✻ ALL NEW EDITION

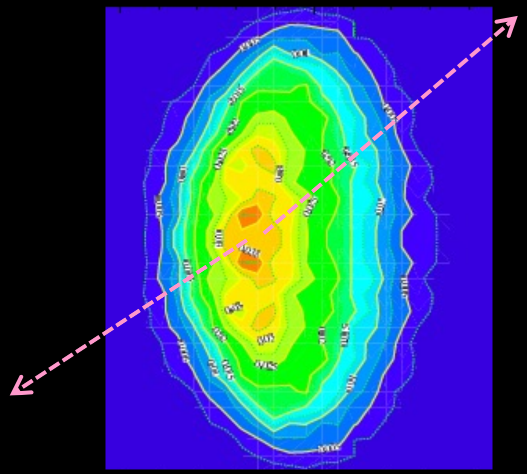
Everything you always wanted to know about jets* … and more

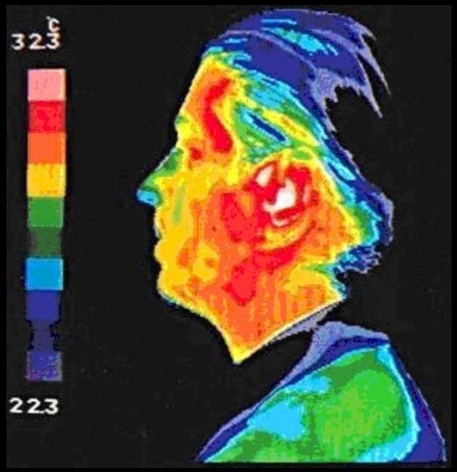
John W. Harris.

* But were afraid to ask

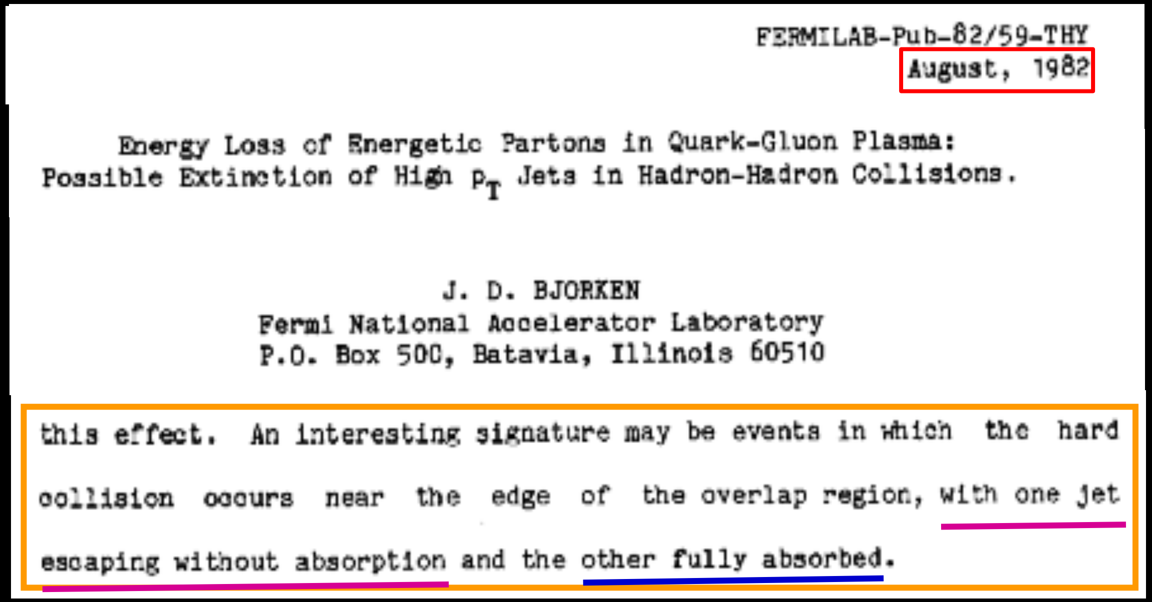
1

History – Early Jet Tomography





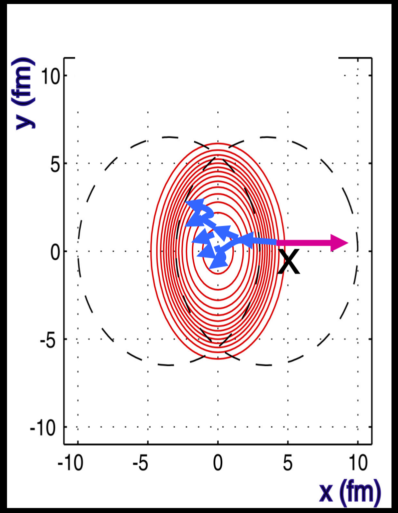
History – High Momentum Particle & Jet Correlations

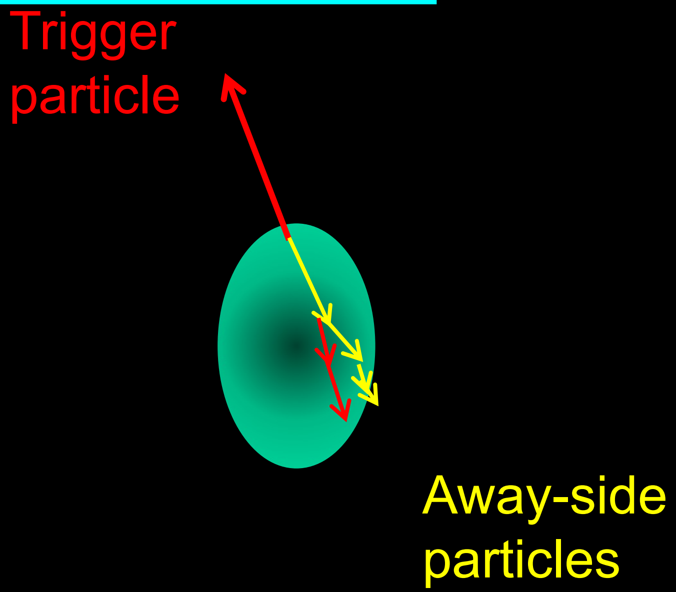

FERMILAB-Pub-82/59-THY
August, 1982

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

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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.

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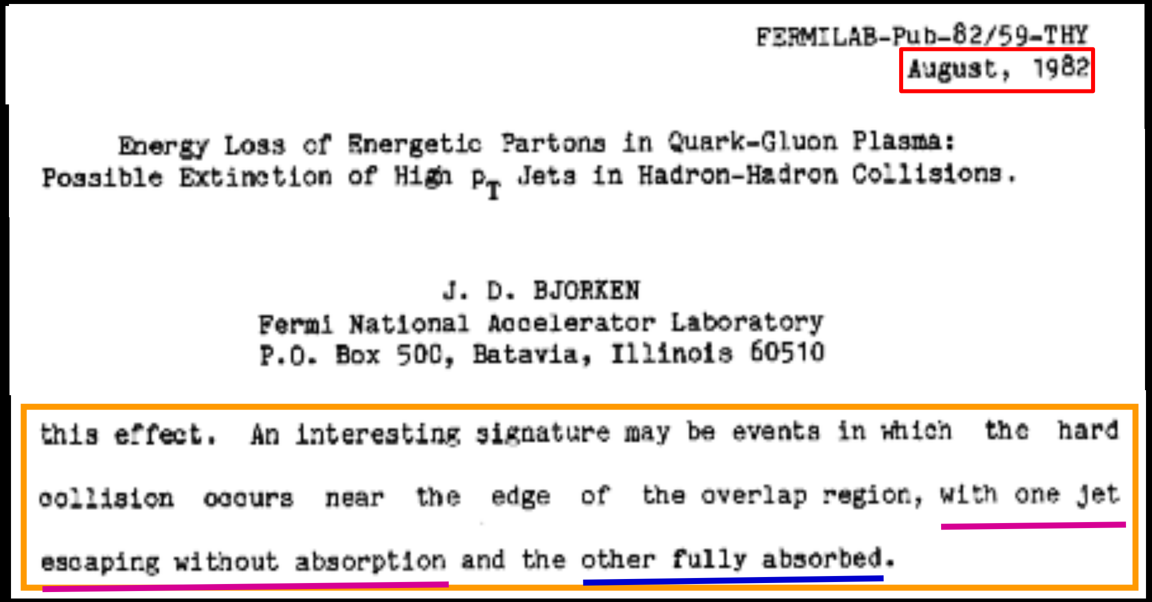
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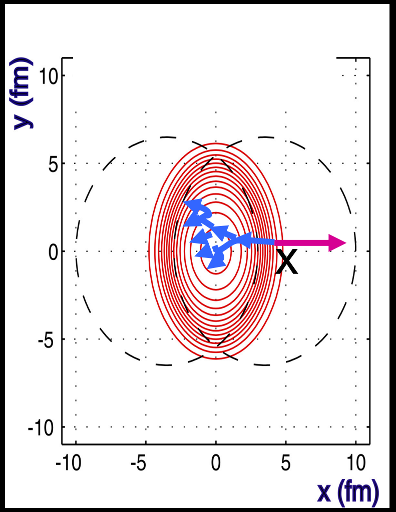
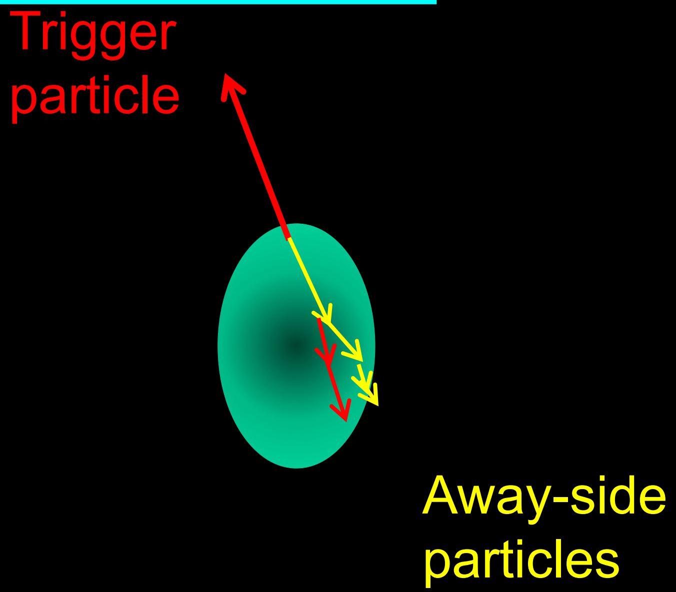
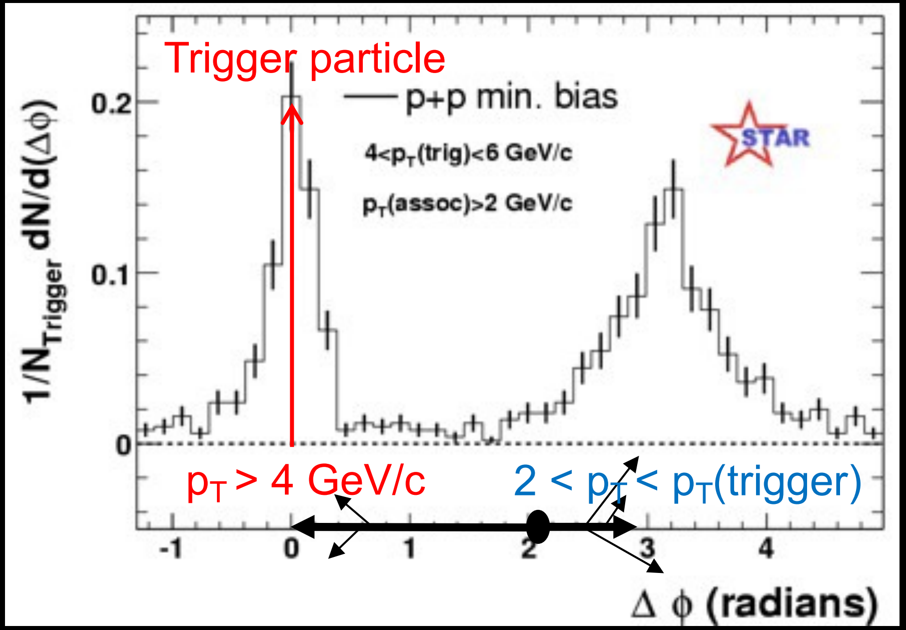




Back-to-back Jets   Away-side jets NOT quenched in pp collisions



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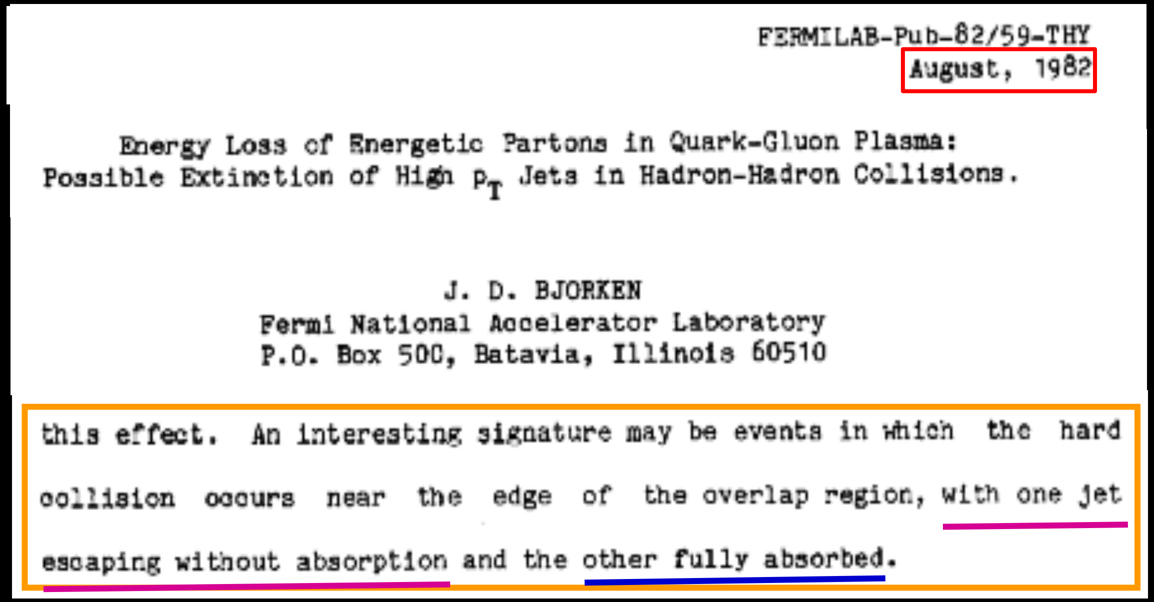
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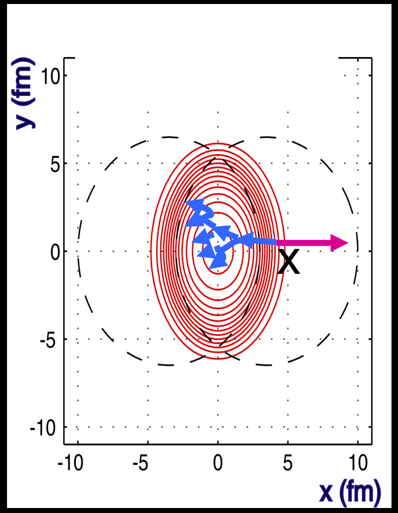
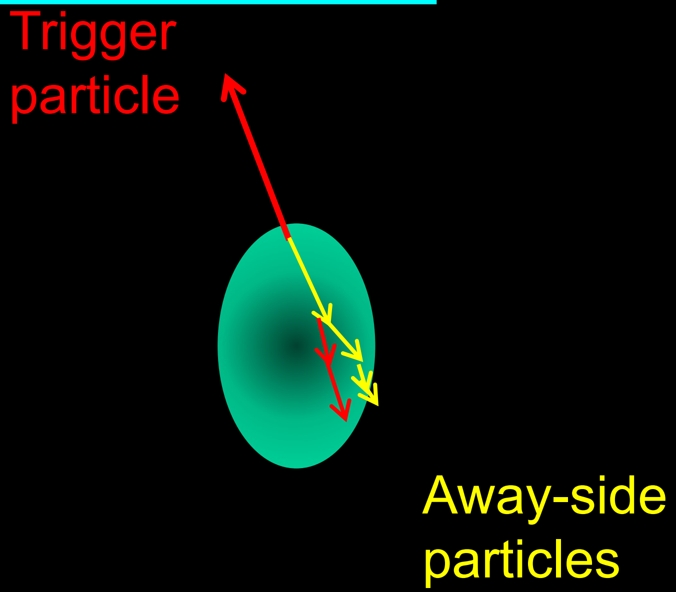




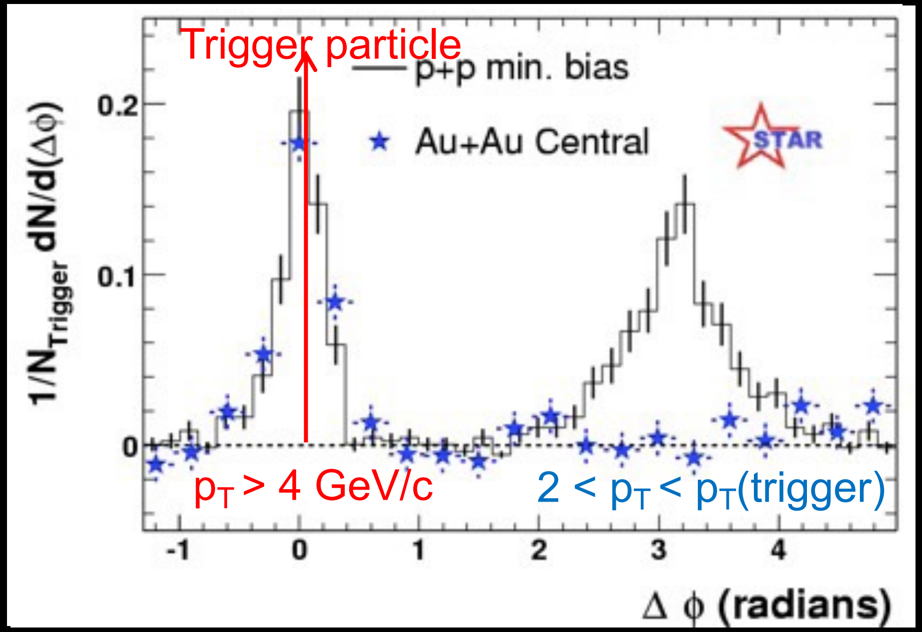
Back-to-back Jets Away-side jets NOT quenched in pp collisions

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

→ *trigger particle origin near surface*

→ strongly interacting medium

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



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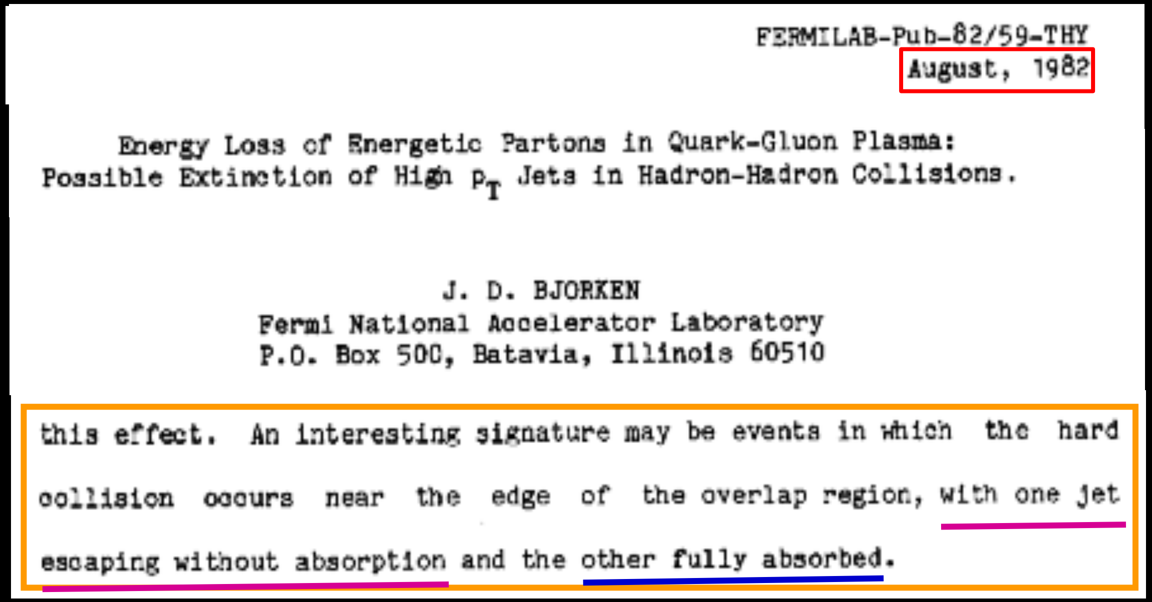

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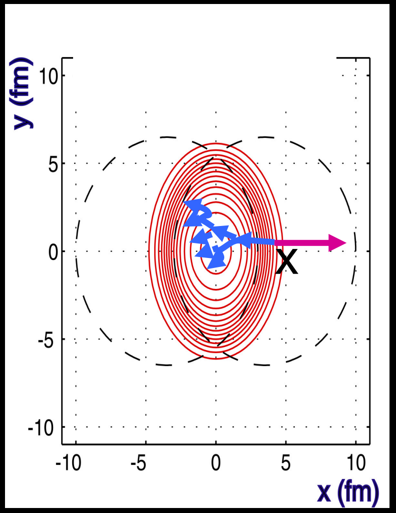
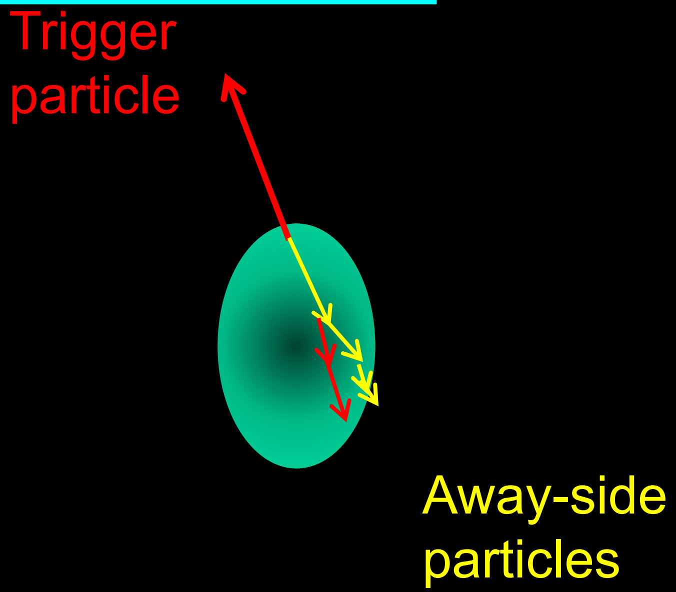




Back-to-back Jets Away-side jets NOT quenched in pp collisions

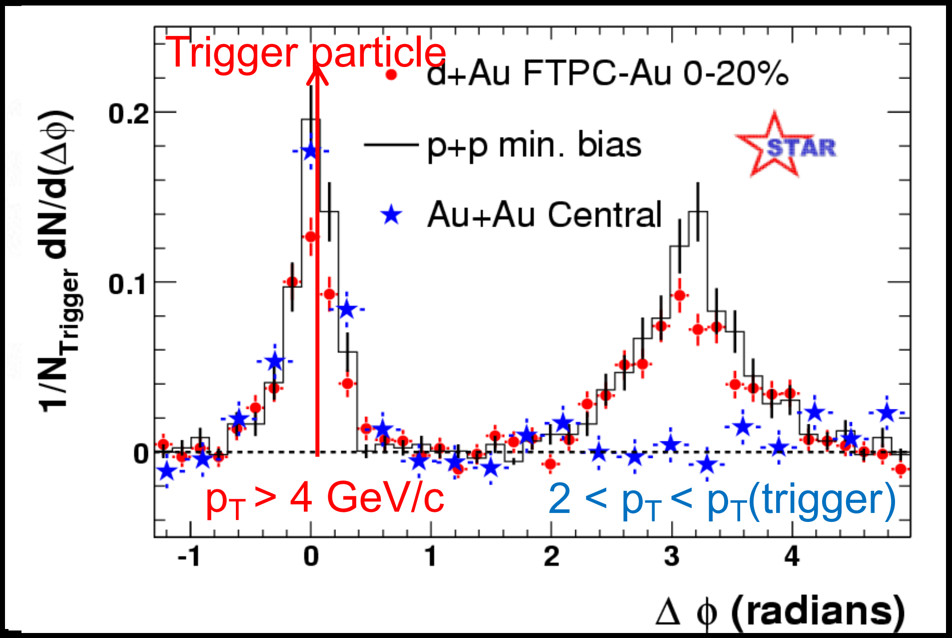
Back-to-back Jets Away-side jets observed as quenched in central Au + Au

