The Strongly Interacting Quark Gluon Plasma: New Energy Frontier

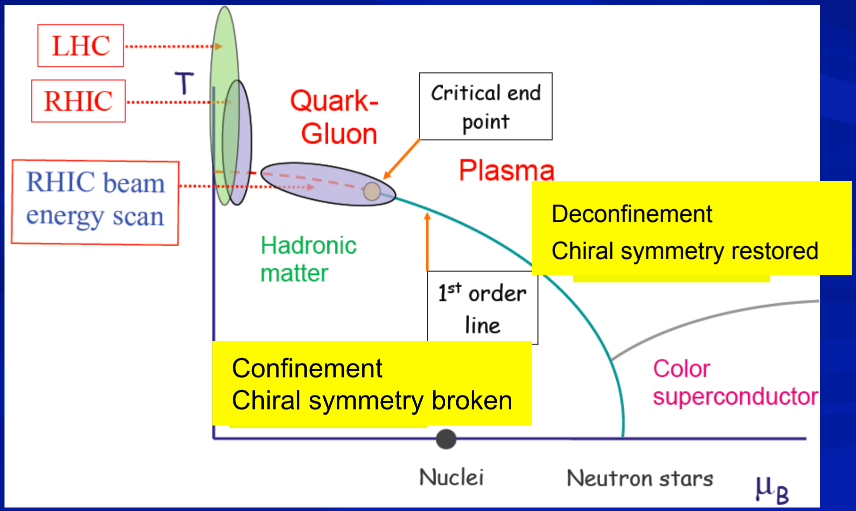
(personal view on a few topics)

ICFP, Kolymbari, Crete, June 10-16, 2012

Itzhak Tserruya

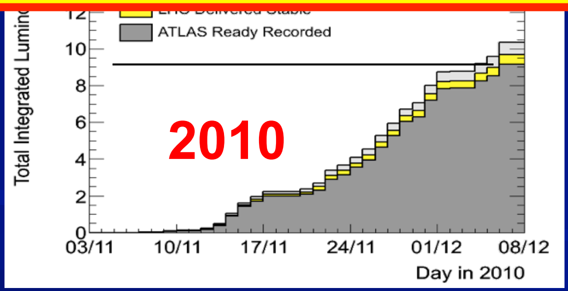
RHIC and LHC (I)

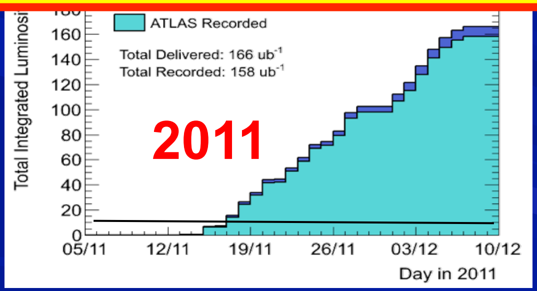
- Common goal - hunting the properties of the sQGP:
  - Equation of state – critical end point
  - Temperature
  - Transport properties: viscosity, speed of sound ...
  - Parton energy loss
  - CSR – the origin of the QCD mass
  - Debye screening radius and deconfinement
  - …



RHIC and LHC (I)

- RHIC: Very successful dozen years of operation.
  - Very flexible machine: pp, dAu, CuCu, AuAu, CuAu, UU
    $\sqrt{s_{NN}}$ = 7 – 200 GeV
    spin program with polarized p beams $\sqrt{s}$ = 200, 500 GeV
  - More than 330 papers in the refereed literature (of which 138 PRL papers).
- *The* question: how LHC results compare to what we have learned from RHIC ? What changes from RHIC to LHC ?
  - Obvious quantitative differences
  - **What is qualitatively different at LHC ?**



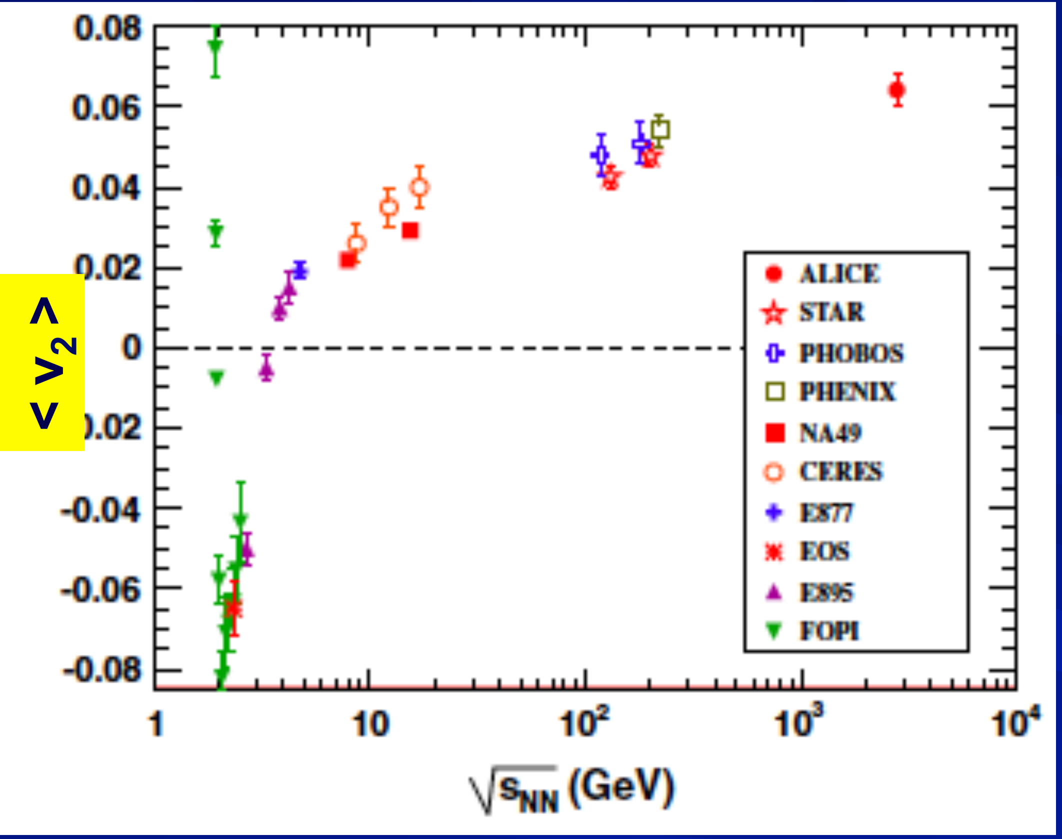


LHC Run	2010	2011
L_{int}	8 μb^{-1}	150 μb^{-1}
N_{evts} (mb)	30-40M	750-800M

Flow

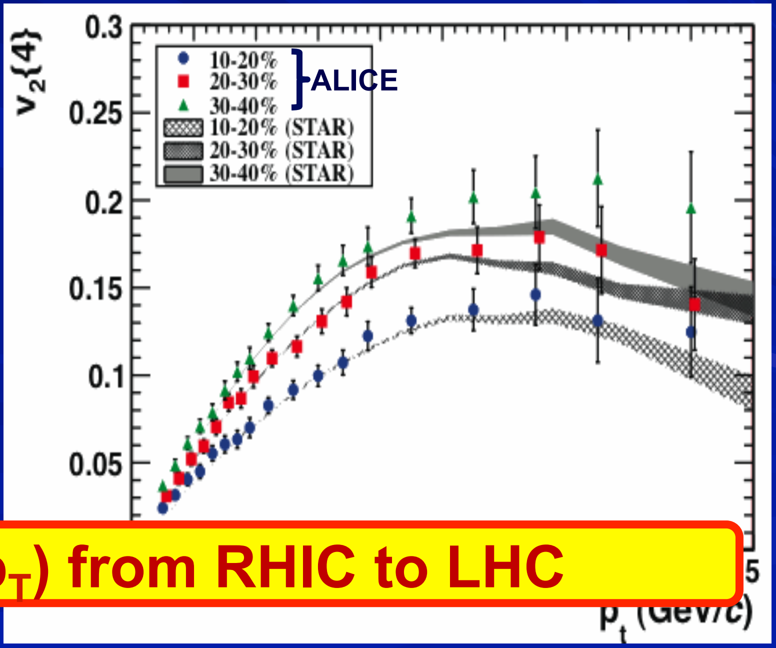
V_2 – Energy dependence

Preliminary, STAR, PHENIX and E895 data



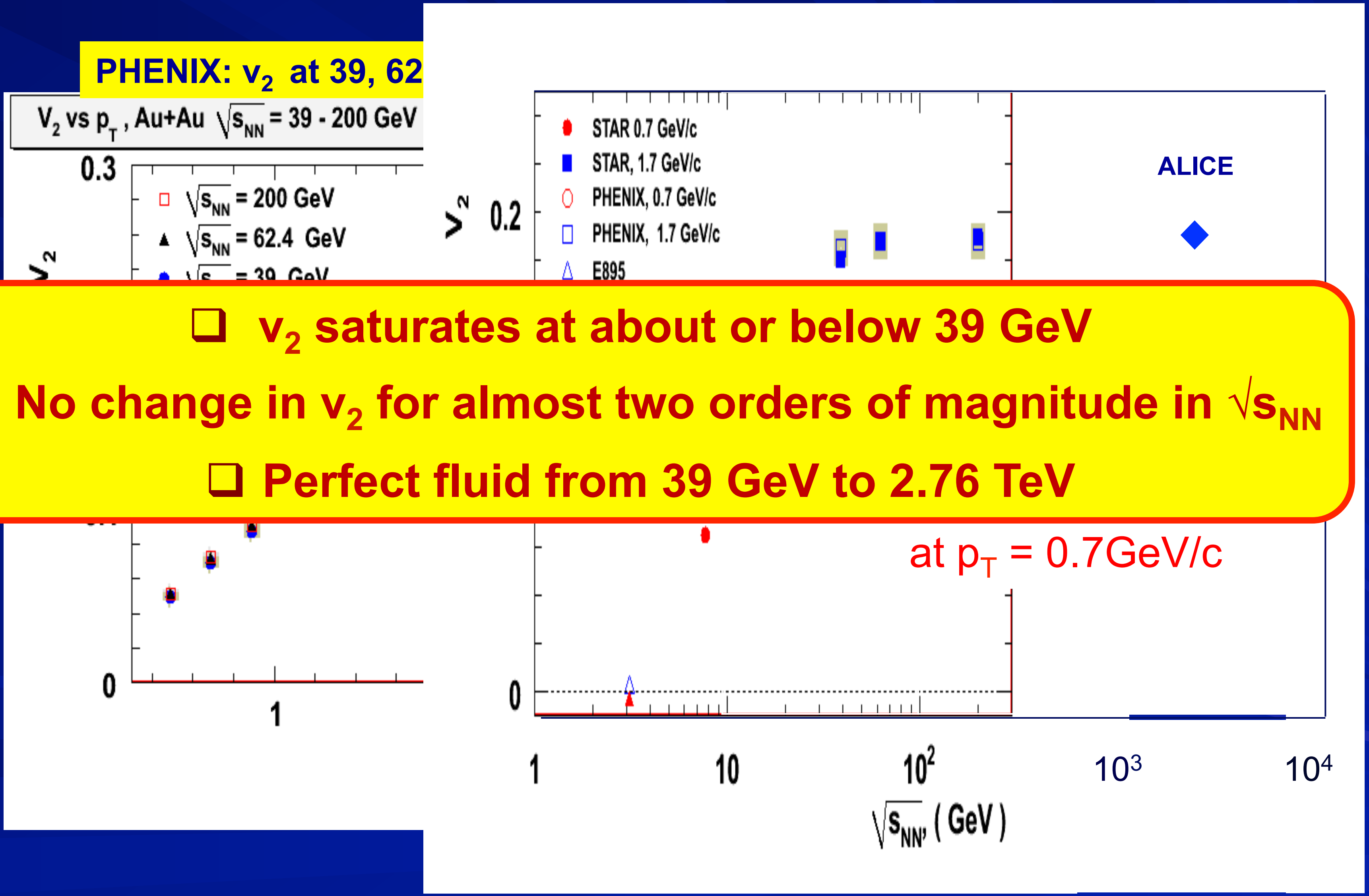
$$< v_2 > = \frac{\int N(p_T) v_2(p_T) dp_T}{\int N(p_T) dp_T}$$

- $<v_2>$ increases by ~20% from RHIC to LHC
- mainly because of the ~20% increase in $<p_T>$



- **no significant change in $v_2(p_T)$ from RHIC to LHC**

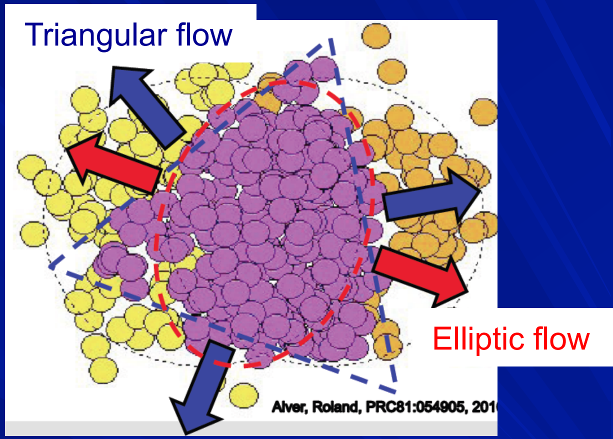
Same v_2 vs p_T from 39 GeV to 2.76 TeV



- ❑ v_2 saturates at about or below 39 GeV
- ❑ No change in v_2 for almost two orders of magnitude in $\sqrt{s_{NN}}$
- ❑ Perfect fluid from 39 GeV to 2.76 TeV

