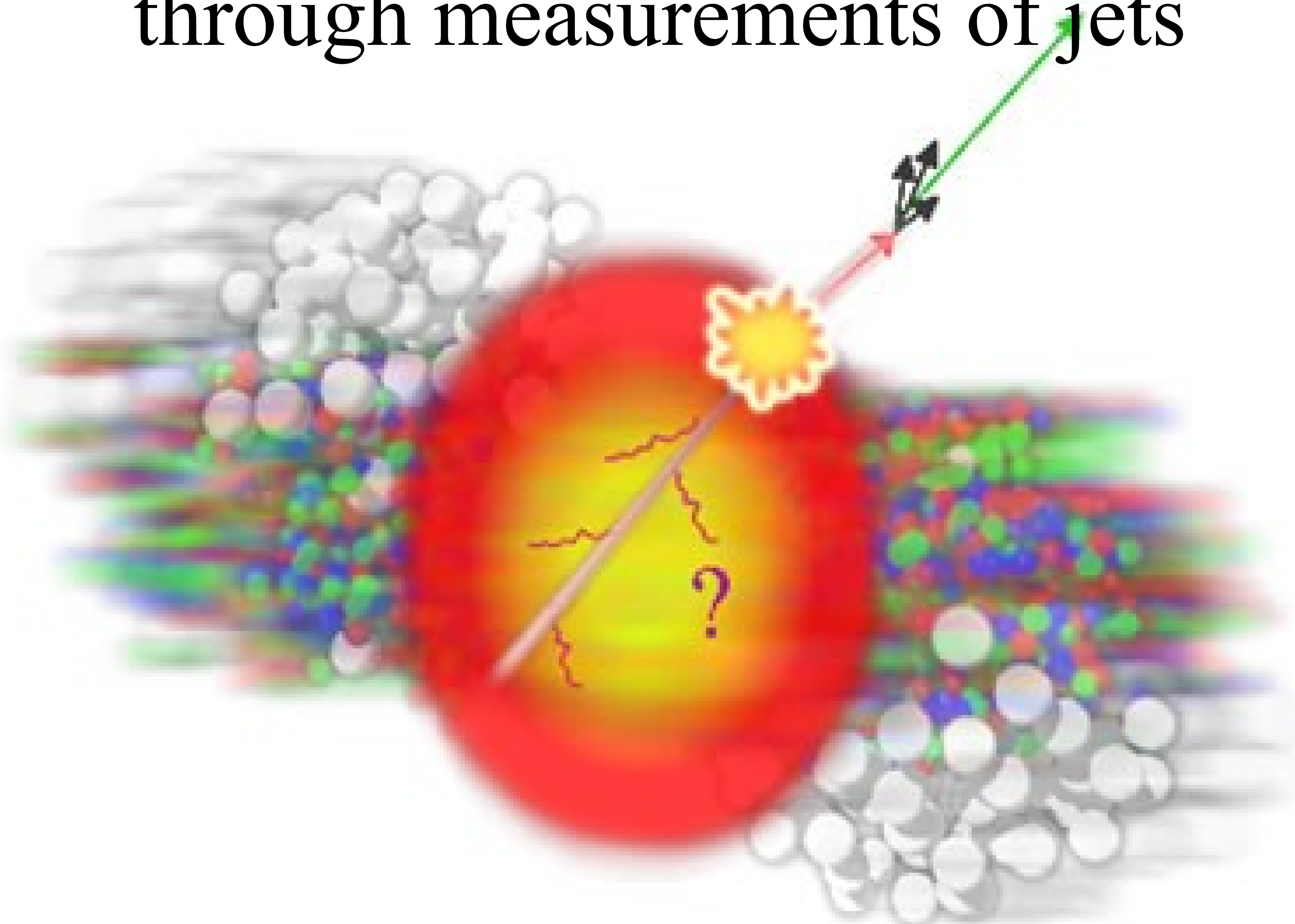
Understanding the Quark Gluon Plasma through measurements of jets



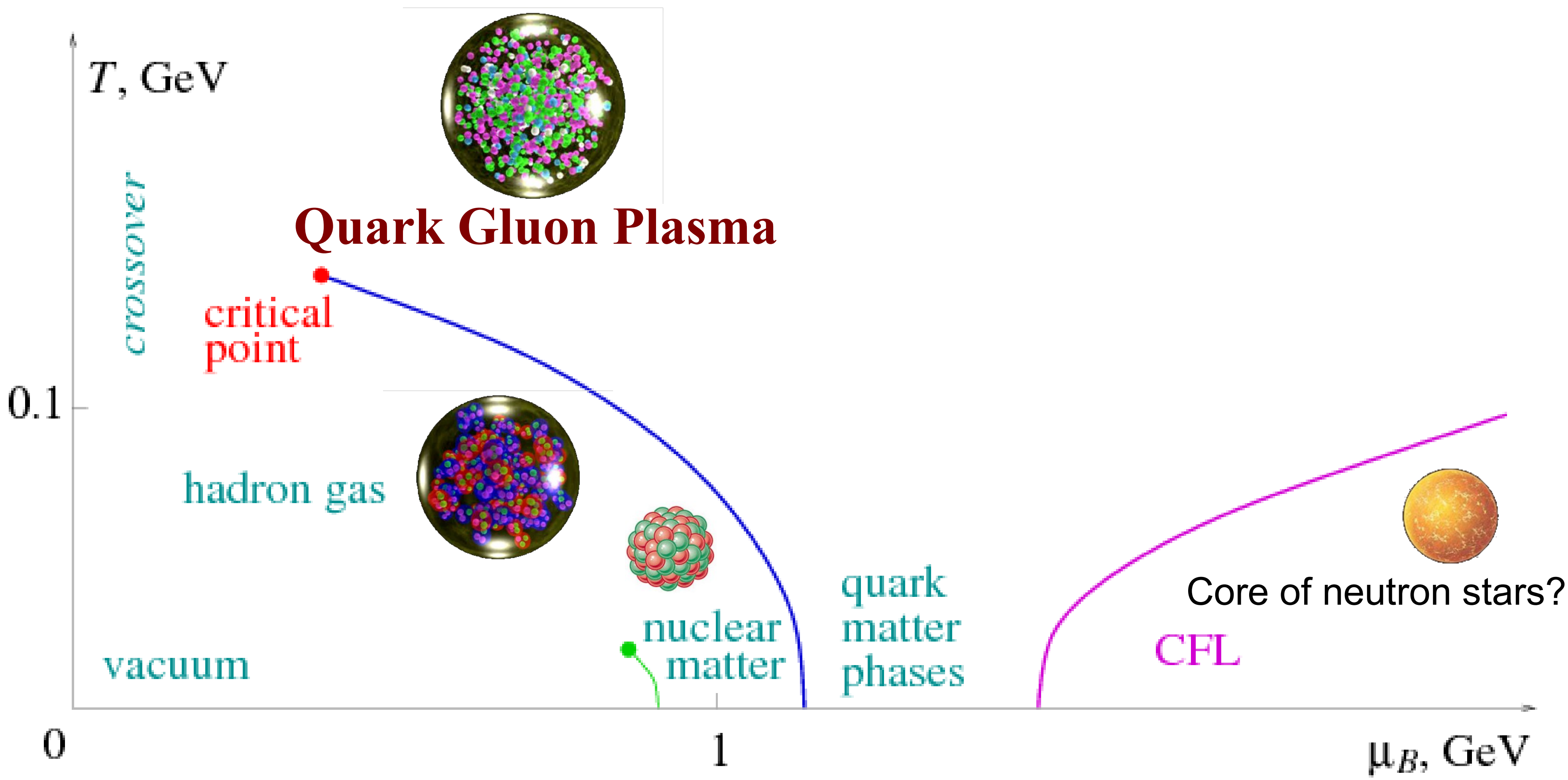
Overview

- What is the QGP?
- 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?
  - Measuring the lost energy

Please interrupt me with questions!

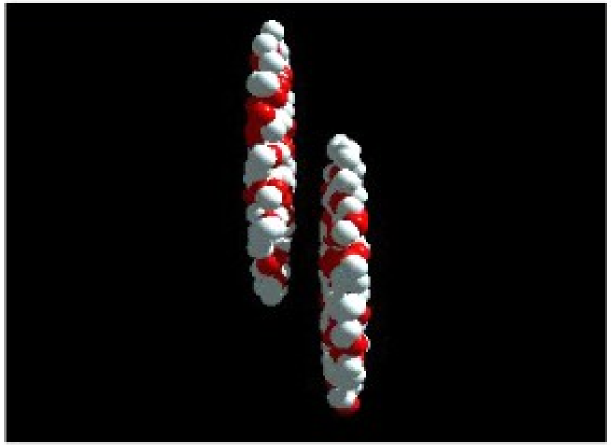
What is the QGP?

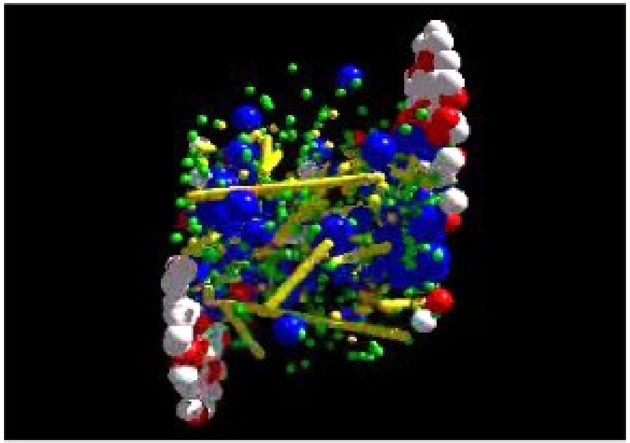
Phase diagram of nuclear matter

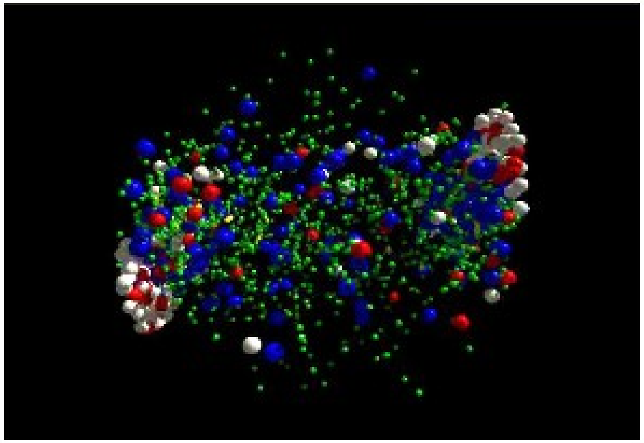


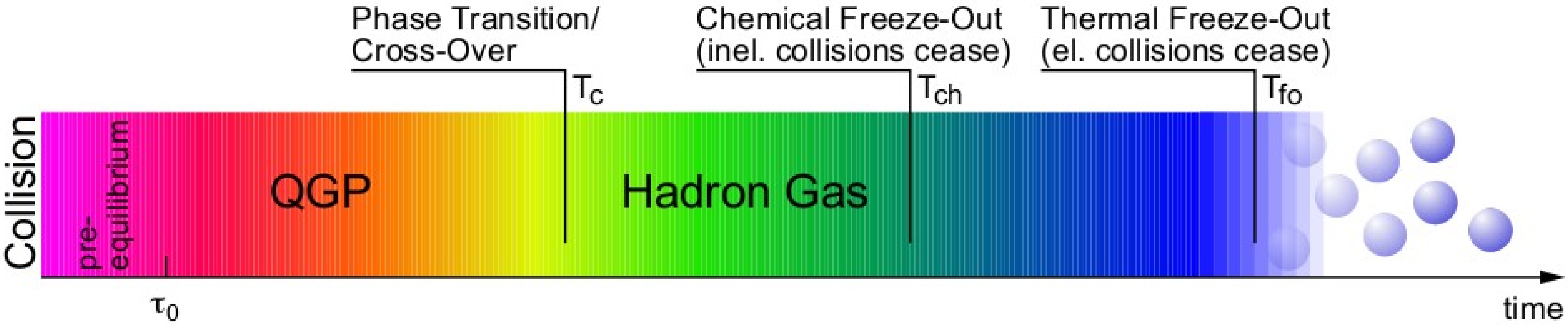
Quark Gluon Plasma – a *liquid* of quarks and gluons created at temperatures above ~170 MeV ($2 \cdot 10^{12}$K) – over a million times hotter than the core of the sun

The phase transition in the laboratory





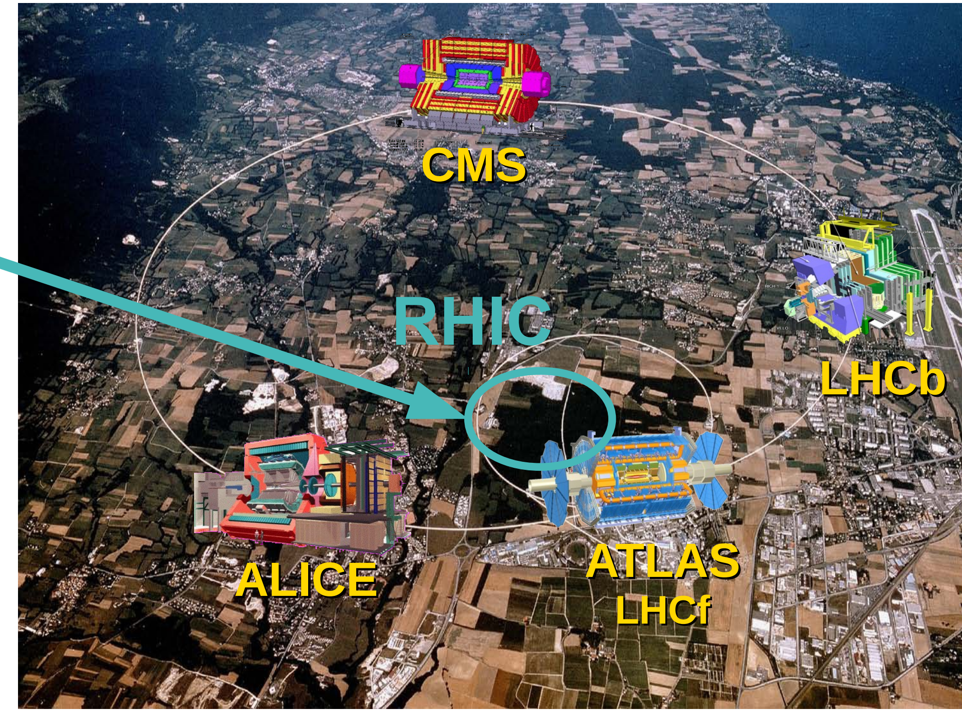




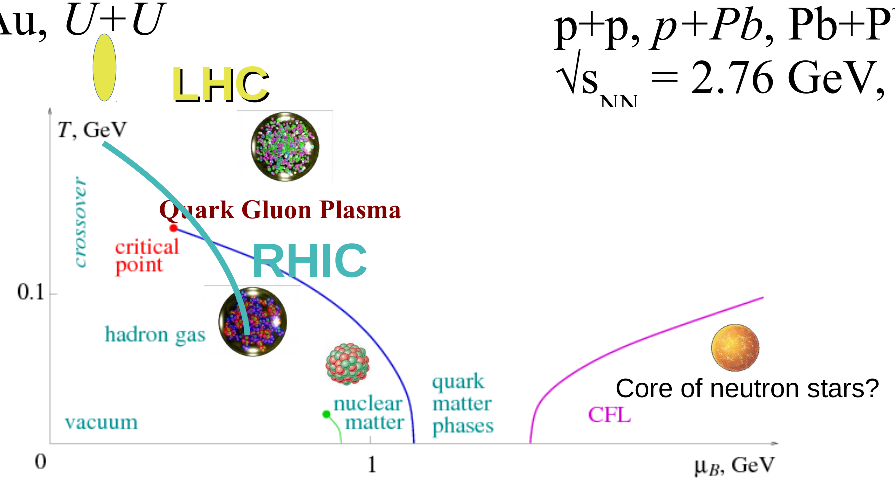
Relativistic Heavy Ion Collider

Upton, NY
1.2km diameter
p+p, d+Au, Cu+Cu, Au+Au, *U+U*
$\sqrt{s_{NN}}$ = 9 - 200 GeV

Large Hadron Collider



Geneva, Switzerland
8.6km diameter
p+p, *p+Pb*, Pb+Pb
$\sqrt{s_{NN}}$ = 2.76 GeV, *5.5 TeV*



Comparison of colliders

	RHIC	LHC	
$\sqrt{s_{NN}}$ (GeV)	9-200	2760, 5500	*center of mass energy*
$dN_{ch}/d\eta$	~1200	~1600	*number of particles*
T/T_c	1.9	3.0-4.2	*temperature*
ε (GeV/fm^3)	5	12, 16	*energy density*
τ_{QGP} (fm/c)	2-4	>10	*lifetime of QGP*

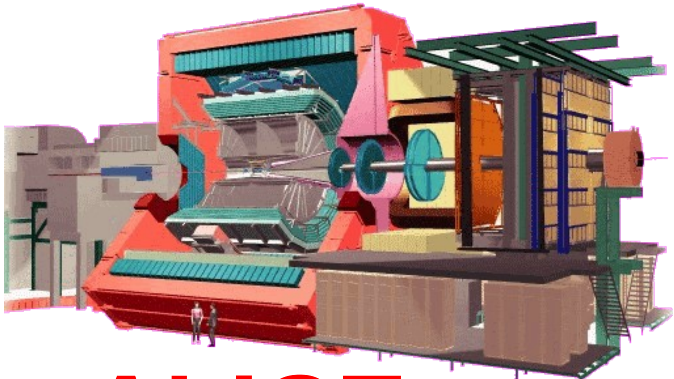
RHIC and LHC:

Cover 2 –3 decades of energy ($\sqrt{s_{NN}}$ = 9 GeV –5 TeV)

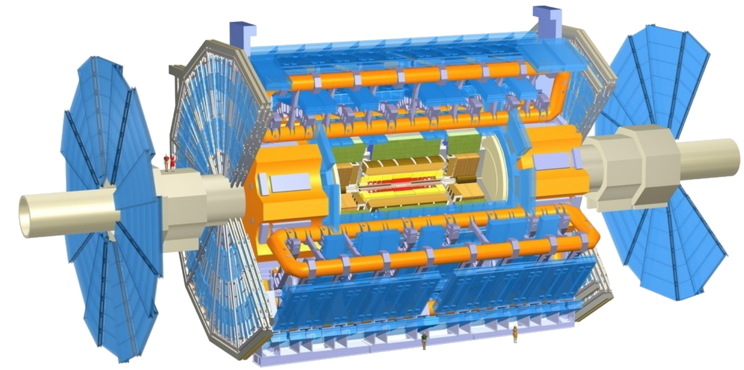
To discover the properties of hot nuclear matter at T ~ 150 –600 MeV

Interesting observables

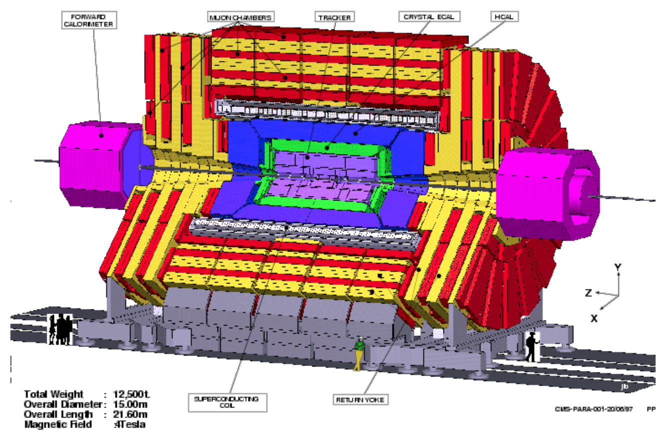
- Different hadronization mechanisms
  → Identify particle types
- Collective motion of particles
  → Low momentum acceptance
- Even common processes are not well understood
  → Do not need 4π acceptance or high rates



