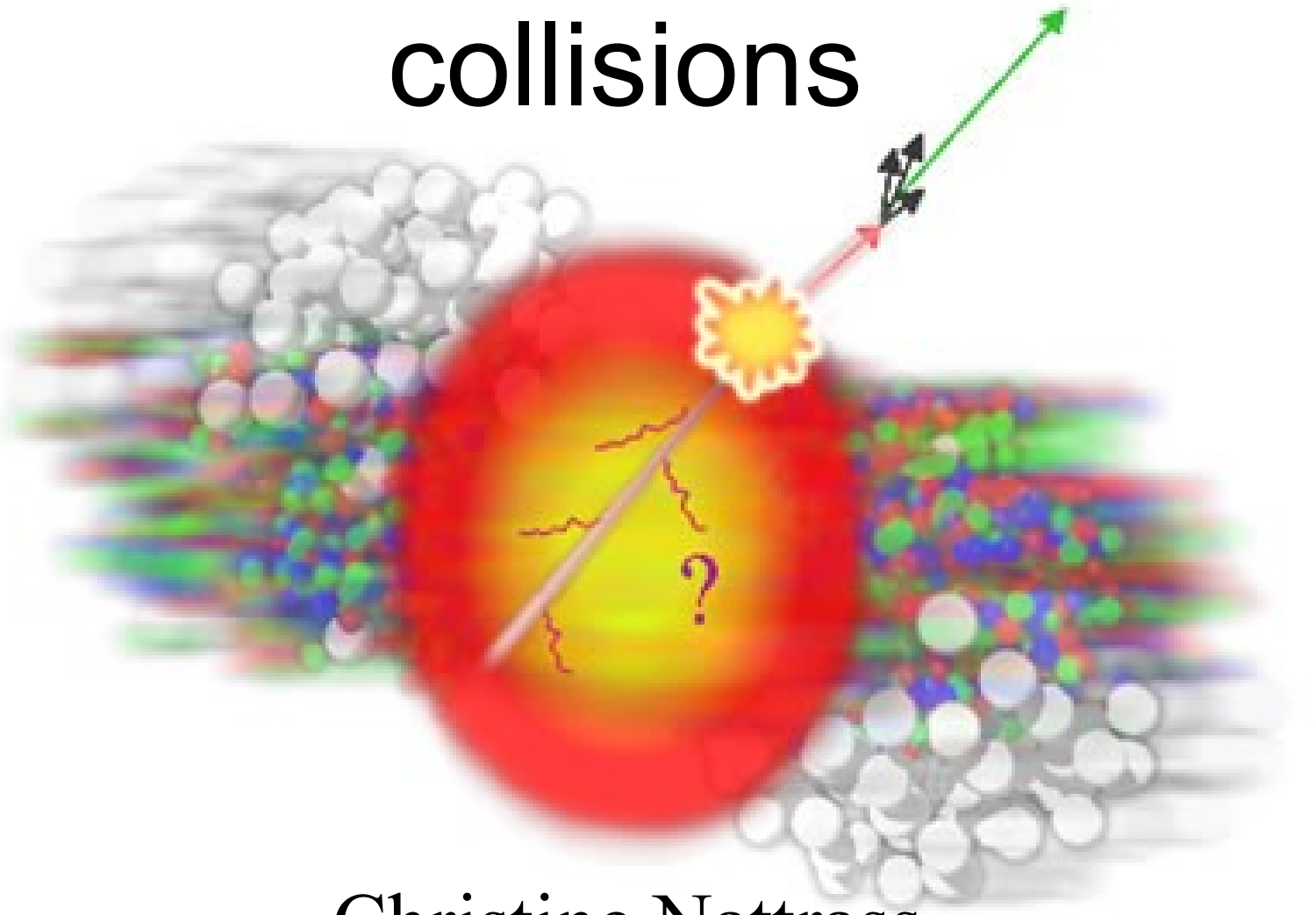
Measurements of jets in heavy ion collisions



Christine Nattrass
University of Tennessee, Knoxville
Largely based on Connors, Nattrass, Reed, & Salur arxiv:1705.01974

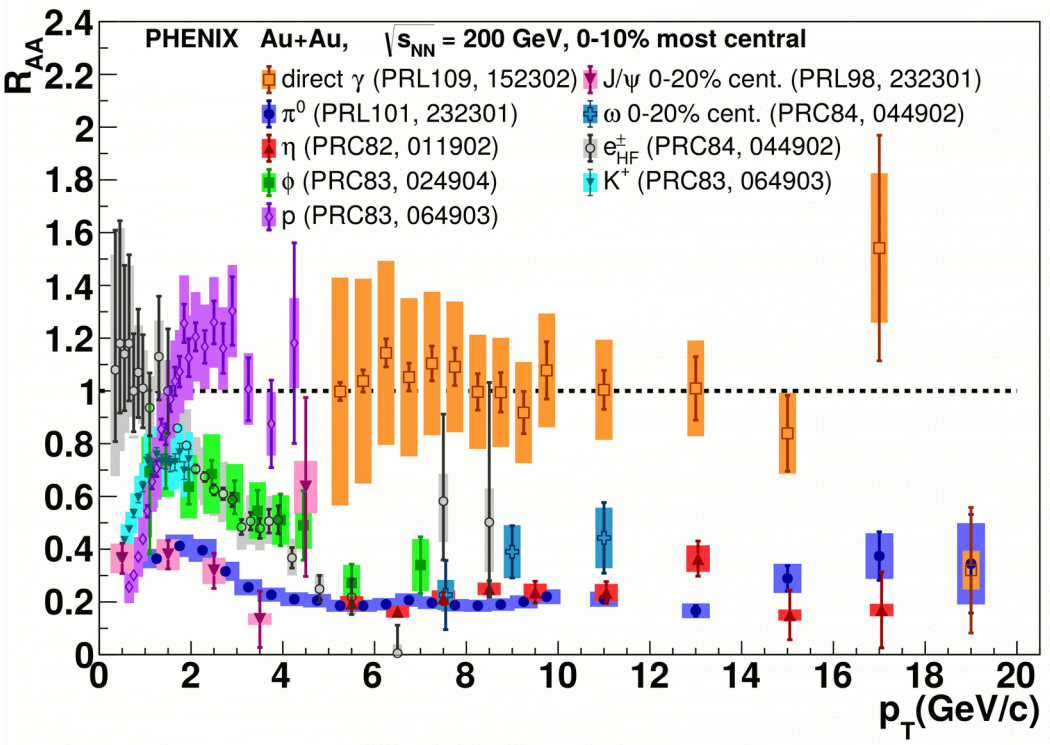
What have we learned?
How do we move forward?

Partonic energy loss

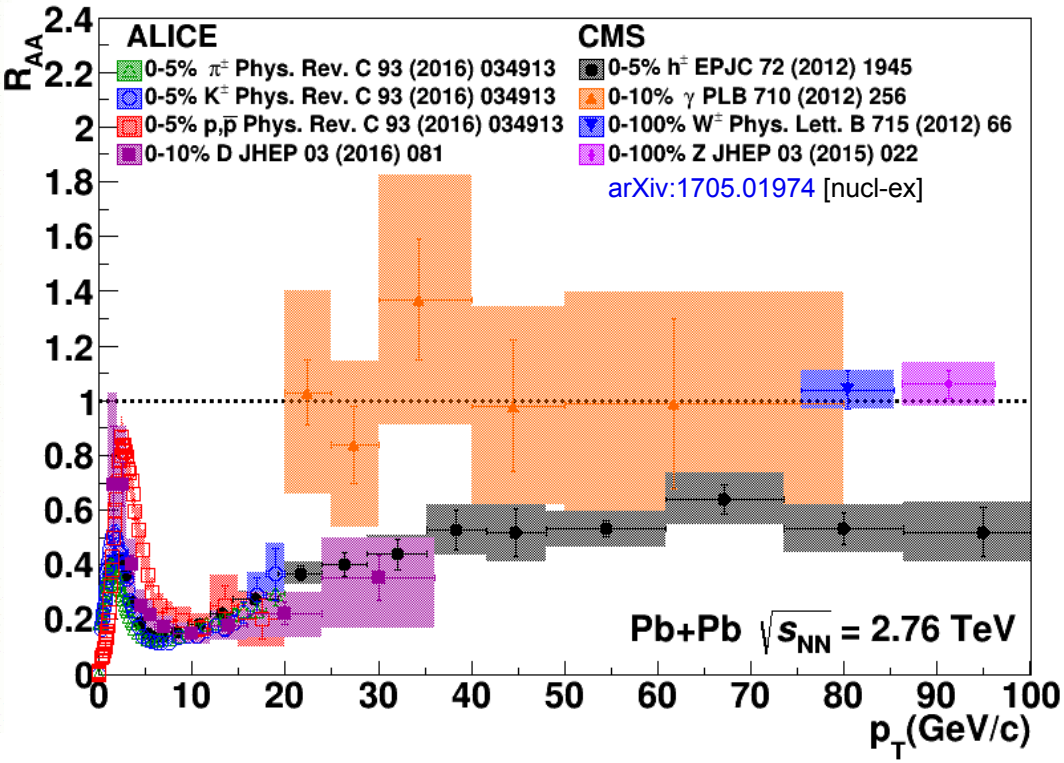
https://onkeymonkey.files.wordpress.com/2013/03/5387946_460s_v1.jpeg

Nuclear modification factor R_{AA}

RHIC

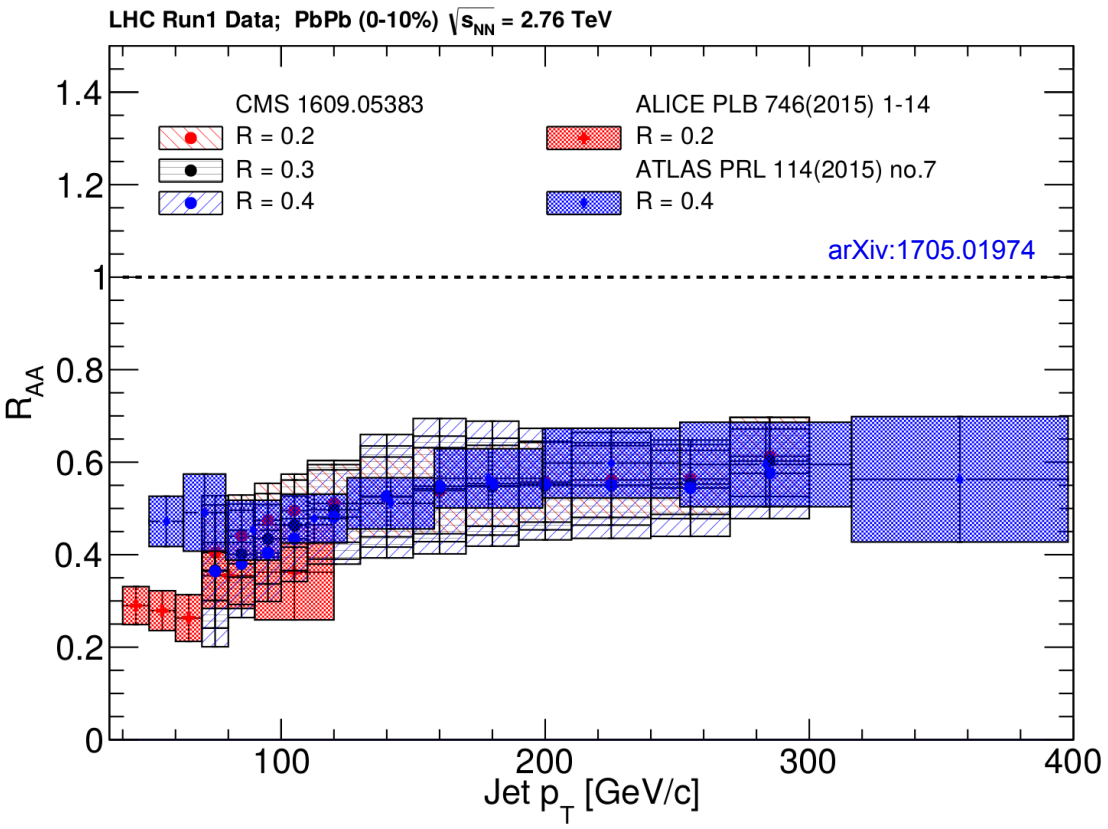


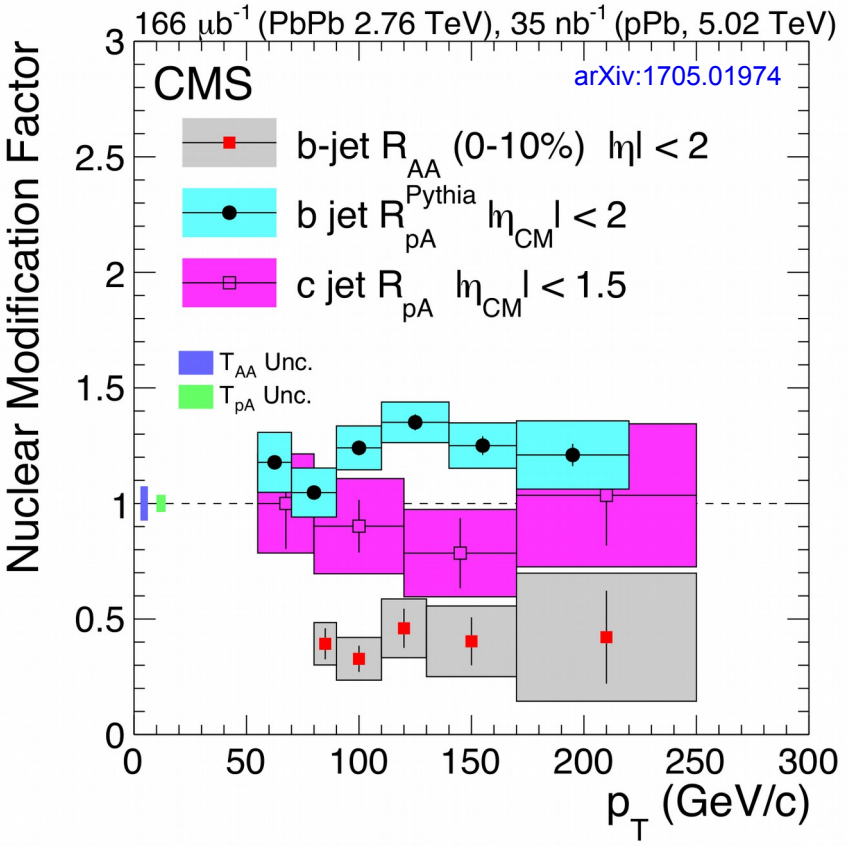
LHC



- *Electromagnetic probes* – consistent with no modification – medium is transparent to them
- *Strong probes* – significant suppression – medium is opaque to them - even heavy quarks!

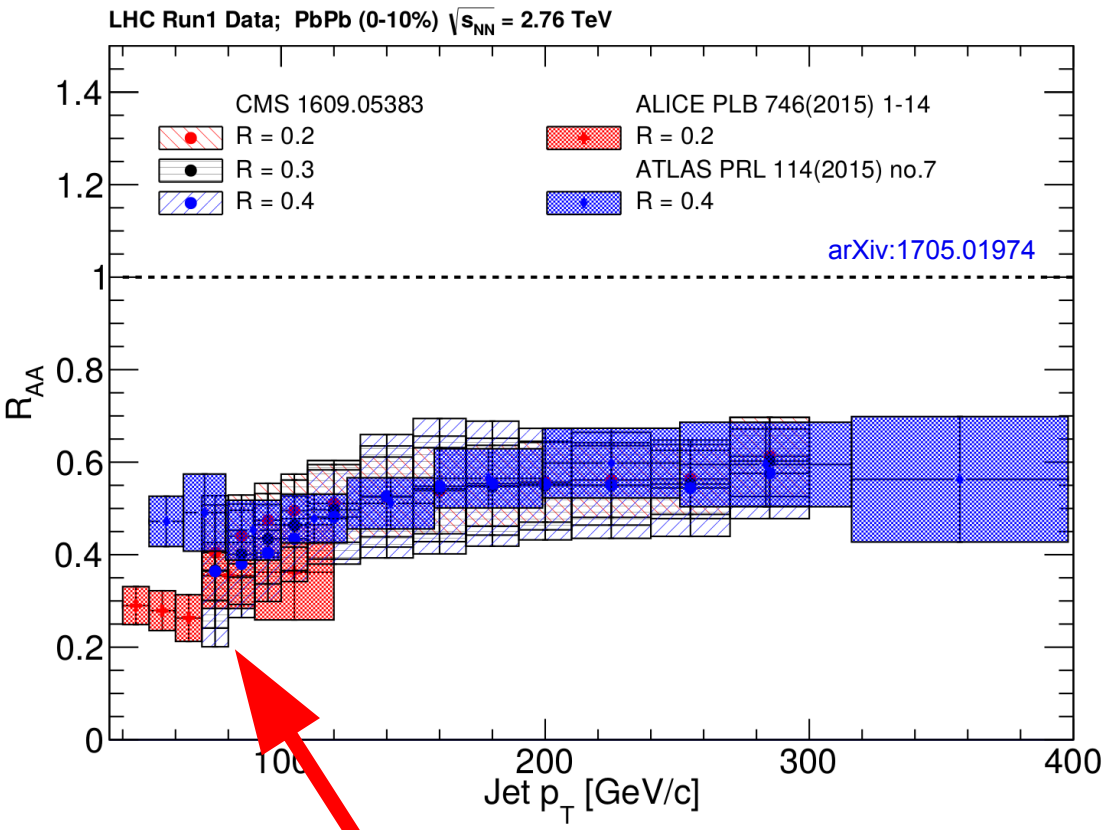
Jet R_{AA}

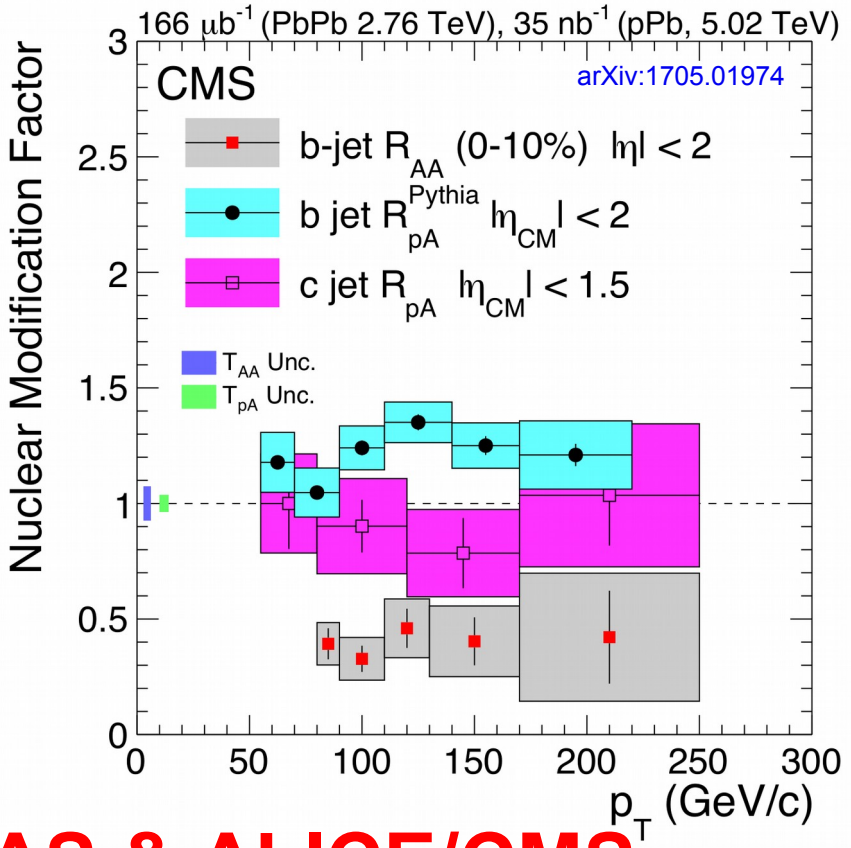




- Jet R_{AA} also demonstrates suppression
- Similar suppression of heavy quark jets?

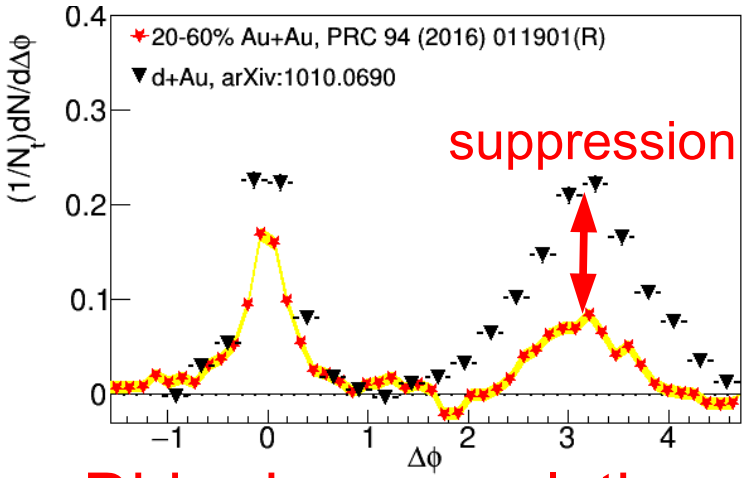
Jet R_{AA}





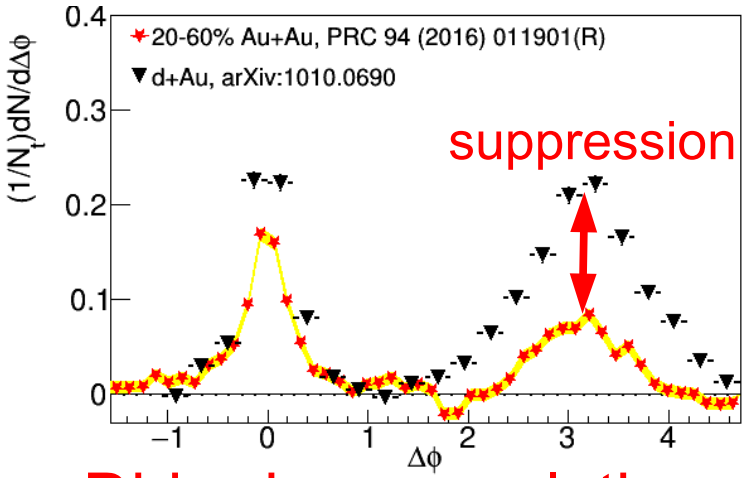
Tension between ATLAS & ALICE/CMS

- Jet R_{AA} also demonstrates suppression
- Similar suppression of heavy quark jets?



