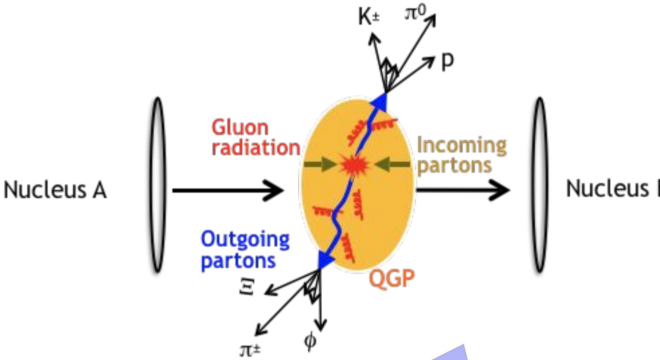
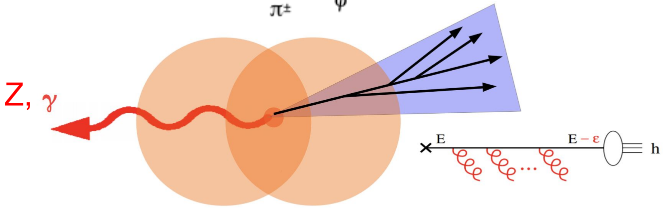
QGP Hard Probes: Jets and γ perspectives

Rencontres QGP-France, Etretat 2018

Aims for the coming years/decades: Fine tuned study of jet-quenching

- Precision measurement of the Energy Loss, **Δ***E*, and its redistribution
  - Light quark sector
    - Suppression from GeV to TeV
    - **Z/**γ/jet/hadron - jet/hadron correlations
  - Heavy quark (c & b) sector
    - Quark mass dependence
    - Identified flavour fragmentation function
- More differential measurements
  - Jet Deflection/Broadening
  - Jet Internal Structure: subjetiness/grooming/mass
- Rarer events → Beyond LHC Run4
  - Lighter ions collisions: Increased luminosity, lower jet background
  - Top Quarks
  - Even more differential measurements





<u>Full understanding of jet-quenching needs validation of models, including their finest details</u>

LHC experiments with direct γ and jet program

ALICE (program up to Run4 so far):

- Jet measurements can potentially go down to p_T = 10 GeV/c
    - 5 GeV/*c* alredy in pp
- Direct thermal photon measurements from 1 GeV/*c*, isolated photon measurements potentially from 10 GeV/*c*
- Excellent PID and low p_T tracking capabilities for jet fragmentation studies and heavy quark-jet tagging
- Improved tracking for Run3/4

ATLAS/CMS (program beyond Run4):

- Jet measurements in pp can potentially go down to p_T = 20 GeV/*c*
- Isolated Photon measurements from 15/20 GeV/*c* in pp/Pb-Pb
- Improved tracking beyond Run4 (I think)

Disclaimer: Not explored what are the capabilities/program from LHCb

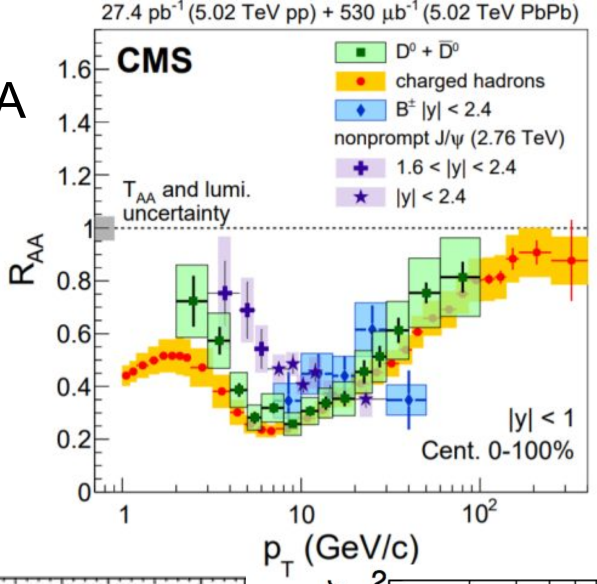
Particle zoo R_{AA}

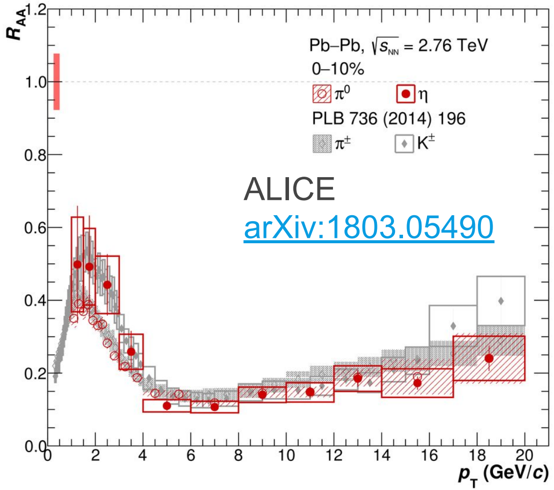
The nuclear modification factor

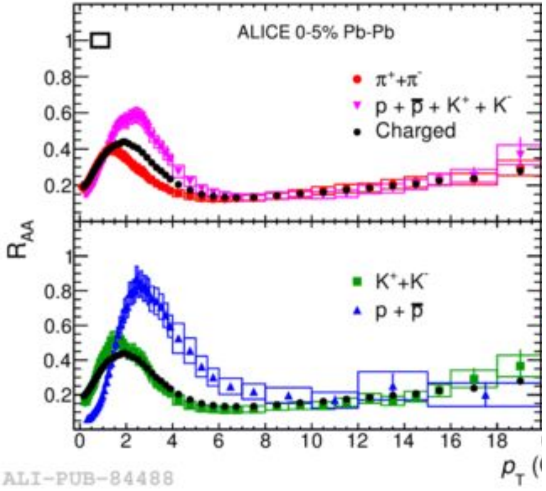
- is flavor and meson/barion dependent at low p_T
- PID has no effect at high p_T

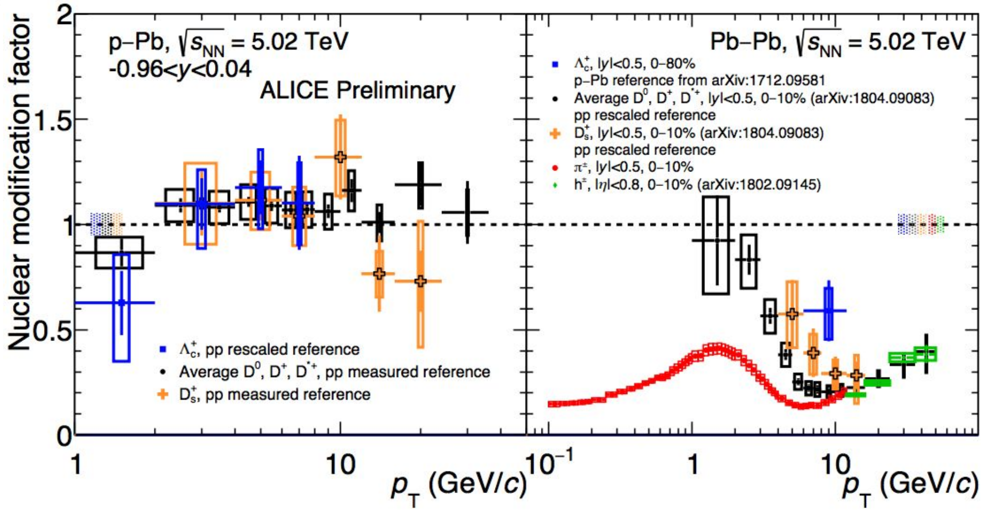
Questions:

- Does particle R_{AA} go to 1 at high p_T?









Particle vs Jet R_{AA}

arXiv:1708.04962

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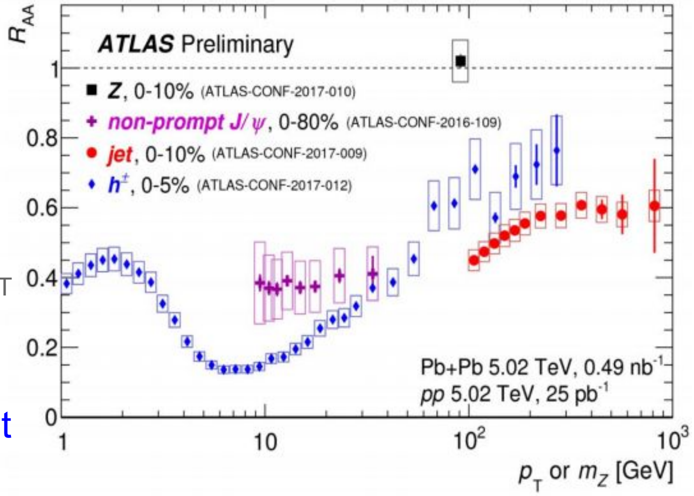
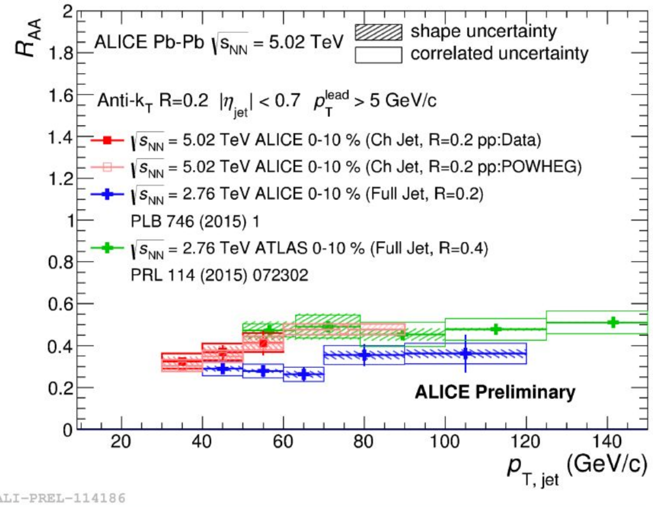
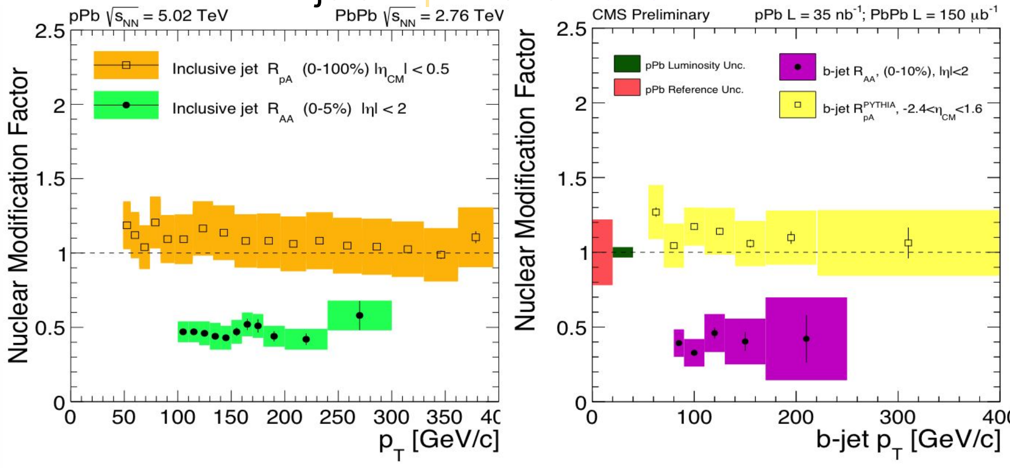




