Jet-induced Medium Response

HP 2023 - The 11th International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions
26-31 March 2023, Aschaffenburg, Germany

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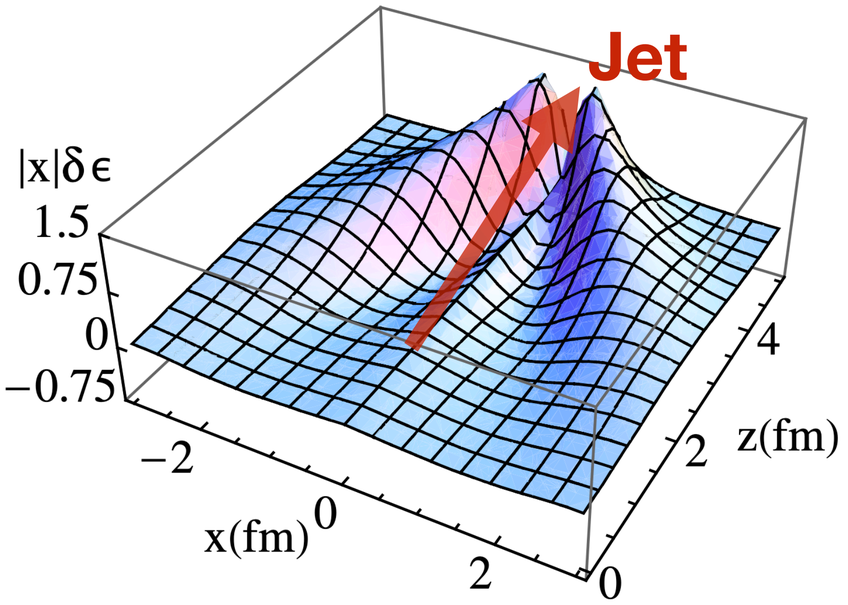
Mutual Interaction : Medium ⇄ Jets

- As jets are modified by medium, the medium is also affected by jets!

G.-Y. Qin et al, PRL 103, 152303 (2009)

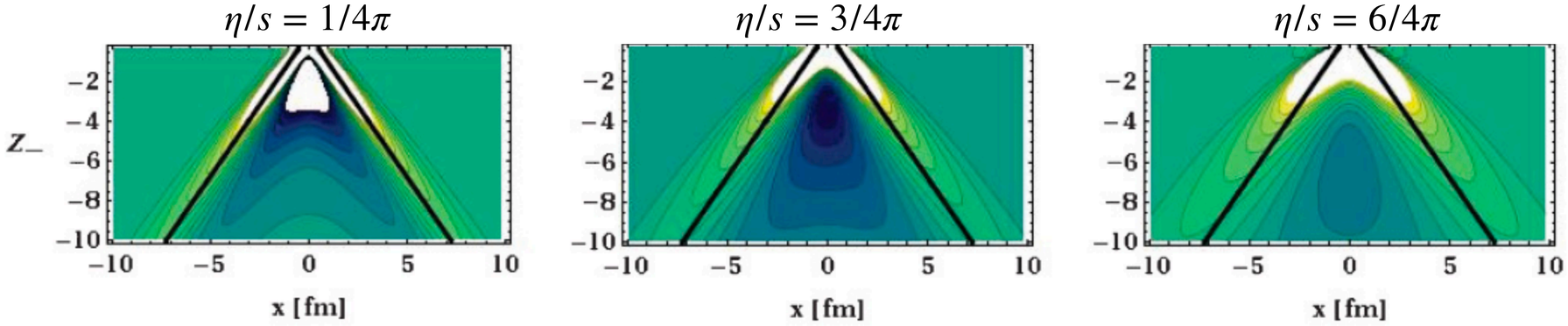


- Structures formed; **Mach cone**, **sonic boom**, **shock wave**, **diffusion wake**, …

Why is medium response important to understand?

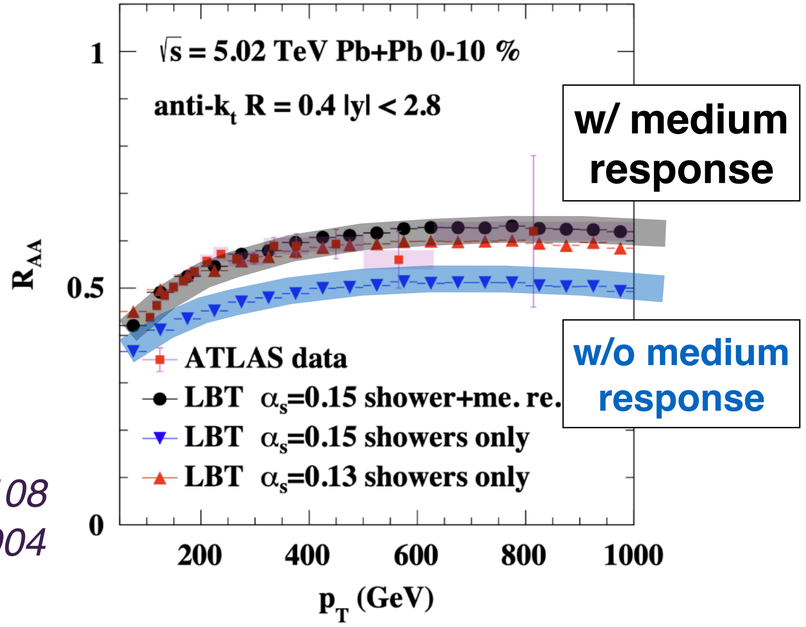
- Essential to describe the jet (sub)structure precisely
- Understanding in **QGP bulk properties** e.g. η/s, sound velocity

R. B. Neufeld, PRC 79 (2009) 054909



- **In-medium thermalization** information e.g. E_{med}, D_{diff}, τ_{th}

- Medium response affects the extraction of **jet transport coefficient**
  ➡ can be related to local gluon density distribution of the medium

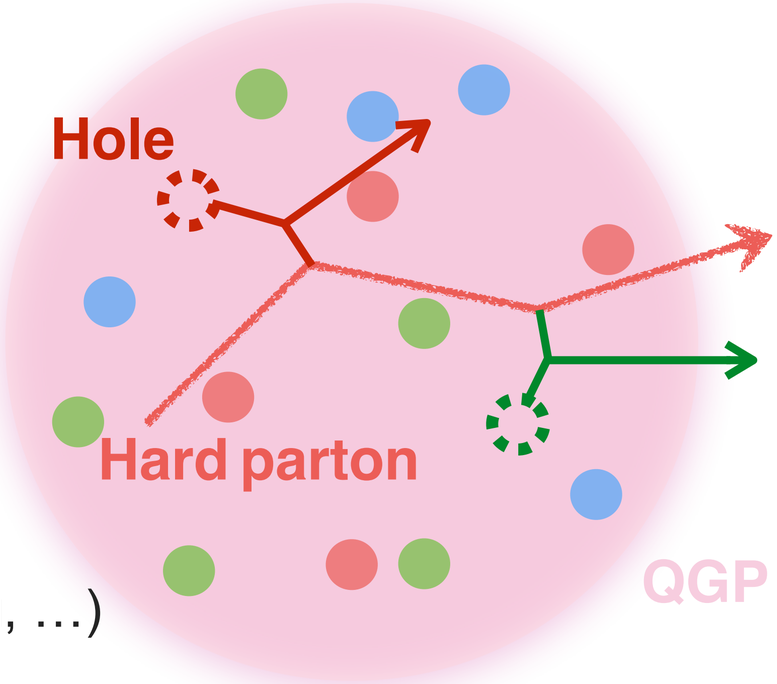


ATLAS, PLB 790 (2019) 108
Yayun He et al, PRC 106 (2022) 044904

Medium Response in Various Models: (1) Recoil

- Different models have different medium response implementation

- **Recoil (Weakly-coupled approach, when $E > E_{\mathrm{med}}$)**
  - ➡ partons in medium scatter with hard parton
  - ➡ "hole" (or "negative") of recoiled medium partons can be propagated and subtracted from the final parton spectra



- **Models with recoil**
  - ➡ **LBT** (T. Luo, S. Cao, Y. He, X.-N. Wang, S.-L. Zhang, G.-Y. Qin, Y. Zhu, …)
    - low virtuality
  - ➡ **MARTINI** (C. Park, S. Jeon, C. Gale, B. Schenke, …)
    - low virtuality
  - ➡ **MATTER** (A. Majumder, S. Cao, G. Vujanovic, M. Kordell, …)
    - high virtuality
  - ➡ **JEWEL** (K. C. Zapp, R. Kunnawalkam Elayavalli, J. G. Milhano, U. A. Wiedemann, ...)
    - re-scatterings of recoil partons with the medium are not implemented yet

Medium Response in Various Models: (2) Hydro

- **Hydrodynamics (Strongly-coupled approach, when $E \lesssim E_{\mathrm{med}}$)**

  ➡ medium fluid with a source term from a jet; $\partial_\mu T^{\mu\nu}_{\mathrm{fluid}} = J^{\nu}_{\mathrm{jet}}$

- **Models with hydrodynamics**

  ➡ **Coupled Jet-Fluid** (Y. Tachibana, N.-B. Chang, G.-Y. Qin, …)
  - Ideal hydro

  ➡ **EPOS3-HQ** (I. Karpenko, M. Rohrmoser, J. Aichelin, P. Gossiaux, K. Werner, …)
  - viscous hydro (vHLLE)
  - source term thermalizes after τ_{th}

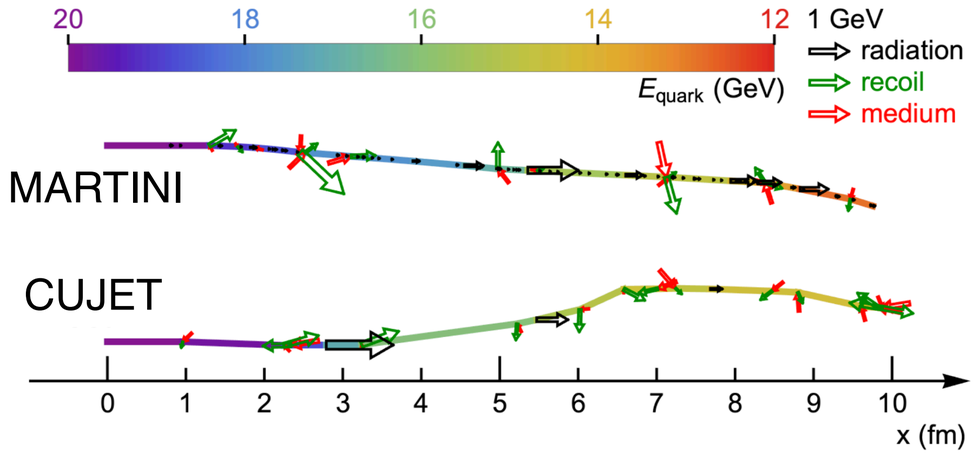
Medium Response in Various Models: (3) Hybrid

- **Hybrid (Recoil+Hydrodynamics)**

  ➡ **(Co)LBT-hydro** (W. Chen, T. Luo, S. Cao, L.-G. Pang, X.-N, Wang, …)
  - LBT + viscous hydro (CLVisc)

  ➡ **JETSCAPE** (JETSCAPE)
  - e.g. MATTER + LBT/MARTINI + viscous hydro (MUSIC)

Shuzhe Shi et al., arXiv:2212.05944



- Other models

  ➡ **Hybrid Strong/Weak Coupling (+ Linearized Hydro)**
  (D. Pablos, Z. Hulcher, J. Casalderrey-Solana, K. Rajagopal, J. G. Milhano D. C. Gulhan, …)

  ➡ **AMPT** (G.-L. Ma, X.-N. Wang, Z. Gao, A. Luo, H.-Z. Zhang, G.-Y. Qin, …)
  - Boltzmann equation based approach

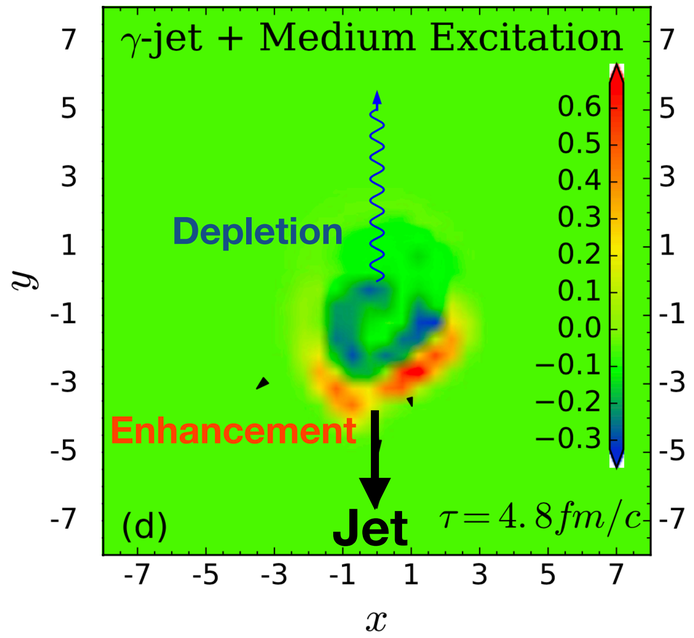
  ➡ **BAMPS** (I. Bouras, Z. Xu, C. Greiner, B. Betz, …)
  - Boltzmann equation based approach

  ➡ **MARTINI + Causal diffusion** (S. Ryu, S. McDonald, C. Shen S. Jeon, C. Gale)

  ➡ …

Structure formed from Medium Response in Models

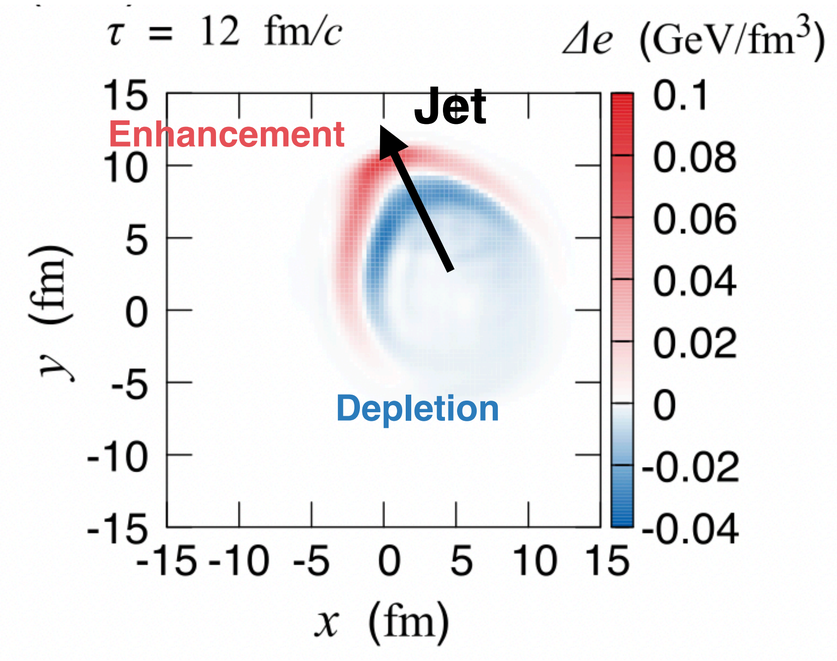
(γ-jet + Medium + Medium Excitation) — (γ-jet + Medium)



CoLBT-hydro (Recoil+Hydro)

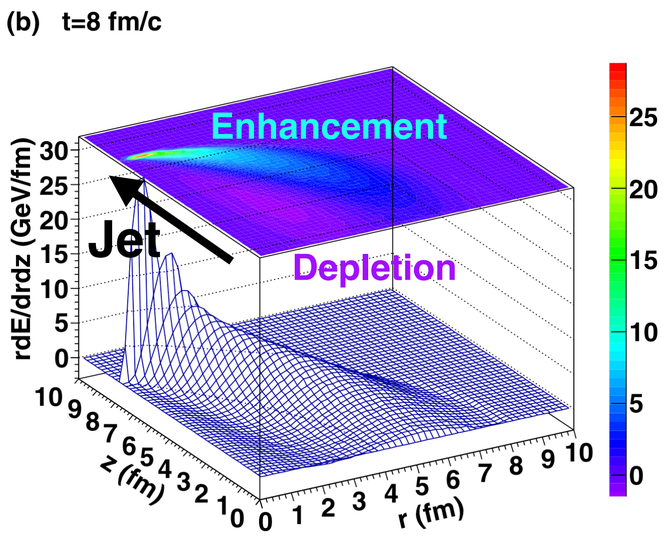
W. Chen et al. PLB 777 (2018) 86

(Whole medium energy density) — (medium w/o jet)



Coupled Jet-Fluid (Hydro)

Y. Tachibana et al. PRC 95, 044909 (2017)



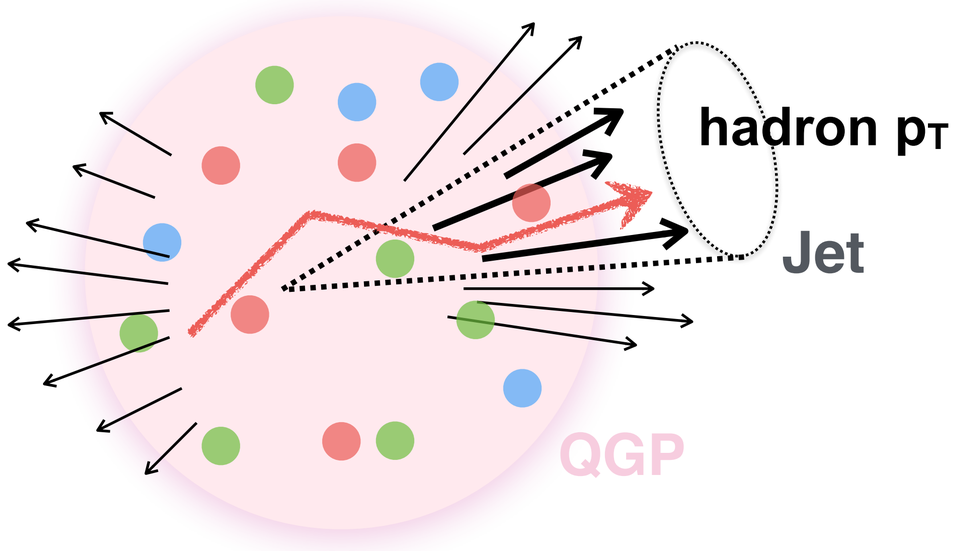
LBT (Recoil)

Y. He et al. PRC 91, 054908 (2015)

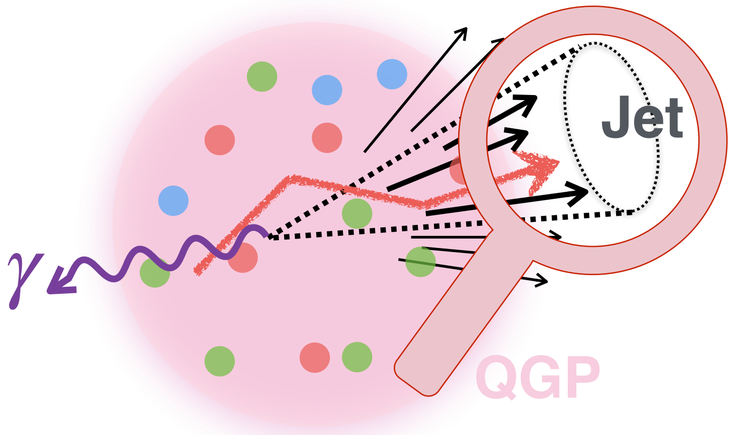
- Enhancement in jet direction; Mach-cone like structure
- Depletion in the opposite direction of jet; diffusion wake

What Jet Observables to investigate Medium Response?

