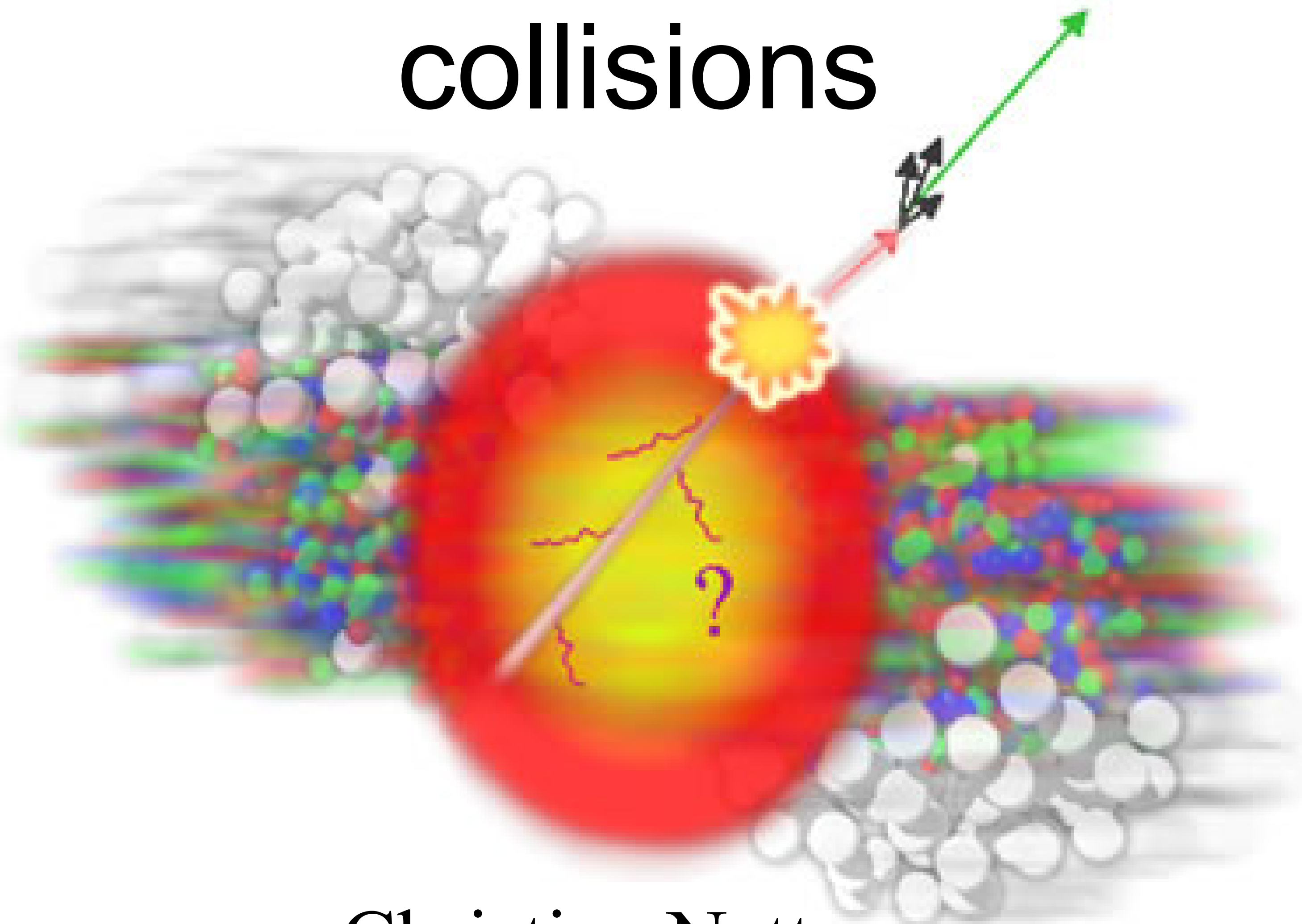
Measurements of jets in heavy ion collisions



Christine Nattrass
University of Tennessee, Knoxville

Largely based on Connors, Nattrass, Reed, & Salur

arxiv:1705.01974, accepted in RMP

I do not care about jets.

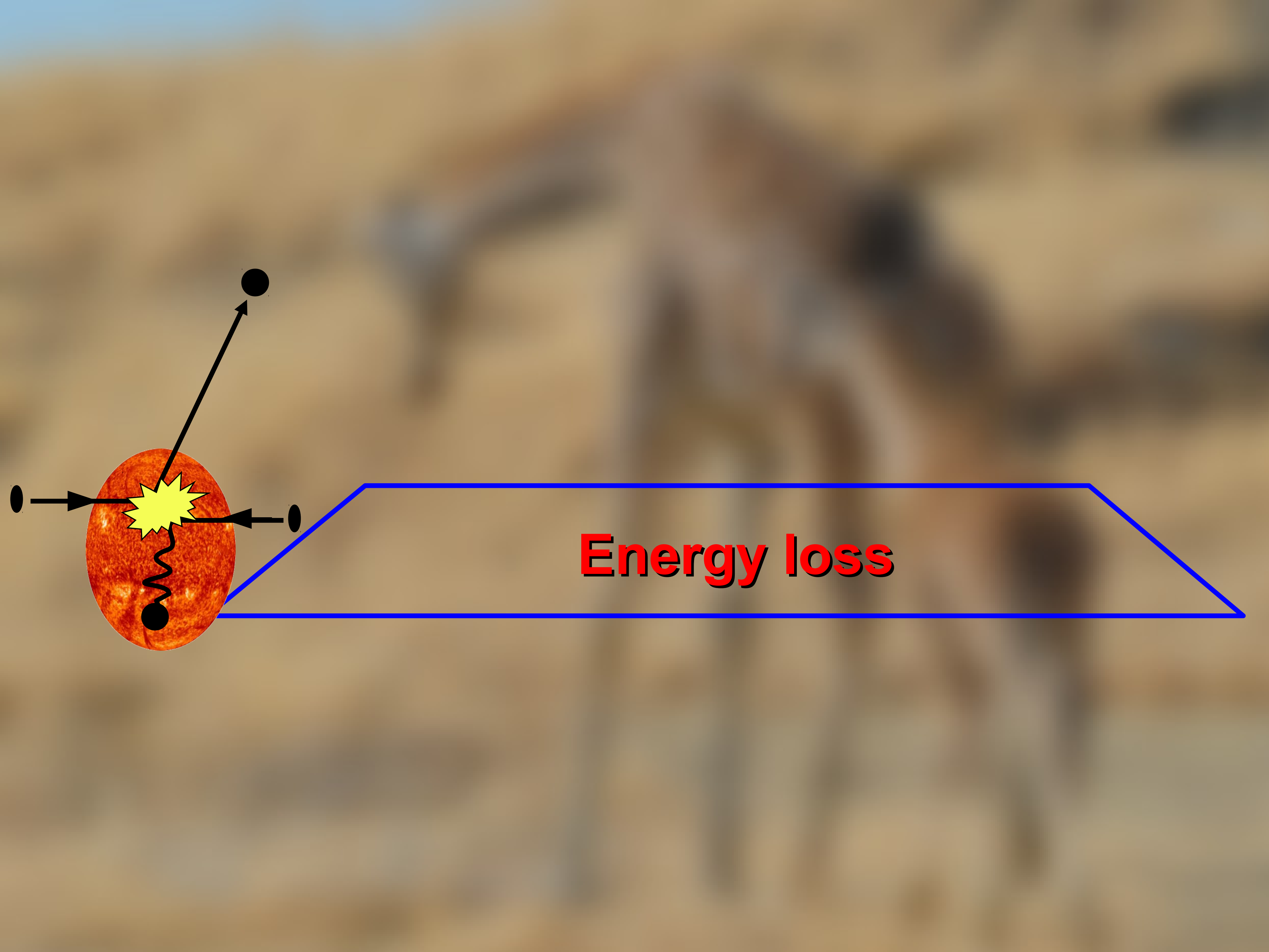
Paraphrased from Sevil Salur

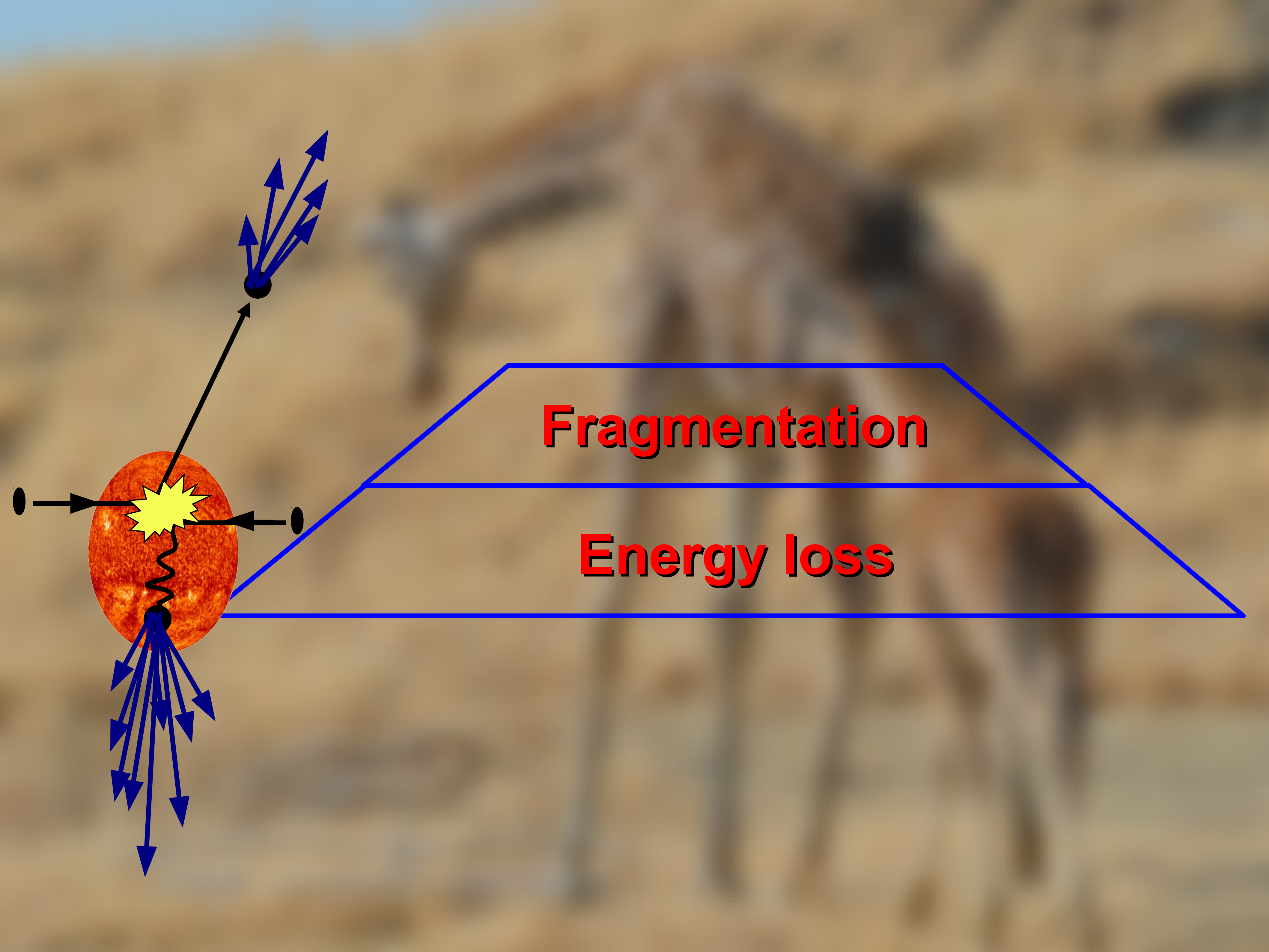
I want to learn about the QGP.