Questions:

- Does particle R_{AA} go to 1 at high p_T?
- Why Jet R_{AA} saturates, unlike particles, does it have some p_T dependence?
  - jet R_{AA} < hadron R_{AA} (at fixed p_T)
  - Inclusive jet and b-jet R_{AA} are similar

B-jets in pPb and PbPb



Particle vs Jet R_{AA}

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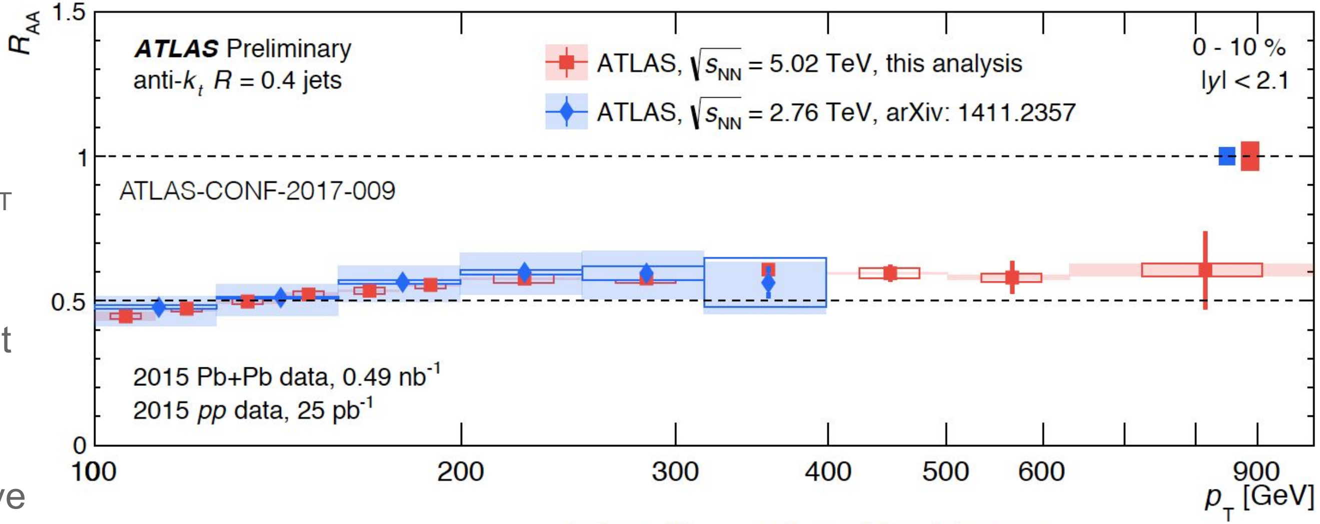


Jets: R_{AA} < 1 out to high p_T

p_T dependence at high p_T suggests:

Single particles: consistent with constant (Log E) dependence

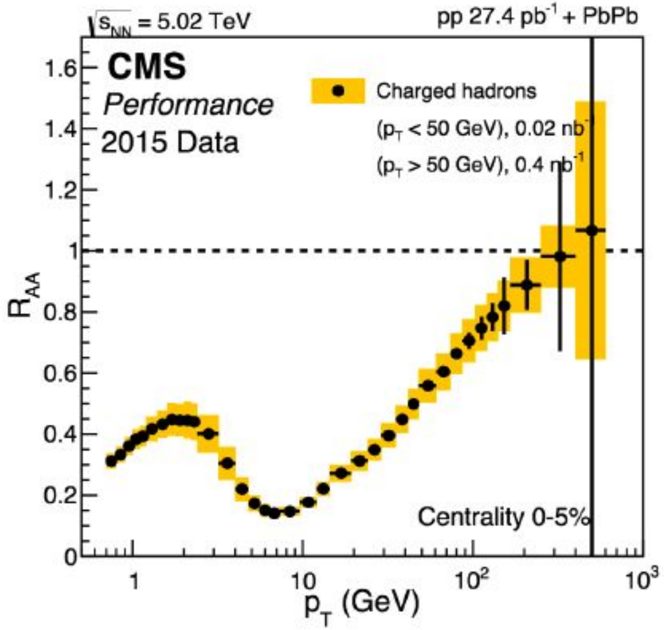
Jets: consistent with increase of ΔE vs E

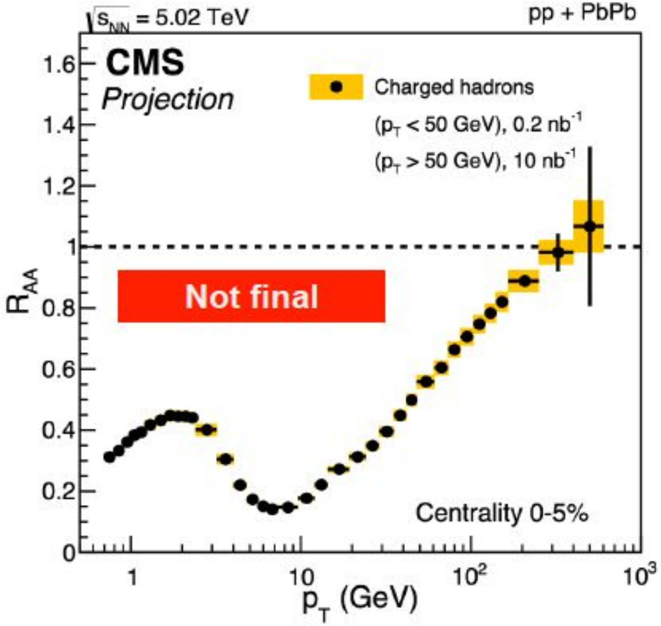
Tentative interpretation: in jets multiple originator partons lose energy

The more partons in jets ⇒ the more ΔE

Interest in checking the jet internal structure

Particle R_{AA} Run3/4 projections



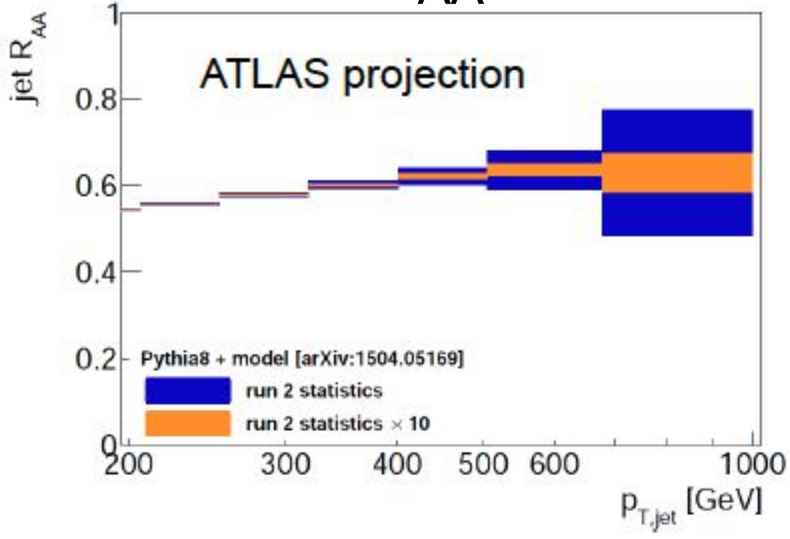


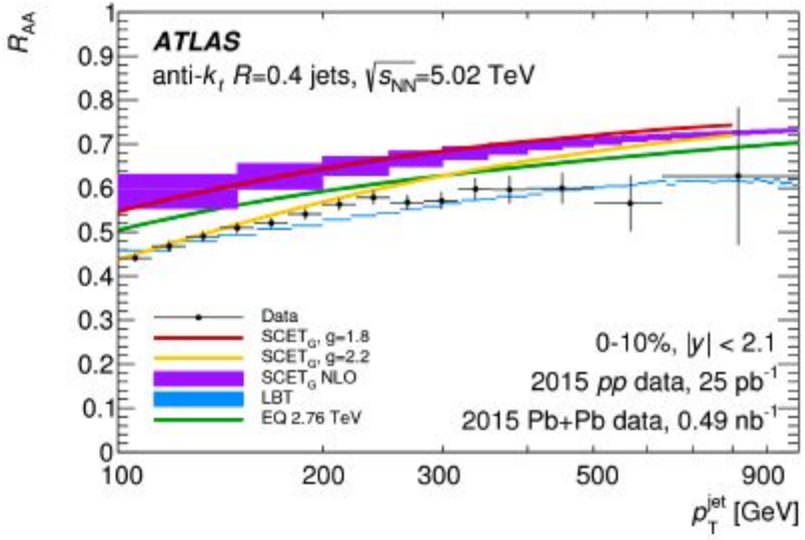
Current data limited precision at very high momentum

With 10 nb^{-1} negligible statistical uncertainty up to p_T = 300 GeV/c. Does R_{AA} reach unity?

Inclusive jet R_{AA} Run3/4 projections

arXiv:1805.05635





Very high precision over wide jet p_T range in LHC Run3/4

- Models predict a small p_T dependence, it can be explored in Run3/4
- Forward high p_T: interplay between flavor and spectral steepness, path length.
- Future runs allow to access higher p_T where the rapidity dependence is stronger.

