The Quark Gluon Plasma at the LHC
Current status and future

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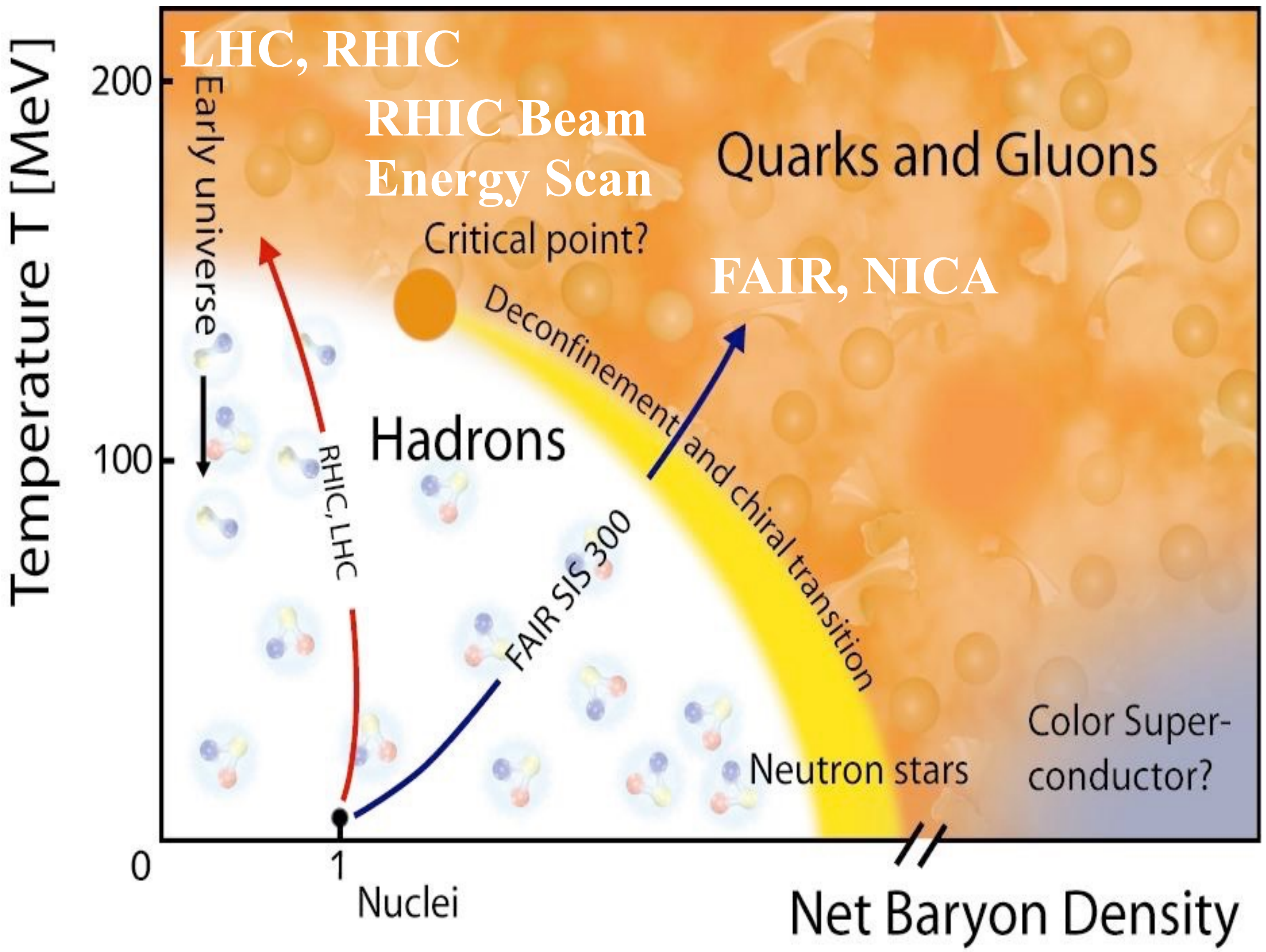
Latest LHC results on Quark-Gluon Plasma

- Why heavy-ion collisions at the Large Hadron Collider?
- Characterizing the Quark-Gluon Plasma
- Selected results… strongly ALICE biased!
- What next?

Why heavy-ions at the LHC?

QCD phase diagram



Nuclear matter at high temperature and high density = Quark Gluon Plasma (QGP)

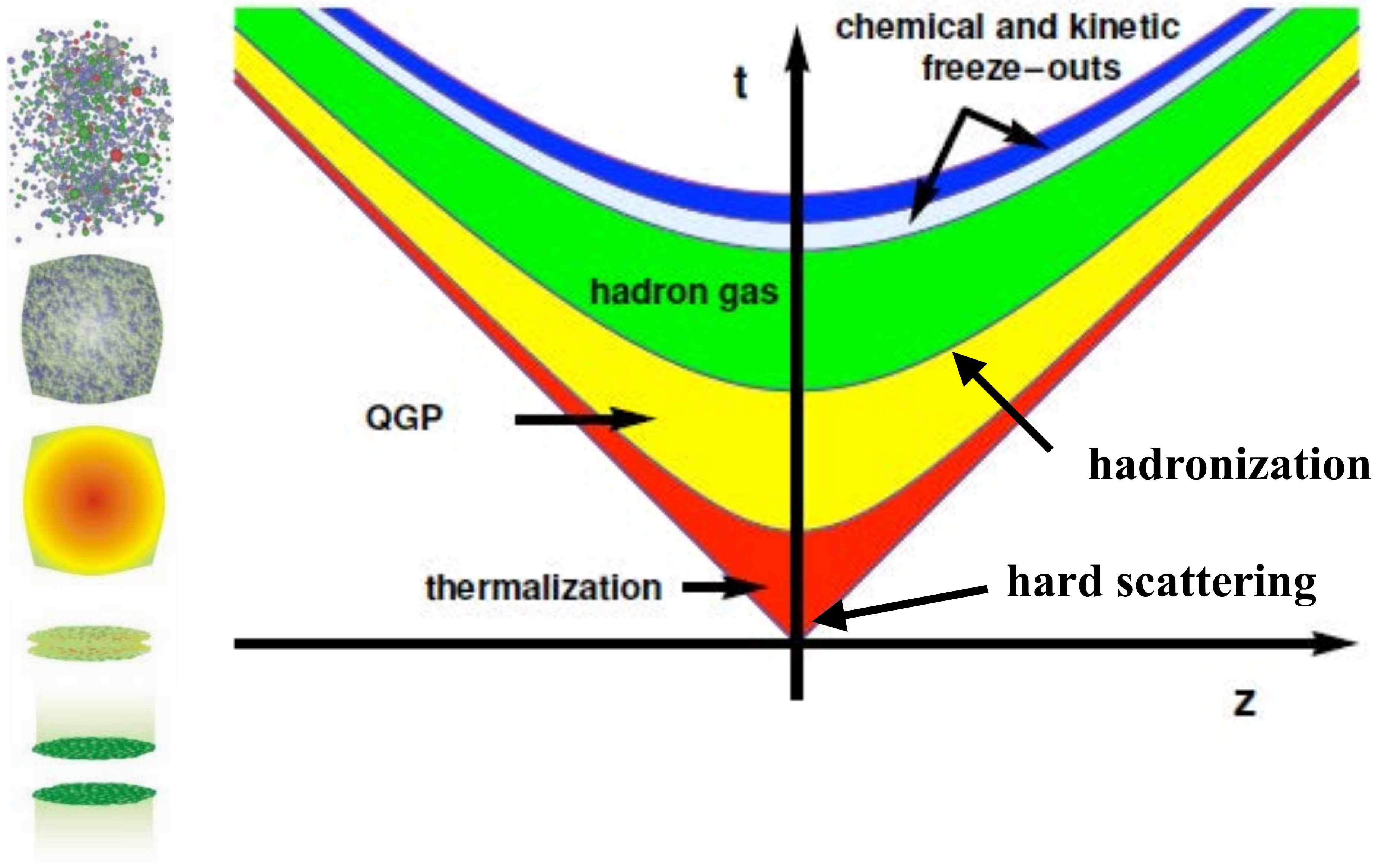
- Partons are deconfined (not bound into composite object)
- Chiral symmetry is restored (partons are massless)
- Behaves as a fluid (well described by hydrodynamics)

At LHC energies: most particles produced during the collisions → very low net baryon density

From lattice QCD: phase transition near T_c = 170 MeV (ε_c = 1 GeV/fm^3)

Heavy-ion collision experiments: search for the QGP phase and characterize it

Space-time evolution of the collision



τ ≃ 20 fm/c
Kinetical freeze-out
Chemical freeze-out

τ ≃ 10 fm/c $T < T_c$
Hadron gas

τ ≃ 1 fm/c $T > T_c$
Thermalized QGP

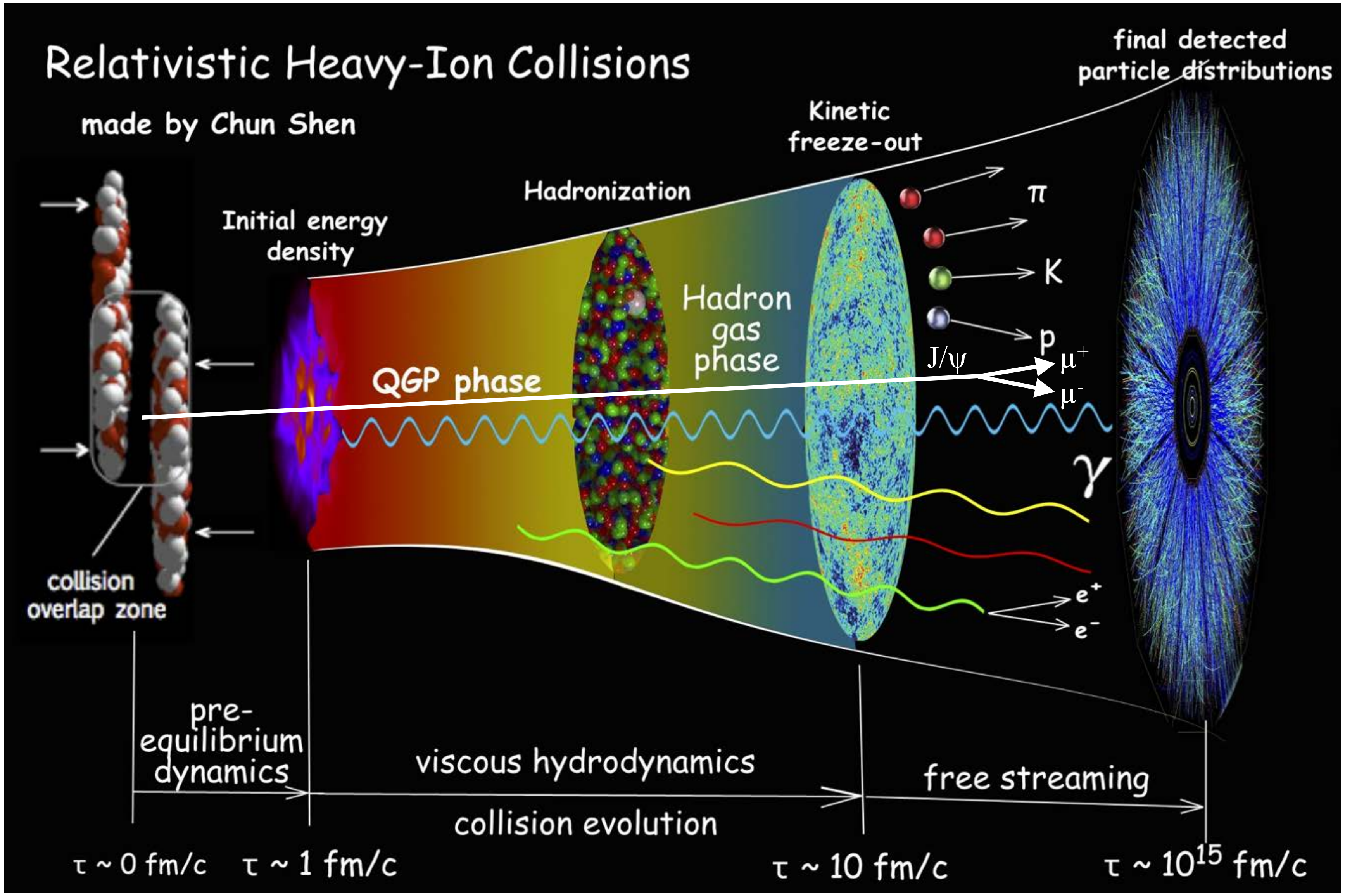
τ ≃ 0
Heavy-ion collision

LHC size and time numbers
1 fm/c ~ 3 10^{-24} s

QGP volume (at decoupling) ≃ 300 fm^3

At high energy: large, hot, dense and long life-time plasma

Characterizing the QGP

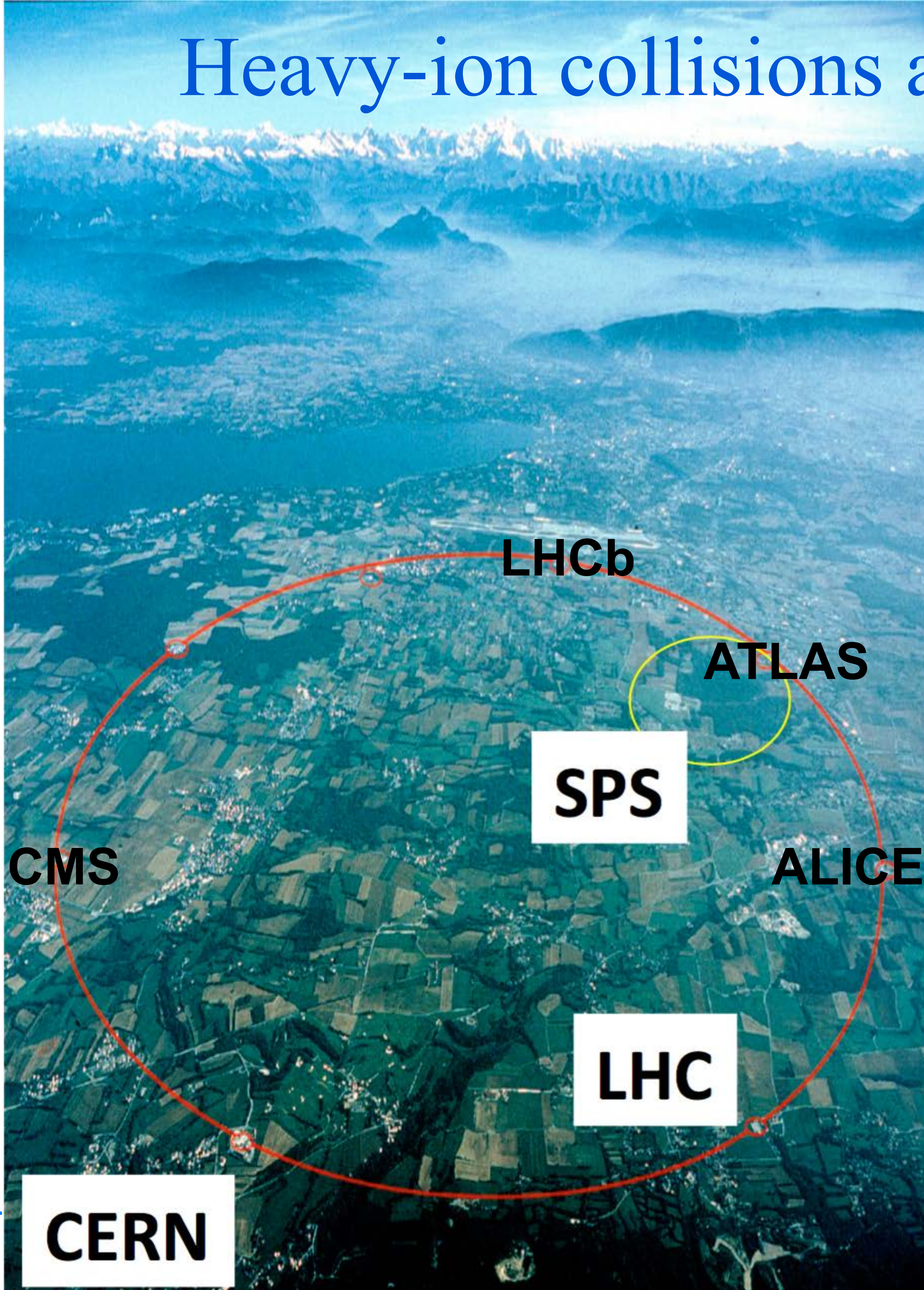


Various probes:

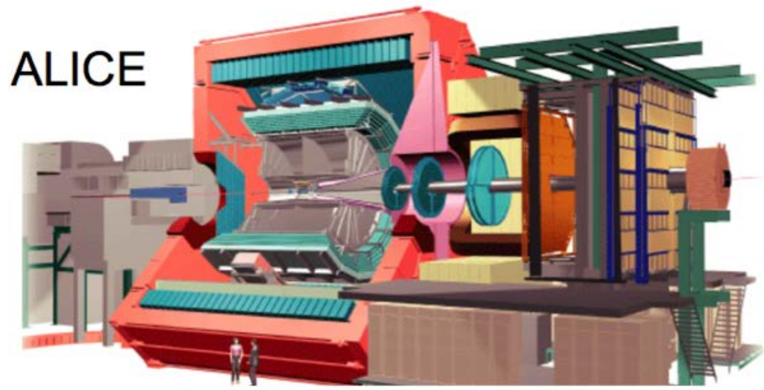
- soft probes (low momentum particles) → medium expansion and hadronization
- electromagnetic radiation (low momentum photons and low mass dileptons) → medium temperature
- high momentum particles and jets → medium opacity and transport coefficients
- quarkonia → QCD potential in medium
- …

Goal: combination of many measurements to sign and characterize the QGP

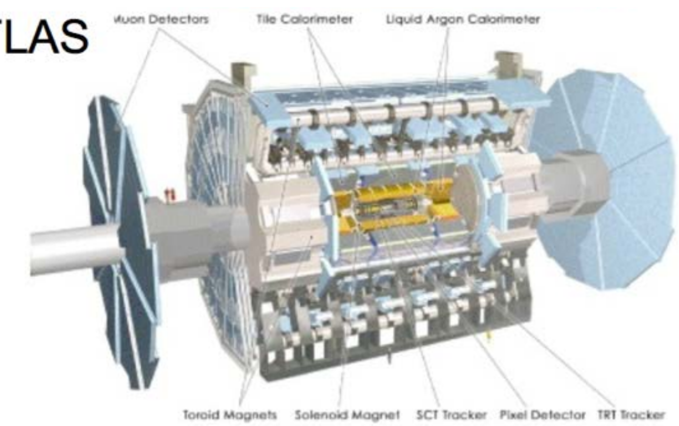
Heavy-ion collisions at the LHC



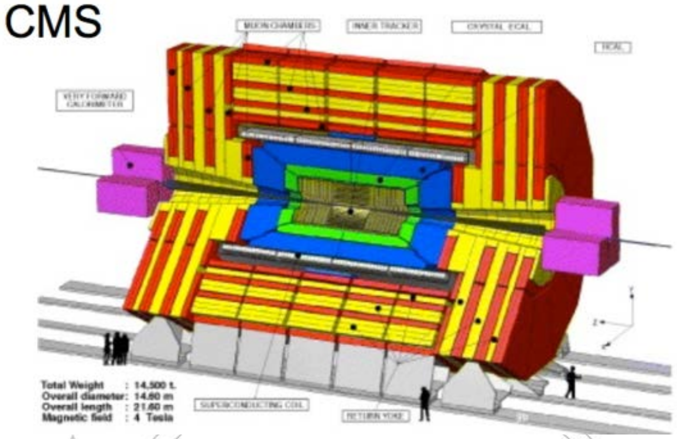
ALICE



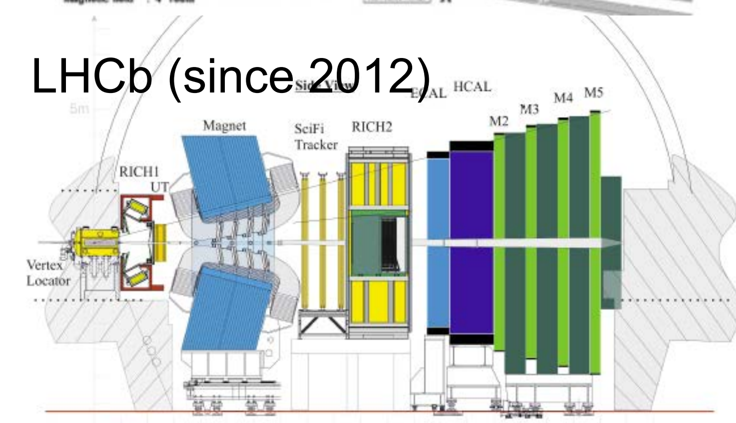
ATLAS



CMS



LHCb (since 2012)



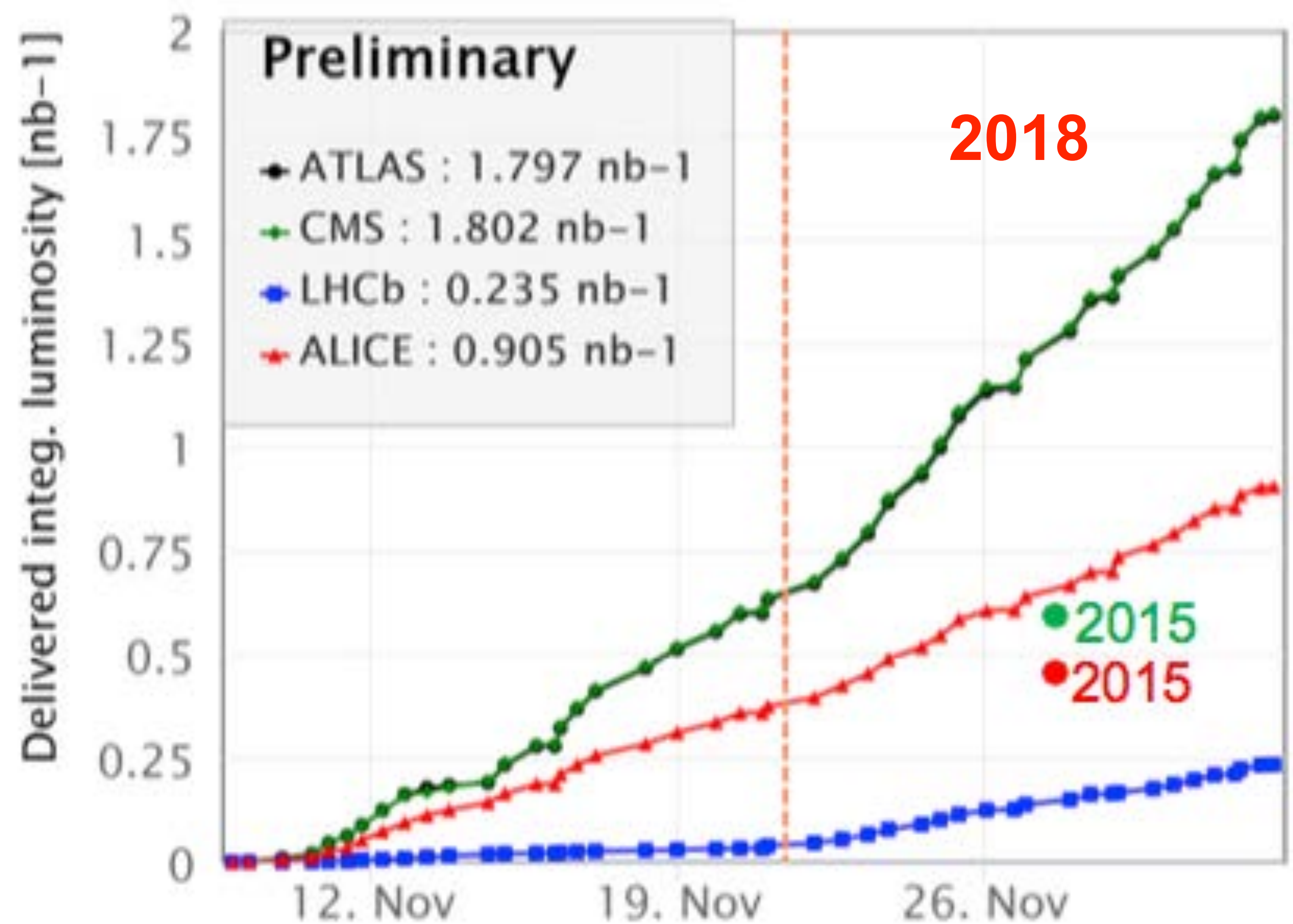
Data samples in LHC Run1 and 2

Heavy-ion collision programme:

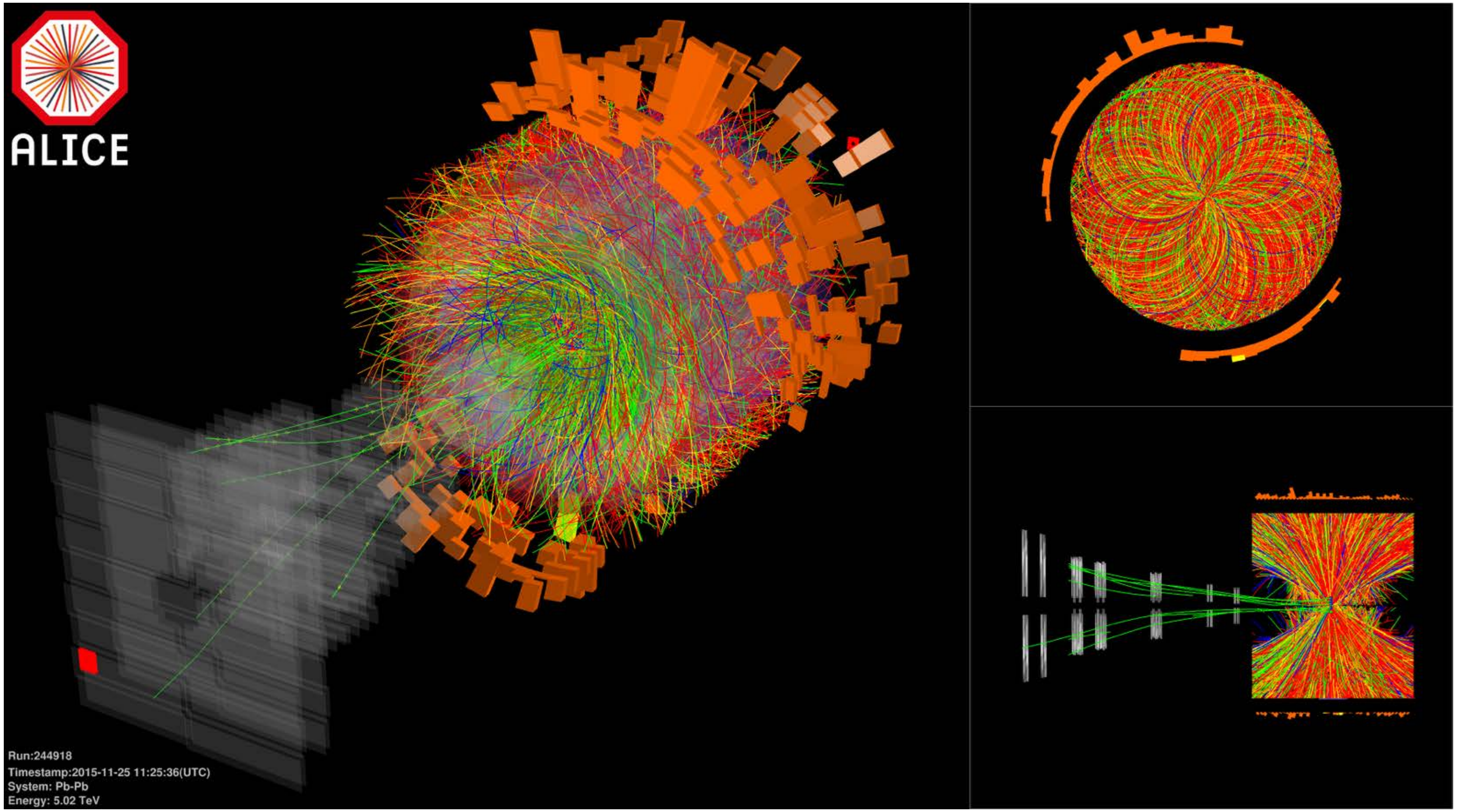
- Pb-Pb: hot nuclear matter formed in central collisions
- pPb: cold nuclear environment (initial/final state)
- pp: test of production models and reference for Pb-Pb and pPb at same energy
- $L_{pp} = A^2 \times L_{AA}$ for rare probes

System	Year	$\sqrt{s_{NN}}$ (TeV)
Pb-Pb	2010-2011	2.76
	2015	5.02
	2018	**5.02**
Xe-Xe	2017	5.44
p-Pb	2013	5.02
	2016	5.02, 8.16
p-p	2011, 2013	**2.76***
	2015, 2017	**5.02***
	2010-2013	7, **8***
	2015-2018	13

***pp reference runs**



Central Pb-Pb collisions in ALICE



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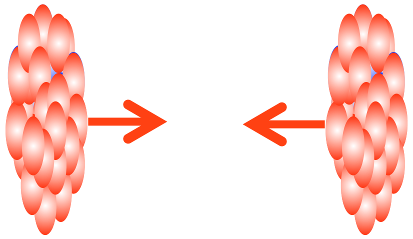
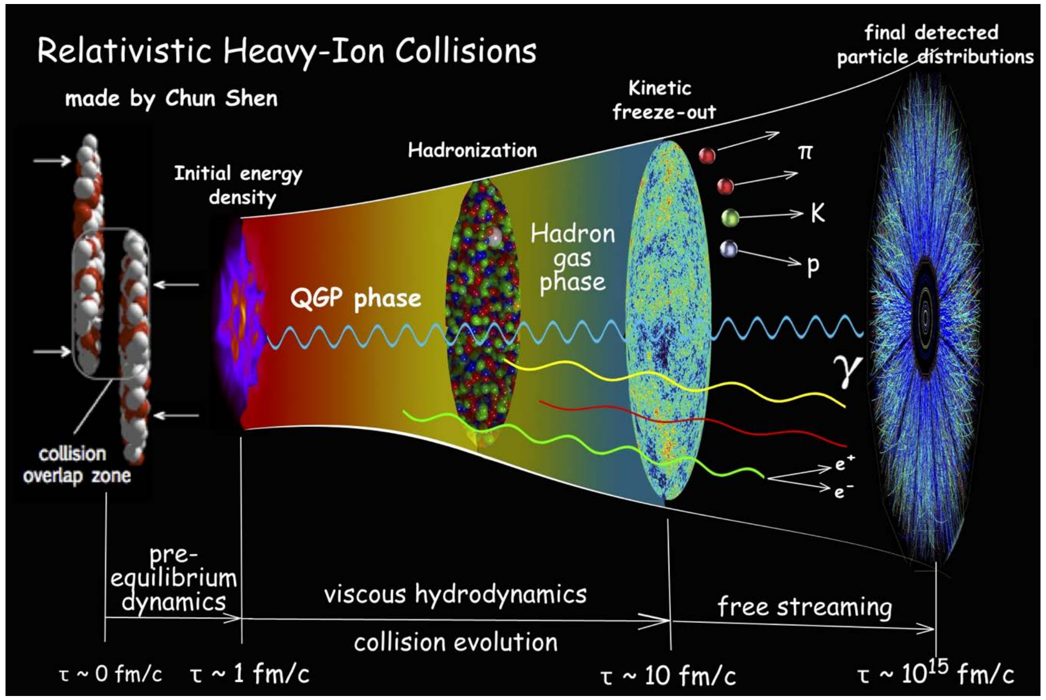


~20k charged particles in 5% most central Pb-Pb collisions!