- **Jet fragmentation function**
- Jet- or Boson-hadron correlation
- Jet shape
- R-dependent nuclear modification factor (R_{AA})
- …



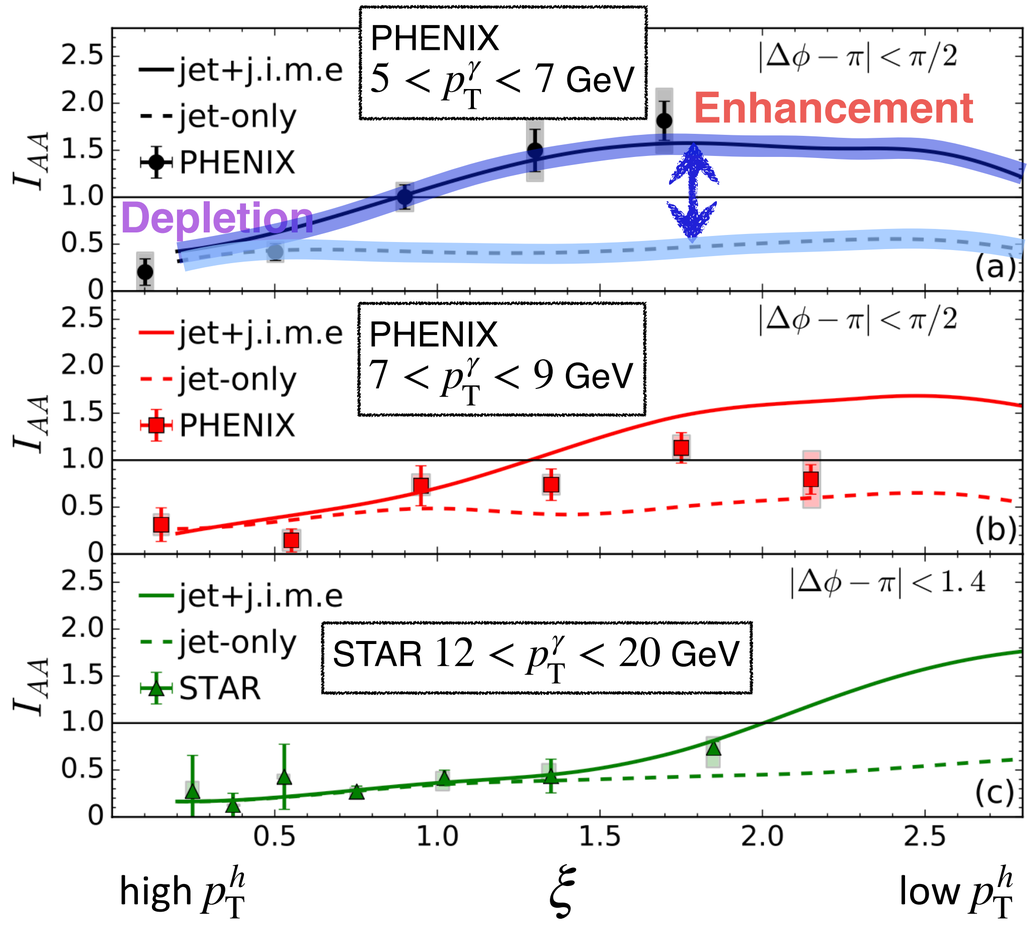
Fragmentation Function in γ-triggered events at RHIC



$$z = p_{\mathrm{T}}^{h}/p_{\mathrm{T}}^{\gamma}$$

$$\xi = \ln(p_{\mathrm{T}}^{\gamma}/p_{\mathrm{T}}^{h}) = \ln(1/z)$$

$$I_{\mathrm{AA}} = \frac{Y_{\mathrm{Pb+Pb}}^{\mathrm{hadron}}/N_{\mathrm{Pb+Pb}}^{\gamma}}{Y_{pp}^{\mathrm{hadron}}/N_{pp}^{\gamma}}$$



w/ medium response

w/o medium response

PHENIX *PRC 102, 054910 (2020)*

STAR *PLB 760 (2016) 689*

CoLBT-hydro

W. Chen et al, PLB 777 (2018) 86

- *Enhancement* of low-p_{T} hadrons, *depletion* of high-p_{T} hadrons
- Overall, **CoLBT-hydro *with*** jet induced medium excitations (**j.i.m.e**) describe the data better than the one *without* the medium response

What Jet Observables to investigate Medium Response?

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- **Jet- or Boson-hadron correlation**
- Jet shape
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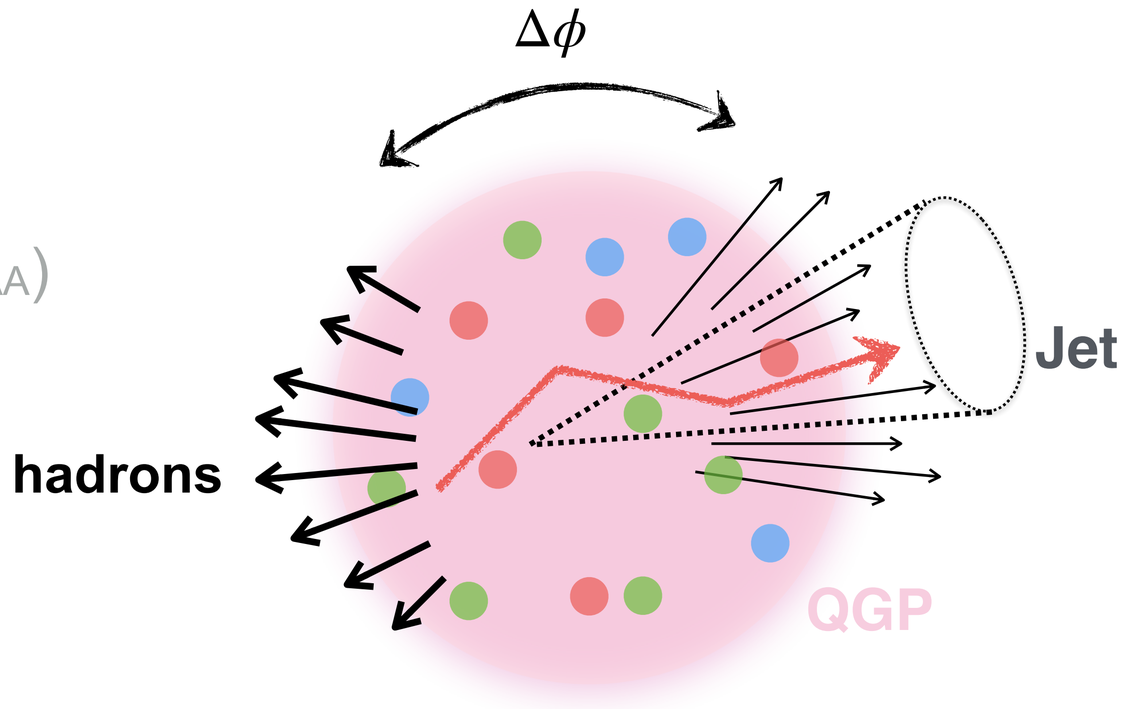
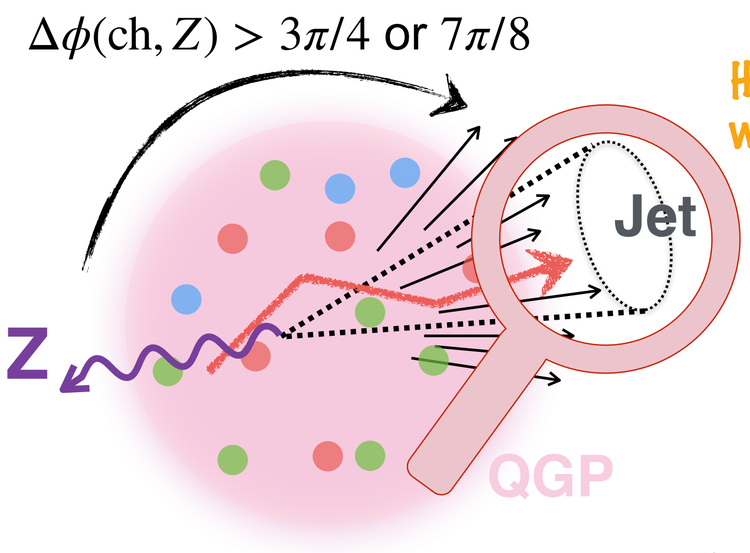
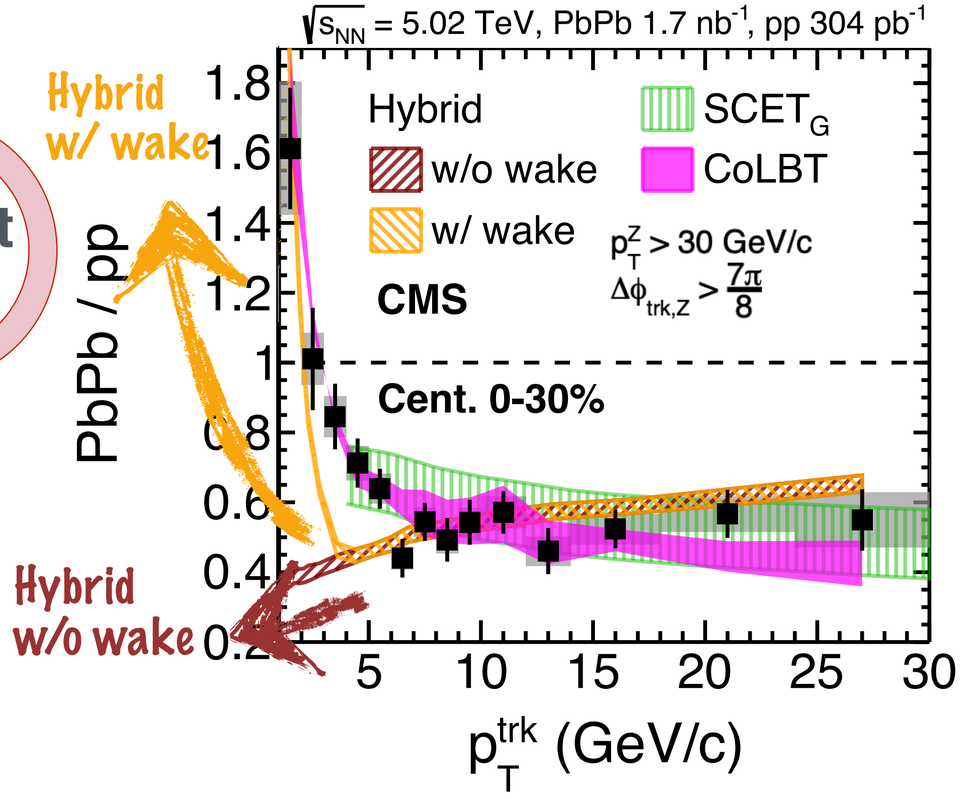
- …



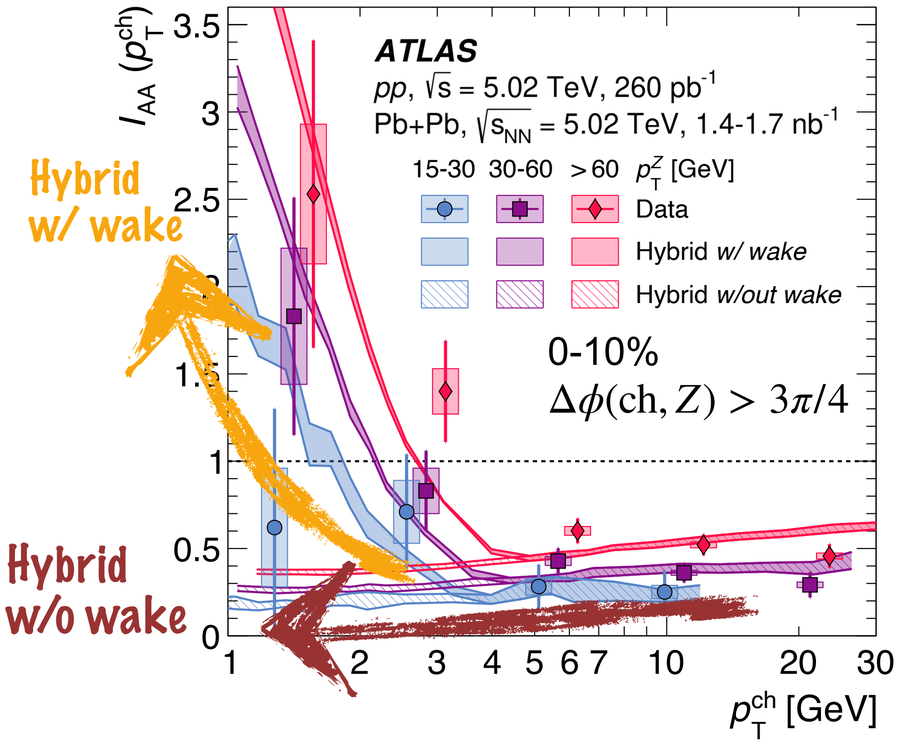
Z-hadron Correlation at LHC: p_T dependence



CMS *PRL 128 (2022) 122301*

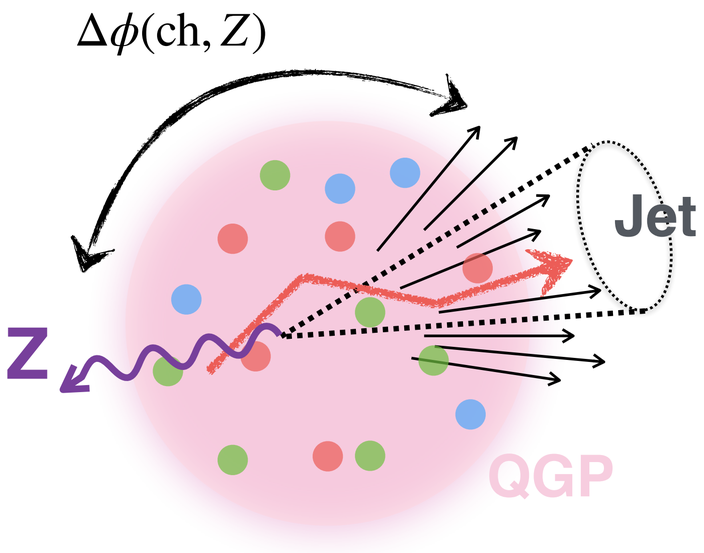


ATLAS *PRL 126 (2021) 072301*

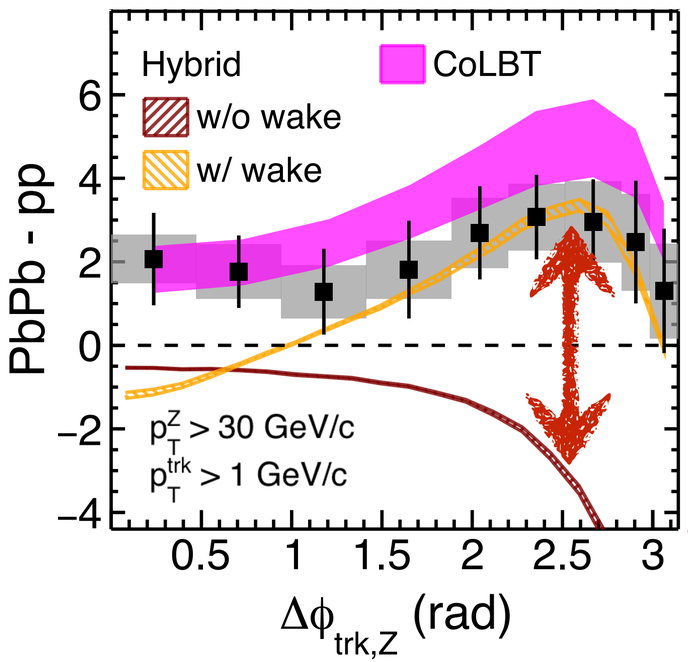


- At low p_T,
  - ➡ Significant difference between w/ and w/o medium response at low hadron p_T
  - ➡ models with medium response (**Hybrid w/ wake** and **CoLBT**) describe the data better
- At high p_T, all models including **SCET$_G$** (no medium response) describe the data well

