Heavy Ions @ the LHC: where do we stand?

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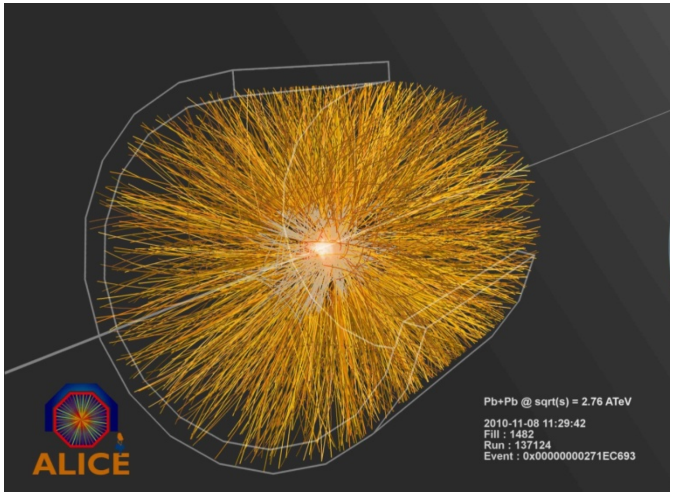
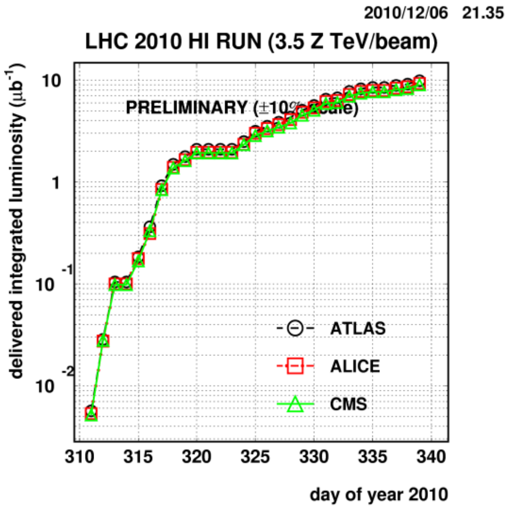
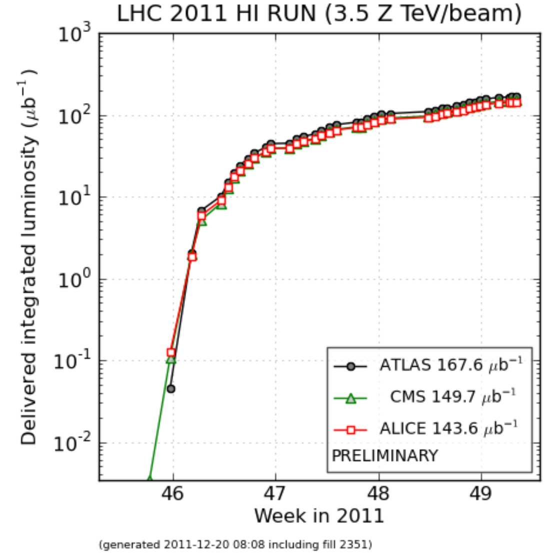
Nuclear collisions at the LHC!







- two successful Pb-Pb runs already
  - 2010 → ~ 10/μb
  - 2011 → ~ 100/μb
- + p-Pb "control" run
  - 2013 → ~ 30/nb

some numbers (2011 Pb-Pb run):

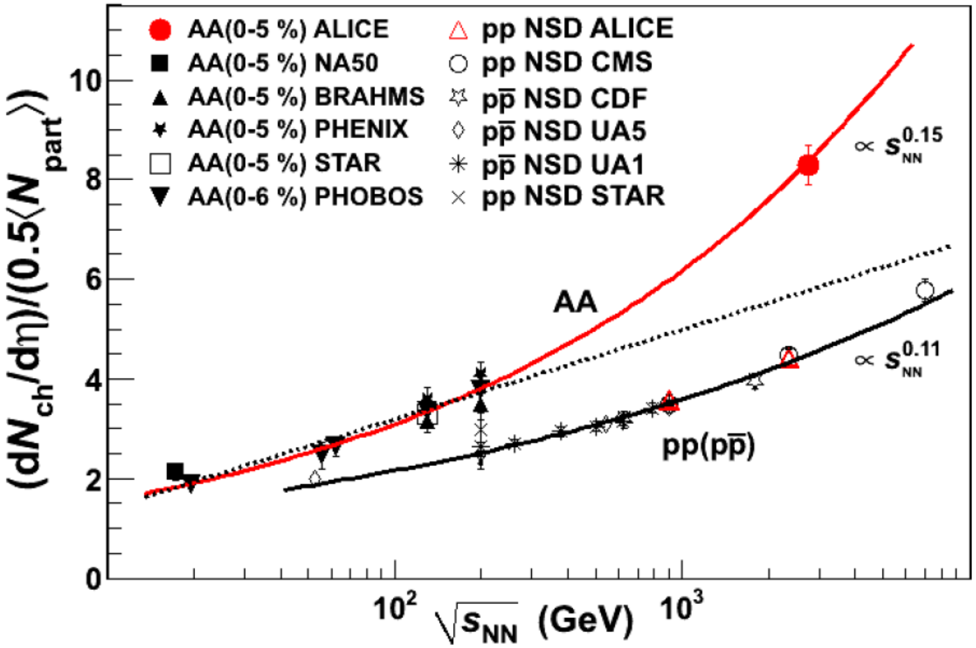
- ~ 1.1 10^8 ions/bunch
- 358 bunches
  - 200 ns basic spacing
- β* = 1 m
- L ~ 5 10^{26} cm^{-2}s^{-1}

→ ~ 4000 Hz interaction rate

Particle multiplicity

for the most central collisions: ~ 1600 charged particles per unit of η

ALICE: PRL105 (2010) 252301



log extrapolation fails (finally!)

2.2 x central Au+Au ($\sqrt{s_{NN}}$=0.2 TeV)

1.9 x pp (NSD) ($\sqrt{s_{NN}}$=2.36 TeV)

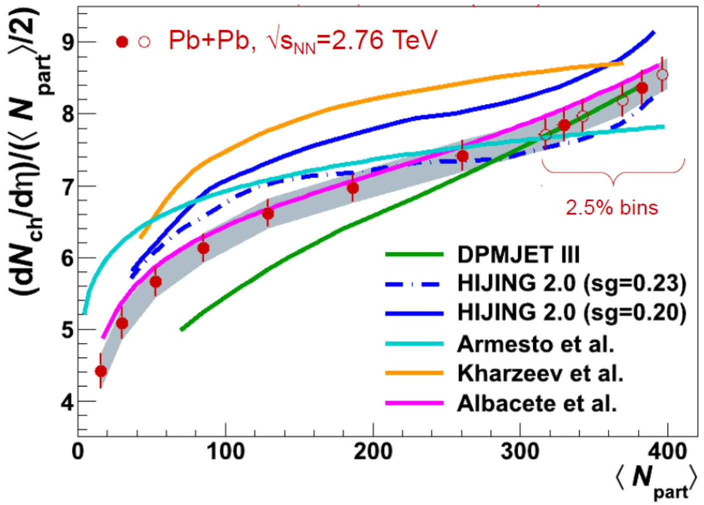
$\sqrt{s_{NN}}$=2.76 TeV Pb+Pb, 0-5% central, |η|<0.5

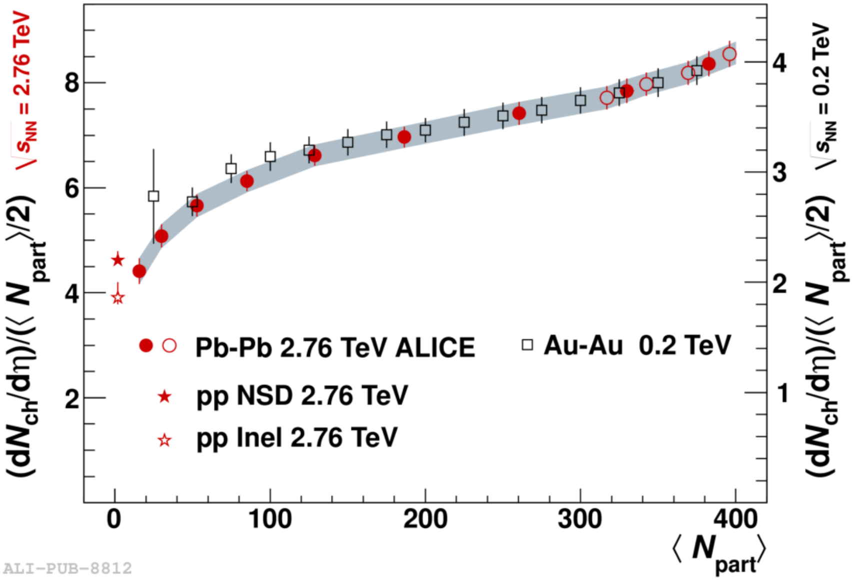
2 dNch/dη / <Npart> = 8.3 ± 0.4 (sys.)

Centrality dependence

- model comparisons
  - DPMJET (with string fusion)
  - HIJING 2.0 (no quenching)
    - centrality-dependent gluon shadowing
    - tuned to multiplicity in 0-5%
  - saturation models

- very similar centrality dependence at LHC & RHIC
  - once corrected for difference in absolute values



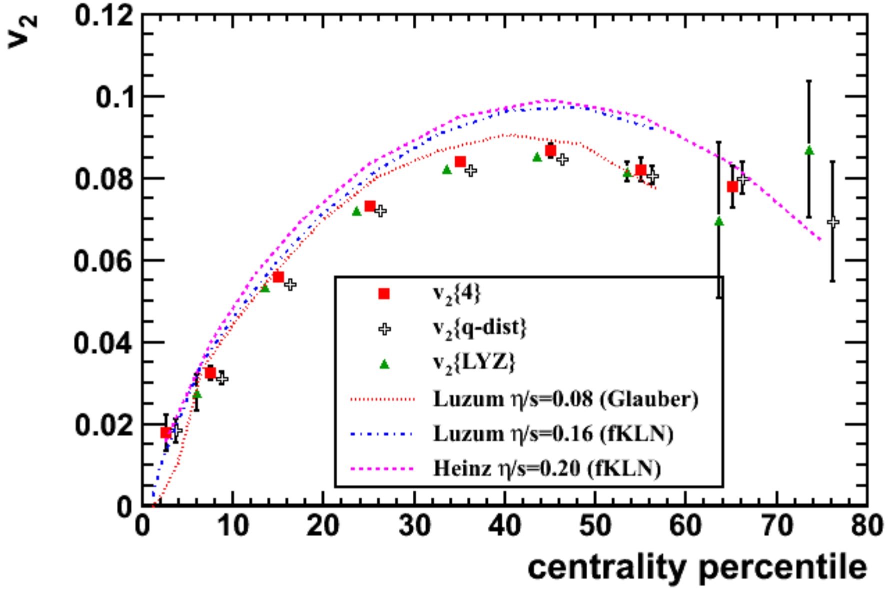


Azimuthal asymmetry

- to quantify the asymmetry:
  → Fourier expansion of the angular distribution:

$$1 + 2v_1\cos(\varphi) + 2v_2\cos(2\varphi) + \ldots$$

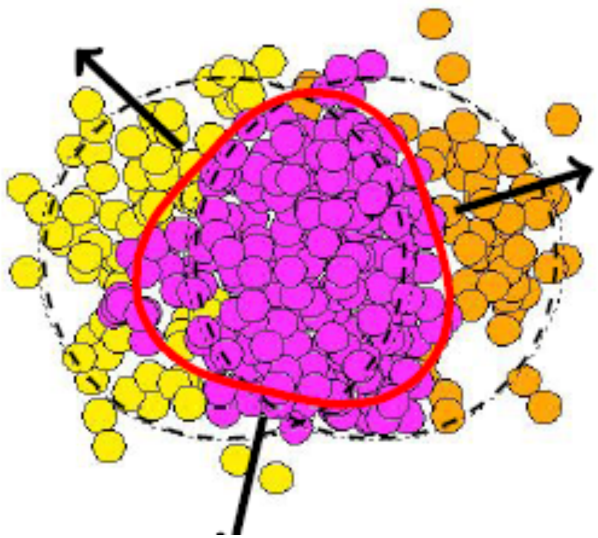
  – in the central detector region (~ 90º) → v_1 ~ 0 → asymmetry quantified with v_2
- v_2 still almost as large as expected by hydrodynamics
  – small increase in η/s wrt RHIC?

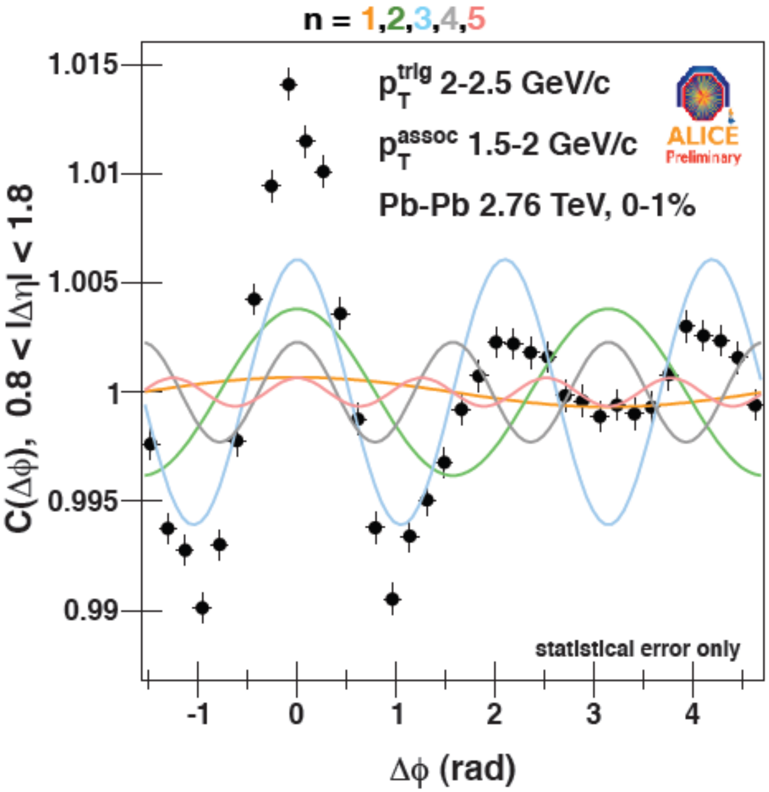


Higher harmonics

- a beautiful phenomenon…

initial state geometrical asymmetries → final state momentum asymmetries

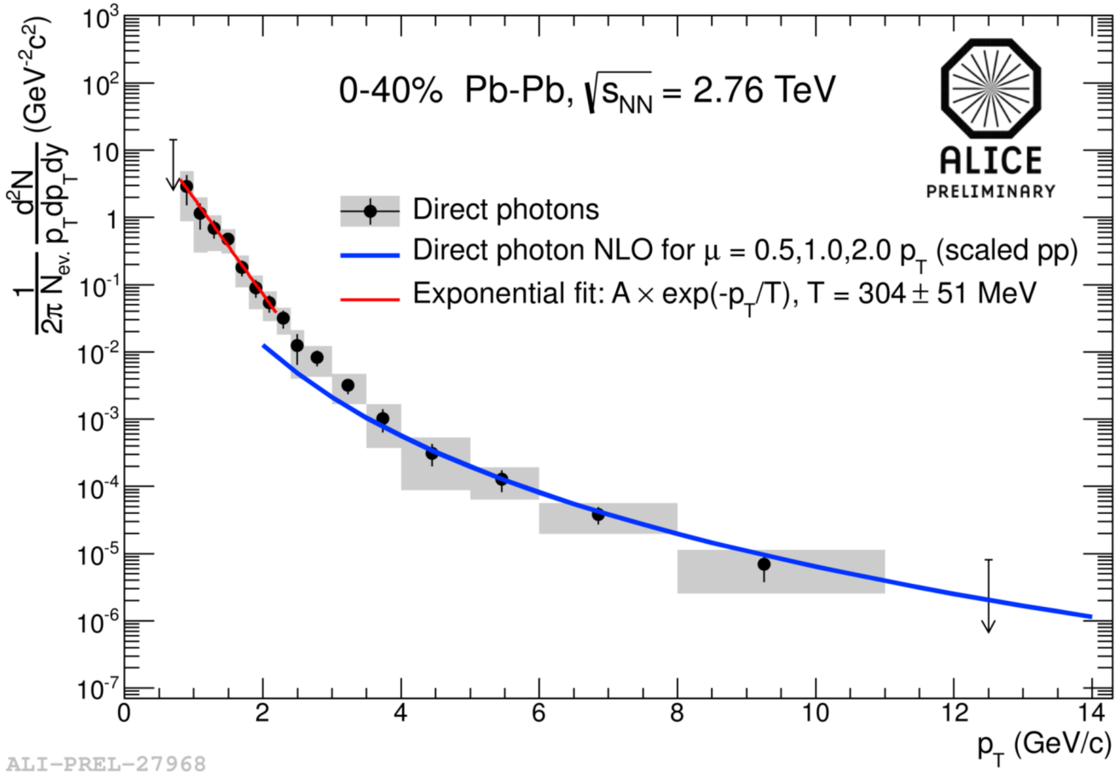




- wonderful tool to study response of medium to initial fluctuations
  → infer medium properties

It shines!

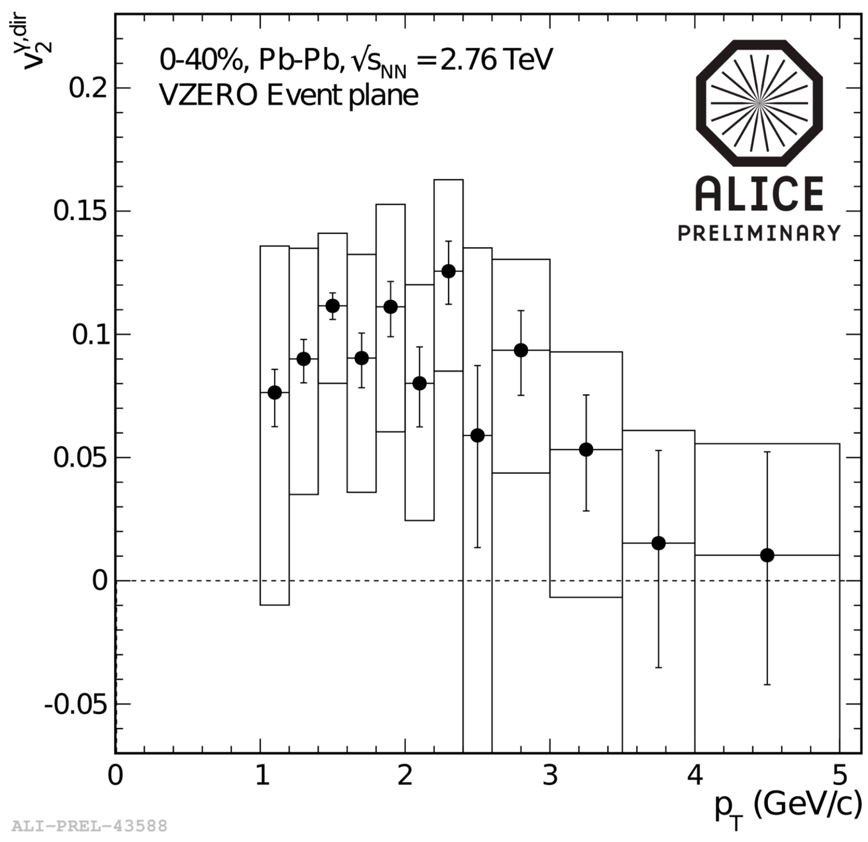
- direct photon spectrum



- “temperature” ~ 300 MeV → largest ever man-made

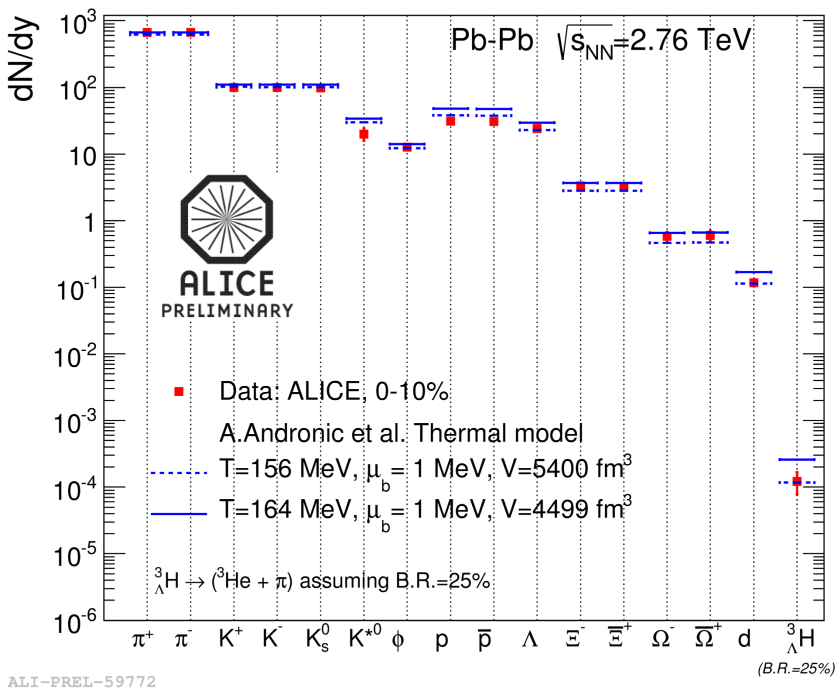
Asymmetrically…?

