Perspectives on jet measurements in heavy ion collisions

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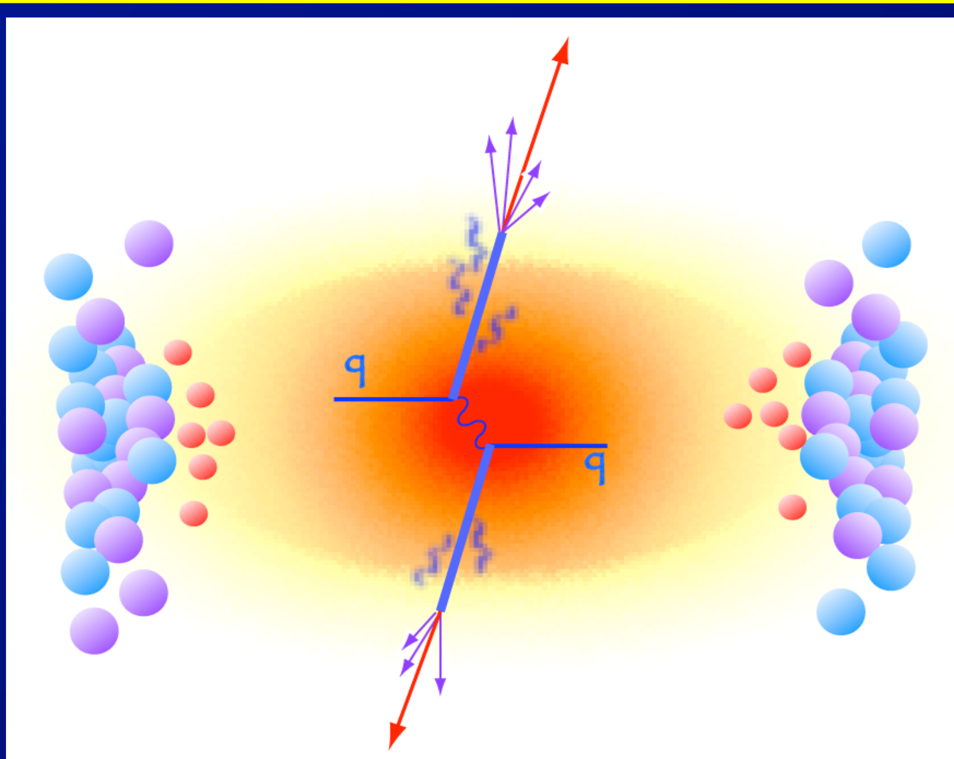
Aug 23, 2012

Thanks to the excellent talks by Gunther and Marco on Monday, this talk does not need to be and makes no pretensions of being comprehensive or complete .

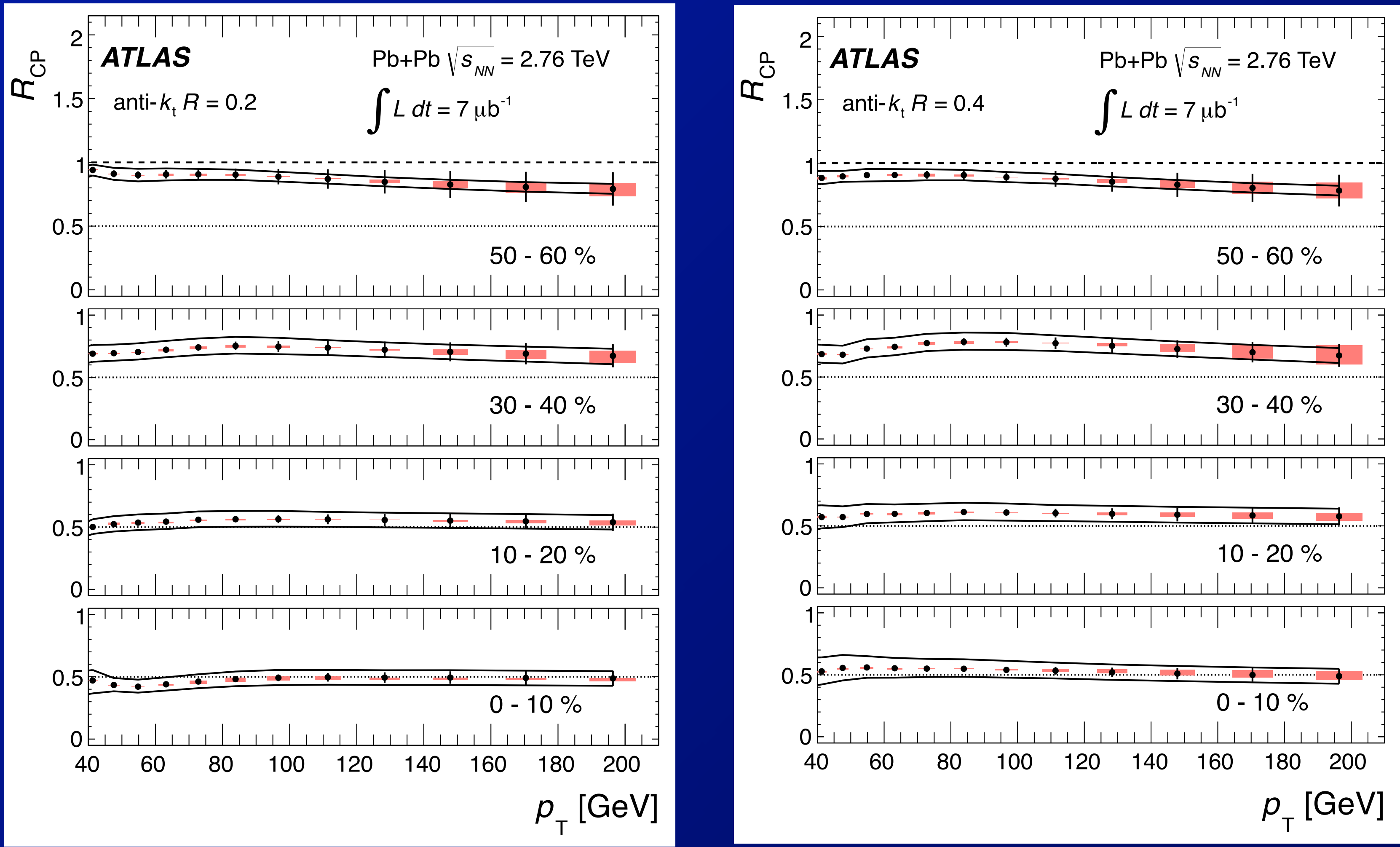
Some thoughts, questions

- How big are the surface biases when measuring inclusive or leading jets?
- How much of the "quenching" is due to average effects and how much is due to "fluctuations"?



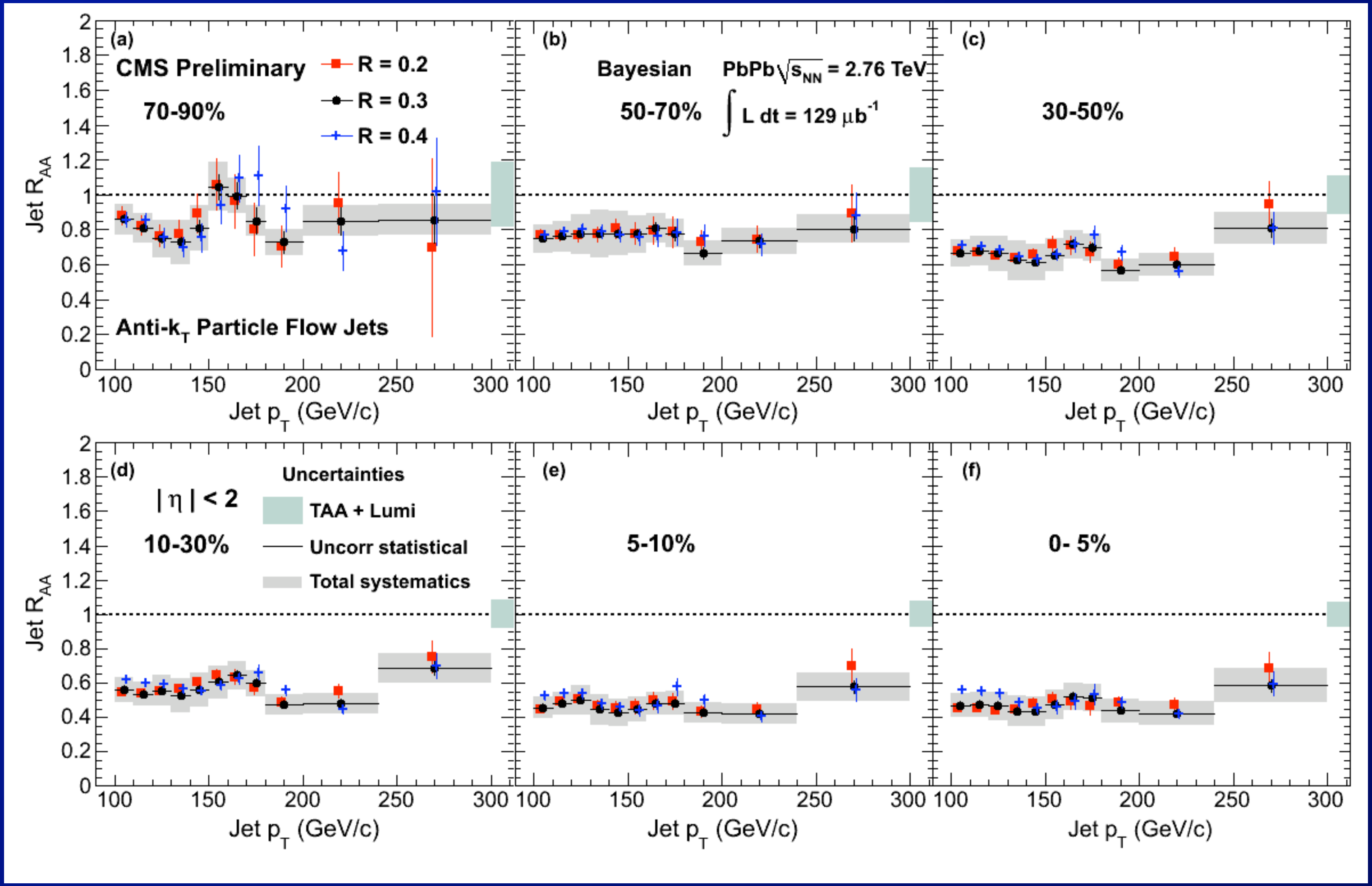
- Do we fully understand the implications of the dijet and γ-jet Δφ distributions?
- What are the experimental consequences of different quark & gluon quenching?

Inclusive jet suppression



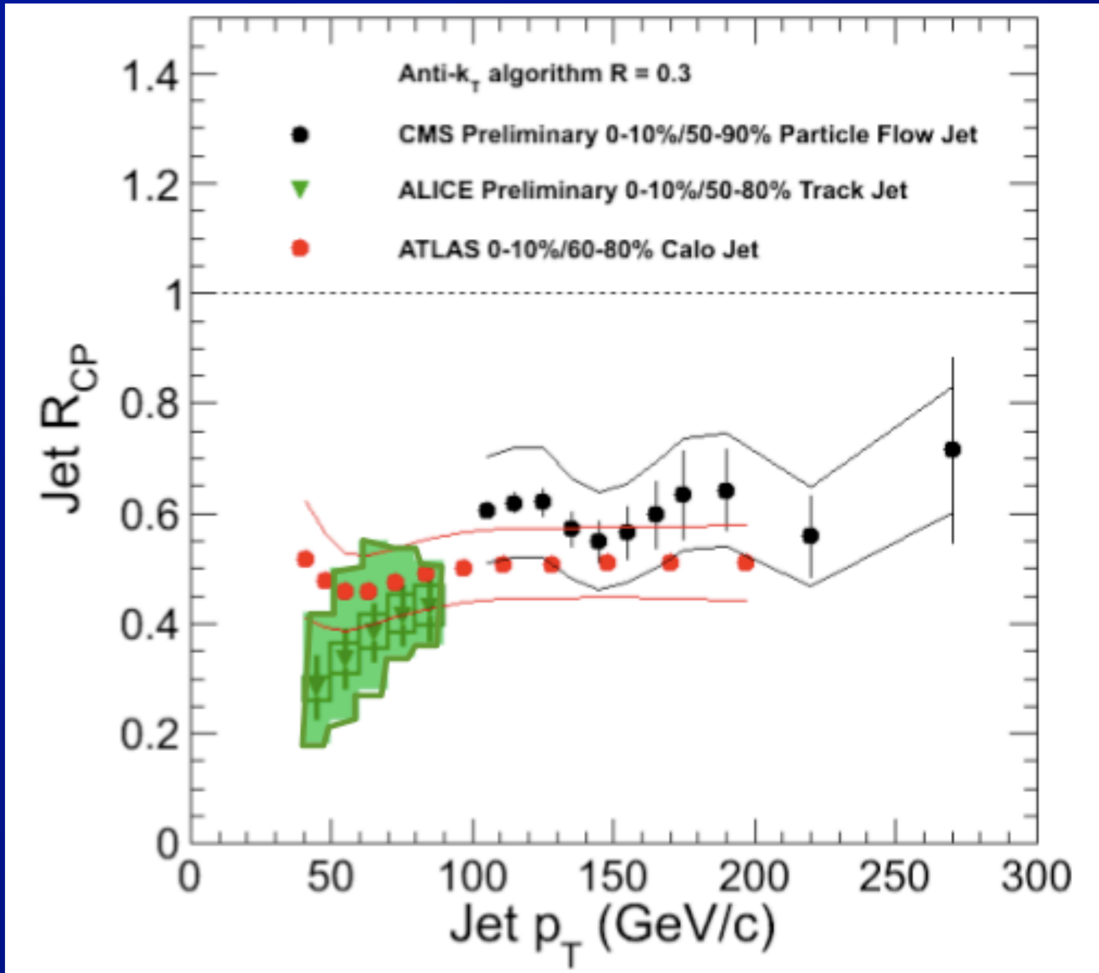
- At most weakly p_T dependent
- To zeroth order, not R dependent
- Take experimental errors seriously!