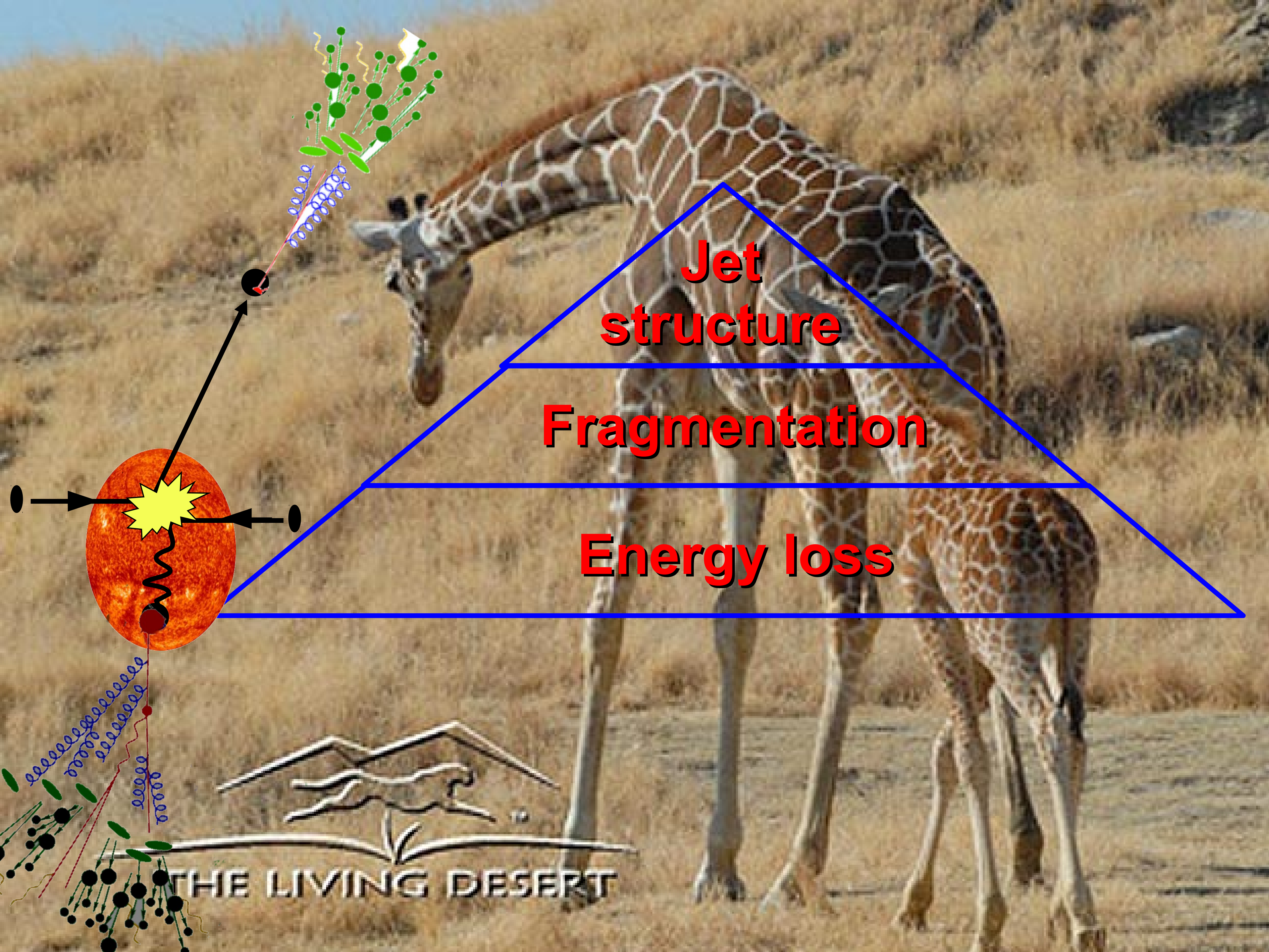
Paraphrased from Sevil Salur

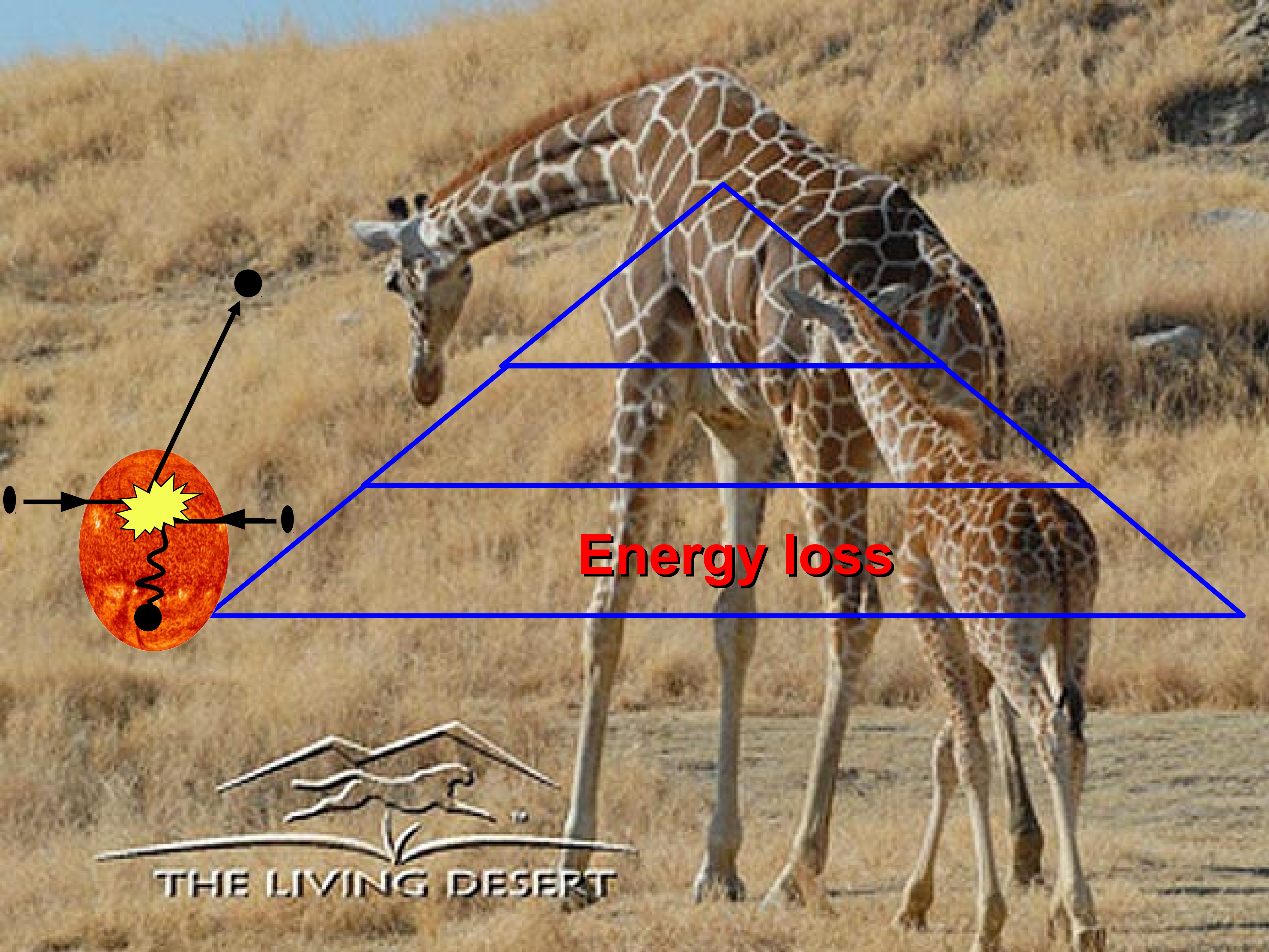
It is 2018. What have we learned?

It is 2018. What have we learned?

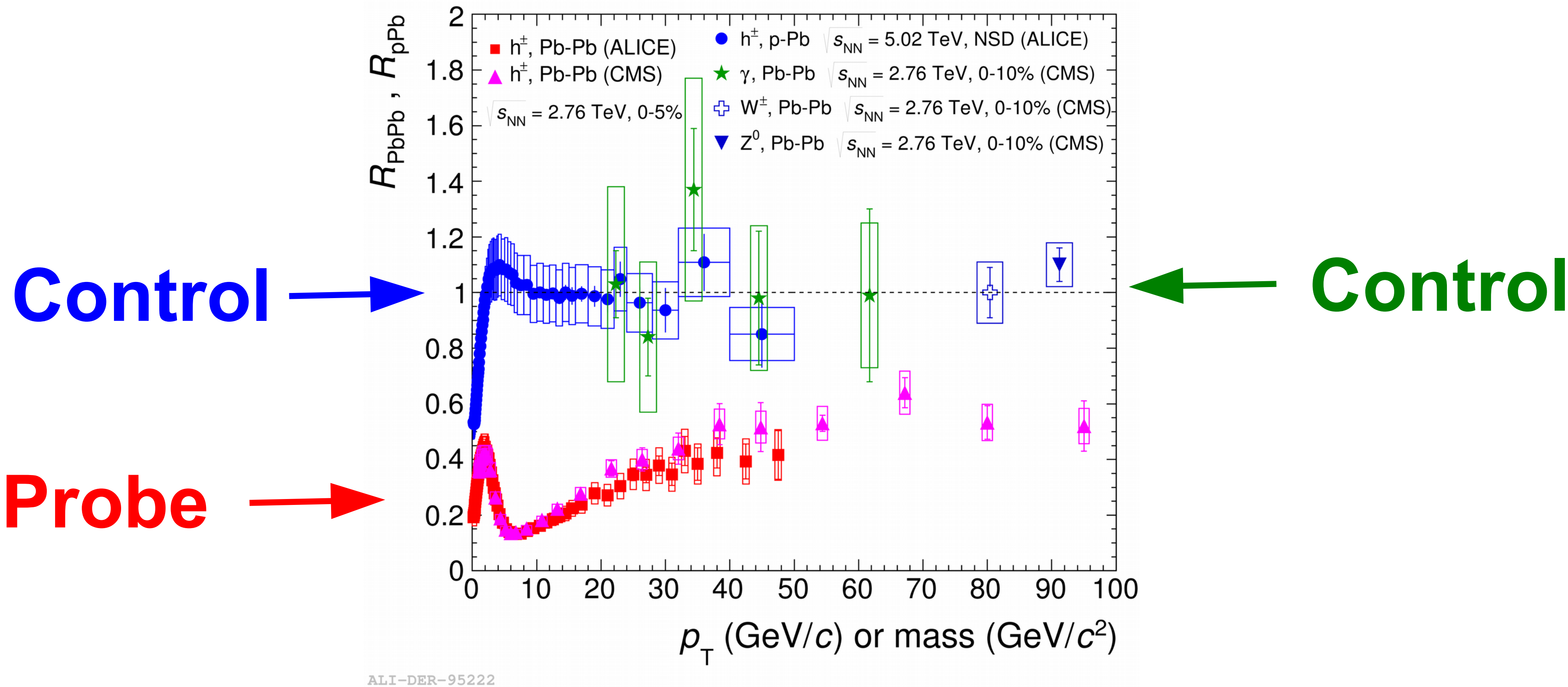

Energy loss


Fragmentation
Energy loss


Jet structure
Fragmentation
Energy loss
THE LIVING DESERT


Energy loss
THE LIVING DESERT

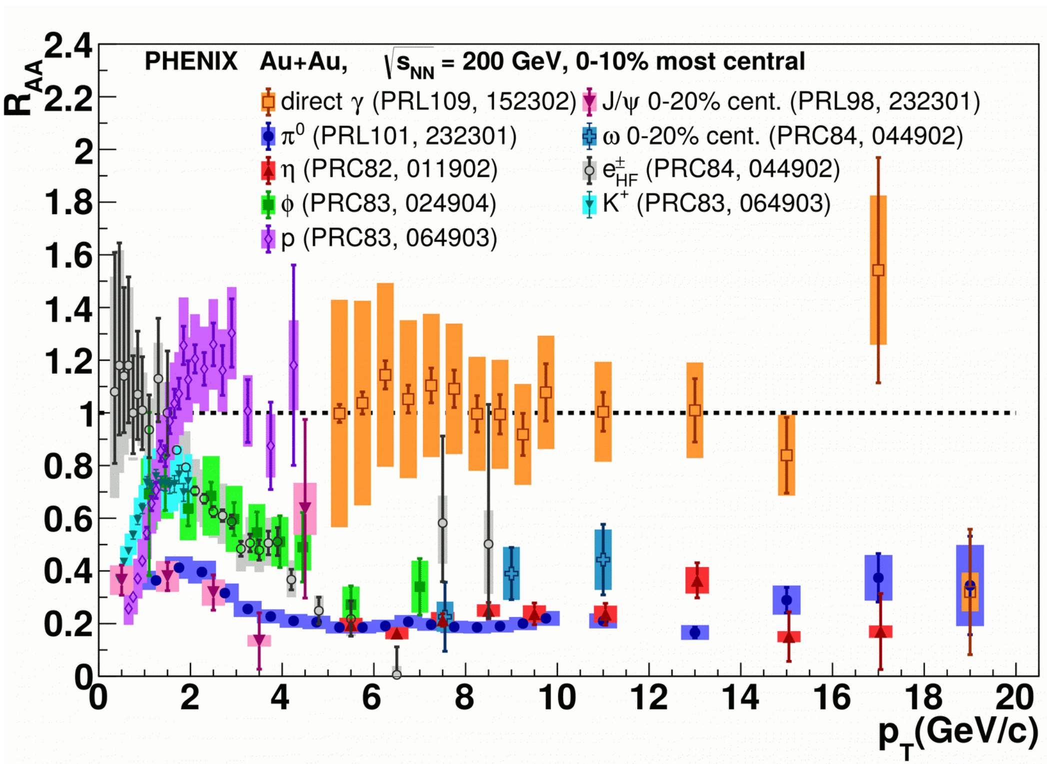
Nuclear modification factor

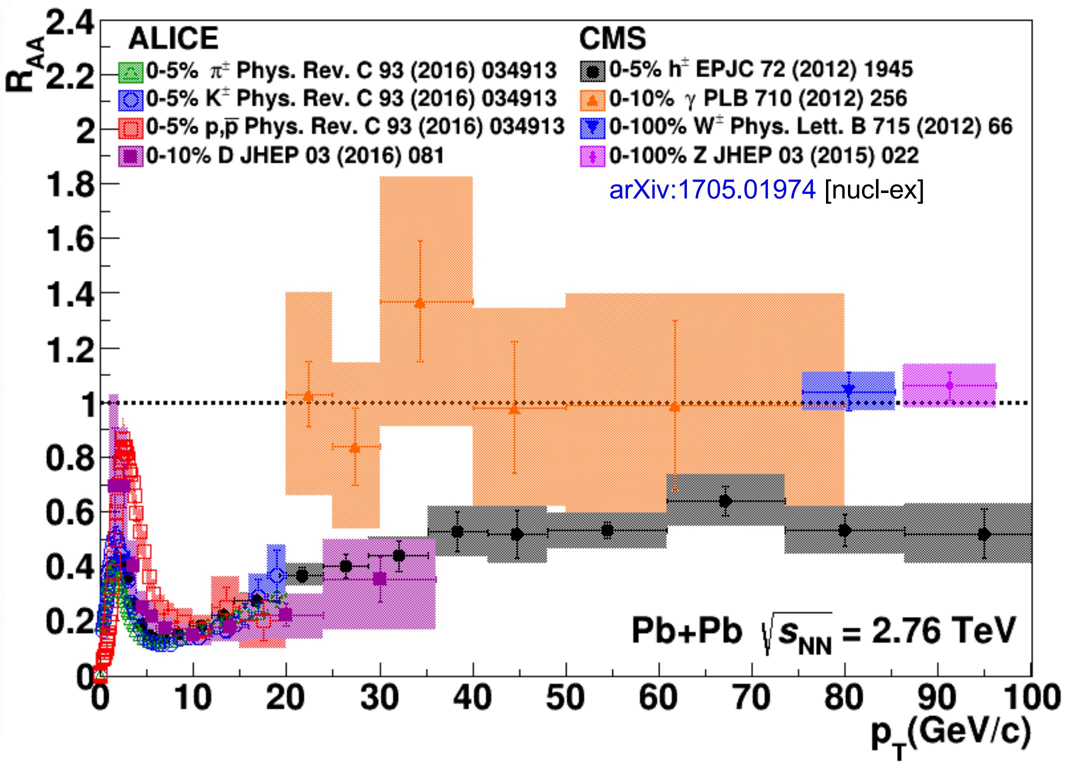


- Charged hadrons (colored probes) suppressed in Pb—Pb
- Charged hadrons not suppressed in p—Pb at midrapidity
- Electroweak probes not suppressed in Pb—Pb

Nuclear modification factor R_{AA}

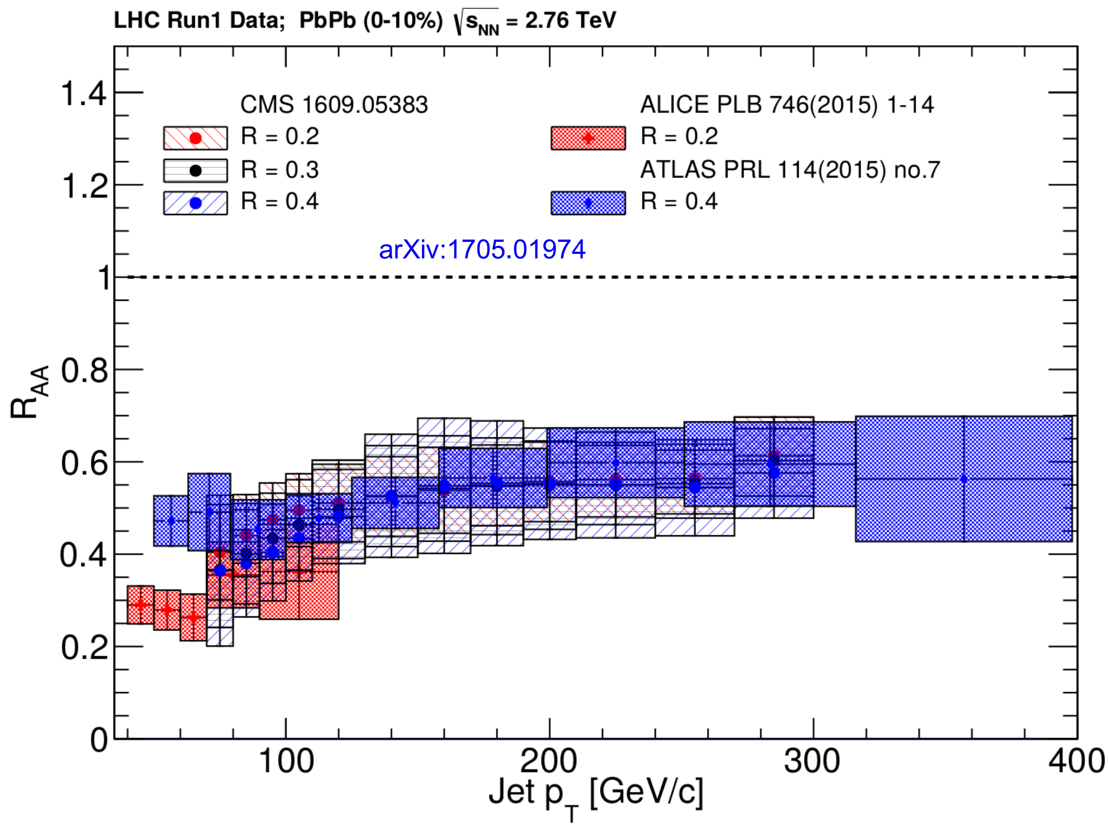
RHIC **LHC**



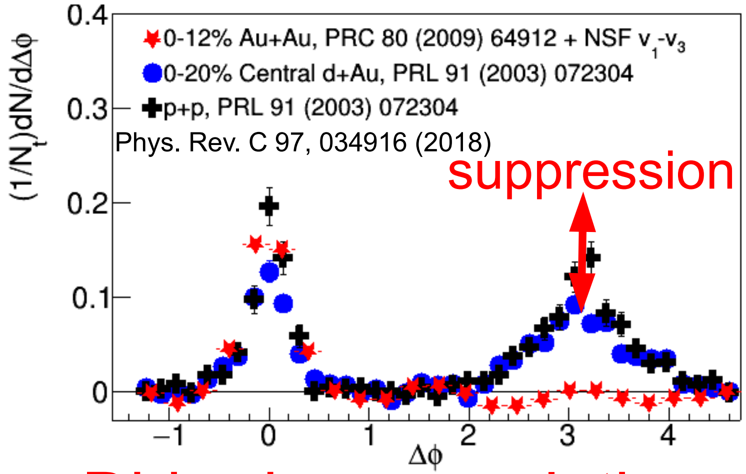


- *Electromagnetic probes* – consistent with no modification – medium is transparent to them
- *Strong probes* – significant suppression – medium is opaque to them - even heavy quarks!