- direct photon v2 in 0-40% Pb-Pb

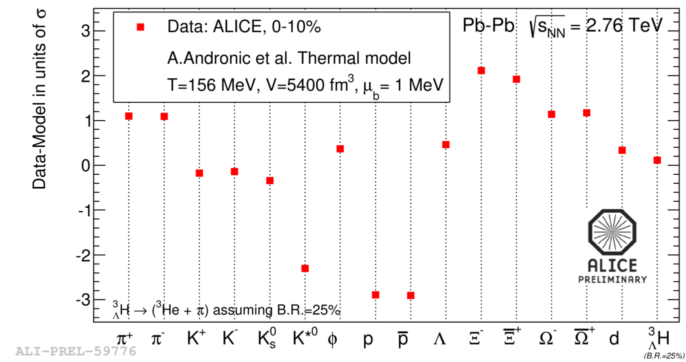


Particle yields

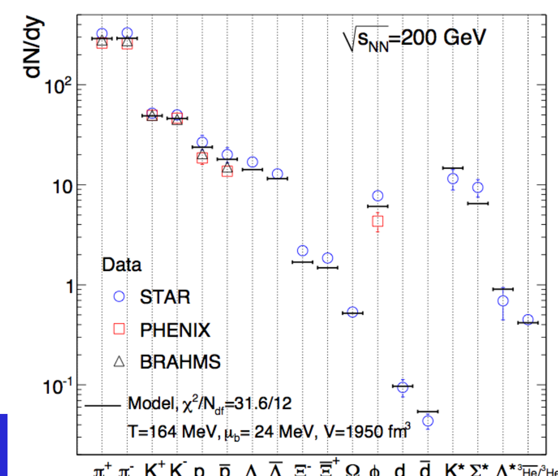
- thermal model fit
  - now including $^{3}_{\Lambda}H$!



- some tension…
  - especially p and K*



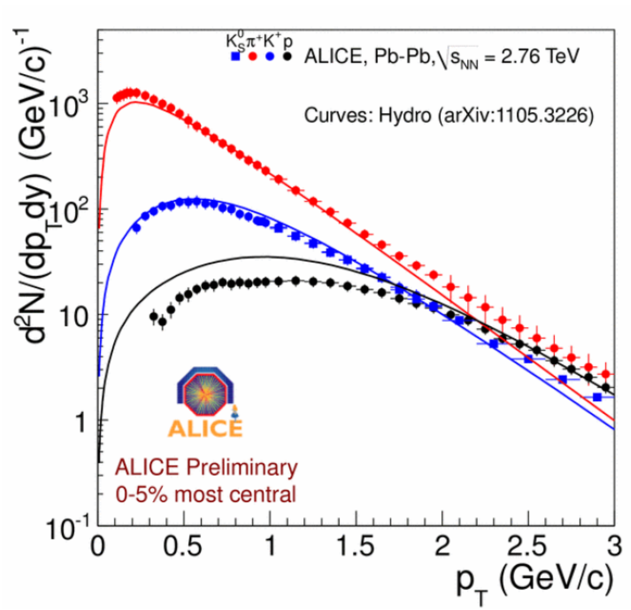
- at RHIC?
  - some tension too?
  - lower precision…

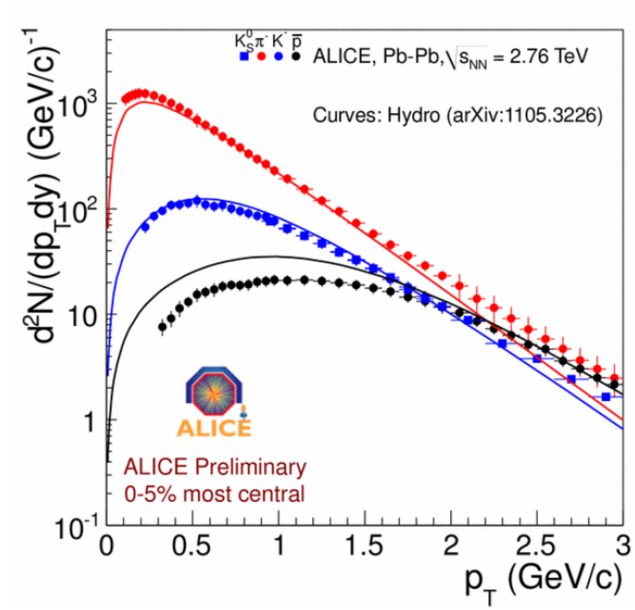


Identified particles

- different particles have different mass → info on collective expansion

positive particles – 0-5% most central **negative particles – 0-5% most central**



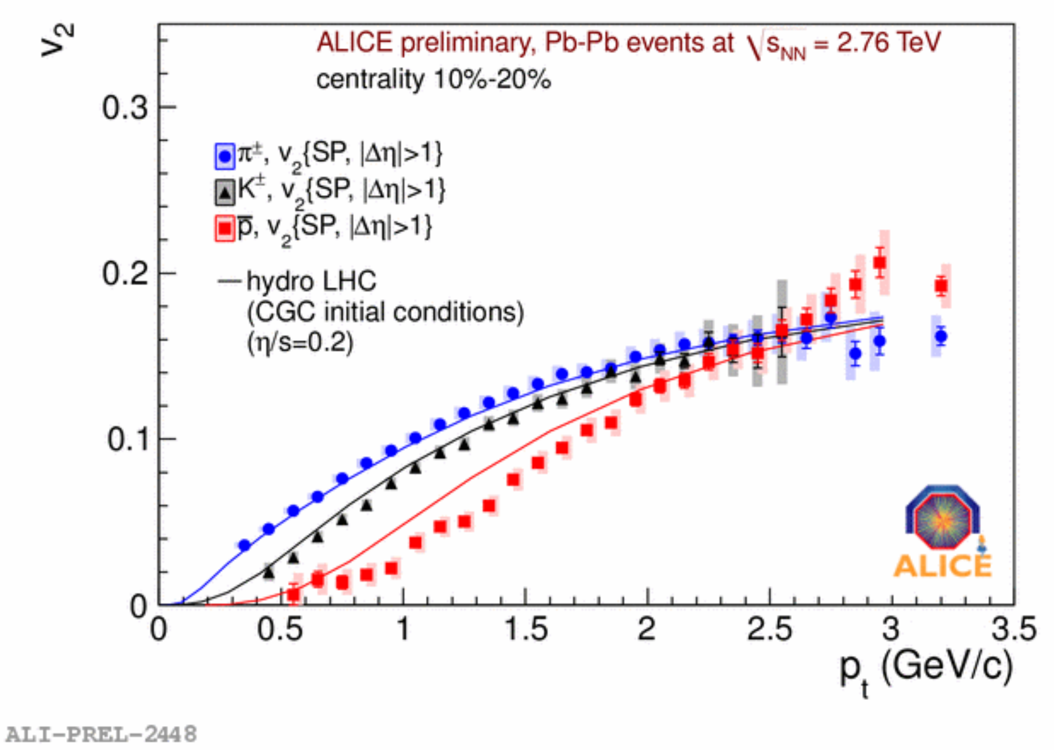


- p_T distributions can be predicted assuming expansion is "hydrodynamical" (i.e.: one common velocity field)

→ OK for π and K, but p seem to "misbehave" (less yield, flatter spectrum)

Azimuthal asymmetry of identified particles

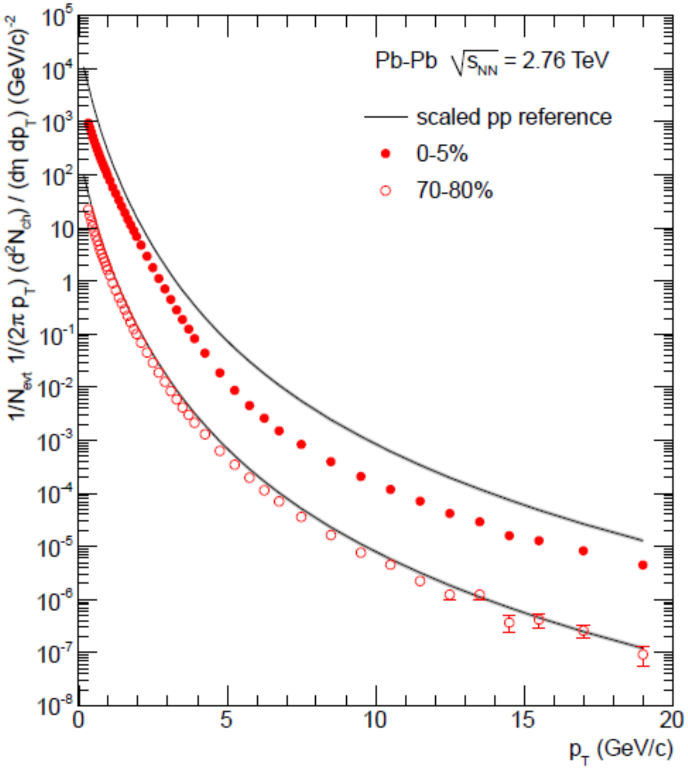
- comparison of identified particles $v_2(p_T)$ with hydrodynamic prediction



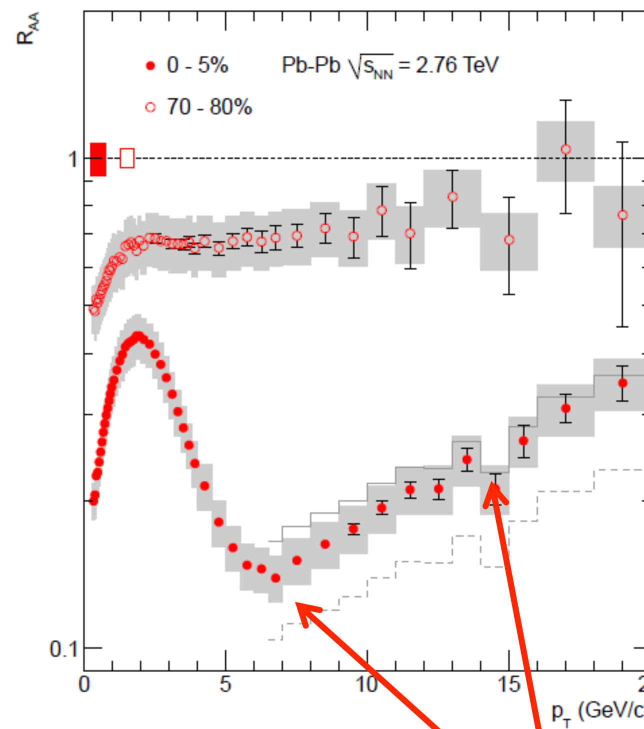
→ again, protons are off…

Strong quenching!

- Pb-Pb significantly below scaled pp for central collisions (filled points)



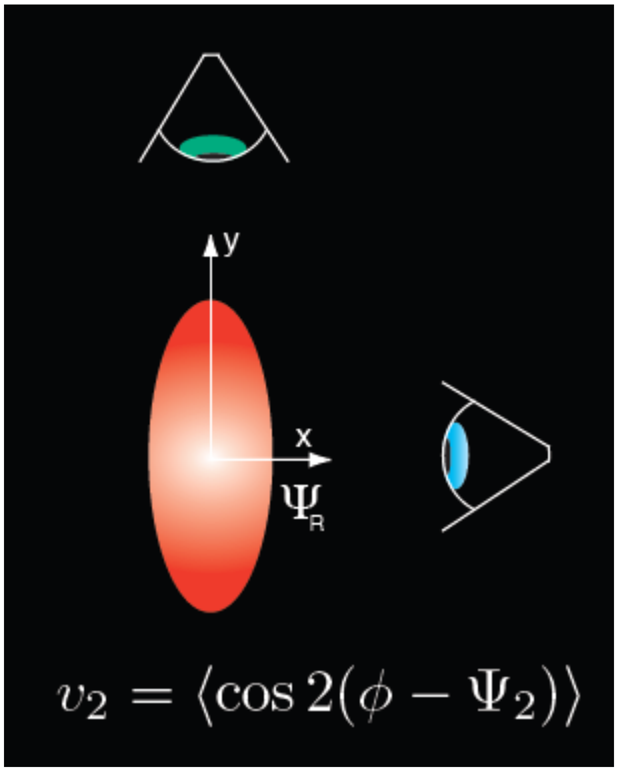
- RAA:

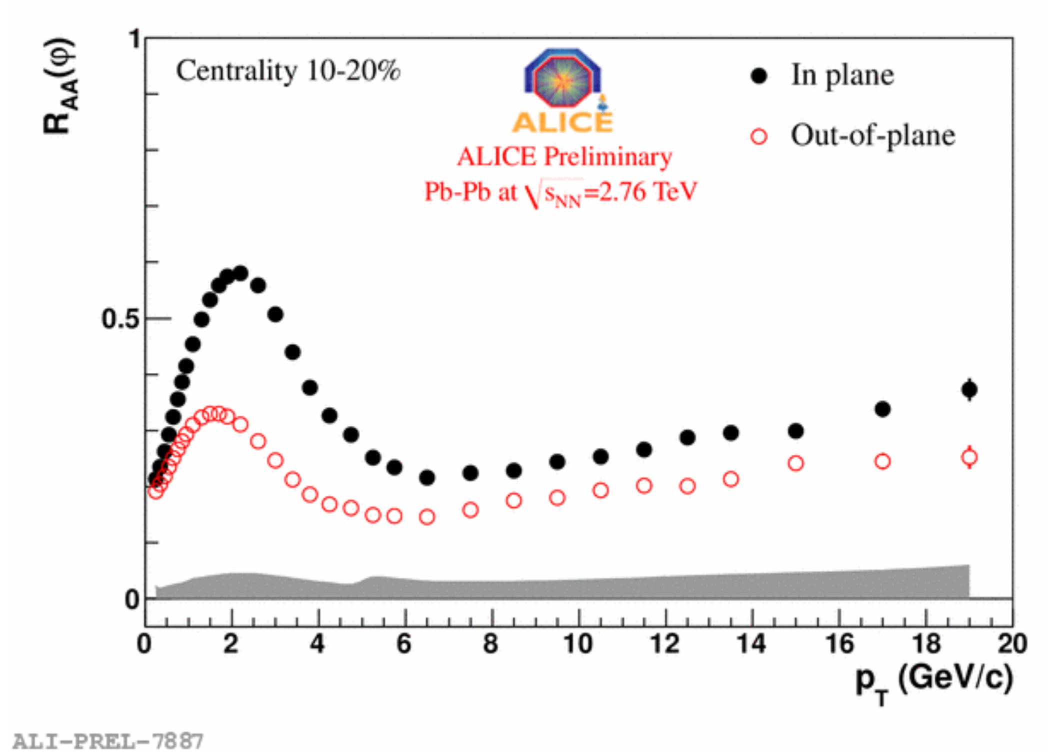


  - minimum around 6-7 GeV (R_{AA} ~ 0.14)
  - clear increase at higher p_T

Strong angular dependence

- significant effect, even at 20 GeV and beyond!

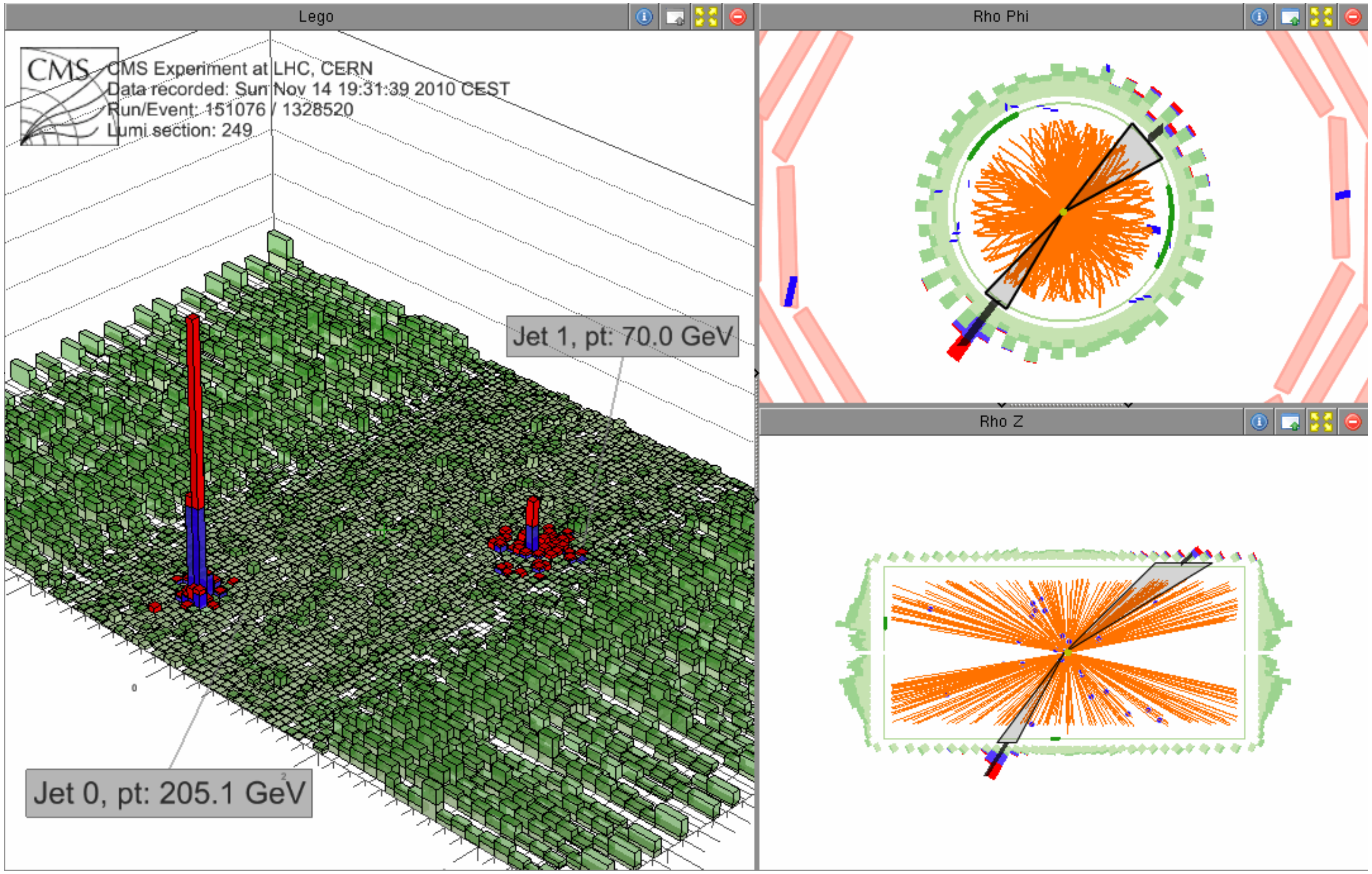




→ sensitivity to path length dependence of energy loss

Di-jet imbalance

- Pb-Pb events with large di-jet imbalance observed at the LHC

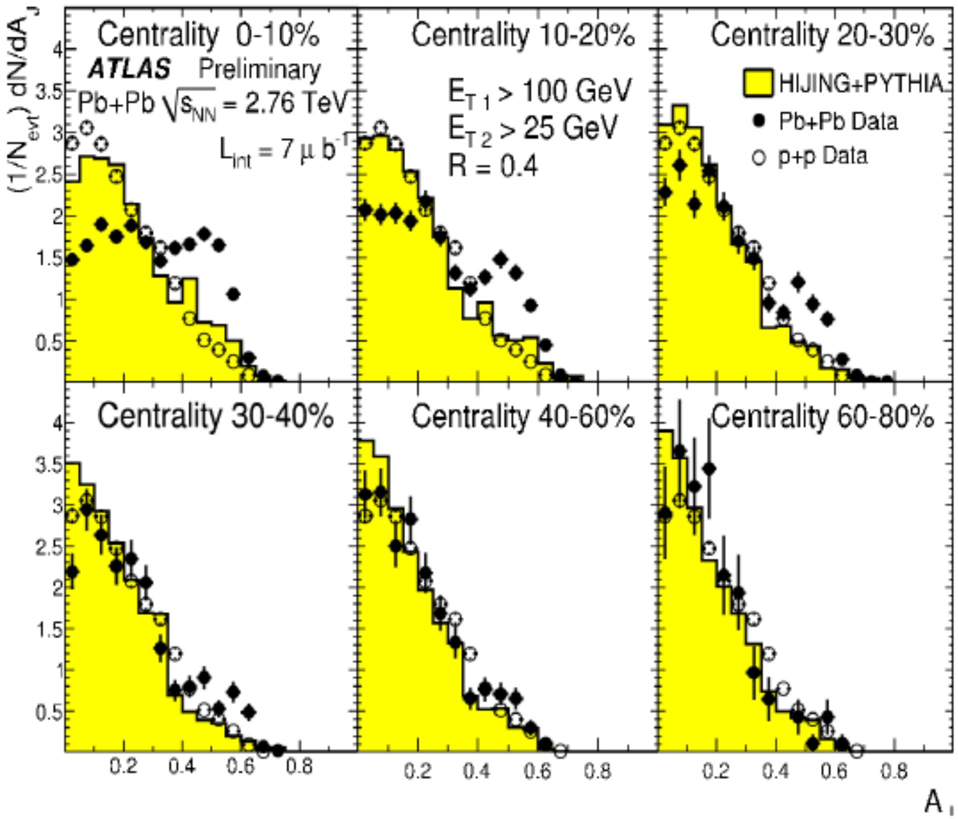


→ recoiling jet strongly quenched!