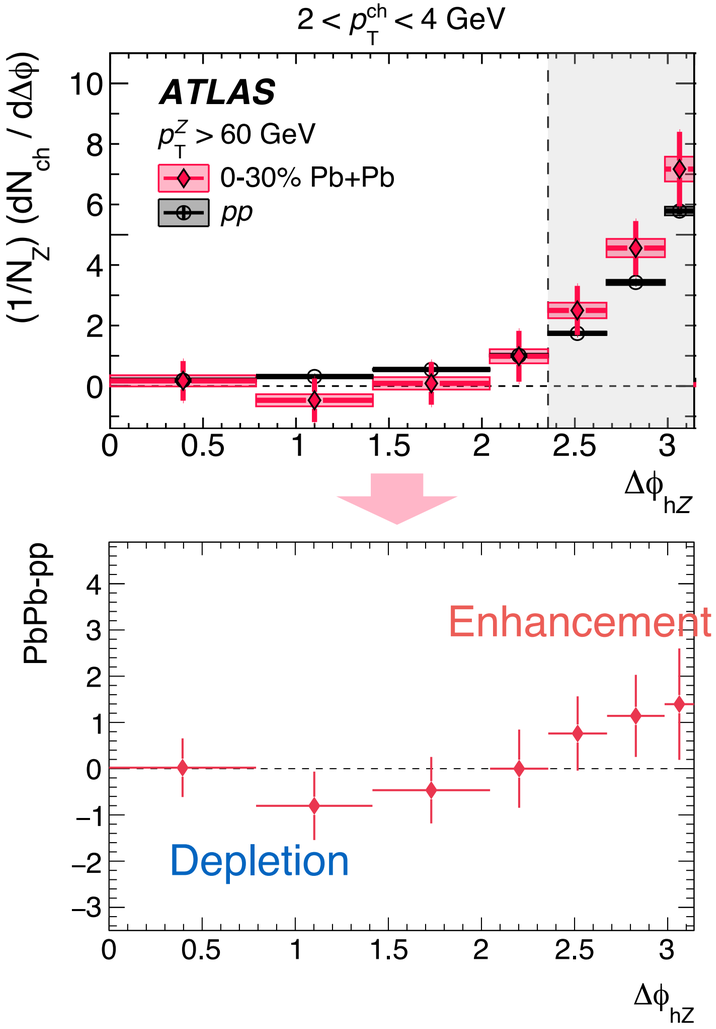
Z-hadron Correlation at LHC: $\Delta\phi$ dependence



CMS *PRL 128 (2022) 122301*



ATLAS *PRL 126 (2021) 072301*



- *Enhancement* of hadrons in jet direction; **medium response**!
- Differences between ***ATLAS*** and **CMS** measurements

  (1) different background subtraction method

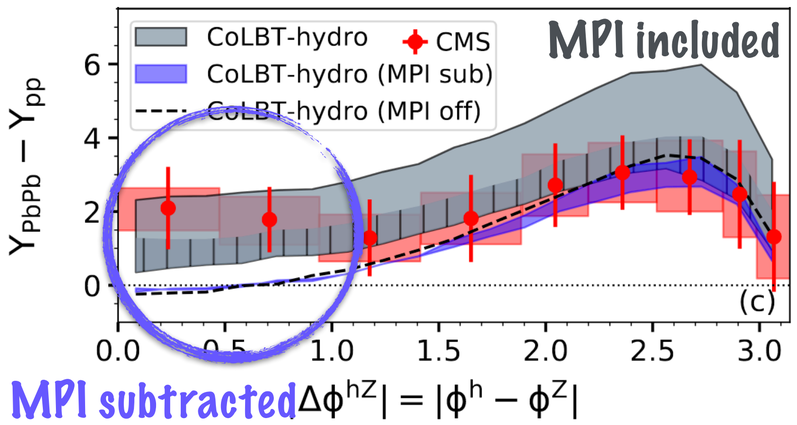
  (2) ***ATLAS*** $2 < p_T^h < 4$ GeV, **CMS** $p_T^h > 1$ GeV

  ➡ In **Z**-boson direction, **ATLAS** shows hint of **diffusion wake**

Z-hadron Correlation at LHC: $\Delta\phi$ dependence

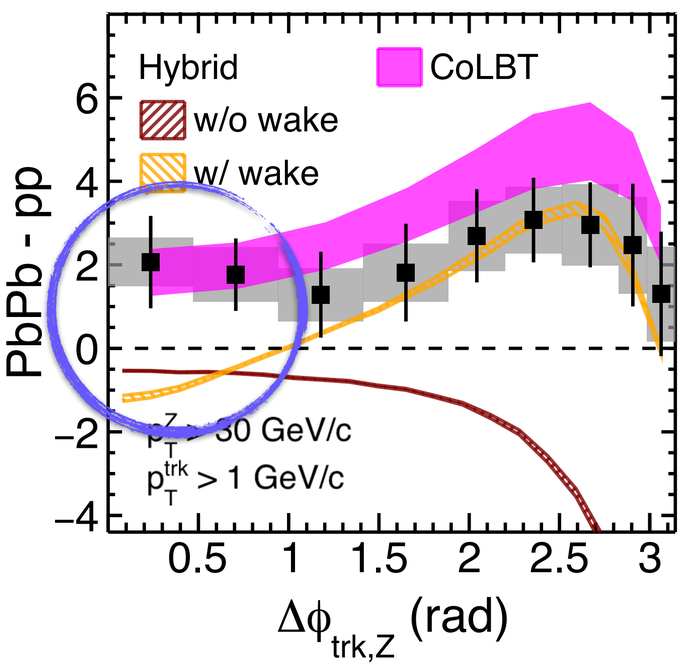
Wei Chen, PRL 127 (2021) 082301

CoLBT-hydro

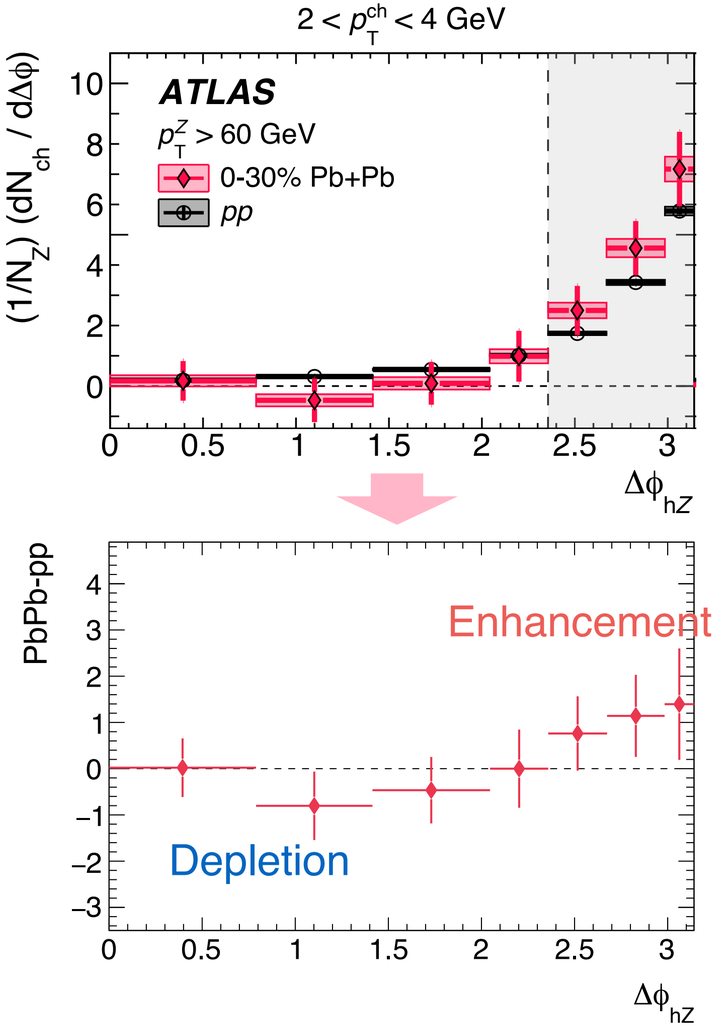


MPI subtracted $\Delta\phi^{hZ}| = |\phi^{h} - \phi^{Z}|$

CMS *PRL 128 (2022) 122301*



ATLAS *PRL 126 (2021) 072301*



- *Enhancement* of hadrons in jet direction; **medium response**!
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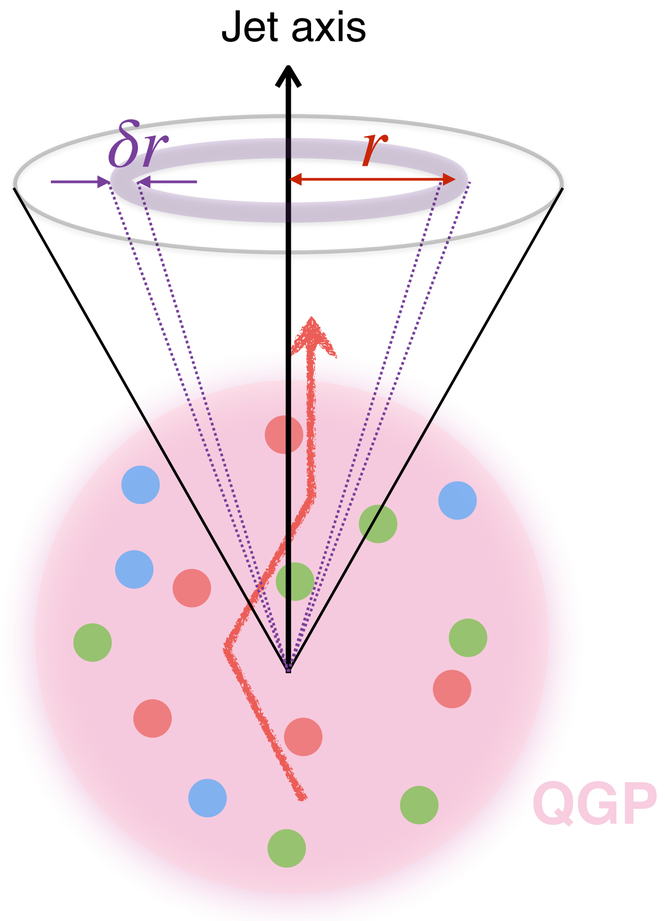
➡ In **Z**-boson direction, **ATLAS** shows hint of **diffusion wake**

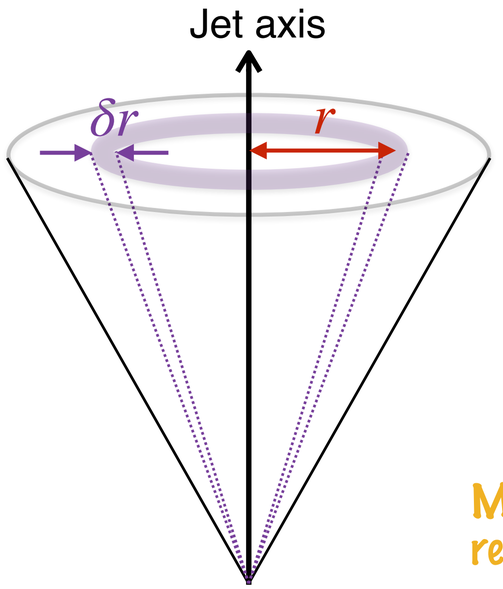
CMS and **CoLBT** shows enhancement by **multi-parton interaction (MPI)**

What Jet Observables to investigate Medium Response?

- Jet fragmentation function
- Jet- or Boson-hadron correlation
- **Jet shape**
- R-dependent nuclear modification factor (R_{AA})
- …

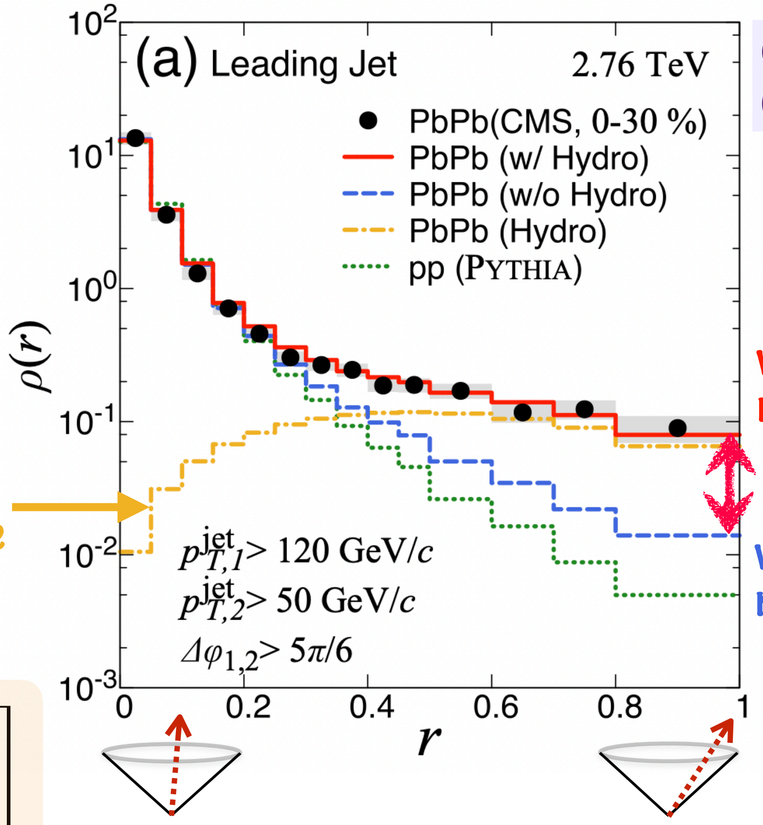


Jet Shape



CMS *JHEP 11 (2016) 055*

Y. Tachibana et al, PRC 95, 044909 (2017)



Medium response

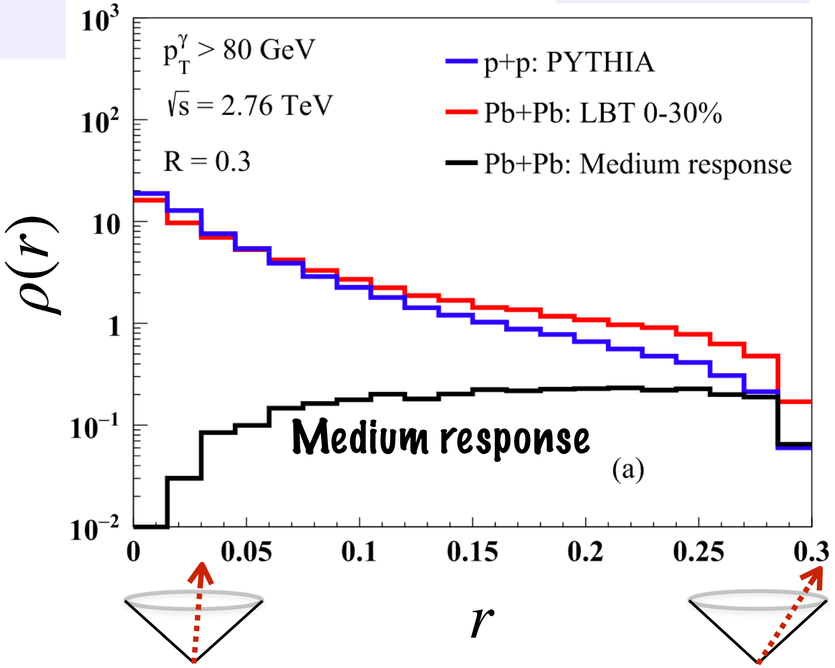
w/ medium response

w/o medium response

Coupled Jet Fluid (Hydro)

T. Luo et al, PLB 782 (2018) 707

LBT (Recoil)

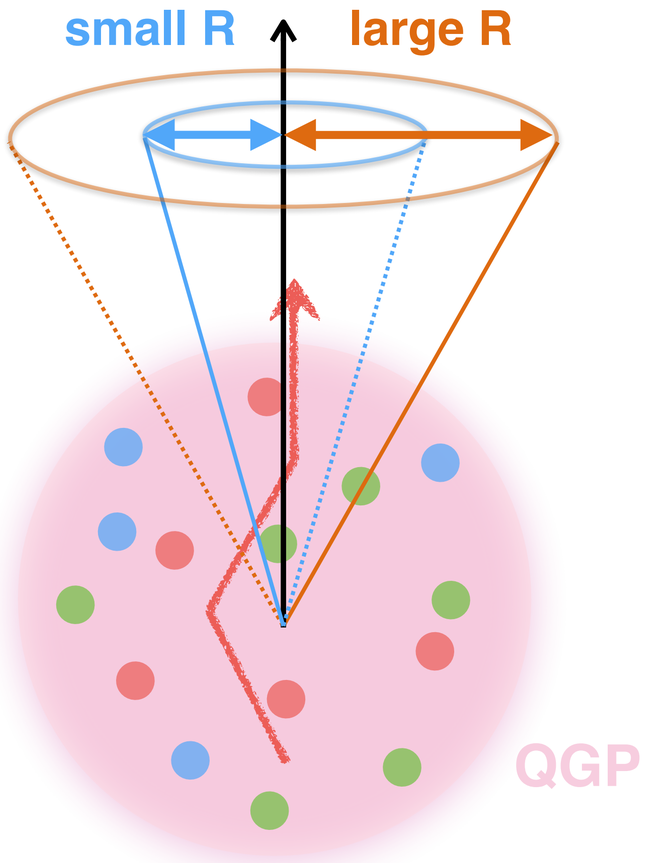


$$\rho_{\text{jet}}(r) = \frac{1}{N_{\text{jet}}} \sum_{\text{jet}} \left[\frac{1}{p_{\text{T}}^{\text{jet}}} \frac{\sum_{\text{trk}\in(\text{r}-\delta\text{r}/2,\text{r}+\delta\text{r}/2)} p_{\text{T}}^{\text{trk}}}{\delta r} \right]$$

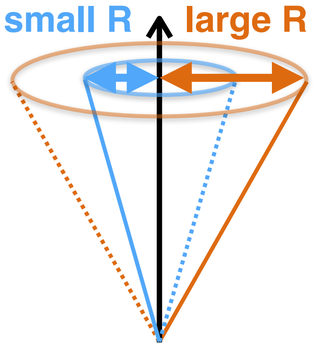
- At *large* angle, ***enhancement*** by medium response
- At *small* angle, negligible effect from medium response

What Jet Observables to investigate Medium Response?

