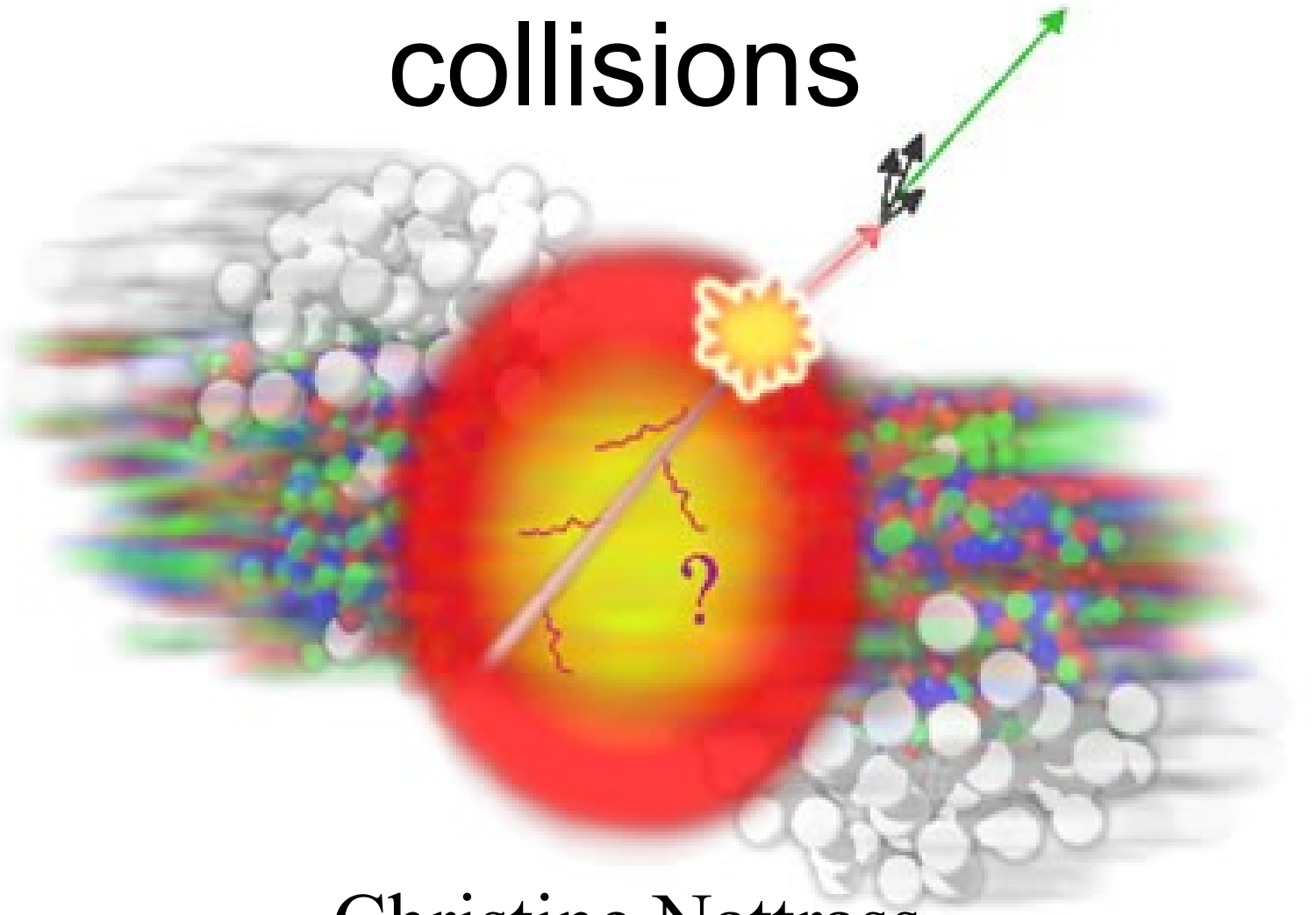
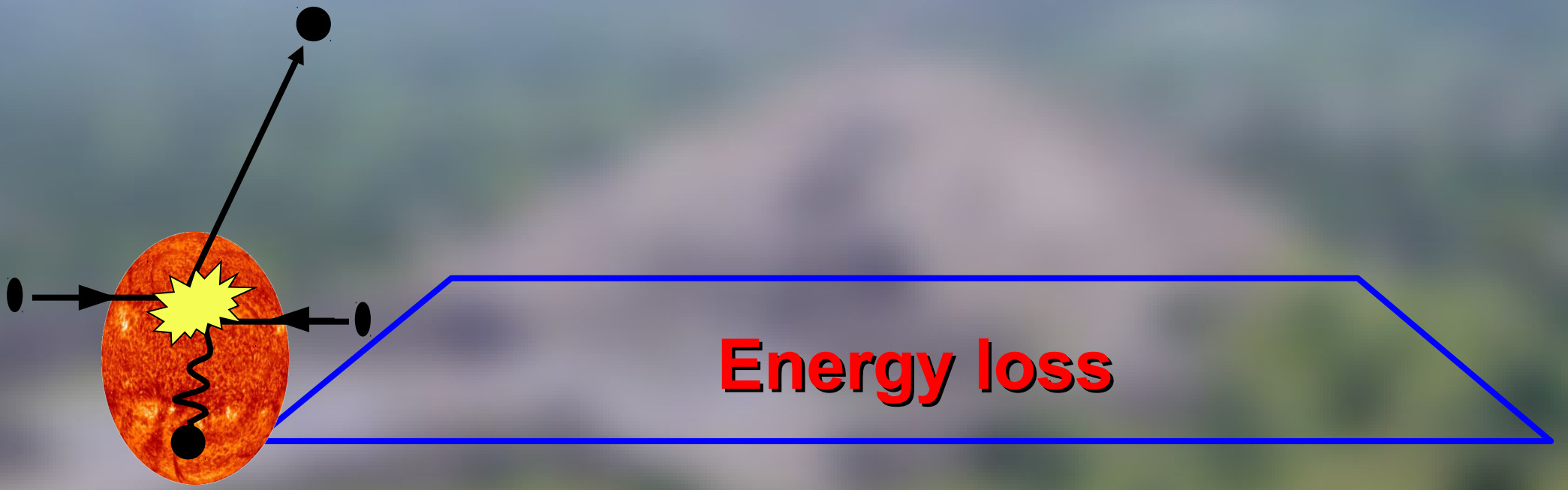
Measurements of jets in heavy ion collisions

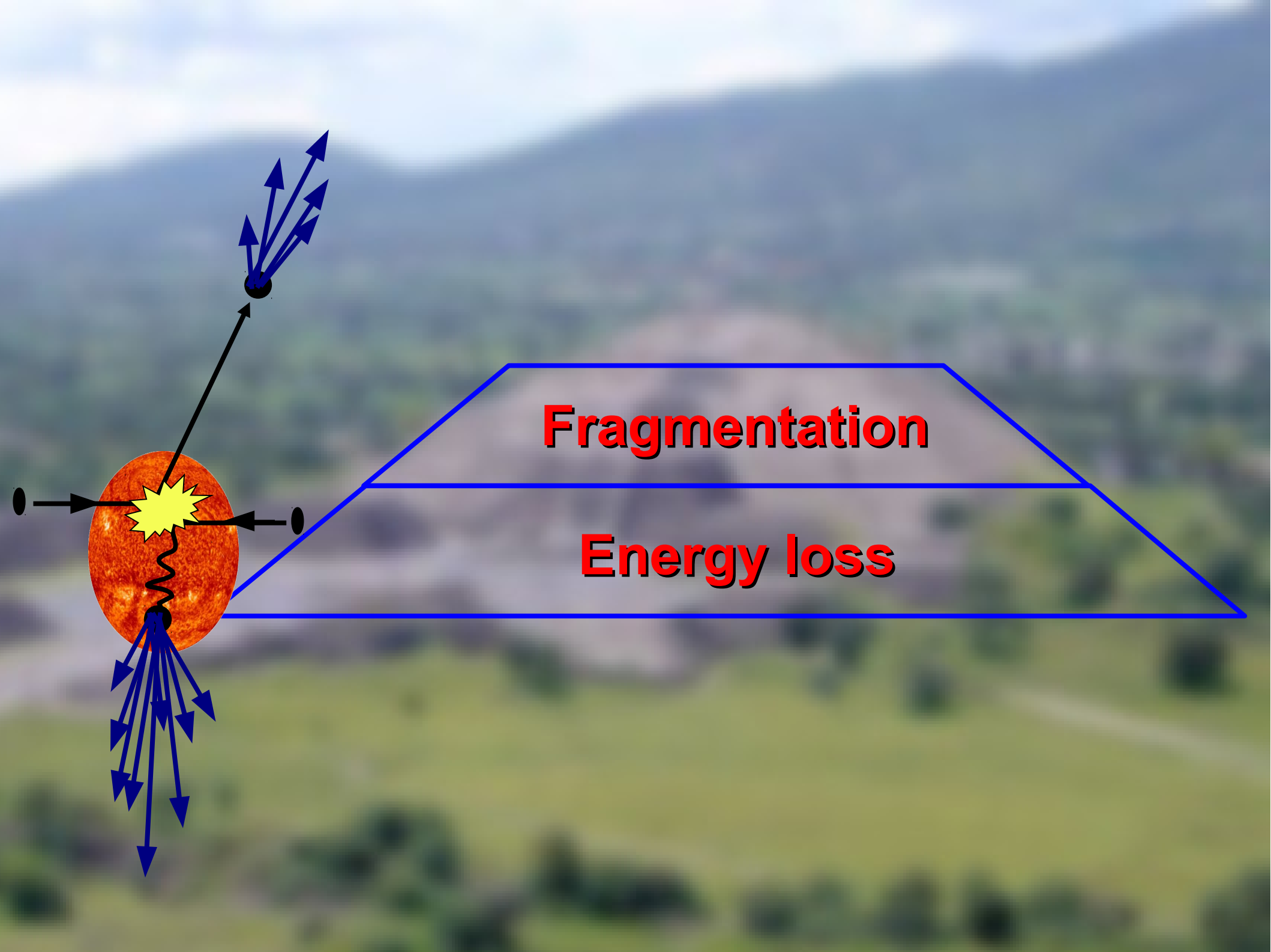


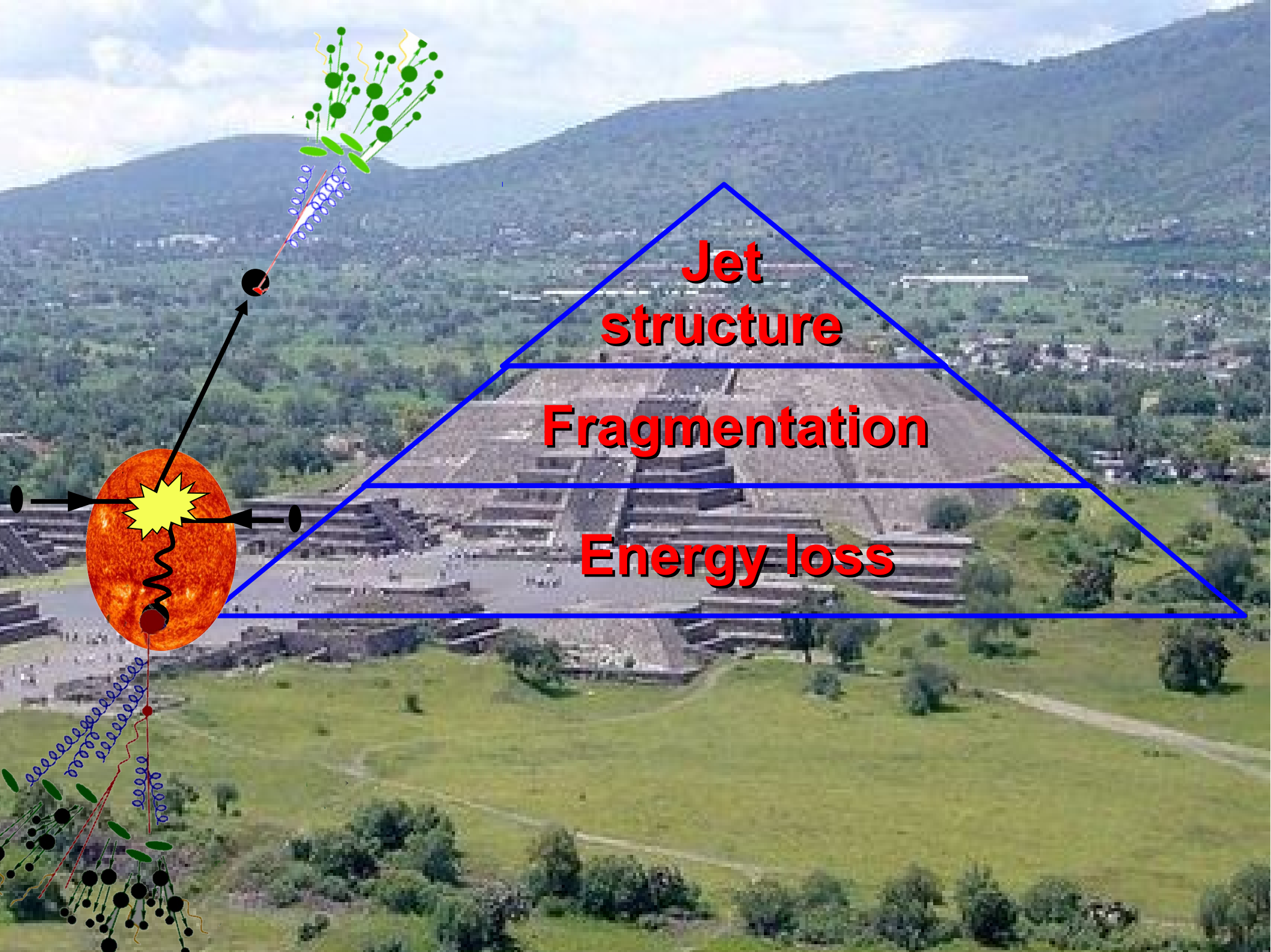
Christine Nattrass
University of Tennessee, Knoxville
Largely based on Connors, Nattrass, Reed, & Salur arxiv:1705.01974