Inclusive jet suppression



- First results on jet R_{AA} @ LHC
  - ⇒ Consistent behavior with ATLAS R_{cp}

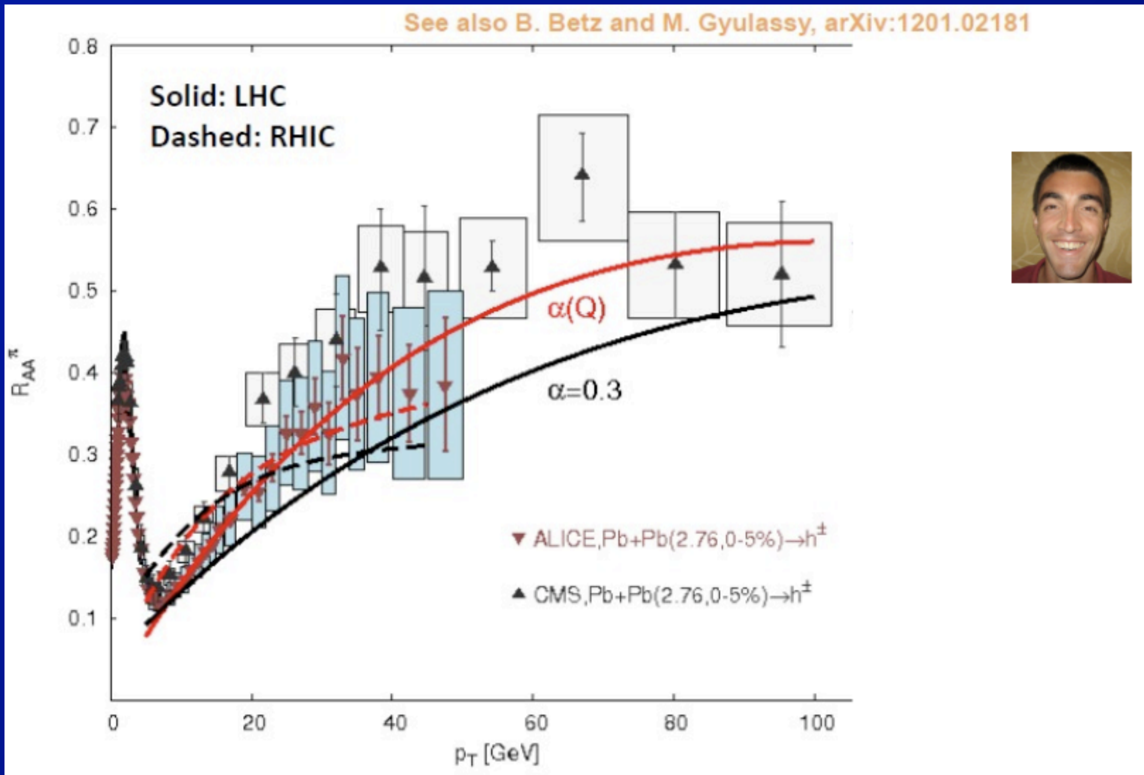
Inclusive jet suppression



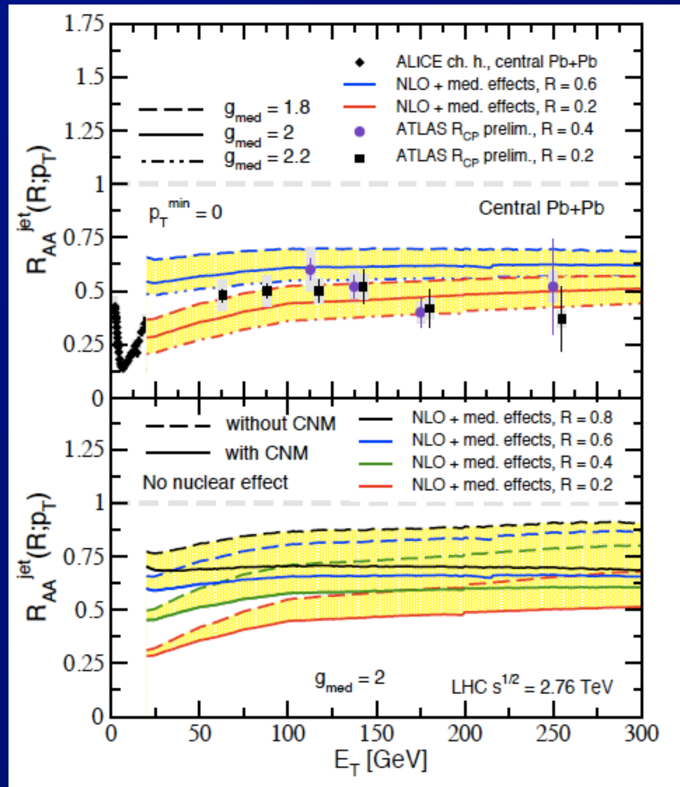
- If suppression is due to average jet ΔE
  - $\Rightarrow$ use $\langle \Delta E/E \rangle = 1 - R_{AA}^{1/(n-2)}$, $R_{AA} = 0.45$, $n = 5.5$
  - $\Rightarrow$ $\Delta E/E \sim 20\%$

Inclusive jet suppression

CUJet

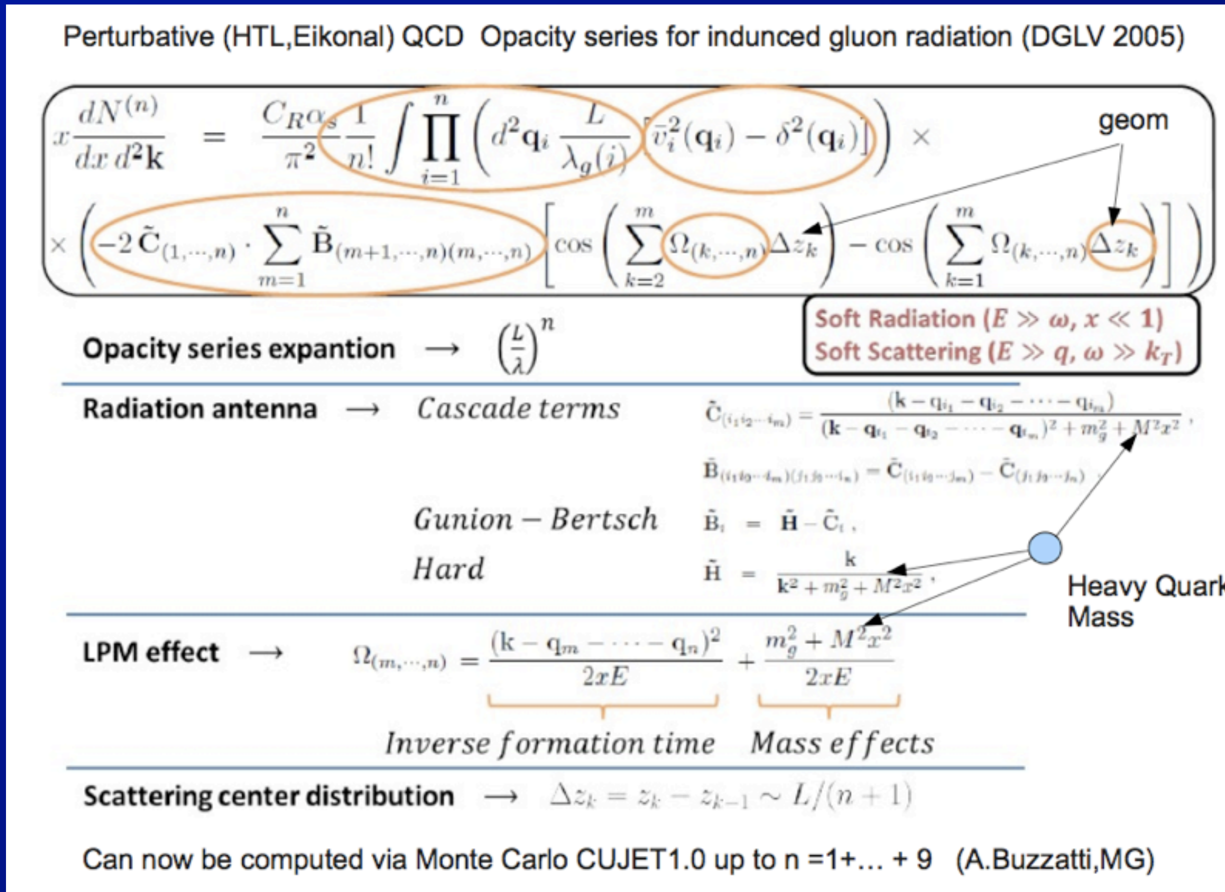


Vitev et al



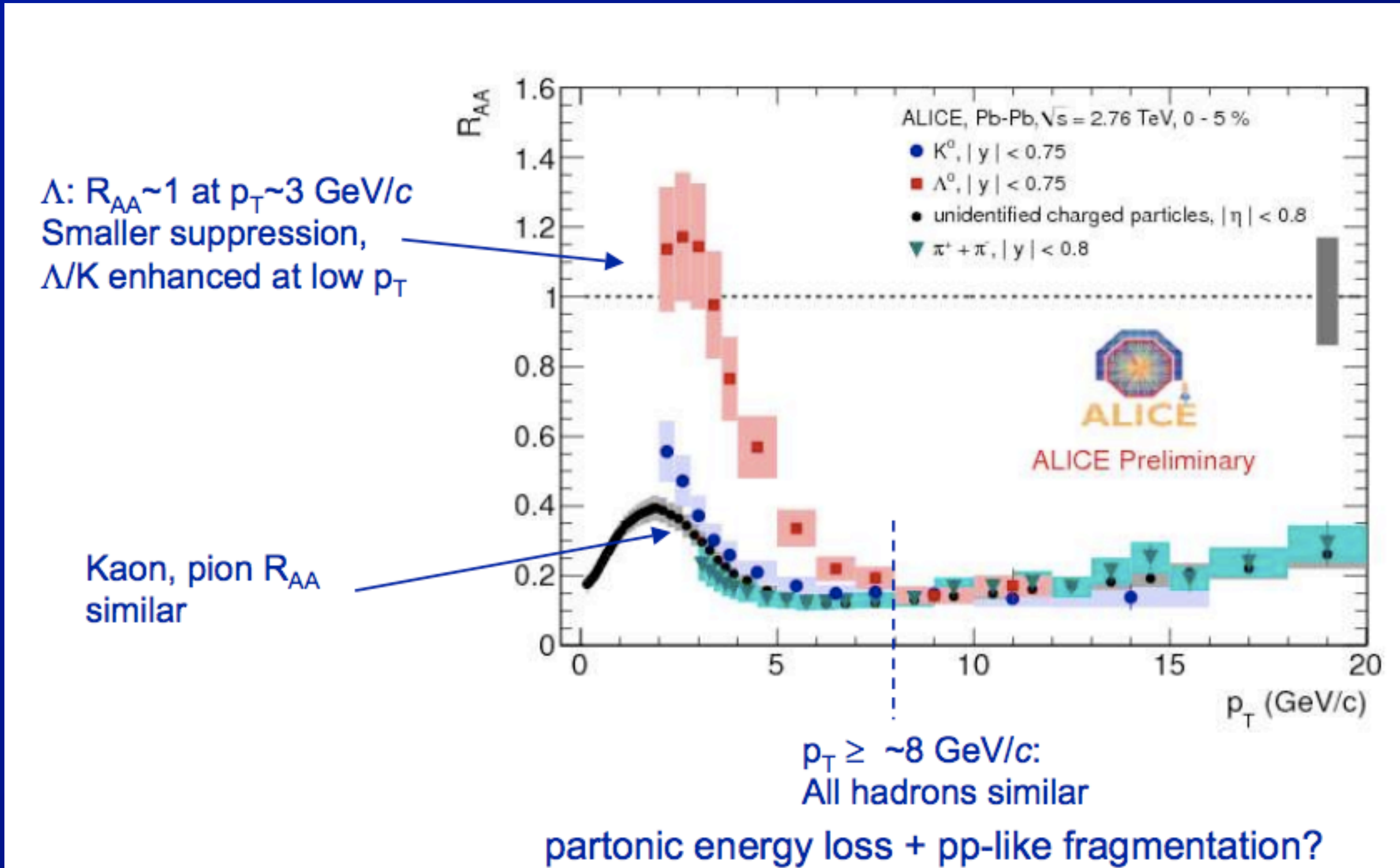
- p_T - independent suppression for p_T > 100 GeV is not what we expected prior to the measurement
  - Is the running coupling in CUJet the solution?
  - What flattens R_{AA} in calculations by Vitev?
  - Different p_T dependence of hadron, jet?