- Jet fragmentation function
- Jet- or Boson-hadron correlation
- Jet shape
- **R-dependent nuclear modification factor (R_{AA})**
- …



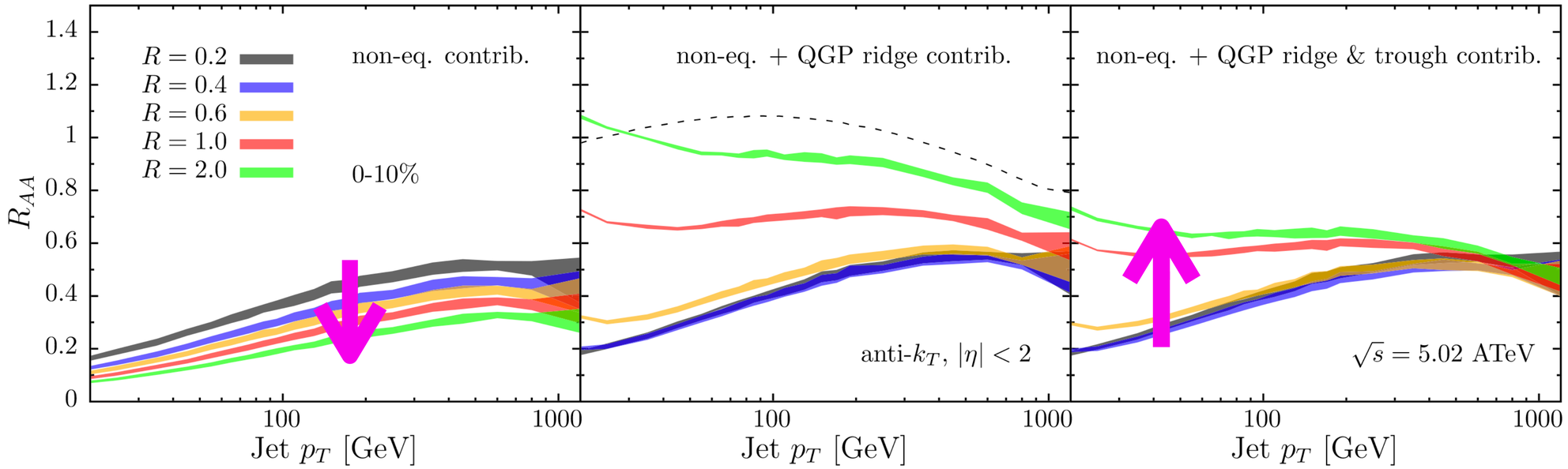
Radius-dependent Jet R_{AA}



Hybrid Strong/Weak Coupling

Daniel Pablos, PRL 124 (2020) 052301

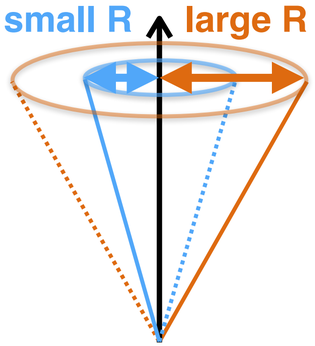
with increasing R …

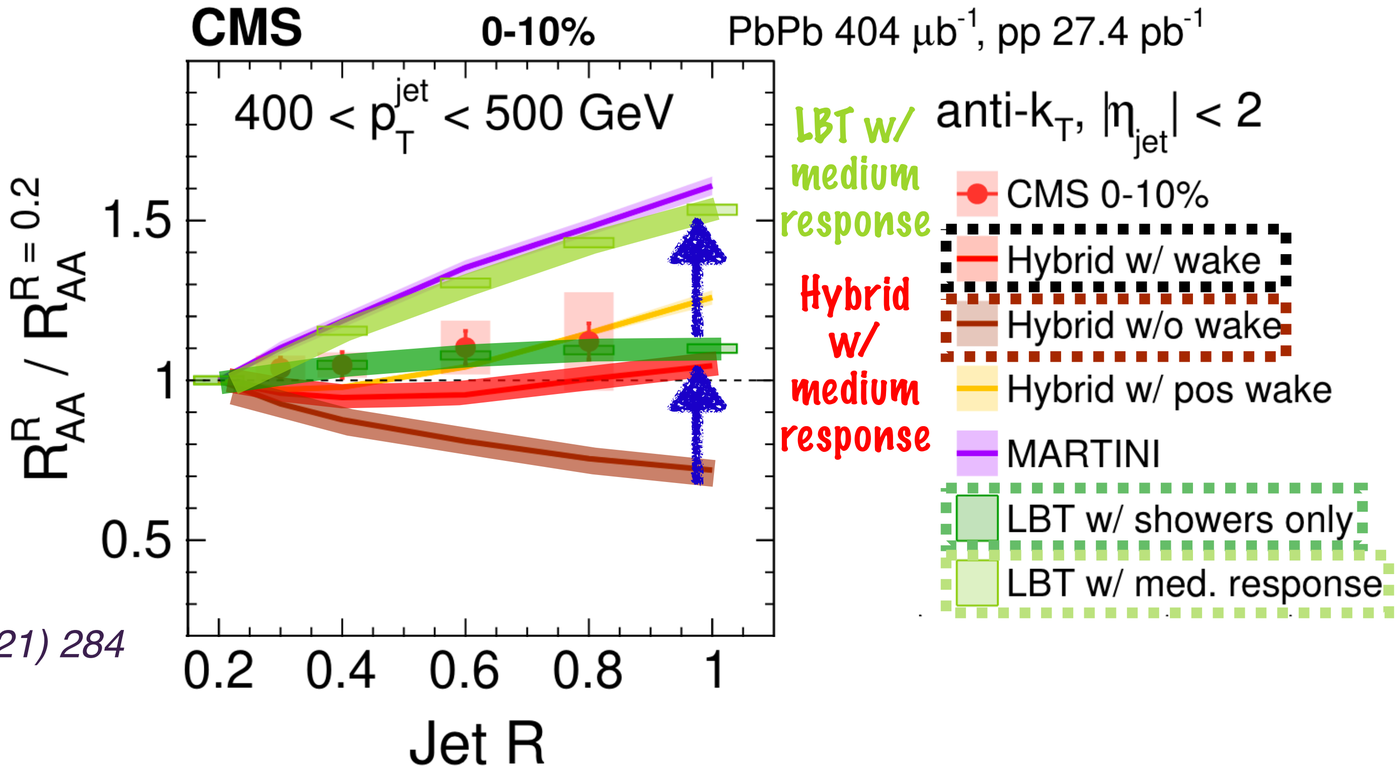


w/o medium response → w/ medium response

- Significantly different picture between w/o and w/ **medium response** in model

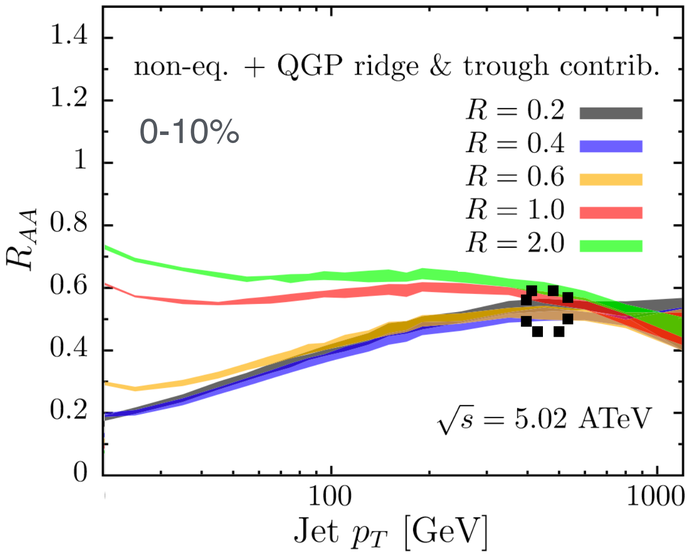
Radius-dependent Jet R_{AA}





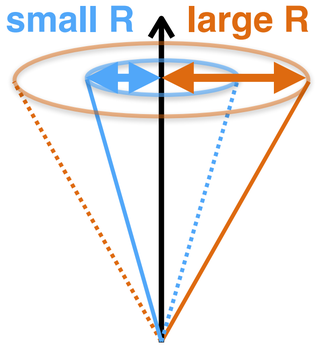
CMS *JHEP 05 (2021) 284*

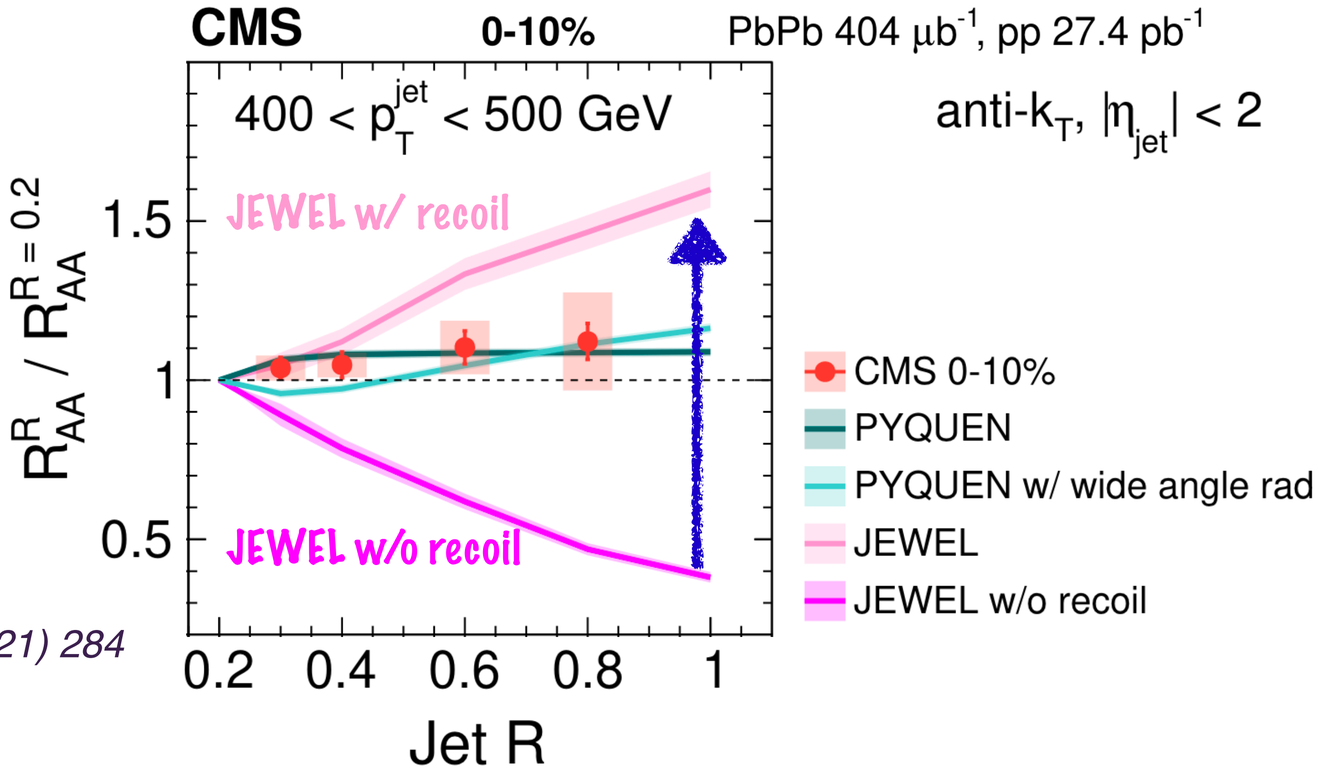
Daniel Pablos, PRL 124 (2020) 052301



- At high jet p_T (400-500 GeV), relatively **small R-dependence** in data
- Medium response increases $R_{\mathrm{AA}}^{\mathrm{R}}/R_{\mathrm{AA}}^{\mathrm{R=0.2}}$ for most models (**Hybrid**, **LBT**, **JEWEL**)

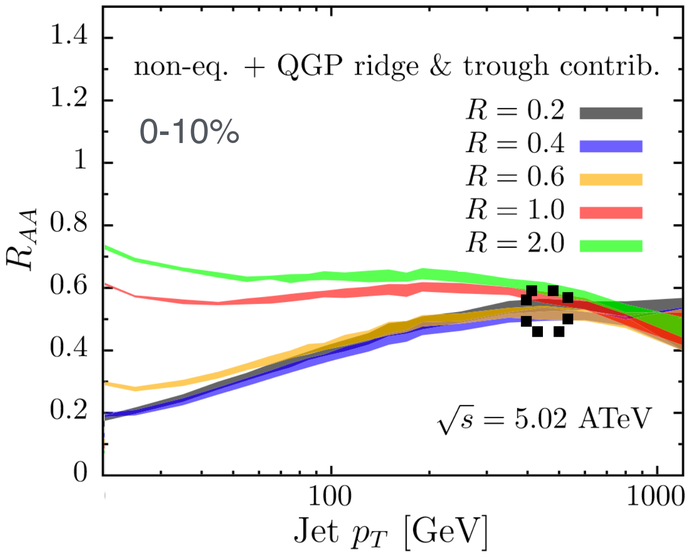
Radius-dependent Jet R_{AA}





CMS *JHEP 05 (2021) 284*

Daniel Pablos, PRL 124 (2020) 052301



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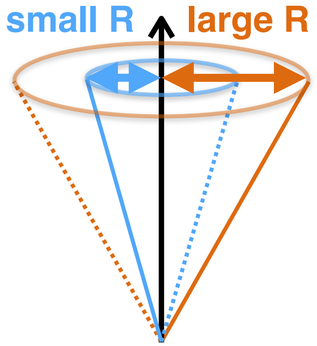
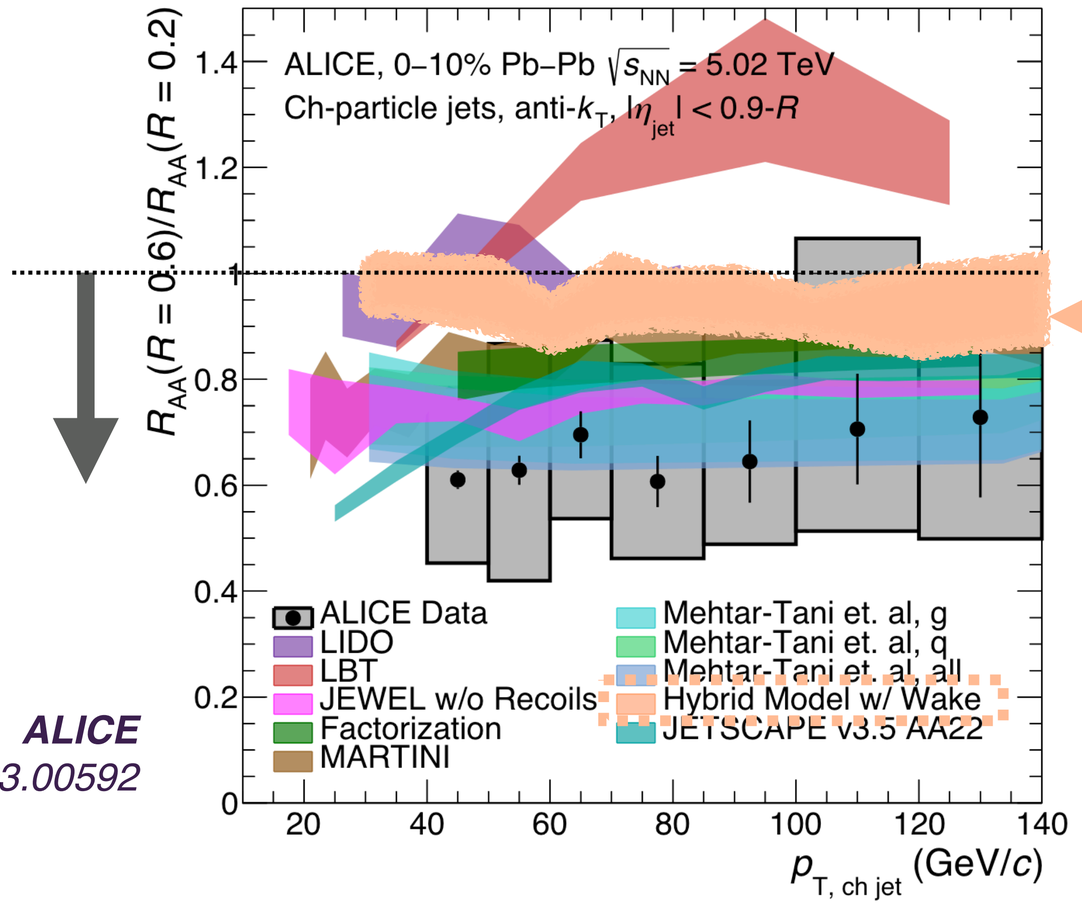
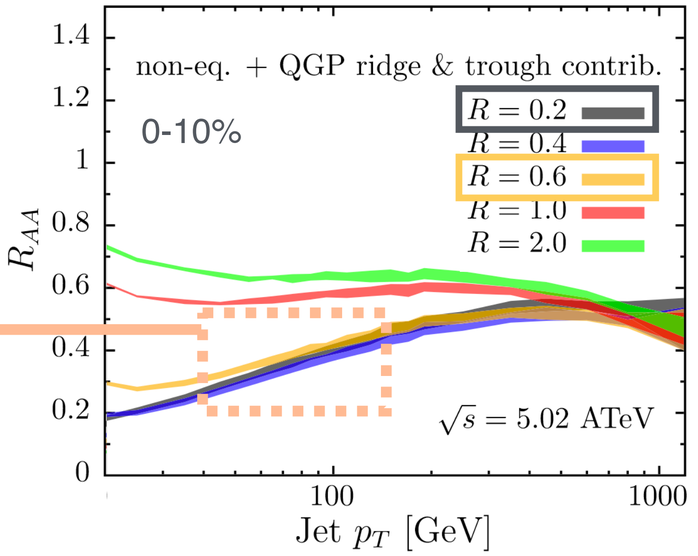
Radius-dependent Jet R_{AA}





