ALL NEW EDITION

Everything you always wanted to know about jets*

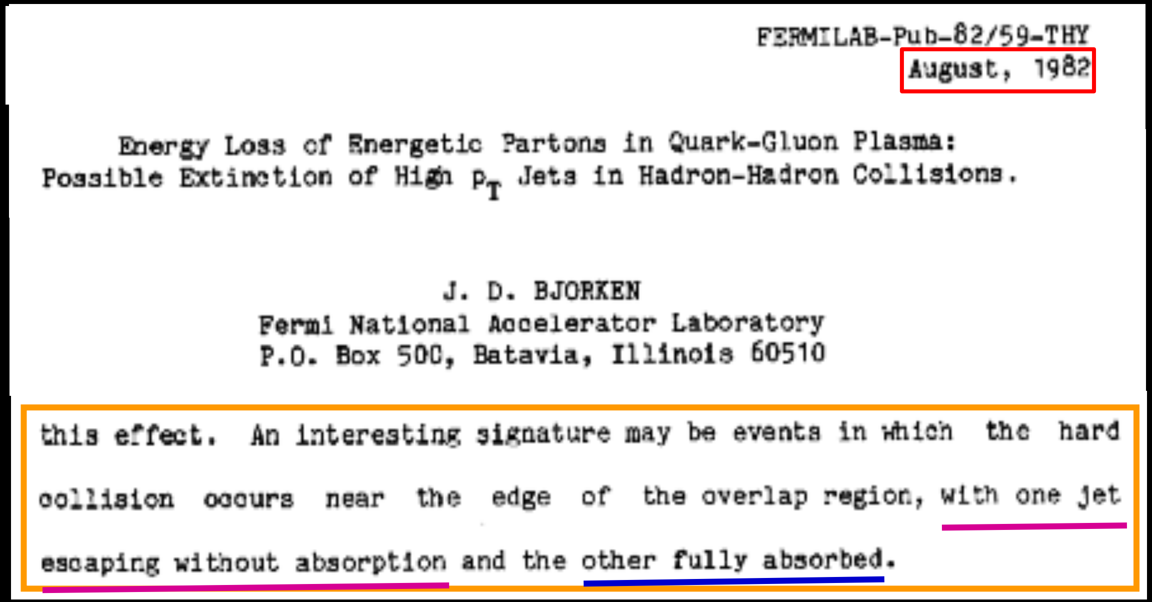
John W. Harris, Ph.D.

#1 Bestselling Author

* But were afraid to ask

1 *History – Early Jet Tomography*

History – High Momentum Particle & Jet Correlations



FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
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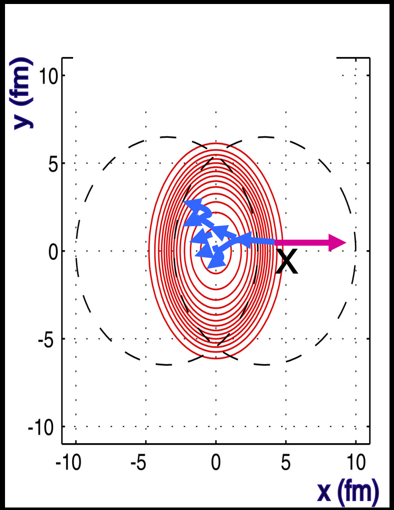
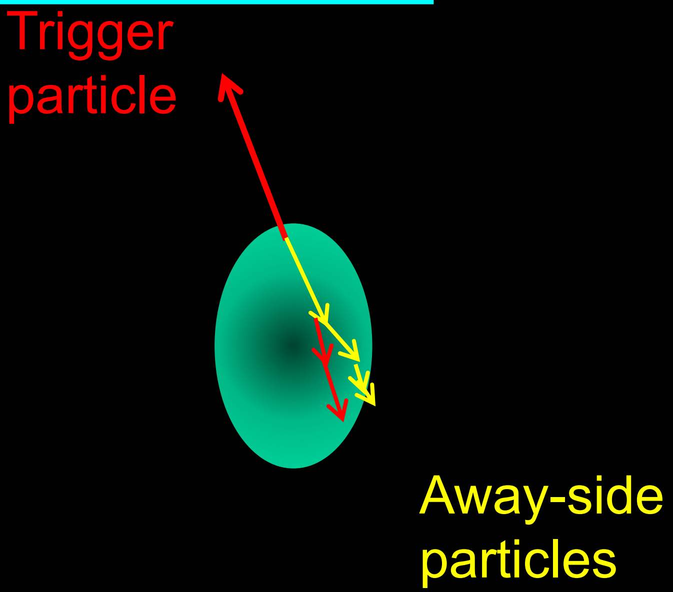
this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

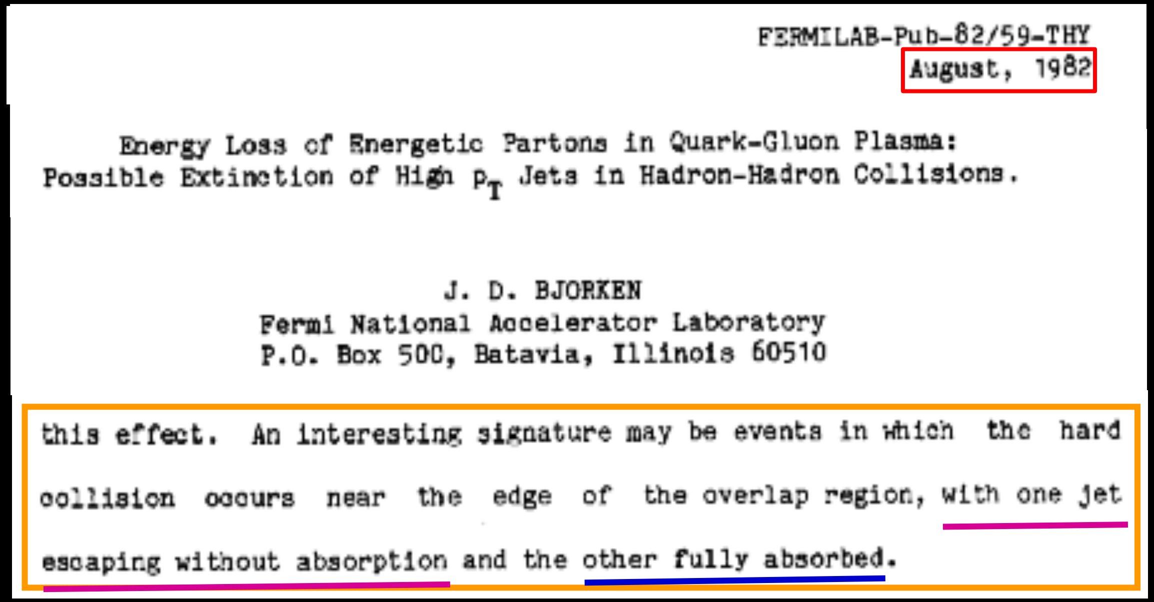




Back-to-back Jets Away-side jets should be quenched
in central heavy-ion collisions

X.-N. Wang, M. Gyulassy, Phys. Rev. Lett. 68 (1992) 1480.

History – High Momentum Particle & Jet Correlations



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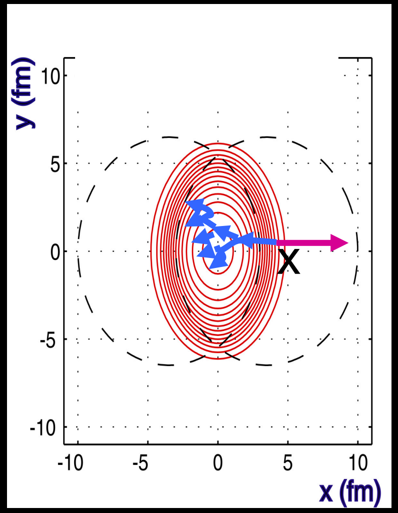
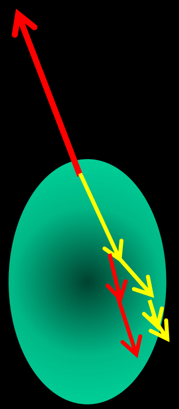




Back-to-back Jets Away-side jets NOT quenched in pp collisions

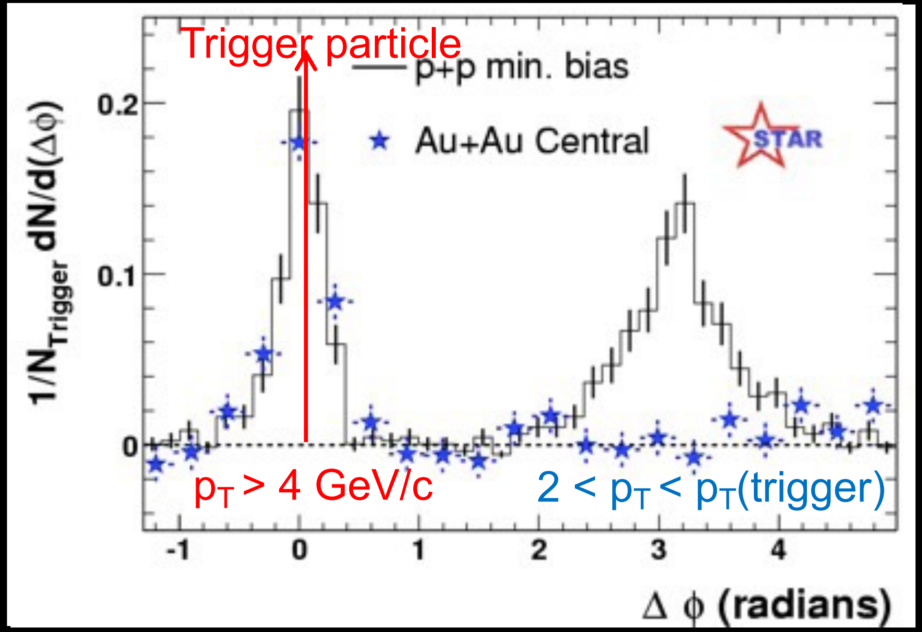
Back-to-back Jets Away-side jets observed as quenched in central Au + Au

Not quenched in Hi Mult d+Au

→ *trigger particle origin near surface*

→ strongly interacting medium

STAR, Phys.Rev.Lett. 91 (2003) 072304



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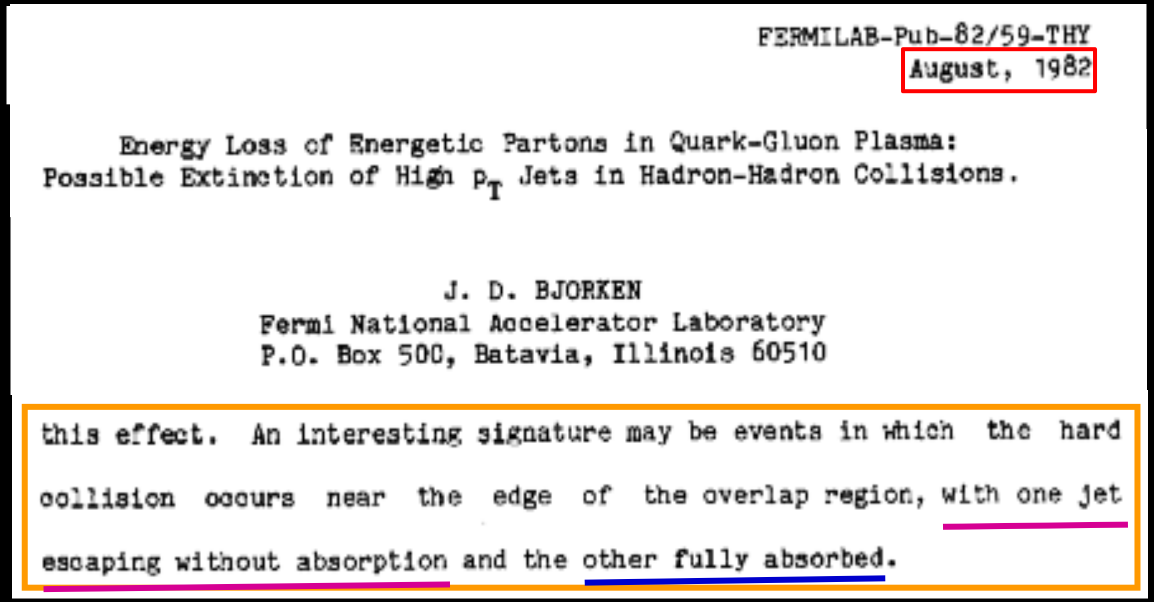
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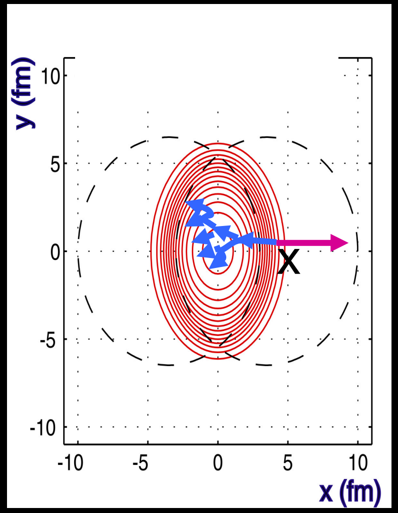

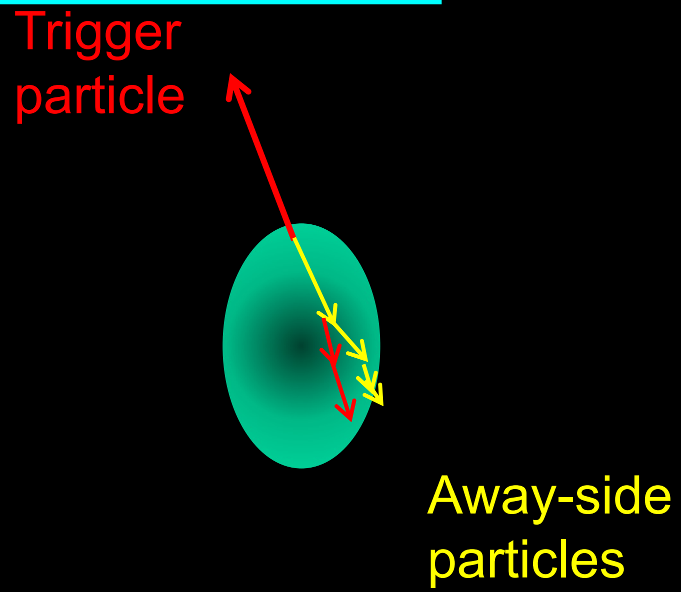

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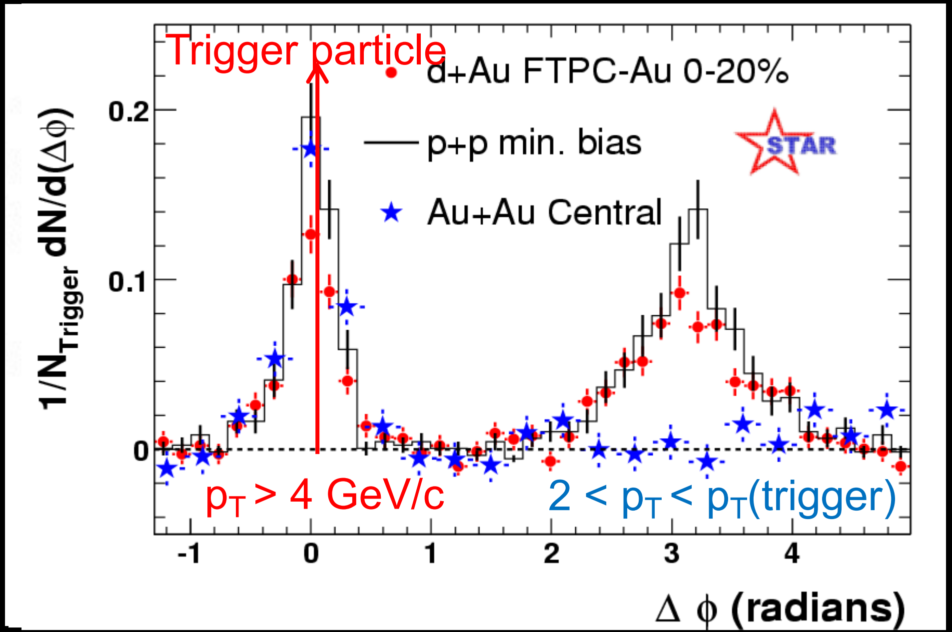


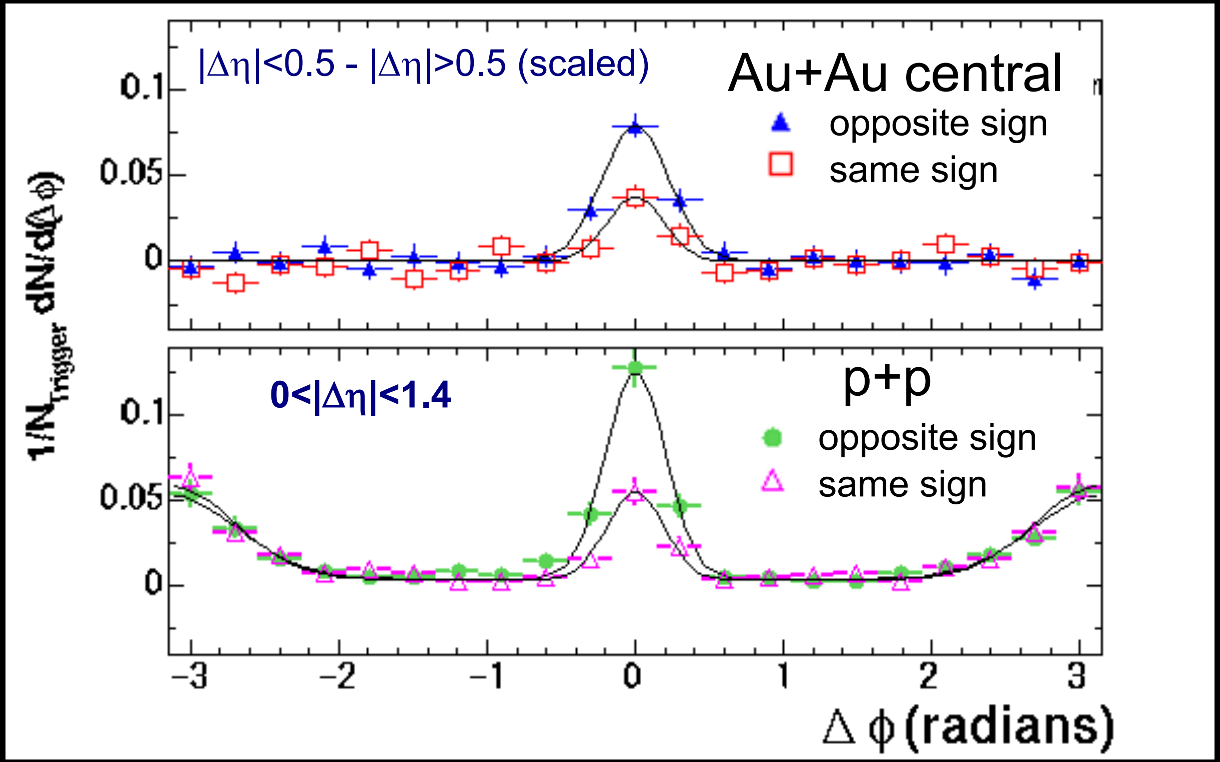
Quenching of Away-side "jet" is a final state effect

Relative Charge Dependence: 1st Jet Substructure Measurements!