Jet R_{AA}



- Jet R_{AA} also demonstrates suppression

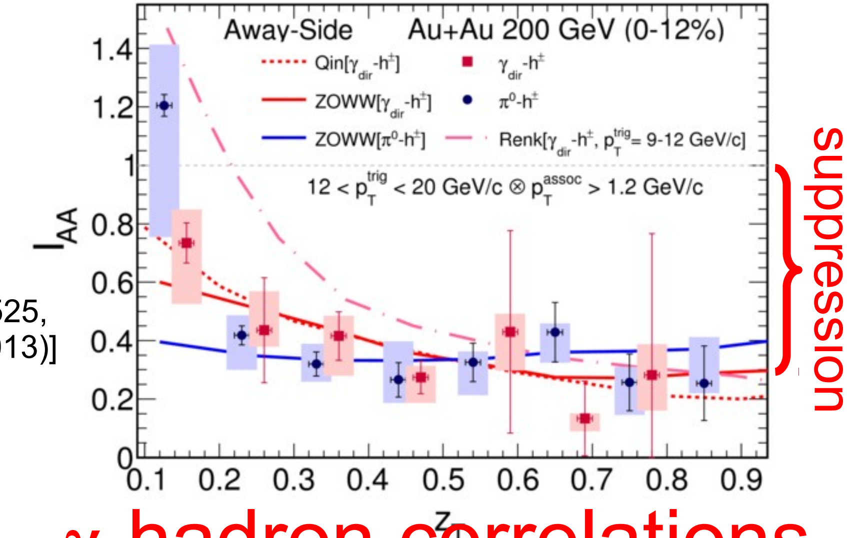


Di-hadron correlations

[Too many to list]

Jet v_2

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



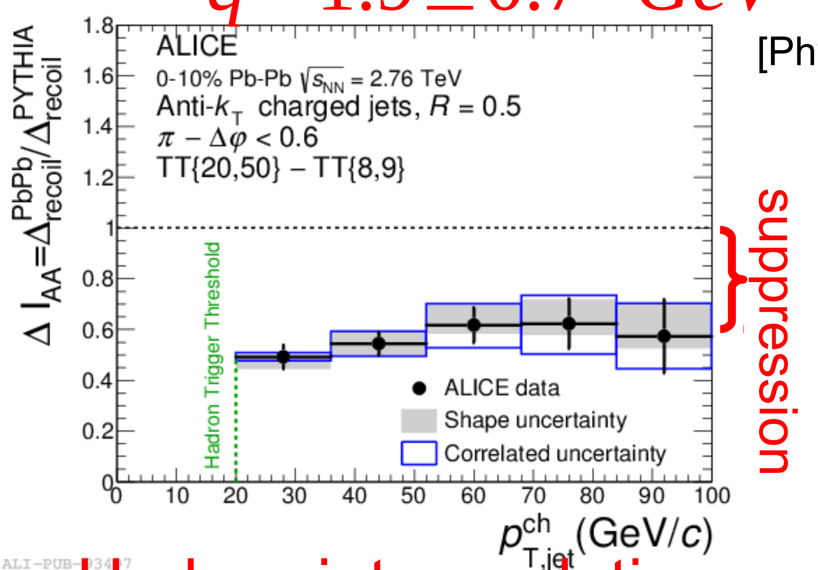
γ-hadron correlations

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

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

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

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



Hadron-jet correlations

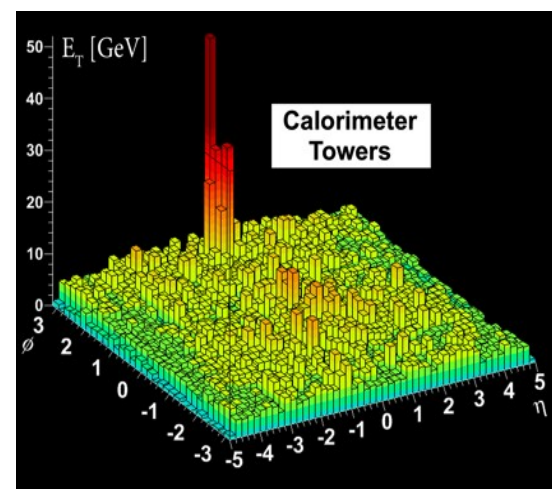
[JHEP 09 (2015) 170, Phys. Rev. C 96, 024905 (2017)]

γ-jet correlations

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

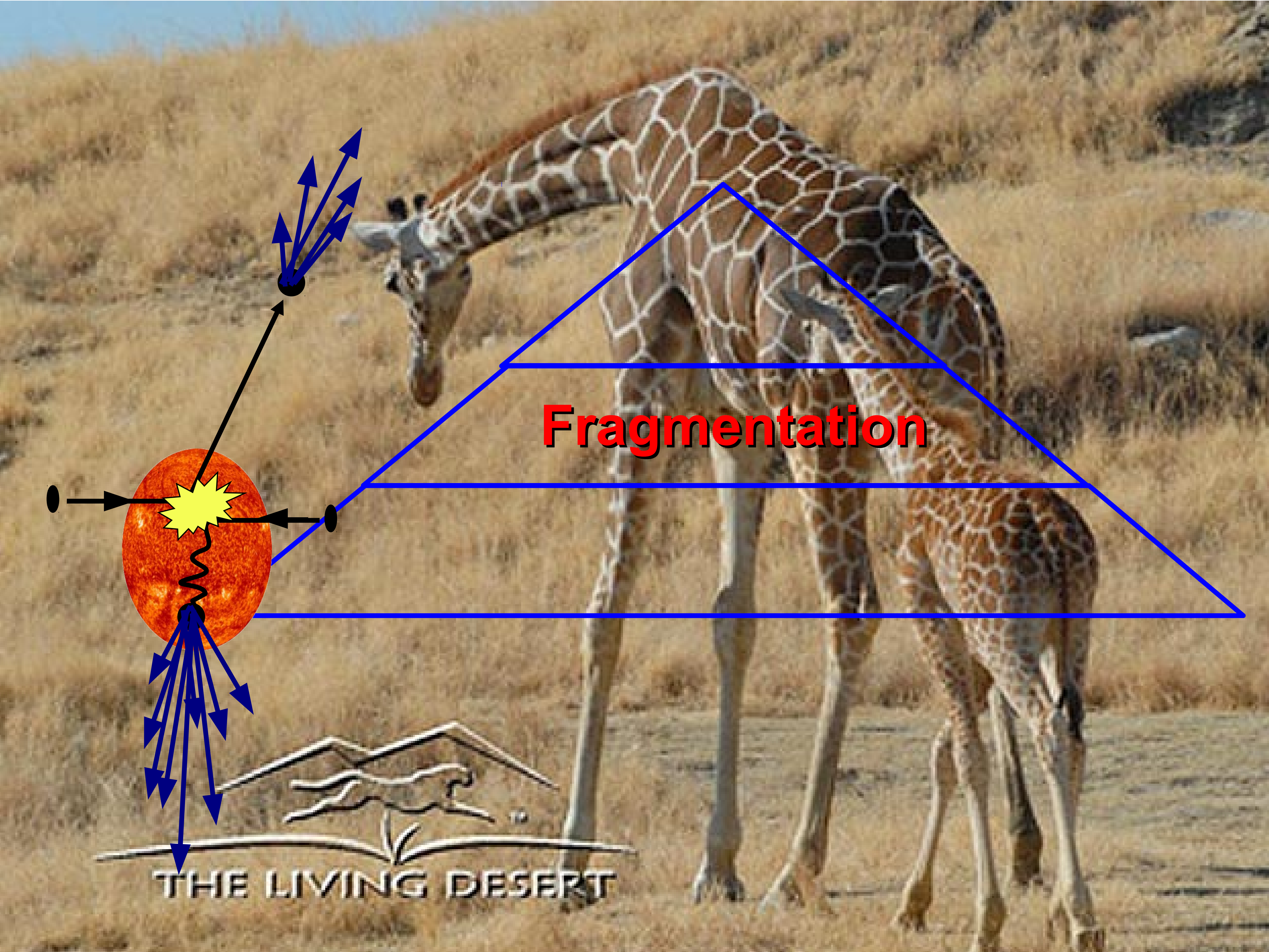
High-p_T hadron v_2

[too many to list]

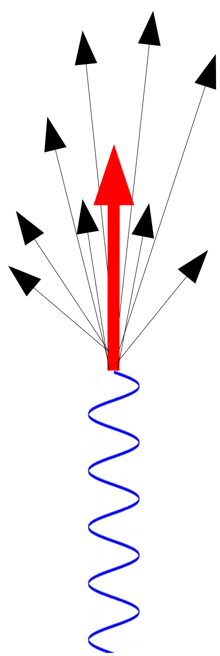


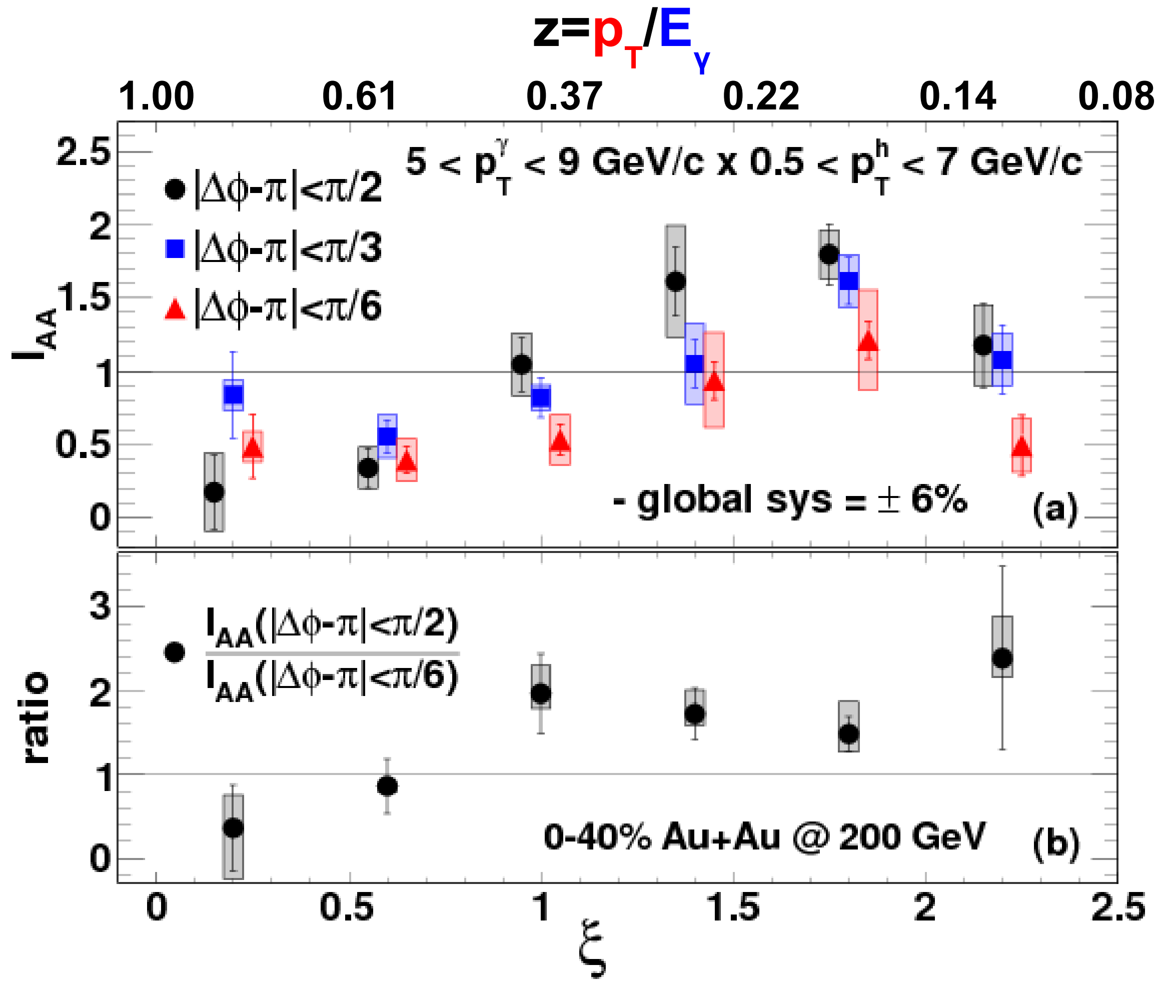
Dijet asymmetry

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


Fragmentation
THE LIVING DESERT

Fragmentations from γ-hadron correlations

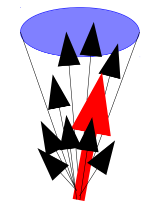


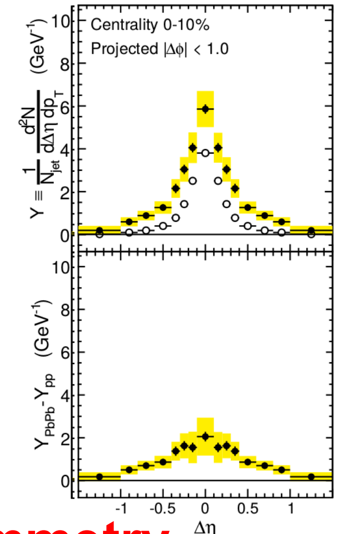


- Enhancement at low z
- Slight suppression at high z

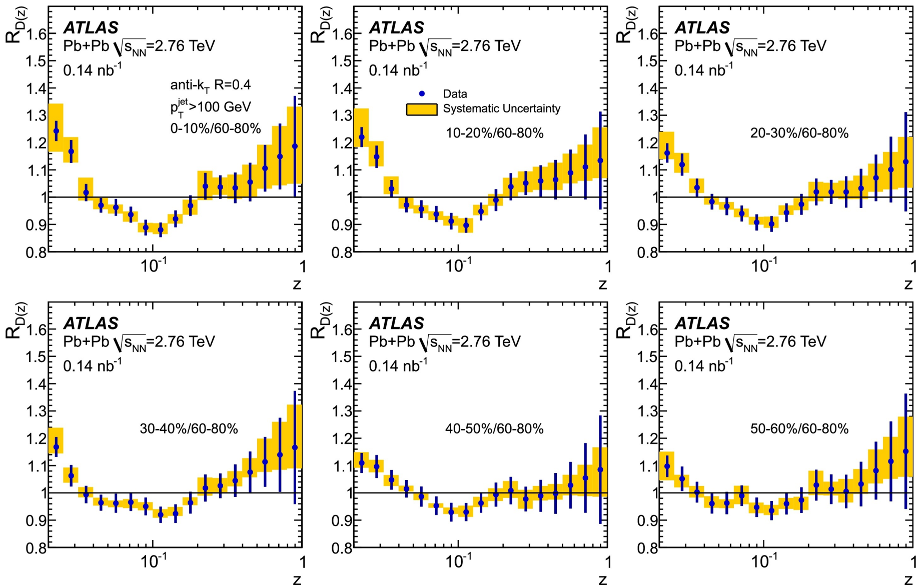
Modified fragmentation

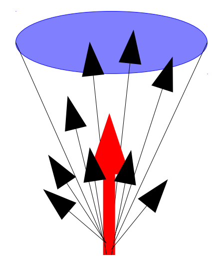
Jet-hadron correlations





Fragmentation functions with jets





$z = p_T / E_\gamma$

Di-hadron correlations

[Lots of papers]

