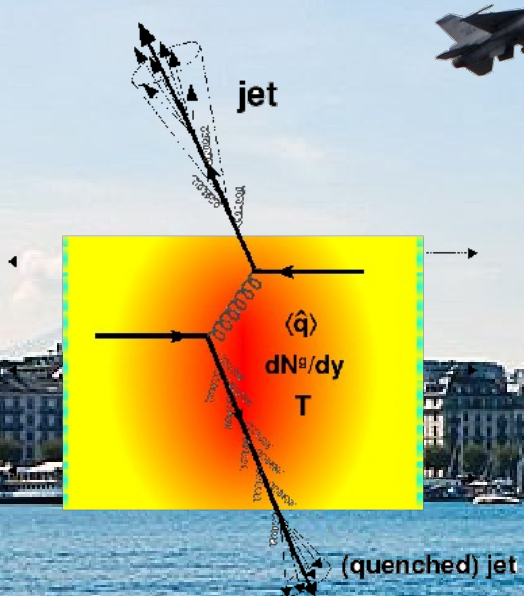
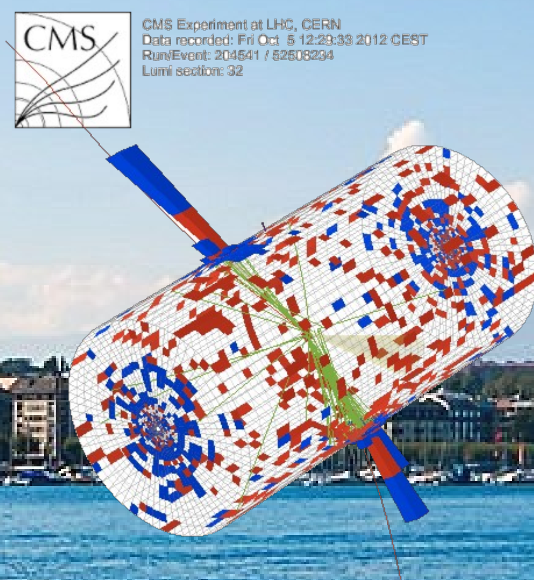
Jets





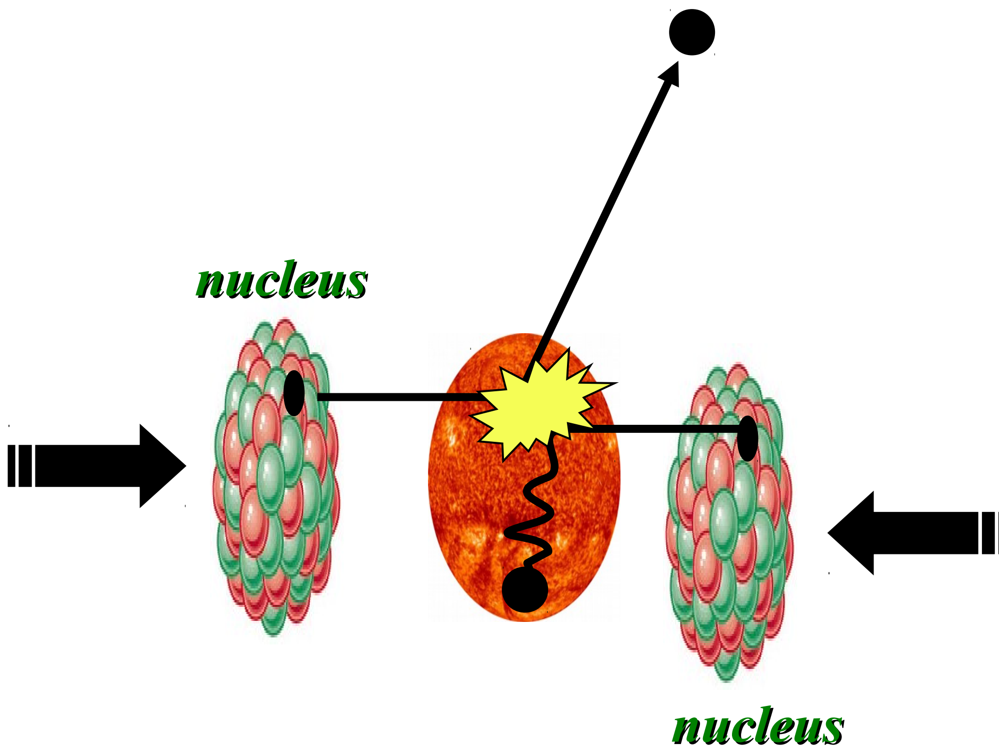
JET'S PIZZA

JETS NY

Overview

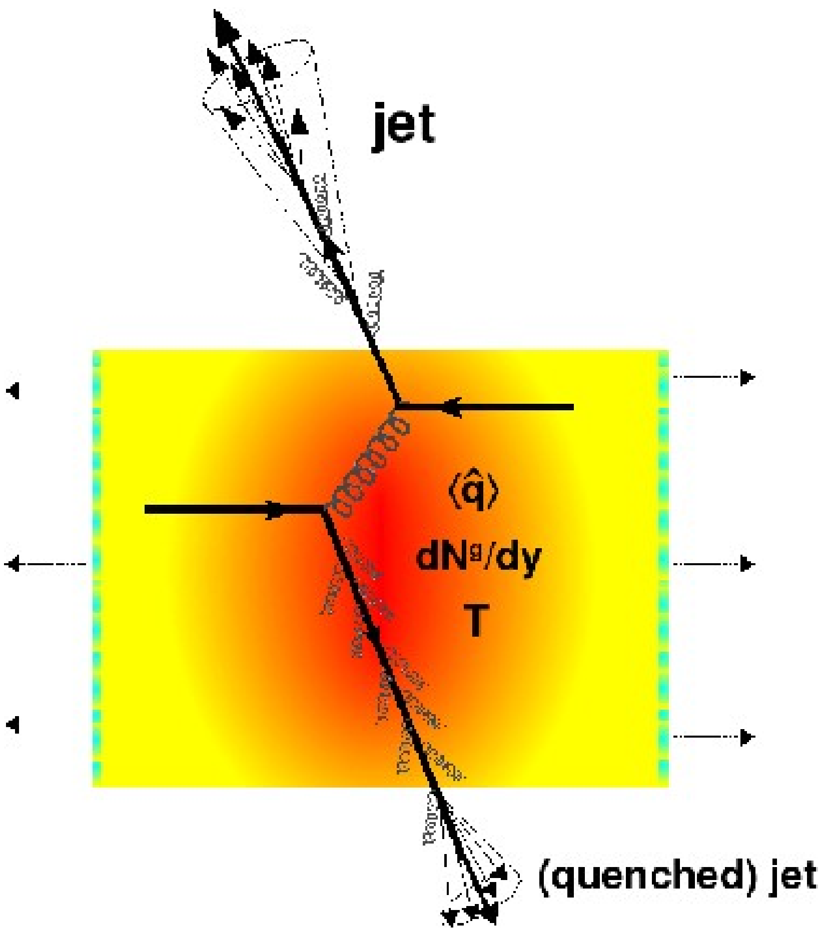
- Jet quenching in a nutshell
  - Partons lose energy in the medium
  - This lost energy makes jets broader and softer
- Towards quantitative understanding
  - Measurement details matter
  - Cold nuclear matter effects?

Jets – the cartoon



Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
We expect the medium to be dense → absorb/modify probe

Quenched jets:
what we're trying to study

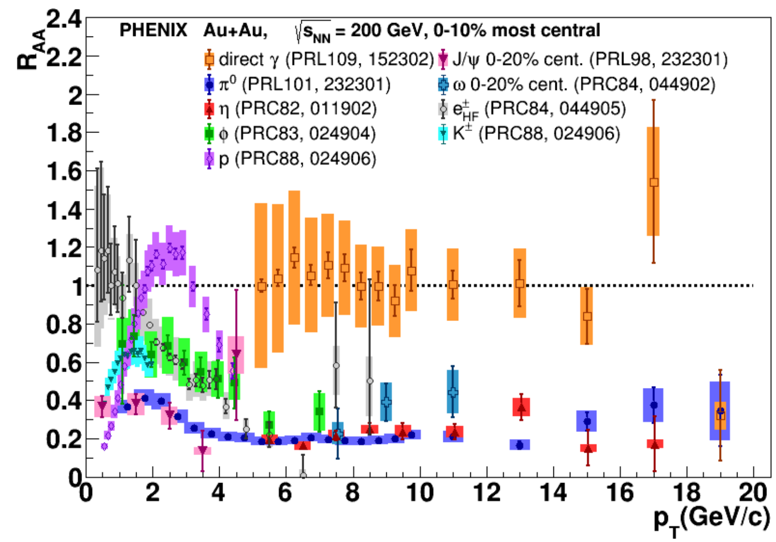


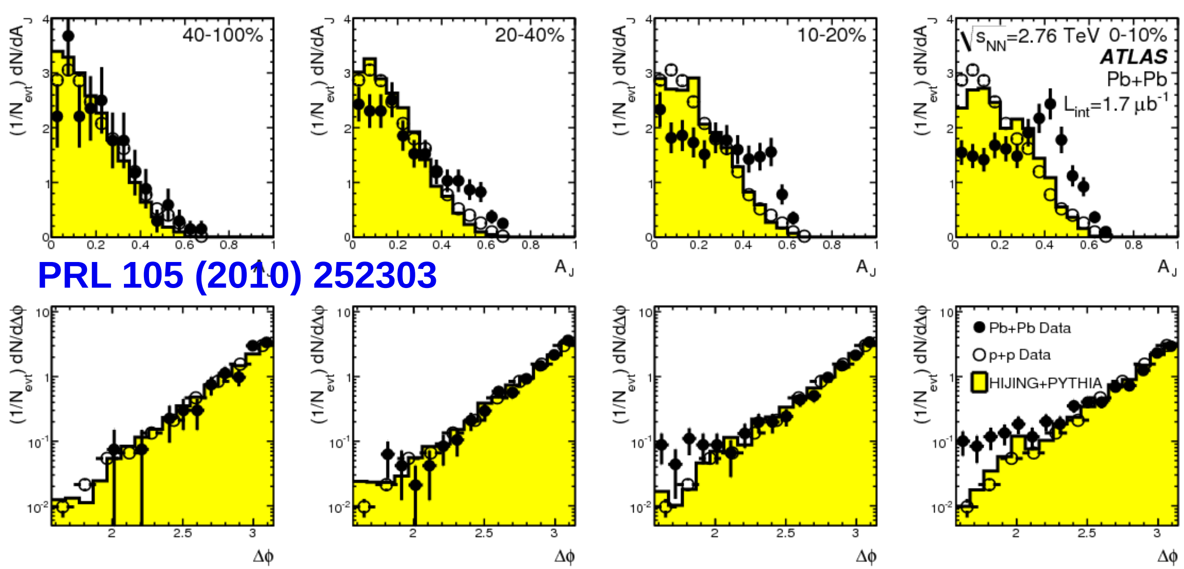
- Softer constituents
- Broader radius

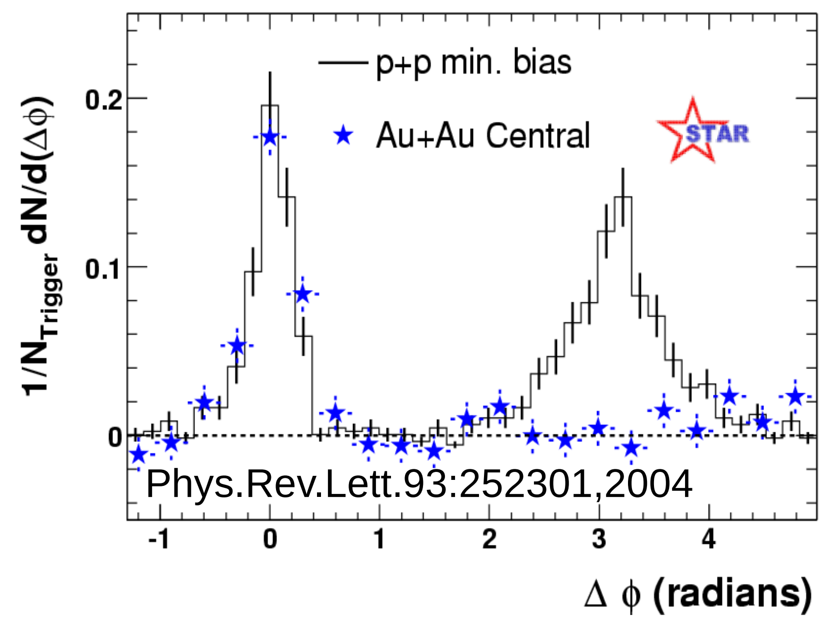
Figure from Nucl.Phys. A827 (2009) 356C-364C arXiv:0902.2488 [nucl-ex]

