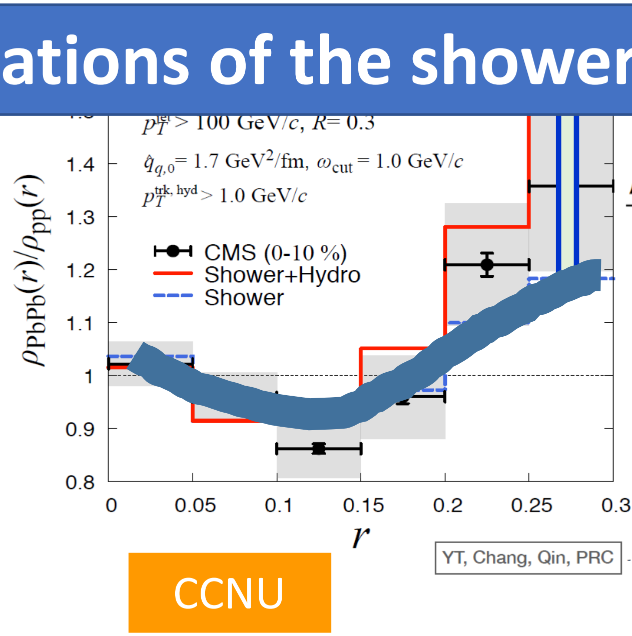


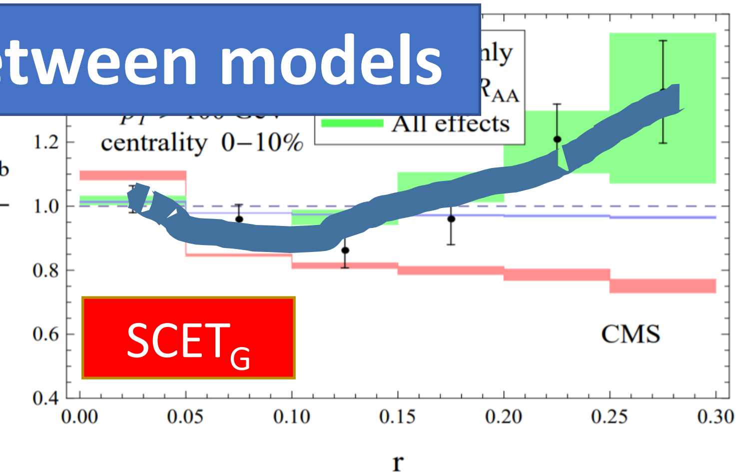
Theoretical Interpretation of the Excess

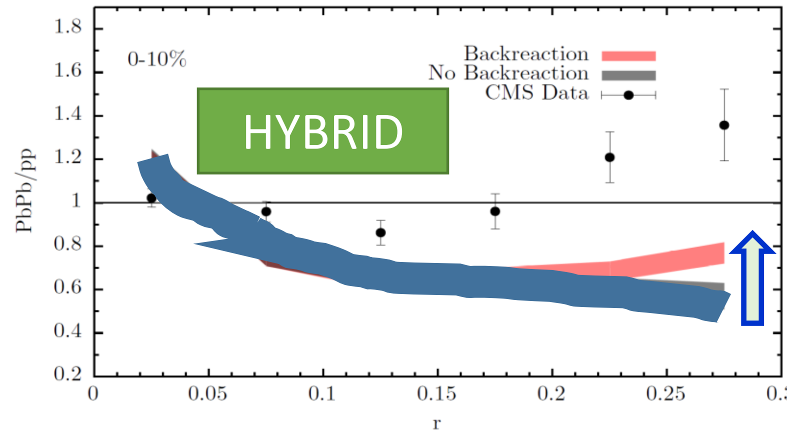
Different modifications of the shower between models

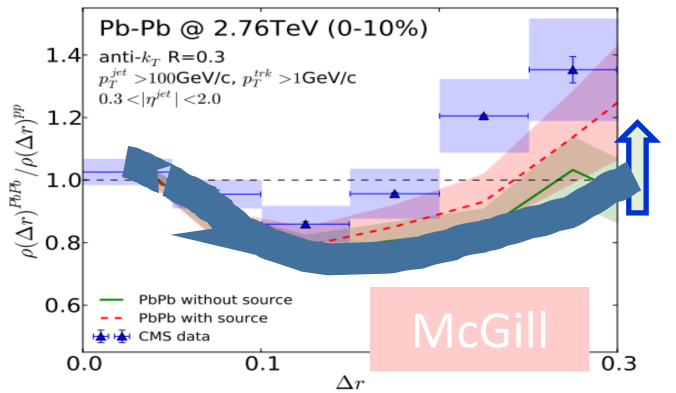


arXiv:1707.01539









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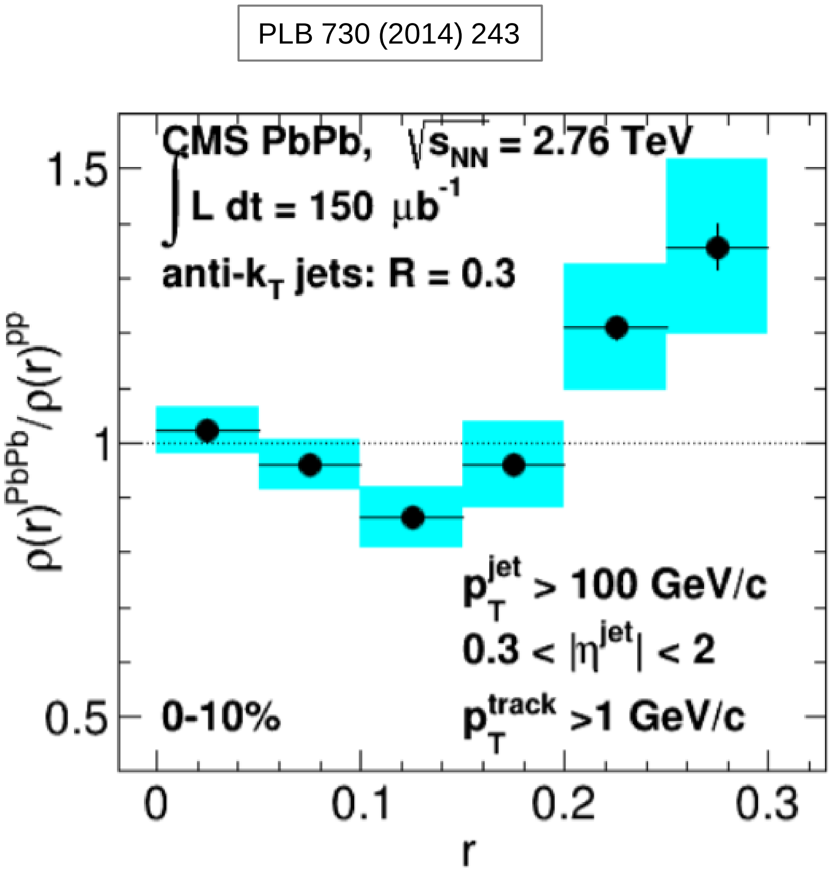
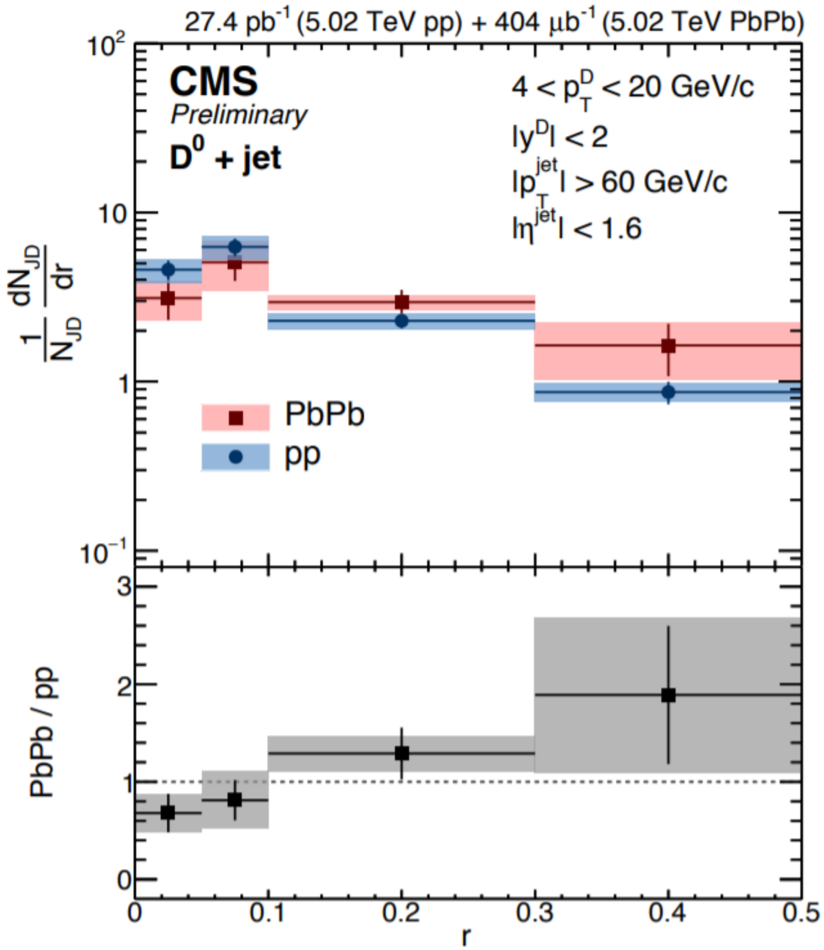
- McGill: medium response + shower

How do we make progress?

(1) Look into the Excess

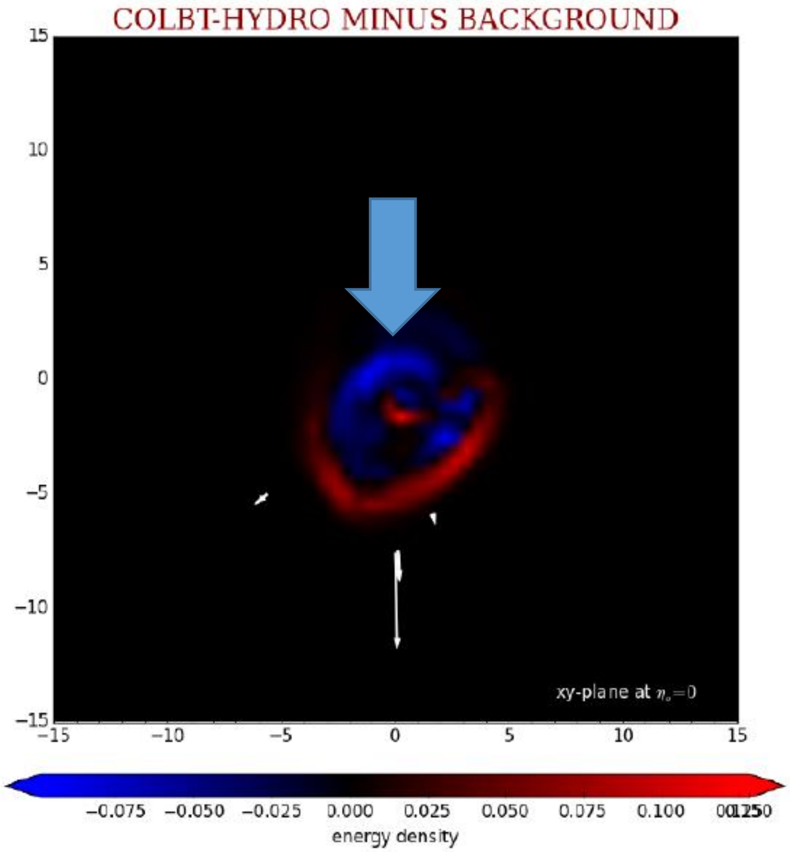


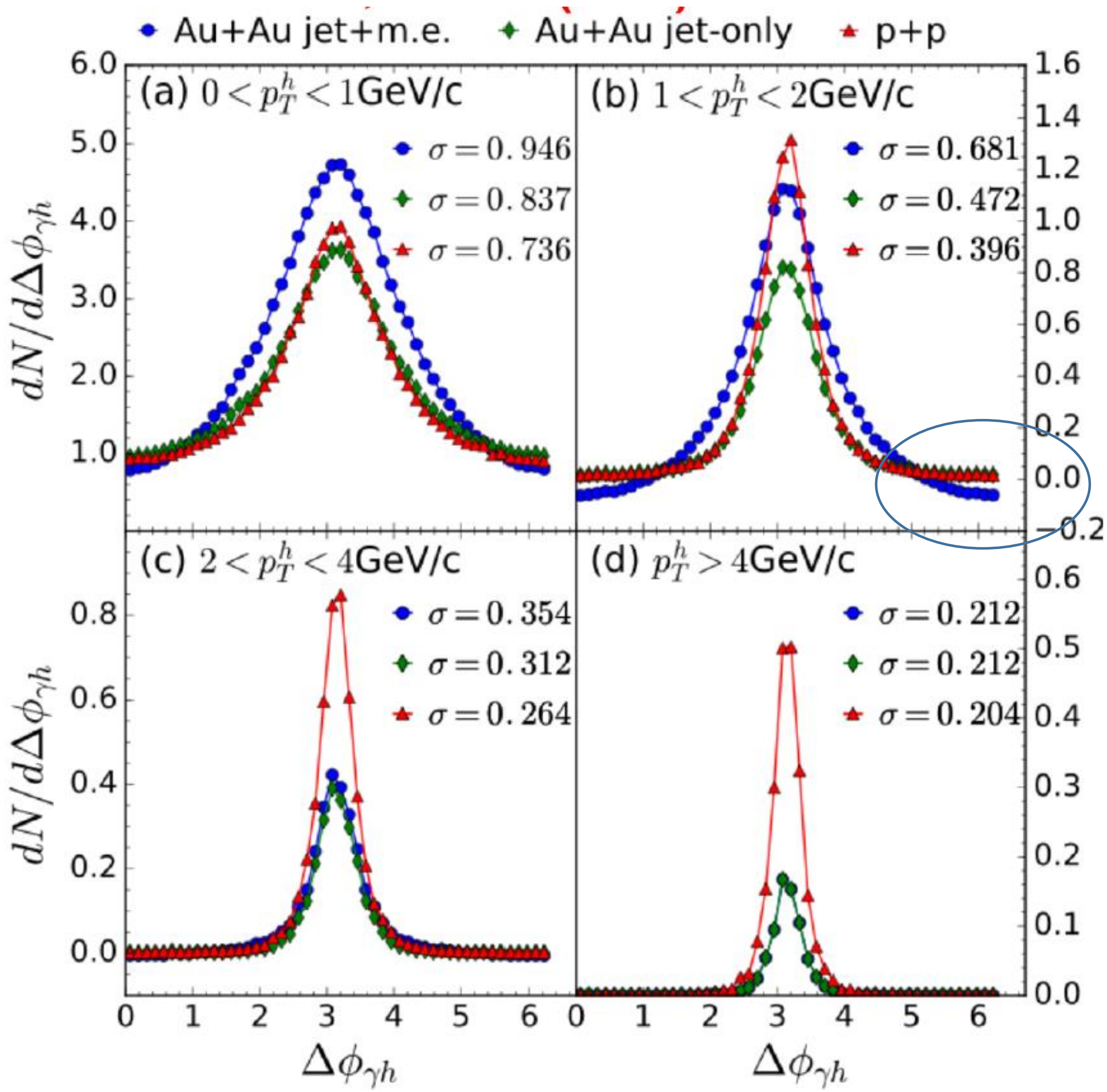


- One possibility is to look at the particle composition which carry the large angle radiation: (exciting opportunity for ALICE)
- An attempt to check the mass dependence with Jet-D correlation from CMS: Hint of longer distance between jet axis and D^0 meson, **relation to D^0 v_2?**

(2) To Measure the Depletion

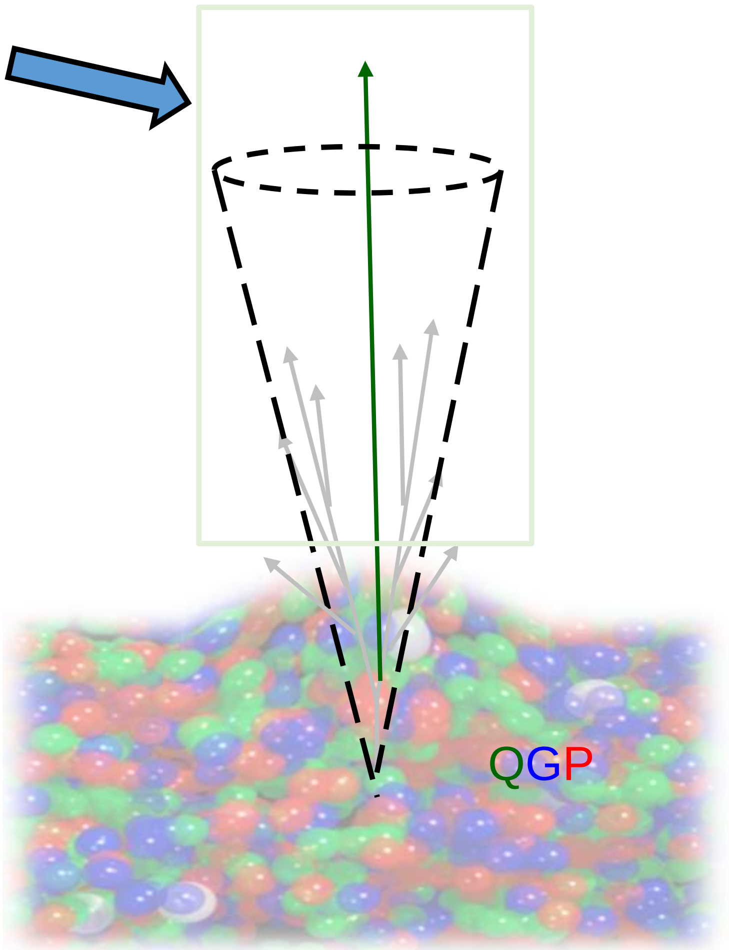
Tan Luo, Xin-Nian Wang





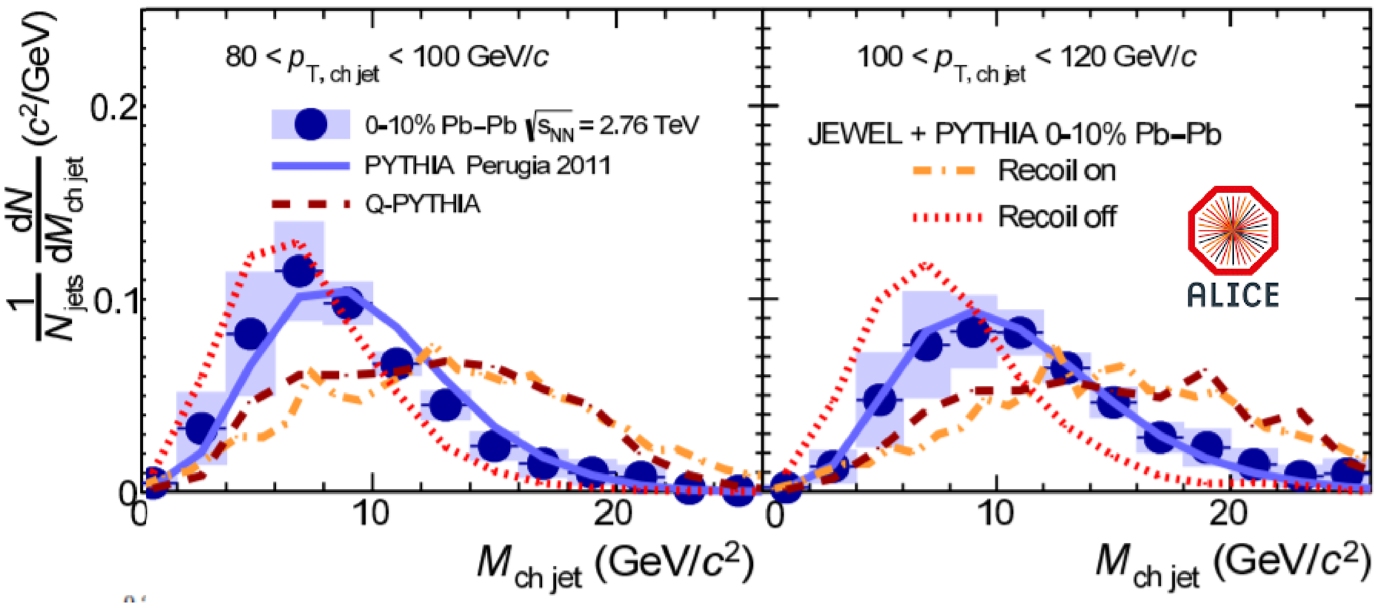
Measure the **near-side associated yield** with photon-jet and Z-jet

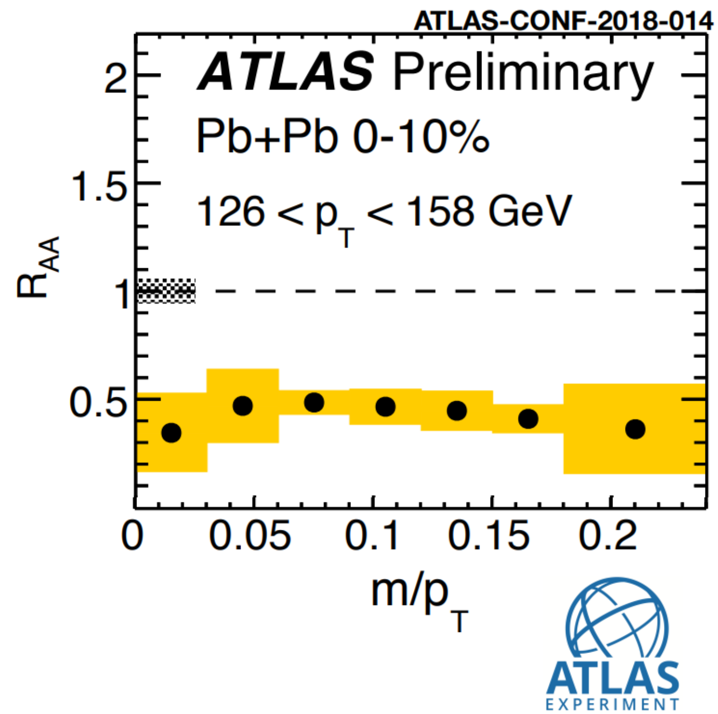
(3) Focus on the Hardest Substructure

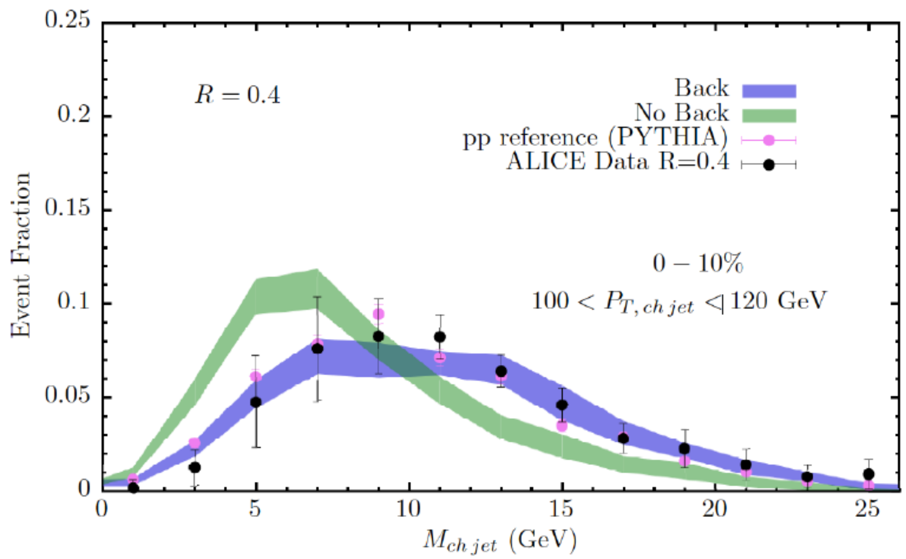


Does the magnitude of quenching depend on the structure of parton shower?
One could **remove the soft radiation** (isolate the hard jet core)

“Ungroomed” Jet Mass





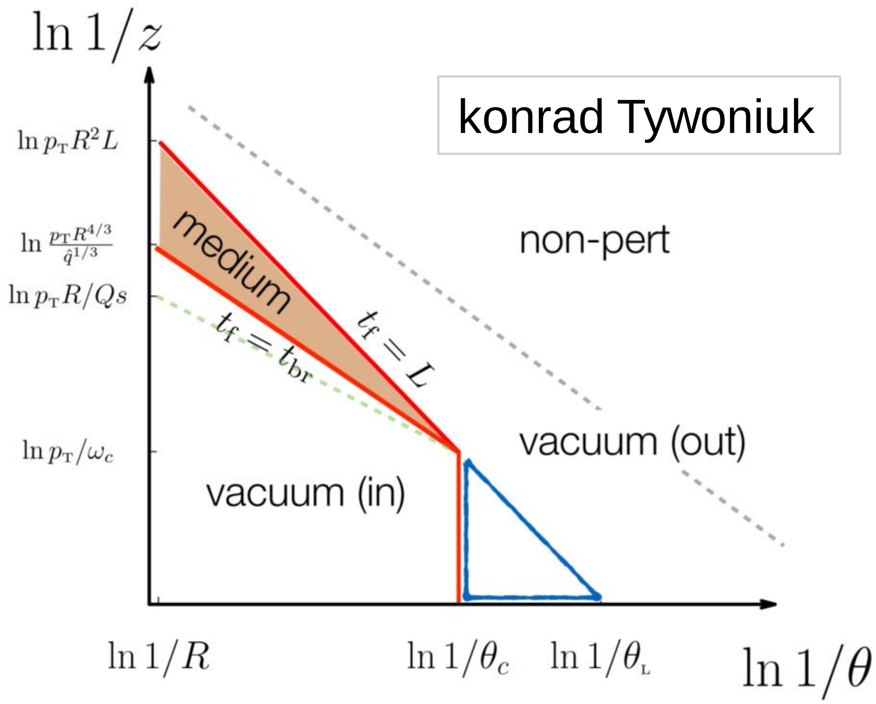


- No modification of the distribution is observed in **ALICE** and **ATLAS** data with respect to pp reference

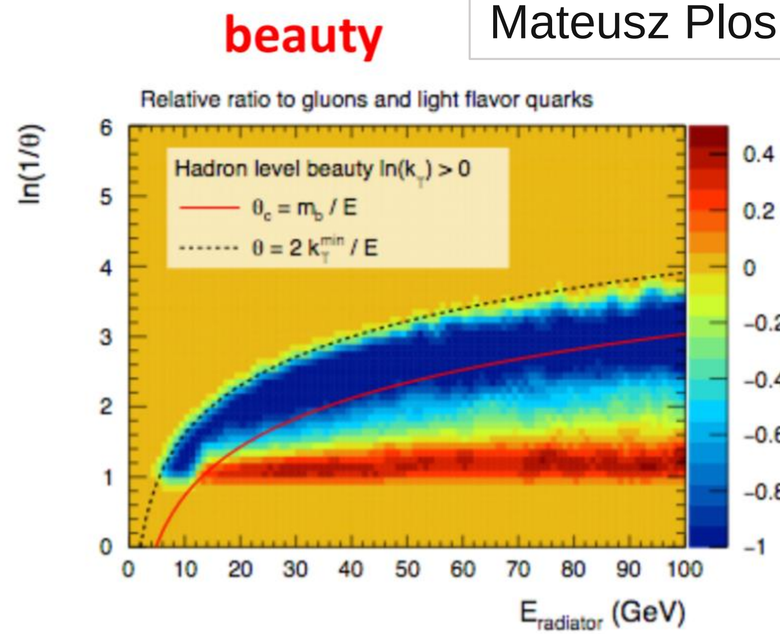
- Cancelling effects from medium modifications of the shower and medium response

