A Large Ion Collider Experiment

Heavy-ion collisions and QGP physics at the LHC with ALICE

Boris HIPPOLYTE (University of Strasbourg - CERN) for the ALICE Collaboration

XXXIII[rd] Rencontres de Physique de la Vallée d'Aoste | La Thuile, Aosta Valley | Tuesday 12 March 2019

Strongly interacting matter in extreme conditions

- Trivial questions and misconceptions

What nuclear physicists think I do?

cosmology (or even archaeology)

What particle physicists think I do?

nuclear physics (or even pile-up study)

What astro-particle physicists think I do?

particle physics (or even yace*)

What my collaborators think I do?

writing a paper (or even a ya^{2}r**)

Acronyms:
* Yet Another Collider Experiment
** Yet Another Administrative Report

Strongly interacting matter in extreme conditions

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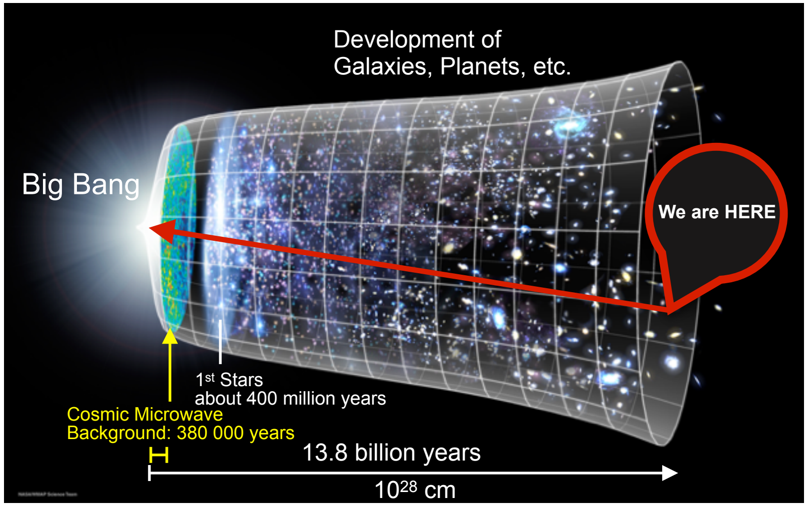
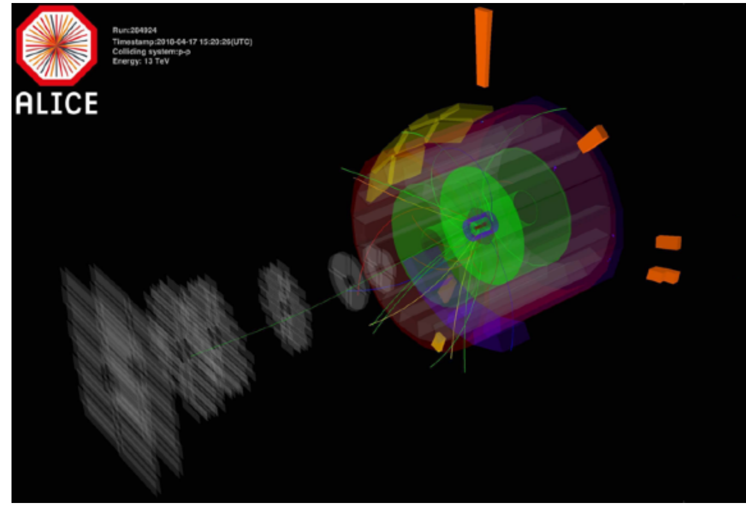
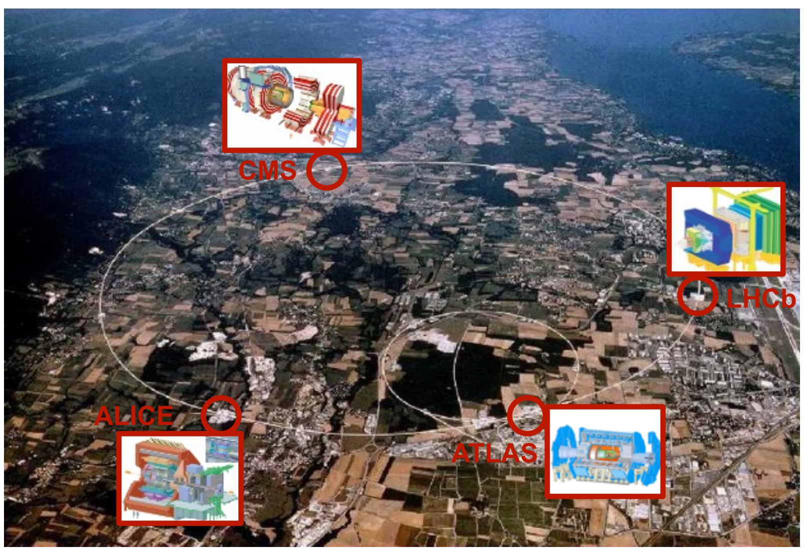
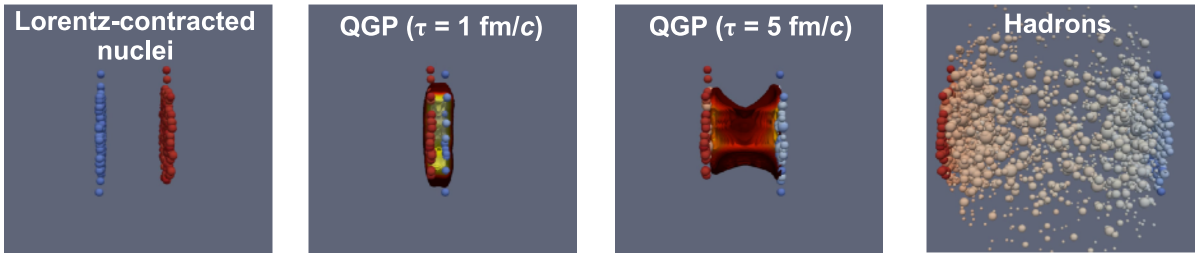






Strongly interacting matter in extreme conditions

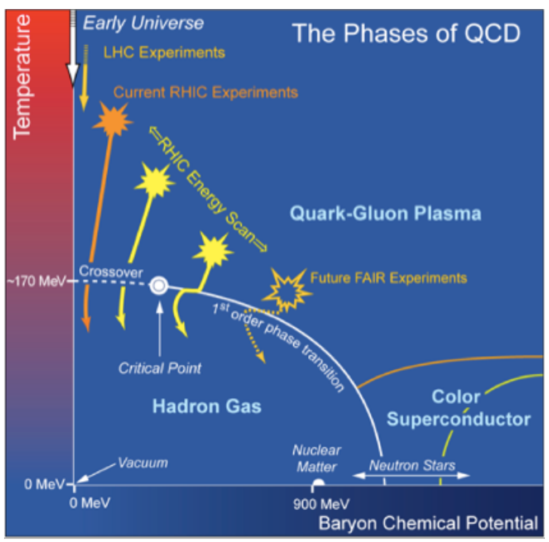
- Fundamental questions: properties of matter for ultra-high energy densities
  - ➡ what are the conditions to create a Quark-Gluon Plasma ?
  - ➡ how does it behave and what are the relevant interaction scales ?
- Global pictures (to be checked)



Simulation: MADAI.us

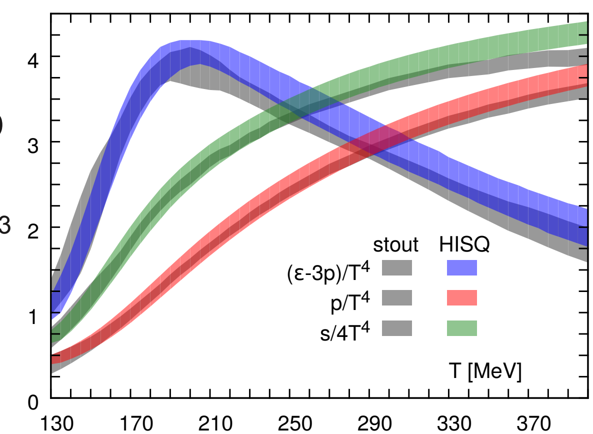
Quark Gluon Plasma (mini-big-bang)

- accelerate and collide nuclei
- extreme energy densities and huge temperature



- Conditions at LHC energies:
  - ➡ high temperature: $O(10^{12}$ K) .
  - ➡ vanishing baryon chemical potential: equal number of particles and anti-particles
- Phase transition predicted by Lattice QCD calculations (state of the art):
  - ➡ $T_C \approx 155$ MeV and $\varepsilon_C \approx 0.5$ GeV/fm^3

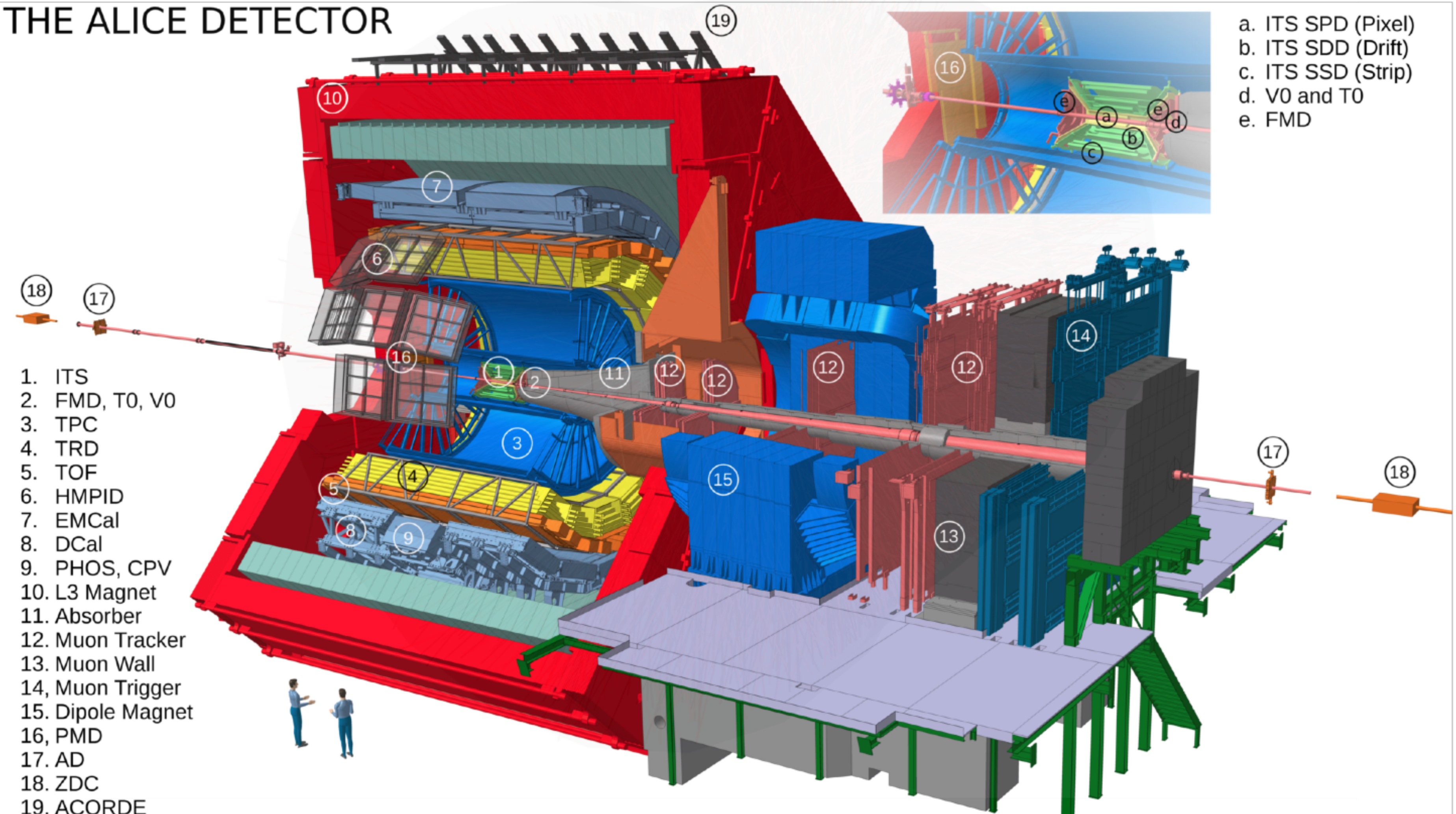
Bazavov *et al.*
Phys. Rev. D90 (2014) 094503



ALICE - A Large Ion Collider Experiment (16 m x 16 m x 25 m)

- robust tracking → central barrel with low material budget (<10%X_0) wide p_T range
- particle identification over a large momentum range
- excellent muon identification down to low p_T at forward rapidity

THE ALICE DETECTOR

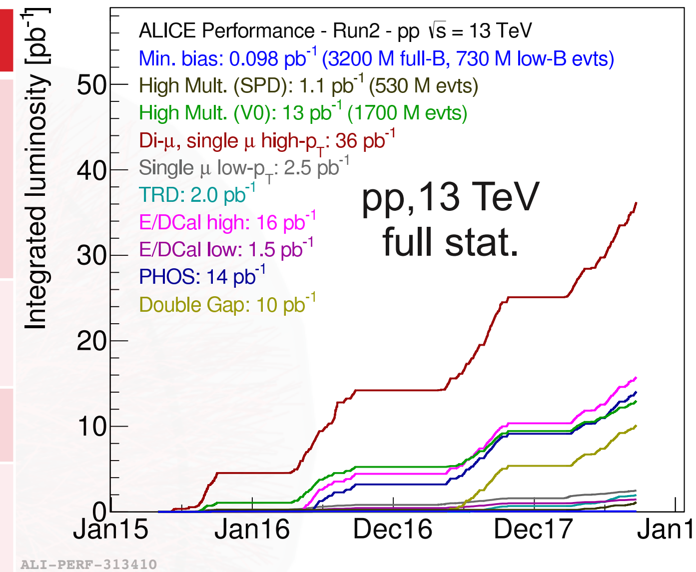


1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14, Muon Trigger
15. Dipole Magnet
16, PMD
17. AD
18. ZDC
19. ACORDE

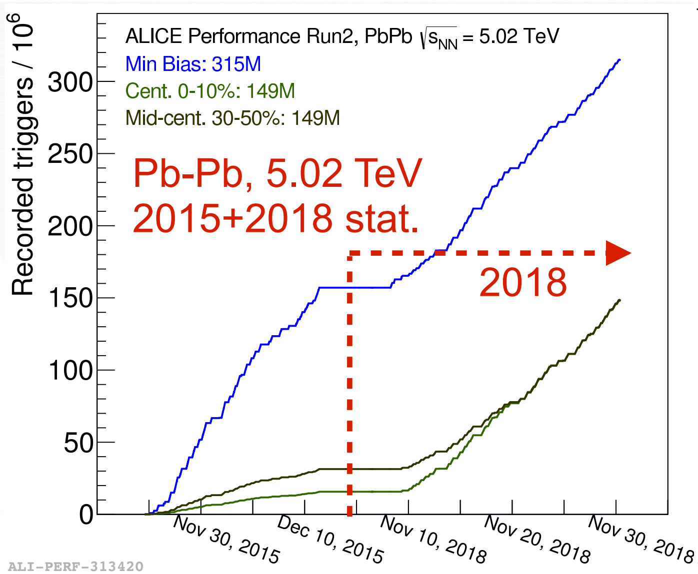
ALICE - colliding systems, energy and datasets