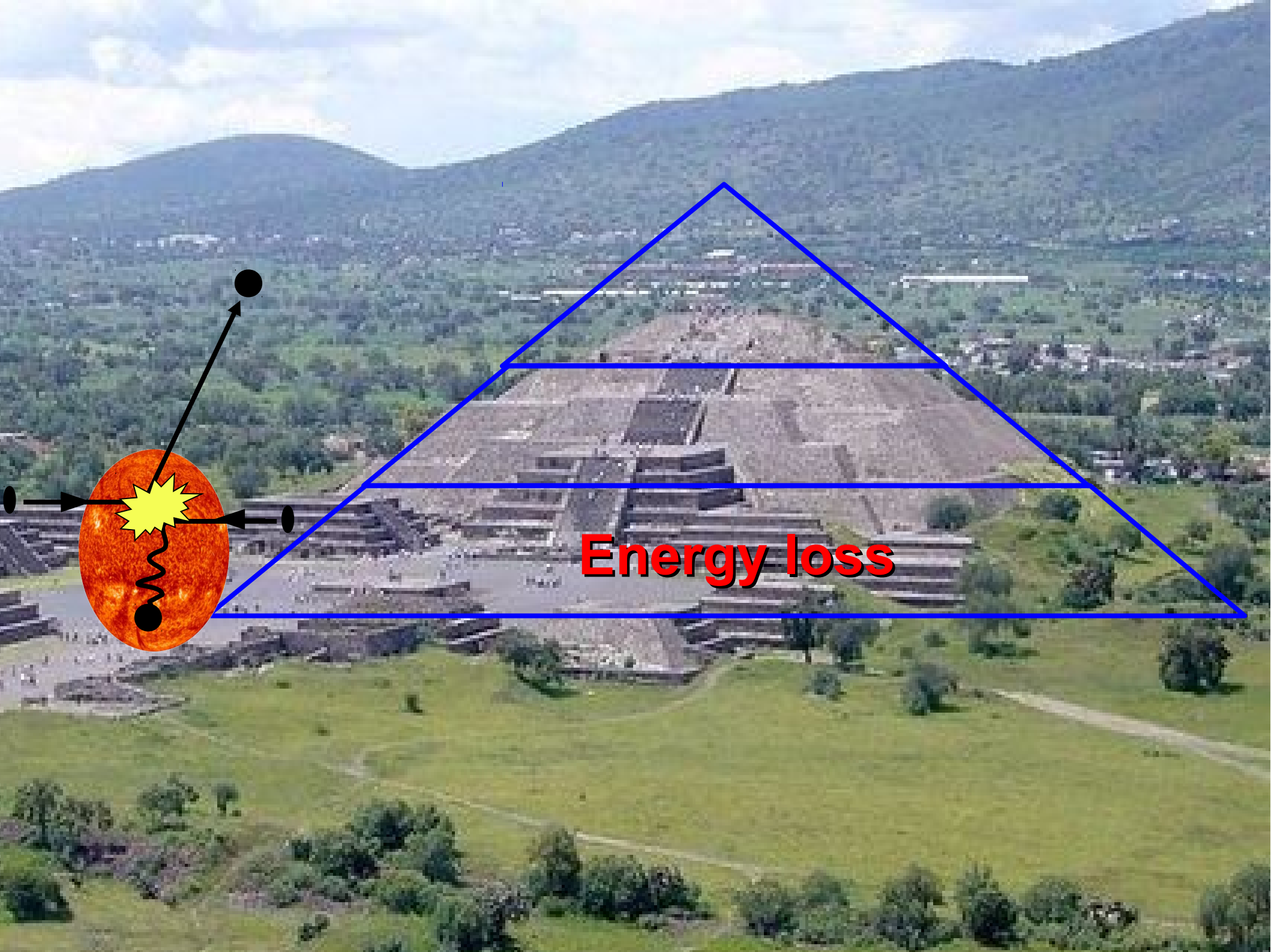
Overview

- Jet quenching in a nutshell
  - Partons lose energy in the medium
  - This lost energy makes jets broader and softer
  - *See also talks from*
    Abhijit Majumder
    Yen-jie Lee
    Justin Frantz
    Laura Havener
    Cesar Luis da Silva
    ...
- Towards quantitative understanding


Energy loss


Fragmentation
Energy loss

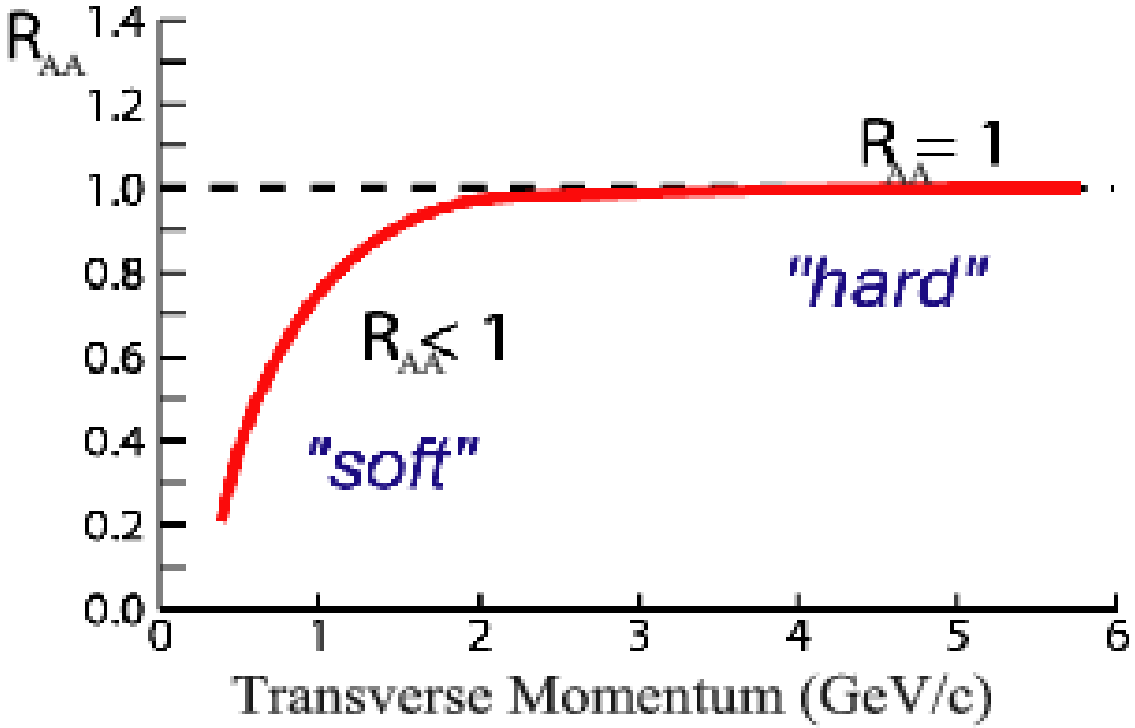

Jet
structure
Fragmentation
Energy loss


Energy loss

Nuclear modification factor

- Measure spectra of probe (jets) and compare to those in p+p collisions or peripheral A+A collisions
- If high-p_T probes (jets) are suppressed, this is evidence of jet quenching

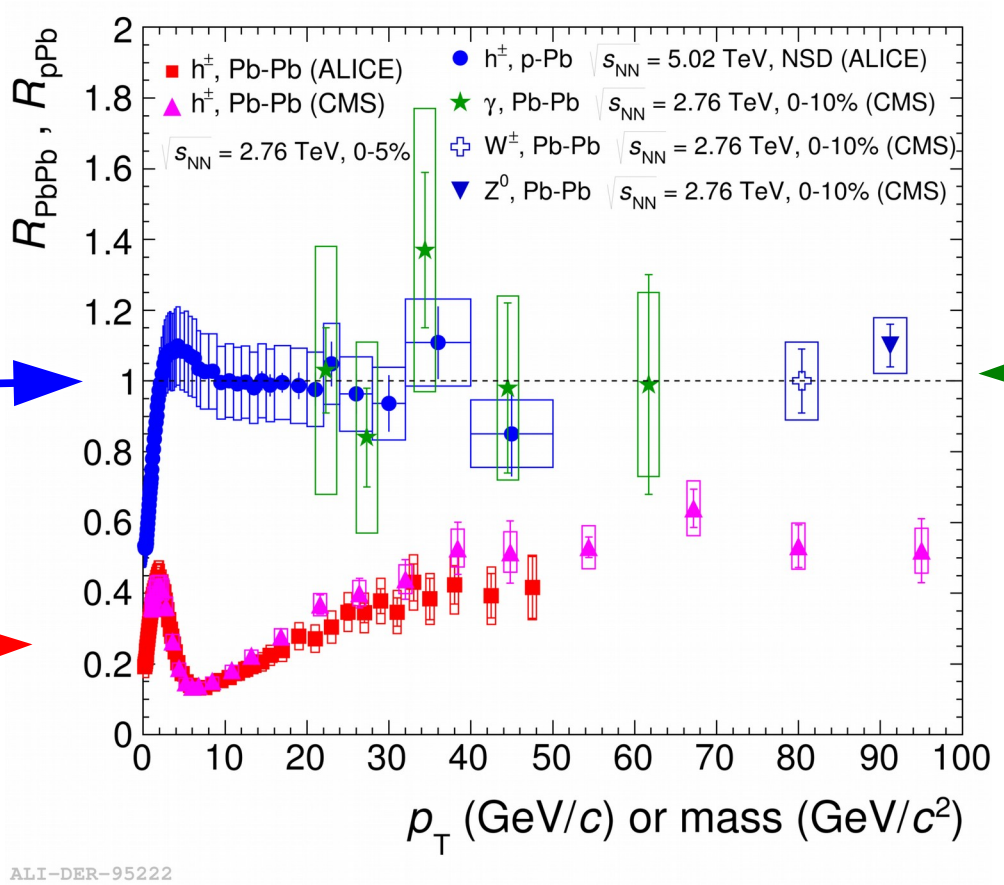
$$R_{AA} = \frac{d^2N_{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{pp}/dp_T d\eta}$$



Enhancement

Suppression

Nuclear modification factor



Control →

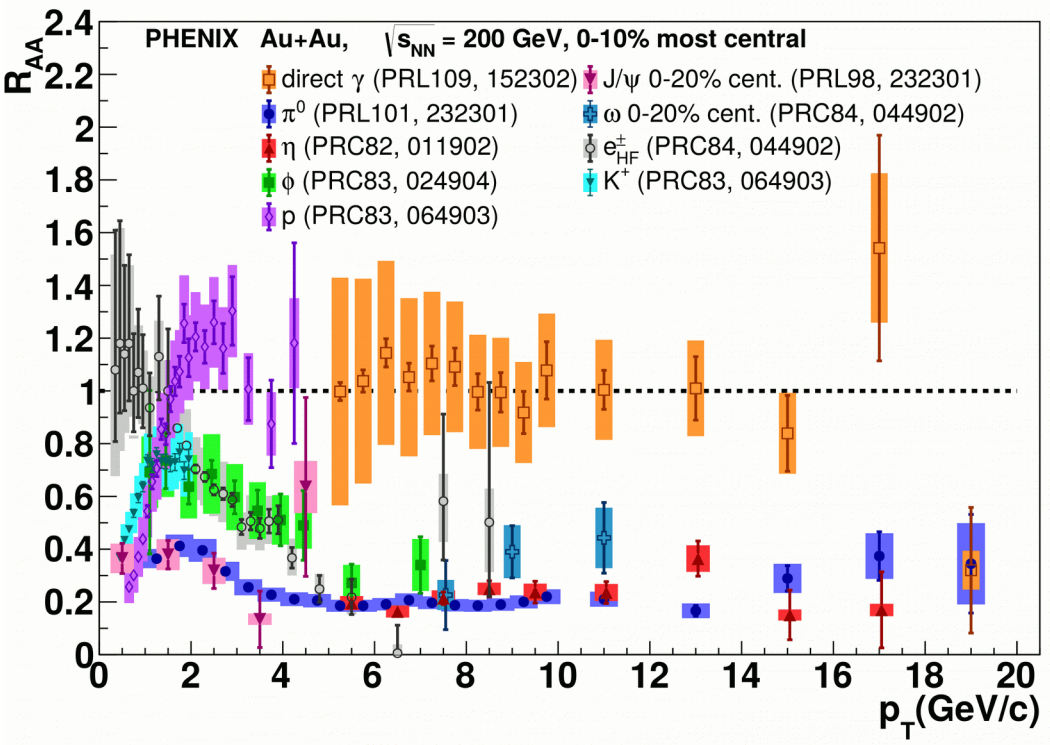
Probe →

← **Control**

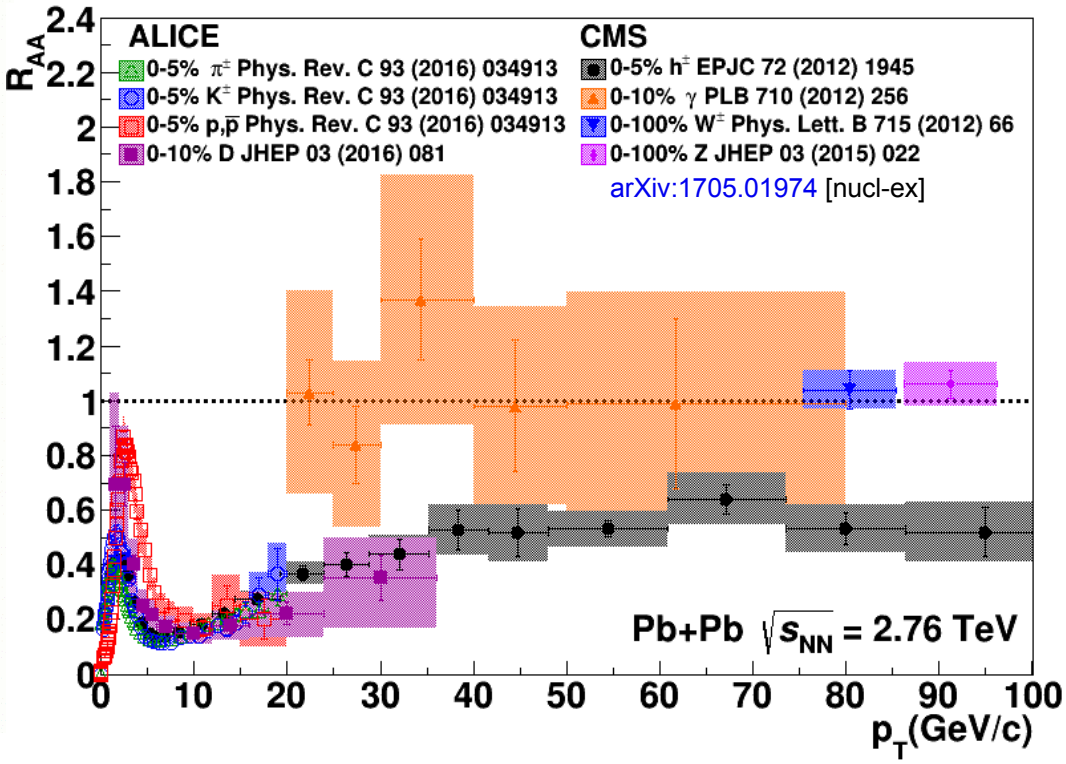
- Charged hadrons (colored probes) suppressed in Pb—Pb
- Charged hadrons not suppressed in p—Pb at midrapidity
- Electroweak probes not suppressed in Pb—Pb