Not quenched in Hi Mult d+Au

→ trigger particle origin near surface

→ strongly interacting medium

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



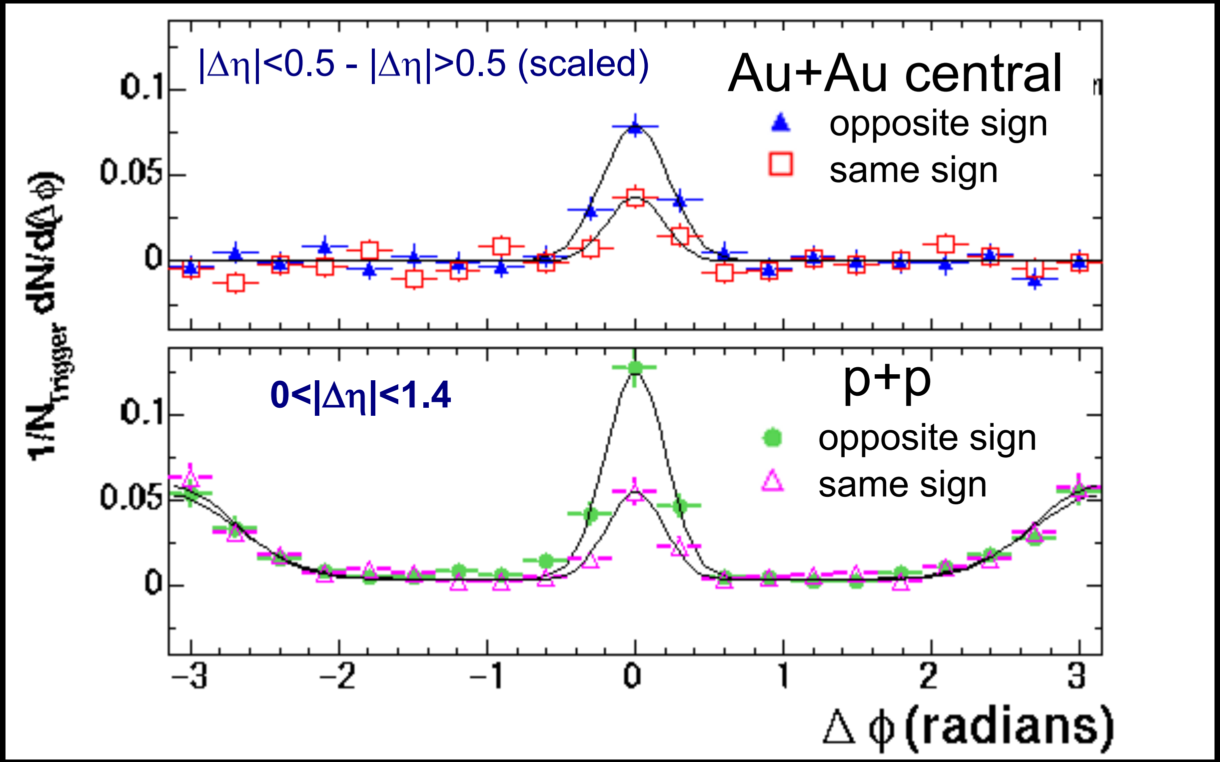
Quenching of Away-side "jet" is a final state effect

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

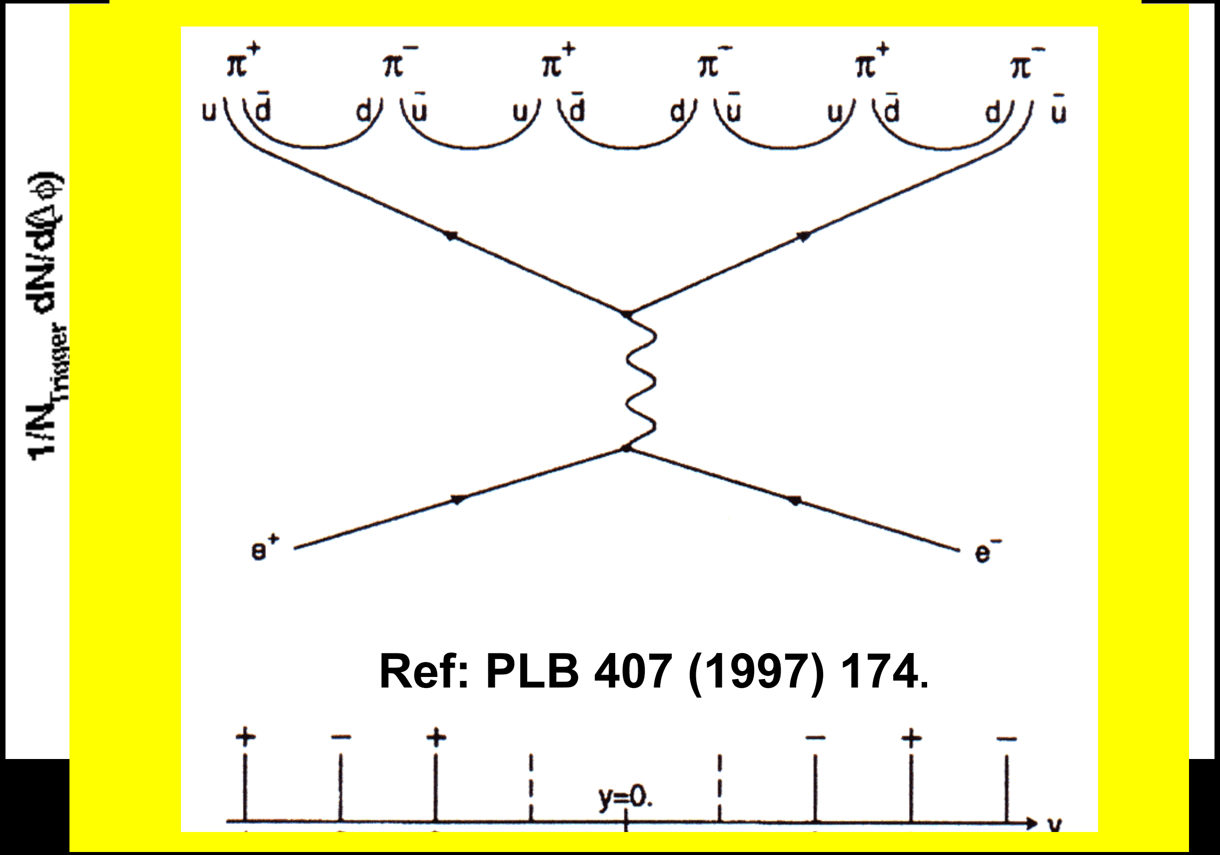
Relative Charge Dependence: 1st Jet Substructure Measurements!

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

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

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

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



Ref: PLB 407 (1997) 174.

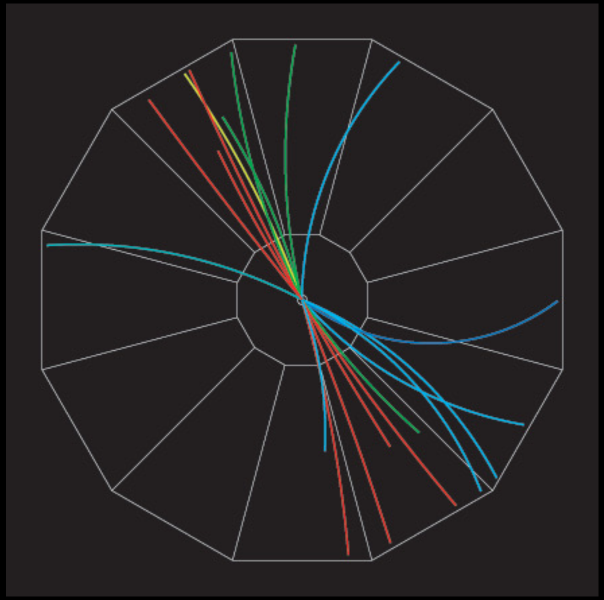
STAR, Phys. Rev. Lett. **90** (2003) 82302

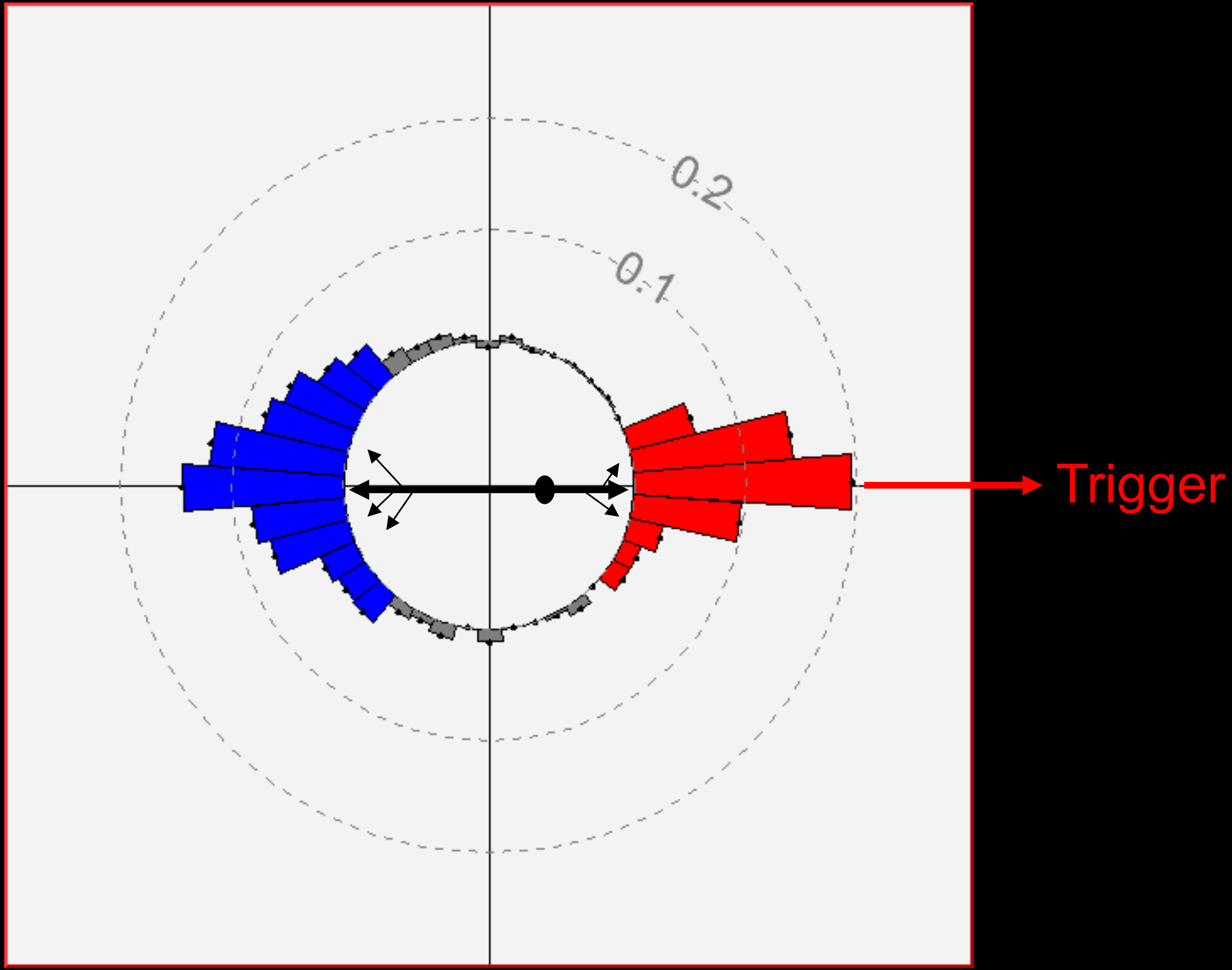
p_T > 4 GeV/c particle production mechanism (jets) same in central Au+Au & pp

Where Does the Energy Go?

Correlations in proton-proton reactions.

Strong back-to-back peaks.

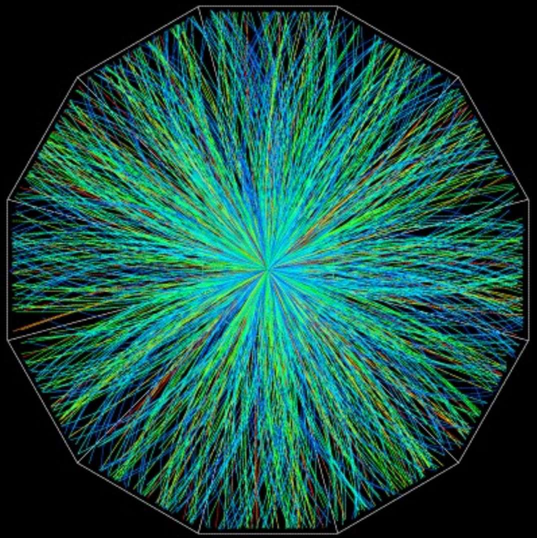


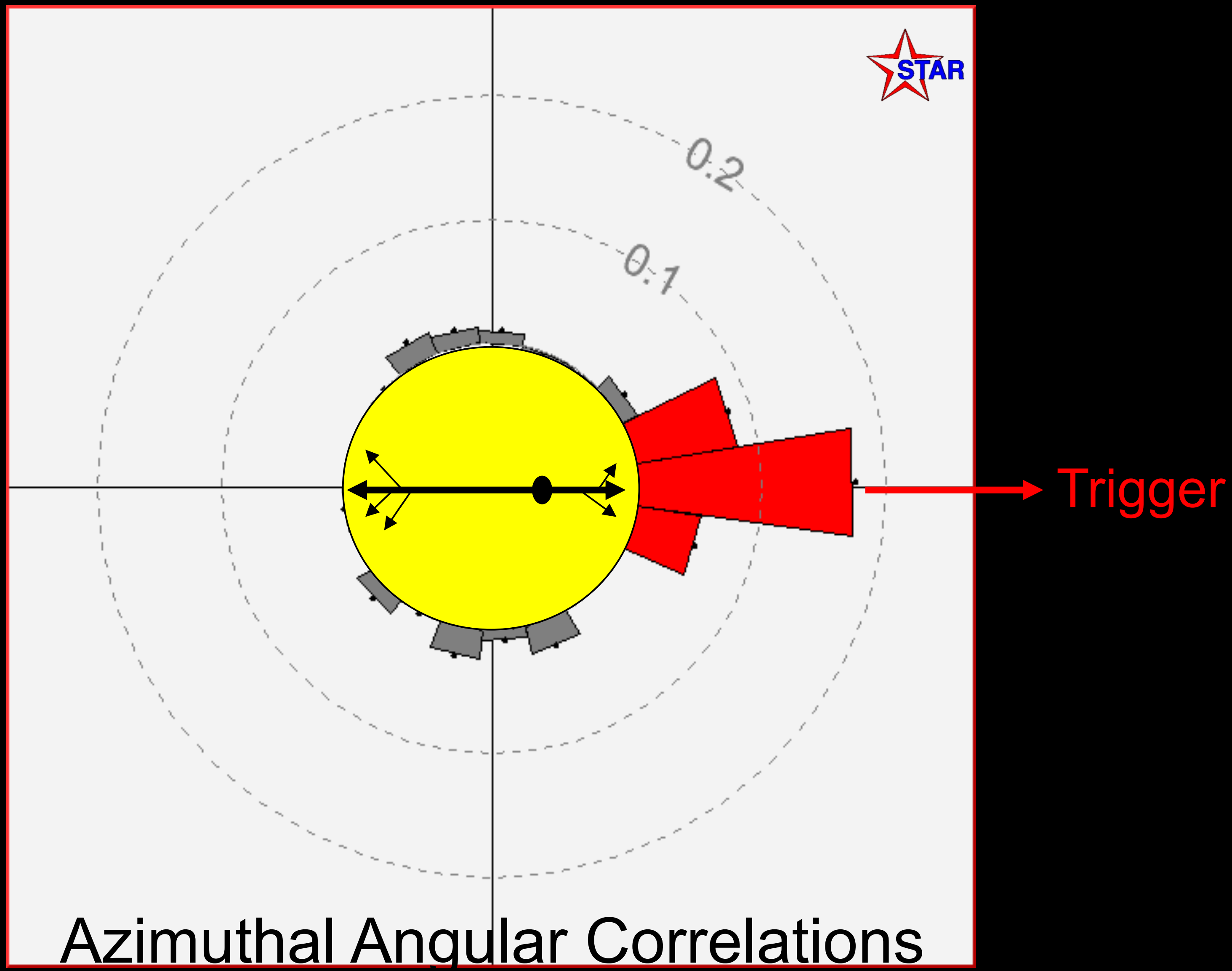


Where Does the Energy Go?

Jet correlations in central Gold-Gold.

Away side jet disappears for particles p_T > 2 GeV

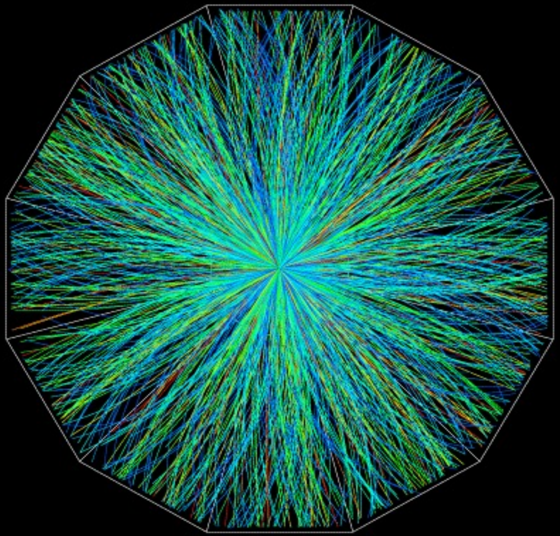


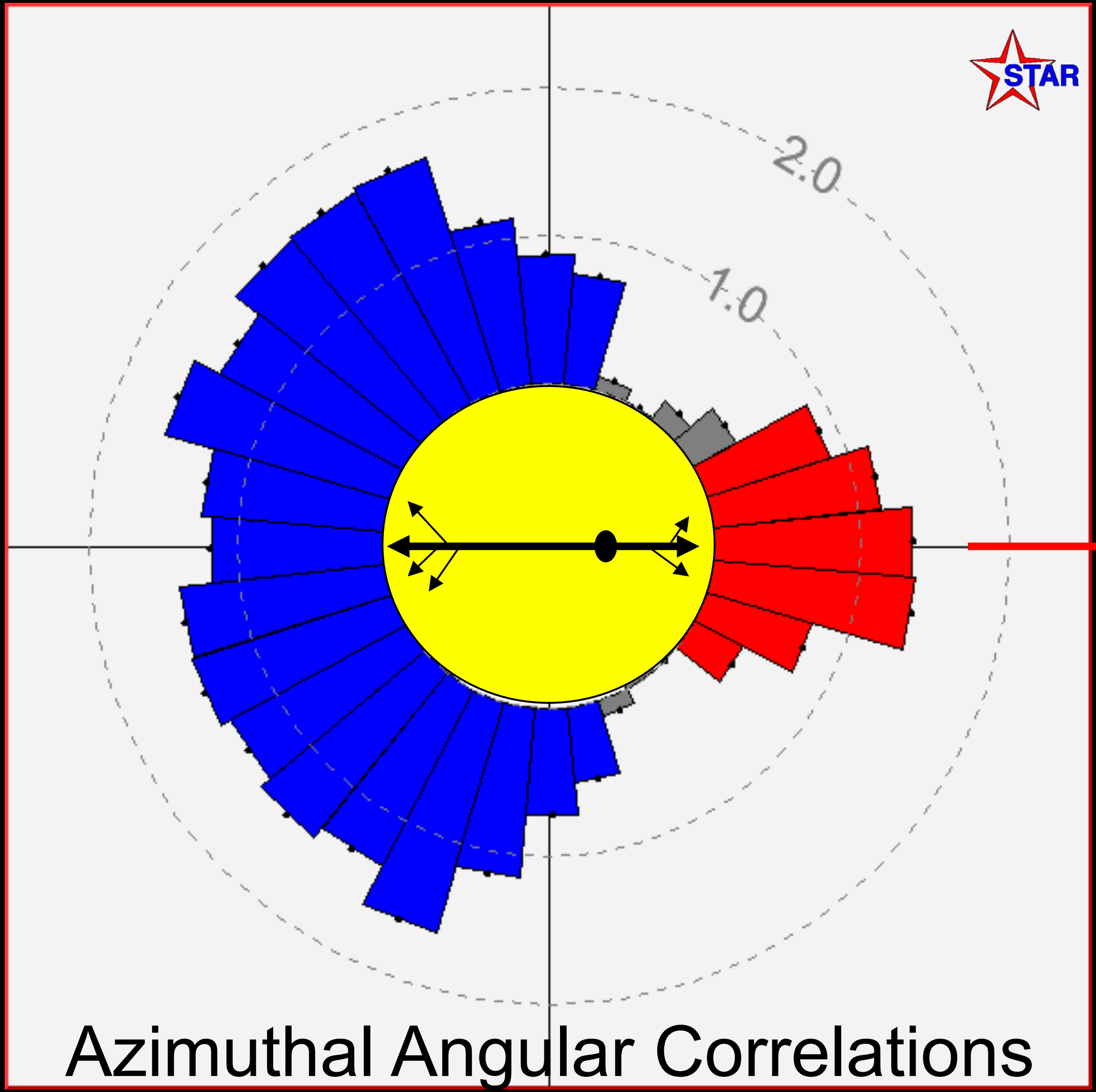


Where Does the Energy Go?

Jet correlations in central Gold-Gold.