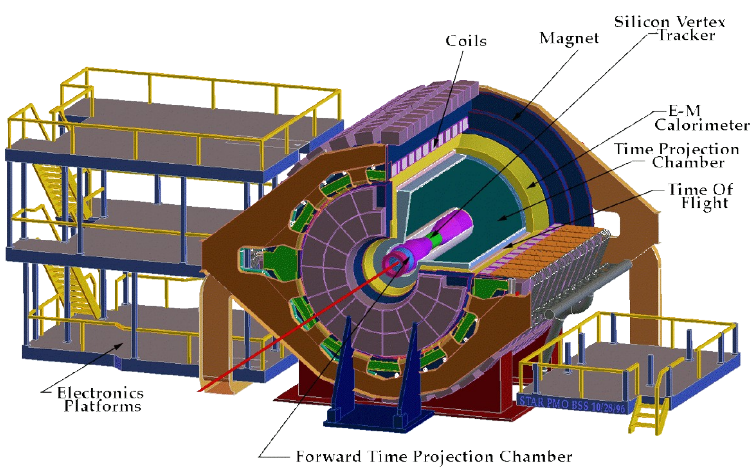
ALICE



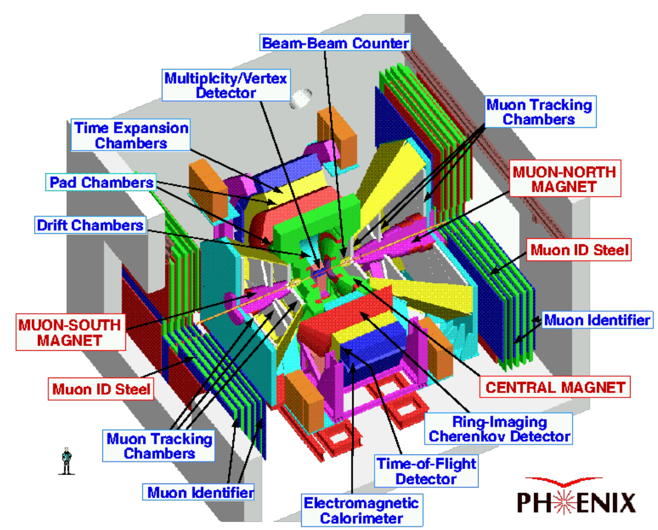
ATLAS



CMS

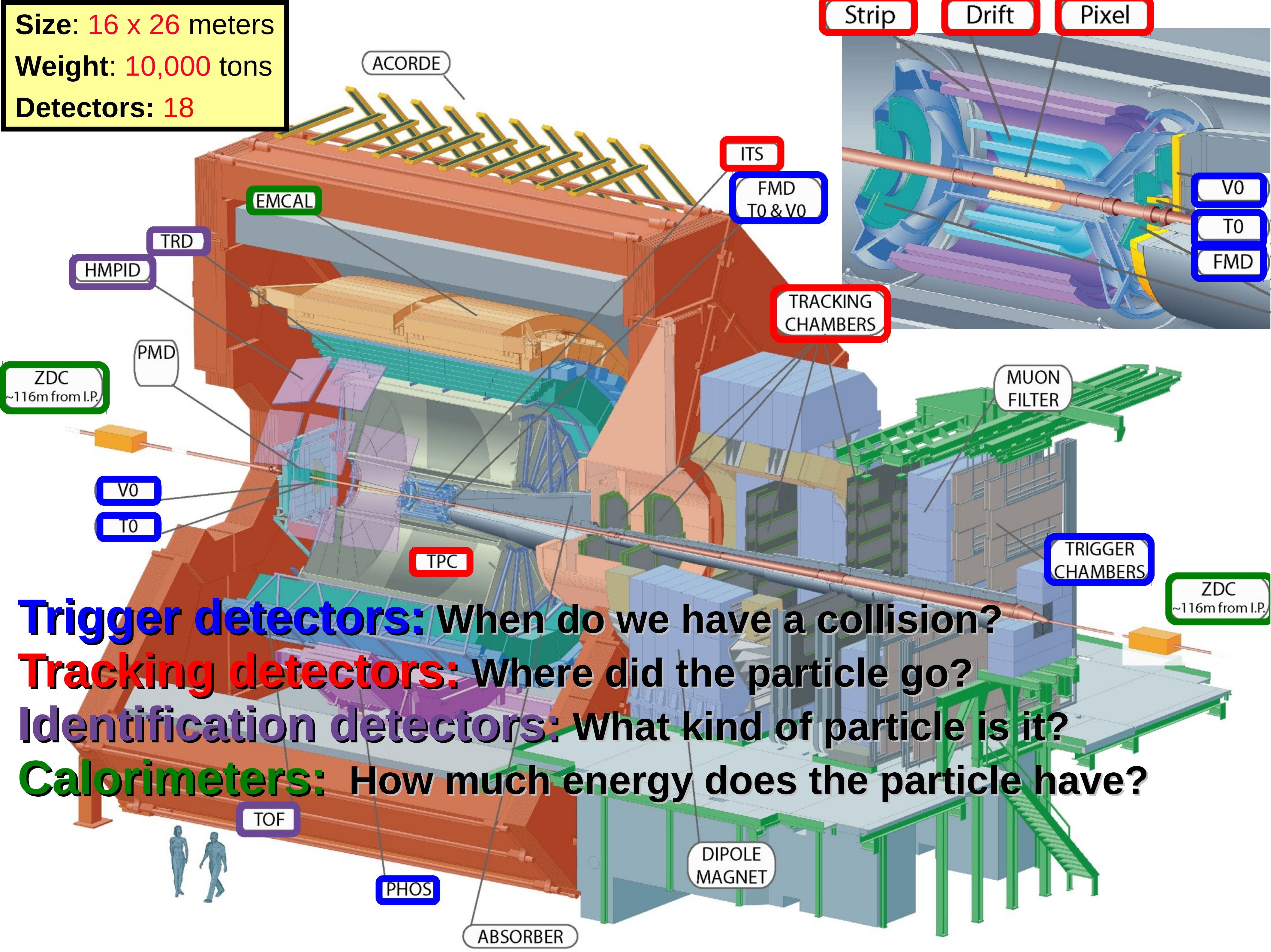


STAR



PHENIX

Size: 16 x 26 meters
Weight: 10,000 tons
Detectors: 18



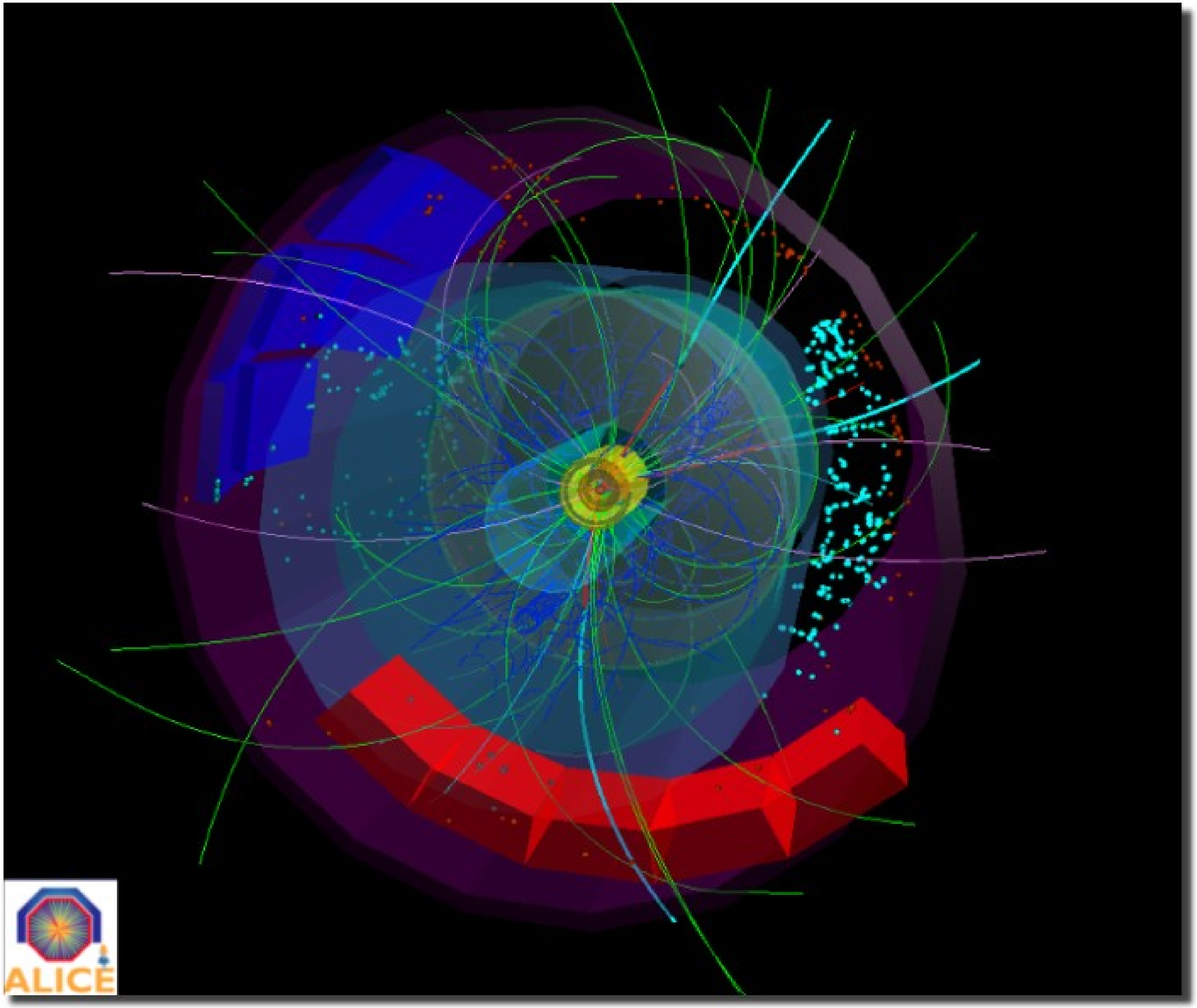
Trigger detectors: When do we have a collision?

Tracking detectors: Where did the particle go?

Identification detectors: What kind of particle is it?

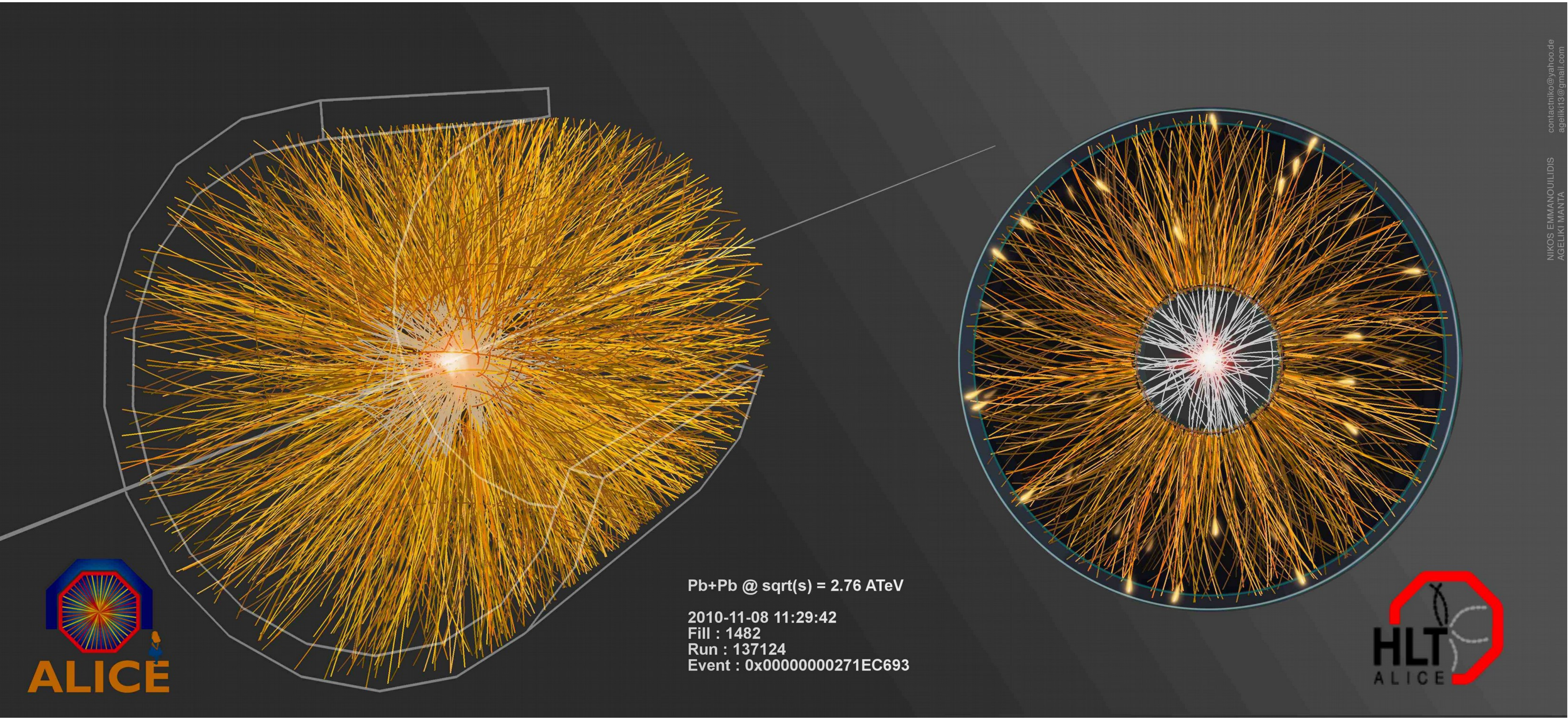
Calorimeters: How much energy does the particle have?

