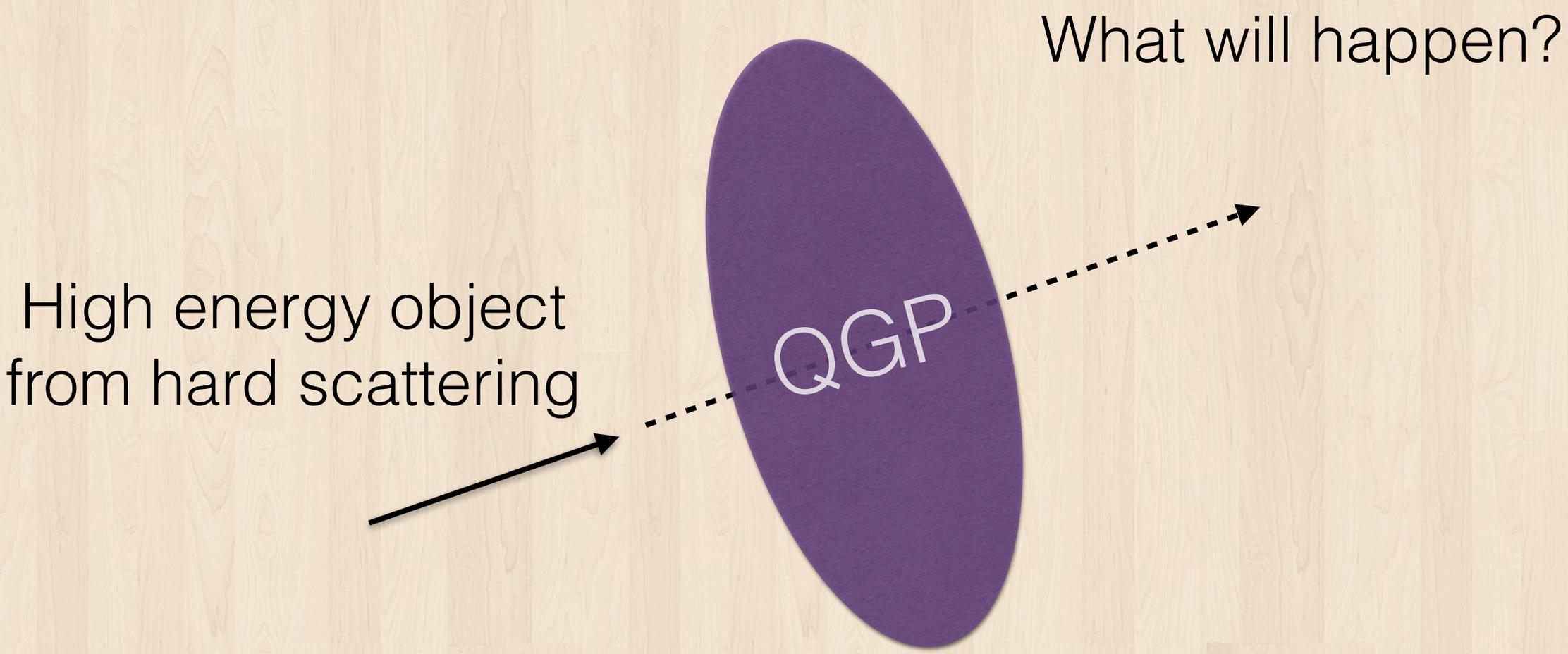
Hard Probes*

Yi Chen (MIT)
LHCP, 2020 May 27

* focus on results from LHC

Hard Probes?

Hard probes



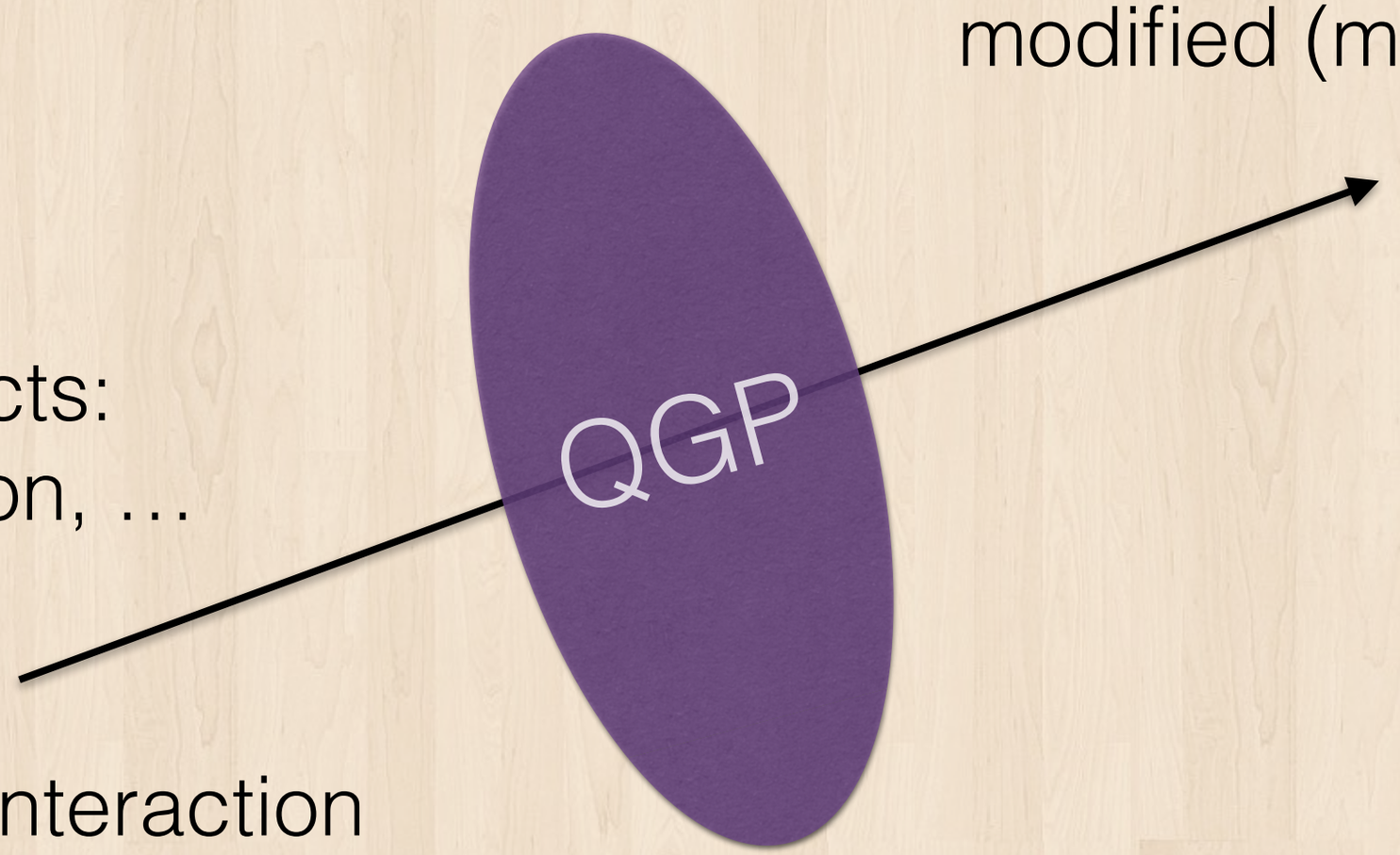
Learn about the QGP from the interaction

QGP = quark gluon plasma

Colorless probes

Doesn't get modified (much)

EWK objects:
photon, lepton, …



Minimal interaction with the medium

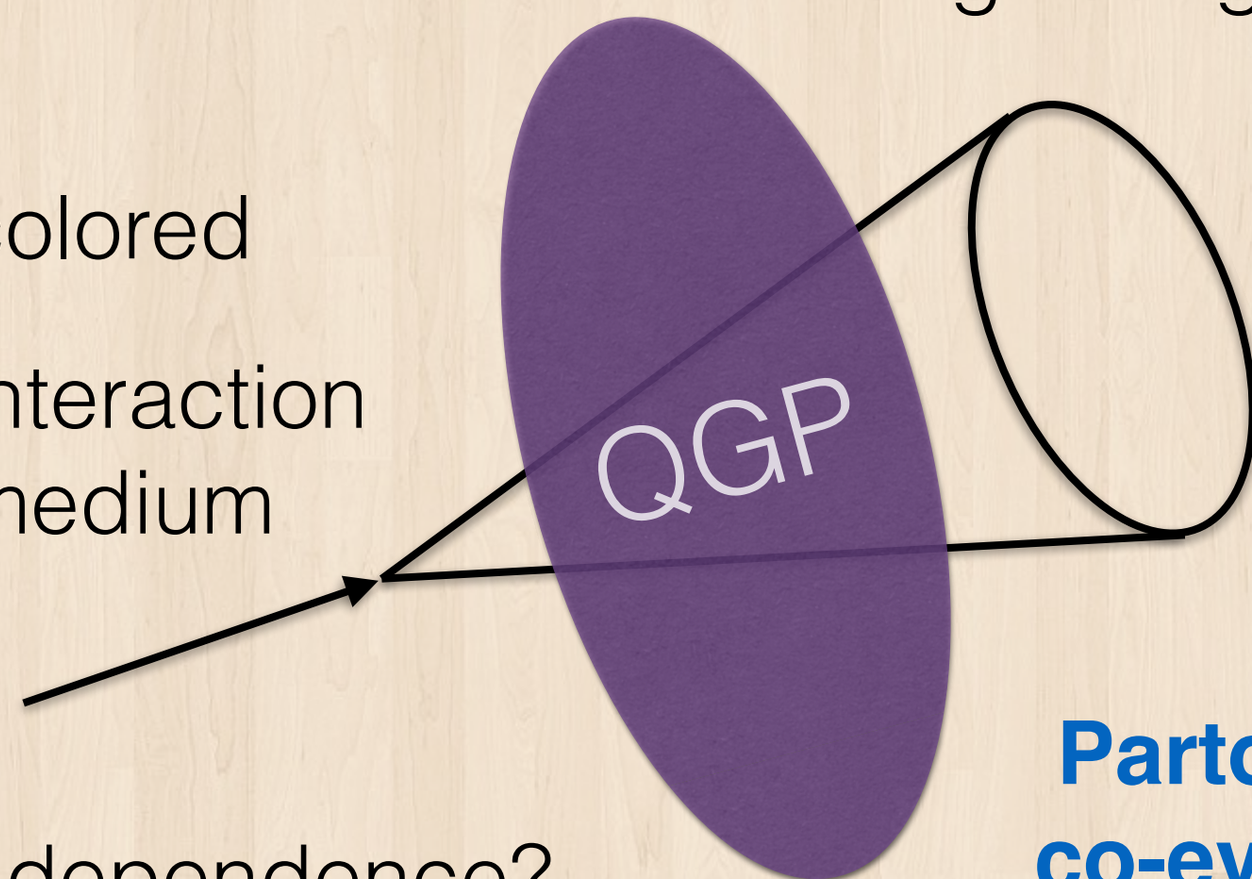
- **Initial state effects**
- **Reference for other things**

Colored probes

Jets = proxy for the originating parton

Parton: colored

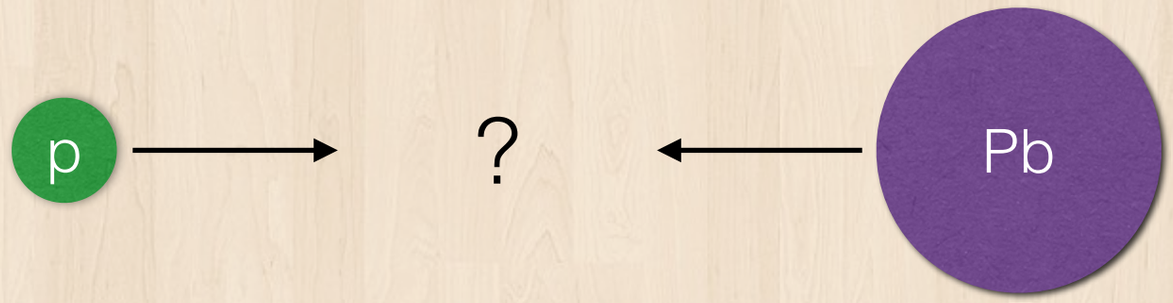
Non-trivial interaction with the medium



Path-length dependence?
Energy loss mechanism?
……

Parton shower co-evolves with QGP

pPb collisions



Much smaller system size compared to PbPb collisions

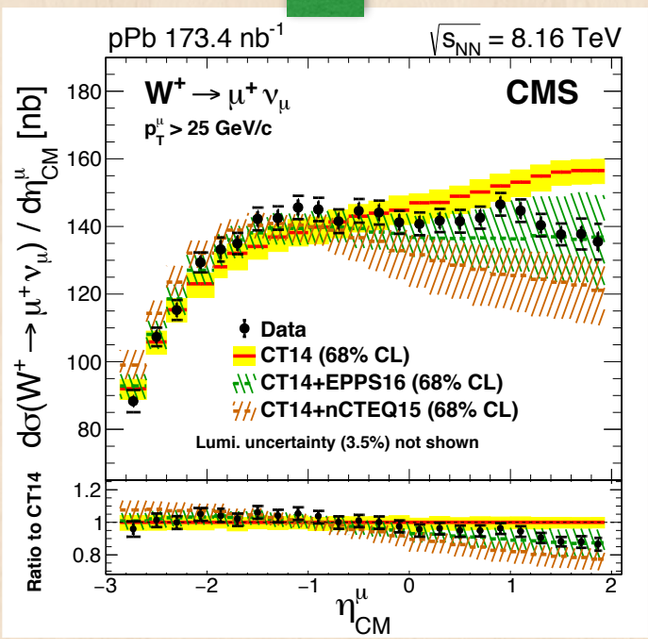
Asymmetric system allows better handle on nuclear PDF (nPDF)

