Jets in QCD matter
Experimental summary

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(CERN)

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HARD PROBES 2018

International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions
30 September 2018 to 5 October 2018 • Aix-Les-Bains • France

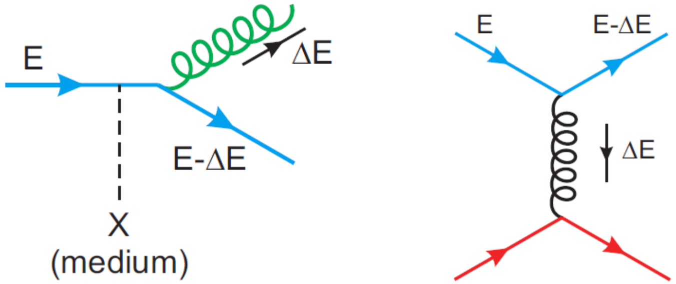
Many, many talks...

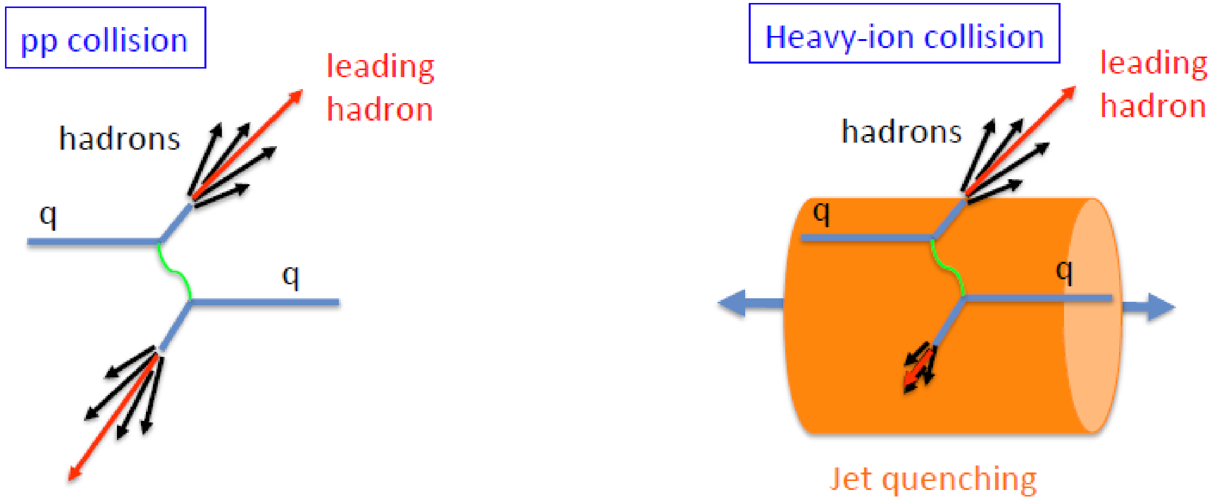
- ~90 talks related to jets out of ~150 parallel talks (both exp+theo)
- my personal (biased) selection in this summary

Jets in QCD medium

- **Parton energy loss (radiative+elastic) leads to jet quenching**
- **Learn something about the medium**

=> e.g. extraction of transport properties: $\hat{q}$





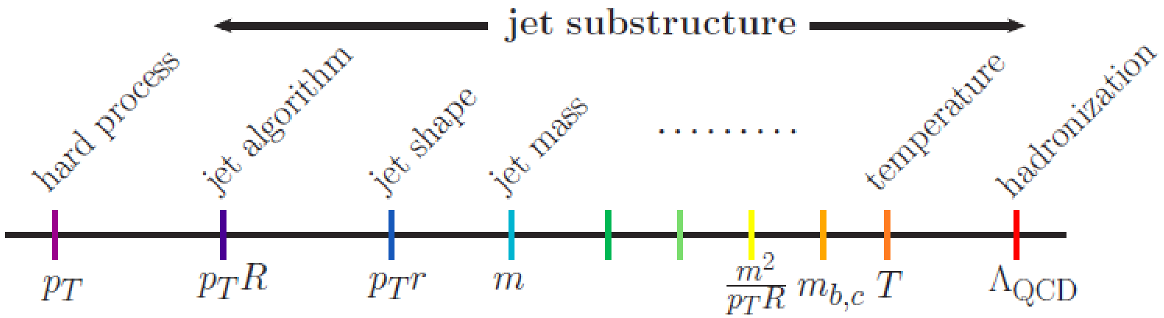
- **needs pp „vacuum“ reference!**
- **most measurements need model comparison**

For different observable we can (and should) study:

- **collision energy dependence RHIC -> LHC**
- **collision system dependence pp -> pA -> AA- > AB**
- **multiplicity/centrality dependence**

Jet observables

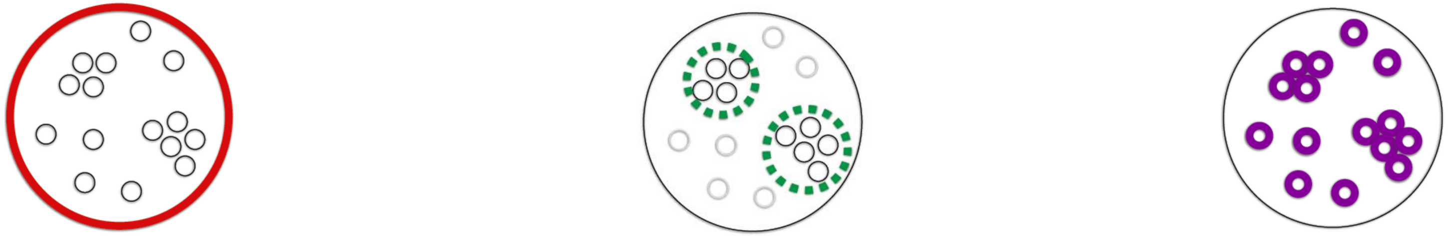
- Do we really understand the QCD vacuum (pp) reference?
- Does radiative energy loss dominate? Is collisional energy loss important?
- Is the quenching different for gluons and quarks, light & heavy flavor?
- Do broad jets lose more energy than narrow jets?
- Where does the lost energy end up?
- What is the microscopic mechanism of parton energy loss?



Relate precise jet modifications to medium properties

Hadron level observables:

- particle spectra/R_{AA},
- h-h or gamma-h correlations
- high p_T v_2

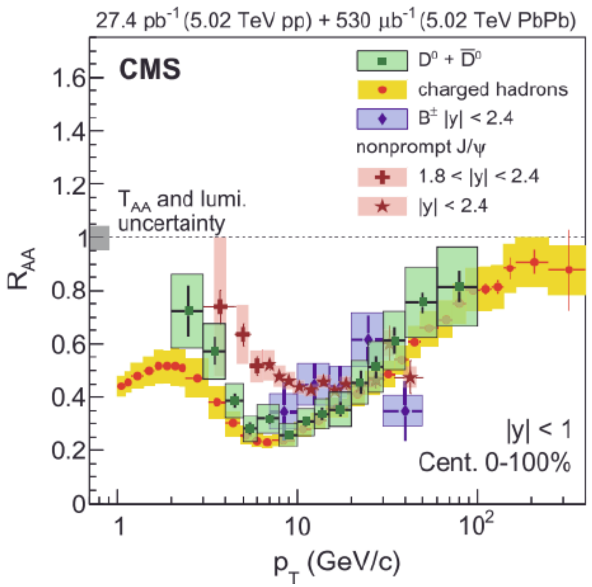


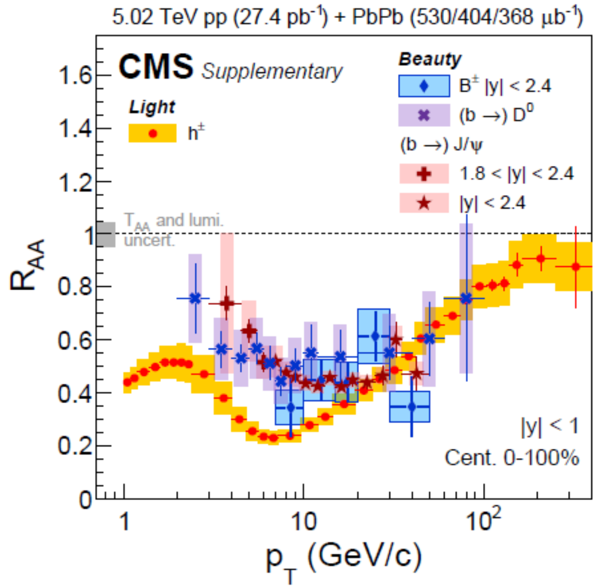
Full jets <-> jet structure (shape, mass, grooming) <-> fragmentation

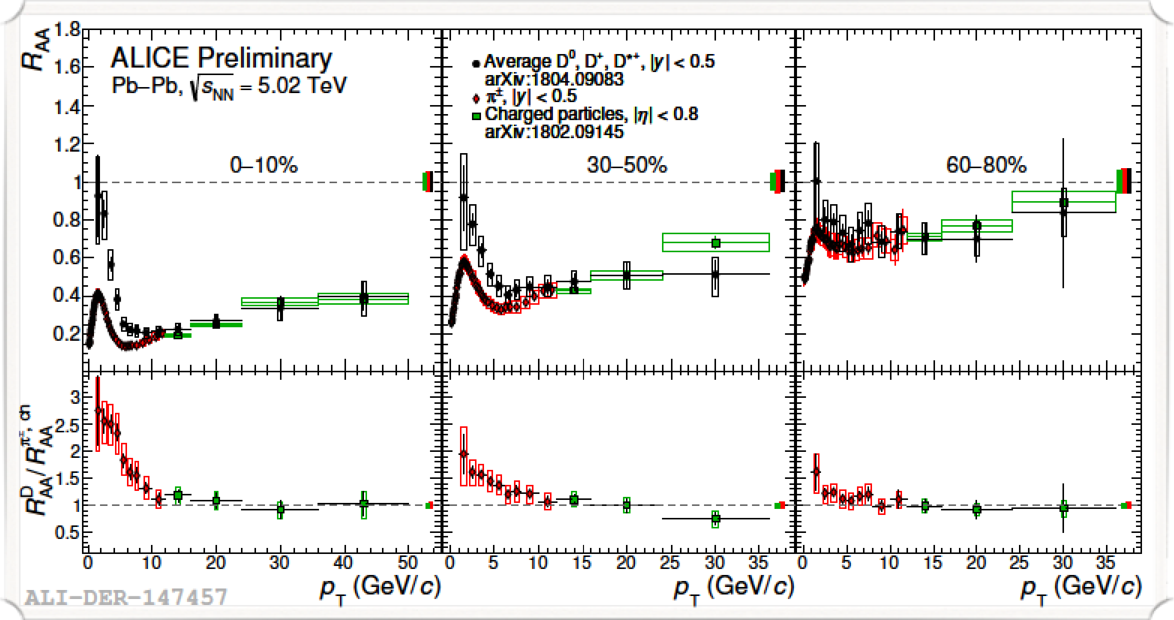
Single particle spectra

- **hadrons at large p_T are from jets**
- **b,c reduced energy loss (color charge, dead cone effect)**
- **seen in open b and b->D**

$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T} \equiv \frac{[medium]}{[vacuum]}$$





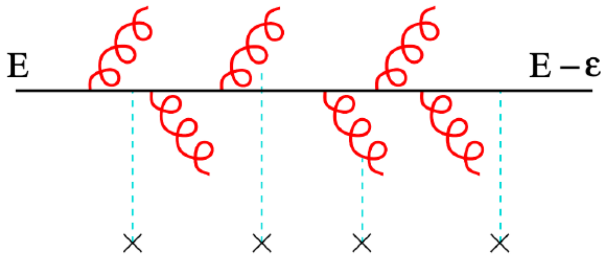


- **Very little effect for D mesons above 10 GeV/c**
  => c quark energy loss same as light flavor
  little difference from gluon jets?

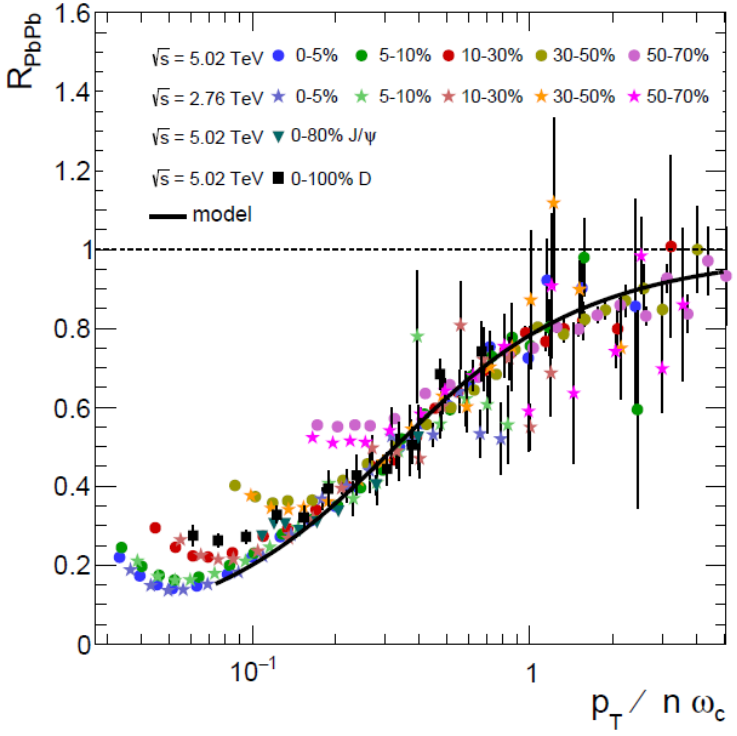
Hao Qiu, Tuesday
Guillaume Falmagne, Tuesday
Fabrizio Grosa ,Tuesday
Cheng-Chieh Peng, Thursday

Simple model for hadron quenching

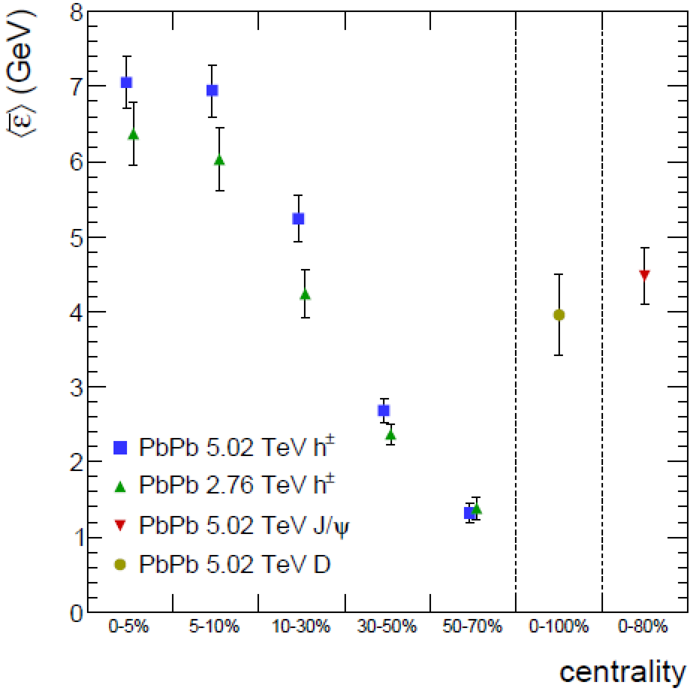
- **quenching weights based on BDMPS**
- **power law pp spectrum**
- **only a single energy loss scale (no medium model)**



scaling of R_{AA} at large pT



average energy loss



$$\frac{d\sigma^h_{AA}}{dy\, dp_\perp} \simeq A^2 \int_0^\infty dx\, \frac{d\sigma^h_{pp}(p_\perp + \bar{\omega}_c\, x)}{dy\, dp_\perp}\, \bar{P}(x)$$

$$\bar{\omega}_c = 1/2\, \hat{q}\, L^2\, \langle z \rangle$$

=> not much to learn from hadron R_{AA}?

Francois Arleo, Tuesday

Charged hadron R_{AA} in Xe-Xe

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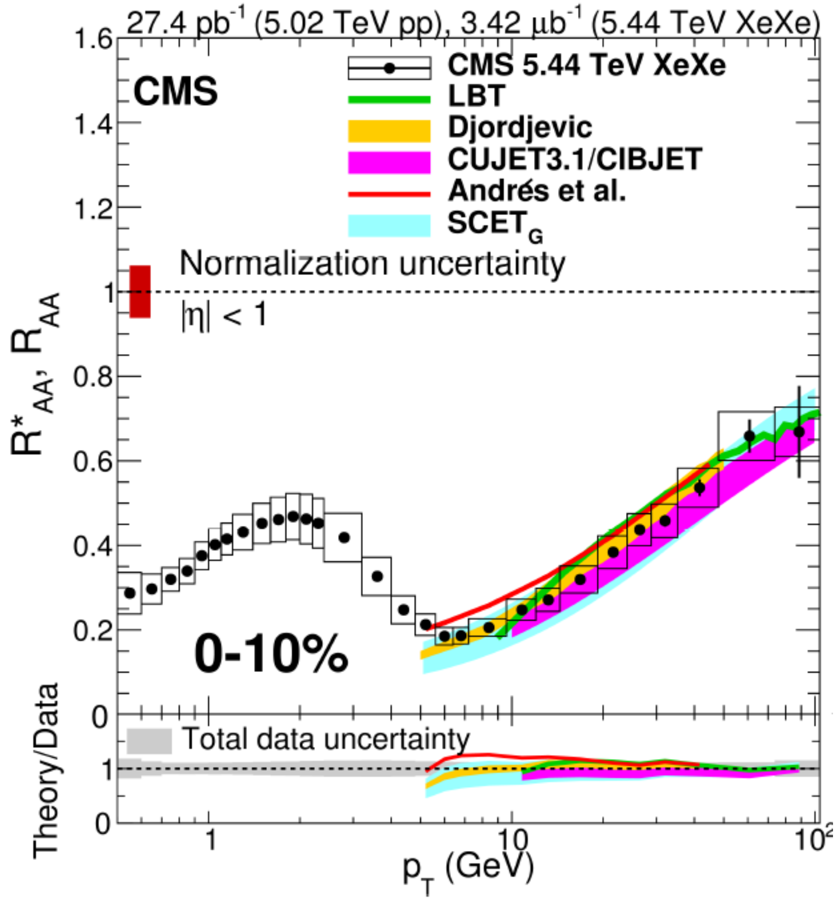
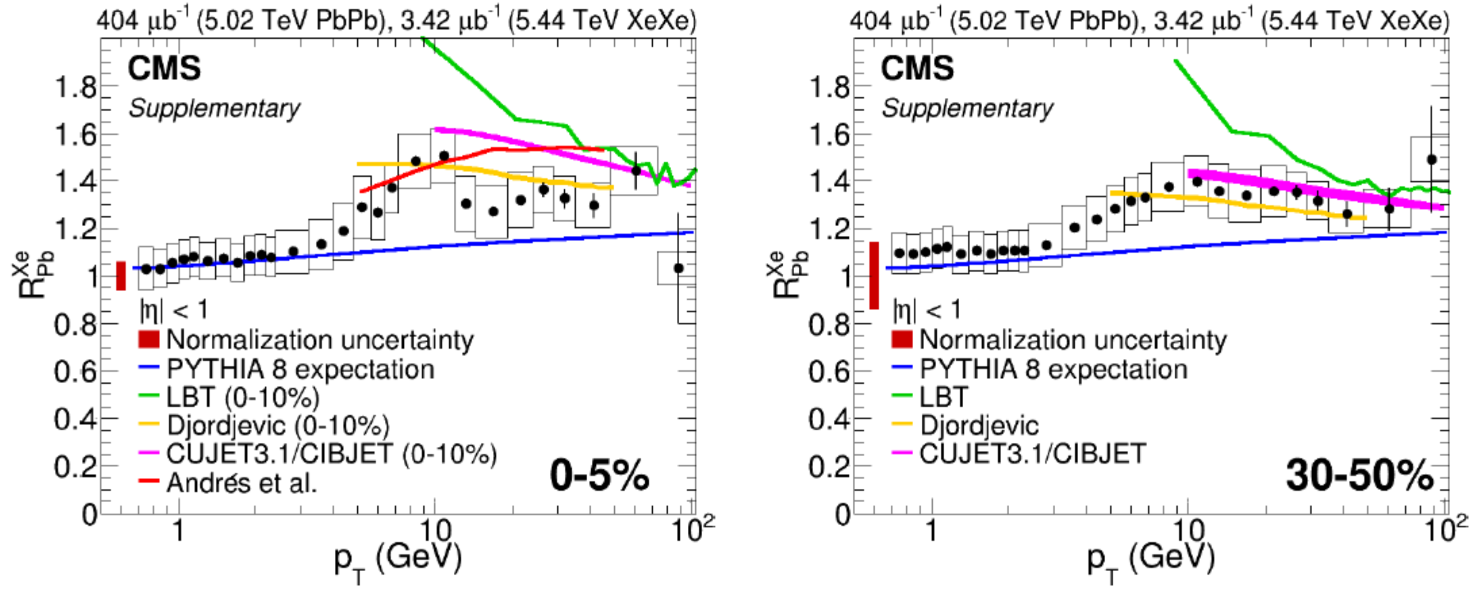
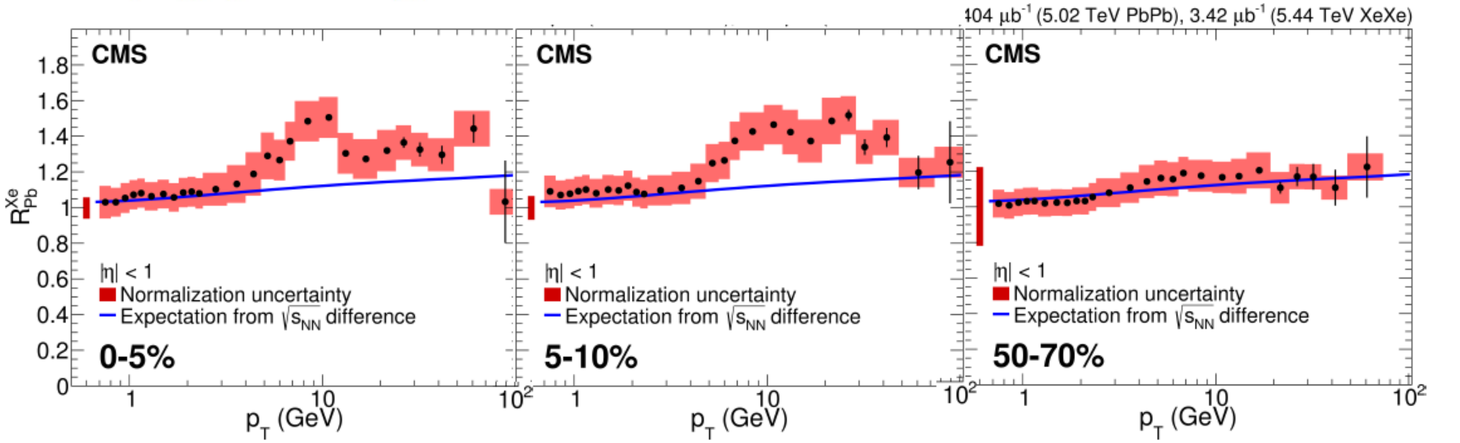
„everybody can describe R_{AA}“



$$R^{Xe}_{Pb}(p_T) = \frac{dN^{XeXe}/dp_T}{dN^{PbPb}/dp_T}\frac{T_{PbPb}}{T_{XeXe}}.$$