ALICE Coll. Phys.Lett. B772 (2017) 567-577

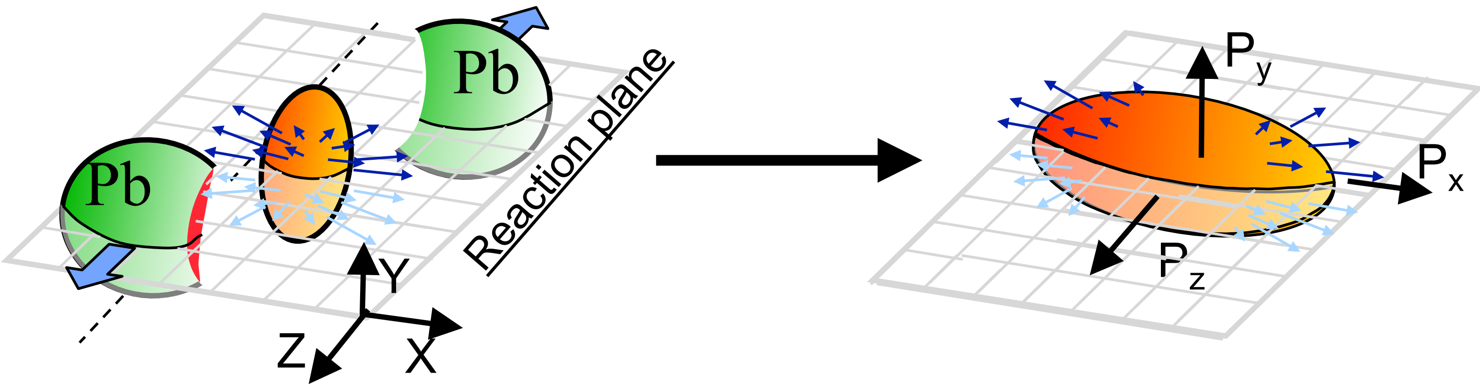
Selected results on LHC Run 1 and 2 heavy-ion campaigns

Identified/charged « soft » particles



Particles at low momenta: probe expansion and hadronization of the QGP

Overlap region in semi-central heavy-ion collisions is asymmetric, in « almond » shape: for interacting matter, spatial asymmetry leads to a momentum anisotropy of final-state particles

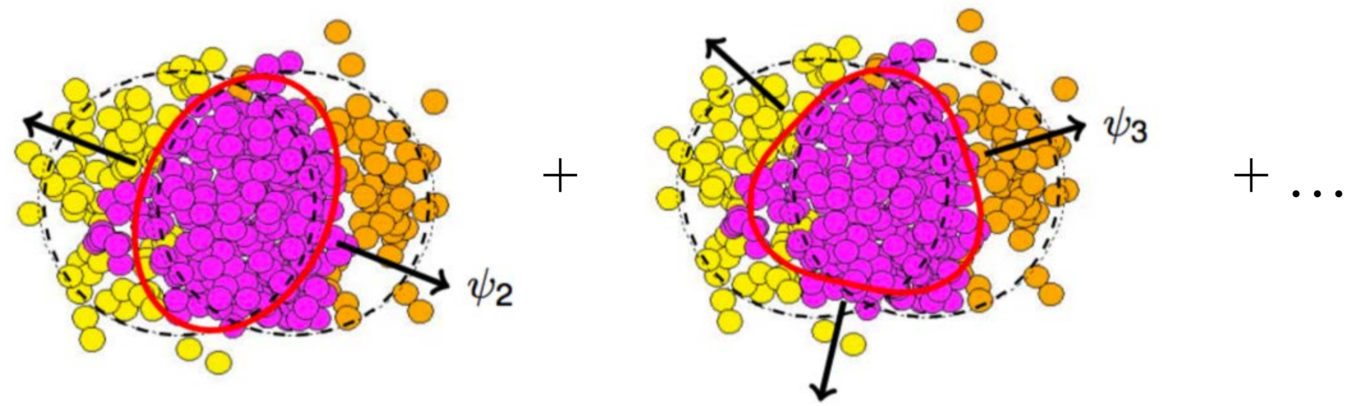


Azimuthal dependence of the particle yield:

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

Ψ_n: symmetry planes

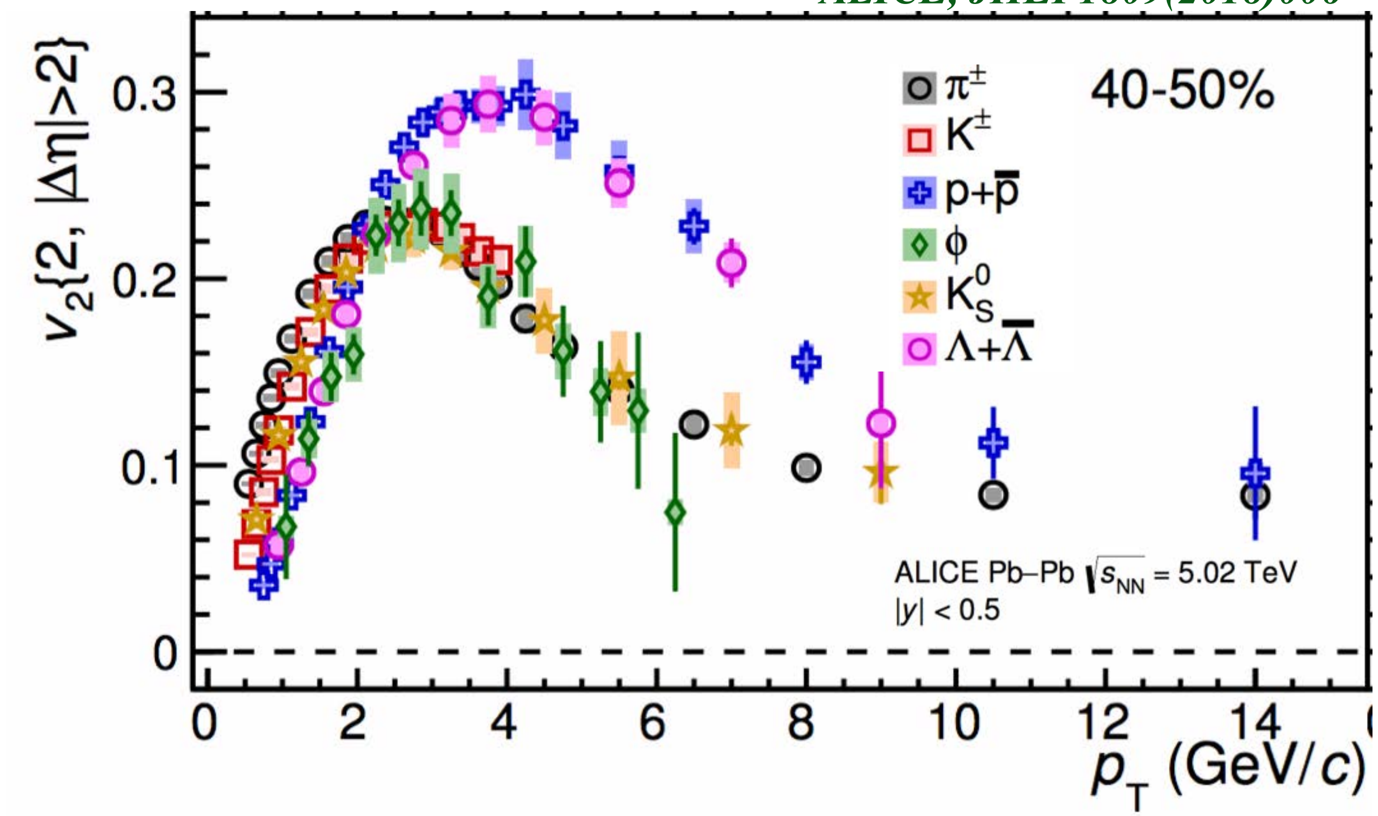
n = 2: elliptic flow   n = 3: triangular flow

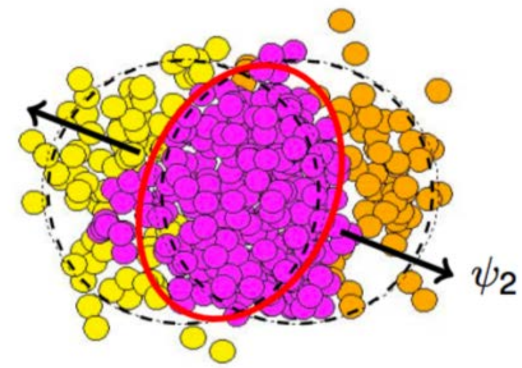


Anisotropic flow is sensitive to the initial geometry and energy density fluctuation, and to the properties of the produced medium

Identified particle flow

ALICE, JHEP1809(2018)006





- Large flow for soft probes in semi-central Pb-Pb collisions confirmed at LHC: QGP is an almost perfect fluid with low viscosity
- Mass ordering at low $p_T < 2$ GeV/c → hydrodynamic flow, very small fluid viscosity
- Baryon vs meson flow at higher p_T : flow at quark-level and recombination?

From data to QGP properties

From measured charged particles spectra and flow to the properties of the QGP fluid with a Bayesian procedure *S. Bass et al., arXiv:1808.02106*

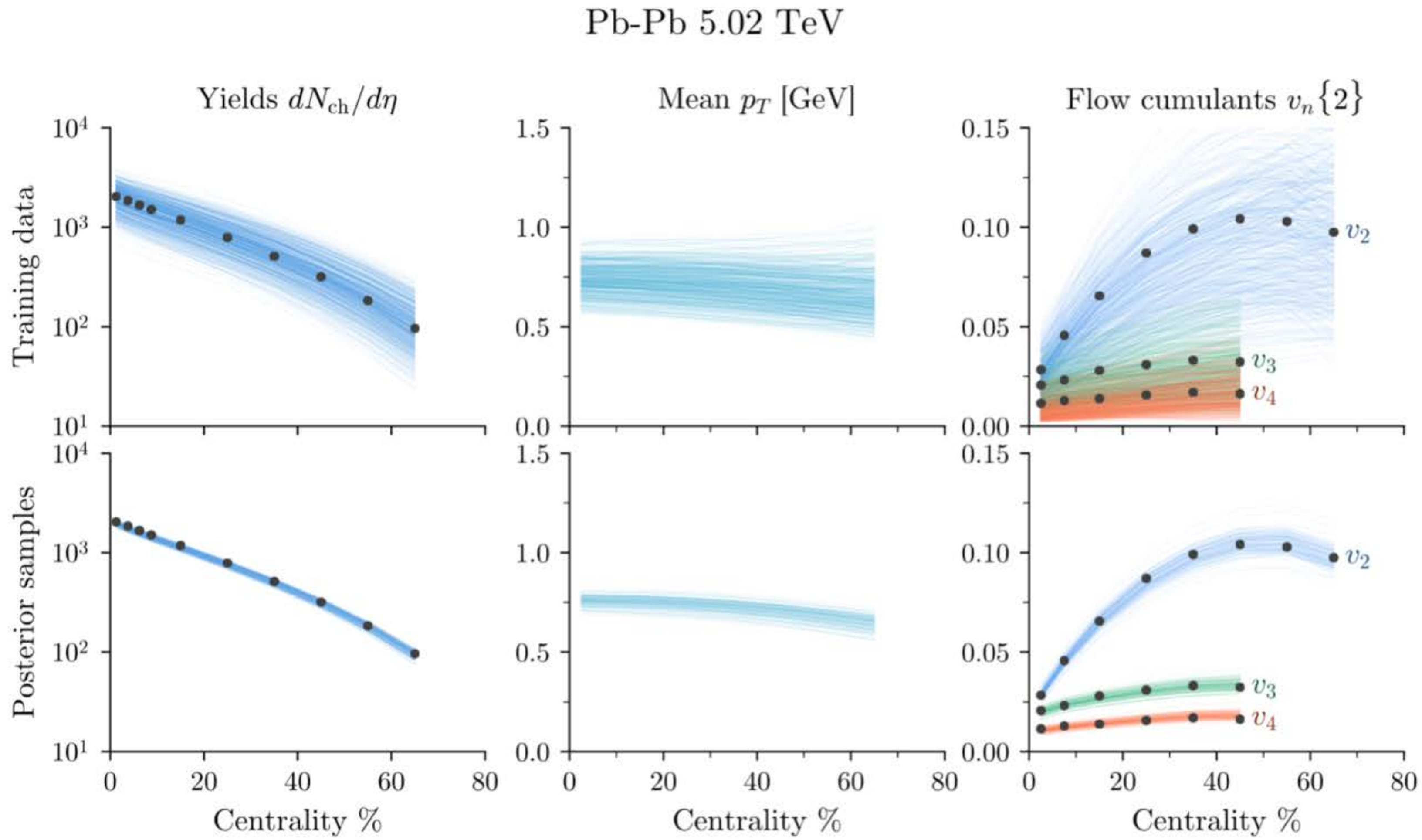


FIG. 7 Simulated observables compared to experimental data for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Top row: explicit model calculations (no emulator) for each of the $d = 500$ design points; bottom row: emulator predictions for $n = 100$ random samples drawn from the posterior. Points with error bars are experimental data from ALICE with statistical and systematic errors added in quadrature [72, 74].

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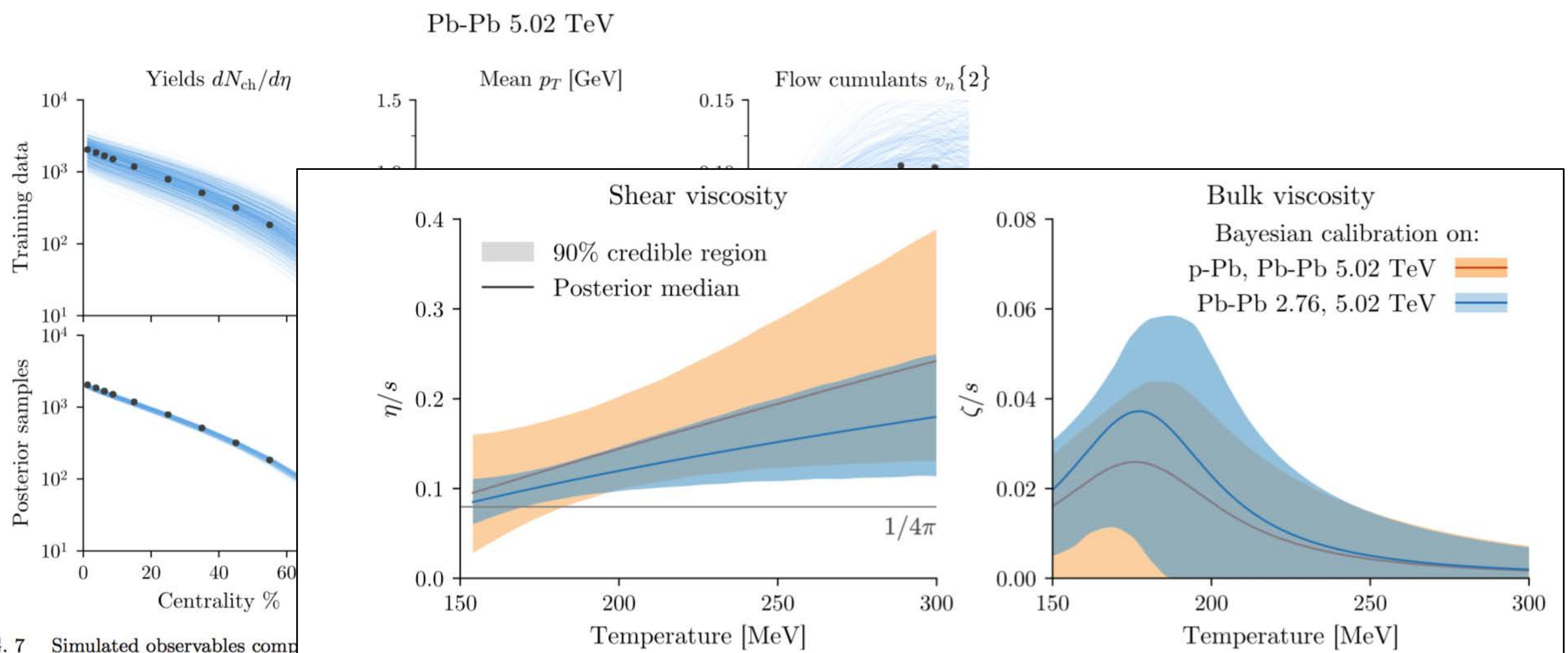