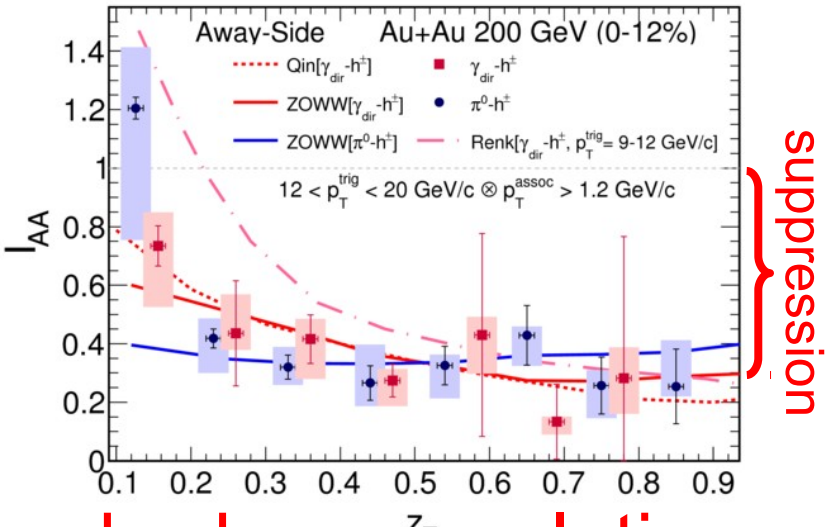
Di-hadron correlations

[Too many to list]



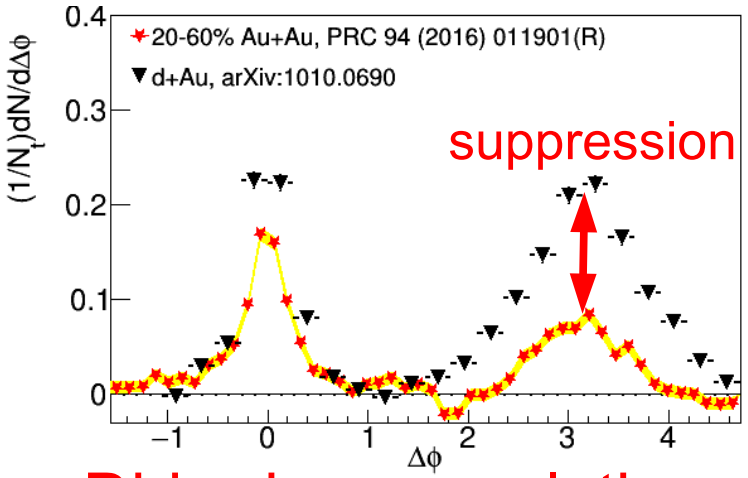
Di-hadron correlations

[Too many to list]



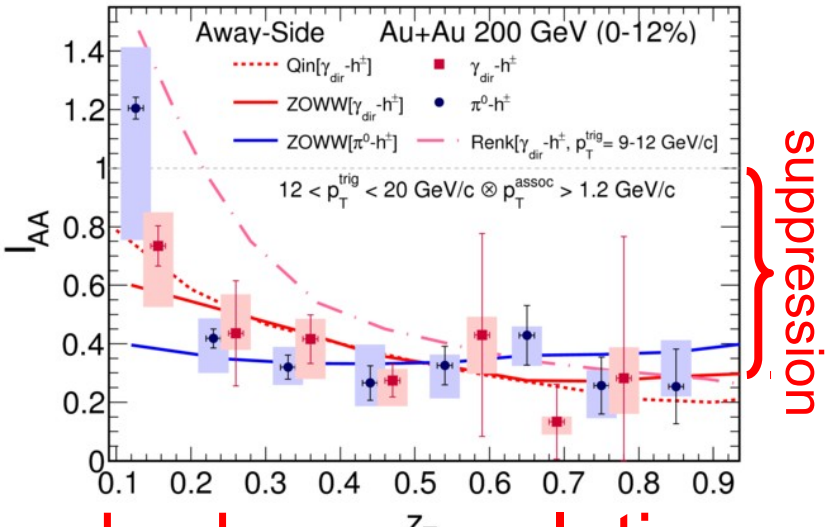
γ-hadron correlations

[Phys.Rev.C80:024908,2009,
Phys.Rev.D82:072001,2010,
Phys.Rev.C82:034909,2010
Physics Letters B 760 (2016)]



Di-hadron correlations

[Too many to list]



γ-hadron correlations

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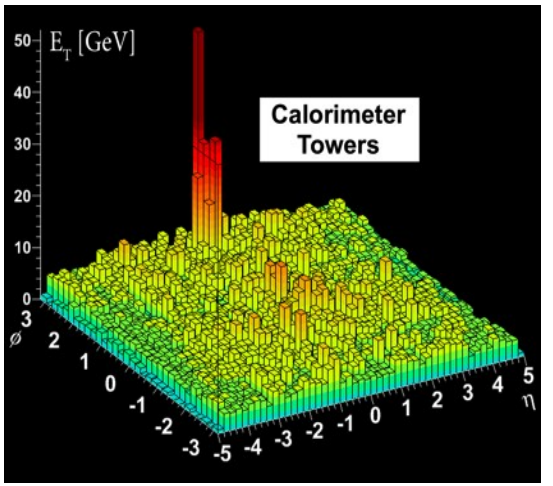
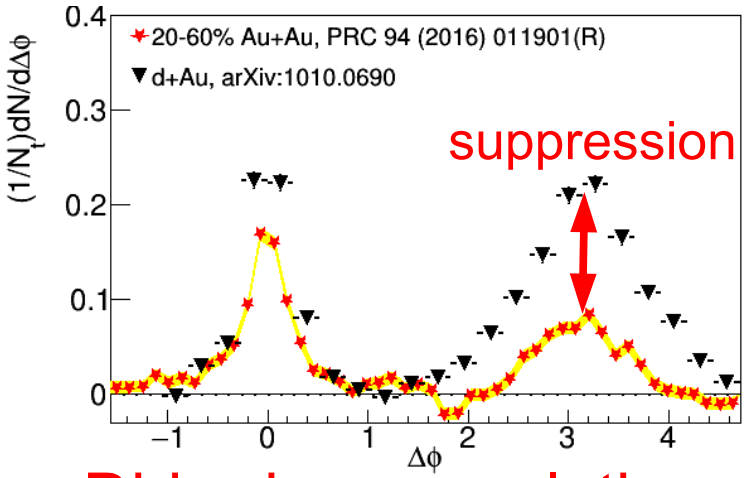


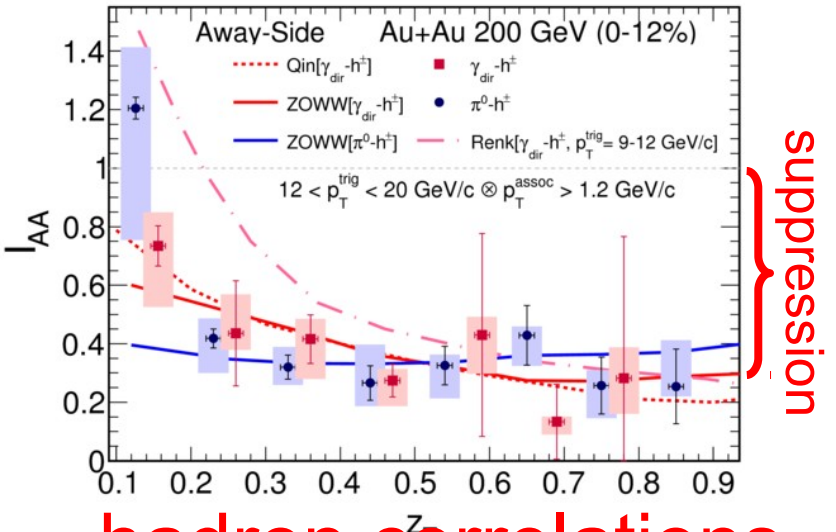
Dijet asymmetry

[Phys.Rev.C84:024906,2011,
Phys. Lett. B 712 (2012) 176,
Phys.Rev.Lett.105:252303,2010,
Phys. Rev. Lett. 119, 062301 (2017)]



Di-hadron correlations

[Too many to list]



γ-hadron correlations

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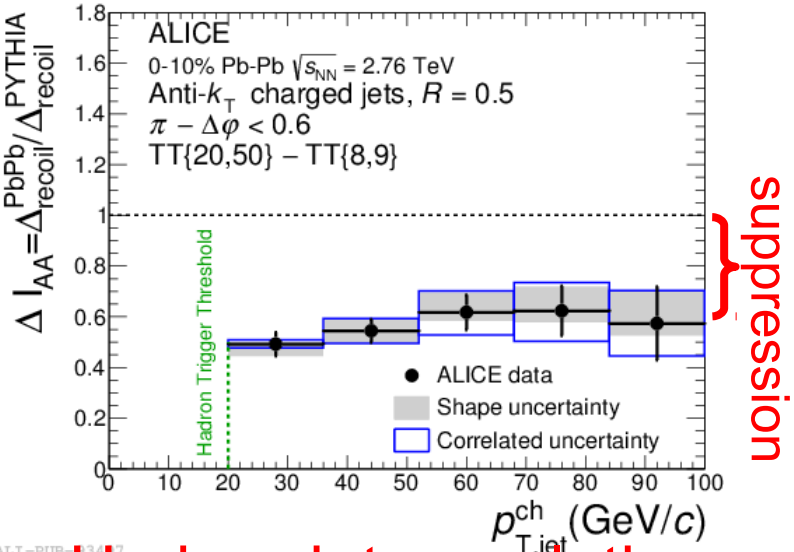
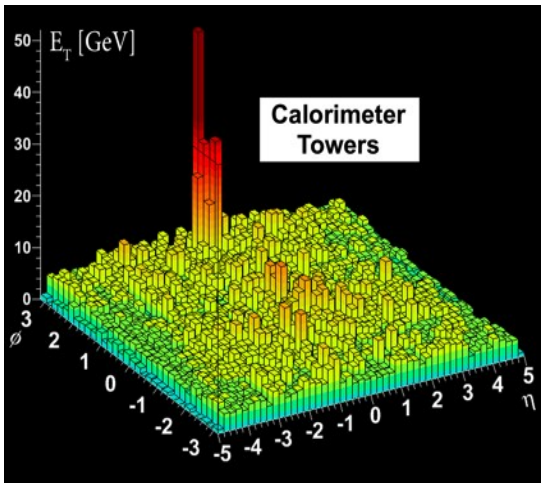
Physics Letters B 760 (2016)]



Hadron-jet correlations

[JHEP 09 (2015) 170,
Phys. Rev. C 96, 024905 (2017)]



Dijet asymmetry

[Phys.Rev.C84:024906,2011,
Phys. Lett. B 712 (2012) 176,
Phys.Rev.Lett.105:252303,2010,
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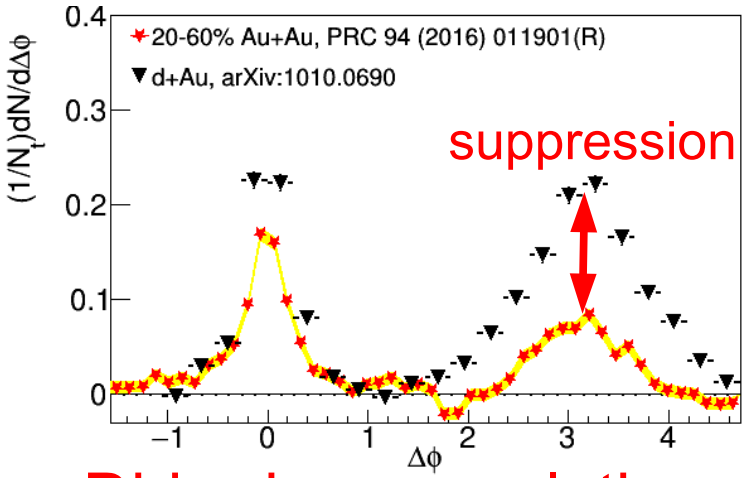

Di-hadron correlations

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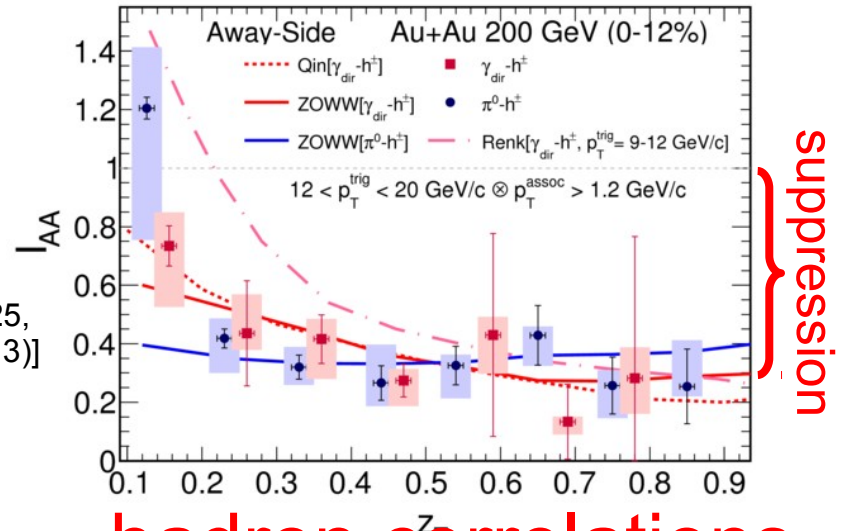
Jet v_2

[Phys.Lett. B 753 (2016) 511-525, Phys. Rev. Lett.111 152301 (2013)]



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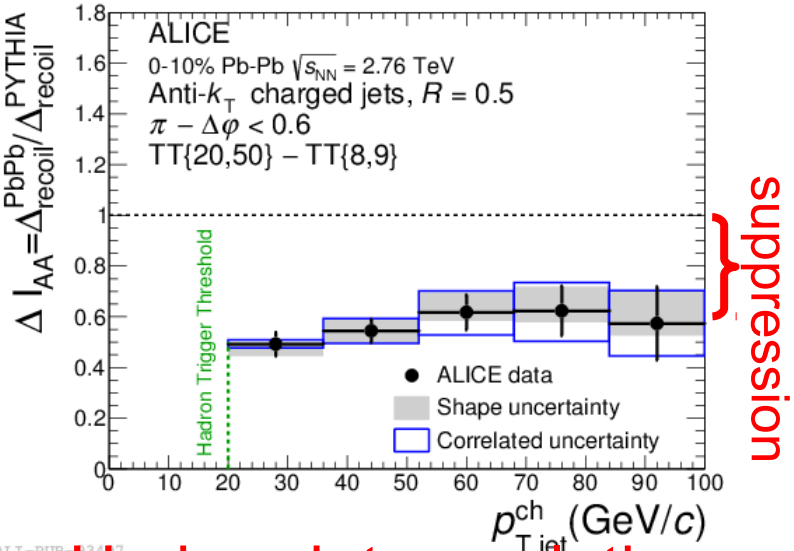
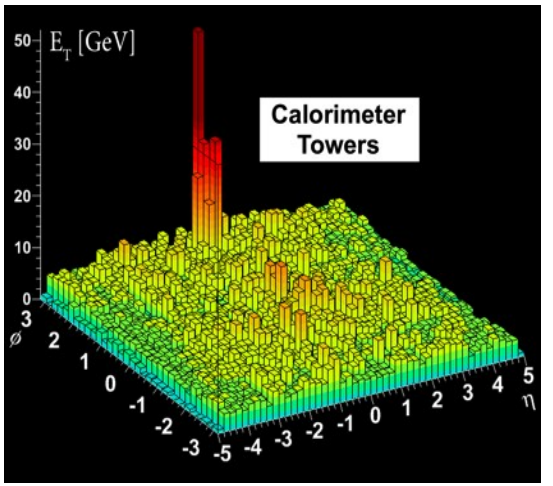


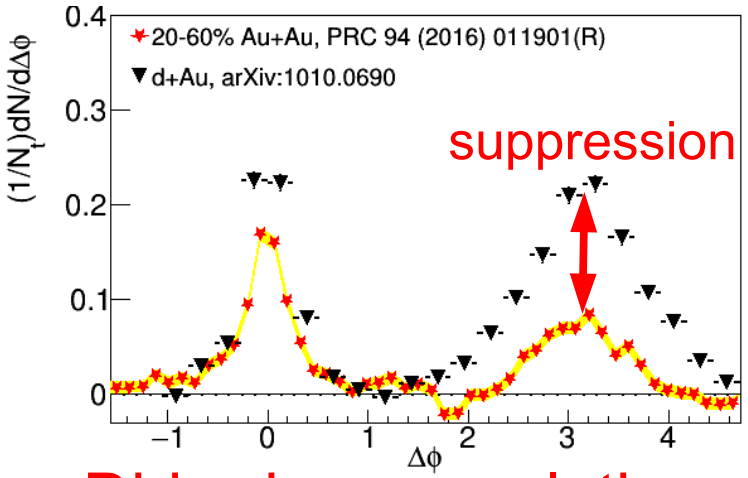
Hadron-jet correlations

[JHEP 09 (2015) 170, Phys. Rev. C 96, 024905 (2017)]



Dijet asymmetry

[Phys.Rev.C84:024906,2011, Phys. Lett. B 712 (2012) 176, Phys.Rev.Lett.105:252303,2010, Phys. Rev. Lett. 119, 062301 (2017)]



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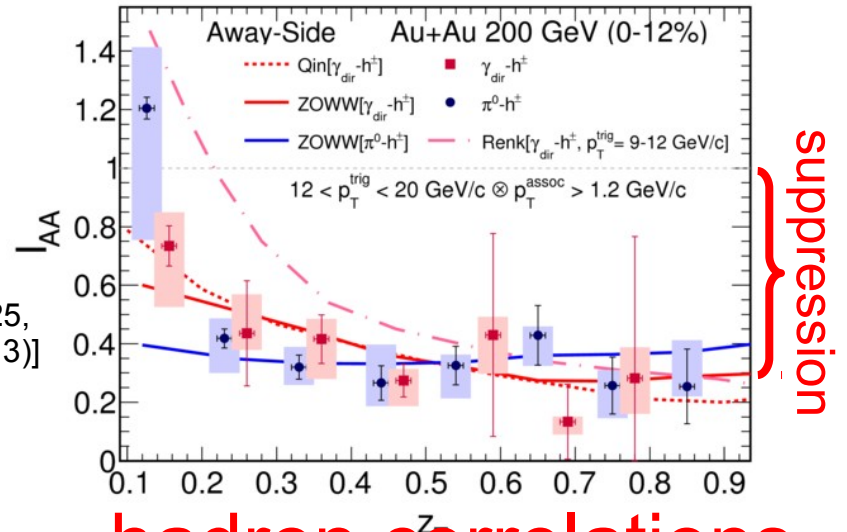

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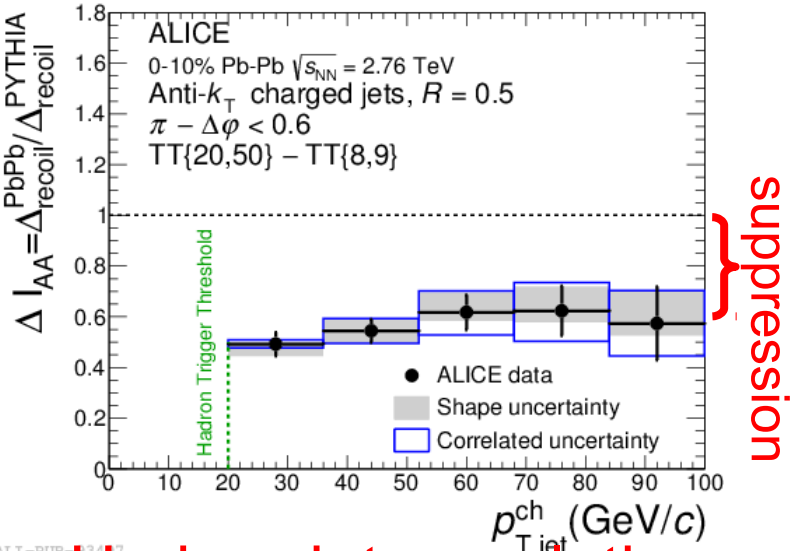
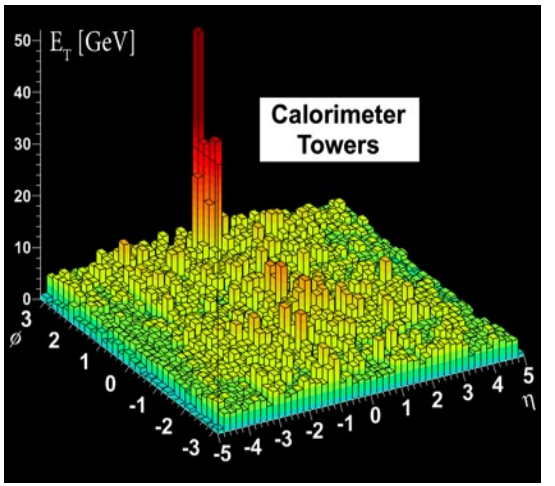


