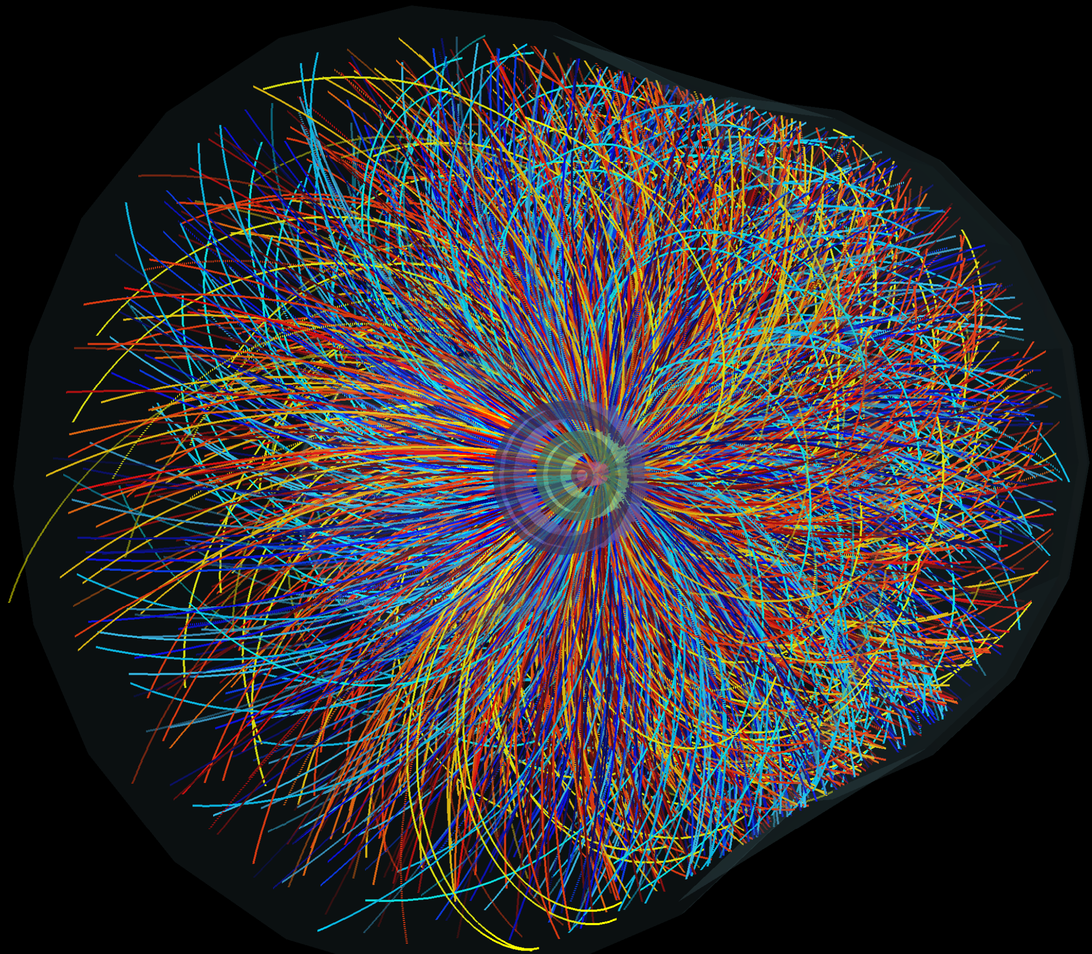
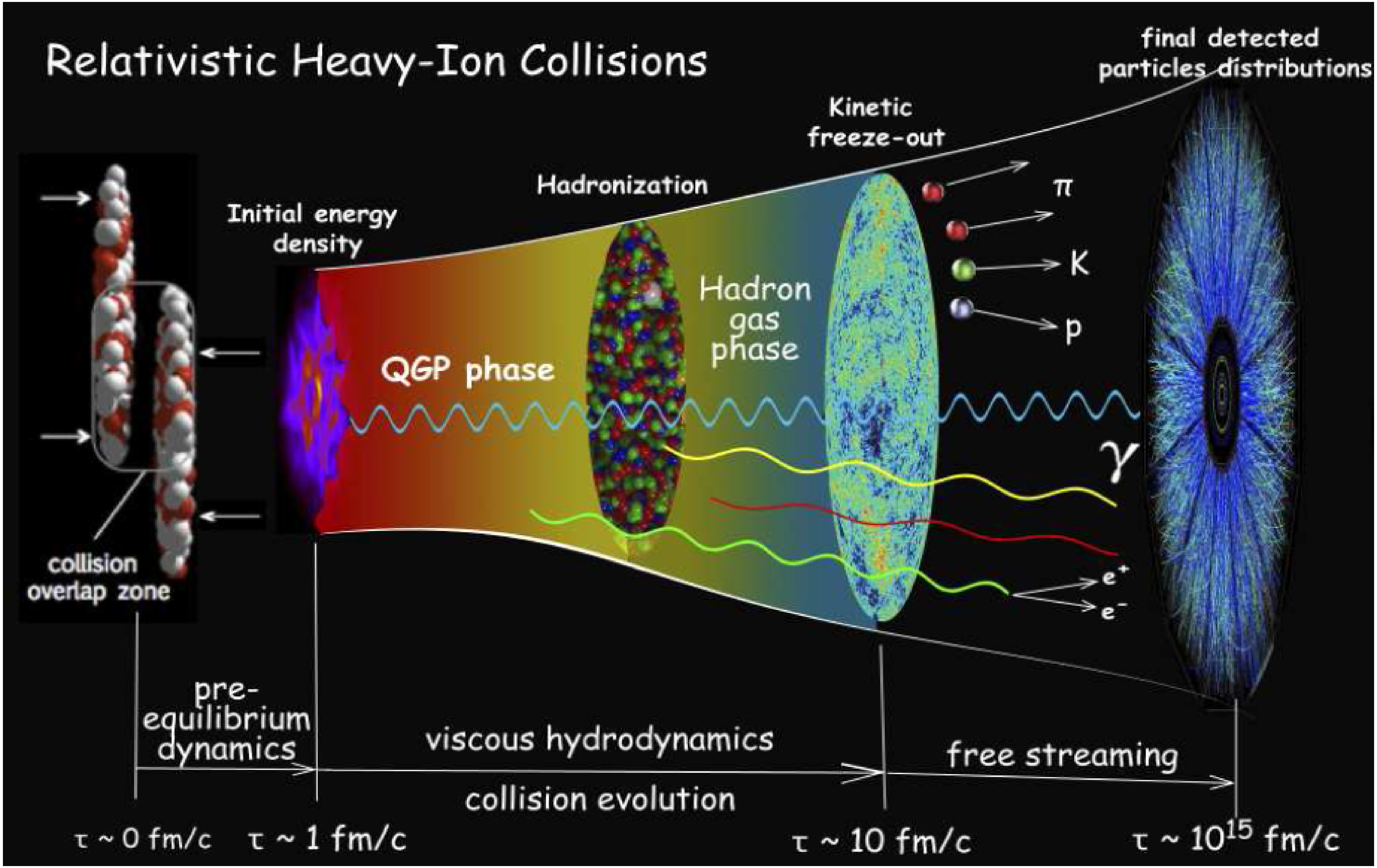
Overview of recent ALICE results



Evgeny Kryshen (CERN, PNPI)
for the ALICE collaboration

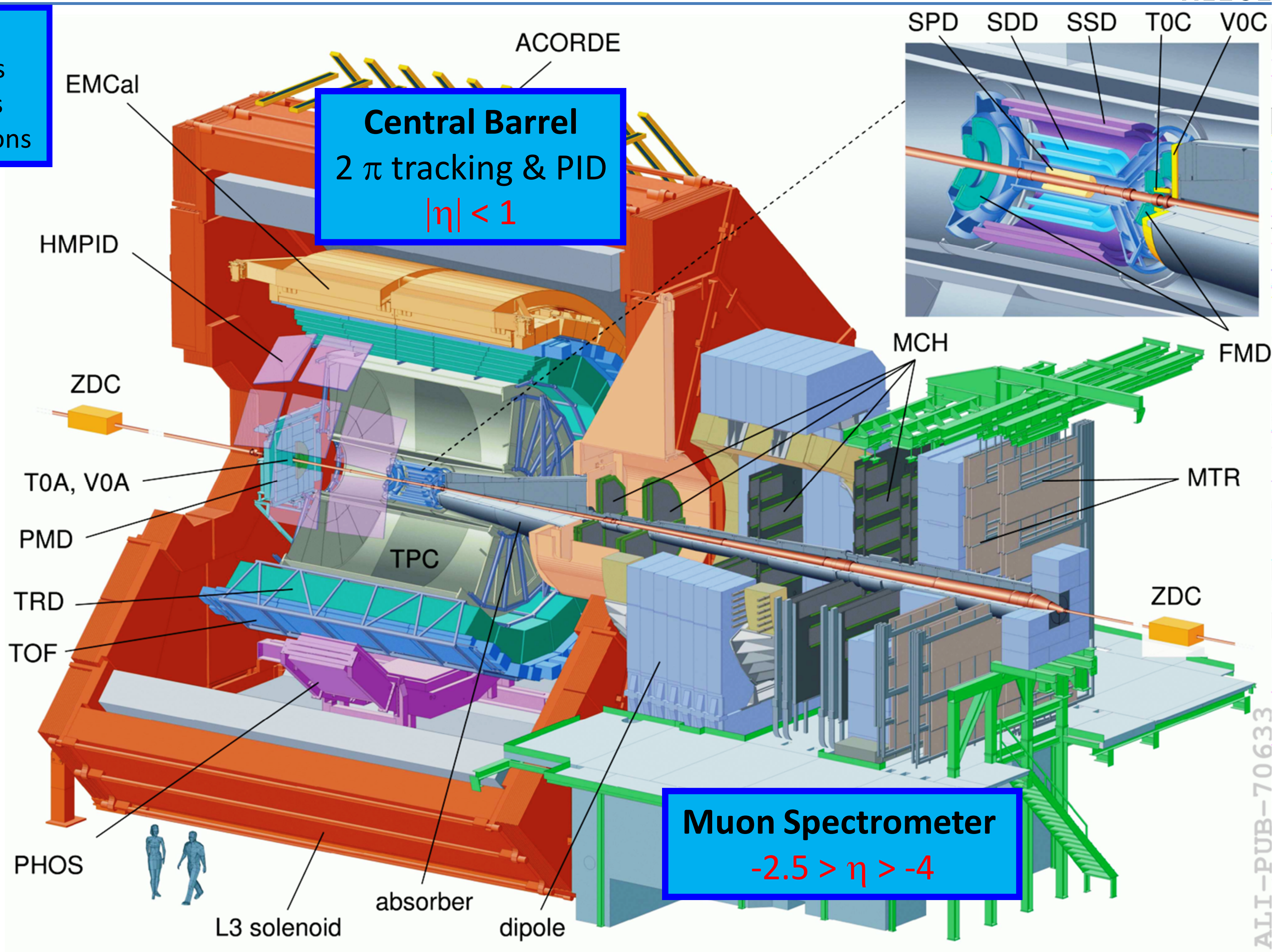
The XXII International Workshop
High Energy Physics and Quantum Field Theory
Samara, Russia, June 24 – July 1, 2015

Relativistic heavy-ion collisions



ALICE experimental setup

Detector:
Length: 26 meters
Height: 16 meters
Weight: 10,000 tons

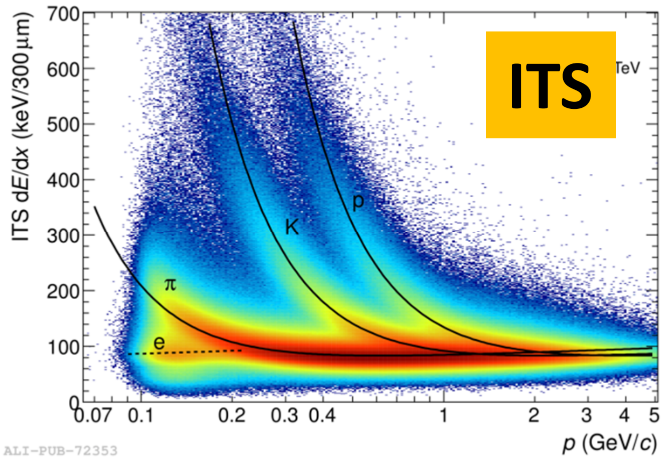


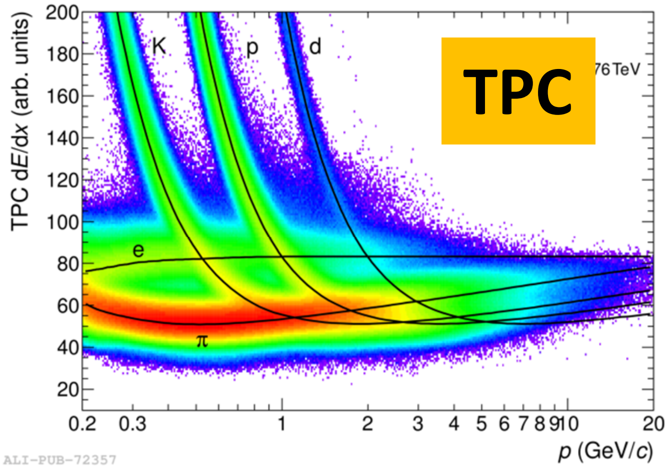
Central Barrel
2 π tracking & PID
$|\eta| < 1$

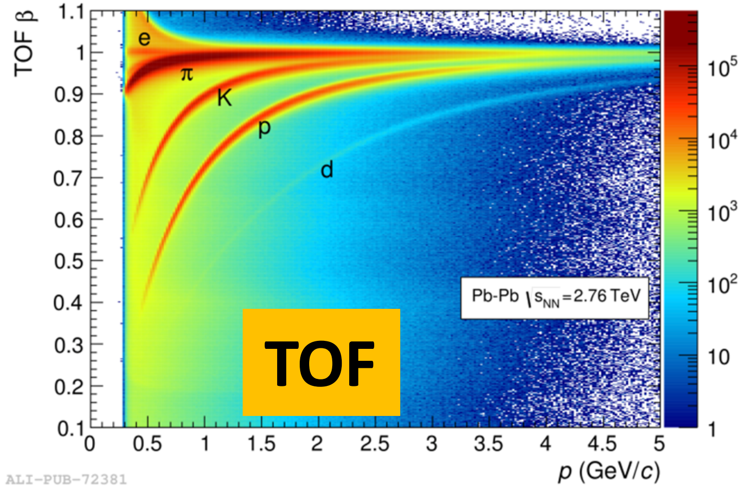
Muon Spectrometer
$-2.5 > \eta > -4$

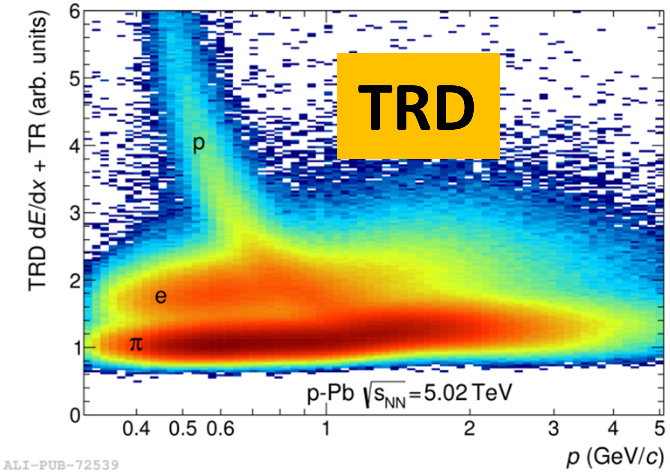
PID, vertexing and tracking capabilities

