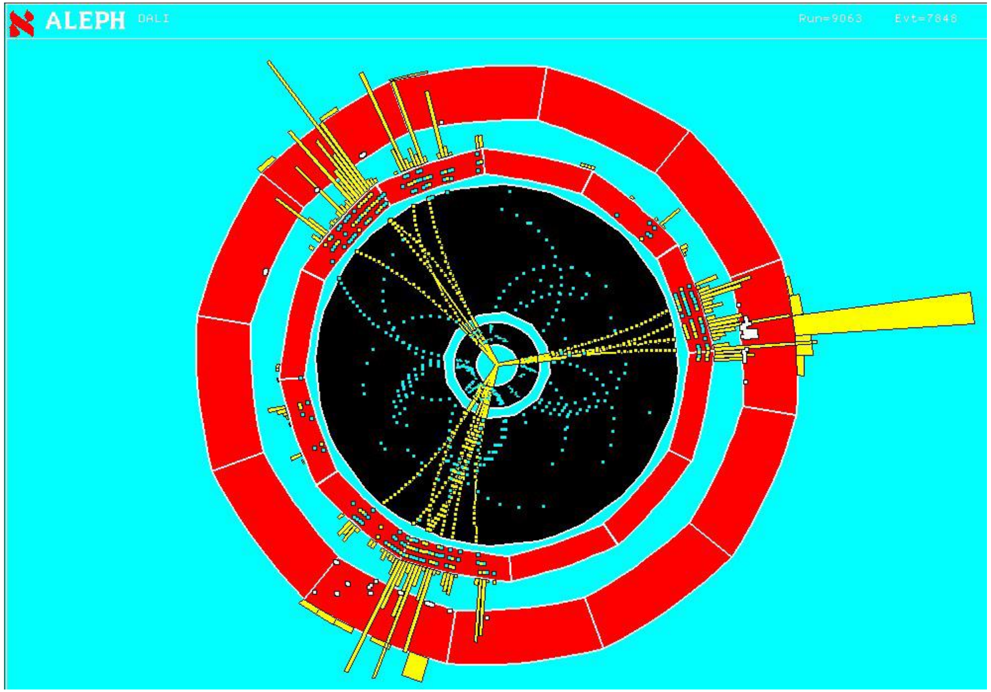
Review of Quark Matter 2018 --Jet modification

Shan-Liang Zhang
Central China Normal University

Jet definition

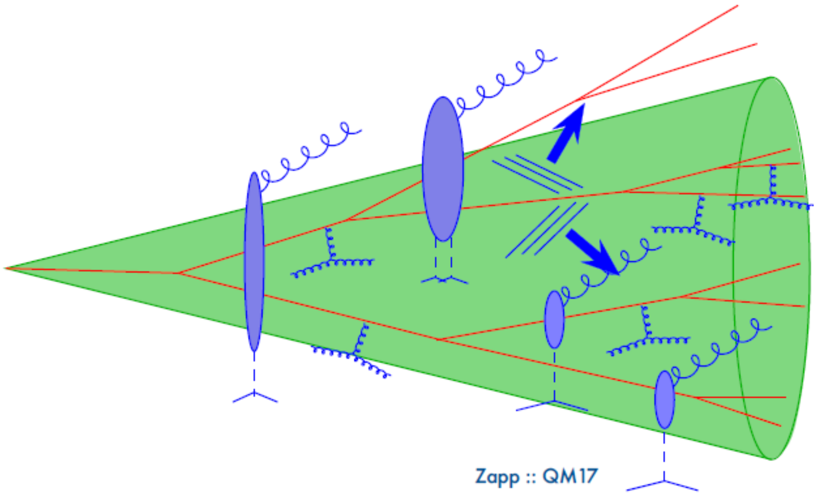


A jet is

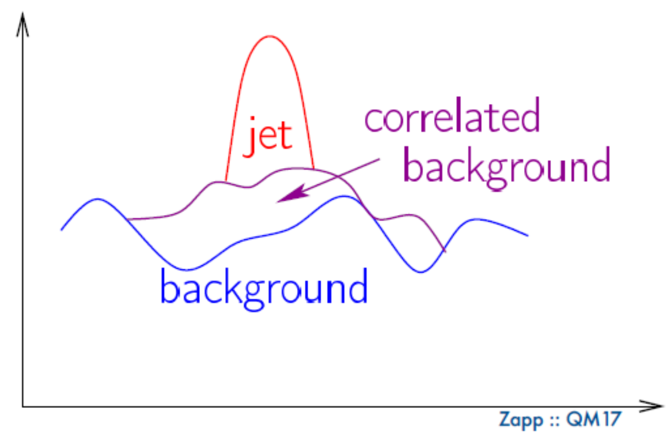
-- a collimated spray of hadrons.

-- result of fragmentation of an energetic quark or gluon from hard scattering .

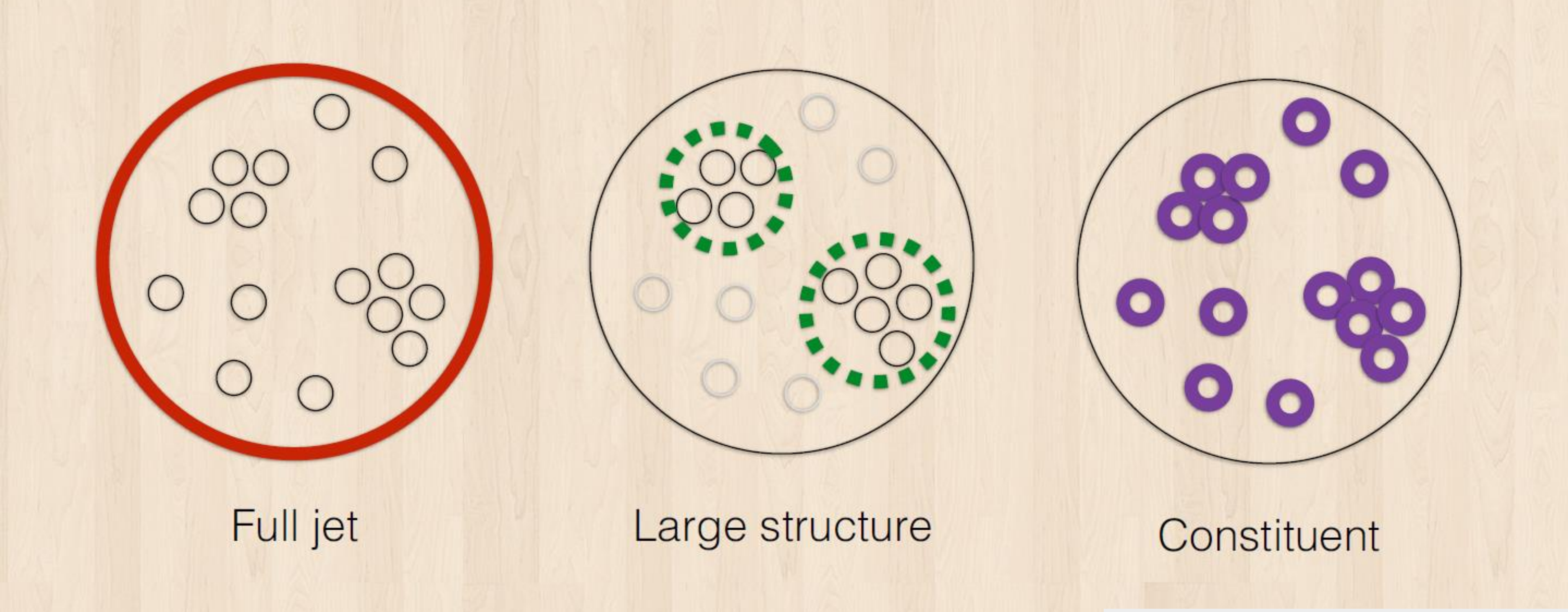
Jet in heavy-ion collisions



- shower constituents exchange [soft] 4-mom and colour with QGP
- interleaved [vacuum]+[medium induced] emission pattern
- some shower constituents decorrelate from jet :: are lost
- some QGP becomes correlated with jet [medium response] :: it is part of the jet

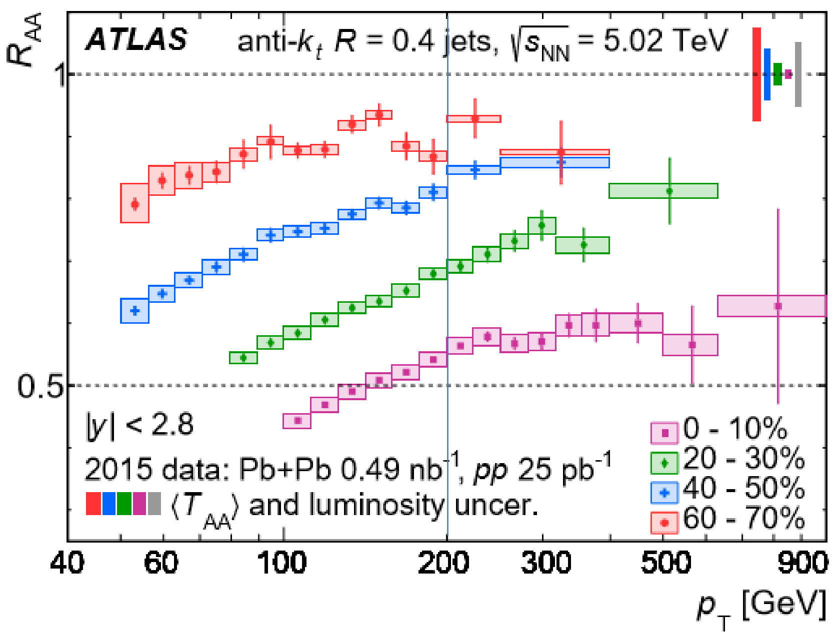


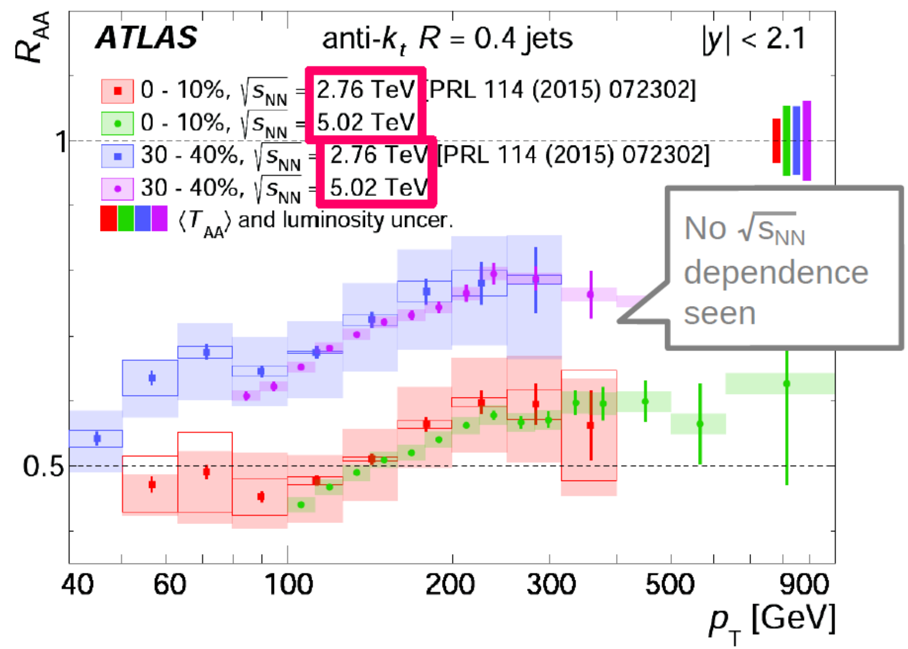
Jet quenching—observables



Jet/hadron RAA	Momentum sharing	Inclusive jet, Z/γ+jet
Z/γ+jet correlations	Jet mass	Jet shape
Di-jet imbalance	Opening angle	Fragmentation function
…	…	…