Many Exciting Developments

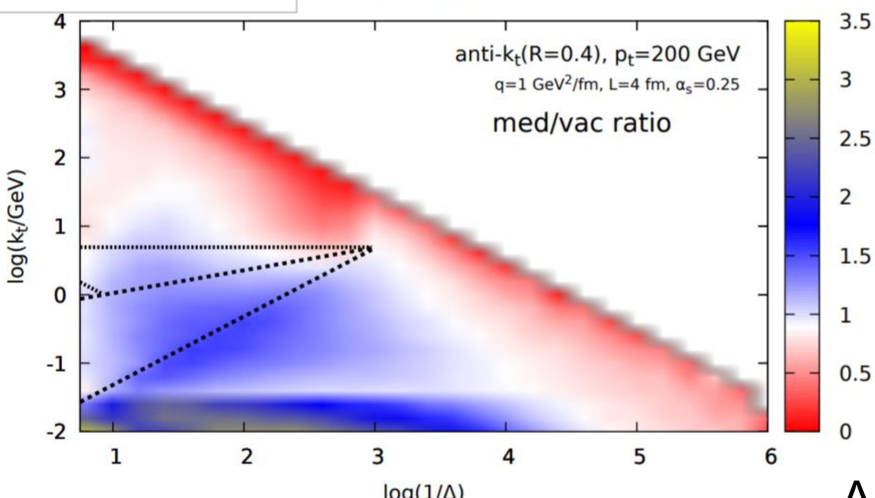
konrad Tywoniuk



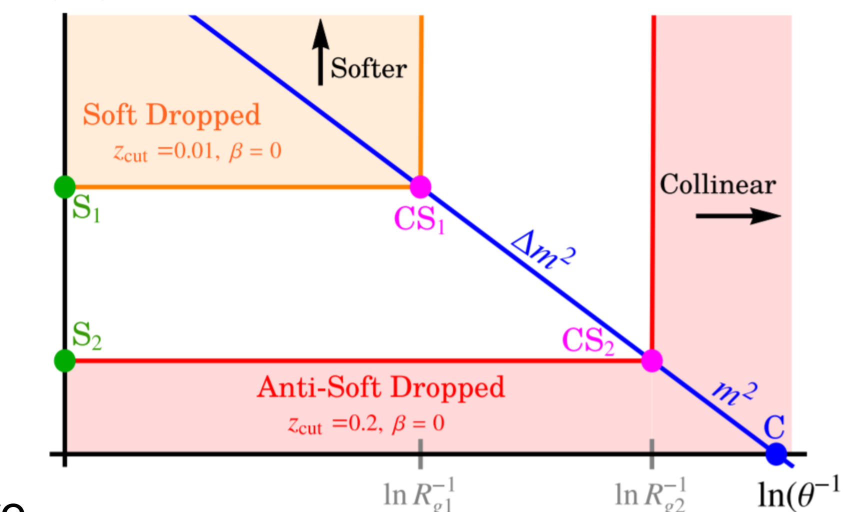
Mateusz Ploskon



Edmond Iancu



Yang-Ting Chien

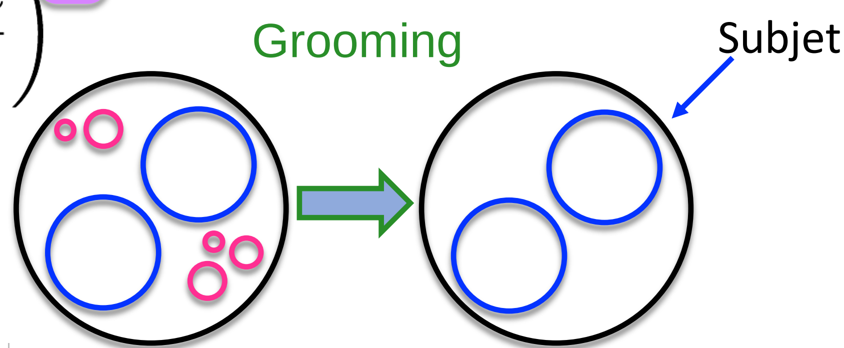


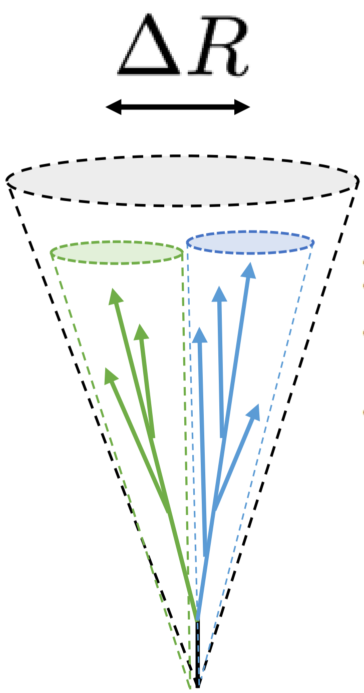
And many more…

Groomed Jet Substructure with Soft Drop

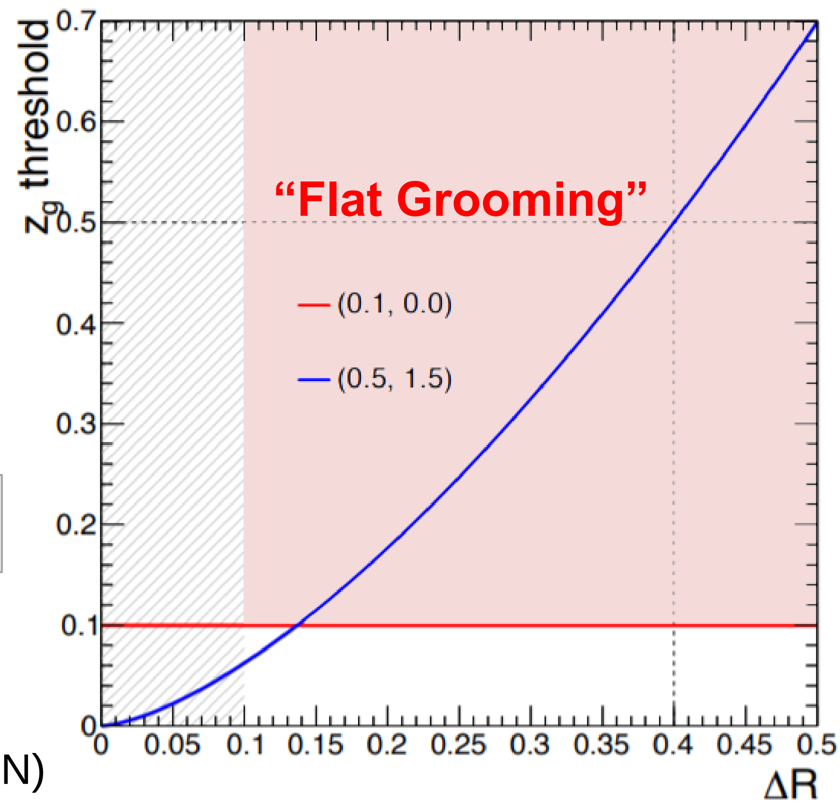
- CMS: used two grooming settings with ΔR>0.1 cut

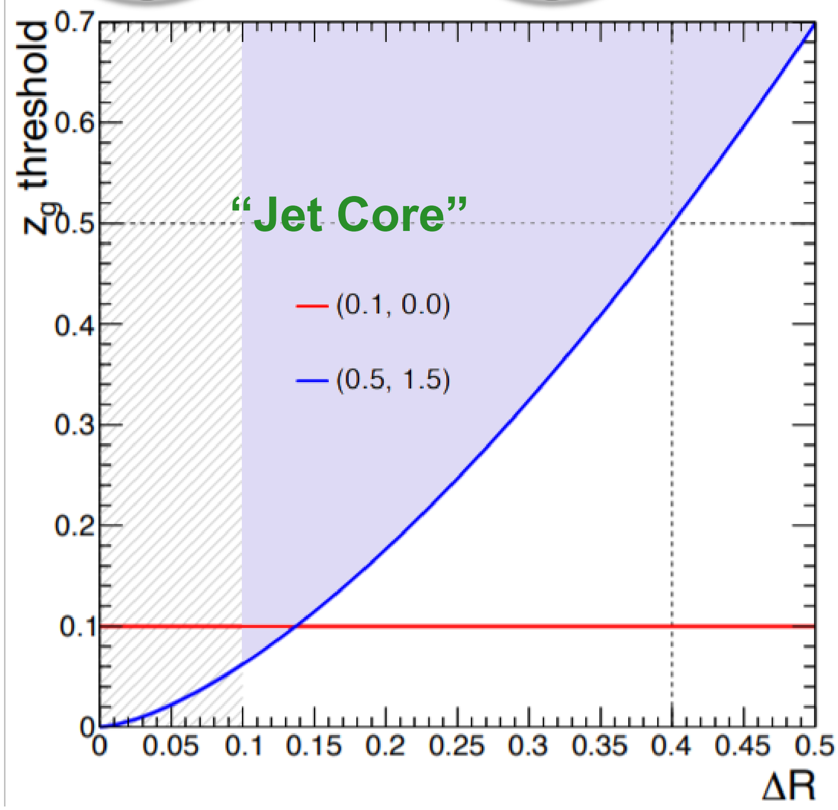
$$z_g \equiv \frac{\min(p_1, p_2)}{p_1 + p_2} > z_{\text{cut}} \left(\frac{\Delta R}{R_0} \right)^{\beta}$$





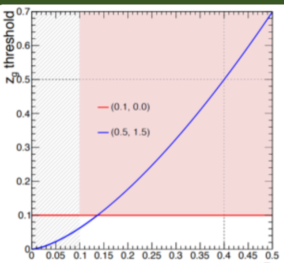
Soft Drop:
JHEP 1405 (2014) 146





Phase diagram
from Yi Chen (CERN)

Groomed Jet Mass

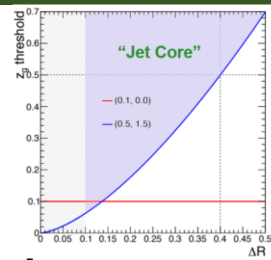


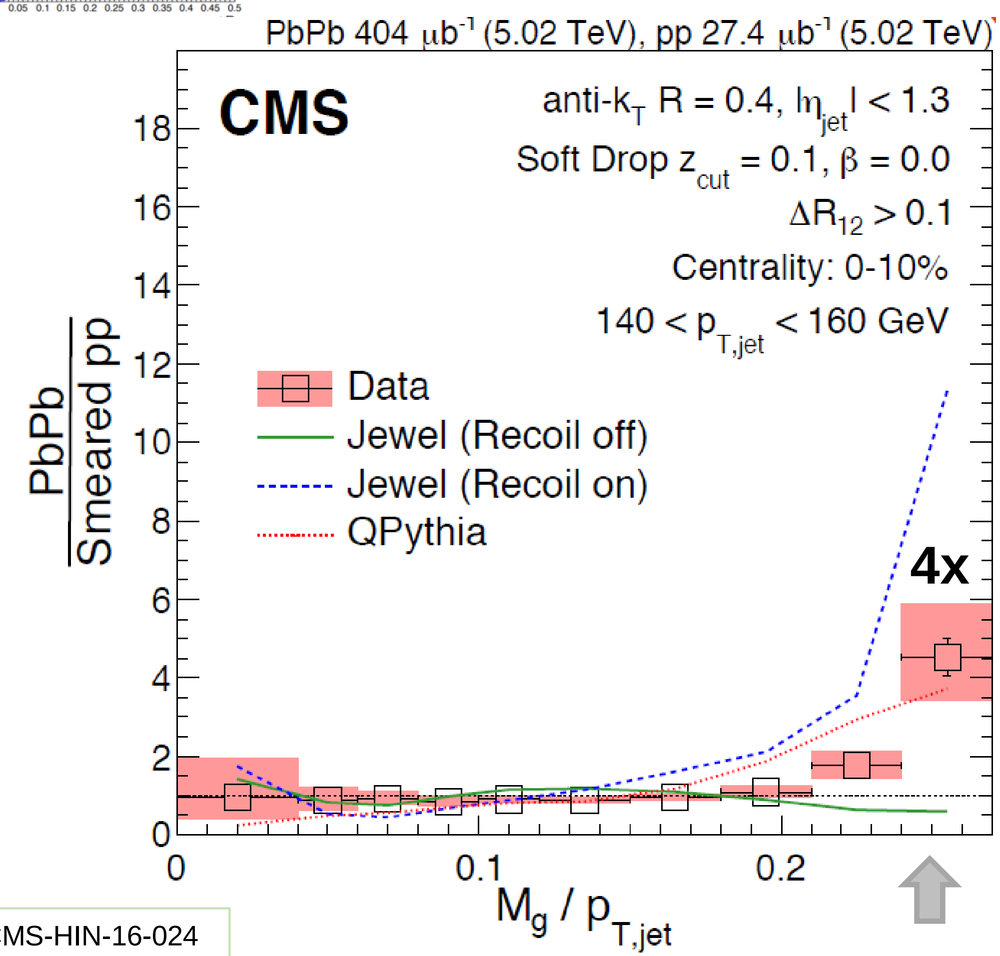
$(z_{cut},\beta) = (0.1,0.0)$ $\Delta R>0.1$

"Flat Grooming"

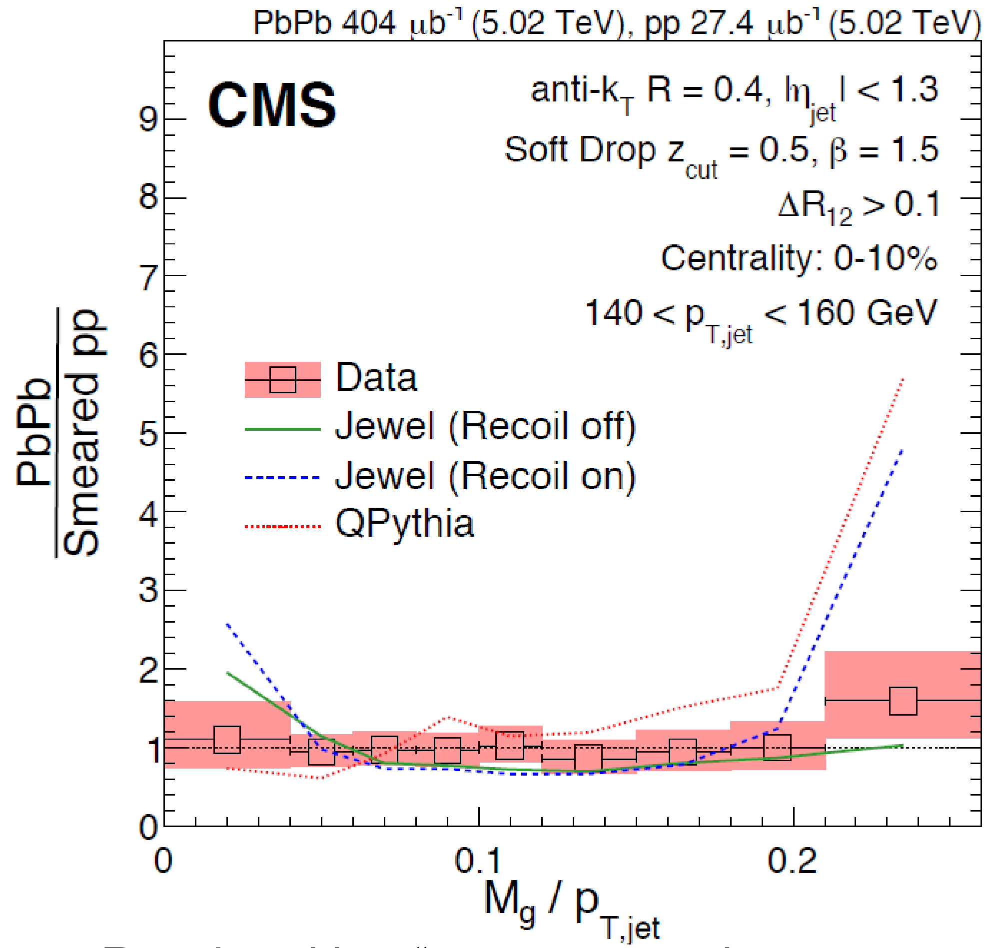
$(z_{cut},\beta) = (0.5,1.5)$ $\Delta R>0.1$

"Jet Core"



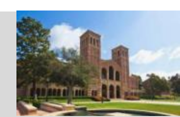


CMS-HIN-16-024

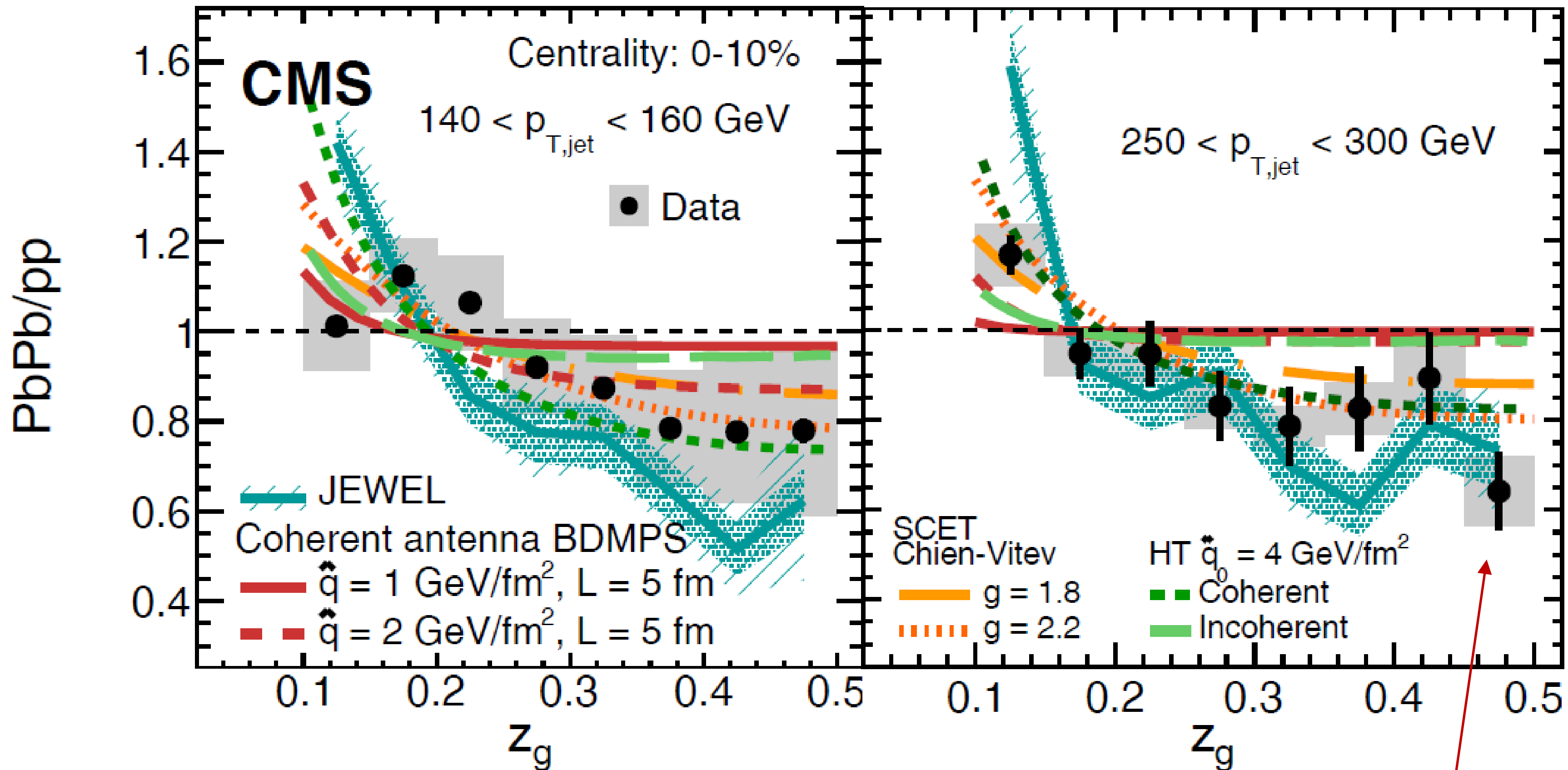


- Enhancement of large mass when looking at a less aggressive grooming setting

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



Momentum Sharing of Subjets



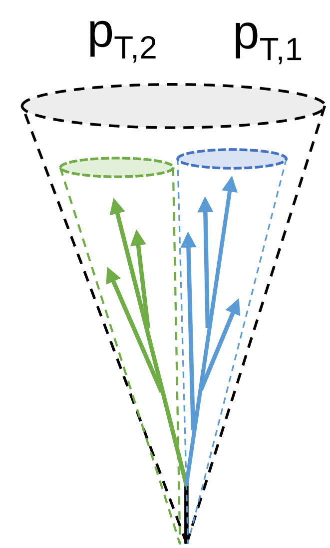
arXiv:1708.09429
PRL 120 (2018) 142302
PRL Synopsis

Quark and gluon Z_g distributions are very similar in pp

Jets with **two hard subjets** (large Z_g) **"relatively"** more suppressed!

Interpretation:

- **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 ΔR spectra and groomed R_{AA} would help**

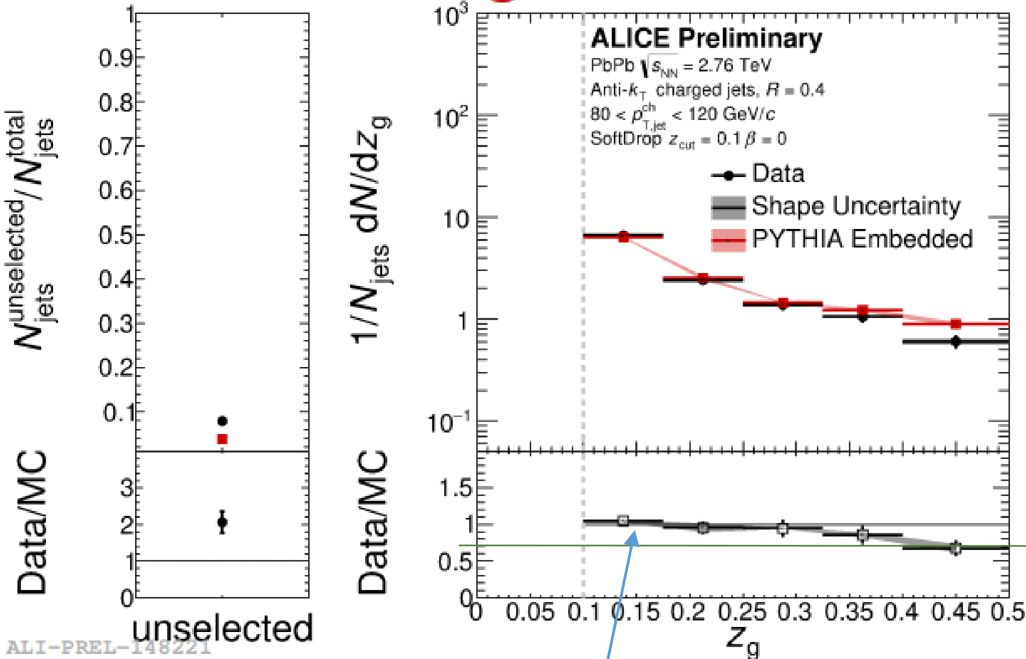


Two hard subjets

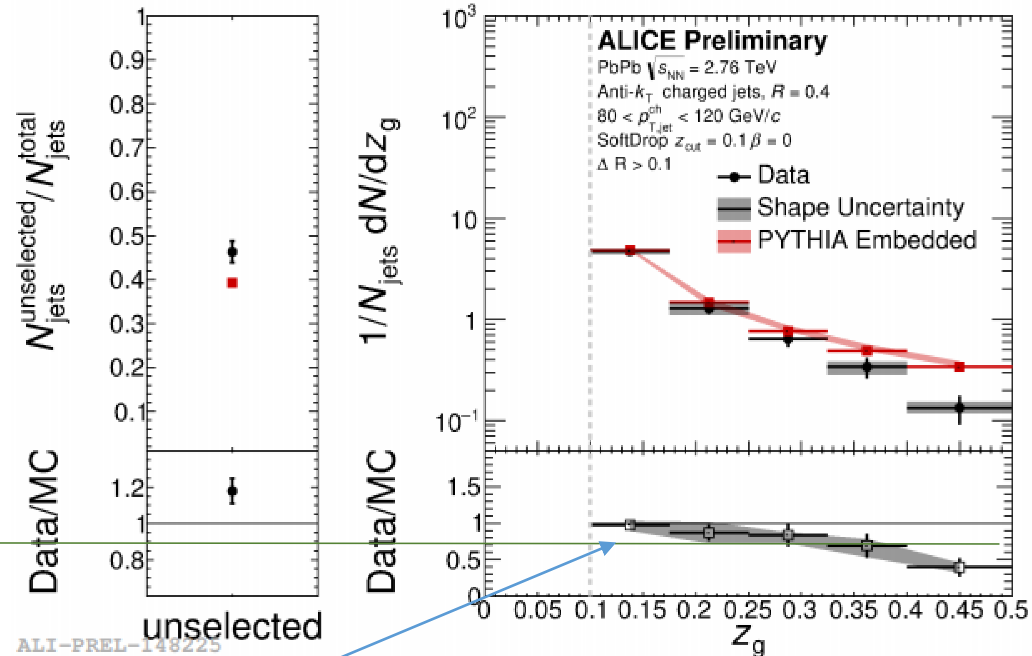
$Z_g \sim 0.5$

Effect of ΔR selection on Z_g spectra

No angular cutoff

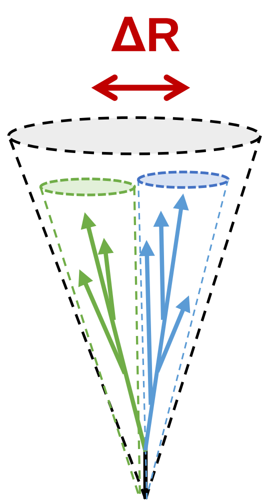


$\Delta R > 0.1$



Normalized by total number of jets

Unselected = Untagged (SD) + cut by ΔR cut



- No enhancement of low Z_g jets, different from JEWEL prediction

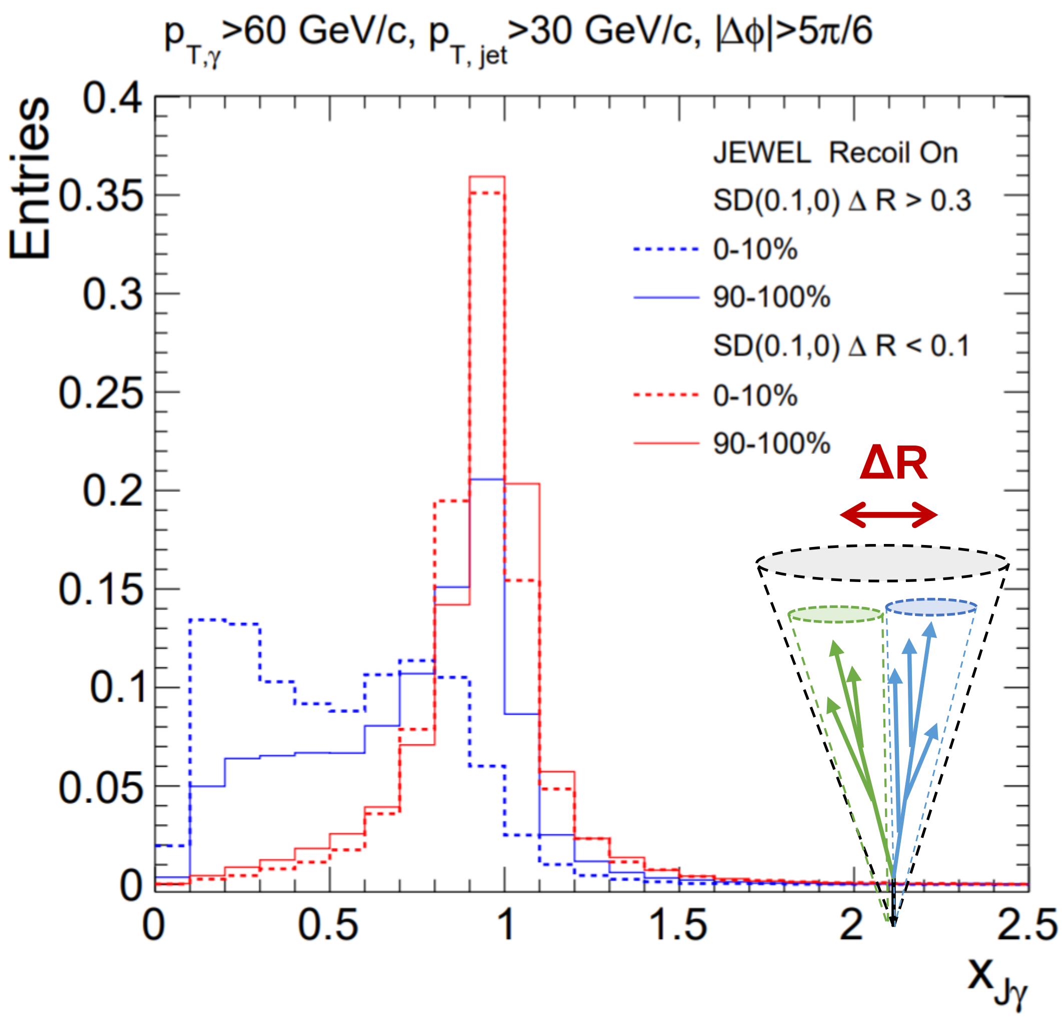
Too high correlation between medium recoil and jet in JEWEL?