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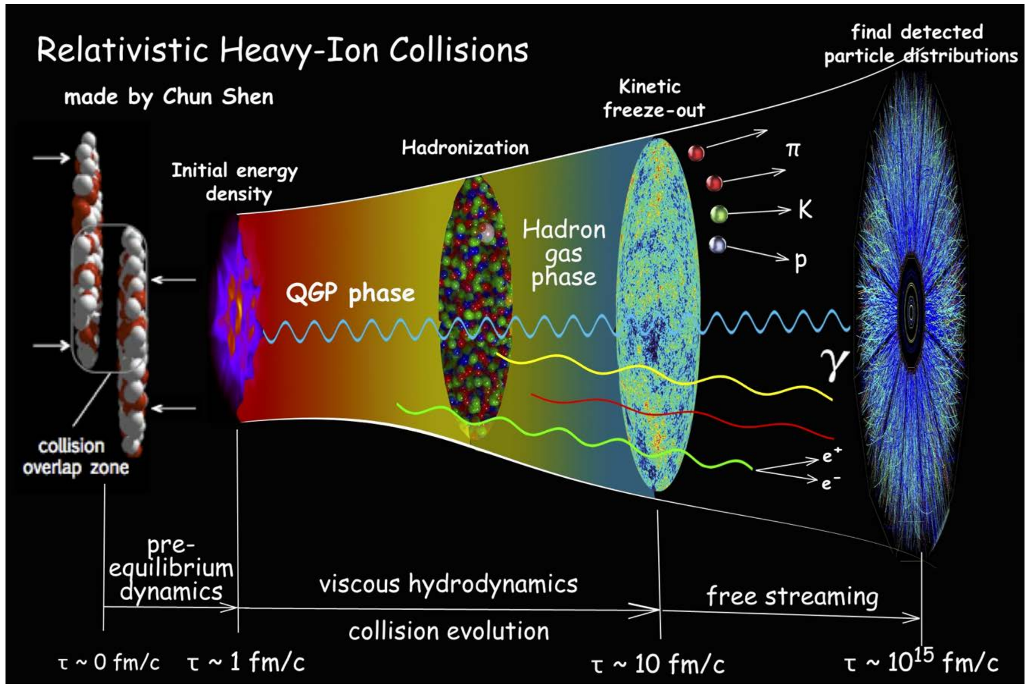
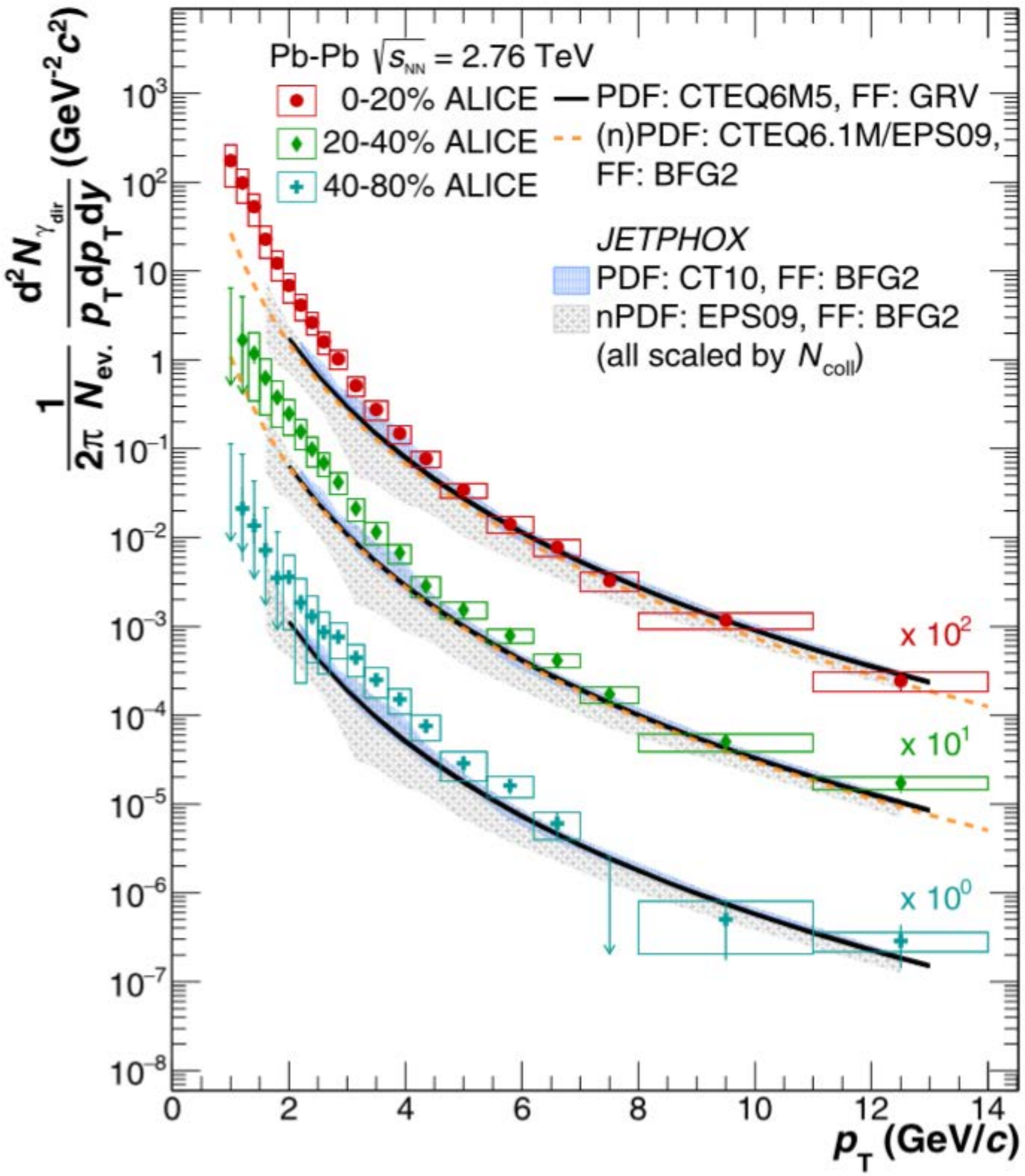
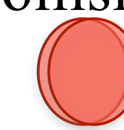
Thermal radiation

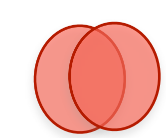


ALICE, PLB 754 (2016) 235-248



central collisions

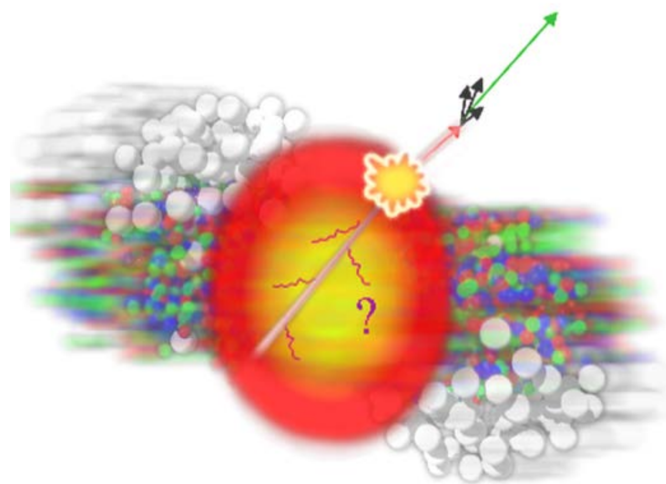




- Photons do not interact with the color charges
- Direct photon yield at low p_T give access to thermal photons emitted by QGP and hadronic gas
- In most central collisions: excess of low p_T direct photons wrt pQCD calculations
- p_T-spectrum described at $p_T < 2.1$ GeV/c by an exponential with an inverse slope parameter: $T_{eff} = (304 \pm 11 \pm 40)$ MeV in central collisions (30% higher than at RHIC)

Jet quenching from charged particles

Jets are quenched from gluon radiation of partons crossing the medium: measure jets or high p_T particles

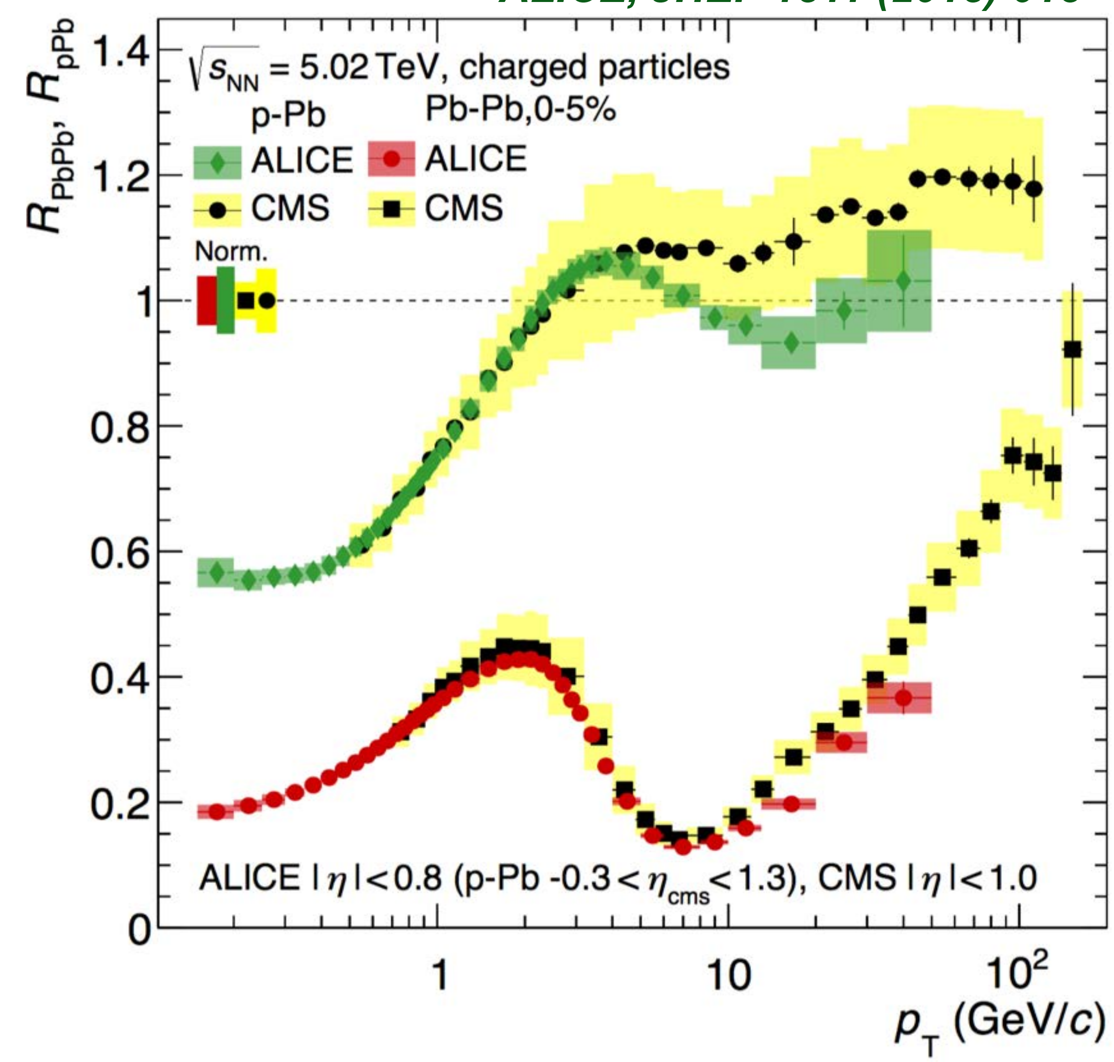


Nuclear modification factor

$$R_{AA} = \frac{dN^{AA}/dp_T dy}{\langle N_{coll} \rangle \, dN^{pp}/dp_T dy}$$

- $R_{AA} = 1$: no modification
- $R_{AA} < 1$: suppression
- $R_{AA} > 1$: enhancement

ALICE, JHEP 1811 (2018) 013

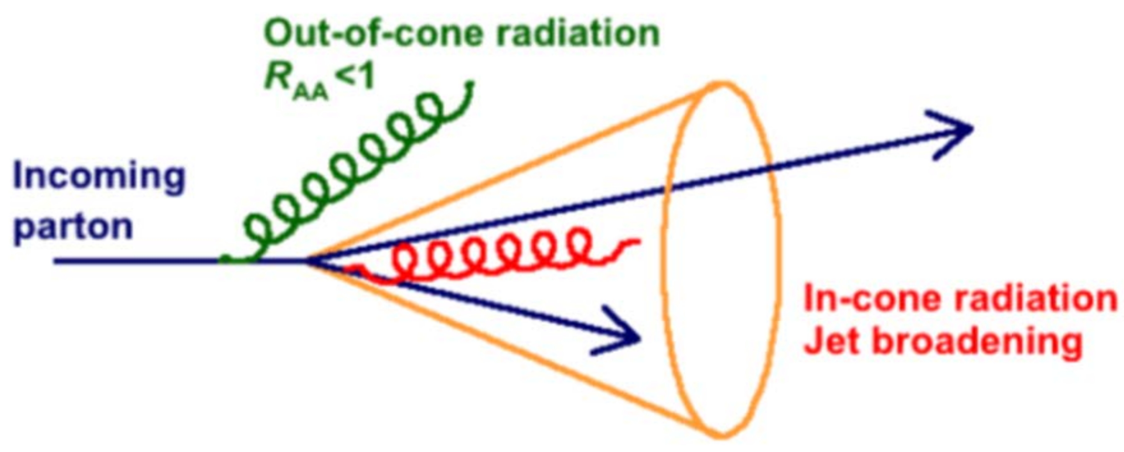


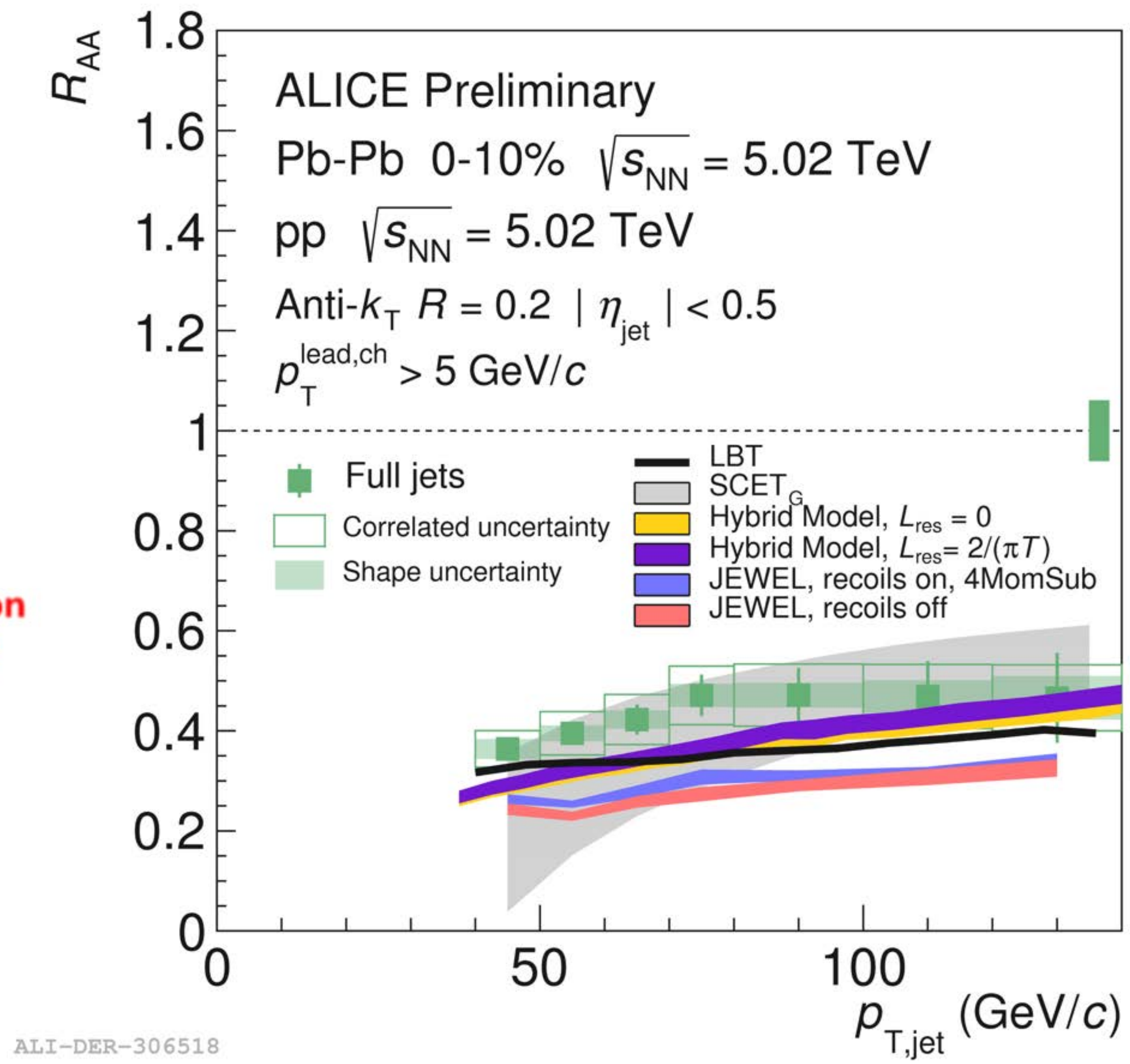
– At high p_T, R_{PbPb} as low as 0.13 → suppression of charged particles from final-state parton energy loss in the hot medium, medium opaque to color probes

– R_{pPb} consistent with unity → effect observed in Pb-Pb is a final-state effect from hot medium

Full jet reconstruction

Full jet reconstructed within a cone



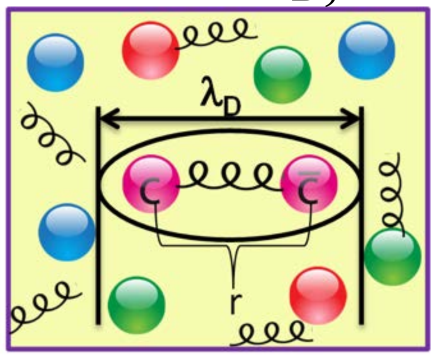


- High suppression of jet production over a large p_T range
- R_{AA} < 1 suggests that the radiated energy is not recovered within the jet cone: large angle and/or low p_T

Probing QGP with quarkonia

- Quarkonia: $c\bar{c}/b\bar{b}$ pair produced in the initial hard collisions
- At $T >> 0$, high density of colour charge in the medium induces Debye screening
- At $T > T_D$, melting of quarkonium state *Matsui, Satz PLB178(1986)*
- Since quarkonia (J/ψ, ψ(2S), Υ(nS),…) have different binding energy and T_D
  → **sequential suppression** of quarkonium states *Karsch, Satz Z.Phys.C51 (1991) 209*