Colorless probes

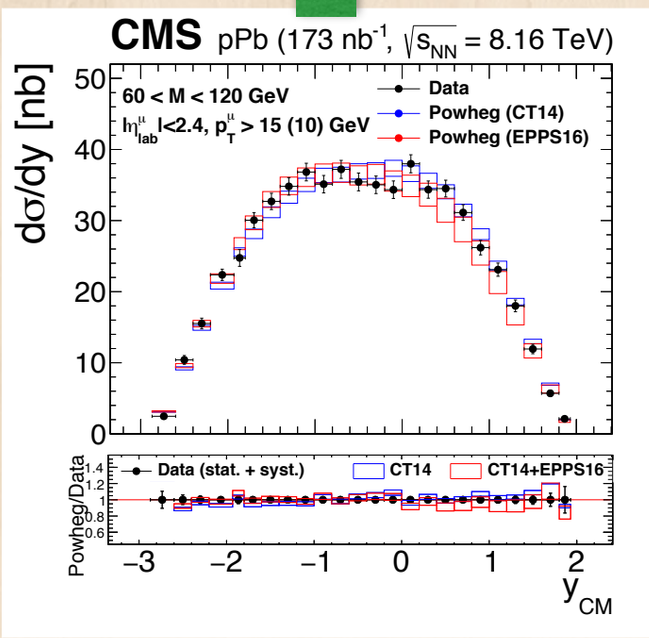
$Z/W^{\pm}$ in pPb

Z/W boson in central rapidity

W

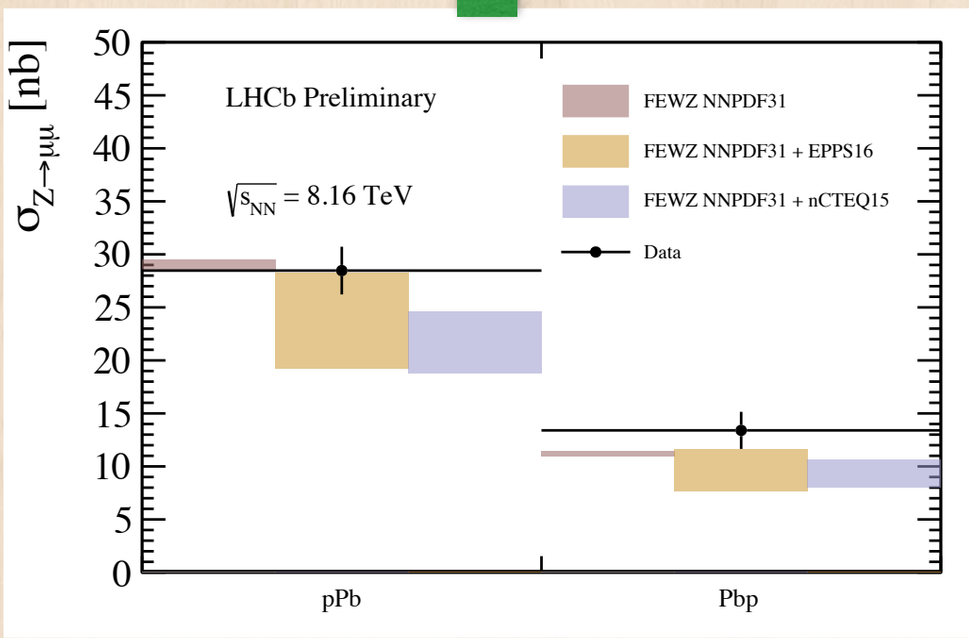


Z



Z boson, 2.0 < η < 4.5

Z



Sensitive to nPDFs and initial state effects

nPDF needed to describe data

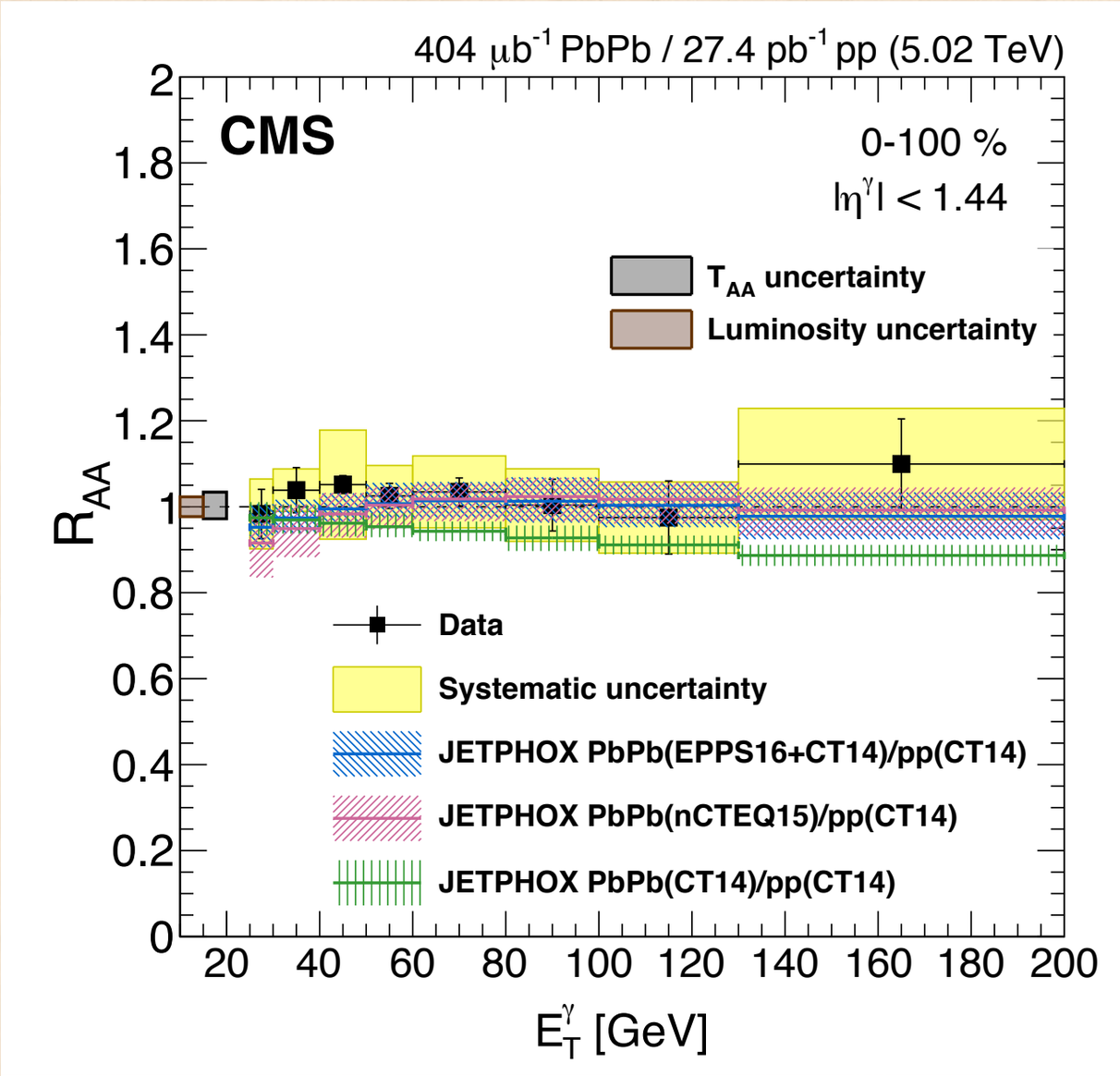
Good synergy between LHC experiments

PLB 800 (2020) 135048, CMS HIN-18-003, LHCb-CONF-2019-003

Photon R_{AA}

R_{AA} = AA cross section / scaled pp cross section

to account for expected number of binary nucleon-nucleon collisions



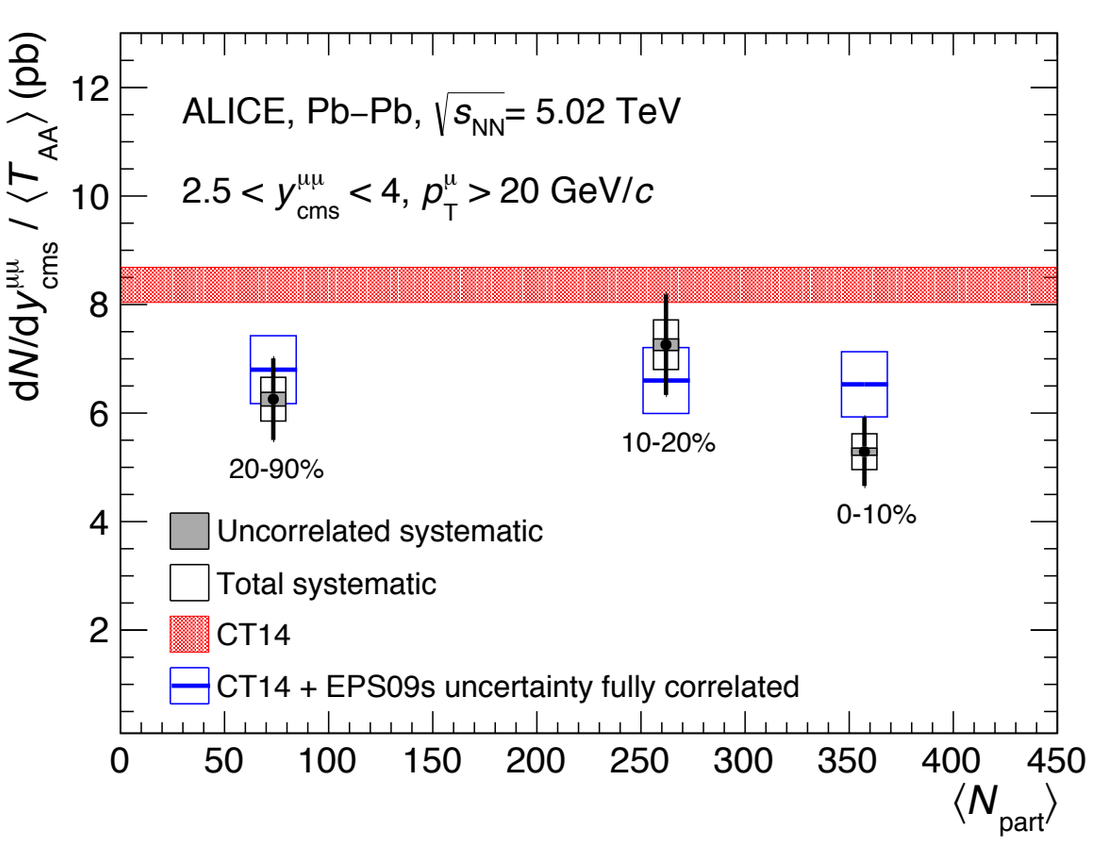
R_{AA} consistent with 1

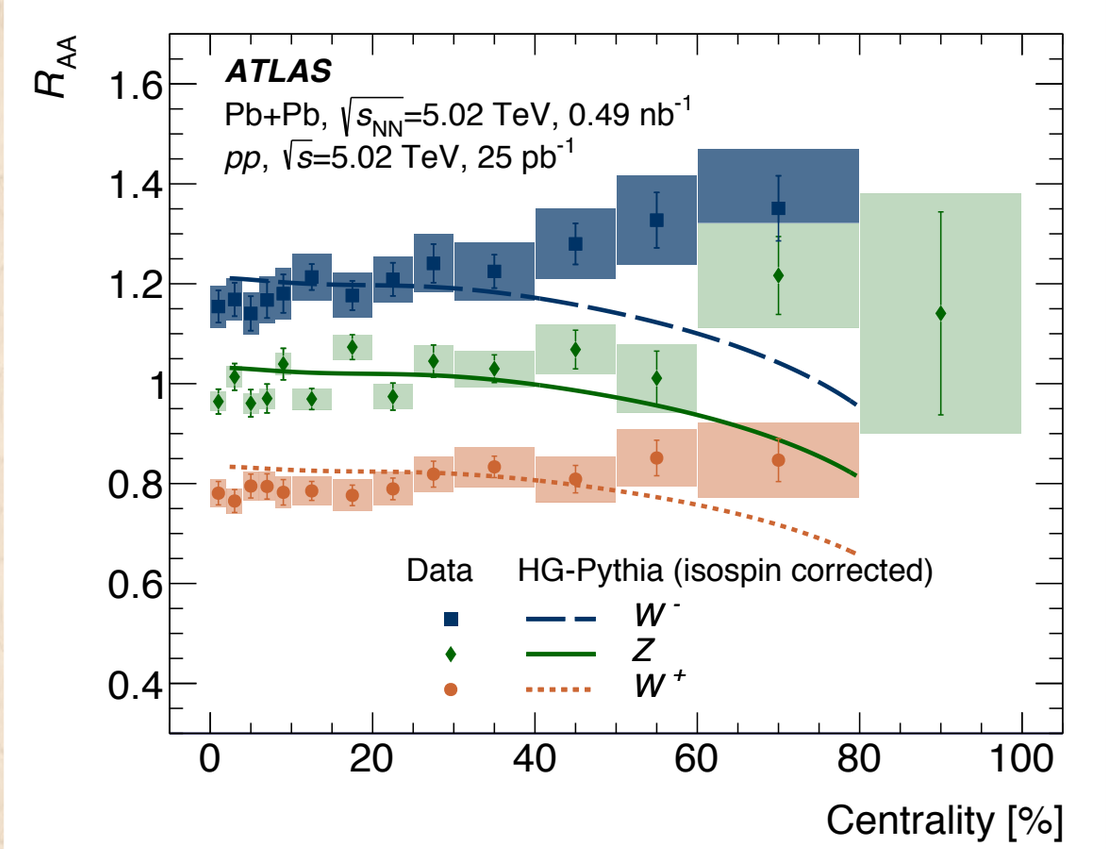
No significant modification for photons

Also consistent with expectations from nPDF

arXiv 2003.12797

$Z/W^{\pm}$ in PbPb





Consistent with no QGP effect
nPDF is needed to describe data

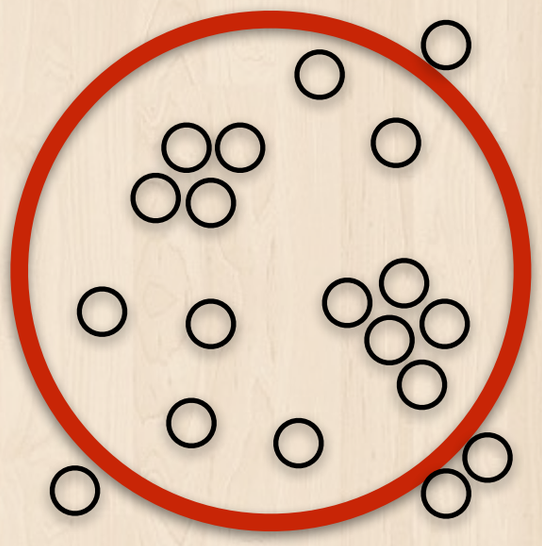
arXiv 2005.11126, PLB 802 (2020) 135262, EPJC 79 (2019) 935

PLB 773 (2017) 408

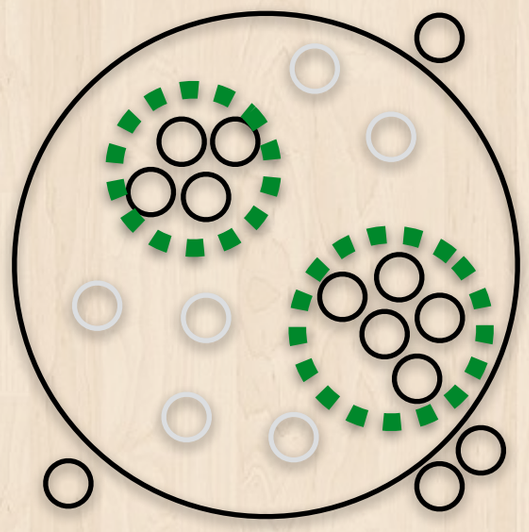
Colored probes: jets*

* Focus on light/inclusive jet results. For heavy flavor results, see next talk from Gian Michele Innocenti

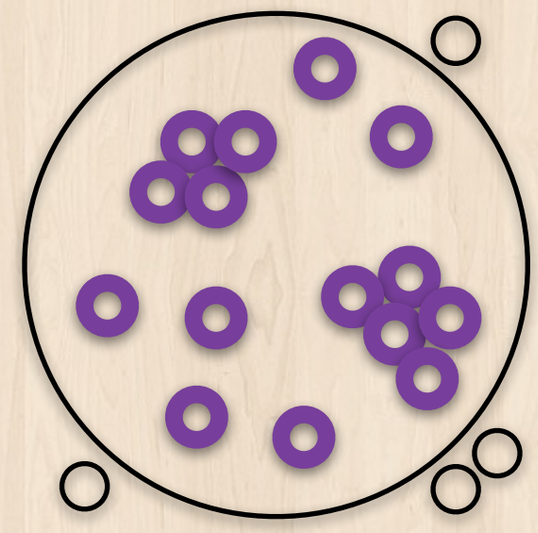
Level of detail



Full jet



Substructure

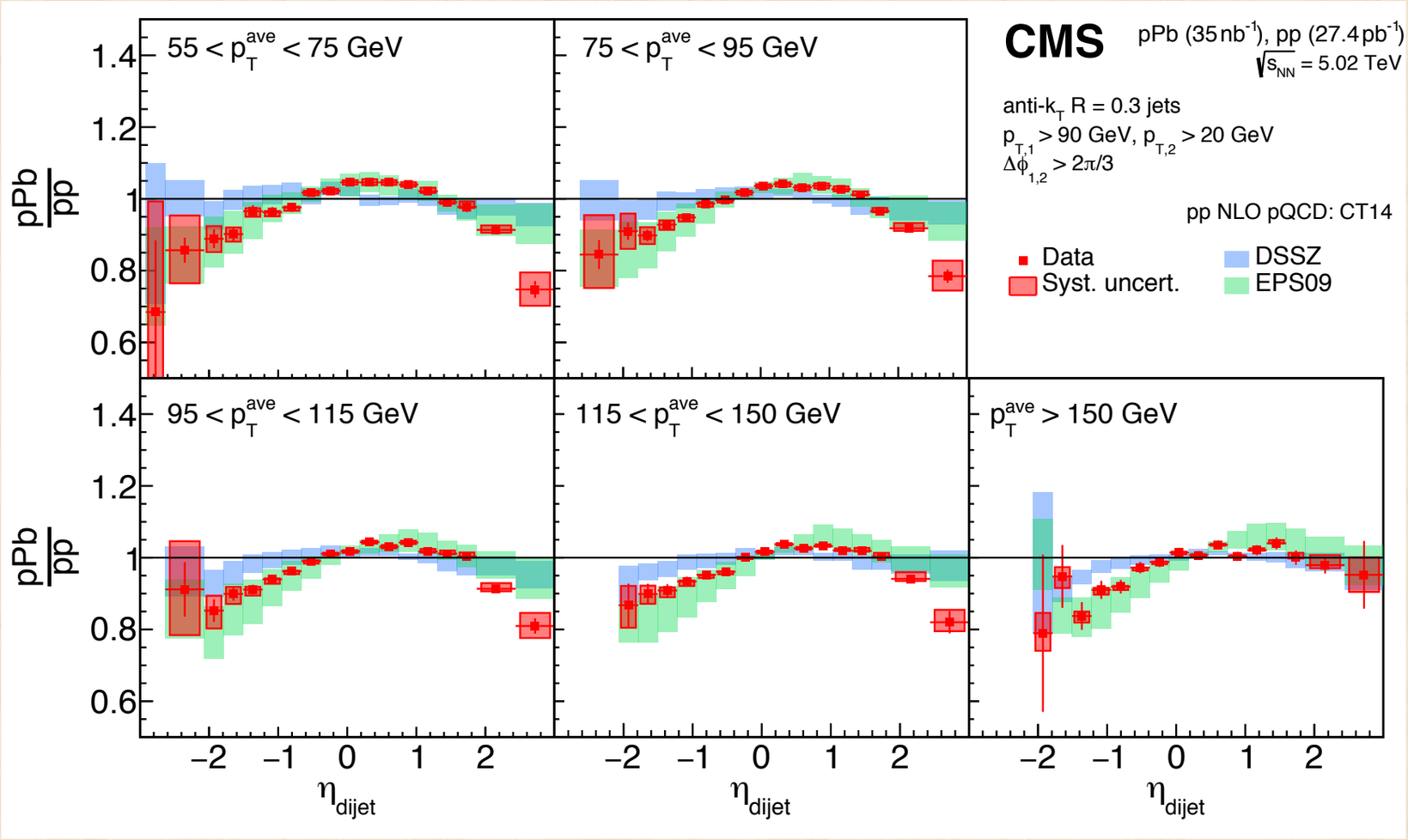


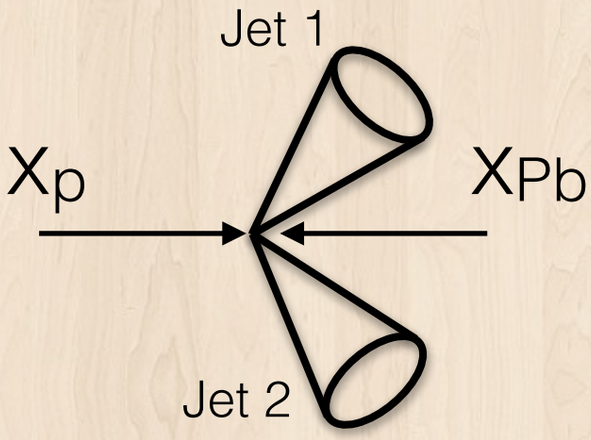
Constituent

Full Jet

Dijet in pPb collisions

Dijet average η can be used to probe nPDF effects





$$\eta_{\text{dijet}} = \frac{1}{2}(\eta_1 + \eta_2)$$

Typical range

$Q \sim p_T^{ave}$

$x_{\text{Pb}} \sim 5 \times 10^{-3} - 5 \times 10^{-1}$

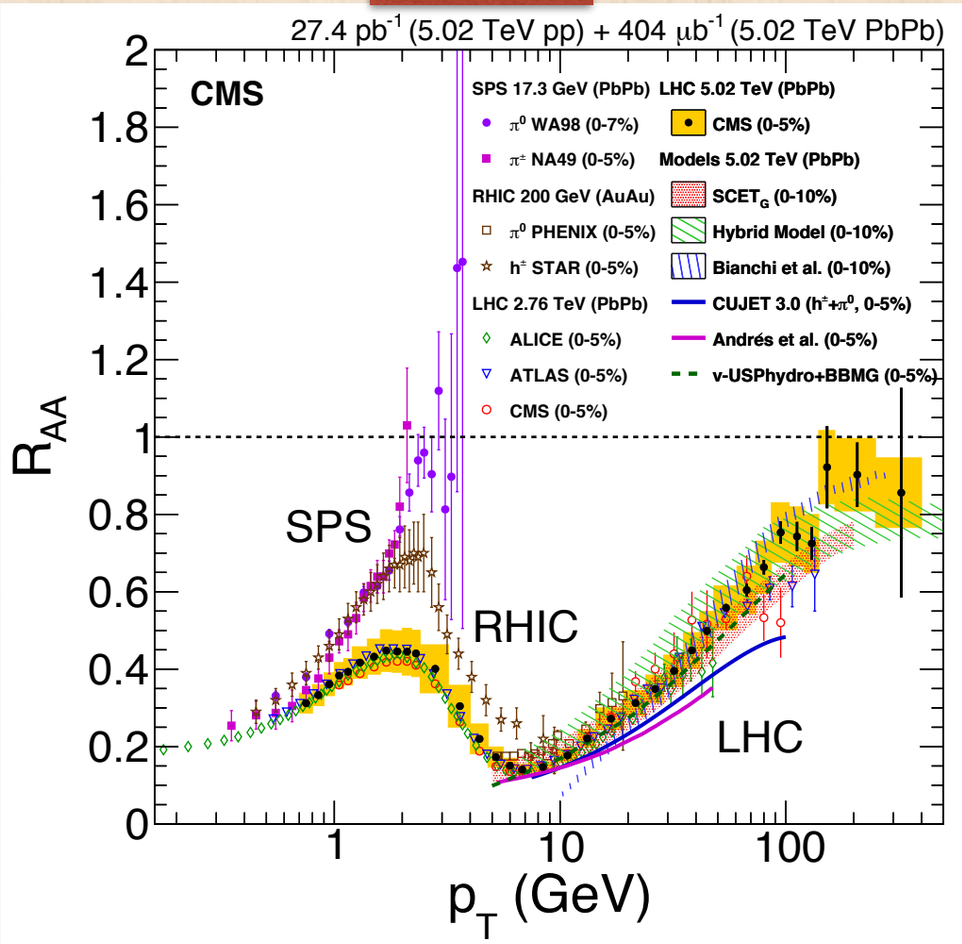
Good discrimination between different PDF sets

PRL 121 (2018) 062002

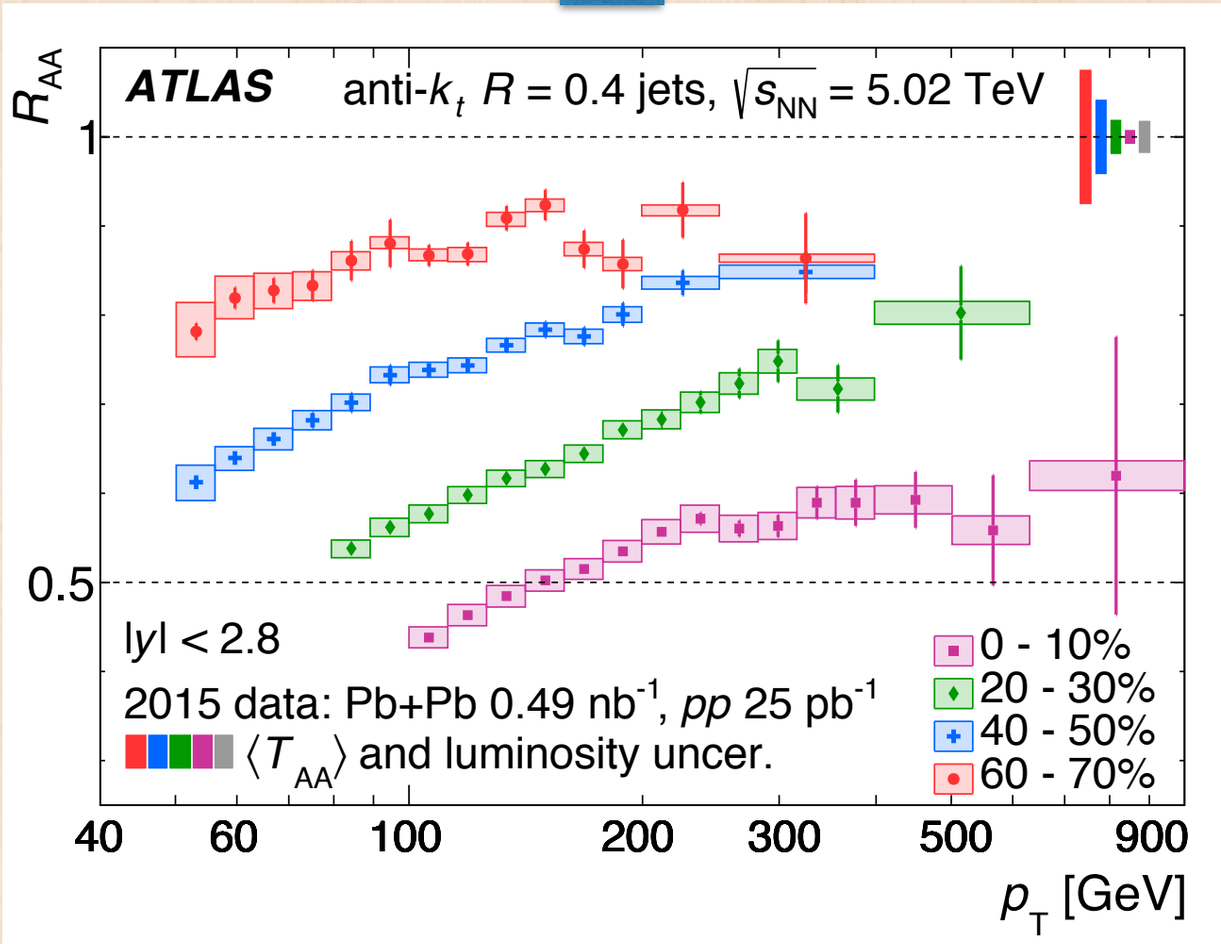
Hadron & Jet R_{AA}

R_{AA} = PbPb cross section / scaled pp cross section

Hadron



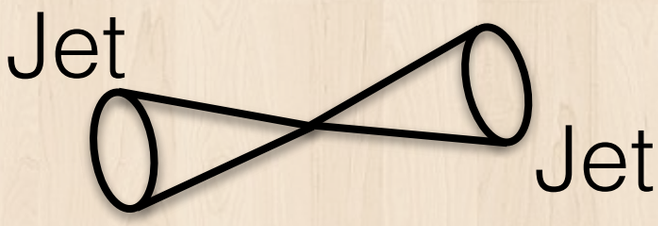
Jet



Hadron R_{AA} approaches 1 towards TeV scale, while jets are suppressed all the way to TeV