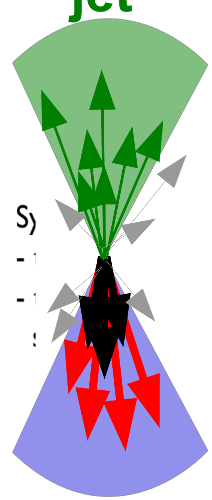
Jet shapes

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

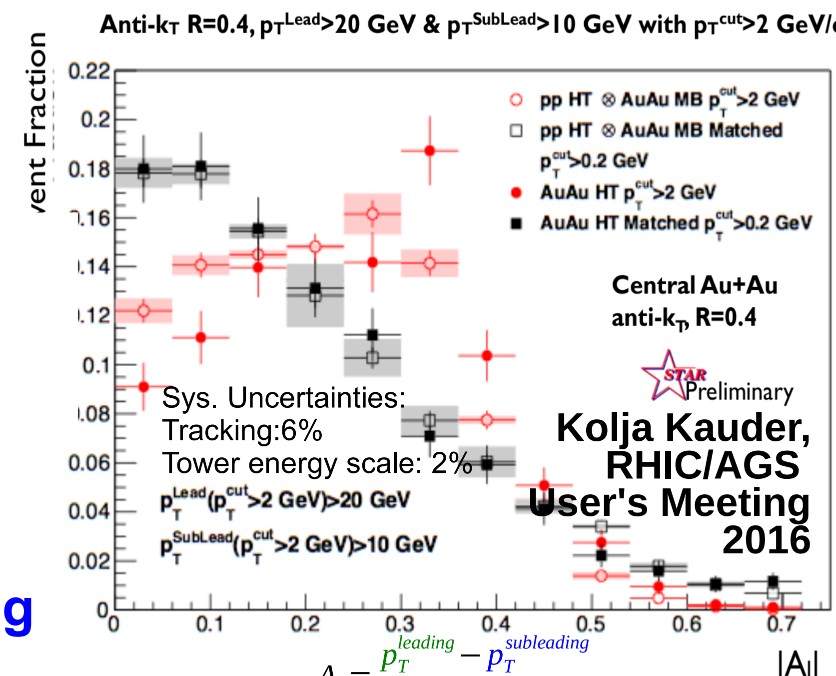
Di-jet asymmetry

arXiv:1609.03878

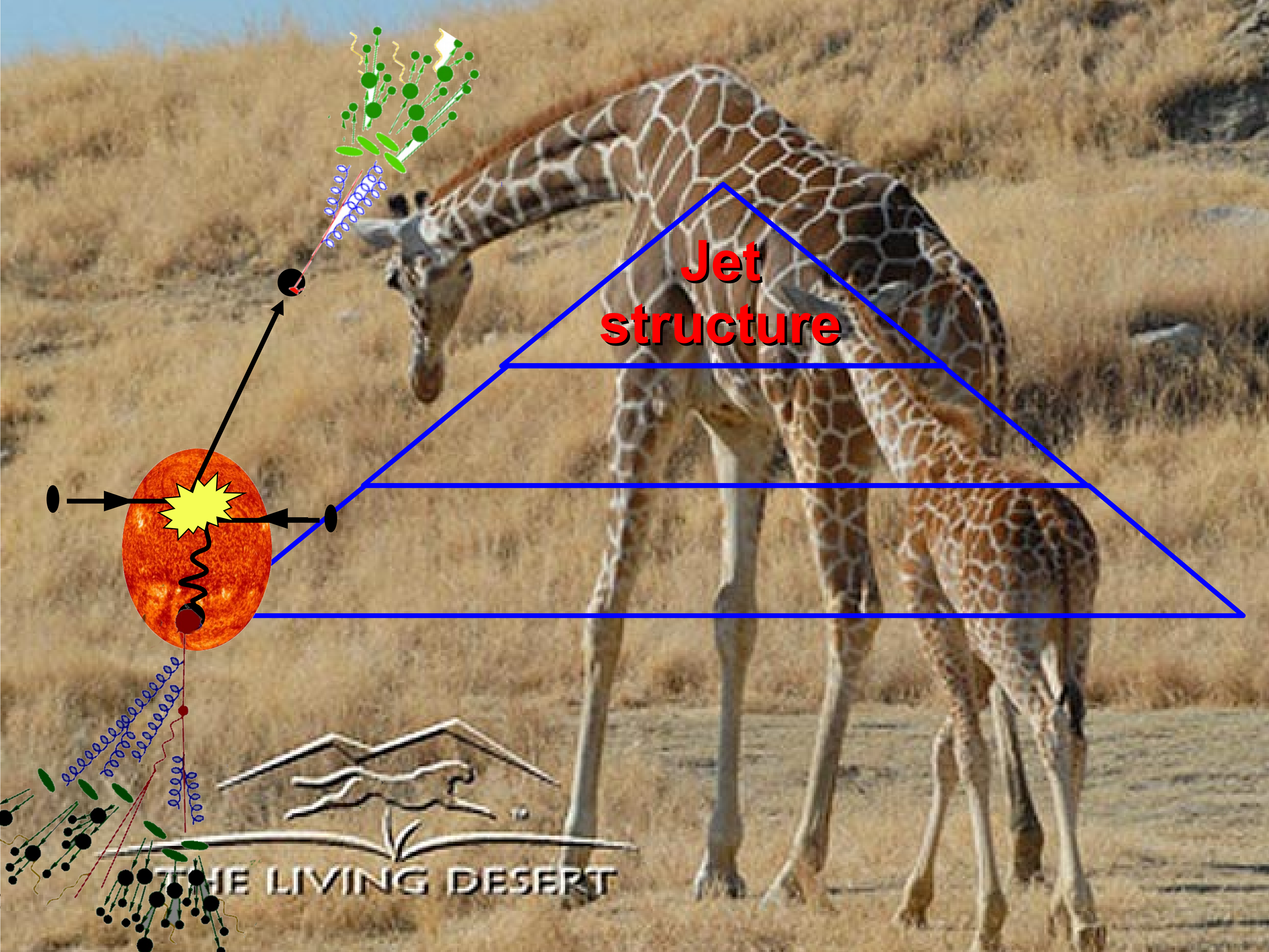
Leading jet



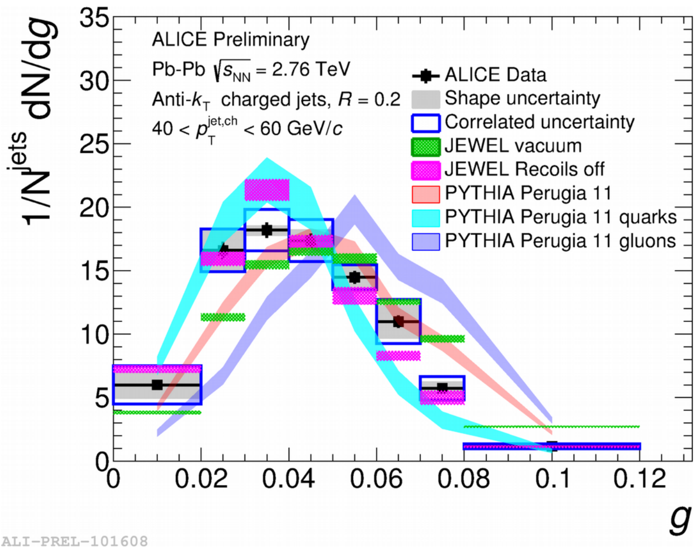
Subleading jet



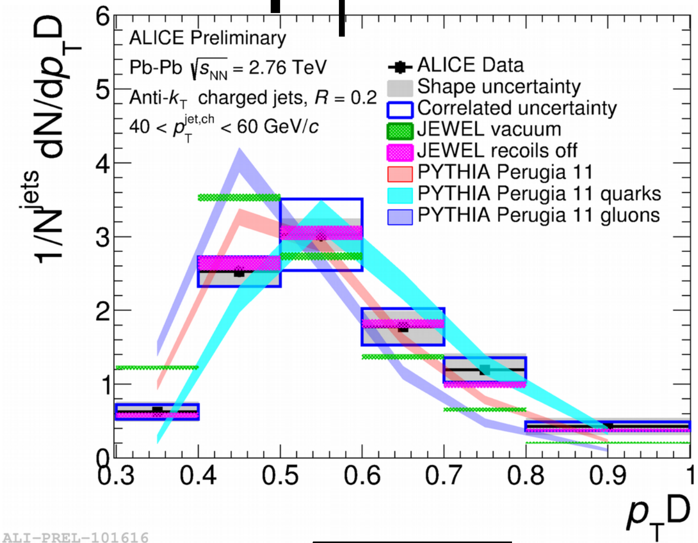
$$A_j = \frac{p_T^{leading} - p_T^{subleading}}{p_T^{leading} + p_T^{subleading}}$$


Jet
structure
THE LIVING DESERT

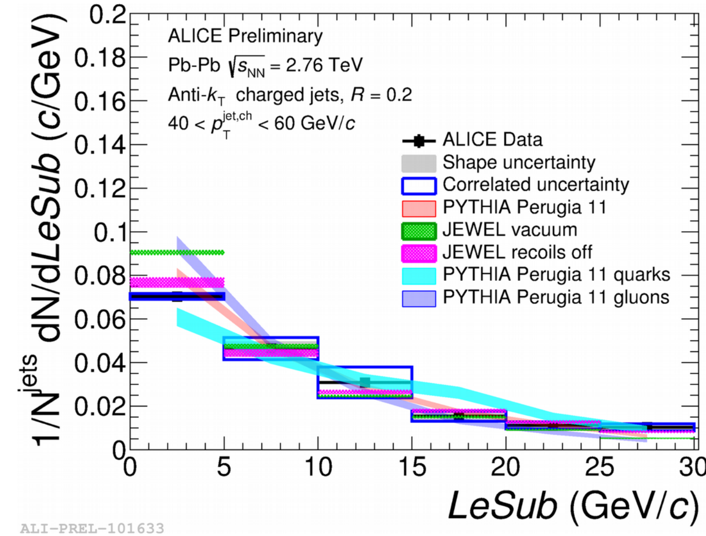
Girth g



Dispersion p_TD



LeSub



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

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

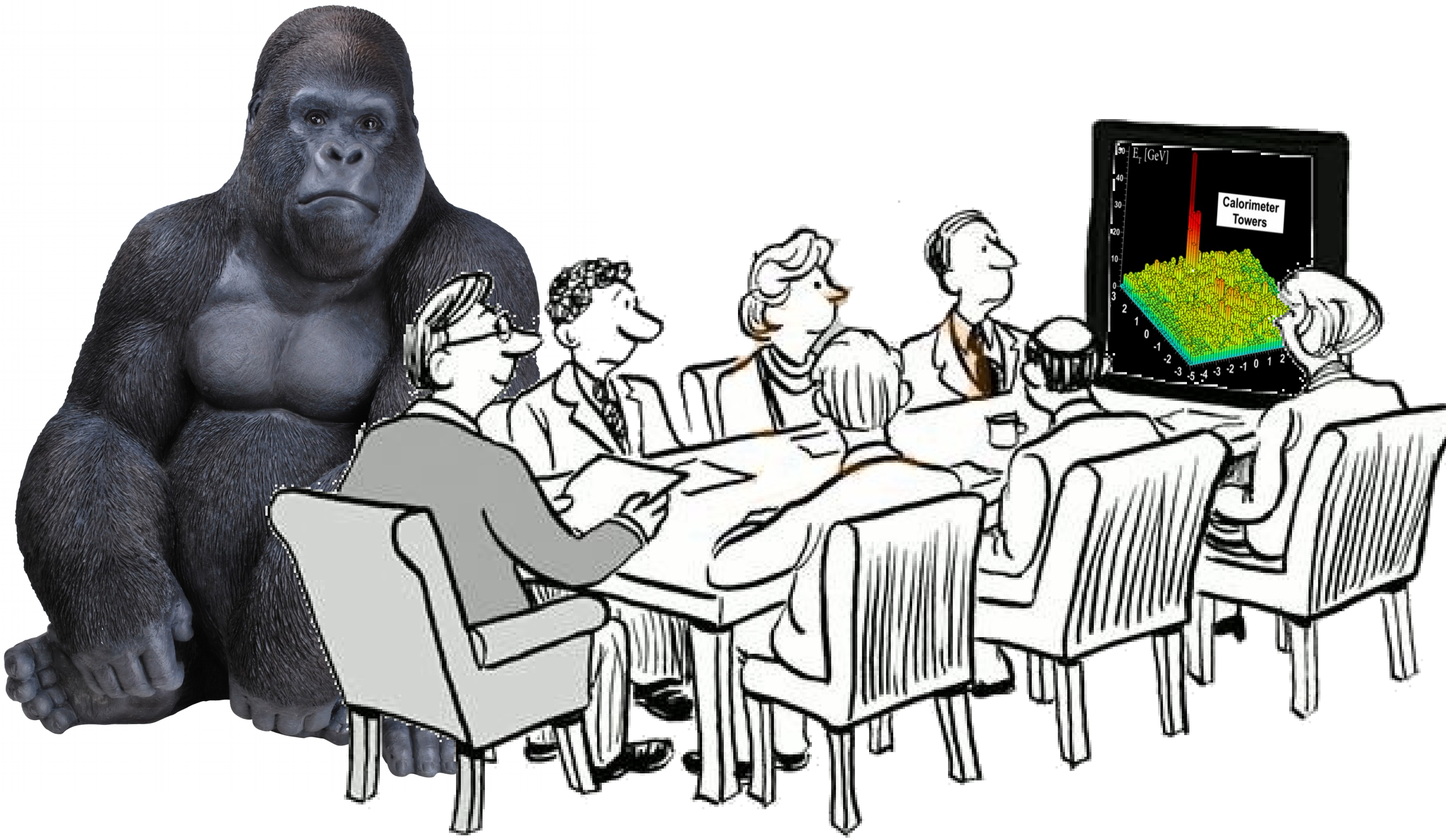
$$LeSub = p_T^{leading} - p_T^{subleading}$$

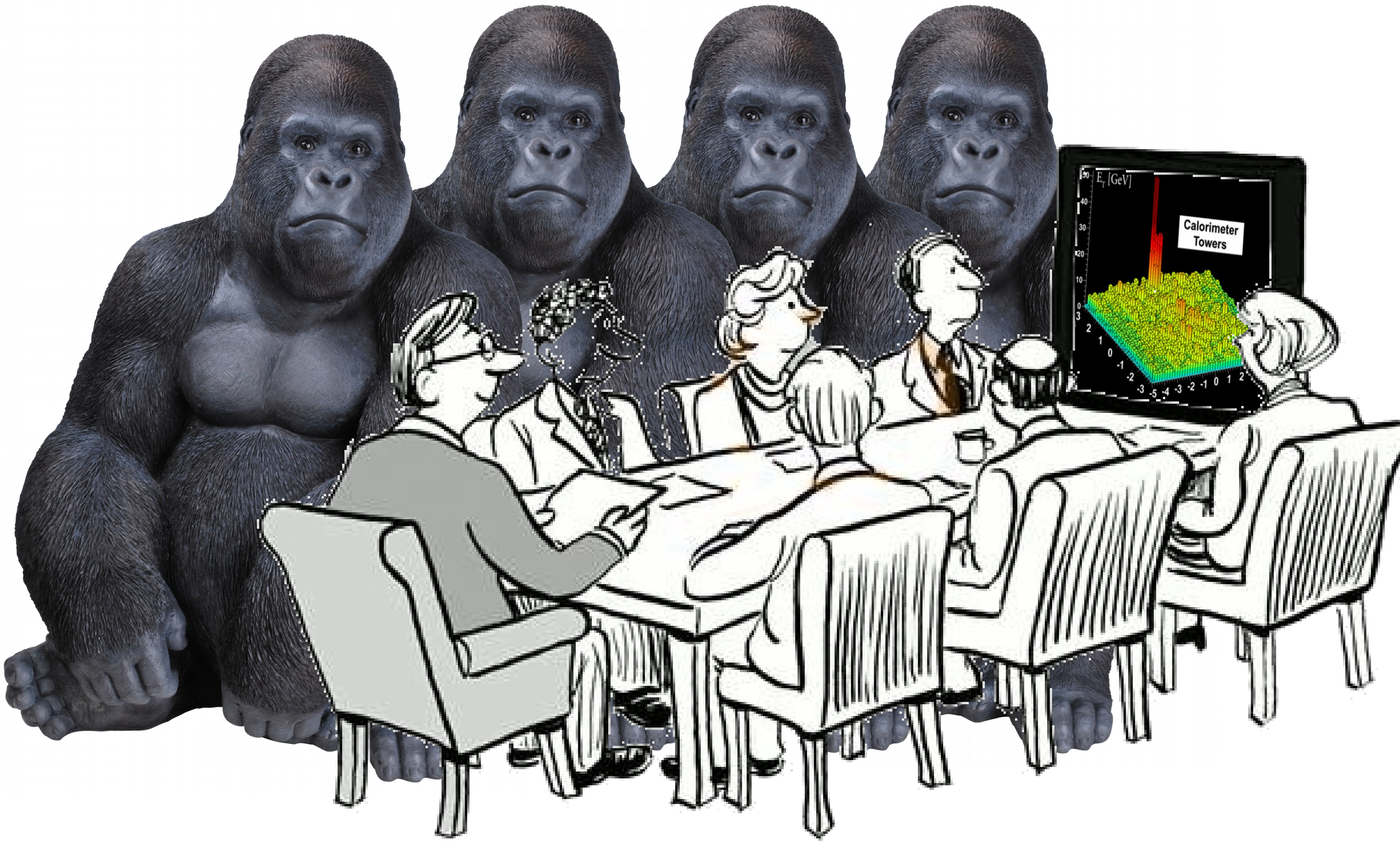
Jets are slightly more collimated than in pp

