Jet Quenching at the LHC

Yen-Jie Lee (MIT)

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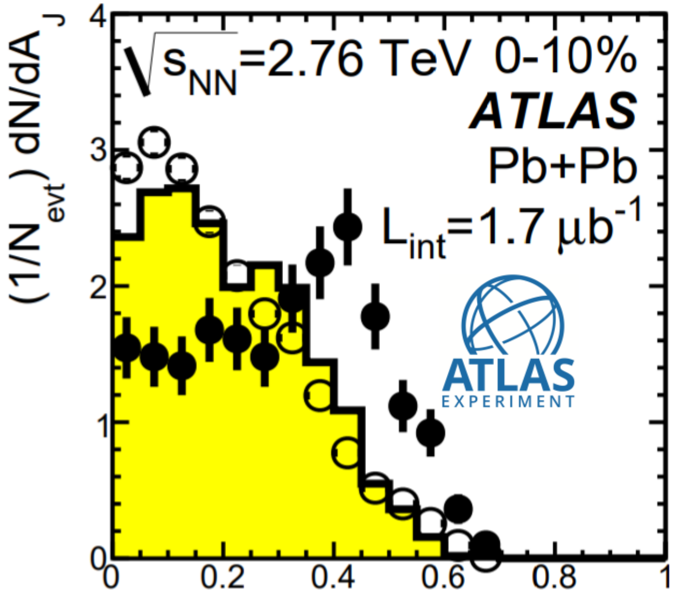
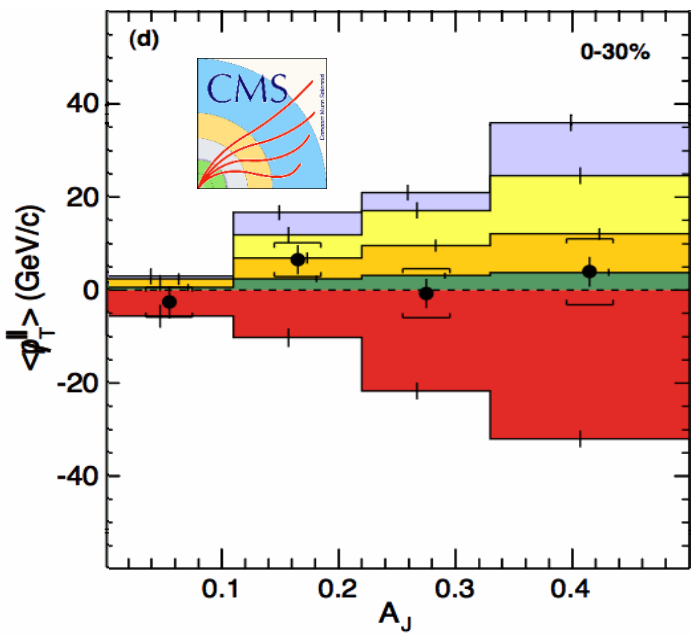
MIT HIG group's work was supported by US DOE-NP

Big Questions to be Addressed with Jets



PRL 105 (2010) 252303

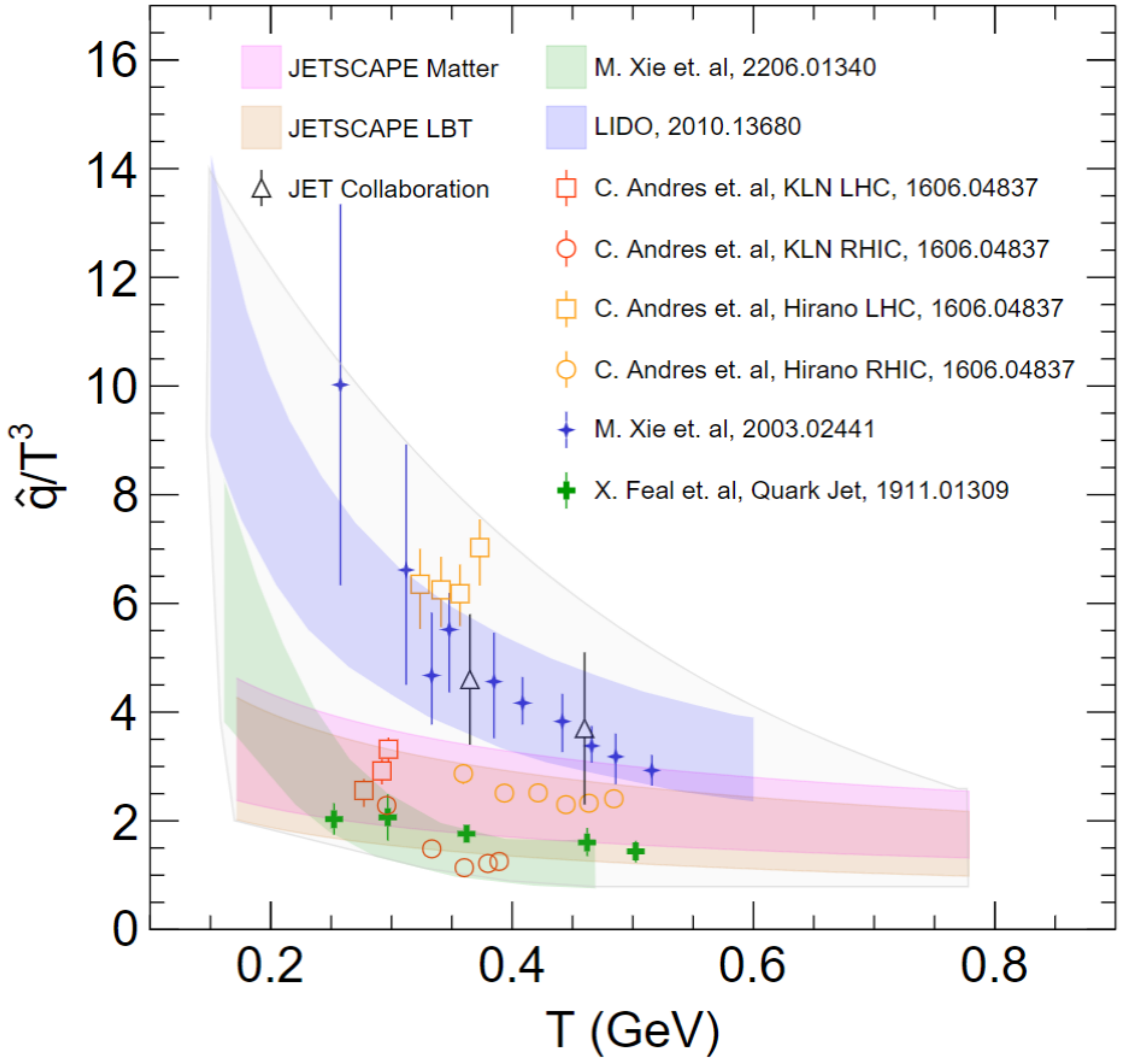


- Extract medium transport properties through jet quenching
  - Scattering power of the QGP
  - Compare to soft probes
- Resolve the constituents of QGP
- Inspect the hard probe induced medium response
- Gain insights into hydrodynamization and hadronization

PRC 84 (2011) 024906

PLB 712 (2012) 176

QGP Transport Properties with RHIC and LHC Run 2 Data



Compilation by YJL, Michael Winn, Liliana Apolinario arXiv:2203.16352

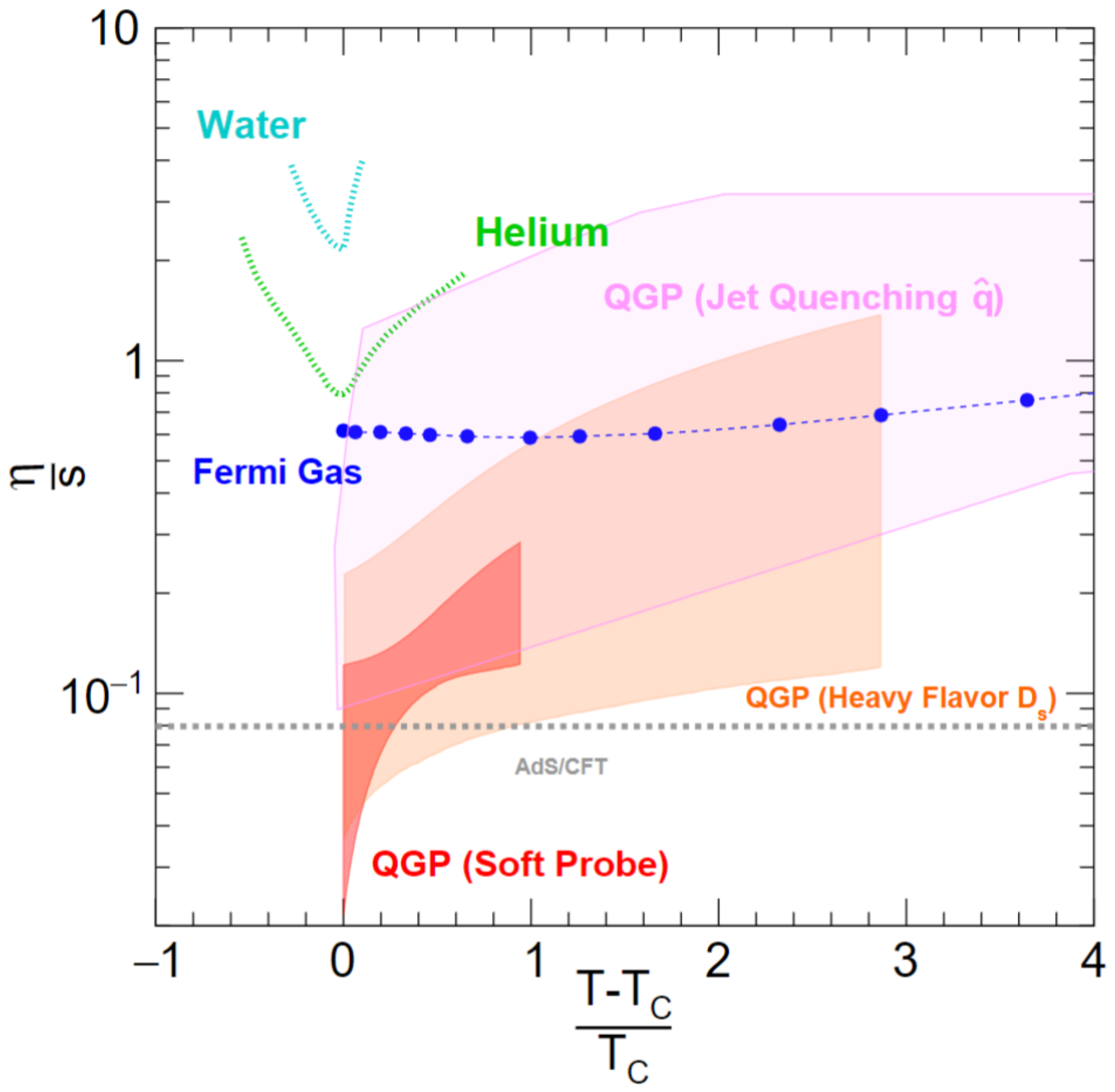
Jet Quenching Parameter $\hat{q}$

- Extracted **mainly** from charged hadron spectra R_{AA} data
  - Xin-Nian's group has extended the list to dihedron and photon hadron
- Decreasing trend vs. T
- Extracted values differ by up to a factor of 5

Remaining Issues:

- Different jet quenching mechanisms in theoretical models
- Different QGP media used in various calculations
- Hadronization of fast moving partons

Medium Properties from Soft and Hard Probes



Compilation by YJL, Michael Winn, Liliana Apolinario arXiv:2203.16352

Specific viscosity has been extracted from soft probes

- Via identified hadron dN/dη, $<p_T>$, v_2, v_3 and v_4
- Main uncertainties from initial state and early time dynamics

To get the big picture of the QGP properties with Run 2 + RHIC data, one could compare the inputs from soft and hard probes:

- **HQ D_s** could be related to specific viscosity by

$$\frac{\eta}{s} = \frac{D_s(2\pi T)}{4\pi k}$$

R. Rapp, H. van Hees, 0903.1096
X. Dong, YJL, R. Rapp, 1903.07709

Where the scale factor k ranges between 1 (strong-coupling limit) and 2.5 (weak coupled)

- **Jet quenching parameter $\hat{q}$** could be related to specific viscosity in the limit of multiple soft scattering by

$$\frac{\eta}{s} = C\frac{T^3}{\hat{q}}$$

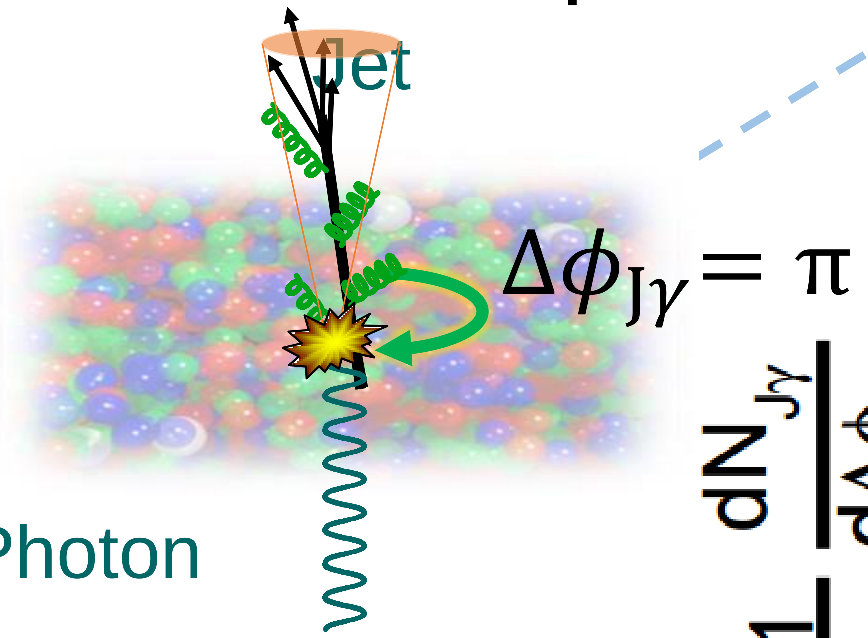
Where the scale factor C is varied between 1.25 and 2.5

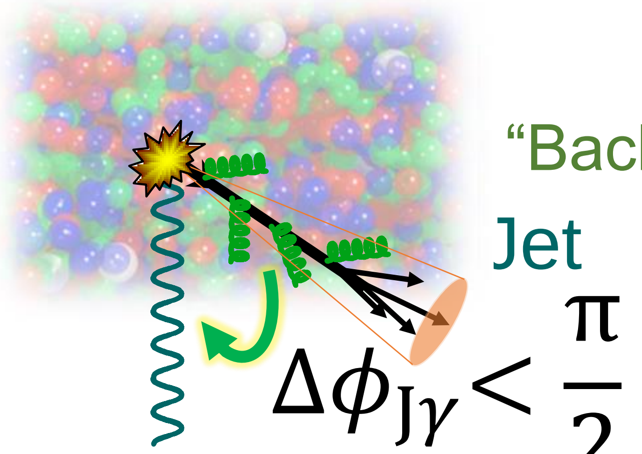
A. Majumder, B. Muller, Xin-Nian Wang PRL 99 (207) 192301
B. Muller PRD 104 (2021) 7, L071501

QGP properties extracted from **hard probes are consistent with the results from soft probes, but within rather large uncertainties**

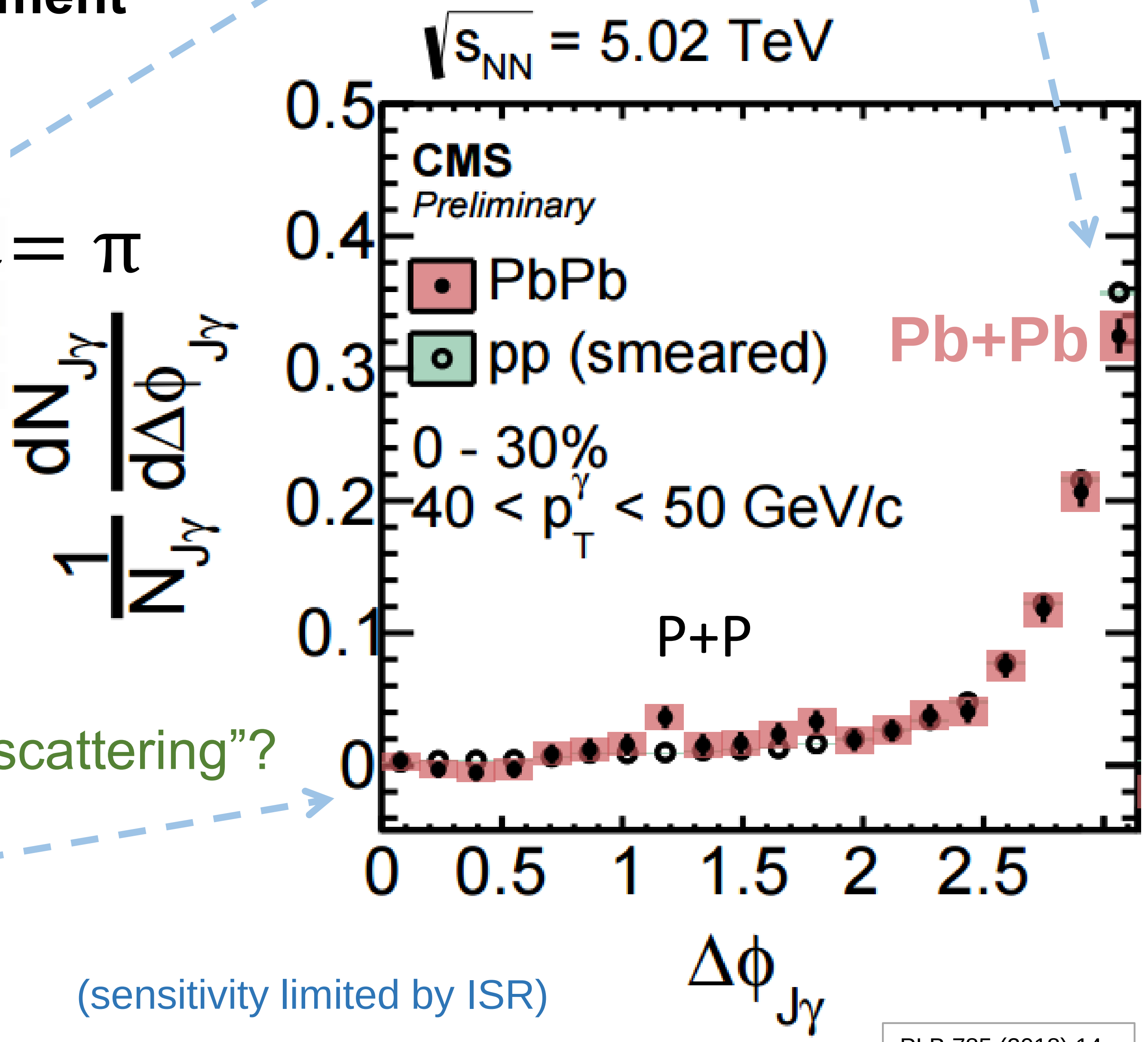
Search for Quasi-Particles in the QGP

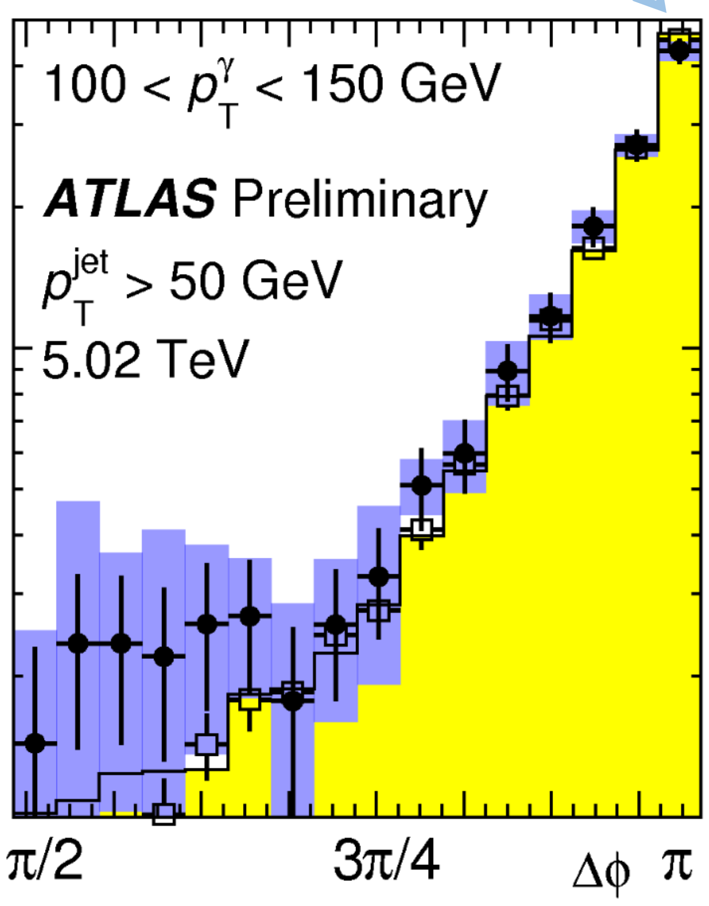
"QGP Rutherford experiment"





"Backscattering"?





(sensitivity limited by ISR)

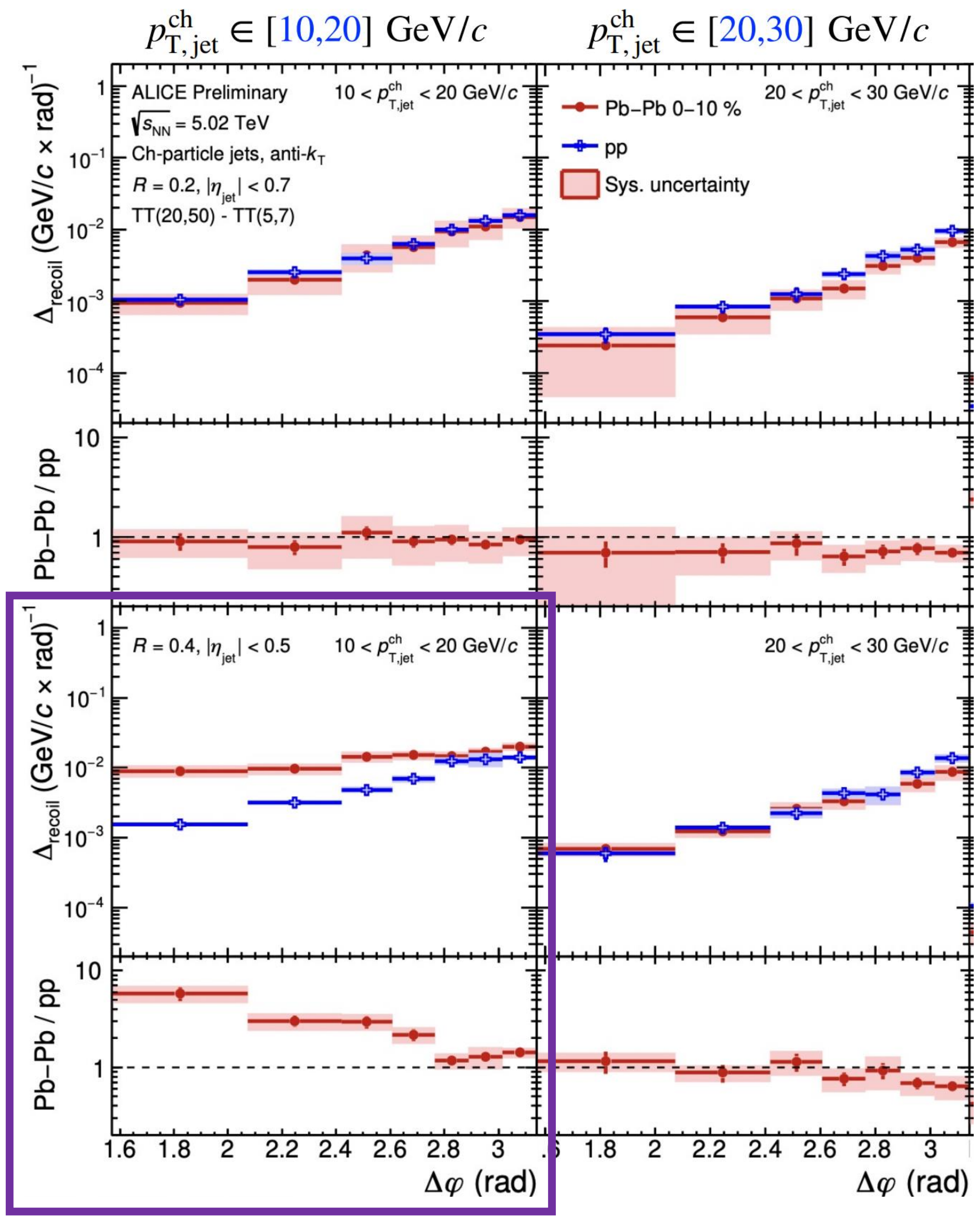
PLB 785 (2018) 14
PLB 718 (2013) 773

Hadron-Charged Jet Δφ in PbPb at 5 TeV

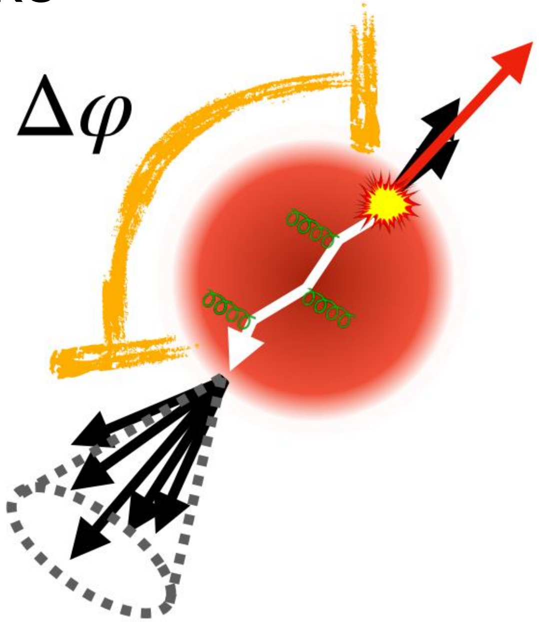
R. Cruz-Torres - QM22

R = 0.2

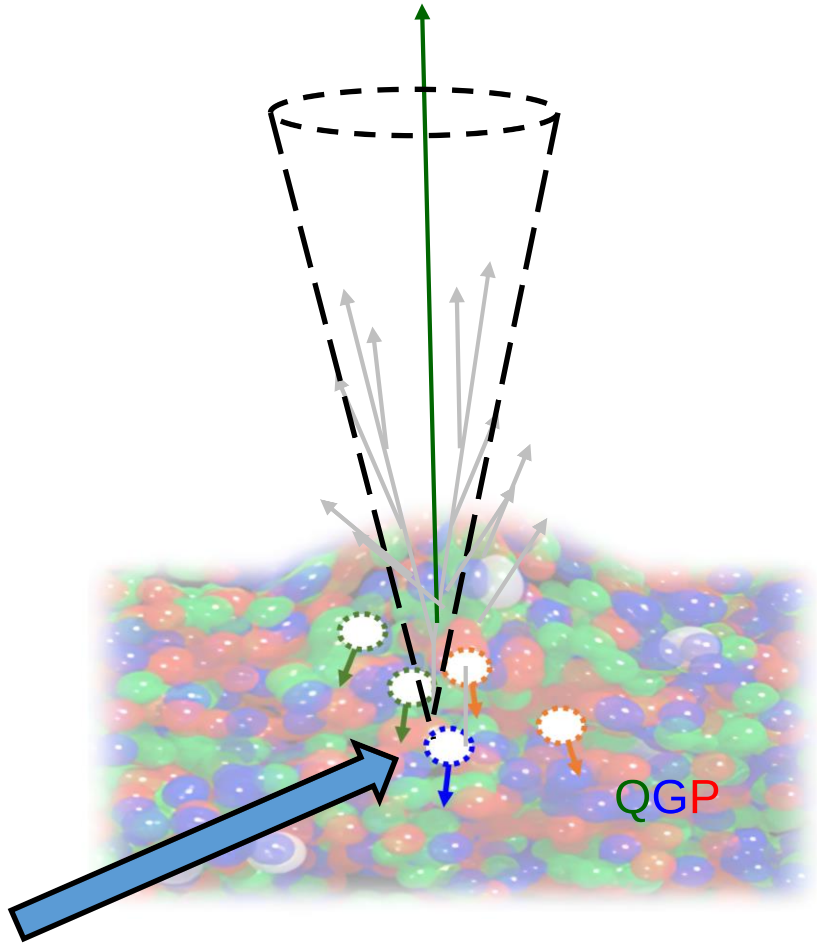
R = 0.4



- No modification with R=0.2 or at higher jet p_T
- Exciting modification of Δφ in Δ_{recoil} for **larger jet area** (R=0.4) and **low jet p_T** (10-20 GeV)!
  - Larger jet yield compared to pp
- **Likely from the wake contribution**
  - Show up at large R and very low p_T
  - Flat jet shape from clustered wake
  - Hybrid model: mainly wake
- **Contribution from ISR and MPI?**
  - MPI: Xin-Nian Wang's group
    PRL 127 (2021) 8, 082301
  - ISR: Korinna Zapp's talk



Parton Flavor Dependence of Parton Energy Loss

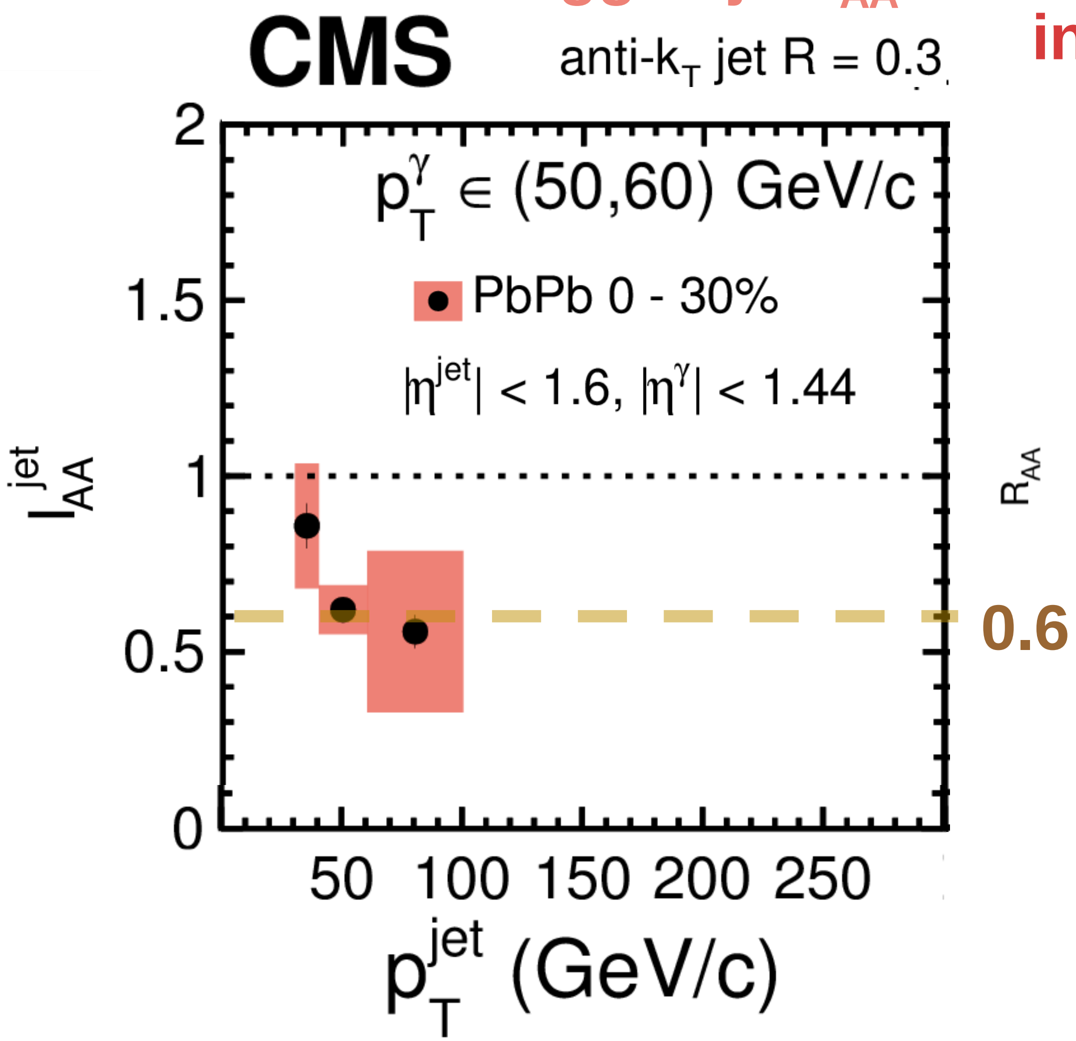


Do gluons lose more energy than the quarks?

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

Photon-tagged Jet R_{AA} vs. Inclusive Jet

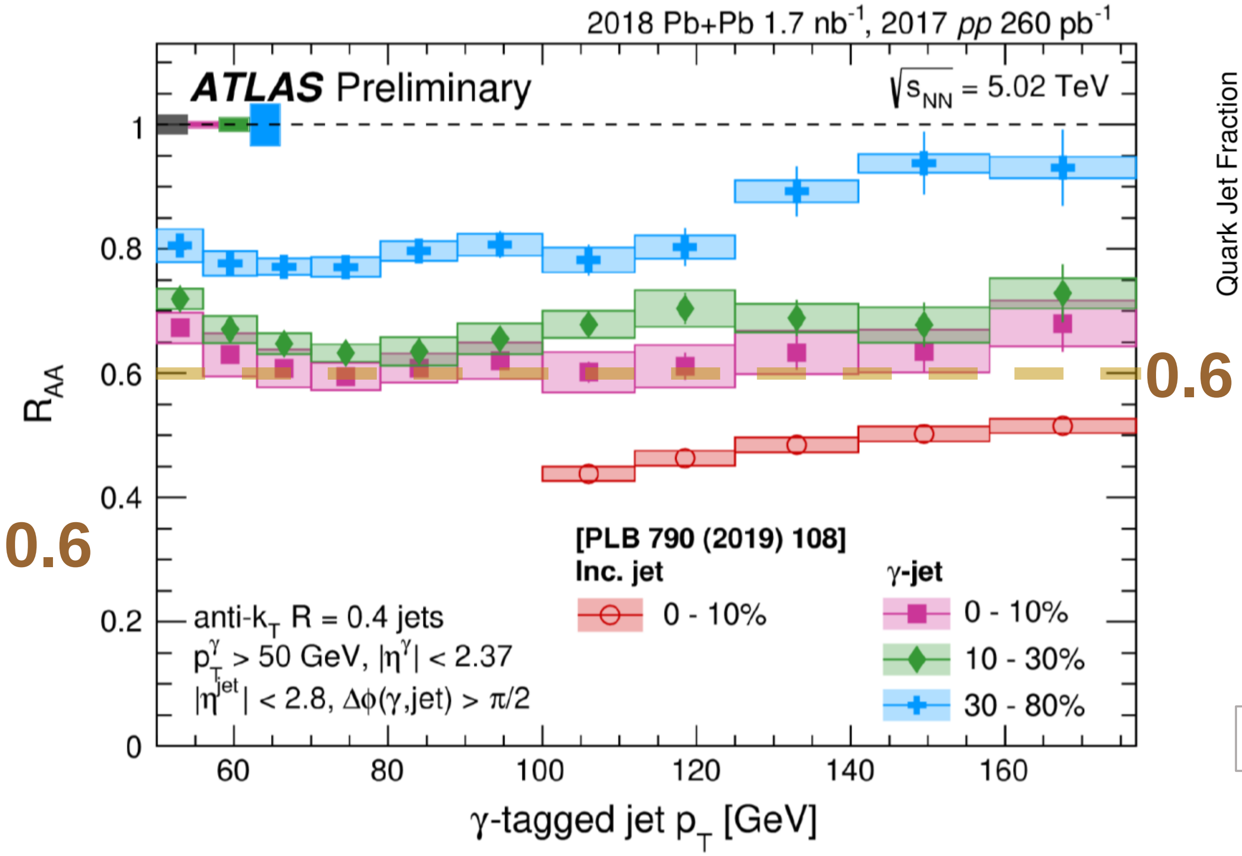
Photon-tagged jet I_{AA}

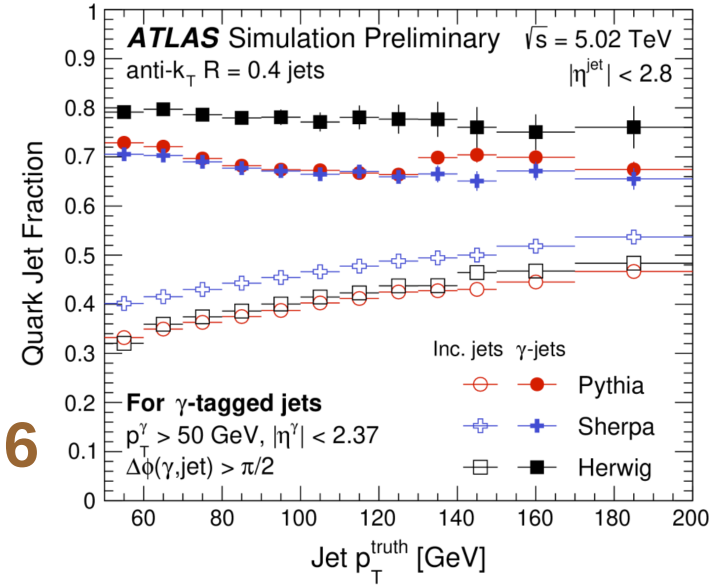


PLB 785 (2018) 14

Photon-tagged jet (Quark fraction ~ 70-80%)

inclusive jet (Quark fraction ~ 30-40%)



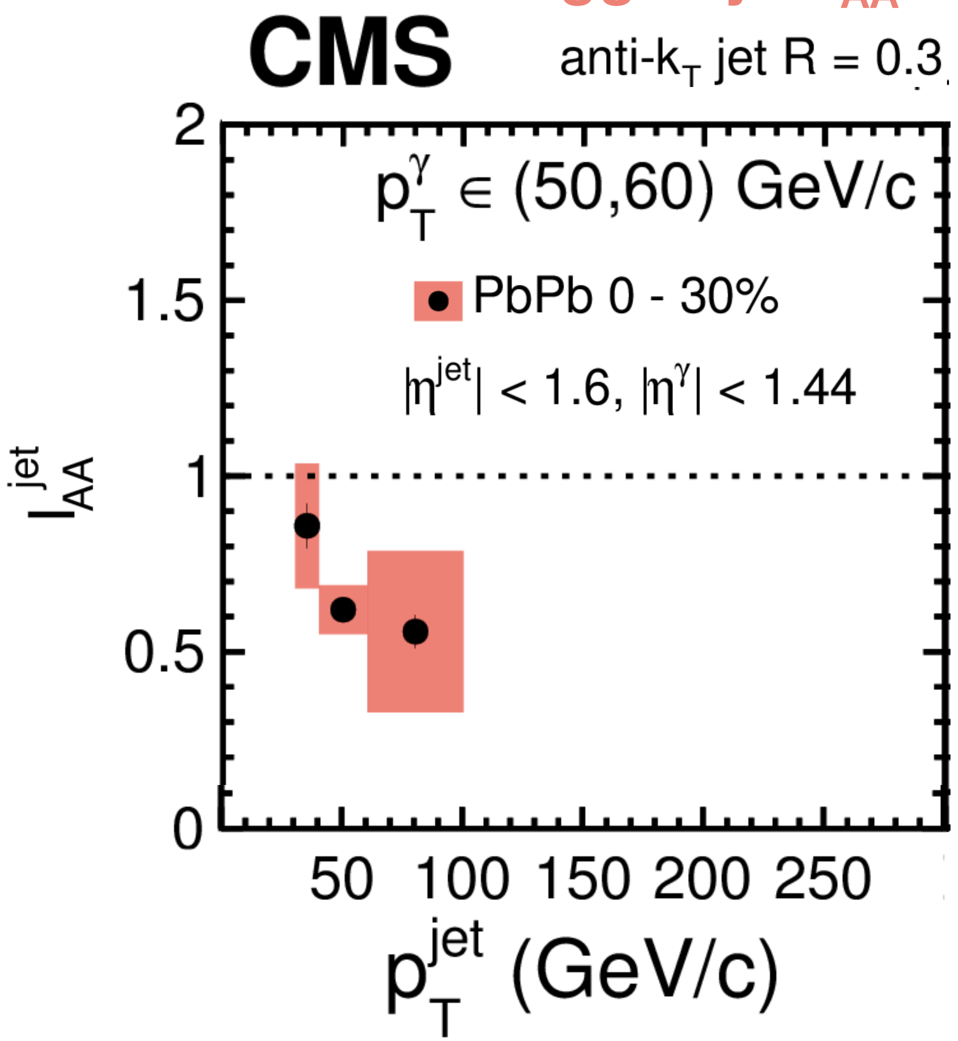


Inclusive jet PLB 790 (2019) 018

- Photon-Jet: CMS I_{AA} ~ ATLAS R_{AA} ~ **0.6**
- Photon-tagged jet R_{AA} > inclusive jet R_{AA}

Photon-tagged Jet R_{AA} vs. Inclusive Jet

Photon-tagged jet I_{AA}



PLB 785 (2018) 14

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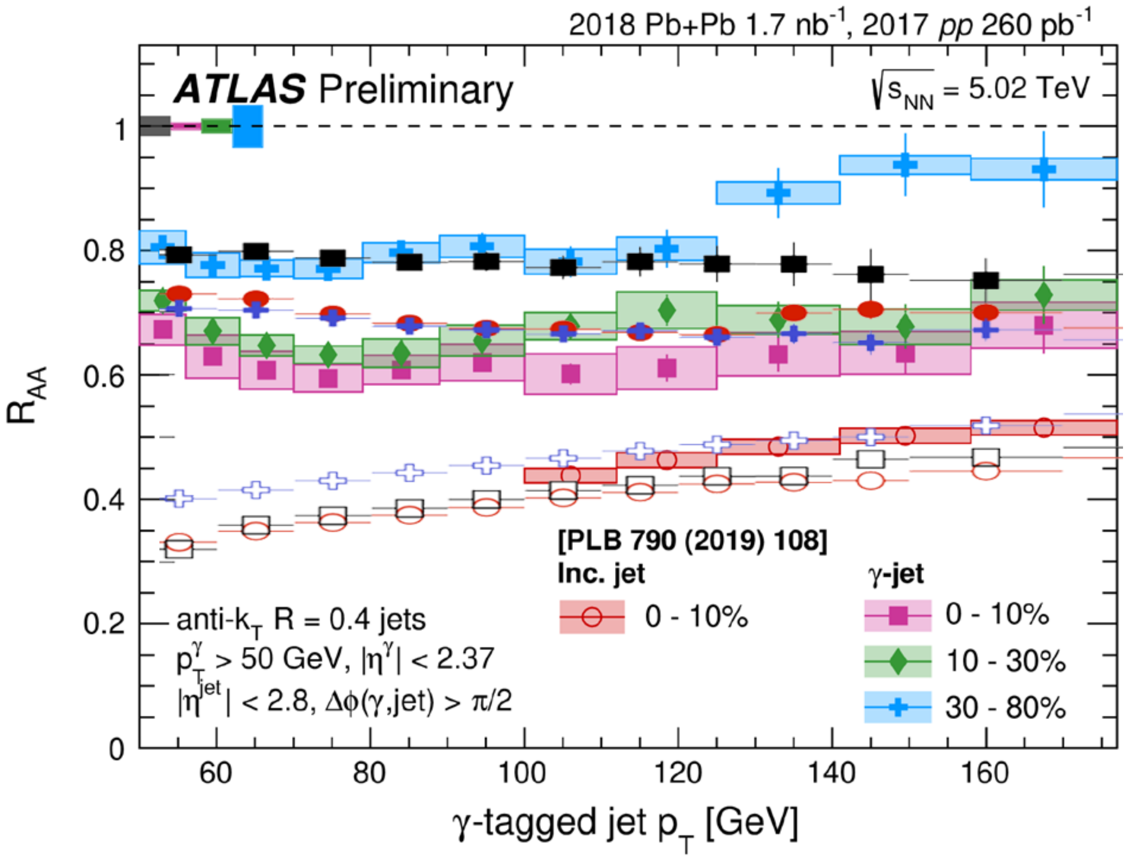
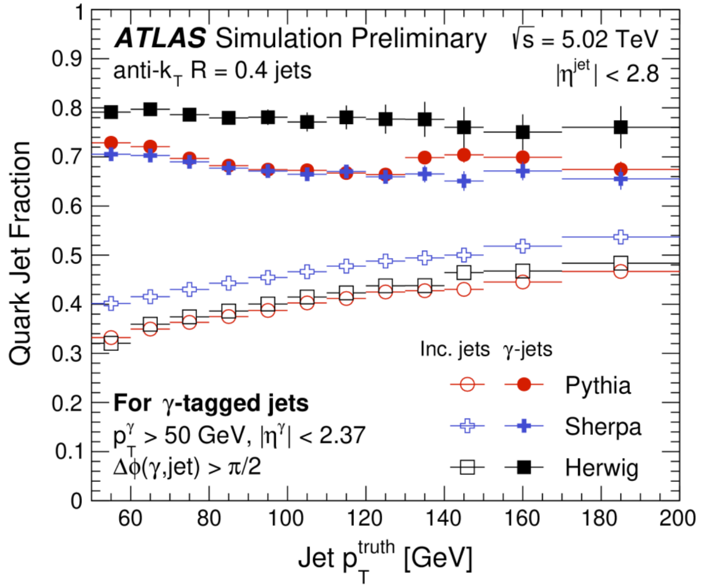


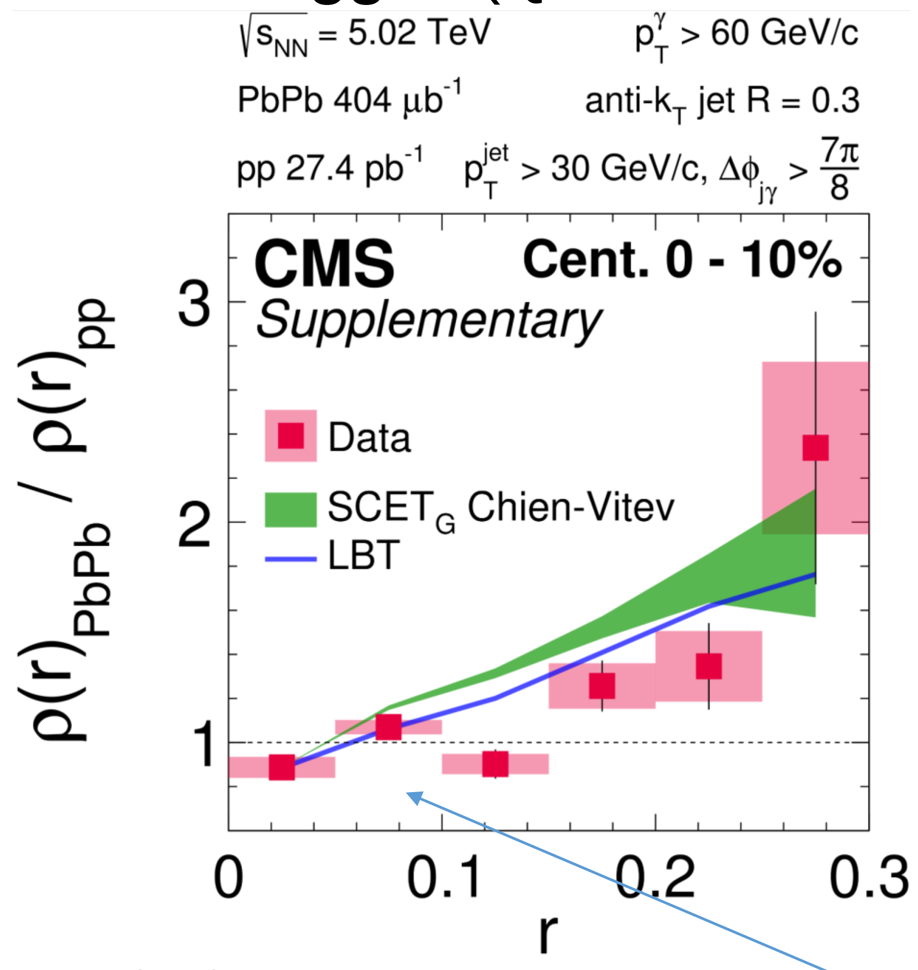


Inclusive jet PLB 790 (2019) 018

- Photon-Jet: CMS I_{AA} ~ ATLAS R_{AA} ~ **0.6**
- Photon-tagged jet R_{AA} > inclusive jet R_{AA}
- Photon-tagged and inclusive jet R_{AA} ~ Quark fraction in ATLAS Sherpa simulation