Hadron-jet correlations

[JHEP 09 (2015) 170, Phys. Rev. C 96, 024905 (2017)]

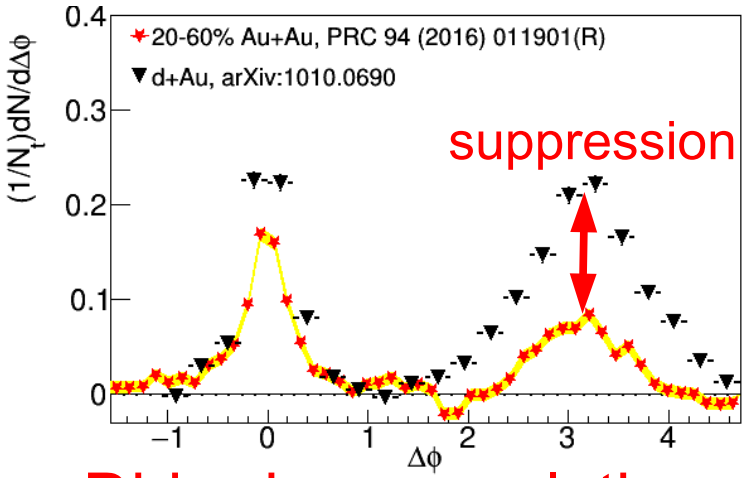
γ-jet correlations

[Phys. Lett. B 718 (2013) 773]



Dijet asymmetry

[Phys.Rev.C84:024906,2011, Phys. Lett. B 712 (2012) 176, Phys.Rev.Lett.105:252303,2010, Phys. Rev. Lett. 119, 062301 (2017)]

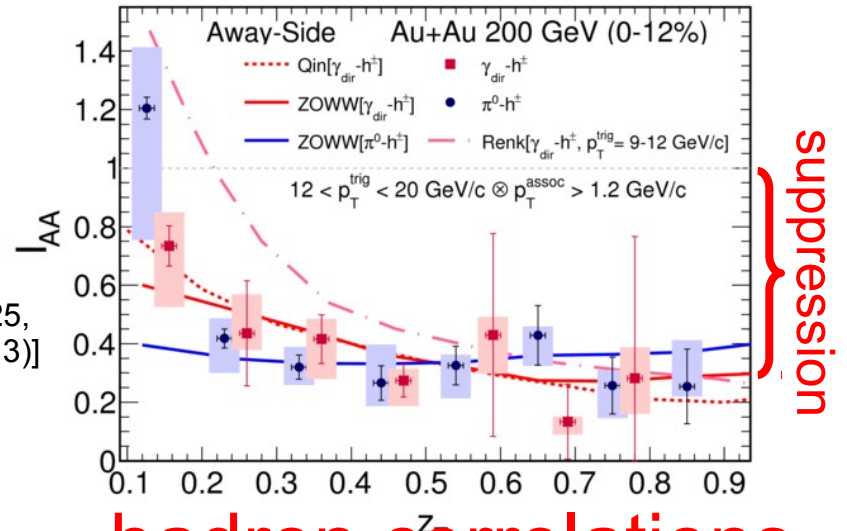


Di-hadron correlations

[Too many to list]

Jet v_2

[Phys.Lett. B 753 (2016) 511-525, Phys. Rev. Lett.111 152301 (2013)]



γ-hadron correlations

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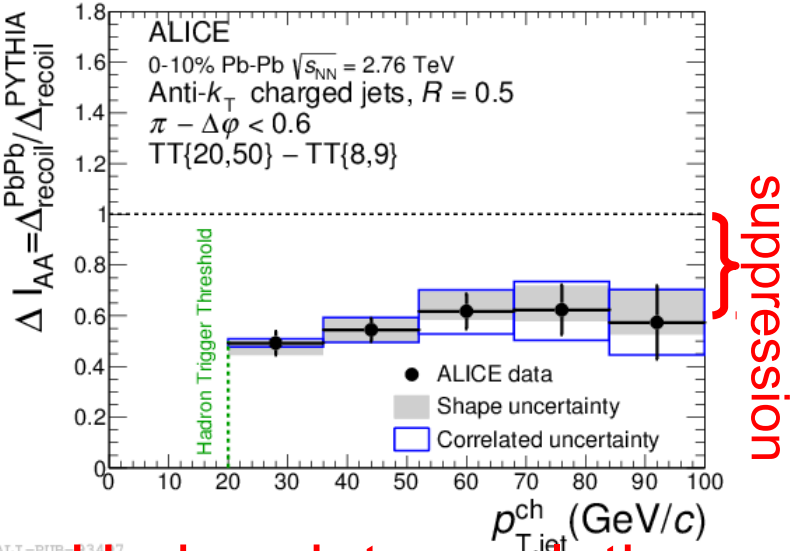


Hadron-jet correlations

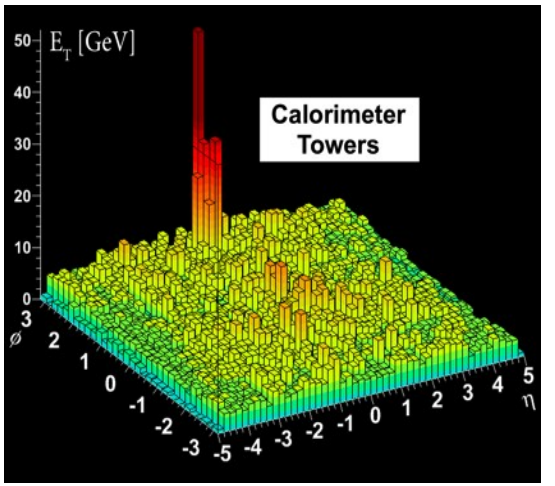
[JHEP 09 (2015) 170, Phys. Rev. C 96, 024905 (2017)]

γ-jet correlations

[Phys. Lett. B 718 (2013) 773]

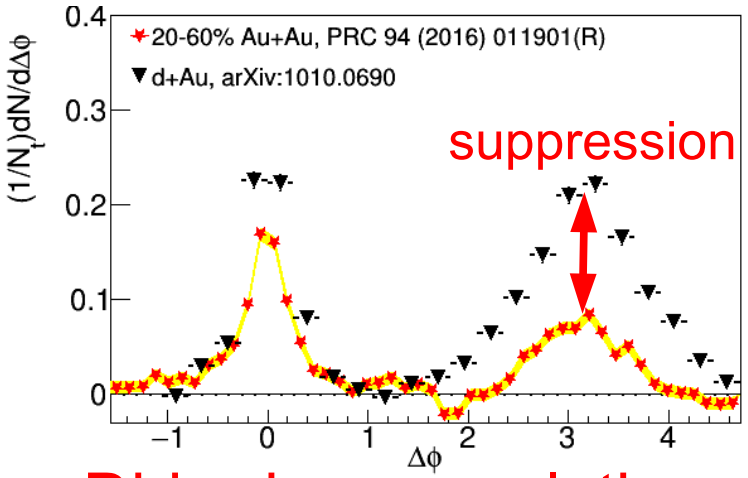
High-p_T hadron v_2

[too many to list]



Dijet asymmetry

[Phys.Rev.C84:024906,2011, Phys. Lett. B 712 (2012) 176, Phys.Rev.Lett.105:252303,2010, Phys. Rev. Lett. 119, 062301 (2017)]

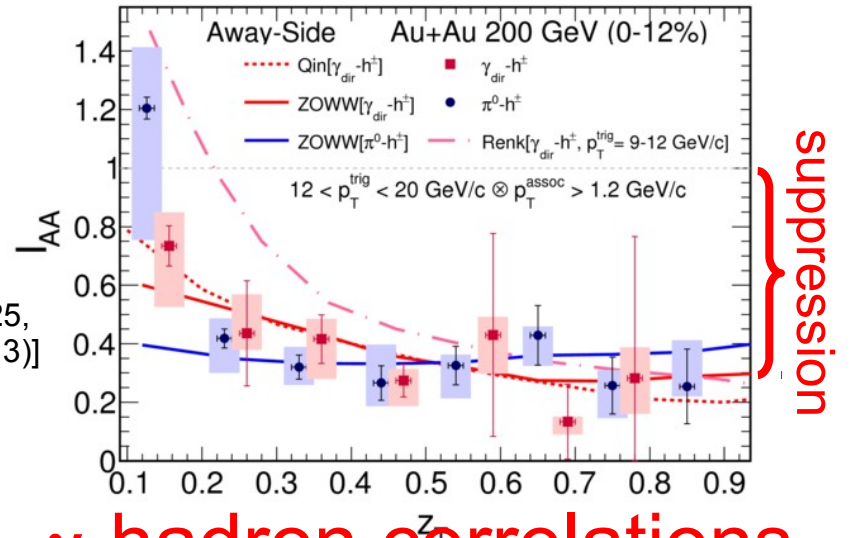


Di-hadron correlations

[Too many to list]

Jet v_2

[Phys.Lett. B 753 (2016) 511-525, Phys. Rev. Lett.111 152301 (2013)]



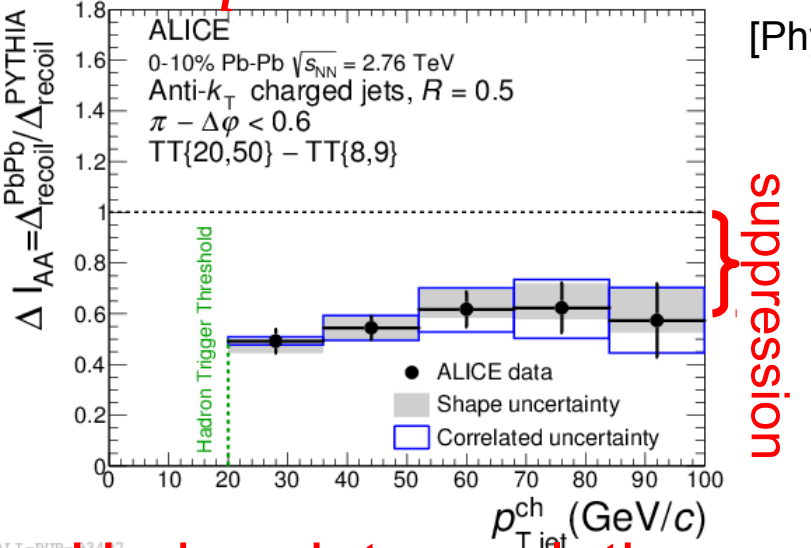
γ-hadron correlations

[Phys.Rev.C80:024908,2009, Phys.Rev.D82:072001,2010, Phys.Rev.C82:034909,2010 Physics Letters B 760 (2016)]

$\hat{q} = 1.2 \pm 0.3 \ GeV^2$ Au+Au $\sqrt{s_{NN}}$ =200 GeV

$\hat{q} = 1.9 \pm 0.7 \ GeV^2$ Pb+Pb $\sqrt{s_{NN}}$ =2.76 TeV

[Phys. Rev. C 90, 014909 (2014)]



Hadron-jet correlations

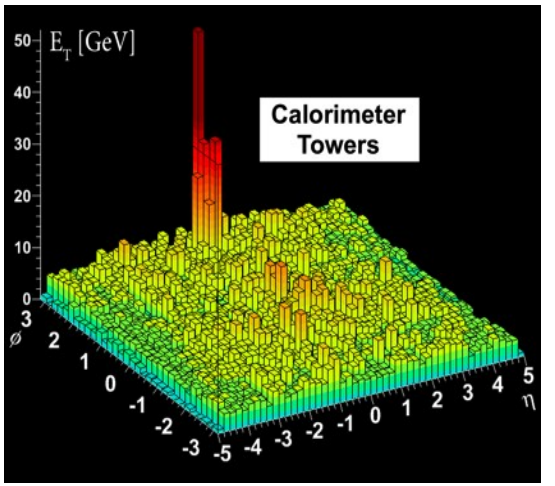
[JHEP 09 (2015) 170, Phys. Rev. C 96, 024905 (2017)]

γ-jet correlations

[Phys. Lett. B 718 (2013) 773]

High-p_T hadron v_2

[too many to list]

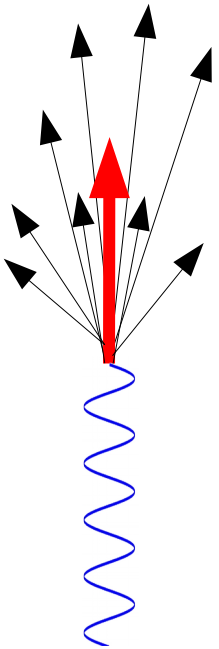


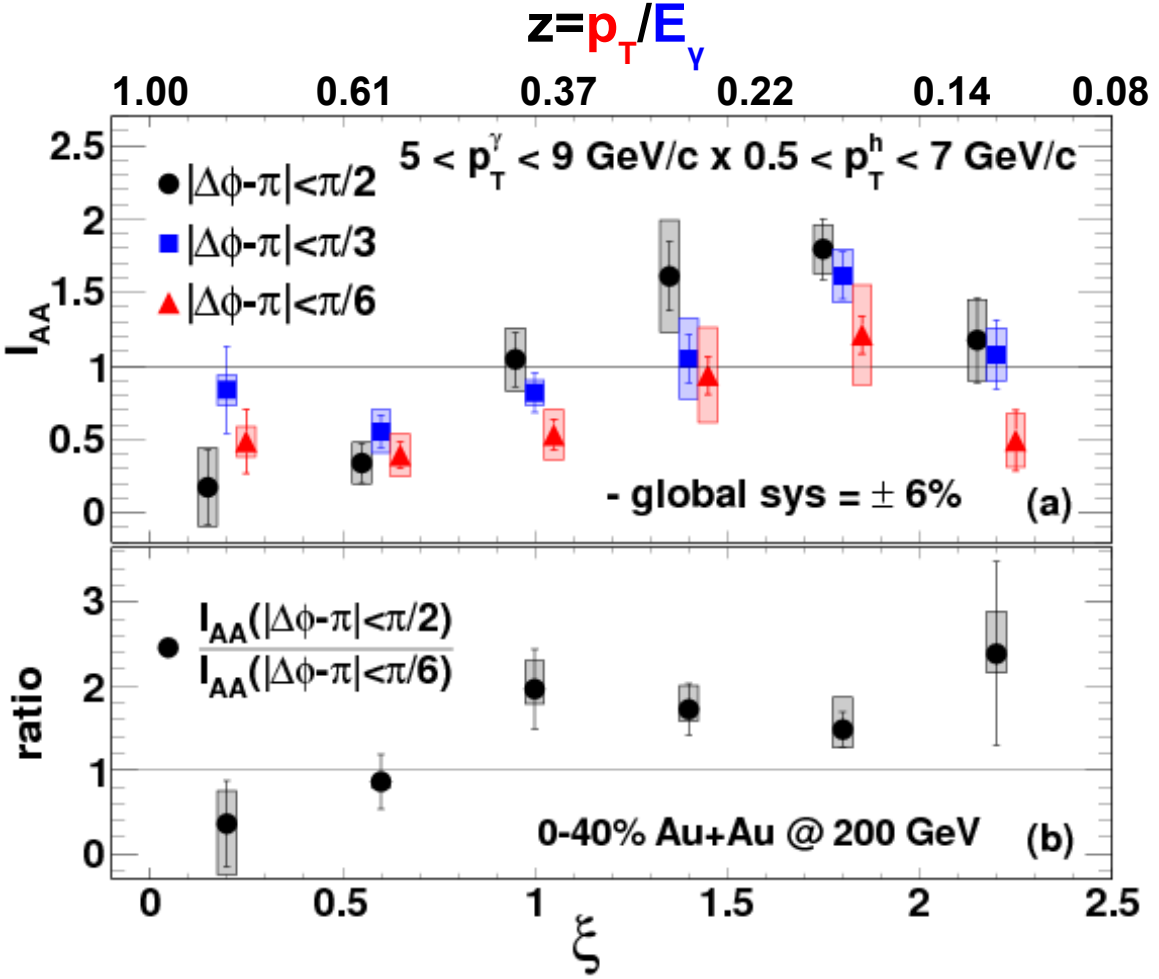
Dijet asymmetry

[Phys.Rev.C84:024906,2011, Phys. Lett. B 712 (2012) 176, Phys.Rev.Lett.105:252303,2010, Phys. Rev. Lett. 119, 062301 (2017)]

https://i.pinimg.com/736x/28/9b/9e/289b9e8e63c56fe8496c0aaafee58183--funny-fat-animals-scout-cookies.jpg