Nuclear modification factor R_{AA}

RHIC

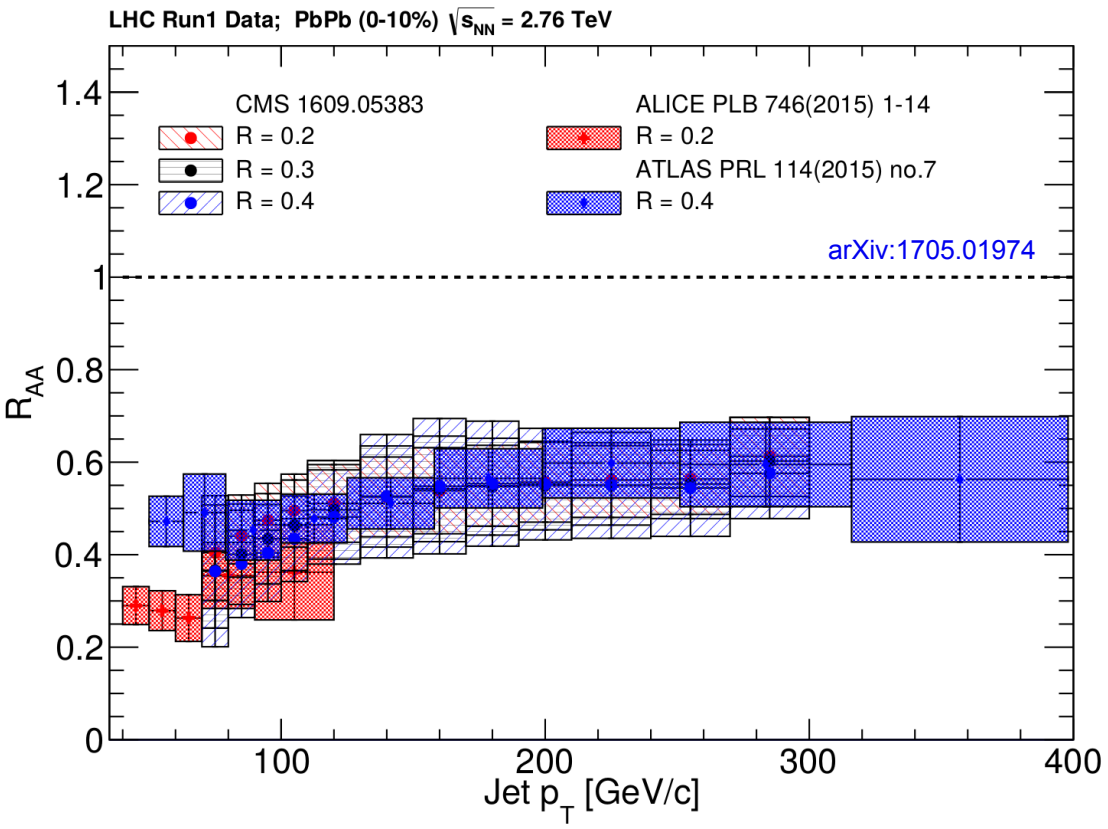


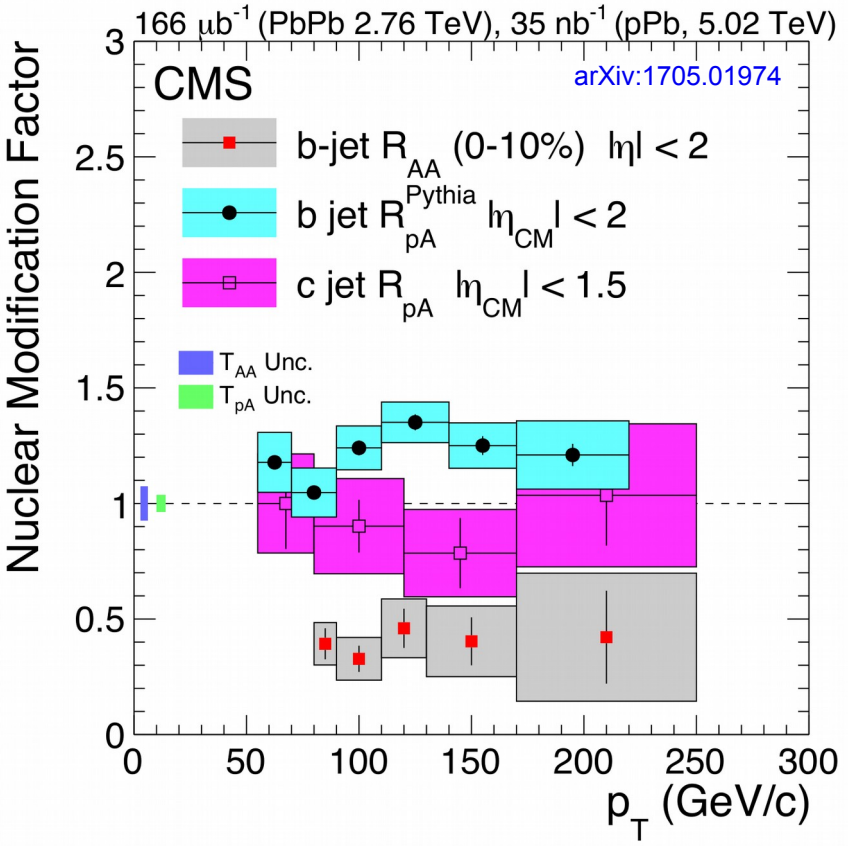
LHC



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

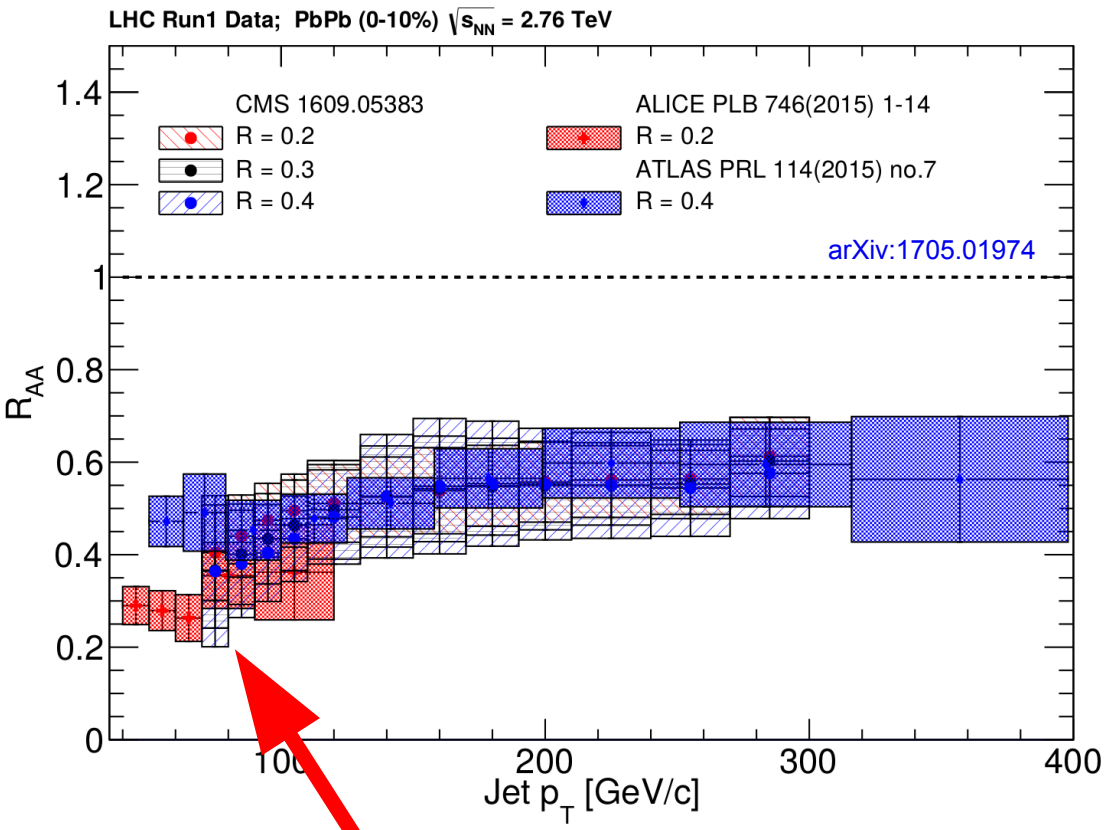
Jet R_{AA}

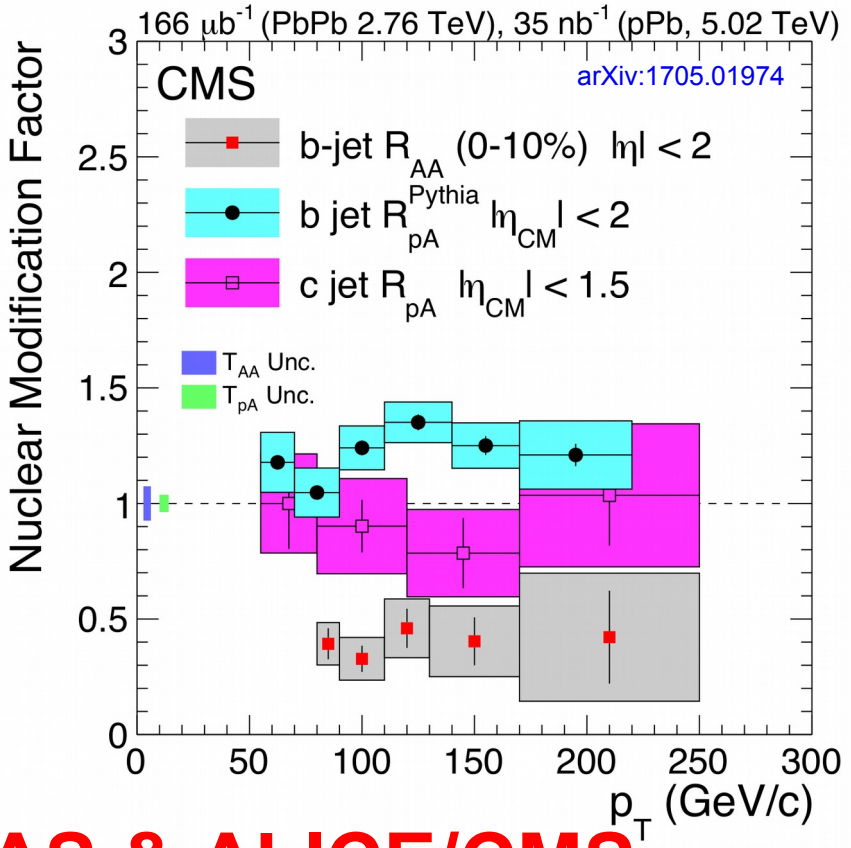




- Jet R_{AA} also demonstrates suppression
- Similar suppression of heavy quark jets?

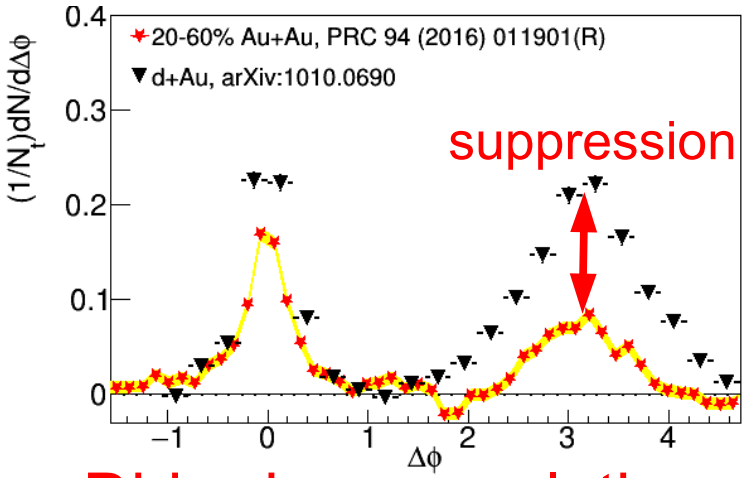
Jet R_{AA}





Tension between ATLAS & ALICE/CMS

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

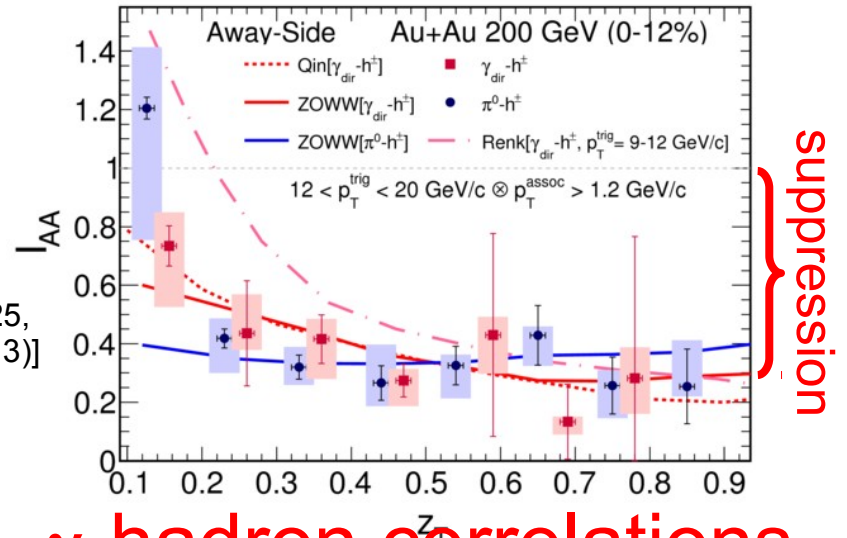


Di-hadron correlations

[Too many to list]

