New results

Hard probes in PbPb at 5 TeV with CMS

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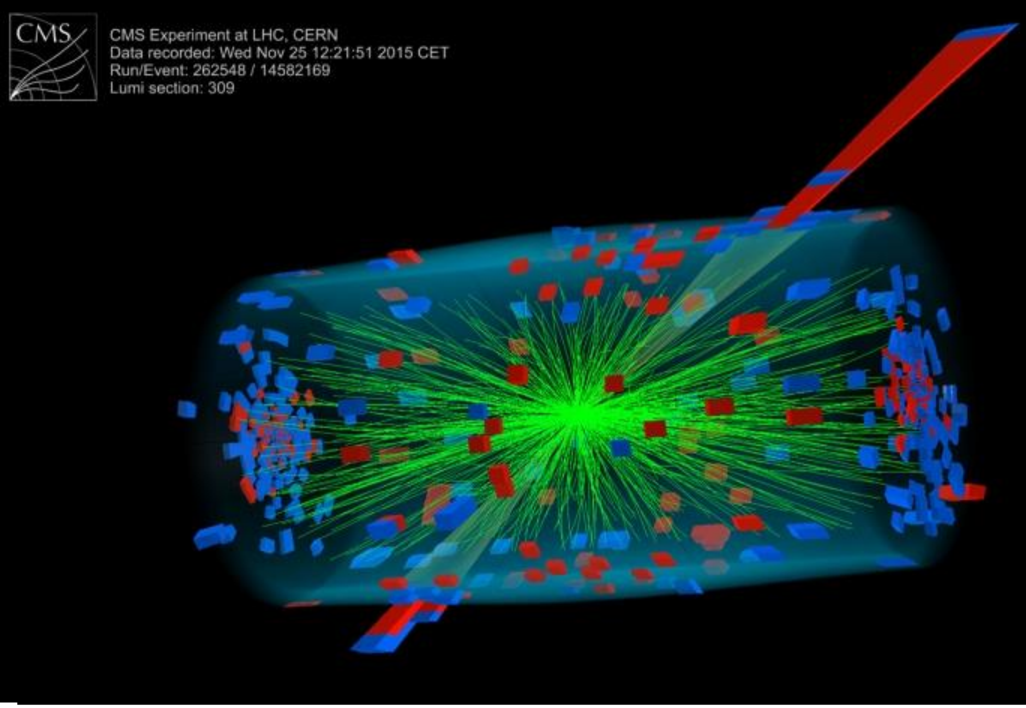
Fourth Annual Large Hadron Collider Physics (LHCP2016)

Lund, Sweden, 13th - 18th June 2016



Run 2 - November 2015

5 TeV PbPb/pp run

Integrated luminosity:

pp 25.8 pb^{-1}

PbPb 404 μb^{-1}

New results related to jet quenching

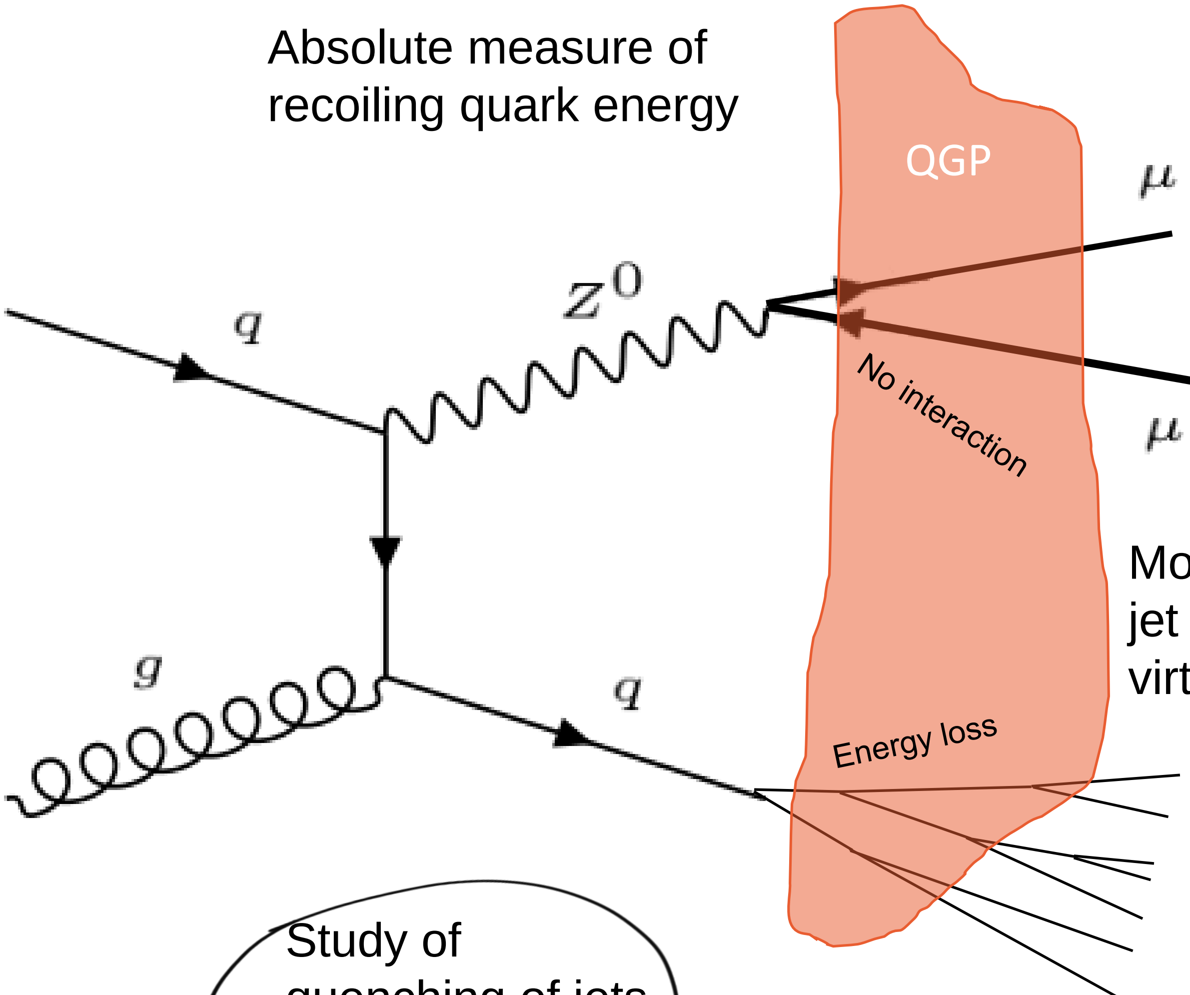
Z-jet properties
CMS-HIN-15-013

Nuclear modification factor of:

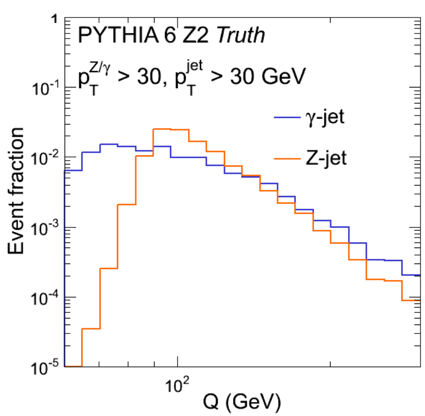
- Charged particles up to 400 GeV
  CMS-HIN-15-015
- D mesons up to 100 GeV
  CMS-HIN-16-001

Jet quenching with Z-jet

Absolute measure of recoiling quark energy



Q^2 needs to be large in order to produce Z



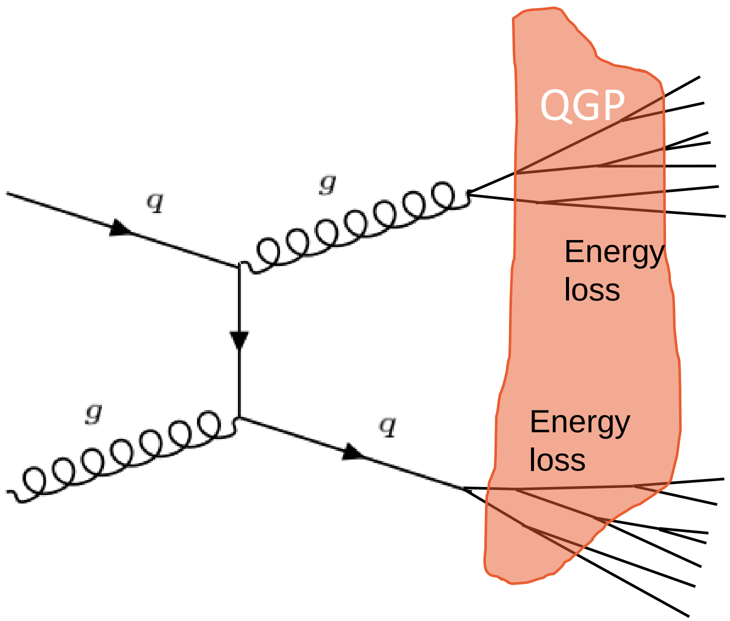
Mostly quark jet with large virtuality

Study of quenching of jets with restricted properties

Price paid: small cross-section

Enough statistics with 5 TeV high luminosity PbPb data!!!

Compared to di-jet



Relative energy loss

Both jets lose energy

Large variety of processes

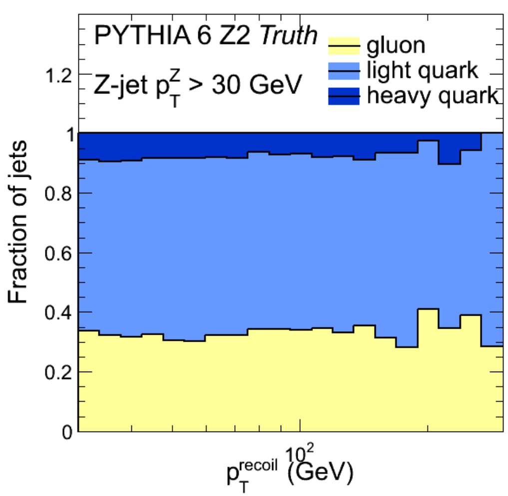
More uncertainty in the jet properties

Useful comparison

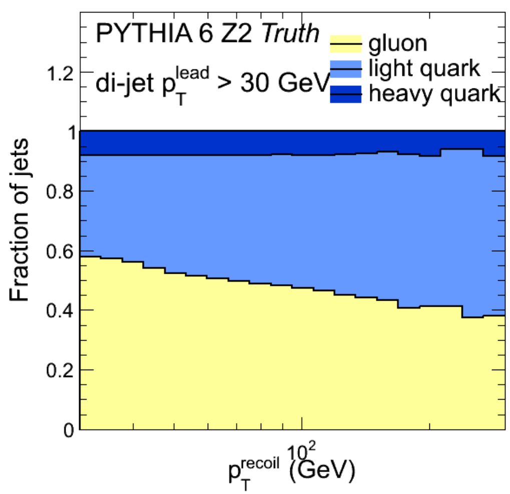
Di-jet: Large abundance of recoiling gluon jets

Z-jet: Mostly recoiling quark jets

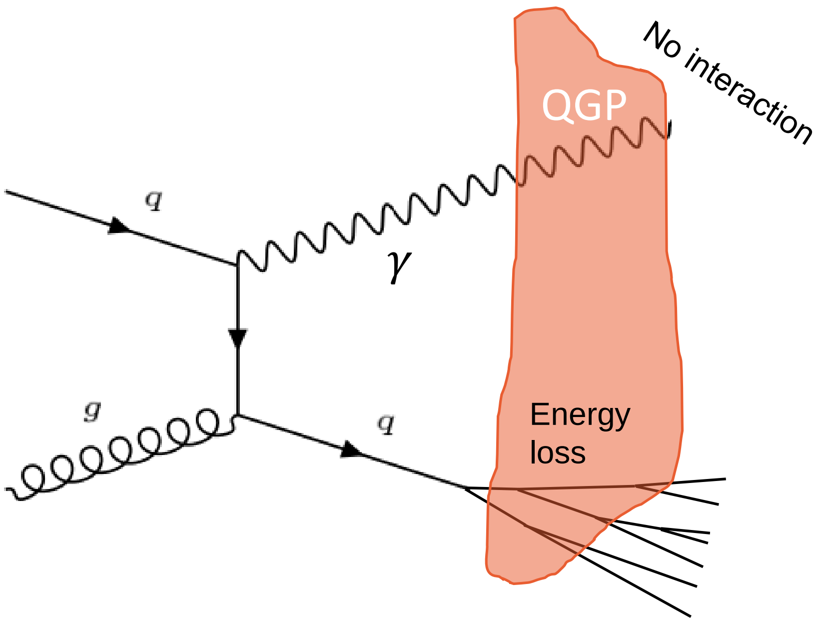
Z-jet



di-jet



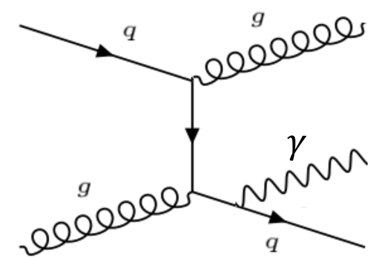
Compared to γ-jet



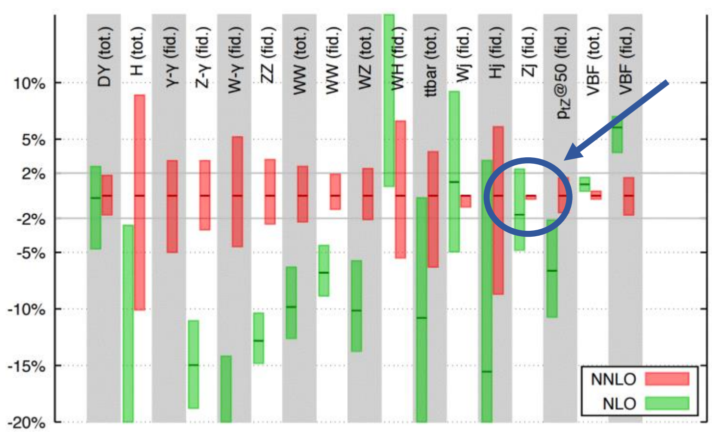
Z-jet is cleaner experimentally

γ-jet events are contaminated by

- Fragmentation photons from dijet events
- Neutral meson decays
- Bremsstrahlung

