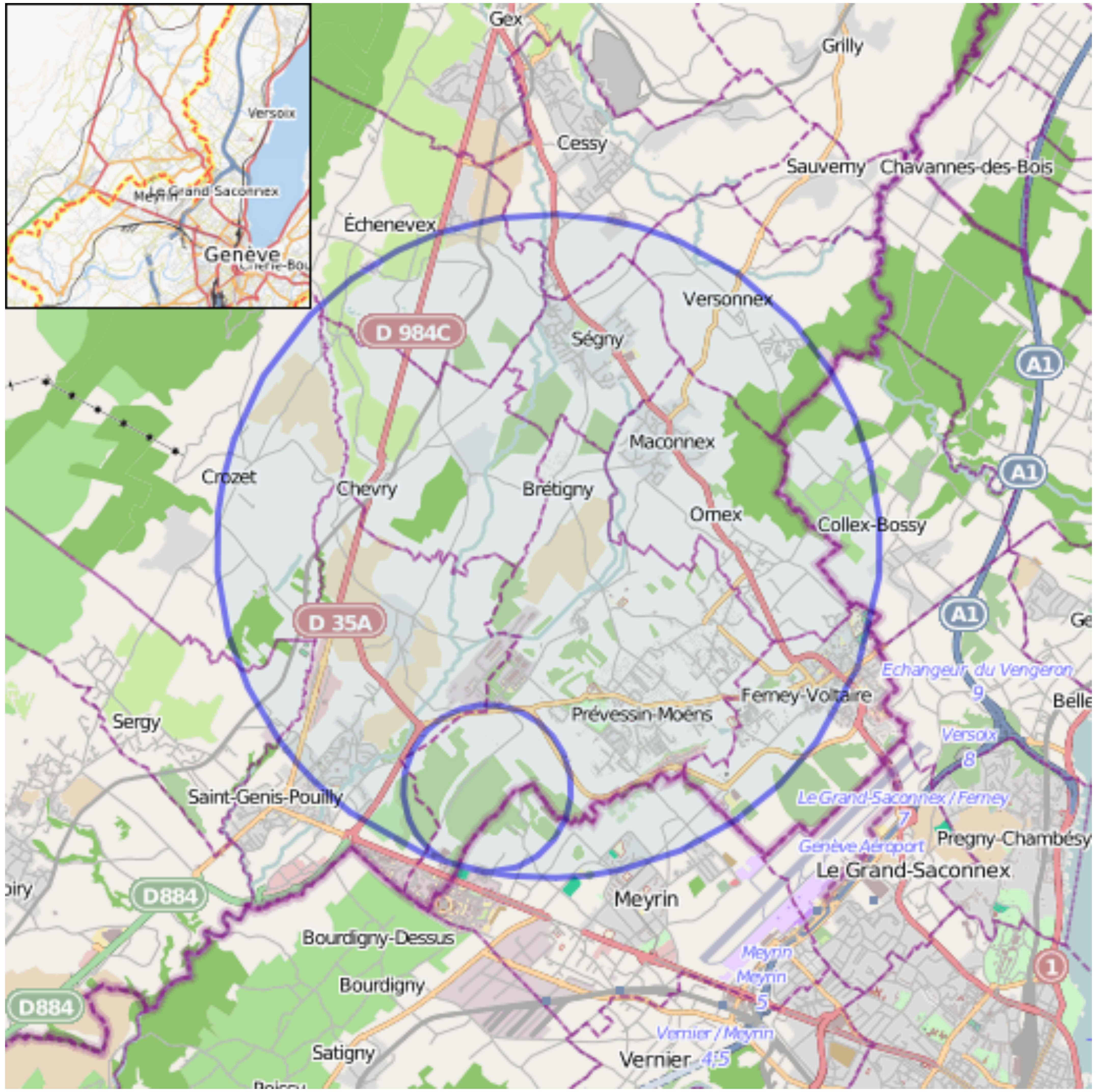
ALICE beyond heavy-ion physics Wonderland

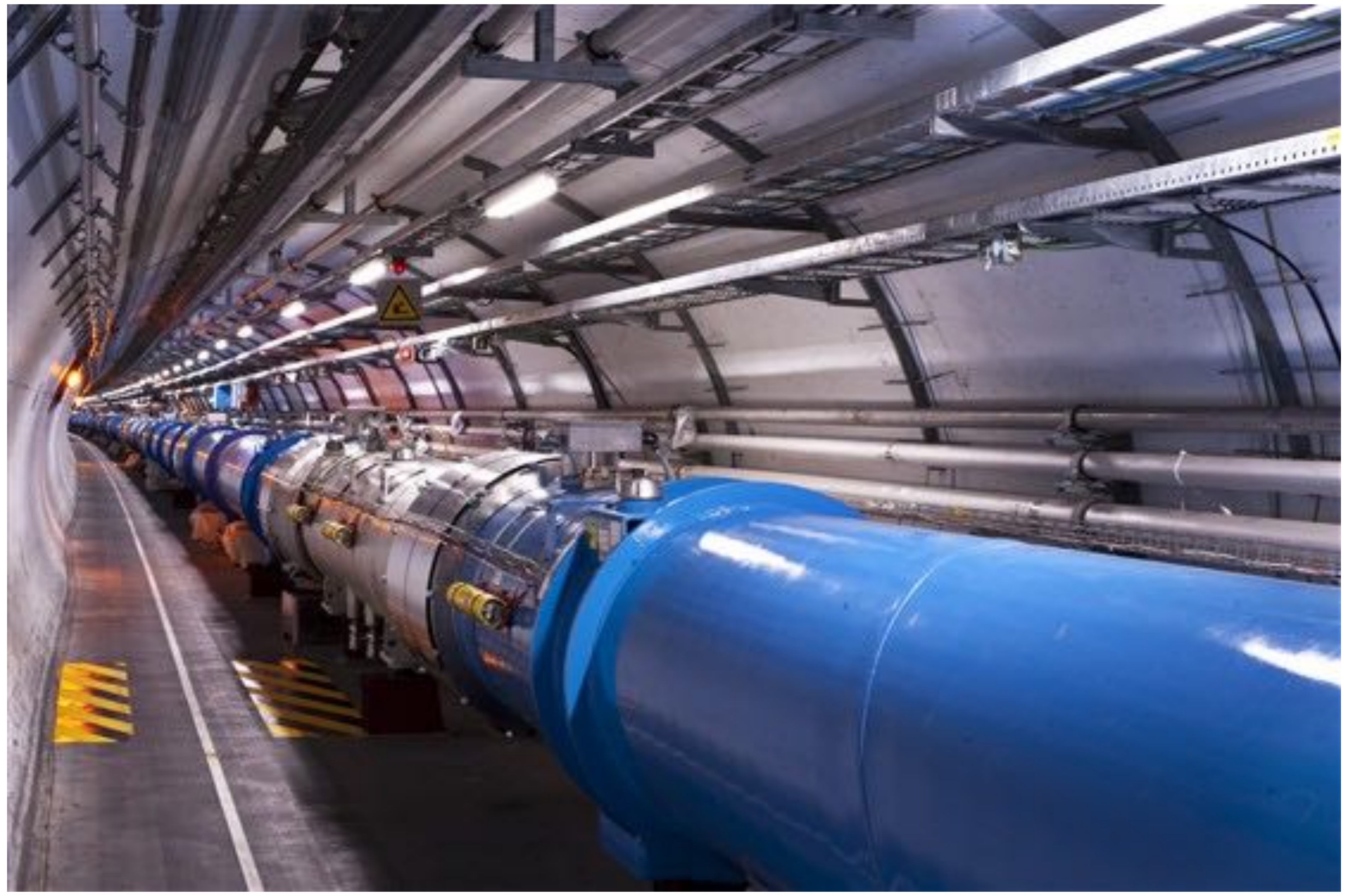
Marek Bombara

(Institute of Physics, Faculty of Science, Pavol Jozef Šafárik University in Košice)

Fyzikální ústav AV ČR, v. v. i., Praha, 17th June 2024

Large Hadron Collider at CERN





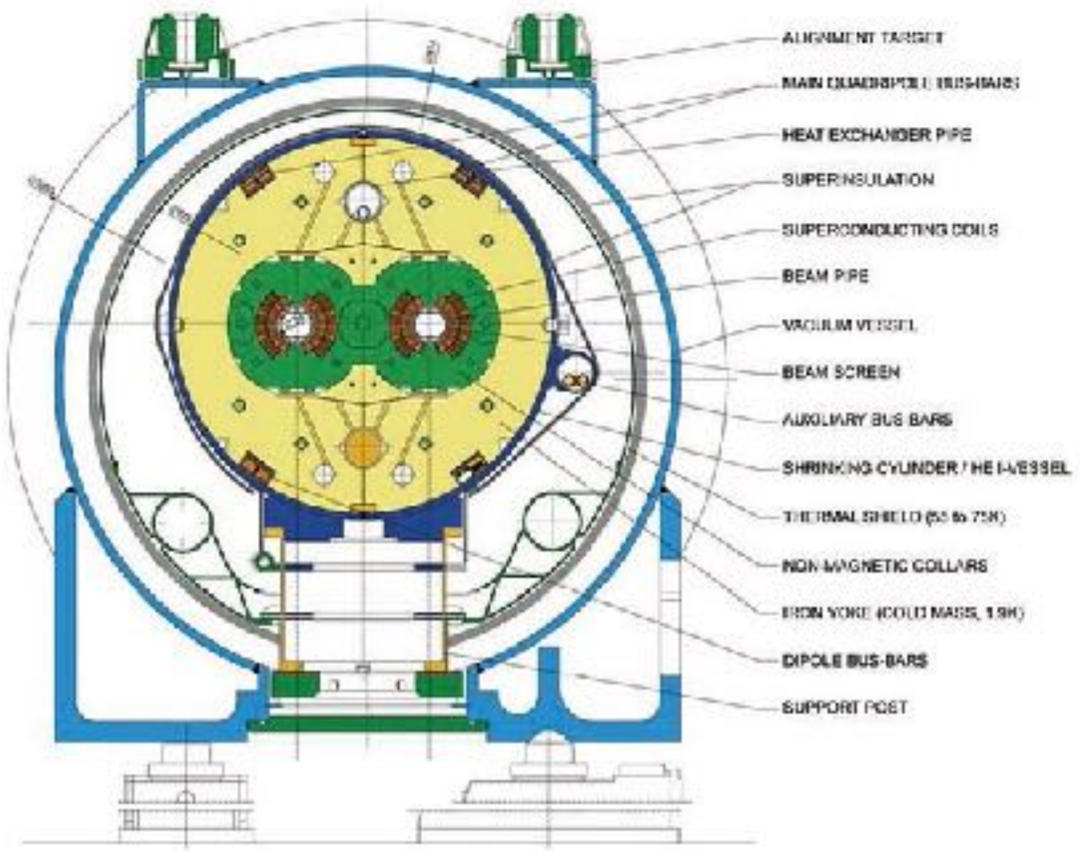
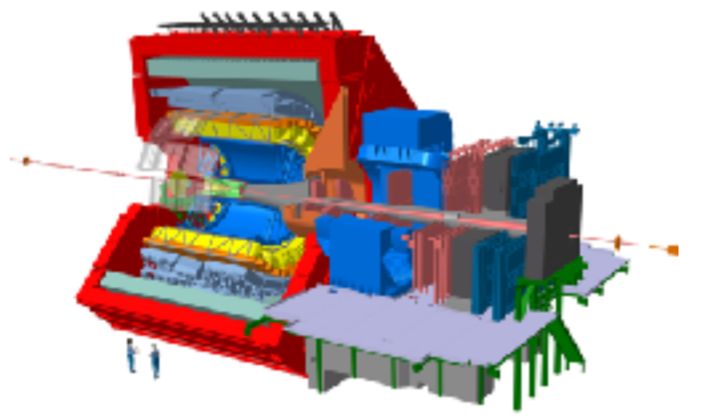
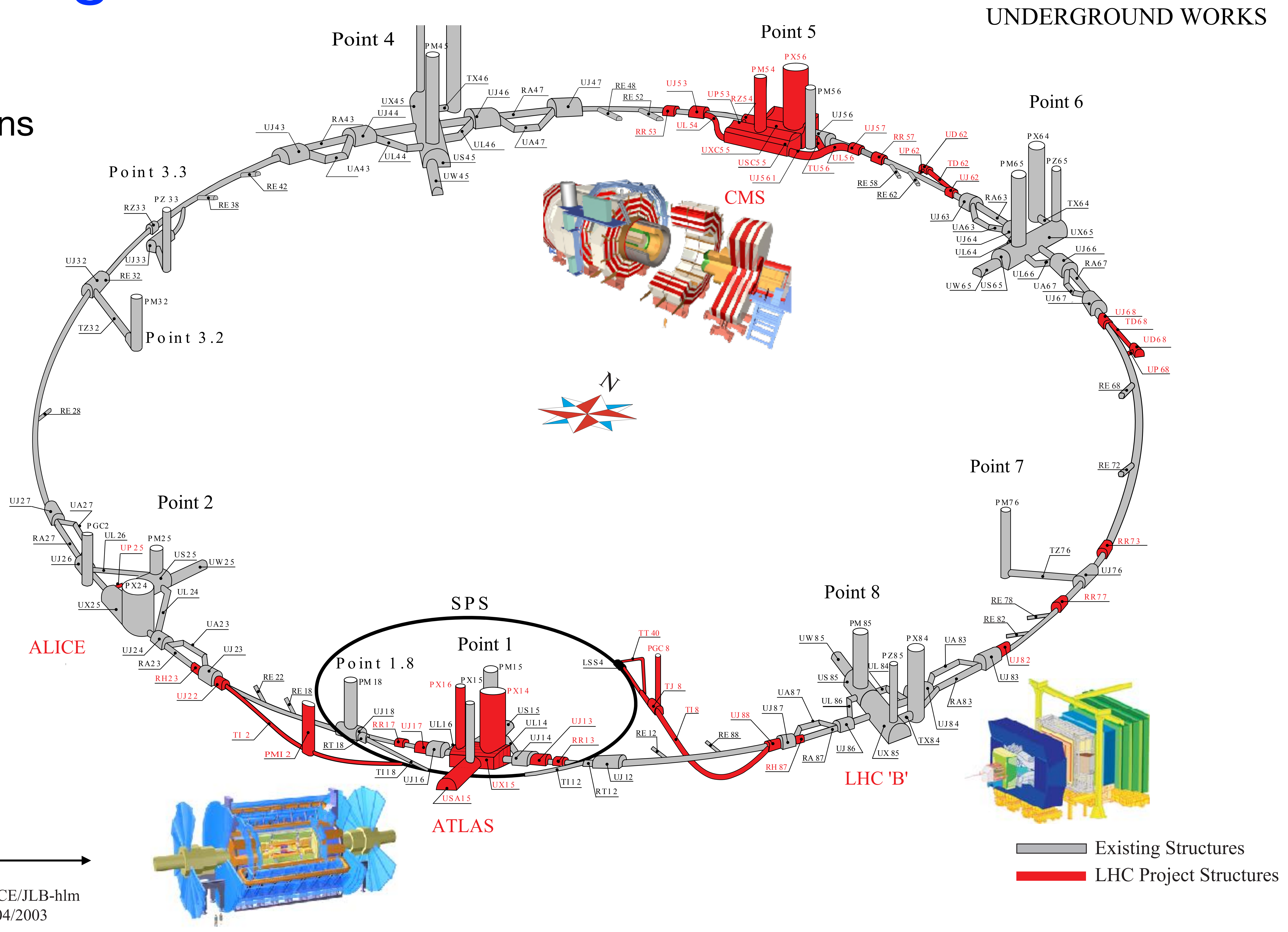