(hints also seen in jet mass measurements)

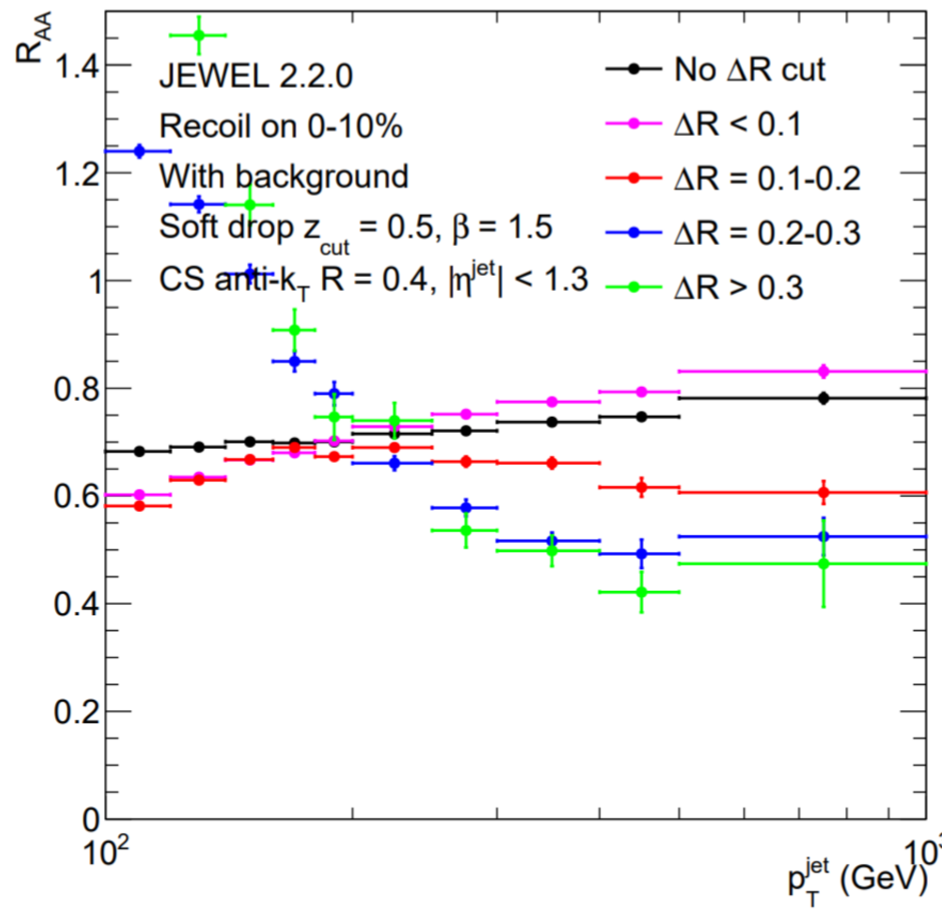
- ΔR cut increase the suppression of large Z_g jets

Harry Andrews (QM2018)

Possible Direction: Hybrid Observable



Konrad *et. al*
arXiv:1808.03689



- Jet tagging with jet substructure: beyond flavor dependence
  Jet structure dependence of jet quenching
- Old Observables + New Excitement

Fluctuation of Jet Quenching

- Sub-jet momentum sharing and groomed jet mass are modified in LHC data. Hint from STAR data (not shown)
- **New Era:** Observables with different grooming settings could provide **stress tests** on theoretical models

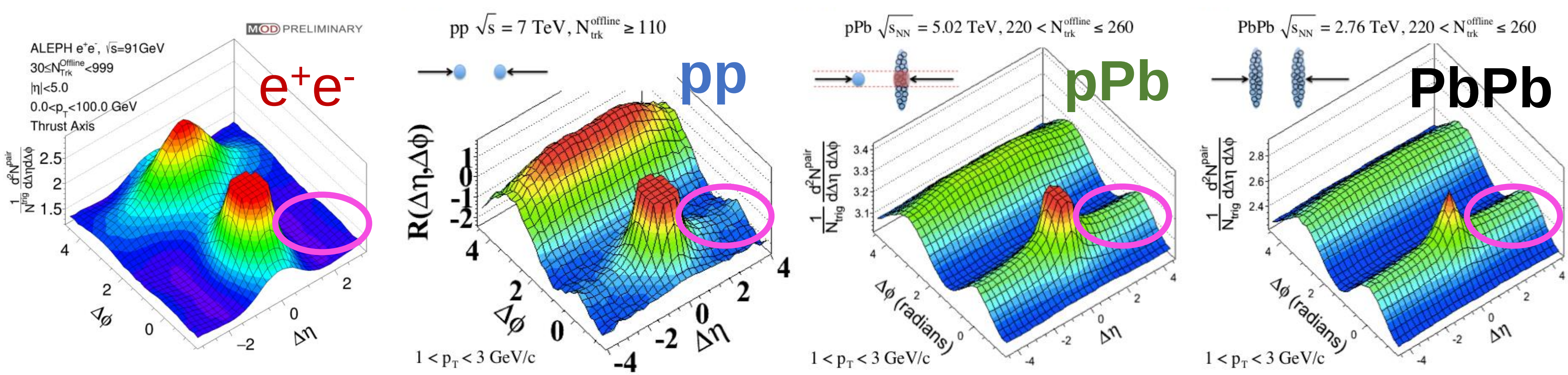
Open issue:

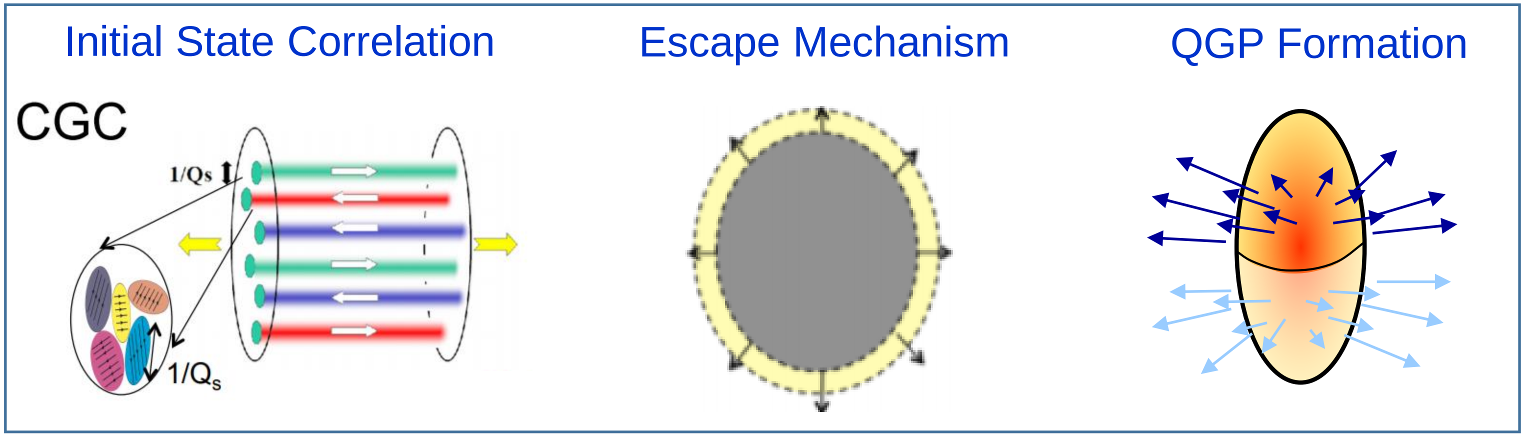
- Sizable effects from UE fluctuation on groomed Zg and mass measurements; difficulty in detector effect unfolding

Possible direction:

- Develop new algorithms with minimal sensitivity to soft background (for instance, use WTA axis)
- Design jet substructure observables which **maximize or minimize** the medium effect (also need to be measurable and calculable)
- Iterative feedback cycle: use the state-of-art generator which is tuned to describe the data for resolution unfolding (ex. JETSCAPE, JEWEL++, QPYTHIA++ …)
- **To extract medium properties from different variables**

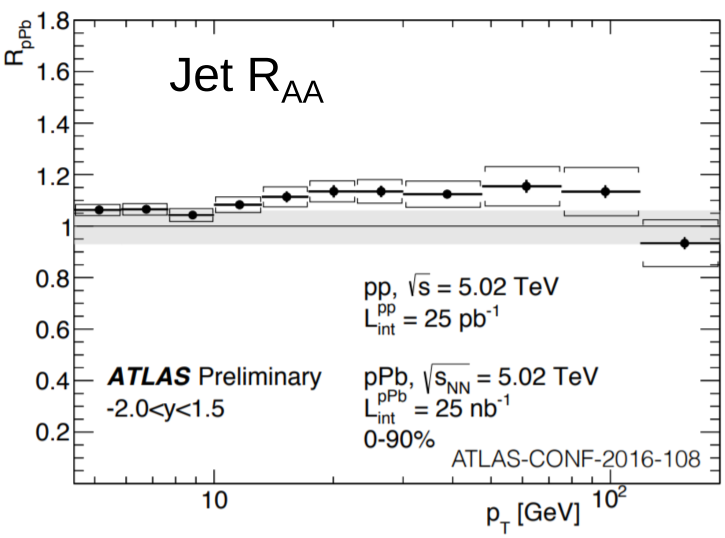
Jet Quenching in Small System

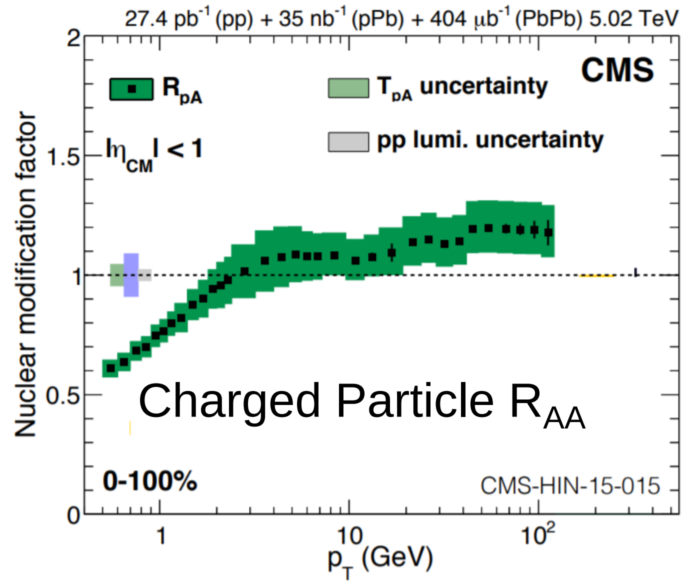


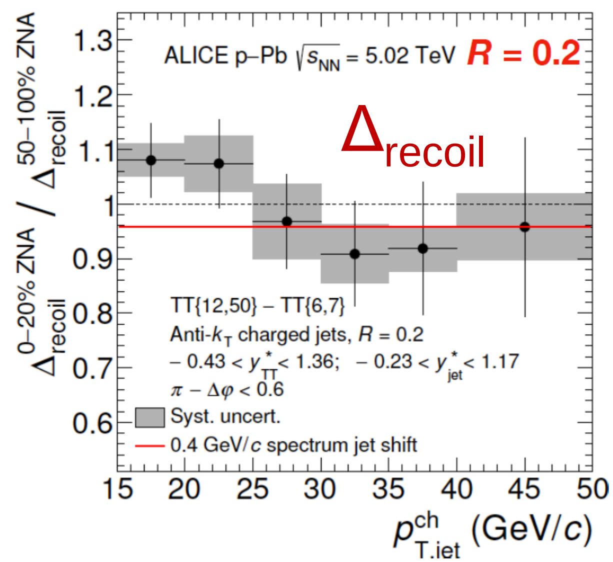


- Collective behavior is observed in small systems down to pp
- Not observed (yet) in high multiplicity e^+e^-
- Have we detected jet quenching in small system?

Jet Quenching in Small System

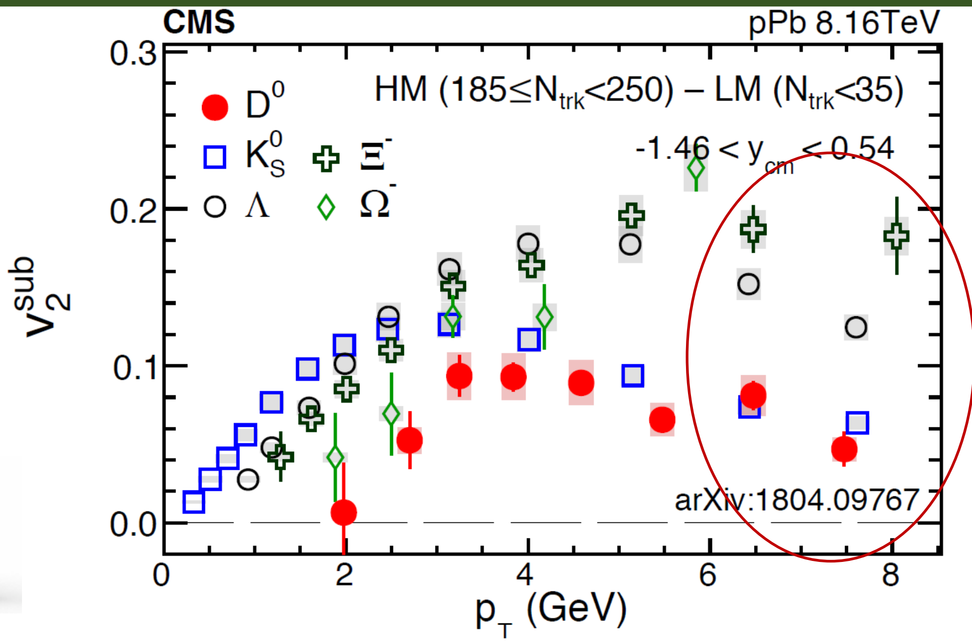


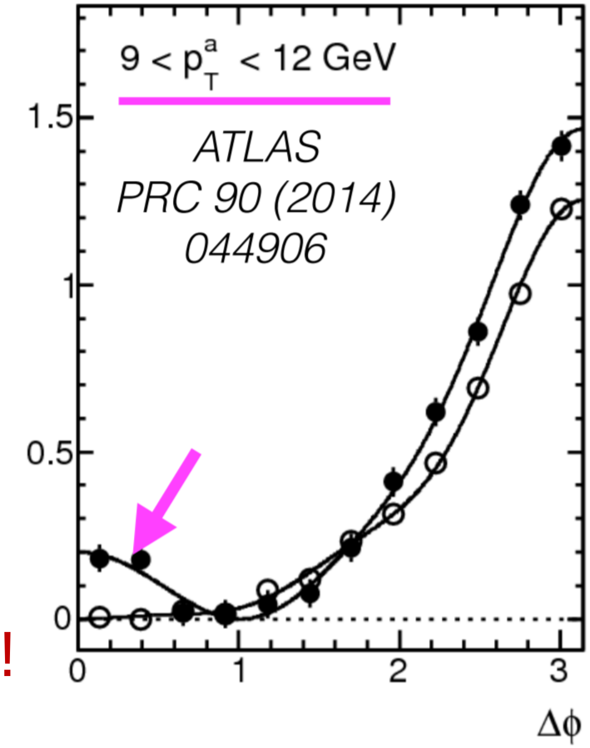




- No suppression observed in pPb collisions from those observables
- Also centrality / activity dependent results:
  Charged Particle Q_{pPb} from ALICE, R_{dAu} in PHOBOS and CMS dijet: need higher accuracy and better event classification
- Indication of suppression (2σ) in PHENIX di-hadron correlation function (shown in this workshop)

Jet Quenching in Small System





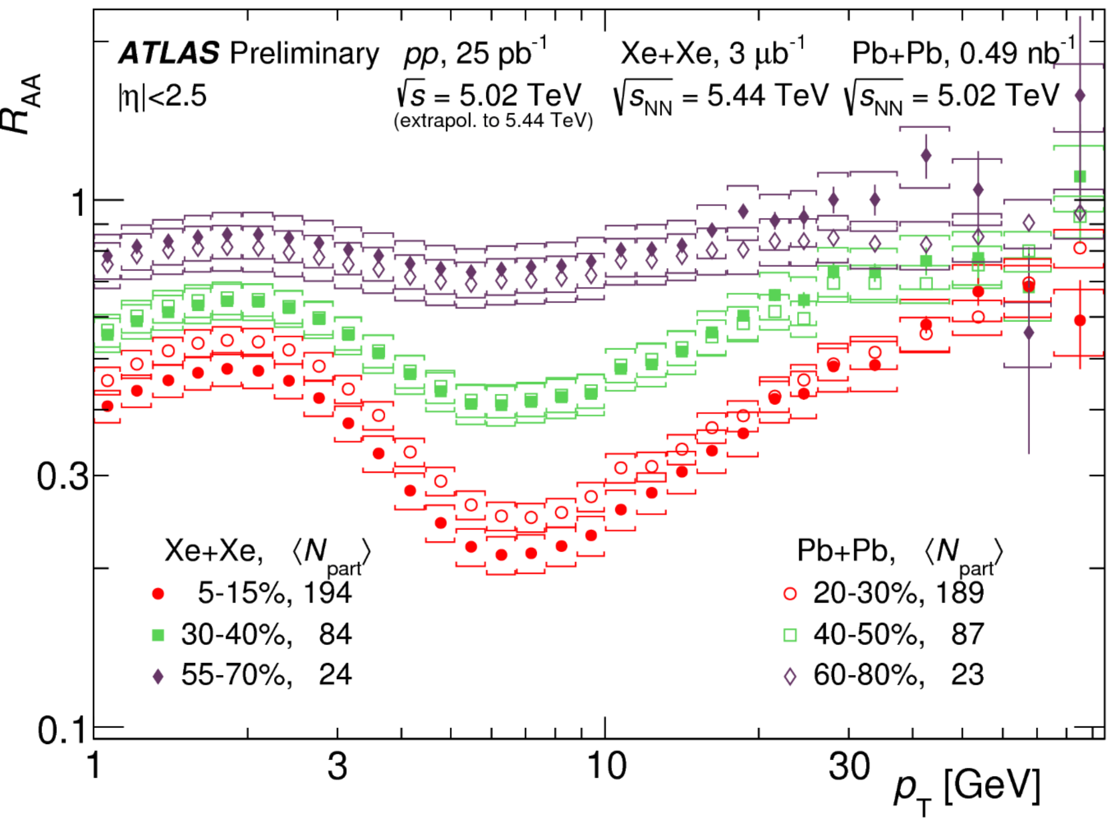
- Sizable v_2 signal at high p_T in identified hadrons!
- Effect of residual non-flow?
- Indication that CGC and/or Escape Mechanism effects in pPb?

Possible Future Direction:

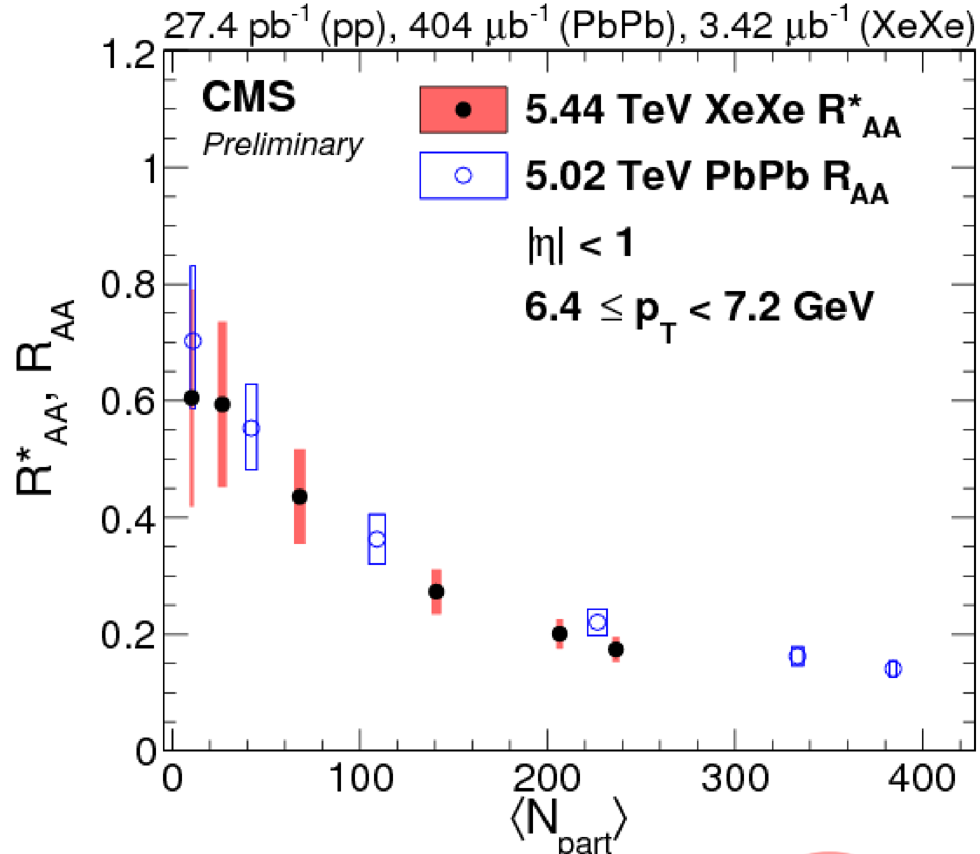
- Crucial to understand the minimum requirement for jet quenching
- Search for additional final state effect in high multiplicity pPb
- Exp: How can we do better in centrality classification?
- Theory: what do we expect? How big is the modification in R_{AA} , photon-jet asymmetry and jet substructure in 0.001% pPb collisions?

Other Ways to Very System Size

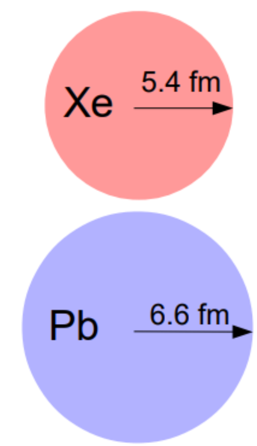
ATLAS-CONF-2018-007

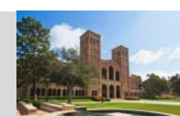


CMS-PAS-HIN-18-004



- **Use smaller ions**
- Charged Particle R_{AA}: Approximate scaling with N_{part}
- Future measurements in even smaller systems like OO, ArAr and KrKr at the LHC could be of interest
- Possibility to perform this survey with sPHENIX at RHIC?





LHC Timeline and CMS Upgrade

LHC | HL-LHC

PbPb 2 nb^{-1} | PbPb 7 nb^{-1} | PbPb 7 nb^{-1}

Run 2	Long shutdown 2	Run 3	Long Shutdown 3	Run 4

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029

CMS Phase 1 Upgrade | CMS Phase 2 Upgrade

- 2016: Major upgrade of L1 trigger
- 2017: 4-Layer Pixel Detector
- 2018 Performance:
  - pp L1 100kHz
  - PbPb L1 **30kHz** (3x of 2015)
  - DAQ: 6 GB/s
    - Up to **6.5 kHz** MinBias events to tape (20x of 2015)

2024-26

- Tracker **|η|<4**
- Muon ID up to **|η|<3**
- High Granularity Calo **1.6<|η|<3.0**
- MIP timing detector
  - 4D vertexing
  - Possible p/K/π PID
- pp L1: 750 kHz
- DAQ: 60 GB/s

LHC and sPHENIX timeline

LHC — HL-LHC

PbPb 2 nb^{-1} | PbPb 7 nb^{-1} | PbPb 7 nb^{-1}

Run 2 | Long shutdown 2 | Run 3 | Long Shutdown 3 | Run 4

2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029

CMS Phase 1 Upgrade | CMS Phase 2 Upgrade

sPHENIX construction

sPHENIX Installation commissioning

First data taking campaign
p+p, p+Au, Au+Au

Second campaign
p+p, Au+Au

RHIC

…EIC

Year	Species	Energy [GeV]	Phys. Wks	Rec. Lum.	Samp. Lum.	Samp. Lum. All-Z
Year-1	Au+Au	200	16.0	7 nb^{-1}	8.7 nb^{-1}	34 nb^{-1}
Year-2	p+p	200	11.5	—	48 pb^{-1}	267 pb^{-1}
Year-2	p+Au	200	11.5	—	0.33 pb^{-1}	1.46 pb^{-1}
Year-3	Au+Au	200	23.5	14 nb^{-1}	26 nb^{-1}	88 nb^{-1}
Year-4	p+p	200	23.5	—	149 pb^{-1}	783 pb^{-1}
Year-5	Au+Au	200	23.5	14 nb^{-1}	48 nb^{-1}	92 nb^{-1}

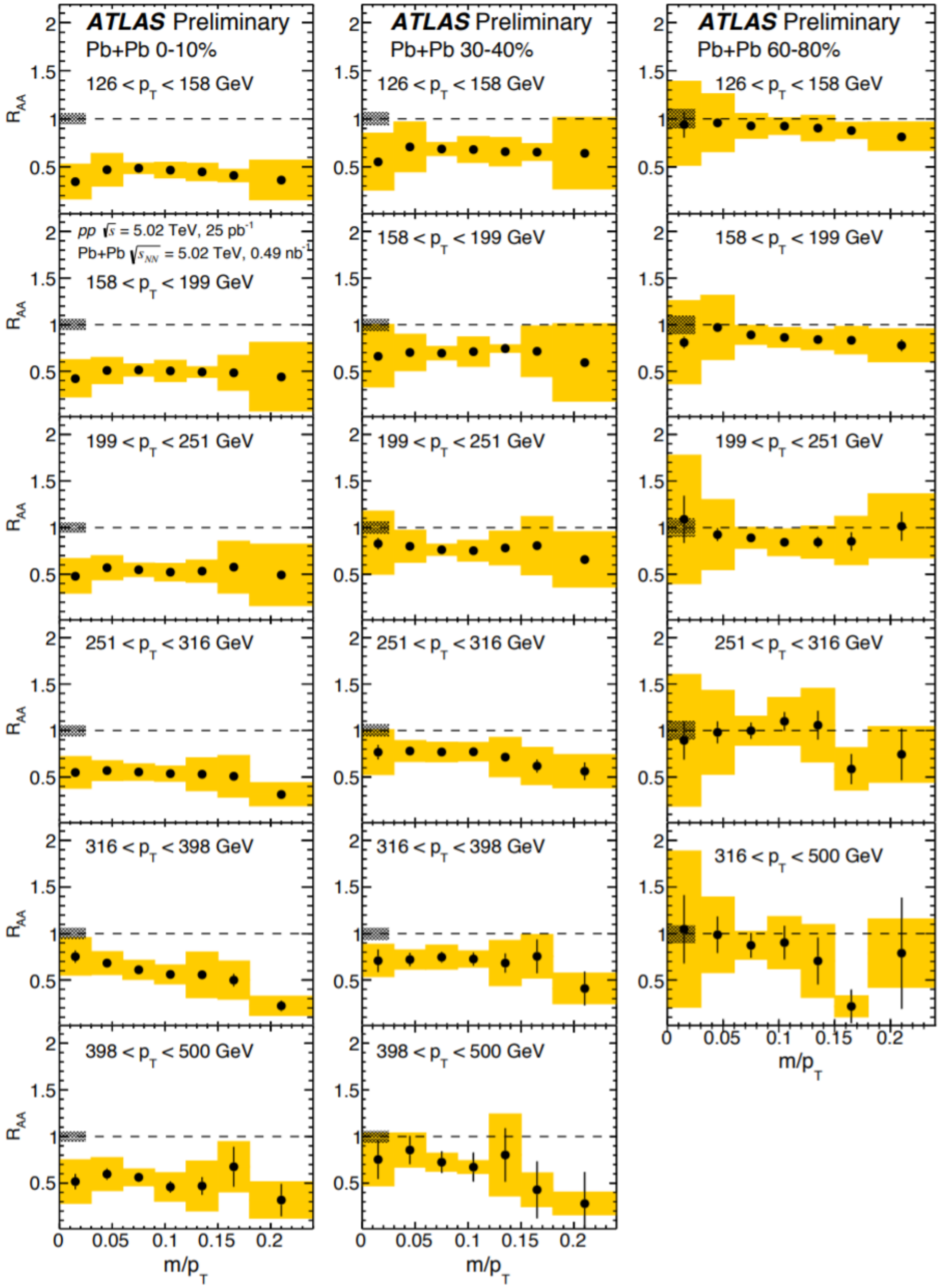
Summary

Final Goal: consistent QGP properties from soft and hard probes

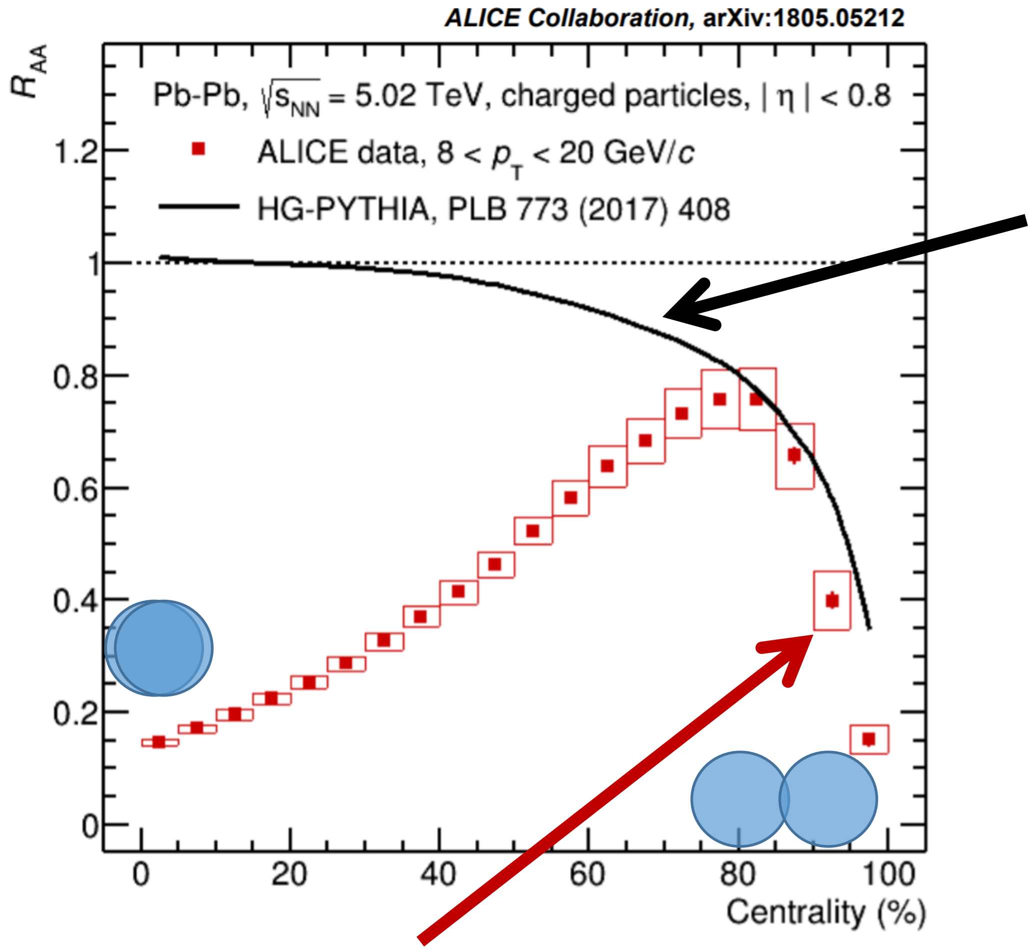
- **Emerging Strongly Interacting Medium**
  - Snapshot of “thermalizing jets” taken by the recorded jet data in the form of modified jet shapes and fragmentation
- **Jet Quenching Mechanism**
  - Indication of larger gluon energy loss than quarks
  - Narrowing of the inclusive jet core
  - Broadening of the photon-tagged jet shape
  - Jet energy loss depends on jet substructure
    “Parton shower shape dependence of jet quenching”
- **Indication of Medium Response Signal**
  - Interpretation of the data: still model dependent
- **Small System and Peripheral Events**
  - Search for jet quenching effect in small system
  - Significant bias in the peripheral AA data