Inclusive jet suppression



- **Uncomfortable question to Miklos:**
  - How far up in p_T can we push GLV?
    - ⇒Parton shower vs single quark
    - ⇒Many vacuum emissions/splittings
    - ⇒Virtuality evolution -- how important?

Hadron R_{AA} : flavor dependence



- No (more) high-p_T flavor anomaly!
- What information is there to dig out of (light) flavor in jets?

History lesson

From my QM 2008 summary talk on high-pT measurements

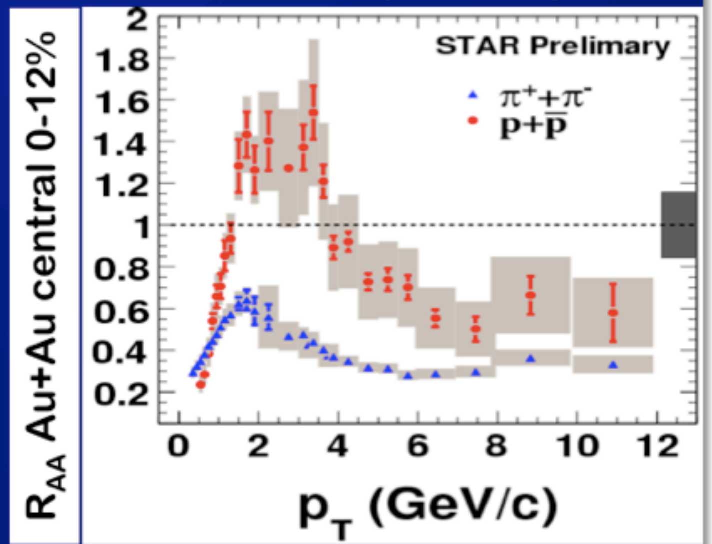
On the other hand …

- This result is very interesting:

$$R^{p}_{AA} > R^{\pi}_{AA}$$

- If protons more sensitive to gluon quenching than pions
  - Naively conclude that gluons lose less energy than quarks???
- Hard to imagine in any quenching scenario!
  - Proton D(Z) modified

From talk by Bedanga

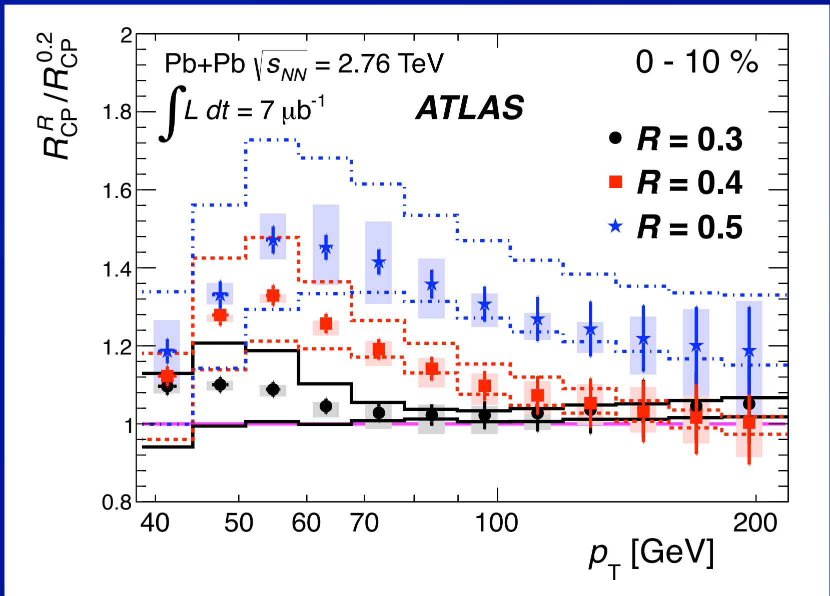


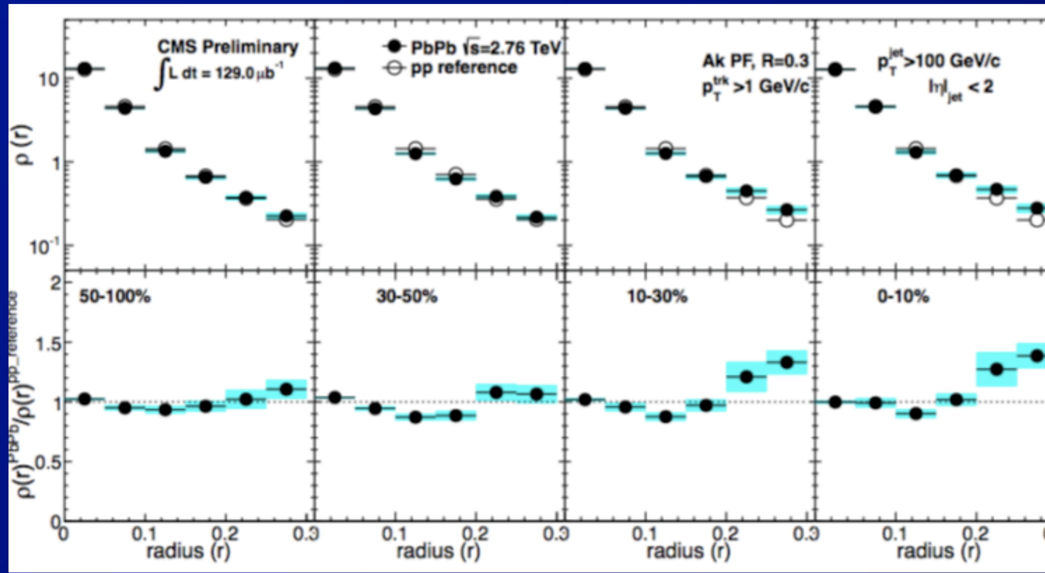
Yet another surprise from RHIC data – but I don't think we understand it yet.

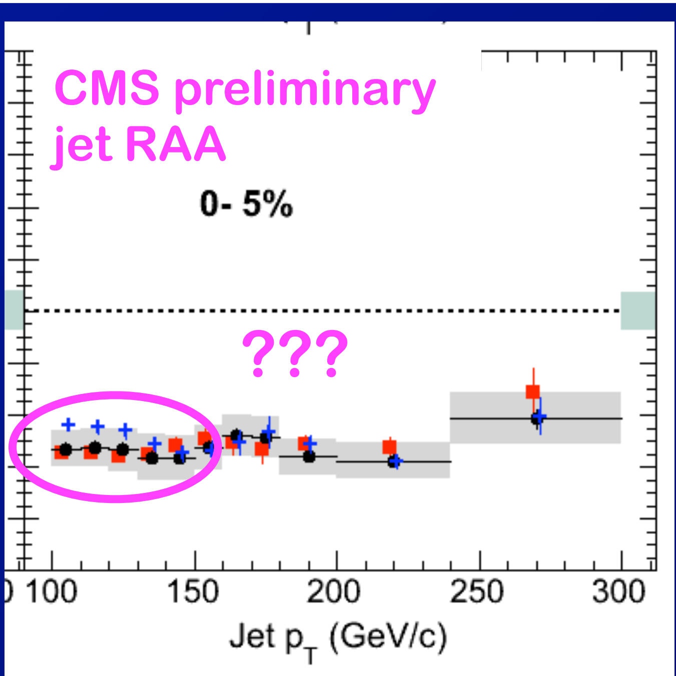
Stay tuned (esp. w/ more statistics)

- At QM08 it was argued quenching didn't follow expectations based on pQCD color-factors …
  - Here is at least one example of Miklos' desire that uncomfortable data go away.

Jet size dependence/broadening



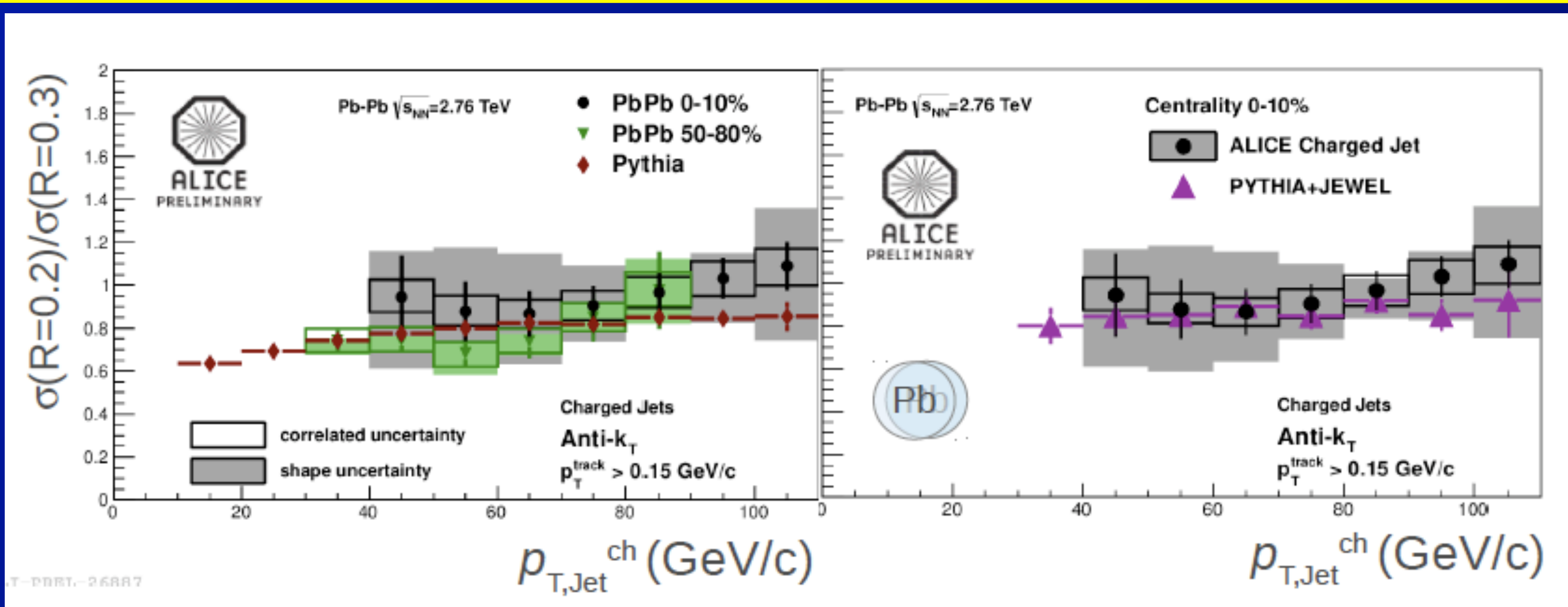


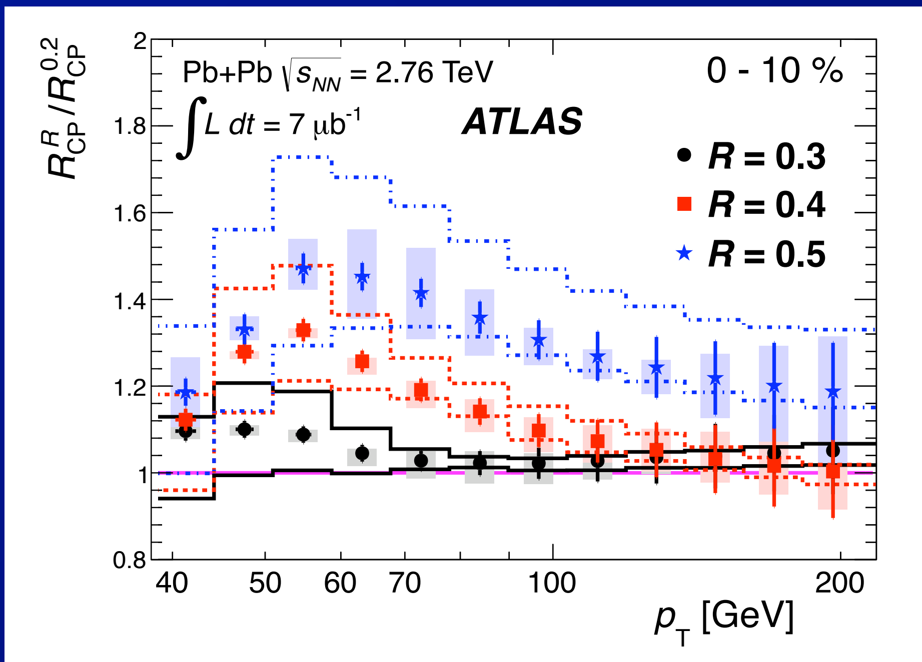


- Multiple indications of broadening of jet
  - But not yet clear that they are consistent (TO DO).
  - Encourage CMS & ALICE to go to larger R, evaluate R_{AA}/R_{cp} ratios canceling common syst.