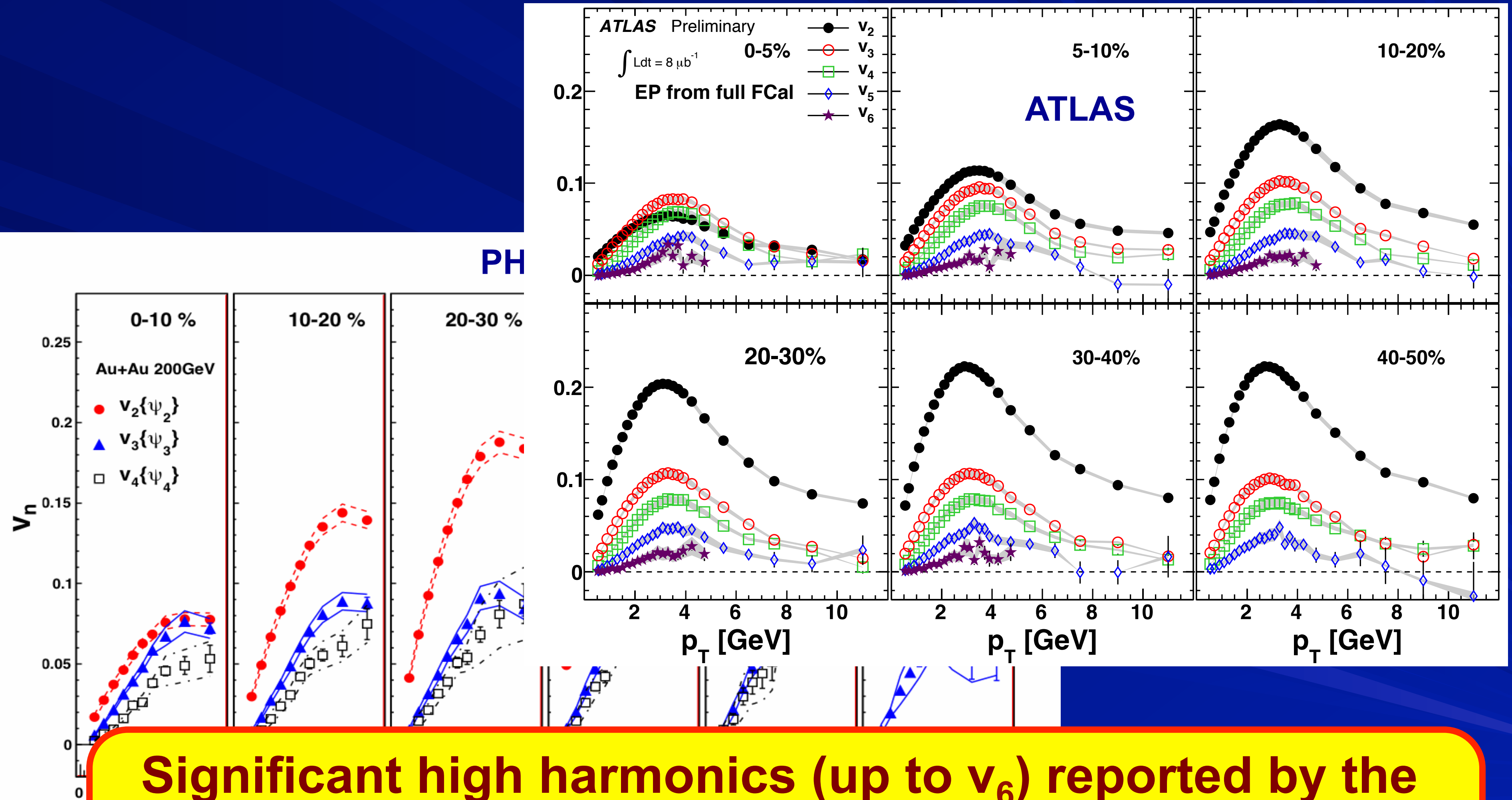
Flow: higher harmonics

$$\frac{d^2N}{d\phi dp_T} \propto 1 + 2\sum_{n=1}^{\infty} v_n(p_T)\cos[n(\phi - \psi_n)]$$



- Triggered by theoretical papers –Alver, Gambeaud, Luzum and Ollitrault, Phys. Rev. C82 (2010) and G-L Ma and X-N Wang arXiv: 1011.5249v2
- The five experiments demonstrated the importance of higher harmonics, and in particular the relevance of v_3 to constrain the η/s value.

Higher Harmonics: p_T dependence



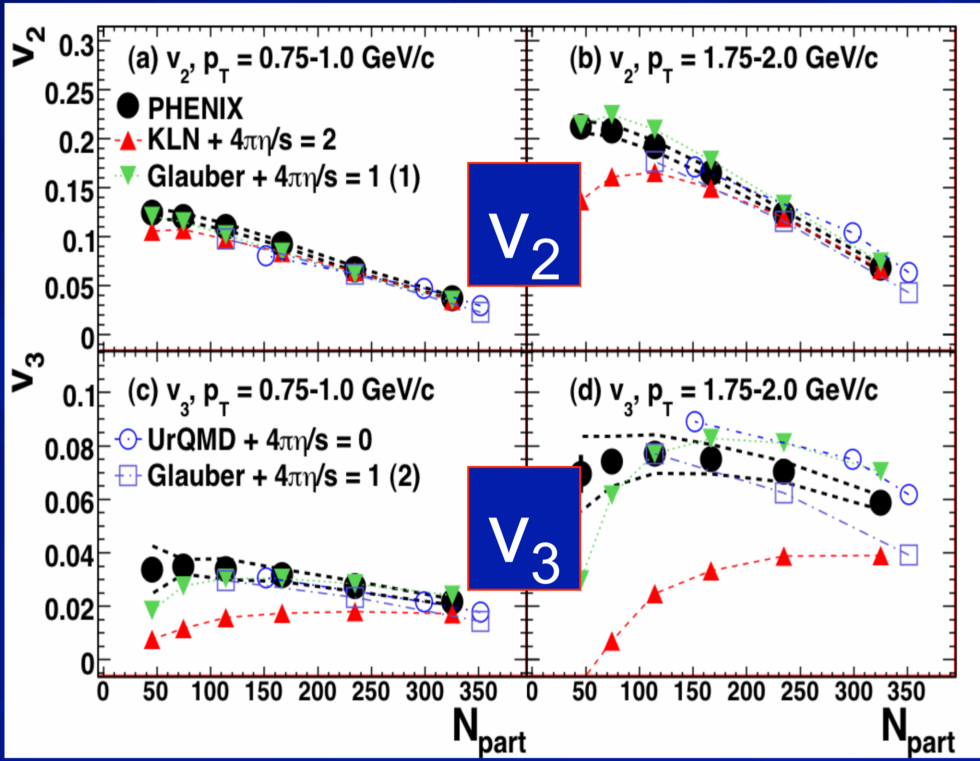
Significant high harmonics (up to v_6) reported by the five experiments over the past year

Same pattern for all n: rise to ~3 GeV then fall

η/s and triangular flow

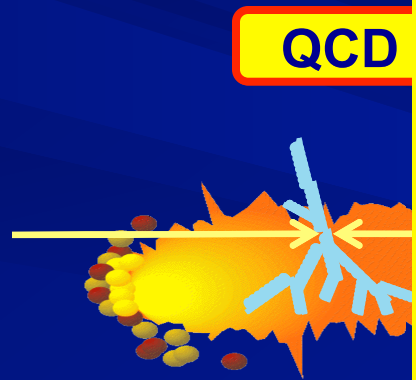
Conjectured Lower bound

- Using v_2 only, remarkable convergence $4\pi\eta/s = 1 - 2$
- Higher harmonics and v_3 in particular provide valuable additional constraints.



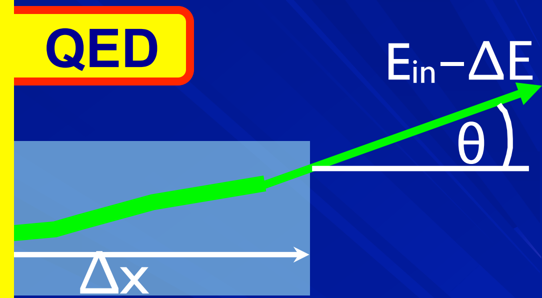
- PHENIX: v_3 seems to prefer low η/s
- The question is whether the η/s value at RHIC and LHC will be similar or not reflecting or not the same medium.

High p_T phenomena → Parton Energy Loss



Observables:

- Inclusive charged hadrons
- Identified hadrons
- Heavy Flavor
- Hadron correlations
- Di-Jets
- γ, Z, W - jet



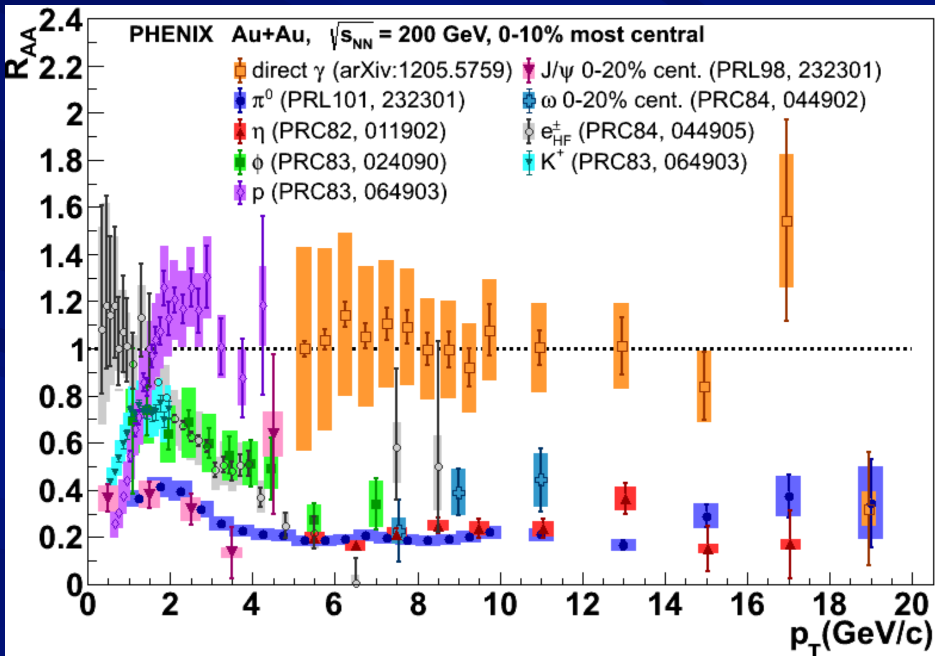
Goal: achieve same level of understanding for partons traversing strongly interacting matter (QCD) as for charged particles in matter (QED)

- Single Hadrons

R_{AA} and R_{CP}

$$R_{AA}(p_t) = \frac{d^2N_{AA}/dp_T d\eta}{N_{coll} d^2N_{pp}/dp_T d\eta}$$

Identified particles R_{AA} or R_{CP}



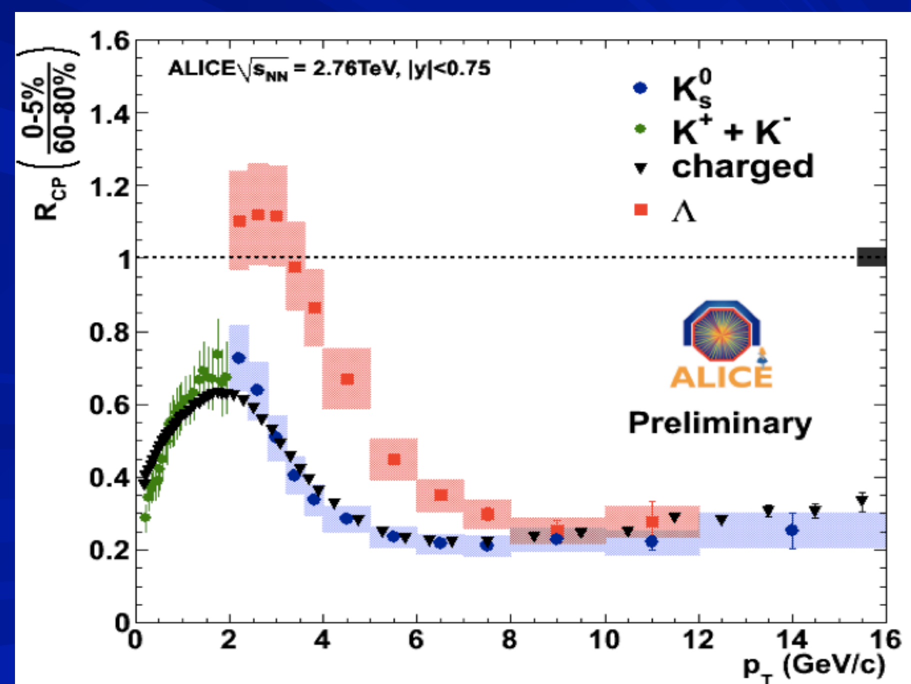
- Interesting hierarchy at low p_T in the suppression pattern observed at RHIC:

Lower R_{AA}

- baryons
- strange mesons, e_{HF}
- light quark (u,d) mesons

- All particles seem to exhibit the same suppression level at high p_T, larger than ~7 GeV/c

- Is the same pattern observed at LHC?