Compare +- correlations to (++ & --)

STAR 200 GeV/nn
4 < p_T(trig) < 6 GeV/c
2 < p_T(assoc.) < p_T(trig)

System	(+-)/(++ & --)
p+p	2.7+-0.6
0-10% Au+Au	2.4+-0.6
Pythia/Jetset	2.6+-0.7



STAR, Phys. Rev. Lett. **90** (2003) 82302

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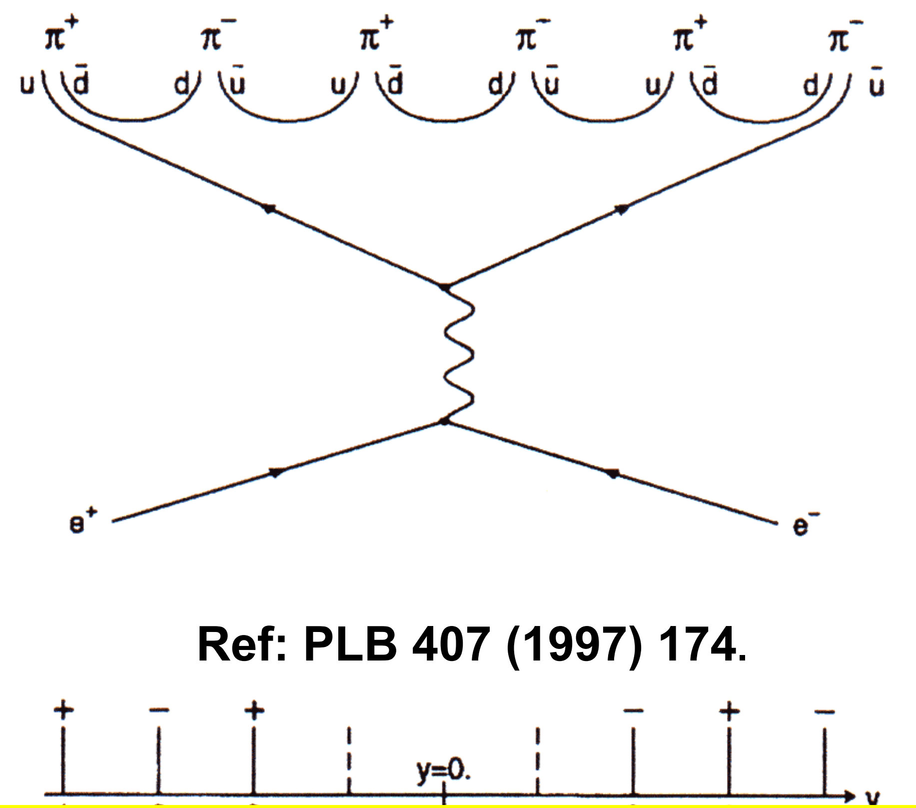
$0<|\Delta\eta|<1.4$

Strong dynamical charge correlations in jet fragmentation → "charge ordering"



Ref: PLB 407 (1997) 174.

STAR, Phys. Rev. Lett. **90** (2003) 82302

p_T > 4 GeV/c particle production mechanism (jets) same in central Au+Au & pp

Where Does the Energy Go?

Color wakes?

J. Ruppert & B. Müller

Mach cone from sonic boom?

H. Stoecker

J. Casalderrey-Solana & E. Shuryak

Cherenkov-like gluon radiation?

I. Dremin

A. Majumder, X.-N. Wang

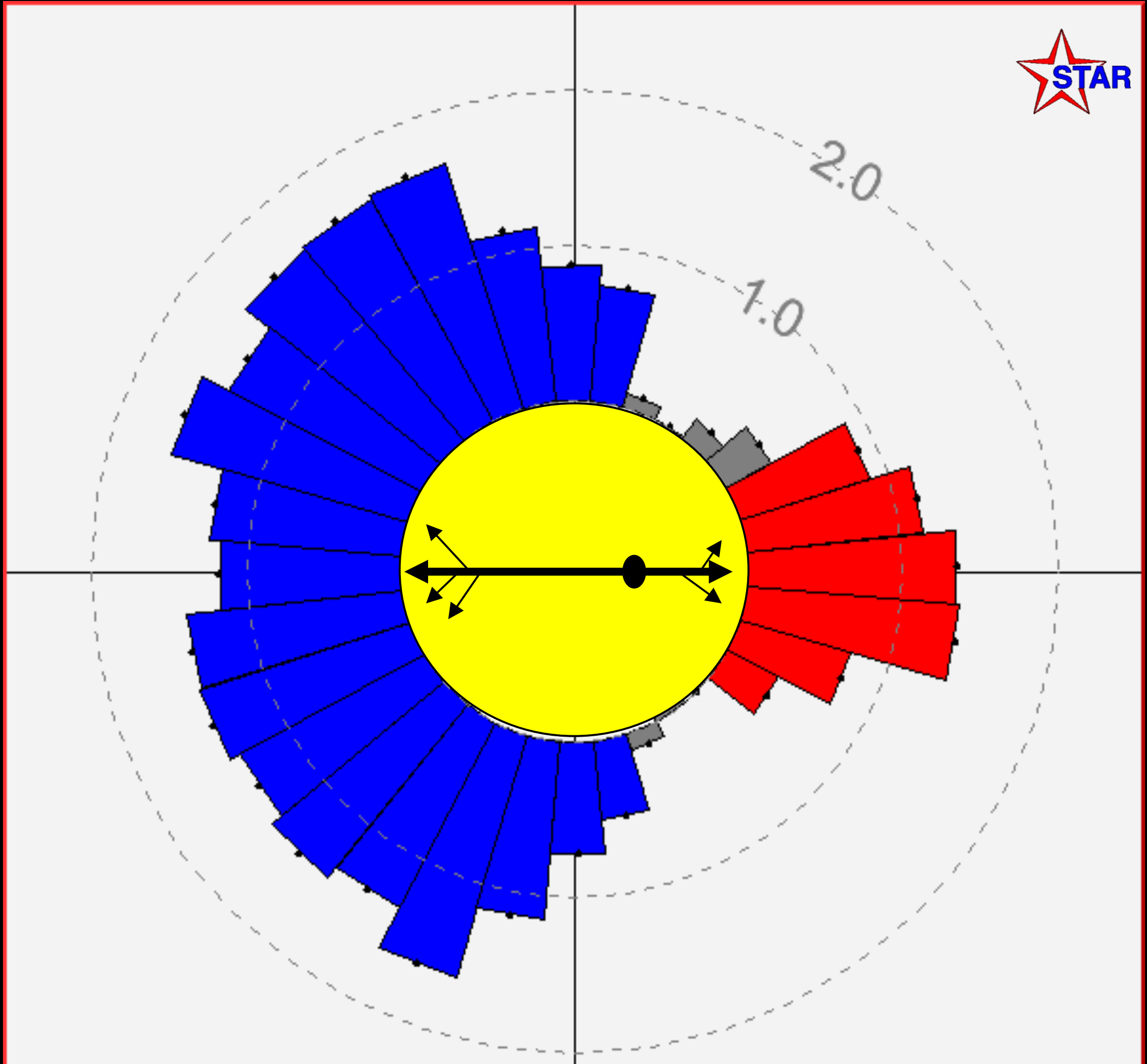
Medium-induced gluon radiation?

Polosa, C. Salgado

Many more

……..

….



Azimuthal Angular Correlations

Lost energy of away-side jet is redistributed to rather large angles!

2

Let's Back up for a Minute and Consider

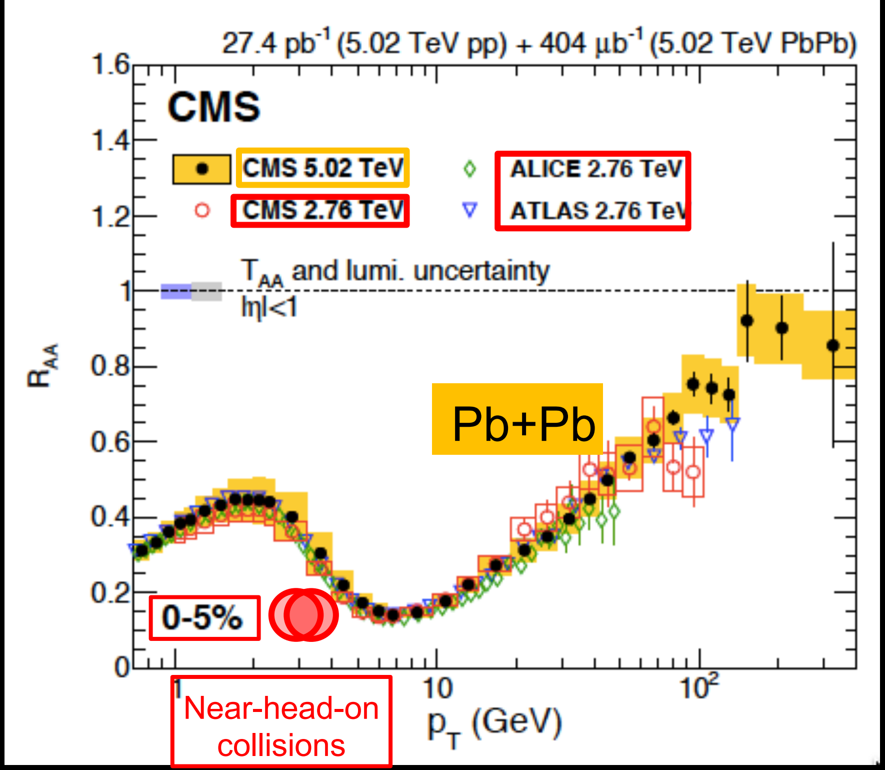
High p_T Single Particles

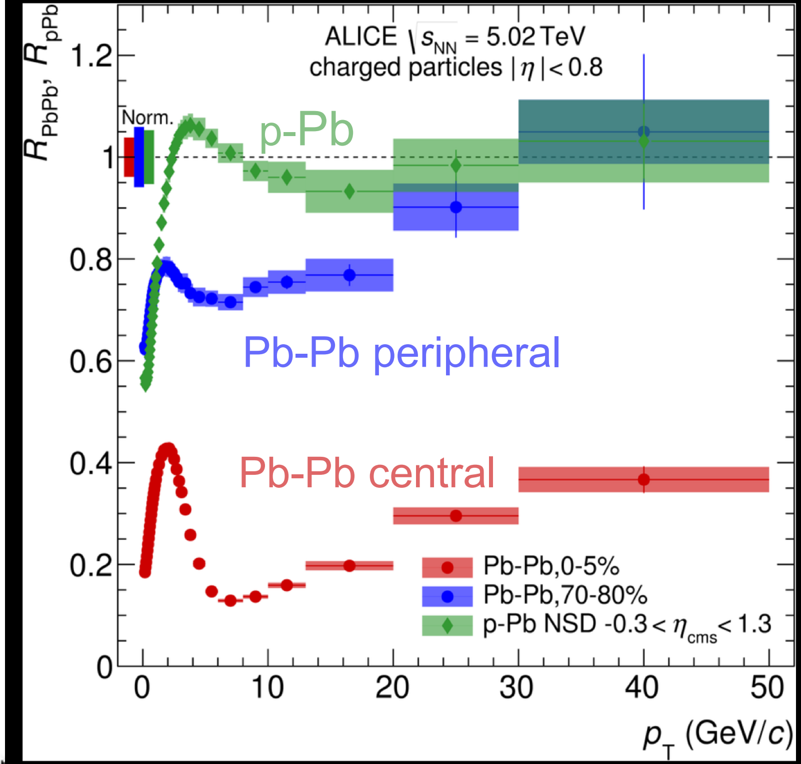
High p_T Charged Hadrons Are Suppressed at LHC!

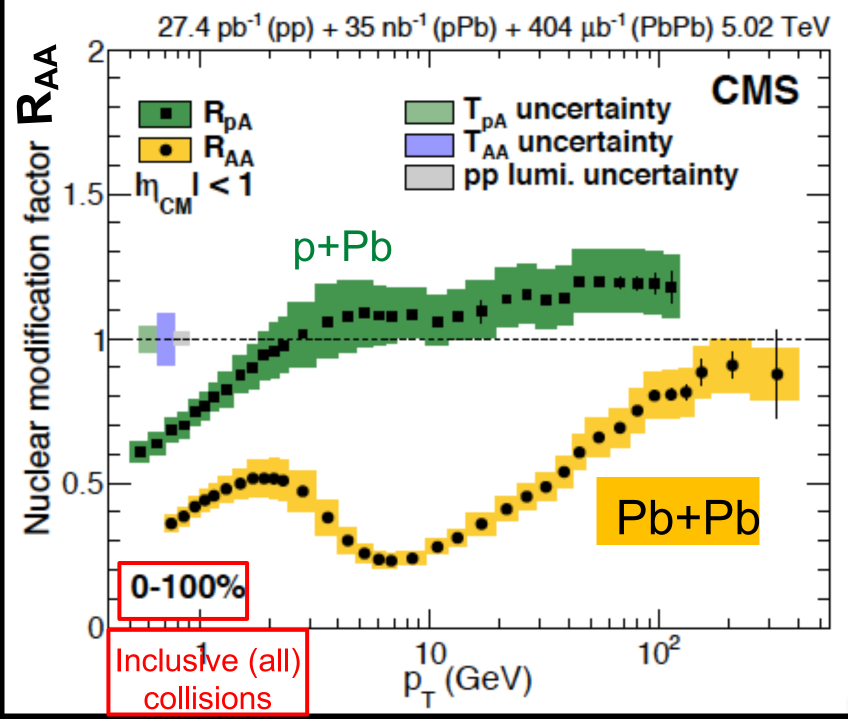
$$R_{AA} = \frac{N_{AA}^{particle}}{N_{coll} N_{pp}^{particle}}$$

R_{AA} < 1 Suppression wrt pp

R_{pPb} ~ 1 similar to pp







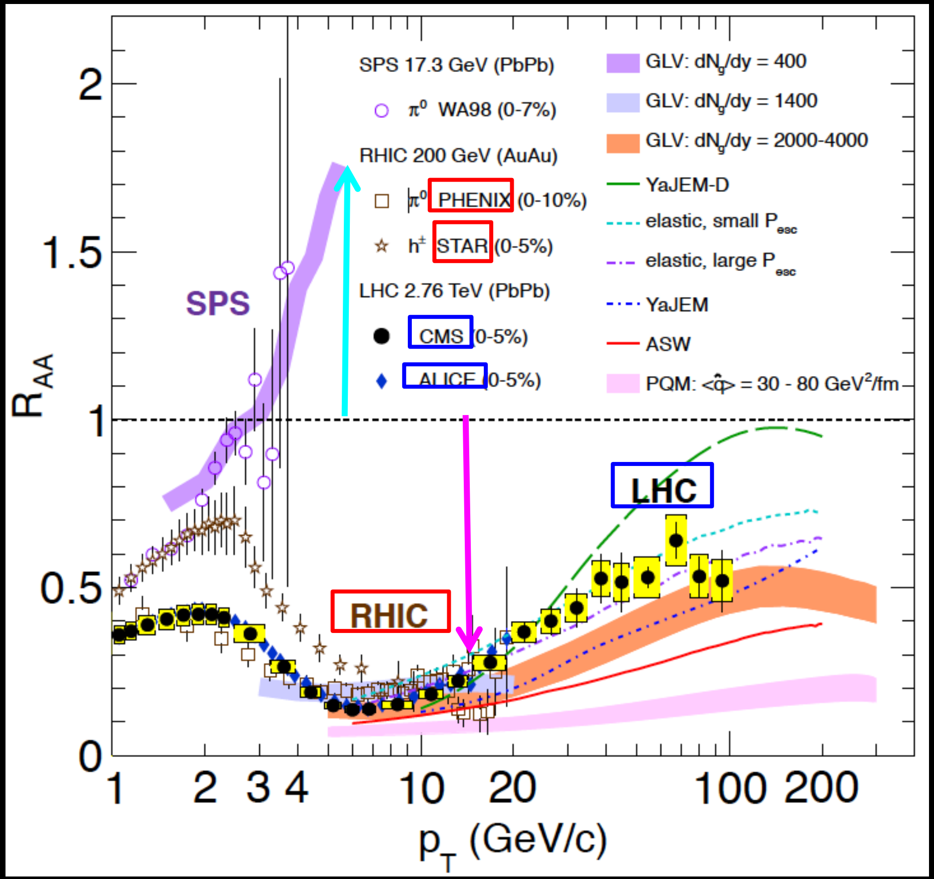
CMS arXiv: 1611.01664

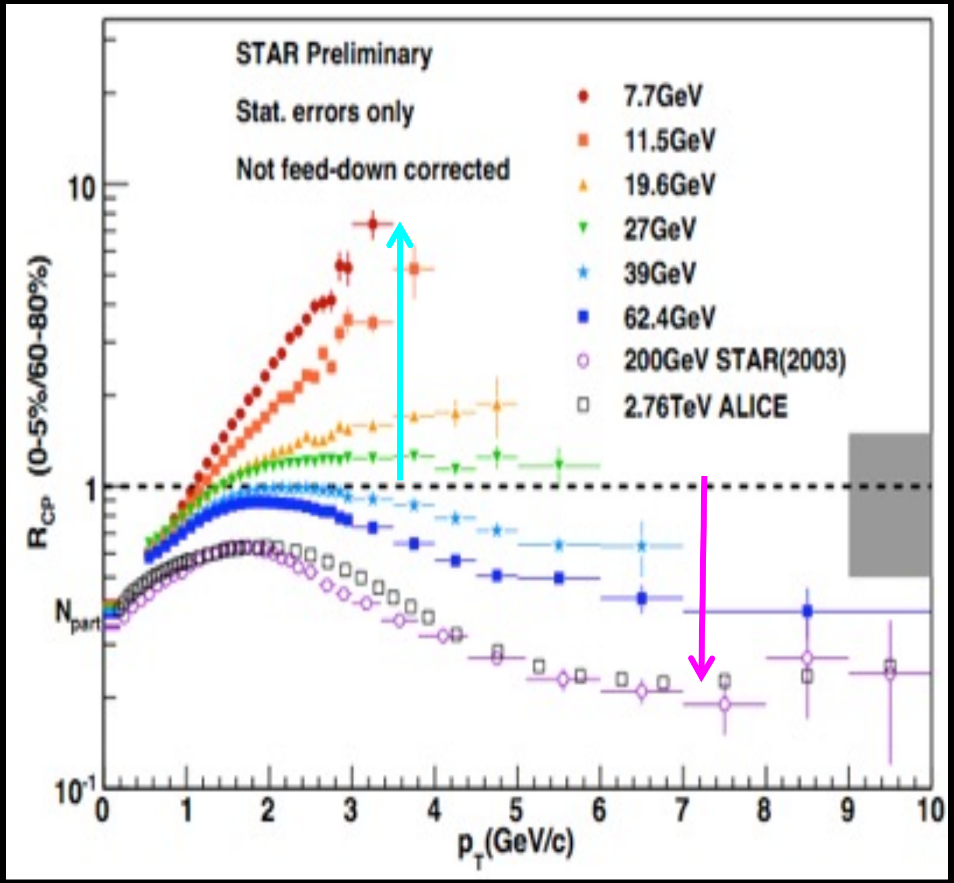
→ *Pb+Pb suppression similar at 2.76 and 5.02 TeV*
→ *nearly goes away at highest p_T*

→ *Pb+Pb suppression central collisions more suppression*

→ *p+Pb not suppressed slight enhancement at high p_T*

High p_T Hadrons Suppressed at LHC & RHIC (also in BES)





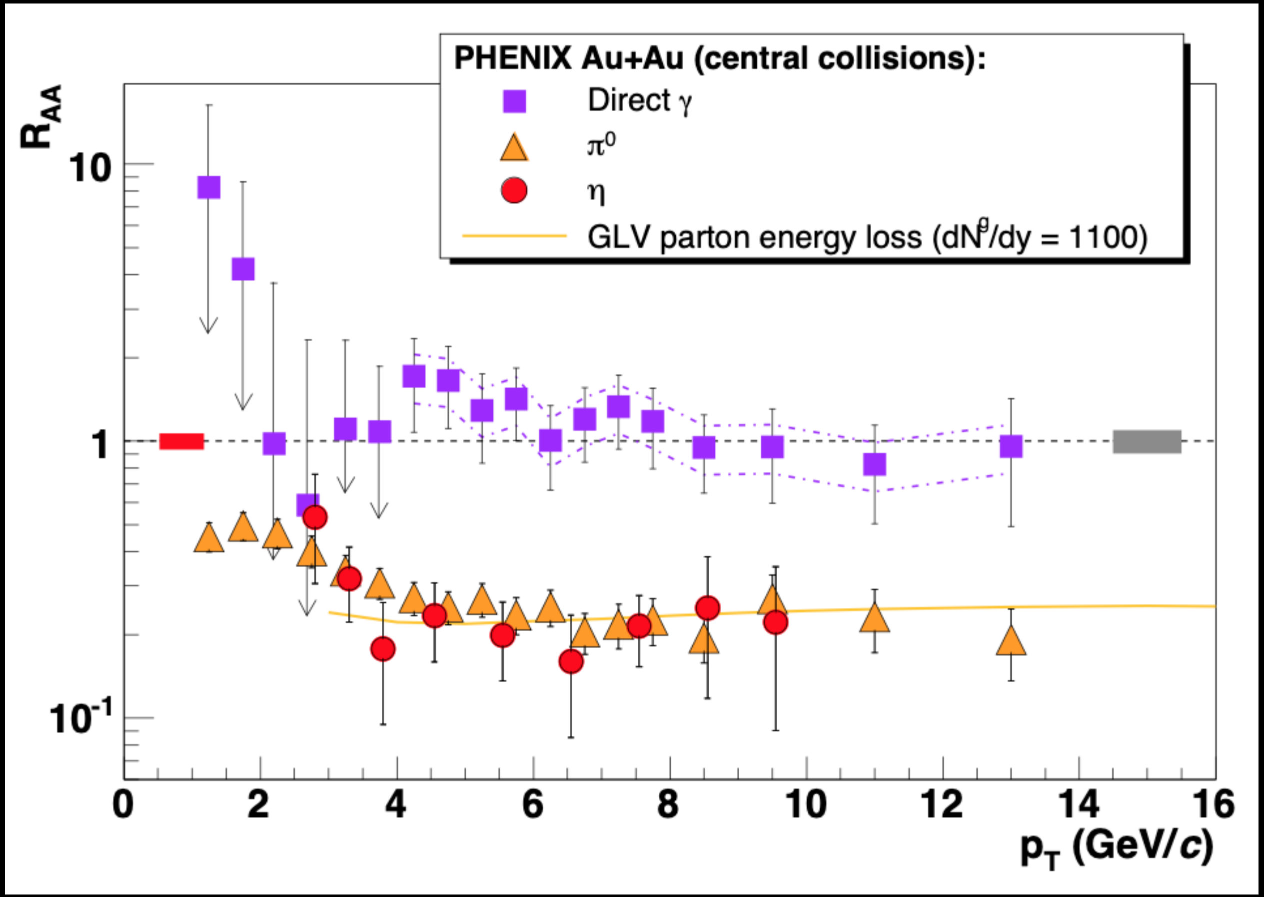
$$R_{AA} = \frac{N_{AA}^{particle}}{N_{coll} N_{pp}^{particle}}$$