Semi-inclusive hadron-jet distributions

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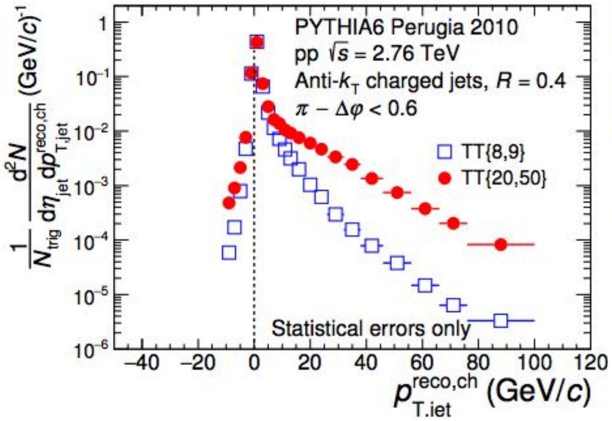
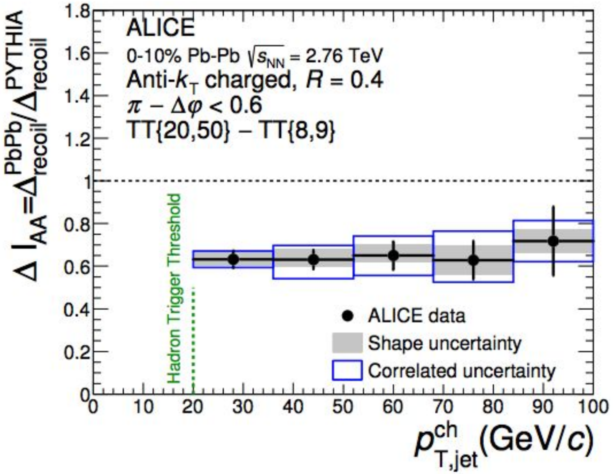
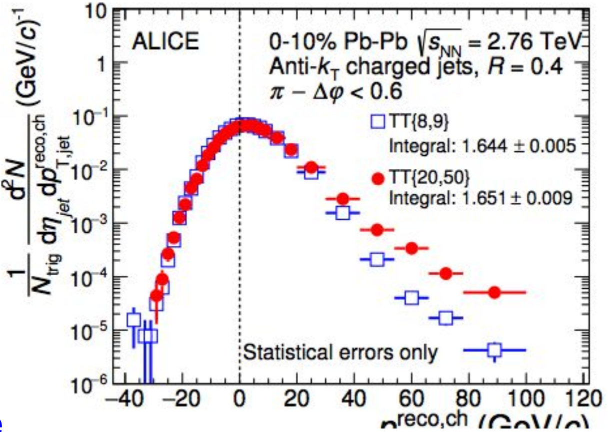
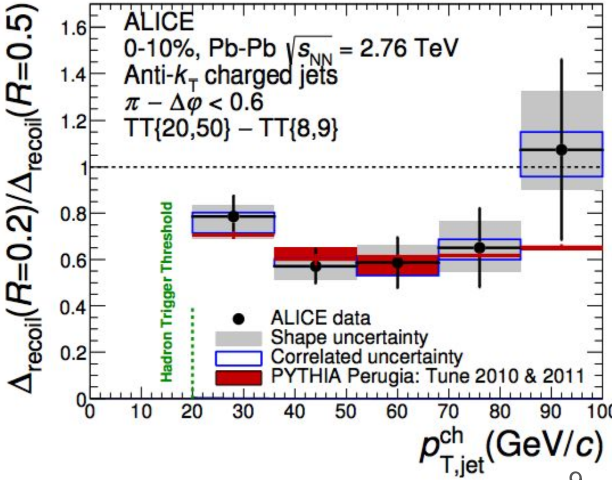
- Main limiting factor for jet reconstruction at low p_T: Underlying event fluctuations
- How to lower the limitation, subtract jet spectra in 2 trigger hadron bins: The bkg jet due to underlying event nature is the same in both hadron triggers at low jet *E*
- ALICE manages to get down to 20 GeV jets with such technique in 0-10% central Pb-Pb collisions
- The comparison of the resulting jet spectra in Pb-Pb and PYTHIA pp shows a strong suppression
- No jet broadening observed when comparing different jet cone size, limited statistic









Can we go to even lower p_T with lower multiplicity environment? → Lighter ions

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Precision measurement of energy loss and redistribution: From low to high p_T

Main tool: X+jet (X=γ,Z,hadron) to measure

- energy loss distribution, specially bosons, with $x_{j\gamma} = p_T^{jet} / p_T^{\gamma}$ or $x_{jZ} = p_T^{jet} / p_T^{Z}$
- jet fragmentation functions $D(p_T^{hadron} / p_T^{\gamma})$ or $D(p_T^{hadron} / p_T^{Z})$

Very low γ,Z,jet p_T measurements:

- Potentially larger sensitivity to medium interaction
- Interest on small systems where low p_T measurements are easier due to the reduced particle multiplicity

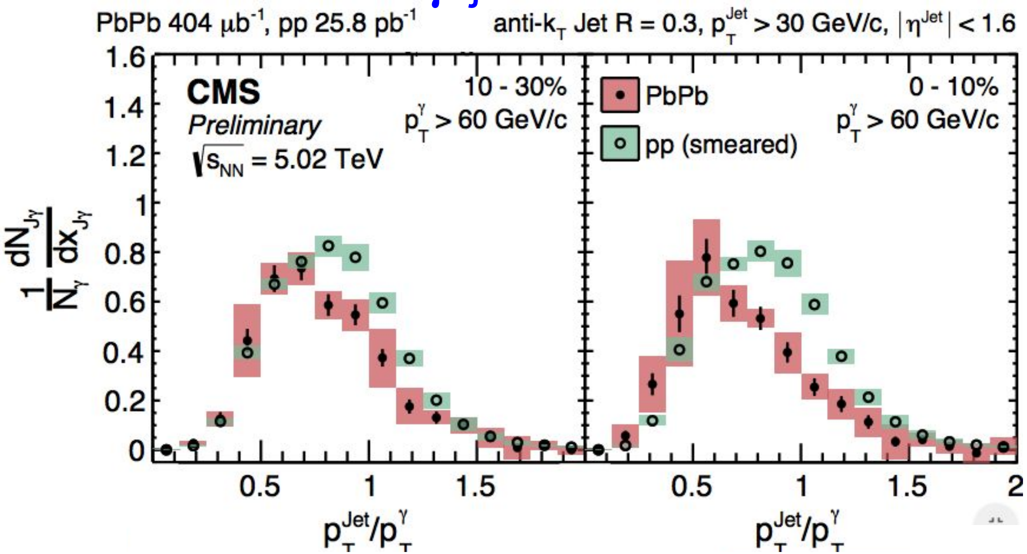
In any case needs work on AA to get lower p_T's

Alternative: go to higher γ/Z p_T so that one can measure the full ΔE distribution

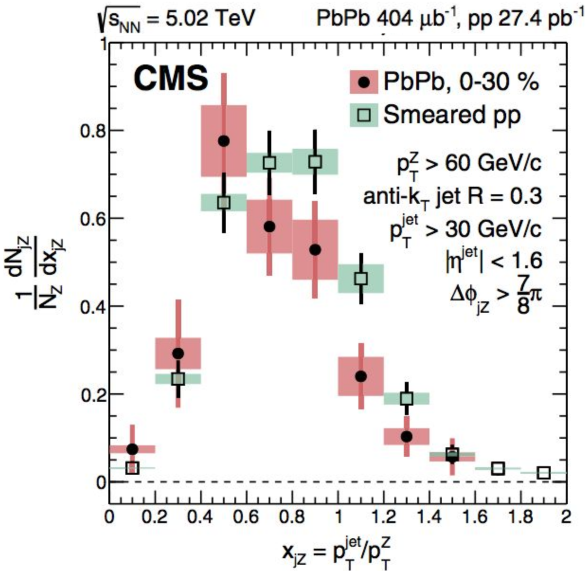
Energy loss via Z/γ-jet correlations

CMS PAS HIN-16-002

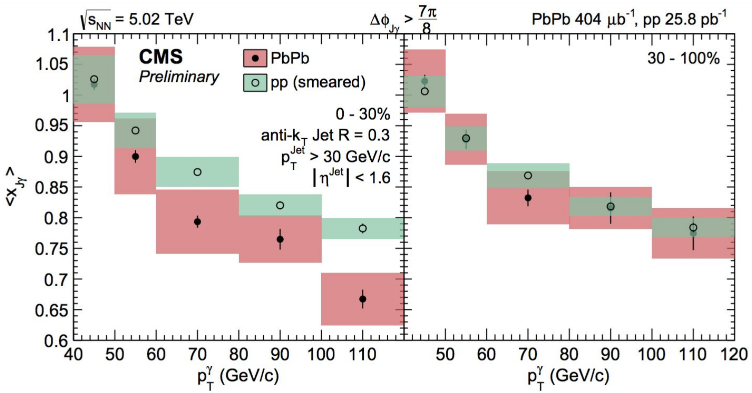
γ-jet



Z-jet



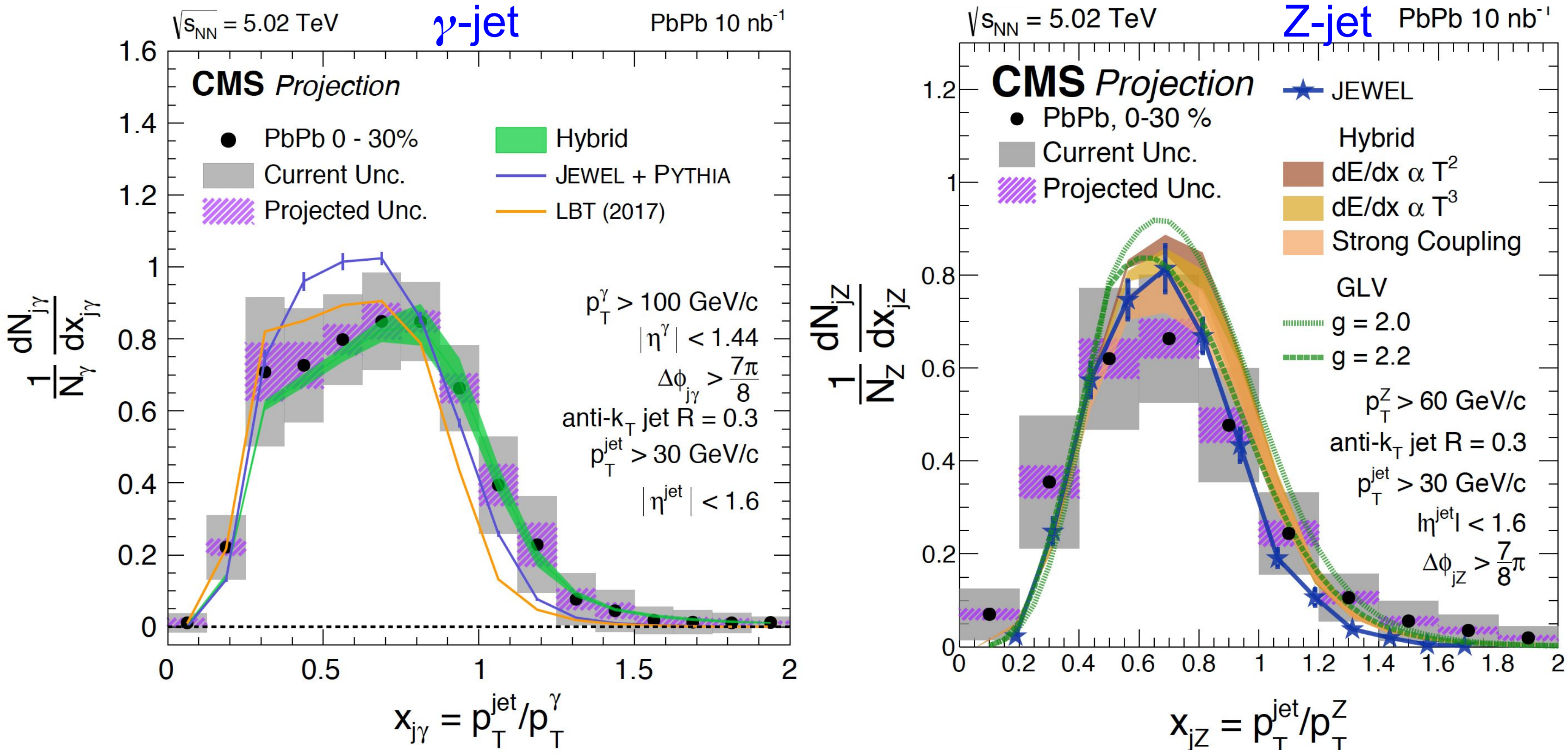
PRL119 (2017) 082301



At low γ trigger energies, uncertainty dominated by jet UE subtraction systematics in central events. In less central, statistical uncertainty still important.