Ways to study jets

- Single particle
- Di-hadron (multi-hadron) correlations
- Fully reconstructed jets



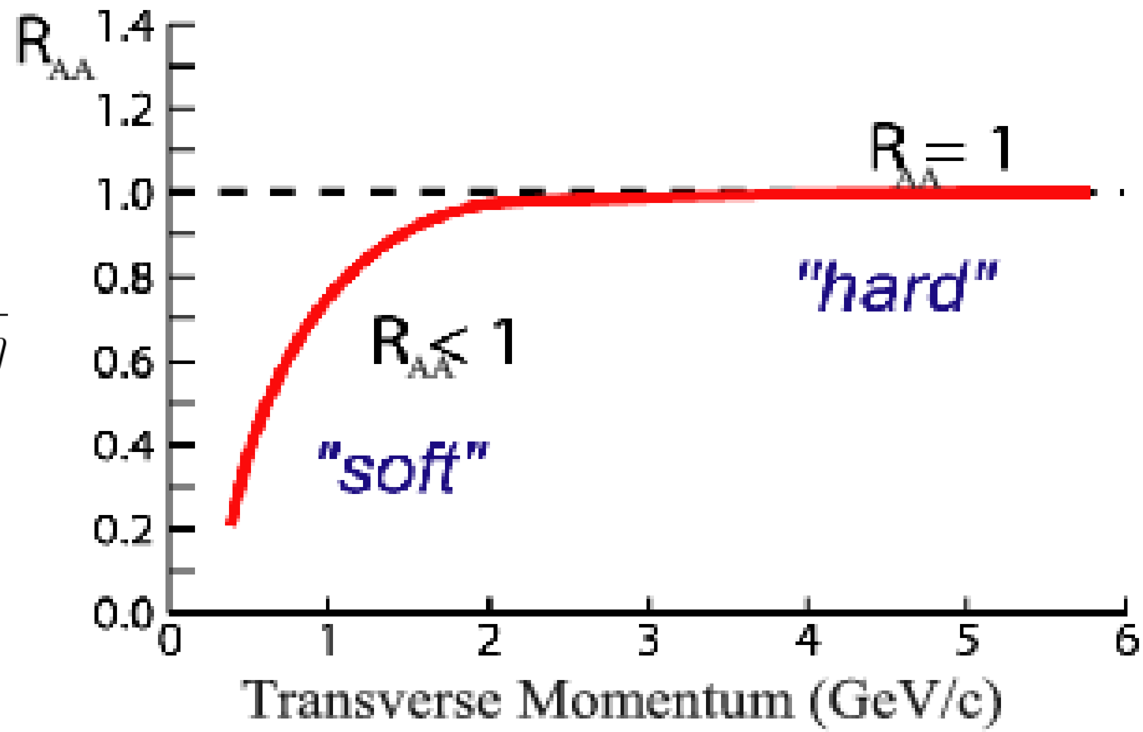




Nuclear modification factor

- 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

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

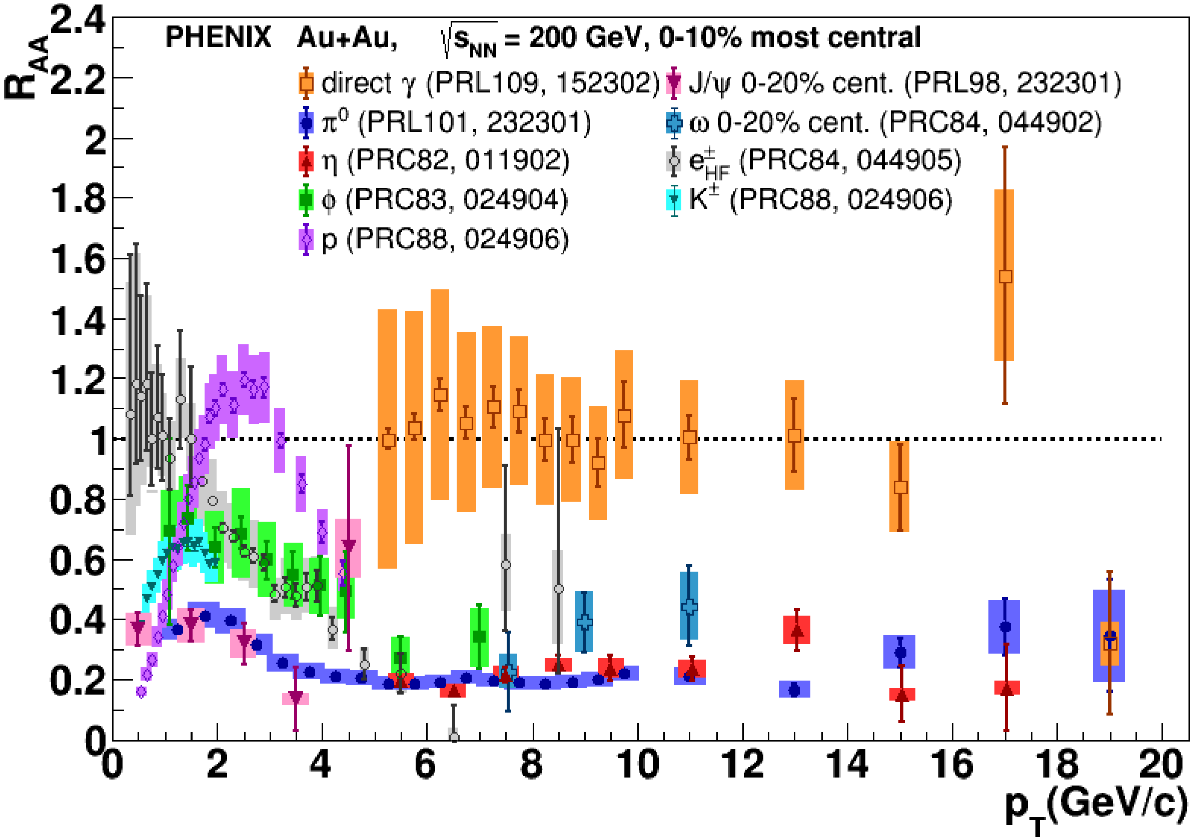


Enhancement

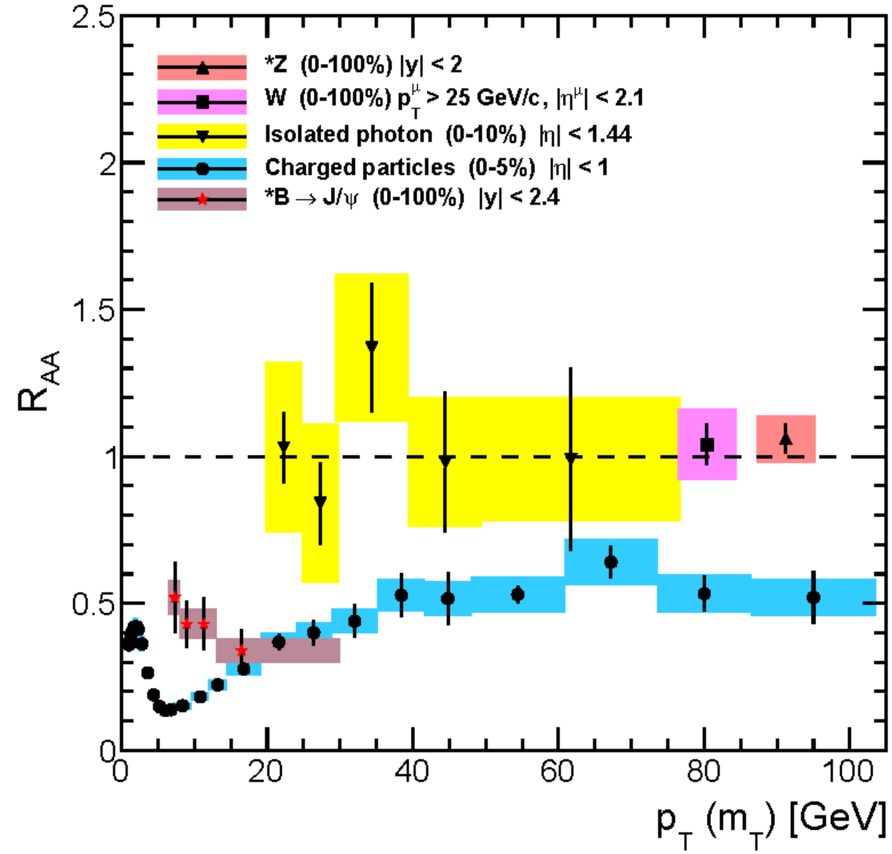
Suppression

Nuclear modification factor R_{AA}

RHIC



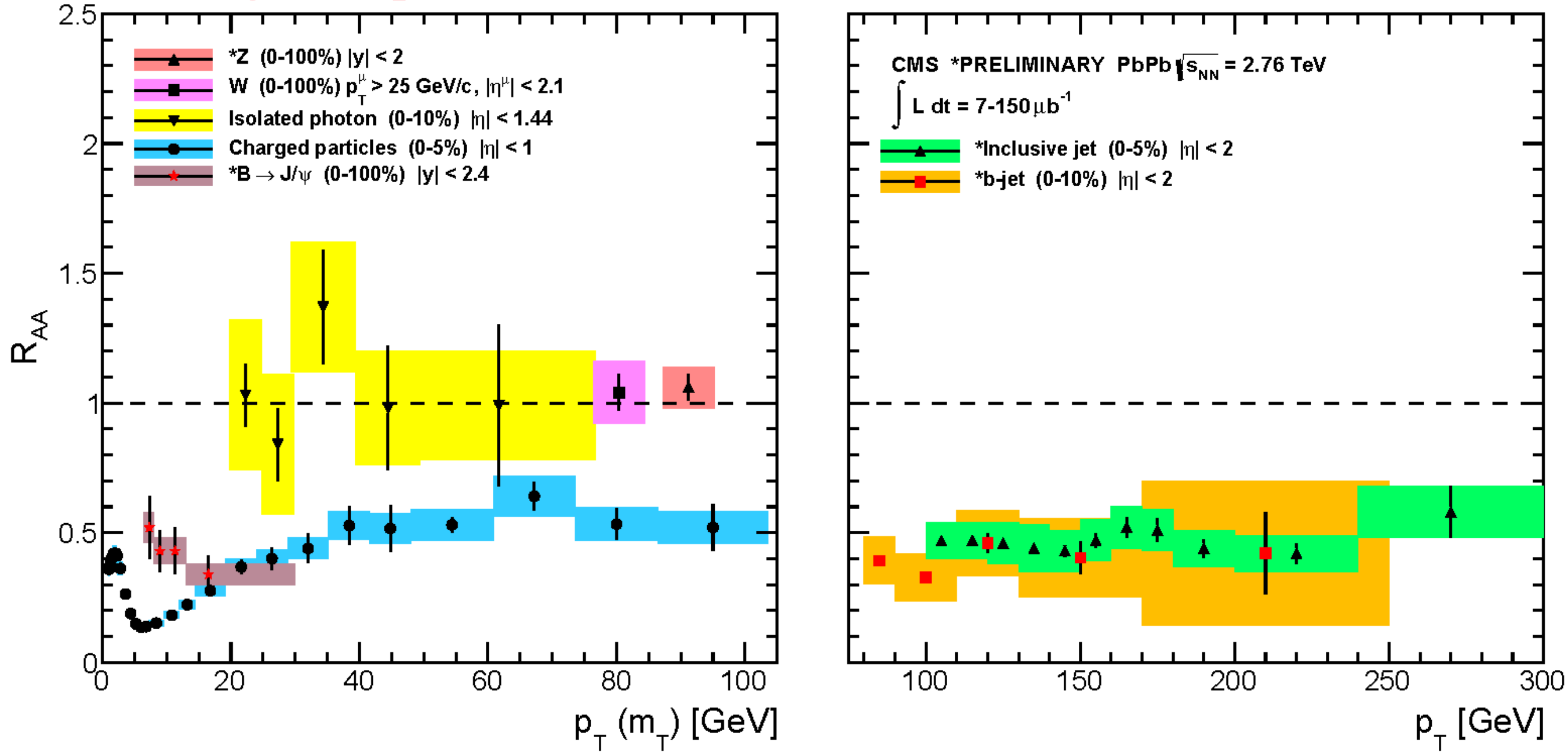
LHC



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