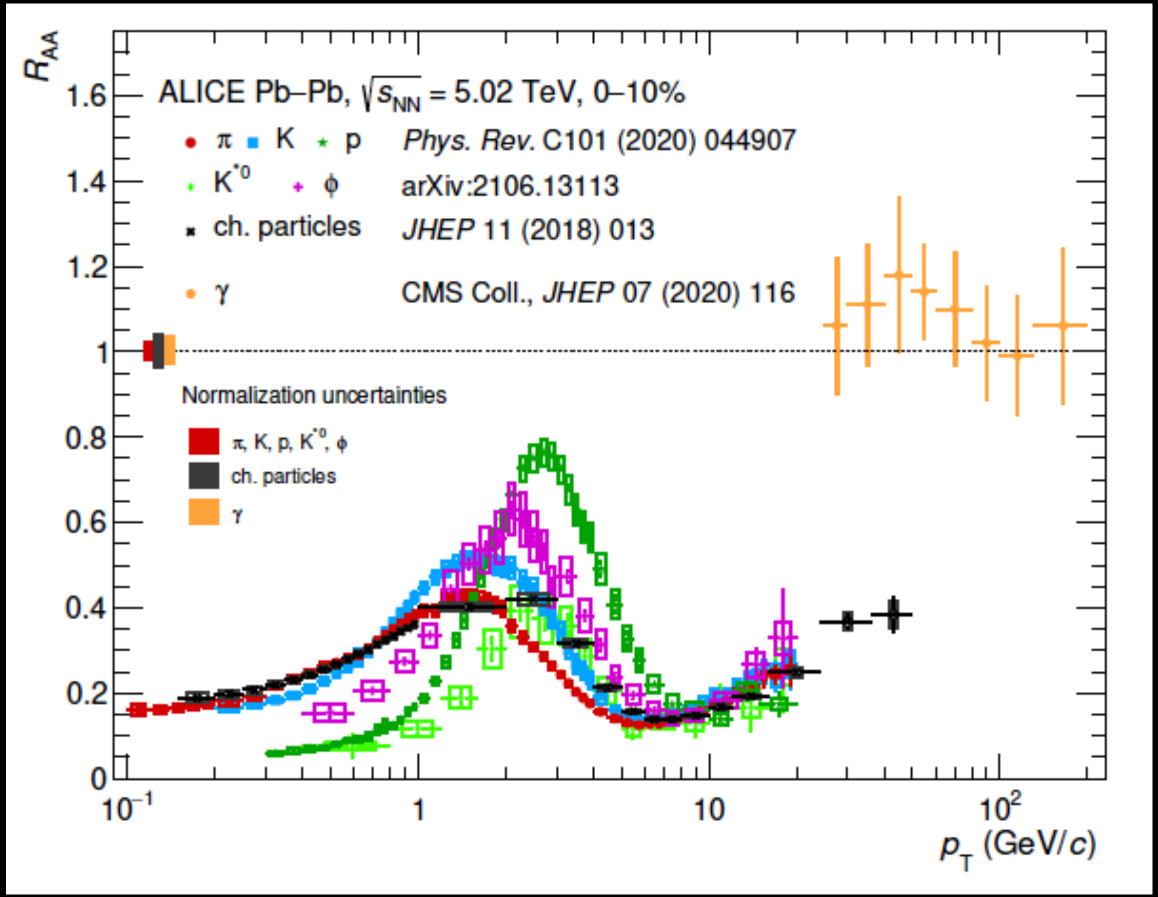
Enhancement at lowest energies
→ initial state effects
(Cronin enhancement)

$R_{CP} = N_{central} / N_{peripheral}$

$\rightarrow R_{AA}$

PID – EM Probes Not Suppressed! …. and Particle Differences!

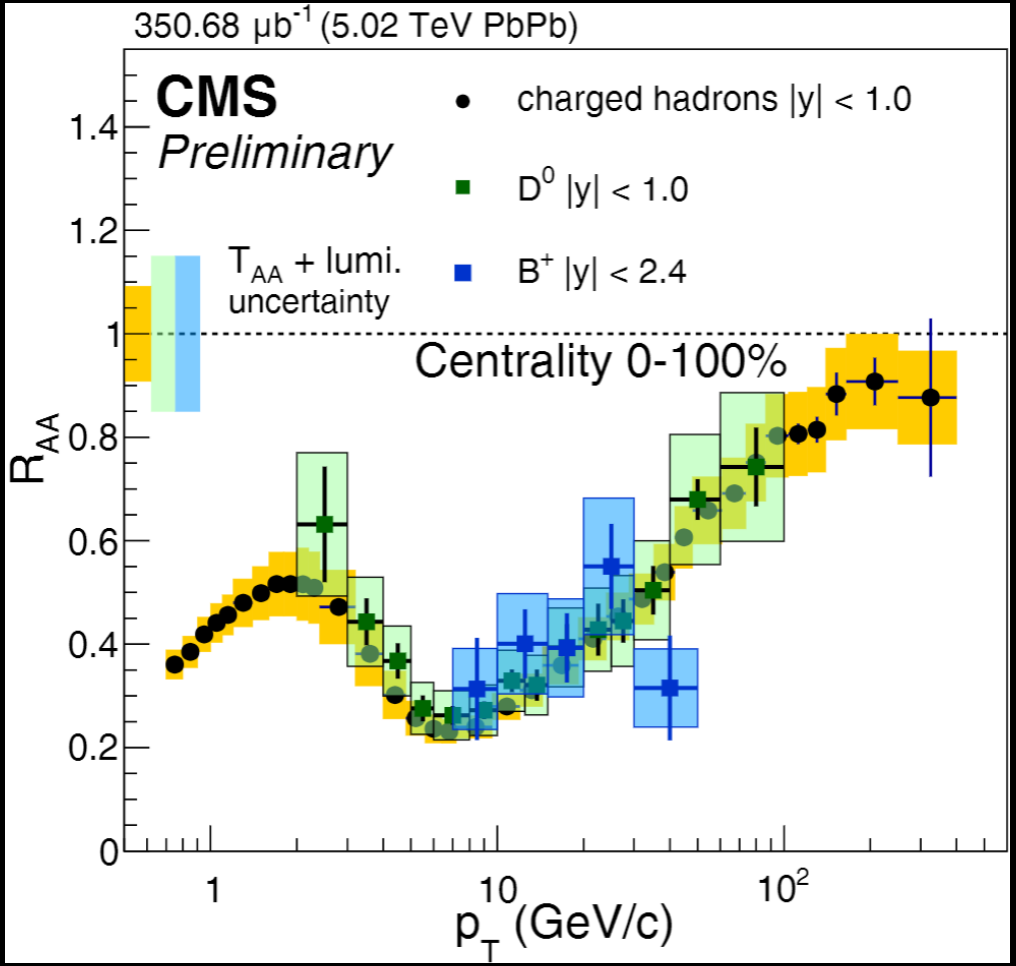


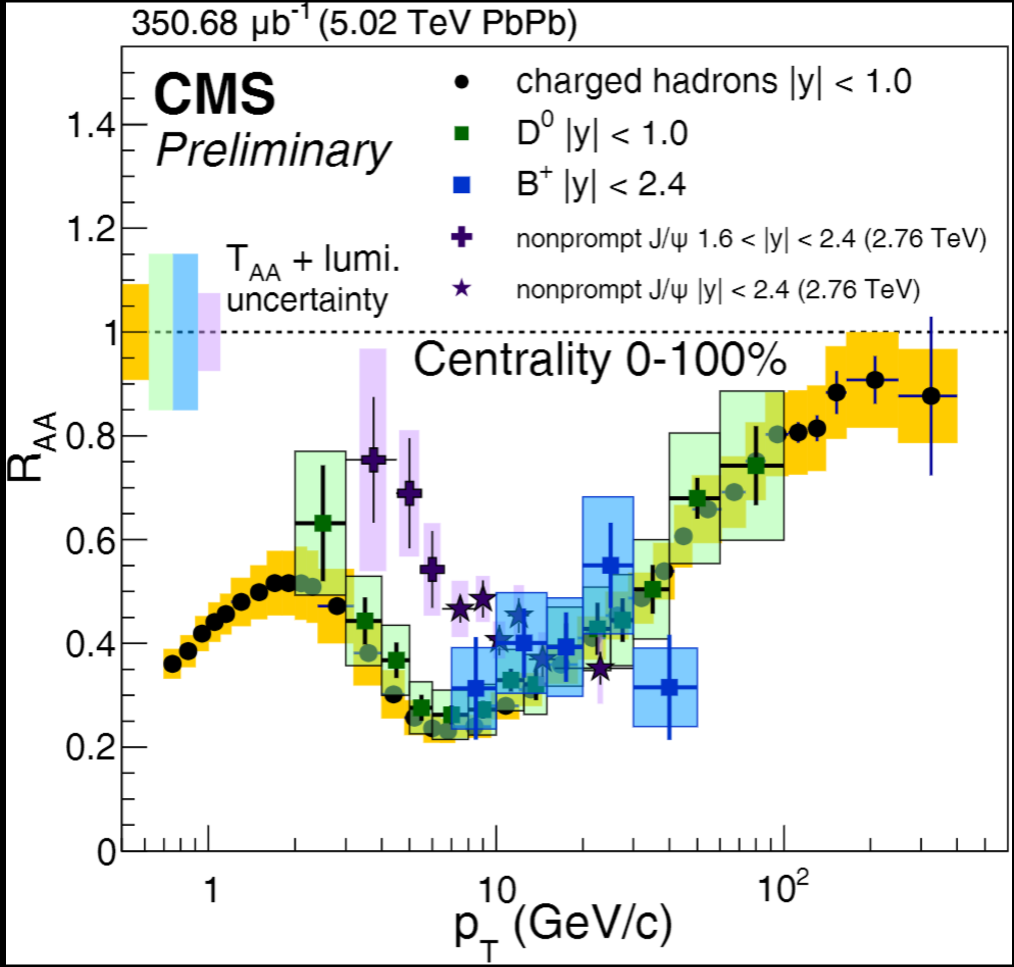


→ *Notice differences in R_{AA} distributions for various particles*

3 *Flavor Dependence*

Flavor Dependence of Inclusive Hadron Suppression





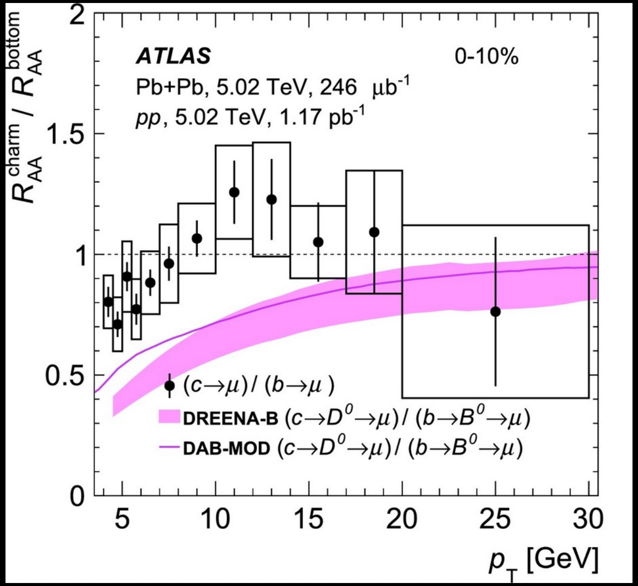
→ *Initially no flavor dependence seen in 5.02 TeV Pb-Pb inclusive data*

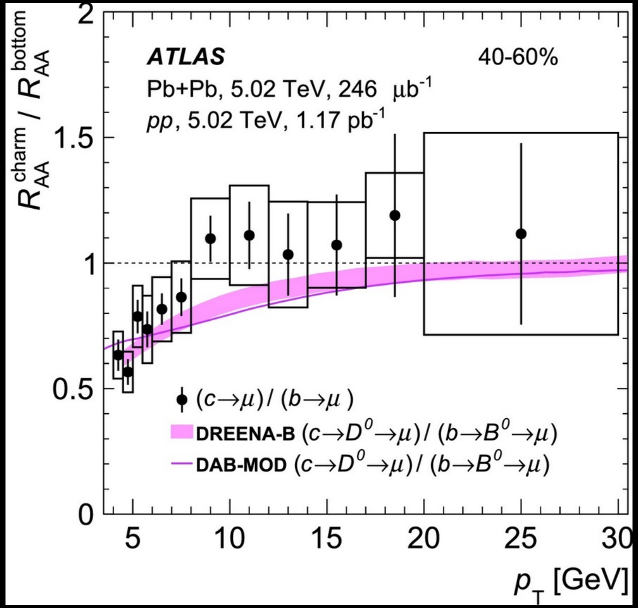
→ *Flavor dependence was seen in 2.76 TeV inclusive data for p_T < 10 GeV/c*

CMS-PAS-HIN-16-001
CMS arXiv: 1611.01664

CMS J/ψ arXiv: 1610.00613

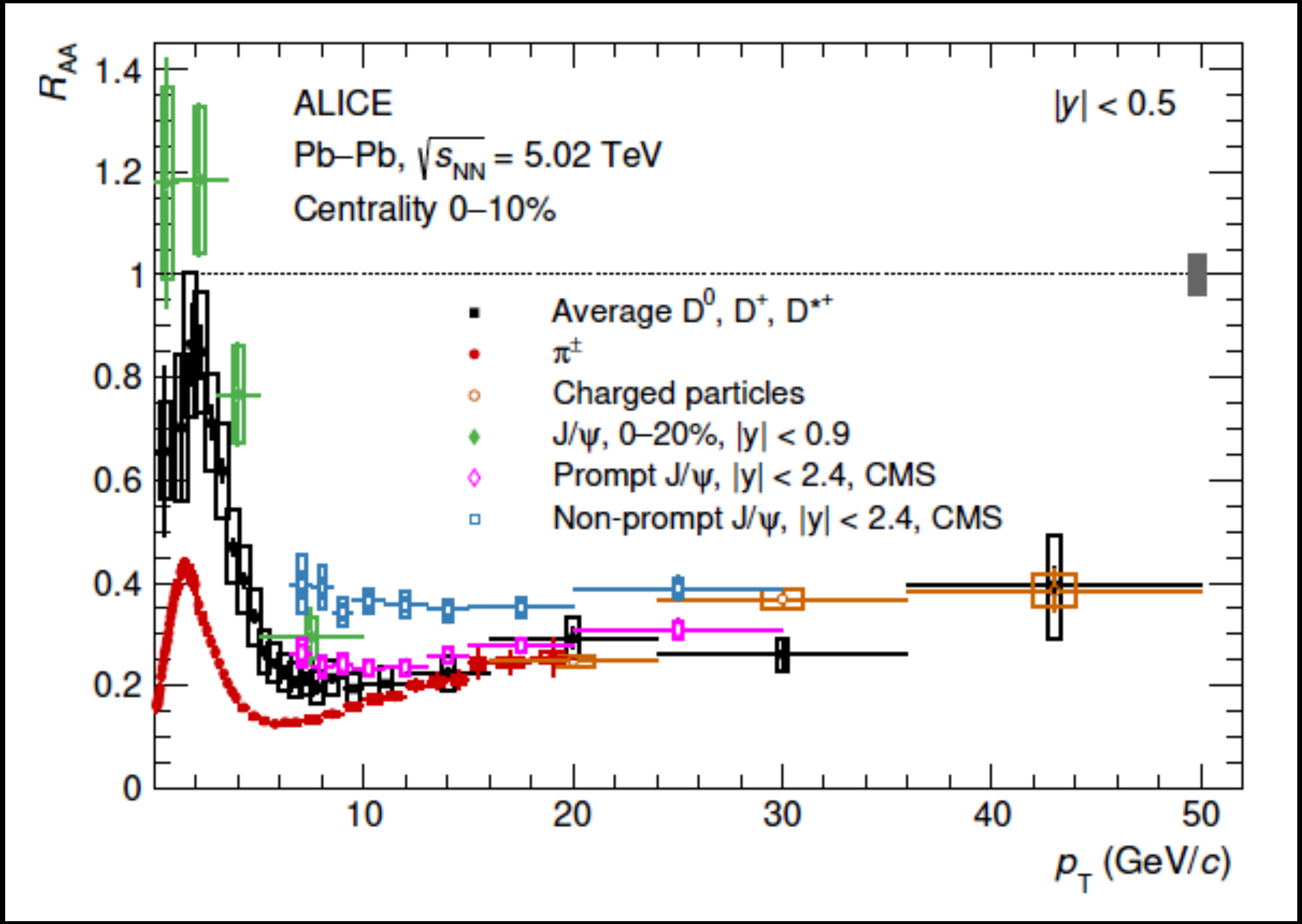
Flavor Dependence of Charm and Beauty (Centrality Selected)





ATLAS, Phys. Lett. B829, 137077 (2022)

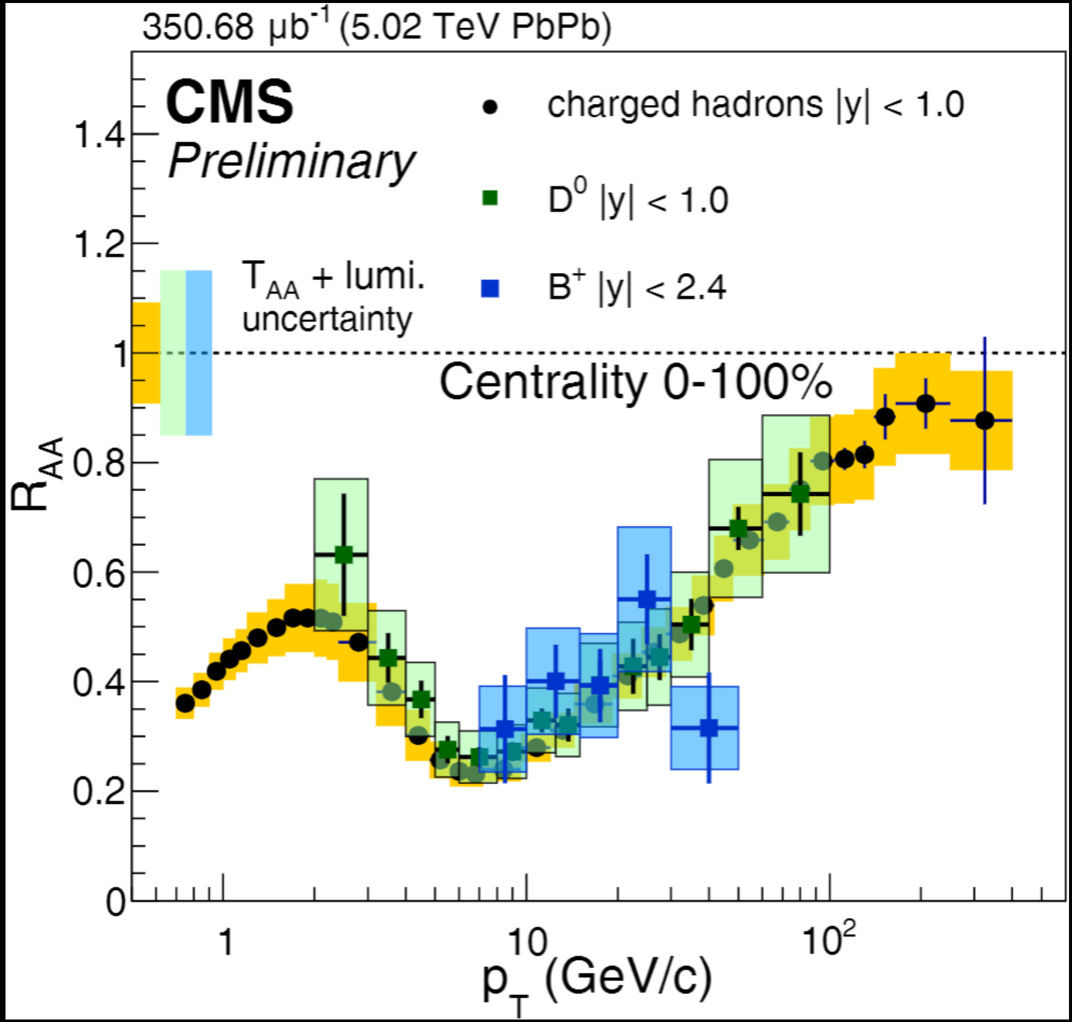
Flavor dependence seen in 5.02 TeV data for $p_T < 10$ GeV/c