Jet v_2

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



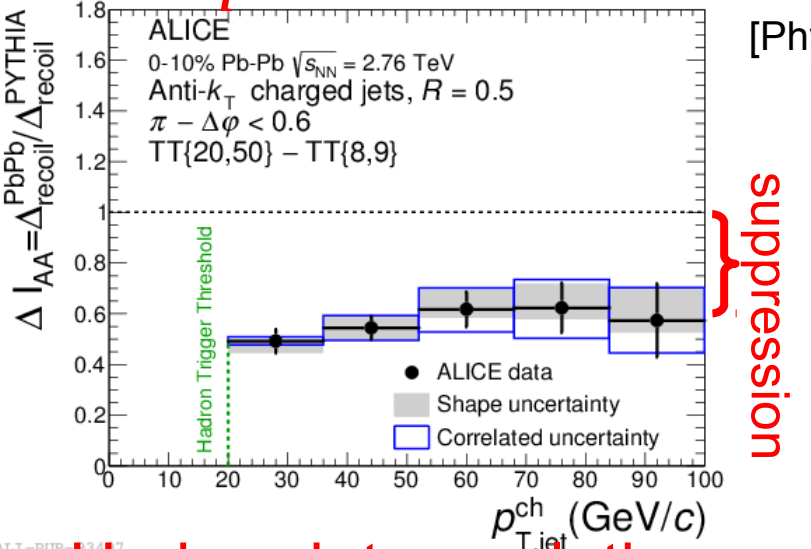
γ-hadron correlations

[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

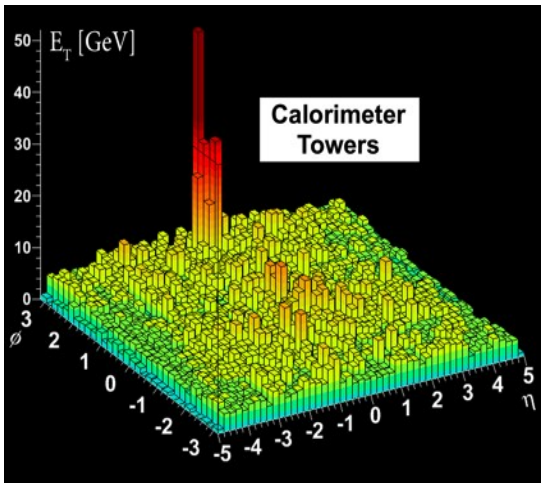
[JHEP 09 (2015) 170, Phys. Rev. C 96, 024905 (2017)]

γ-jet correlations

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

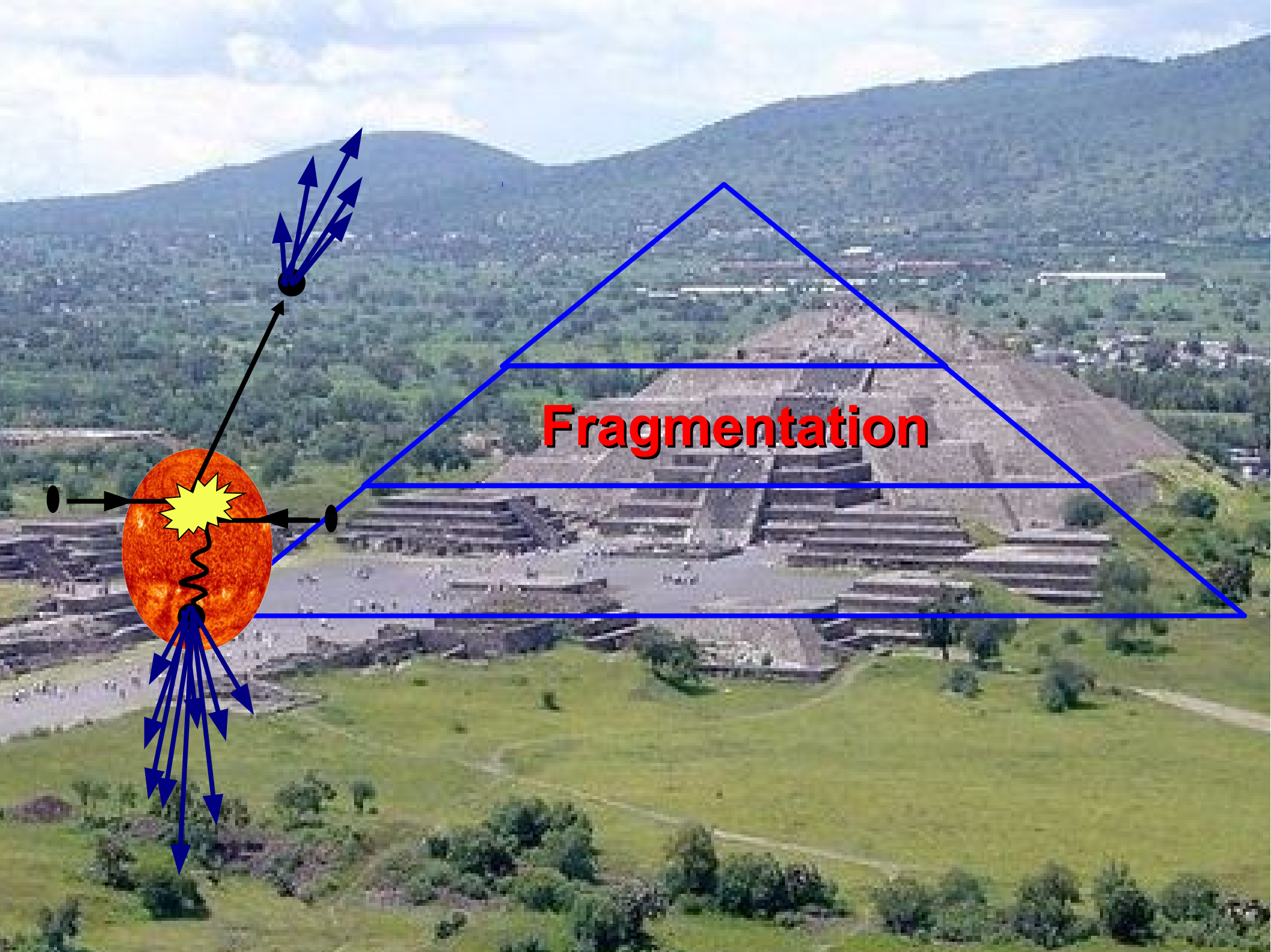
High-p_T hadron v_2

[too many to list]

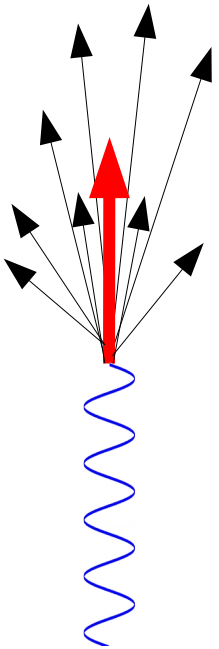


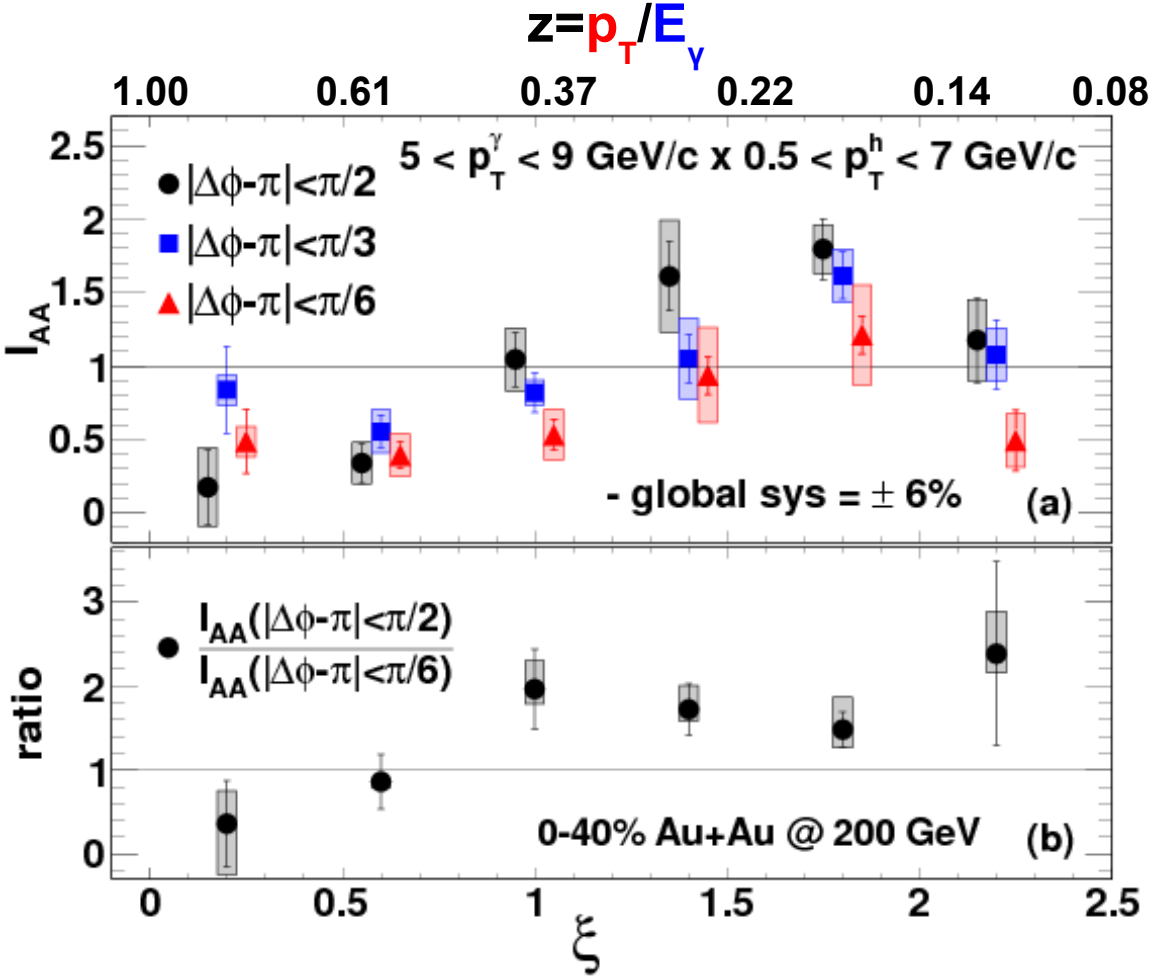
Dijet asymmetry

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


Fragmentation

Fragmentations from γ-hadron correlations

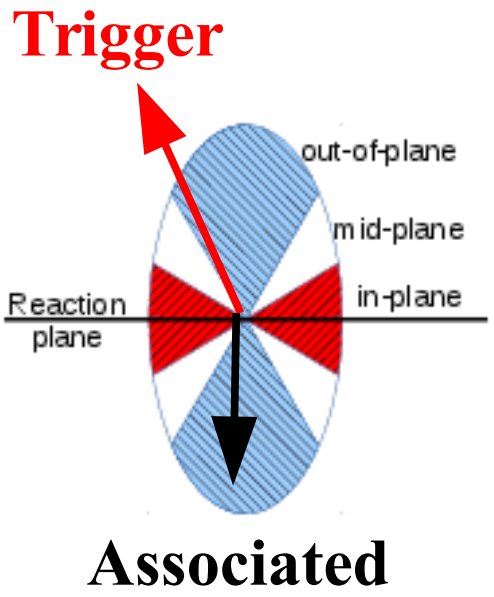


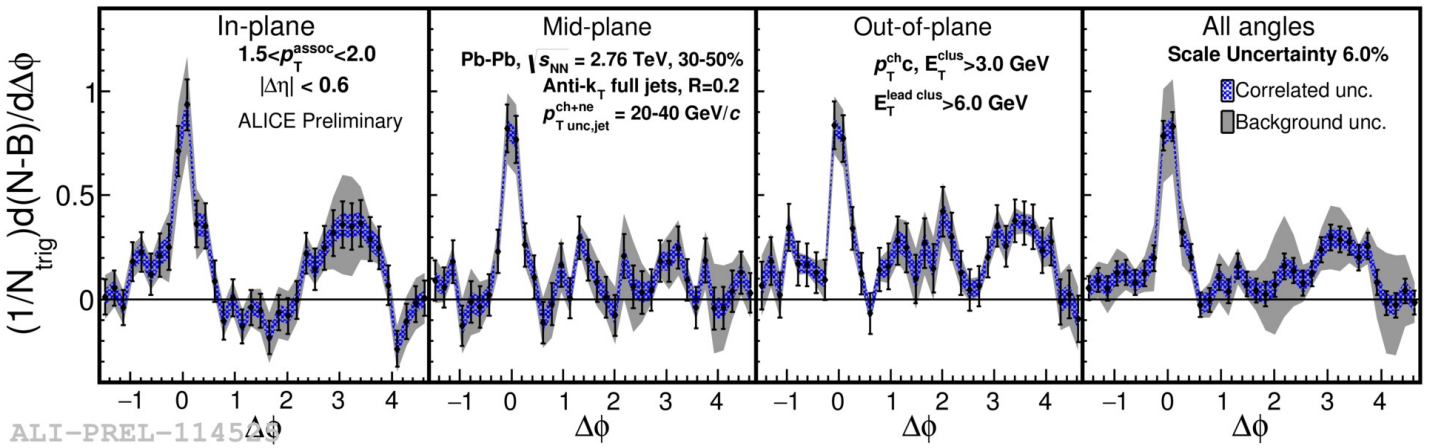


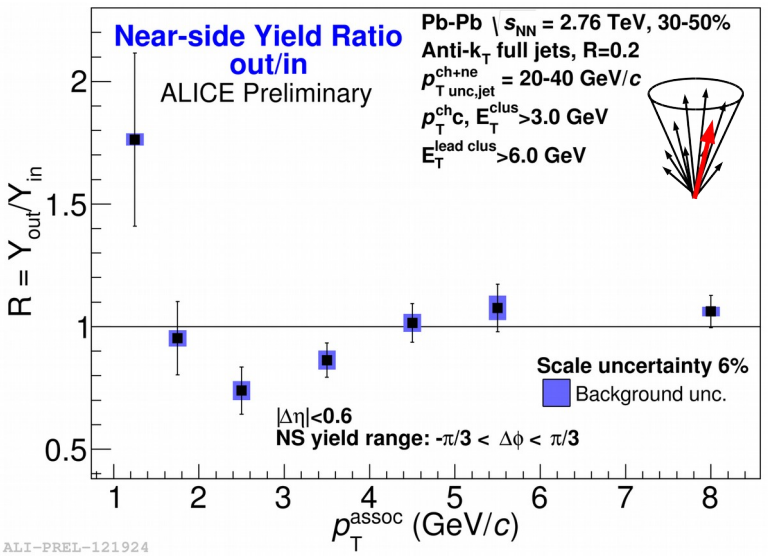
- Enhancement at low z
- Slight suppression at high z

