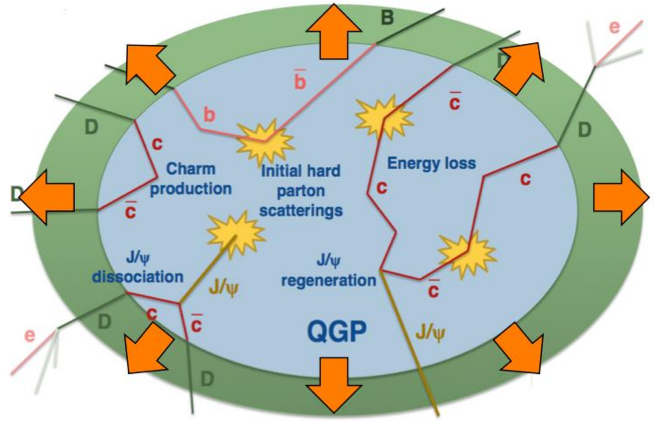
… on Wednesday…



QCD matter at the LHC: what have ~~we~~ I learned so far?

(a personal overview)

Federico Antinori

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Conclusions

- 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 regeneration?
  - double ridge in p-Pb, pp → signal of collectivity, what about quenching?
- … + rich harvest of other results
  - system still very close to thermodynamic equilibrium and ideal hydro behaviour
  - strong jet quenching, up to highest jet energies
    - no evidence of angular decorrelation
    - angular dependence: sensitivity to path length dependence
  - indication of parton-mass ordering in heavy flavour quenching
  - hints of final-state effects in p-Pb? (ψ(2S), Υ)
- the future looks bright → high stats HF, stay tuned!
  - Run 2: O(10) increase in statistics, int lumi for Pb-Pb, p-Pb
  - Run 3: O(100) increase, ALICE 2.0 upgrade!

today…

What next?

Some open points for Run 2

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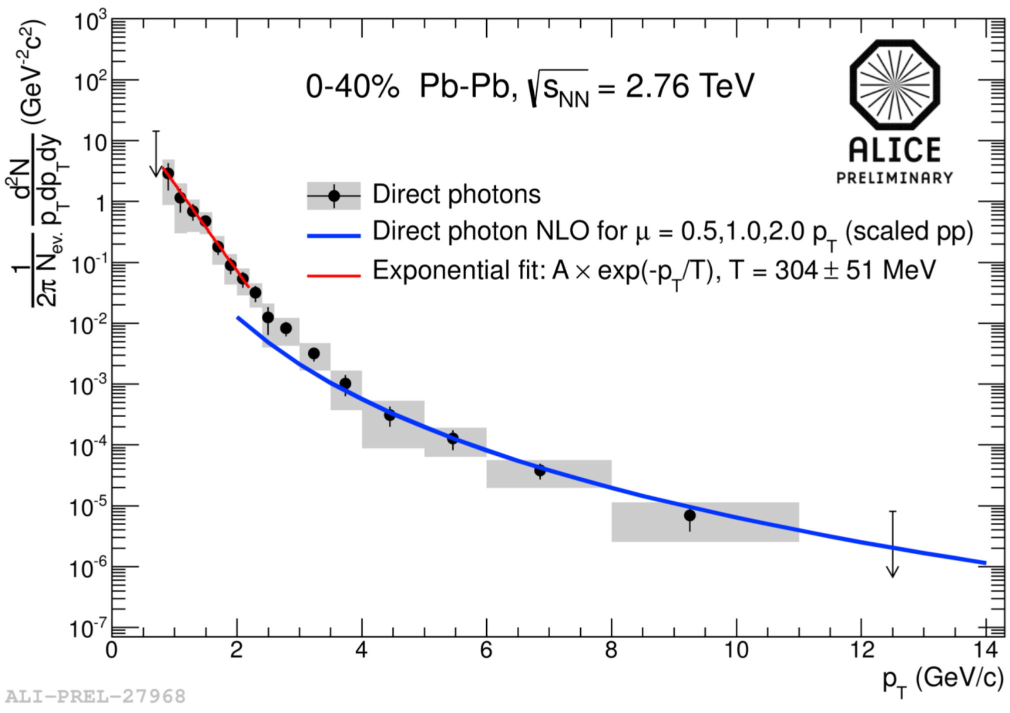
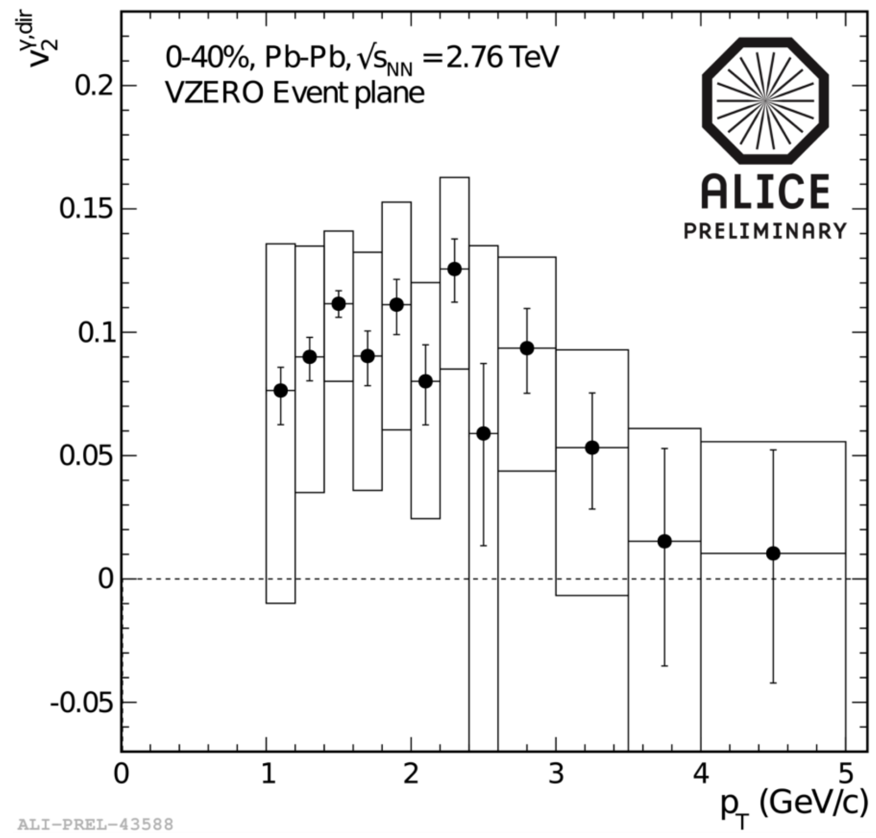
QGP radiation?

- direct photon spectrum
- direct photon v_2

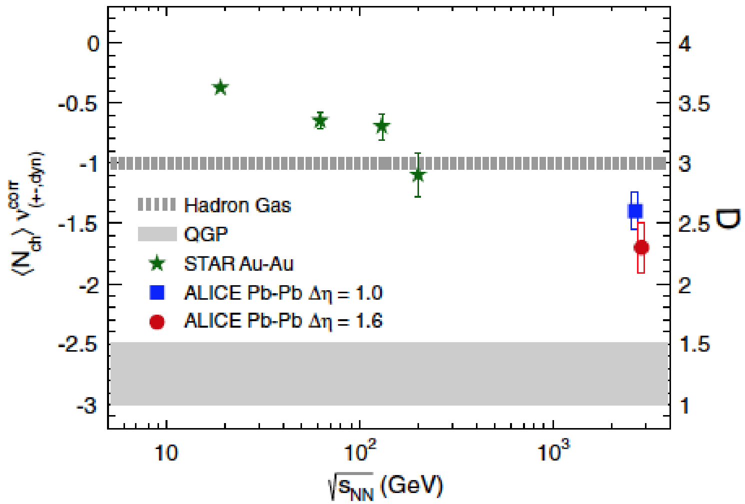




- key measurement for Run 2
- enough stats for thermal dileptons?

Fluctuations: what next?

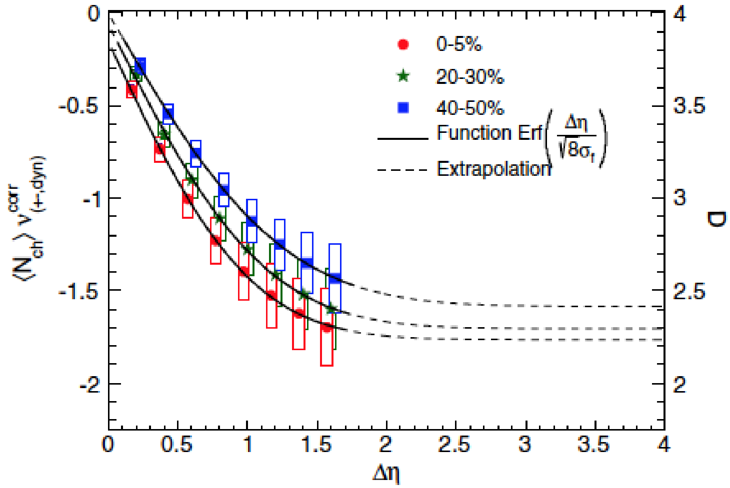
- e.g.: net charge fluctuations
- sensitive to charge of carriers!
  - but can be “diluted” in final state…



Phys. Rev. Lett. 110, 152301 (2013)

- fluctuations decrease
  - with increasing centrality
  - with increasing Δη

  (diffusion of hadrons in y?)



- baryon number, strangeness fluctuations → connect to lattice QCD
- but analysis “phase space” is huge…

→ needs immediate attention

Low-p_T D

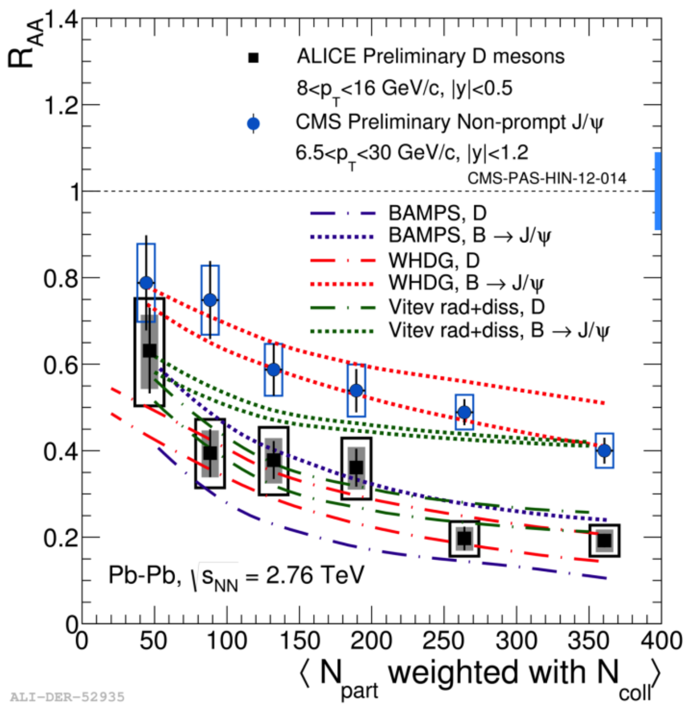
- charm thermalisation/flow
- baseline for J/ψ

- ongoing efforts (pp, p-Pb)
- Pb-Pb needs statistics

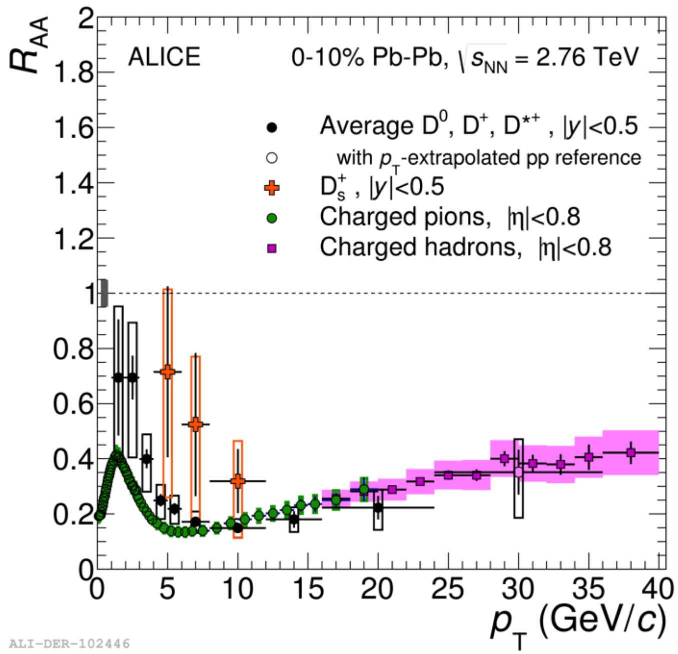
→key item for Run 3, but we should push in Run 2!

R_{AA}: Flavour Dependence

- indication of $R_{AA}(b) > R_{AA}(c)$!



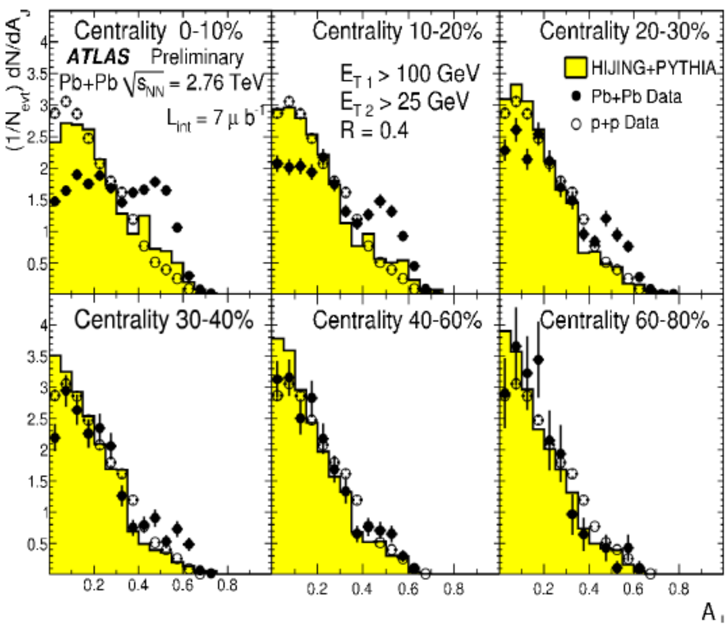
- … but are D and π different?

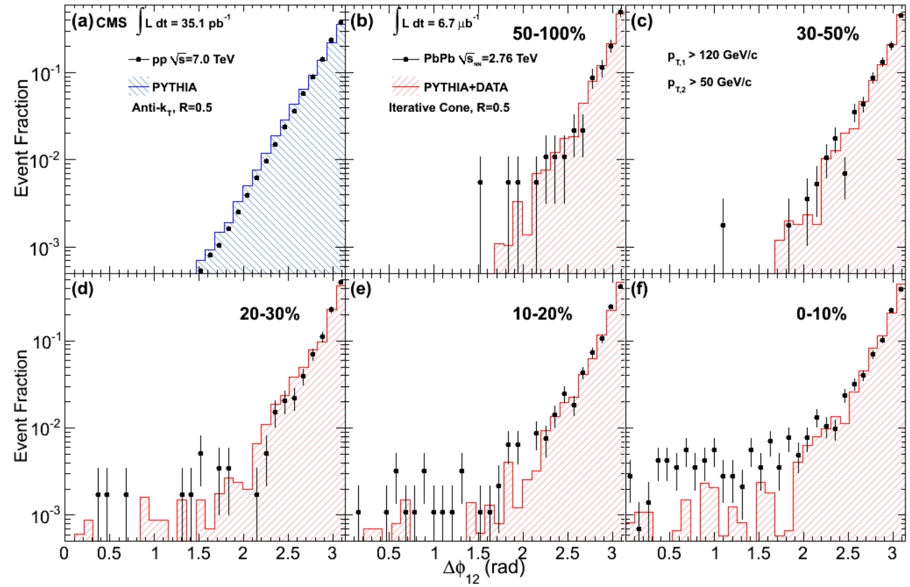


- and how about the D_s?

HF correlations?

- very strong quenching, but no angular decorrelation





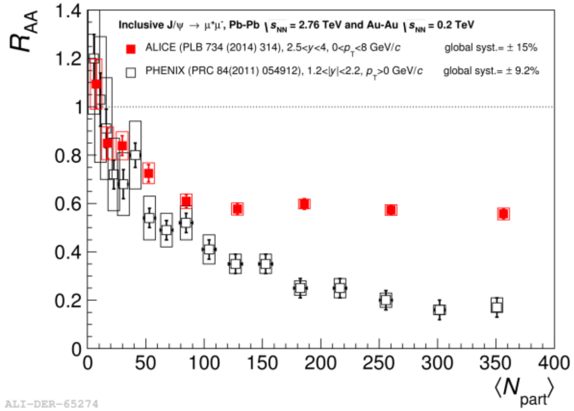
- how about charm?
- events with two reconstructed D very rare

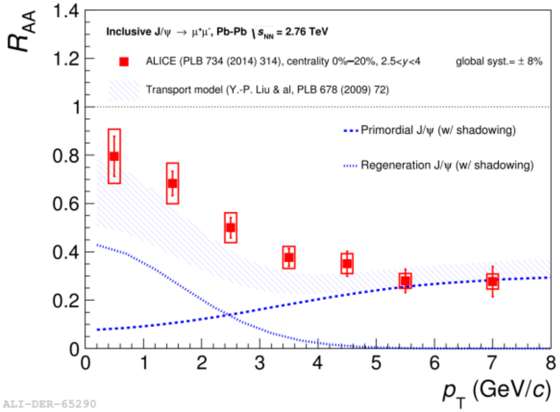
→ study e^+-e^- correlations?

→ how about e-μ?

J/ψ v_2

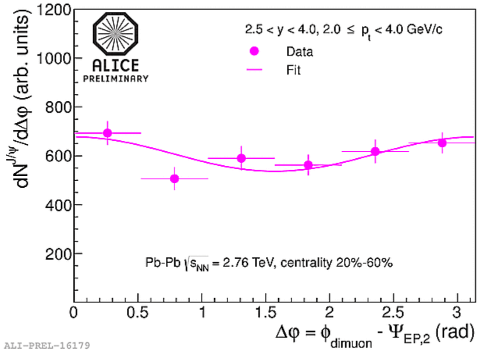
- recombination in charm sector
  - charm strongly coupled to medium → thermalisation?
  - indication of recombination from J/ψ R_{AA}





- √s dependence!
- measure low-pT charm!
- how about J/ψ v_2?

  → 5σ within reach in Run 2!

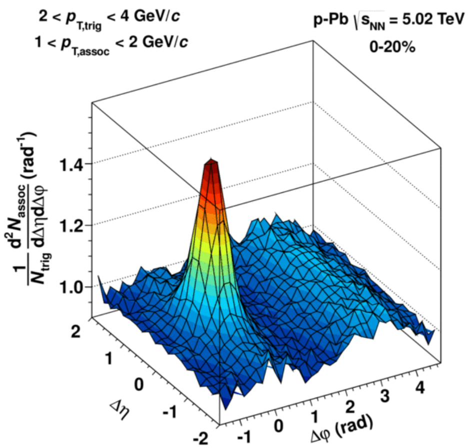


The Double Ridge

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

[ALICE, PLB719 (2013) 29]

0-20%



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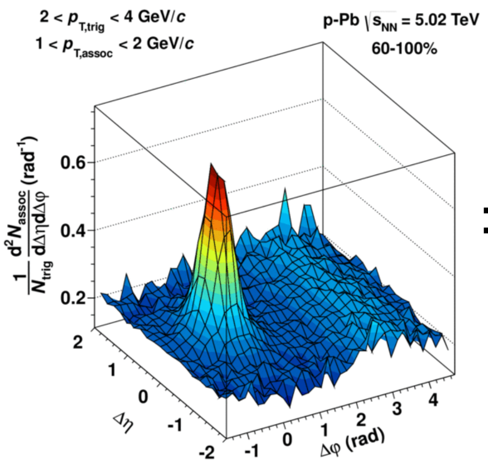
60-100%



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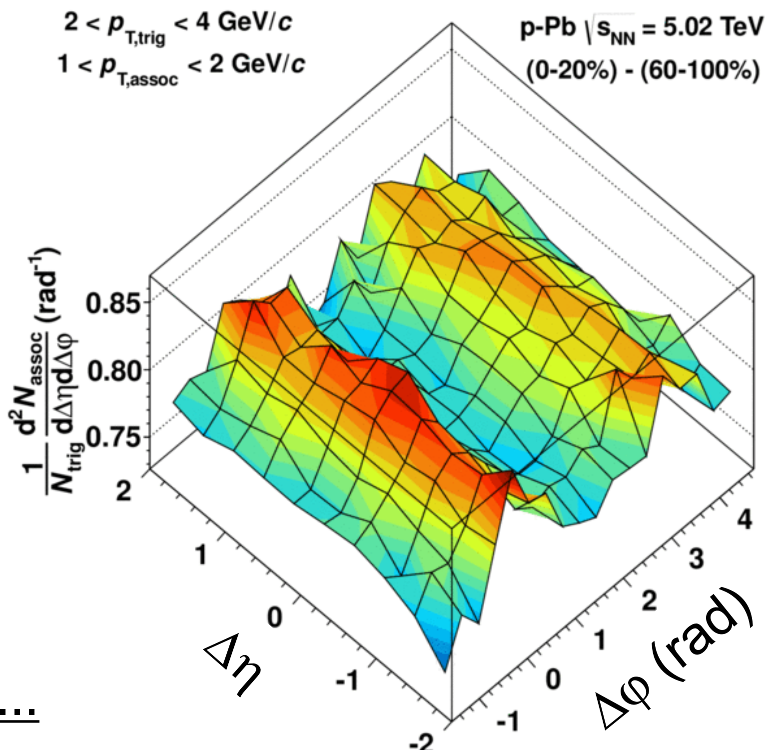


- the ridge is doubled!

→ <u>the origin of this structure is still unclear...</u>

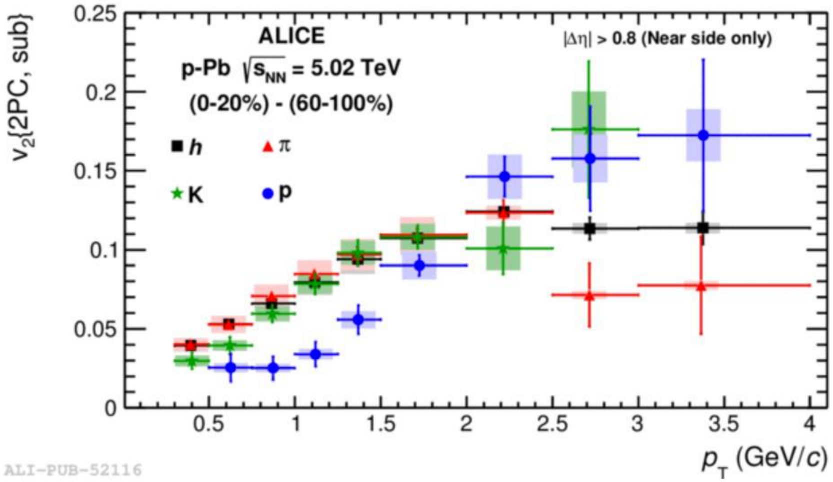
similar structure observed in Pb-Pb is attributed to hydrodynamic flow…

CGC-glasma graphs can also produce symmetric ridges?