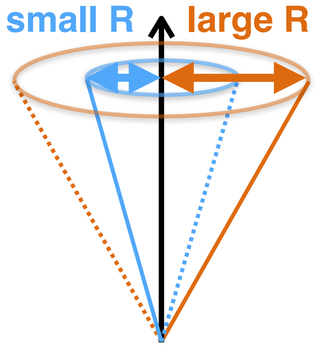
ALICE
arXiv:2303.00592

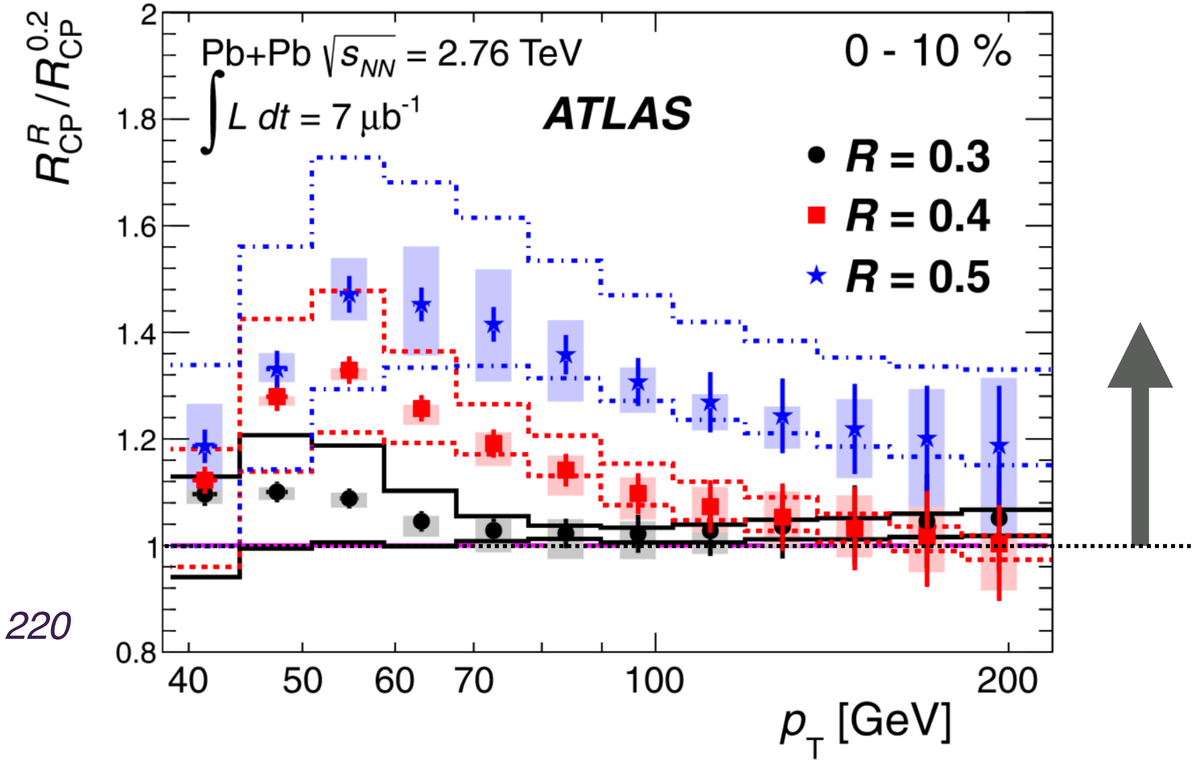
Daniel Pablos, PRL 124 (2020) 052301



- At low jet p_T (40-140 GeV), **ALICE** data shows R_{AA} (R=0.6) < R_{AA} (R=0.2)
- Various model (with and without medium response) *do* or *do not* describe data

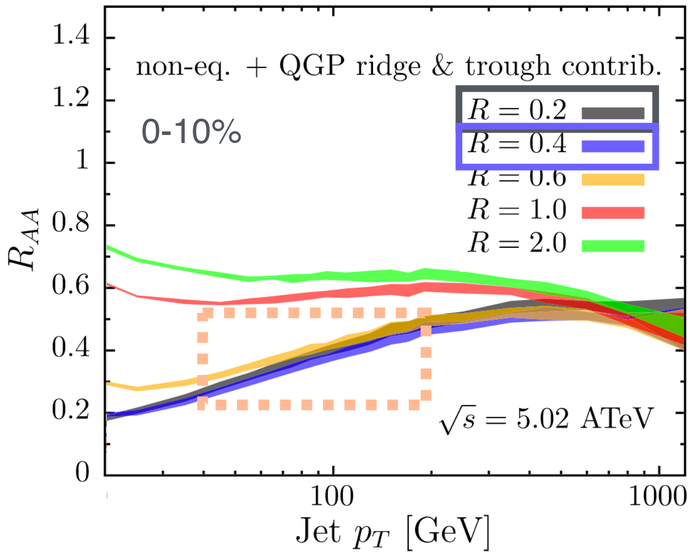
Radius-dependent Jet R_{AA}





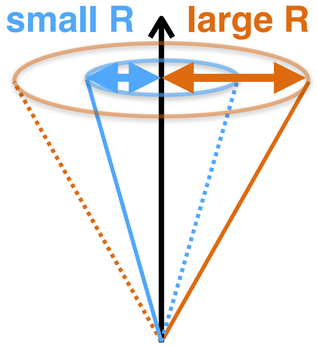
ATLAS *PLB 719 (2013) 220*

Daniel Pablos, PRL 124 (2020) 052301



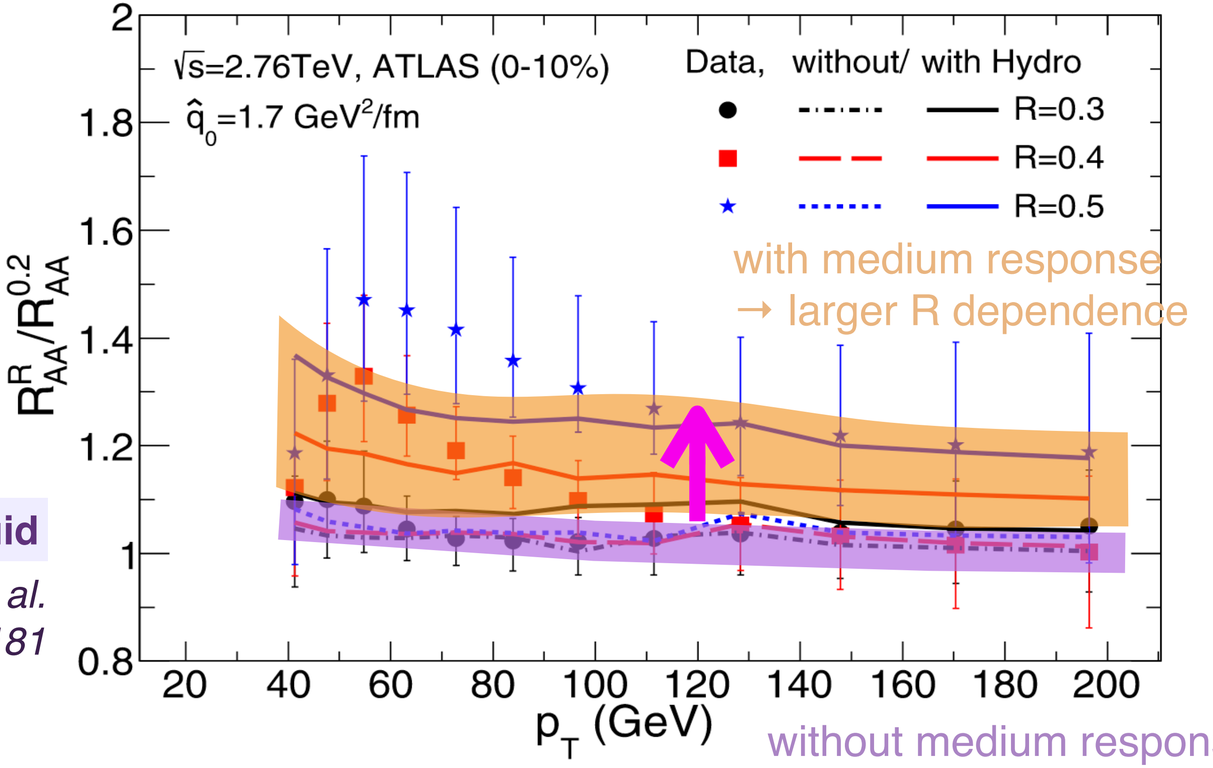
- At low jet p_T (40-200 GeV), **ATLAS** data shows R_{CP} (R=0.5) > R_{CP} (R=0.2)
  - ➡ tension between **ALICE** and **ATLAS**

Radius-dependent Jet R_{AA}



Coupled jet-fluid

N.-B. Chang et al.
PLB 801 (2020) 135181

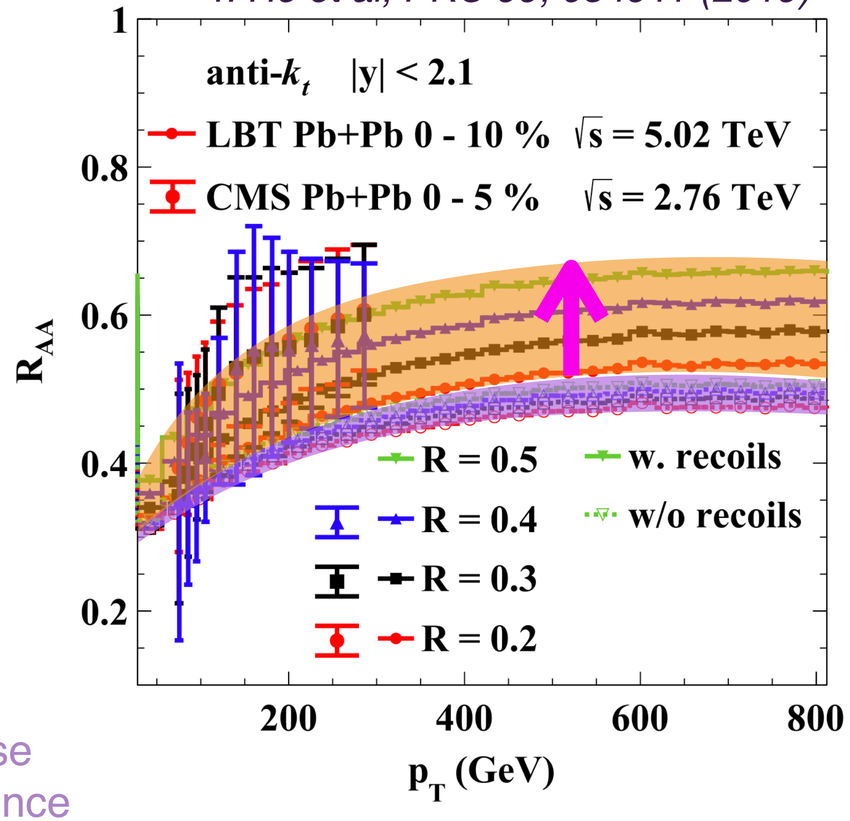


with medium response
→ larger R dependence

without medium response
→ negligible R dependence

LBT

Y. He et al, PRC 99, 054911 (2019)

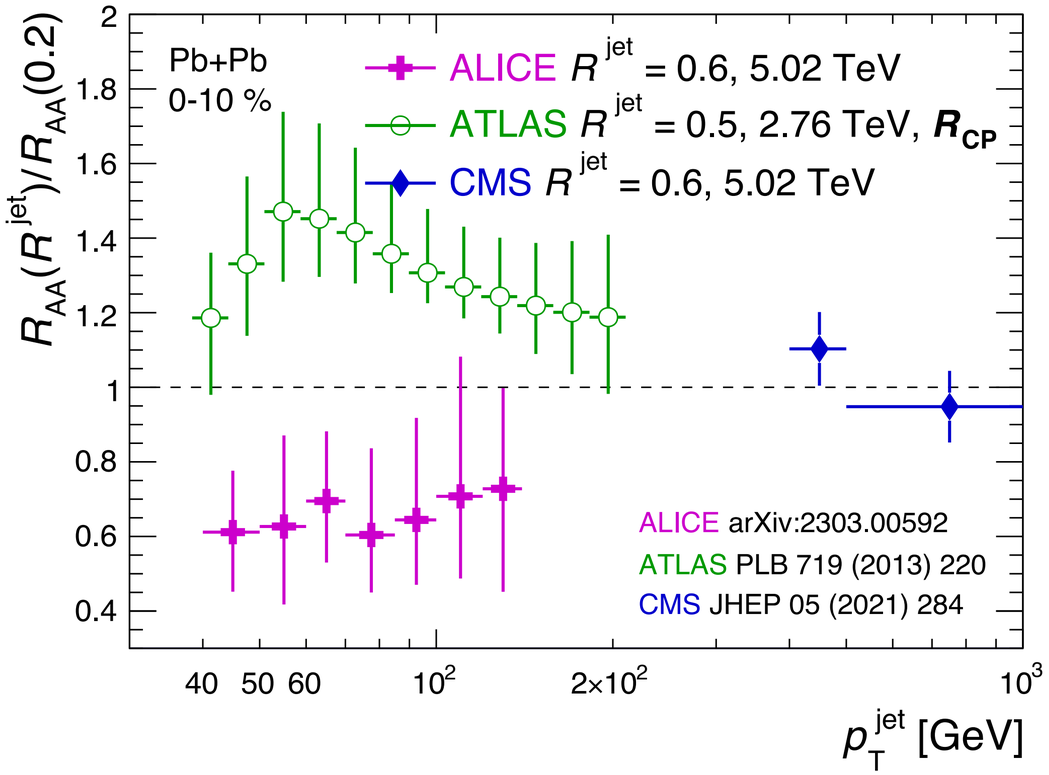


with increasing R …

- At low jet p_T (40-200 GeV), **ATLAS** data shows R_{CP} (R=0.5) > R_{CP} (R=0.2)
  - ➡ tension between **ALICE** and **ATLAS**
- Some models (e.g. **Coupled jet-fluid**, **LBT**) with medium response describe **ATLAS** data

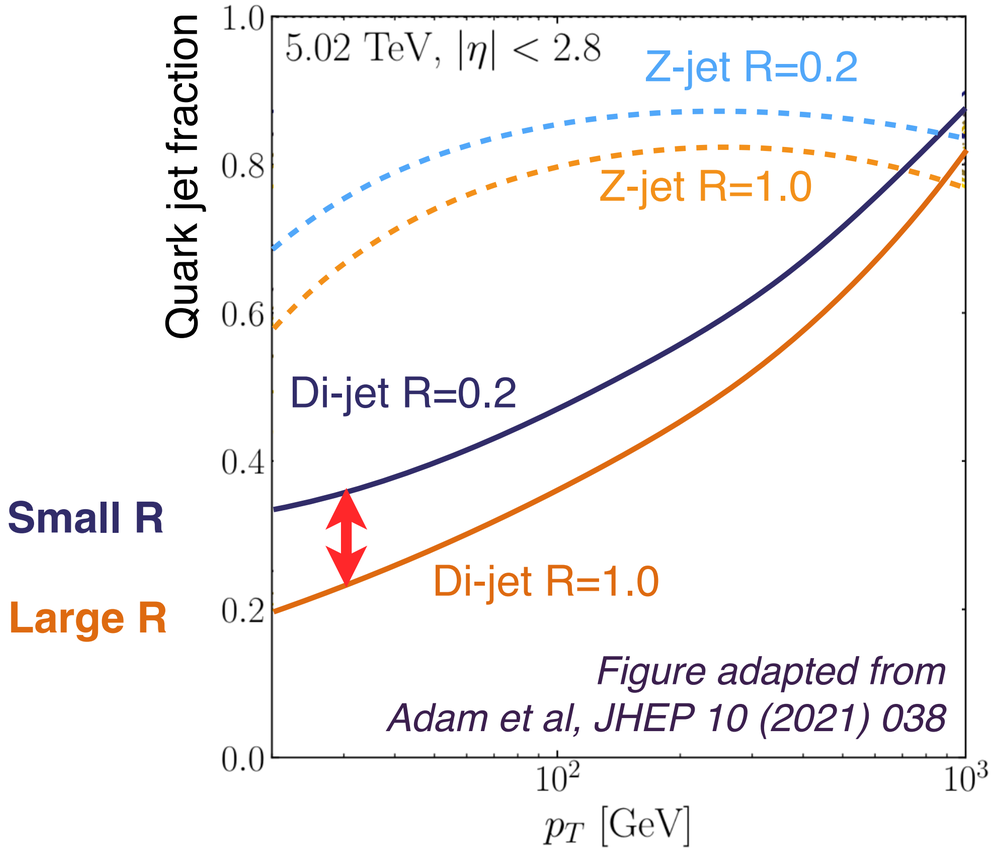
Radius-dependent Jet R_{AA}

- Tension between ALICE and ATLAS measurements; but, there are differences:
  - ➡ ALICE charged-particle jets vs. ATLAS all jets
  - ➡ ALICE $\mathbf{R_{AA}}(0.6)/\mathbf{R_{AA}}(0.2)$ vs. ATLAS $\mathbf{R_{CP}}(0.5)/\mathbf{R_{CP}}(0.2)$
  - ➡ ALICE uses new machine learning technique vs. ATLAS fake-jet rejection via fragmentation requirement
  - ➡ different η ranges
    - ALICE: R_{AA}(R=0.6); $|\eta|<0.3$, R_{AA}(R=0.2); $|\eta|<0.7$
    - ATLAS: $|\eta|<2.1$