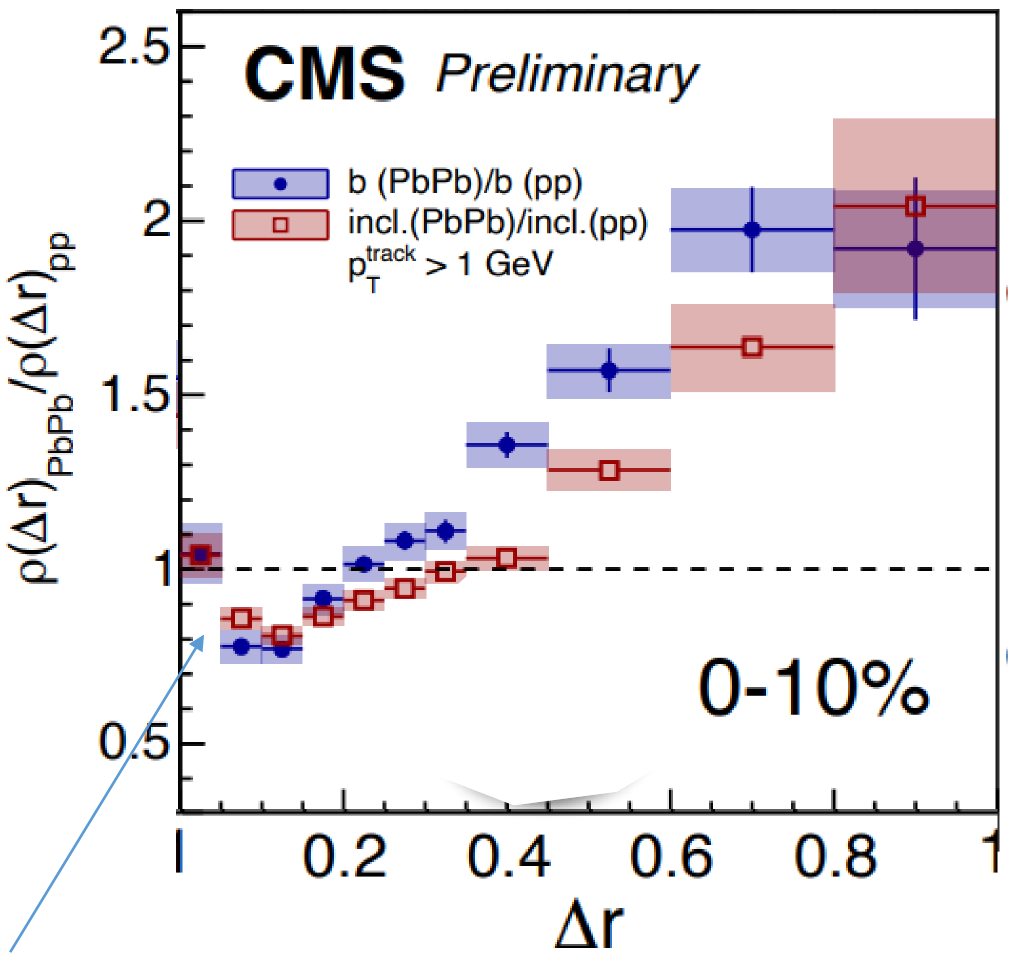
Photon-Tagged Jet and Inclusive Jet Shape

Photon-tagged (Quark Enriched)



PRL 122 (2019) 15, 152001

Inclusive (Quark + Gluon) & **b jet**



LBT: Xin-Nian Wang *et. al*

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

- 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

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

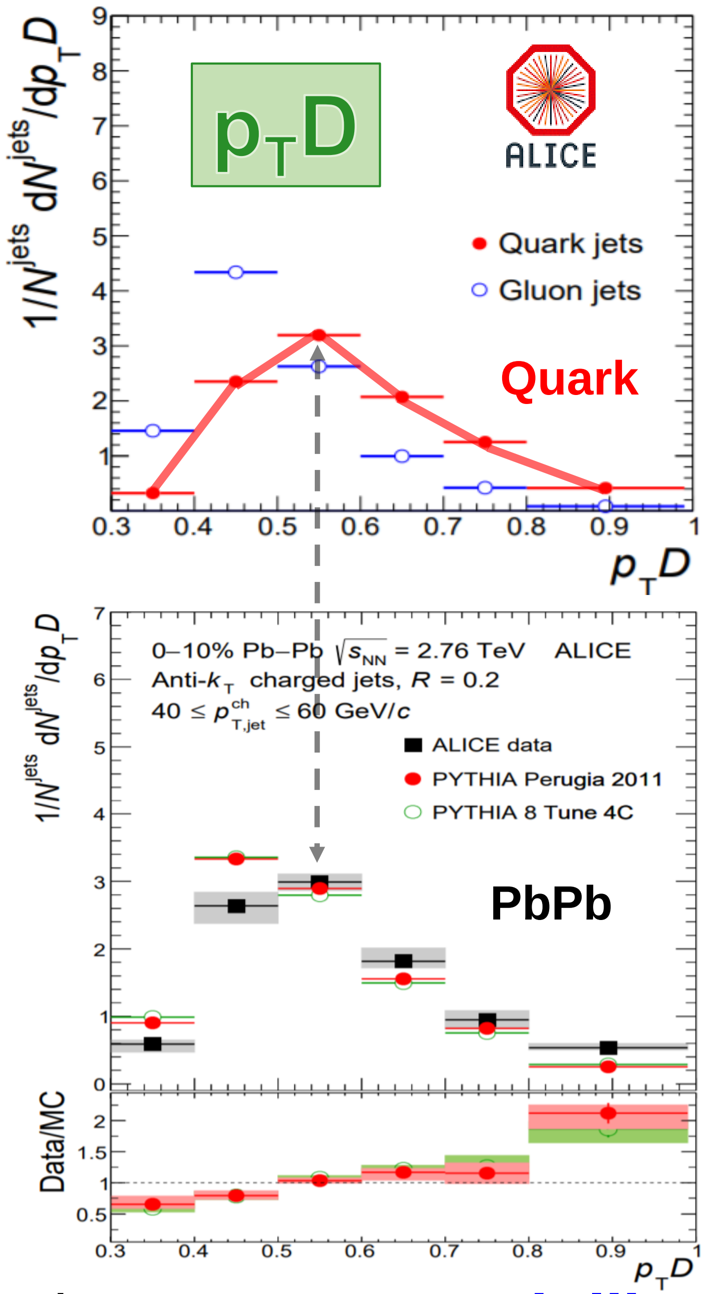
JHEP 10 (2018) 13

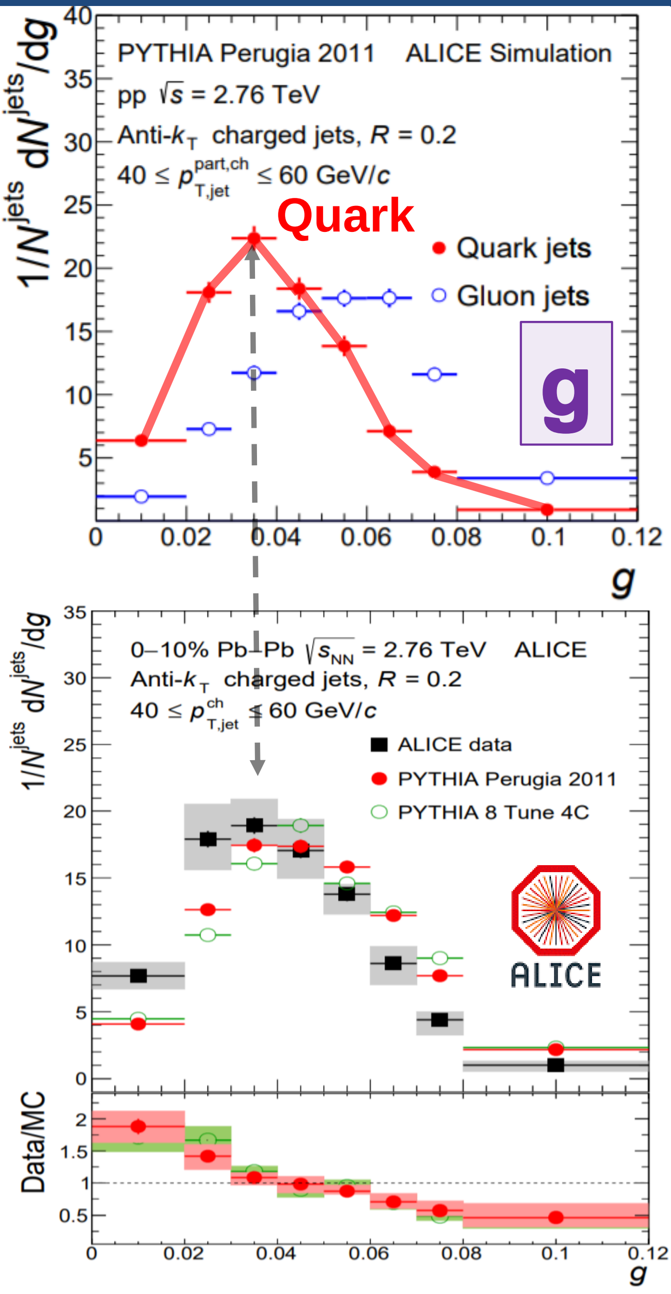
ALICE Simulation

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

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

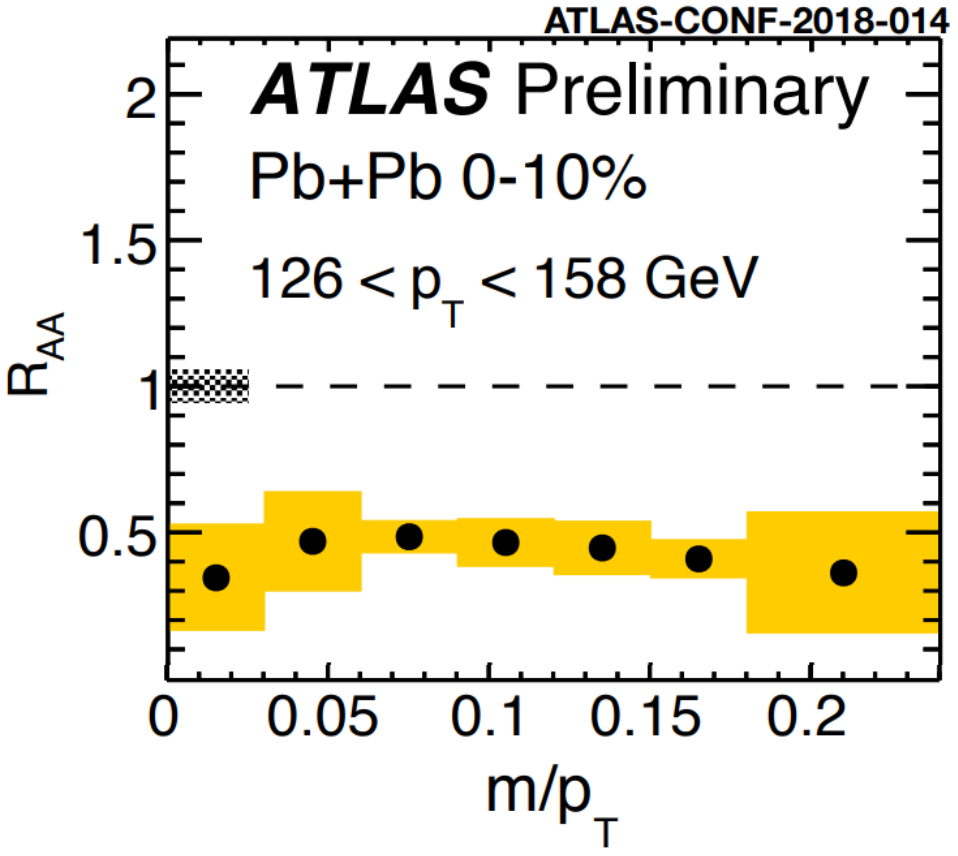
ALICE Data

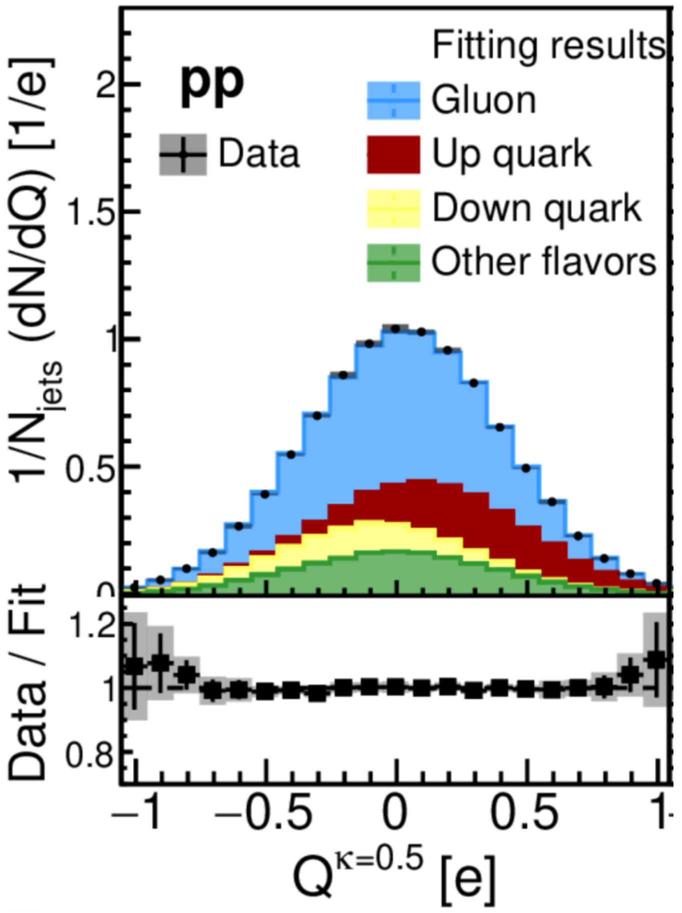




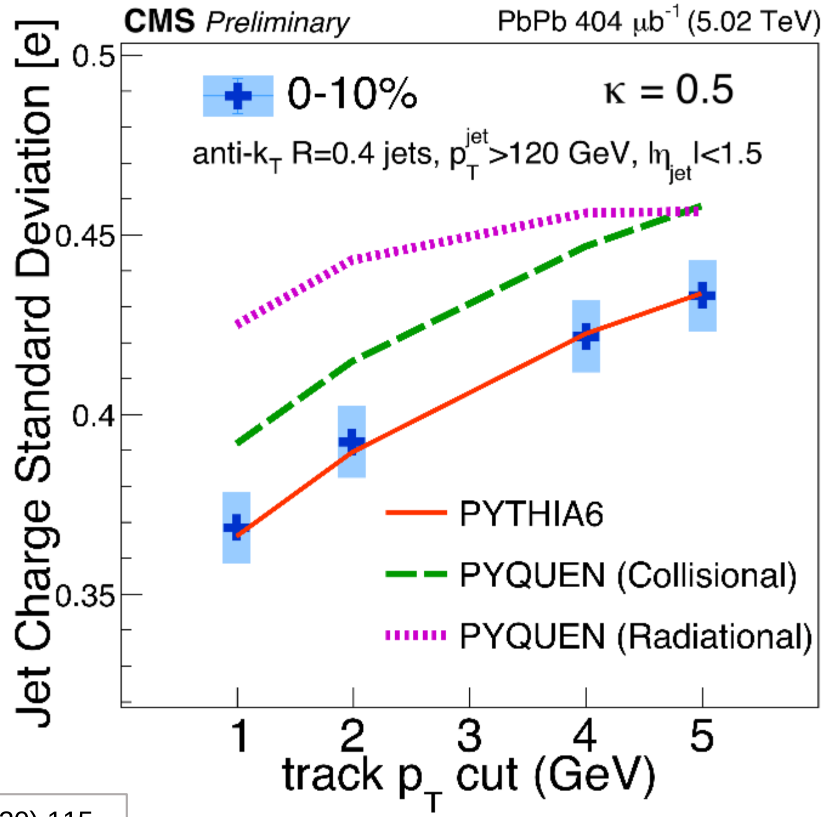
- Charged jets in PbPb are more **Quark-like** in those observables

Jet Mass and Some Puzzles in Jet Charge





JHEP 07 (2020) 115



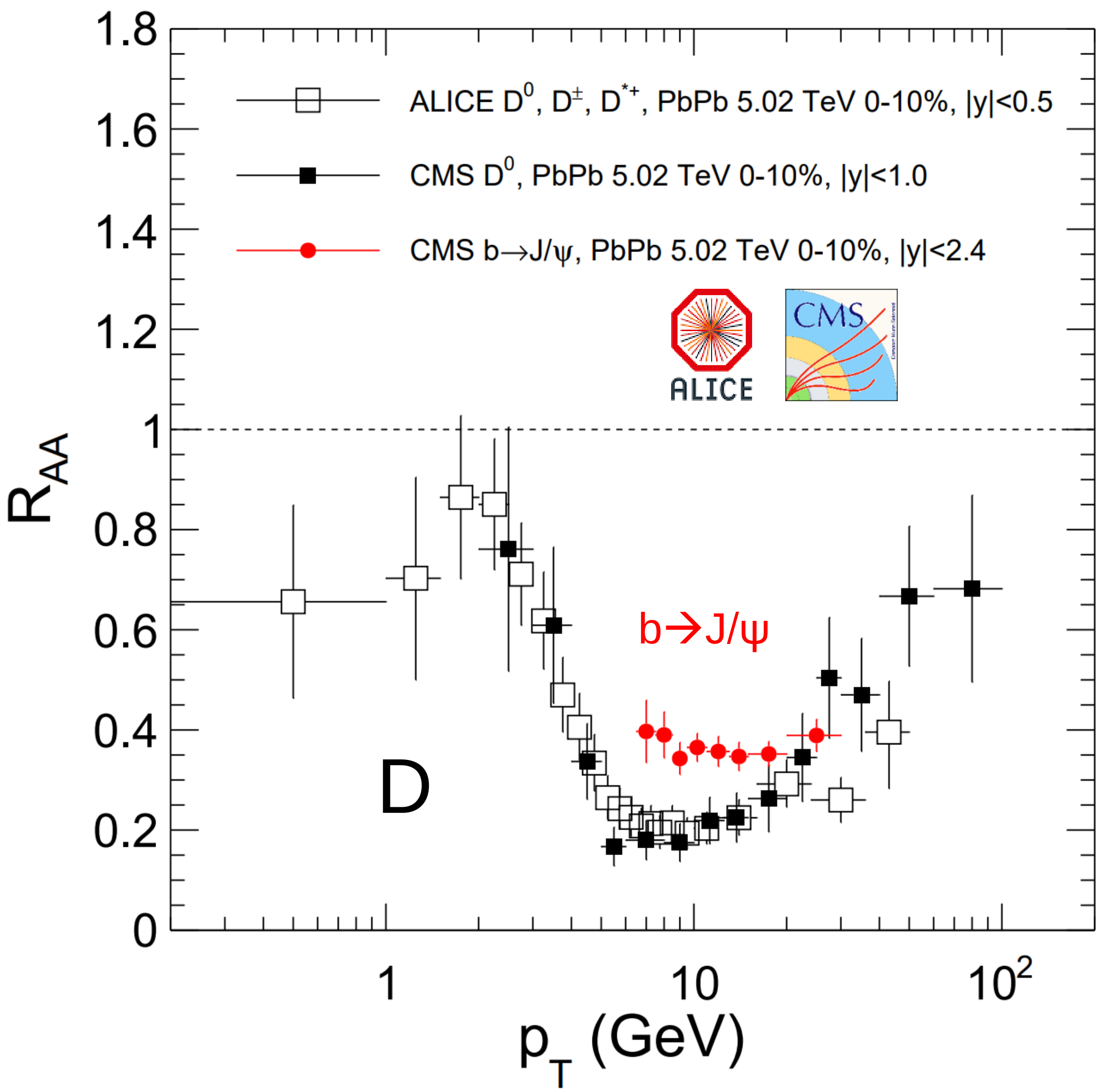
$$Q^\kappa = \frac{1}{(p_T^{\text{jet}})^\kappa} \sum_{i \in \text{jet}} q_i p_{T,i}{}^\kappa.$$

- **No modification of jet mass**
  - Cancellation of *narrowing* due to selection bias and *broadening* from medium response/wake in JEWEL and HYBRID
  - Modification observed in groomed jet mass

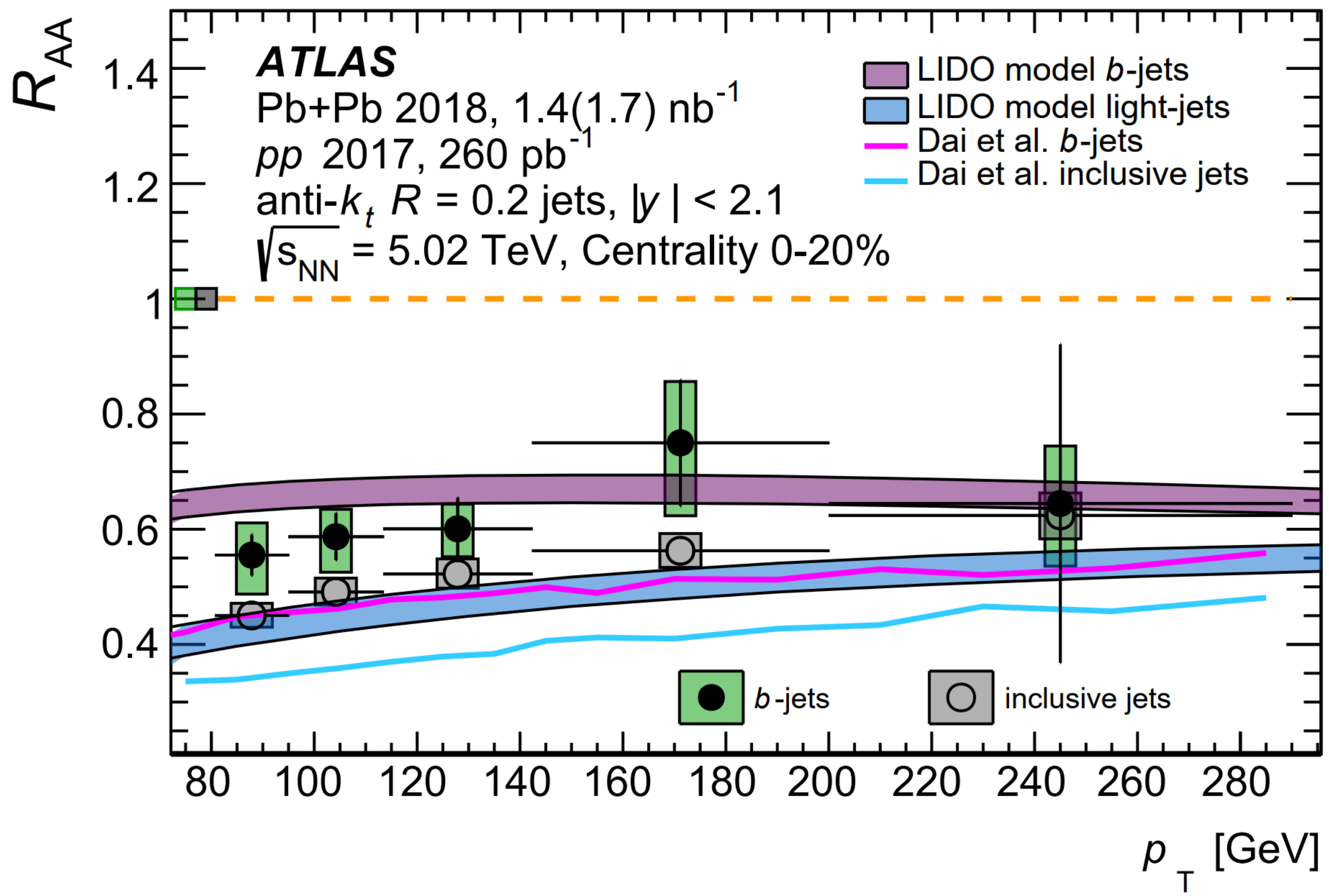
- **Gluon Q^k width narrower than Up+Down quark**
- Removing gluons will **increase** the jet charge width

- Jet charge width is unmodified
  - **Model independent**
  - **What's going on?**

Beauty vs. Charm vs. Light Flavor R_{AA}

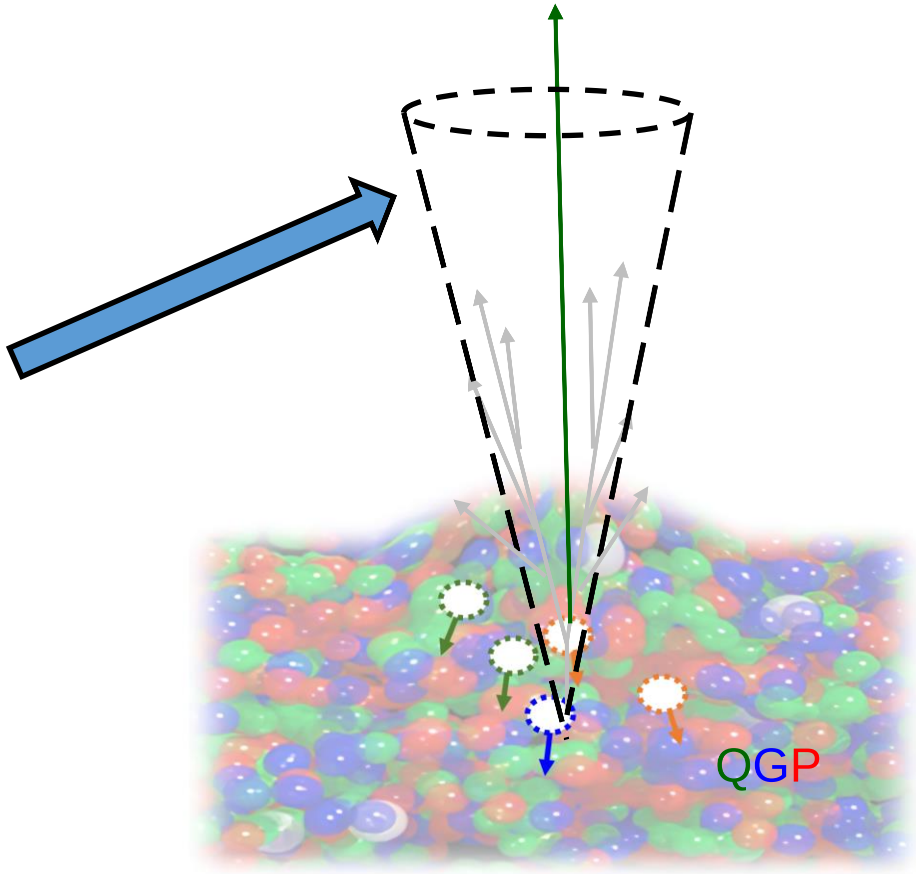


Observation of the mass dependence at low p_T and disappearance the effect at high p_T



- Significant difference between **b-jet** and **inclusive jet** observed by ATLAS at high jet p_T
- Around 50% of b-jet from gluon splitting process
  - b-jet R_{AA} ~ 0.5-0.6 ~ (1-gluon splitting fraction)

Groomed Jet Substructure: Focus on the Jet Core

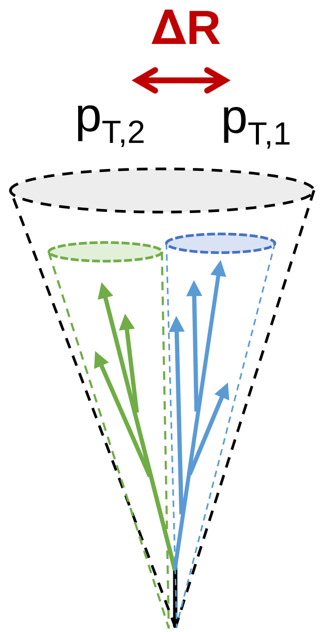


Fluctuation of Jet Quenching:

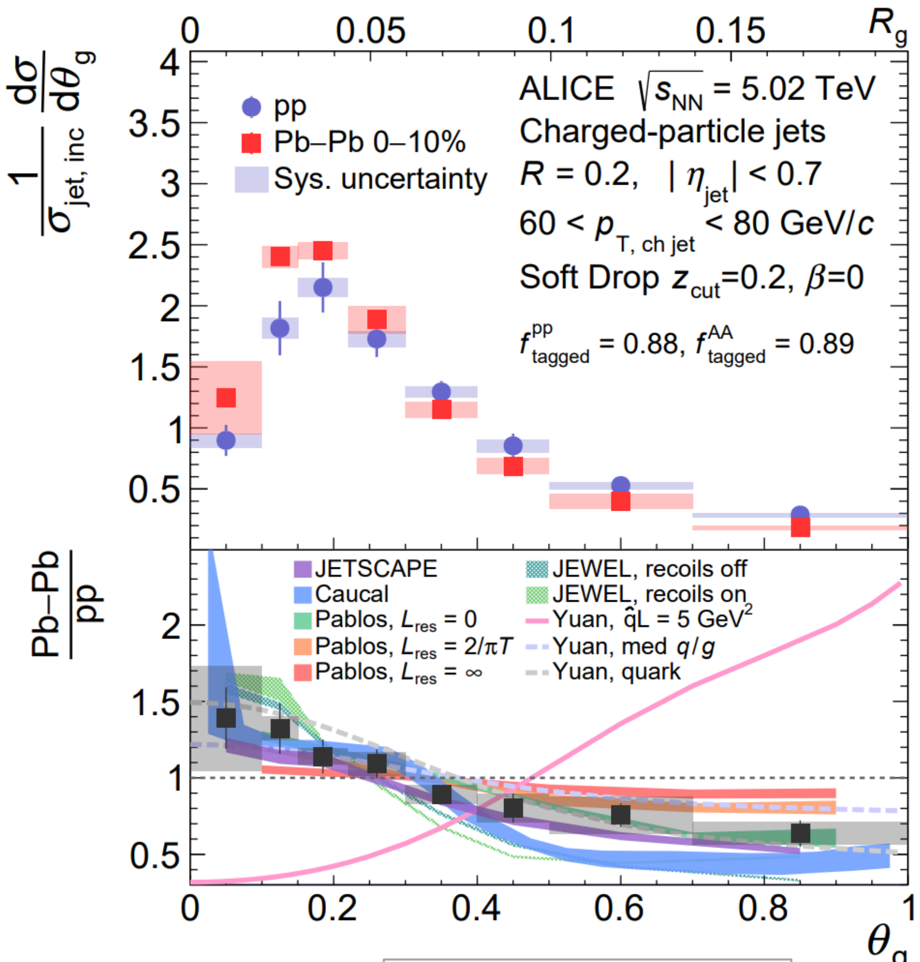
Shower shape dependence of energy loss

Groomed Subjet Opening Angles

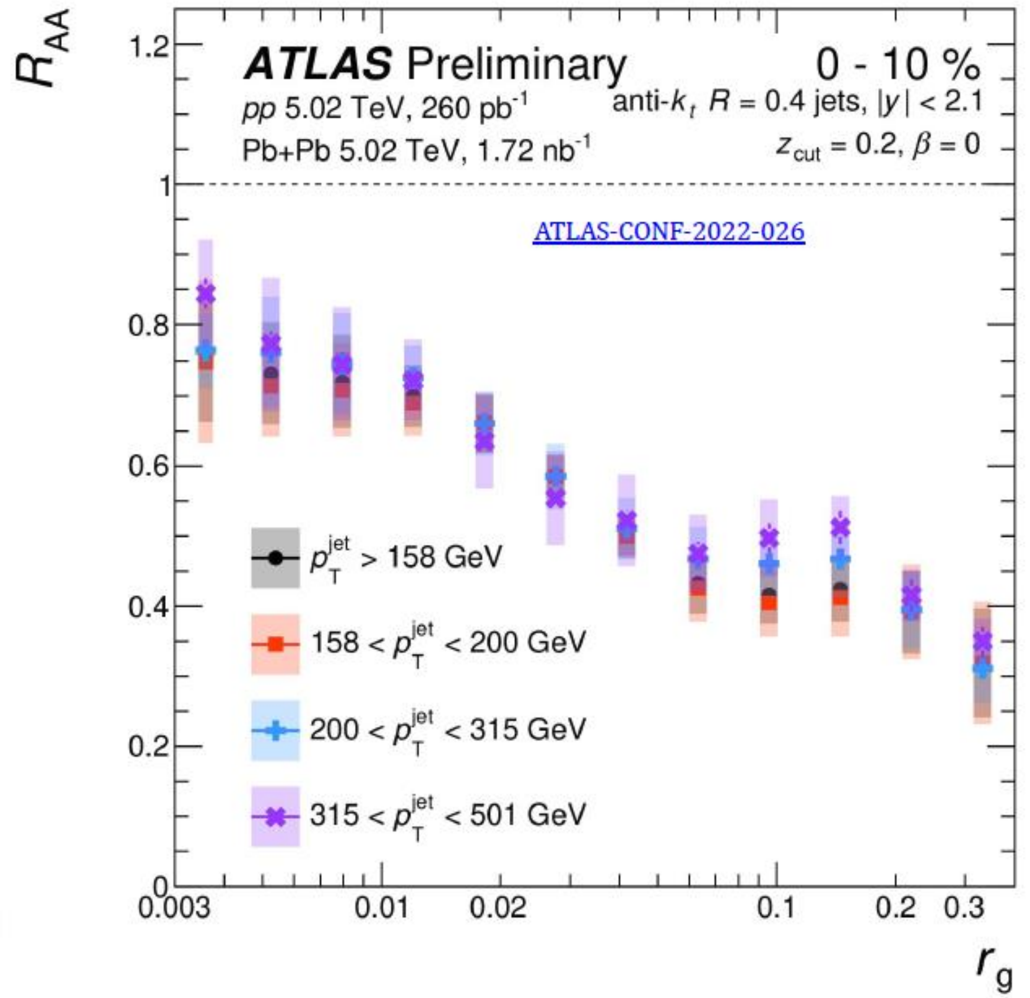
$$\theta_g = r_g = \frac{\Delta R}{R}$$



Two hard subjets
$Z_g \sim 0.5$



PRL 128 (2022) 10, 102001

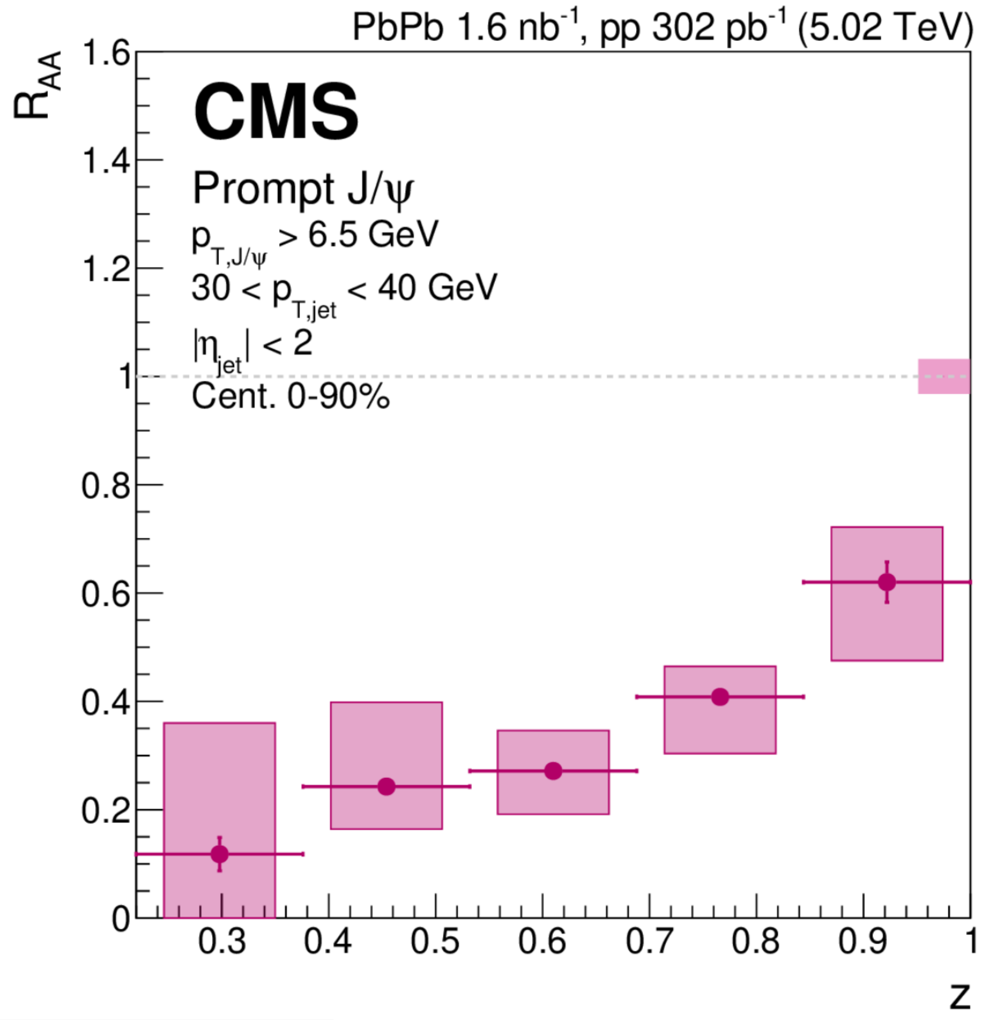


- Progress on the θ_g :
  - Jet Narrowing for inclusive charged jet
  - Decent description from **JETSCAPE**, **hybrid**, **JEWEL**

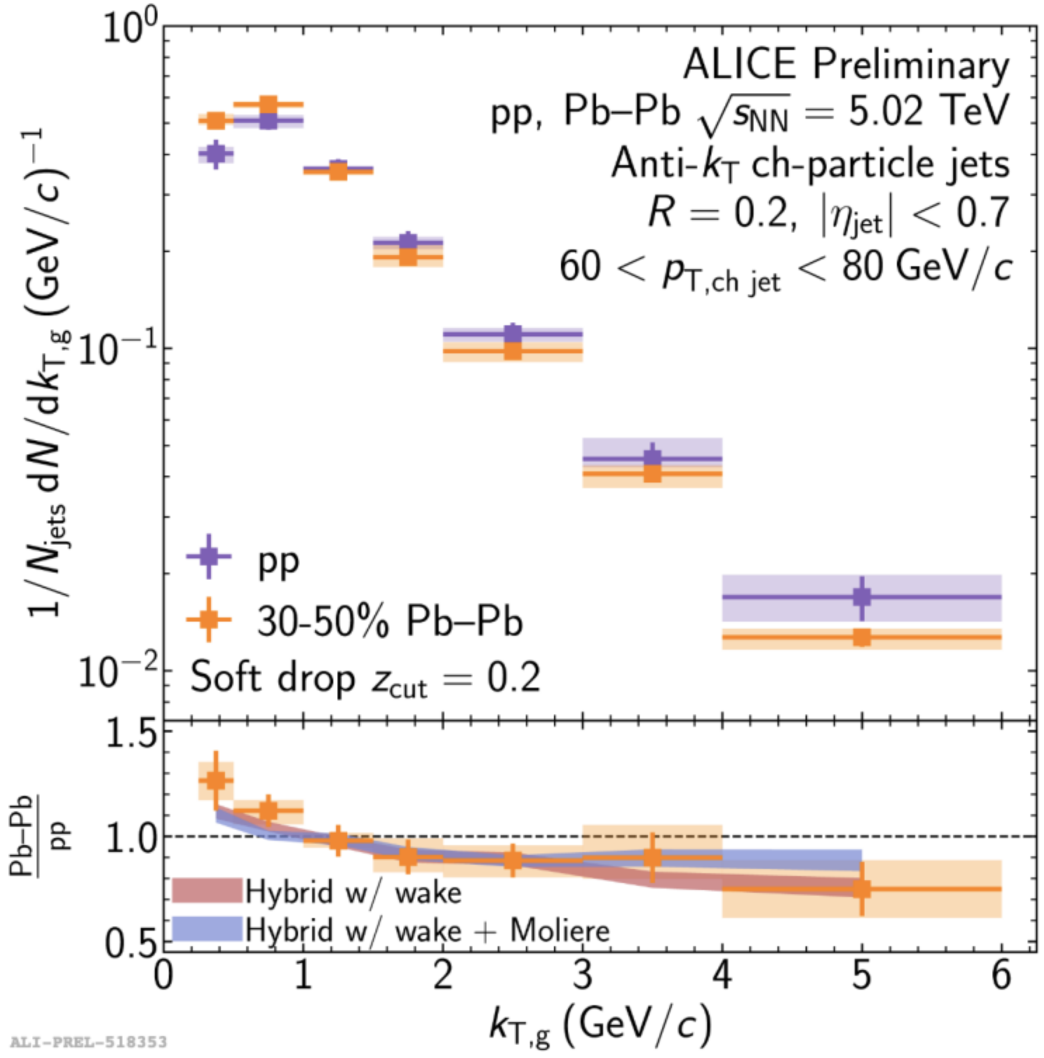
- Progress on absolute normalization:
  - First measurement of R_{AA} vs r_g
  - Jets with small r_g are less suppressed

However, models with different underlying mechanism describe the data trend

Jet Narrowing Effect in Inclusive Jets



PLB 825 (2021) 136842

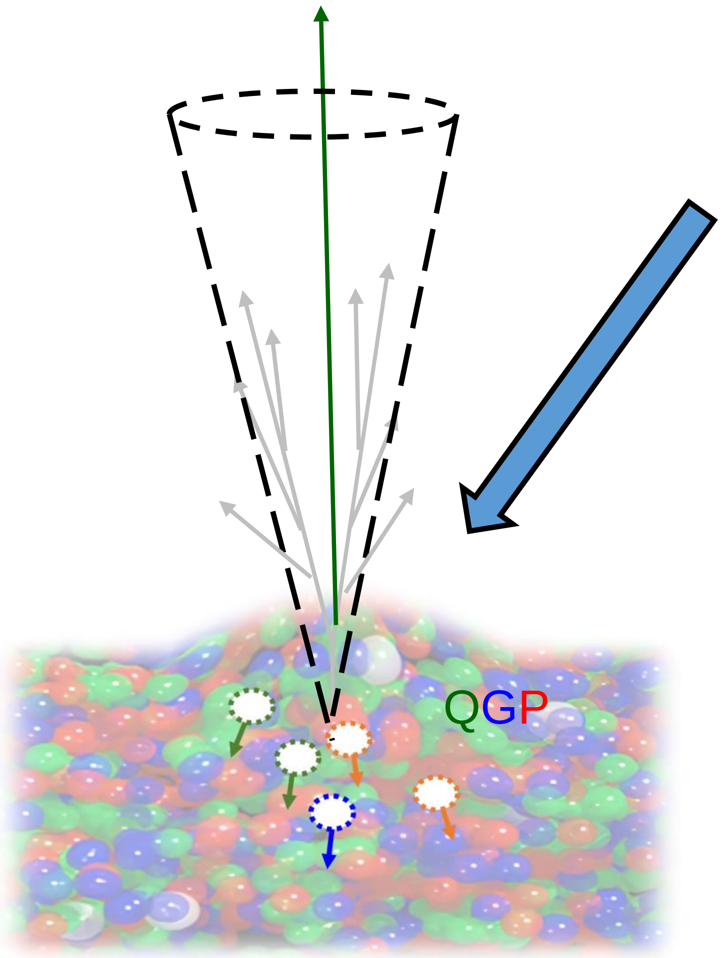


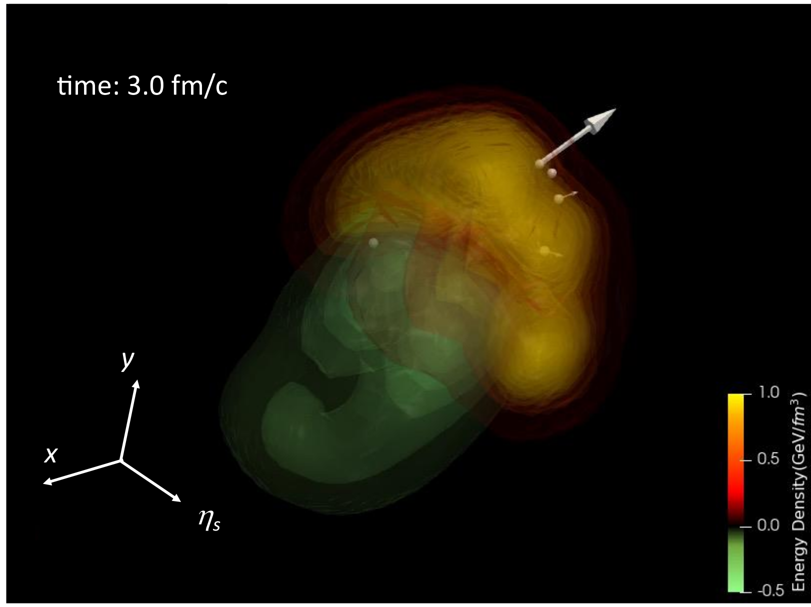
- Jets with a prompt J/ψ: hardening of the J/ψ FF in PbPb collision

- PbPb data tend to have lower $k_{T,g}$
- Described by Hybrid model, sensitive to Moliere

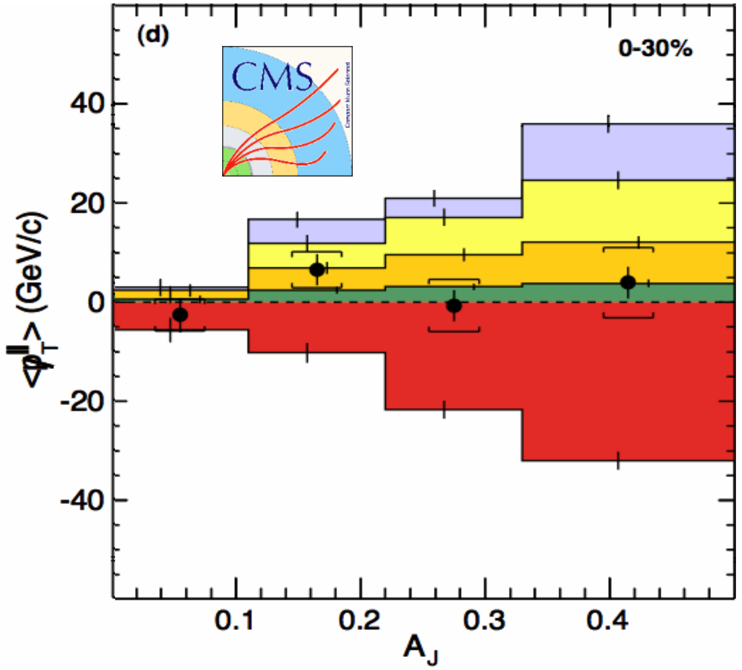
Need to move on from inclusive jet to photon-tagged jet!

