Results from the LHC Heavy-Ion Programme: an Overview

Federico Antinori
INFN, Padova, Italy and CERN, Geneva, Switzerland

Istituto Nazionale
di Fisica Nucleare
Sezione di Padova

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a (personal!) choice of results…

- Pb-Pb collisions
  - correlations
  - direct photons
  - particle yields
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    - di-jet imbalance
    - modified fragmentation
  - quarkonia
  - heavy flavour
- p-Pb collisions
  - nuclear modification factor
  - quarkonia
  - signs of collectivity
- conclusions

Ultrarelativistic AA Collisions

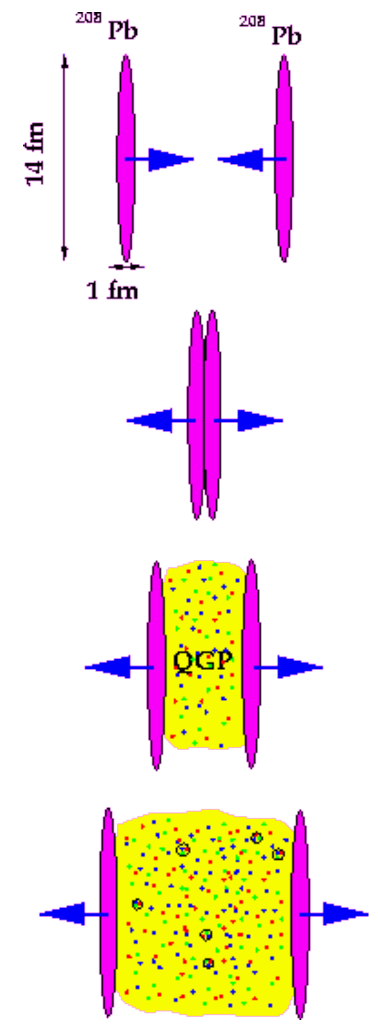
basic idea:

compress large amount of energy in small volume

→ produce a "fireball" of hot matter:

temperature O(10^{12} K)

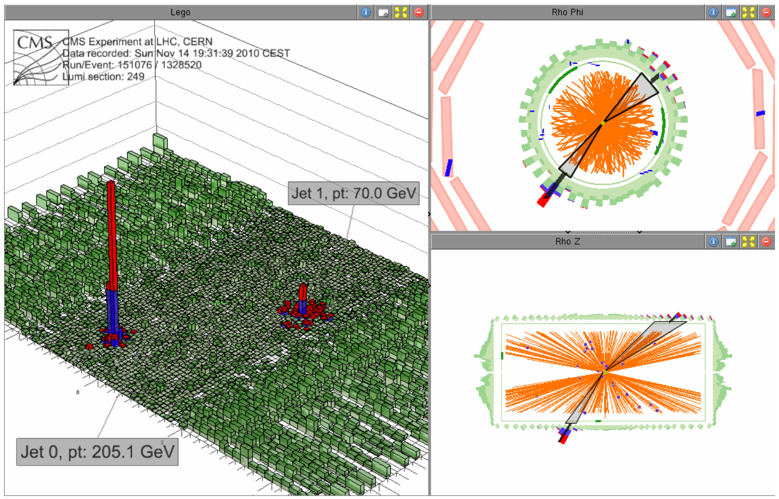
- ~ 10^5 x T at centre of Sun
- ~ T of universe @ ~ 10 μs after Big Bang

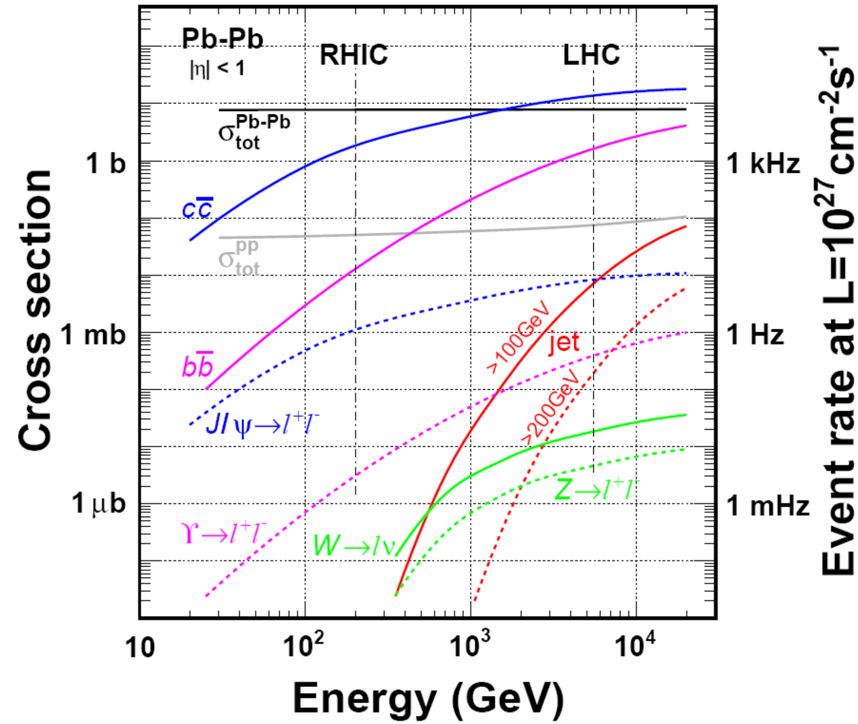


- extreme conditions: how does matter behave?
  - → study the fireball properties
  - QCD predicts state of deconfined quarks and gluons (Quark-Gluon Plasma)
  - evidence for deconfinement already at lower energy (CERN-SPS, BNL-RHIC)
  - LHC: controlled probes → properties of QCD medium

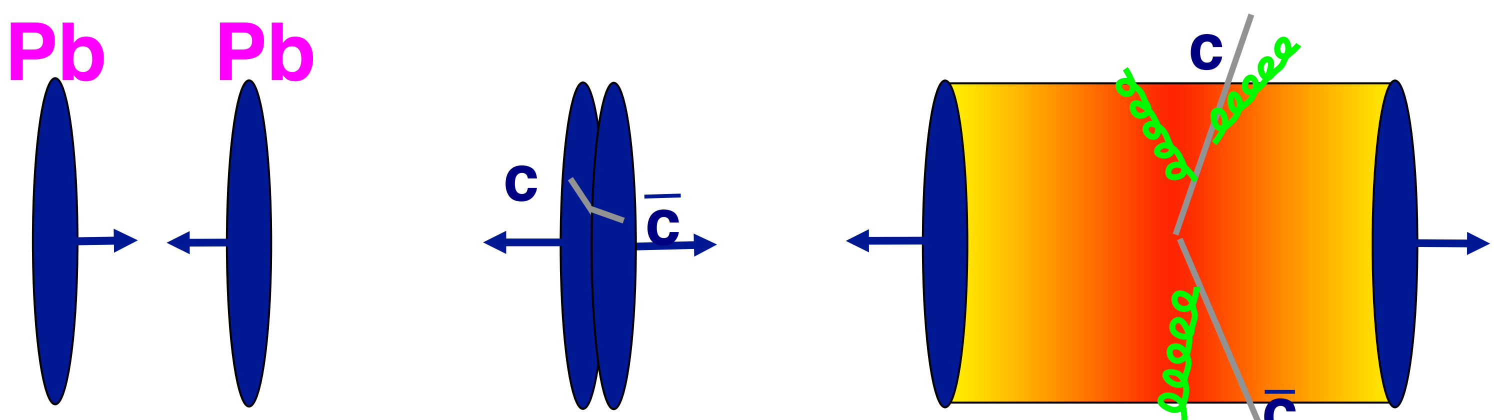
Nuclear collisions at the LHC

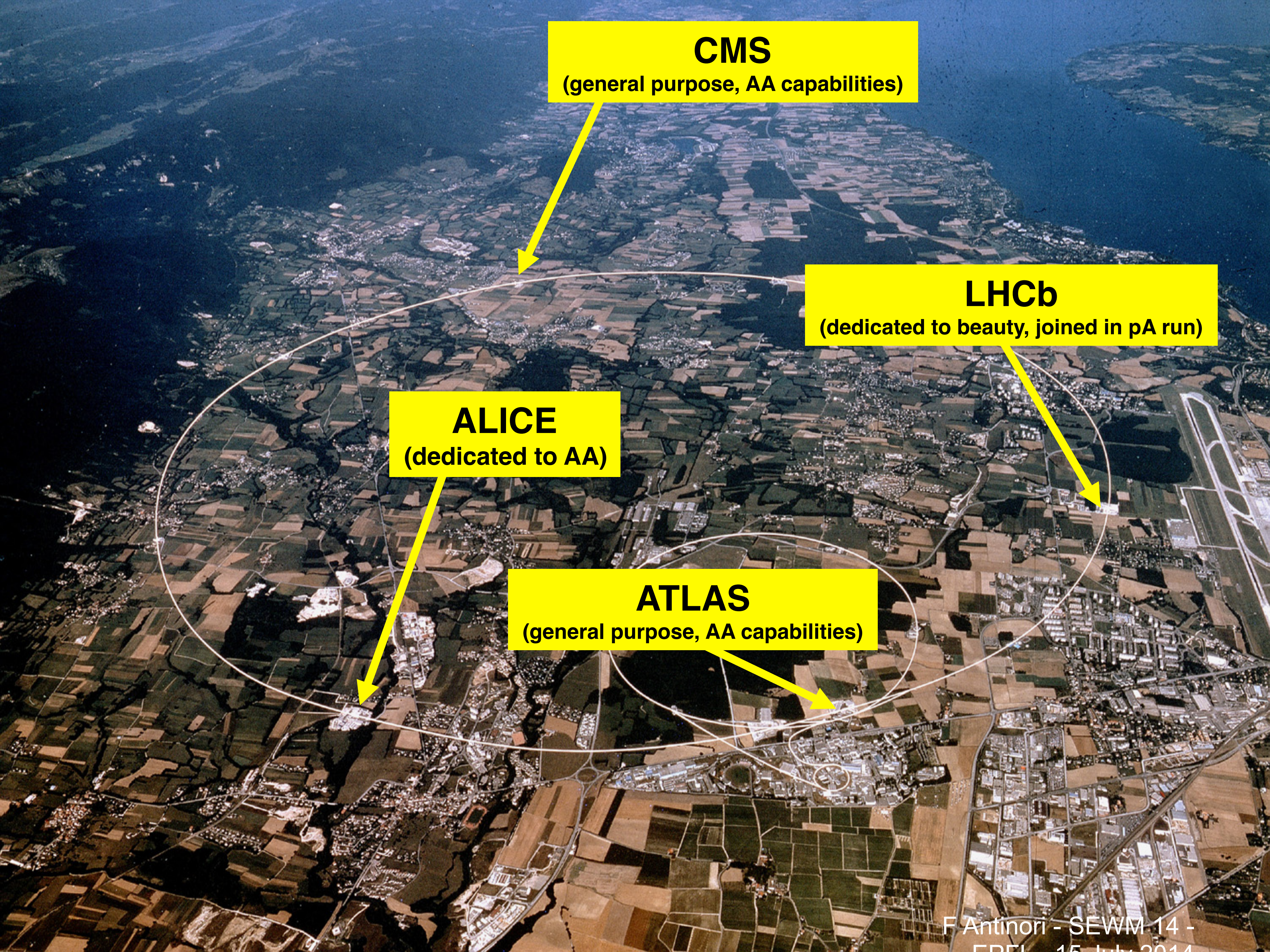
- large cross-section for "hard probes"



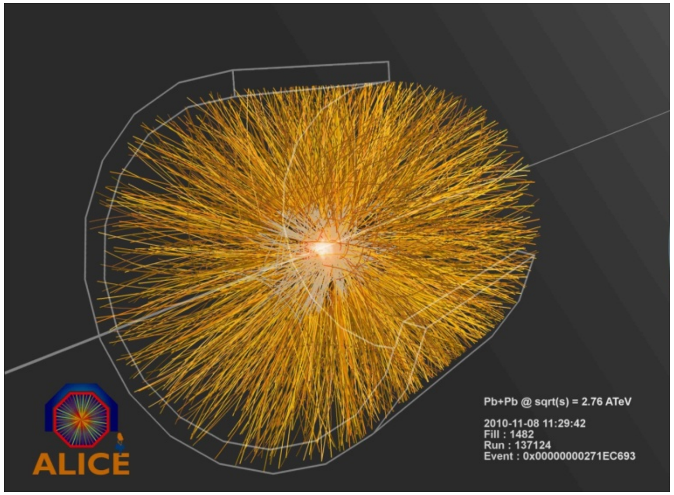


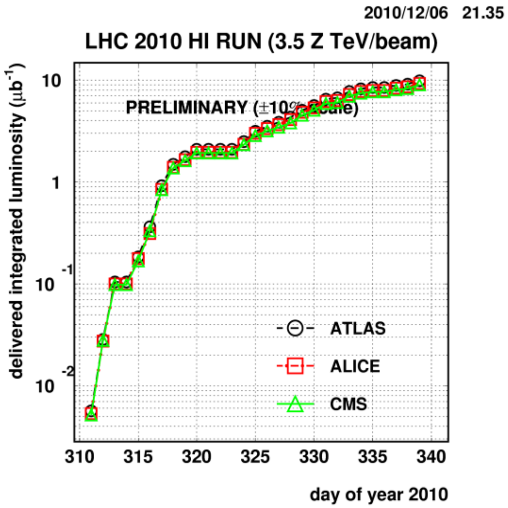
→ novel tools to probe QCD medium
e.g. heavy flavour:

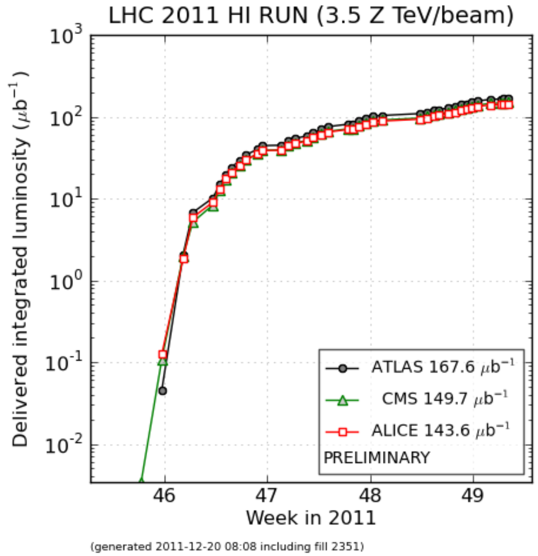



CMS
(general purpose, AA capabilities)
LHCb
(dedicated to beauty, joined in pA run)
ALICE
(dedicated to AA)
ATLAS
(general purpose, AA capabilities)

Heavy Ions in Run 1







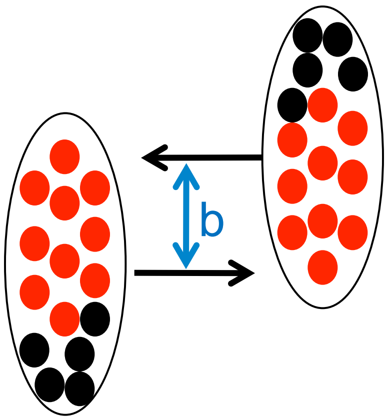
- two successful Pb-Pb runs already
  - 2010 → ~10/μb
  - 2011 → ~150/μb
- + p-Pb "control" run
  - 2013 → ~ 30/nb

some numbers (2011 Pb-Pb run):

- ~ 1.2 10^{8} ions/bunch
- 358 bunches
  - 200 ns basic spacing
- β^* = 1 m
- L ~ 5 10^{26} $cm^{-2}s^{-1}$

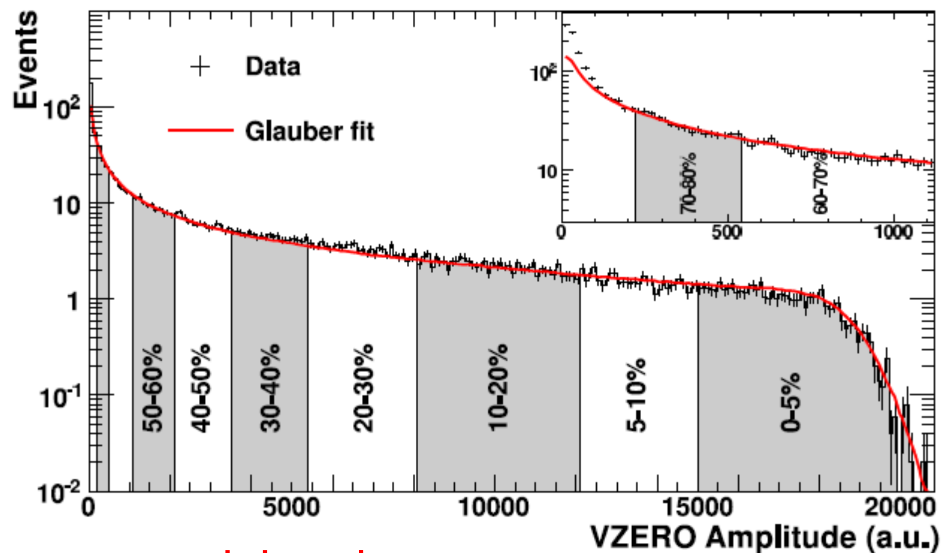
→ ~ 4000 Hz interaction rate

Geometry of a Pb-Pb collision



- central collisions
  - small impact parameter b
  - high number of participants → high multiplicity
- peripheral collisions
  - large impact parameter b
  - low number of participants → low multiplicity

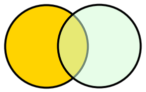
for example: sum of the amplitudes in the ALICE V0 scintillators →



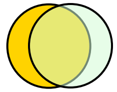
reproduced by Glauber model fit (red):

- random relative position of nuclei in transverse plane
- Woods-Saxon distribution inside nucleus
- simple model of particle production
- deviation at very low amplitude expected due to non-nuclear (electromagnetic) processes

peripheral



central

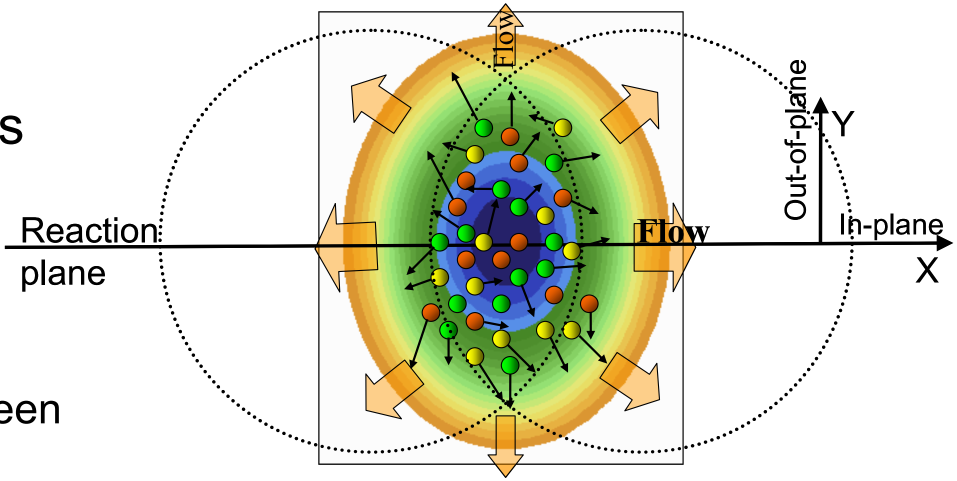


Azimuthal asymmetry

… in the transverse momentum distribution of produced particles

- why is it important?
- non-central collisions are asymmetric in azimuth

azimuth = angle in the plane of the screen



→ transfer of this asymmetry to momentum space provides a measure of the strength of collective phenomena