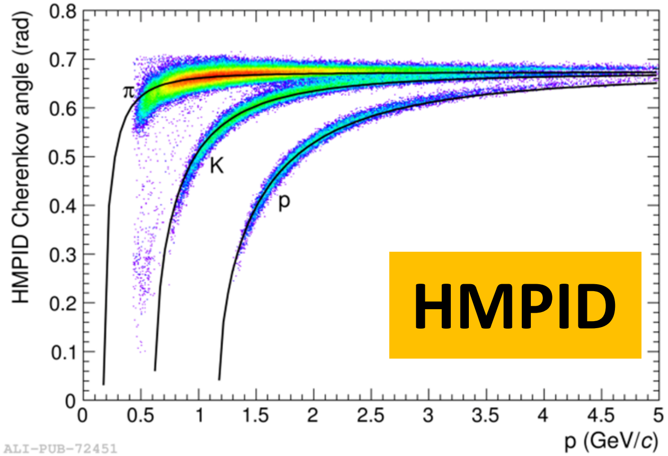
ALICE

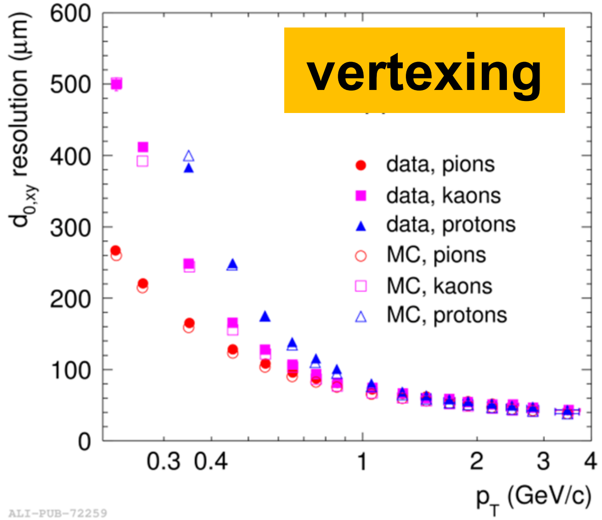












- particle identification (practically all known techniques)
- extremely low-mass tracker ~ 10% of X_0
- excellent vertexing capability
- efficient low-momentum tracking – down to ~ 100 MeV/*c*

Int.J.Mod.Phys. A29 (2014) 1430044

ALICE data taking harvest

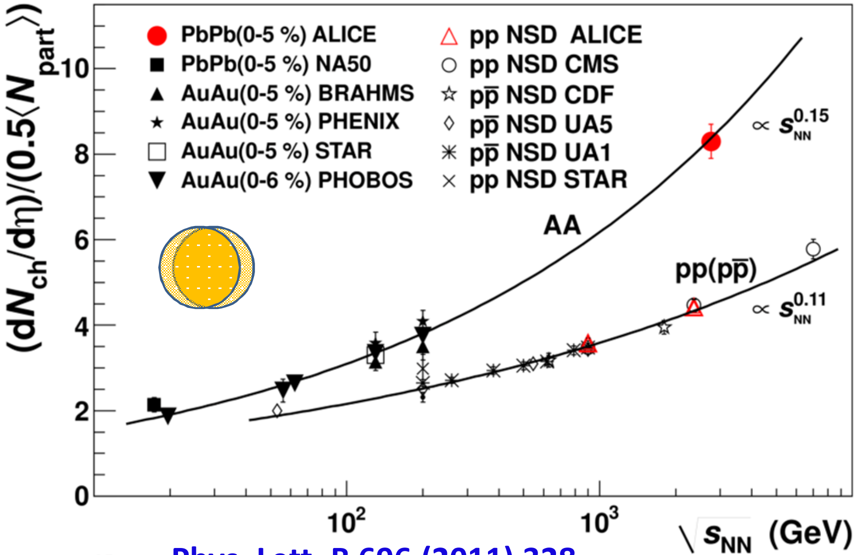
System	Year	Energy	∫ L dt
Pb-Pb	2010	2.76 TeV	10 μb^{-1} *
Pb-Pb	2011	2.76 TeV	0.1 nb^{-1} **
pp	2010	7 TeV	11 nb^{-1} *
pp	2011	2.76 TeV	1.1 nb^{-1} *
pp	2011	7 TeV	4.8 nb^{-1} *
pp	2012	8 TeV	9.7 pb^{-1} **
p-Pb	2013	5.02 TeV	15 nb^{-1} **
Pb-p	2013	5.02 TeV	15 nb^{-1} **

* Minimum bias triggers

** Rare triggers (muon, EMCAL, PHOS etc)

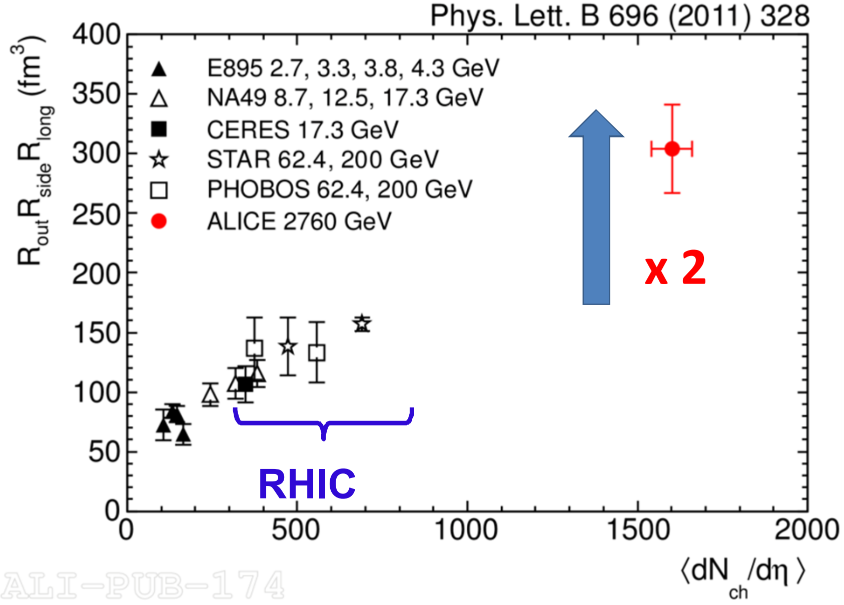
Global properties

Energy density ~ 3 x RHIC ~ 10 GeV/fm³

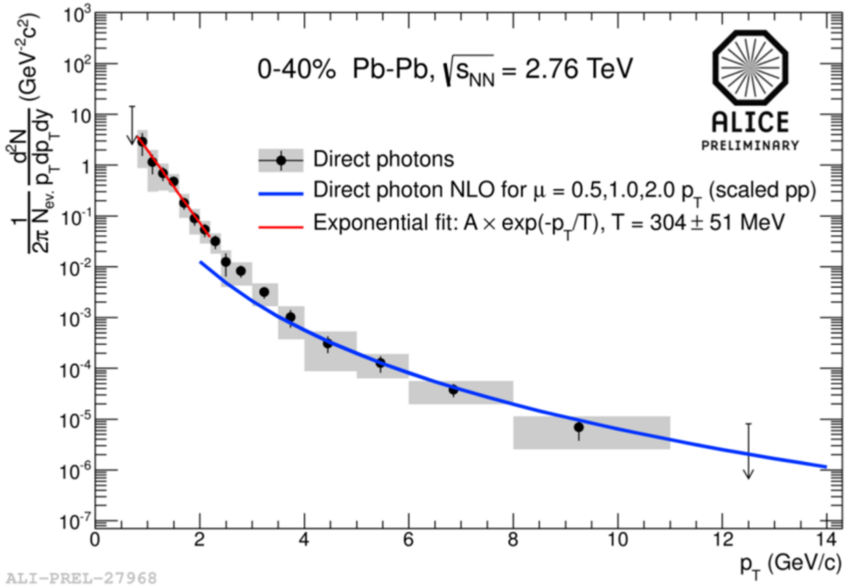


Phys. Lett. B 696 (2011) 328

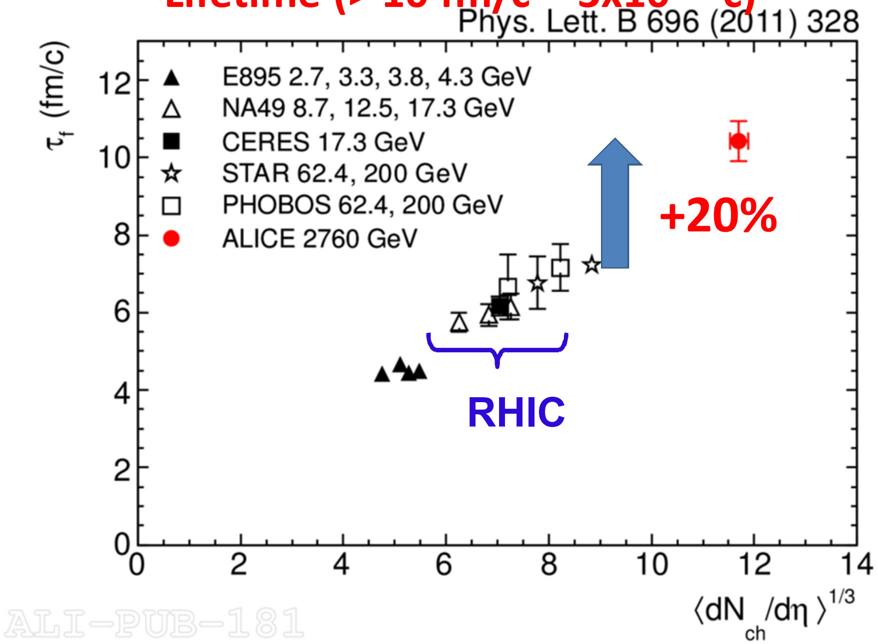
Volume ≈ 2 x RHIC (R³ ≈ 300 fm³)



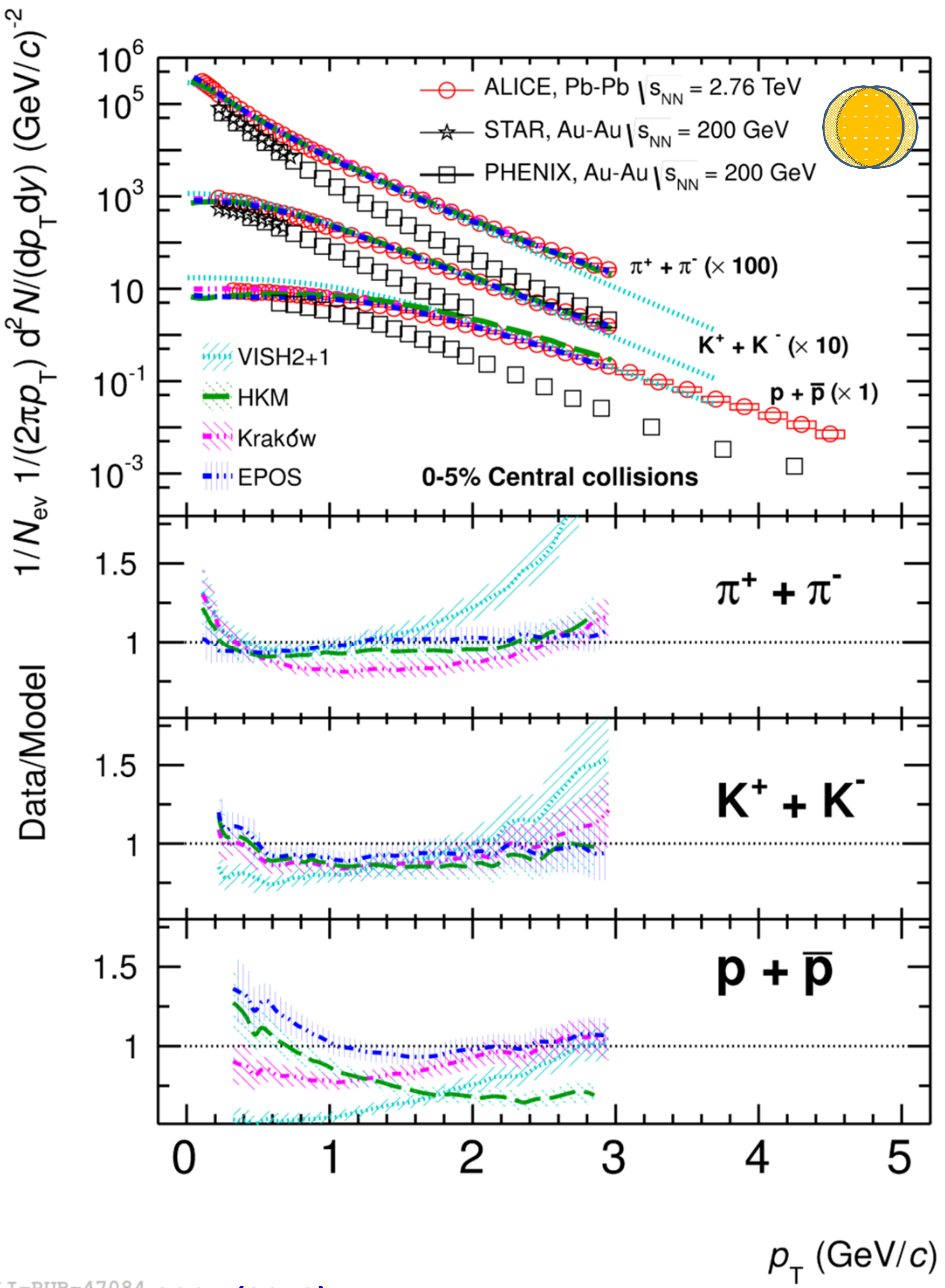
Photon T = 304±51 MeV ~ 1.4 x RHIC



Lifetime (> 10 fm/c ~ 3x10⁻²³ c)



Low p_T particle production



PRL 109, 252301 (2012)

- Low p_T particle spectra ($p_T < 3$-4 GeV/c) sensitive to bulk properties and collective radial flow
- Particle spectra harder than at RHIC
- Low-p_T identified particle spectra in central Pb-Pb collisions are well described by modern hydrodynamic models

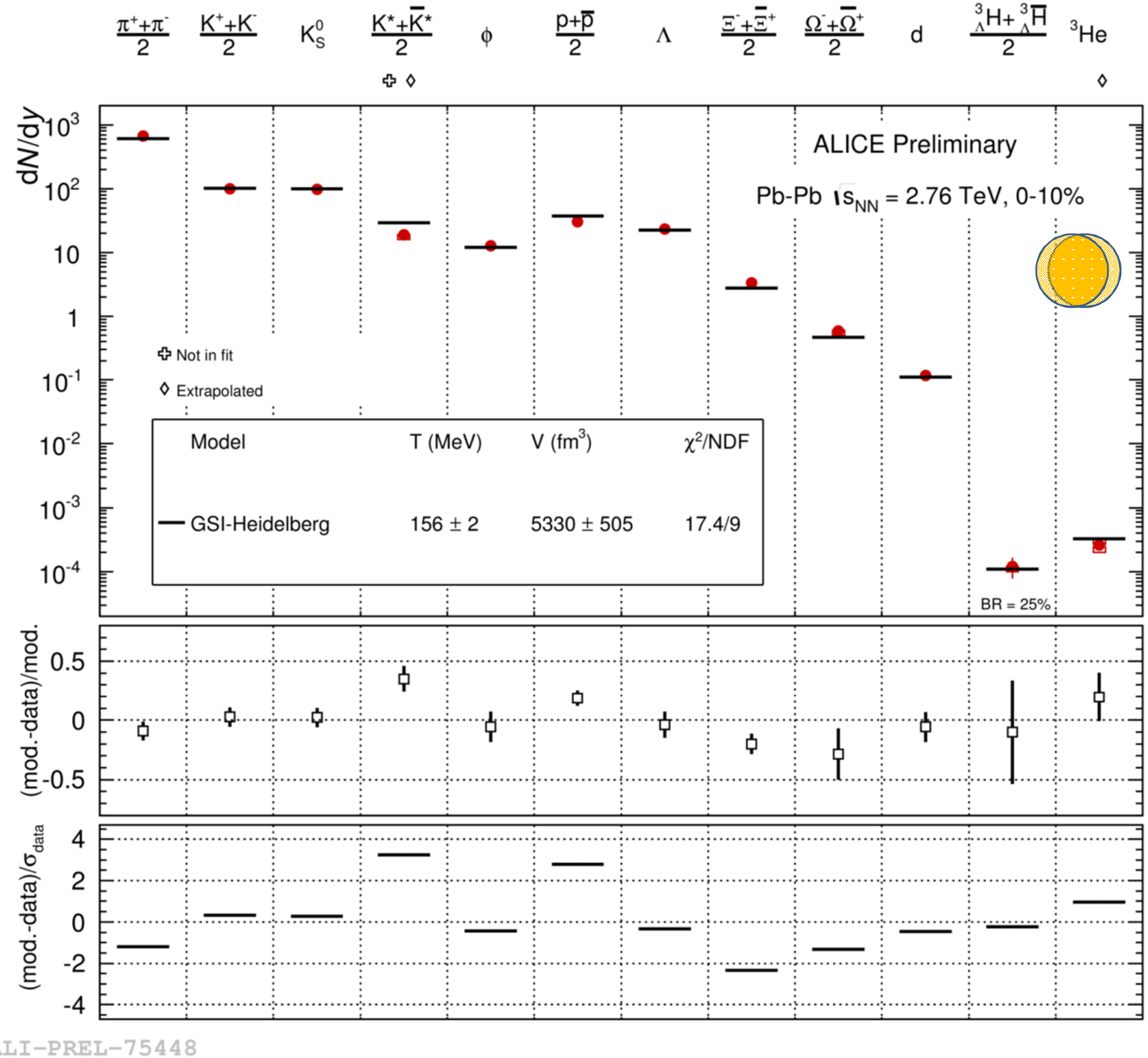
"Blast-Wave" fits to p_T spectra:

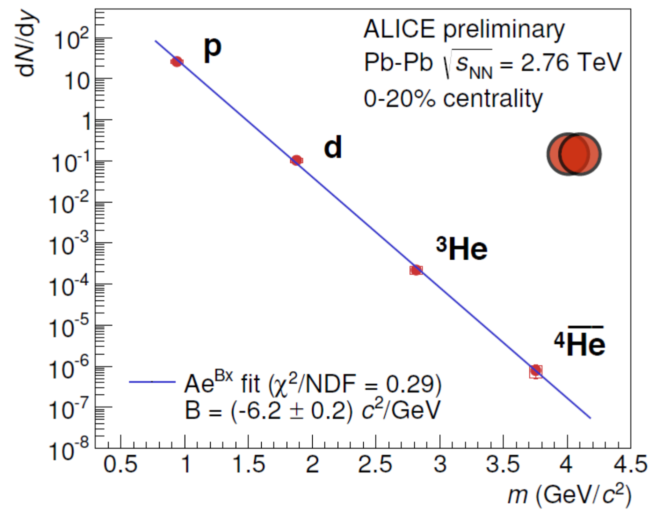
→ **Radial flow velocity <β> ≈ 0.65**
(10 % larger than at RHIC)

→**Kinetic freeze-out temp. T_K ≈ 95 MeV**
(same as RHIC within errors)

Particle yields vs thermal model

Thermal model: hadron yields as produced in **chemical equilibrium**, described with baryon chemical potential μ_B and freeze-out temperature T, A. Andronic et al. NPA772 (2006) 167



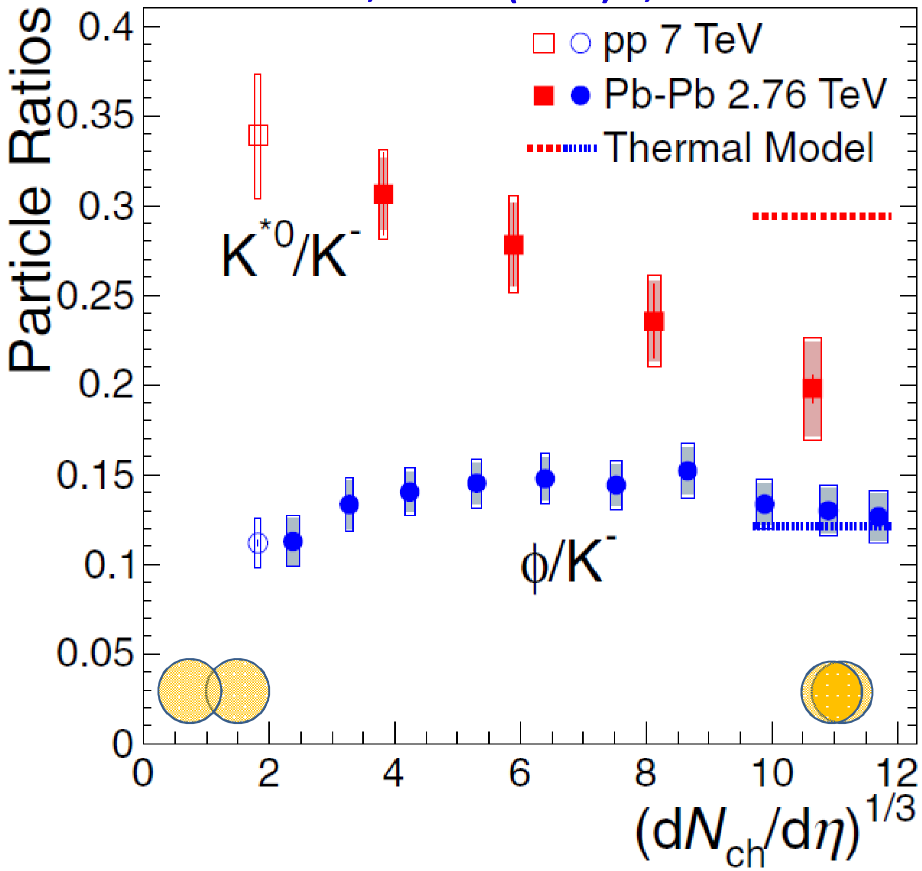


Yields in Pb-Pb well described with a **single temperature T_{ch}~156 MeV**

Deviations for K* and p
final-state interactions?

other mechanisms under investigation (flavour hierarchy, non-equilibrium etc)

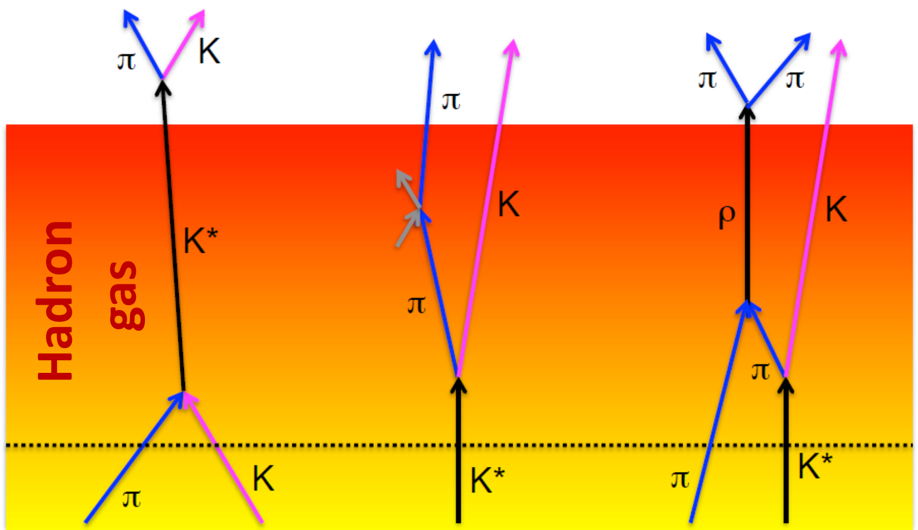
K* suppression



K*/K shows clear suppression going from pp and peripheral Pb-Pb collisions to central Pb-Pb

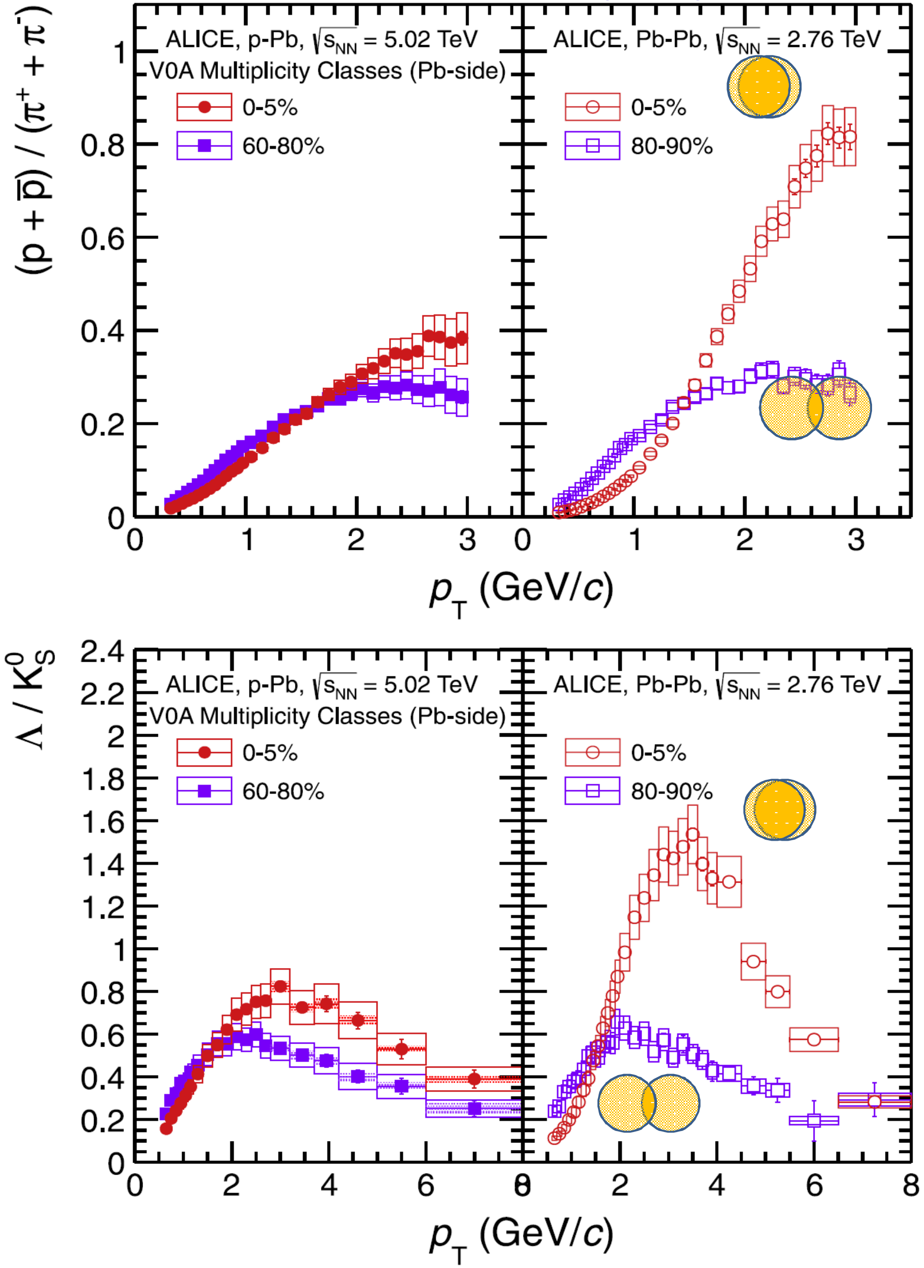
not observed in ϕ/K

Most favoured explanation:
rescattering of the decay daughters **with final-state** hadronic medium
τ_{K*} (~4 fm/c) ≪ τ_ϕ



Baryon enhancement

ALICE, PLB 728 (2014) 25



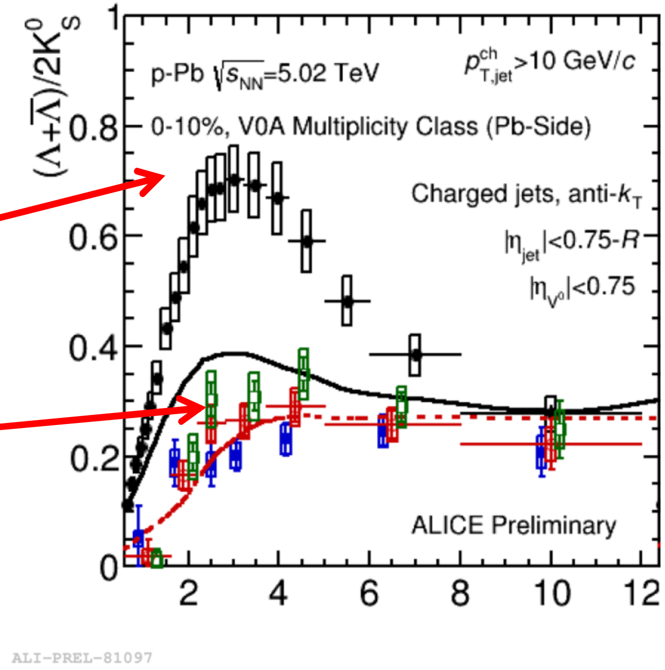
Strong centrality dependence in Pb-Pb:

- **p/π (Λ/K_s) ratio enhanced at mid p_T**
- depletion in the low-p_T region

Similar effects observed **in p-Pb**

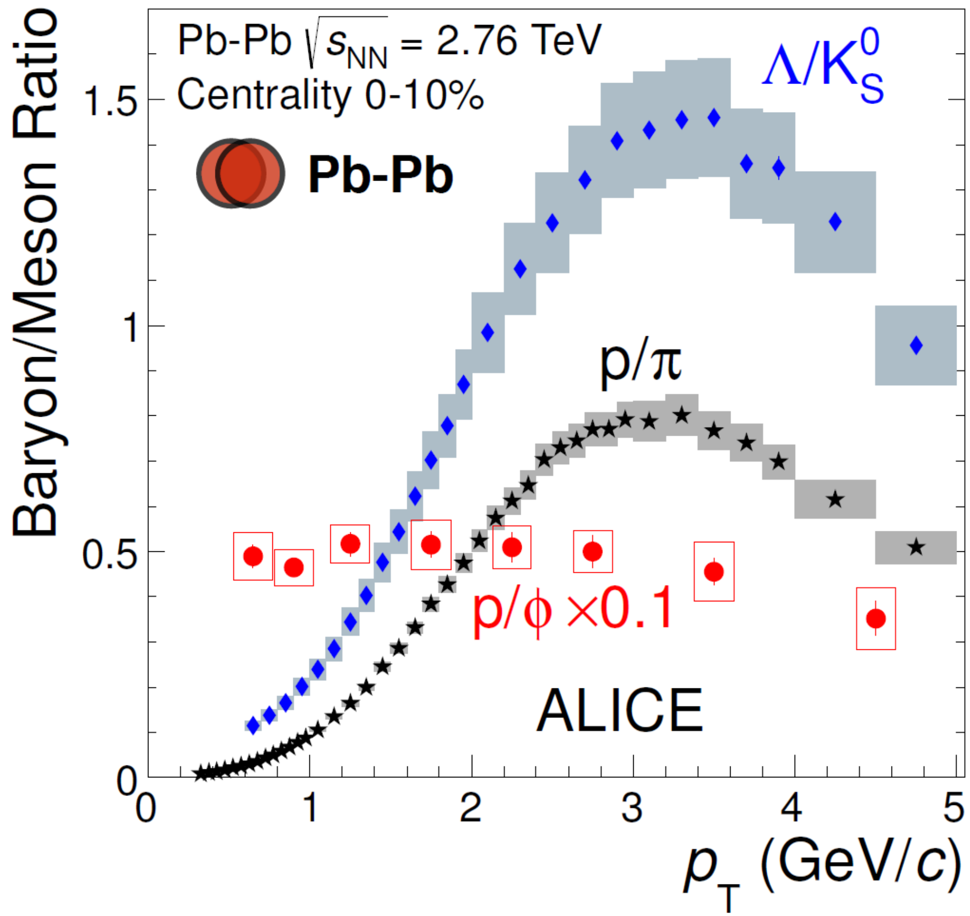
inclusive particles

no enhancement in jets



Baryon enhancement is a bulk effect,
attributed to p_T spectra modifications.
Radial flow?