Nuclear modification factor R_{AA}

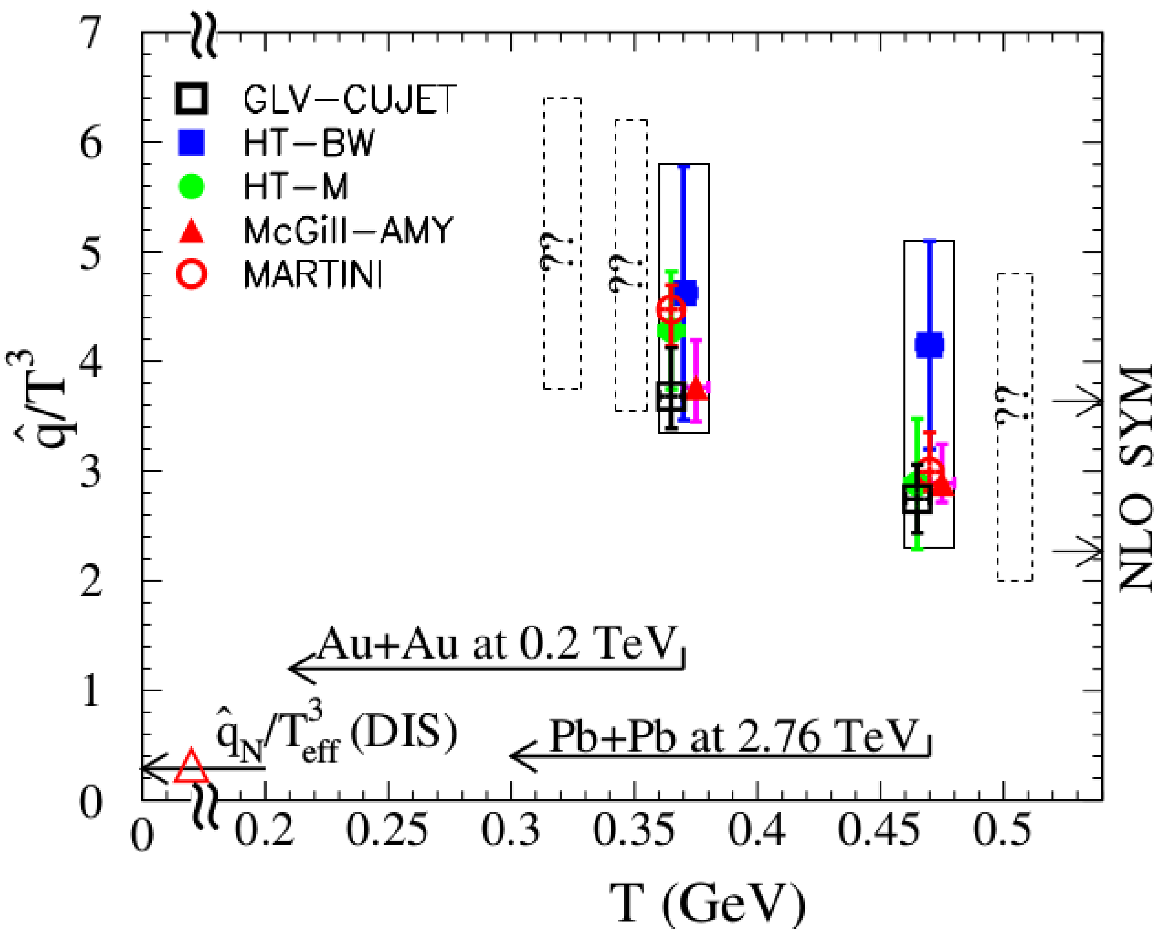
Single particles **Jets**



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

Quantifying $\hat{q}$

Phys. Rev. C 90, 014909 (2014)



Jet Collaboration: For a 10 GeV quark traveling 4 fm

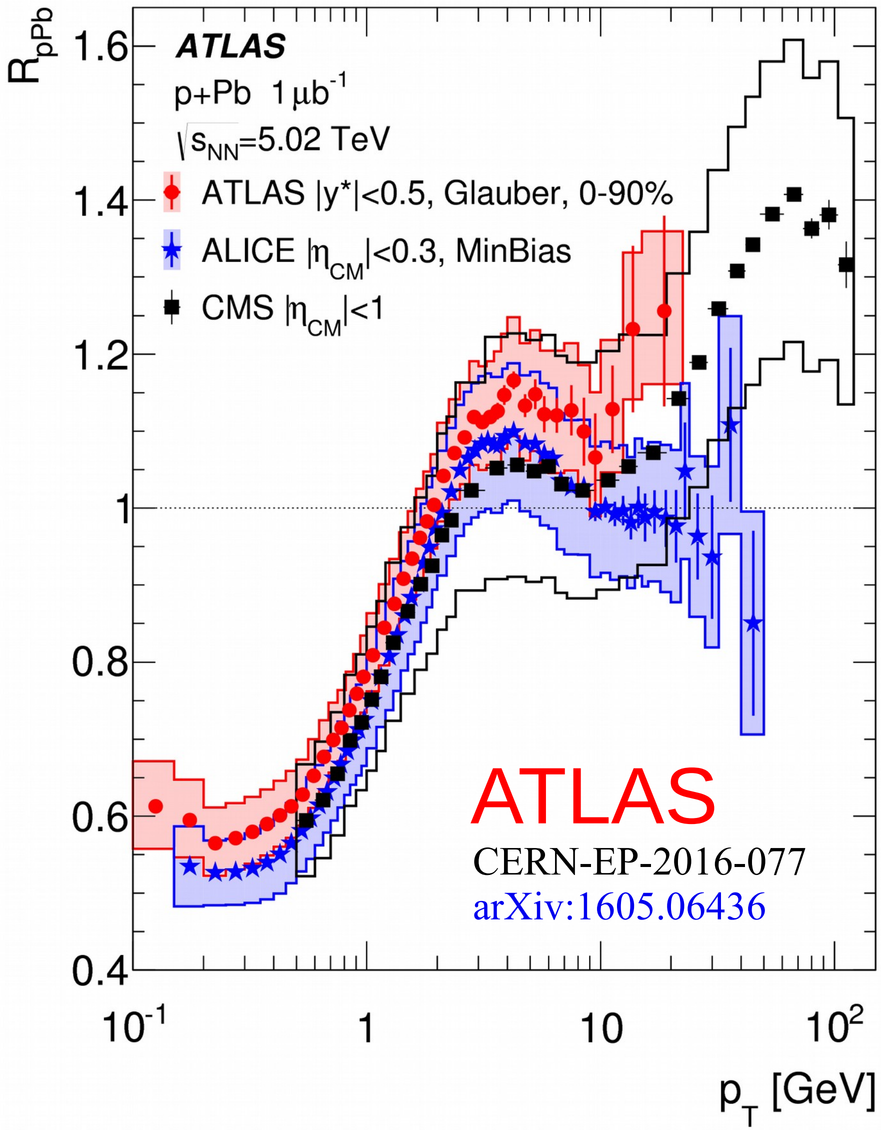
$\hat{q}$ ≈1.2±0.3 GeV^2/fm at τ_0=0.6 fm/c in Au+Au at $\sqrt{s_{NN}}$=200 GeV →loses 2.2 Gev

$\hat{q}$≈1.9±0.7 GeV^2/fm in Pb+Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV →loses 2.8 Gev