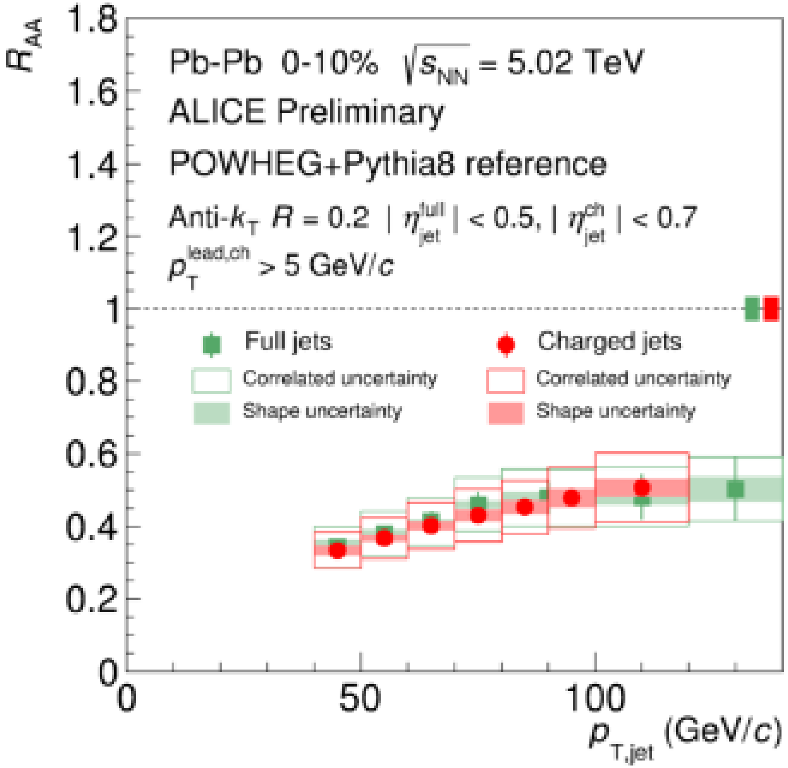
Suppression of inclusive jet

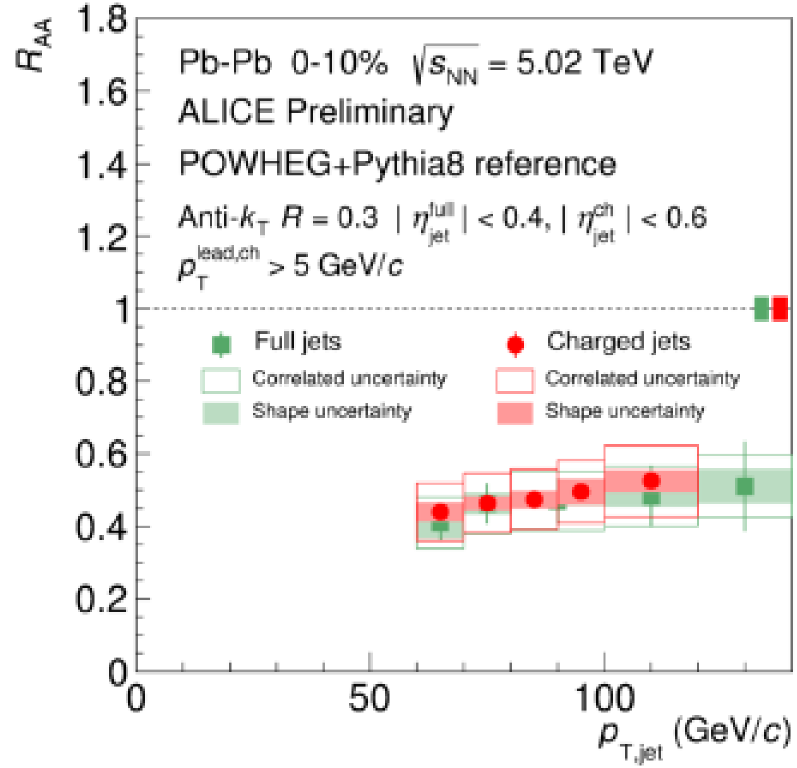




- Quenching time becomes longer.
- The parton spectrum becomes flatter.
- The relative fraction of quarks and gluons changes.

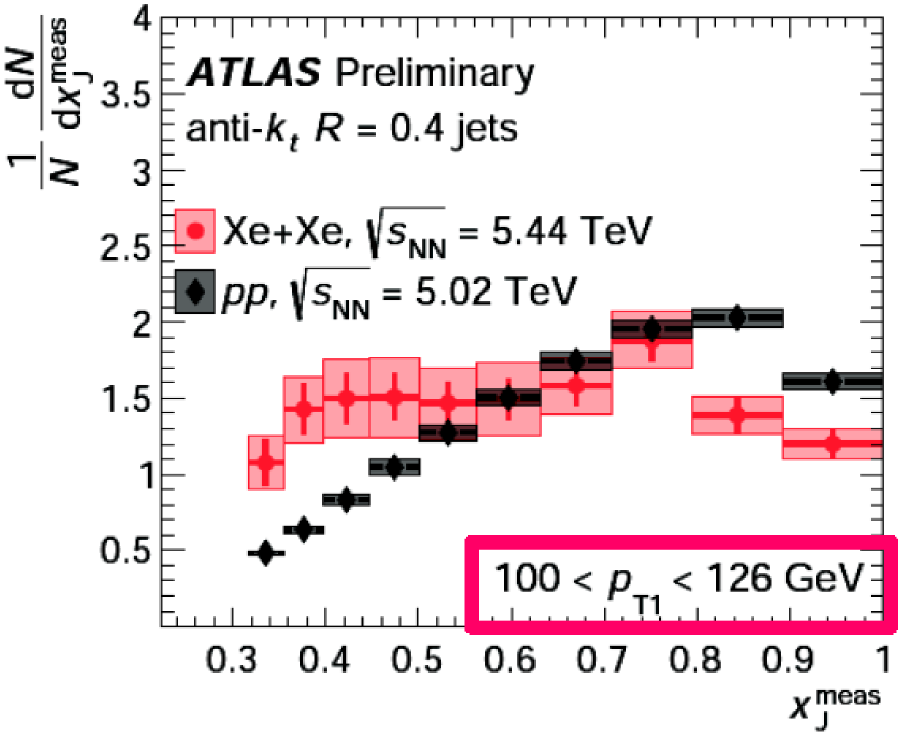
Suppression of inclusive jet

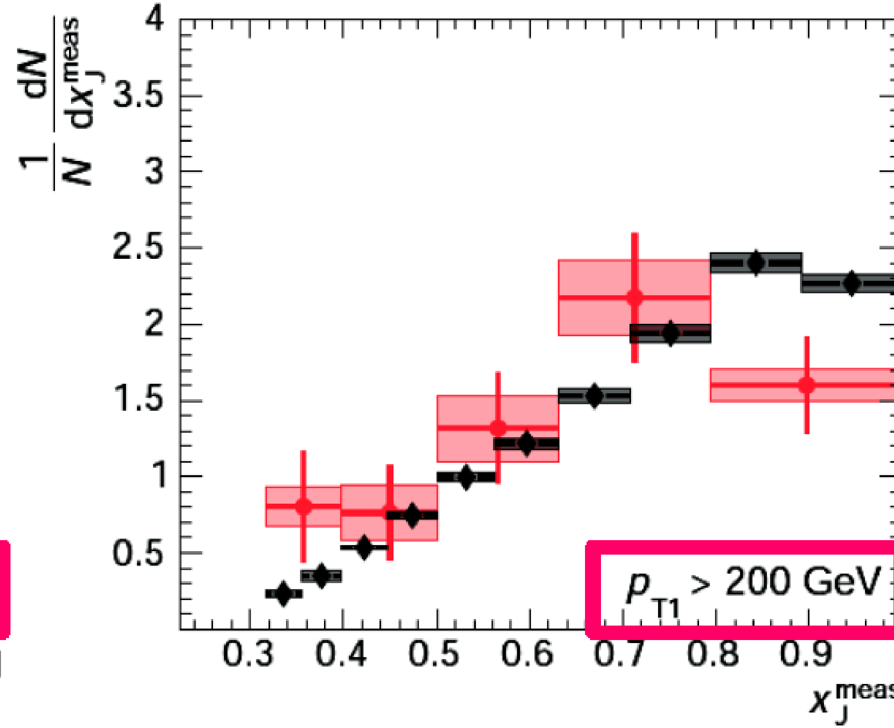




Full and charged jet R_{AA} is consistent

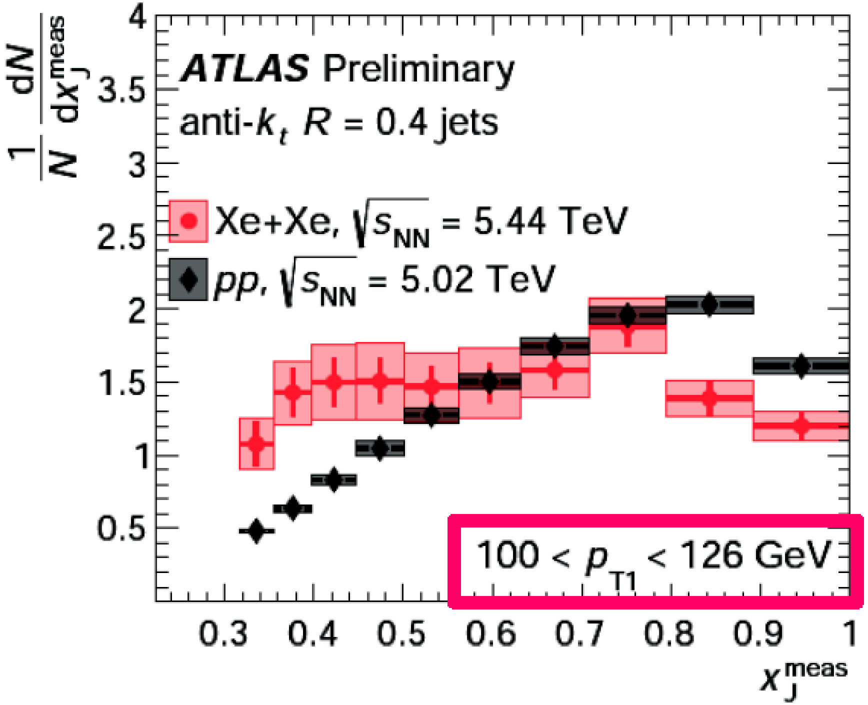
Momentum imbalance

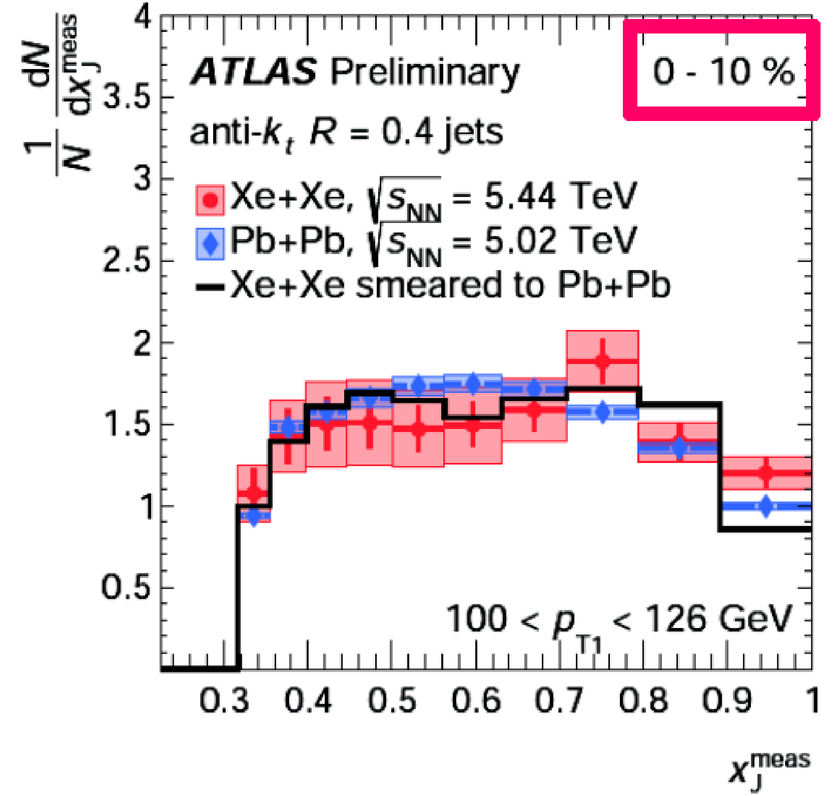




Larger dijet asymmetry decreases with increasing jet pT

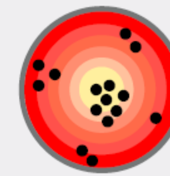
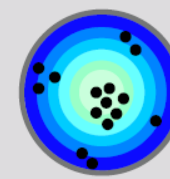
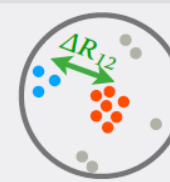
Momentum imbalance





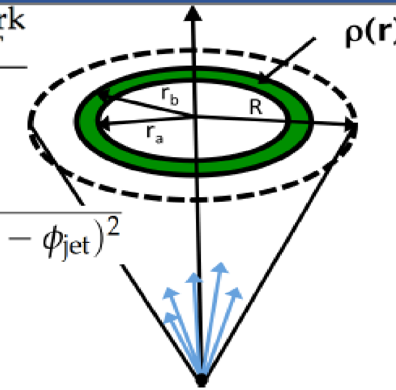
Consistent in same **centrality percentiles**