Away side jet reappears in particles $p_T > 200$ MeV





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

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

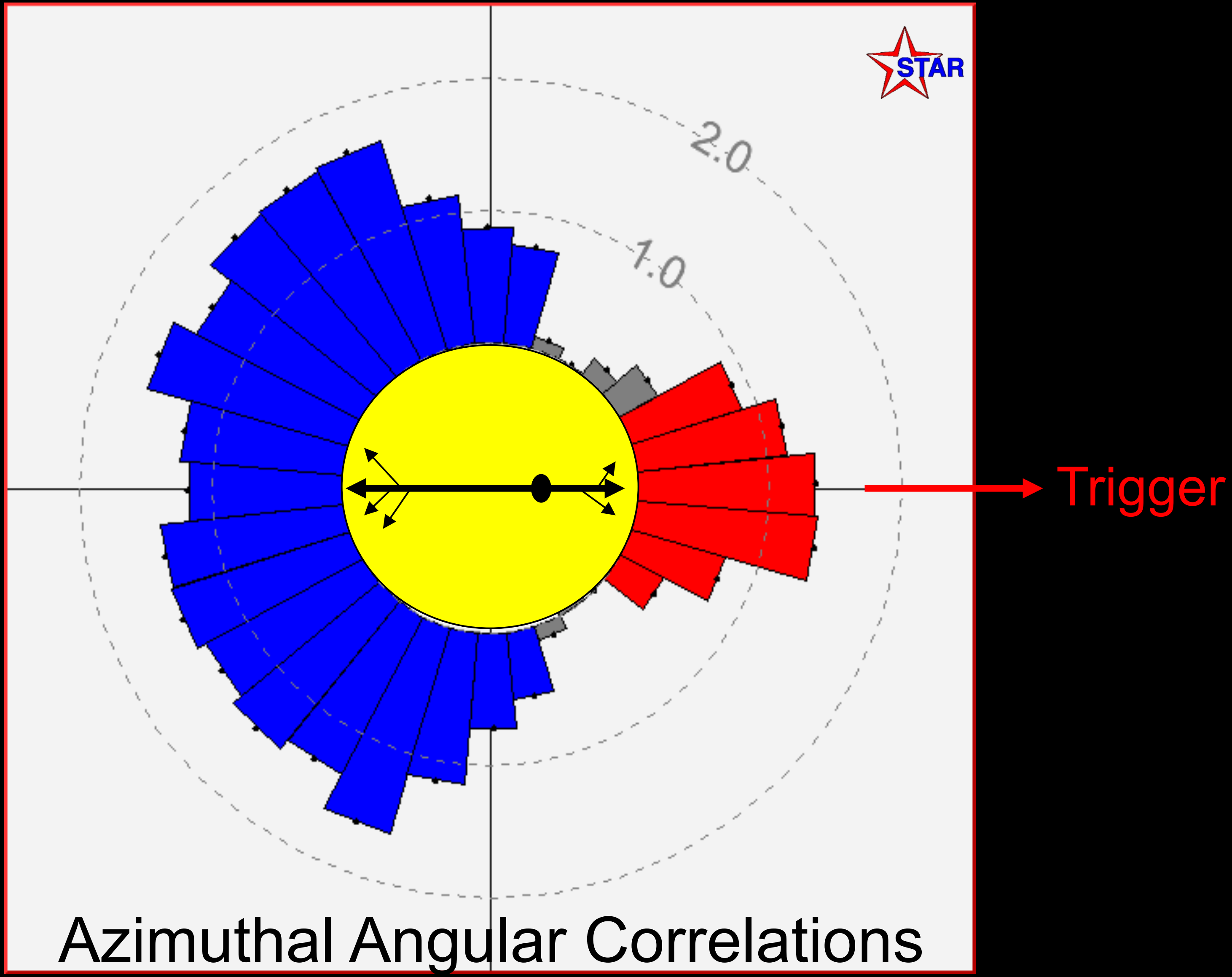
Medium-induced gluon radiation?

Polosa, C. Salgado

Many more

……..

….

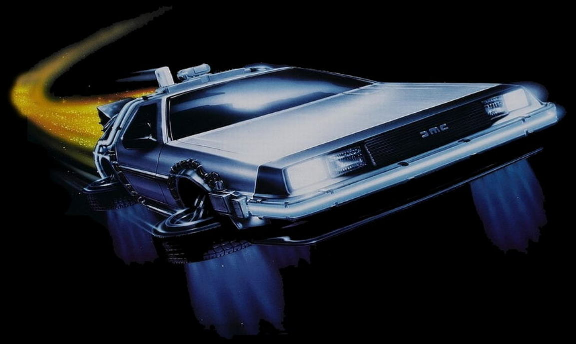


Lost energy of away-side jet is redistributed to rather large angles!

★ 2

Let's Get "Back to the Future" –

Consider High p_T Single Particles

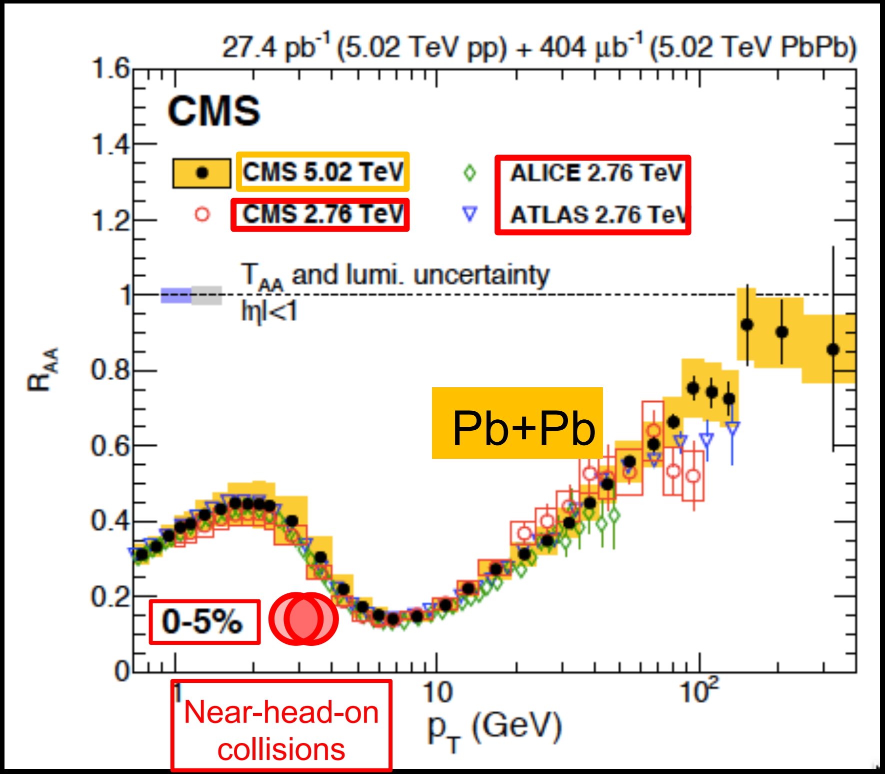


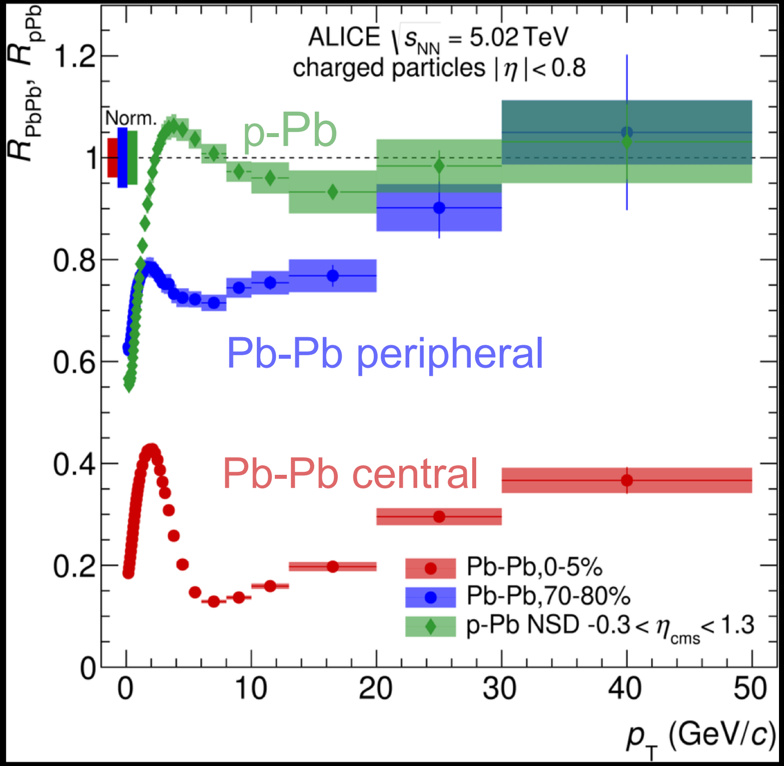
High p_T Charged Hadrons Are Suppressed at LHC!

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

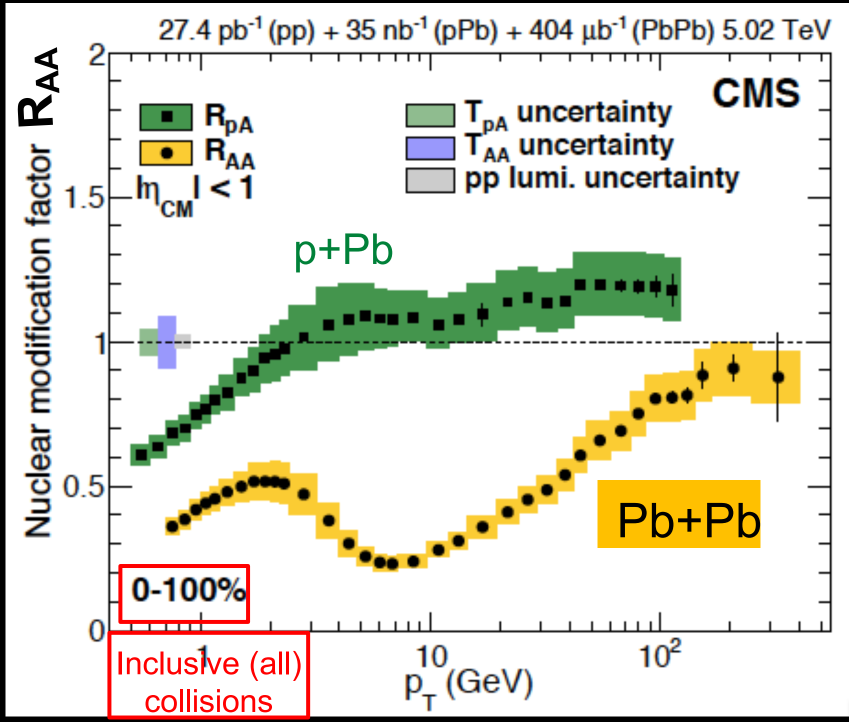
$R_{AA} < 1$ Suppression wrt pp

$R_{pPb} \sim 1$ similar to pp





ALICE arXiv:2211.04384



CMS arXiv: 1611.01664

→ *Pb+Pb suppression similar at 2.76 and 5.02 TeV*

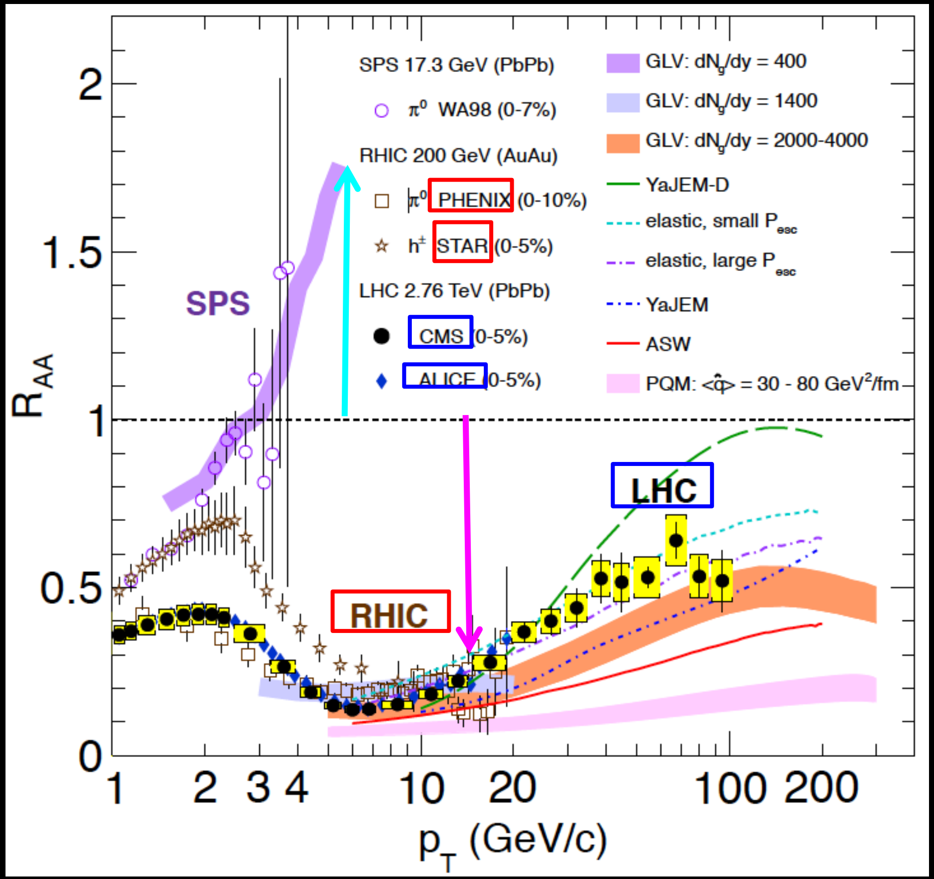
→ *nearly goes away at highest p_T*

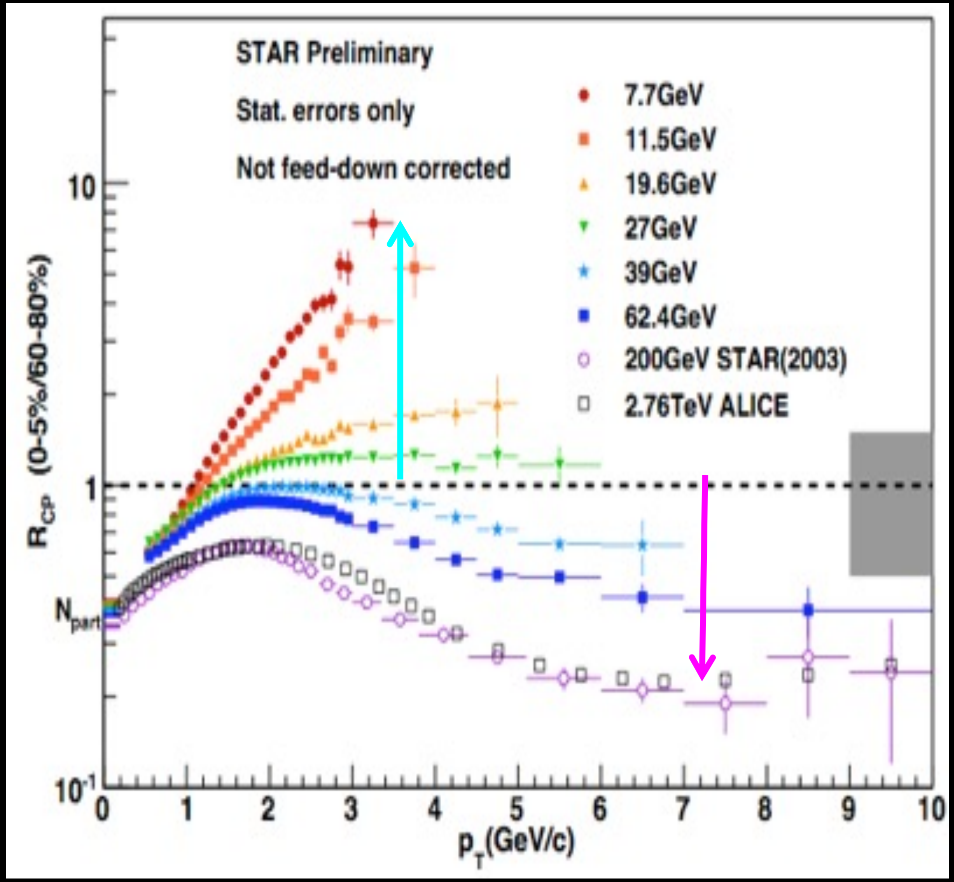
→ *No suppression in p+Pb*

→ *In Pb+Pb suppression increases with system size*

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

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





STAR, PoS CPOD2013, 002 (2013)

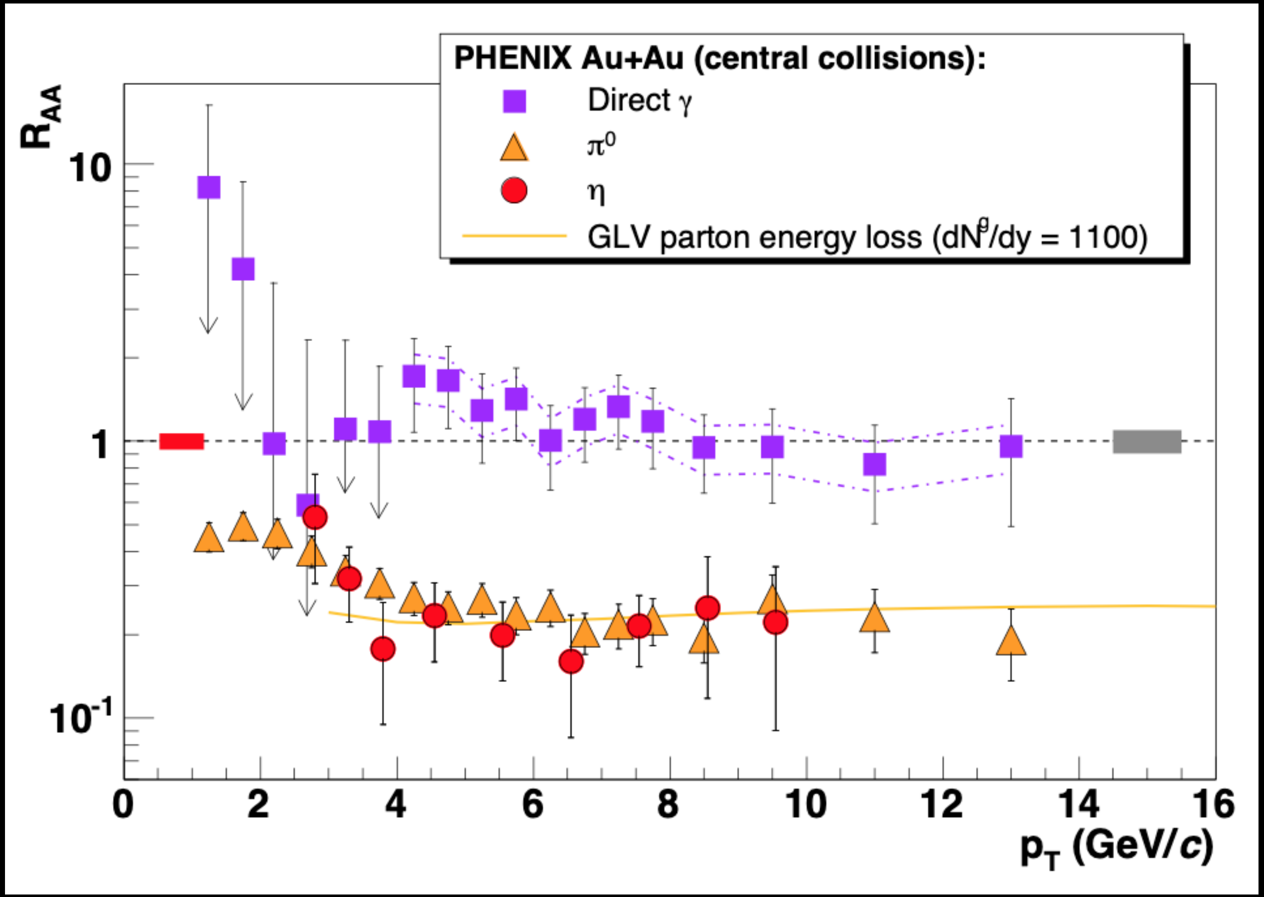
$$R_{AA} = \frac{N_{AA}^{particle}}{N_{coll} N_{pp}^{particle}}$$

Enhancement at lowest energies
→ collective transverse flow
(dominates below ~ 27 GeV)

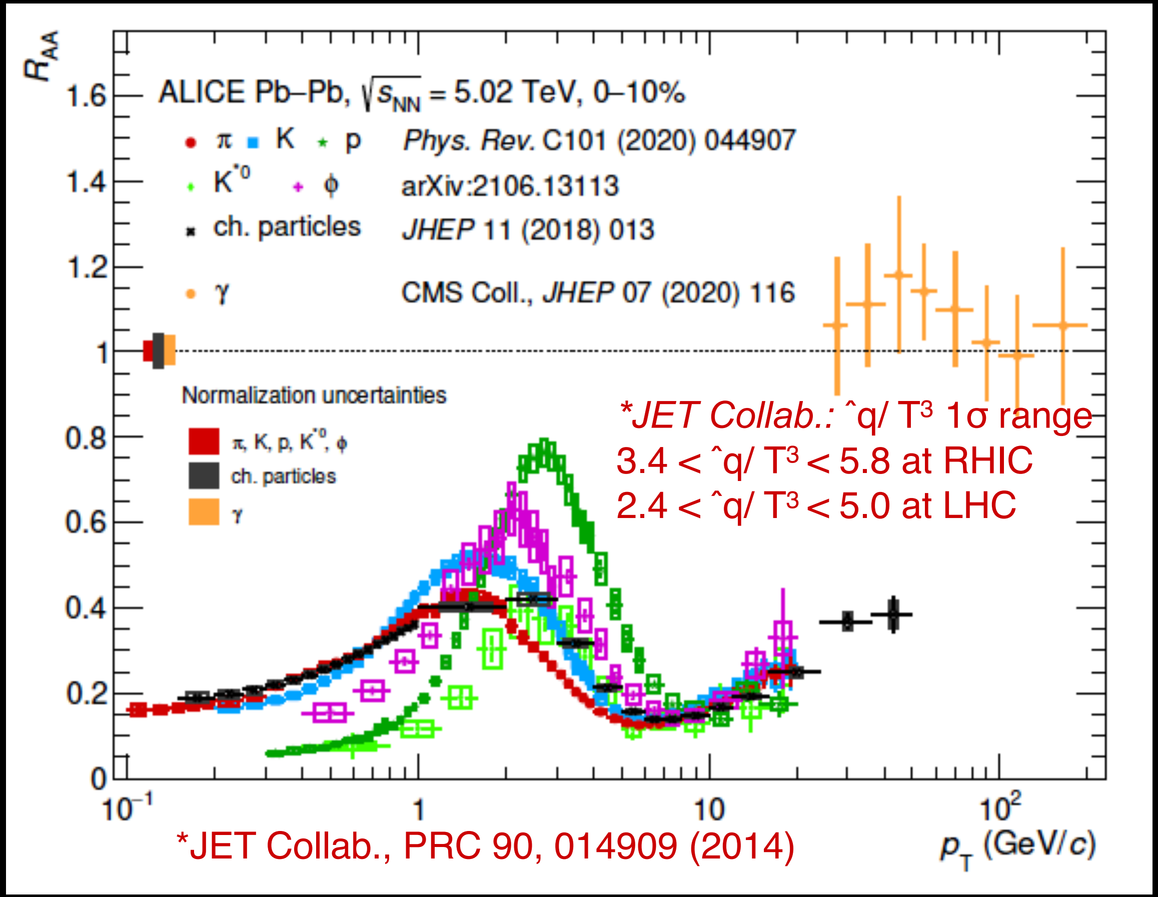
$R_{CP} = N_{central}/N_{peripheral}$

$\rightarrow R_{AA}$

PID – EM Probes Not Suppressed! ..&.. R_{AA} Particle Differences!



PHENIX PRL 96 (2006), 202301



ALICE arXiv:2211.04384

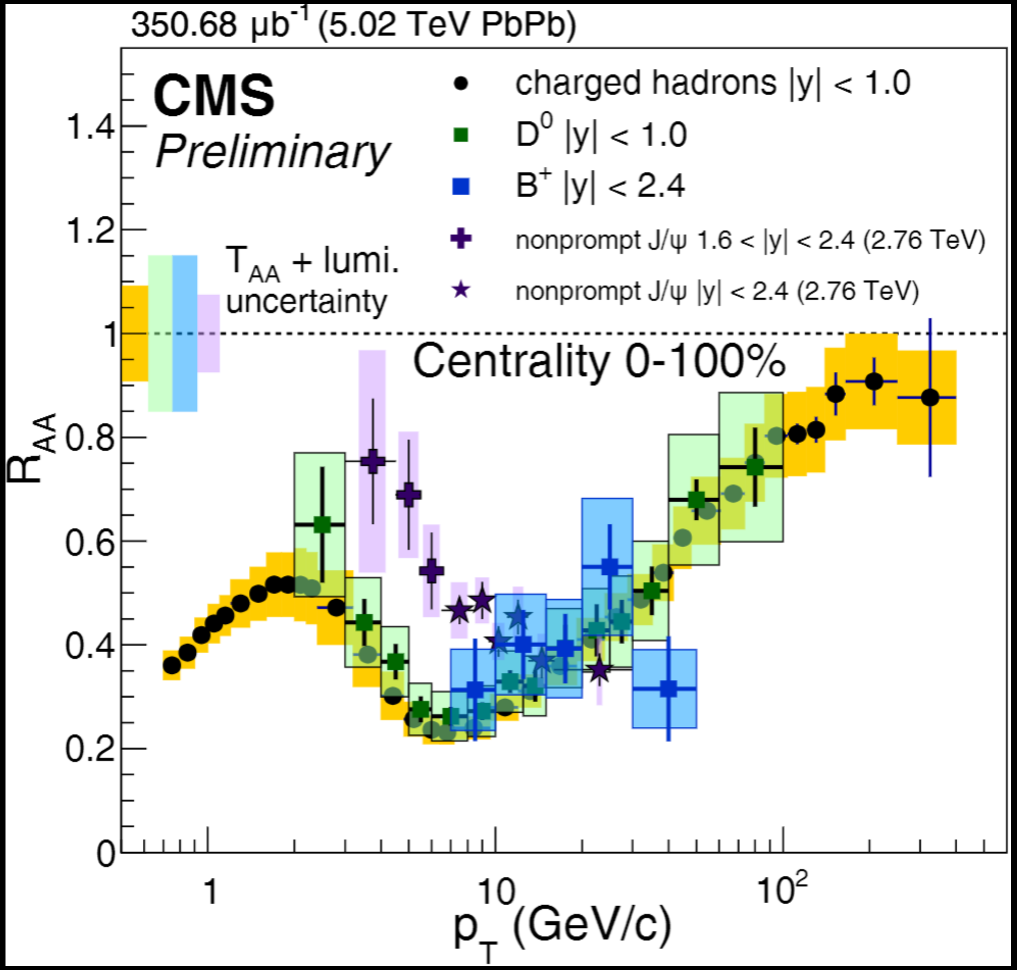
→ *EM probes unaffected at RHIC & LHC*
[Hadron suppression a final state effect!]