p/ϕ ratio in Pb-Pb



Test baryon enhancement:

- p: 938 MeV/c^2 *qqq*
- ϕ: 1018 MeV/c^2 *qq*

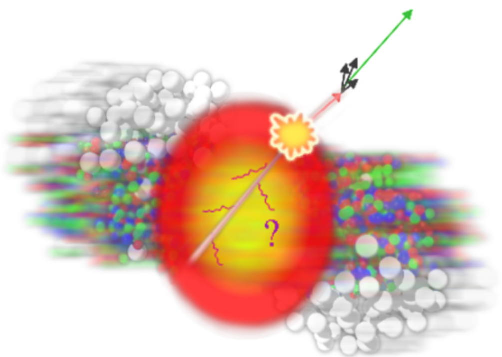
p/ϕ ratio is constant:

spectral shapes are **very similar if particles have similar mass**

the data seems to indicate that **mass is the main parameter driving particle spectra** (as foreseen by hydro)

In-medium energy loss

- Partons travel ~4 fm in the high colour-density medium created in central Pb-Pb collisions
- Energy loss mainly due to medium-induced gluon radiation



- Nuclear modification factor:

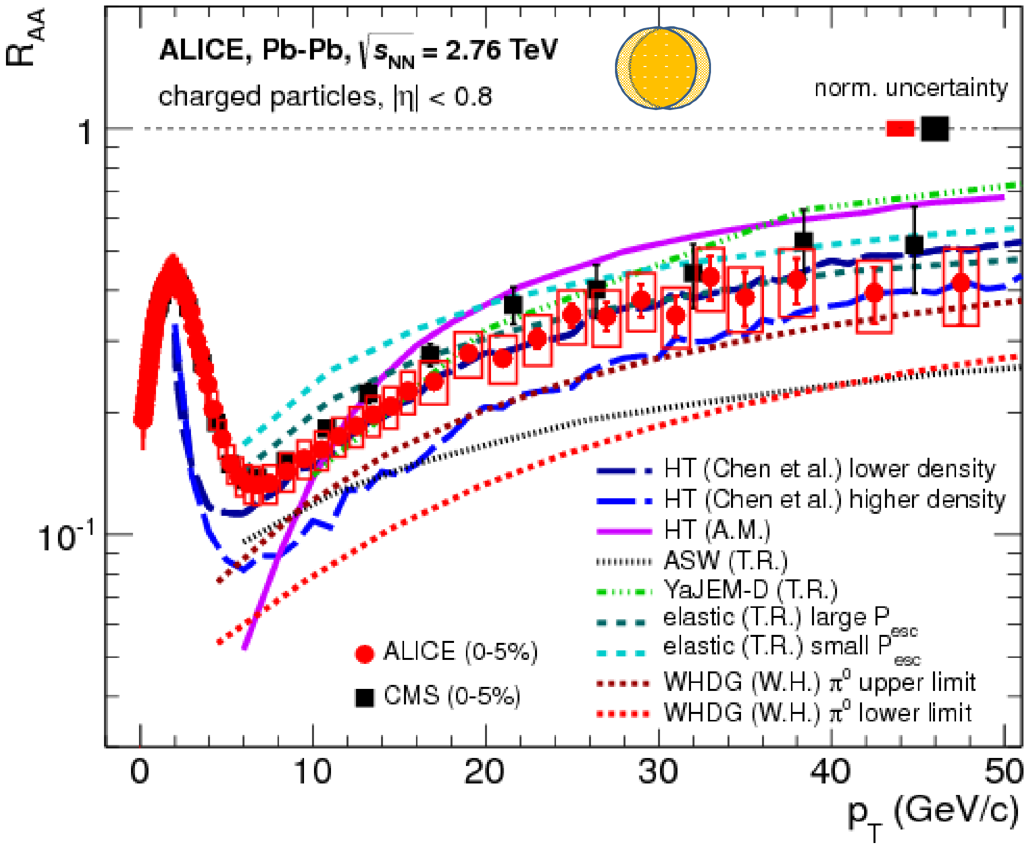
yield in Pb-Pb

$$R_{AA}(p_T) = \frac{(1/N_{evt}^{AA})\, d^2N_{ch}^{AA}/d\eta\, dp_T}{\langle N_{coll}\rangle (1/N_{evt}^{pp})\, d^2N_{ch}^{pp}/d\eta\, dp_T}$$

yield in pp

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

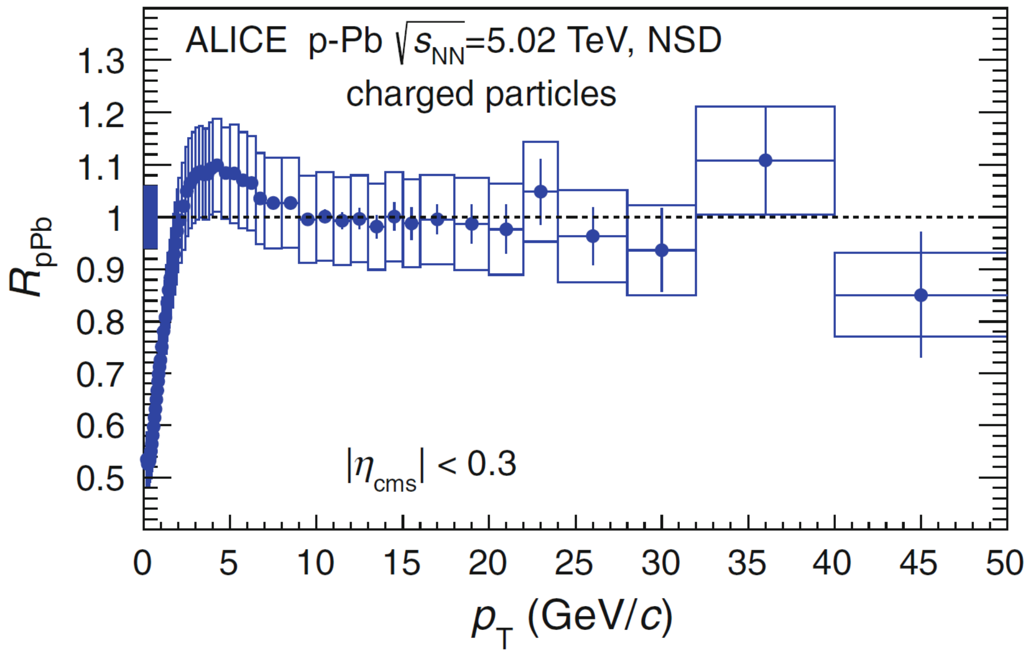
ALICE, PLB 720 (2013) 52

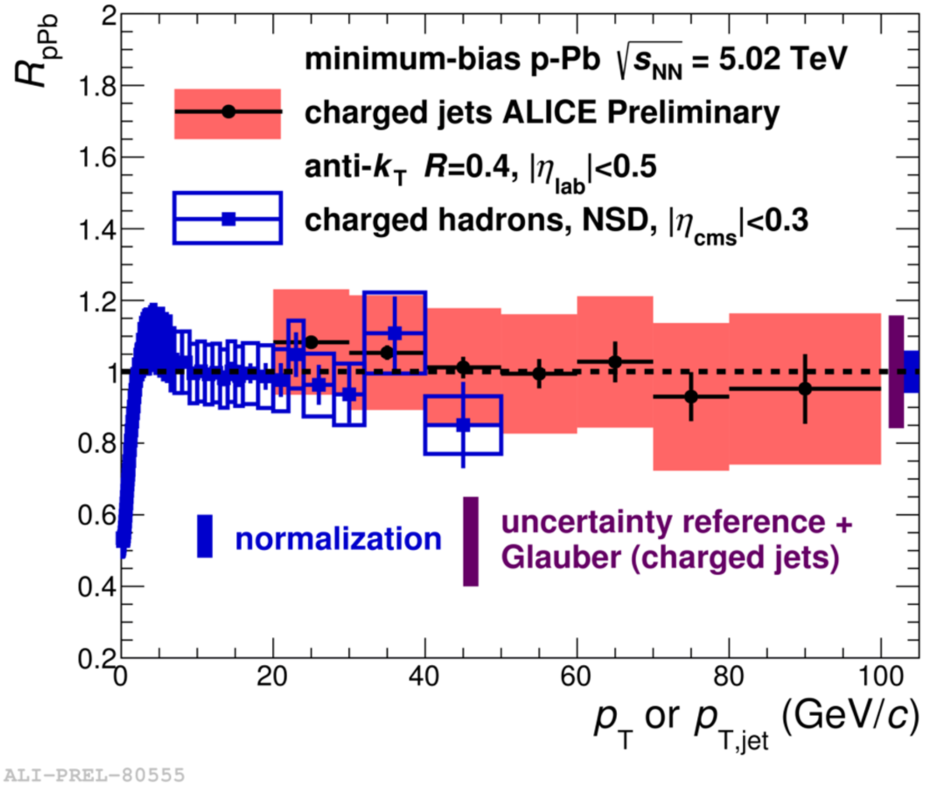


- suppression stronger than at RHIC
- strongest for p_T ~6-7 GeV/c
- Essential constraint for parton energy loss models

No modification in p-Pb

ALICE, EPJ C74 (2014) 3054

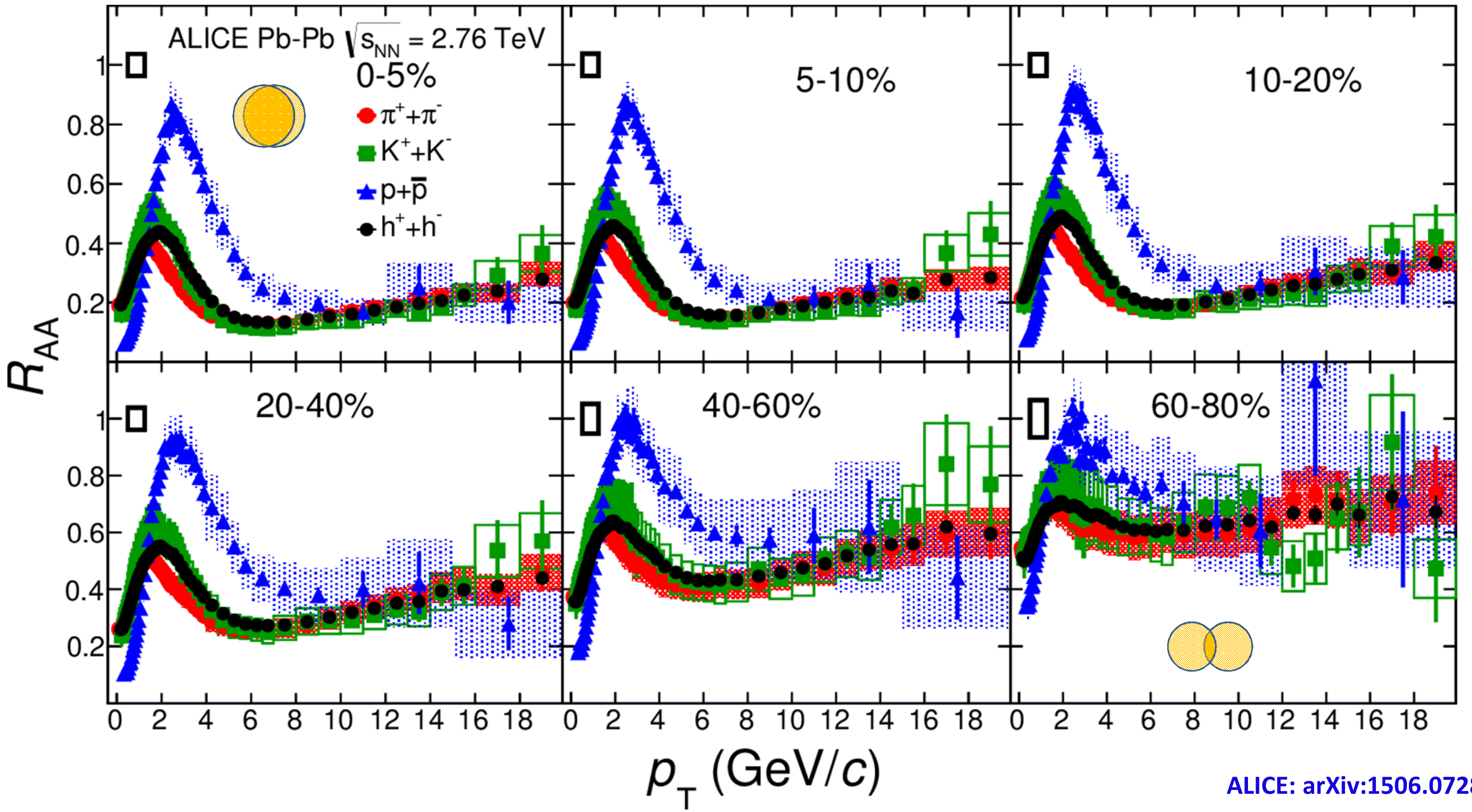




ALICE results on charged particle R_{pPb} and charged jet R_{pPb} consistent with no modification

Strong suppression in Pb-Pb is a final-state effect due parton in-medium energy loss

Suppression of light flavour



ALICE: arXiv:1506.07287

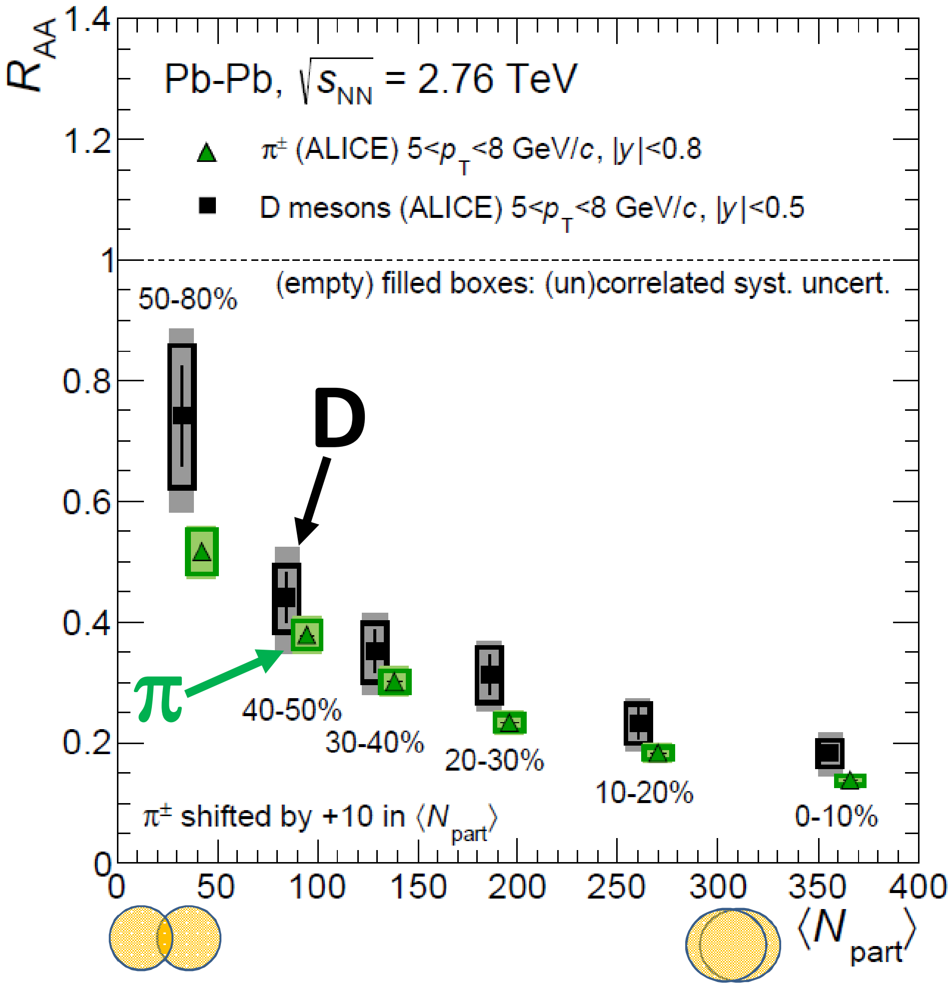
p_T < 8 GeV/c: R_{AA} for π and K compatible and smaller than R_{AA} for p.