Quenched Energy and Medium Response





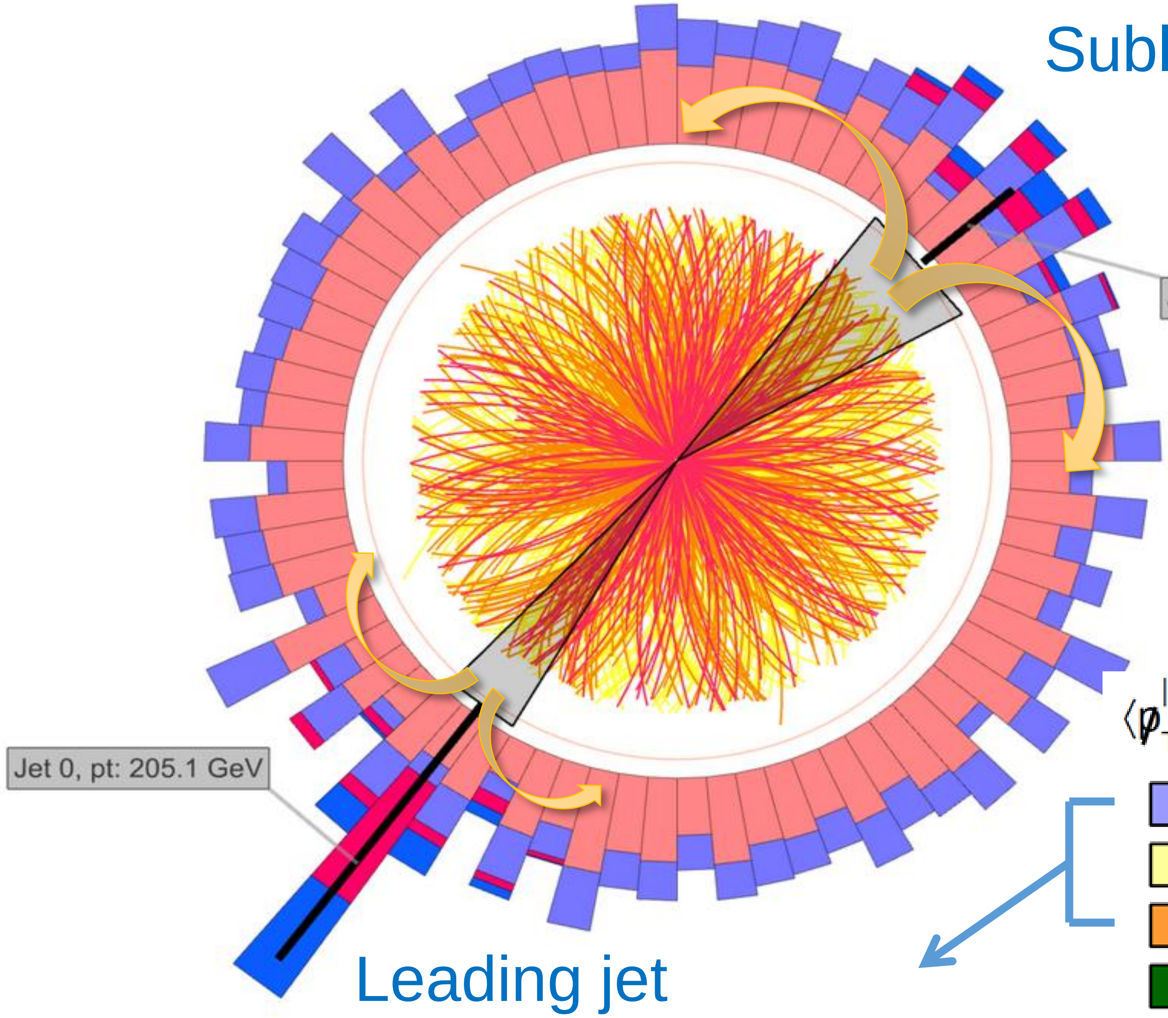
Xin-Nian Wang et. al

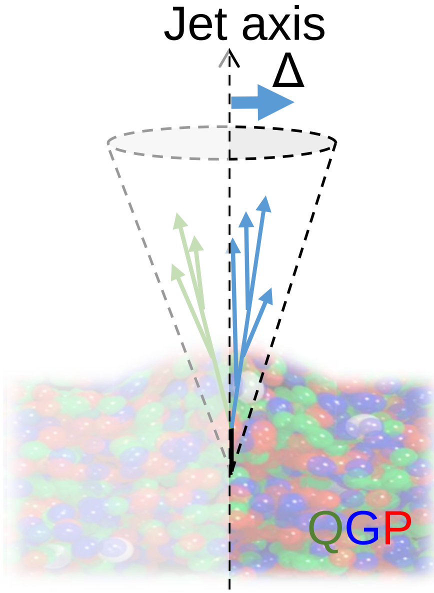


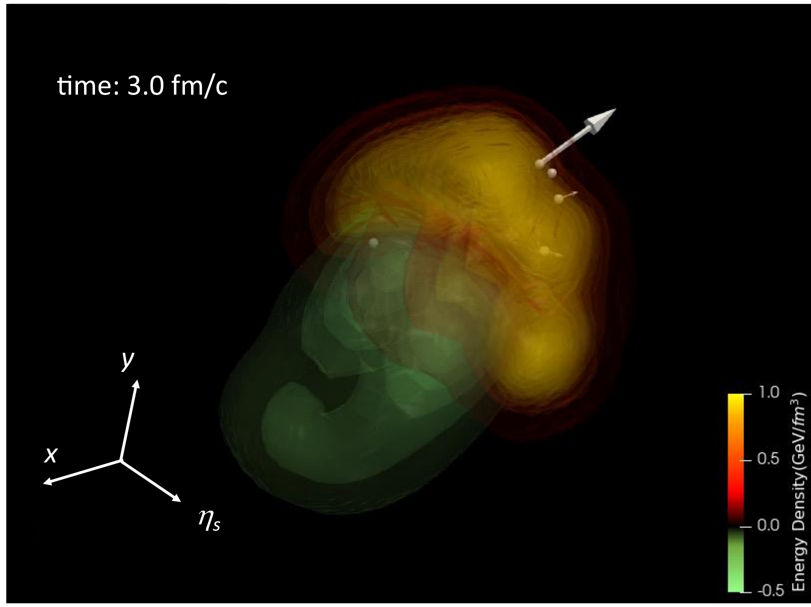
Do we see medium response?

PRC 84 (2011) 024906

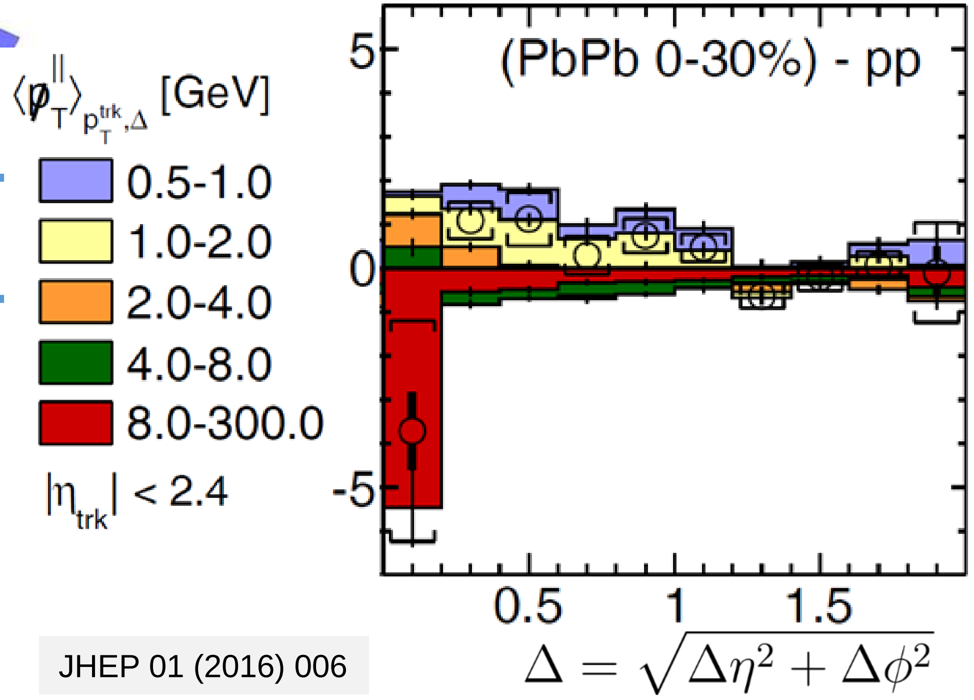
Where does the Quenched Energy Go?







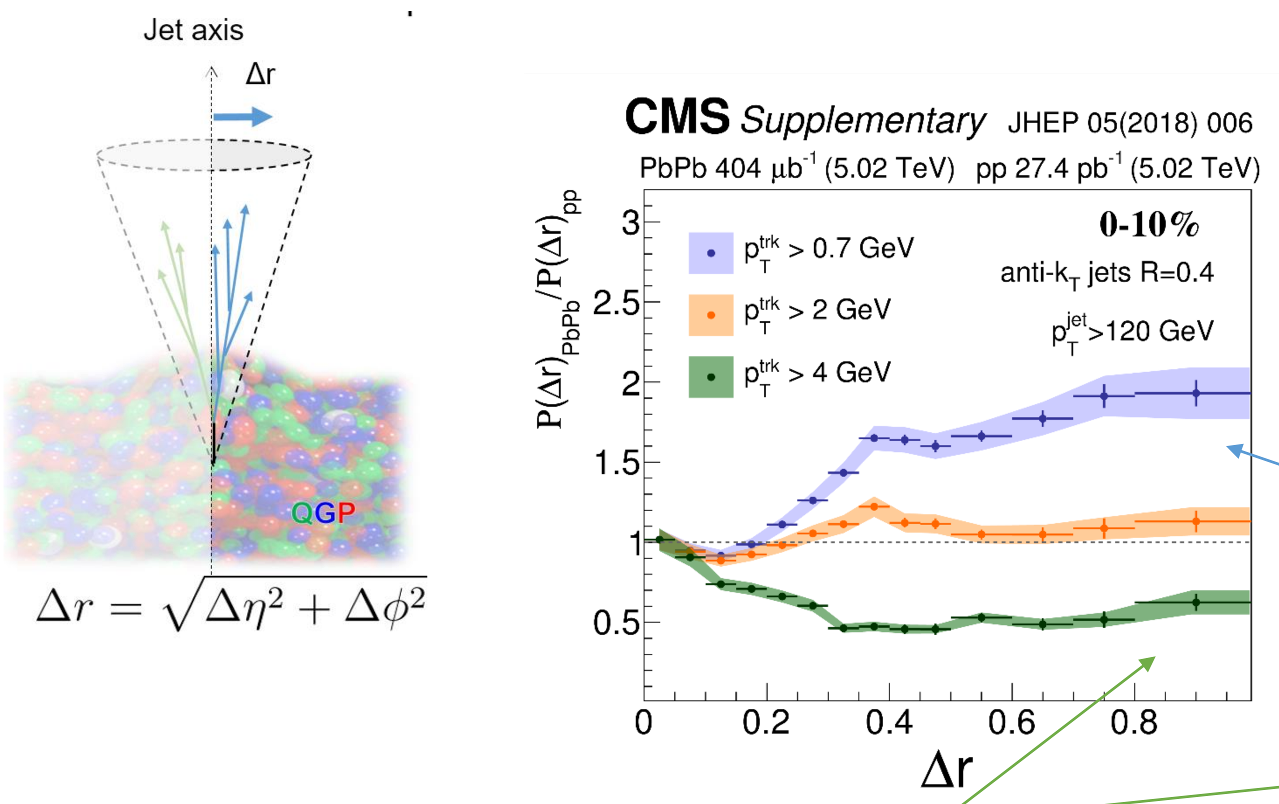
Xin-Nian Wang et. al

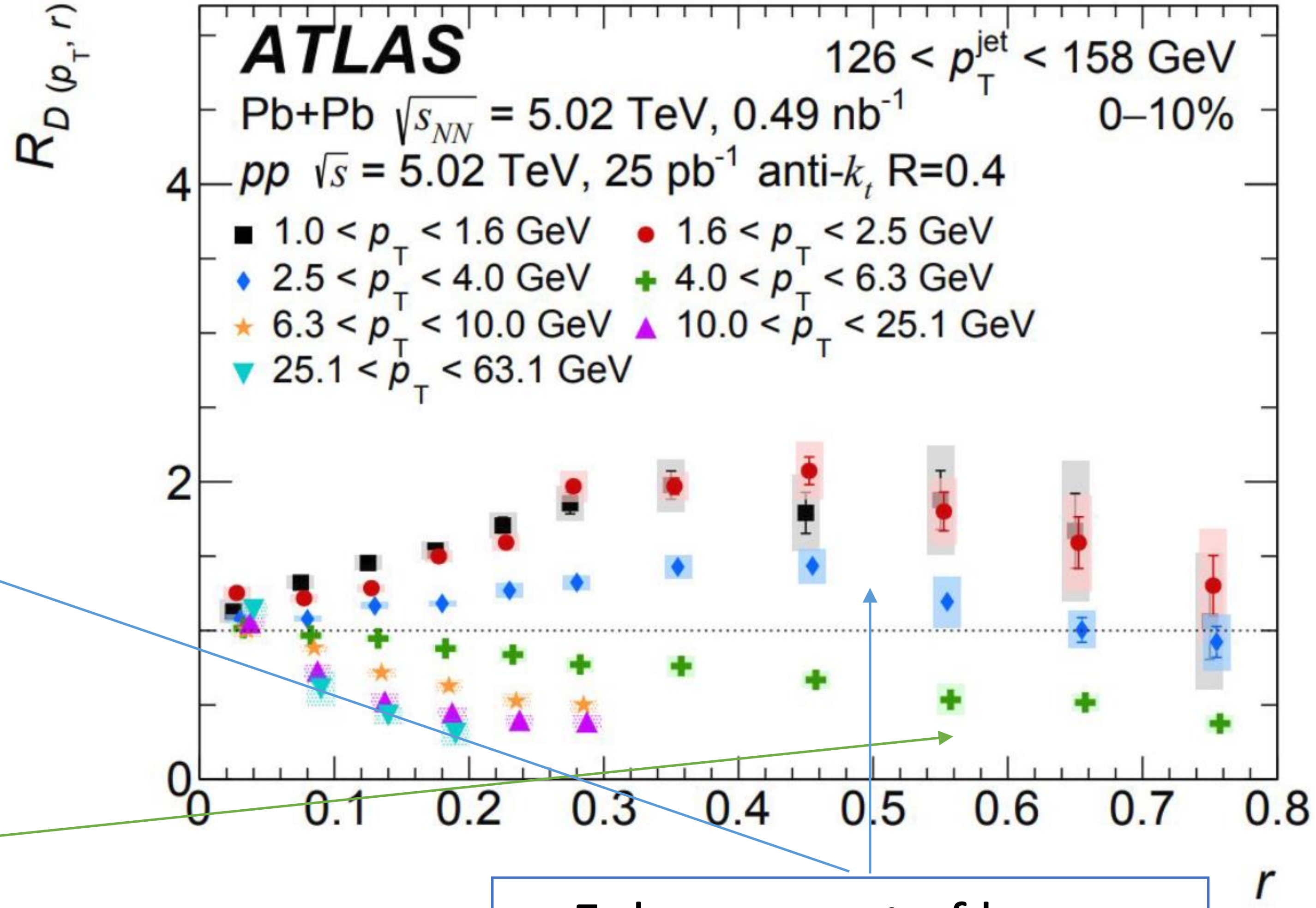


JHEP 01 (2016) 006

- Quenched energy carried by **low momentum particles!**
- Momentum balance recovered with particles up to Δ ~ 2

Excess in Jet-Hadron Correlation





Depletion of high p_T charged particles at large Δr

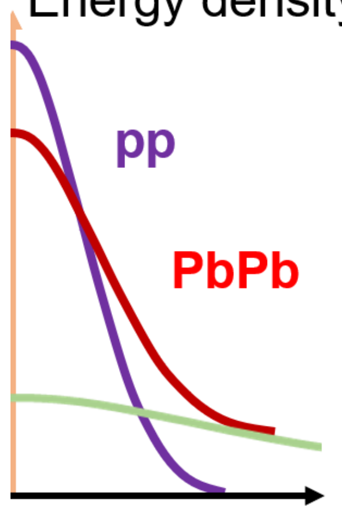
Enhancement of low p_T charged particles at large Δr

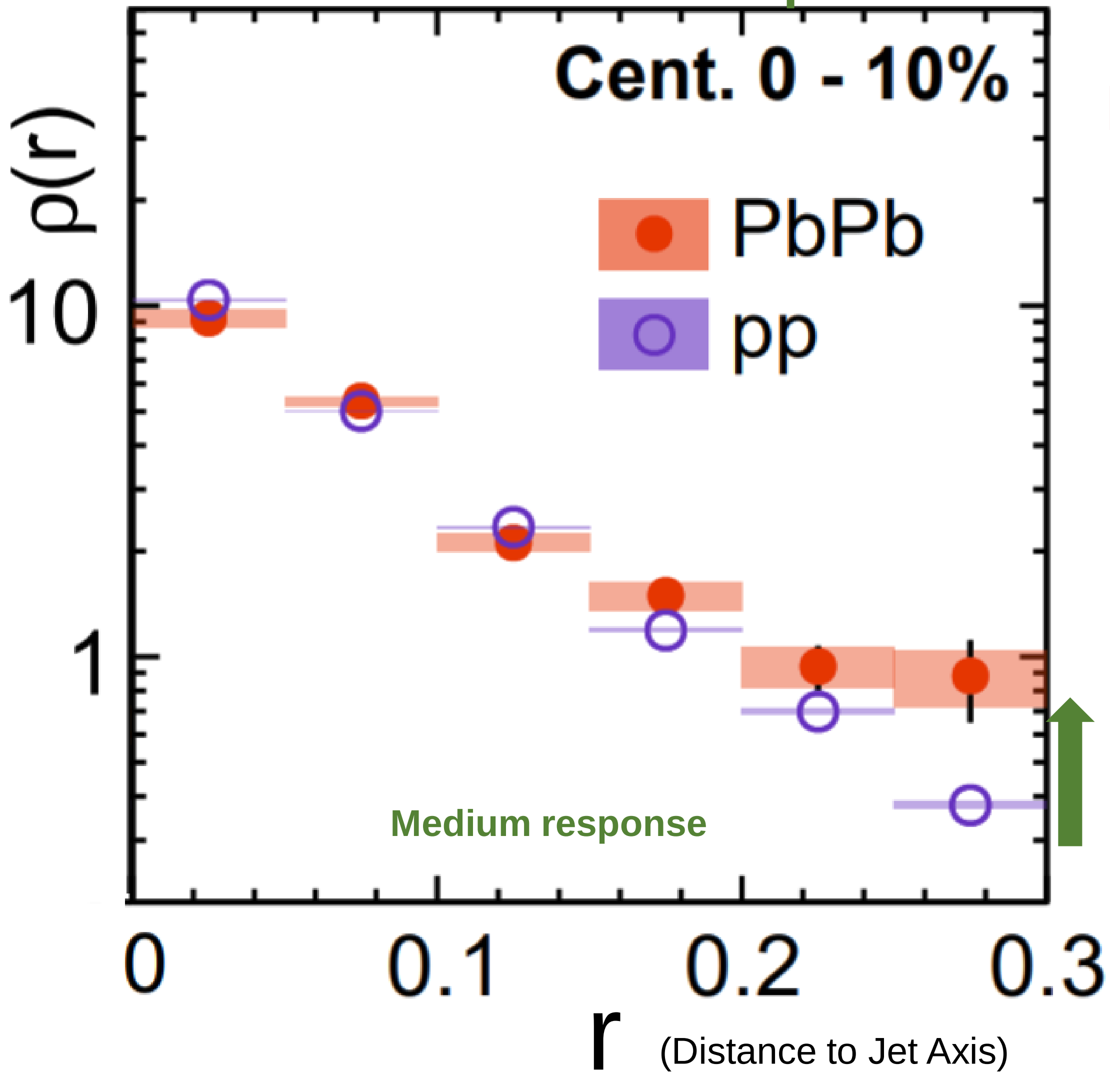
Interpretations of the low p_T enhancement at large ΔR include **medium response**, **medium induce radiation / splitting**, and **vacuum-like emissions out of the medium** (Edmond Iancu QM'18)

Quark Jet Shape Modification

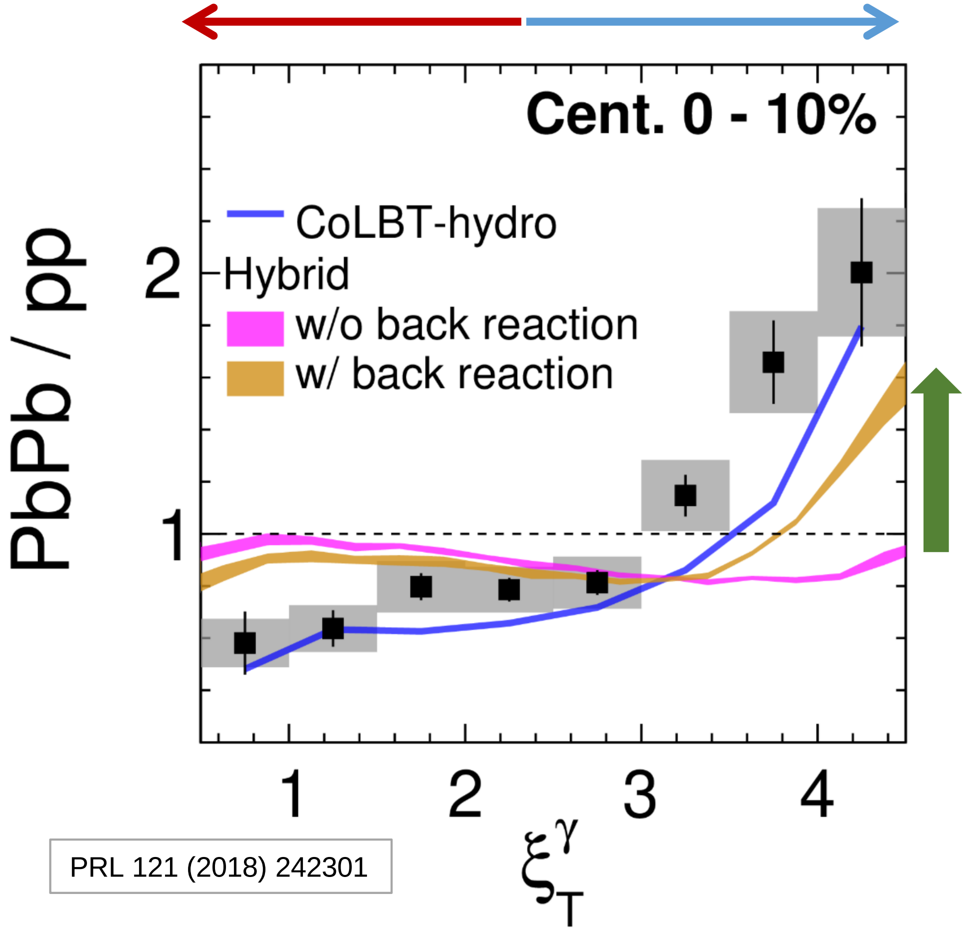
PRL 122 (2019) 152001

Radial Shape





Constituent Momentum Spectrum



PRL 121 (2018) 242301

- **Broadening** of the quark-enriched jet shape in $|r|<0.3$, enhancement of **low momentum particles** in jet
- Strong indication of QGP **medium response**
- **However, interpretation of the data is highly model dependent**

Hybrid Model
Krishna Rajagopal et.al

CoLBT-hydro
Xin-Nian Wang et.al

To Separate Models: Large Area Jet R_{AA}

R=0.2

500 GeV

R=1.0

500 GeV

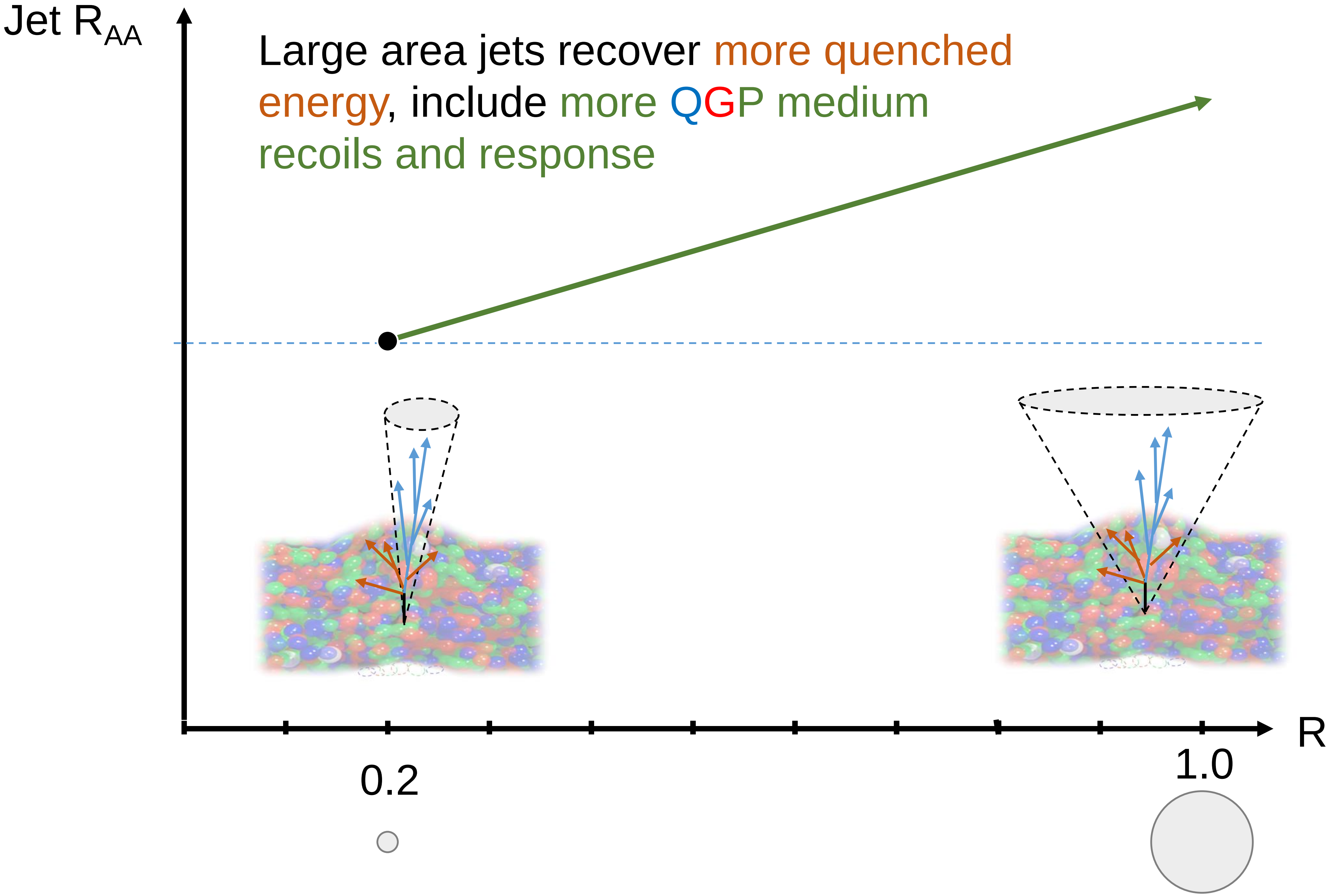
Accept **narrow** Jets

Accept Both **narrow and wide** jet

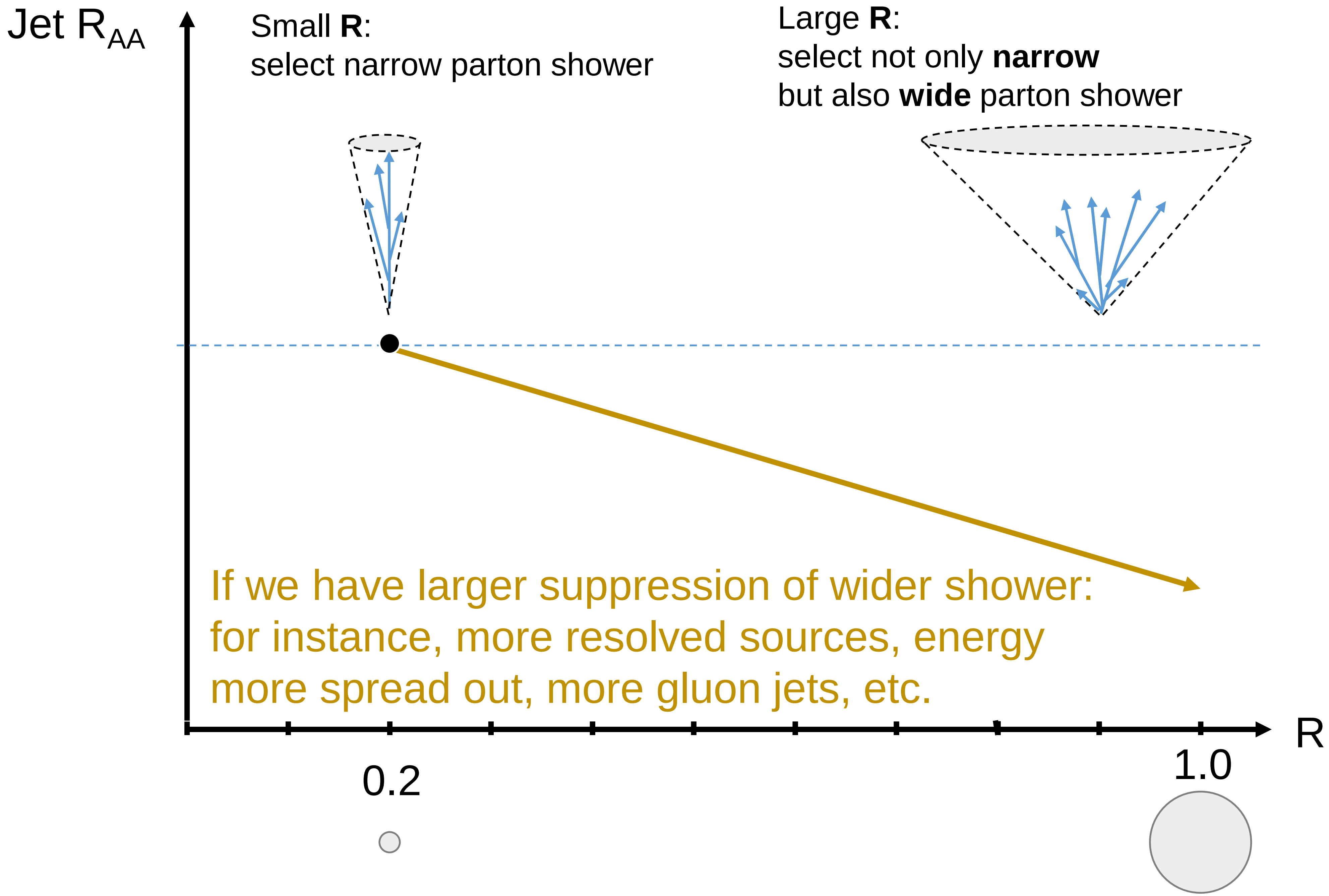
- Measure large area jet (include wide parton shower) to provide
- Further test of the jet quenching models

Recovery of Quenched Energy

Large area jets recover more quenched energy, include more QGP medium recoils and response

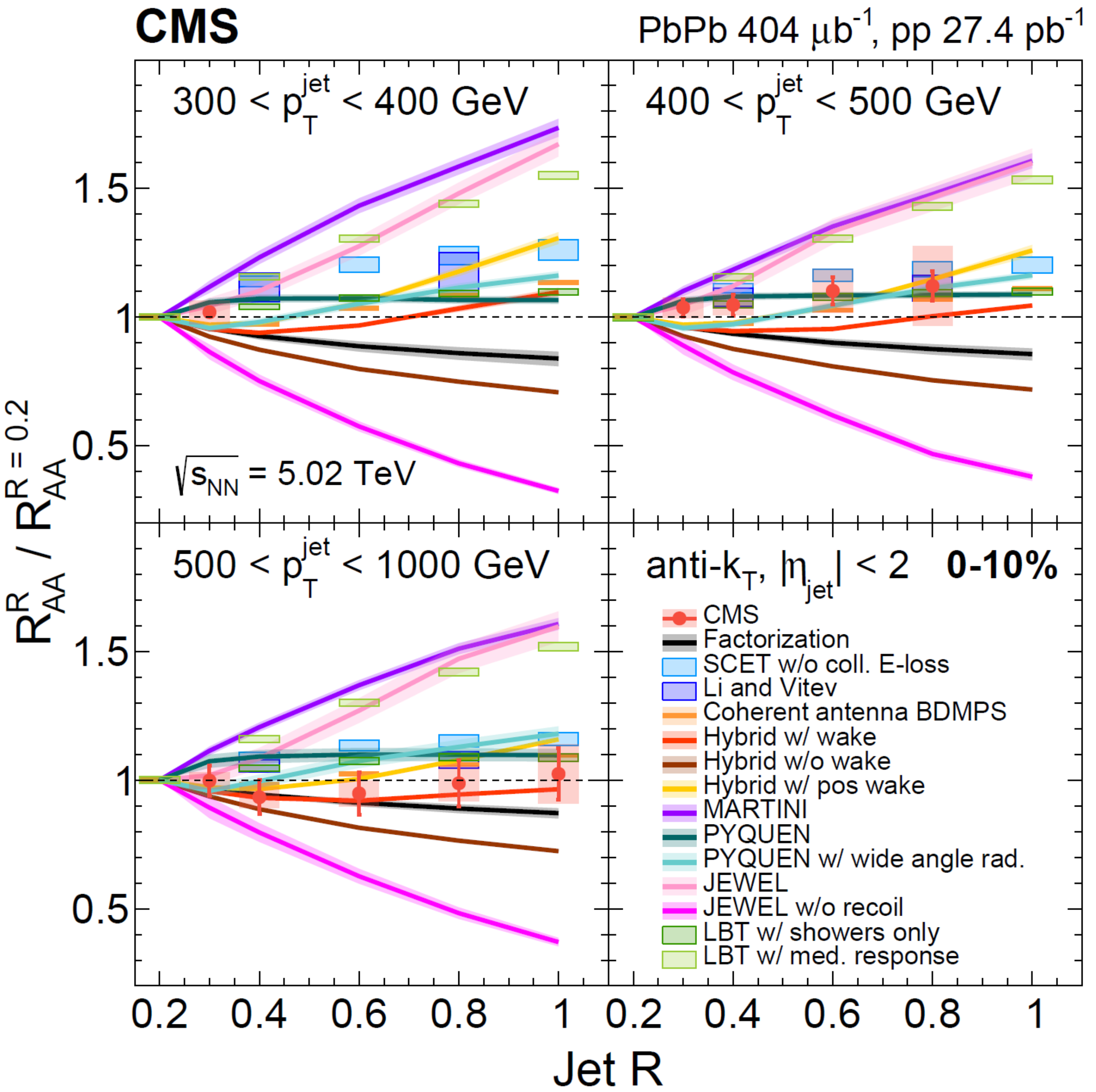


Fate of Wider Jets

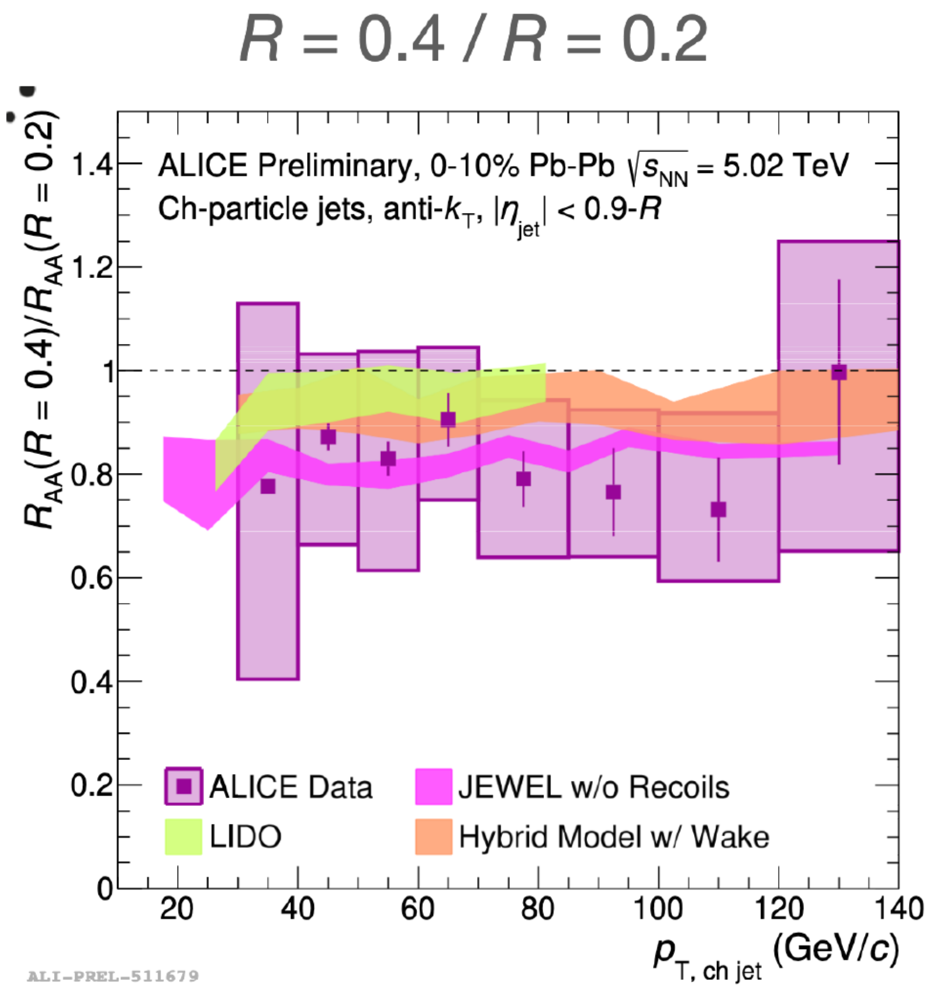


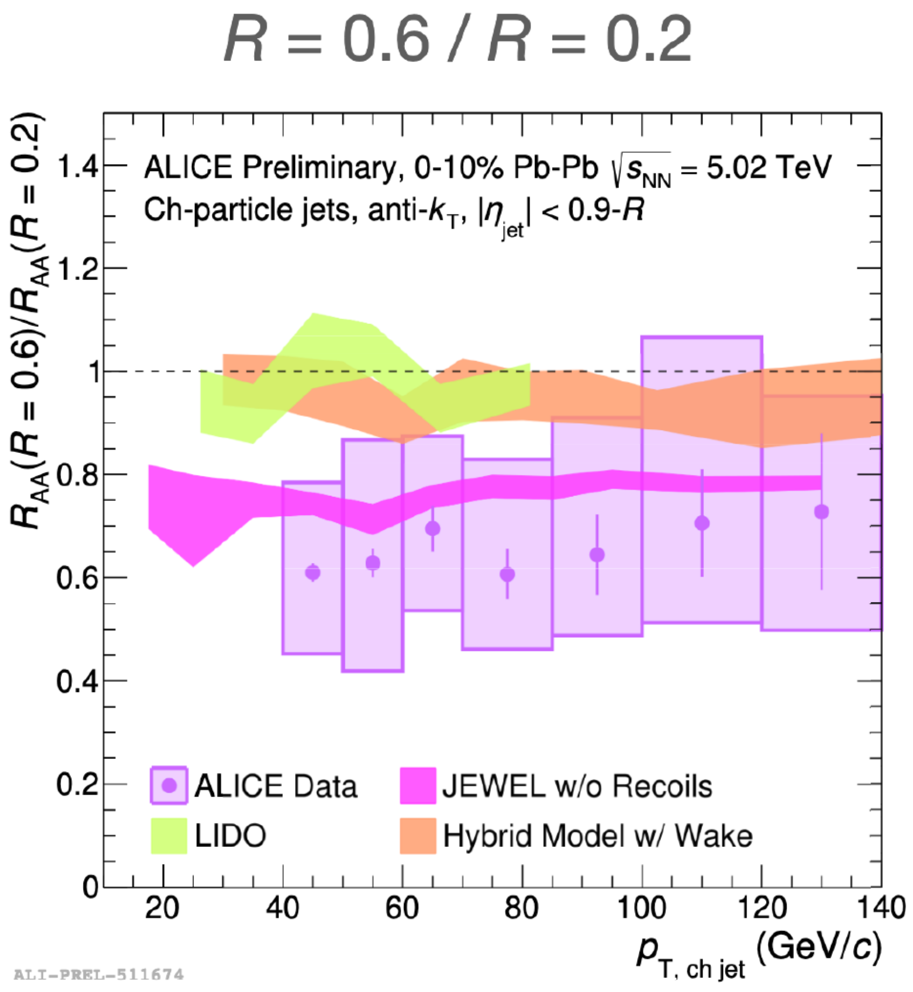
Jet R_{AA} Ratios vs. R in 0-10% PbPb at 5 TeV

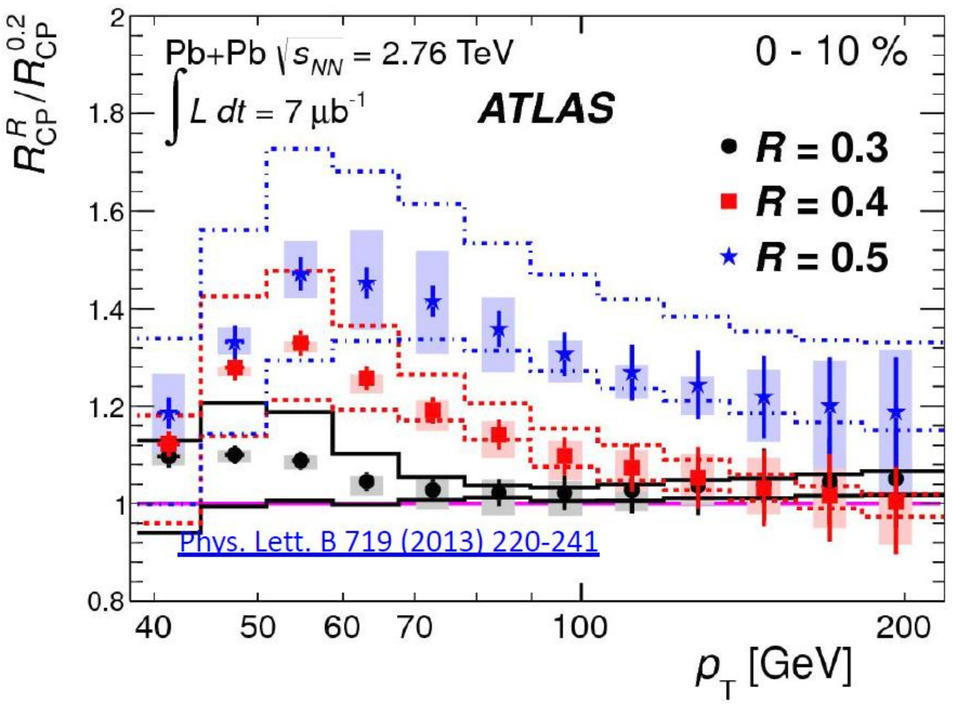
- Different trends from models and analytic calculations
- CMS jet R_{AA} data shows weak dependence on jet R
- New constraint to theoretical models!



Jet $R_{AA(CP)}$ Ratios vs. (Charged) Jet p_T in 0-10% PbPb



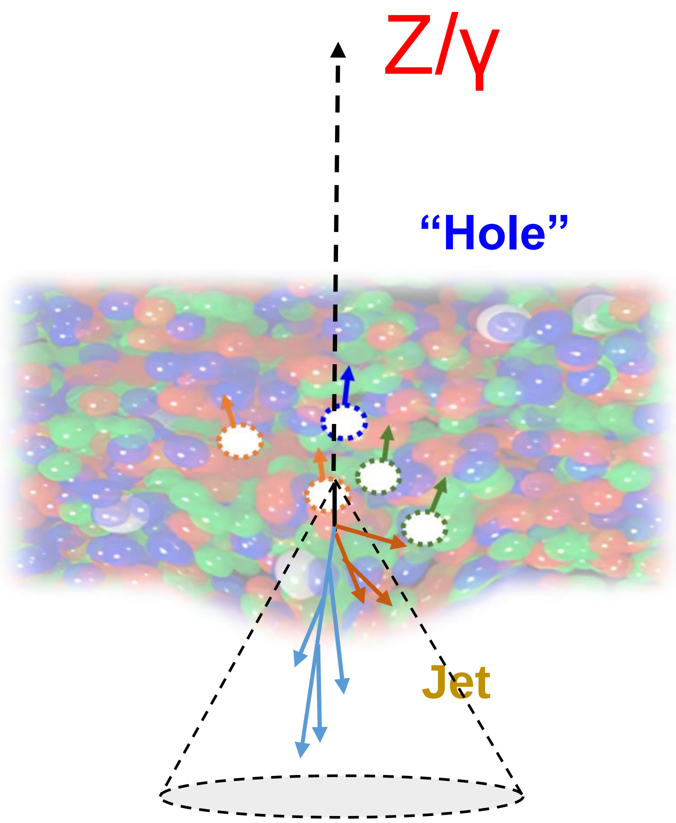




- Indication of larger suppression for R=0.6 charged jets
    - Taking ratio of R_{AA} from different $|\eta_{jet}|$ intervals
- Hybrid and LIDO overpredict the ALICE data (ML based)

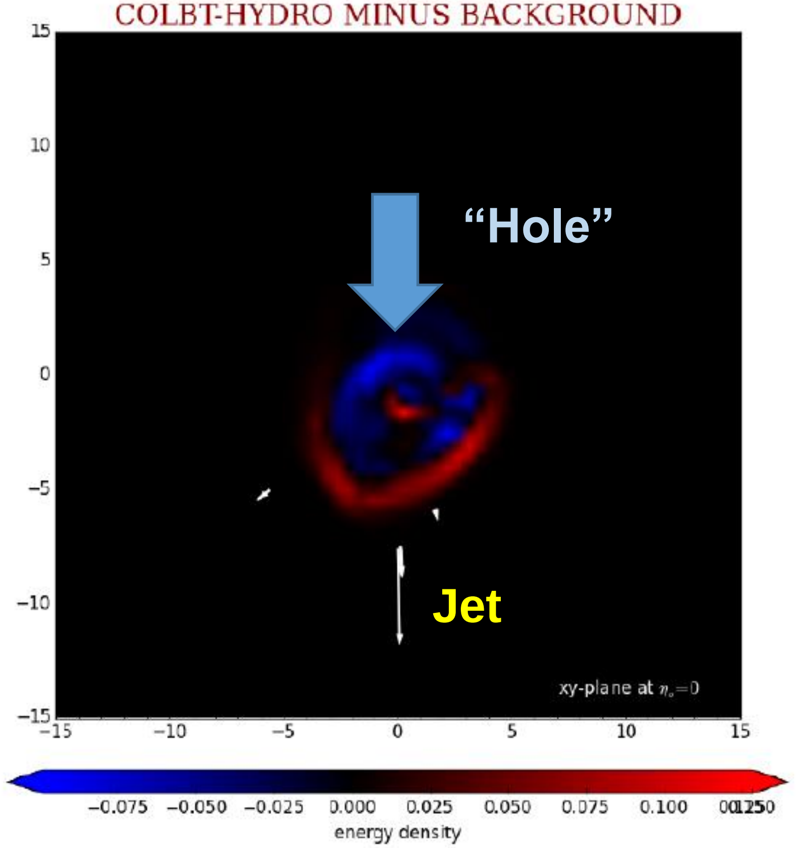
- Recall: ATLAS R_{CP} at 2.76 TeV "Recovery of quenched energy"

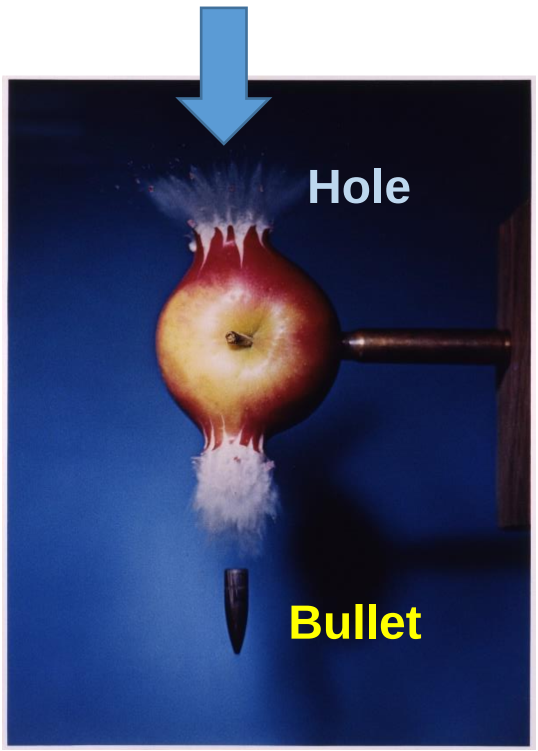
To Separate Models: "Depletion" due to Medium Recoil

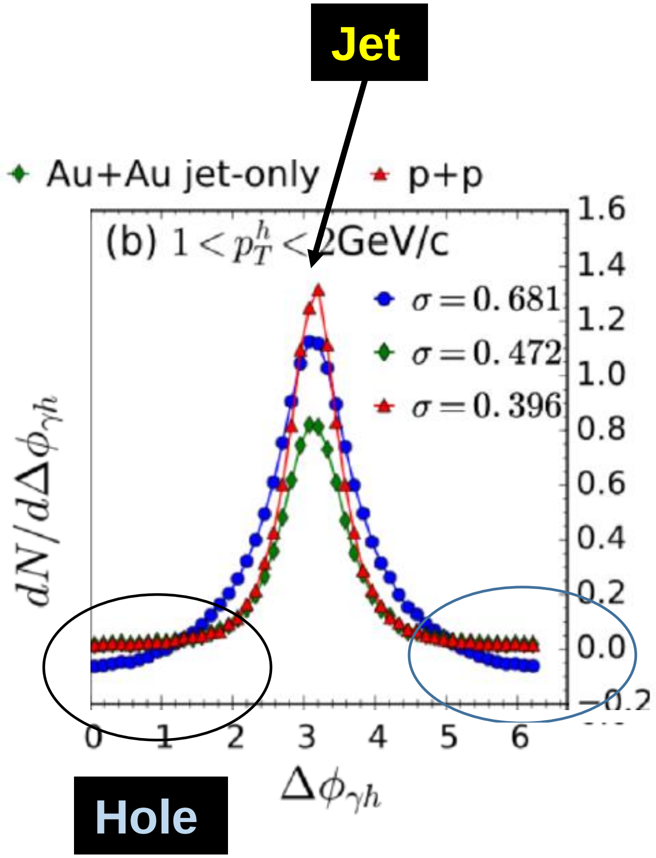


CoLBT

Tan Luo, Xin-Nian Wang

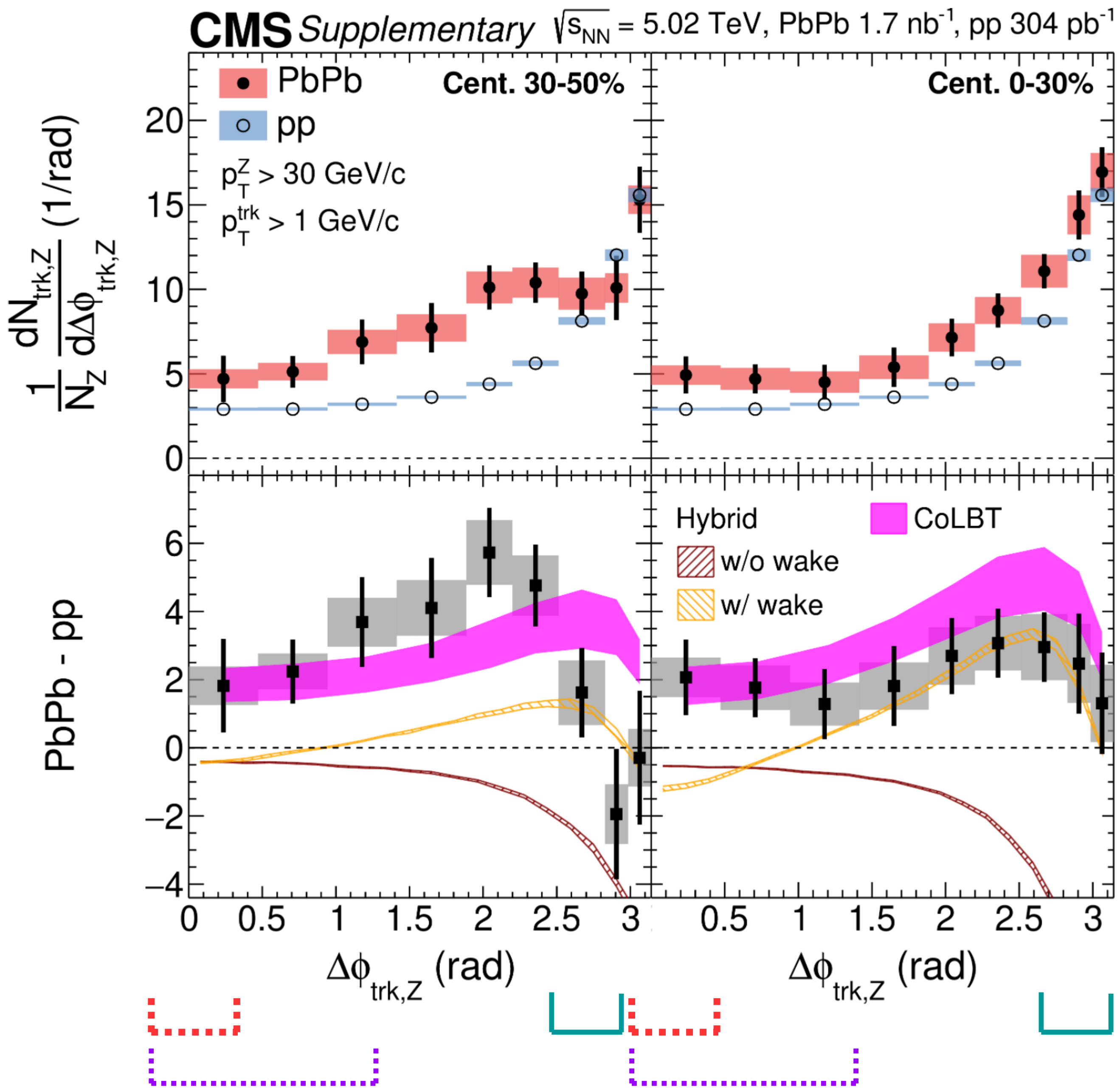






Measure the **boson-side associated yield** with photon-jet and **Z-jet**

Z-hadron Δφ in PbPb at 5.02 TeV

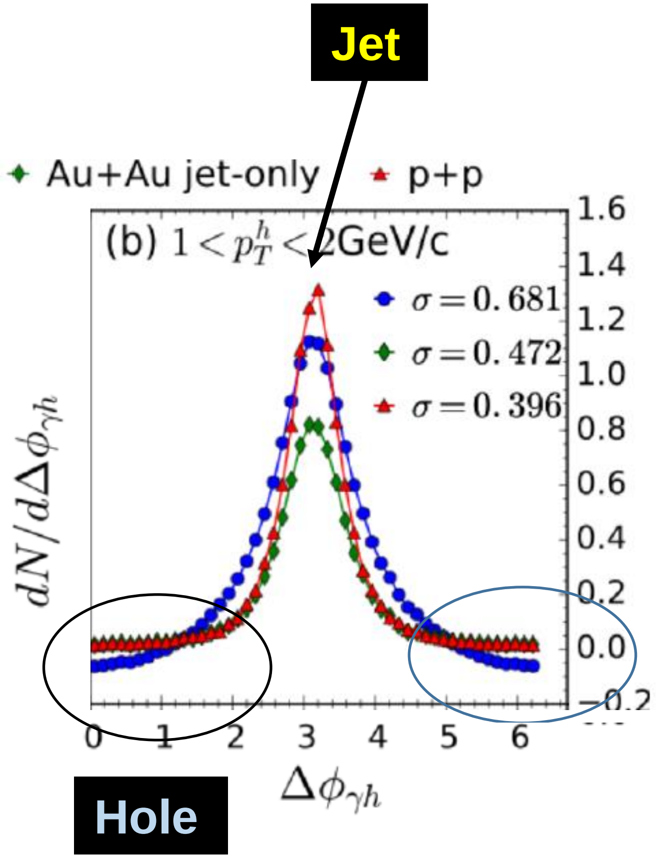


Hybrid Model:

$\Delta\varphi_{trk,Z}$ ~ π trend similar when **including** medium response

$\Delta\varphi_{trk,Z}$ < π/2 underestimated by Hybrid

Full wake negative at **$\Delta\varphi_{trk,Z}$ ~ 0**
(w/ diffusion) in Hybrid model
Medium response treatment may be too simple.