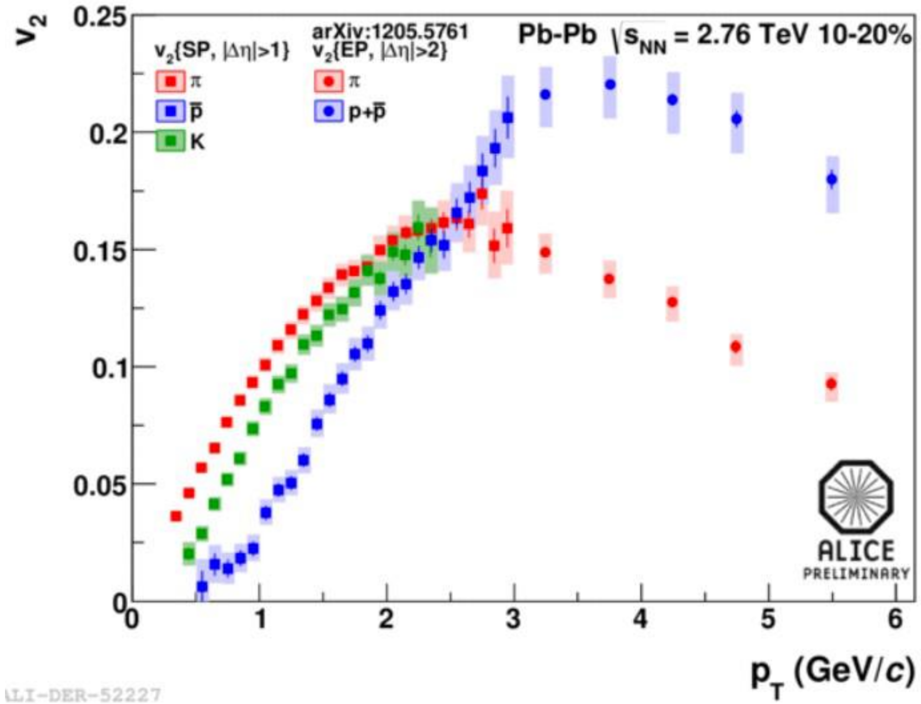
Identified particles

- how does the correlation depend on the particle species?

p-Pb



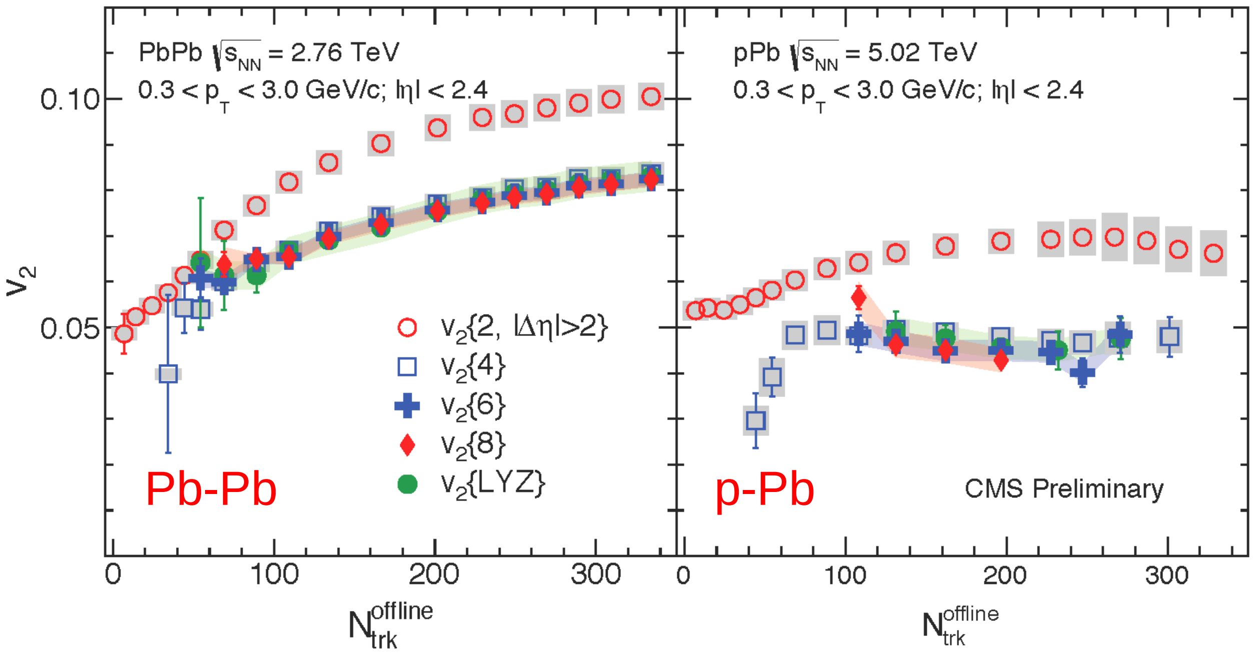
Pb-Pb



- p-Pb remarkably similar to Pb-Pb.
  - where particle species dependence is attributed to collective flow!

Multiparticle correlations

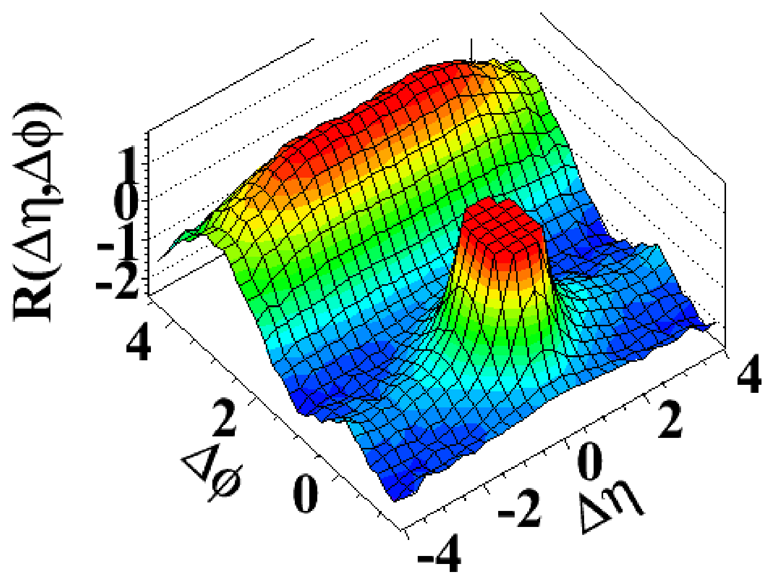
- v2 calculated with higher order cumulants



- again: p-Pb very similar to Pb-Pb
- azimuthal asymmetry is a true multi-particle effect, in both systems!

Ridges in pp

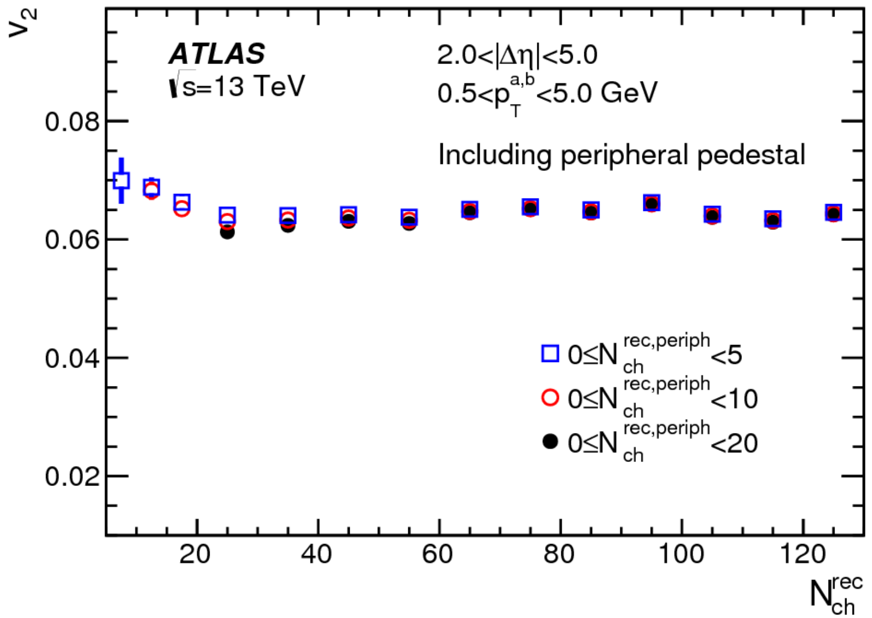
- near side ridge first seen by CMS



[CMS, JHEP 1009 (2010) 091]

- ATLAS: double ridge from 13 TeV

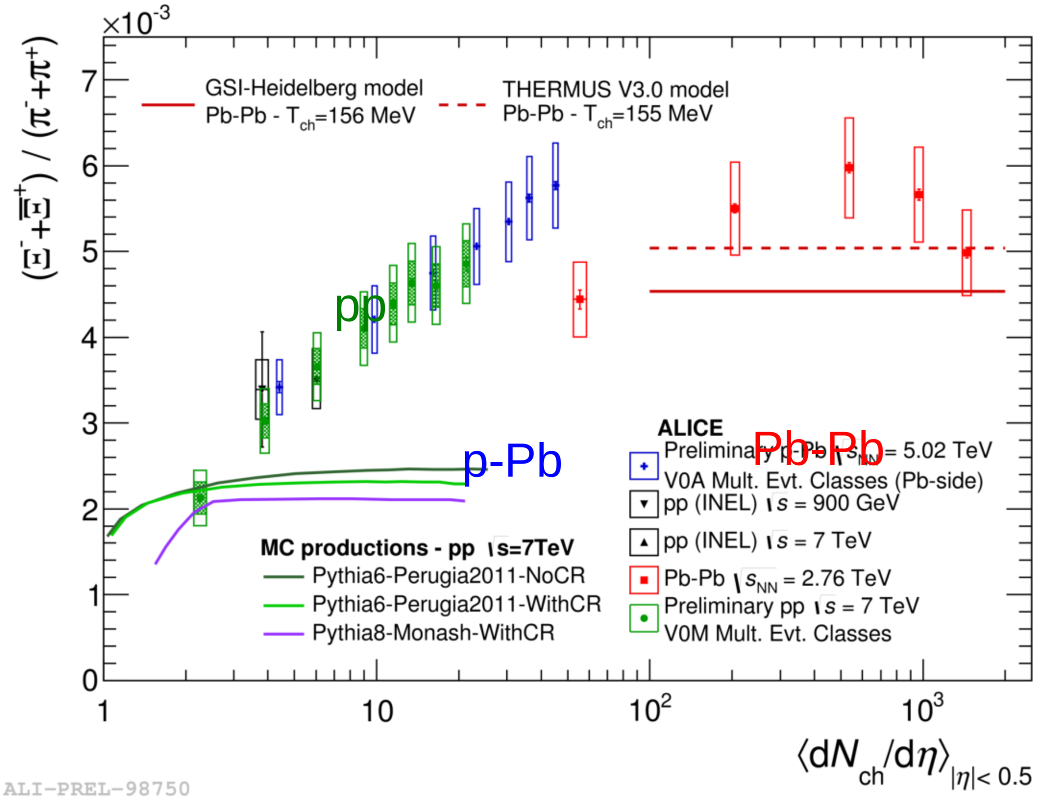
→ all the way to low multiplicity?!



(depends crucially on subtraction…)

Multi-strange baryons in pp, p-Pb

- e.g.: Ξ/π

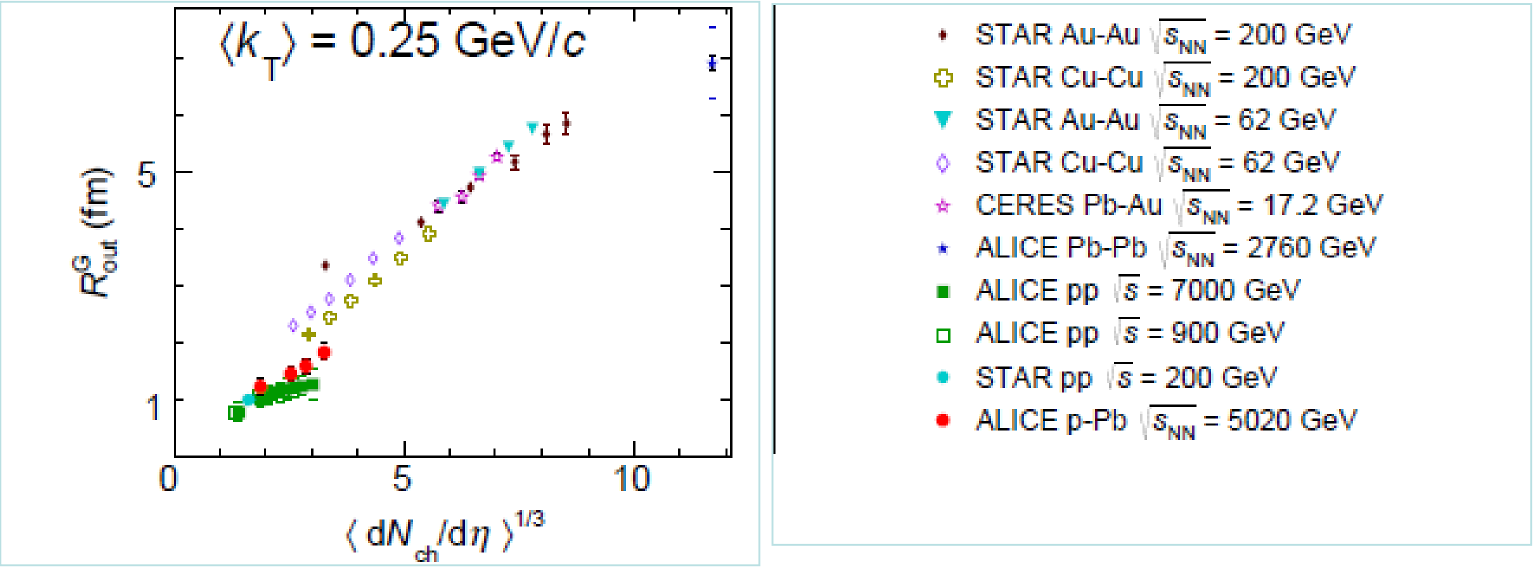


- significant enhancement at high multiplicity
  - up to Pb-Pb levels!
- similar behaviour in pp, p-Pb
- not described in PYTHIA

- smooth onset of collectivity from min-bias pp to p-Pb to Pb-Pb?

How about quenching?

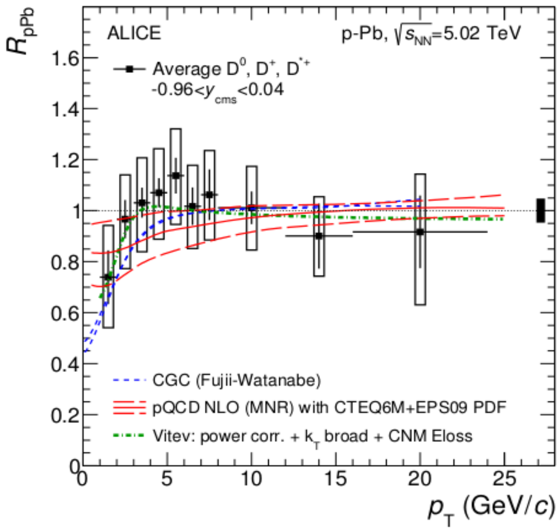
- should it be there?
  - does collectivity imply quenching?
- could it be there, just very small?
  - pp, pA not so small, after all…

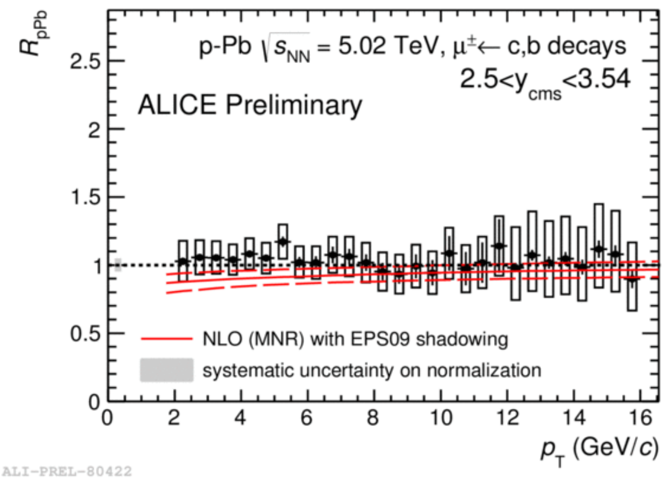


- how about initial state effects?

Could charm come to rescue?

- no quenching observed in RpPb





- what about v_2?
  - wouldn't observation of charm v_2 in pp, pA be a signal of quenching?
  - … or could charm know about geometry w/o interacting with medium? (CGC?)
- in any case, observation of charm v_2 in pp, p-Pb would be a sure hit!!!

… and many more… e.g.:

- Pb-Pb
  - correlation between quenching end e-by-e shape?
    - → ESE quenching
  - medium response? (e.g.: Mach cone)

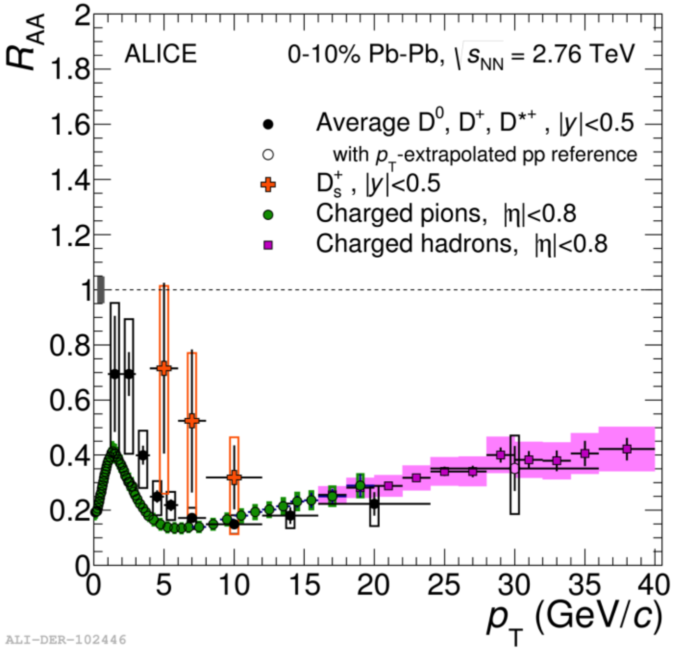
- small systems
  - low-p_T charm?
  - any sign of jet modifications at high multiplicity?
  - can we clarify the onset of v_2 with high-stats p-Pb data?
  - what can we learn from the study of fluctuations?

- searches
  - nuclear states? glueballs? pentaquarks? dark photons?

Higher stats is not enough…

- increased statistiscs → lower statistical uncertainties…

- … but many measurements have large systematic uncertainties!
  - e.g.:



→ in Run 2 we need to work a lot on the systematics!

How do we attack systematics? (i)

- some of it will naturally improve with more statistics
  - e.g.: feed-down corrections: we usually quote them in the systematics

- improving the control of tracking/reconstruction
  - in some Run1 analyses ~4% syst per track provides dominant source of syst error

- going the extra mile!
  - in some cases, a systematic effect is found, but not corrected for
  - its magnitude is included in the systematics
  - this may be justified in a few cases, but in general it is bad scientific practice!

- not being conservative!
  - some time people feel that being conservative with systematics is more “serious”
  - an over-estimated error is WRONG, just like an under-estimated one
  - and it is unprofessional: one deliberately decreases the information from the analysis!

How do we attack systematics? (ii)

- calculating it properly…
  - rms, not max!!! → it must be used in quadrature!!!

- not counting statistical fluctuations as systematic variations!
  - unfortunately, this is a common mistake…
  - sometimes variations (e.g. cuts) are made, and the difference is taken in the systematics!
  - we must always ask ourselves if the variation is statistically significant!

  → use Barlow's Criterion!

Barlow's Criterion

- consider systematic checks as pass/fail tests
  - is the discrepancy between two variations of analysis statistically significant?
- if not → do nothing (do NOT add discrepancy to systematics!!!)
- if yes → try to find what is going on (and correct for it!)

  → only incorporate difference in systematics as last resort
- see R Barlow: arXiv:hep-ex/0207026
  - for more
  - for practical recipes
  - … and it is a very pleasurable read, too!

Simple examples…

- main analysis: sample A
  - result: $x_A \pm \sigma_A$
- alternate analysis: sample B
  - result: $x_B \pm \sigma_B$
- difference: $\Delta = | x_A - x_B |$ → when is it significant?

→ how much is the expected statistical fluctuation?

in general: $\sigma_\Delta^2 = \sigma_A^2 + \sigma_B^2 - 2\rho\sigma_A\sigma_B$ (ρ = correlation coefficient)

- special case: $B \cap A = \emptyset$ → $\sigma_\Delta^2 = \sigma_A^2 + \sigma_B^2$
- special case: $B = A$ → $\sigma_\Delta^2 = 0$
- special case: $B \subset A$ → $\sigma_\Delta^2 = \sigma_B^2 - \sigma_A^2$

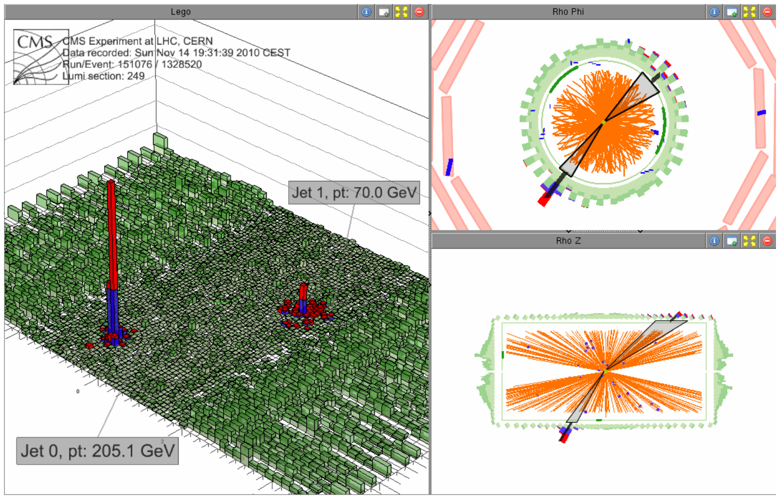
ধন্যবাদ!

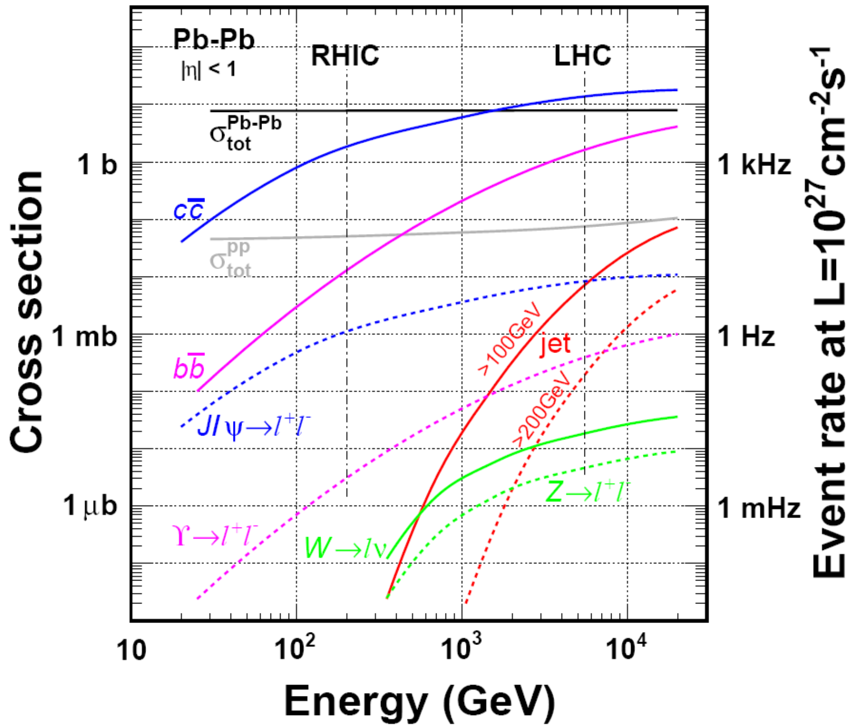
धन्यवाद!