p_T >10 GeV/c: R_{AA} for π, K and p are compatible

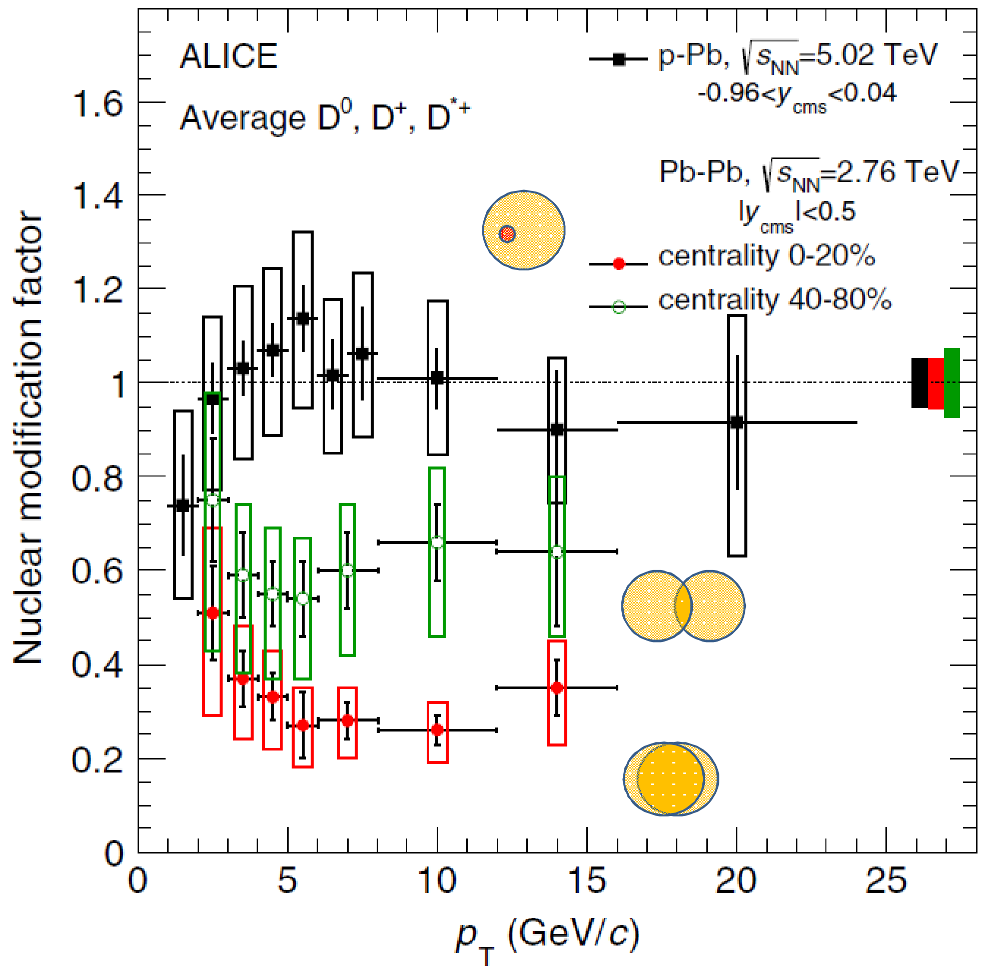
No modification of jet chemistry

D nuclear modification factor

ALICE: arXiv:1506.06604



ALICE, PRL 113 (2014) 232301



- **Strong suppression of prompt D** mesons in central collisions compatible with suppression of charged hadrons at high p_T.
- D meson $\mathbf{R_{pPb}}$ **consistent with no modification** in cold nuclear matter

J/ψ suppression in Pb-Pb

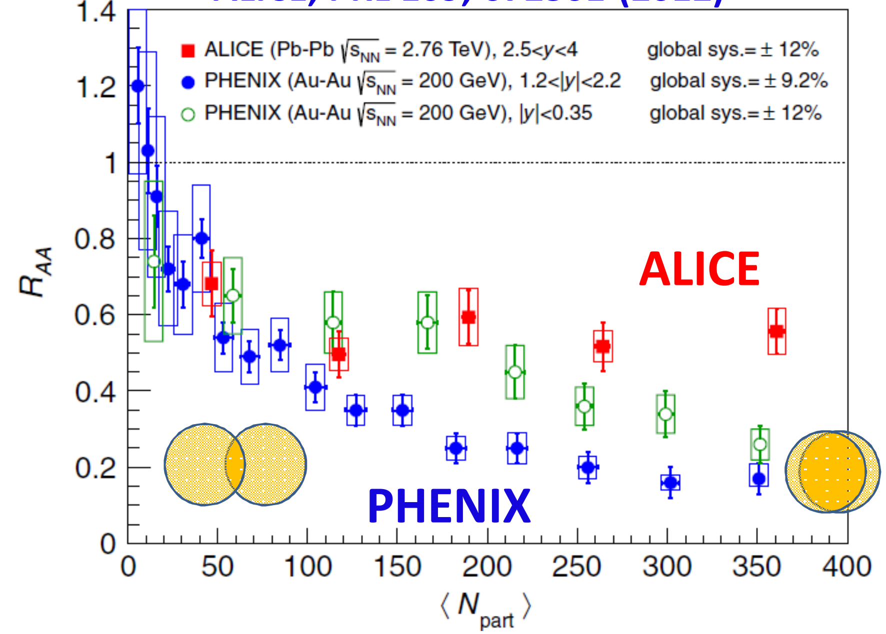
Two competing processes:

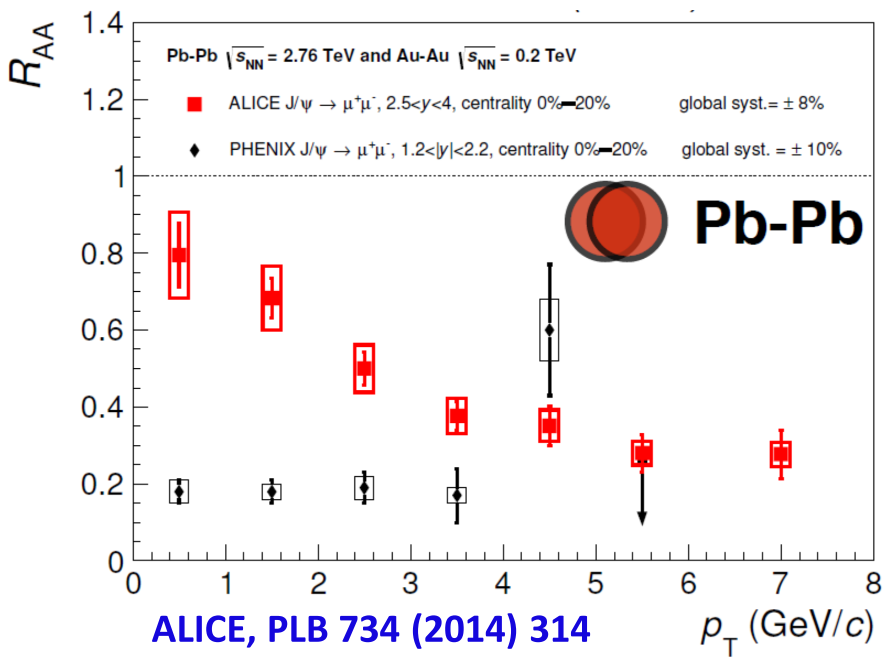
- **Melting** of quarkonium states in QGP
- **Regeneration** (~60 c-cbar pairs per central event @ 2.76 TeV)

Strong **evidence of regeneration** processes:

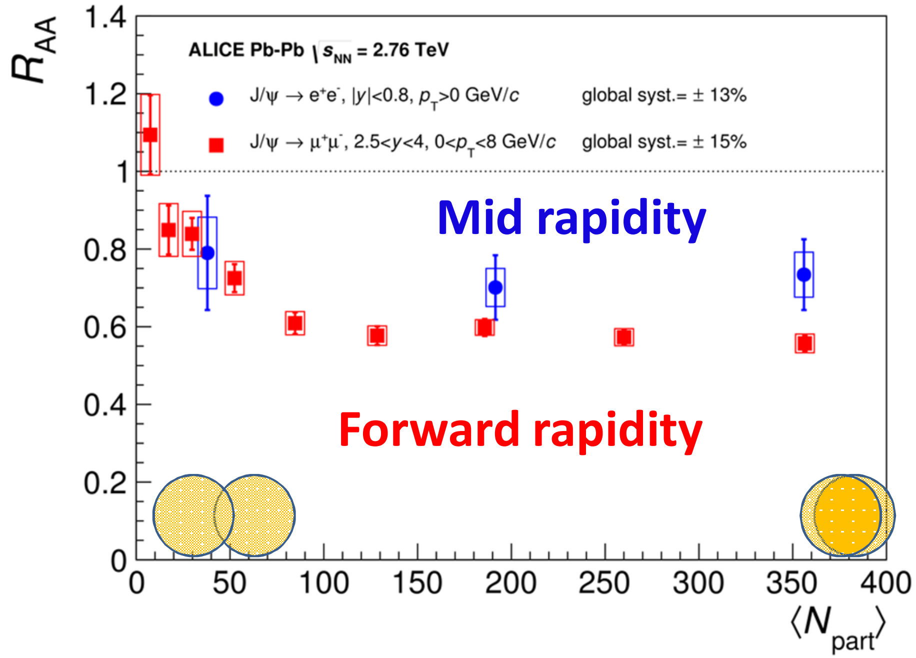
- Suppression smaller than at RHIC
- Suppression smaller at midrapidity
- Suppression smaller at low p_T

ALICE, PRL 109, 072301 (2012)





ALICE, PLB 734 (2014) 314



J/ψ suppression in p-Pb

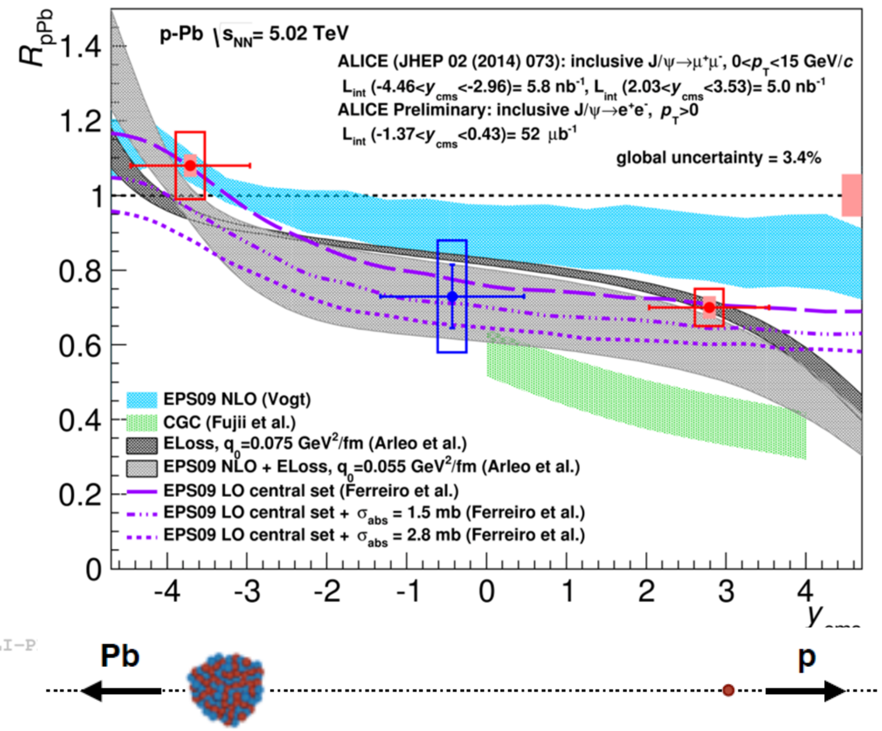
ALICE

R_{pPb} decreases towards p-going direction (lower Bjorken x in Pb) **in agreement with shadowing models**

CNM effects estimated with R_{pPb} x R_{Pbp} assuming:

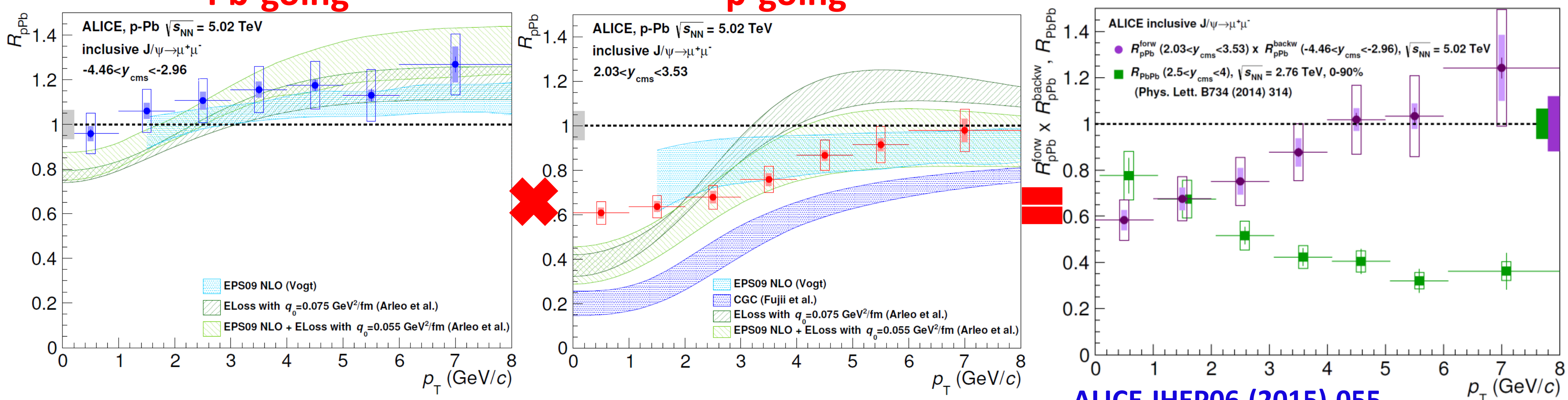
- Factorization of shadowing effects
- 2->1 kinematics for J/ψ production

CNM not enough to explain suppression at high-p_T
→ Evidence for **hot nuclear matter effects in Pb-Pb**