JHEP 04 (2017) 039, PLB 790 (2019) 108

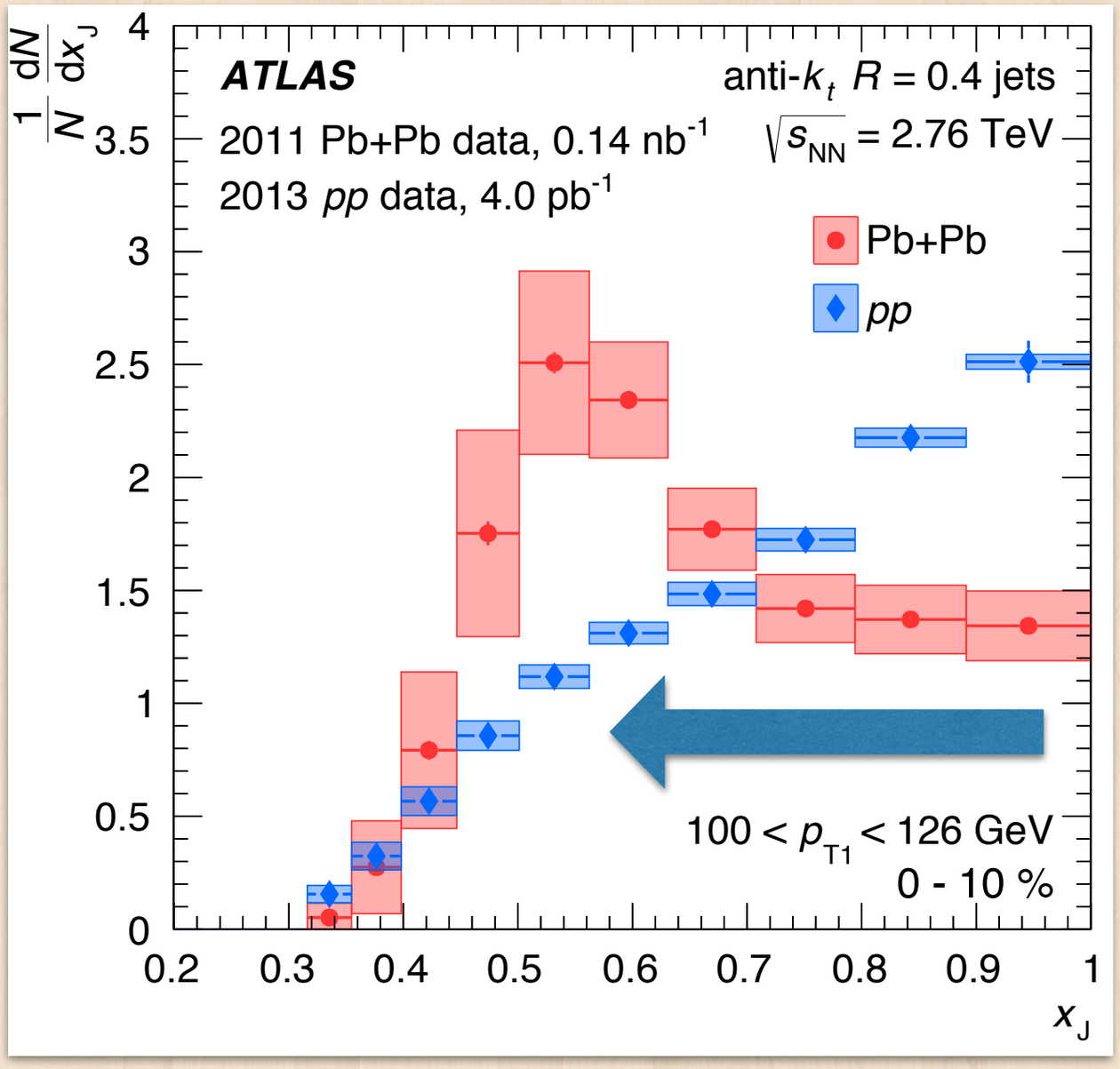
Dijet balance



Momentum balance of leading dijets

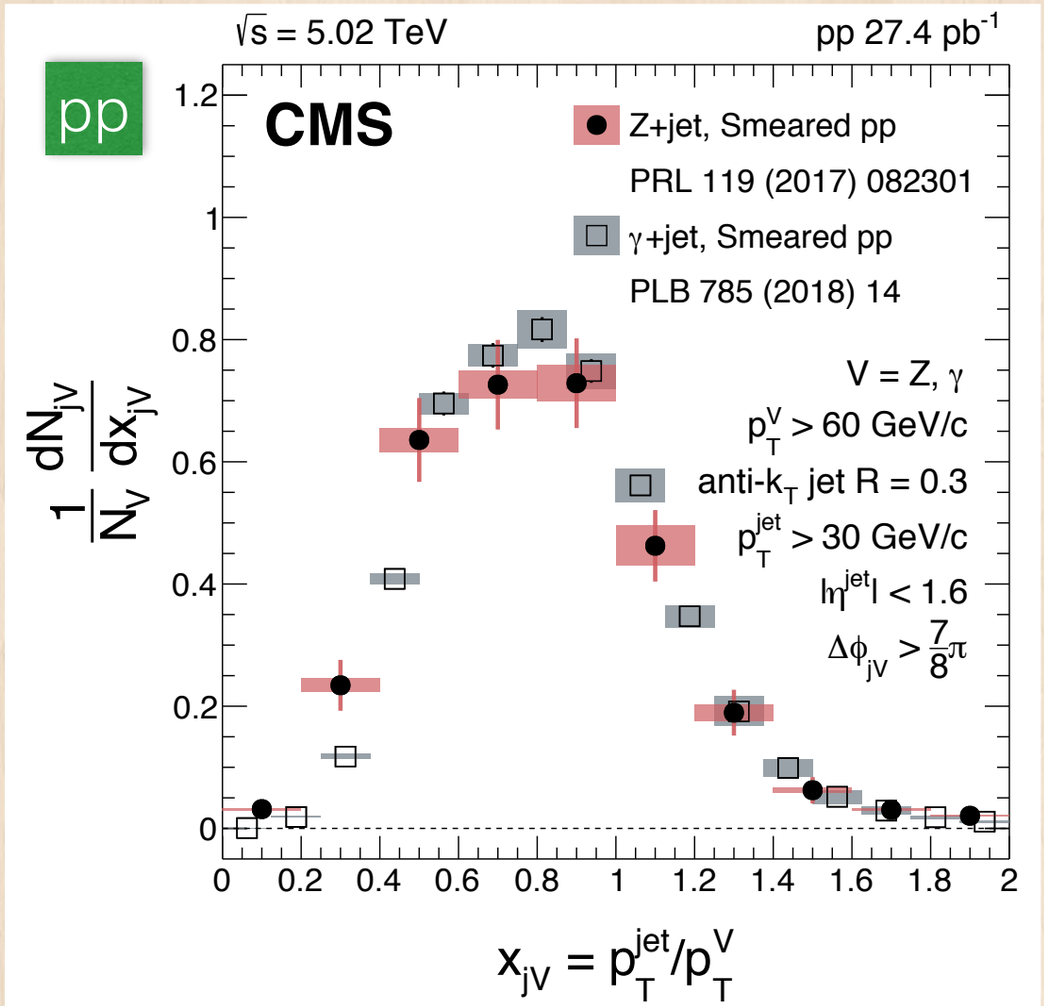
$$x_J = \frac{p_{T,2}}{p_{T,1}}$$

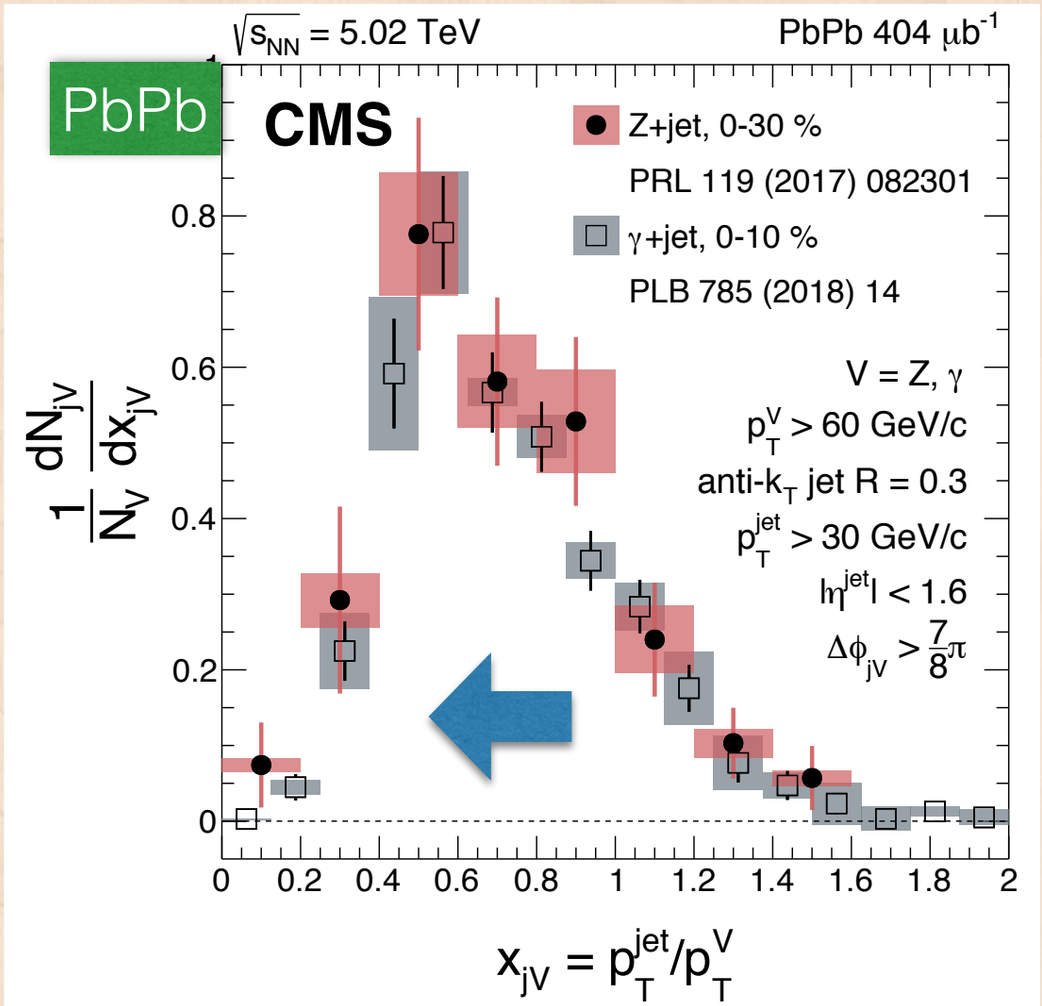
If there is energy loss, we will tend to see unbalanced dijets