Backup slides

ATLAS Jet Mass



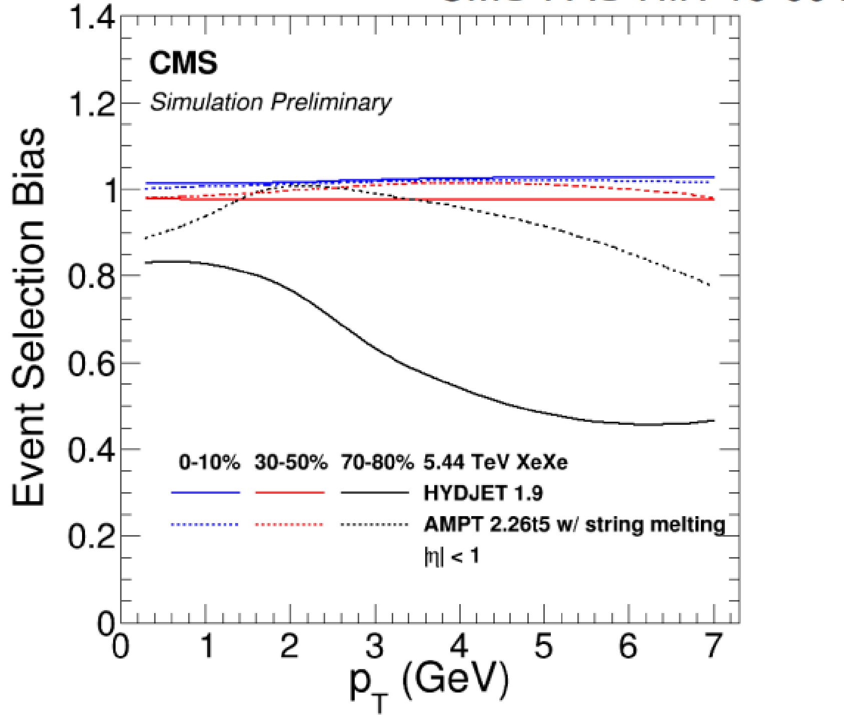
Centrality Selection Bias



Incoherent superposition of PYTHIA events according to the # of multi-parton interaction in HIJING

Amount of bias: Process dependent! (i.e, can not be resolved by using # of Z boson as scale factor)

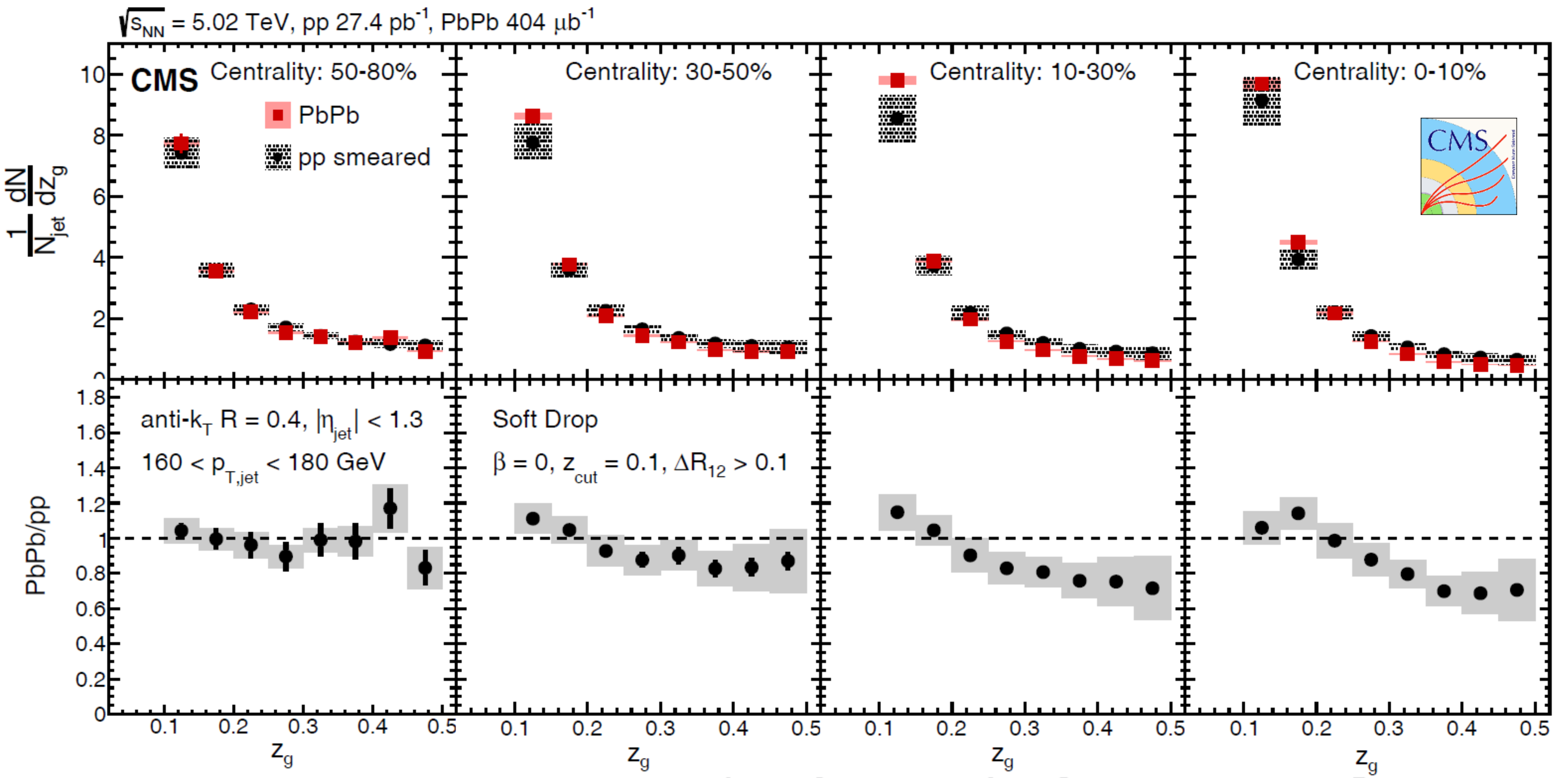
CMS-PAS-HIN-18-004



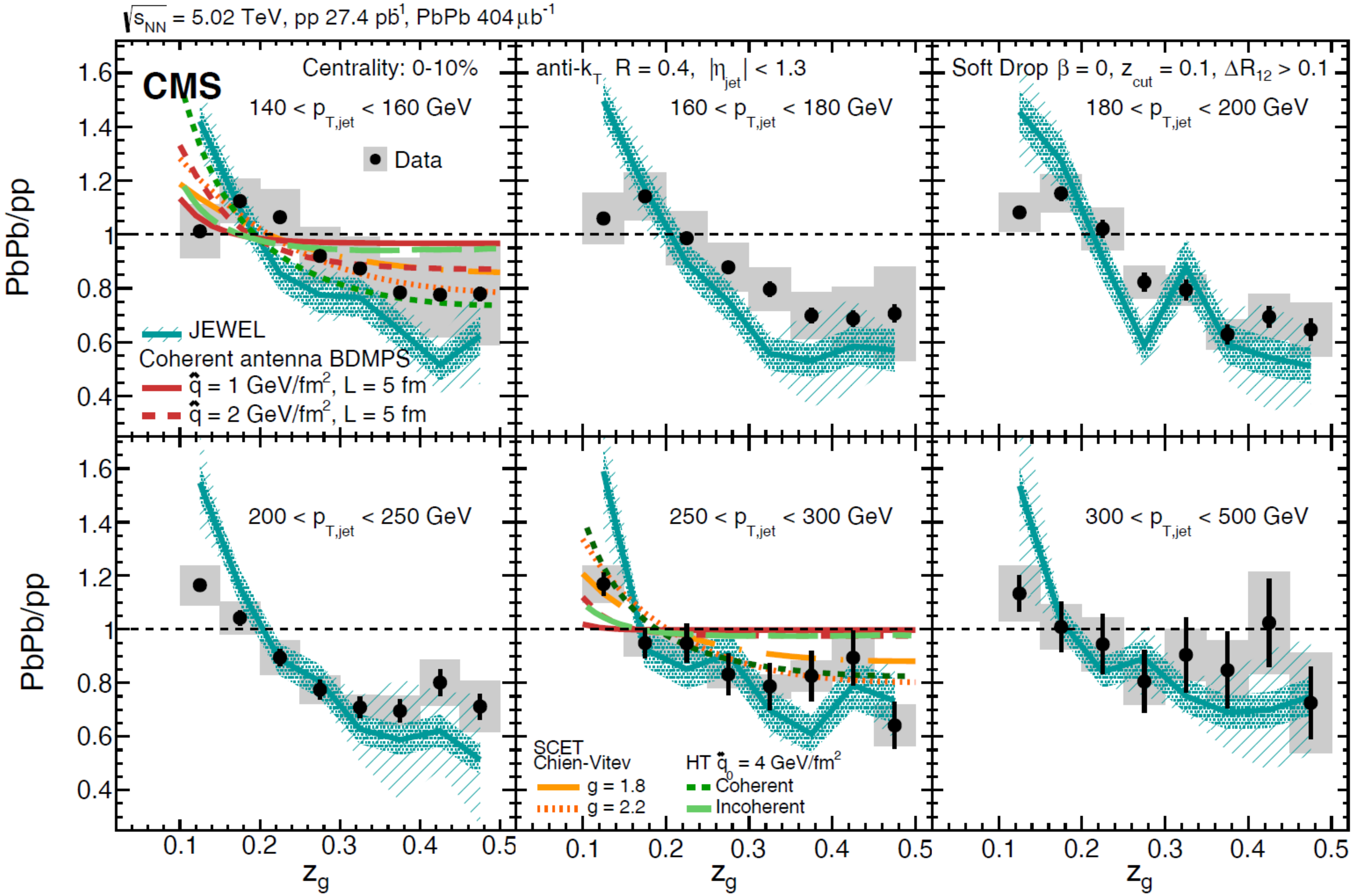
Austin Baty (QM'18)

- Selection bias plays a very important role in peripheral events
- Models which interpreted peripheral data as cold nuclear effects are **wrong**

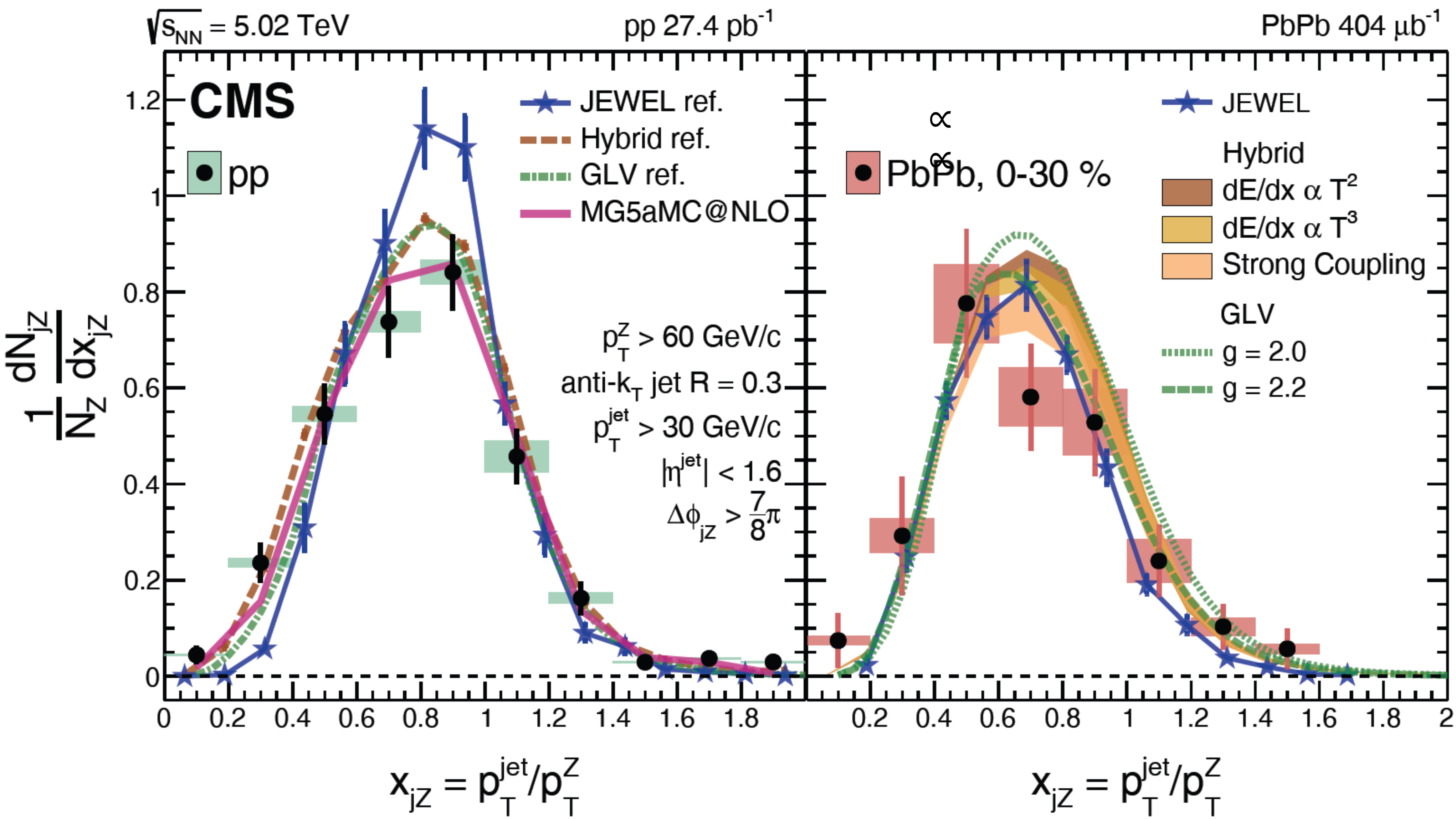
CMS Groomed Jet Splitting Function



CMS Groomed Jet Splitting Function



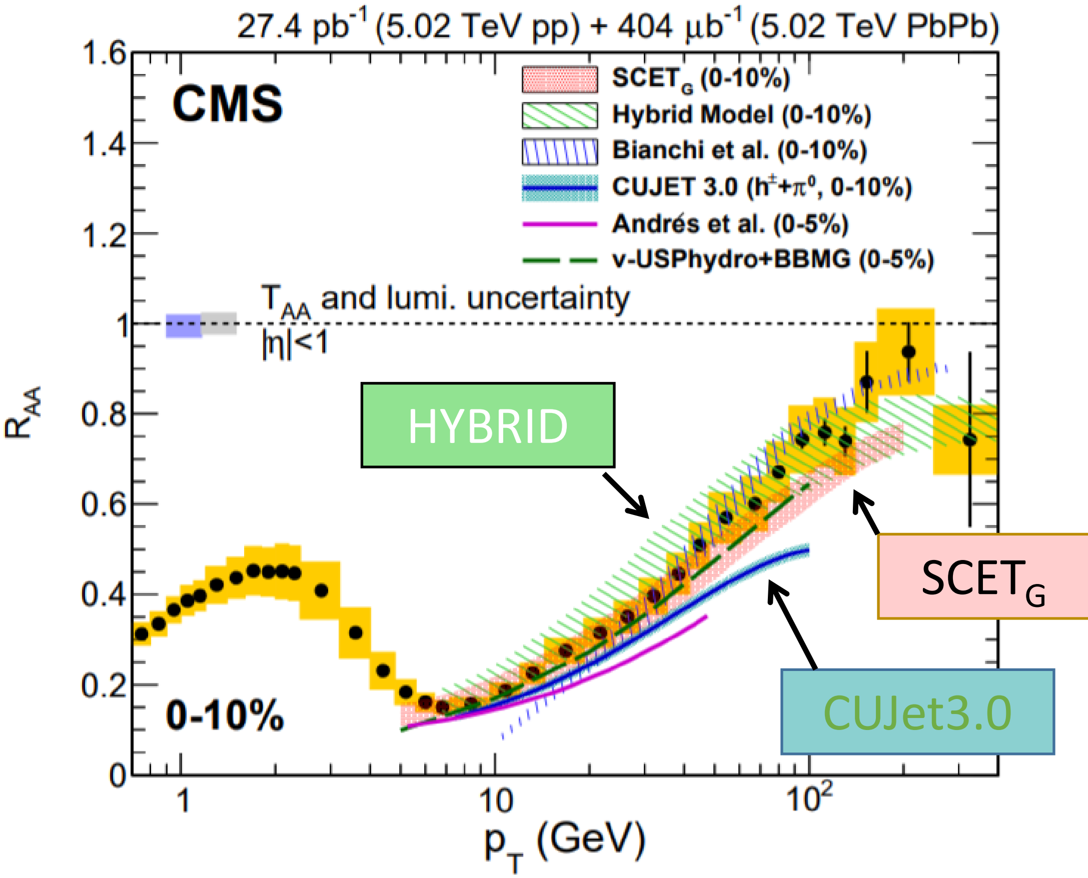
Z-Jet vs calculations



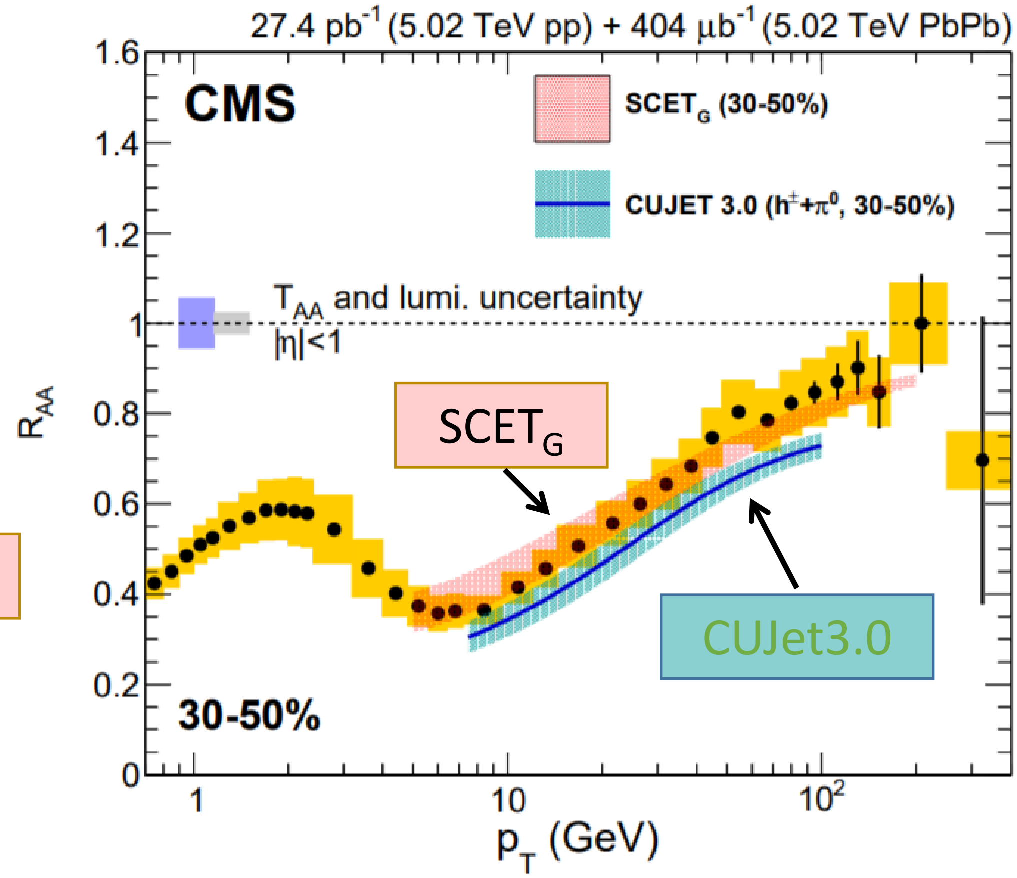
- Important to have correct pp baseline
- Reasonable agreement between data and theory curves from JEWEL, HYBRID and GLV

Charged Particle R_{AA} vs. Theoretical Models

0-10%



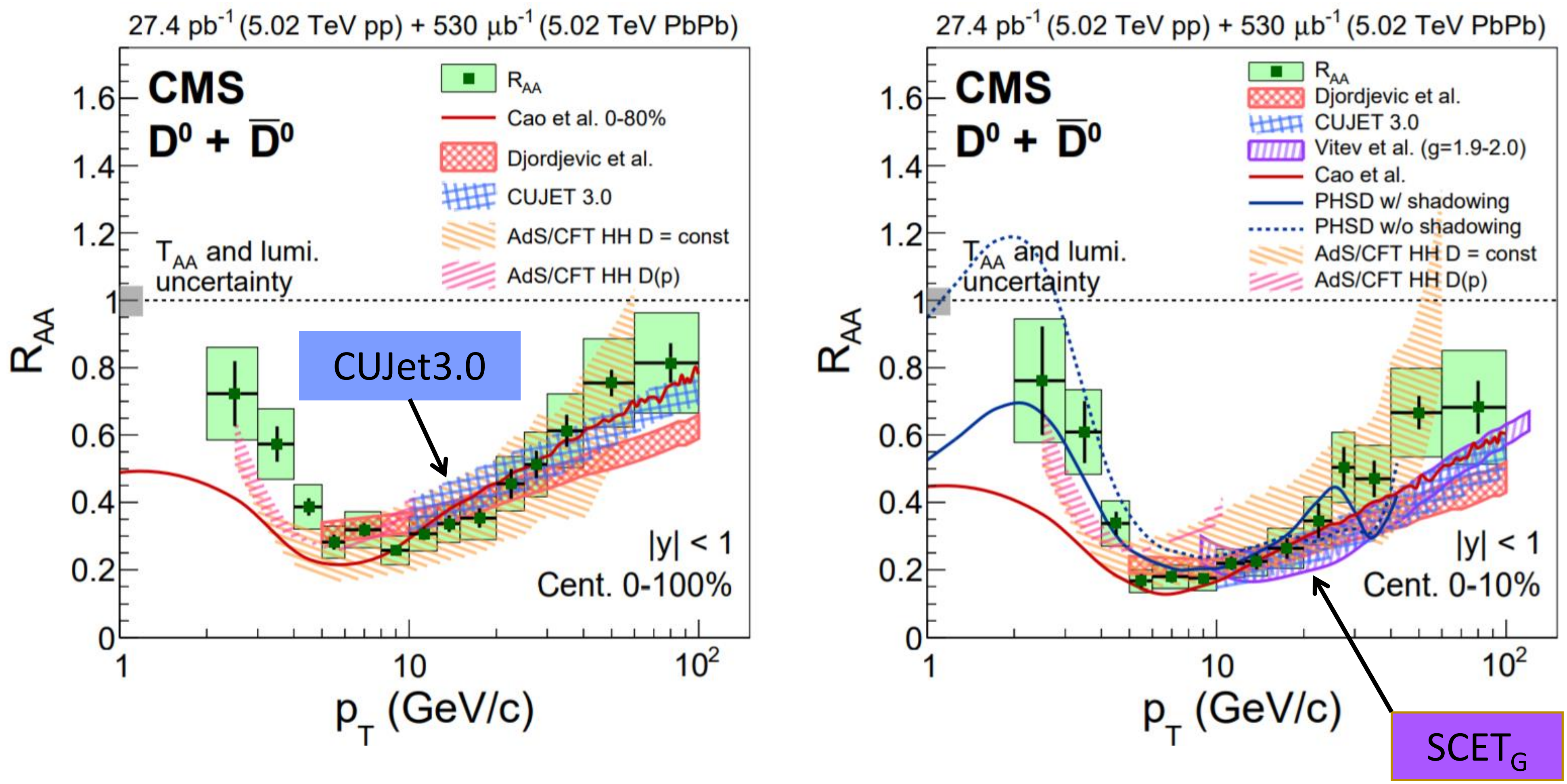
30-50%



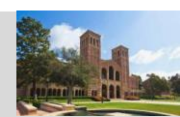
- General trend described by pQCD based and Hybrid models
- A full description of the R_{AA} is still challenging for some models

Description of the D^0 Meson Data

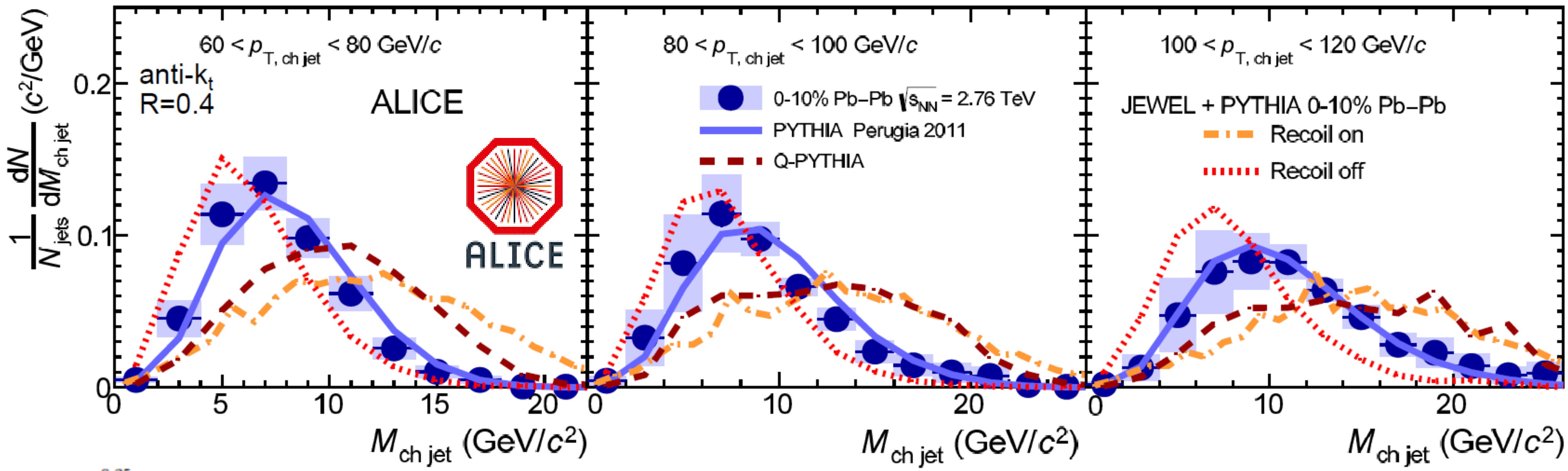
arXiv:1708.04962

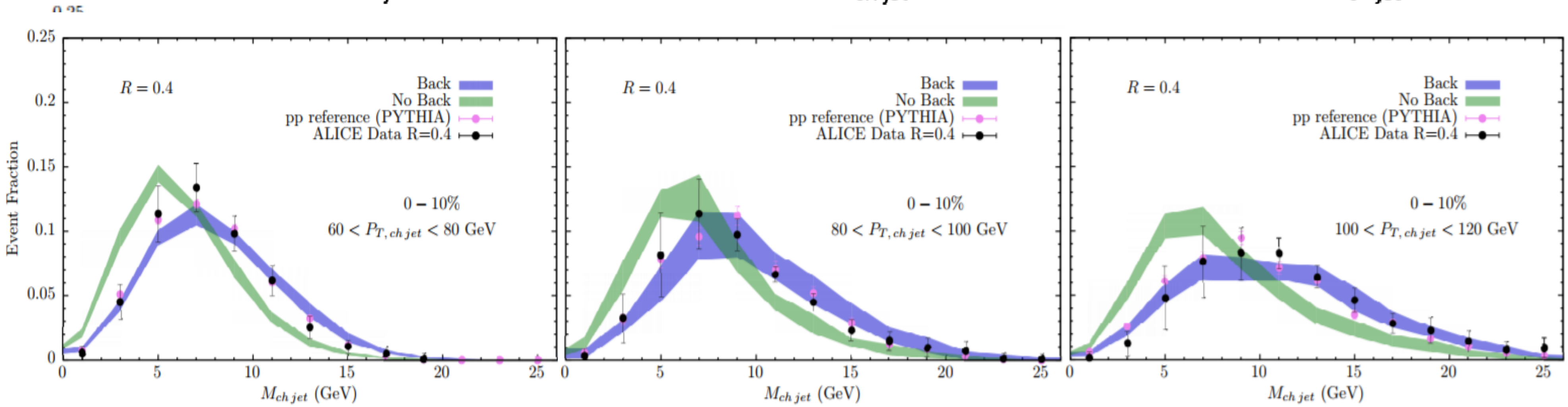


- At high D^0 p_T: Trend captured by pQCD and AdS/CFT based models
- Reasonable description of the data could be achieved
- Details doesn't work perfectly, especially the slope of the D^0 R_{AA} vs. p_T



ALICE Charged Jet Mass

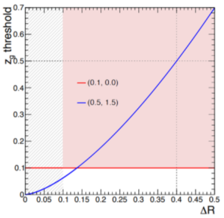




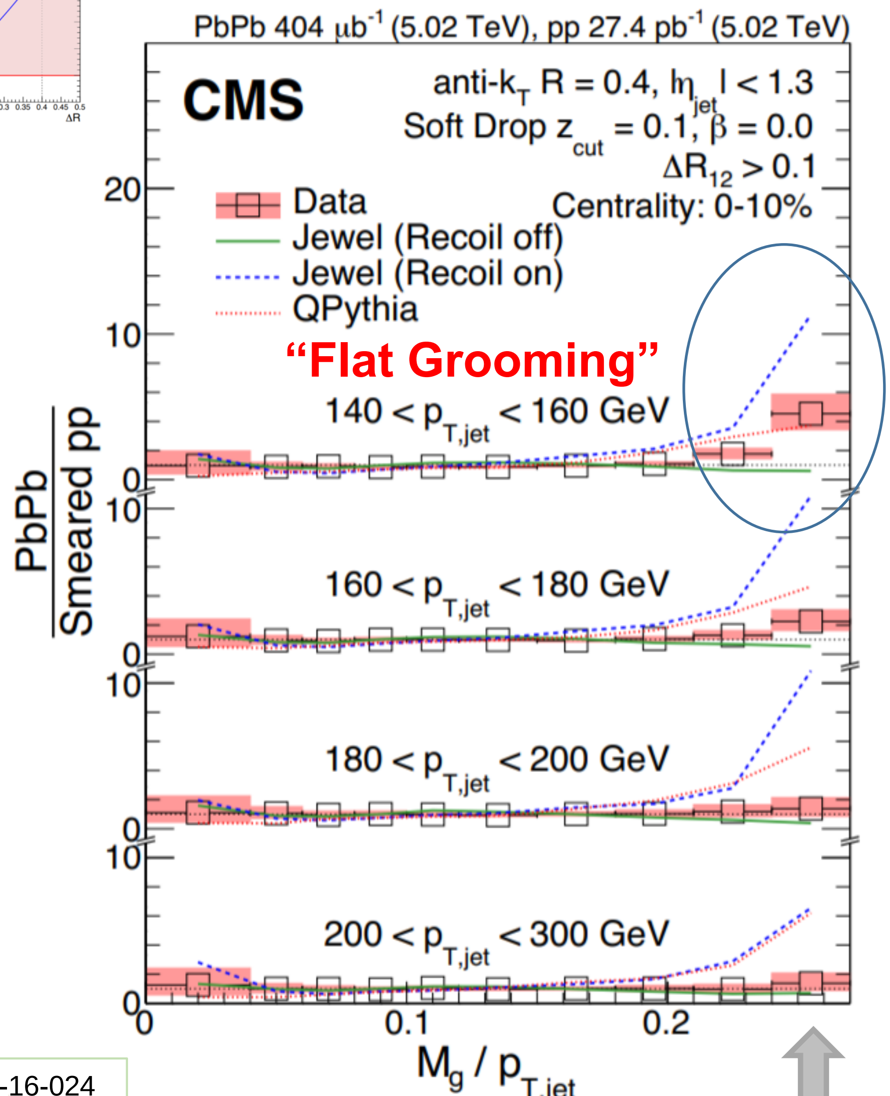
- Data sit between **JEWEL** recoil on and off
- HYBRID need medium recoil to describe the ALICE data