Fig.: https://en.wikipedia.org/wiki/Large_Hadron_Collider

Large Hadron Collider at CERN

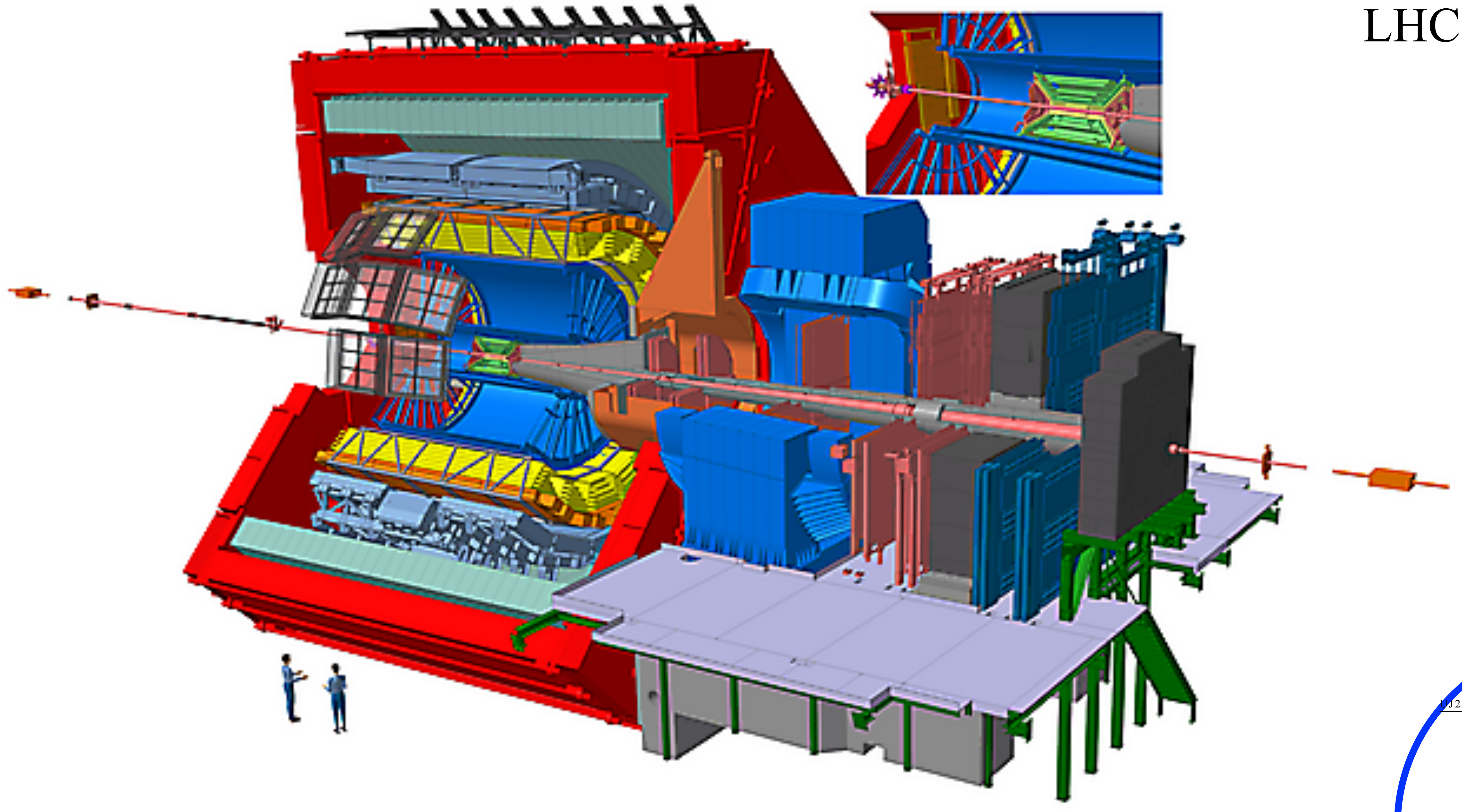
The LHC (Large Hadron Collider) accelerates protons and lead ions to ~TeV energies, built 50-150 m underground in tunnel with circumference 27 km

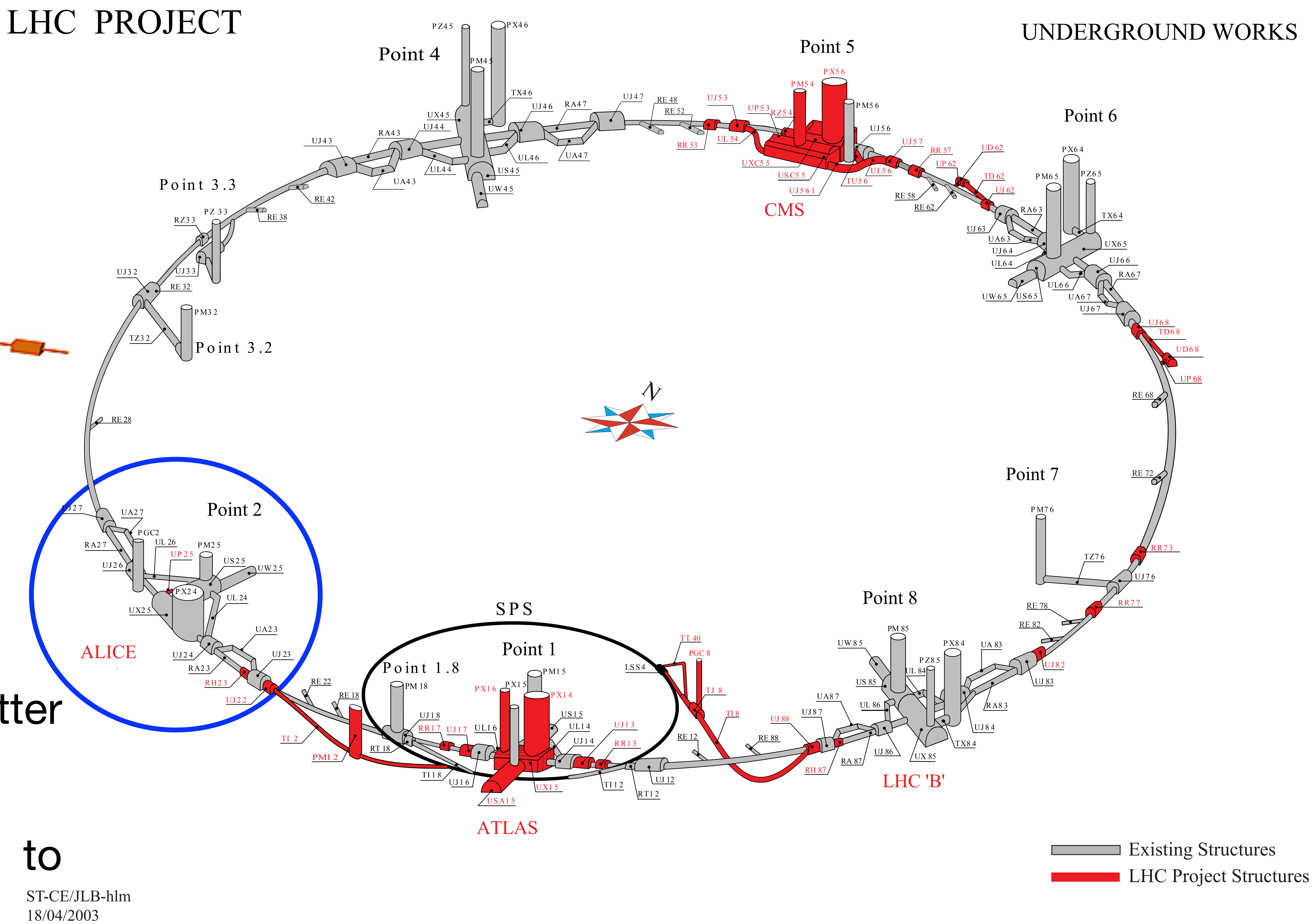




Slovakia (KE, BA)

ALICE (A Large Ion Collider Experiment) at the LHC





- dedicated to study hot and dense nuclear matter in heavy ion collisions
- crucial part of the physics programme is to study pp and p–Pb collisions

Why do we study heavy-ion collisions?