p+p collisions



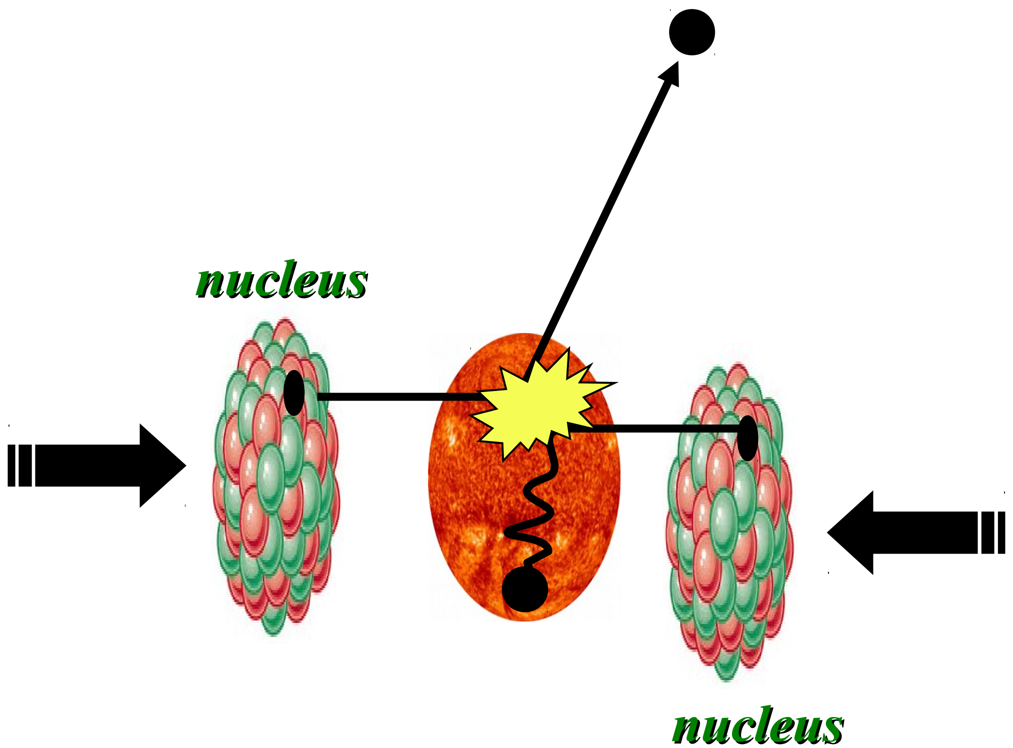
3D image of each collision

Pb+Pb collisions



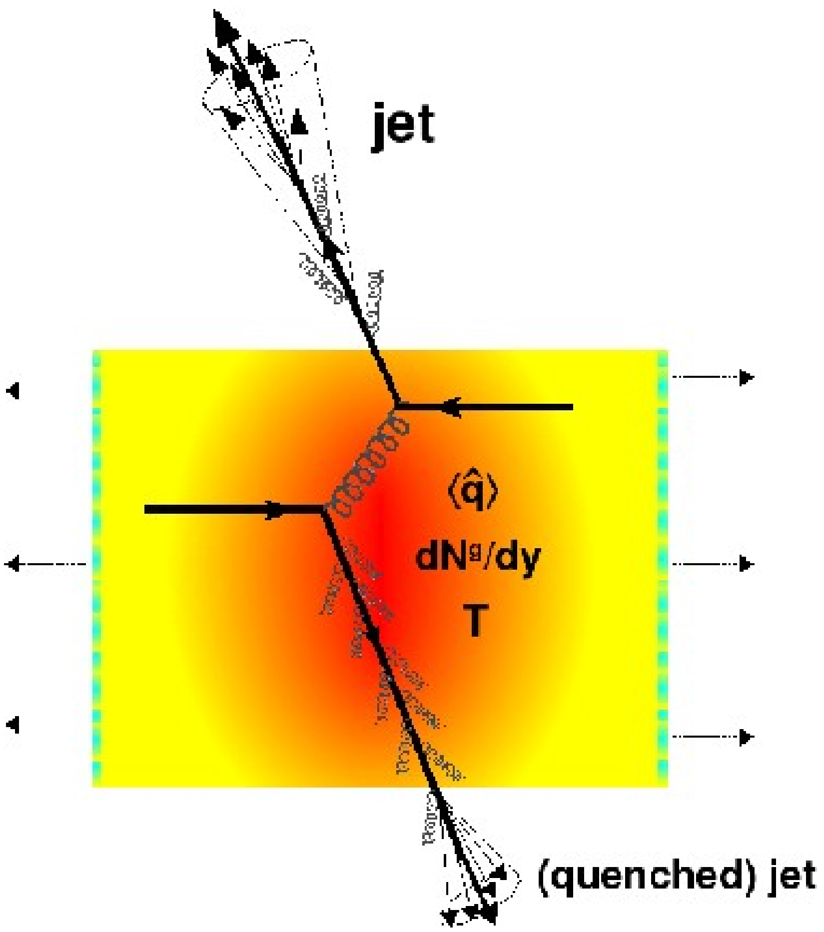
Jet quenching in a nutshell

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

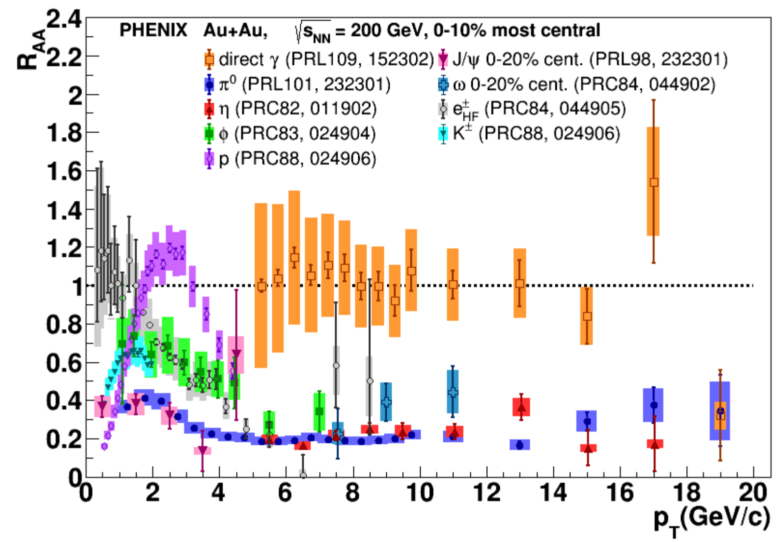


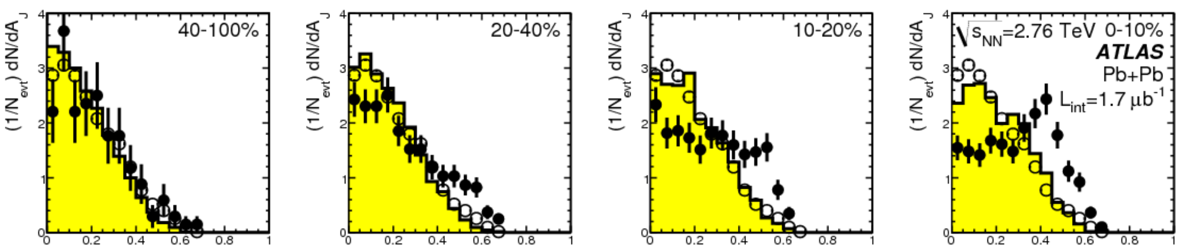
- Softer constituents
- Broader radius

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

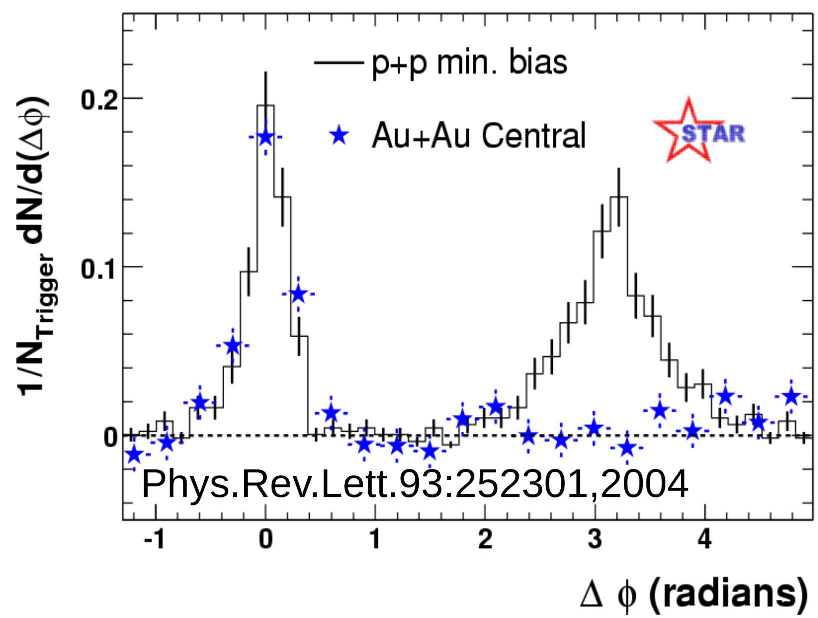
Ways to study jets

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





PRL 105 (2010) 252303

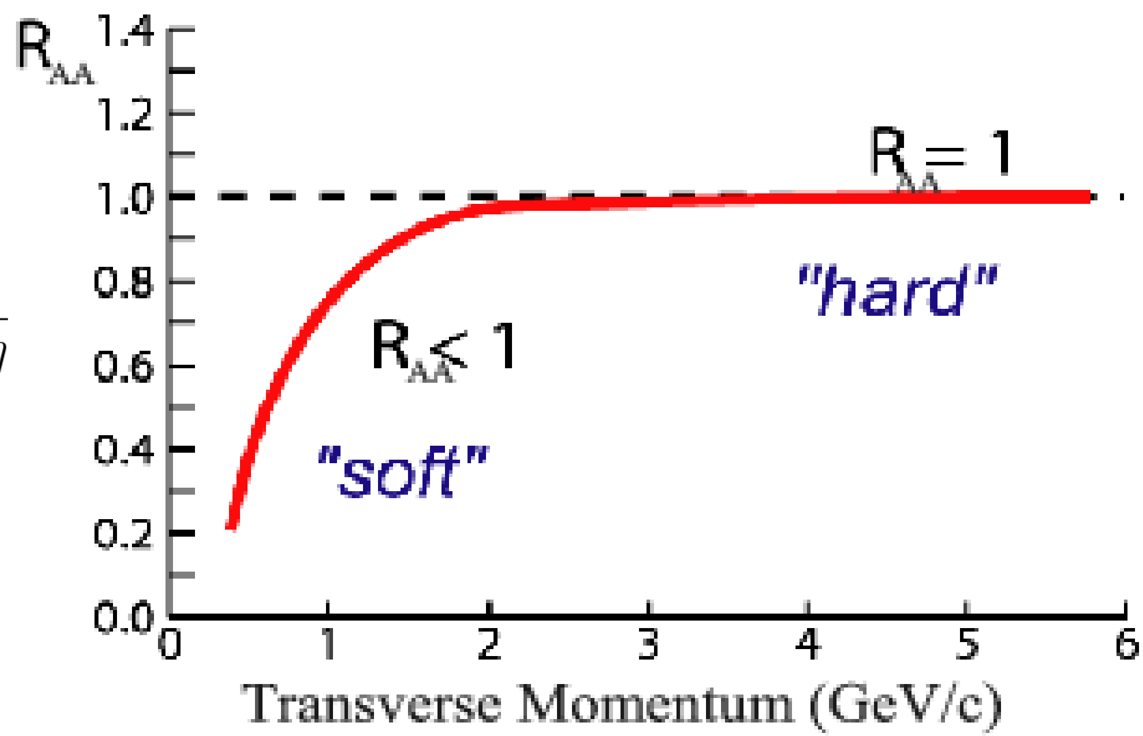


Phys.Rev.Lett.93:252301,2004

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

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

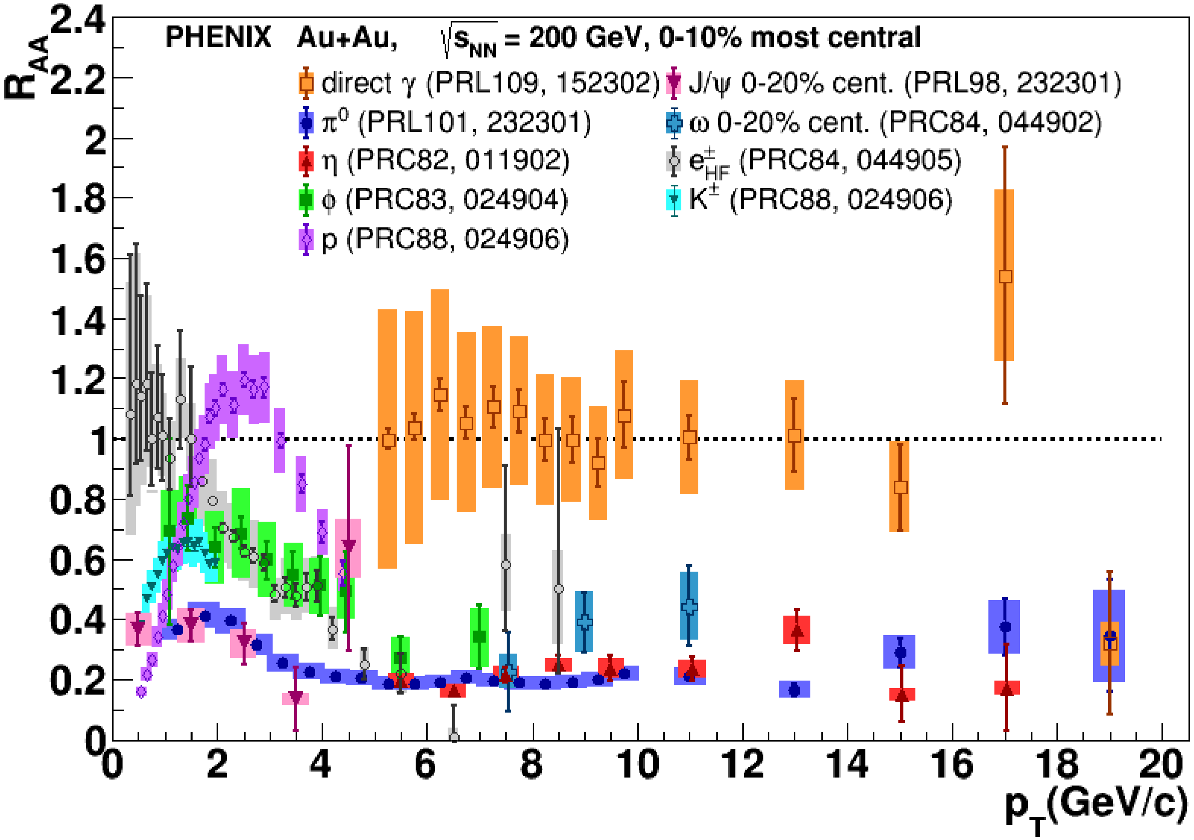


Enhancement

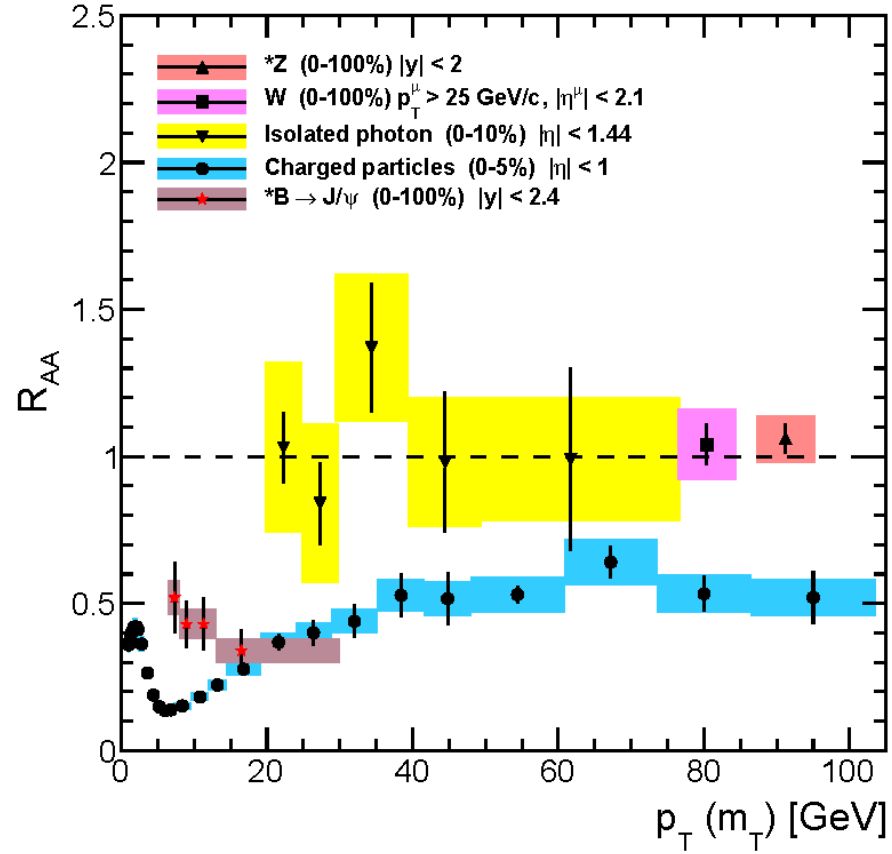
Suppression

Nuclear modification factor R_{AA}

RHIC



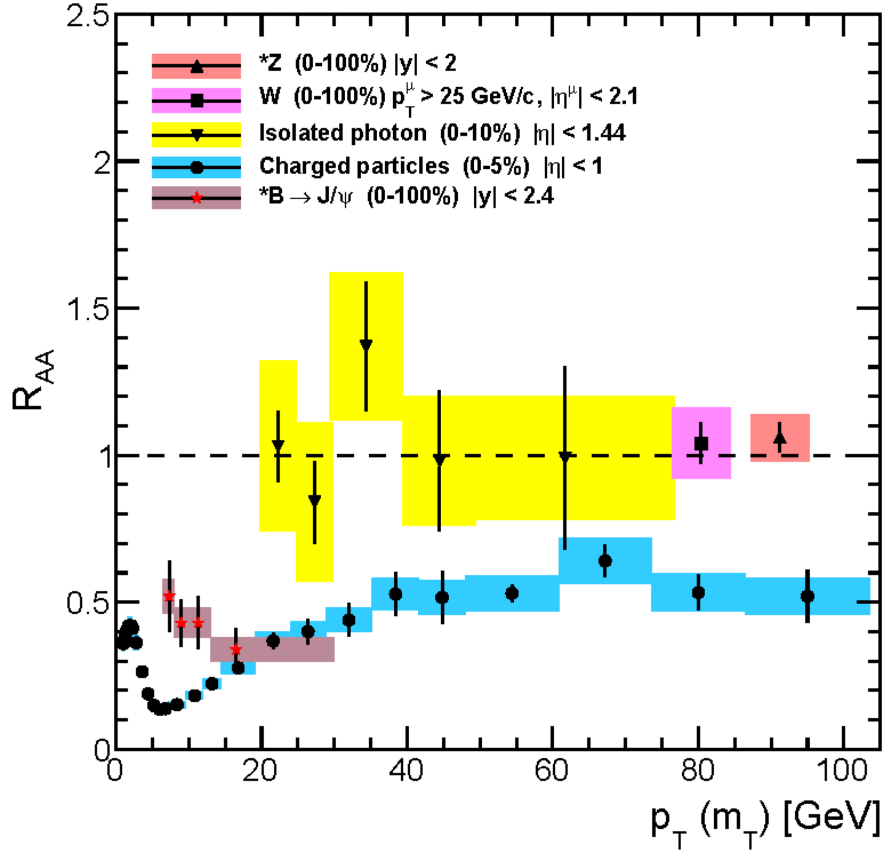
LHC

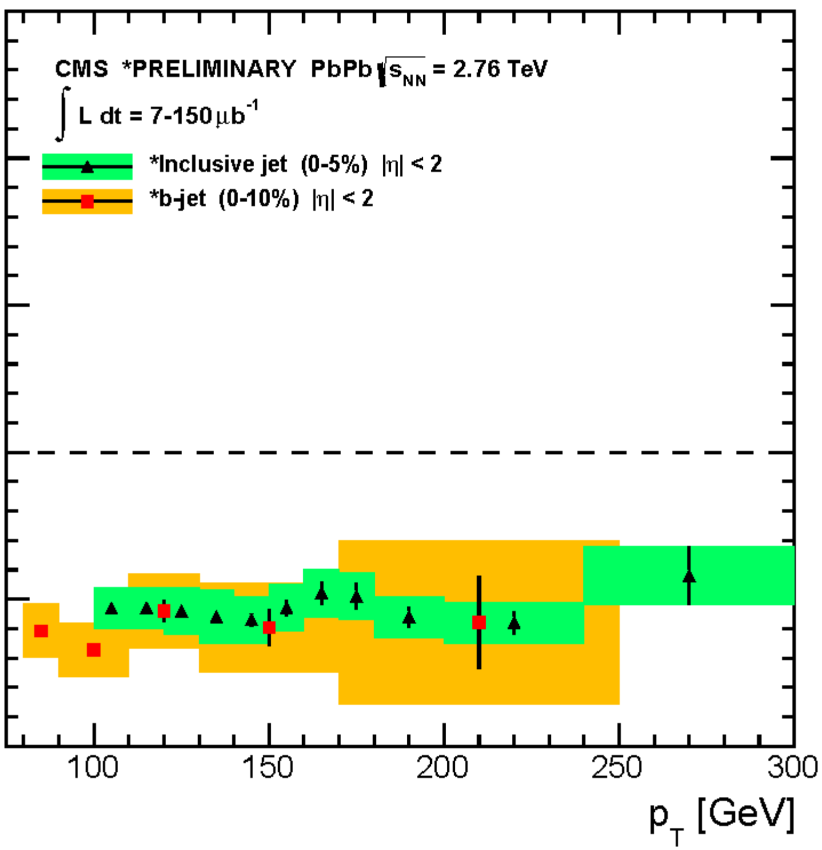


- *Electromagnetic probes* – consistent with no modification – medium is transparent to them
- *Strong probes* – significant suppression – medium is opaque to them

Nuclear modification factor R_{AA}

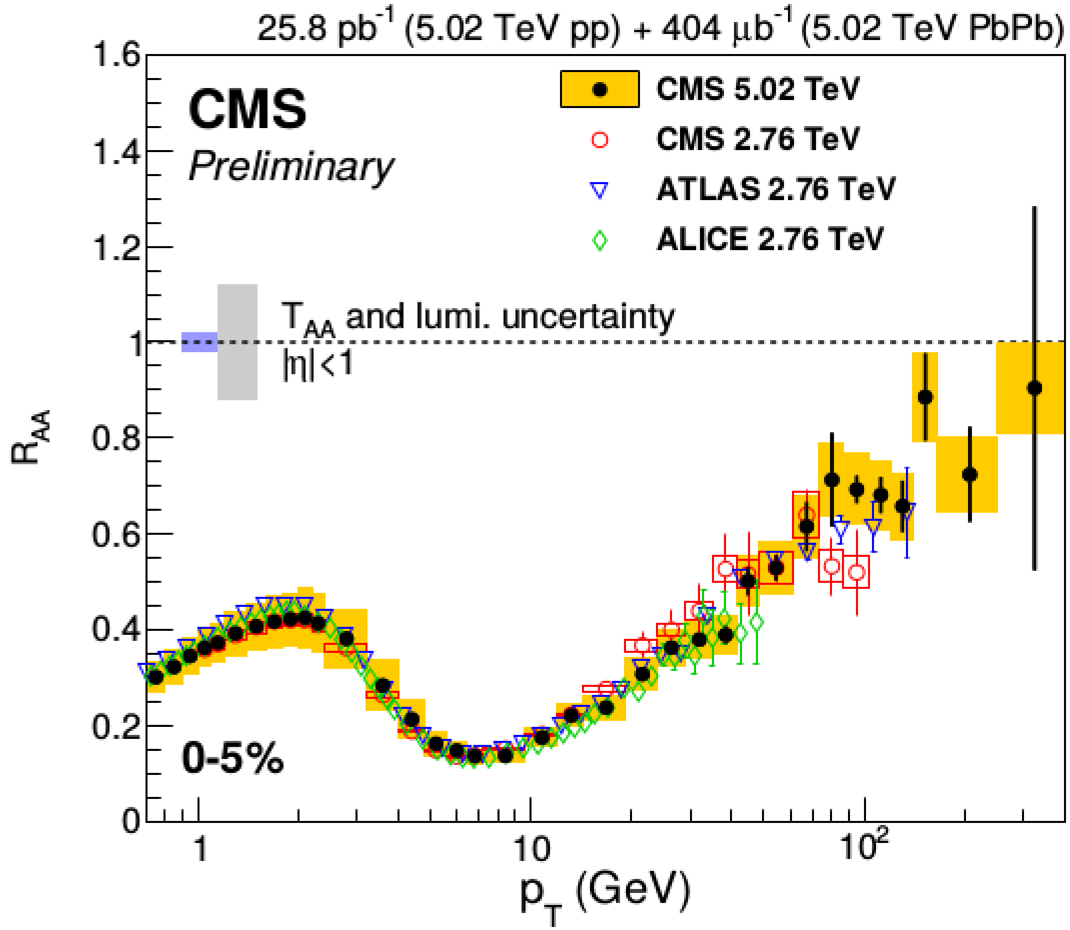
Single particles **Jets**





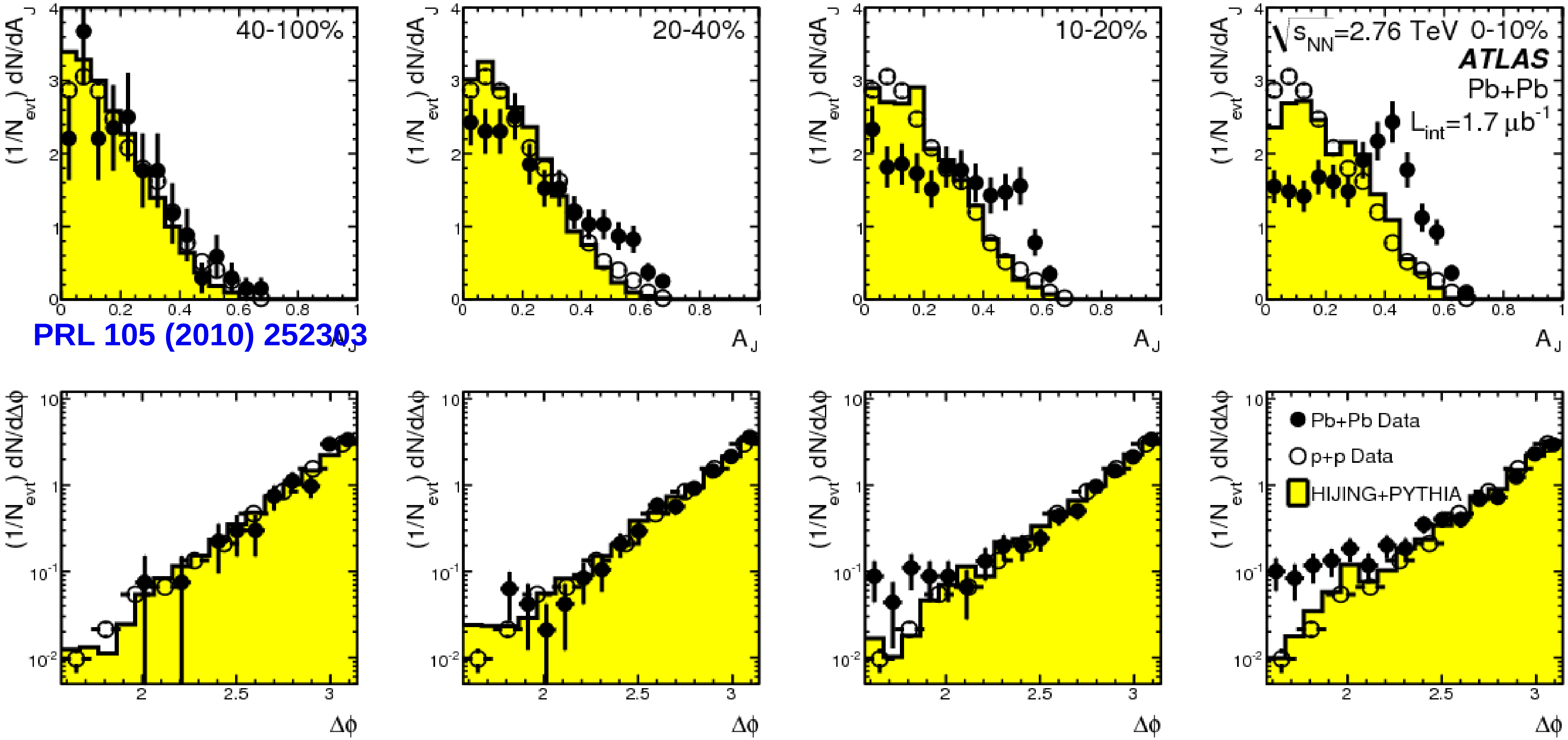
- *Electromagnetic probes* – consistent with no modification – medium is transparent to them
- *Strong probes* – significant suppression – medium is opaque to them

Nuclear modification factor R_{AA}
Single particles at the LHC



- Reaches 1 at very high p_T
- Must happen due to causality
- Feature of all QCD-inspired models

Di-jet asymmetry

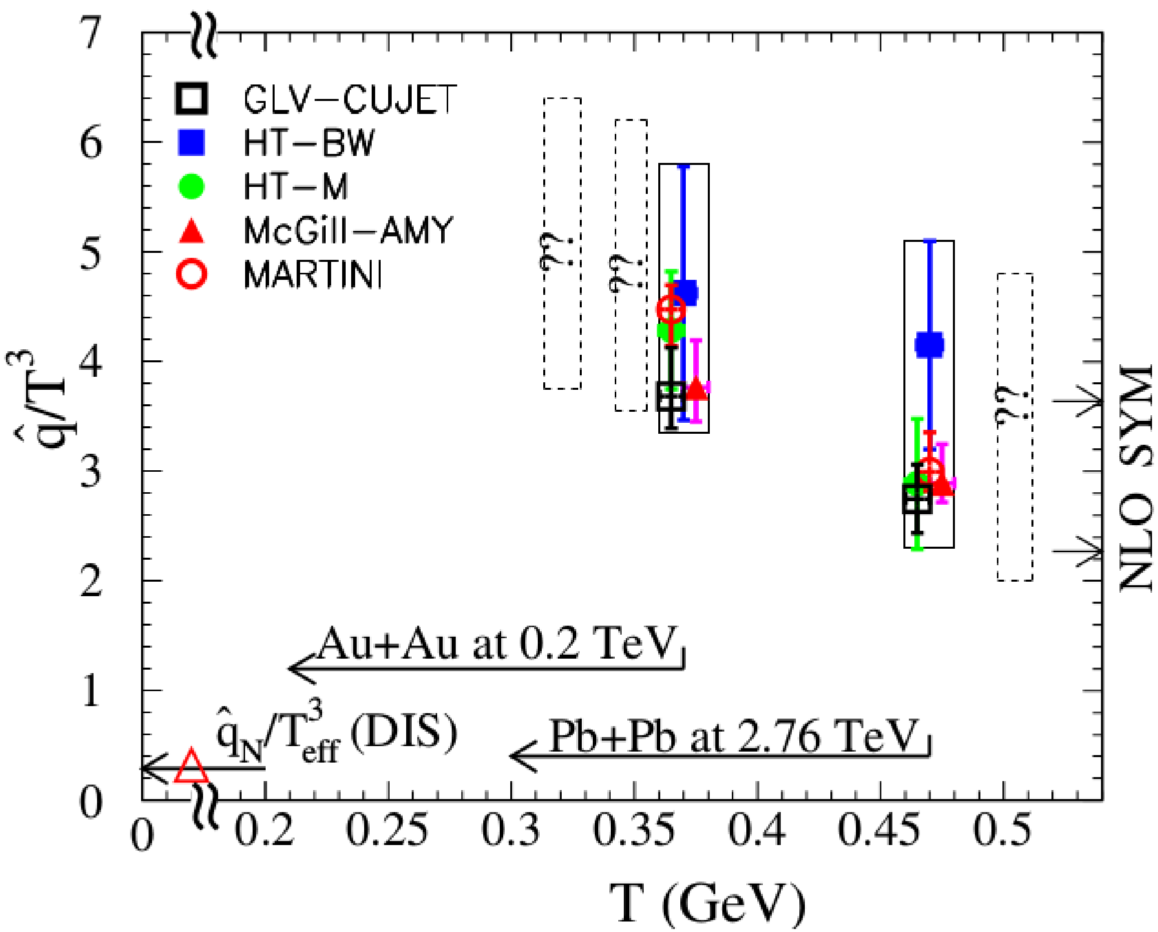


PRL 105 (2010) 252303

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

Quantifying $\hat{q}$

Phys. Rev. C 90, 014909 (2014)



Jet Collaboration: For a 10 GeV quark traveling 4 fm

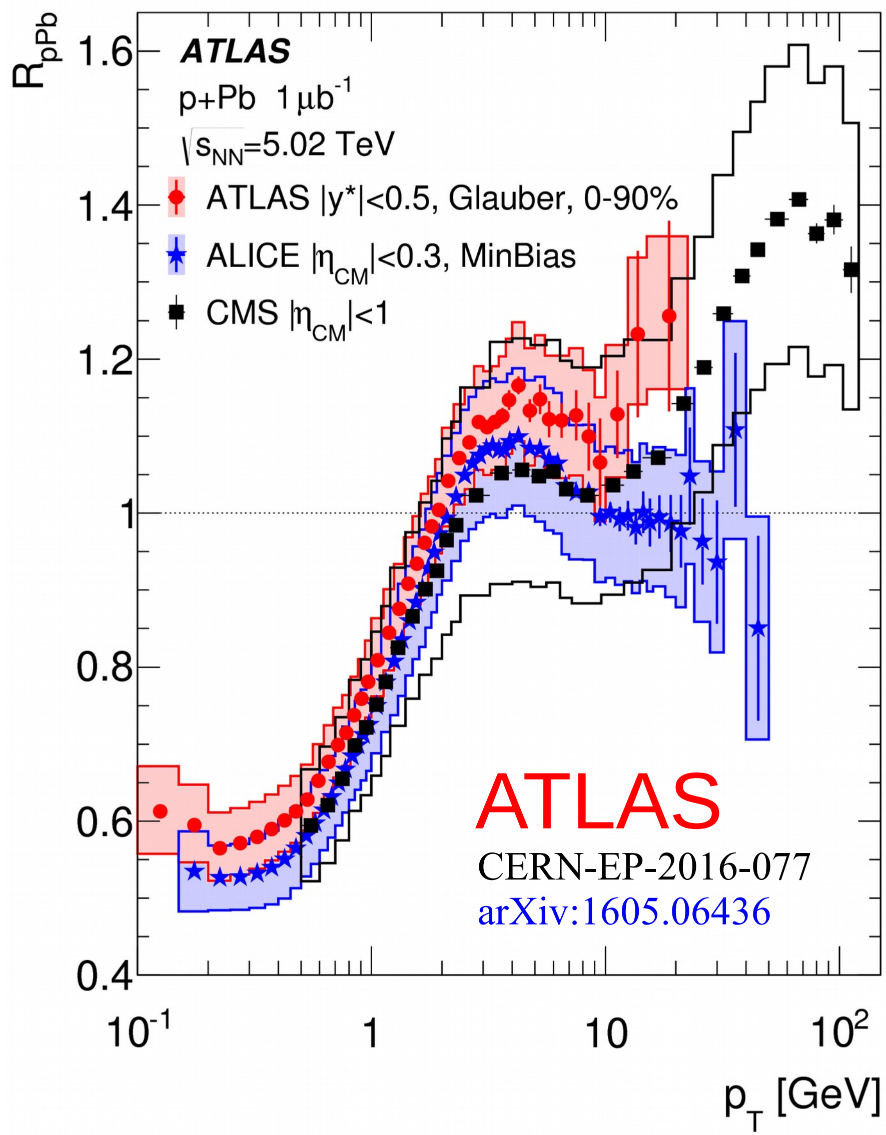
$\hat{q}$ ≈1.2±0.3 GeV^2/fm at τ_0=0.6 fm/c in Au+Au at $\sqrt{s_{NN}}$=200 GeV →loses 2.2 Gev

$\hat{q}$≈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



Towards quantitative understanding

What is a jet?

A jet is what a jet finder finds.