- Large mean free path
  - particles stream out isotropically, no memory of the asymmetry
  - extreme: ideal gas (infinite mean free path)
- Small mean free path
  - larger density gradient → larger pressure gradient → larger momentum
  - extreme: ideal liquid (zero mean free path, hydrodynamic limit)

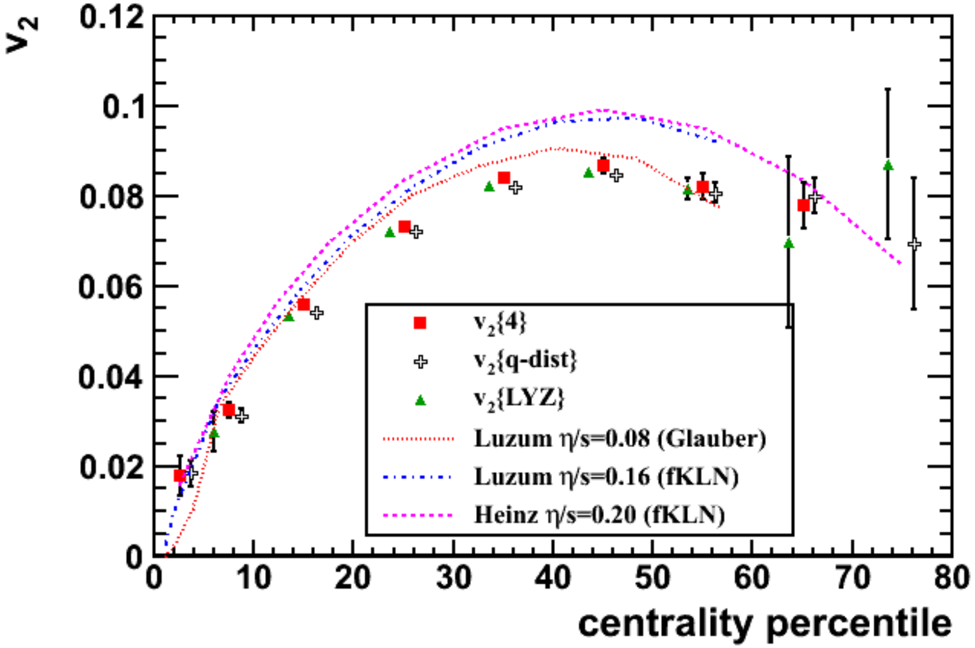
Azimuthal asymmetry

- 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 ($\vartheta \sim 90°$) → $v_1 \sim 0$ → asymmetry quantified with v_2

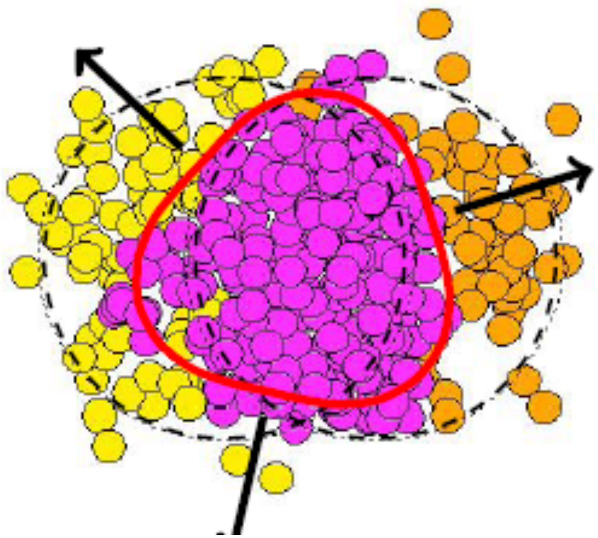
- experimentally: v_2 ~ as large as expected by hydrodynamics

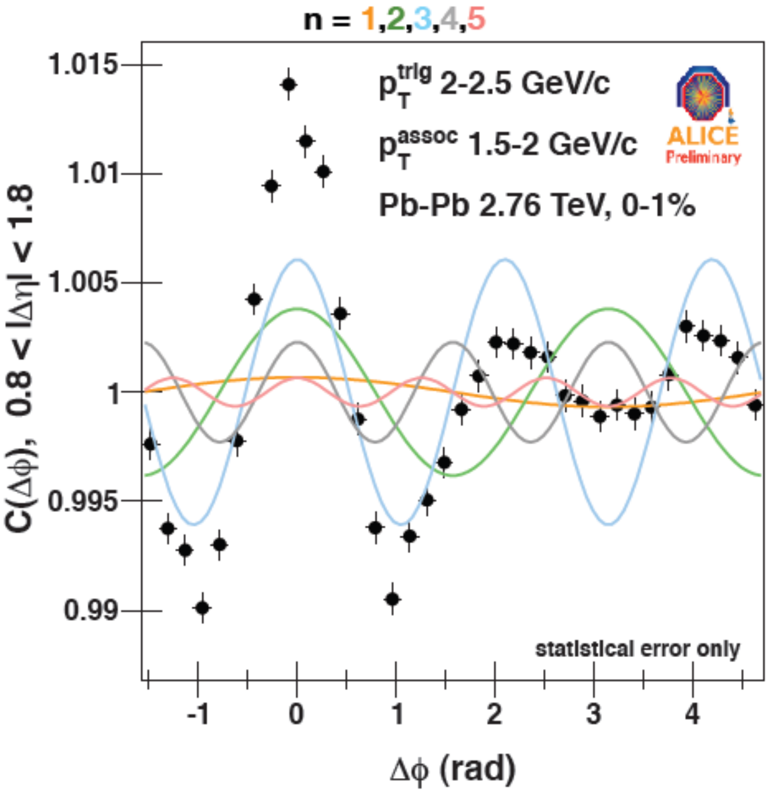


Higher harmonics

- a beautiful tool…

initial state geometrical asymmetries → final state momentum asymmetries

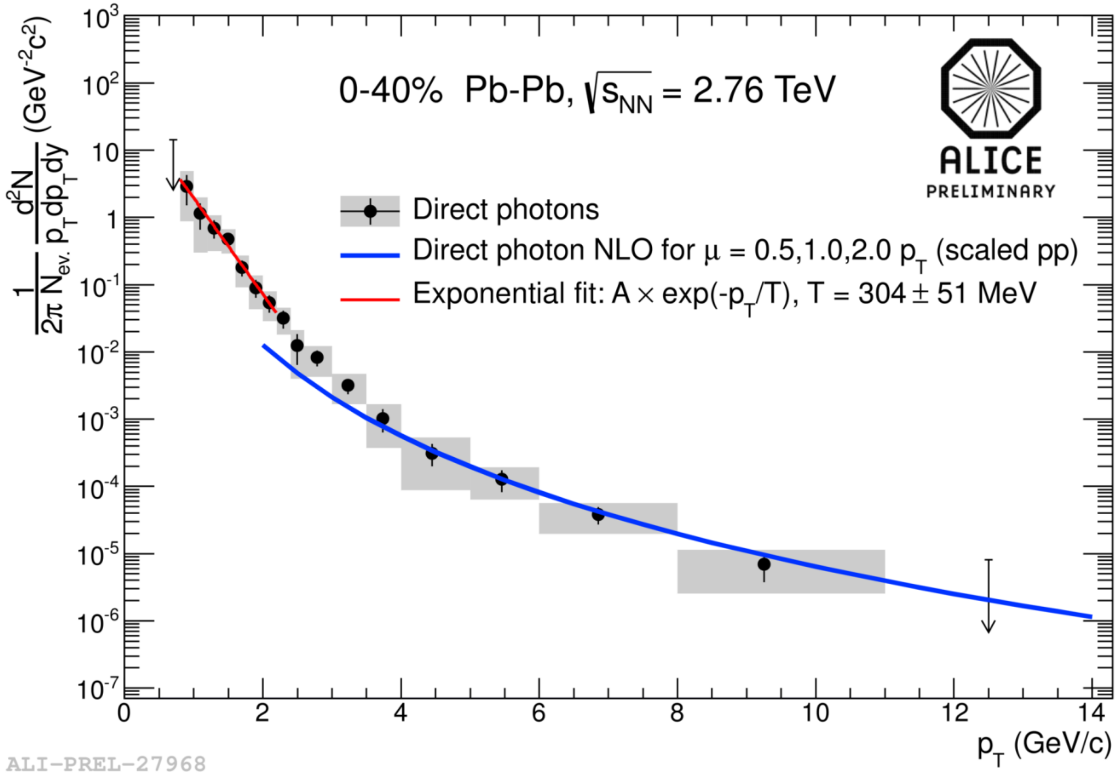




- connects final state distribution to initial state fluctuations, via medium transport

The QGP shines!

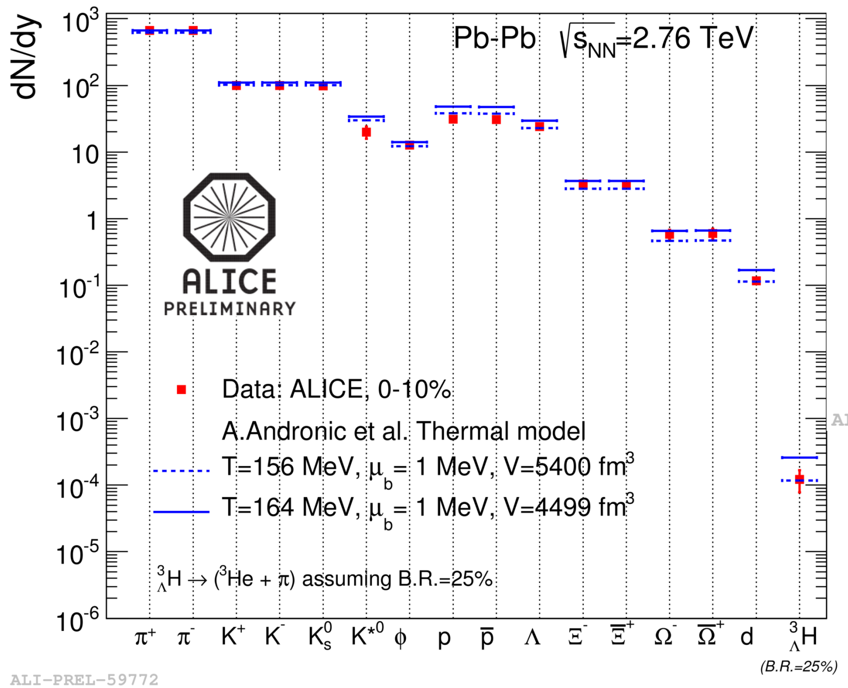
- p_T spectrum of (direct) photons emitted at LHC



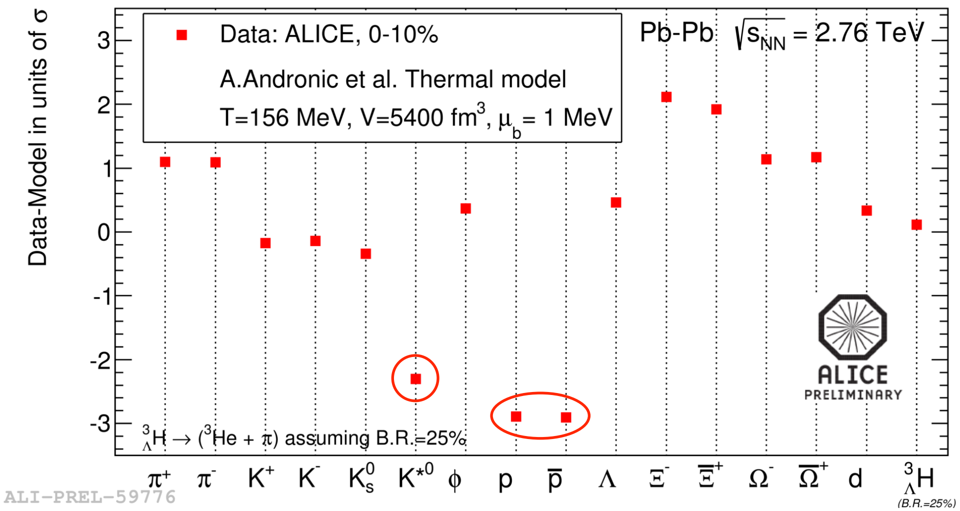
- "temperature" ~ 300 MeV (→ largest ever man-made, btw…)

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?

High p_T suppression

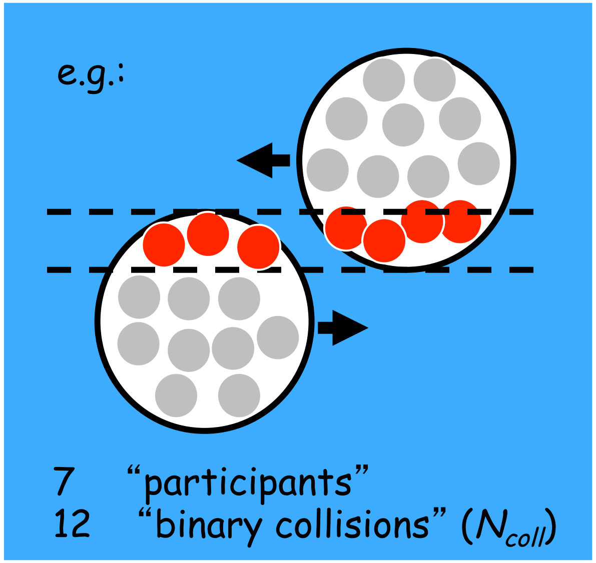
- production of particles at high p_T
  - above 2-3 GeV/c, say
- is expected to scale like the number of binary nucleon-nucleon collisions:

$$\left.\frac{dN}{dp_T}\right|_{AA} = \langle N_{coll} \rangle \left.\frac{dN}{dp_T}\right|_{pp}$$

- can be modified by nuclear effects
  - e.g.: particles can lose energy when traversing the QCD plasma fireball ("jet quenching")
    → suppression of particle production at high p_T
- define a "nuclear modification factor" R_{AA}

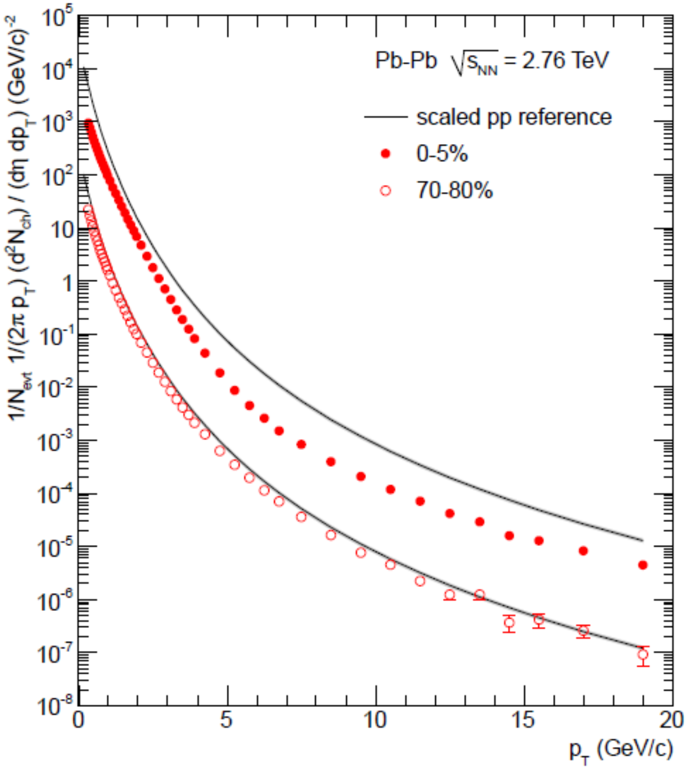
$$R_{AA} = \frac{\left.\frac{dN}{dp_T}\right|_{AA}}{\langle N_{coll} \rangle \left.\frac{dN}{dp_T}\right|_{pp}}$$

- in the absence of nuclear effects → $R_{AA} = 1$

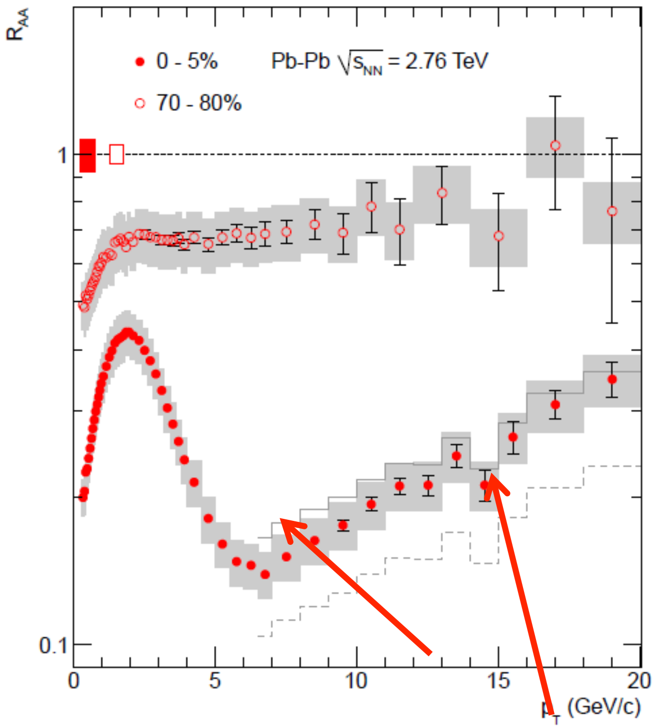


Strong quenching

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



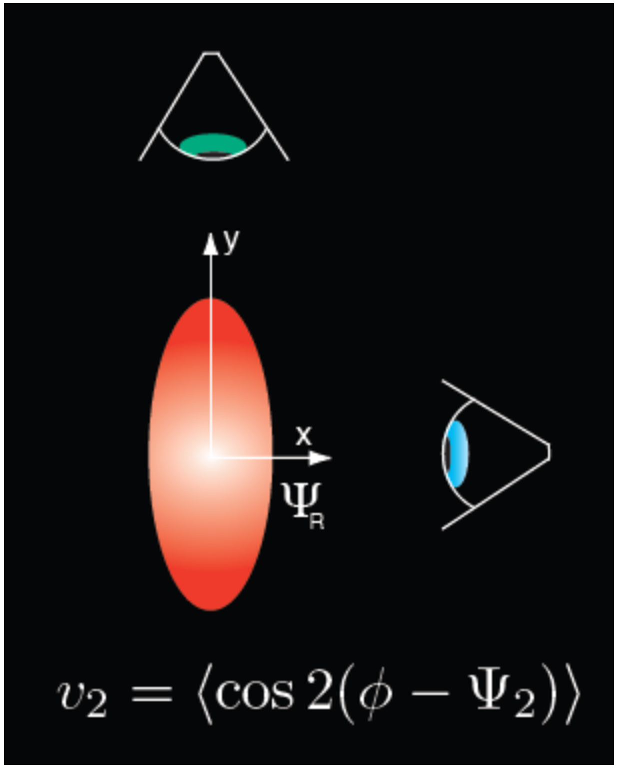
- R_{AA}:

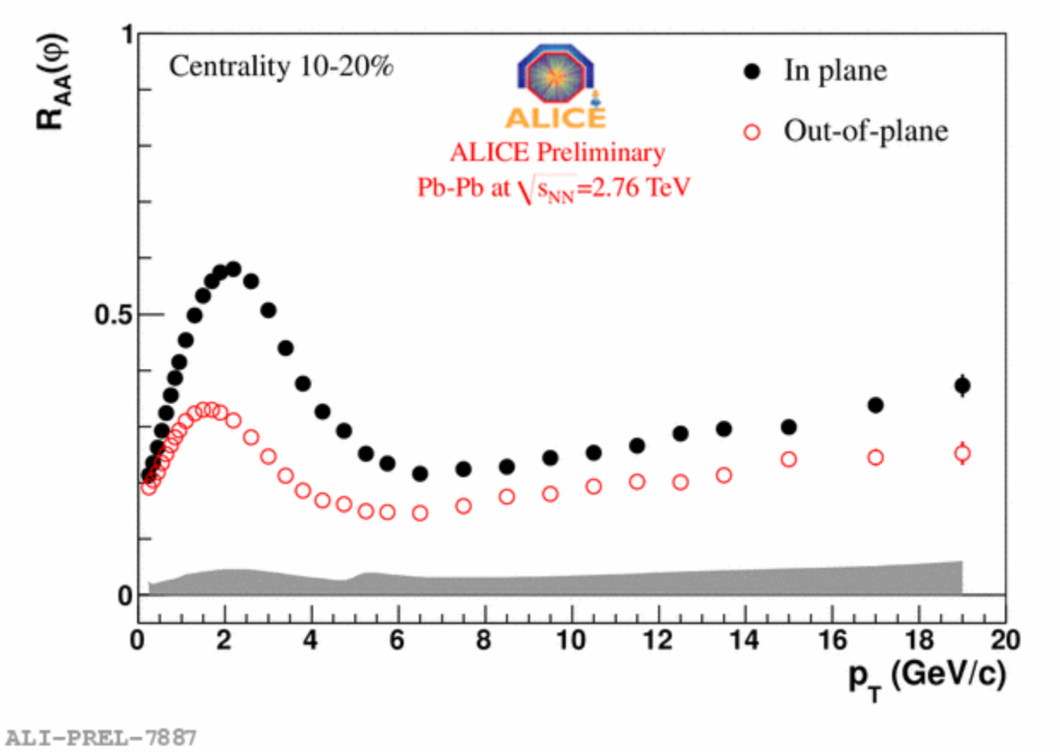


  - minimum around 6-7 GeV (R_{AA} ~ 0.14)
  - clear increase at higher p_T

Strong angular dependence

- significant effect, even at 20 GeV and beyond!

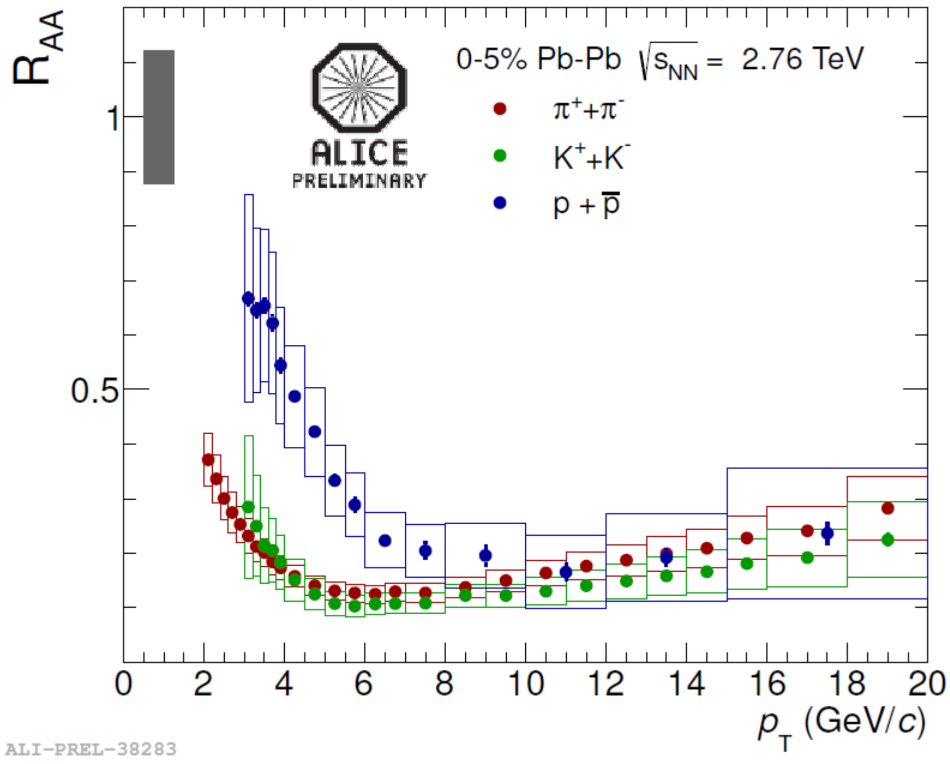




→ sensitivity to path length dependence of energy loss

Dependence on particle species

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

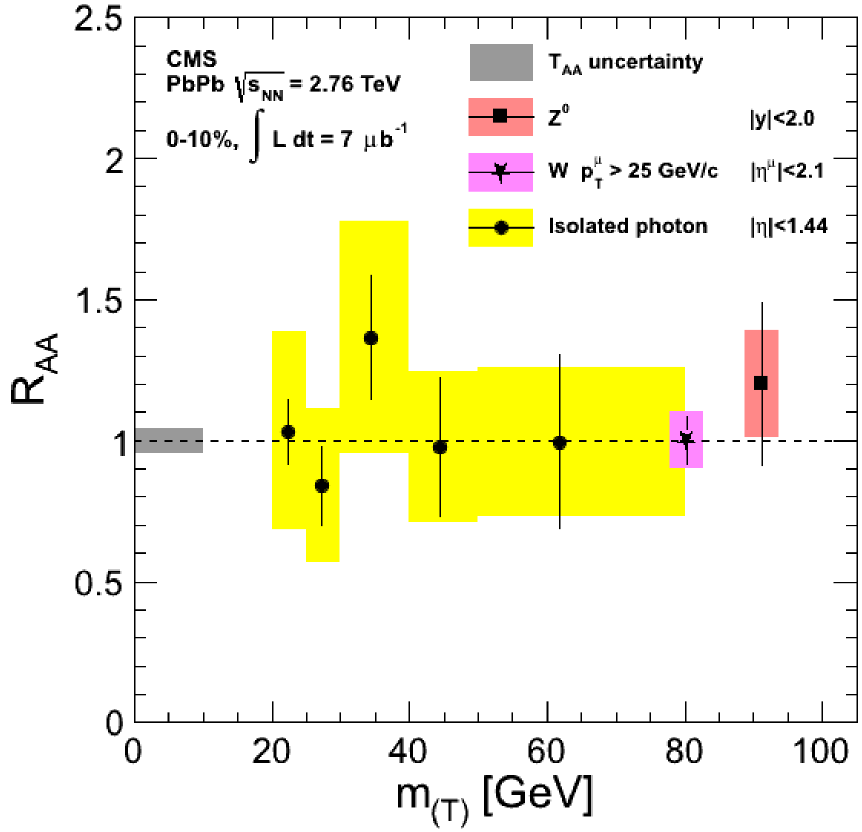


→ sensitivity to hadronisation in medium

R_{AA} for vector bosons

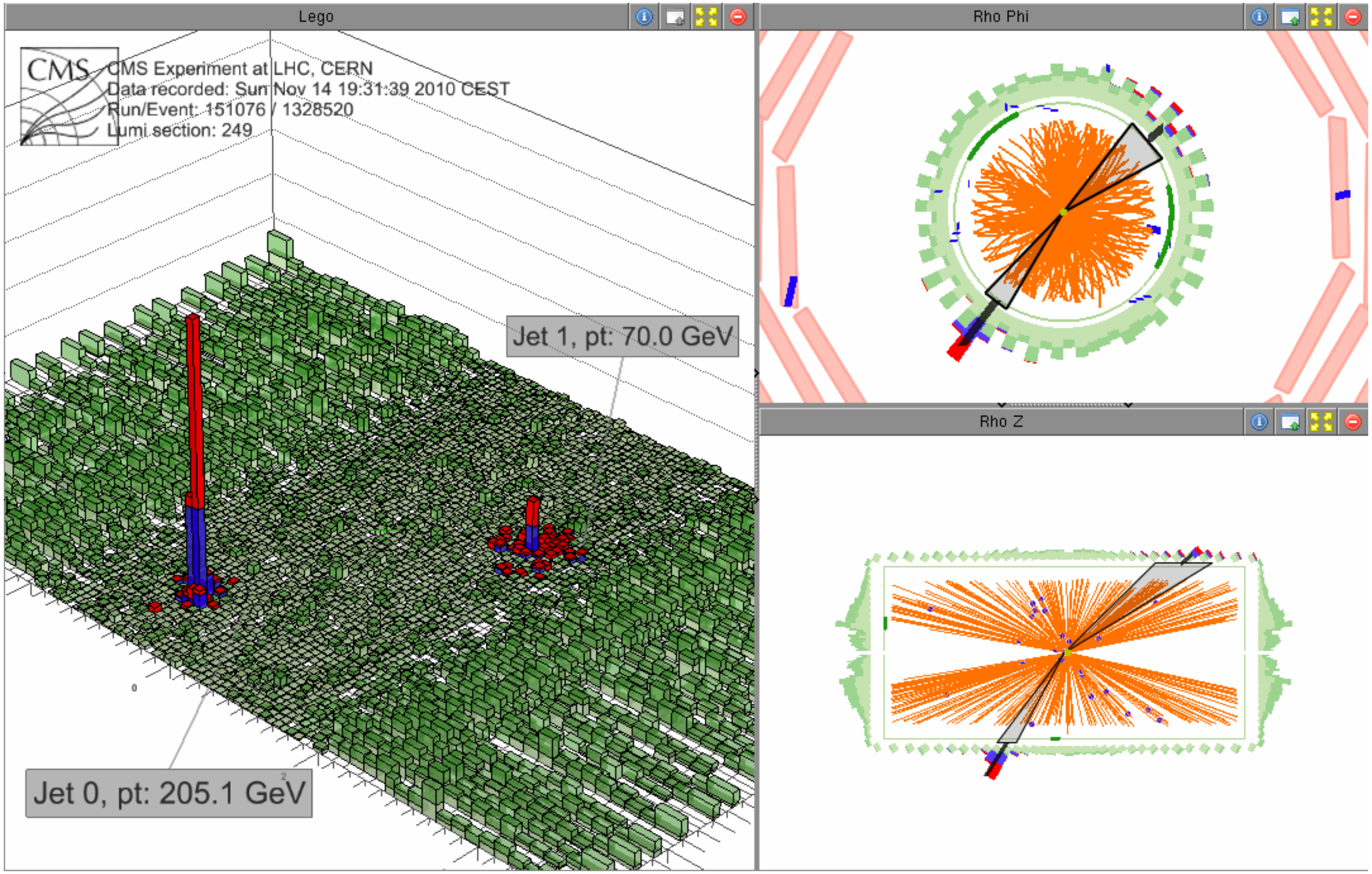
- electroweak probes, on the other hand, are unmodified

→ (essential cross check!)



Di-jet imbalance

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

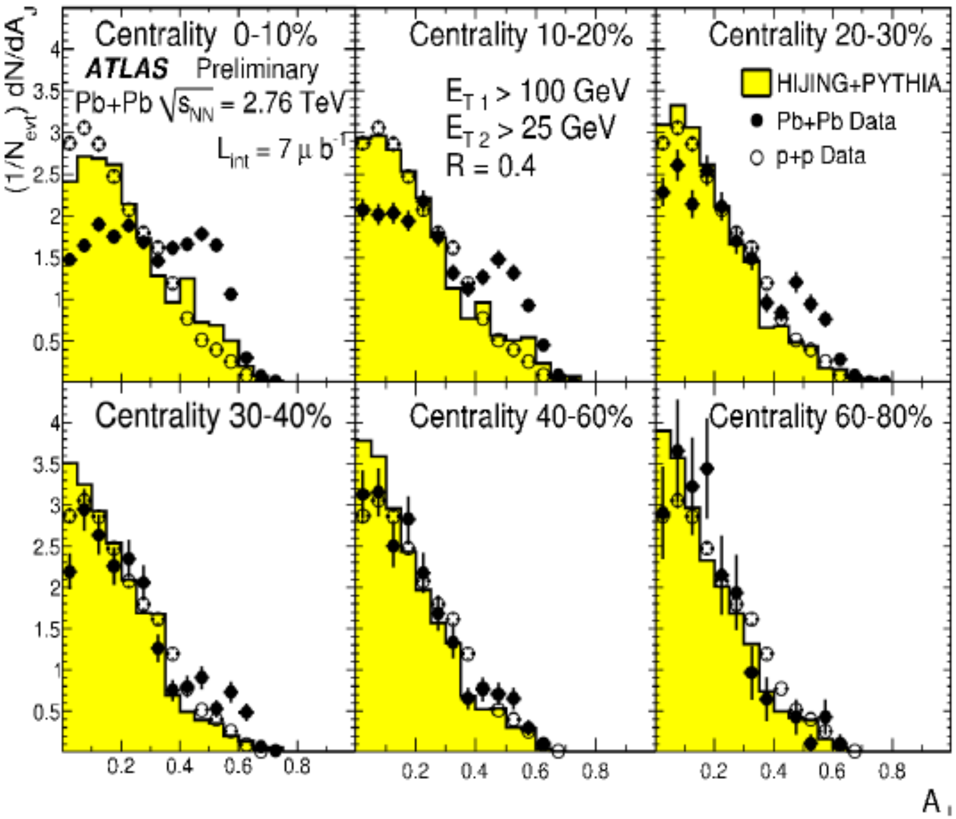


→ recoiling jet strongly quenched!

CMS: arXiv:1102.1957

Di-jet imbalance

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



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

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

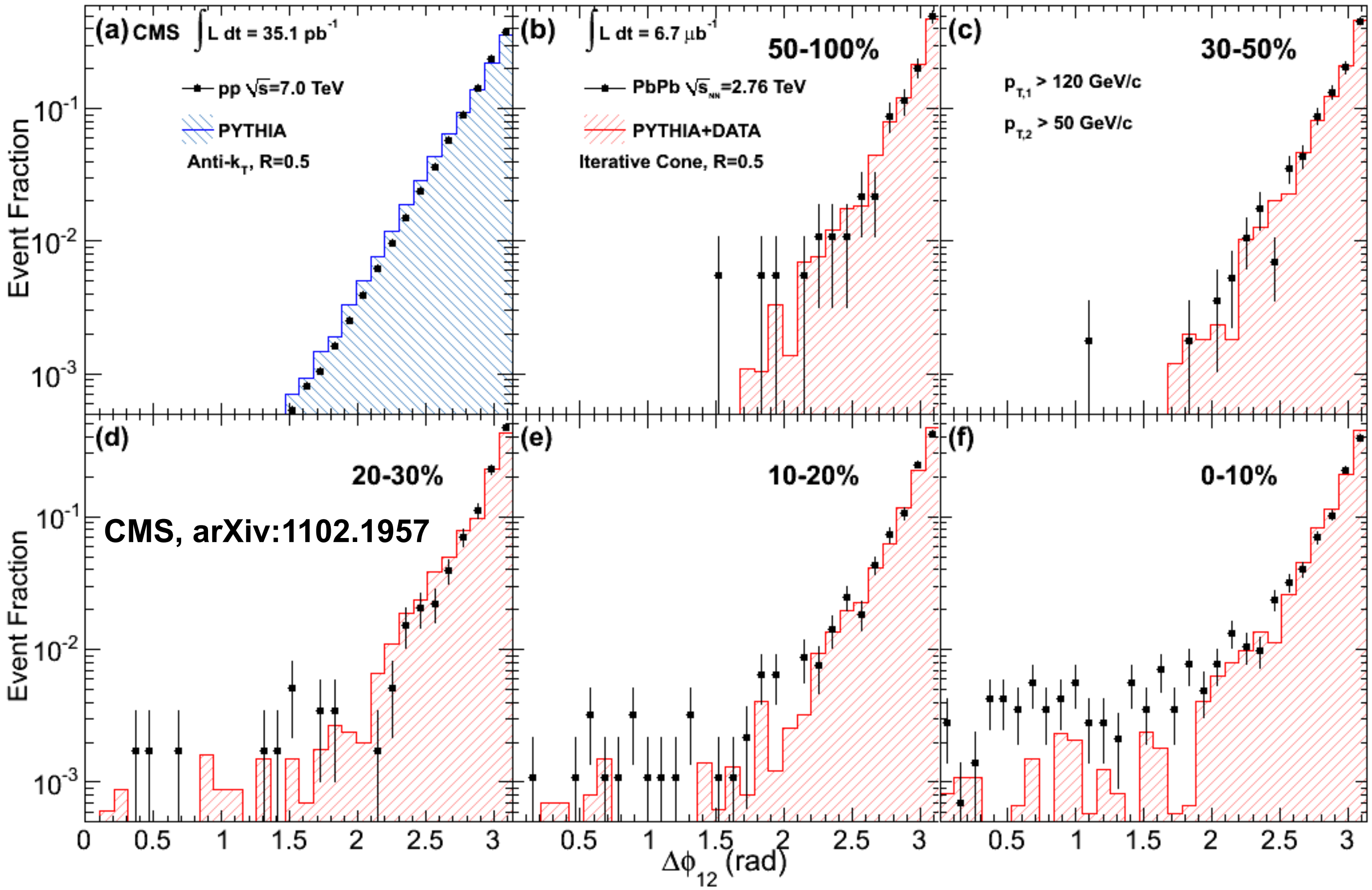
- with increasing centrality:

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

ATLAS: PRL105 (2010) 252303

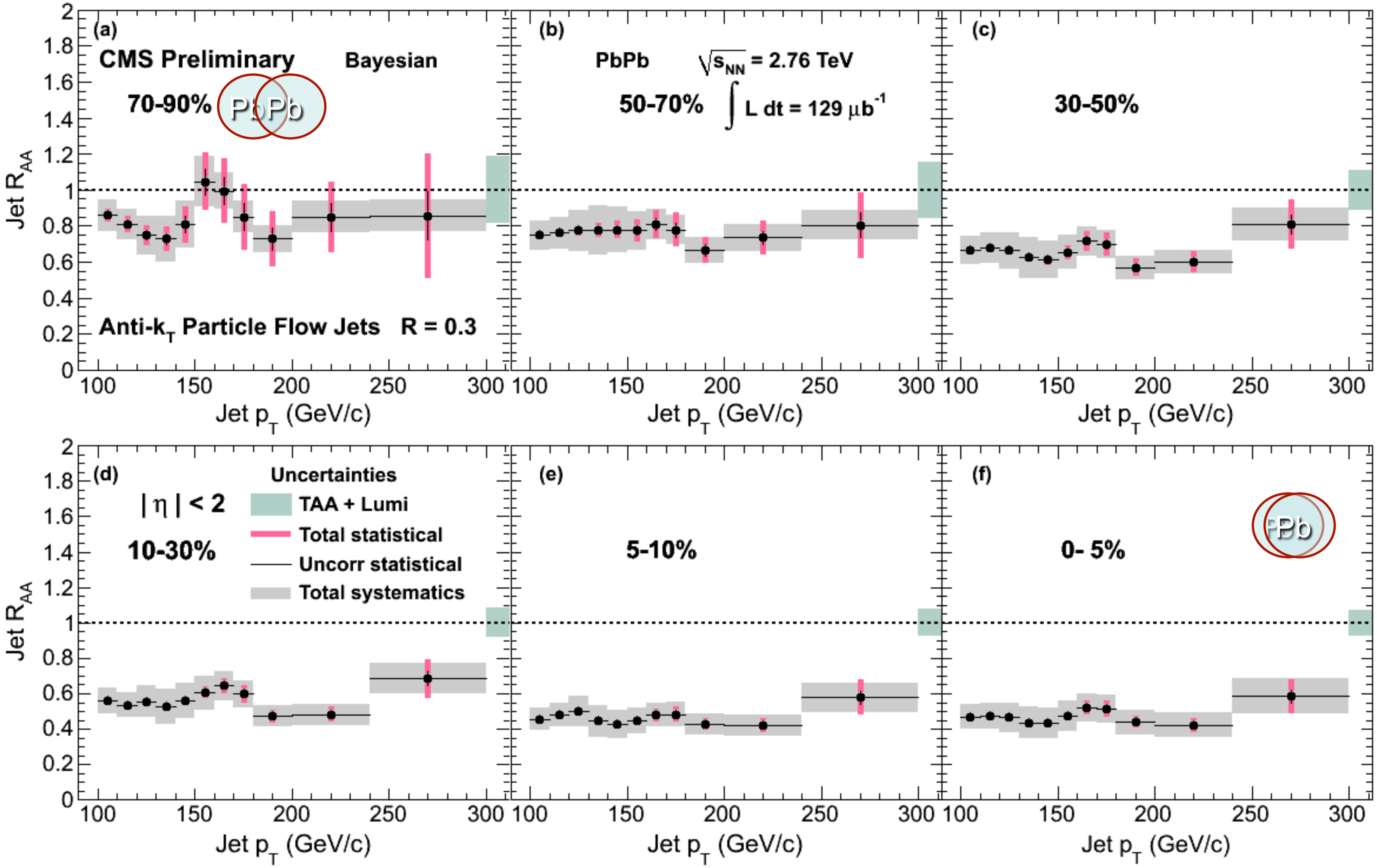
Di-jet Δφ

- no visible angular decorrelation in Δφ wrt pp collisions!



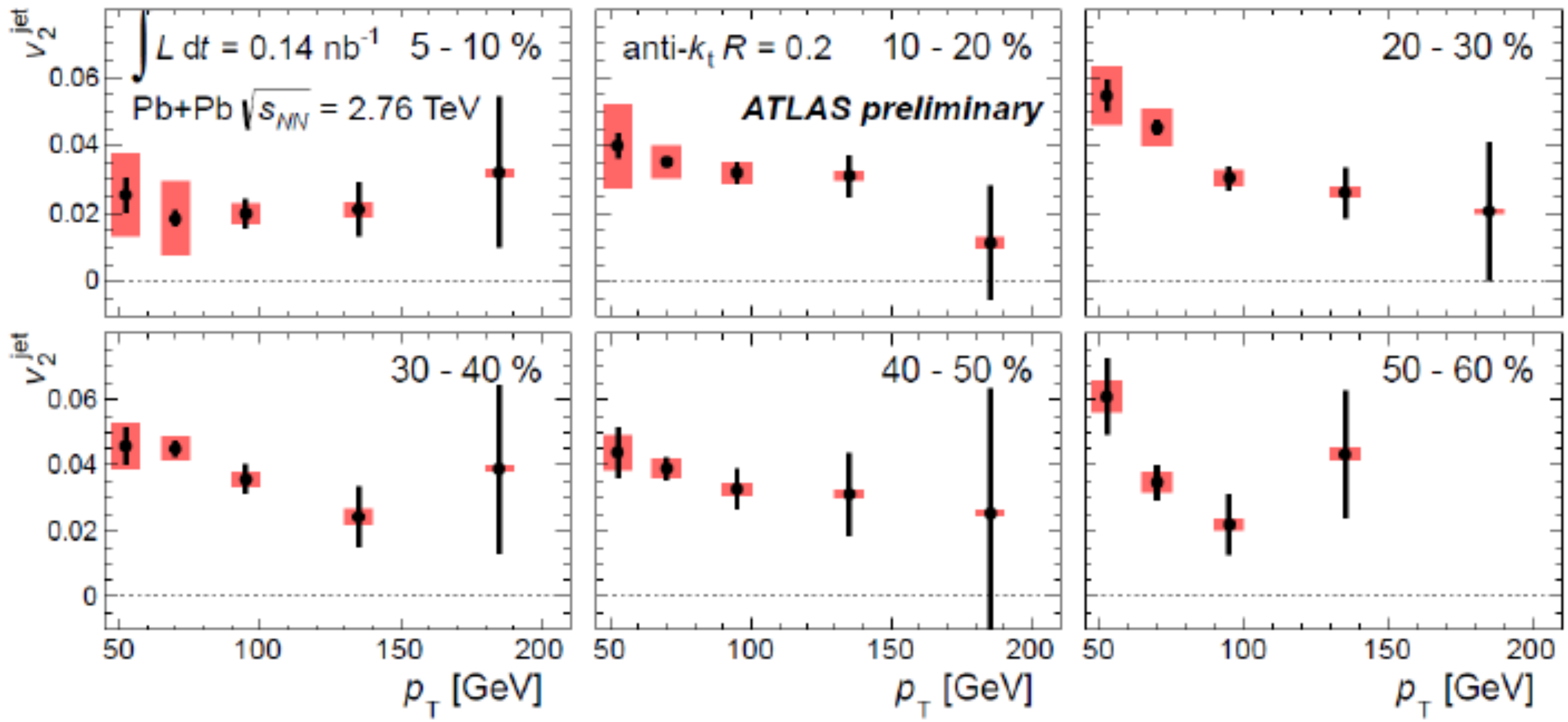
→ large imbalance effect on jet energy, but very little effect on jet direction!

Jet R_{AA}



CMS PAS HIN-12-004

Jet v_2

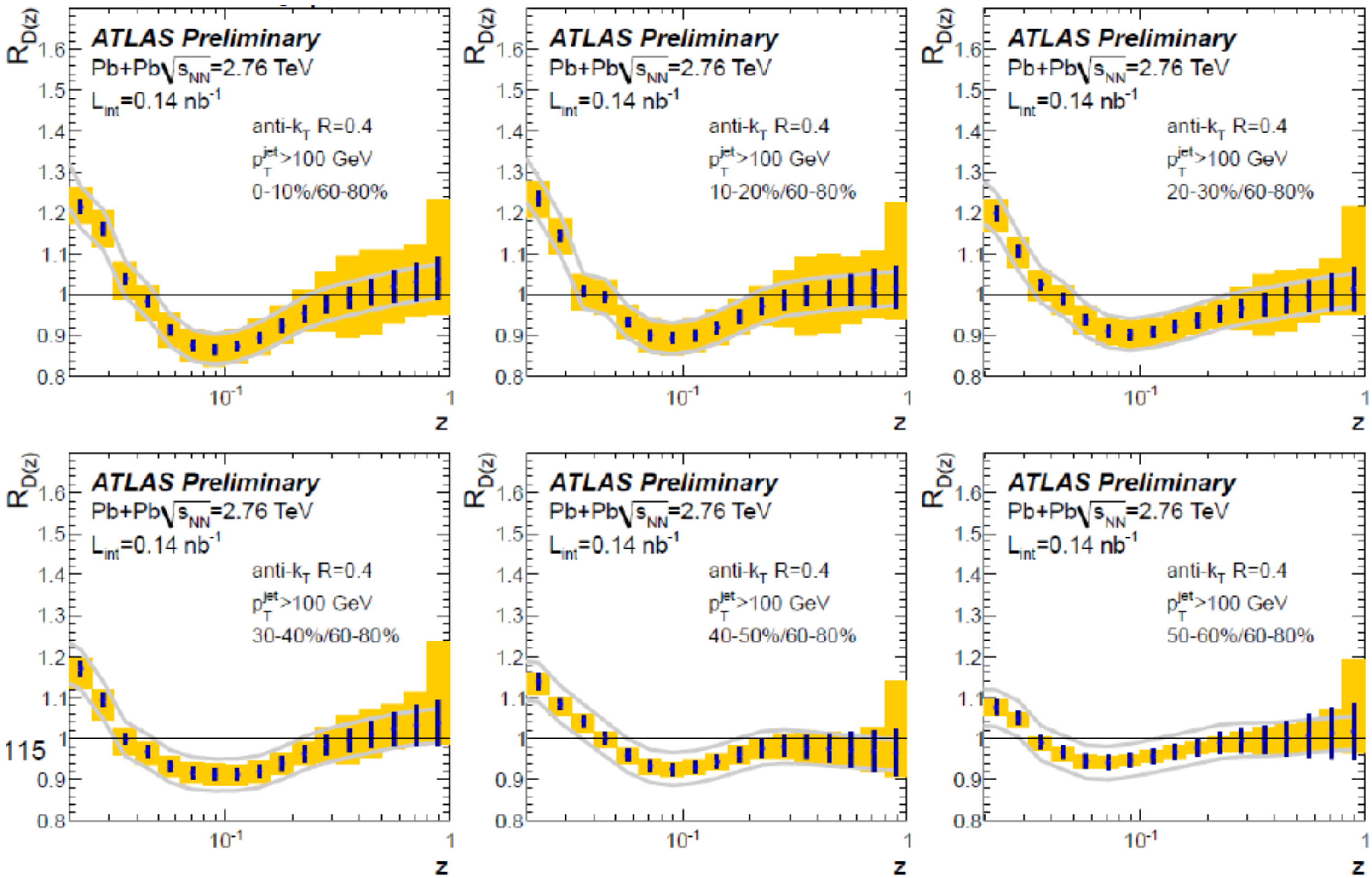


ATLAS-CONF-2012-116

- substantial azimuthal asymmetry up to highest jet energies!

Jet fragmentation is modified

- ratio of Pb-Pb and pp Fragmentation Functions



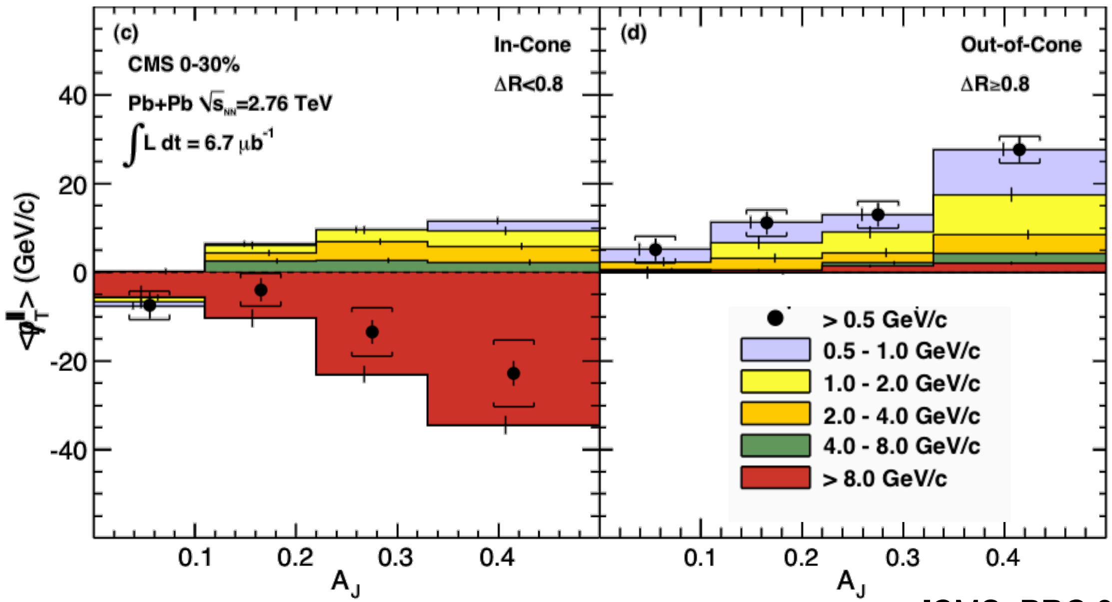
$z = p_T(\text{track})/p_T(\text{jet})$

ATLAS-CONF-2012-115

Where does the energy go?

- look at missing p_T projected on leading jet axis

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

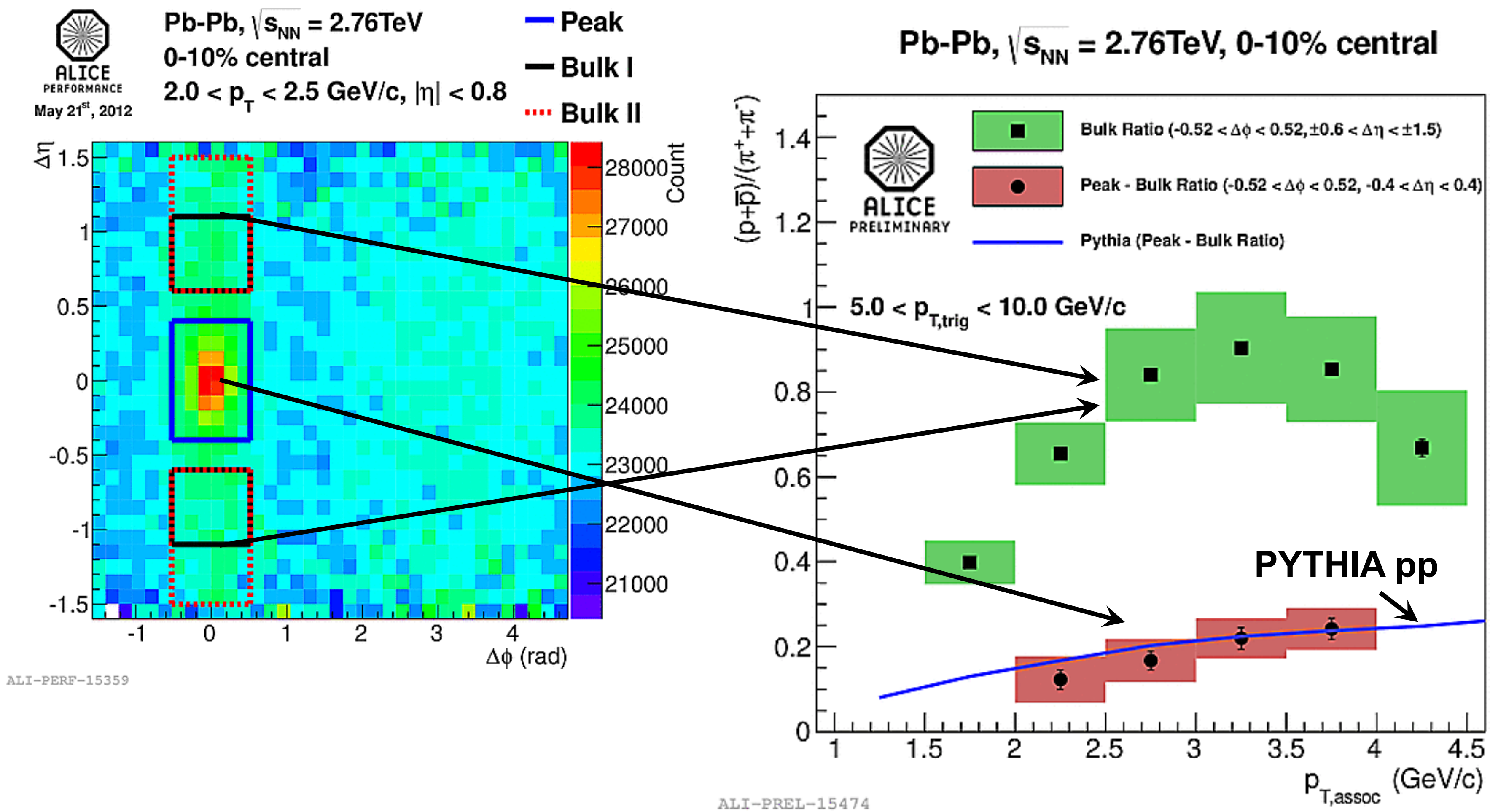


[CMS: PRC 84 (2011) 024906]

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

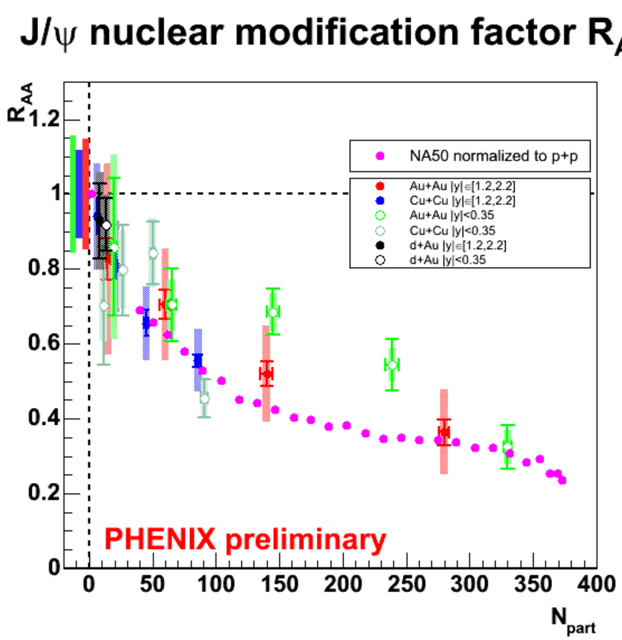
Particle composition

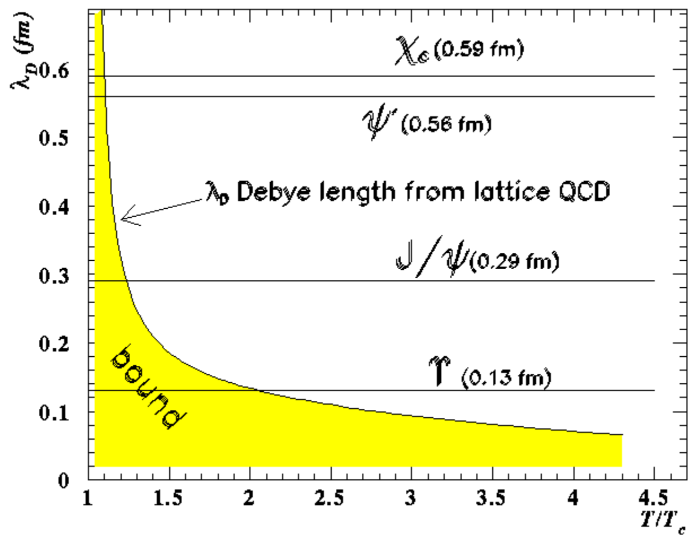
- peak excess particle composition similar to pp!