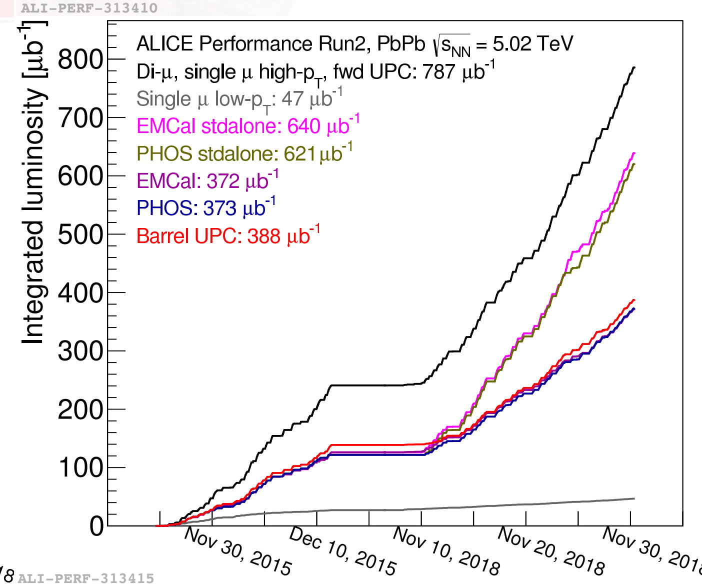
- ➡ almost 10 years of operation at the Large Hadron Collider (runs 1 & 2)
- ➡ just finished run 2 (December 2018) with the largest collected statistics

System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
pp	2009-2013 2015,2017 2015-2018	0.9, 2.76, 7, 8 5.02 13	~200 μb^{-1}, ~100 nb^{-1}, ~1.5 nb^{-1}, ~2.5 nb^{-1} ~1.3 nb^{-1} ~25 nb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	~15 nb^{-1} ~3 nb^{-1}, ~25 nb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
Pb-Pb	2010-2011 2015-**2018**	2.76 **5.02**	~75 μb^{-1} ~250 μb^{-1}, **~1 nb^{-1}**

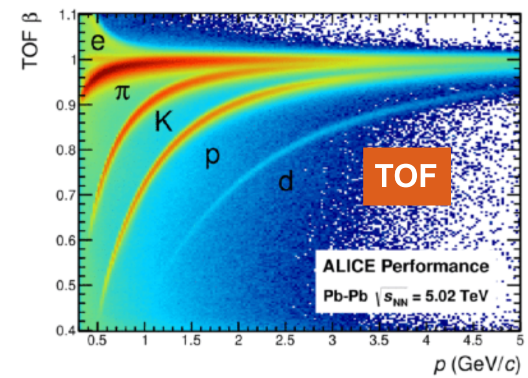


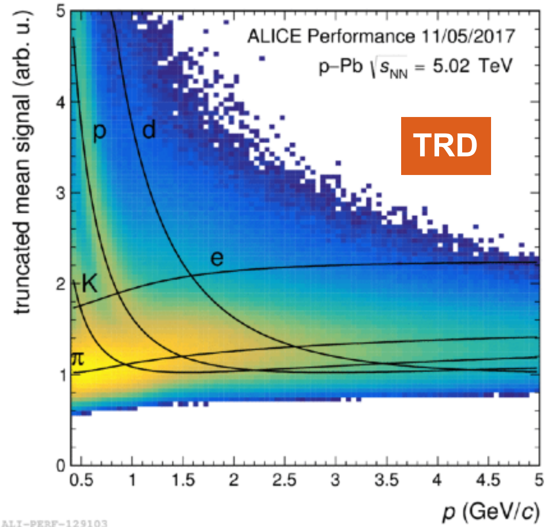
- ➡ 2018 Pb-Pb data-taking
  - min. bias ~ 1x 2015
  - central ~ 9x 2015
  - mid. central ~4x 2015
- ➡ rich trigger menu

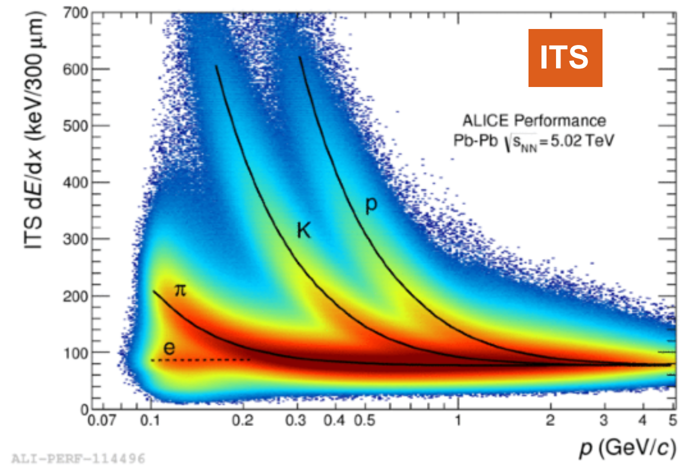




ALICE - particle identification performance



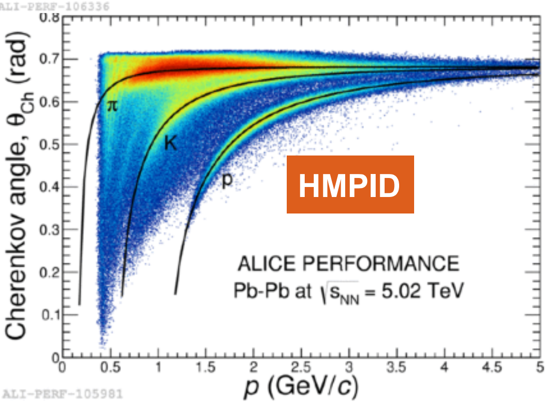


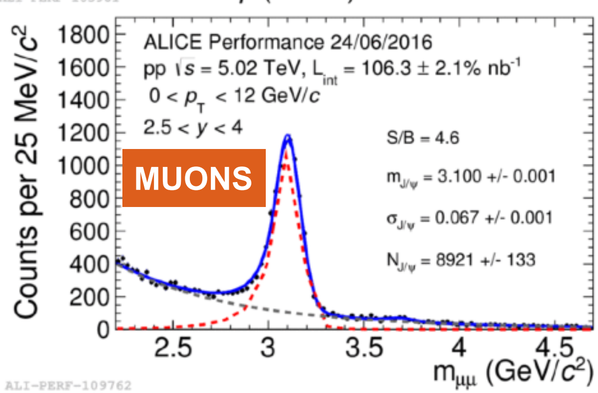


✓ Lowest material budget tracker

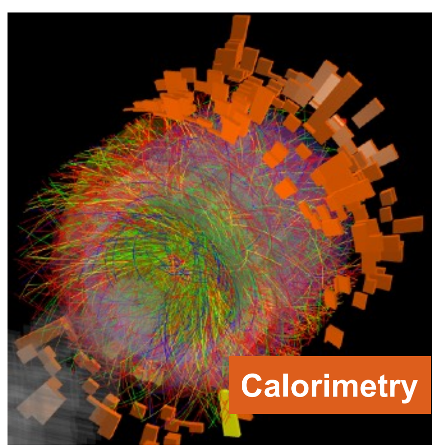
✓ Particle identification in a wide momentum range

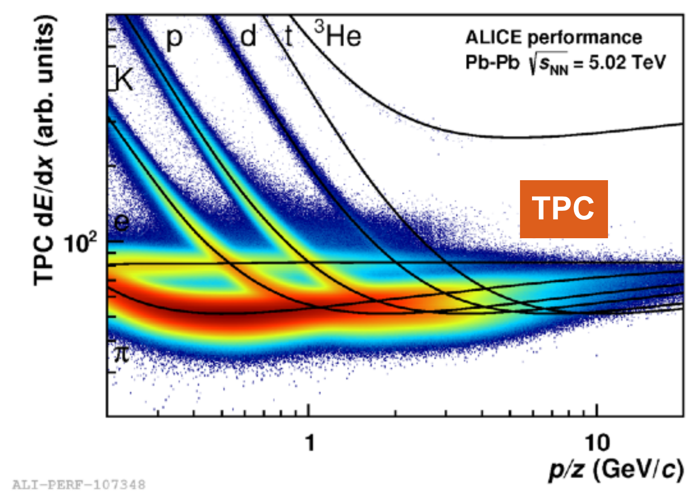
✓ Jets in the Calorimeters



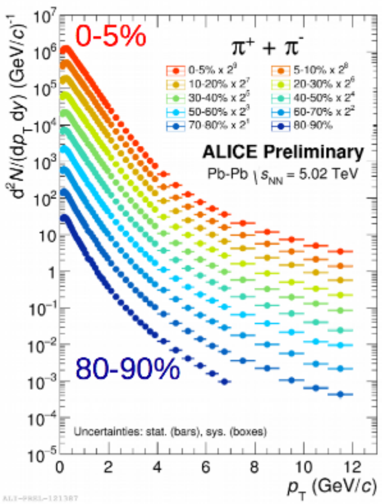


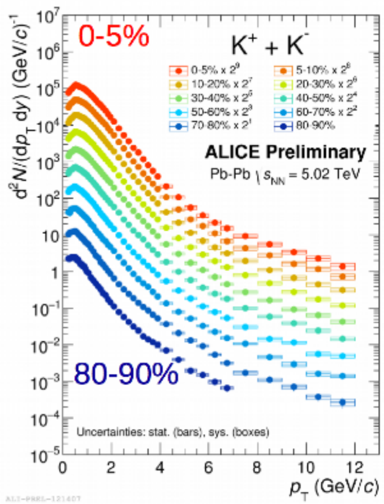
Int. J. Mod. Phys. A29, 1430044 (2014)