CMS: arXiv:1102.1957

Di-jet imbalance

- imbalance quantified by the di-jet asymmetry variable A_J:



$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \qquad E_{T1} > 100\,GeV \quad E_{T2} > 25\,GeV$$

$$R = 0.4 \qquad |\eta| < 2.8$$

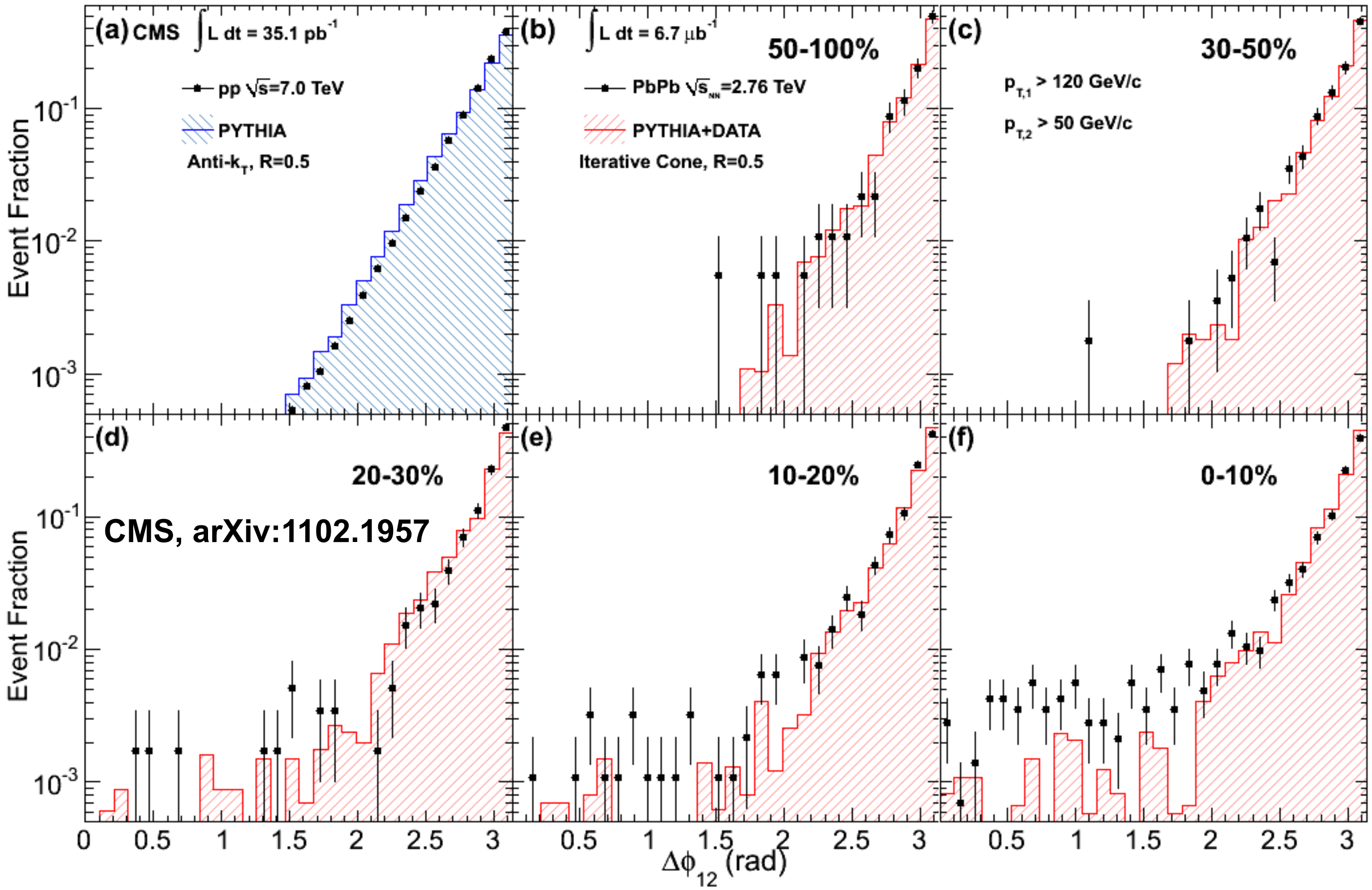
- with increasing centrality:

→ enhancement of asymmetric di-jets with respect to pp
  - & HIJING + PYTHIA simulation

ATLAS: PRL105 (2010) 252303

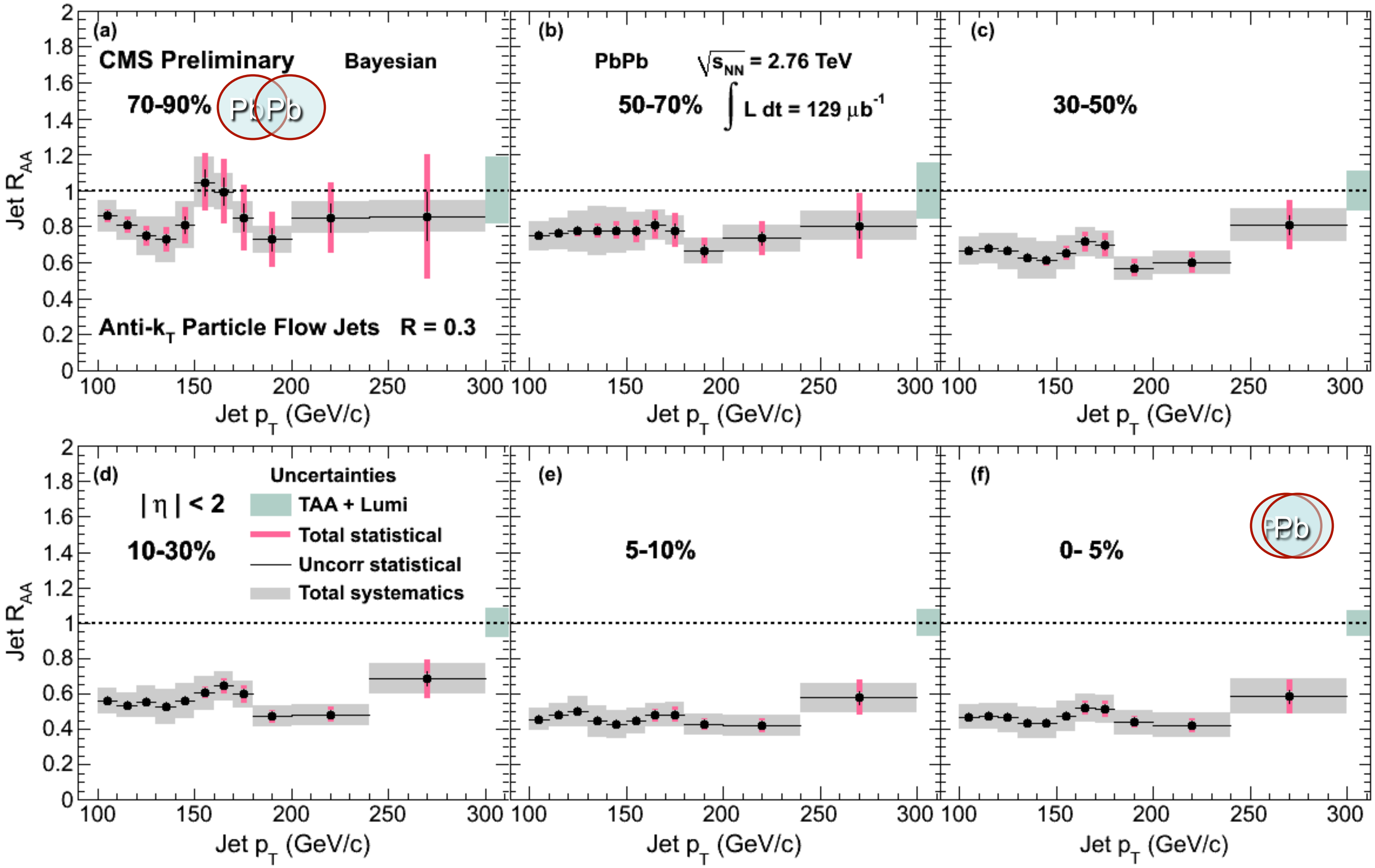
Di-jet Δφ

- no visible angular decorrelation in Δφ wrt pp collisions!



→ large imbalance effect on jet energy, but very little effect on jet direction!

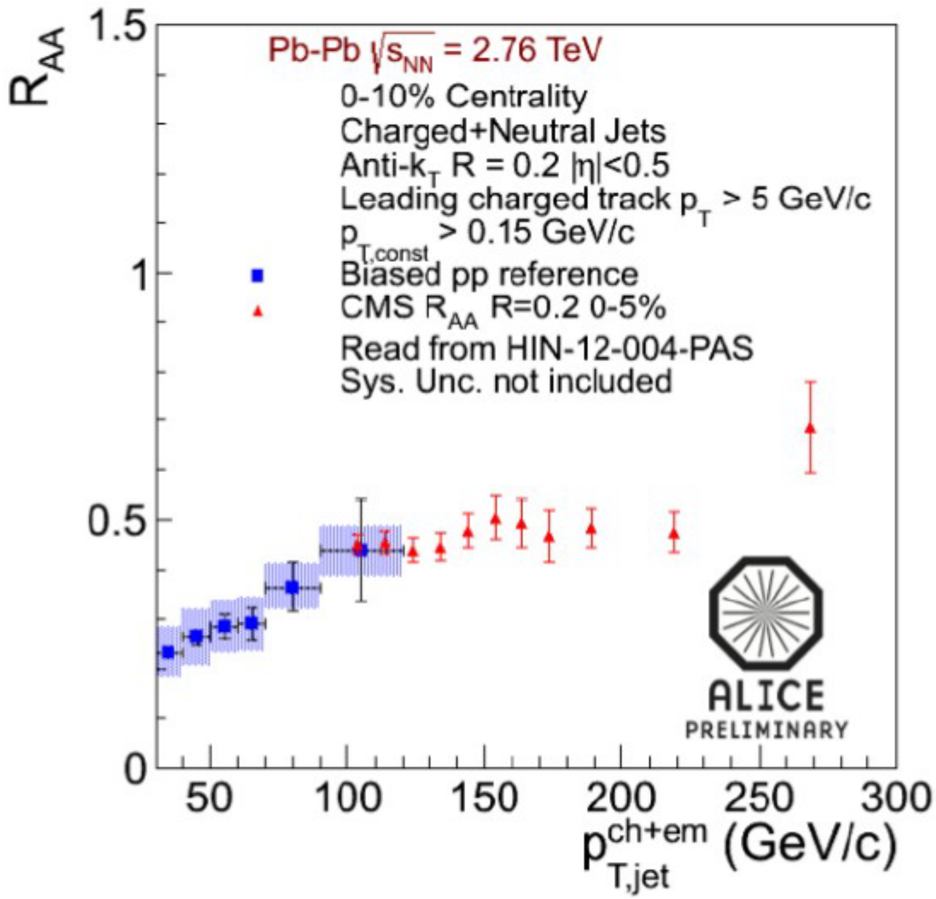
Jet R_{AA}



CMS PAS HIN-12-004

Jet R_{AA}, low p_T

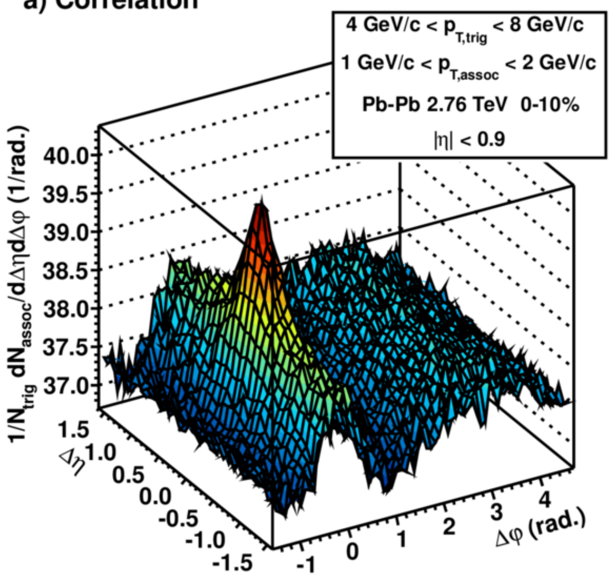
- change of behaviour at low p_T? it seems to decrease further…



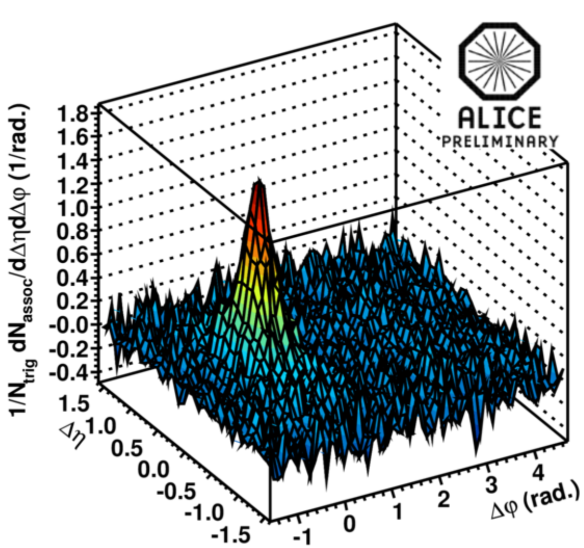
- caveat: orange and mandarin…

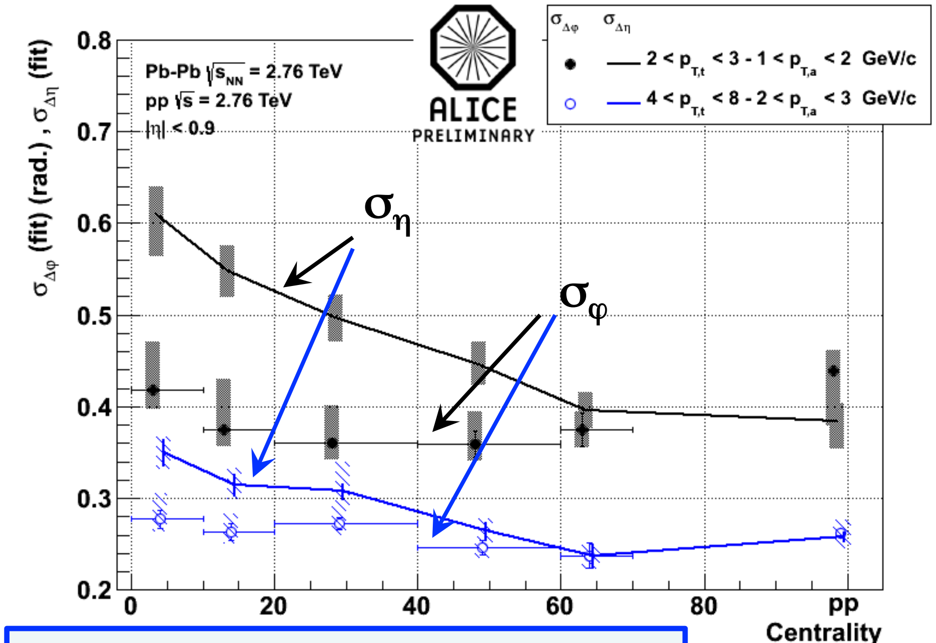
Near-side broadening

a) Correlation



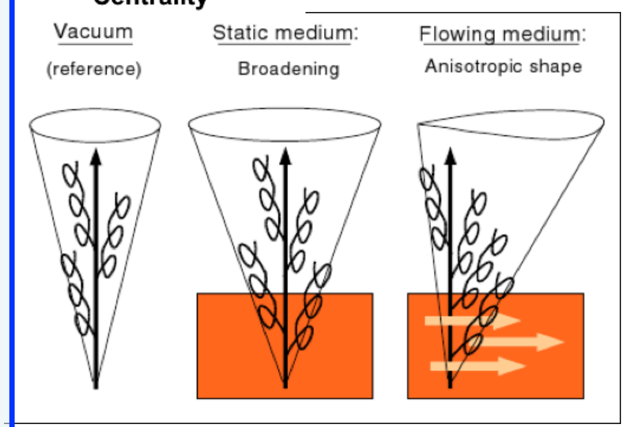
b) η-gap subtracted





Evolution of near-side-peak σ_η and σ_φ with centrality: Strong σ_η increase for central collisions

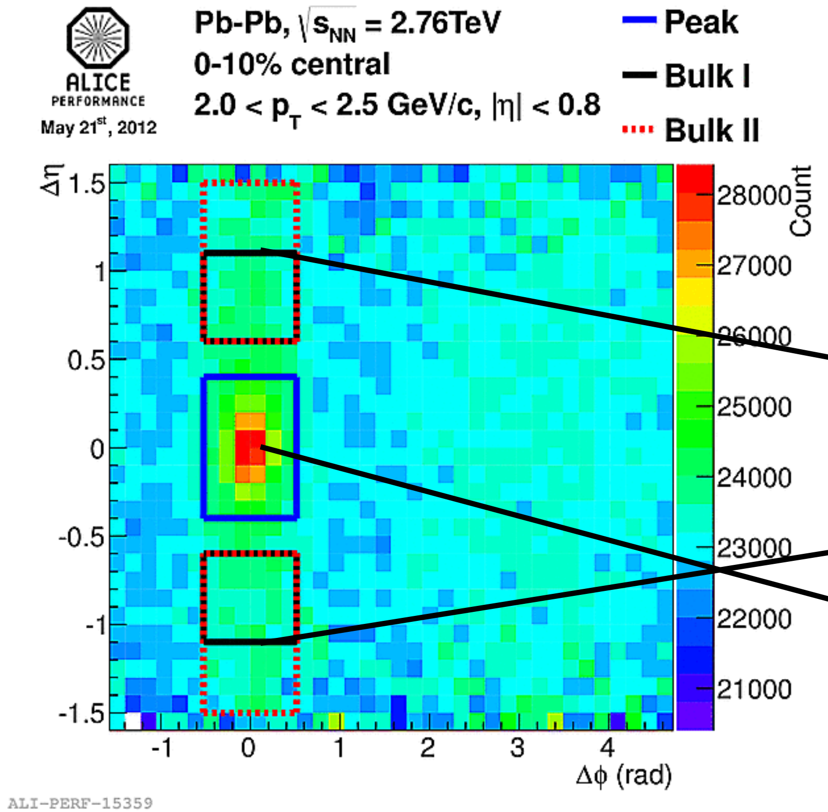
Interestingly: AMPT describes the data very well
Influence of flowing medium?

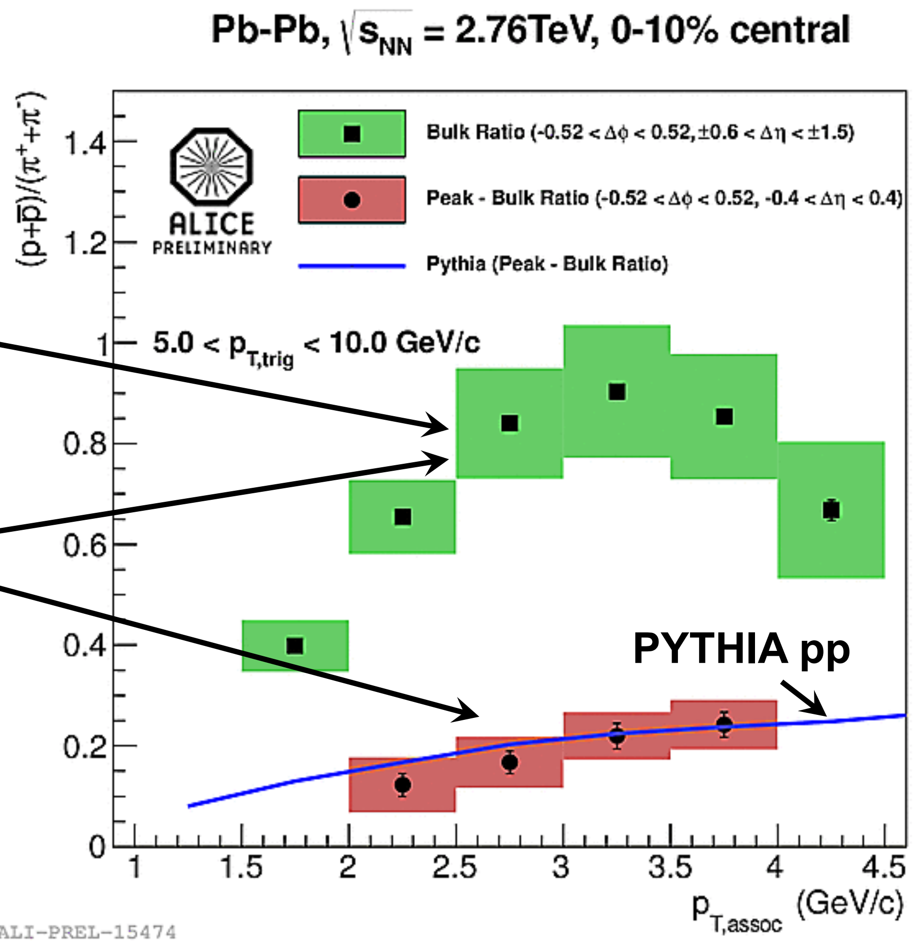


N.Armesto et al., PRL 93, 242301

Particle composition

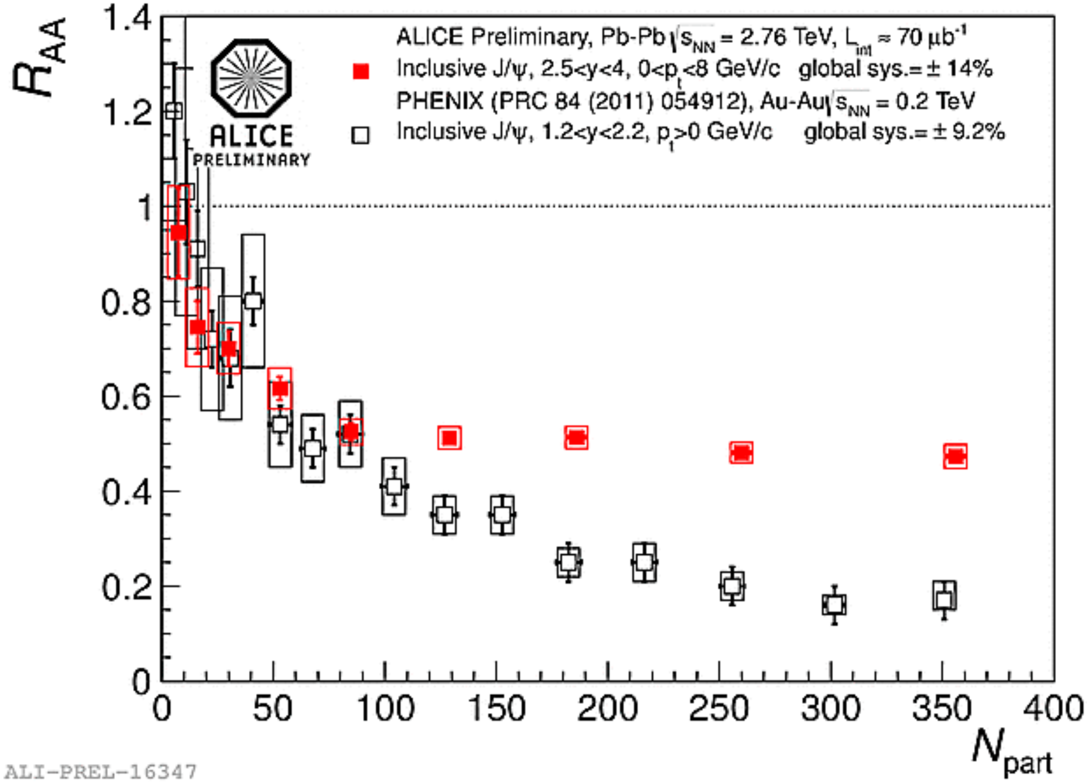
- peak excess particle composition similar to pp!