PLB 774 (2017) 379

Z/γ-jet balance





Electroweak probes “tags” initial parton energy

A significant shift in the Z/γ-jet balance is observed

PRL 119 (2017) 082301, PLB 785 (2018) 14

Constituents

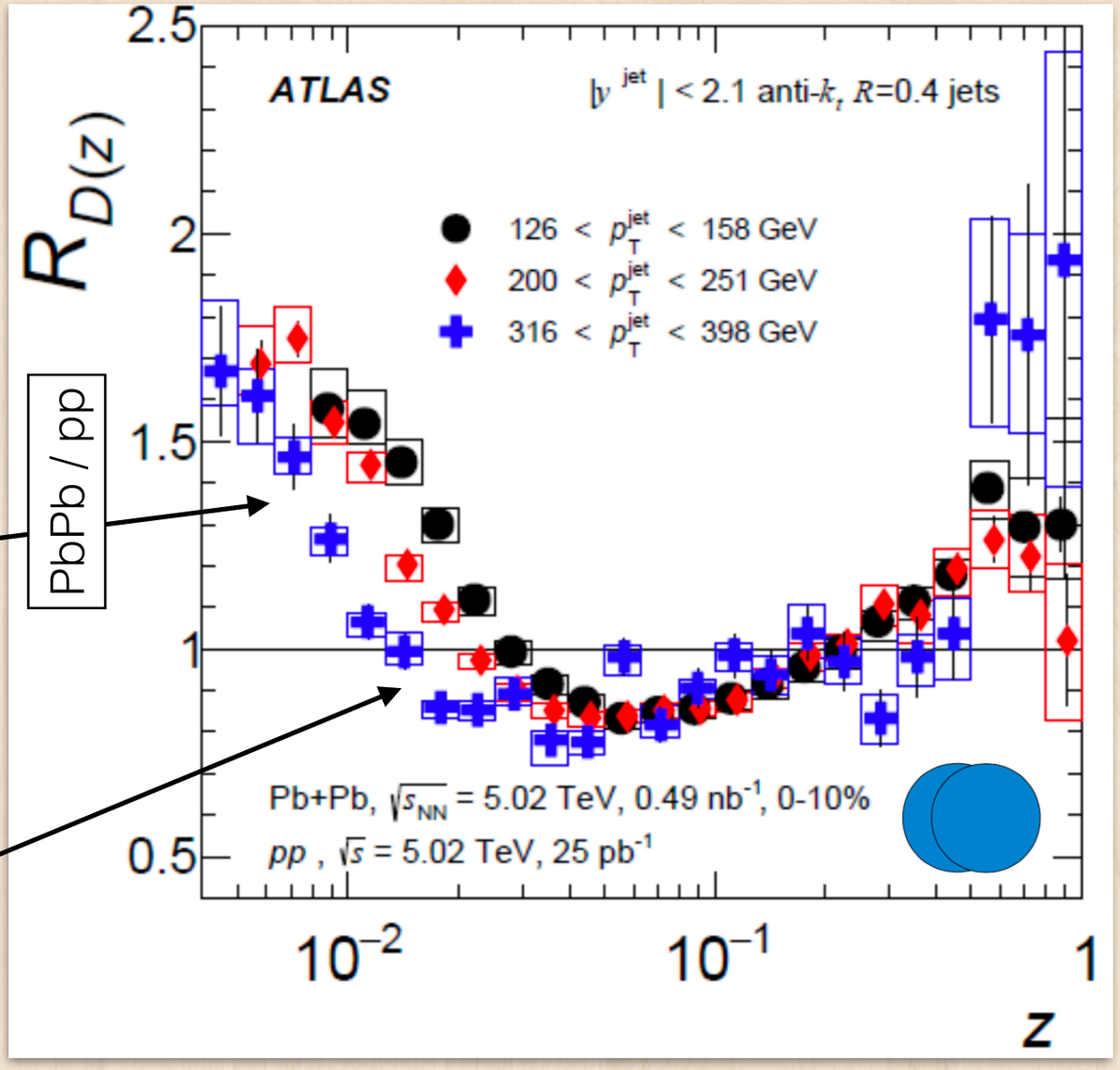
Jet fragmentation

z = fraction of jet momentum carried by track

R = Fragmentation ratio
PbPb / pp

Enhancement of low energy tracks

Relative suppression of moderate energy tracks



PRC 98 (2018) 204908, for CMS see PRC 90 (2014) 024908

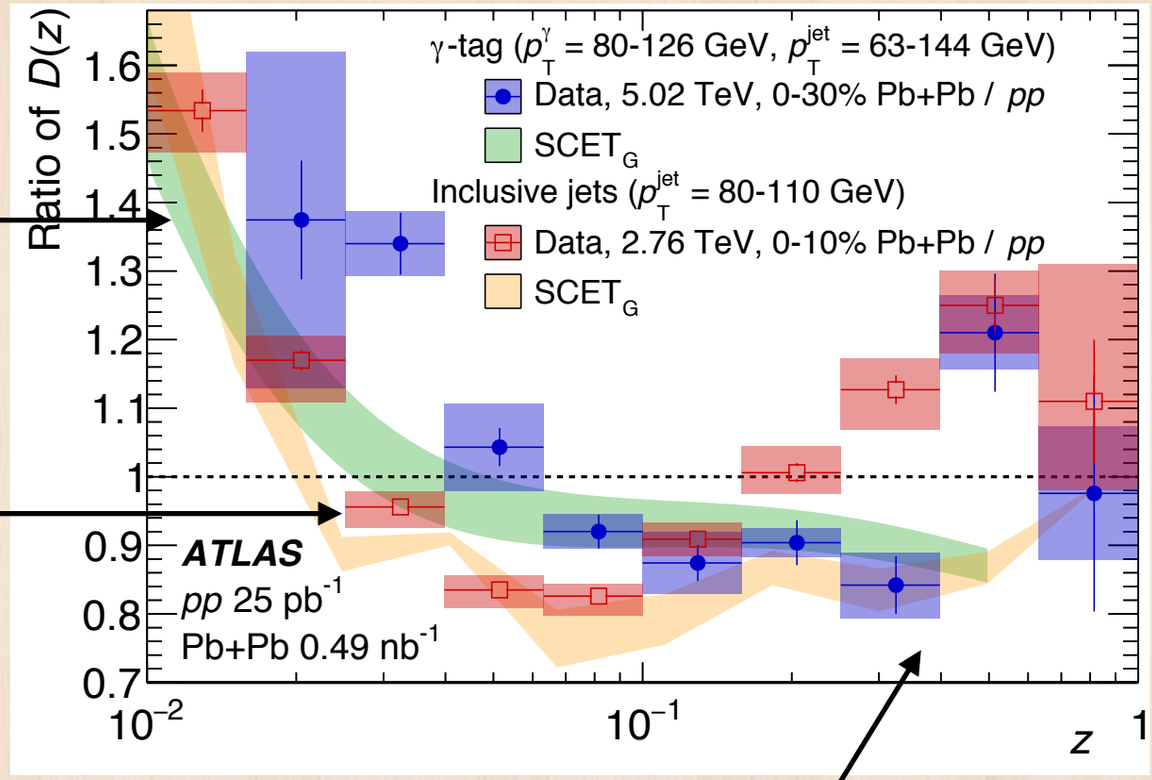
γ-jet fragmentation

Similar overall structure

Low-z enhancement

Moderate-z suppression

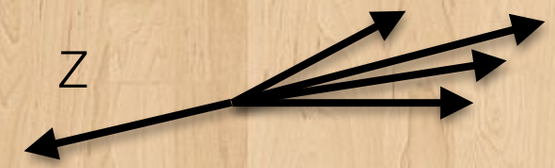
Inclusive jet **Photon-tagged jet**

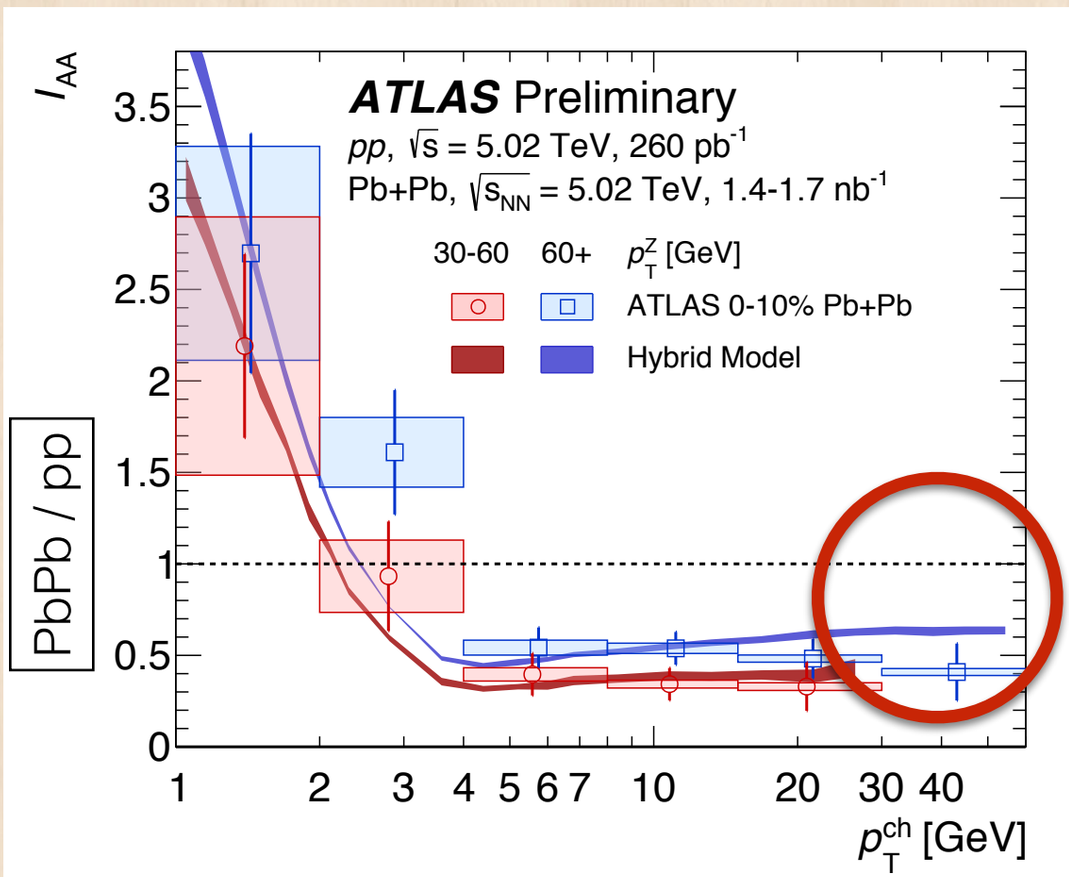


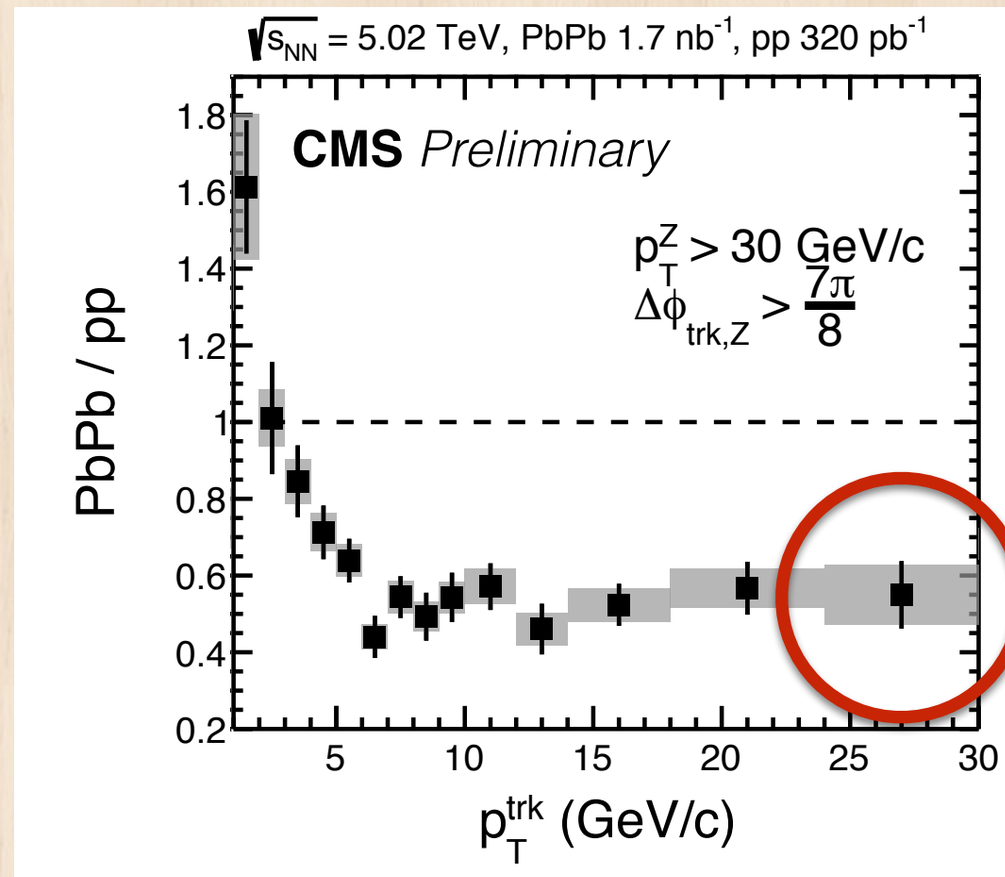
Some sign of lower enhancement at high z for γ-tagged jets

PRL 123 (2019) 042001, for CMS see: PRL 121 (2018) 242301

Z-tagged yields



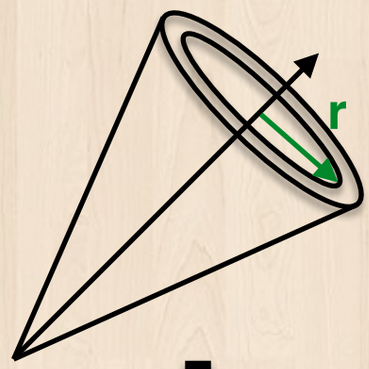


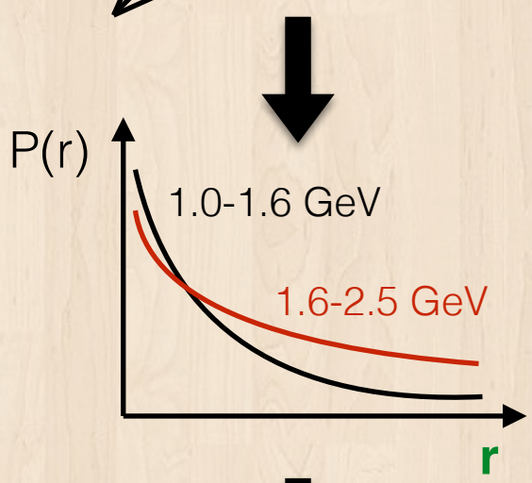


Suppression of high momentum associated particle

Radial profiles

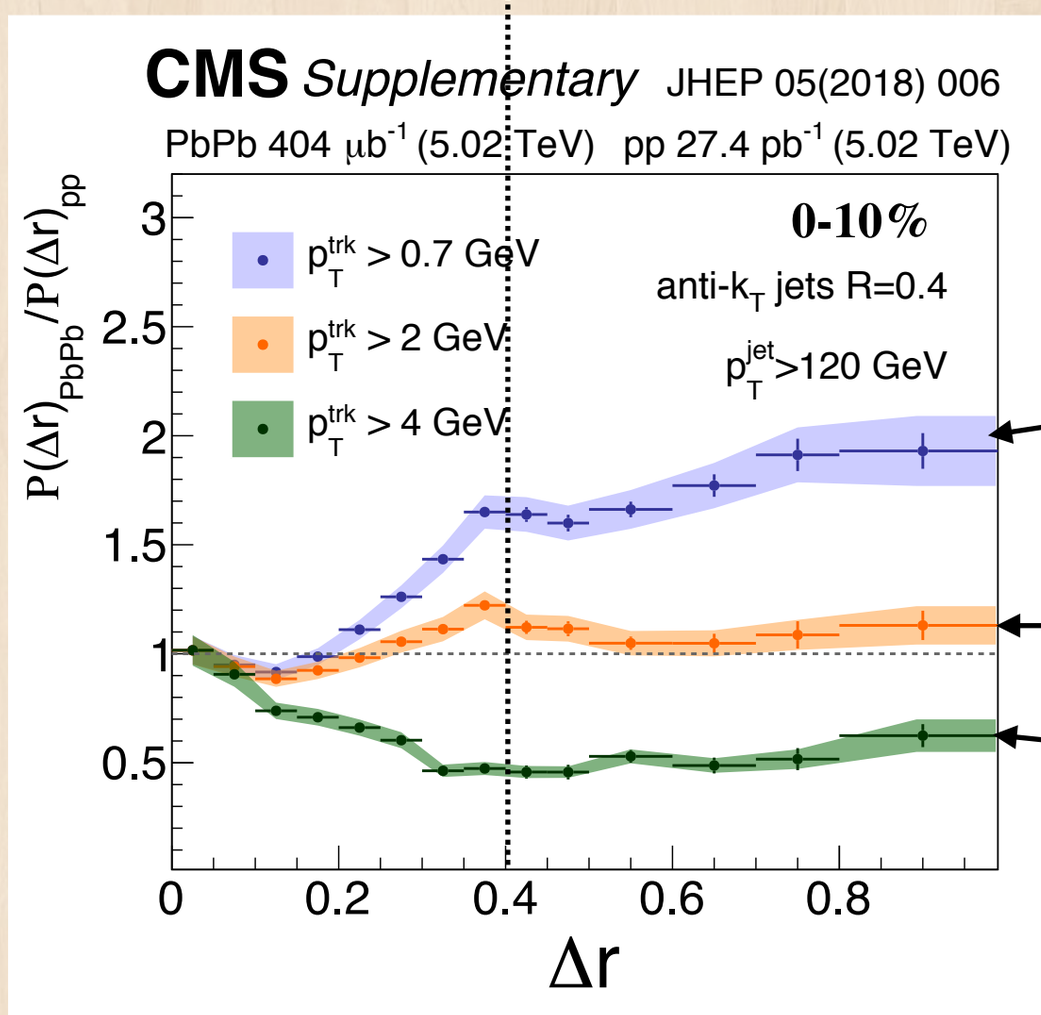
Inclusive jet





PbPb / pp

Inside jet ⟷ Outside jet



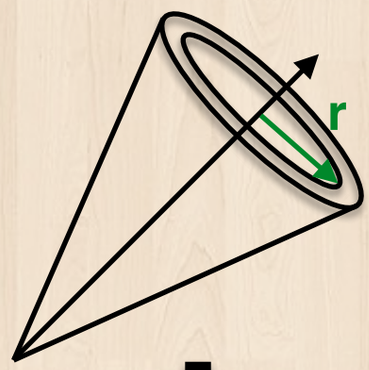
Energy outside jet cone is mostly low energy particles

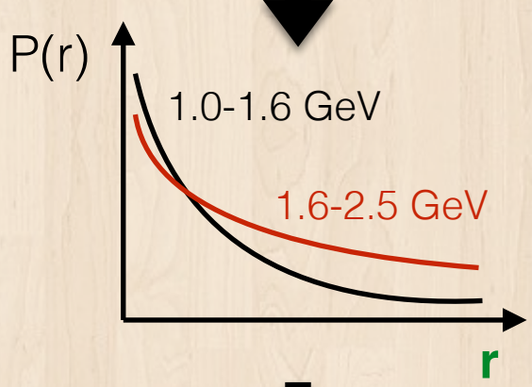
CMS: JHEP 05 (2018) 006, ATLAS: PRC 100 (2019) 064901

See also JHEP 01 (2016) 006

Radial profiles

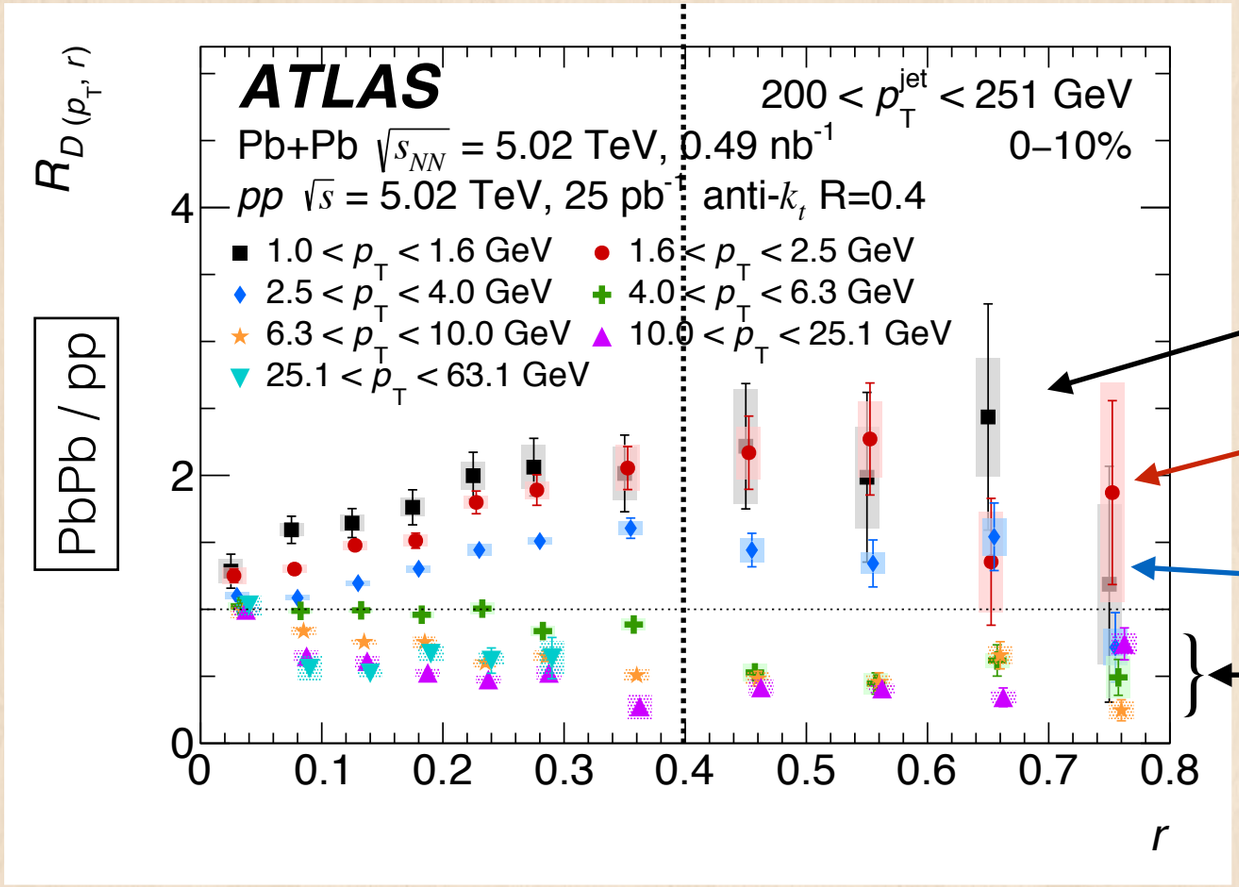
Inclusive jet





PbPb / pp

Inside jet ⟷ Outside jet



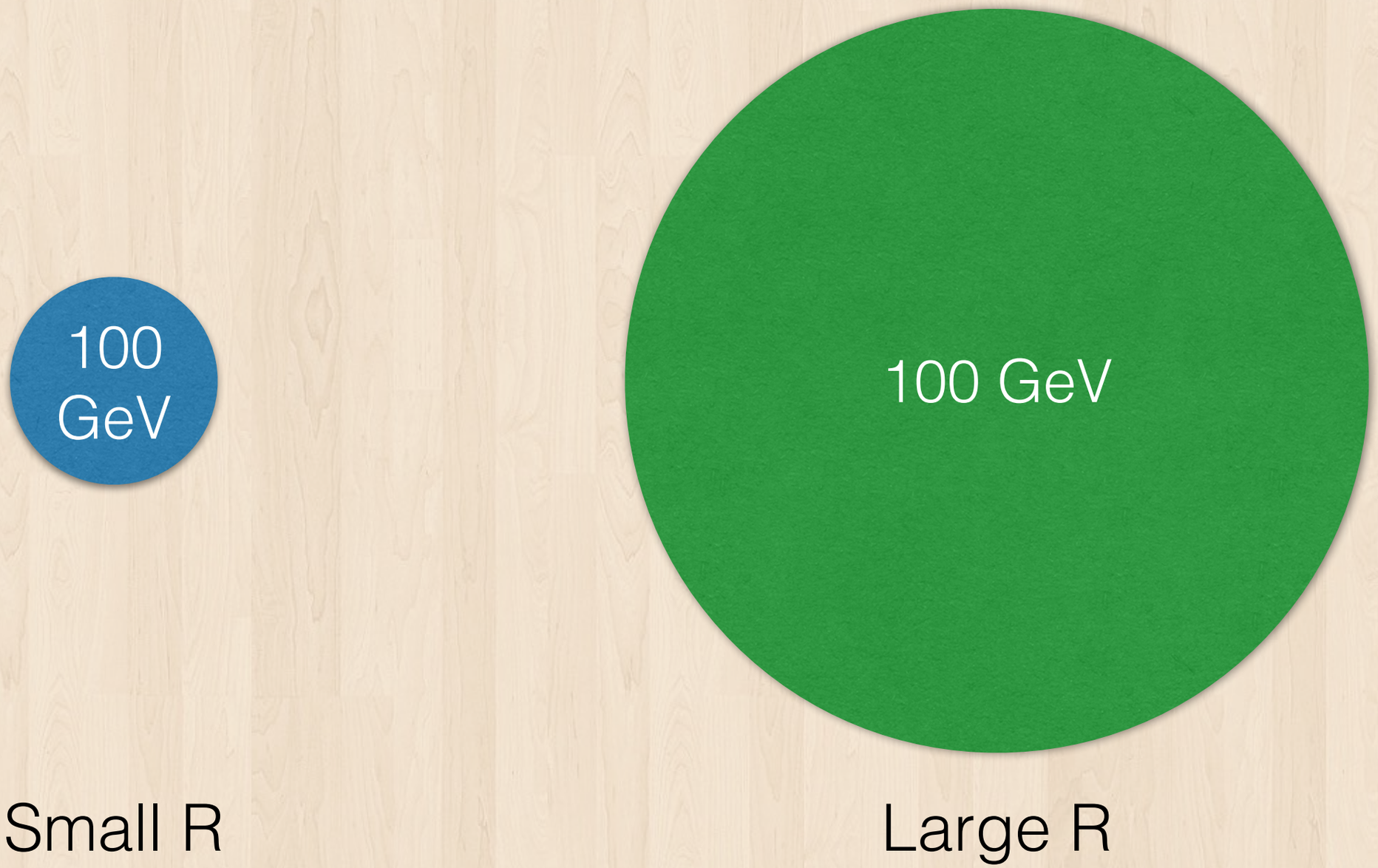
Energy outside jet cone is mostly low energy particles

If we enlarge the jet size, can we recover the energy?

Large R jets

Jet population

Jet clustering ensures concentrated energy in O(R)



Jet population

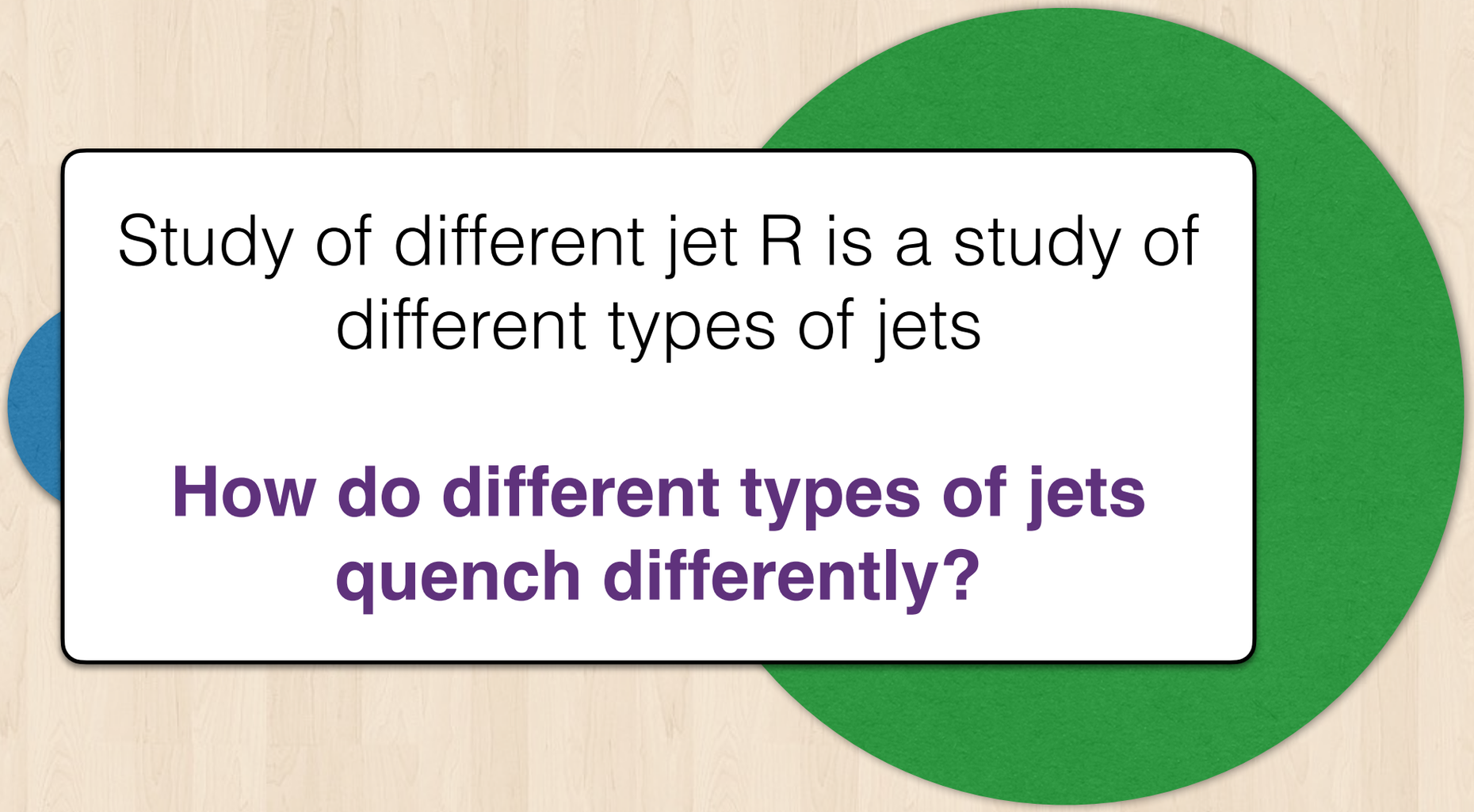
Jet clustering ensures concentrated energy in O(R)