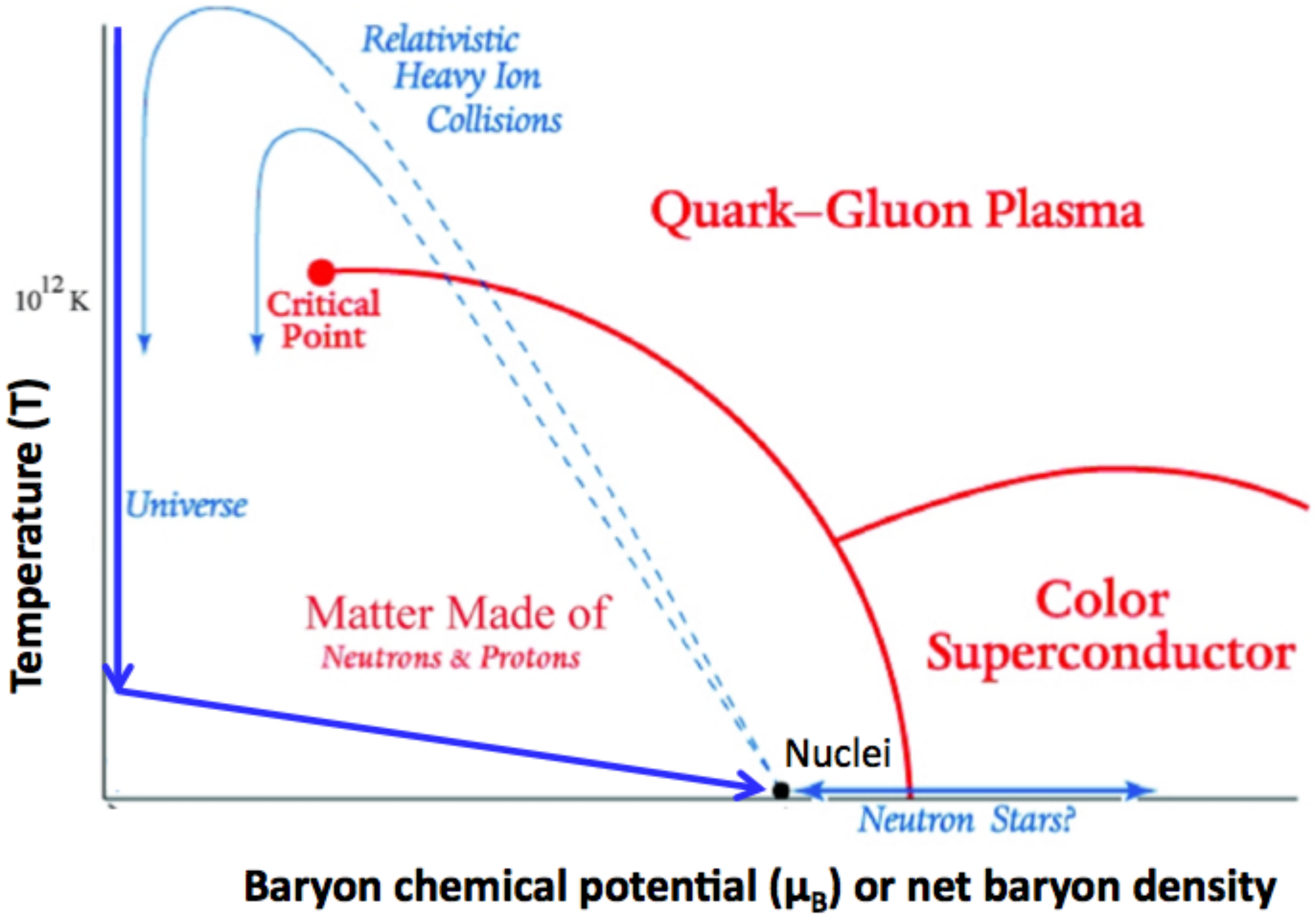
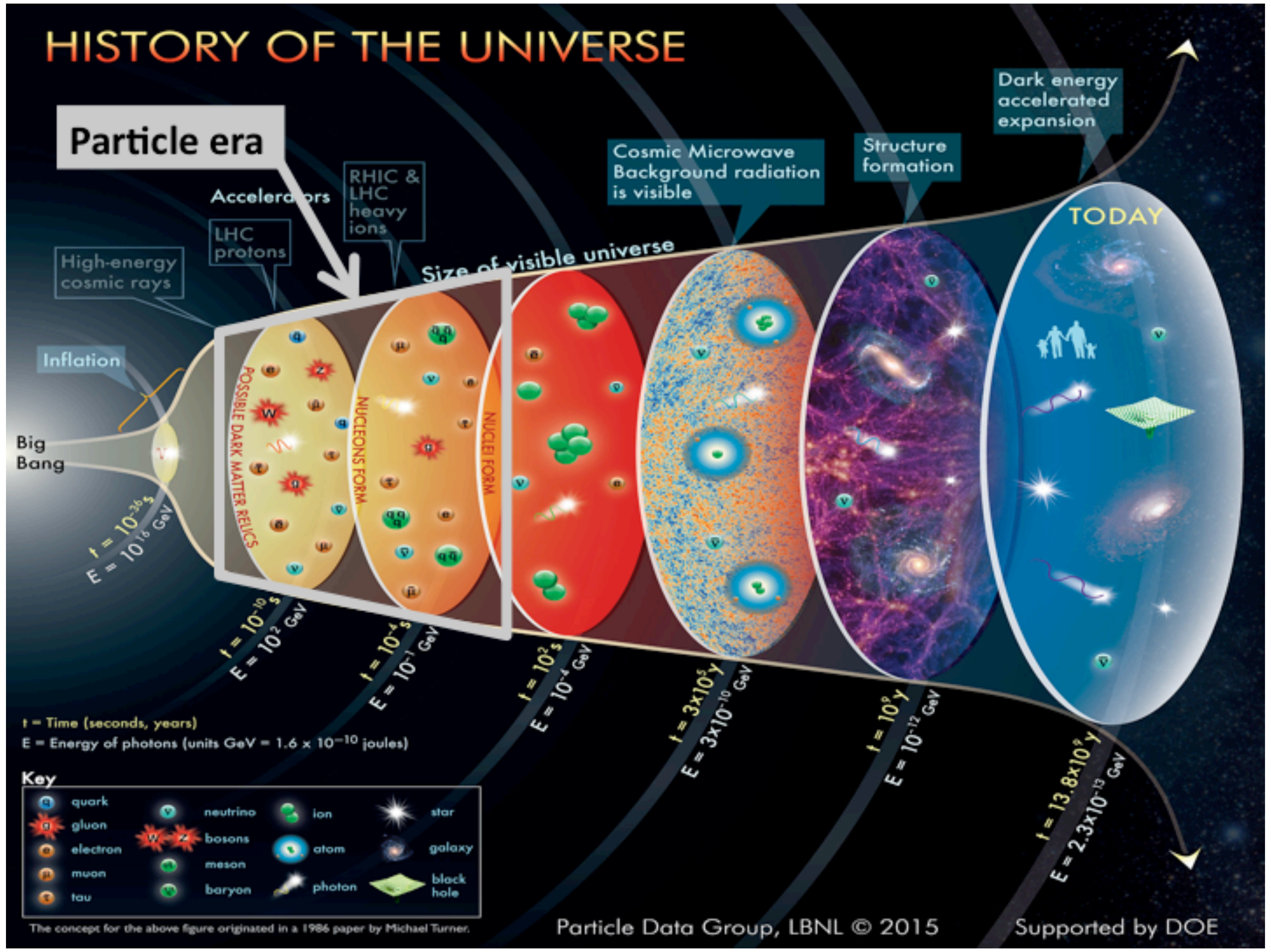


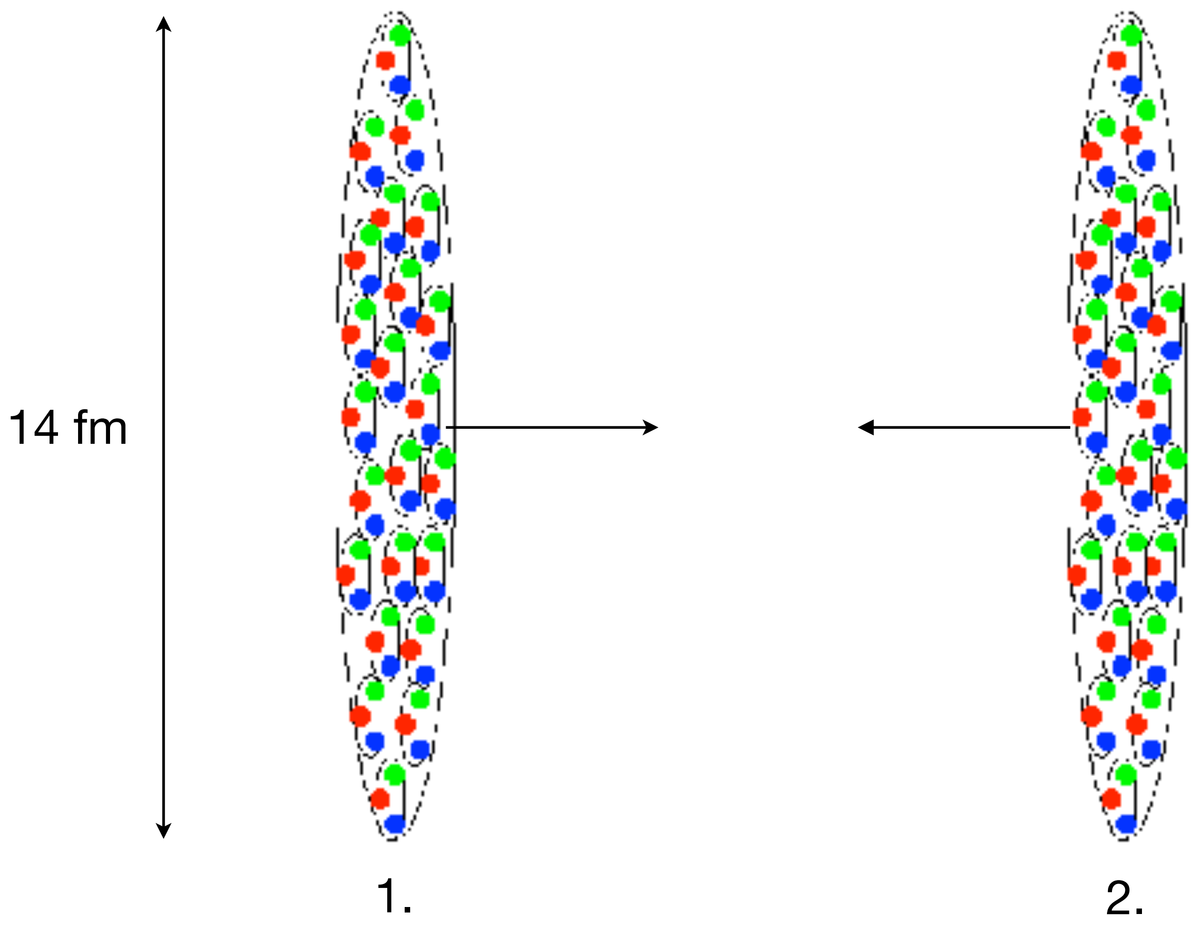
Fig: http://inspirehep.net/record/1397855/plots



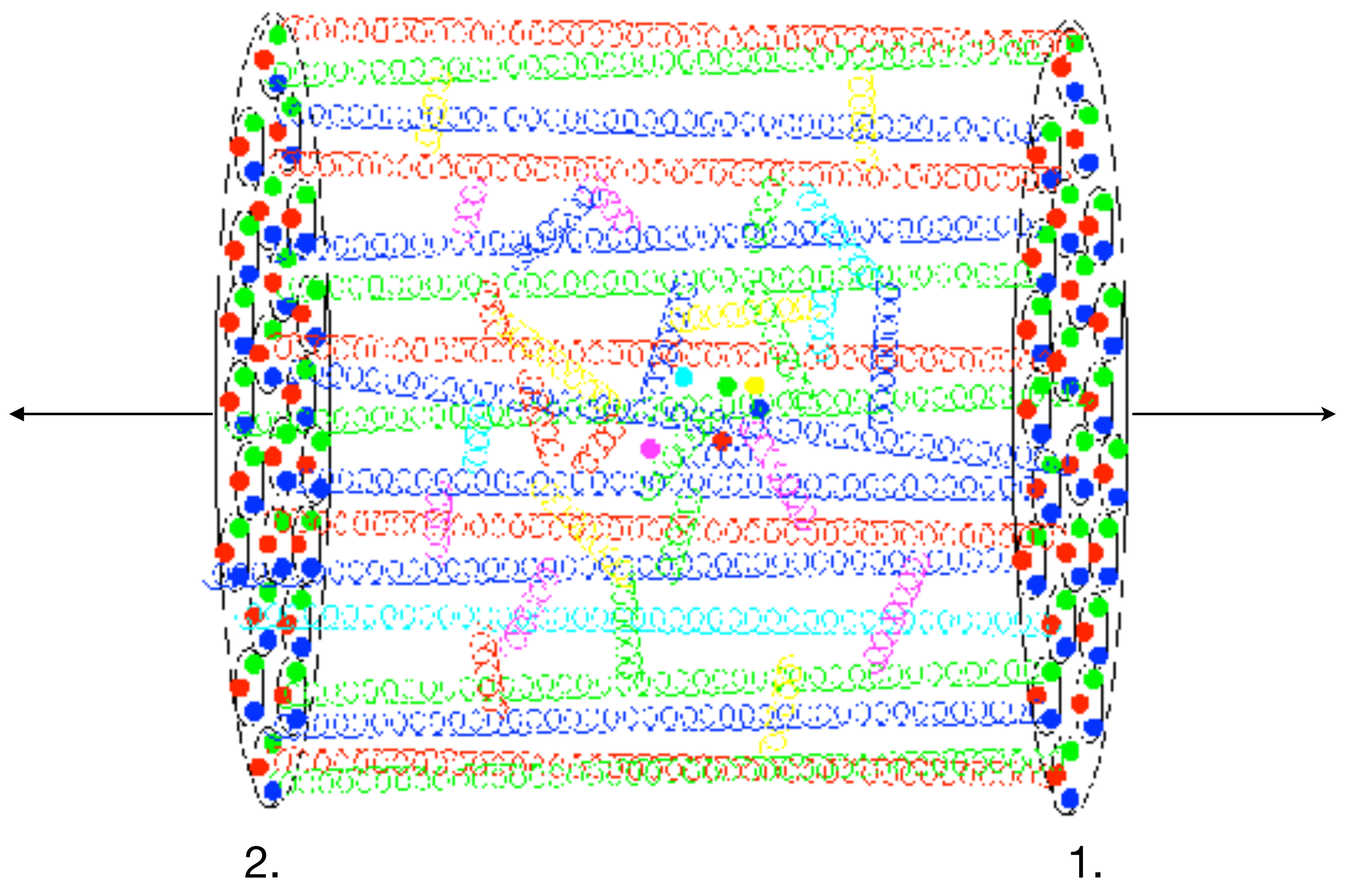
- to explore the QCD matter phase diagram
- unique opportunity to study primordial matter from the Big Bang epoch in the laboratory