Jet structure observables

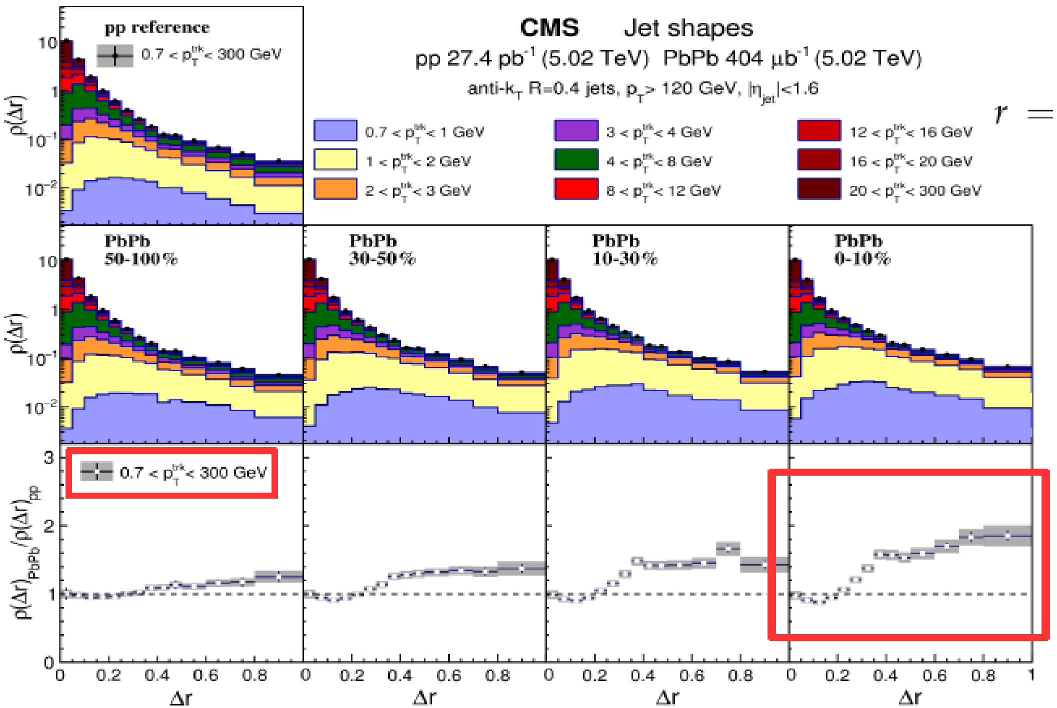
fragmentation function	$D(z) = \left\langle \sum_{i\in \text{jet}} \delta(z - p_{ti}/p_{t,\text{jet}}) \right\rangle_{\text{jets}}$	
differential jet shape	$\rho(r) = \frac{1}{p_\perp^{\text{jet}}} \sum_{\substack{k \text{ with} \\ \Delta R_{kJ}\in[r,r+\delta r]}} p_\perp^{(k)}\,,$	
girth ≡ broadening	$g = \frac{1}{p_\perp^{\text{jet}}} \sum_{k\in J} p_\perp^{(k)} \Delta R_{kJ}\,,$	
jet mass, groomed & ungroomed	$m^2 = \left(\sum_{i\in(\text{sub})\text{jet}} p_i^\mu \right)^2$	
z_g, ΔR_{12}	$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} > z_{\text{cut}} \left(\frac{\Delta R_{1,2}}{R_J} \right)^\beta$	

Jet shape of inclusive jet

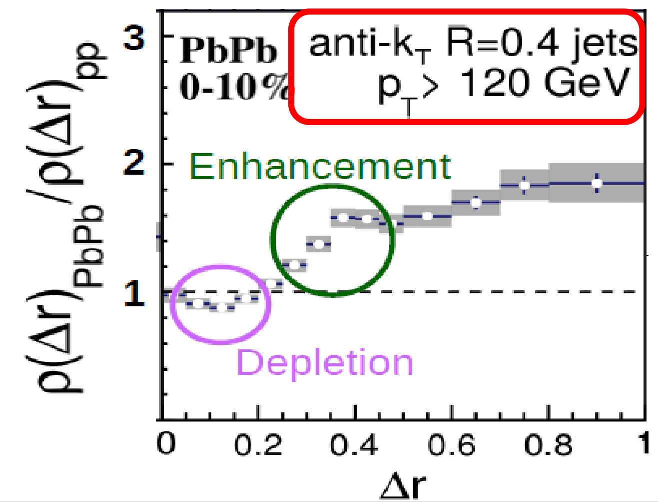
$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{jets}}\Sigma_{jets}\frac{\Sigma_{tracks\in(r_a,r_b)}p_T^{trk}}{\Sigma_{tracks}p_T^{trk}}$$



$$r = \sqrt{(\eta_{track}-\eta_{jet})^2+(\phi_{track}-\phi_{jet})^2}$$



ρ(r) normalized to unity over **r < 1**.

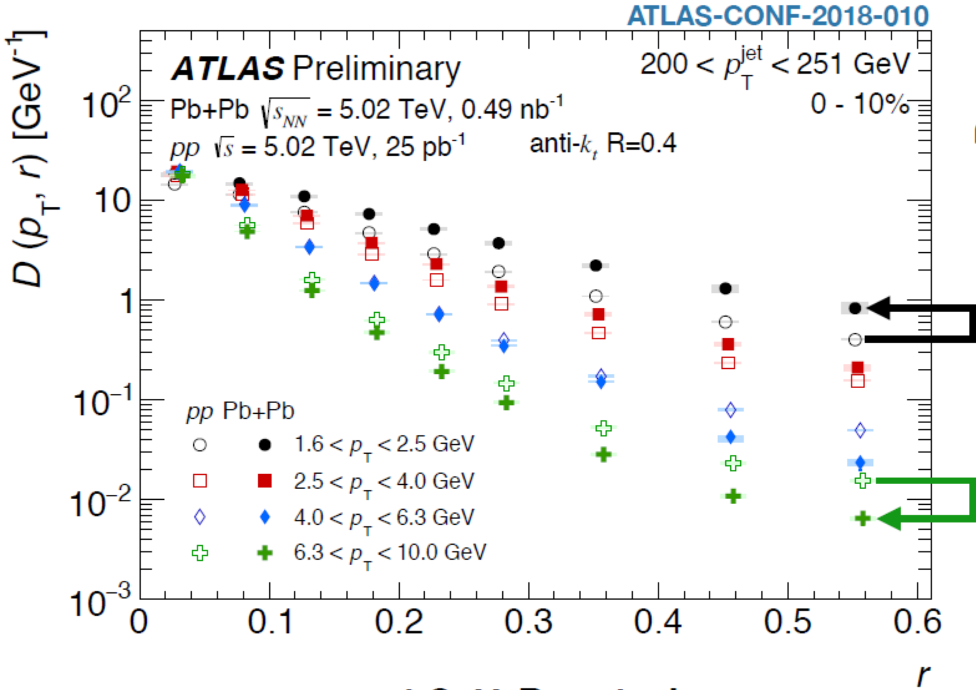


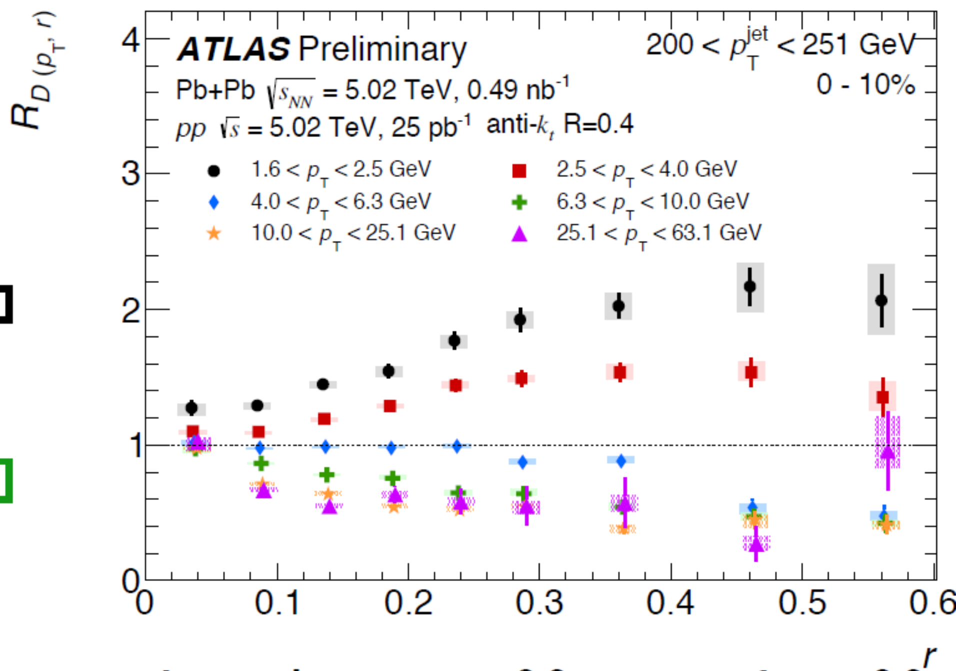
PbPb – > A **larger fraction of jet energy** carried at **large distances** from the jet axis.

Jet shape of inclusive jet

$$D(p_{\mathrm{T}}, r) = \frac{1}{N_{\mathrm{jet}}} \frac{1}{2\pi r} \frac{\mathrm{d}^2 n_{\mathrm{ch}}(r)}{\mathrm{d}r\,\mathrm{d}p_{\mathrm{T}}}$$

$$R_{D(p_{\mathrm{T}},r)} = \frac{D(p_{\mathrm{T}}, r)_{\mathrm{Pb+Pb}}}{D(p_{\mathrm{T}}, r)_{pp}}$$



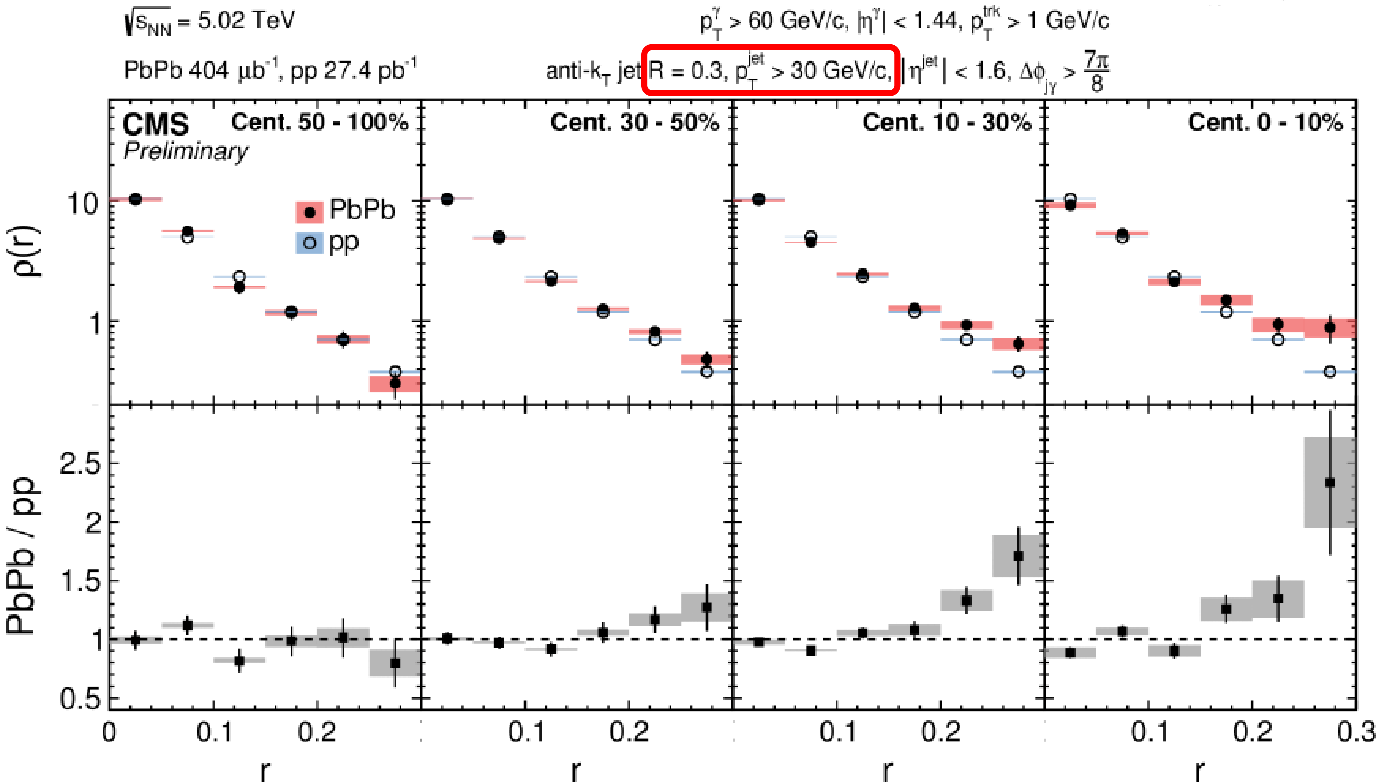


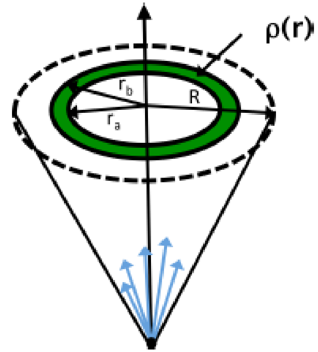
p_{T} < 4 GeV: Broadening
p_{T} > 4 GeV: Narrowing

Increasing up to r = 0.3, constant for r > 0.3
Decreasing up to r = 0.3, constant for r > 0.3

Jet shape of γ+jet

$$\rho(r) = \frac{1}{\delta r}\frac{\sum_{\text{jets}} \sum_{\text{trk}\in[r_a,r_b)} (p_T^{\text{trk}}/p_T^{\text{jet}})}{\sum_{\text{jets}} \sum_{\text{trk}\in[0,r_f)} (p_T^{\text{trk}}/p_T^{\text{jet}})}$$

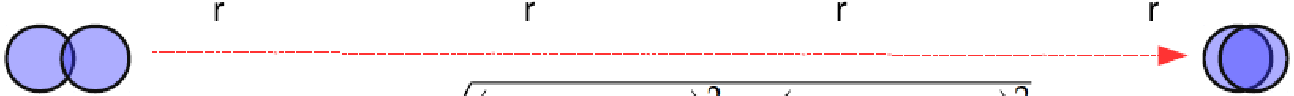




ρ(r) normalized to unity over **r < 0.3**.