Quarkonium suppression

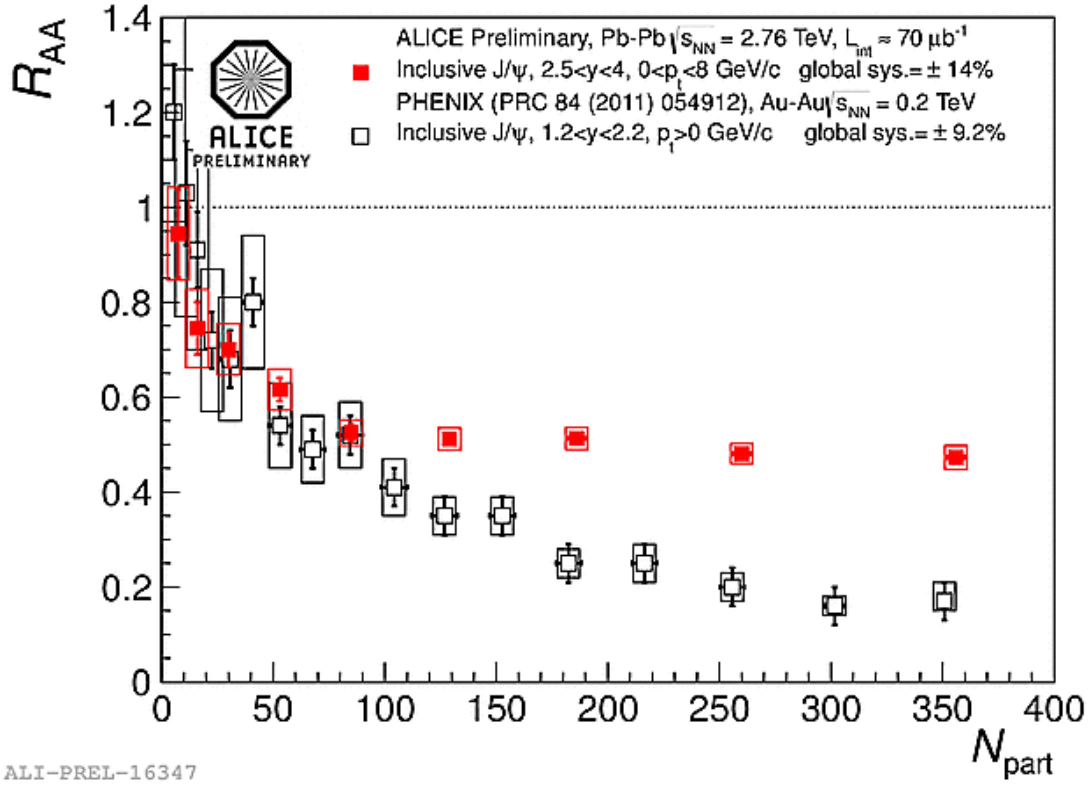
- QGP signature proposed by Matsui and Satz, 1986
- $Q\bar{Q}$ potential screened in QGP for $r > \lambda_D$ (Debye length)
  - → binding suppressed for states with $r > \lambda_D$
- substantial suppression at SPS & RHIC
  - – effect similar at the two machines





J/ψ suppression at the LHC

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



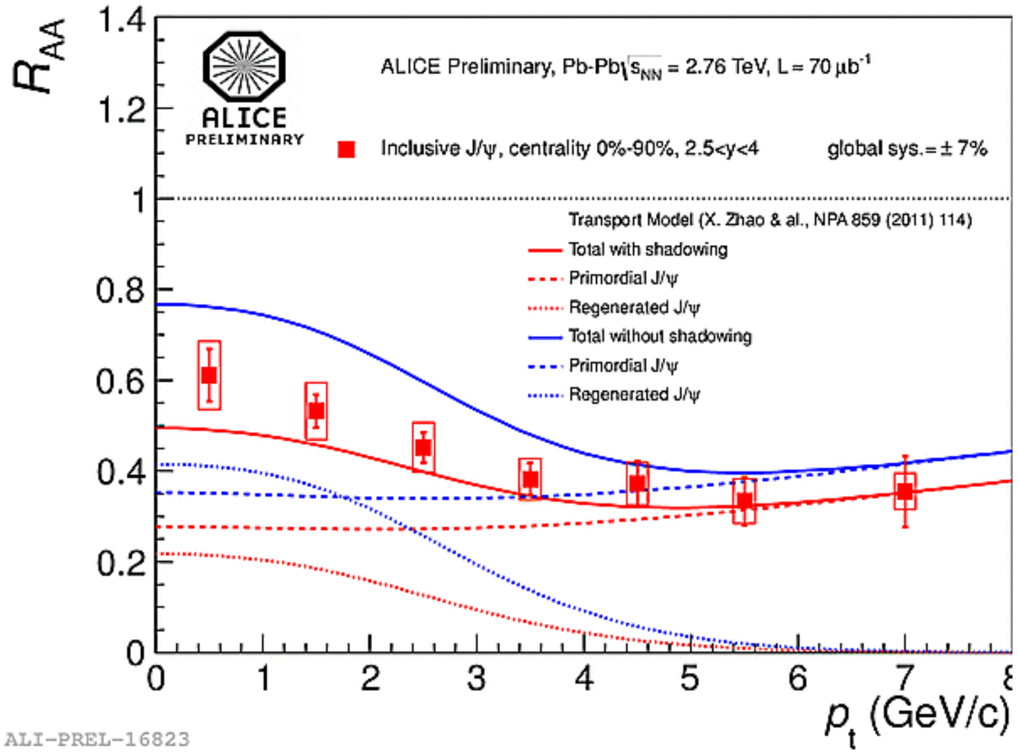
→ less suppression than RHIC
(PHENIX, $1.2 < y < 2.2$, $p_T > 0$)

→ weaker centrality dependence

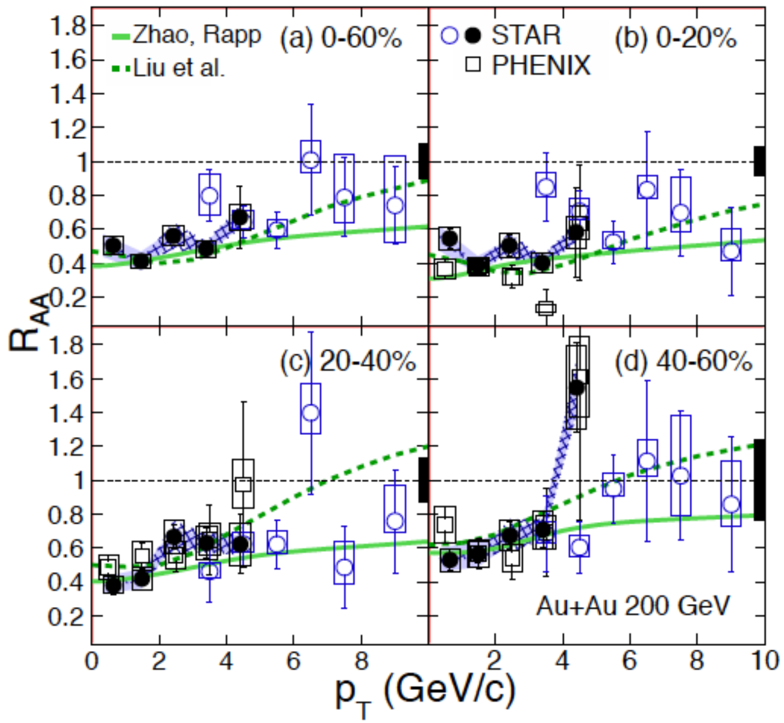
→ new regime wrt RHIC!
→ c-cbar coalescence?

J/ψ R_{AA}: p_T dependence

- decreases with p_T



- at RHIC: opposite behaviour

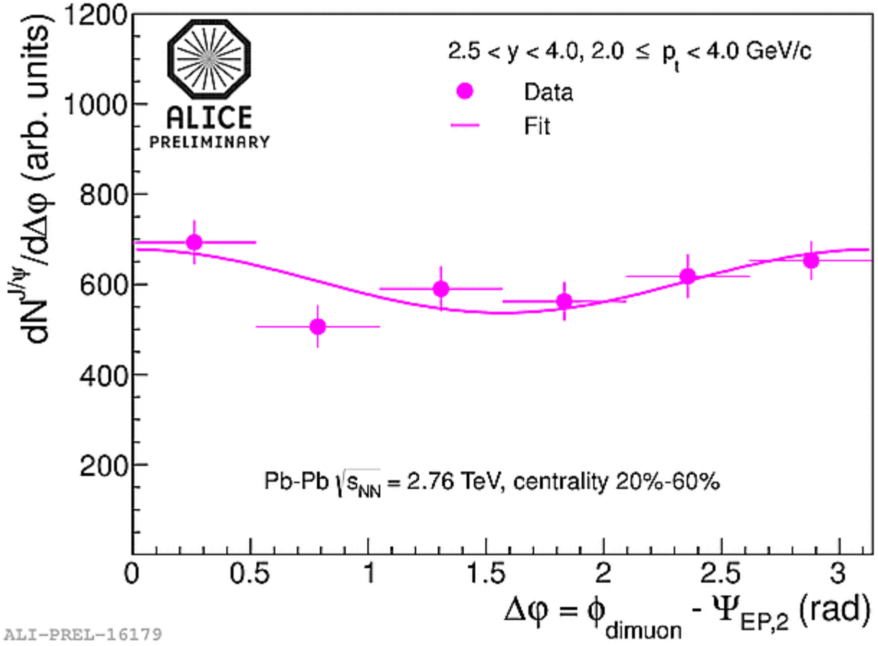


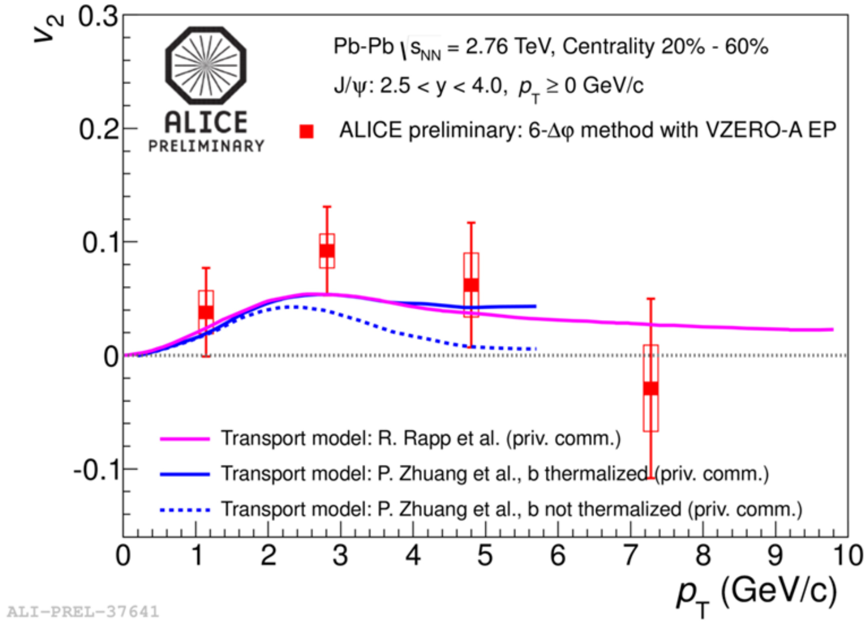
[STAR, arXiv:1310.3563]

- consistent with coalescence models!

J/ψ flow?

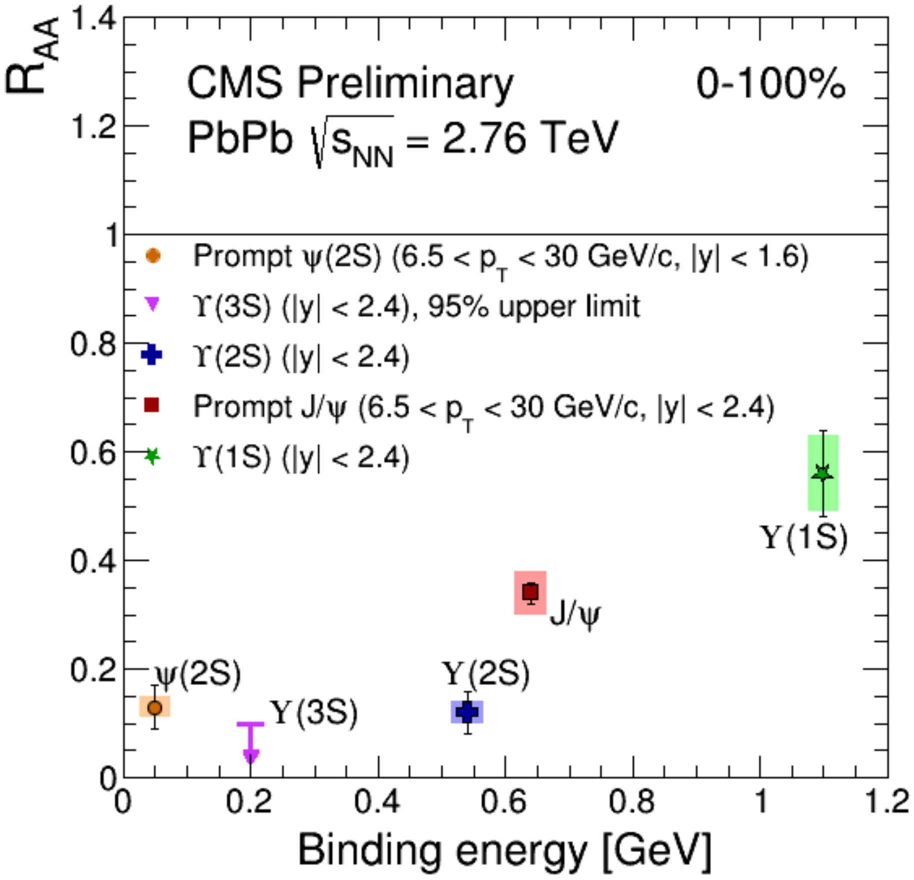
- some hint for a modulation…?





- more statistics needed!

Bottomonium suppression



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

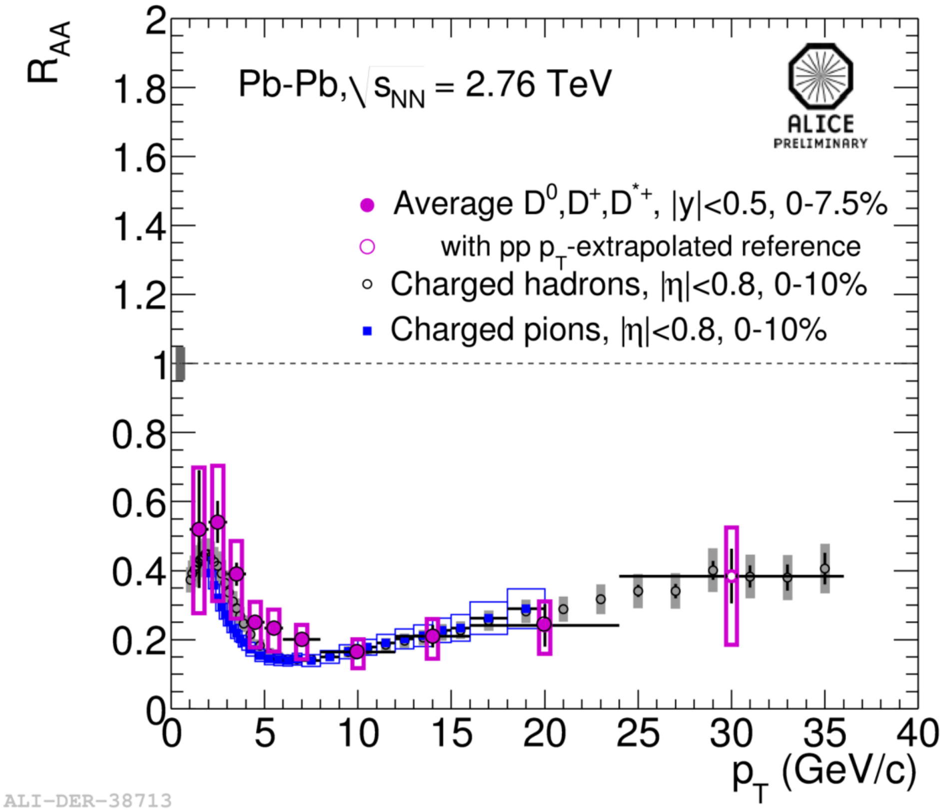
Charm and beauty: ideal probes

- study medium with probes of known colour charge and mass
  - → e.g.: energy loss by gluon radiation expected to be:
  - – parton-specific: stronger for gluons than quarks (colour charge)
  - – flavour-specific: stronger for lighter than for heavier quarks (dead-cone effect)

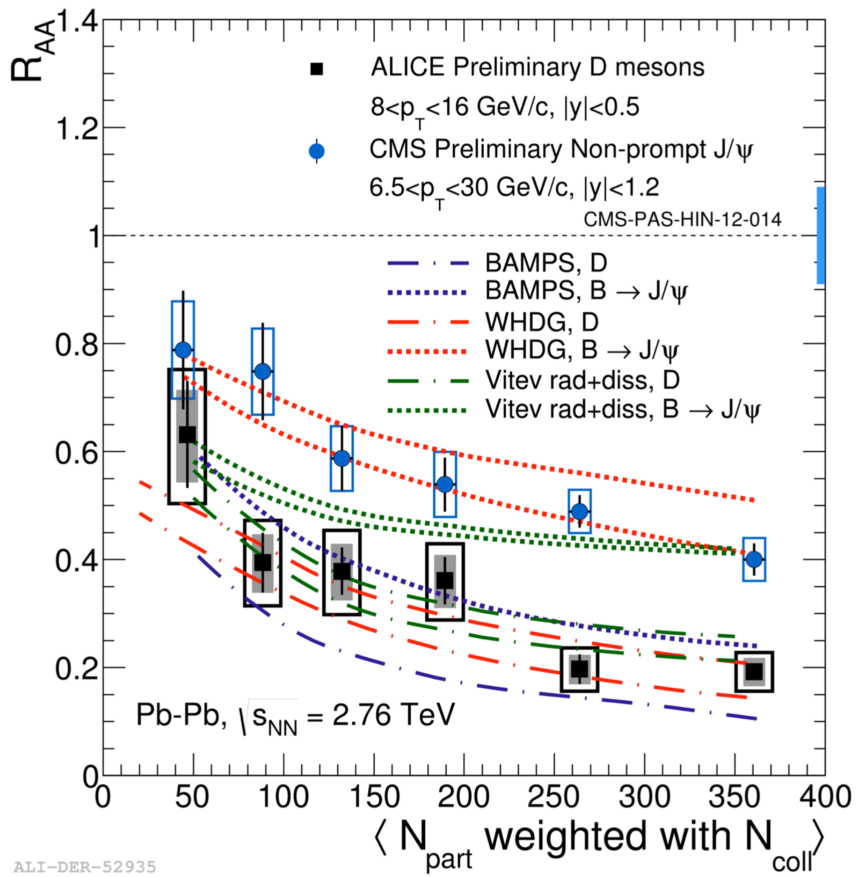
- study effect of medium on fragmentation
  - – (no extra production of c, b at hadronization)
  - → independent string fragmentation vs recombination
  - – e.g.: D^+_s vs D^0, D^+

- + measurement important for quarkonium physics
  - – open $Q\overline{Q}$ production natural normalization for quarkonium studies
  - – B meson decays non negligible source of non-prompt J/ψ

R_{AA}: Flavour Dependence!