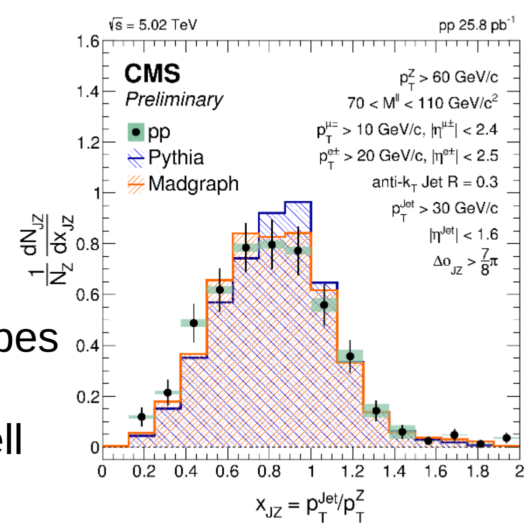


Gavin Salam's talk on Tuesday:
Scale factors at NLO



And also theoretically

Madgraph describes p_T asymmetry between quite well



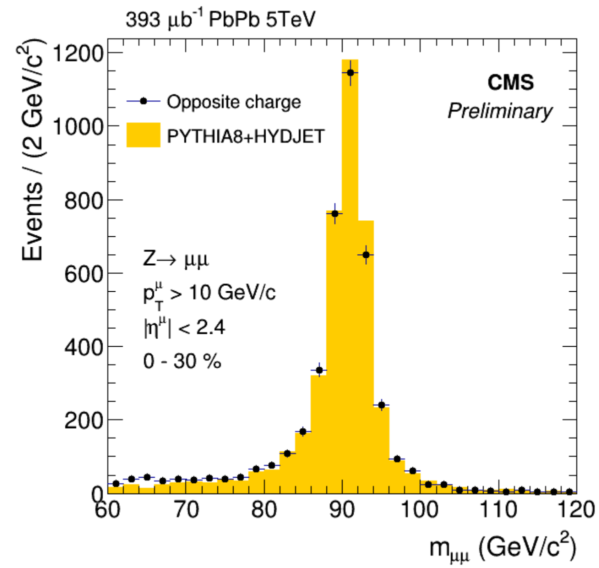
Z-jet - Analysis

Find Z:

Triggers: Double γ, Double μ

Channels: Zee Zμμ, $70 < m_{ll} < 110$ GeV

p_T^Z : 40, 50, 60, 80, ∞ GeV



Find jets:

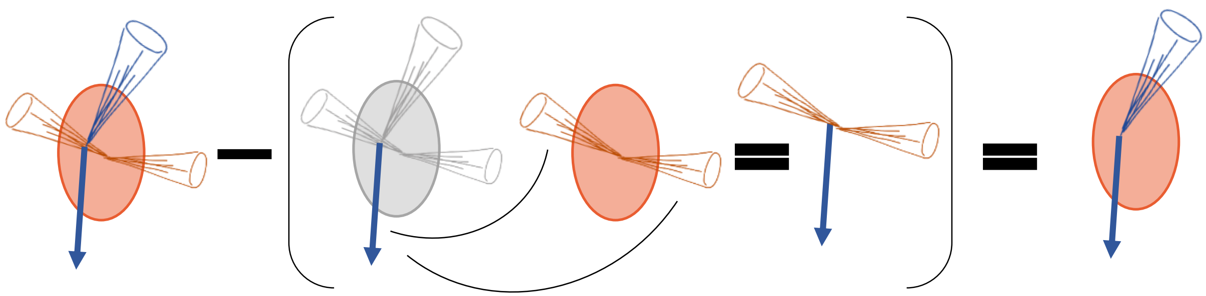
Anti-k_T R =0.3, In PbPb: UE subtraction

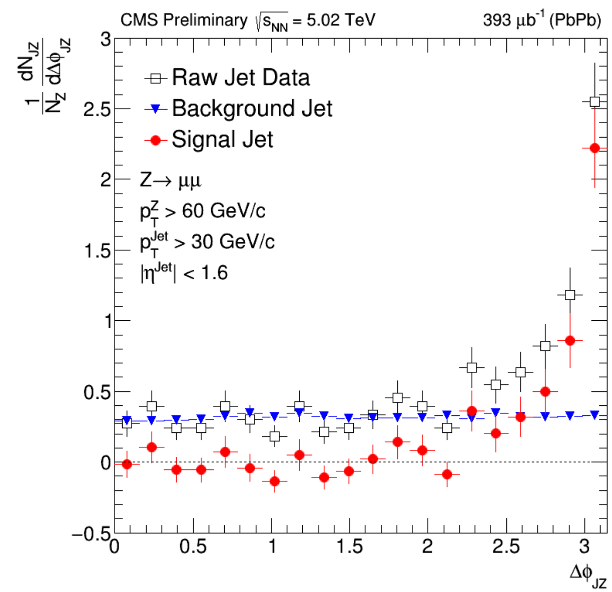
$p_T^{jet} >$ 30 GeV

No unfolding for p_T^{jet} resolution:
Jets in pp are smeared to account for the larger resolution in PbPb due to large UE

Make Z-jet pairs

Z in the event is correlated with all jets and background is subtracted by event mixing:

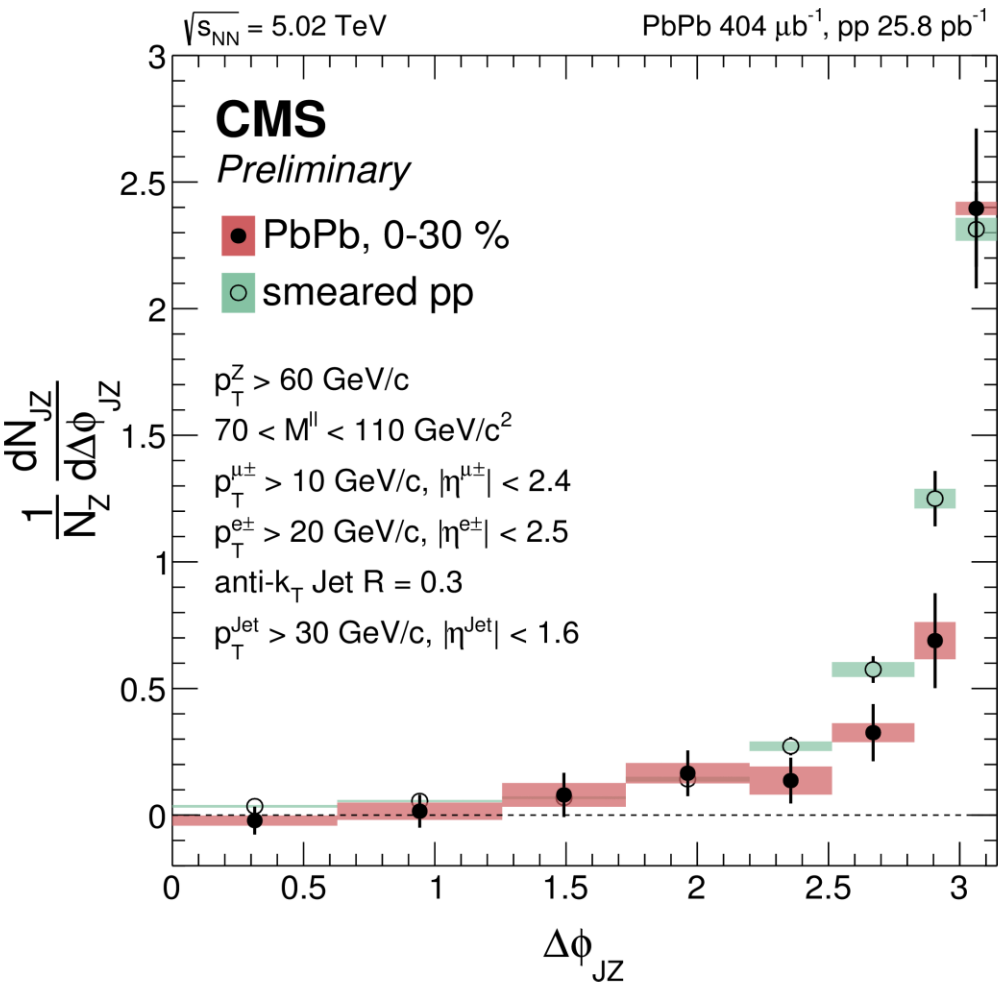




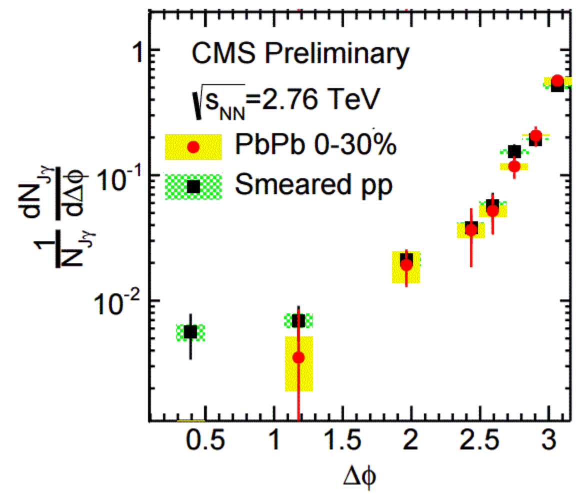
Azimuthal correlations

CMS-HIN-13-006

Narrower azimuthal angle correlations in PbPb (2σ)



Not observed at 2.76 TeV

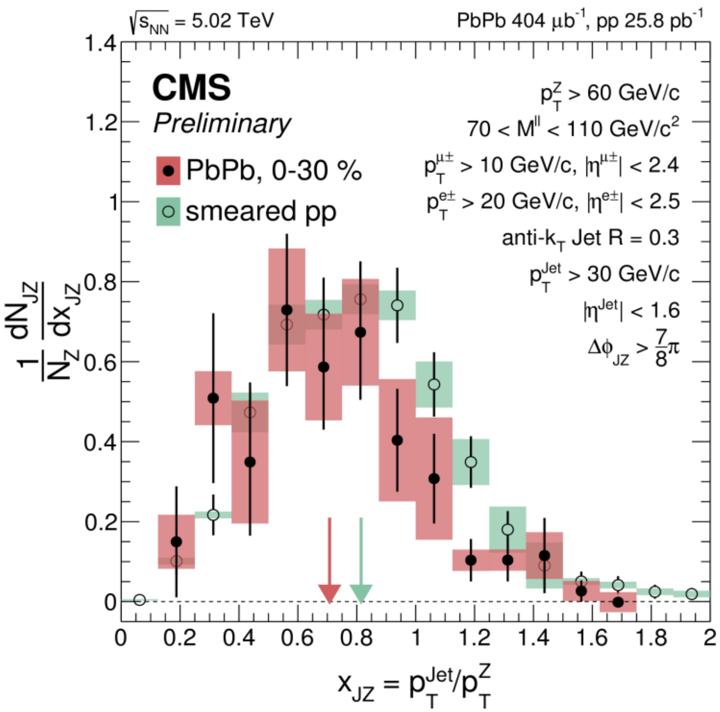


Could be statistical fluctuation or could be because Z+2jet events are less likely to pass 30 GeV cut after quenching