Austin Batey, Tuesday

arXiv:1809.00201

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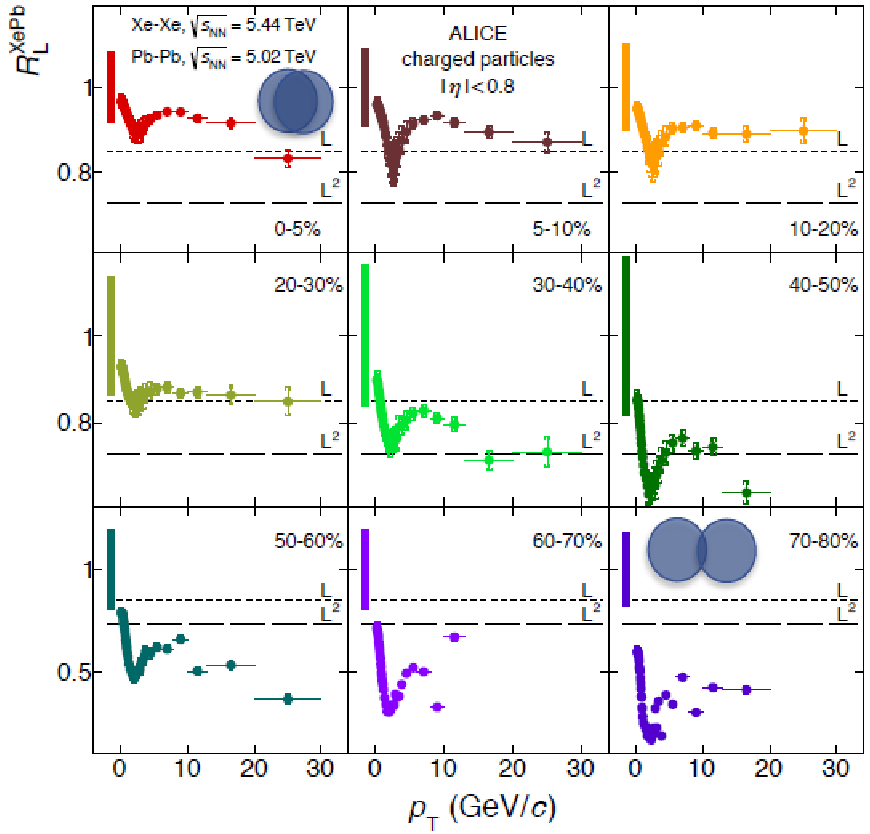
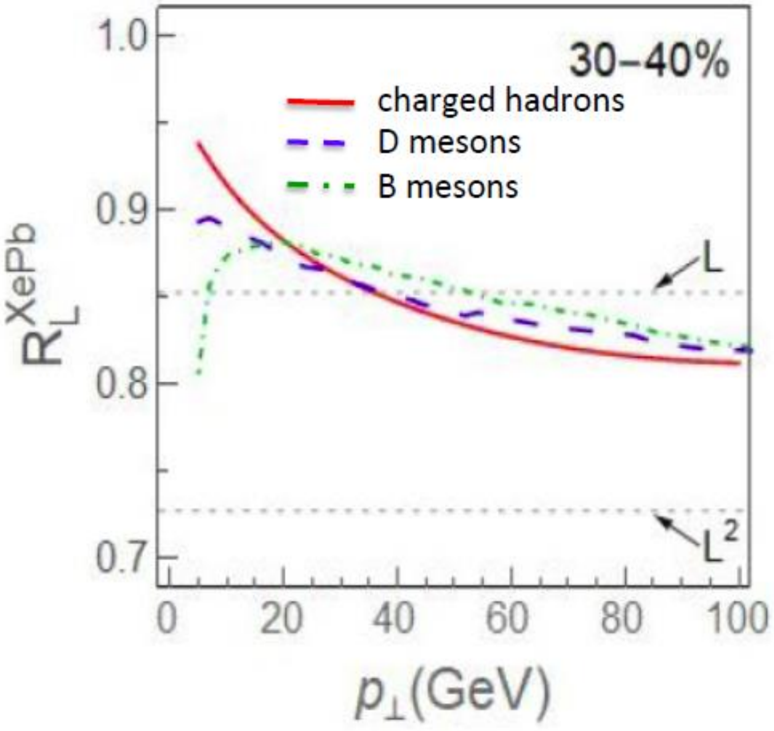
- **system size dependence from Xe-Xe and Pb-Pb R_{AA}**



$$R_{AA} \approx (1 - \xi T^a L^b)$$

$$\Delta E/E \sim \eta T^a L^b$$

M. Djorjevic et al., arXiv:1805.04030



$$R_L^{XePb} \equiv \frac{1 - R_{XeXe}}{1 - R_{PbPb}} \approx \frac{\xi T^a L^b_{Xe}}{\xi T^a L^b_{Pb}} \approx \left(\frac{A_{Xe}}{A_{Pb}}\right)^{b/3}$$

Jacek Otwinowski, Tuesday
Magdalena Djordjevic, Thursday

Charged particle R_{AA} in Xe-Xe

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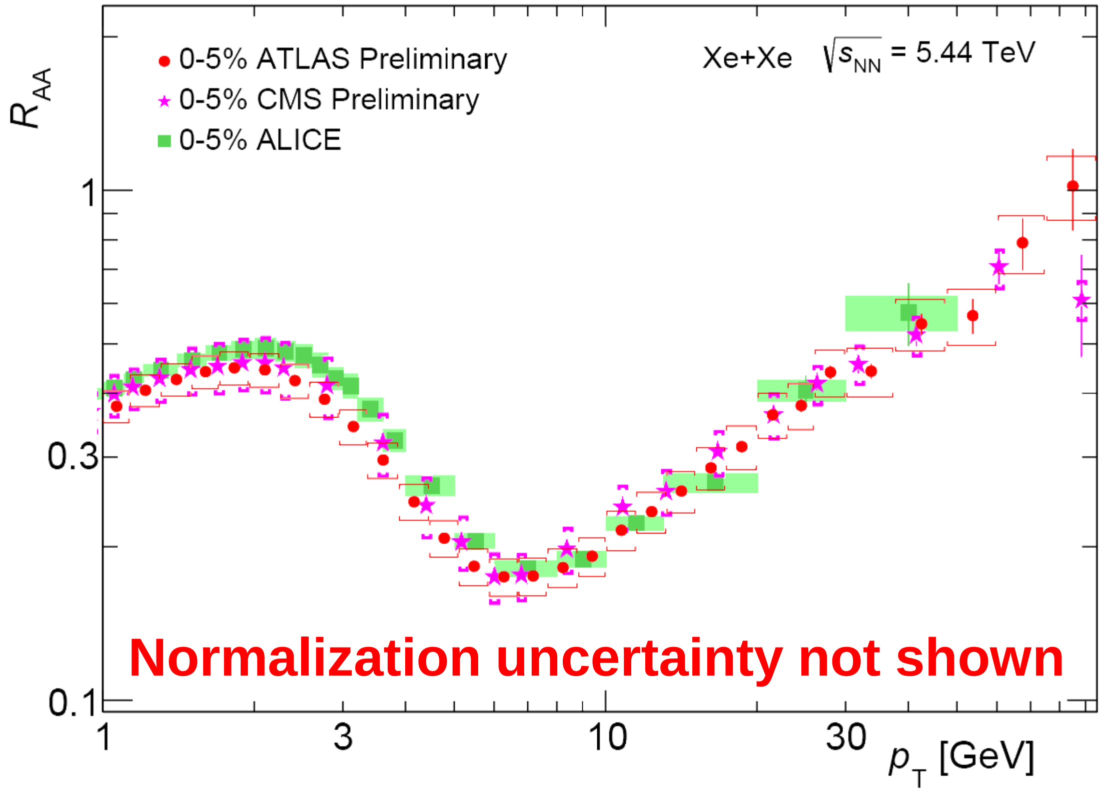
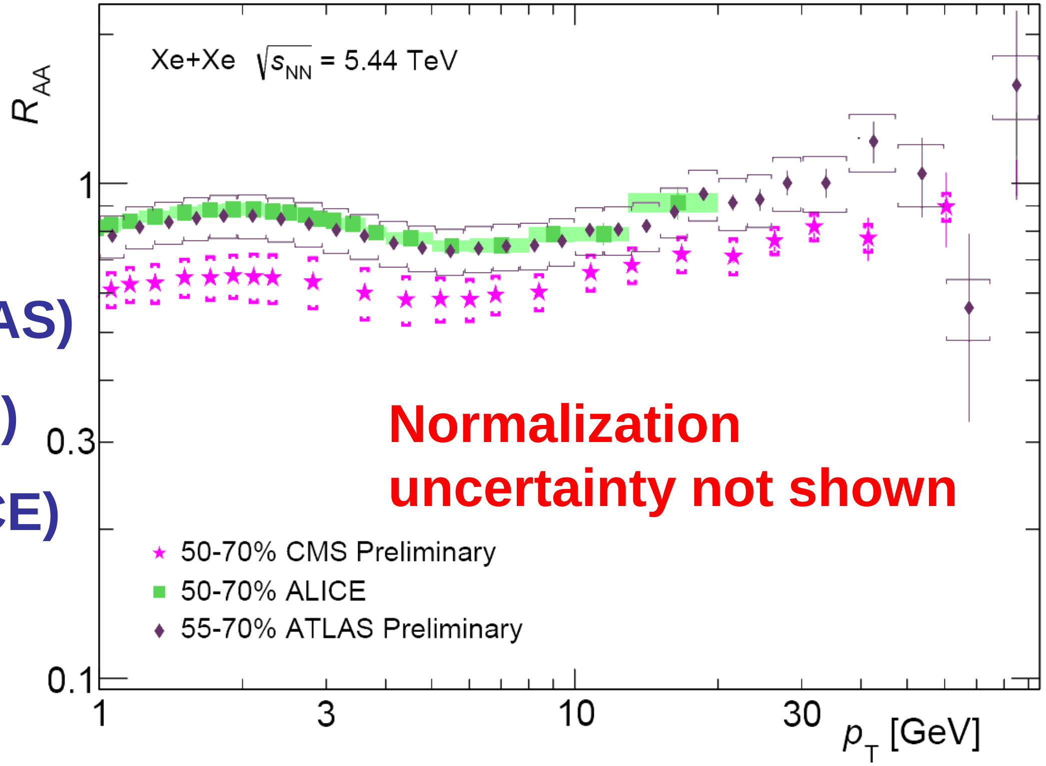
- **Comparison of the LHC experiments**
- **good agreement in central collisions**



|η| < 2.4 (ATLAS)
|η| < 1.0 (CMS)
|η| < 0.8 (ALICE)



- **difference in peripheral -> to be followed up**

Petr Balek, Tuesday
Austin Batey, Tuesday
Jacek Otwinowski, Tuesday

R_{AA} in peripheral Pb-Pb collisions

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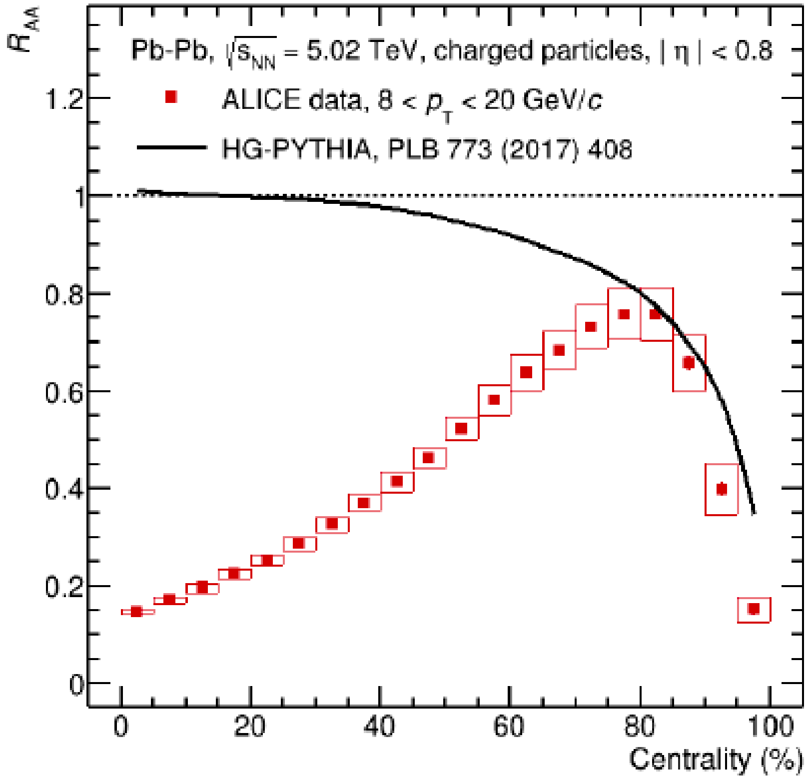
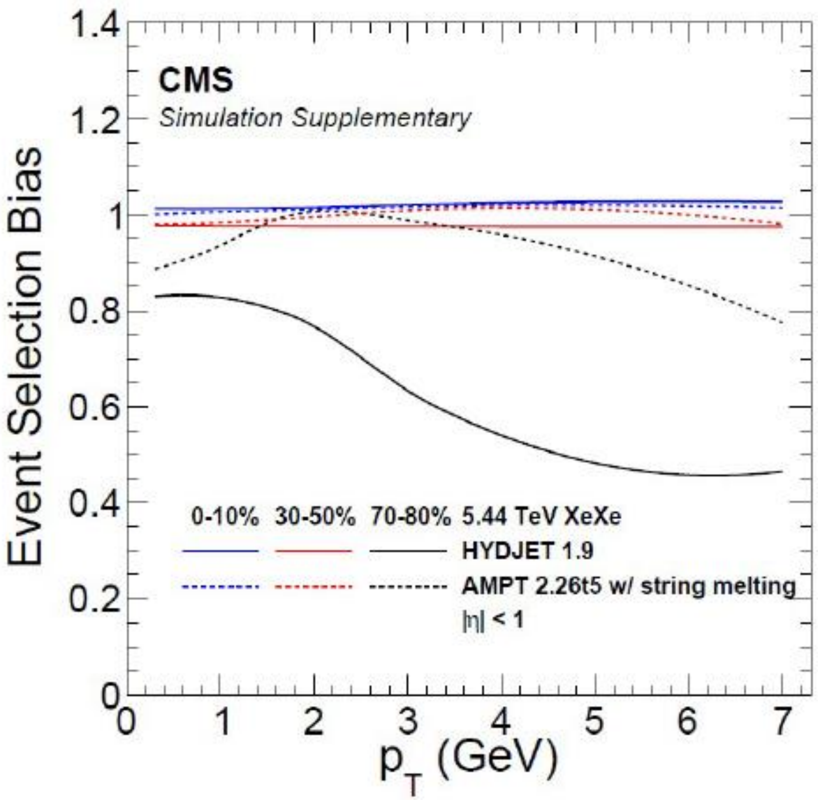
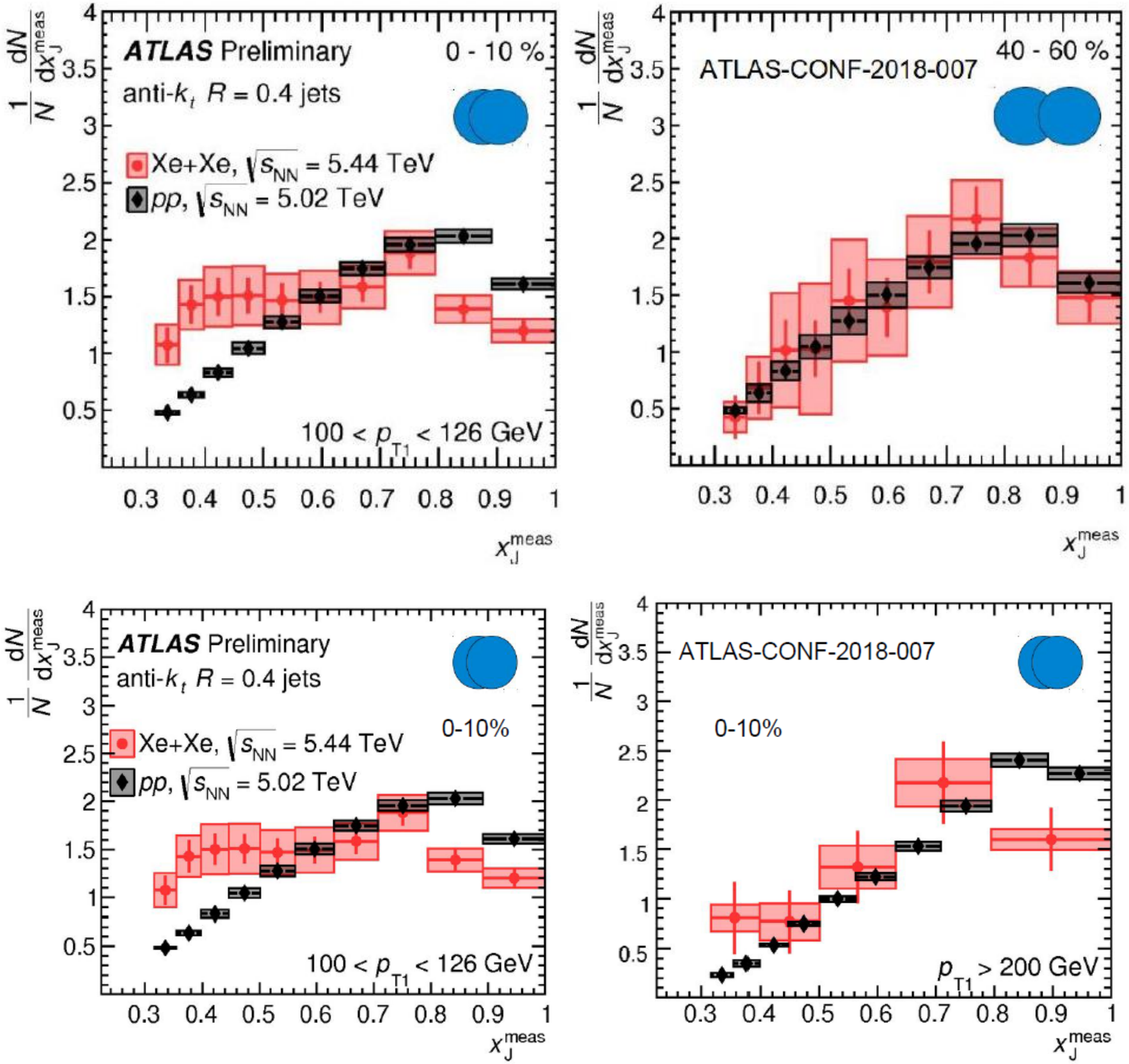
- in contrast to central collisions, peripheral collisions suffer from biases
- actual amount of jet quenching unclear