Grazie!

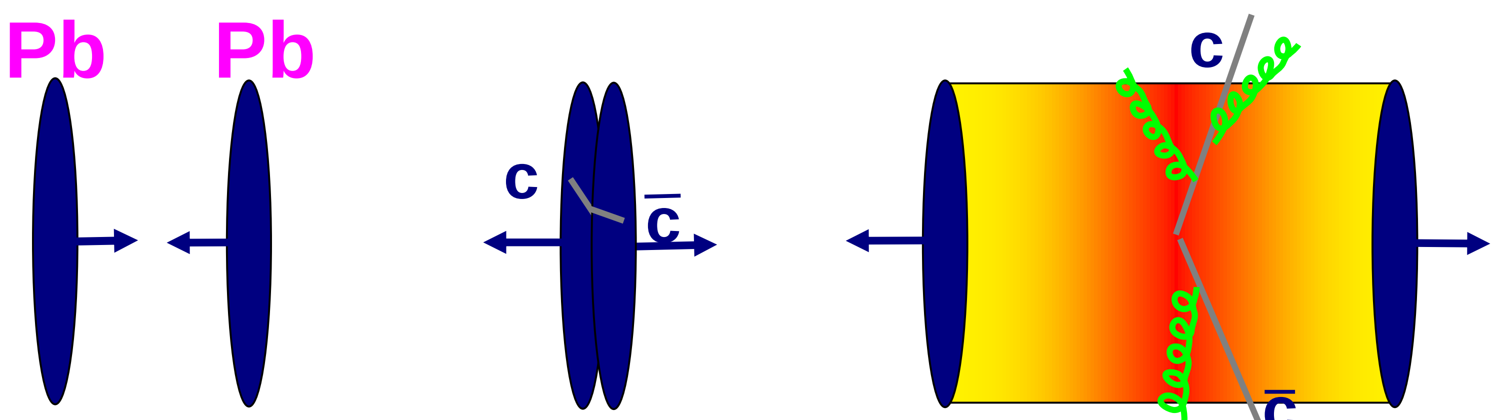
Nuclear collisions at the LHC

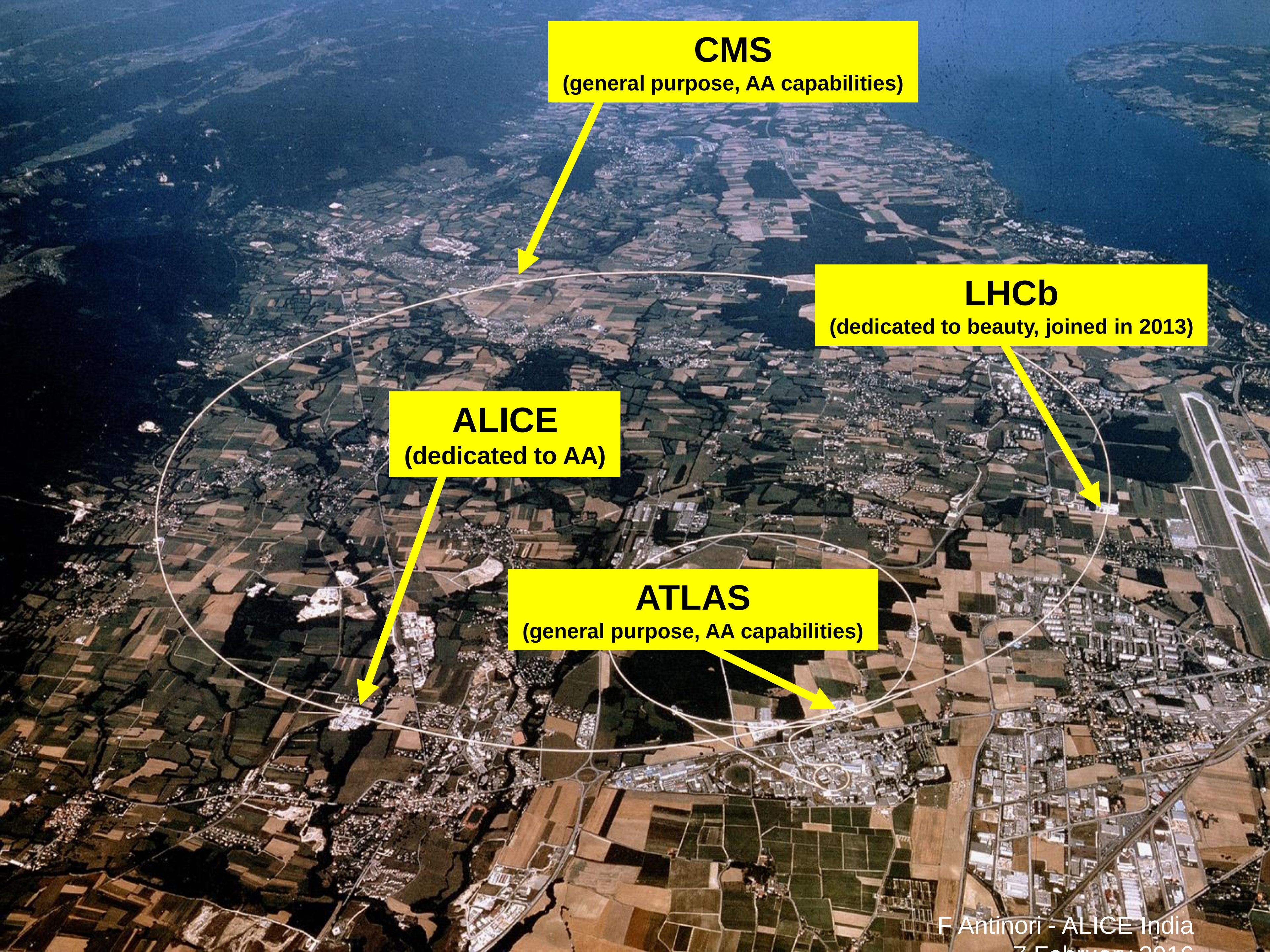
- large cross-section for "hard probes"



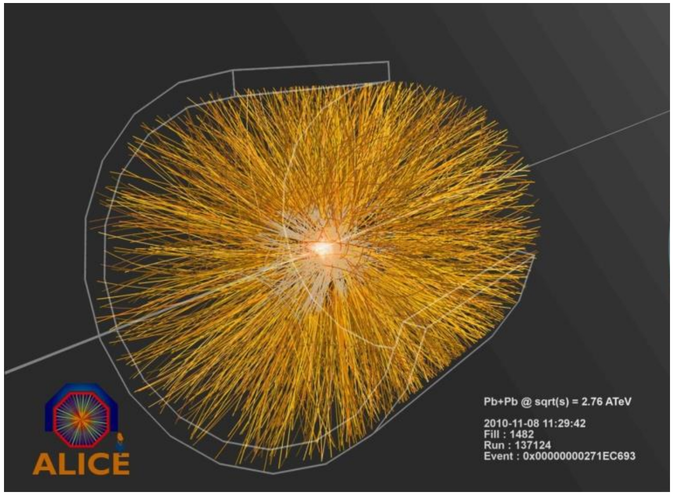


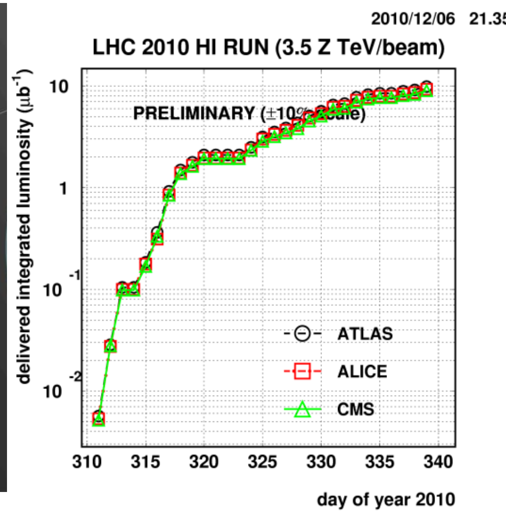
→ novel tools to probe QCD medium
in particular: heavy flavour:

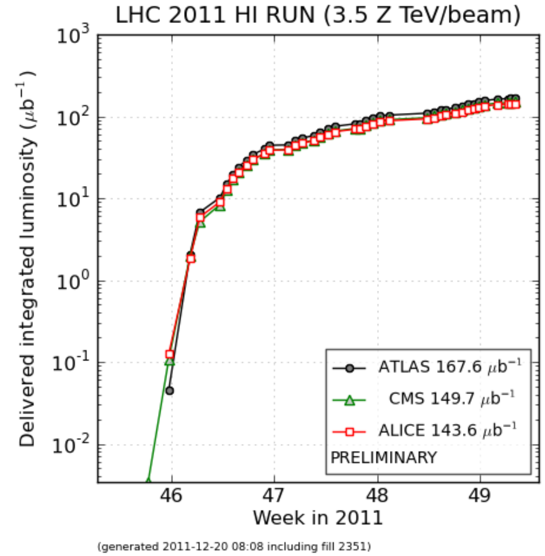



CMS
(general purpose, AA capabilities)
LHCb
(dedicated to beauty, joined in 2013)
ALICE
(dedicated to AA)
ATLAS
(general purpose, AA capabilities)

Nuclear collisions at the LHC!



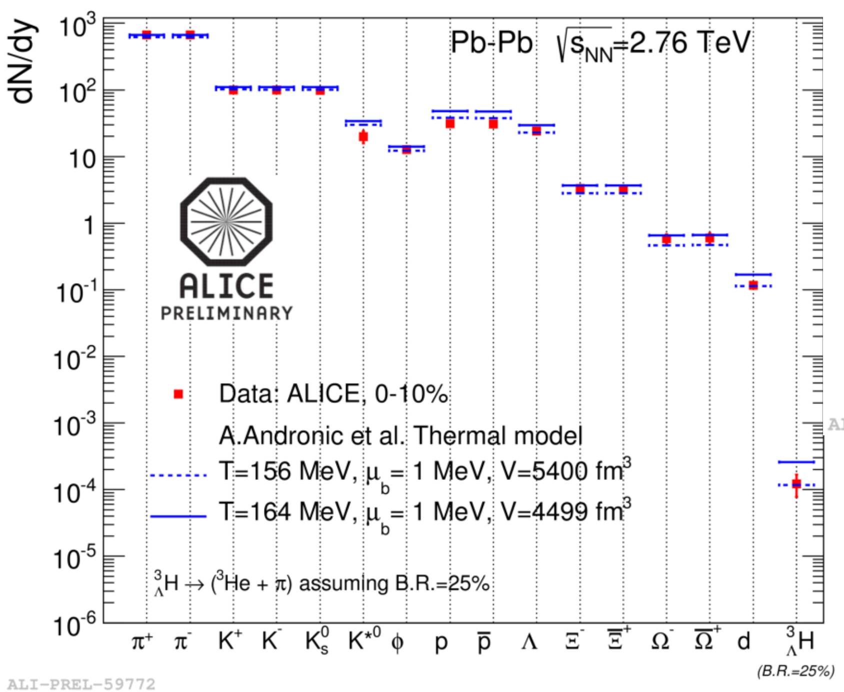




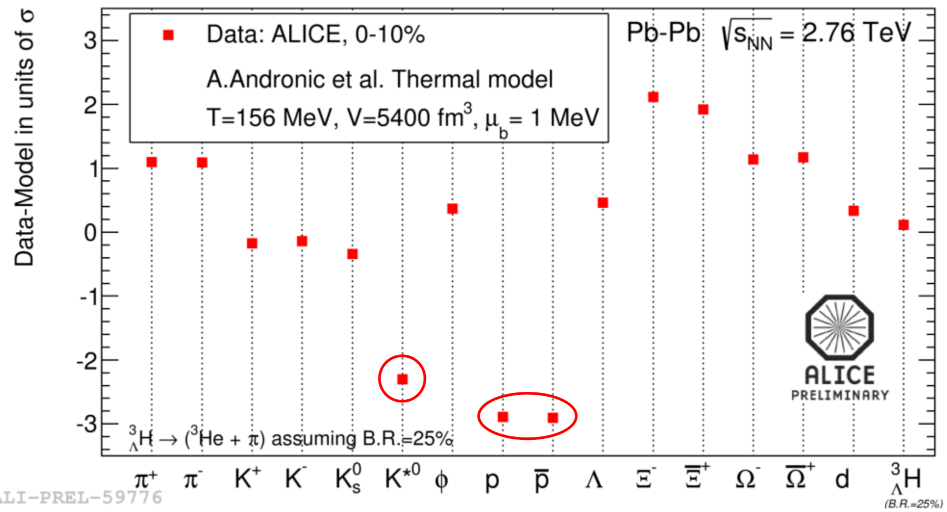
- three successful Pb-Pb runs already
  - 2010 → $\sqrt{s_{NN}}$ = 2.76 TeV, L_{int} ~ 10/μb
  - 2011 → $\sqrt{s_{NN}}$ = 2.76 TeV, L_{int} ~150/μb
  - 2015 → $\sqrt{s_{NN}}$ = 5.02 TeV, L_{int} ~ 500/μb
- + p-Pb "control" run
  - 2013 → $\sqrt{s_{NN}}$ = 5.02 TeV, L_{int} ~ 30/nb
- + pp "reference" runs in 2010 and 2013 (2.76 TeV), 2015 (5.02 TeV)

Particle yields

- ~ thermodynamic equilibrium
  - T ~ 156 MeV
  - now including $^{3}_{\Lambda}H$!



- … but with some tension
  - especially p and K*



- origin of deviations?
  - feed down from resonance decays?
  - sequential freeze-out?
  - non-equilibrium freeze-out?

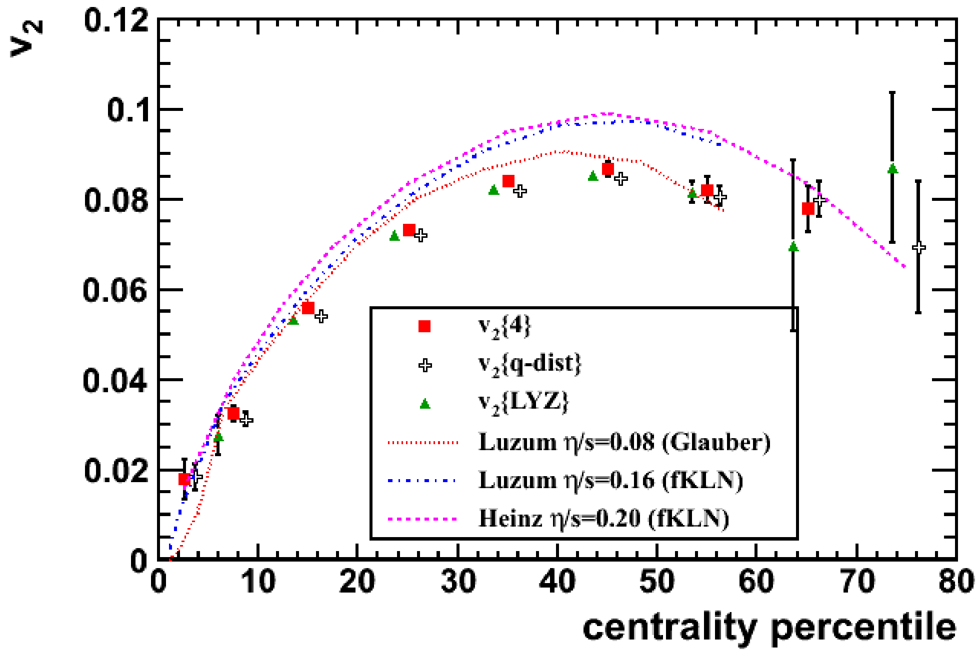
Azimuthal asymmetry

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

  $$\propto 1+2v_1\cos(\varphi-\psi_1)+2v_2\cos(2[\varphi-\psi_2])+\ldots$$

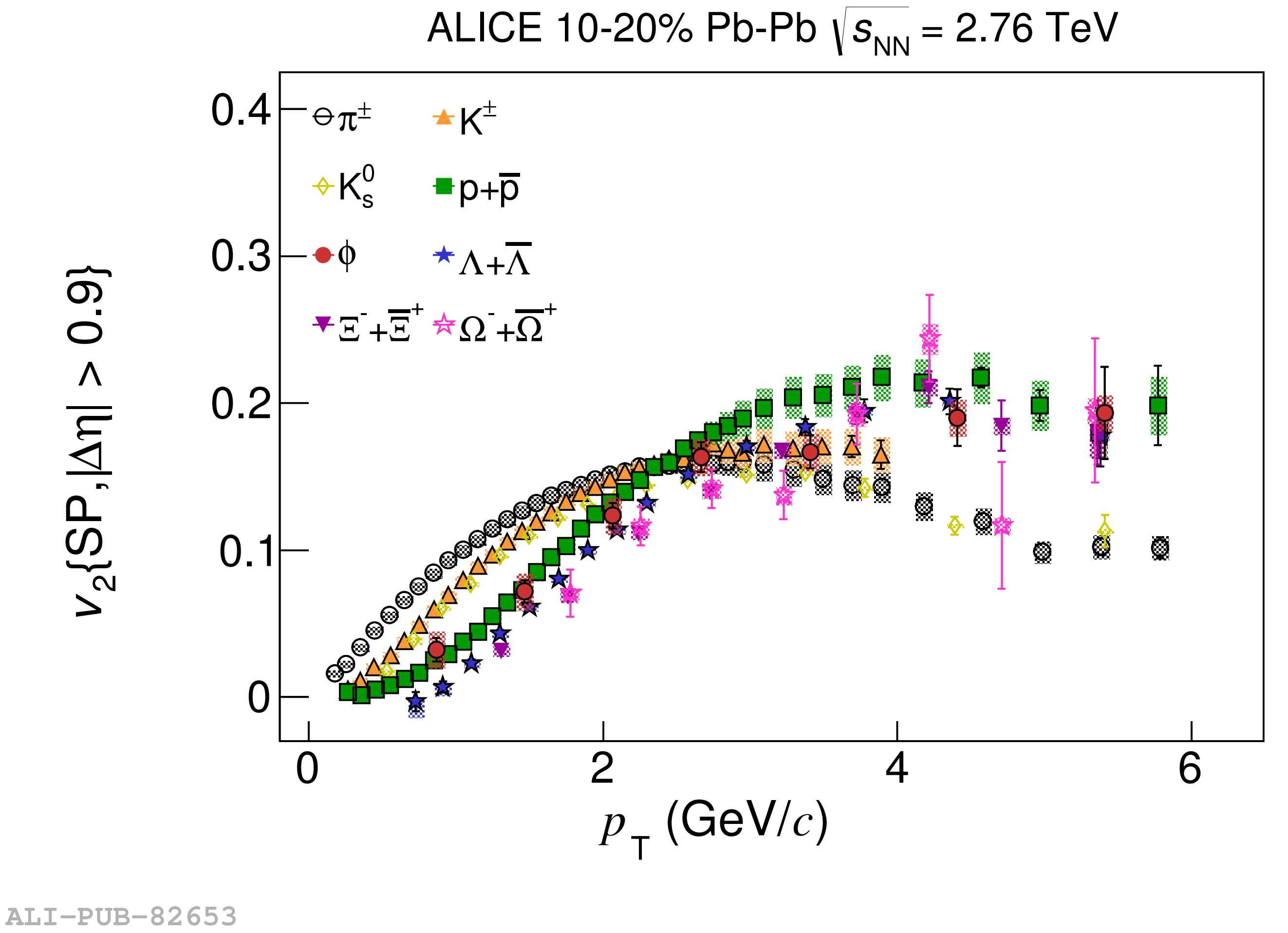
  – in the central detector region ($\vartheta \sim 90^{\circ}$) → $v_1 \sim 0$ → asymmetry quantified with v_2