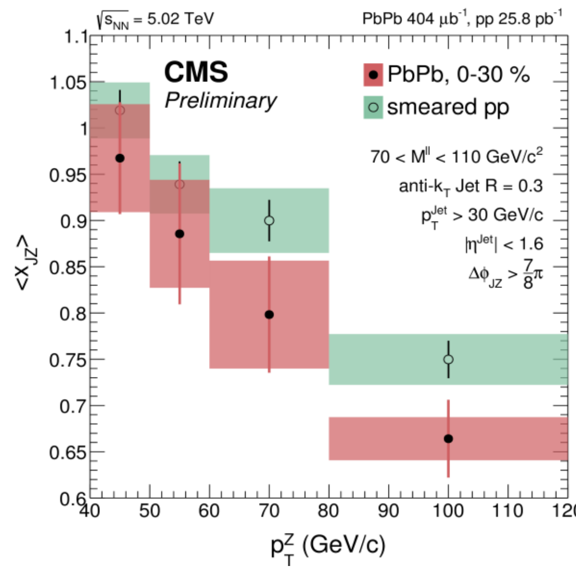
High statistics γ-jet measurement at 5 TeV is needed

Momentum imbalance

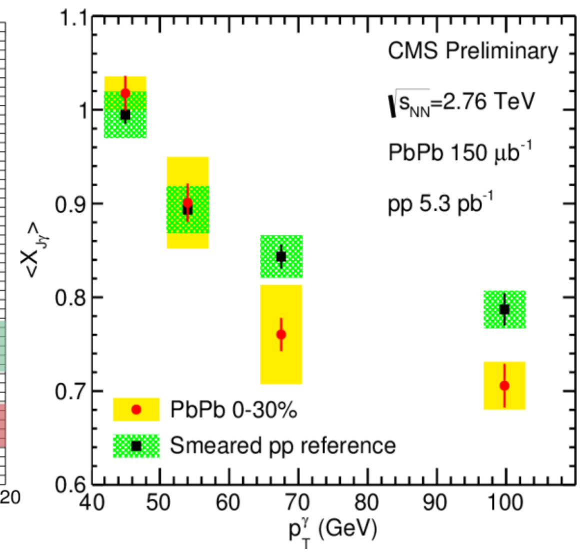
CMS-HIN-13-006



Z-jet 5 TeV



γ-jet 2.76 TeV



Lower bound of 6 GeV on amount of lost energy by jets at ~60 GeV

- Actual energy loss is larger because jets that lose large amount of energy fall below the p_T^Z threshold

Similar amount of shift in p_T due to quenching for jets in 5 TeV Z-jet and in 2.76 TeV γ-jet events

- Note: the imbalance in pp for Z-jet and γ-jet are already slightly different due to differences in scale of interaction (Q) and center-of-mass energy

Jet quenching with spectra

Nuclear modification factor

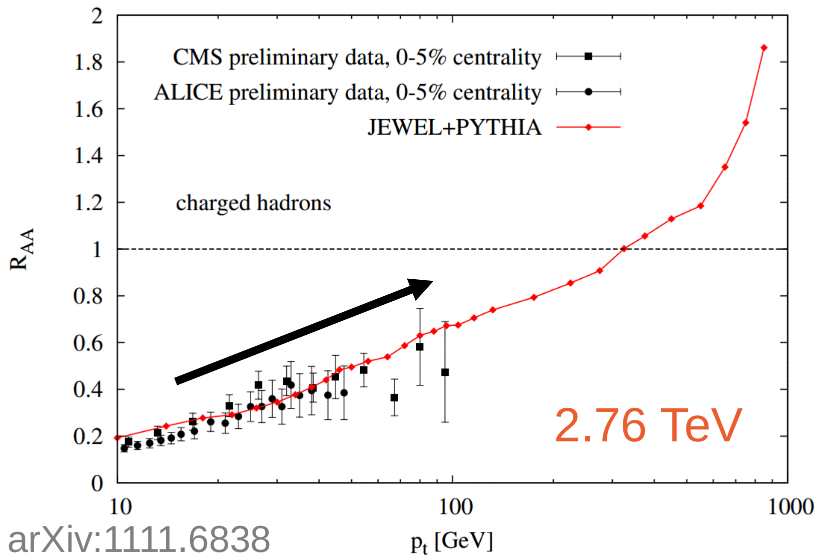
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T\,d\eta}{\langle T_{AA}\rangle\, d^2\sigma^{pp}/dp_T\,d\eta}$$

Going from jets to hadrons

Factors other than the amount of quenching on jets come into play:

- Shape of the spectrum
- Fragmentation functions

Question 1: Quenching at very high p_T



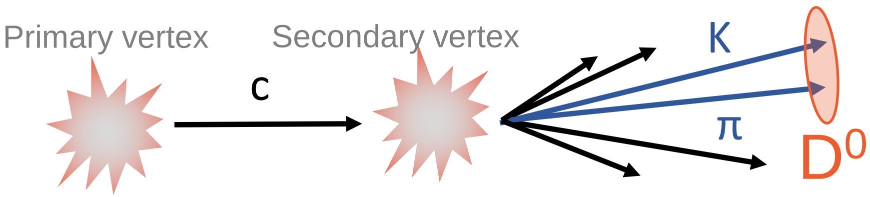
arXiv:1111.6838

Rising trend at high p_T

- Charged particles are likely to come from high p_T jets with little quenching and hard fragmentation
- Jet quenching can produce enhancement in R_{AA} by multiple scattering

Question 2: Center of mass energy dependence of energy loss

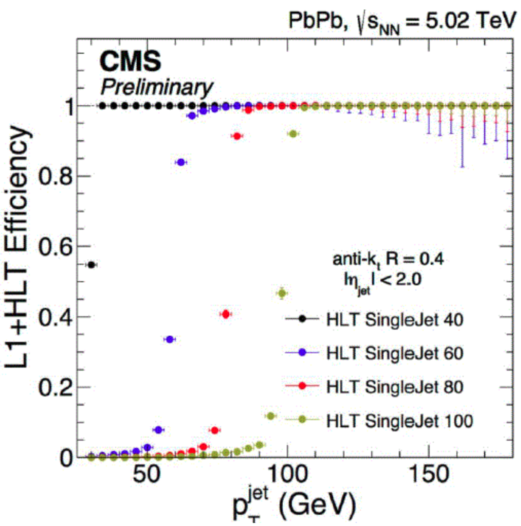
Question 3: How does energy loss differ for heavy flavor vs light flavor? D meson vs charged particle R_{AA}

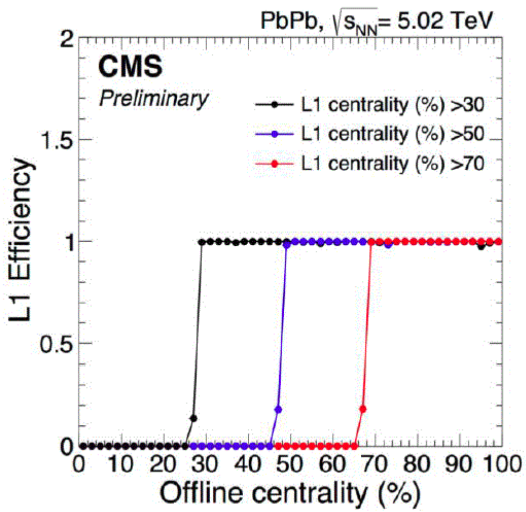


Charged hadron R_{AA} - Analysis

Triggers used in the analysis

Minimum bias, jet and centrality triggers are used





Trigger combination is done by matching jet counts, e.g.

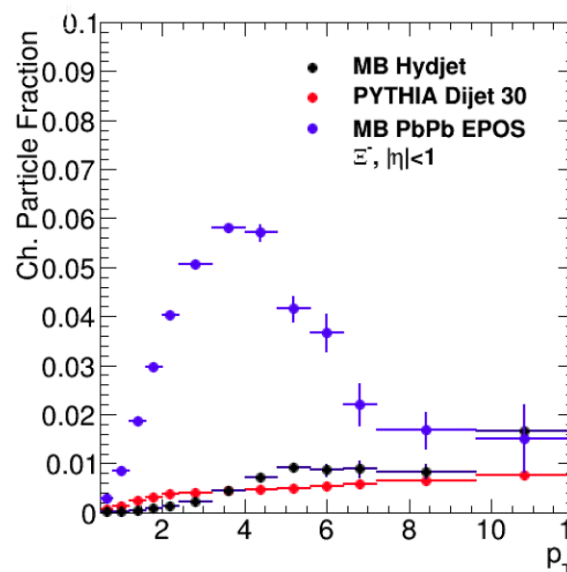
$$Scale|_{jet40} = \frac{N^{MB}_{pt>60}}{N^{jet40}_{pt>60}}$$

At given jet p_T only the highest p_T fully efficient trigger is used

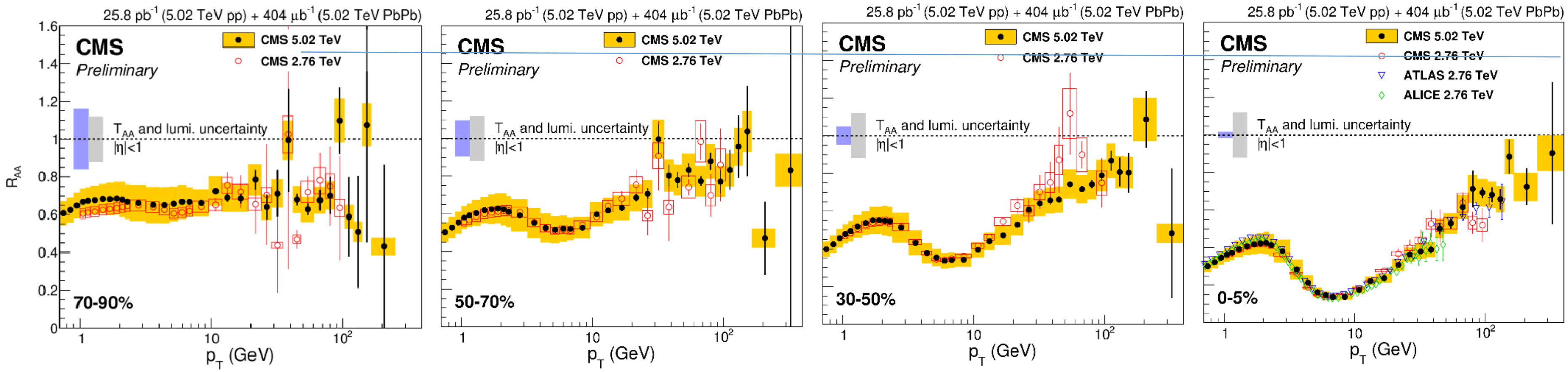
Corrections

Efficiency, misreconstruction corrections derived from MC are applied on data track-by-track basis

Correct for changing primary particle composition
- Σ, Ξ, Ω have a much lower efficiency than π, K, p
- Relative abundances depend on MC generator



Centrality and $\sqrt{s_{NN}}$ dependence



Flat as a function of p_T
  Peripheral events are significantly suppressed doesn't converge to 1

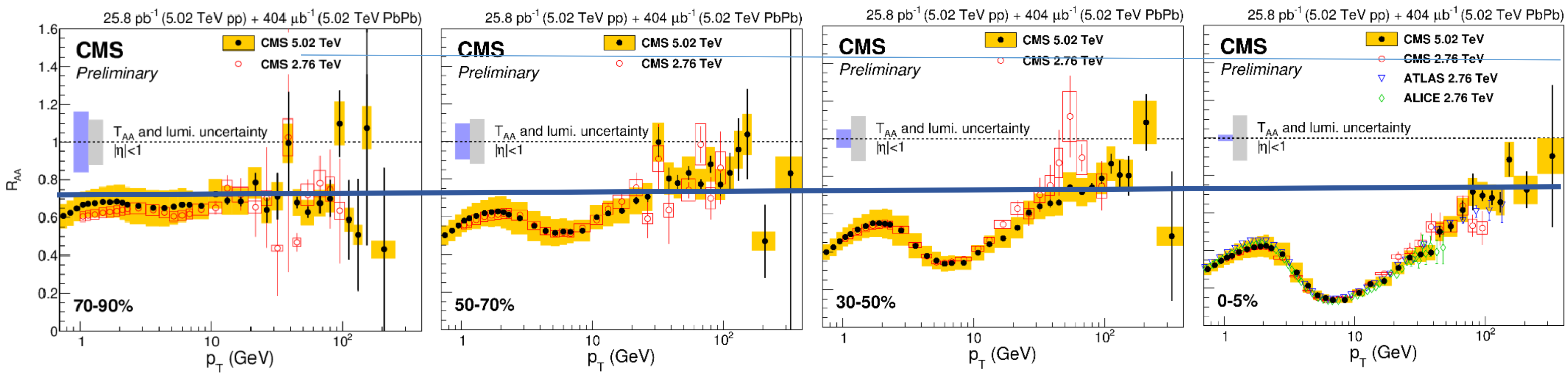
By going to central events

At low p_T spectrum is more and more suppressed
At high p_T larger slope as a function of p_T