J/ψ suppression at LHC

- LHC: 2.5 < y < 4, p_T > 0 (ALICE)



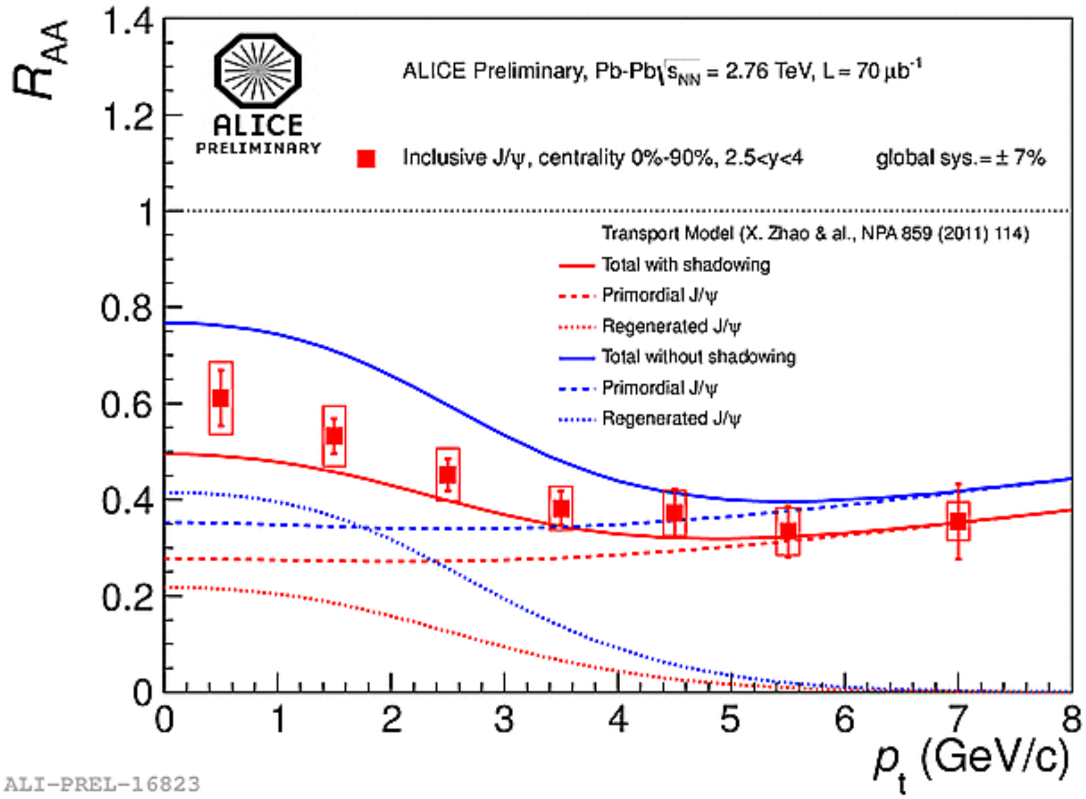
→ less suppression than RHIC: 1.2 < y < 2.2, p_T > 0 (PHENIX)

→ centrality dependence is much weaker! what's going on?

→ c-cbar coalescence?

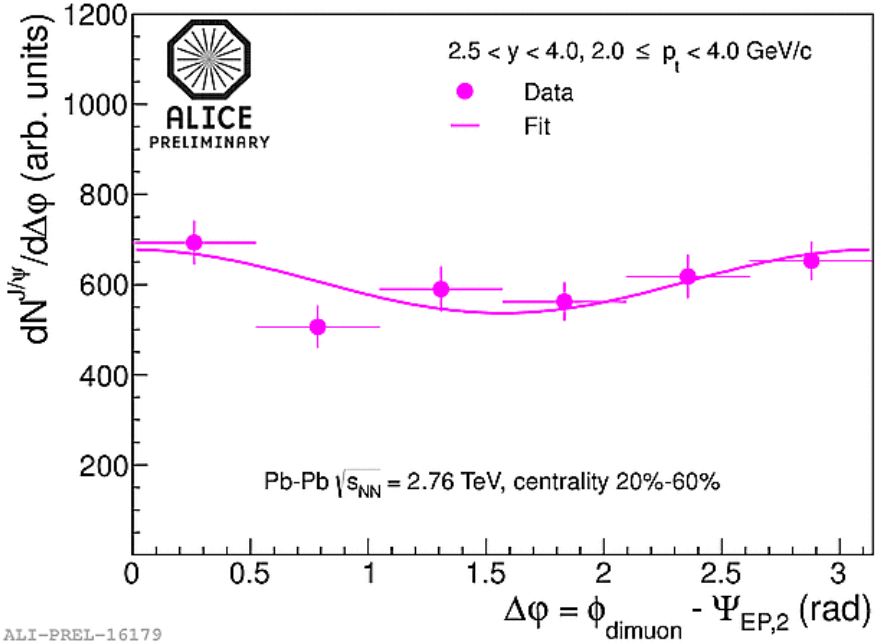
J/ψ R_{AA}: p_T dependence

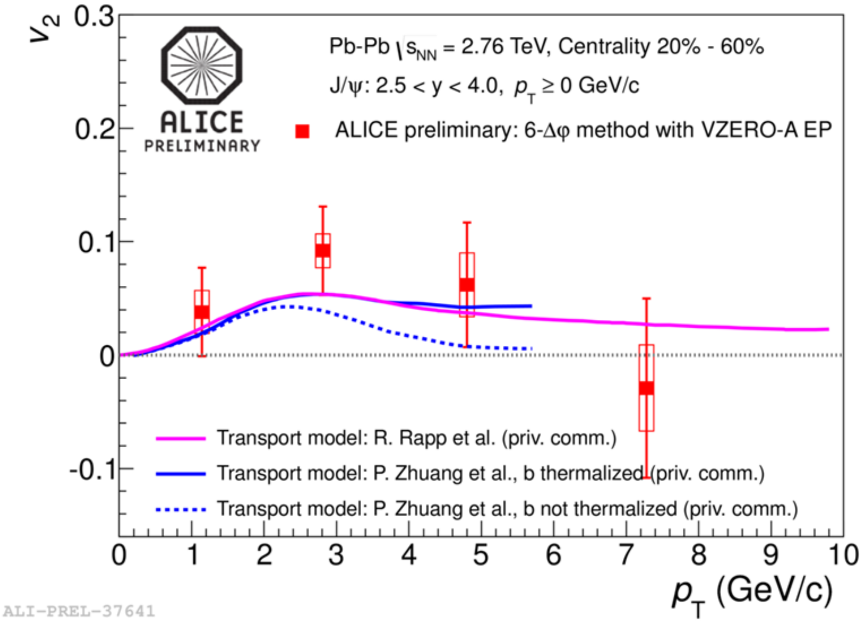
- consistent with coalescence models



J/ψ flow?

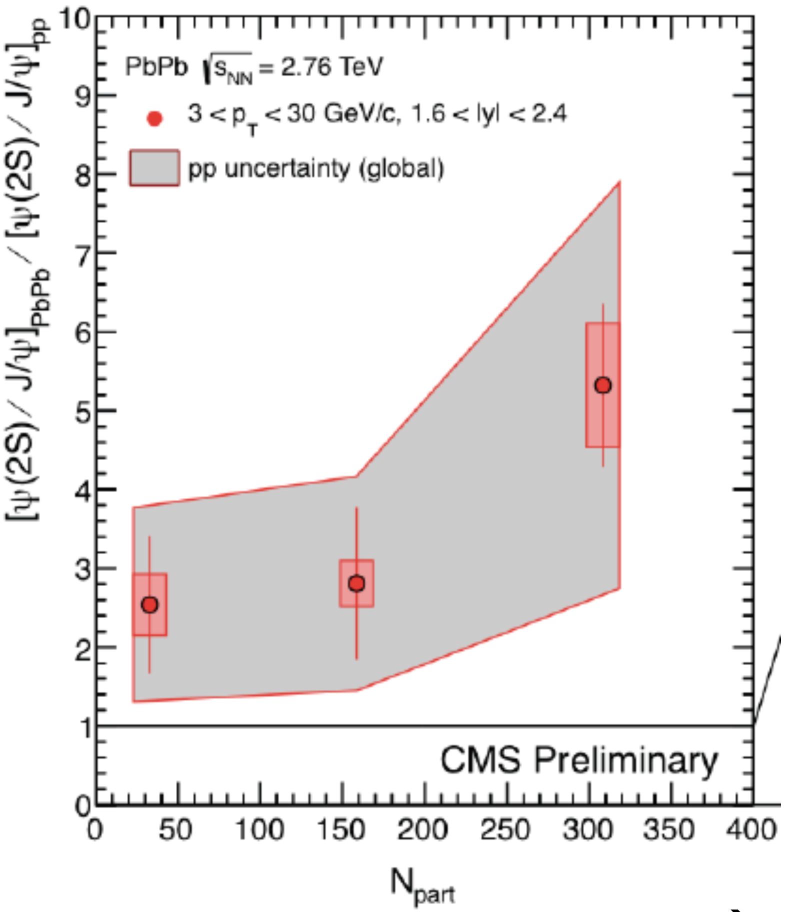
- some hint for a modulation…?

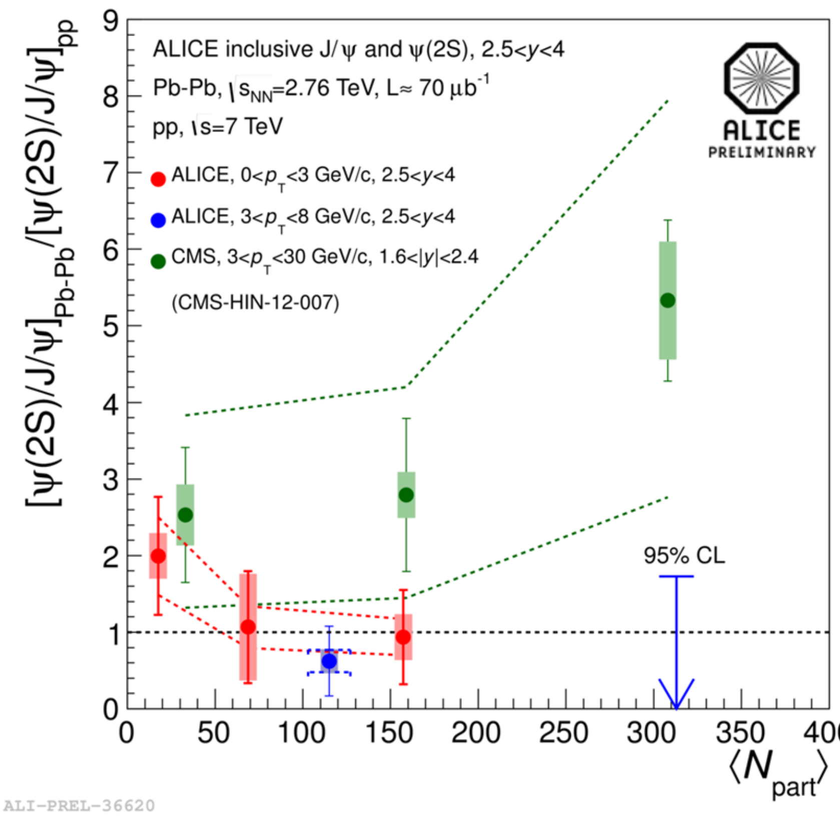




What about ψ'?

- ψ' less suppressed than J/ψ? (CMS)
- not confirmed by ALICE…

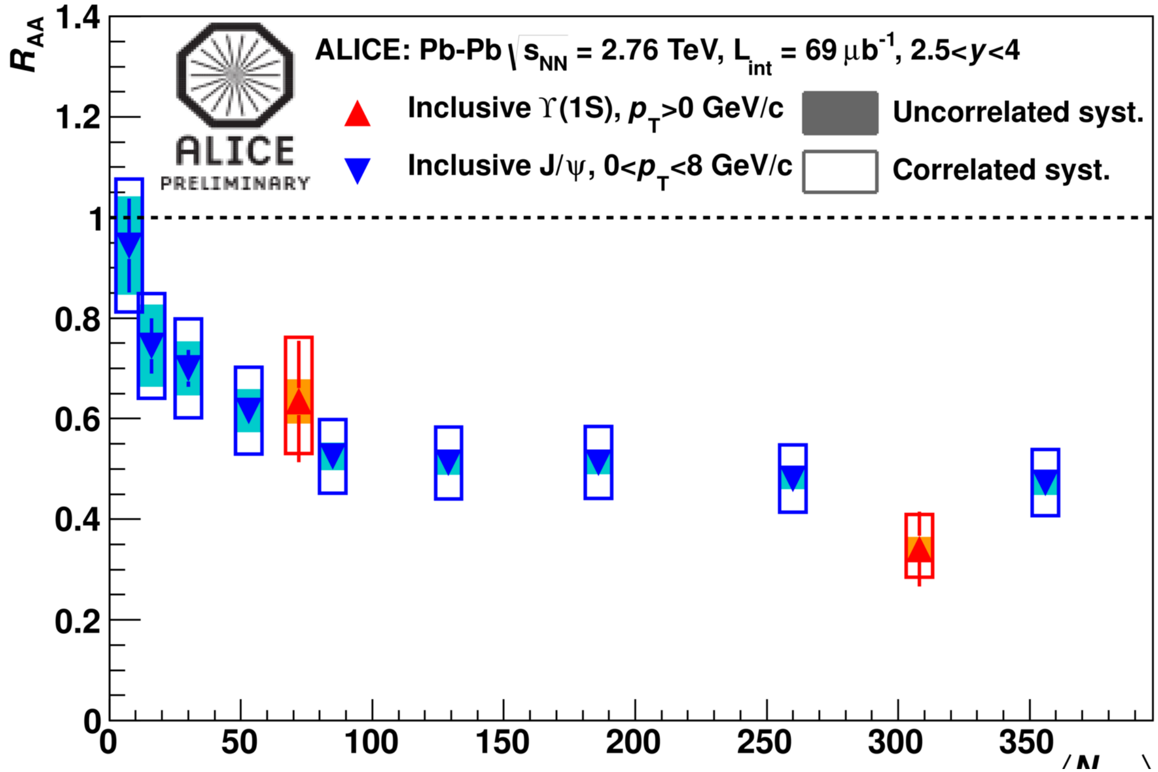




→ à suivre…

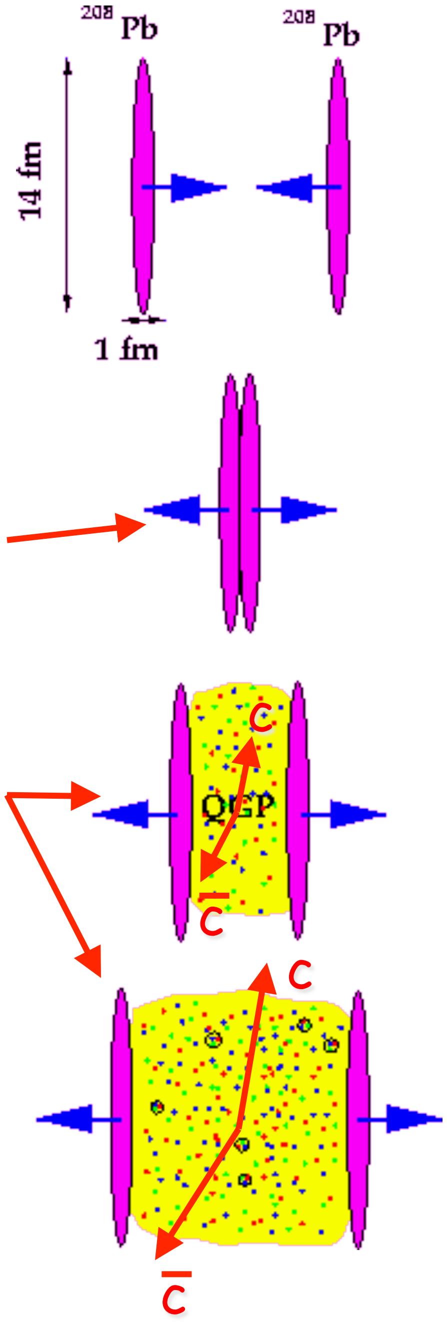
Υ (1S)

- Υ(1S) R_{AA} (compared with J/ψ R_{AA})



Heavy Flavours

- a very promising tool: probe the system with heavy quarks: c (charm) and b (beauty)
- these are produced in pairs in the initial impact between the two nuclei …
- …they propagate through the quark and gluon soup…
- … and finally emerge carrying out information on the system properties



Theoretically...

$$\langle \Delta E \rangle \propto \alpha_s C_R \, \hat{q} \, L^2$$

average energy loss

Casimir coupling factor

transport coefficient of the medium

distance travelled in the medium

→ R.Baier et al., Nucl. Phys. **B483** (1997) 291 ("BDMPS")

Energy loss for heavy flavours is expected to be reduced:

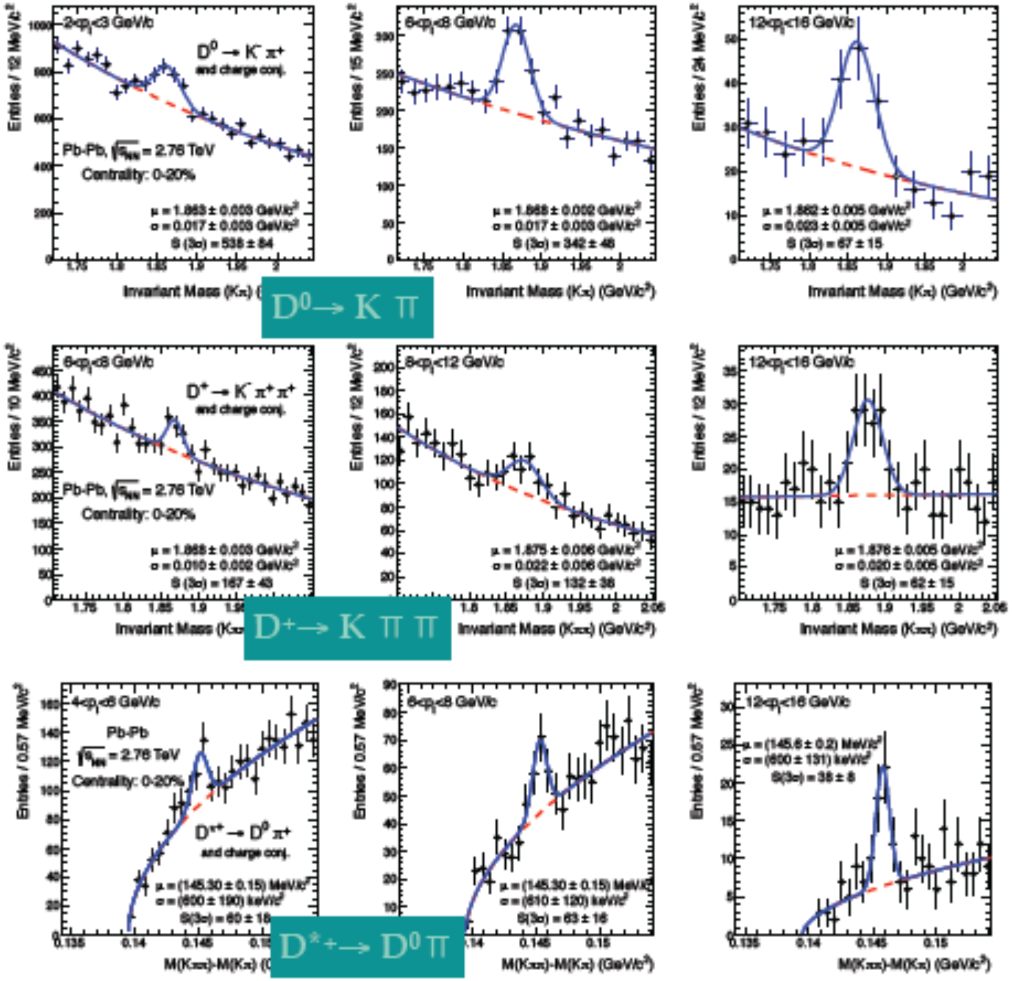
i) Casimir factor

- light hadrons originate from a mixture of gluon and quark jets, heavy flavoured hadrons originate from quark jets
- C_R is 4/3 for quarks, 3 for gluons