CoLBT: Xin-Nian Wang et. al

- Good agreement with PbPb data in 30-50%.
- MPI jet quenching contributed to small Δφ excess

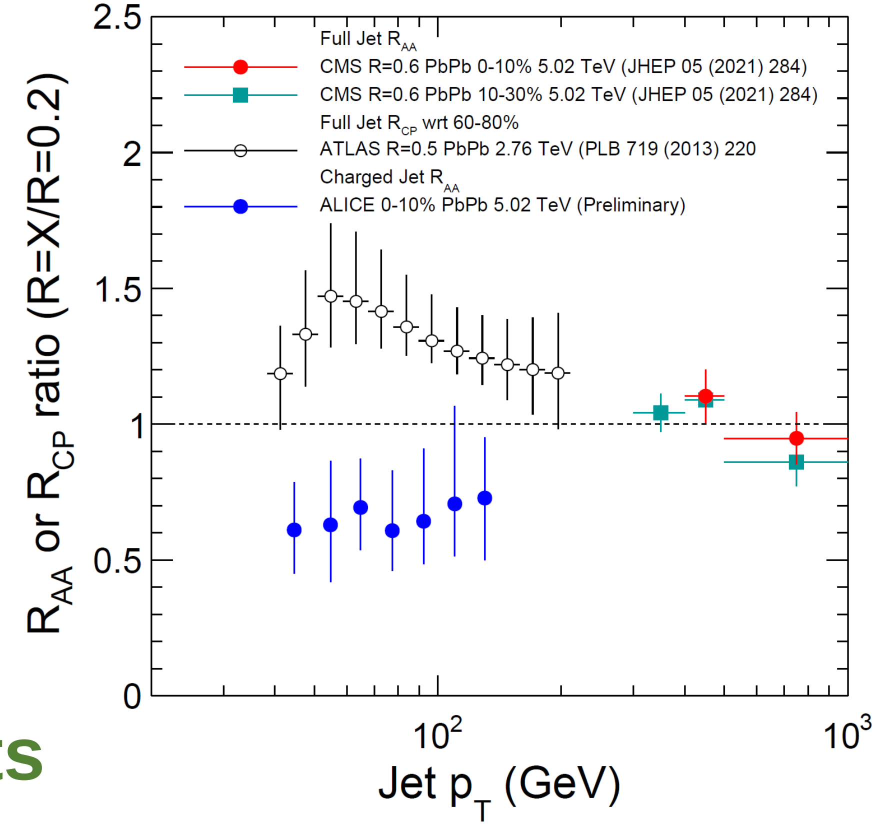
Future Plan at the LHC

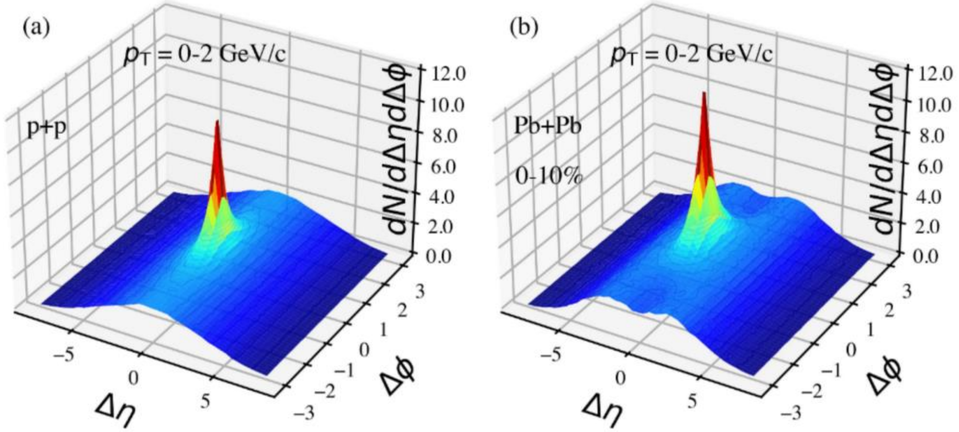
- **Move to photon/Z-tagged jet and jet substructure:**
  - Reduce “survival bias” effect
  - Further constraint the medium-induced broadening effect and jet quenching parameter

- **Improve the precision of large radius jet data**
  - Push the large area jet frontier with high statistics Run 3 data
  - Solve the tension between **ALICE** and **ATLAS** at low jet p_T

- **Search for elastic scattering with medium constituents**
  - Photon/Z + intermediate p_T (sub)jet or hadrons
  - Photon/Jet-D angular correlation

- **Direct observation of medium response and recoil**
  - γ/Z-tagged Δφ-Δη correlation function with Run 3 data





Yang, Luo, Chen, Pang, Wang, arXiv:2203.03683

LHC — pO, OO, pPb — **HL-LHC**

PbPb 1.8 nb^{-1} | PbPb 7 nb^{-1} | PbPb 7 nb^{-1}

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

LHCb SMOG | LHCb SMOG2 (x100 higher rate)

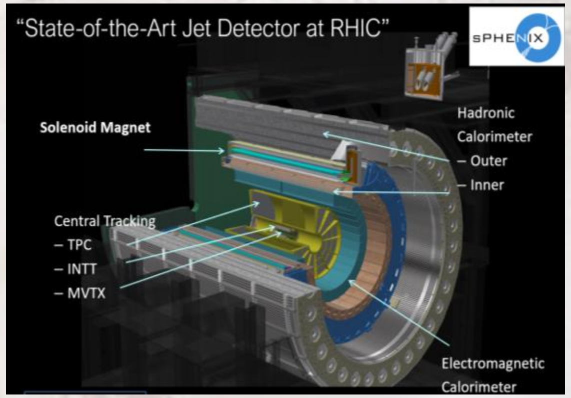
CMS/ATLAS Phase 1 Upgrade | CMS/ATLAS Phase 2 Upgrade

ALICE Upgrade (fast readout 50kHz) | ALICE LS3 Upgrade → New Detector (Run5)

… | 2018 | 2019 | 2020 | 2021 | **2022** | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032

sPHENIX construction

sPHENIX Installation commissioning



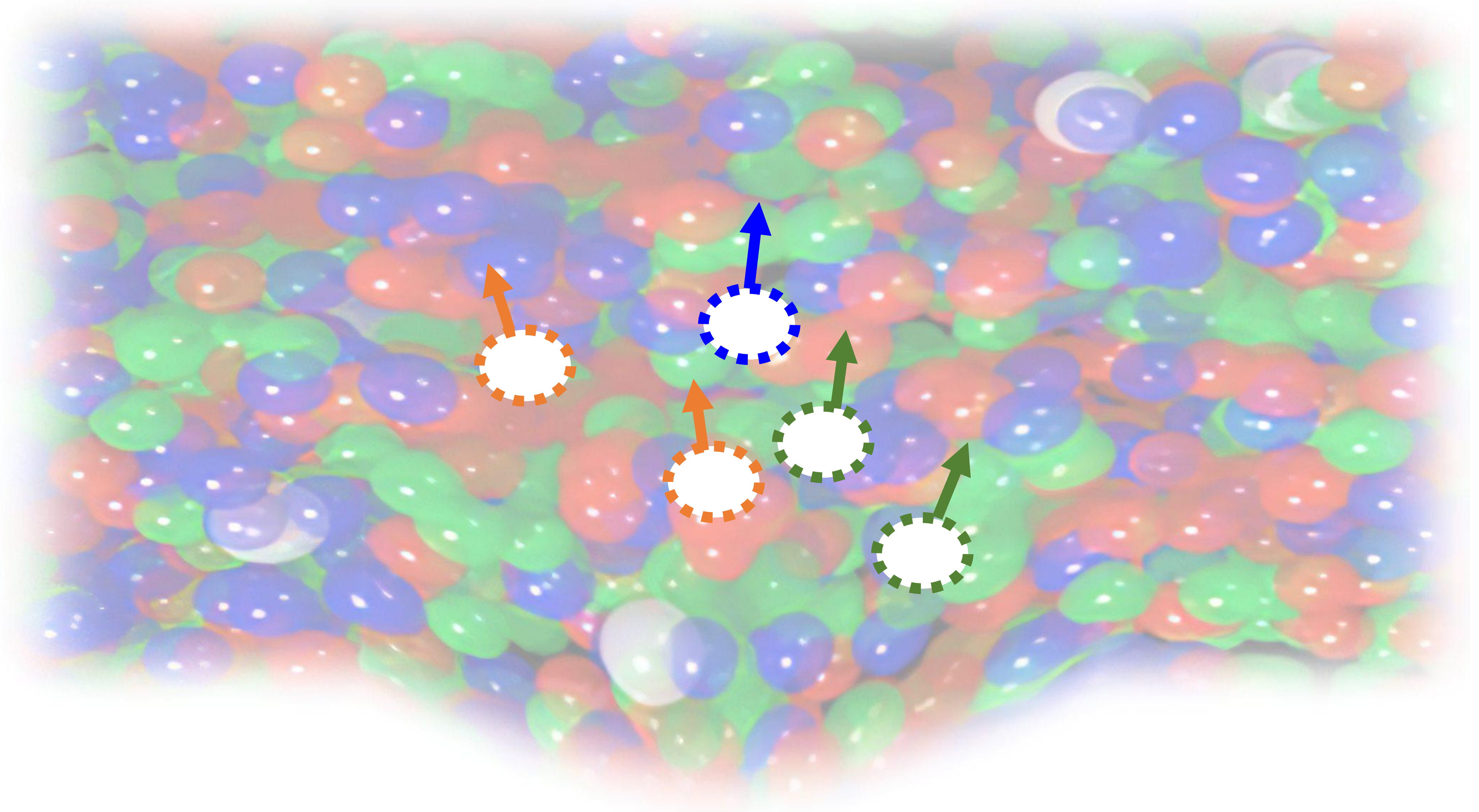
Run 1 | Run 2 ?

RHIC — pp, pAu | pp, ArAr, OO — **EIC**

AuAu 30 nb^{-1} | AuAu 30 nb^{-1}

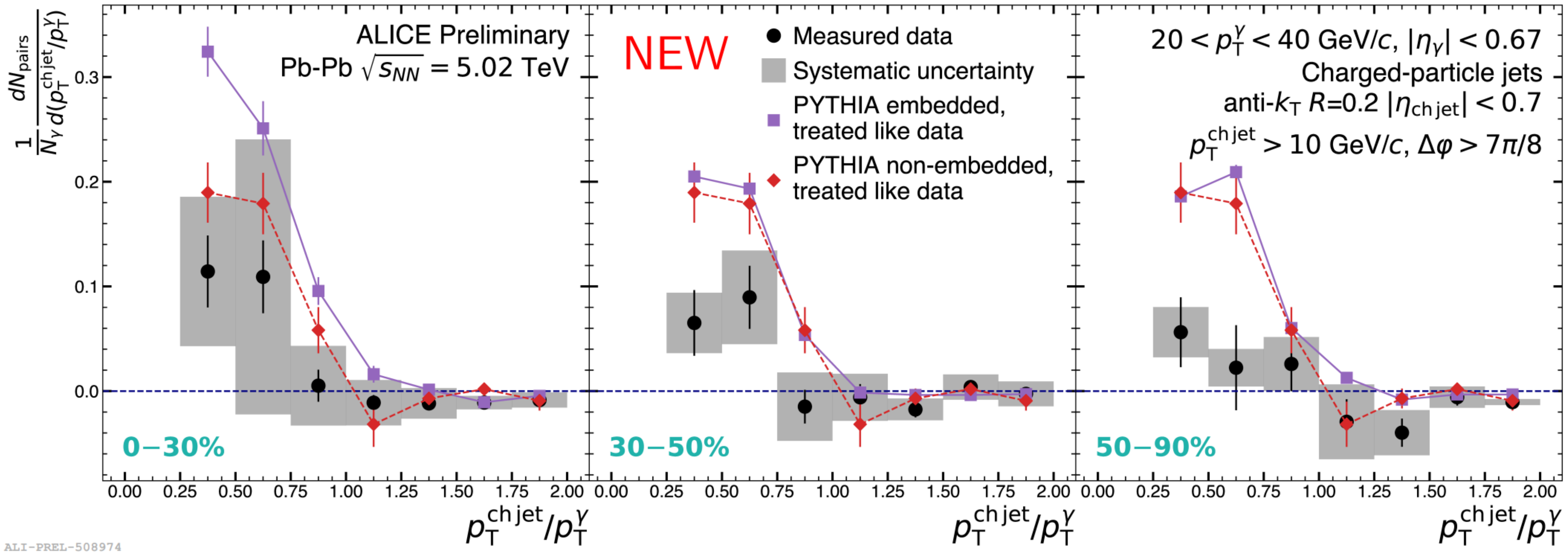
Exciting future jet physics program in the next 10 years and beyond!

Backup Slides



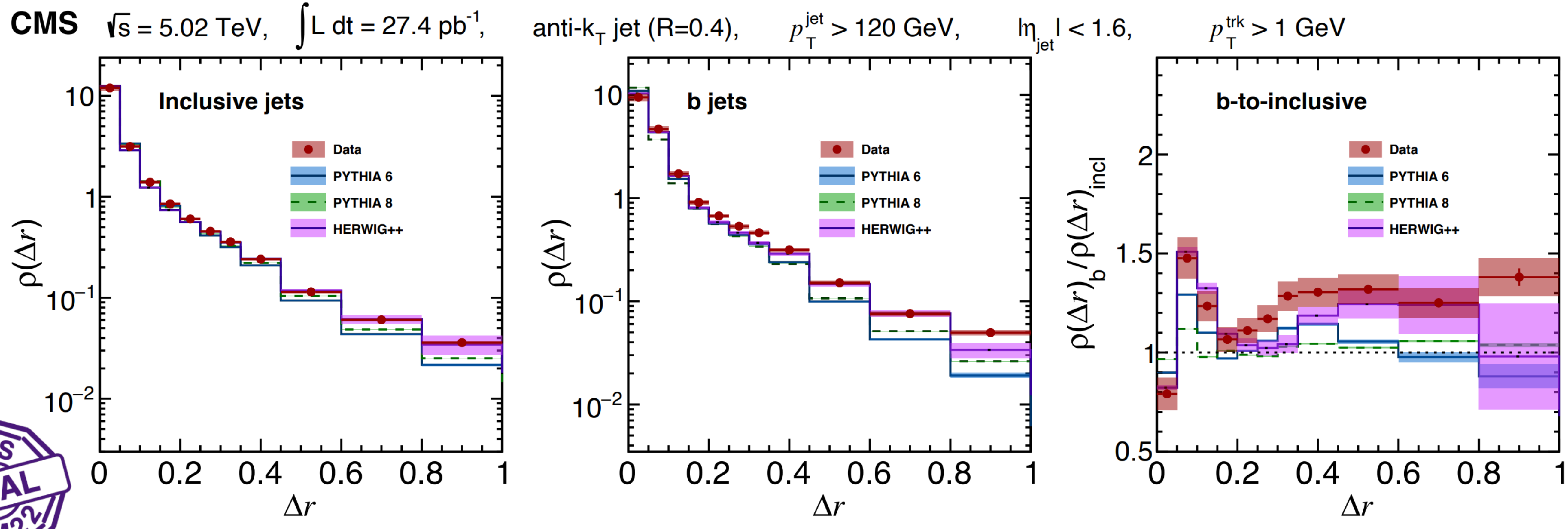
ALICE Photon-Jet

Momentum imbalance $p_T^{\text{ch jet}}/p_T^{\gamma}$ with PYTHIA comparison



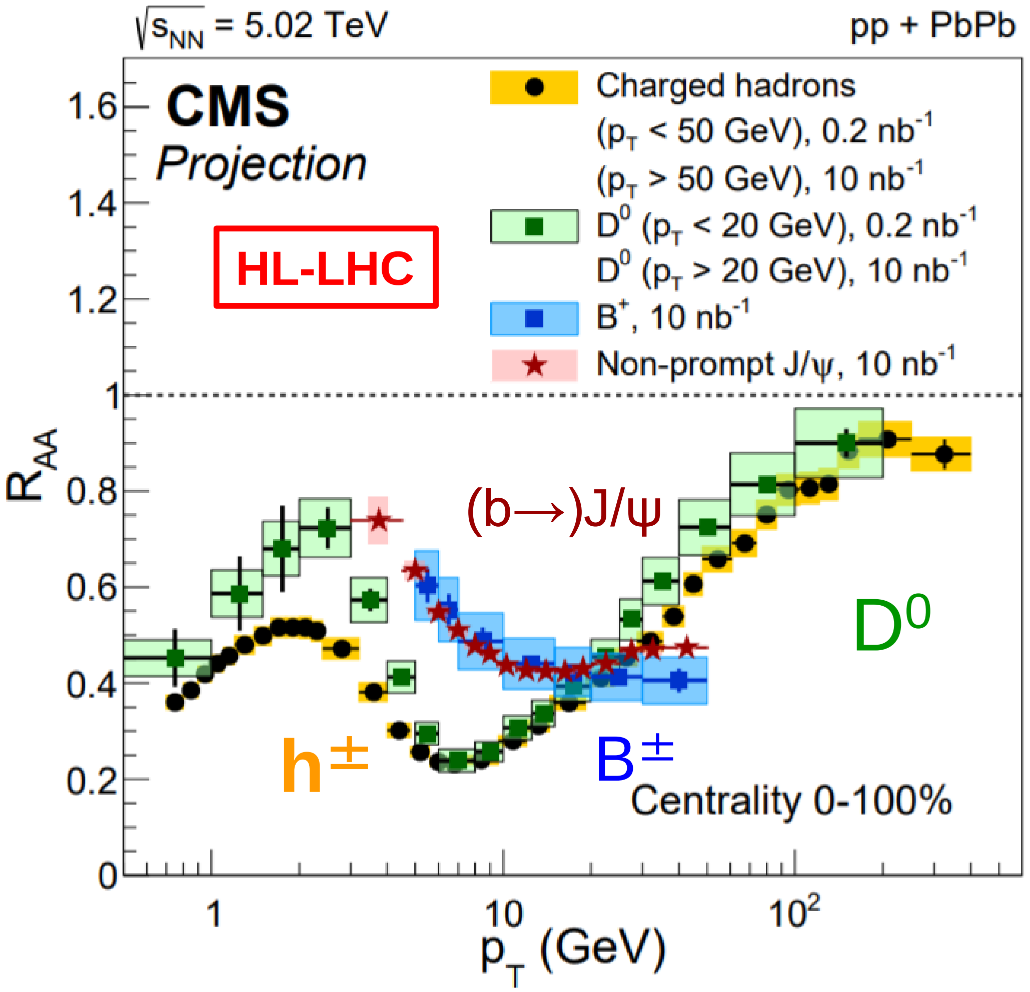
Shape difference in PYTHIA from detector effects

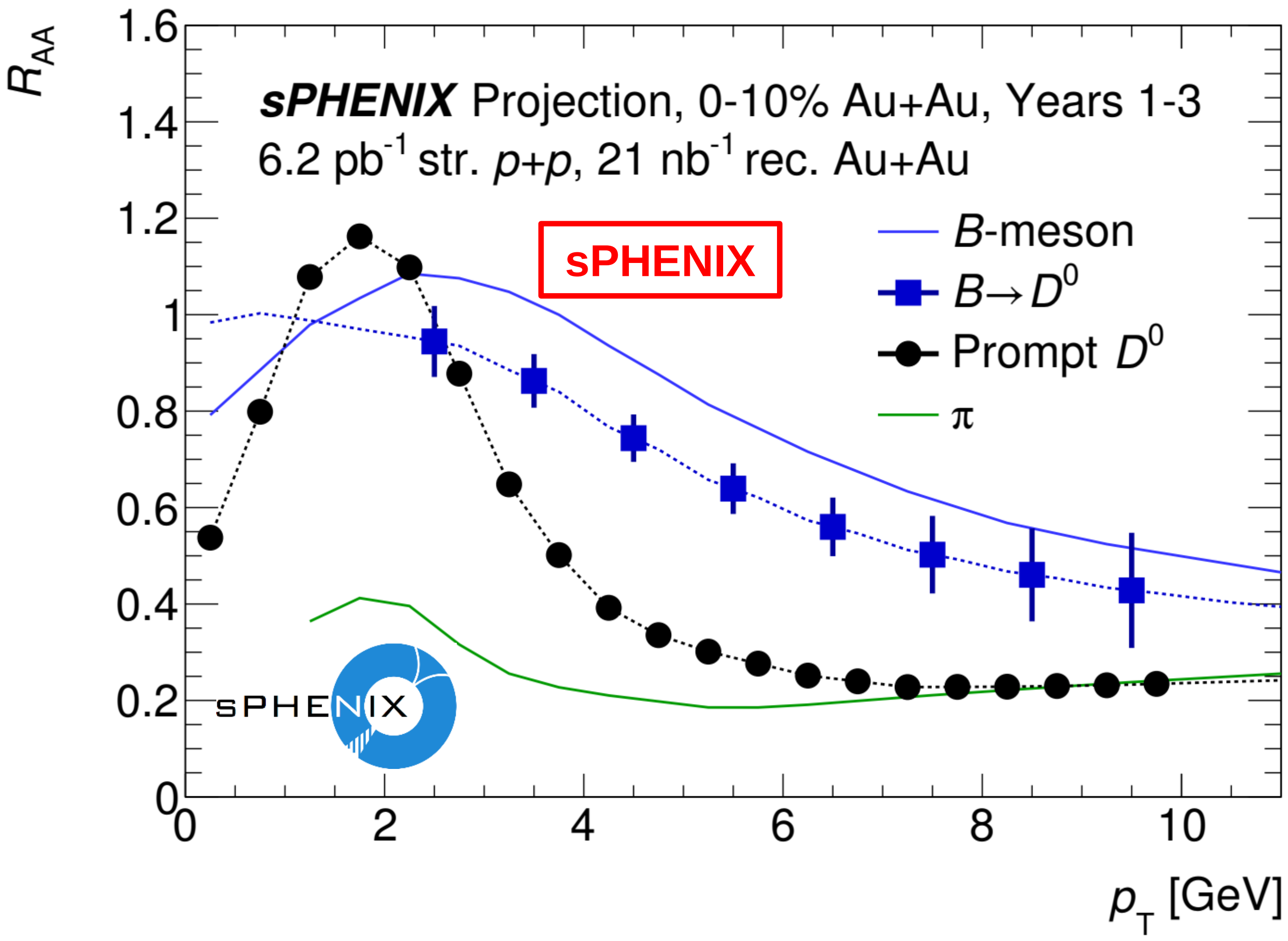
b-jet shape in pp



JHEP 05 (2021) 054

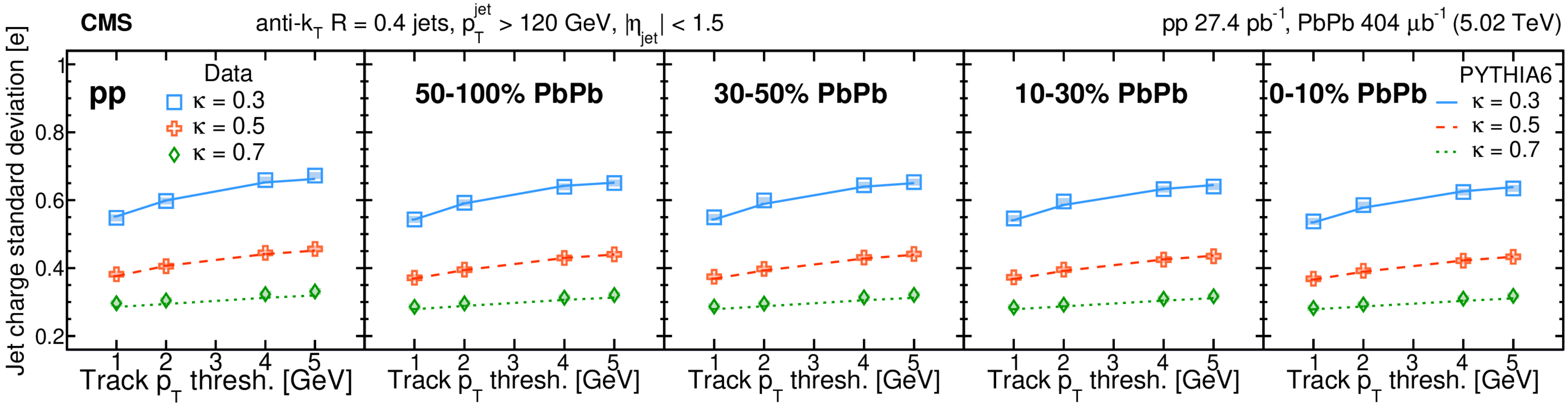
Heavy Flavor vs. Light Flavor

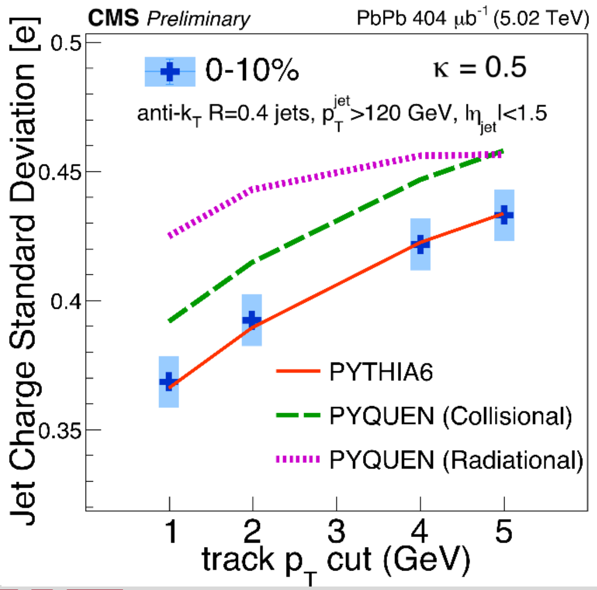




- Expect significantly better accuracy with HL-LHC data and future sPHENIX data

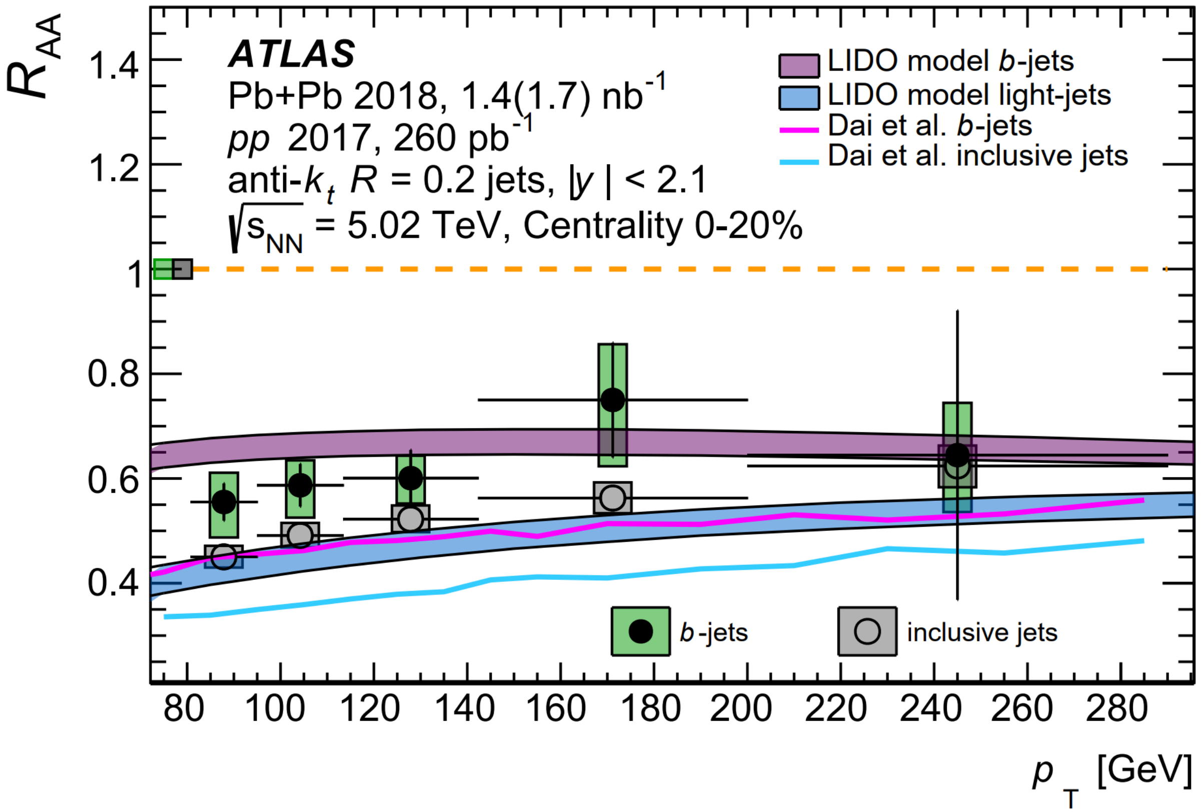
Jet Charge

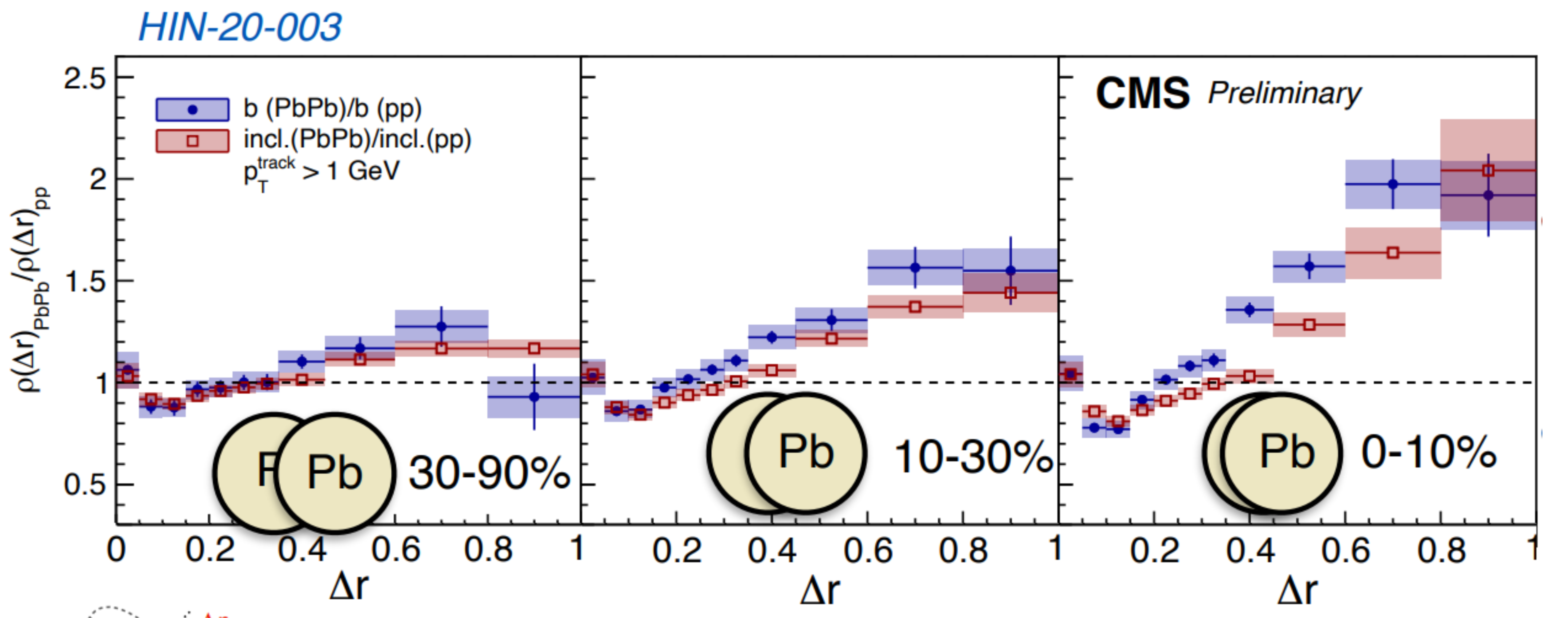


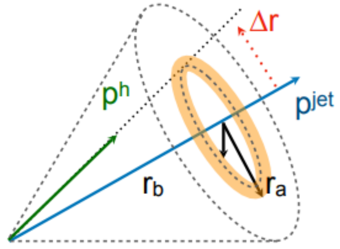


Unmodified jet charge

b-jet vs. Light jet

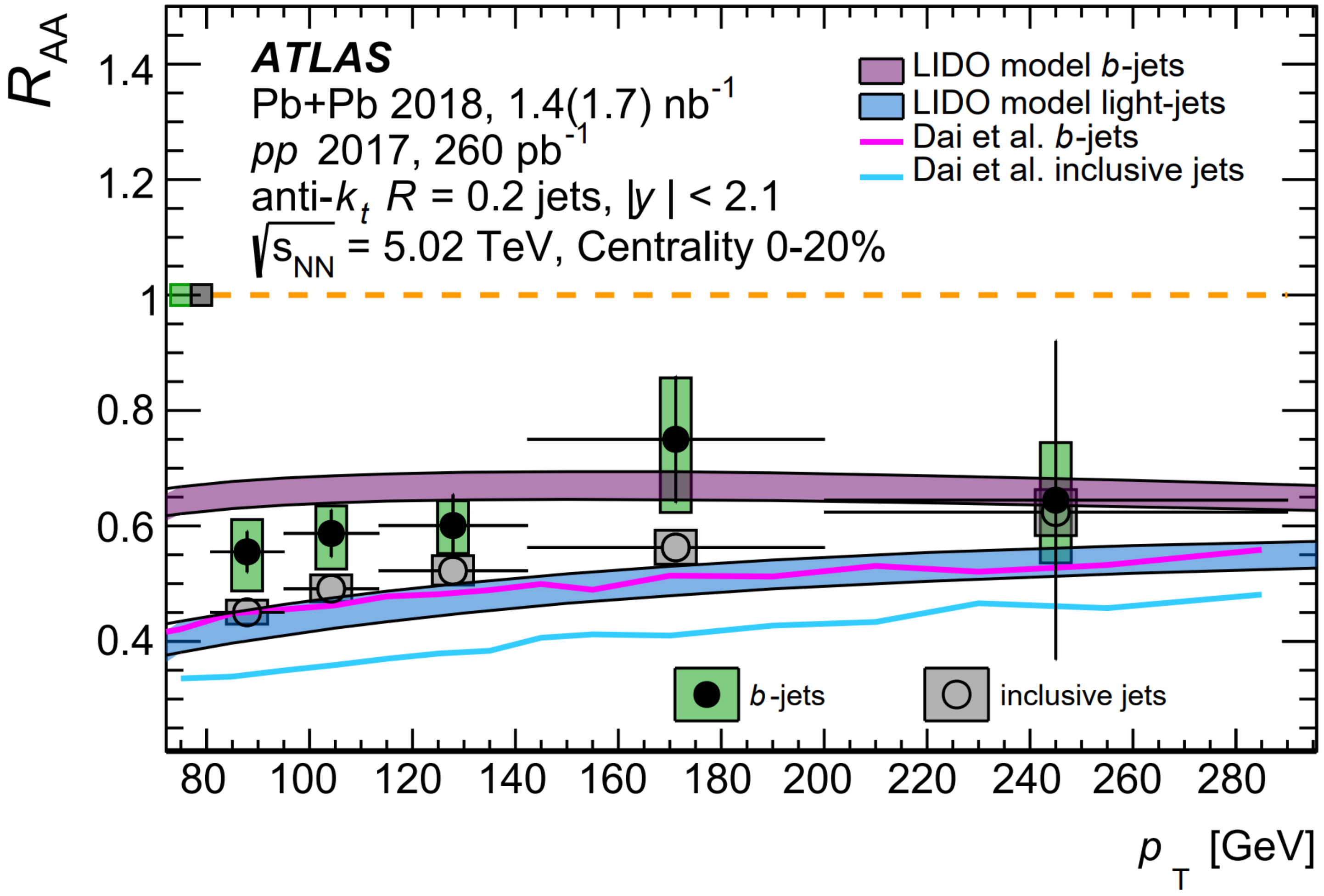




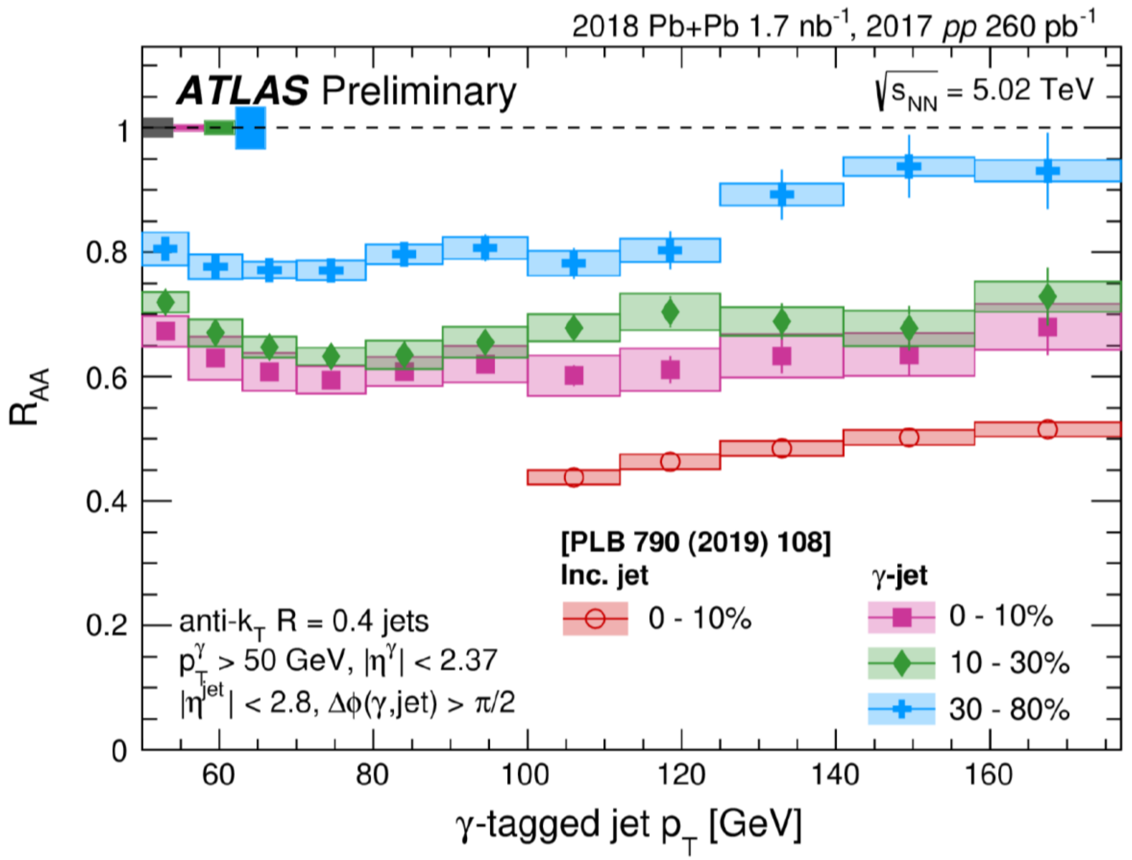


$$\rho(\Delta r) = \frac{1}{\delta r}\frac{\sum_{\text{jets}}\sum_{\text{particle}\in(\Delta r_a,\Delta r_b)} p_T^{\text{trk}}}{\sum_{\text{jets}}\sum_{\text{trk}} p_T^{\text{trk}}}$$

b-jet vs. photon-tagged jet

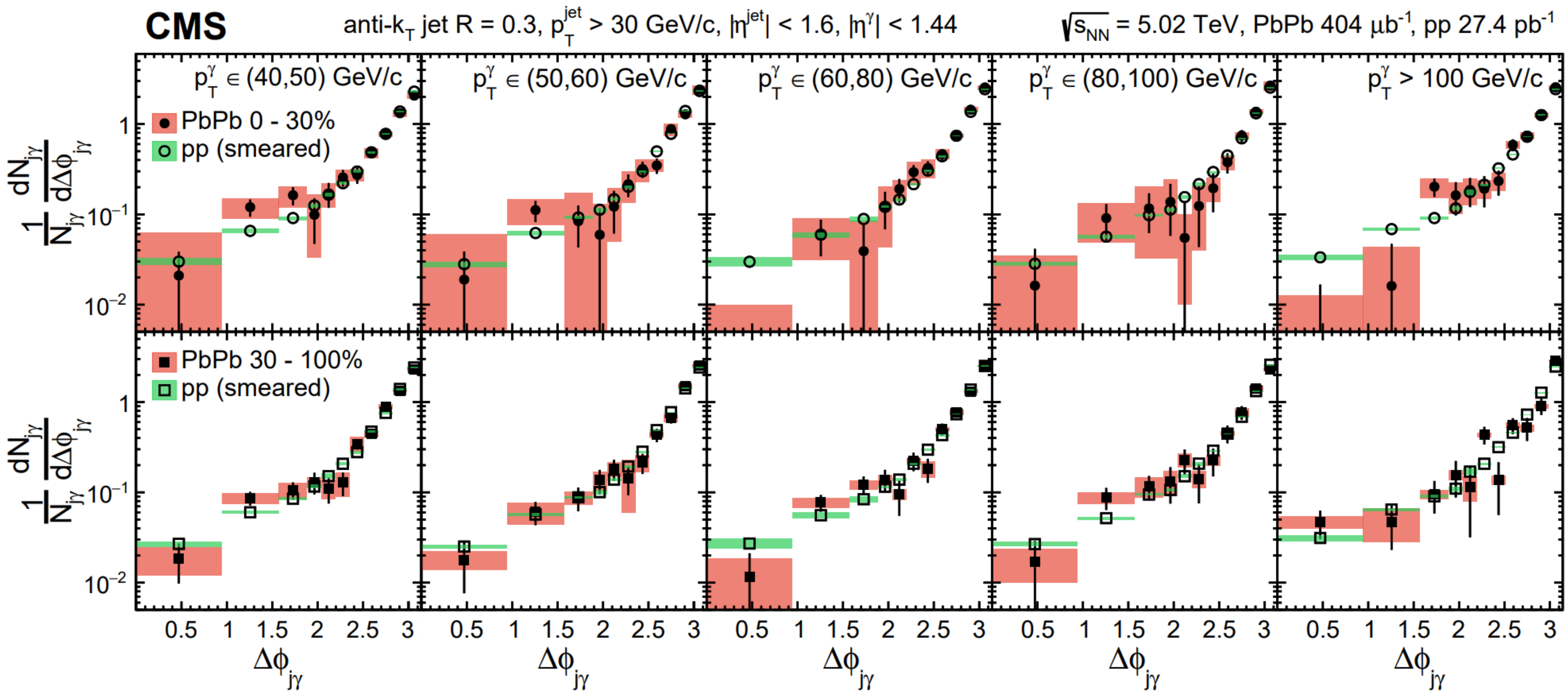


Photon-tagged jet and **inclusive jet**



Similar supporession between b-jet (~50% from gluon splitting) and photon-tagged jet (~20-30% gluon jet)