No significant change with respect to 2.76 TeV in the values of R_{AA}

Centrality dependence

The high p_T points are slightly above the value in peripheral collisions (not significant)



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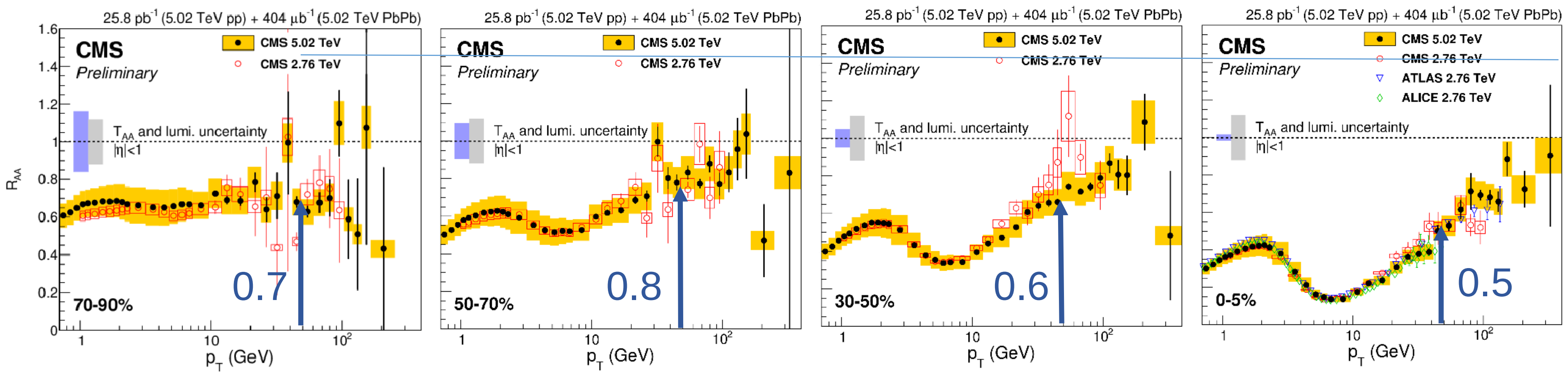
Centrality dependence

e.g., at 50 GeV…



Flat as a function of p_T

Peripheral events are significantly suppressed doesn't converge to 1

By going to central events

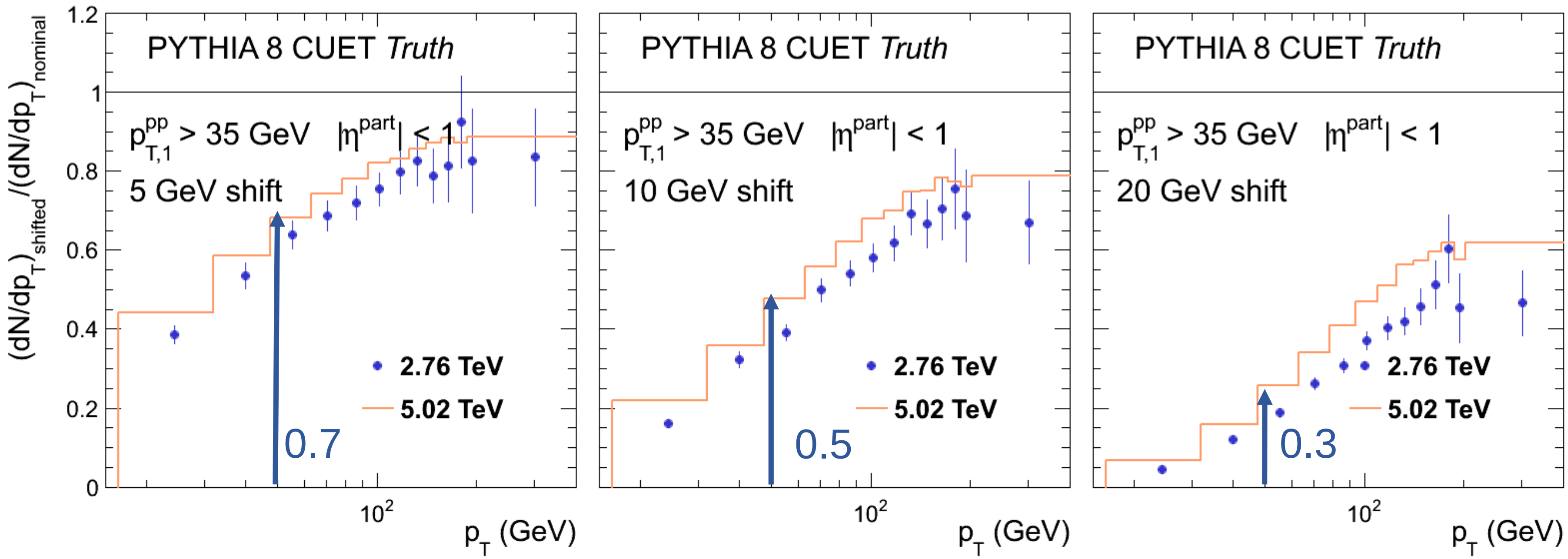
At low p_T spectrum is more and more suppressed

At high p_T larger slope as a function of p_T

No significant change with respect to 2.76 TeV in the values of R_{AA}

Shape of spectrum

Quick check: Shift spectrum in PYTHIA by a constant energy



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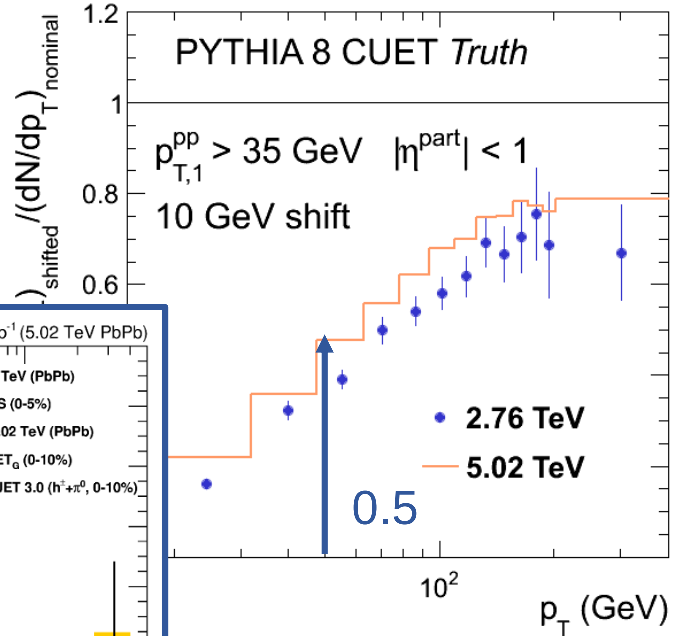
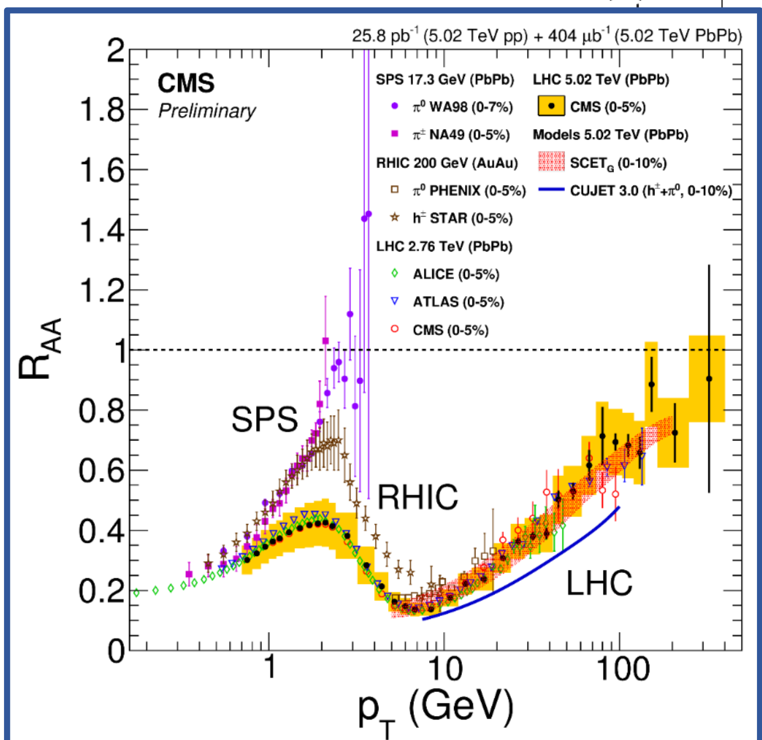


Things to notice
- After 200 GeV starts to flatten out
  - Makes the JEWEL calculations continuously increasing trend more interesting
  - What happens in data is unclear due to statistics
- 2.76 TeV is below 5.02 TeV because of less steep slope

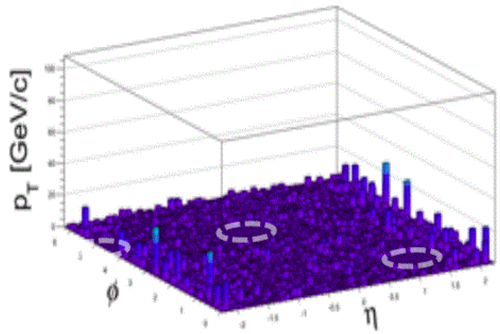


Most like the 0-5% centrality result
- Goes to 0.8 200 GeV

D meson R_{AA} - Analysis

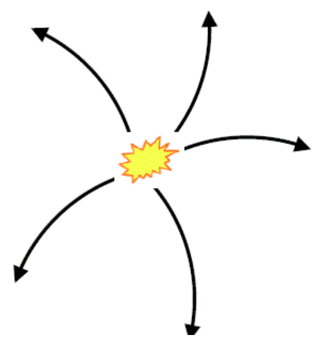
L1

Jet algorithm with online background subtraction



Online track reconstruction in the full event

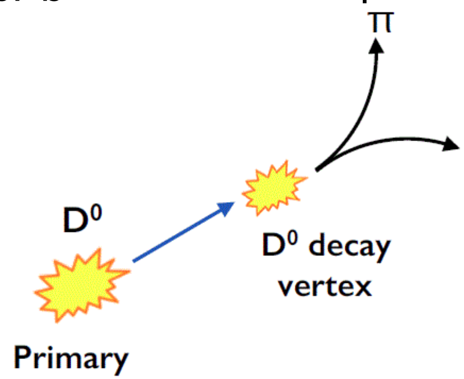
$p_T > 2$ GeV for pp, 8 GeV for PbPb



HLT

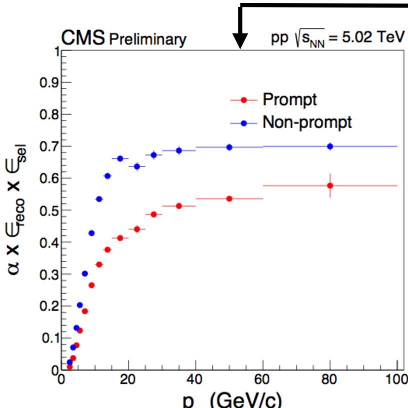
Online D^0 reconstruction

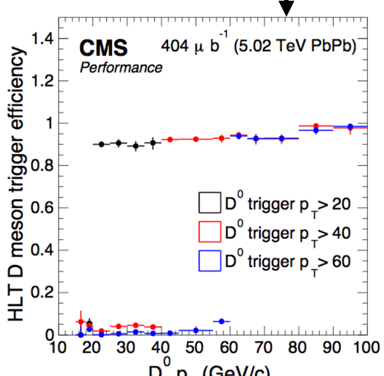
Reduced rate with loose vertex requirement



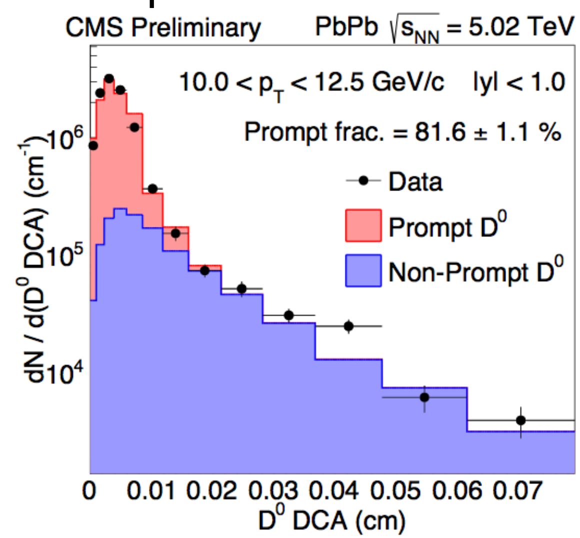
Corrections

$$\left.\frac{d\sigma^{D^0}}{dp_T}\right|_{|y|<1.0} = \frac{1}{2}\frac{f_{prompt}}{\Delta p_T}\frac{\left.N^{D^0}\right|_{|y|<1.0}}{(\mathrm{Acc}\times\epsilon)_{prompt}\cdot \mathrm{BR}\cdot\alpha_{prescale}\cdot\epsilon_{trigger}\cdot\mathcal{L}}$$