Jets in principle

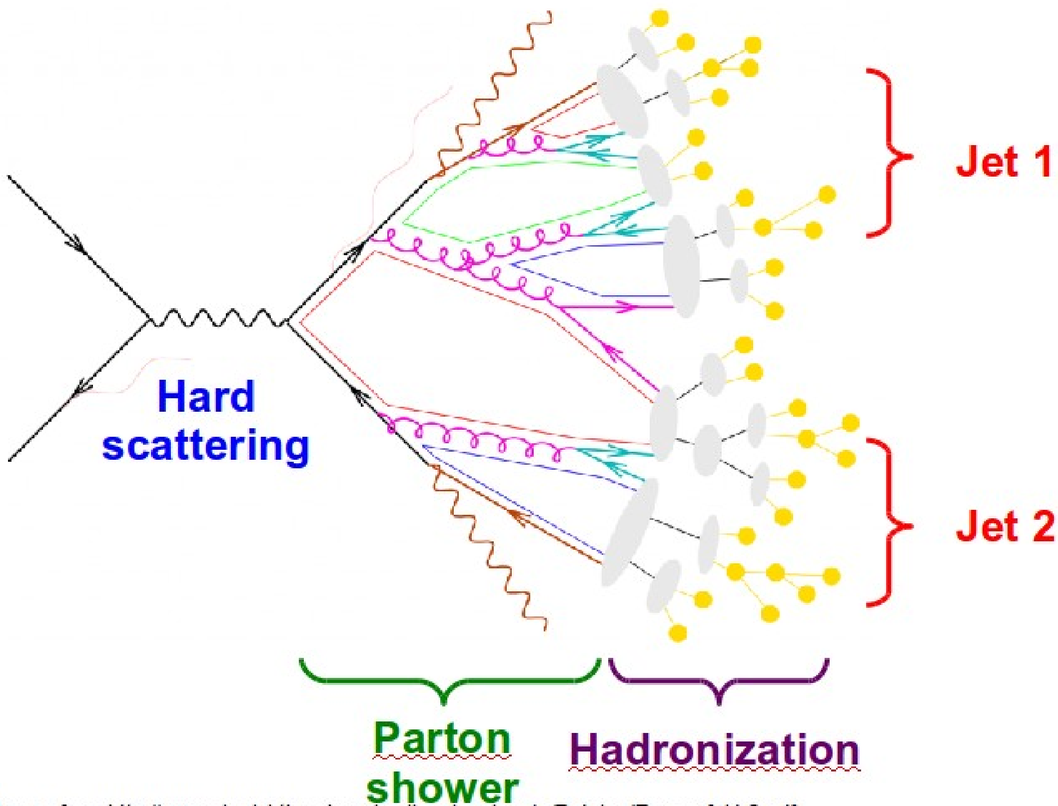
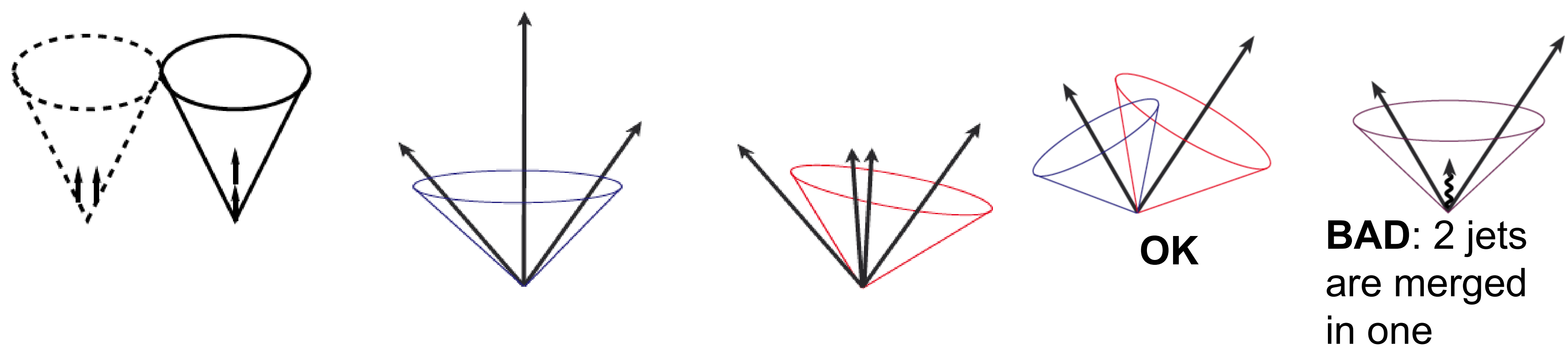


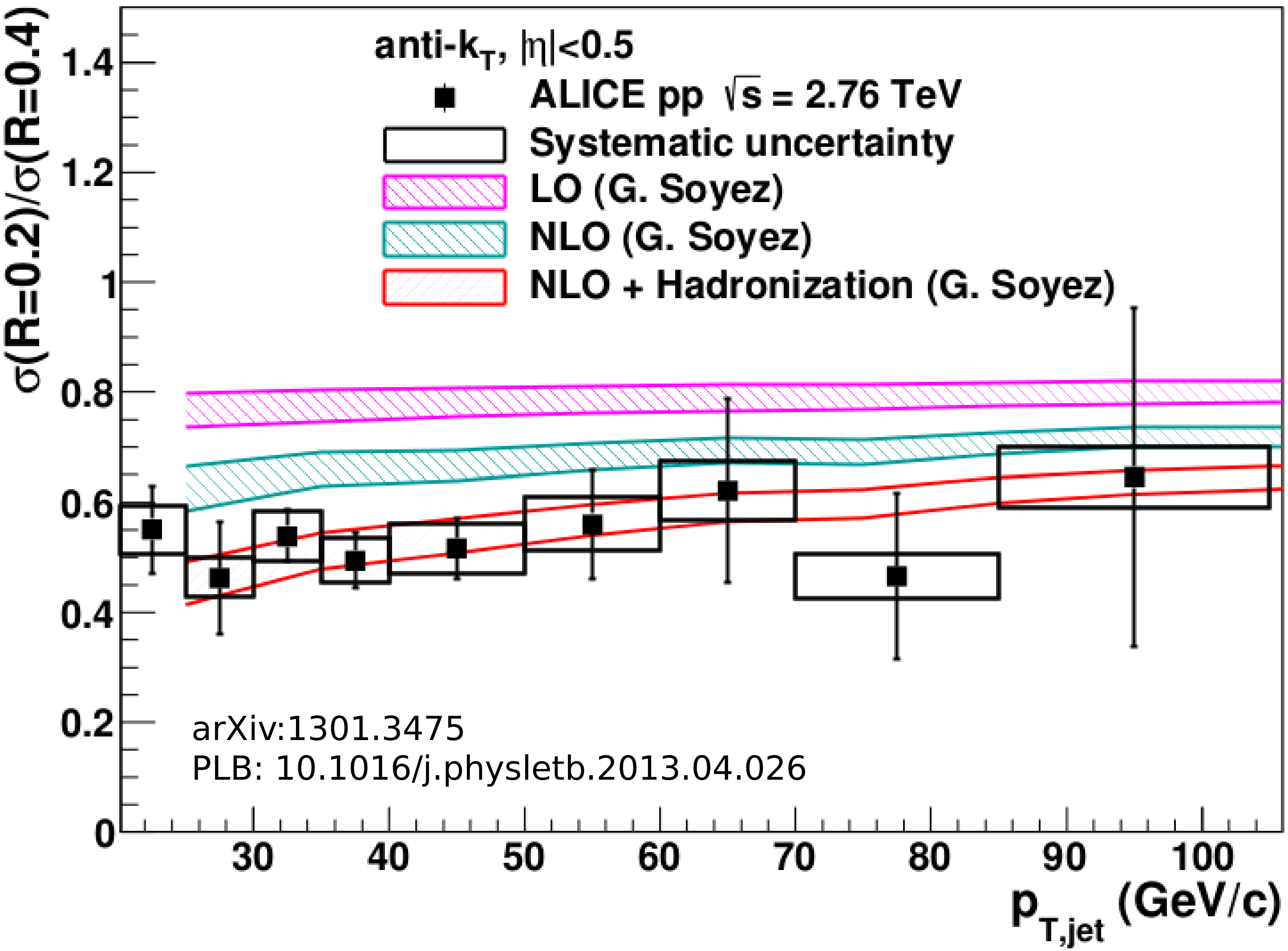
Image from http://www.gk-eichtheorien.physik.uni-mainz.de/Dateien/Zeppenfeld-3.pdf

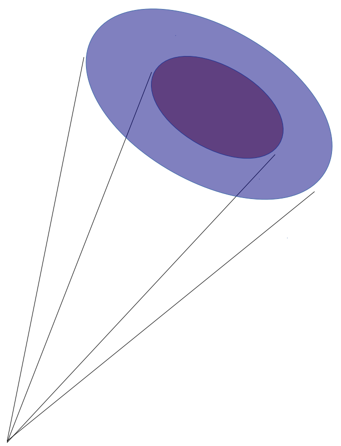
- Jet measures **partons**
- Hadronic degrees of freedom are integrated out
- Algorithms are infrared and colinear safe



Full jet ratios in pp

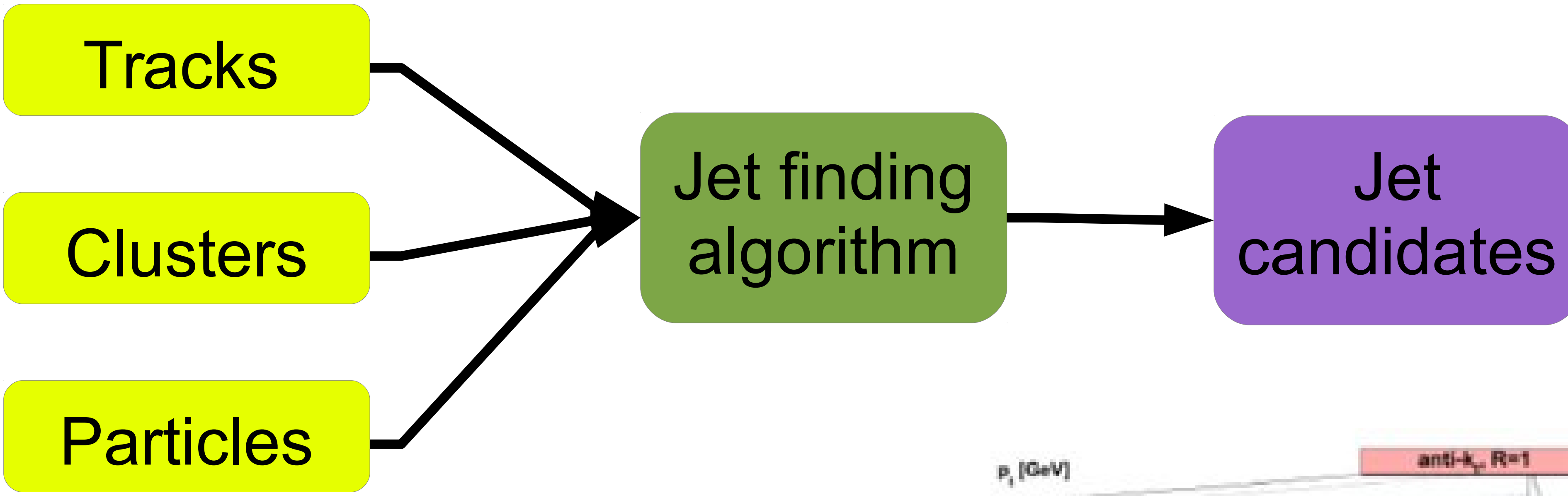
$\sqrt{s}$ = 2.76 TeV, R = 0.2, 0.4 Inclusive



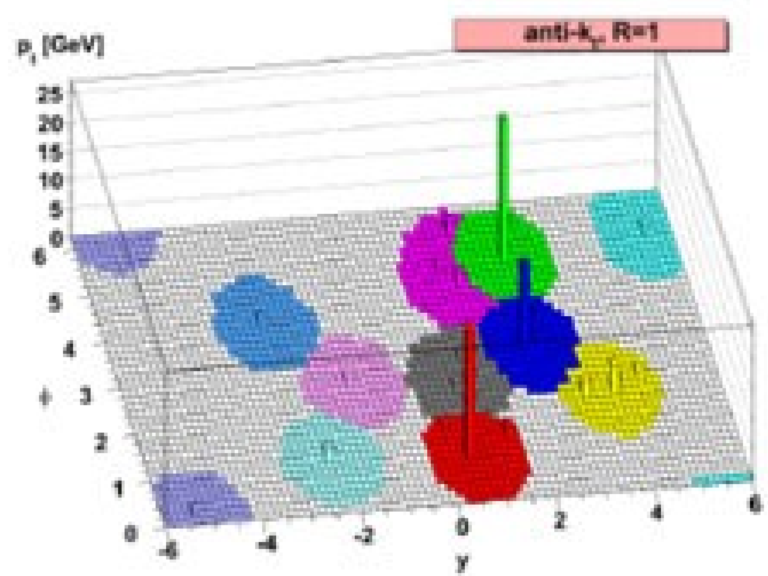


Hadronization is important even in pp collisions!

Jet finding algorithms

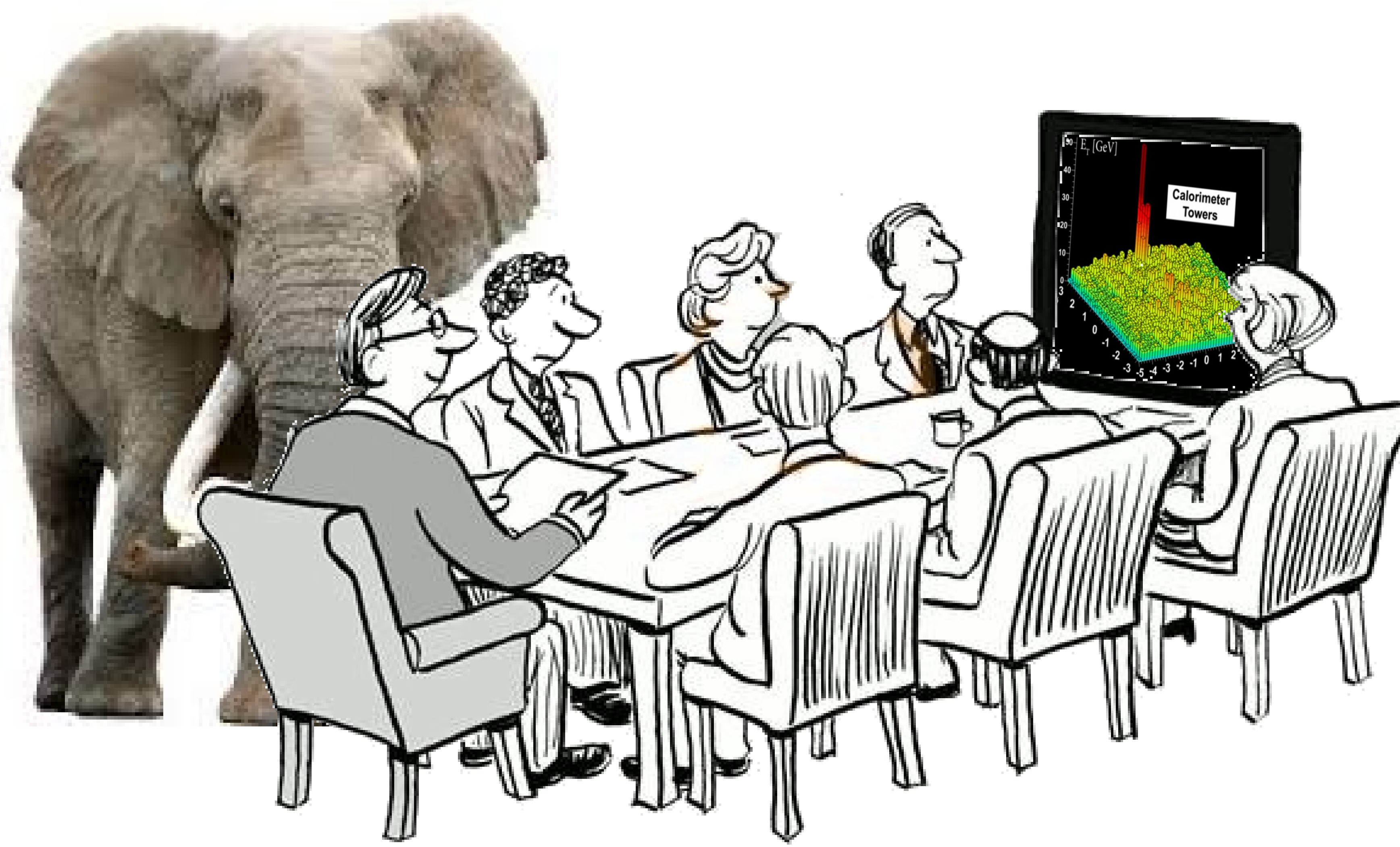


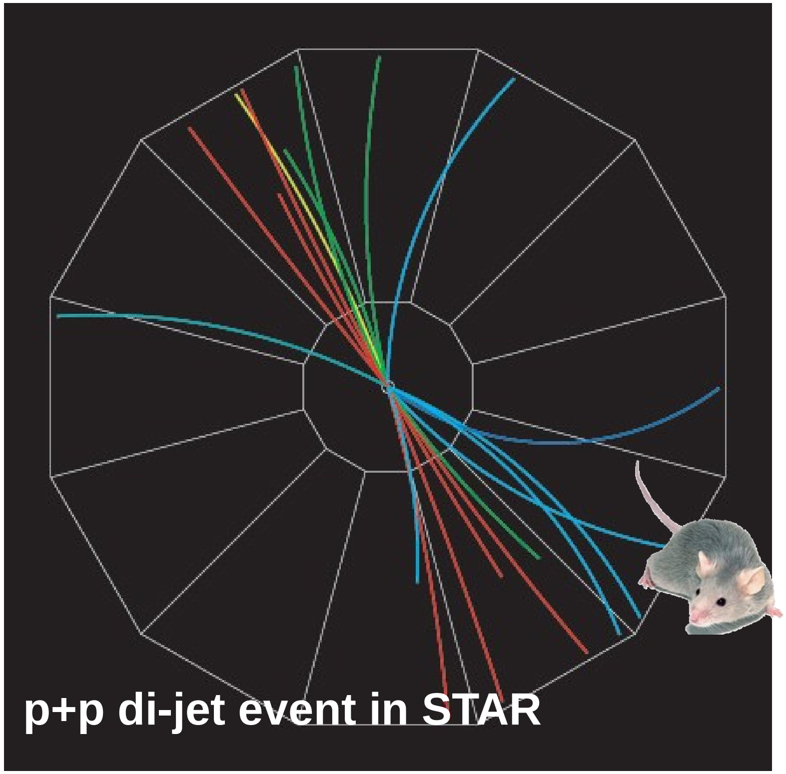
- Any list of objects works as input
- Use the same algorithm on theory & experiment
- Output only as good as input