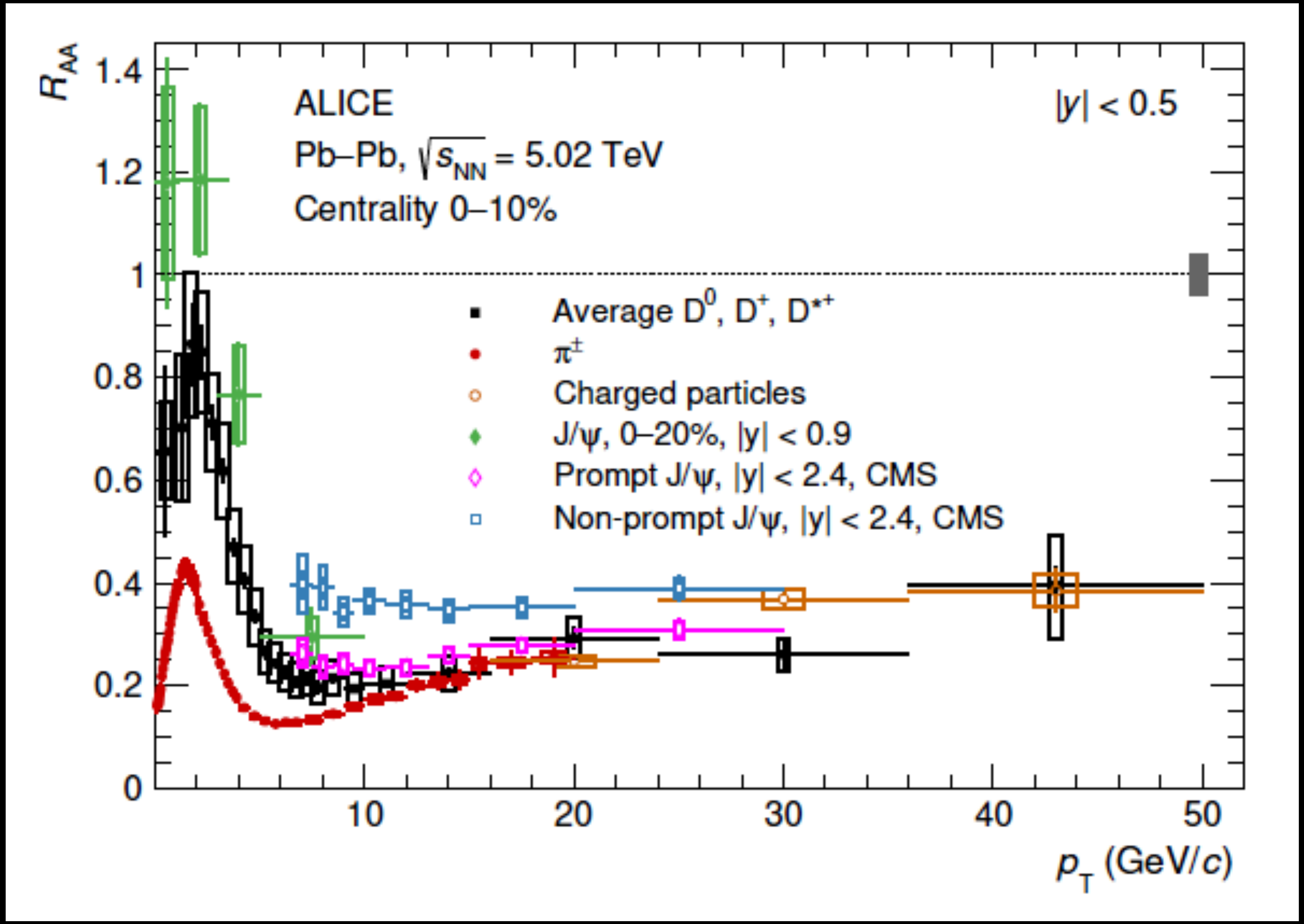
→ *LHC results extend to higher p_T*
→ *Particle-specific effects at low p_T*
[R_{AA} affected by collective flow & recombination]
→ *Universal behavior of "light" hadrons at high p_T*

3

Flavor Dependence

Flavor Dependence of Identified-Hadron Suppression





CMS, arXiv: 1611.01664,1610.00613

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

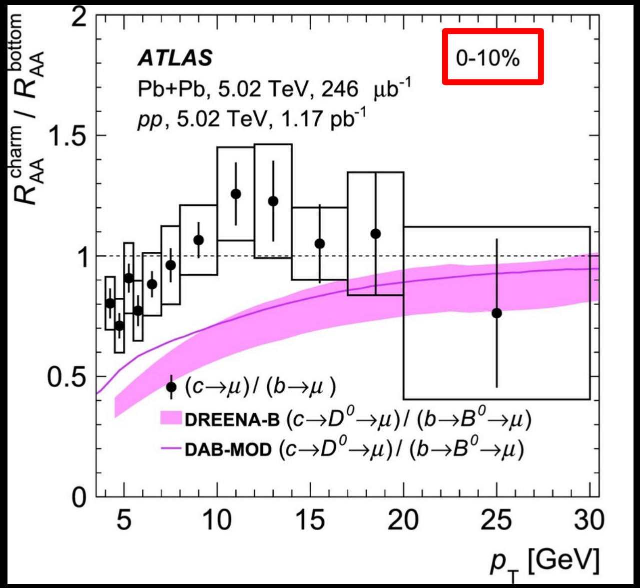
→ Flavor dependence seen in inclusive CMS data for p_T < 10 GeV/c

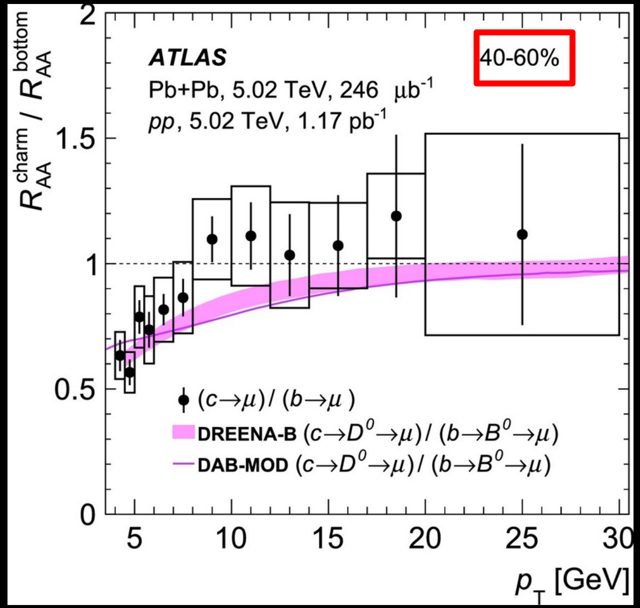
Enhanced suppression hierarchy (J/ψ, D, π) observed in 0-10% central collisions

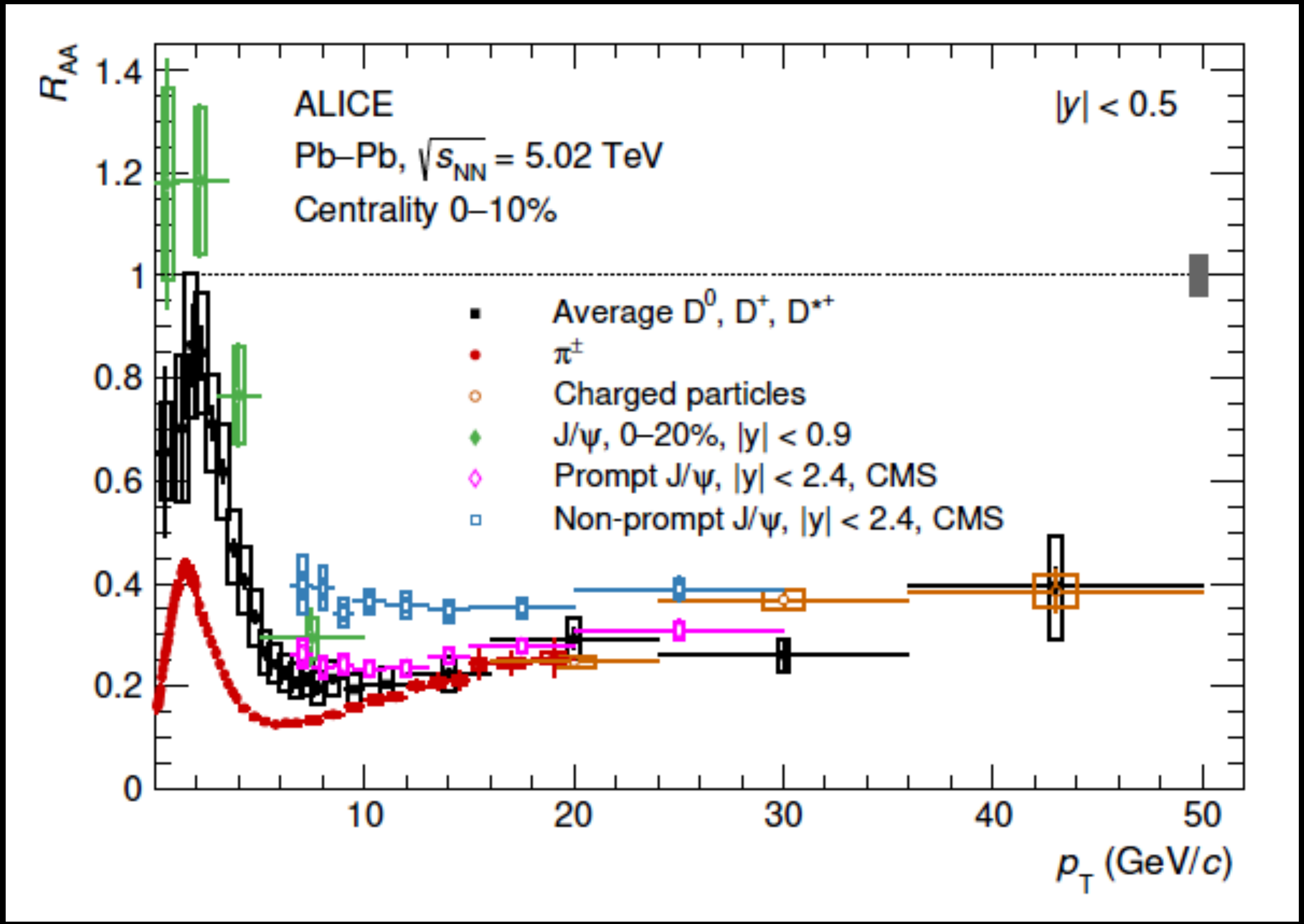
Flavor Dependence of Charm and Beauty (Centrality Selected)

Charm/bottom flavor dependence in 5.02 TeV data & Dreena

Dreena: D. Zigic et al., J. Phys. G 46, 085101 (2019)







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

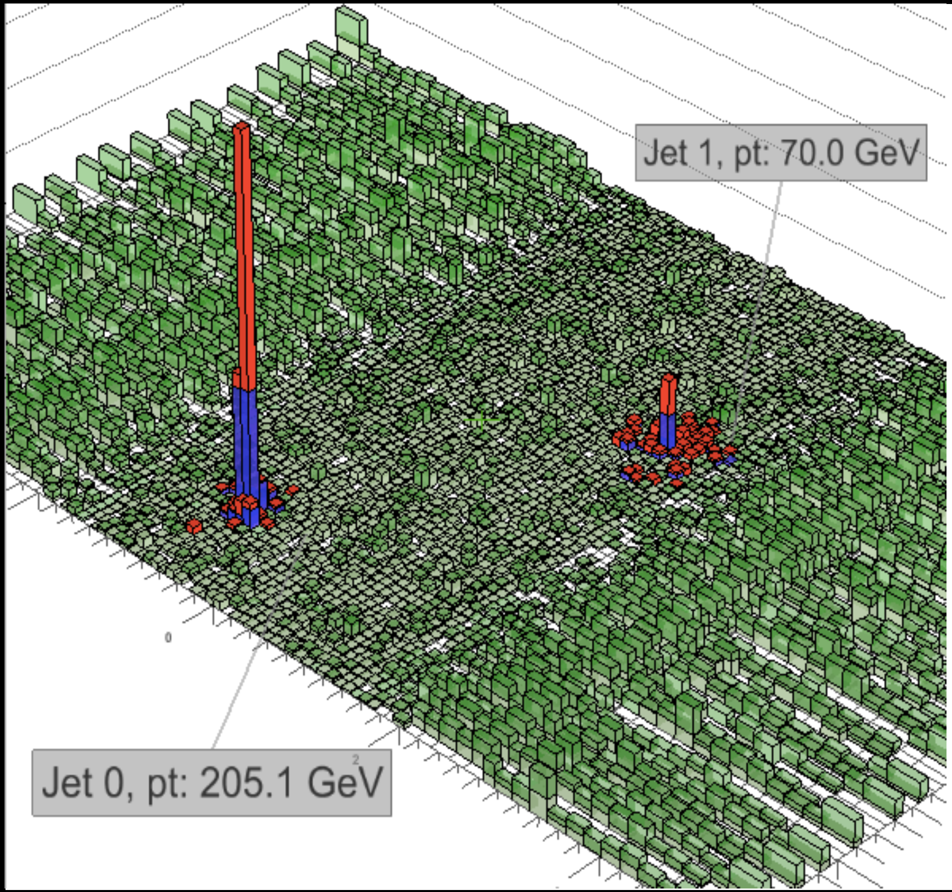
ALICE, arXiv:2211.04384 [nucl-ex] (2022)

★ 4 ***Jets***

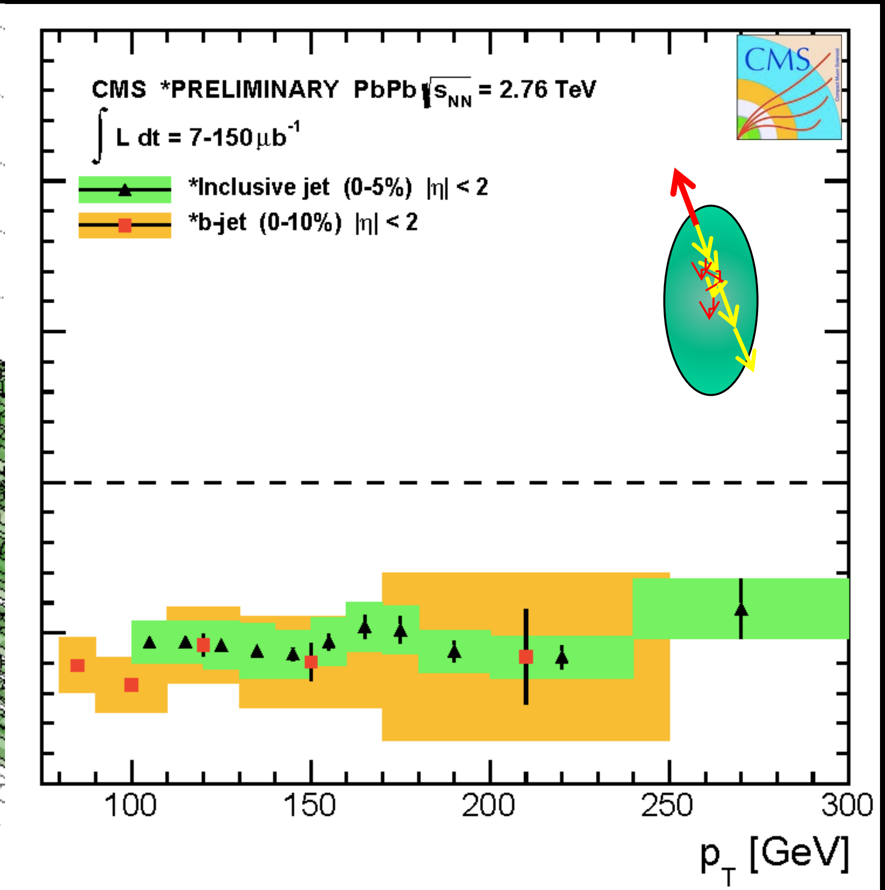
Jets Are Quenched to Highest p_T

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

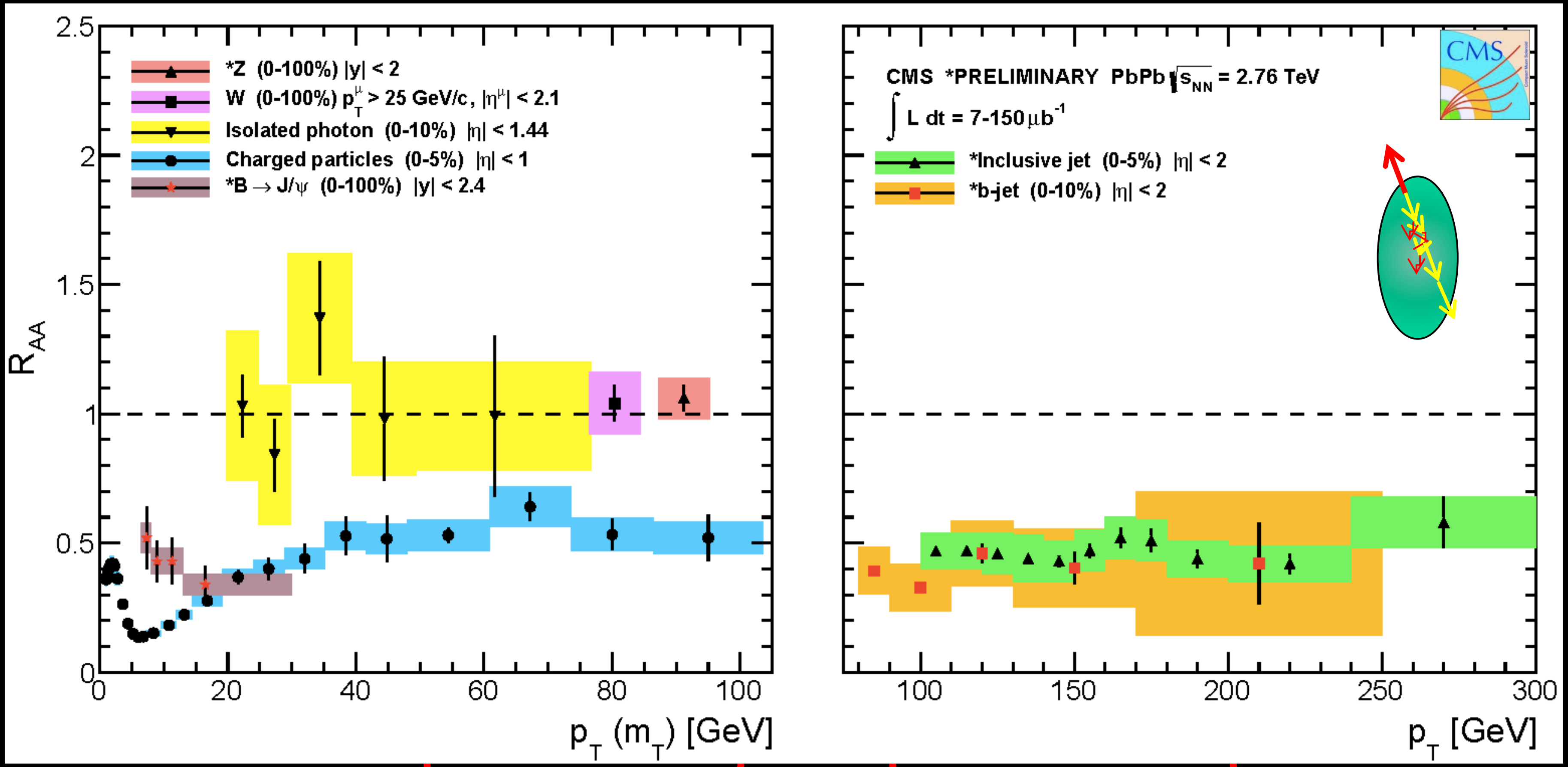
Is there a flavor independence at high p_T?