- experimentally: v_2 ~ as large as expected by hydrodynamics

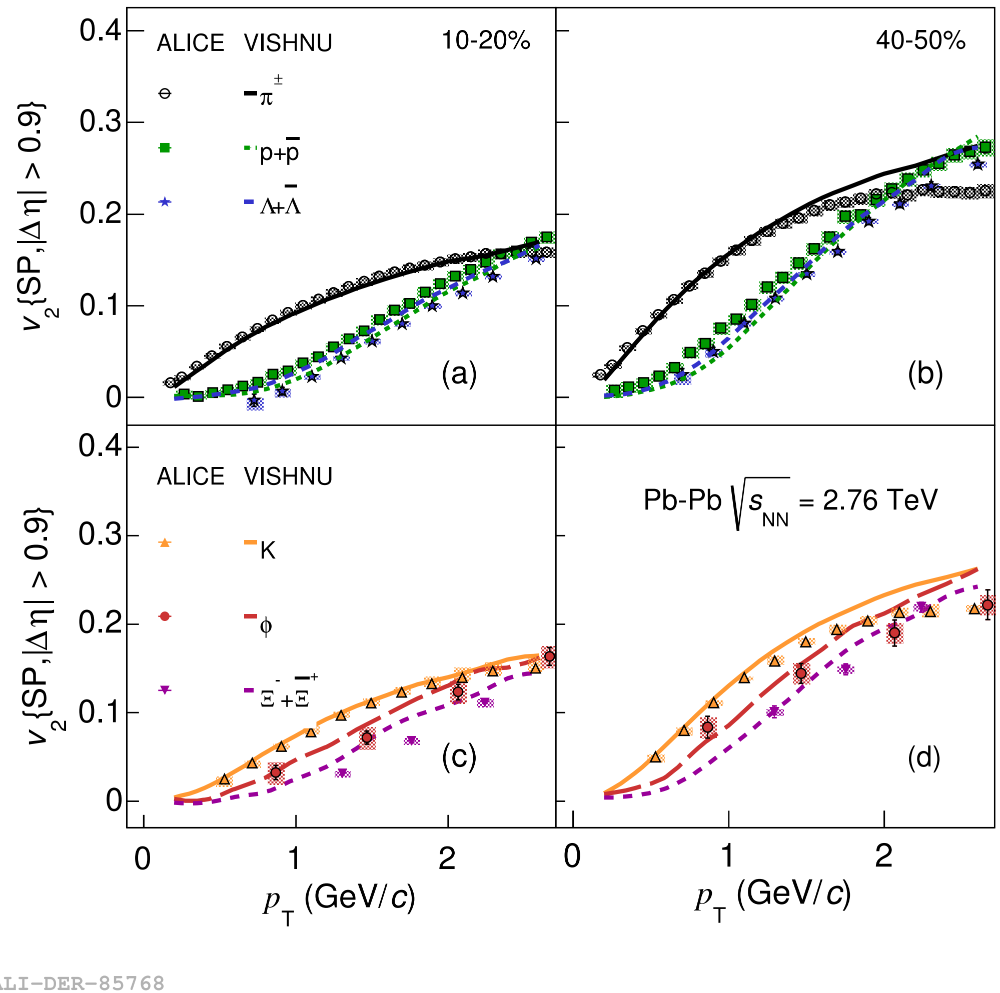


Identified Particles v_2

•



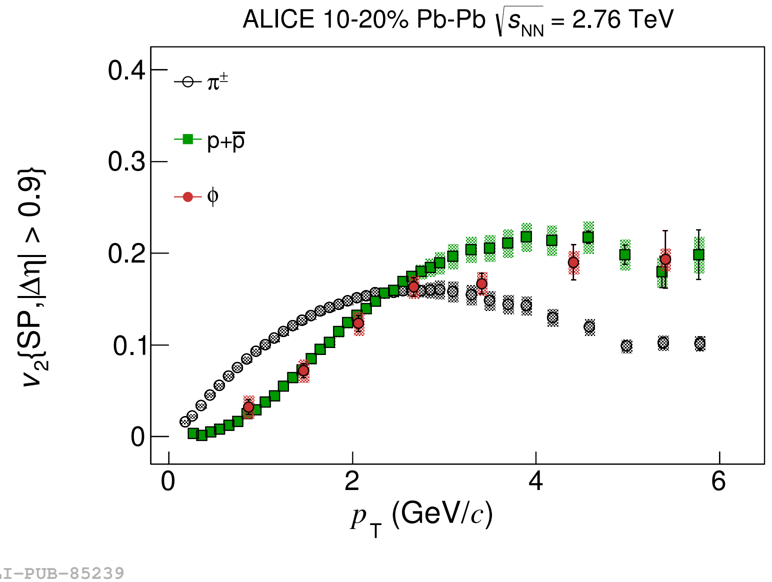
Comparison with hydro

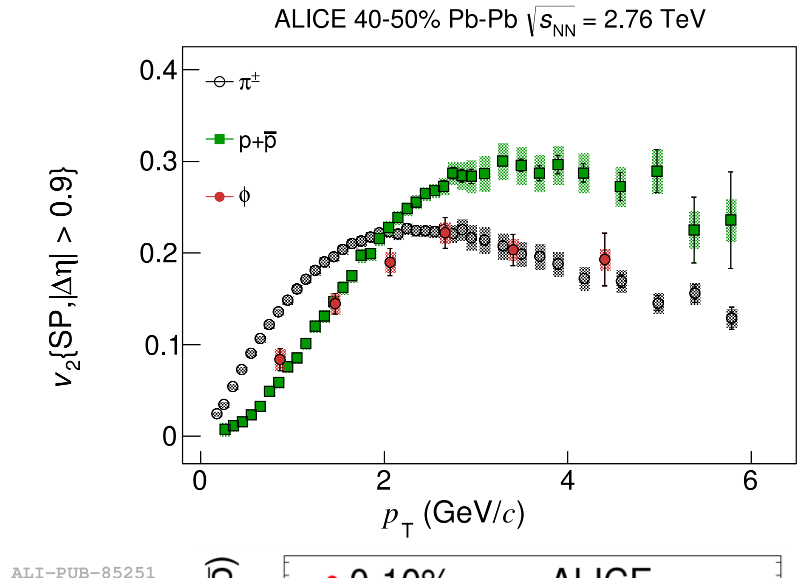


- proton v_2 underestimated
- Λ v_2 overestimated

→ mass ordering not preserved in VISHNU due to the hadronic cascade

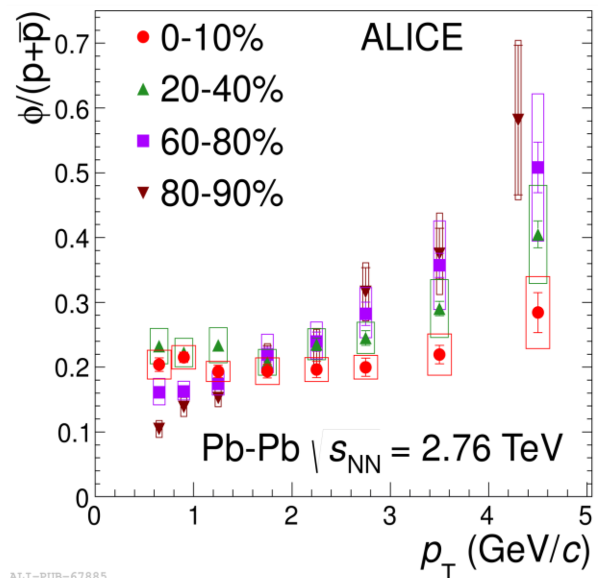
The Φ



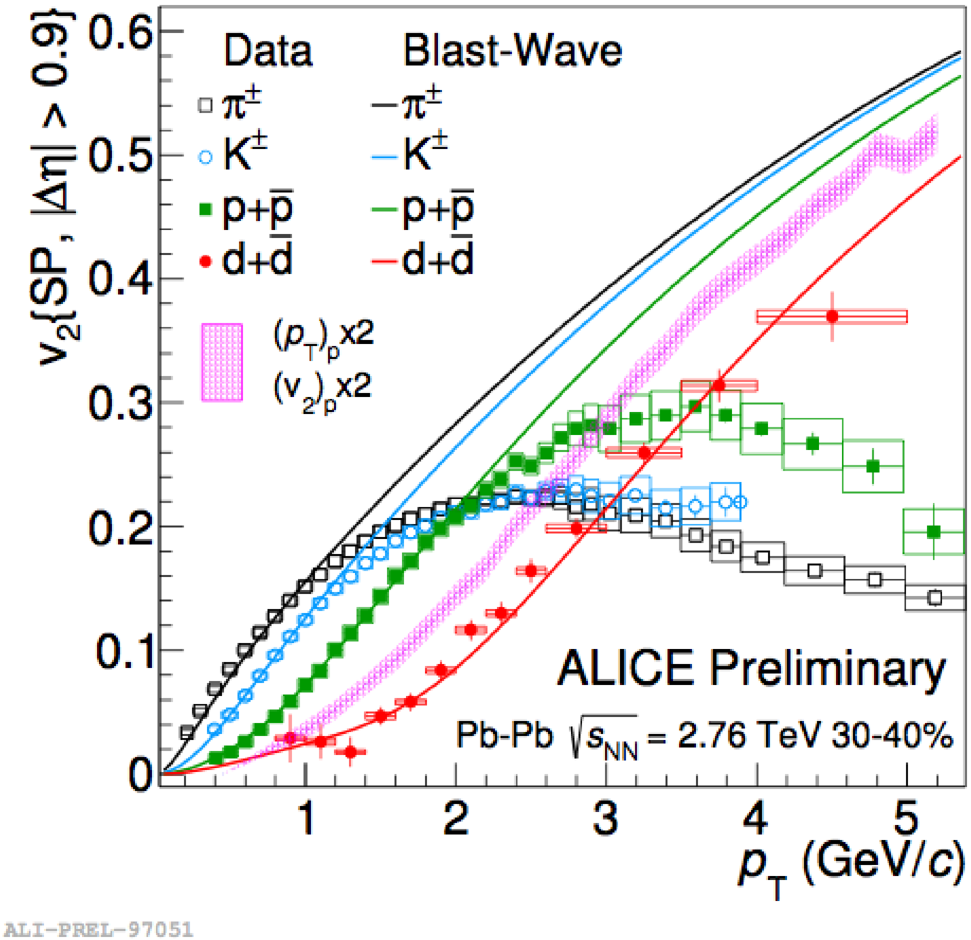


- low p_T ($p_T < 2$ GeV/c): mass ordering
- intermediate p_T ($2 < p_T < 6$ GeV/c):
  - in peripheral events, the Φ behaves like a pion
  - but in central events, it behaves like a proton!
- similar story from particle spectra →

→ it seems that m, not n_q, is in control



The deuteron

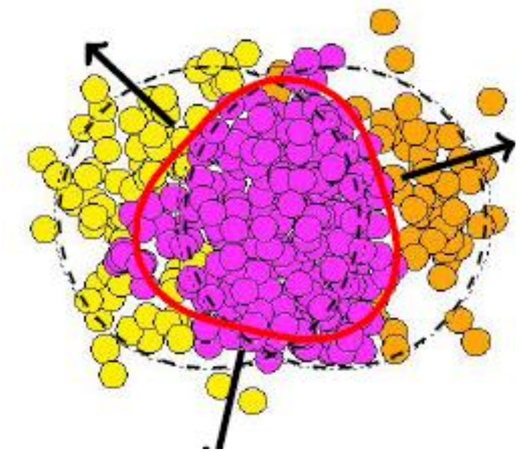


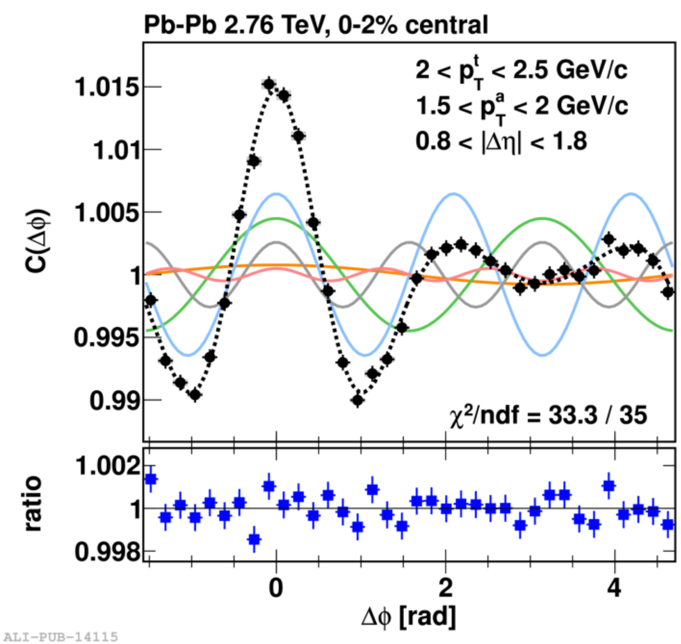
- simple coalescence model does not describe deuteron v_2
- blast-wave prediction from π/K/p fit does a decent job
- how do we understand this?
  - how does the fragile d flow like a π?

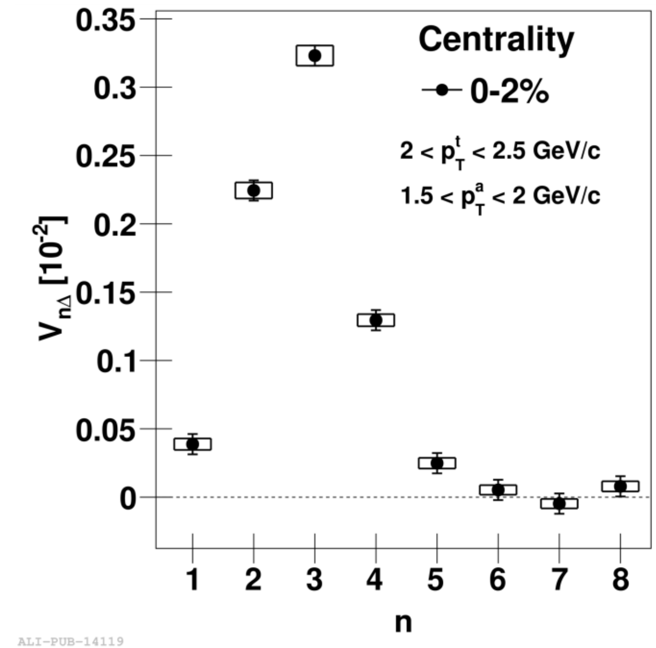
Higher harmonics

- a beautiful tool…

initial state geometrical asymmetries ⟶ final state momentum asymmetries







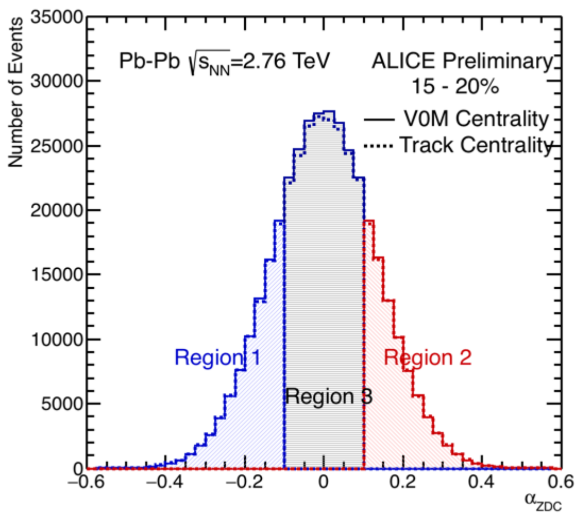
[ALICE: PLB 708 (2012) 249]

- connects final state distribution to initial state fluctuations
  - via medium transport

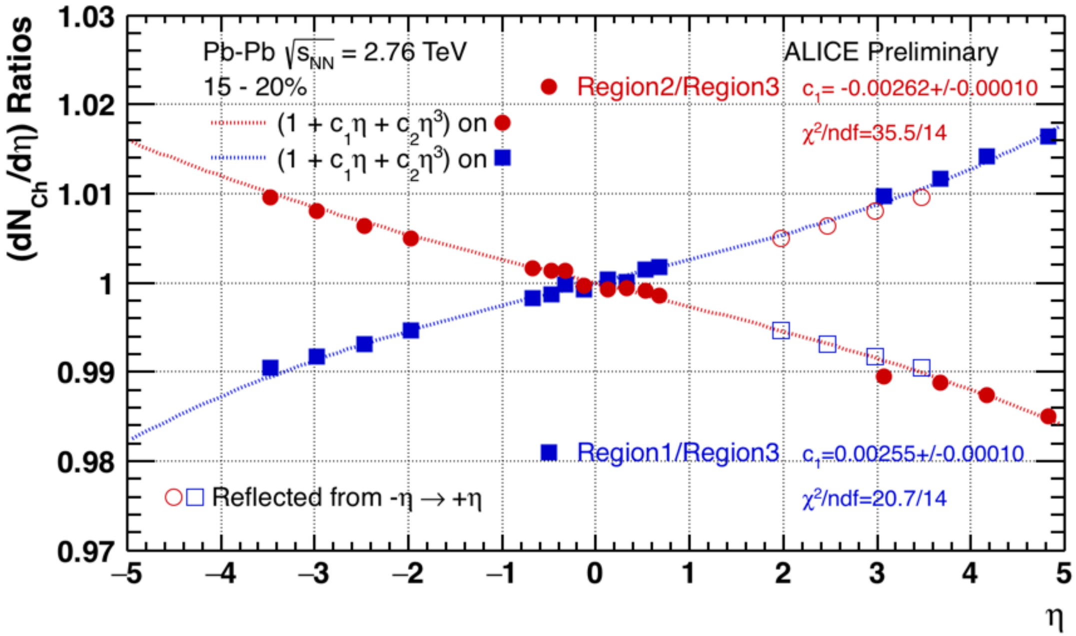
Longitudinal asymmetry

- event-by-event fluctuations

asymmetric events in ZDCs → effects on η distribution



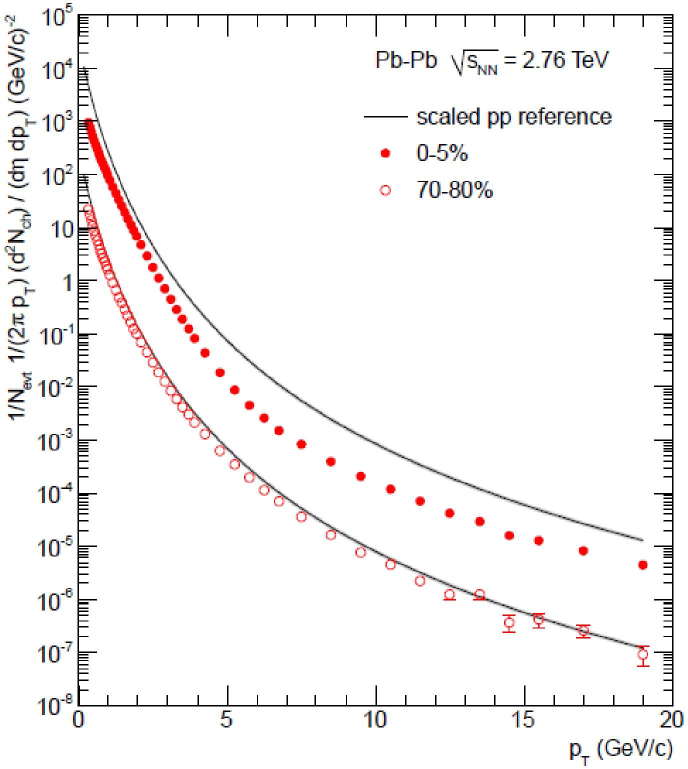
$\alpha_{ZDC} = (ZDC_1 - ZDC_2) / (ZDC_1 + ZDC_2)$



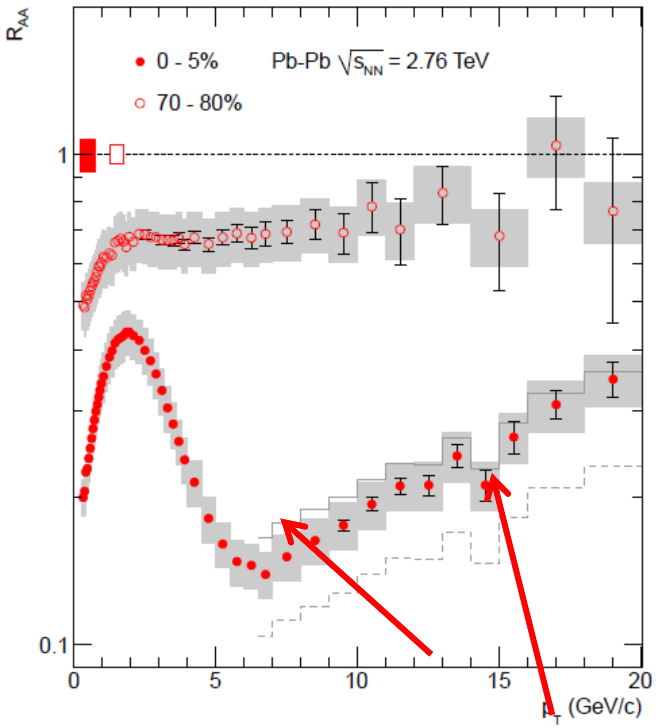
- a new event classifier?

Very strong quenching

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



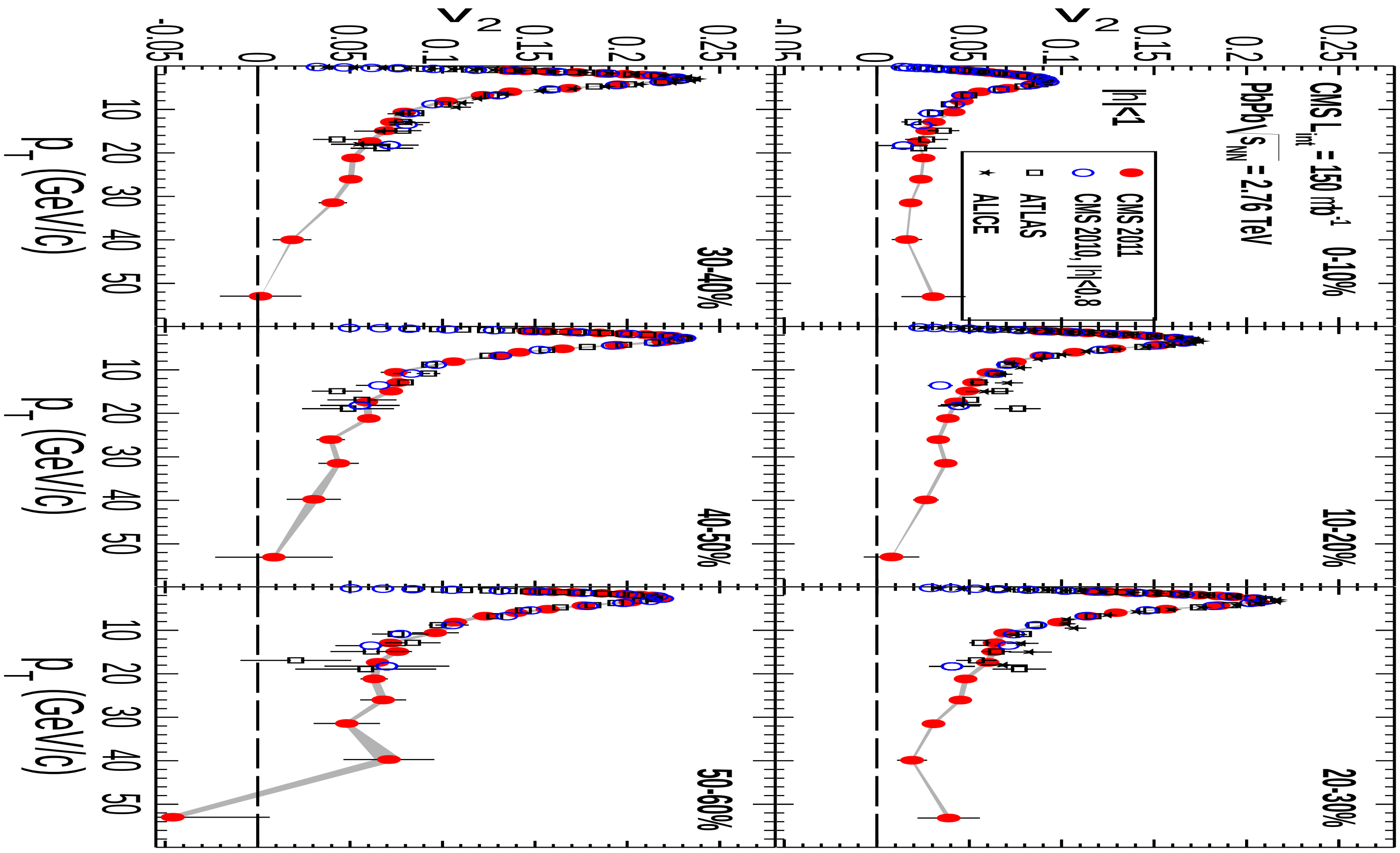
- R_{AA}:



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

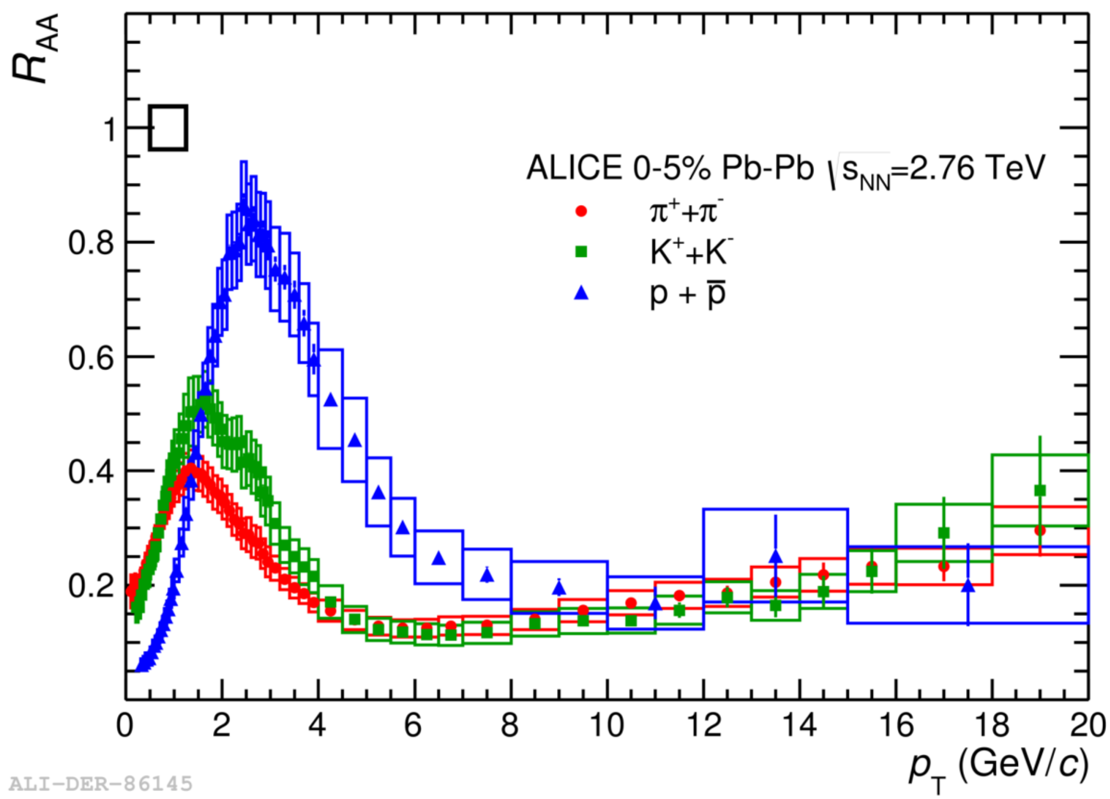
v_2 persists to very high p_T

- angular dependence of quenching



Dependence on particle species

- particle mass / type (baryon/meson) dependence of suppression
  - e.g.: proton enhancement

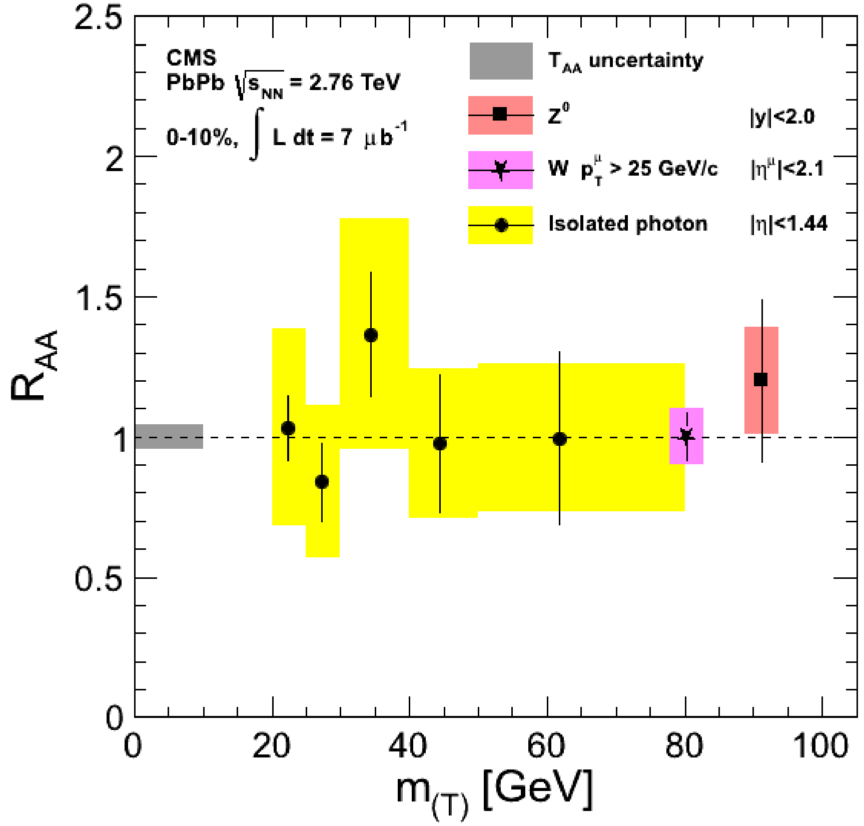


→ sensitivity to hadronisation in medium

R_{AA} for vector bosons

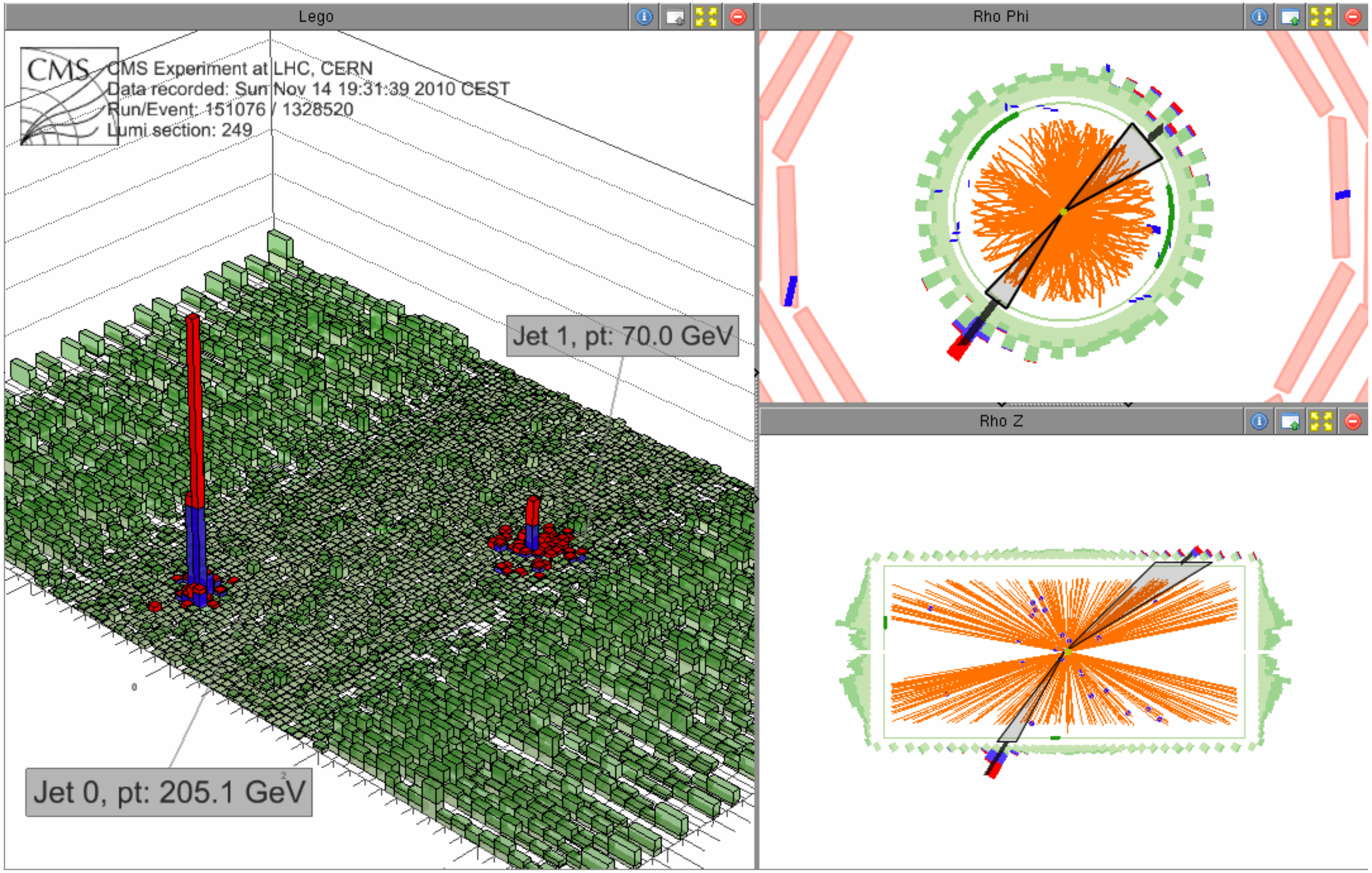
- electroweak probes, on the other hand, are unmodified

→ (essential cross check!)



Di-jet imbalance

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

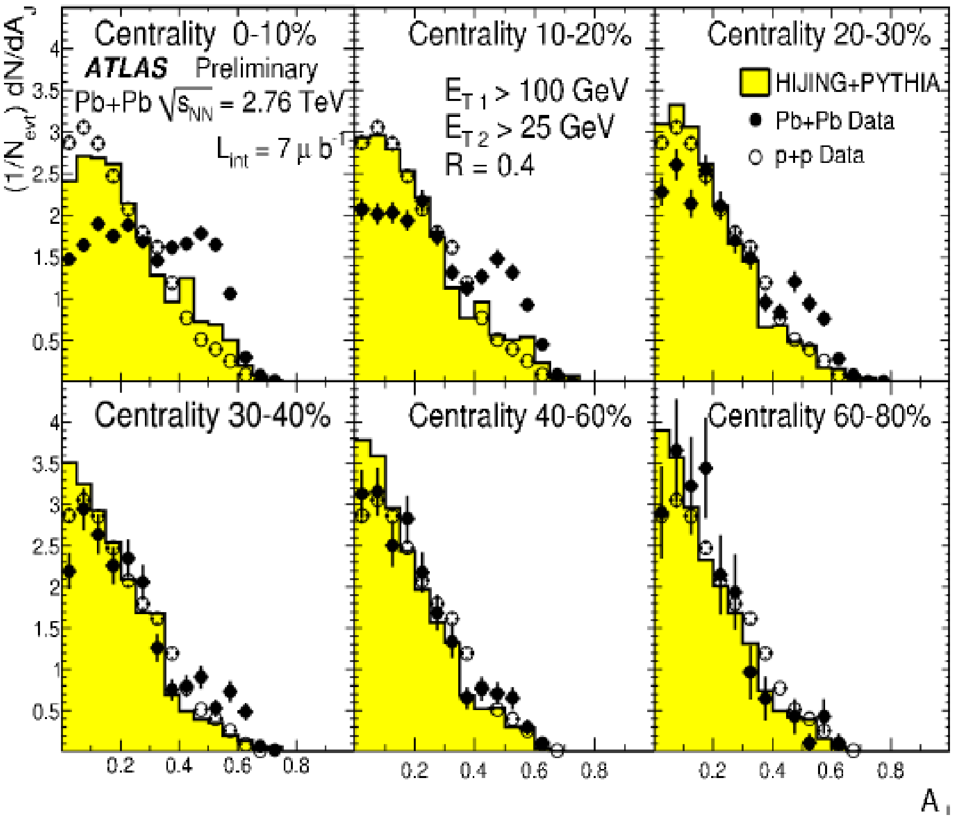


→ recoiling jet strongly quenched!

CMS: arXiv:1102.1957

Di-jet imbalance

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



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

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

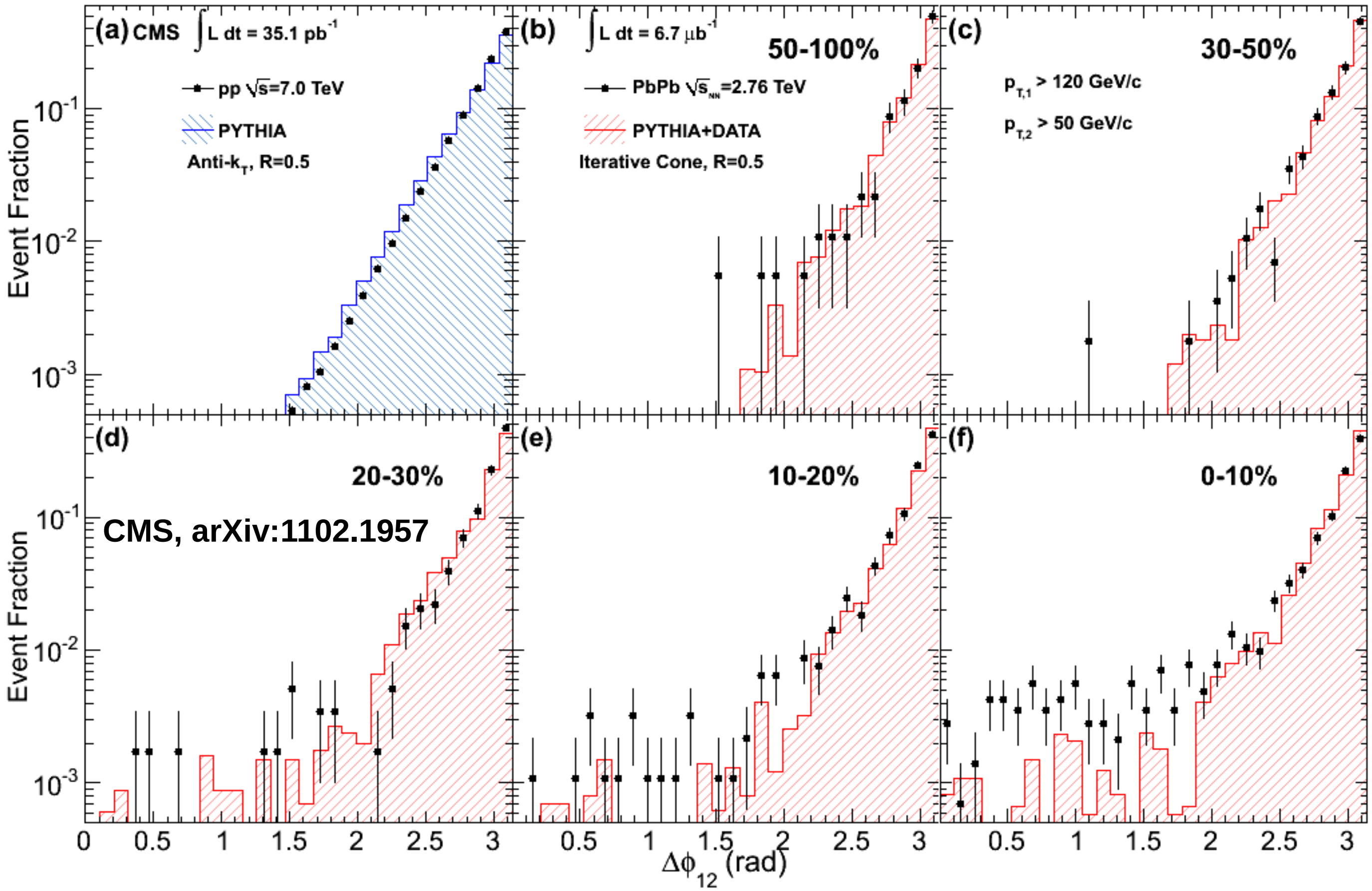
- with increasing centrality:

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

ATLAS: PRL105 (2010) 252303

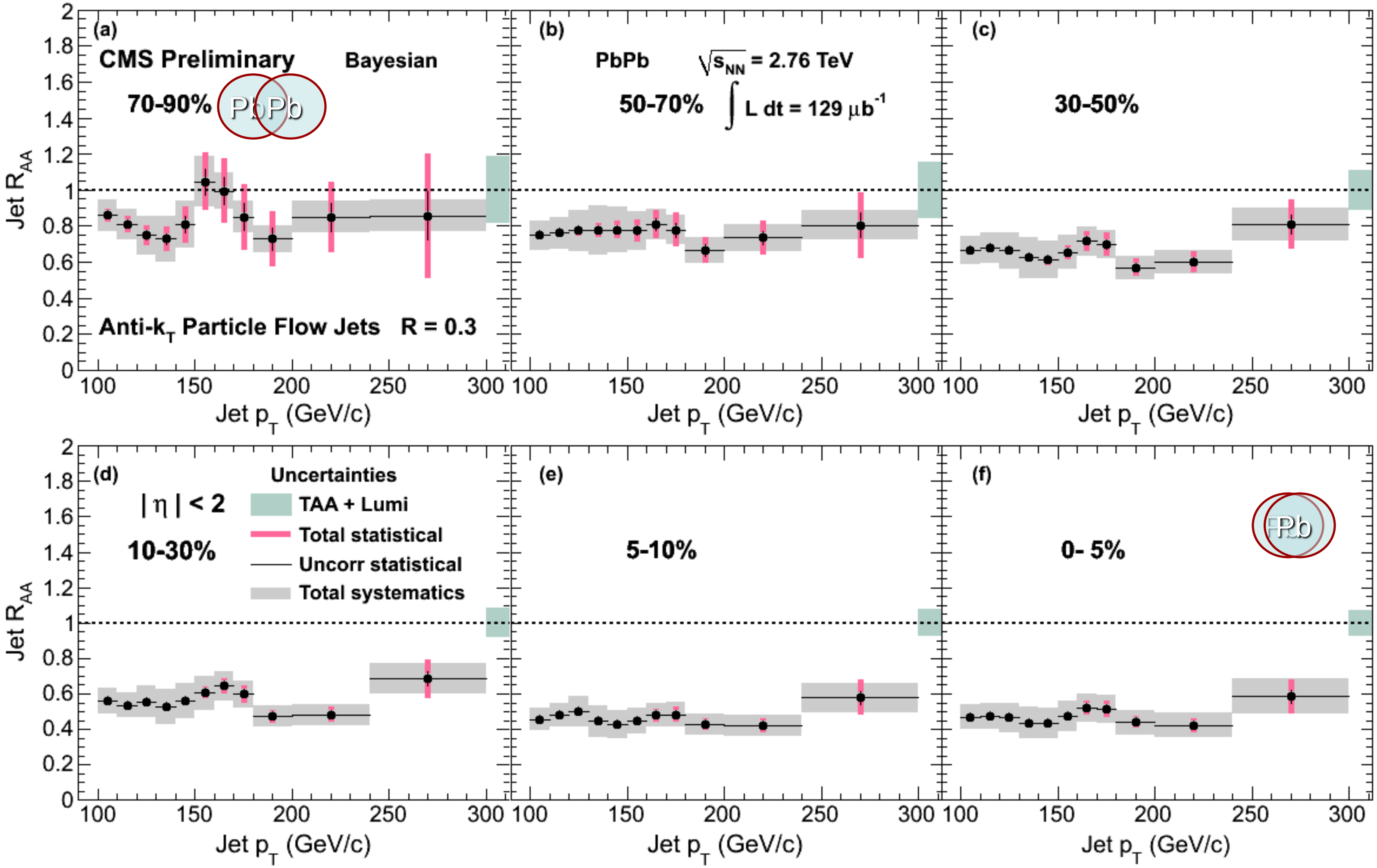
Di-jet Δφ

- no visible angular decorrelation in Δφ wrt pp collisions!



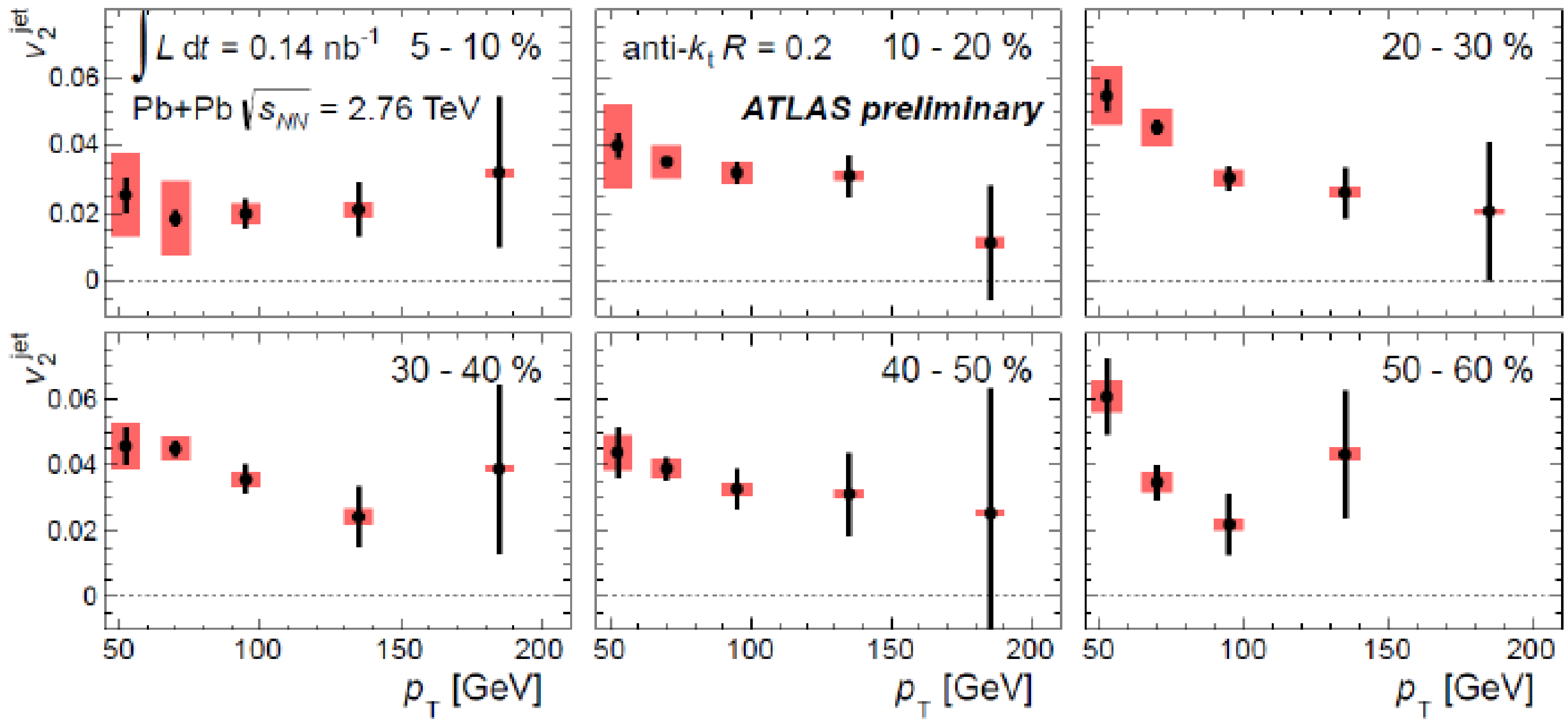
→ large imbalance effect on jet energy, but very little effect on jet direction!