Results are corrected for detector resolution, particle reco.

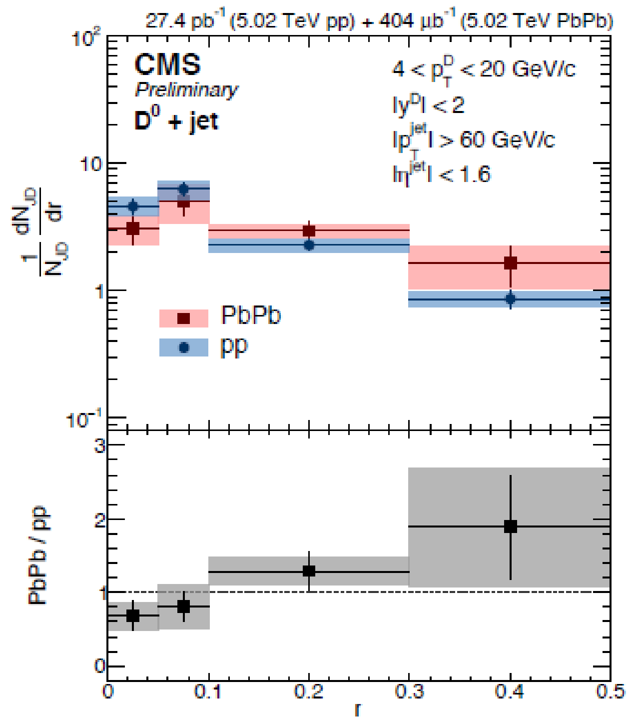
pp results are **NOT** smeared.



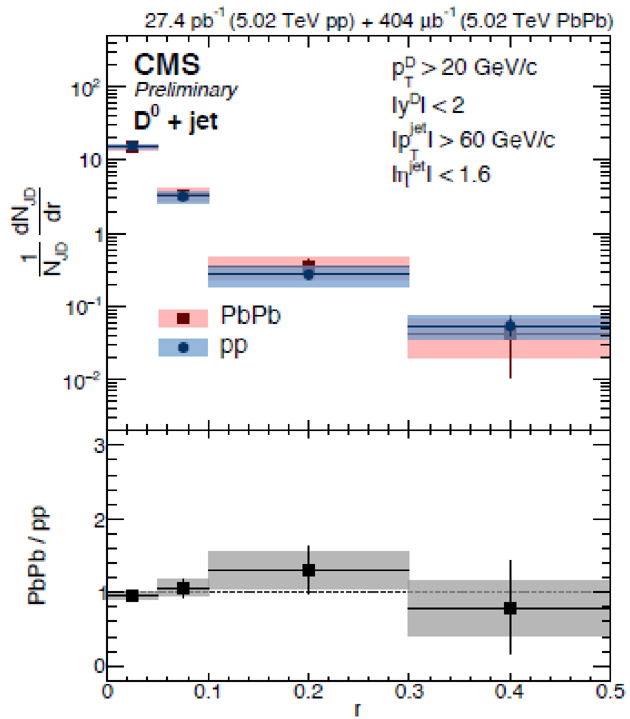
$$r = \sqrt{(\eta_{\text{track}} - \eta_{\text{jet}})^2 + (\phi_{\text{track}} - \phi_{\text{jet}})^2}$$

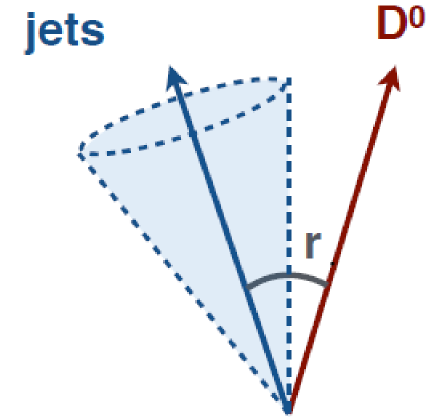
Radial profile of D0 mesons in jets

Low D p_T: $4 < p_T^D < 20$ GeV/c



High D p_T: $p_T^D > 20$ GeV/c





$$r = \sqrt{\Delta\phi_{JD}^2 + \Delta\eta_{JD}^2}$$

The final distribution is normalized to unity in r < 0.3

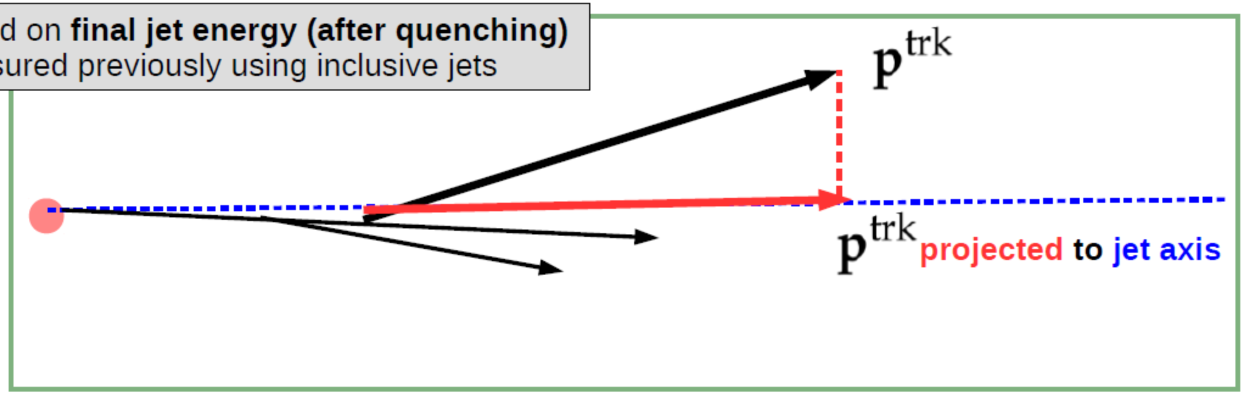
- The ratio of PbPb over pp:
- Low D p_T: increases as a function of r
  - ➡ Hint that D^0 are further from jet axis in PbPb than pp
- High D p_T: consistent with unity

CMS-PAS-HIN-18-007

Fragmentation function

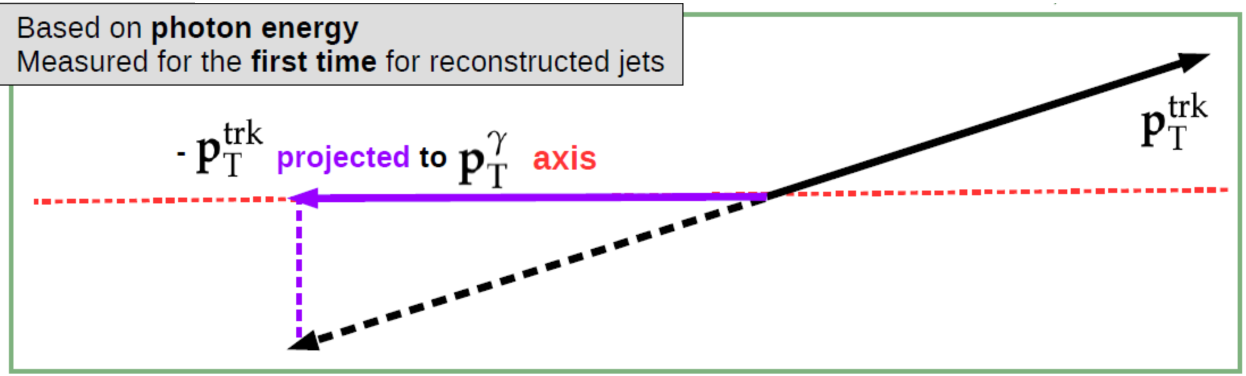
- Based on **final jet energy (after quenching)**
- Measured previously using inclusive jets

$$\xi^{\rm jet} = \ln \frac{|\mathbf{p}^{\rm jet}|^2}{\mathbf{p}^{\rm trk} \cdot \mathbf{p}^{\rm jet}}$$

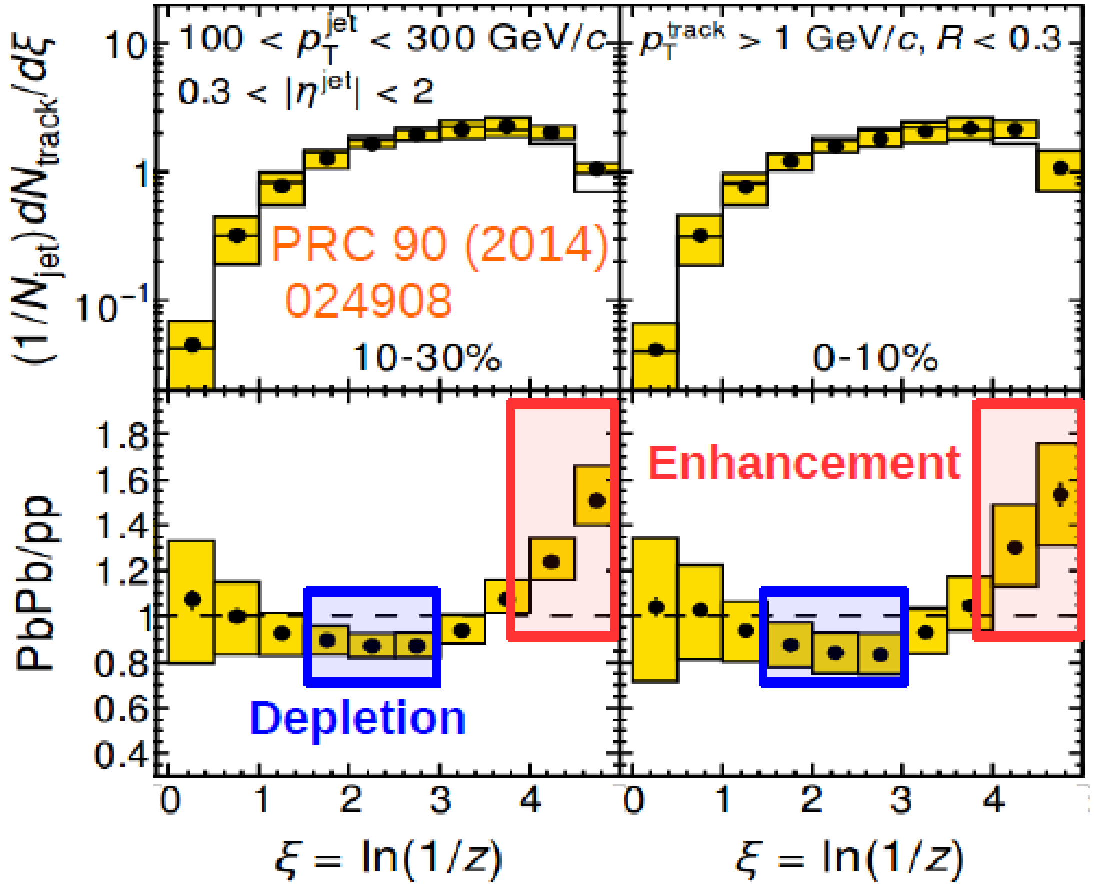


- Based on **photon energy**
- Measured for the **first time** for reconstructed jets