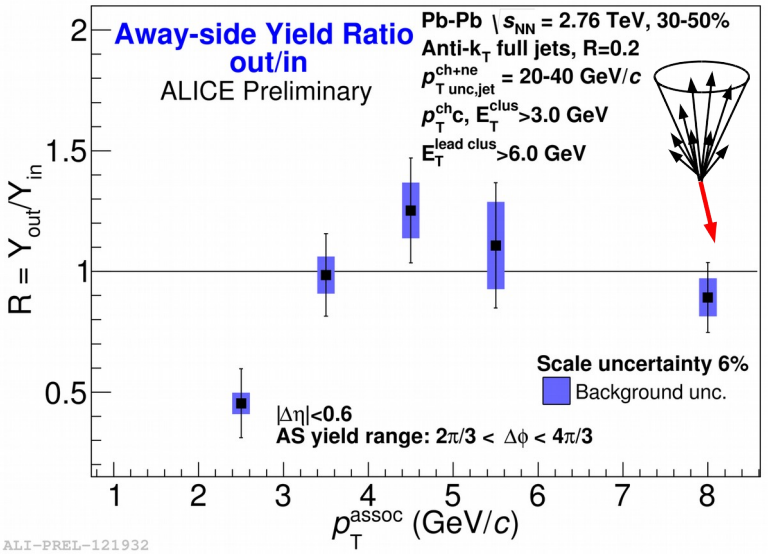
Jet-hadron correlations vs reaction plane

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









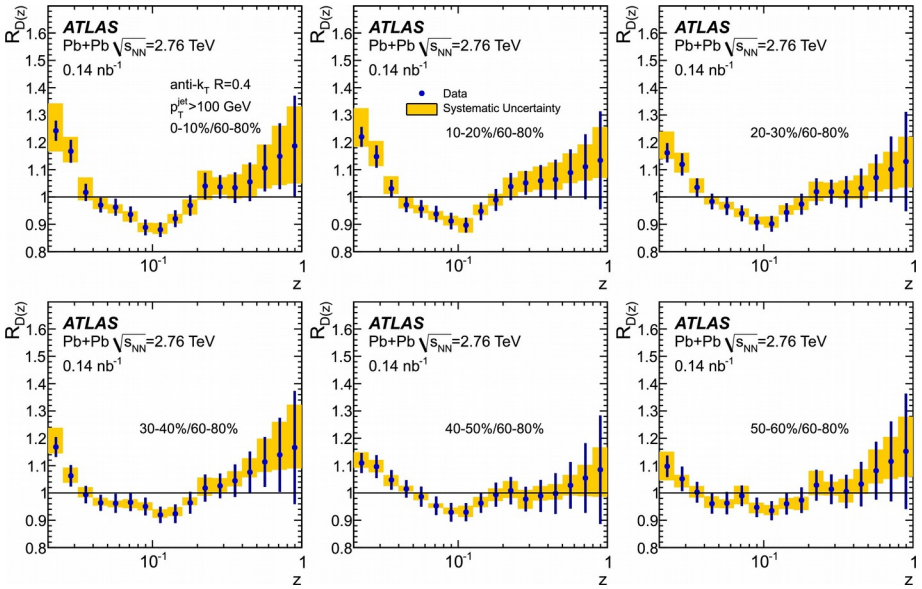
- No modification of constituents relative to reaction plane

  → 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)]

Modified fragmentation

Fragmentation functions with jets



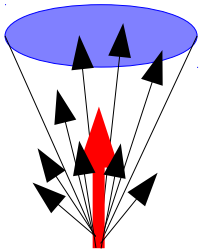
$z=p_T/E_\gamma$

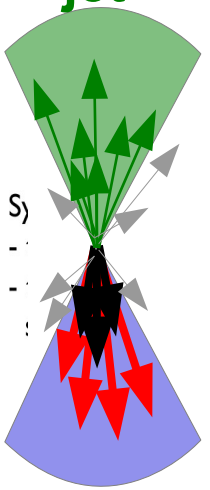
Di-hadron correlations

[Lots of papers]

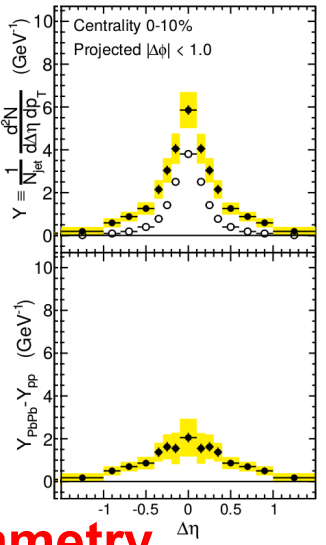
Jet shapes

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



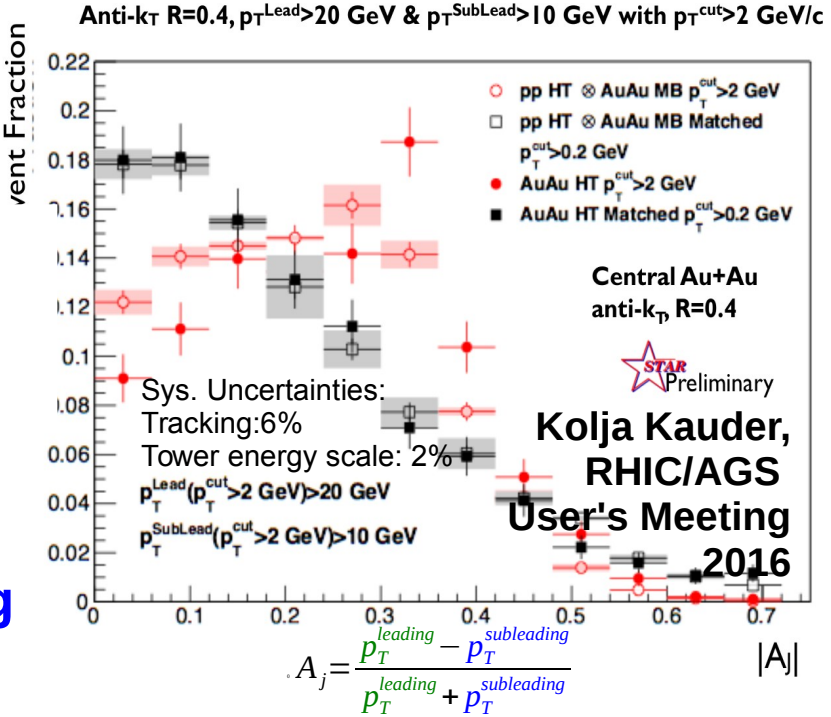


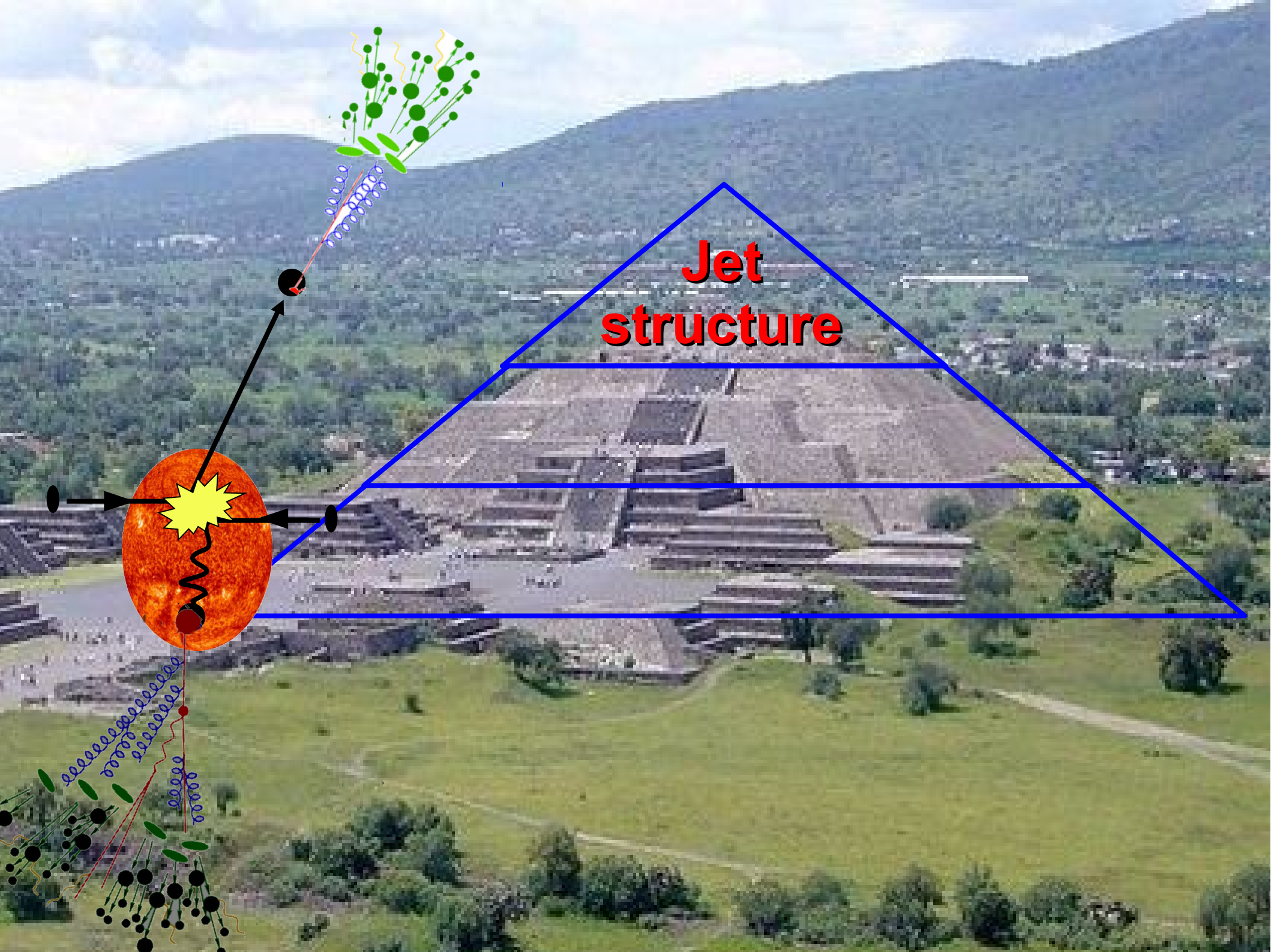
Jet-hadron correlations



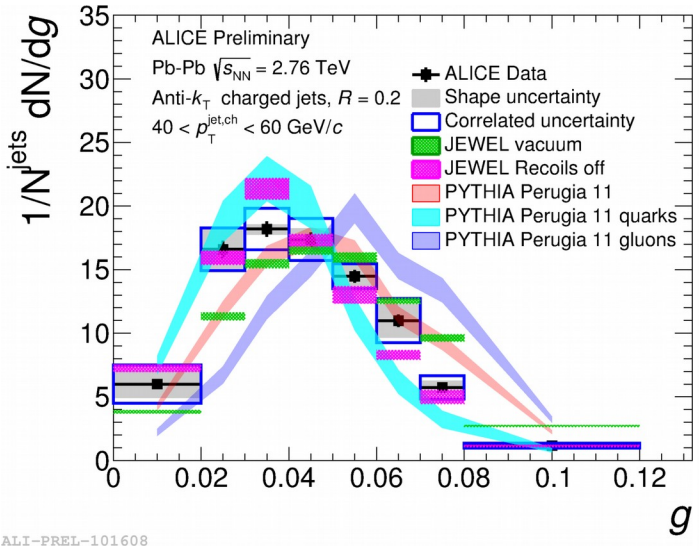
Di-jet asymmetry

arXiv:1609.03878

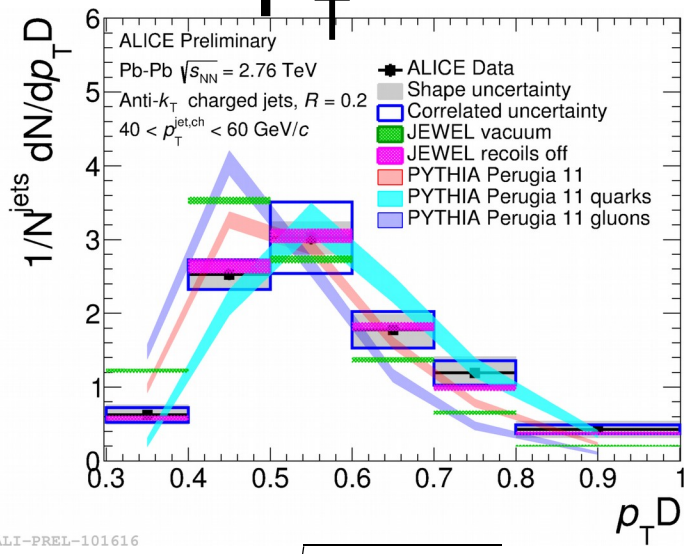



Jet
structure

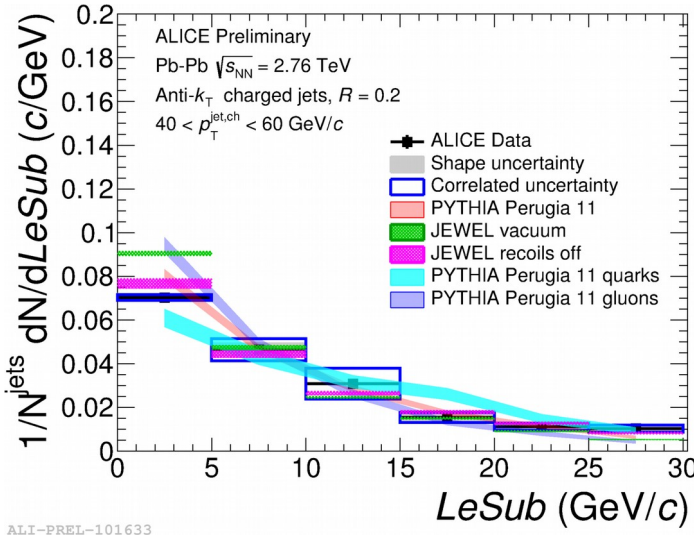
Girth g



Dispersion $p_T D$



LeSub



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

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

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

Jets are slightly more collimated than in pp

Agrees with PYTHIA

See also jet grooming (*Yen-jie Lee*)


E_T [GeV]
Calorimeter Towers

I do not care about jets.

Paraphrased from Sevil Salur

I want to learn about the QGP.

Paraphrased from Sevil Salur

It is 2017. What have we learned?

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- Qualitative confirmation of our model for partonic energy loss

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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.