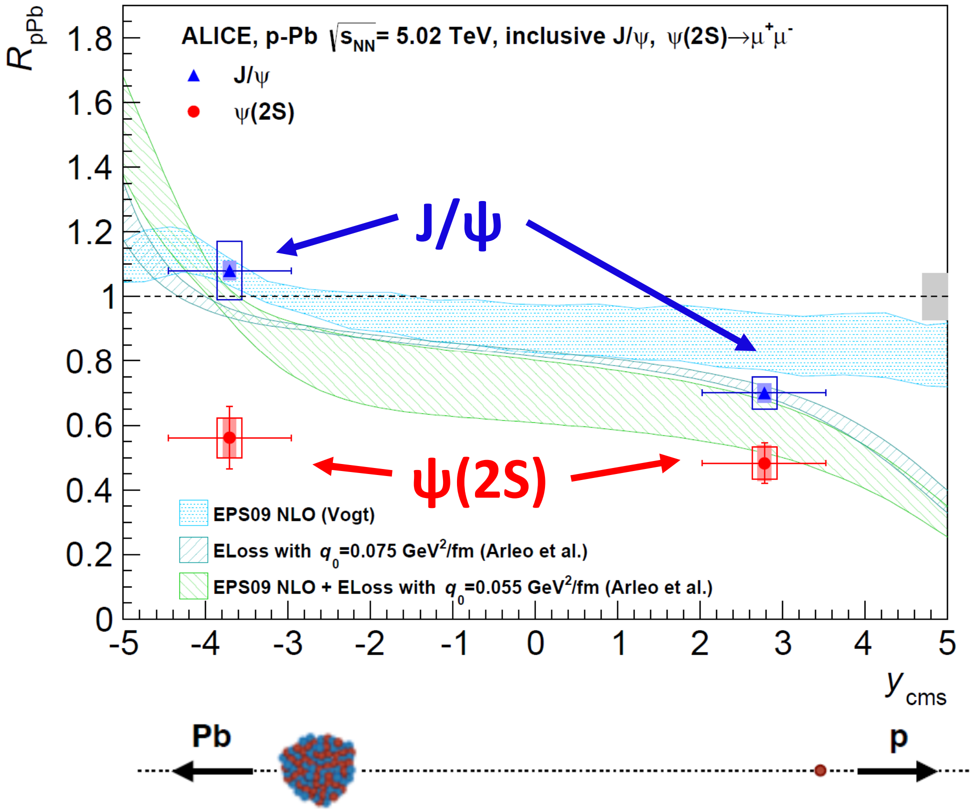
Pb-going

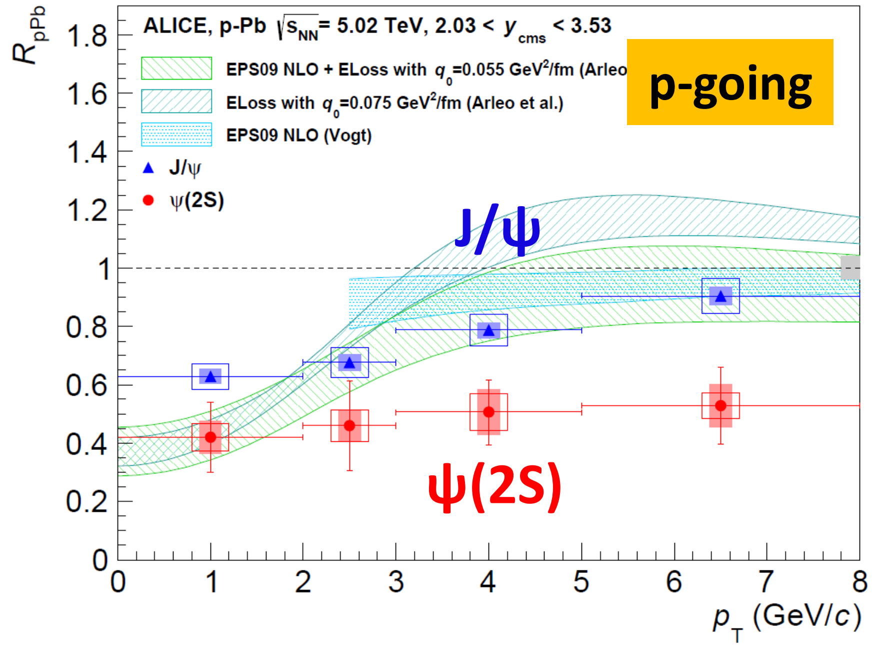
p-going

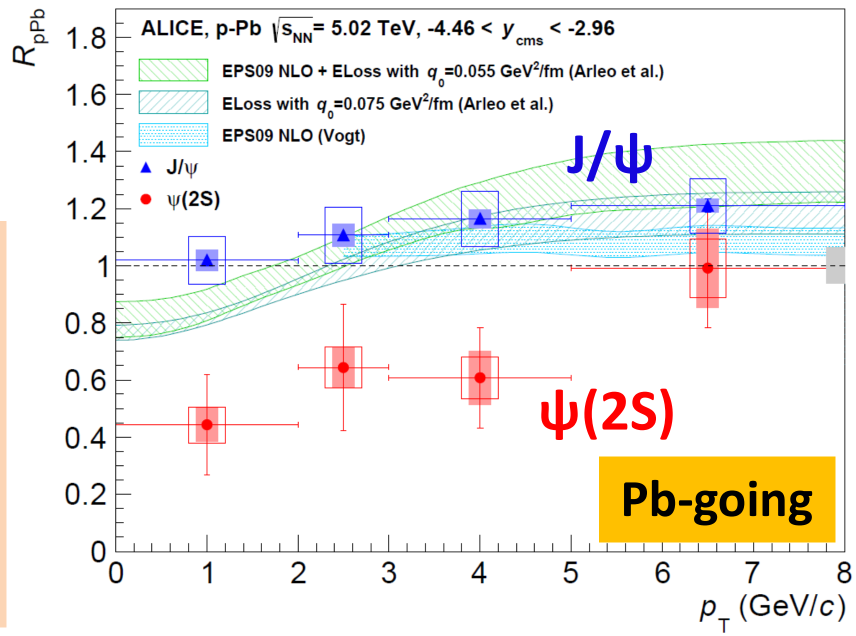


ALICE JHEP06 (2015) 055

ψ(2S) suppression in p-Pb





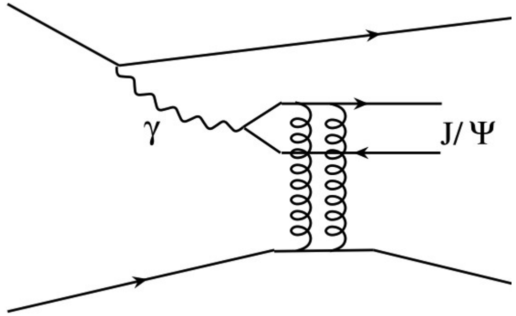


- Strong ψ(2S) suppression wrt J/ψ cannot be explained by initial state effects
  → **Clear indication for final state effects**
- **Difficult to explain with *cc* pair break-up** by interaction in CNM (short crossing time)

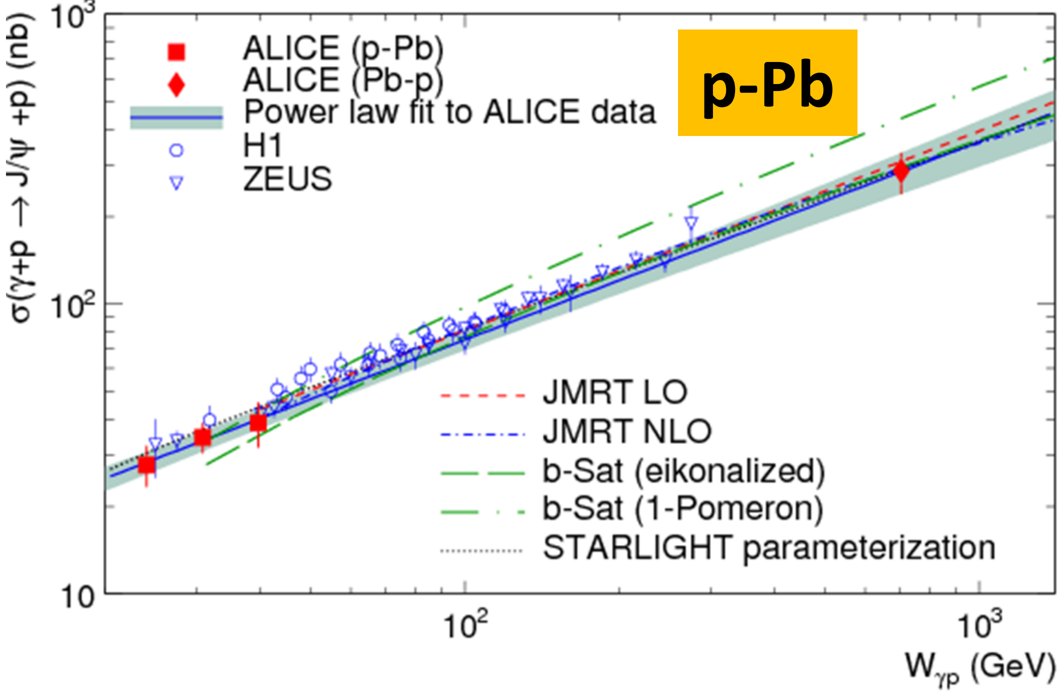
ALICE, JHEP 12 (2014) 073

J/ψ in ultraperipheral collisions

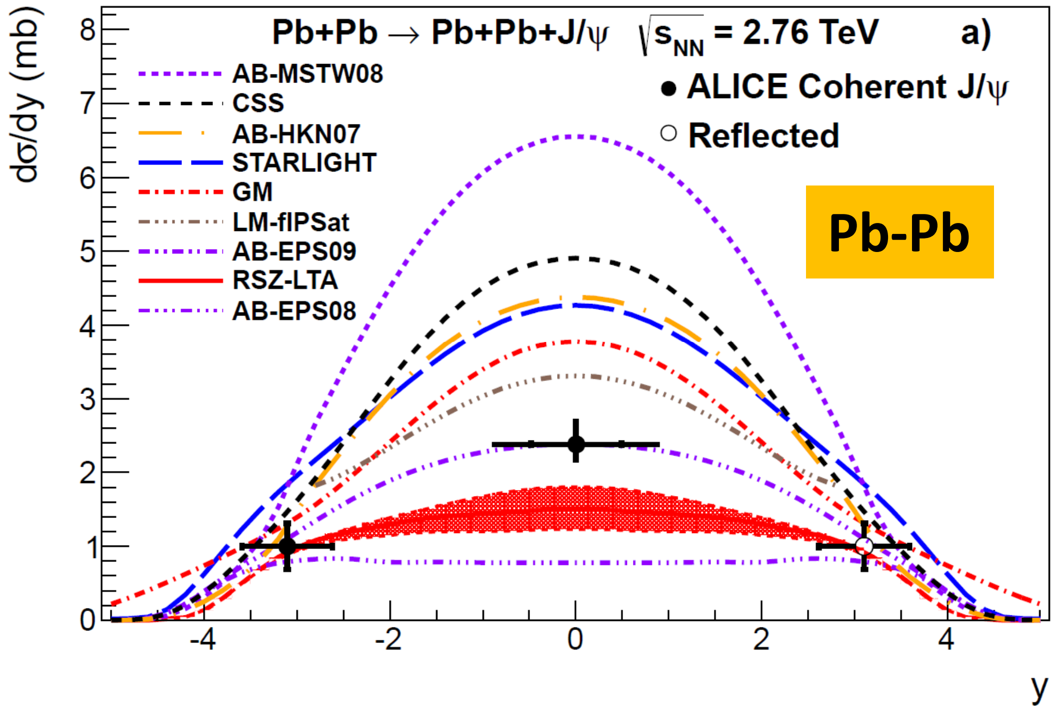
- Ultraperipheral collisions: $b > R_1+R_2$
  - →Hadronic interactions strongly suppressed
  - →Large flux of quasi-real photons from Pb nuclei
- pQCD LO: coherent **J/ψ cross section ~ (gluon density)^2**



ALICE, PRL 113, 232504 (2014)



ALICE, PLB718 (2013) 1273, EPJ C 73 (2013) 261

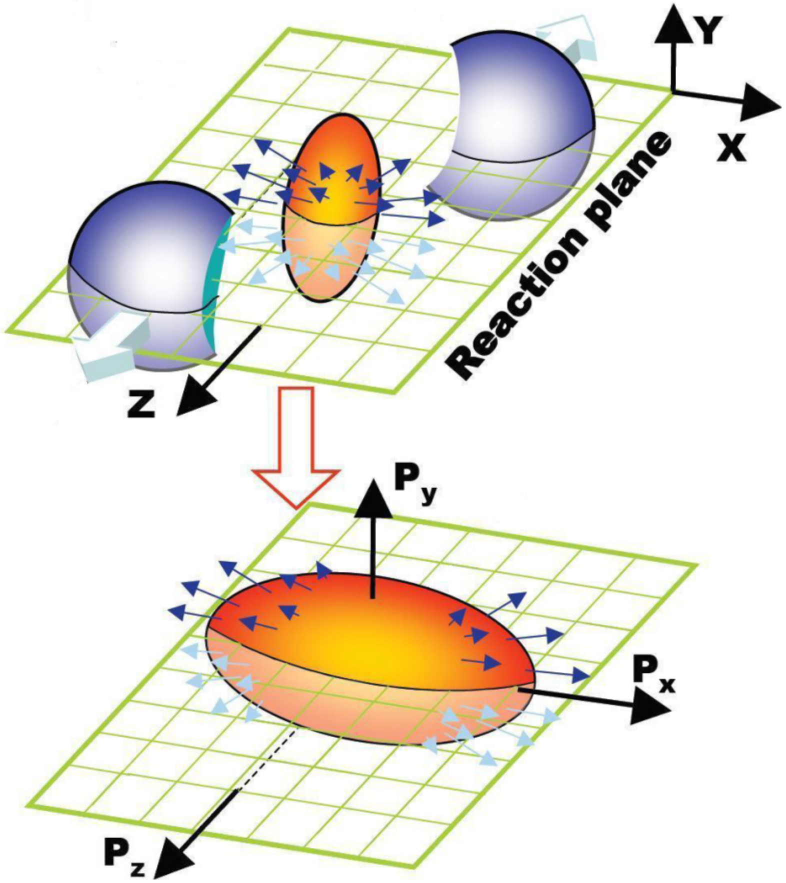


No significant change in the gluon density behaviour between HERA and LHC energies

Best agreement with EPS09 shadowing (shadowing factor ~0.6 at x ~ 10^{-3})

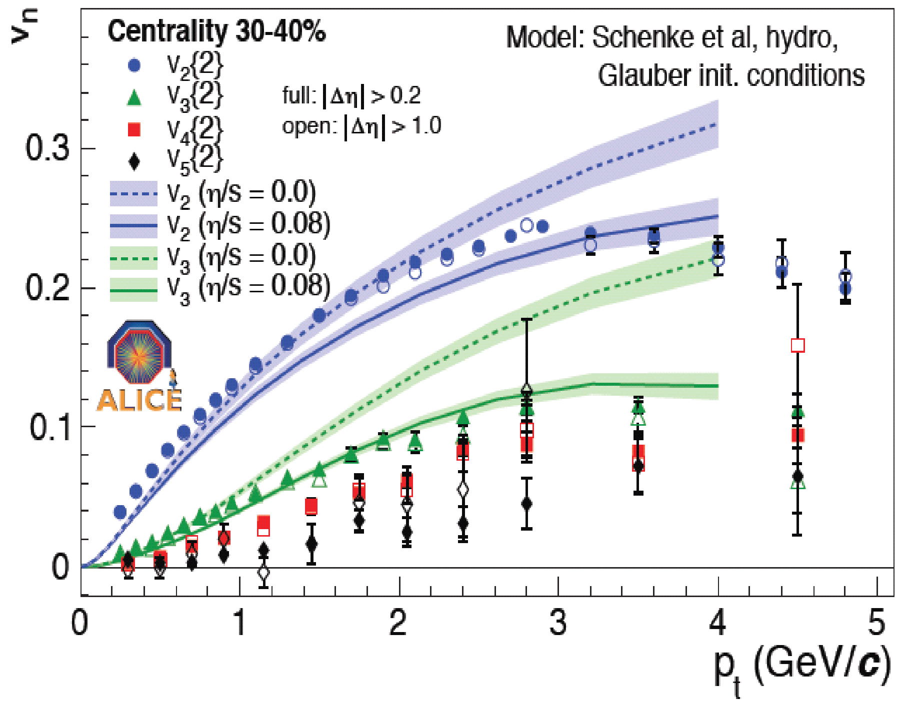
Anisotropic flow

Spatial asymmetry transforms into momentum space:



$$\frac{dN}{d(\varphi_i - \Psi_n)} \sim 1 + 2\sum_{n=1} v_n \cos[n(\varphi_i - \Psi_n)]$$