ALICE, arXiv:2211.04384 [nucl-ex] (2022)

Flavor Dependence of Inclusive D and B Hadron Suppression

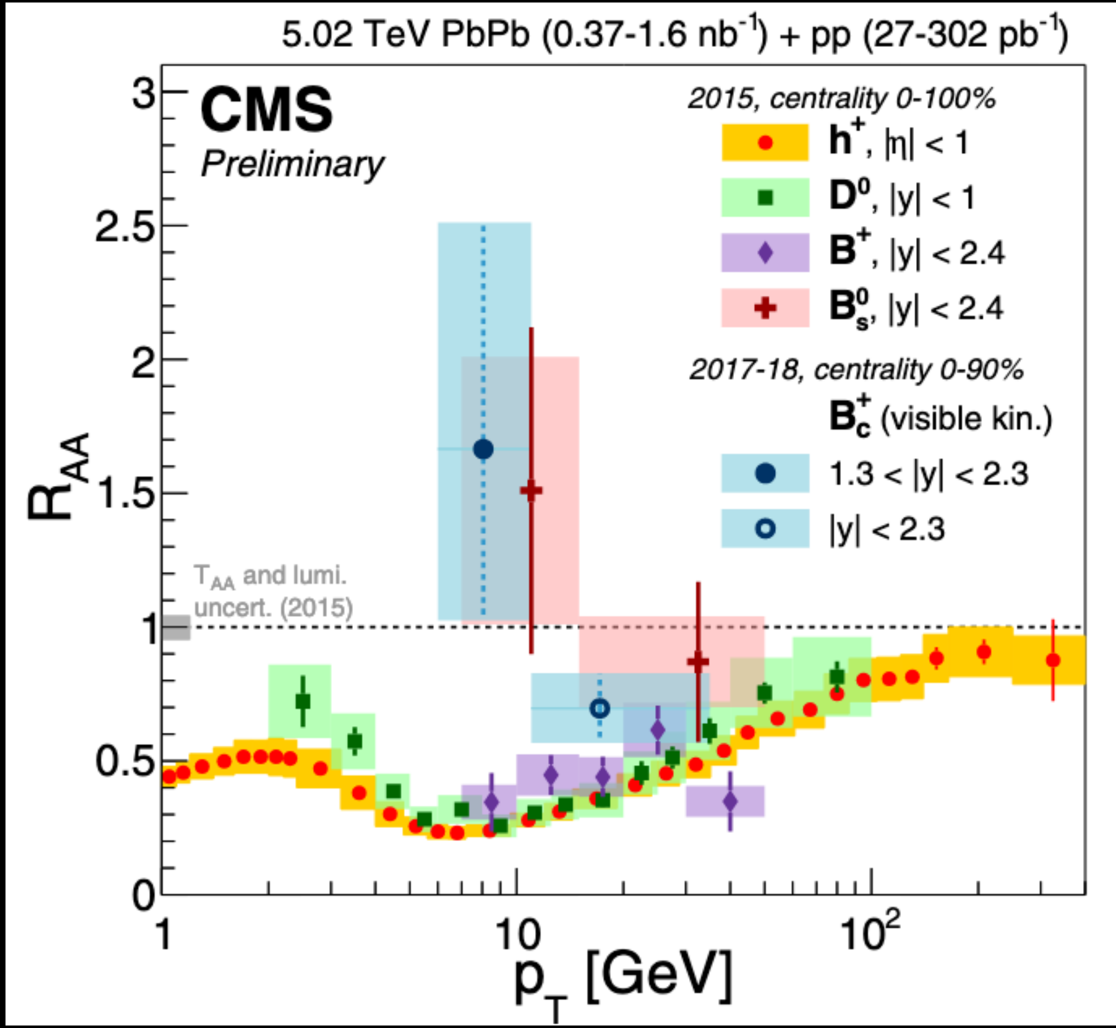
Previous Data



Statistics

→

Inclusive



Note also B^0_s

CMS, EPJ Web Conf. 259, 12011 (2022)

4

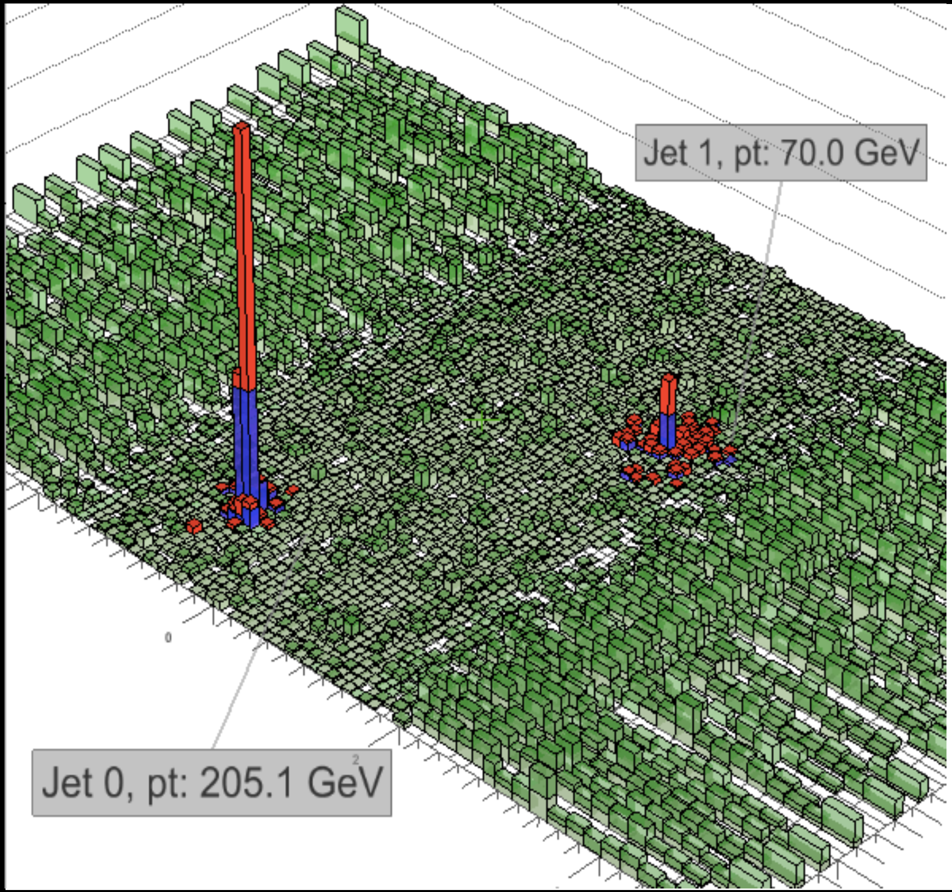
Jets

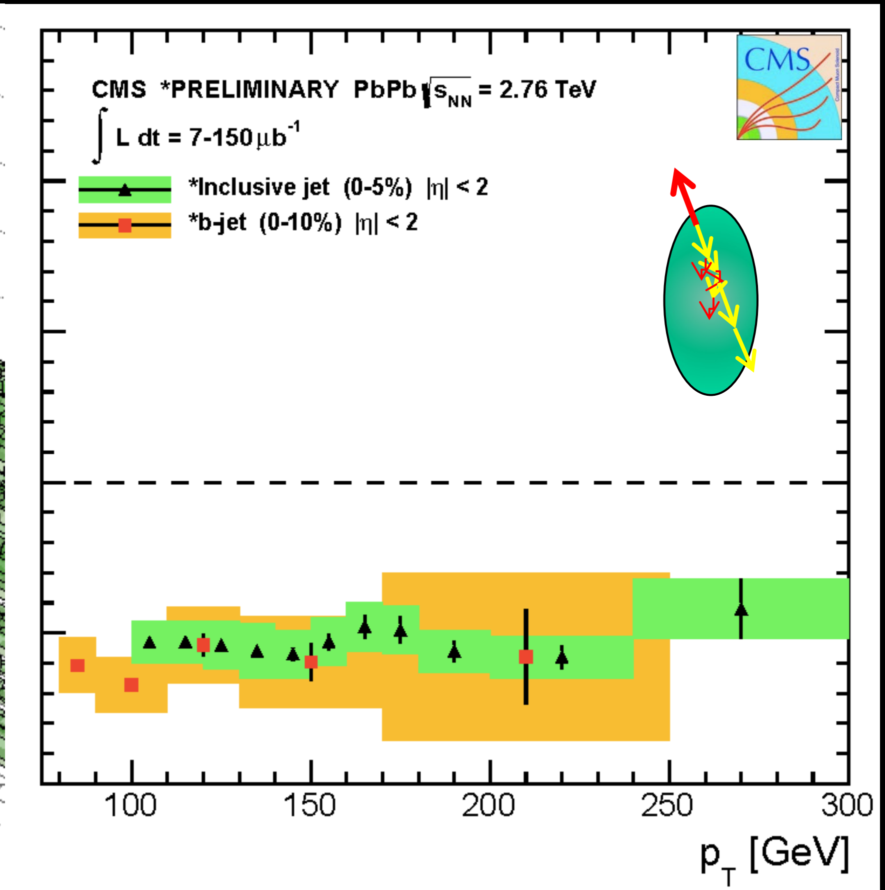
Jets Are Quenched to Highest p_T

EPJC 72 (2012) 1945
PLB 715 (2012) 66
PLB 710 (2012) 256

High p_T Particles

High p_T Jets





Jets quenched – to largest jet p_T

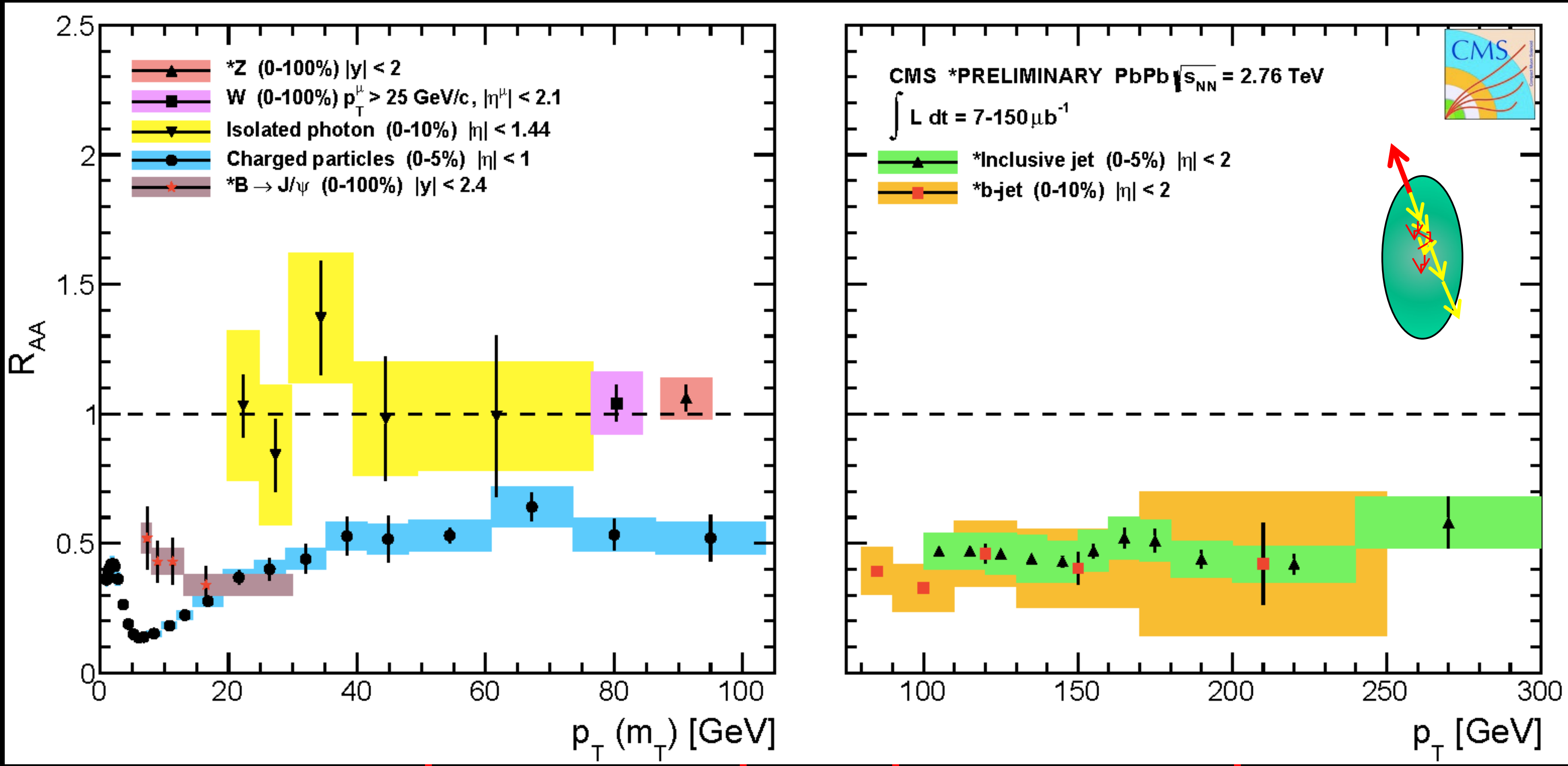
Is there a flavor independence?

Jets Are Quenched to Highest p_T

EPJC 72 (2012) 1945
PLB 715 (2012) 66
PLB 710 (2012) 256

High p_T Particles

High p_T Jets

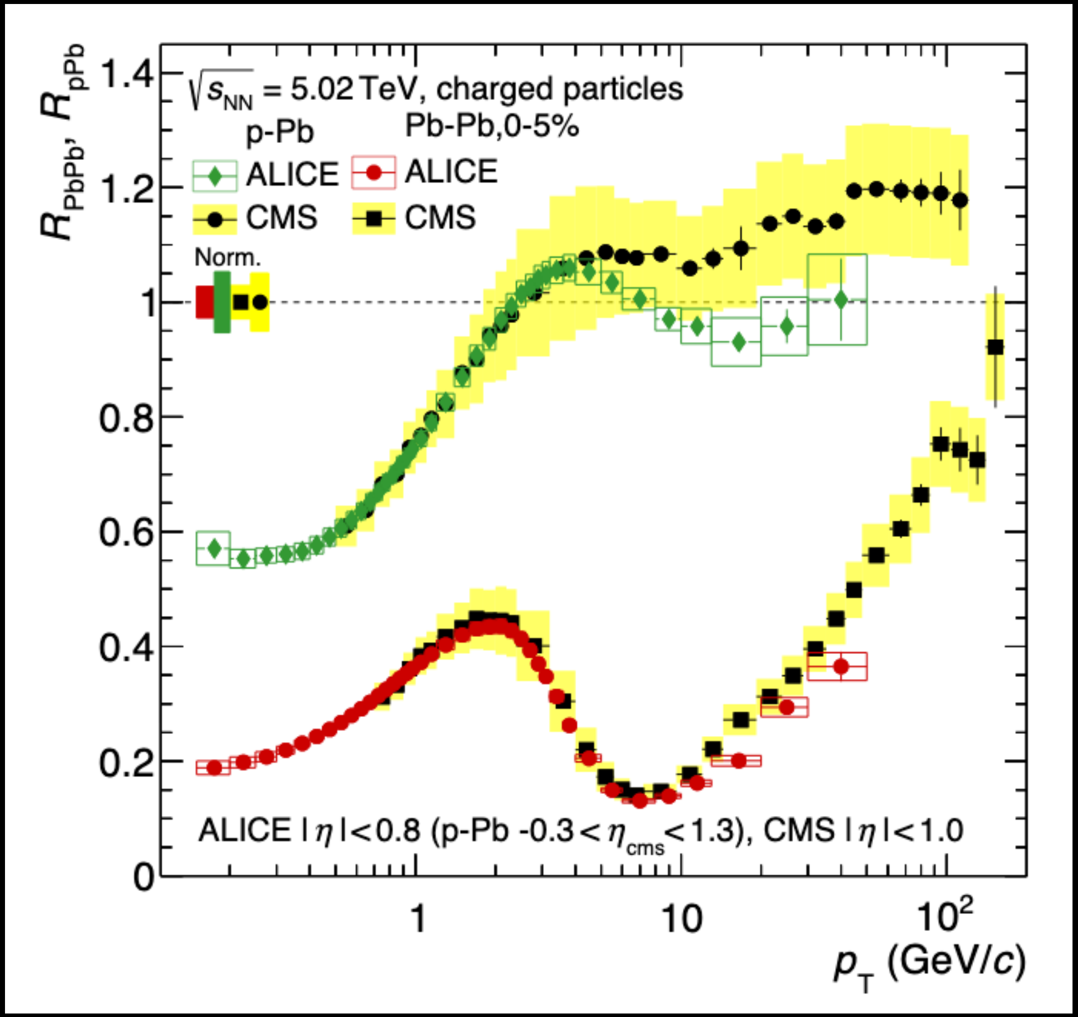


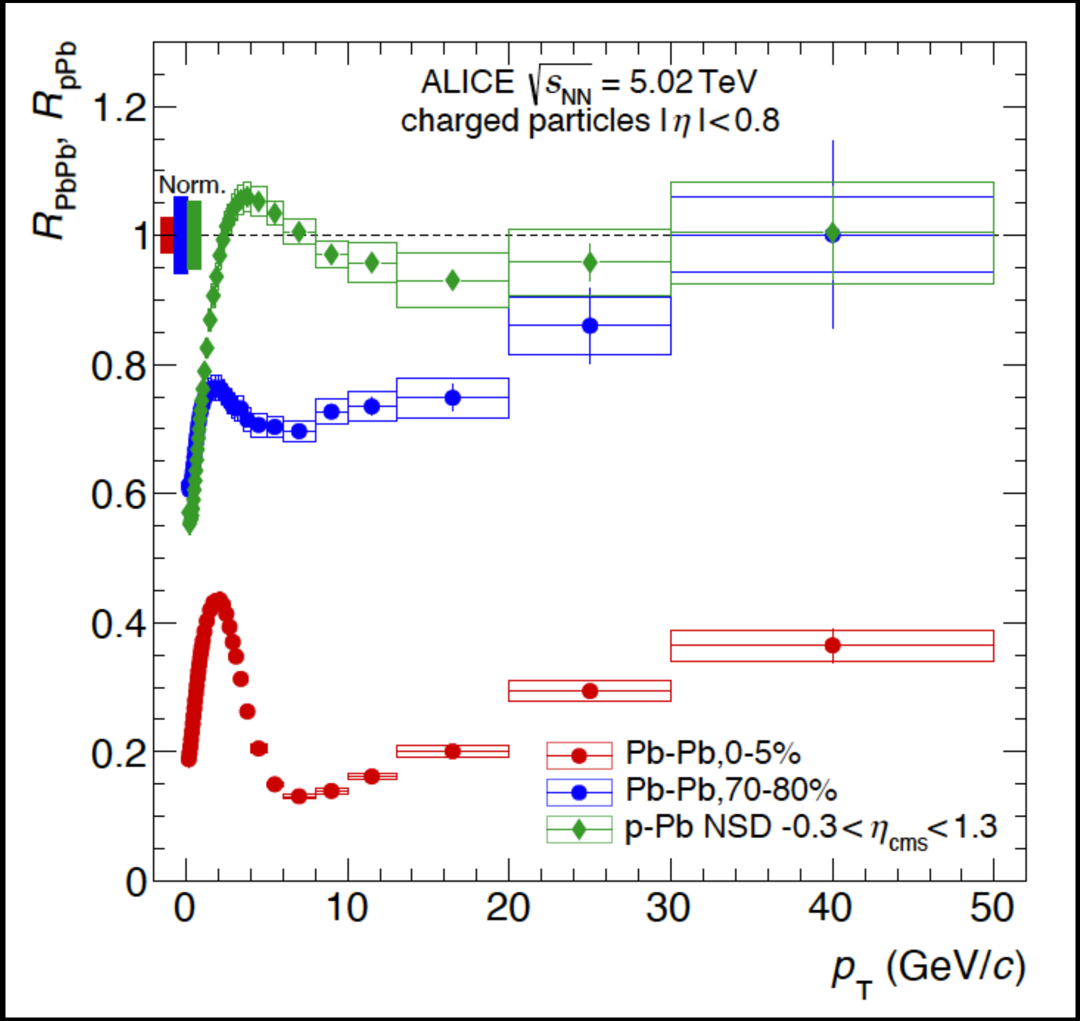
Same range of parton p_T

Jets quenched – to largest jet p_T

Is there a flavor independence?