Jet R_{AA}



CMS PAS HIN-12-004

Jet v_2

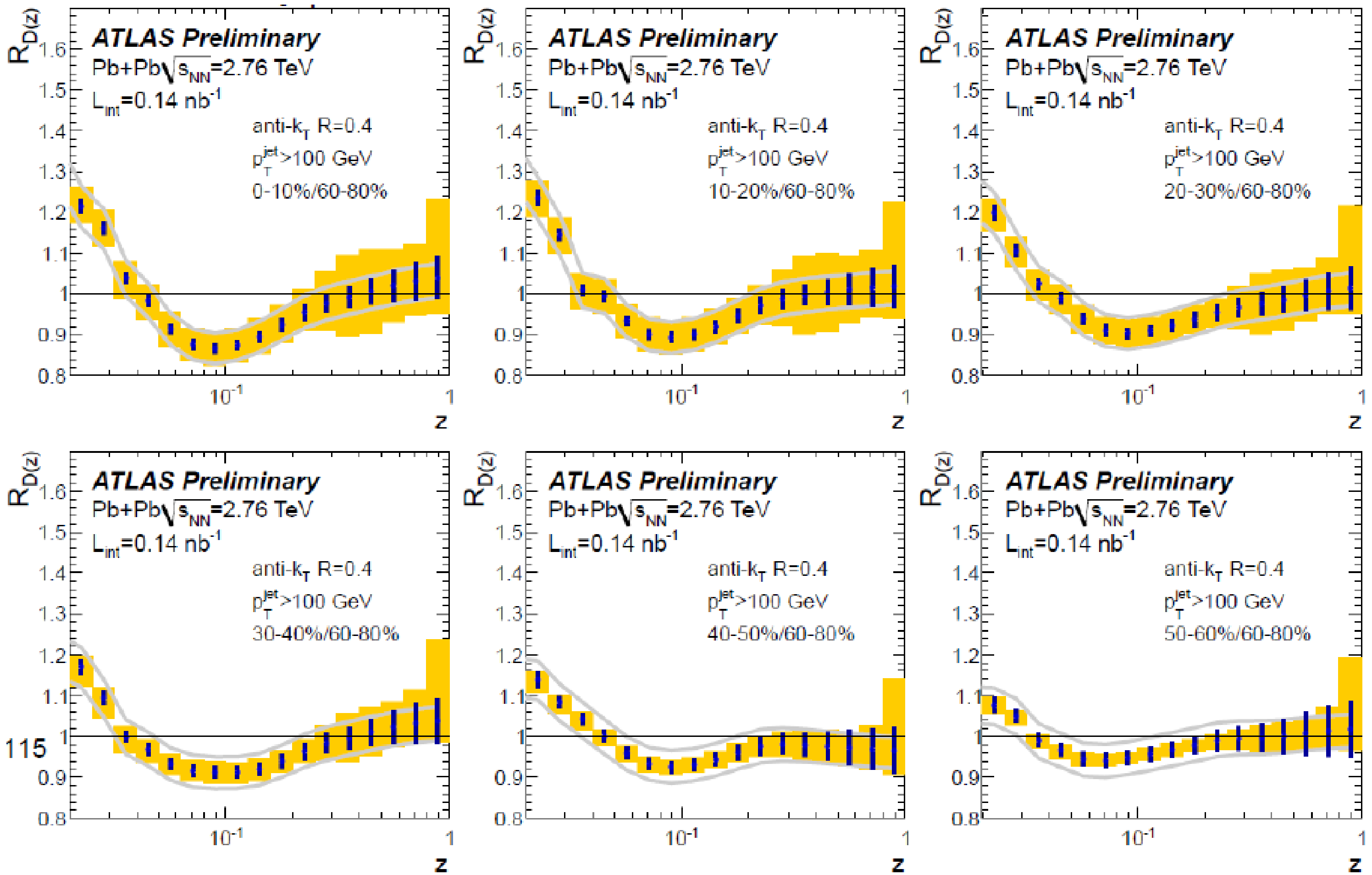


ATLAS-CONF-2012-116

- substantial azimuthal asymmetry up to highest jet energies!

Jet fragmentation is modified

- ratio of Pb-Pb and pp Fragmentation Functions



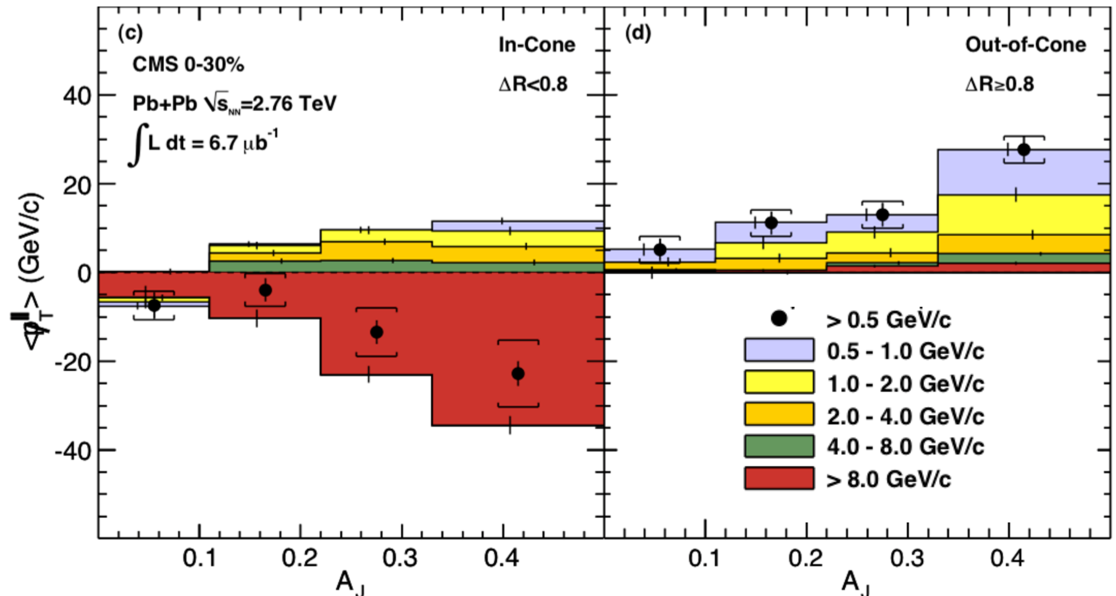
$z = p_T(\text{track})/p_T(\text{jet})$

ATLAS-CONF-2012-115

Where does the energy go?

- look at missing p_T projected on leading jet axis

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

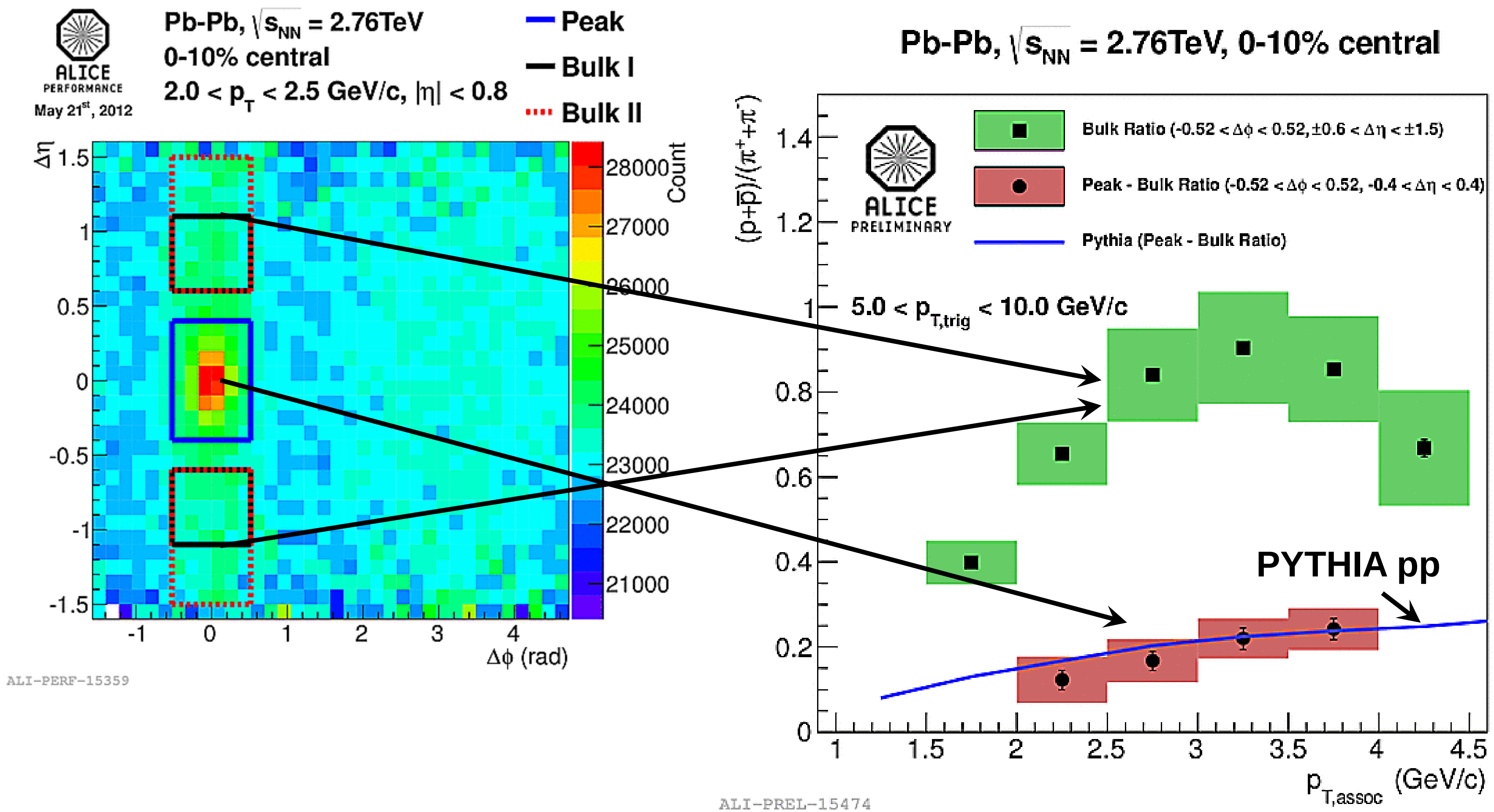


[CMS: PRC 84 (2011) 024906]

- the energy reappears, degraded, outside of the jet cone…

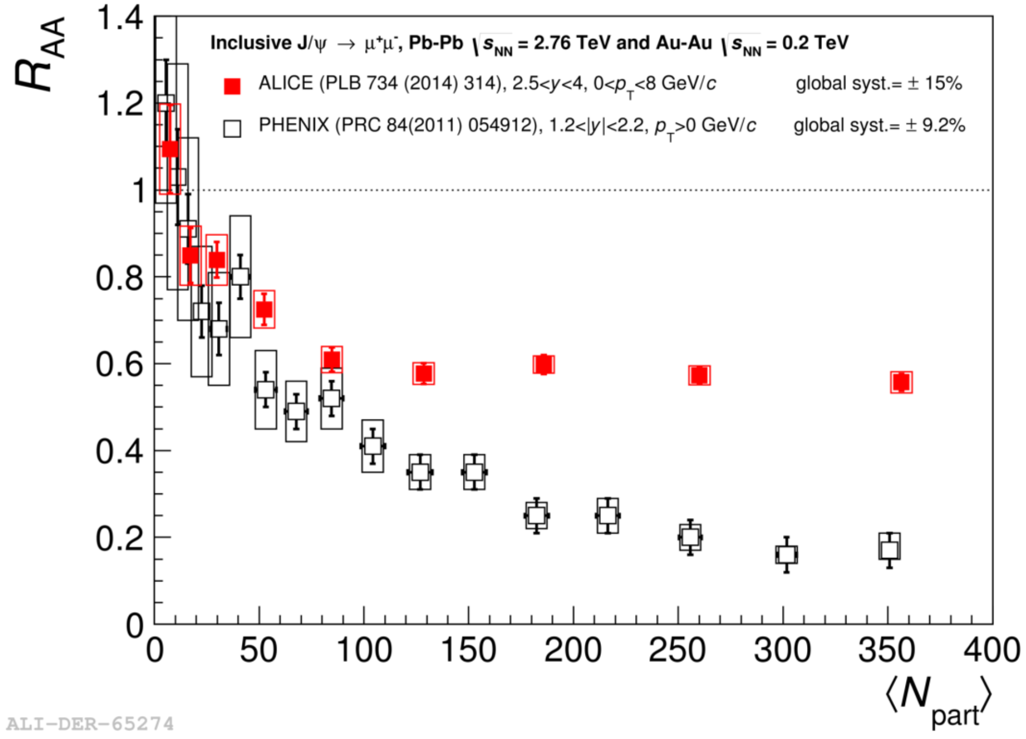
Particle composition

- peak excess particle composition similar to pp!



J/ψ suppression at the LHC

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



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

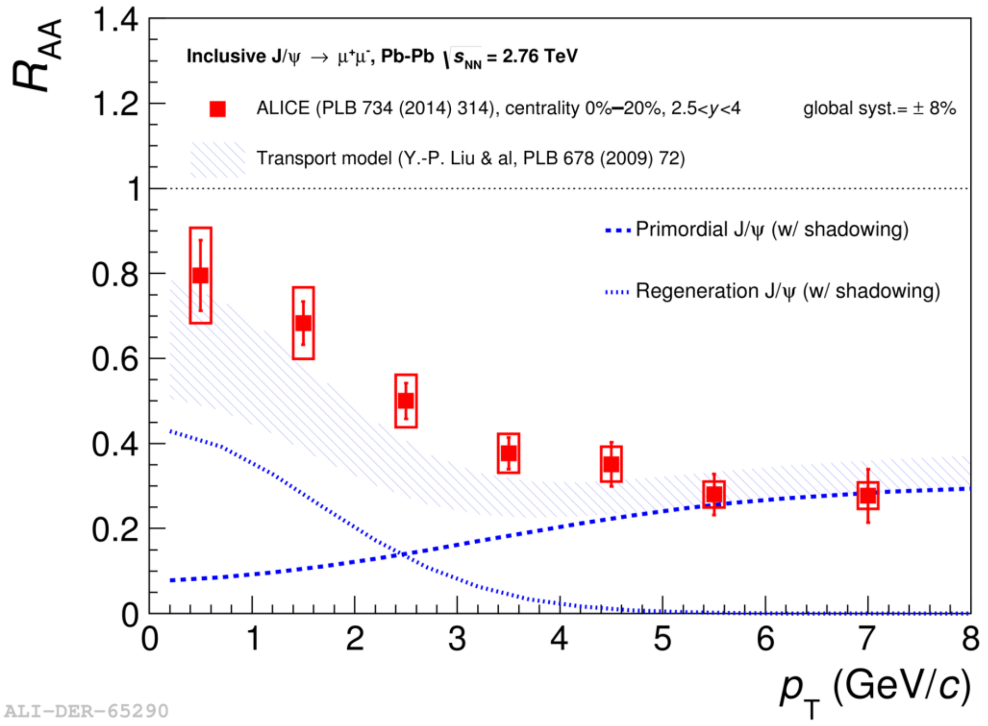
→ weaker centrality dependence

→ new regime wrt RHIC!

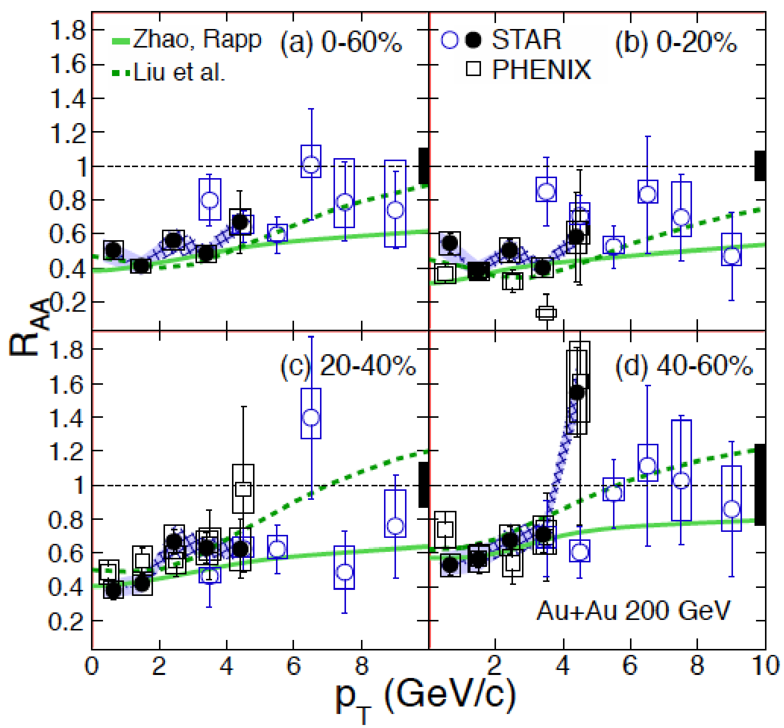
→ c-cbar coalescence?

J/ψ R_{AA}: p_T dependence

- decreases with p_T



- at RHIC: opposite behaviour

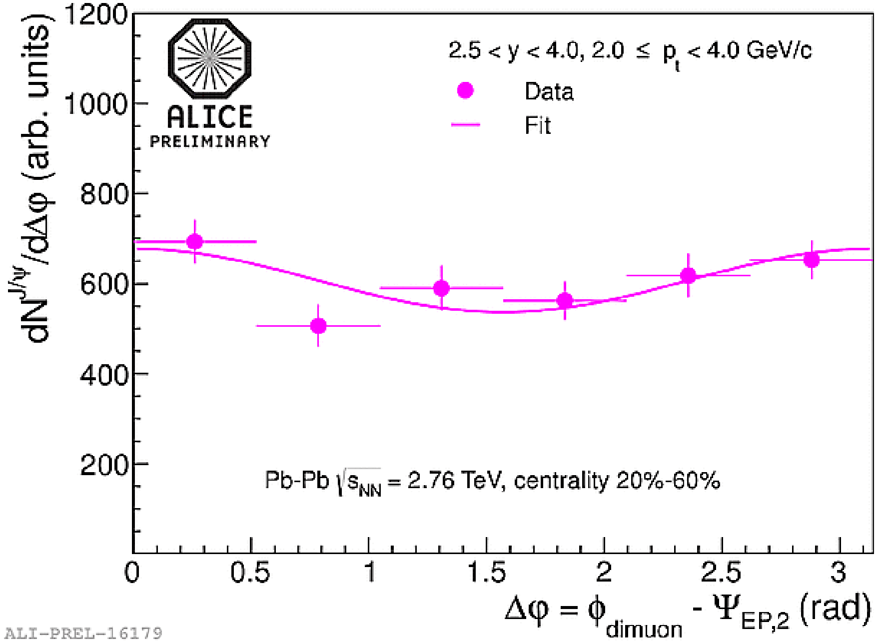


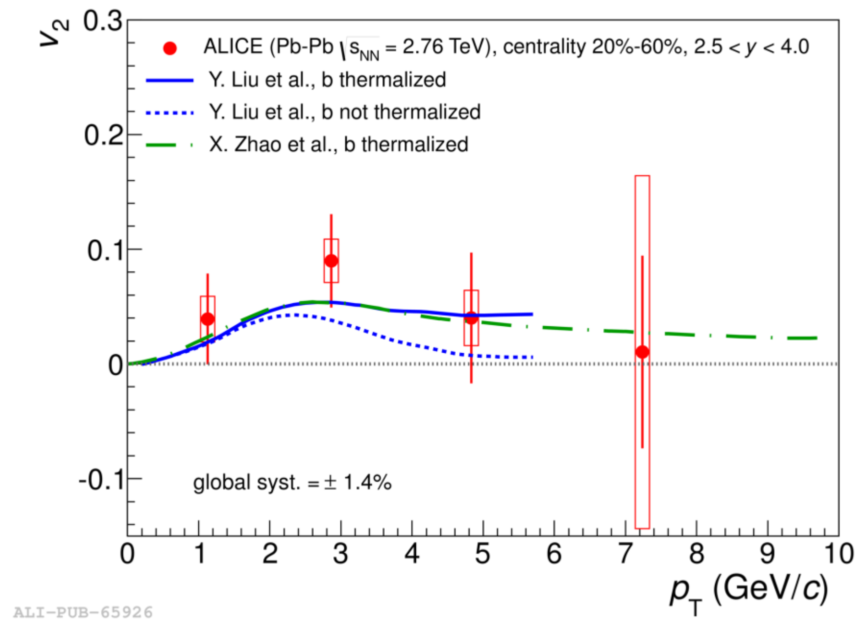
[STAR, arXiv:1310.3563]

- consistent with regeneration models

J/ψ flow?

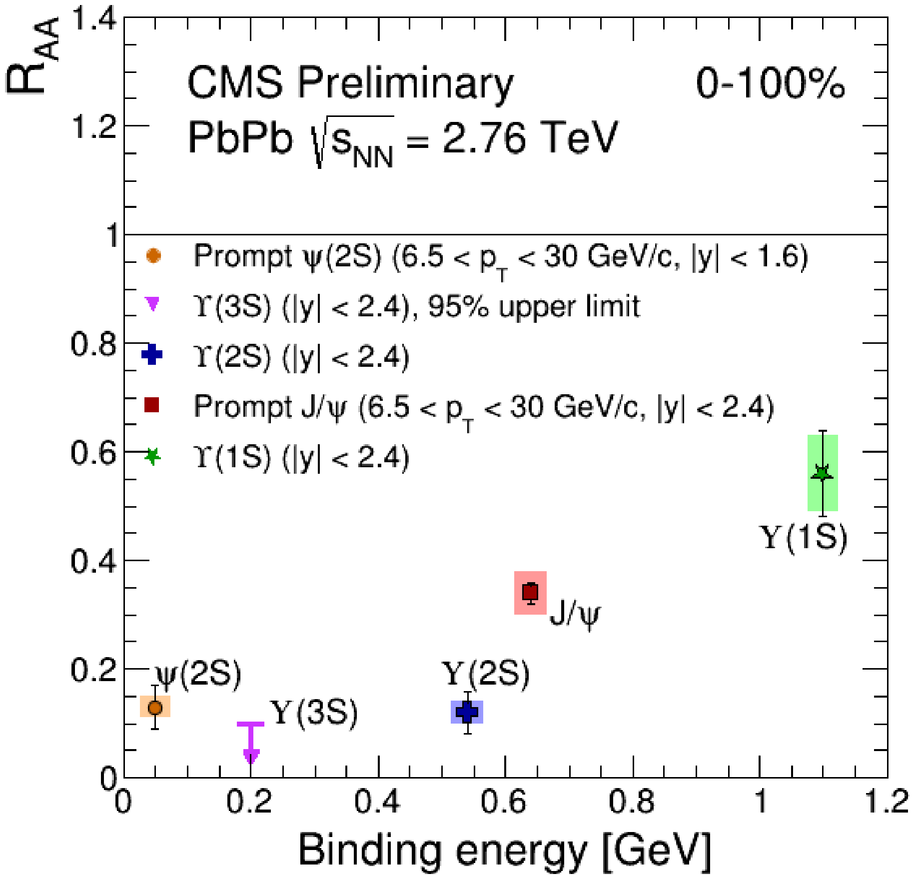
- hint for a modulation…





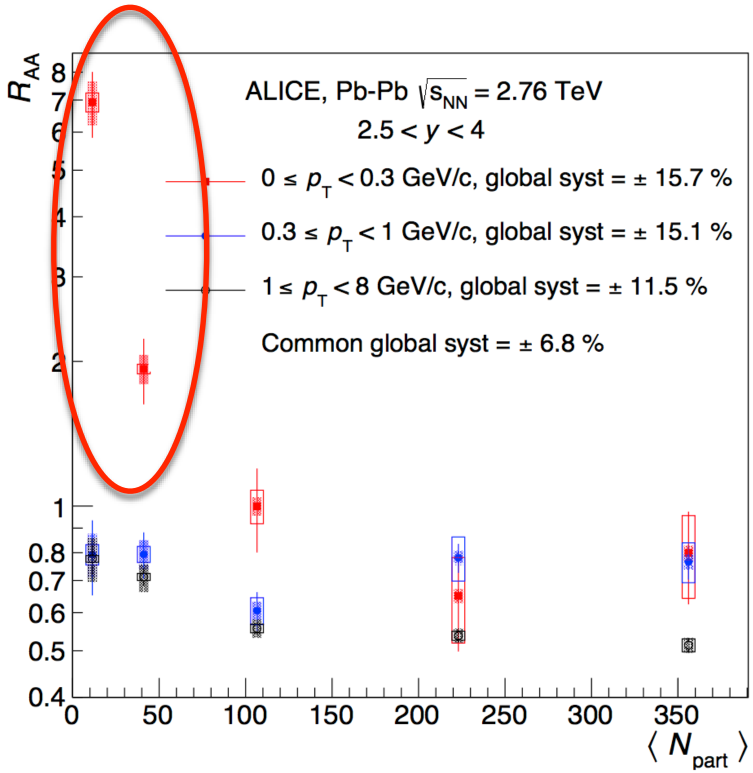
- more statistics coming!