Little Bang in ultrarelativistic heavy ion collisions

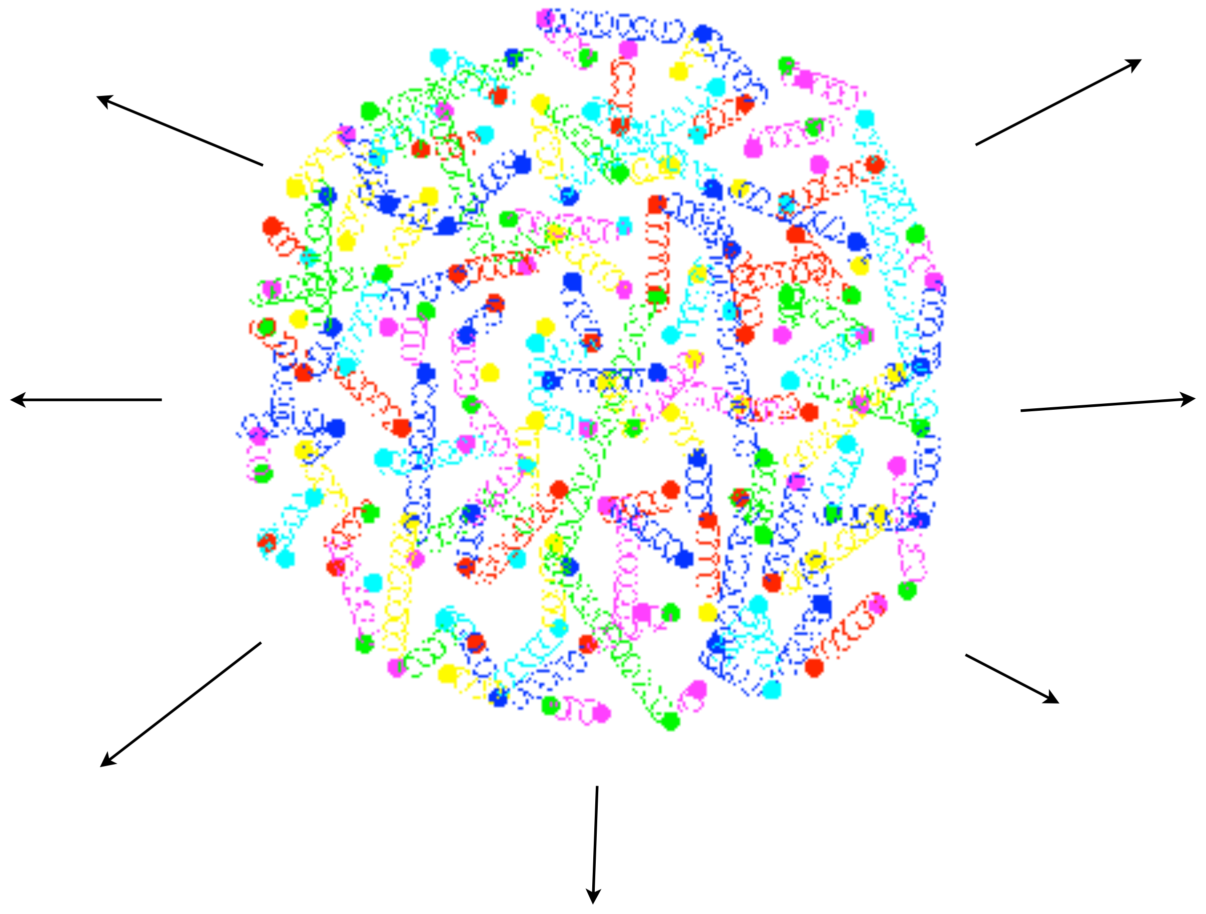
1. Before collision



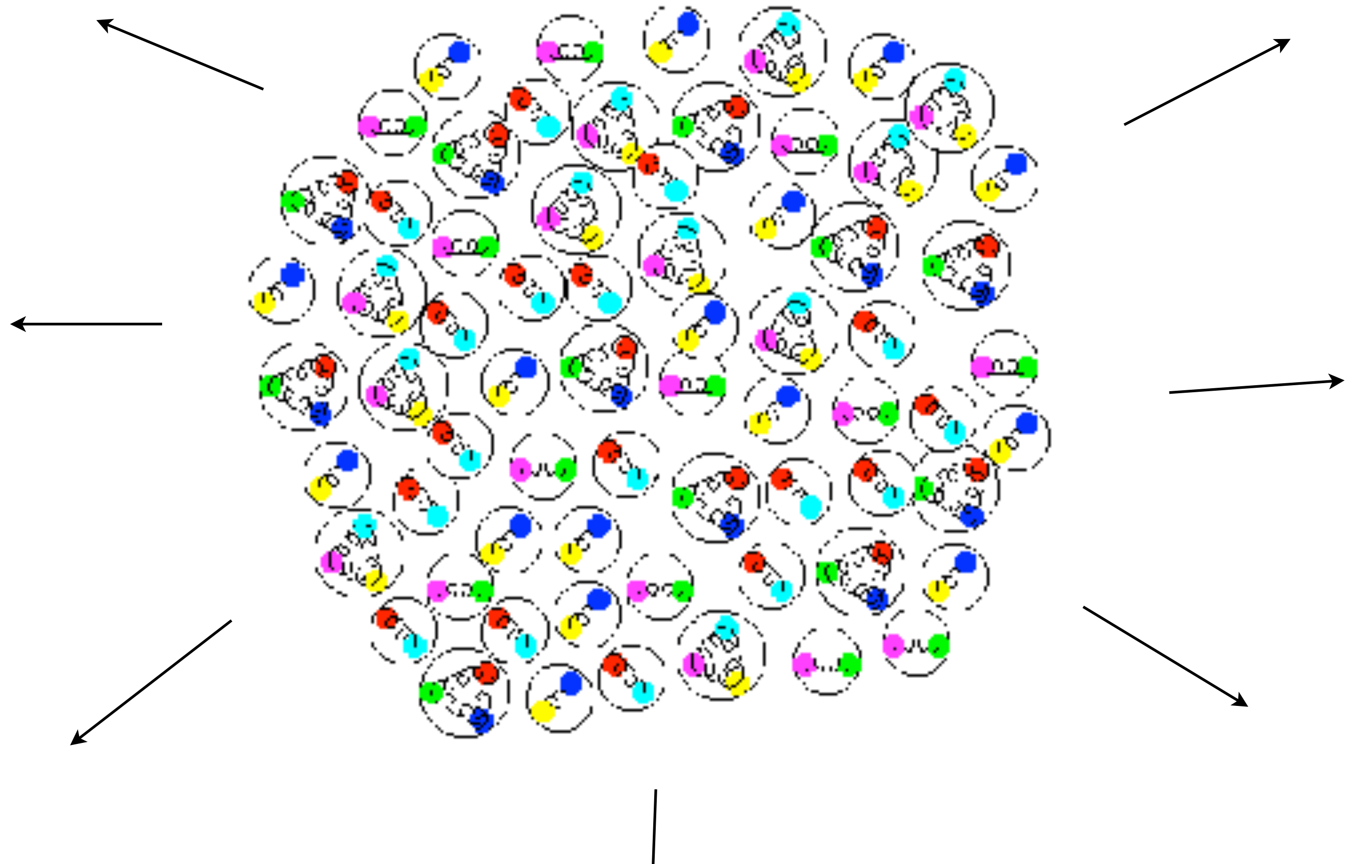
2. After collision



3. Quark-gluon plasma

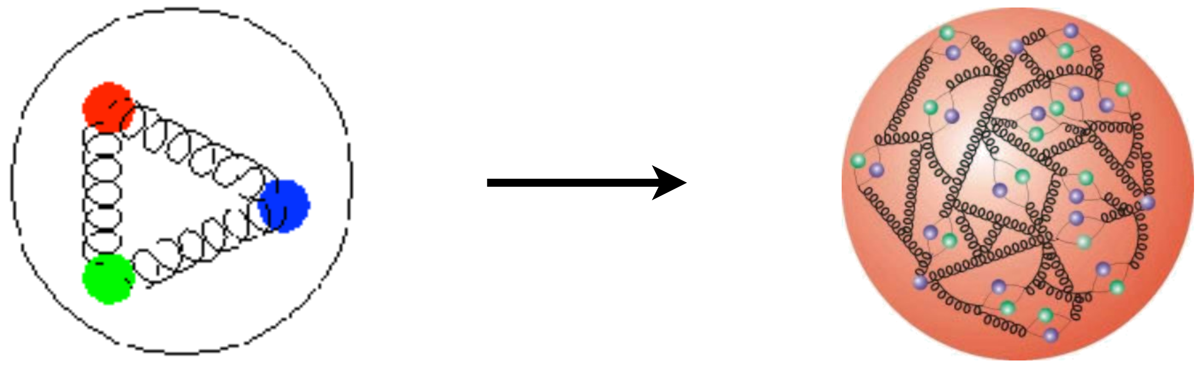


4. After hadronization

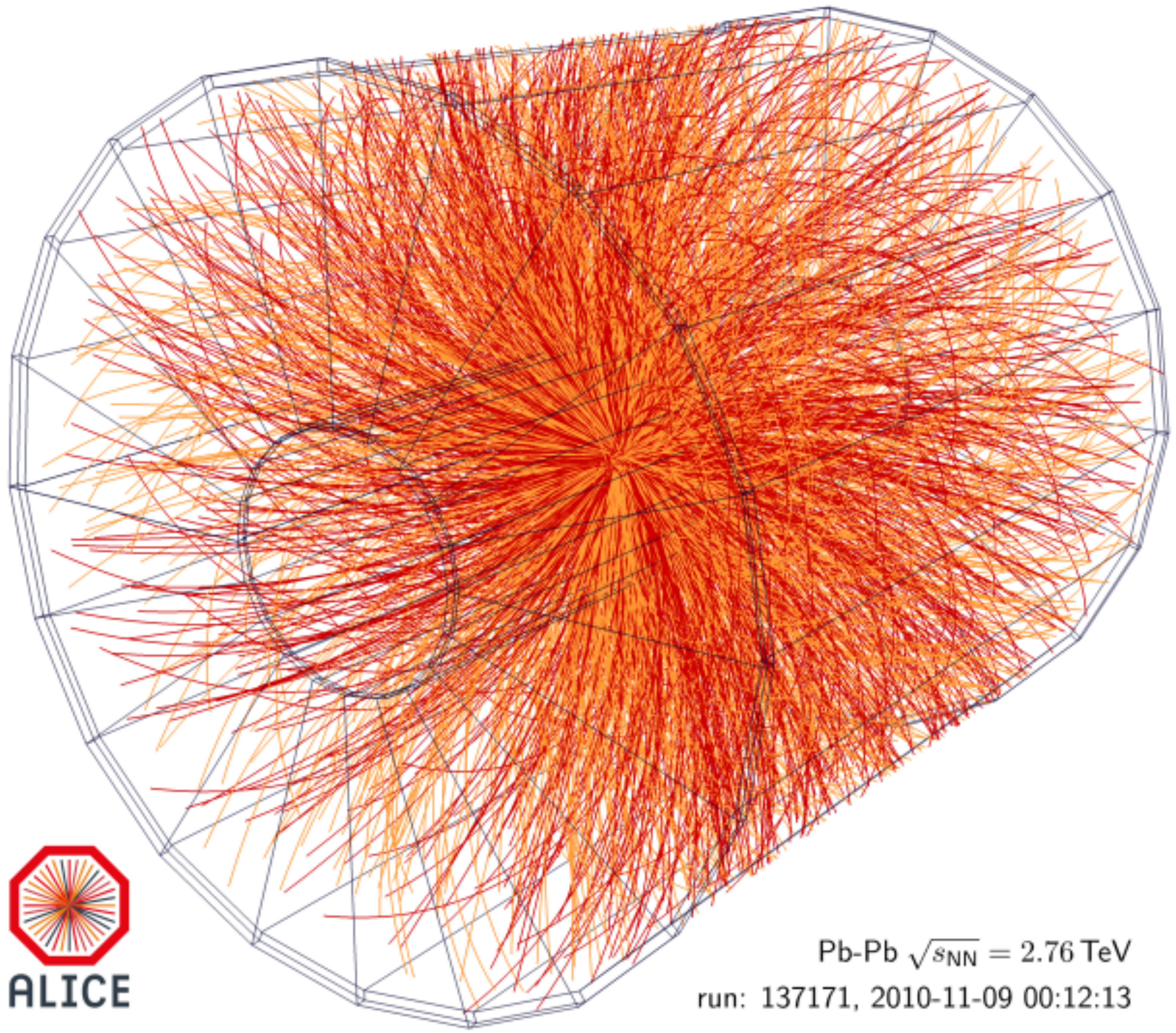


Partons - common name for gluons, quarks and antiquarks.
Hadrons consist of partons (mostly of quarks and antiquarks).
Most known hadrons are proton and neutron.