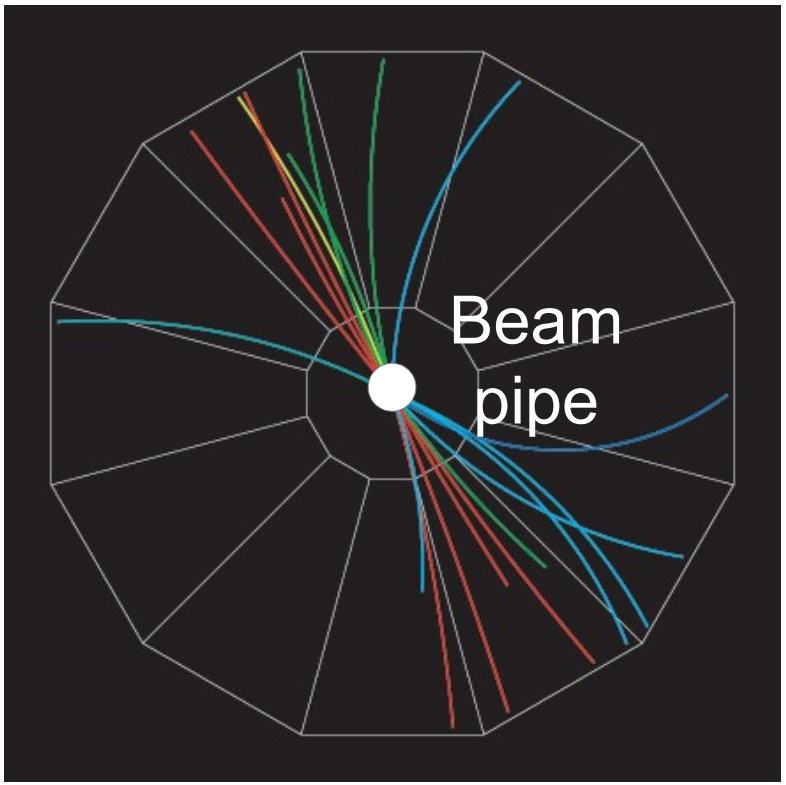
What is a jet?

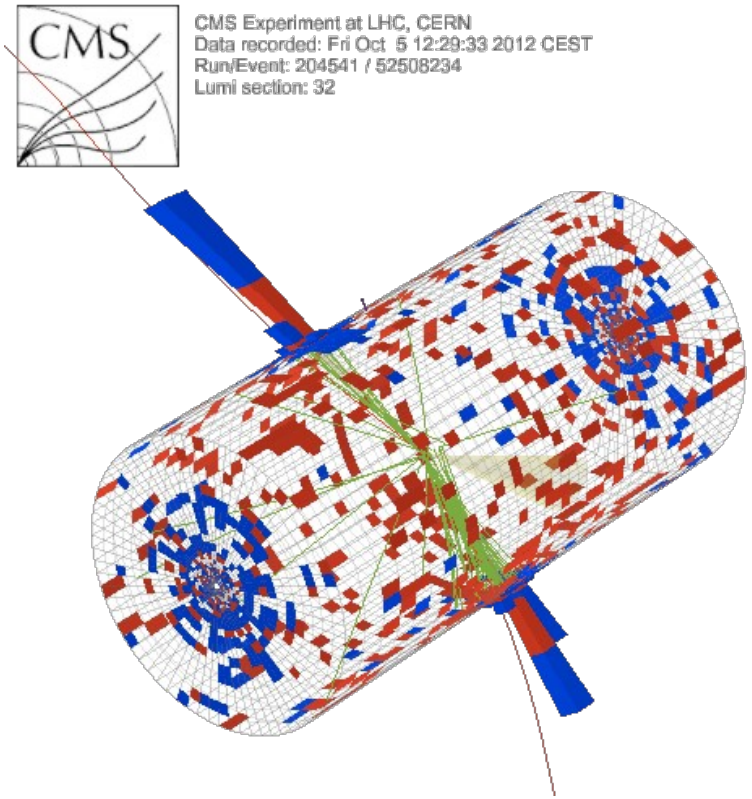
What is a jet?

A measurement of a jet is a measurement of a parton.

What is a jet?

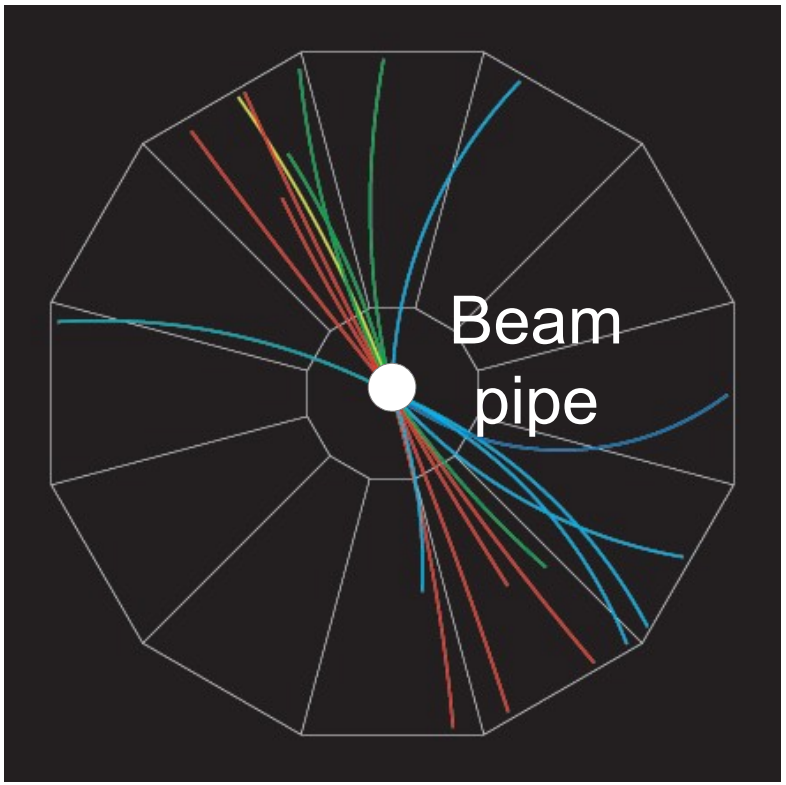
p+p → dijet

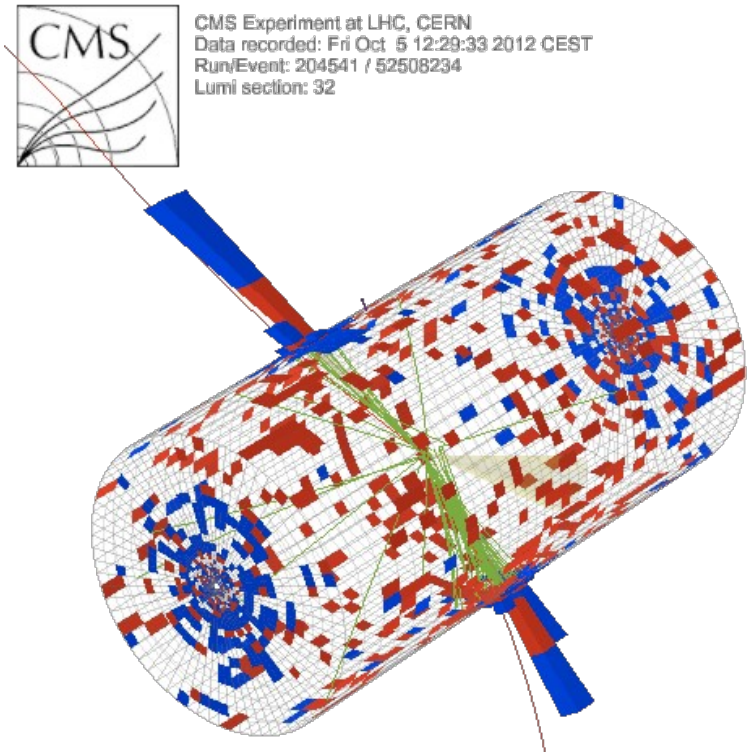




What is a jet?

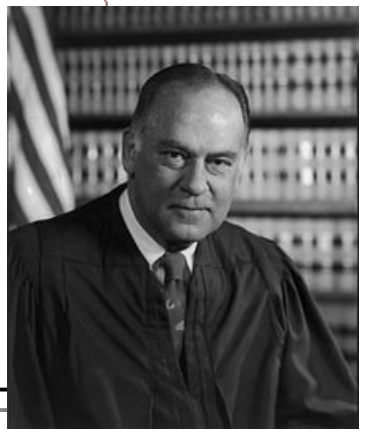
p+p → dijet





"I know it when I see it"

US Supreme Court Justice Potter Stewart,
Jacobellis v. Ohio



Jet finding in pp collisions

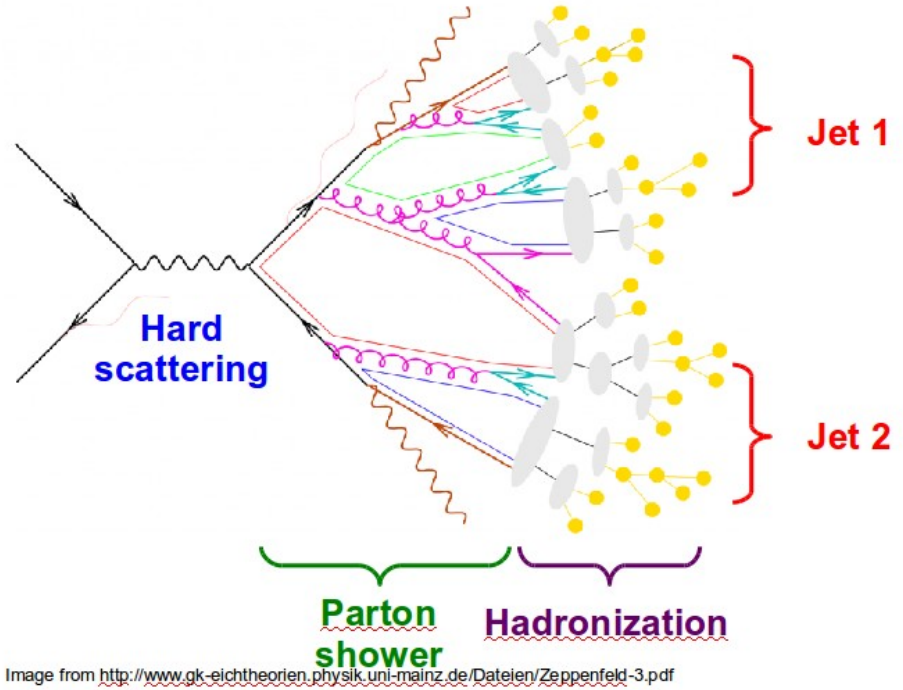


Image from http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

- 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

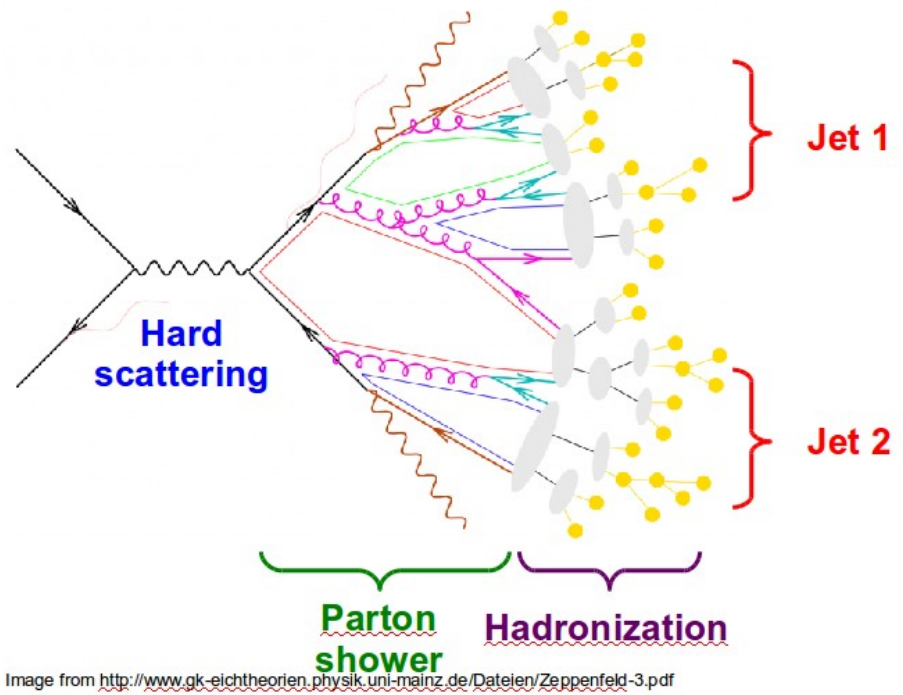


Image from http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

- Jet finder: groups final state particles into jet candidates
  - Anti-k_T algorithm
    JHEP 0804 (2008) 063 [arXiv:0802.1189]
- Combinatorial jet candidates
- Energy smearing from background
- Sensitive to methods to suppress combinatorial jets and correct energy
- Focus on narrow/high energy jets

http://walkthewilderness.net/animals-of-india-72-asiatic-elephant/

http://walkthewilderness.net/animals-of-india-72-asiatic-elephant/


What you see depends on what you're looking for
http://walkthewilderness.net/animals-of-india-72-asiatic-elephant/

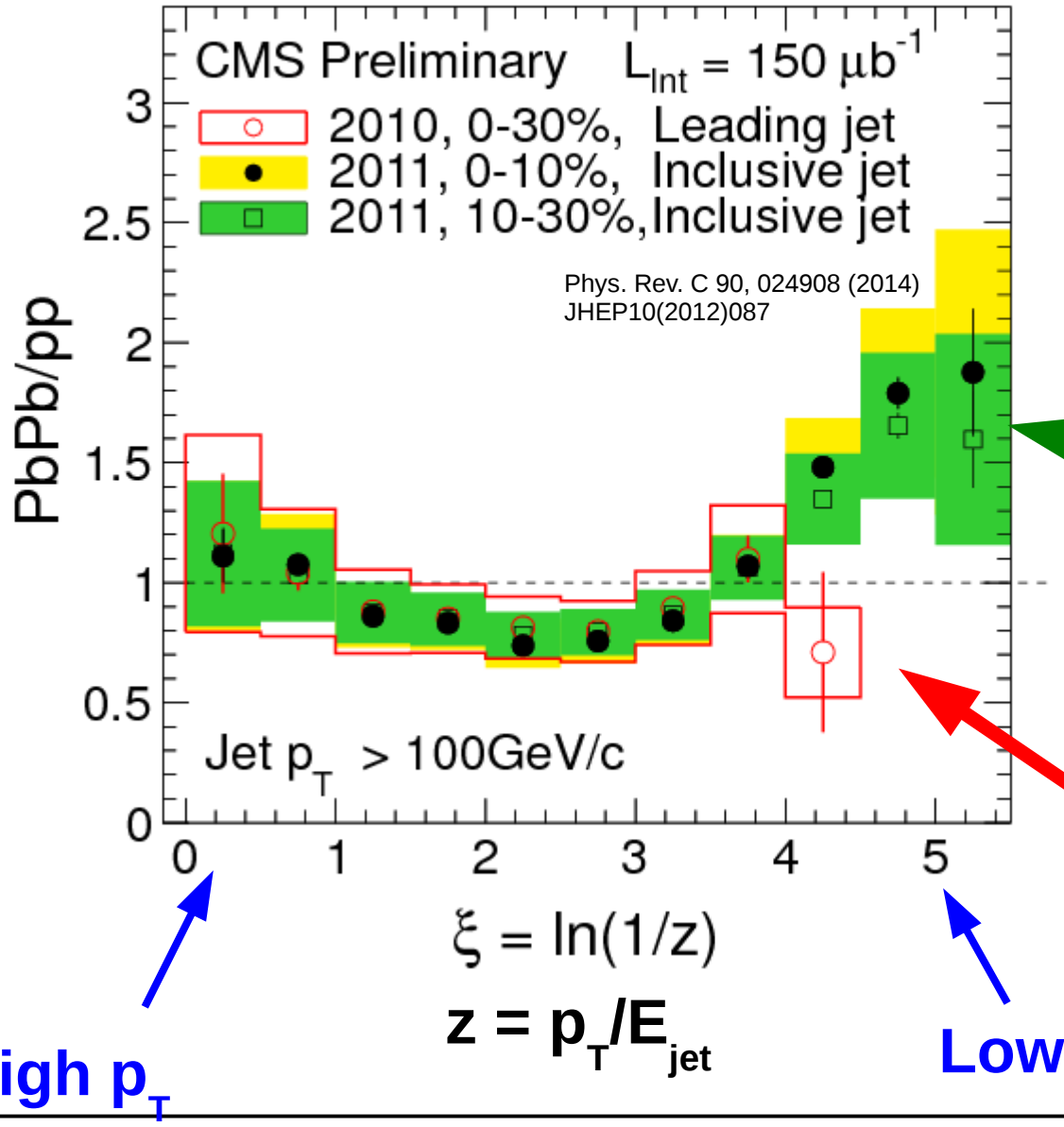
Bias & background

- **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

http://walkthewilderness.net/animals-of-india-72-asiatic-elephant/

Wiki: “A **white elephant** is a possession which its owner cannot dispose of and whose cost, particularly that of maintenance, is out of proportion to its usefulness.