Fragmentations from γ-hadron correlations

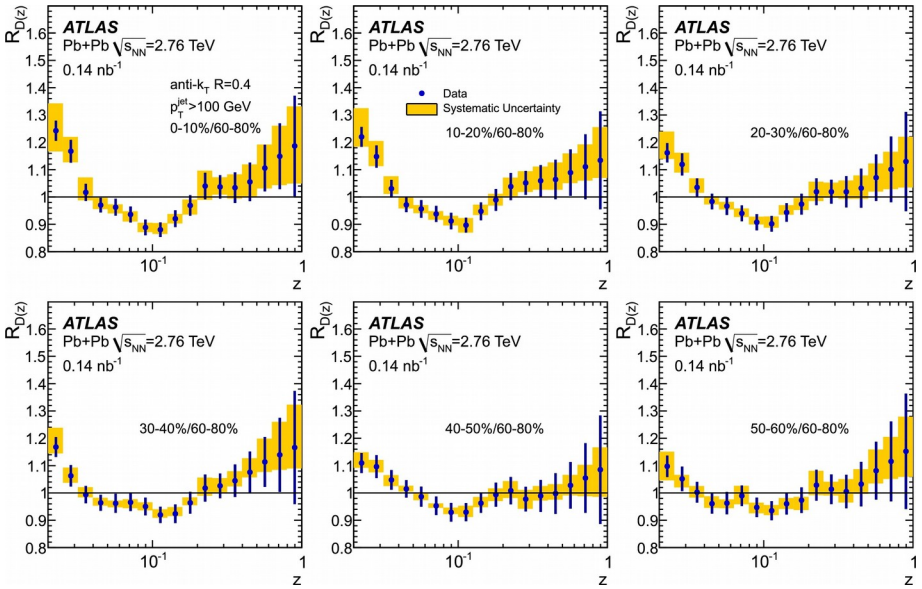


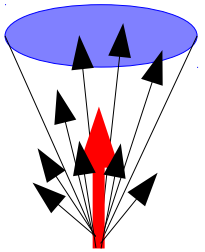


- Enhancement at low z
- Slight suppression at high z

Modified fragmentation

Fragmentation functions with jets

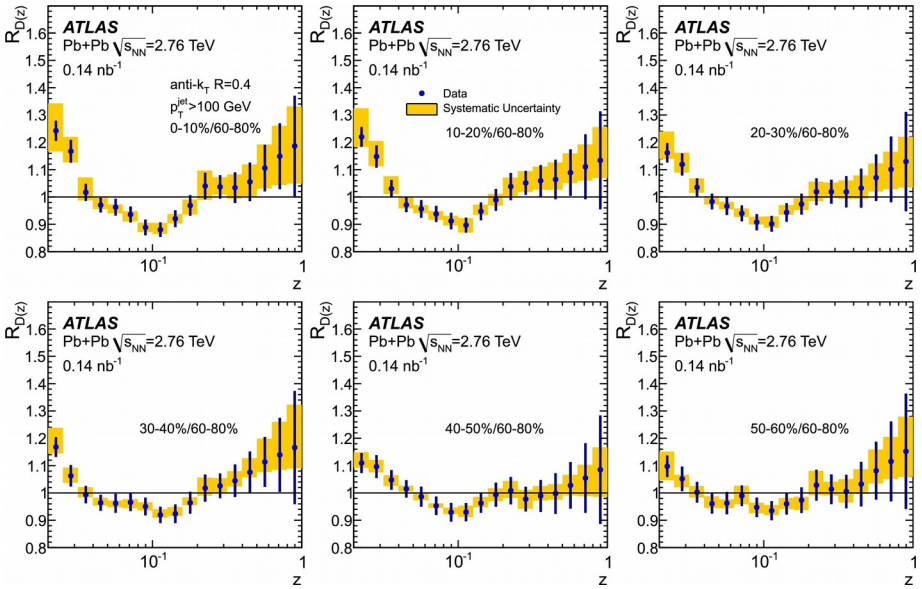


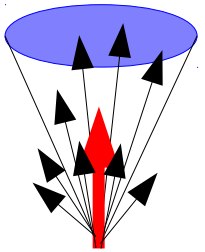


$z=p_T/E_y$

Modified fragmentation

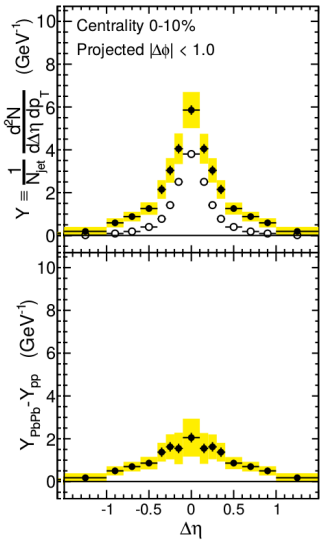
Fragmentation functions with jets





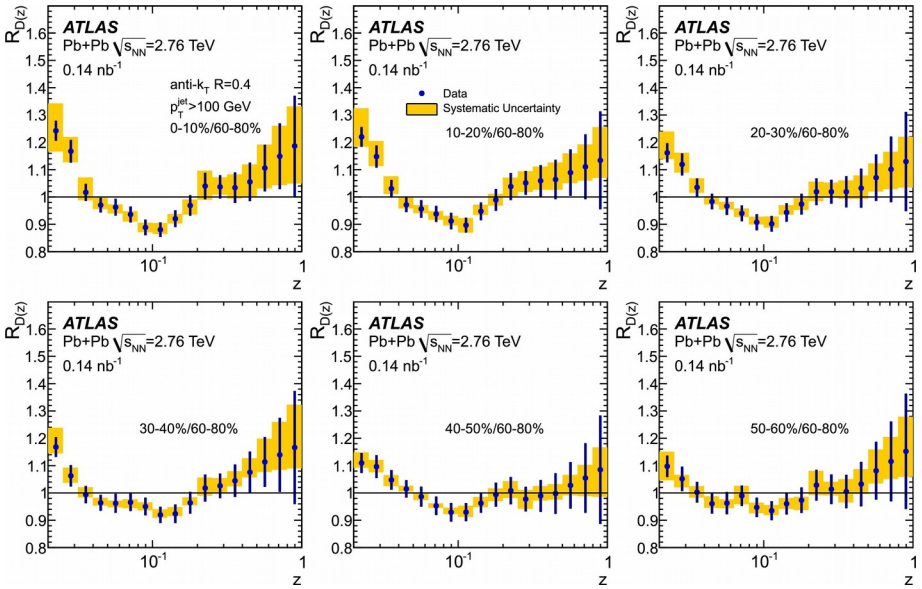
$z=p_T/E_\gamma$

Jet-hadron correlations

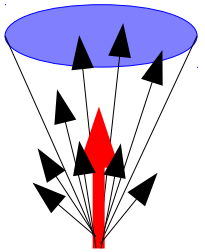


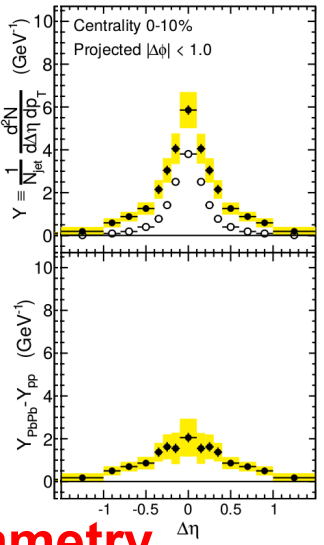
Modified fragmentation

Fragmentation functions with jets



$z=p_T/E_J$



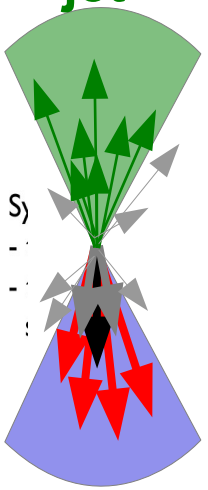


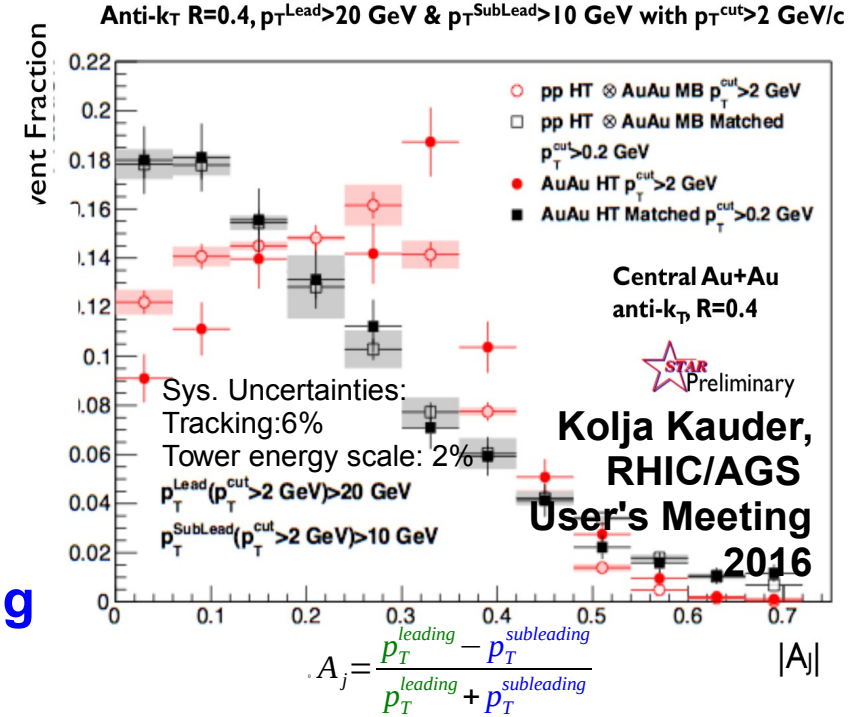
Jet-hadron correlations

Di-jet asymmetry

arXiv:1609.03878

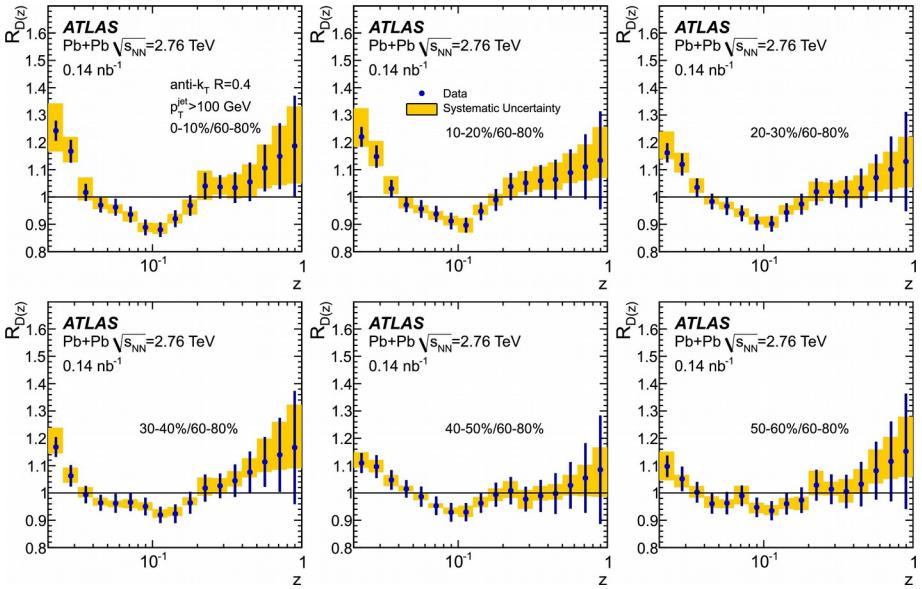
Anti-k_T R=0.4, p_T^{Lead}>20 GeV & $p_T^{SubLead}$>10 GeV with p_T^{cut}>2 GeV/c





Modified fragmentation

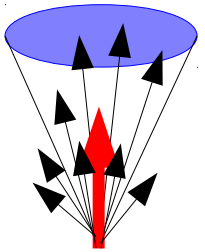
Fragmentation functions with jets



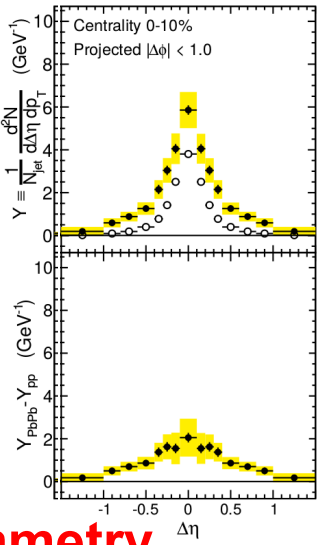
$z=p_T/E_{jet}$

Di-hadron correlations

[Lots of papers]



Jet-hadron correlations



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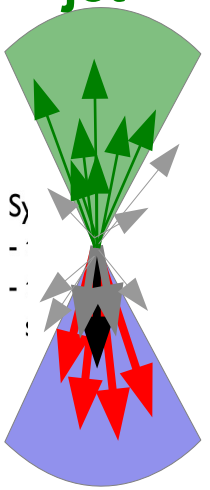
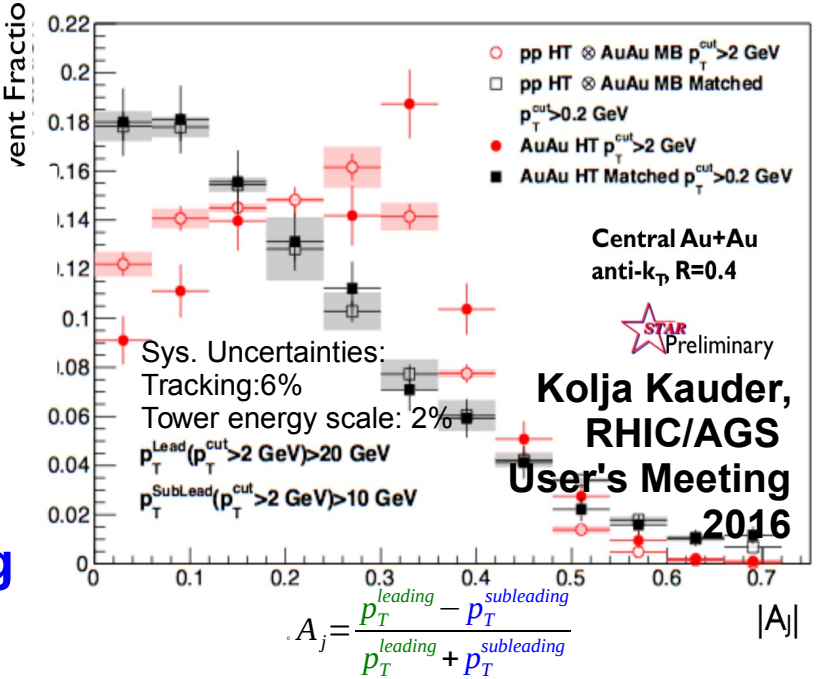
Anti-k_T R=0.4, p_T^{Lead}>20 GeV & $p_T^{SubLead}$>10 GeV with p_T^{cut}>2 GeV/c

Leading jet

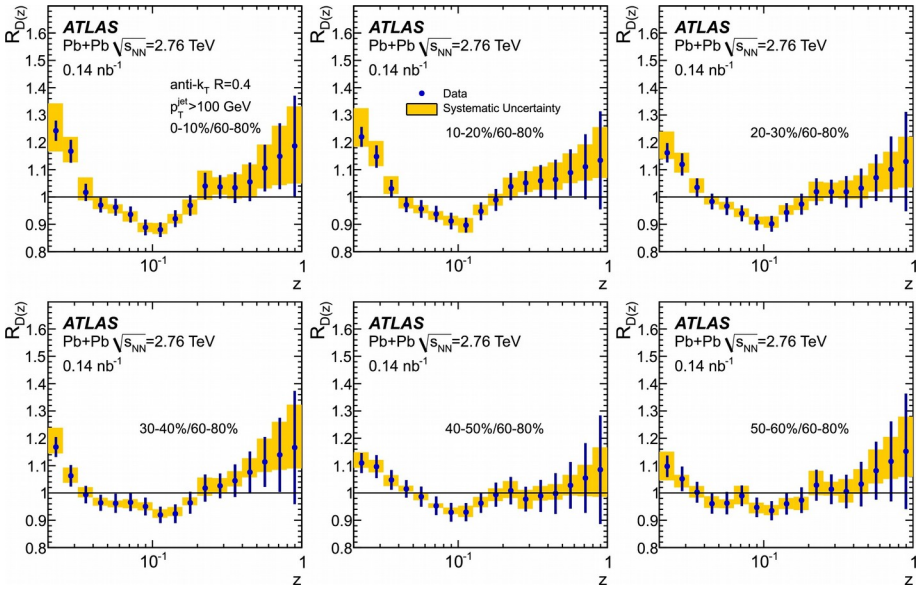


Subleading jet



Modified fragmentation

Fragmentation functions with jets



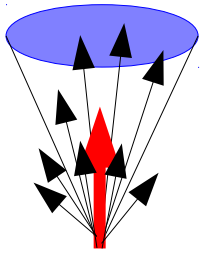
$z=p_T/E_J$

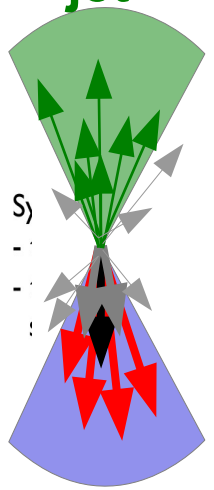
Di-hadron correlations

[Lots of papers]

Jet shapes

[arXiv:1708.09429,
arXiv:1512.07882,
arXiv:1704.03046]





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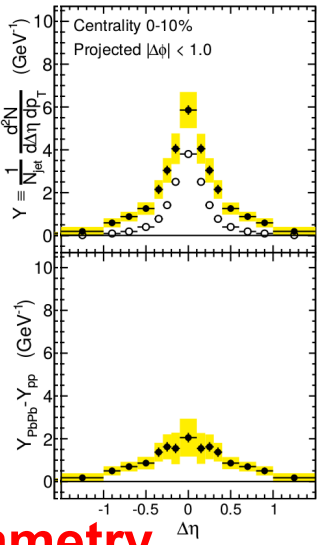
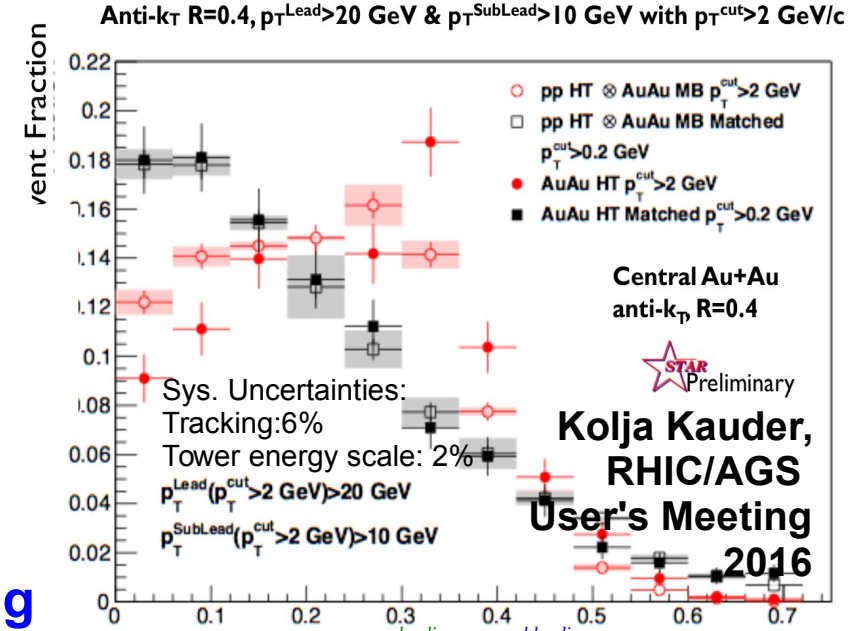


Di-jet asymmetry

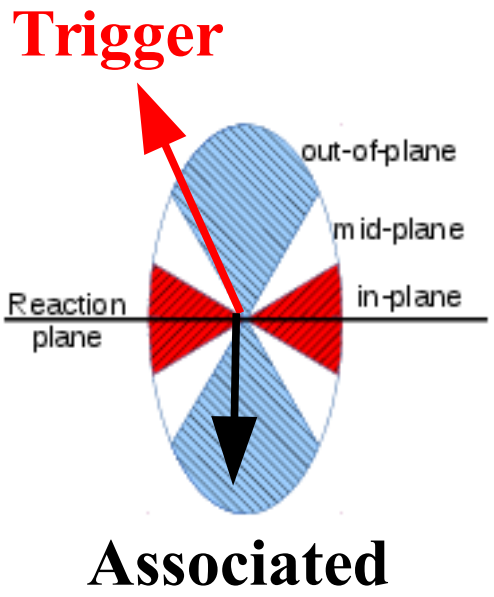
arXiv:1609.03878

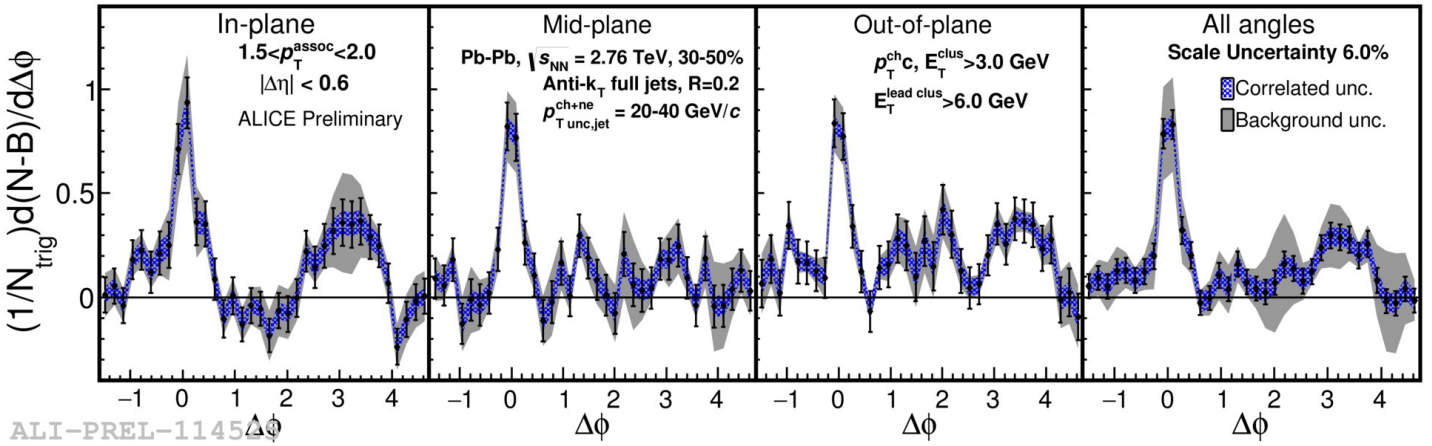
Anti-k_T R=0.4, p_T^{Lead}>20 GeV & $p_T^{SubLead}$>10 GeV with p_T^{cut}>2 GeV/c

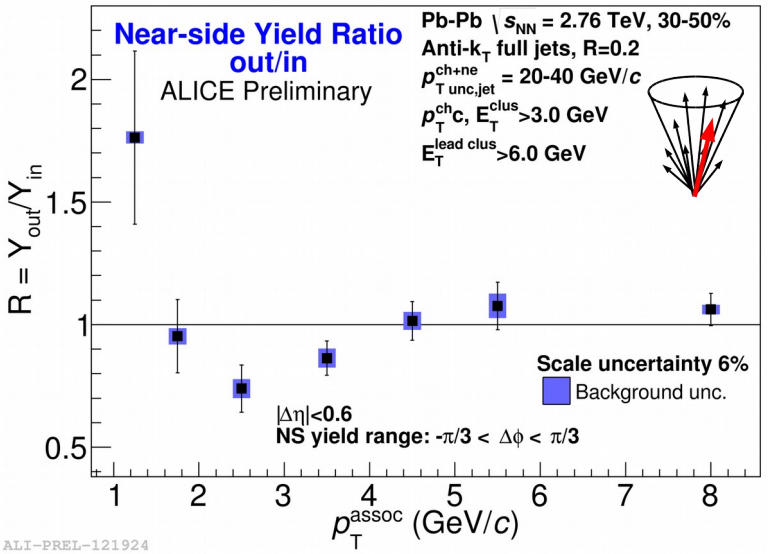


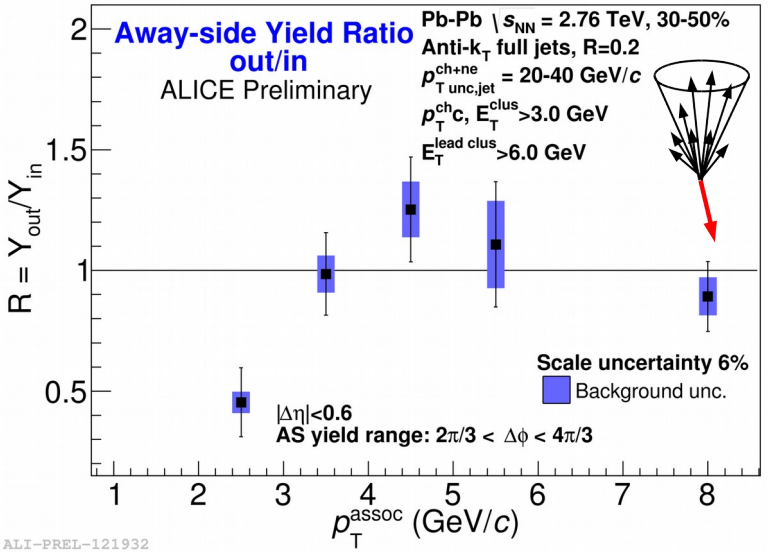
Jet-hadron correlations vs reaction plane