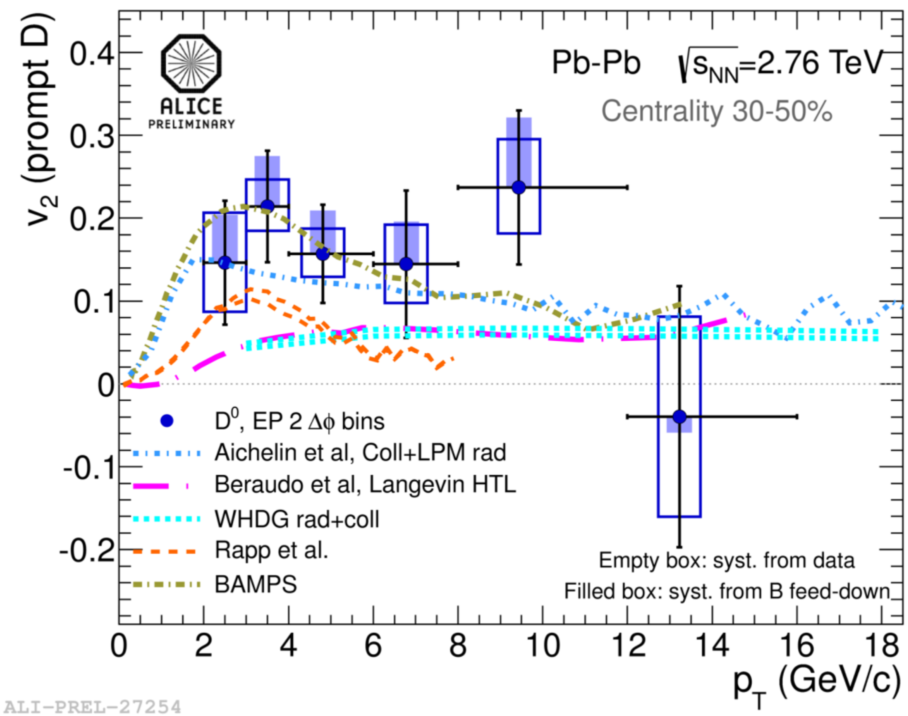
- indication of $R_{AA}(b) > R_{AA}(c)$!



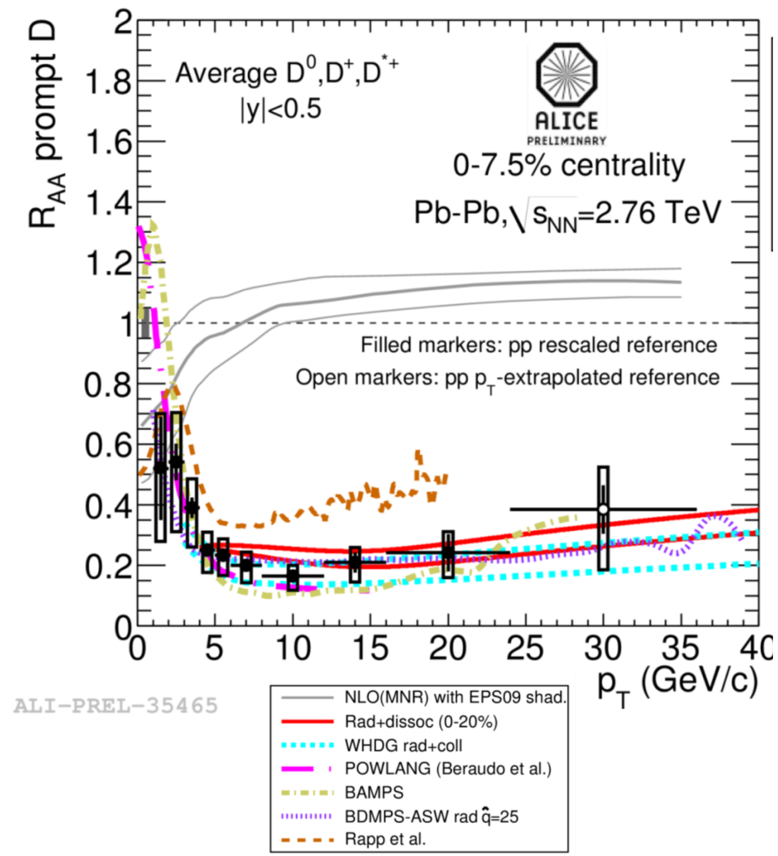
- p_T < 8 GeV/c:
  - hint of less suppression than for π ?
- p_T > 8 GeV/c
  - same suppression as for π…

D meson v_2

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

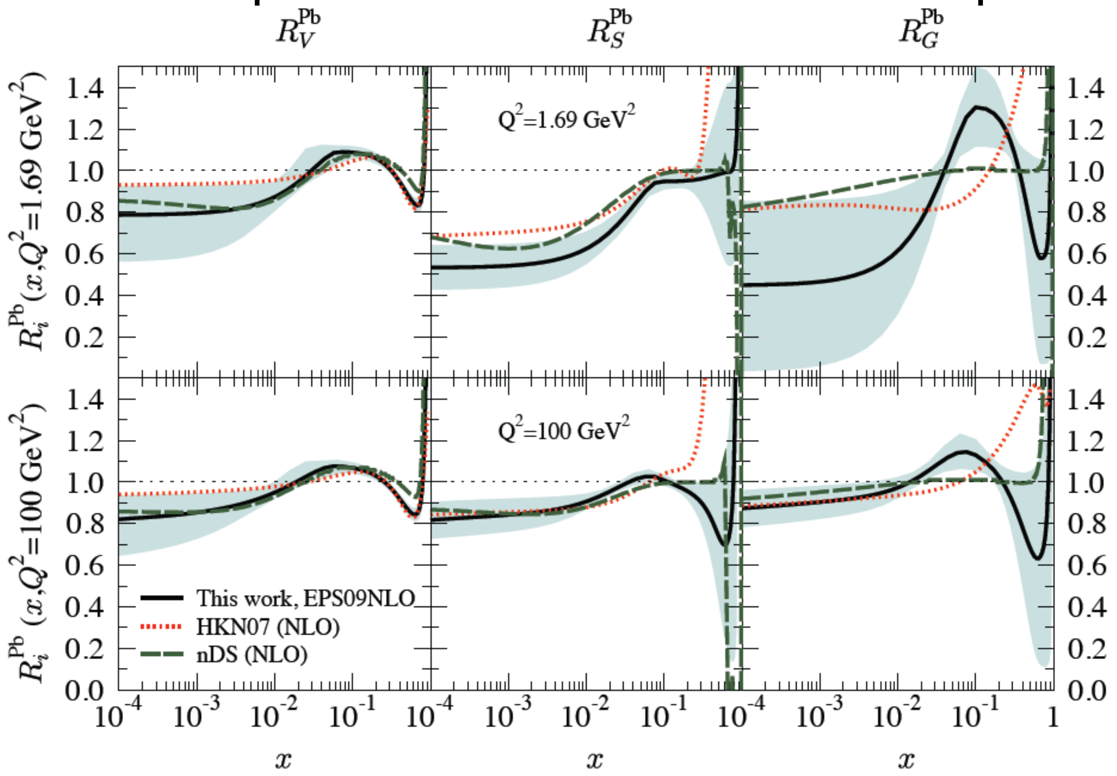


- theory must describe simultaneously v_2 and R_{AA} …



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

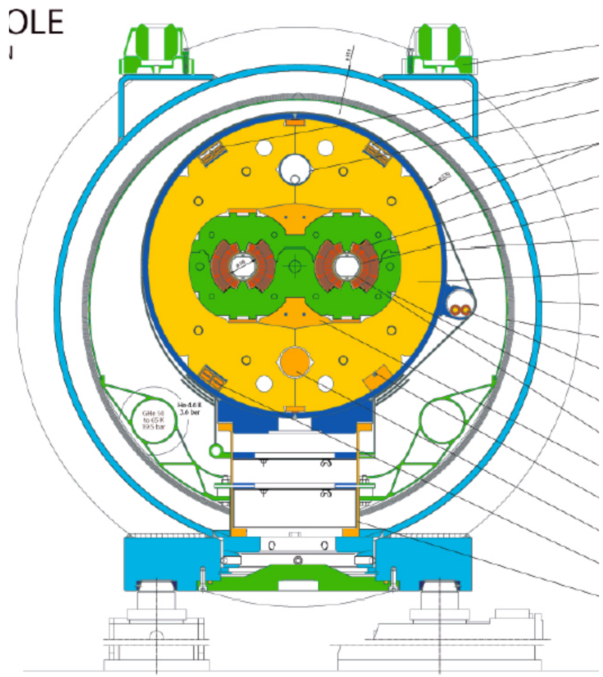
[K J Eskola et al: JHEP04(2009)065]

→ uncertainty on "trivial" nuclear effects baseline

→ measure p-Pb collisions!!!

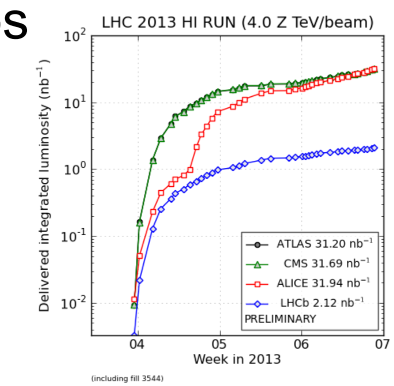
p-Pb collisions in the LHC!

- 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!



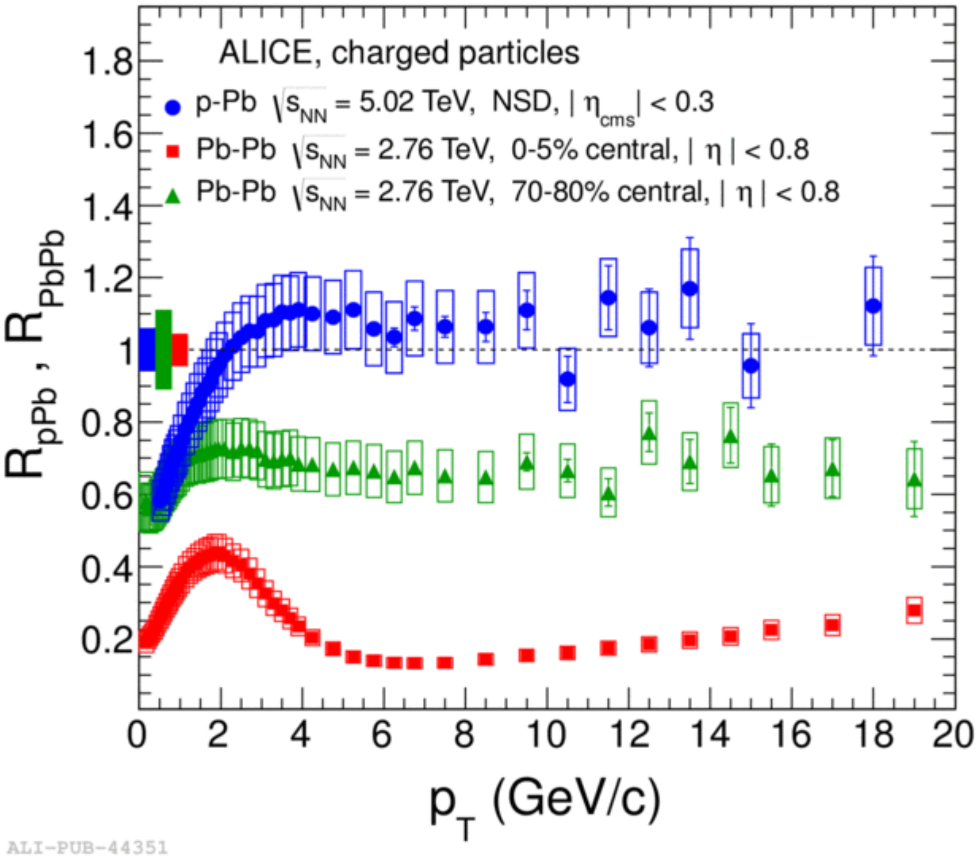
- adjust length of closed orbits!
  - – to compensate different speeds
- different RF freq for two beams at injection and ramps
- short low lumi pilot run (a few hours) on 12/9/2012
- first run in Jan-Feb 2013!

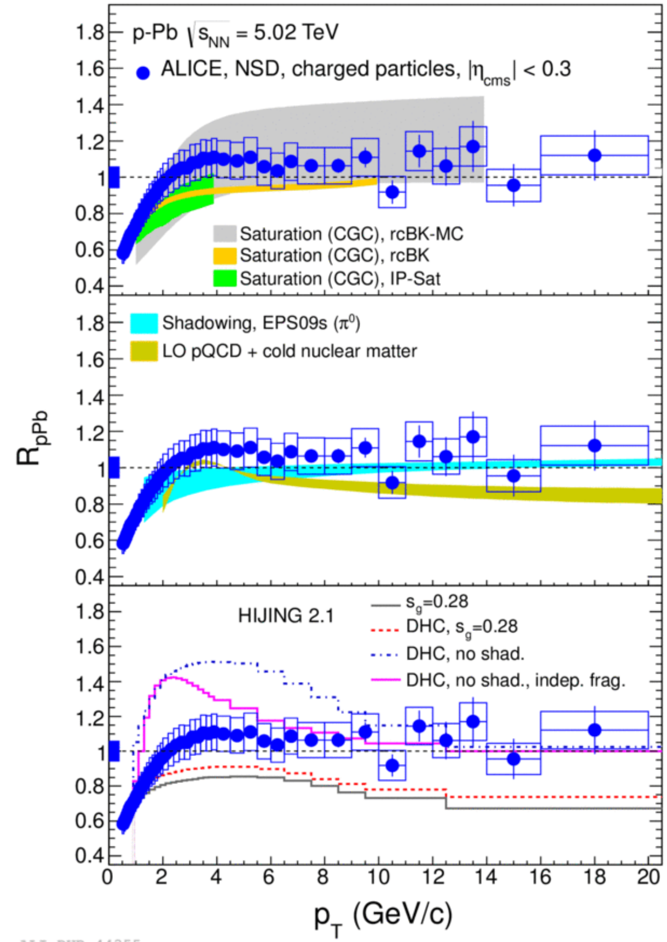
→ ~ 30/nb



Control experiment: R_{pPb}

- measurement of nuclear modifications in initial state

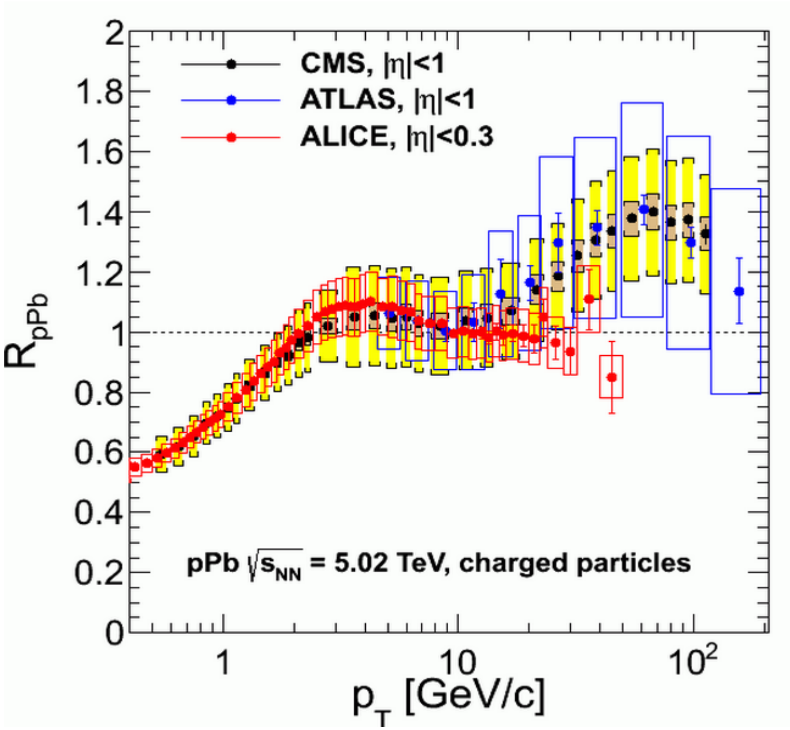




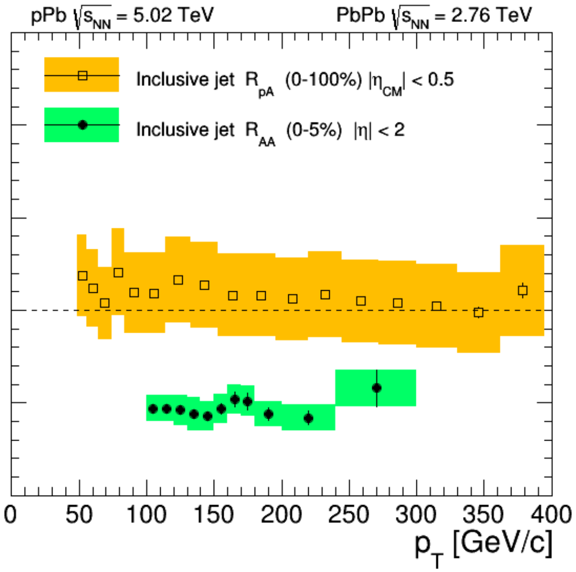
- $R_{pA} \sim 1$ for $p_T > 3$ GeV/c → confirms quenching is due to QCD medium

High-p_T puzzle!

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



- but not for jets?

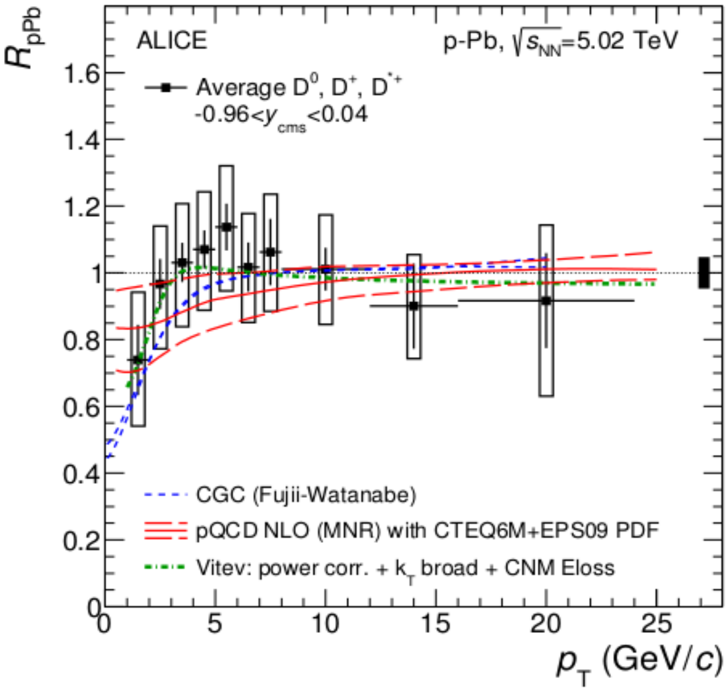


- results rely on interpolated pp reference…
  - → need pp data at 5 TeV!