Jets in p-Pb & Pb-Pb at LHC

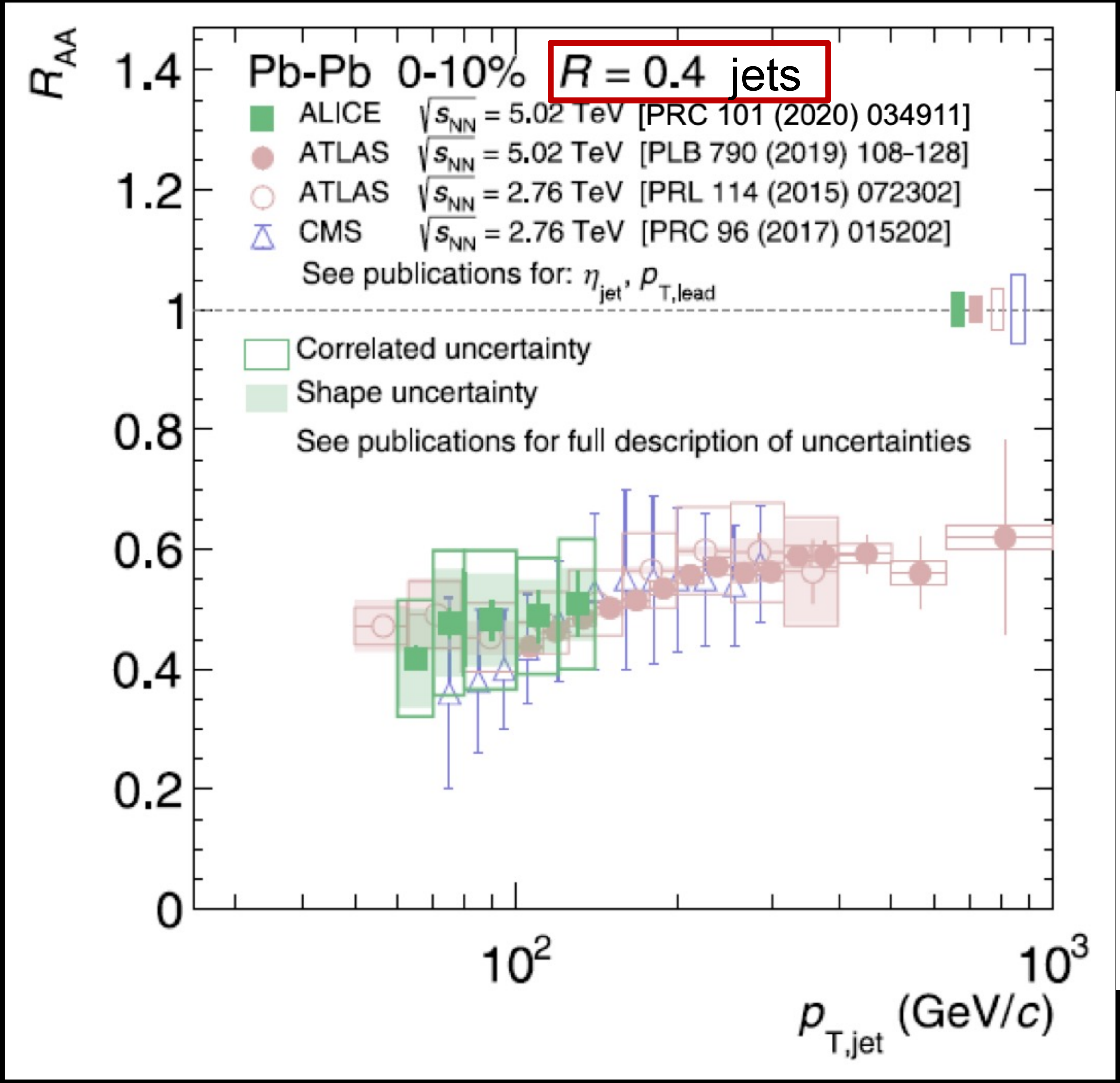


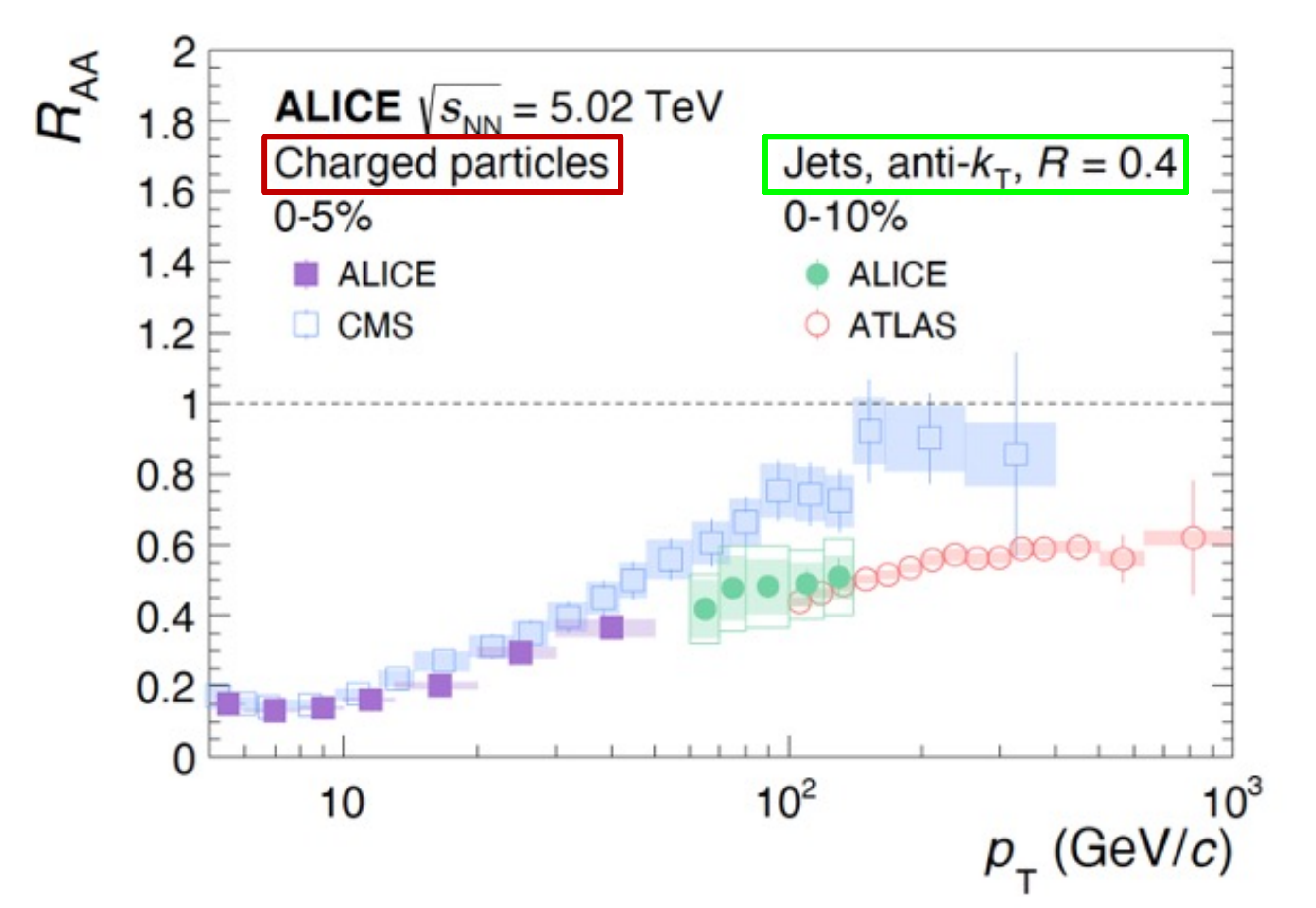


ALICE ≈ CMS: $R_{p\text{-}Pb}$ (jet) ≈ 1

$R_{Pb\text{-}Pb}$ (jet)<<1
Jets quenching increases with centrality

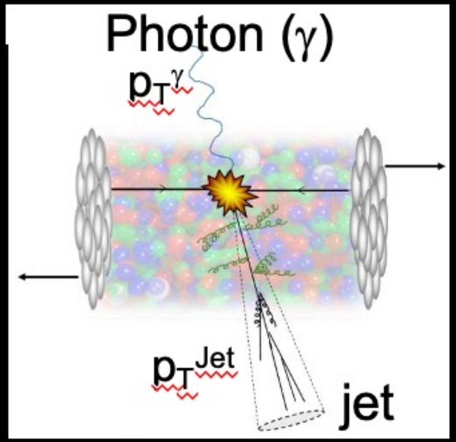
Jets & High p_T Charged Particles Measured over Large p_T Range

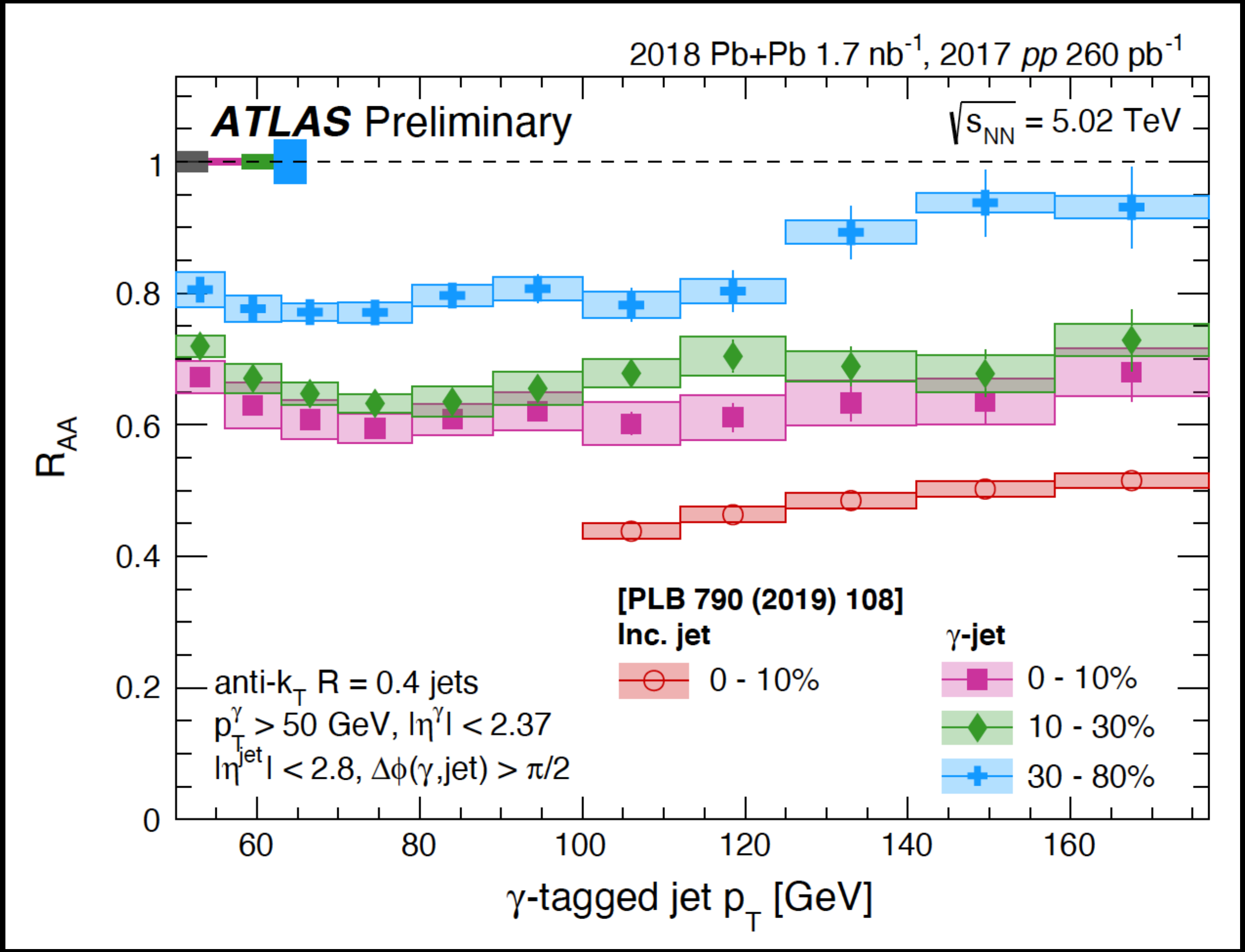




Jets: γ-tagged and inclusive jets

ATLAS-CONF-2022-019





Centrality dependence

0-10% central: R_{AA} (γ-tagged jets) > R_{AA} (inclusive jets)

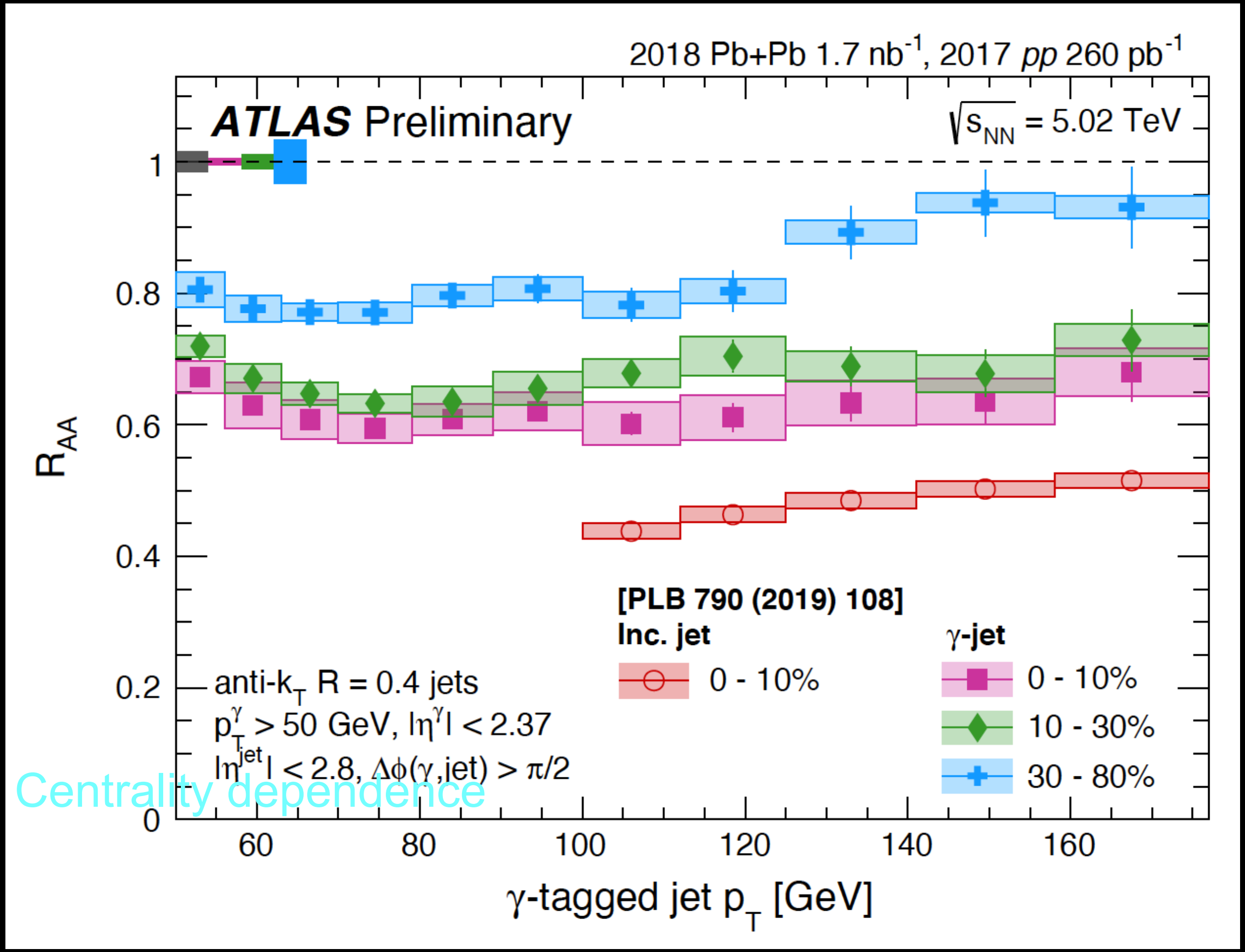
Gluons more suppressed than quarks - color factor!

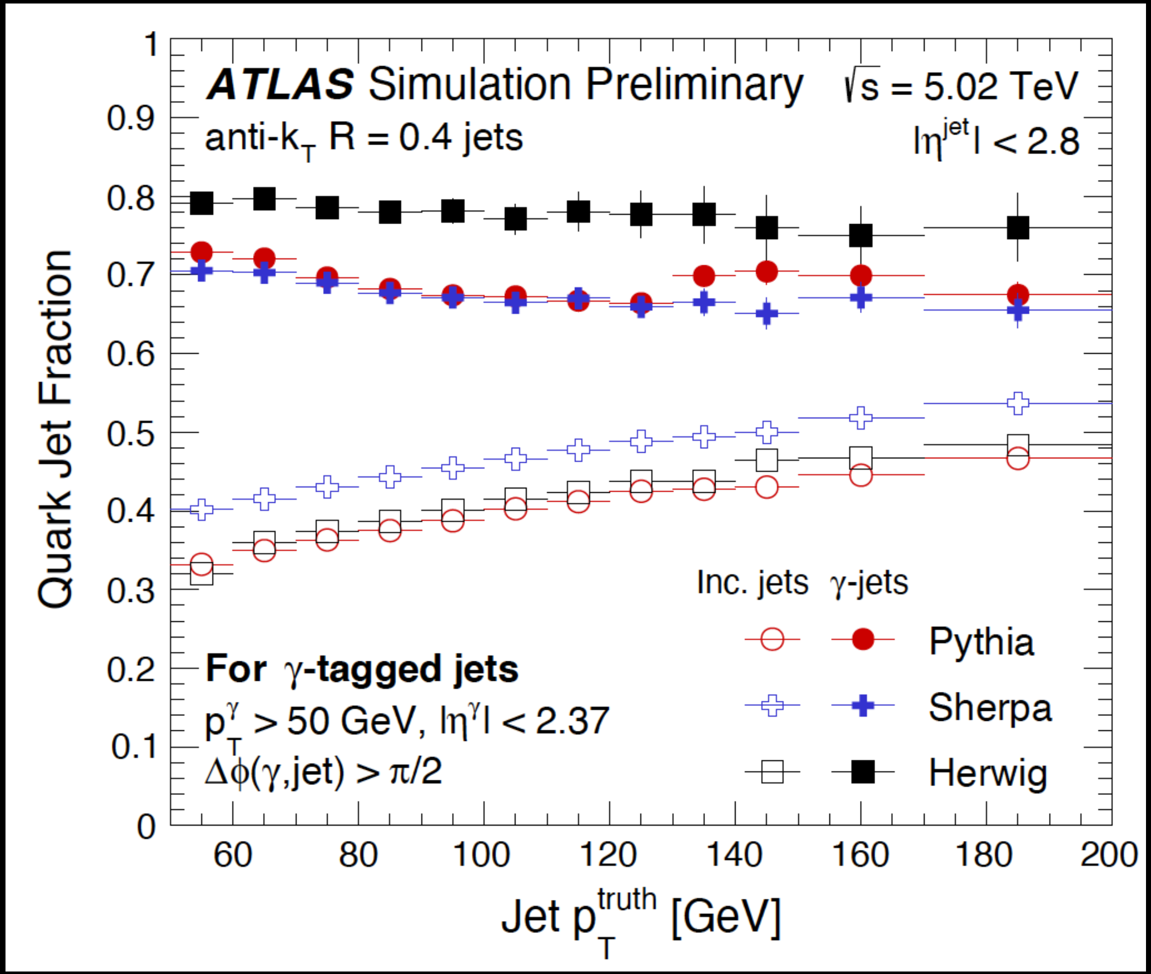
γ-tagged jet spectra harder than inclusive! -> larger R_{AA}

But check: Quark/gluon fractions!