Austin Batey, Tuesday
Jacek Otwinowski, Tuesday

Di-jet imbalance in Xe-Xe

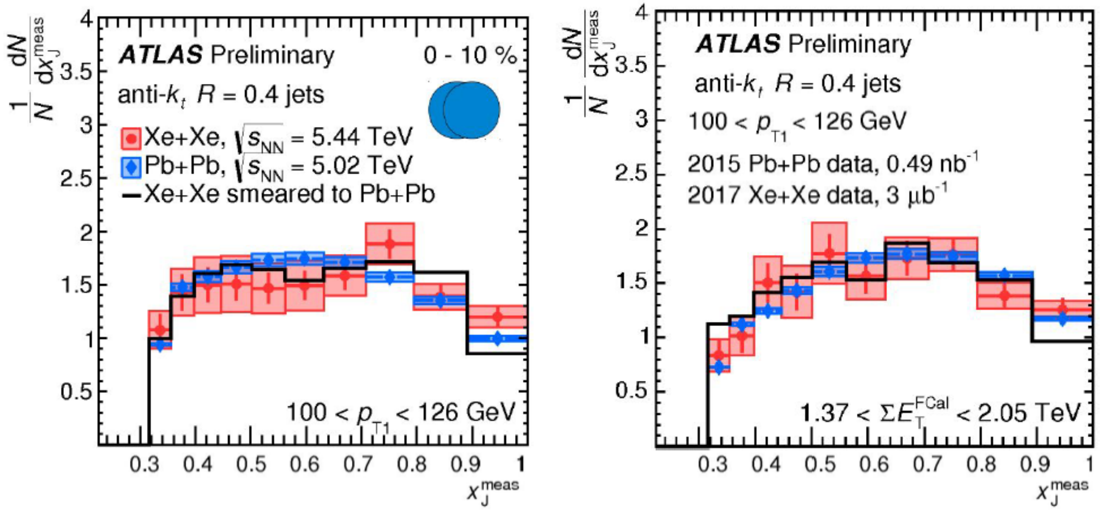


$$x_J \equiv p_{T_2}/p_{T_1}$$

- **larger asymmetry than in pp**
- **peripheral Xe-Xe consistent with pp**
- **less di-jet asymmetry at large p_T**

- **Consistent with results ín Pb-Pb**

ATLAS-CONF-2018-007



Radim Slovak, Thursday

Di-jet asymmetry from STAR

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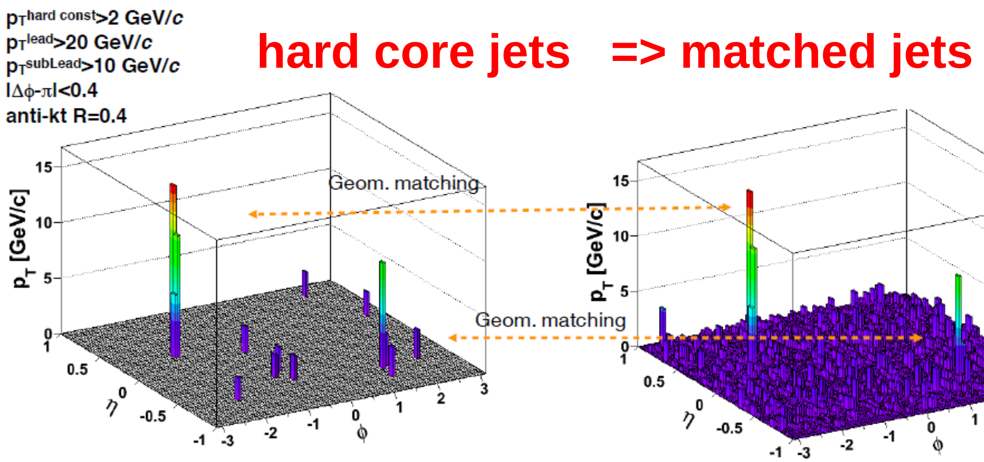
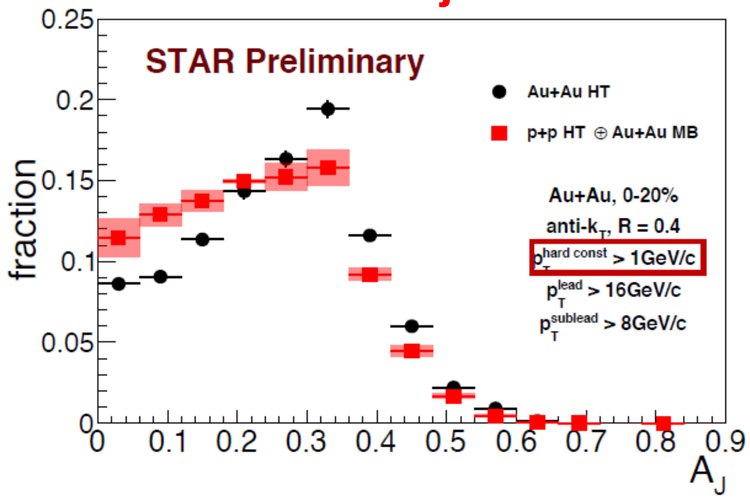
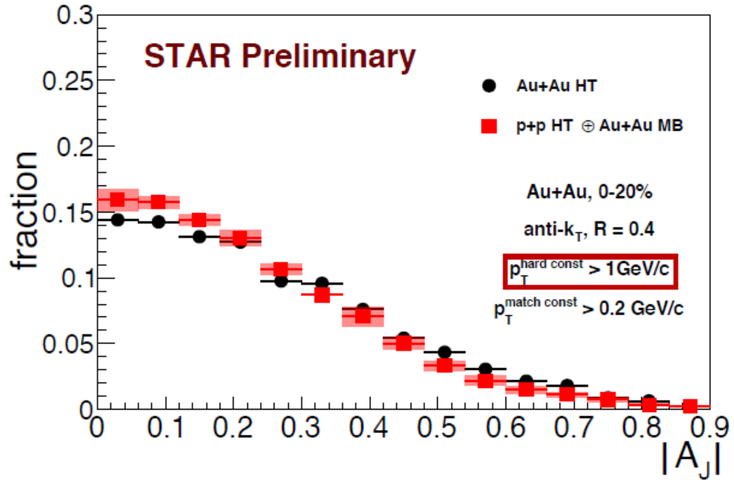
$$A_J = \frac{p_T^{\mathrm{Lead}} - p_T^{\mathrm{SubLead}}}{p_T^{\mathrm{Lead}} + p_T^{\mathrm{SubLead}}}$$



$p_T^{\text{hard const}} > 2$ GeV/c cut → removes almost all background

geometric matching $p_T^{\text{match const}} > 0.2$ GeV/c → no combinatoric jets, recover all constituents

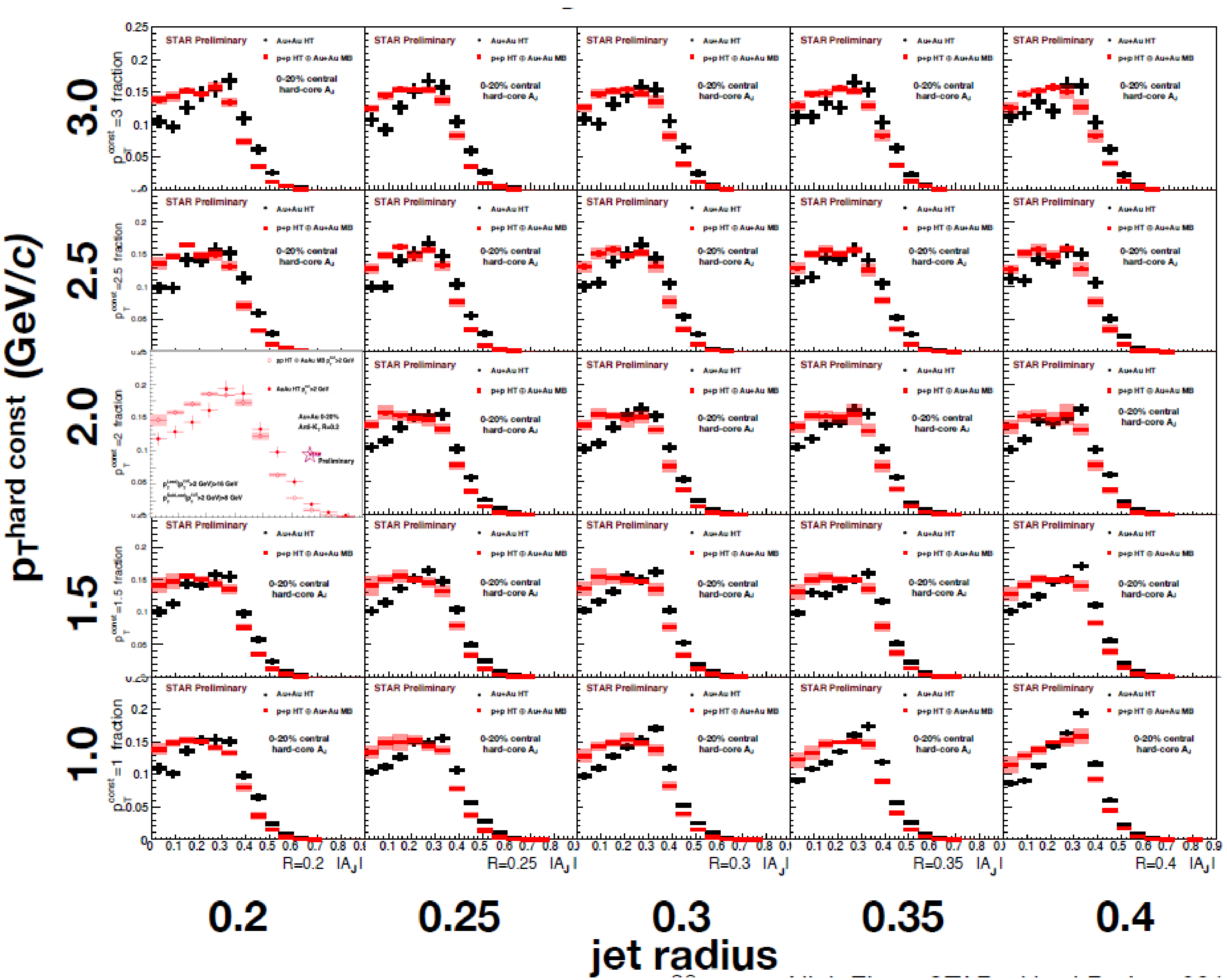


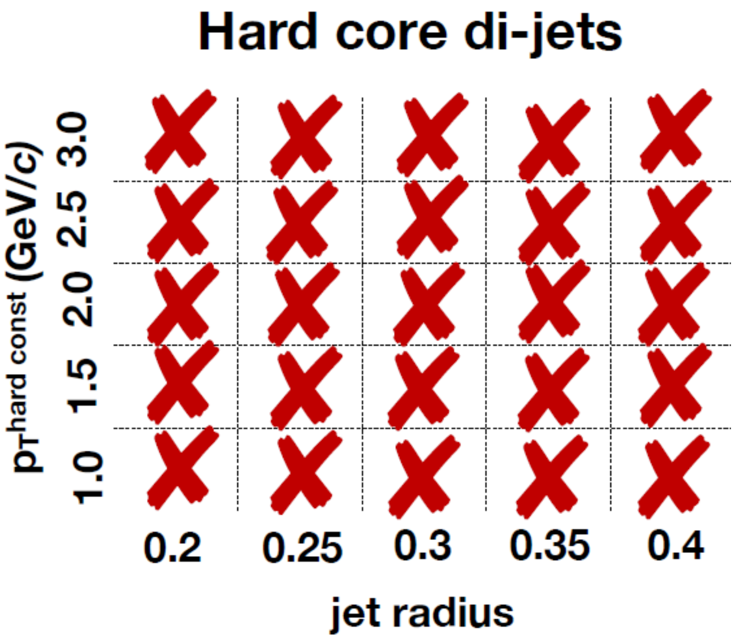


- **Variation of jet radii and p_T hard cutoff, compare to pp**
- **Statistical test (Kolmogorow-Smirnow) for compatibility**

Nick Elsey, Tuesday

Hard core jets

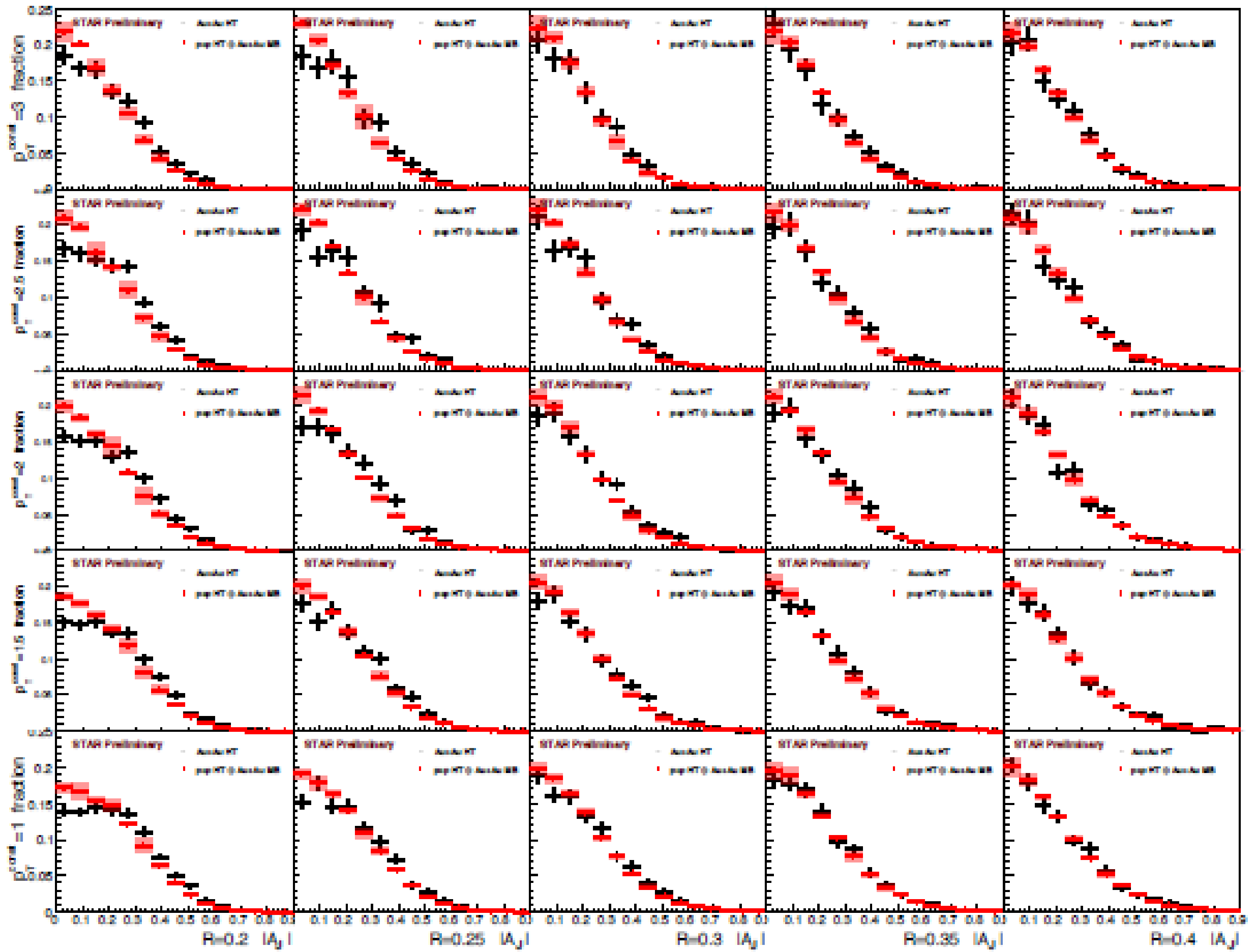


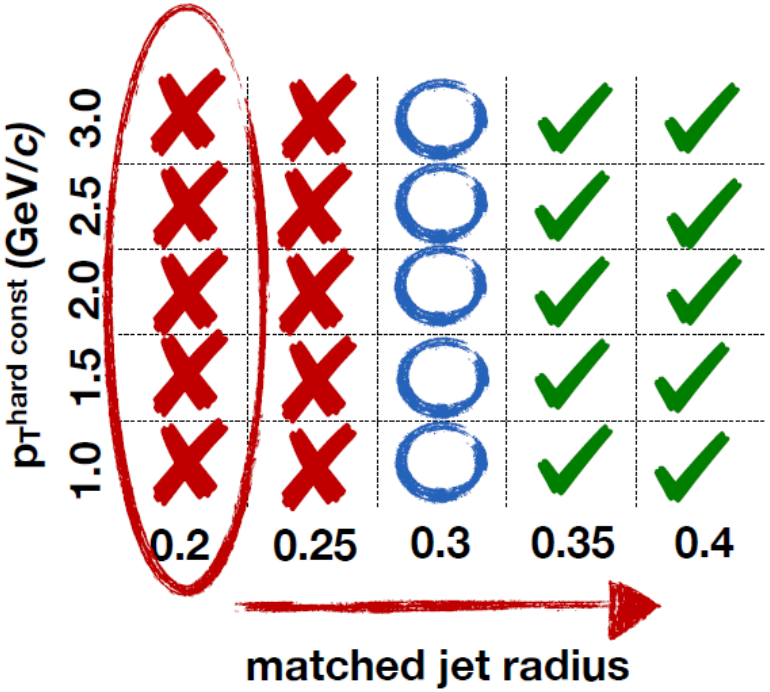


- „lost" energy goes to soft particles (< 1 GeV/c)

Nick Elsey, Tuesday

Matched jets





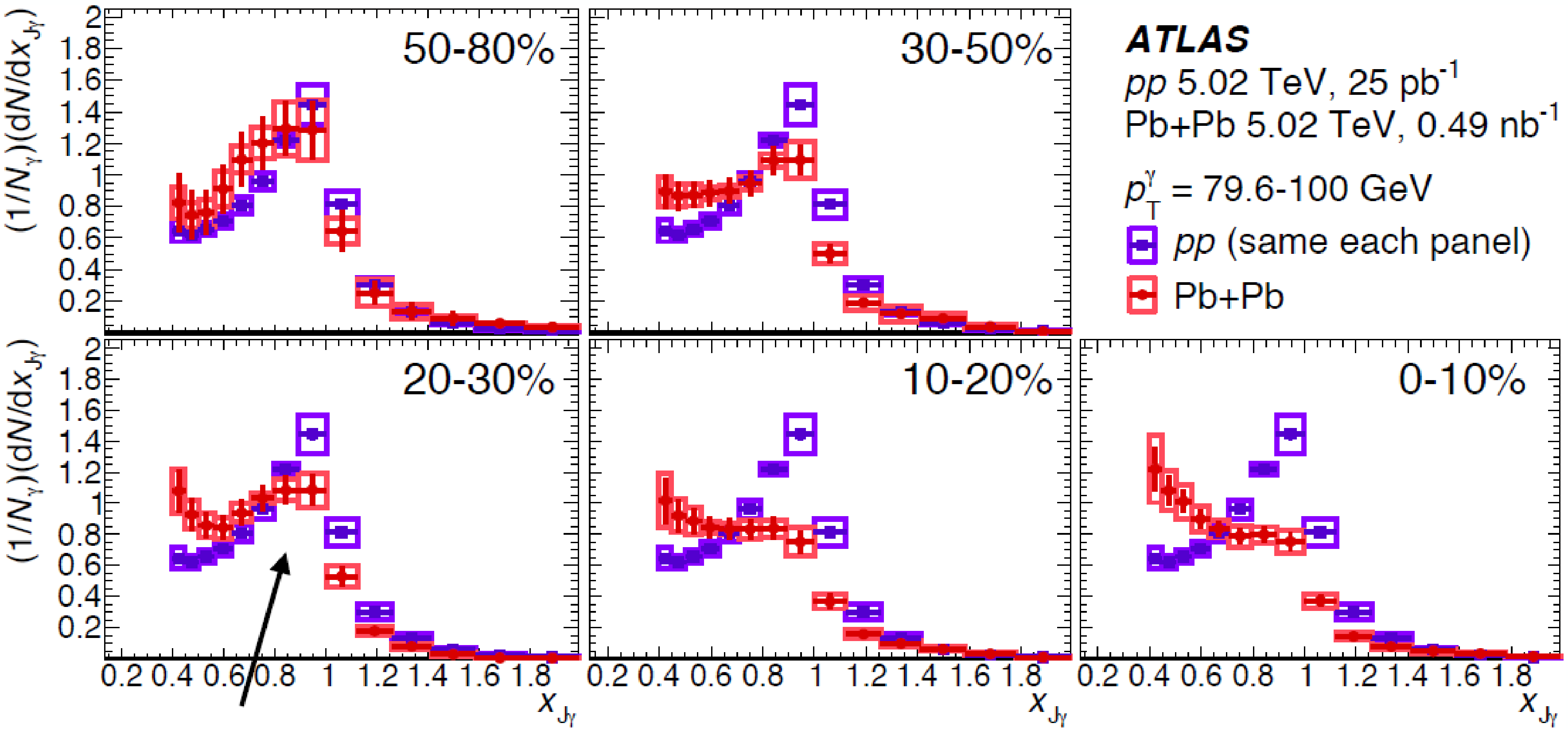
- **Hard core jet R=2**
- **Increase matched jet R ~0.35 recovers energy**
- **different from LHC**