Precision energy loss via Z/γ-jet correlations: Run3/4 Projections

LHC Run3/4 projections with 10 nb^{-1}



CMS-PAS-FTR-17-002

Stronger constrains to models with this precision

Jet Deflection

Angular distribution of recoil jet relative to trigger axis

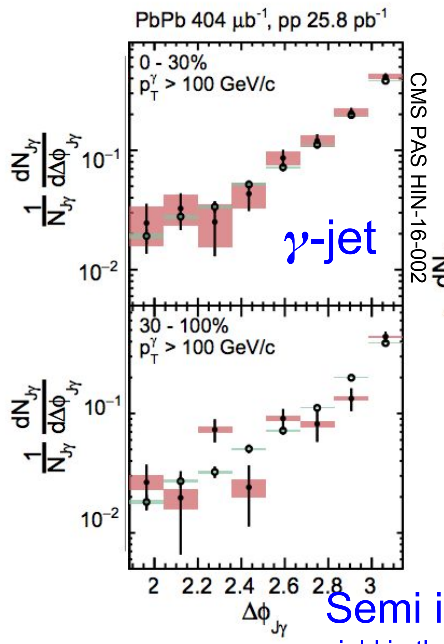
- Trigger: hadron, jet, boson (γ, Z, W)
- Boson cleanest since it isn't affected by the medium
- Hadron and jet much higher statistics + tool to probe geometry

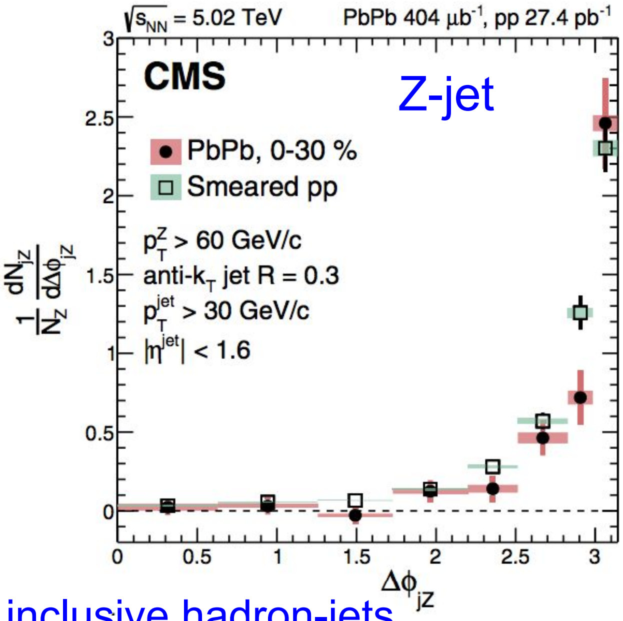
Coherent scattering of recoil jet

- In competition with shower broadening
- Significant if early in-medium

No evidence for jet deflection within uncertainties: Rule out or not with Run3/4 data

Can new tracking improve angular resolution for jet deflection? Lowering the trigger p_T might increase sensitivity to effect. Higher stat will help





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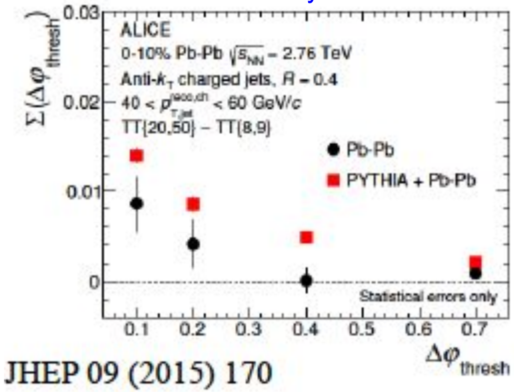
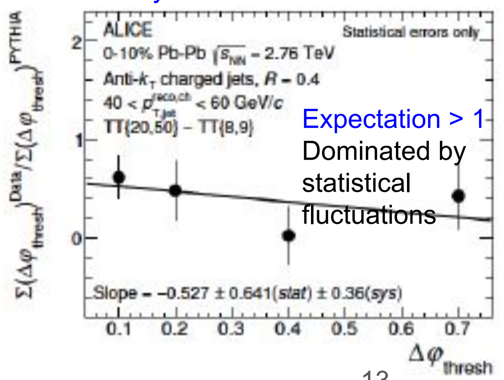
Semi inclusive hadron-jets

yield in the tail of the distribution beyond a threshold





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Jet structure observables

fragmentation function

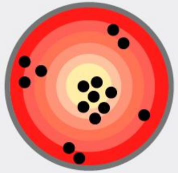
$$D(z) = \left\langle \sum_{i \in \text{jet}} \delta(z - p_{ti}/p_{t,\text{jet}}) \right\rangle_{\text{jets}}$$

differential jet shape

$$\rho(r) = \frac{1}{p_\perp^{\text{jet}}} \sum_{\substack{k \text{ with} \\ \Delta R_{kJ} \in [r, r+\delta r]}} p_\perp^{(k)},$$

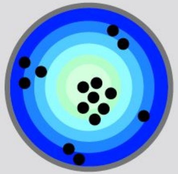
girth ≡ broadening

$$g = \frac{1}{p_\perp^{\text{jet}}} \sum_{k \in J} p_\perp^{(k)} \Delta R_{kJ},$$



jet mass, groomed & ungroomed

$$m^2 = \left(\sum_{i \in (\text{sub})\text{jet}} p_i^\mu \right)^2$$

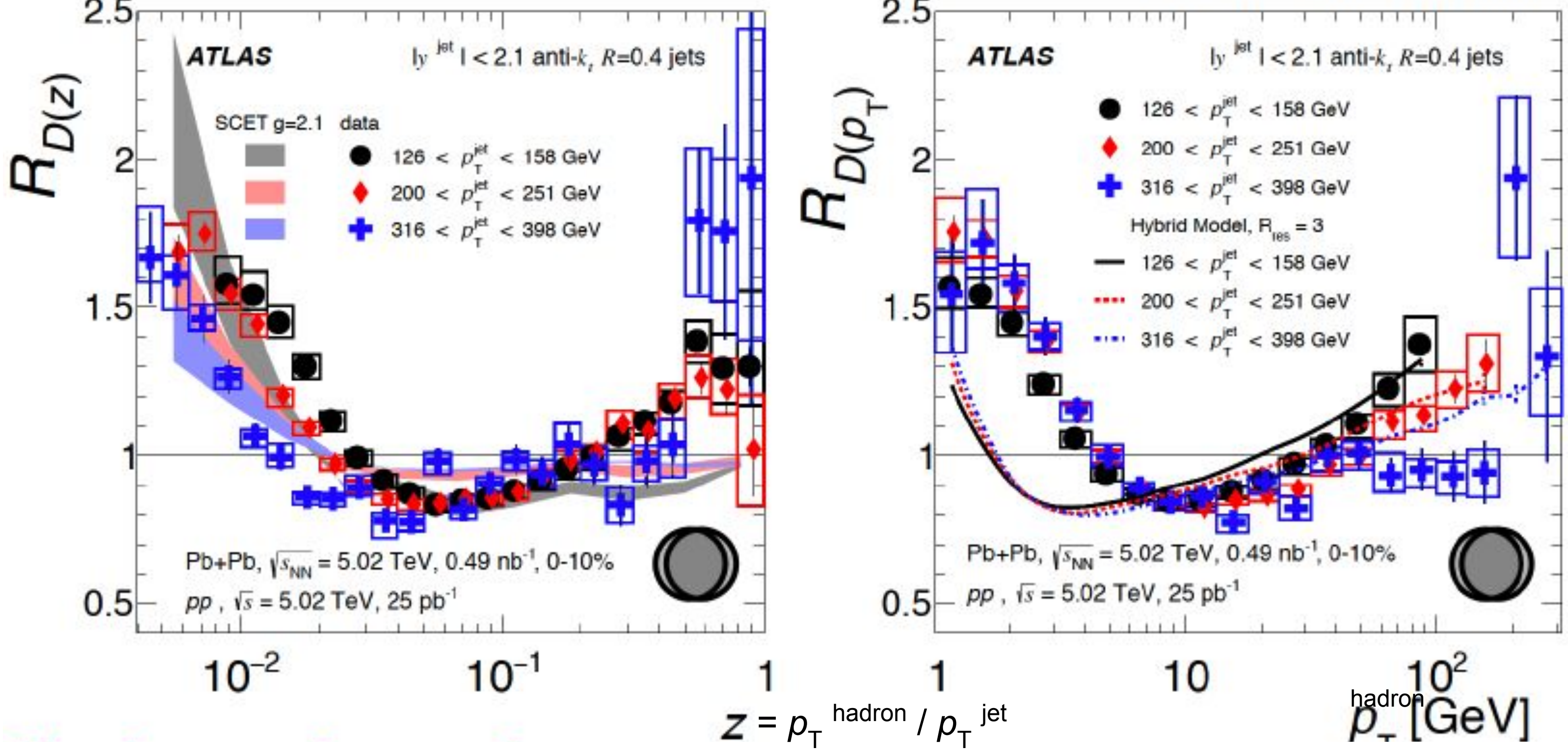


z_g, ΔR_{12}

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

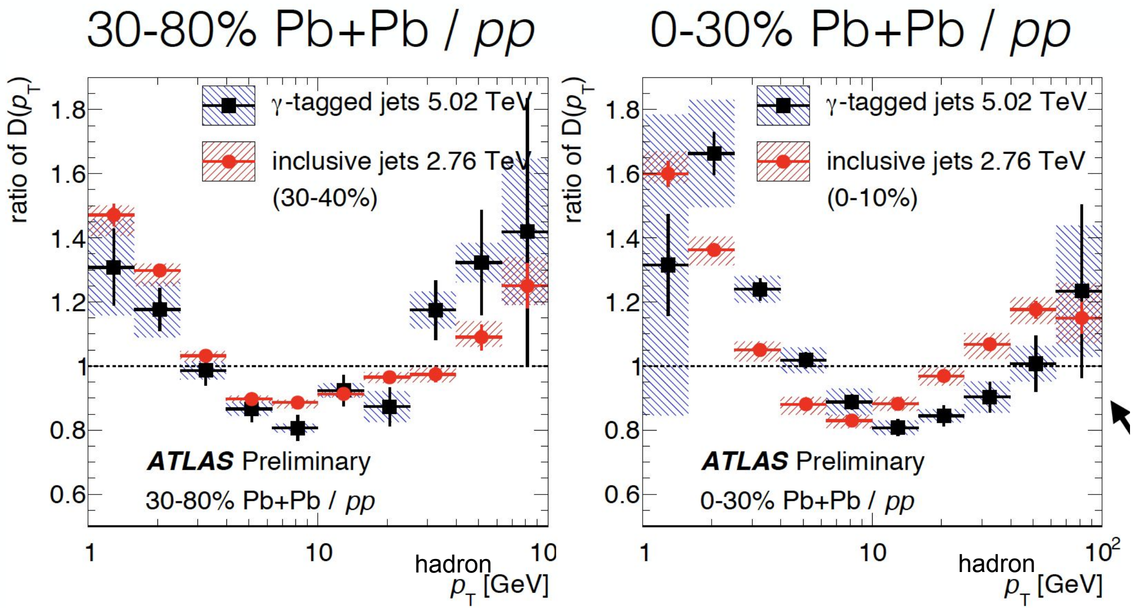
Jet internal structure: Fragmentation function