Full jets
1) signal+bkgd
2) bkgd dominated
3) bkgd RPF fit









- No modification of constituents relative to reaction plane

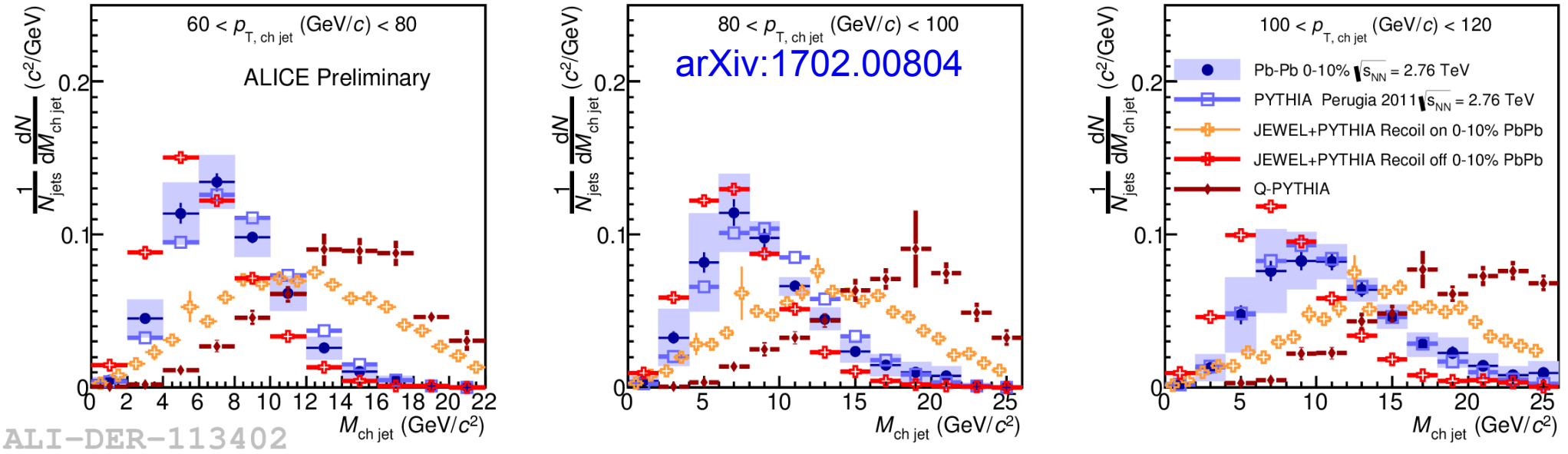
  → Jet-by-jet fluctuations more important than path length [PLB 735 157(2014)]

  – Also needed to explain high p_T v_2 [PRL 116 252301 (2016)]

Jet structure

https://i.pinimg.com/736x/a7/42/bc/a742bc8c2dcb0ad8bb47576a7f106c9a--images-of-animals-x-rays.jpg

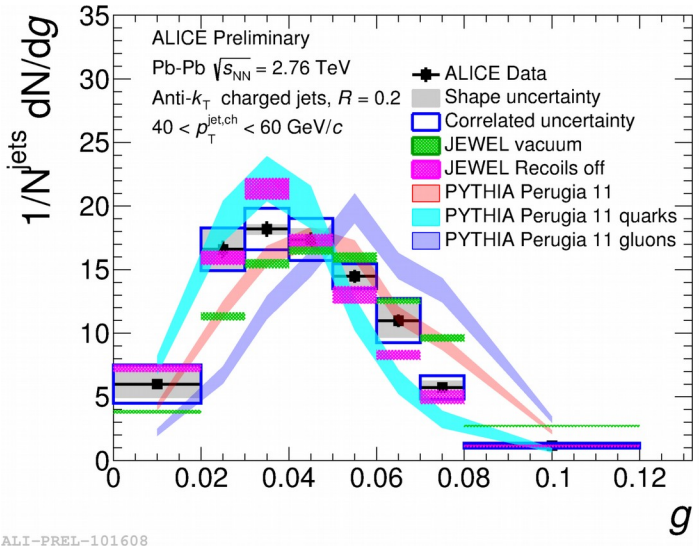
Jet mass



$$M = \sqrt{p^2 - p_T^2 - p_z^2} \qquad p = \sum_{i=1}^{n} p_{T_i} \cosh \eta_i \qquad p_z = \sum_{i=1}^{n} p_{T_i} \sinh \eta_i$$

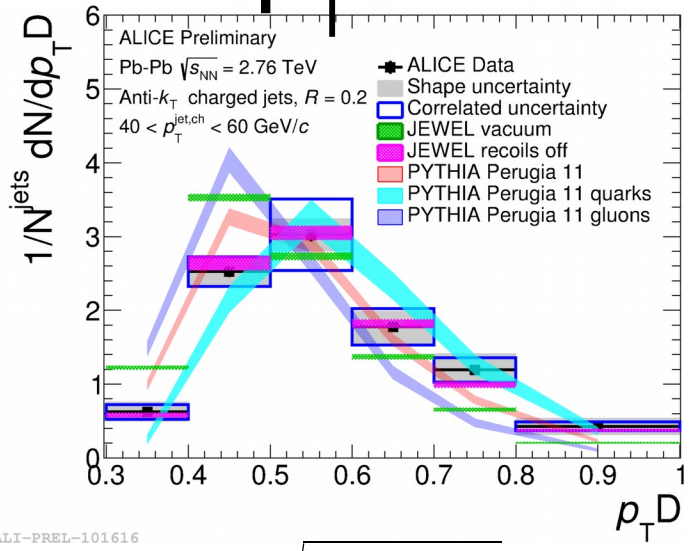
- Quenching models (JEWEL, Q-PYTHIA) show a larger mass than pp-like PYTHIA jets
- Pb-Pb measurement can discriminate among these predictions

Girth g



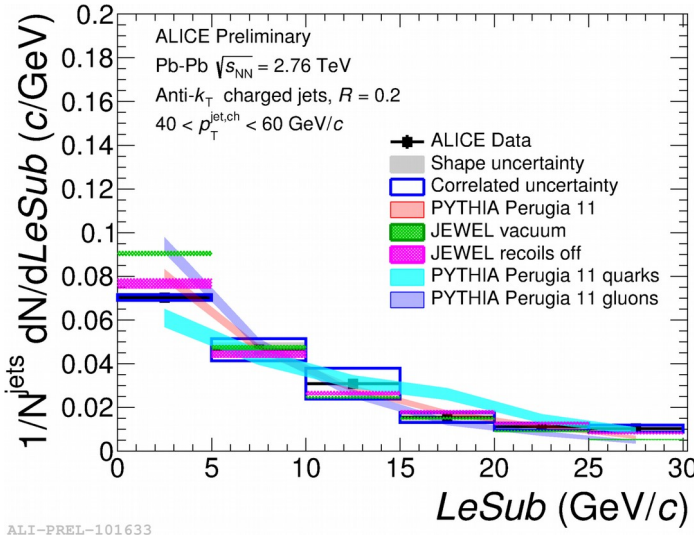
$$g = \sum_{i \in jet} \frac{p_T^i}{p_T^{jet}} r_i$$

Dispersion $p_T D$



$$p_T D = \frac{\sqrt{\sum_{i \in jet} (p_T^i)^2}}{\sum_{i \in jet} p_T^i}$$

LeSub

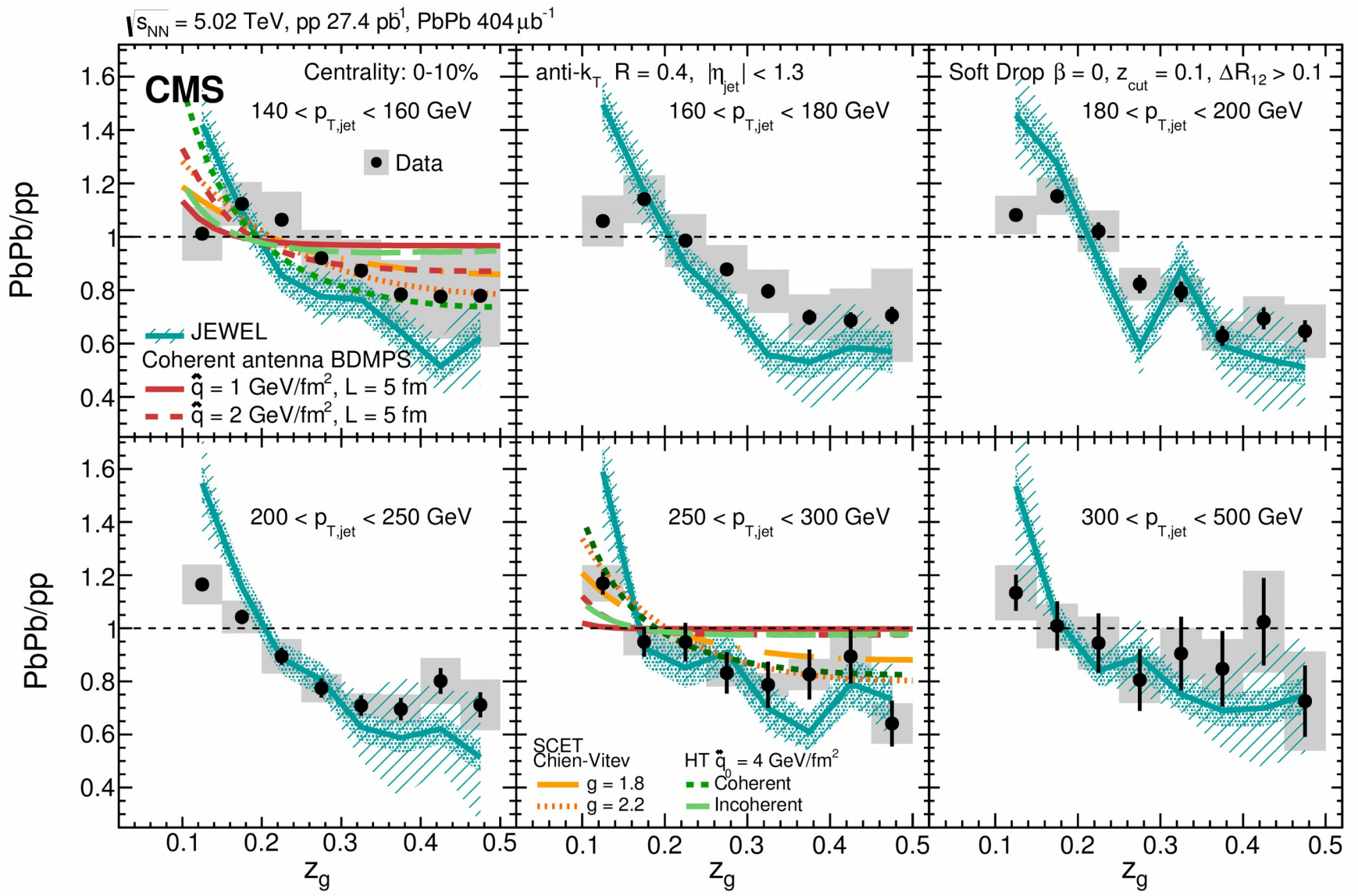


$$LeSub = p_T^{leading} - p_T^{subleading}$$

Jets are slightly more collimated than in pp

Agrees with PYTHIA

Splitting function



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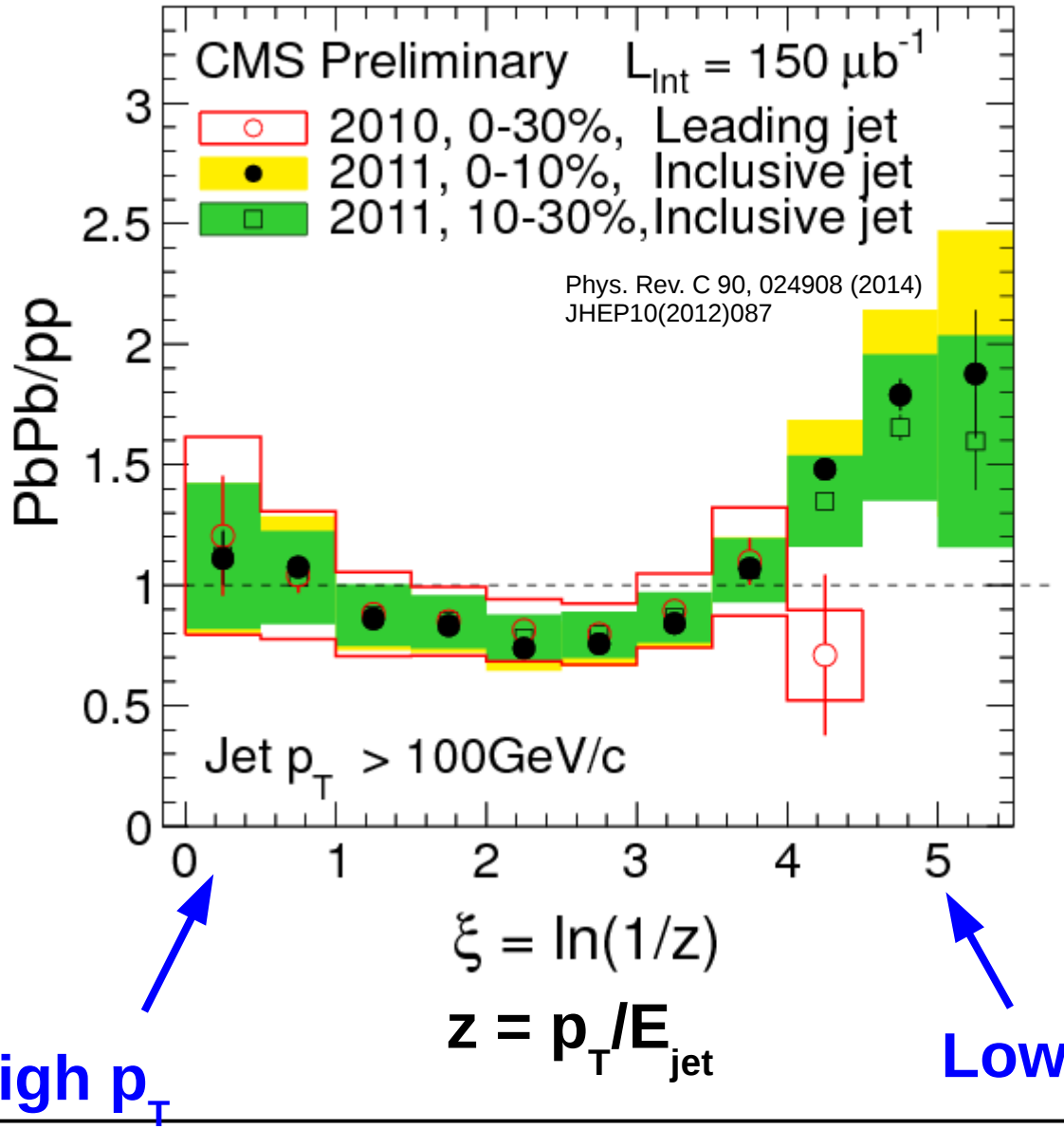
  - Using mostly hadron spectra
- We have not gotten many quantitative constraints out of other observables.
- We don't *truly* know if they are actually sensitive to the physics we want to measure.
- Theoretical calculations sensitive to things we might not have under control.

What you see depends on where you look



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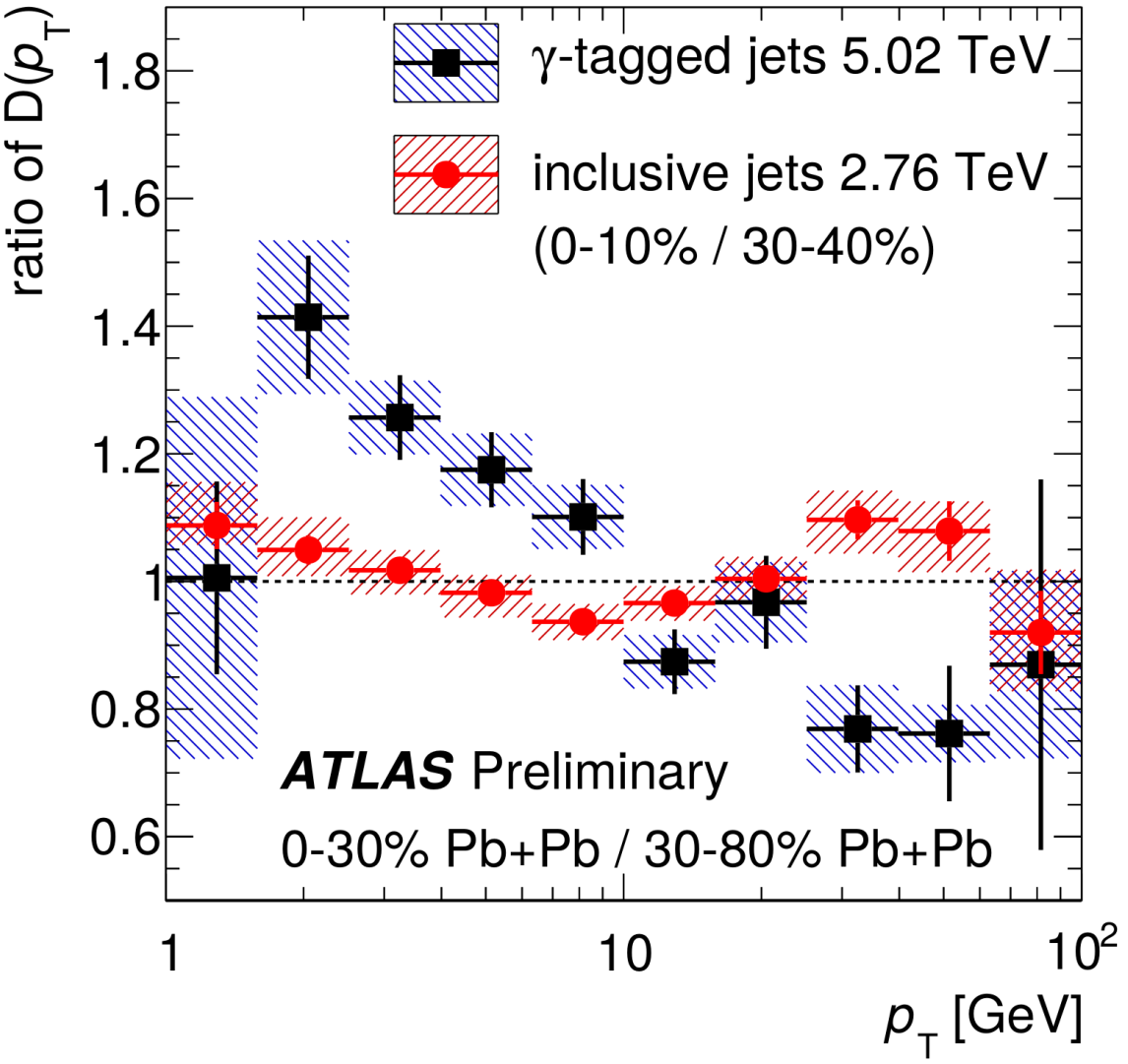
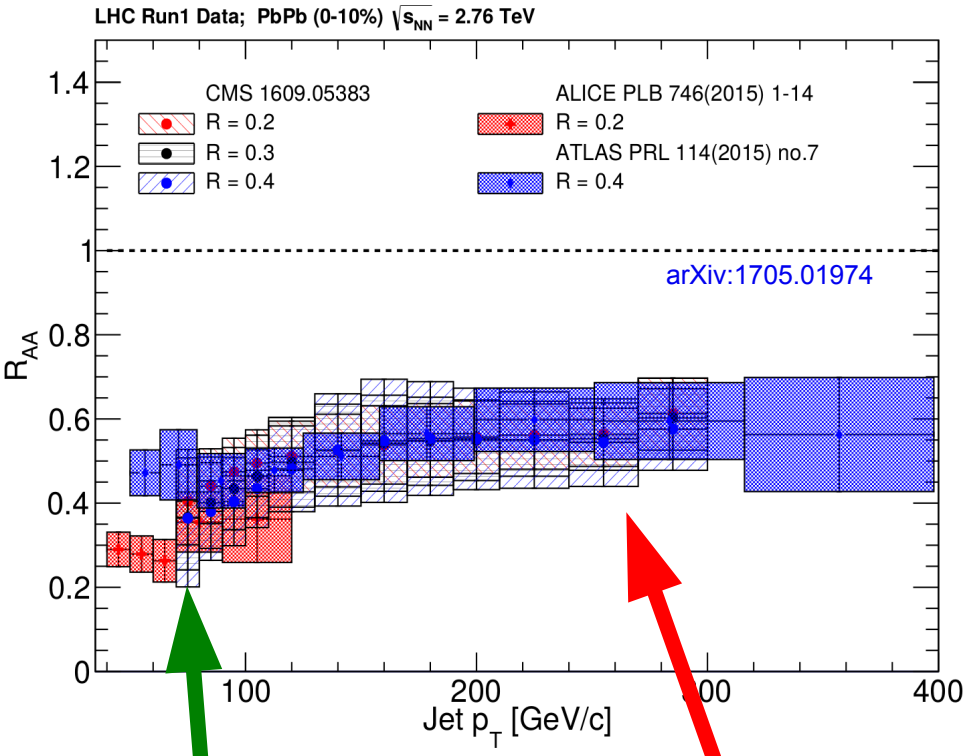


ATLAS

Background subtraction method:

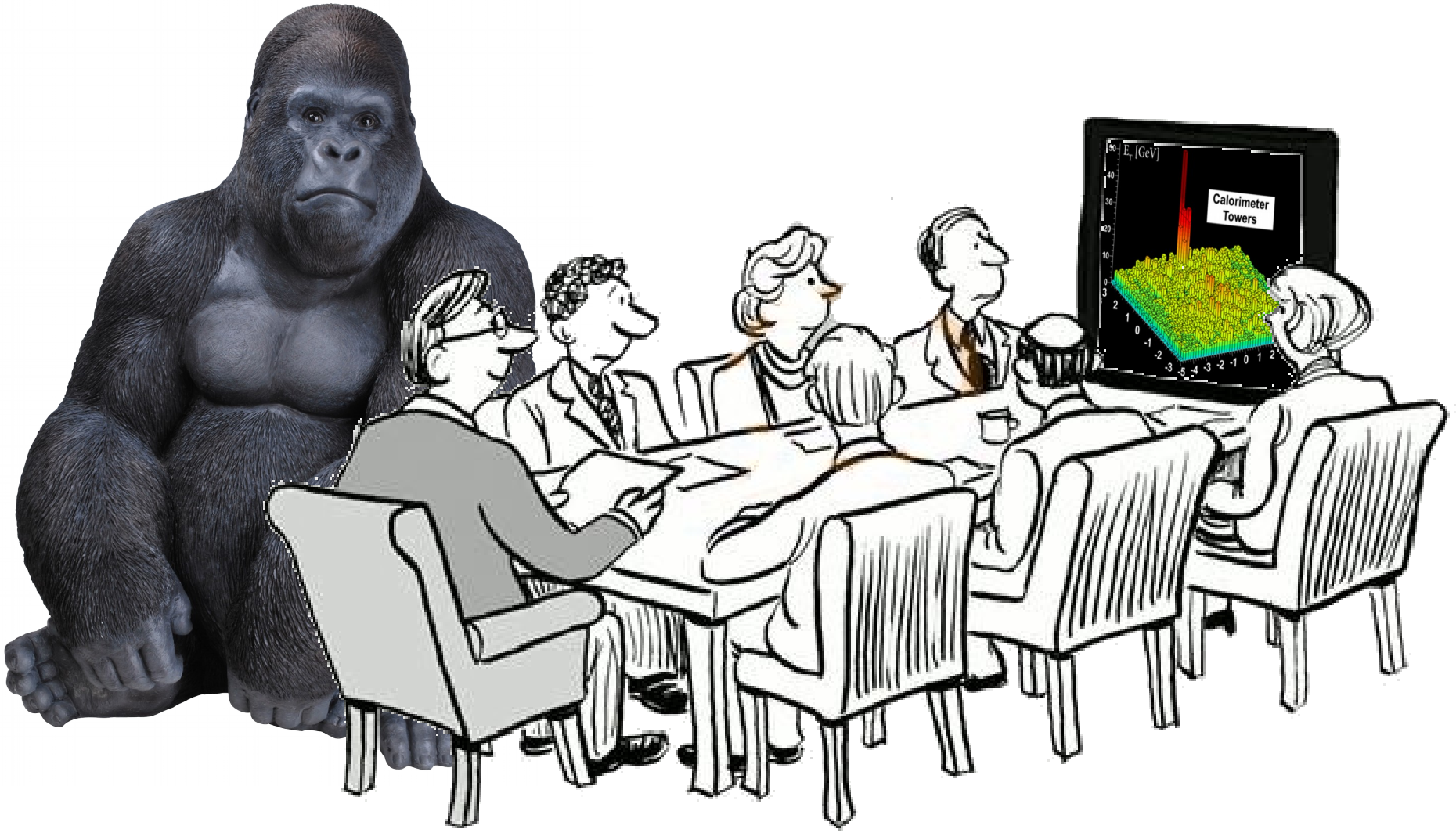
- Iterative procedure
  - **Calorimeter jets:** Reconstruct jets with R=0.2. v_2 modulated <Bkgd> estimated by energy in calorimeters excluding jets with at least one tower with $E_{tower} > \langle E_{tower} \rangle$
    Track jets: Use tracks with p_T>4 GeV/c
  - Calorimeter jets from above with E>25 GeV and track jets with p_T>10 GeV/c used to estimate background again.
- Calorimeter tracks matching one track with p_T>7 GeV/c or containing a high energy cluster E >7 GeV are used for analysis down to E_{jet} = 20 GeV



But they do matter down here!