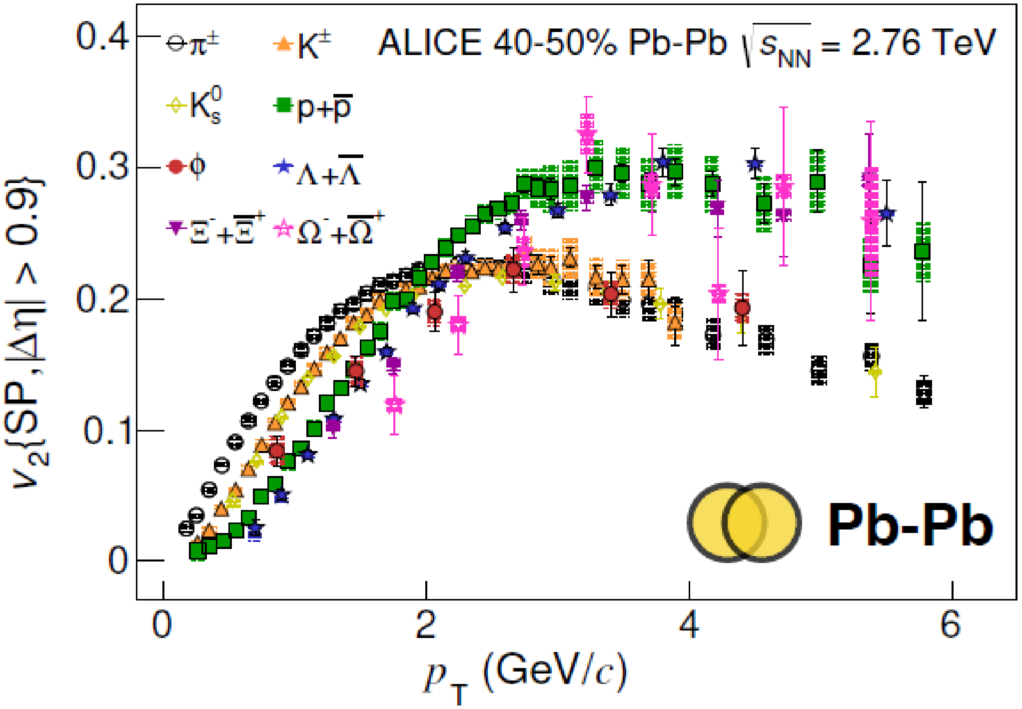
ALICE, PRL 107, 032301 (2011)

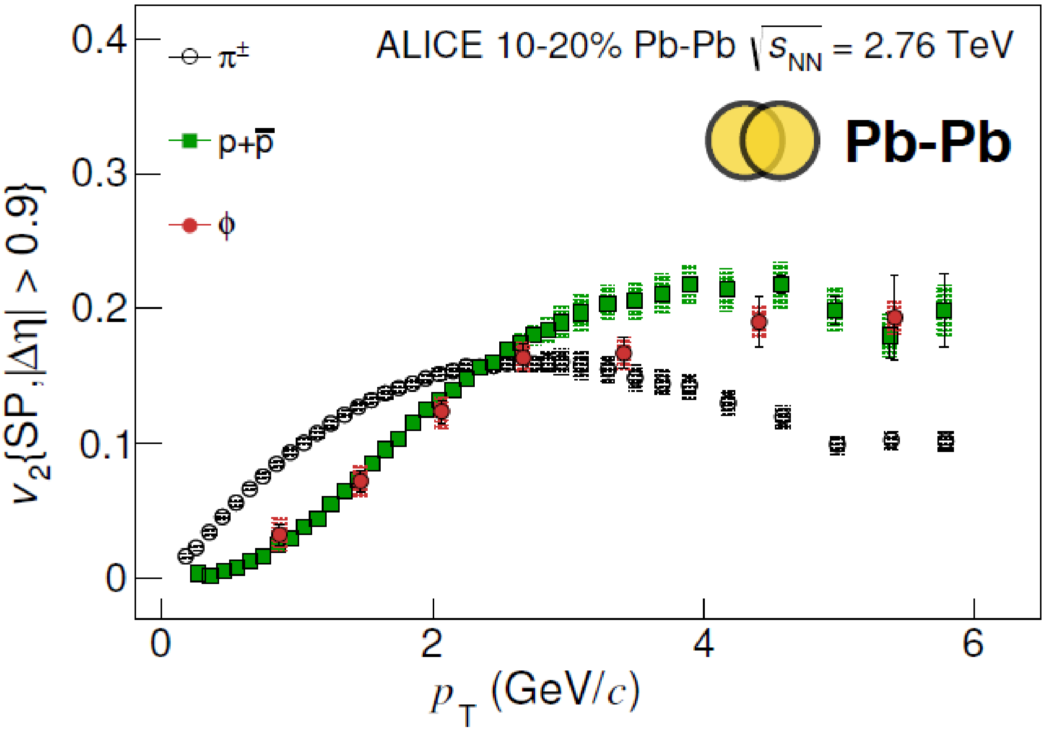


- Large elliptic flow (v_2) observed at RHIC confirmed at LHC
- v_2 vs p_T well described by hydrodynamics of strongly coupled medium with low shear viscosity
- η/s close to quantum lower limit $1/4\pi$ (AdS/CFT bound)

Identified particle v_2

v_2 measured for $\pi^{\pm}$, $K^{\pm}$, K^0_S, p, ϕ, Λ, Ξ, Ω





ALICE, arXiv:1405.4632

- **Mass ordering at low p_T** driven by radial flow
- ϕ v_2 at low p_T follows proton v_2
- Overall qualitative **agreement with viscous hydrodynamics**

Initial state fluctuations with odd moments

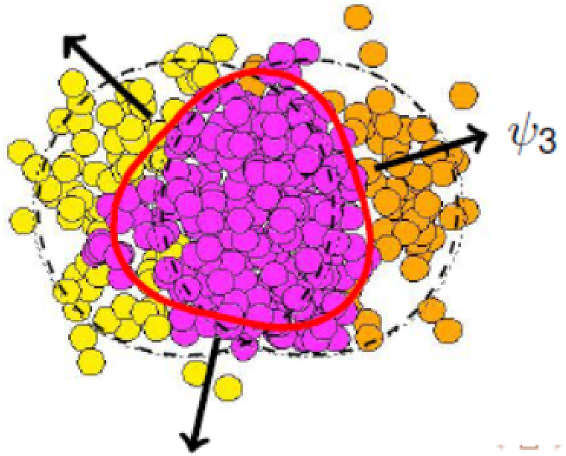
- Ideal case: symmetric shape, odd moments (v_3, v_5 …) should be 0
- Initial state fluctuations result in nonzero odd moments

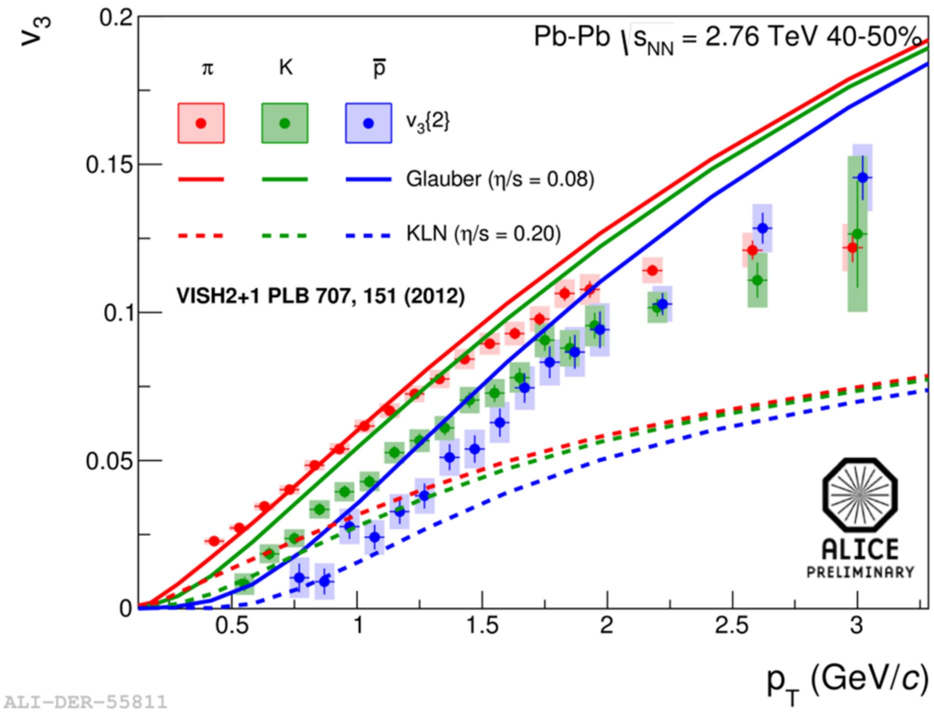
Triangular flow (v_3):

- show mass ordering similar to v_2
- sensitive to initial state conditions
- sensitive to viscosity-to-entropy ratio

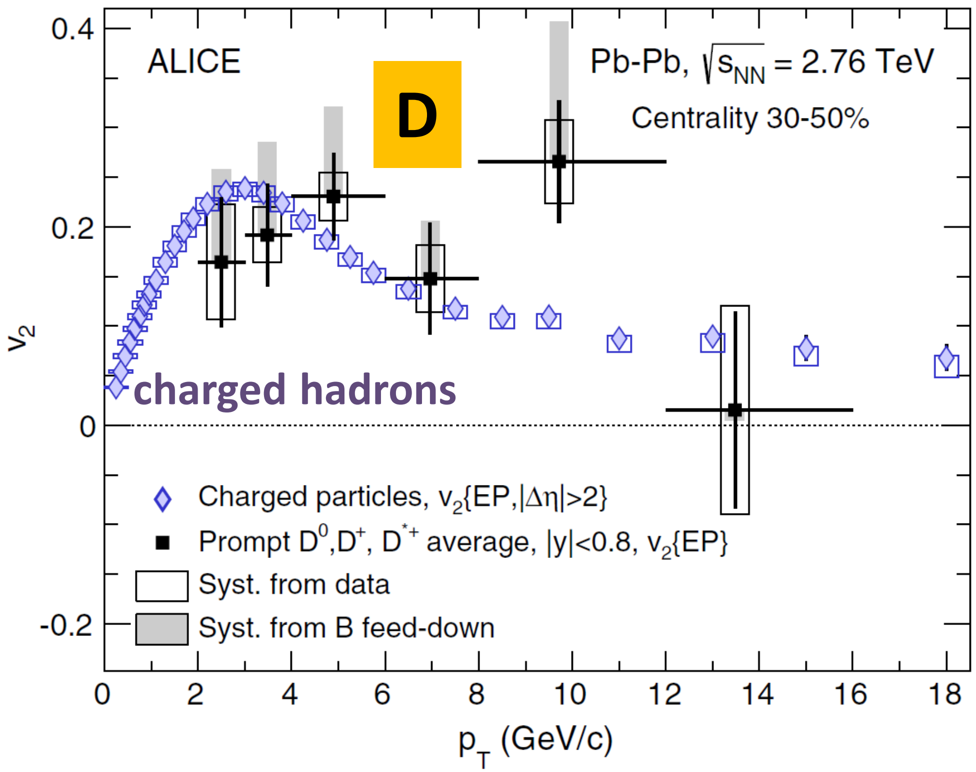
Odd moments provide promising tools to constrain the models. Example:

- VISH2+1 model with CGC initial conditions and η/s = 0.20 (tuned to reproduce identified particle v_2) underestimates triangular flow

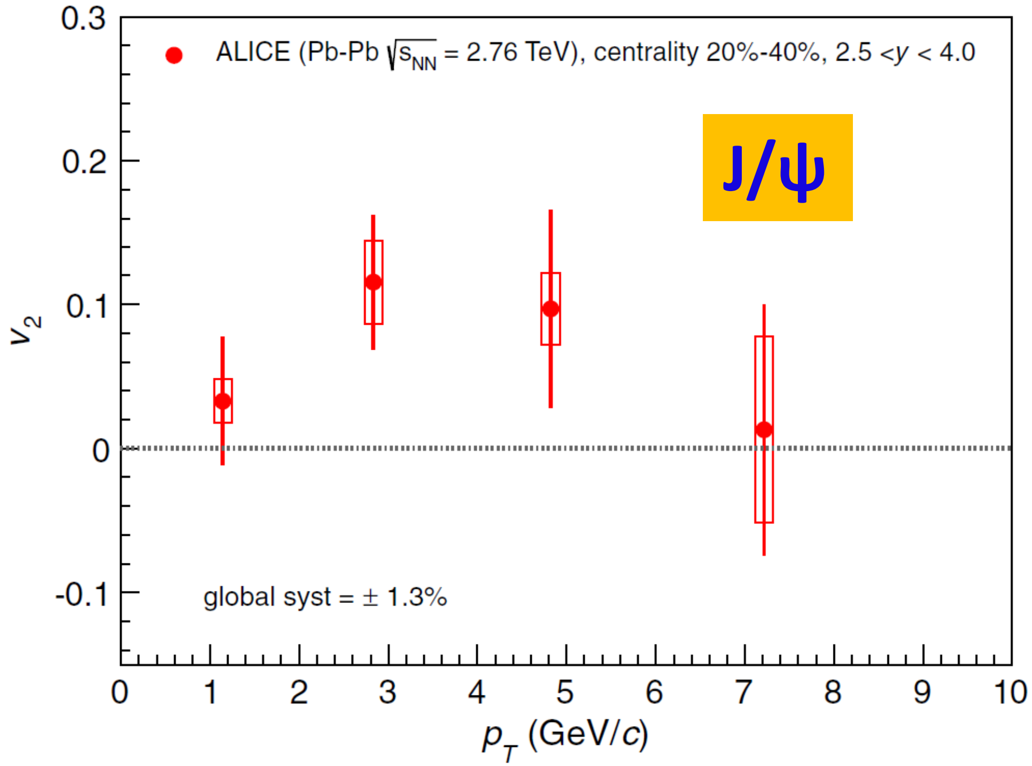




Charm flow?



ALICE, PRL 111 (2013) 102301



ALICE, PRL 111 (2013) 162301

Non-zero D-meson elliptic flow:

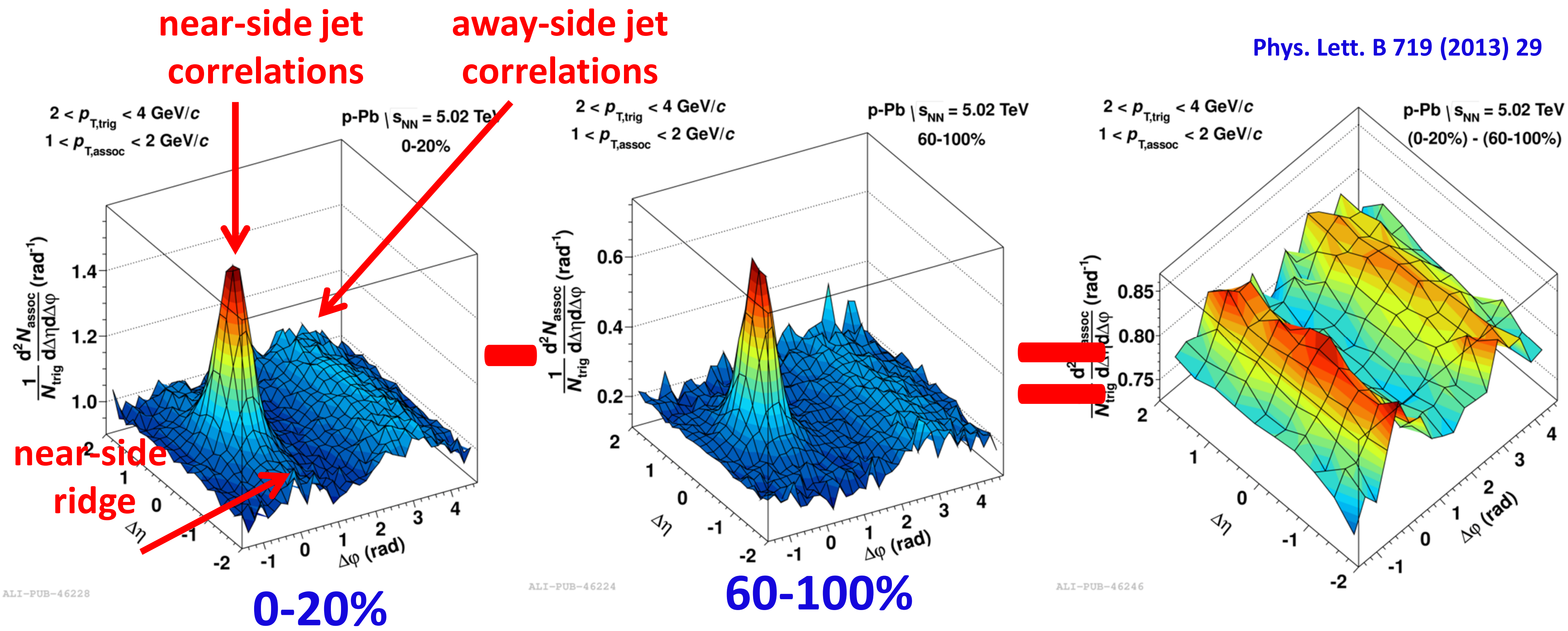
- consistent among D-meson species
- comparable to v_2 of light hadrons
- Thermalization of heavy quarks?