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

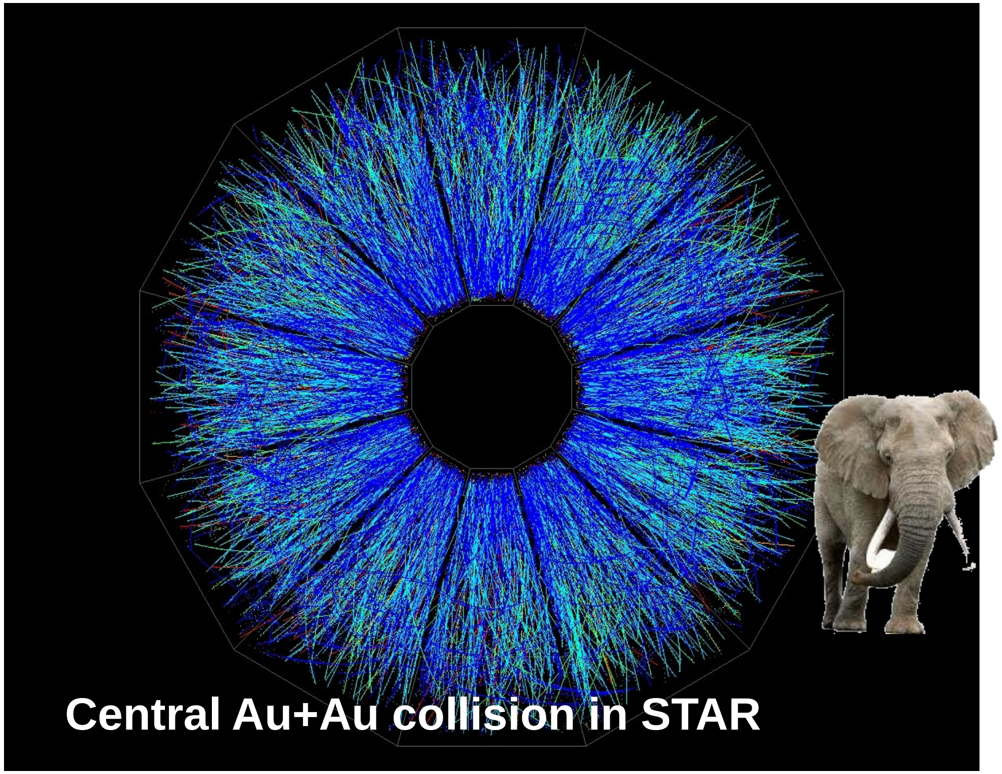
Bias & Background





Signal

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

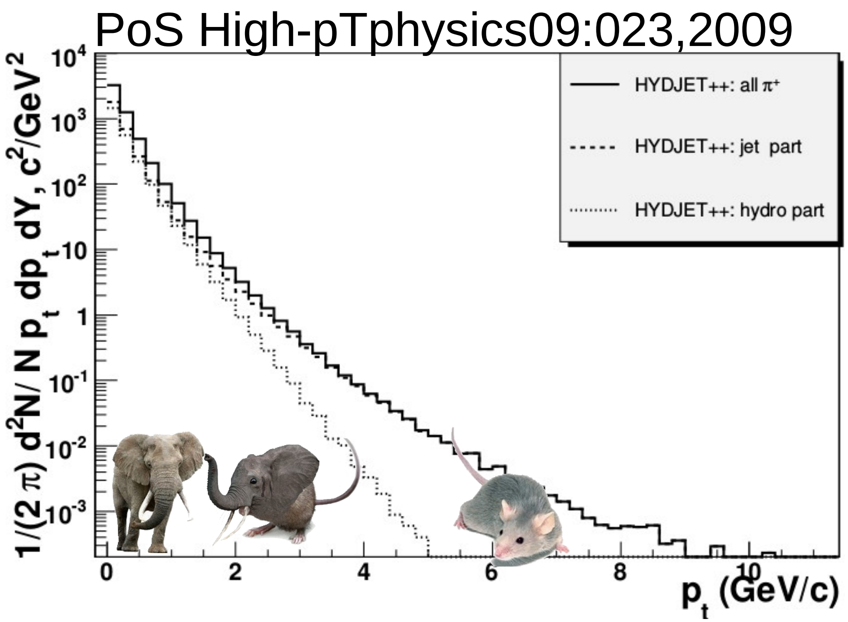


Background

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

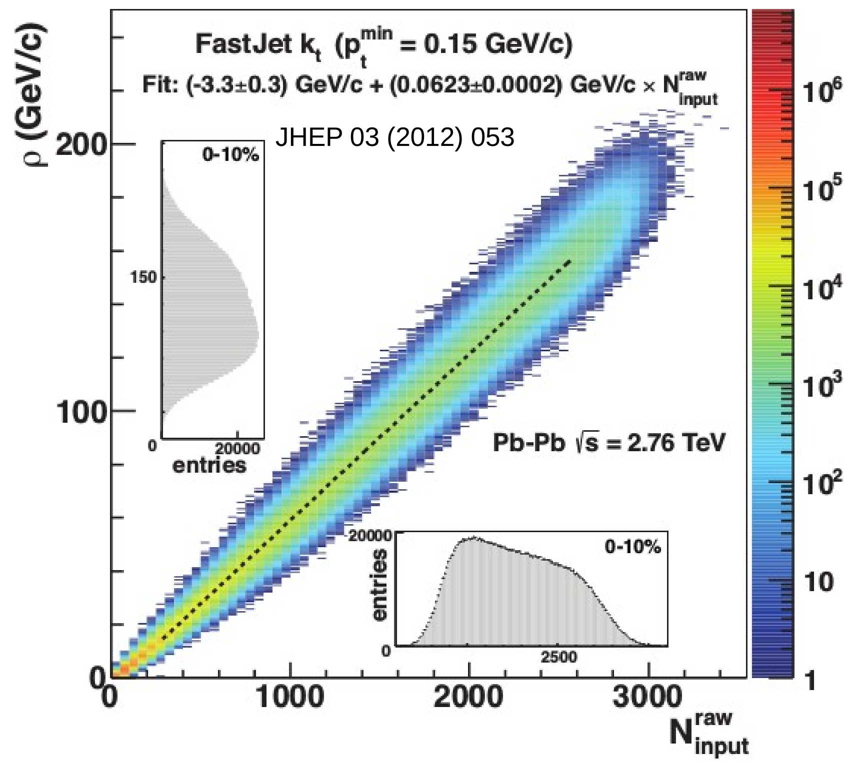
Focus on high p_T

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



Focus on smaller angles

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



ALICE/STAR

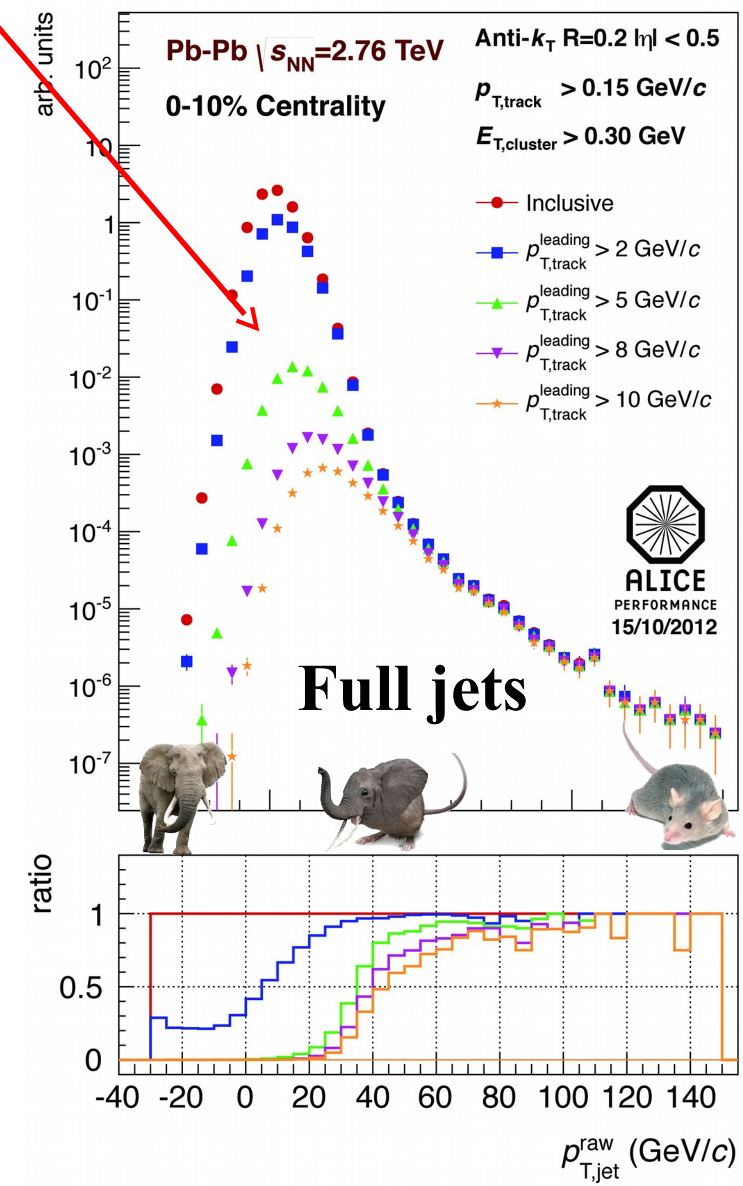
Combinatorial "jets"

- 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:

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

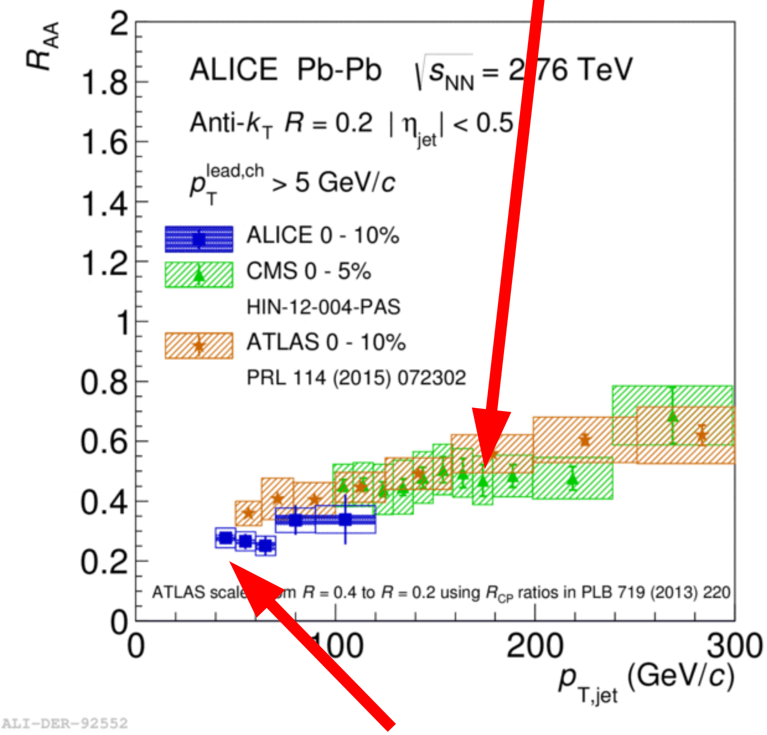
Where $p^{rec}_{\mathrm{T,jet}}, A$ comes from FastJet anti-k_T algorithm



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

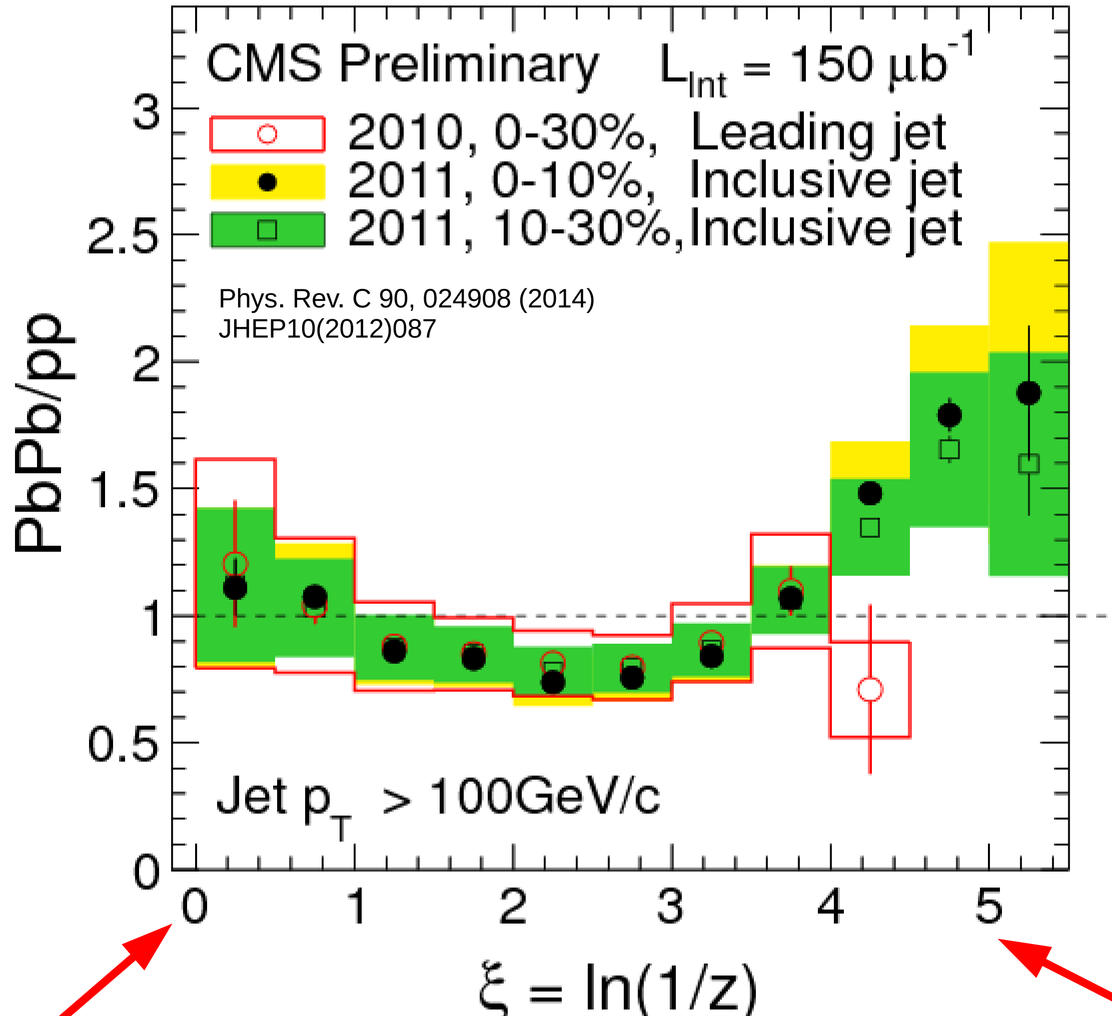
http://www.boredpanda.com/animal-camouflage/

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

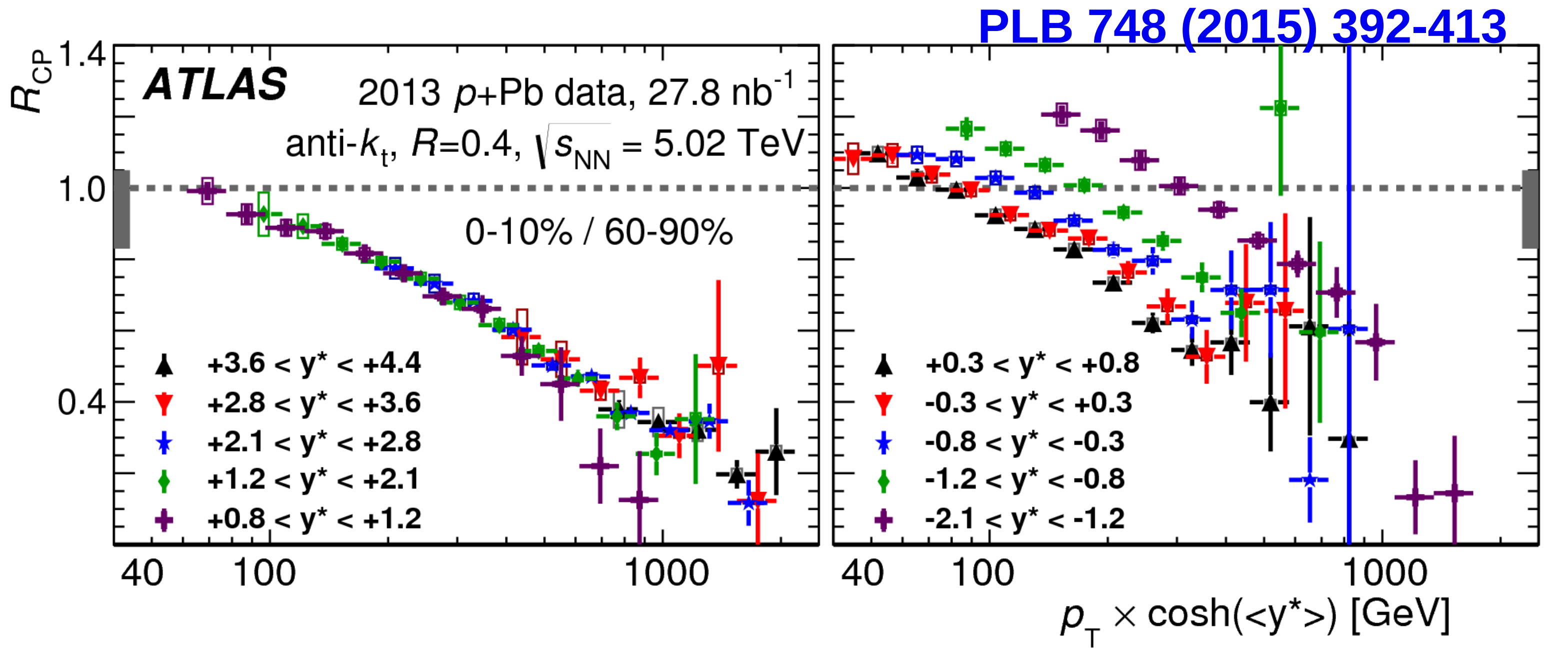


High p_T

$z = p_T/E_{jet}$

Low p_T

Cold Nuclear Matter effects

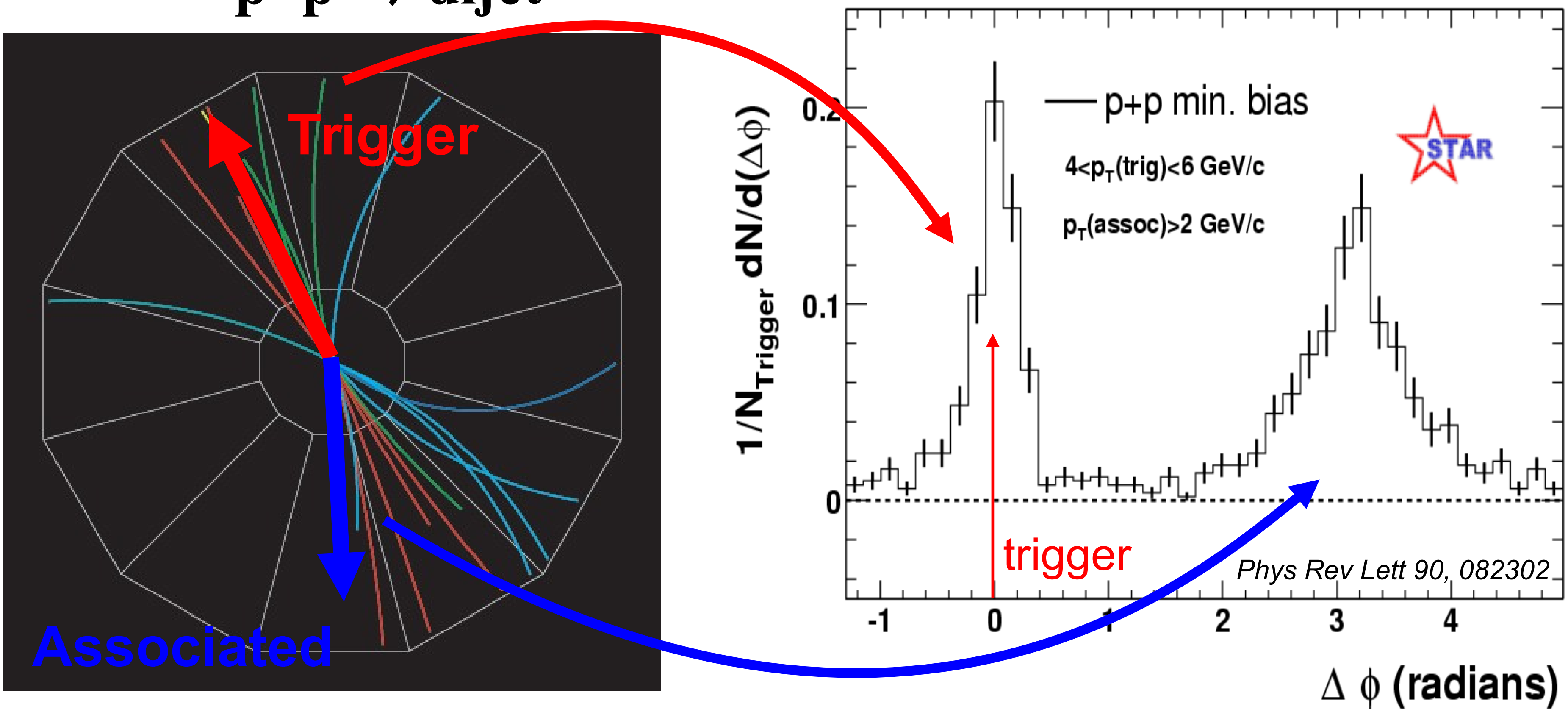


- No indication of modified jet structure in cold nuclear matter (d+Au and p+Pb collisions) [Phys.Rev.C73:054903,2006, Phys.Rev.Lett.96:222301,2006]
- Minimum bias R_{pPb}, R_{dAu} for charged particles, jets consistent with 1 [Phys.Rev.Lett.98:172302,2007,Phys.Rev.C81:064904,2010,Phys. Rev. Lett. 110 (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)]