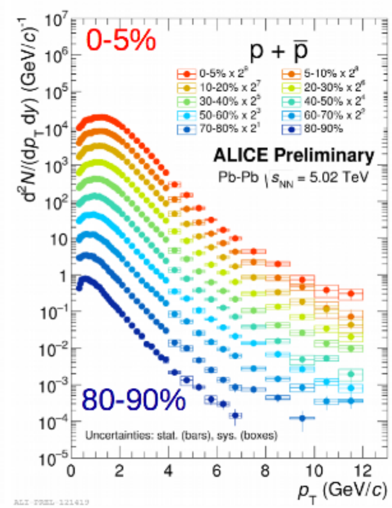


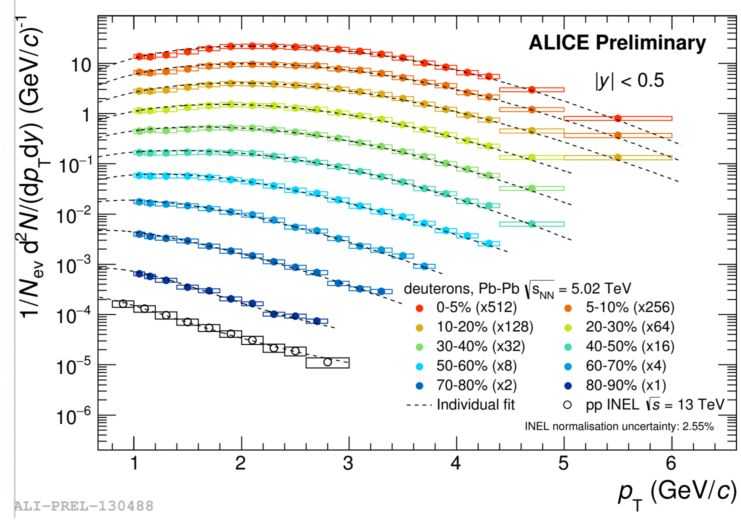


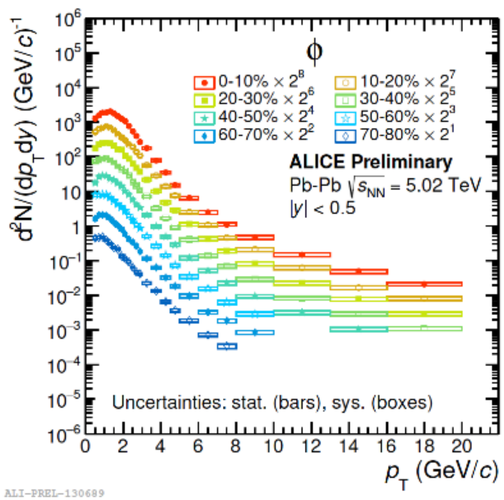
ALICE - particle spectra

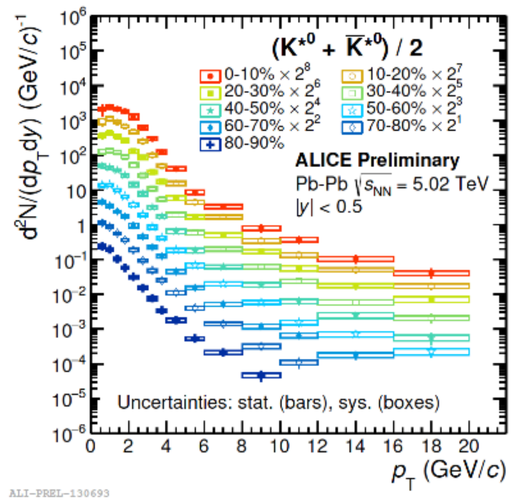


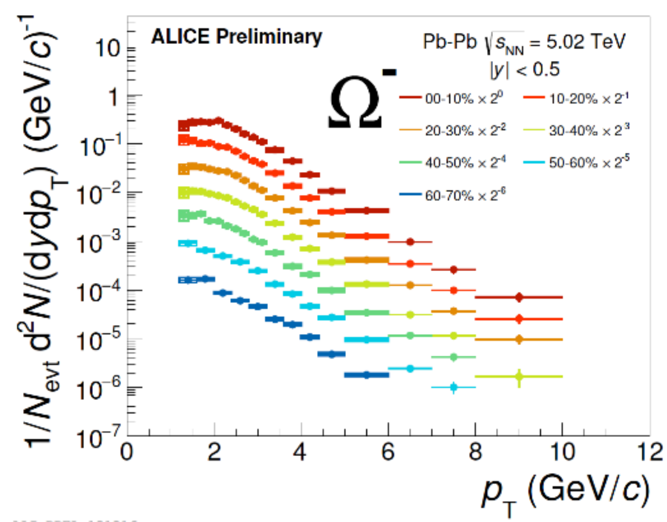








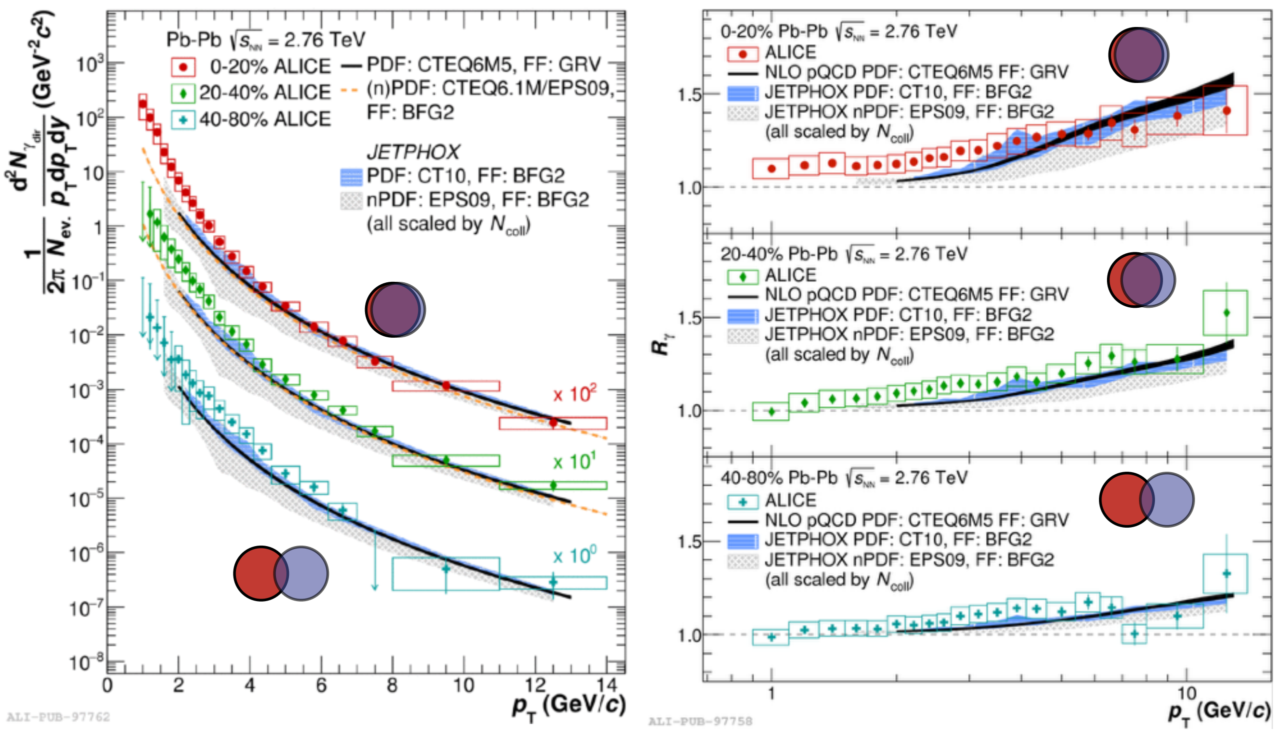




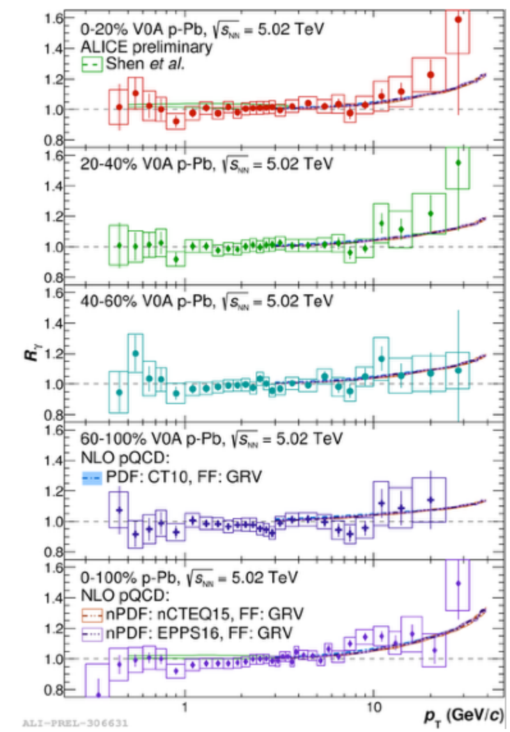
Strongly interacting matter in extreme conditions

- Global experimental observables (back-up slides for "older results")
  - ➡ correlated volume at freeze-out (Bose-Einstein correlations): ~5000 fm^3
  - ➡ estimation of the energy density (particle production and flow): ~10-15 GeV/fm^3
  - ➡ temperature (direct photon production): $T_{eff} \approx 297 \pm 12^{(stat)} \pm 41^{(syst)}$ MeV $\gg T_C$

ALICE, Pb-Pb collisions Phys. Lett. B754 (2016) 235-248



ALICE Preliminary, p-Pb collisions

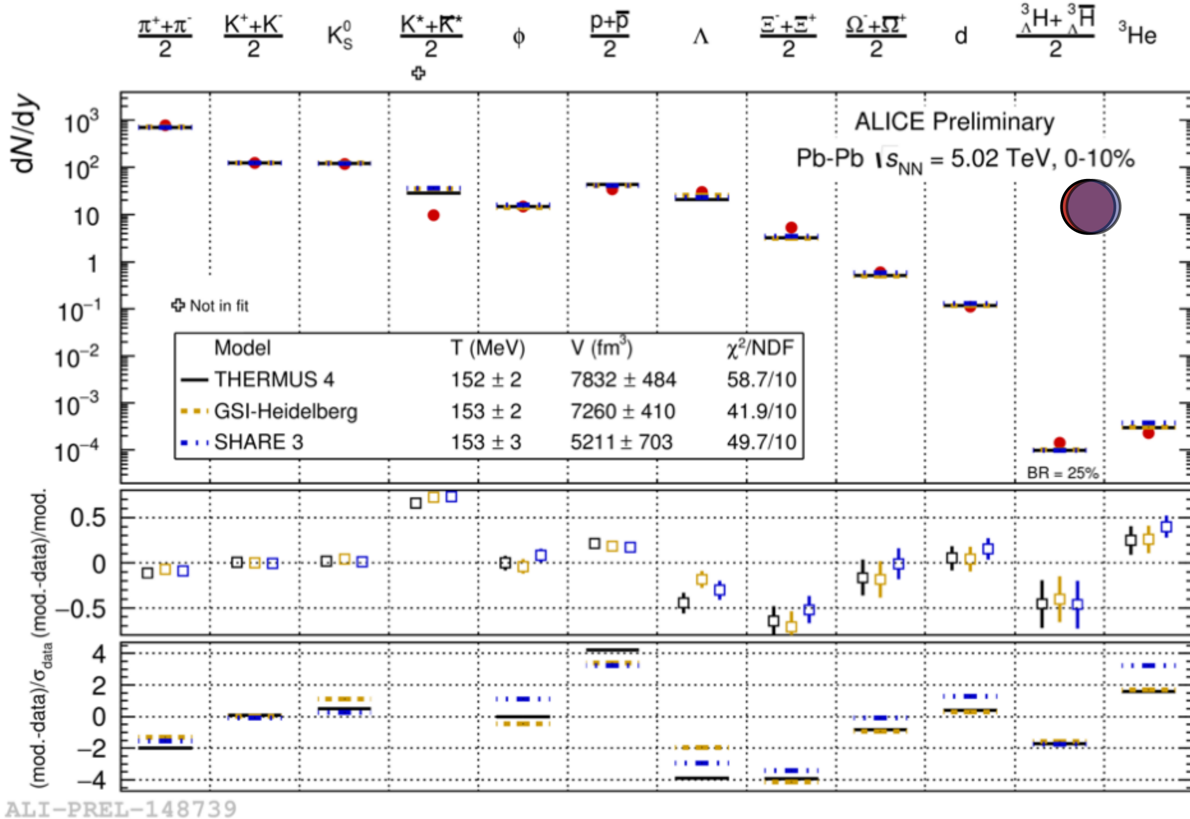


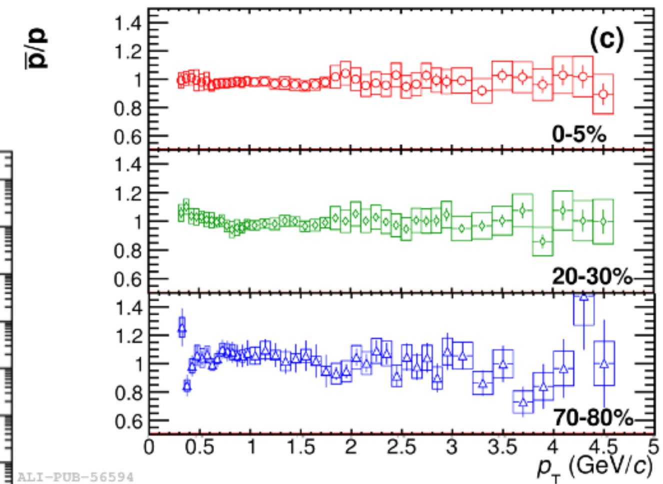
- Large thermal radiation in Pb-Pb collisions

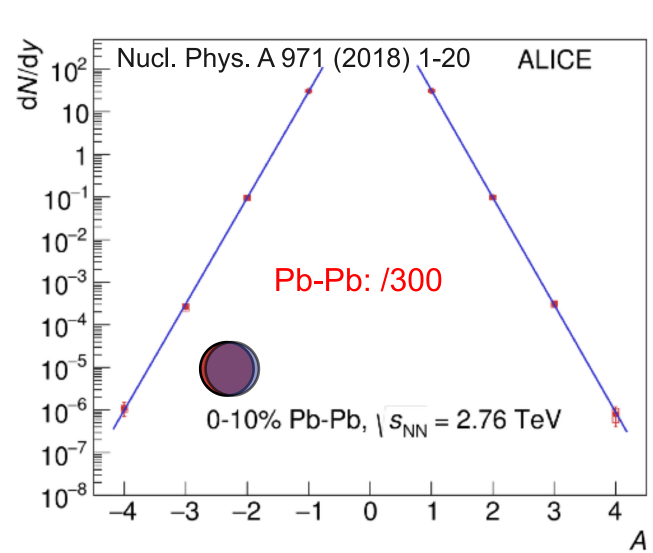
- Cross-checked with p-Pb collisions:
  - ➡ data agrees with pQCD predictions
  - ➡ no evidence currently for thermal radiation

Strongly interacting matter in extreme conditions

- Global experimental observables (back-up slides for "older results")
  - ➡ anti-particle-to-particle ratio ~ 1 → μ_B ~ 0 MeV







- ➡ hadrochemistry for central Pb-Pb collisions
  - at thermodynamic equilibrium…
  - strangeness enhancement !
  - even for nuclei and hypernuclei

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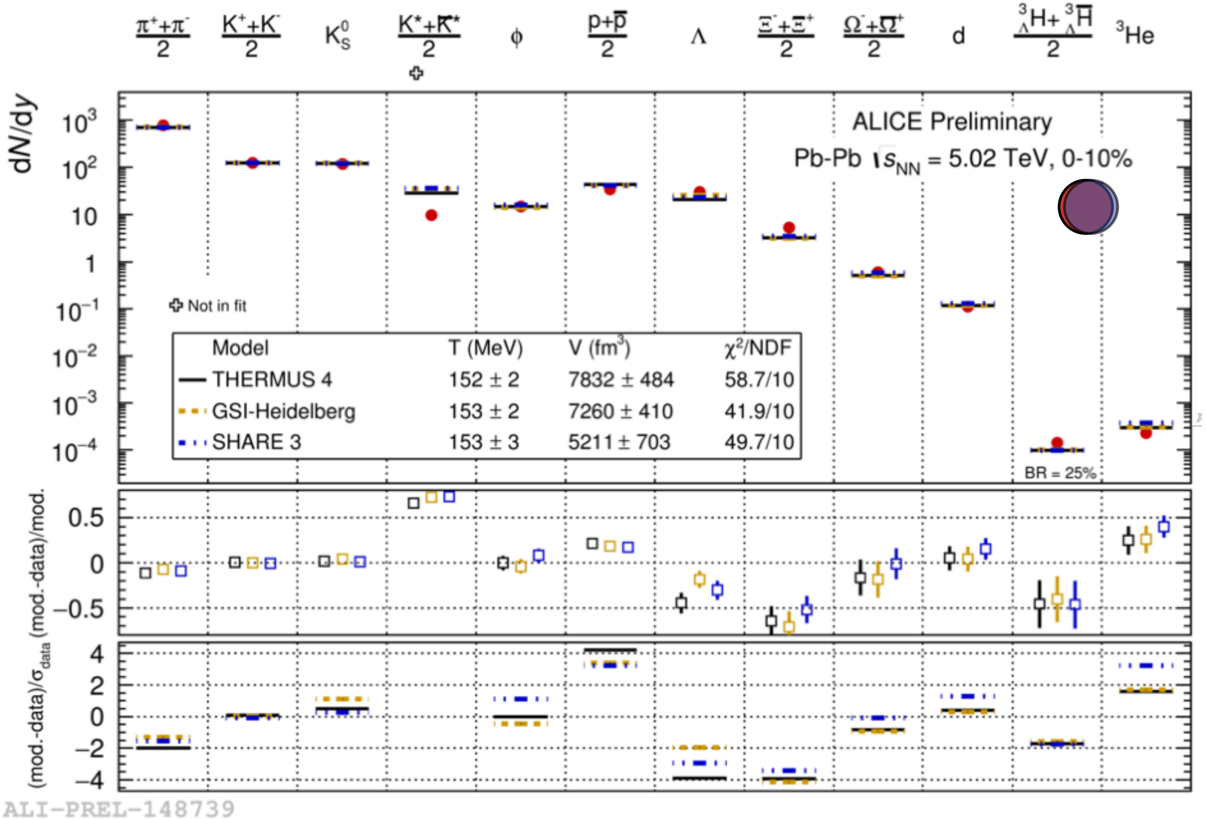