⇒But profile also necessary

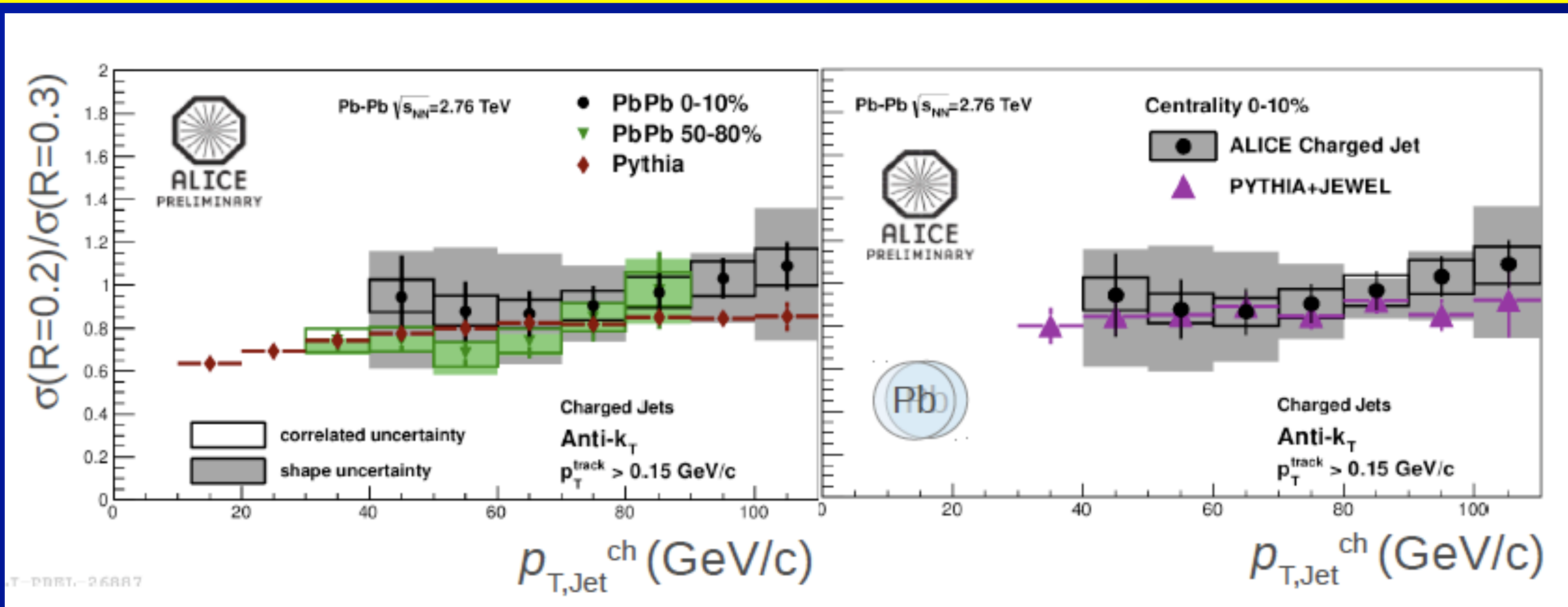
Consistency re: jet broadening?

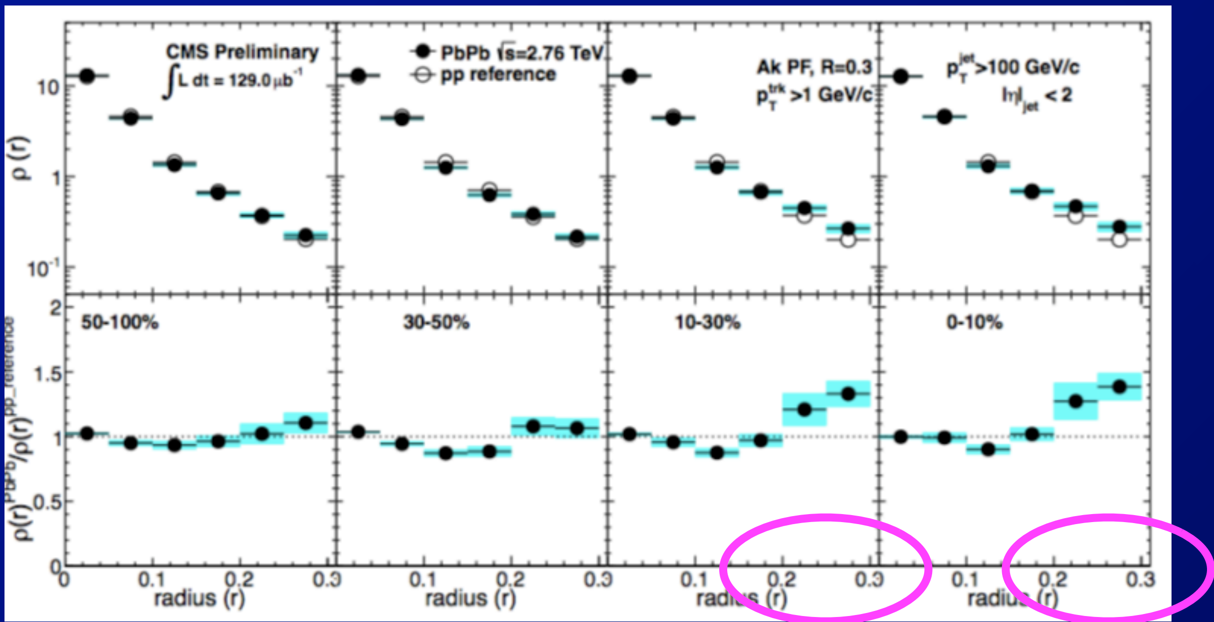




- ATLAS, CMS, and ALICE all agree that R = 0.2, 0.3 suppression difference <~ 15%

Consistency re: jet broadening?

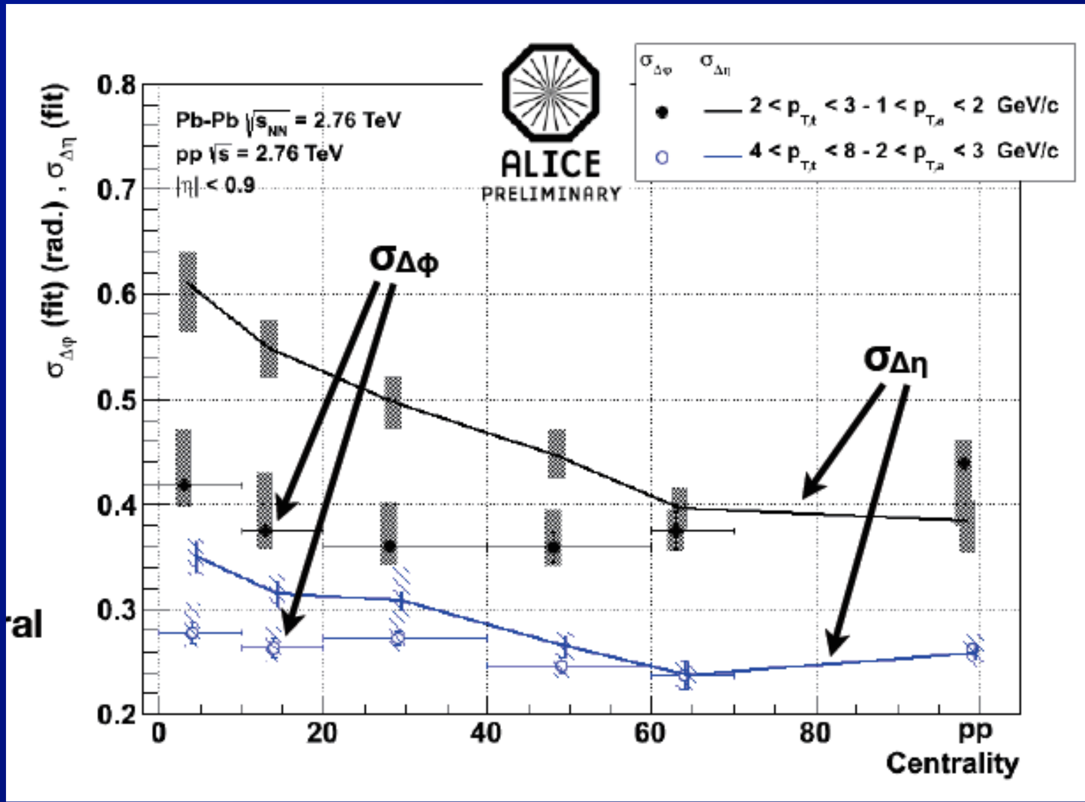




- Detailed quantitative consistency check required.

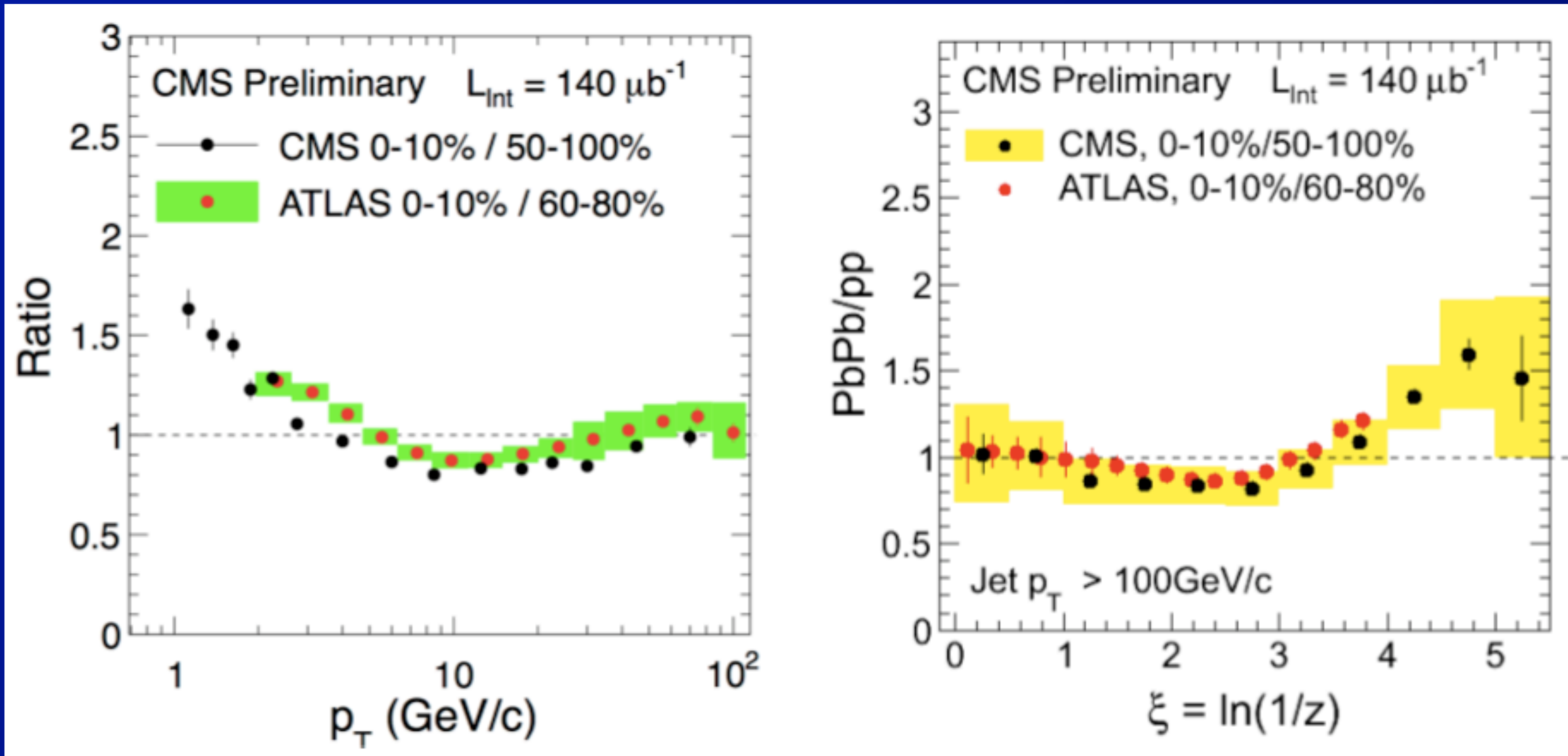
Jet size dependence/broadening

dihadron "near-side" correlations, width in Δη and Δφ



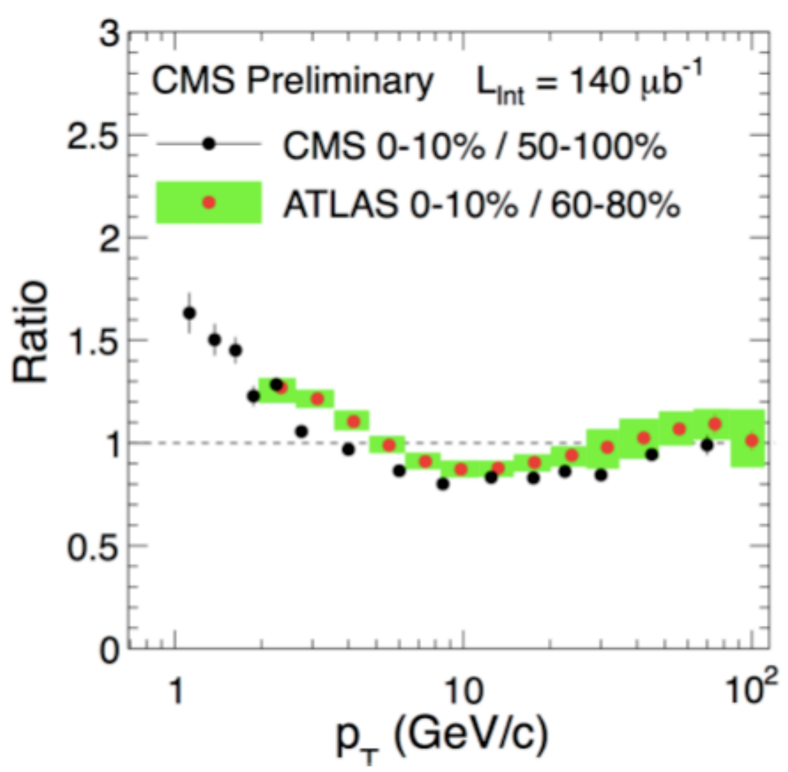
- ALICE observes broadening in η but not φ
  - Is this really due to jets?
    - ⇒If so, radial profiles not sufficient
    - ⇒And jet suppression should depend on R
      - » How much?