Constituent biases don't matter that much up here

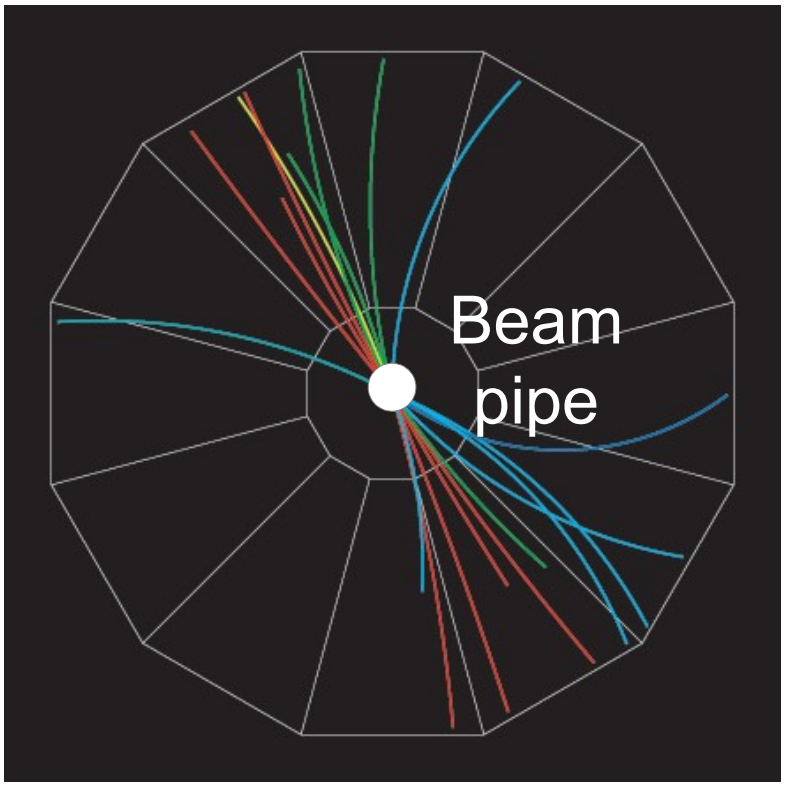
Phys. Lett. B 719 (2013) 220-241

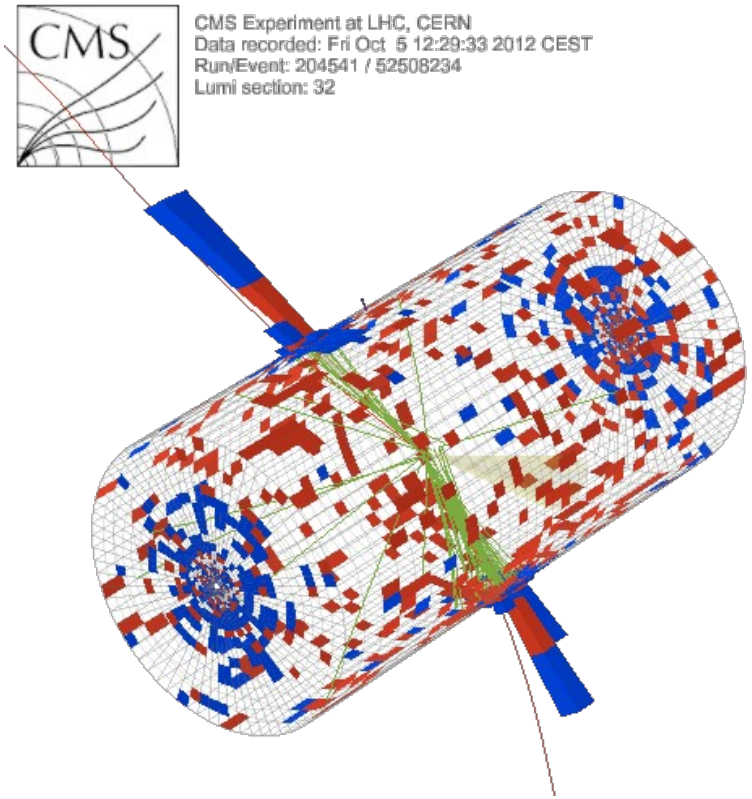

E_T [GeV]
Calorimeter Towers

What is a jet?

What is a jet?

p+p → dijet





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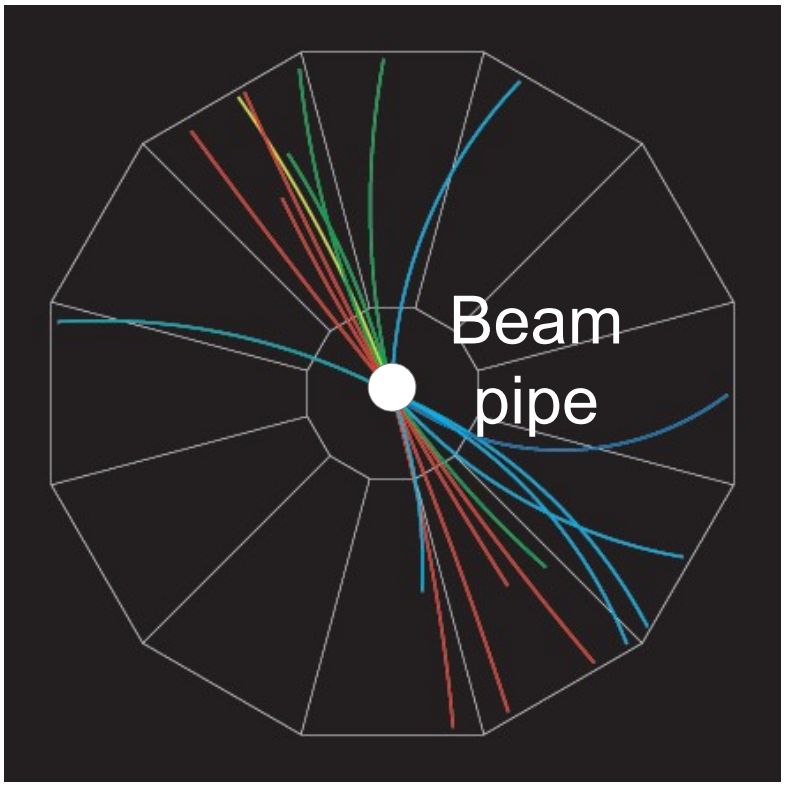
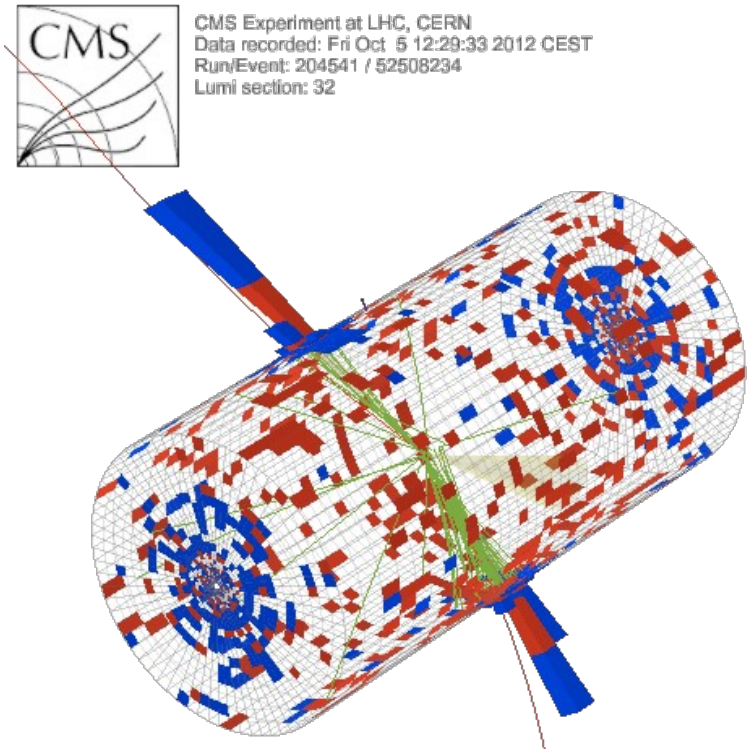
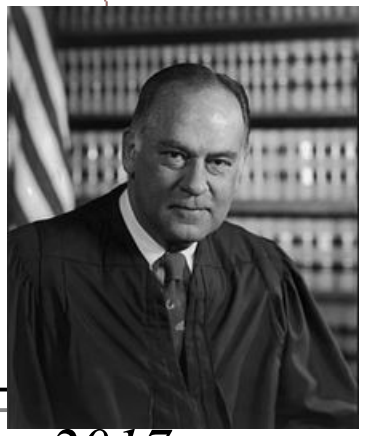




"I know it when I see it"

US Supreme Court Justice Potter Stewart,
Jacobellis v. Ohio



Jet finding in pp collisions

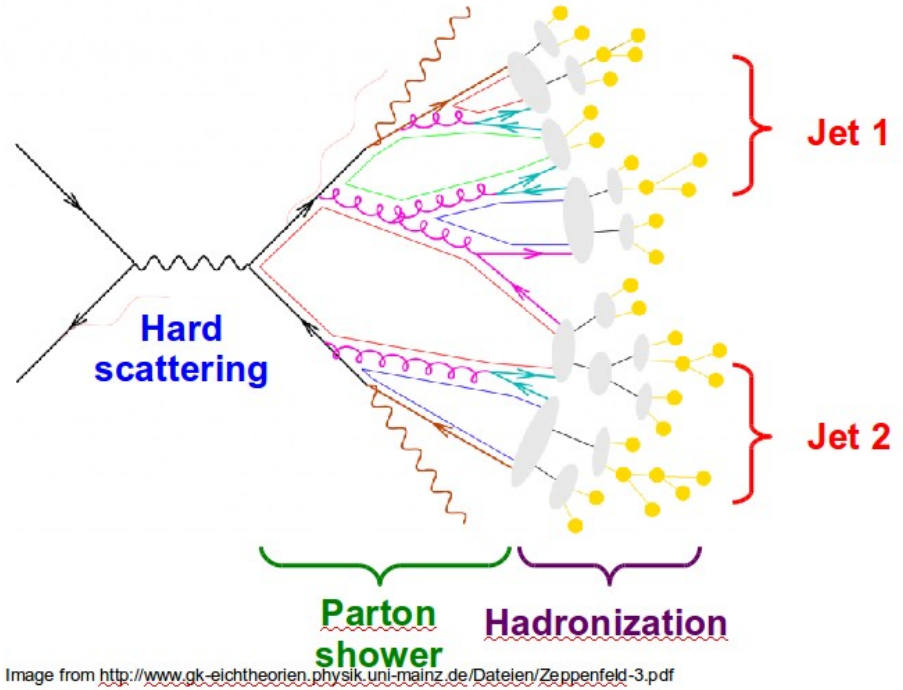


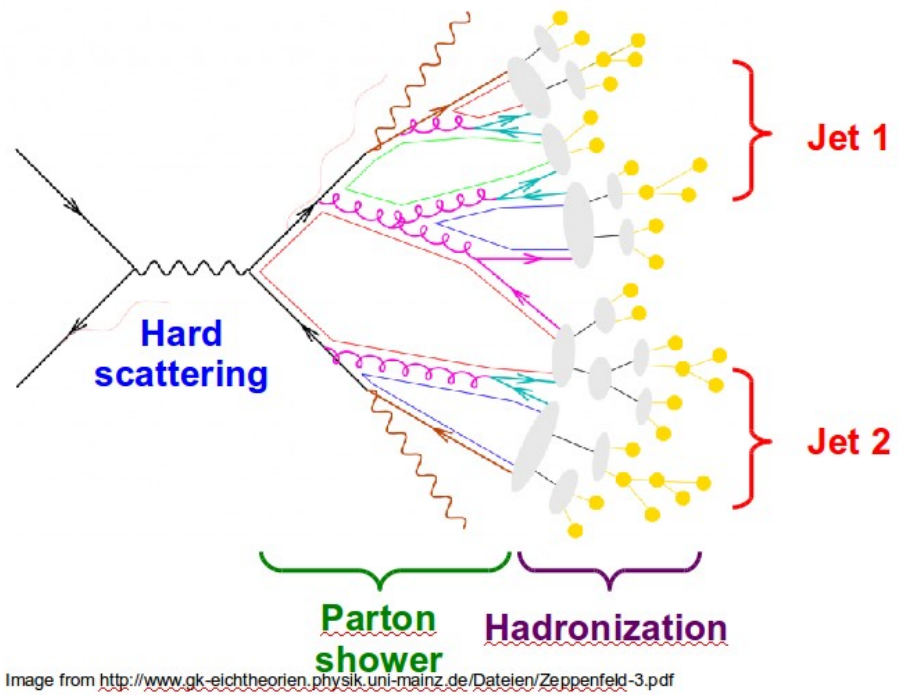
Image from http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

- Jet finder: groups final state particles into jet candidates
  - Anti-k_T algorithm
    JHEP 0804 (2008) 063 [arXiv:0802.1189]
- Depends on hadronization
- Ideally
  - Infrared safe
  - Colinear safe

Snowmass Accord: Theoretical calculations and experimental measurements should use the same jet finding algorithm. Otherwise they will not be comparable.

A jet is what a jet finder finds.

Jet finding in AA collisions



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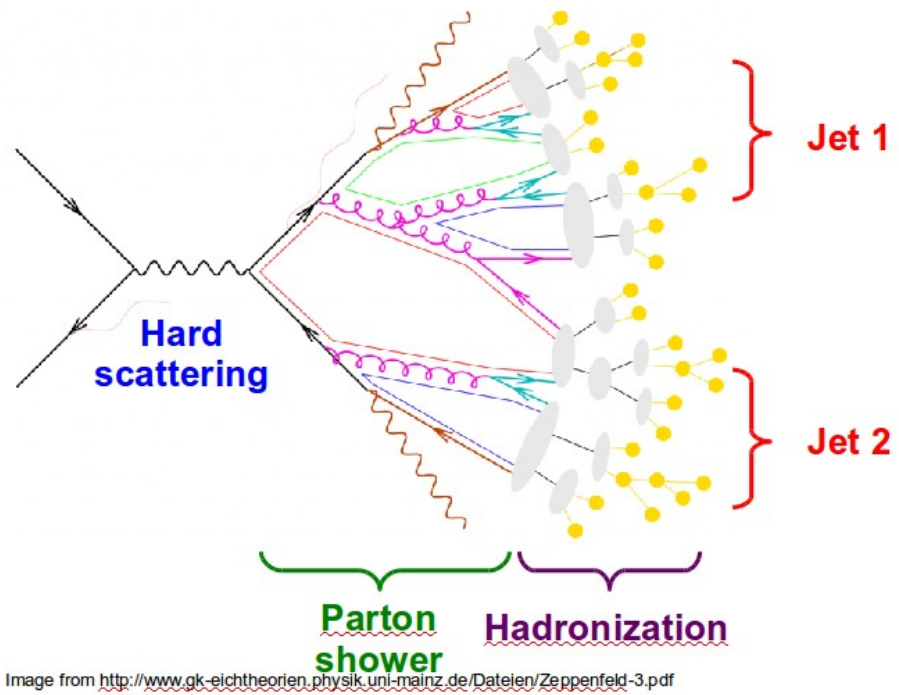
- Energy smearing from background
- Large, fluctuating, correlated background
- Sensitive to methods to suppress combinatorial jets and correct energy
- Focus on narrow/high energy jets

Jet finding in AA collisions



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We need an accord on how to treat background

The invisible gorilla

http://www.theinvisiblegorilla.com/

Bias & background

- **Experimental background subtraction methods:** complex, make assumptions, apply biases
- **Survivor bias:** Modified jets probably look more like the medium
- **Quark/Gluon bias:**
  - Quark jets are narrower, have fewer tracks, fragment harder [Z Phys C 68, 179-201 (1995), Z Phys C 70, 179-196 (1996),]
  - Gluon jets reconstructed with k_T algorithm have more particles than jets reconstructed with anti-k_T algorithm [Phys. Rev. D 45, 1448 (1992)]
  - Gluon jets fragment into more baryons [EPJC 8, 241-254, 1998]
- **Fragmentation bias:** Experimental measurements explicitly select jets with hard fragments

What should we measure?

Jupiter and the Monkey

Jupiter promised a royal reward to the one whose offspring should be deemed the handsomest.

The monkey came with the rest, and presented a flat-nosed, hairless, ill-featured young monkey.

A general laugh saluted her on the presentation of her son.

She resolutely said; "He is at least in the eyes of me, his mother, the dearest, handsomest, and most beautiful of all."

http://aesopsfables.org/F9_Jupiter-and-the-Monkey.html
Abbreviated

What should we measure?