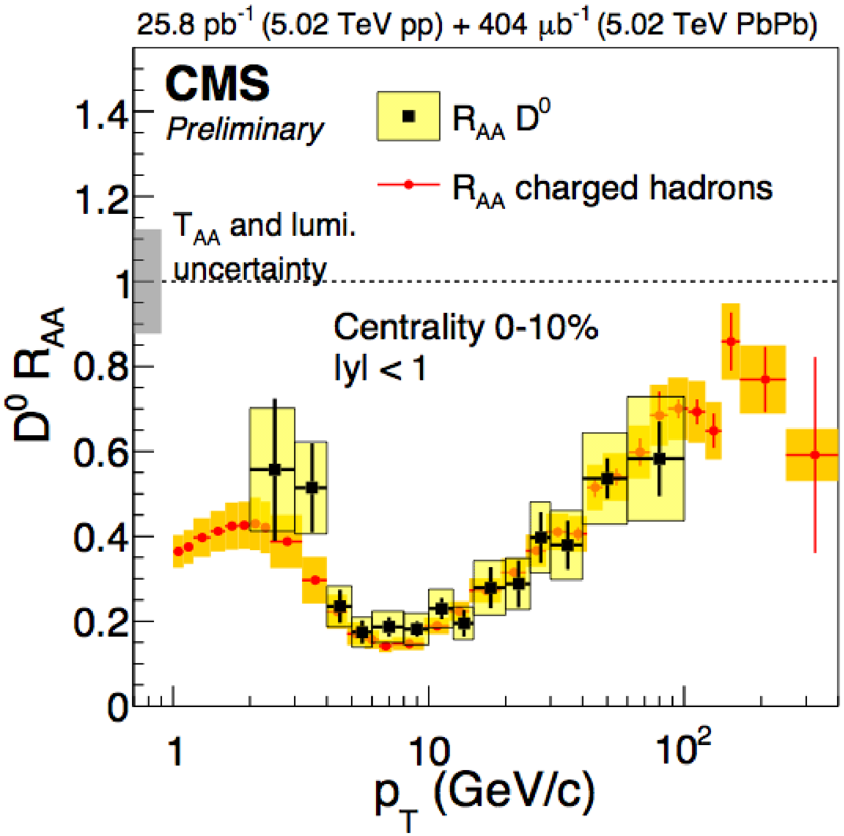




First data-driven extraction of prompt fraction in HI collisions



Flavor dependence of quenching



No indication of sizeable difference between D^0 and charged particle R_{AA}

This does not necessarily mean that energy loss by c-jet and light quark jet are the same

- c-jet fragmentation and shape of spectra is slightly different
- Large fraction of c-jets come from gluon splitting

Conclusions

New results of hard probes in 5 TeV PbPb collisions provide new data to constrain models

Previously un-probed rare events:

- Z-jet events with $p_T^Z > 80$ GeV
- Charged particle RAA measurement reach up to 400 GeV
- D^0 suppression is measured up to 100 GeV

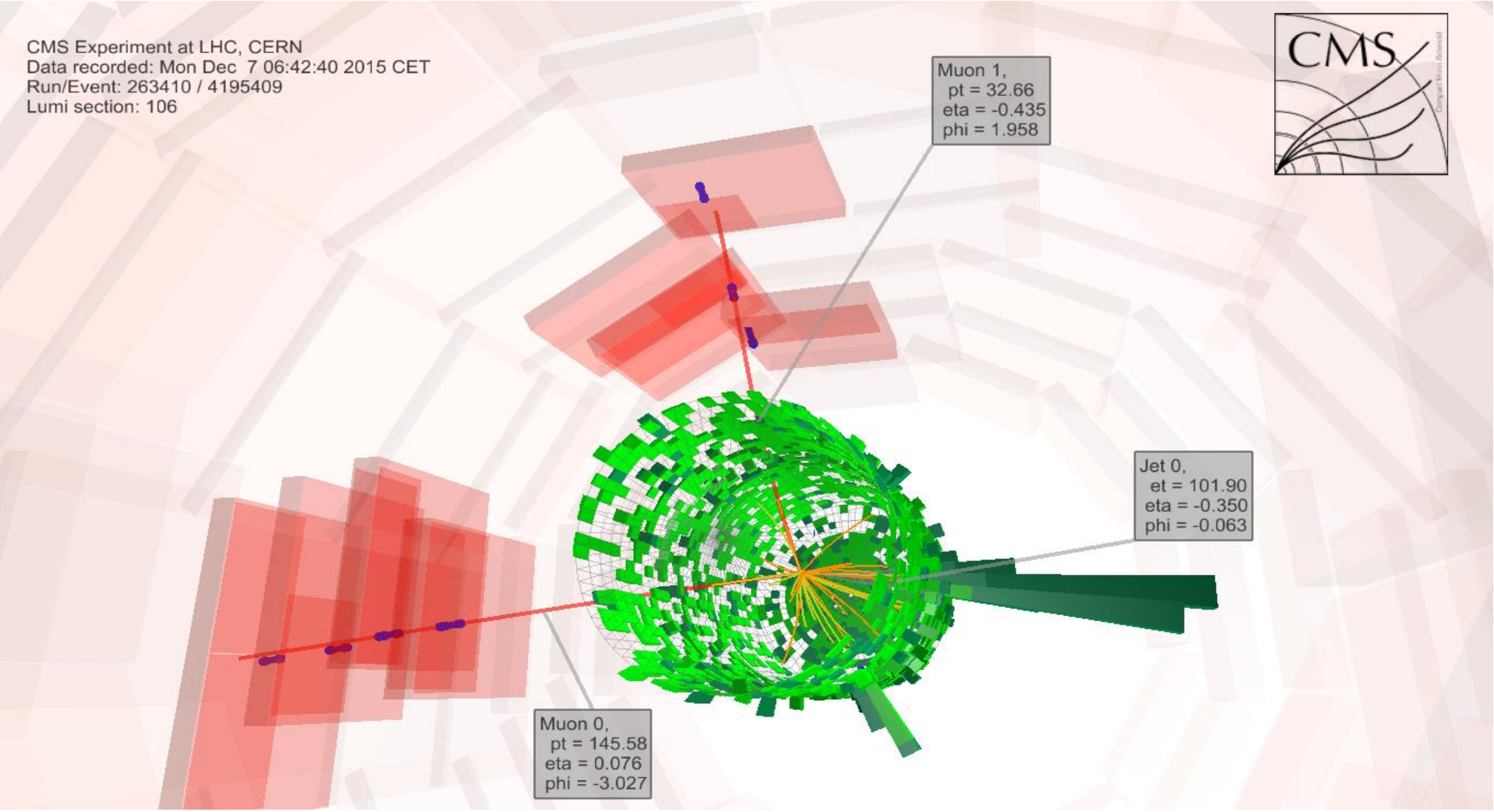
The new results contain information on dependence of quenching on

- Center of mass energy
- Light quark vs. gluon, light quark/gluon vs. heavy quark
  - *or more generally fragmentation of jets*

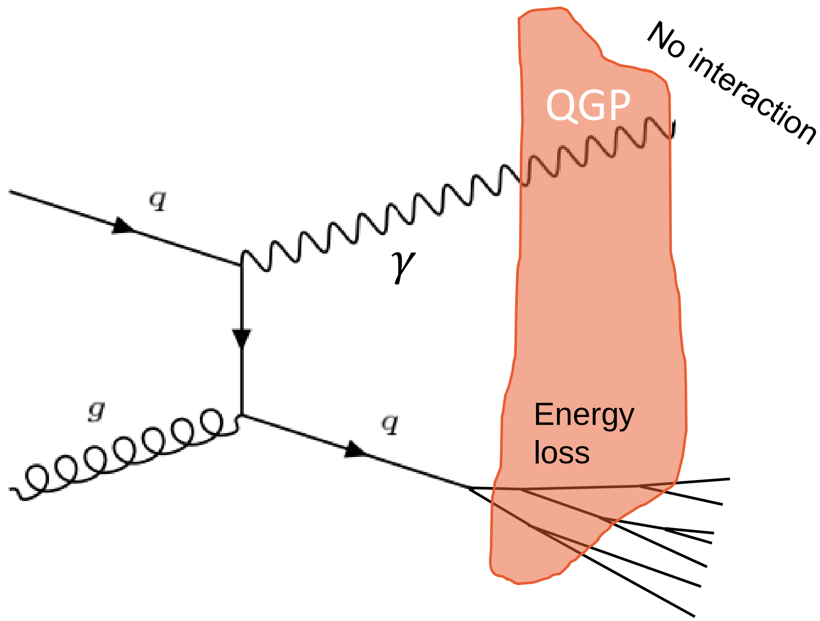
Hints of narrowing of azimuthal angle correlations

Back-up

Zjet event display



Compared to γ-jet

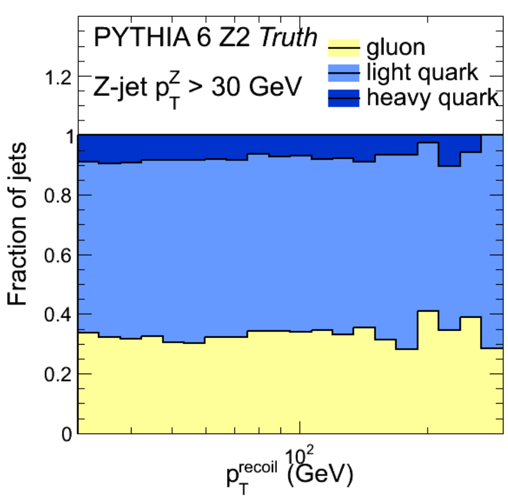


Same tree level Feynman diagrams but Z is massive

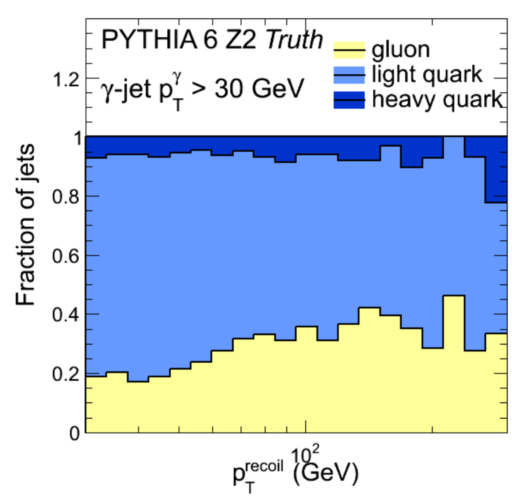
As a result in Z-jet events:

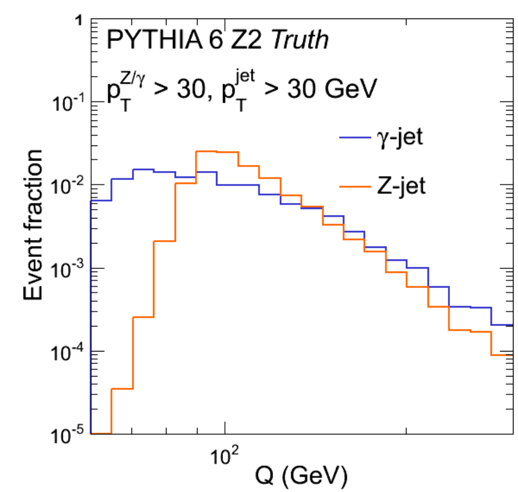
- Slightly different recoiling jet flavor composition
- Q is larger
- Recoiling jets have higher virtuality