Radius-dependent Jet R_{AA}: Discussion

- Quark/gluon fraction difference in different R
  - ➡ **Larger R** → less quark (more gluon) fraction → more E-loss (**Lower R_{AA}**)



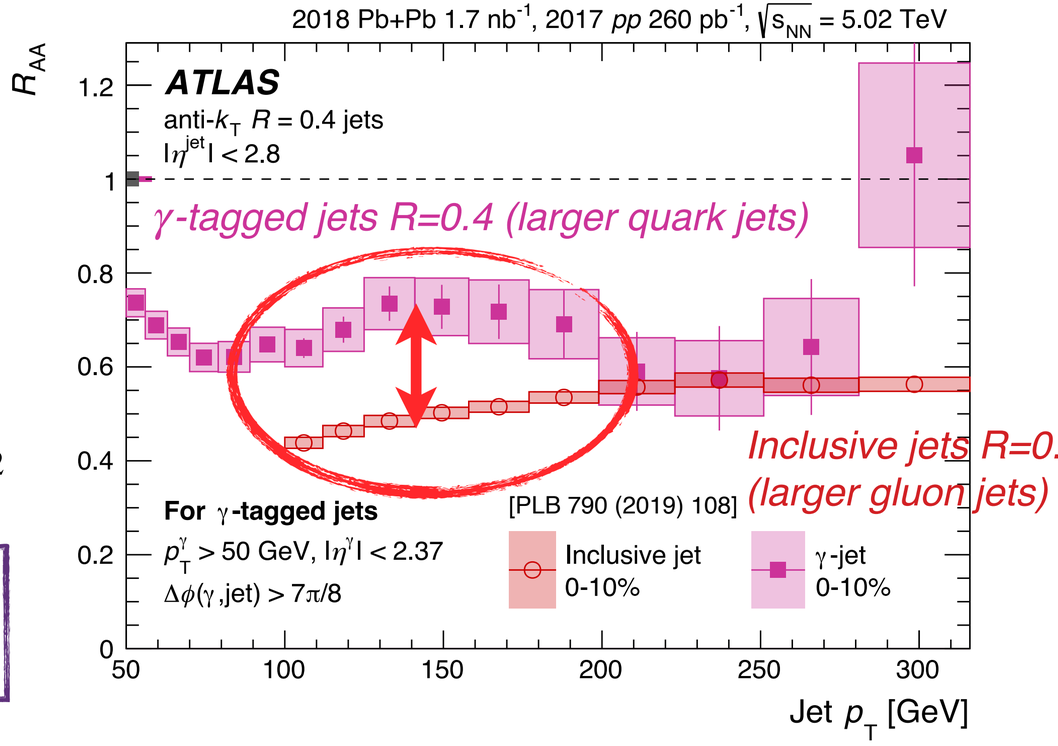
Impact of ***color-charge*** *difference on R_{AA}*

$$\langle \Delta E_g \rangle \propto \alpha_s C_R \hat{q} L^2$$

Casimir color factor
4/3 for quarks
3 for gluons

$$\Delta E_{gluon} > \Delta E_{quark}$$

ATLAS *arXiv:2303.10090*



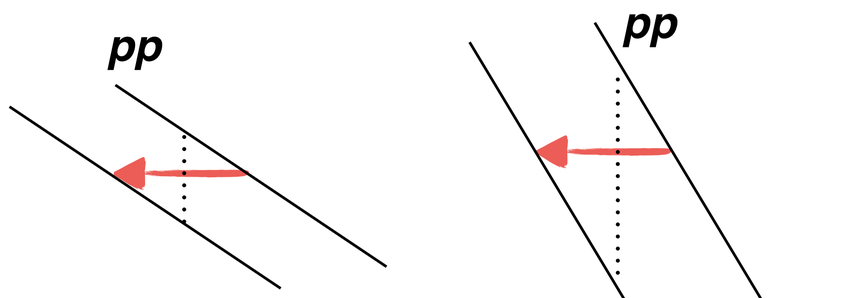
- **Forward rapidity** → more quark (less gluon) fraction → less E-loss (**Higher R_{AA}**) *arXiv:2210.07901*
- One could utilize **R_{AA} of boson-tagged jets** or **jets at forward rapidity** (dominated by quark-jets) to de-weight the *color-charge dependent E-loss* effect in the double R_{AA} ratio

Radius-dependent Jet R_{AA}: Discussion

- In ***pp*** collisions, different p_T slope results in different R_{AA}

  ➡ **steeper p_T distribution** → **Lower R_{AA}**

For the same energy loss,

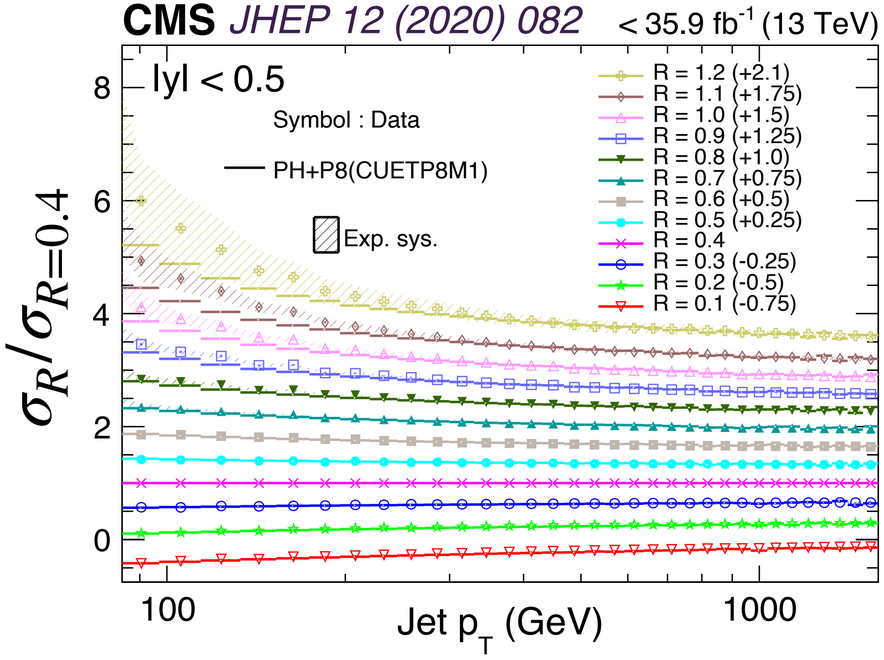


flatter
p_T distribution in *pp*
→ higher R_{AA}

steeper
p_T distribution in *pp*
→ lower R_{AA}

Radius-dependent Jet R_{AA}: Discussion

- In ***pp*** collisions, different p_T slope results in different R_{AA}
  - ➡ **steeper p_T distribution** → **Lower R_{AA}**

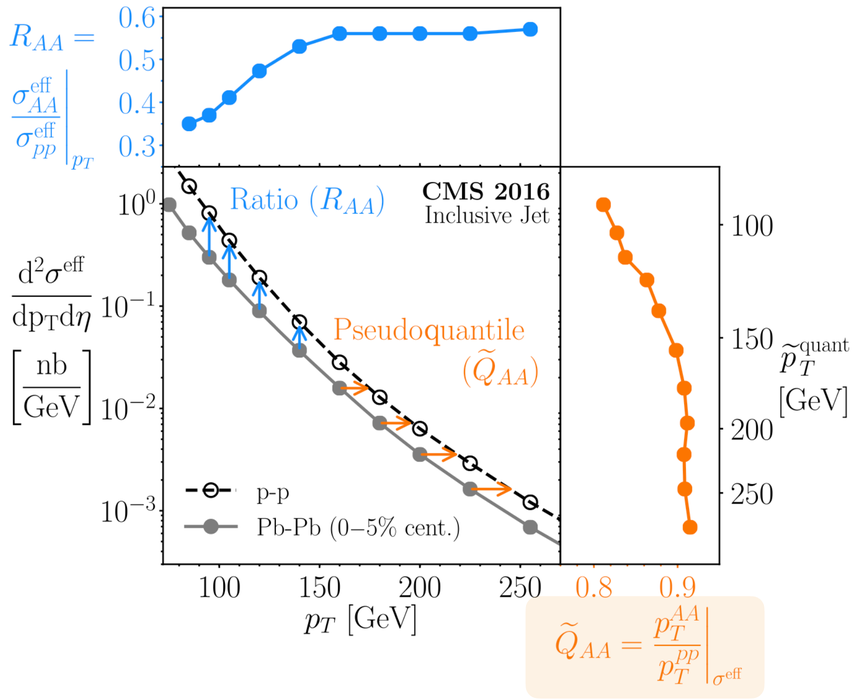


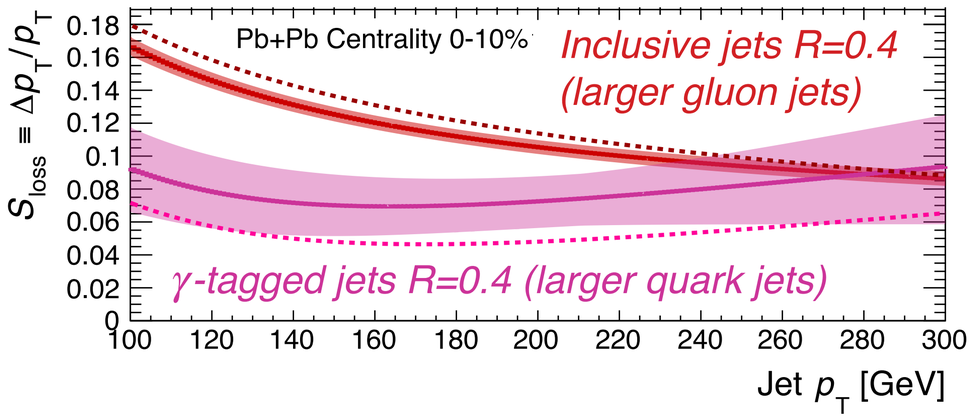
S_{loss} or Q_{AA} to mitigate the effect from p_T slope difference

$$S_{\mathrm{loss}} \equiv \frac{(p_{\mathrm{T}}^{\mathrm{pp}} - p_{\mathrm{T}}^{\mathrm{PbPb}})}{p_{\mathrm{T}}}$$

- Different R have different p_T slope in pp collisions
- Instead of R_{AA}, other observables (e.g. **S_{loss}**, **Q_{AA}**) can be measured to de-weight the p_T slope effect

J. Brewer et al, PRL122 (2019) 222301





***ATLAS** arXiv:2303.10090*

Summary

- *Jets are modified by medium and simultaneously modify the medium*
- Understanding medium response is important
  - ➡ **precise jet measurements, QGP bulk properties, in-medium thermalization information**, …
- Medium response sensitive observables
  - ➡ e.g. Jet-hadron correlation, fragmentation functions, shape, R-dependent R_{AA},
    jet mass, axis difference, angularity, baryon/meson ratio, …
- **Models predict significant differences** in these observables w/ and w/o medium response
  - ➡ Some data and models are consistent with medium response
- **More systematic studies** between different models is crucial
- **Precise experimental measurements for various observables** can help constraining models

List of talks related

Experiment

ALICE R-dependent R_{AA} by C. Pliatskas on Tue. 9:00 AM

STAR Jet Shape by T. Pain on Tue. 11:10 AM

ALICE Acoplanarity broadening by Y. HOU on Tue. 12:10 PM

STAR Baryon-to-Meson Ratio in Jet by G. D-GAU on Tue. 3:40 PM

ALICE Jet mass and angularity by E. Lesser on Tue. 5:10 PM

ATLAS Color-charge dependent jet quenching using photon+jets by C. McGinn on Wed. 9:00 AM

PHENIX Jet measurements on Wed. 2:20 PM

ALICE Angle between jet axis by R. C-Torres on Wed. 5:50 PM

STAR Photon-jet and hadron-jet correlations by Y. He on Thu. 9:40 AM

Theory

JEWEL+v-USPhydro by L. Barreto on Tue. 9:00 AM

3D structure of jet-induced diffusion wake by Z. Yang on Tue 9:40 AM

Minijet quenching in jet+hydro evolution by C. Gale on Tue. 11:10 AM

Comparative multi-probe study of jet energy-loss by R. M.-Yazdi on Tue. 2:20 PM

Efficient description of medium response by J. C-Solana on Tue. 3:20 PM

Enhancement of baryon-to-meson ratios by G.-Y. Qin on Wed. 9:20 AM

Forward jet measurements by D. Pablos on Wed. 11:10 AM

Probing short-length structure of QGP by K. Rajagopal on Wed. 11:50 AM

Unbiased quantification of jet energy loss by J. M. Silva on Wed. 2:00 PM

Thermalization of a jet wake by F. Zhou on Thu. 3:20 PM

Multi-scale jet-medium interactions by Y. Tachibana on Thu. 3:40 PM

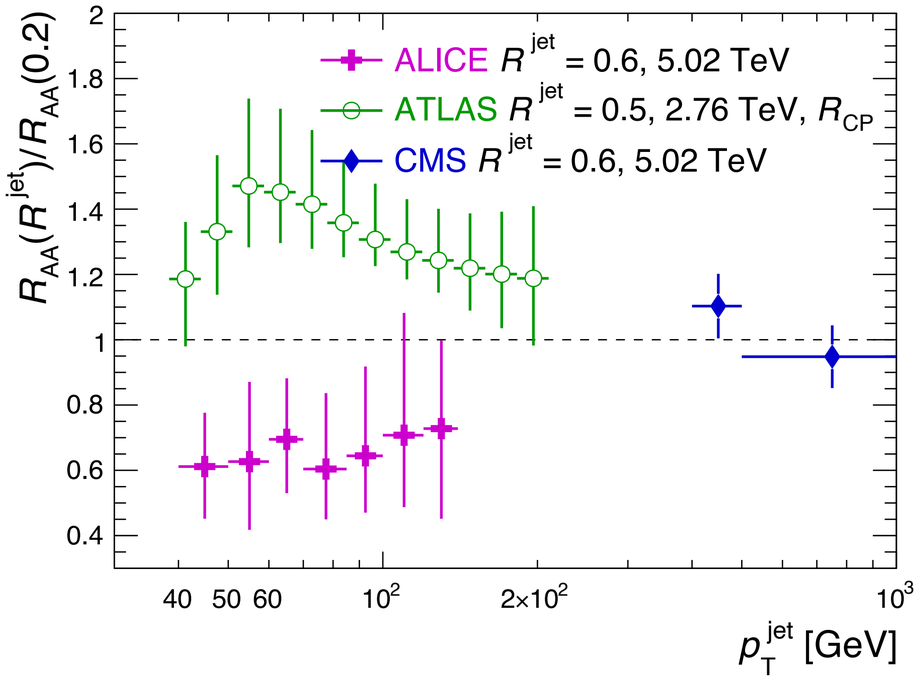
BACK UP

Takeaway (1)

- Enhancement of soft particles at large angles in jets
  - ➡ *Significant medium response effect found*
- In opposite-jet direction, tension in hadron yield between data (***ATLAS*** and **CMS**)
  - ➡ different background subtraction method introduce different physics interpretation
    (1) diffusion wake vs. (2) MPI

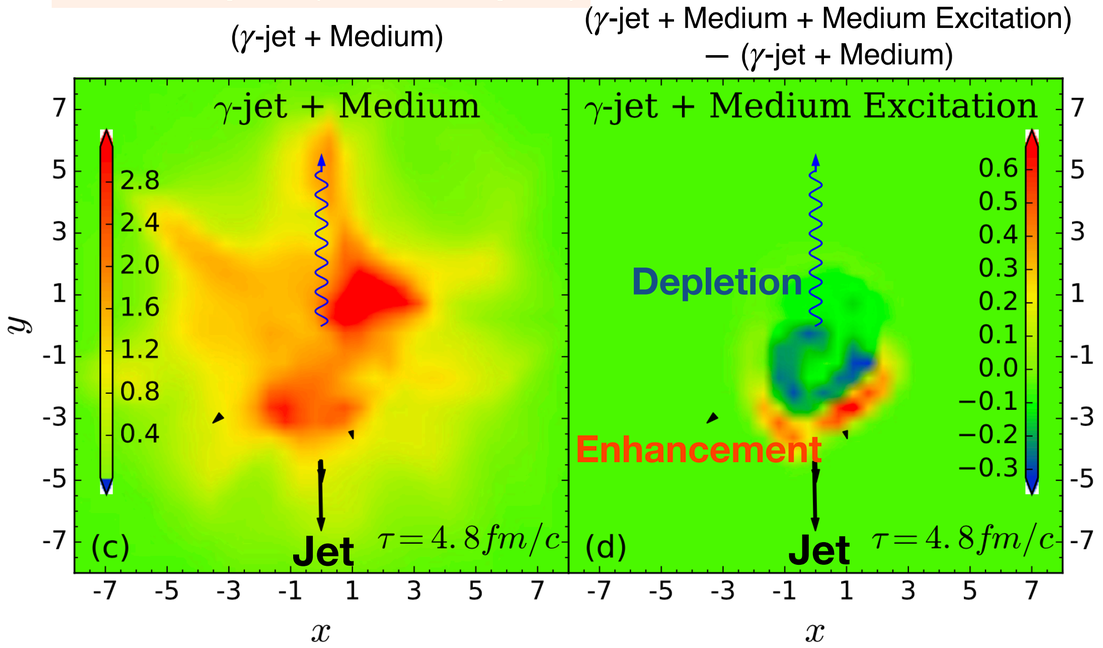
Takeaway (2) : Radius-dependent Jet R_{AA}