Path length dependence

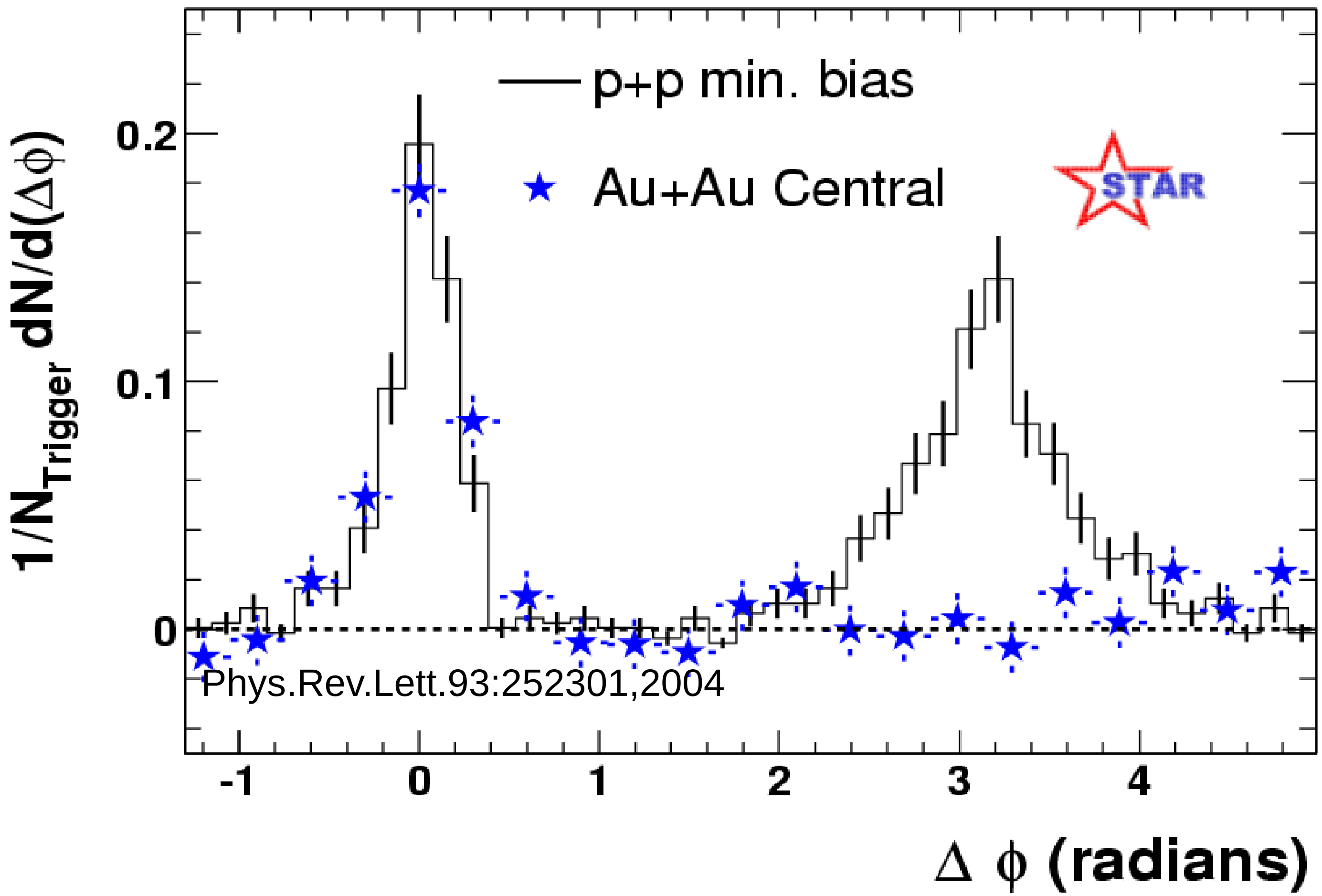
Jets – azimuthal correlations

p+p → dijet

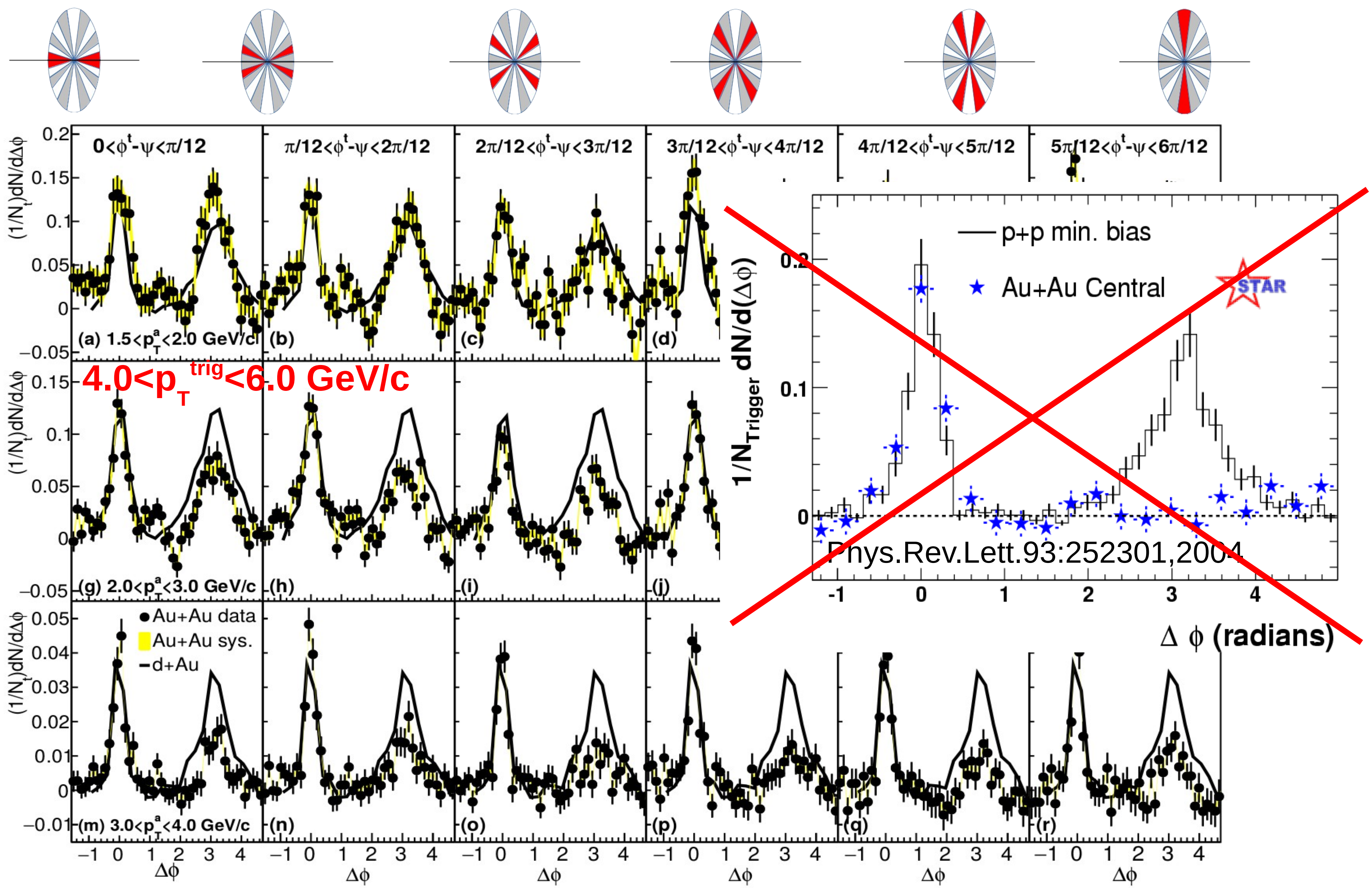


Select high momentum particles → biased towards jets

Azimuthal correlations

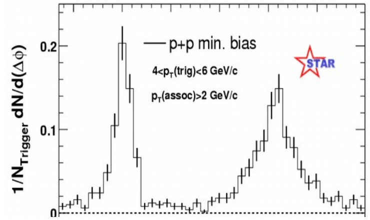


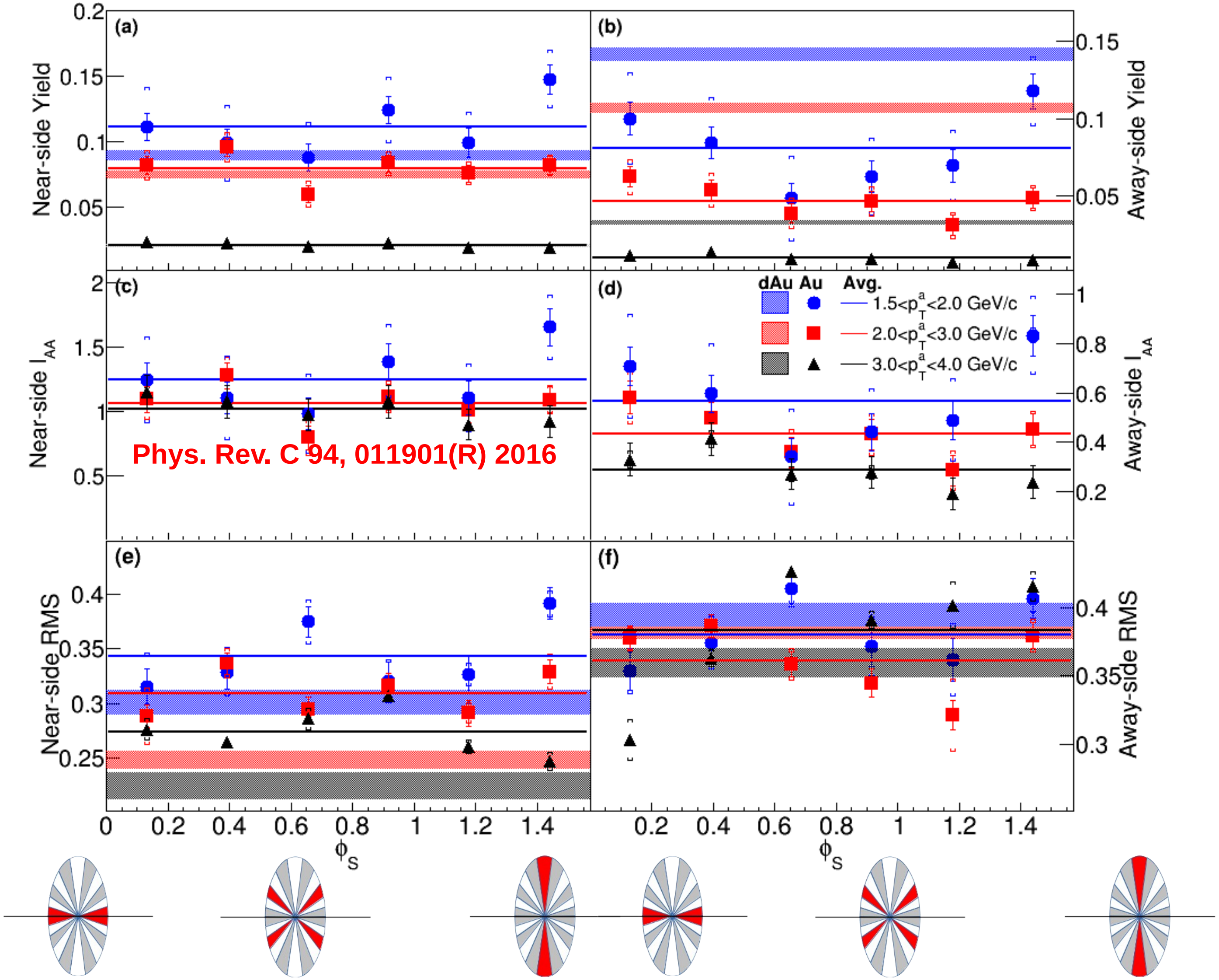
Dihadron correlations



Sharma, Mazer, Stuart, Nattrass: [(Phys. Rev. C 93, 044915 2016)]

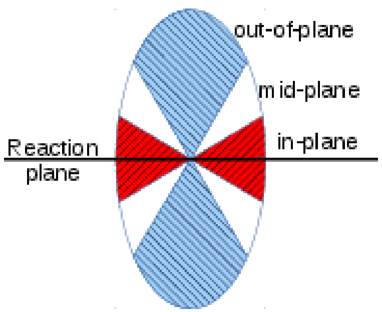
Dihadron correlations

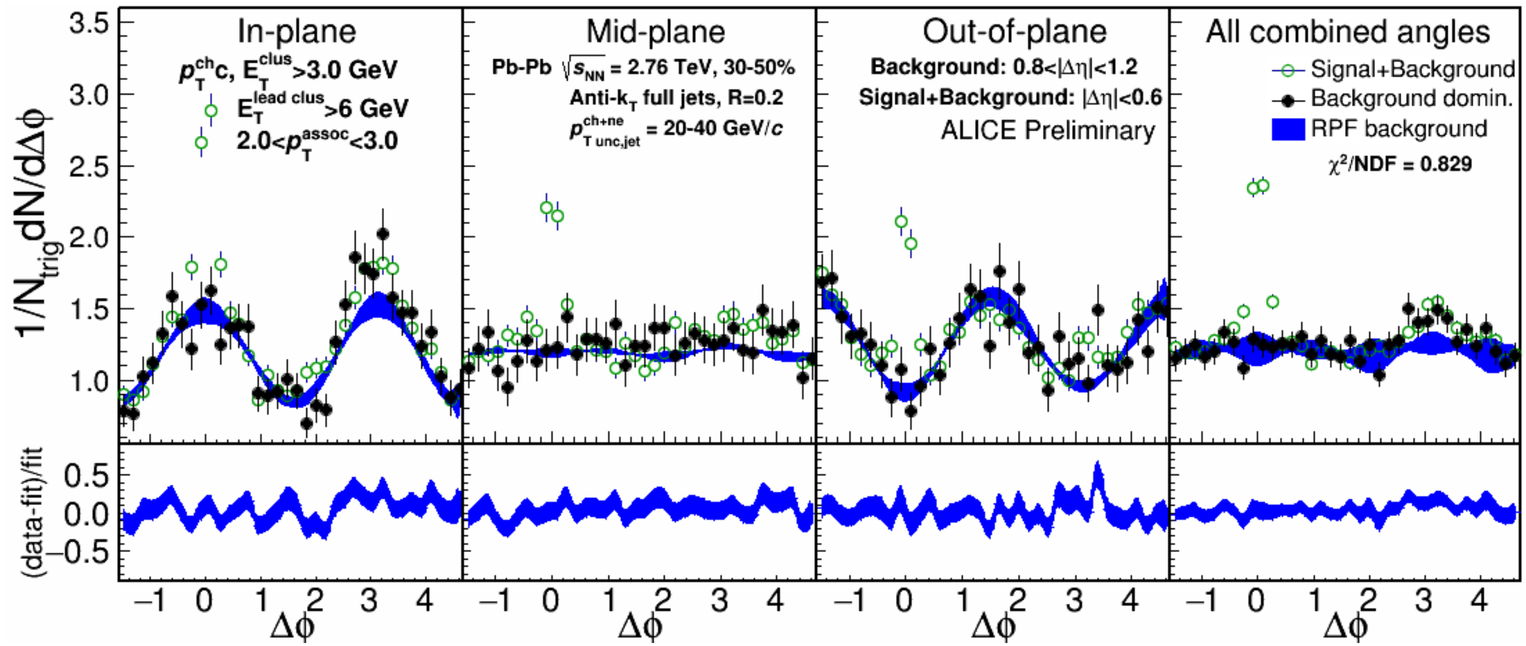




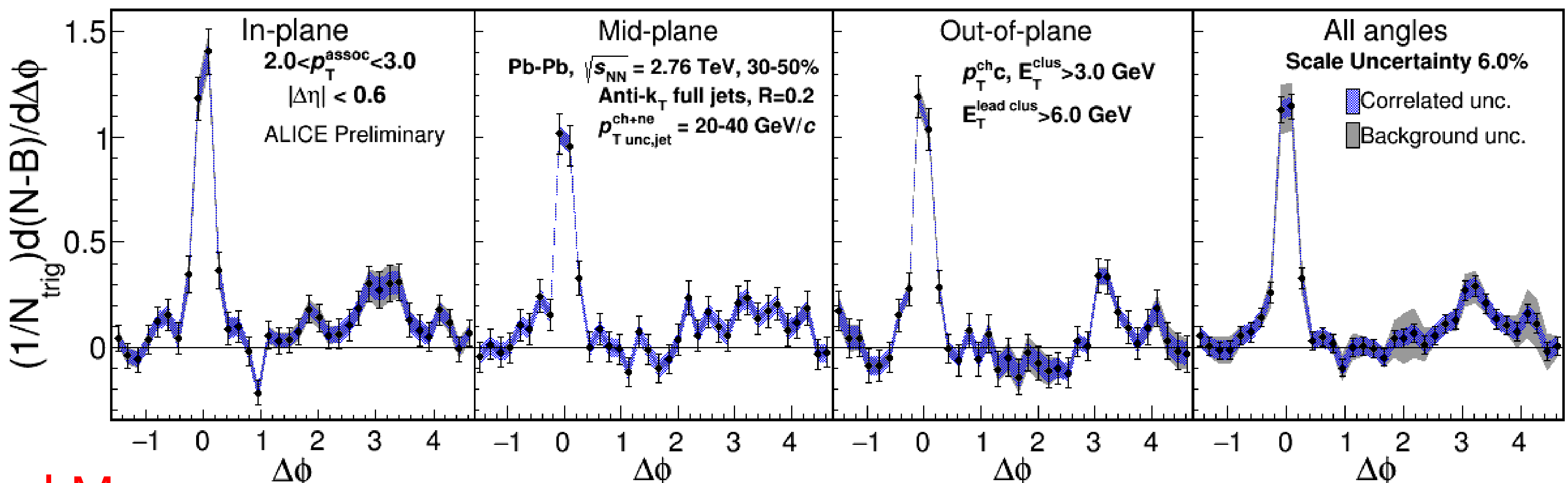
2.0-3.0 GeV/c p_T^{assoc}

1) signal+bkgrd
2) bkgrd dominated
3) bkgrd RPF fit





Correlation function



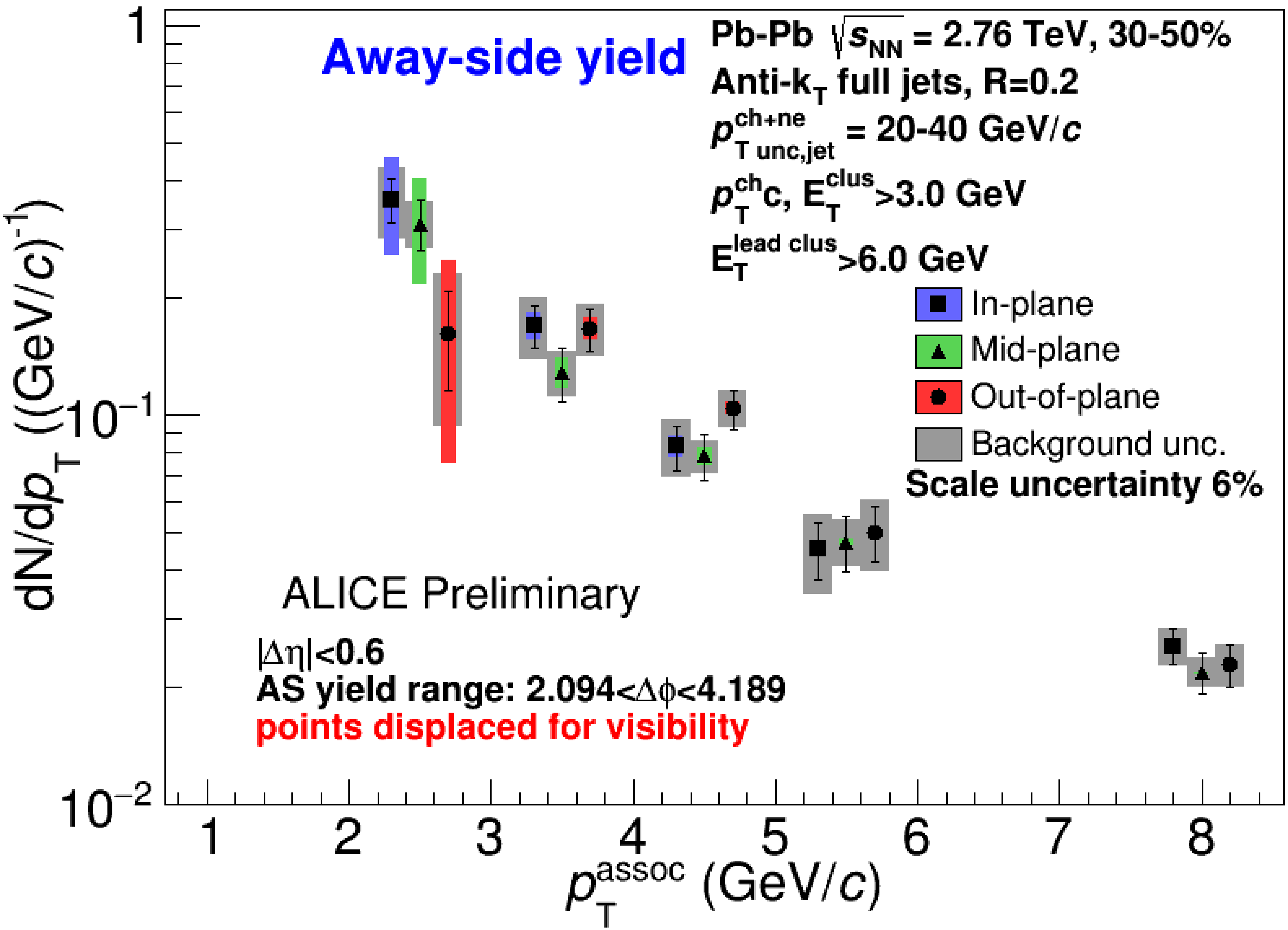
Joel Mazer
Hot Quarks 2016

- Away side clearly there and suppressed

44

Away-side jet yields vs EP

Jets 20-40 GeV/c, 30-50% centrality



Within uncertainties of current statistics, no event plane ordering

- Different effects in different p_T associated bins

Competing effects
1) Quenching
2) Bremsstrahlung
3) etc

Joel Mazer
Hot Quarks 2016

Little/no path length dependence?

- Path length dependence naively predicted by every model
  - No path length dependence seen in rxn plane dependent A_j either
- Insufficient sensitivity?
- Statistical variation in energy loss is more important than path length dependence
  - J. G. Milhano and K. C. Zapp, “Origins of the di-jet asymmetry in heavy ion collisions,” arXiv:1512.08107
  - F. Senzel, O. Fochler, J. Uphoff, Z. Xu, and C. Greiner, “Influence of multiple in-medium scattering processes on the momentum imbalance of reconstructed di-jets,” J. Phys. G42 no. 11, (2015) 115104, arXiv:1309.1657 [hep-ph].

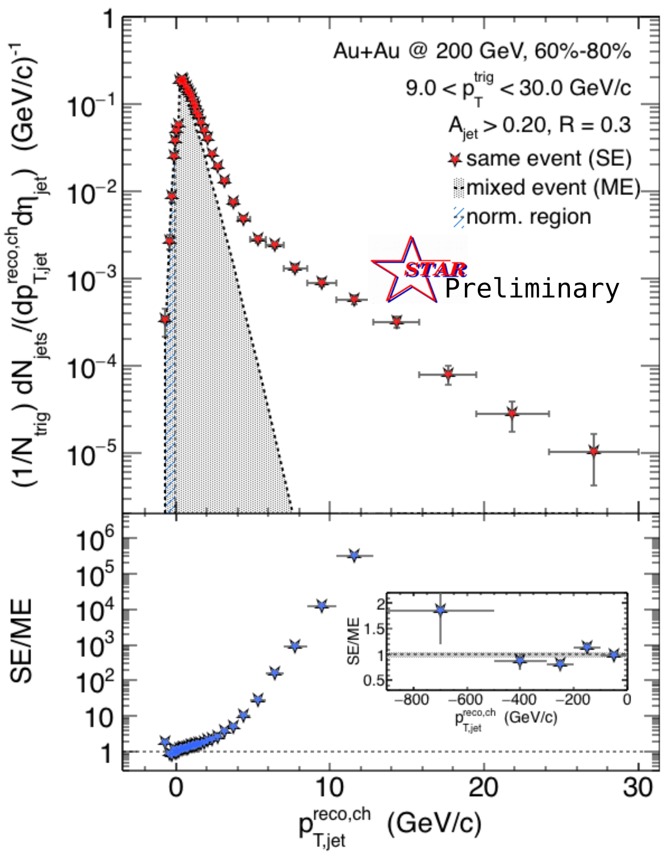
Conclusions

- 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 for 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

Event mixing

Peripheral

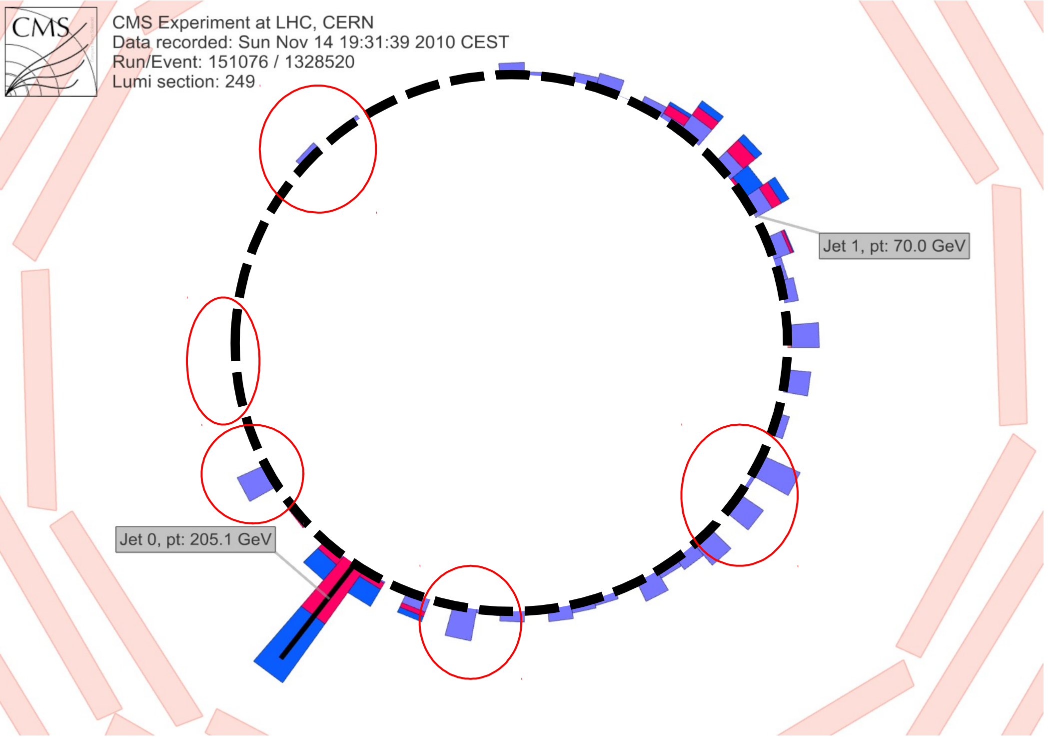


- Reference spectrum: peripheral collisions
- Much less combinatorial background compared to most central data
- Excellent signal/background ratio down to 3 GeV/c
- Requires normalization at low p_T
- All physical correlations treated like jets

Alex Schmah, Hard Probes 2015

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



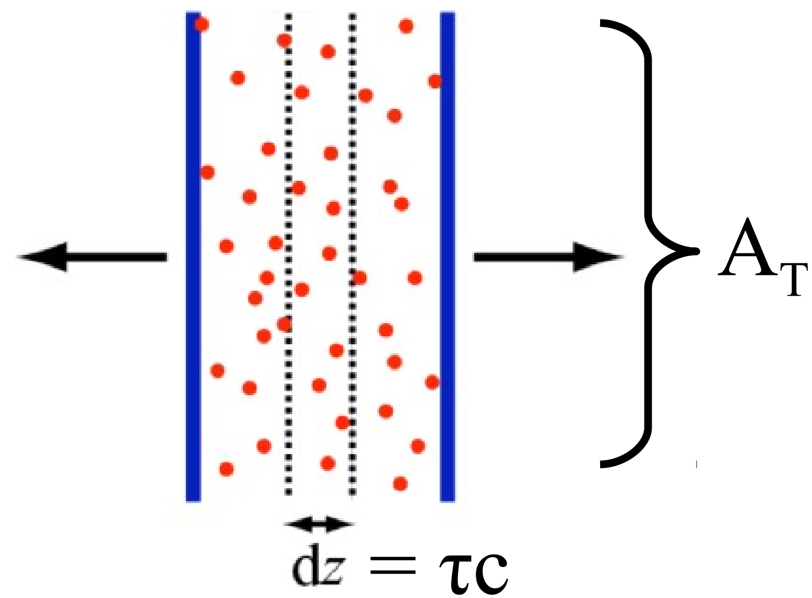
Fake Jets: After the background subtraction, some local fluctuations remain!
Fluctuations will deteriorate the jet resolution in central events.

Sevil Salur 49

QGP Energy Density

How can we estimate the energy density?