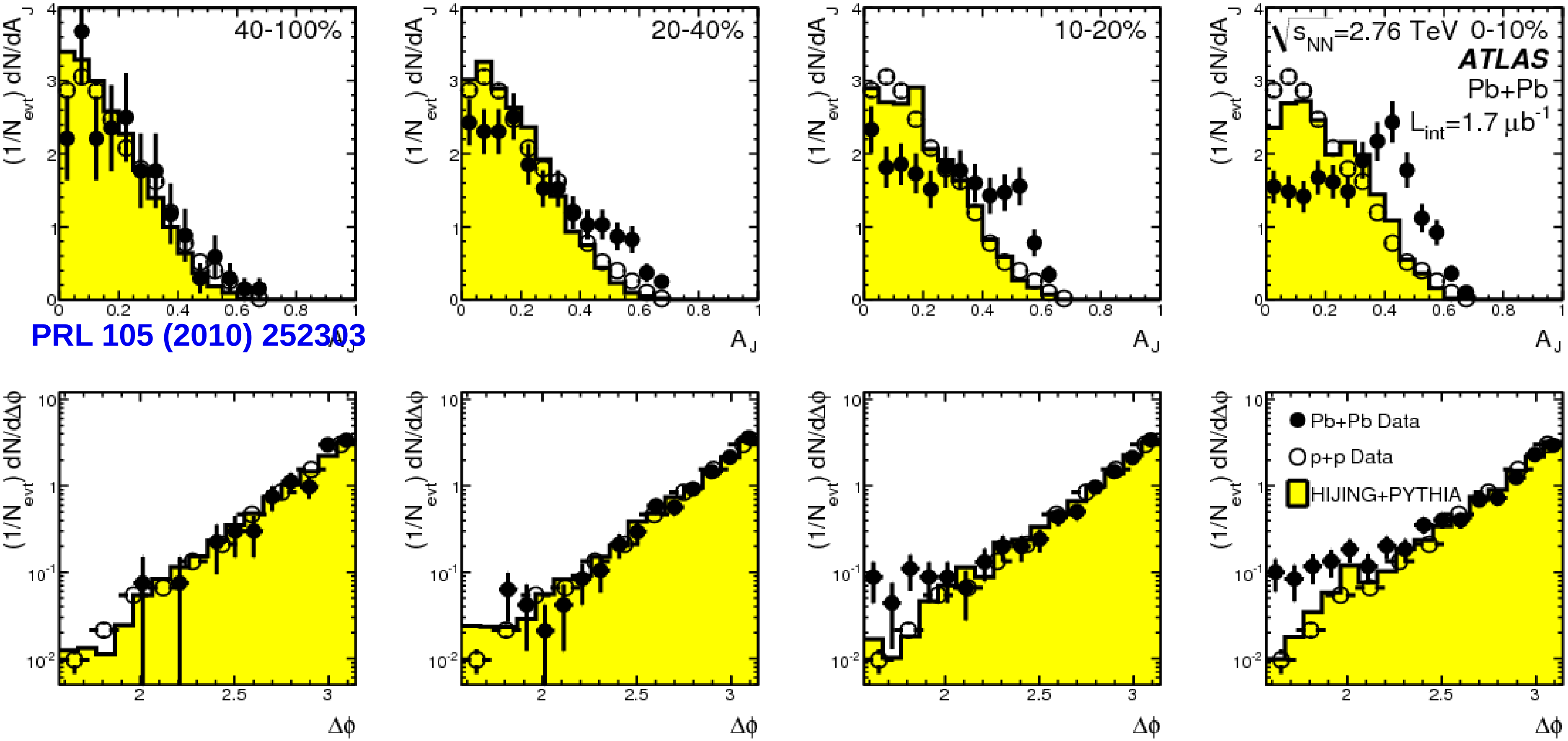
$$\hat{q} = Q^2/L$$

Q = Momentum transfer from parton to medium
L = path length

p+Pb as a control



Di-jet asymmetry

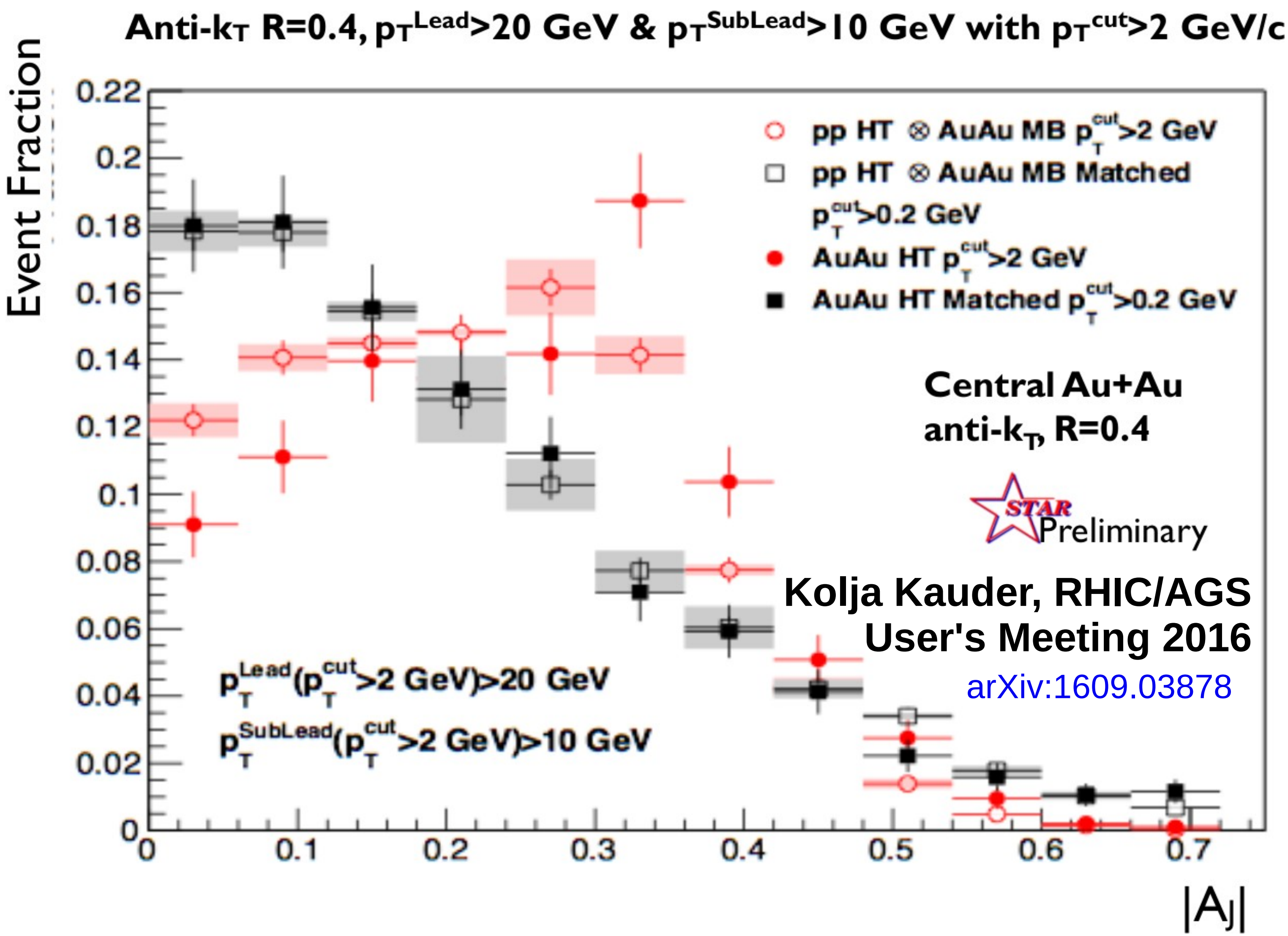


PRL 105 (2010) 252303

$$A_j = \frac{p_T^{Leading\ jet} - p_T^{Subleading\ jet}}{p_T^{Leading\ jet} + p_T^{Subleading\ jet}}$$

Di-jet asymmetry

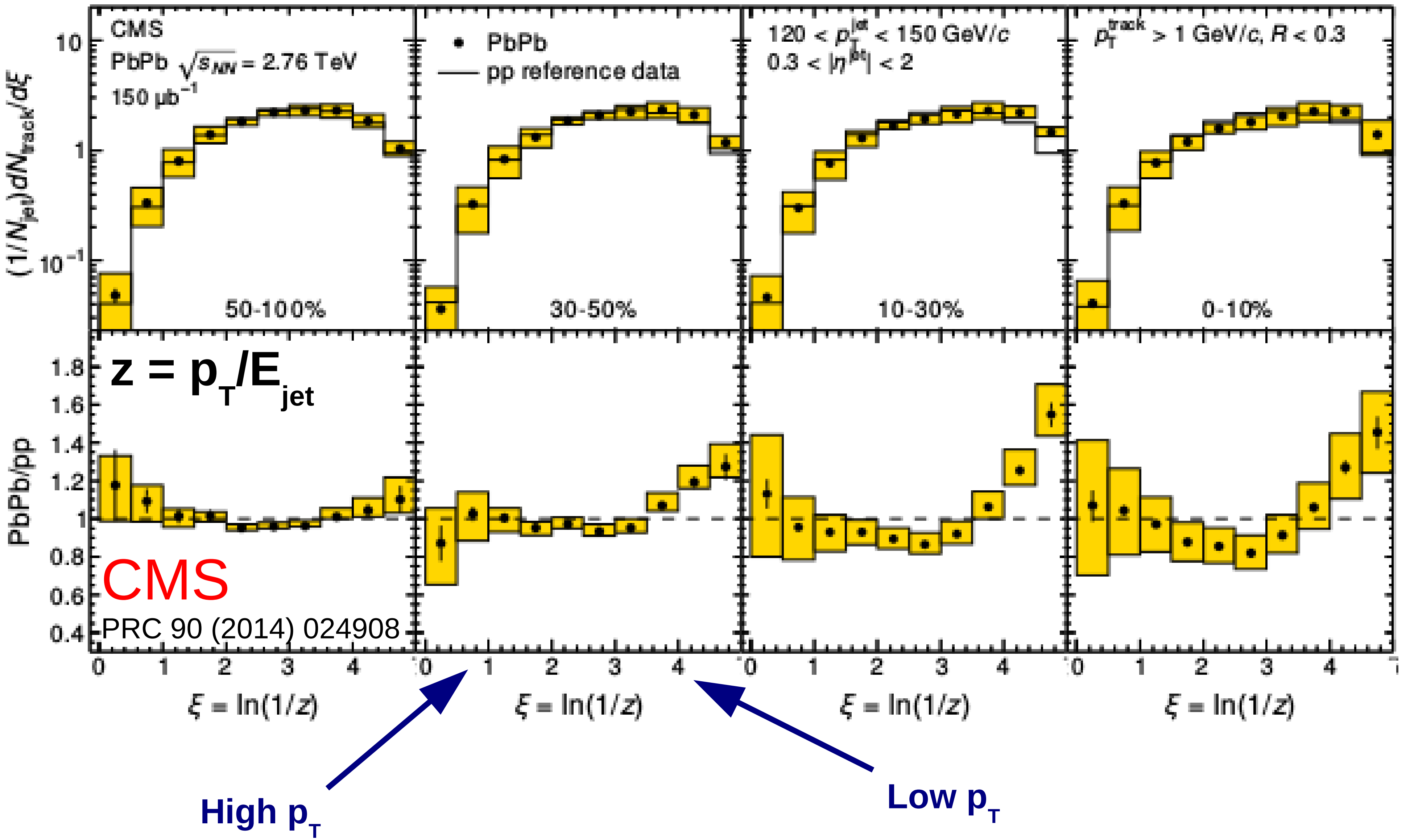
Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%



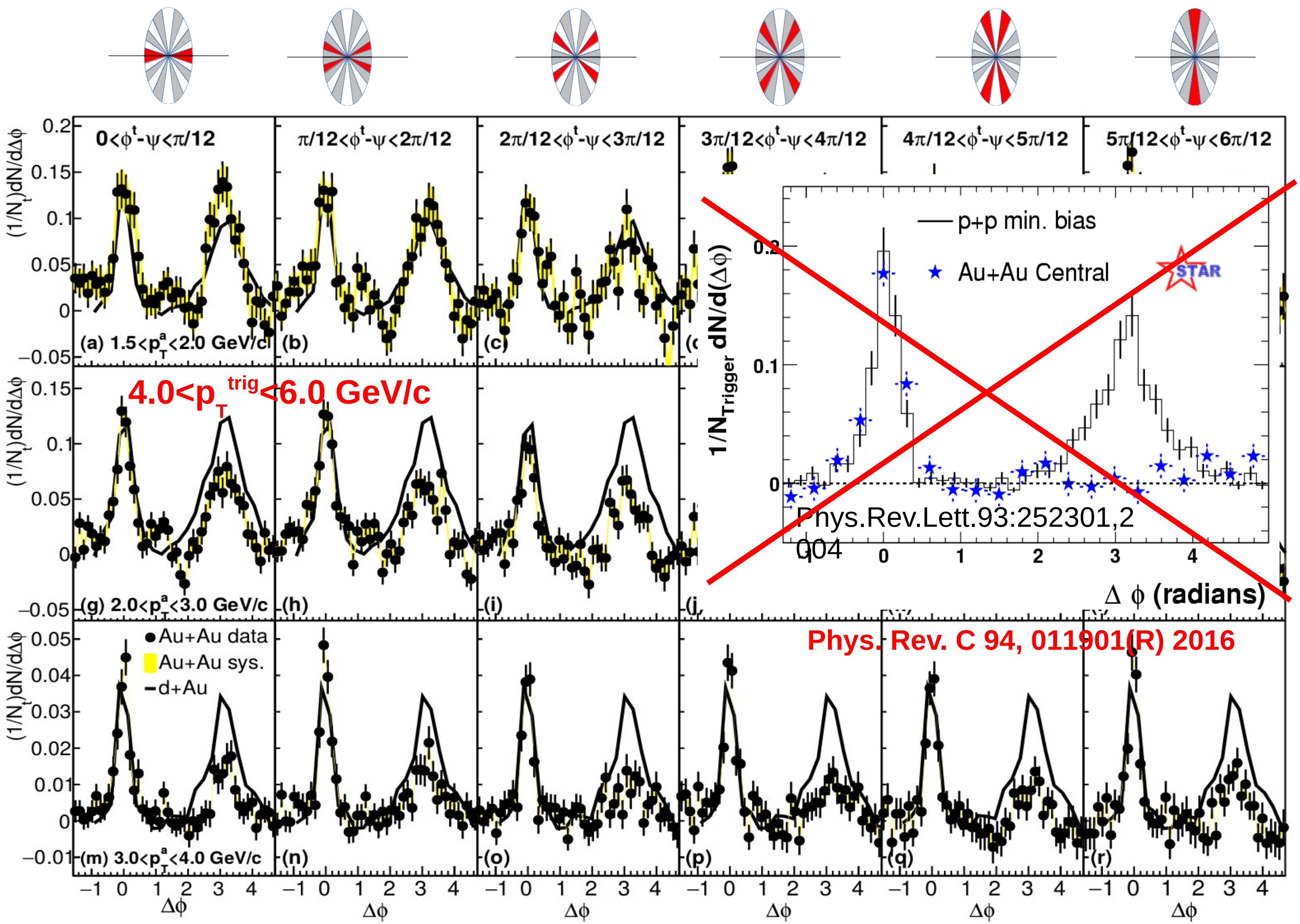
Au+Au di-jets more imbalanced than p+p for p_{Tcut}>2 GeV/c