- At high p_T, mild R-dependence found in **CMS**
- At low p_T, tension between data (**ATLAS** vs. **ALICE**)
- Interpretation of R-dependence R_{AA} (*complicated*!)
  - ➡ medium response
  - ➡ color-charge difference
  - ➡ p_T shape difference in pp collisions
  - ➡ …
- Tensions between various models
  - ➡ further **systematic studies** will be needed
- Future beneficial measurements
  - ➡ jets with high quark fraction
    e.g. jets at forward rapidity,
    boson-tagged jets,
    inclusive jets at RHIC, …



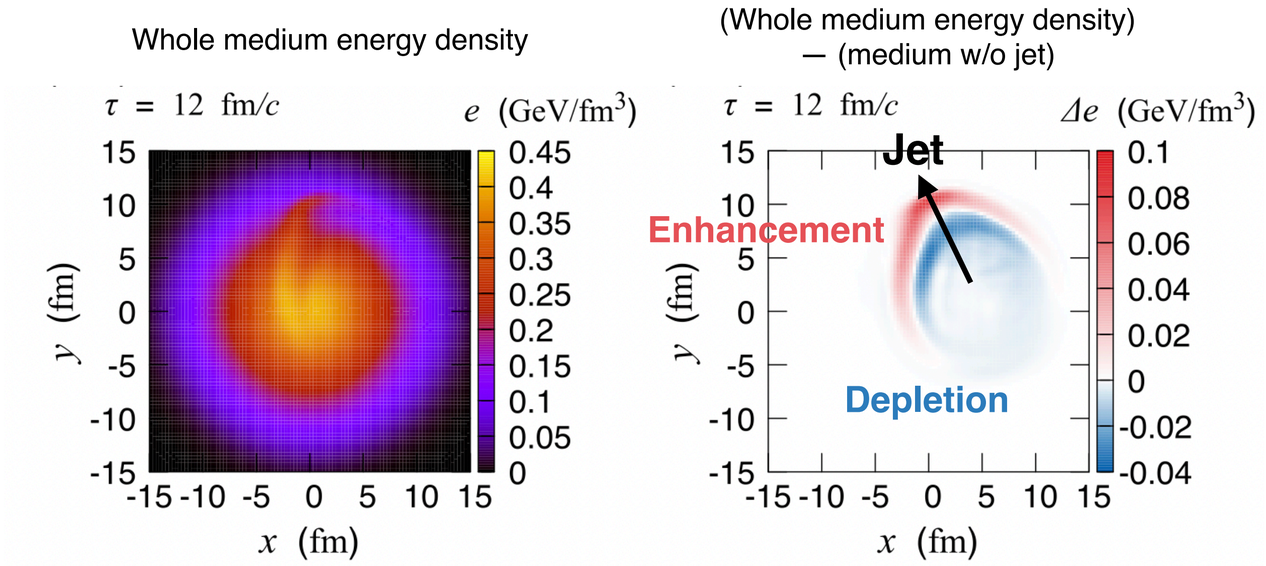
Structure formed from Medium Response in Models

CoLBT+Hydro (Recoil + Hydro)



W. Chen et al. PLB 777 (2018) 86

Coupled Jet-Fluid (Hydro)

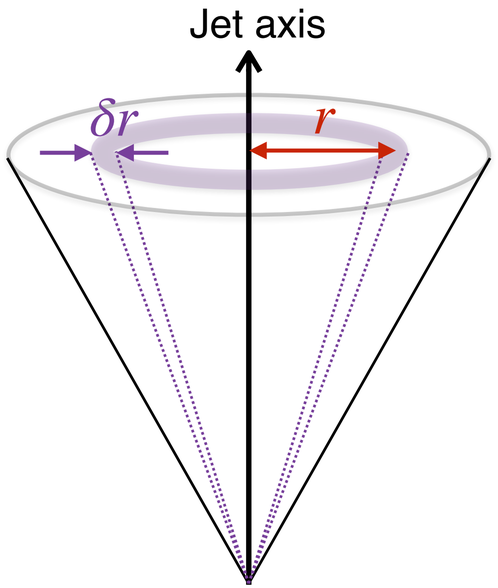


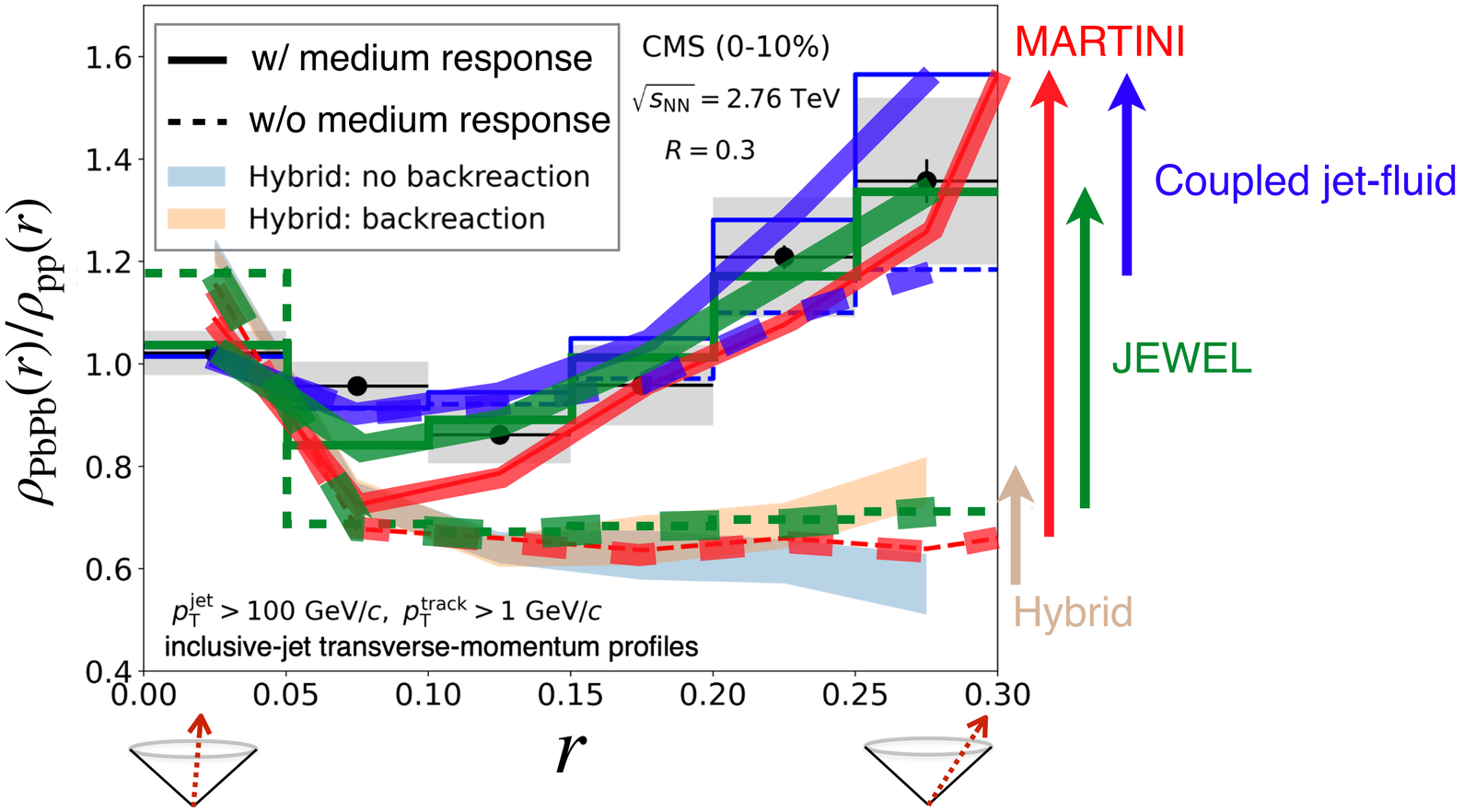
Y. Tachibana et al. PRC 95, 044909 (2017)

- Enhancement in jet direction; Mach-cone like structure
- Depletion in the opposite direction of jet; diffusion wake

Jet Shape

CMS, PLB 730 (2014) 243





$$\rho_{\mathrm{jet}}(r) = \frac{1}{N_{\mathrm{jet}}} \sum_{\mathrm{jet}} \left[\frac{1}{p_{\mathrm{T}}^{\mathrm{jet}}} \frac{\sum_{\mathrm{trk}\in(\mathrm{r}-\delta\mathrm{r}/2,\mathrm{r}+\delta\mathrm{r}/2)} p_{\mathrm{T}}^{\mathrm{trk}}}{\delta r} \right]$$

- At *large* angle,
  all models predict ***enhancement*** by medium response

MARTINI, NPA 982 (2019) 643

JEWEL, JHEP 1707 (2017) 141

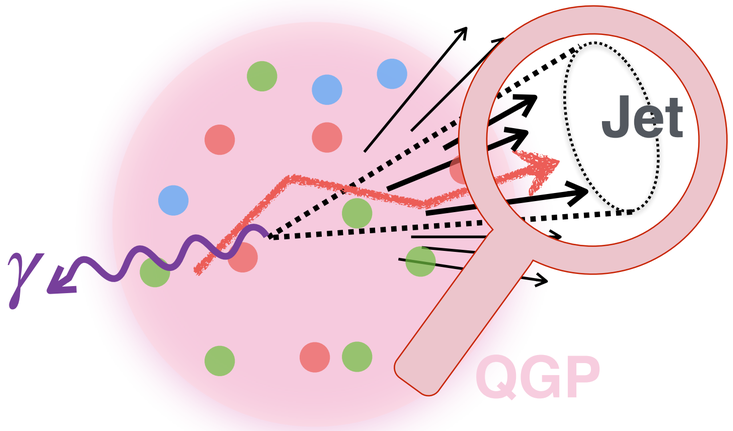
Coupled jet-fluid, PRC 95 (2017) 044909

Figure adapted from Rey Cruz-Torres' slides

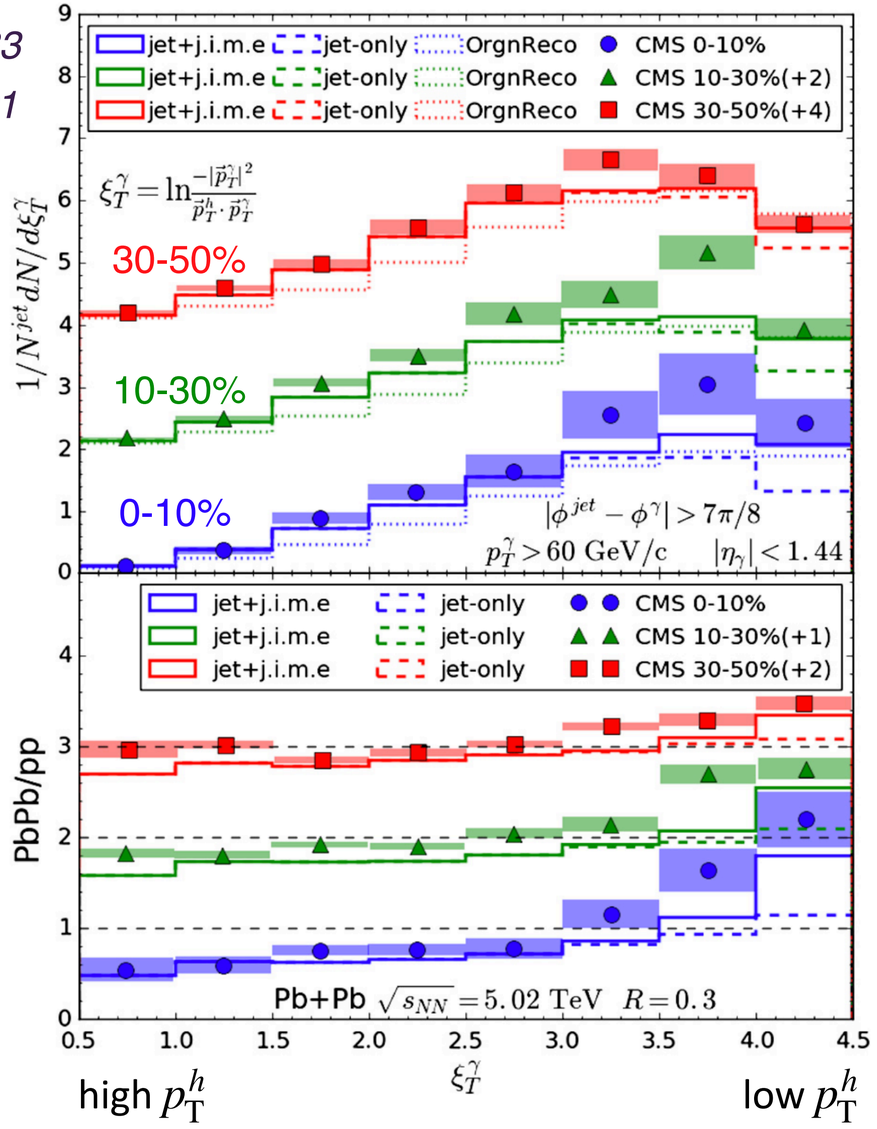
γ-Jet Fragmentation Function at LHC

Wei Chen et al., PLB 810 (2020) 135783

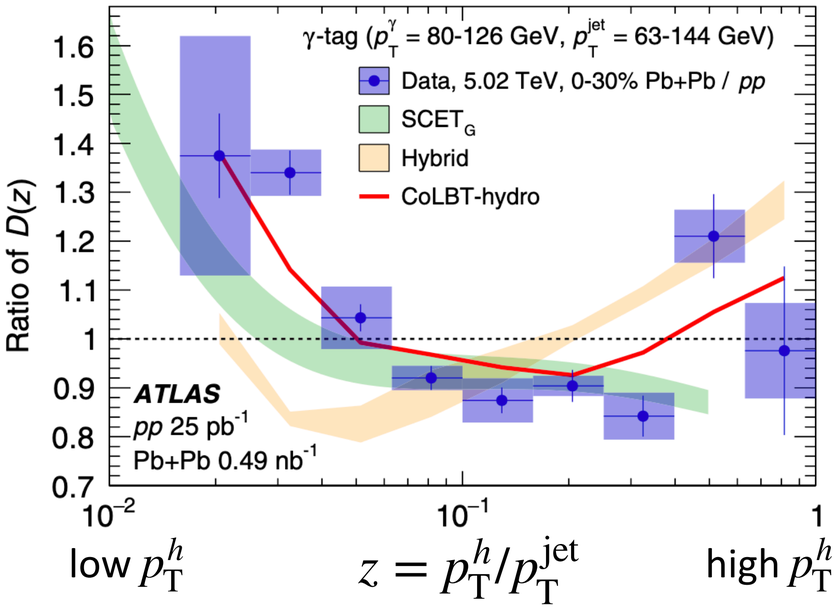
***CMS** PRL 121 (2018) 242301*



$$\xi_{\mathrm{T}}^{\gamma} = \ln \frac{-|\vec{p}_{\mathrm{T}}^{\gamma}|^2}{\vec{p}_{\mathrm{T}}^{\mathrm{h}} \cdot \vec{p}_{\mathrm{T}}^{\gamma}}$$