ATLAS-CONF-2017-005



- high p_T: sensitive to parton shower modification
- low p_T: sensitive to medium response?
- No projections for 10 nb^{-1}

Jet internal structure: Fragmentation function, γ tagged jets



ATLAS-CONF-2017-074

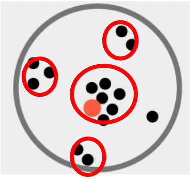
p_T^γ = 79.6-125 GeV/c
p_T^{jet} = 63.1-144 GeV/c

- Similar pattern in inclusive and gamma tagged jets
- The more central the events, the pattern is less compatible
  - Gluon vs quark E-loss?
  - Interest to measure γ-c jet, γ-b jet fragmentation function for full $\boldsymbol{\Delta}E$ of q vs g
  - Also select more groomed jets, intact core → q jets

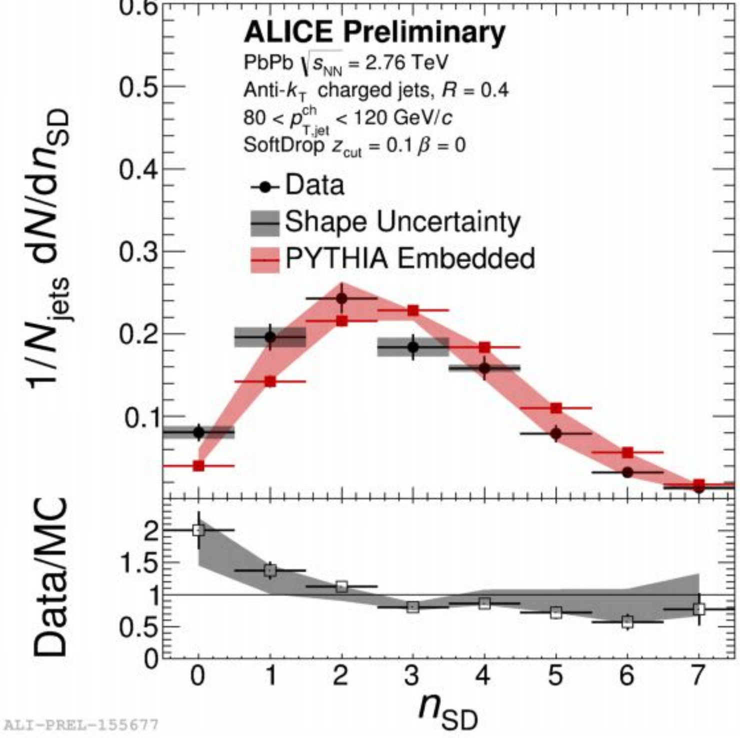
Statistics hungry differential measurements only at reach from Run3/4 and even beyond?

Jet substructure n_{SD}

Number of soft-drop splittings:



- Re-cluster a jet found with anti-kT with Cambridge-Aachen.
- Check for each splitting if it fulfills the soft-drop condition.
- Number of soft drop splittings in medium is only slightly shifted to lower values in contrast to expectation (medium response would shift splittings above the cut by adding momentum)
- Rather, enhancement in number of untagged jets; trend to lower n_{SD}
- Jet substructure in first order unmodified despite large energy loss in the medium.

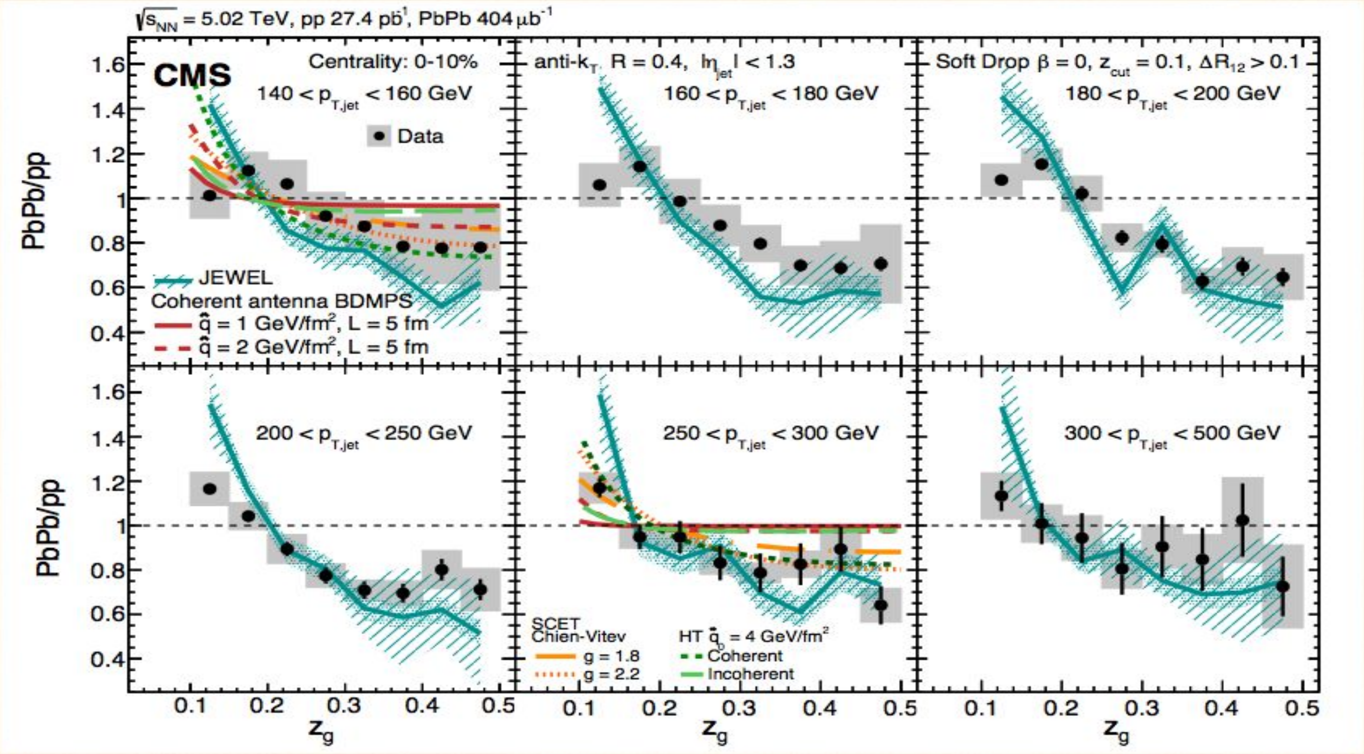


- Data statistical uncertainty can be highly reduced in coming runs
- What happens at lower pT? Semi-inclusive jet measurements could help?
- And at higher? Need more statistics
- Can new tracking improve angular resolution for jet deflection?

Jet substructure, z_g,

Clear modification in large range of jet P_T

Still, not enough precision to distinguish models



JEWEL generator

Multiple medium-induced gluon bremsstrahlung (coherent)

Soft collinear effective theory: modified gluon splitting function

Higher twist calculation

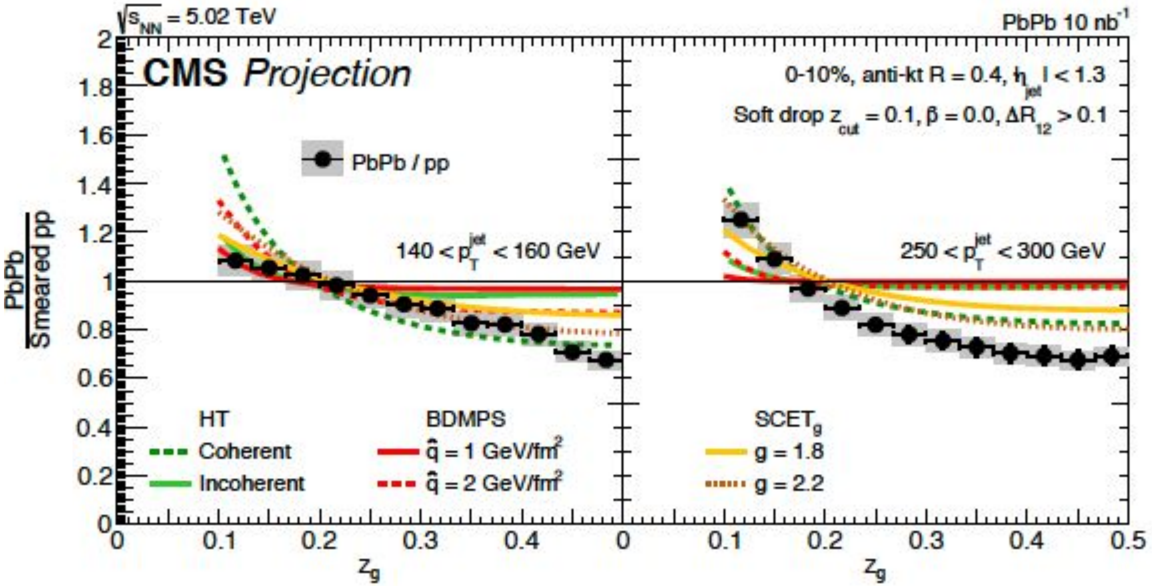
Jet substructure, z_g, Run3/4 projection

Can we probe the evolution of the medium using jet substructure techniques?

Experimental tools: p_T dependence, angular separation, mass. 10 nb^{-1} will allow us to study the p_T dependence of jet substructure modifications in detail.

- z_g, related to the angular separation of 2 main jet droplets
- Can new tracking improve intra-jet angular resolution?

z_g shown as example
Run 3/4 will tell us what variables are the more interesting or the ones to be dropped



CMS-PAS-FTR-17-002

Rare events

Isolate events in which at least one jet was heavily modified or not modified at all

Tools: A_j/x_j as done during LHC Run1. Studies were limited by statistics

New opportunities with more data.

With the selections one applies, systematically go to extreme

Jets with exotic substructure that are super rare in pp: Hard to predict what the unknown will bring

For anything that is rare: smaller ion favorable in order to accumulate more rare events

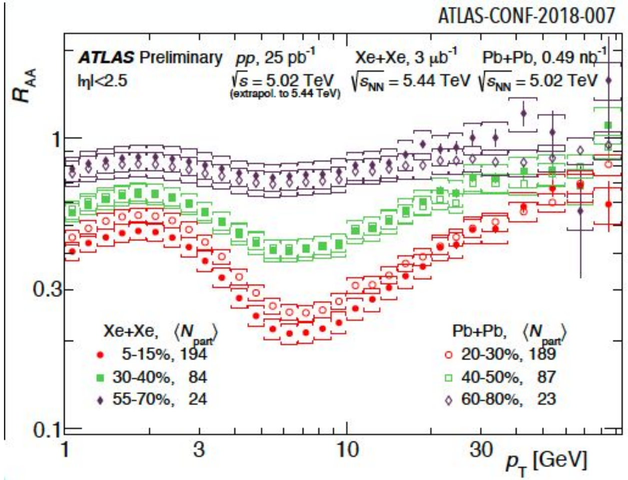
Lighter ions

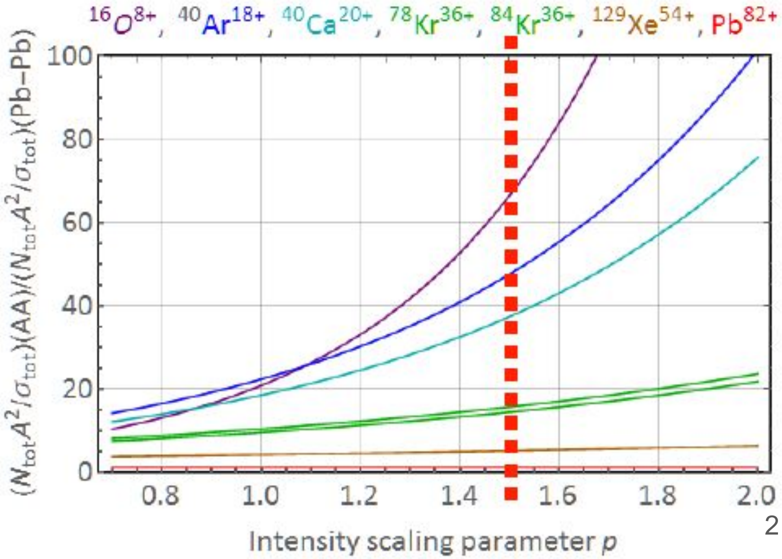
What did we learn with Xe-Xe?