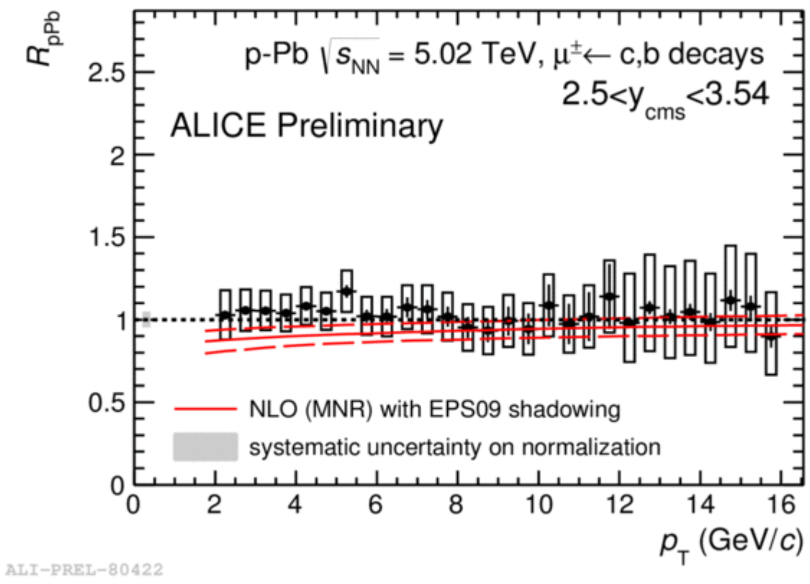
à suivre…

R_{pPb} for Heavy Flavours

- D mesons



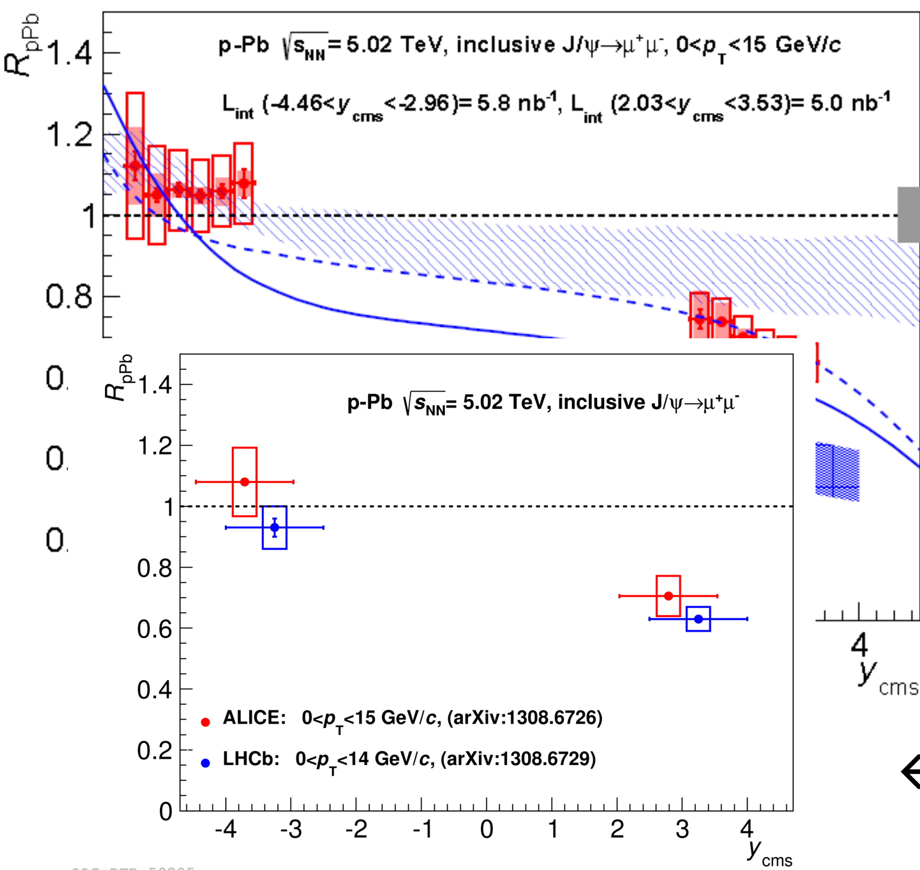
- HF muons



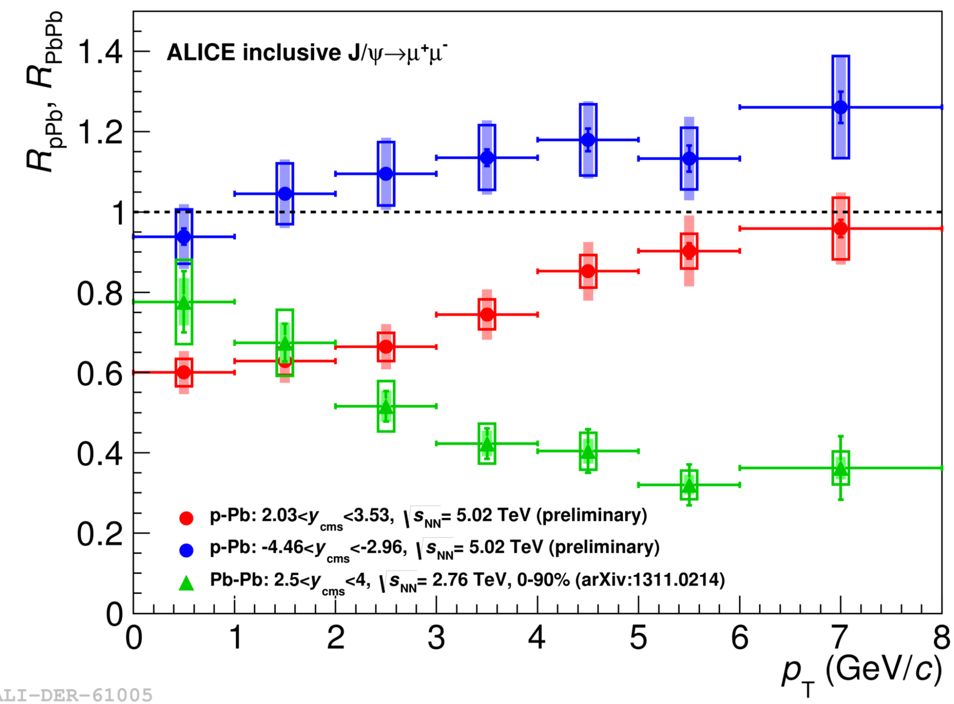
→Pb-Pb suppression not due to initial state

J/ψ in p-Pb

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



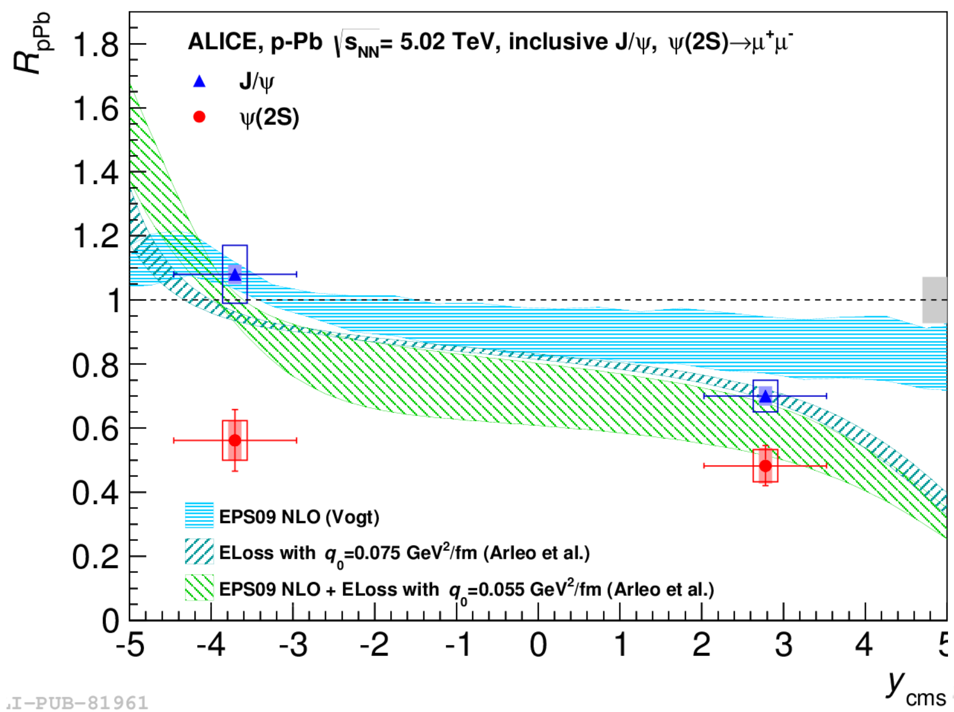
- R_{pPb} back to 1 at high p_T
  - opposite behaviour for Pb-Pb!

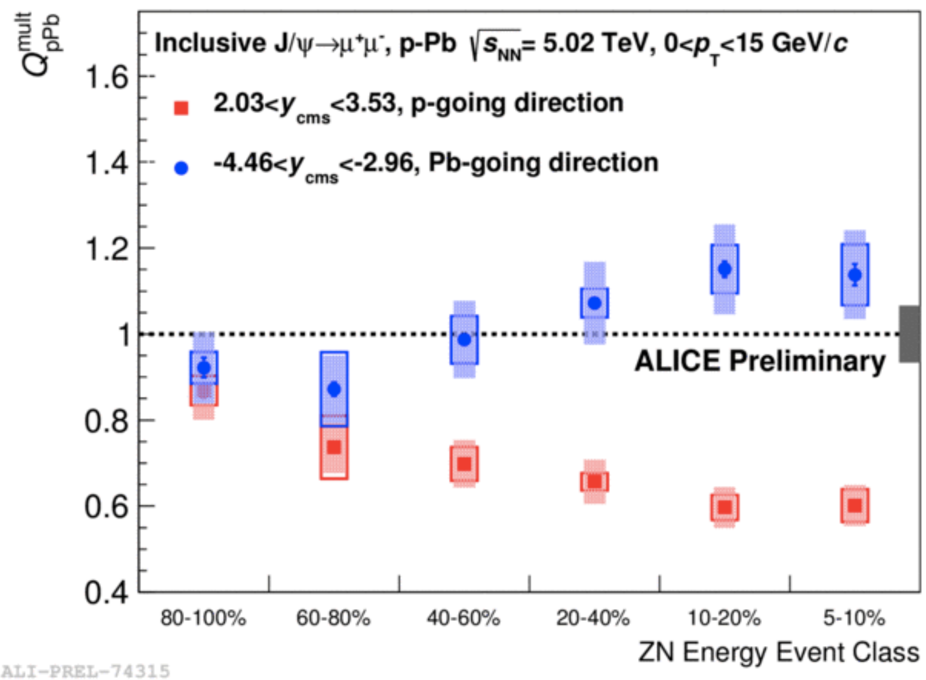


← LHCb joins the Heavy-Ion club!

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

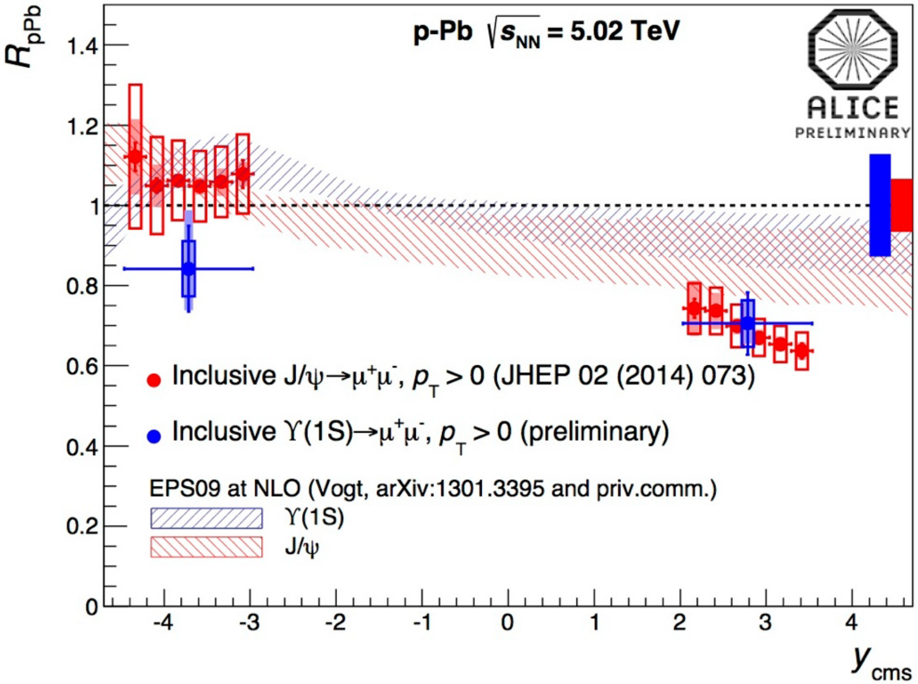


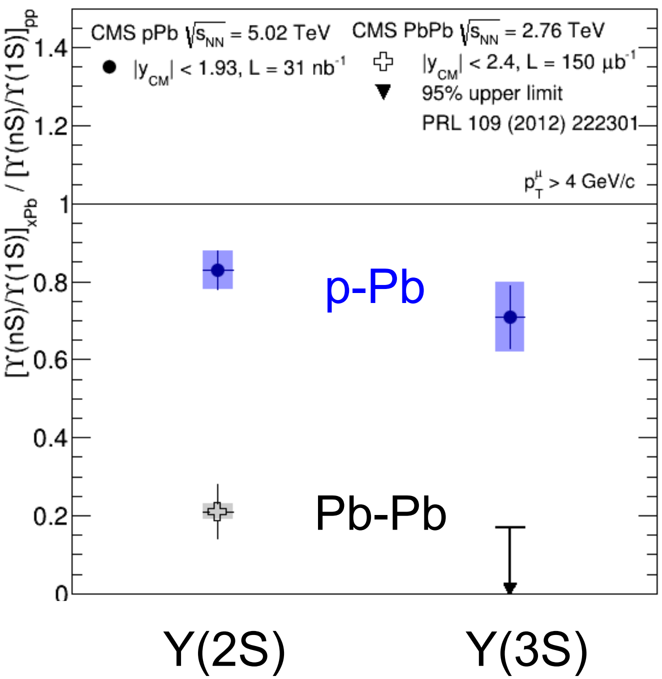


→ indication of final state effects?

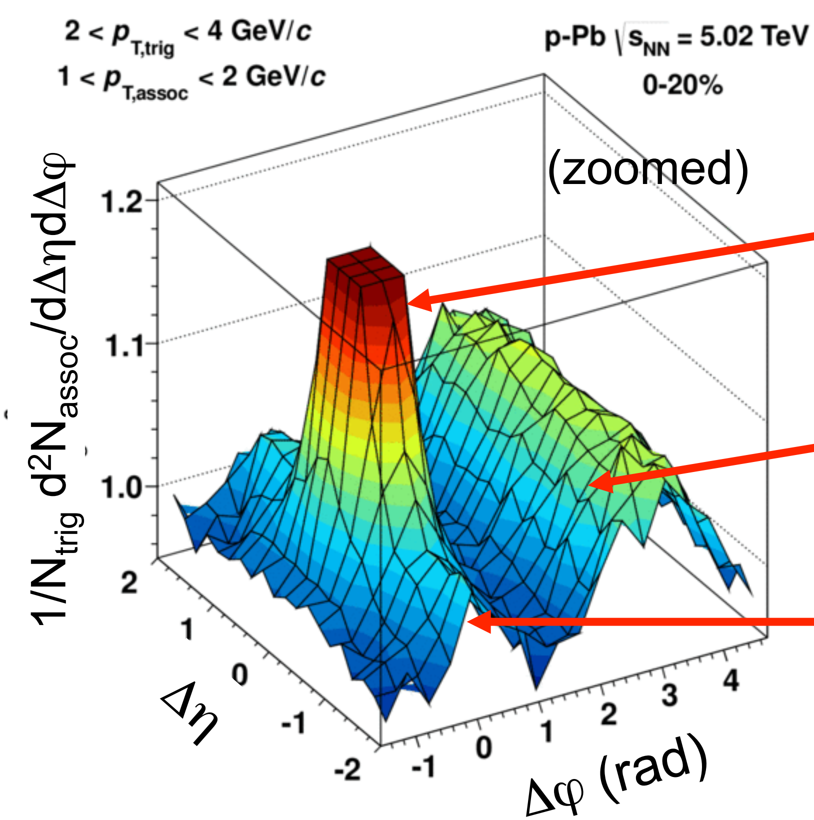
Bottomonia in p-Pb

- 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

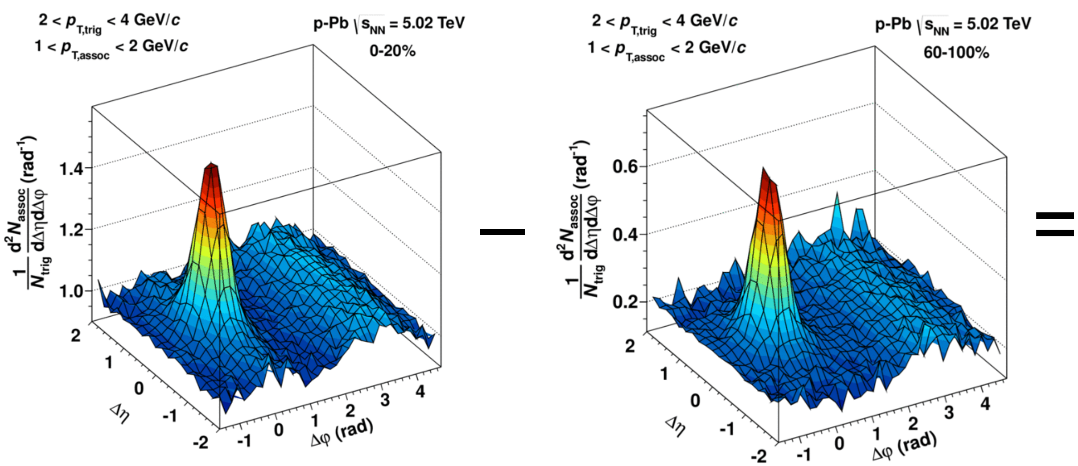
  first observed by CMS [PLB718 (2013) 795]

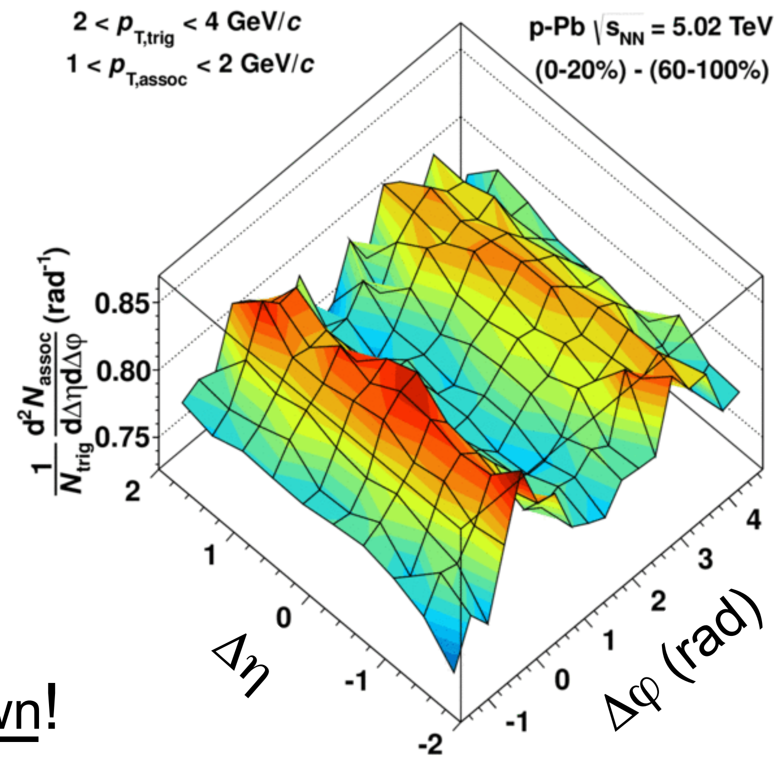
The Double Ridge

- 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%   60-100%





- the ridge is doubled!