Jets: γ-tagged and inclusive jets

ATLAS-CONF-2022-019





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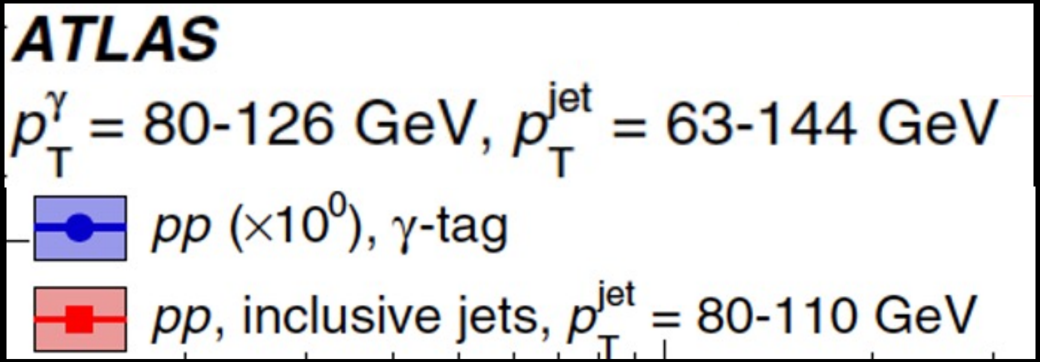
Quark Jet Fraction (γ-tagged jets) >> (inclusive jets)

More quarks in γ-tagged jets than inclusive jets

5 *Jet Fragmentation and Jet Broadening*

Fragmentation Functions in pp for γ-tagged vs Inclusive Jets

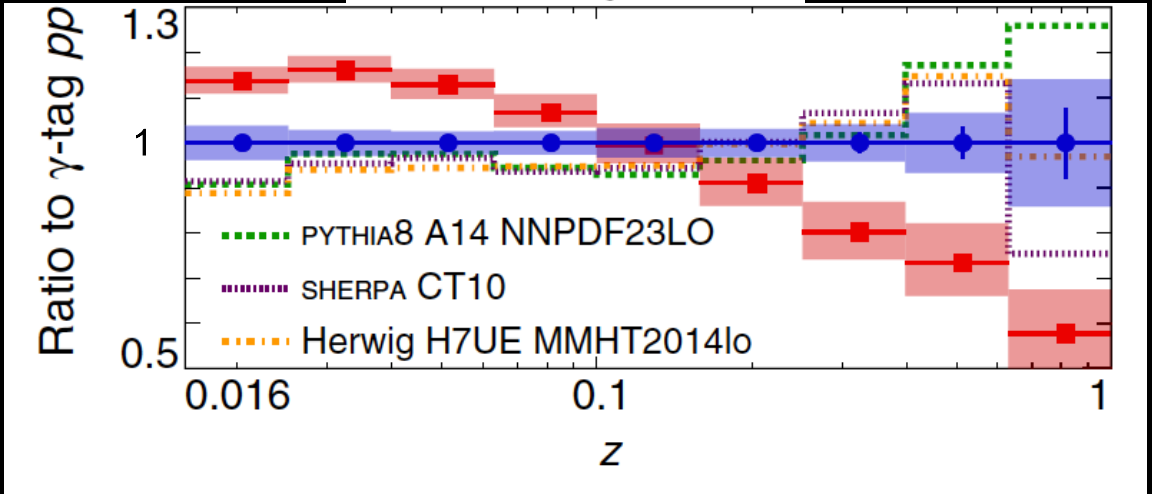


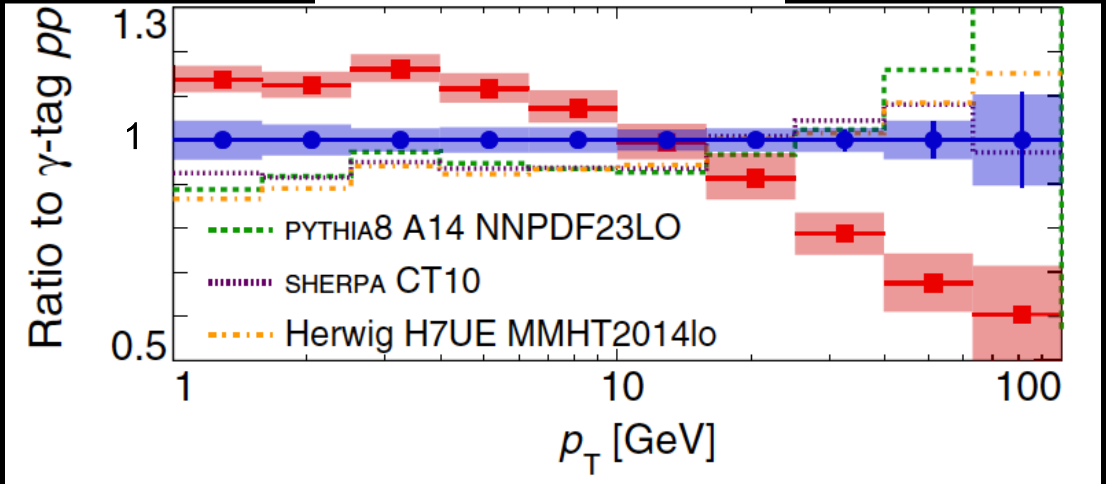
pp interactions:
R (inclusive jets) / (γ-tagged jets) < 1 at high z and p_T
R (inclusive jets) / (γ-tagged jets) > 1 at low z and p_T

Quark Jet Fraction (γ-tagged jets) >> (inclusive jets)
Harder spectrum (γ-tagged jets) than inclusive!

$$D(z) = \frac{1}{N_{jet}} \frac{dN_{trk}}{dz}$$

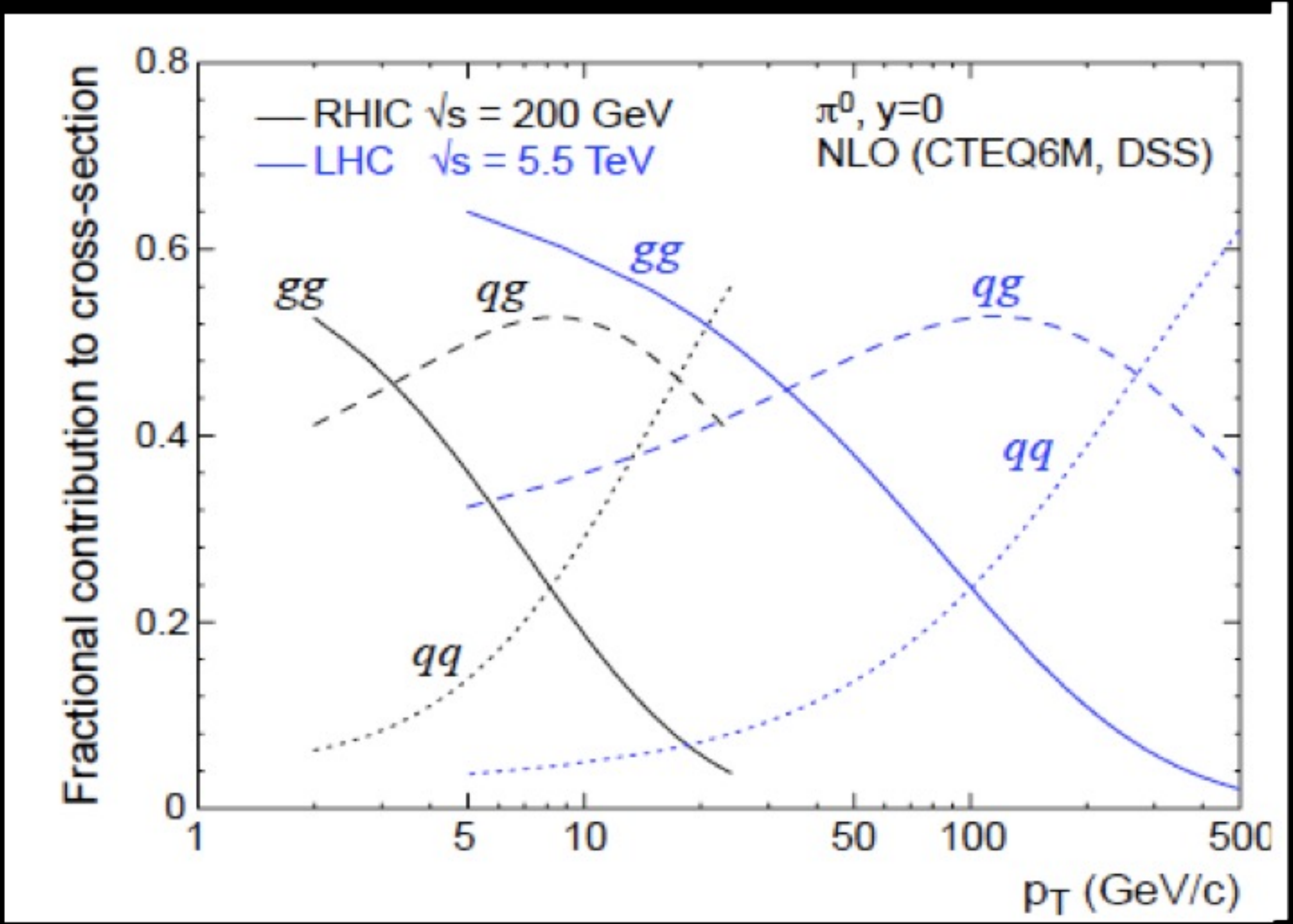
$$D(p_T^{trk}) = \frac{1}{N_{jet}} \frac{dN_{trk}}{dp_T^{trk}}$$





Remember: Initial Parton Scattering Differences vs √s

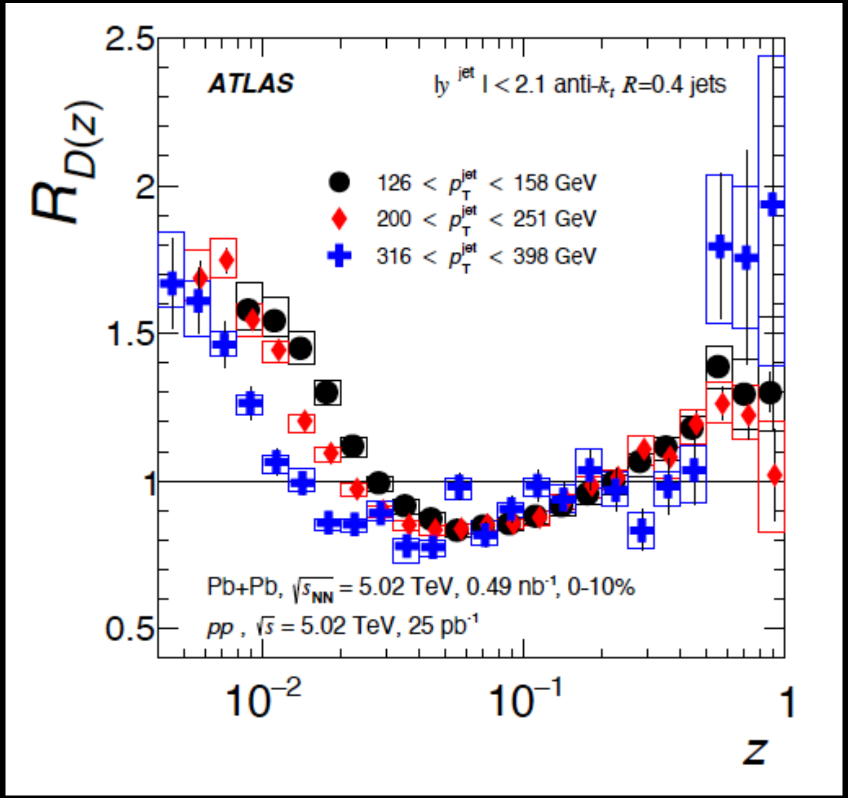
RHIC vs LHC

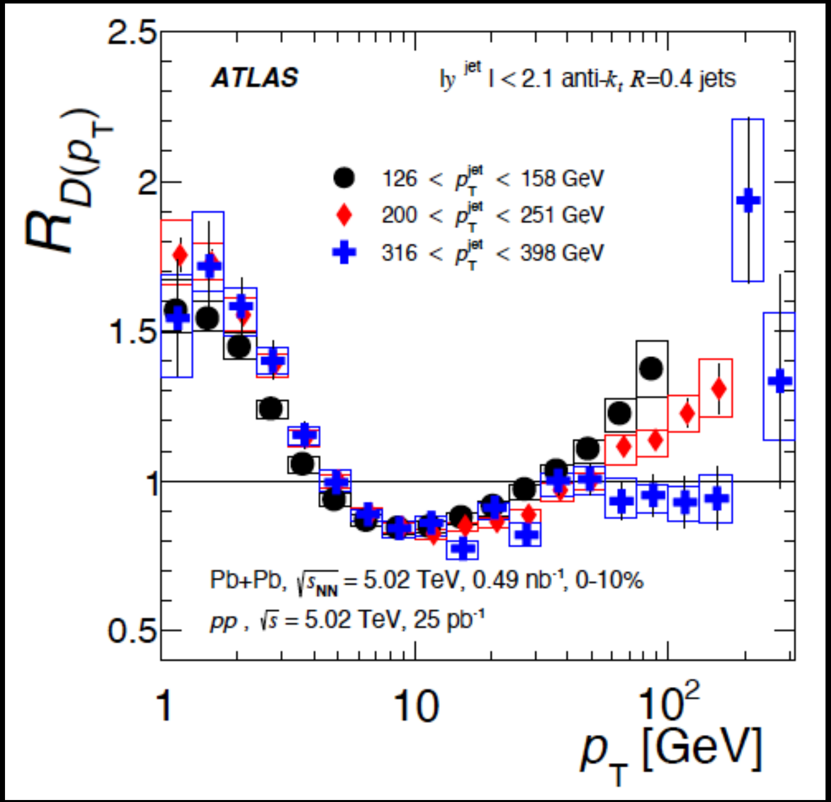


Jets: Fragmentation Functions in Pb-Pb Collisions

$$D(z) = \frac{1}{N_{\text{jet}}} \frac{dN_{\text{trk}}}{dz}$$

$$D(p_T^{\text{trk}}) = \frac{1}{N_{\text{jet}}} \frac{dN_{\text{trk}}}{dp_T^{\text{trk}}}$$

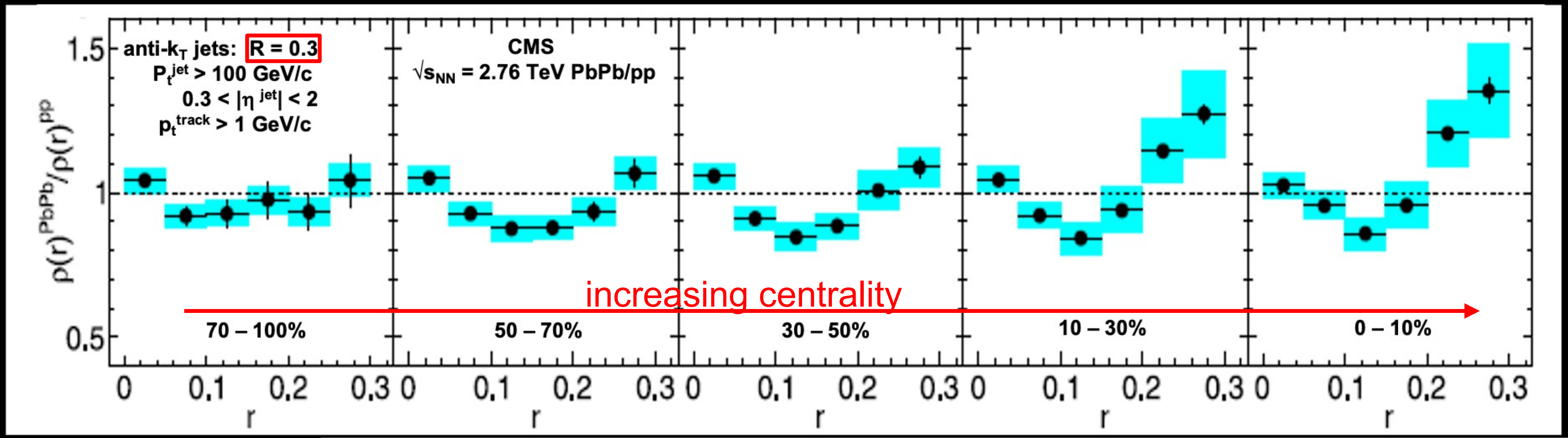


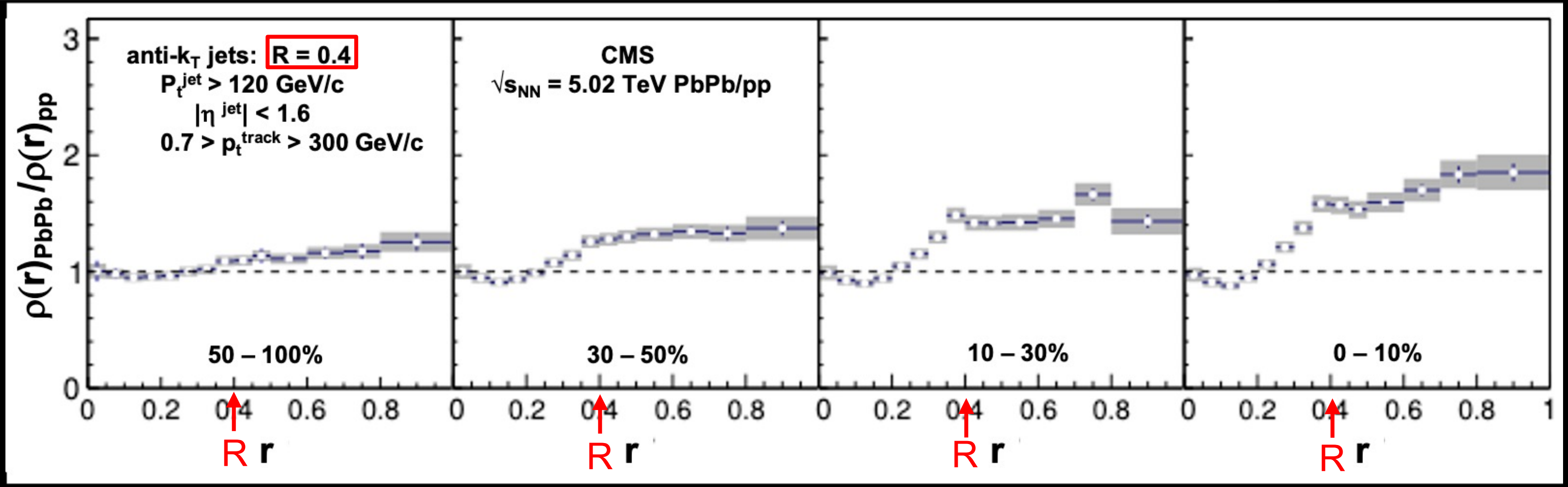


Enhancement at low and high z and p_T
Suppression at intermediate z and p_T

Intermediate z and p_T medium int's -> move lower
High z and p_T dominated by leading hadrons –
Also large initial parton virtuality -> less int's