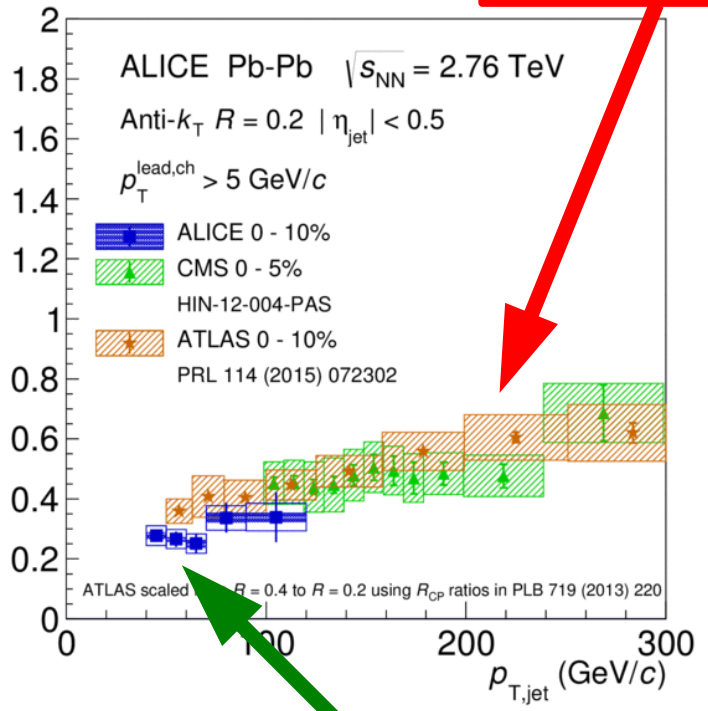
What you see depends on where you look



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

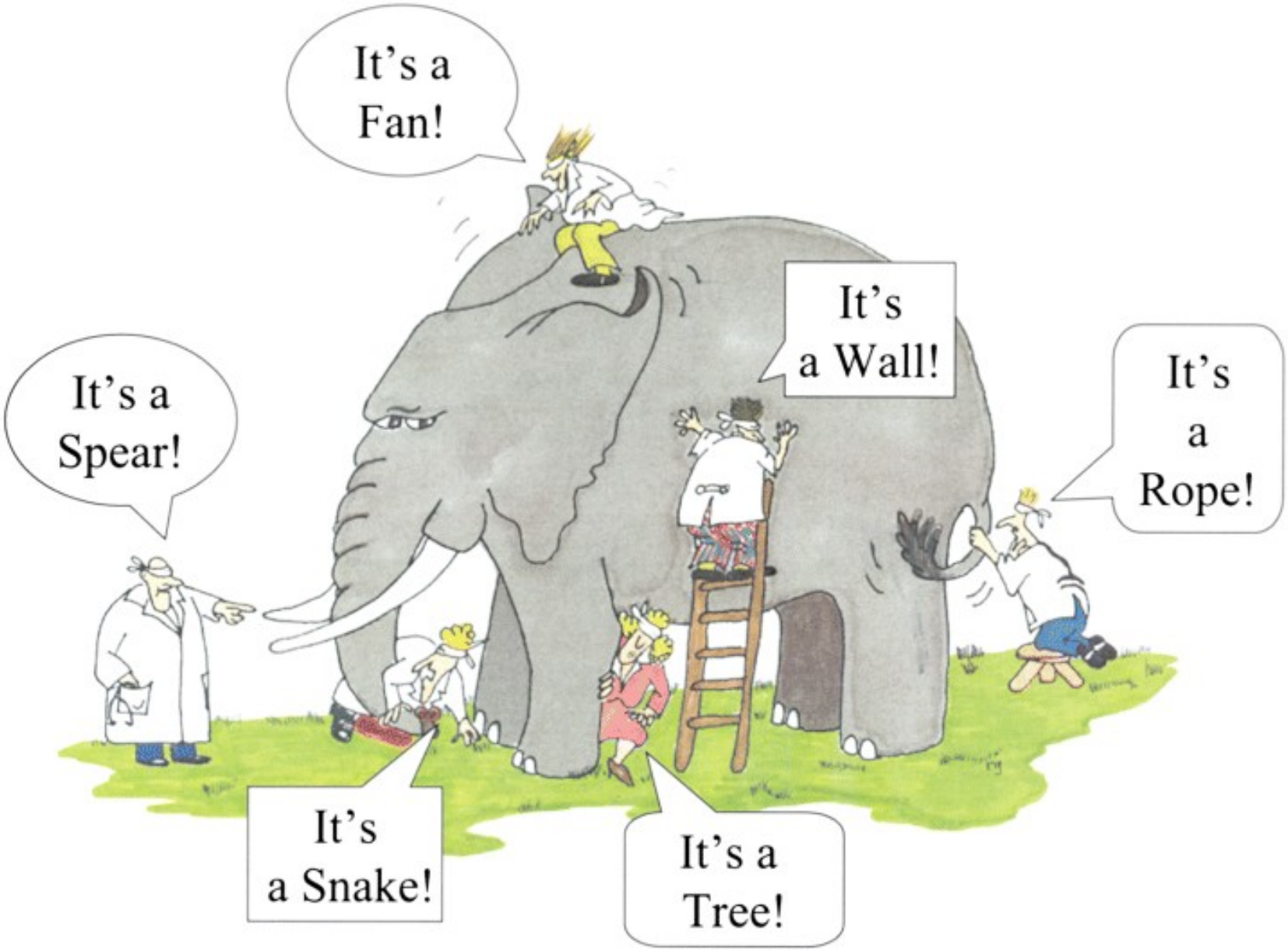


Constituent biases don't matter that much up here

But they do matter down here!

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

Blind men and the elephant

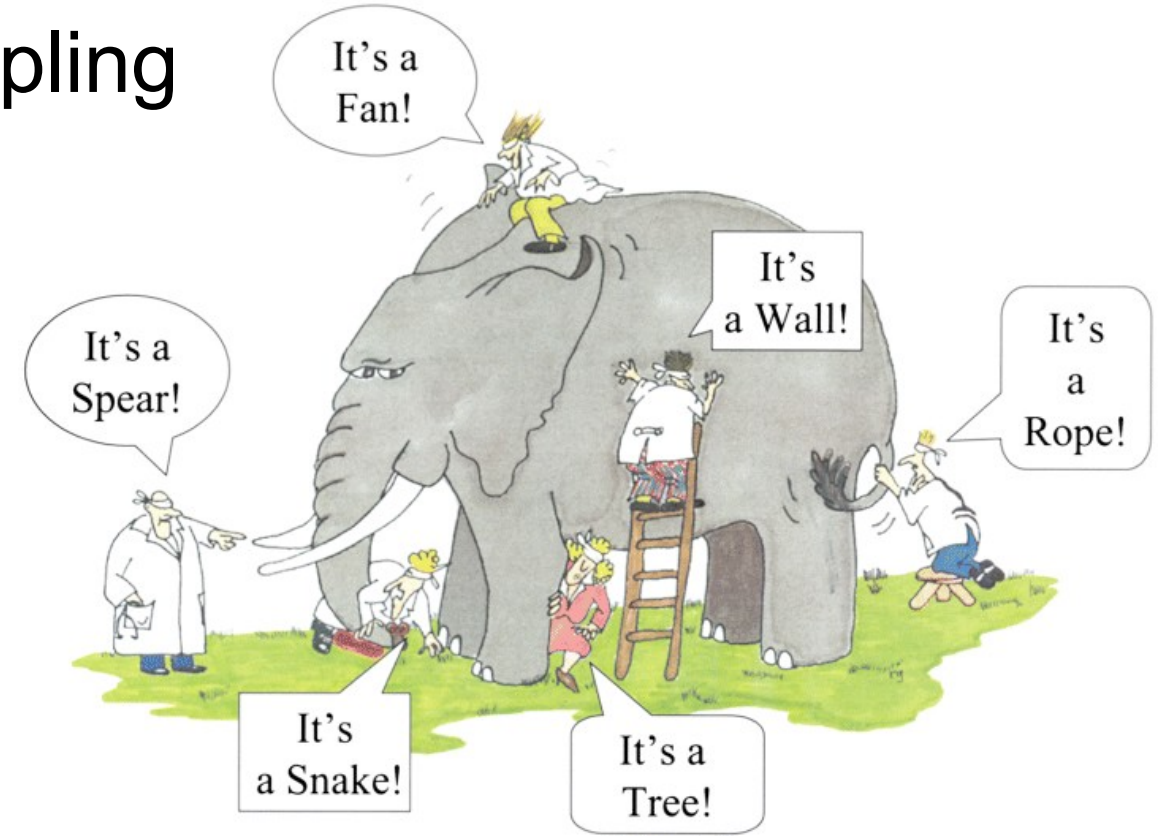


Lessons from the Blind men and the elephant

Balaji Viswanathan

https://balajiviswanathan.quora.com/Lessons-from-the-Blind-men-and-the-elephant

- Ignore judgment
- Be careful in giving/receiving advice
- Improve your sampling
- Collaborate
- World is complex



Lessons from measurements of jets

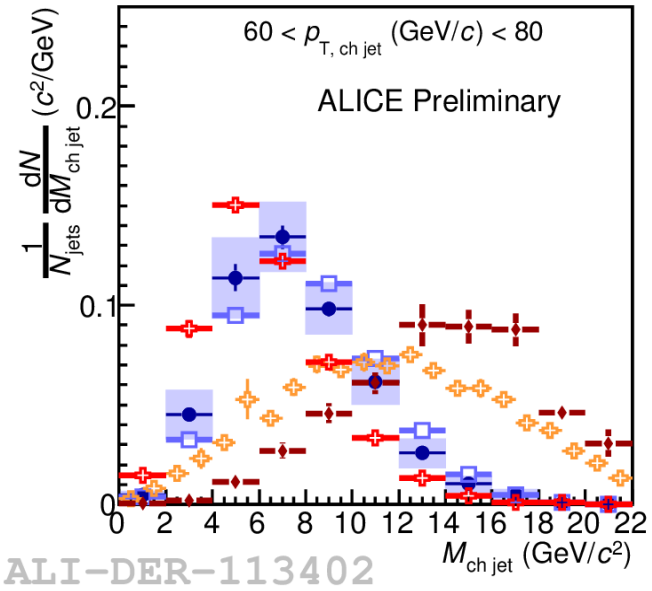
- **Understand bias** – it's a tool, not a dirty word
  - What you see depends on what you look for
  - Listen to the data – not what you want to hear
- **Make quantitative comparisons to theory**
  - We should look for new observables... but we should make sure they're sensitive and that we know
  - Need realistic models where we can apply experimental methods to models – Jetscape is coming!