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

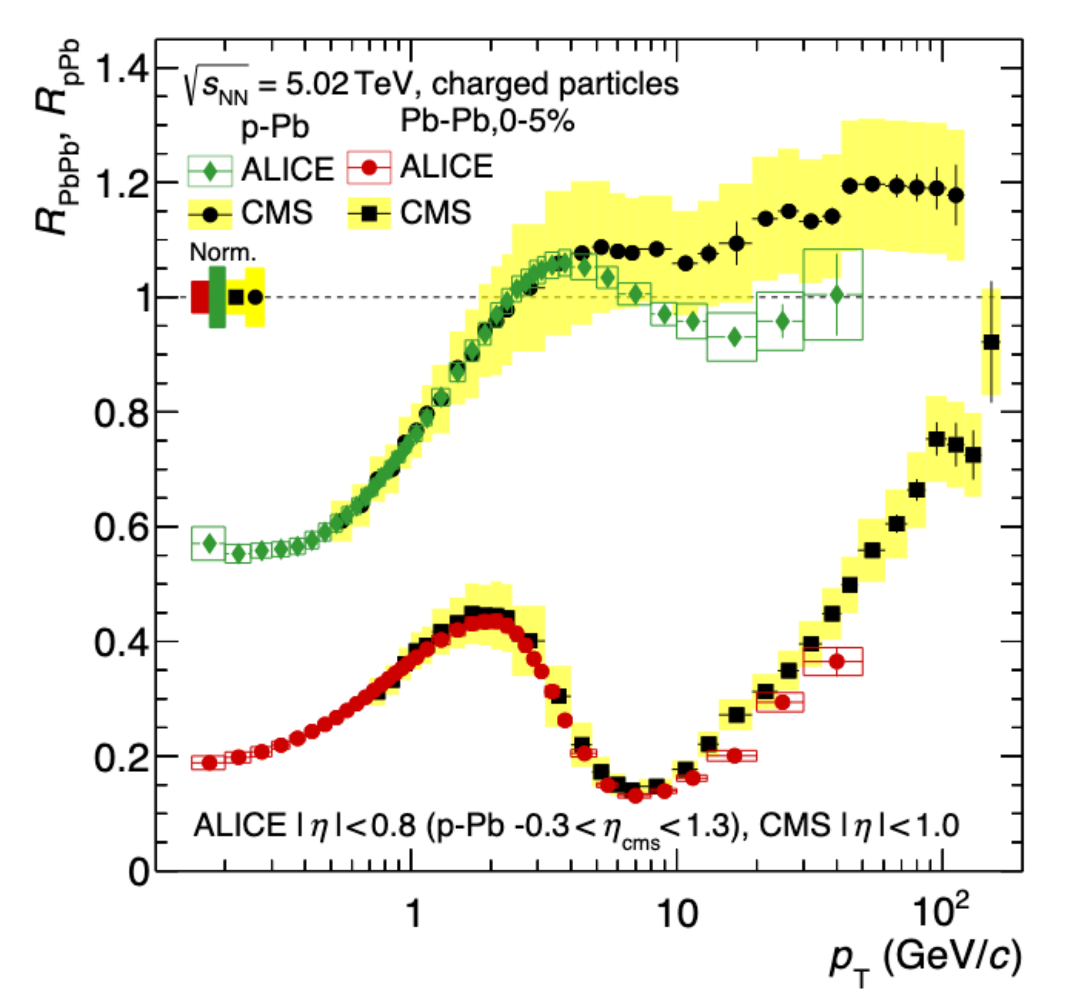


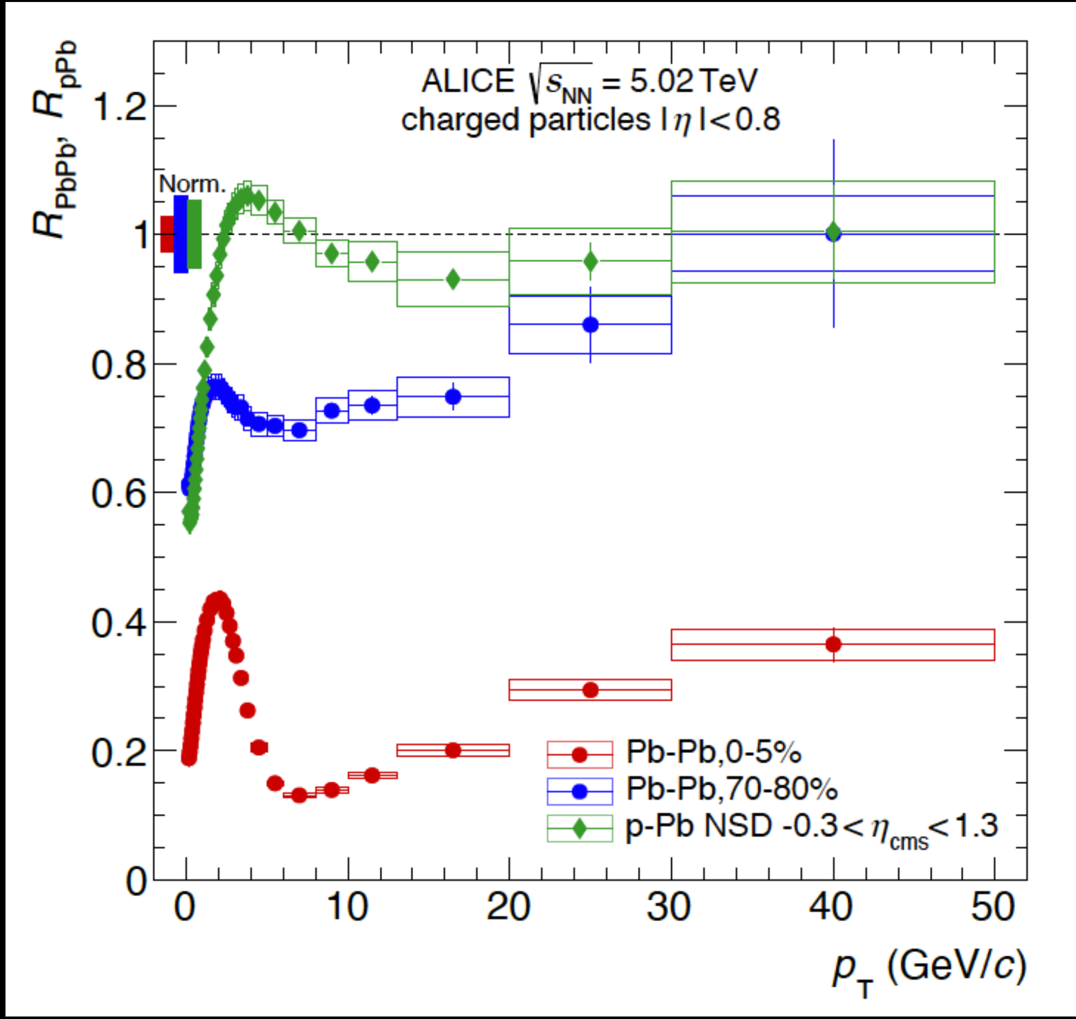
Same range of parton p_T

Jets quenched – to largest jet p_T

Is there a flavor independence at high p_T?

Jets in p-Pb & Pb-Pb at LHC



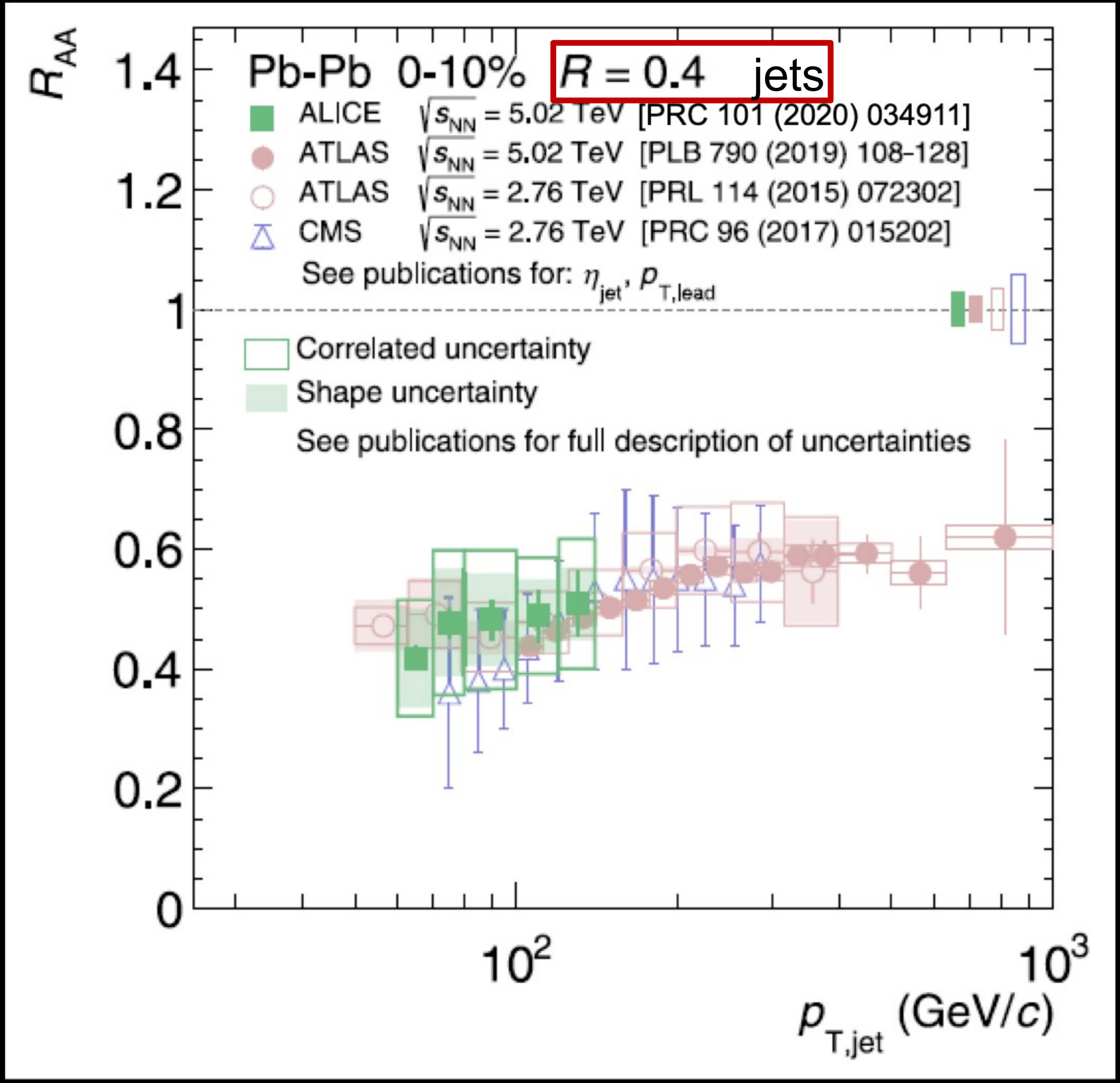


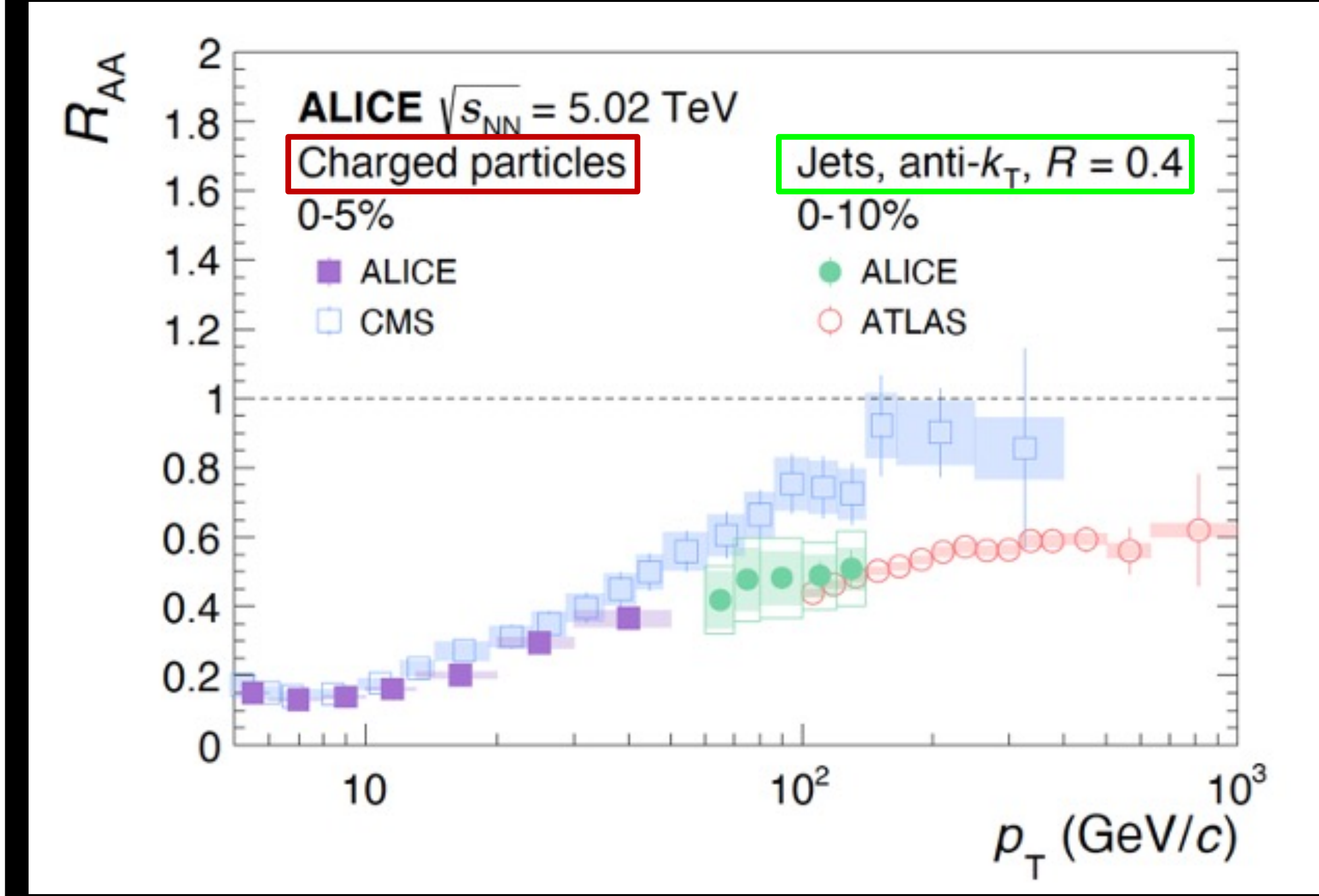
ALICE ≈ CMS: $R_{p\text{-}Pb}$ (jet) ≈ 1

$R_{Pb\text{-}Pb}$ (jet)<<1

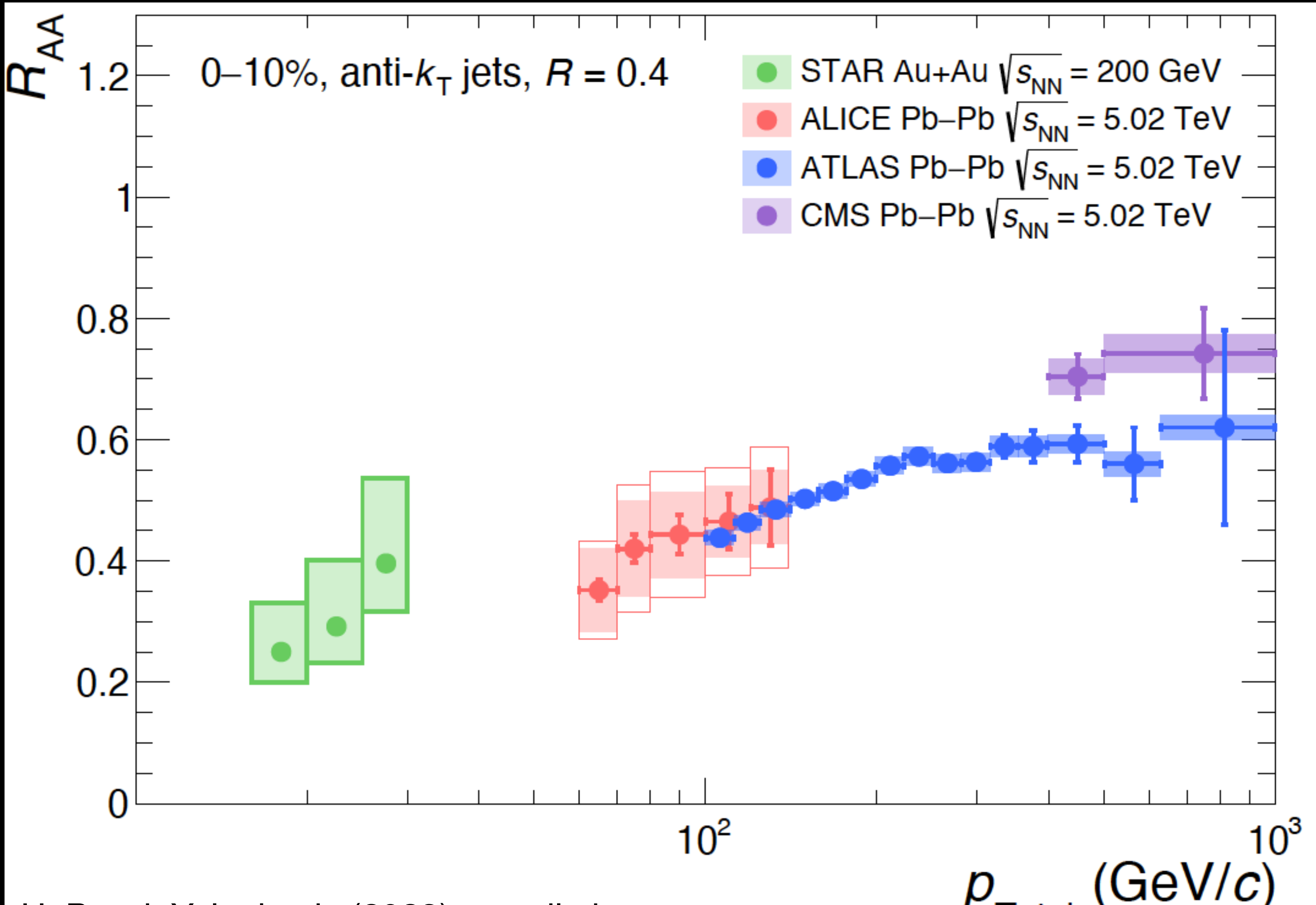
Jets quenching increases with centrality

Jets & High p_T Charged Particles Measured over Large p_T Range





Jets at RHIC and LHC Heavy-ion Collisions over Entire p_T Range



H. Bossi, Yale thesis (2023) compilation

Be aware of differences in jet measurements:

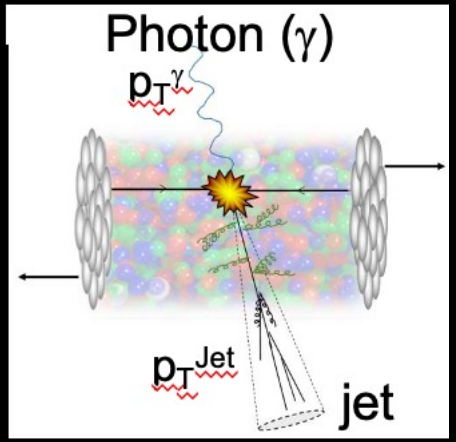
CMS and ATLAS – Calorimeters

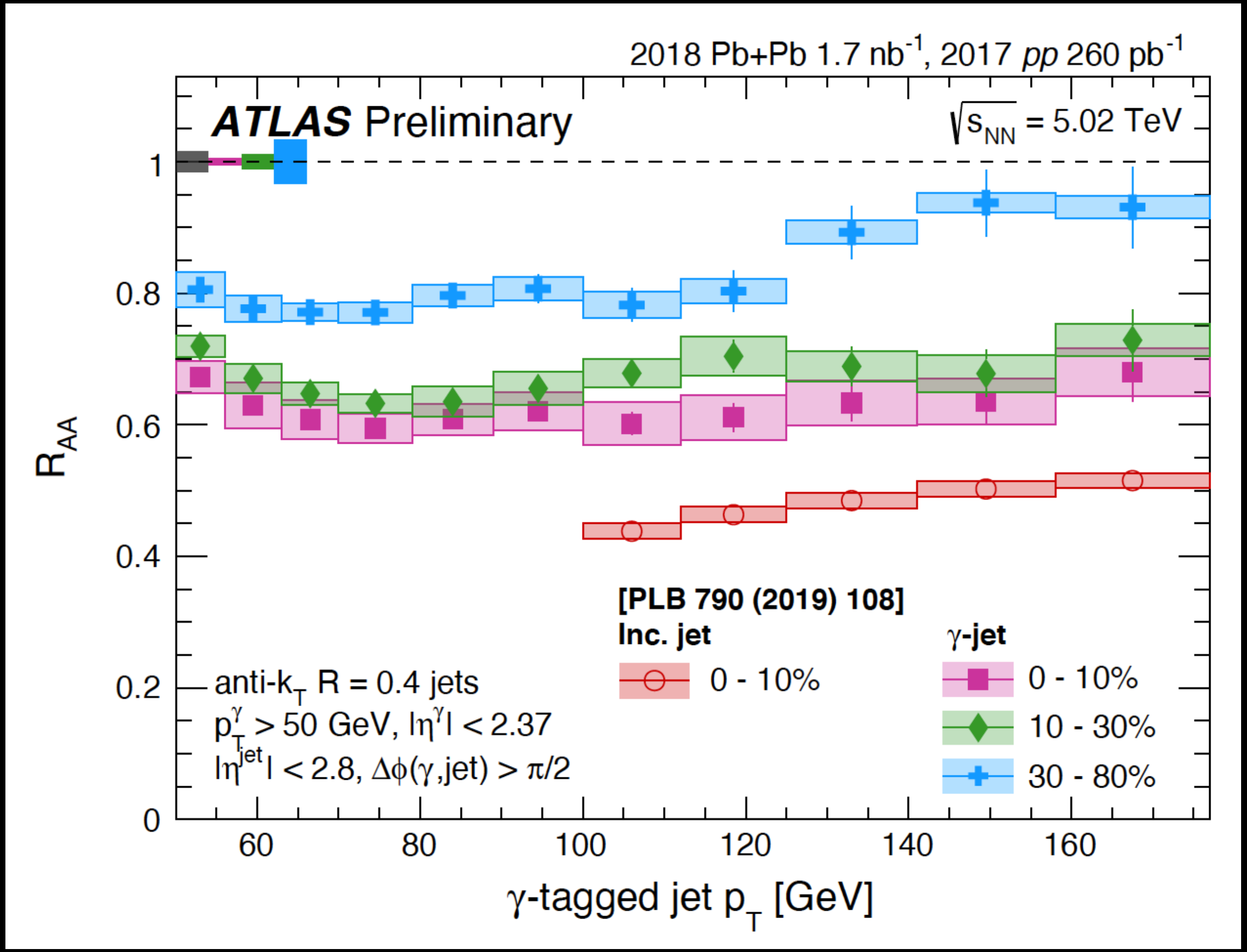
ALICE – EM Cal + charged particles

STAR – Charged particles

Jets: γ-tagged and inclusive jets

ATLAS-CONF-2022-019





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

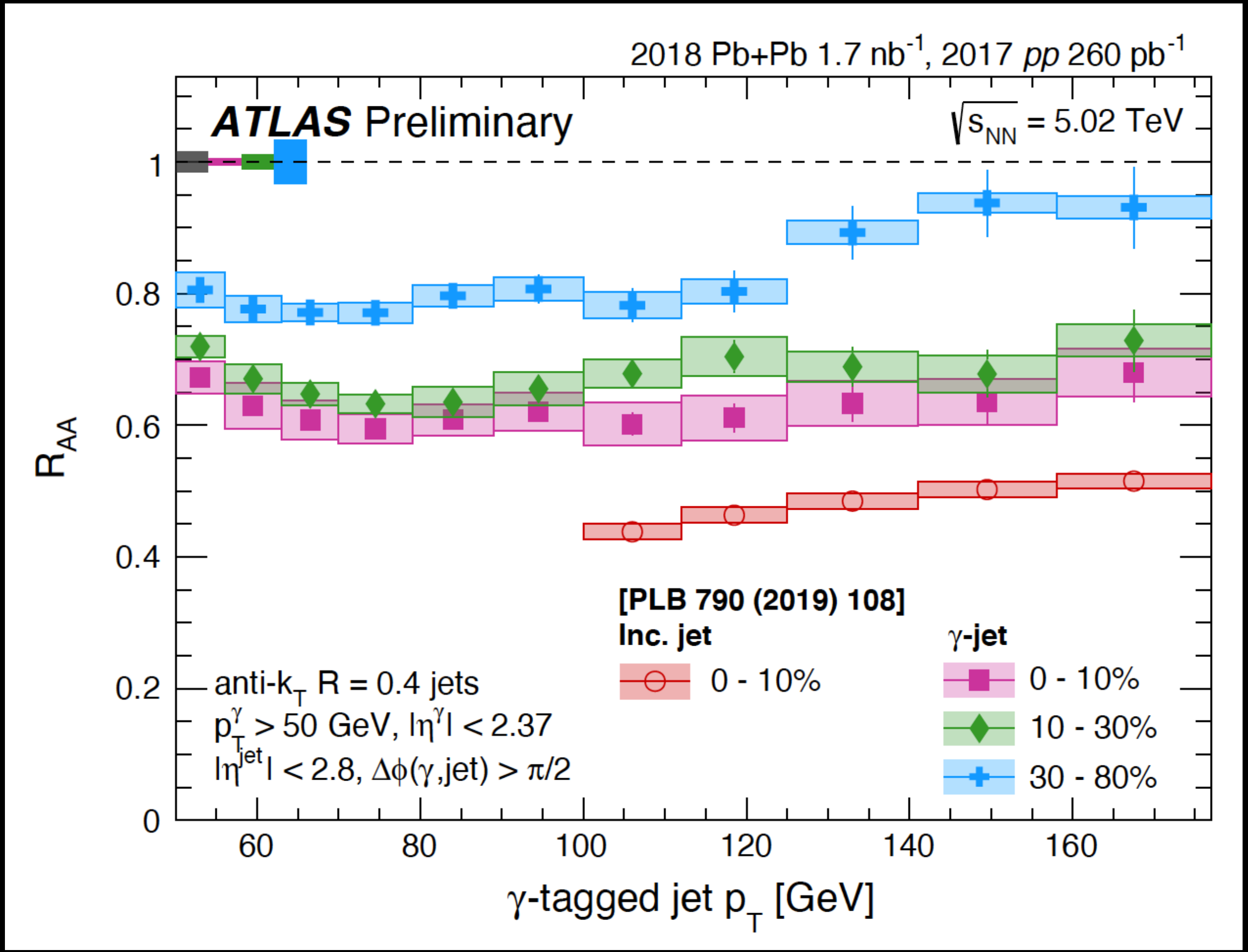
Gluons more suppressed than quarks - color factor!