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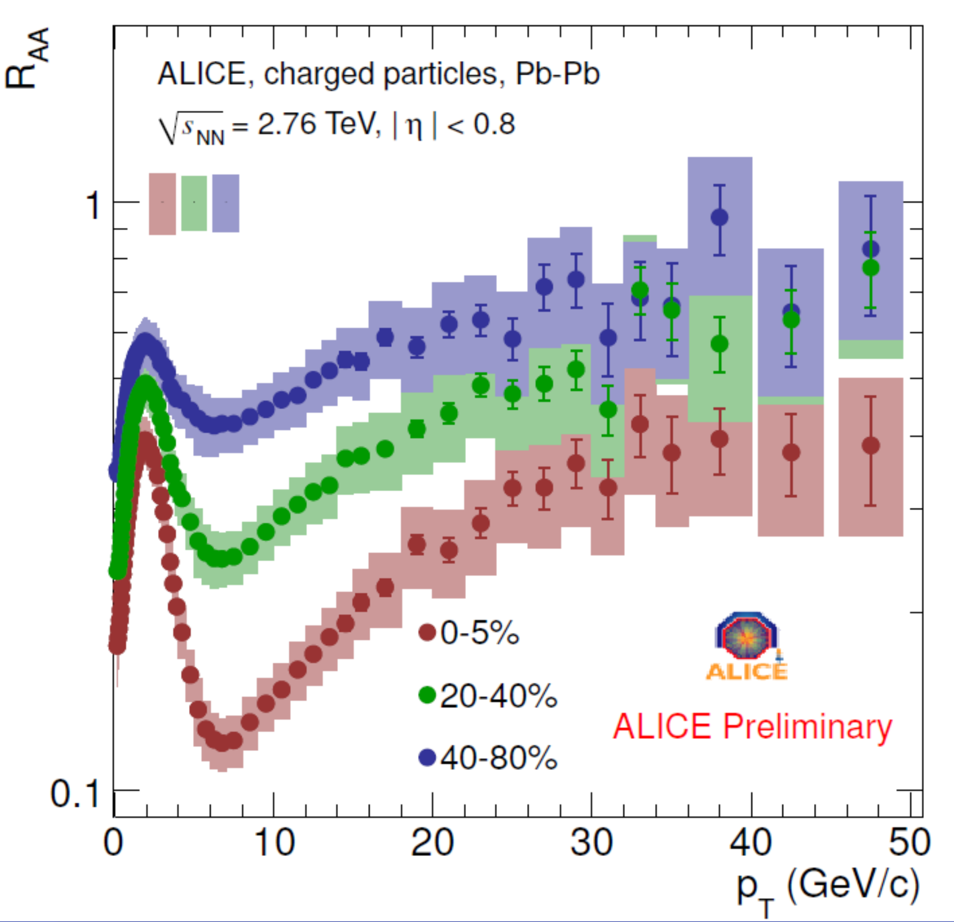
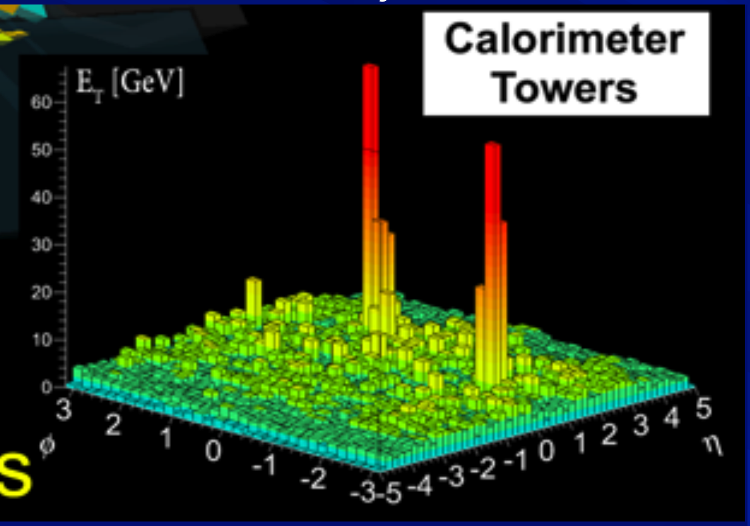
Charged Particle R_{AA} up to p_T = 100 GeV/c



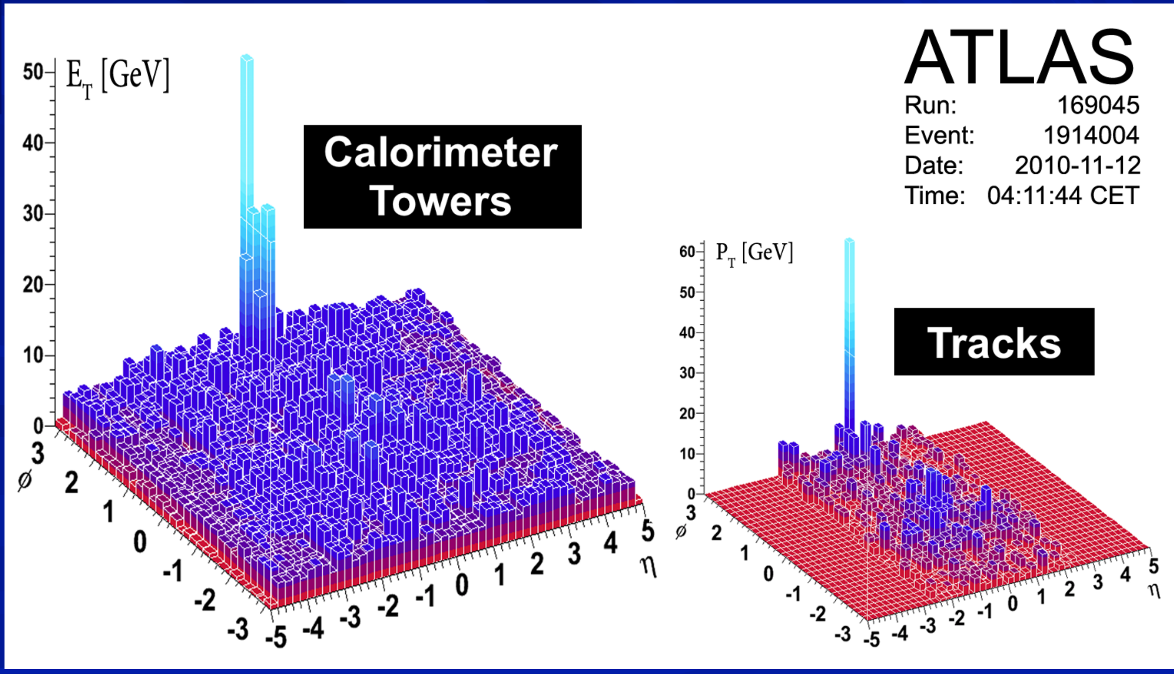
- Maximum suppression at p_T ≈ 6-7 GeV/c
- Almost no suppression at p_T > 50 GeV/c for all centralities
- R_{AA}@RHIC ≈ R_{AA}@LHC in the p_T range of overlap

Jets

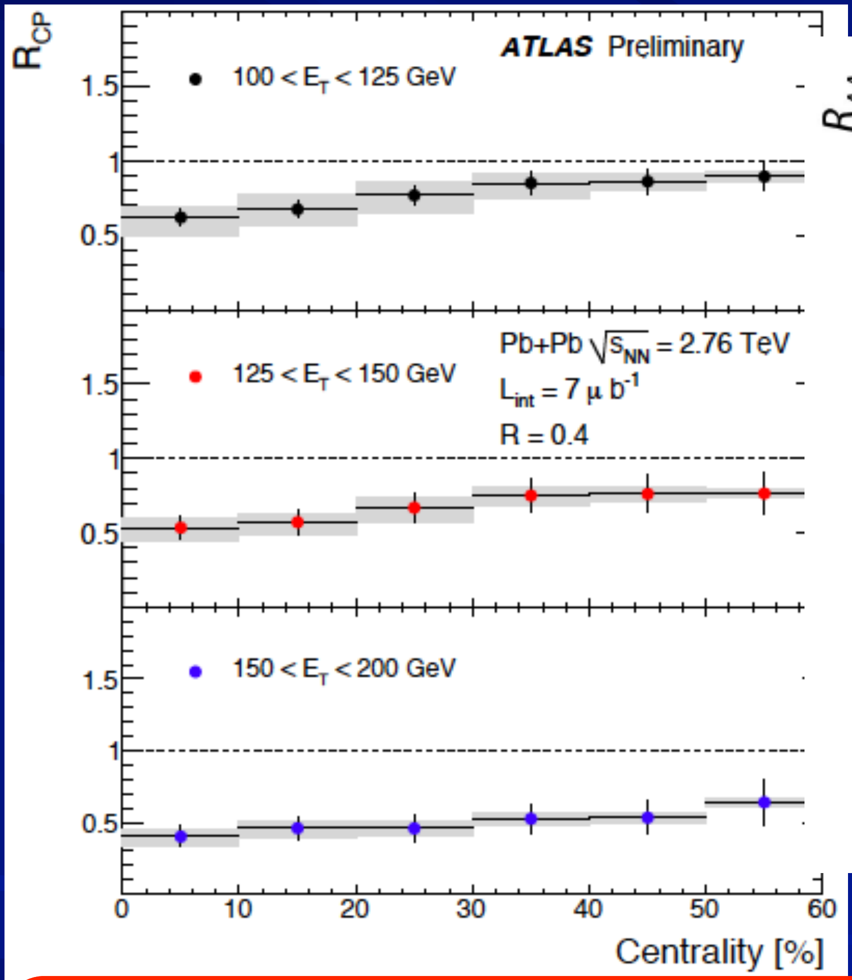
ATLAS: two jet event

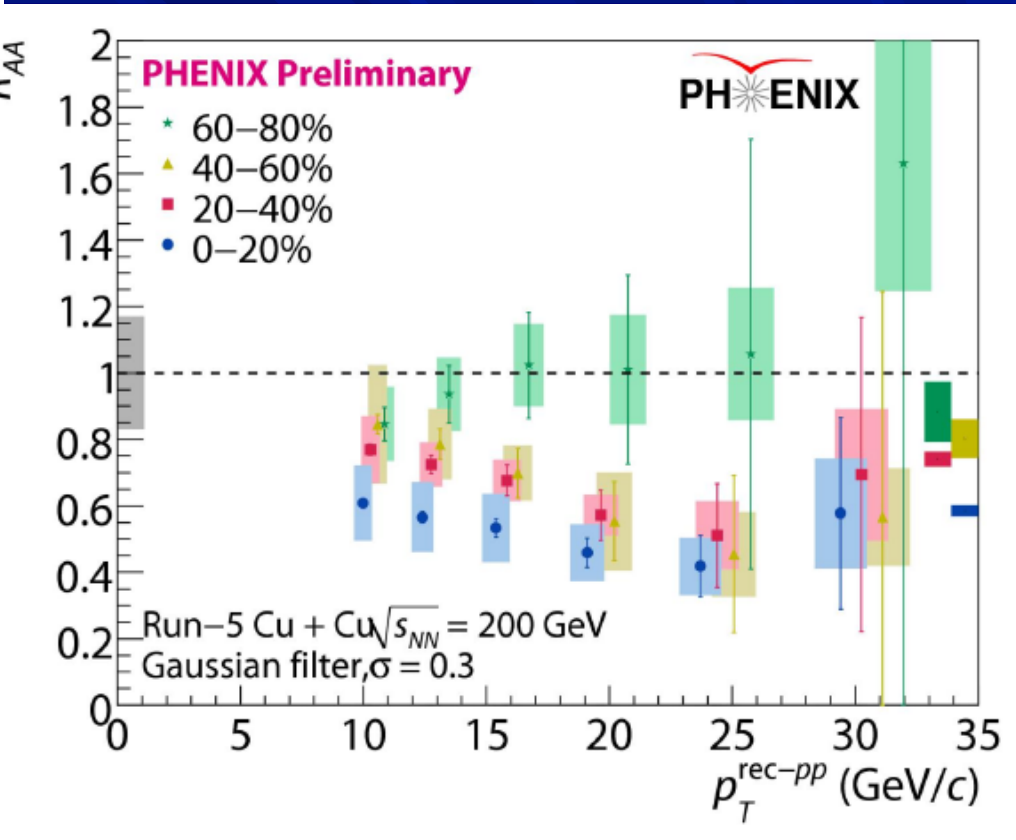


ATLAS: single jet event



Jet suppression

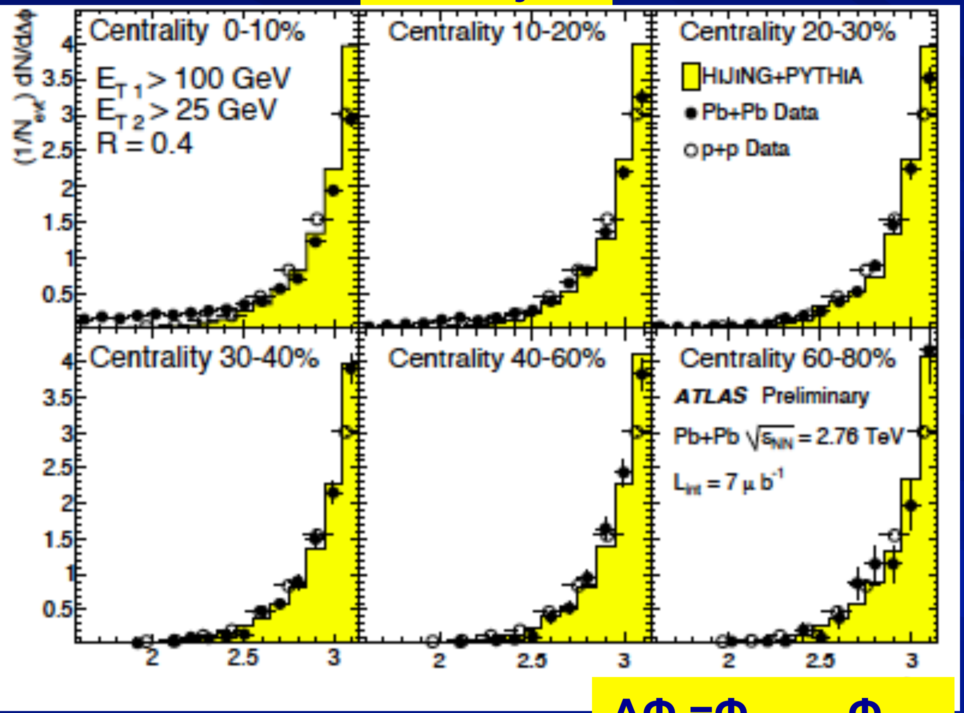




Jet yield suppressed in central collisions by about a factor of 2
Suppression level independent of jet energy
Similar level of suppression at RHIC