Agrees with PYTHIA

The invisible gorilla

http://www.theinvisiblegorilla.com/


E_T [GeV]
Calorimeter
Towers


Calorimeter
Towers

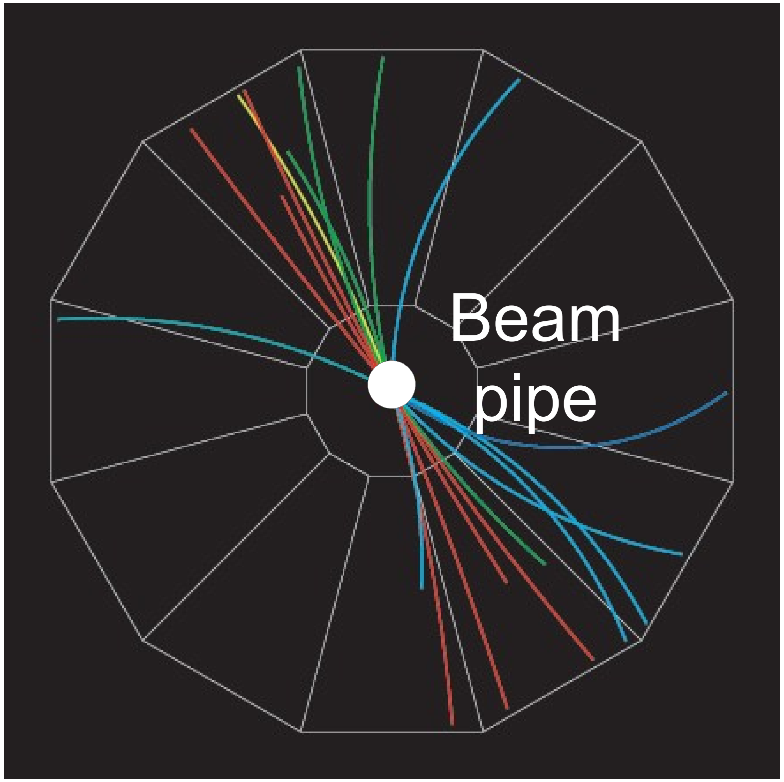
What is a jet?

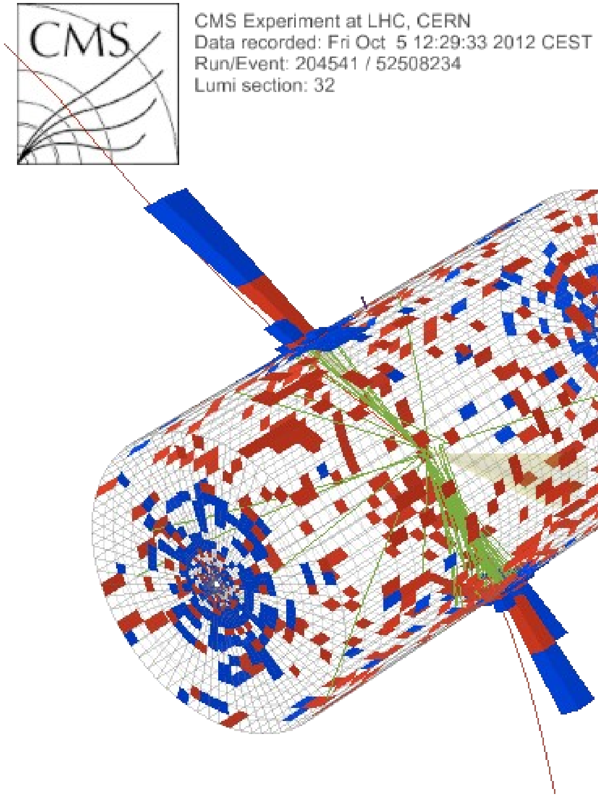
What is a jet?

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

What is a jet?

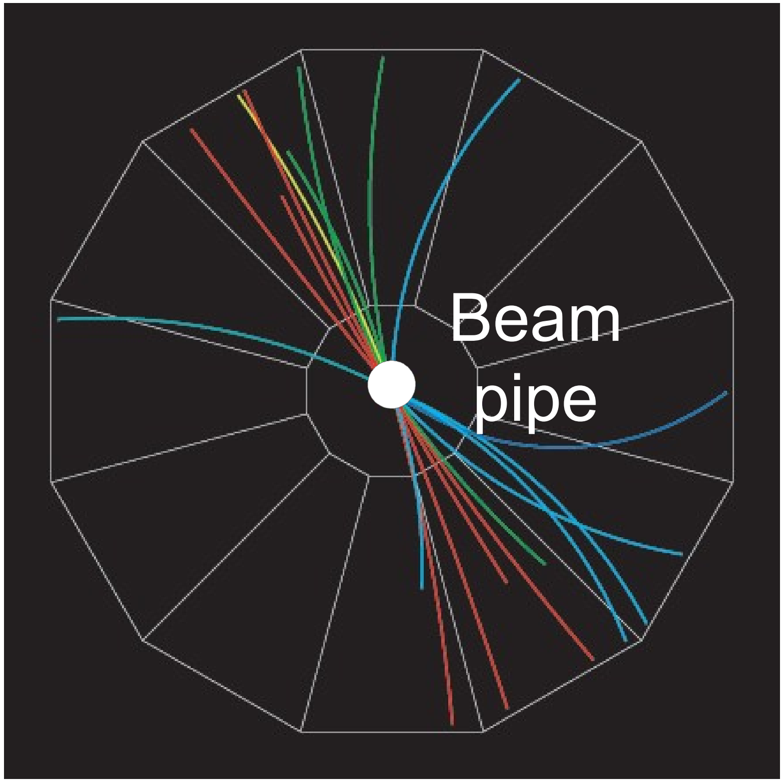
p+p → dijet

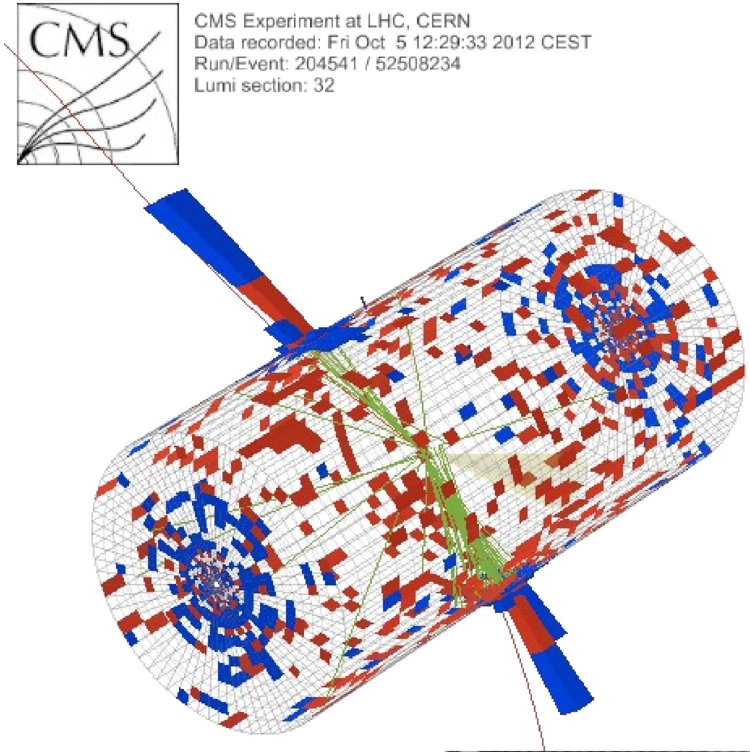




What is a jet?

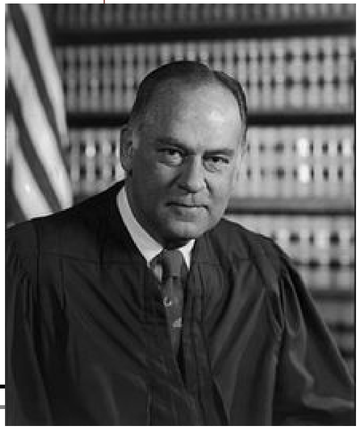
p+p → dijet





"I know it when I see it"

US Supreme Court Justice Potter Stewart,
Jacobellis v. Ohio



Jet finding in pp collisions

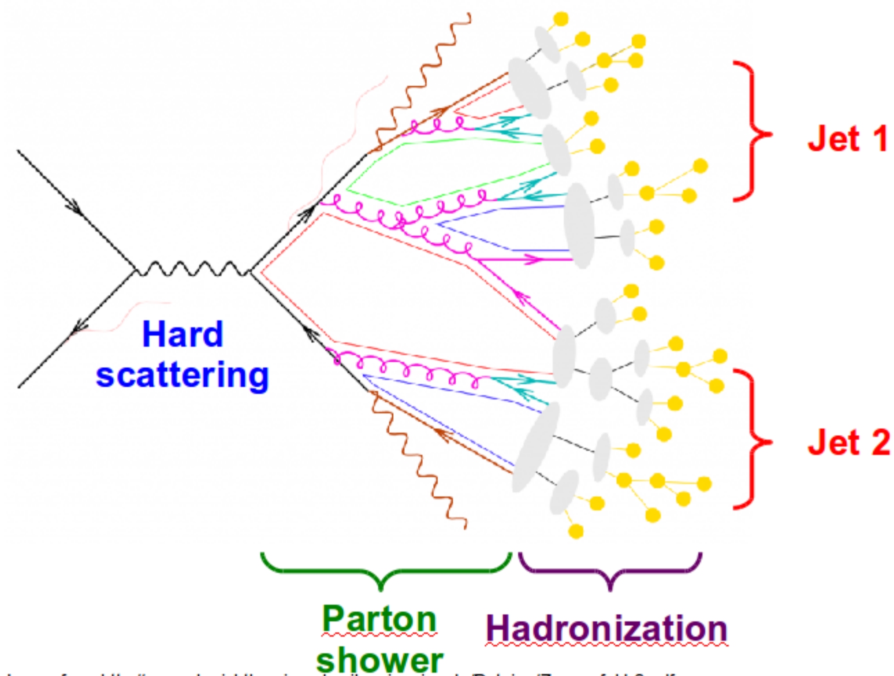


Image from http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

- 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

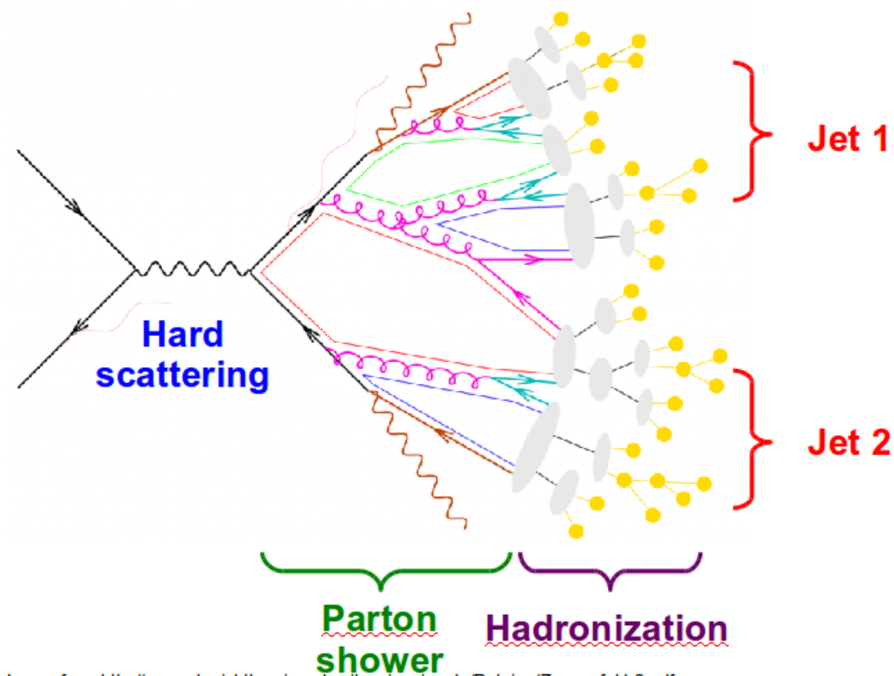


Image from http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

- 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/

Background is a solved problem.
– Unnamed

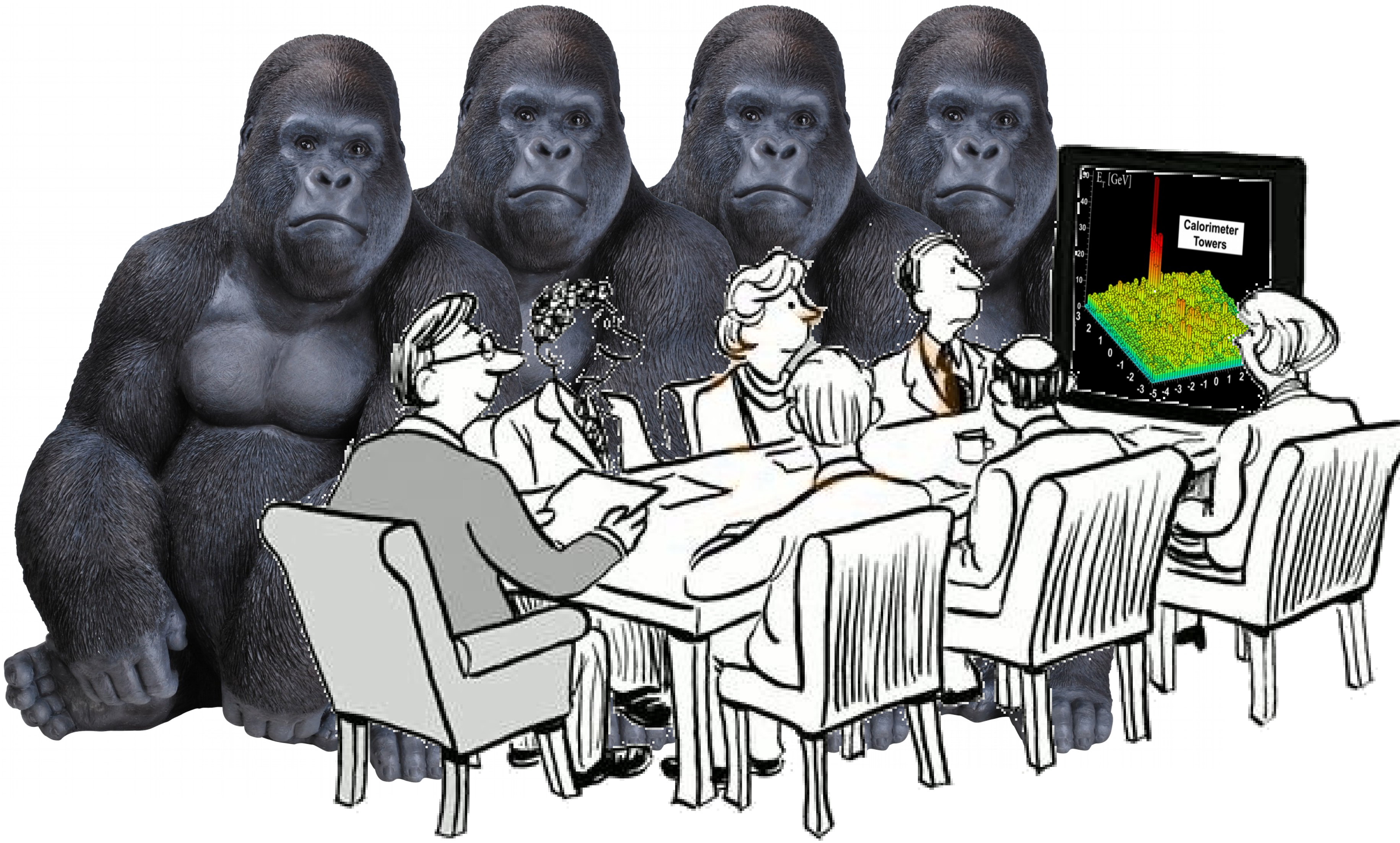
Wiki: “A **white elephant** is a possession which its owner cannot dispose of and whose cost, particularly that of maintenance, is out of proportion to its usefulness.