***ATLAS** PRL 123, 042001 (2019)*

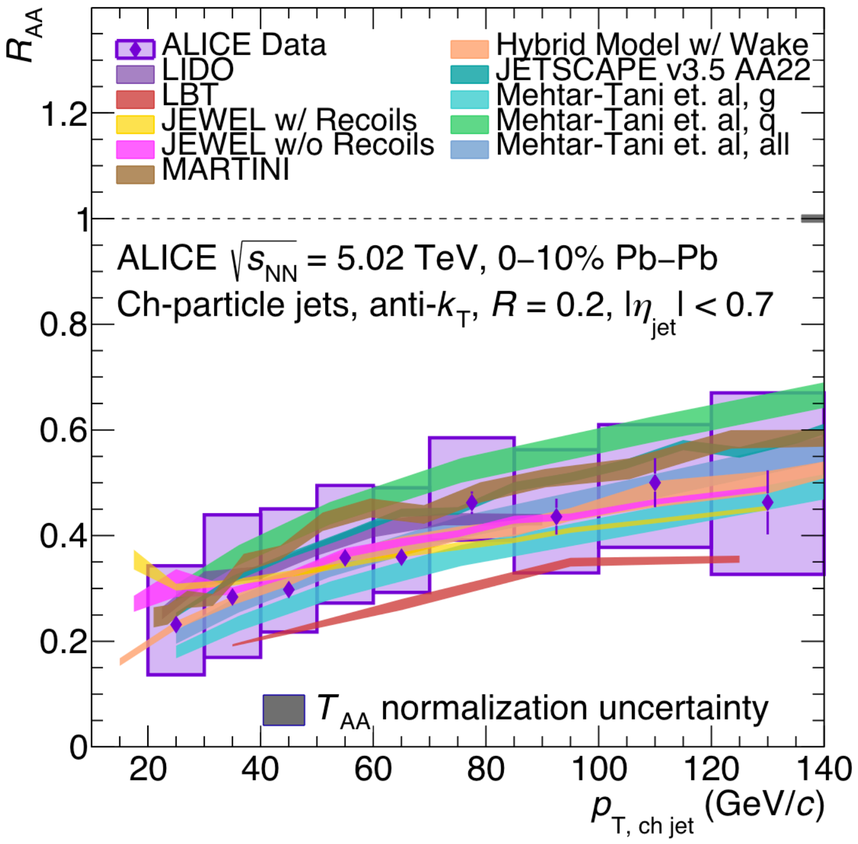


R-dependent Jet R_{AA}

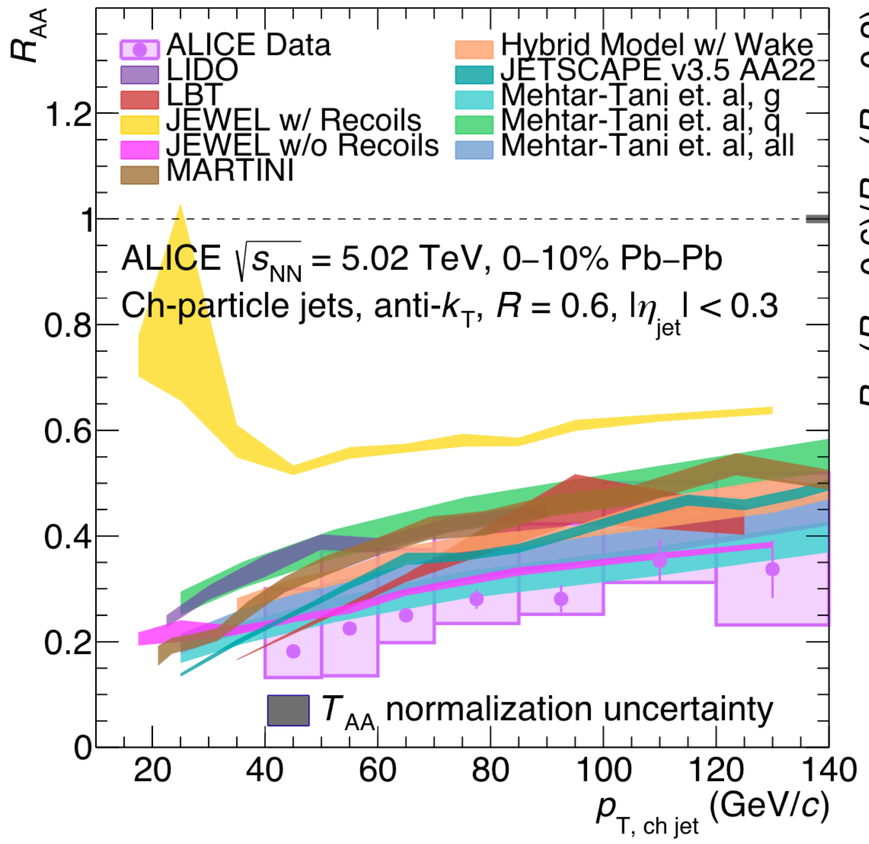
0-10%

ALICE arXiv:2303.00592v1

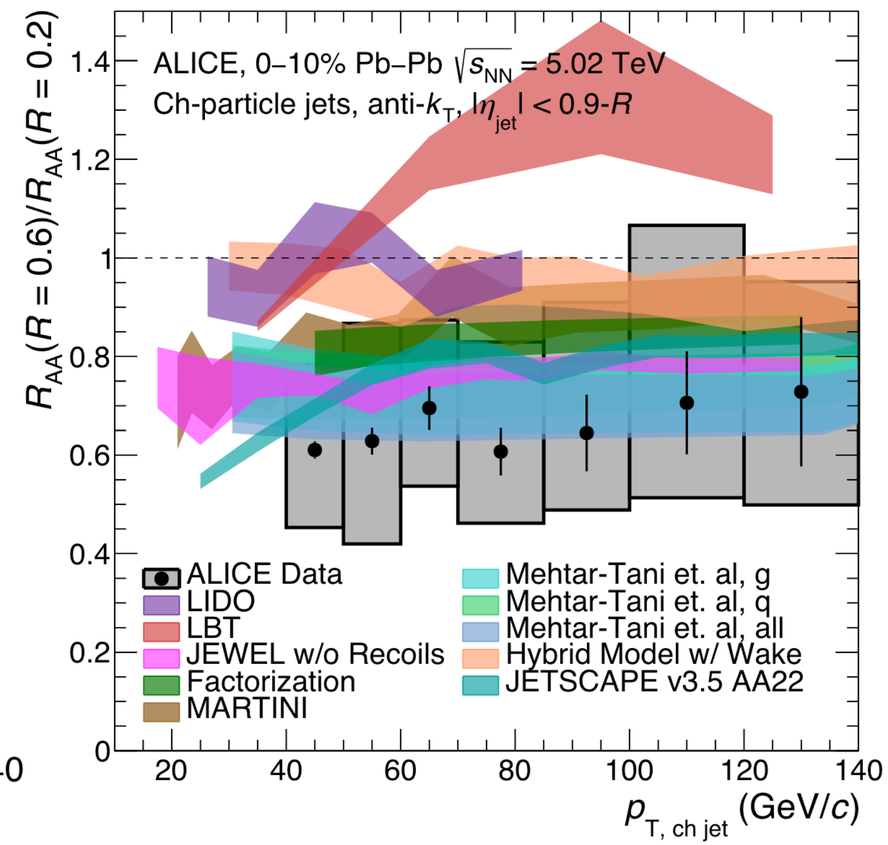
R_{AA} (R=0.2)



R_{AA} (R=0.6)



R_{AA} (R=0.6) / R_{AA} (R=0.2)



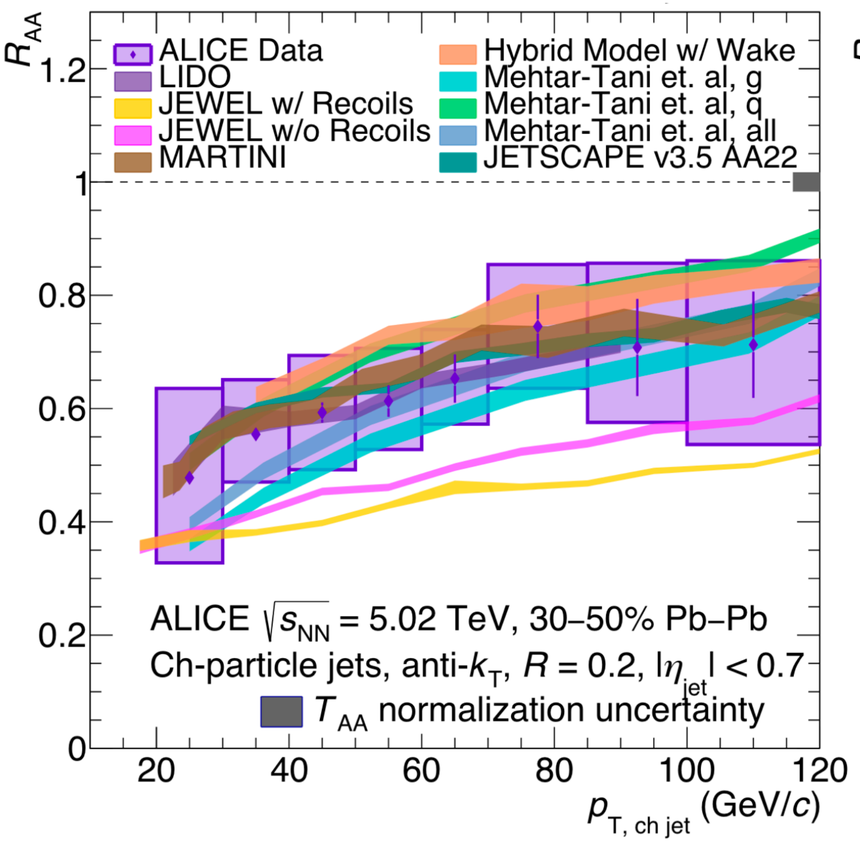
- Data compared with many models, and some models include medium response
- Some models describe double R_{AA} ratio but not individual R_{AA}, or vice versa

R-dependent Jet R_{AA}

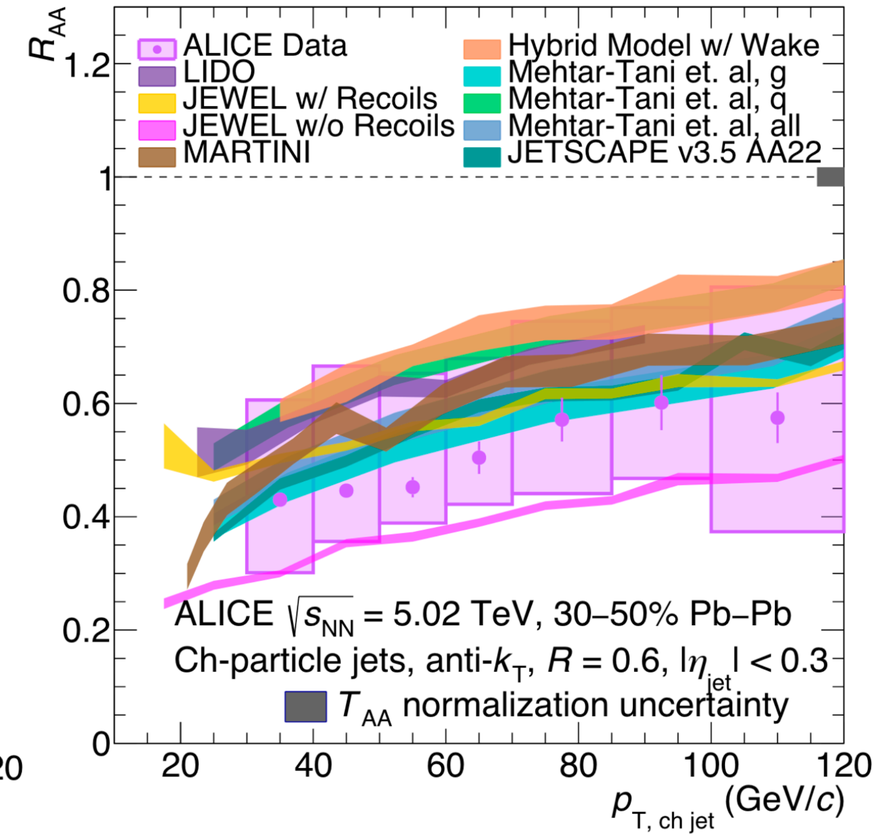
30-50%

ALICE arXiv:2303.00592

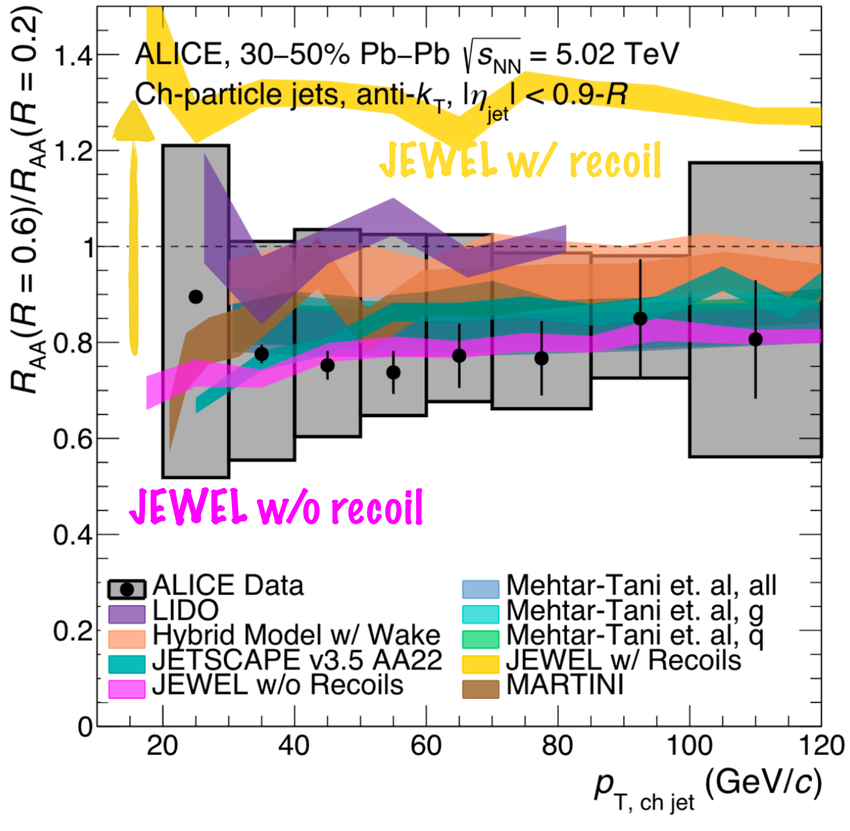
R_{AA} (R=0.2)



R_{AA} (R=0.6)

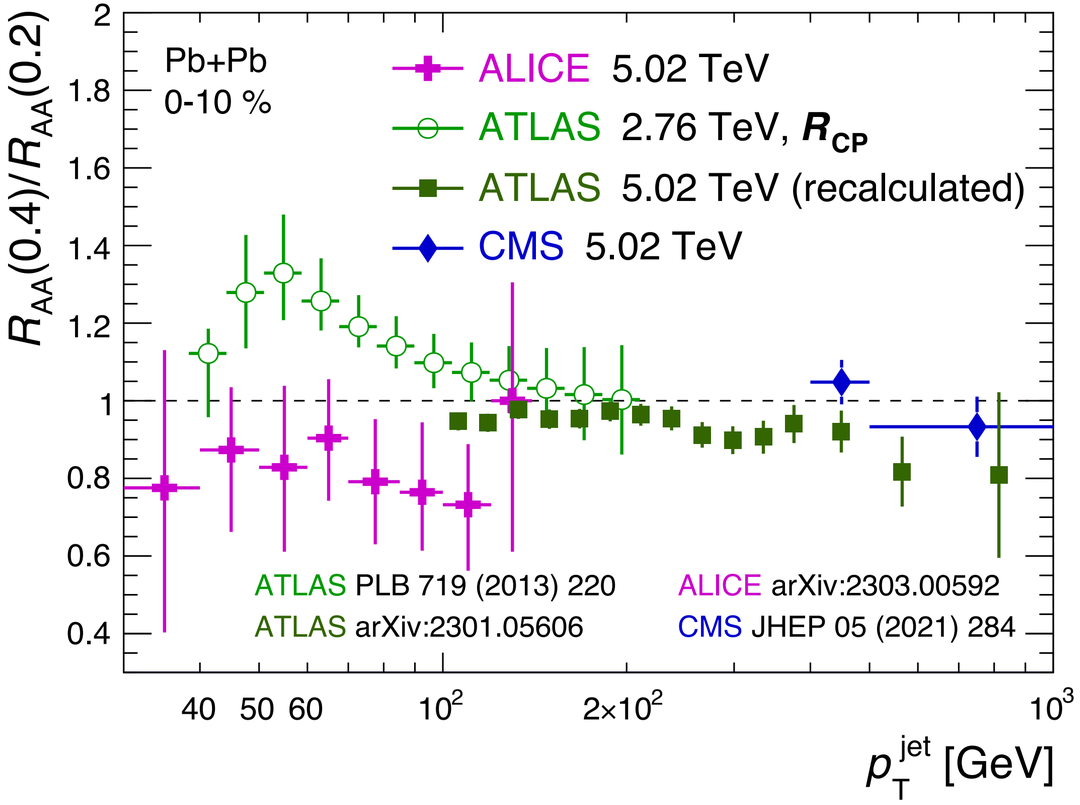


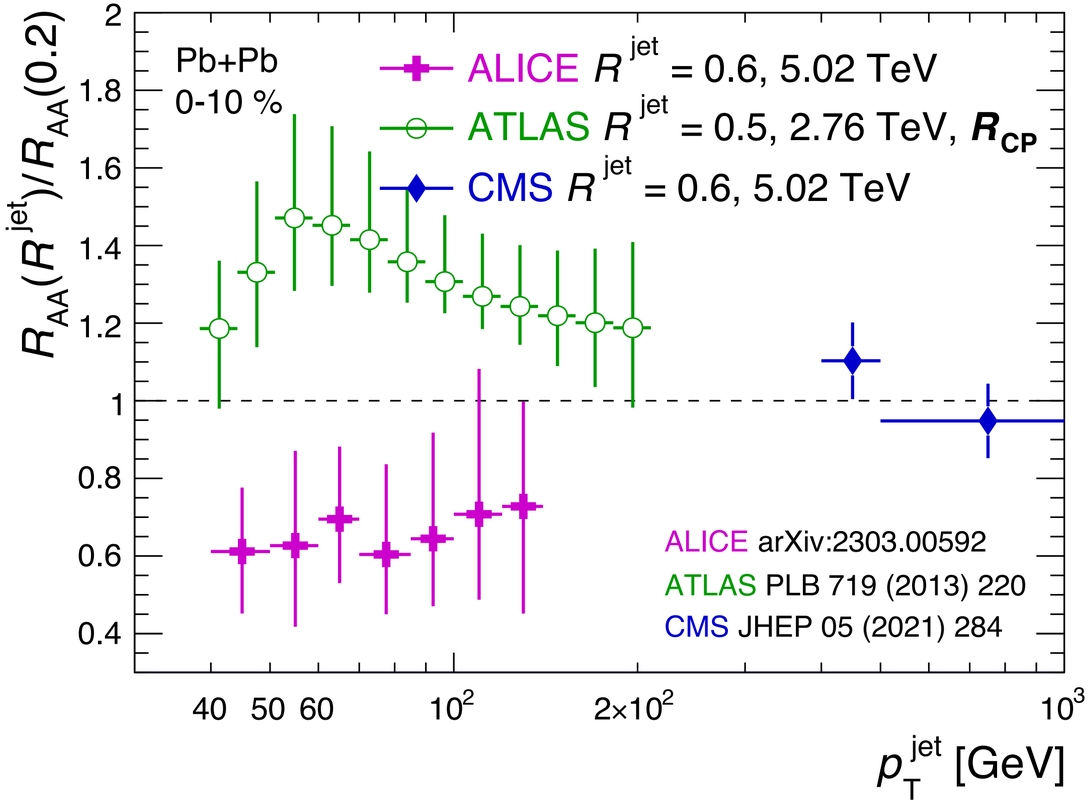
R_{AA} (R=0.6) / R_{AA} (R=0.2)



- Data compared with many models, and some models include medium response
- Some models describe double R_{AA} ratio but not individual R_{AA}, or vice versa

R-dependent Jet R_{AA}





Radius-dependent Jet R_{AA}: Discussion

- Rapidity difference in different R
  - ➡ **Forward rapidity** → more quark (less gluon) fraction → less E-loss (**Higher R_{AA}**)

arXiv:2210.07901

forward rapidity

mid-rapidity