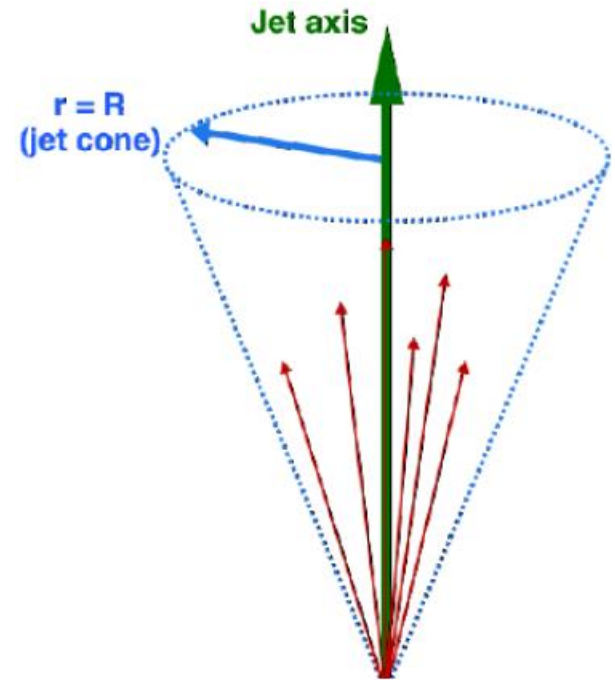
$$\xi^{\gamma}_{\rm T} = \ln \frac{-|\mathbf{p}^{\gamma}_{\rm T}|^2}{\mathbf{p}^{\rm trk}_{\rm T} \cdot \mathbf{p}^{\gamma}_{\rm T}}$$



FF of inclusive jet

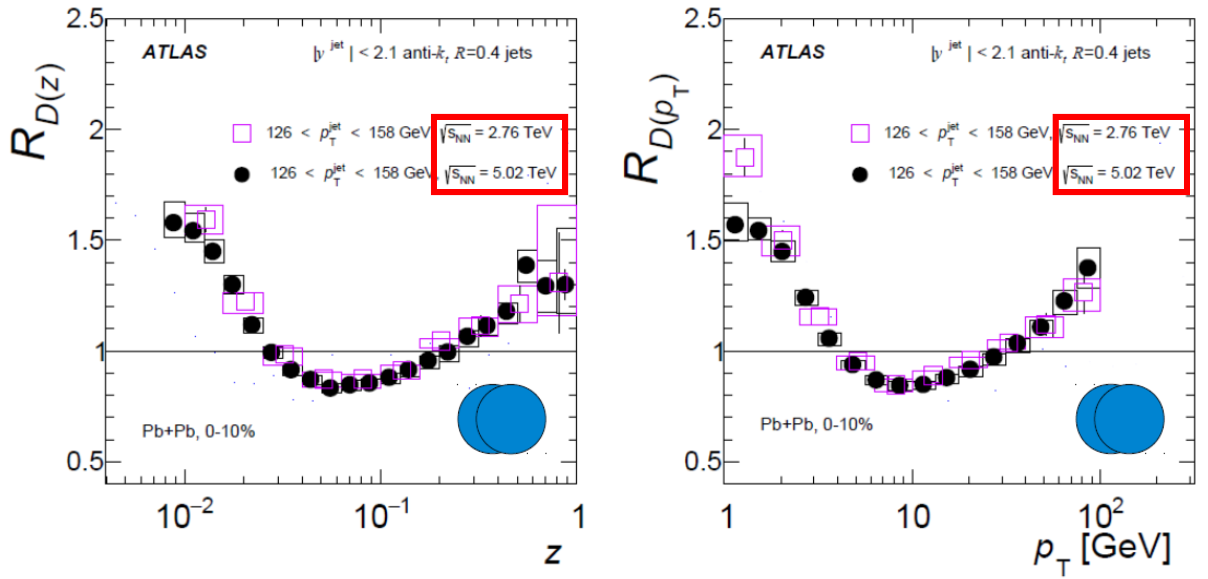


$$z = \frac{p_{\parallel}^{\text{track}}}{p^{\text{jet}}}, \quad \xi = \ln\frac{1}{z},$$

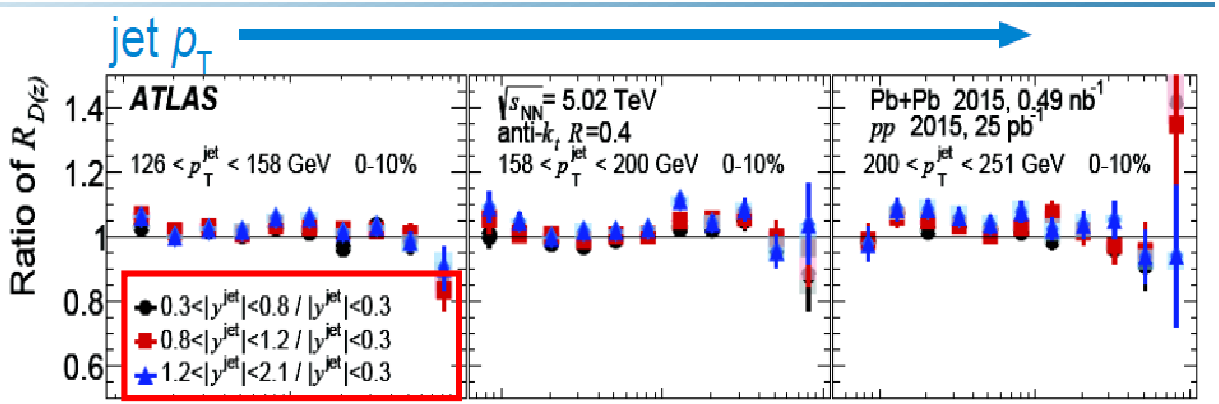


(high ξ – > low-pT particle)

Rapidity dependence and collision energy dependence



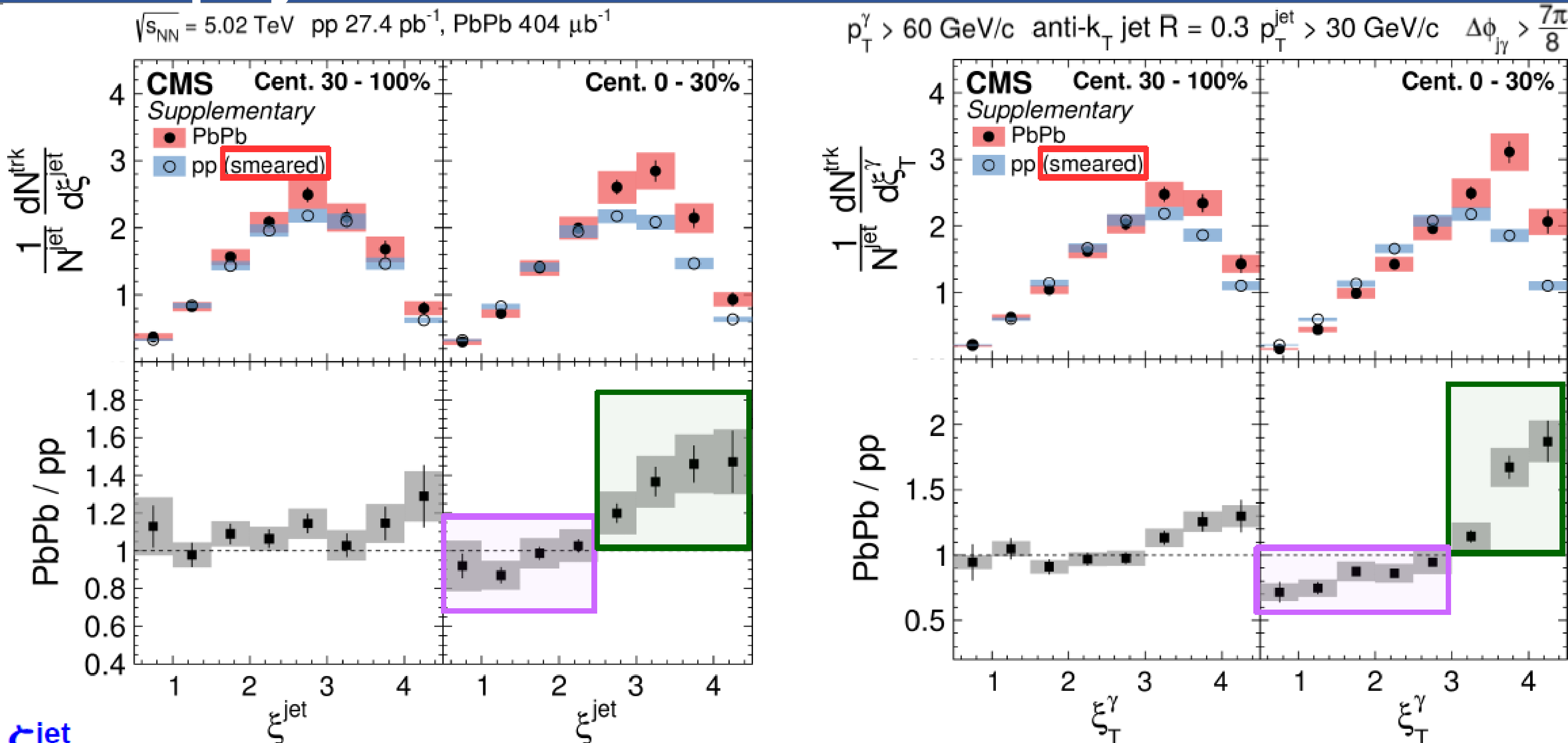
$$z = \frac{p_{\parallel}^{\text{track}}}{p^{\text{jet}}}, \quad \xi = \ln\frac{1}{z},$$



- No dependence on the collision energy.
- No significant rapidity dependence

arXiv:1805.05424

FF of γ+jet



ξ^{jet}

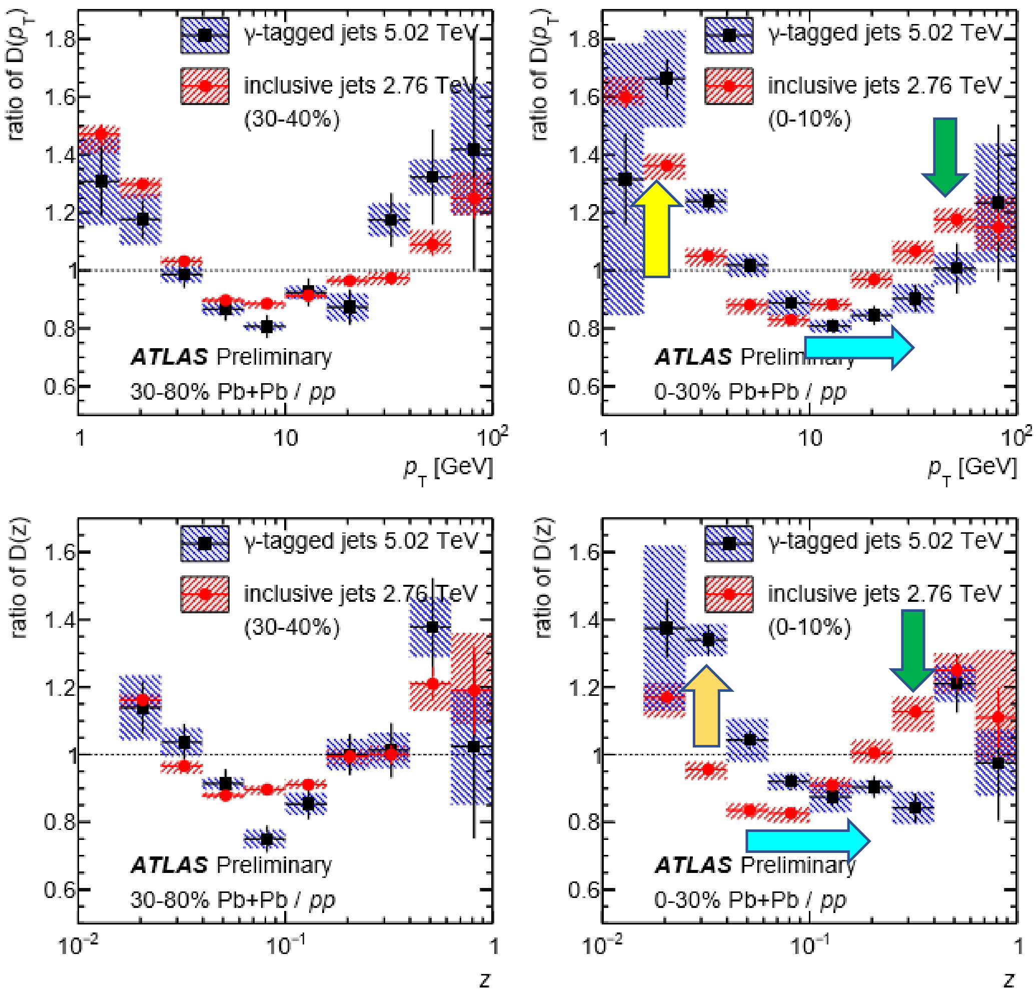
- Based on reconstructed jet energy (energy after quenching)
- ξ^{jet} shifted to left compared to ξ_T^γ
  - Out-of-cone radiation, photon+multijet

ξ_T^γ

- Based on photon energy
- ξ_T^γ modified stronger compared to ξ^{jet}

arXiv:1801.04895

FF of γ+jet vs inclusive jet



$$z = \frac{p_{\parallel}^{\text{track}}}{p^{\text{jet}}}, \quad \xi = \ln \frac{1}{z},$$

Familiar pattern of modification in peripheral collisions.