HYBRID

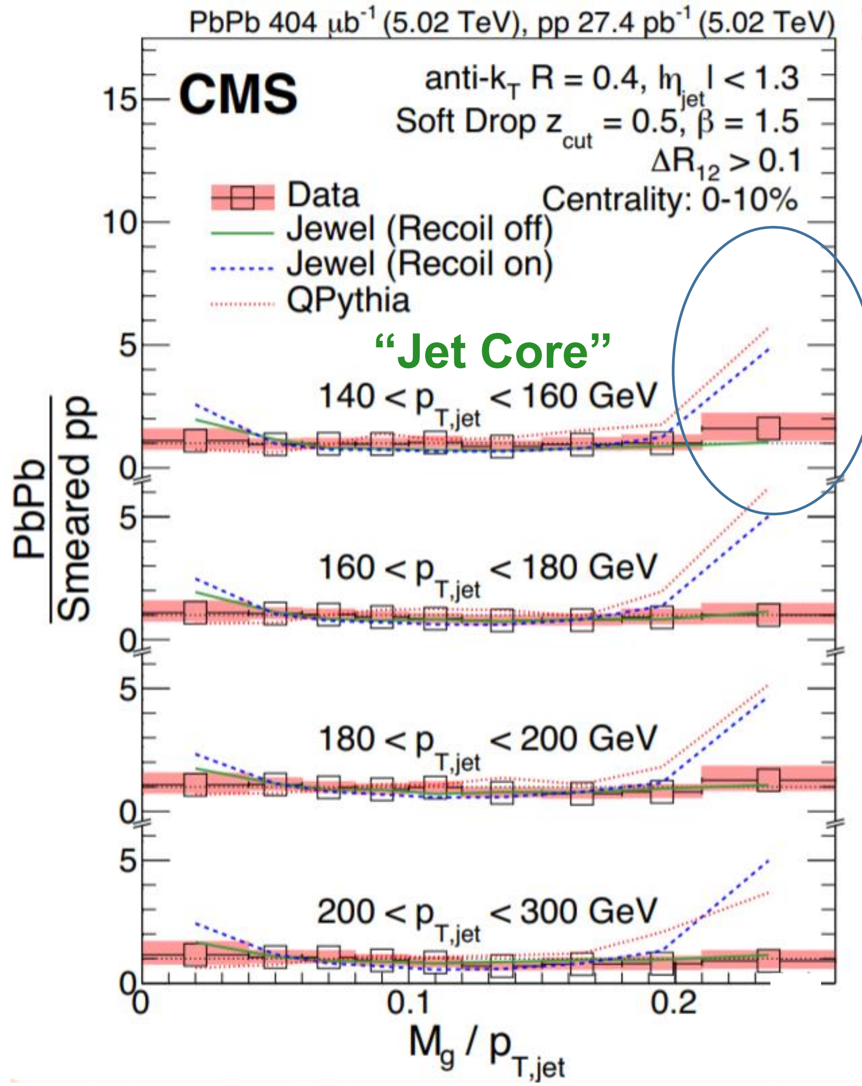
Groomed Jet Mass

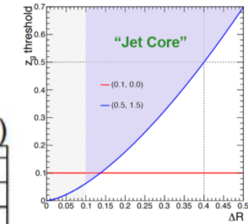


(z_{cut},β) = (0.1,0.0) ΔR>0.1



(z_{cut},β) = (0.5,1.5) ΔR>0.1



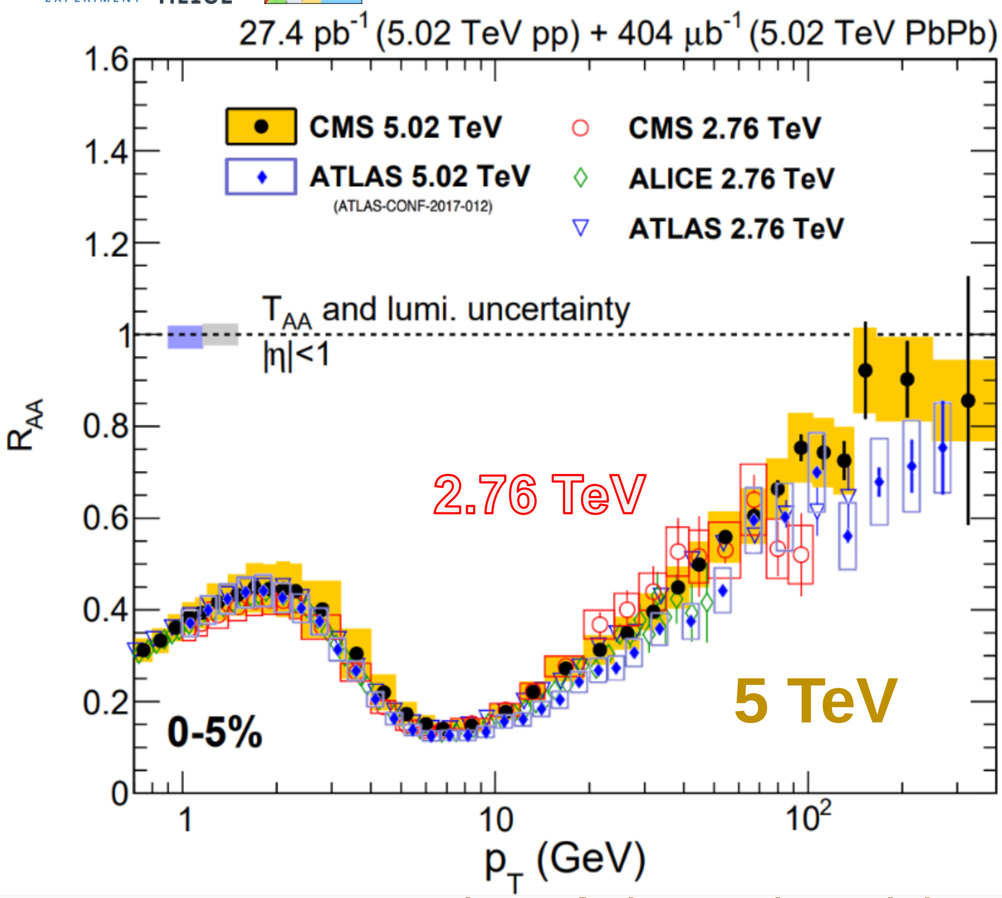


CMS-HIN-16-024

- 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"

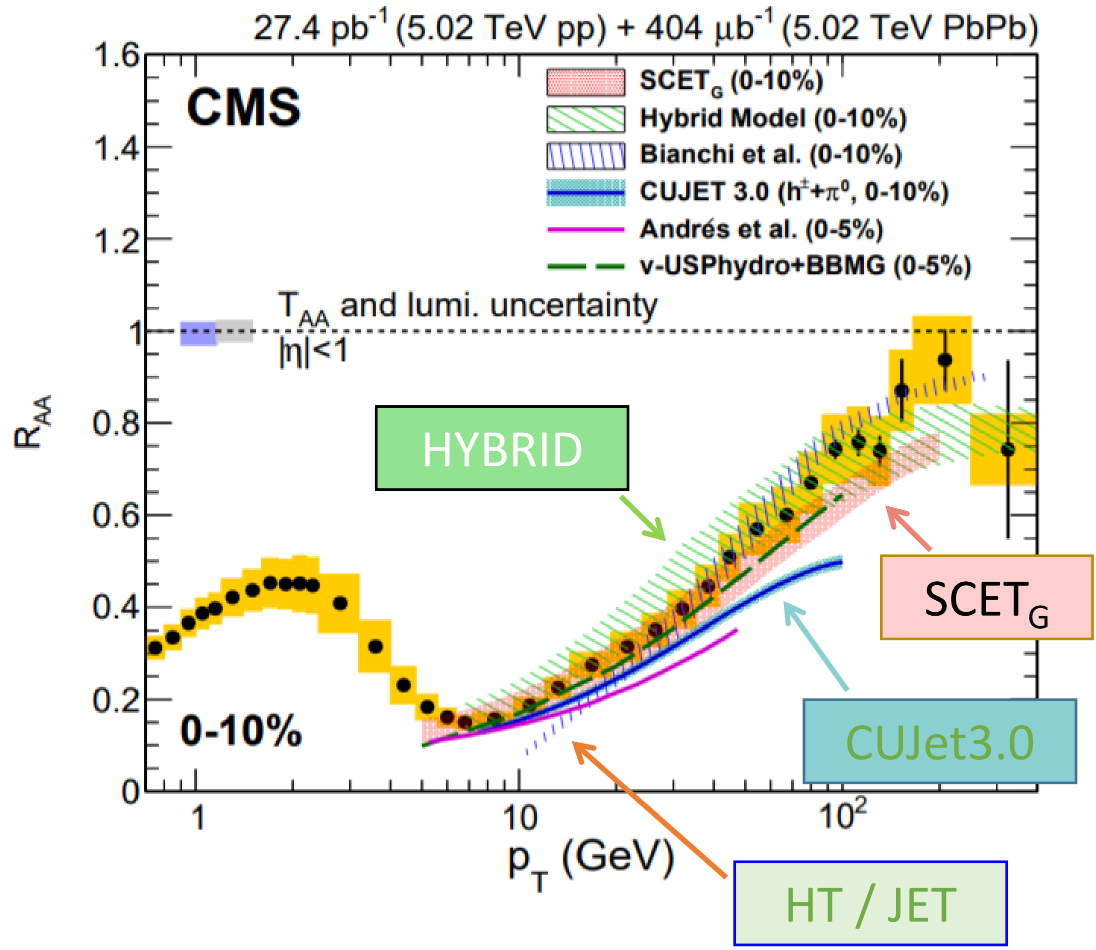
Charged Particle R_{AA}

ATLAS-CONF-2017-012



- 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

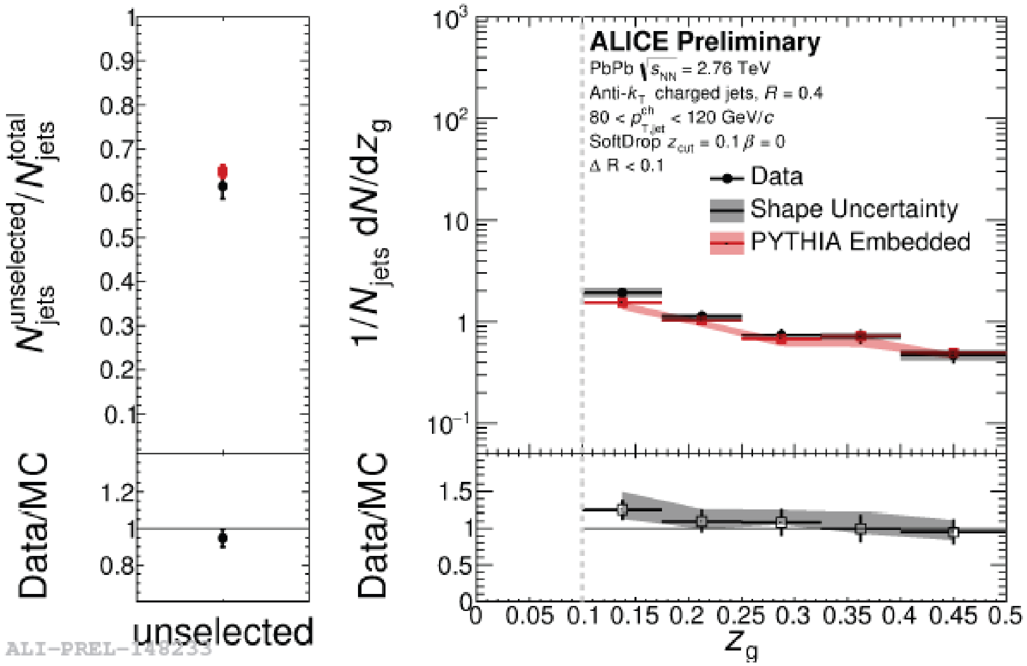
JHEP 04 (2017) 039



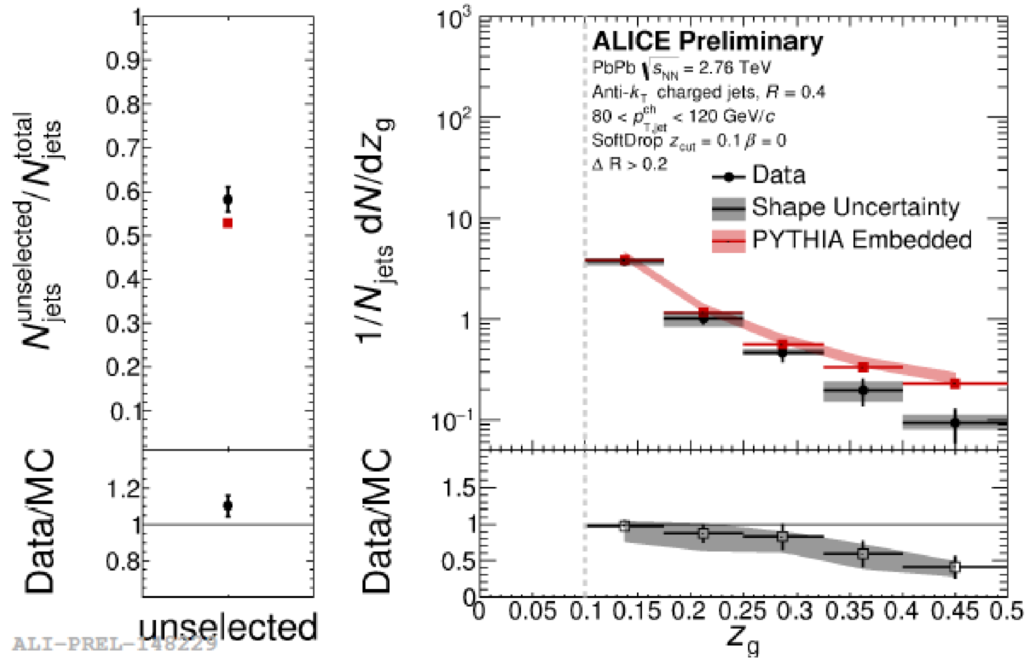
- General trend described by both **pQCD** and **Hybrid** models
- Description of the R_{AA} over the whole p_T range is still challenging

Collimated jets vs. Large Opening Angle

$\Delta R < 0.1$

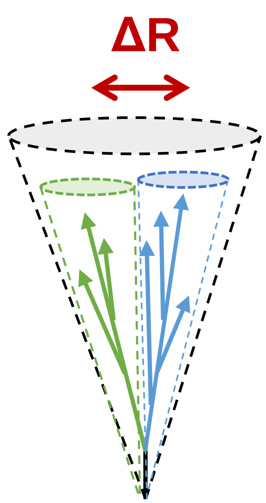


$\Delta R > 0.2$



Normalized by total number of jets

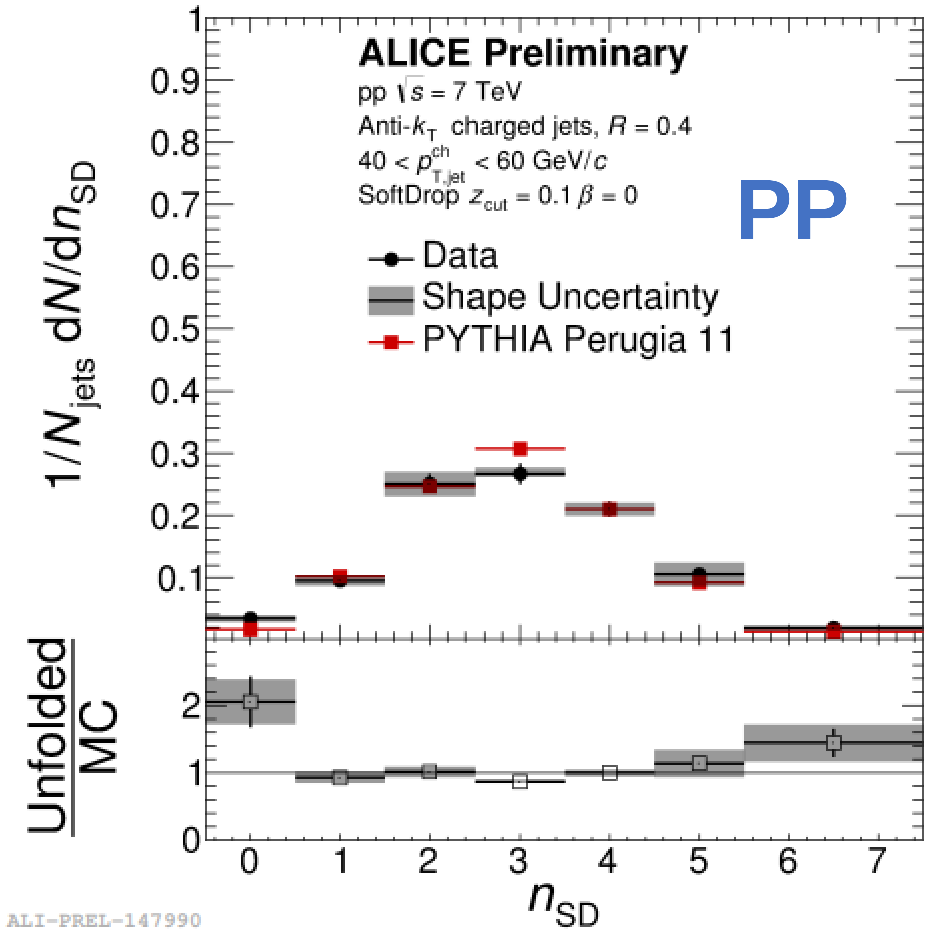
Unselected = Untagged (SD) + cut by ΔR cut

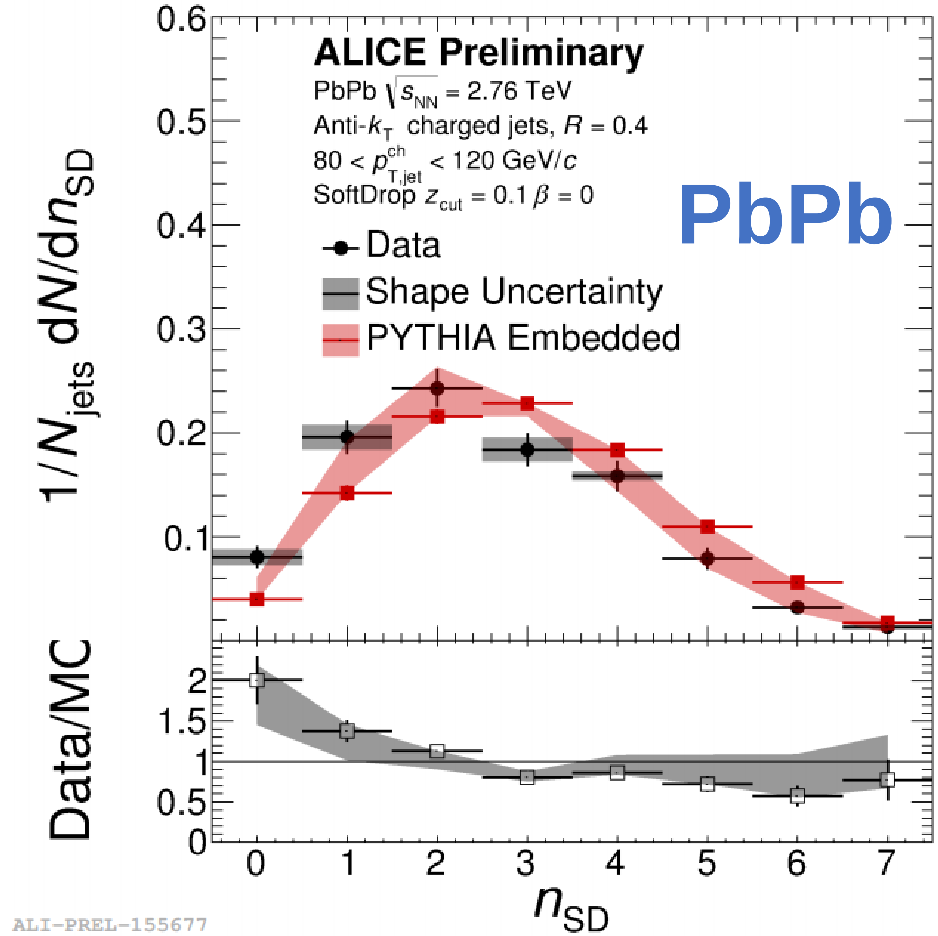


- Small or no modification of “collimated jets” (small ΔR between subjets)
- Larger ΔR cut (ΔR >0.2 large opening angle between subjets): Significant suppression at large Z_g

Harry Andrews (QM2018)

Recursive Splittings



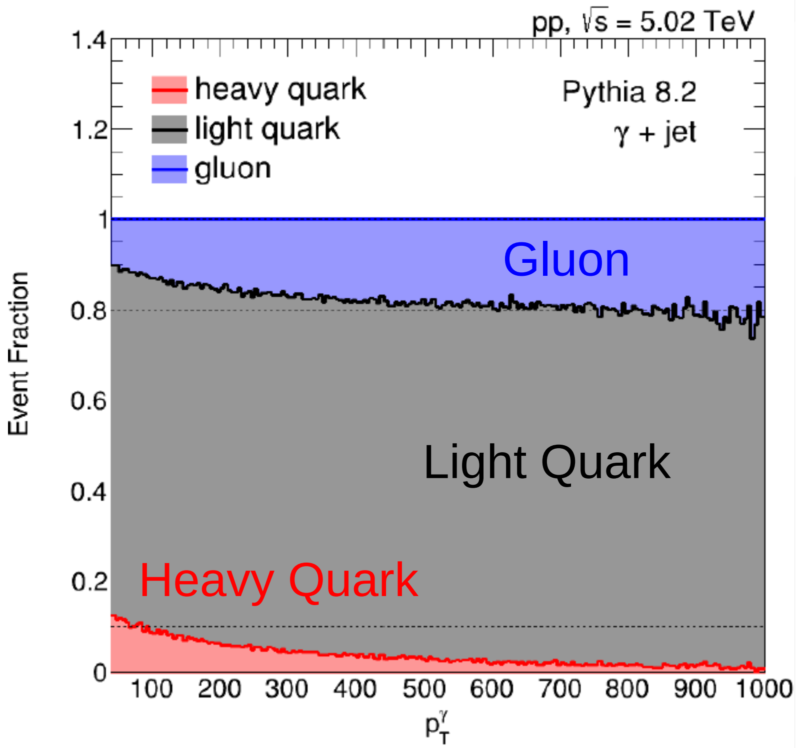


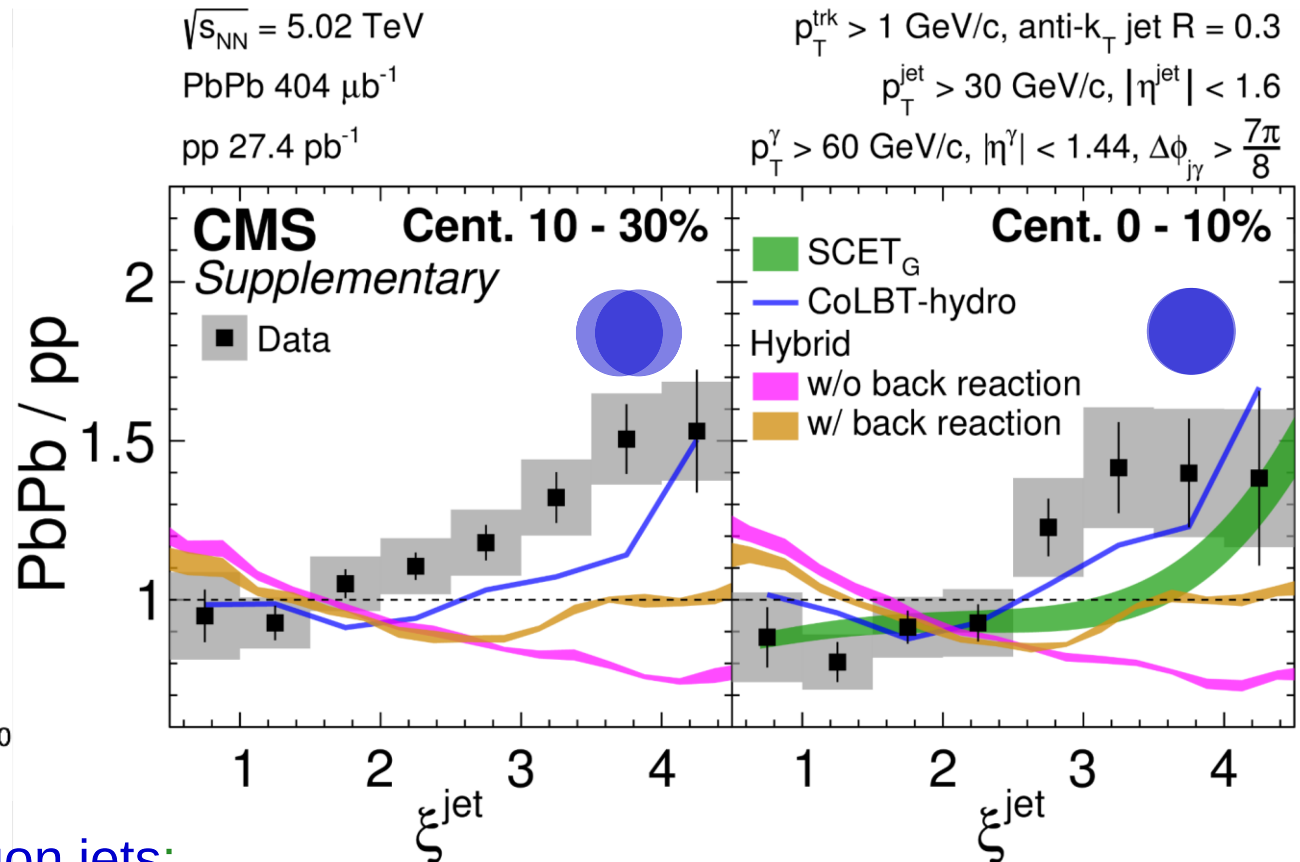
- No enhancement in the number of splitting passing Soft Drop in PbPb compared to pp

Harry Andrews (QM2018)

Photon-Tagged Fragmentation Function

From Kaya Tatar (MIT)



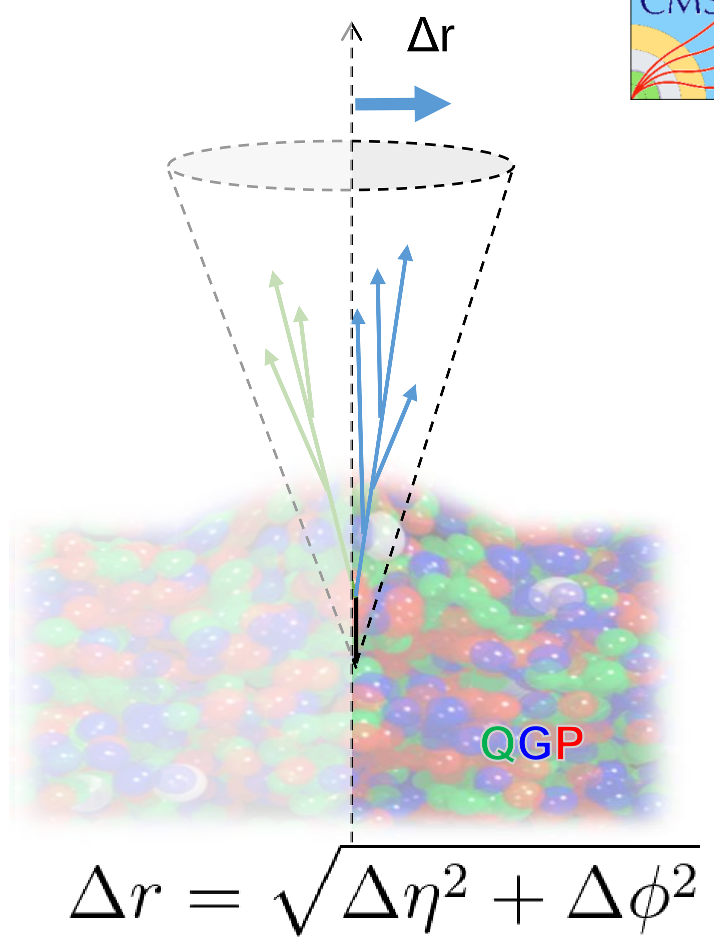


- Decrease the population of gluon jets: **>70%** of the tagged jets are quark jets