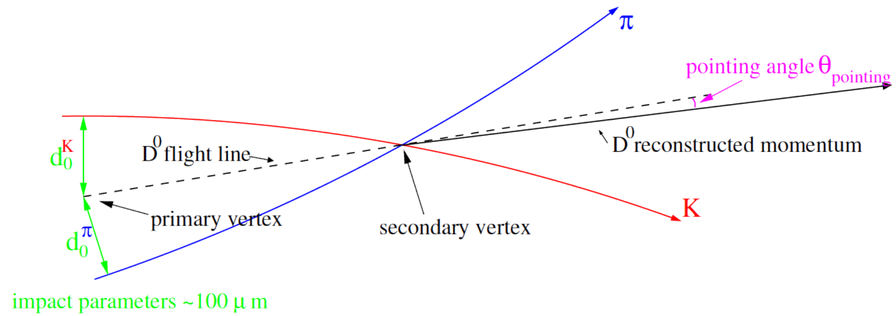
ii) dead-cone effect

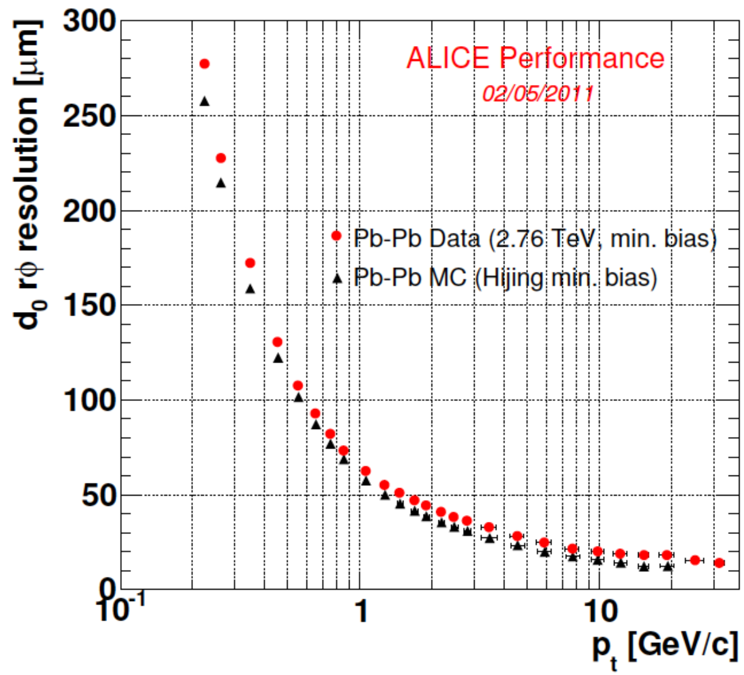
- gluon radiation expected to be suppressed for $\theta < M_Q/E_Q$
  [Dokshitzer & Karzeev, Phys. Lett. **B519** (2001) 199]
  [Armesto et al., Phys. Rev. D69 (2004) 114003]

Reconstructed D mesons!

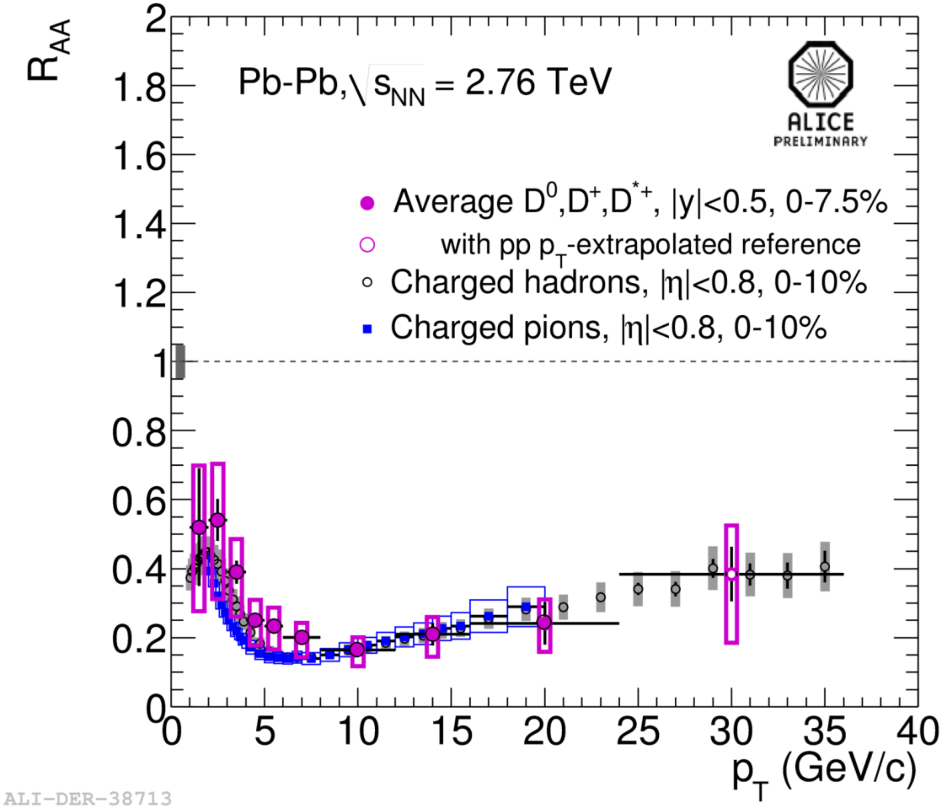


D⁰, D⁺ and D*⁺ signals in p_t bins for 0-20%CC



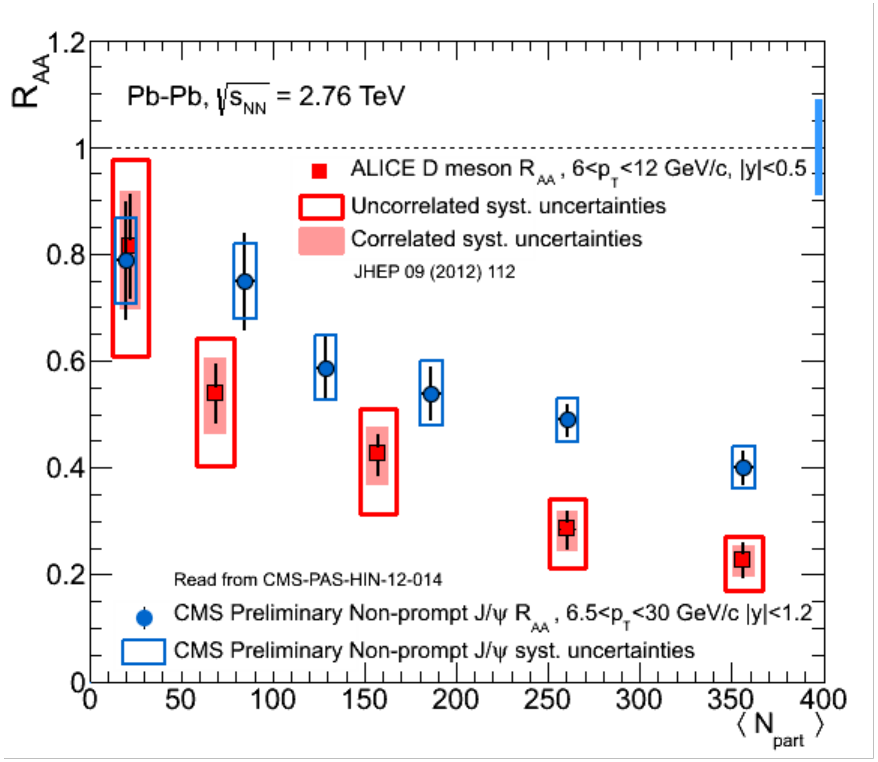


Heavy Flavours R_{AA}



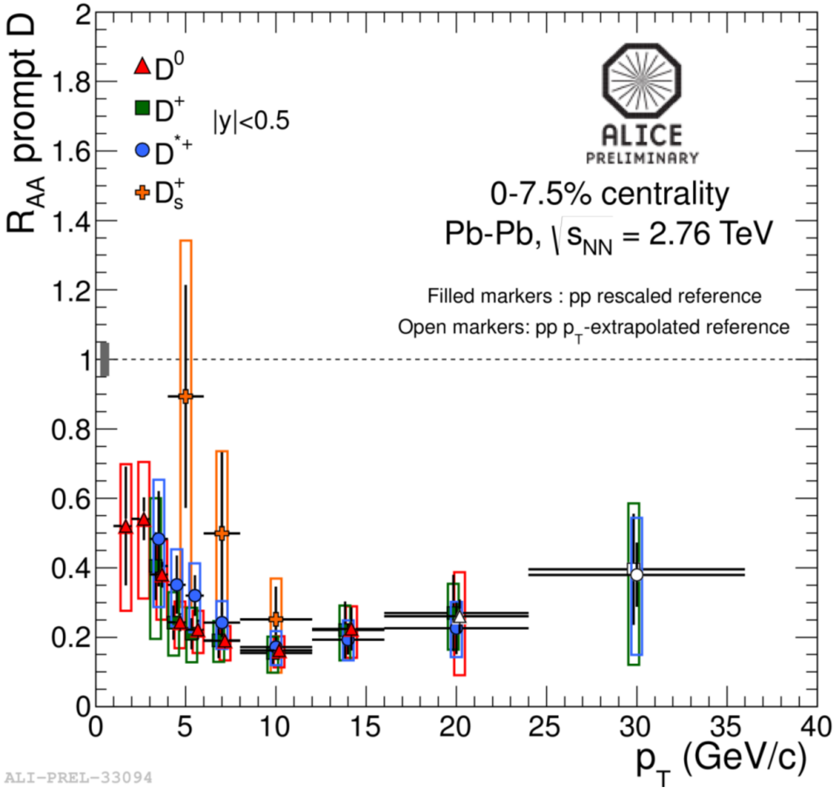
- p_T < 8 GeV/c:
  - hint of less suppression than for π ?
- p_T > 8 GeV/c
  - same suppression as for π…

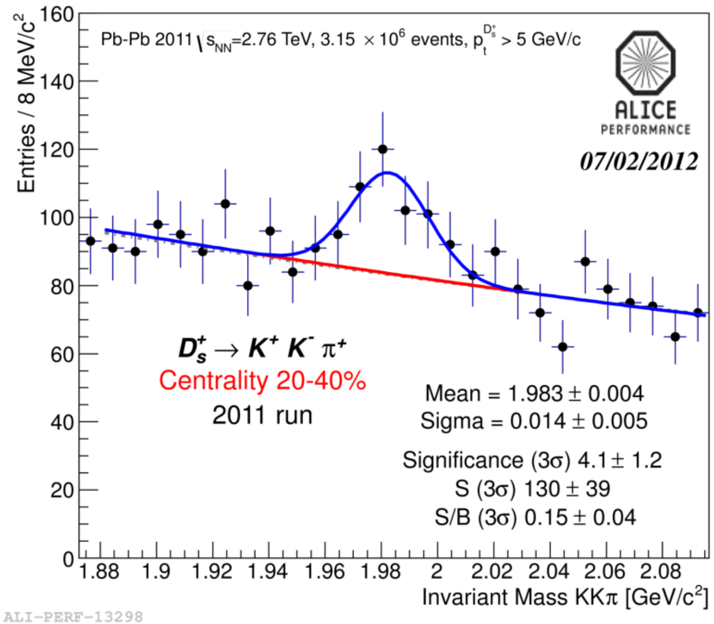
- \+ indication of less suppression for beauty?



The D_s

- HF in-medium hadronisation!

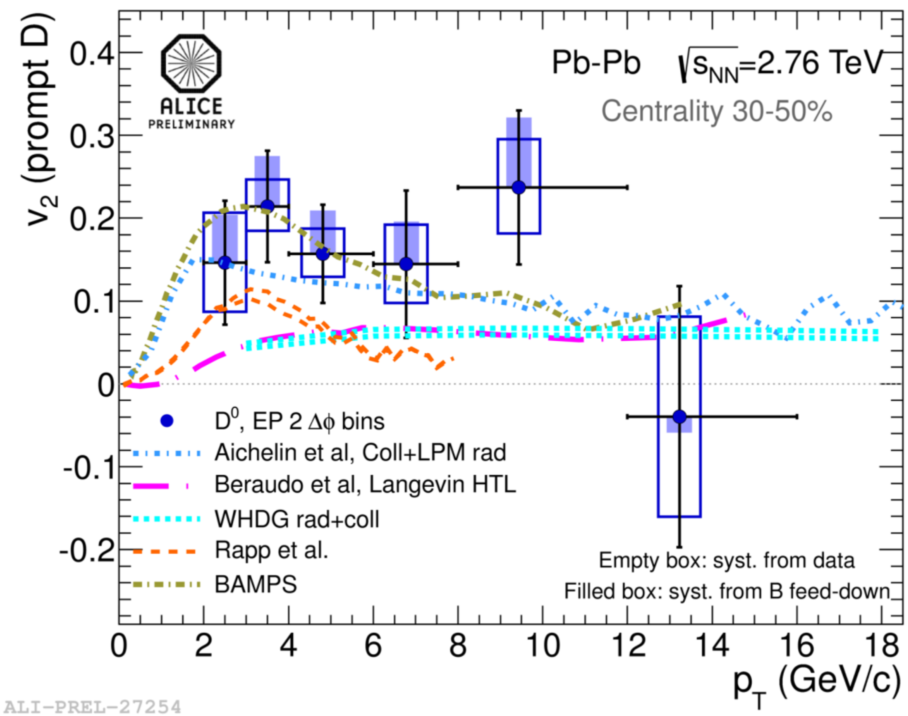




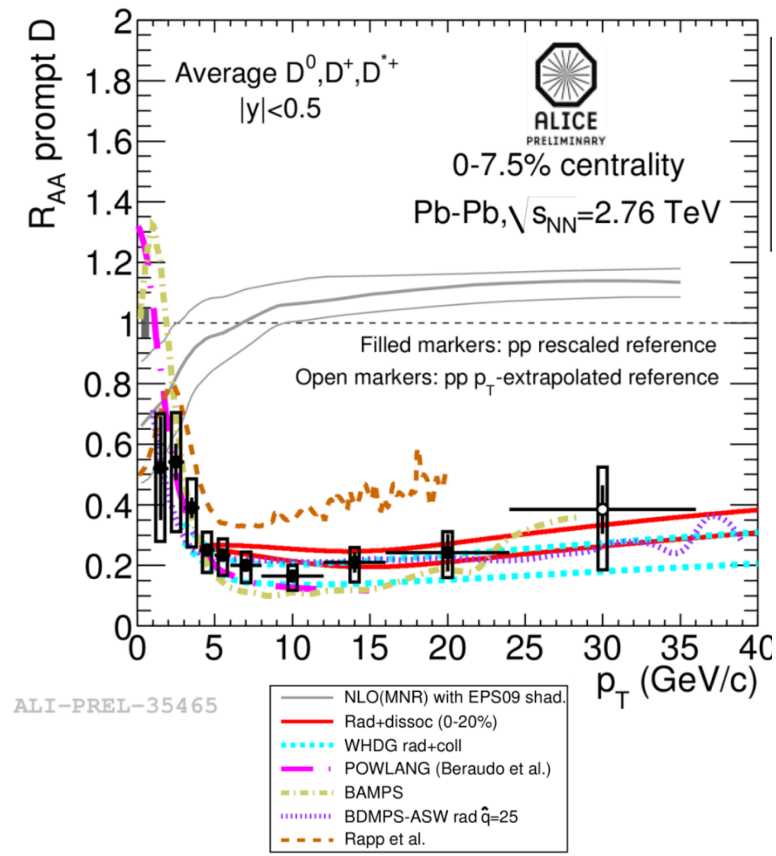
- a hint of strangeness enhancement?
- more stats needed!

D meson v_2

- Hint of non-zero v_2
  - consistent with strong coupling of c to medium

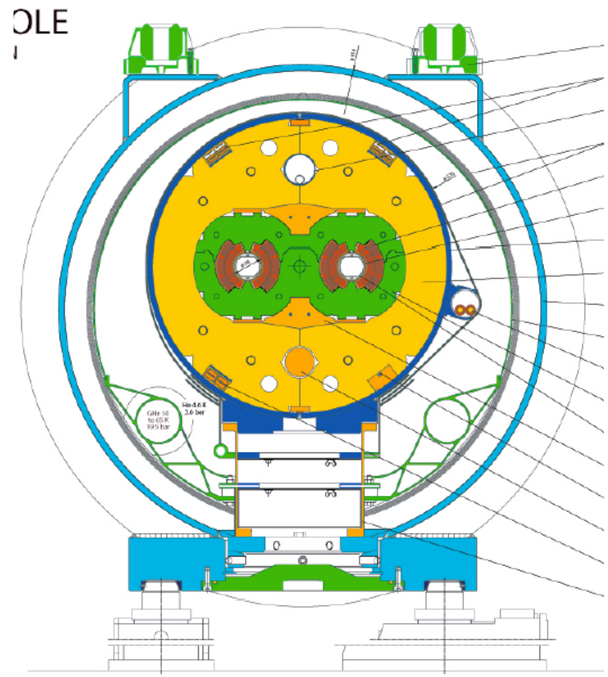


- theory must describe simultaneously v_2 and R_{AA} …



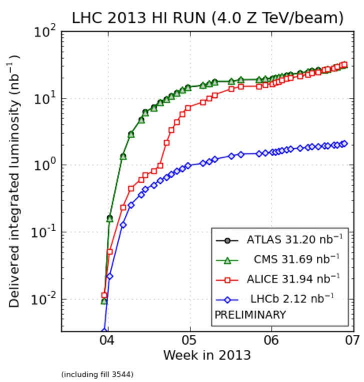
p-Pb collisions in the LHC!

- tricky, but can be done…
- 2-in-1 design…
  - → identical bending field in two beams
  - → locks the relation between the two beam momenta:
    p (Pb) = Z p(proton)
  - ➔ different speeds for the two beams!

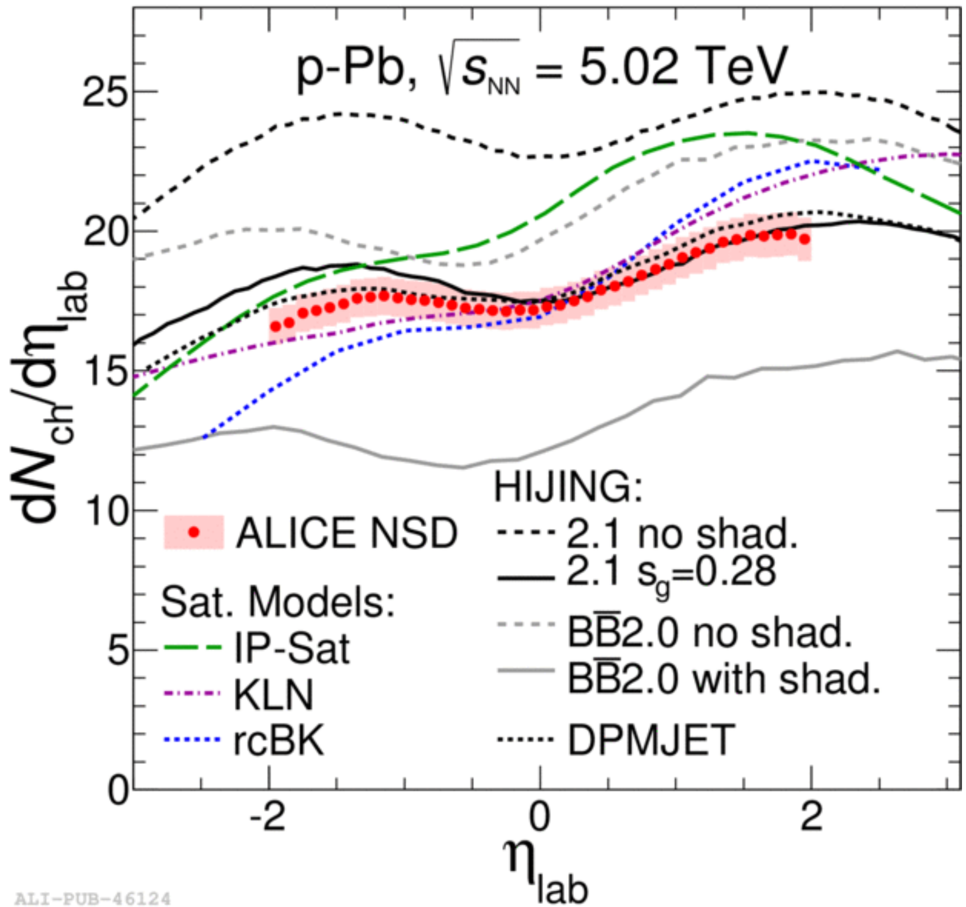


- adjust length of closed orbits!
  - – to compensate different speeds
- different RF freq for two beams at injection and ramps
- short low lumi pilot run (a few hours) on 12/9/2012
- first run in Jan-Feb 2013!