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

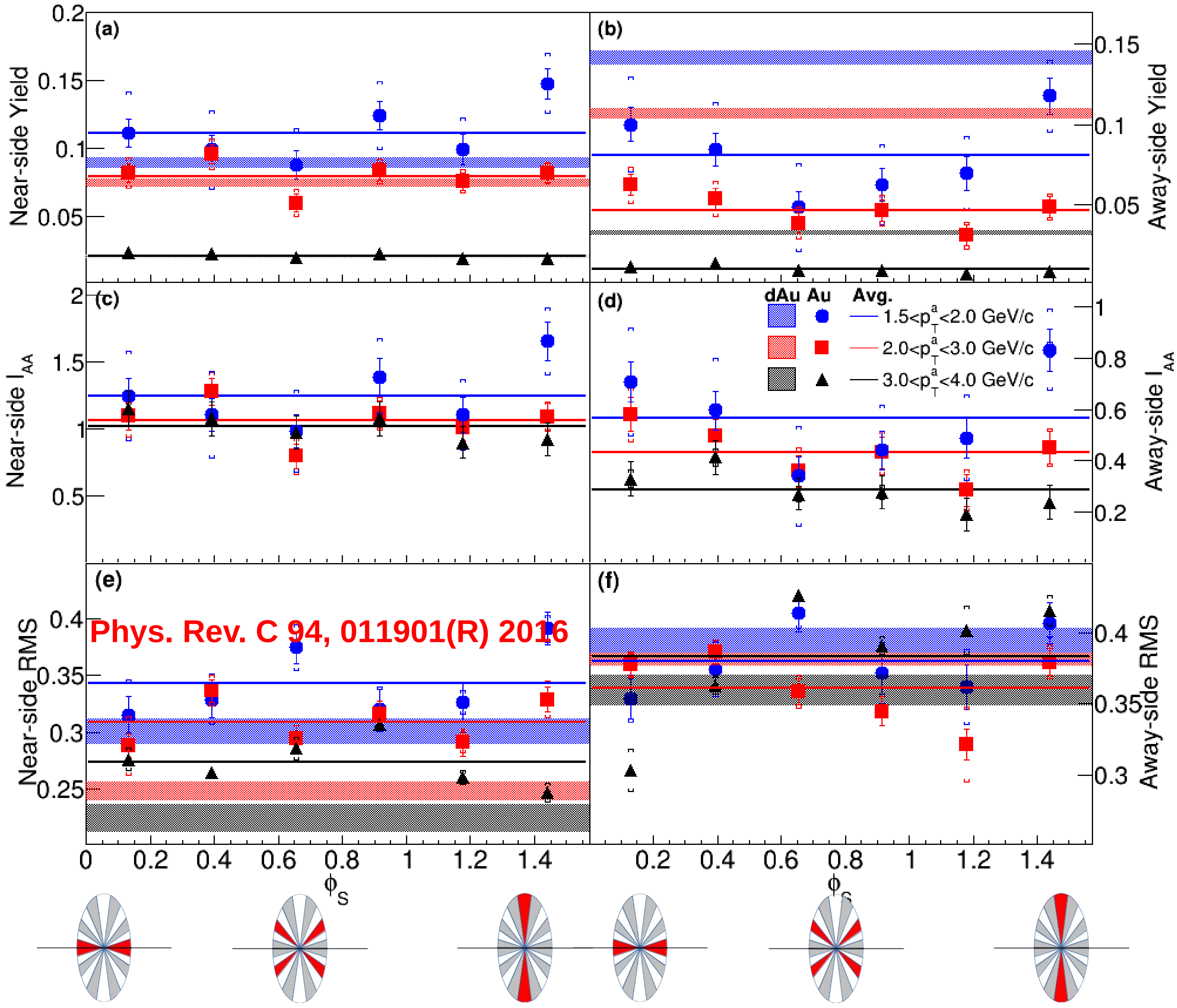
Fragmentation functions



Dihadron correlations



Dihadron correlations



What is a jet?

A jet is what a jet finder finds.

Jets in principle

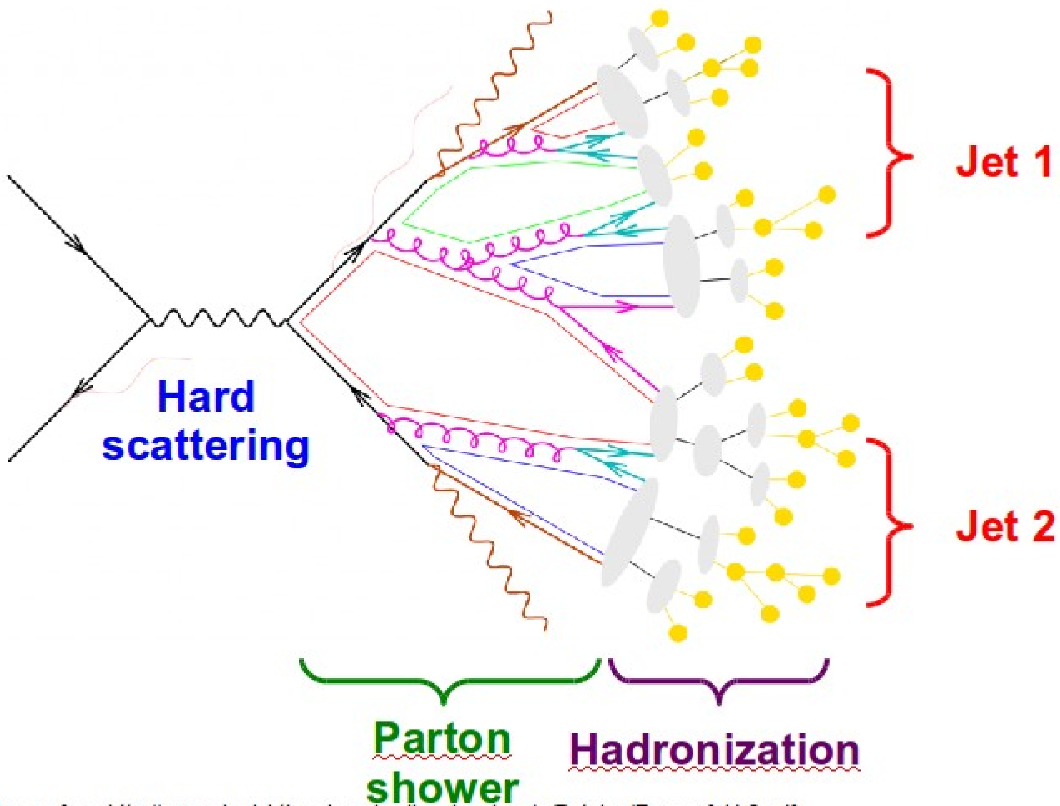
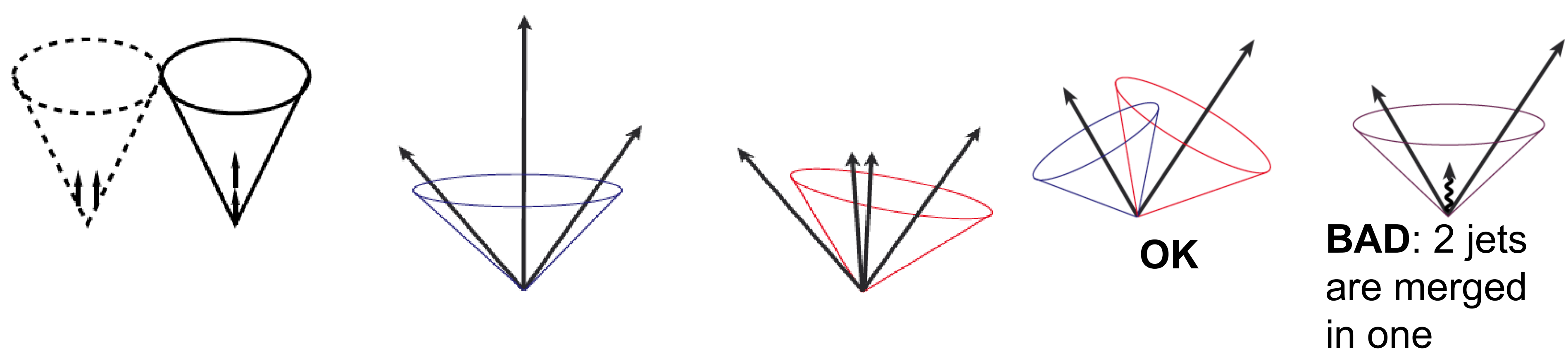


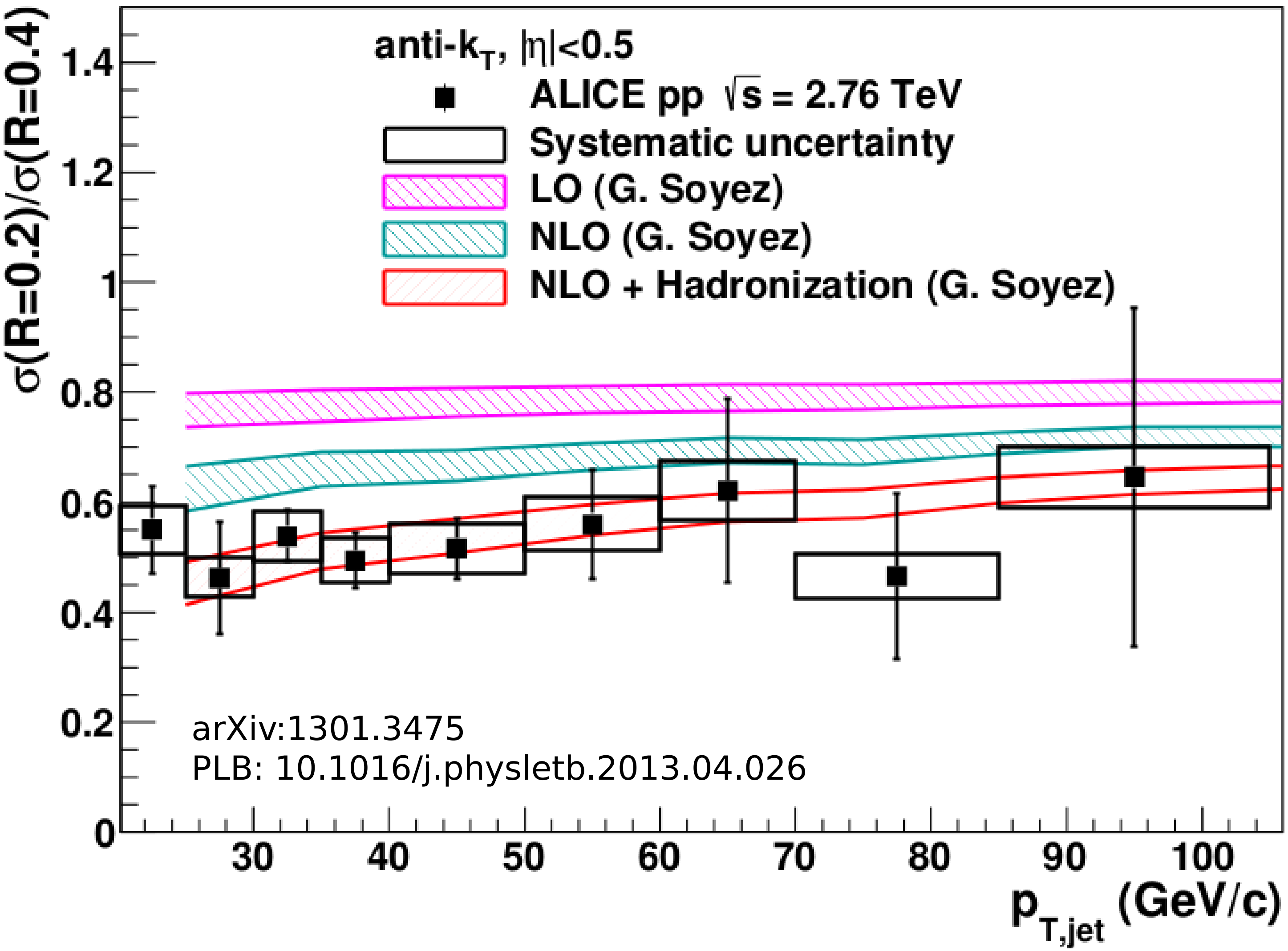
Image from http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