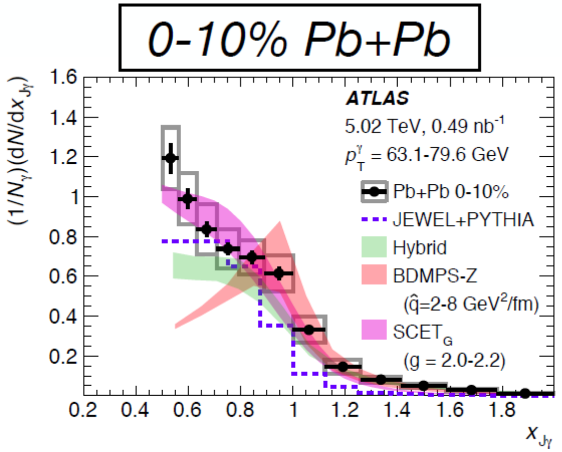
Nick Elsey, Tuesday

Photon tagged jets in ATLAS

- in pp peak at one (=no energy loss)
- 50-80% central => similar to pp

$x_{J\gamma} = p_T^{jet} / p_T^{\gamma}$ (for $\Delta\phi > 7\pi/8$)





Dennis V. Perepelitsa, Tuesday

γ-jet and π^0-jet correlations

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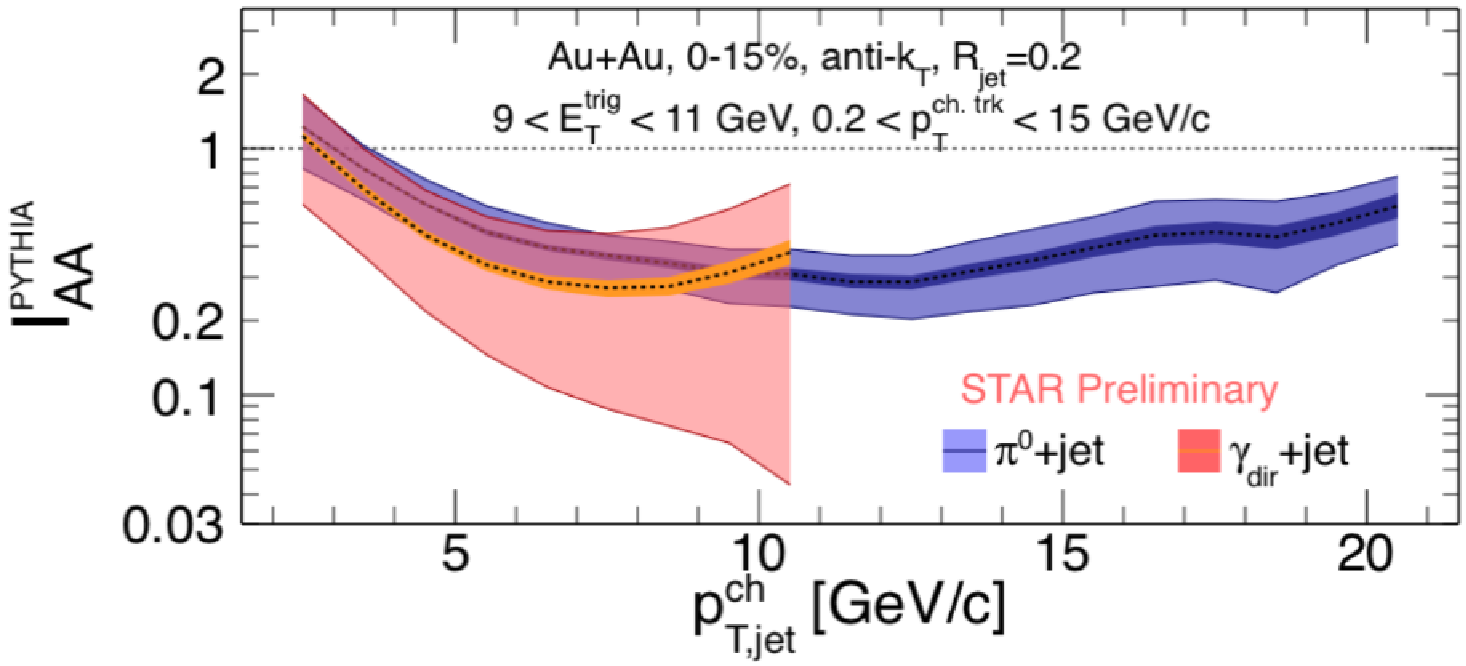
- **azimuthal correlation averaged over away-side region**



$$I_{AA} = \frac{Y_{AA}}{Y_{pp}}$$

- **recoil jet supression similar for γ and π^0 triggered correlations**
- **Kinematic range of jets down to very low p_T**

N. Sahoo, Tuesday

Jet spectra in pp collisions

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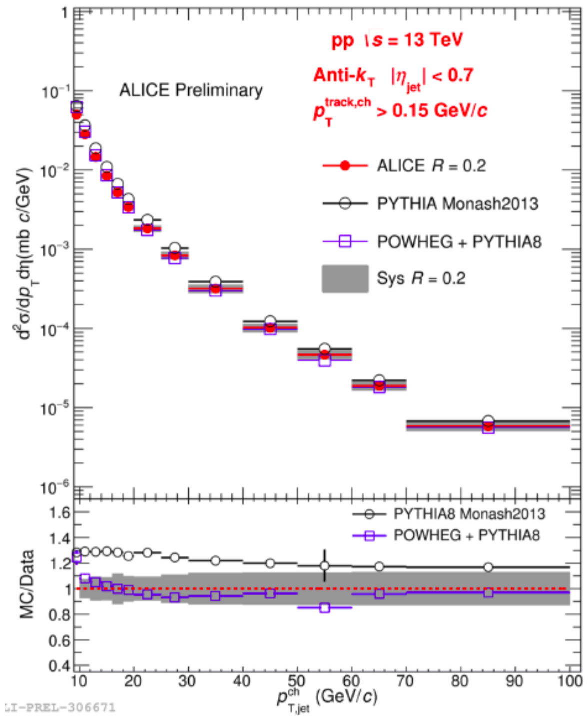
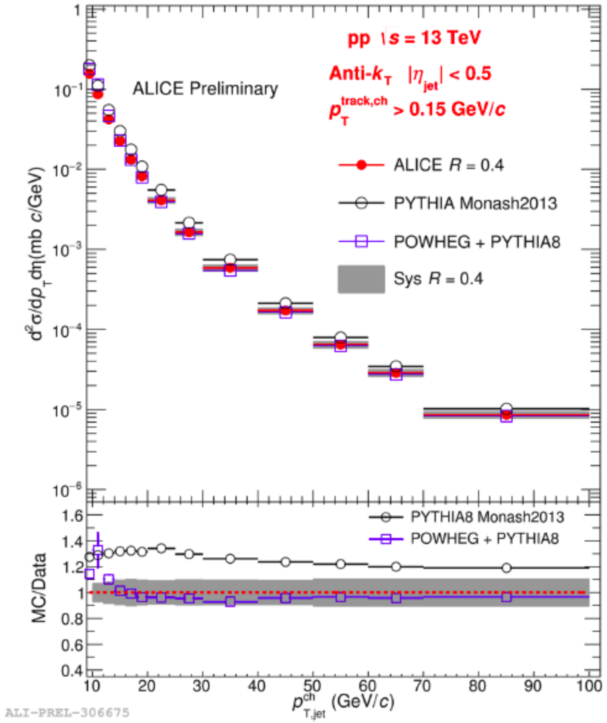
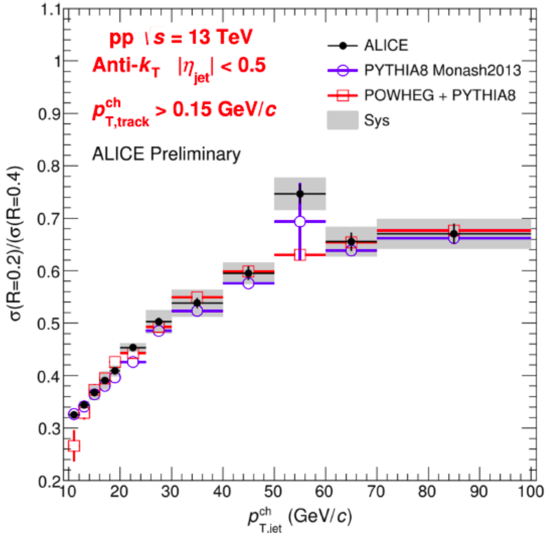
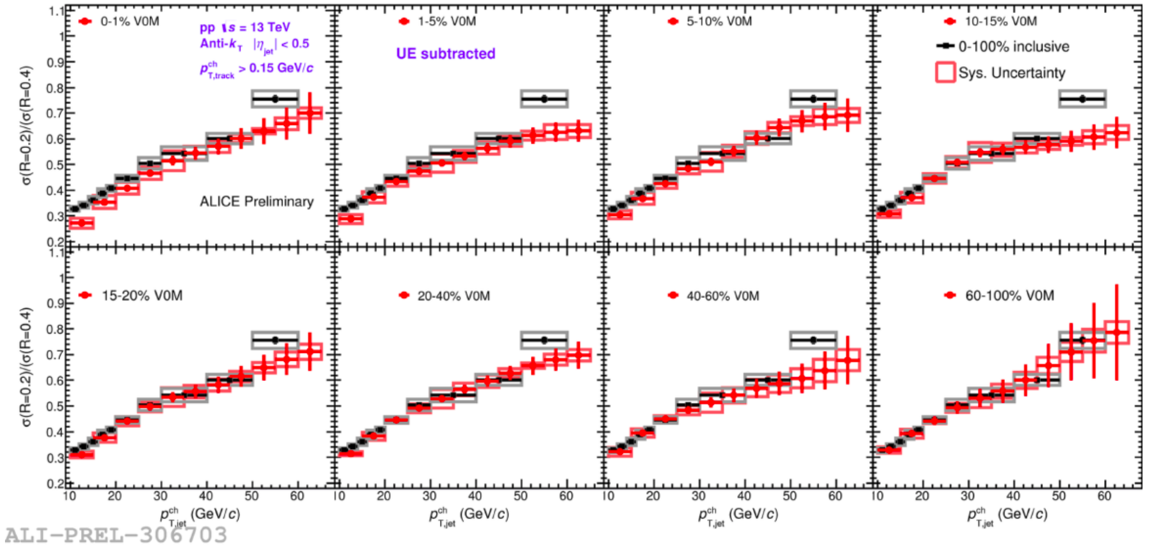








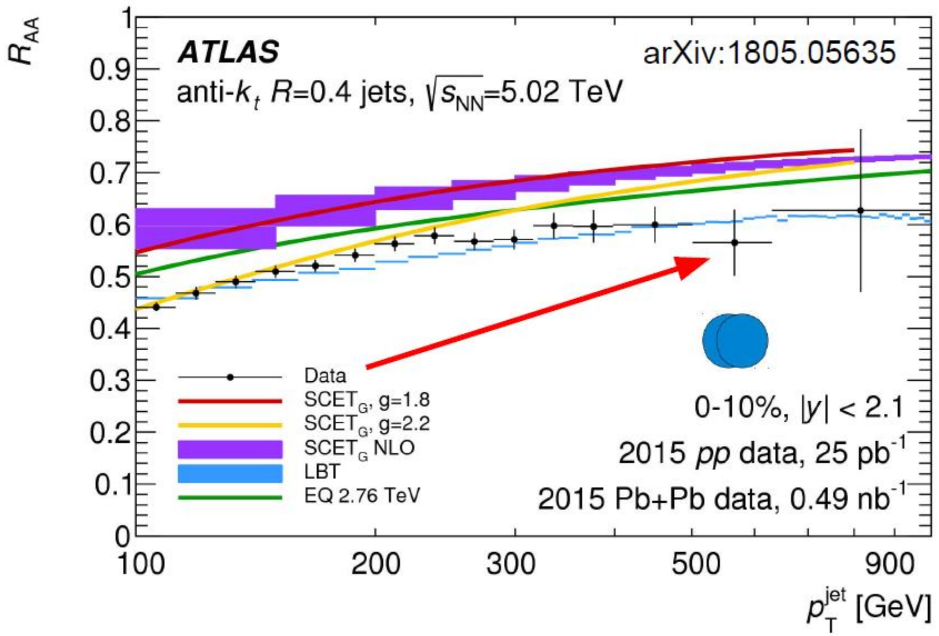
- **Jets at „low p_T" down to 10 GeV/c**
- **Pythia 8 not perfect reference, normalization issue?**
- **very weak multiplicity dependence**

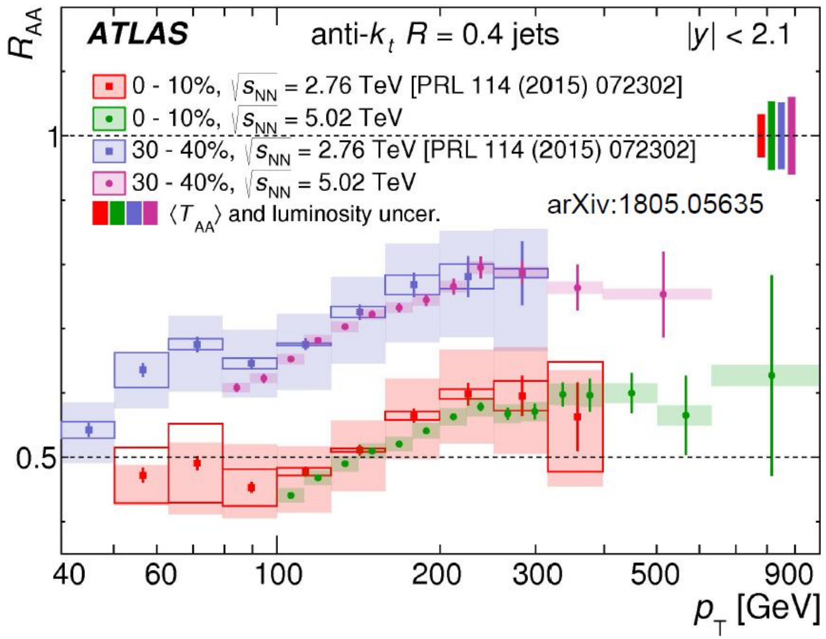
Markus Fasel, Wednesday

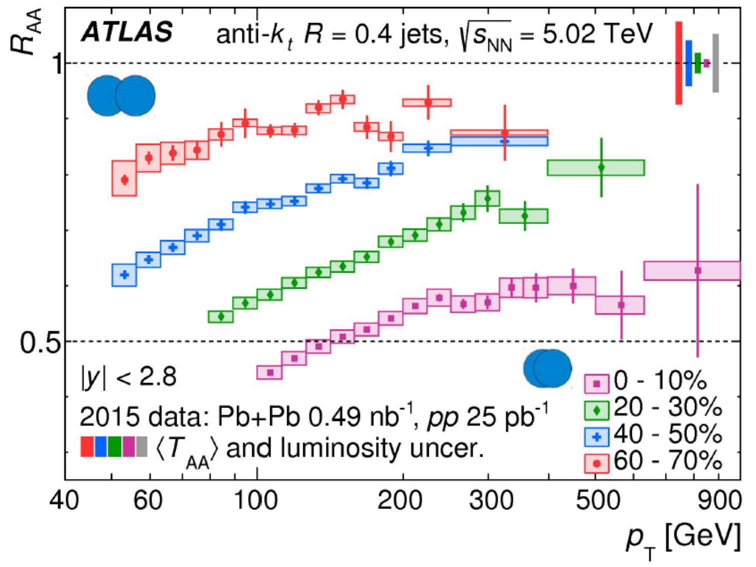
Jet R_{AA}

arXiv:1805.05635

- **Significant jet quenching up to ~1TeV**
- **Trend by all models, data well described by LBT**





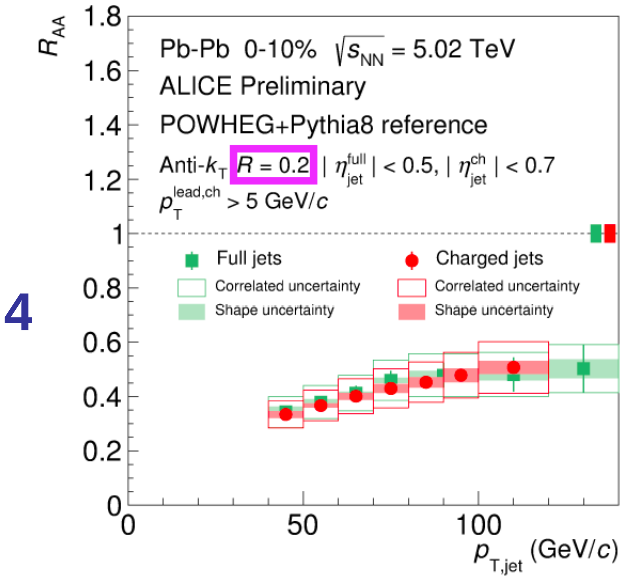


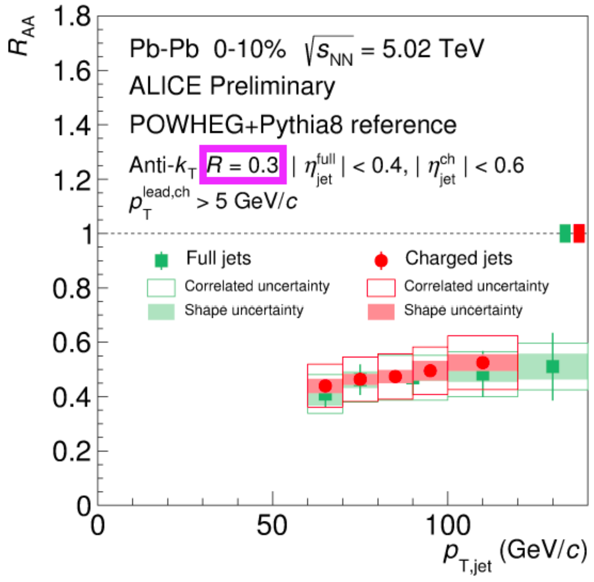
- **Jet R_{AA} does not change with collision energy (similar to hadron R_{AA})**
- **=> balance of increased energy loss and harder production spectrum at larger √s**