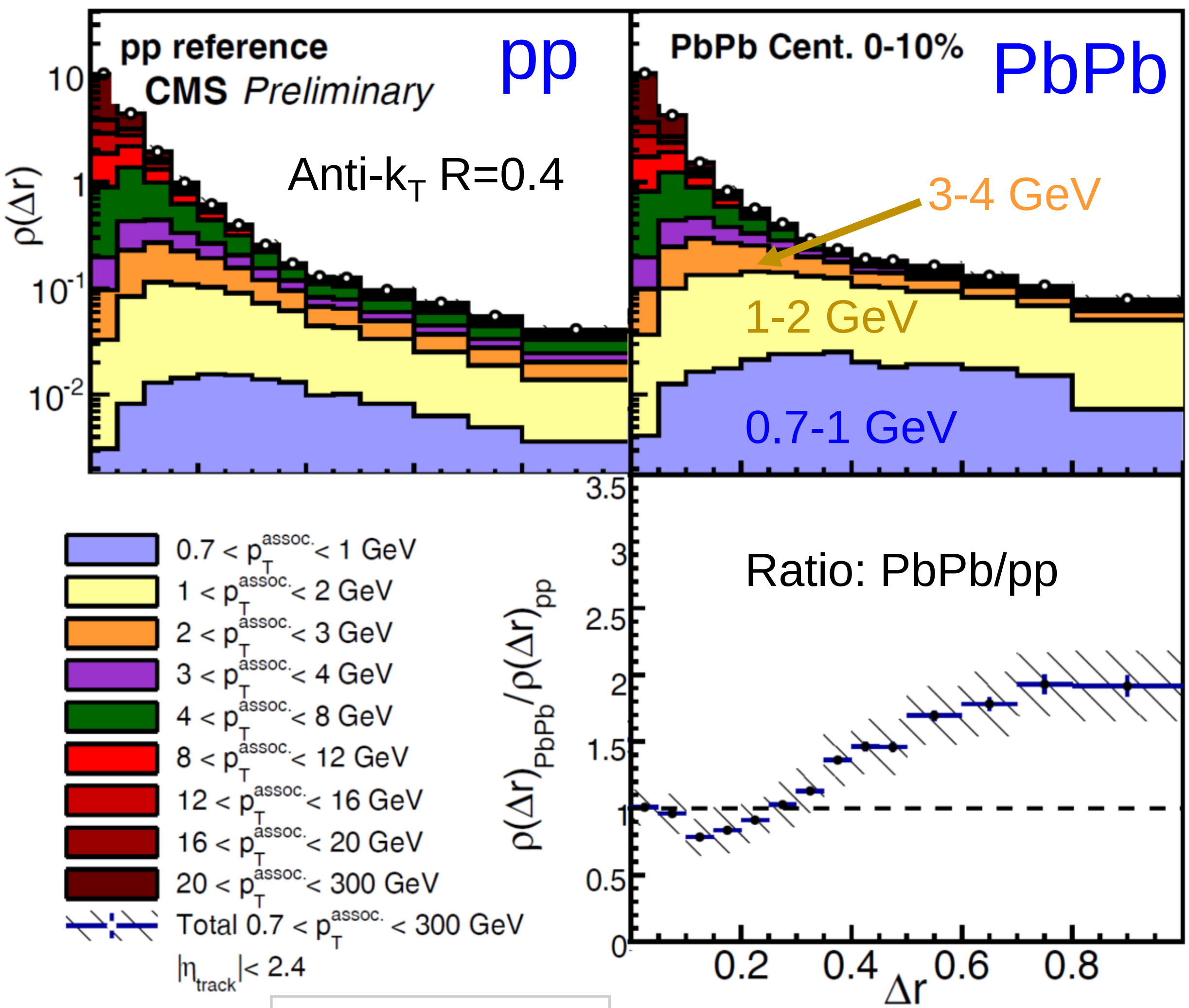
- Observation of modified jet fragmentation function in PbPb with respect to pp
  - No significant high z (or small $\xi=\ln(1/z)$) enhancement observed
  - CMS only measured down to $\xi>=0.5$ (or $z <= 0.7$)
  - It would be good to have high p_T associated jet version of this analysis

Jet Transverse Structure

Jet shapes in pp and PbPb at 5.02 TeV



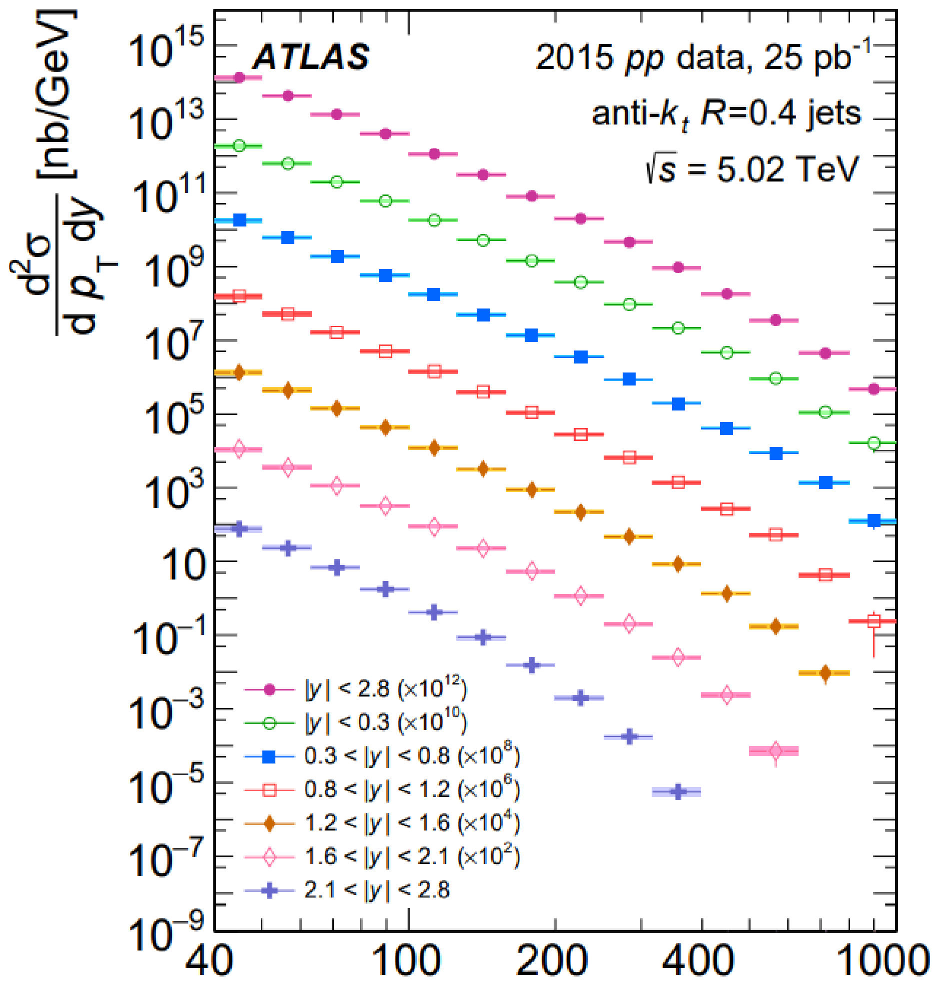
$$\Delta r = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

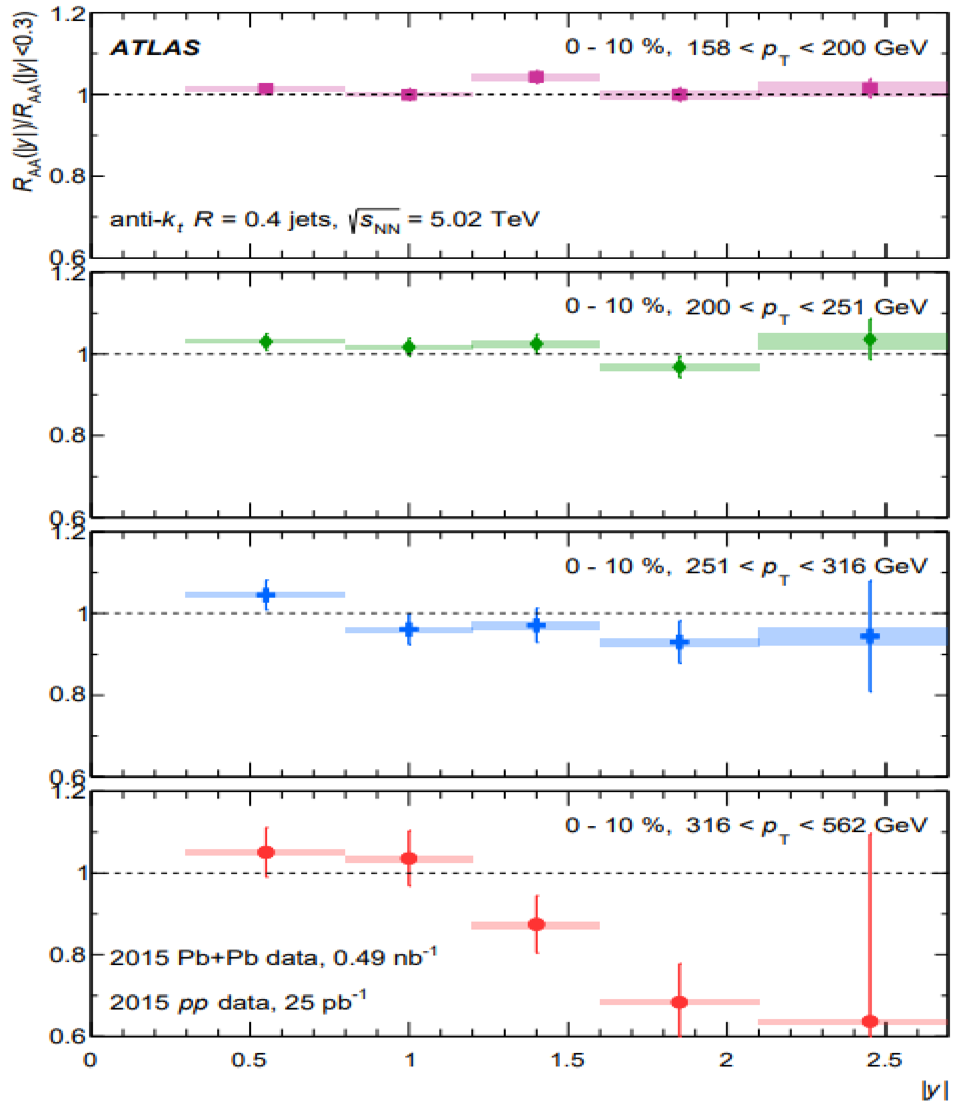


CMS-PAS-HIN-16-020
arXiv 1803.00042

- 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**

Jet R_{AA} vs. Rapidity

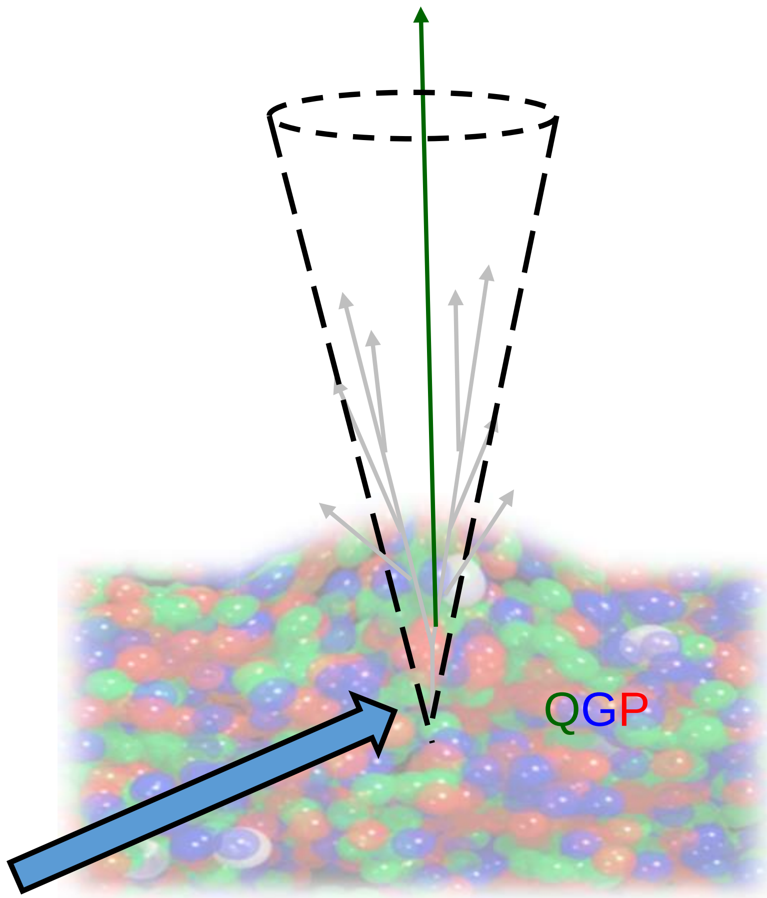




arXiv 1805.05635

- 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.

Flavor Dependence of Parton Energy Loss



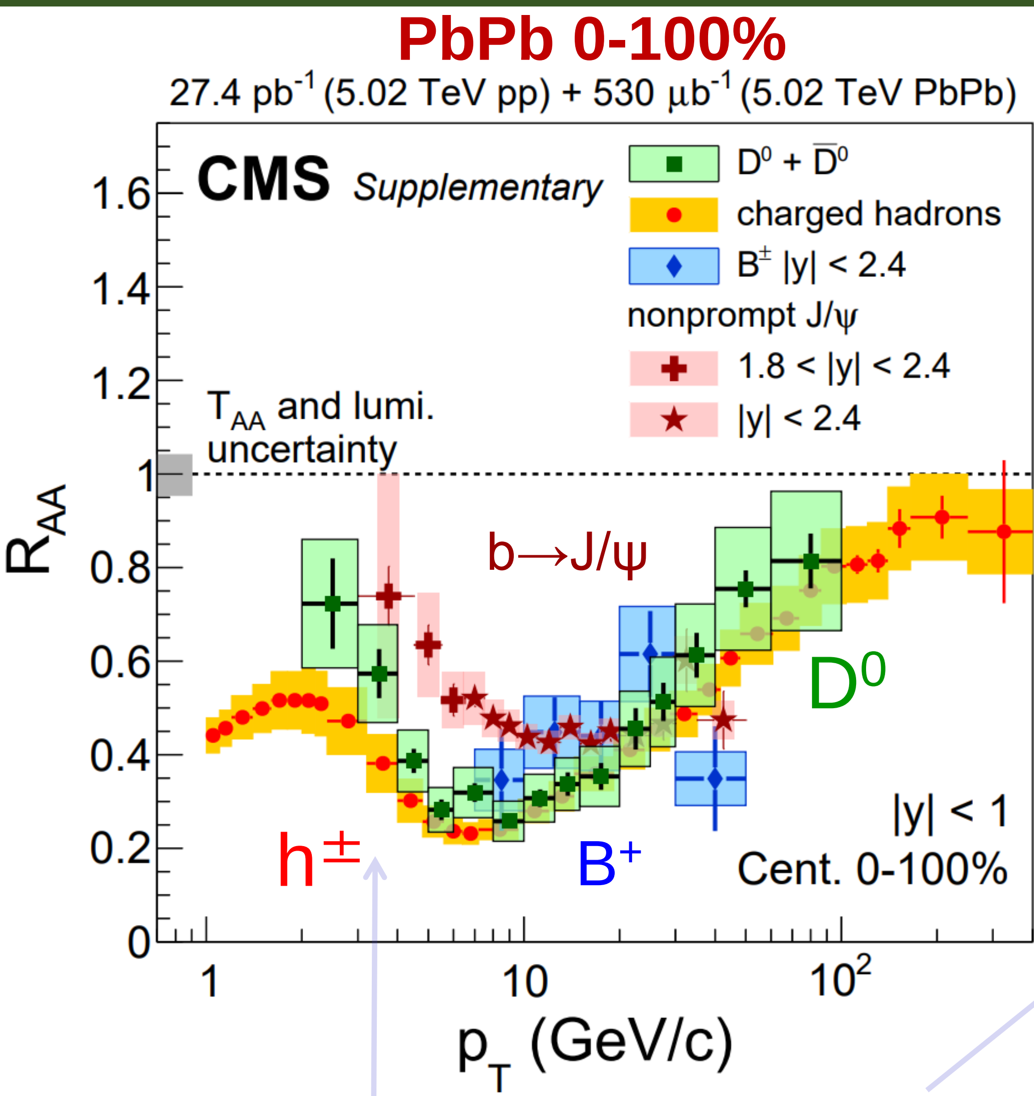
Do light quarks lose more energy than heavy quarks?

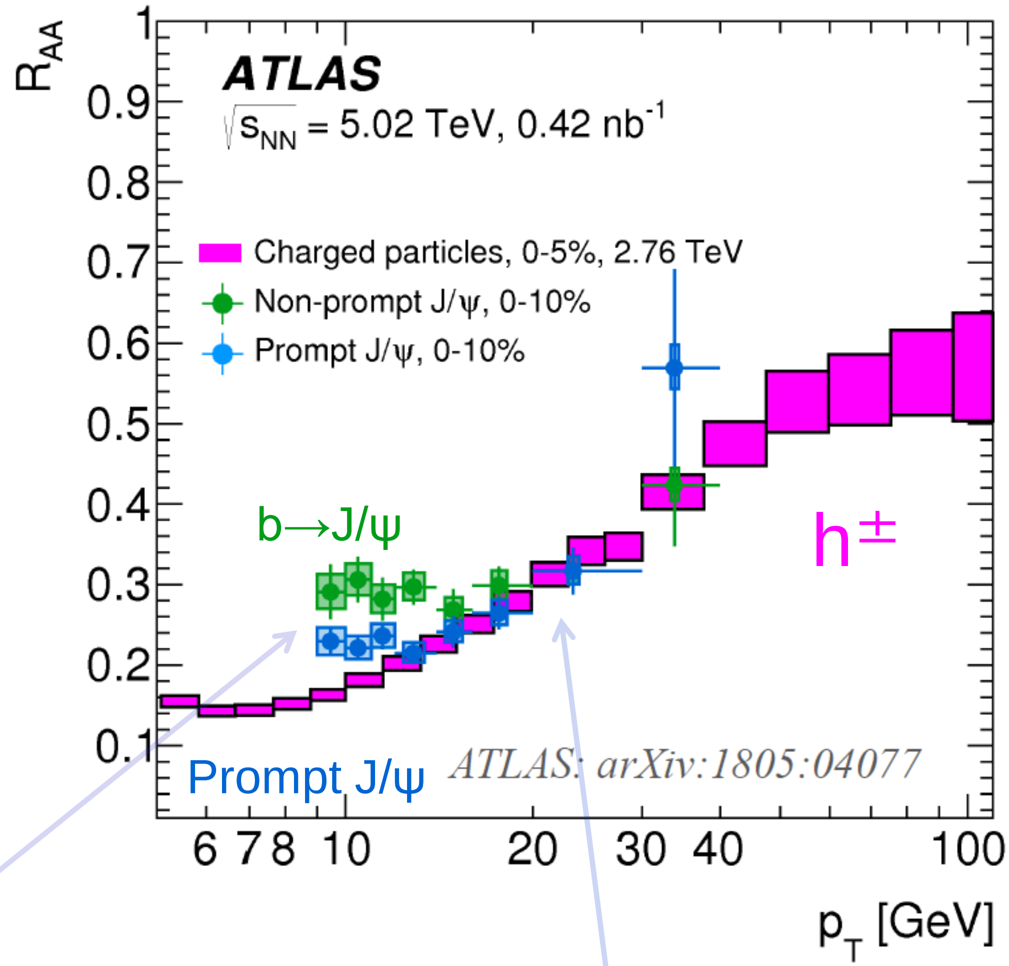
Dead-cone effect at low meson p_T, disappearance at high meson p_T

Do gluons lose more energy than the quarks?

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

Flavor Dependence of Parton Energy Loss





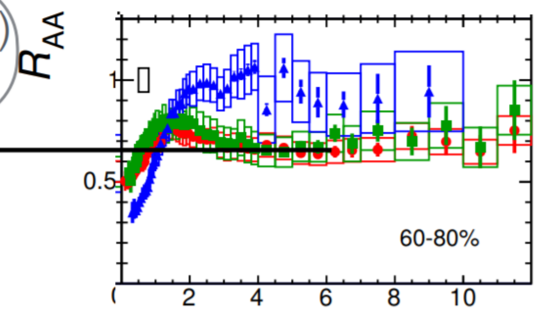
- R_{AA} is meson flavor dependent at low p_T; disappearance of the effect at high p_T
- Consistent with the expectation from parton flavor dependent energy loss

- Prompt J/ψ R_{AA} ~ Charged particle R_{AA} at high p_T: FF+parton energy loss in play
- Relevance of the fragmentation process for the interpretation of low pT J/ψ?

R_{AA} in peripheral events

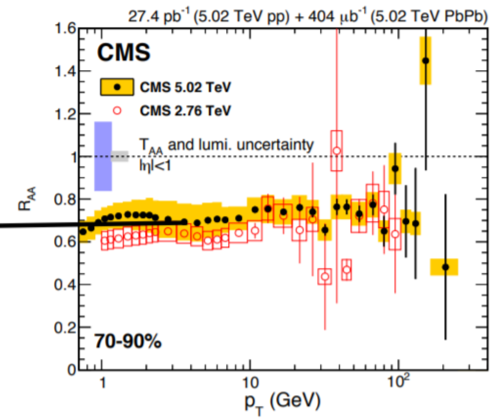
M. Spousta (ATLAS)
Tues. 12:10pm

N. Jacazio (ALICE)
Wed. 4:50pm



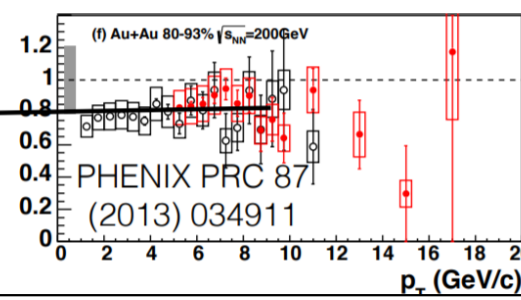
60-80% Pb+Pb, R_{AA} = 0.65
$<N_{part}>$ = 23 (ATLAS similar)
<1% *p*+Pb (0-5% in Glauber-Gribov!)

Y.-J. Lee (CMS)
Monday 12:10pm



70-90% Pb+Pb, R_{AA} = 0.7
$<N_{part}>$ = 11
~20-30% *p*+Pb

S. Zharko (PHENIX)
Wed. 10:40am



80-93% Au+Au, R_{AA} = 0.8
$<N_{part}>$ = 5
~50-70% *p*+Pb

54

decreasing N_{part}

From Dennis Perepelisa QM'17

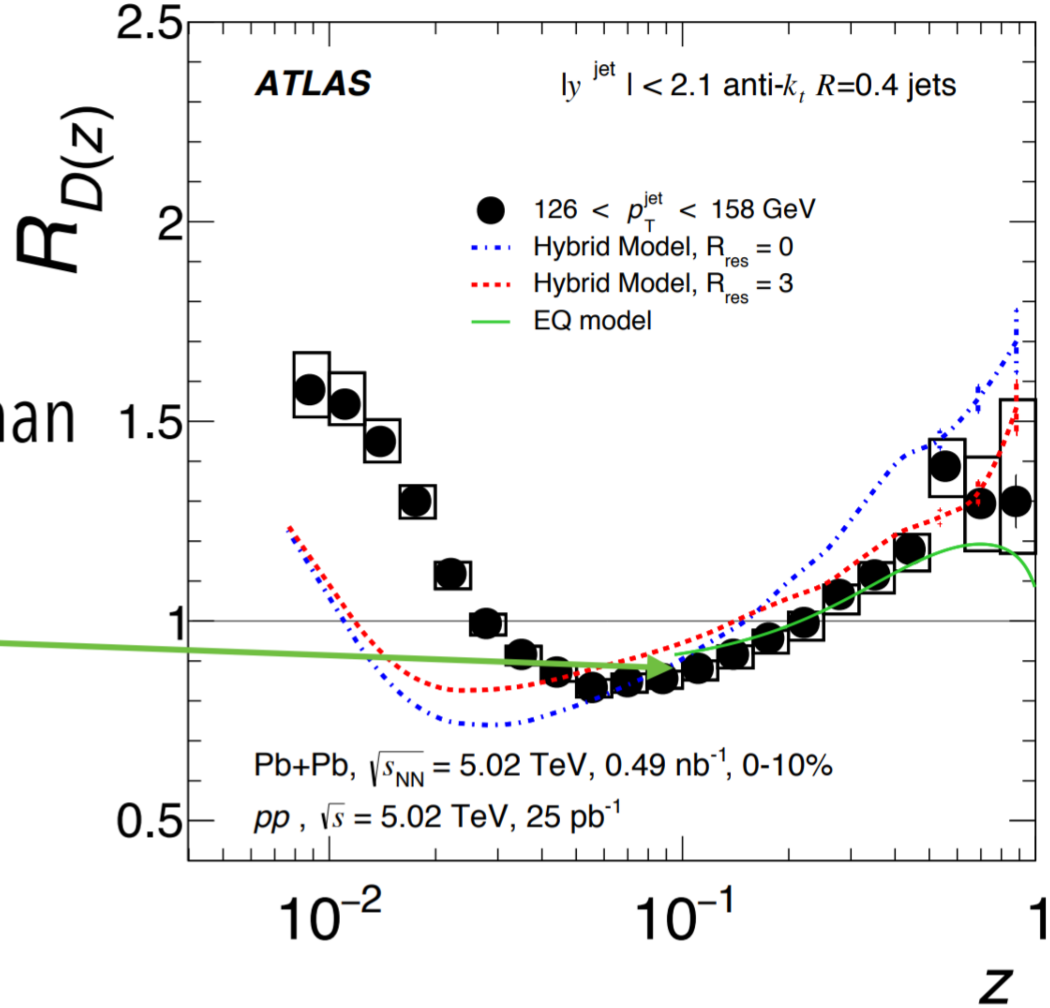
With ALICE data analysis (also CMS generator studies) shown in QM'18

Models which interpreted these data as cold nuclear effects are wrong

Interpreting Single Jet Measurements in Pb+Pb Collisions at the LHC

Martin Spousta[a], Brian Cole[b] 1504.05169

larger energy loss for gluons than quarks followed by pythia fragmentation



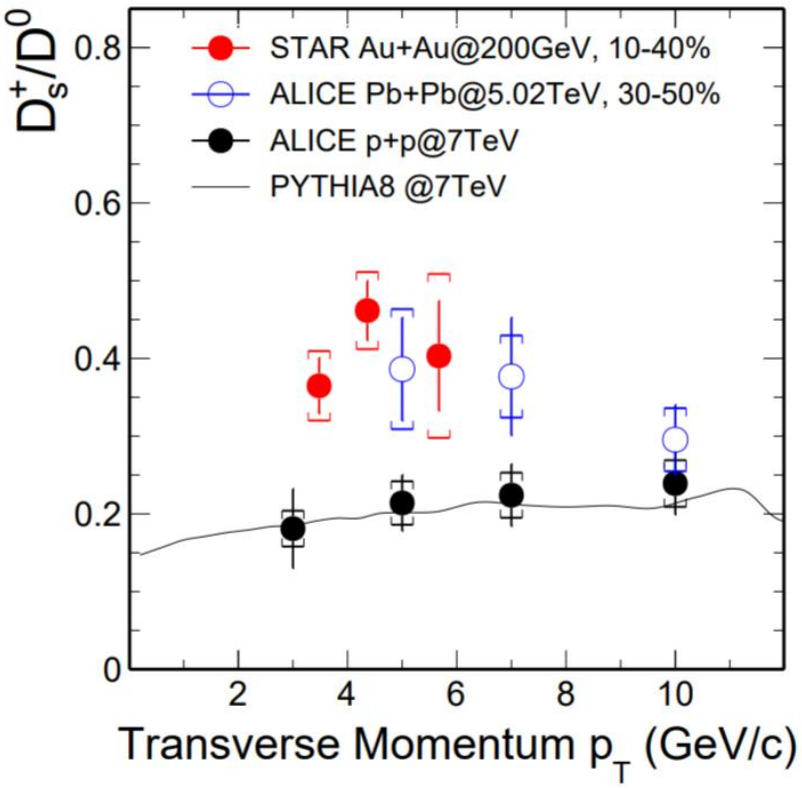
Total Charm Production Cross-section

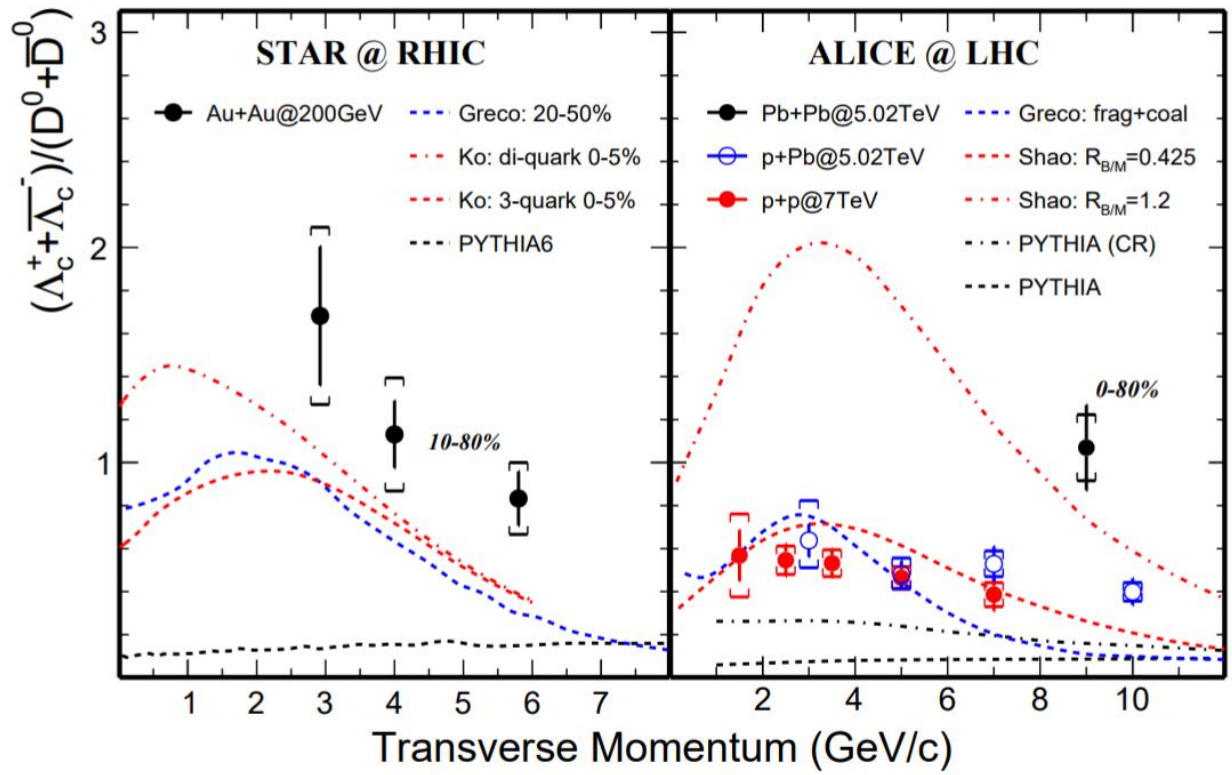
Total Charm Production Cross Section

Charm Hadron		Cross Section dσ/dy (μb)
Au+Au 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28*
	Total	**152 ± 13 ± 29**
p+p 200 GeV	**Total**	**130 ± 30 ± 26**