→ ~ 30/nb



$dN_{ch}/d\eta$

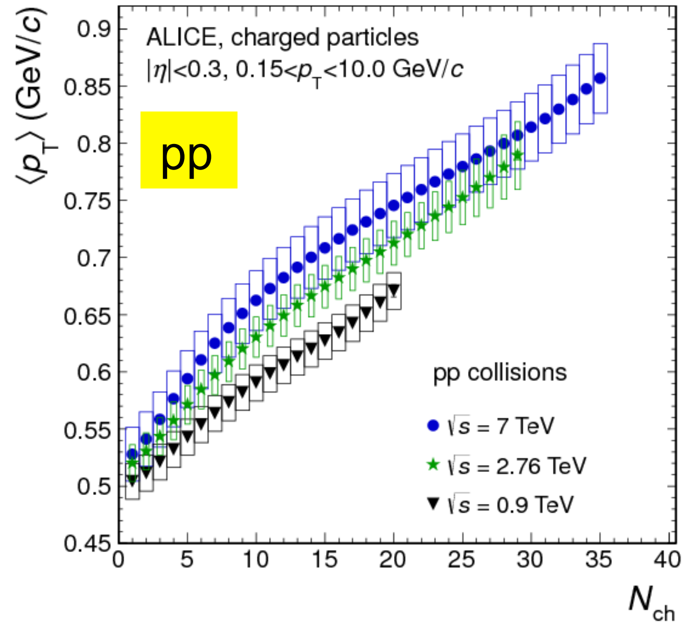


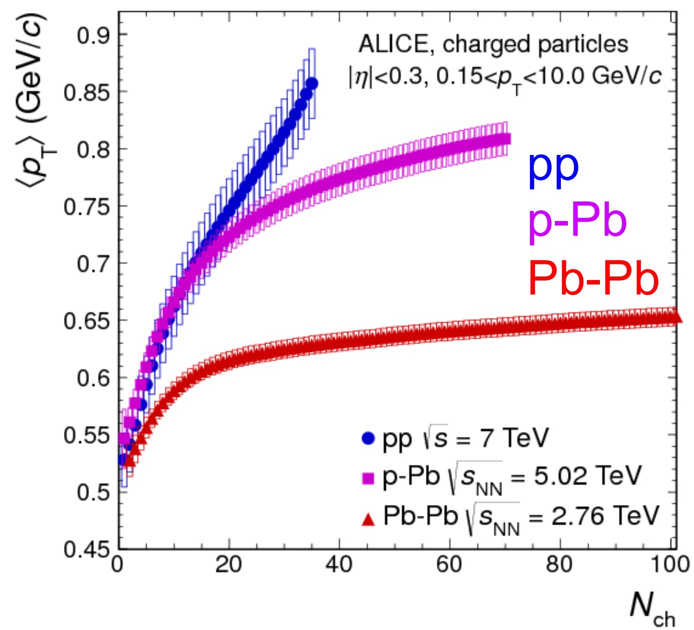
- saturation predictions seem to have too steep η dependence…

$\langle p_T \rangle$ vs. N_{ch}

arXiv:1307.1094

- pp: weak √s dependence
- p-Pb follows pp for $N_{ch} < 15$
  - 90% σ in pp
  - 50% σ in p-Pb
  - 18% in Pb-Pb
- for $N_{ch} > 40$, p-Pb ~ // Pb-Pb
  - 1% σ in p-Pb
  - 70% in Pb-Pb



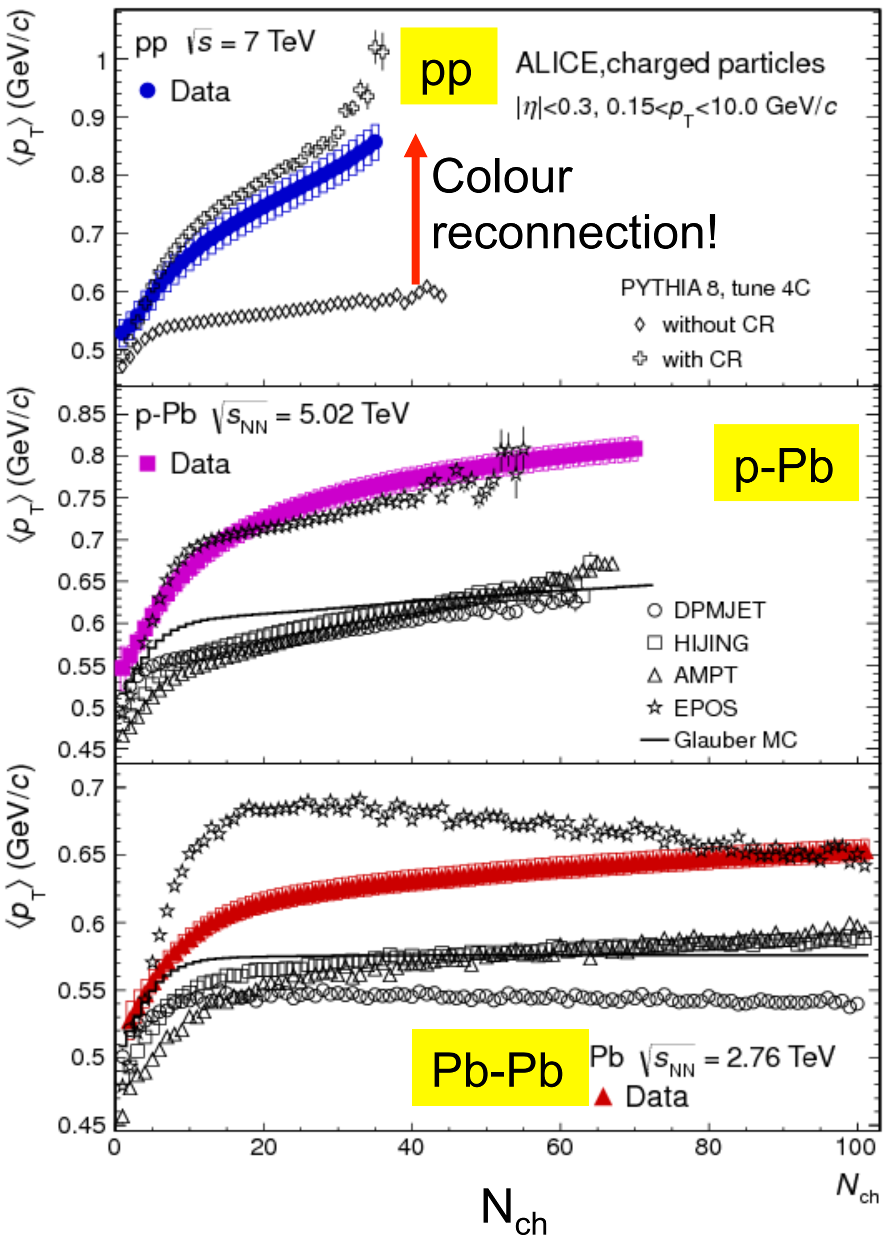


pp,p-Pb,Pb-Pb

$<p_T>$ vs. N_{ch}

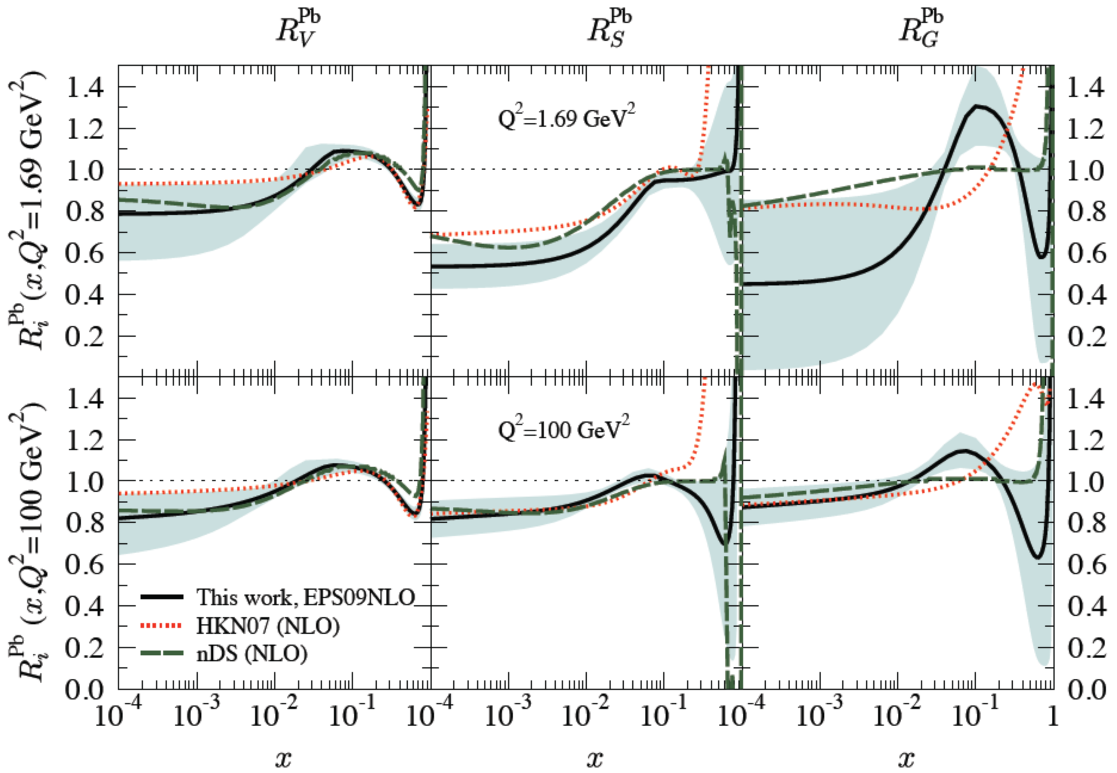
ALICE, arXiv:1307.1094

- Color reconnection very important to describe $<p_T>$ in pp
- DPMJET, HIJING, AMPT fail to describe $<p_T>$ in p-Pb and Pb-Pb
- Superposition of independent pp collisions (Glauber approach) fails in p-Pb and Pb-Pb
- EPOS (1.99, v3400, collective effects by parameterization) in the right ballpark (p-Pb)



Gluon shadowing…

- different parton **distribution functions in protons and nuclei**



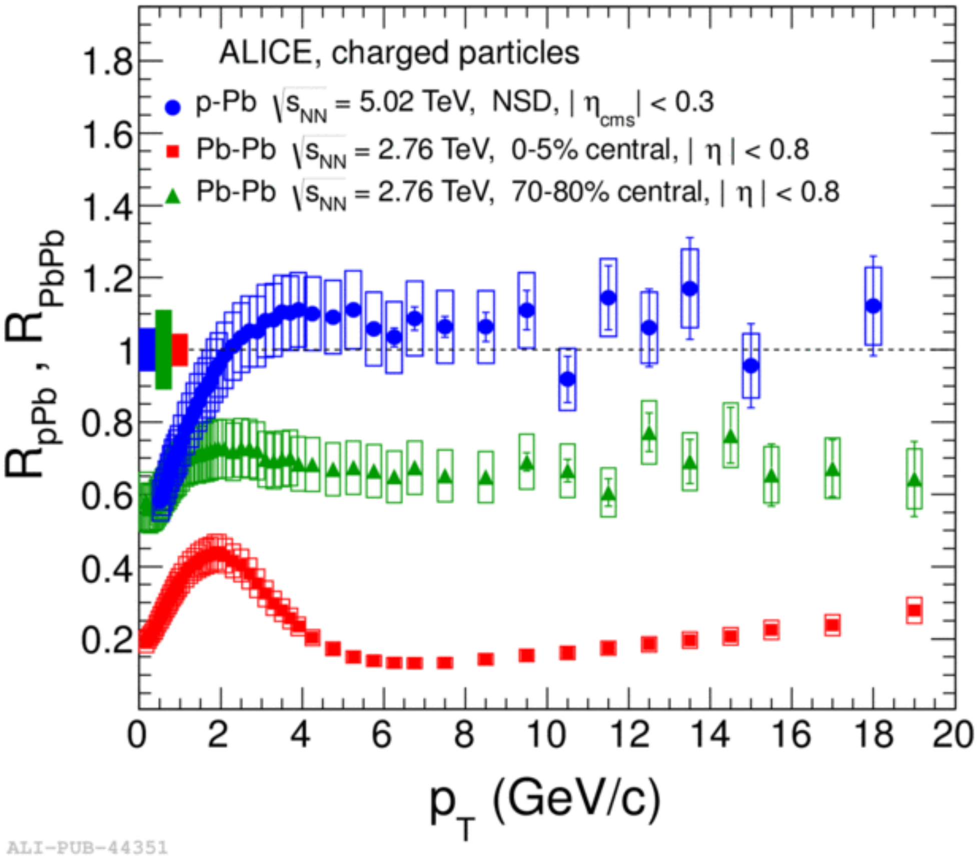
x = fraction of nucleon momentum carried by gluon

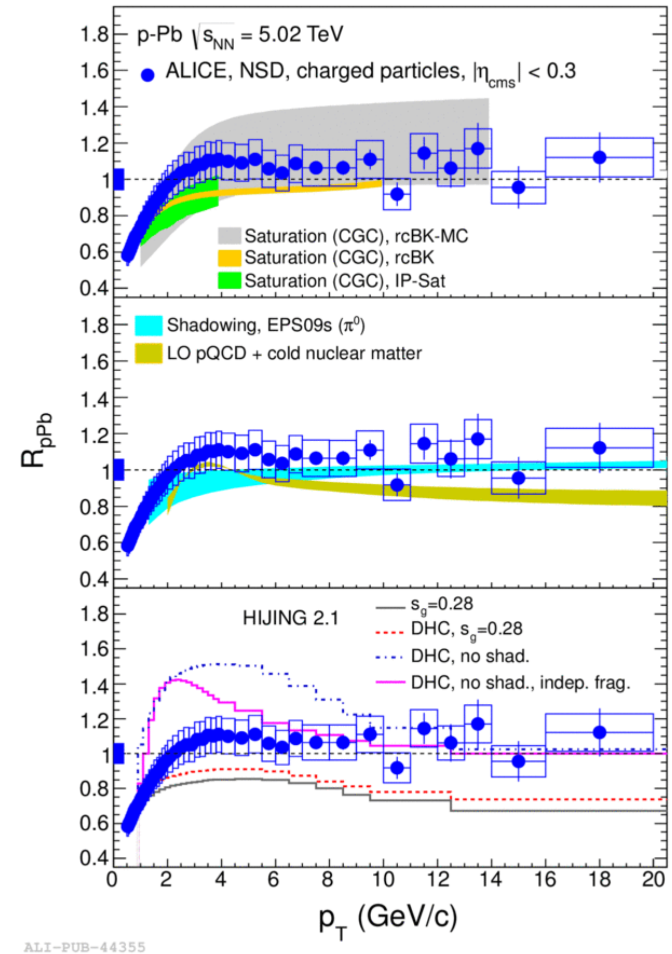
- a priori, large uncertainty
  → measure p-Pb collisions!!!

[K J Eskola et al: JHEP04(2009)065]

Control experiment: R_{pPb}

- measurement of nuclear modifications in initial state

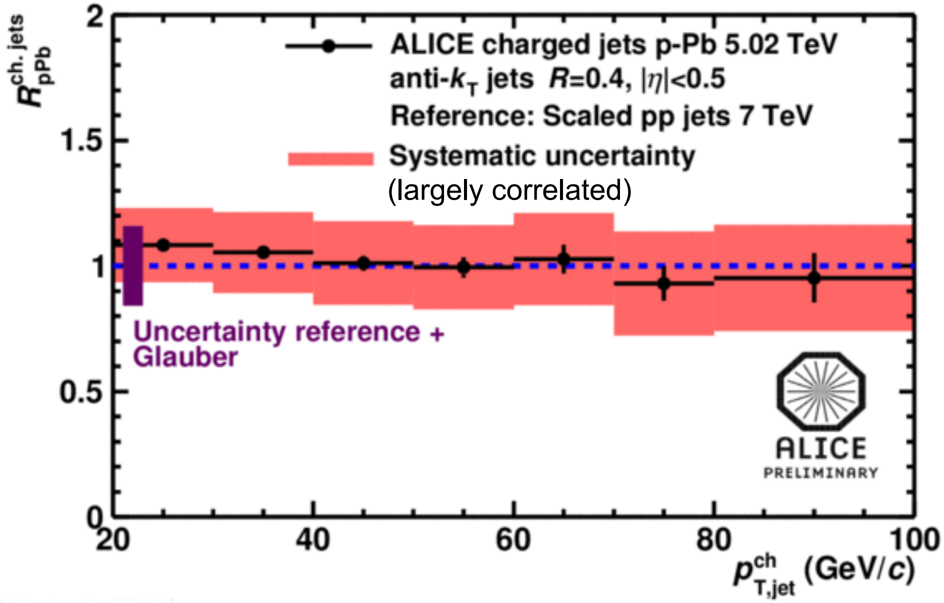


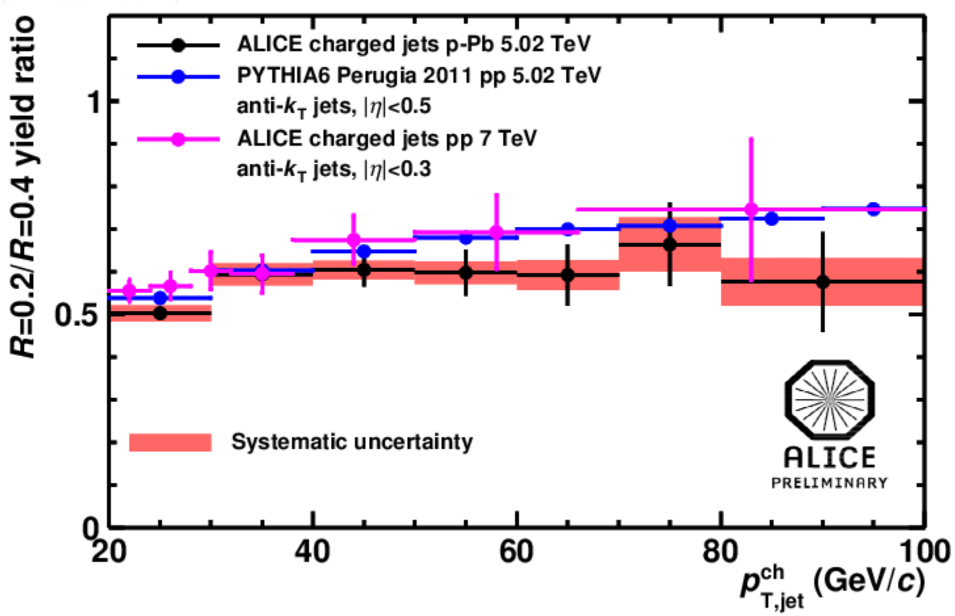


- $R_{pA} \sim 1$ for $p_T > 3$ GeV/c → confirms quenching is due to QCD medium

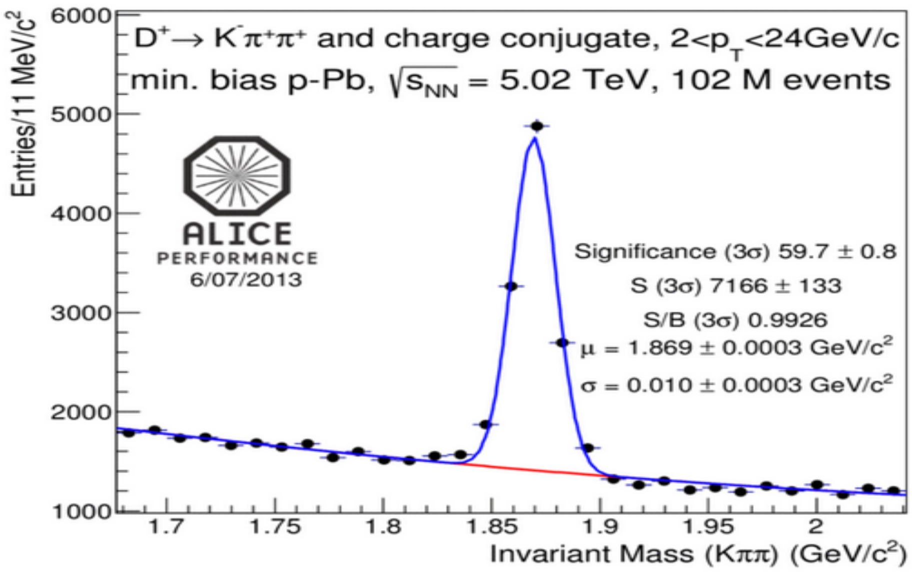
R_{pPb} for charged jets

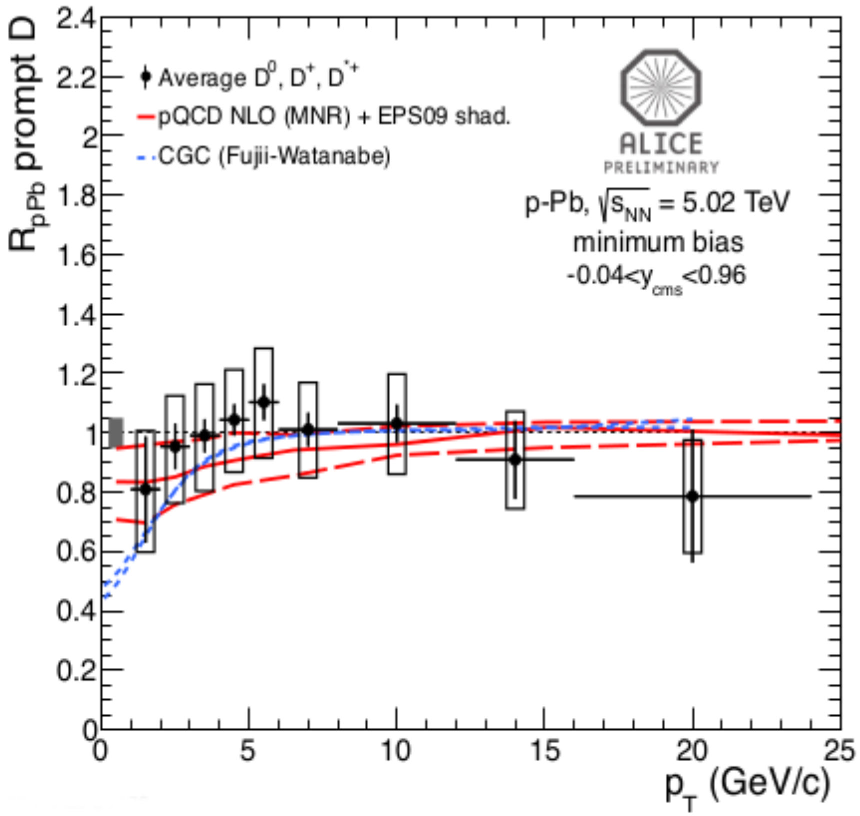
- Charged jet spectrum in minimum bias p-Pb with anti-k_T for R=0.2 and 0.4 in $|\eta_{lab}|<0.5$
- Reference spectrum for pp using 7 TeV data and scaled with PYTHIA6 (Perugia 2011)
- No sign of nuclear modification
  - Nuclear modification factor consistent with unity within large uncertainties
  - Jet structure ratio consistent with that in pp