Hint for **non-zero J/ψ v_2**

- not observed at RHIC
- Significance up to 3.5 σ
- **Qualitative agreement with** transport models including **regeneration**

Discovery of double ridge in p-Pb

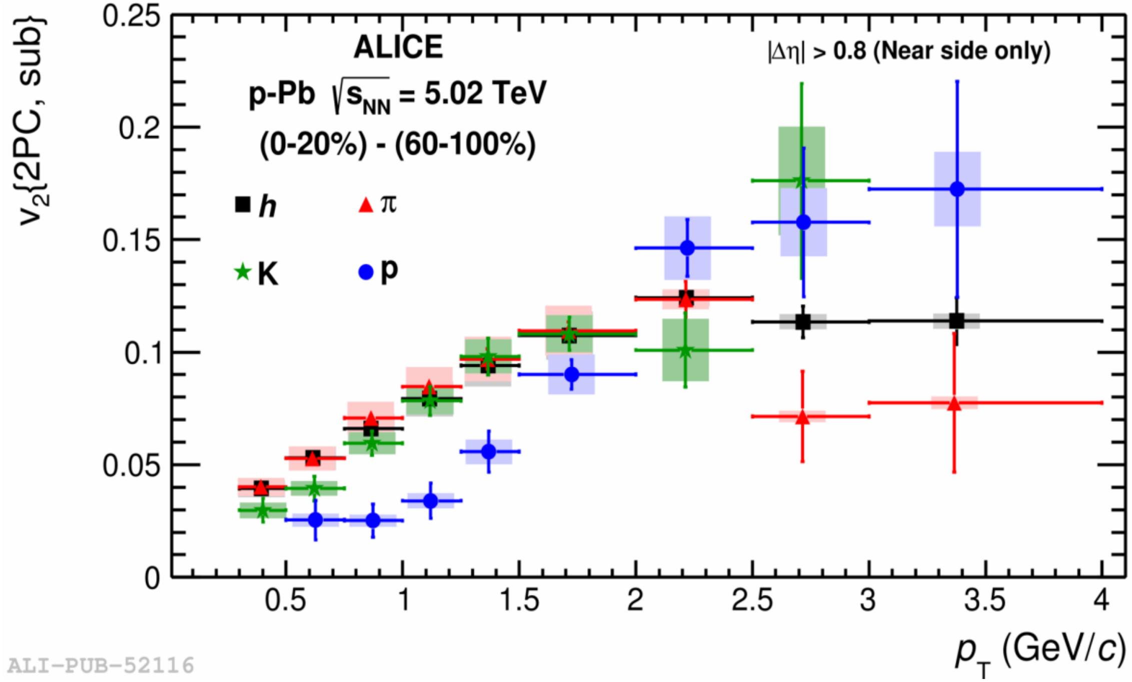
- Near-side ridge first observed by CMS in p-p and p-Pb collisions
- New method proposed by ALICE: subtract the jet contribution (per-trigger yields in low-multiplicity events) from the structure in high-multiplicity events

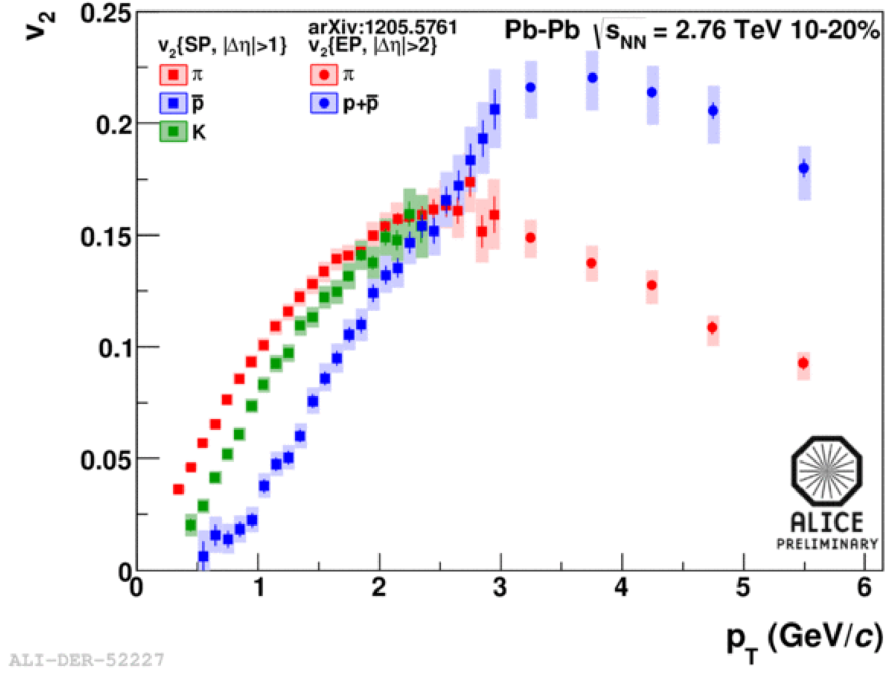


Double ridge resembles the structure attributed to collective flow in Pb-Pb

Collective flow in pA?

ALICE, PLB 726,164 (2013)





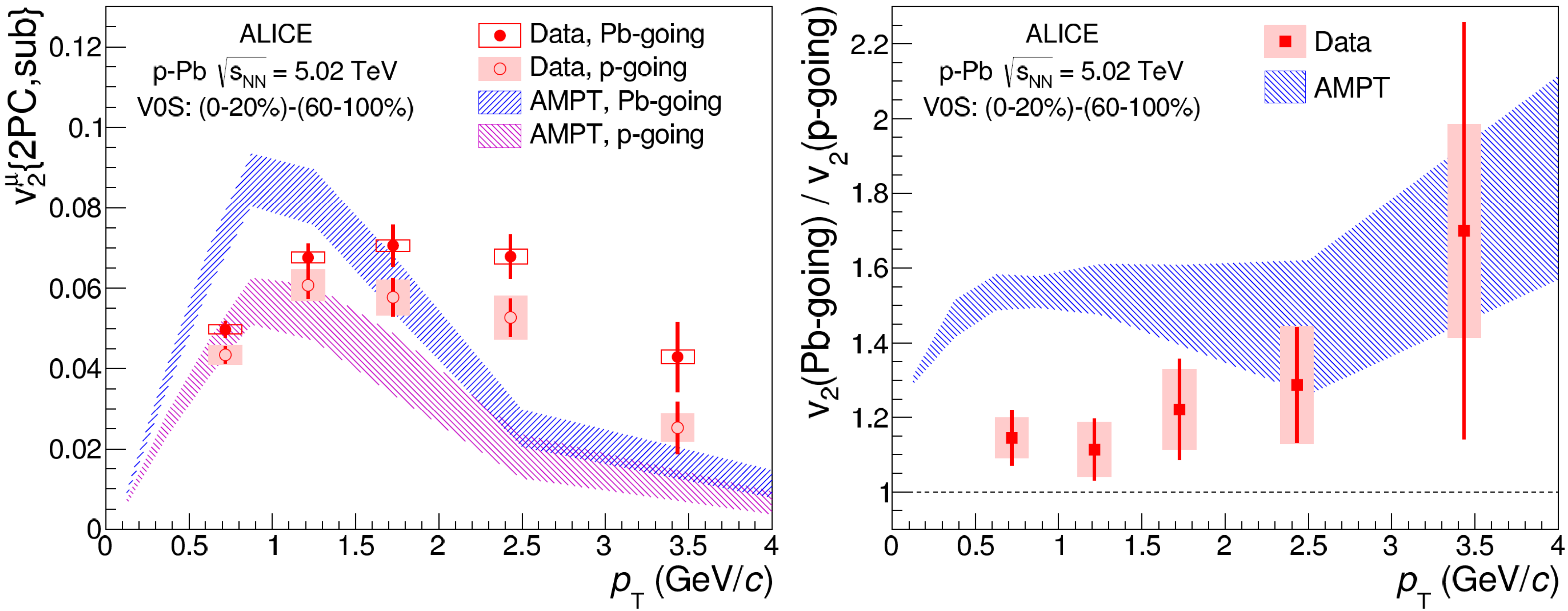
Clear indication for mass ordering in p-Pb
Resembles Pb-Pb and supports "flow" picture

Pb-Pb: mass ordering, interpreted in terms of collective radial and elliptic flow

- Models including hydrodynamical expansion can describe the observations
- Alternative interpretations:
  - CGC: many-gluon correlations, Dusling, Venugopalan, PRD 87 (2013) 094034
  - MPIs and "colour reconnections", e.g. Ortiz et al, PRL 111 (2013) 042001

Forward-central correlations in p-Pb

v_2 extracted from correlations of muons (2.5 < |η| < 4) and track(lets) in |η|<1

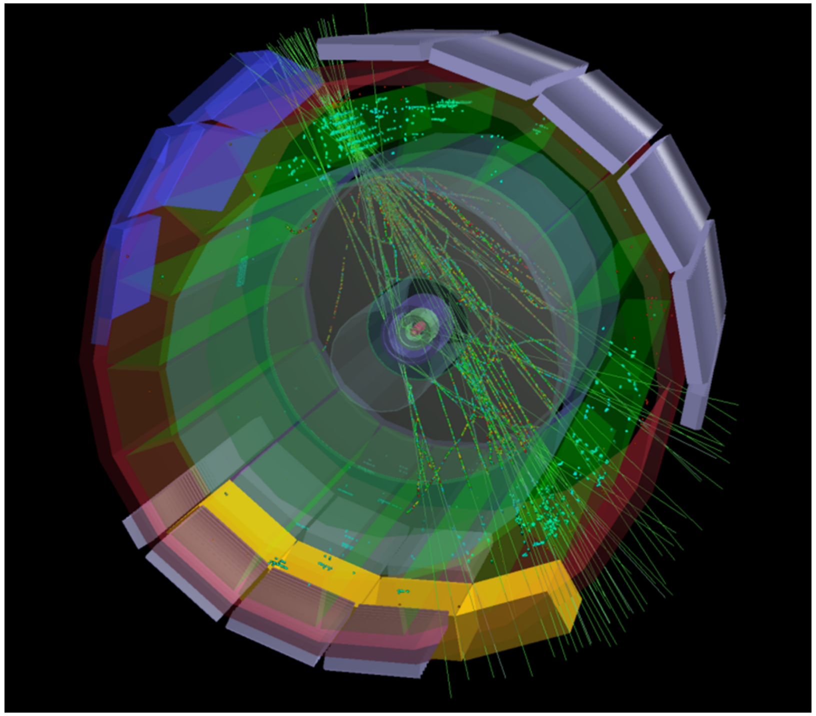


- **v_2(Pb-going) > v_2(p-going)** as qualitatively expected in hydro
- Quantitatively different p_T and η dependence in data compared to AMPT model
- Possible scenarios at p_T > 2 GeV/c (dominated by heavy flavour muons):
  - v_2 (heavy flavour) > 0
  - Different composition of the parent distribution and their v_2

ALICE, arxiv:1506.08032

Run 2 preparation and restart

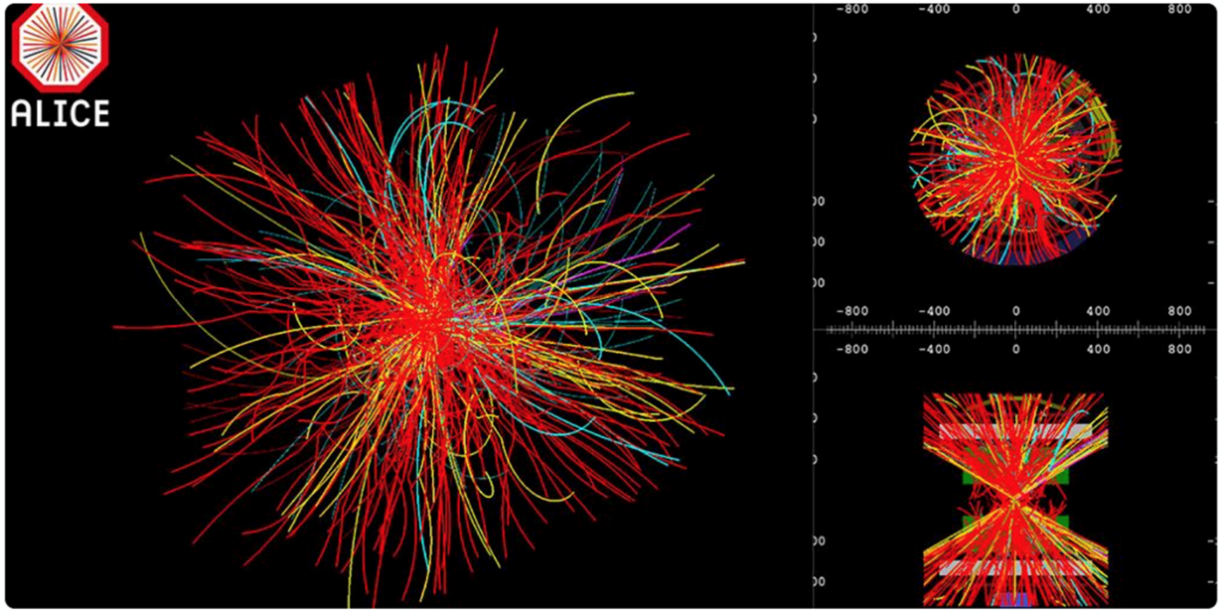
Commissioning with cosmics



Entering 13 TeV LHC Era

The Economist
@TheEconomist

Scientists at CERN announce a milestone turning knobs at the #LHC: this one goes to #13TeV econ.st/1dkYzqJ



6/7/15, 10:44 AM

149 RETWEETS | 136 FAVORITES

Conclusions

ALICE obtained a wealth of physics results from Run1 data:

- Hadron yields in Pb-Pb well described by thermal model. Deviations probably attributed to rescatterings after chemical freeze-out
- Baryon enhancement driven by mass-dependent radial flow
- Strong suppression at high-p_T is due parton in-medium energy loss, no jet chemistry modification observed
- Hints of heavy quark thermalization
- Signals of J/ψ regeneration
- Shadowing effects with photoproduced J/ψ
- Puzzle of ψ(2S) suppression in p-Pb
- Azimuthal flow: hydrodynamics at work, establish QGP as strongly interacting liquid
- Collective phenomena in p-Pb

Entering the precision measurement era:

- Successful commissioning and restart after long shutdown
- Looking forward for Pb-Pb collisions at 5 TeV in November 2015