proton at the TeV scale:



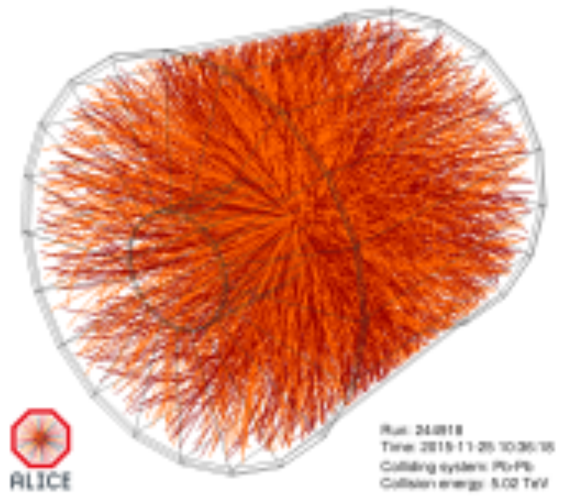
Heavy-ion collision in ALICE

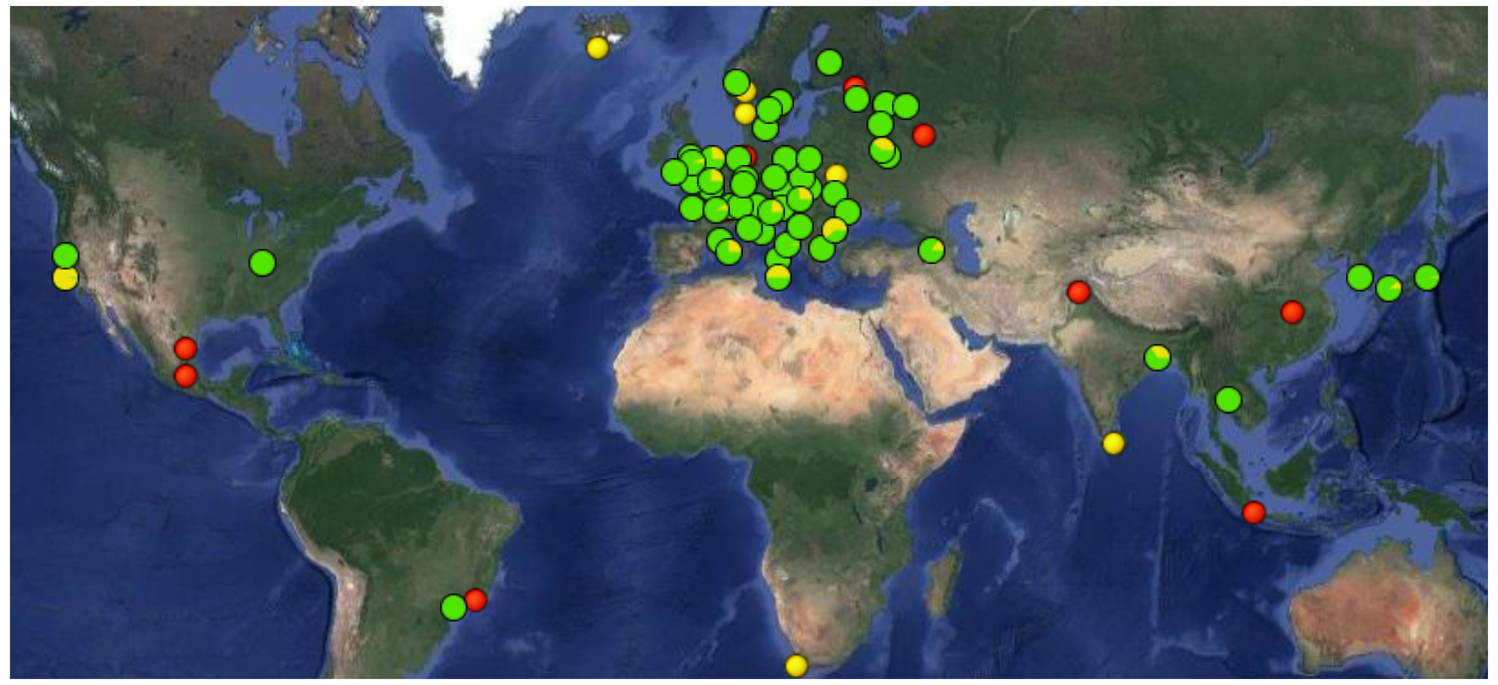


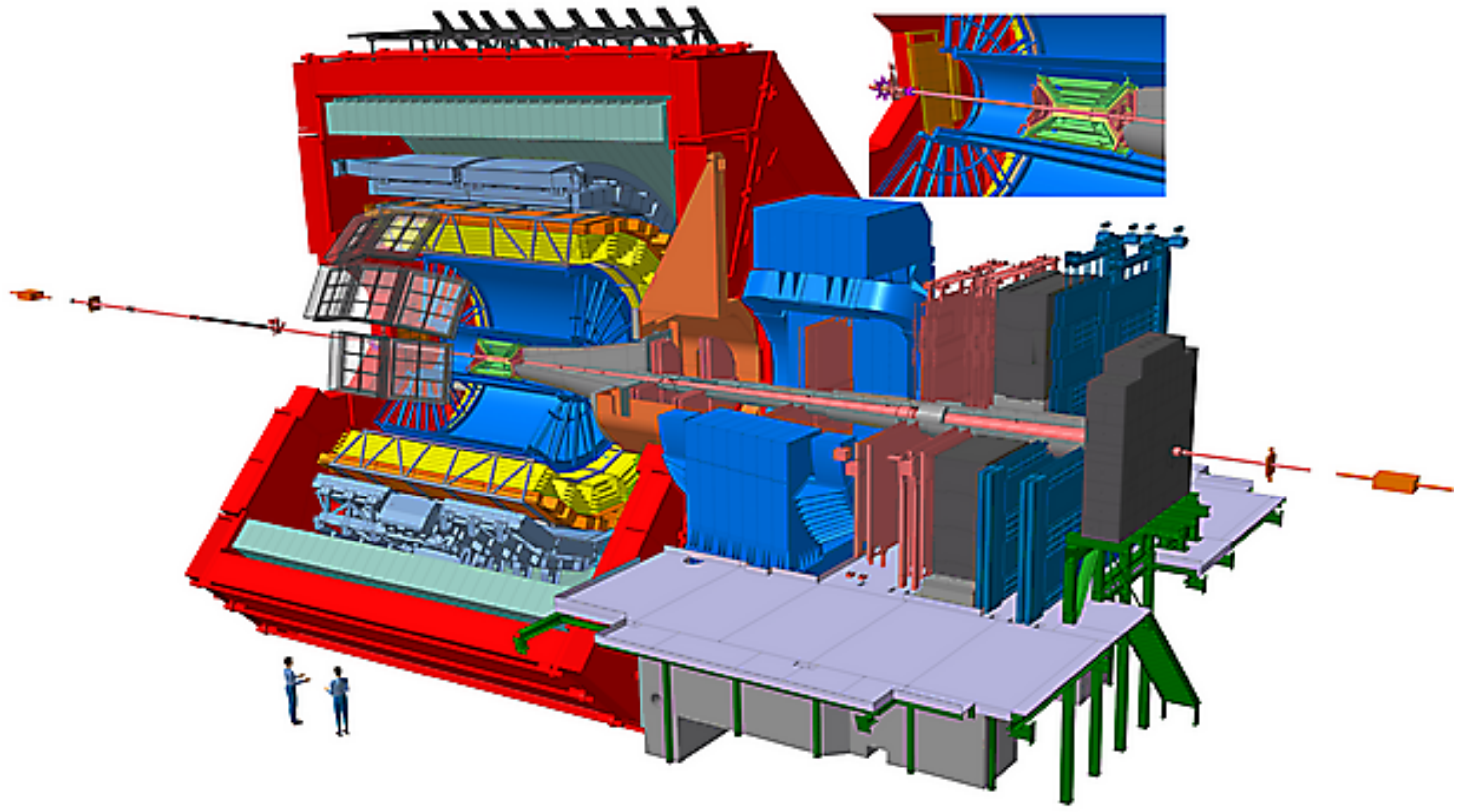
example of Pb–Pb collision seen by the ALICE detector

- hadrons created in the collision leave traces in the detector
- traces → hadron properties → quark-gluon plasma properties
- advantage of the ALICE detector - excellent at particle identification down to low momenta + designed to deal with high-multiplicity track environment
- disadvantage of ALICE detector - slow main tracking detector → not suitable for very rare processes (like top quark or Higgs boson creation)

Heavy-ion collisions analysis

$\sum$  $= \sim 10^9 \Rightarrow$

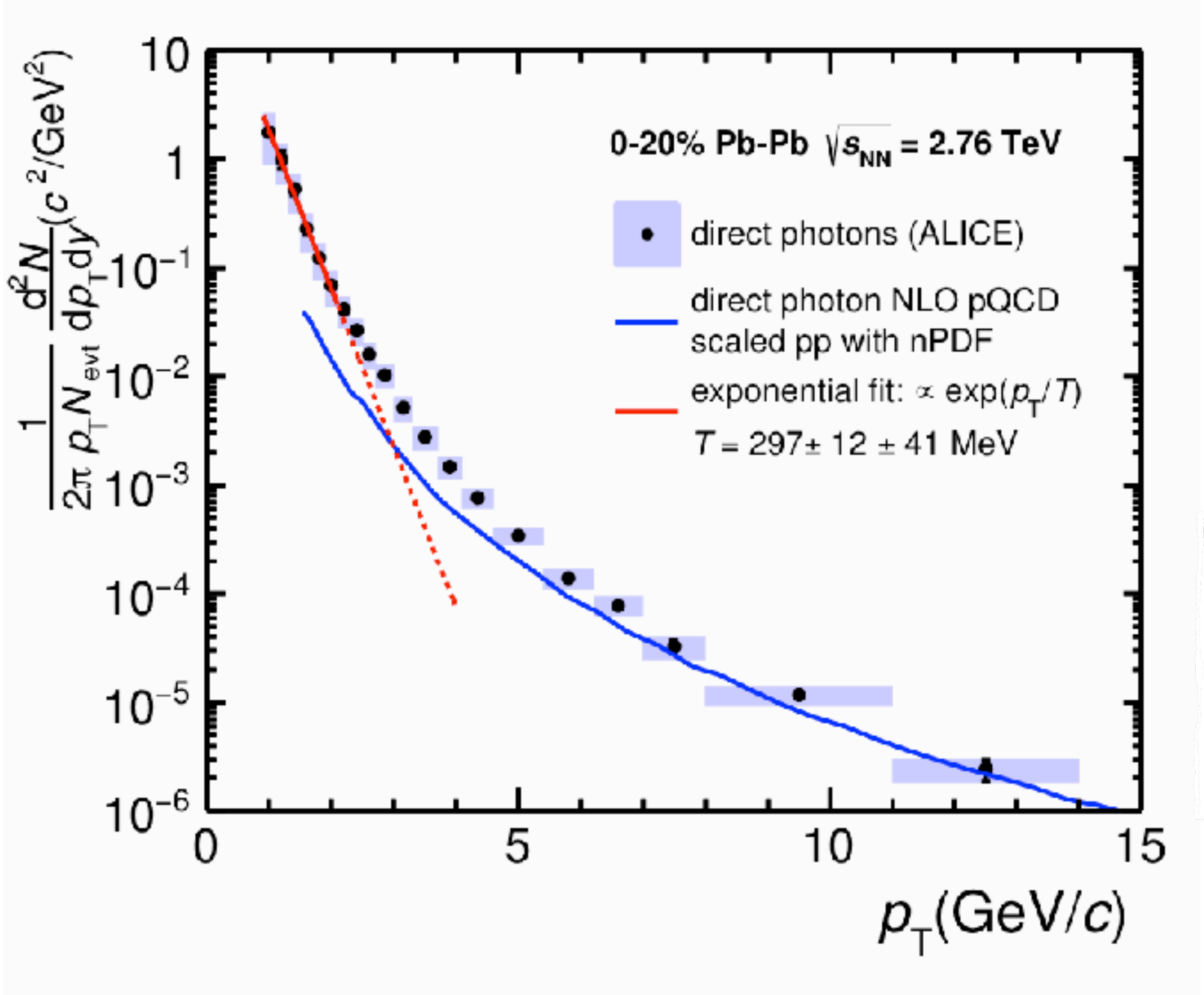




- billions of reconstructed collisions (pp, Pb-Pb,...)
- trillions of particles for the analysis
- enormous and specific demands on hardware and software