Workshop on the Definition of Jets in a Large Background

https://www.bnl.gov/jets18/index.php

June 25-27

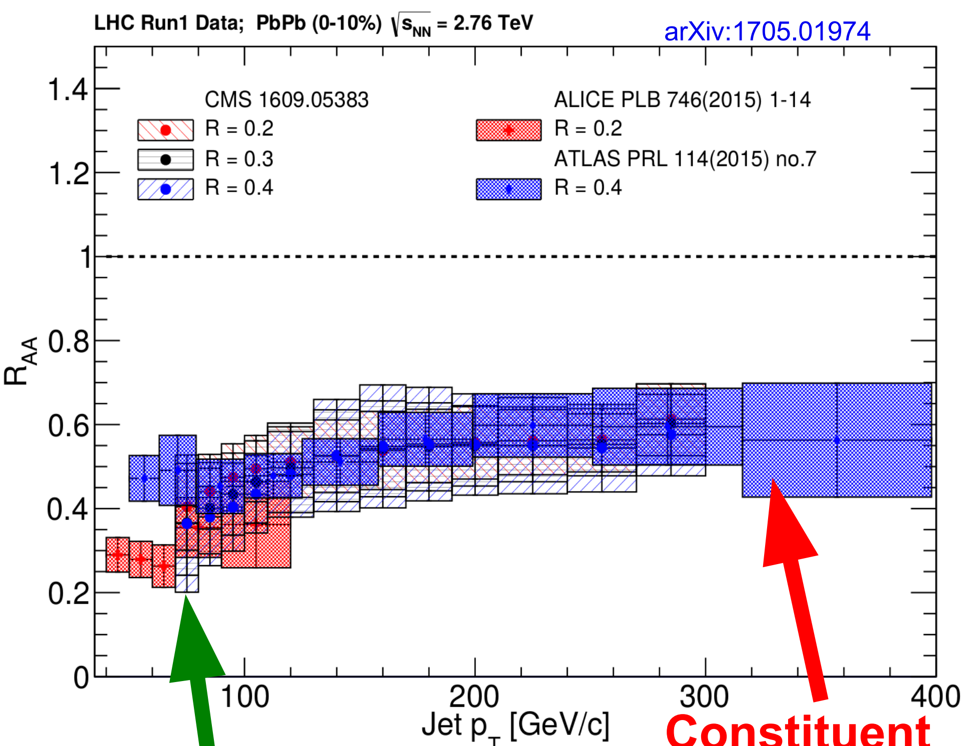
We don't fully understand the background



ATLAS

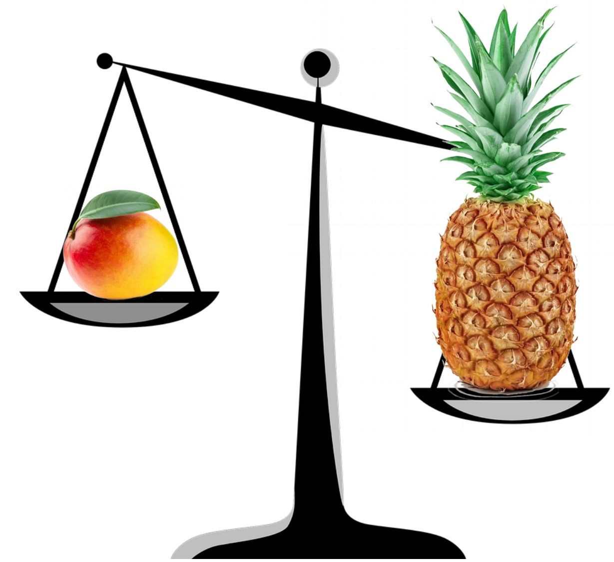
Background subtraction method:

- 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



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

ATLAS



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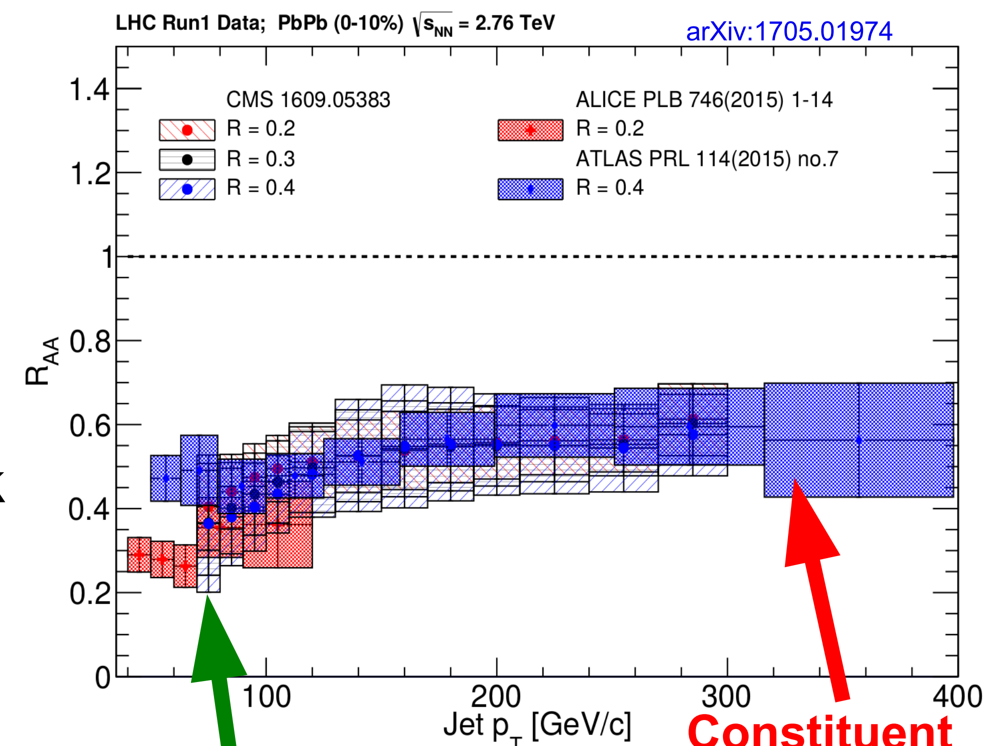


But they do matter down here!

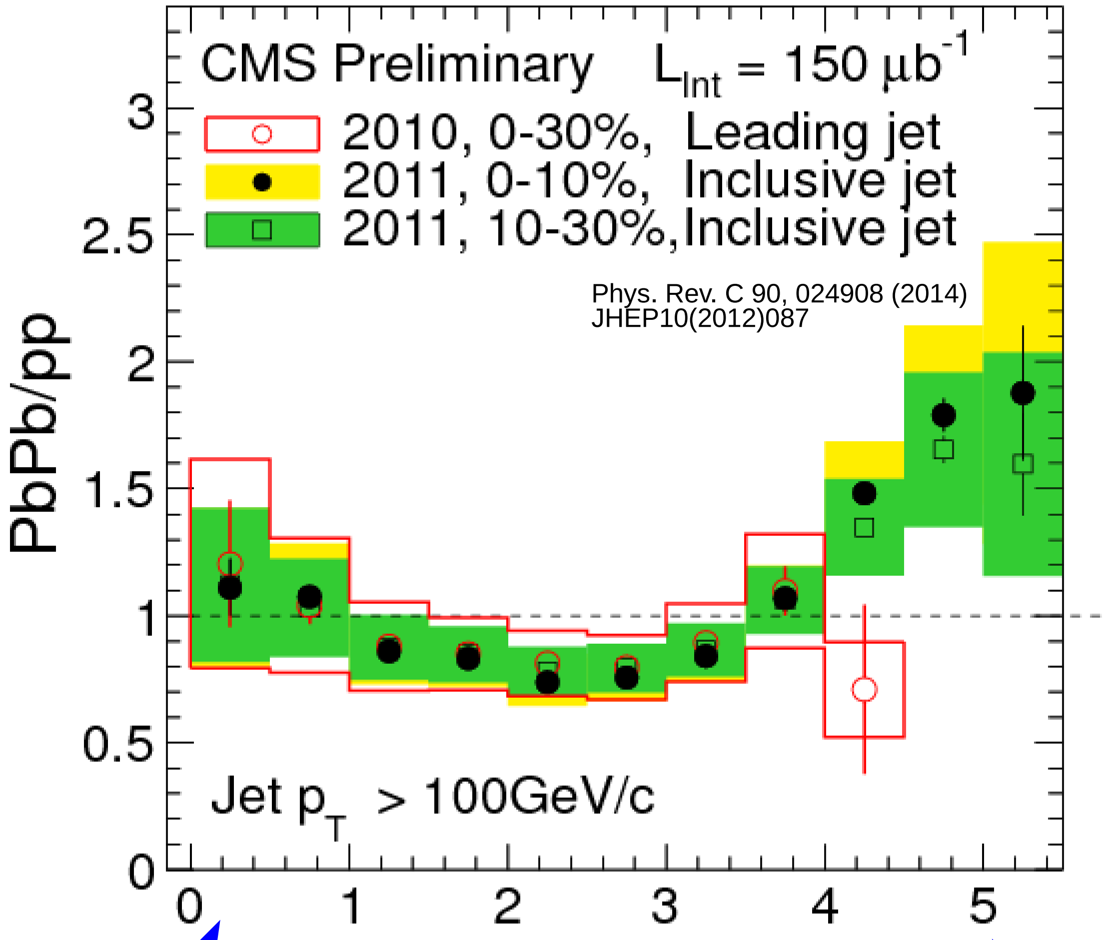
Constituent biases don't matter that much up here

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

Different jets are different.

– Rosi Reed

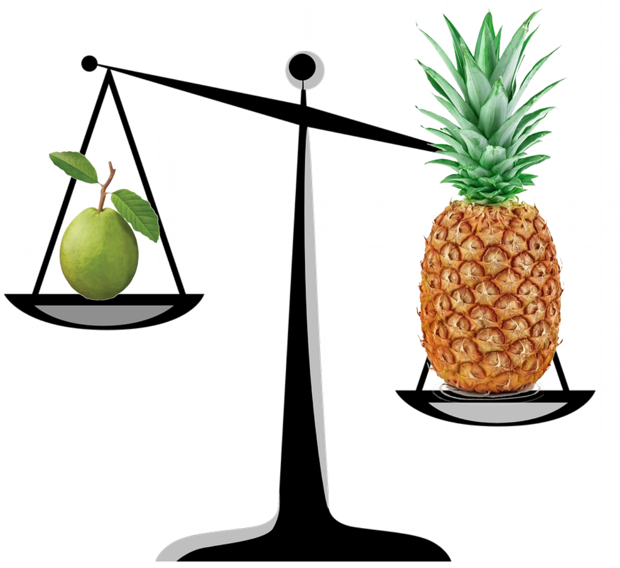
What you see depends on where you look



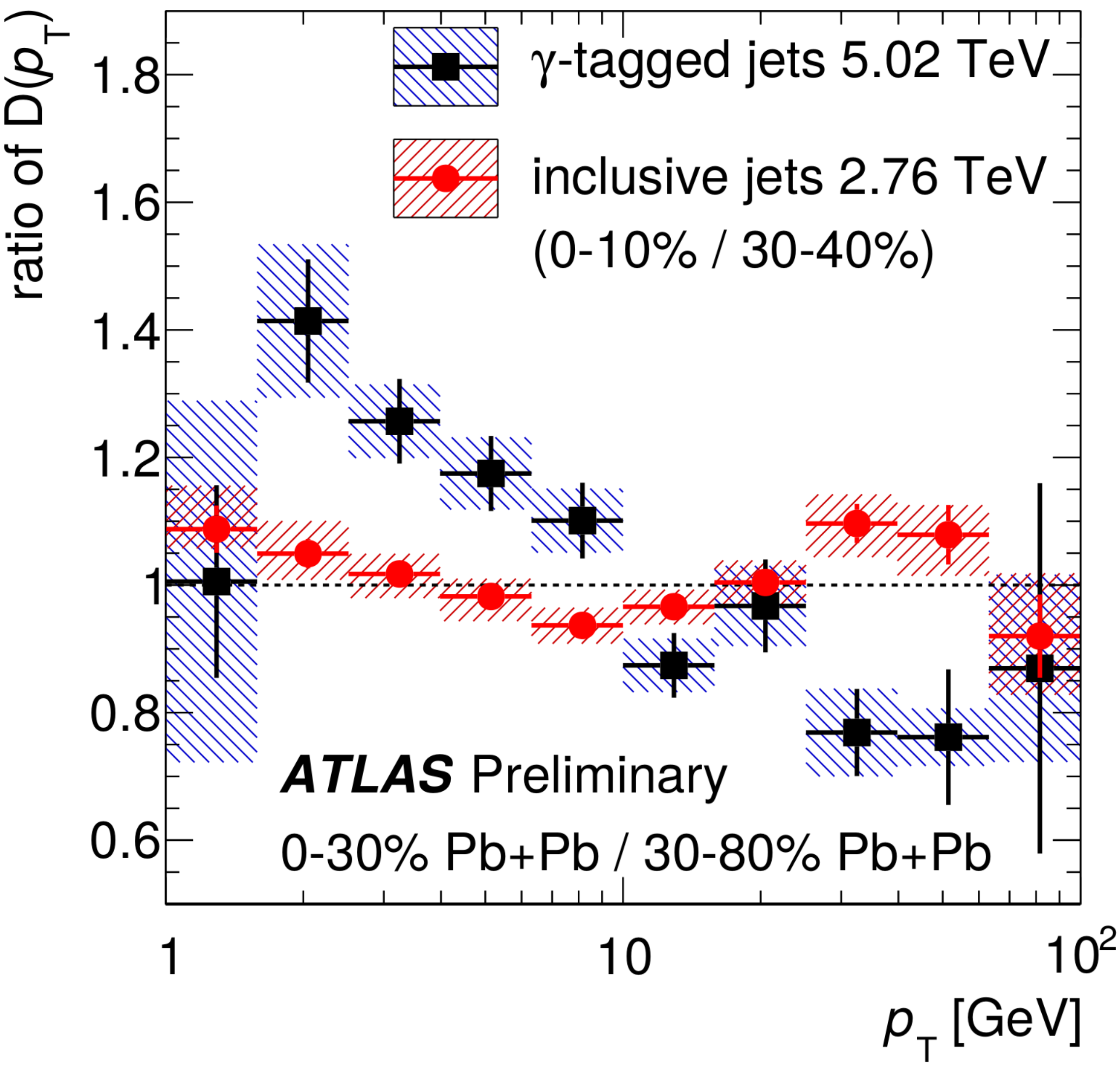
$z = p_T/E_{jet}$

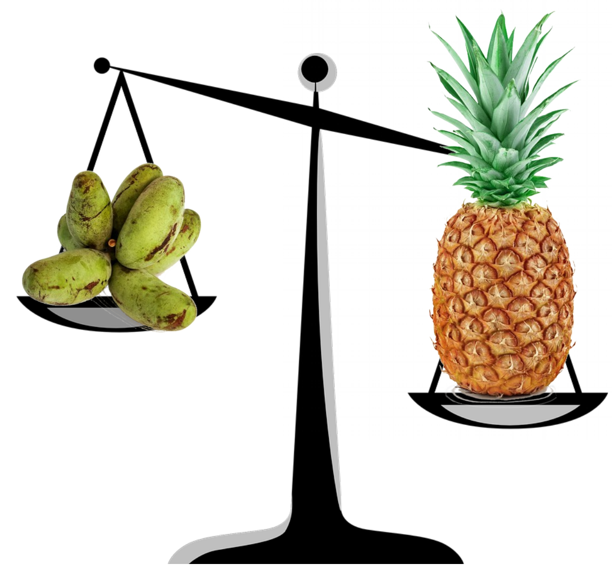
High p_T

Low p_T



What you see depends on where you look





What should we measure?