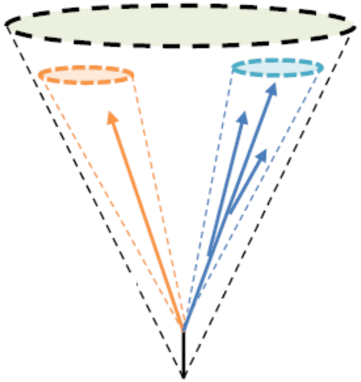
In central collisions:

- Shift of mid-pT minimum
- Enhancement at low-*Pt and z*
- Suppression at large-pT and z

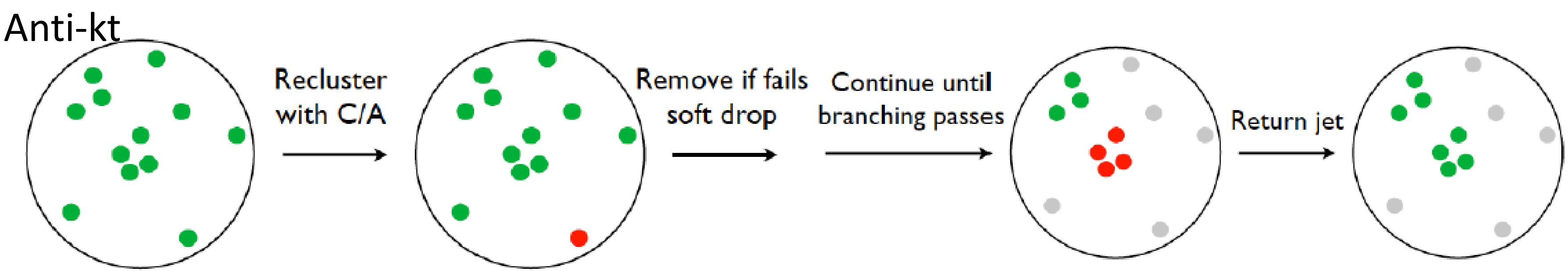
ATLAS-CONF-2017-074

Subjet Reconstruction

- Jet grooming removes soft divergences and uncorrelated background
- “Soft-drop” primarily removes late-stage soft gluon emission
- Common technique in HEP - introduced in heavy-ion collisions



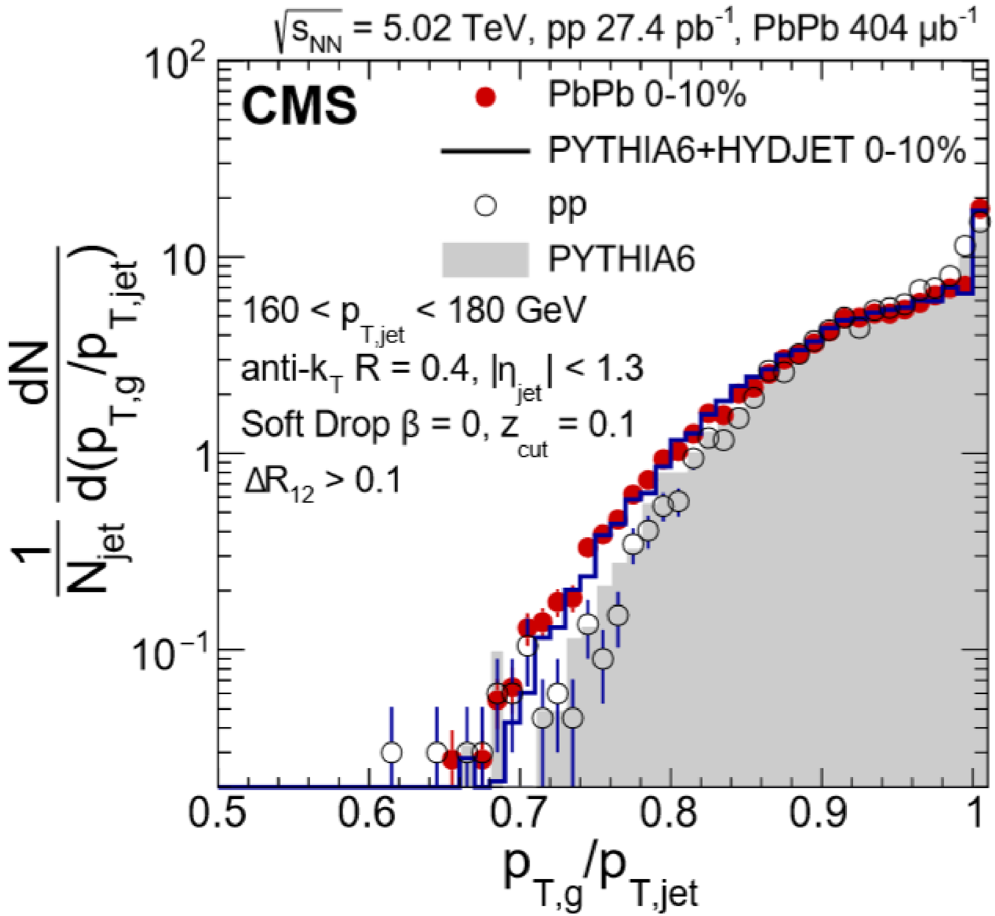
Soft Drop Condition: $z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} > z_{\text{cut}} \left(\frac{\Delta R_{1,2}}{R_J}\right)^{\beta}$

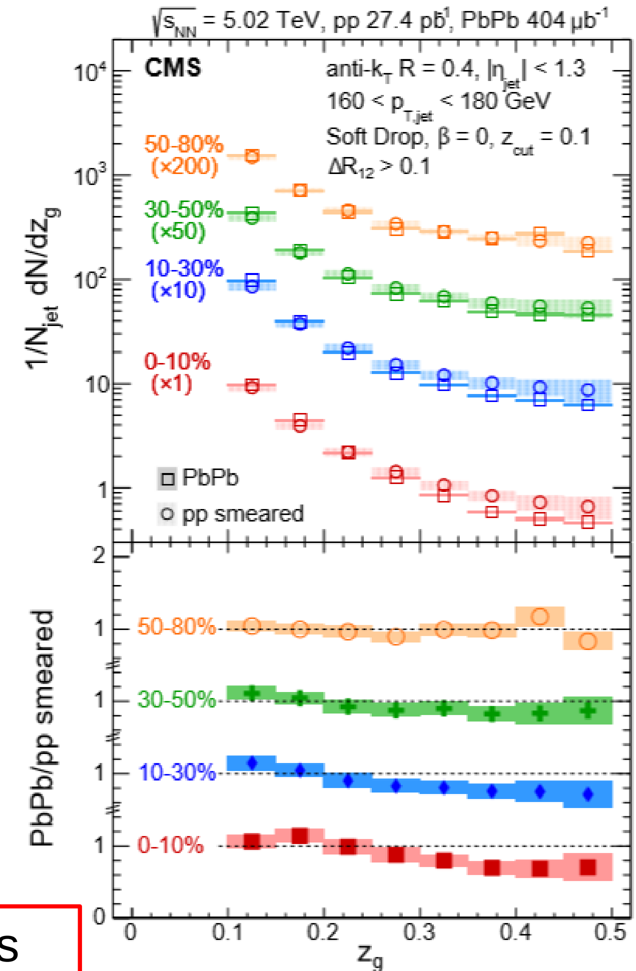


- Subjets reconstructed using constituents of full jets, reclustered via C/A algorithm[1] to Impose ***angularly---ordered structure***
- Clustering iterates up the jet fragmentation chain, discarding branches until a pair is found that satisfies the “SoftDrop” identification criteria