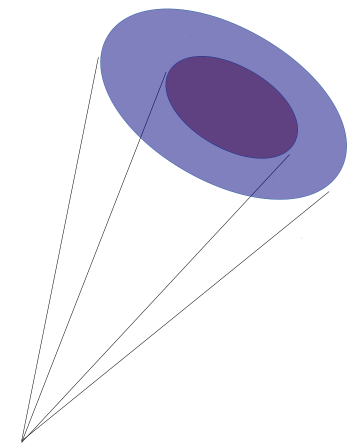
- Jet measures **partons**
- Hadronic degrees of freedom are integrated out
- Algorithms are infrared and colinear safe



Full jet ratios in pp

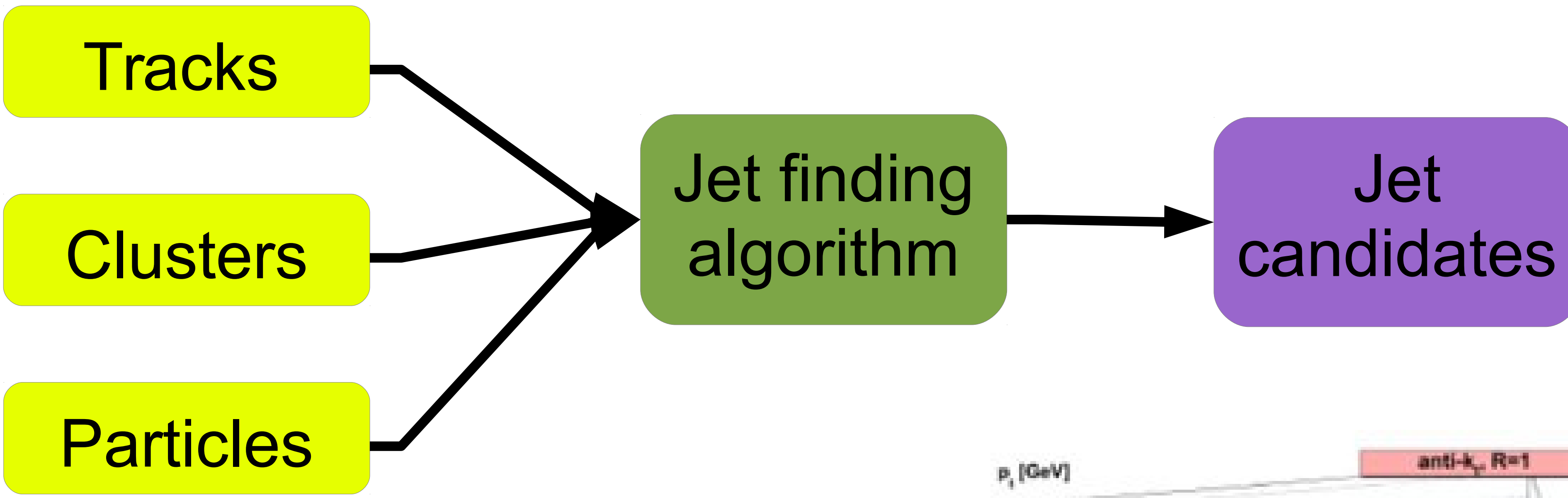
$\sqrt{s}$ = 2.76 TeV, R = 0.2, 0.4 Inclusive



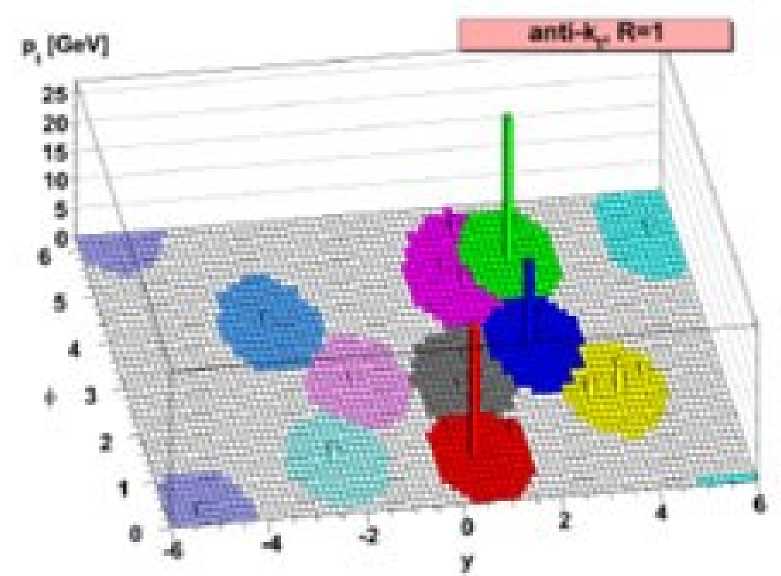


Hadronization is important even in pp collisions!

Jet finding algorithms

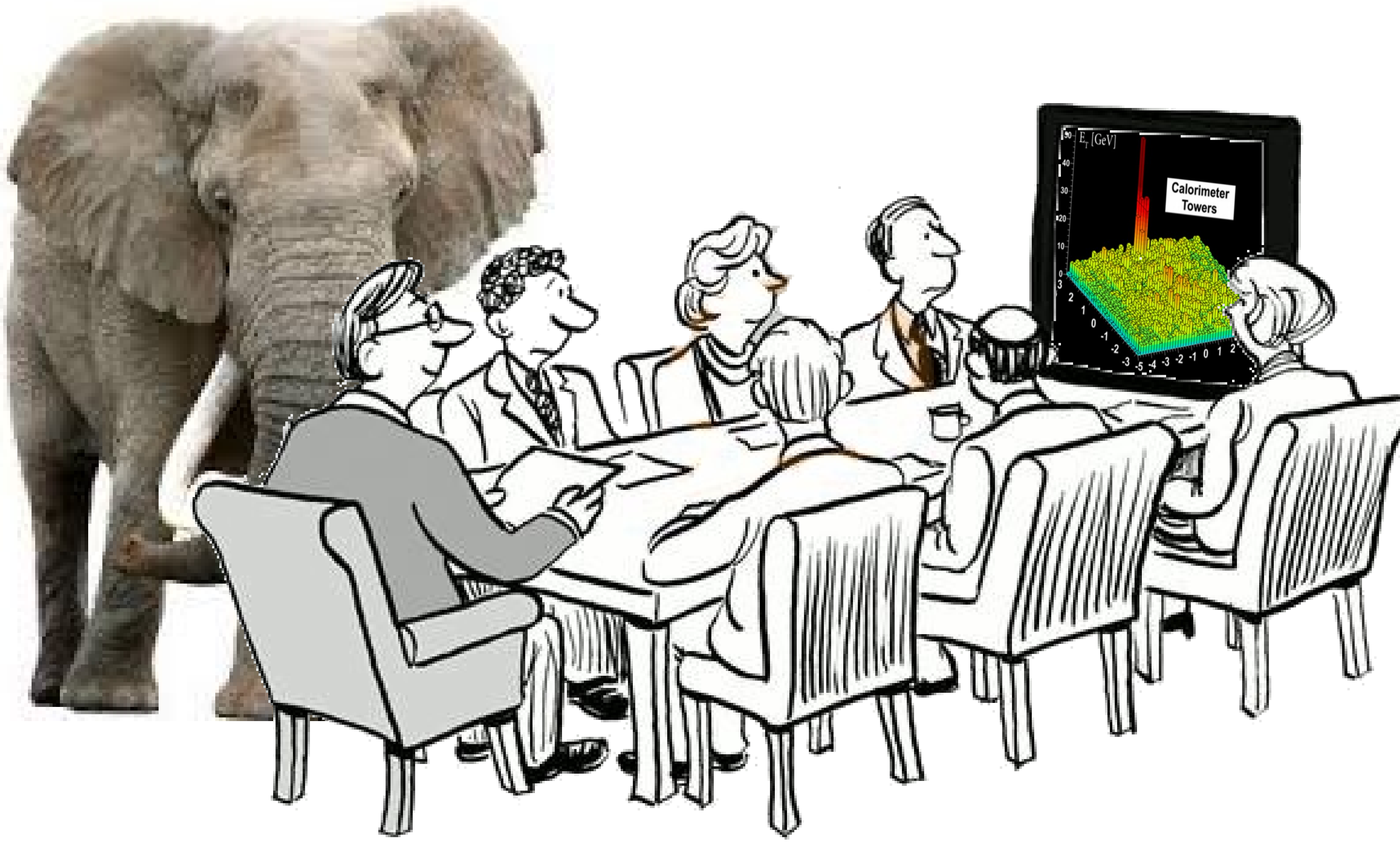


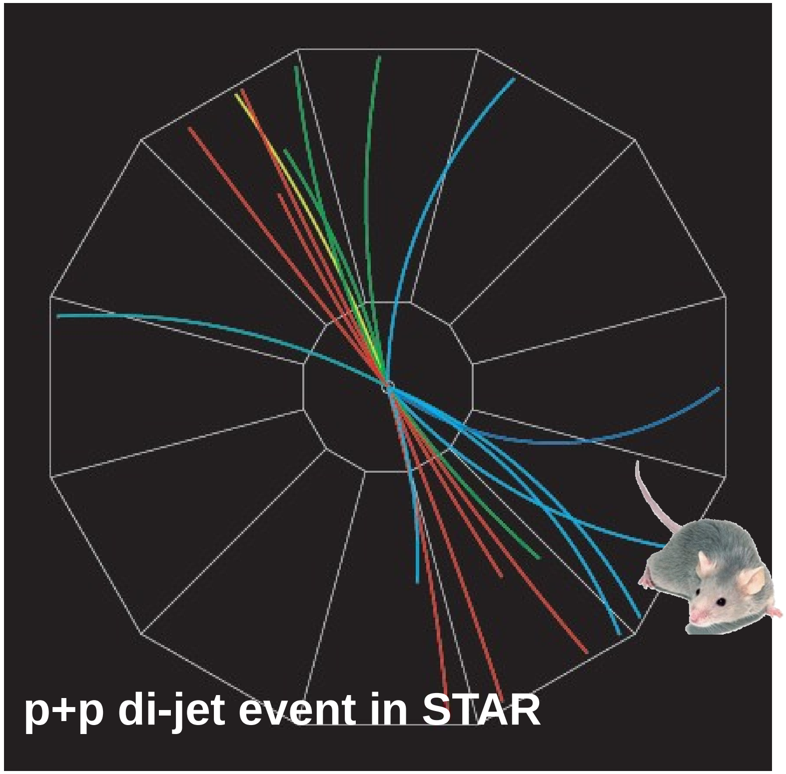
- Any list of objects works as input
- Use the same algorithm on theory & experiment
- Output only as good as input

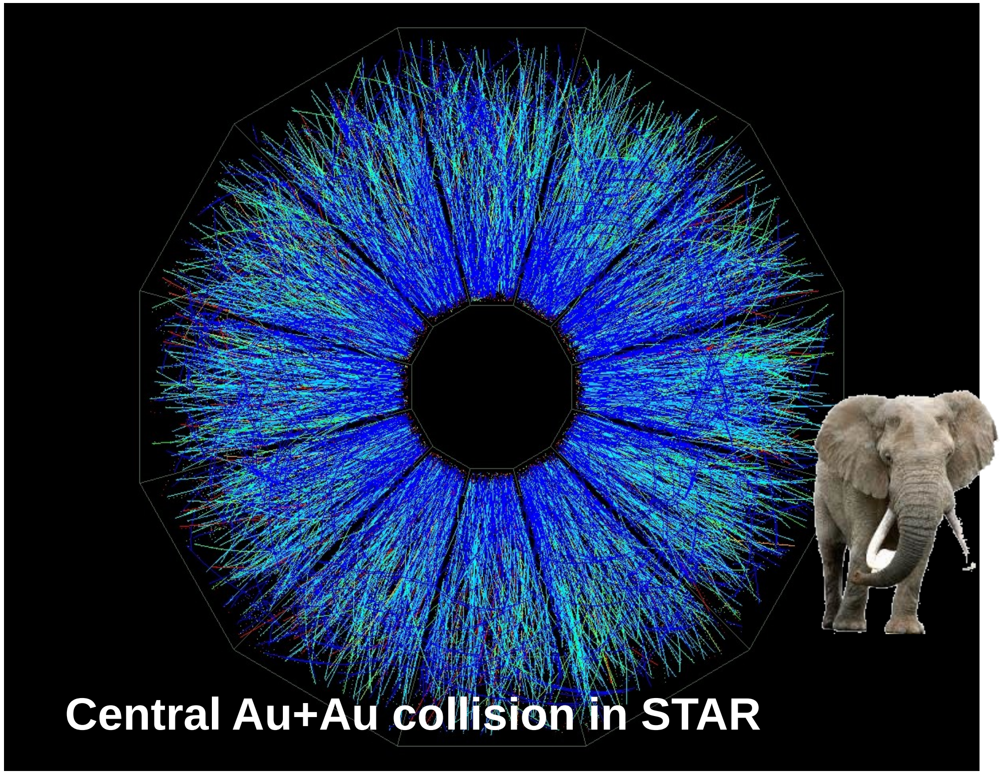


M. Cacciari, G. P. Salam, G.Soyez, JHEP 0804:063,2008

Bias & Background







Signal

- Harder
- Correlated with rxn plane
- Low p_T modifications
- Flavor modifications?