Bottomonium suppression

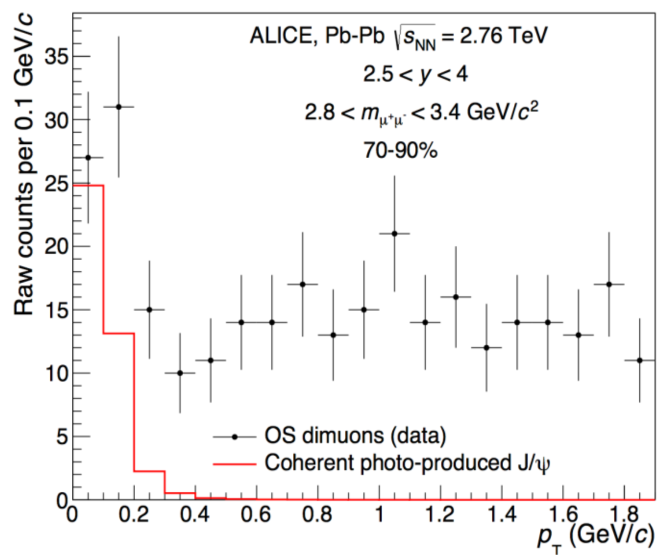


- stronger suppression for less bound Y states
  - very efficient melting: Y(3S) not measurable (upper limit only)

Very soft J/ψ excess

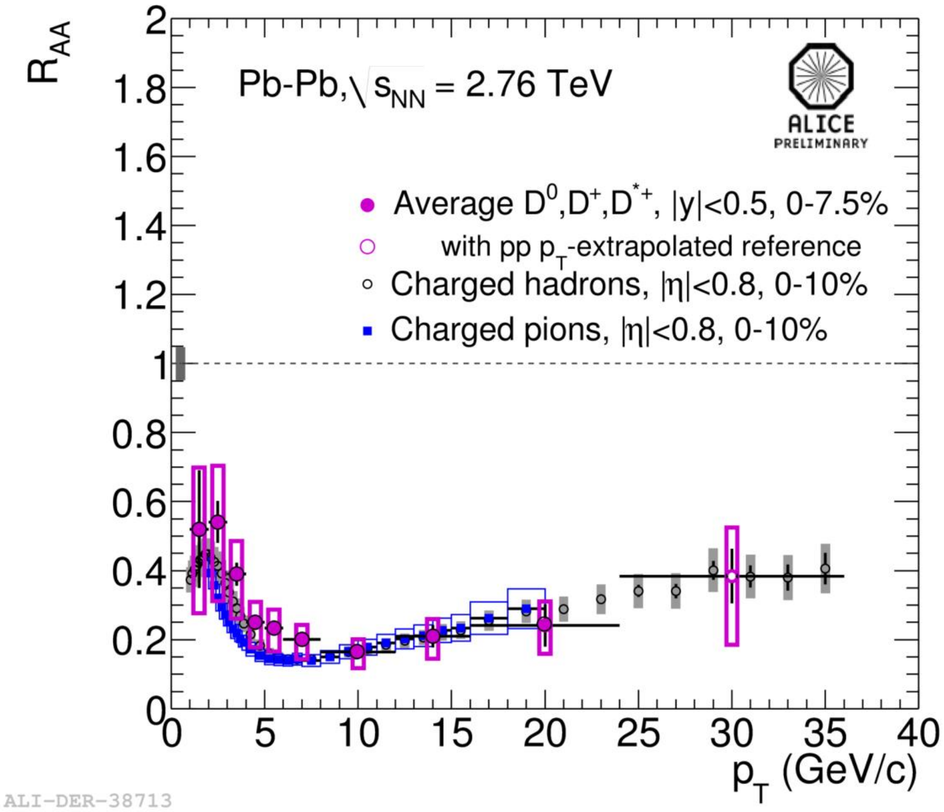


- strong enhancement in R_{AA} for p_T < 0.3 GeV/c
- p_T-shape consistent with STARLIGHT EM

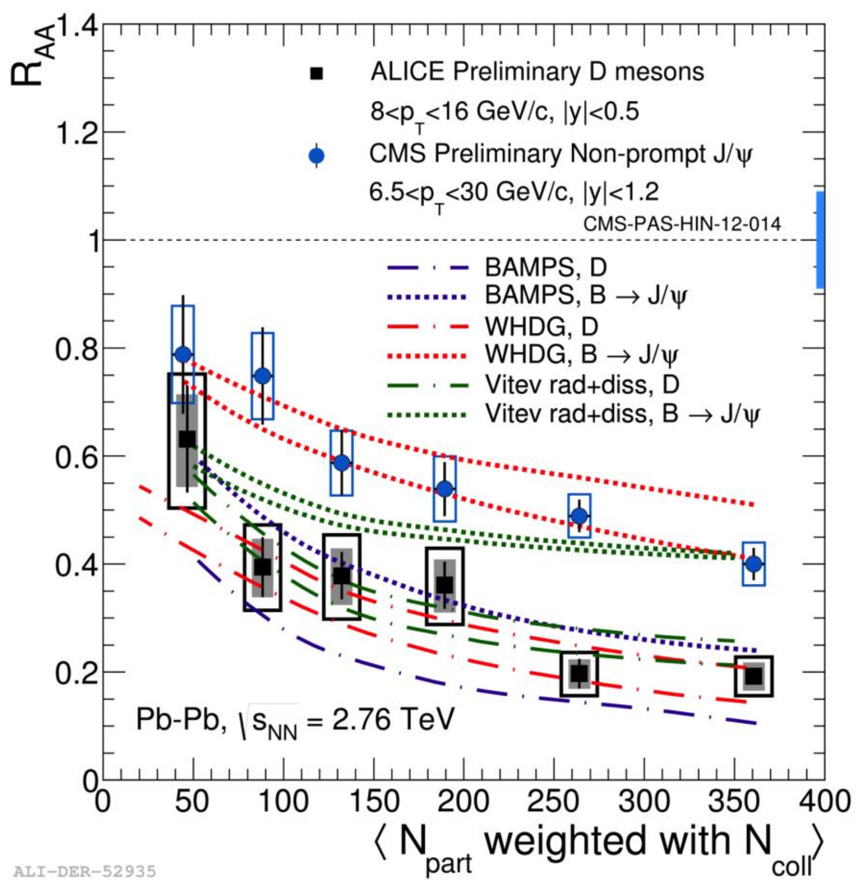


- observation of EM production in hadronic collisions?
- no theoretical calculation exists!

R_{AA}: Flavour Dependence!



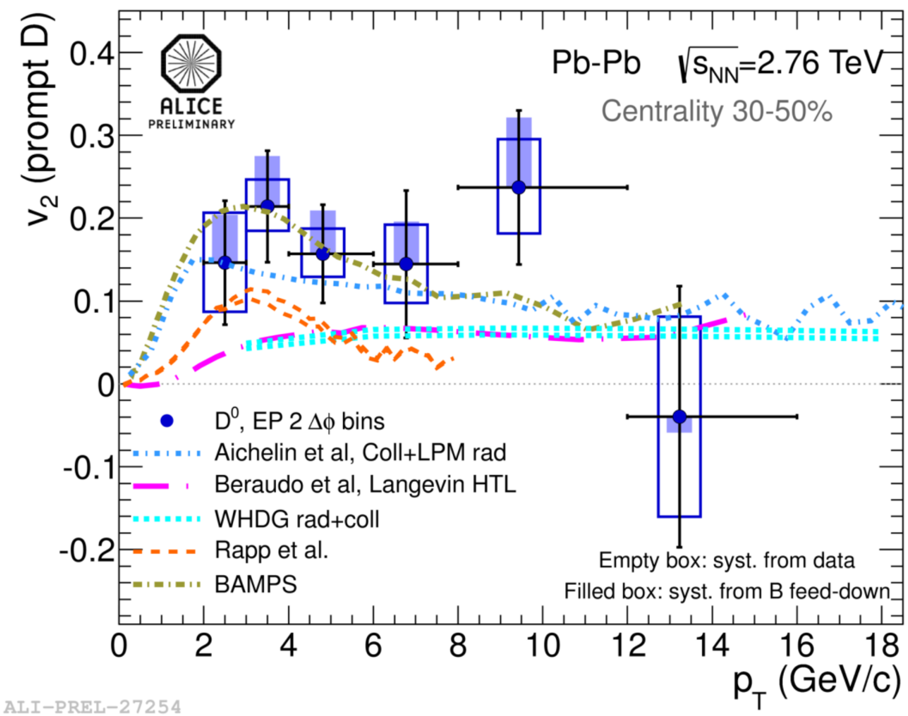
- indication of $R_{AA}(b) > R_{AA}(c)$!



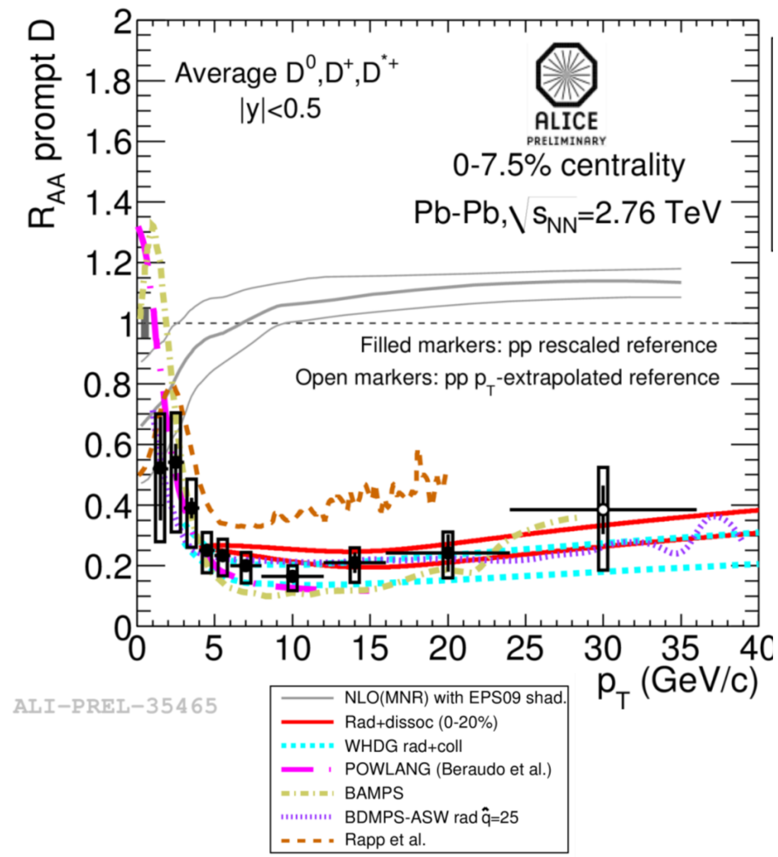
- p_T < 8 GeV/c:
  - hint of less suppression than for π ?
- p_T > 8 GeV/c
  - same suppression as for π…

D meson v_2

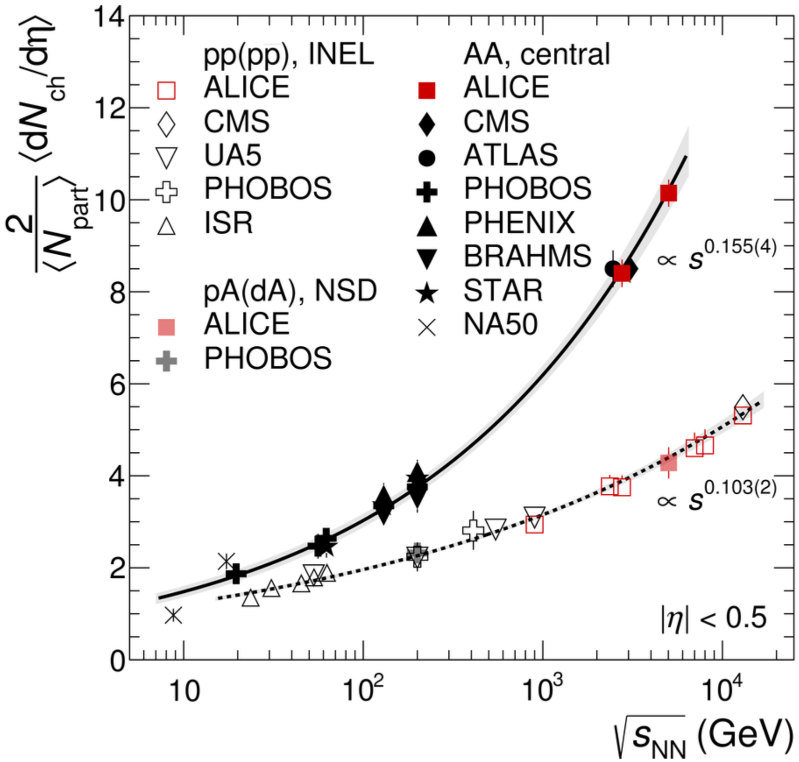
- indication of non-zero v_2
  - consistent with strong coupling of c to medium

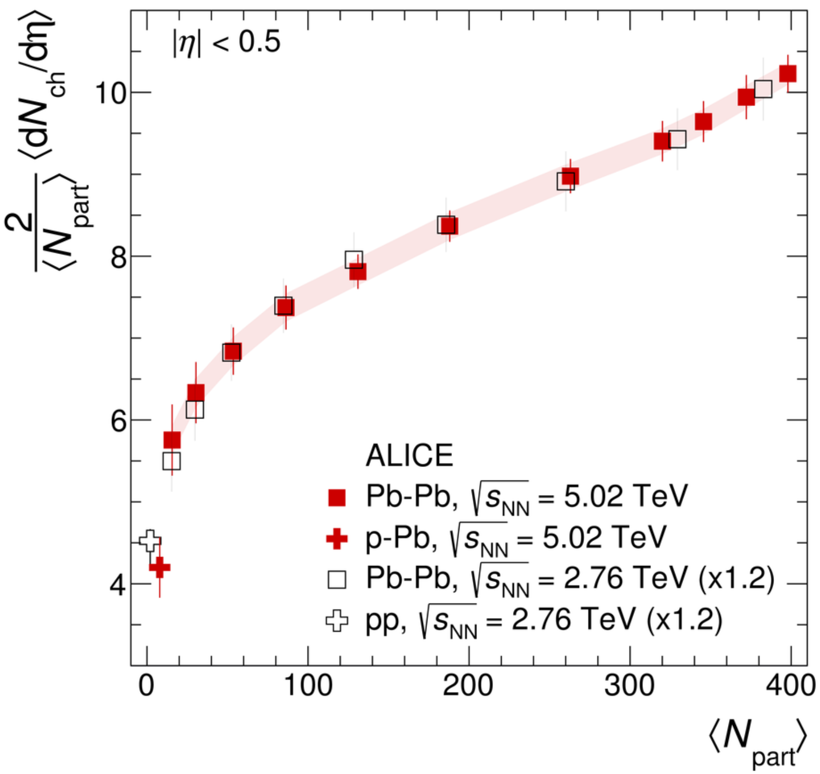


- theory must describe simultaneously v_2 and R_{AA} …



5.02 TeV: multiplicity





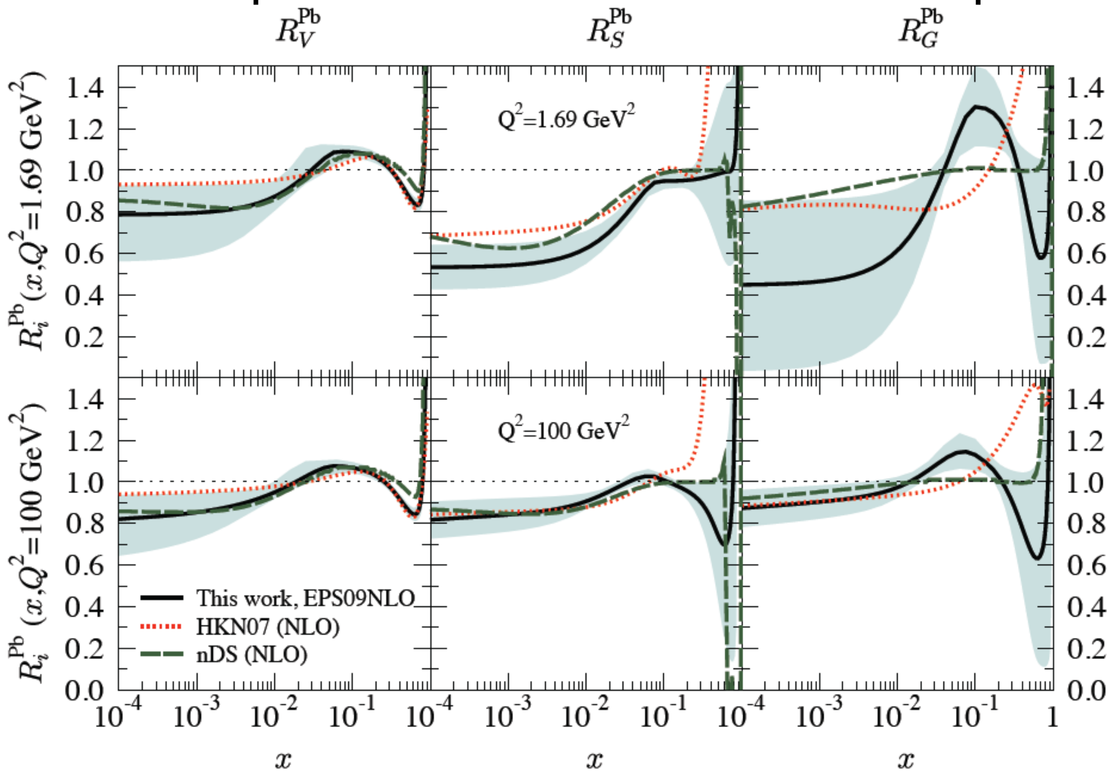
- √s dependence steeper than pp
- follows trend established at 2.76 TeV

- centrality dependence ~ indep of √s

[ALICE, arXiv:1512.06104]

Parton shadowing…

- complication in interpretation of Pb-Pb results:
  different parton distribution functions in protons and nuclei



x = fraction of nucleon momentum carried by parton

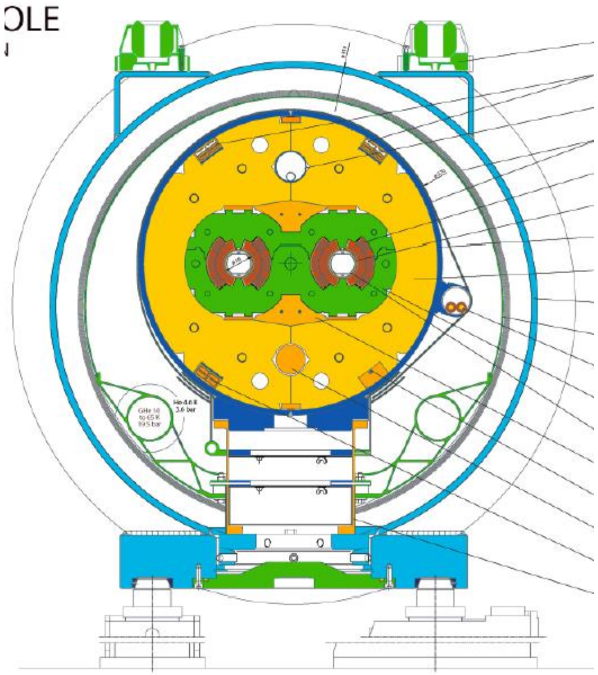
[K J Eskola et al: JHEP04(2009)065]

→ uncertainty on "trivial" nuclear effects baseline

→ measure p-Pb collisions!!!

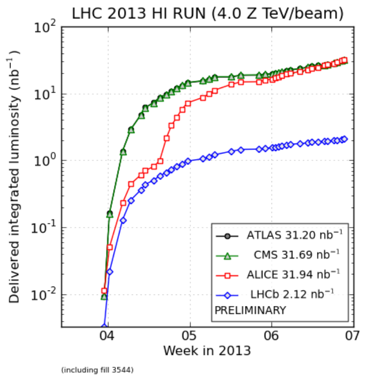
p-Pb collisions in the LHC!

- 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!



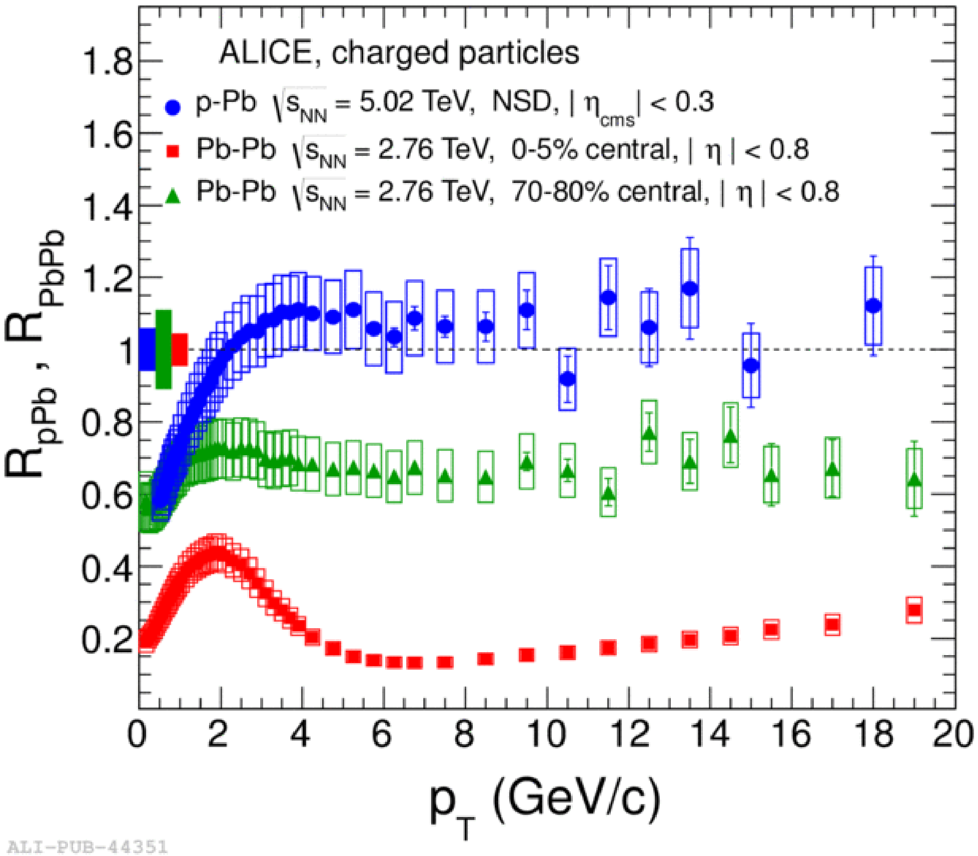
- adjust length of closed orbits!
  – to compensate different speeds
- different RF freq for two beams at injection and ramps
- short low lumi pilot run (a few hours) on 12/9/2012
- first run in Jan-Feb 2013!