ALICE top highlights (subjective selection)

Highest man-made temperature



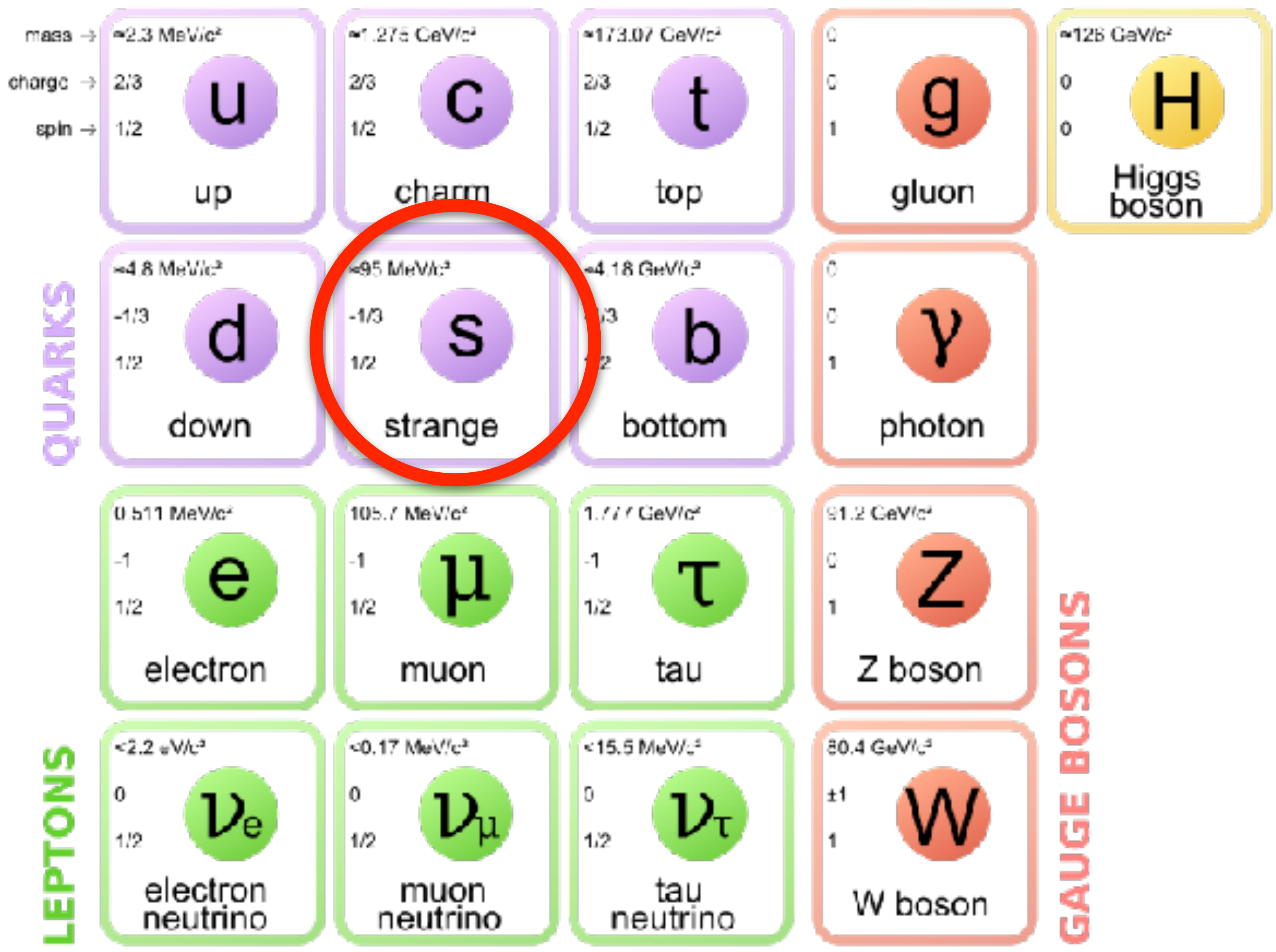
On 13 August 2012 scientists at CERN's Large Hadron Collider, Geneva, Switzerland, announced that they had achieved temperatures of over 5 trillion K and perhaps as high as 5.5 trillion K. The team had been using the ALICE experiment to smash together lead ions at 99% of the speed of light to create a quark gluon plasma – an exotic state of matter believed to have filled the universe just after the Big Bang.

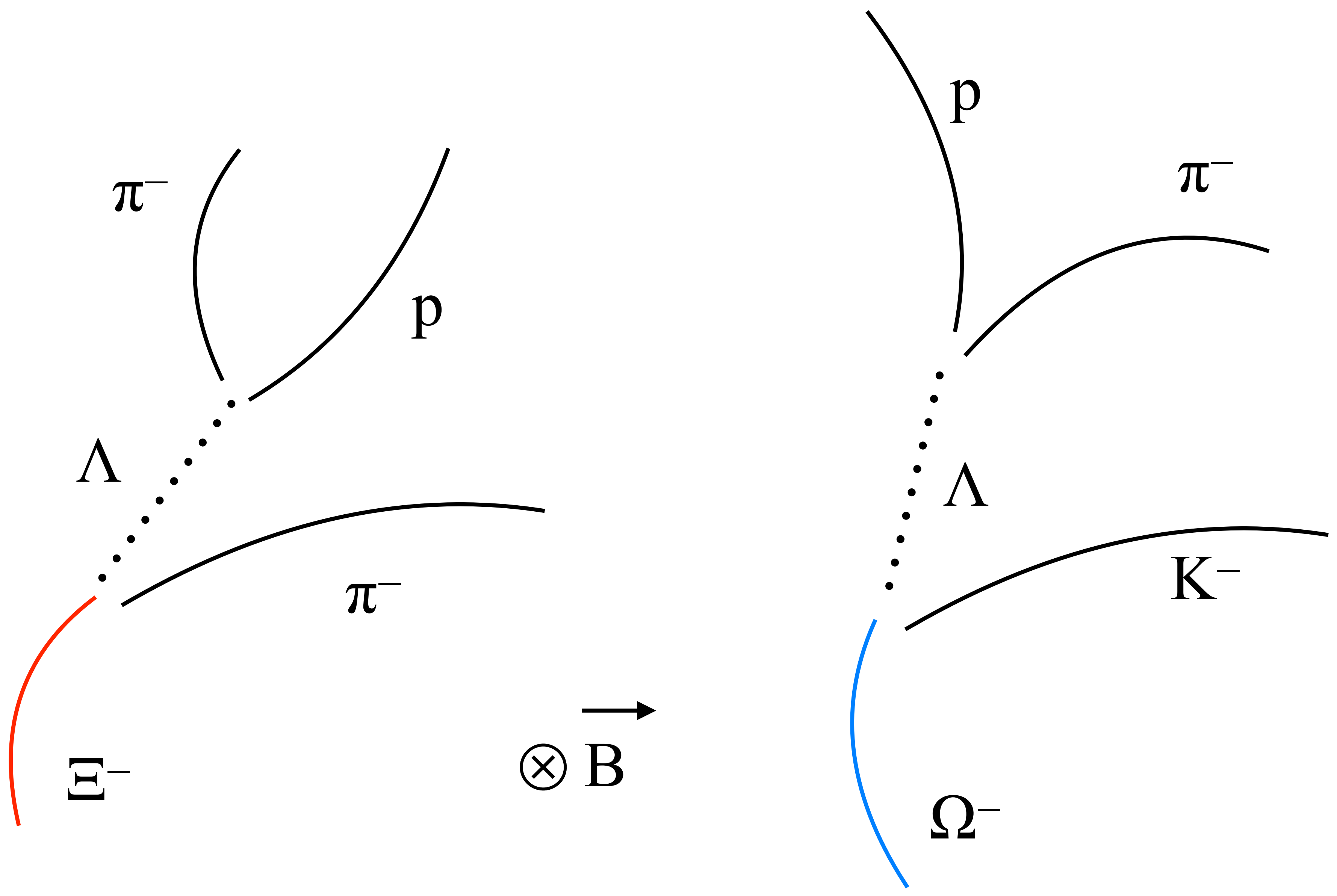
- temperature 5.5×10^{12} K
- more than ~10^5 times higher than a temperature in the middle of the Sun
- presumably only hypernovas could produce higher temperature in the recent Universe

Strangeness

Strange hadrons with weak decay:

$$K^0(d\bar{s}), \Lambda(uds), \Xi^-(dss), \Omega^-(sss)$$



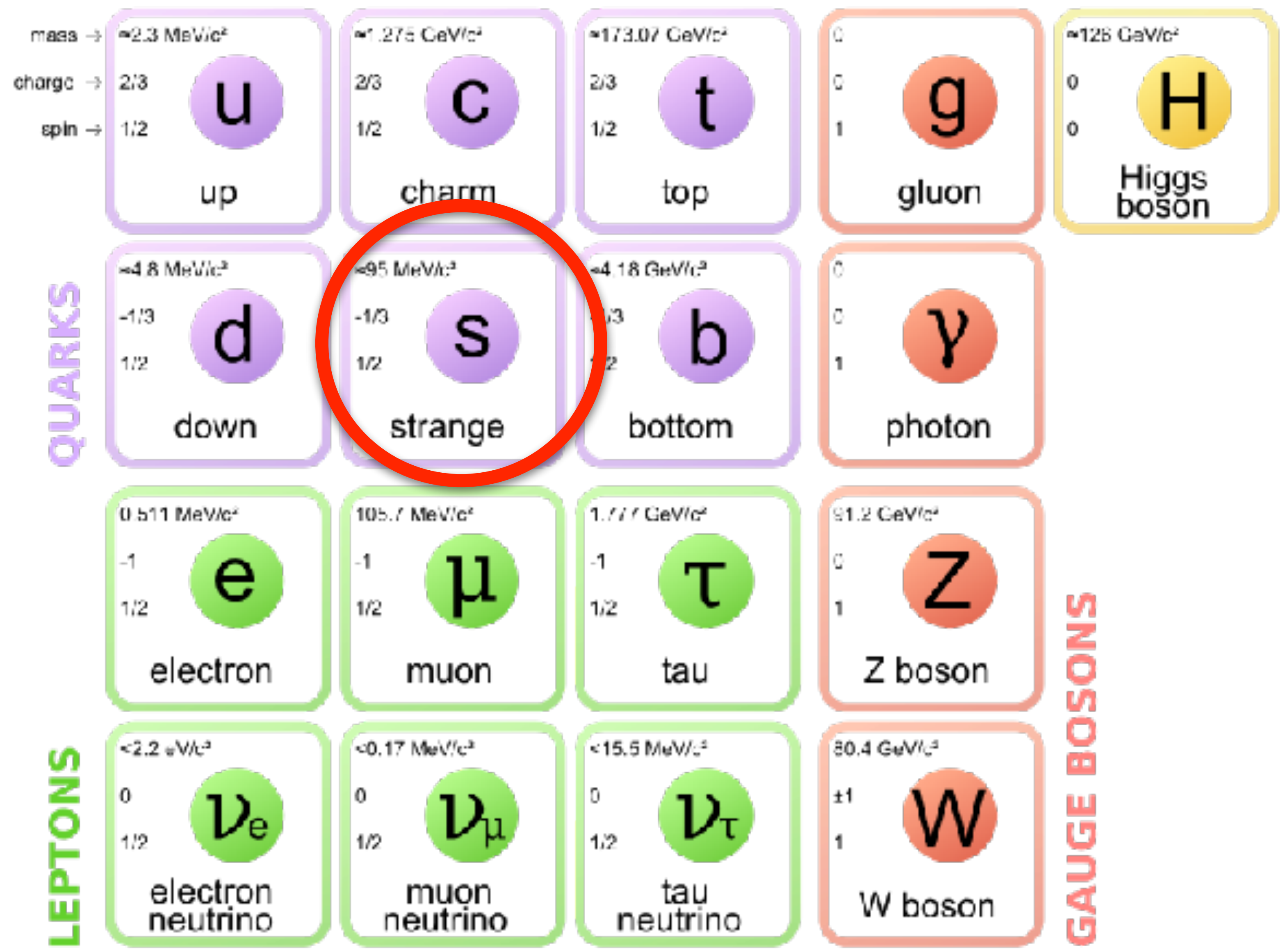


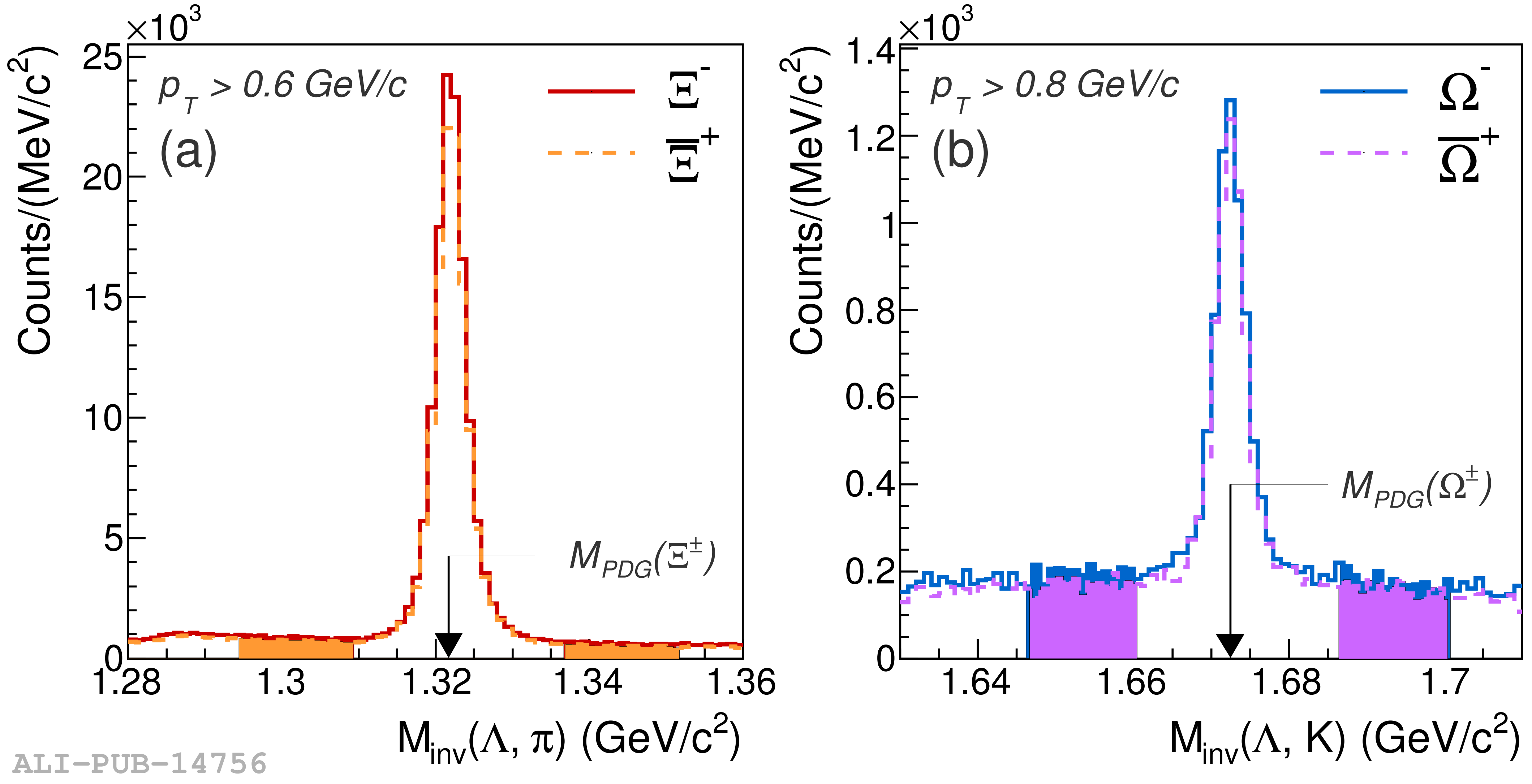
Weak decays of strange particles are reconstructed and identified in the detector up to very high momenta.

Strangeness

Strange hadrons with weak decay:

$$K^0(d\bar{s}), \Lambda(uds), \Xi^-(dss), \Omega^-(sss)$$



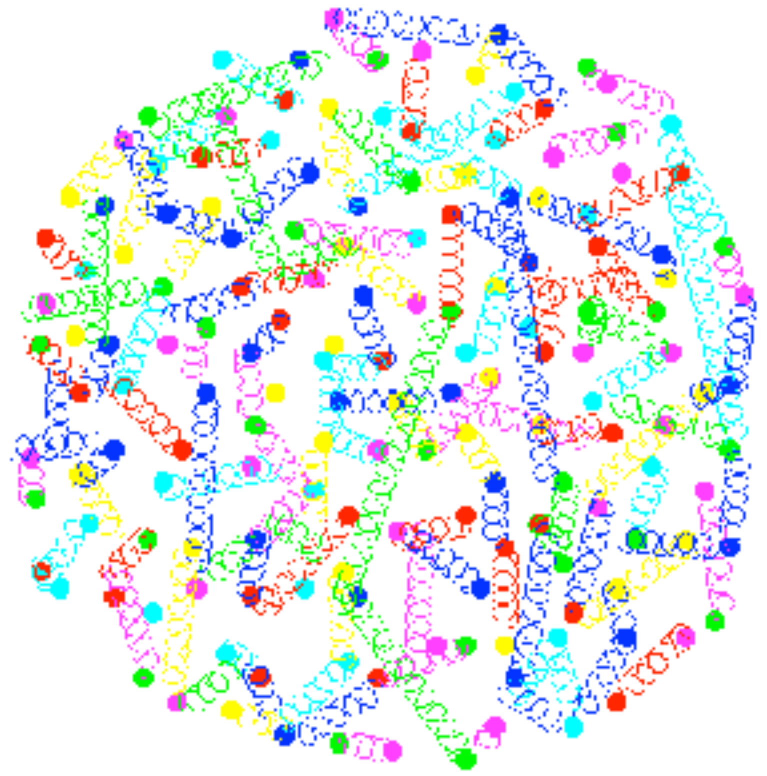


Strange particle production is obtained by analysing invariant mass distribution of the (assumed) decay products.

Strangeness enhancement

- Originally proposed as a signature of QGP [J. Rafelski, B. Müller, Phys. Rev. Lett. 48 (1982) 1066–1069]
- Production of strange quarks in QGP should be energetically favoured and faster than production in hadron gas
- The signature was confirmed by experiments at SPS, RHIC and LHC

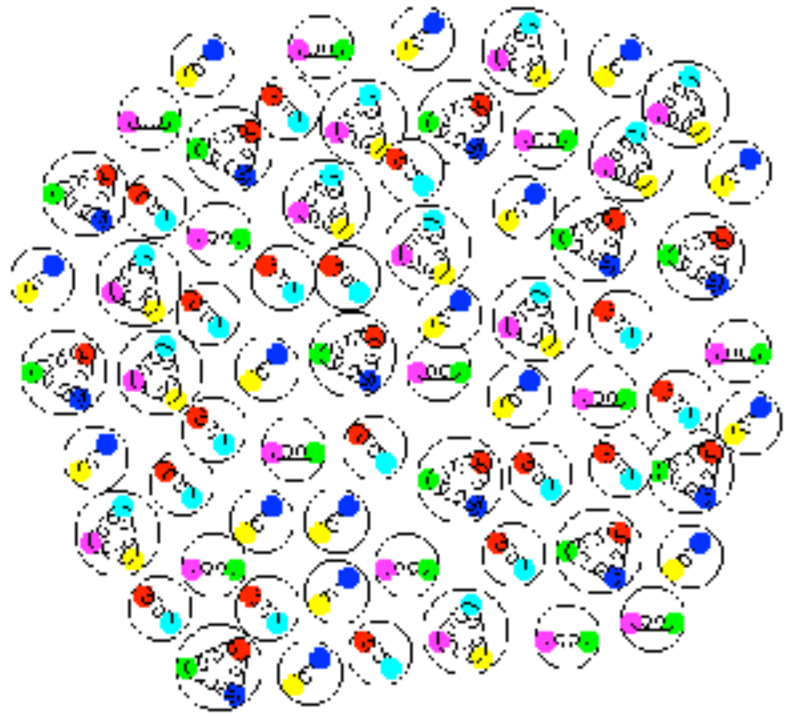
quark-gluon plasma



$$g + g \to s + \bar{s}$$
$$g + g \to s + \bar{s}$$
$$q + \bar{q} \to s + \bar{s}$$

$\Omega^-(sss)$

hadron gas

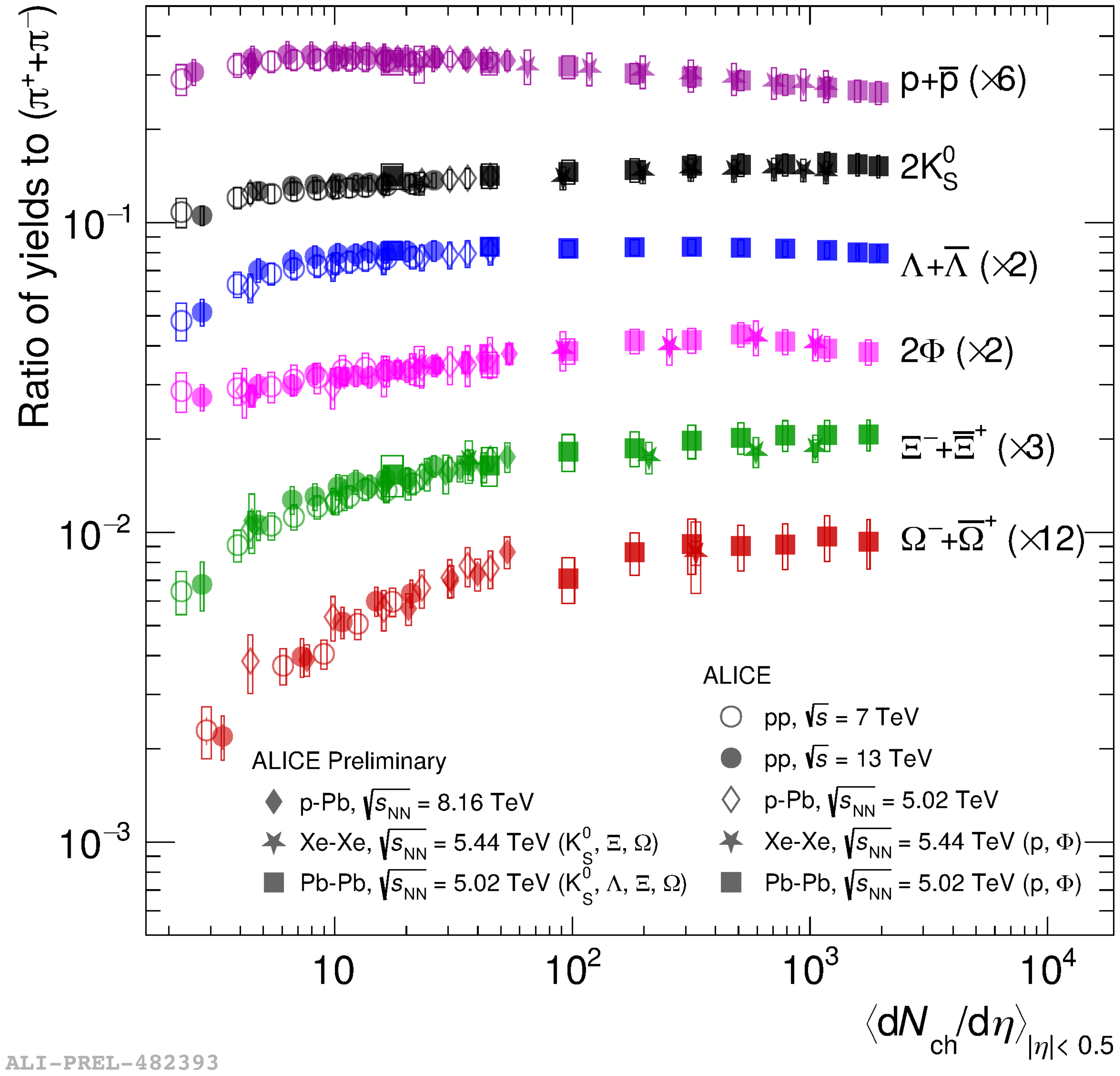


$$p + \pi^- \to \Lambda^0 + K^0$$
$$\Lambda^0 + \pi^- \to \Xi^- + K^0$$
$$\Xi^- + \pi^0 \to \Omega^- + K^0$$

Ω^-

Strangeness enhancement also in pp and p-Pb!