Z-jet

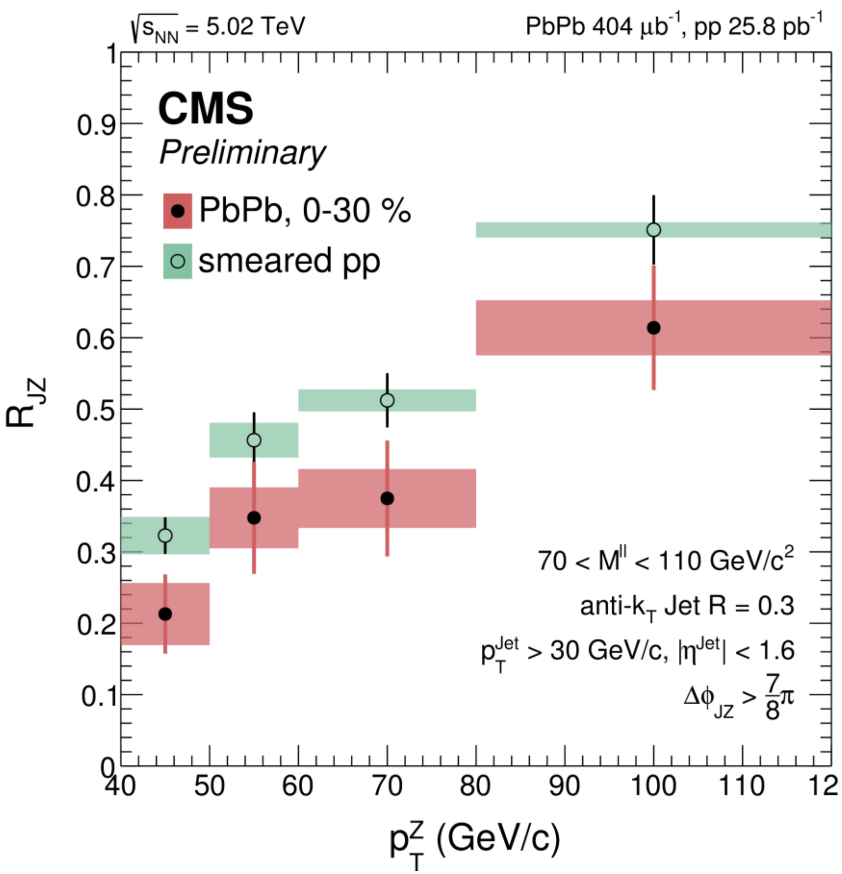


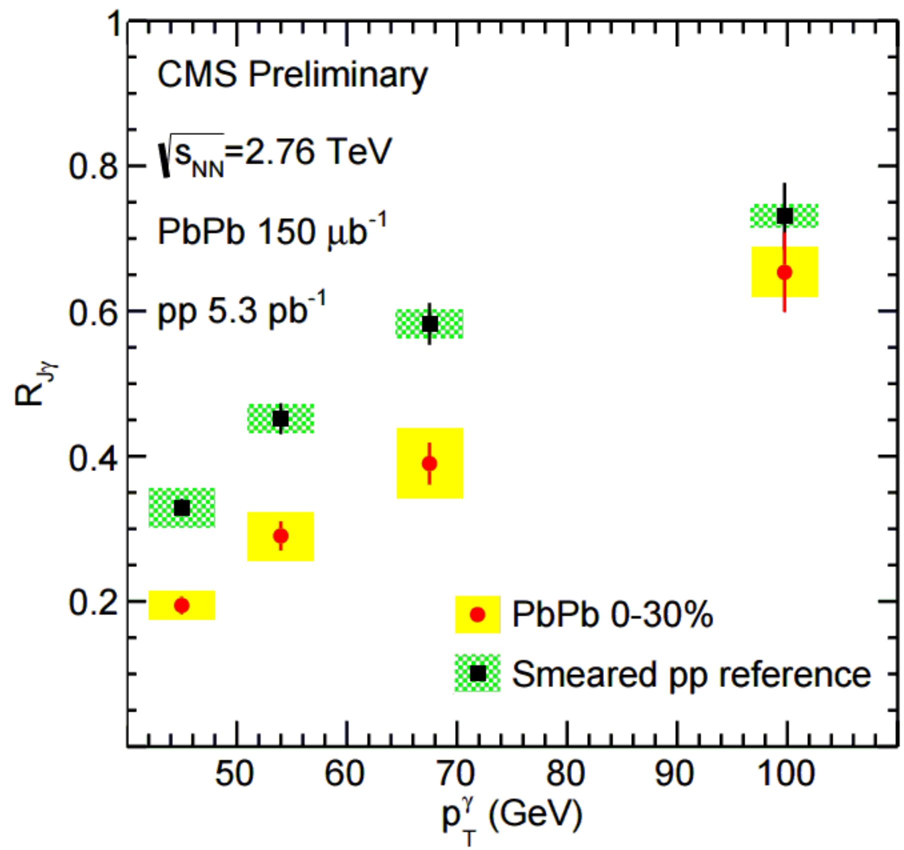
γ-jet





Number of Z's with recoiling jets

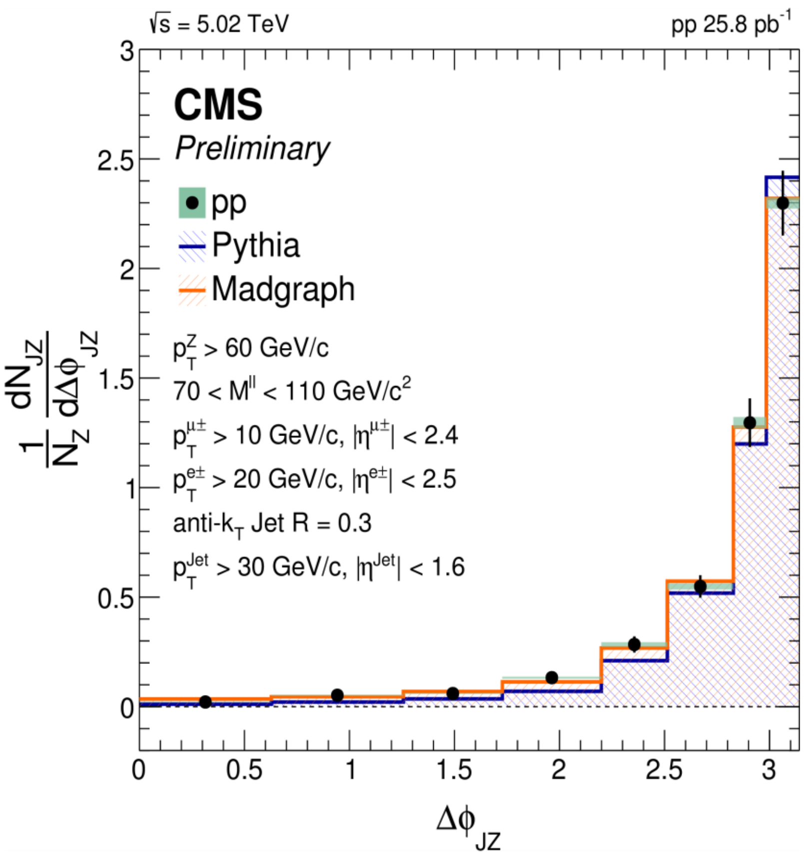


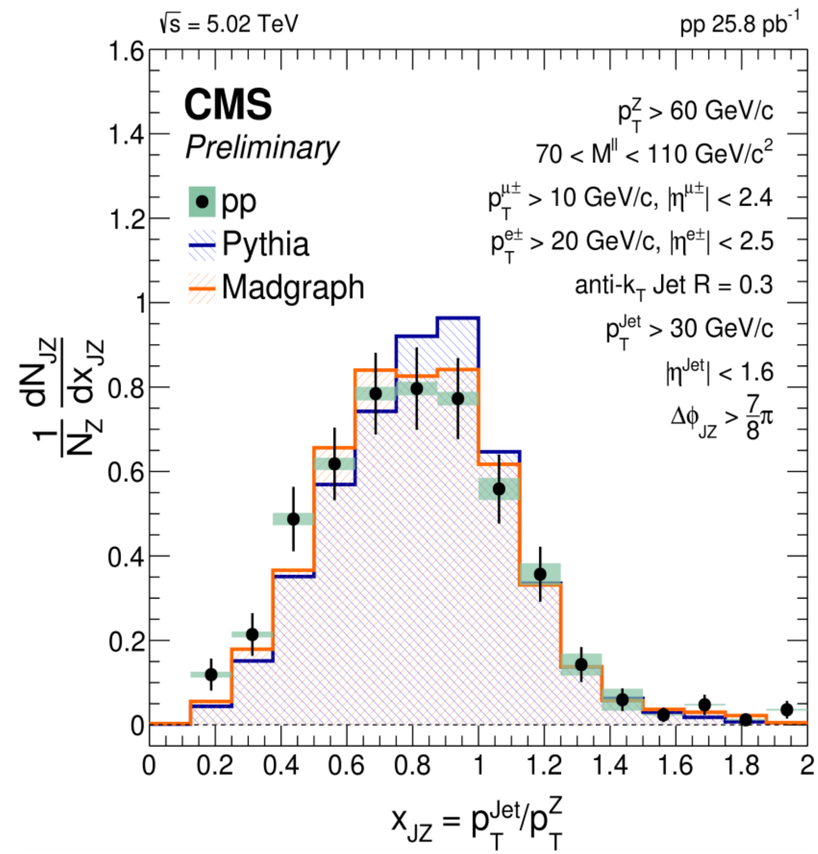


At Low p_T less number of Z with recoiling jet decreases because jets fall below the p_T threshold due to second jet and resolution effects for pp

In PbPb in addition to these effects there is quenching

Comparison to MC for pp





pp data with reconstruction effects while MC are particle level

Better agreement with Madgraph

Systematic uncertainties for RAA

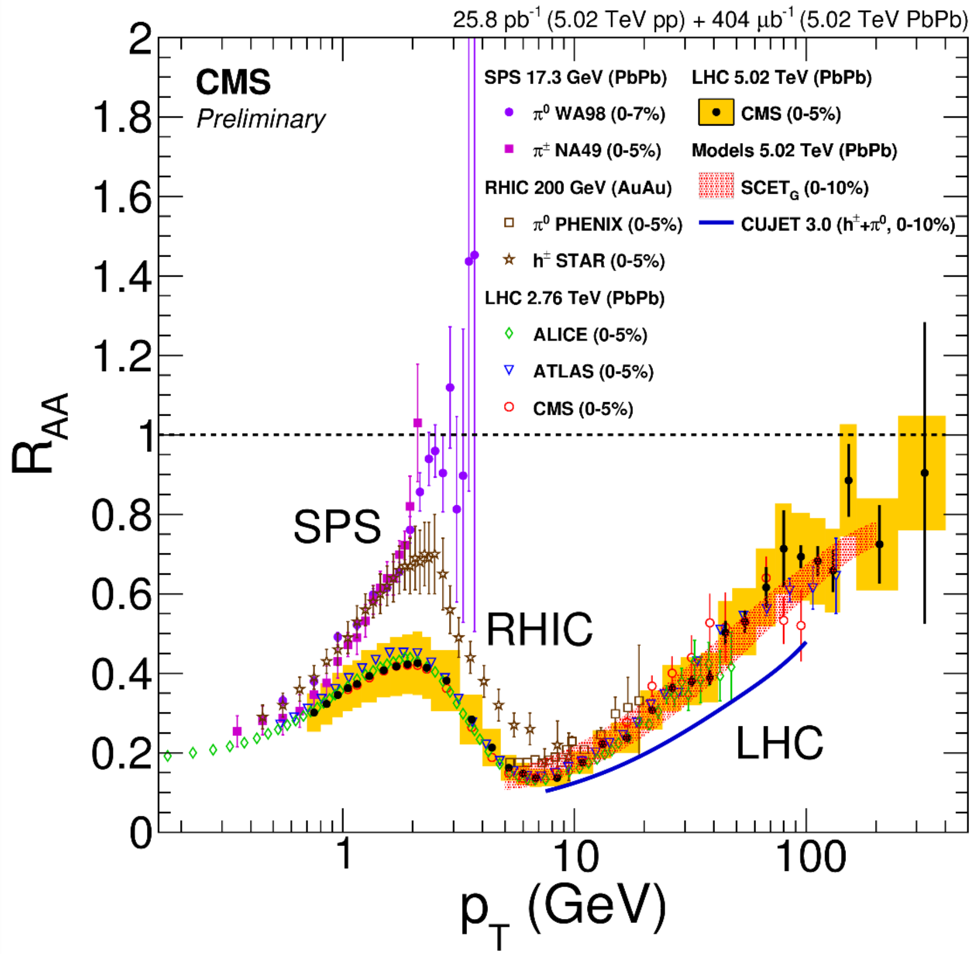
Sources	Uncertainty [%]
Event-selection correction	<1
Momentum resolution	1.5
Particle species composition	1.5–15.5
Fraction of misreconstructed tracks	3
Tracking correction non-closure	5
Tracking efficiency	6.5
Track selection	4
Pileup	3
Trigger combination	0–2.5
Luminosity	12
Glauber-model uncertainty	1.7–16
R_{AA} uncertainty	10–17