R_{pPb} for D



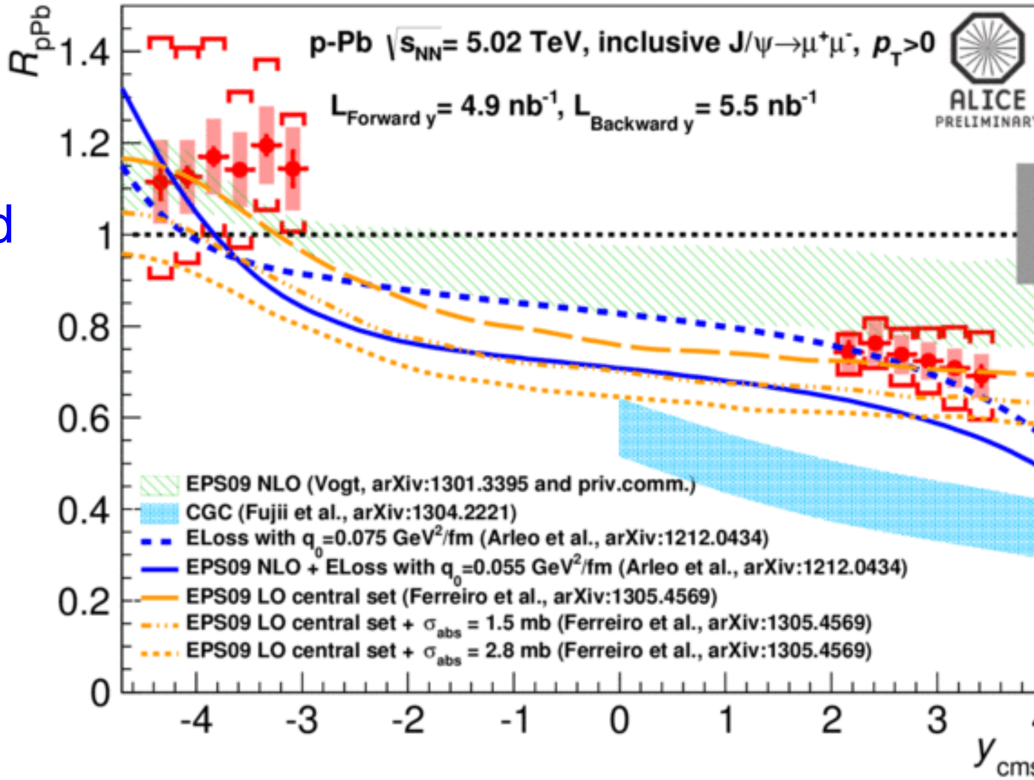


- Reference constructed using data at 7 TeV scaled by FONLL

- R_{pPb} for D-mesons consistent and unity (within large) uncertainty
- both CGC and shadowing calculations describe the data

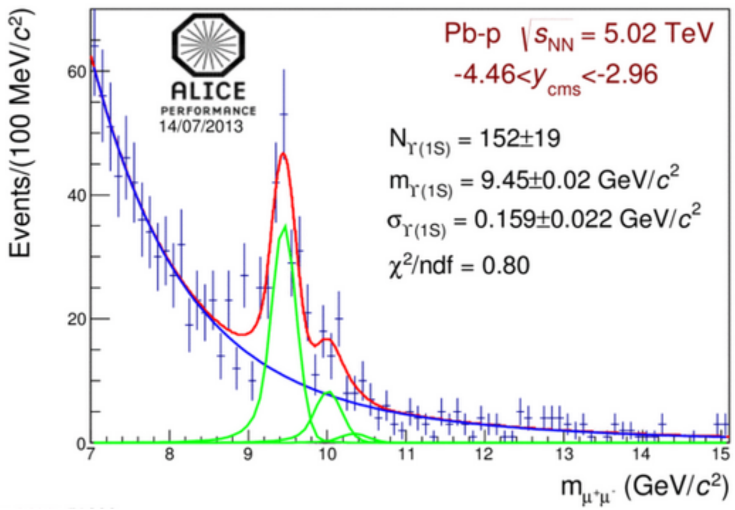
R_{pPb} for J/ψ

- Uncertainty on R_{pPb} dominated by uncertainty of pp reference (constructed by interpolation)

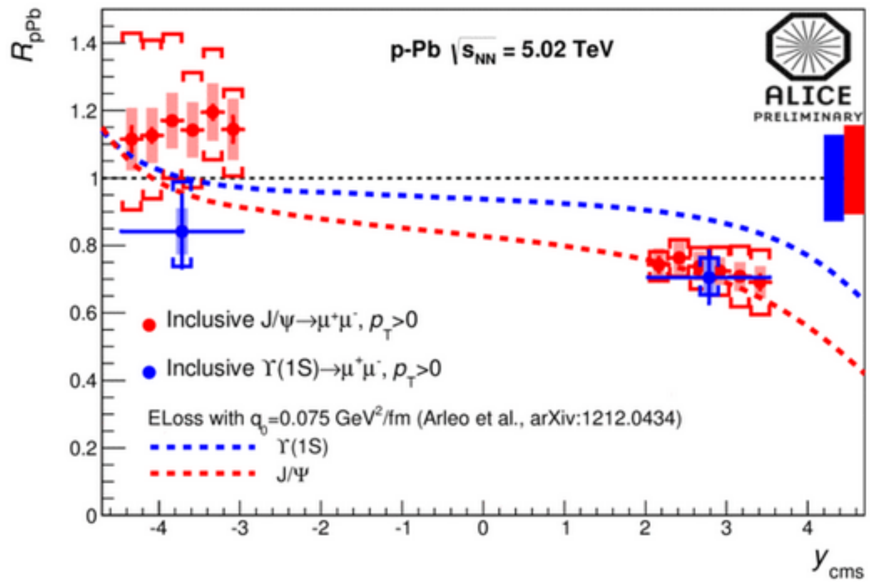


- Comparison with models
  - Good agreement with models incorporating shadowing (EPS09 NLO) and/or a contribution of coherent parton energy loss
  - CGC model (Fujii et al.) disfavored by the data

R_{pPb} for Υ(1S)

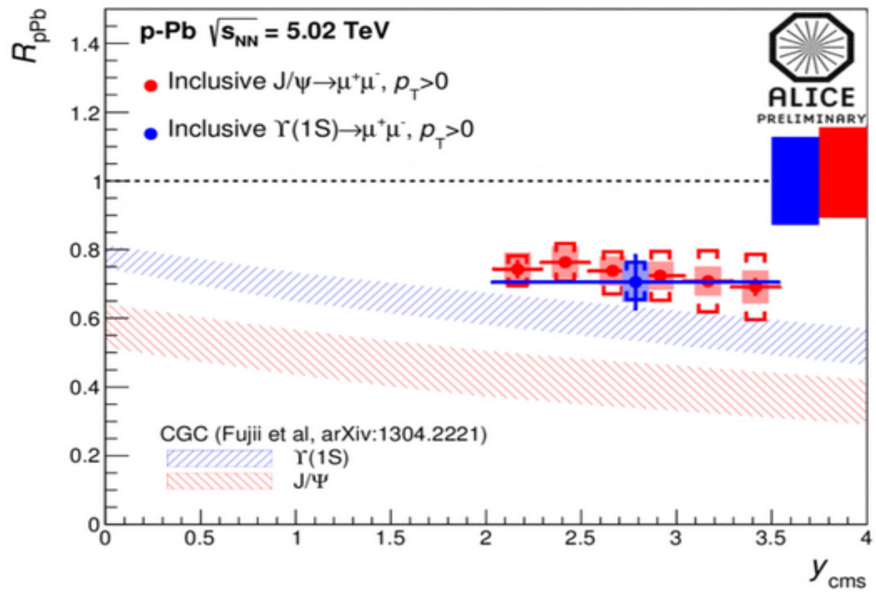


ALICE,

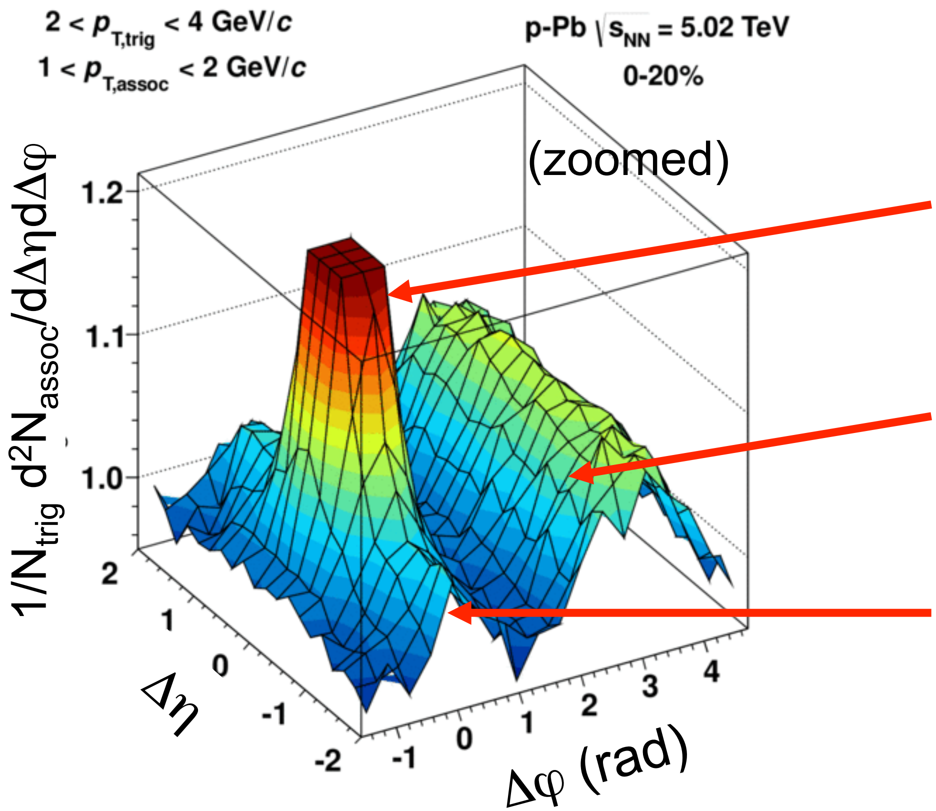


- Reference constructed by interpolation

- combined dataset provides strong constraints to models!



The Ridge



$2 < p_{T,trig} < 4$ GeV/c
$1 < p_{T,assoc} < 2$ GeV/c
20% highest multiplicity

Near-side jet
($\Delta\varphi \sim 0$, $\Delta\eta \sim 0$)

Away-side jet
($\Delta\varphi \sim \pi$, elongated in $\Delta\eta$)

Near-side ridge
($\Delta\varphi \sim 0$, elongated in $\Delta\eta$)

PLB719 (2013) 29

- in addition to near side peak and away-side recoil…

  … there's an additional near side ridge in p-Pb

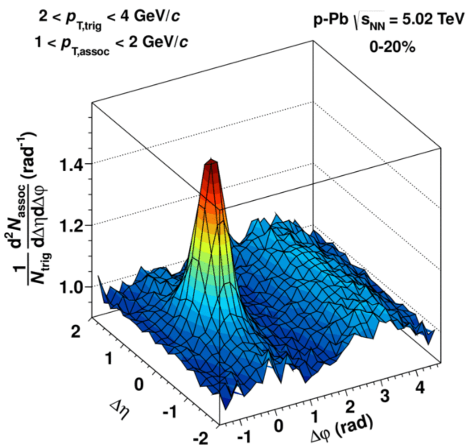
  first observed by CMS [PLB718 (2013) 795]

The Double Ridge

- Can we separate the jet and ridge components?
  - in 60-100% no ridge seen, similar to pp
    → what remains if we subtract 60-100%?

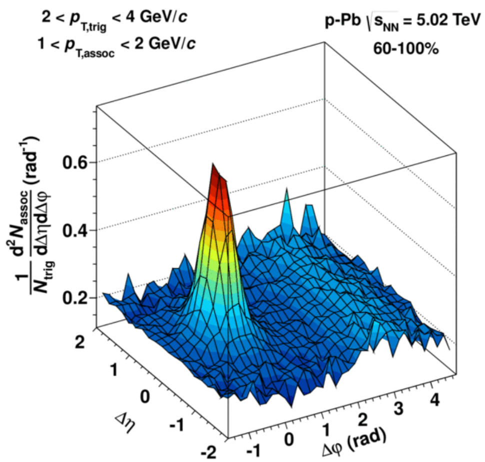
PLB719 (2013) 29

0-20%



−

60-100%



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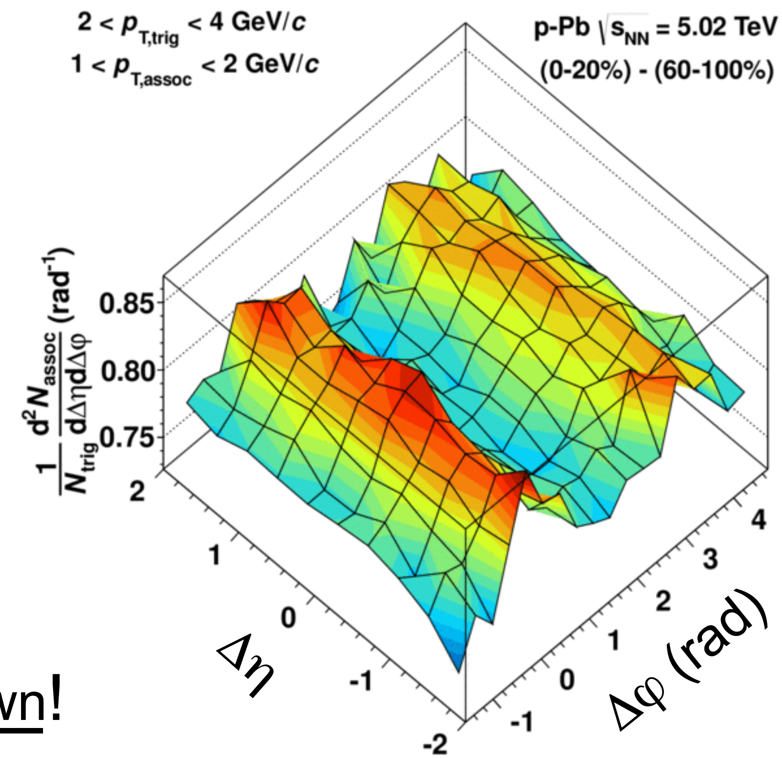


- the ridge is doubled!

  first observed by ALICE, then confirmed by ATLAS

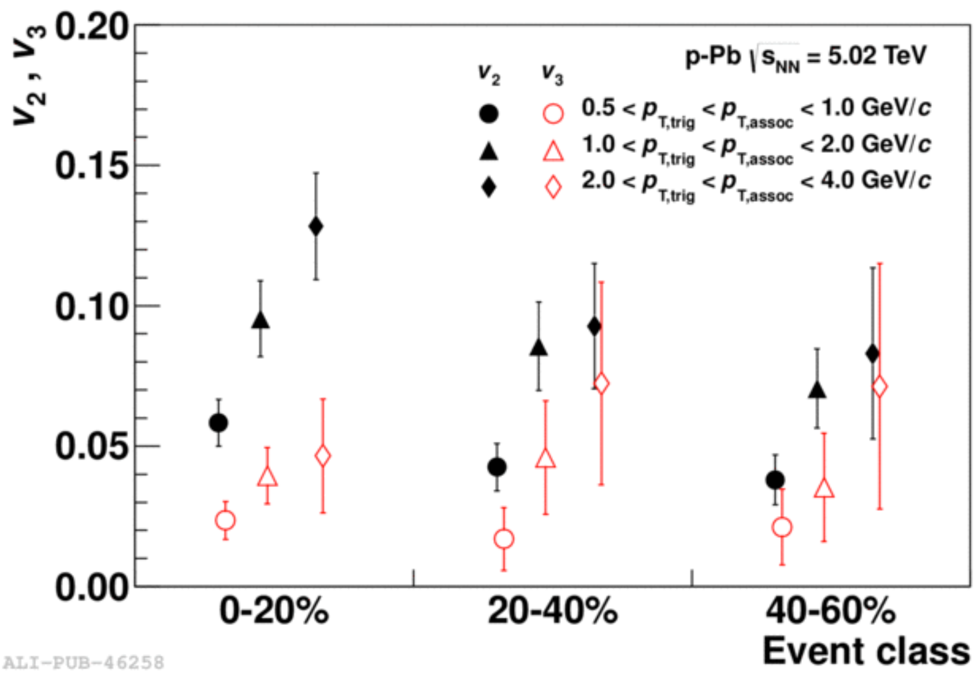
→ <u>the origin of this structure is still unknown</u>!

a similar structure observed in Pb-Pb is attributed to hydrodynamic flow!

CGC-glasma graphs also produce symmetric ridges!