Total charm X-section follows ~ N_{bin} scaling from p+p to Au+Au
However, charm hadron fractions are different from p+p to Au+Au collisions

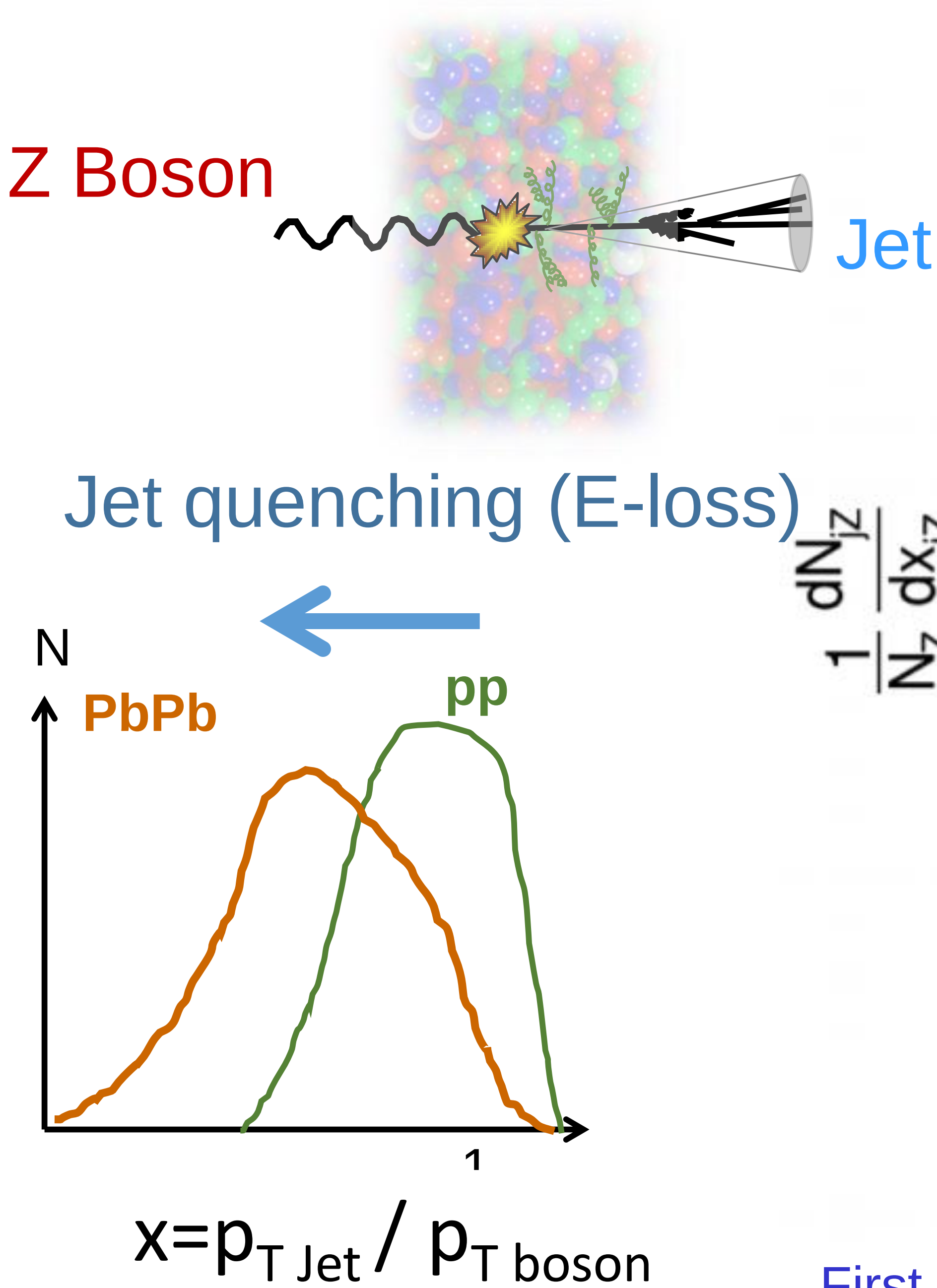
Heavy Quark Hadronization

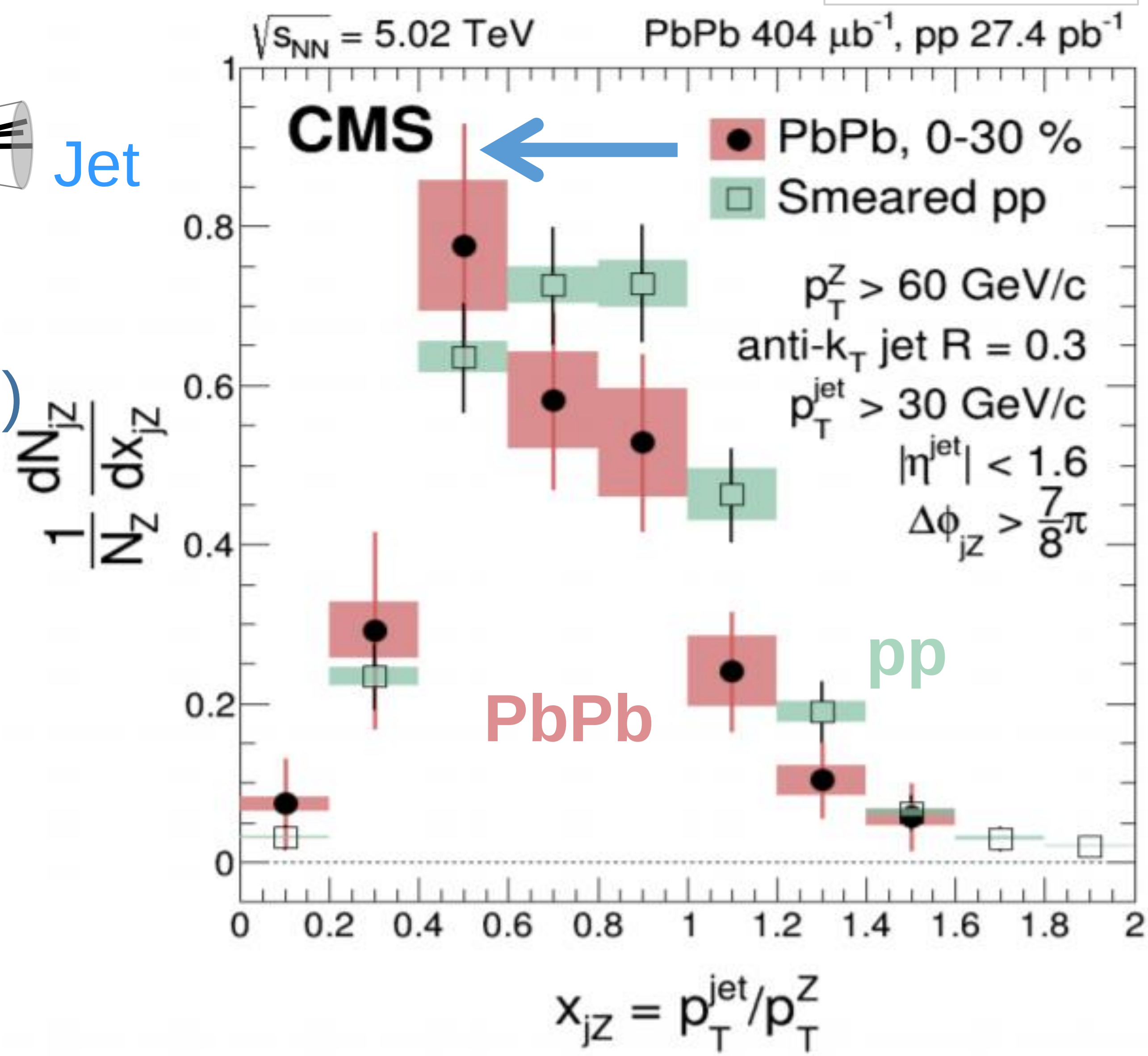




Z-Jet in pp and PbPb at 5.02 TeV

PRL 119 (2017) 082301
PRL cover



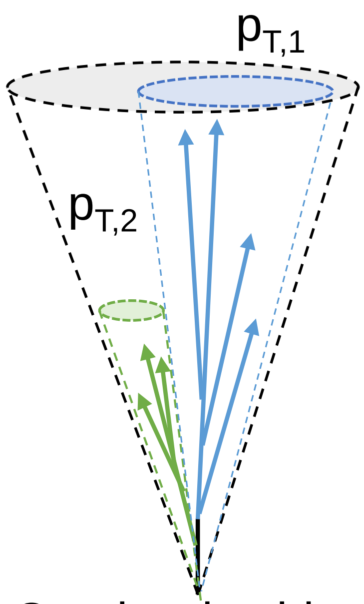


First Z-jet measurement in PbPb collisions at 5 TeV

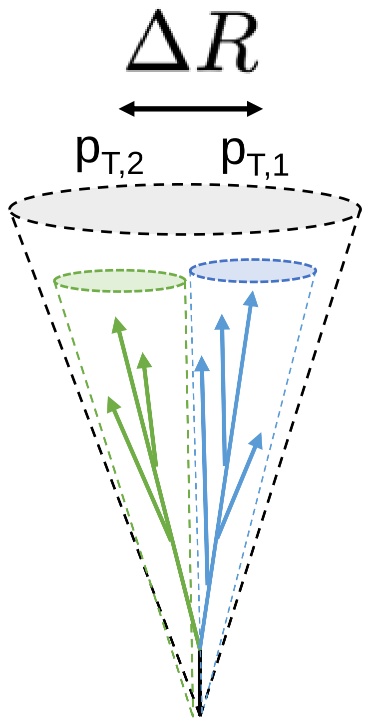
Z_g vs. ΔR Phase Space

Momentum Sharing of Subjets

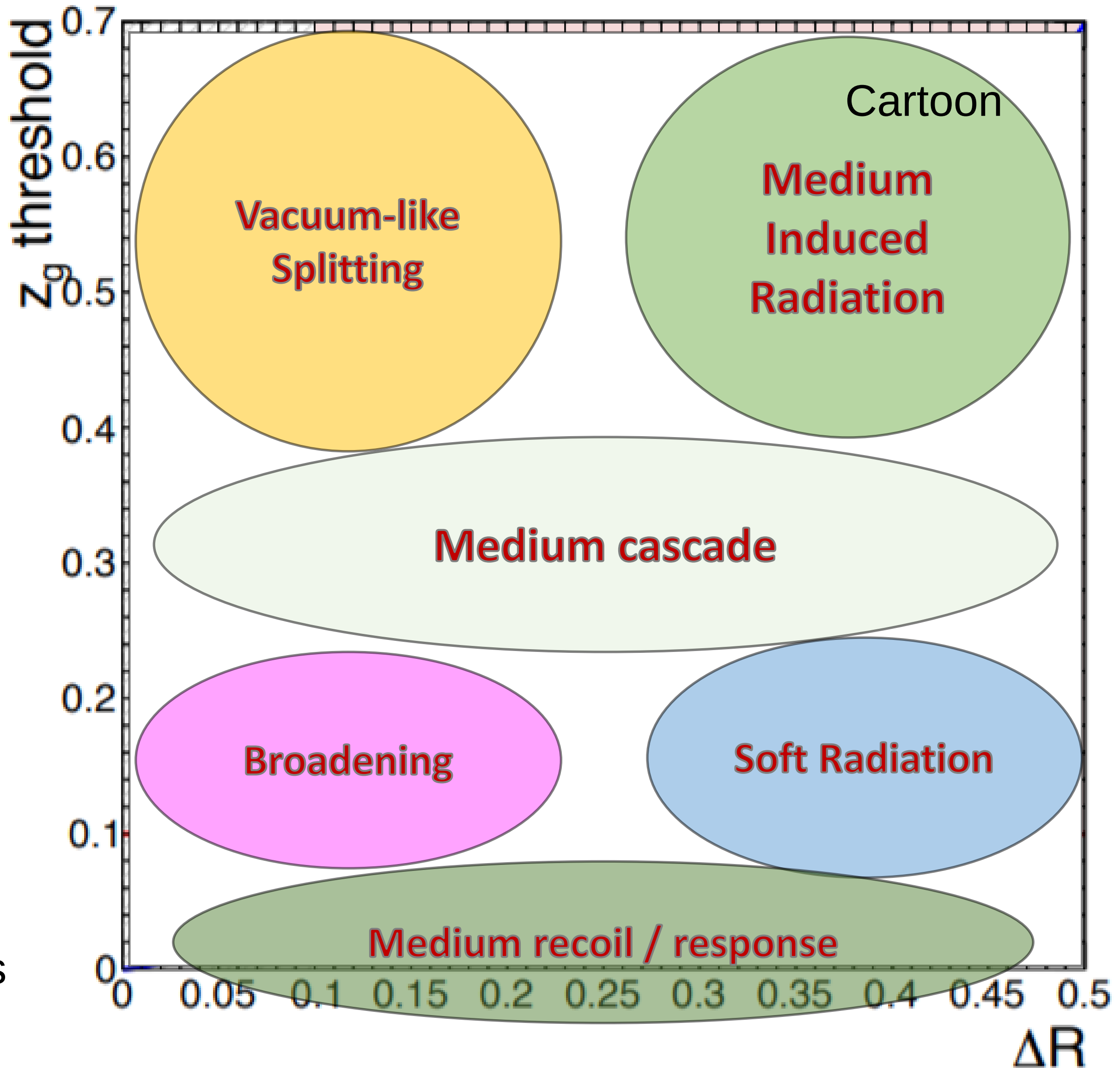
$$Z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$



One hard subjet
Z_g small



Two hard subjets
$Z_g \sim 0.5$

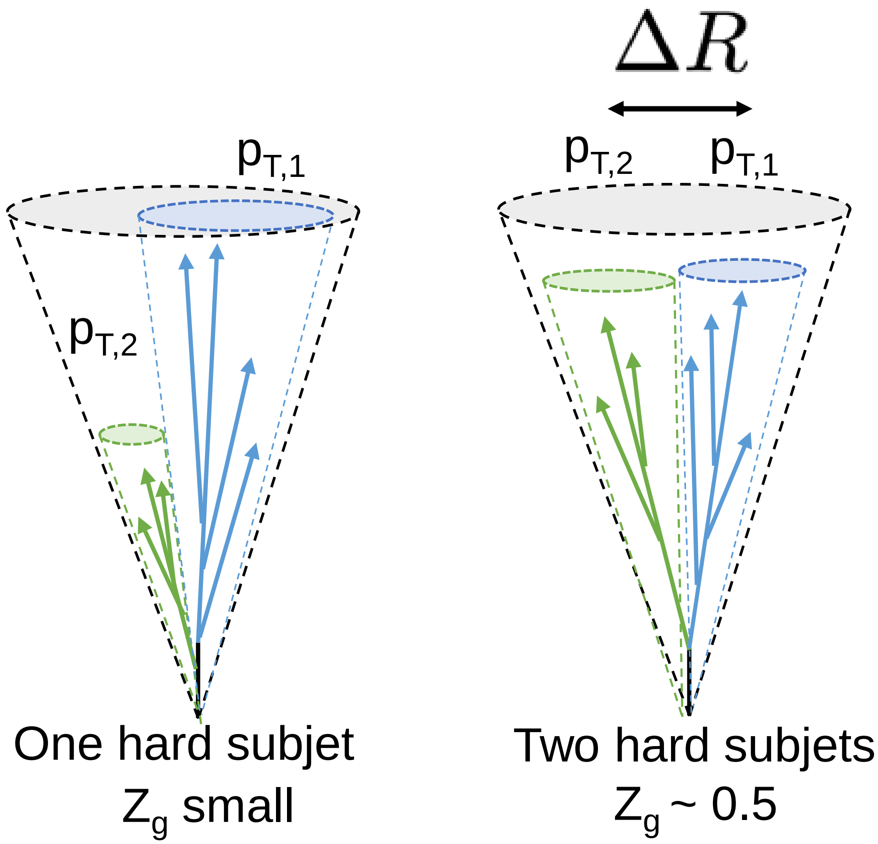


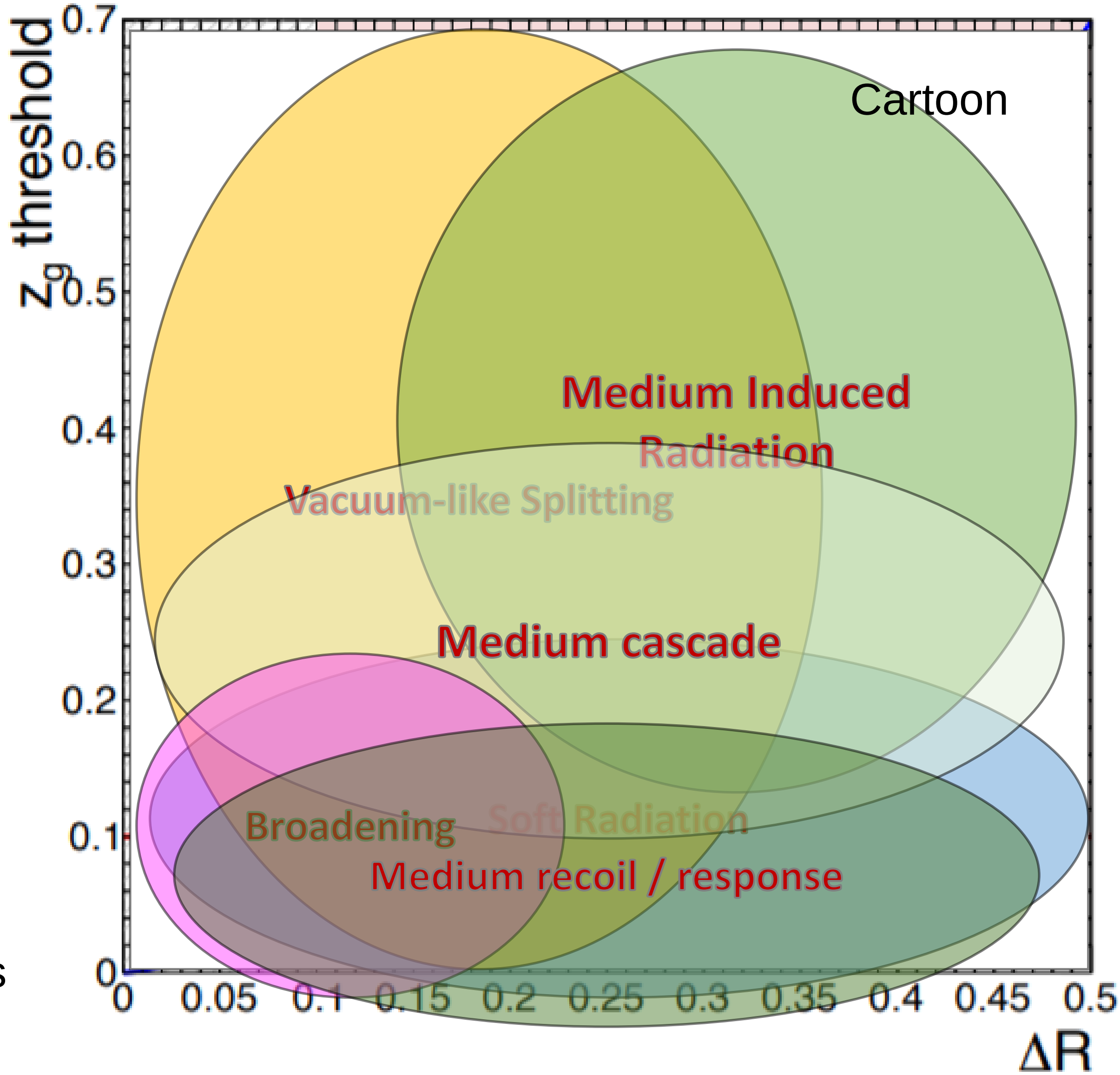
Ideal world, different phase space correspond to different physics

Z_g vs. ΔR Phase Space

Momentum Sharing of Subjets

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

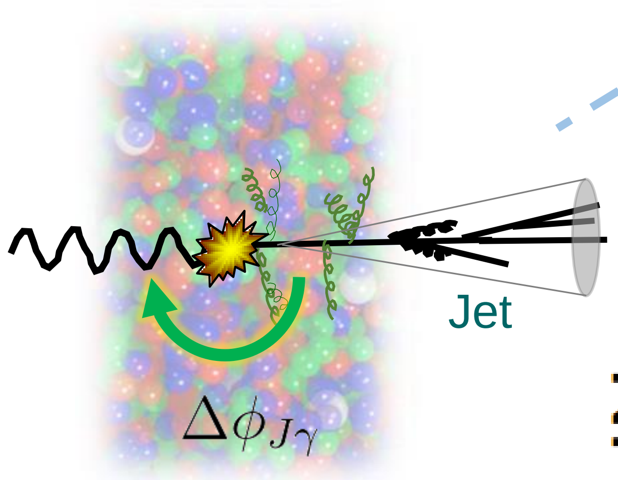


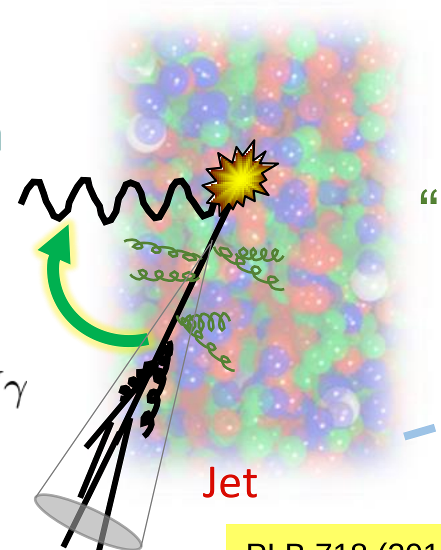


- **The reality may be much more complicated than that**
- The excitement: One could construct different observables which are sensitive to different part of the phase space and provide stress test on models

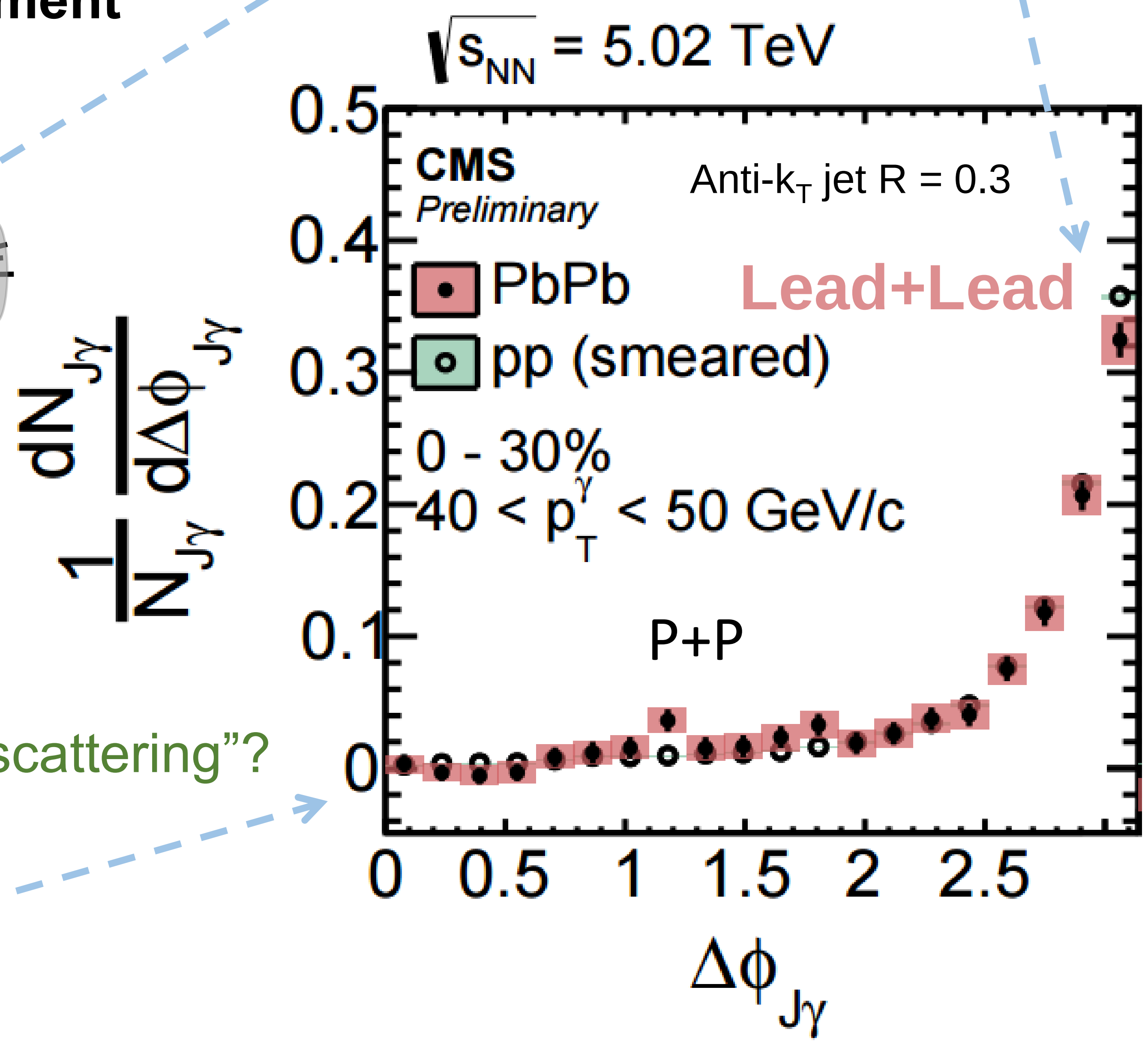
Search for Quasi-Particles in the QGP

"QGP Rutherford experiment"





"Backscattering"?