Collimated

Collimated, or diffuse

Jet population

Jet clustering ensures concentrated energy in O(R)



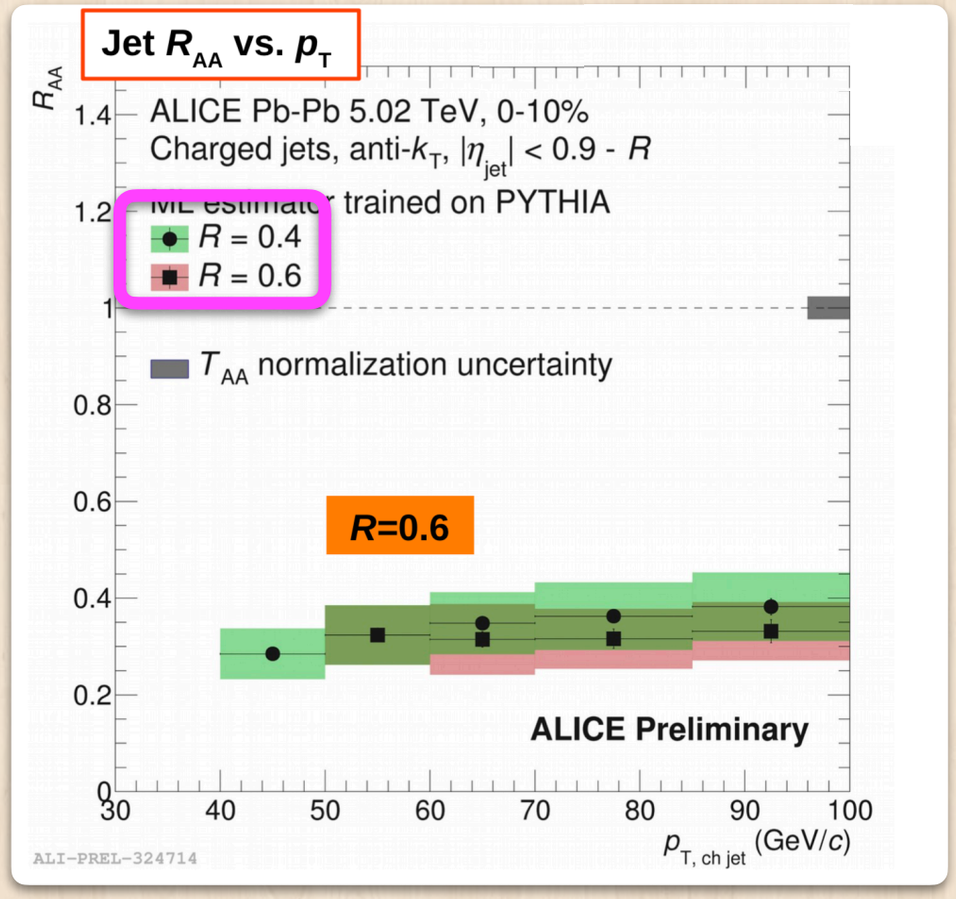
Study of different jet R is a study of different types of jets

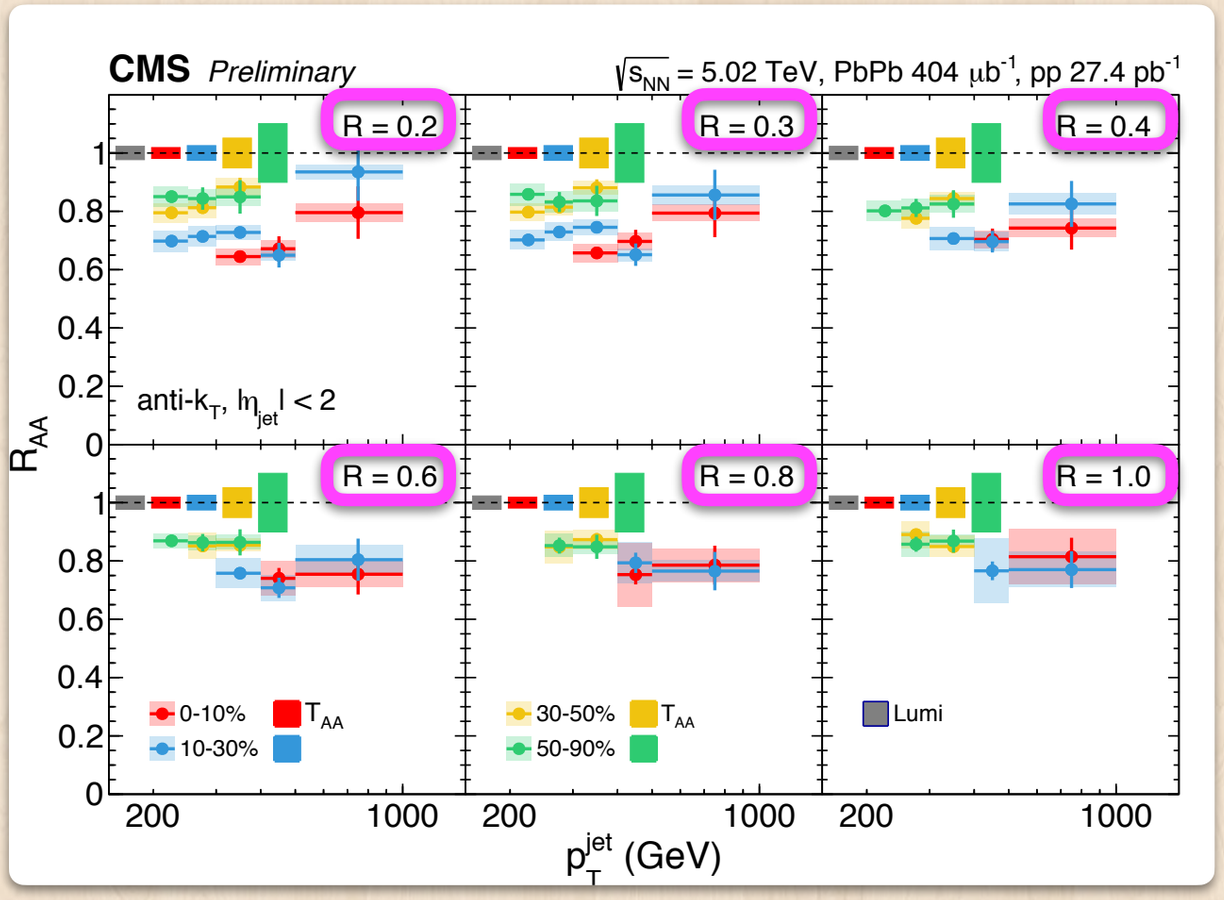
How do different types of jets quench differently?

Collimated

Collimated, or diffuse

Large R jets





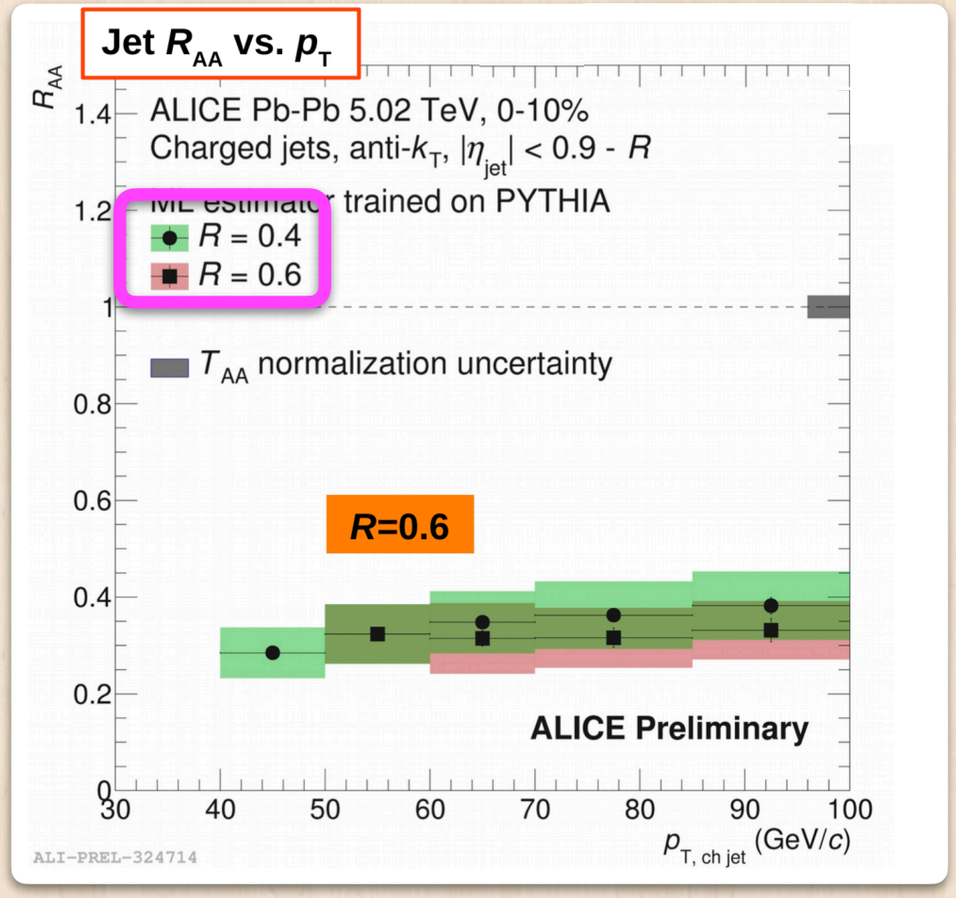
Novel use of ML techniques to go low in momentum

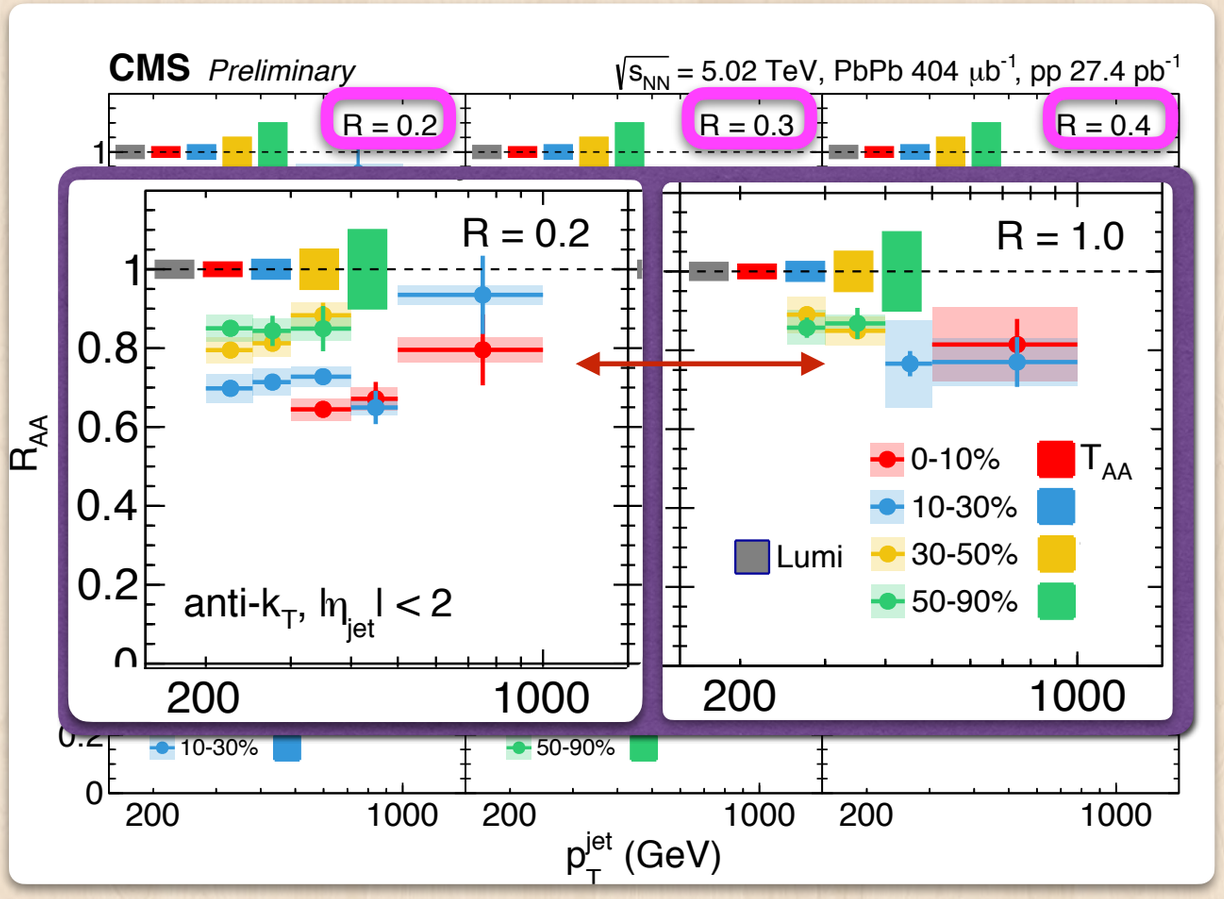
Suppression for all jet radii!
Very mild R-dependence

Jet population is different

ALICE Preliminary, CMS HIN-18-014

Large R jets





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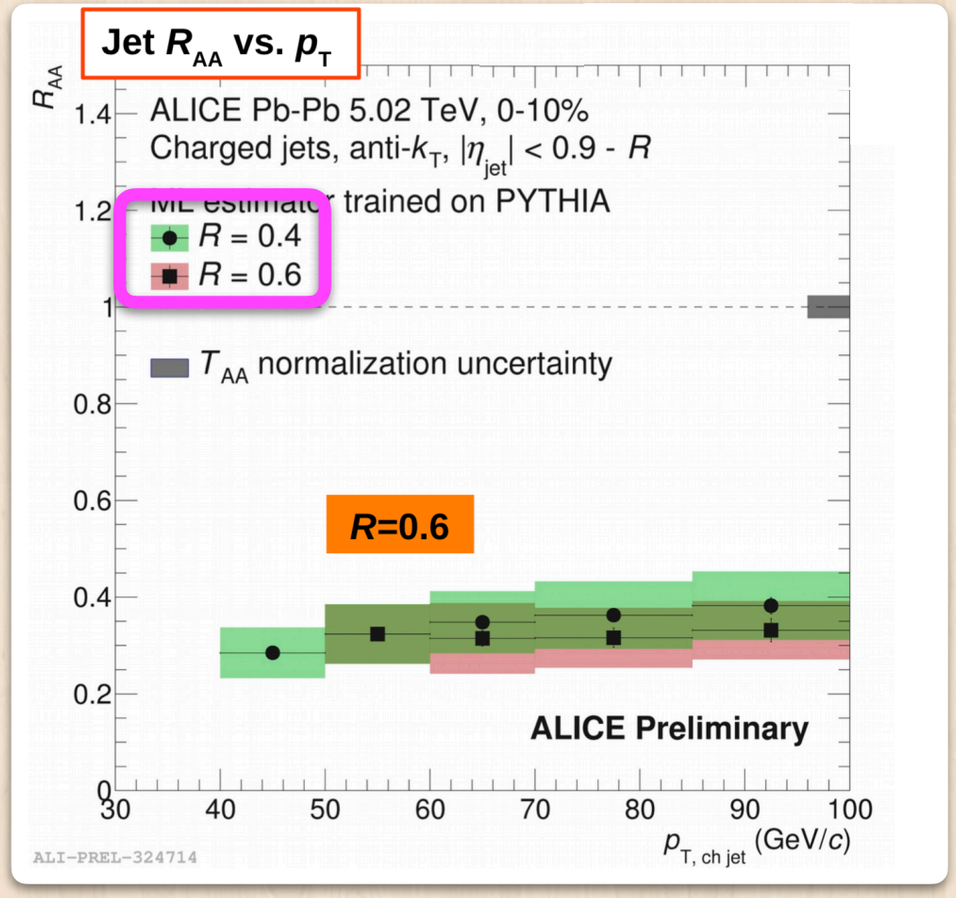
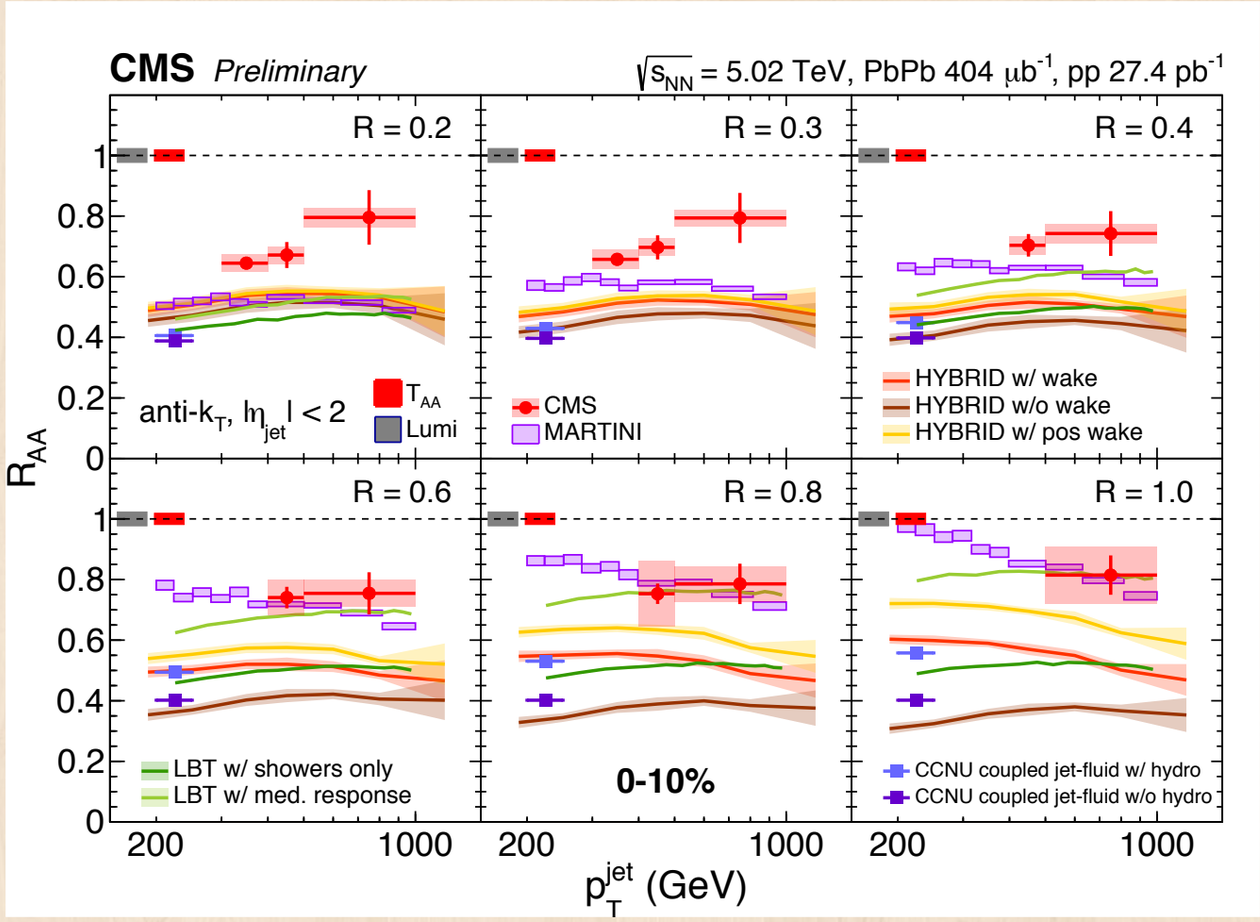