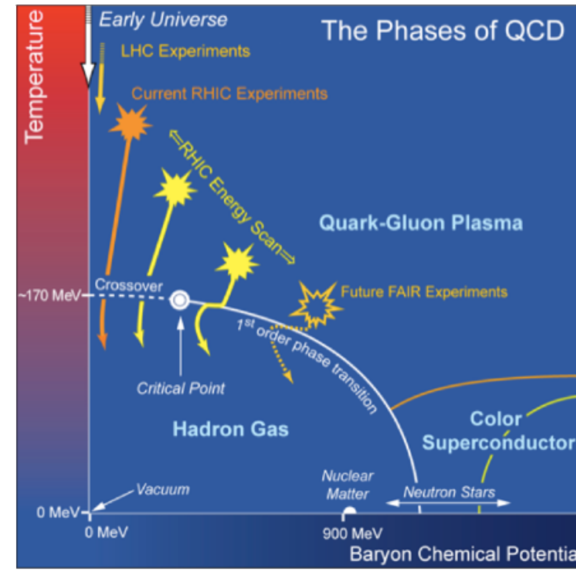

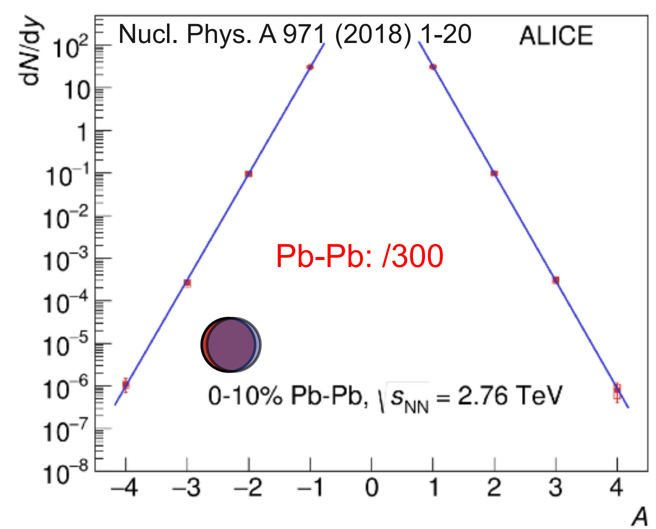

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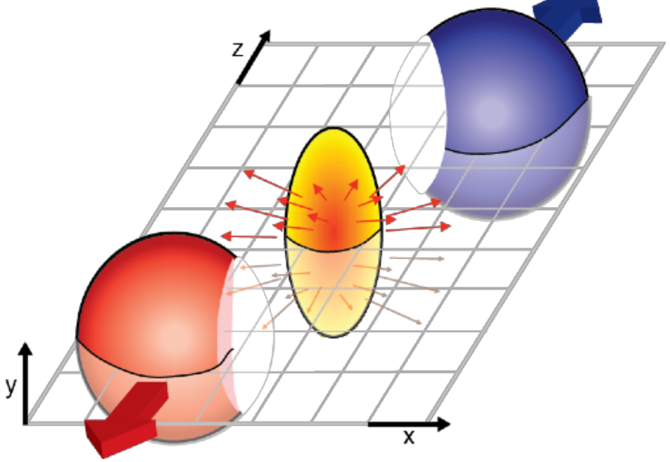
Characterisation of the Quark-Gluon Plasma

- Eccentricity, flow coefficients and fluctuations

non-central collisions:



Initial **coordinate** space anisotropy

- The reaction plane contains the beam direction and the centers of the colliding nuclei

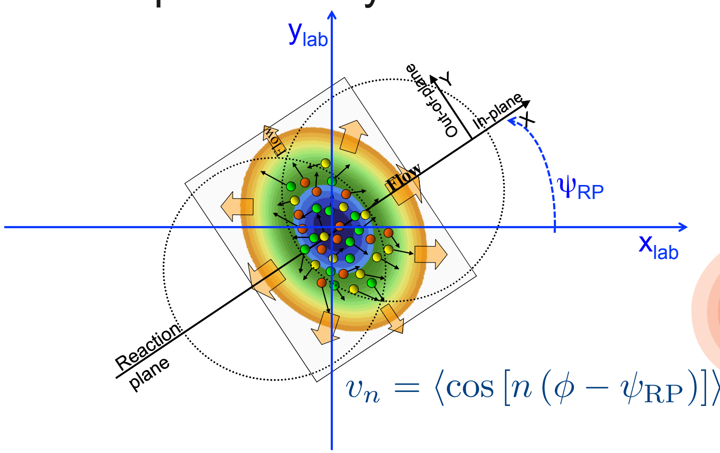
Anisotropy in azimuthal angle described by a Fourier series:

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Phi_n)$$

EXPERIMENTAL RESULTS

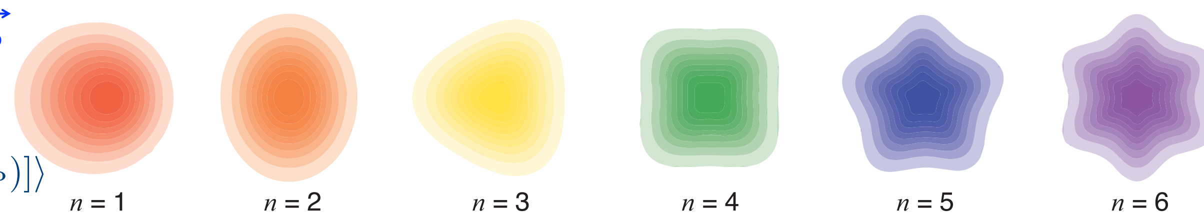
- ➡ very precise measurements of flow coefficients
- ➡ 2nd order (v_2) dominates in non-central collisions v_n
- ➡ v_n decreases with increasing n: typical of viscous fluid (damping)
- ➡ Odd harmonics with weak centrality dependence: fluctuations

experimentally:



CLEAR EVIDENCE

- ➡ How the system behaves collectively with $v_n \propto \varepsilon_n$
- ➡ Initial fluctuations propagated by a viscous fluid



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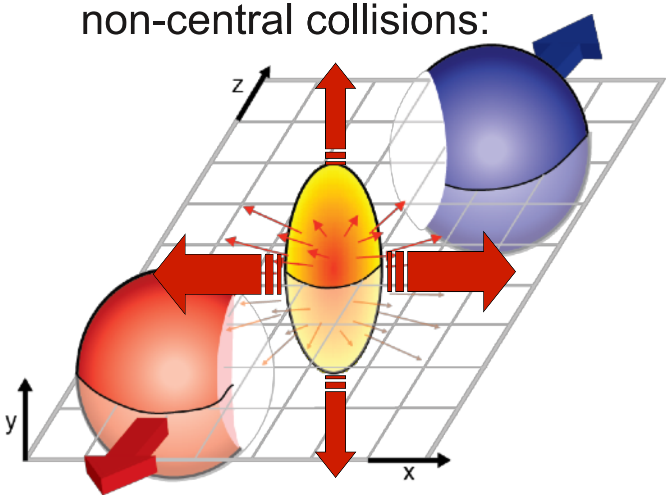
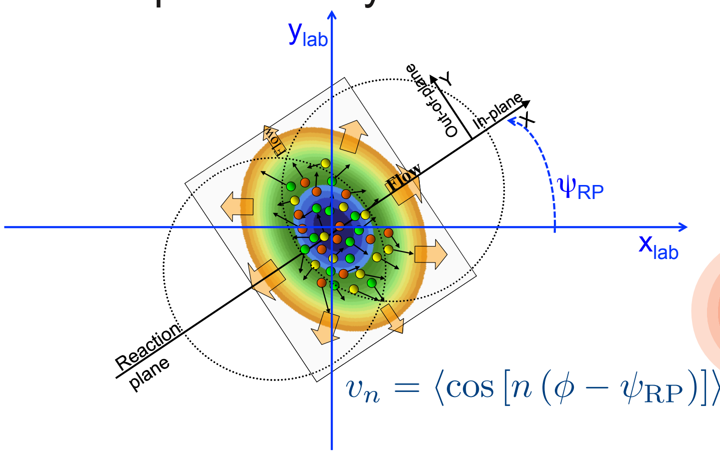


Initial **coordinate** space anisotropy

→ **momentum** space anisotropy

experimentally:



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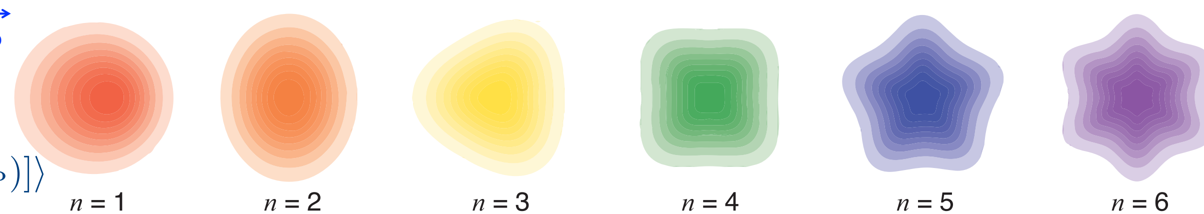
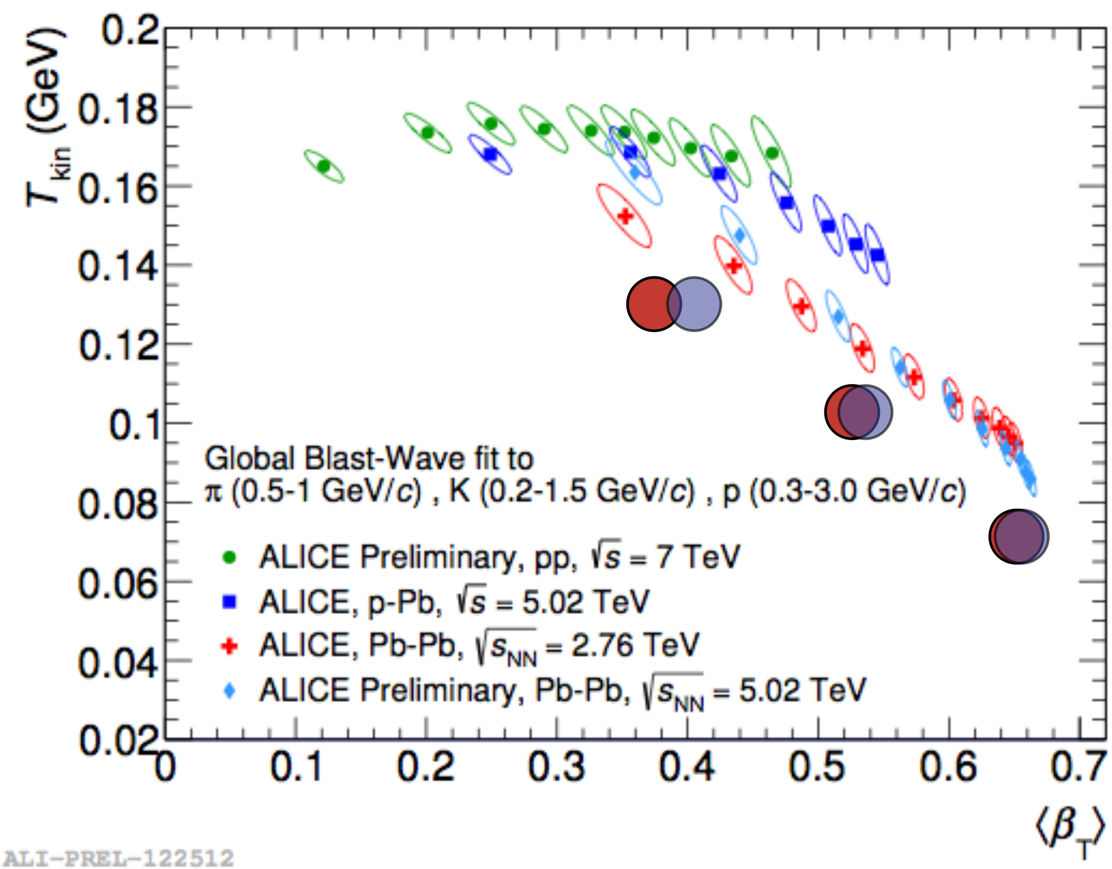


Characterisation of the Quark-Gluon Plasma

- Radial flow from simple blast-wave parameterisation at the LHC



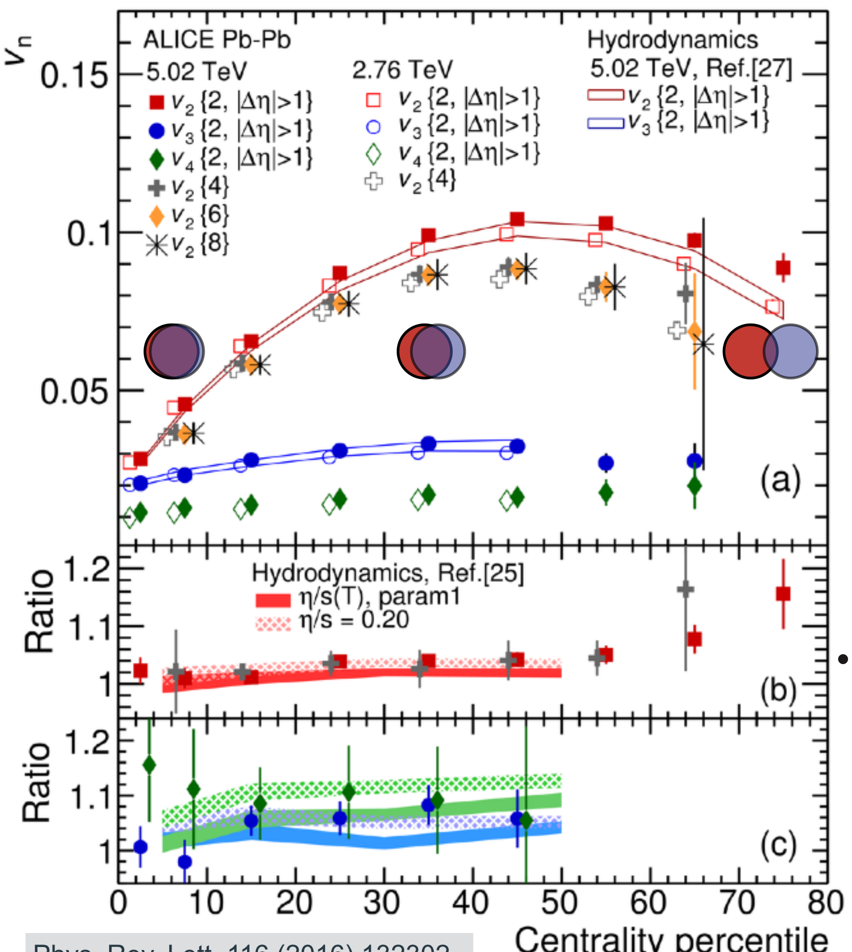
Simple parameterisation of radial expansion

- ➡ kinetic parameter extracted from mass dependence of spectra
- ➡ T_{kin}: kinetic freeze-out temperature
- ➡ β_T: radial flow velocity