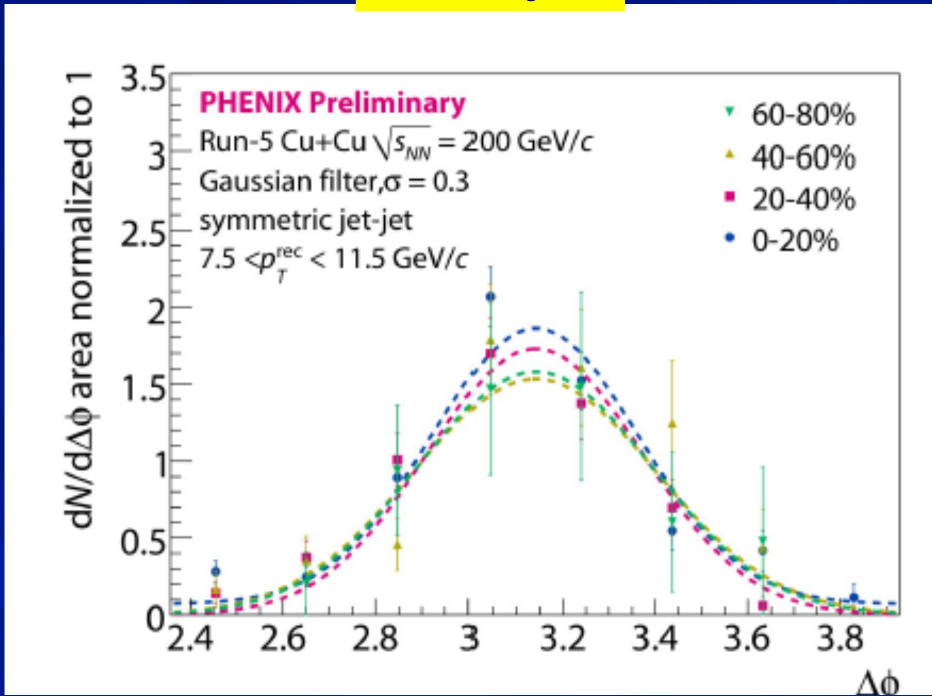
Angular correlation: dijets

LHC dijets



$\Delta\Phi = \Phi_{jet1} - \Phi_{jet2}$

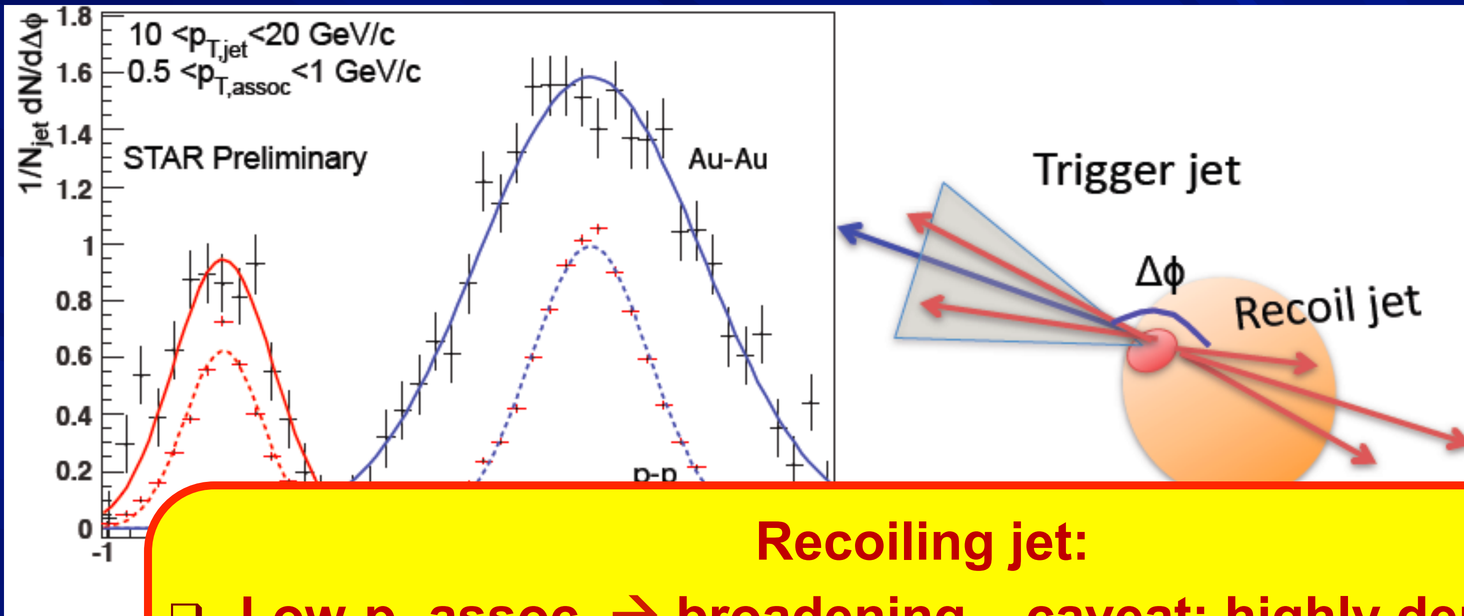
RHIC dijets

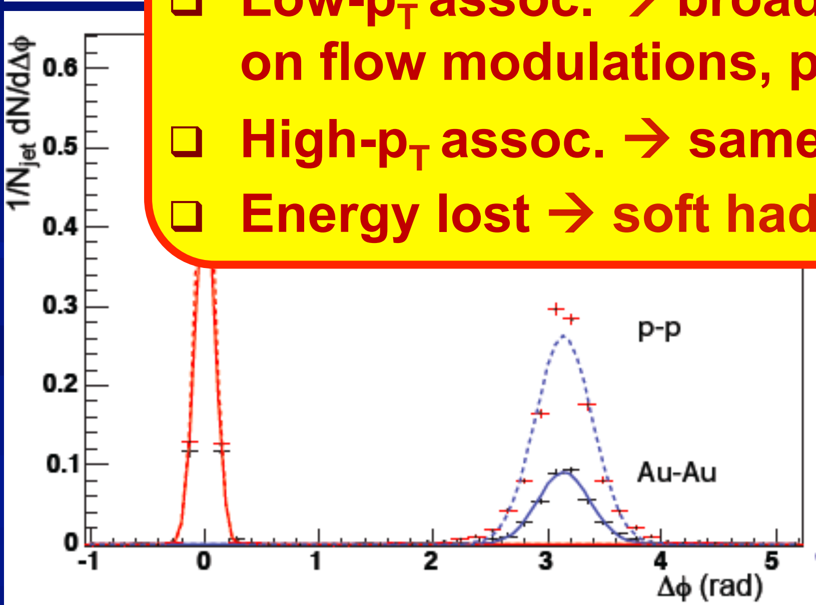


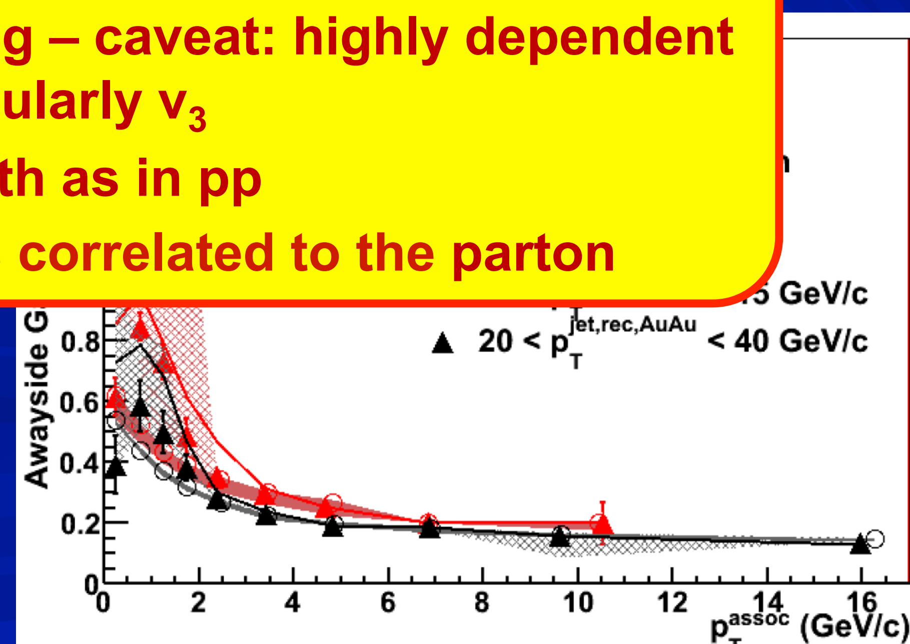
- Mostly back-to-back dijets
- Same angular correlation as in pp for all centralities

- Similar results at RHIC from dijets in Cu+Cu collisions

Jet-hadron correlations at RHIC



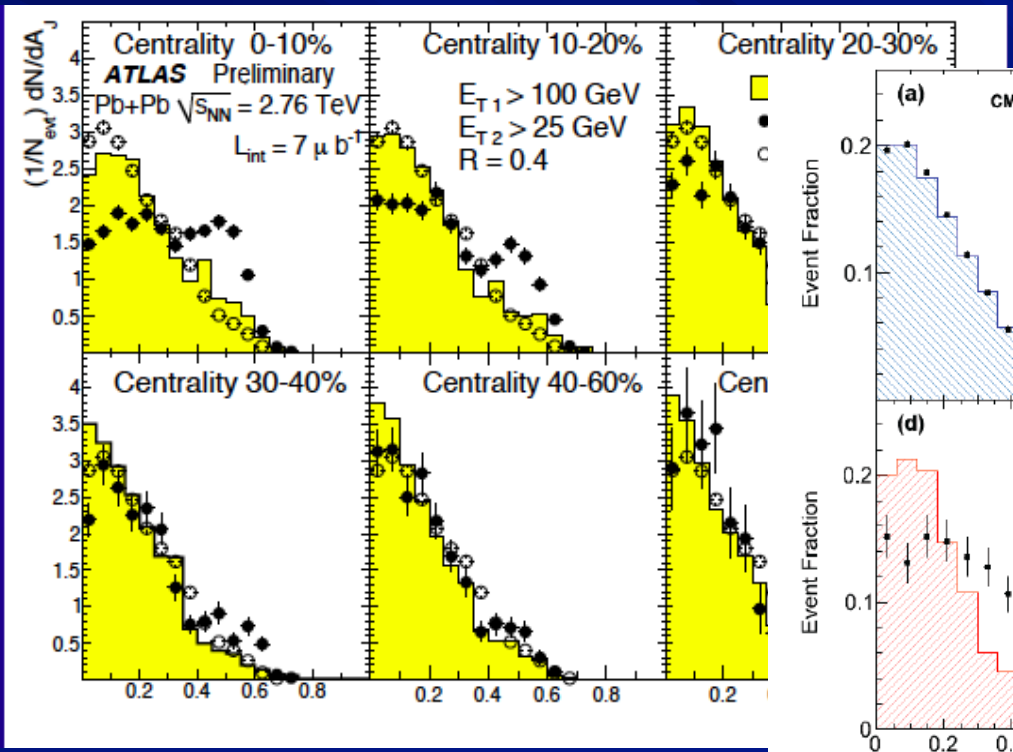


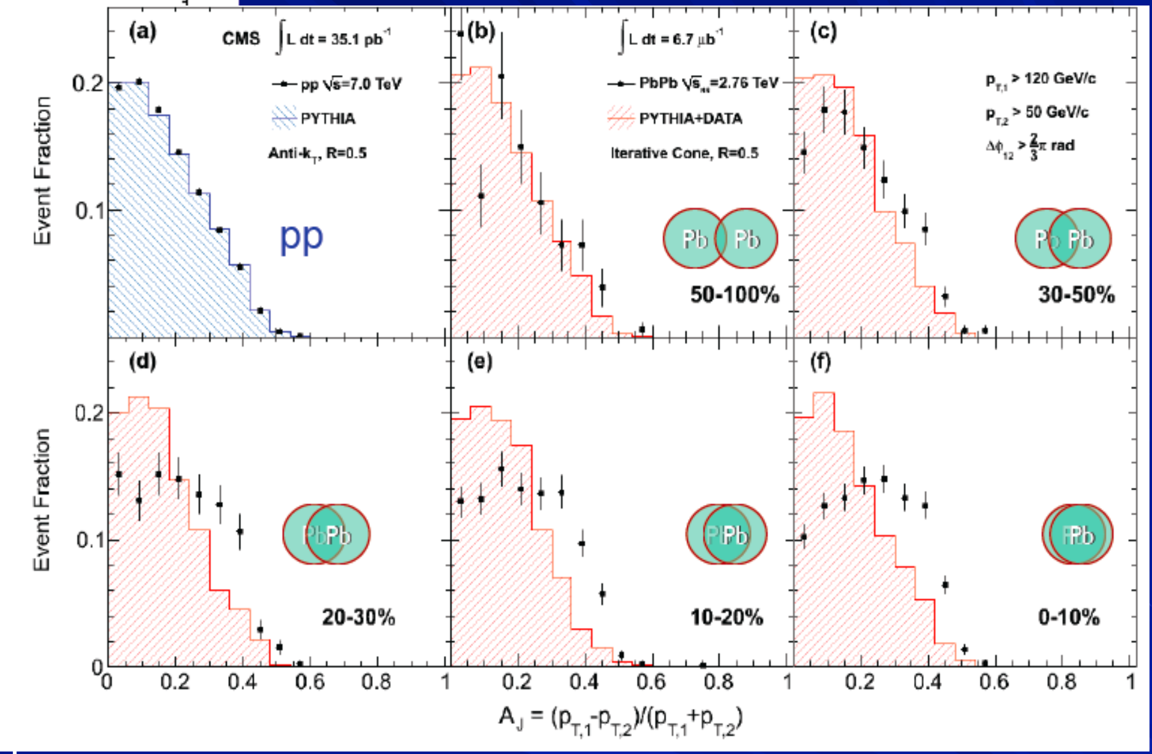


Recoiling jet:

- **Low-p_T assoc. → broadening – caveat: highly dependent on flow modulations, particularly v_3**
- **High-p_T assoc. → same width as in pp**
- **Energy lost → soft hadrons correlated to the parton**

Dijet energy balance: LHC





Dijet energy balance characterized by the asymmetry parameter:

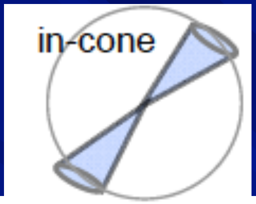
$$A_j = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

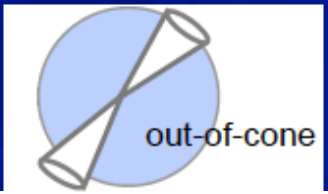
- **Very similar results from CMS**

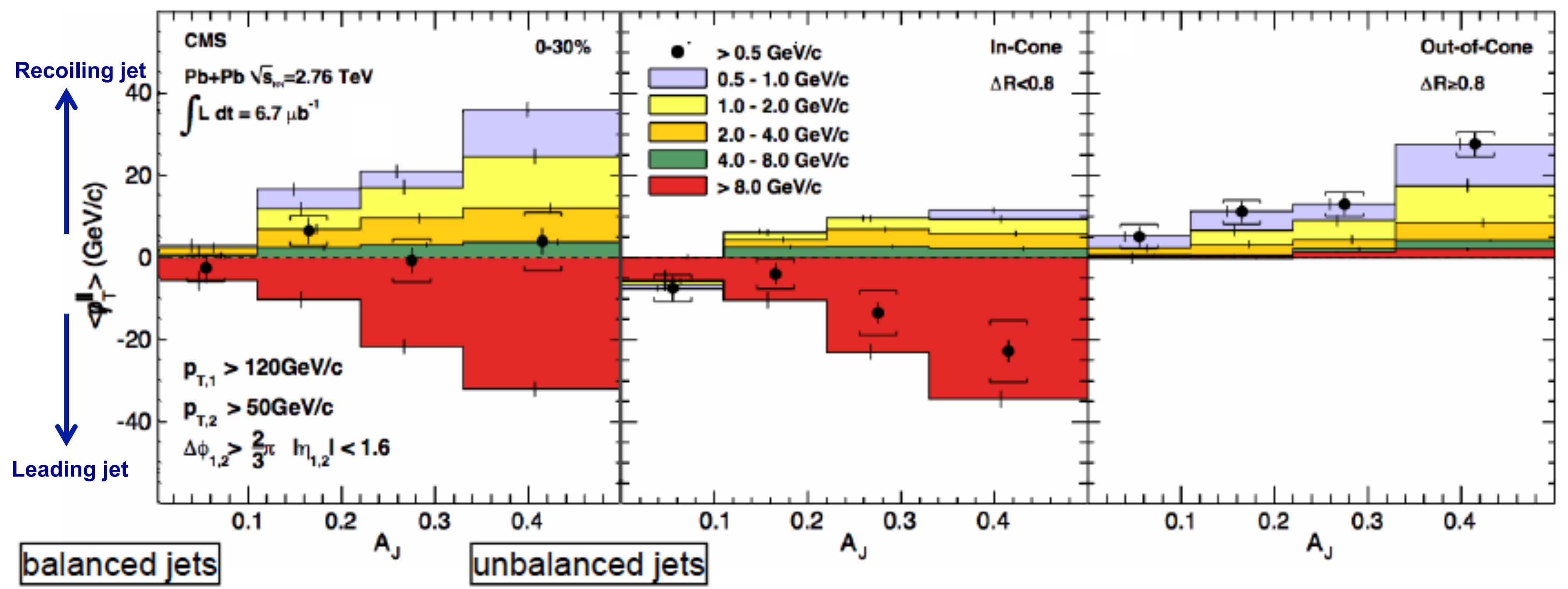
- **Energy imbalance grows with centrality**

Where does the energy go?

$$\not{p}_{T}^{\parallel} = \sum_{\text{Tracks}} -p_{T}^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$





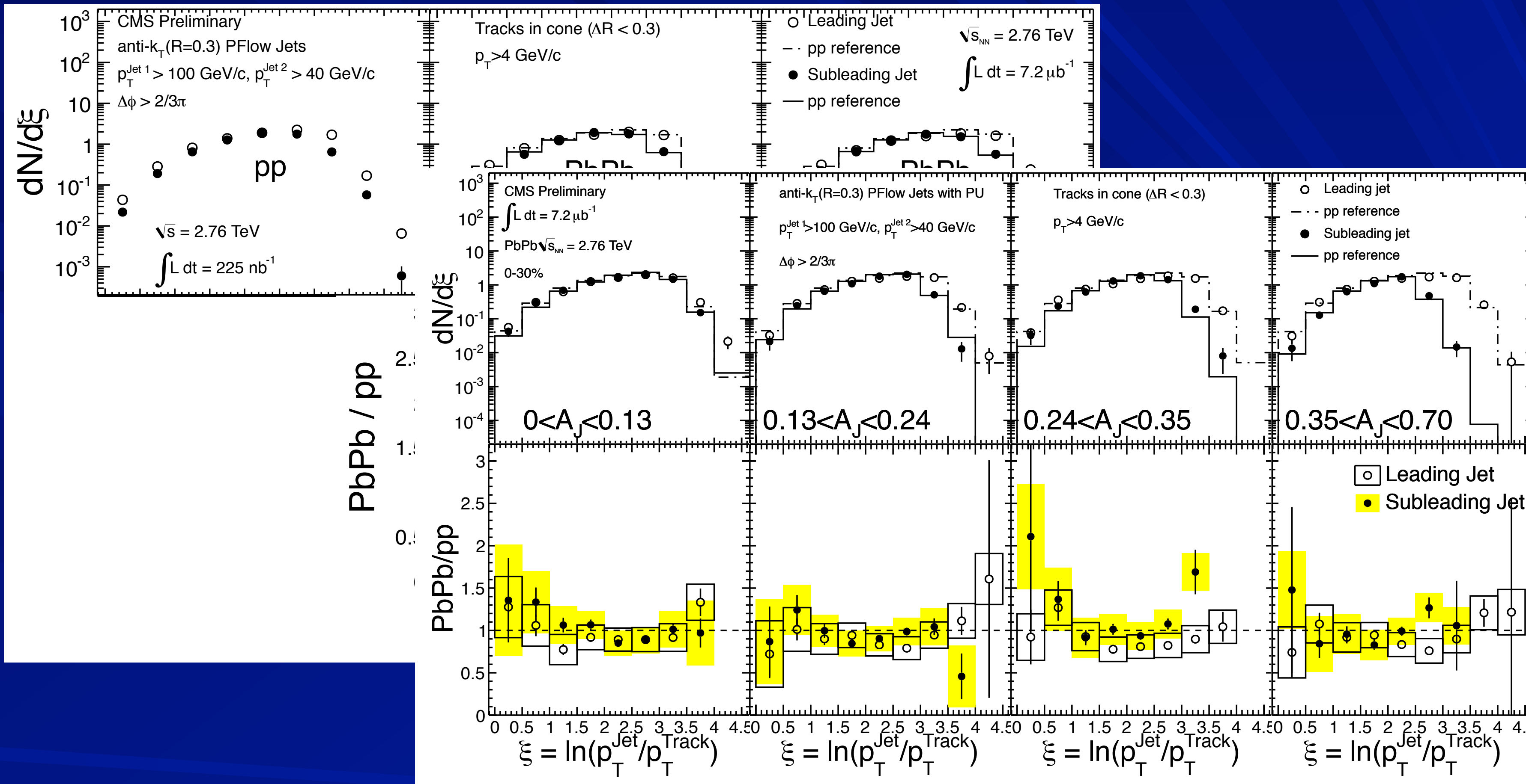


Full event is balanced

Imbalance in-cone:
Excess of high pt tracks towards leading jet

Imbalance out-of-cone:
Low-pt tracks out of cone
Excess of low pt tracks towards the recoiling jet

Fragmentation functions at LHC



Fragmentation functions unmodified

Consistent with jets fragmenting in vacuum

Jets LHC vs RHIC

- Jets are suppressed $R_{CP} \rightarrow 0.5$
  - Mostly back to back – No deflection
- Dijets
  imbal
- Comp
  (0.5
  angles wrt the away side jet
  - Fragmentation functions unmodified

- Jets are suppressed $R_{AA} \rightarrow 0.5$
  - Mostly back to back – No deflection *but away side jet*
  bit
  cks
  s wrt
  pp collisions
  - *Fragmentation functions modified*

- Qualitatively different behavior of low pt (10-40 GeV/c) and high p_T (> 100 GeV/c) jets?

or

- Effect of selection cuts?

ATLAS jets: leading E_T > 100 GeV

second E_T > 25 GeV

FF $p_{T,track}$ > 2 GeV/c

CMS jets: leading p_T > 120 GeV/c

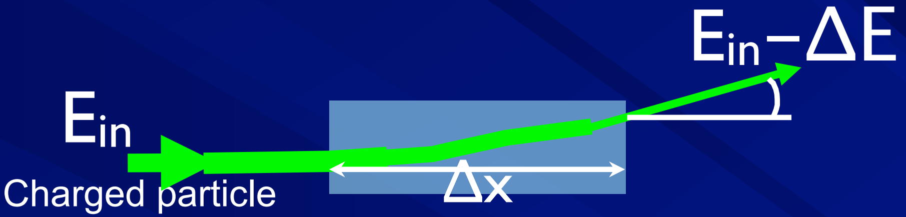
subleading p_T > 50 GeV/c

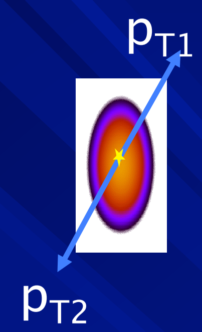
FF $p_{T,track}$ > 4 GeV/c

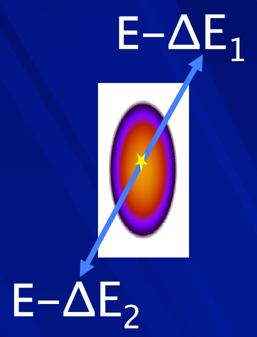
STAR: jet-hadron correlations

Jets p_T = 10 – 40 GeV/c

assoc. hadrons p_T > 0.2 GeV/c

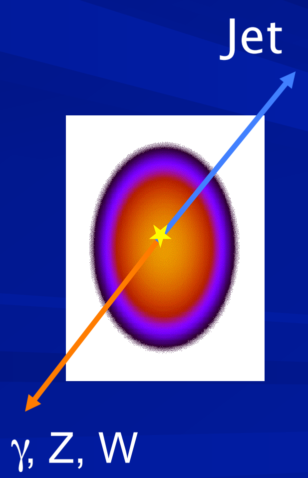






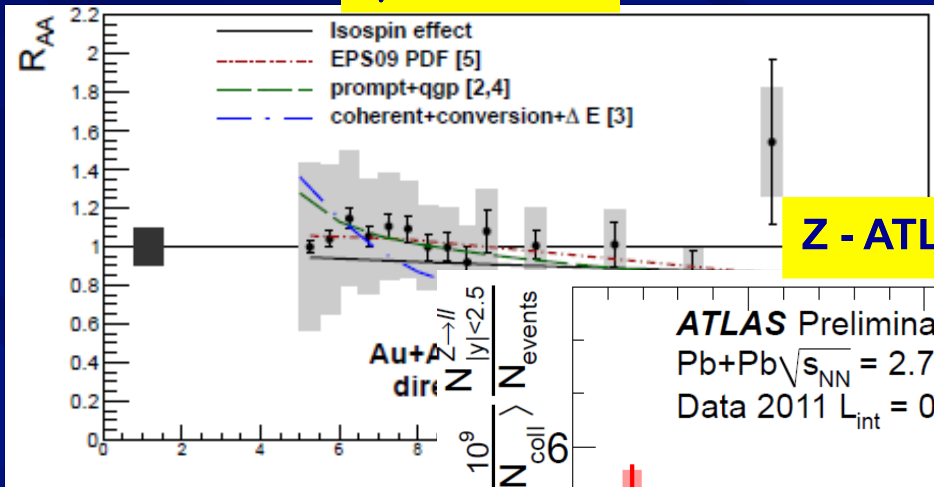
- Calibrated Probes:

γ, Z – Jet

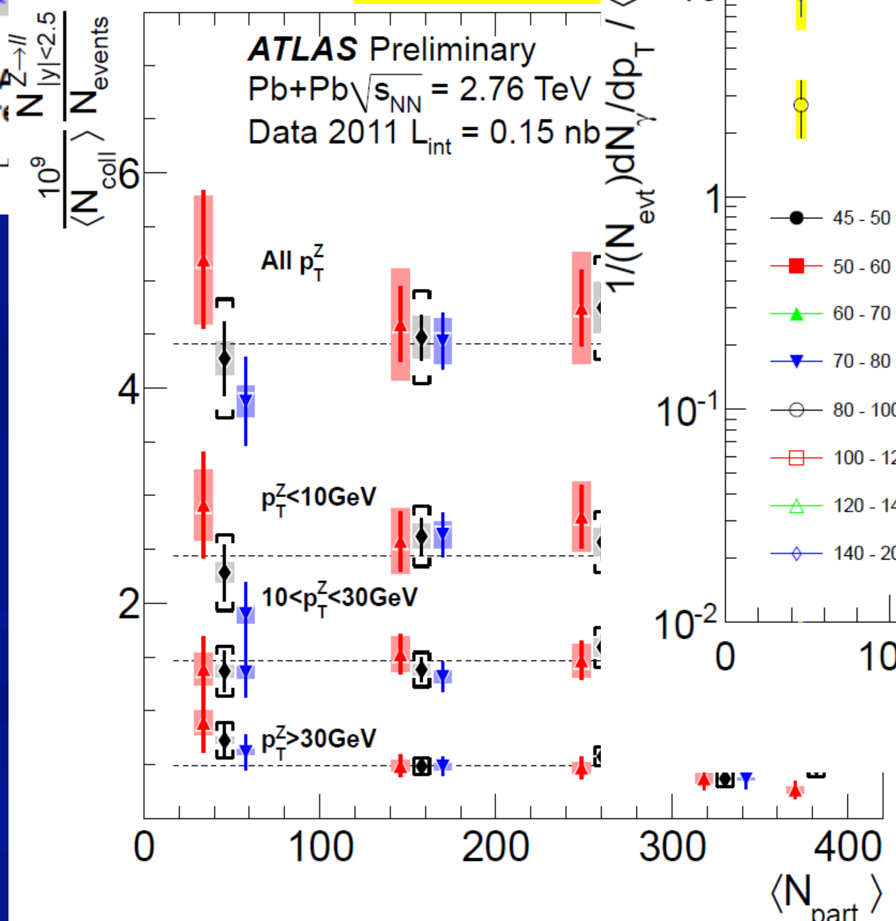


Electroweak Probes - Binary Scaling

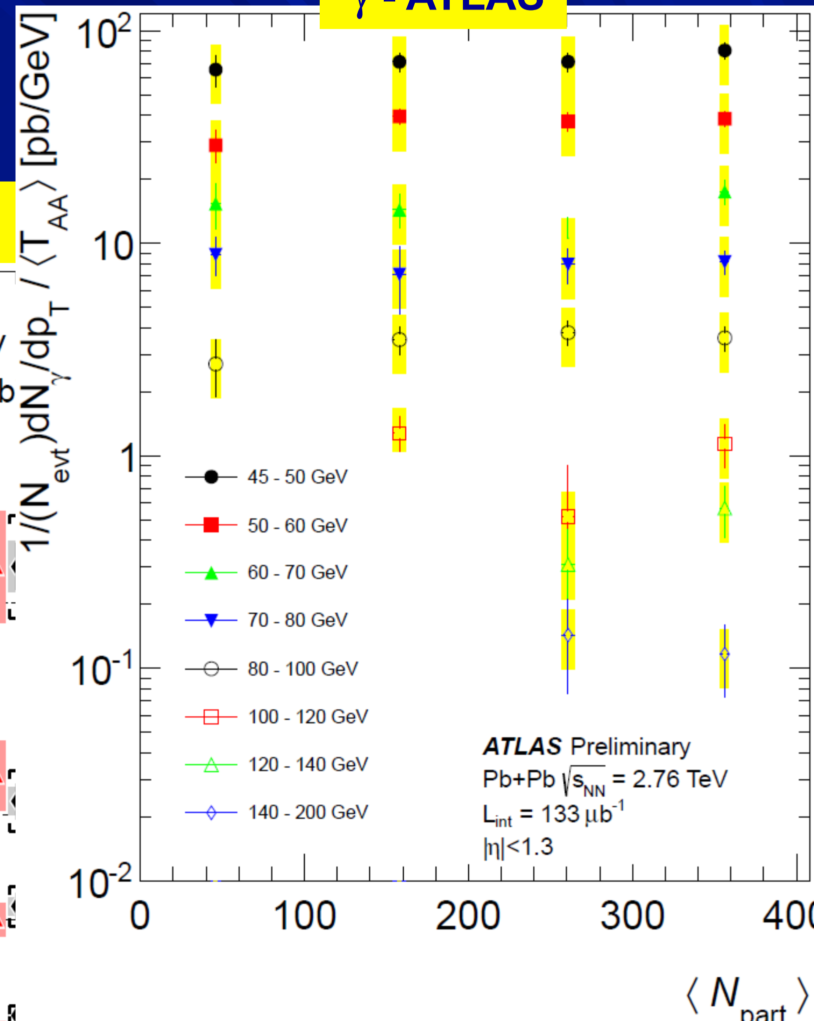
γ – PHENIX



Z - ATLAS

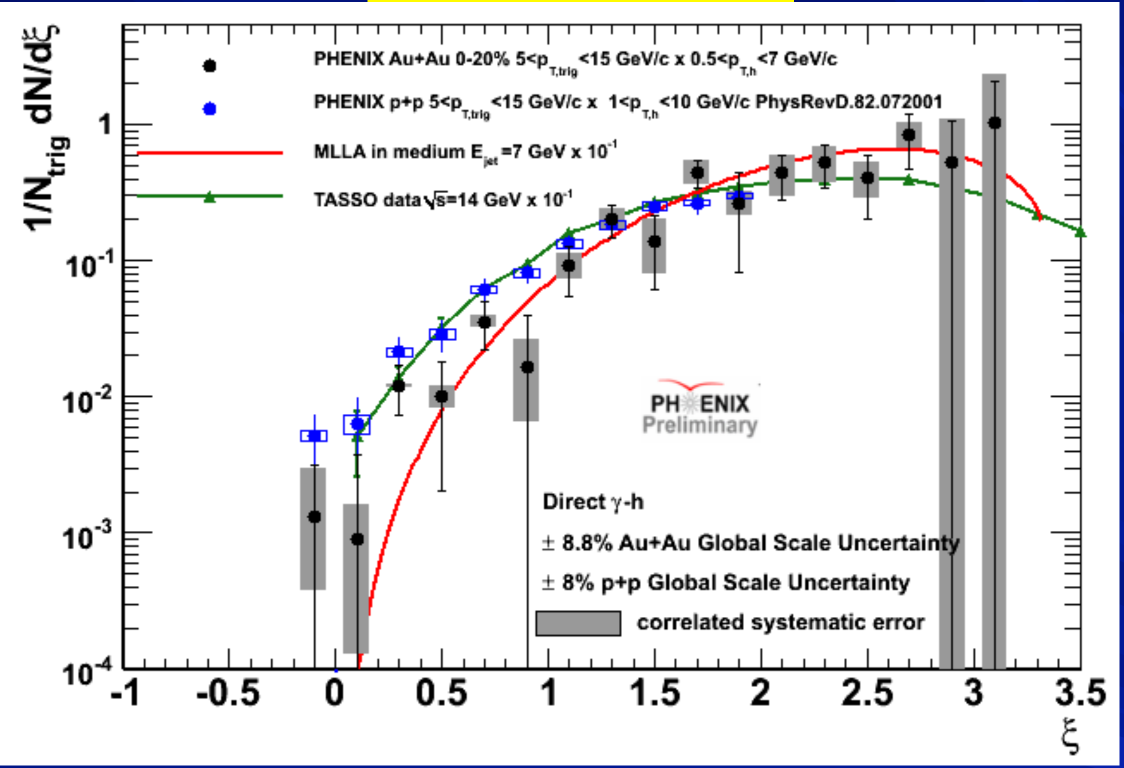


γ - ATLAS



Fragmentation function at RHIC

γ – jet correlations



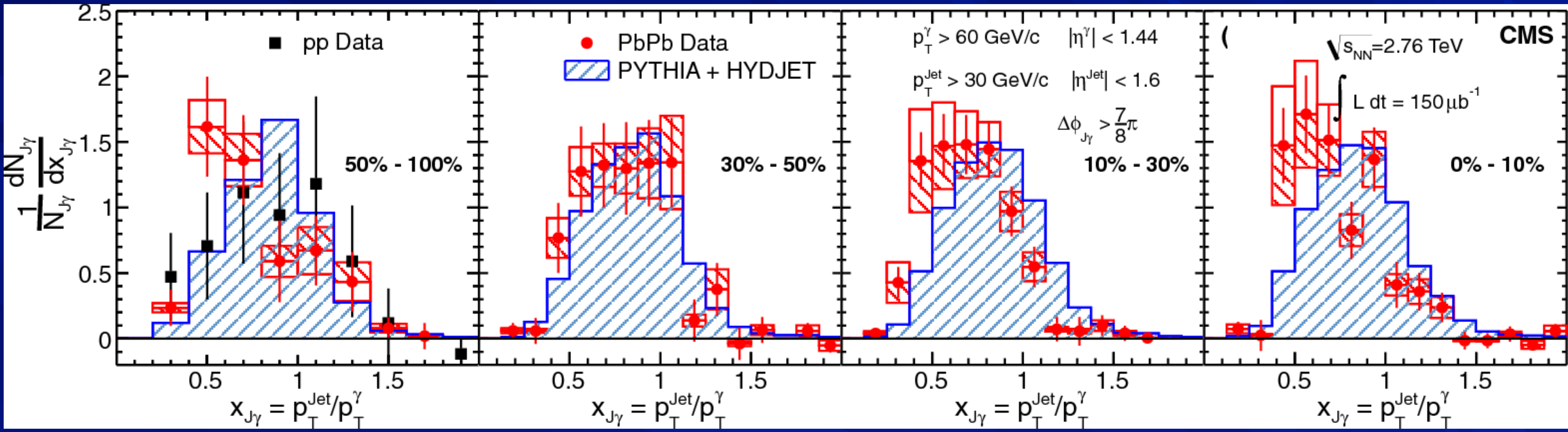
$$\xi = -\ln\left(\frac{p_T^h}{p_T^\gamma}\right)$$

- Au+Au fragmentation function modified compared with pp
  - Smaller yield at low ξ (high p_T)
  - Slightly higher yield at high ξ (low p_T)