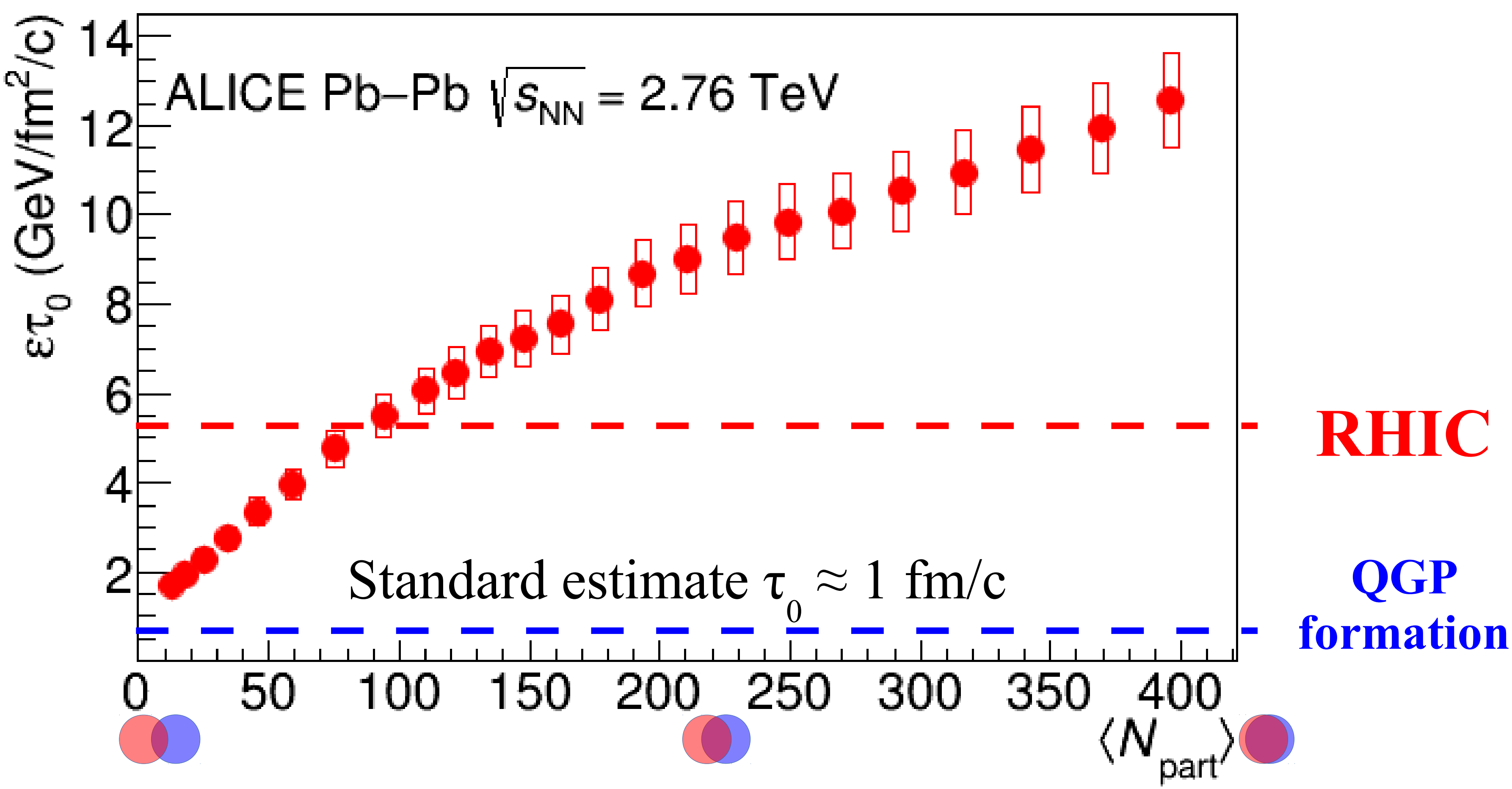
- Transverse energy (E_T)
  - sum of particle energies in transverse direction
- Volume $V = A_T \tau c$
- τ = formation time
- Energy density ε



$$\epsilon = \frac{1}{V}\frac{dE_T}{dy} = \frac{J}{A_T \tau c}\frac{dE_T}{d\eta}$$

- QGP formation for $\varepsilon > 0.5$ GeV/fm^3

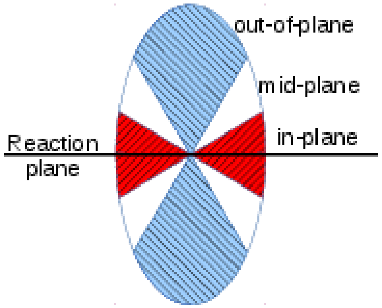
Energy density

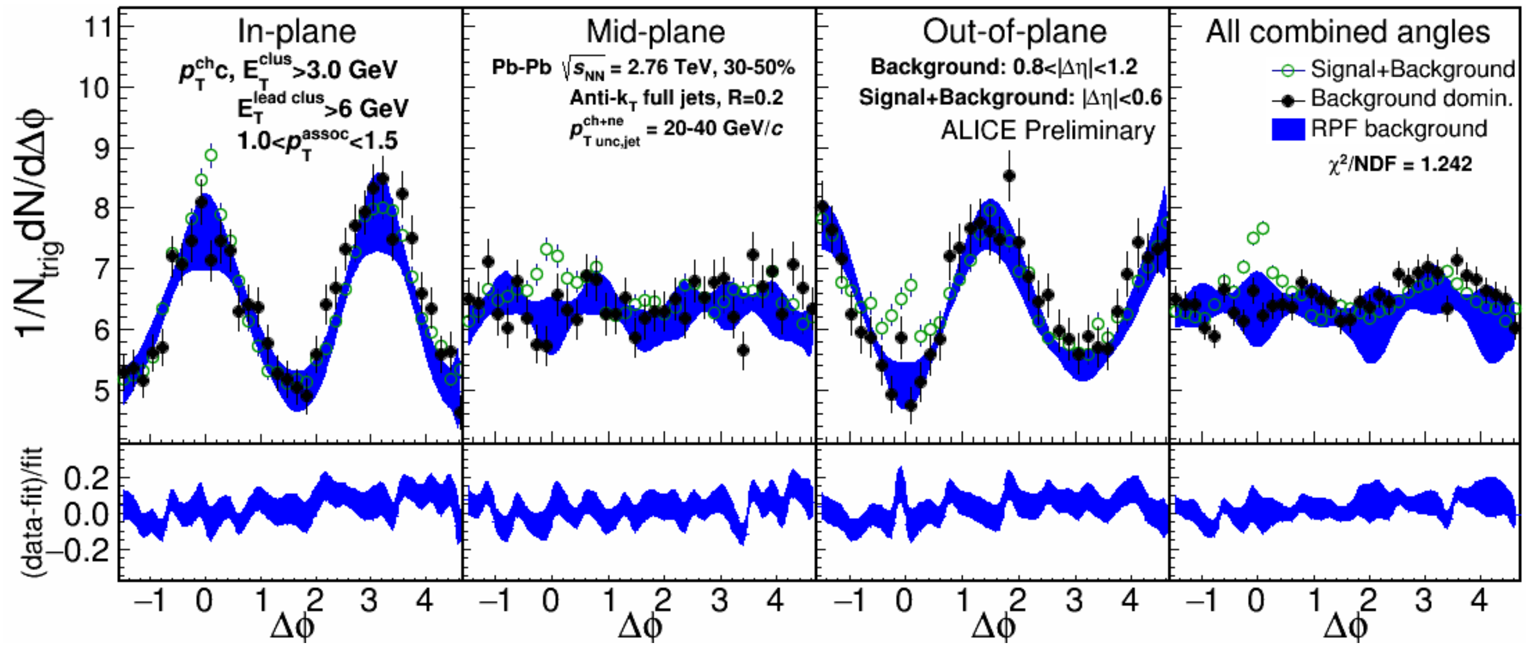


$$\epsilon = \frac{1}{A c \tau_0} \frac{dE_T}{dy}$$

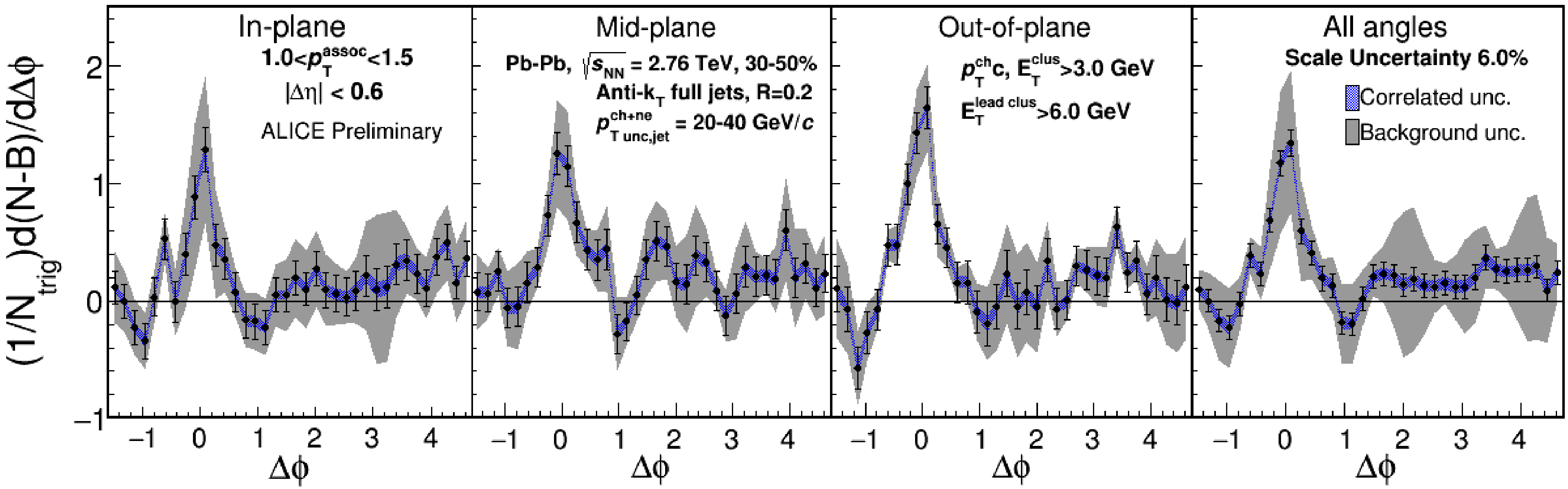
1.0-1.5 GeV/c p_T^{assoc}

1) signal+bkgrd
2) bkgrd dominated
3) bkgrd RPF fit





Correlation function

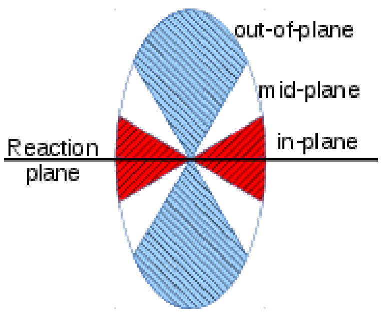


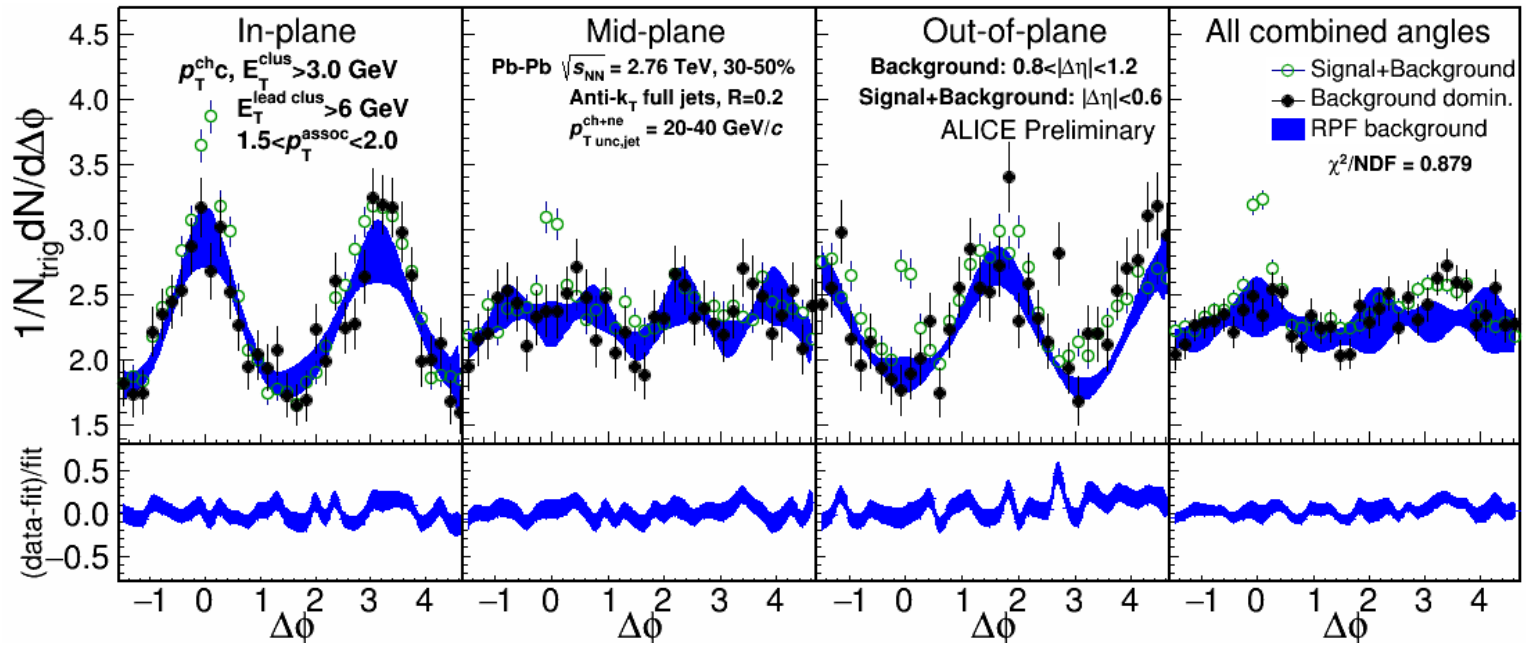
- Uncertainties dominated by statistics
- Background uncertainty is non-trivially correlated point-to-point

53

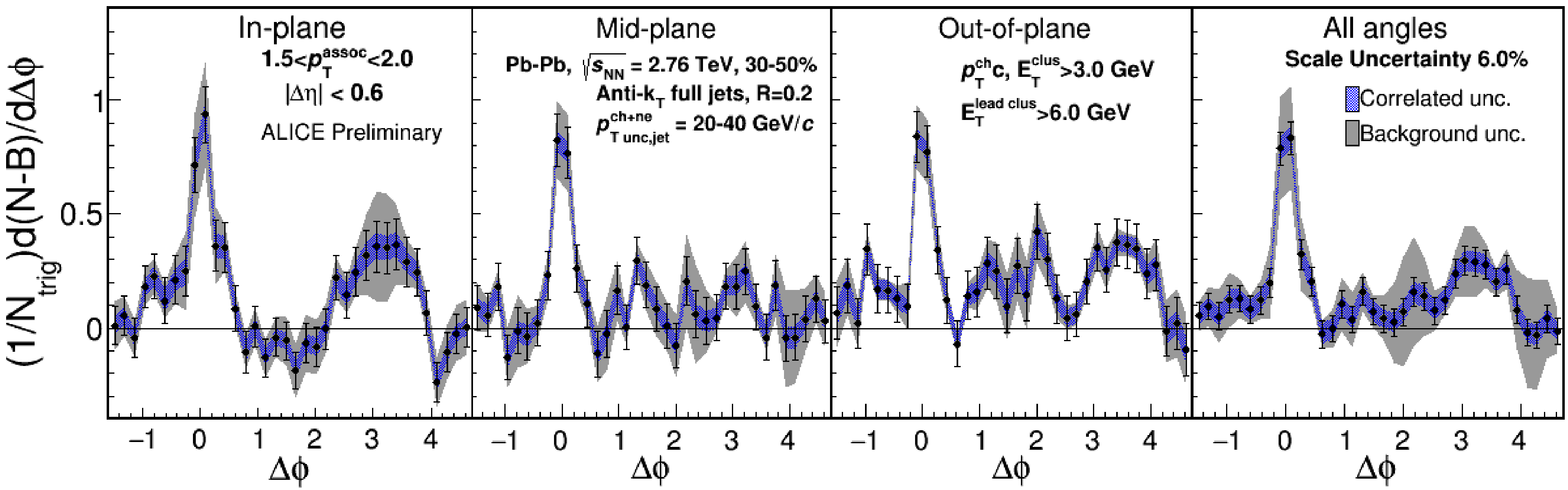
1.5-2.0 GeV/c p_T^{assoc}

1) signal+bkgrd
2) bkgrd dominated
3) bkgrd RPF fit





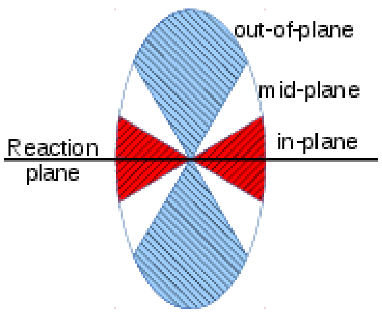
Correlation function

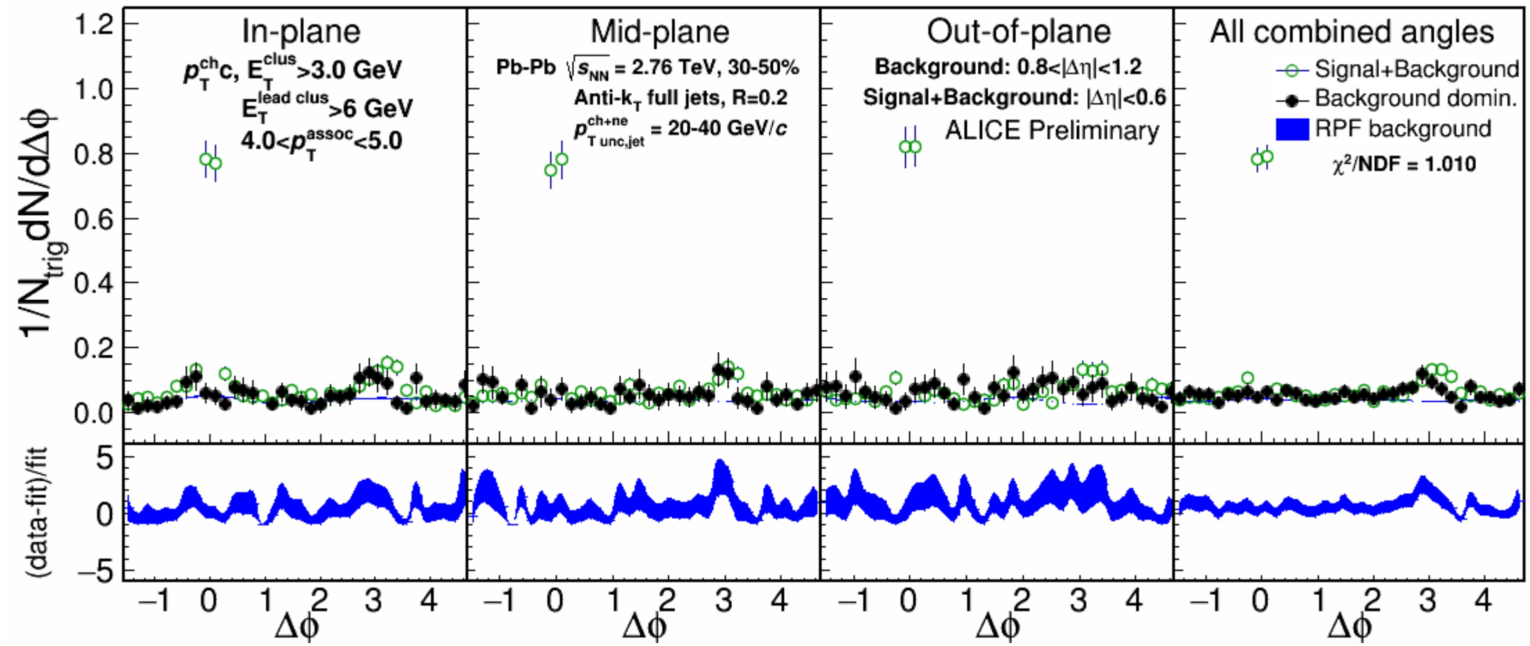


- v_3 and v_4 components important
- Background uncertainty is non-trivially correlated point-to-point