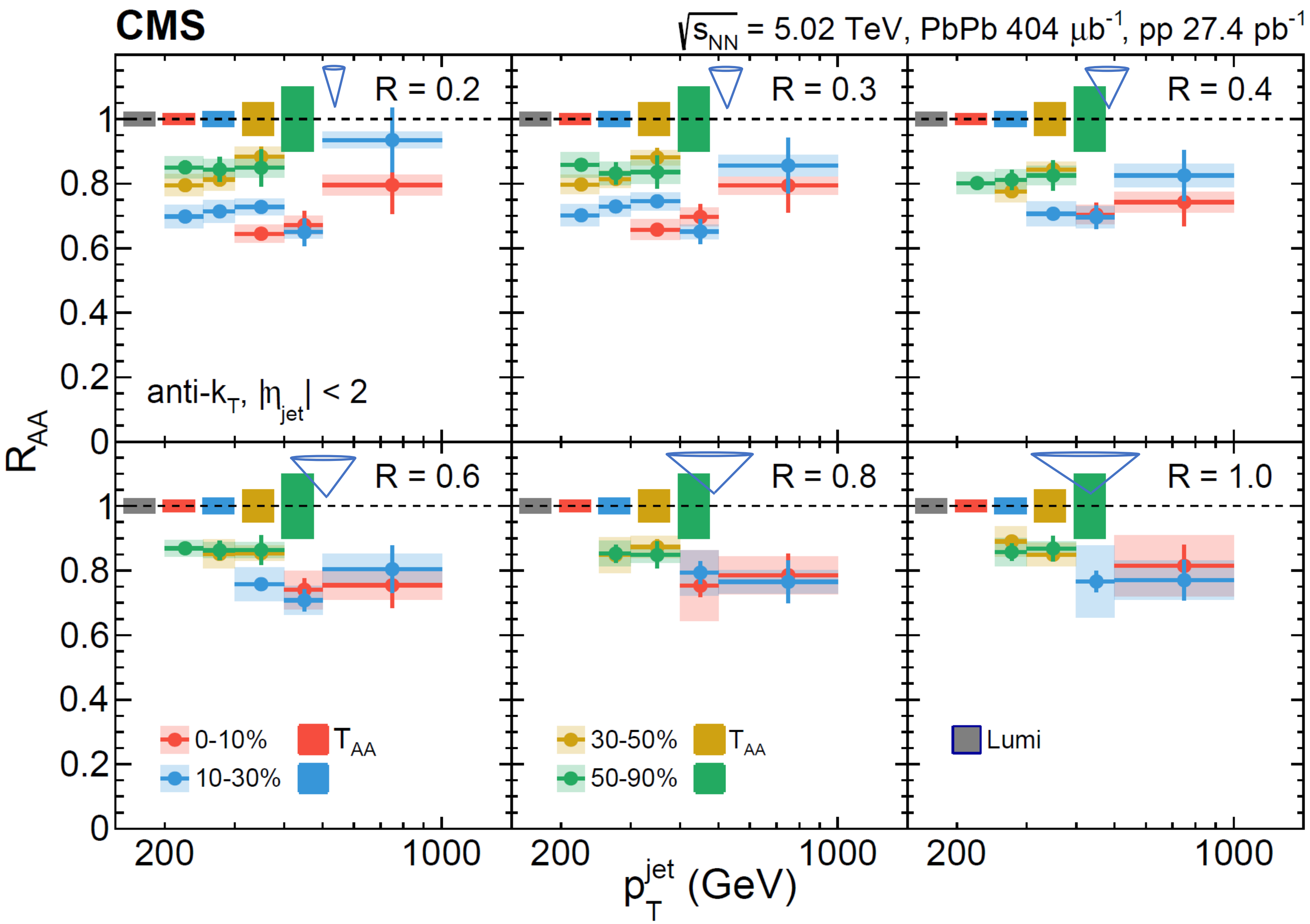
CMS Photon-Jet Azimuthal Angle Correlation



- No sign of modification within the uncertainties

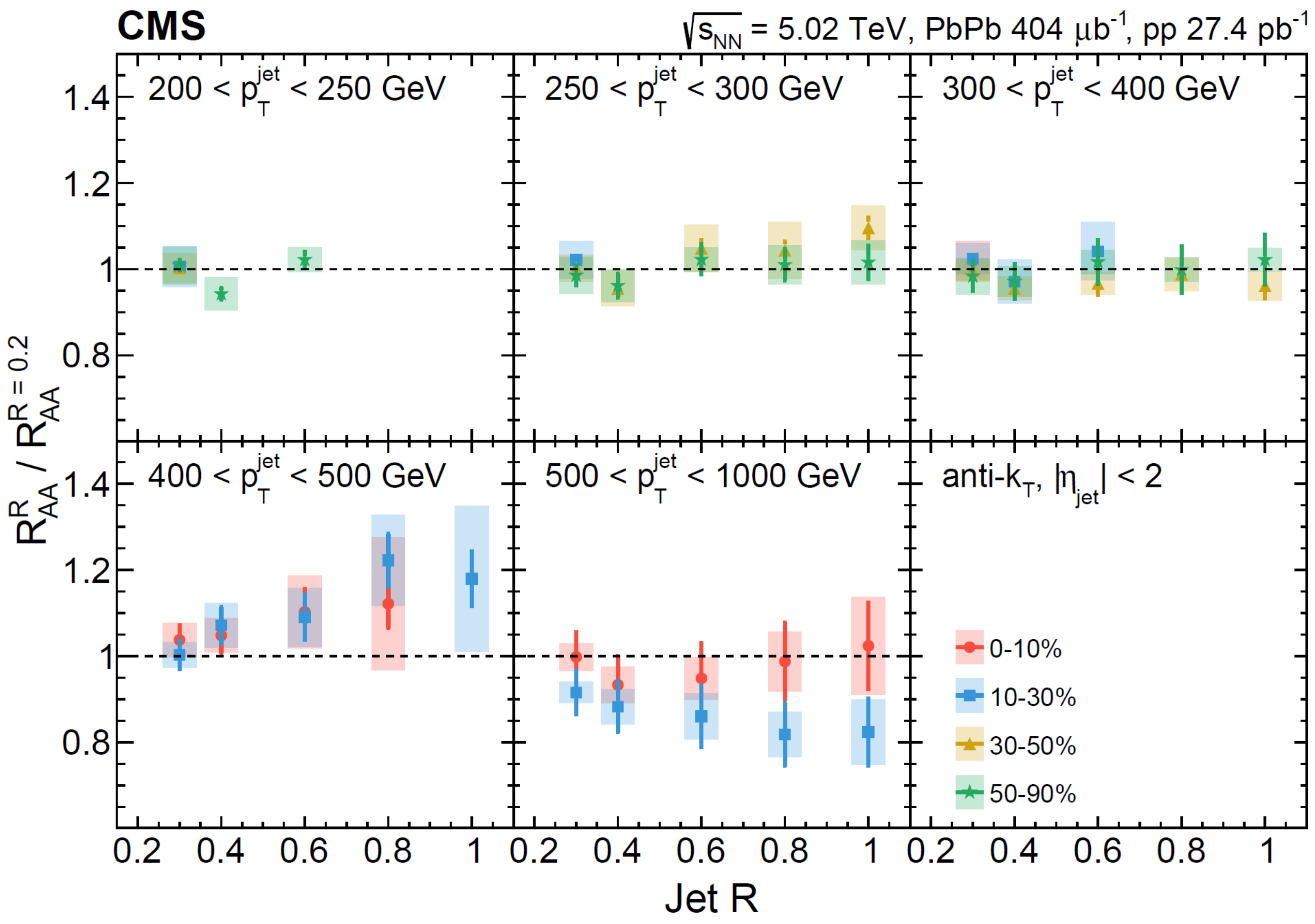
PLB 785 (2018) 14

Jet R_{AA} in Different Centrality Bins



- Large radius jets at high p_T are **suppressed by a factor of around 20-30%**
- Less suppression in the peripheral events

Jet R_{AA} Ratios in Different Centrality Bins



R_{AA} ratios are close to 1 (except 10-30%)

Quenched Energy Flow at RHIC

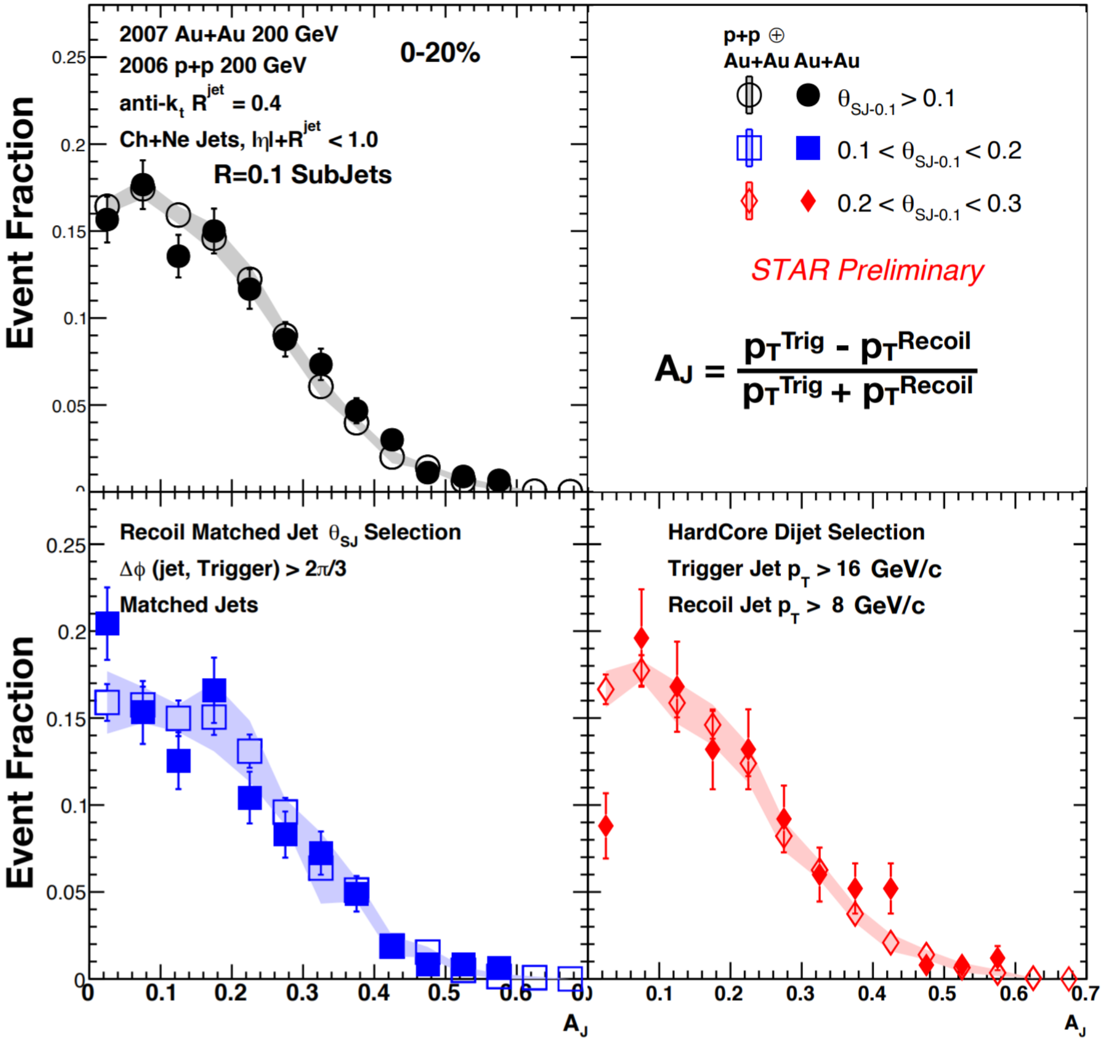
Slide shown by RKE, HP 2018

Matched

A_J

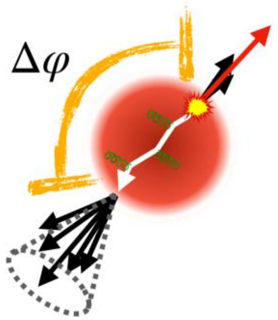
p_T^{const} > 0.2 GeV/c

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



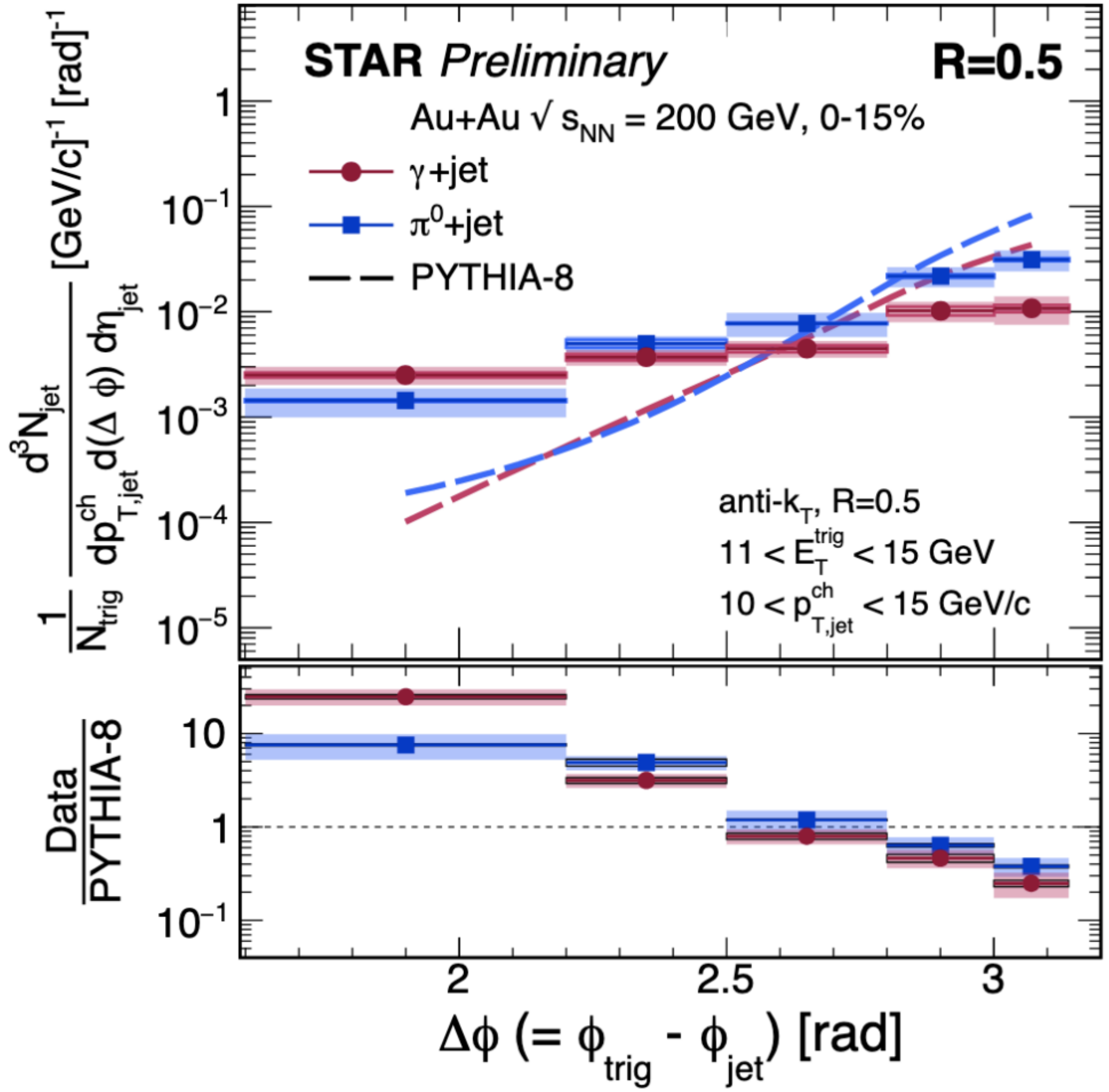
- STAR high tower triggered A_J : lost energy recovered within R=0.4
- On the other hand, STAR h-Jet and PHENIX γ-hadron correlations (not shown): the quenched energy goes to large angle

Photon-Charged Jet Azimuthal Angle Difference in AuAu at 5 TeV



R. Cruz-Torres - QM22

Derek Anderson
QM22



- No significant modification with R=0.2 or at higher jet p_T

- Modification of $\Delta\varphi$ in Δ_{recoil} for larger jet area (R=0.4) and low jet p_T (10-20 GeV)
  - Larger jet yield compared to pp

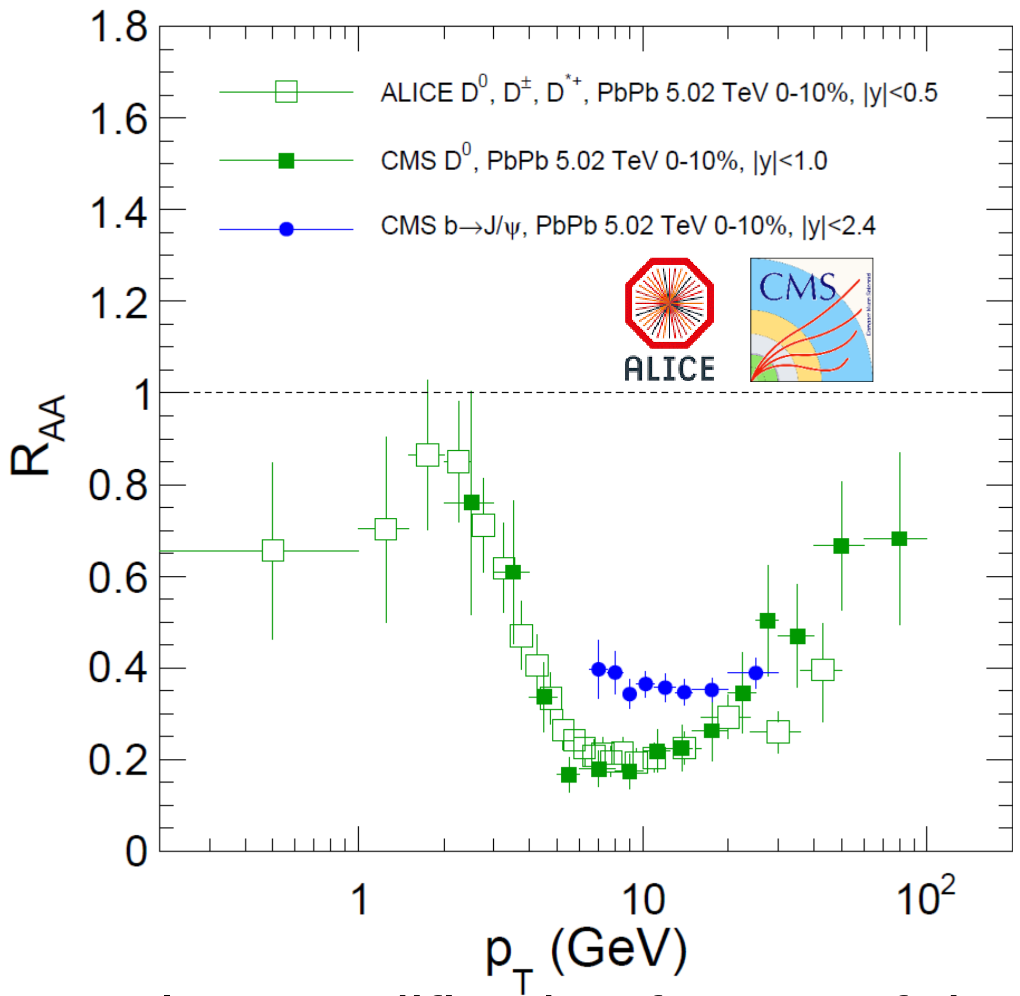
- Likely from the wake contribution (See also hybrid model calculation)
  - Show up at large R and very low p_T
  - Flat jet shape

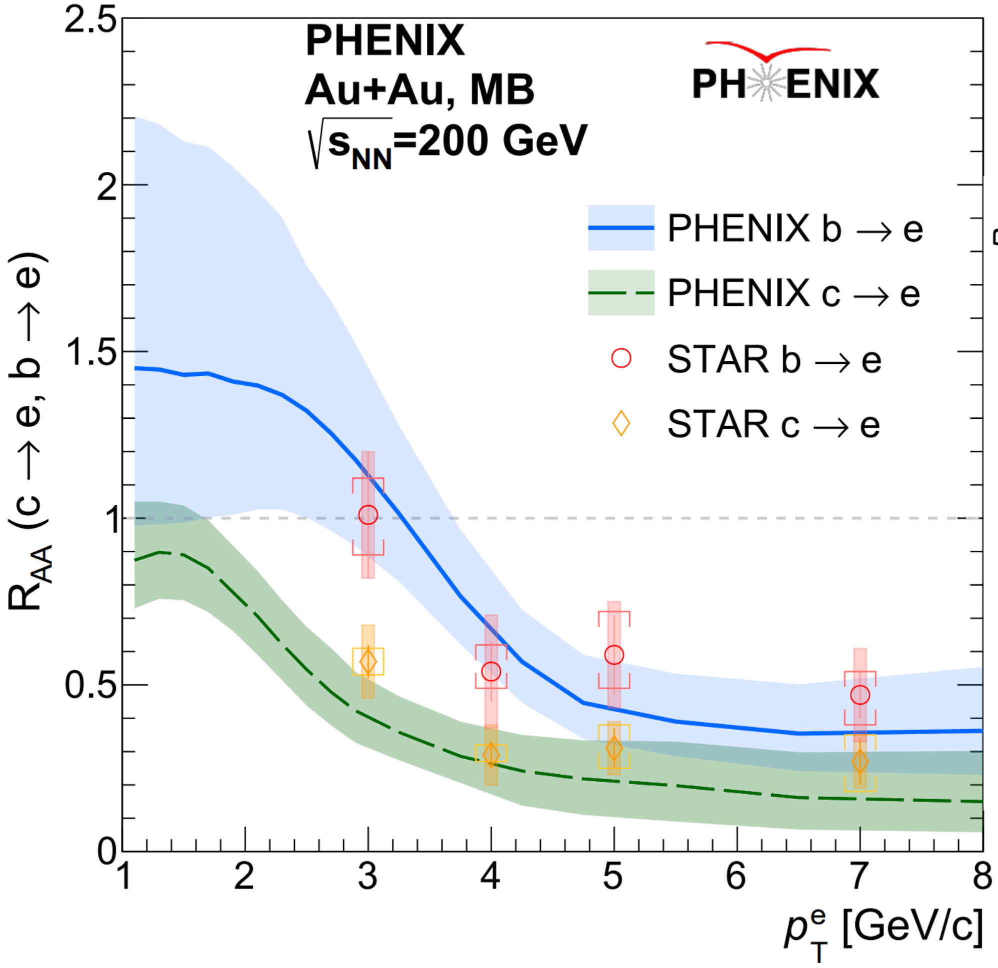
- Contribution from ISR and MPI? (Korinna Zapp's talk)

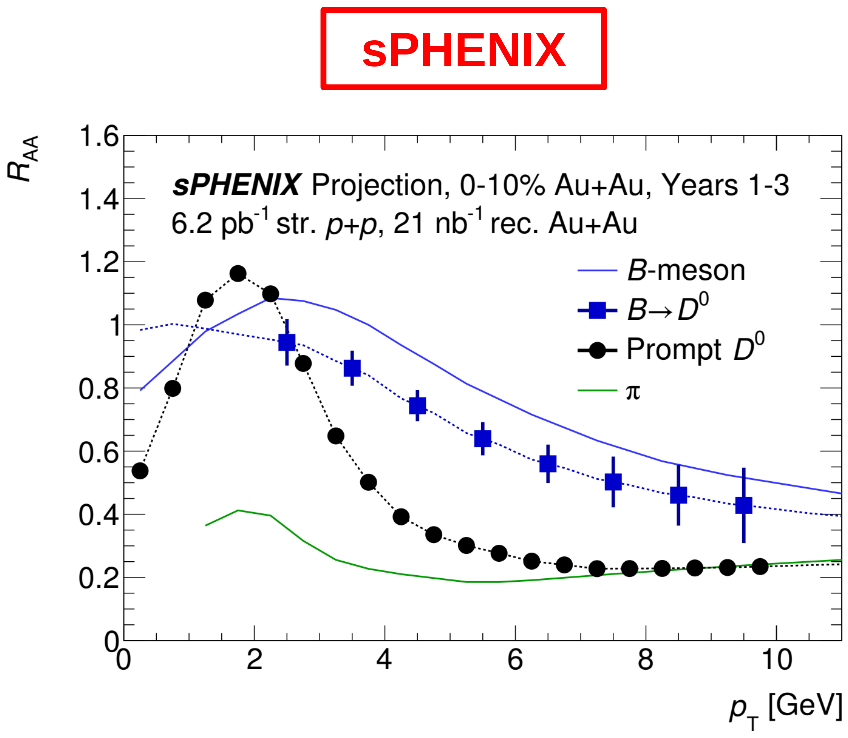
- It would be very interesting to look into the structure of those jets and the R dependence of the effect

- Similar effect from STAR compared to **PYTHIA-8**
- Would be very interesting to repeat this with full jet in sPHENIX and real pp data

Beauty vs. Charm Hadrons

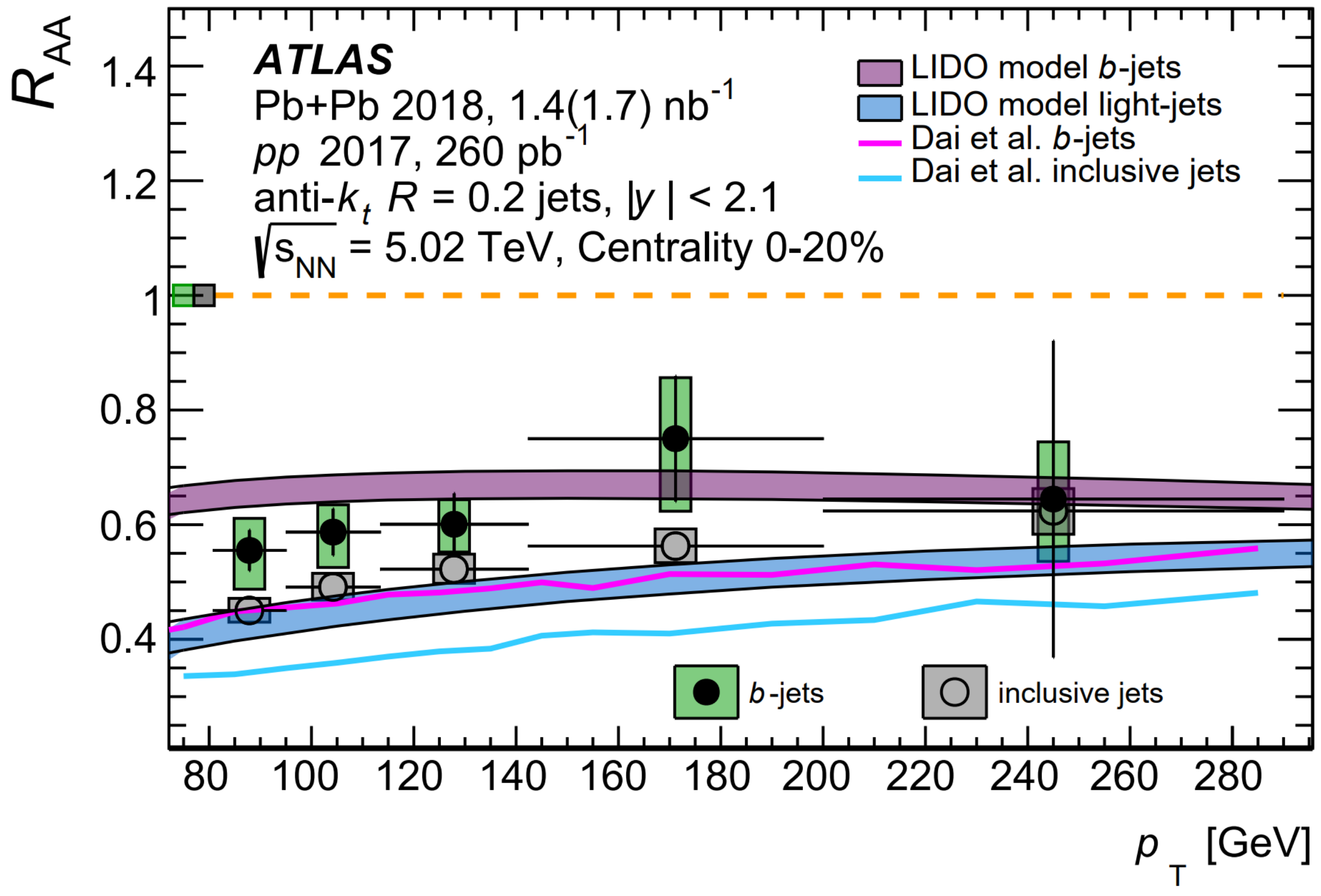


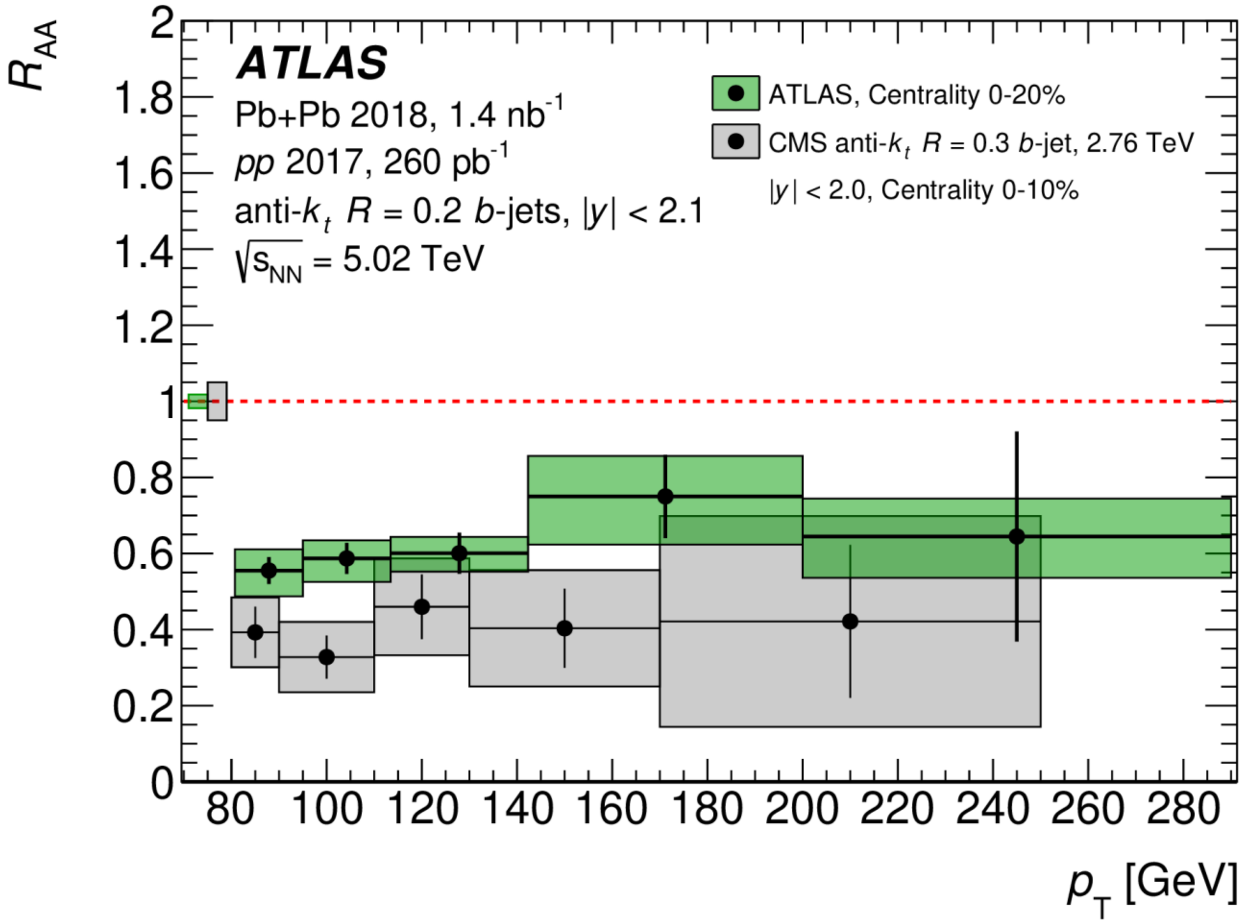




- Nuclear modification factors of depends on quark mass:
  - ALICE and CMS data though various fully / partially reconstructed decay channels at LHC
  - STAR and PHENIX HF electron data at RHIC
  - Observation of the mass dependence at low p_T and disappearance at high p_T
- Expect high precision data from future LHC Run 3+4 and sPHENIX with fully reconstructed hadrons

b-jet vs. Inclusive Jet

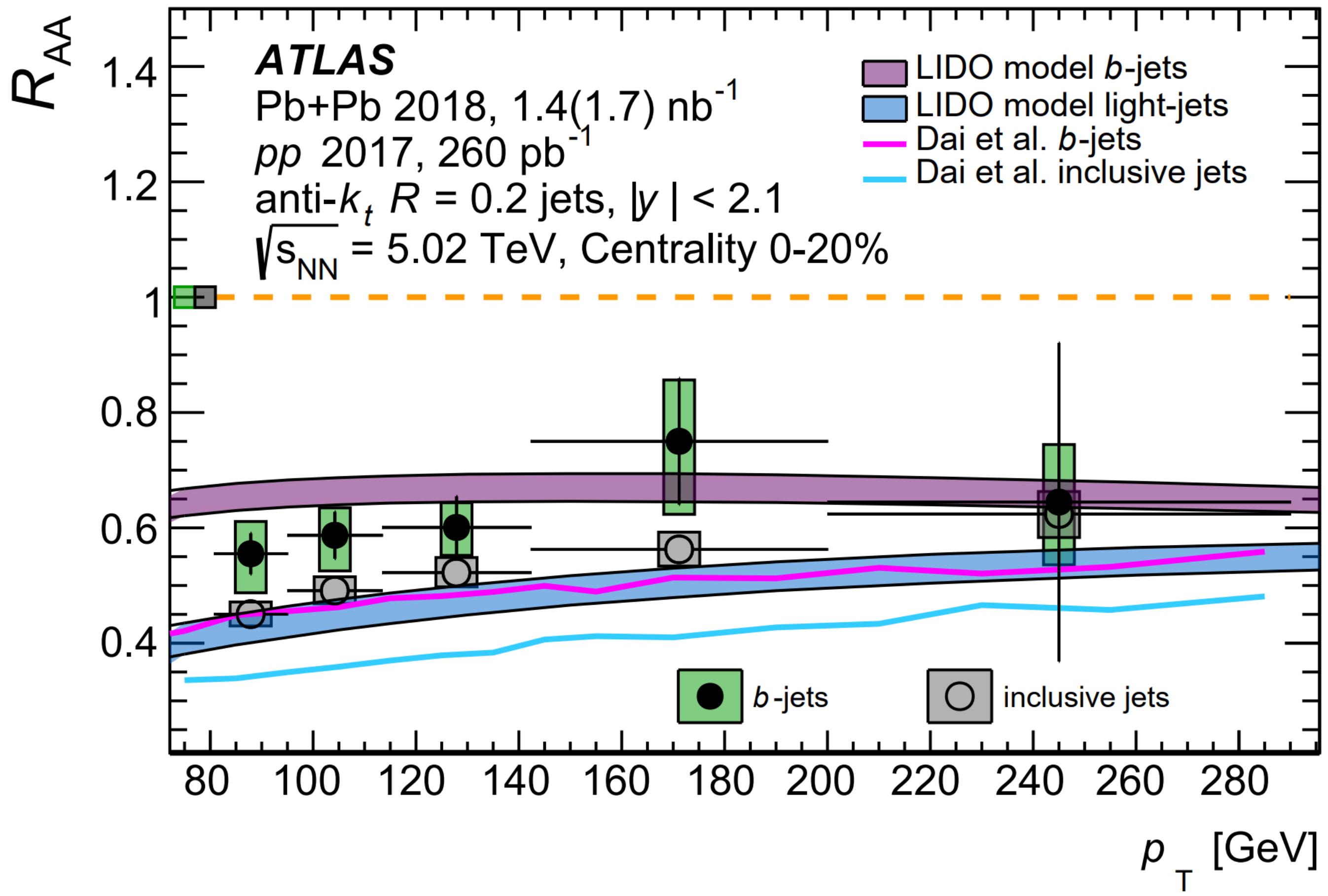


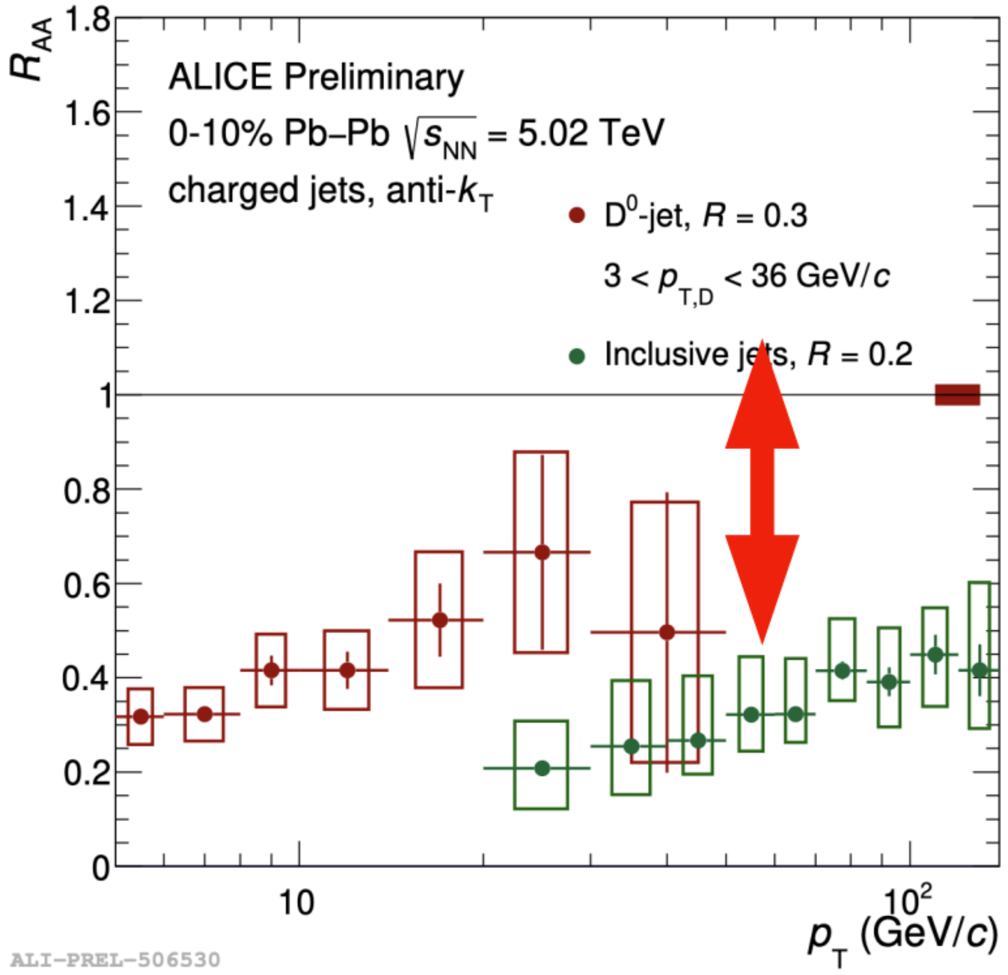


- Significant difference between **b-jet** and **inclusive jet** observed by ATLAS at high jet p_T
- Around 50% of b-jet from gluon splitting process
  - b-jet R_{AA} ~ 0.5-0.6 ~ (1-gluon splitting fraction)

- **ATLAS b-jet R_{AA} at 5.02 TeV** systematically higher than **CMS data at 2.76 TeV**
- Note the difference in collision energy and R parameter.

D^0-jet, b-jet and Inclusive Jet

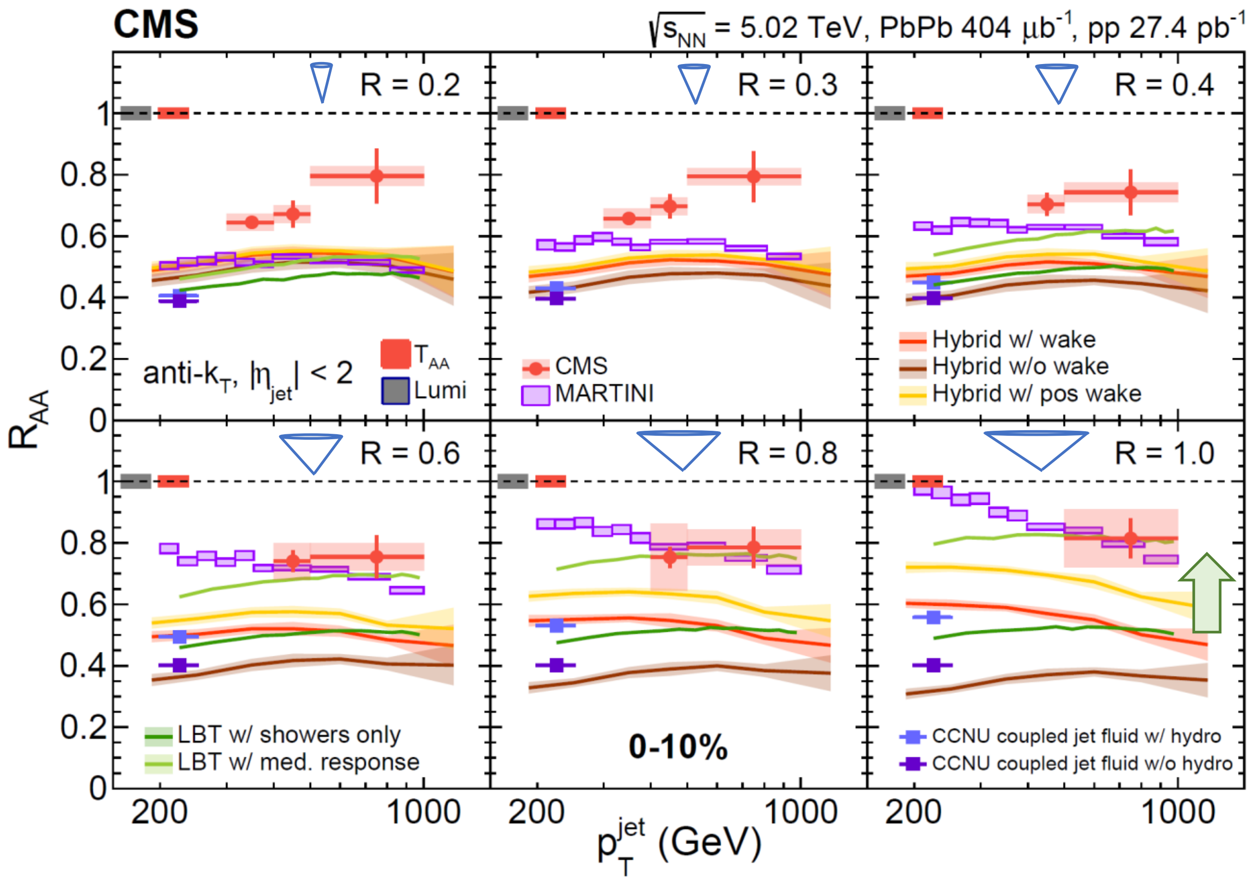


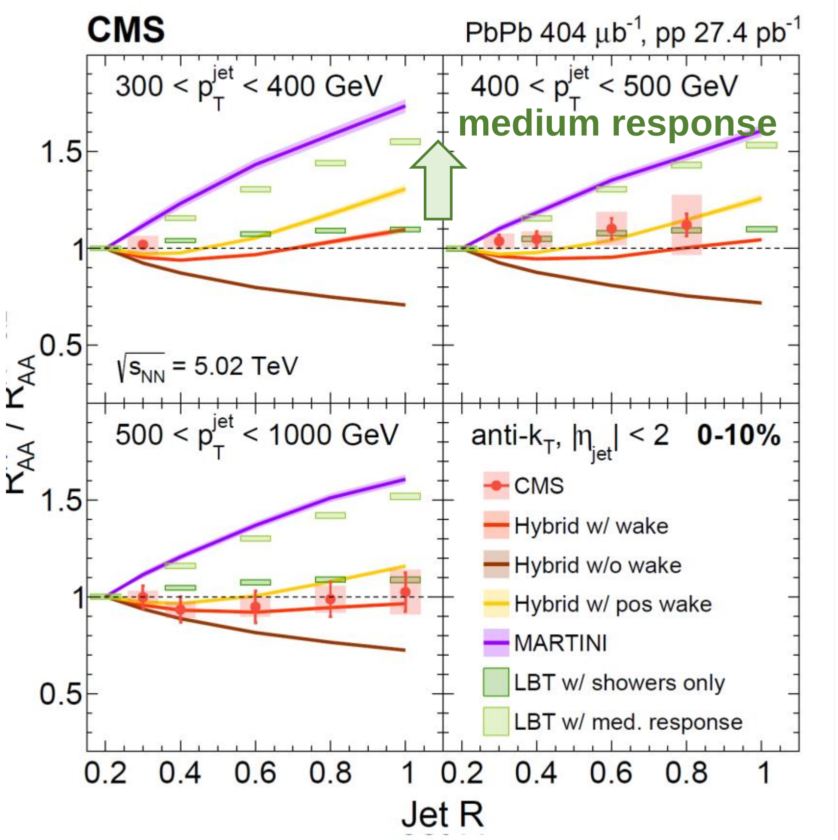


- Significant difference between **b-jet** and **inclusive jet** observed by ATLAS at high jet p_T
- Around 50% of b-jet from gluon splitting process
  - b-jet R_{AA} ~ 0.5-0.6 ~ (1-gluon splitting fraction)

- Indication of less suppression for **D^0-jet** than **inclusive jet** from ALICE

Jet R_{AA} vs. Monte Carlo

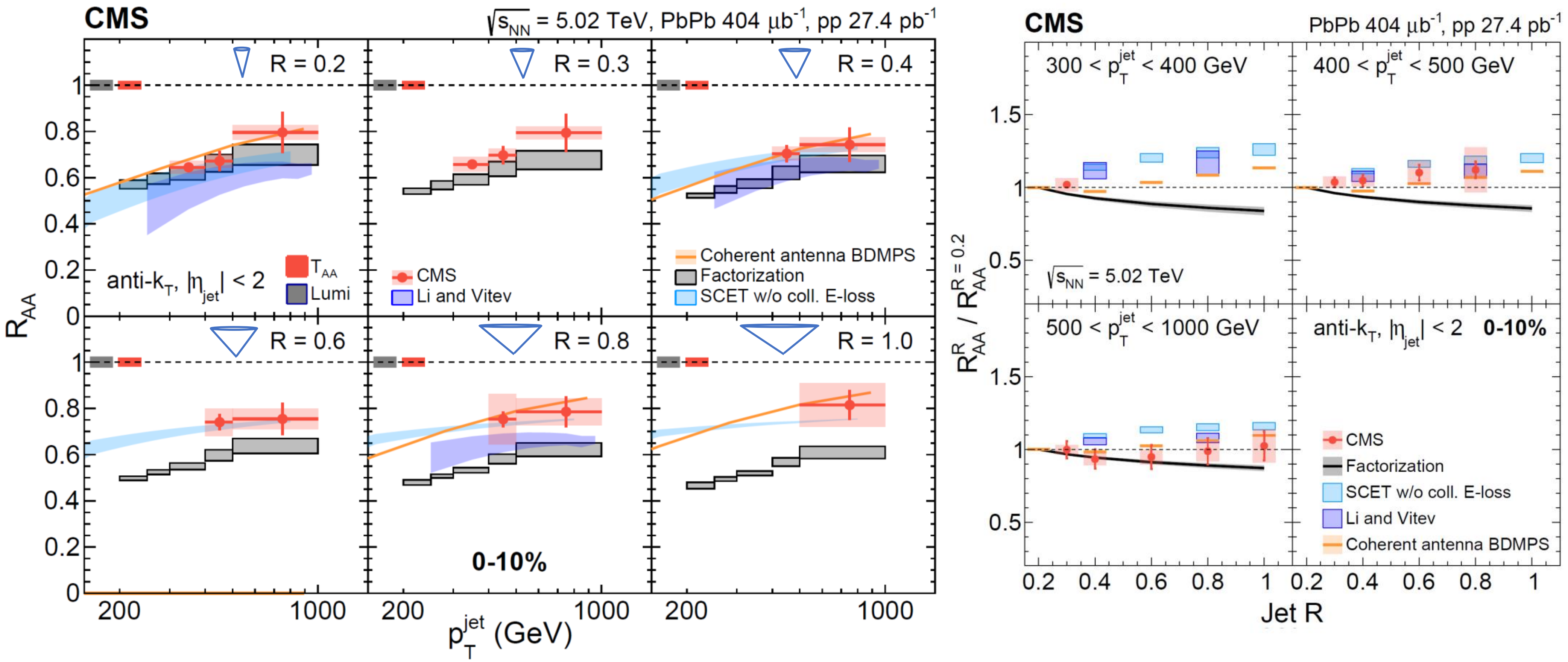




- **MARTINI:** Jet propagate (McGill-AMY) in evolving hydrodynamic medium. Overestimates R dep.
- **LBT:** Recoil thermal partons and their propagation in the dense medium are described by a 3+1D viscous hydro model. Shows the importance of **medium response**. Overestimates R dependence.
- **Hybrid:** A hybrid model of pQCD (for shower generation) and AdS/CFT drag force. Diffusion wake reduces the jet suppression. Overestimate the jet suppression.
- **CCNU jet-fluid:** includes both collisional, splitting and p_T broadening in a viscous hydro medium. Shows the importance of hydrodynamic component increases as a function of R

MARTINI PRC 80 (2019) 054913 | LBT PRC 99 (2019) 054911 | Hybrid JHEP 03 (2017) 135 | CCNU jet-fluid PRC 94 (2016) 024902