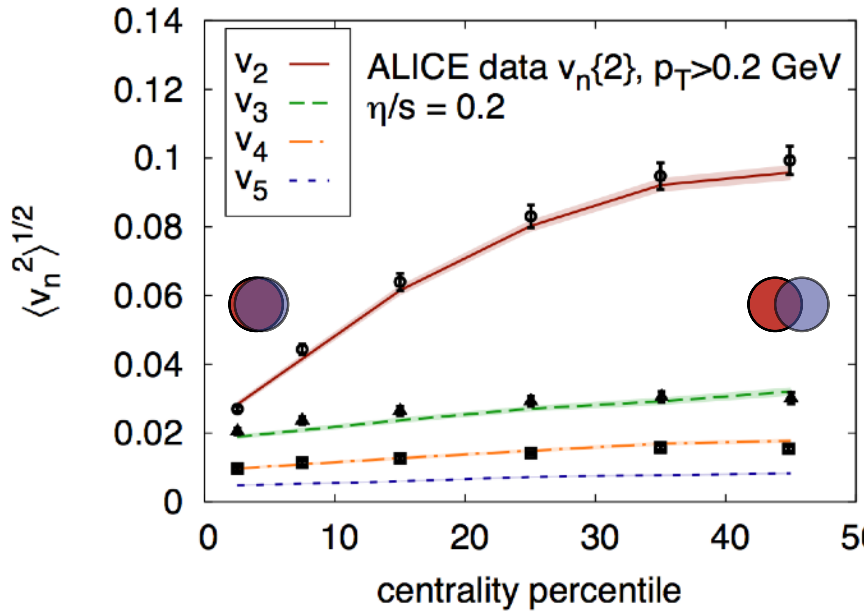
Run 2 for Pb-Pb: largest β_T ever observed

Characterisation of the Quark-Gluon Plasma

- Anisotropic flow and hydro transport coefficients for Pb-Pb at the LHC



Phys. Rev. Lett. 116 (2016) 132302



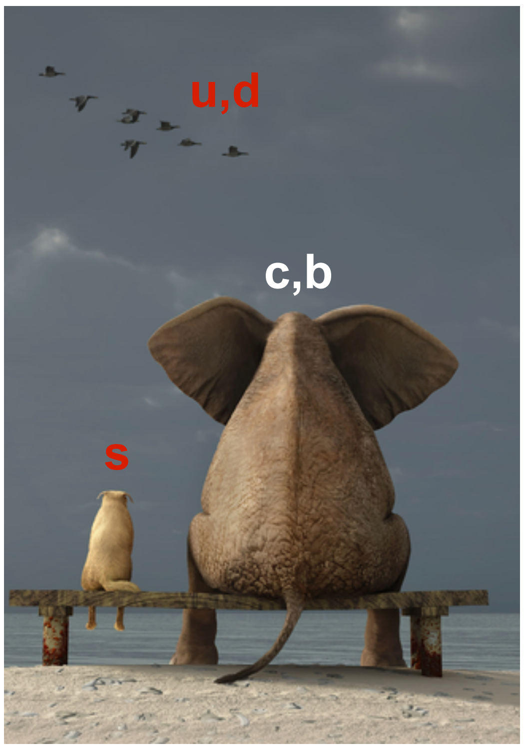
- Anisotropic flow v_n integrated in range $0.2< p_T <5.0$ GeV/c as a function of centrality
  - ➡ Ratios computed between 5.02 and 2.76 TeV results.
  - ➡ From 2.76 to 5.02 TeV over centrality range 0-50%, the average increases are:

    (3.0±0.6)% for v_2 (4.3±1.4)% for v_3 (10.2±3.8)% for v_4

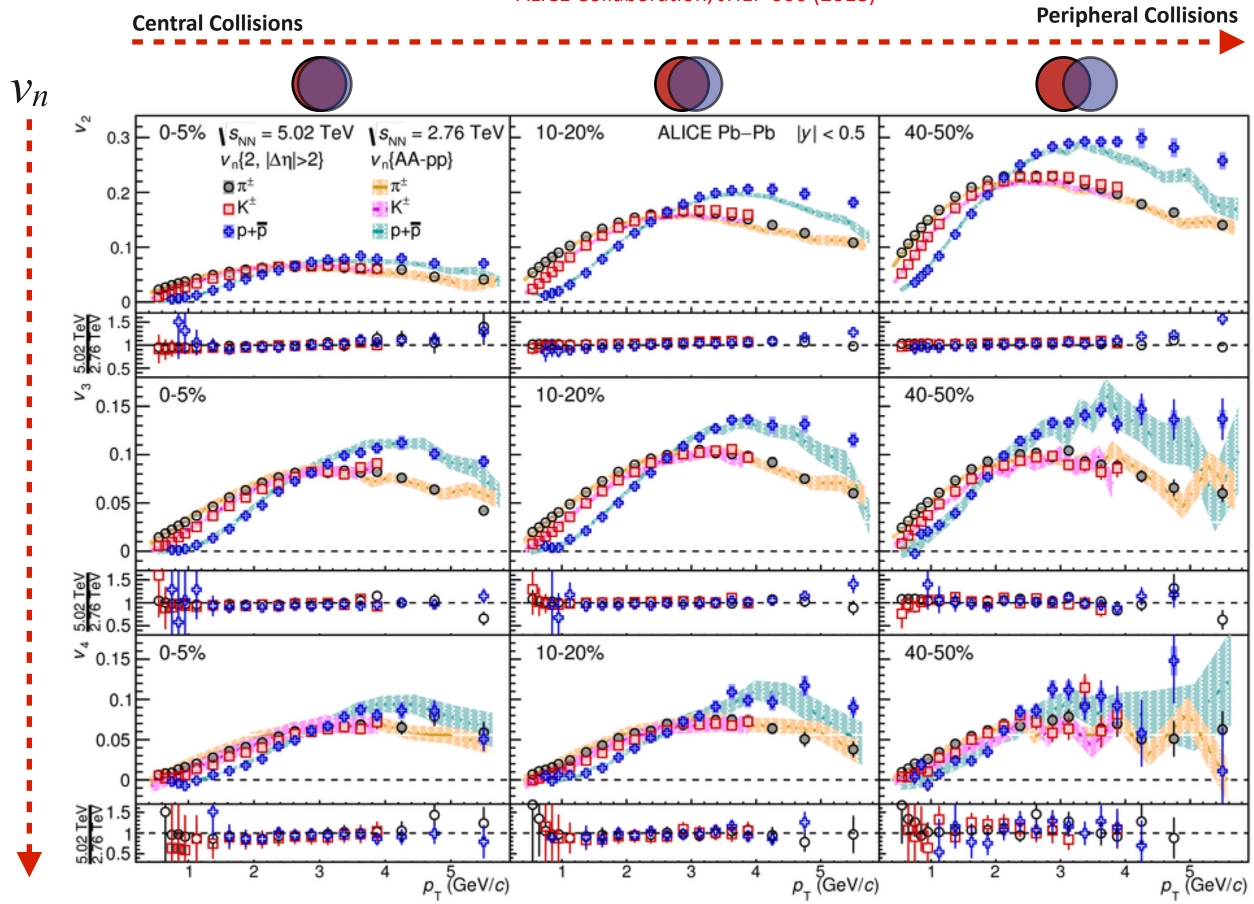
➡ Results compatible with predictions from state-of-the-art hydrodynamic (3D+1 e-by-e relativistic viscous) models

Measurement of the light and strange quarks flow

- evidence that the Quark Gluon Plasma expands as a perfect liquid
  - ➡ hydrodynamic behaviour with lowest shear viscosity / entropy density (η/S) that is possible
  - ➡ more differential analysis (centrality and energy) for the light and strange flavours



ALICE Collaboration, JHEP 006 (2018)



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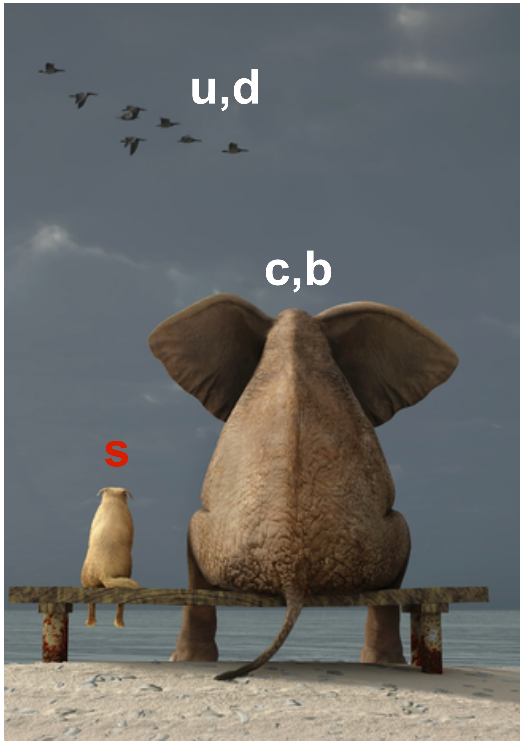

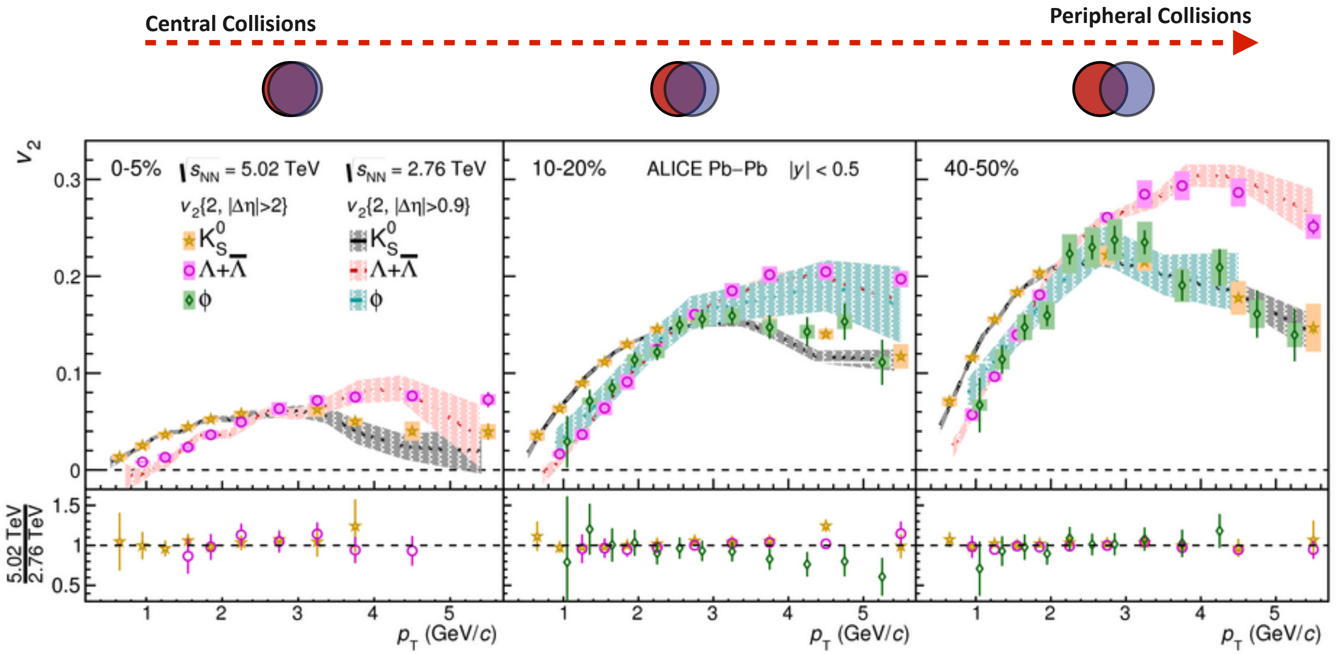

Observation that even the charm quarks flow

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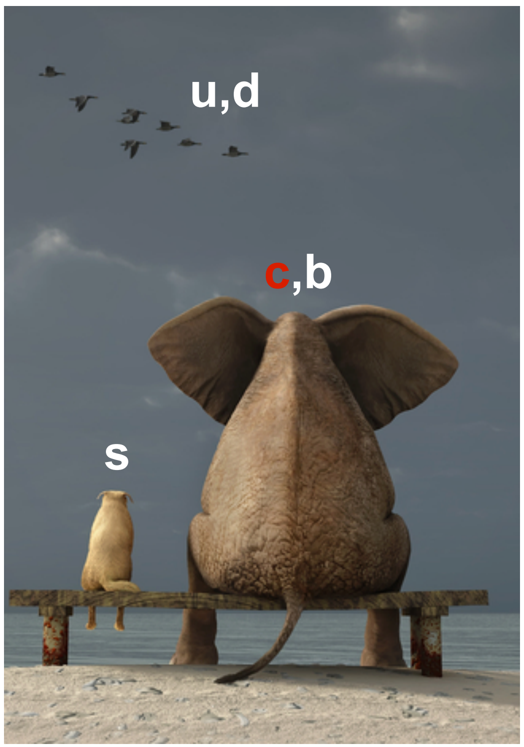
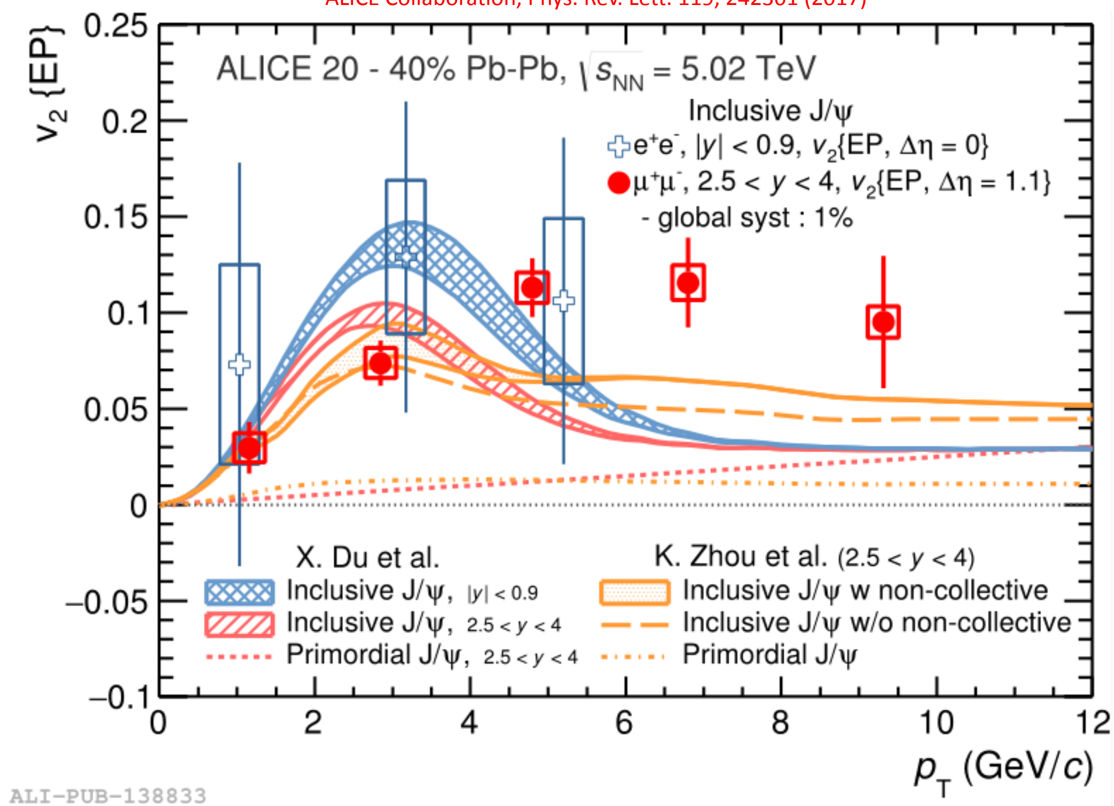
- investigate precisely if charm flows just as light flavours do