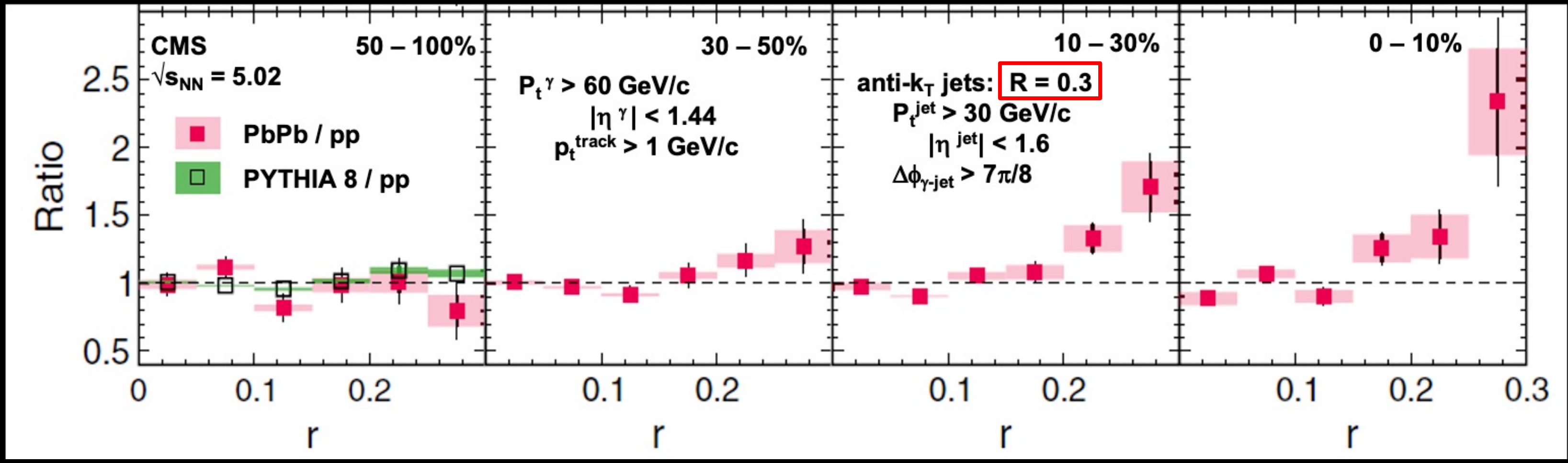
PbPb Jet Shapes: Broadening



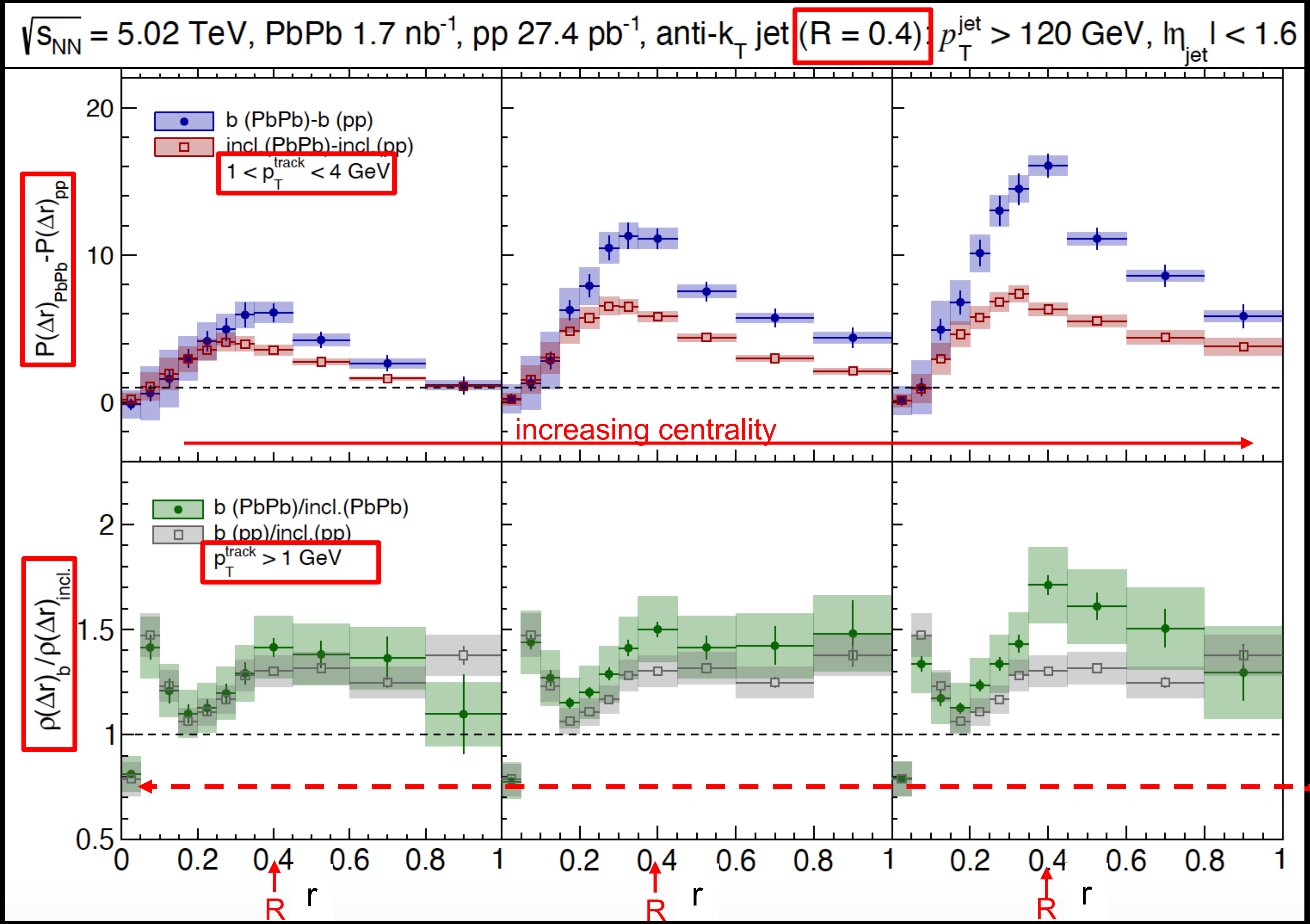


Broadening beyond R

γ - jets



PbPb b-Jet Broadening



b-jets broader than inclusive jets
-> increases with centrality
also beyond R!

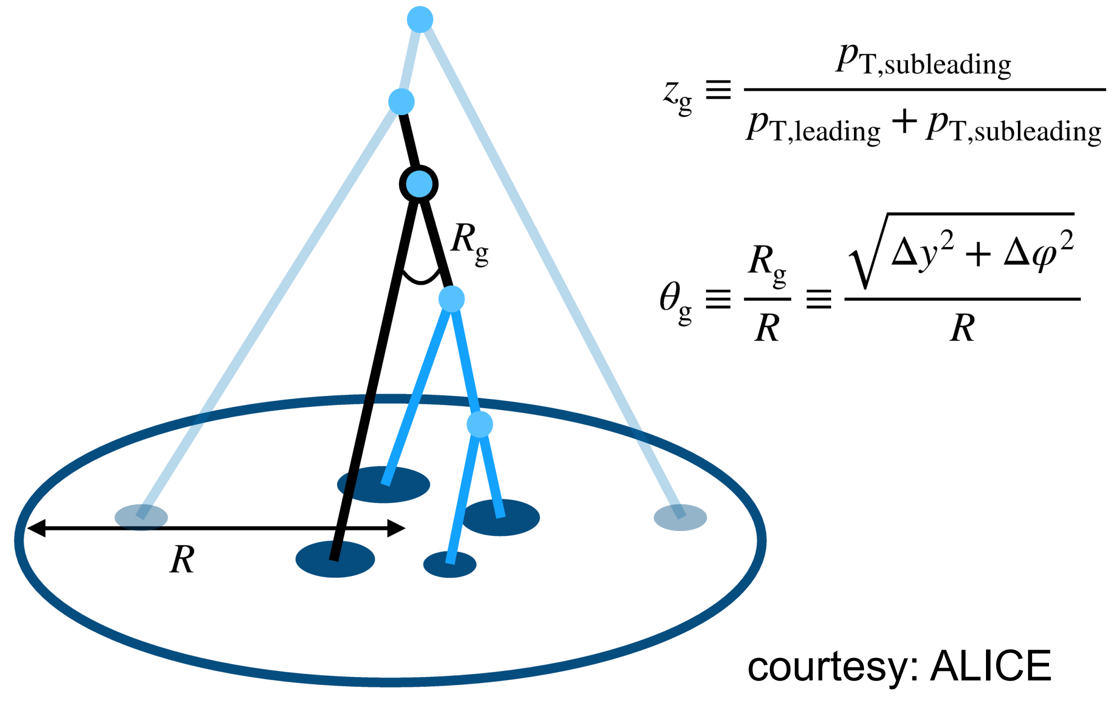
Wake for b-jets vs inclusive?

Indication of Dead-cone in PbPb?

CMS, PAS-HIN 20-003 (2022)

6 *Jet Substructure*

Groomed Jet Substructure



Soft Drop Approach attempts to reconstruct the shower history of the jet, to try to determine parton energy loss mechanisms in the medium

- Reconstruct jet with anti-k_T
- Re-cluster with C/A to get angular ordering inside the parton shower.
- Undo the last clustering step and check

$$z > z_{cut} \ (\Delta R/R_0)^{\beta}$$

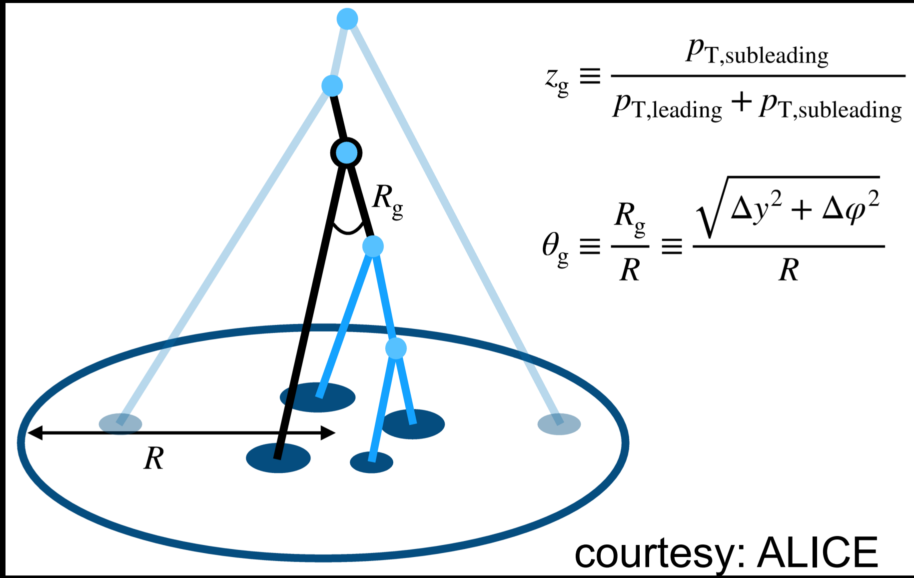
- Discard softer subjet and repeat.

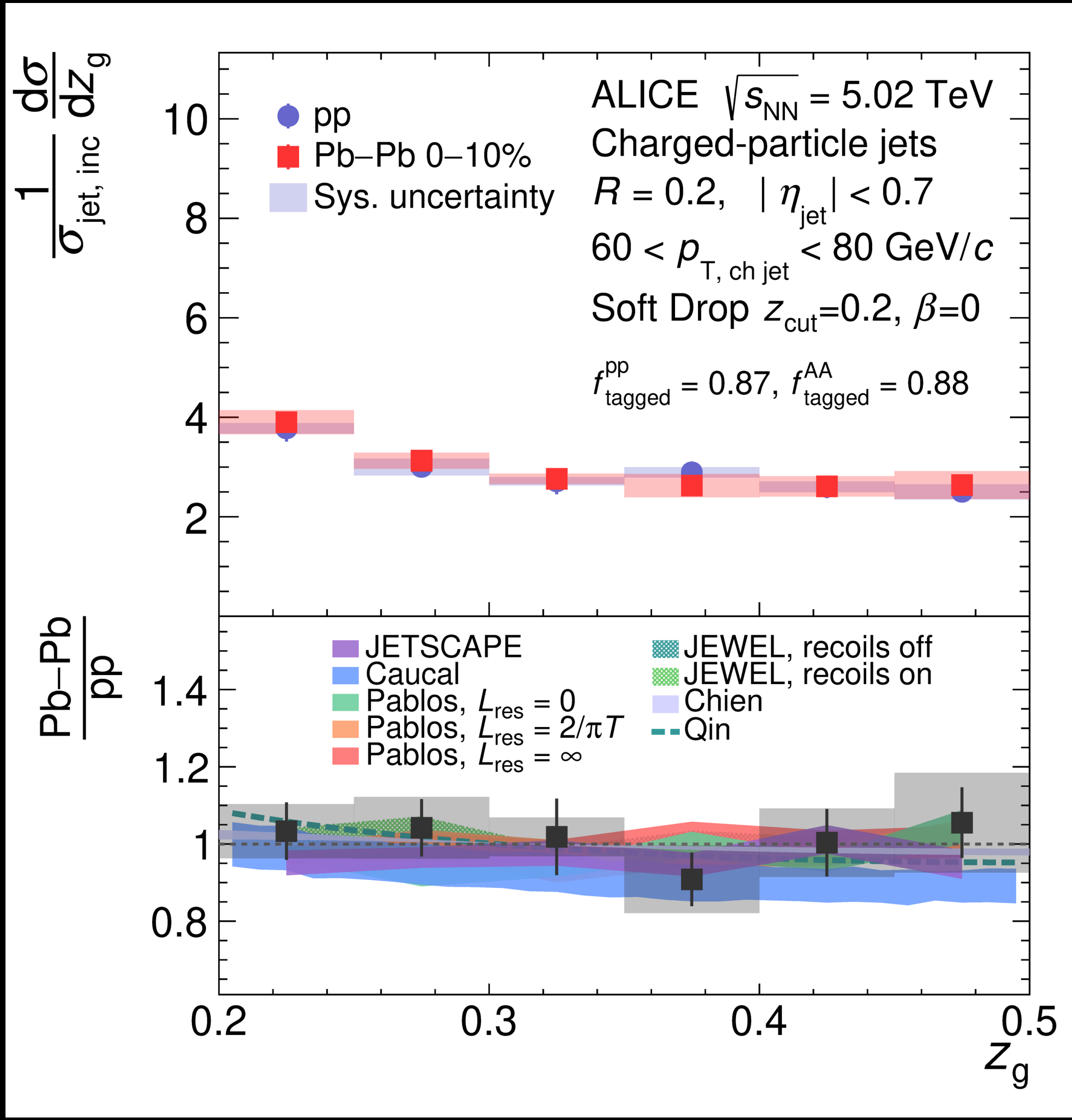
Splittings described by the

z_g - momentum fraction of 1st splitting
R_g- angular separation of 1st splitting

Soft Drop:
M. Dasgupta et al. JHEP 1309 (2013) 029.
A. Larkoski et al, JHEP 1405 (2014) 146.

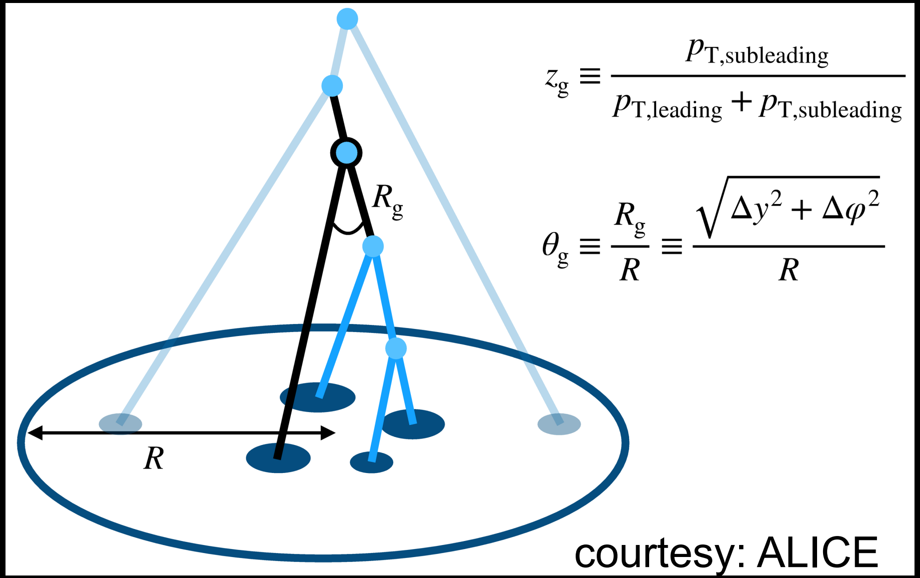
Soft Drop z_g in PbPb

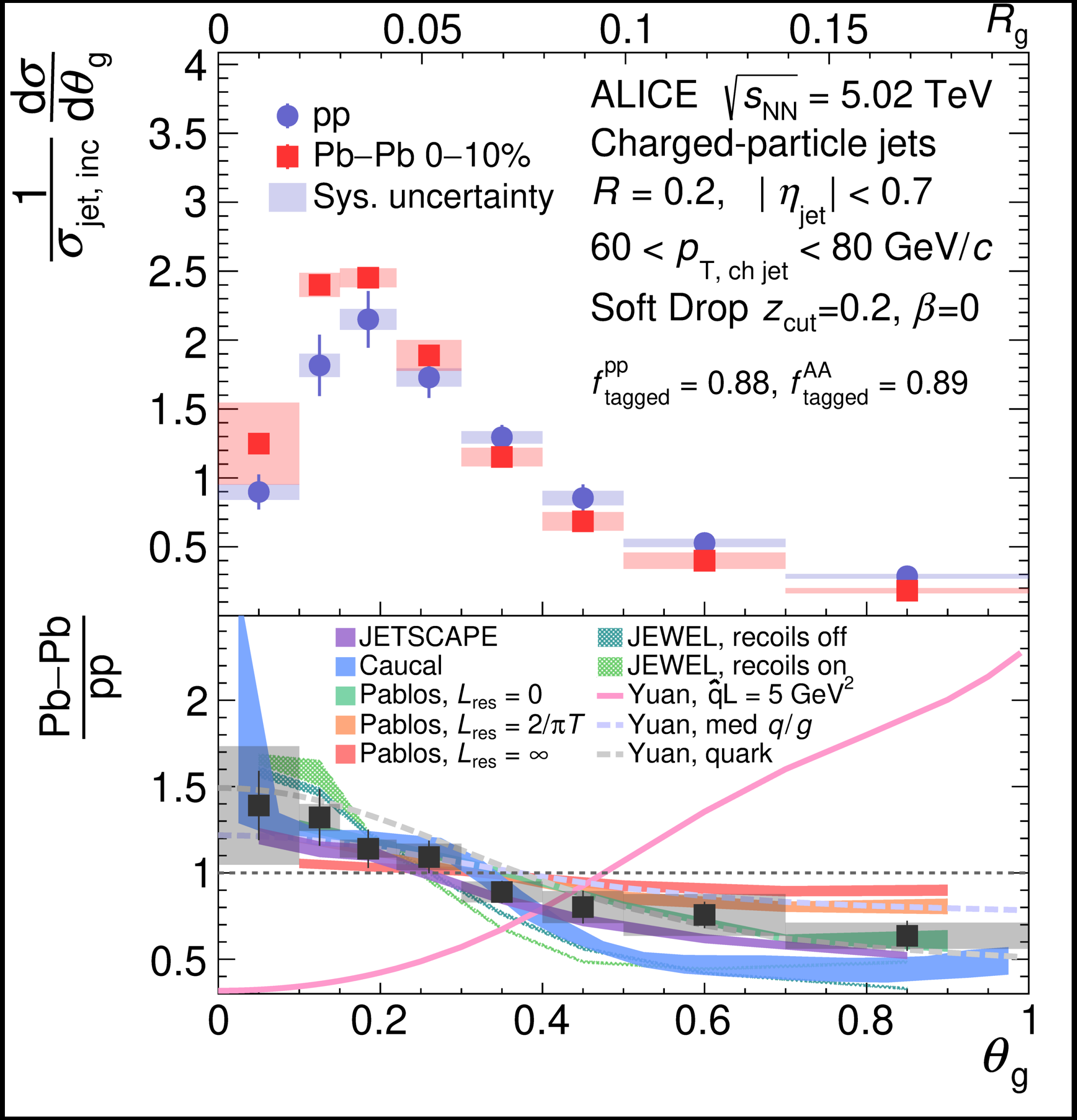




No observable modification of the z_g distribution in Pb-Pb compared to pp

Soft Drop θ_g in PbPb

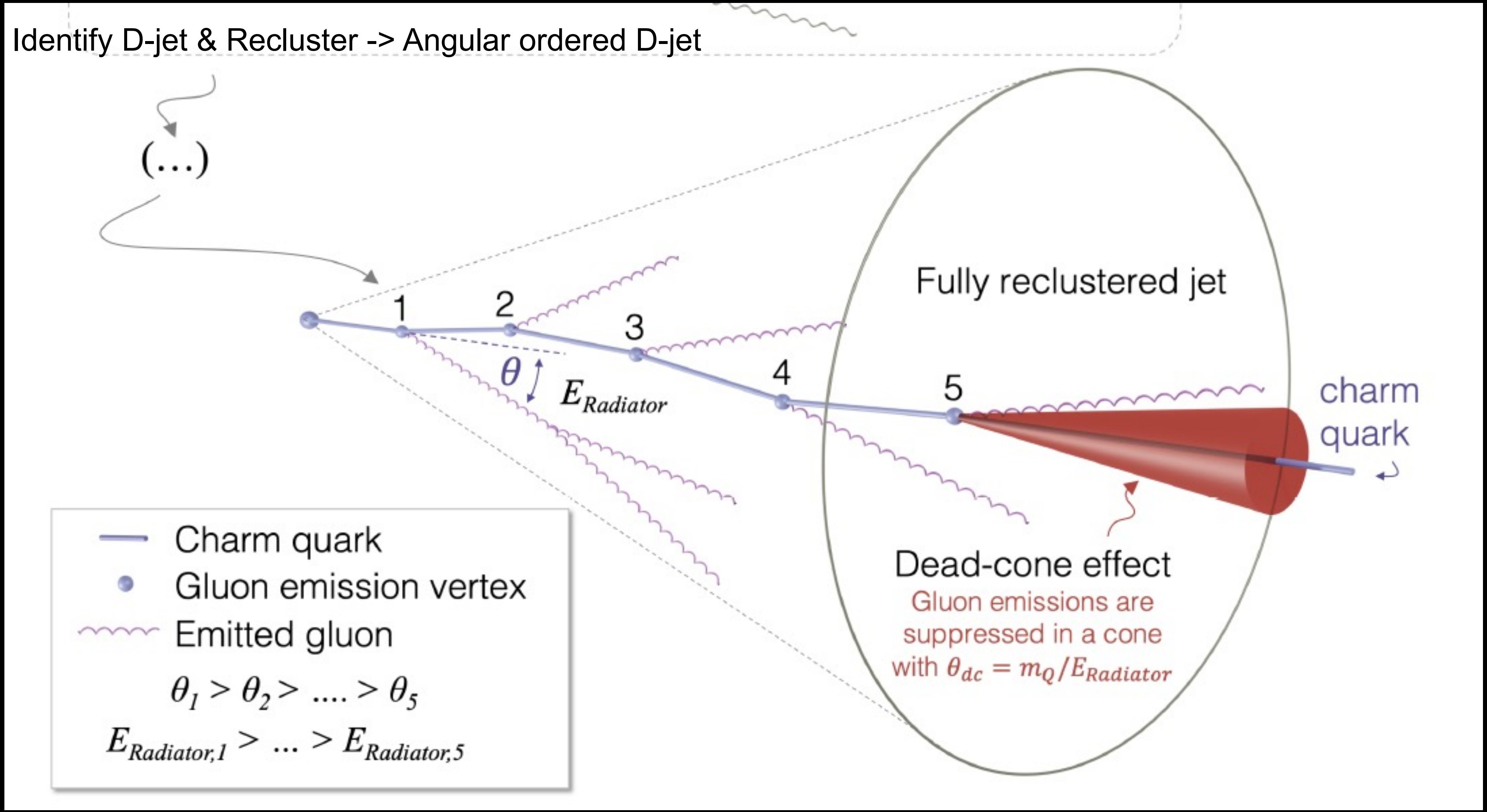




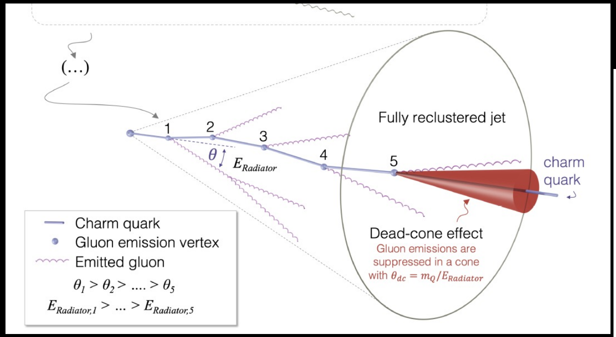
- *Observe narrowing of the θ_g (= R_g/R) distribution in PbPb/pp*
  - *Expected due to color coherence*
- *E-loss models reproduce narrowing of θ_g distribution*
  - *Also by those without color coherence by E-loss induced change in q/g fraction*