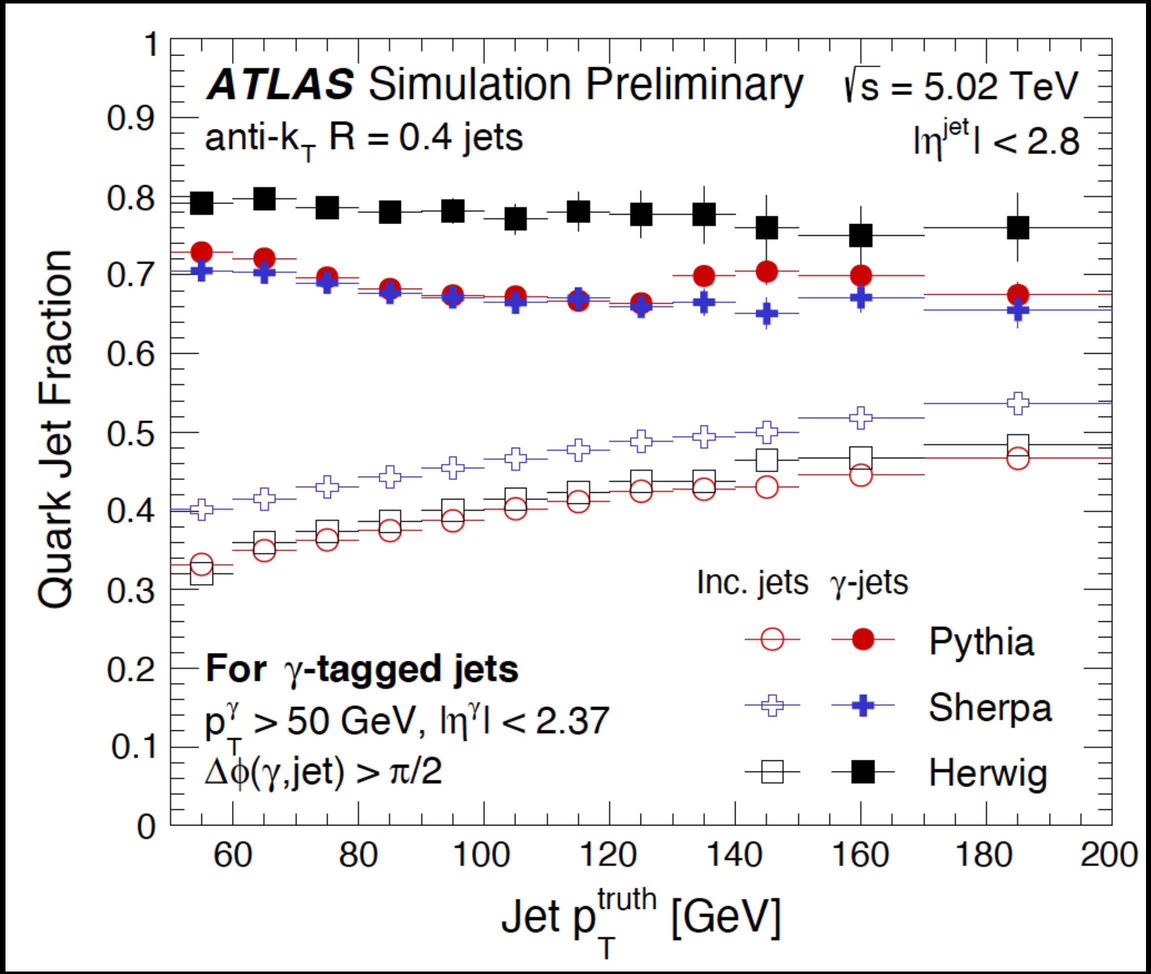
γ-tagged jet spectra harder than inclusive! -> larger R_{AA}

But check: Quark/gluon fractions!

Jets: γ-tagged and inclusive jets

ATLAS-CONF-2022-019





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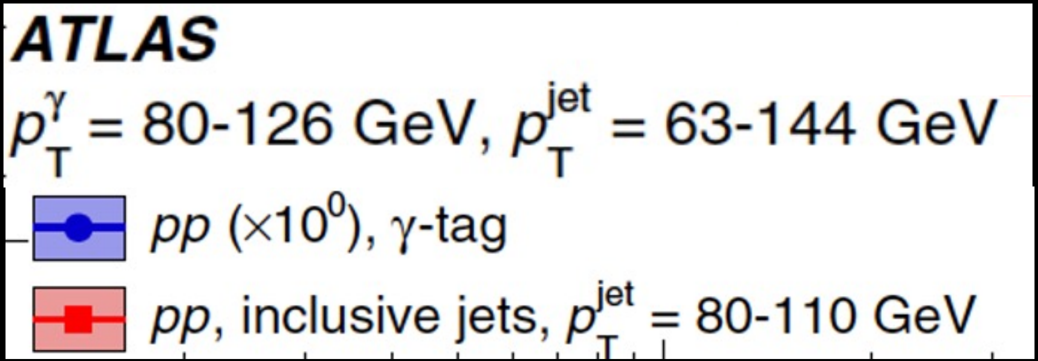
Gluons more suppressed than quarks - color factor!
γ-tagged jet spectra harder than inclusive! -> larger R_{AA}
But check: Quark/gluon fractions!

Quark Jet Fraction (γ-tagged jets) >> (inclusive jets)
More quarks in γ-tagged jets than inclusive jets

5

Jet Fragmentation and Jet Broadening

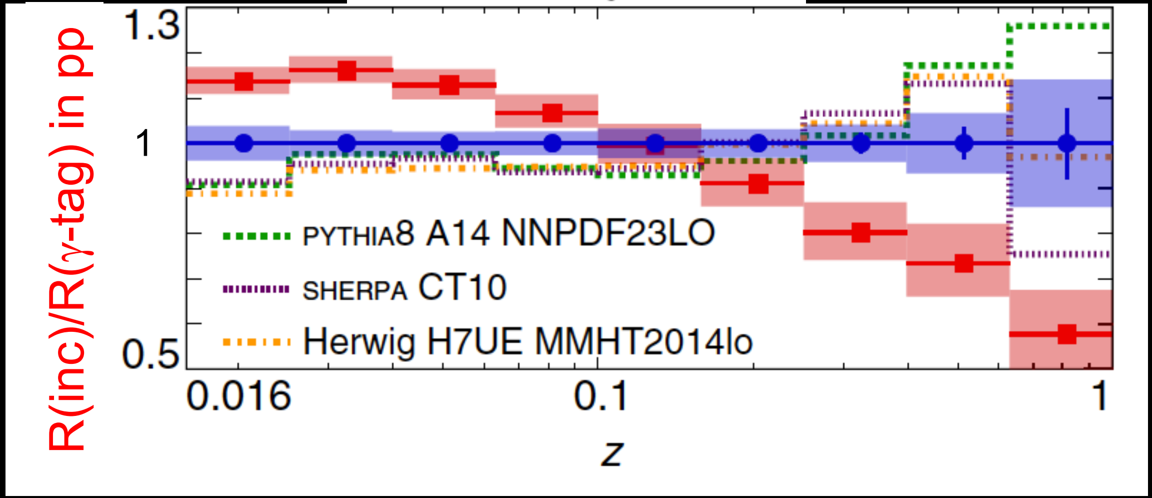
Fragmentation Functions in pp for γ-tagged vs Inclusive Jets



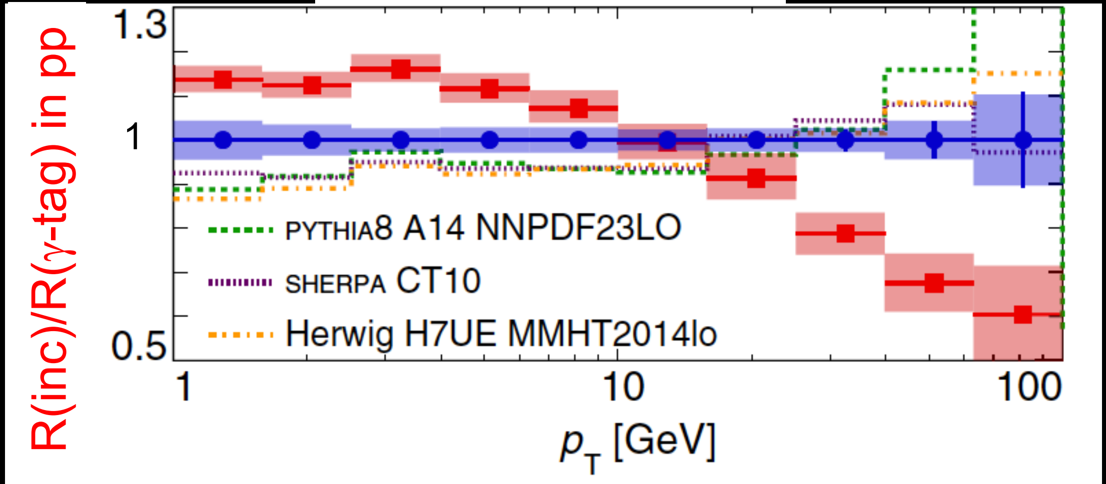
pp interactions:
R (inclusive jets) / (γ-tagged jets) < 1 at high z and p_T
R (inclusive jets) / (γ-tagged jets) > 1 at low z and p_T

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

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



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

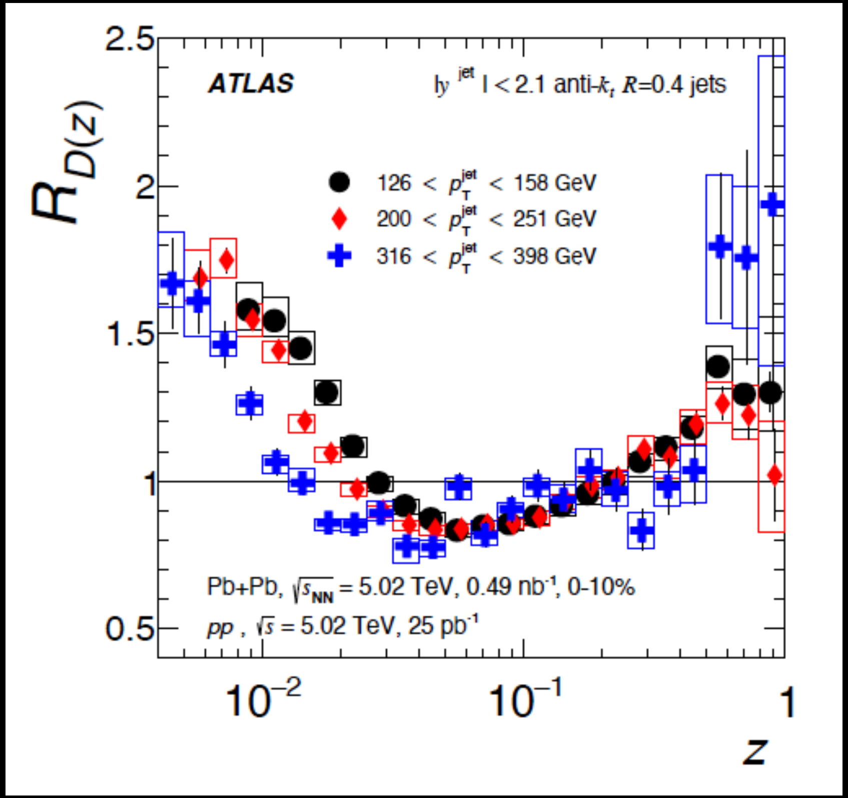


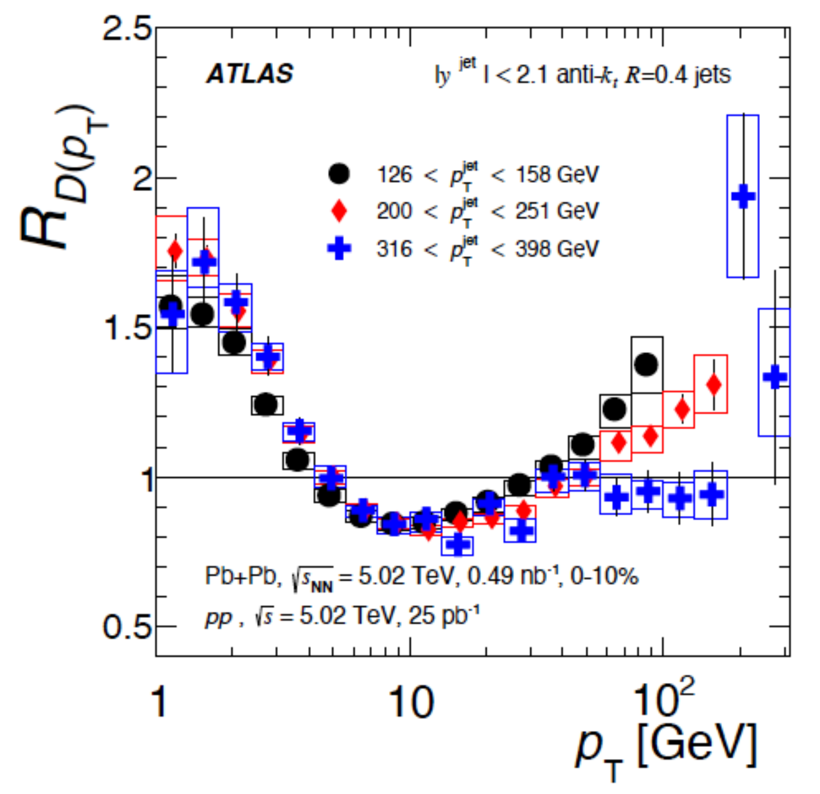
ATLAS, PRL123, 042001 (2019)

Jets: Fragmentation Functions in Central Pb-Pb Collisions

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

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



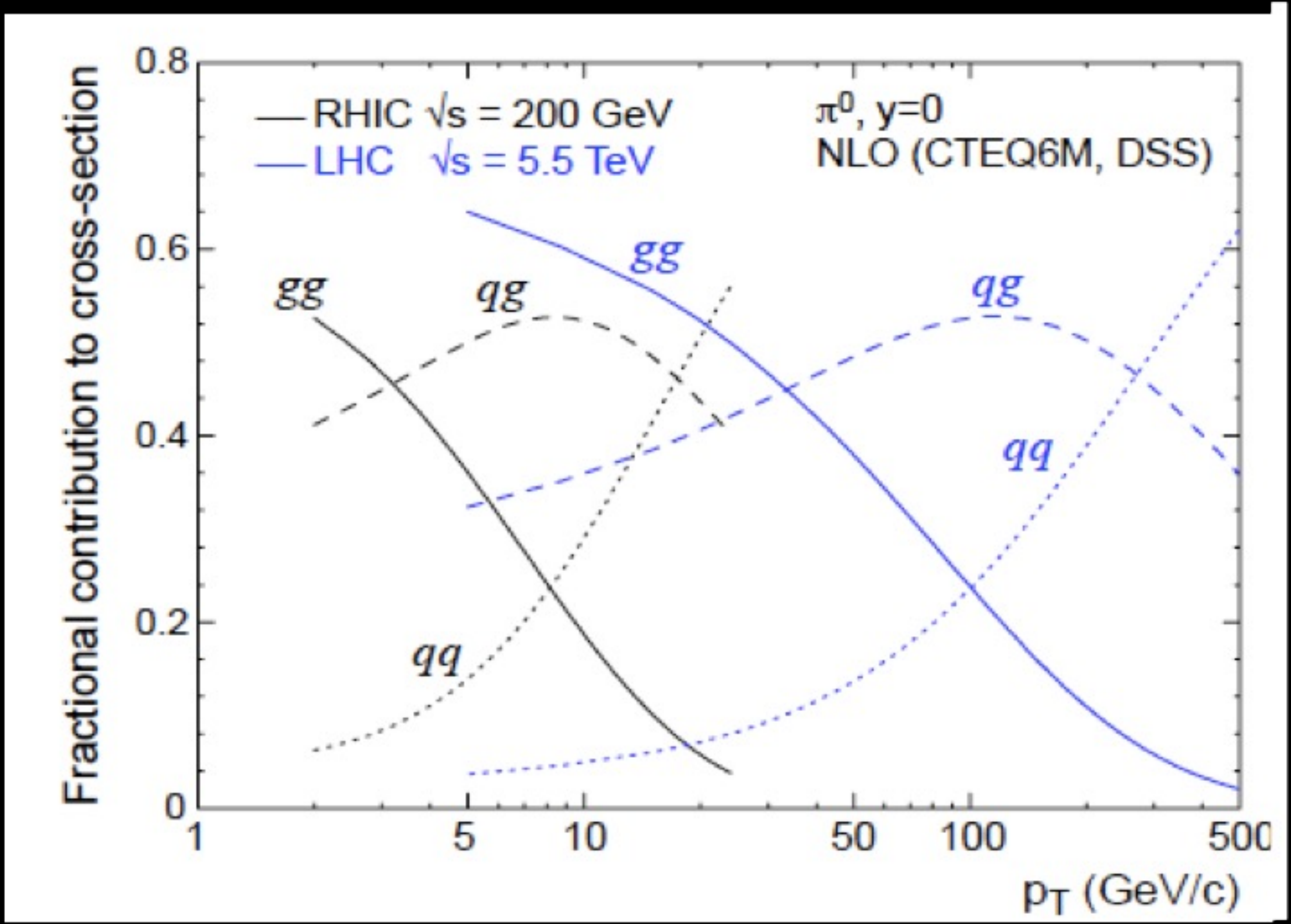


Enhancement at low and high z and p_T
Suppression at intermediate z and p_T
Intermediate z and p_T medium int's -> move lower

Higher jet p_T dominated by qq interactions & quarks
High z and p_T dominated by leading hadrons
Leading hadrons (narrow jets) -> less int's

Remember: Initial Parton Scattering Differences vs √s

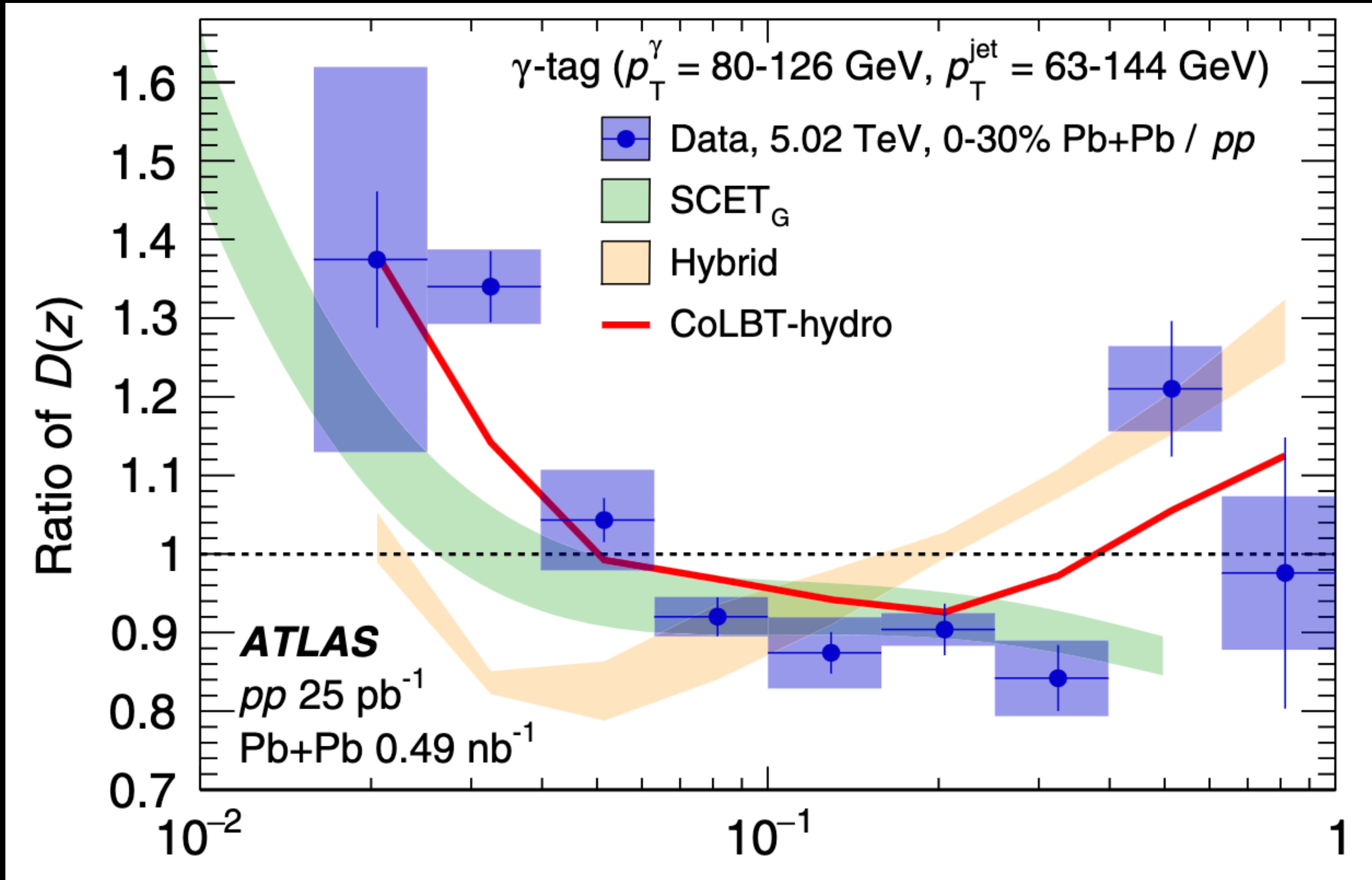
RHIC vs LHC



Fragmentation Functions for γ-tagged in Pb-Pb vs pp

$D_{PbPb}(z)$ / $D_{pp}(z)$

γ-tagged Jets



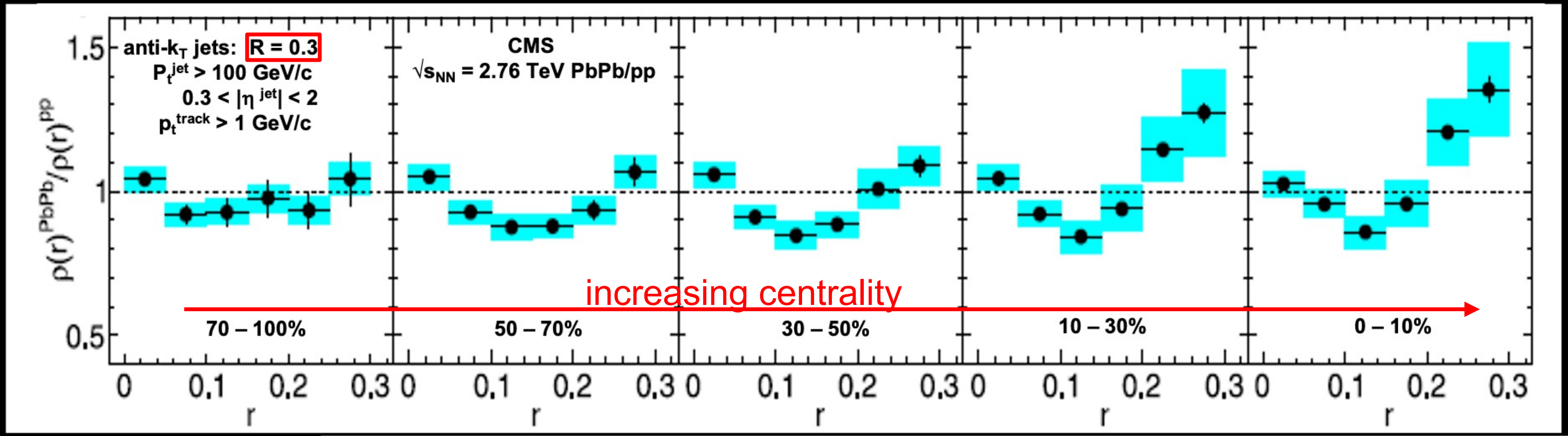
ATLAS, PRL 123, 042001 (2019)