ALICE Collaboration, Phys. Rev. Lett. 119, 242301 (2017)



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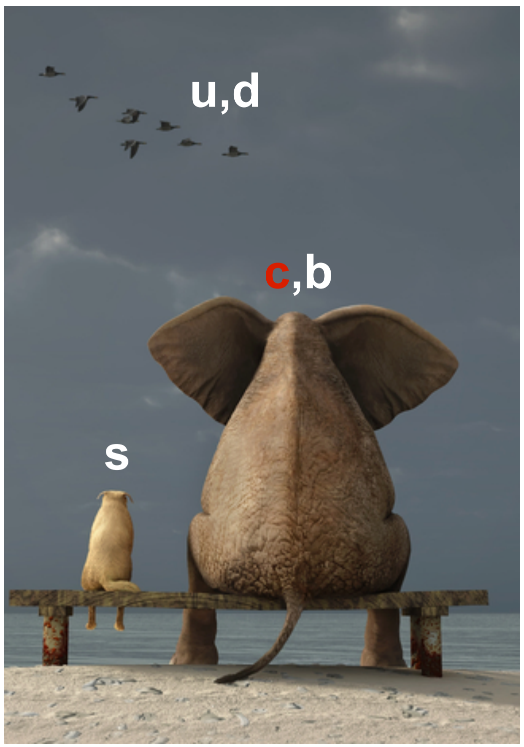
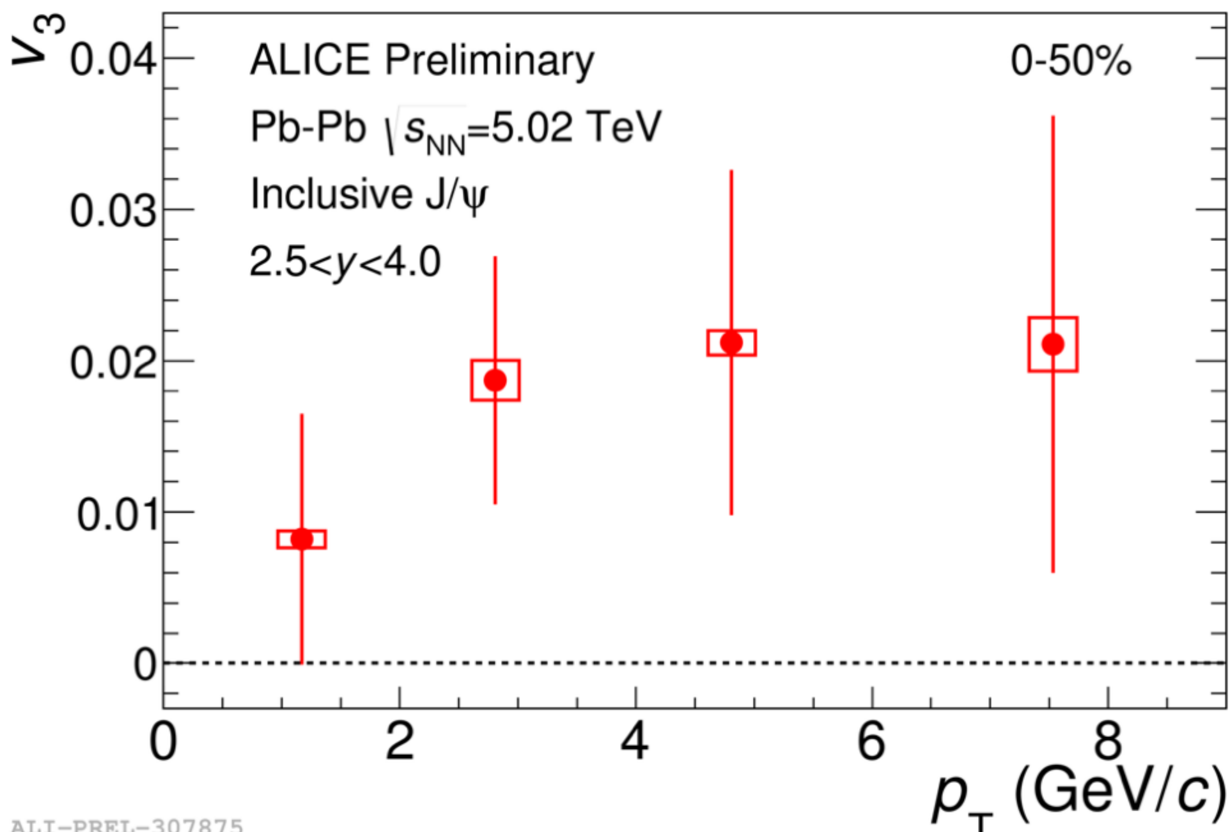
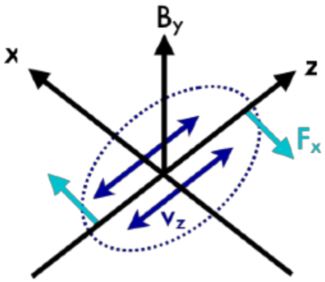


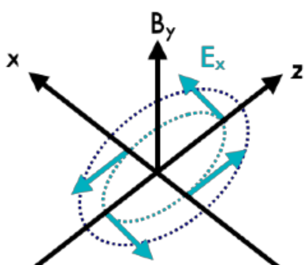


Additional observation for the charm quark flow

- probing the strong electric and magnetic fields in Pb-Pb collisions
  - ➡ affects the azimuthal distribution of particles (v1) depending on charge
  - ➡ compare v_1 of positive and negative particles

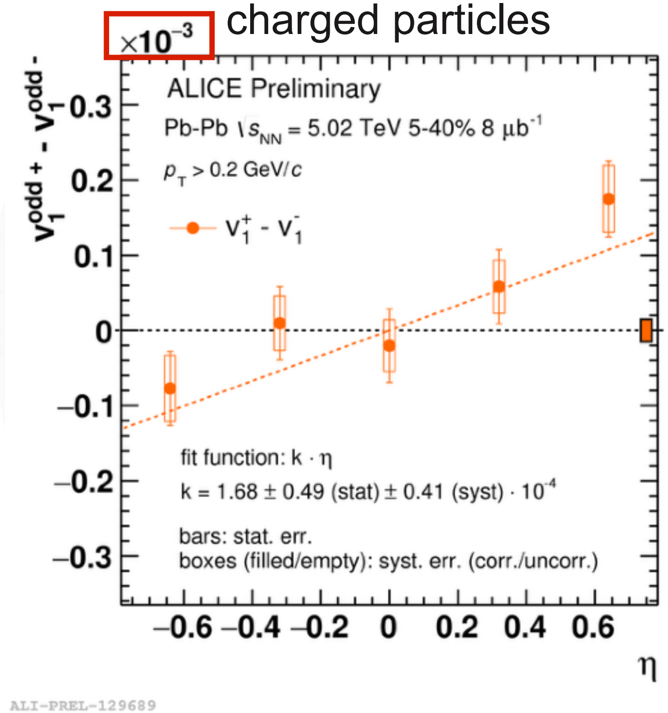


$$\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$$

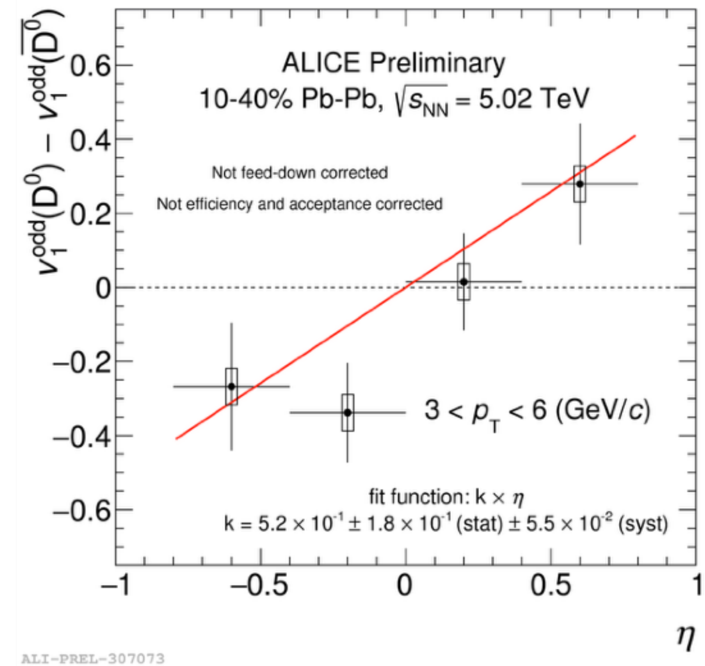


$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

charged particles



D-mesons (new preliminary)

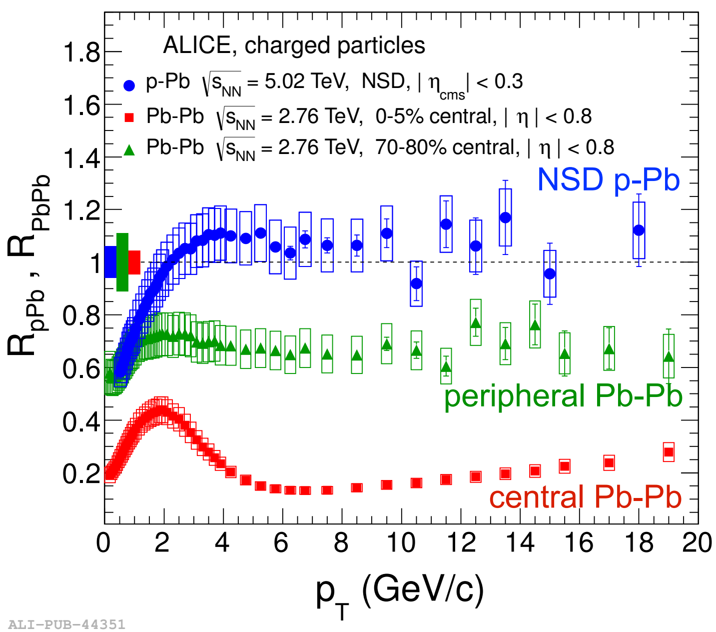


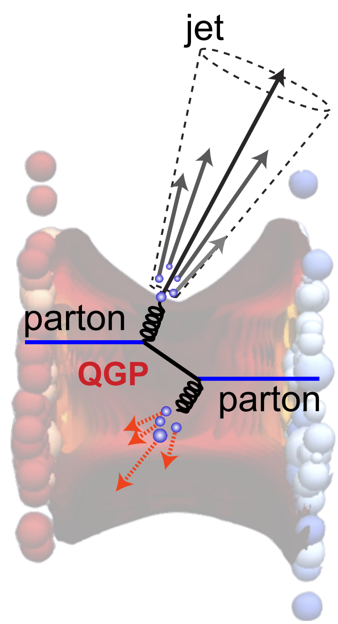
- ➡ effect small for all (charged) hadrons (scale x10^{-3})
- ➡ much stronger effect for D-mesons (early production of c-quarks)
- ➡ new window on early times and QGP conductivity (with more statistics)

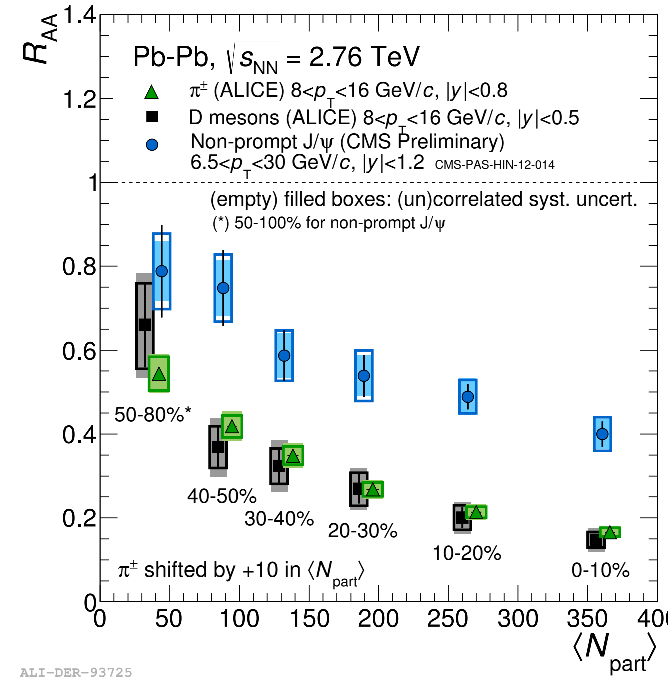
Opacity of the QGP and nuclear modification factor

- Estimate the opacity of the created medium
  - ➡ R_{AA} is called the nuclear modification factor
  - ➡ R_{AA} equals unity means no modification at all

$$R_{\mathrm{AA}} = \frac{\mathrm{AA}}{\mathrm{rescaled\ pp}} = \frac{d^2N_{\mathrm{AA}}/dp_{\mathrm{T}}dy}{\langle N_{\mathrm{coll}}\rangle d^2N_{\mathrm{pp}}/dp_{\mathrm{T}}dy}$$