***T < T*$_D$,**



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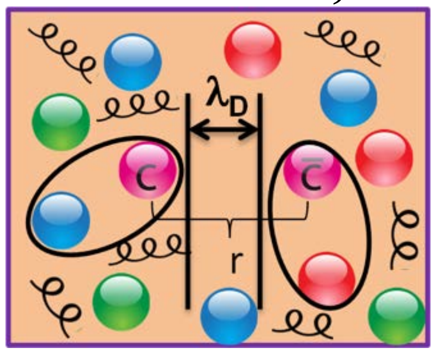
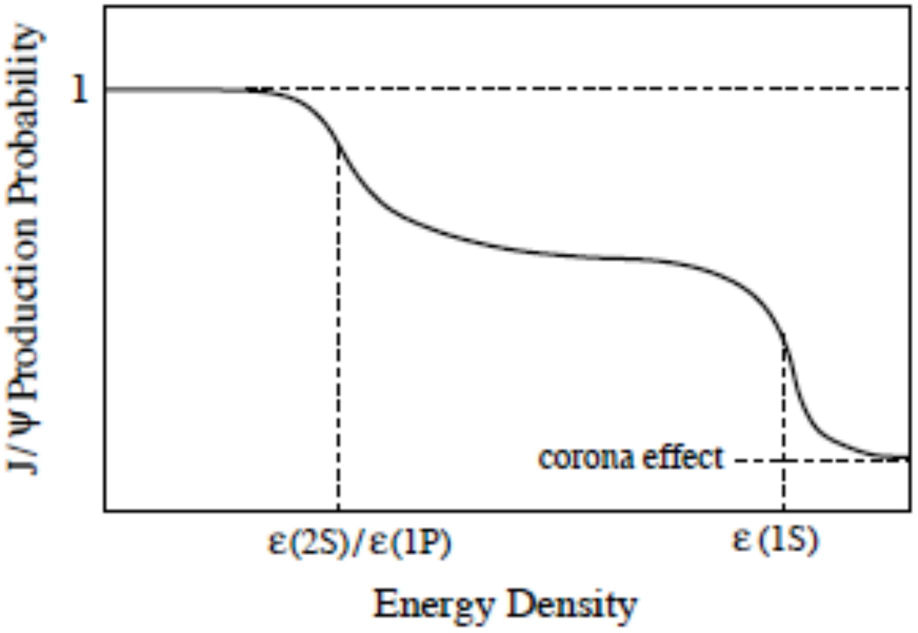


prompt J/ψ in pp ≃ 10% ψ(2S) + 30% χ_C + 60% direct J/ψ



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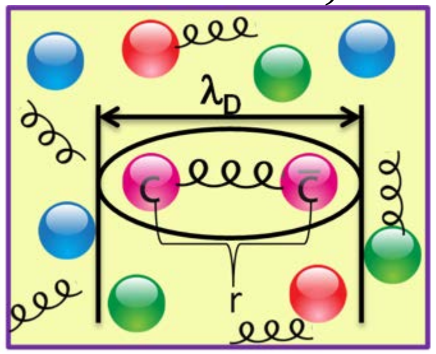

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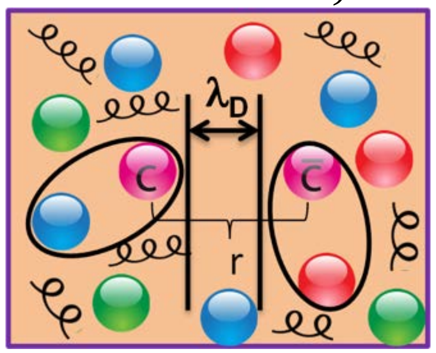

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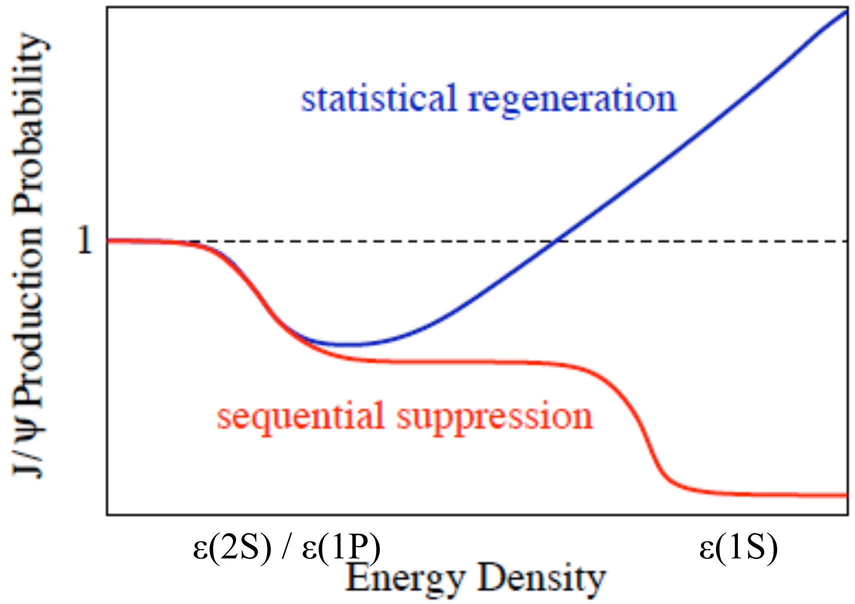


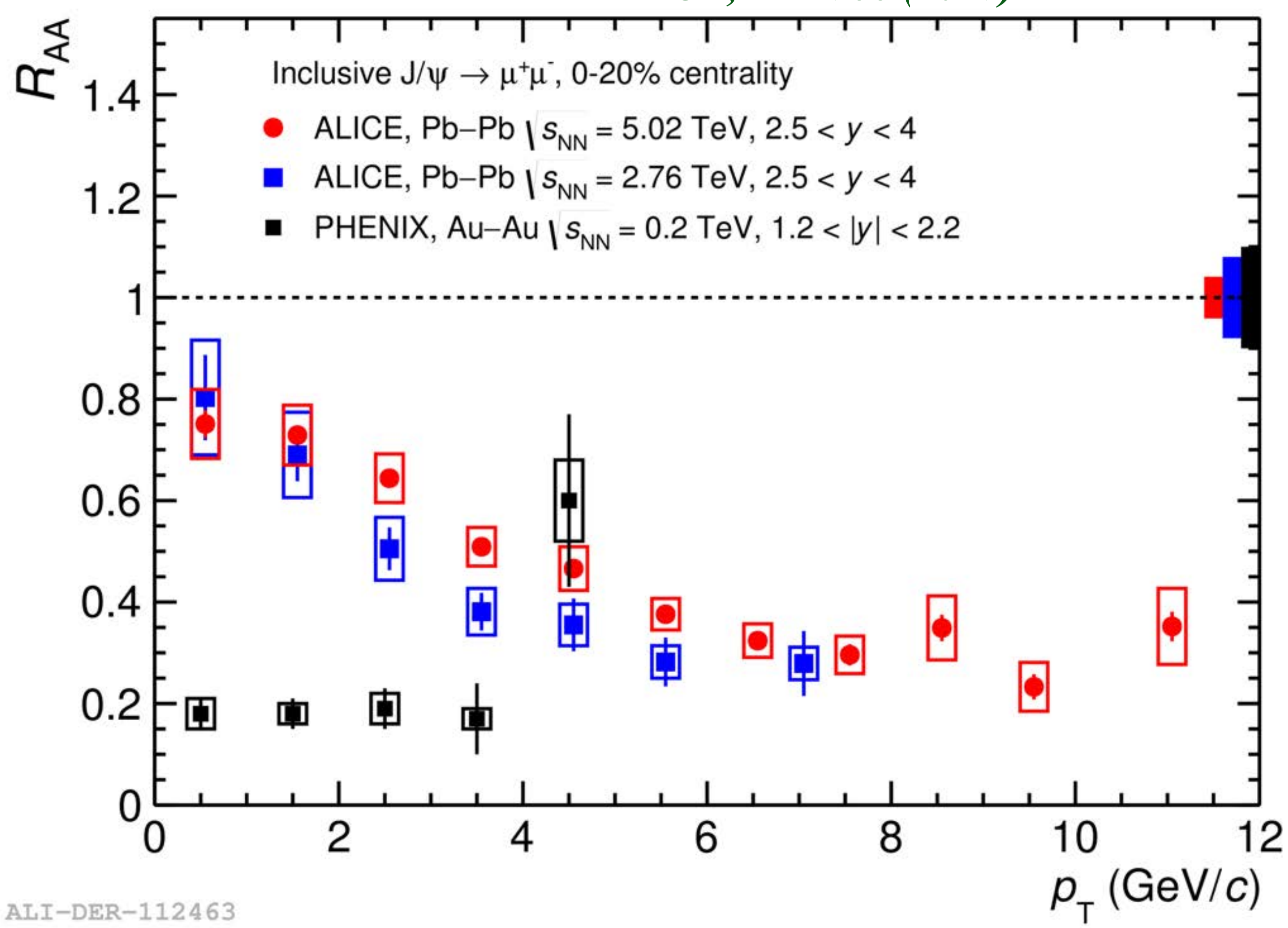
Or regeneration?

- Total charm cross-section increases with energy
- c and $\bar{c}$ combination in the QGP or at the phase boundary
  → regeneration of J/ψ *Braun-Munzinger, Stachel PLB490(2000)* *Thews et al. PRC62(2000)*

➡ J/ψ enhancement (depending on open charm cross-section)
- Small regeneration expected for bottomonia

Quarkonium production

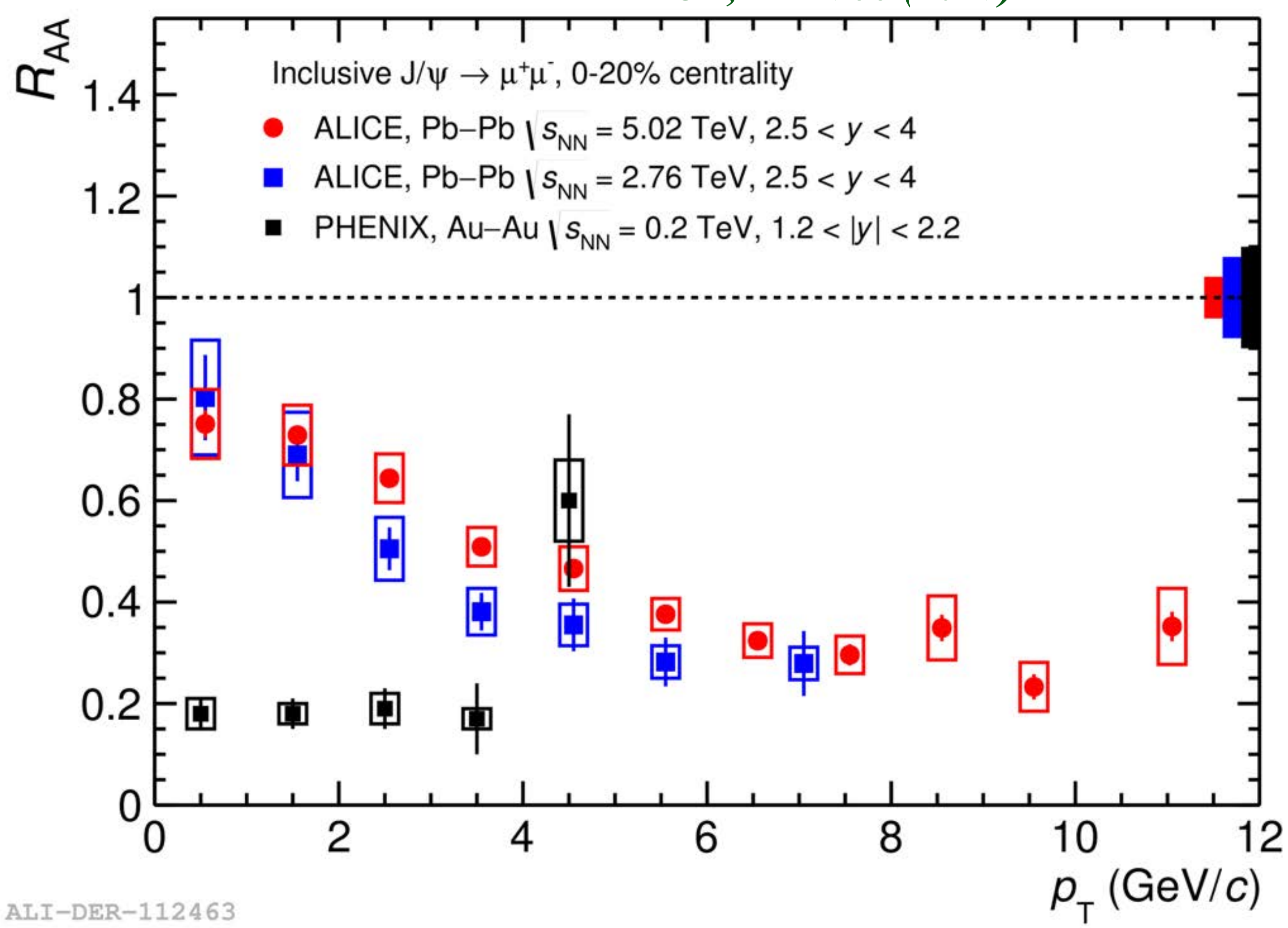
J/ψ production



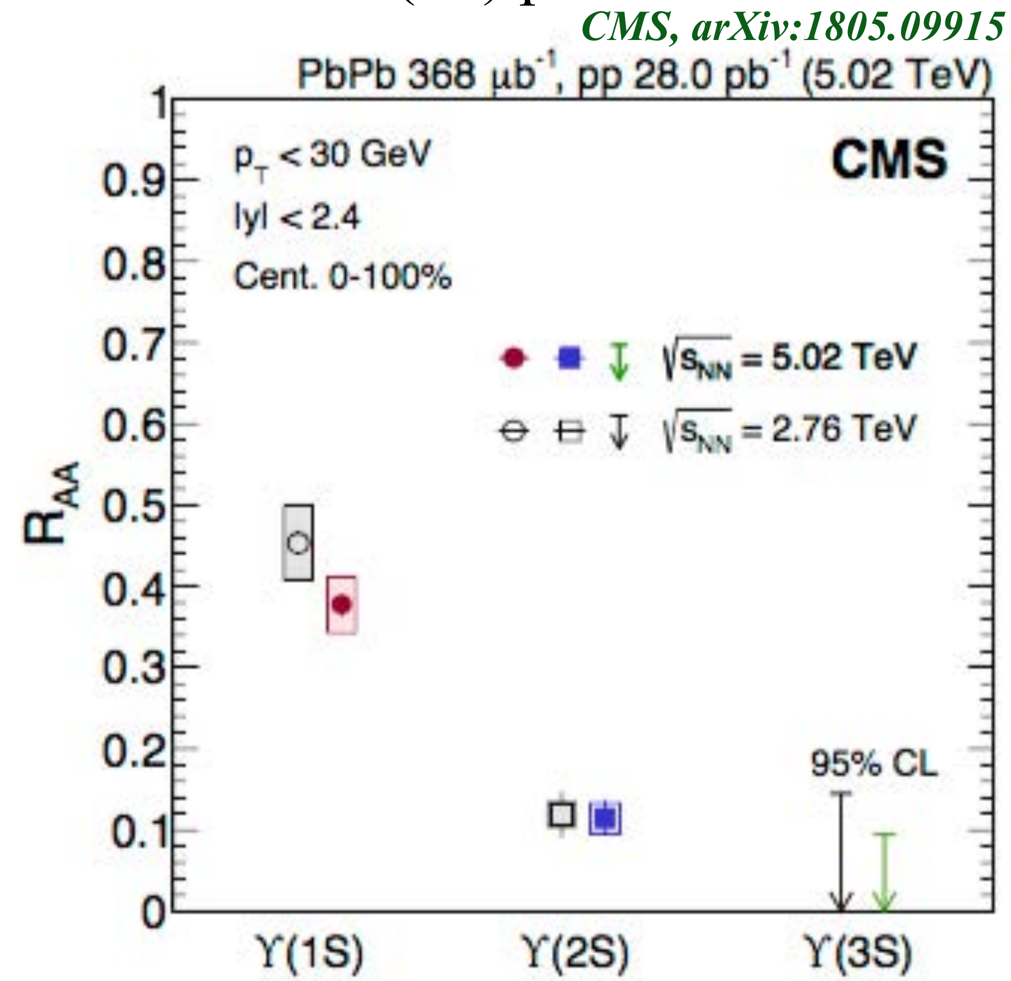
J/ψ suppression at low p_T: less suppression at LHC wrt RHIC → regeneration (low p_T) and color screening (larger p_T) at LHC?