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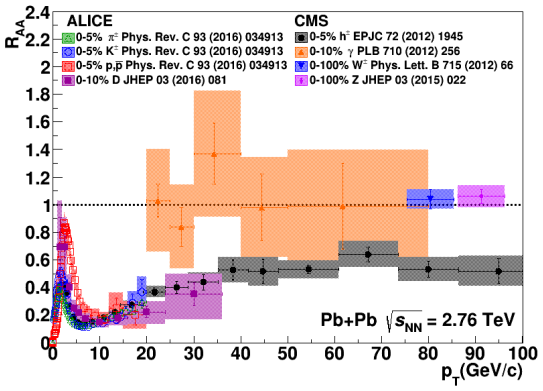

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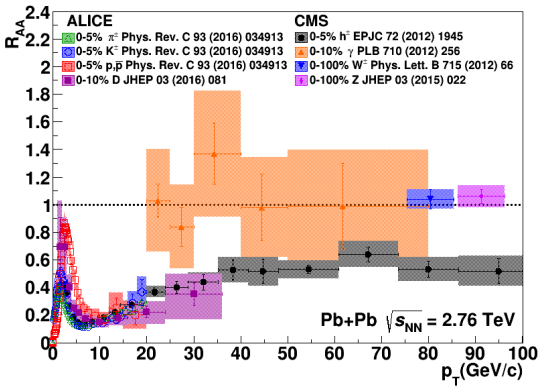

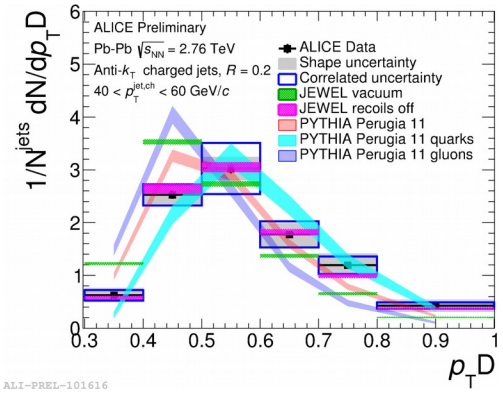

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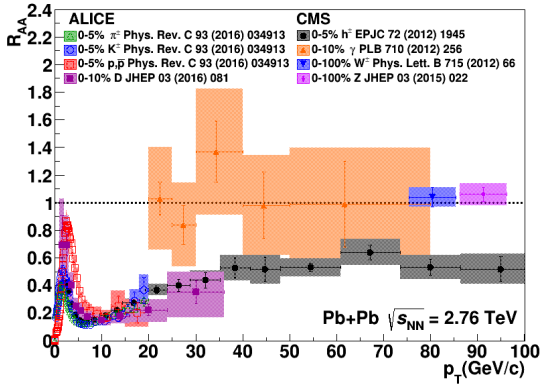

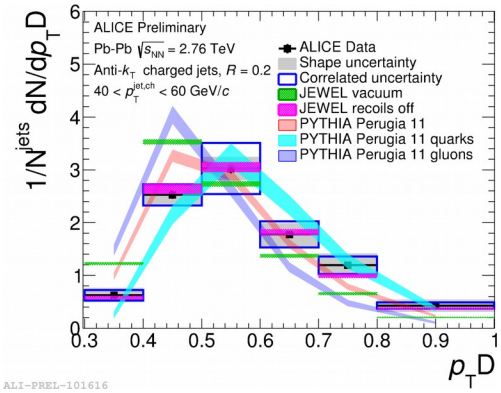

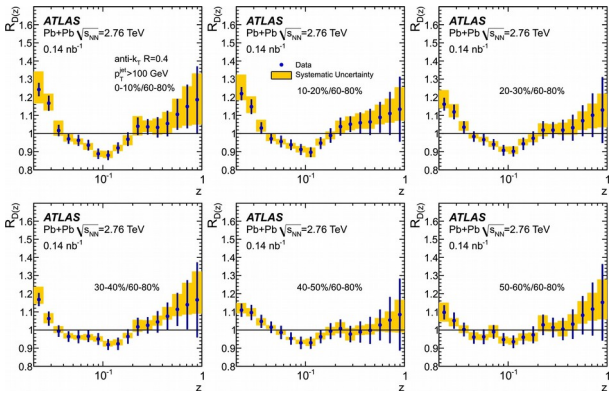

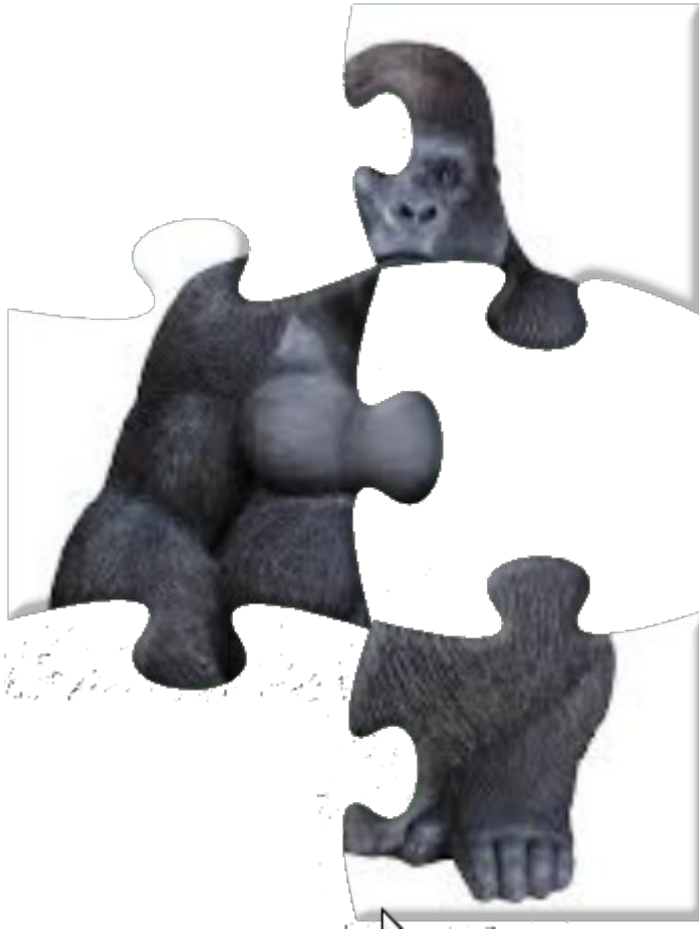

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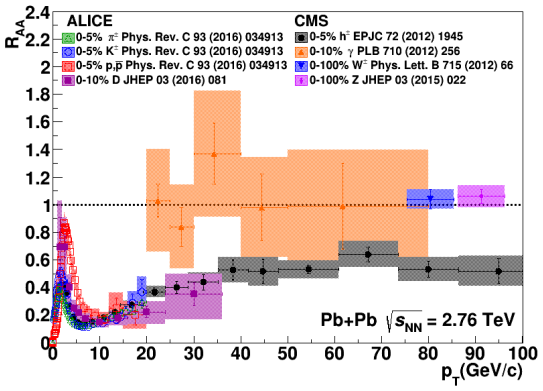

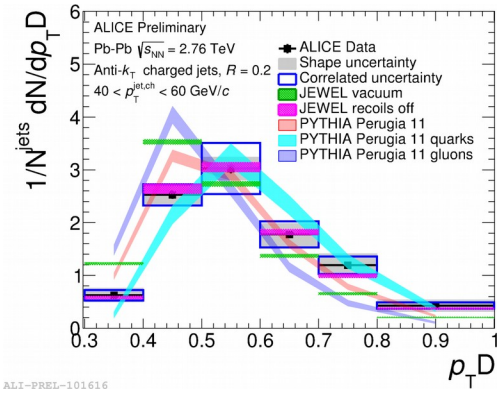

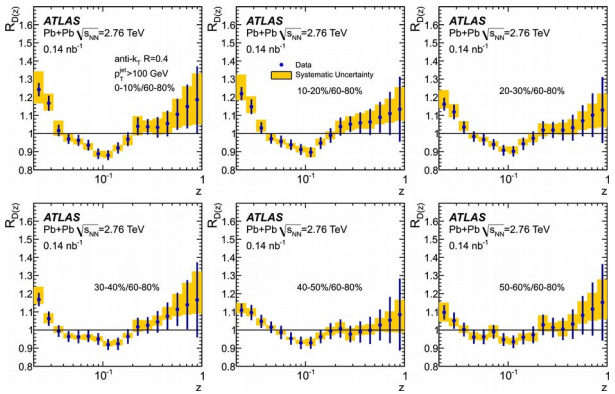

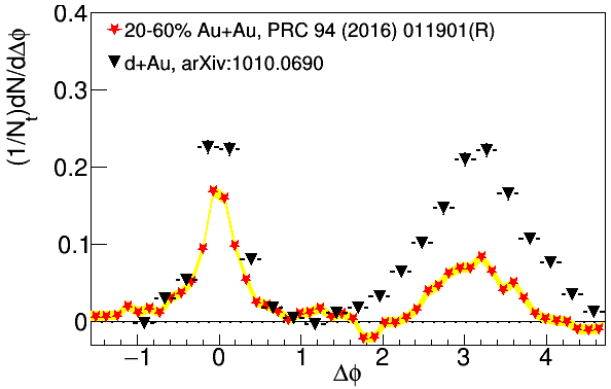

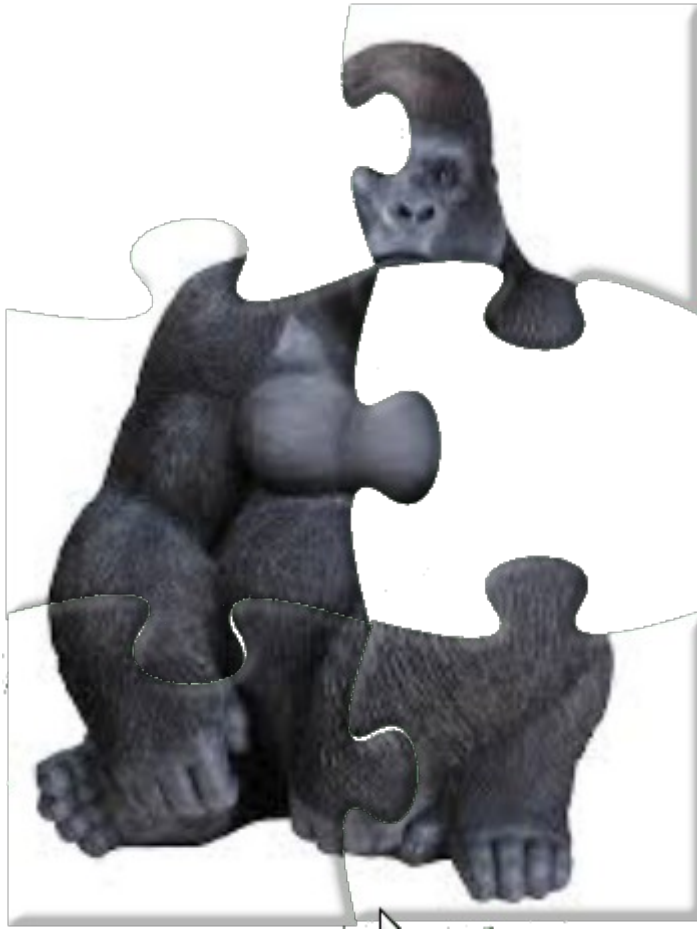

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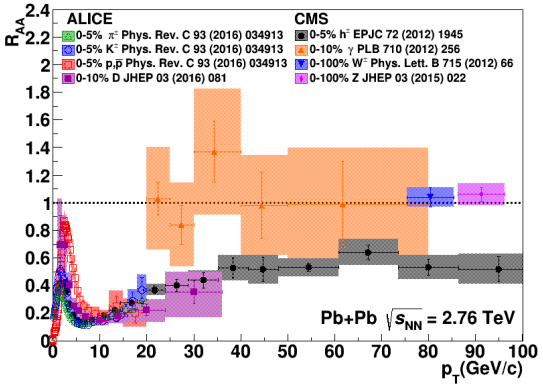
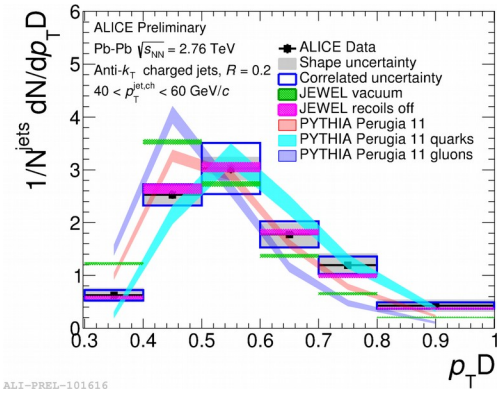
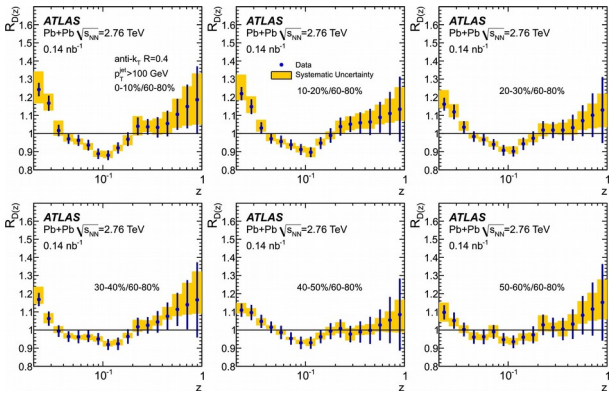
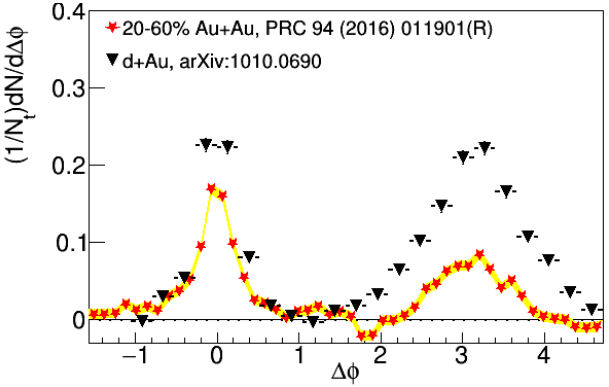
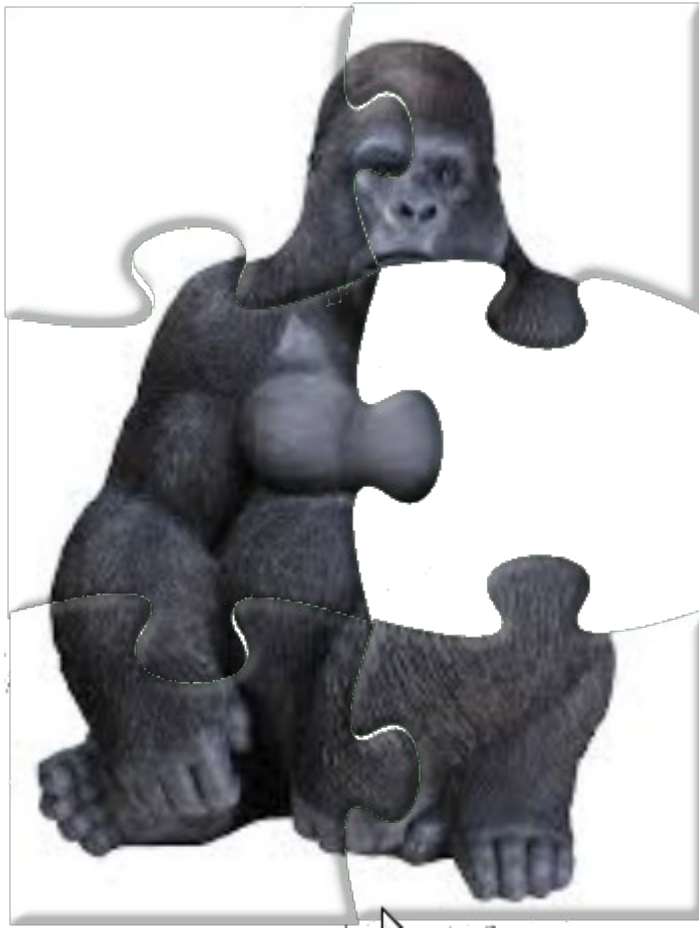
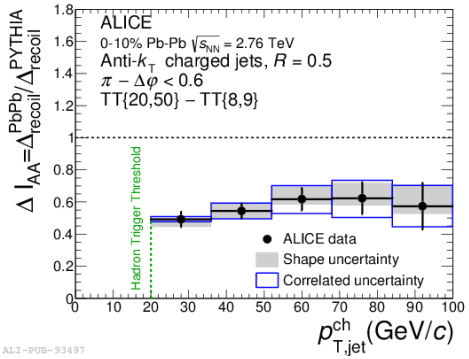




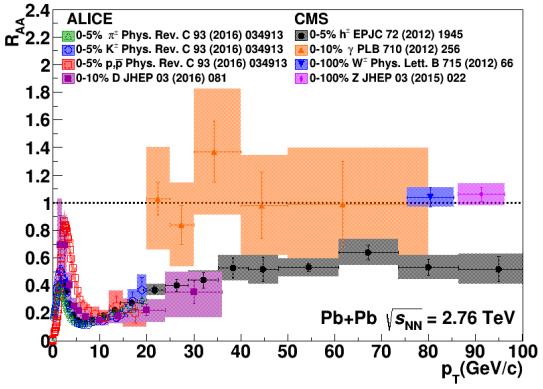


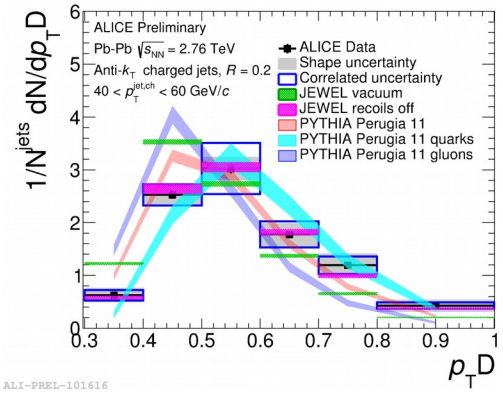


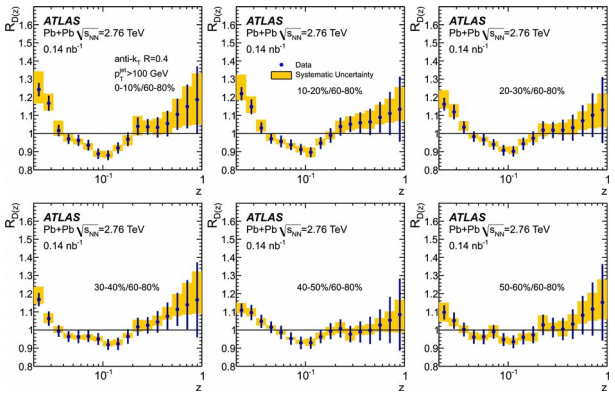


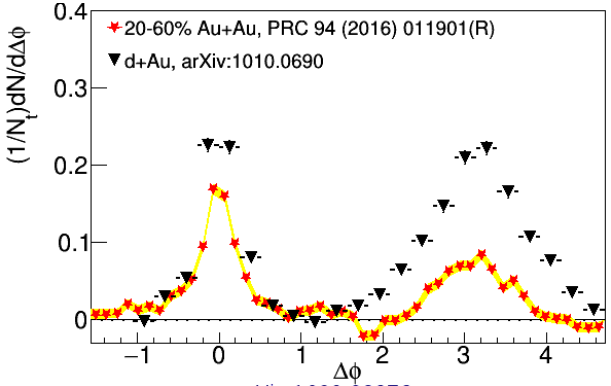


What should we measure?

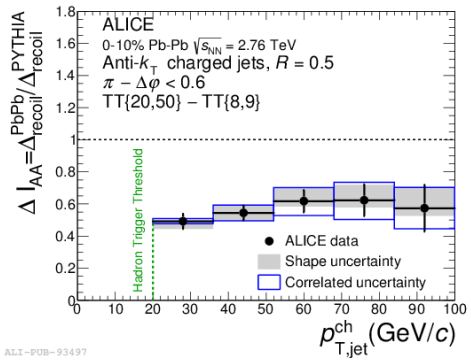


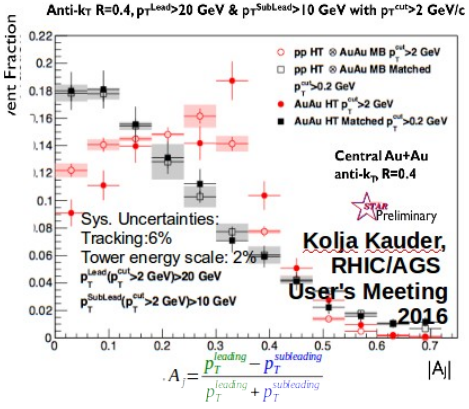


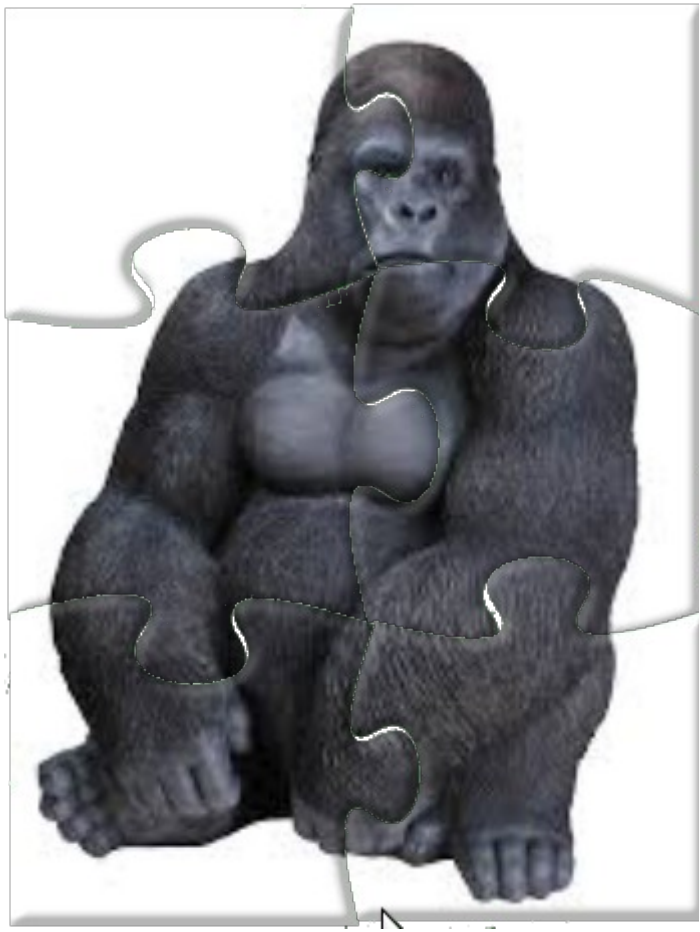




arXiv:1609.03878







Learning about the QGP from jets

- The JETSCAPE collaboration is an NSF funded multi-institutional effort to design the next generation of event generators to simulate the physics of ultra-relativistic heavy-ion collisions. It involves teams of theoretical and experimental physicists, computer scientists, and statisticians from nine institutions.

Lessons from measurements of jets

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  - Report correlation between uncertainties
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- **Make quantitative comparisons to theory**
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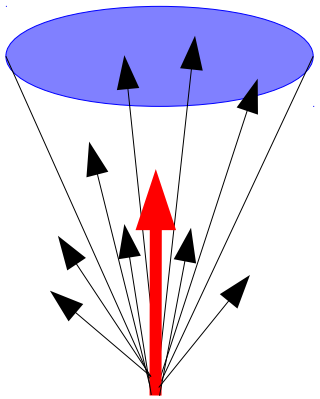
    - Report spectra without T_{AA}!
    - Report point-to-point correlations
- **Make more differential measurements**
- **We need an accord on how to treat background**
  - Experimental cuts matter and are unavoidable
  - Clear definition and implementation of background, biases (via Rivet?)
  - Summer 2018?