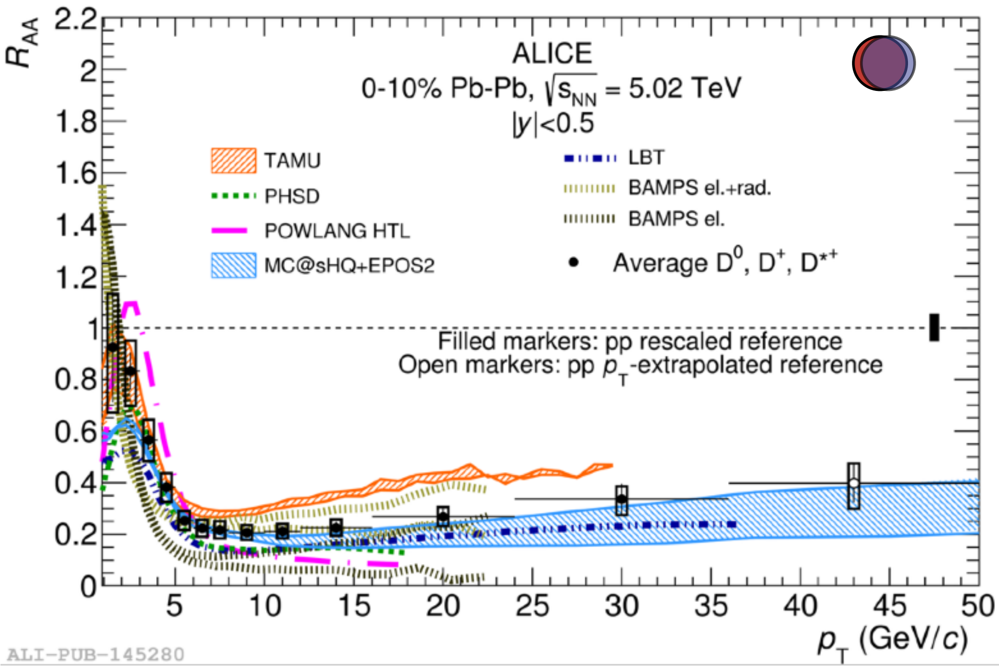


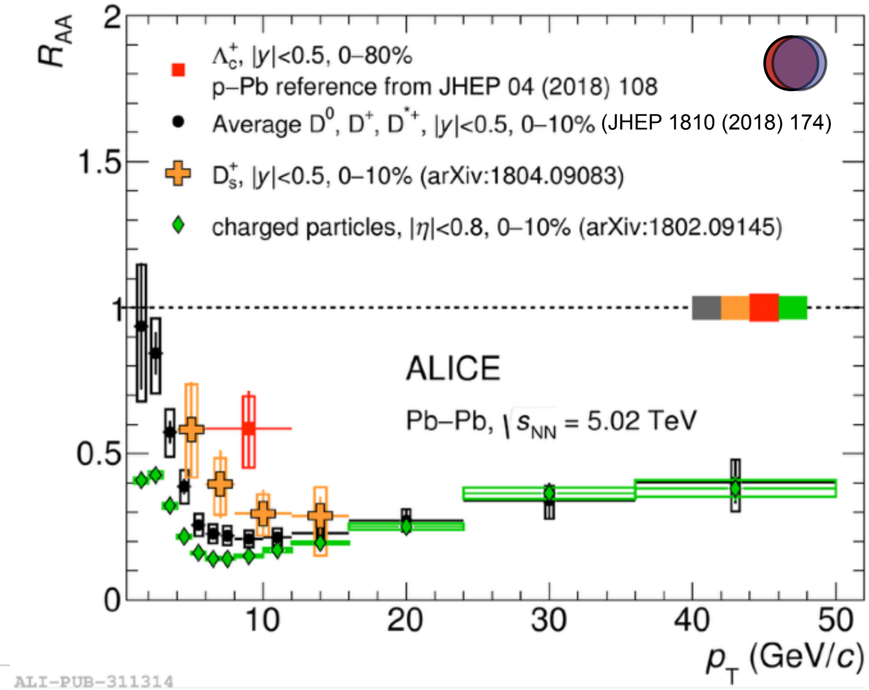
- ➡ strong suppression (quenching) in Pb-Pb collisions
- ➡ p-Pb collisions is a control experiment for the nuclear modification factor
- ➡ first clear mass-dependence energy loss in the medium

Opacity of the QGP and nuclear modification factor

- nuclear modification factor for open charm

ALICE Collaboration, JHEP 1810 (2018) 174





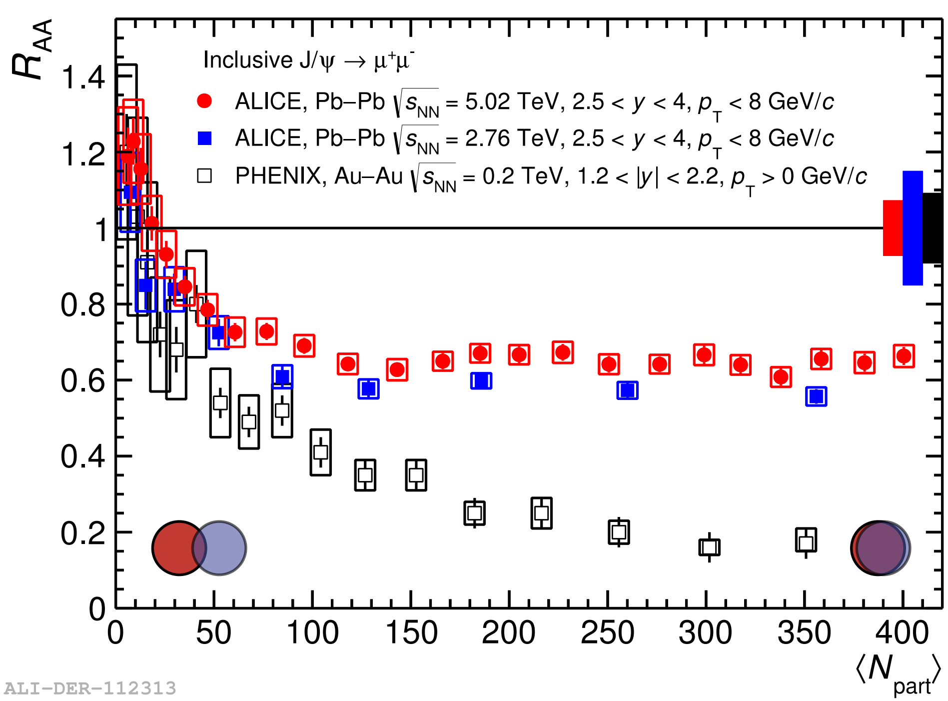
$h^{\pm} < D < D_s < \Lambda_c$

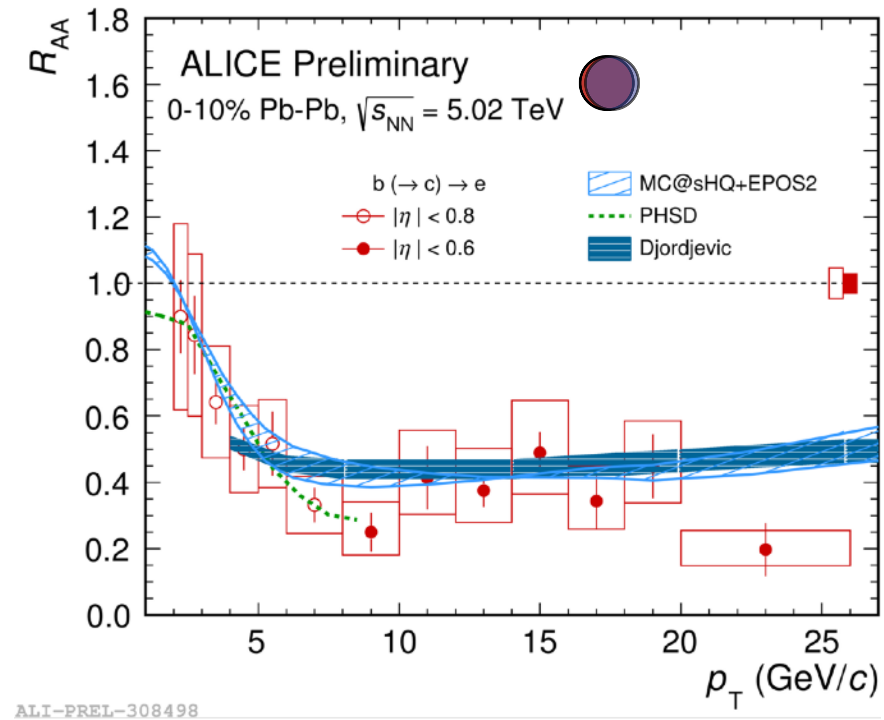
→ significant constraint on quenching models!

→ sensitive to radial flow, hadronisation

Opacity of the QGP and nuclear modification factor

- nuclear modification factor for charm (forward J/ψ) and beauty (central e⁻)
  - ➡ Evolution of J/ψ suppression with collision energy in the forward region (2.5 < y < 4)
  - ➡ Electrons from beauty hadron decay at mid-rapidity (direct measurement of beauty-electron RAA using DCA analysis to separate beauty from light and charm hadron decays)



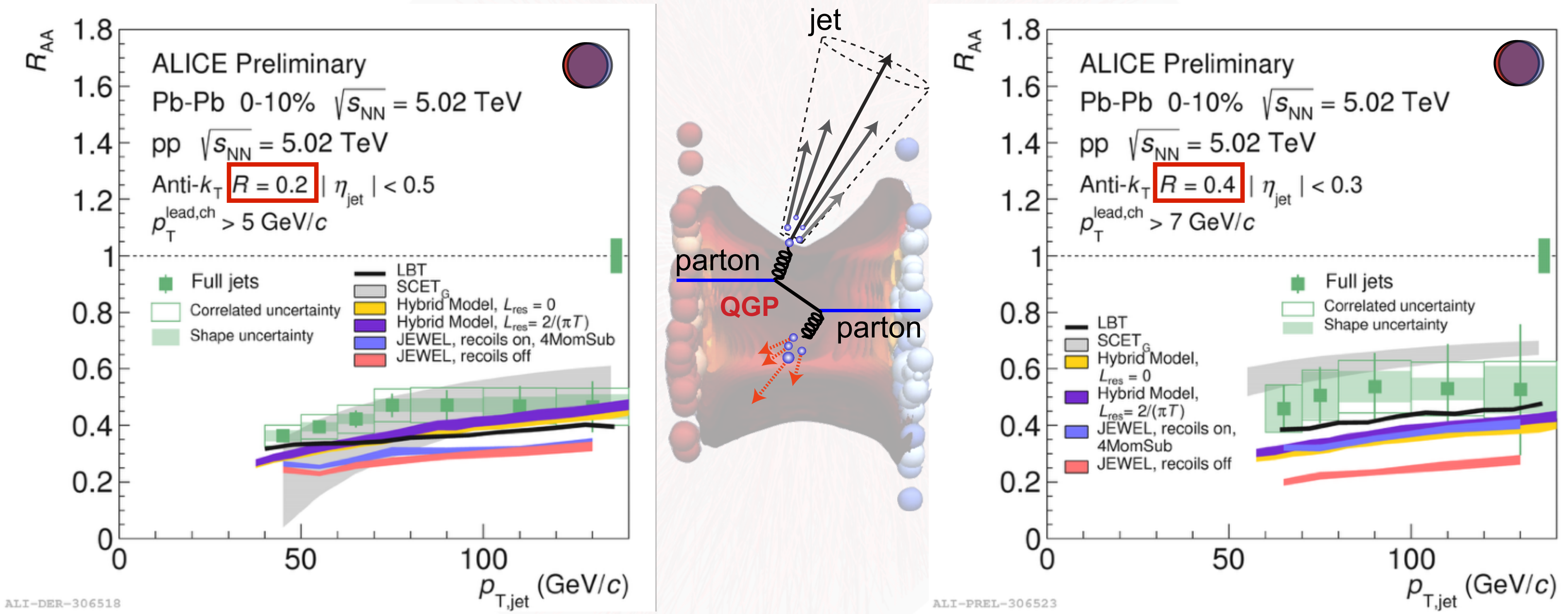


- coalescence / regeneration models consistent with data

- Significant suppression in 0-10% described by models that include mass-dependent energy loss

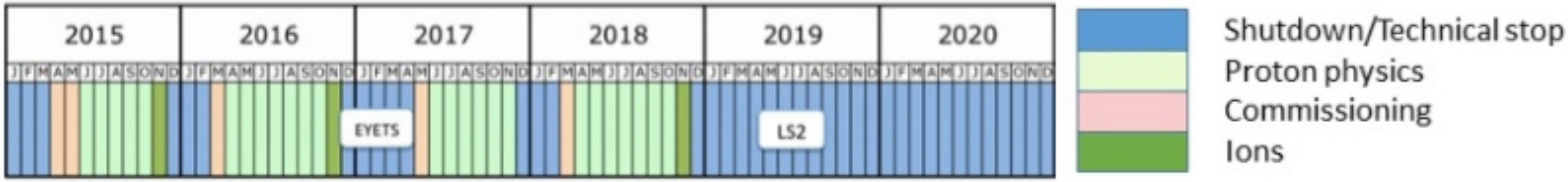
Opacity of the QGP and nuclear modification factor

- Inclusive Jet R_{AA} for collisions of Pb-Pb at 5.02 TeV
  - ➡ Low momentum important to understand how the energy is redistributed
  - ➡ Energy loss has energy dependence
  - ➡ Unique measurement down to p_T = 40 GeV/c



- ➡ Only weak dependence seen in data on jet resolution R (new preliminary results)
- ➡ Challenge to some models (stronger jet resolution R dependence than data)

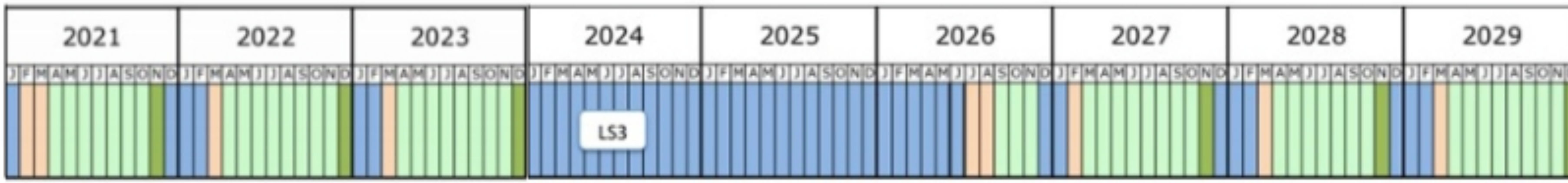
ALICE - the timeline



Run2 : $\mathcal{L}_{integrated}^{Pb-Pb} = 1.0\ nb^{-1}$

LS2 upgrades

- ➡ LHC injector upgrades, Pb-Pb rate → 50 kHz (Run2 ~10 kHz)
- ➡ ALICE upgrades: **ITS, TPC, MFT, Readout, FIT, O²**



Run3: $\mathcal{L}_{integrated}^{Pb-Pb} = 6.0\ nb^{-1}$

Run4 : $\mathcal{L}_{integrated}^{Pb-Pb} = 7.0\ nb^{-1}$

Run3 + Run4

Physics goals
- ➡ Macroscopic QGP properties with unprecedented precision
- ➡ Microscopic parton dynamics underlying QGP properties