JHEP05(2014)146

Momentum Sharing





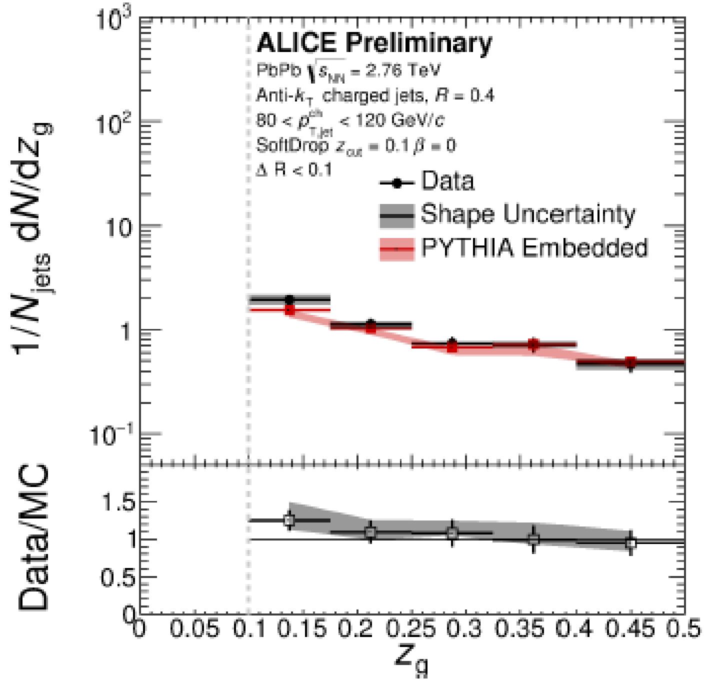
PhysRevLett.120.142302

Deviation in more central events

Momentum Sharing

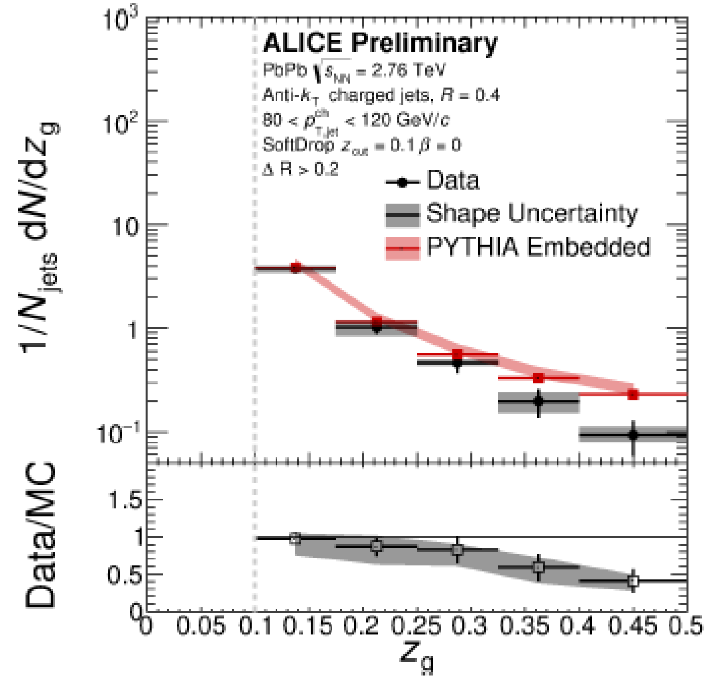
Collimated splitting

$\Delta R < 0.1$



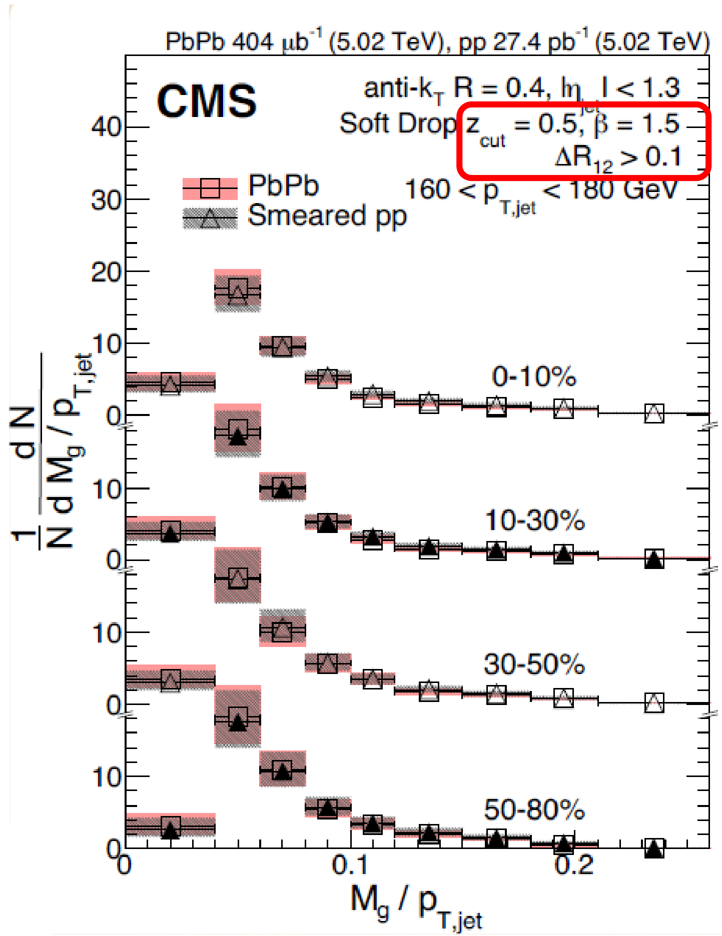
large angle splitting

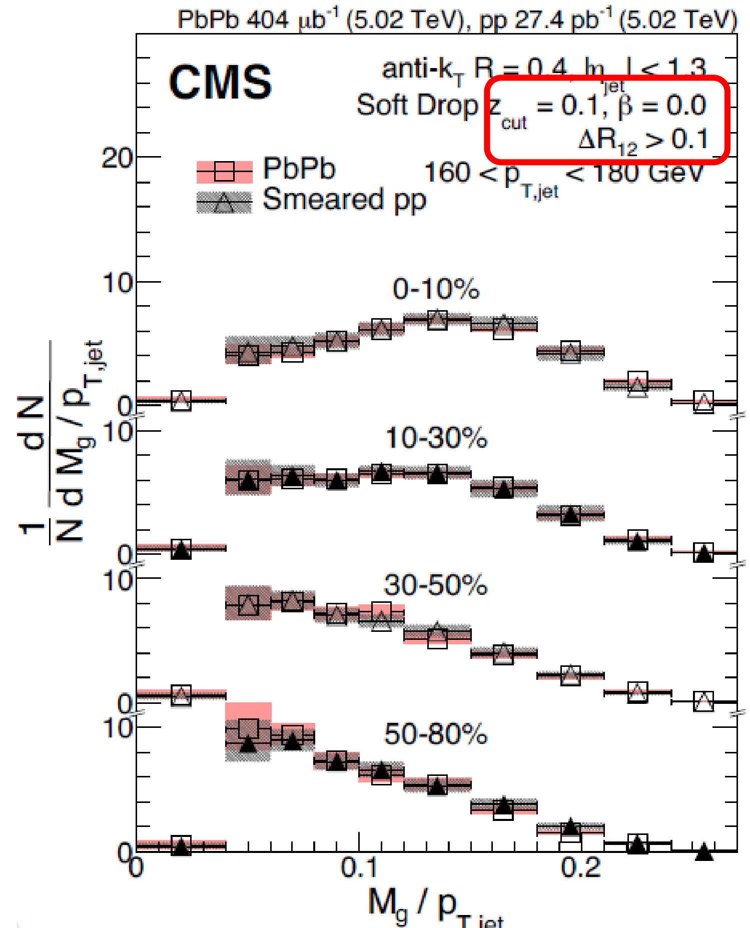
$\Delta R > 0.2$



❖Overall enhancement of collimated splittings and suppression of large angle splittings

Groomed Jet Mass

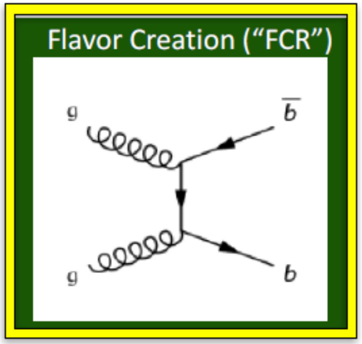


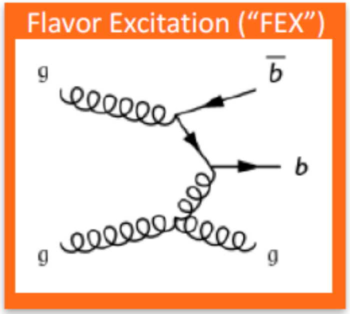


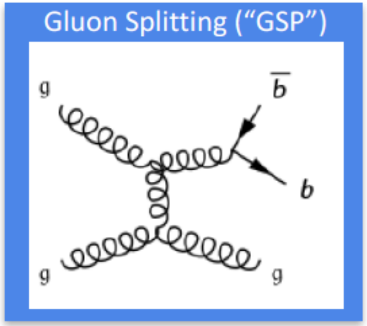
Good agreement between PbPb and smeared pp

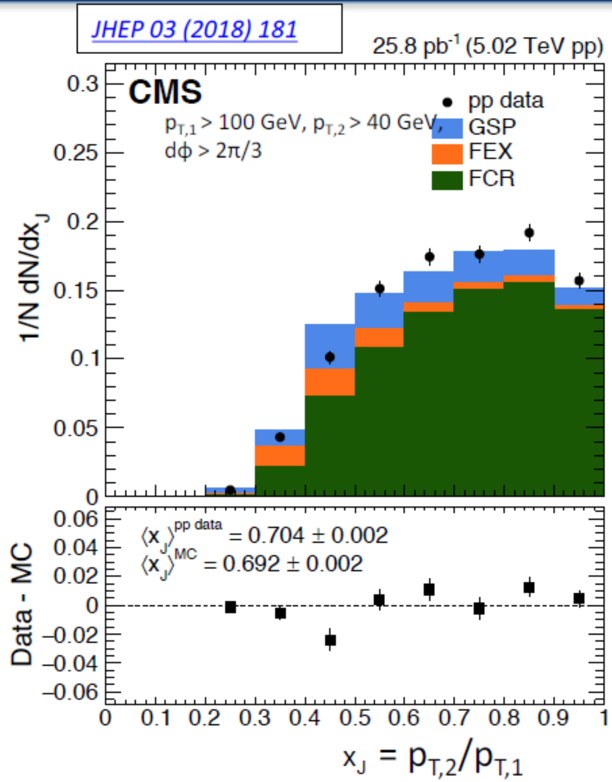
arXiv 1805.05145

B---Jet Production Mechanisms



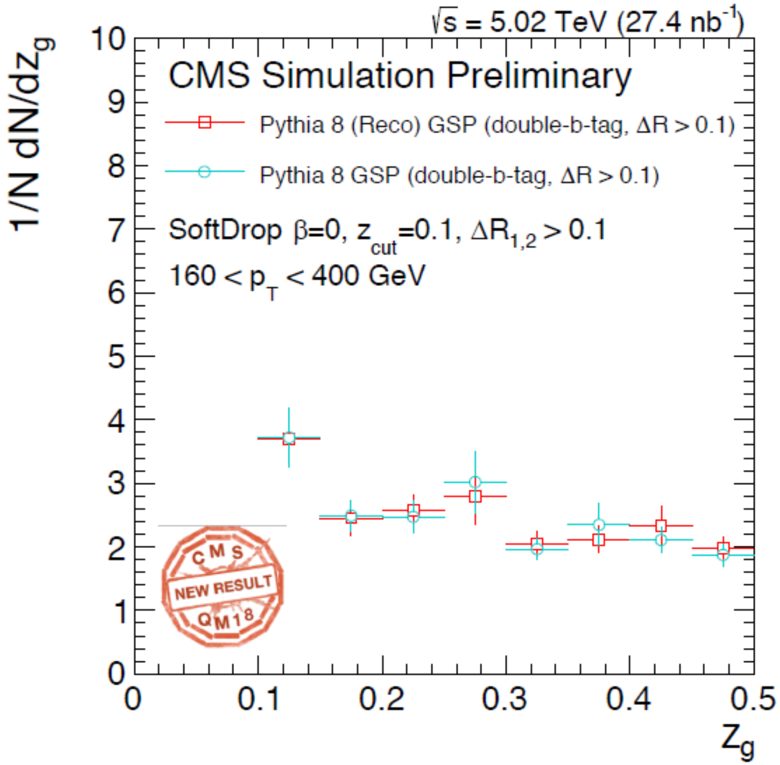


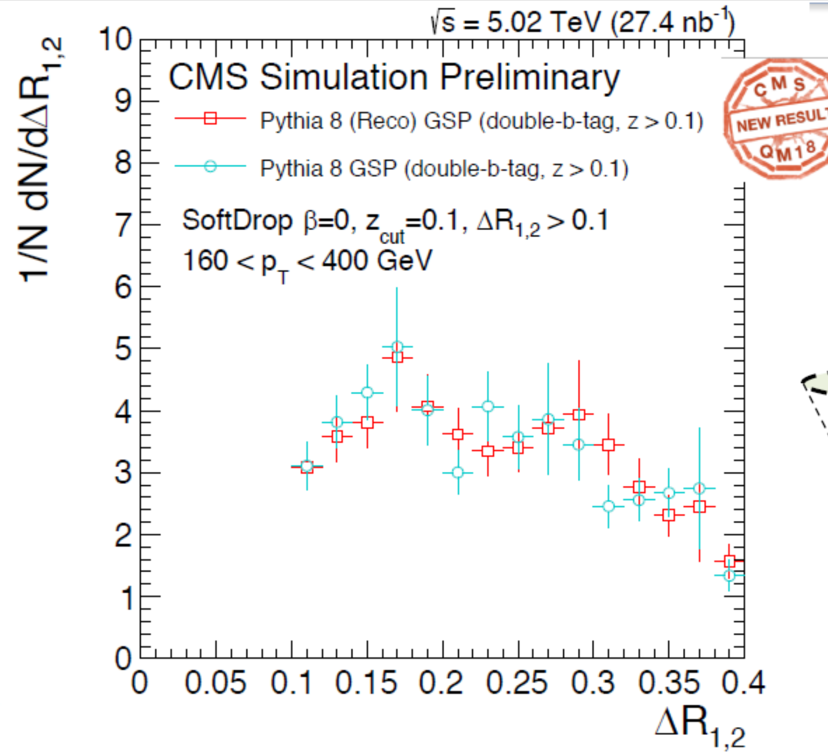


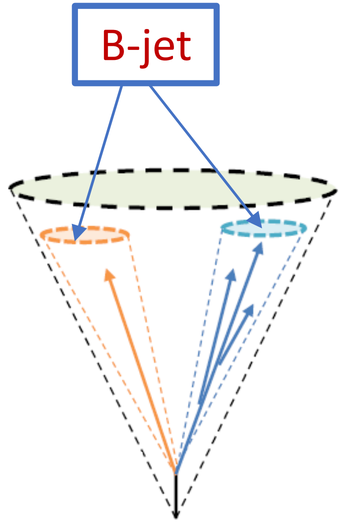


- Selections of back-to-back jets dramatically improve leading---order "purity"
  – Removes the bulk of gluon-splitting (GSP) contributions to measurement
  – Isolates pure b-quark energy loss (though w/o contributions from late gluon emission)
- *Subjet double-b tagging provides access to the final-state gluon-splitting (g->bb) subprocess*

CMS subjet flavour tagging







- Wide-angle gluon-splitting jets ($\Delta R_{1,2}$ ~ 0.2) have a balanced subjet splitting distribution
  - Important to note that ***this is a small subset*** of total GSP jet contribution
  - B-tagging + reconstruction methodology confirmed by Pythia8 simulation

CMS-DPN-2018

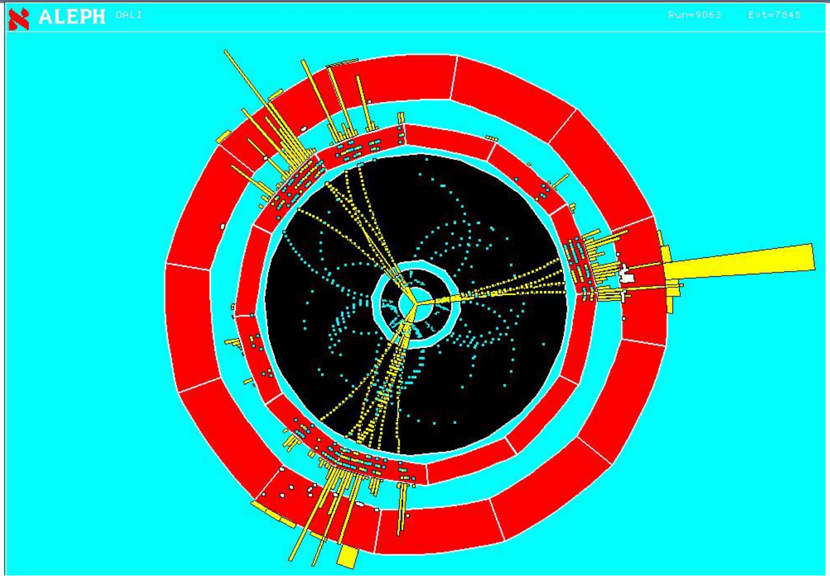
Summary

- Full jet
  -- RAA is dependent on centrality but independent on collision energy.