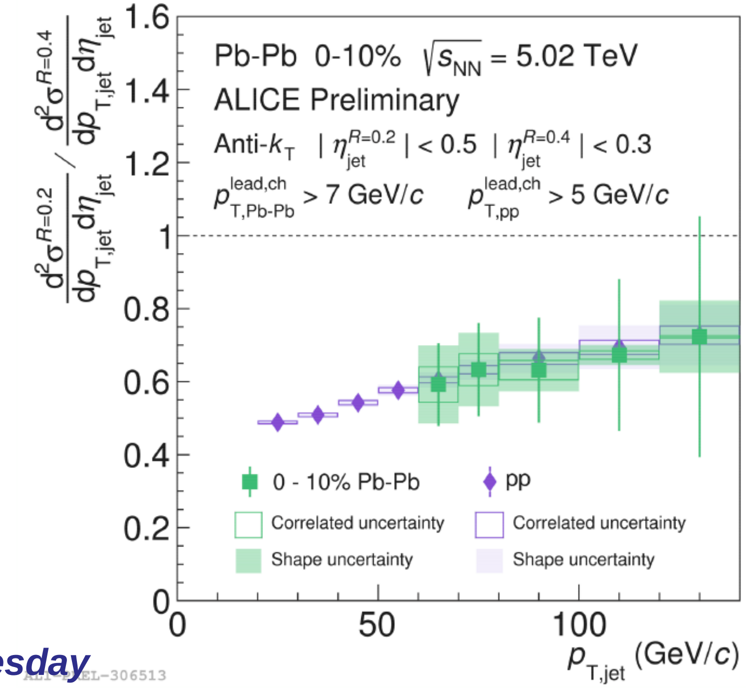
Radim Slovak, Thursday

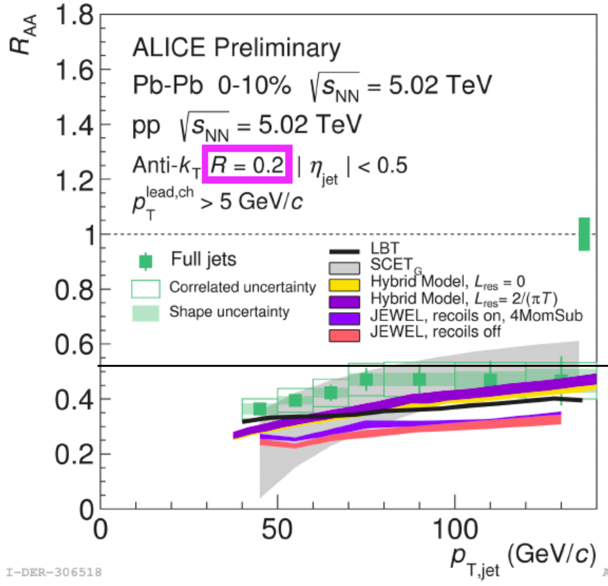
Jets in Pb-Pb collisions

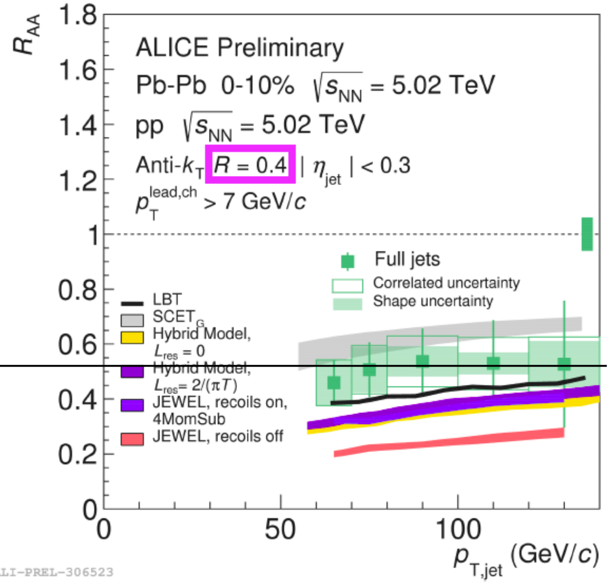
- **Jets at lower p_T down below 100 GeV/c, above in agreement with ATLAS**
- **Full jets similar to charged jets**
- **almost no energy recovered from R=0.2->R=0.4**
- **no significant modification for R=0.2/0.4**





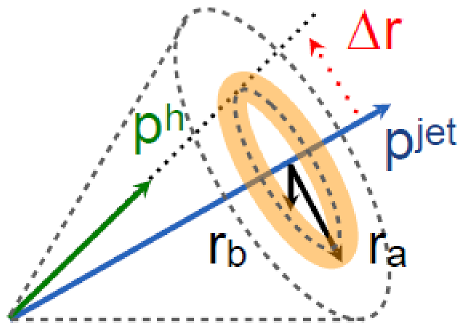






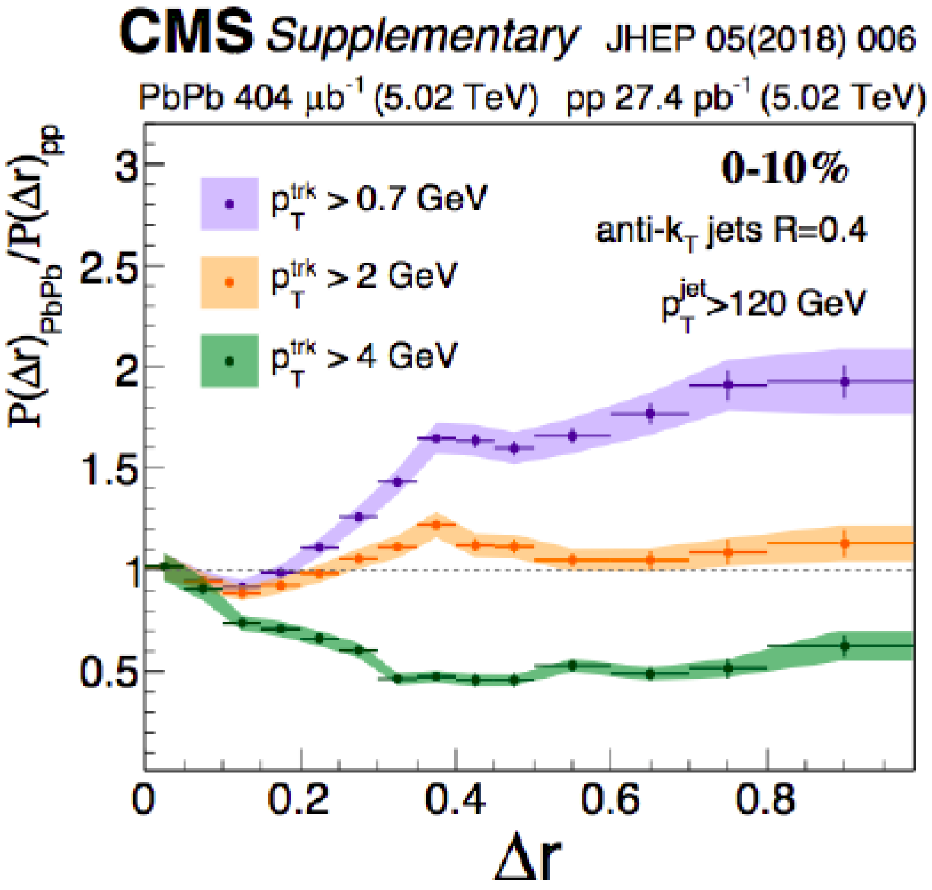
James Mulligan, Wednesday

Jet radial shape in Pb-Pb



$$P(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\rm jet}}\sum_{\rm jets}\left\{\sum_{{\rm tracks}\in(r_a,r_b)} p_T^{\rm trk}\right\}$$

- **Low p_T enhancement at large Δr**
- **„lost“ jet energy is redistributed to soft fragments at very large radii**



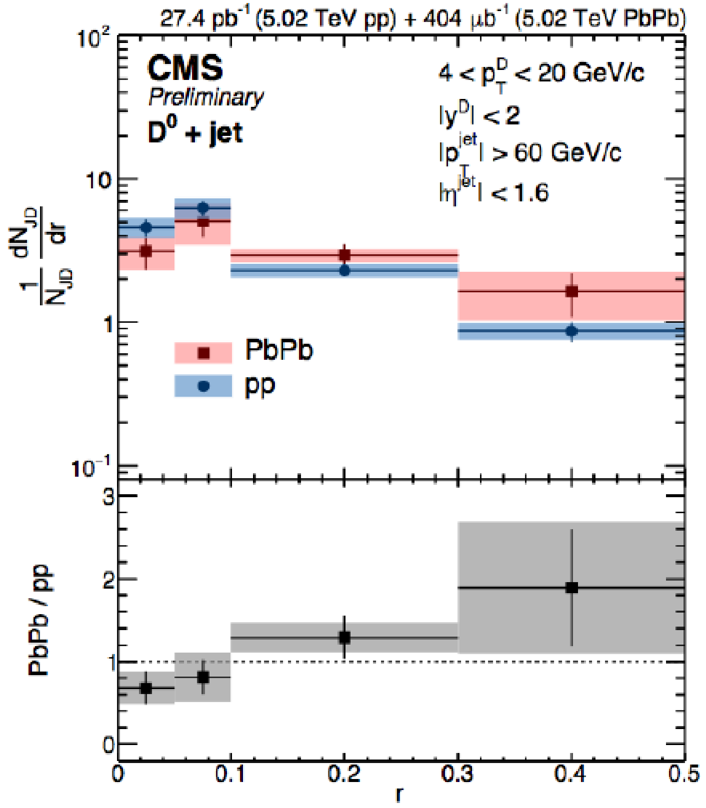
Xiao Wang, Thursday

D mesons in jets

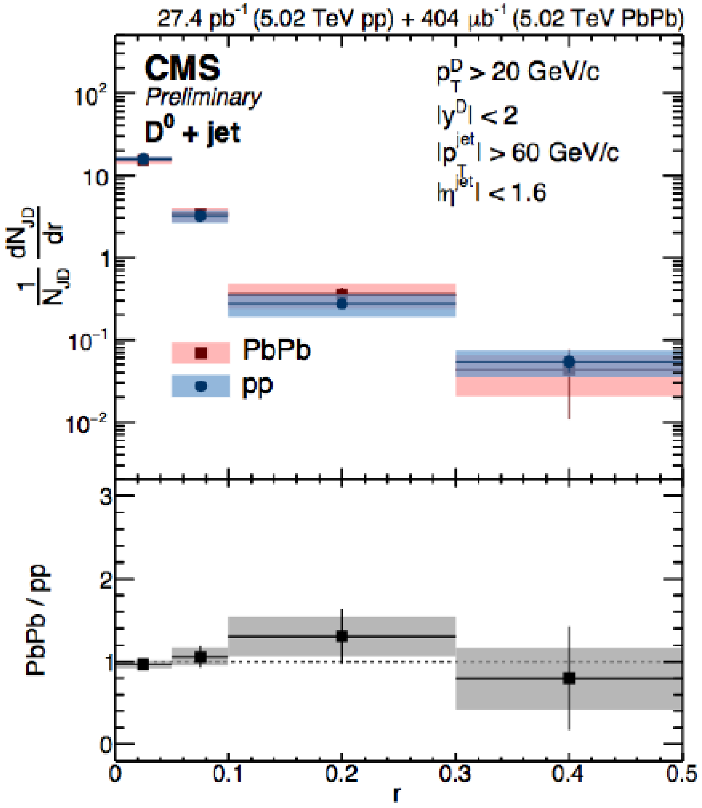
- D^0 and jet from same hard scattering

Michael Peters, Tuesday

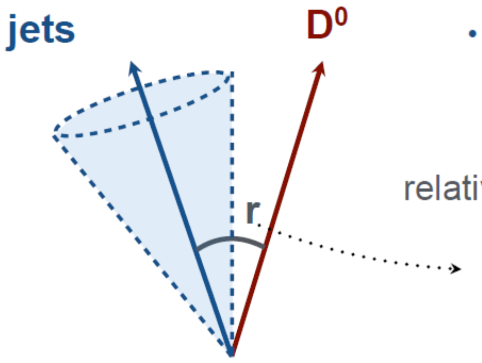
Low D p_T: $4 < p_T^D < 20$ GeV/c



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



- Iterative PU-subtracted PF jets
- anti-k_T, R = 0.3
- $p_T^{jet} > 60$ GeV/c
- $|\eta^{jet}| < 1.6$



relative η,Φ between D^0 and jets

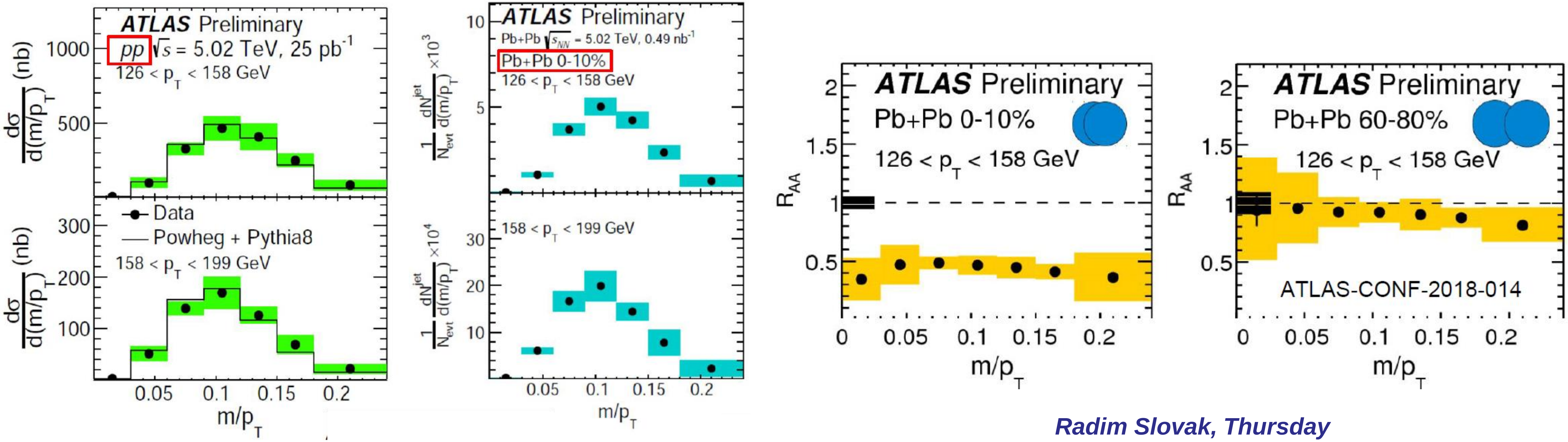
$$r = \sqrt{\Delta\phi_{JD}^2 + \Delta\eta_{JD}^2}$$

- **high p_T: D^0 from c-jet, small modification in the medium**
- **low p_T: more D^0 from gluon splitting -> hint larger angle in Pb-Pb (diffusion?)**

Jet mass measurement

ATLAS-CONF-2018-014

- **Invariant mass of the jet fragments** $M \sim z\theta^2$
- **small mass: narrow jet, few constituents**
  large mass: broad jet, many constituents
- **No significant modification of the shape observed => all jet masses equally suppressed**
- **Overall suppression consistent with the inclusive jet R_{AA}**

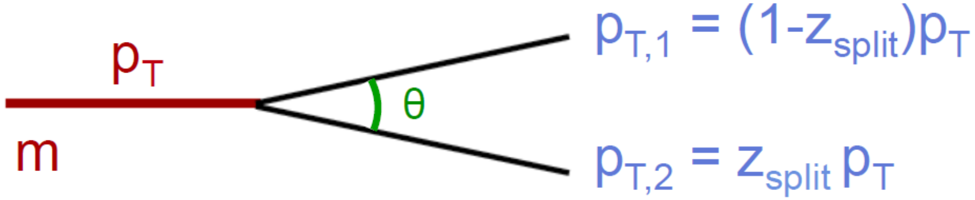


Radim Slovak, Thursday

phase space of jet splitting (Lund plane)

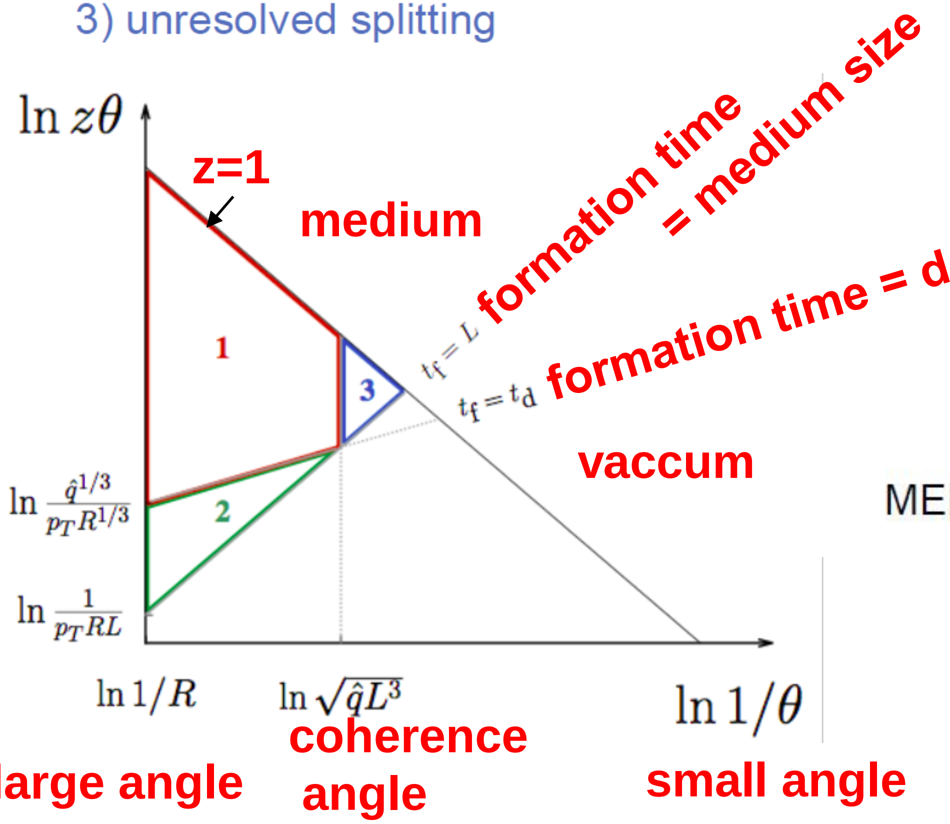
- **Splitting in vaccum (QCD)**
- **Splitting in medium**

3 regions for a splitting happening in medium
1) vacuum splitting inside medium
2) medium-induced splitting → not uniform in Lund plane
3) unresolved splitting

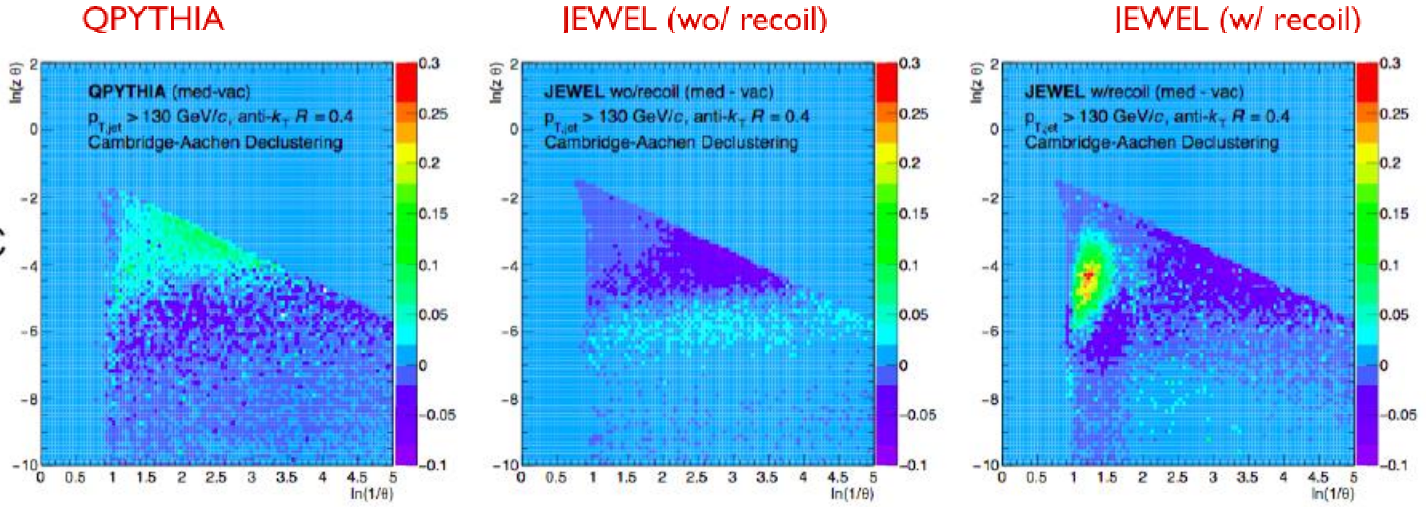


in principle could be measured

or used to define grooming parameters
=> microscopic details of energy loss



MED-VAC

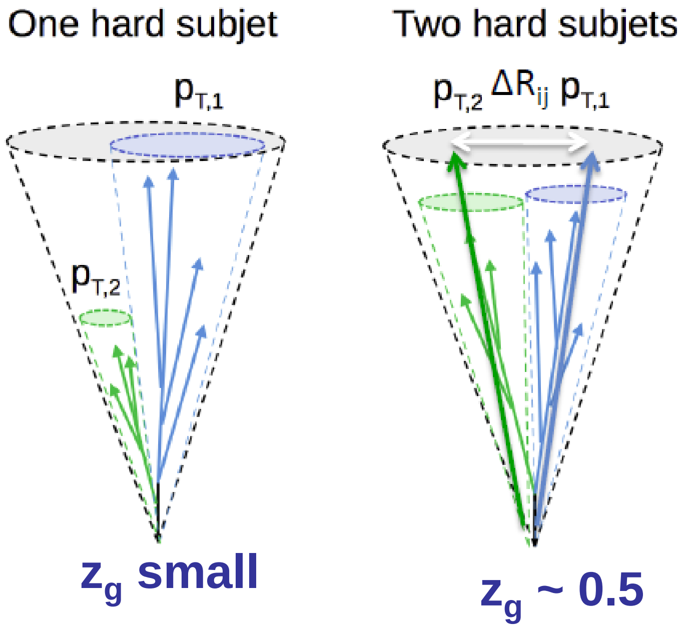


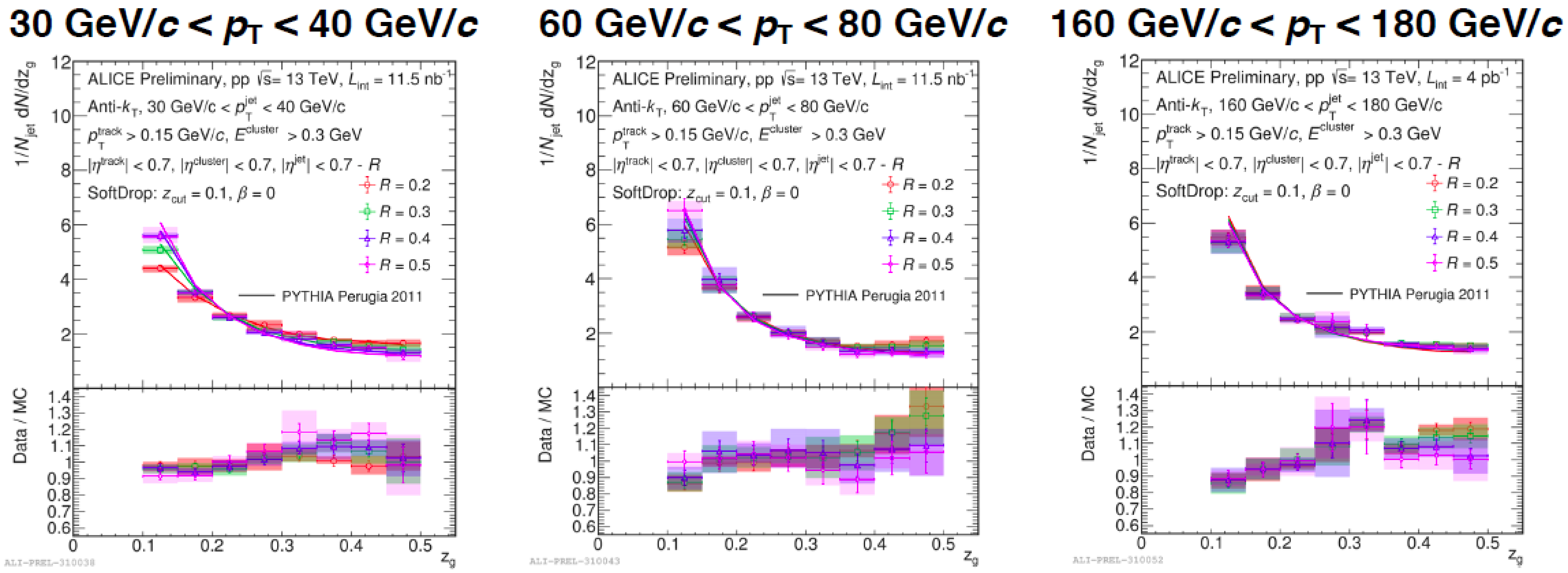
Marta Verweij, Wednesday

Jet grooming in pp collisions

- soft drop grooming to remove large angle soft radiation, UE, background
- recluster the jet (Cambridge-Aachen)
- Remove the softer branch unless $z_g = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{cut} \left(\frac{\Delta R_{ij}}{R_0}\right)^{\beta}$
- Controlled by β and z_{cut}