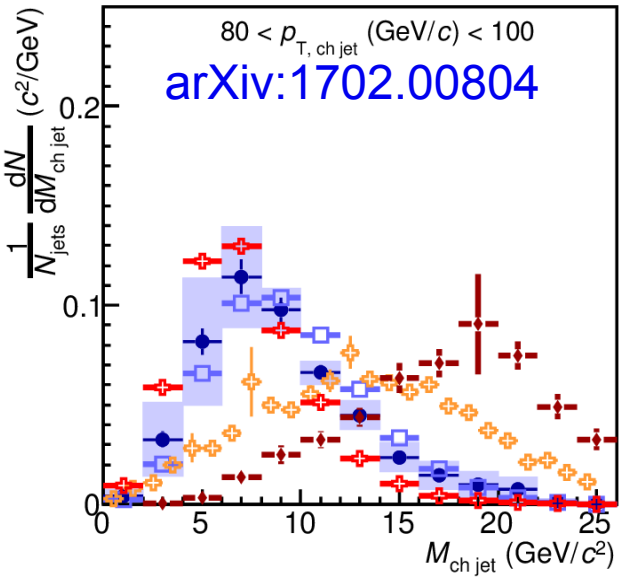
Scott Moreland, Thursday

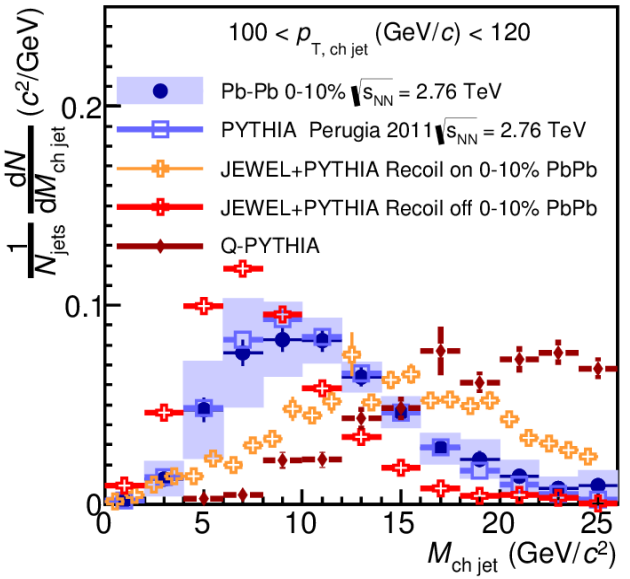
Abhijit Majumder, Tuesday

- **Make more differential measurements**
- **We need an accord on how to treat background**
  - Experimental cuts matter and are unavoidable

Jet mass



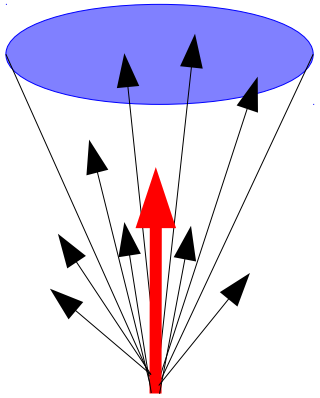


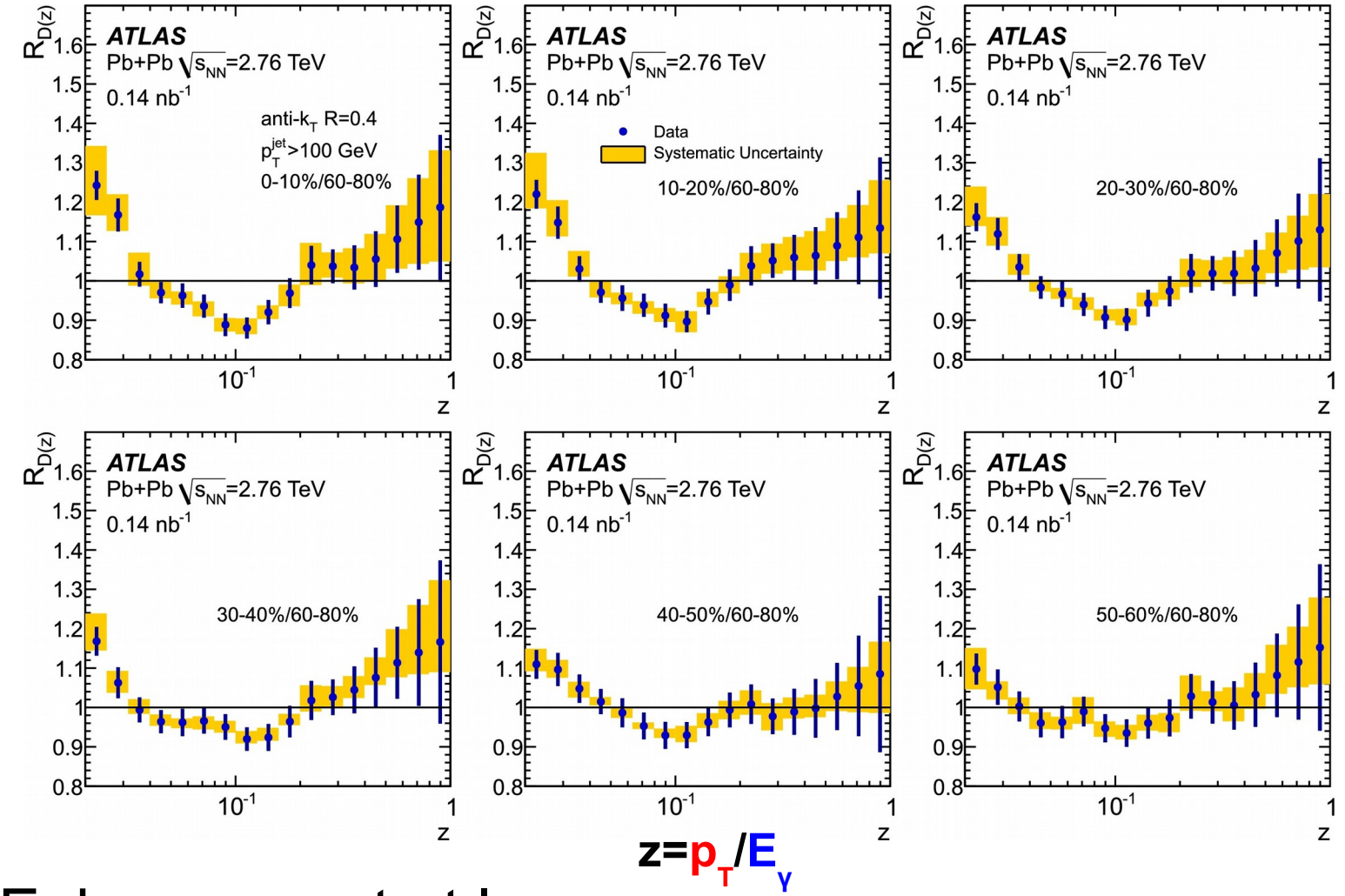


$$M = \sqrt{p^2 - p_T^2 - p_z^2} \qquad p = \sum_{i=1}^{n} p_{T_i} \cosh \eta_i \qquad p_z = \sum_{i=1}^{n} p_{T_i} \sinh \eta_i$$

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

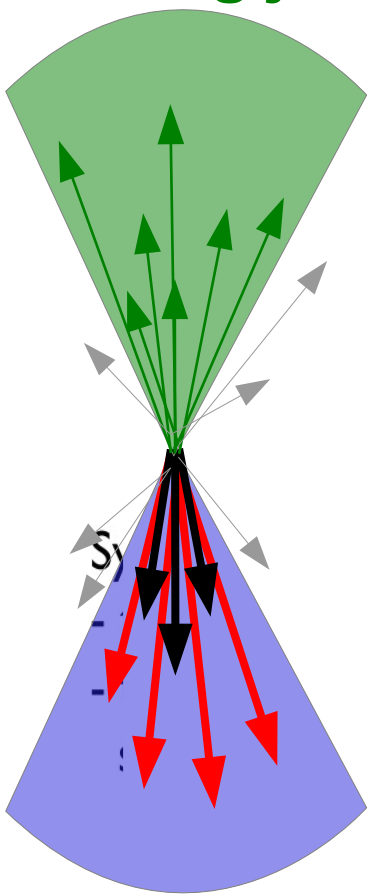
Modified fragmentation



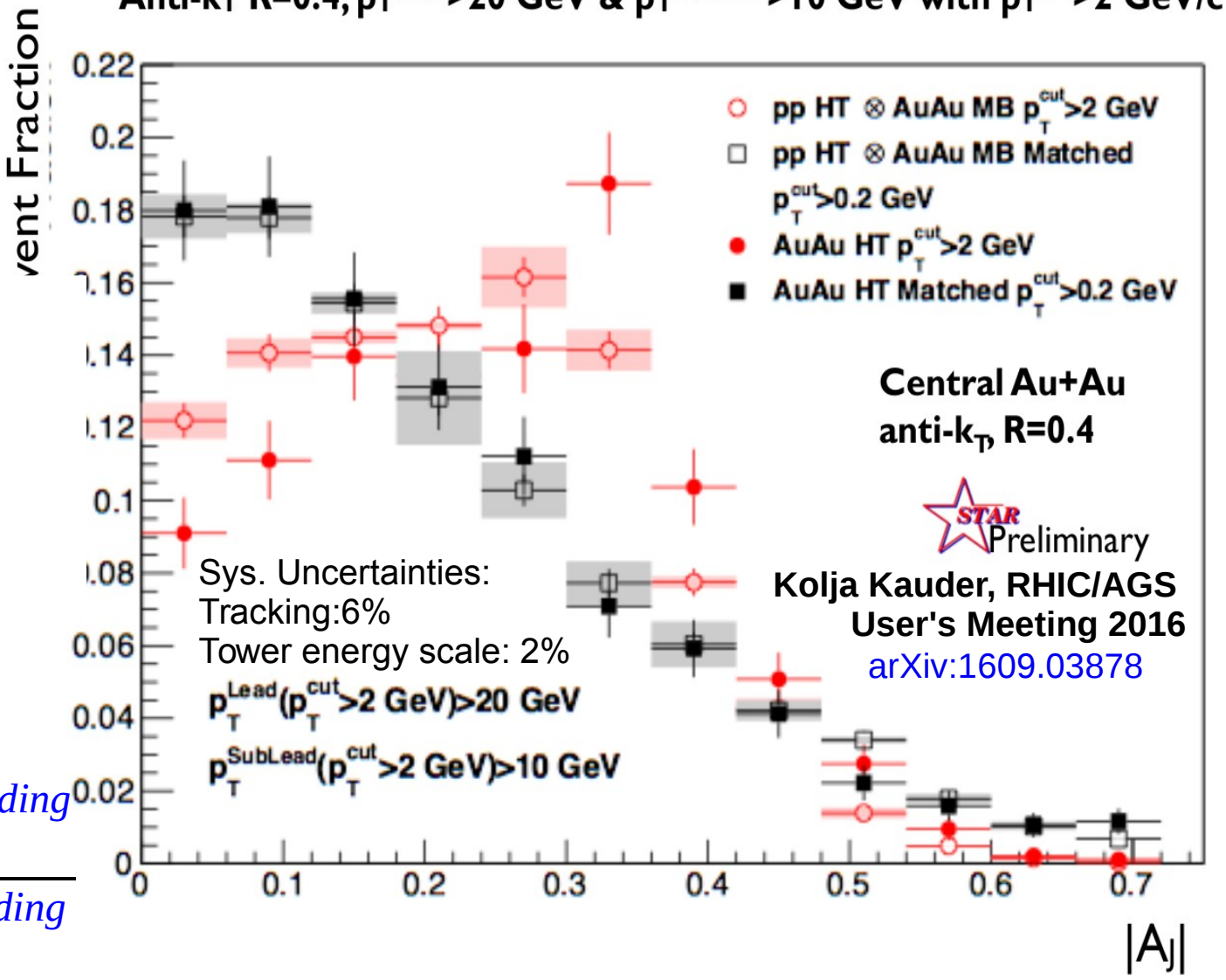


- Enhancement at low z
- No modification/enhancement at high z?

Di-jet asymmetry



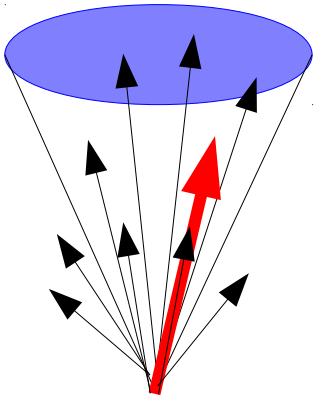
$$A_j = \frac{p_T^{leading} - p_T^{subleading}}{p_T^{leading} + p_T^{subleading}}$$

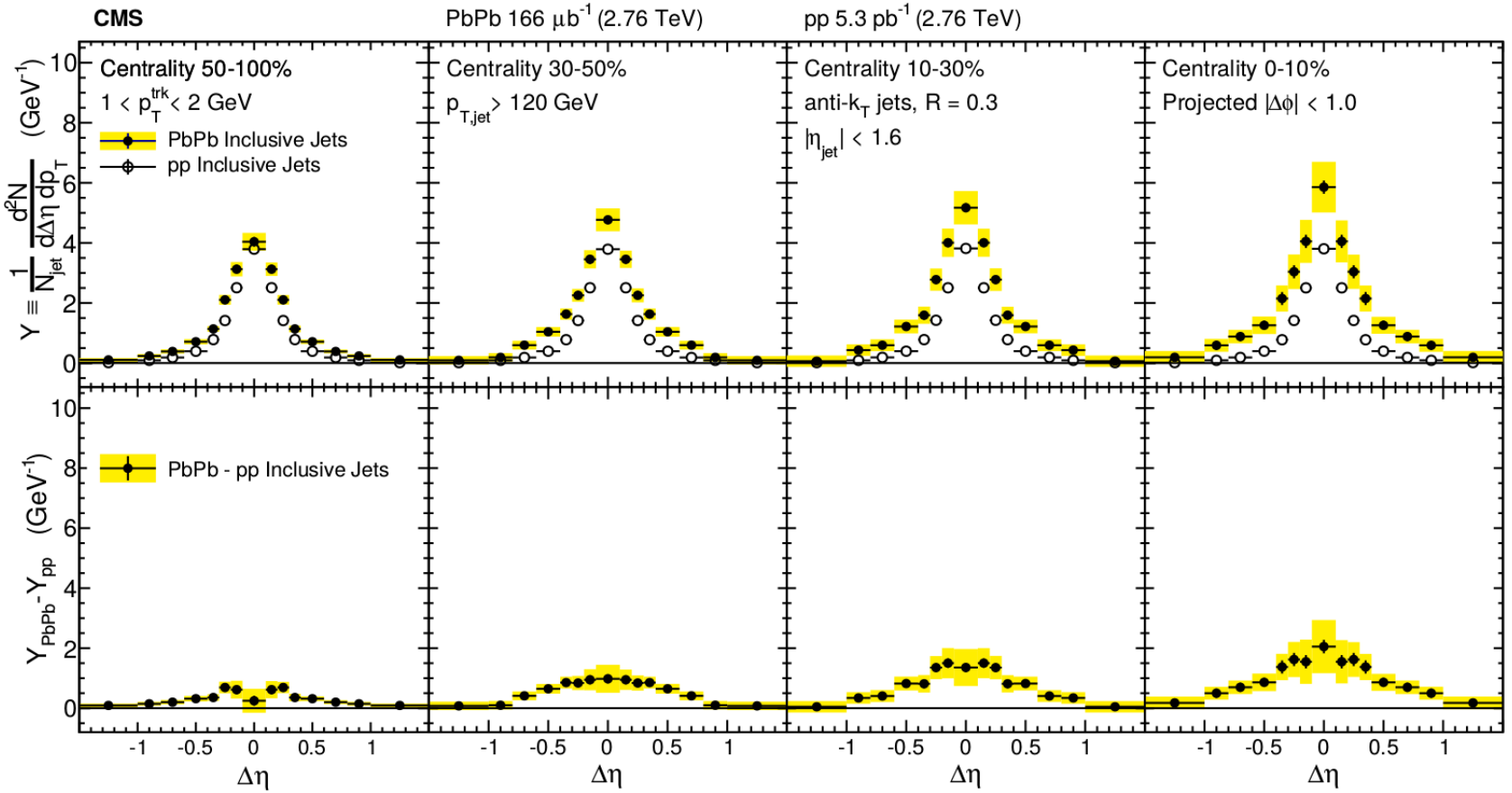


Au+Au di-jets more imbalanced than p+p for p_{Tcut}>2 GeV/c

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]