Novel use of ML techniques to go low in momentum

Wide range of predictions on the R-dependence from theories

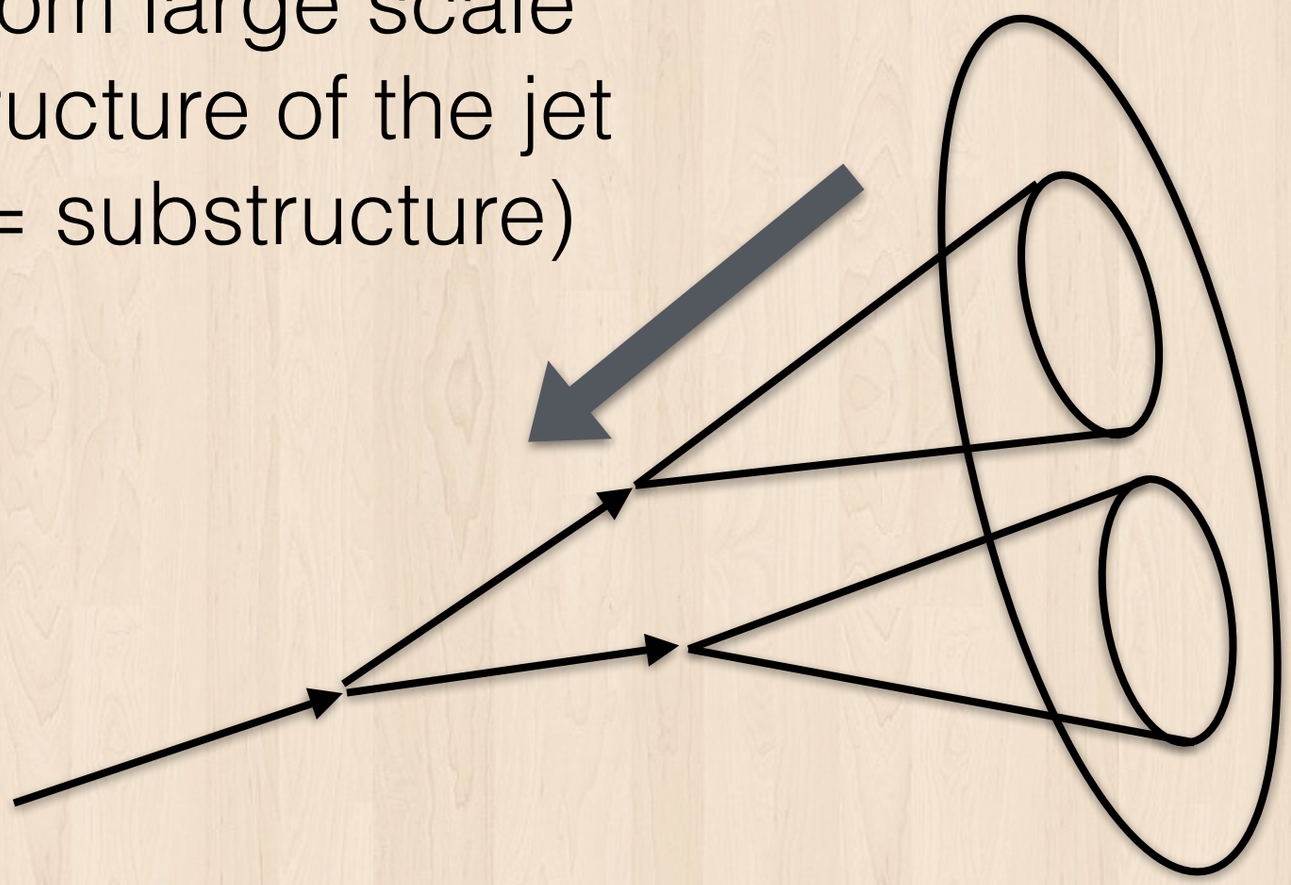
Jet population is different

ALICE Preliminary, CMS HIN-18-014

Substructure

Jet substructure

Infer shower history from large scale structure of the jet (= substructure)



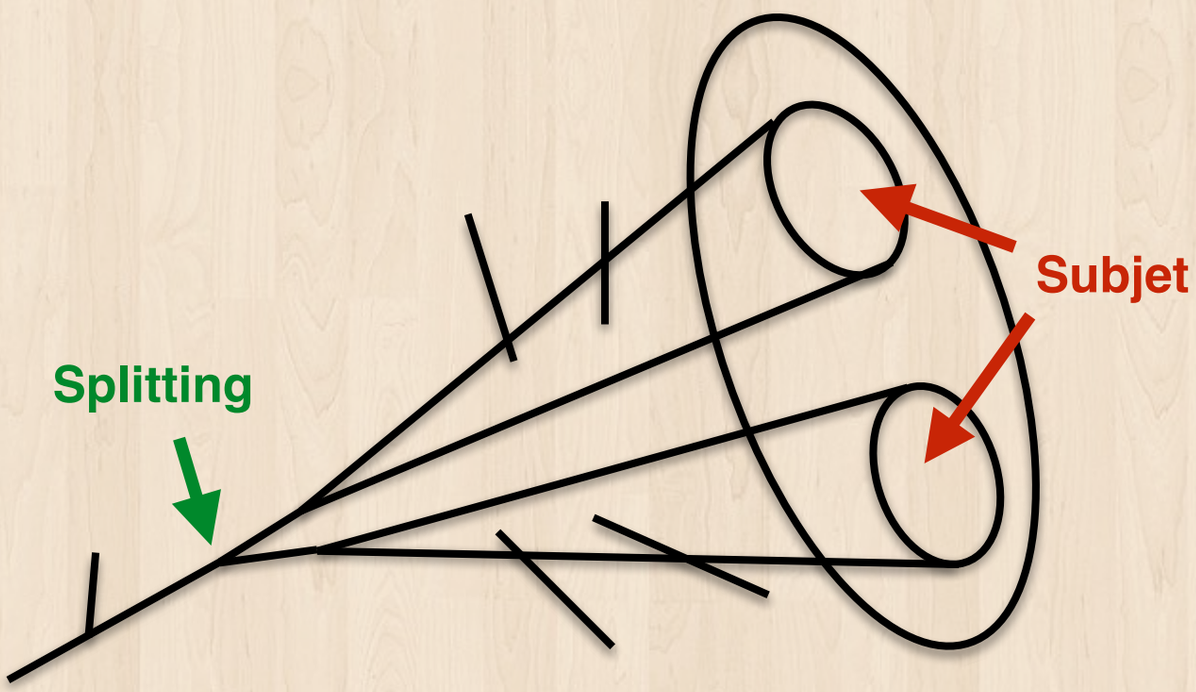
Classify jets using jet substructures

How do different types of jets quench differently?

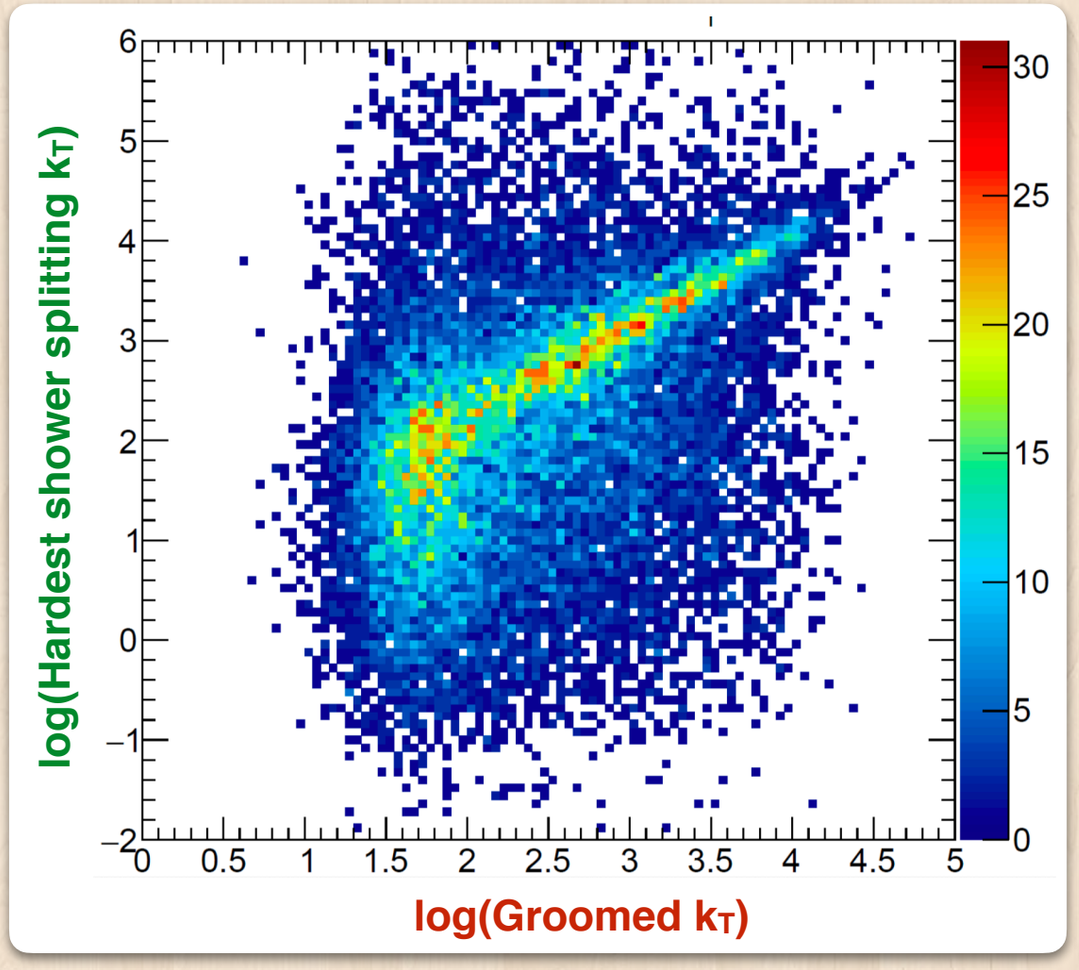
Jet grooming

For example SoftDrop/mMDT

Subjet: proxy for the hardest shower splitting

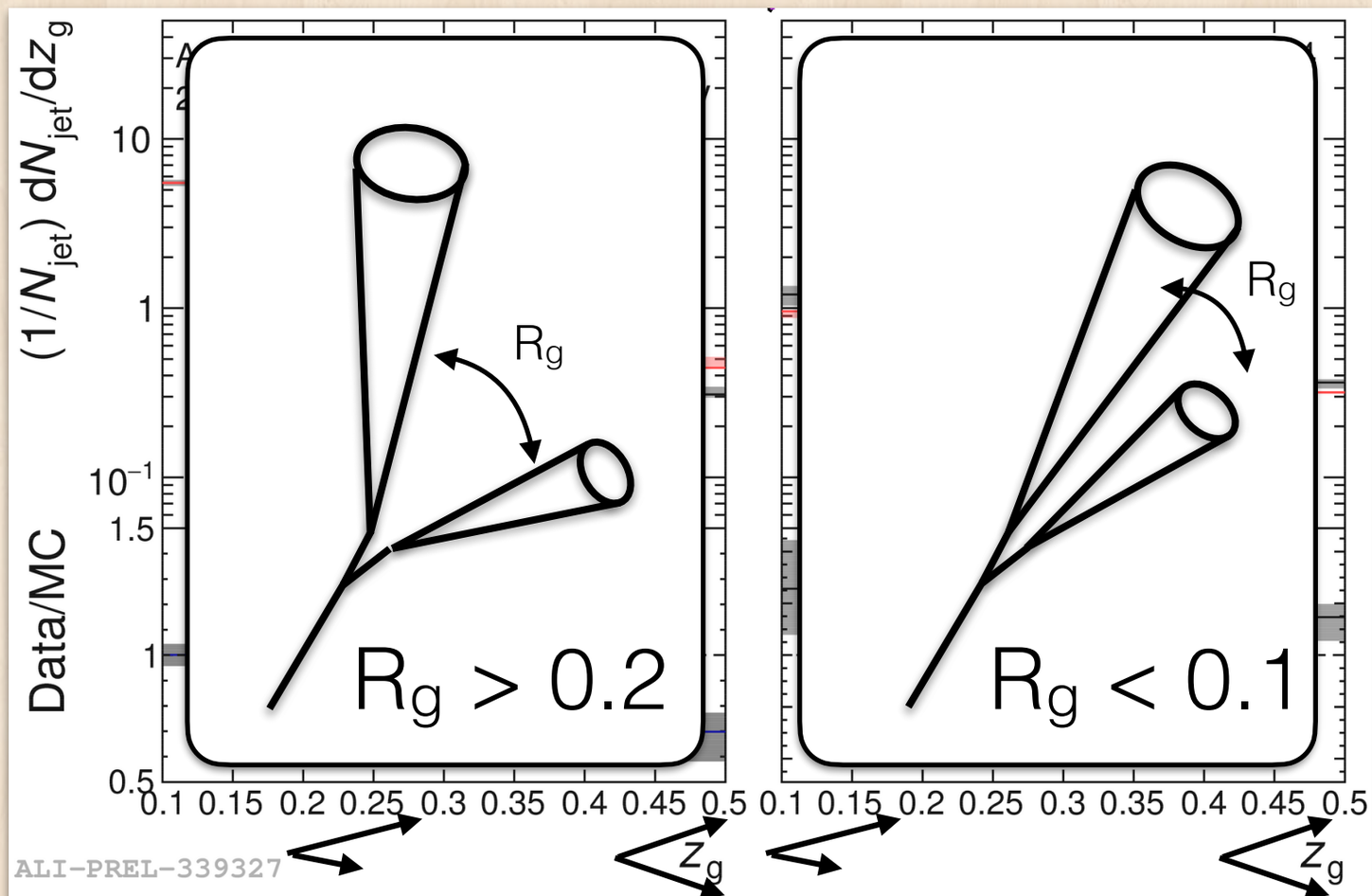


Background-subtracted jet in PbPb



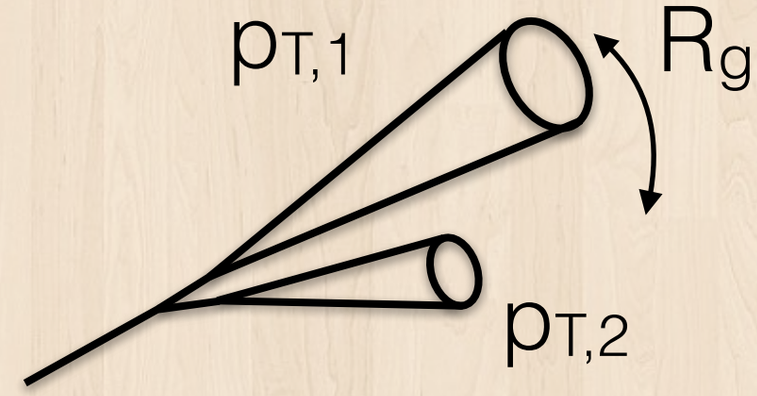
Identified subjets are correlated with the parton shower

Momentum sharing



$$z_g \equiv \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$$

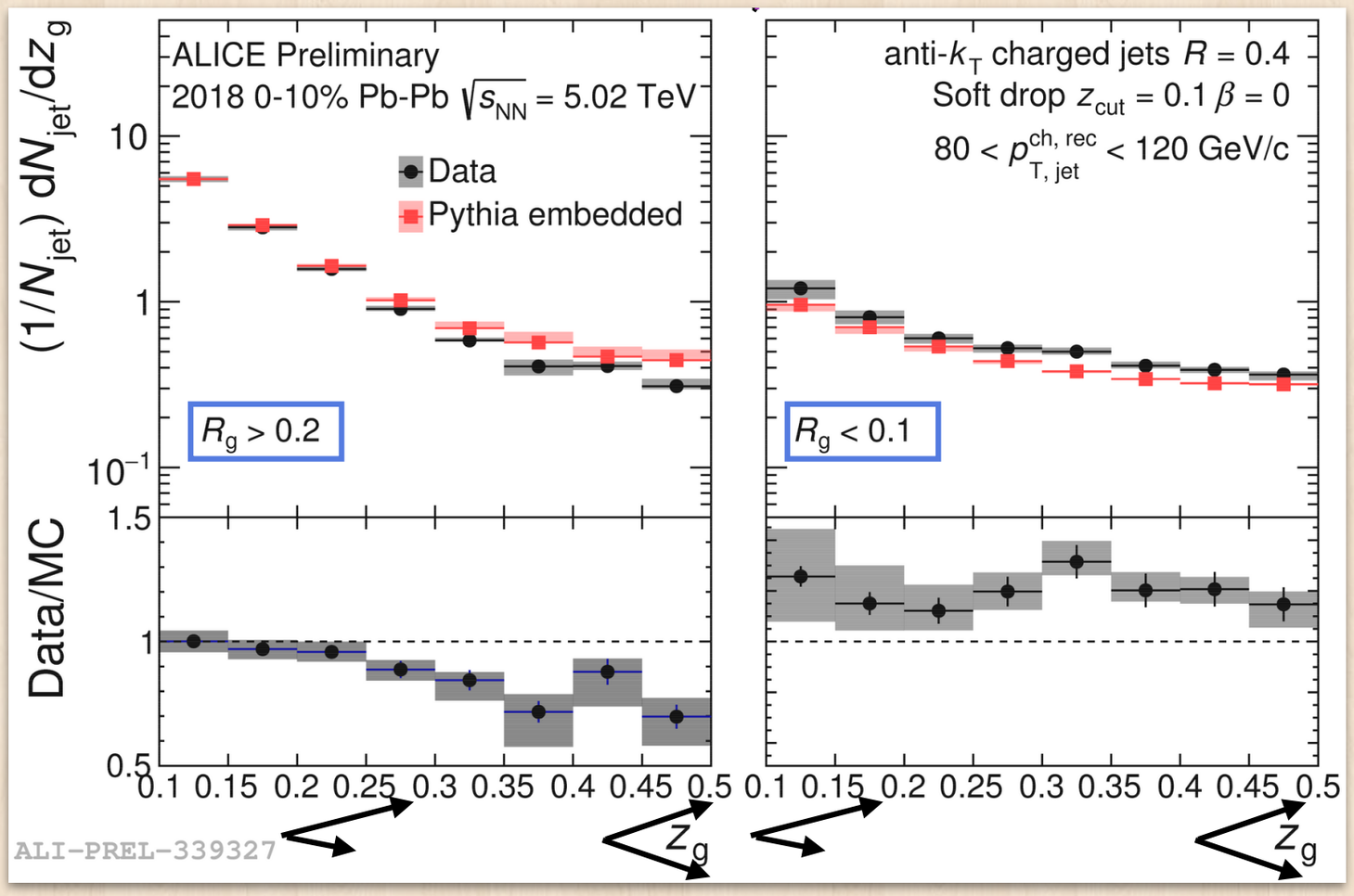
p_T fraction carried by softer subjet



Large-angle balanced subjets suppressed

Medium resolving the subjets inside wider jets?