γ-Jet Momentum Balance

$p_T^{\gamma} > 60$ GeV/c $|\eta| < 1.44$

$p_T^{Jet} > 30$ GeV/c $|\eta| < 1.6$

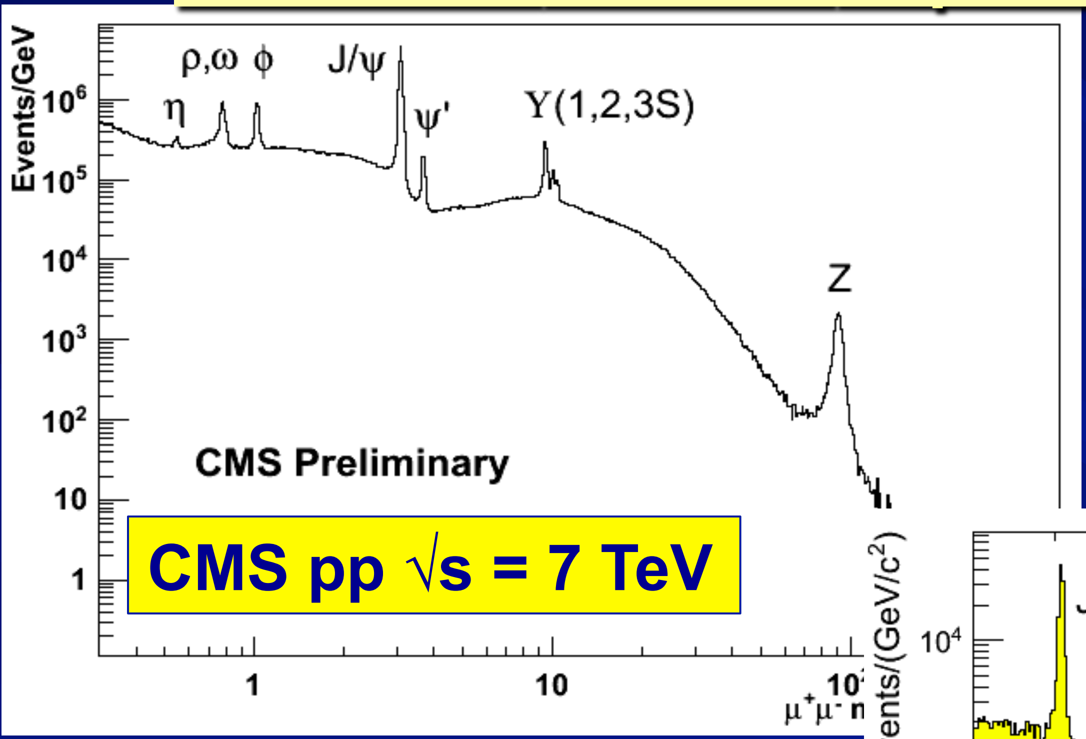


Submitted to PLB, arXiv:1205.0206

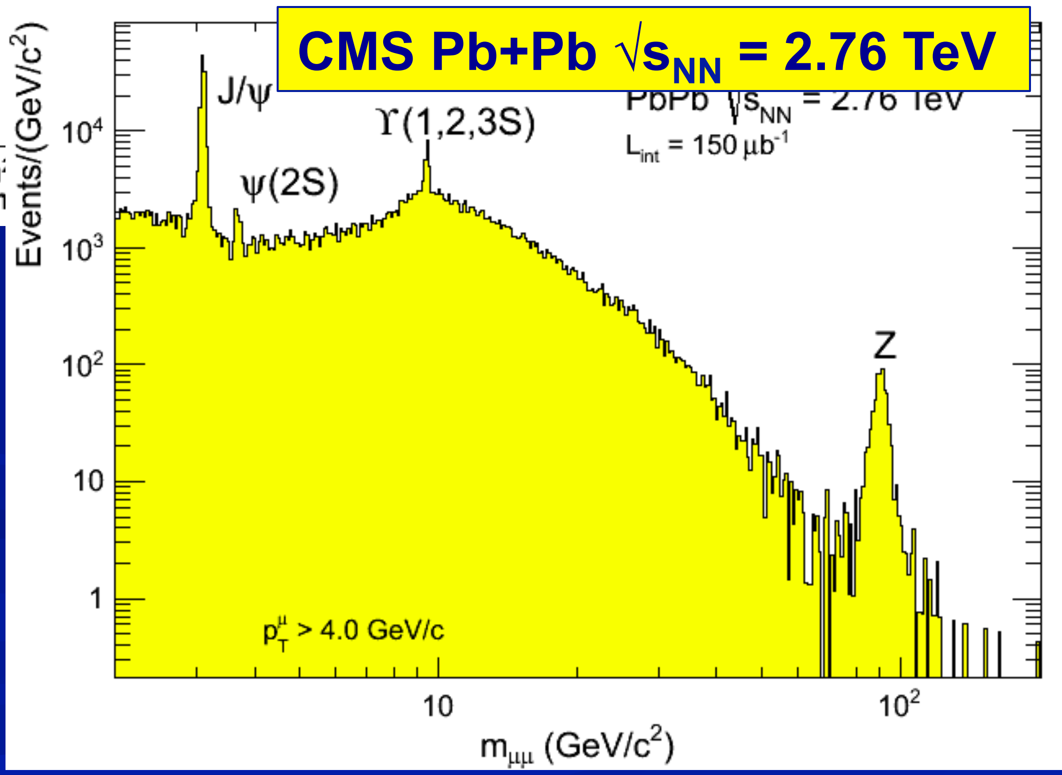
- Momentum ratio shifts/decreases with centrality
  (jets below the 30 GeV/c p_T threshold not included)

- Quarkonia and Bottomonia: Debye screening - deconfinement

The di-muon spectrum at LHC



- Superb data
- Textbook spectra

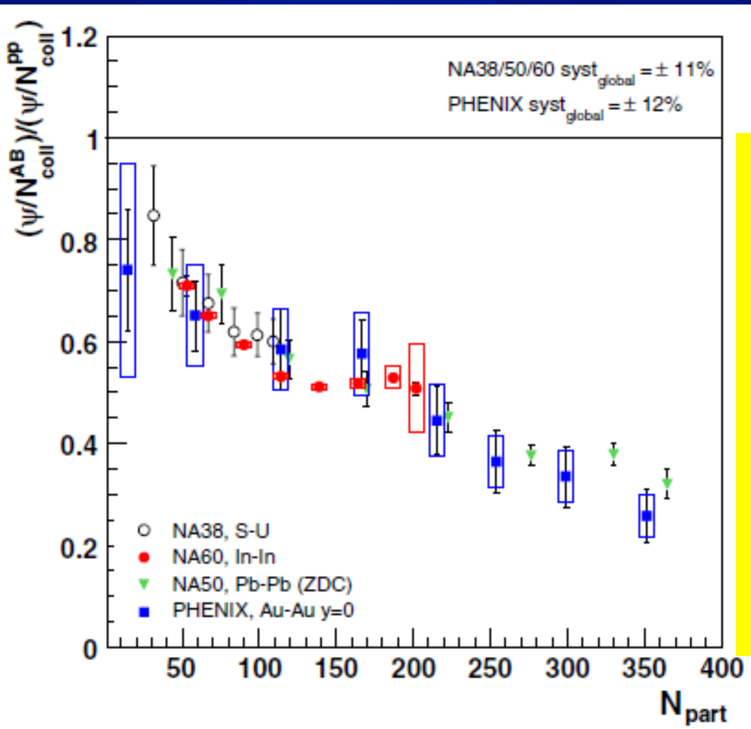


J/Ψ or the endless saga

- After more than 25 years since the classic Matsui and Satz paper - PLB 178, 416 (1986) - there is not a detailed understanding of the J/Ψ production and its behavior in relativistic heavy ion collisions.

- Two big surprises from the RHIC and SPS data

1. Same suppression at SPS and RHIC



Possible effects:

Suppression

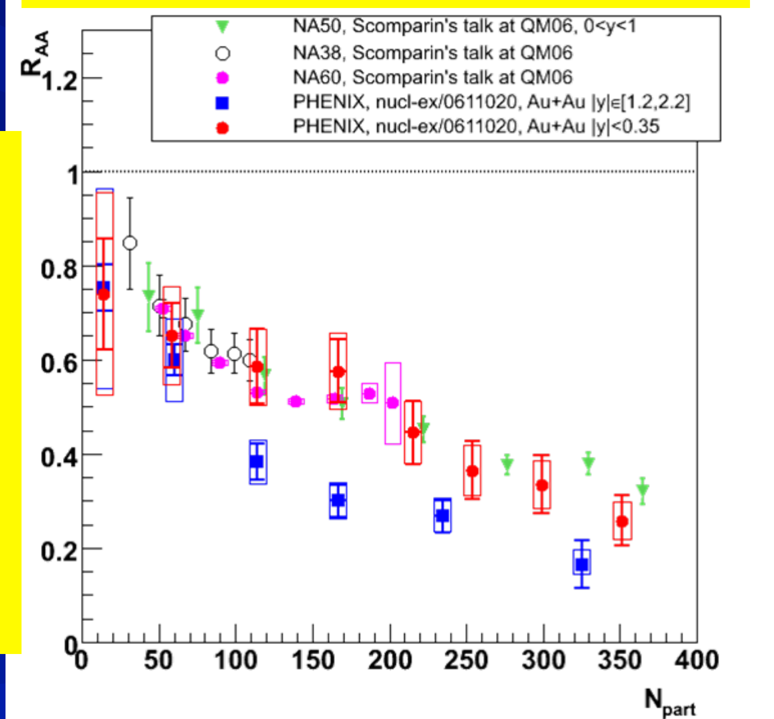
<u>Sequential melting</u>

Gluon saturation / shadowing

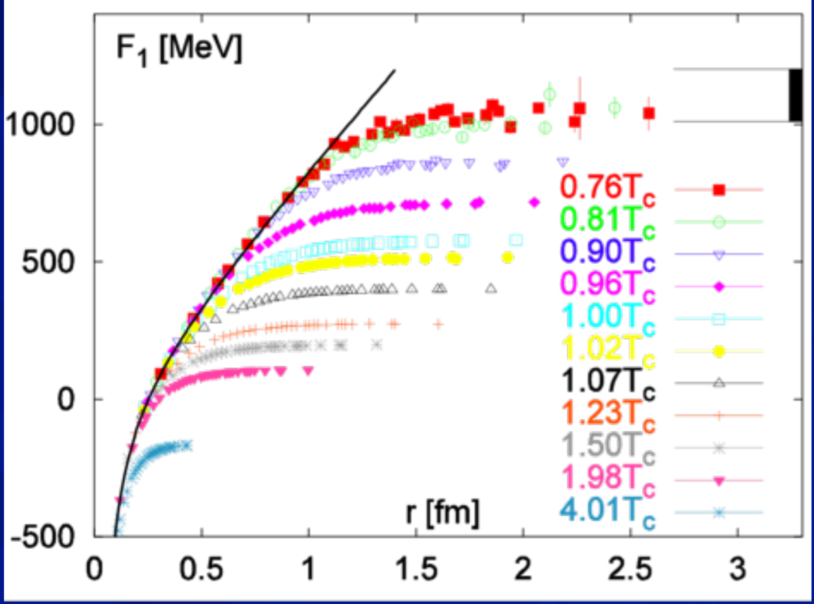
<u>Regeneration</u>

All together

2. Larger suppression at forward rapidity



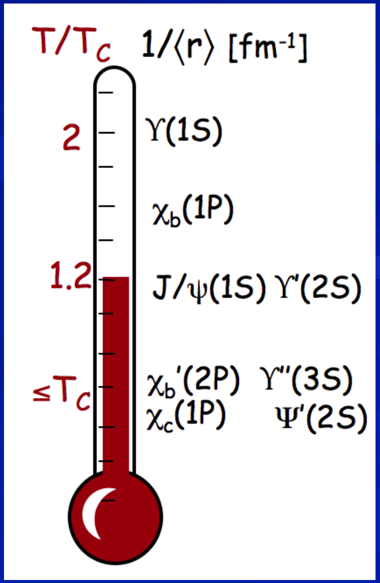
Sequential melting



- No binding when screening radius < binding radius (Debye screening)

State	J/ψ (1S)	χ_c (1P)	ψ' (2S)	Υ (1S)
m (GeV/c^2)	3.10	3.53	3.68	9.46
r_0 (fm)	0.50	0.72	0.90	0.28

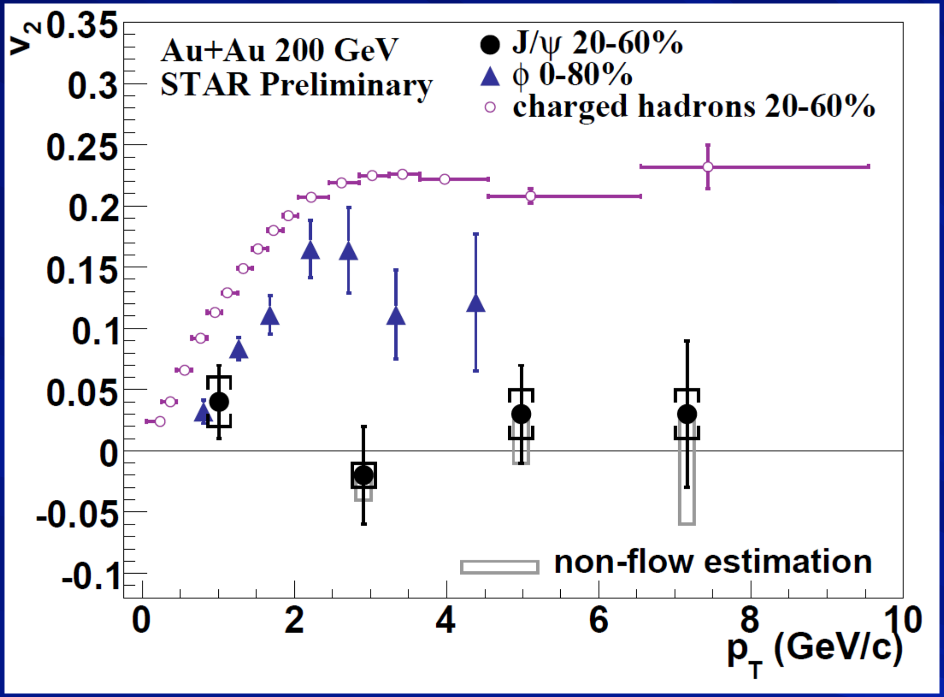
State	χ_b (1P)	Υ' (2S)	χ_b' (2P)	Υ'' (3S)
m (GeV/c^2)	9.99	10.02	10.26	10.36
r_0 (fm)	0.44	0.56	0.68	0.78



- Different radii of bound states lead to sequential melting of the states with increasing temperature

J/Ψ elliptic flow at RHIC

(testing the recombination hypothesis)



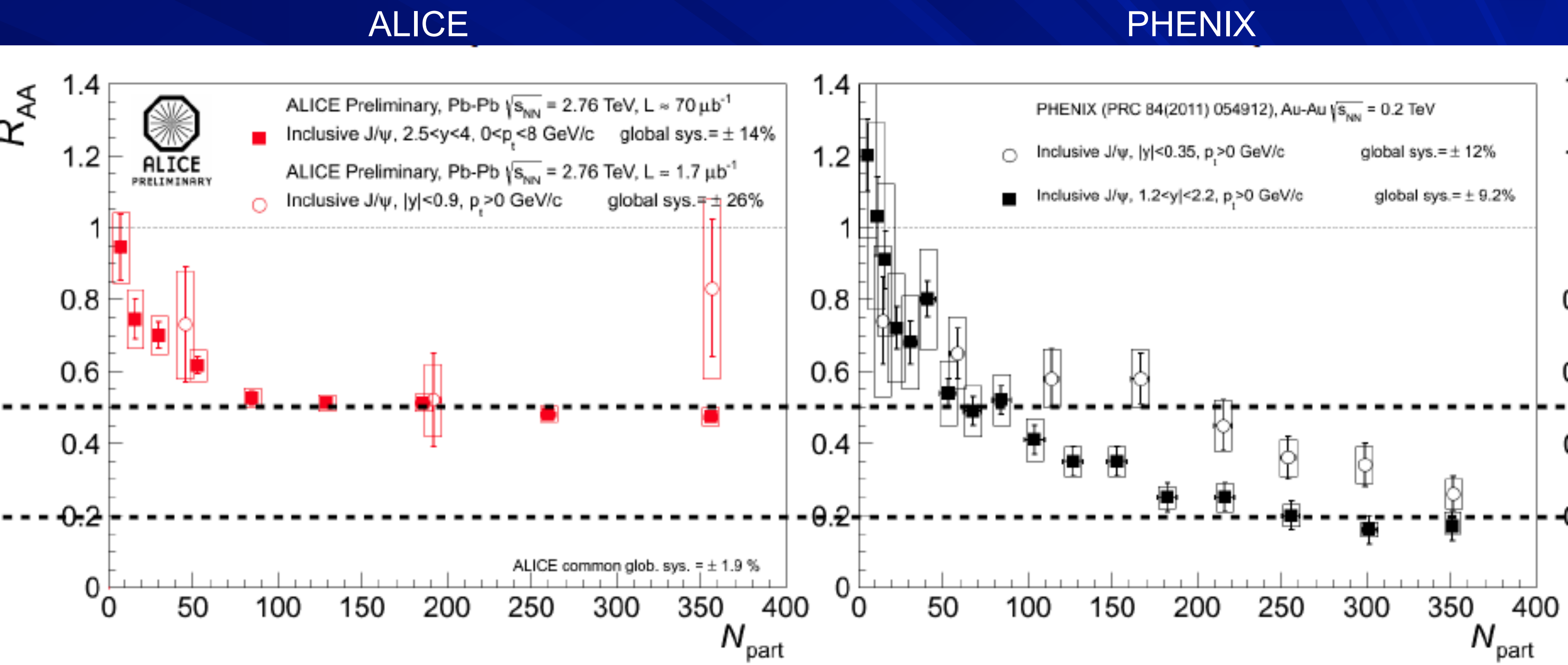
J/ψ v_2 at RHIC:

- Consistent with zero within error bars
- Does not provide supporting evidence for ccbar recombination at RHIC

❑ **Higher precision data are needed**

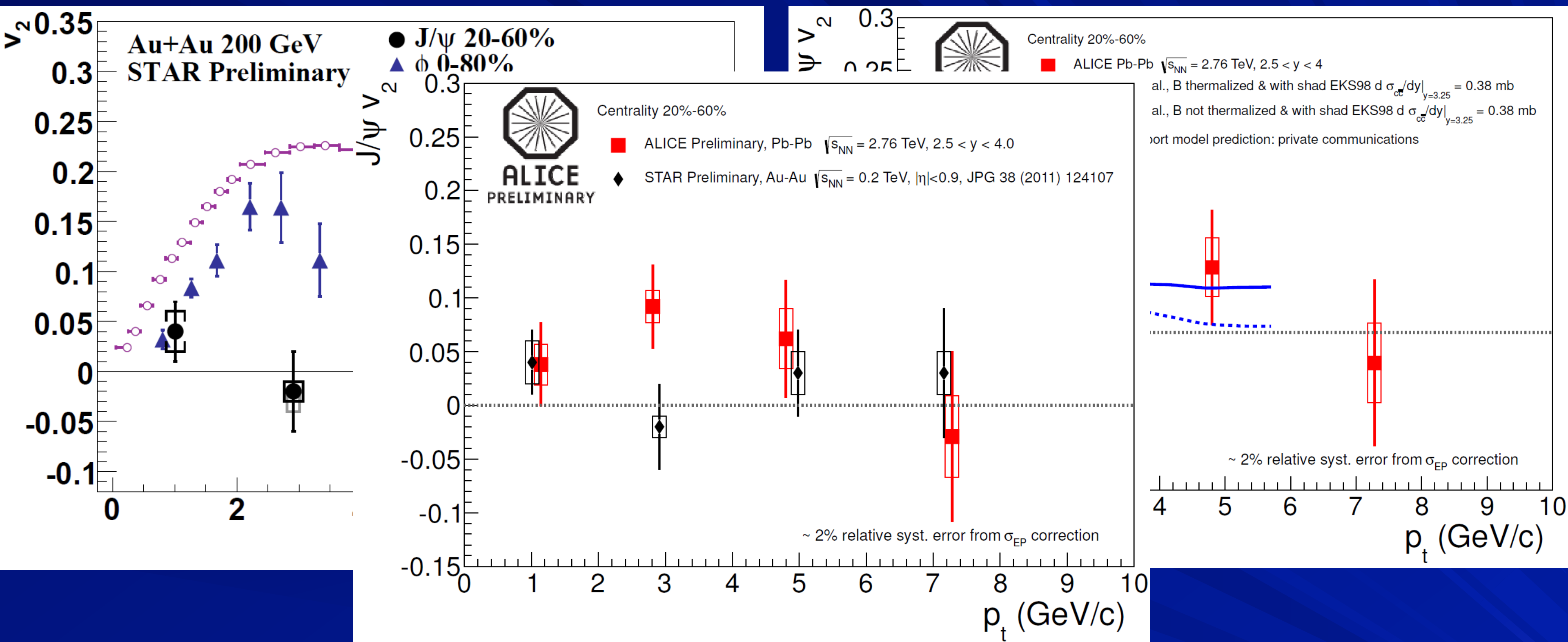
Similar as RHIC (|y|<0.35)

J/ψ at RHIC and LHC different ?



Not a clear situation at LHC mid-rapidity. Significance limited by the precision of the pp reference data

J/Ψ elliptic flow



J/ψ v_2 at RHIC: consistent with zero

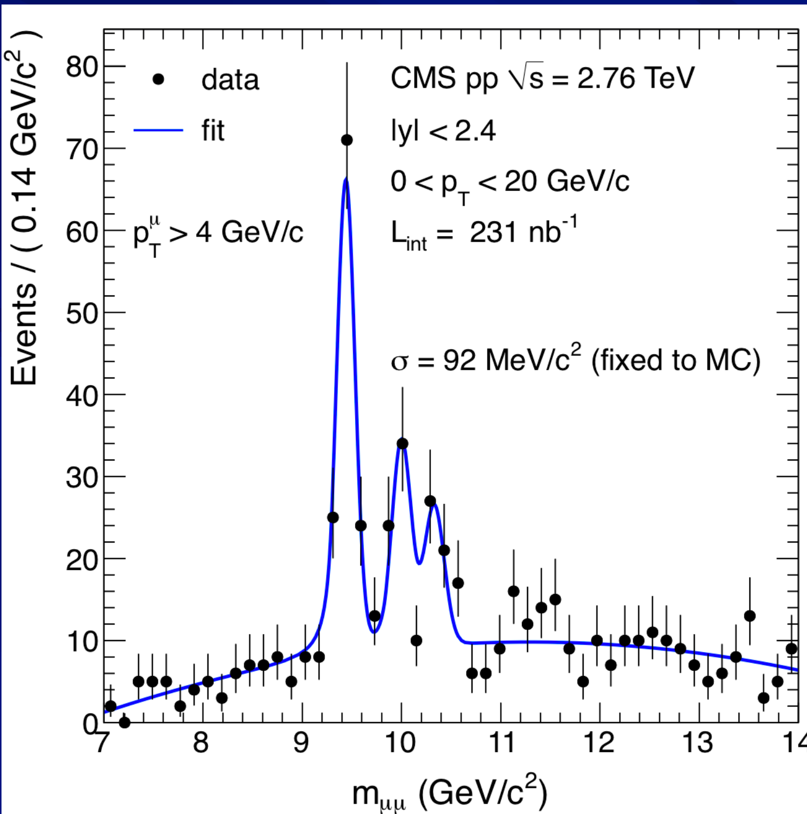
J/ψ v_2 at LHC: non-zero at intermediate pt (2-4 GeV/c) but significance = 2.2 σ

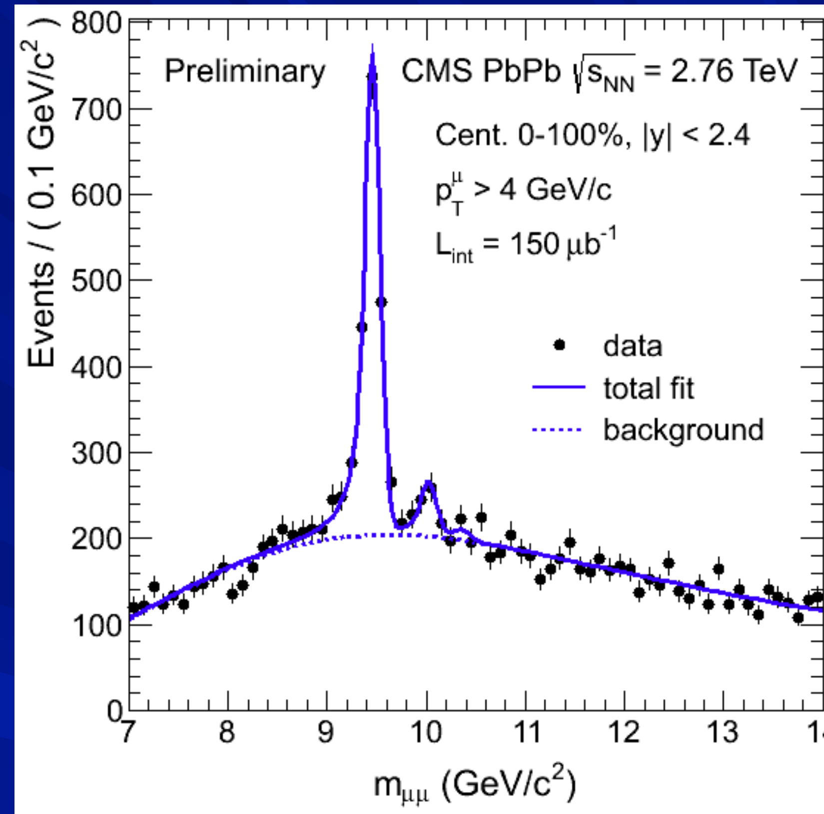
Model prediction for v2 shown here succeeds well at reproducing J/ψ RAA.

- Higher precision data are needed

Similar as RHIC (|y|<0.35)

Υ suppression

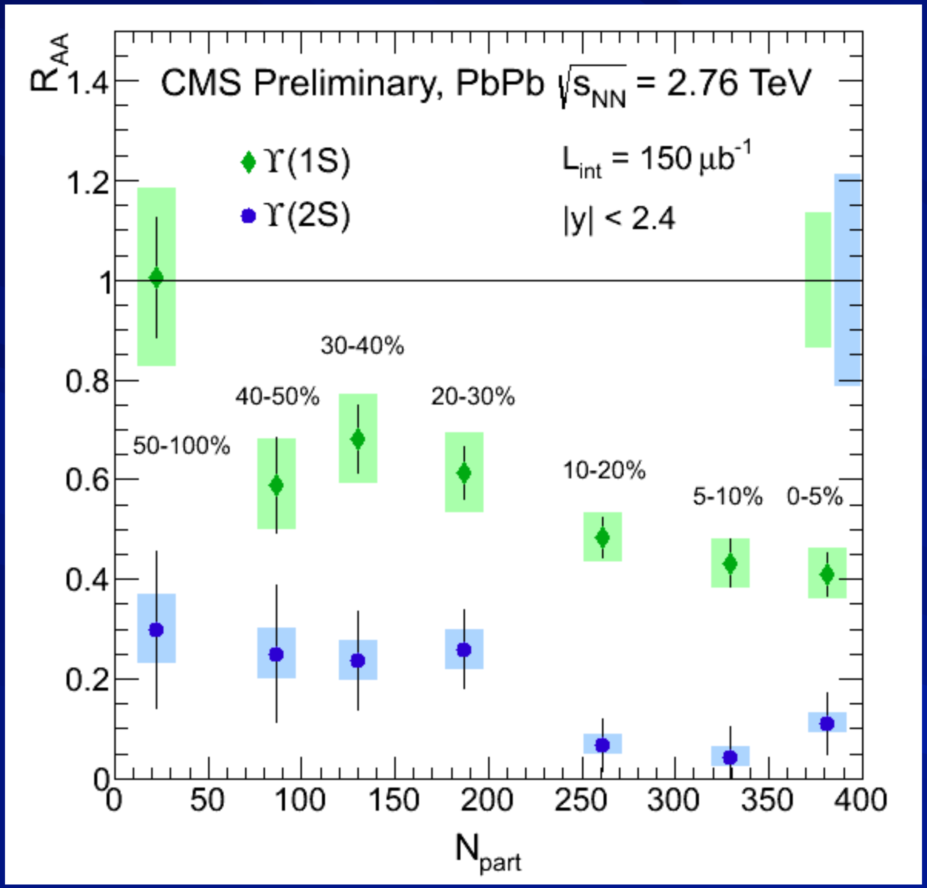




NY(2S)/NY(1S)|pp = 0.56 ± 0.13 ± 0.01 NY(2S)/NY(1S)|PbPb = 0.12 ± 0.03 ± 0.01

NY(3S)/NY(1S)|pp = 0.21 ± 0.11 ± 0.02 NY(3S)/NY(1S)|PbPb < 0.07

Υ(1S) and Υ (2S) R_{AA}



Υ(1S) 52±9% direct

consistent with complete! suppression of feed down states (~50%)

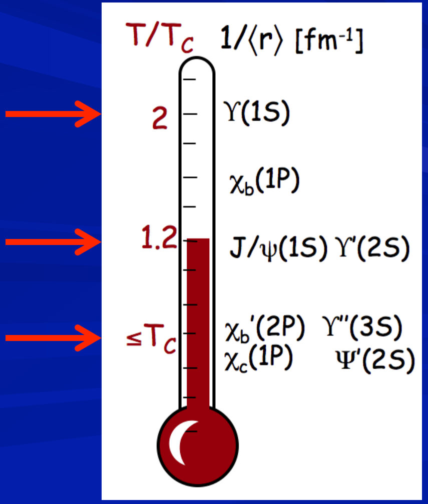
Υ(2S) Strong suppression

up to 5 x stronger suppression than Υ(1S)

Comparable suppression to J/ψ

Υ(3S) disappeared

upper limit Υ(3S) / Υ(1S) < 1% (95% CL)



- Consistent with expectations
- CNM ?
- Need comparable RHIC data

Summary

- LHC has opened a new energy frontier in the study of the sQGP.
- Most of the paradigms established at RHIC seem to hold at the LHC.
- Matter formed at the LHC is *qualitatively* similar to the one formed at RHIC: strongly interacting matter behaving as a perfect liquid with very low viscosity.
- Common goal of RHIC and LHC: precise data with multiple observables at various energies to characterize the sQGP and constrain the theoretical models.