- Similar quenching effects at same multiplicity

Arguments in favor of light-ion running

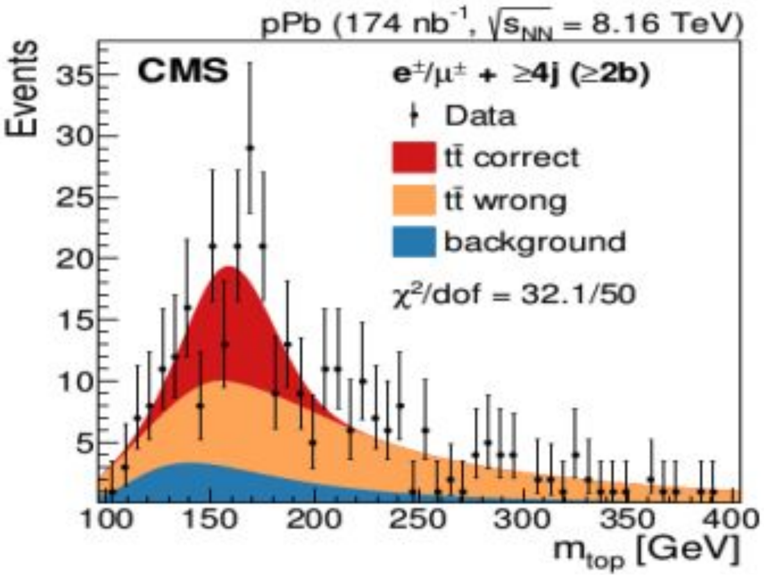
- higher luminosities by the machine
- increased rates for hard probes
- understanding the onset of jet quenching
- decreased systematics from the UE in jet and other measurements

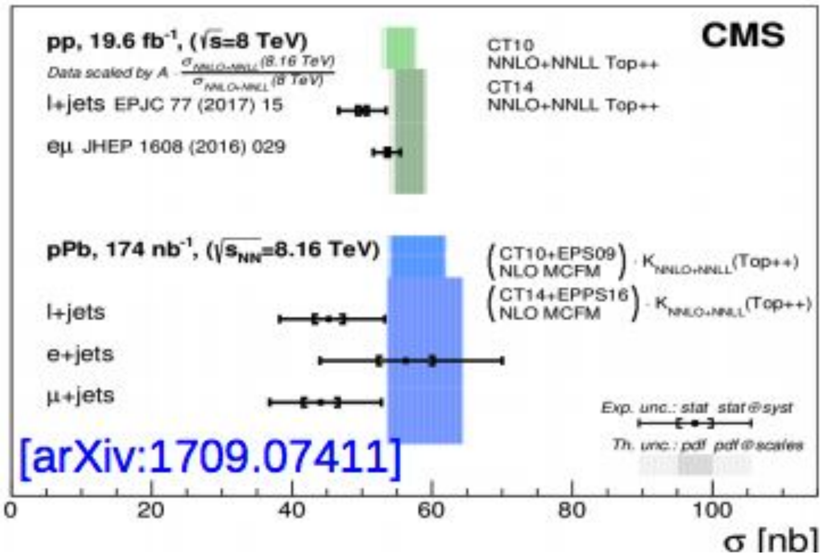




Top quarks

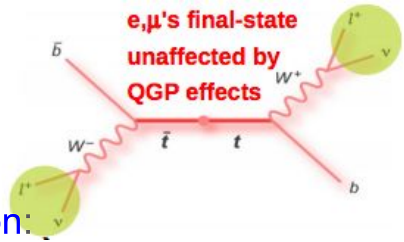
Top quarks measurement is feasible, at least in pPb, as shown by CMS





- Studies of high x gluon PDF in Pb possible with top quarks
- QGP properties Hydro predictions: strong time-dependence due to its expansion and cooldown

Top quarks: Chronography



top-antitop (t-tbar) production offers a unique opportunity to study QGP time evolution:

- Consider the decay chain t → b + W → q-qbar (jets to be measured)
- Those jets start interacting with the medium later than “standard” jets due to a series of time delays:
    - Top quarks lifetime (at rest) is 0.15 fm/c and the W’s lifetime is 0.09 fm/c
    - When the W boson decays hadronically, the resulting colour-singlet quark-antiquark (q-qbar) pair is not immediately resolved by the medium: decoherence time.
    - Only the part of the QGP that remains after the sum of decay and decoherence times is “seen” by the jets in the chain.

- To probe jet quenching and its time dependence in t-tbar production, measure the invariant mass M_{jj} of the dijet system that is produced from hadronic W decays.
    - In pp events, M_{jj} is closely related to the W mass, modulo final-state-radiation (FSR) effects.
    - The difference in reconstructed M_{jj} in central ion-ion (AA) collisions as compared to pp will be our measure of jet quenching.

See arXiv 1711.02105 and presentation at HL-LHC workshop

Top quarks

Total Time delay

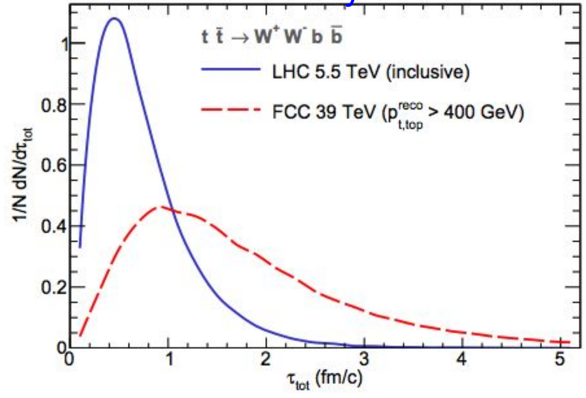
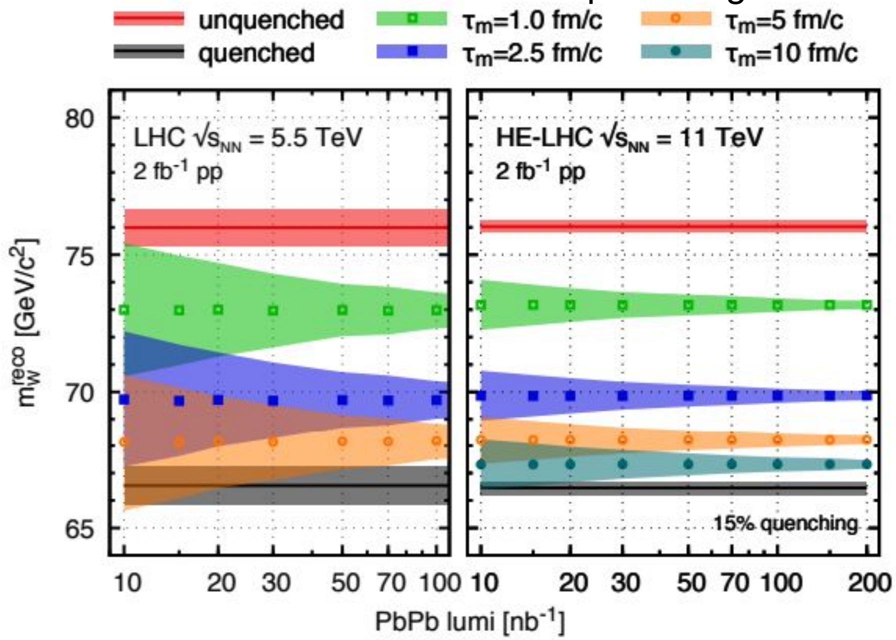


FIG. 1. Distribution of $\tau_{\rm tot}$ for events that pass all reconstruction cuts and have a top-quark candidate (independently of the reconstructed top-quark and W-boson masses).

Maximum quenching time Tm



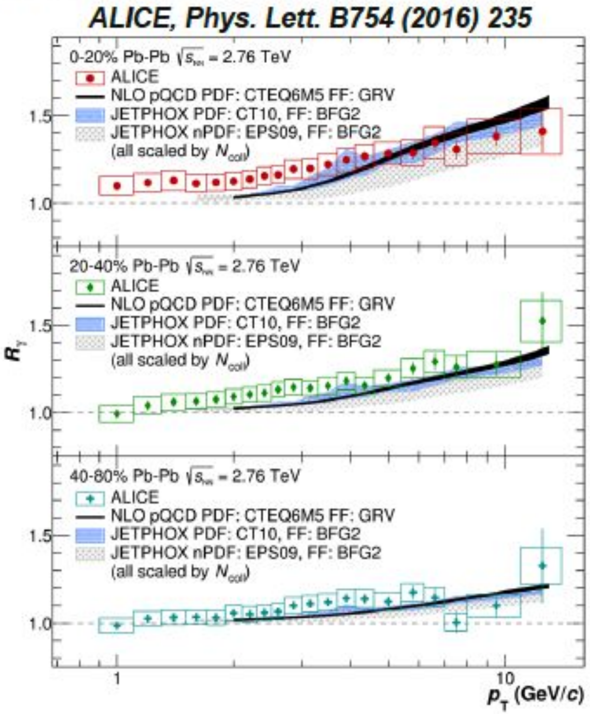
Production estimates

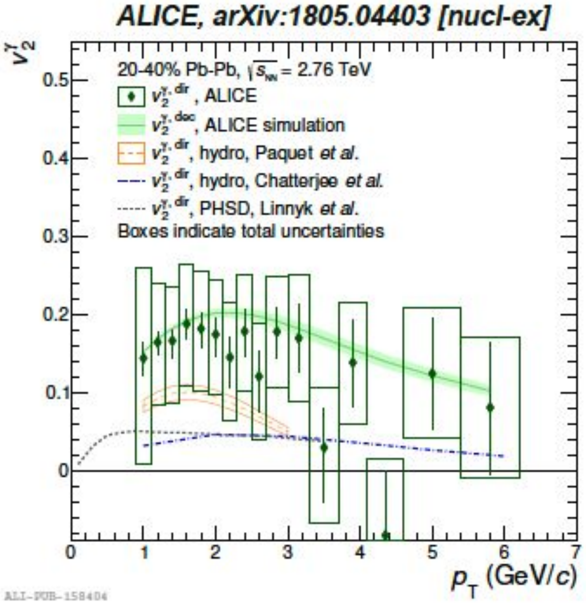
- LHC (nominal Lint): 500–750 t-tbar in Pb-Pb, p-Pb. 5.000 (in ℓ+jets)
- FCC (updated Lint): 1–3 million t-tbar pairs in Pb-Pb,p-Pb
- HE-LHC: 5.000 (leptonic)–30.000 (ℓ+jets) visible counts

System	$\sqrt{s_{\rm NN}}$ (TeV)	$\mathcal{L}_{\rm int}$	$t\bar{t}$ $\sigma_{\rm tot}$	$t\bar{t} \to b\bar{b}\ell\ell\nu\nu$ yields	single-t $\sigma_{\rm tot}$	$tW \to b\ell\ell\nu\nu$ yields
PbPb	5.5	10 nb^{-1}	3.4 μb	450	2.0 μb	30
pPb	8.8	1 pb^{-1}	59 nb	750	27 nb	50
PbPb	39	33 nb^{-1}	300 μb	1.5×10^5	80 μb	8000
pPb	63	8 pb^{-1}	3.2 μb	4×10^5	775 nb	2.1×10^4

Thermal photons?