Momentum sharing



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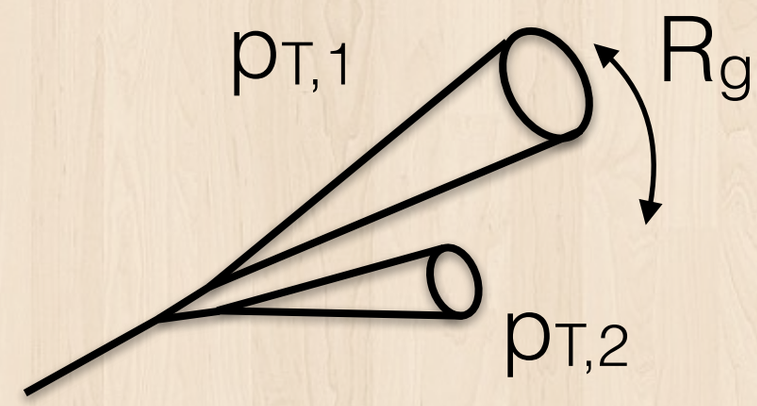
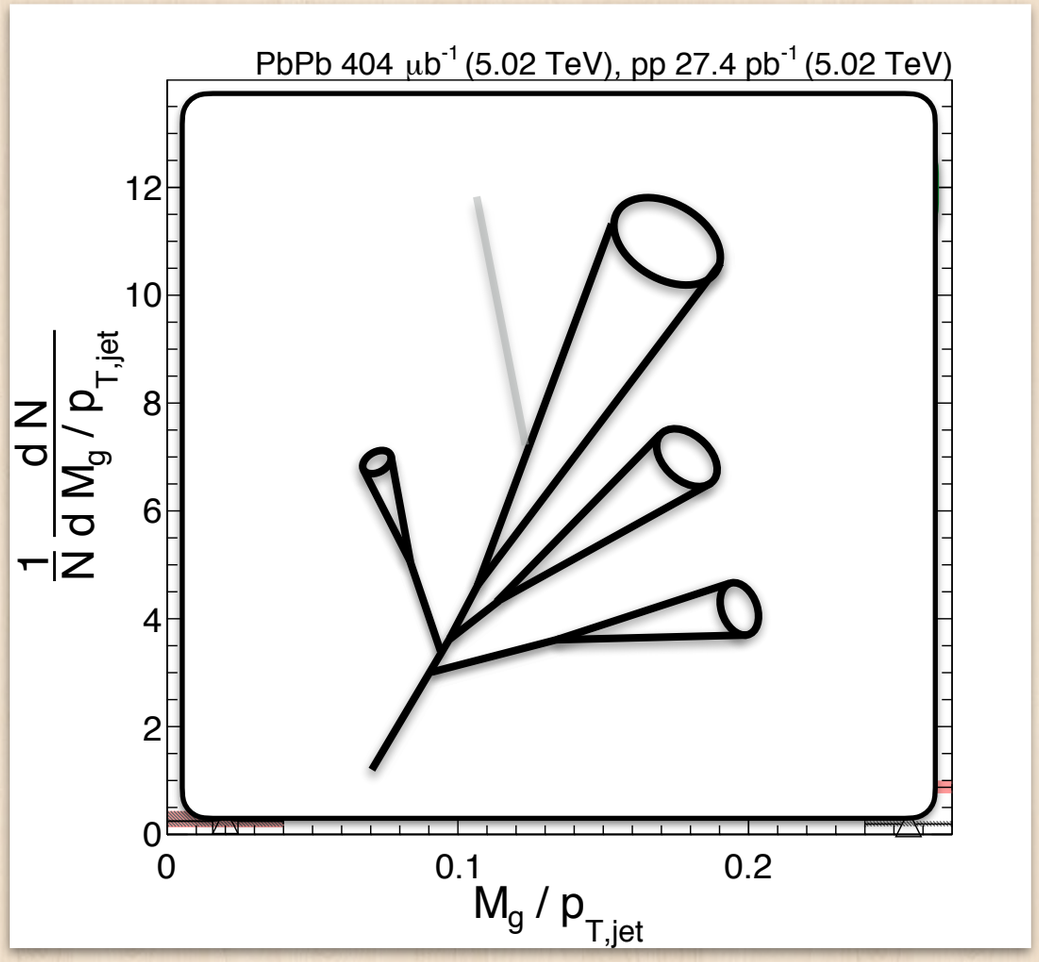
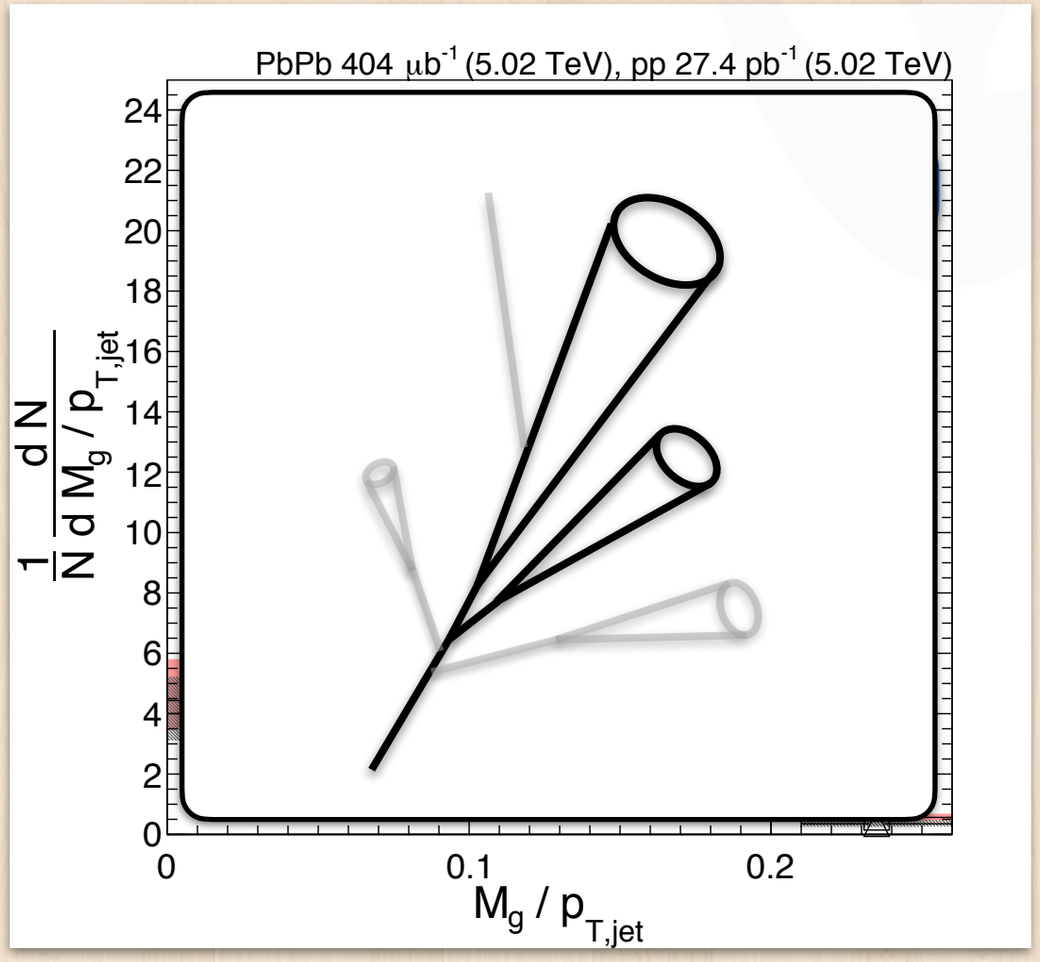


Large-angle balanced subjets suppressed

Medium resolving the subjets inside wider jets?

Groomed jet mass





full jet

Hint of larger mass

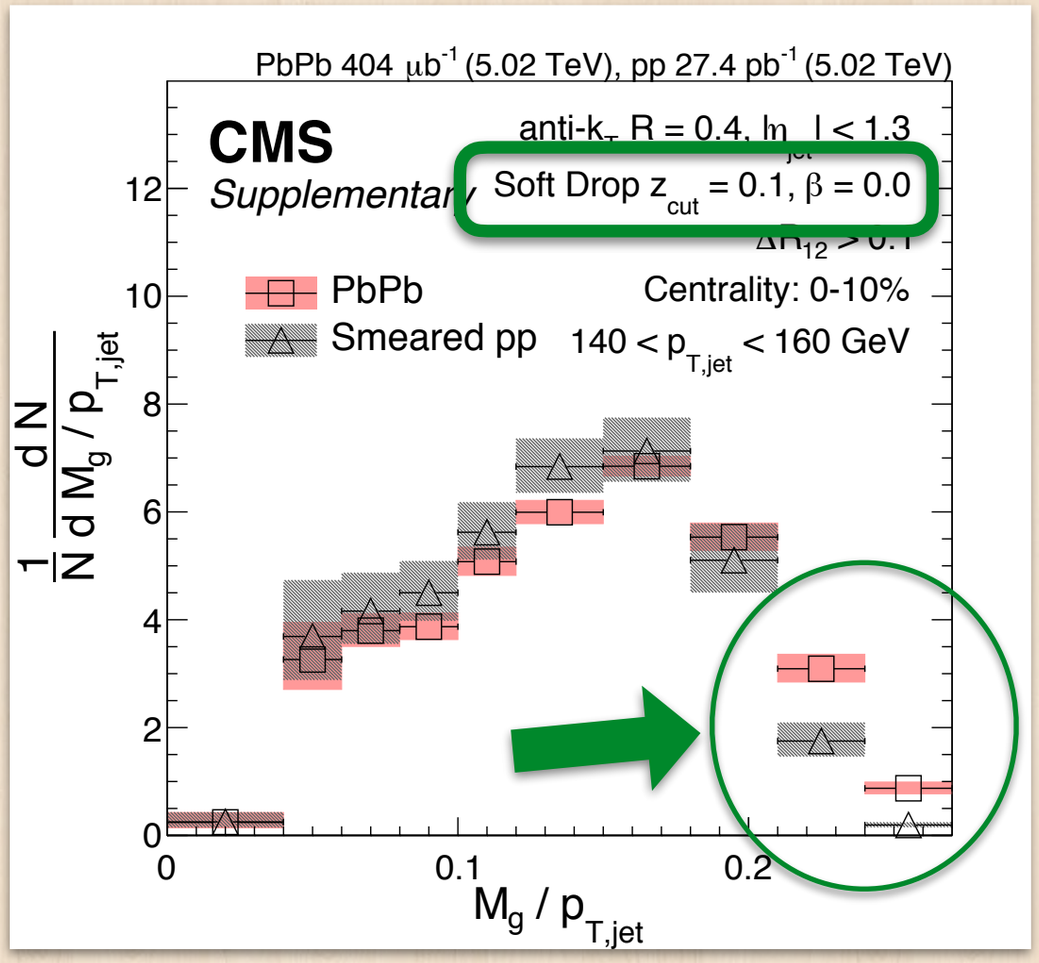
core of the jet

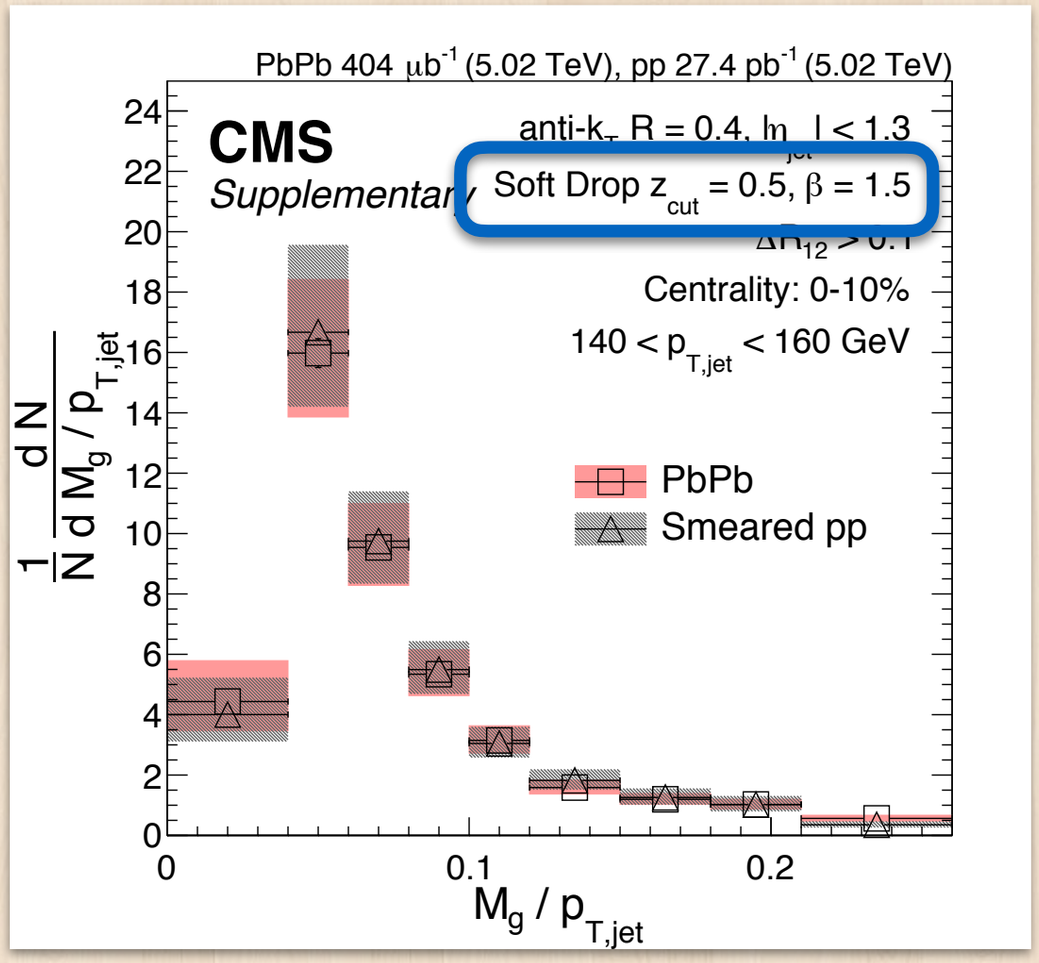
pp ~ PbPb

Points to large angle modification in the jet for mass

JHEP 10 (2018) 161

Groomed jet mass





full jet

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core of the jet

pp ~ PbPb

Points to large angle modification in the jet for mass

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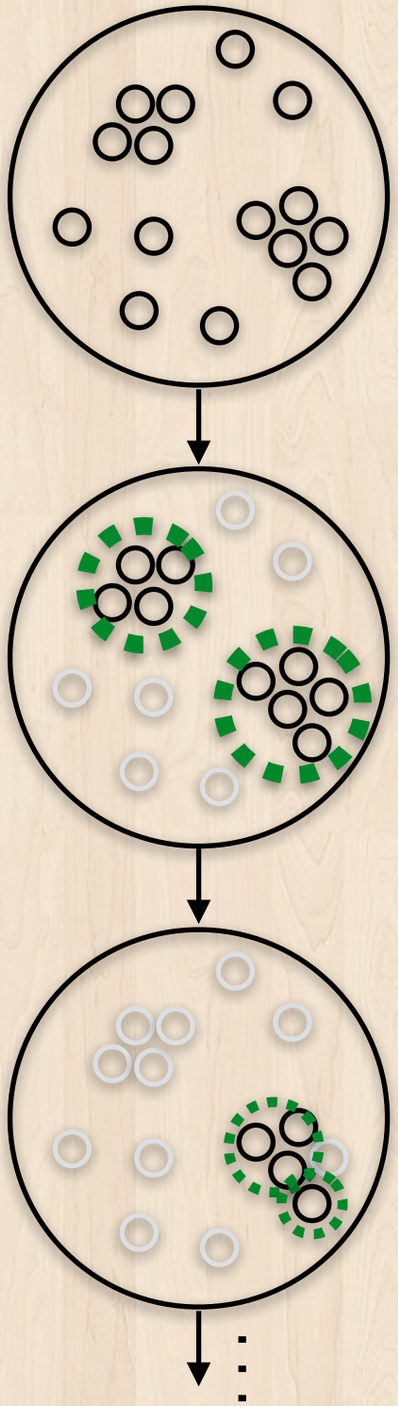
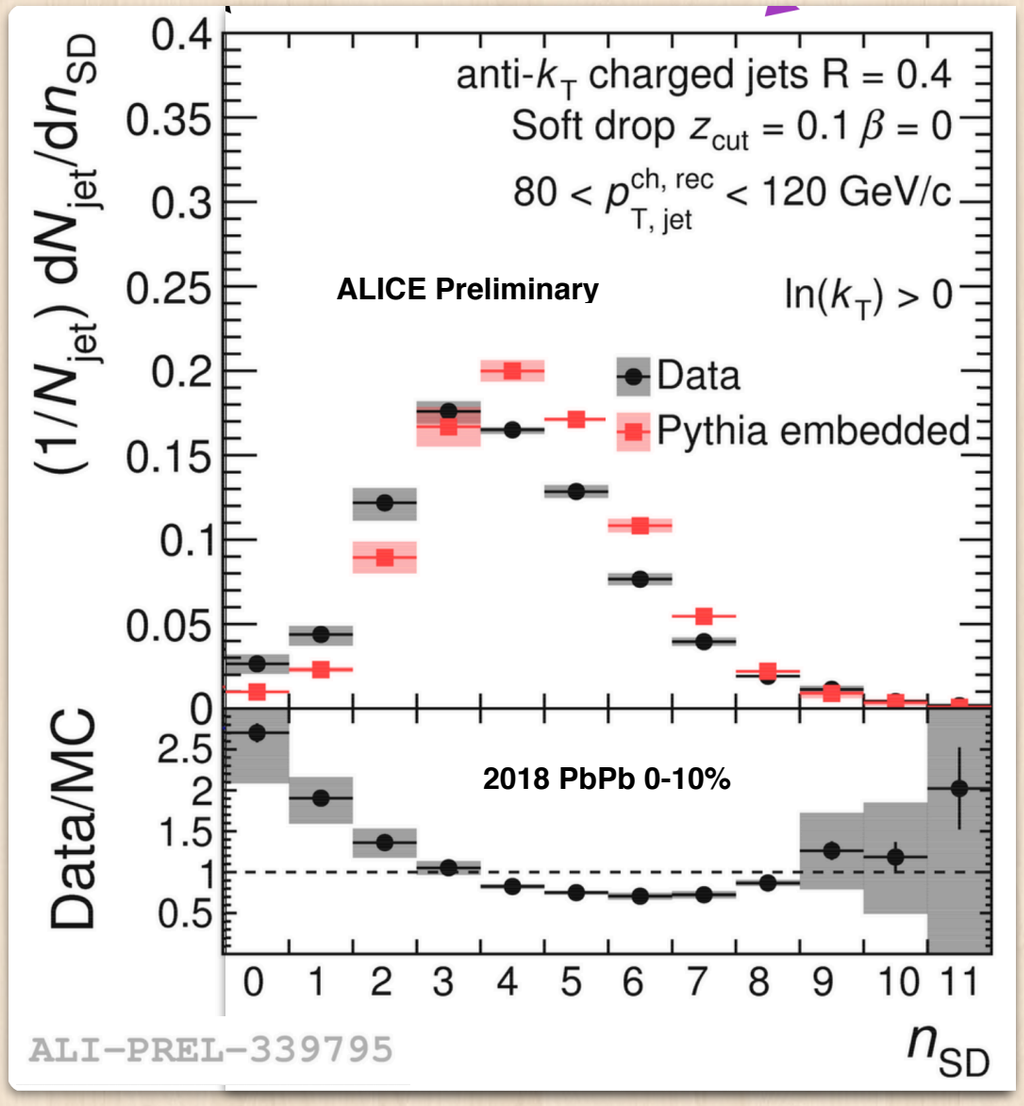
Grooming count



Count how many times we can groom a jet before nothing is left

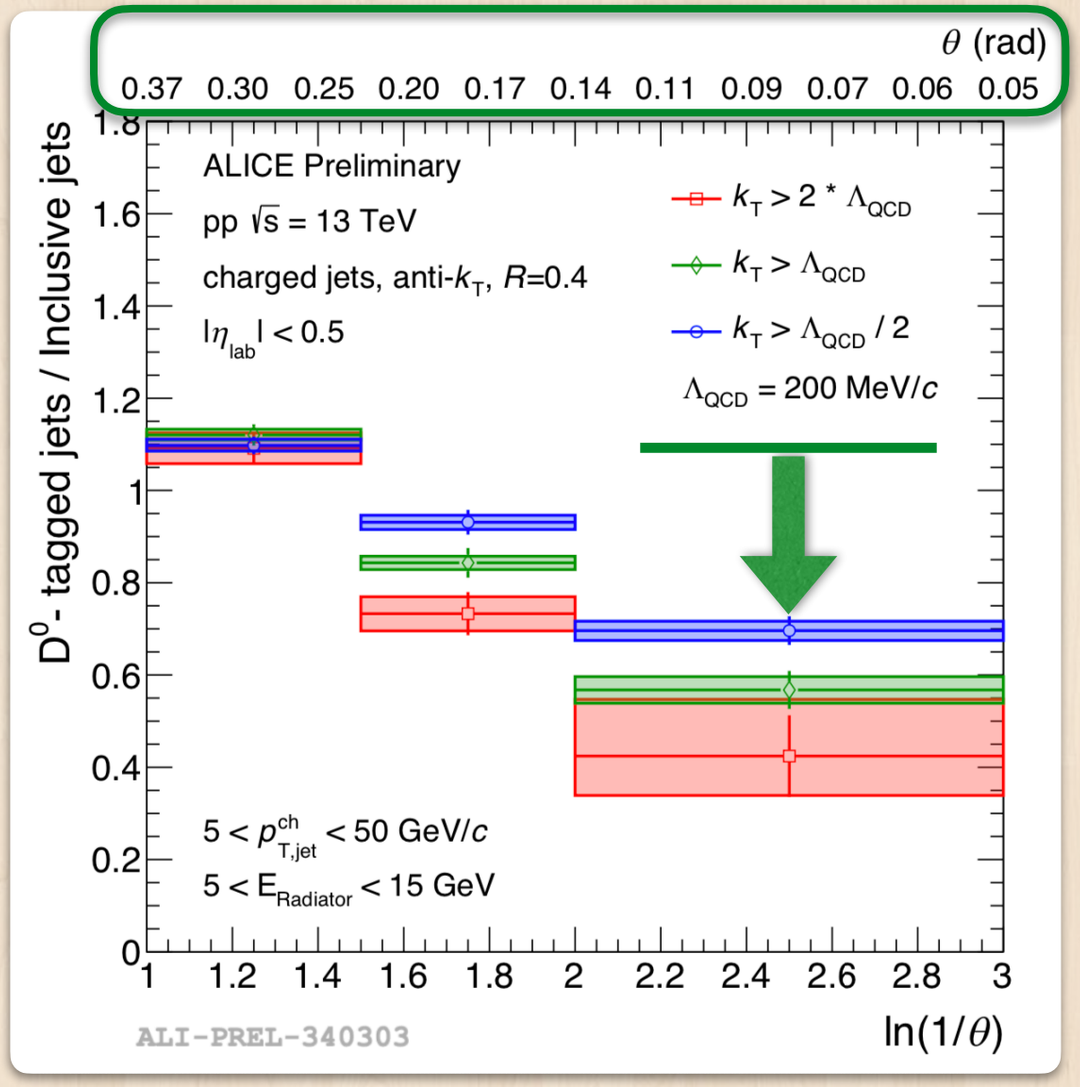


Information on number of shower splittings (vacuum)

Data favors smaller n_{SD}

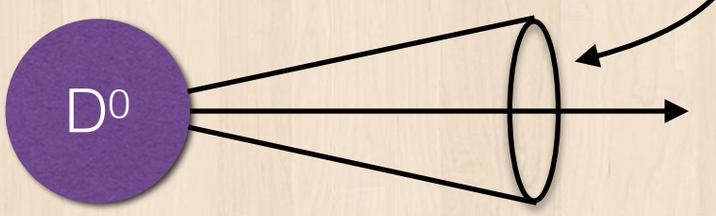
Consistent with z_g observations

Dead-cone effect



Dead-cone effect: heavy object less likely to radiate in the moving direction

Small angle structure in heavy flavor jets



Future measurement in PbPb?