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

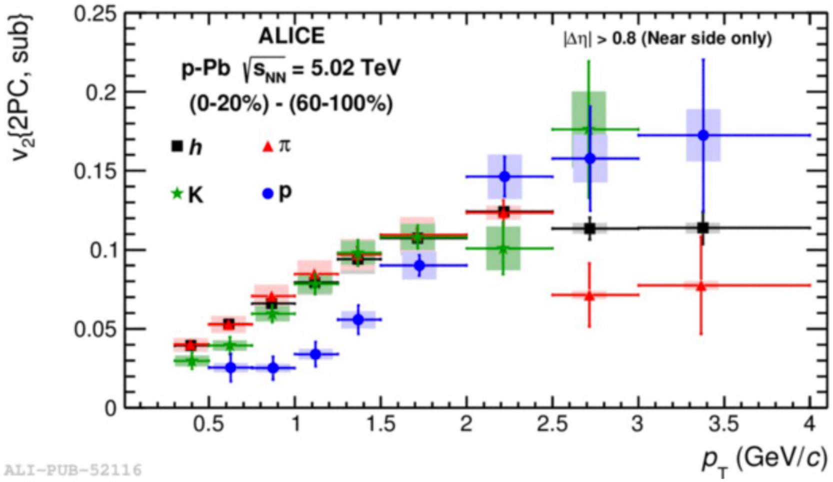
similar structure observed in Pb-Pb is attributed to hydrodynamic flow…

CGC-glasma graphs can also produce symmetric ridges?

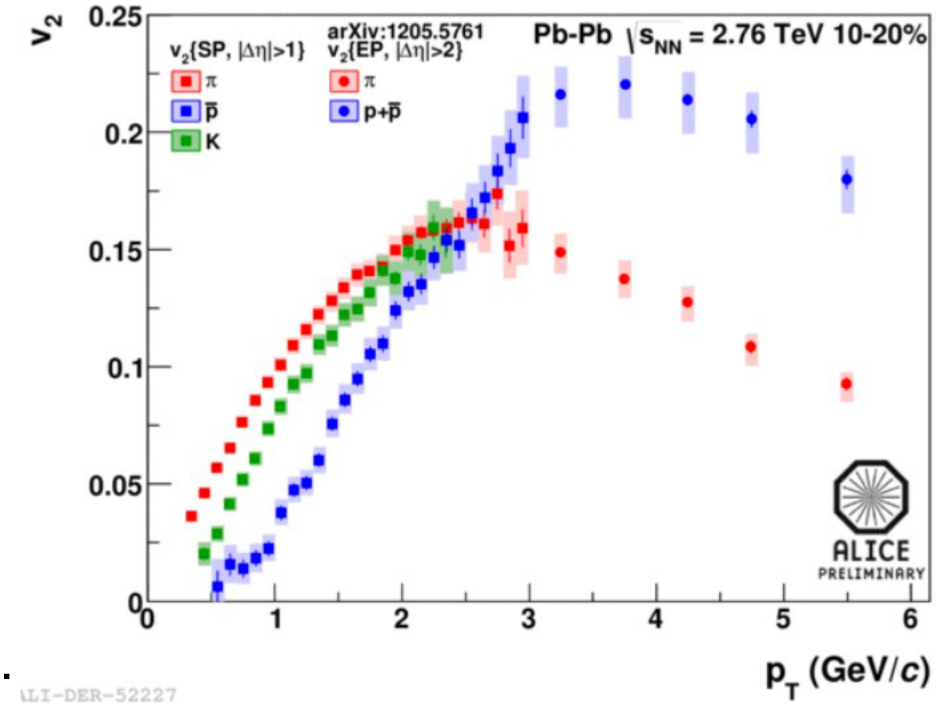
Identified particles

- how does the correlation depend on the particle species?

p-Pb



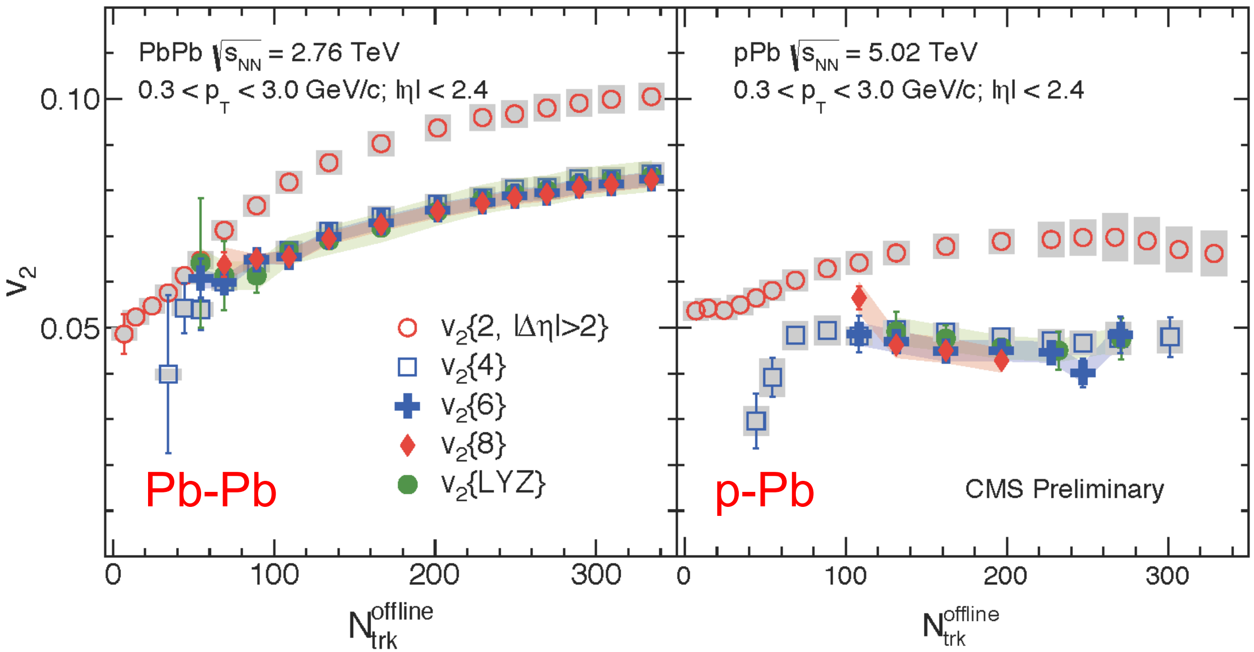
Pb-Pb



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

Multiparticle correlations

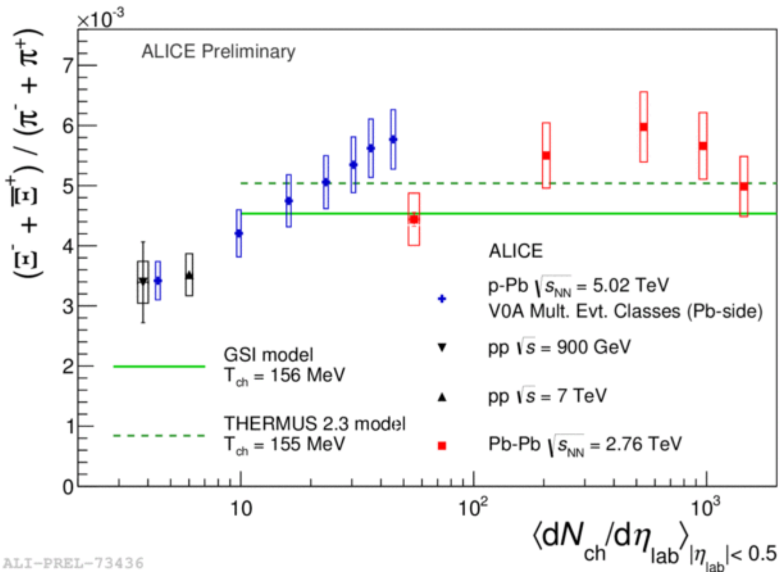
- v2 calculated with higher order cumulants

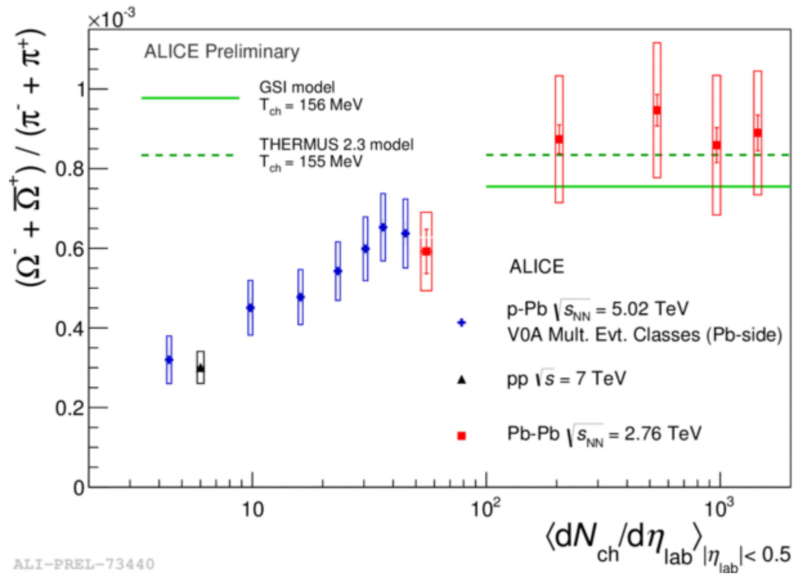


- again: p-Pb very similar to Pb-Pb
- azimuthal asymmetry is a true multi-particle effect, in both systems!

Multi-strange baryons

- p-Pb smoothly bridges Ξ, Ω abundances from pp to Pb-Pb values!





→ onset of collective effects in p-Pb?

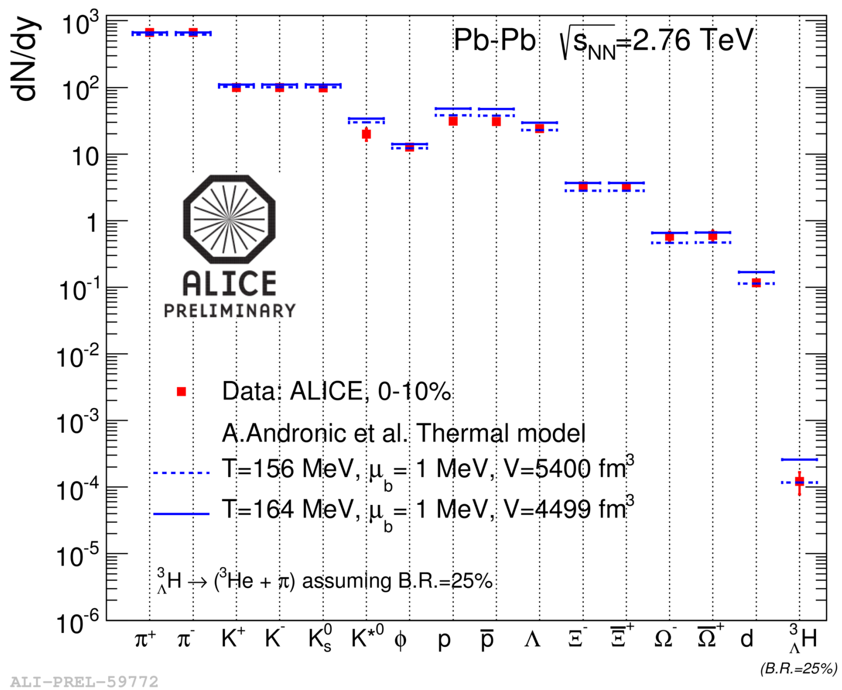
Conclusions

- 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 recombination?
  - double ridge in p-Pb (and pp?) → signal of collectivity? parton saturation?
- … one outstanding puzzle…
  - is R_{pPb} enhanced at high p_T?
- … + 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) in p-Pb)
- the future looks bright → stay tuned!
  - Run 2: O(10) increase in statistics, int lumi
  - Run 3: O(100) increase, ALICE 2.0 upgrade!

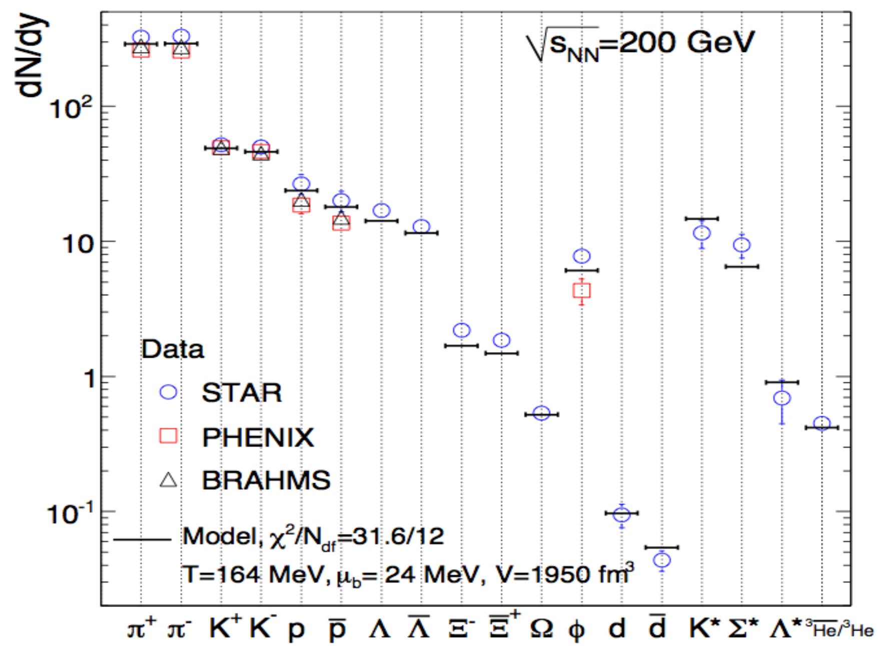
Thank you!

Particle yields

- ~ at thermodynamic equilibrium…
  - now including ${}^{3}_{\Lambda}H$!

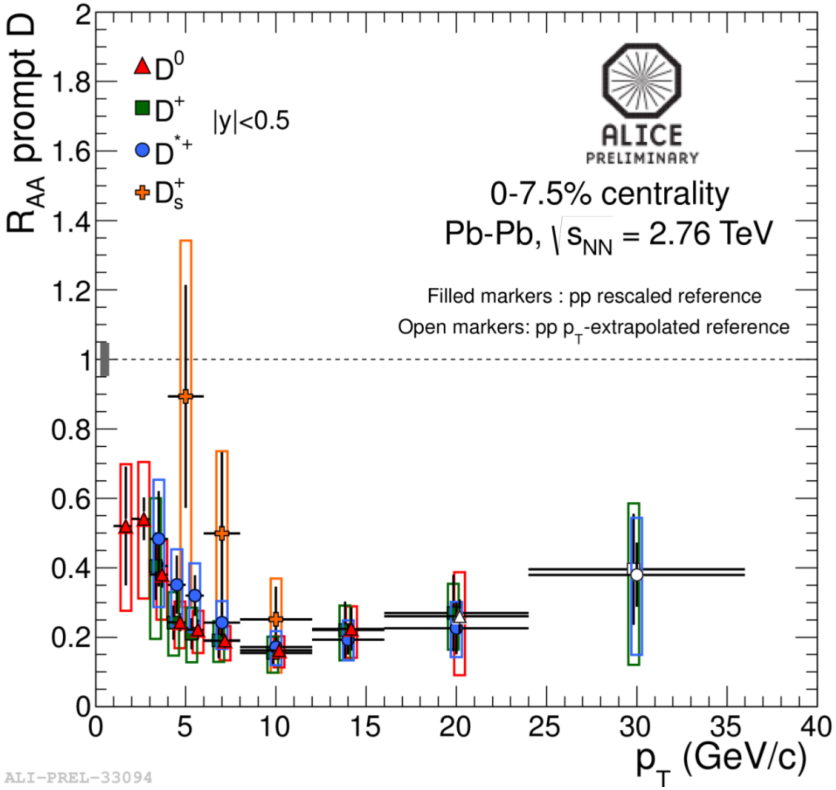


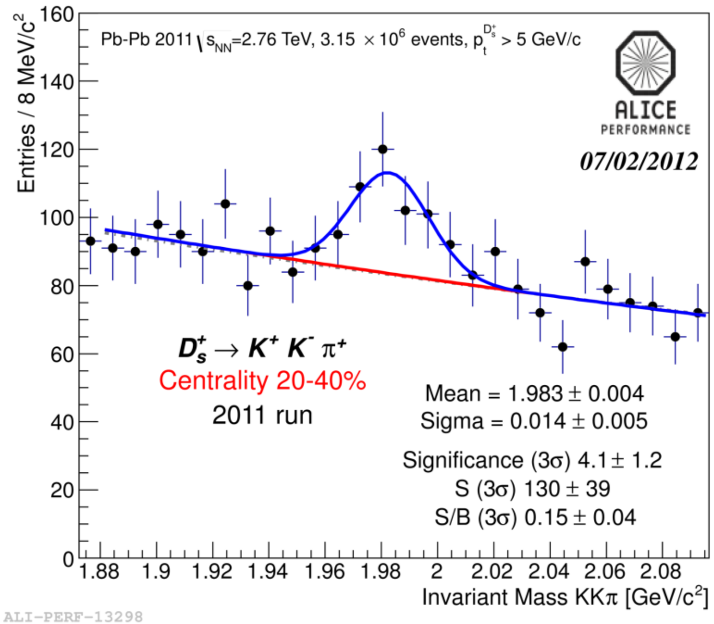
- at RHIC?
  - some tension too?
  - higher precision needed…



The D_s

- HF in-medium hadronisation!





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