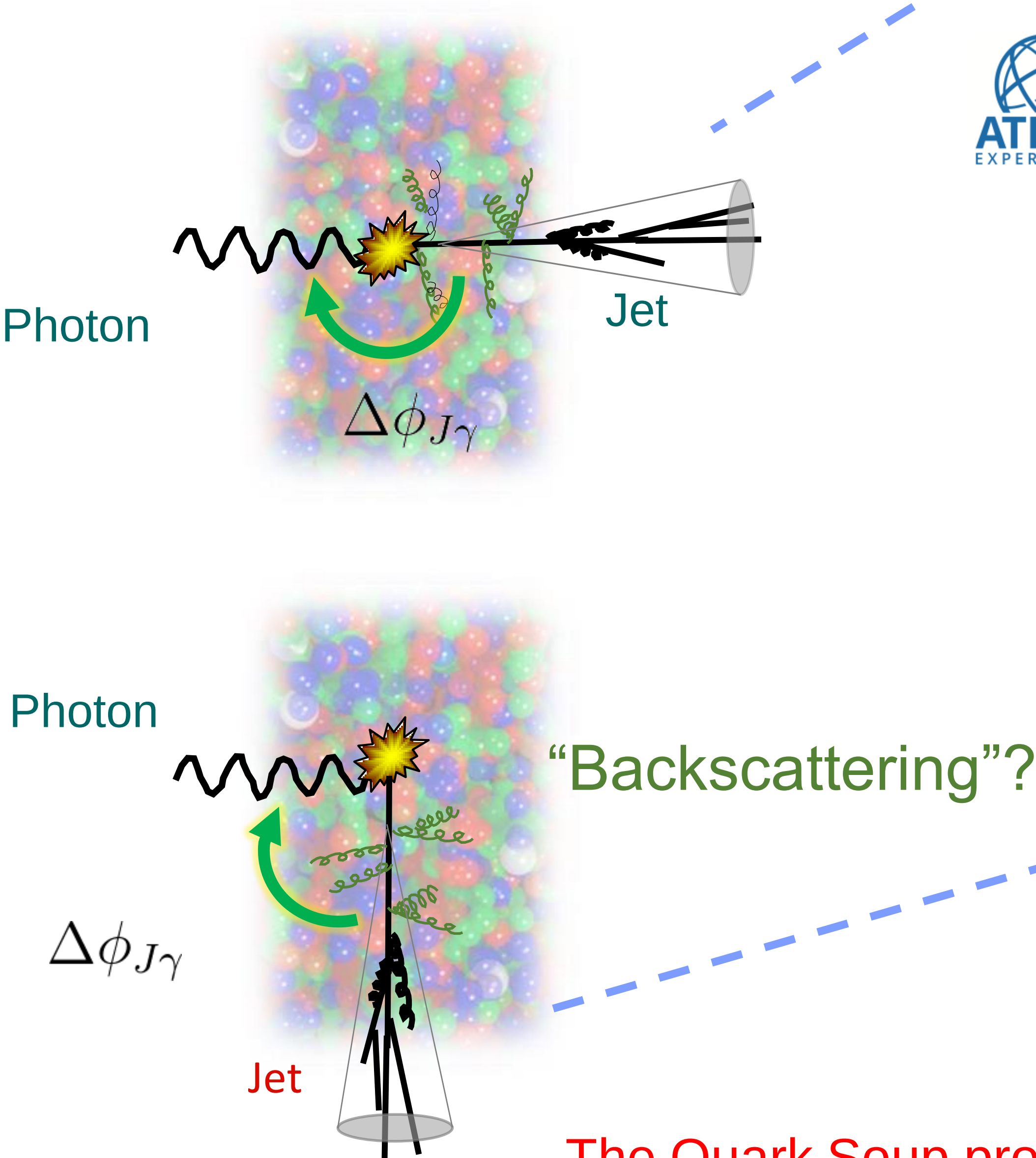
PLB 718 (2013) 773

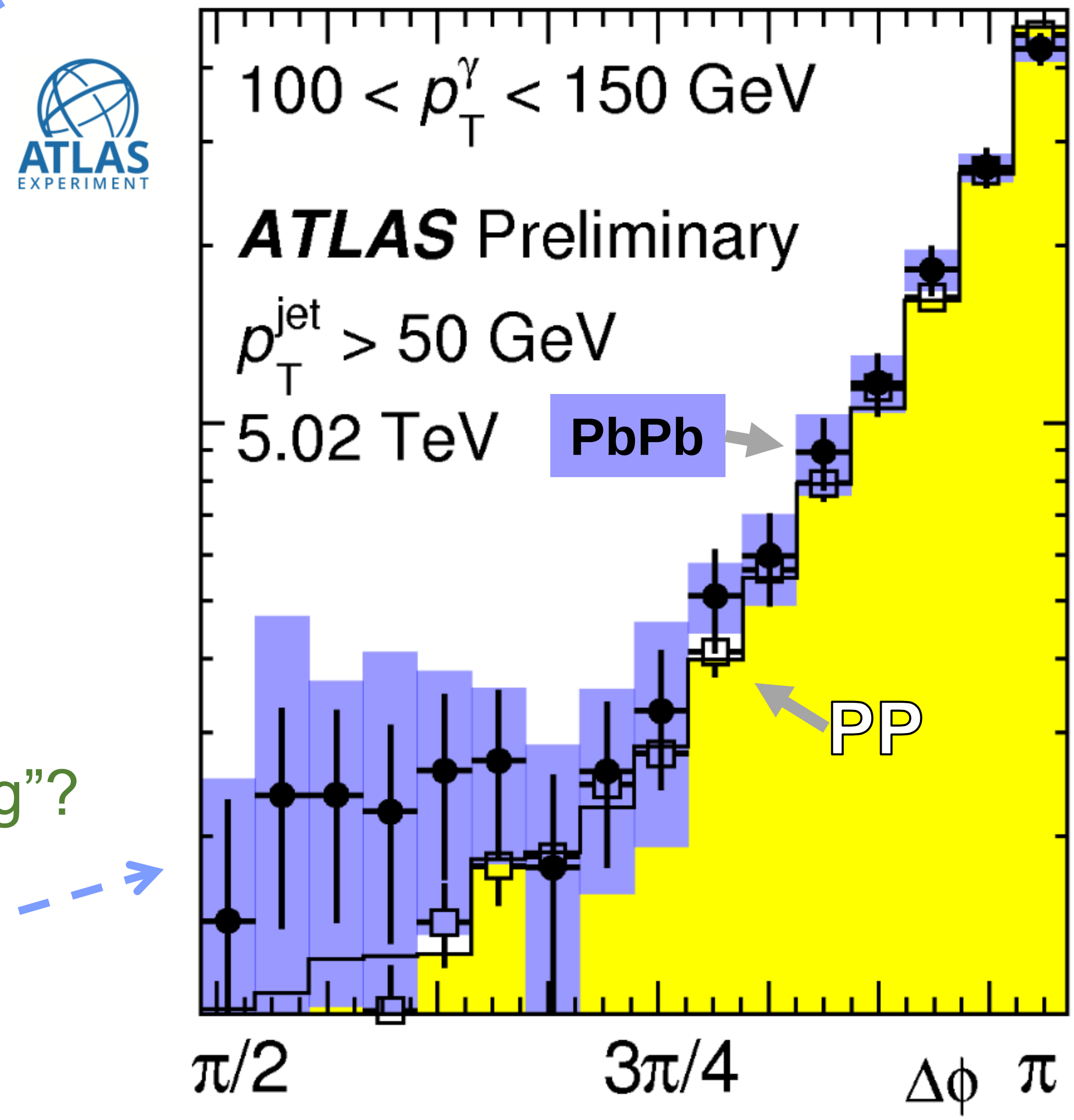
CMS-PAS-HIN-16-002 (2017)

The Quark Soup probed is very smooth!

Search for Quasi-Particles in the QGP

"QGP Rutherford experiment"

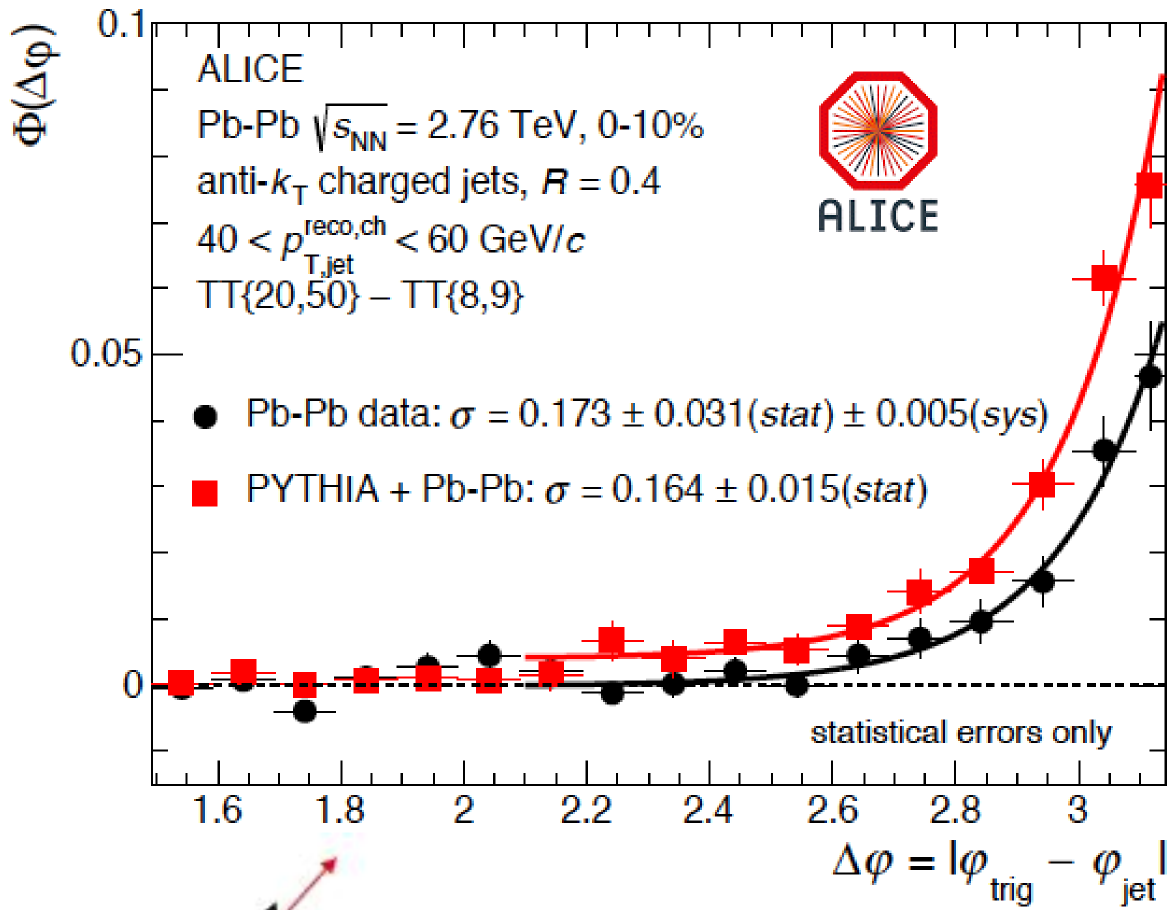


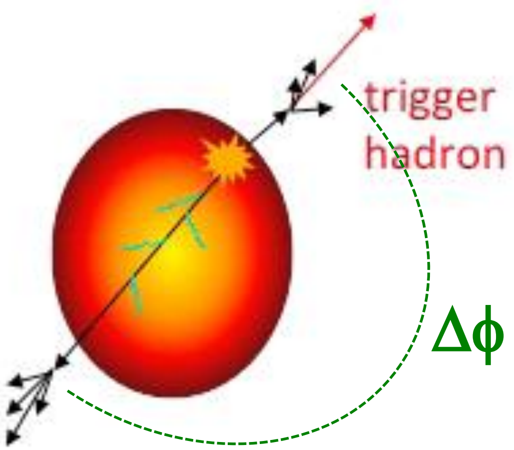


The Quark Soup probed is very smooth!

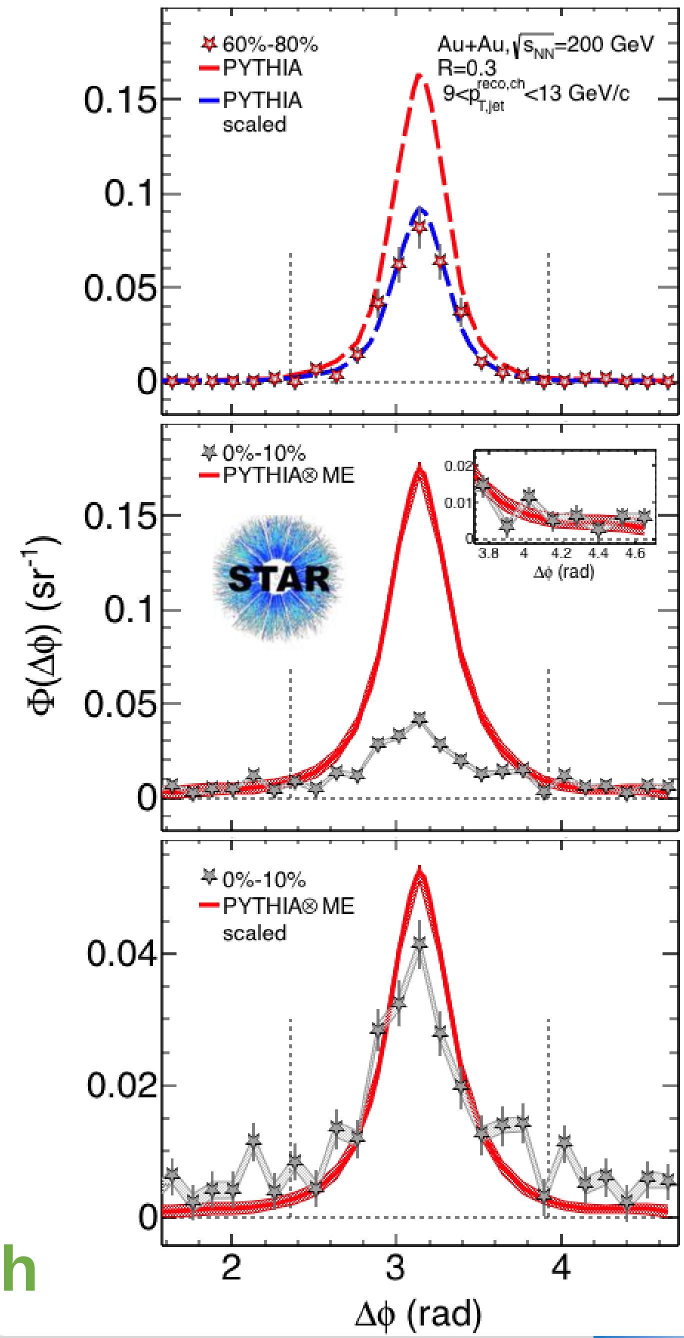
ATLAS-CONF-2016-110

QGP Rutherford Experiment





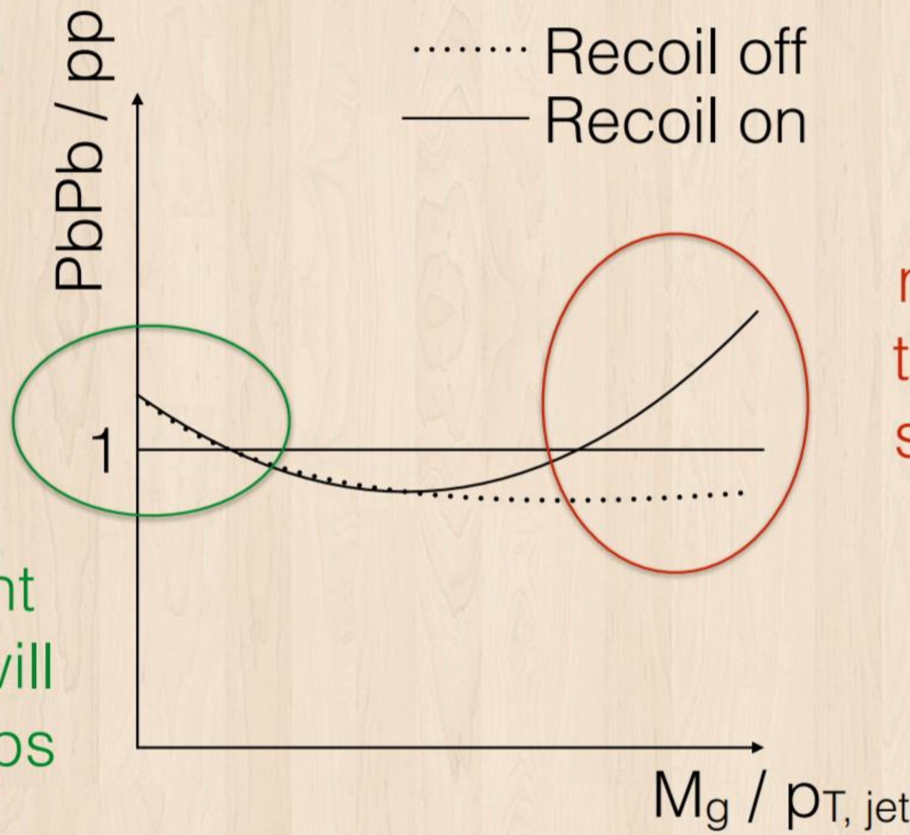
No significant broadening
(Also in LHC Photon-Jet,
Dijet measurements)
QGP probed looks **smooth**



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

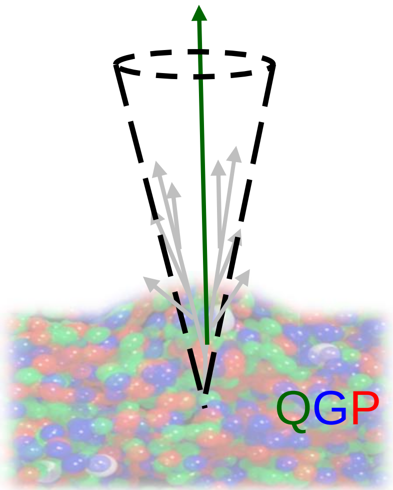


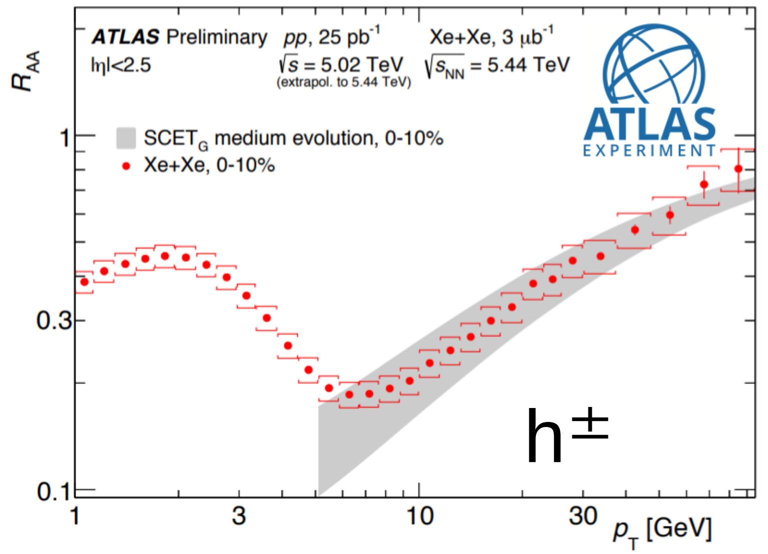
The rise in large mass tail is due to the recoil particles scattered at larger angles

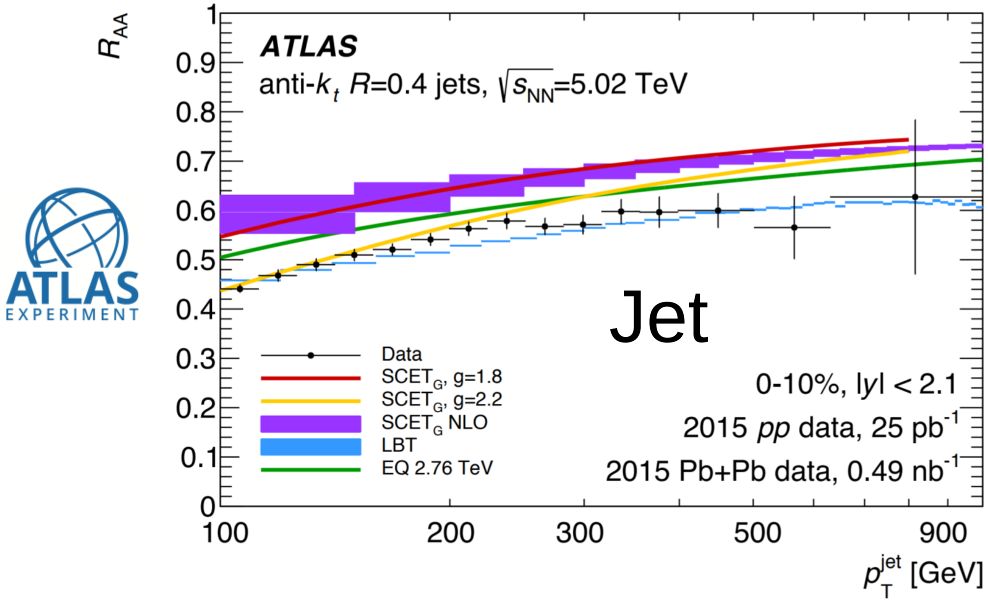
From Yi Chen (MIT)

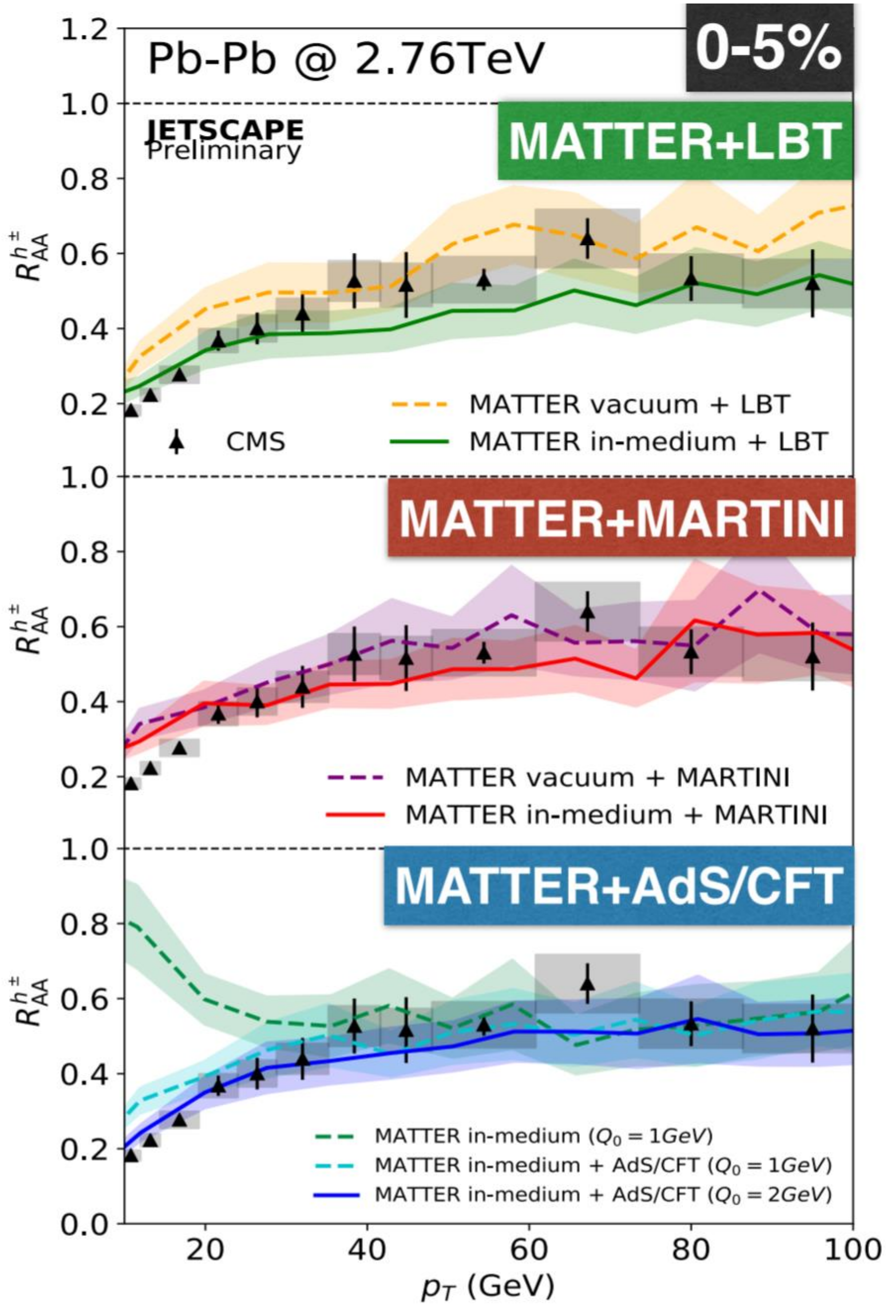
Moreover, groomed jet mass distributions in pp with CMS selection criteria are similar between quark and gluon jets (due to the ΔR cut)

Charged Particle and Jet R_{AA}



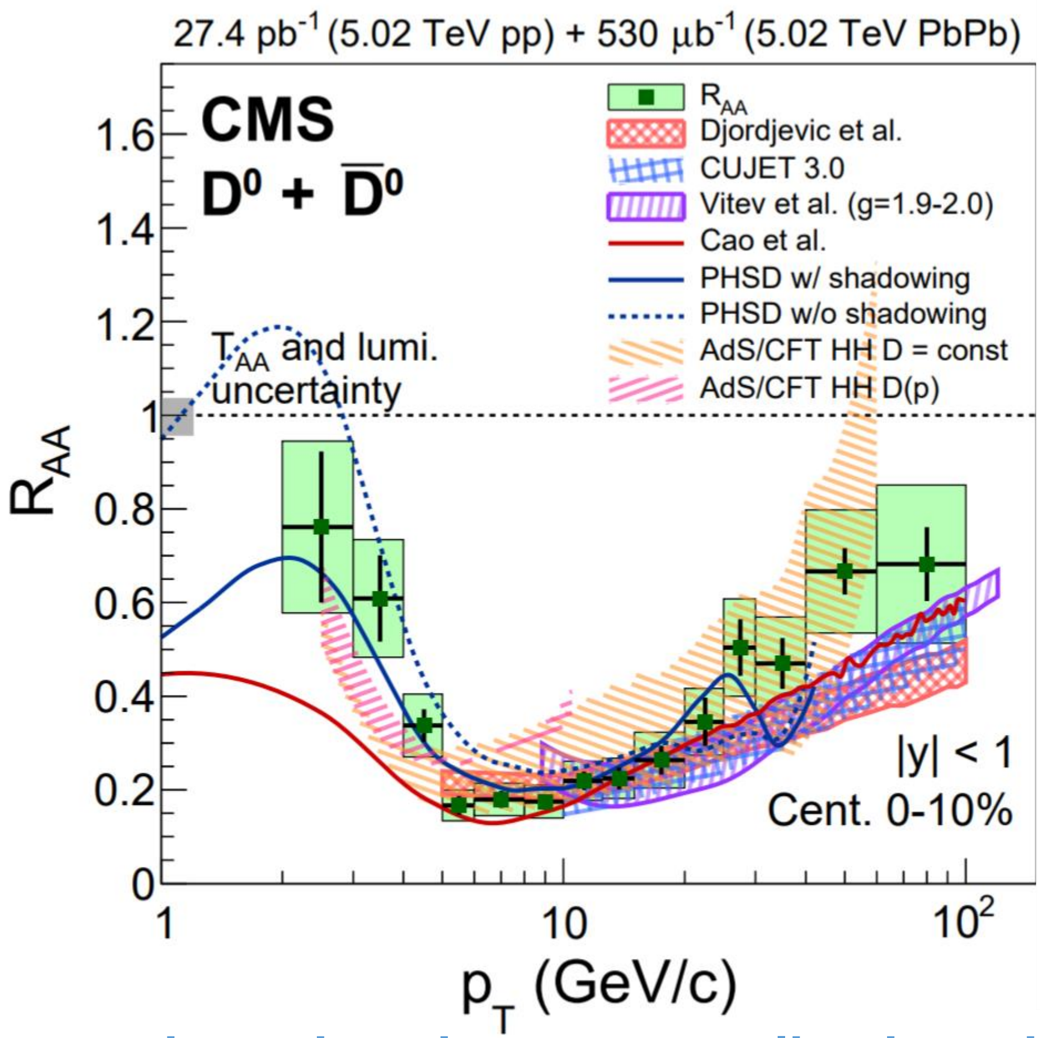


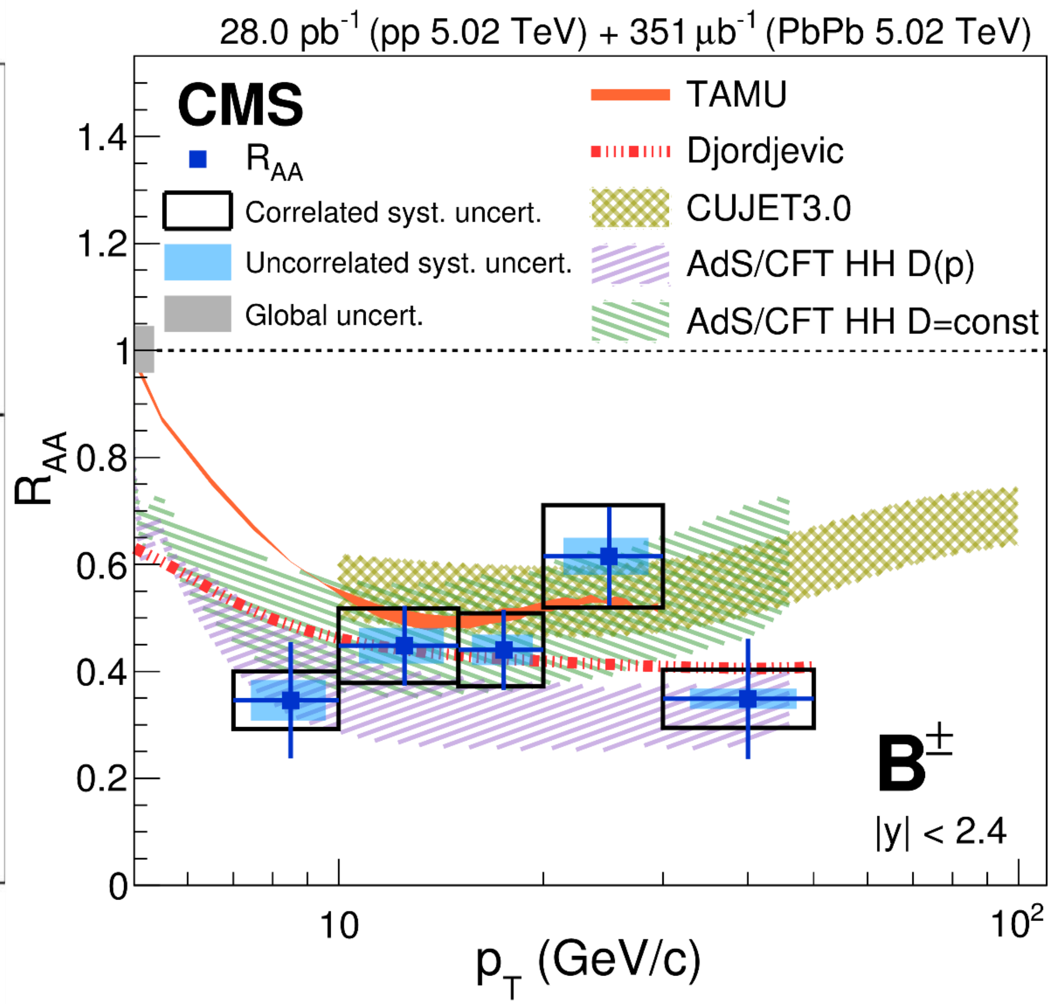




Impression: with tuning, models with different underlying physics could fit the data
(both strong and weak coupling calculations)

Heavy Flavor Meson R_{AA}





- **Both weak and strong coupling based models** describe the charged hadron, charm and beauty meson R_{AA} data
- Within pQCD world, models with very different level of complexity describe the data
- No significant difference between beauty and inclusive (di-)jet results (not shown, need better accuracy)