- Constituents
  -- Jet shape: large fraction of energy is far from jet axis.
  -- Jet fragmentation: enhancement at low Pt and suppression at high pt.
  -- D-meson tagged jet: low pt D meson is modified.

- Groomed jet
  -- momentum sharing: modified in central collisions and enhancement of collimated splittings and suppression of large angle splittings
  -- groomed jet mass: no evidence modification
  -- flavor tagging: identify small-angle double-b production(QSP)

Jet definition



A jet is

-- a collimated spray of hadrons.

-- result of fragmentation of an energetic quark or gluon from hard scattering .

- Two classes of jet finding algorithms:

  -- cone algorithms

  -- sequential recombination algorithms (k_t, anti-k_t and C/A)

- Jet algorithms should be infra-red and collinear safe, i.e. result must not change when

  -- adding a soft particle

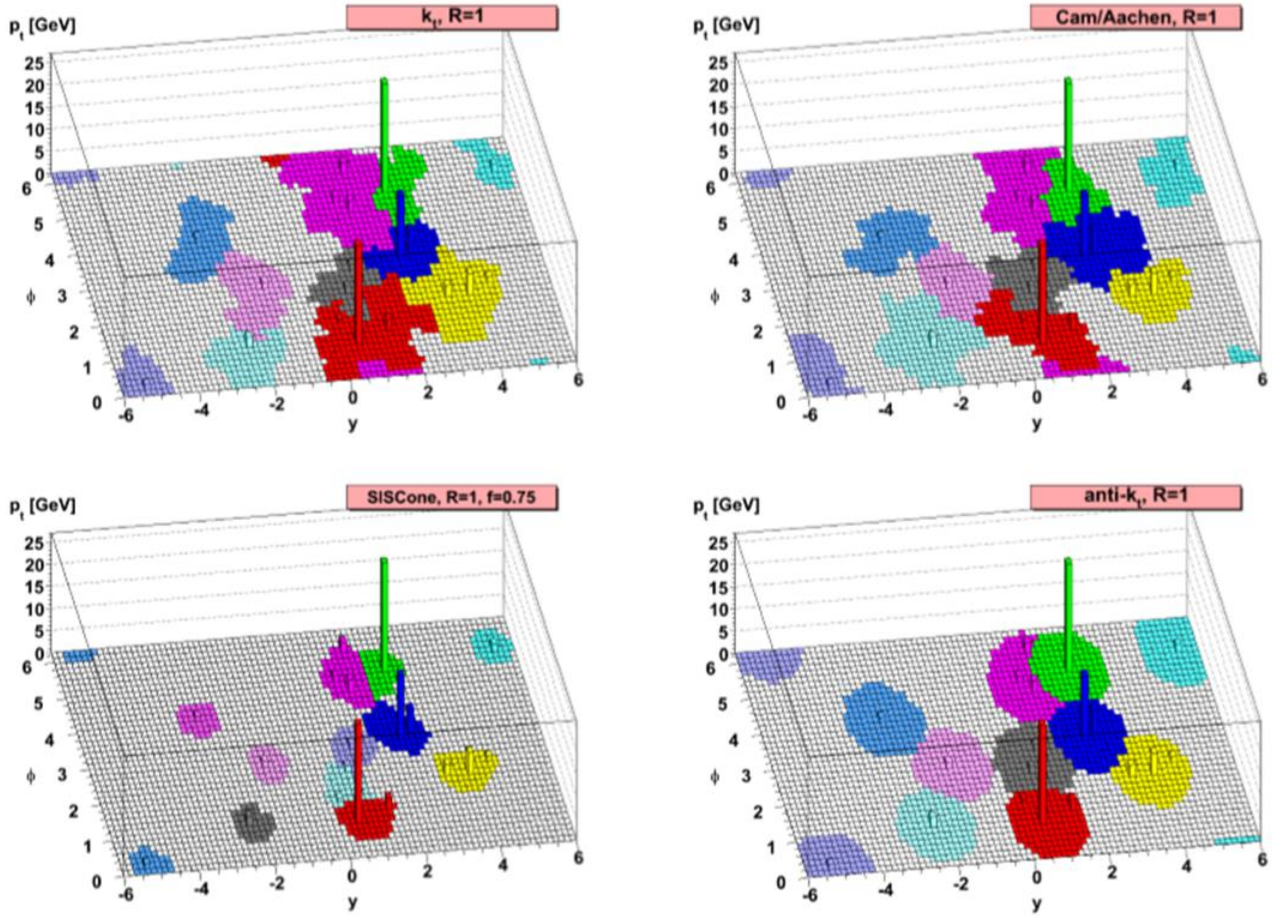
  -- splitting a particle into two collinear ones

Catani, Dokshitzer, Seymour, Webber, Nucl. Phys. B 406 (1993) 187
Ellis, Soper, Phys. Rev. D 48 (1993) 3160

Dokshitzer, Leder, Moretti, Webber, JHEP 9708 (1997) 001

Cacciari, Salam, Soyez, JHEP 0804 (2008) 063

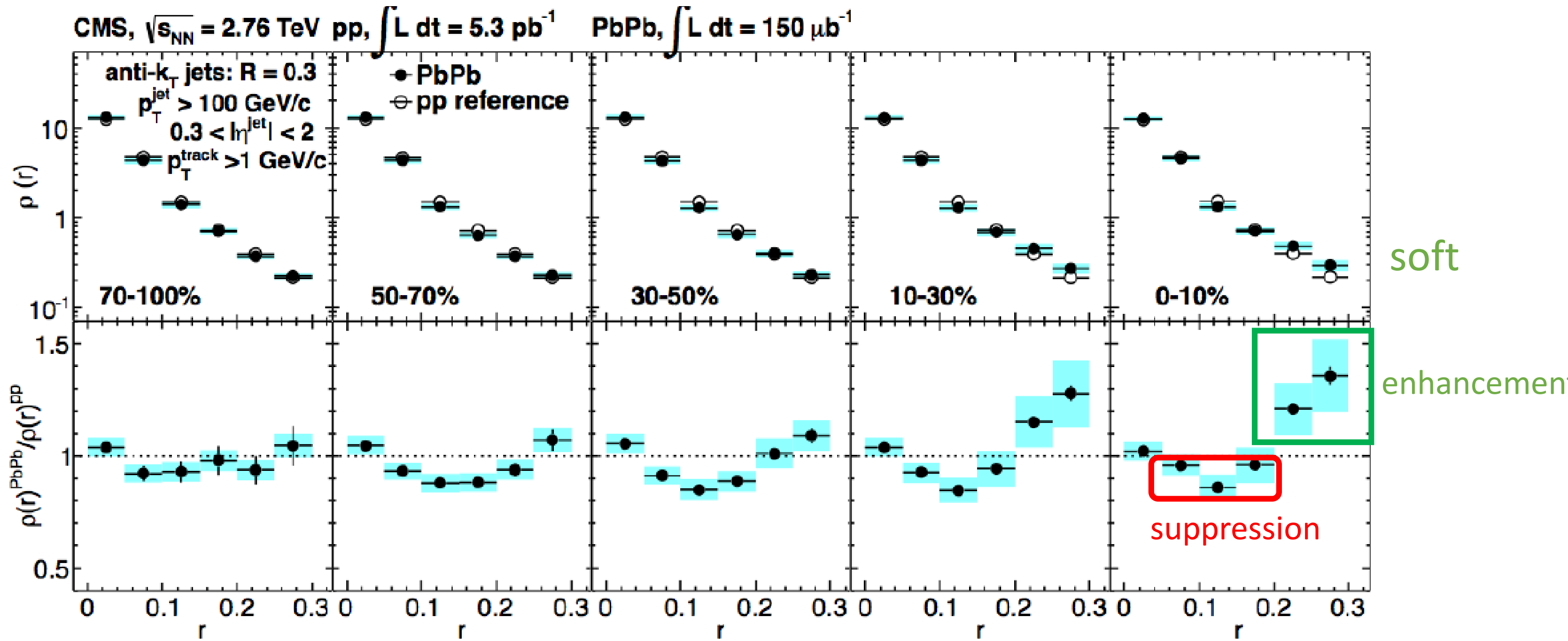
Jet algorithms



Cacciari, Salam, Soyez, JHEP 0804 (2008) 063

Jet shape of inclusive jet

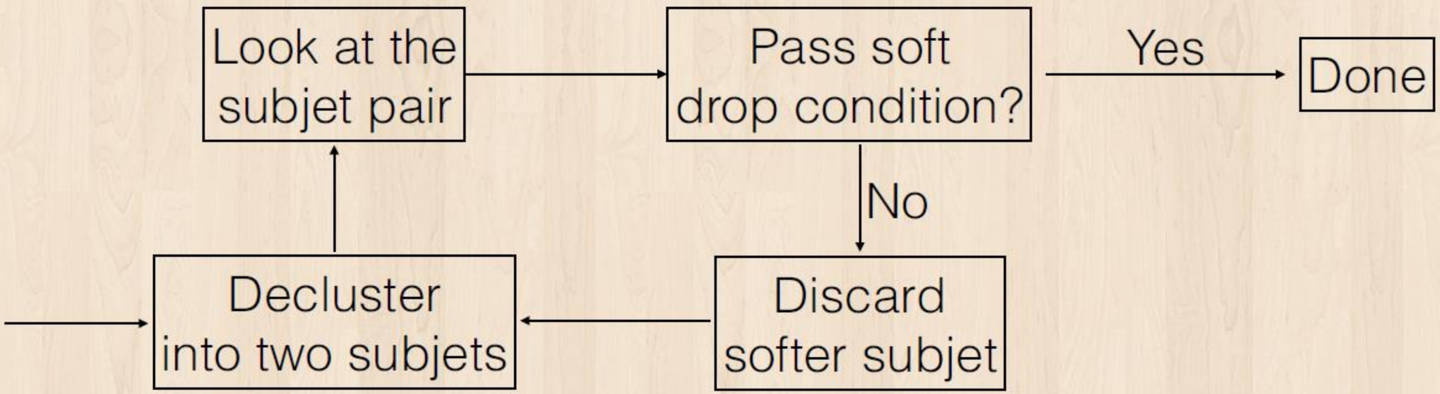
$$\rho(r) = \frac{1}{\delta r} \frac{\sum_{\text{jets}} \sum_{\text{trk} \in [r_a, r_b)} (p_T^{\text{trk}} / p_T^{\text{jet}})}{\sum_{\text{jets}} \sum_{\text{trk} \in [0, r_f)} (p_T^{\text{trk}} / p_T^{\text{jet}})}$$



PbPb – > A **larger fraction of jet energy** carried **large distances** from the jet axis.

mMDT / soft drop grooming

Soft drop condition: $z_{\mathrm{g}} \equiv \frac{\min(p_{\mathrm{T}\,1}, p_{\mathrm{T}\,2})}{p_{\mathrm{T}\,1} + p_{\mathrm{T}\,2}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$



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Inclusive jet measurements

- Measurements of inclusive jet suppression:
  - Phys. Lett. B 719 (2013) 220 … Pb+Pb @ 2.76 TeV
  - Phys. Rev. Lett. 114 (2015) 072302 … pp, Pb+Pb @ 2.76 TeV
  - Phys. Lett. B 748 (2015) 392-413 … p+Pb @ 5.02 TeV
  - arXiv: 1805.05645 … pp, Pb+Pb @ 5.02 TeV
- Measurements of jet substructure via fragmentation functions:
  - Phys. Lett. B739 (2014) 320 … Pb+Pb @ 2.76 TeV
  - Eur. Phys. J. C 77 (2017) 379 … pp, Pb+Pb @ 2.76 TeV
  - arXiv: 1706.02859 … pp, p+Pb @ 5.02 TeV
  - arXiv: 1805.05424 ... pp, Pb+Pb @ 5.02 TeV
  - ATLAS-CONF-2018-009 … Pb+Pb @ 5.02 TeV (γ+jet)
- Jet substructure via jet mass: ATLAS-CONF-2018-014
- Dijet measurement in XeXe: ATLAS-CONF-2018-007

Jet measurements in CMS

- Measurements of inclusive jet suppression
  - PRC 84 (2011) 024906 …PbPb @2.76 TeV
  - PLB 712 (2012) 176-197 …PbPb @2.76 TeV

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- Measurements of jet subtracture
  - JHEP 10 (2012) 087 …pp,PbPb @2.76 TeV
  - PLB 718 (2013) 773-794 …pp,PbPb @2.76 TeV
  - JHEP 01 (2016) 006 …pp,PbPb @2.76 TeV

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HIN-16-024 , HIN-16-020, HIN-16-005, HIN-16-014, HIN-16-002, HIN-15-013, HIN-15-011, HIN-14-016, HIN-12-013, HIN-12-003, HIN-12-002, HIN-11-010, HIN-11-013, HIN-10-004