- Soft exponential component of photon p_T spectrum: T~300 MeV
- Direct photon elliptic flow: v2 > 0, and close to charged hadrons (late emission?)
- Future measurement (Run3/4): reduce stat./syst. uncertainty
  - No projections
  - Main source: Material budget uncertainty.
    - How to reduce? calibrate with a well know changeable material probe inside the detector.





Are there thermal photons in small systems? No indications yet, limited by systematics also. Recent ALICE paper on pp collisions arXiv:1803.09857

Summary

HL-LHC

- Opportunity to get higher precision than on Run1-2 analysis (precise measurement of **Δ***E*) and open the possibility to do more differential studies with heavy quarks and jet substructures

HE-LHC/FCC

- Light ions: Increased luminosity, reduced jet systematic uncertainties with lower multiplicities
- Top quarks: Quenching chronography
- Imagine more differential jet measurements to get the fine details of the **Δ***E*, in bins of jet-sub structures, etc. It would need close collaboration with theory and early studies once Run3/4 tells us what are the relevant selections

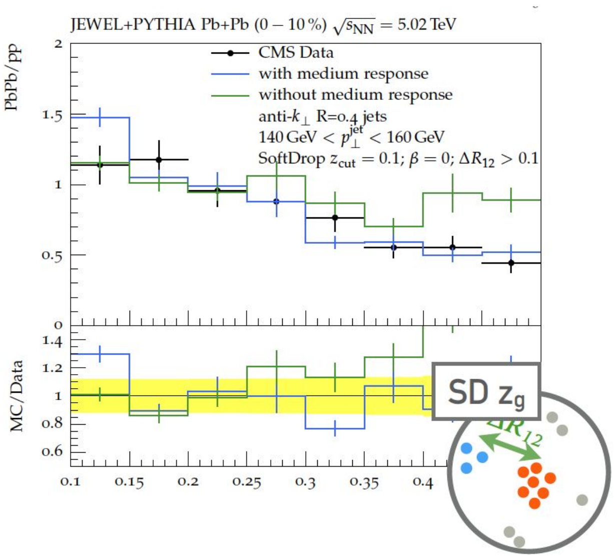
Draft editable of summary document can be found in this link

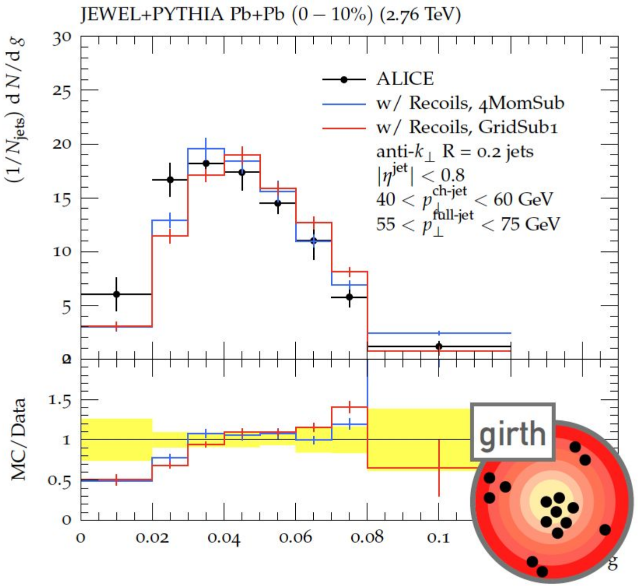
back-up

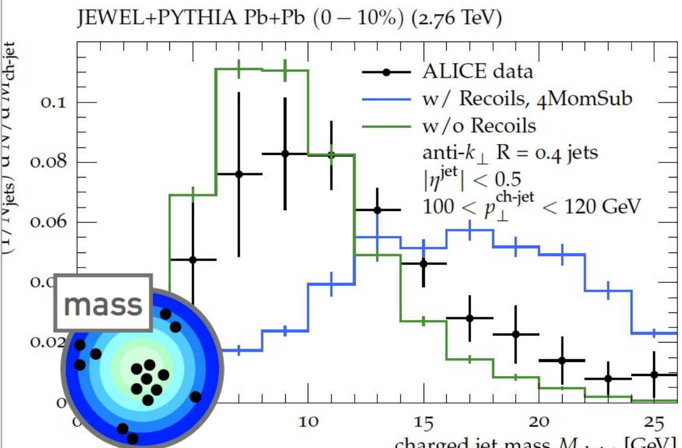
JEWEL v. data

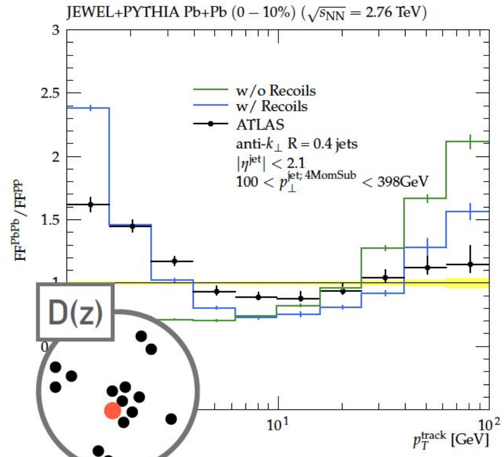
- arXiv:1707.01539, by Milhano, Wiedemann and Zapp with medium response