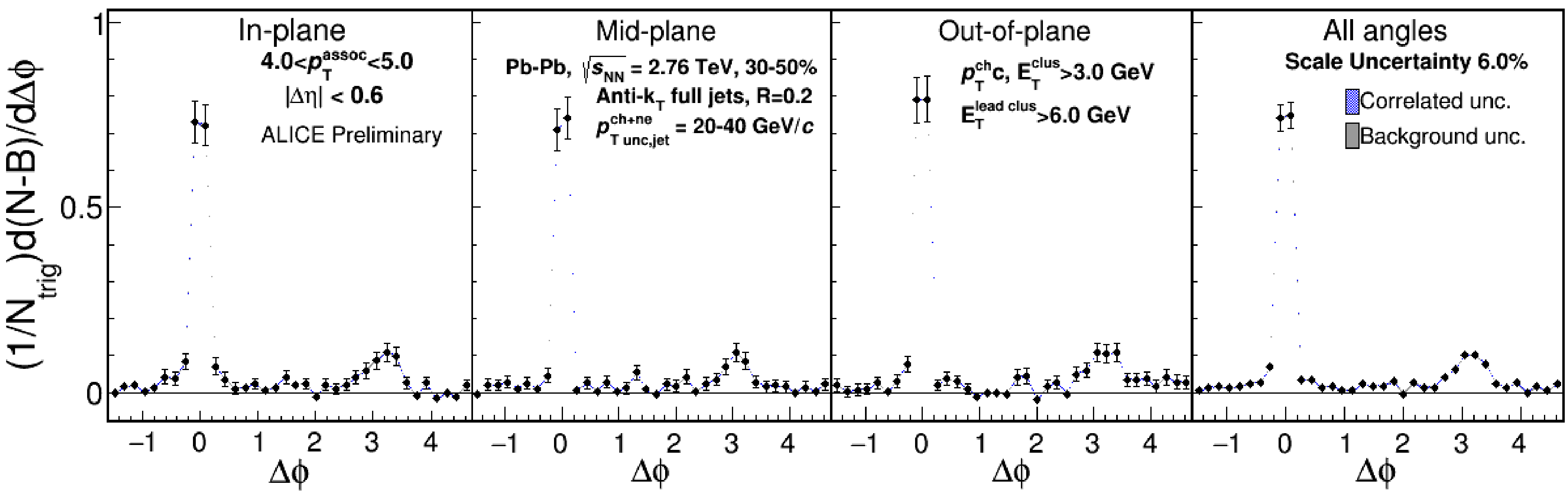
4.0-5.0 GeV/c p_T^{assoc}

1) signal+bkgrd
2) bkgrd dominated
3) bkgrd RPF fit





Correlation function

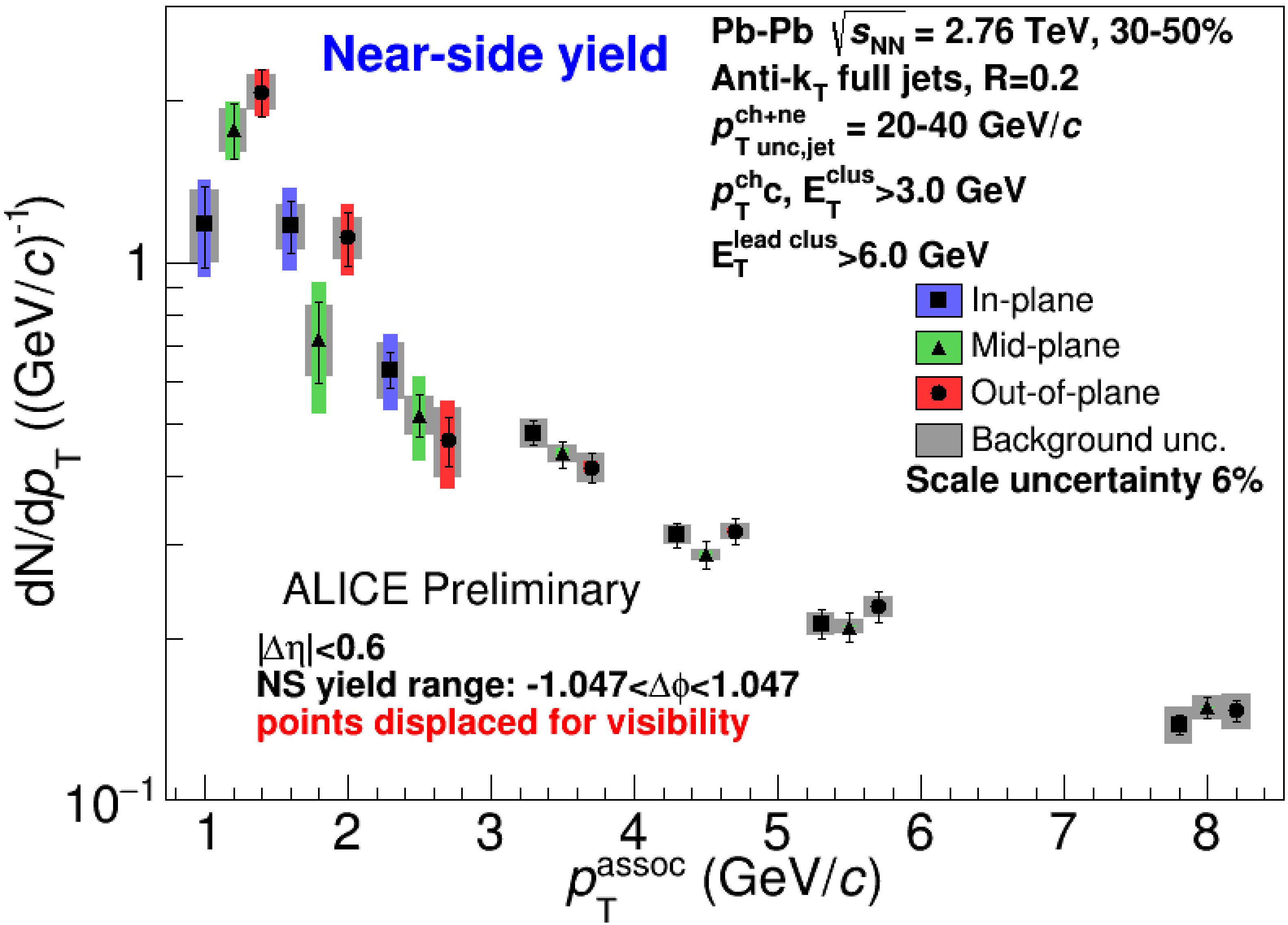


- Background level negligible

55

Near-side jet yields vs EP

Jets 20-40 GeV/c, 30-50% centrality

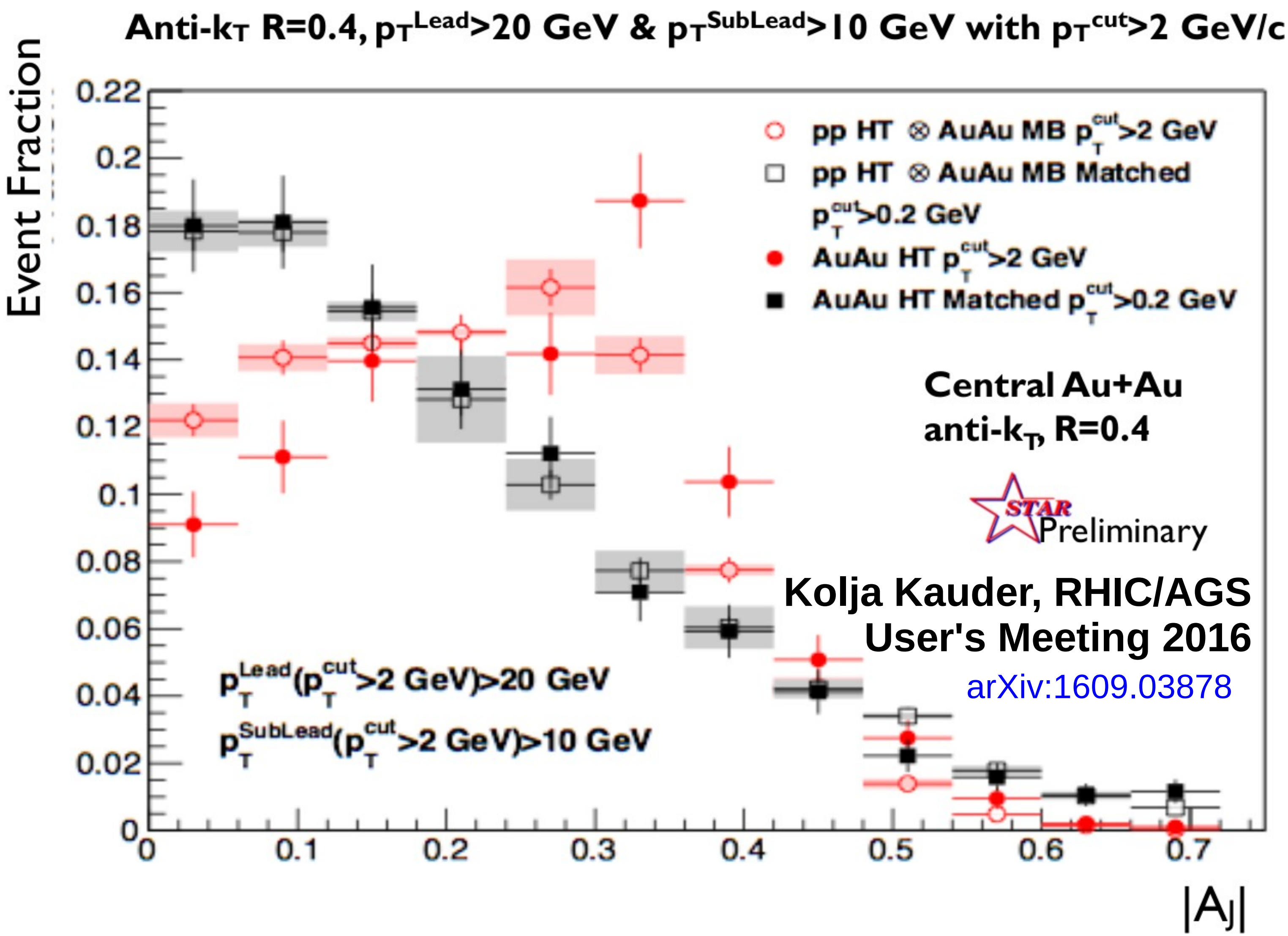


Within uncertainties of current statistics, no event plane ordering

- Different effects in different p_T associated bins

  Competing effects
  1) Quenching
  2) Bremsstrahlung
  3) etc

Di-jet asymmetry

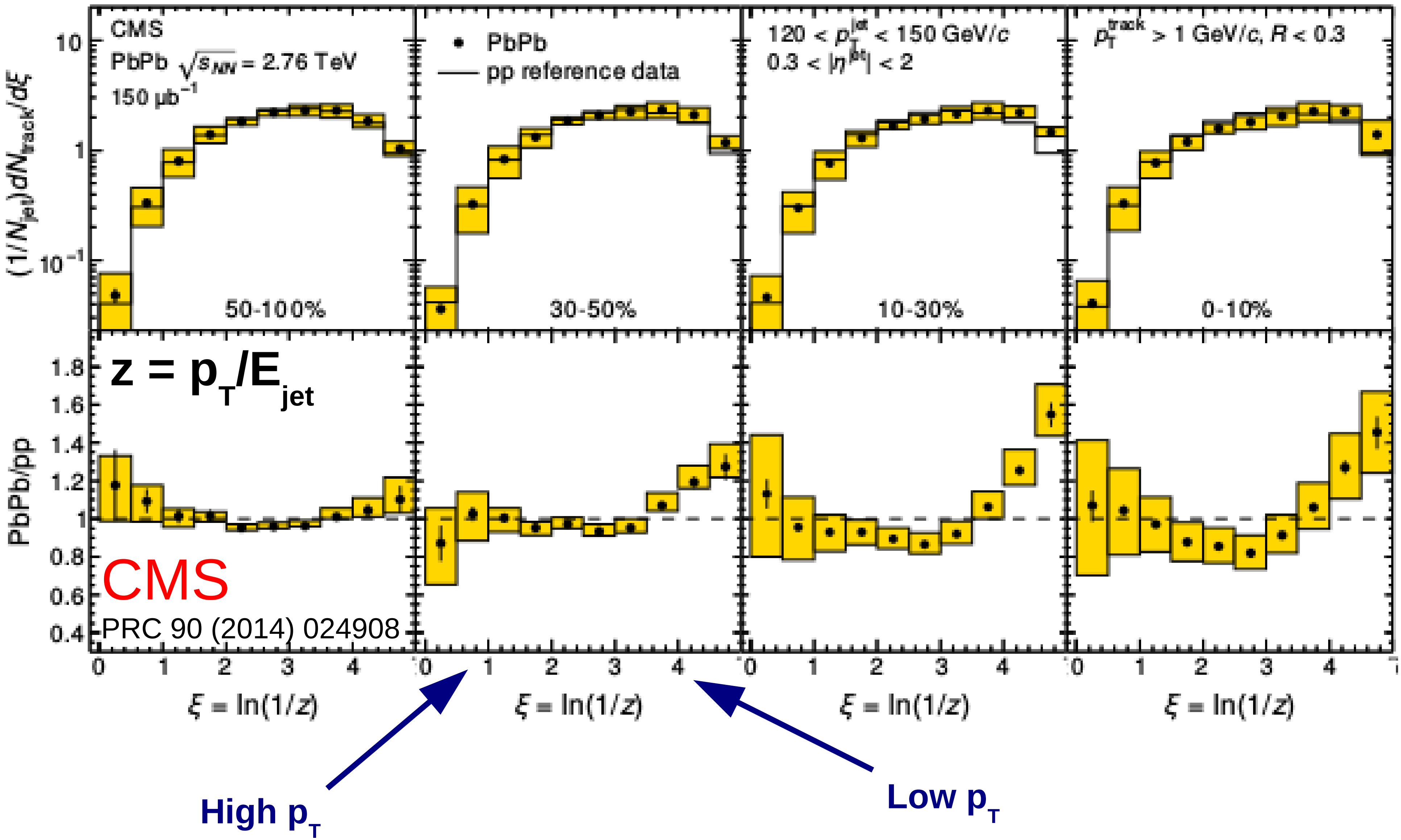


Sys. Uncertainties:
- tracking eff. 6%
- tower energy scale 2%

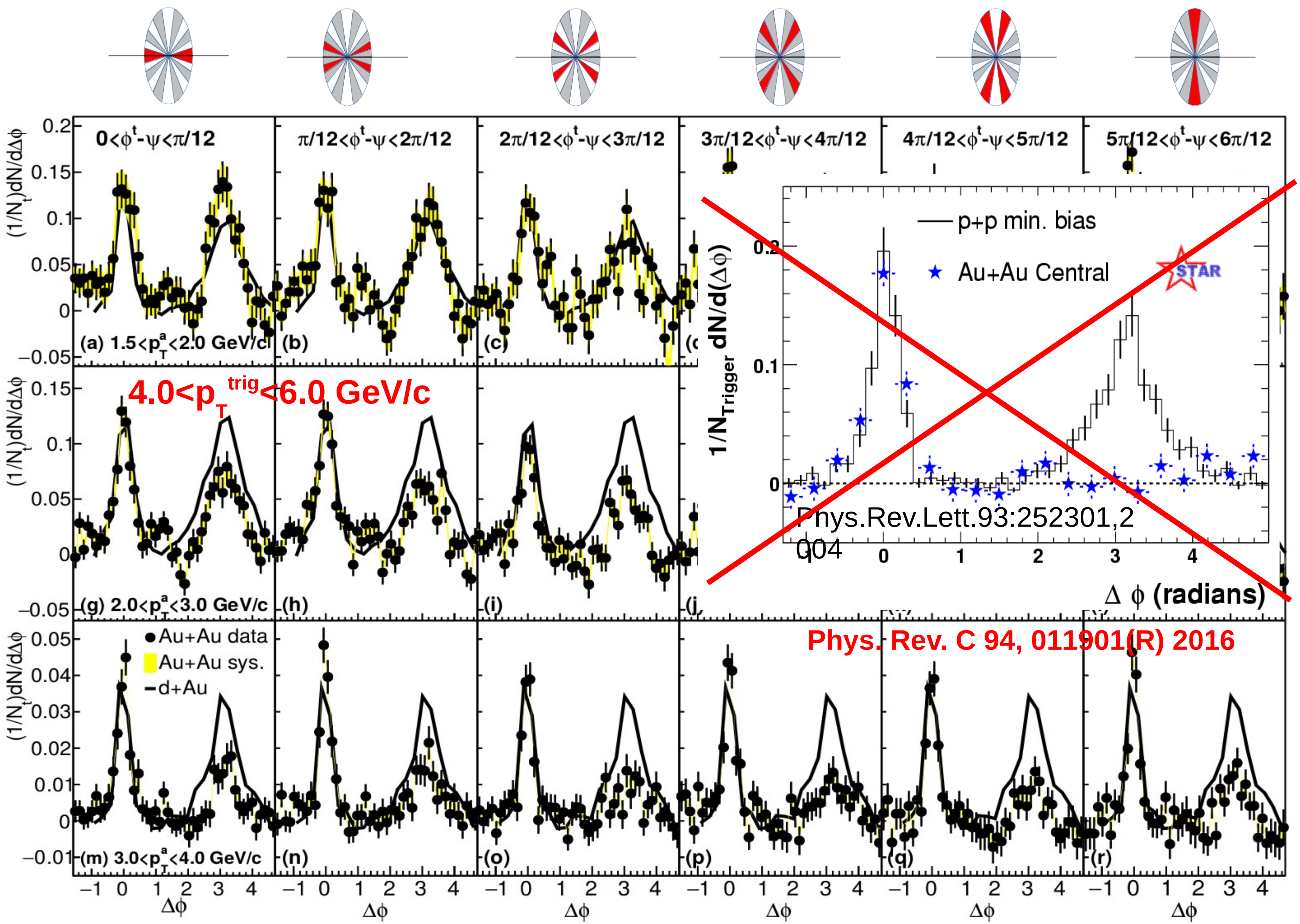
Au+Au di-jets more imbalanced than p+p for p_{Tcut}>2 GeV/c

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

Fragmentation functions



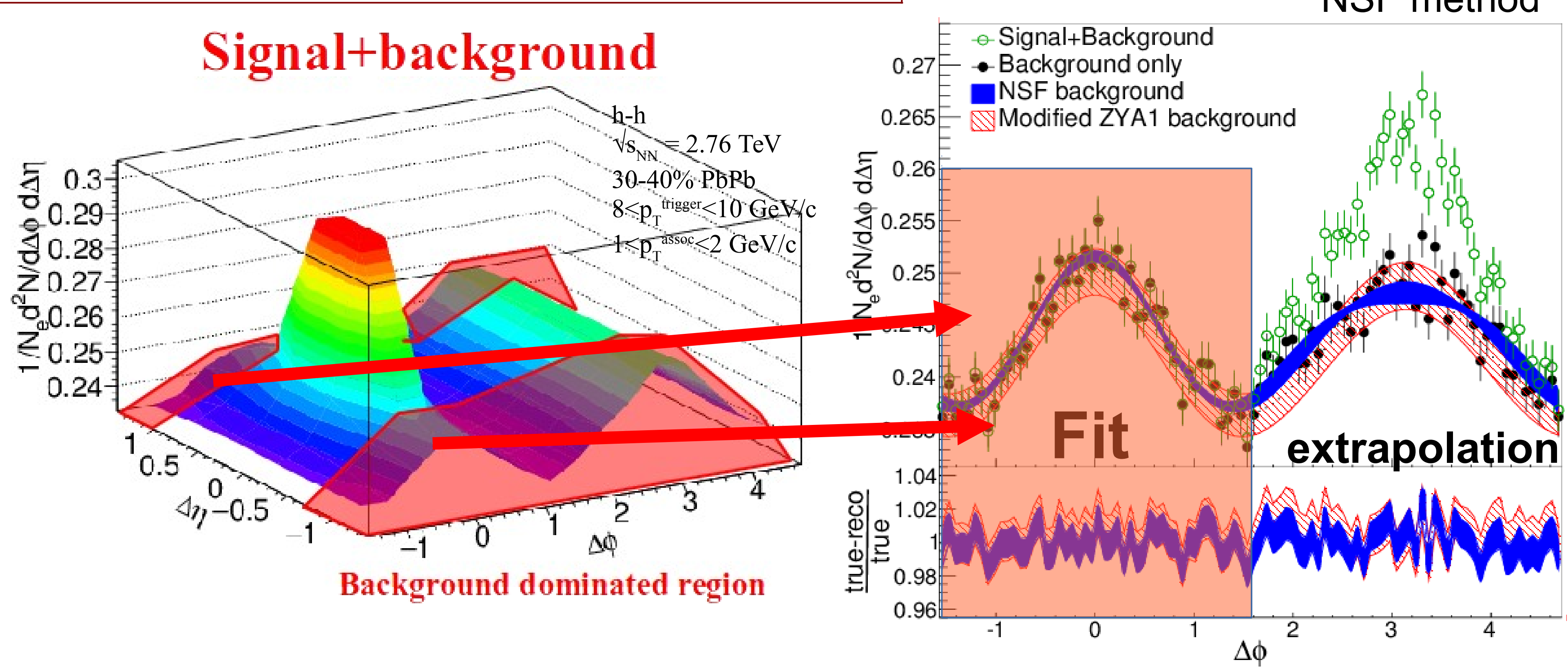
Dihadron correlations



Reaction plane fit (RPF) method

TOY MODEL

- Signal is negligible at large Δη and small ΔΦ region.



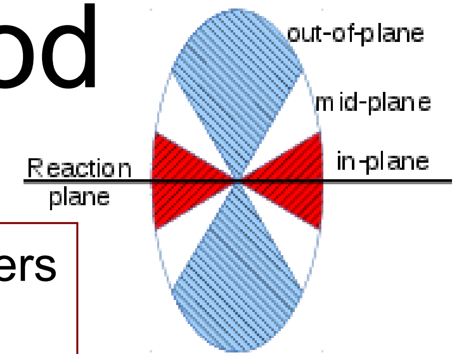
- Project signal+background over $0.8 < |\Delta\eta| < 1.2$
- Fit background in $|\Delta\varphi| < \pi/2$
- Fitting till 4th order v_n term, total 6 fit parameters: B, v_2^{assoc}, v_2^{trig}, $v_3^{assoc} \times v_3^{trig}$, v_4^{assoc}, and v_4^{trig}

Sharma, Mazer, Stuart, Nattrass: (Phys. Rev. C 93, 044915 2016)

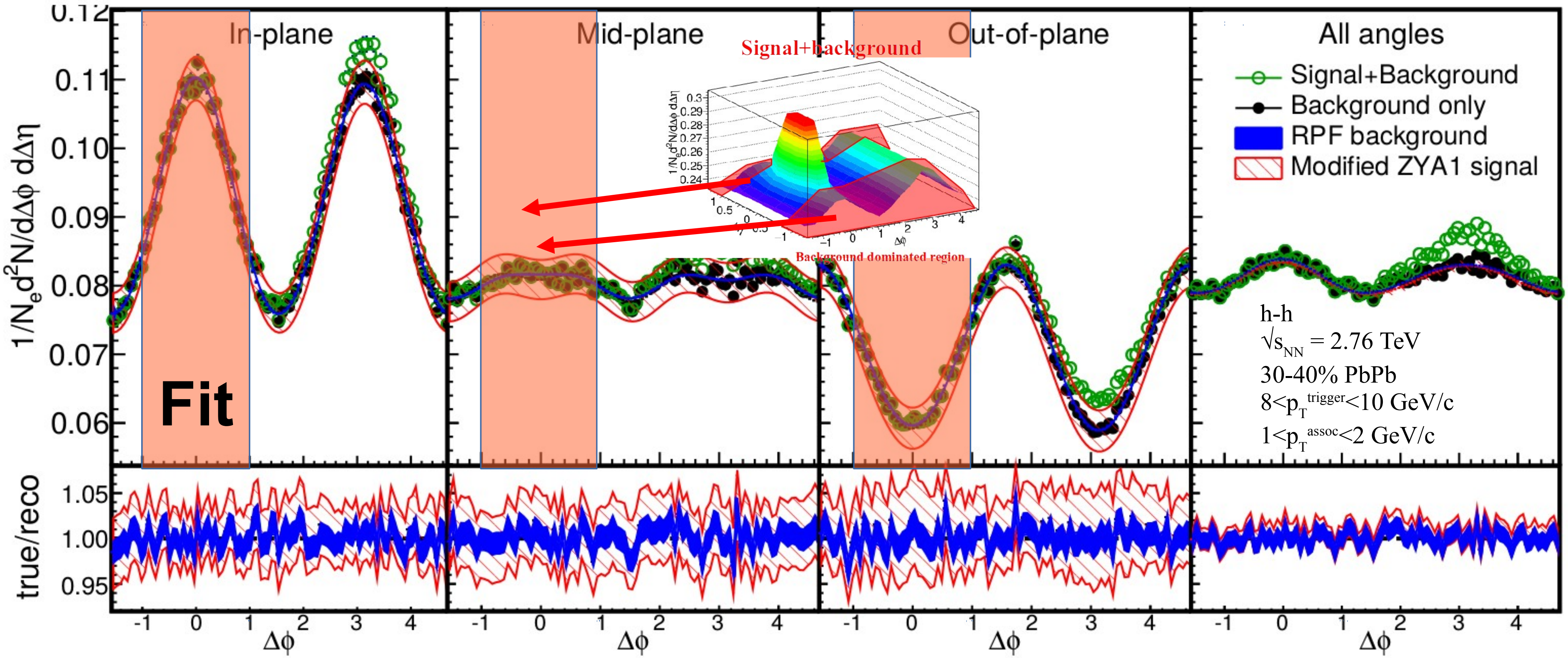
Nattrass, Sharma, Mazer, Stuart, and Bejnood: (Phys. Rev. C 94, 011901(R) 2016)

Reaction plane fit (RPF) method

30-40% central (simulation) TOY MODEL



- Each orientation has different functional form, but require same parameters
- More robust method, now have a higher constrained background with more information going into fit



Project signal+background over $0.8<|\Delta\eta|<1.2$

- v_n and B extracted
- Fewer assumptions and bias than ZYAM while having much smaller errors