Quarkonium production

J/ψ production



Y(nS) production

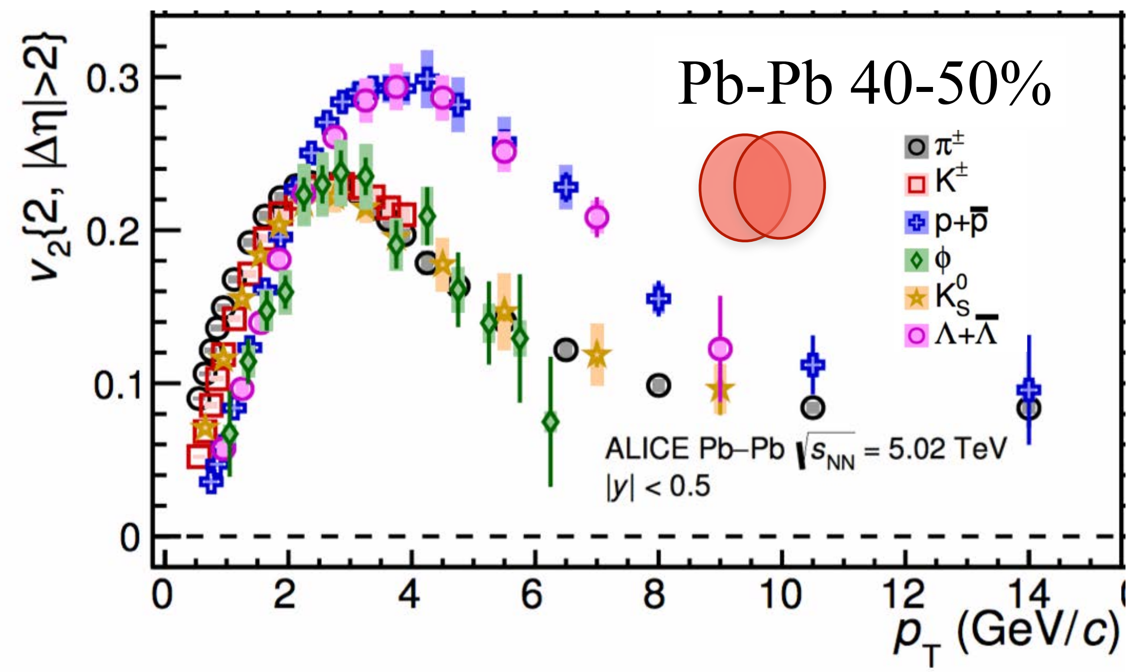


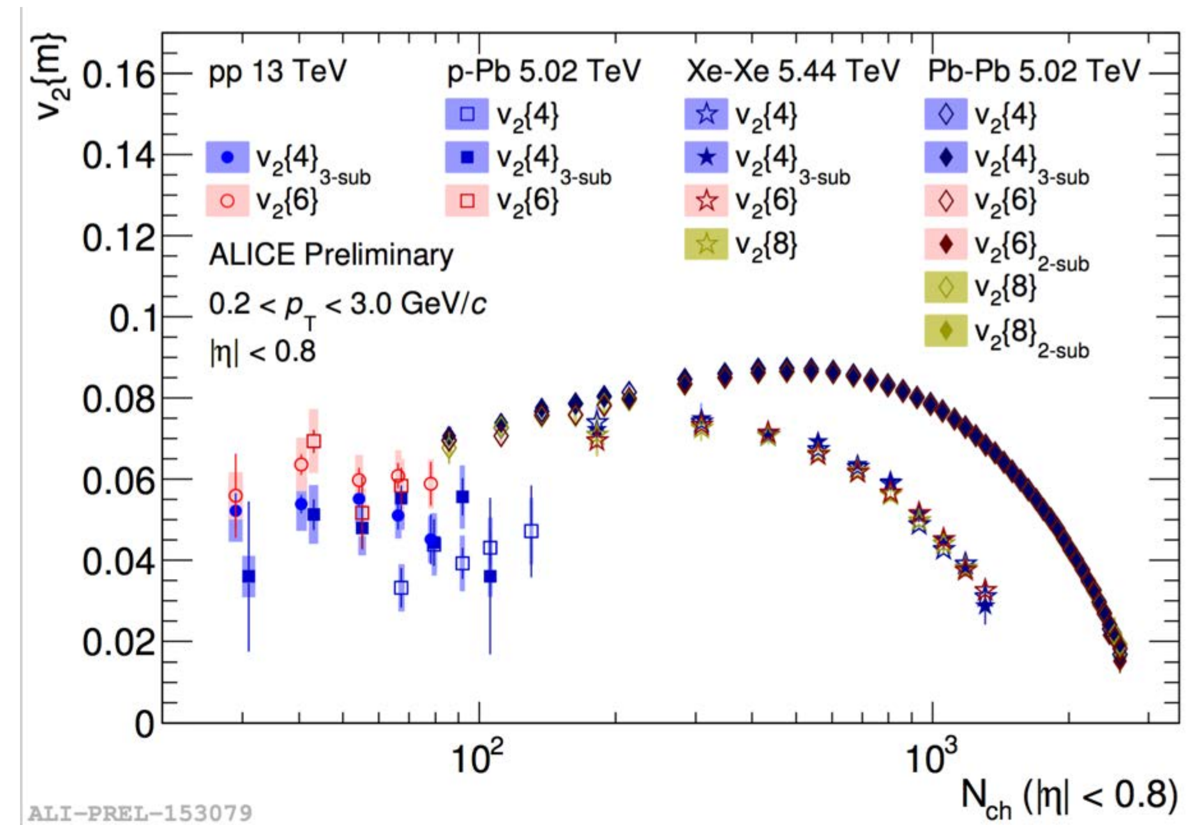
J/ψ suppression at low p_T: less suppression at LHC wrt RHIC → regeneration (low p_T) and color screening (larger p_T) at LHC?

- No sign of Υ(3S)
- Results consistent with sequential suppression of Υ(nS) states: $T_D \approx 3.5T_c$, $1.3T_c$ and $1T_c$ for the Υ(1S), Υ(2S), and Υ(3S) states
- Suppression by comovers (comoving medium) also possible explanation

Unexpected results in pp and p-Pb

pp and p-Pb collisions not as simple: collective-like effects observed in small systems for high multiplicity events





- E.g. similar flow effect in pp and p-Pb, comparable to Pb-Pb at similar event multiplicity and similar behavior for identified charged particles in p-Pb wrt Pb-Pb
- Droplet of QGP in small systems? Or effect from initial-state or hadronisation in high multiplicity environment?

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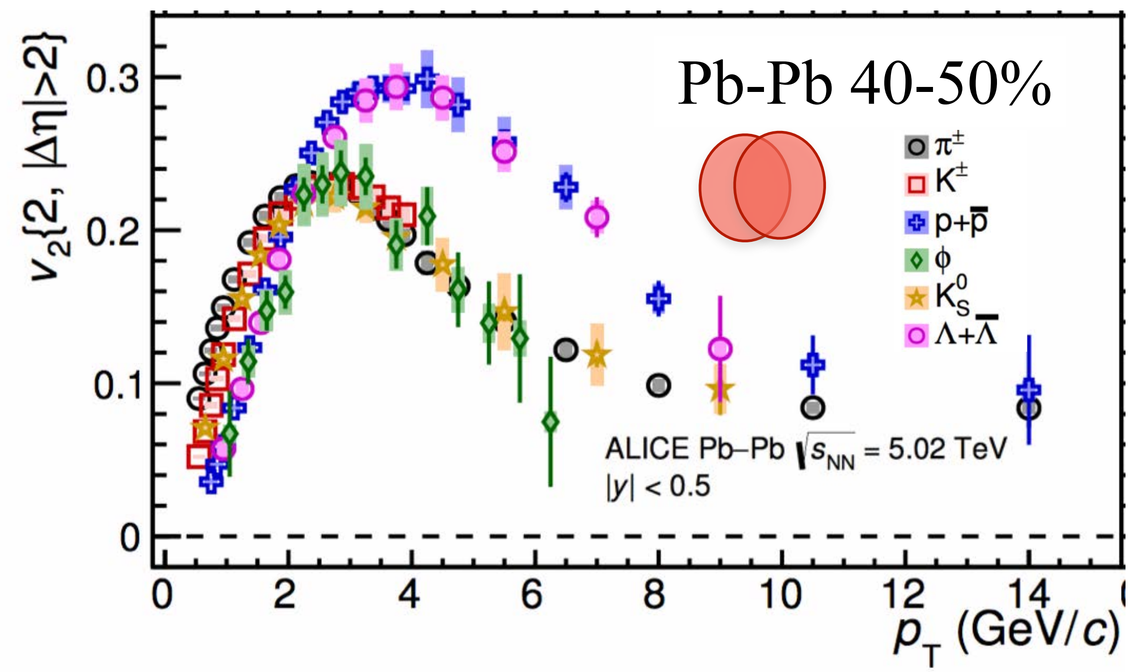

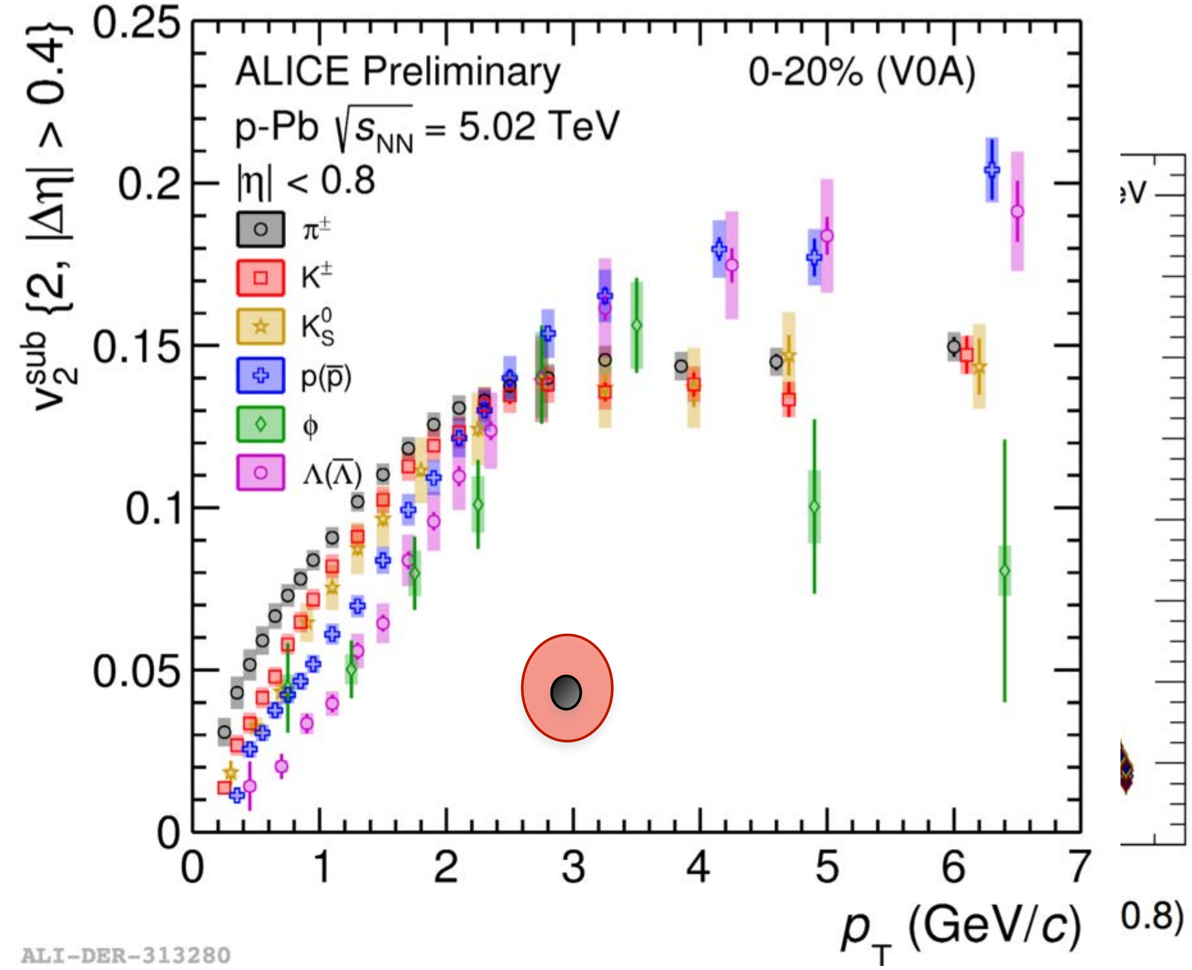

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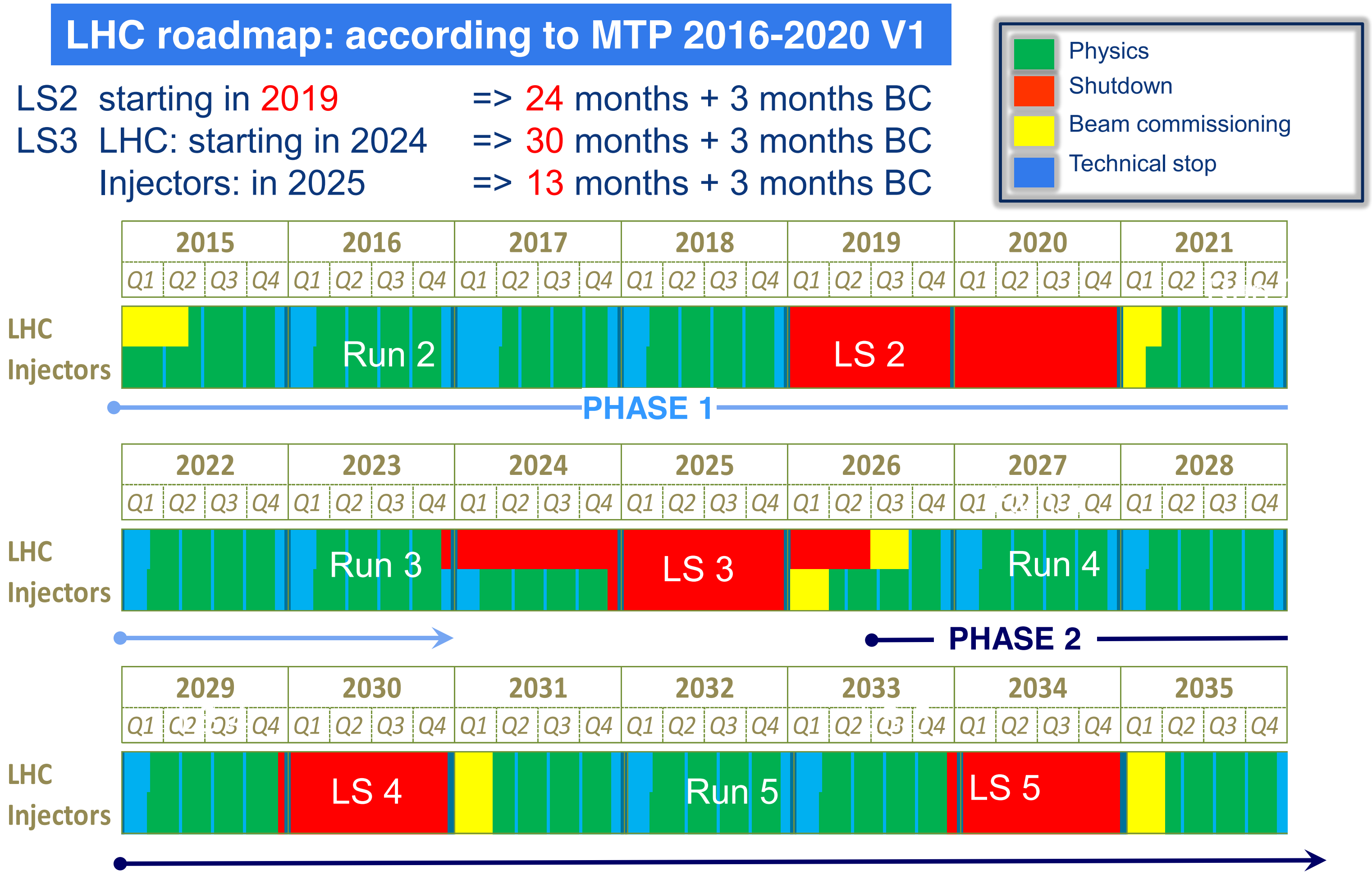
What next at the LHC?

LHC Run 3/4 heavy-ion programme

- Increase in delivered luminosity in Pb-Pb (L_{PbPb}=13/nb) and p-Pb, and pp with low pile-up conditions
- ALICE/ATLAS/CMS/LHCb upgrades
- Fixed-target at LHC (LHCb, ALICE?)