Groomed Jet Substructure – Dead-cone in pp Collisions

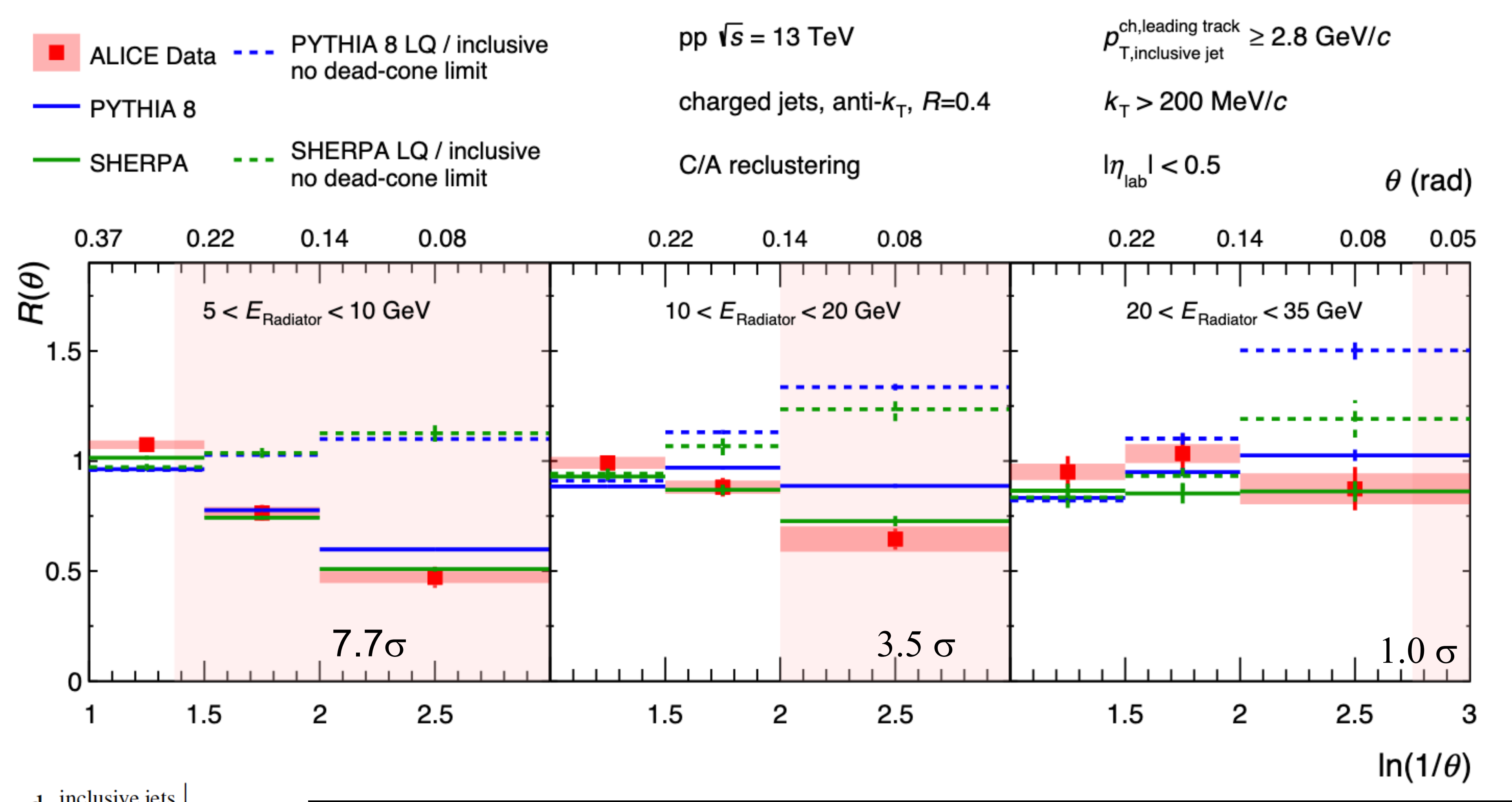
ALICE, Nature 605 (2022) 440-446



Groomed Jet Substructure – Dead-cone in pp Collisions



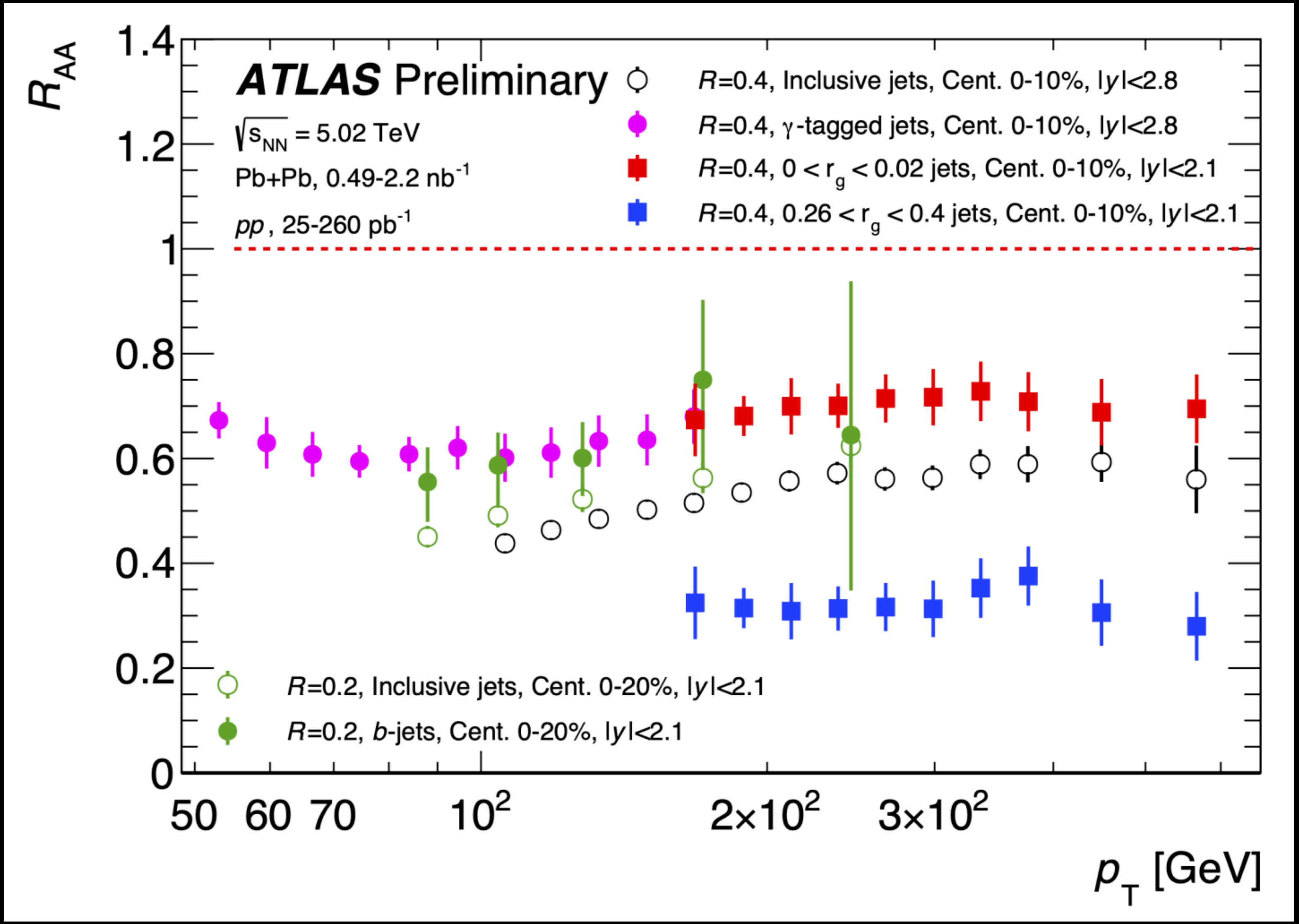
ALICE, Nature 605 (2022) 440-446



Ratio D-jets to inclusive

$$R(\theta) = \frac{1}{N^{\mathrm{D^0\,jets}}} \frac{\mathrm{d}n^{\mathrm{D^0\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg/ \frac{1}{N^{\mathrm{inclusive\,jets}}} \frac{\mathrm{d}n^{\mathrm{inclusive\,jets}}}{\mathrm{d}\ln(1/\theta)} \Bigg|_{k_{\mathrm{T}}, E_{\mathrm{Radiator}}}$$

γ-tagged jets and b-jets



R_{AA} (γ-tagged) ~ R_{AA} (narrow jets)

R_{AA} (inclusive) < R_{AA} (γ-tagged)

R_{AA} (wide jets) < R_{AA} (narrow jets)

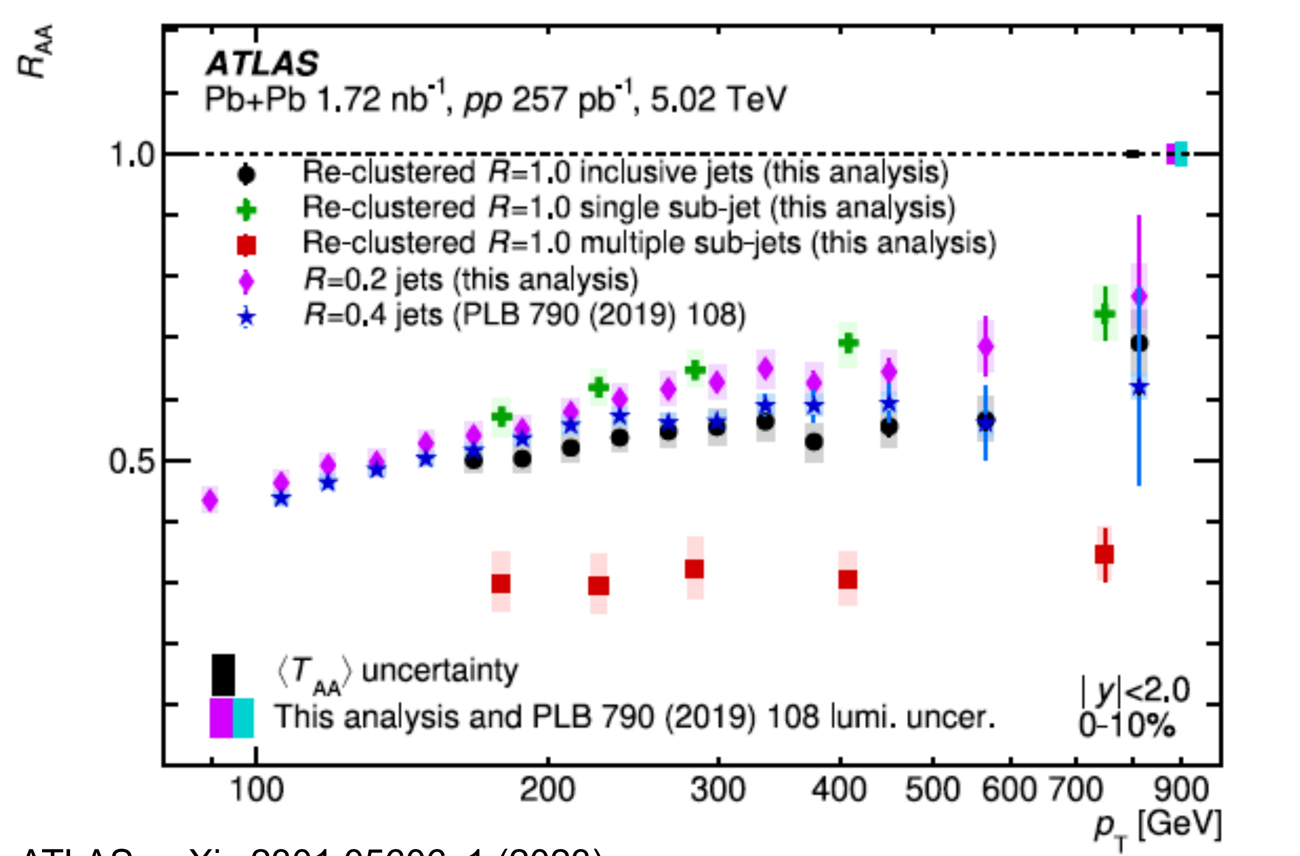
R_{AA} (b-jets) ~ > R_{AA} (inclusive)

Substructure and Large Radius (R = 1) Reclustered Jets

Procedure:
- Re-cluster all found anti-kt R = 0.2 jets into R = 1 jets also using anti-kt.
- The large-radius jet constituents are further re-clustered using the kt algorithm to obtain splitting parameters to get the p_T and Θ for the hardest splitting in the jet.

Note kinematic range of 158 < p_T < 1000 GeV.

Production of R = 1 re-clustered inclusive jets is suppressed more than R = 0.2 or R = 0.4 jets.



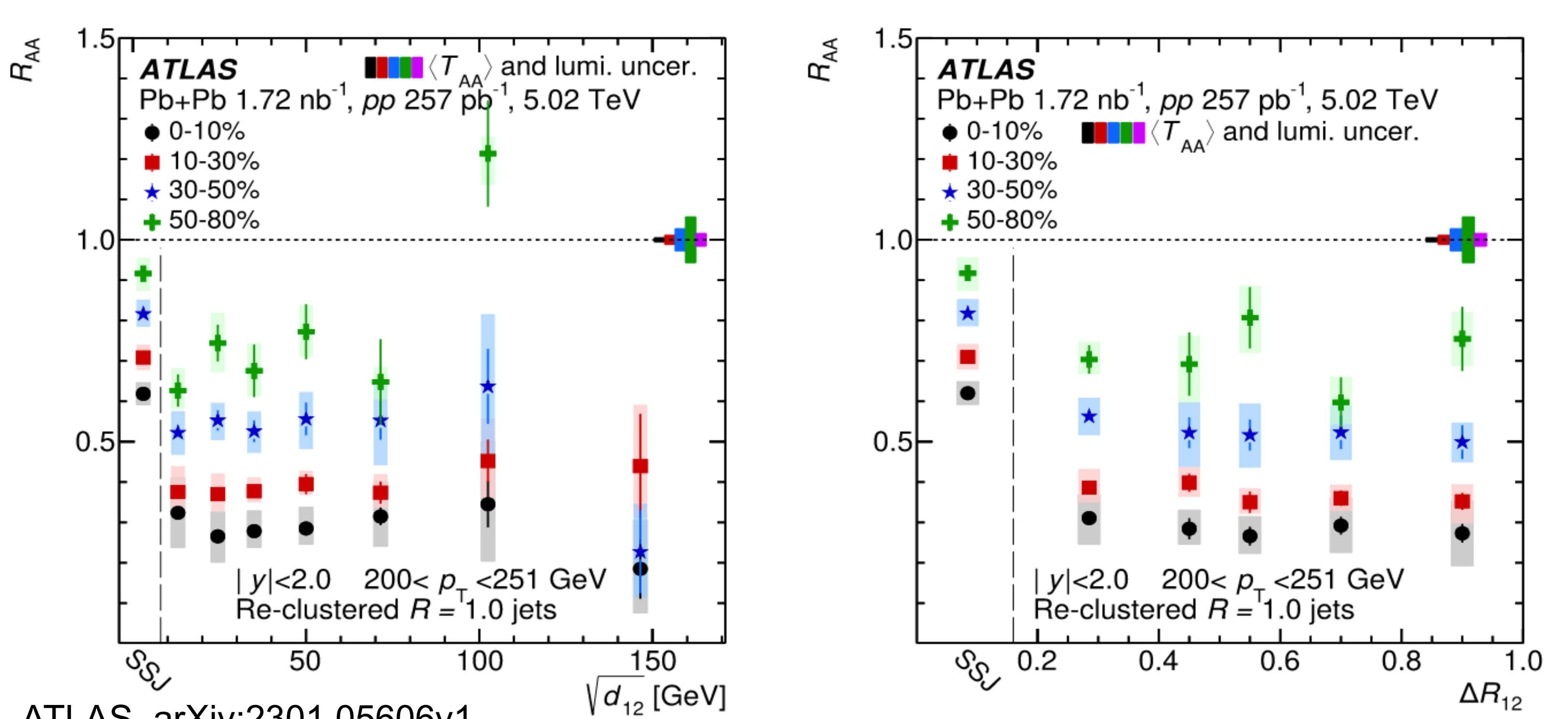
ATLAS, arXiv:2301.05606v1 (2023)

R_{AA} (multiple sub-jets) << R_{AA} (single sub-jets)
-> jets with hard internal splittings lose more energy!
-> role of color decoherence in the jet quenching?

Substructure and Large Radius (R = 1) Reclustered Jets

- R_{AA} of large-radius jets with single sub-jet compared with the R_{AA} for large-radius jets with a more complex substructure having a non-zero ΔR_{12}.

- Consistent with scenario in which the medium cannot resolve partonic fragments below a certain transverse scale!



ATLAS, arXiv:2301.05606v1 (2023)

$$\Delta R_{12} = \sqrt{\Delta y_{12}^2 + \Delta\phi_{12}^2}, \ \sqrt{d_{12}} = \min(p_{T1}, p_{T2}) \times \Delta R_{12}.$$

Is there a limit?

Summary 1

"Early History"

- 1982 – Bjorken, FNAL Pub 82/59-THY predicted energy loss of partons in QGP
- 1992 – Wang & Gyulassy, PRL 68 (1992) 1480, Gluon Shadowing and Jet Quenching in AA
- 2003 – STAR, PRL 90 (2003) 82302 on relative charge dependence, *"1st Jet substructure in AA" IMHO*
- 2003 – STAR, PRL 91 (2003) 072304, Disappearance of Away-side Jet in AuAu
  Lost energy of away-side jet redistributed to larger angles

Summary 2

2001-2023:

- Jets & High p_T Charged Hadrons Are Suppressed at RHIC (down to low √s) and LHC(to high p_T) in AA

  EM Probes NOT, pA NOT
- Flavor Dependence (Hierarchy) of Inclusive Hadron Suppression (q, g, s, c, b) in AA
- PbPb: R_{AA} (inclusive jets) < R_{AA} (γ-tagged jets) -> Gluons more suppressed than quarks - color factor!
- Jet Fragmentation & Shapes

  Intermediate z and p_T medium interactions -> move to lower z and p_T

  High z and p_T dominated by leading hadrons – also large initial parton virtuality -> fewer interactions

  Quark and gluon fractions of initial parton scatterings differ in NLO

  Jets broaden with increased centrality vs pp, spread beyond R

  b-jets broader than inclusive jets (wake?), dip at smallest r (dead-cone?)
- Jet Substructure

  Observe narrowing of the θ_g (= R_g/R) distribution in PbPb/pp -> expected due to color coherence

  Dead-cone observed for Charm Jets

  Broader jets more suppressed than narrower ones

  b-jet suppression ~ inclusive jets

  R = 1 re-clustered inclusive jets more suppressed than R = 0.2 or R = 0.4 jets

  R = 1 multiple sub-jets more suppressed than R = 1 single sub-jets

  Jets with hard internal splittings lose more energy -> Role of decoherence?

Outlook -> Disentangle/understand time evolution of jet splittings: info on parton energy loss & int's w. QGP

Thank you for your attention!

Thanks to Hannah Bossi, Laura Havener and Berndt Müller
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