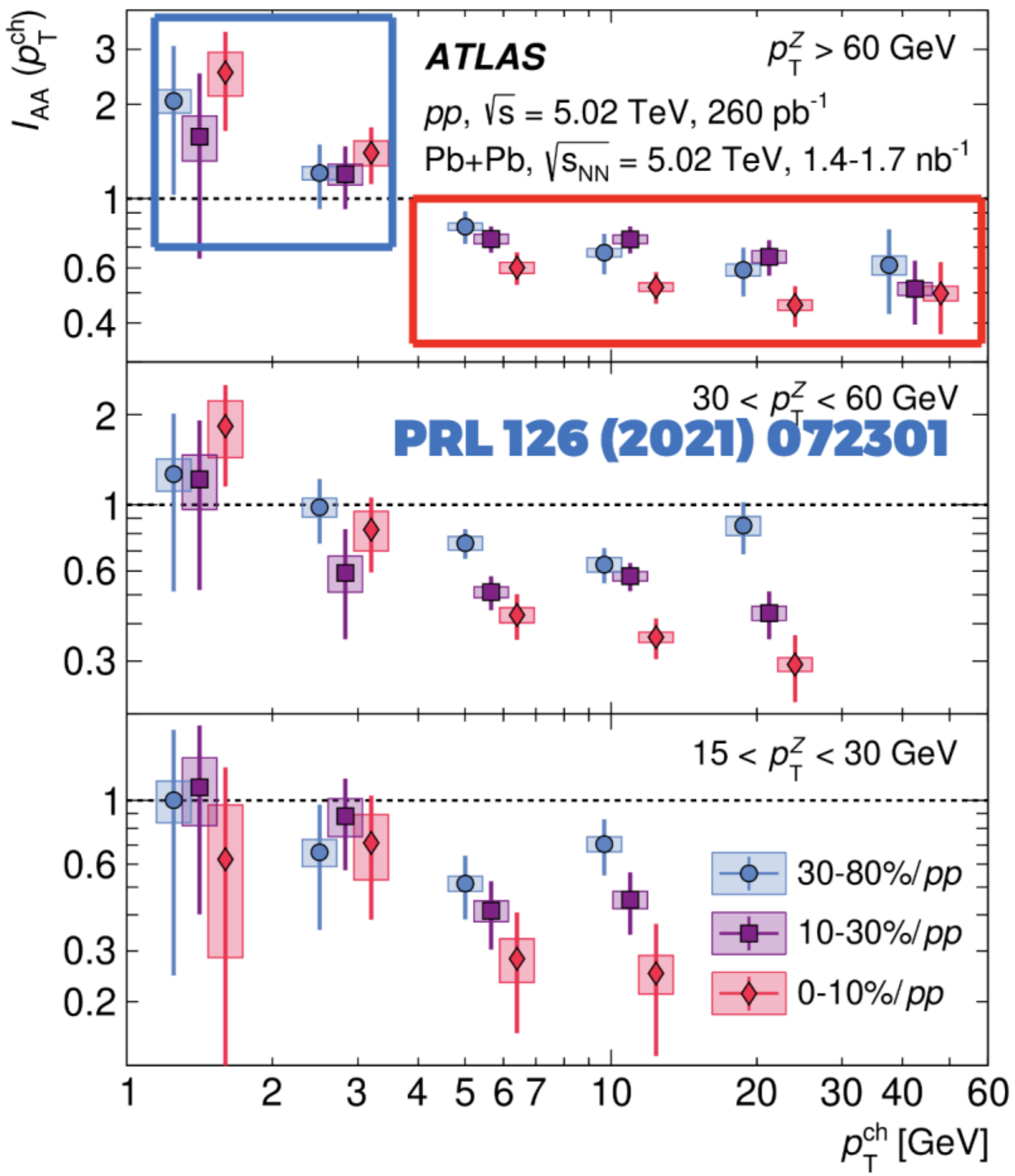
Jet R_{AA} vs. Calculations

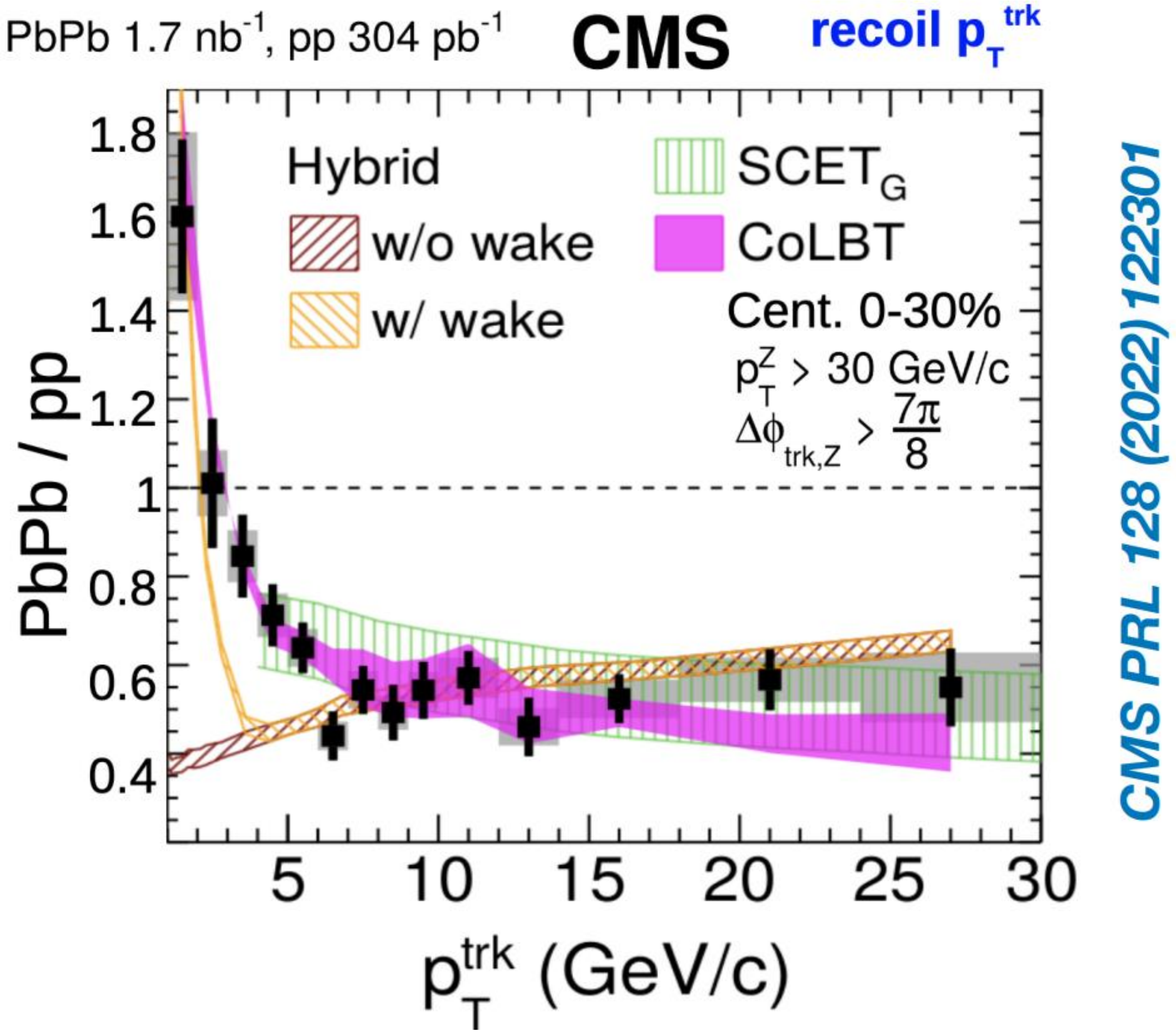


- **Factorization:** Factorization of jet cross sections. Medium-modified jet functions extracted from jet R_{AA} at R=0.2 & 0.4. Underestimates R dependence: **factorization breaks down for large area jet?**
- **$SCET_G$:** without collision energy loss, soft-collinear effective theory based method coupled with a Glauber gluon medium. Good agreement with the data.
- **Li and Vitev:** $SCET_G$ with collision energy loss and cold nuclear matter effect. Slightly underestimate R_{AA}
- **Coherent Antenna BDMPS**: an analytical approach that resums multiple emissions to leading logarithmic accuracy including radiative energy loss and color coherence effects. General agreement with data

Factorization PRL 122 (2019) 252301 | Li and Vitev JHEP 1907 (2019) 148 | $SCET_G$ w/o coll E. loss: JHEP 1905 (2016) 023 | Coherent antenna BDMPS: PRD 98 (2018) 051501

Z-tagged Hadron Spectra

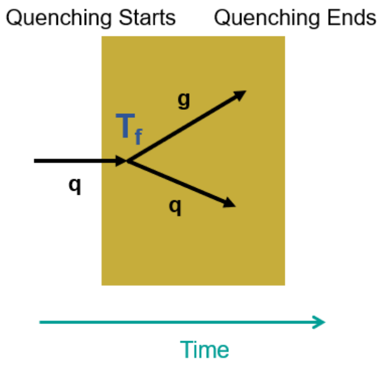




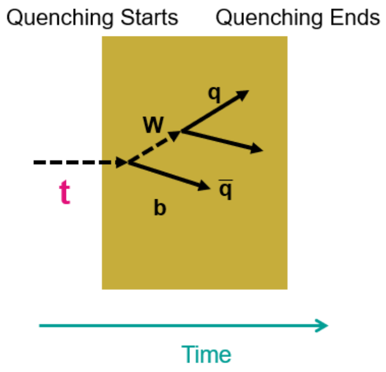
- Low p_T particle enhancement reported by ATLAS & CMS
- Associated with medium response in CoLBT and **Hybrid** model

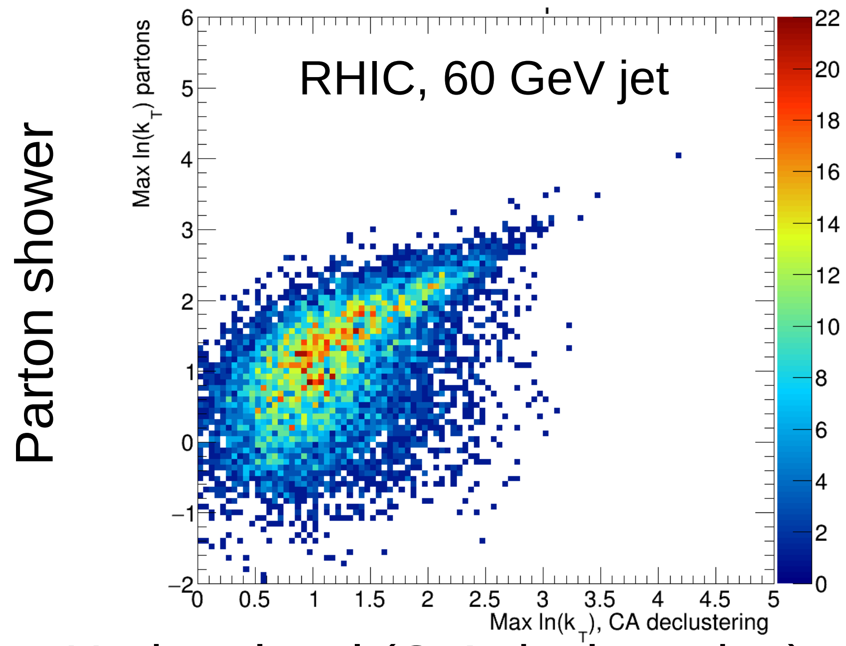
Time Dependent Evolution of QGP

Formation Time (T_f) Tagging

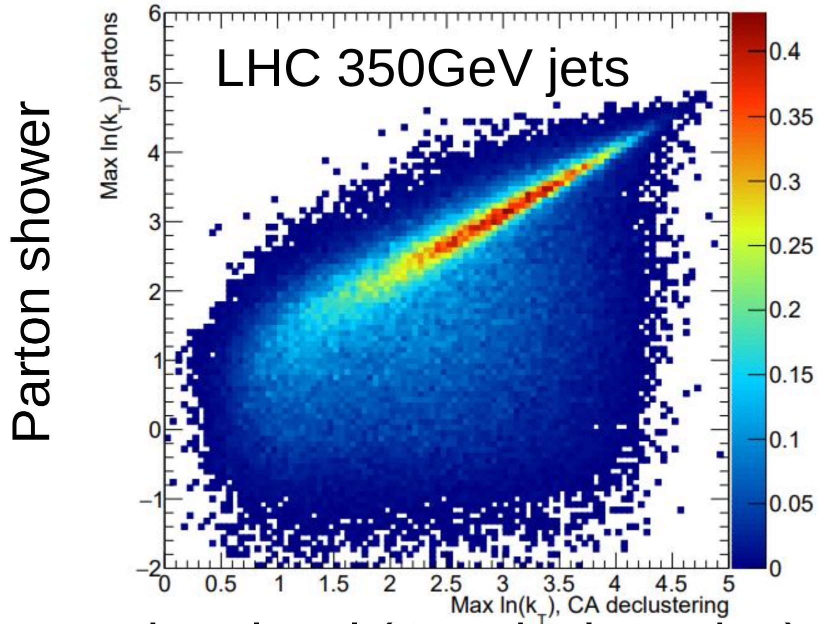


Boosted Top

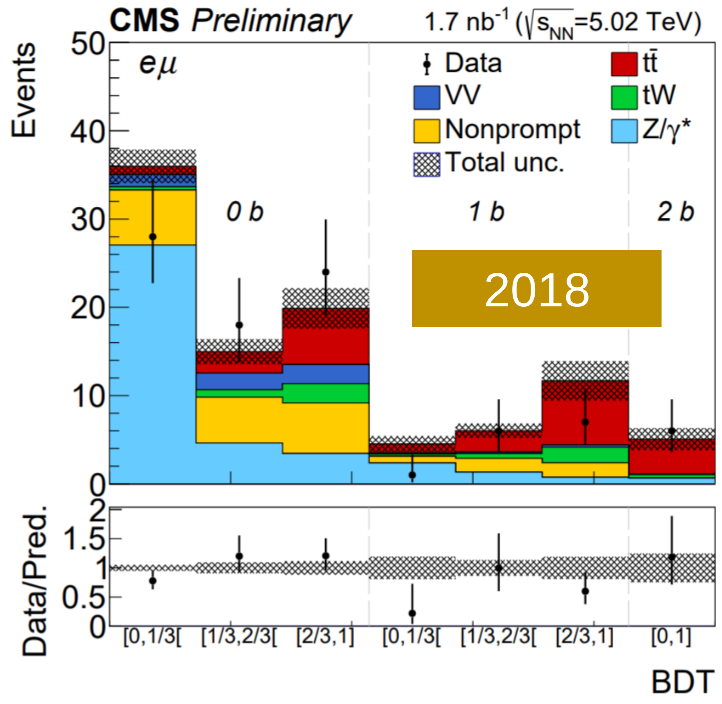




Hadron level (C-A declustering)



Hadron level (C-A declustering)



2018 data: 3.8σ

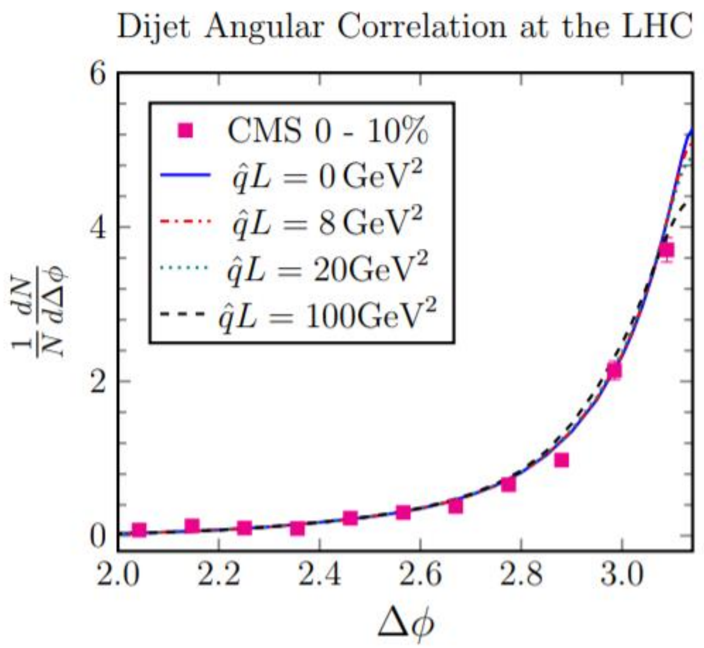
Observation of Top production in Run 3

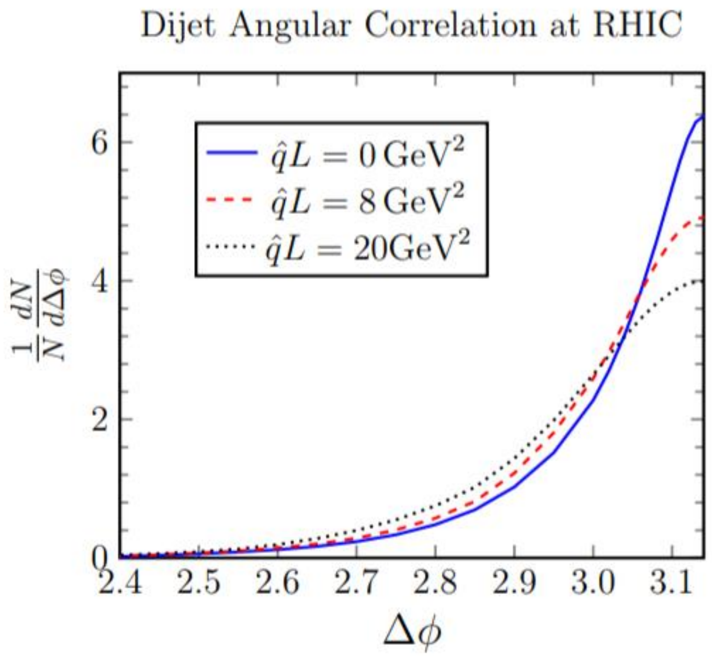
Yi Chen + YJL + EMMI Jet taskforce

QGP Rutherford Experiment

- First sign of modified azimuthal angle correlation between trigger particle and jet at low jet p_T and large R
  - Why is the effect goes away so fast vs. jet p_T and R?

- Possible Follow-up:
  - Measurement with photon(Z)-tag and pp reference from data
  - Backscattering:
    - Need next level of accuracy and resolution at small ΔΦ and high statistics at large ΔΦ at LHC
    - High statistics photon(Z)-jet
    - Perform Photon-D, DDbar and D in jet with LHC expts and sPHENIX
  - Broadening effect at ΔΦ~π:
    - More promising at RHIC energy where the correlation is less affected by initial state radiation (sPHENIX)
    - New observables which work around the ISR effect

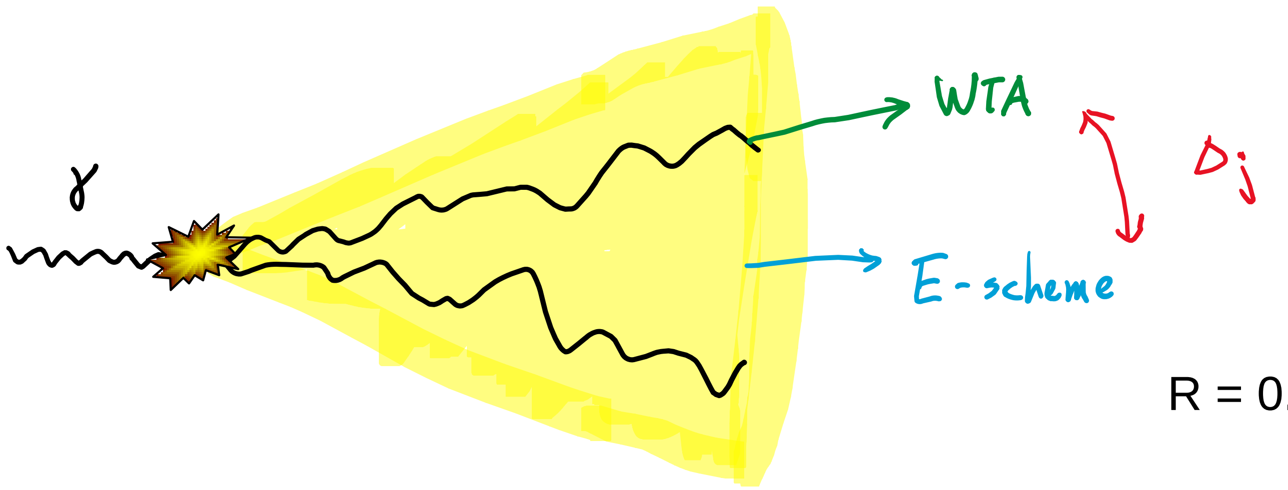




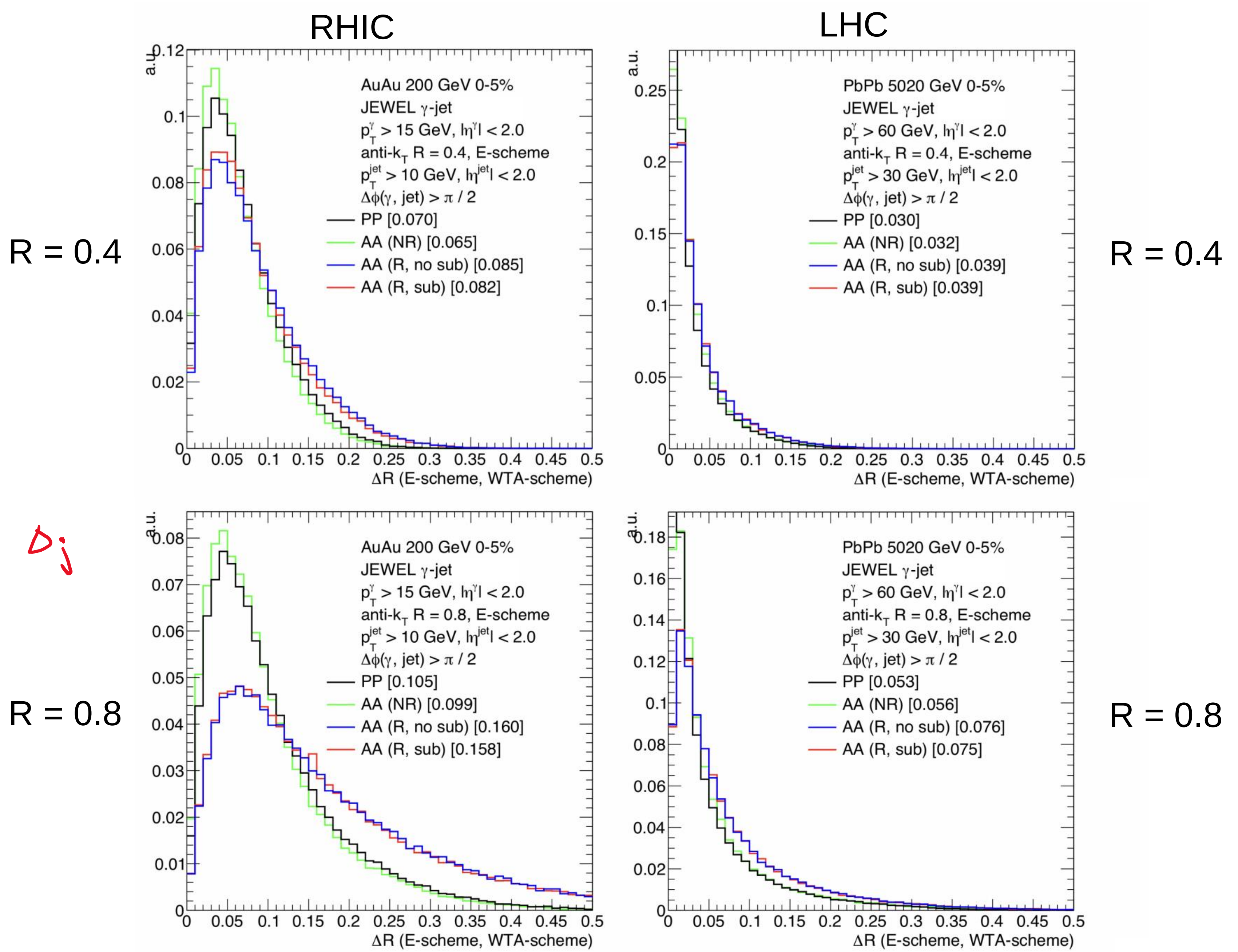
Mueller, Wu, Xiao and Yuan
PRD 95 (2017) 3, 034007
PLB 763 (2016) 208

Future Measurement: Photon-tagged Jet Δ_j (WTA, E-scheme)

- The angular separation of jet axes (Δ_j) calculated with **energy weight ("E-scheme")** and a **winner-take-all (WTA)** scheme
- **WTA** follows the leading energy flow, has larger sensitivity to $\hat{q}$ than **E-scheme**, where the effects are averaged out



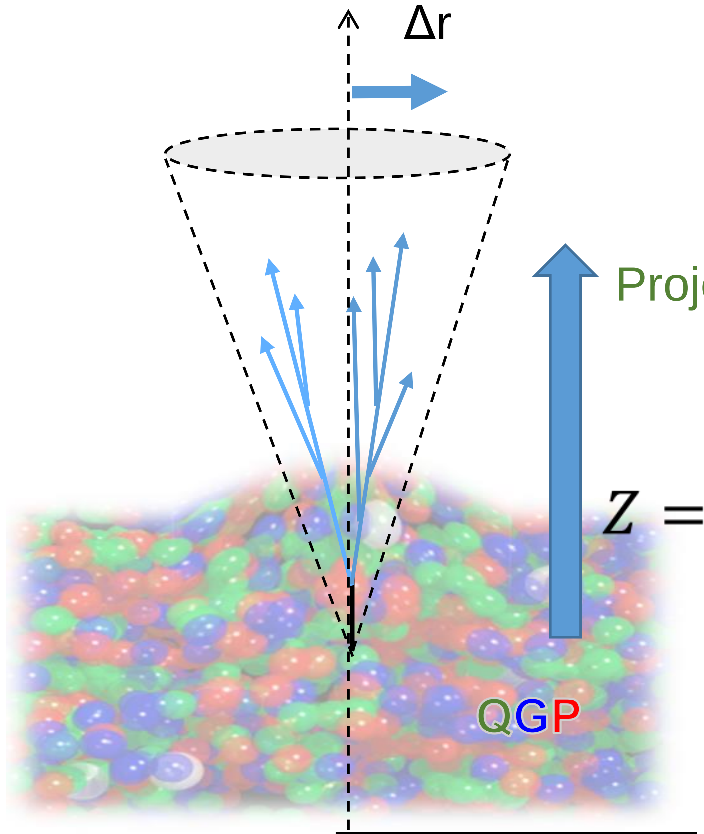
- Significant modification of Δ_j predicted by studies with photon-tagged jet with JEWEL



Yi Chen, Kaya Tatar, YJL

Jet Longitudinal Structure

Jet axis



Projection to jet axis

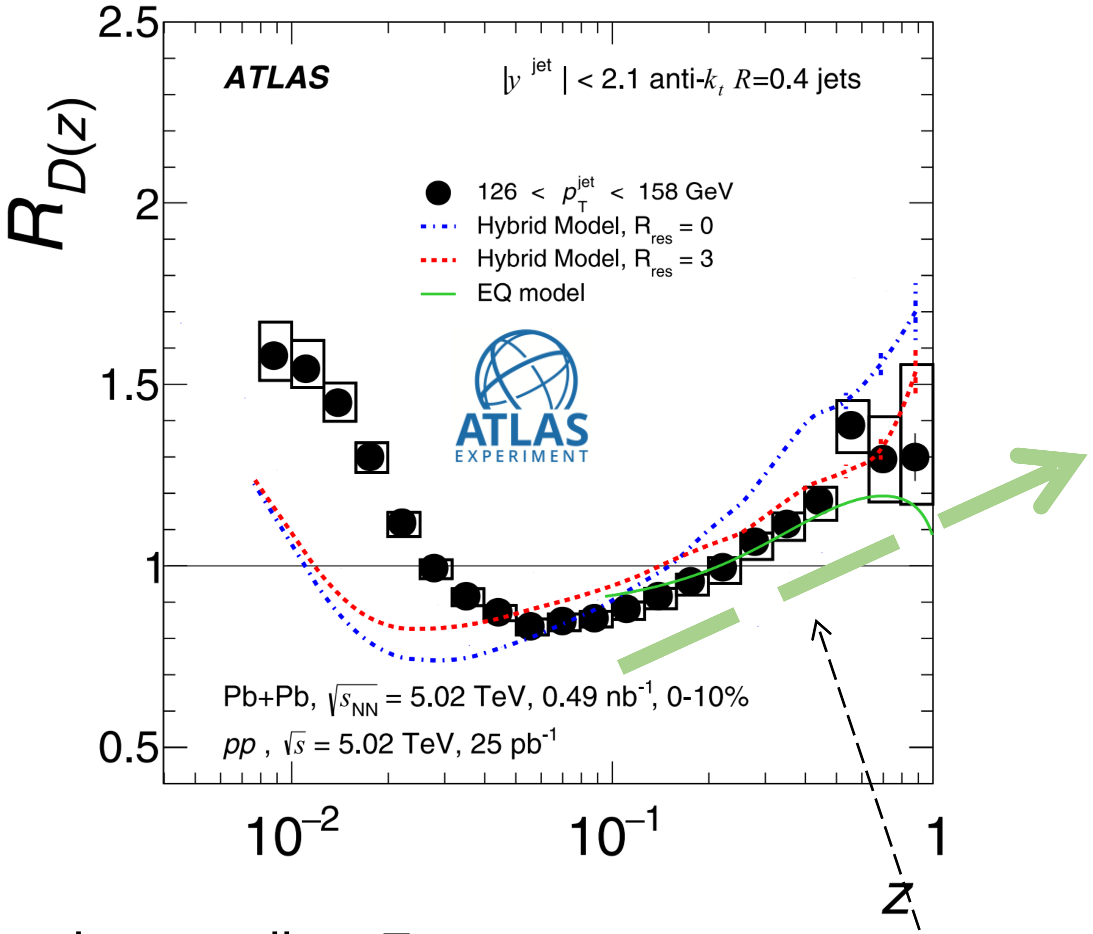
$$Z = \frac{p_T^{Trk} \cos \Delta r}{p_T^{Jet}}$$

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

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

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

PRC 98 (2018) 024908



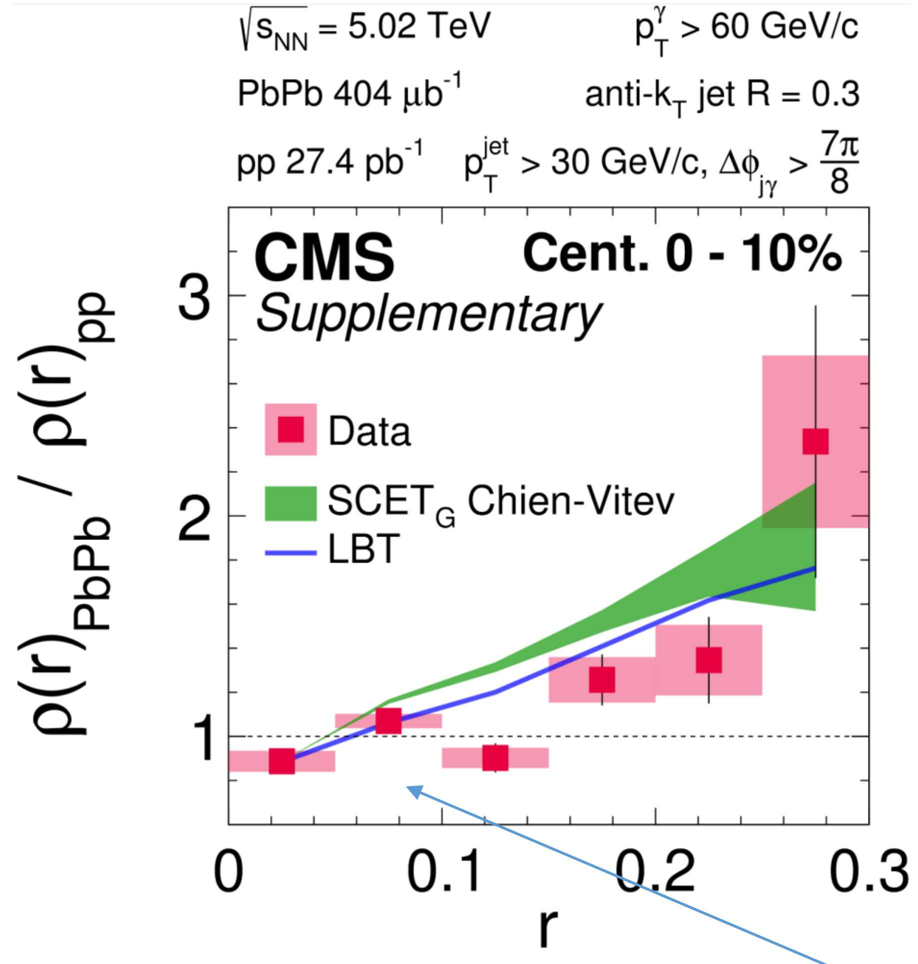
- Enhancement at low p_T (low Z) and depletion at intermediate Z
- Enhancement at large z (high p_T particles in jet): **smaller gluon/quark ratio** in PbPb
- High Z region: Weak or no dependence on the jet p_T

See discussions in Frank Ma, thesis (2013)
EPJC 76 (2016) 2, 50 Martin Spousta, Brian Cole

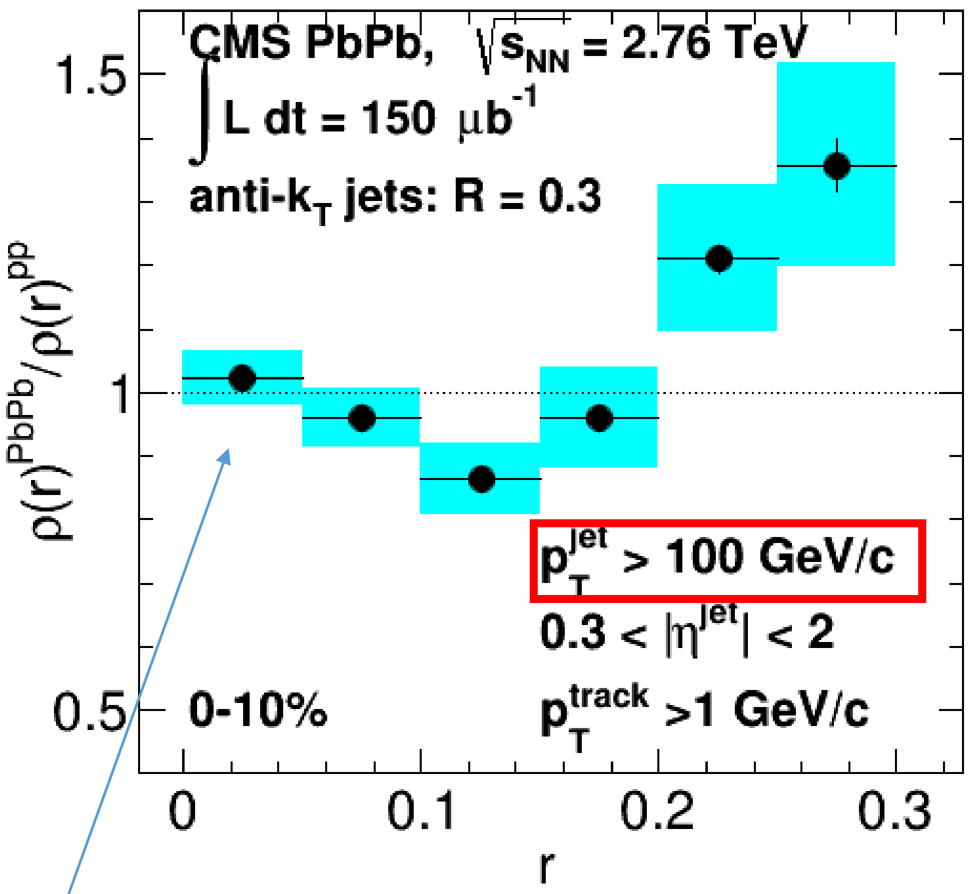
If switch to γ-tagged jet (mainly quarks), will this enhancement go away?

Photon-Tagged Jet and Inclusive Jet Shape

Photon-tagged (Quark Enriched)



Inclusive (Quark + Gluon)



CMS-HIN-18-006
PRL 122 (2019) 15, 152001

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

- 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
- Follow up with high p_T photon-tagged jet

Parton Flavor Dependence of Jet Energy Loss

Current status:

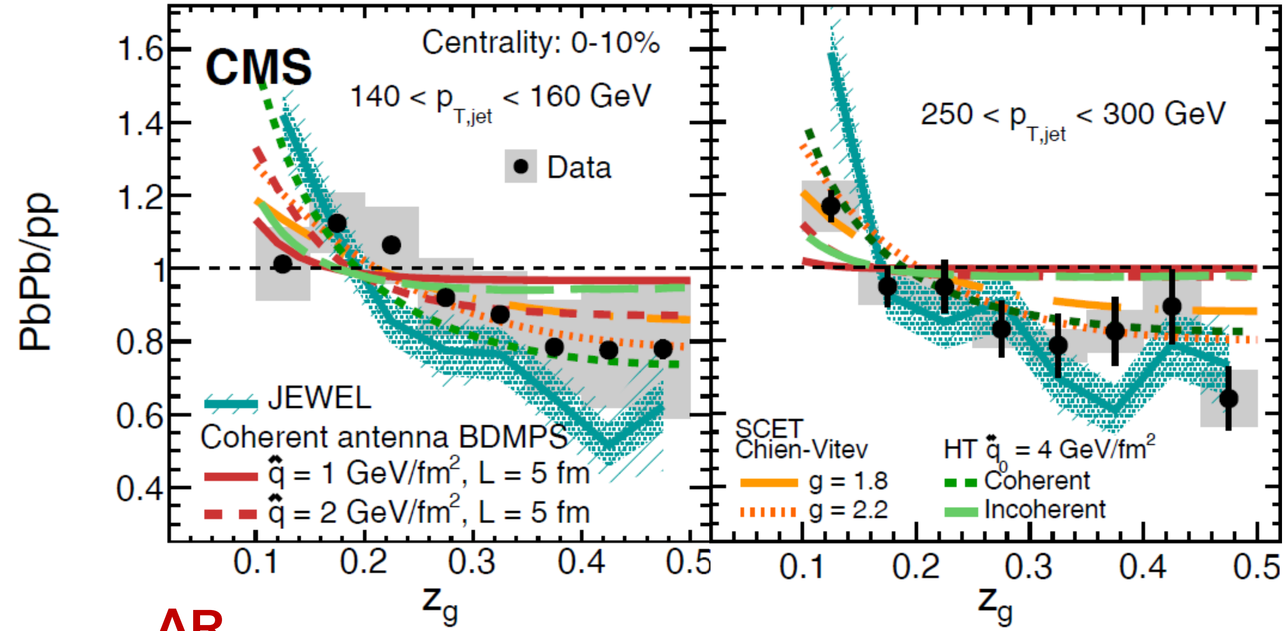
- Heavy quarks lose less energy than the light flavor:
  - Established in LHC and RHIC though model comparisons
- Larger gluon jet suppression than quark: collected hints from various jet substructure observables
  - Nice ATLAS jet and charged particle R_{AA} measurements vs. η (not shown)
  - To the 0^{th} approximation, jet R_{AA} ~ quark fraction at the LHC

Possible follow-up:

- Photon-tagged jet charge
- 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

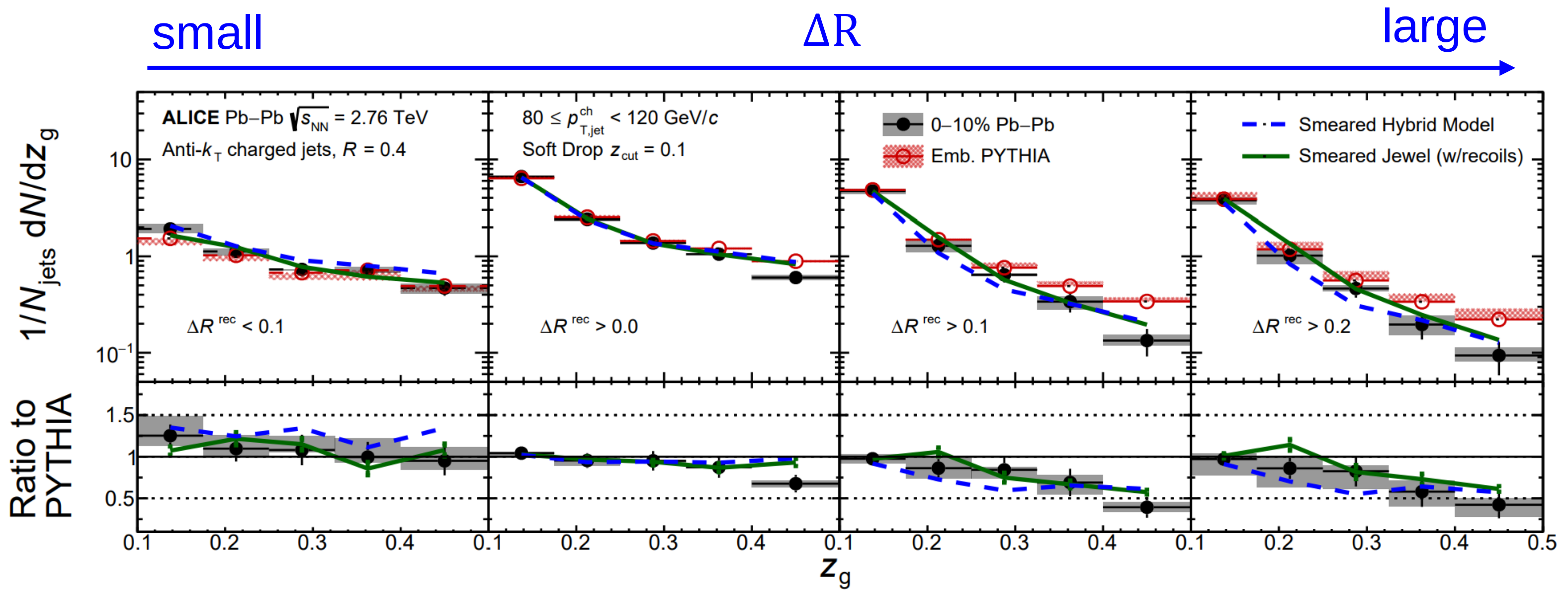
DDbar, Jet-D and γ-D correlation, HF jet FF and shape

Momentum Sharing of Subjets



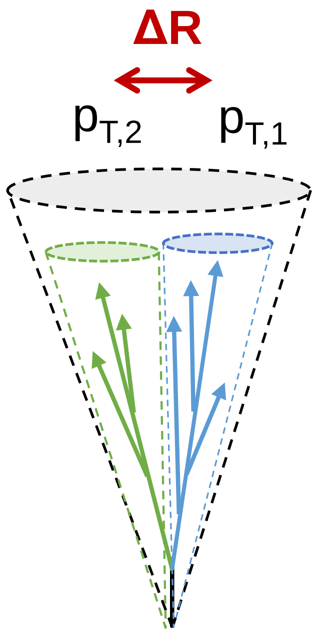
PRL 120 (2018) 142302

Z_{cut}=0.1, β=0
ΔR>0.1



PLB 802 (2020) 135227

Z_{cut}=0.1, β=0
Scan on ΔR cuts



Two hard subjets
Z_g ~ 0.5

Quark and gluon Z_g distributions are very similar in pp

Jets with **two hard subjects** (large Z_g) more suppressed

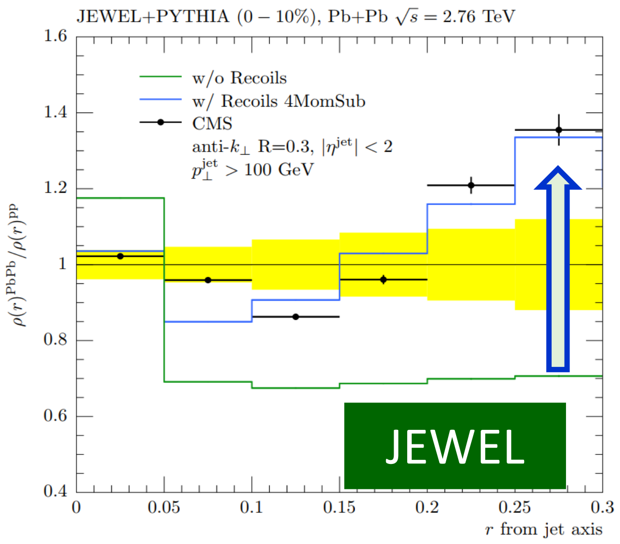
Interpretation:

- **JEWEL**: enhancement of low Z_g jets (due to **medium recoil**)
- **$SCET_G$**: modification due to medium **induced splitting function**
- **HT** & Coherent antenna BDMPS: prefer **coherent energy loss**

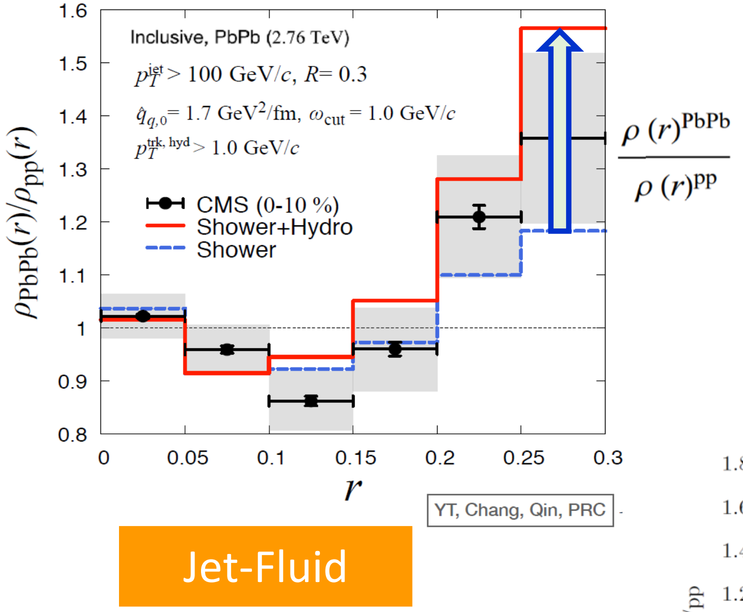
Motivates ΔR measurements!