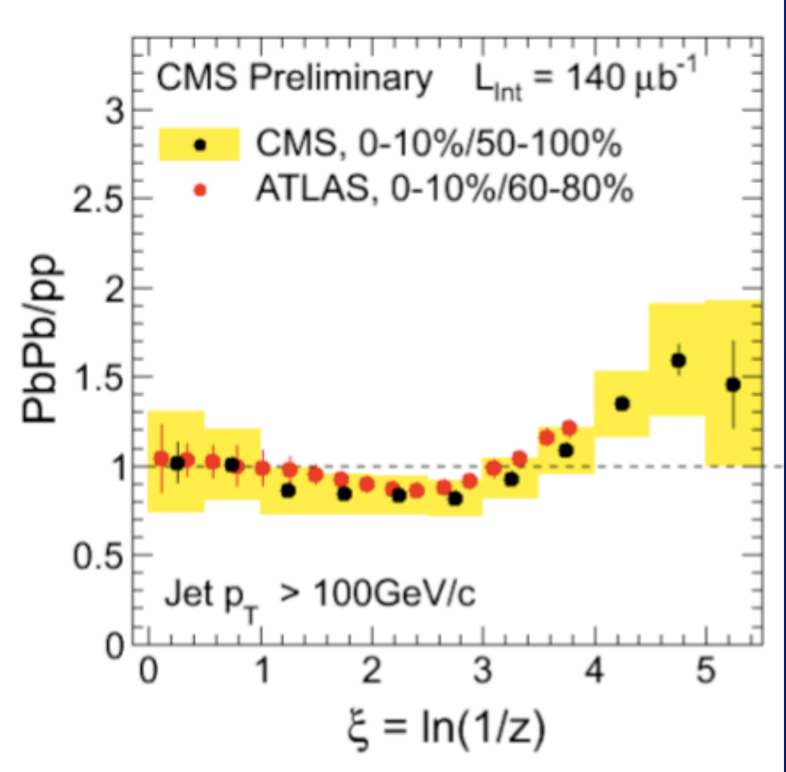
Inclusive jet fragmentation



- Unambiguous observation of modifications in measured jets
  - We are not only observing what's left over after everything else has been quenched.
    - ⇒But, what fraction of jets are modified?
    - ⇒How much variation jet-to-jet?

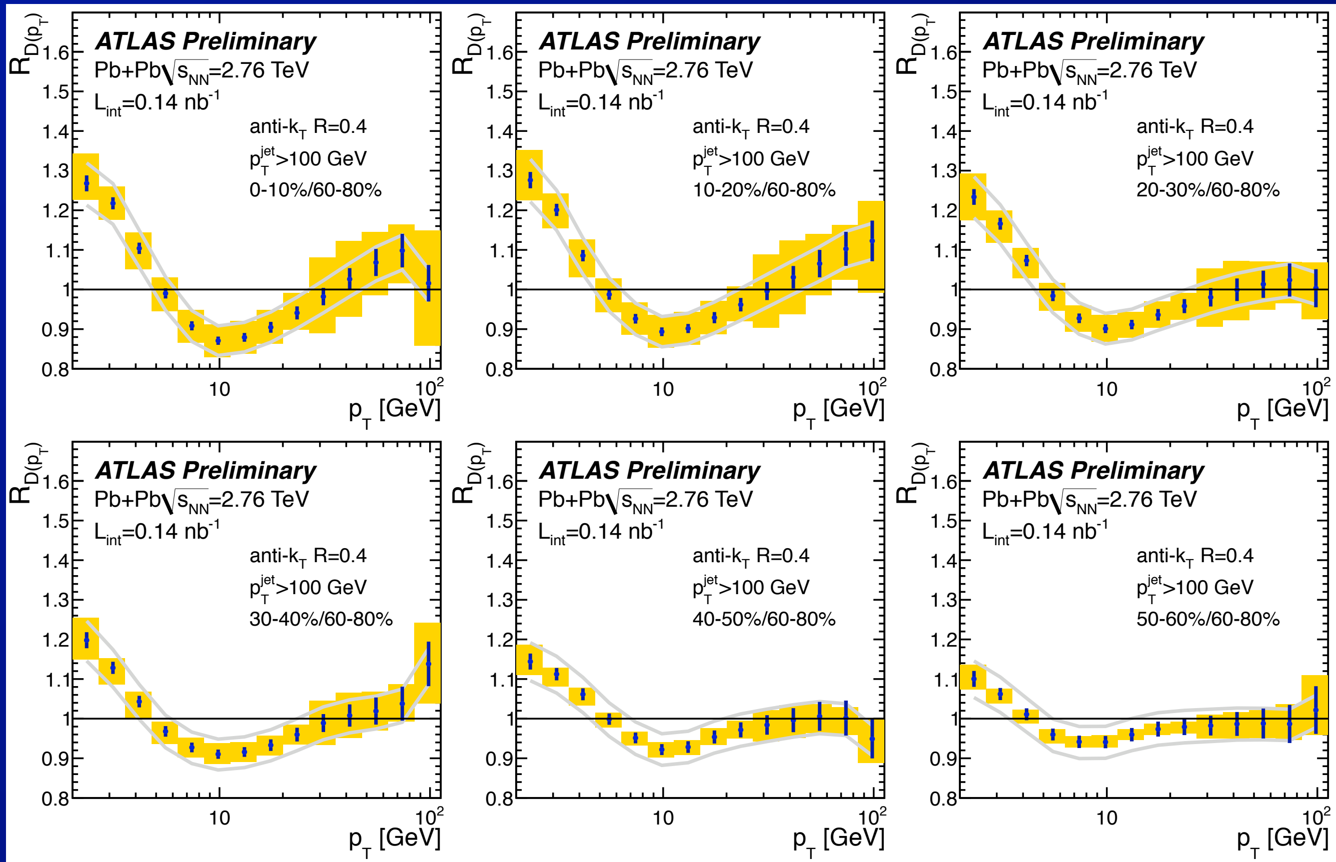
Inclusive jet fragmentation





- **First direct handle on the p_T dependence of modifications of the parton shower.**
  - ⇒**Important to determine whether modification is p_T or z dependent.**
  - ⇒**How to determine whether low-p_T enhancement is from PS or from medium?**

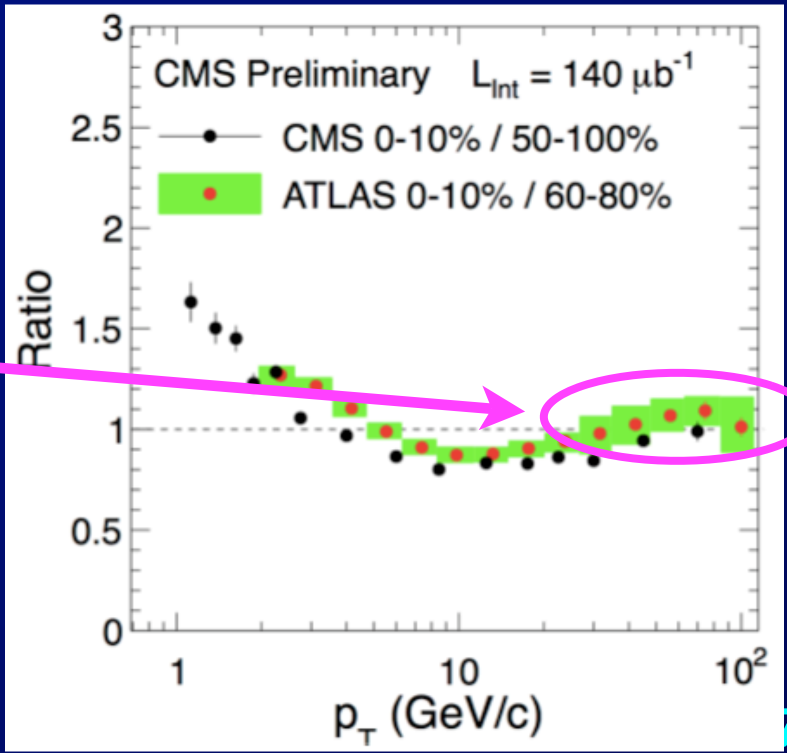
Inclusive jet fragmentation



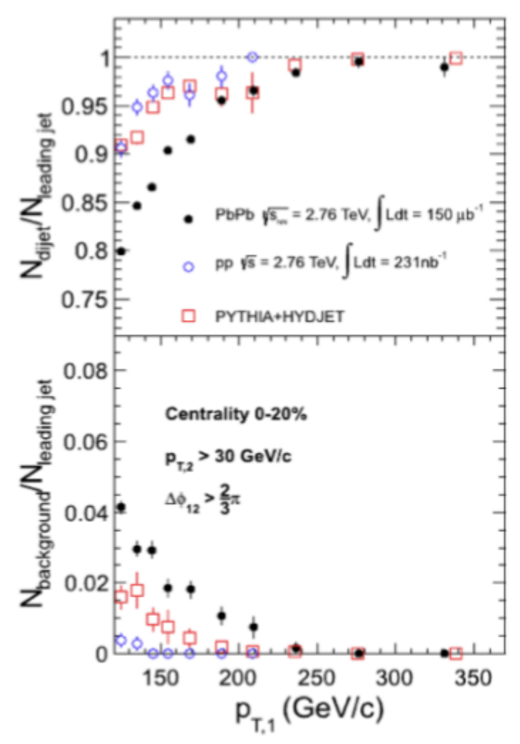
- Is it obvious that the p_T or z scale of the modification should be centrality independent?
  - In my opinion, not obvious.
    - ⇒Naively, both energy loss or collimation effects should depend on L (centrality)

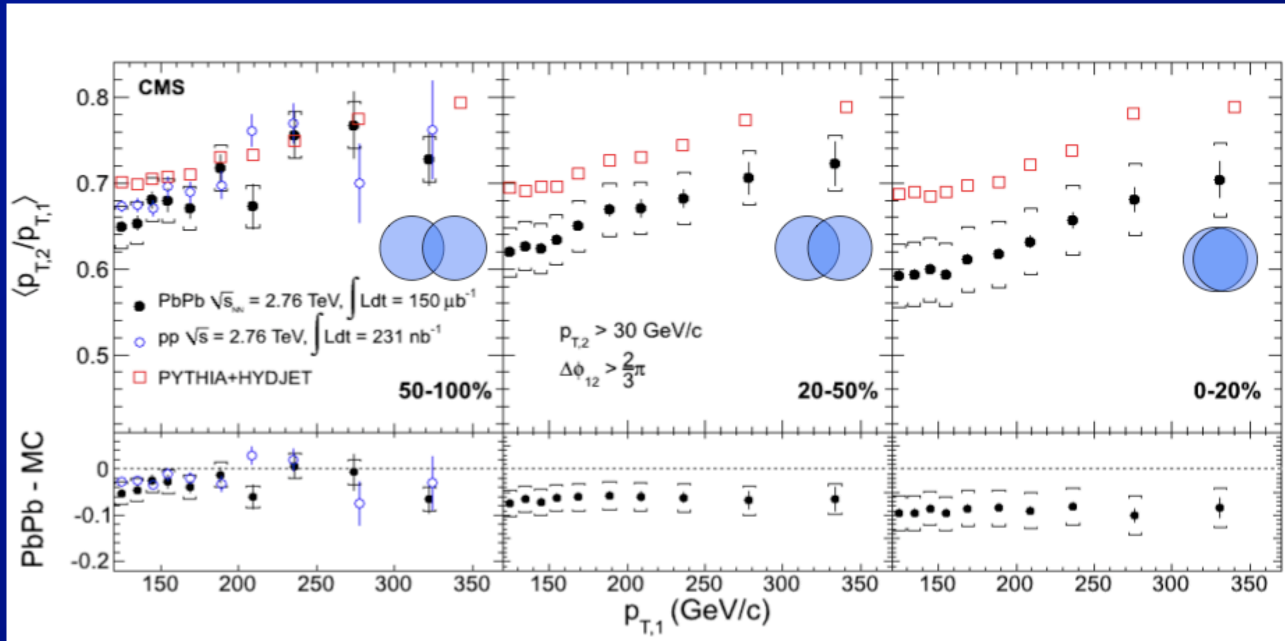
Inclusive jet fragmentation

- What are the consequences of using quenched jet p_T for fragmentation?
- A simple toy model:
  - Jet loses energy via collimation.
    - ⇒Modes (hadrons) with $p_T > x$ are unaffected.
    - ⇒Jet energy is reduced
- This toy model would yield an ENHANCEMENT in $D(p_T)$ or $D(z)$ for $p_T > x$ when using reduced jet energy.
    - ⇒Critical to control
- Are we seeing at large z Kopeliovich's pre-hadrons?
    - ⇒Can they survive QGP?