What should we measure?

Jupiter and the Monkey

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

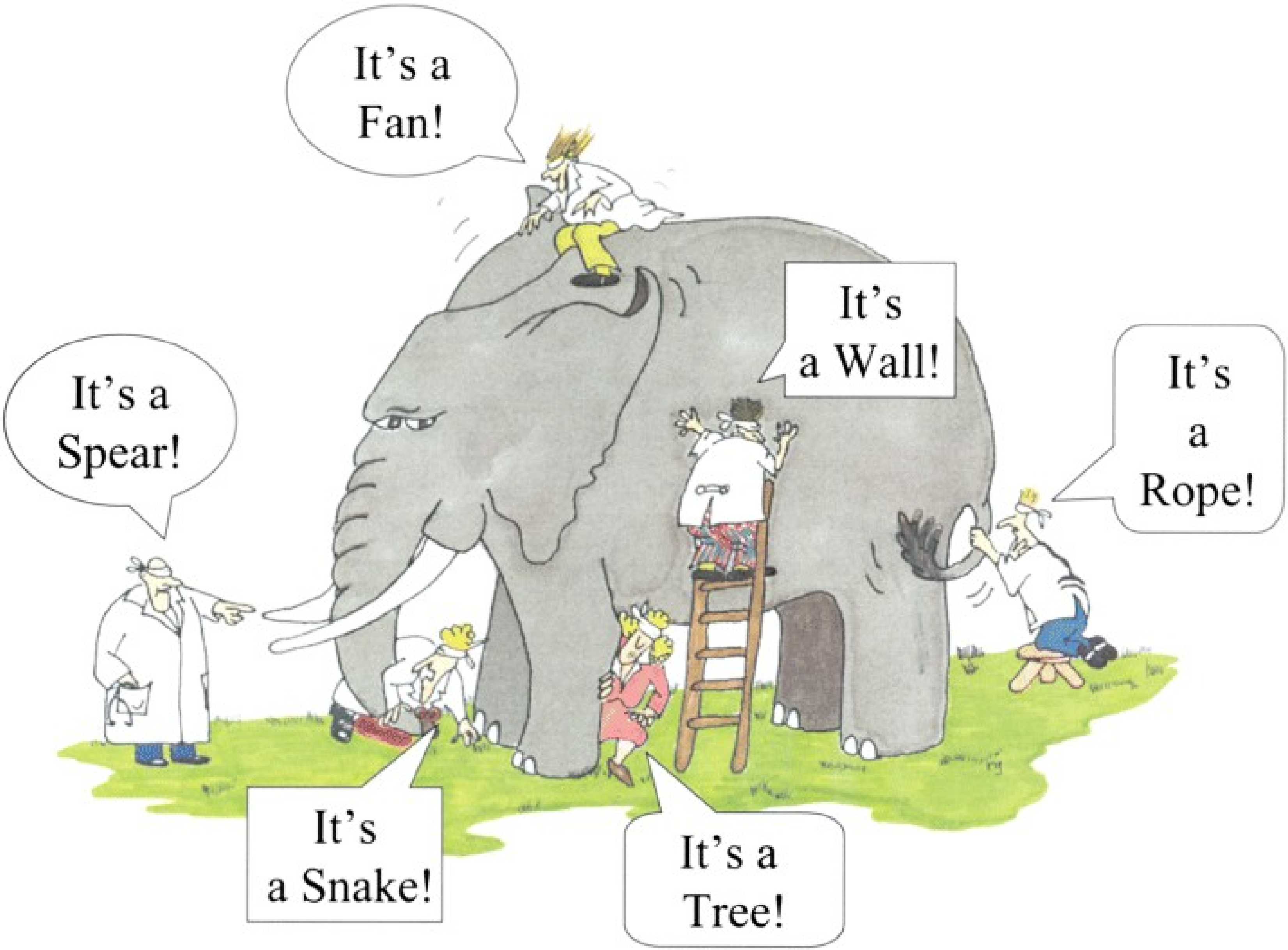
The monkey came with the rest, and presented a flat-nosed, hairless, ill-featured young monkey.

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

Blind men and the elephant



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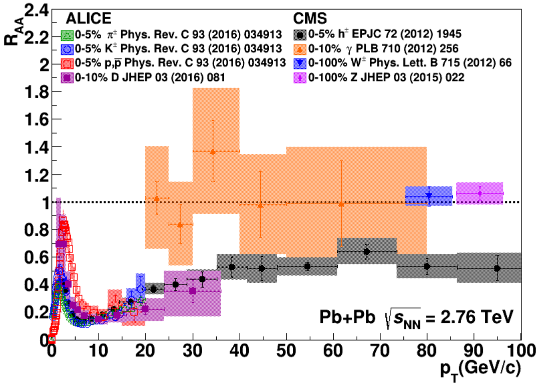

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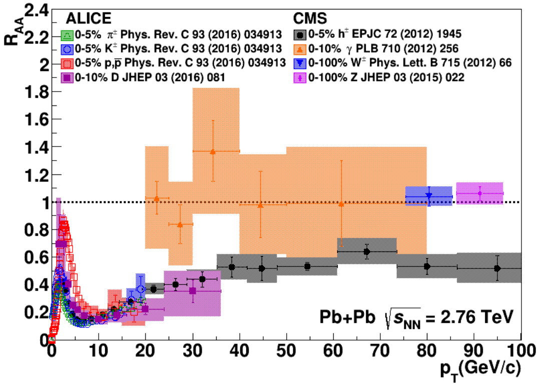

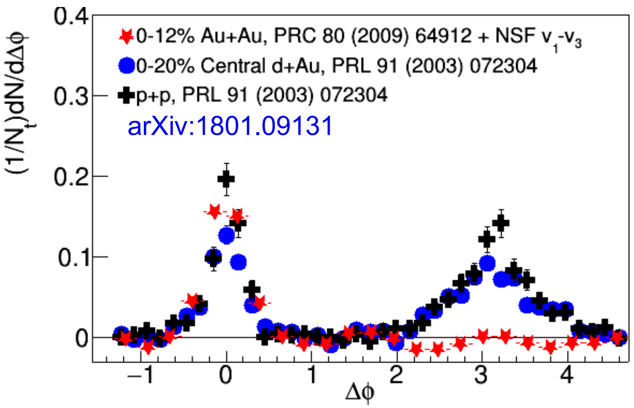

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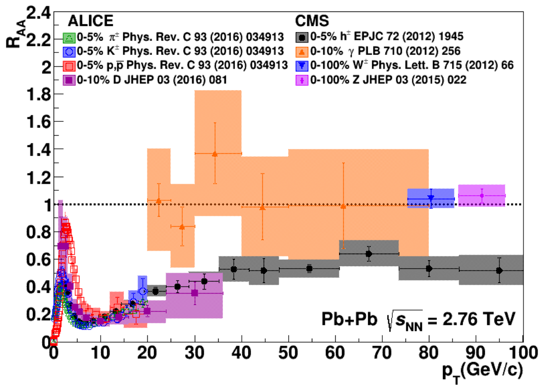

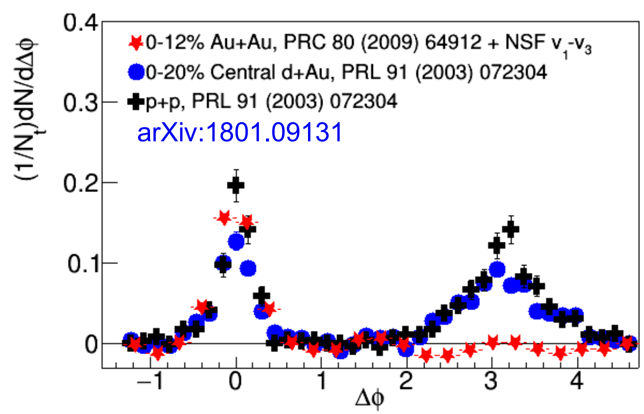

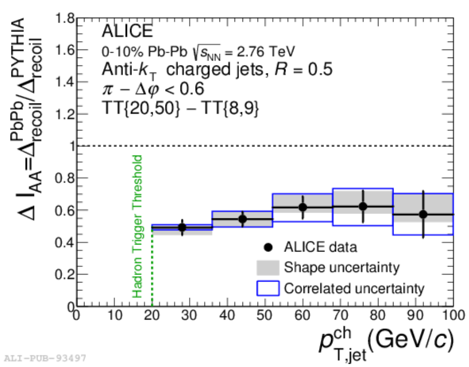

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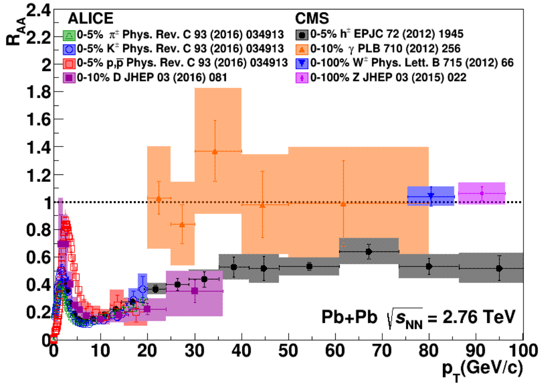

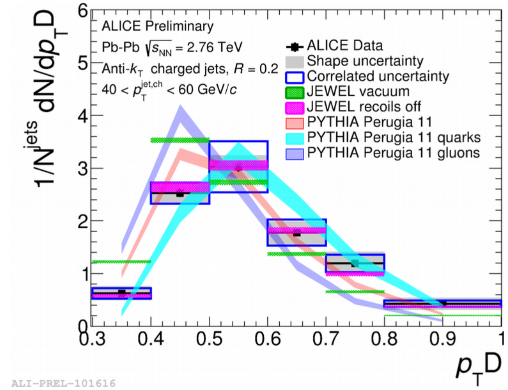

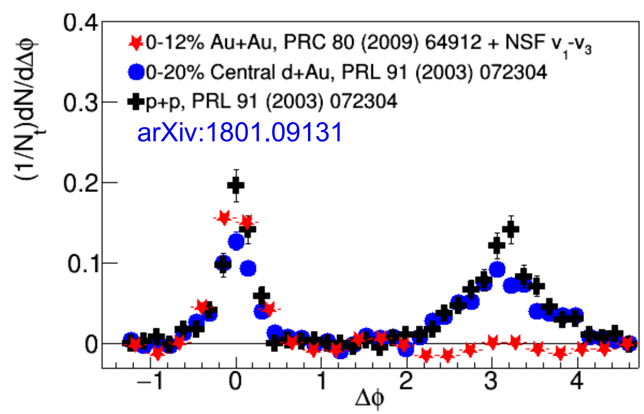

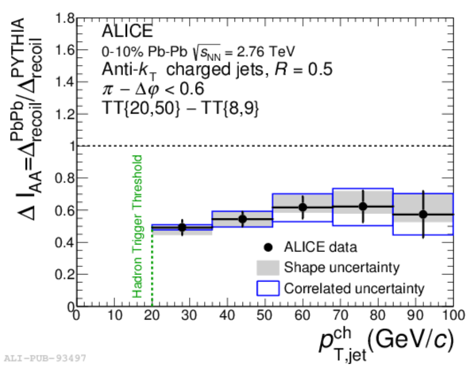

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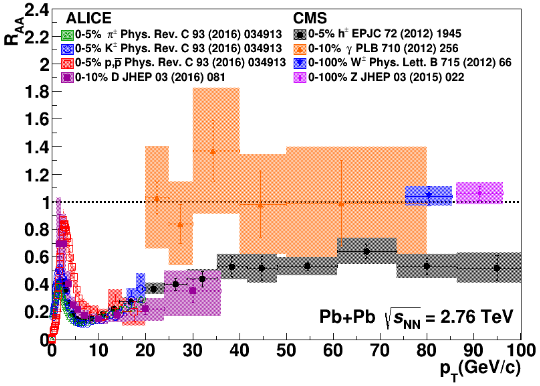
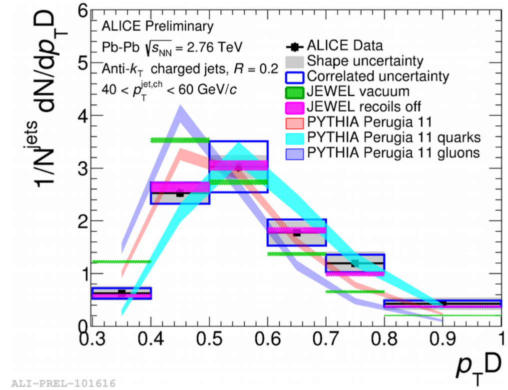
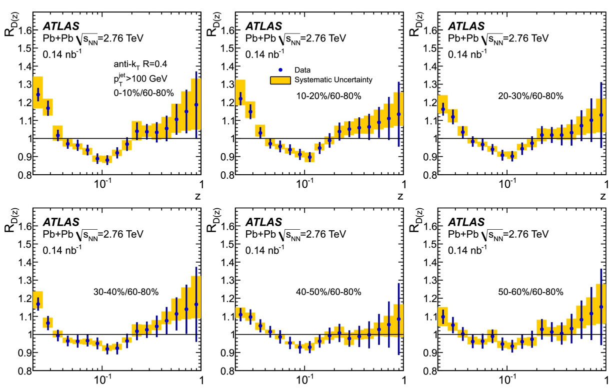
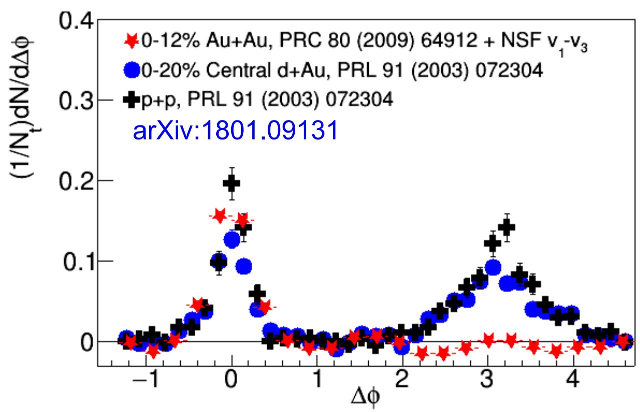
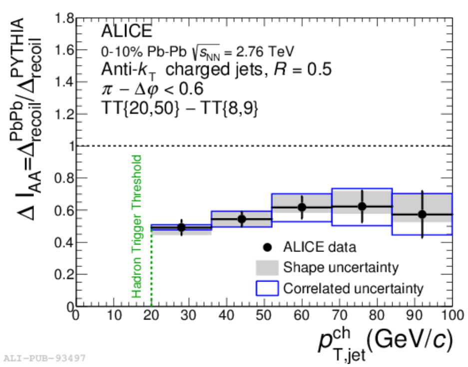