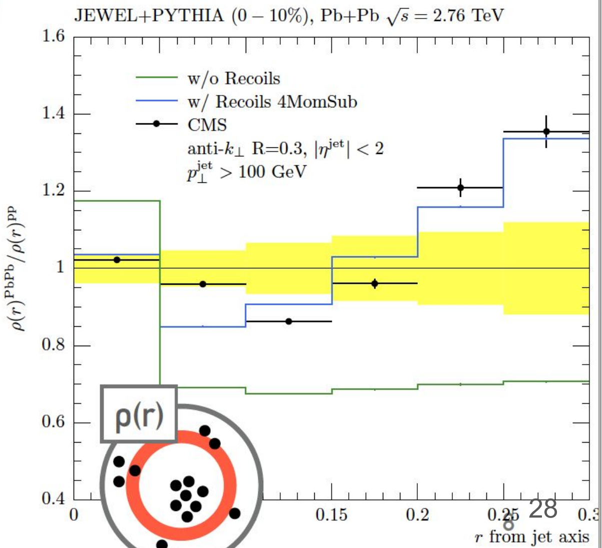
Gavin P. Salam at QM2018





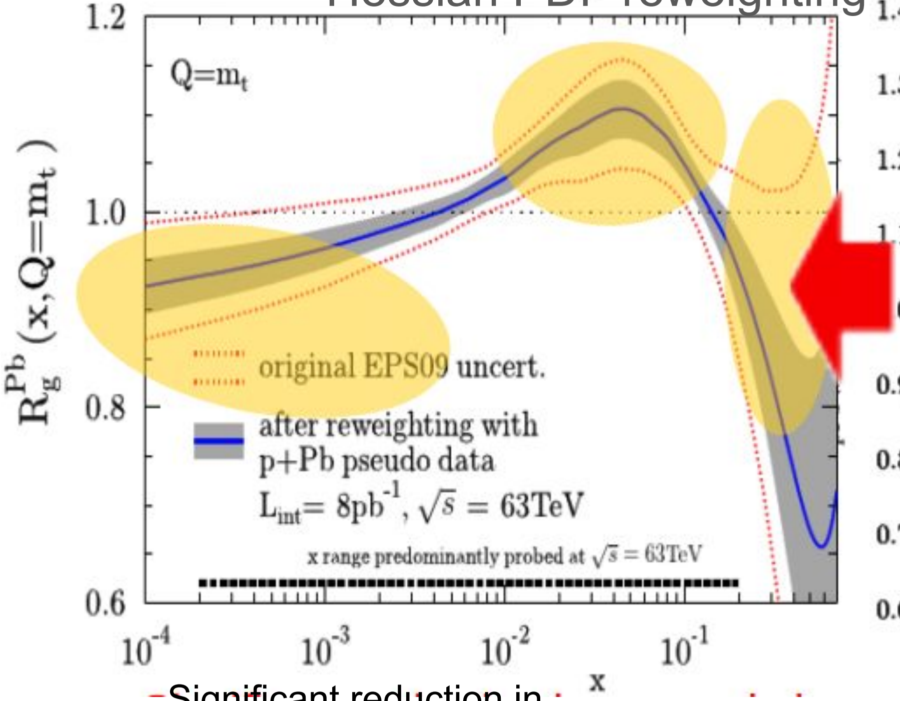






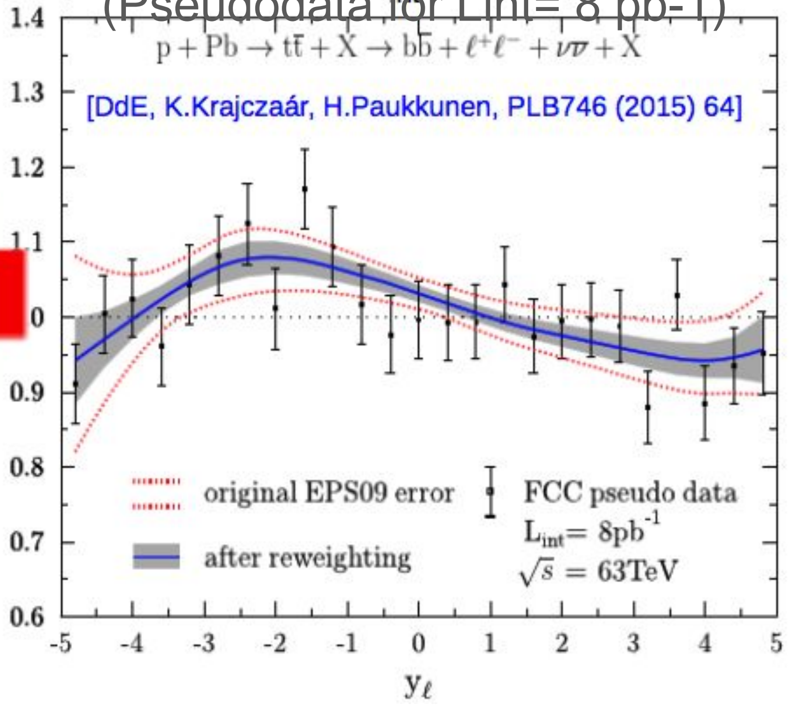
Top quarks

Improved gluon density via Hessian PDF reweighting

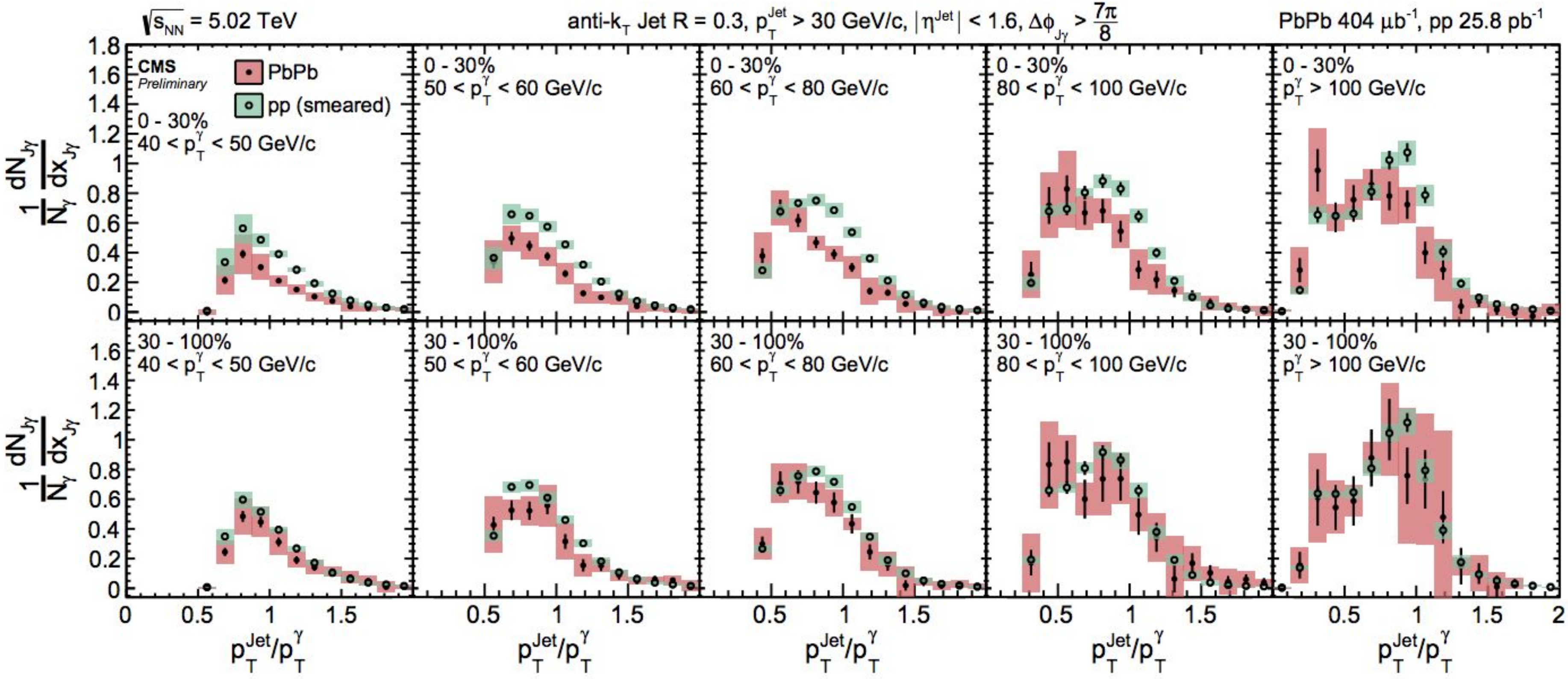


Significant reduction in uncertainties at low-x (x<10-2), antishadowing (x~0.05) and EMC (x~0.5) regions

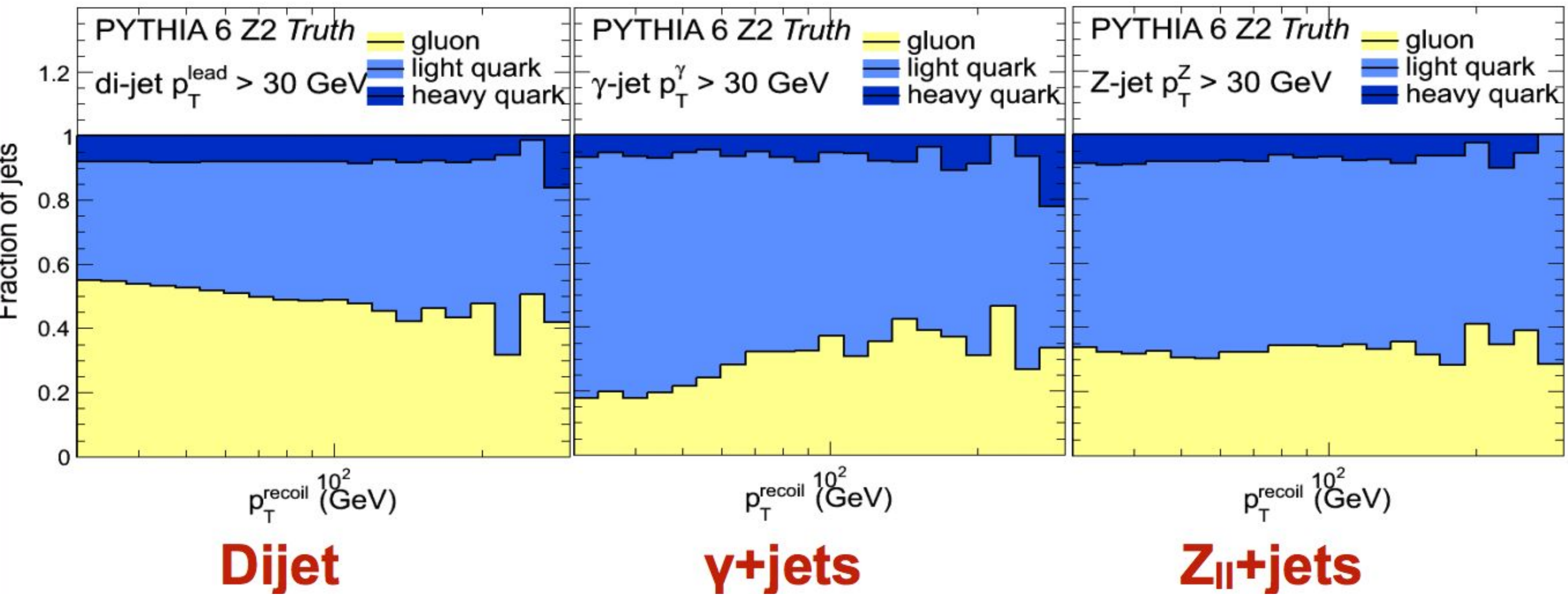
Isolated lepton y-distrib. after cuts: (Pseudodata for Lint= 8 pb-1)



nPDF effects (lepton): ±10% Strong constraining power


√sNN = 5.02 TeV
anti-kT Jet R = 0.3, pT Jet > 30 GeV/c, |ηJet| < 1.6, ΔφJγ > 7π/8
PbPb 404 μb-1, pp 25.8 pb-1
CMS Preliminary
PbPb
pp (smeared)
0 - 30%
40 < pTγ < 50 GeV/c
50 < pTγ < 60 GeV/c
60 < pTγ < 80 GeV/c
80 < pTγ < 100 GeV/c
pTγ > 100 GeV/c
30 - 100%
1/Nγ dNJγ/dxJγ
pTJet/pTγ

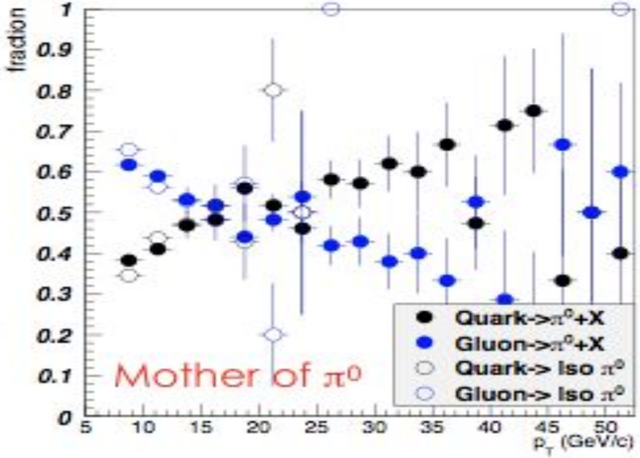
Quark and gluon jet fractions



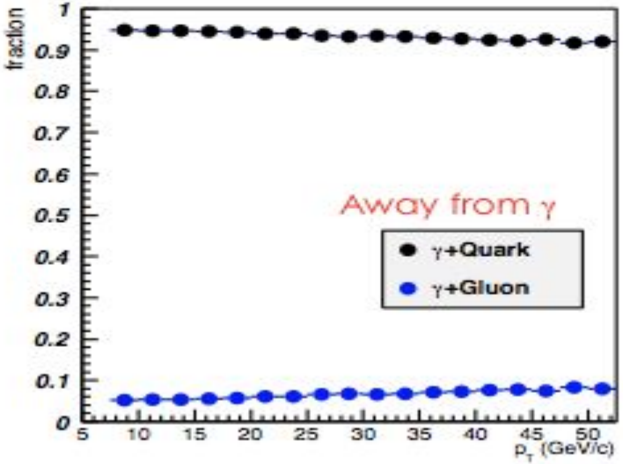
- Dijet has greater fraction of gluon relative to both boson+jets
- Z and γ + jets fraction comparable above 70 GeV, also to di-jet?
- Below 70, γ has greater fraction quark than Z

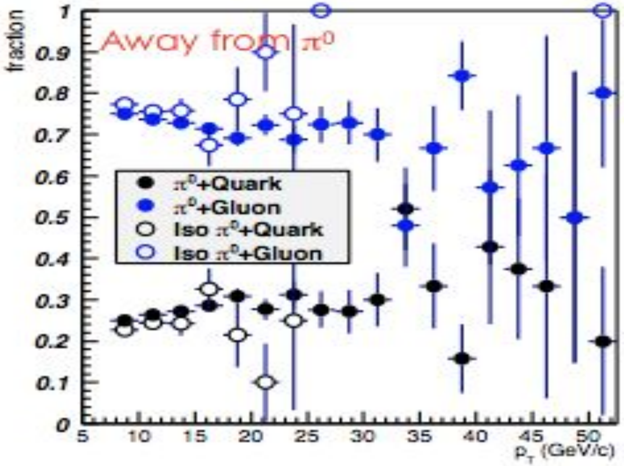
Particle-Parton correlation

- Hard π^0 (p_T > 25 GeV)
  - Mostly originated from quarks
- Prompt photons:
  - correlated with quarks > 90%
- π^0 (and frag photons)
  - correlated with gluons > 60 %, with and without isolation
- Frag photons originated from quarks only
- Isolation does not seem to favor the one or the other type of parton



pp @ 7 TeV





Inclusive vs b Jet RAA