Background

- Softer
- Correlated with rxn plane
- Large fluctuations/hot spots
- Combinatorial background
- Degraded energy resolution

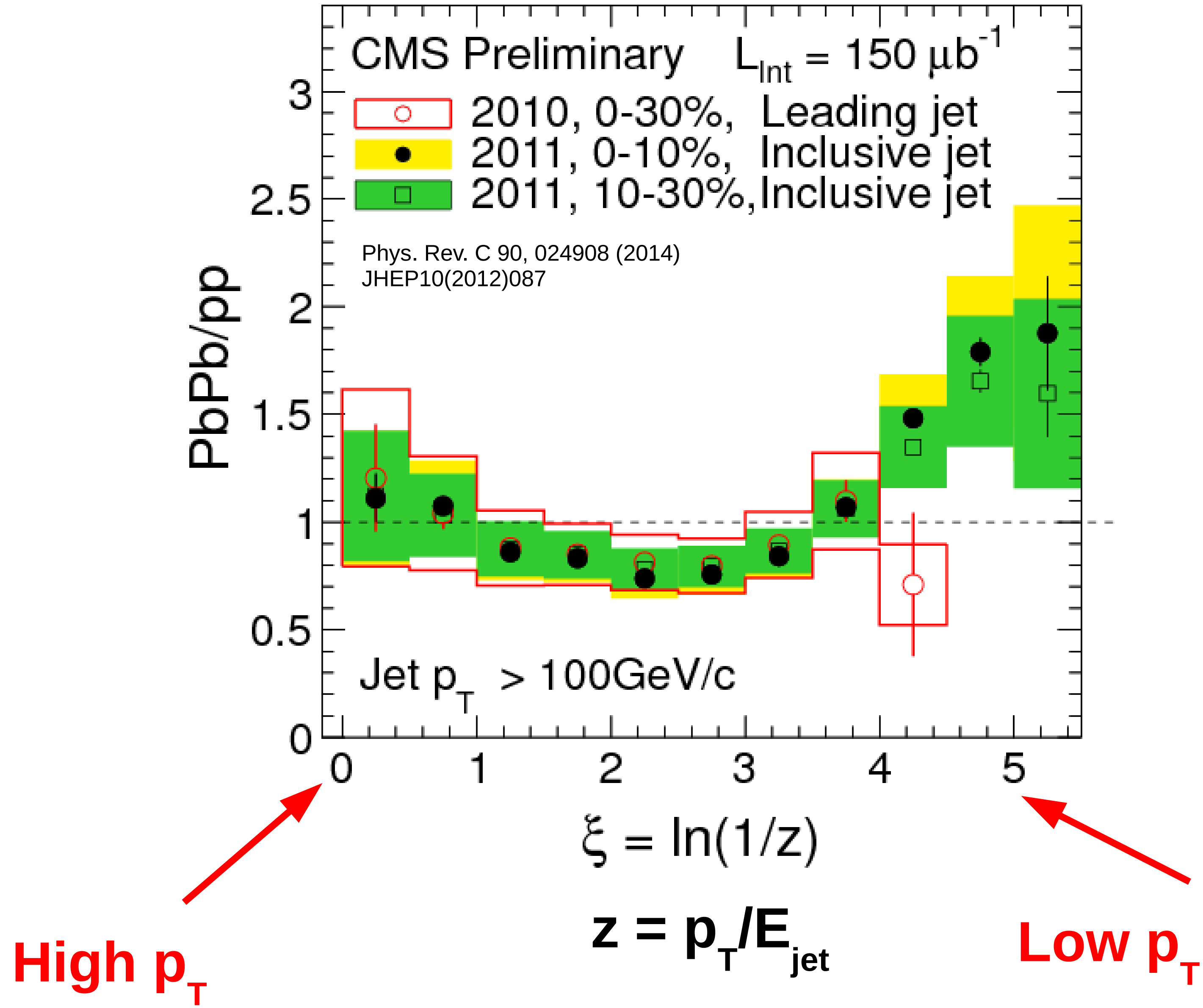
http://www.boredpanda.com/animal-camouflage/

Bias

- **Modified jets probably look more like the medium**
- **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]**

http://www.boredpanda.com/animal-camouflage/

What you see depends on where you look

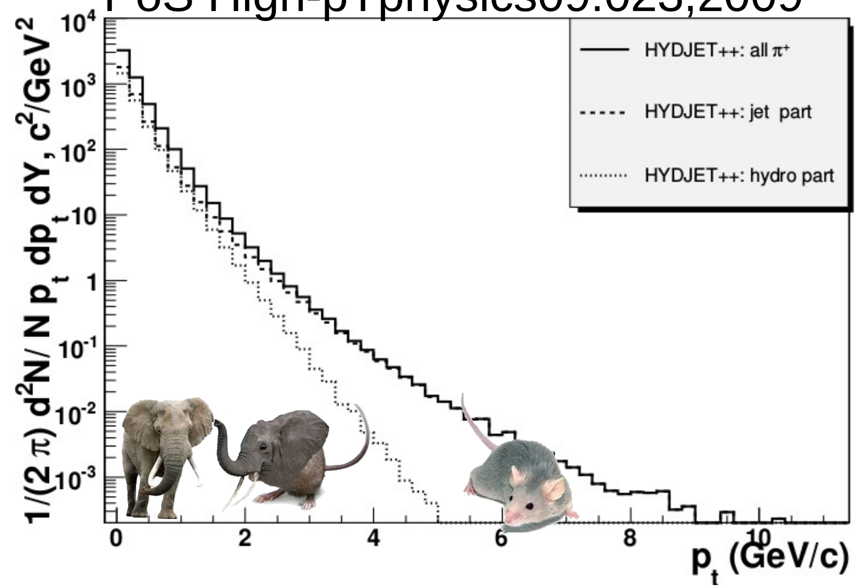


$z = p_T/E_{jet}$

Focus on high p_T

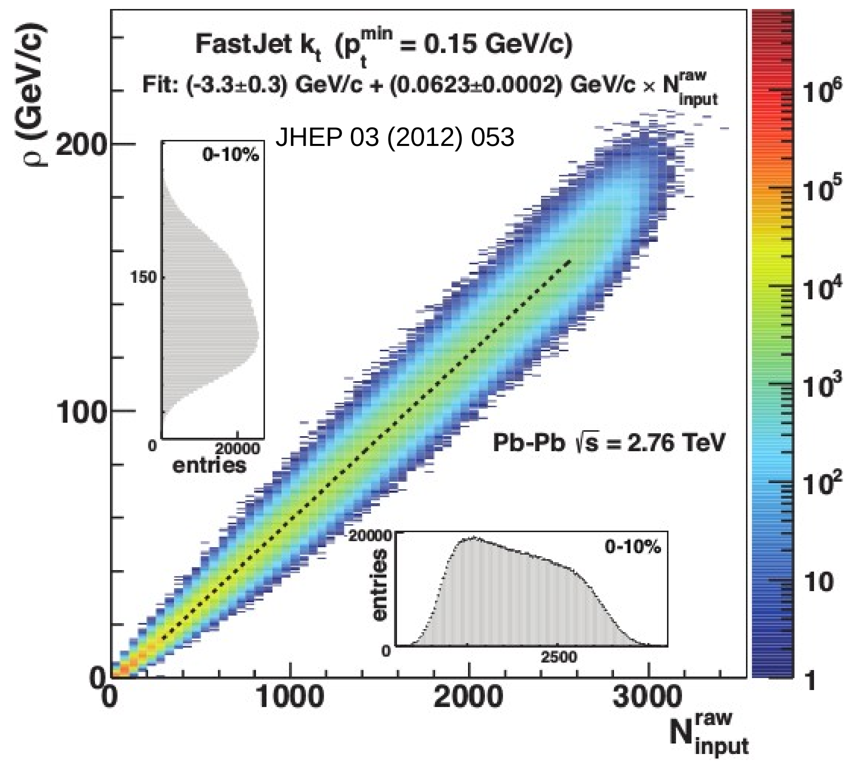
- Pros:
  - Reduces combinatorial background
- Cons:
  - Cuts signal where we expect modifications
  - Could bias towards partons which have not interacted
  - Biases sample towards quarks

PoS High-pTphysics09:023,2009



Focus on smaller angles

- Pros
  - Background is smaller
  - Background fluctuations smaller
- Cons:
  - Modifications expected at higher R
  - Biases sample towards quarks



ALICE/STAR

Combinatorial "jets"

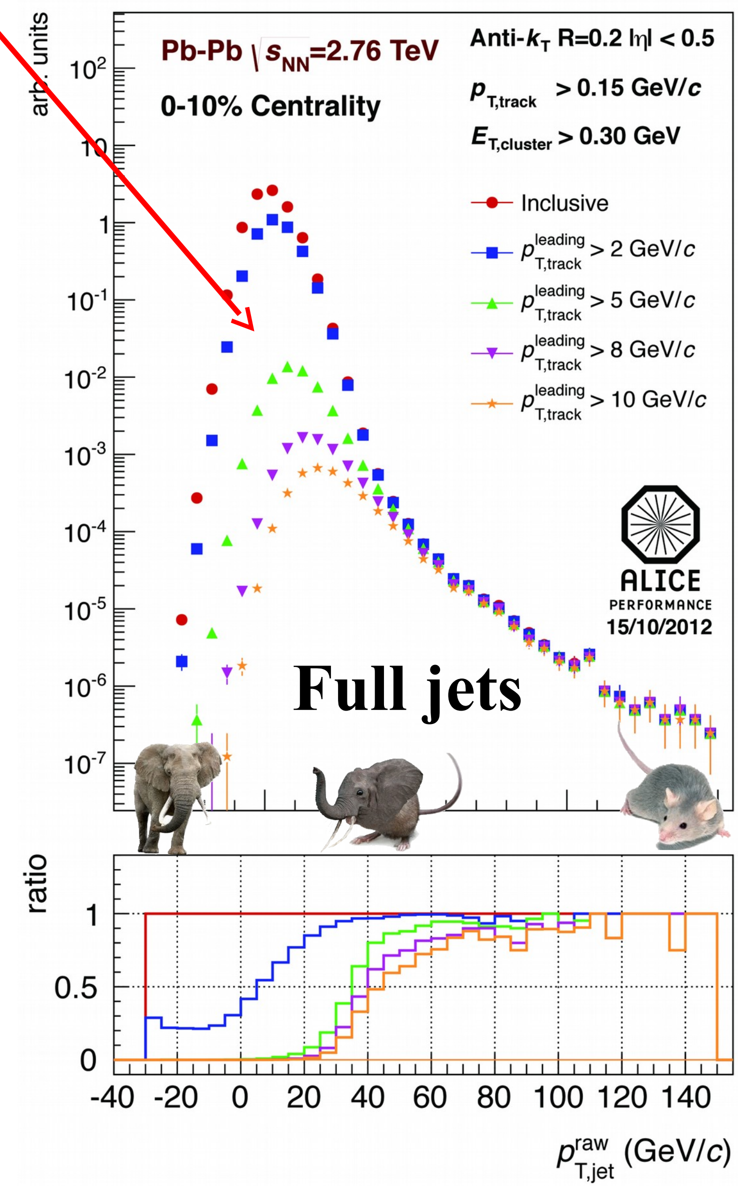
- Estimate combinatorial jet contributions and its fluctuations from data
- Require leading track $p_T > 5$ GeV/c
  - Suppresses combinatorial "jets"
  - Biases fragmentation
- No threshold on constituents
- Limited to small R