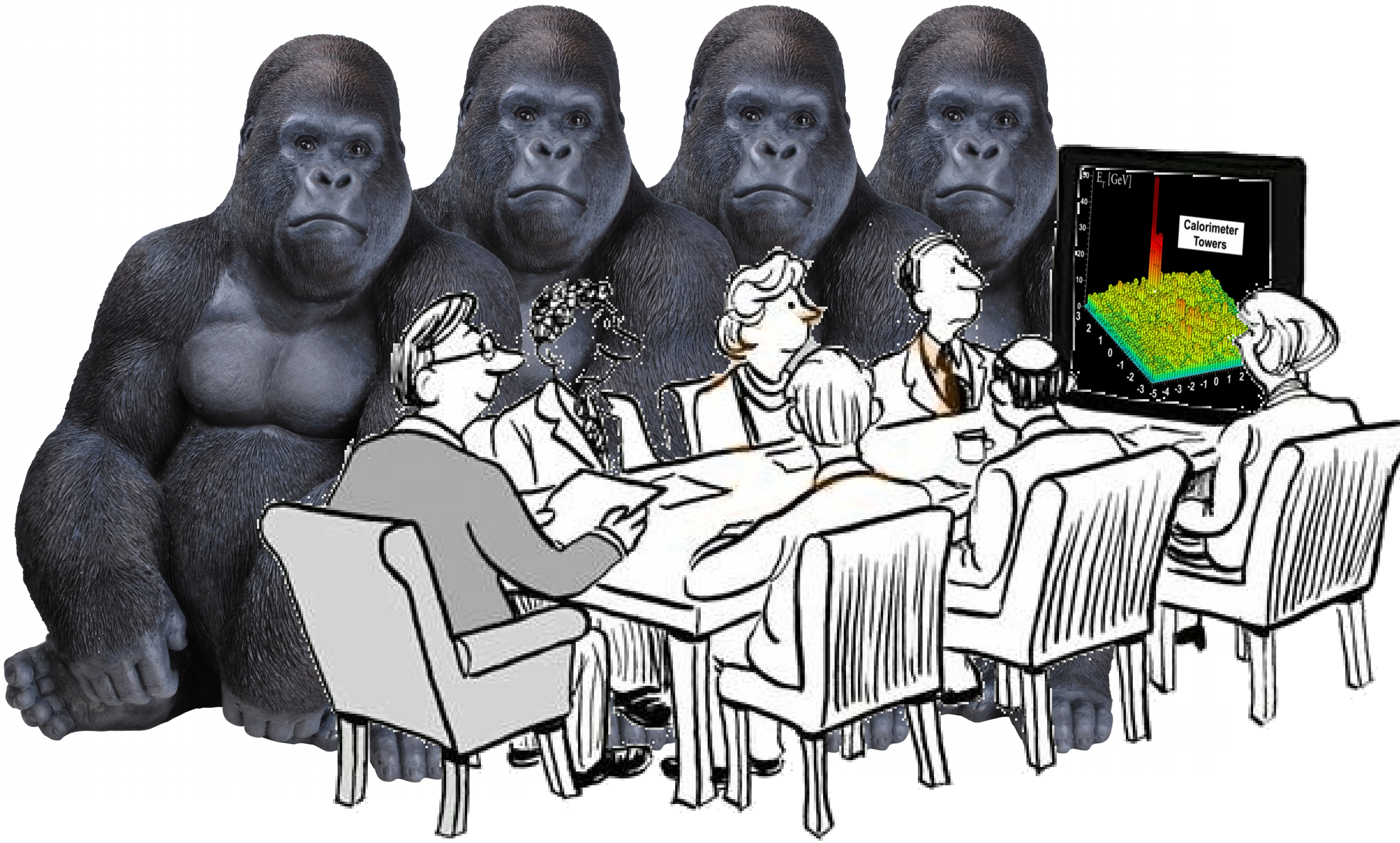


What should we measure?

Everything

We don't fully understand the background

We need to look at the whole picture



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...but we don’t know which observables are most sensitive.

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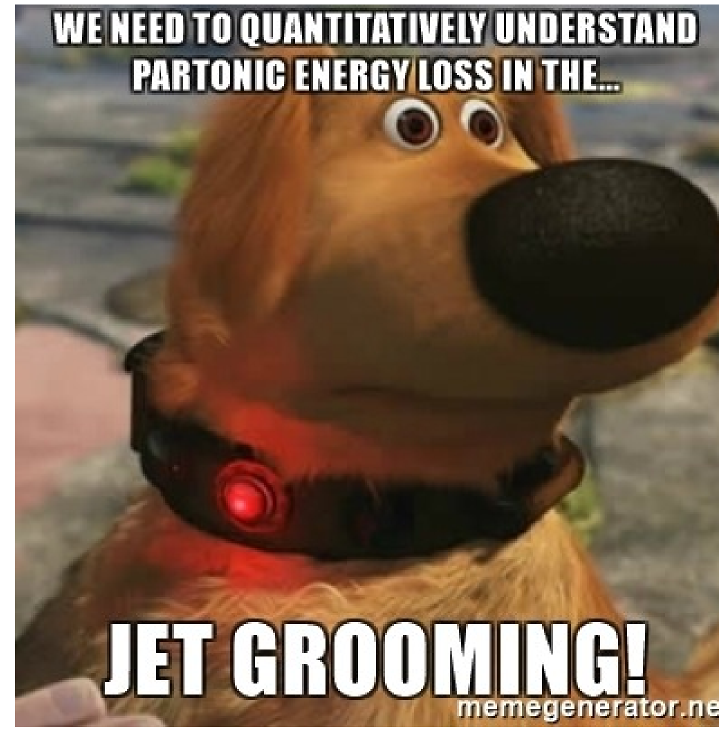

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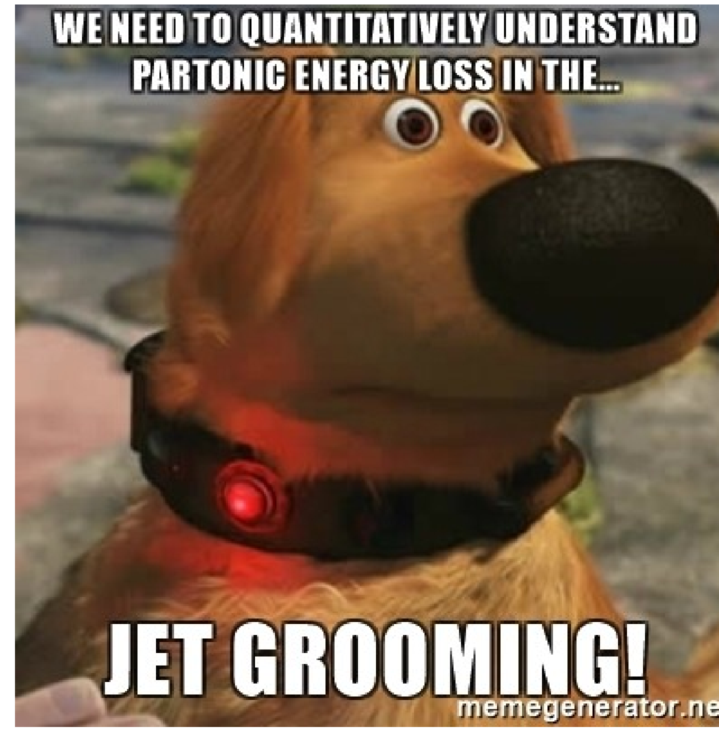
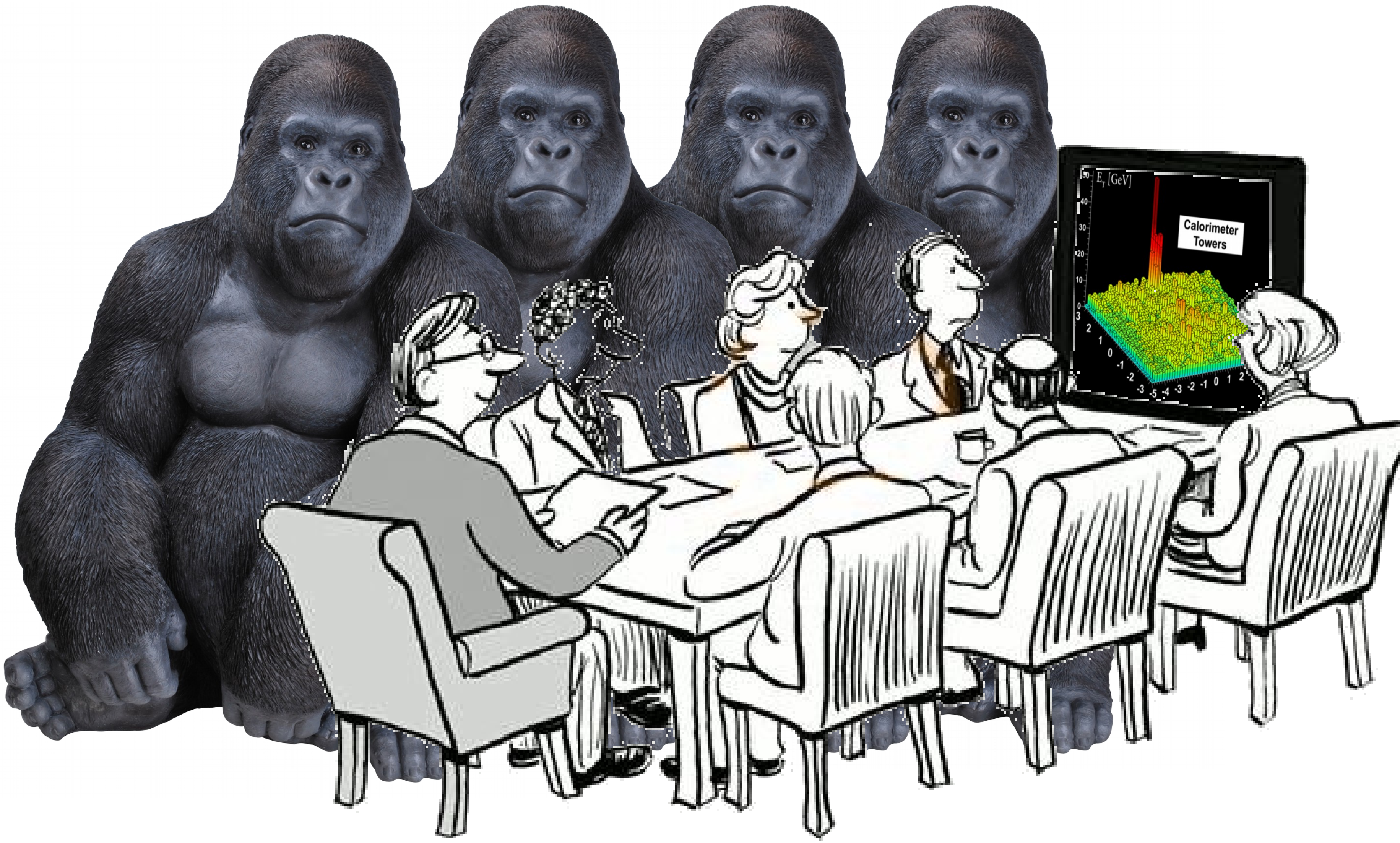


We don't fully understand the background

We need to look at the whole picture

We don't know which observables are best

We haven't learned that much from jets

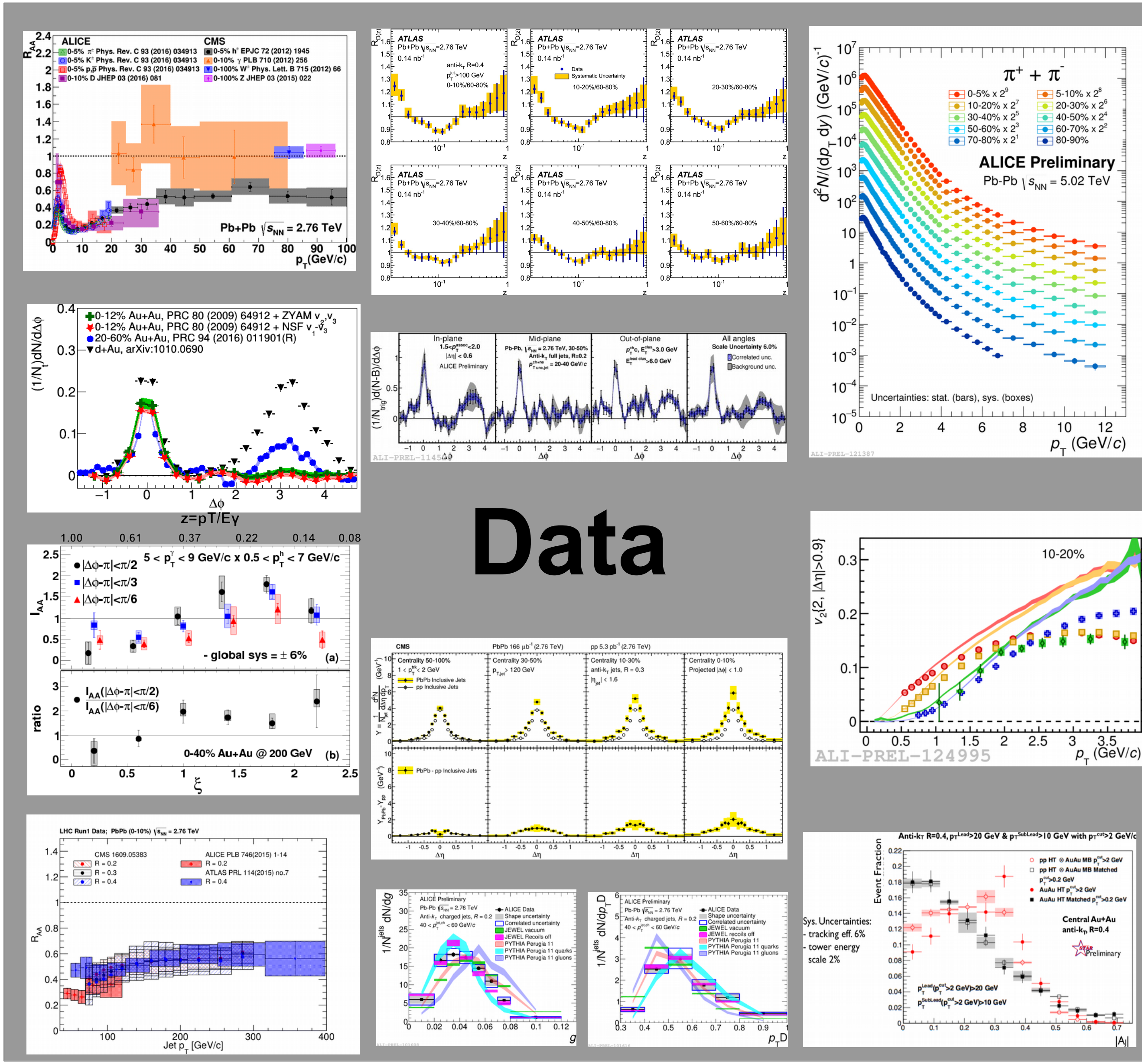


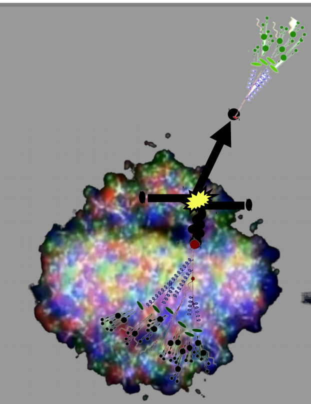
The way forward

- **Understand bias and background**
  - What you see depends on what you look for
  - Listen to the data – not what you want to hear
- **Make quantitative comparisons to theory**
  - Need realistic models where we can apply experimental methods to models
- **Make more differential measurements**
  - But figure out which observables are most sensitive

JETSCAPE

JETSCAPE





Realistic theoretical calculations

Bayesian Statistical Analysis

Constraint of QGP properties