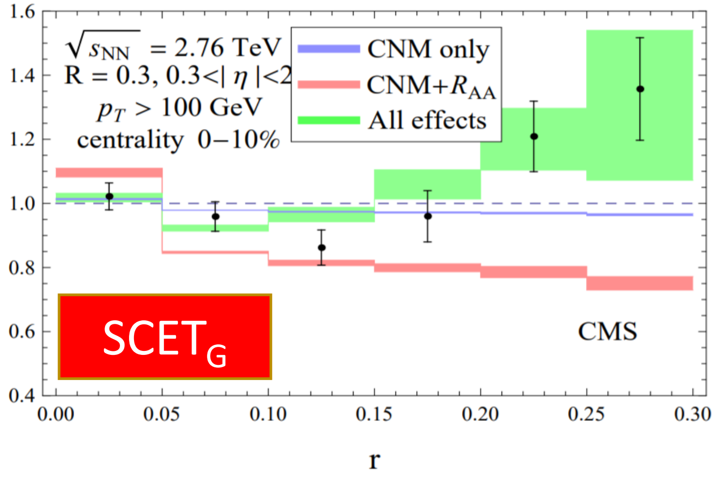
- ALICE showed that the Z_g is more modified for charged jets with large ΔR:
  - Smaller modification of Z_g for collimated jets
  - Large suppression of jets with large ΔR and Z_g

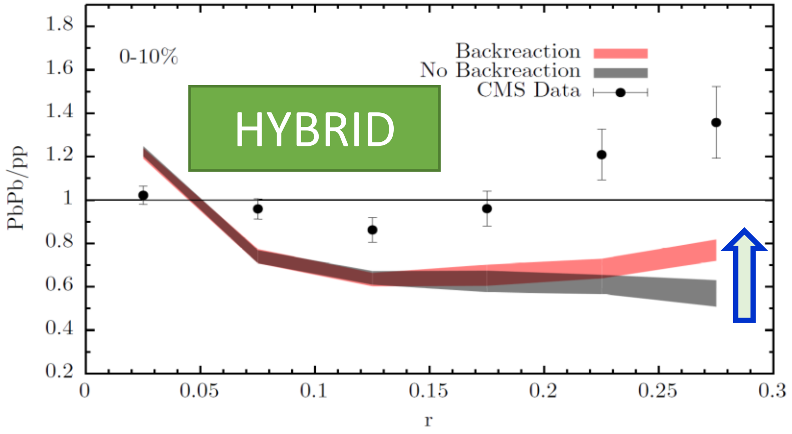
Theoretical Interpretation of the CMS Jet Shape

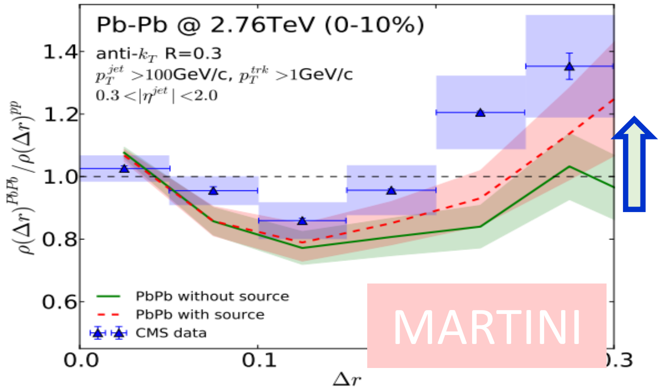


arXiv:1707.01539





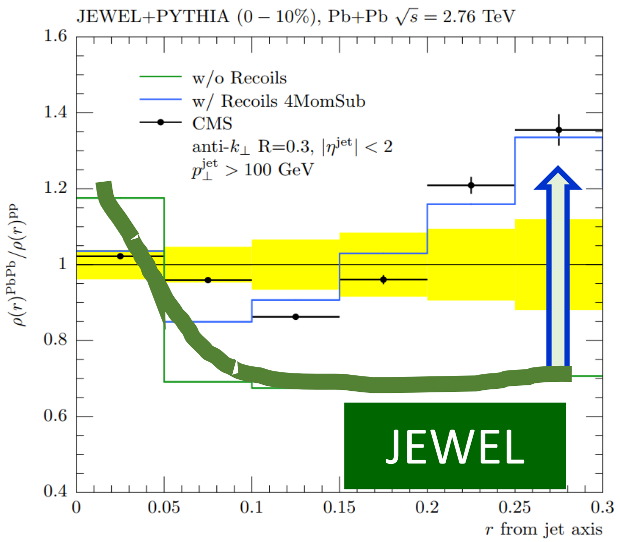




Different explanations of the large angle enhancement in jet shape measurement

- $SCET_G$: Splitting function (large angle radiation)
- JEWEL & JETSCAPE: medium recoil parton
- Jet-Fluid: recoil parton + hydro dynamical evolution
- HYBRID: fully thermalized medium response
- MARTINI: medium response + shower

Theoretical Interpretation of the CMS Jet Shape



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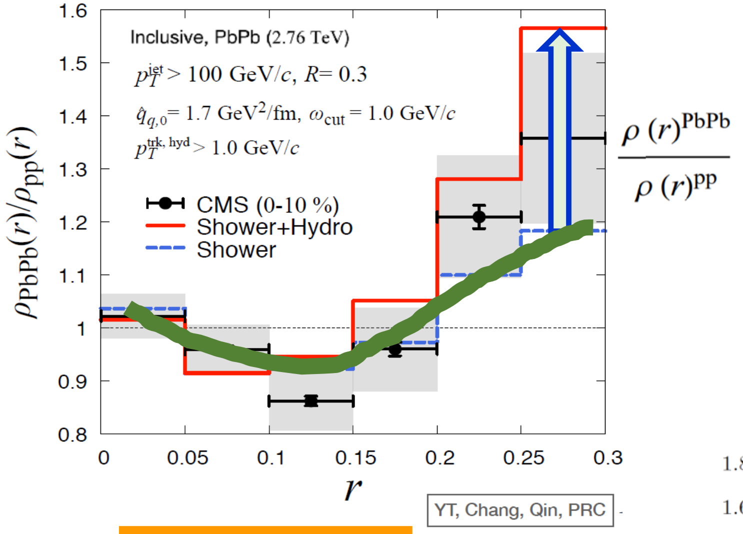
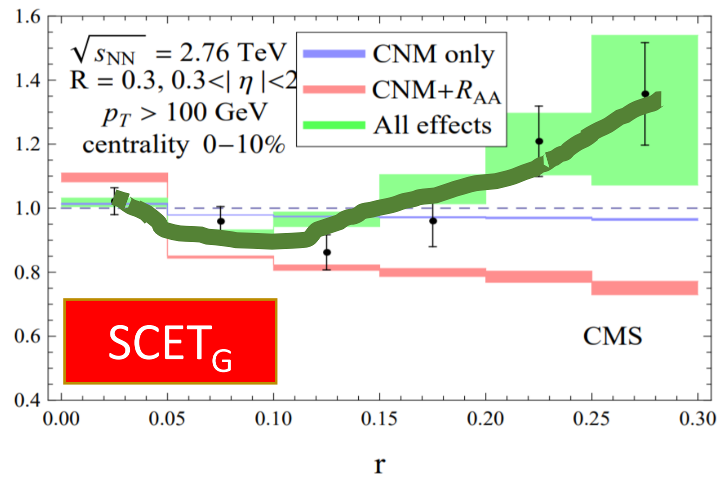
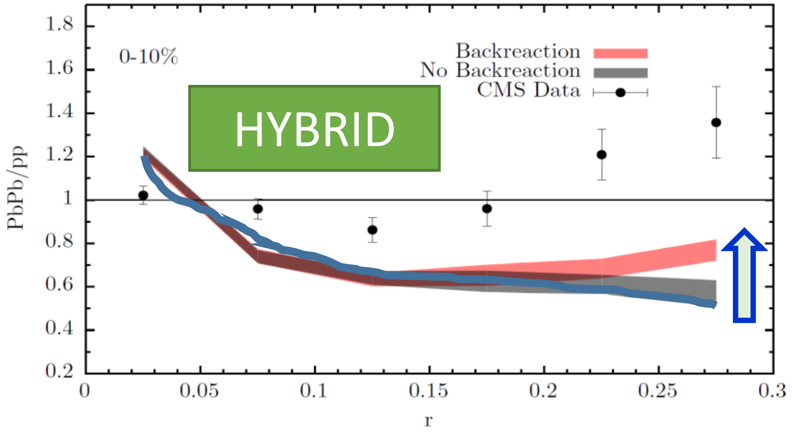


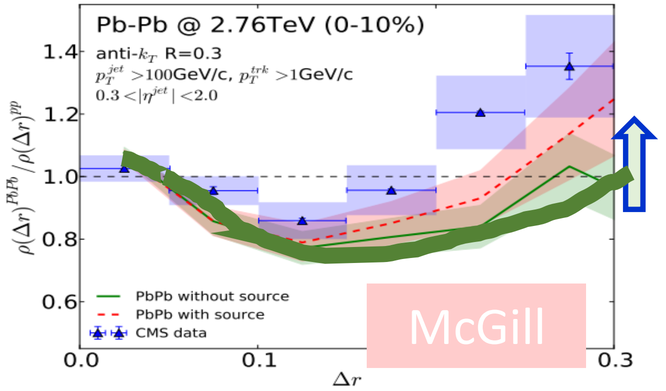
Jet-Fluid



Modifications of the shower

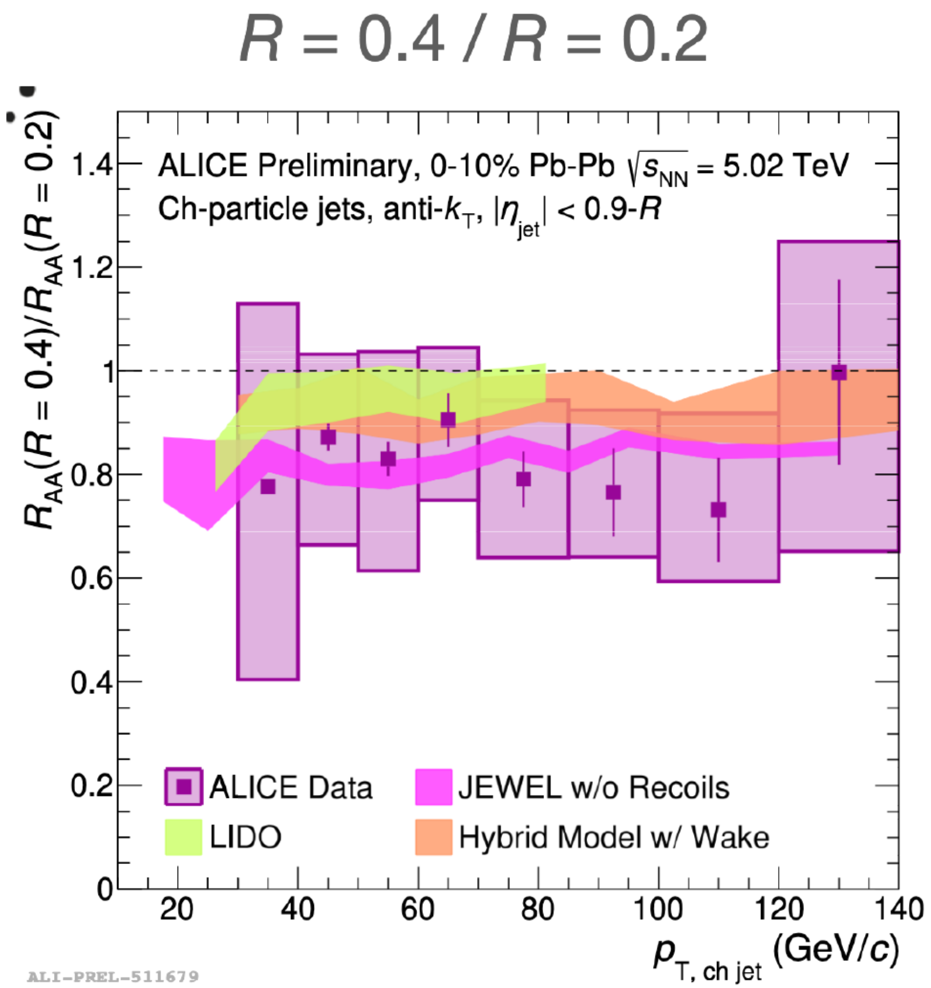


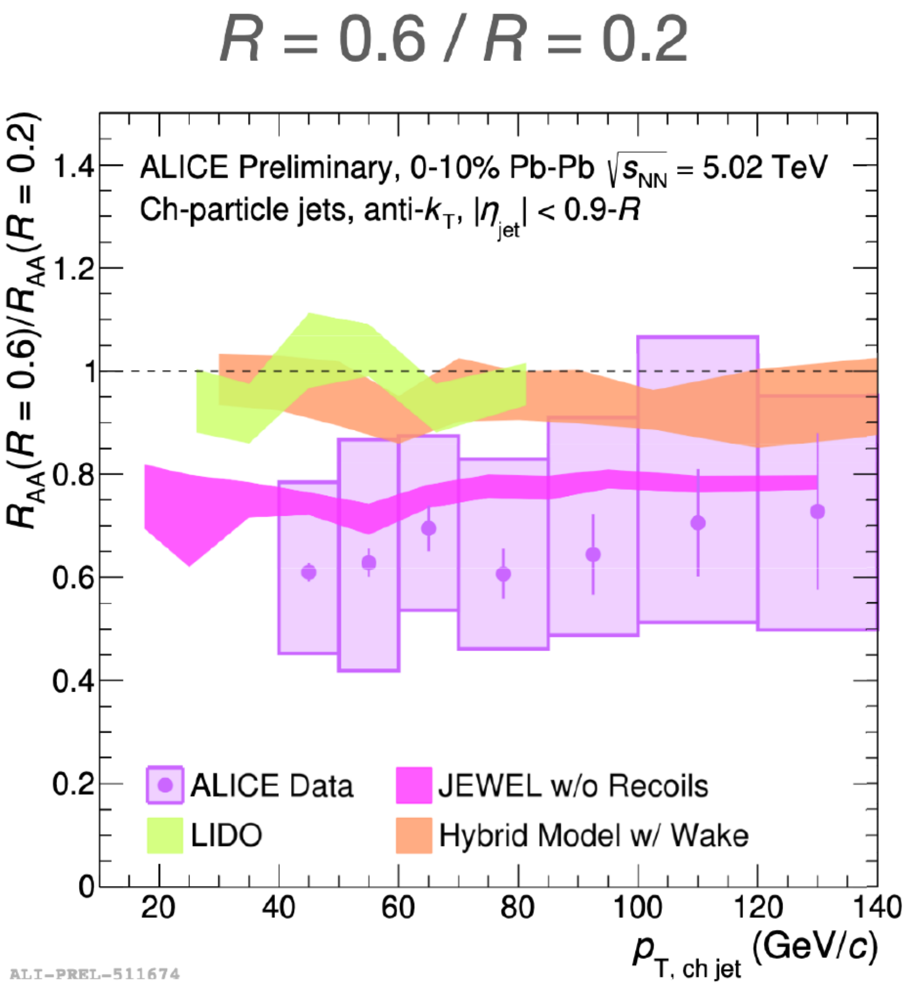
Models with very different underlying mechanisms give reasonable description of the inclusive jet shape!



How do we make progress?

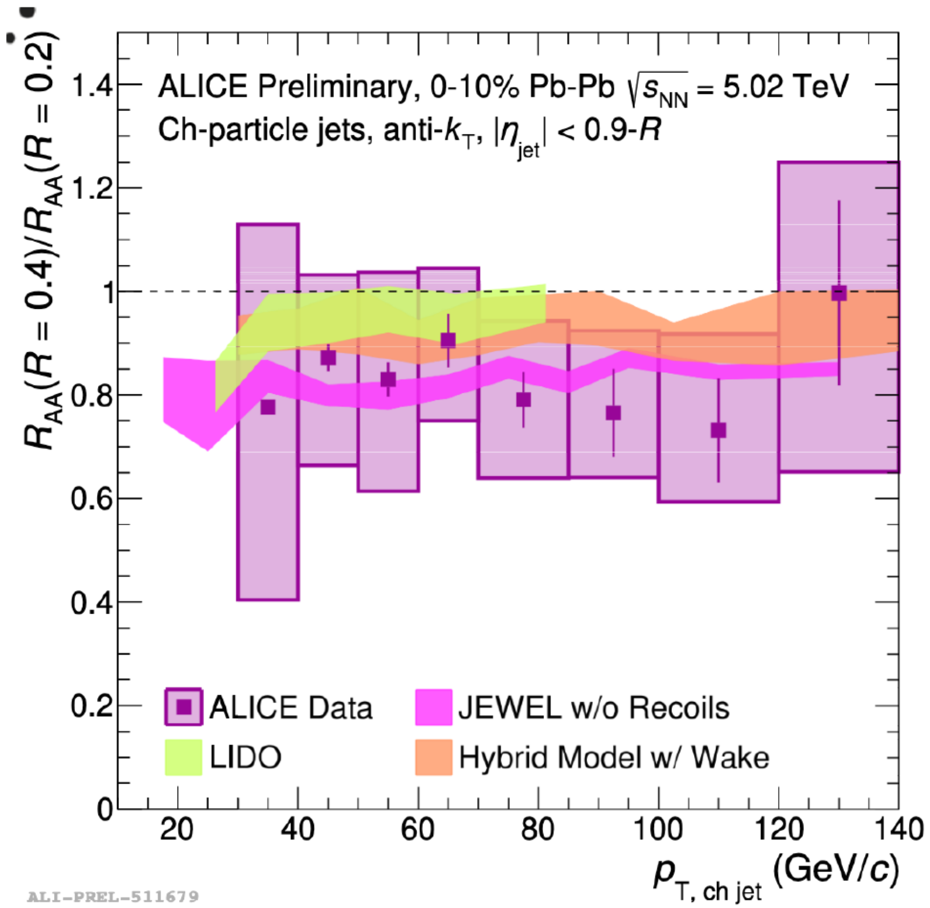
Jet R_{AA} Ratios vs. Charged Jet p_T in 0-10% PbPb

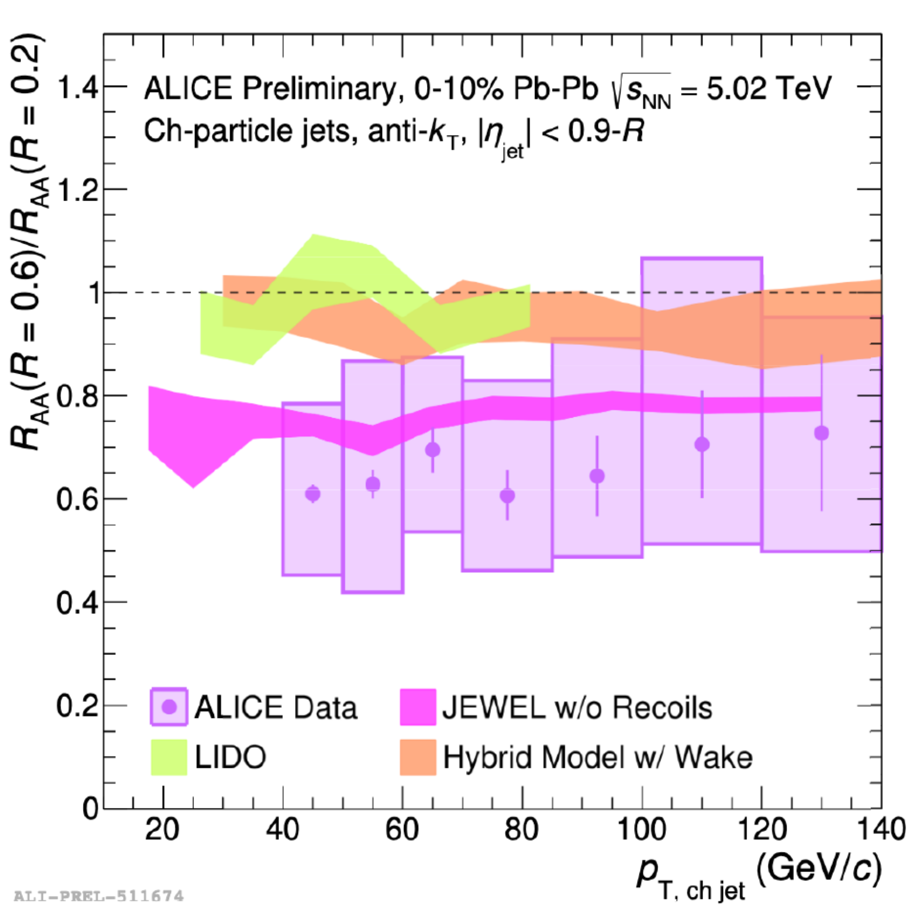


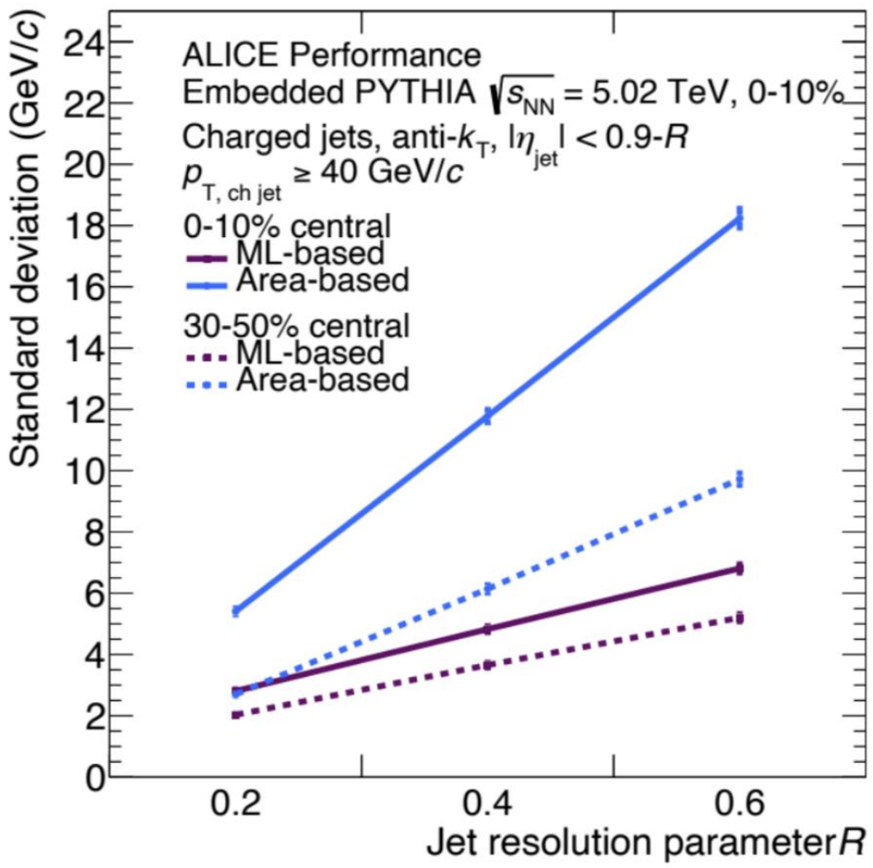


- Indication of larger suppression for R=0.6 charged jets
  - Taking ratio of R_{AA} from different $|\eta_{jet}|$ intervals
- Hybrid and LIDO overpredict the ALICE data.

Jet R_{AA} Ratios vs. Charged Jet p_T in 0-10% PbPb







- Indication of larger suppression for R=0.6 charged jets
  - Taking ratio of R_{AA} from different $|\eta_{jet}|$ intervals
- **Hybrid** and **LIDO** overpredict the ALICE data.
- ML based method: how big is the effect from fragmentation bias?

- ML based algorithm significantly reduce background fluctuation

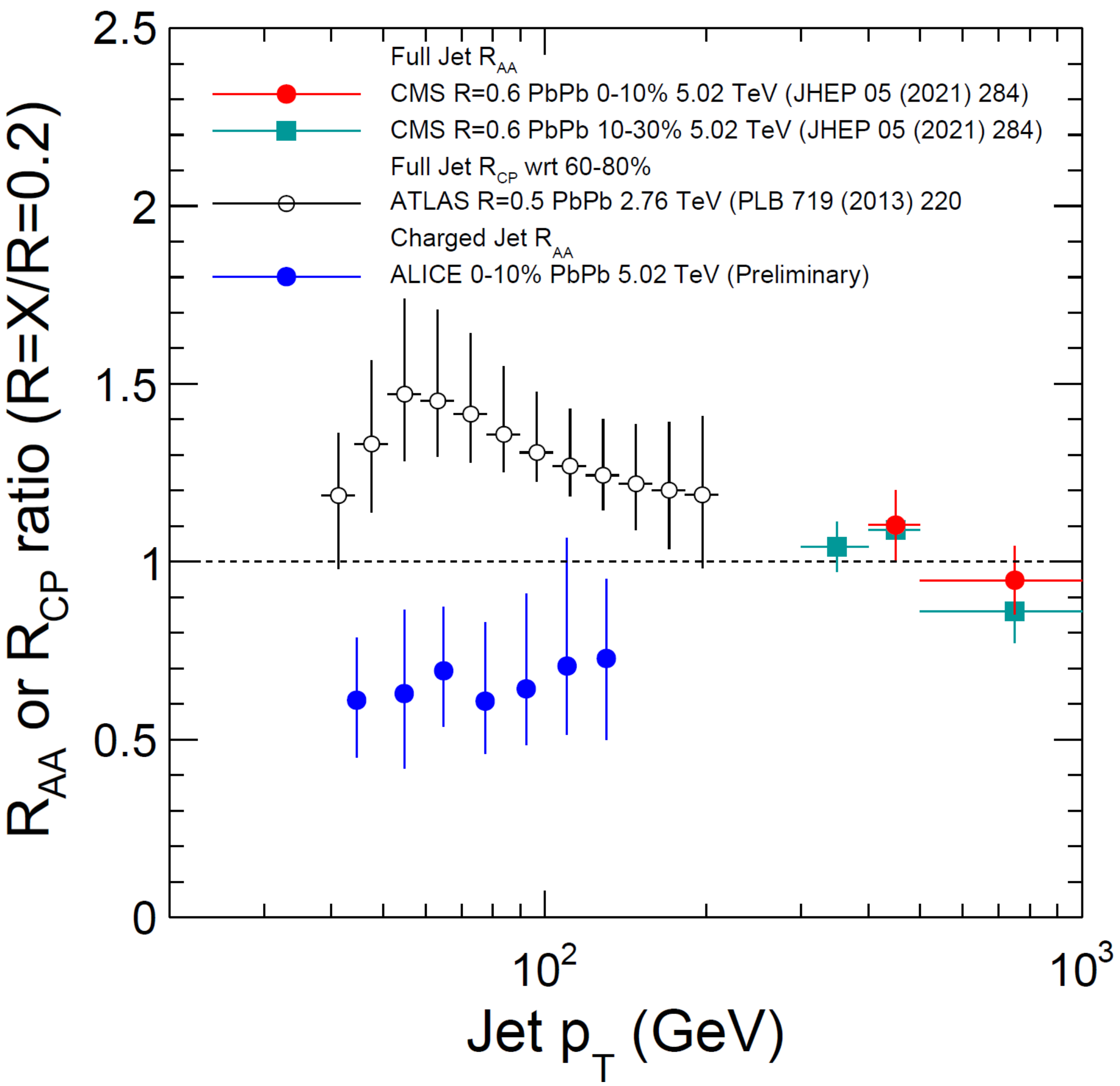
Large Area Jet

- Exciting works from the HI jet community
  - Predictions from models and calculations diverge
  - Strong experimental effort toward large area jet

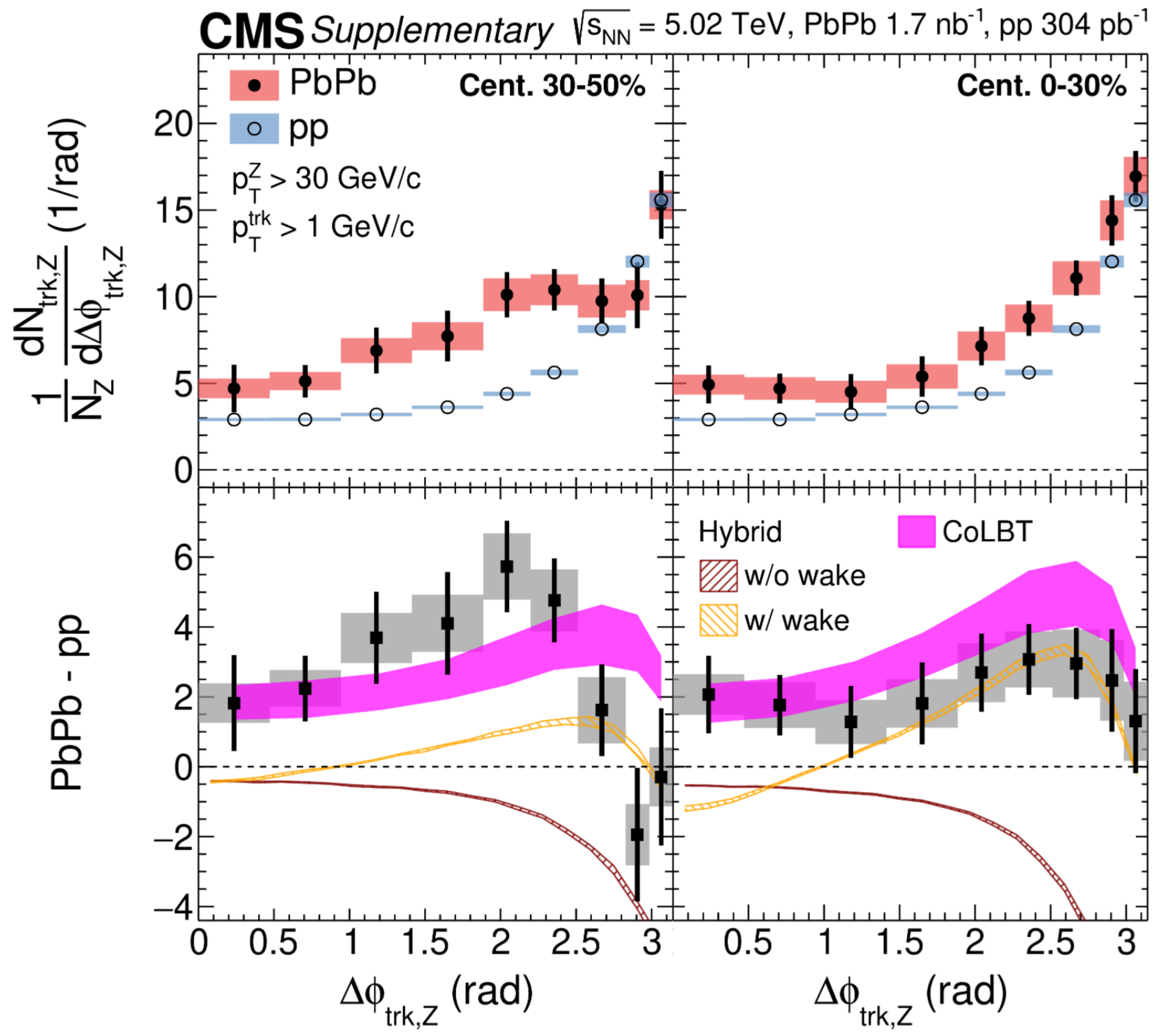
- Different picture between **ATLAS R_{CP}** (+STAR $R^{0.2/0.5}$) and ALICE ML Charged Jet R_{AA} at low p_T
  - Charged Jet vs. Full Jet
  - Different collision energies

- Possible future direction:
  - CMS & ATLAS measurement of large area jet R_{AA} at low p_T
  - sPHENIX full jet R_{AA} at RHIC
  - Photon-tagged large area jet spectra and substructure

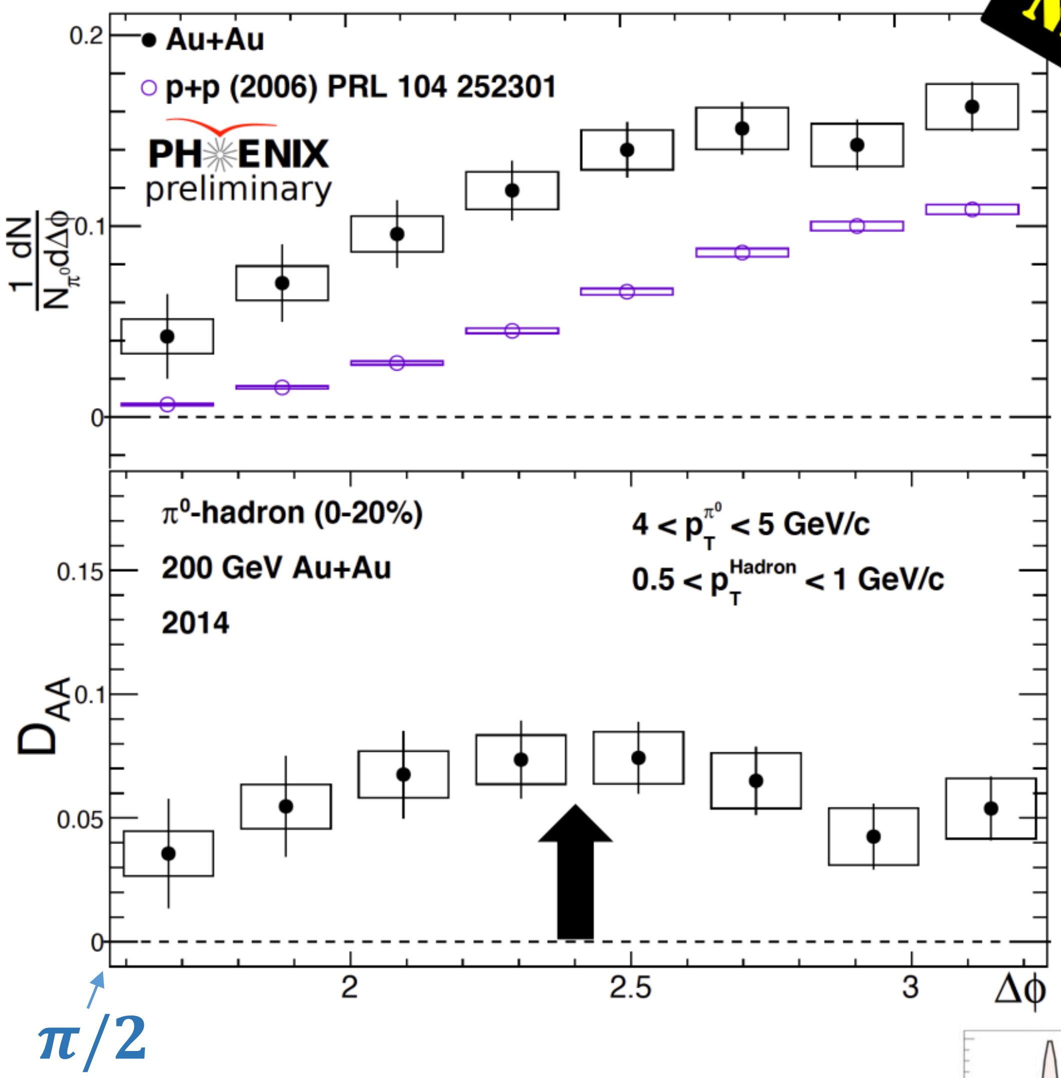
- Facilitate communication between theorists and experimentalists on the background subtraction method
  - Theorists did not perform the same background subtraction as the experimentalists
  - Experimentalists: a better job documenting the algorithms, and use data-driven method to account for FF modification
  - The worry is that part of the medium response signal could be partially suppressed due to the background subtraction method introduced by the experimentalist, and reconstruction bias due to machine learning algorithm or detector limitation



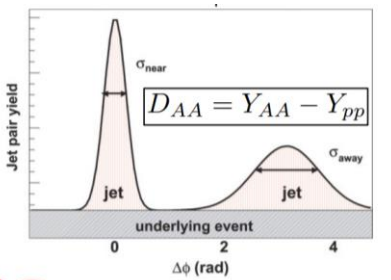
Z-hadron Δφ in PbPb at 5.02 TeV



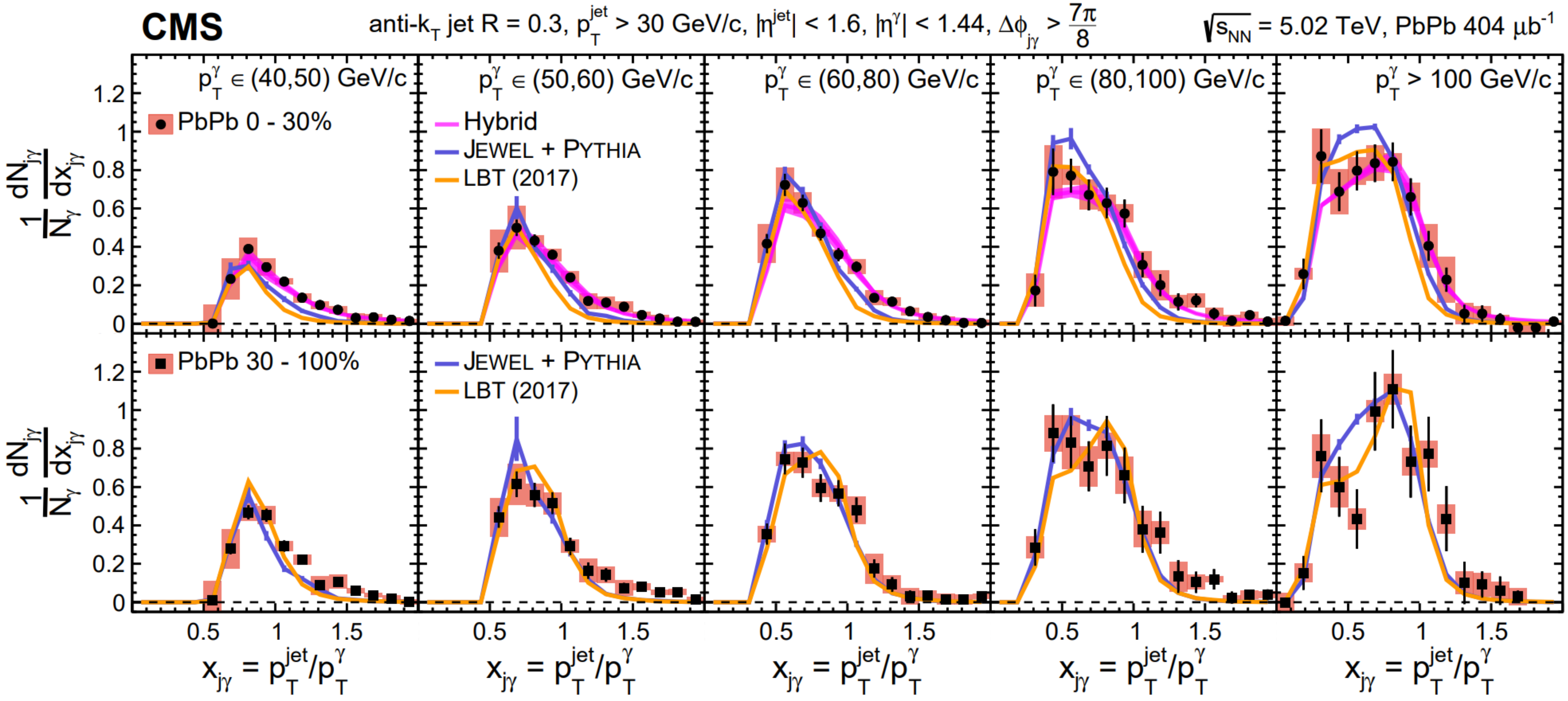
NEW!



PHENIX: Enhancement of low p_T associated particle away from the jet peak also in π^0-hadron correlation at RHIC



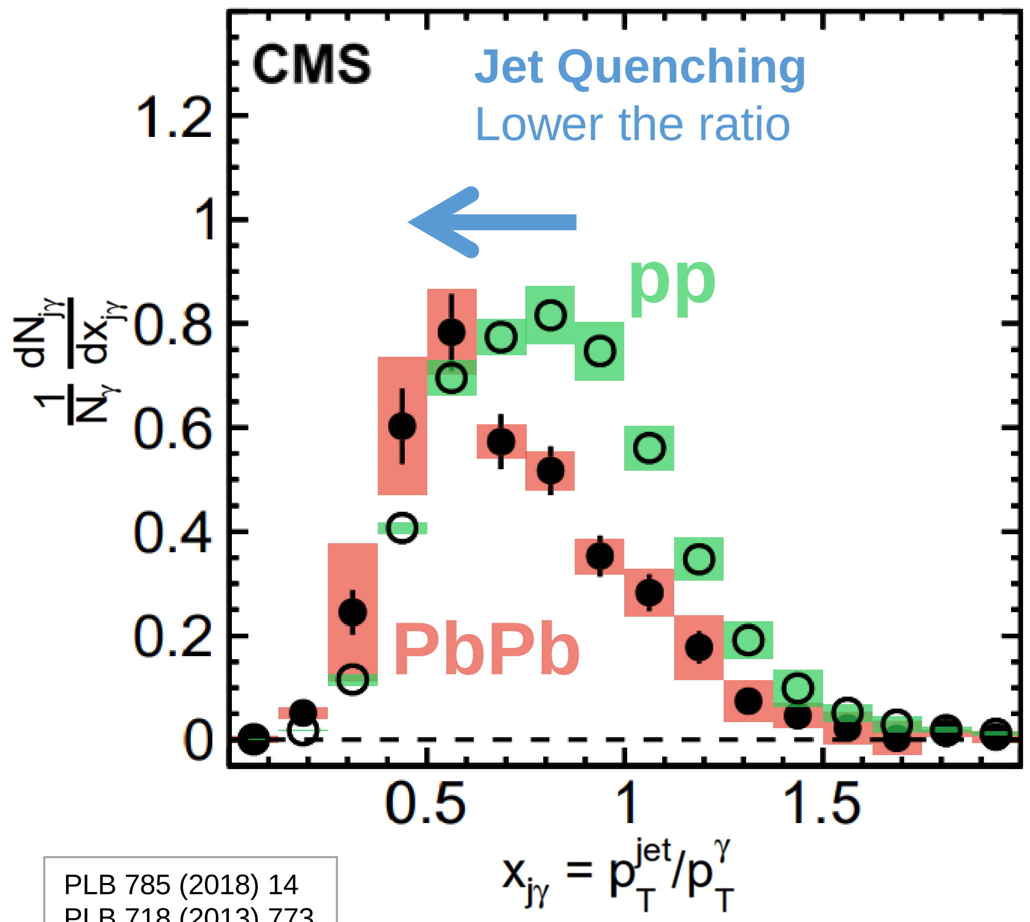
Photon-Jet Asymmetry



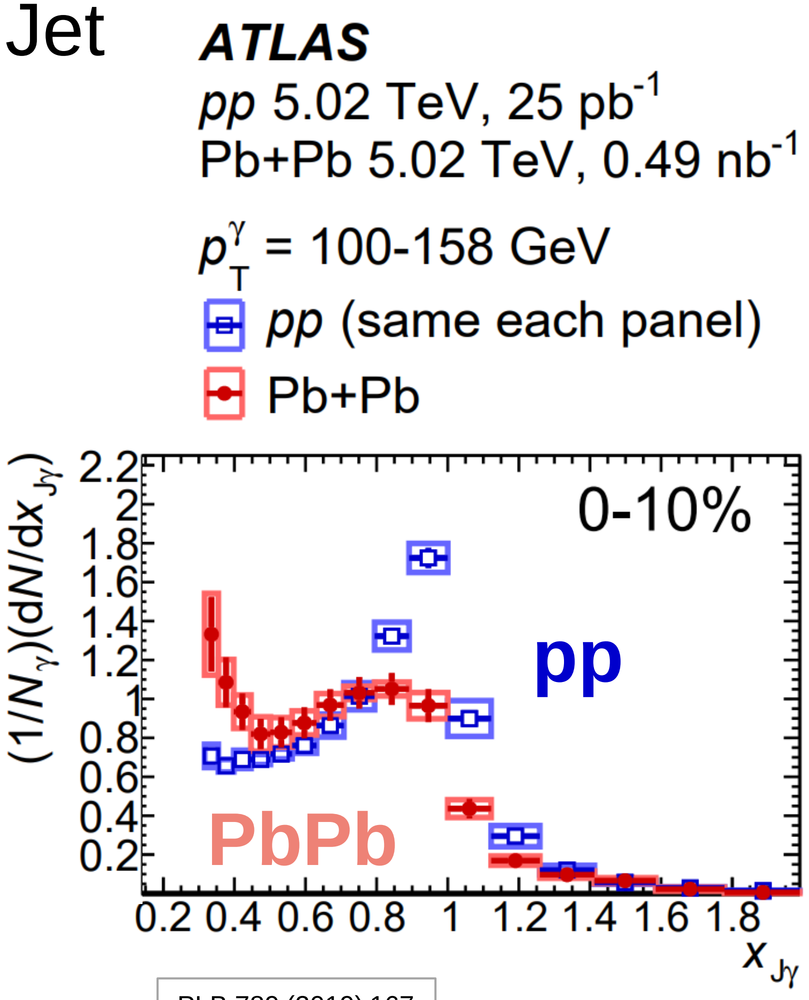
LBT: Xin-Nian Wang *et. al*

Transverse Momentum Ratio of Quark-enriched Jet and Boson

Photon + Jet

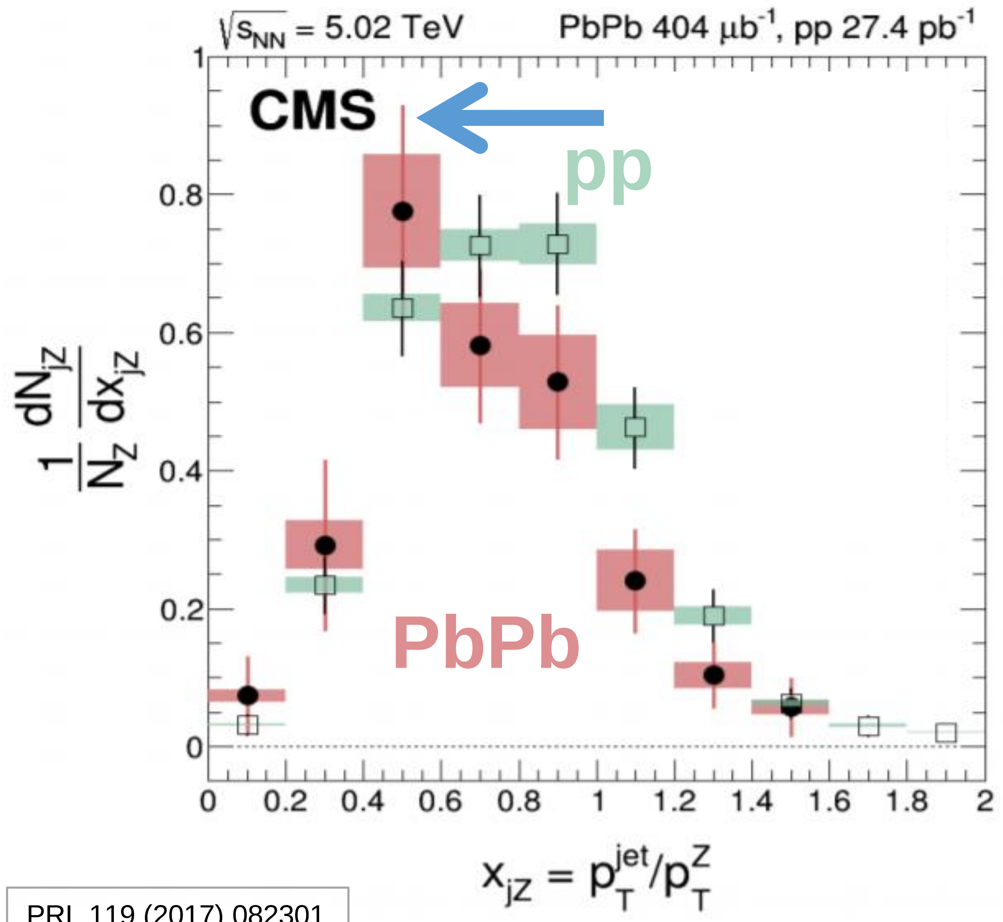


PLB 785 (2018) 14
PLB 718 (2013) 773



PLB 789 (2019) 167

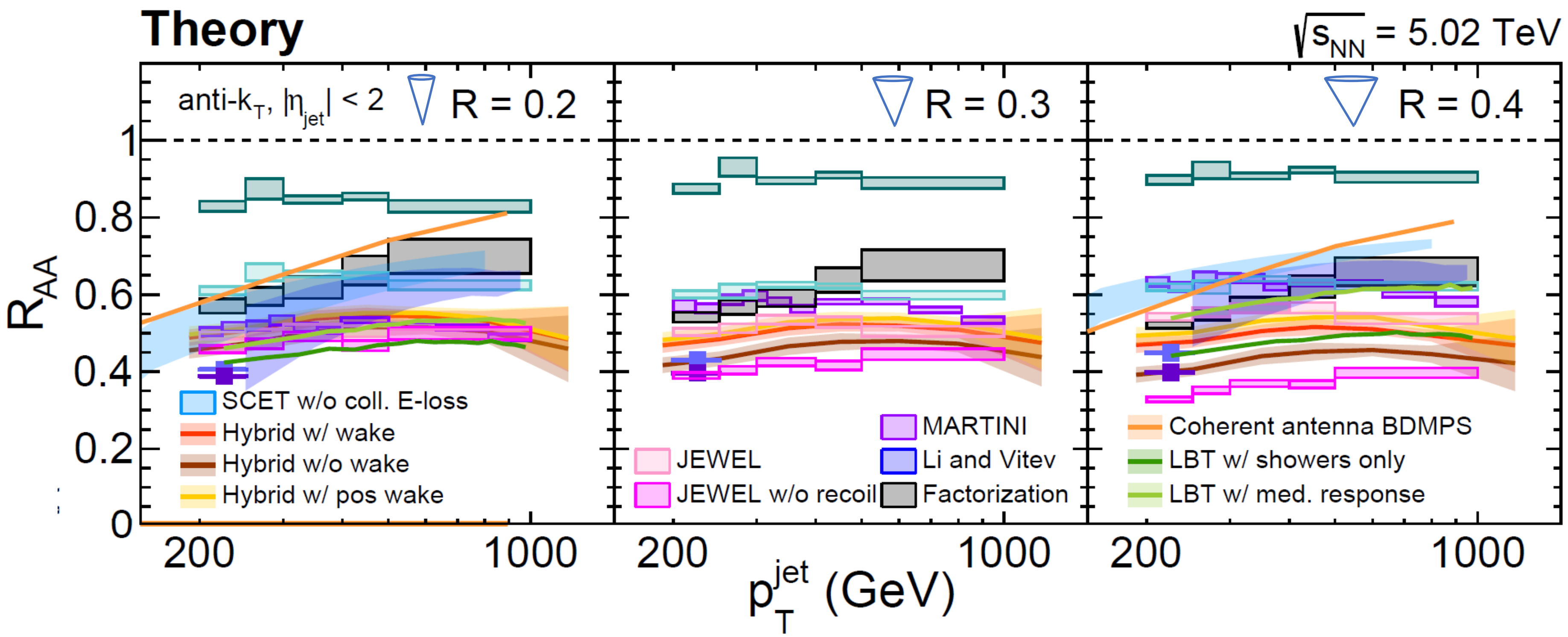
Z^0 boson + Jet



PRL 119 (2017) 082301

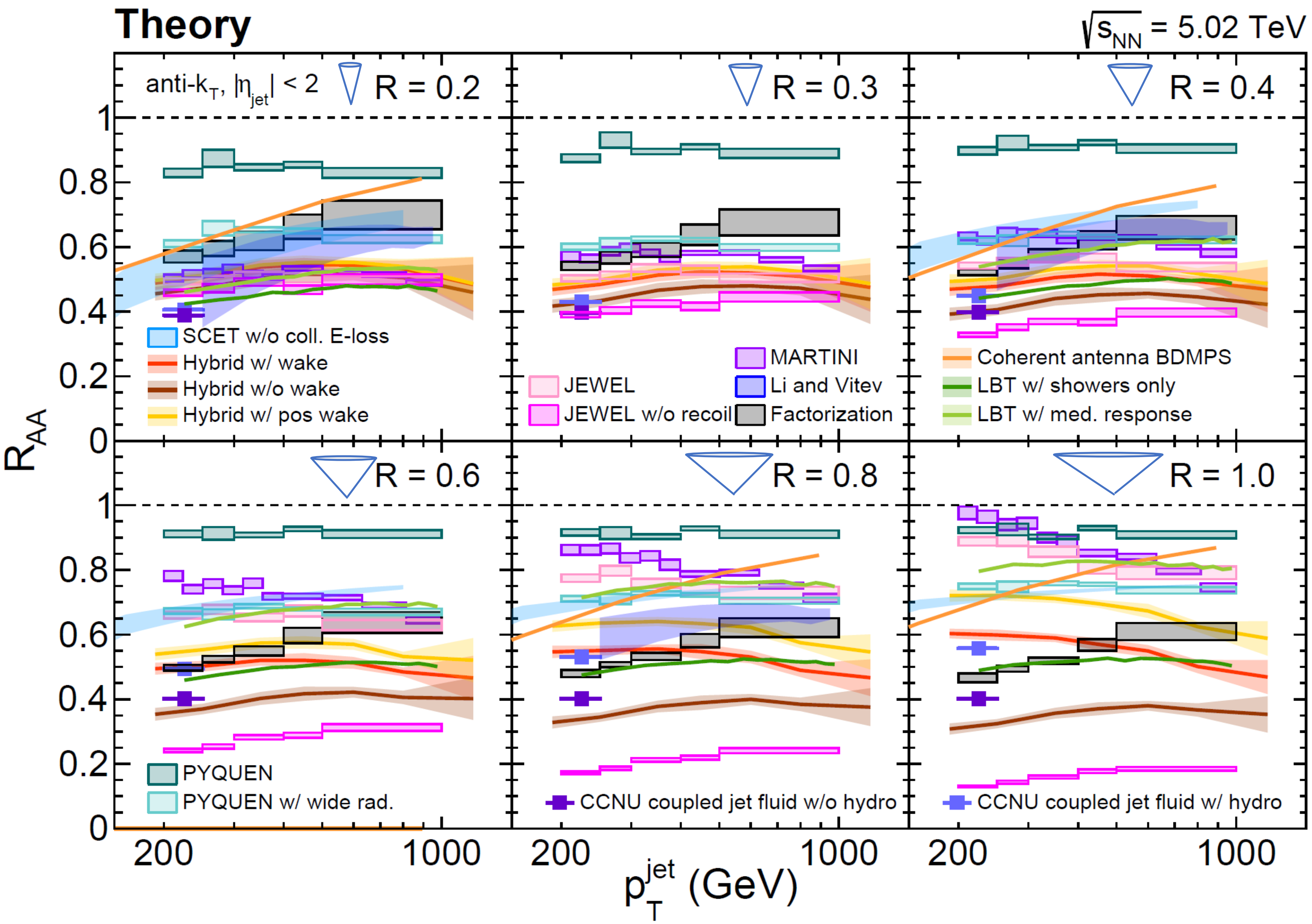
- Photons and Z bosons are not affected by QGP
  → **Quark-enriched jet (70% quark) to boson momentum ratio lowered**