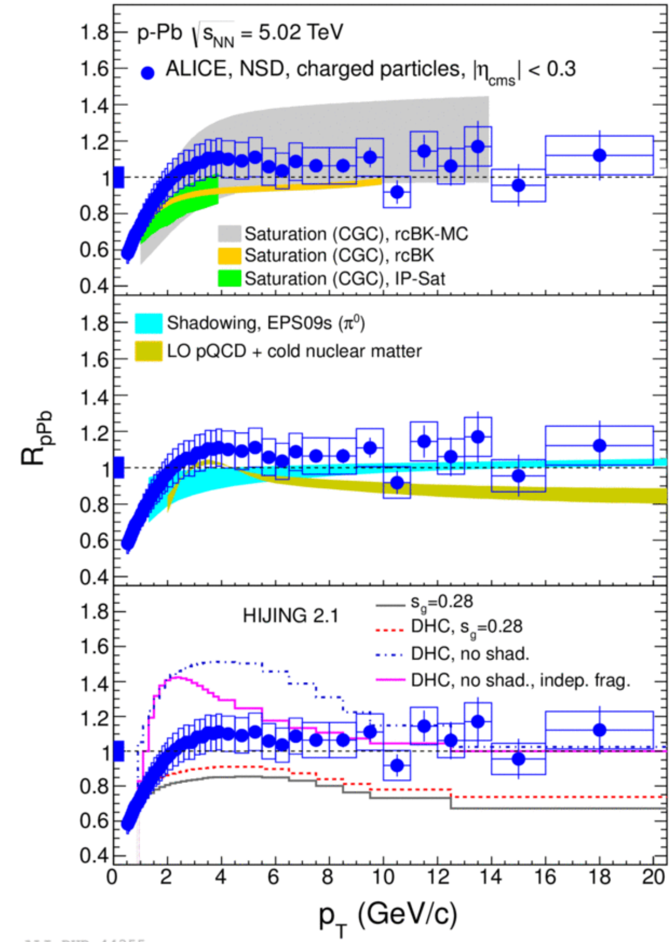
→ ~ 30/nb



Control experiment: R_{pPb}

- measurement of nuclear modifications in initial state

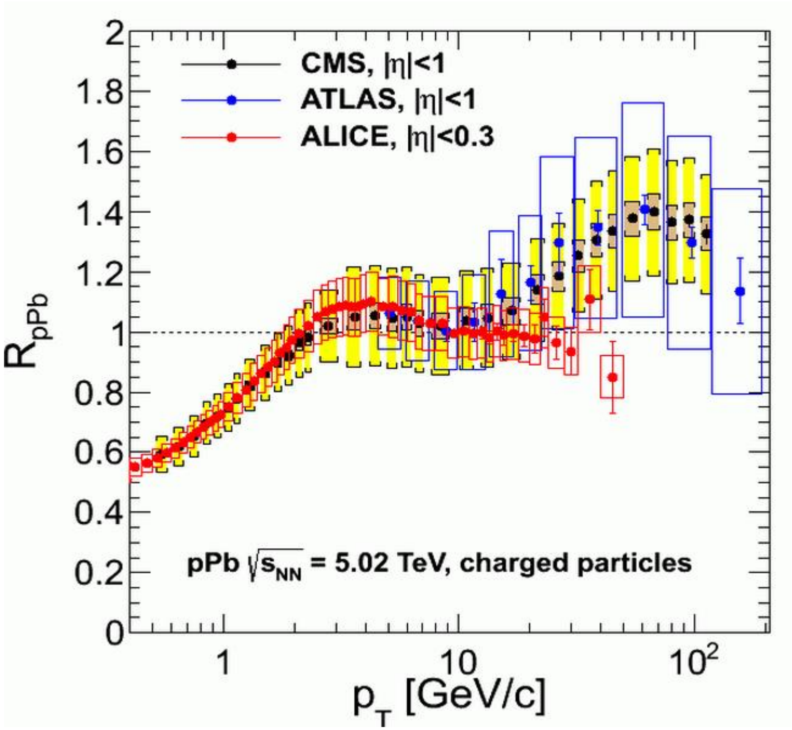




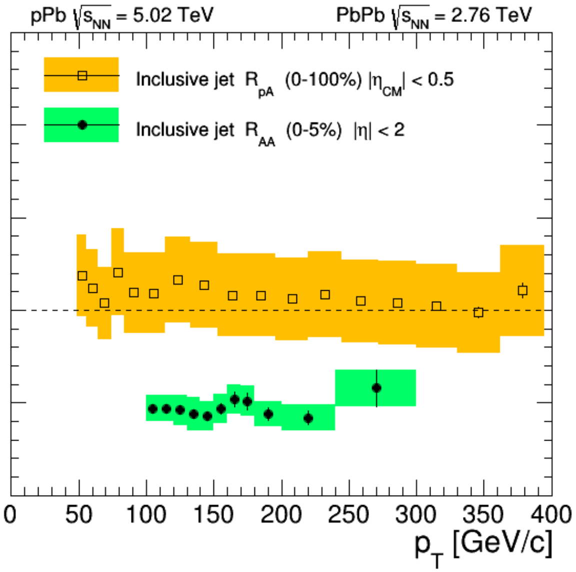
- R_{pA} ~ 1 for p_T> 3 GeV/c → confirms quenching is due to QCD medium

High-p_T puzzle!

- high-p_T R_{pA} from CMS: enhancement??
  - similar picture from ATLAS (not from ALICE)



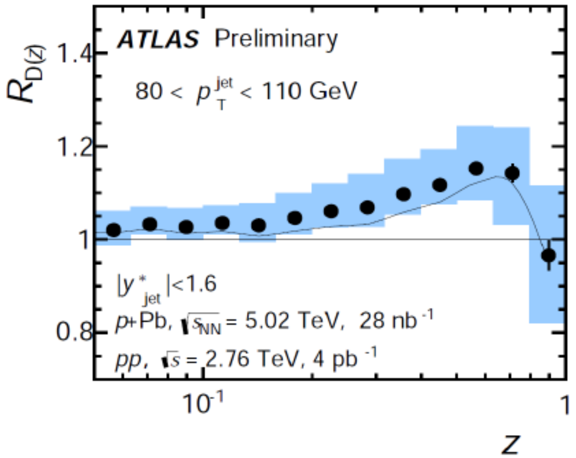
- but not for jets?



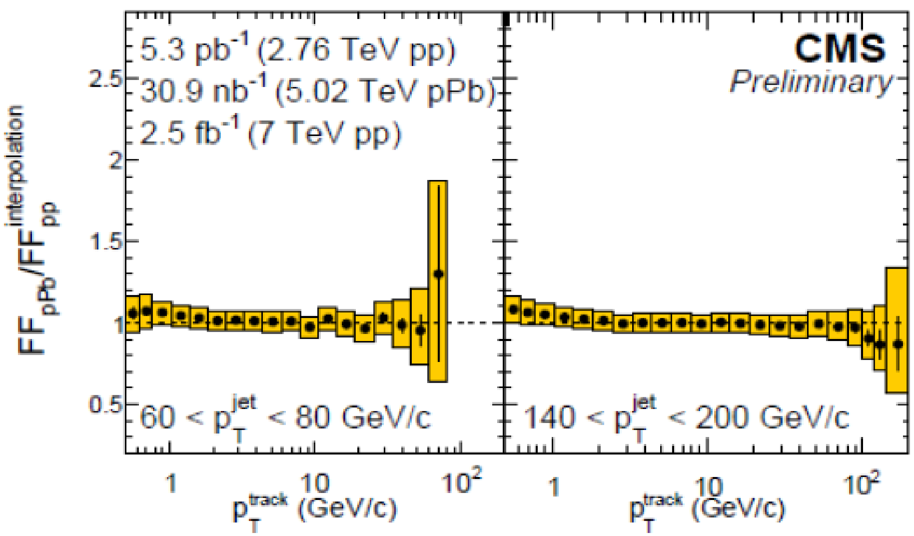
→ modification of fragmentation function?

Being resolved…?

→ fragmentation function (Hard Probes 2015)



- ATLAS sees modification…

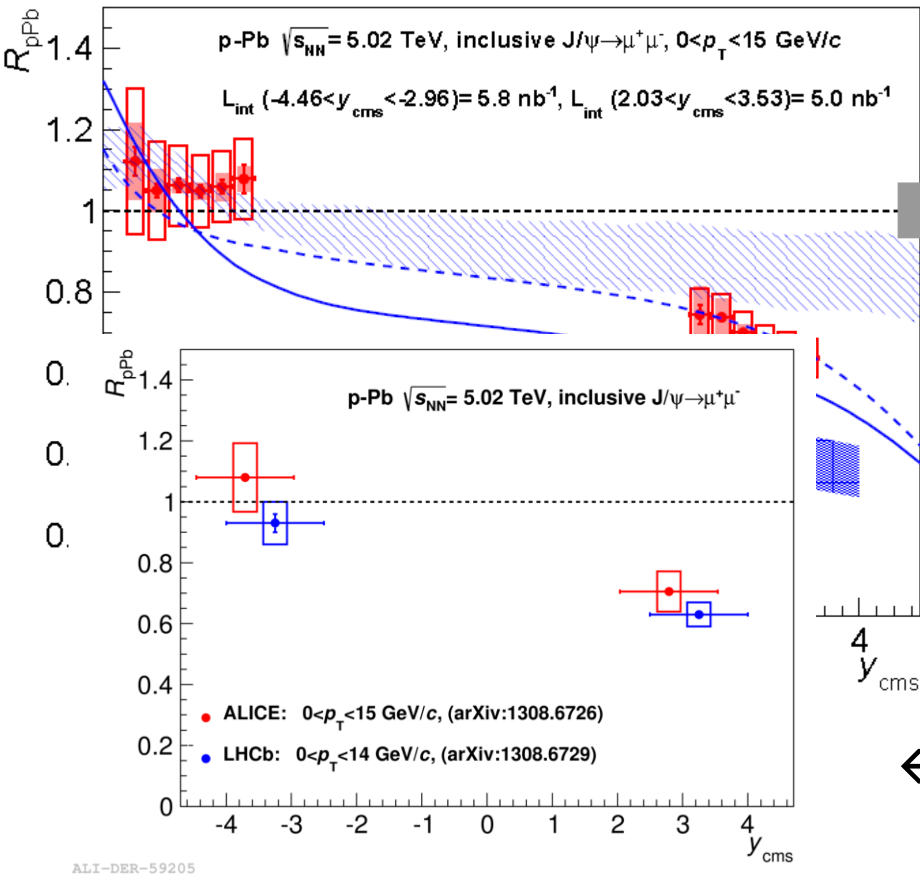


- but CMS does not…
- RpPb relies on interpolated pp ref

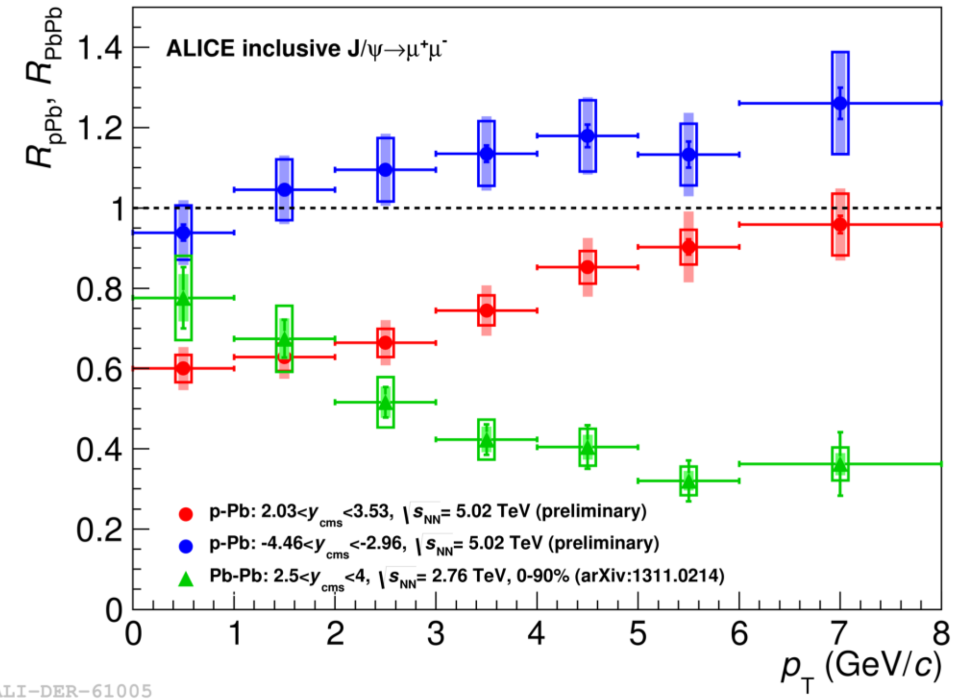
→ pp reference at 5 TeV needed…

J/ψ in p-Pb

- R_{pPb} consistent with shadowing
  - p_T-integrated



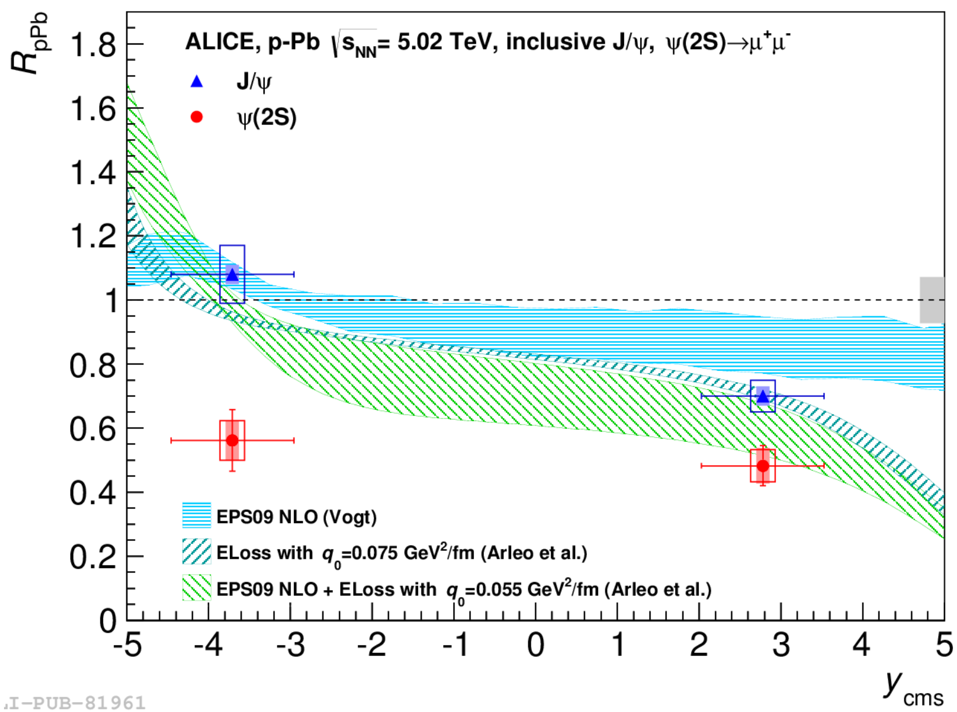
- R_{pPb} back to 1 at high p_T
  - opposite behaviour for Pb-Pb!

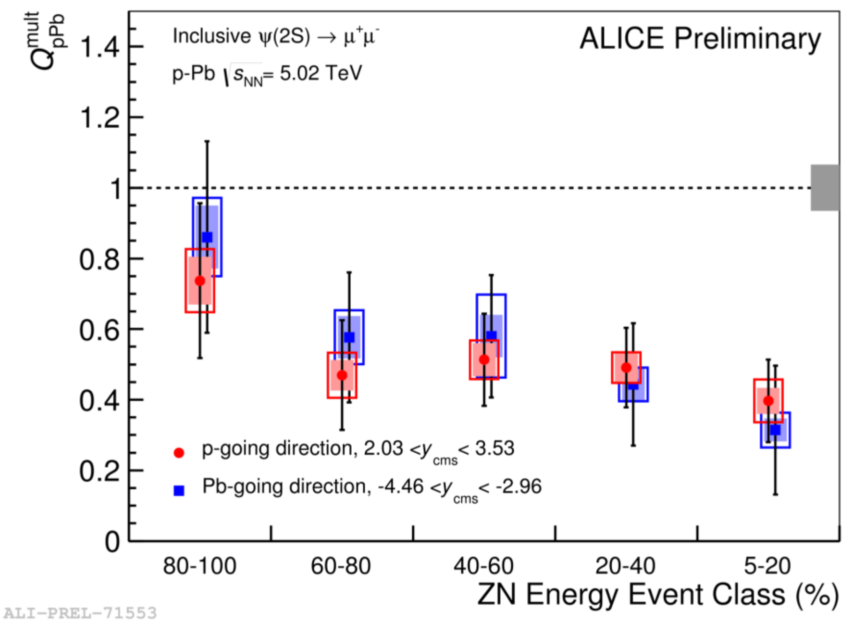


← LHCb joins the Heavy-Ion club!

ψ(2S) in p-Pb

- surprise: more suppressed than J/ψ!
  - how can shadowing (initial state) do that?
  - at odds with shadowing in Pb hemisphere
- more "active" events → larger effect
  - i.e.: effect increases with multiplicity

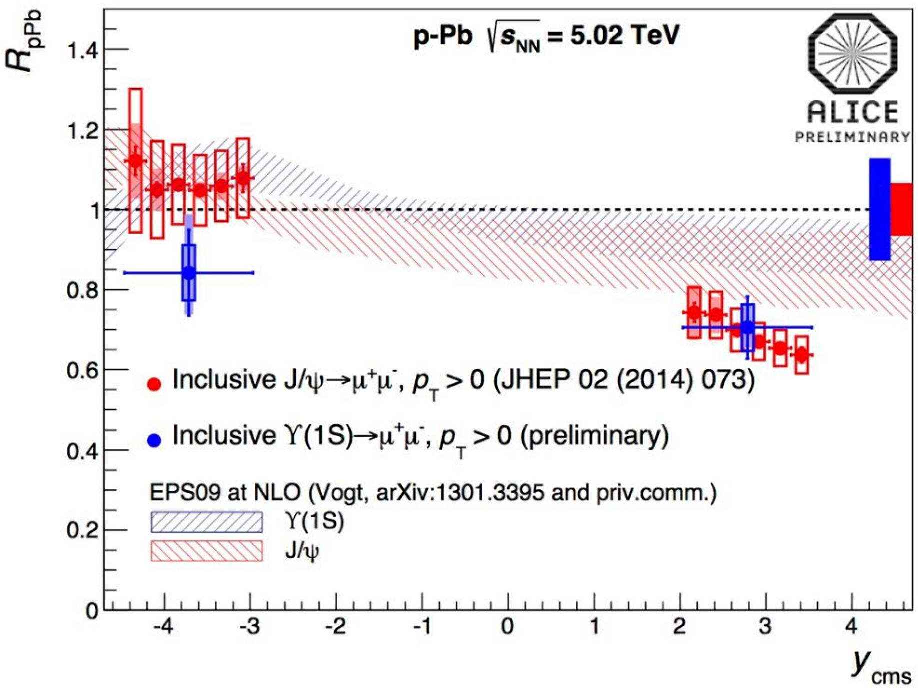


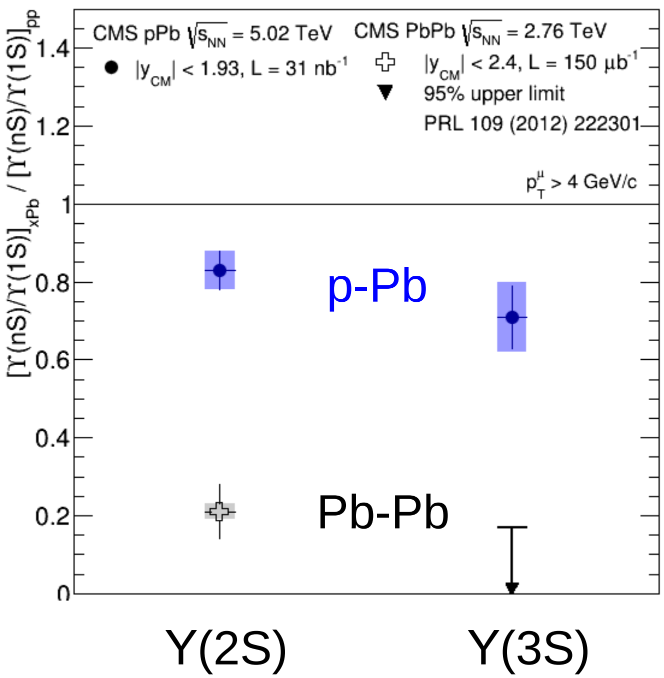


→ indication of final state effects?

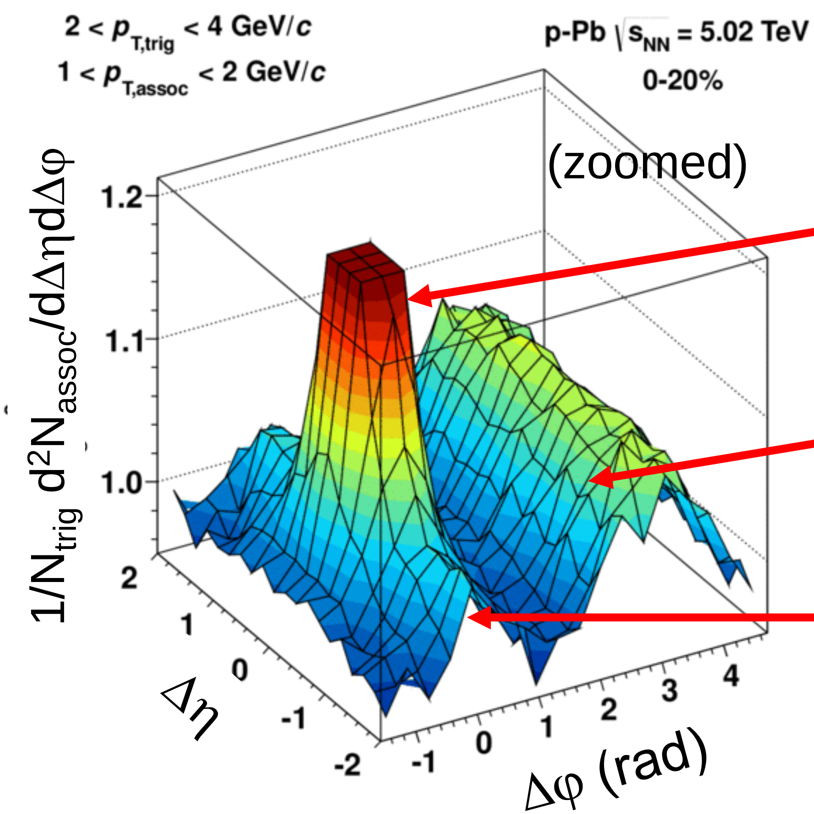
Bottomonia in p-Pb

- Y(1S) ~ OK with shadowing
- excited states more suppressed





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]

- direct photons
- fluctuations
- J/psi v2
- Dpi/K