Dijets: CMS 2011 data





- If I understand the content of the plots:
  - 80% of leading jets have a partner @ 125 GeV
  - fraction decreases w/ increasing p_T
  - The missing pairs are not in $<p_{T2}/p_{T1}>$
    - ⇒So is the "true" $<p_{T2}/p_{T1}>$ more strongly dependent on leading jet p_T?

Fragmentation functions?!

Fragmentation functions

- Distribution of associated track p_T in cone, relative to measured jet p_T
  - plot $Z = p_{T,\,track}/p_{T,jet} \cos(\Delta R)$, $\xi = \ln(1/z)$ and track p_T
  - **No direct connection to parton p_T at scattering**

F. Abe et al., "Jet-fragmentation properties in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV", *Phys. Rev. Lett.* **65** (1990) 968, doi:10.1103/PhysRevLett.65.968.

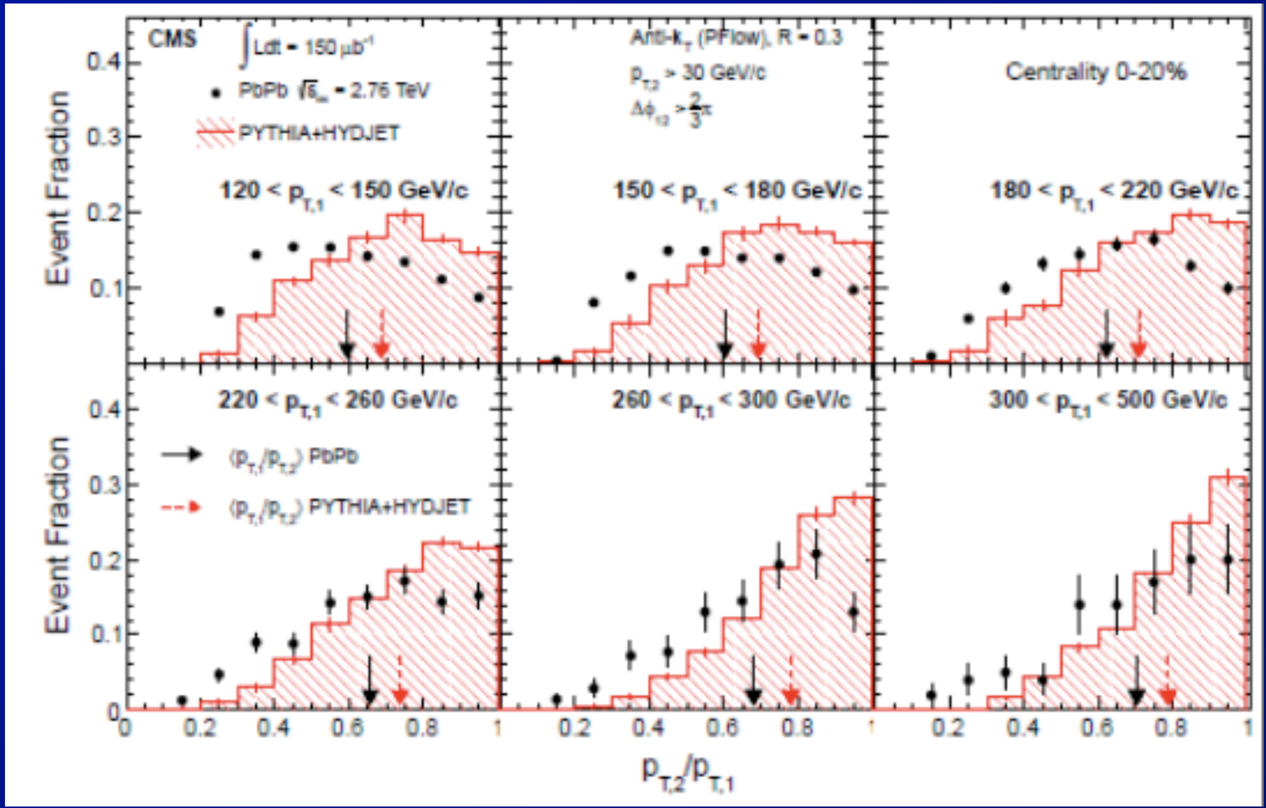
- VOLUME 65, NUMBER 8 PHYSICAL REVIEW LETTERS

Leading-order QCD calculations agree very well with measurements of jet production in proton-antiproton collisions over a large center-of-mass energy ($\sqrt{s}$) range.[1,2] The transformation of outgoing quarks and gluons into jets of hadrons should also be described by QCD, but the hadronization process involves nonperturbative effects which prevent quantitative predictions. The distribution of the jet momentum among charged hadrons is described phenomenologically by the fragmentation function $D(z) = (1/N_{jets})dN_{charged}/dz$, where we define $z = P_{\parallel}/|\mathbf{P}_{jet}|$, with $P_{\parallel}$ being the momentum component of a hadron along the axis of a jet with momentum $\mathbf{P}_{jet}$.

Jets are defined as
which are found witl
The cluster energy is
cone of radius $R \equiv$ (
about the cluster cen
as the vector sum of
were applied to obta
from the cluster qua
the CTC, an energy
+30% is applied to e
the nonlinear calorim
the magnetic field c

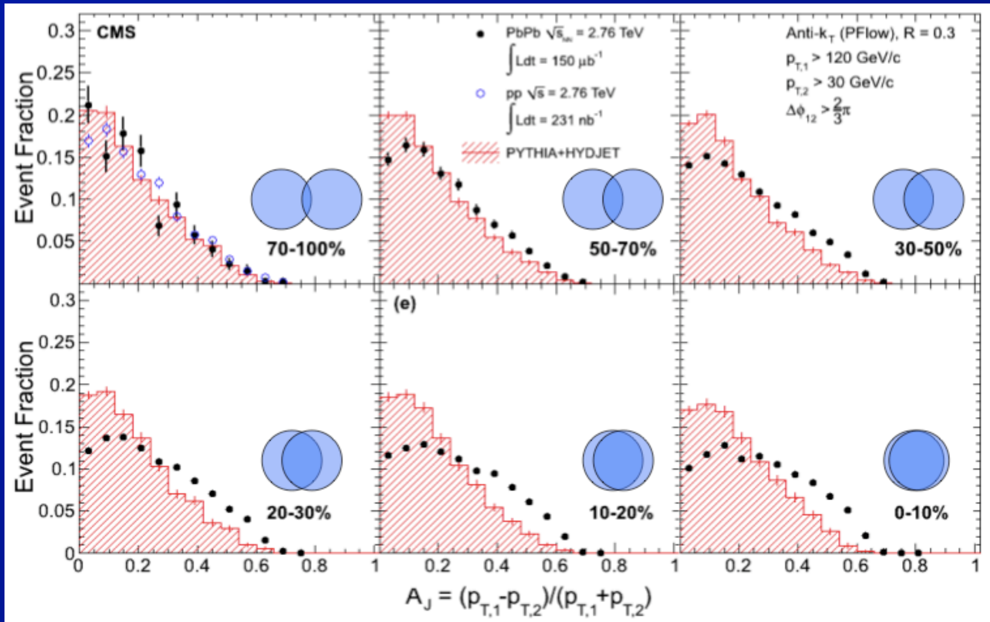
- Gunther took the words out of my mouth.

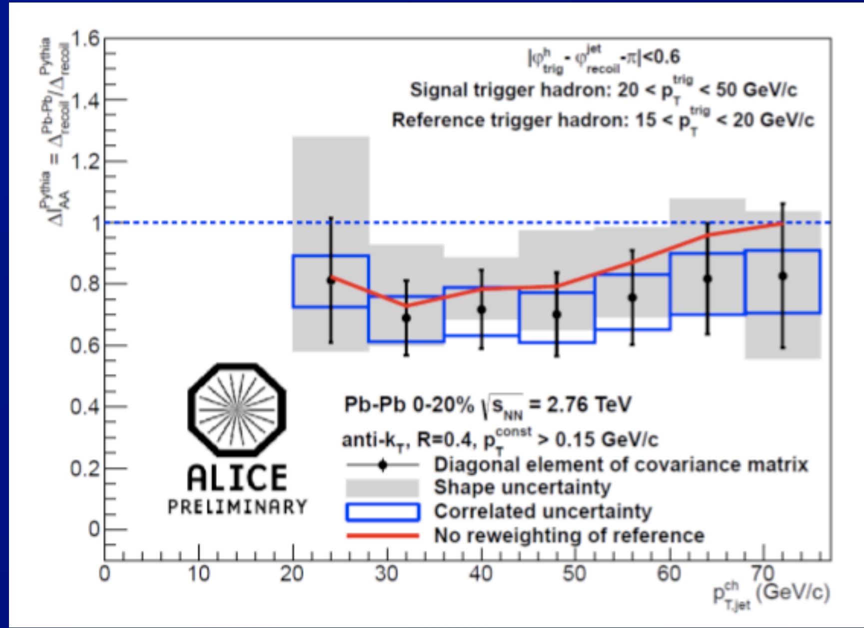
Dijets: CMS 2011 data



- Clear demonstration that the effects of differential quenching extend to high p_T
  - what is role of jet flavor (quark, gluon, heavy)?
    - ⇒In particular, gg vs qg.
    - ⇒Experimental handles?

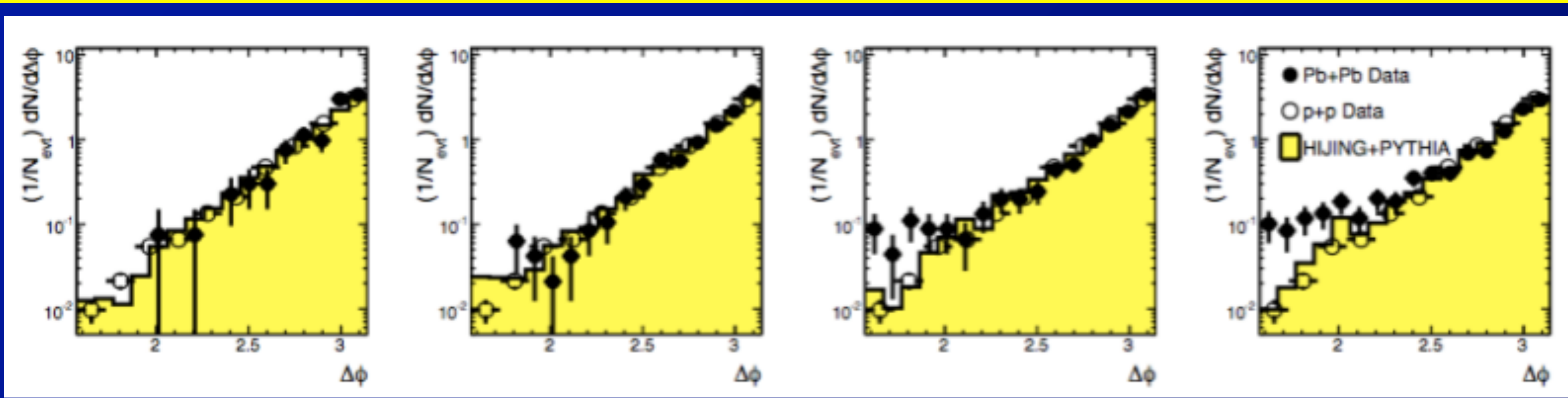
hadron-jet vs dijet?

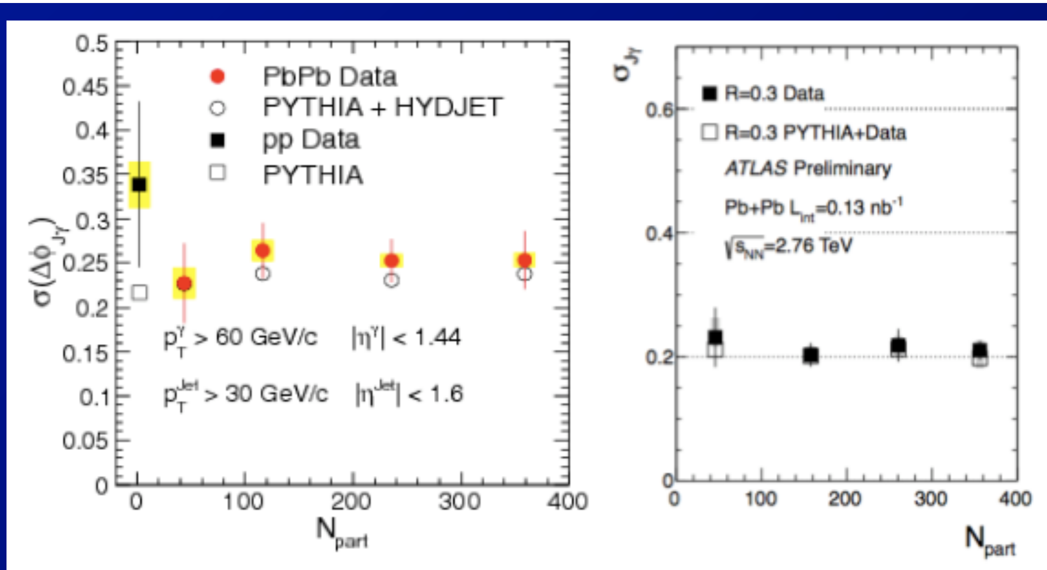




- Assuming that leading jet and the trigger hadron have similar bias, these don't look consistent
  - But, Torsten says the hadron is more surface biased than jet
    - ⇒So shouldn't the effects on balance jet be even greater?
      - » Due to the (relatively) low hadron p_T?