CERN Yellow report
arXiv:1812.06772



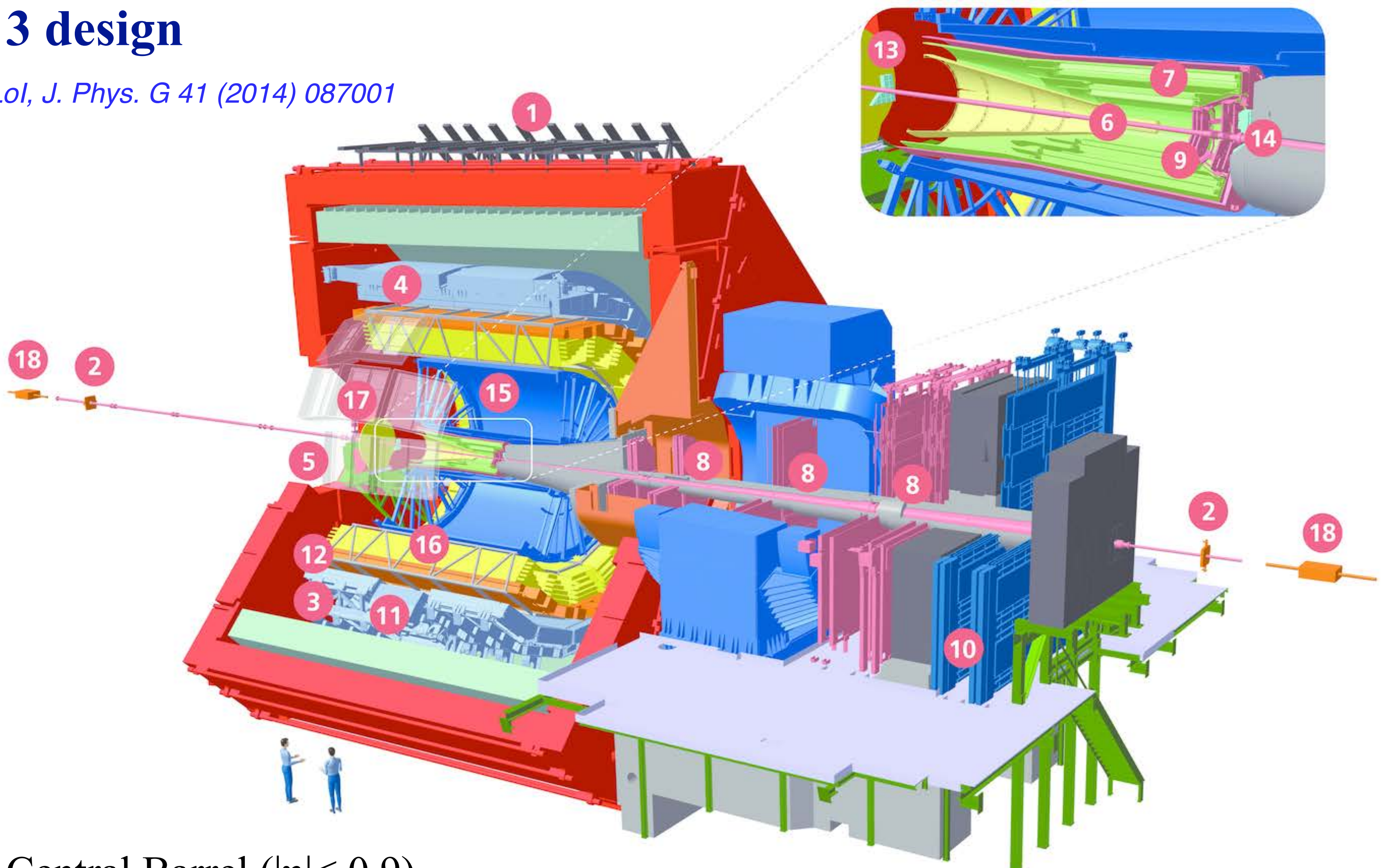
Beyond 2030 (LHC Run 5/6)

- Possible new detectors in ALICE
- Upgrade of LHCb
- Lighter ions in LHC?
- HE-LHC (LHC $\sqrt{s_{NN}}\times2$)
- FCC-hh (LHC $\sqrt{s_{NN}}\times7$)

ALICE upgrade

Run 3 design

ALICE LoI, J. Phys. G 41 (2014) 087001



1. **ACORDE** | ALICE Cosmic Rays Detector
2. **AD** | ALICE Diffractive Detector
3. **DCal** | Di-jet Calorimeter
4. **EMCal** | Electromagnetic Calorimeter
5. **HMPID** | High Momentum Particle Identification Detector
6. **ITS-IB** | Inner Tracking System - Inner Barrel
7. **ITS-OB** | Inner Tracking System - Outer Barrel
8. **MCH** | Muon Tracking Chambers
9. **MFT** | Muon Forward Tracker

- Central Barrel ($|\eta| < 0.9$)
- Muon Spectrometer ($2.5 < \eta < 4$)
- Upgrade Run3/4
  - –New Silicon Tracker: charm and beauty with the Central Barrel
  - – Muon Forward Tracker: charm and beauty (and quarkonia) with the Muon Spectrometer
  - – Continous readout (50-100 kHz in Pb-Pb) to get 10/100x higher statistics: new readout electronics

ALICE upgrade

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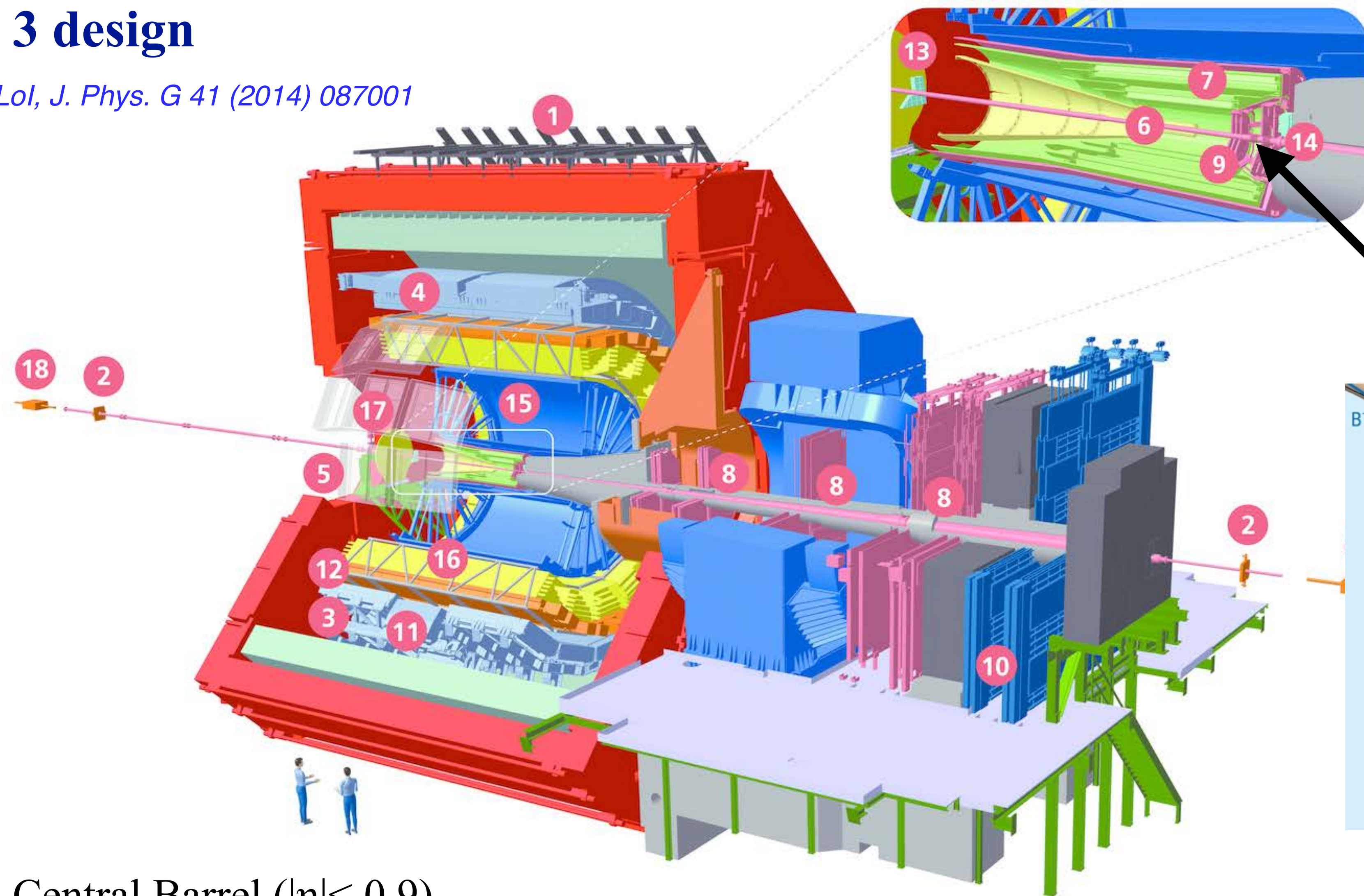

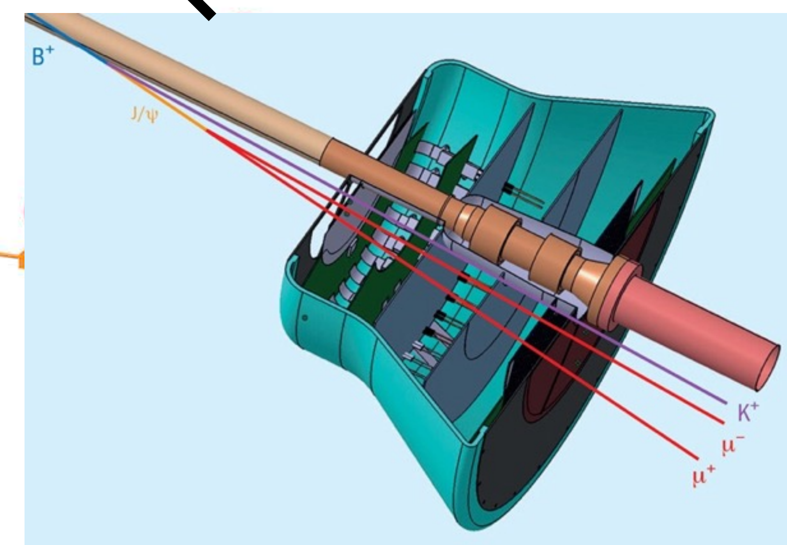

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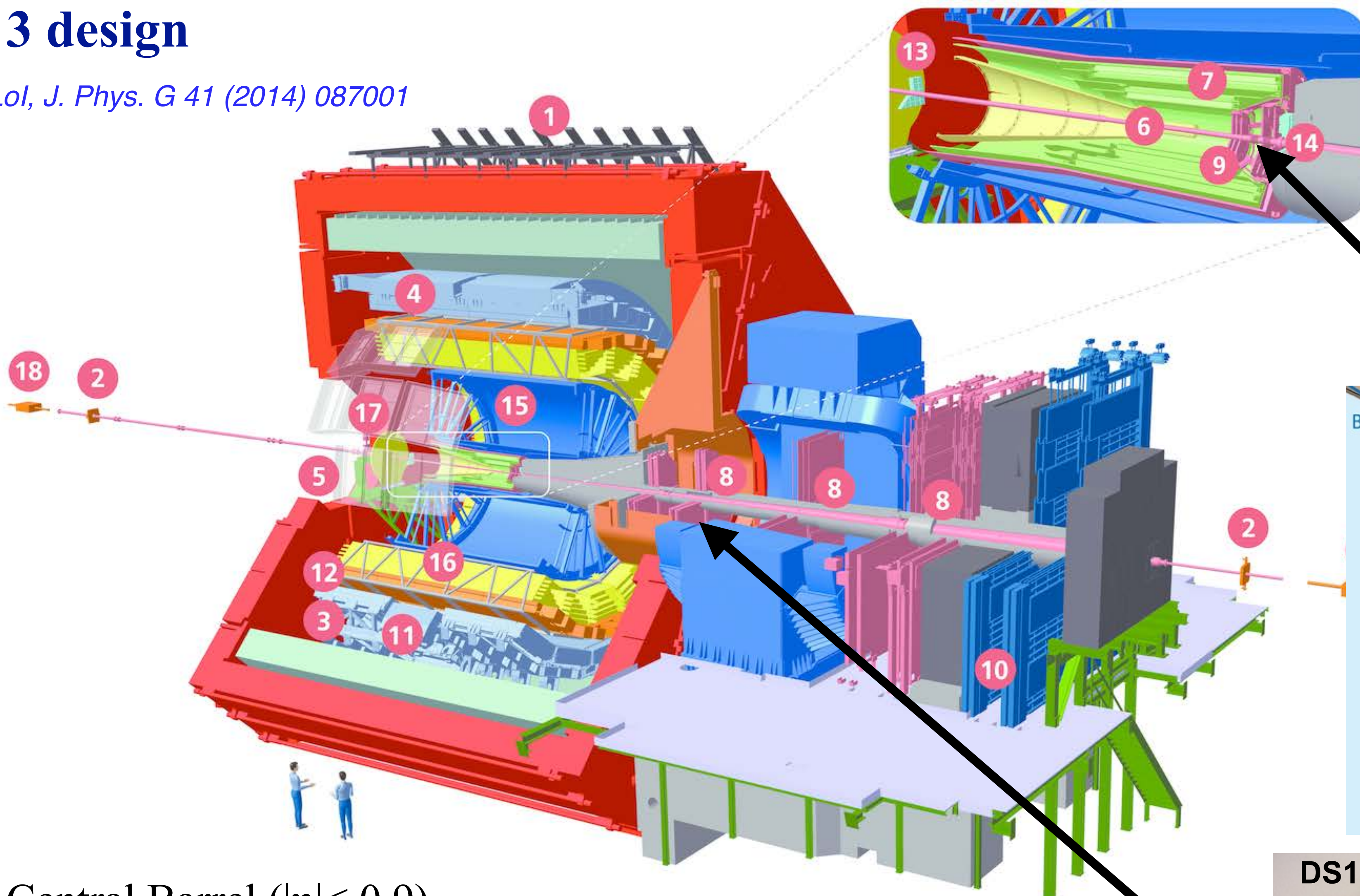

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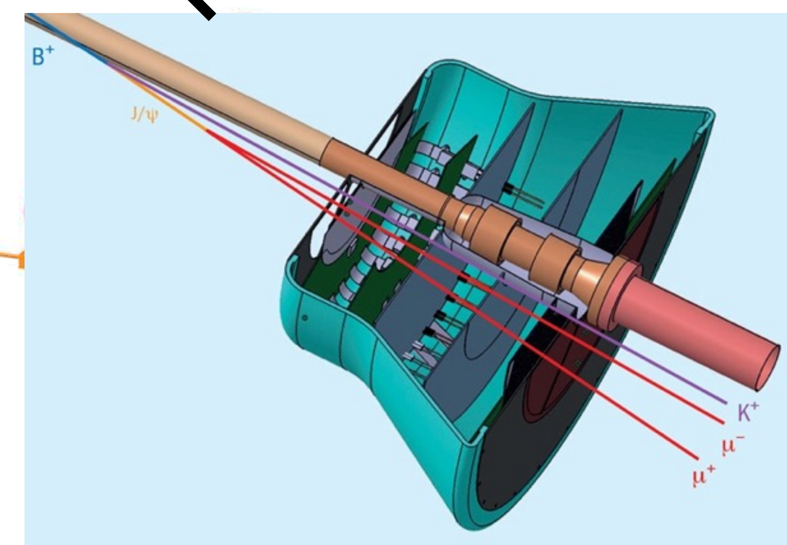

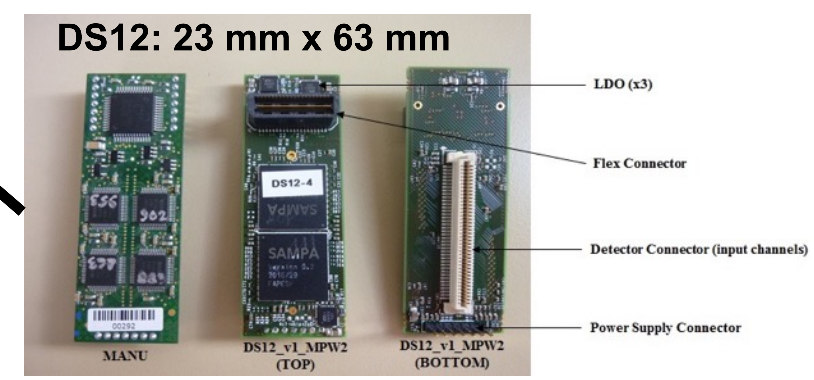

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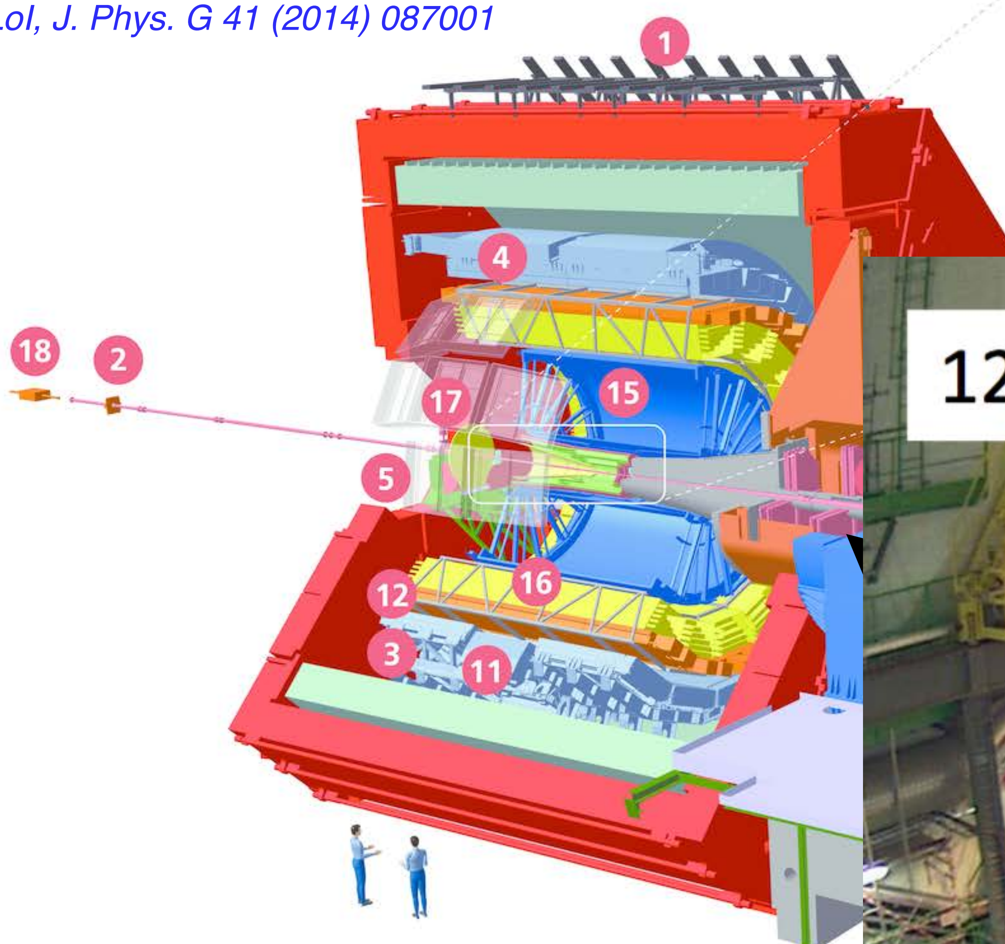
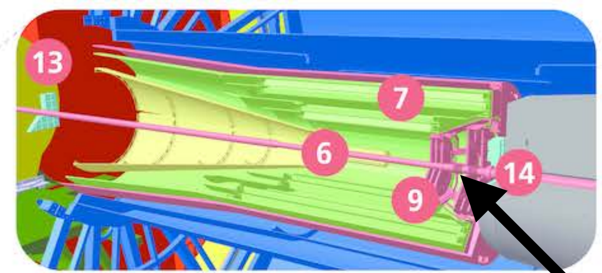
- Muon Spectrometer ($2.5 < \eta < 4$)
- Upgrade Run3/4
  - New Silicon Tracker: charm and beauty with the Central Barrel
  - Muon Forward Tracker: charm and beauty (and quarkonia) with the Muon Spectrometer
  - Continous readout (50-100 kHz in Pb-Pb) to get 10/100x higher statistics: new readout electronics