⇒ Access the jet splitting





Results from pp:

z_g distribution differentially in R and p_T

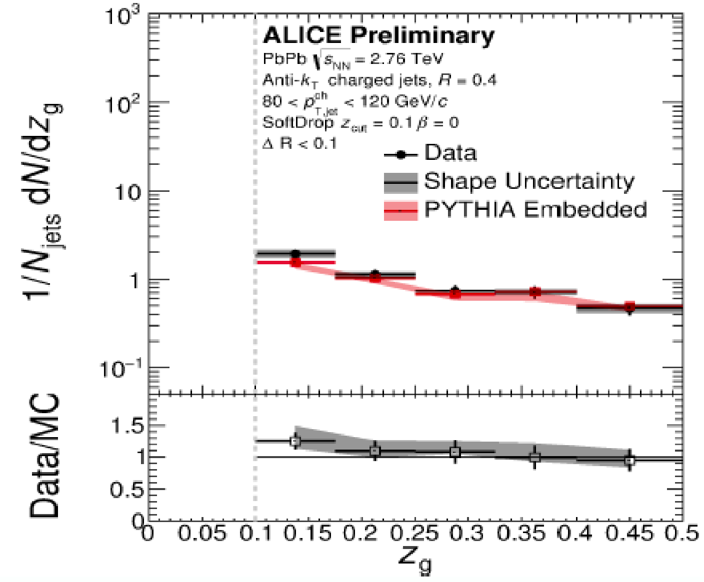
no p_T dependence at large p_T

at low p_T R dependence -> non-perturbative effects

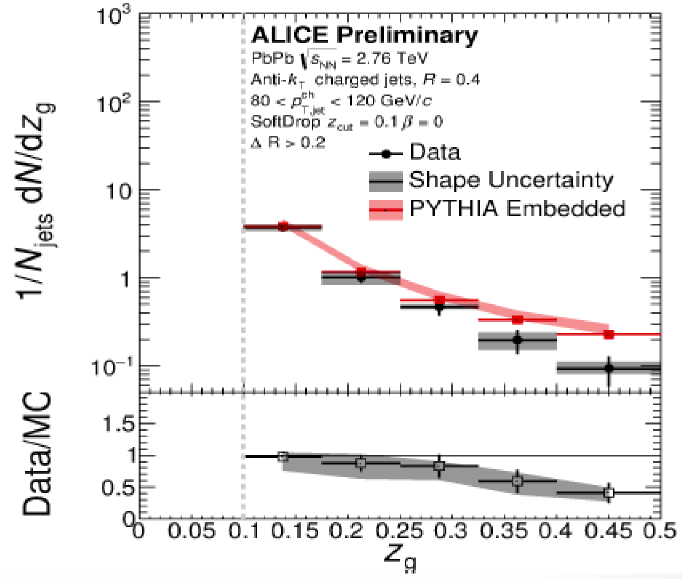
Markus Fasel, Wednesday

Jet substructure ALICE

$\Delta R < 0.1$ cut — Collimated splittings

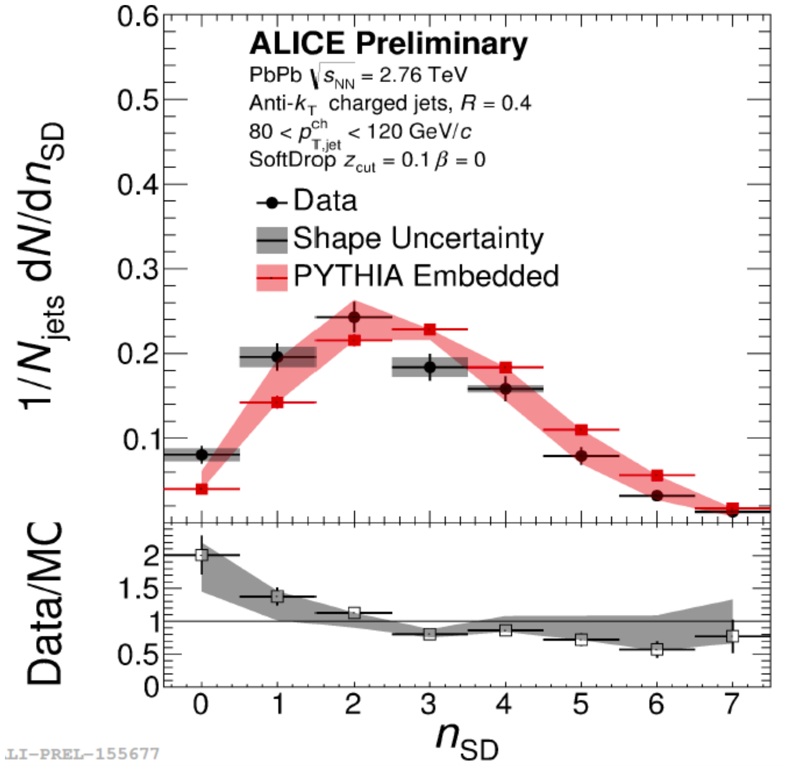


$\Delta R > 0.2$ cut — Large Angle splittings



- Large angle splittings enhanced
- Collimated splittings suppressed

- **recursive soft drop => follow the parton shower**

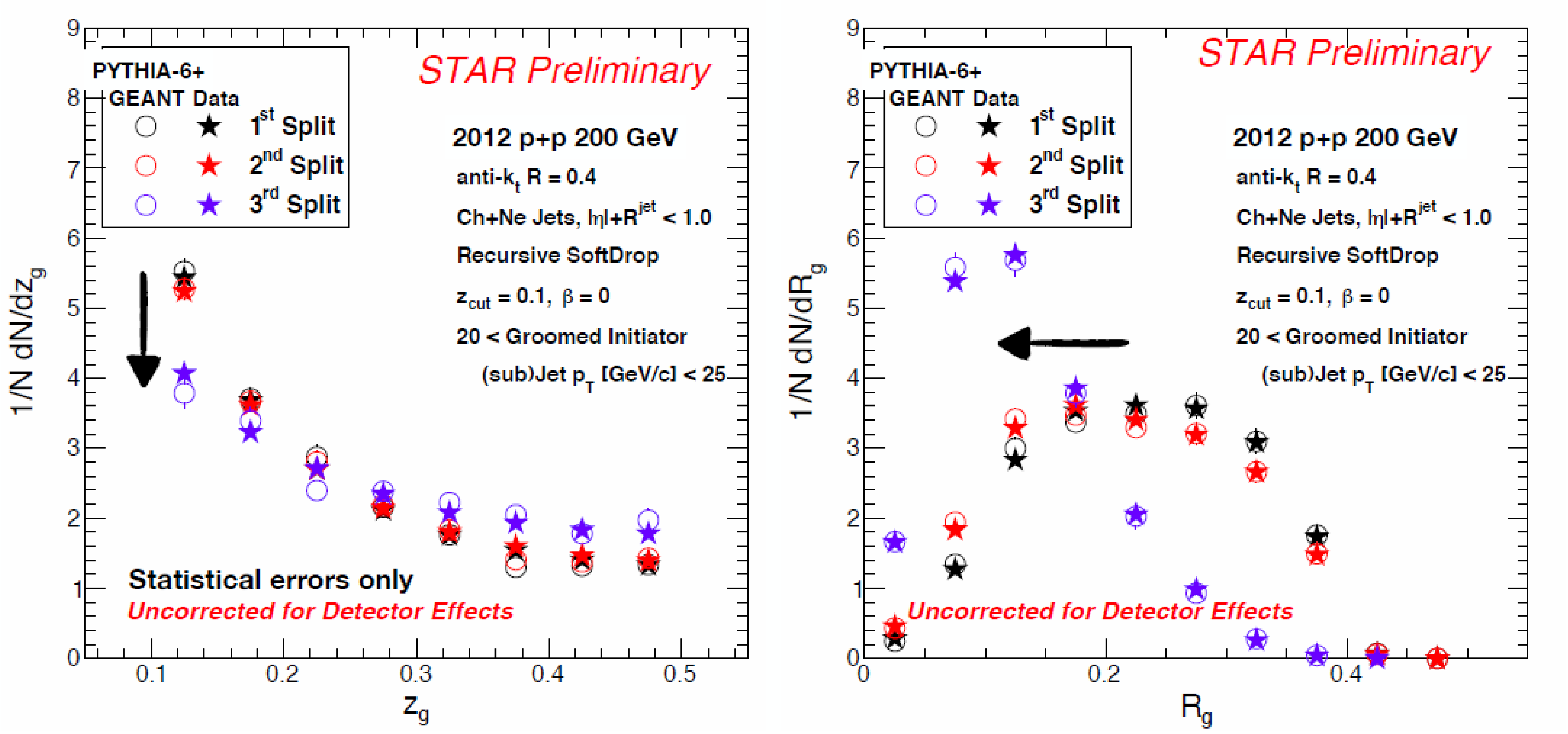


Number of semi-hard splittings consistent with vacuum ref.

Nima Zardoshti, Thursday (plenary)

Jet substructure STAR

- recursive soft drop => follow the parton shower



- Splitting changes from 1st/2nd -> 3rd
- Reproduced by PYTHIA

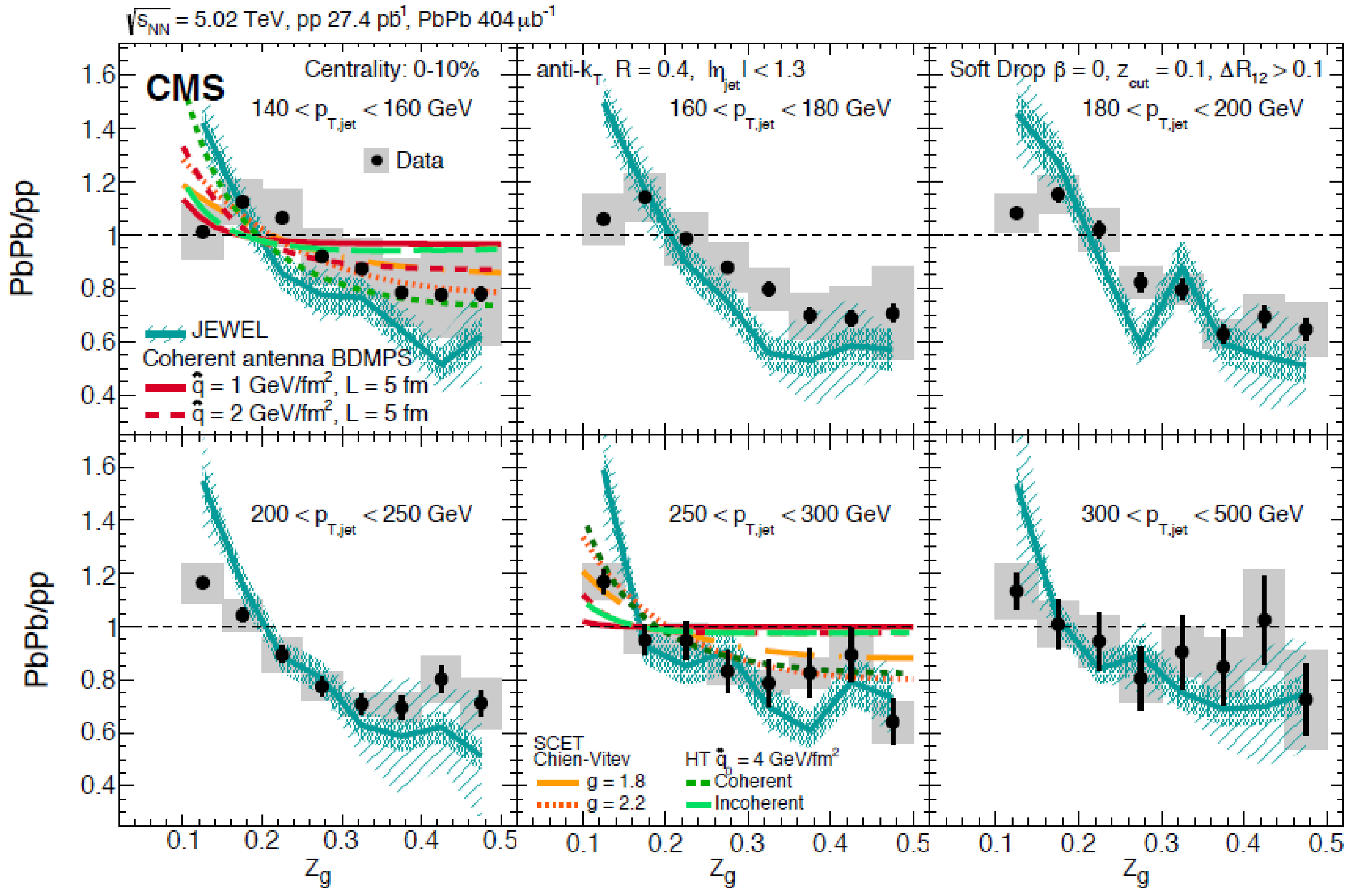
Raghav Kunnawalkam Elayavalli, Thursday (plenary)

Jet grooming in Pb-Pb

HARD PROBES 2018

PRL 120 (2018) 142302

(z_{cut} = 0.1, β = 0.0) : flat grooming



Multiple medium-induced gluon bremsstrahlung (coherent):
Phys. Lett. B 345 (1995) 277
Nucl. Phys. B 483 (1997) 291
Nucl. Phys. B 484 (1997) 265
JHEP 04 (2017) 125

JEWEL:
JHEP 03 (2013) 080
arXiv:1707.04142
arXiv:1707.01539

Soft collinear effective theory: modified gluon splitting function: arXiv:1608.07283

Higher twist calculation: arXiv:1707.03767

- strong modification of z_g in central collisions
- branching is more imbalanced

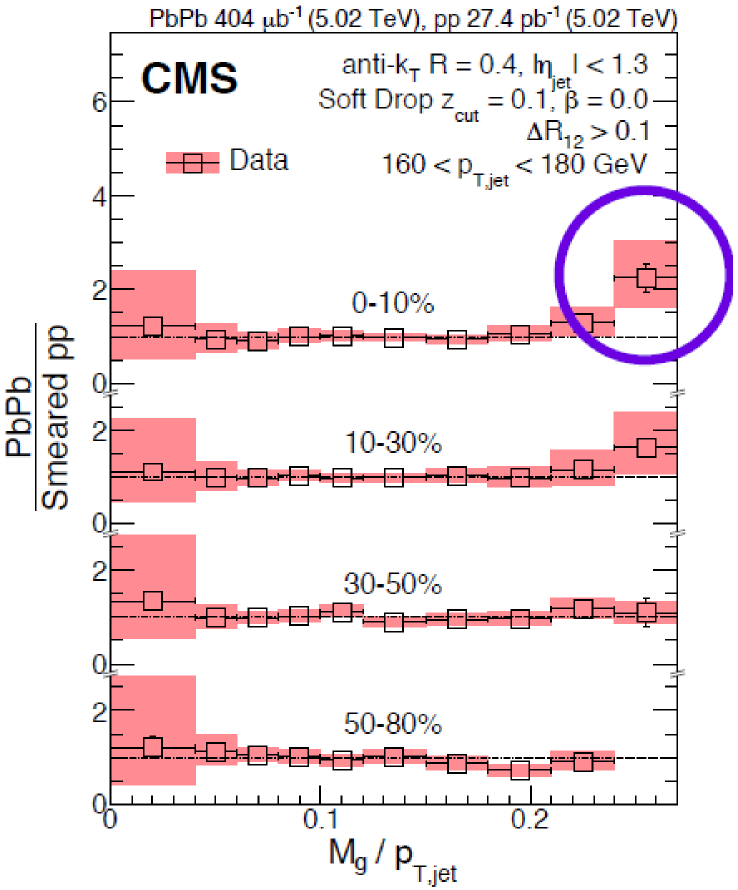
Dhanush Anil Hangal (plenary)