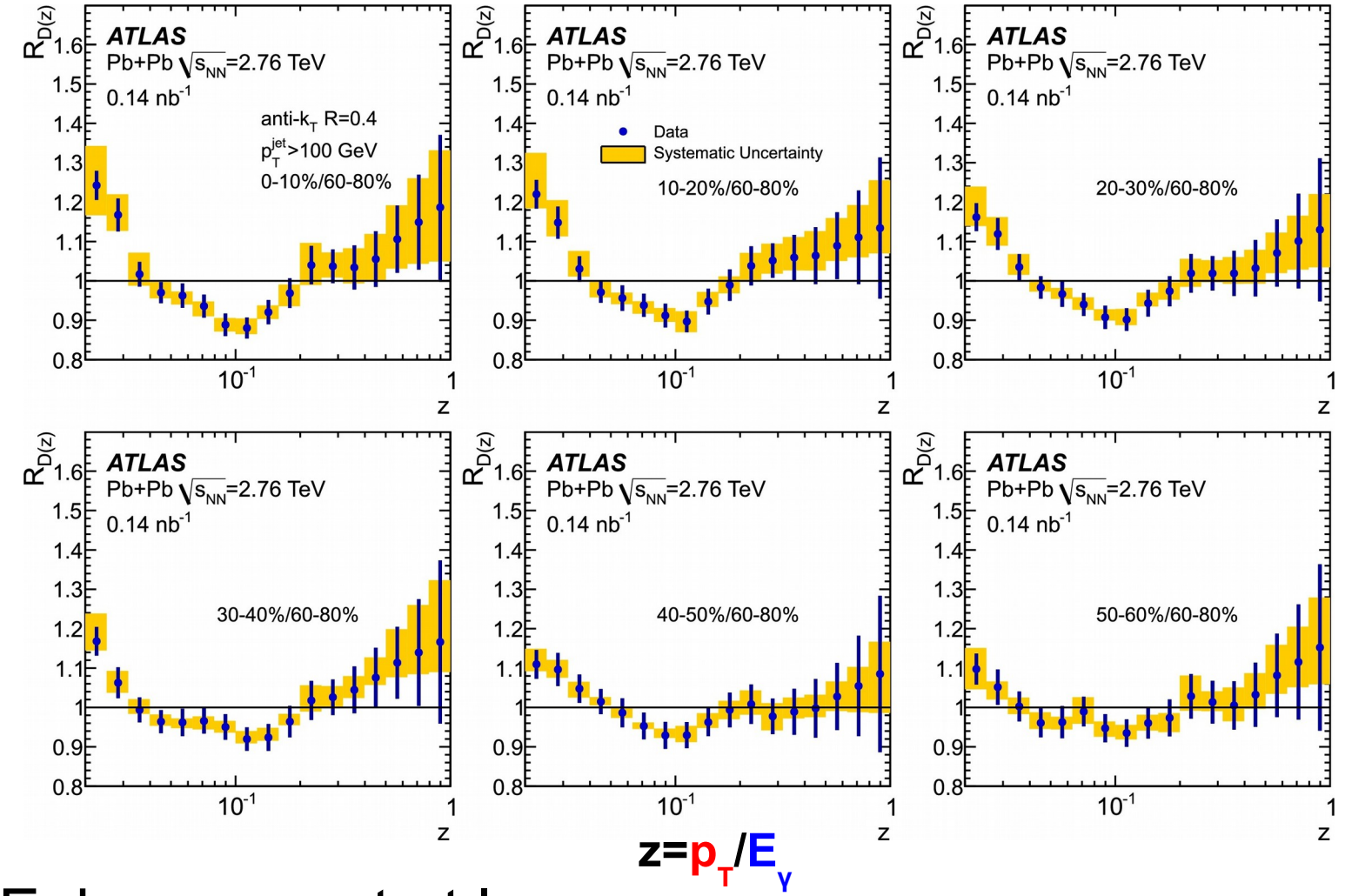
Connors, Nattrass, Reed, & Salur

arxiv:1705.01974

Thank you!

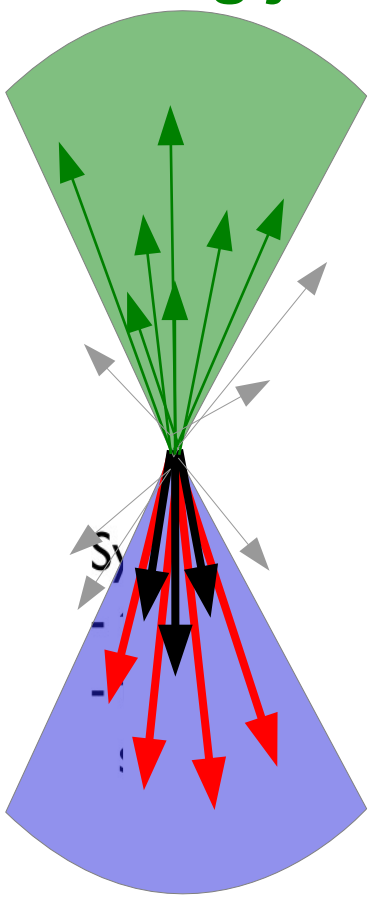
Modified fragmentation



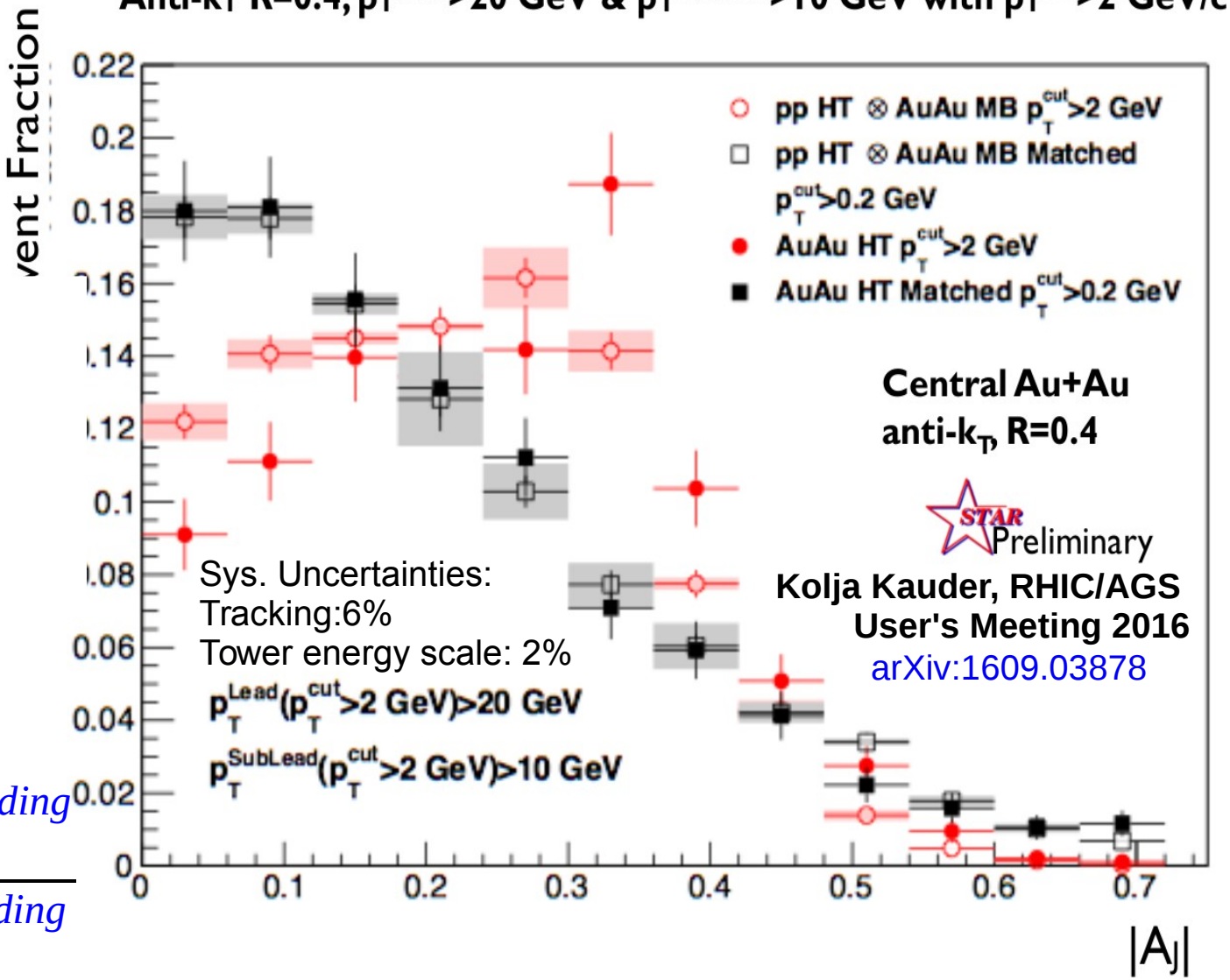


- Enhancement at low z
- No modification/enhancement at high z?

Di-jet asymmetry



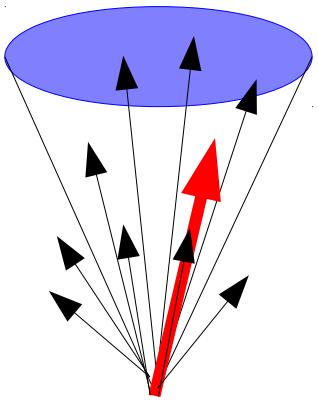
$$A_j = \frac{p_T^{leading} - p_T^{subleading}}{p_T^{leading} + p_T^{subleading}}$$

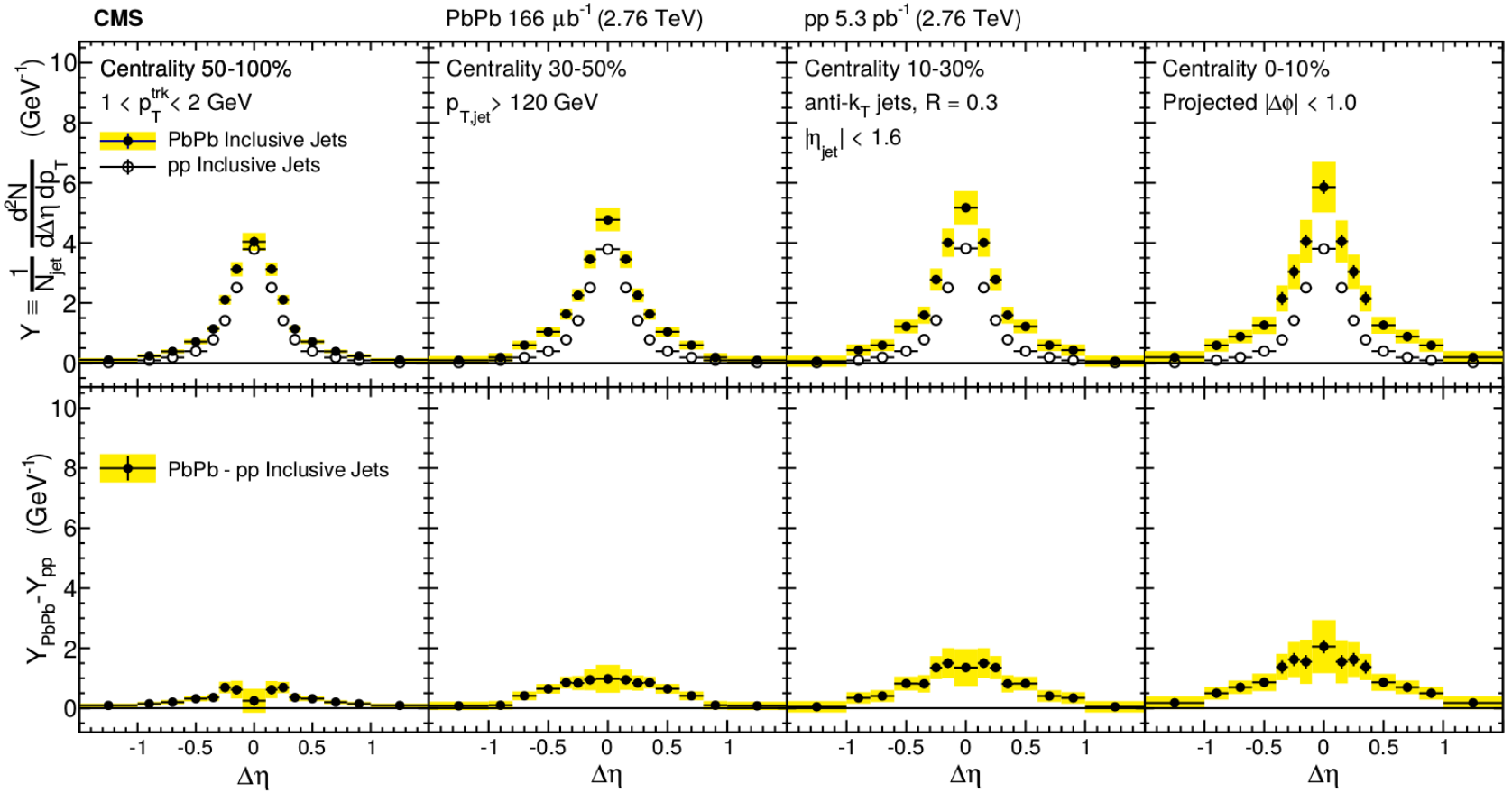


Au+Au di-jets more imbalanced than p+p for p_{Tcut}>2 GeV/c

Au+Au A_J ~ p+p A_J for matched di-jets (R=0.4)

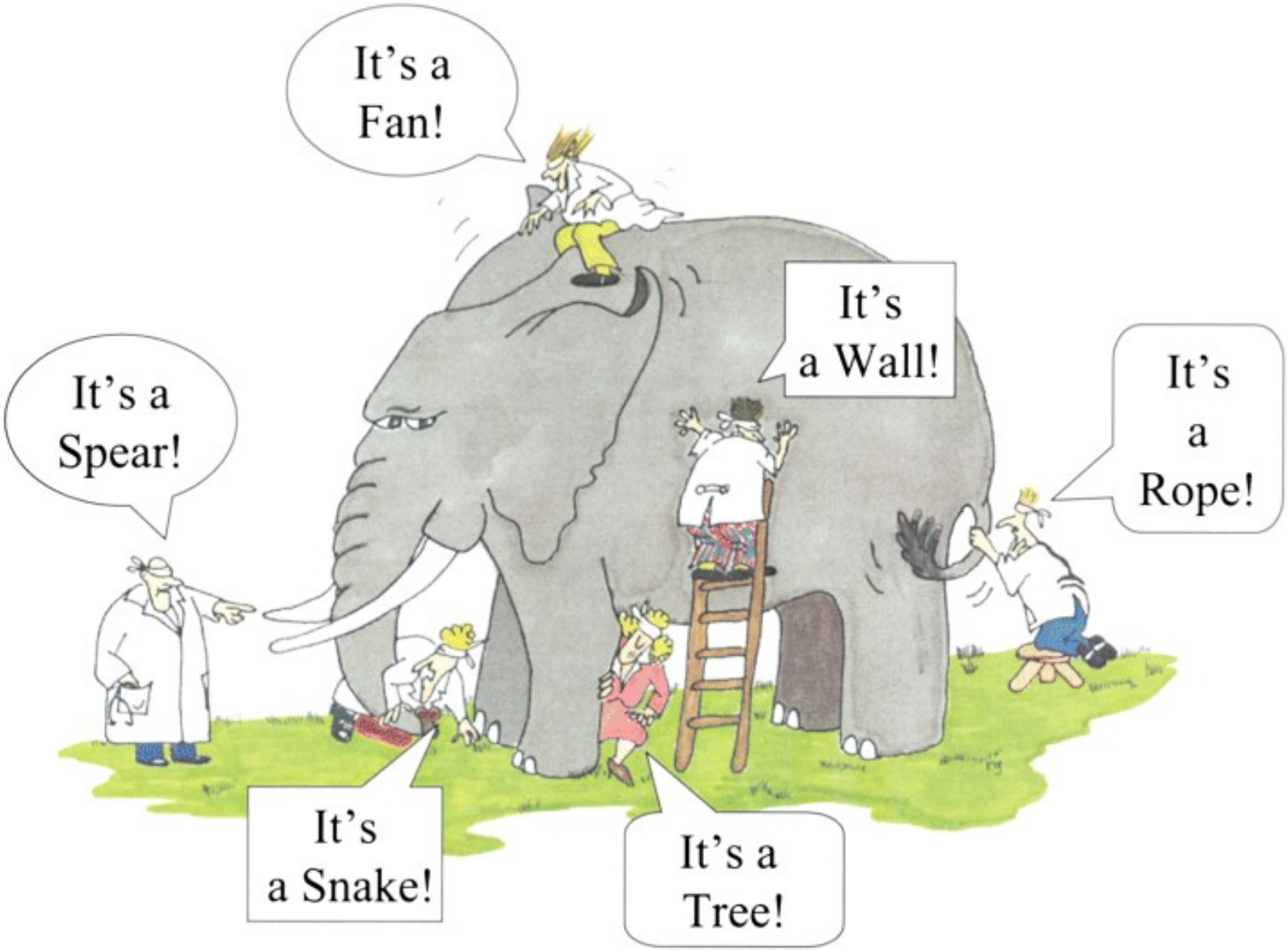
Jet-hadron correlations





- Jets are broader, constituents are softer
- Also seen in:
  - Di-hadron correlations [Lots of papers]
  - Jet shapes [arXiv:1708.09429, arXiv:1512.07882, arXiv:1704.03046]
  - Dijet asymmetry with soft constituents [PRL119 (2017) 62301]

Blind men and the elephant



V1 estimates

What have we learned?

/Funny/2011/9/20/Funny_Animals_Pictures_mhsqs.jpg

https://i.pinimg.com/736x/b1/06/40/b10640a9668443428d0228a7dc4e5a92--see-no-evil-evil-cats.jpg

Hear no evil, see no evil, speak no evil

Wikipedia:

- There are various meanings ascribed to the monkeys and the proverb including associations with being of good mind, speech and action.
- In the Western world the phrase is often used to refer to those who deal with impropriety by turning a blind eye.

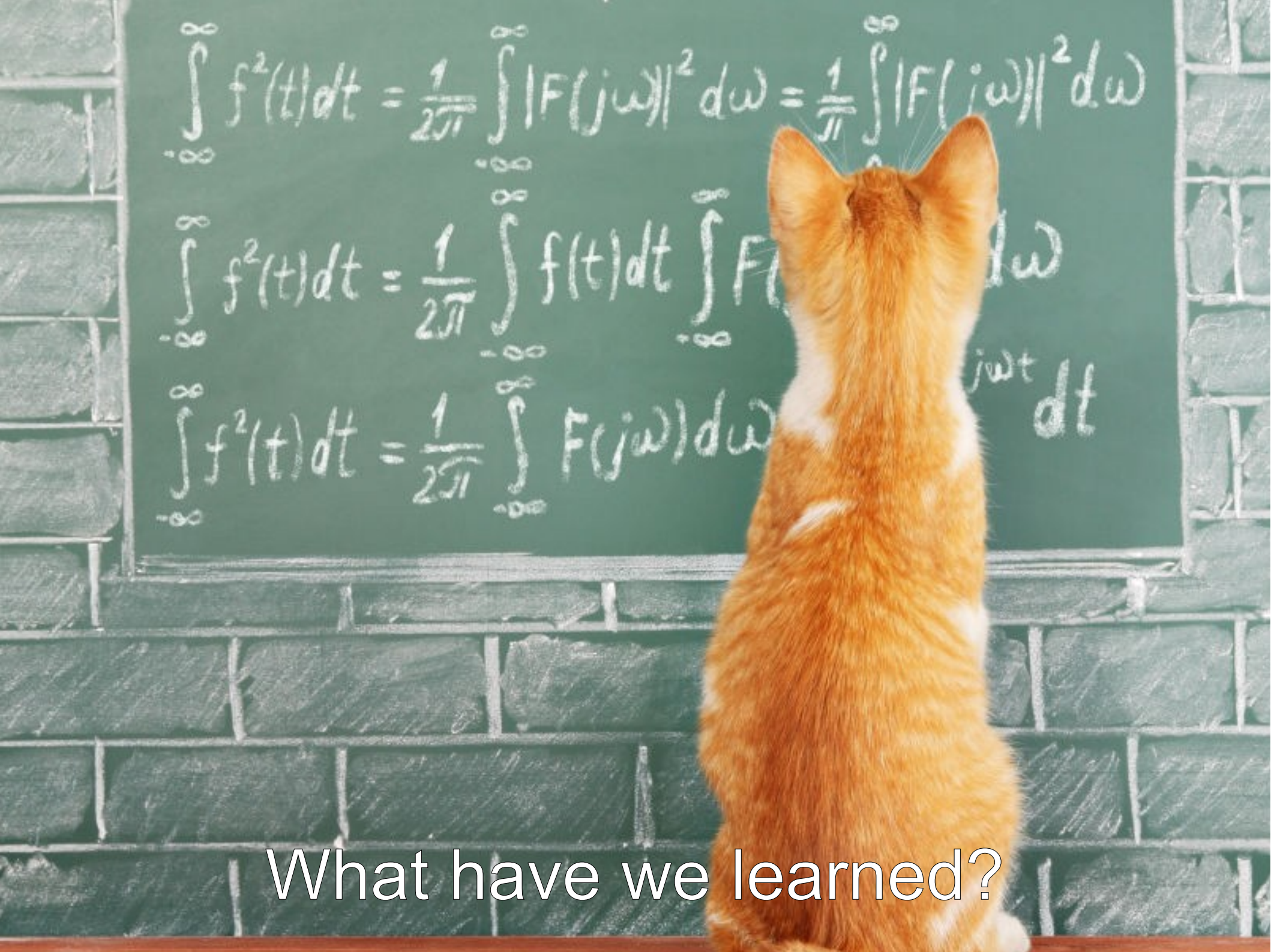
Partonic energy loss

http://i.huffpost.com/gen/1111048/images/o-TIRED-KITTEN-facebook.jpg

Broadening and Softening

Jet structure

http://www.kestrel.ws/erasmus/pics/cat-xray_body.jpg


What have we learned?