Parton color-charge dependence (q vs g) of jet quenching in QGP

$D_{PbPb/pp}$ (γ-tagged jets) > 1 at low z

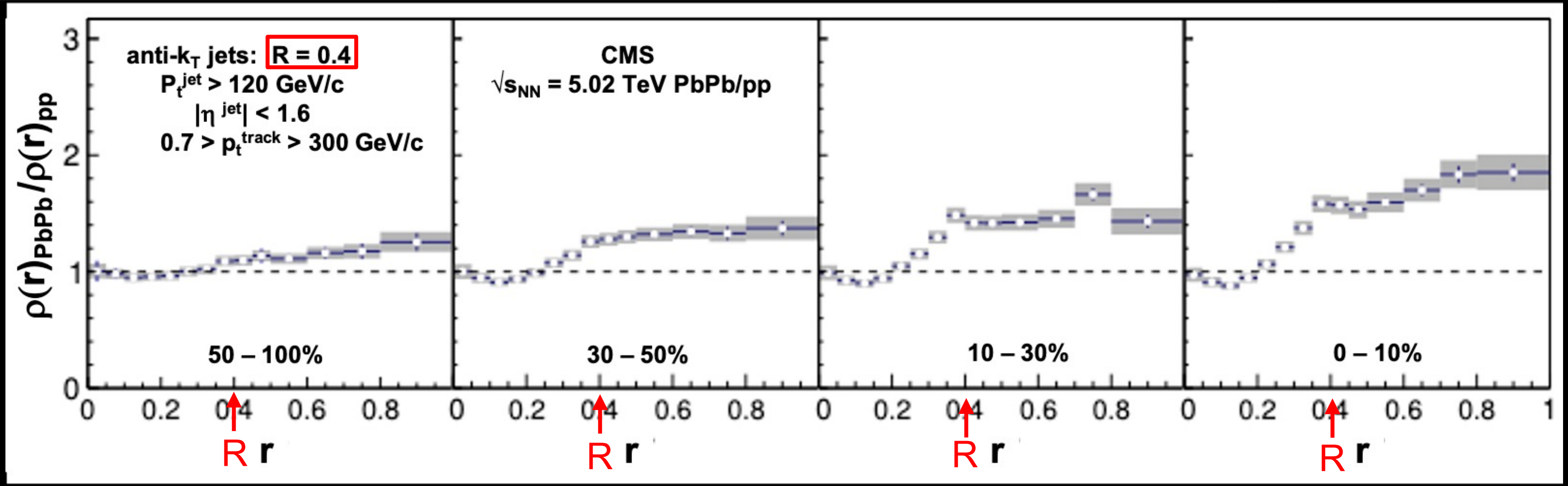
Compare to theoretical models
$SCET_G$ and CoLBT+hydro successful at z < 0.5

PbPb Jet Shapes: Broadening



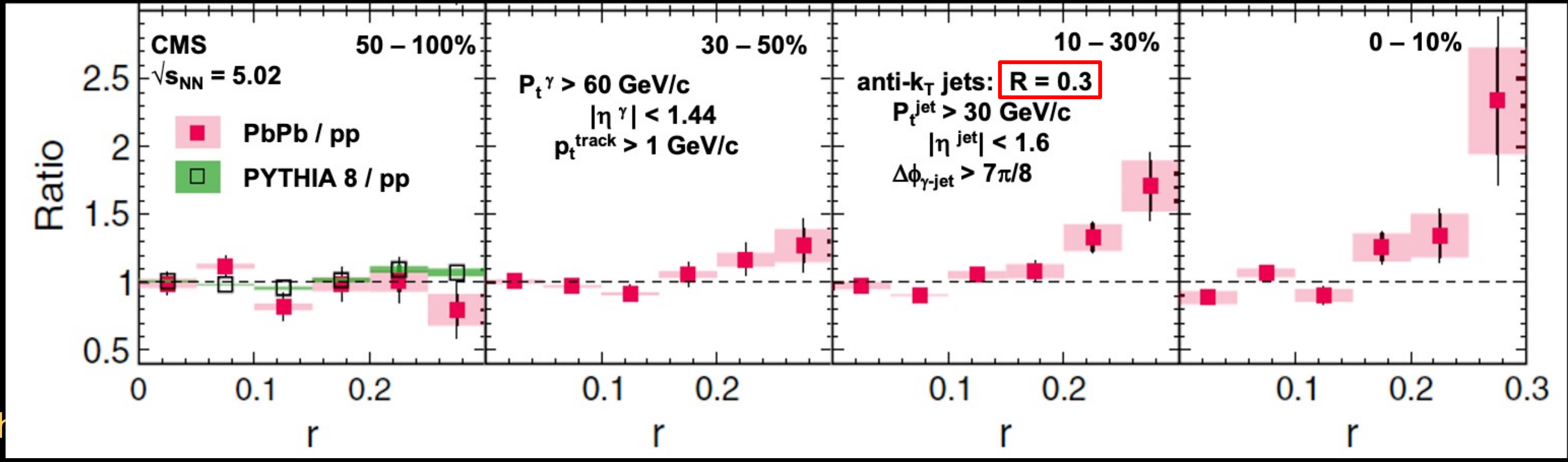
r = distance from jet axis

R is anti-k_T jet radius parameter

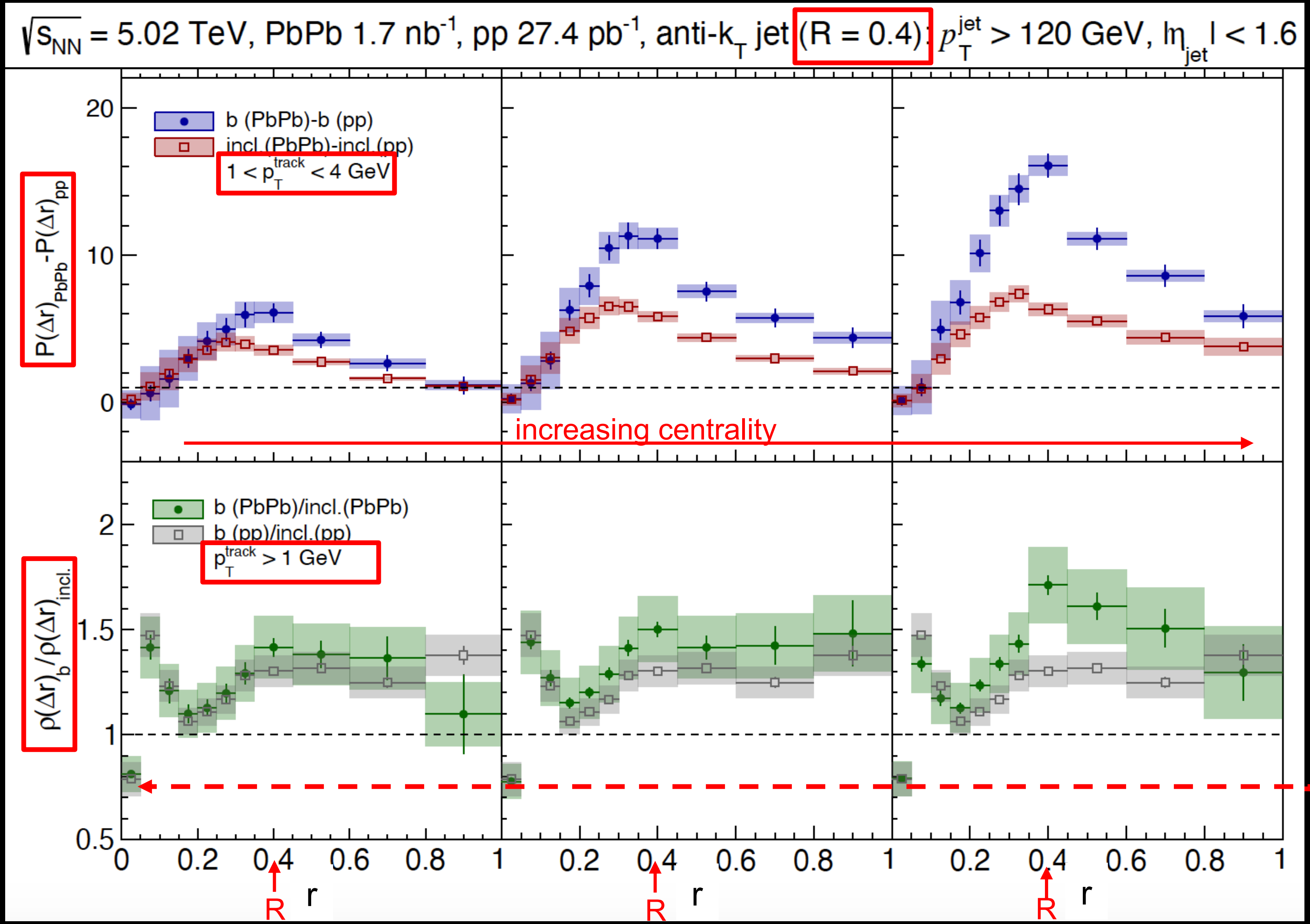


Broadening beyond R

γ - jets



PbPb b-Jet Broadening



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

Wake for b-jets vs inclusive?

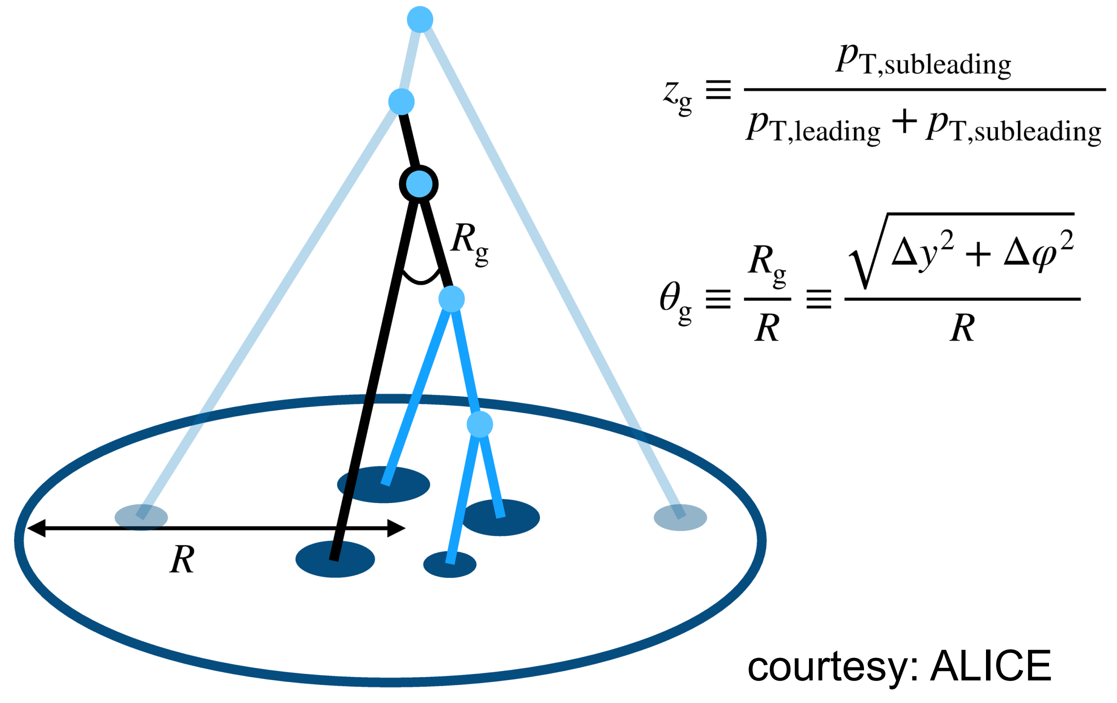
Indication of Dead-cone in PbPb?

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

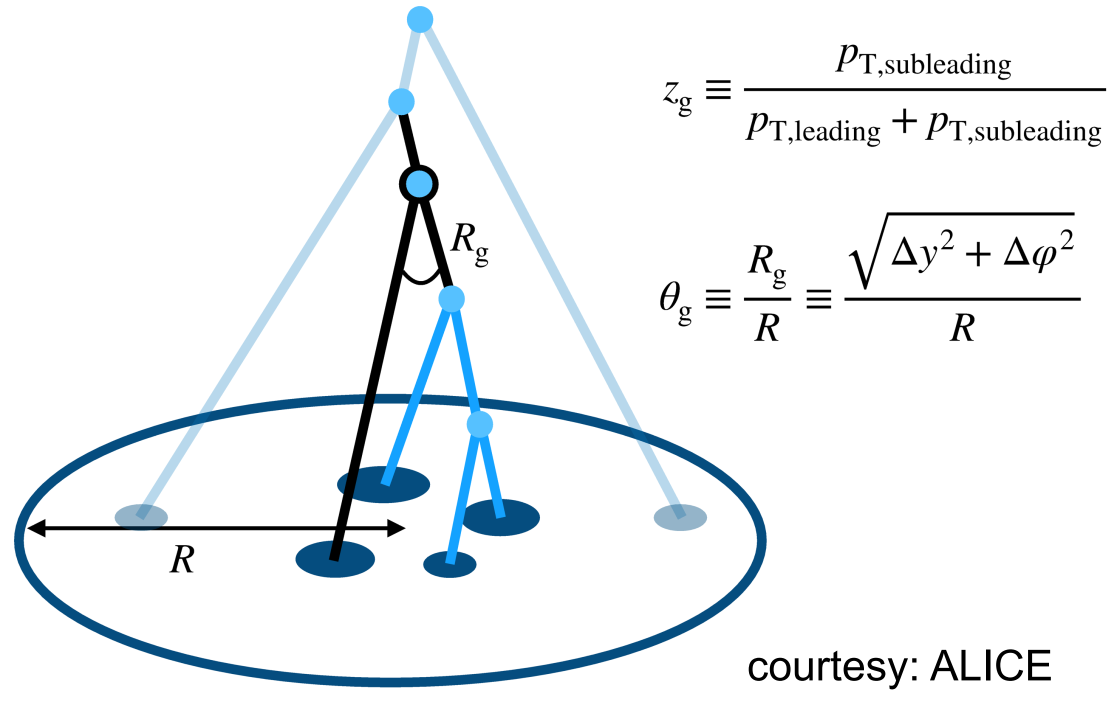
R_g- angular separation of 1st splitting

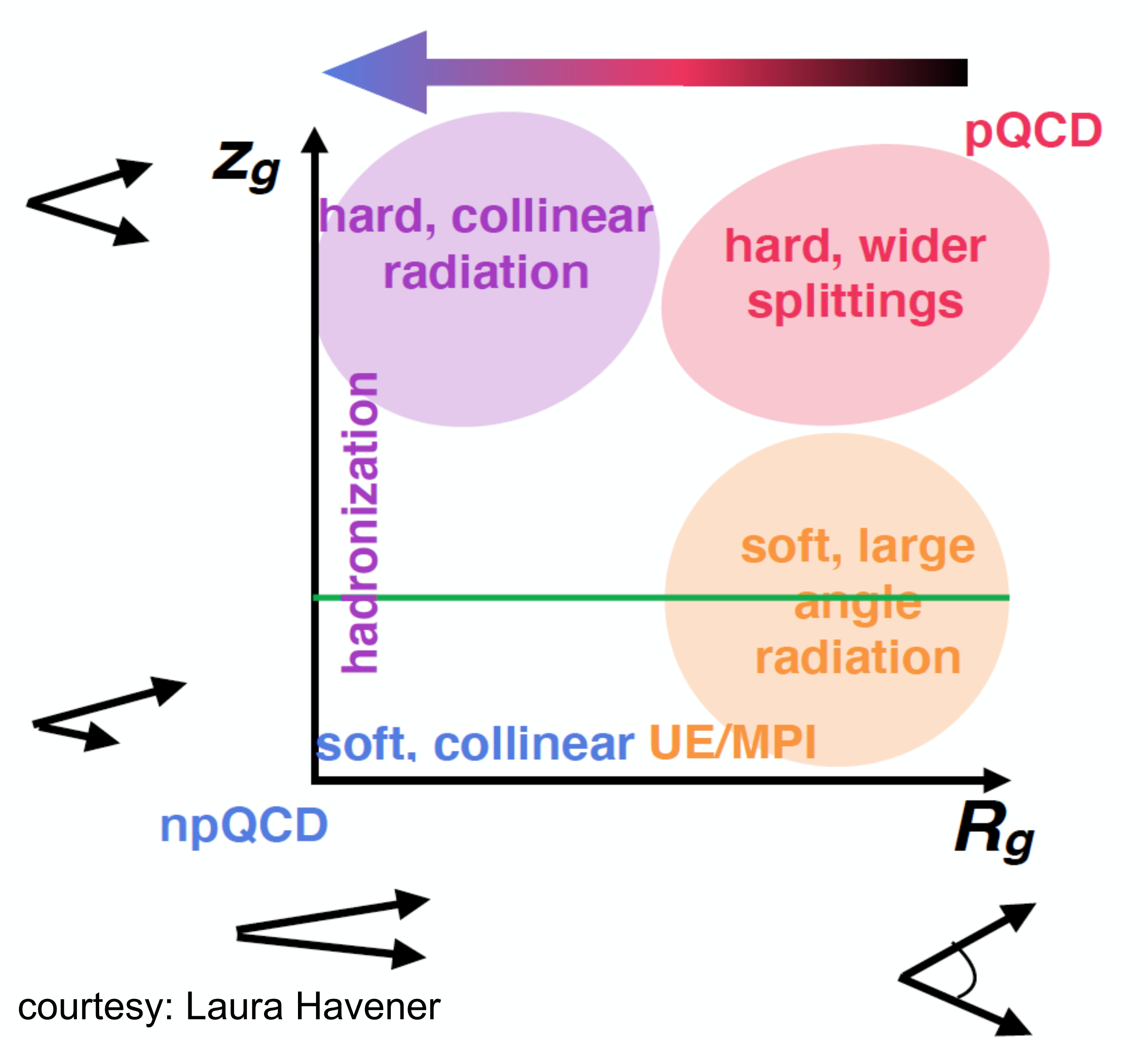
Soft Drop:

M. Dasgupta et al. JHEP 1309 (2013) 029.

A. Larkoski et al, JHEP 1405 (2014) 146.

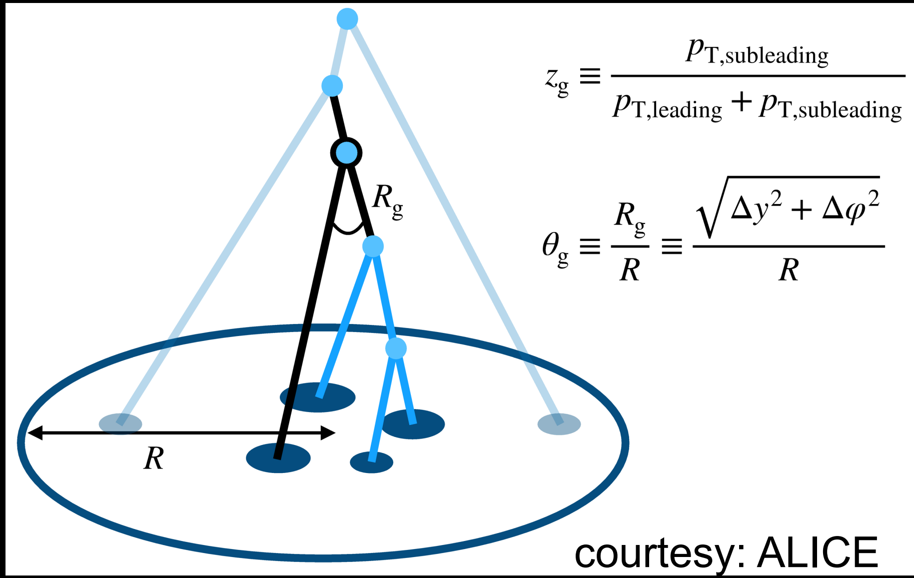
Groomed Jet Substructure

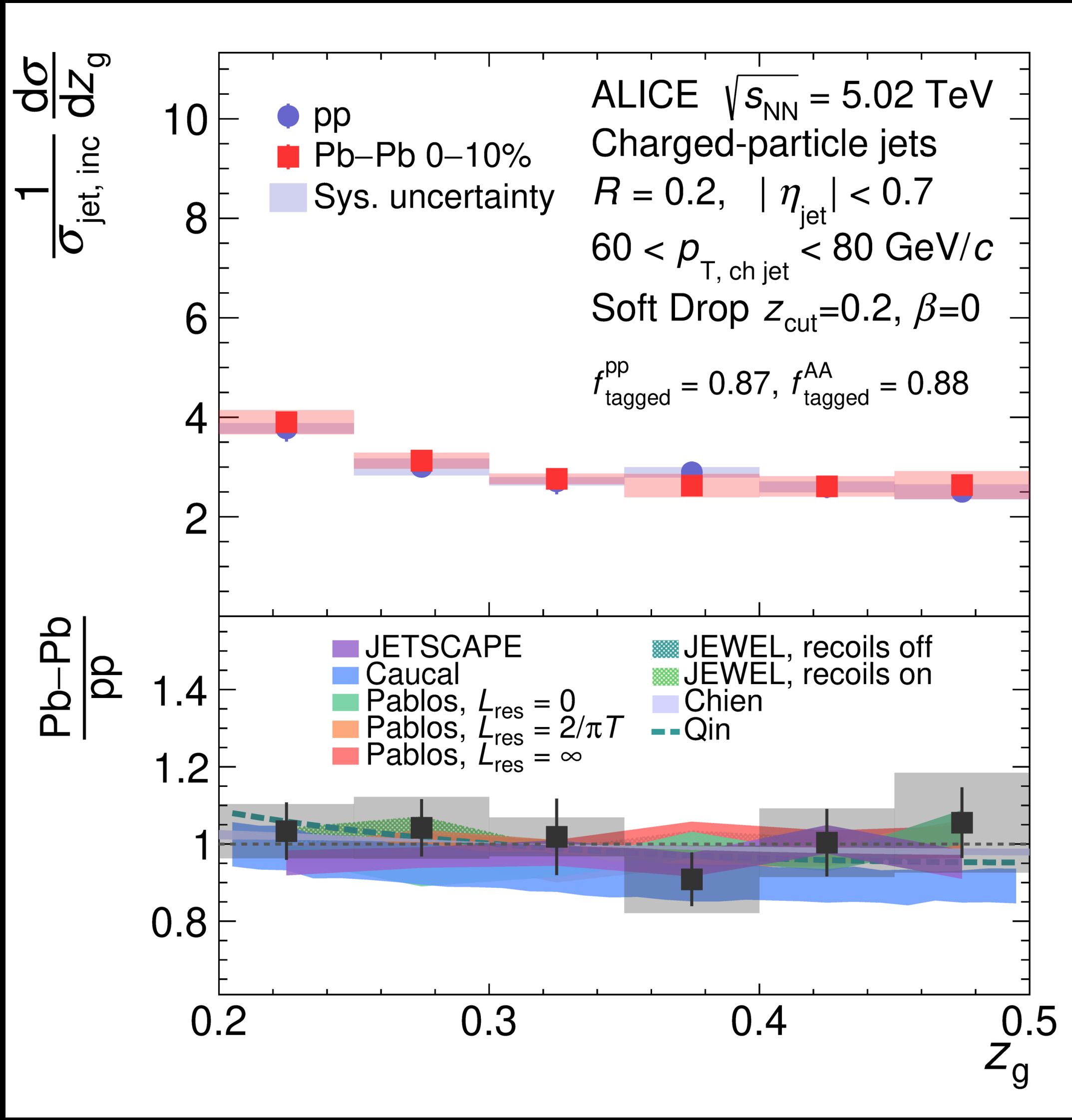




Soft Drop:
M. Dasgupta et al. JHEP 1309 (2013) 029.
A. Larkoski et al, JHEP 1405 (2014) 146.