No need for unfolding

Data driven check using D* decays

Doesn’t include pp lumi uncertainty of 12% as it will go down in the future

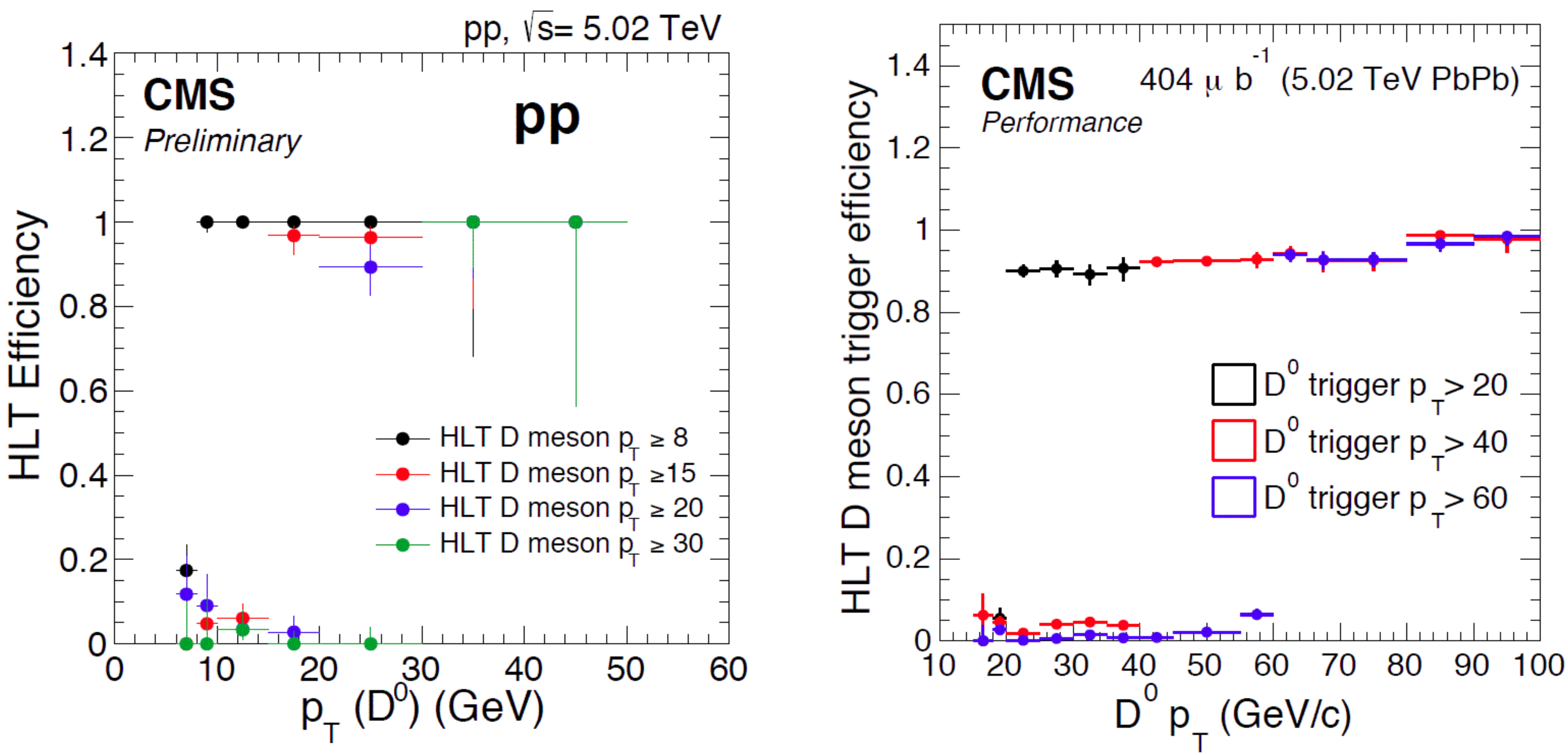
R_{AA} for different $\sqrt{s_{NN}}$



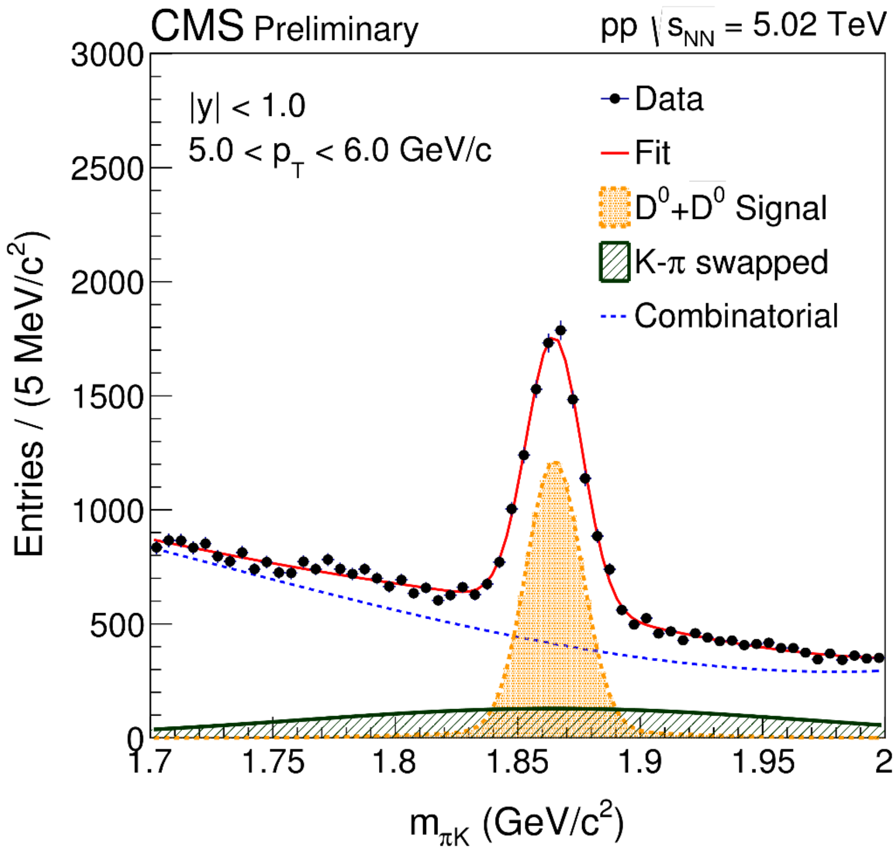
Hint of larger energy loss at 5.02 TeV

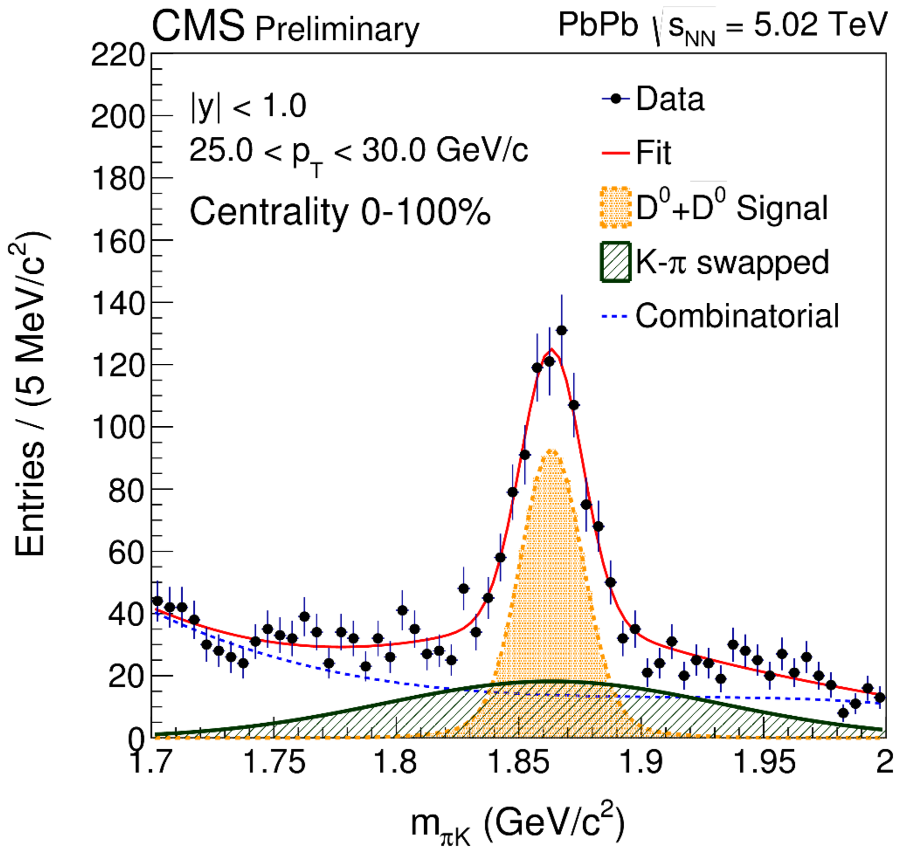
Although the spectra at higher $\sqrt{s_{NN}}$ is flatter the R_{AA} is very similar

D meson trigger performance



Fit to invariant mass





Uncertainties on D R_{AA}

- **Signal extraction systematics**

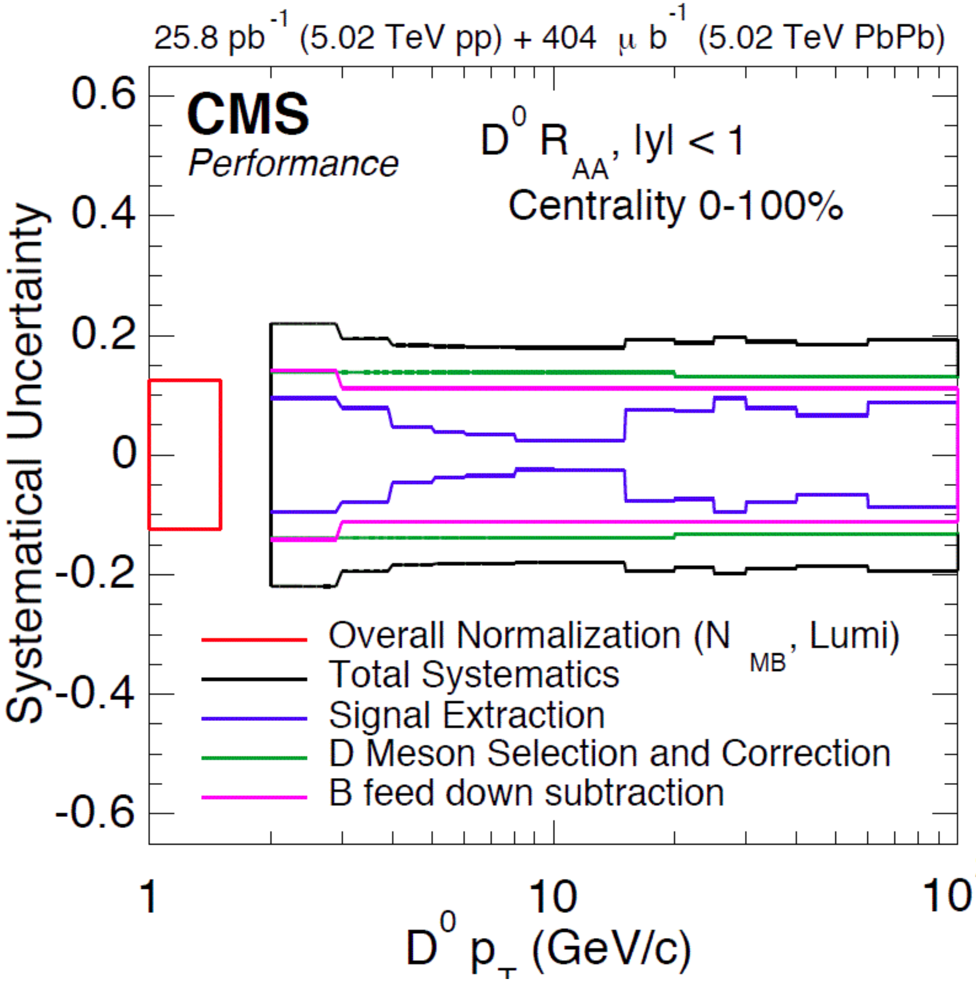
- Varying signal and background fit functions

- **D meson selection:**

- Comparing data and MC data driven efficiencies of the different cut selections
- Systematic on trigger efficiency
- Tracking efficiency systematic: (evaluated data driven with 2 and 4 prongs D^0 decays!)