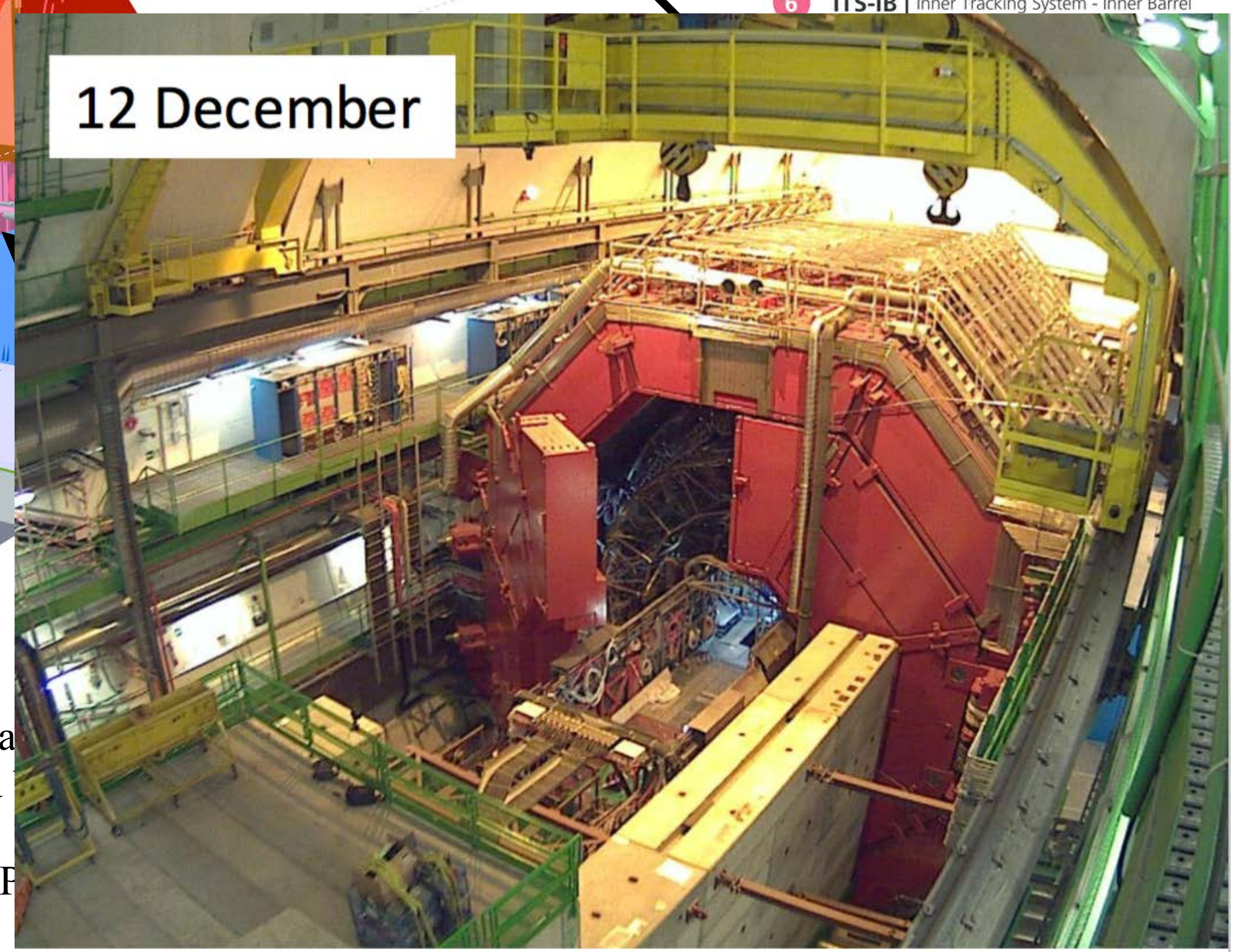
ALICE upgrade

Run 3 design

ALICE LoI, J. Phys. G 41 (2014) 087001







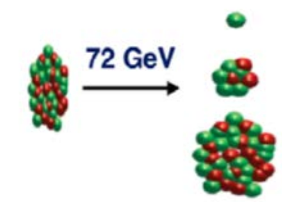
- Central Barrel (|η|< 0.9)
- Muon Spectrometer (2.5 < η < 4)
- Upgrade Run3/4
  - –New Silicon Tracker: charm and bea
  - – Muon Forward Tracker: charm and the Muon Spectrometer
  - – Continous readout (50-100 kHz in P statistics: new readout electronics

Fixed-target at LHC: QGP perspective

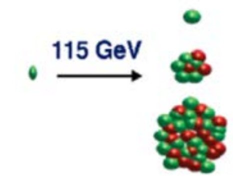
Study the **quark-gluon plasma** between SPS and RHIC energies:

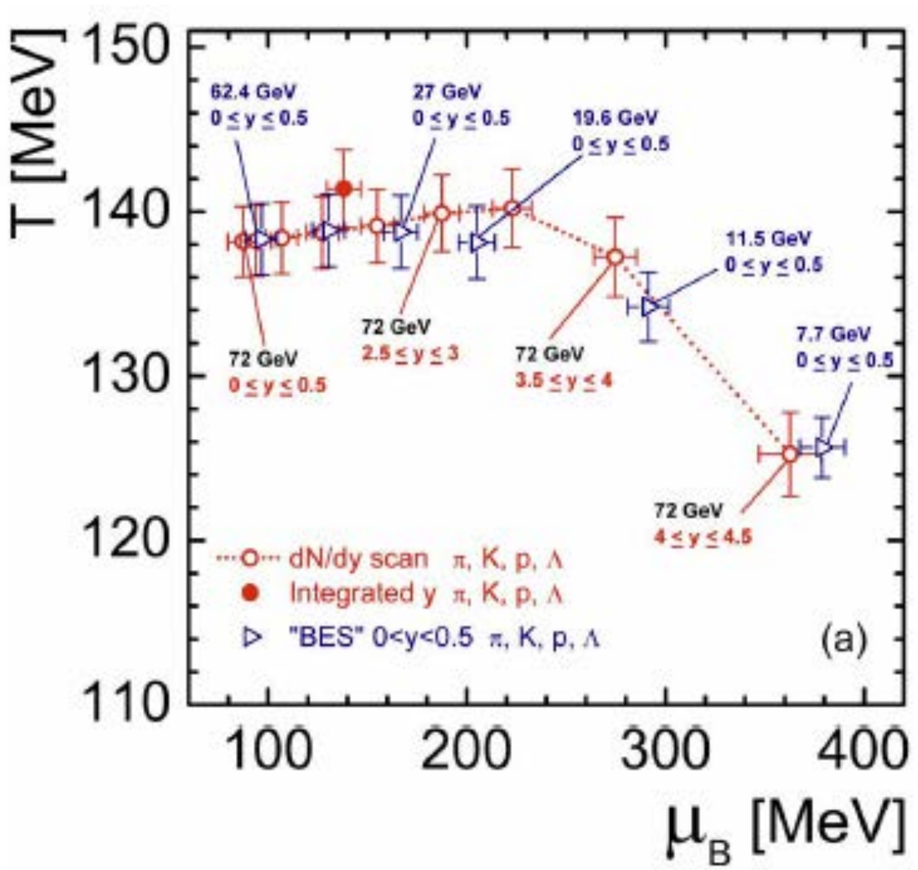
- Charm and beauty (including χ_c for charmonium family)
- Drell-Yan process
- Access a broad rapidity coverage to scan the phase space diagram

2.76 A TeV Pb beam

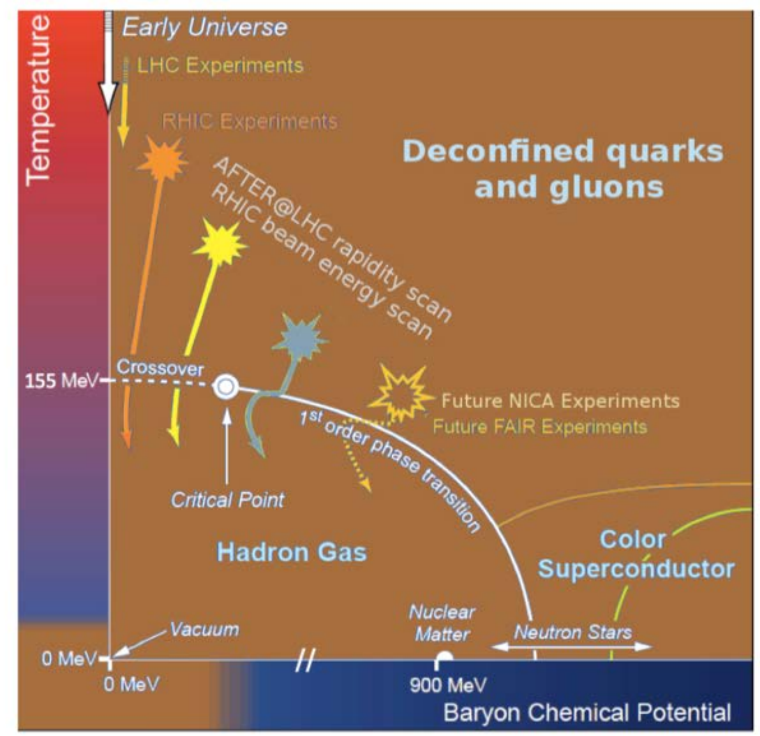


7 TeV proton beam





arXiv:1807.00603



- Already in LHCb with a low density gas target (SMOG)
- Investigations/projects ongoing in **ALICE** and **LHCb** (already in Run 3) for the implementation of fixed-target setups at high luminosity

Summary

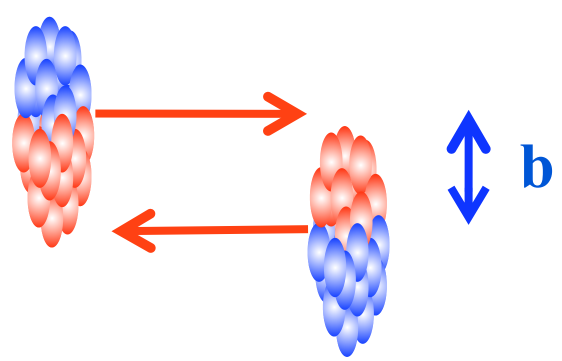
- Ultra-relativistic heavy-ion collisions at LHC aim at studying the quark gluon plasma
- The measurements of various probes, soft or hard, allow to characterize the created medium [many probes/results were not discussed in this talk…]
- From Run 2 data, access to new probes thanks to the high luminosity and increase precision on QGP parameter extraction. 2018 Pb-Pb data analysis ongoing!
- High multiplicity events in pp and pPb collisions show similar behavior as Pb-Pb collisions: studies remain to be done to understand the observed features
- Long Shutdown 2 at LHC has now started and detector upgrades are ongoing: Run 3 will start in 2021!

back-up slides

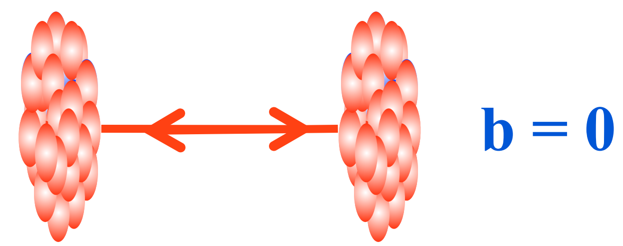
Collision geometry: few definitions

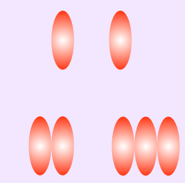
Centrality of the collisions: overlap of two nuclei

semi-central collision



central collision





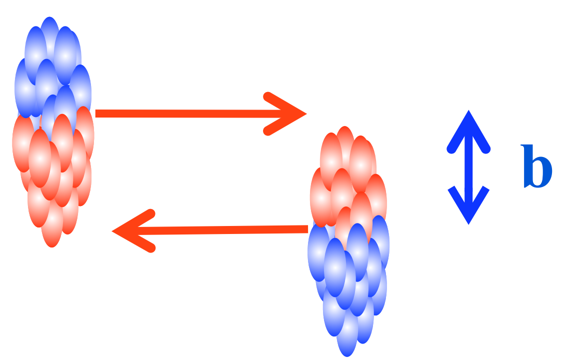
	N_{part} = 2	N_{coll} = 1
	N_{part} = 5	N_{coll} = 6
Pb-Pb cent.	N_{part} = 360	N_{coll} = 1500
p-Pb cent.	N_{part} = 16	N_{coll} = 15

Impact parameter of the collision: b
Number of participants nucleons: N_{part}
Number of binary collisions: N_{coll}

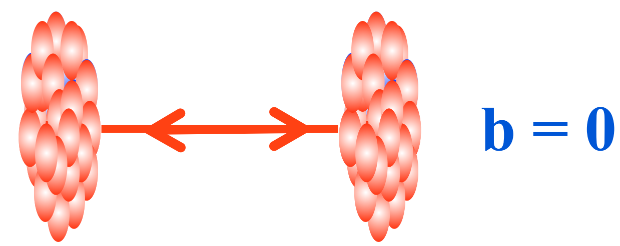
Collision geometry: few definitions

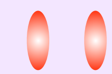
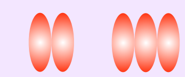
Centrality of the collisions: overlap of two nuclei

semi-central collision



central collision



	$N_{part} = 2$	$N_{coll} = 1$
	$N_{part} = 5$	$N_{coll} = 6$
Pb-Pb cent.	$N_{part} = 360$	$N_{coll} = 1500$
p-Pb cent.	$N_{part} = 16$	$N_{coll} = 15$

Impact parameter of the collision: b
Number of participants nucleons: N_{part}
Number of binary collisions: N_{coll}

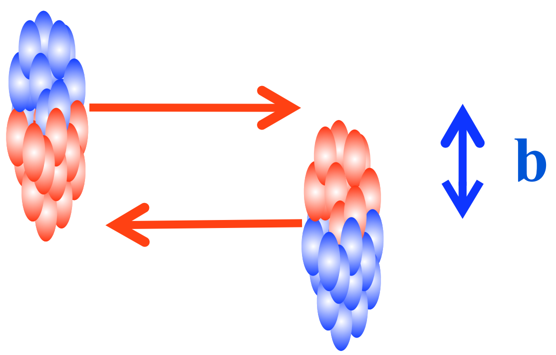
Event centrality determination

- Cannot measure b, N_{part}, N_{coll} directly
- Multiplicity measurements with forward or central detectors (charged particles multiplicity - π, K, p… -, spectator neutrons, …)
- Use Glauber model to map the measured multiplicities in A-A collisions to b, N_{part} and N_{coll}

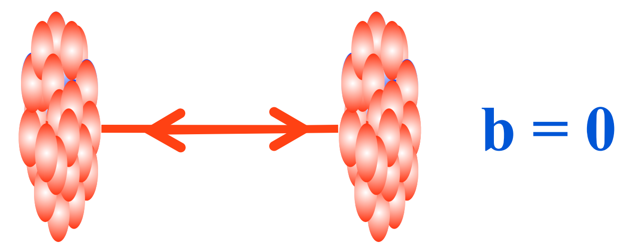
Collision geometry: few definitions

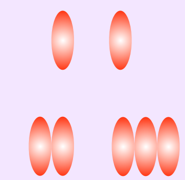
Centrality of the collisions: overlap of two nuclei

semi-central collision



central collision





(2 nucleons)	N_{part} = 2	N_{coll} = 1
(5 nucleons)	N_{part} = 5	N_{coll} = 6
Pb-Pb cent.	N_{part} = 360	N_{coll} = 1500
p-Pb cent.	N_{part} = 16	N_{coll} = 15

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