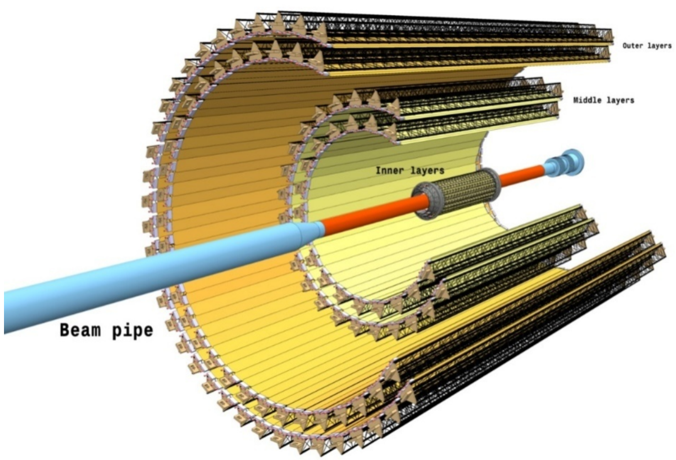
Data taking
- ➡ Experiment's request > 10/nb (ALICE: 10/nb + 3/nb at 0.2 T)
- ➡ In line with projections from the Large Hadron Collider team

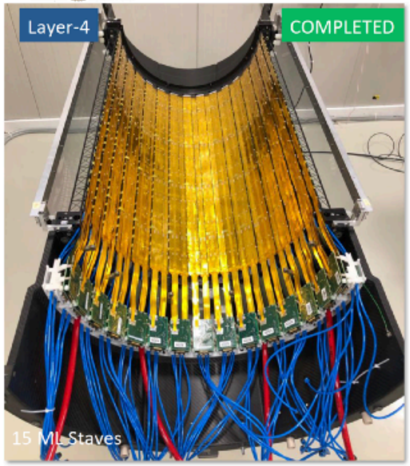
LS2 (2019-21) upgrades - tracking particles close to Interaction Point

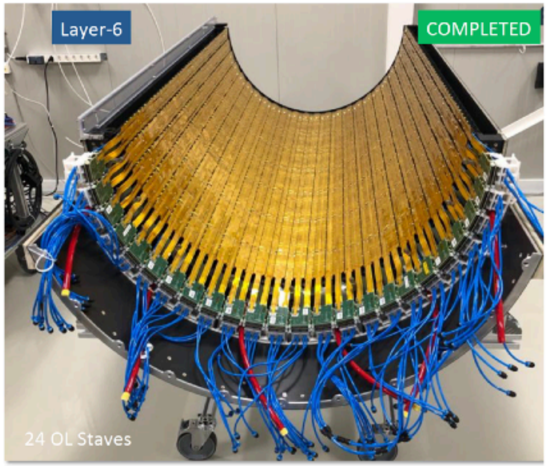
Brand new Inner Tracking System:

➡ **taking 20% of chip module assembly, installation and calibration of upgraded ITS**

- 7 layers (10 m^2) silicon pixel (MAPS) sensor tracker
- 22-406 mm to Interaction Point with spatial resolution O(5 μm)



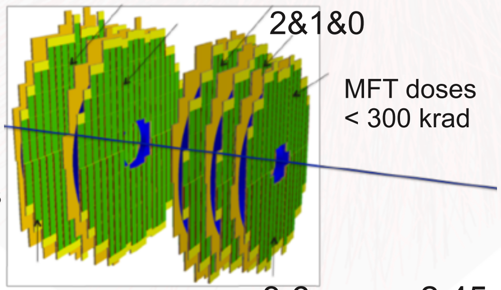




➡ B_s, B_c, Λ_b , b-jet measurements

Muon Forward Tracker:

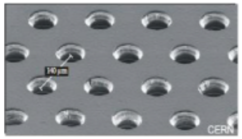
- 920 silicon pixel sensors (0.4 m^2)
- 280 ladders of 2 to 5 sensors each
- -76.8 cm < z < -46.0 cm



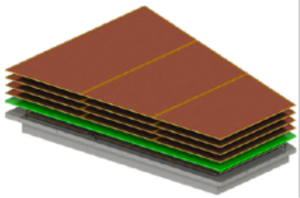
➡ More precise measurements of heavy flavour and low mass dileptons

Time Projection Chamber:

- New readout chambers using GEM
- New electronics for continuous readout (SAMPA)

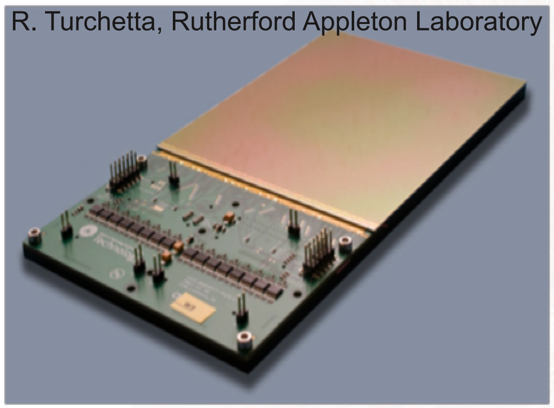


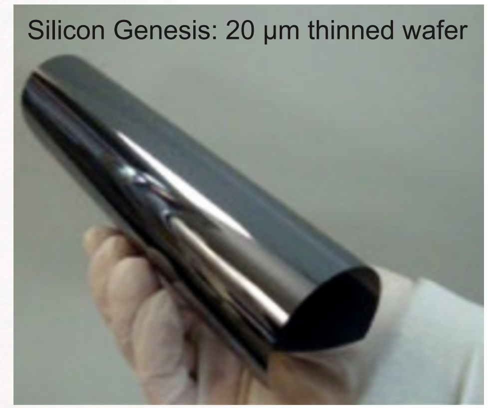
Electron microscope photograph of a GEM foil



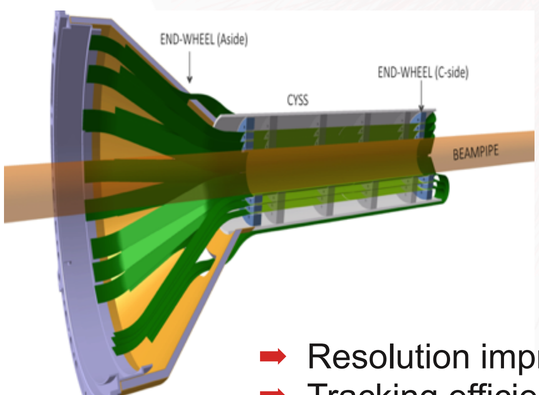
LS3 (2024-26) upgrades - a novel and flexible inner tracking system

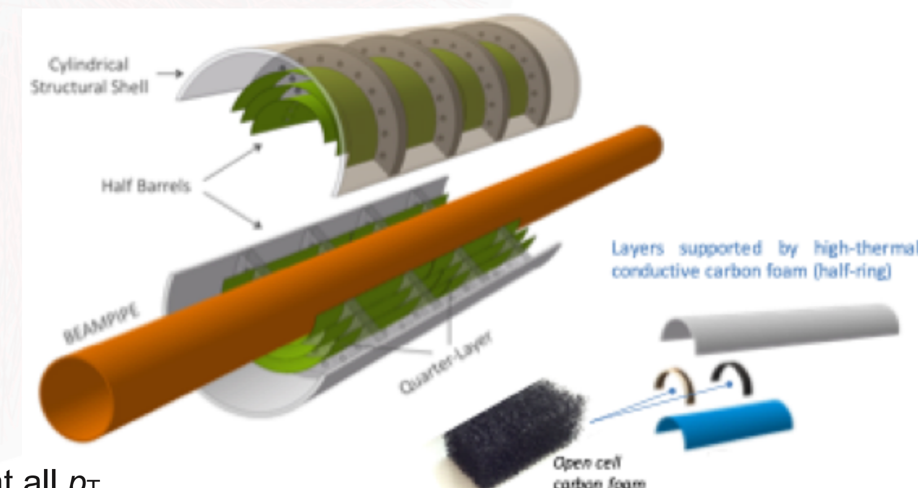
- Reduced material budget → “zero-mass” tracker
- located closer to the beam pipe
- Silicon stitching → fabrication of 10x10 cm^2 sensors
- Thinning to ~30 μm → curved (cylindrical) sensors


R. Turchetta, Rutherford Appleton Laboratory


Silicon Genesis: 20 μm thinned wafer

- Conceptual design, full integration with:
- ITS outer barrels
- MFT





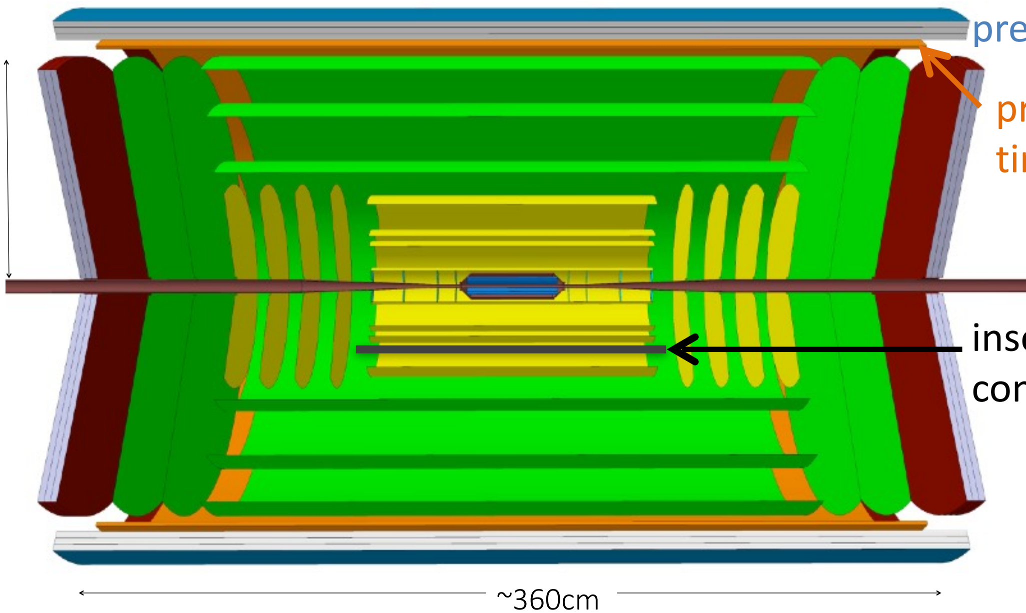
➡ Resolution improved: x2 at all p_T
➡ Tracking efficiency improved: x2 at low p_T (~50 MeV/c)

LS4$^{(2030-31)}$ upgrades - a new "all-MAPS" detector (CDR stage)

ALICE

- ➡ Tracker: ~10 tracking barrel layers (blue, yellow and green) based on CMOS sensors
- ➡ Hadron ID: TOF with outer silicon layers (orange)
- ➡ Electron ID: pre-shower (outermost blue layer)

Extended rapidity coverage:
up to 8 rapidity units + FoCal



Preliminary studies

Magnetic Field
- B = 0.5 or 1 T

Spatial resolution
- Innermost 3 layers: $\sigma \sim 1\mu m$
- Outer layers: $\sigma \sim 5\mu m$

Time Measurement
Outermost layer integrates high precision time measurement ($\sigma_t < 30ps$)

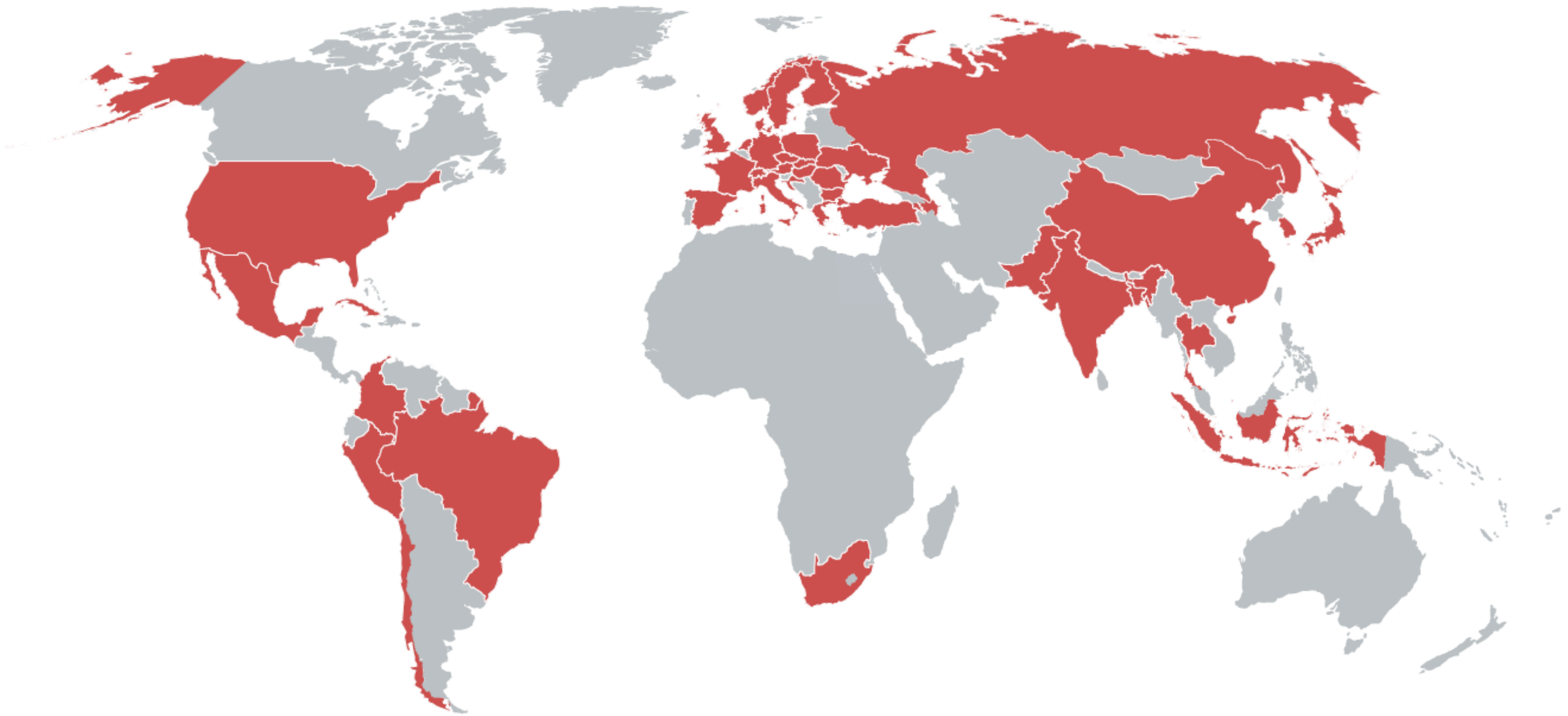
Thermal radiation (dileptons and photons)
- ➡ Characterisation: temperature, size and shape of thermal source vs. time

Heavy flavour, quarkonia
- ➡ detailed study of heavy quarks recombination and b-quark diffusion coefficient

Softest pions
- ➡ coherent production ? Bose-Einstein condensate ? Disoriented chiral condensate ?

ALICE - The Collaboration

41 countries, 176 institutes, 1898 members



Thanks for your attention !