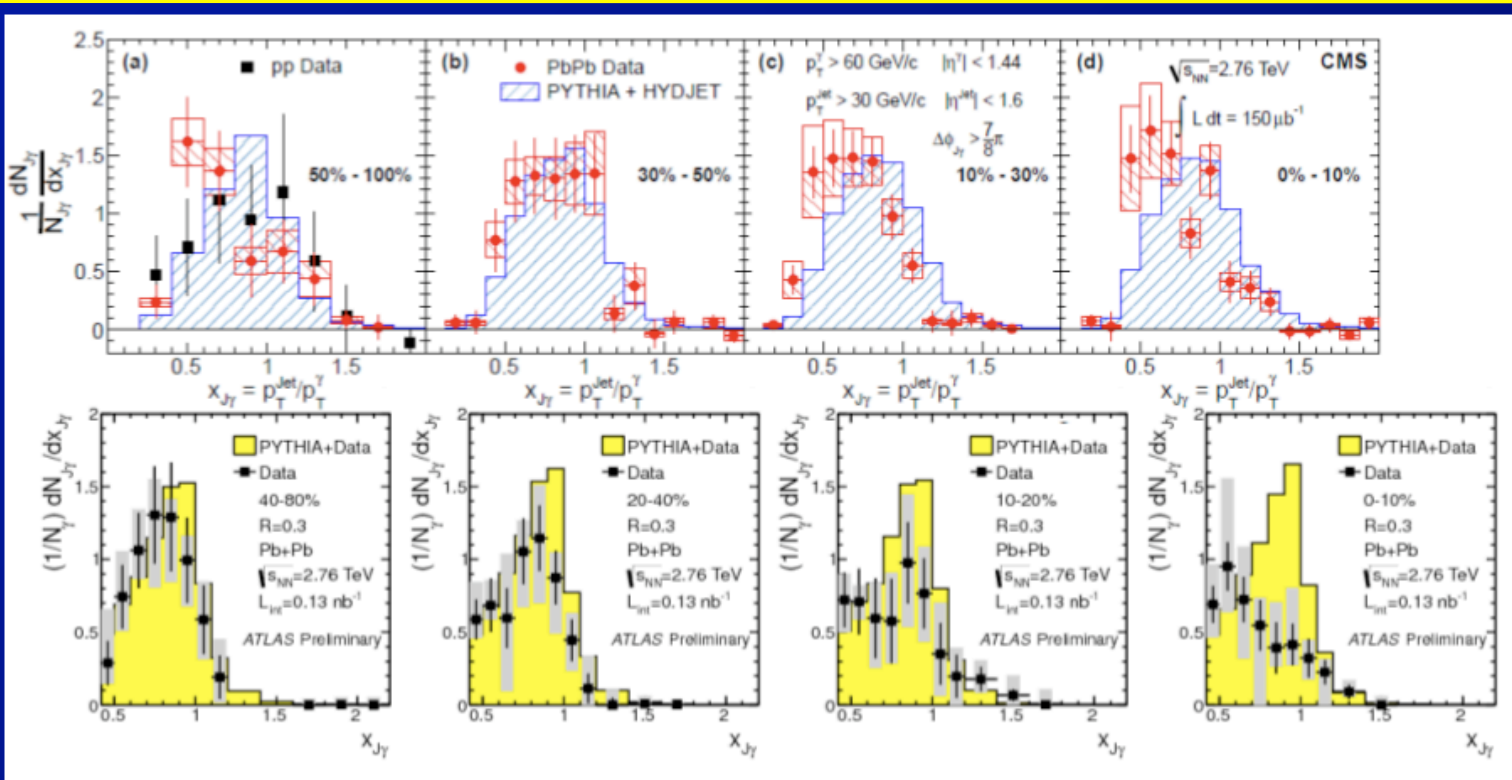
Dijet (and gamma-jet) acoplanarity





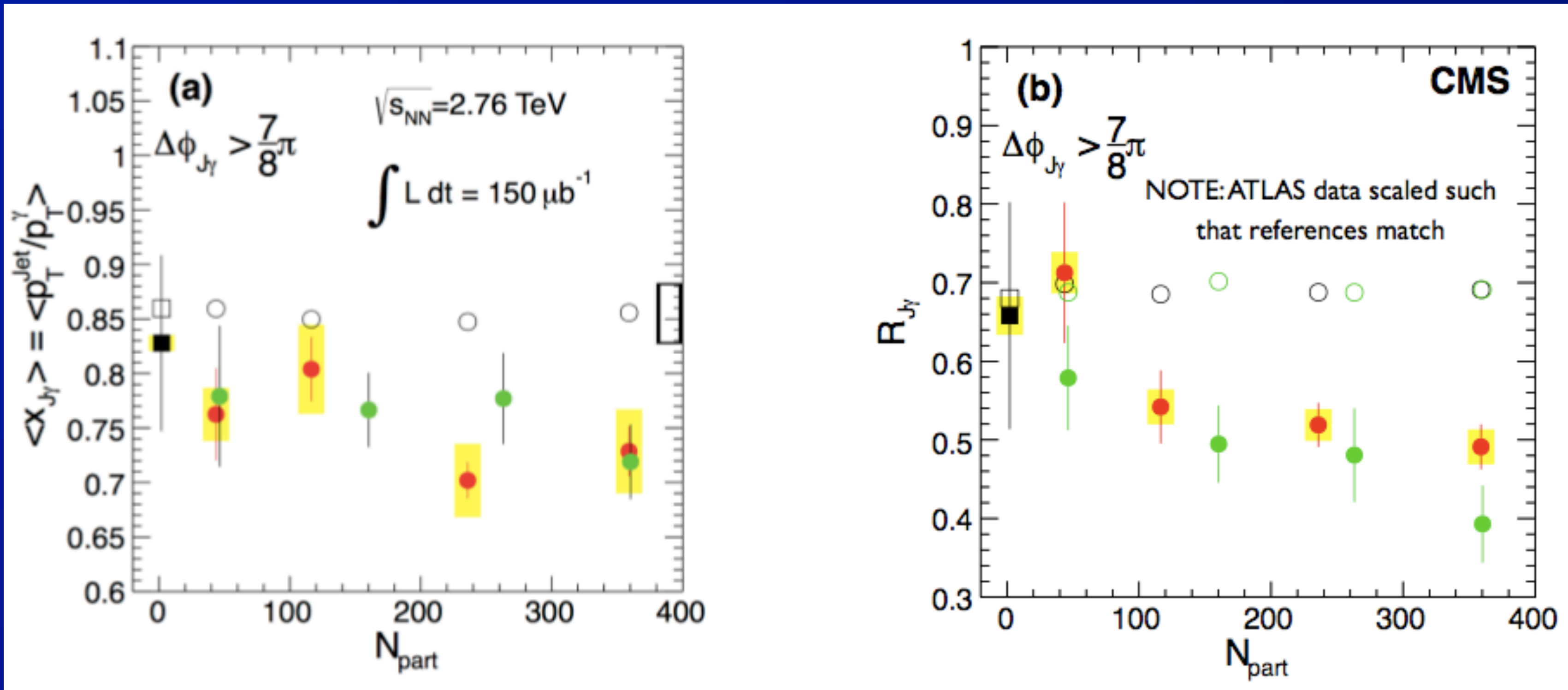
- **Stringent constraint on theory.**
  - Want to see calculations using GLV, ASW, HT, JEWEL, YAJEM, … of either dijet acoplanarity or k_T
    - ⇒No ostriches!

Gamma-jet



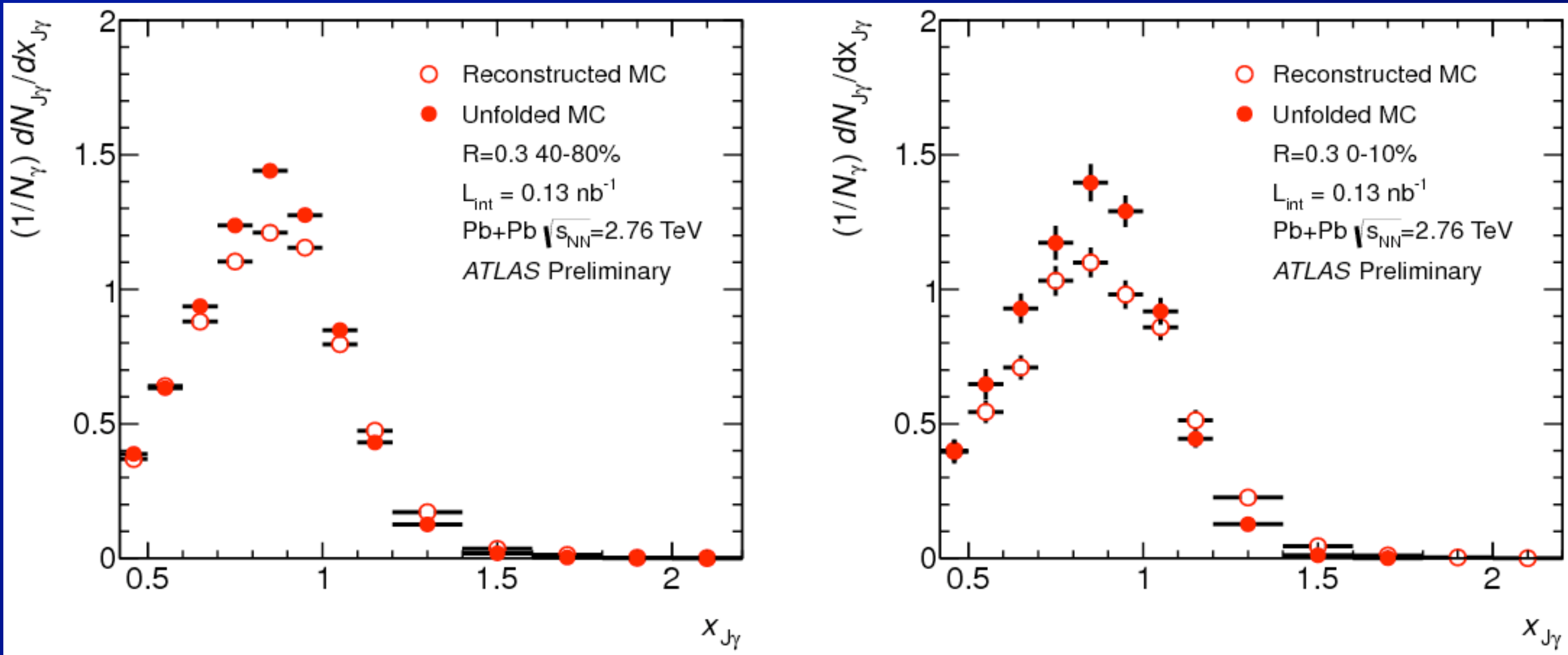
- One difference wrt dijet:
  - ⇒jets ~ 90% quark jets
  - ⇒But still see large quenching effects
- Is this result consistent with a 20% average reduction in jet energy (from jet R_{AA})
  - ⇒Especially considering flavor …

Gamma-jet



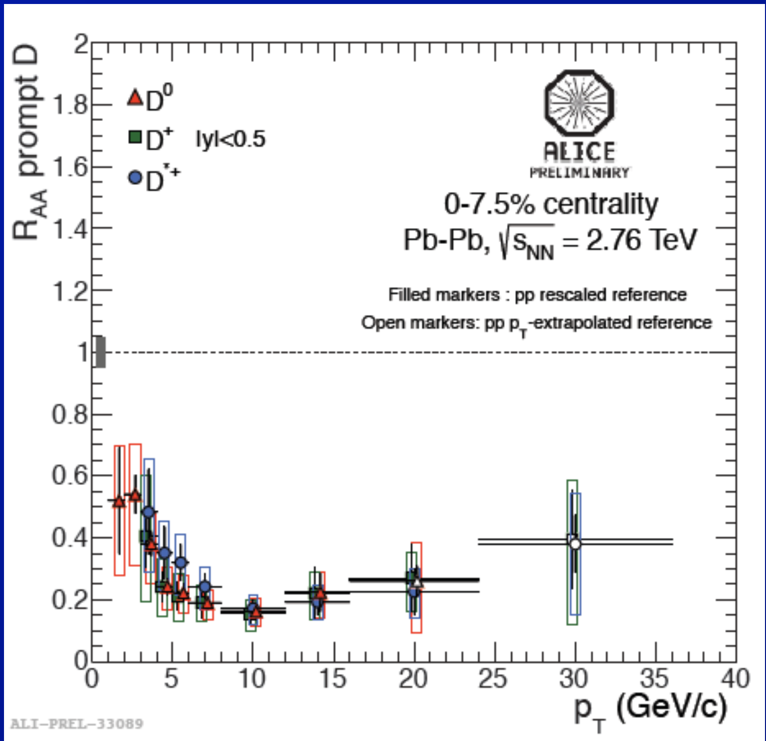
- Compared to dijet results:
  - Comparable shifts in <xj> and greater reduction in balance jet yield?!
    - ⇒But not an apples-to-apples comparison
    - ⇒Can we choose closer photon and leading jet p_T ranges to do better?