Jet R_{AA} vs. R



Models tuned by small R data at low p_T, predicts jet R_{AA} ~ 0.4-0.6

Jet R_{AA} vs. R



Models tuned by small R data **predict very different large area jet R_{AA}!!!**

Discussion (1)

- From inclusive jet substructure measurements, **"jet narrowing"** effect is observed.
  - Ungroomed observables with **large impact from high p_T particles** (**p_TD**, **g**, core of **radial profile**) show significant narrowing signal.
  - Ungroomed observables with **large impact from low p_T particles** at large angle (mass, jet charge Q^k, FF) are less(not) modified
  - Groomed observables (reduce impact from large angle radiation) shows jet narrowing / hardening (d_{12}, θ_g, N_{SD}, Z_g, R_g, $k_{T,g}$ …)

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

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

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

→ Significant impact from gluon suppression and inclusive **jet selection bias** (select unquenched jets): enhancing the quark jet and less quenched jets

$$Q^\kappa = \frac{1}{(p_T^{\text{jet}})^\kappa} \sum_{i \in \text{jet}} q_i {p_{T,i}}^\kappa.$$

κ=0.3, 0.5, 0.7

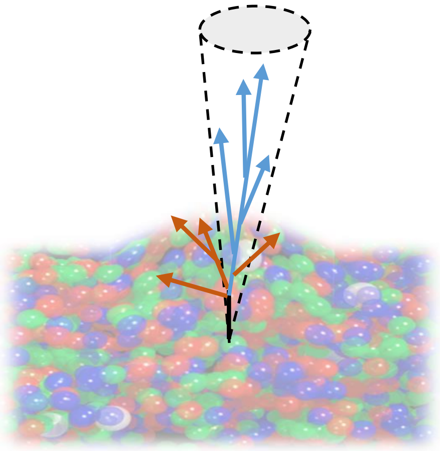
- Possible way forward:
  - Focus on substructure observables with less bias: photon- and Z-tagged jets
  - Changed the way we present the data: quantile PRL 122 (2019) 22, 222301
  - Change the jet p_T definition:
    - (1) Groomed jet p_T: enhance the selection bias
    - (2) Collinear dropped jet p_T: enhance the quenching signal
  - Look into specific physics process such as boosted W/Z and Top with high statistics data

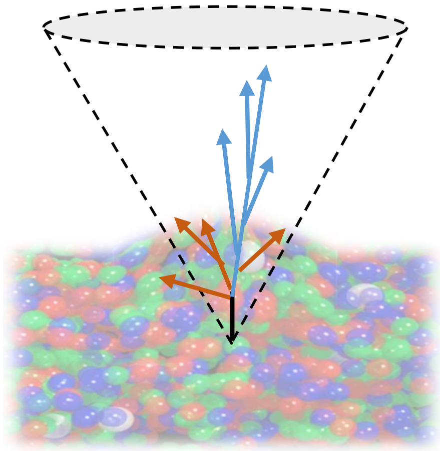
Discussion (2)

- Large area jet spectrum provided new constraints on jet quenching due to the inclusion of particles at large angle and the inclusion of wide parton shower
- Most models which were extremely successful for the description of small area jet failed to describe the data

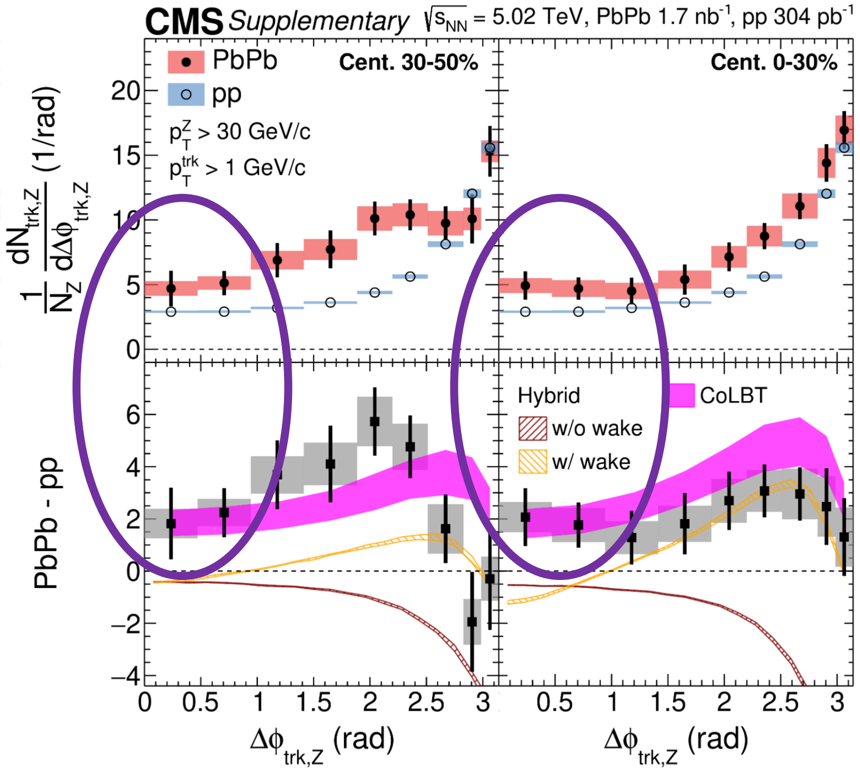
Discussion (2)

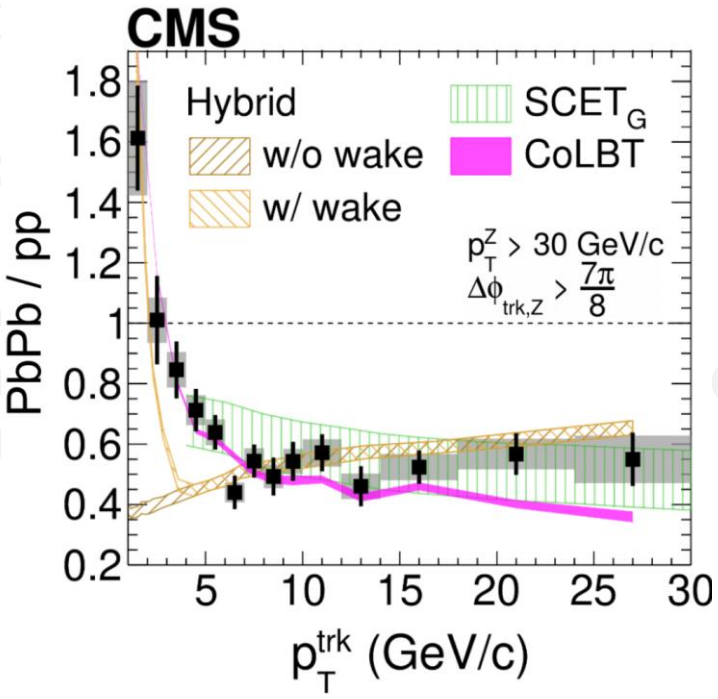
- Large area jet spectrum provided new constraints on jet quenching due to the inclusion of particles at large angle and the inclusion of wide parton shower
- Most models which were extremely successful for the description of small area jet failed to describe the data
- Models with medium response tend to overshoot the large jet R_{AA} data at high p_T which may indicate **too tight correlation** between medium response and the mother parton direction or **too small suppression of the wide parton shower**

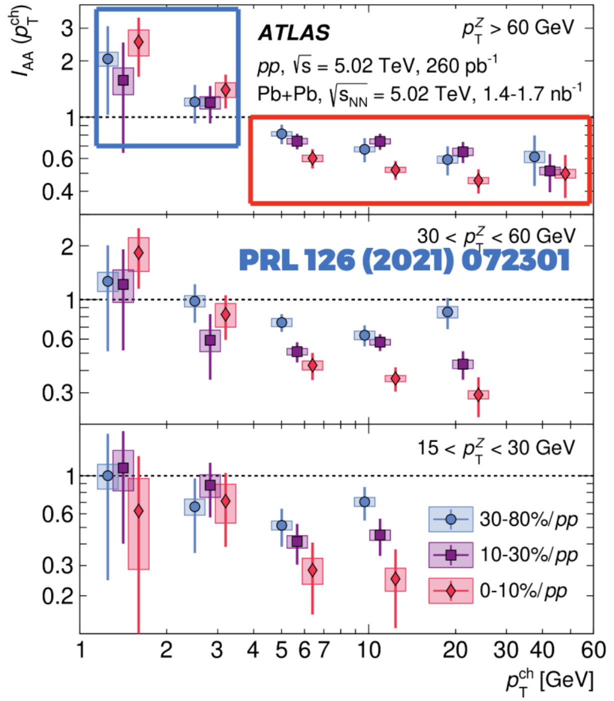




Discussion (3)







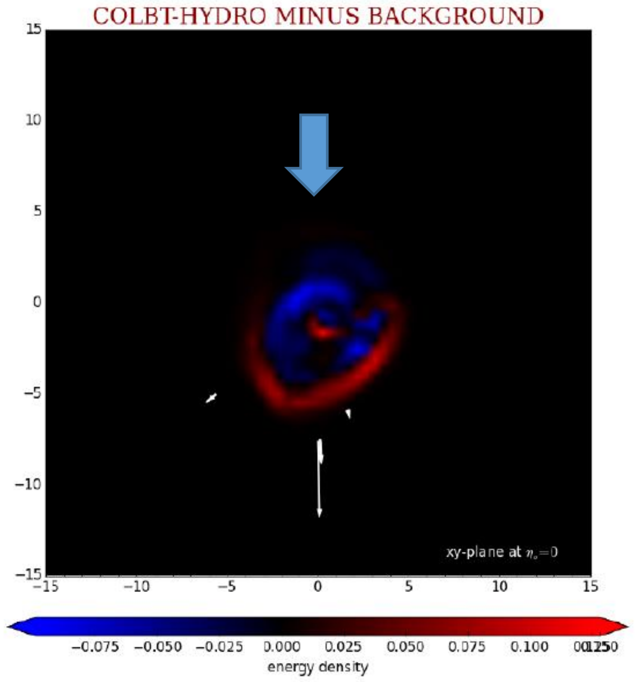
- On the other hand, calculations which don’t have detailed QGP modeling or medium are also in good agreement with the data.
- Z-tagged hadron spectra showed new signal of associated particles near the color-neutral Z boson (“**jetless” jet quenching analysis**, therefore, include all kinds of parton showers)
- Models / calculations are relatively more successful in the description of Z-tagged hadron spectra in the jet side
- Need to improve our understanding of the medium response: (1) particle composition (2) how the medium response change with parton shower (3) isolate the signal of medium recoil

Measure the "Depletion" with Z-hadron Correlation

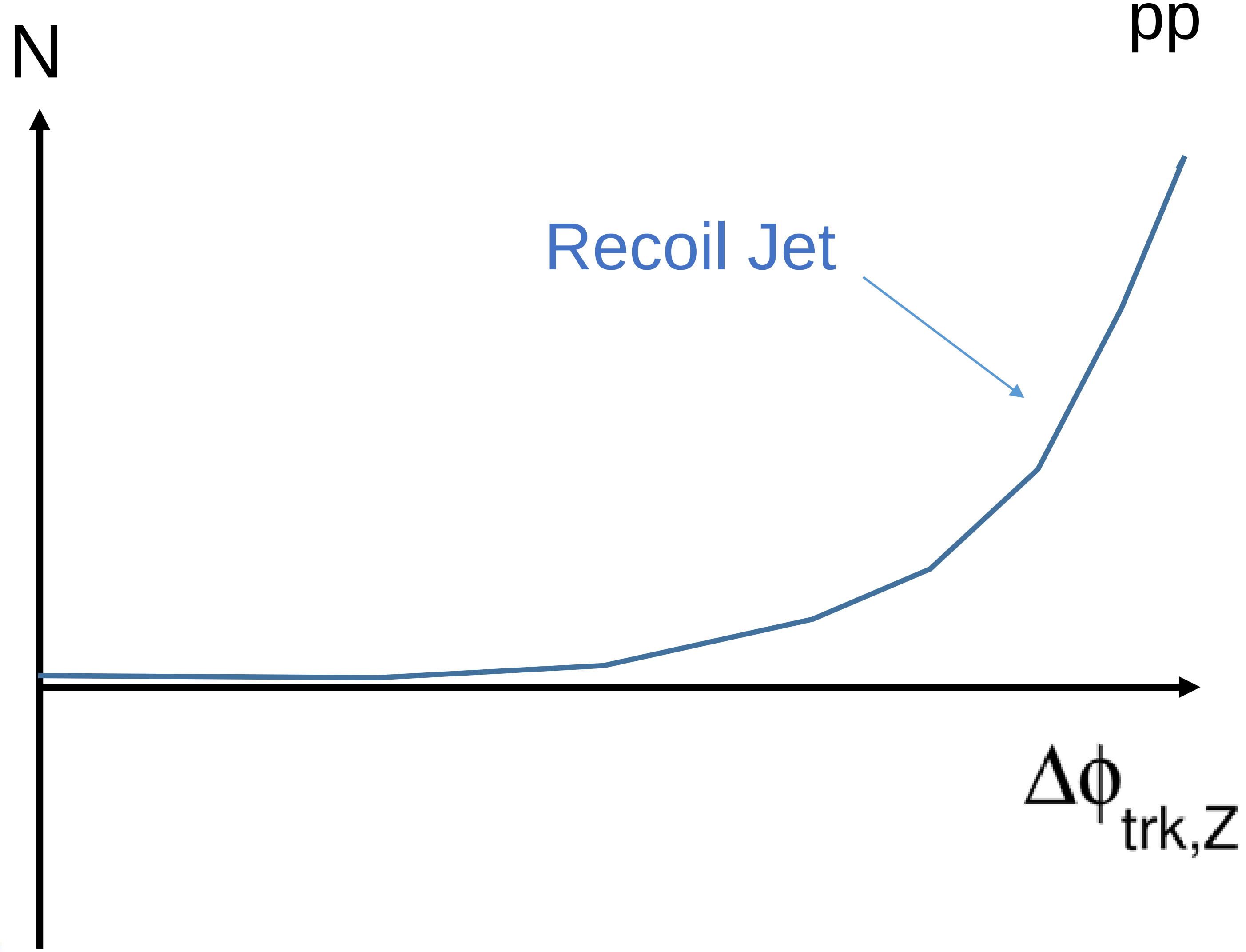
CoLBT

Tan Luo, Xin-Nian Wang

Photon-Jet



Artist's impression



HYBRID

Zach Hulcher, Daniel Pablos, Krishna Rajagopal

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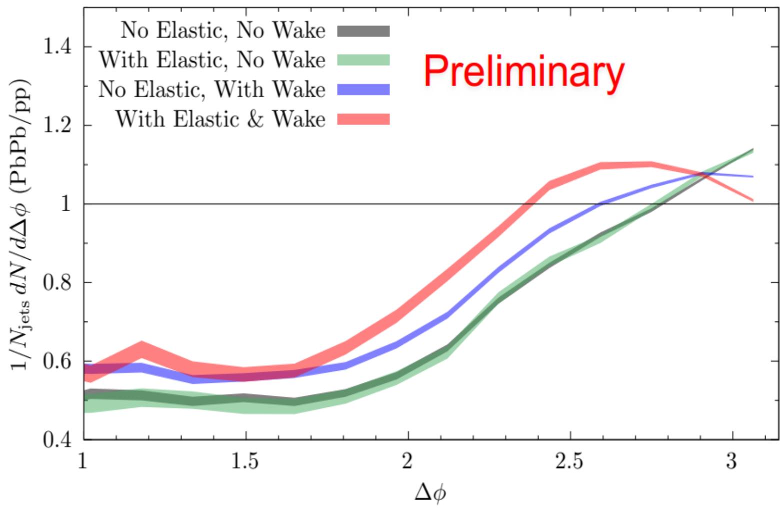


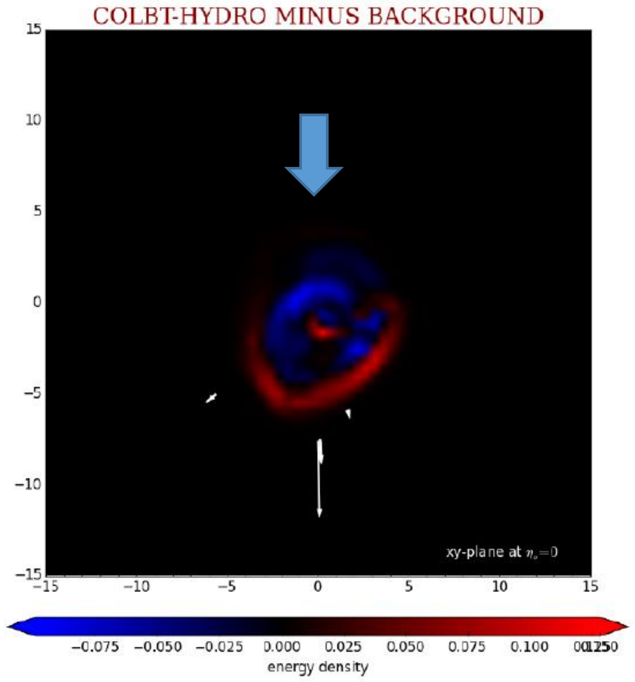
Measure the **boson-side associated yield** with photon-jet and Z-jet

Measure the “Depletion” with Z-hadron Correlation

CoLBT

Tan Luo, Xin-Nian Wang

Photon-Jet



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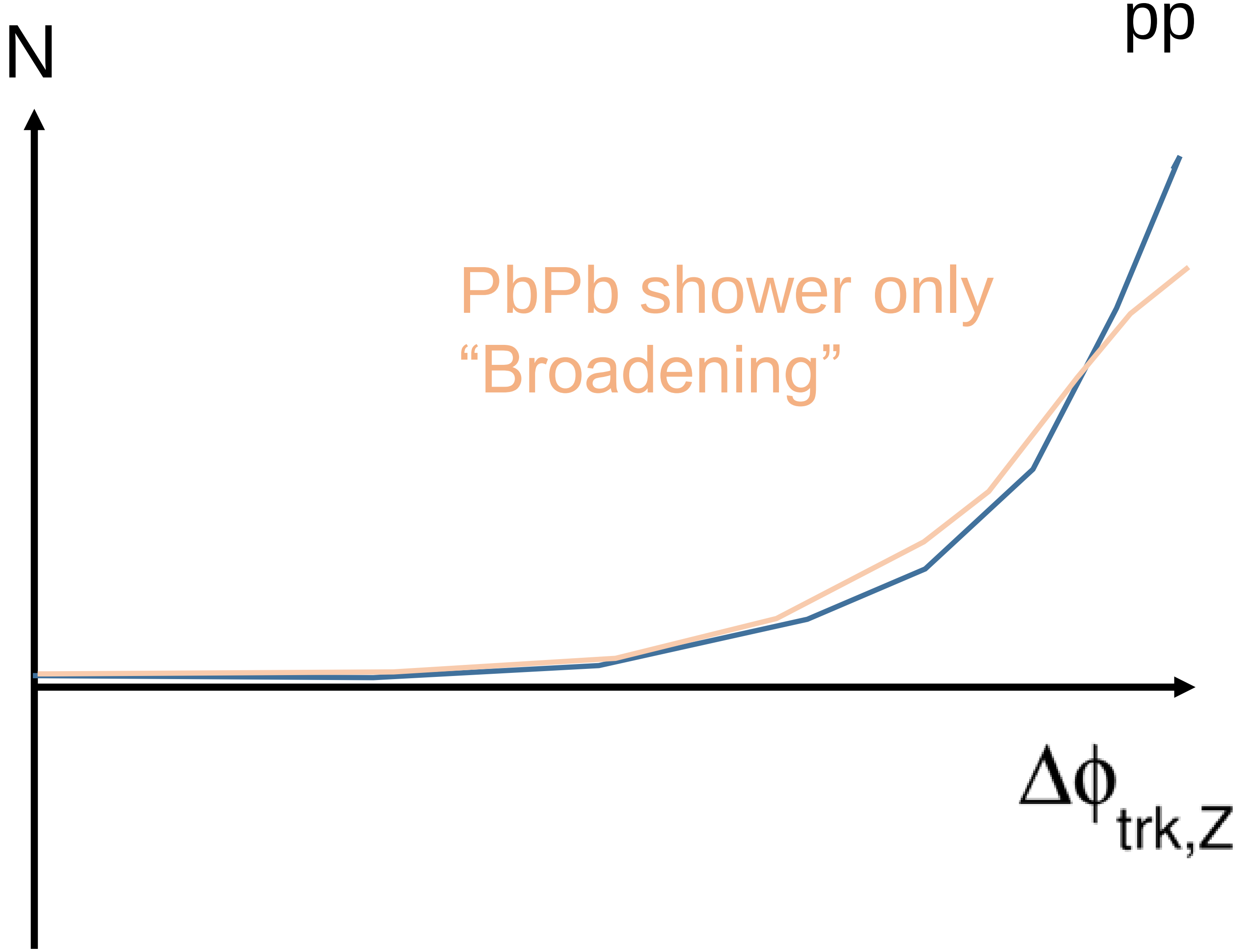
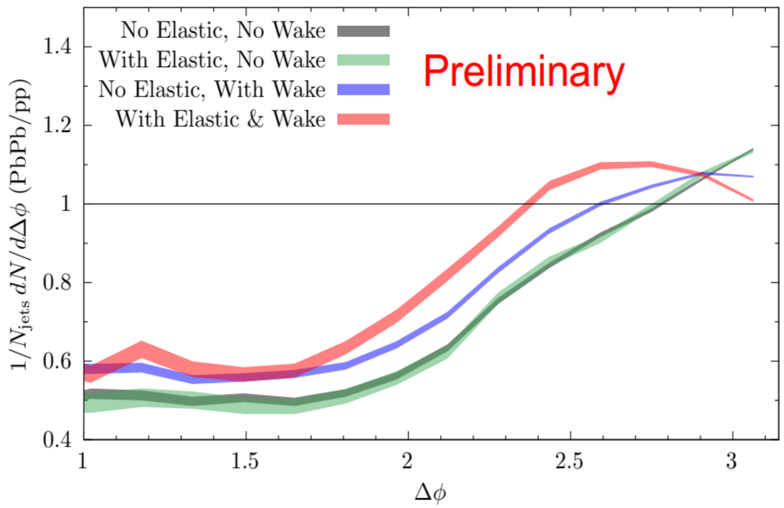


HYBRID

Zach Hulcher, Daniel Pablos, Krishna Rajagopal

Z-Jet



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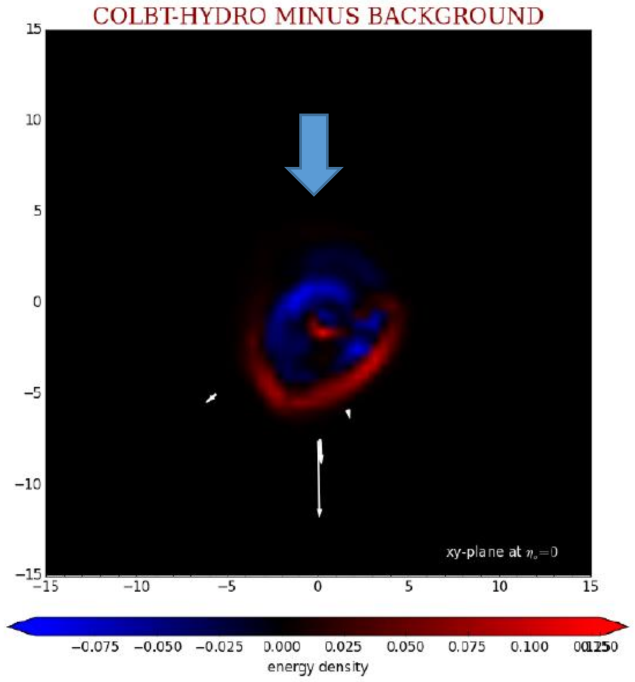

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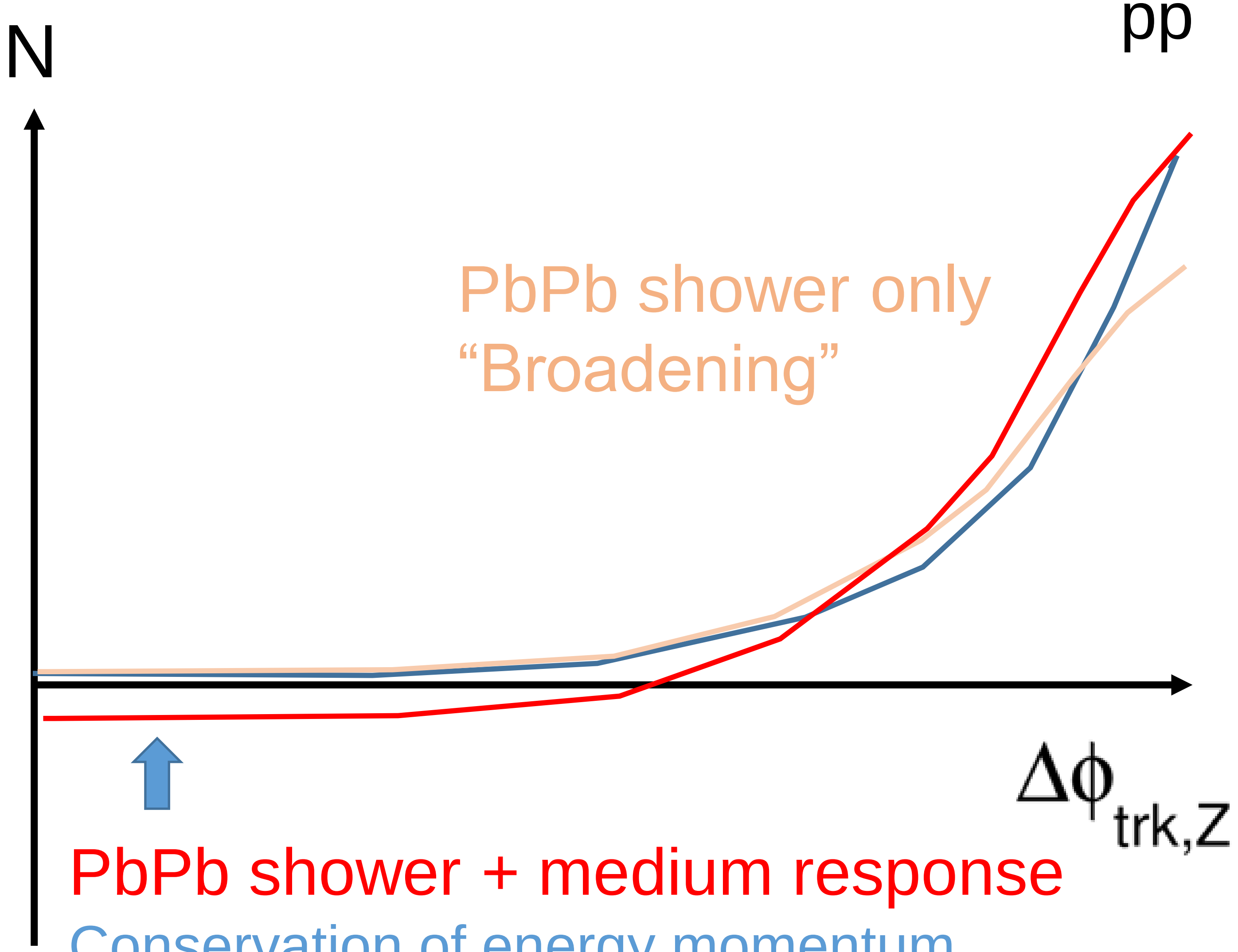


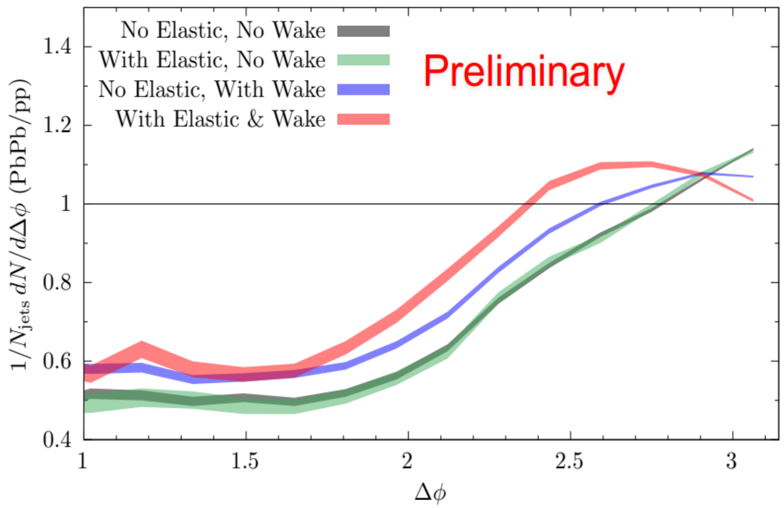
PbPb shower + medium response

Conservation of energy momentum

HYBRID

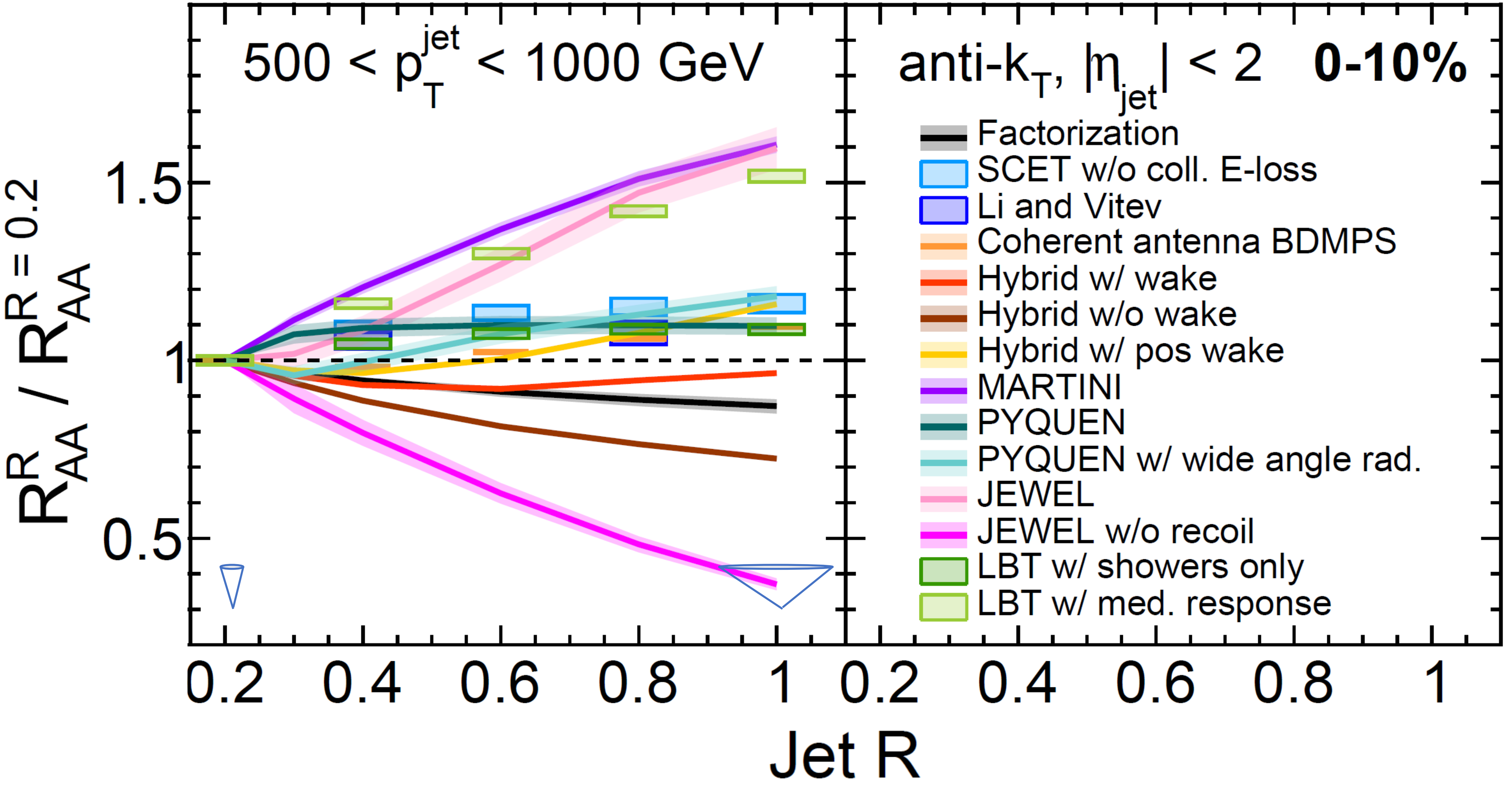
Zach Hulcher, Daniel Pablos, Krishna Rajagopal

Z-Jet



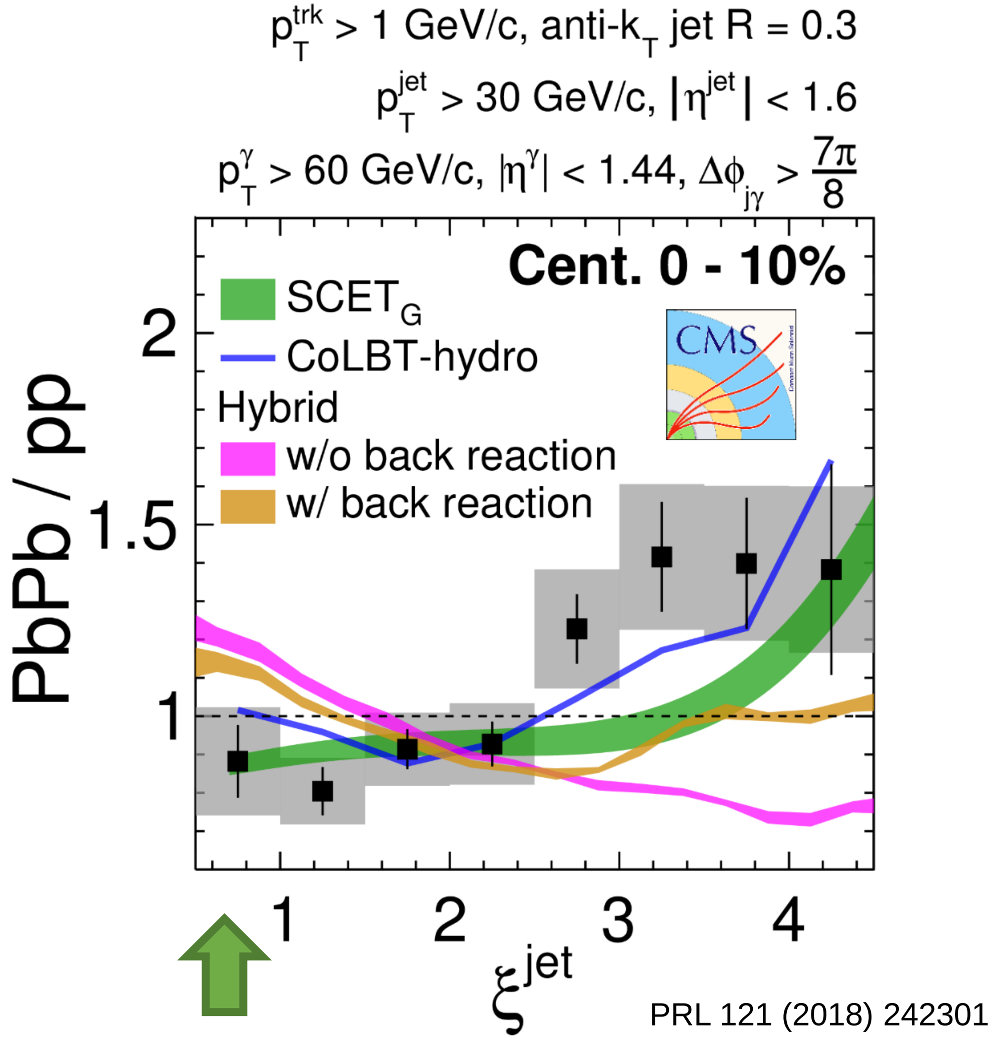
Measure the **boson-side associated yield** with photon-jet and Z-jet

Jet R_{AA} ratios vs. R in 0-10% PbPb at 5 TeV



Competition between different mechanisms (collisional and radiative energy loss, pQCD vs. AdS/CFT, including/excluding medium recoil and responds, re-scattering…)

Jet Longitudinal Structure



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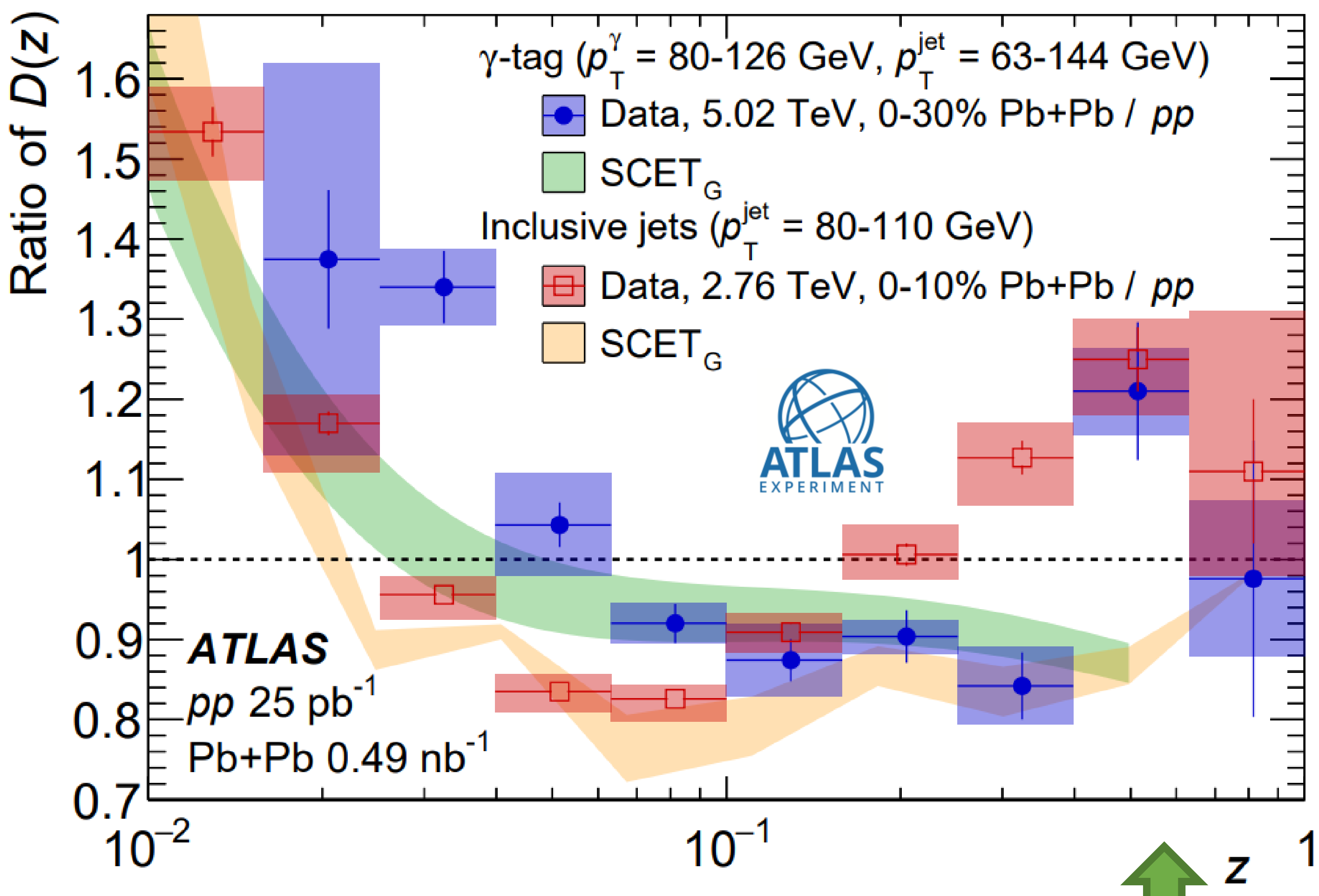
$R_{D(z)}$ = PbPb / pp



High p_T particle (Low ξ)

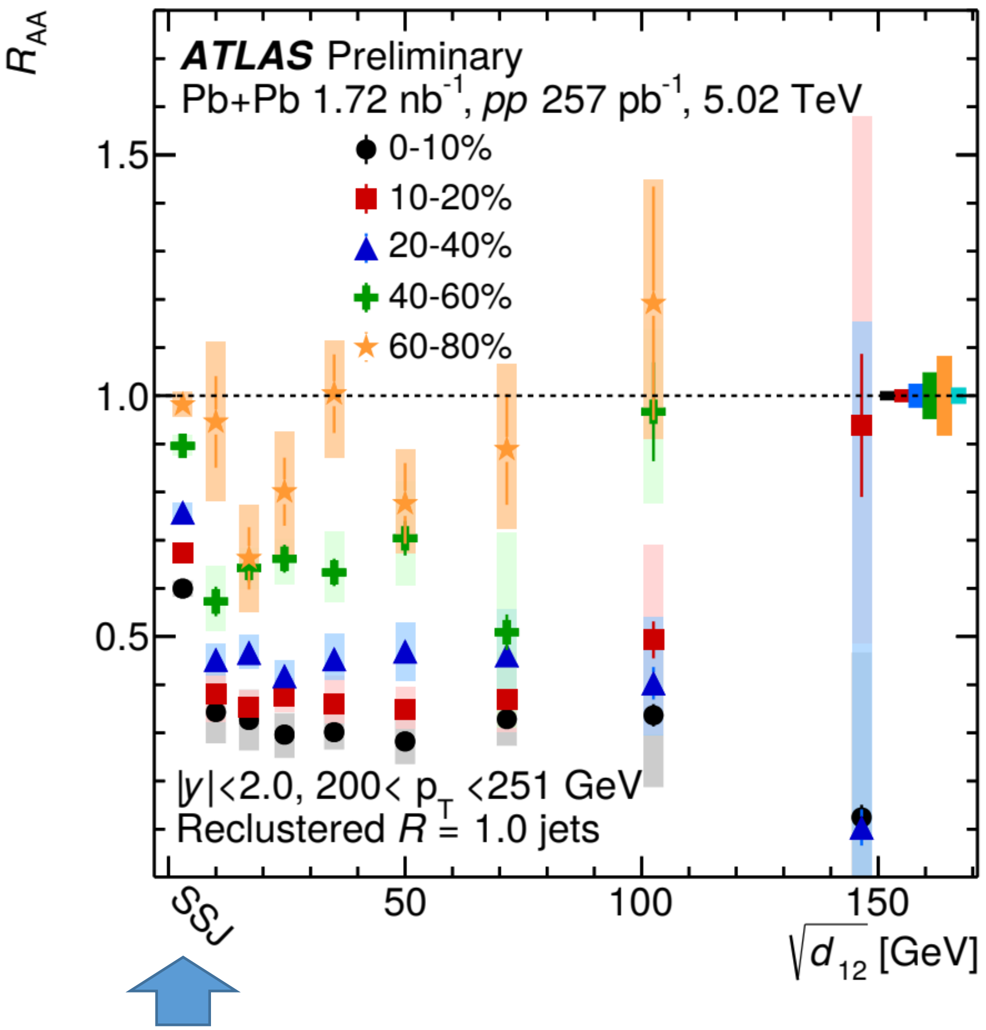
CoLBT: Xin-Nian Wang *et. al*

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

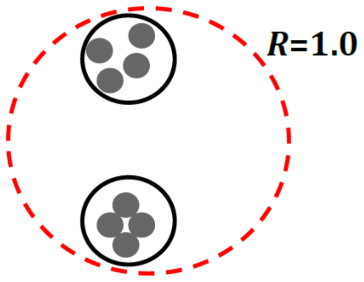
High p_T particle (High Z)

Inside the jet cone: High p_T particle enhancement is smaller in **photon-tagged jet** compared to **inclusive jet**

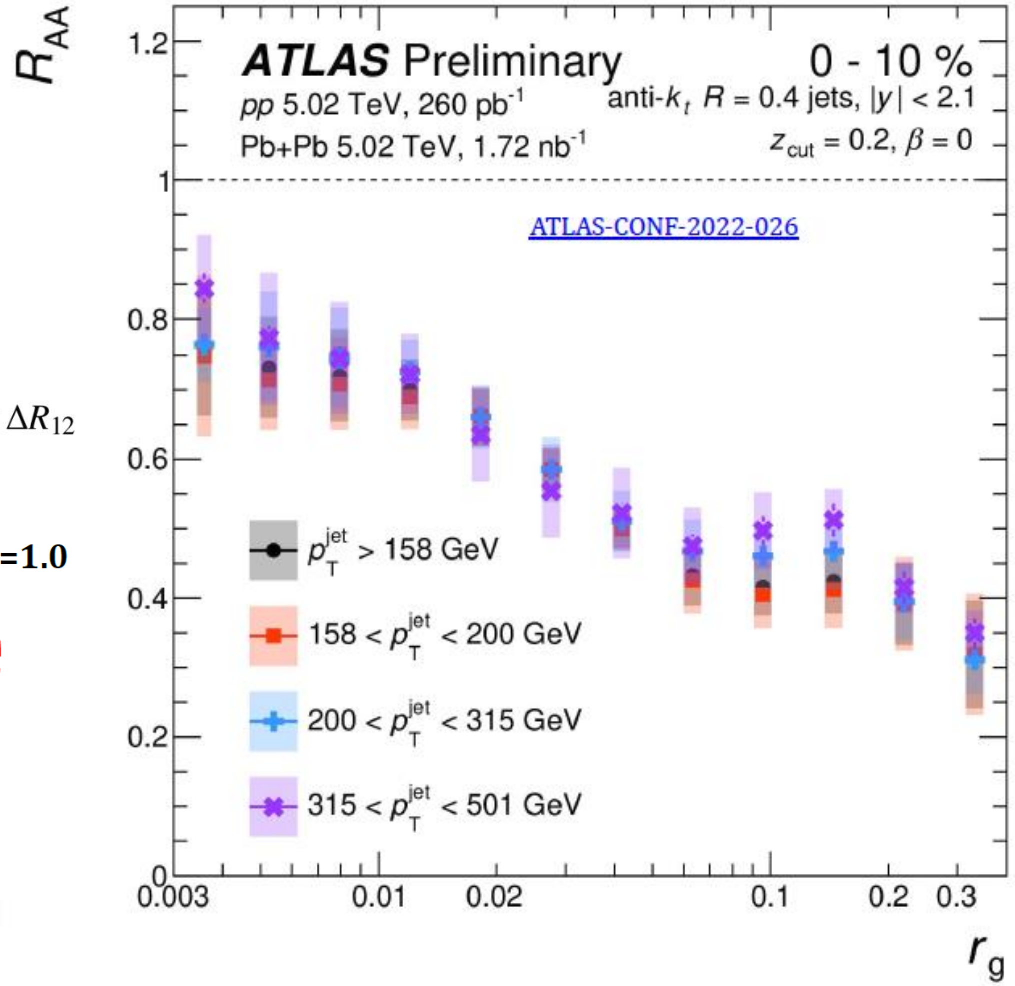
Jet Narrowing Effect in Inclusive Jets



$$\sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \times \Delta R_{12}$$



Cartoon from Martin Rybar



- Large scale jets:
  - R_{AA} of **Jets with single subjet (SSJ)**> Jets with multiple subjets
- Note that there is a two-step reclustering in this analysis (could in principle be different from groomed R=1.0 with soft drop for instance)

- Progress on absolute normalization:
  - First measurement of R_{AA} vs r_g
  - Jets with small r_g are less suppressed