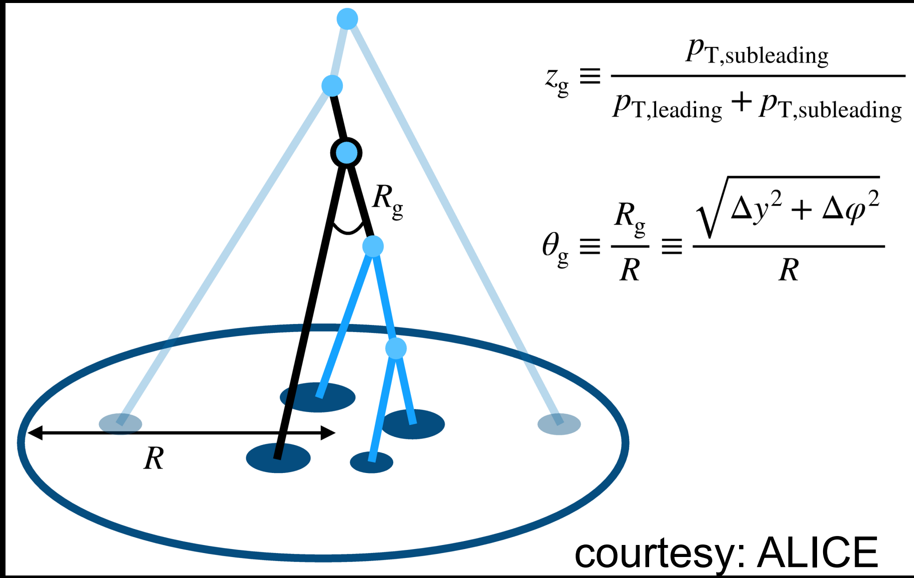
Soft Drop z_g in PbPb

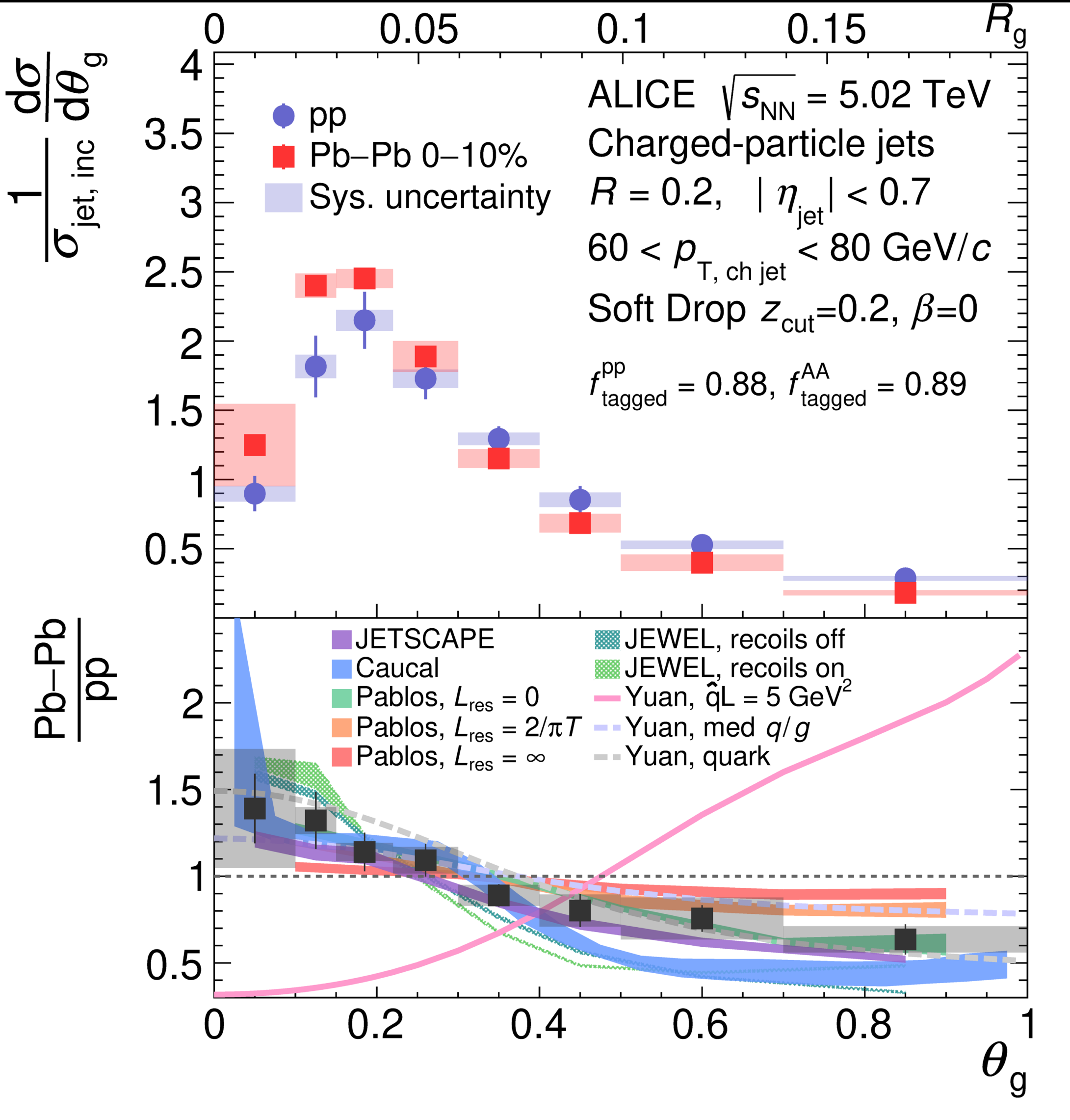




No observable modification of the z_g distribution in Pb-Pb compared to pp

Soft Drop θ_g in PbPb

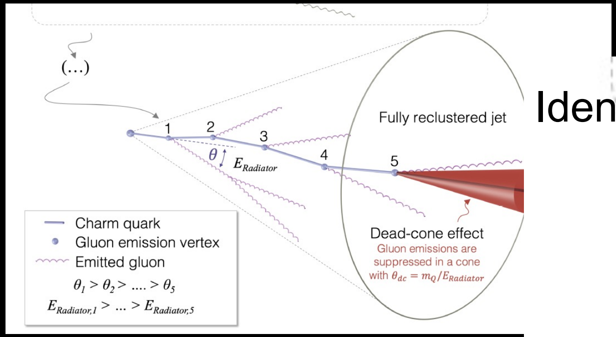




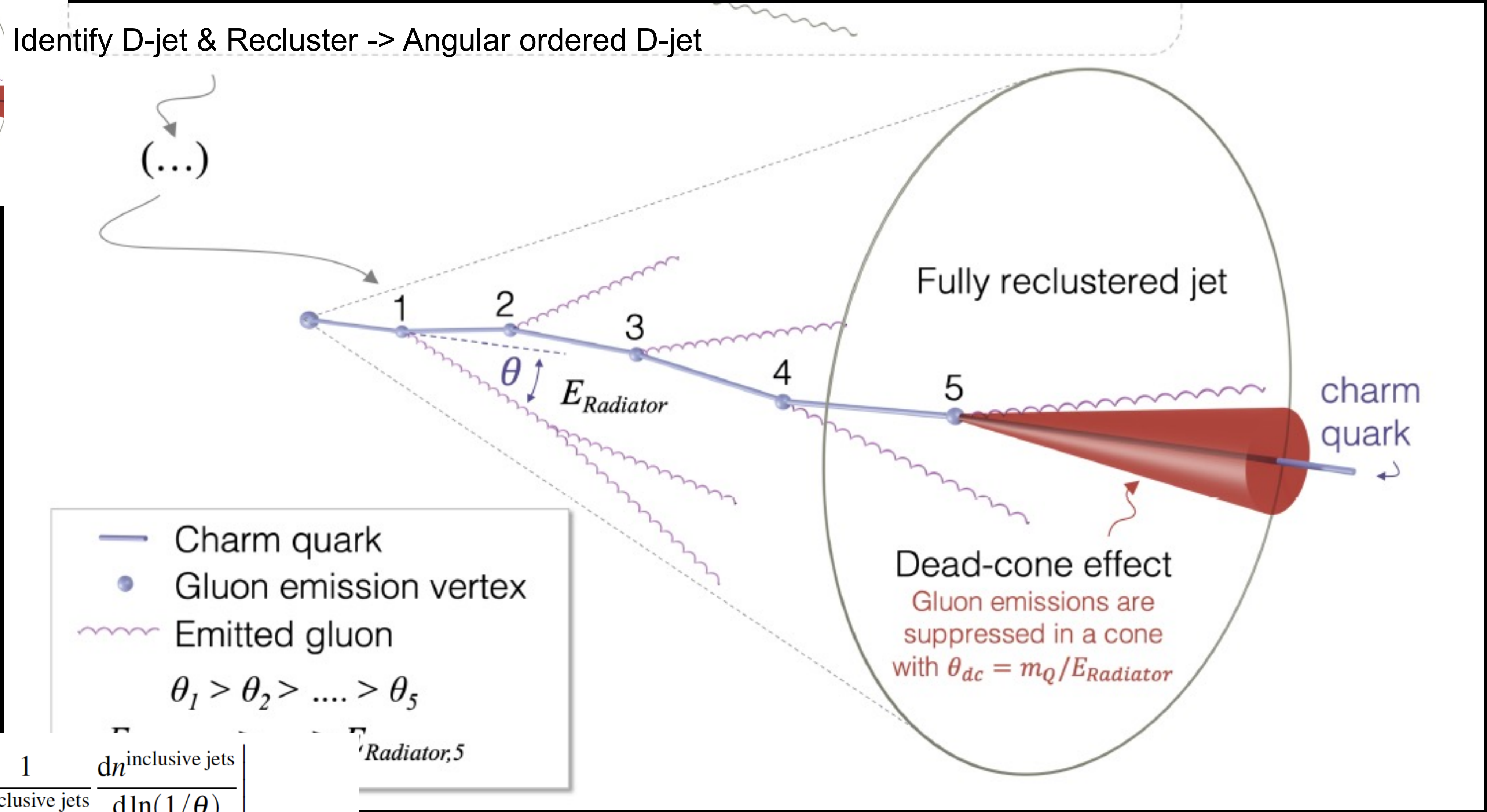
- *Observe narrowing of the θ_g (= R_g/R) distribution in PbPb/pp*
  - *Expected due to color coherence*
- *E-loss models reproduce narrowing of θ_g distribution*
  - *Also by those without color coherence by E-loss induced change in q/g fraction*

Groomed Jet Substructure – Dead-cone in pp Collisions

ALICE, Nature 605 (2022) 440-446



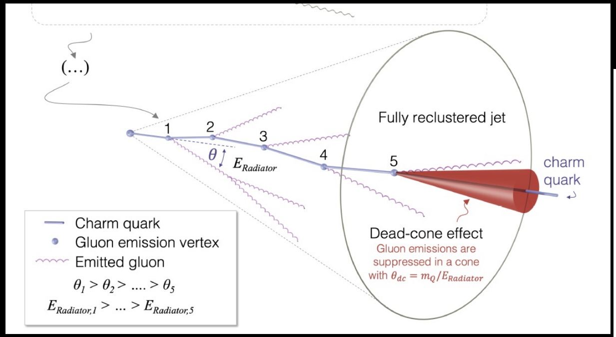
Identify D-jet & Recluster -> Angular ordered D-jet



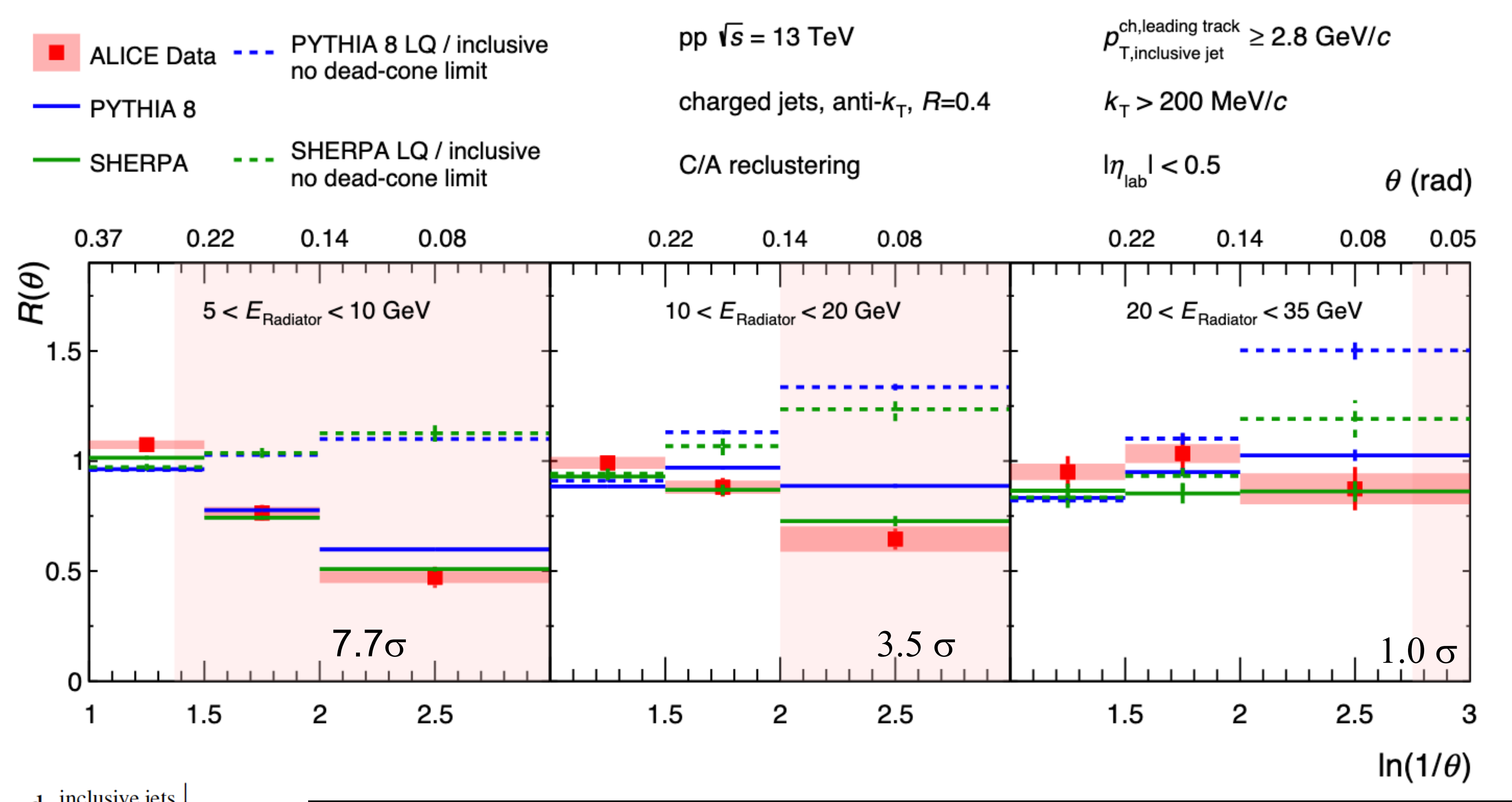
Ratio D-jets to inclusive

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

Groomed Jet Substructure – Dead-cone in pp Collisions



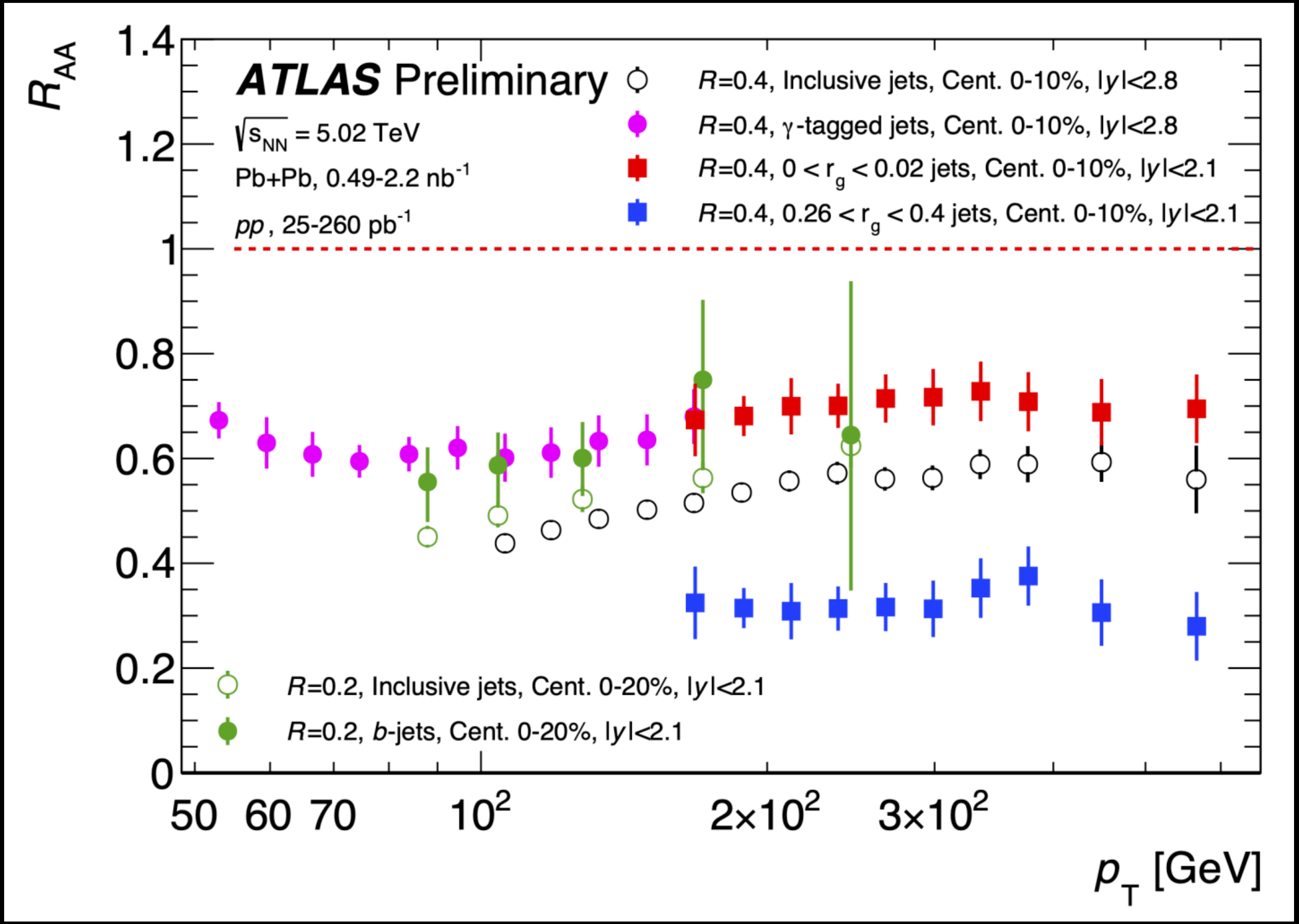
ALICE, Nature 605 (2022) 440-446



Ratio D-jets to inclusive

$$R(\theta) = \frac{1}{N^{D^0\text{ jets}}} \frac{dn^{D^0\text{ jets}}}{d\ln(1/\theta)} \Bigg/ \frac{1}{N^{\text{inclusive jets}}} \frac{dn^{\text{inclusive jets}}}{d\ln(1/\theta)} \Bigg|_{k_T, E_{Radiator}}$$

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

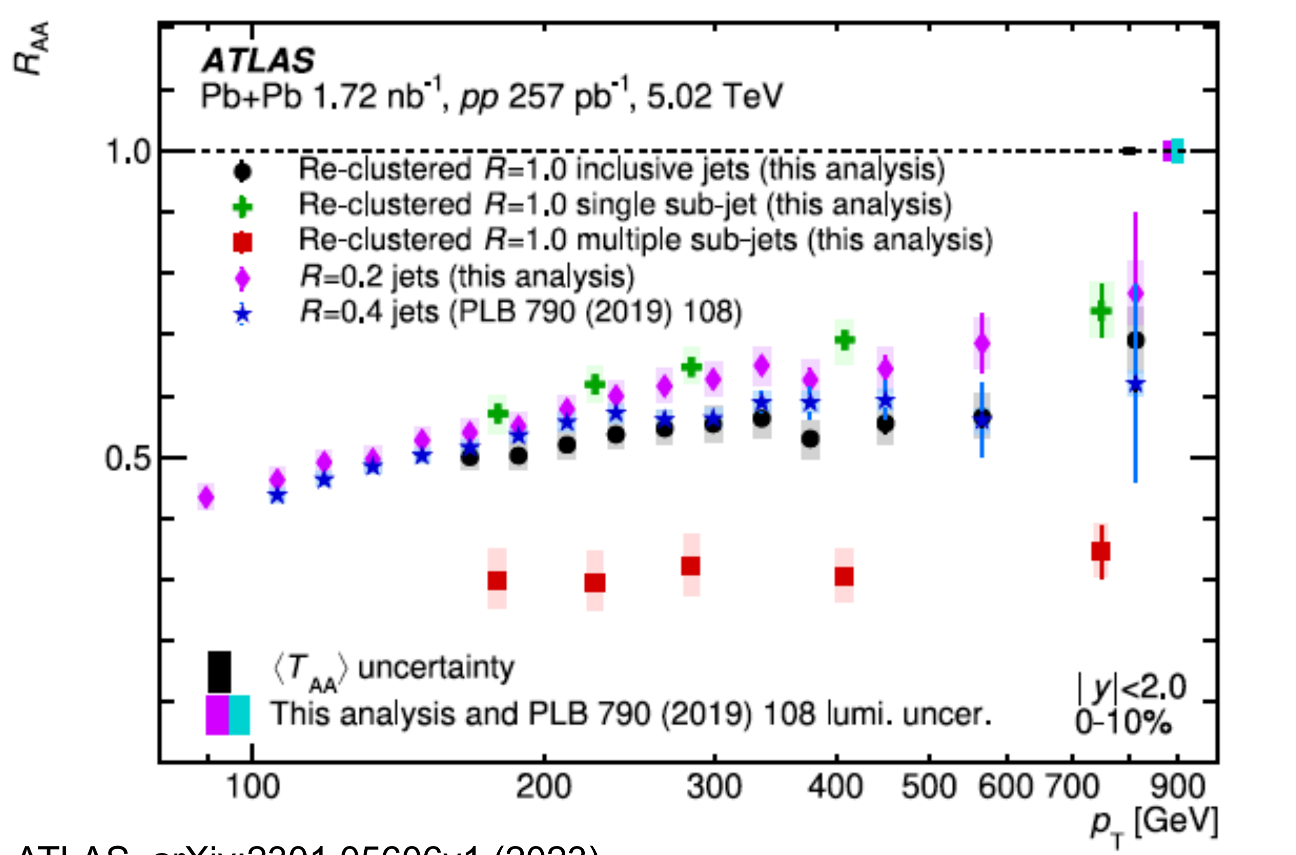
Procedure:

- 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!
-> seek to learn the role of color decoherence in the jet quenching!

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 on Gluon Shadowing and Jet Quenching in AA
- 2003 – STAR, PRL 90 (2003) 82302 on relative charge dependence, *"1st Jet substructure in AA"*
- 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 Hadrons suppressed at RHIC (to low √s) and LHC(to high p_T) in AA
  $3.4 < \hat{q}/T^3 < 5.8$ at RHIC $2.4 < \hat{q}/T^3 < 5.0$ at LHC
- 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 int's -> move lower
  High z and p_T dominated by leading hadrons -> less int's
  Quark and gluon fractions in initial parton scatterings differ in NLO
  Jets broaden with increased PbPb 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 in pp (use in heavy-ions to study micro-substructure)
  Broader jets more suppressed than narrower ones
  b-jet suppression ~ inclusive jets
  R = 1 re-clustered inclusive jets suppressed more 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?

Thank you for your attention!

Thanks to Hannah Bossi, Laura Havener and Berndt Müller for contributions/discussions!

*I have not been able to include in the time allotted:
Di-jet asymmetry, jet v_2, event shape engineering, energy-energy correlations, among other approaches.
Sincere apologies for any important results not presented…