Ridge harmonics

- long-range –p-Pb structures can be expressed as harmonics

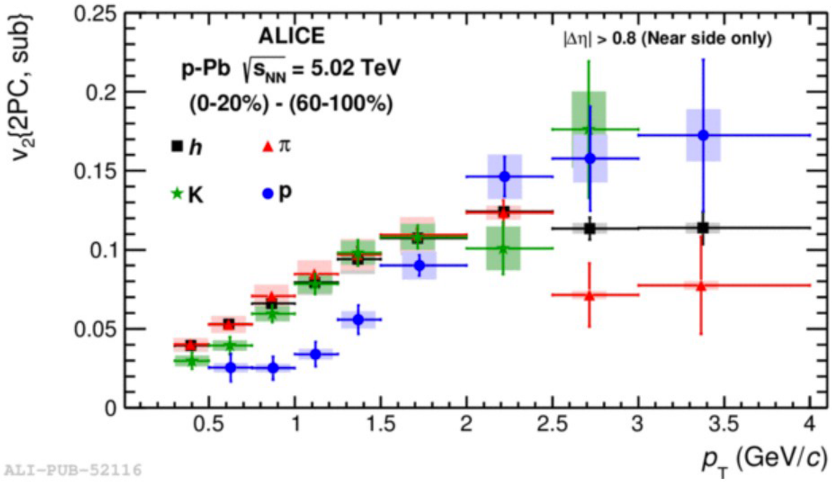


→ substantial v_2 (and even v_3…)

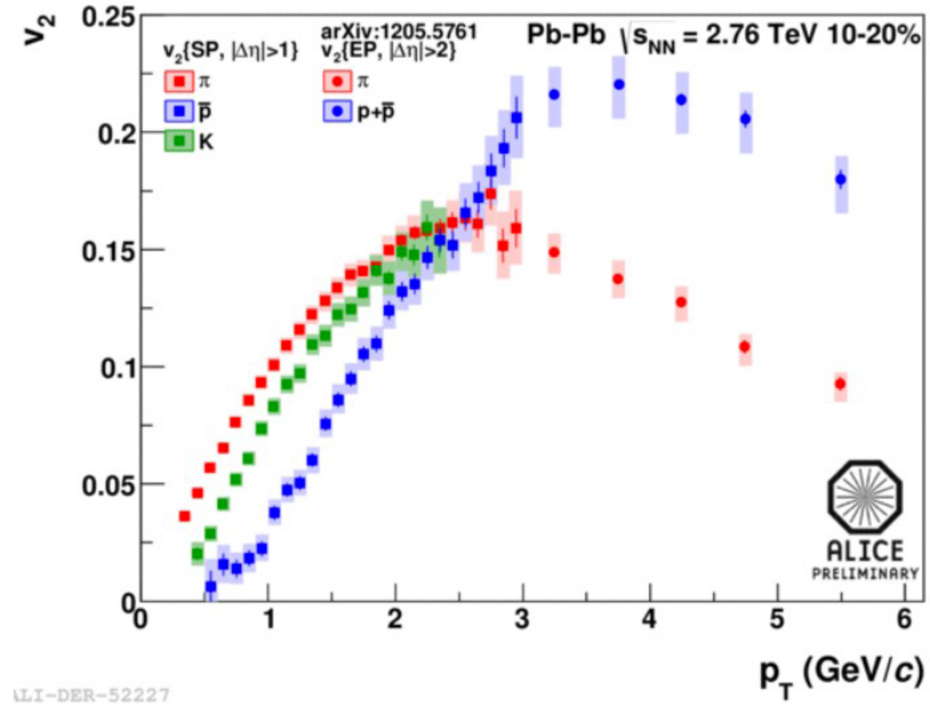
Identified particles

- how does the correlation depend on the particle species?

p-Pb



Pb-Pb

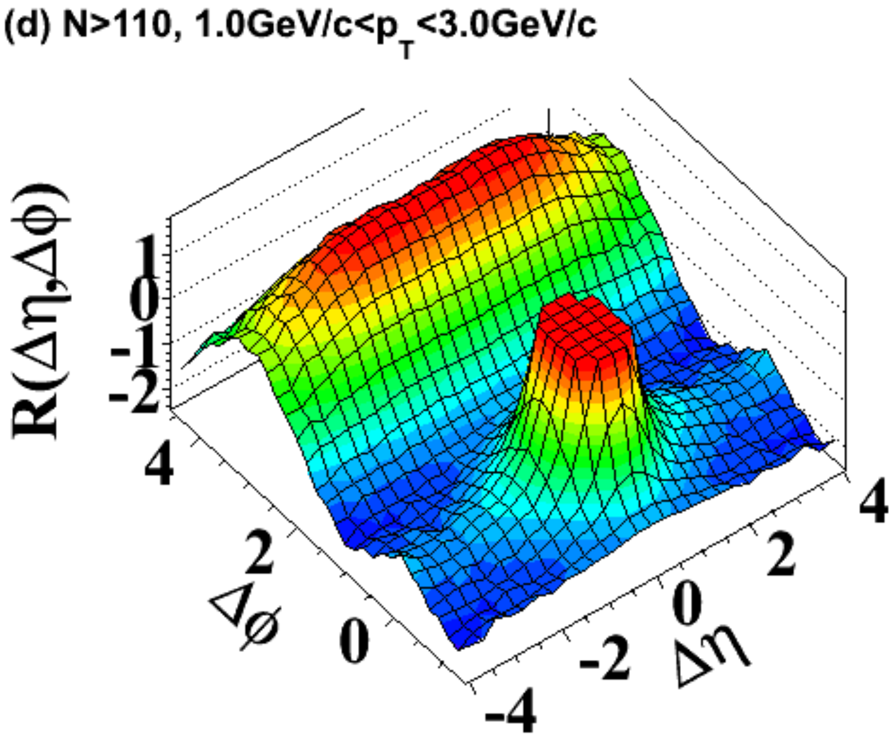


- remarkably similar to Pb-Pb…

- whatever it is we are on to something big…

…and how about the pp ridge?

- CMS has observed a near-side ridge in high multiplicity pp

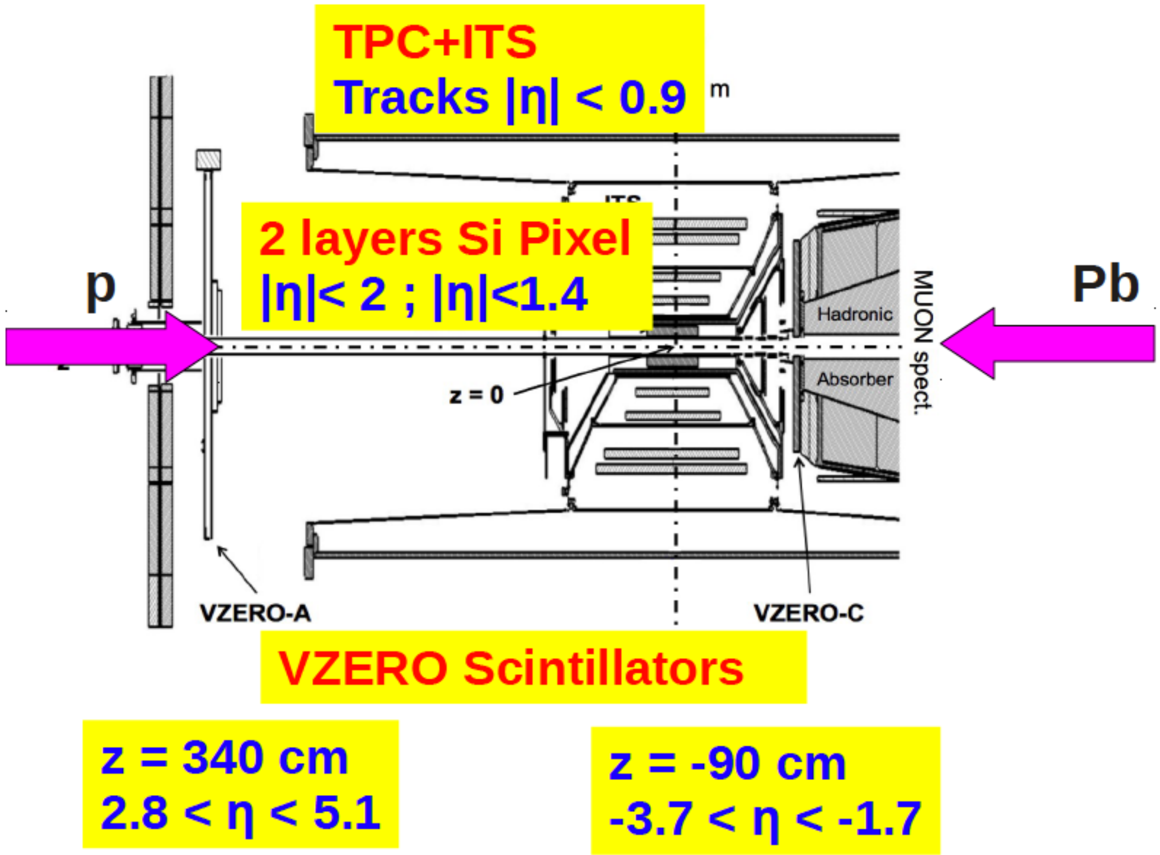


[CMS, JHEP 1009 (2010) 091]

- is it doubled on the away-side?
- how about the harmonics?
- particle id dependence?

Centrality in p-Pb?

- can geometry be related to multiplicity?



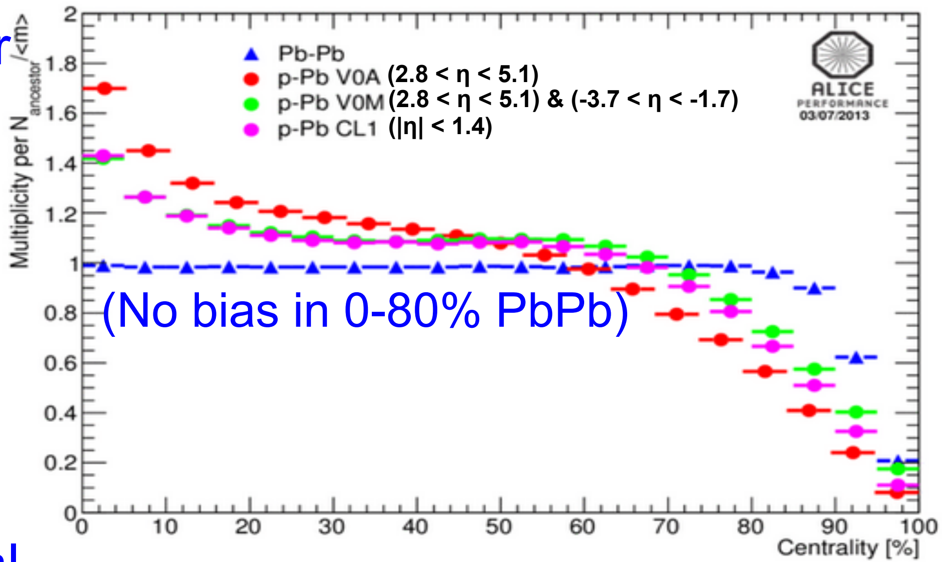
some estimators (ALICE):

- CL1: cluster in 2nd pixel layer
- V0M: VZERO-A+C multiplicity
- V0A: VZERO-A multiplicity

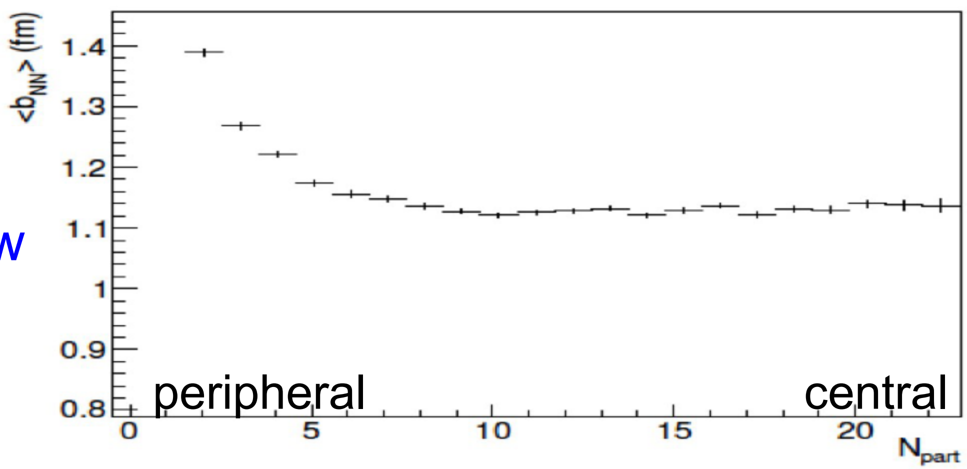
Centrality biases!

- $\langle N_{coll} \rangle$ from Glauber seems not to be the right scaling variable for usual centrality estimators
- Multiplicity per N_{part} strongly biased in p-Pb
- In HIJING: mean NN impact parameter increases in peripheral collisions
  - →softer collisions than average?
- veto for high-p_T processes in low multiplicity classes…

Multiplicity per N_{part} / Mean NBD

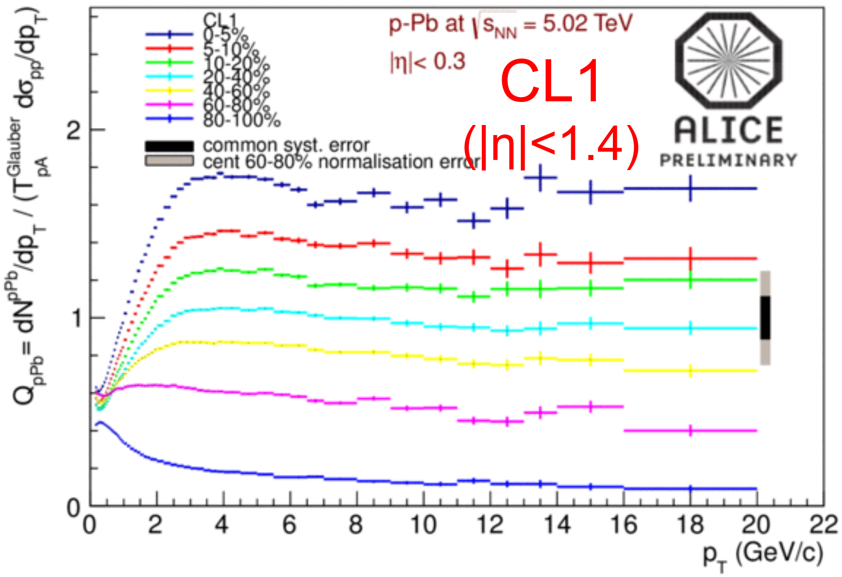


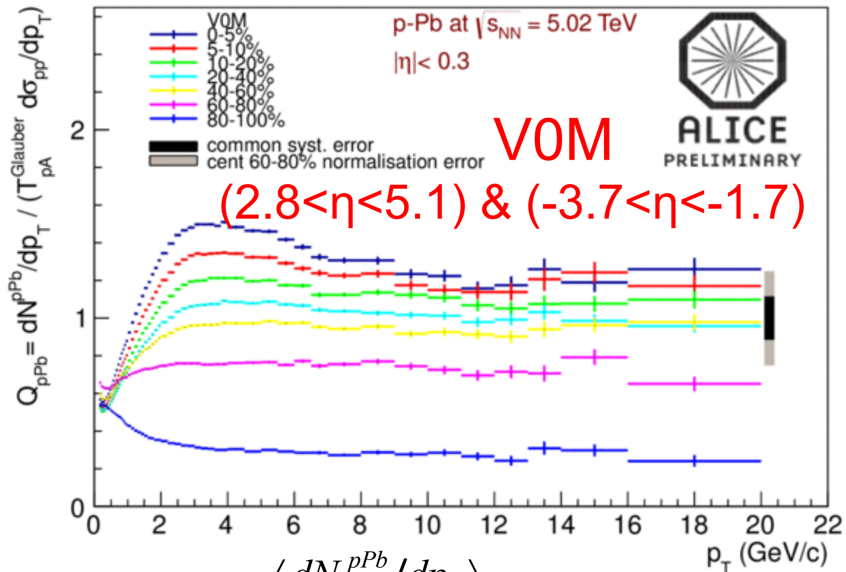
Mean NN impact parameter



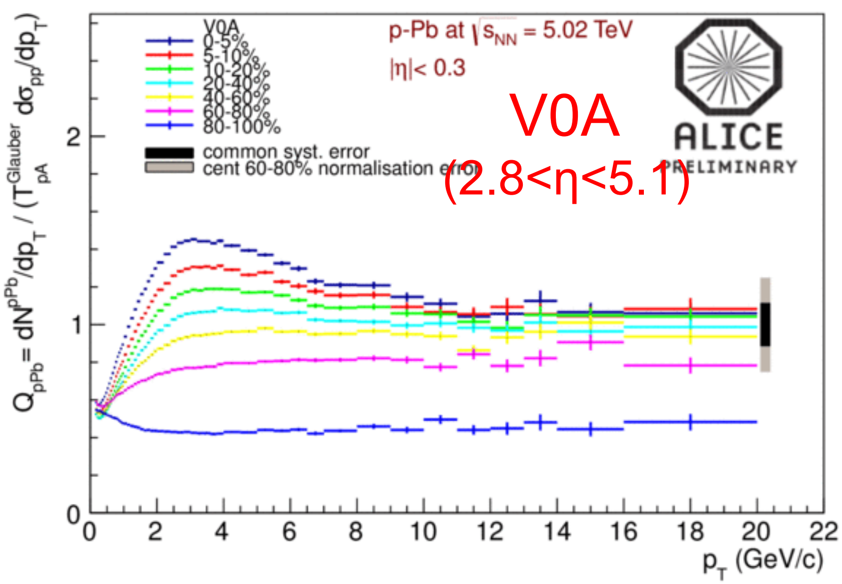
Q_{pPb} (not R_{pPb})

$$Q_{pA}(p_T;cent)=\frac{d\,N^{pA}/d\,p_T}{N_{coll}^{Glauber}\,d\,N^{pp}/d\,p_T}$$





$$Q_{pPb,cent}=\langle N_{cent}^{Glauber}\rangle\frac{\langle dN^{pPb}/dp_T\rangle_{cent}}{dN^{pp}/dp_T}$$

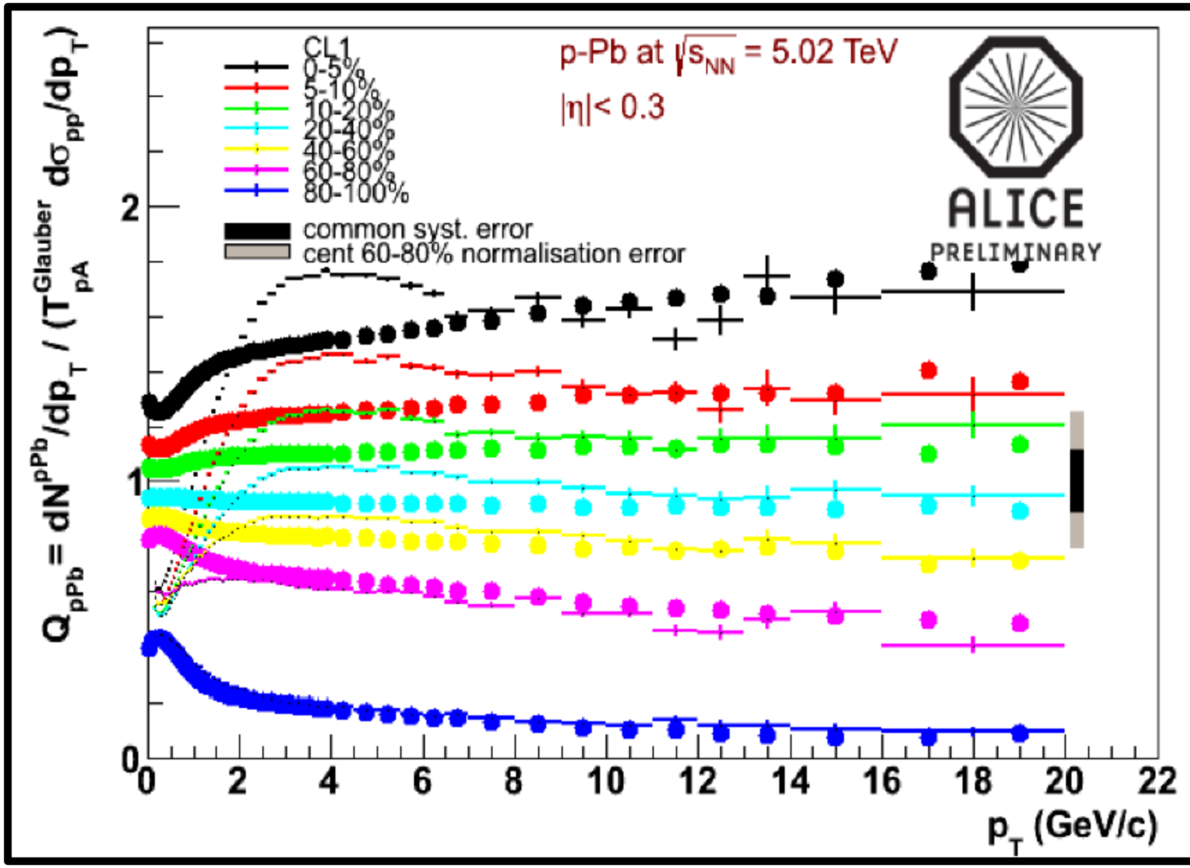


- Not an R_{pPb} measurement!
  - not 1 in absence of nuclear effects!!!
- spread reduces: CL1→V0M→V0A
- jet veto in CL1, less in V0A

Toy model: Glauber + Pythia

- add N_{coll} Pythia events
  - Ncoll from Glauber
- slice in multiplicity
  - just like real data
- high pT bias ~ incoherent superposition of pp!

→ Glauber Ncoll x pp:
not the proper pA ref.



→ full dynamical biases must be taken into account!

Conclusion

- the LHC has ushered in a new era for ultrarelativistic AA collisions
  - abundance of hard probes
  - state-of-the-art collider detectors (ALICE, + AA capabilities in ATLAS, CMS)

- Run 1: two major discoveries…
  - new regime for J/ψ production → evidence for recombination!
  - double ridge in p-Pb (and pp?) → signal of collectivity? saturation?

- …+ rich harvest of other results
  - heavy flavour: indications of flavour dependence of quenching (finally!)
  - jets:
    - very strong quenching: R_{AA}, FF “flat” up to highest available jet energies
    - “signs of life” at low p_T (R_{AA}, FF, broadening)
  - photons:
    - high “inverse slope” direct photons with v_2 ?!

- next: dig deeper!

ALICE Outlook (i)

- 2013-14: Long Shutdown 1
  - complete Transition Radiation Detector
  - install Di-jet electromagnetic CALorimenter (DCAL)

- 2015-17: Run 2 → complete approved ALICE "1/nb" programme
  - Pb-Pb, pp rare triggers int lumi: Run1 x 10
    - high stats jets and di-jets (to 100-200 GeV)
    - → high stats quarkonia (J/ψ v_2, central J/ψ, Y)
  - Pb-Pb, pp min bias: Run1 x 10
    - increase stats for charm, id particle correlations, event shape engineering, …
  - p-Pb: Run1 x 10 !

ALICE Outlook (ii)

- 2018: Long Shutdown 2
  - ALICE Upgrades (new beam pipe, new ITS, high rate, …)

- 2019 – …: ALICE 2.0!
  - continuous read-out → 10/nb min bias (Run 2 int lumi x 10, Run 2 min bias x 100-1000!)
  - → heavy flavour: Λ_c, D_s, B, "dream" stats D
  - → quarkonia: high stats ψ', χ_c, Υ(2/3s), …
  - → virtual photons: thermal emission, v_2!, chiral symmetry restoration
  - → jets: detailed study of fragmentation (id. particle, HF tagging, correlations, …)
  - → other collision systems (p-Pb, Ar-Ar?, …)

Thank You!