Summary

Summary

- **Colorless probes: nPDF, initial state effects, reference for colored probes**
- Jet quenching: energy goes outside jet area as soft particles
- Large R jet are suppressed: only very mild R dependence. Jet population
- Substructure: information on shower history

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Looking forward to exciting new results in the near future!

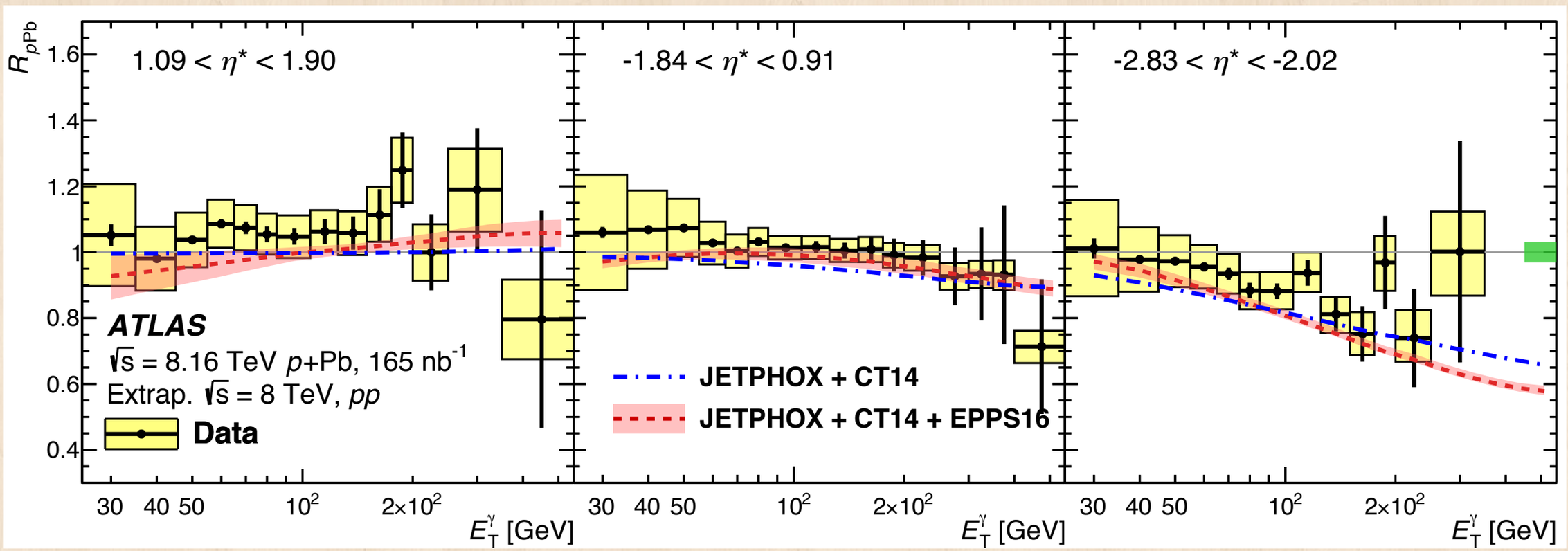
Thank you!

The MIT Group's work is supported by DOE-NP

Backup Slides Ahead

Isolated photons in pPb

R_{pPb} = pPb cross section / scaled pp cross section



Good probe for initial state effects

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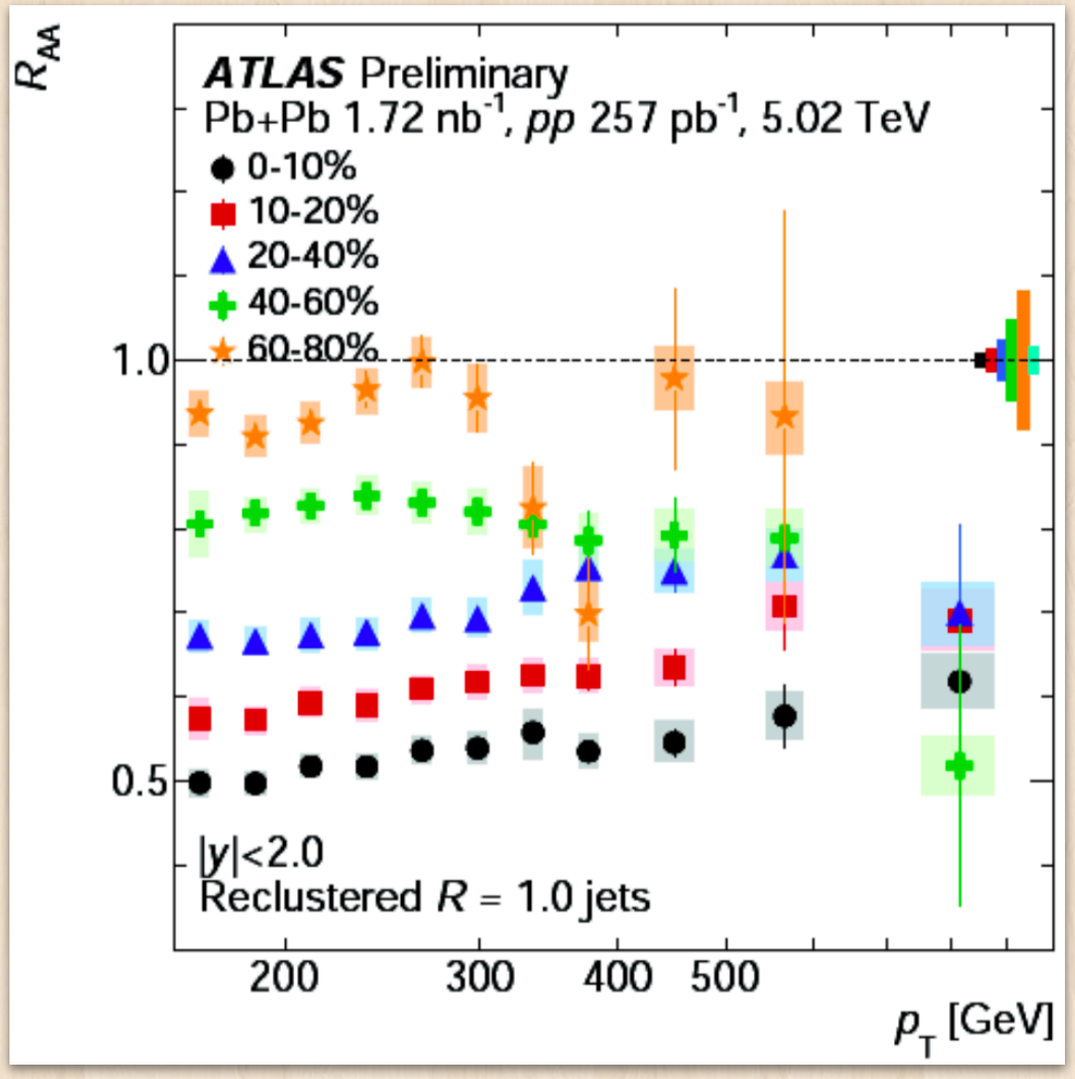
Reclustered jets

Input (calorimeter) → R = 0.2 PT > 35 GeV → R = 1.0



Special population of R = 1.0 jets with 35 GeV constituents

"Cleaned" jets: less soft part

Similar R_{AA} as inclusive jets

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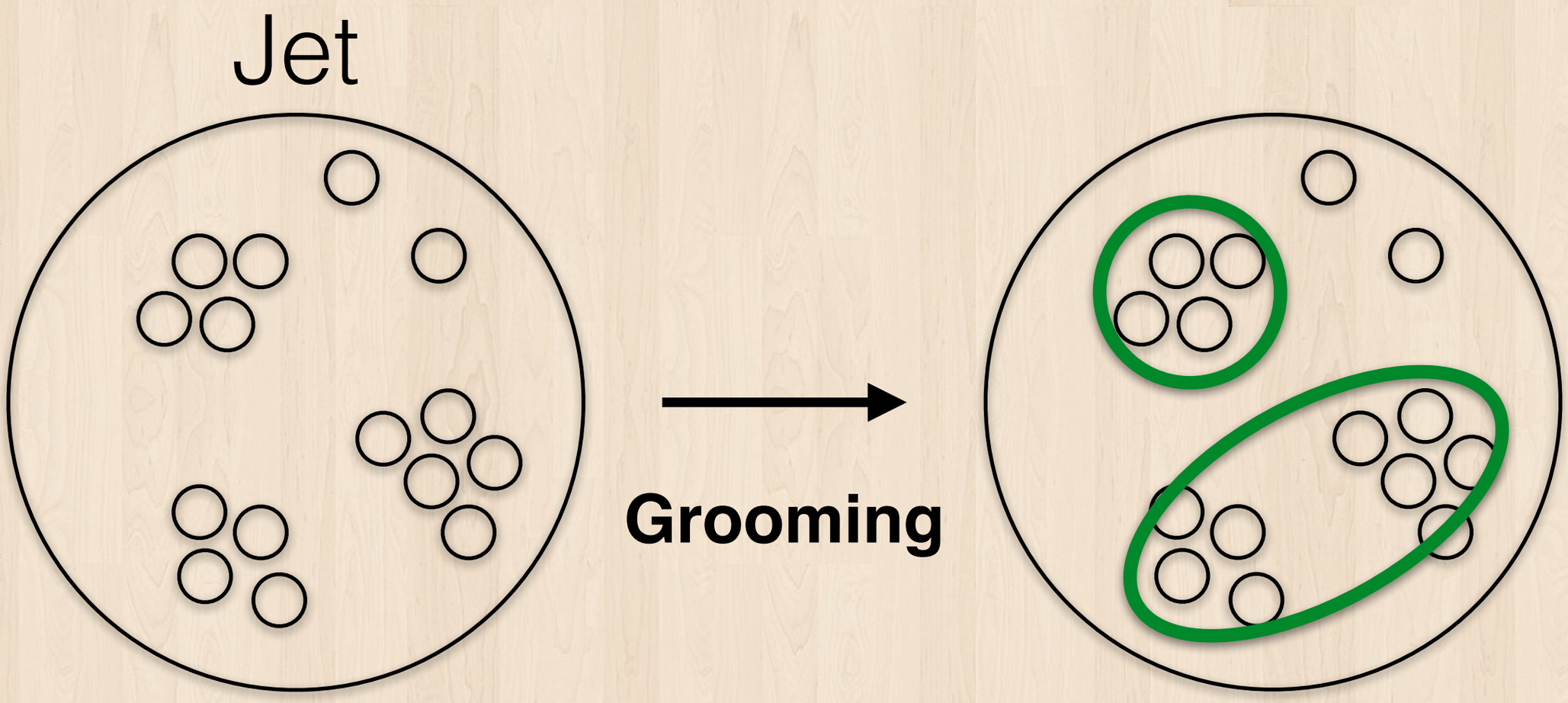
Jet grooming



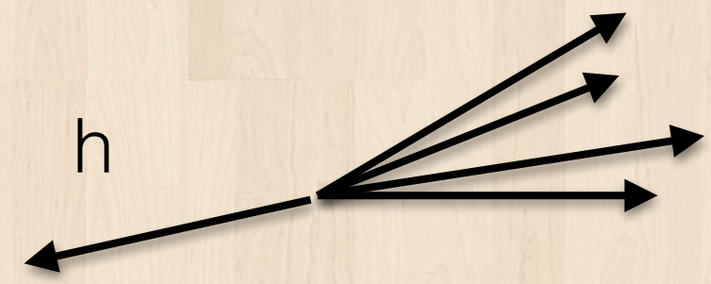
large scale structure ("subjet")

RAA formula

$$R_{\mathrm{AA}} \equiv \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{dN^{\mathrm{PbPb}} / dX}{dN^{\mathrm{pp}} / dX}$$

cf. associated yield

Also established in RHIC



Track p_T (GeV)

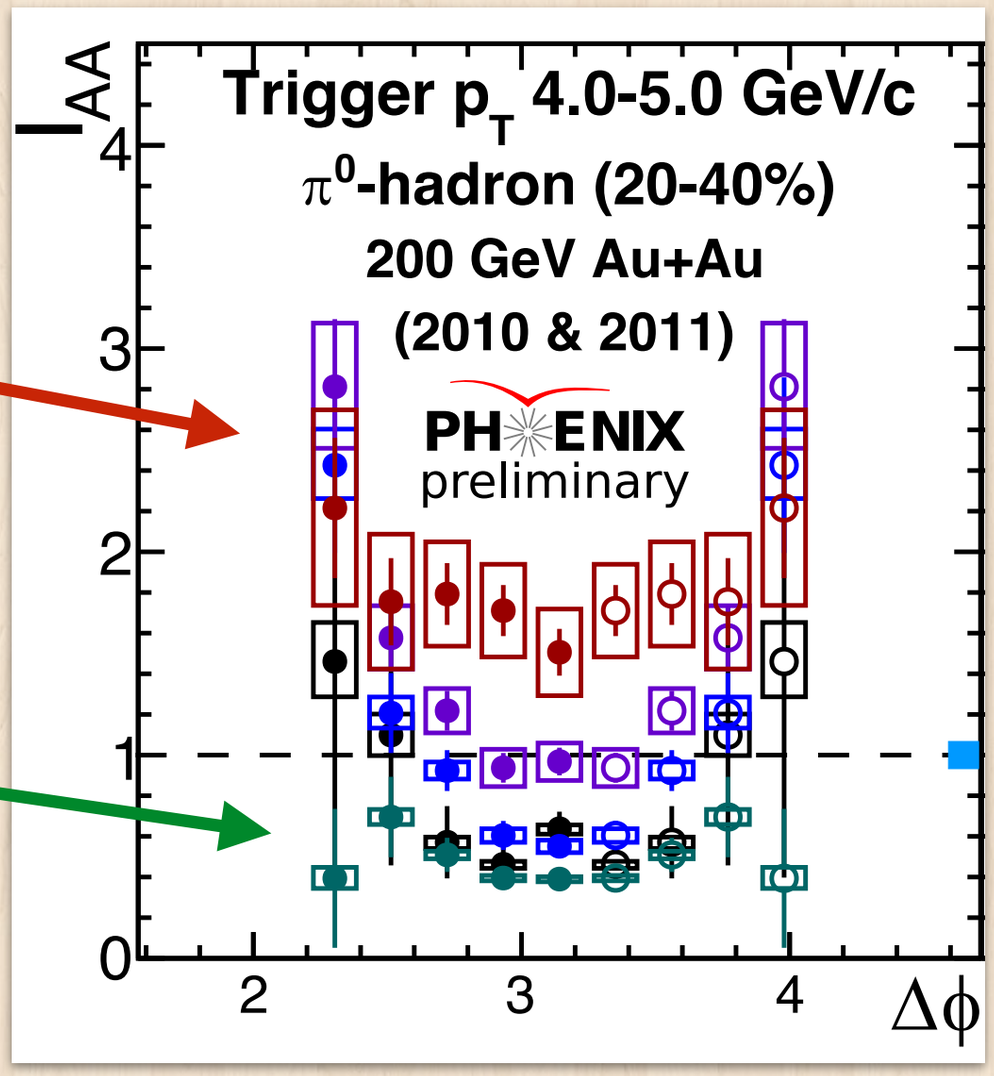
0.5-1.0

1.0-2.0

2.0-3.0

3.0-5.0

5.0-7.0



±1

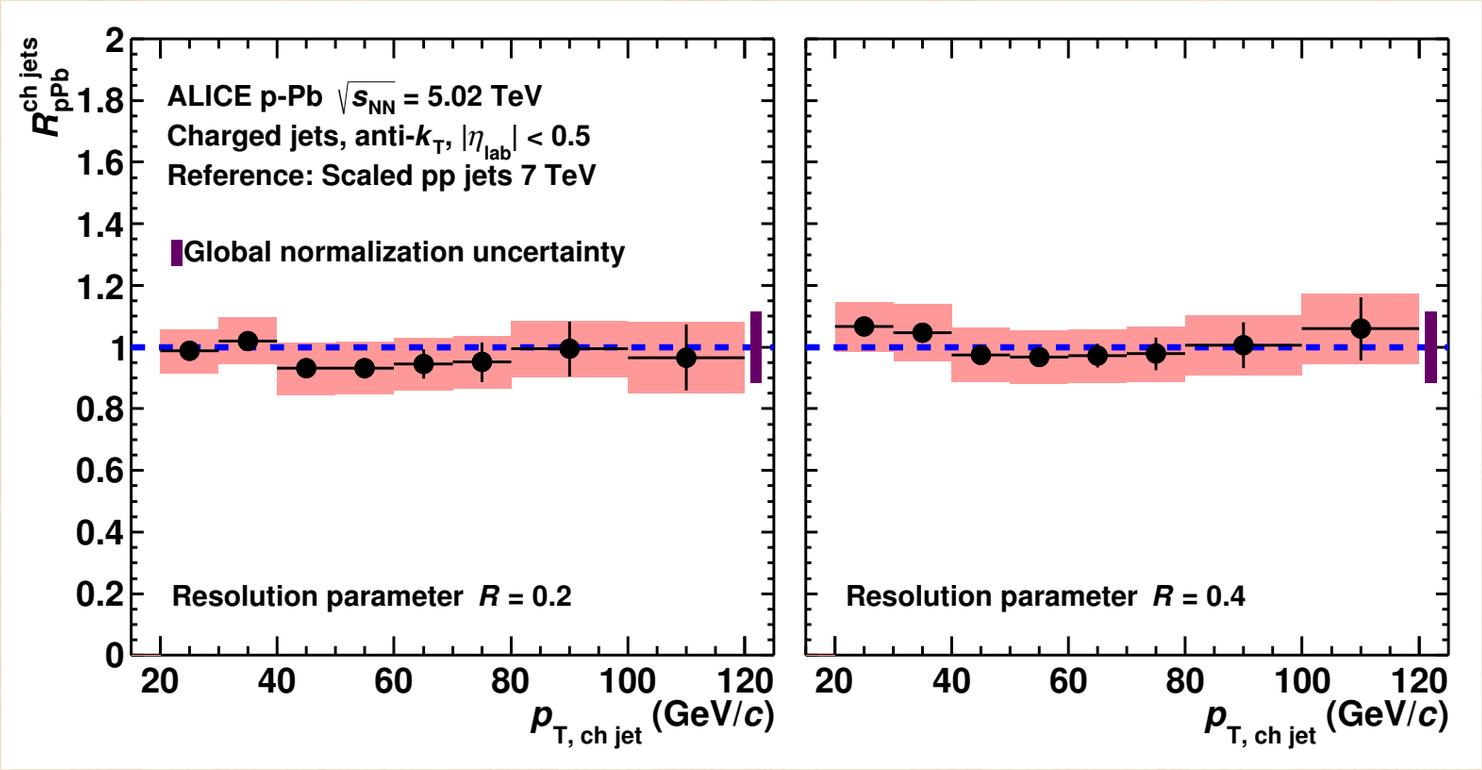
Relative enhancement of low energy particles

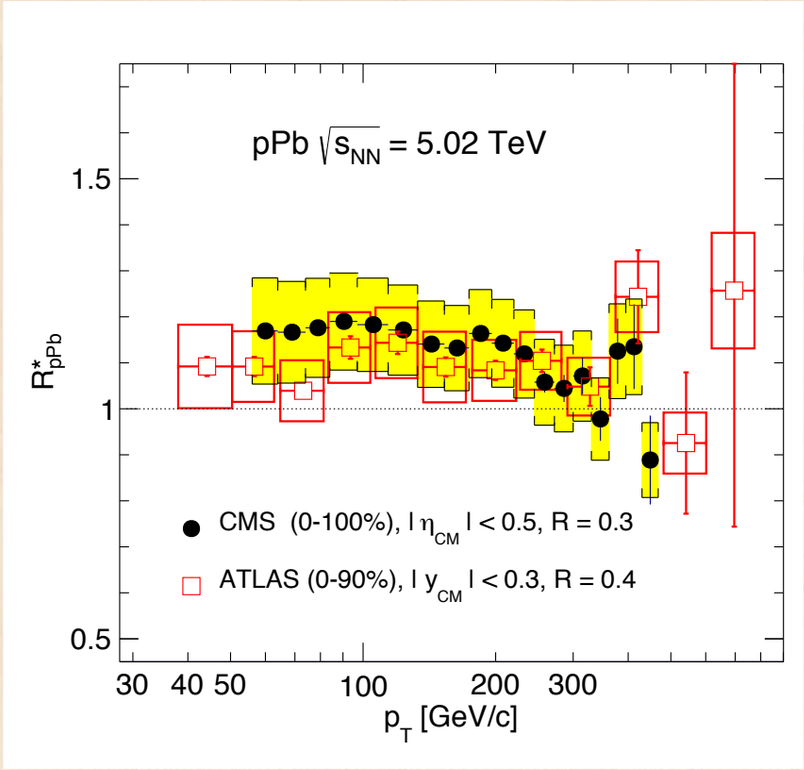
Extends far up to ±1 in azimuthal angle

Jets in pPb collisions

R_{pPb} = pPb cross section / scaled pp cross section

to account for expected number of binary nucleon-nucleon collisions





No suppression of jets observed inclusively

PLB 749 (2015) 68, EPJC 76 (2016) 372, PLB 748 (2015) 392