Mass of the groomed jet

HARD PROBES 2018

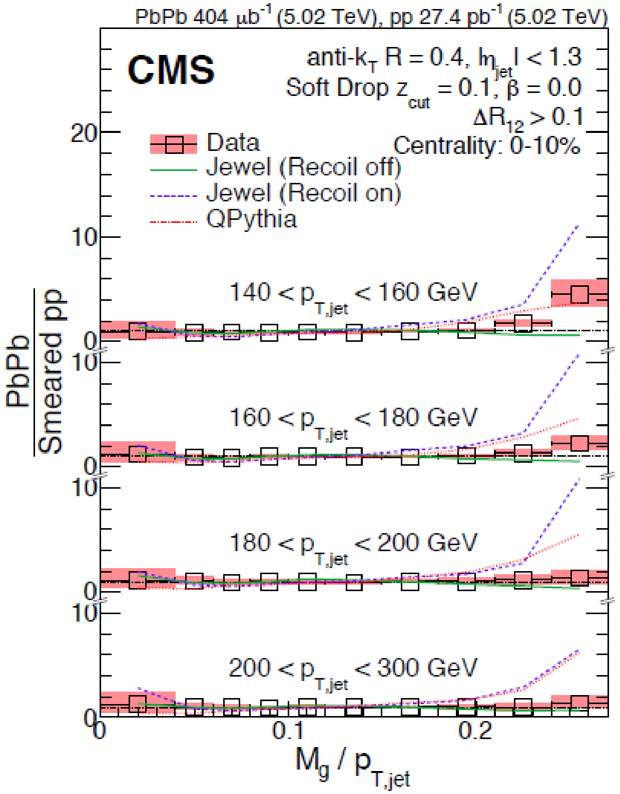
arXiv:1805.05145

(z_{cut} = 0.1, β = 0.0) : flat grooming

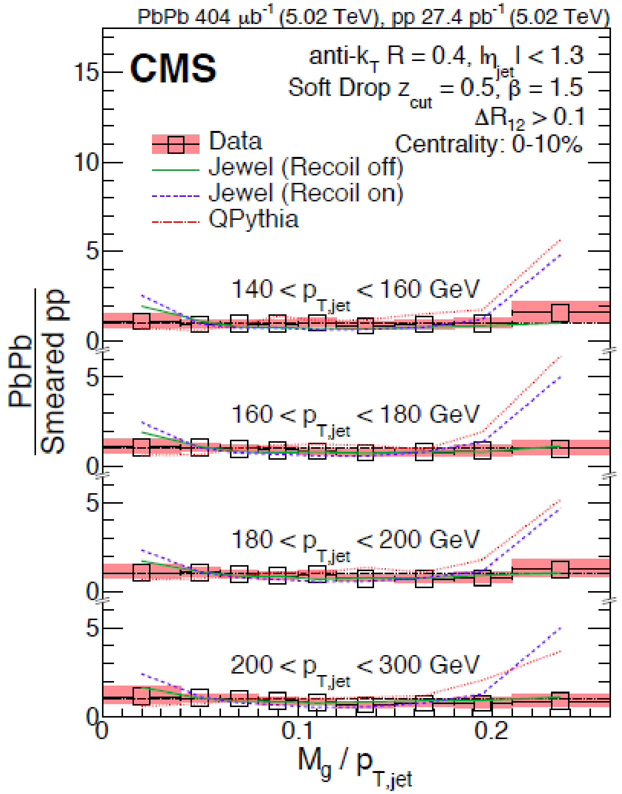


Higher jet p_T

(z_{cut} = 0.1, β = 0.0) : flat grooming



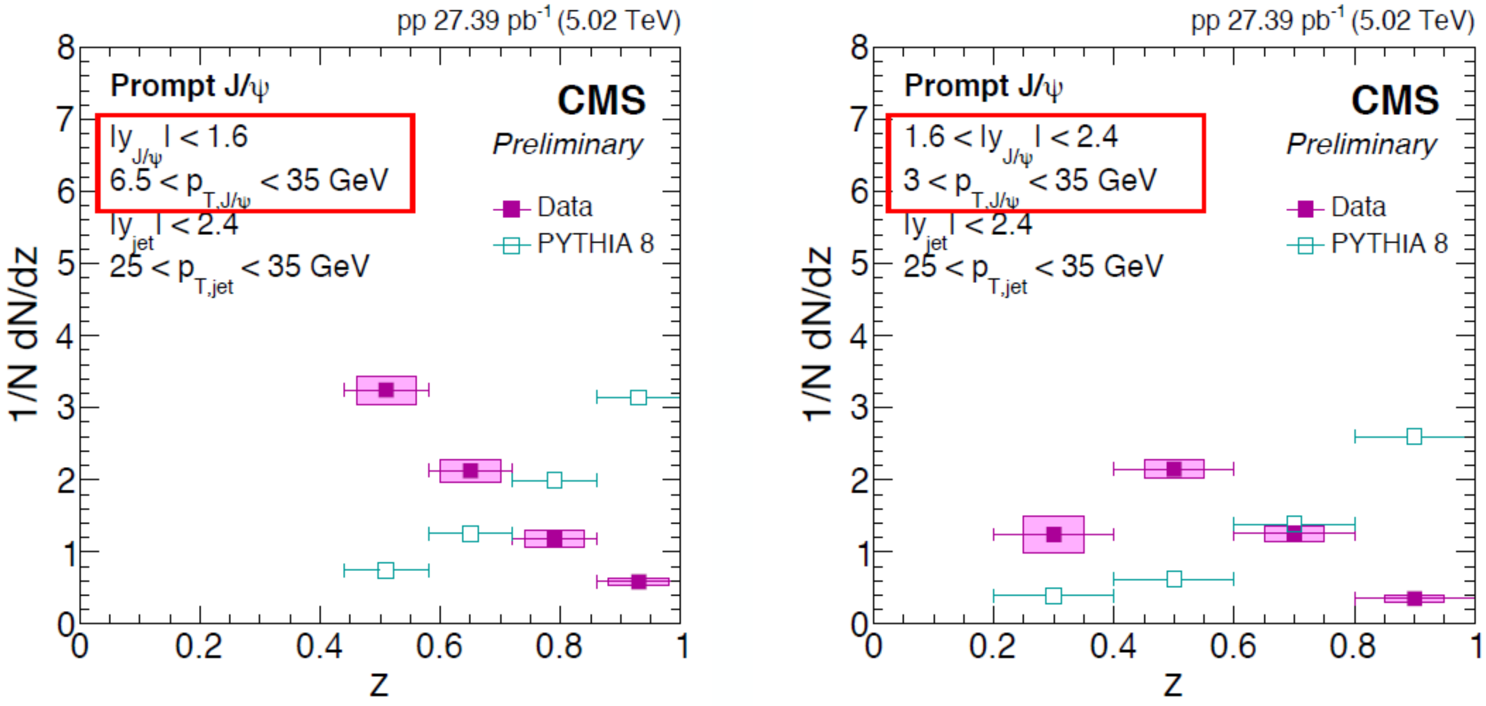
(z_{cut} = 0.5, β = 1.5) : jet core



- **enhancement only for central Pb-Pb at large $M_g/p_{T,jet}$**
- **challenge for models (stronger modification expected)**

Dhanush Anil Hangal (plenary)

J/Ψ in jets (pp)



Different behaviour in data and Pythia

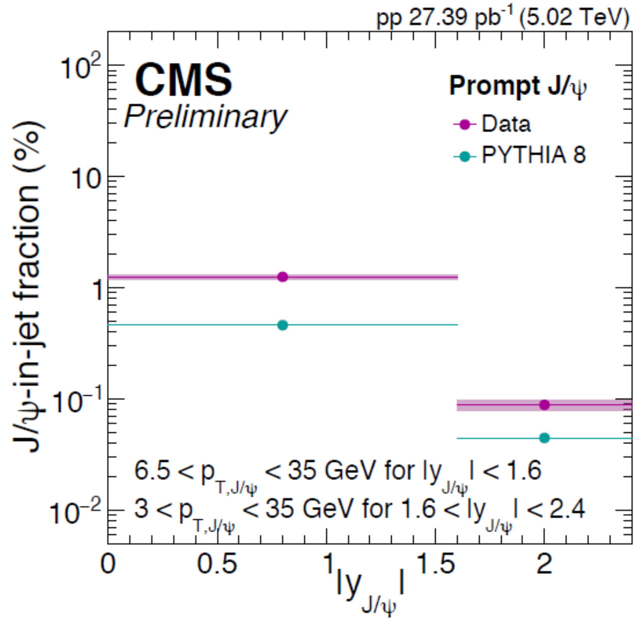
J/ψ are less isolated in data

CMS PAS HIN-18-012

- Fragmentation function?

$$z = \frac{p_{T,J/\psi}}{p_{T,jet}}$$

- Fraction of J/ψ produced in jets?



- **2 x more J/Ψ in jets compared to PYTHIA**

=> How in Pb-Pb?

Batoul Dibab, Wednesday

Medium modification of FF

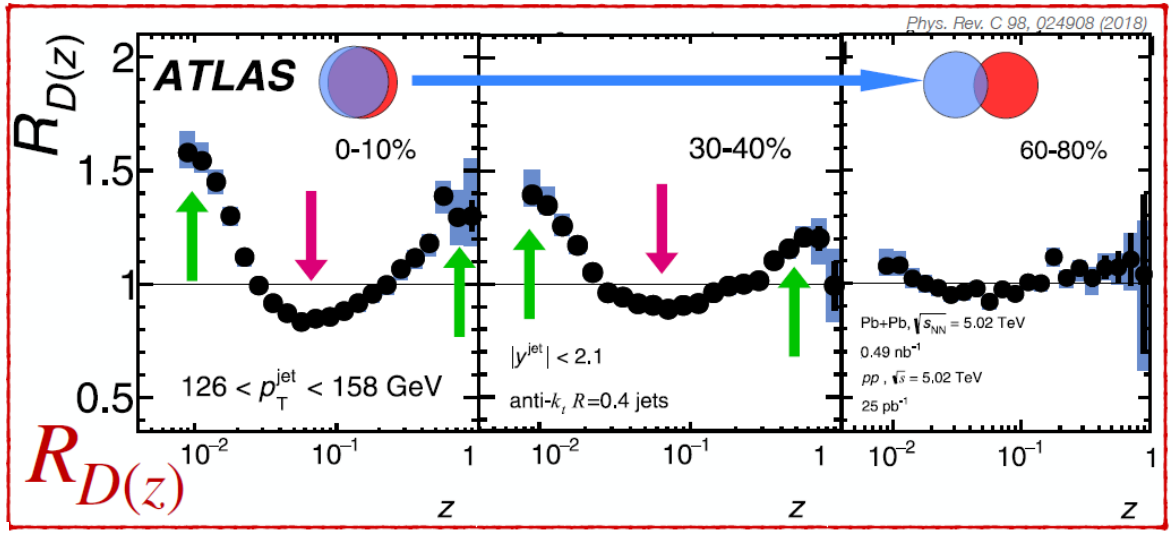
HARD PROBES 2018

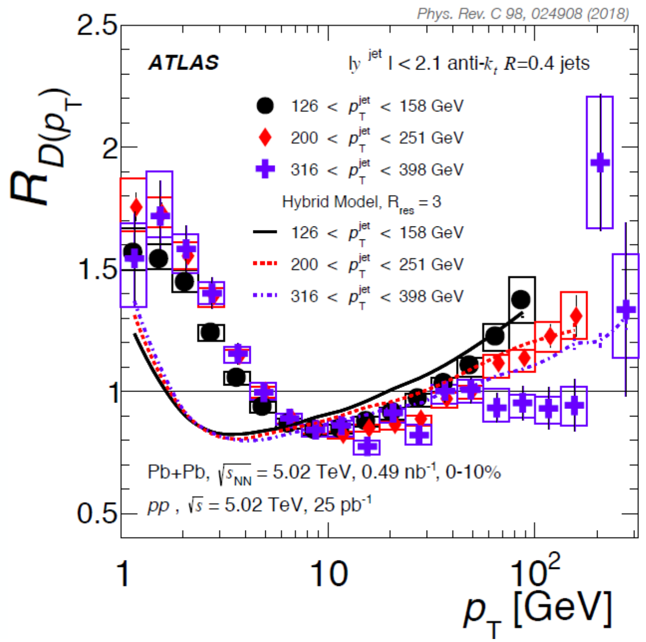
$$D(p_T) \equiv \frac{1}{N_{jet}} \frac{dn_{ch}}{dp_T}$$

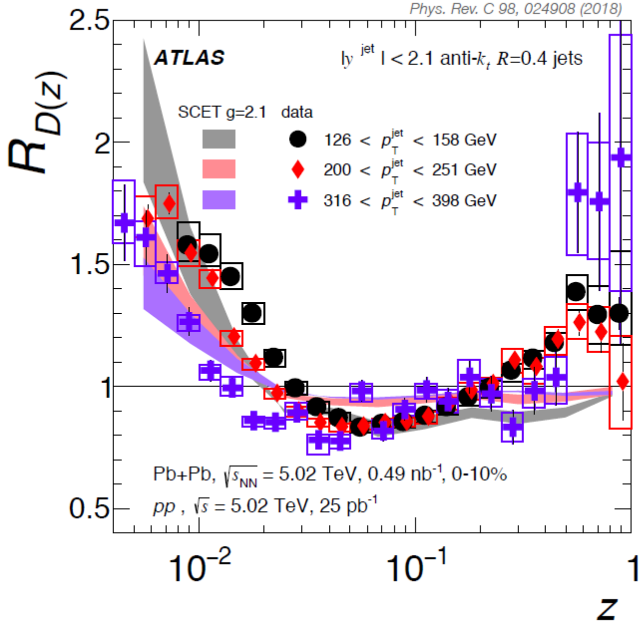
$$D(z) \equiv \frac{1}{N_{jet}} \frac{dn_{ch}}{dz} \quad [z \equiv p_T \cos(\Delta R)/p_T^{jet}]$$

$$R_{D(p_T)} \equiv \frac{D(p_T)_{PbPb}}{D(p_T)_{pp}} \quad R_{D(z)} \equiv \frac{D(z)_{PbPb}}{D(z)_{pp}}$$

- **relative enhancement of soft and hard fragments**
- **depletion of intermediate z fragments**
- **peripheral collisions: pp FF recovered**



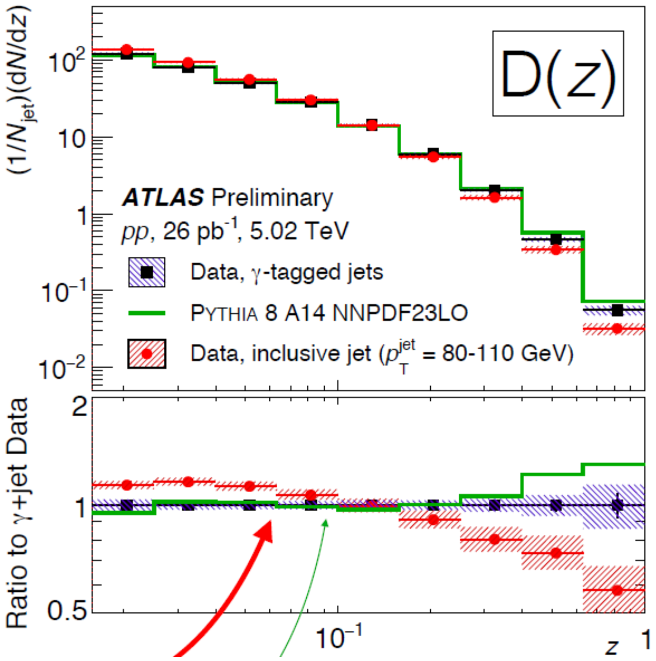




- **Medium response ~ p_T scaling** — **low p_T**
- **Fragmentation effects ~ z scaling** — **high p_T**
- **Hybrid Model describes high p_T**
- **SCET describes low p_T**

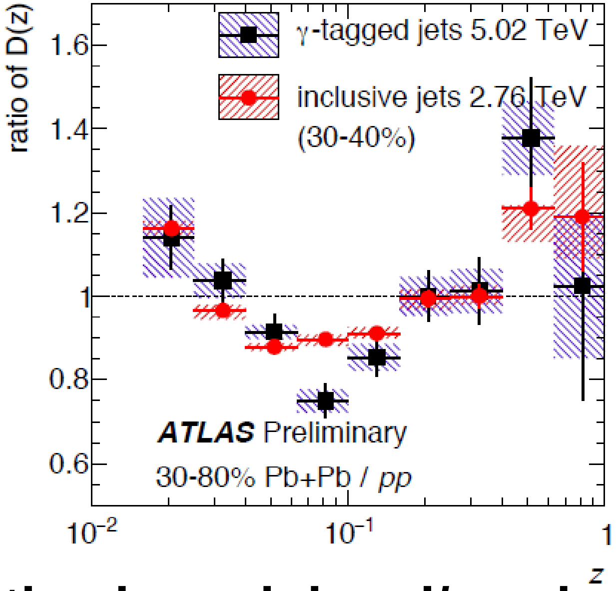
Akshat Puri, Thursday (plenary)

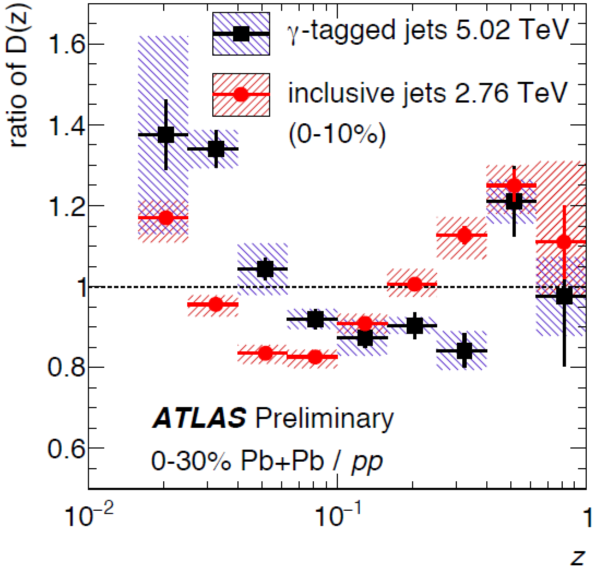
Photon-tagged FF in ATLAS

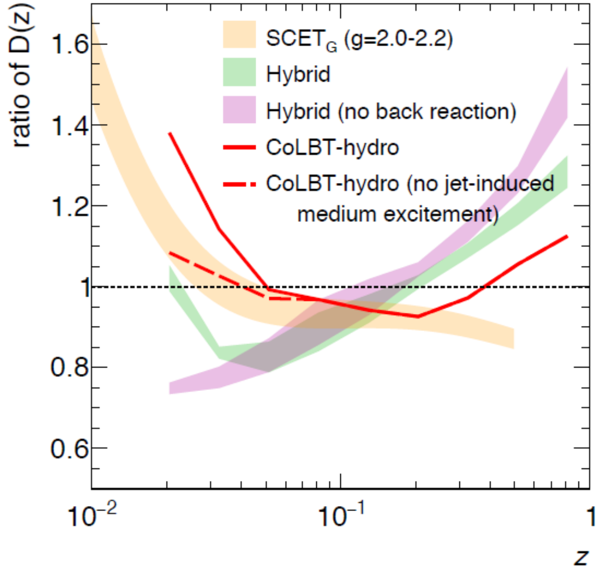


$D(z = p_T^h / p_T^{jet})$

- **FF in inclusive jets: gluon-dominated => softer**
- **FF in gamma-tagged jets: quark-dominated**





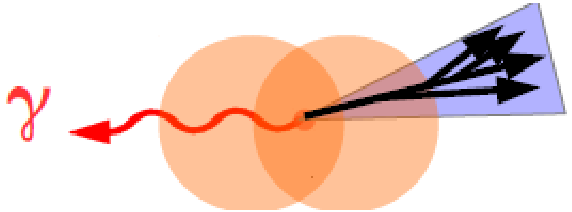


- **More similar modification in peripheral/semi-central events**
- **Larger differences for more central collisions => difference gluon/quark or selection effect?**
- **Detailed model comparisons needed**

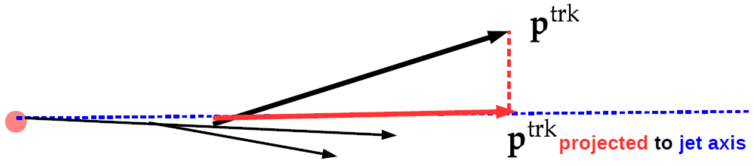
Dennis V. Perepelitsa, Tuesday

Photon-jet measurements

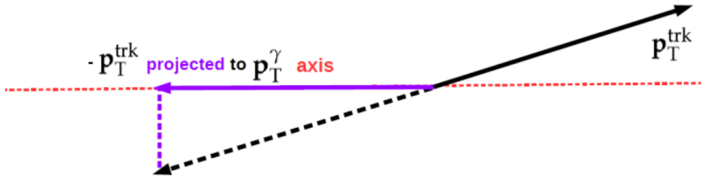
- **Photon defines the initial jet energy**
- **Strongly enhances quark jets**
- **Ideal for fragmentation and quenching studies**

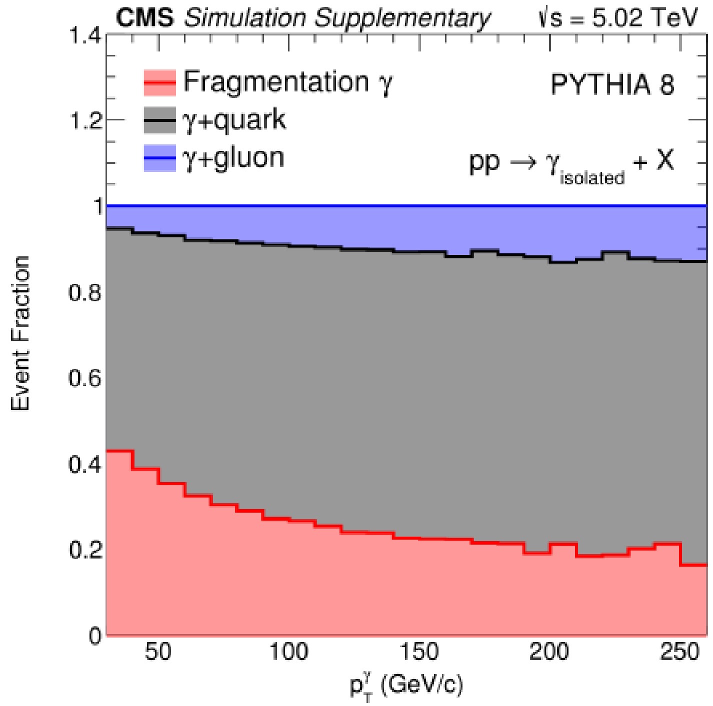


$$\xi^{jet} = \ln \frac{|\mathbf{p}^{jet}|^2}{\mathbf{p}^{trk} \cdot \mathbf{p}^{jet}}$$



$$\xi_T^{\gamma} = \ln \frac{-|\mathbf{p}_T^{\gamma}|^2}{\mathbf{p}_T^{trk} \cdot \mathbf{p}_T^{\gamma}}$$