- **B-feed down uncertainty**

- Obtained by comparing f_{prompt} estimation with alternative method based on decay length and with FONLL-based predictions



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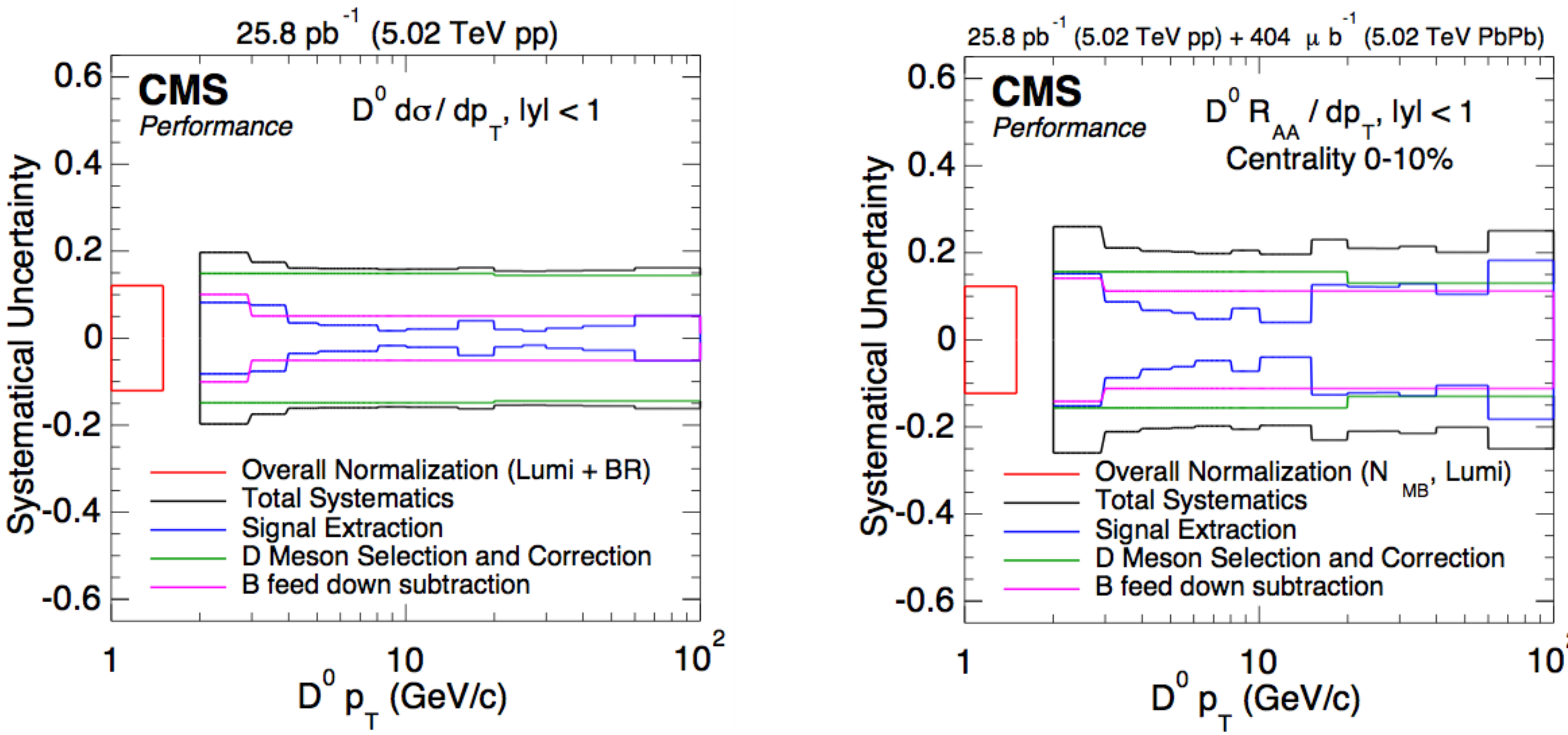

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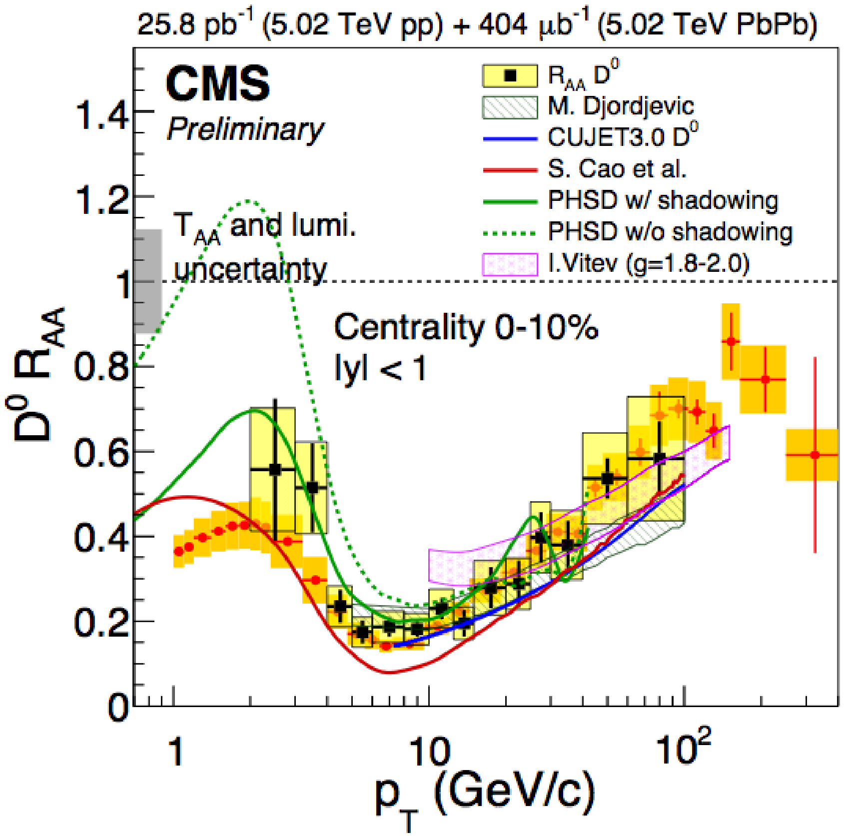

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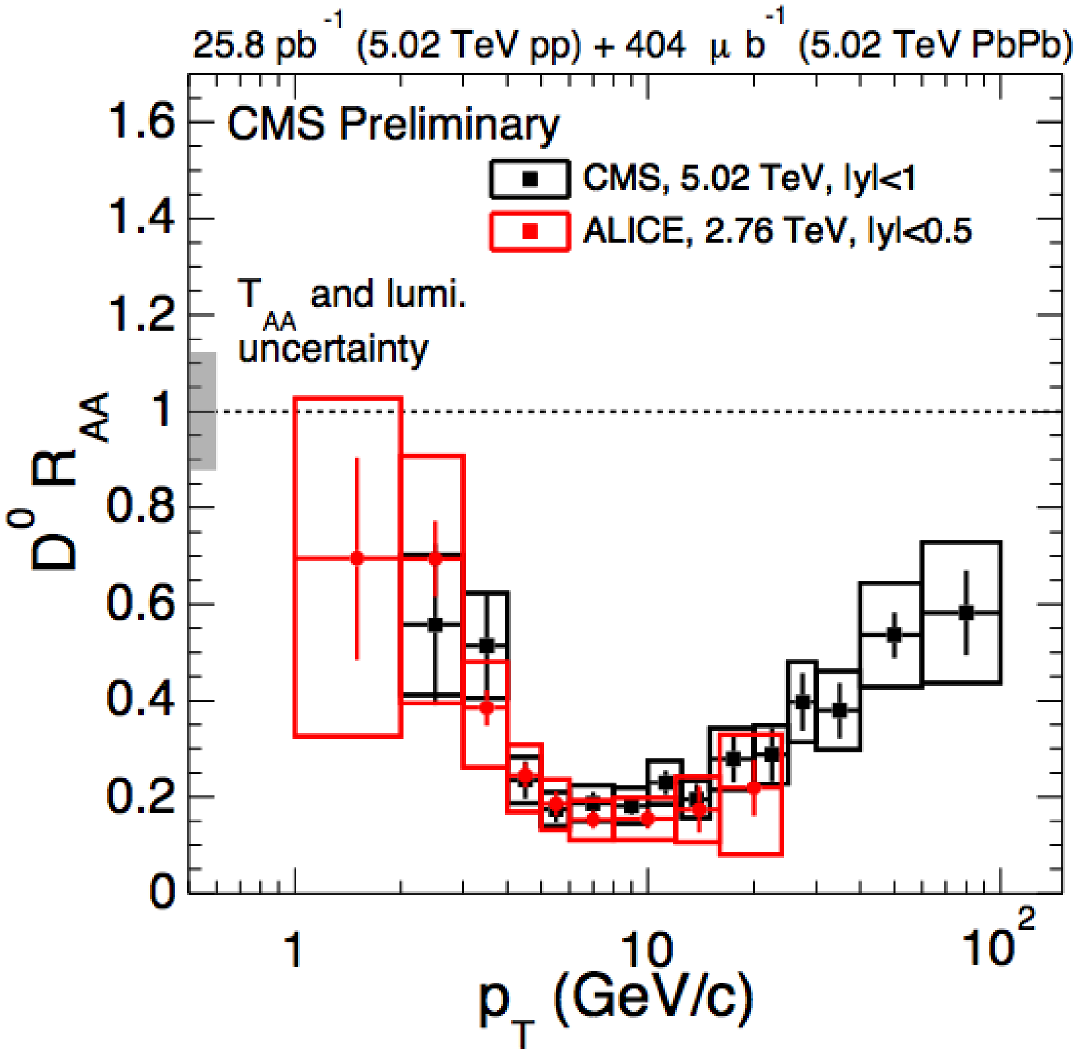
This does not necessarily mean that energy loss by c-jet and light quark jet are the same

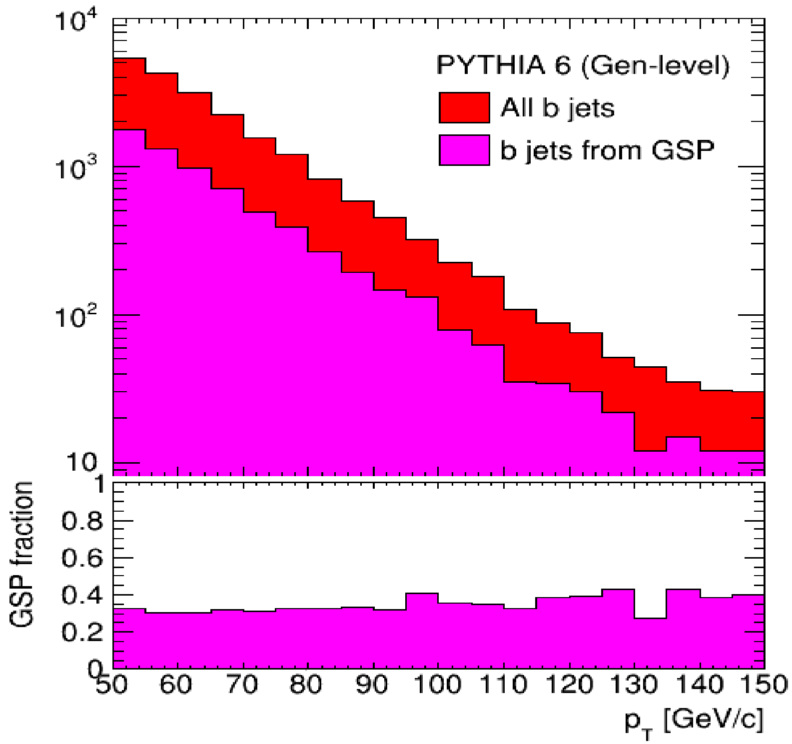
- c-jet fragmentation: shape of spectra is slightly different
- Large fraction of c-jets come from gluon splitting

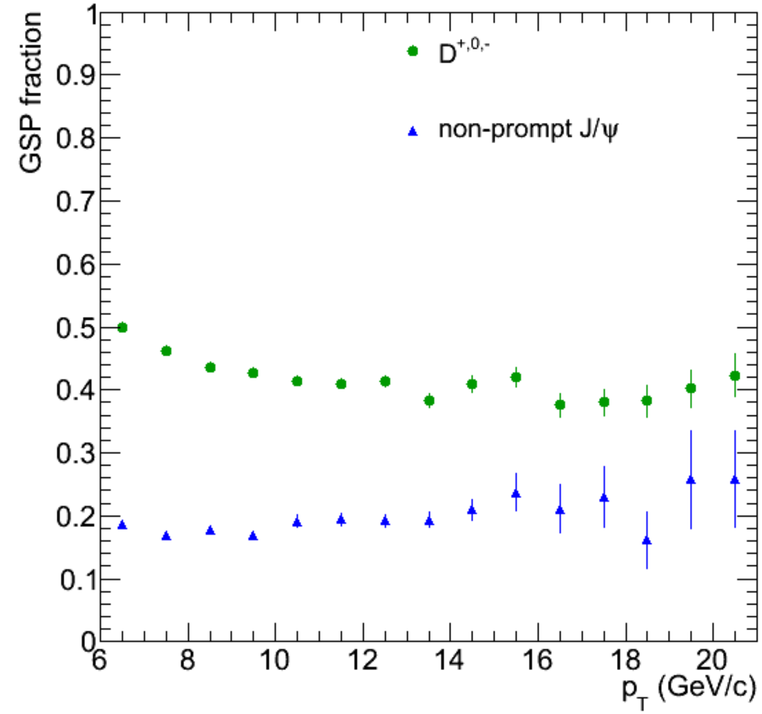
New results provide more constraints on quenching models

Compared to ALICE



Gluon splitting fraction





More contribution from gluon splitting in c than in b