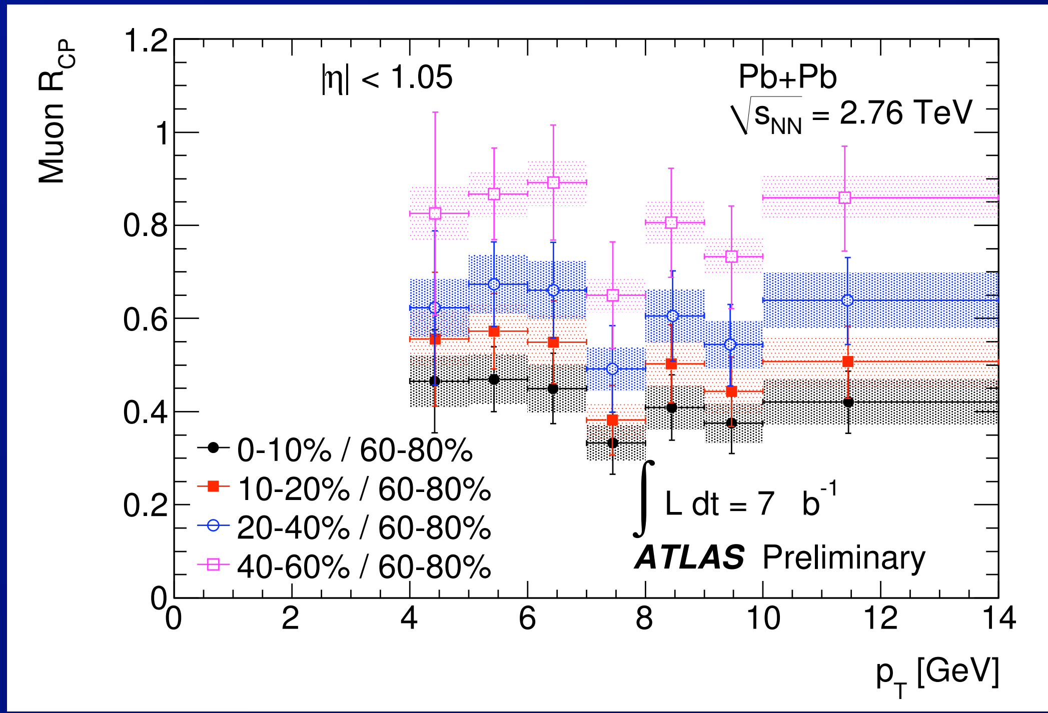
Gamma-jet truth x_J

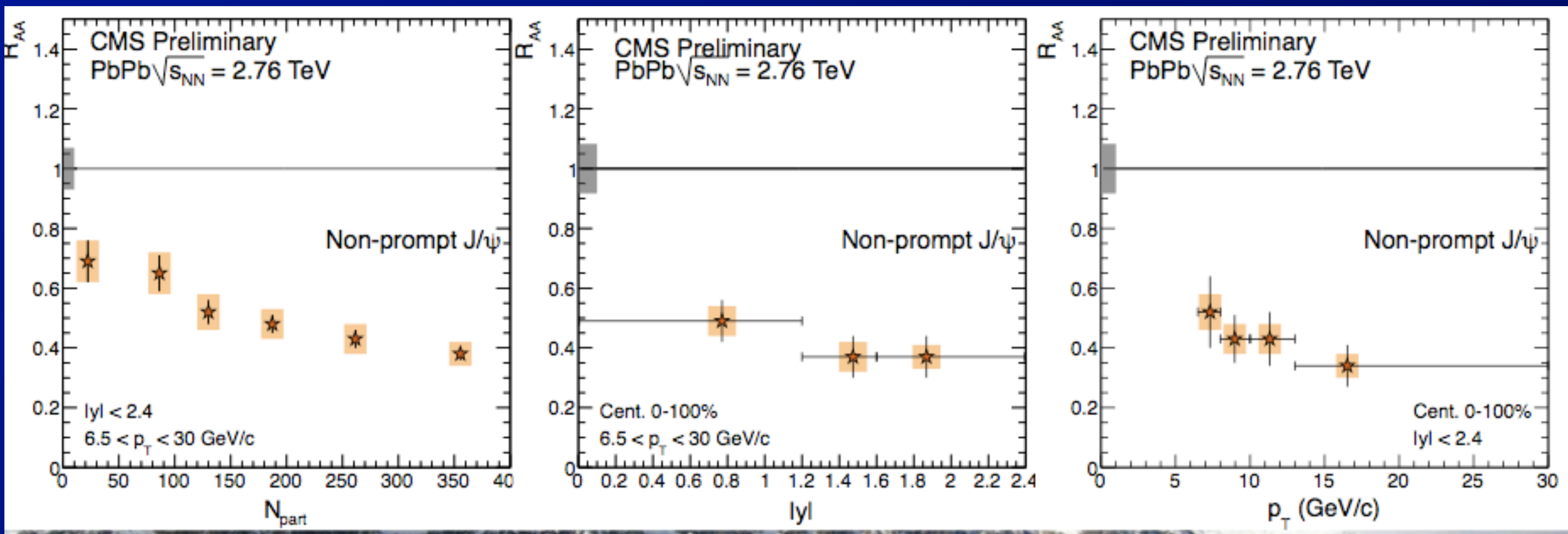


- Truth gamma-jet x_J distribution quite broad for photon p_T in [60,90] GeV
  - Includes back-to-back requirement
    - ⇒Beware assumption that photon “calibrates” the balance jet energy.

Heavy flavor @ moderate p_T







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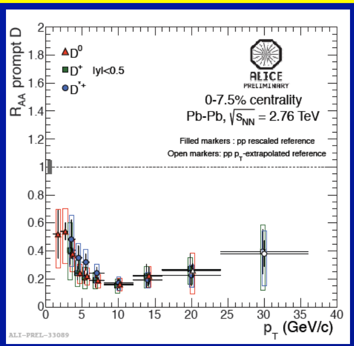

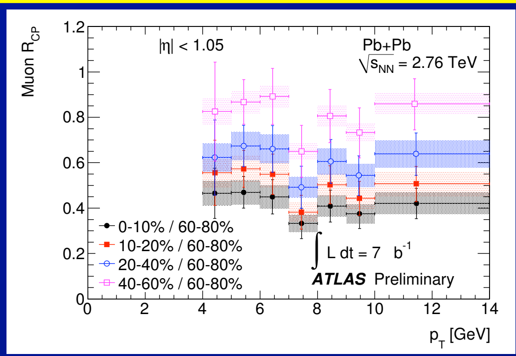

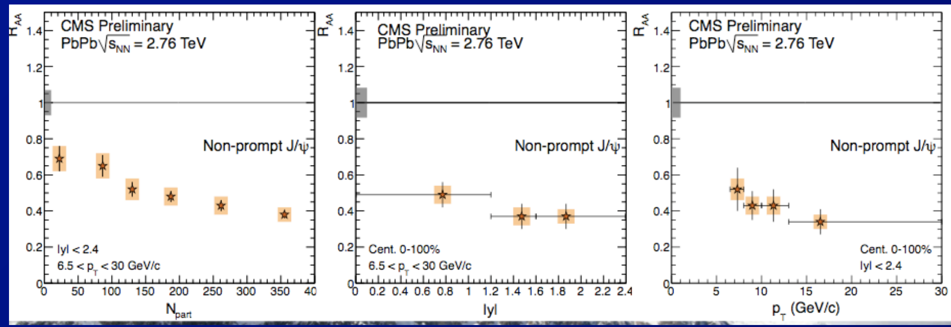

- Charm with p_T >> m suppressed similar to hadrons, less suppression for p_T ~ m
  - ⇒Quark (charm) vs quark+gluon (hadrons)?
- We see heavy flavor and (better) bottom suppressed by a factor of 2.5.
  - –we don't see a rise in bottom R_{AA}, R_{cp}
    - ⇒But, the muon, electron, non-prompt J/ψ do not reflect actual bottom kinematics.
    - ⇒Need B mesons or B jets at lower p_T.
      - » But how low do we have to go?

More general comments, thoughts, instigations

Some of the following is meant to be “tongue in cheek” and is not intended as an attack on or criticism of any specific person or persons

Theory-experiment comparisons

- Subject of much discussion

  ⇒ much of it misdirected in my opinion.

- My view: 2 useful approaches

  1. Experimental data is unfolded to correct for UE resolution and JES as far as possible. Systematic uncertainties cover corrections not made.

     ⇒ Direct corrected data-theory comparison

  2. Theoretical calculation produces "events" w/ products of hard scattering, including back-reaction. Events are given to experiments, run through GEANT simulation of detector response, and are embedded (overlaid) on Pb+Pb events.

     ⇒ Direct raw data, theory+response comparison

Theory-experiment comparisons

- What SHOULD NOT be done (in my opinion):
  - Theoretical calculation produces complete events including underlying event. Description of the underlying event (esp. the fluctuations) is not compared to data. A mock-up of the experimental jet reconstruction is performed and compared directly to uncorrected data.
    - ⇒We have multiple examples. Well intentioned, but not constructive in my opinion.
    - ⇒At least one of those has led to false conclusions being drawn in my opinion.
- 3 fatal problems with above
  - UE fluctuations not same as data
  - Different jet reconstruction & subtraction
  - Detector response not modeled !!!!!

Need for accurate quenching MC

- We now see that jet fragmentation is, indeed, modified by medium.
  - Though, on average, only slightly.
- This must have consequences for detector response to Pb+Pb jets.
  - Each experiment should have data-driven test of the effects, but:
    - ⇒ Ultimately, a quenching MC capable of reproducing the modifications will be necessary to reduce systematic errors.
- Cannot happen overnight, but the goal is essential for the success of the jet physics program.

Avoiding Berndt's Hell

- Berndt's vision of hell (paraphrased) has theorists chained to computers running quenching MC calculations to compare to uncorrected Pb+Pb jet measurements.
  - To avoid that hell, the experiments should maximally undo detector effects to produce data that can be directly compared to theory.
    - ⇒But to be successful, we will need a MC that can be used to properly evaluate detector response to quenched jets.
    - ⇒That MC will necessarily be improved iteratively (a la PYTHIA).
      - » The more accurate, the more precise the data.

Berndt's heaven

I propose an alternative that I will call "Berndt's heaven".

- In that heaven, the experimentalists are chained to computers running MC calculations using code the theorists provide.
  - The experimentalists slave away to evaluate how their detector performs for the modified jets and correct their data.
  - The theorists compare their beautiful analytic (or MC) calculations to corrected data.
    - ⇒ In the case that it's necessary to do more direct comparison, the experimentalists follow my approach #2 using real detector response and real underlying event.

Brian's hell

- Theorist has favorite hydro calculation which he/she uses to evaluate jet quenching.
  - Since hydro works so well, theorist concludes that it must also describe the Pb+Pb underlying event.
  - Theorist implements a jet reconstruction algorithm with subtraction guessing at aspects of an experiment's method that are subtle and/or not clearly described in a paper.
  - Theorist forgets that detectors are not ideal.
  - Theorist produces a result claiming that it represents what the experiment would have measured.

Wrap up

Historical perspective (2)

From talk by BAC at Intersections 2009

I claim no unique insight on this slide -- this is what we were all planning for

But, we can be happy that the "new era" has arrived

Jets @LHC: Prospects

- LHC will usher in new era for jet quenching
  - High-statistics studies of full jets.
    - ⇒ ~ 10^6 jets w/ E_T > 100 GeV for 0.5 nb^{-1}
  - W/ large-acceptance tracking, calorimetry
- Single jets:
  - R_{AA}, frag. functions, J_T
  - versus centrality, $\Delta\phi$ from reaction plane
- Di-jets:
  - Differential quenching, acoplanarity
- γ-jets:
  - Jet z, frag. function, acoplanarity
- Heavy flavor tagged jets

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Historical perspective (3)

From talk by BAC at Intersections 2009

Done except for more than one algorithm

Jets @ LHC: Considerations

- In order to have a rigorous Pb+Pb jet program @ LHC we must:
  - Use more than one algorithm
    - ⇒Different sensitivity to background
    - ⇒Different sensitivity to modified jets
    - ⇒Different false jet rates
  - Use more than one jet "size"
    - ⇒Different sensitivity to background
    - ⇒Different sensitivity to modified jets
    - ⇒Different false jet rates
  - Be able to reject false jets
  - Be able to unfold "background" effects

Historical perspective (3)

From talk by BAC at Intersections 2009

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Summary/conclusions

- We've come a long way since start of the LHC Pb+Pb program
  - Results have produced significant evolution(s) in the understanding of quenching

    ⇒But do we all agree on what we've learned?
  - We have a substantial set of jet measurements that cover many of our original goals.

    ⇒However, we have a huge amount of work ahead to improve measurements and understand their implications.
  - We are now seeing measurements with b-tagged or separated heavy flavor

    ⇒The heavy quarks at RHIC ~~are understood?~~

Summary/conclusions

- We are making progress in measuring the full properties of a hard parton shower embedded in QGP.
  - See modifications of fragmentation
  - See indirect indications of broadening
  - Preliminary direct observations of broadening
  - We are well started on the program of gamma-jet measurements.
    - ⇒But our picture is far from complete.
- The jet physics program is still quite new
  - Experimental techniques will evolve and measurements will improve.