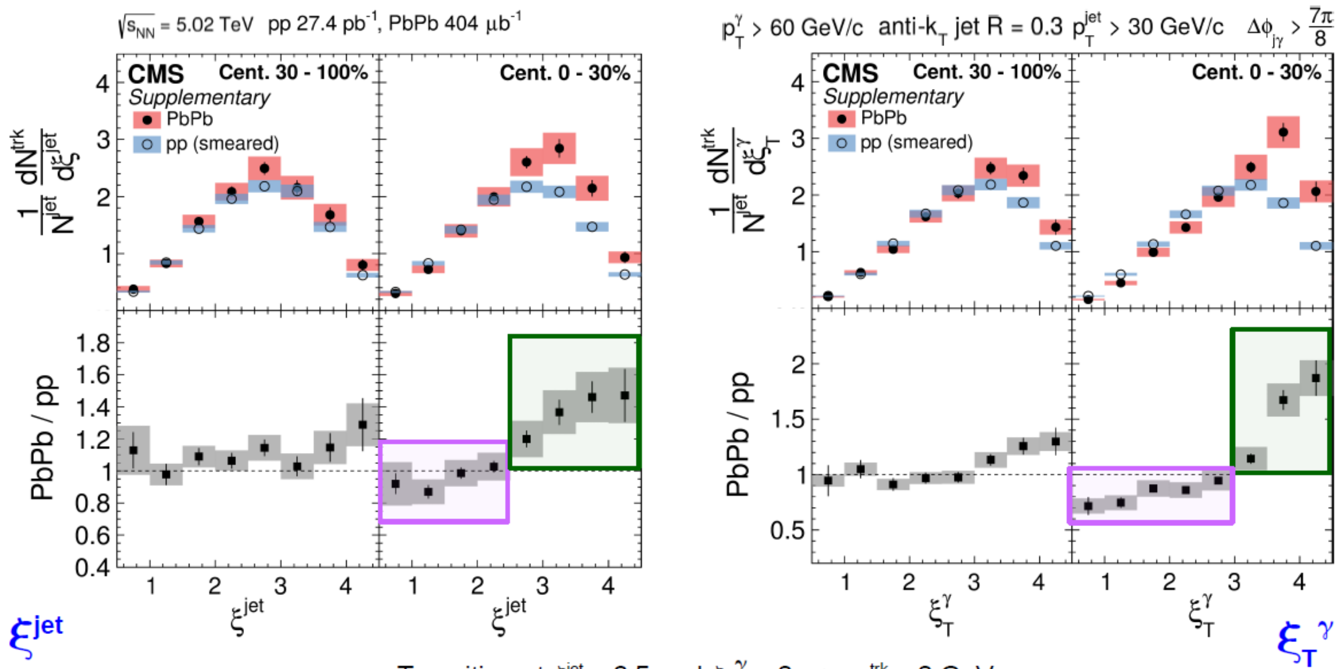




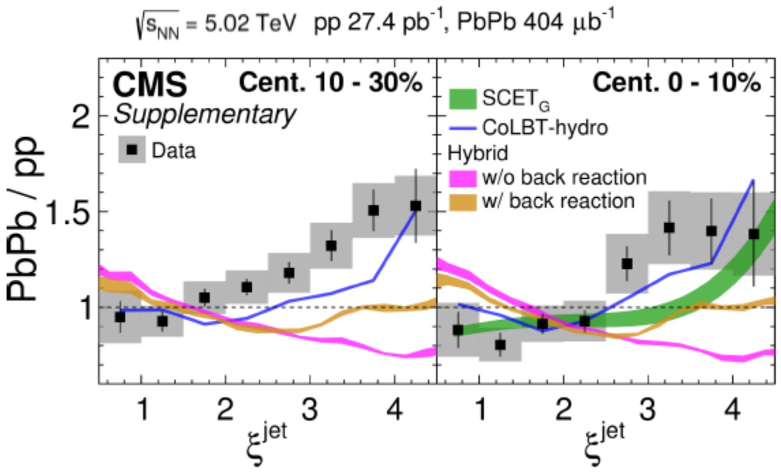
Kaya Tatar, Tuesday

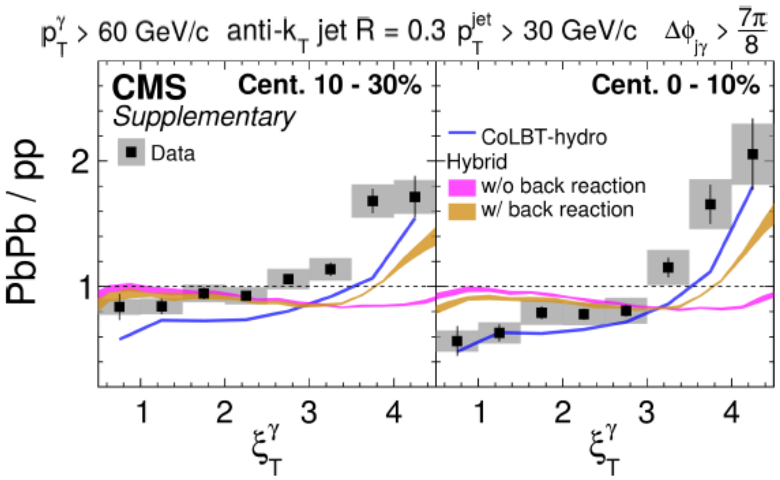
Photon-tagged FF

- **Photon tagged jets**
- **Enhanced quark jet contribution**
- **Strong enhancement at low p_T**
- **Suppression at large p_T**
- **Larger than model predictions**



Transition at $\xi^{jet} \approx 2.5$ and $\xi_T^\gamma \approx 3$ –> $p_T^{trk} \approx 3$ GeV





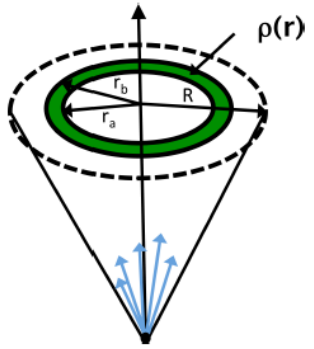
Kaya Tatar, Tuesday

Photon-tagged jet shape

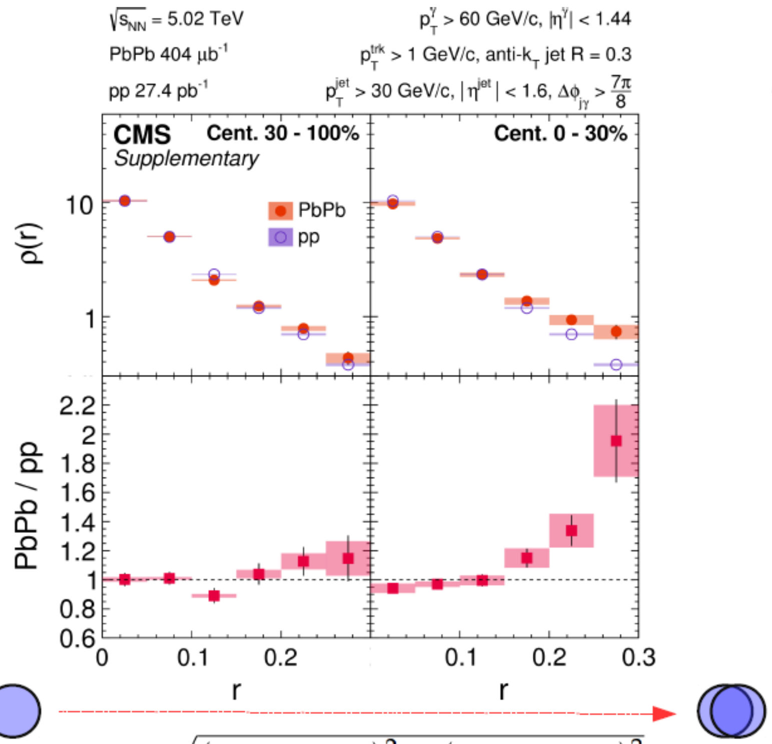
Kaya Tatar, Tuesday

- In central collisions large fraction of energy at large R

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

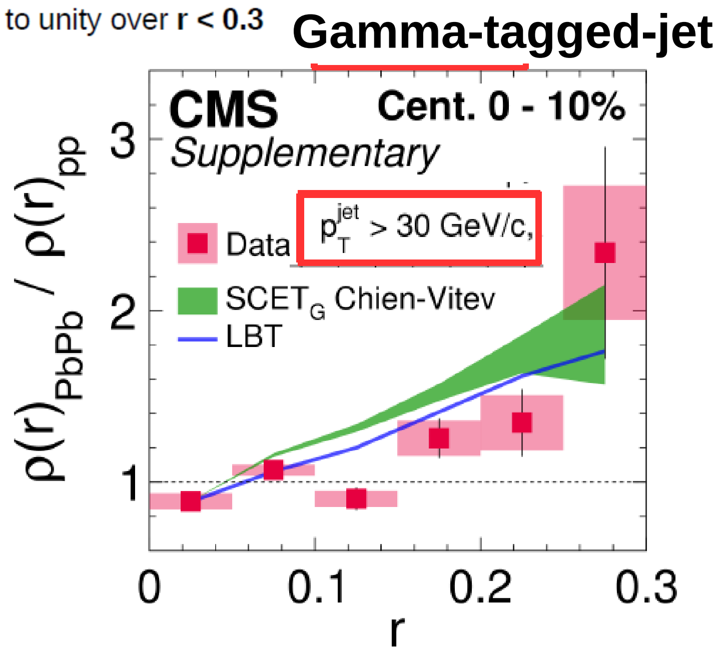


- increased quark jet fraction in gamma-tagged jets?
- or effect from different jet p_T

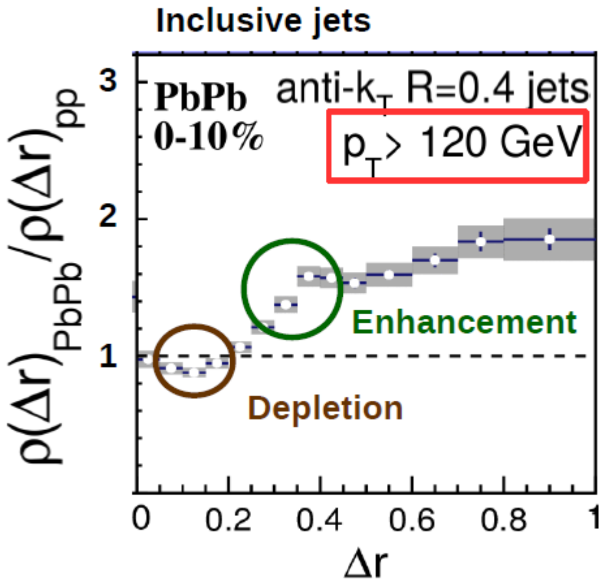


$$r = \sqrt{(\eta_{\text{track}} - \eta_{\text{jet}})^2 + (\phi_{\text{track}} - \phi_{\text{jet}})^2}$$

arXiv:1809.08602

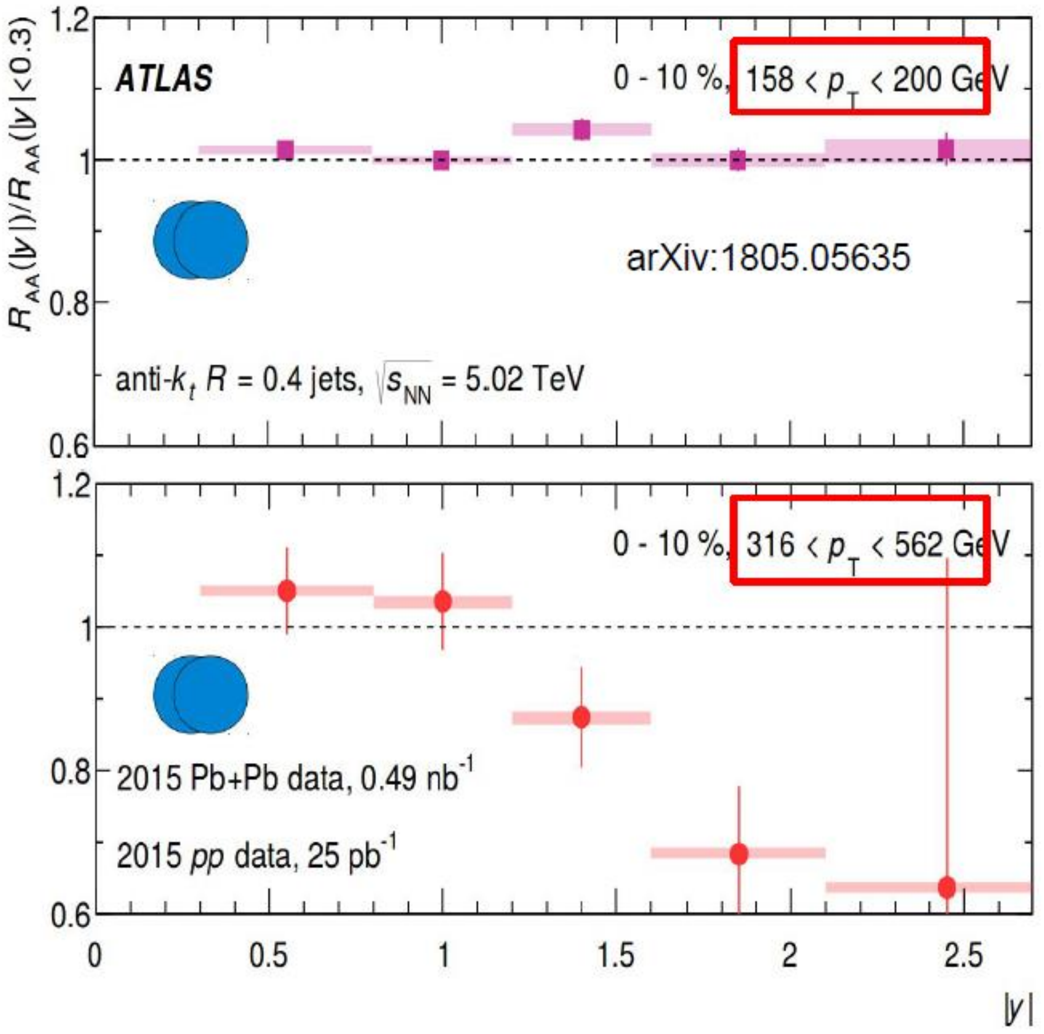


JHEP 05 (2018) 006



Quark vs. gluon jets: rapidity dependence

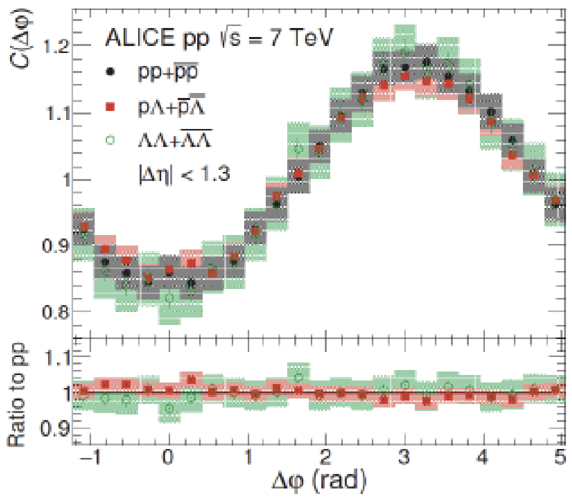
- **More quark jets at larger y expected**
- **Quark jets should lose less energy than gluon jets**
- **But production spectra at forward y are falling more steeply**



arXiv:1805.05635

Radim Slovak, Thursday

Deuterons in Jets (pp)



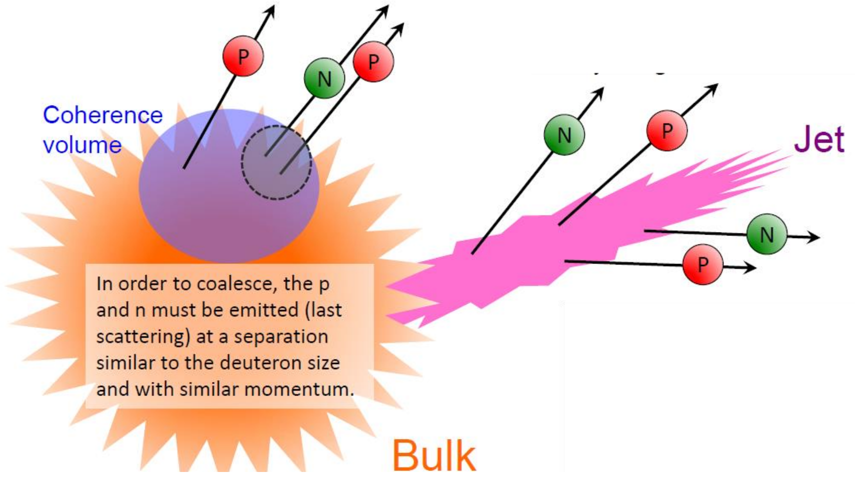
Eur. Phys. J. C (2017) 77:569

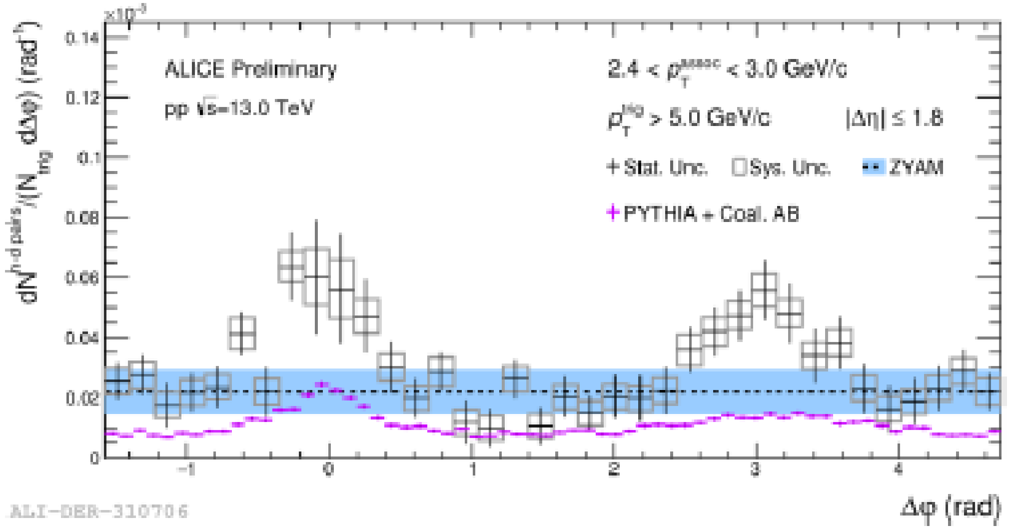
- **How are deuterons formed in Jets -> Coalescence?** *Brennan Schaefer, Tuesday*

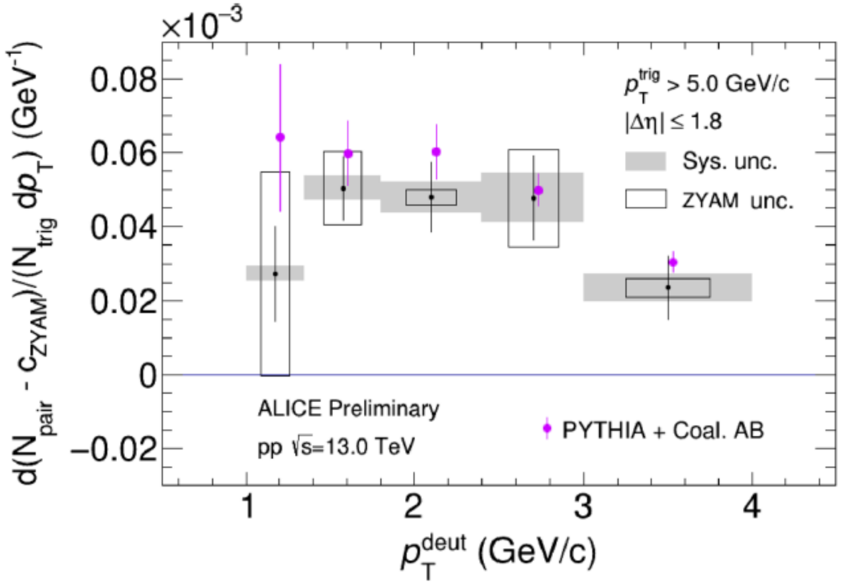
$$E_d \frac{d^3 N_d}{d p_d^3} = B_2 \left(E_p \frac{d^3 N_p}{d p_p^3} \right)^2$$

d binding energy: ~2 MeV

coalescence: p_0 = 100 MeV/c







Summary of the summary

many measurements covering a wide range of jet observables presented at this conference

- **also in pp there are still surprises**
- **no significant effect of quark/gluon differences in jet quenching**
- **energy from quenching ends up in soft fragments and large radii**
- **For many jet observables, peripheral AA and pp are very similar**

  => no large CNM effects; no large jet quenching in peripheral AA

- **With possible QGP in p-A (or even high mult. pp):**

  => Will there be jet quenching?

  => How to measure it?

- **new observables for jet substructure will provide additional insight**
- **need for systematic model comparisons of all observables**