Measured spectra:

$$p_{T,jet}^{unc} = p_{\mathrm{T,jet}}^{rec} - \rho\, A$$

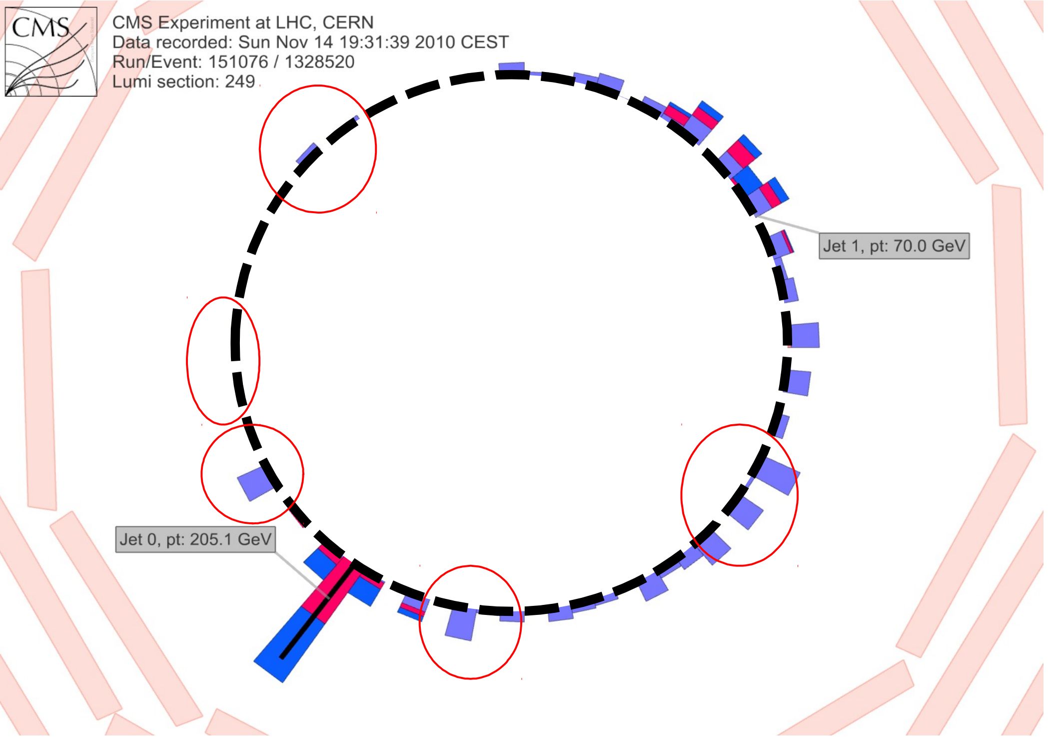
Where $p_{\mathrm{T,jet}}^{rec}, A$

comes from FastJet anti-k_T algorithm



CMS: Iterative Pile-Up Event Background Subtraction

Background is estimated
- for each calorimeter ring of constant η
- subtracted before jet finding
- re-iterated after excluding the jets found in the first iteration



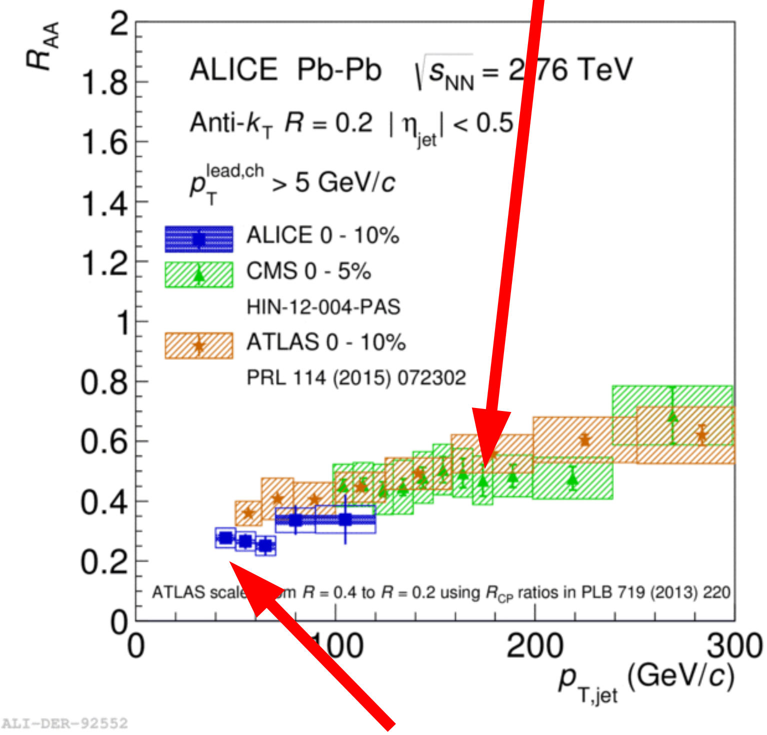
Fake Jets: After the background subtraction, some local fluctuations remain!
Fluctuations will deteriorate the jet resolution in central events.

Sevil Salur 28

ATLAS

- 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



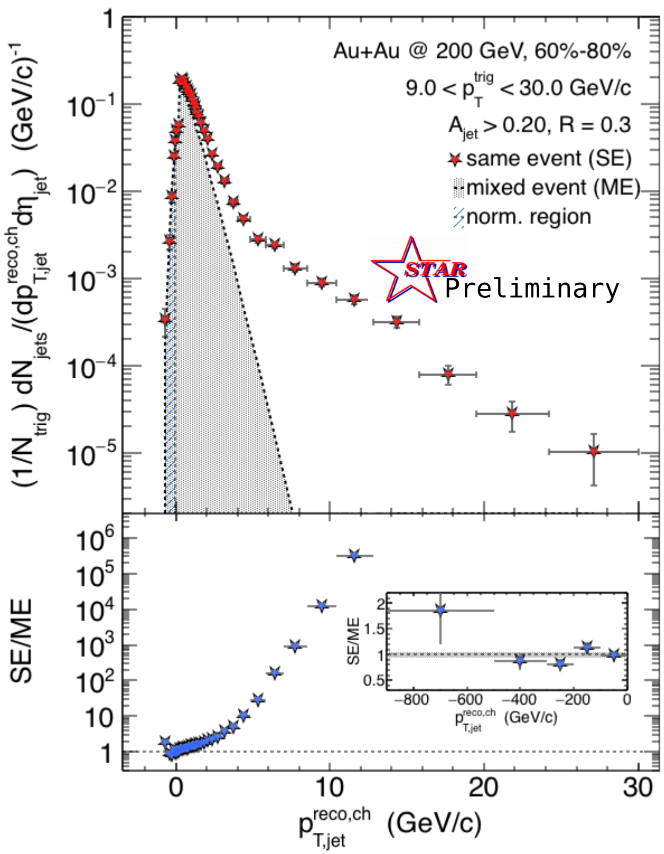
But they do matter down here!

Definitely imposes a bias, especially at 20 GeV!
We should treat that bias as a tool, not a handicap

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

Event mixing

Peripheral

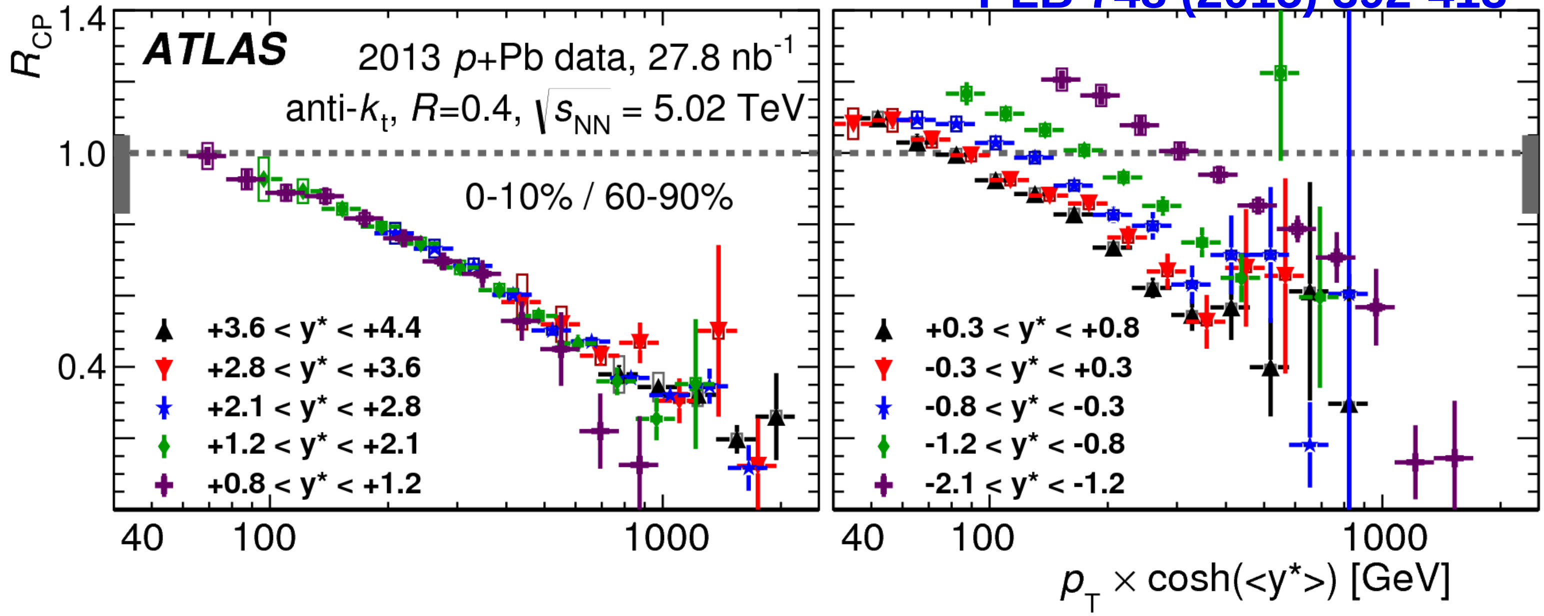


- Reference spectrum: peripheral collisions
- Much less combinatorial background compared to most central data
- Excellent signal/background ratio down to 3 GeV/c
- Requires normalization at low p_T
- *All physical correlations treated like jets*

Alex Schmah, Hard Probes 2015

Cold Nuclear Matter effects

PLB 748 (2015) 392-413



- No indication of modified jet structure in cold nuclear matter (d+Au and p+Pb collisions) [Phys.Rev.C73:054903,2006, Phys.Rev.Lett.96:222301,2006]
- Minimum bias R_{pPb}, R_{dAu} for charged particles, jets consistent with 1 [Phys.Rev.Lett.98:172302,2007,Phys.Rev.C81:064904,2010,Phys. Rev. Lett. 110 (2013) 082302, arXiv:1605.06436]
- Indications of modification at forward rapidities from dihadron correlations [Phys. Rev. Lett. 107, 172301 (2011)]
- Centrality dependence observed [PLB 748 (2015) 392-413, Phys. Rev. Lett. 116, 122301 (2016)]

Conclusions

- What to remember
  - A jet is not a parton
  - All jet measurements are biased
  - Background subtraction/suppression methods are important
  - Beware Cold Nuclear Matter effects!
- Challenges to the field
  - Cross check between experiments using the same method
  - Experimentalists: explain method/measurement to theorists!
  - Theorists: don't ignore the method!

Many thanks to Rosi Reed, Sevil Salur, and Megan Connors for many productive discussions