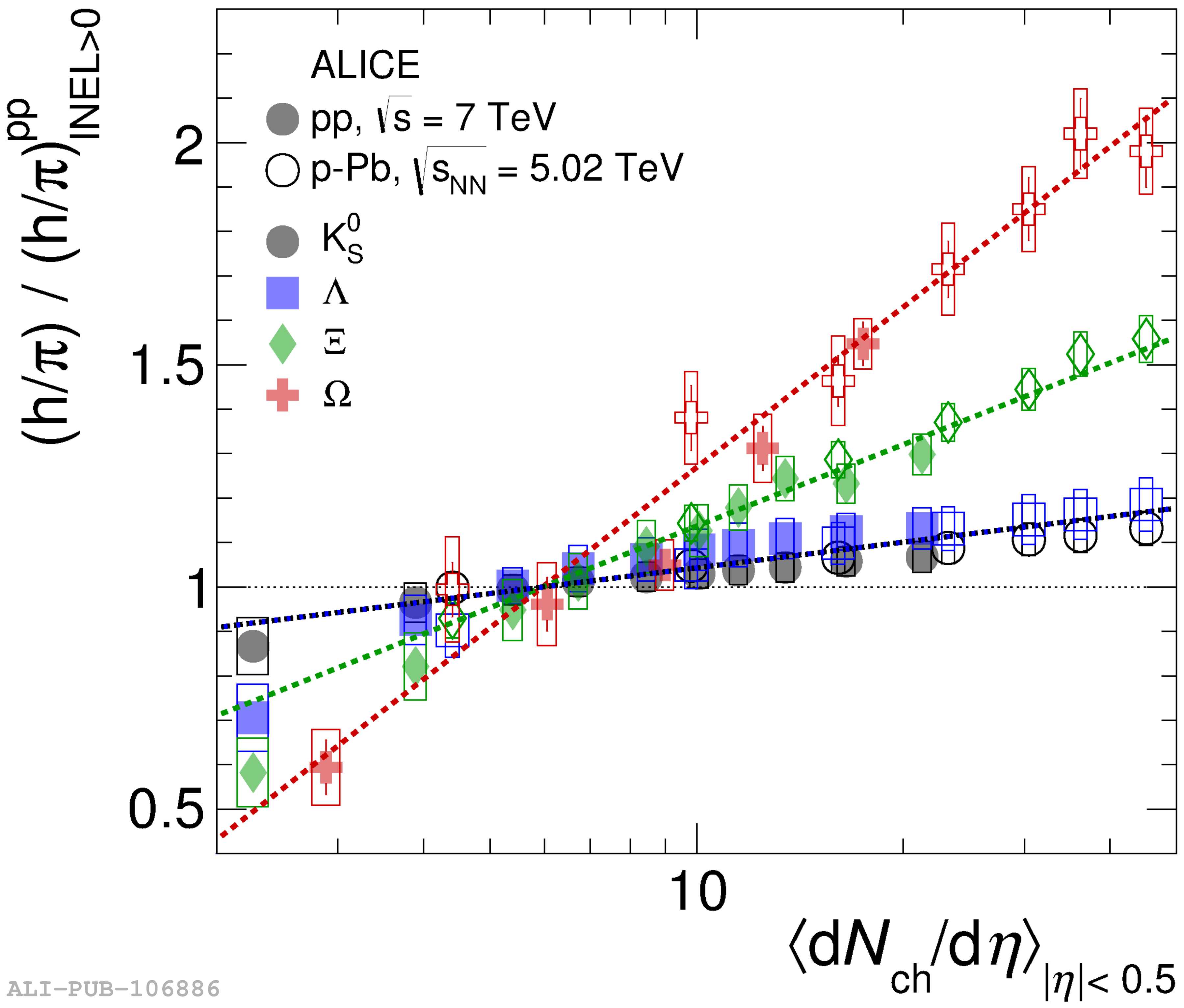
Enhancement hierarchy is determined by number of valence quarks in the hadron!



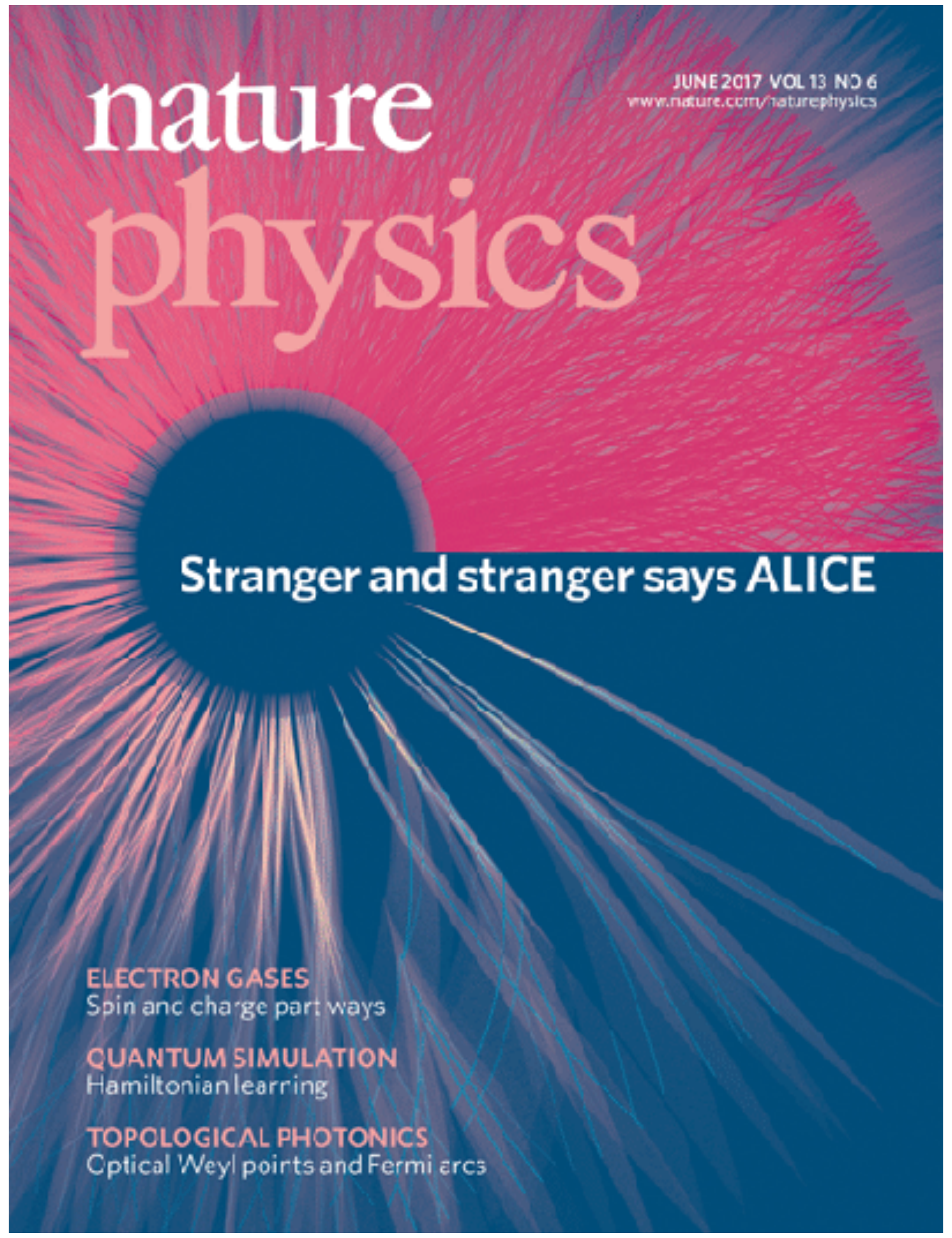
- strangeness enhancement clearly visible for pp a p–Pb collisions with high multiplicity
- one of the indications that some form of parton matter can be created also in pp collision (there are also models which do not require QGP)

Strangeness enhancement also in pp and p-Pb!

Enhancement hierarchy is determined by number of valence quarks in the hadron!



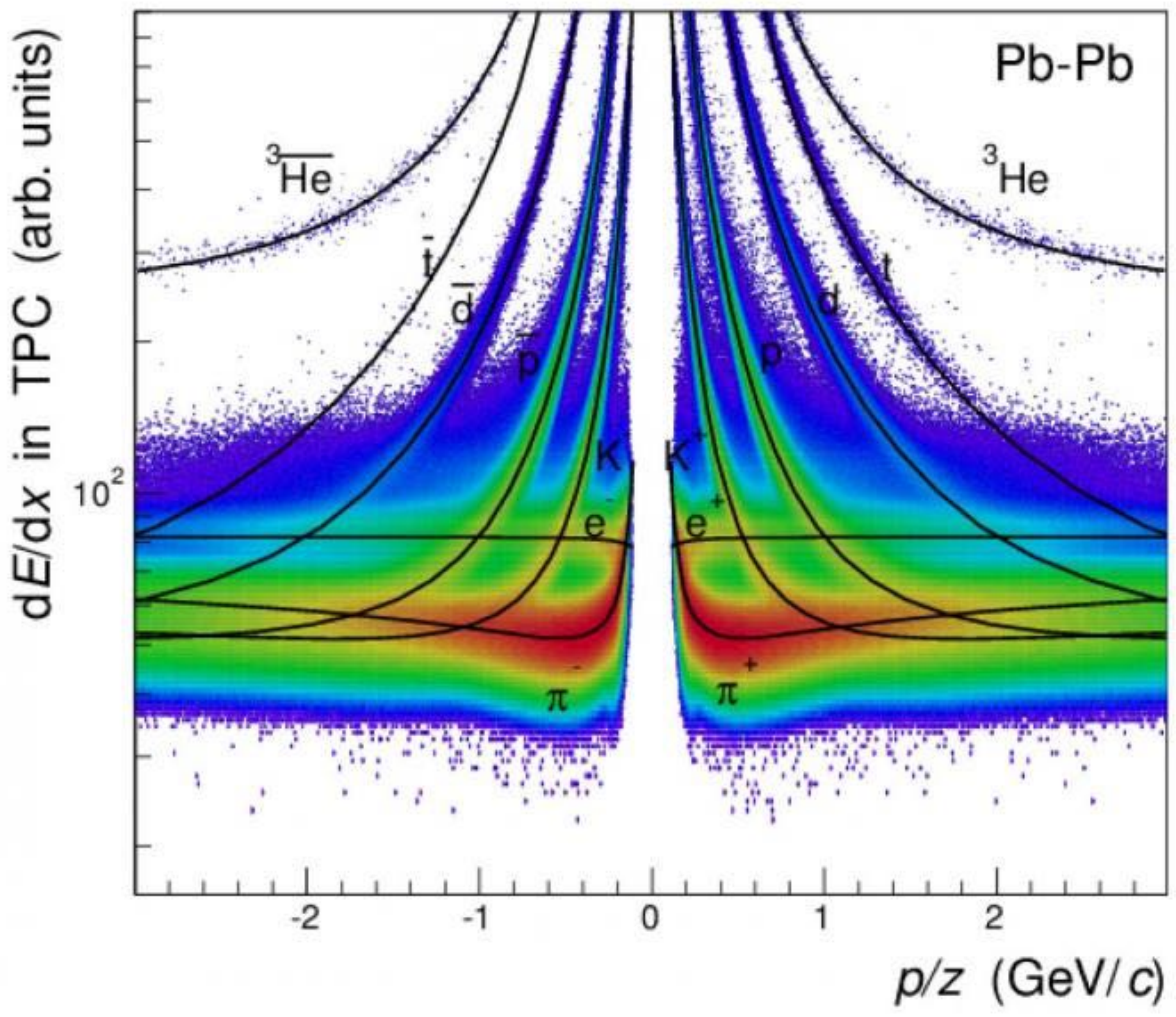
- strangeness enhancement clearly visible for pp a p–Pb collisions with high multiplicity
- one of the indications that some form of parton matter can be created also in pp collision (there are also models which do not require QGP)



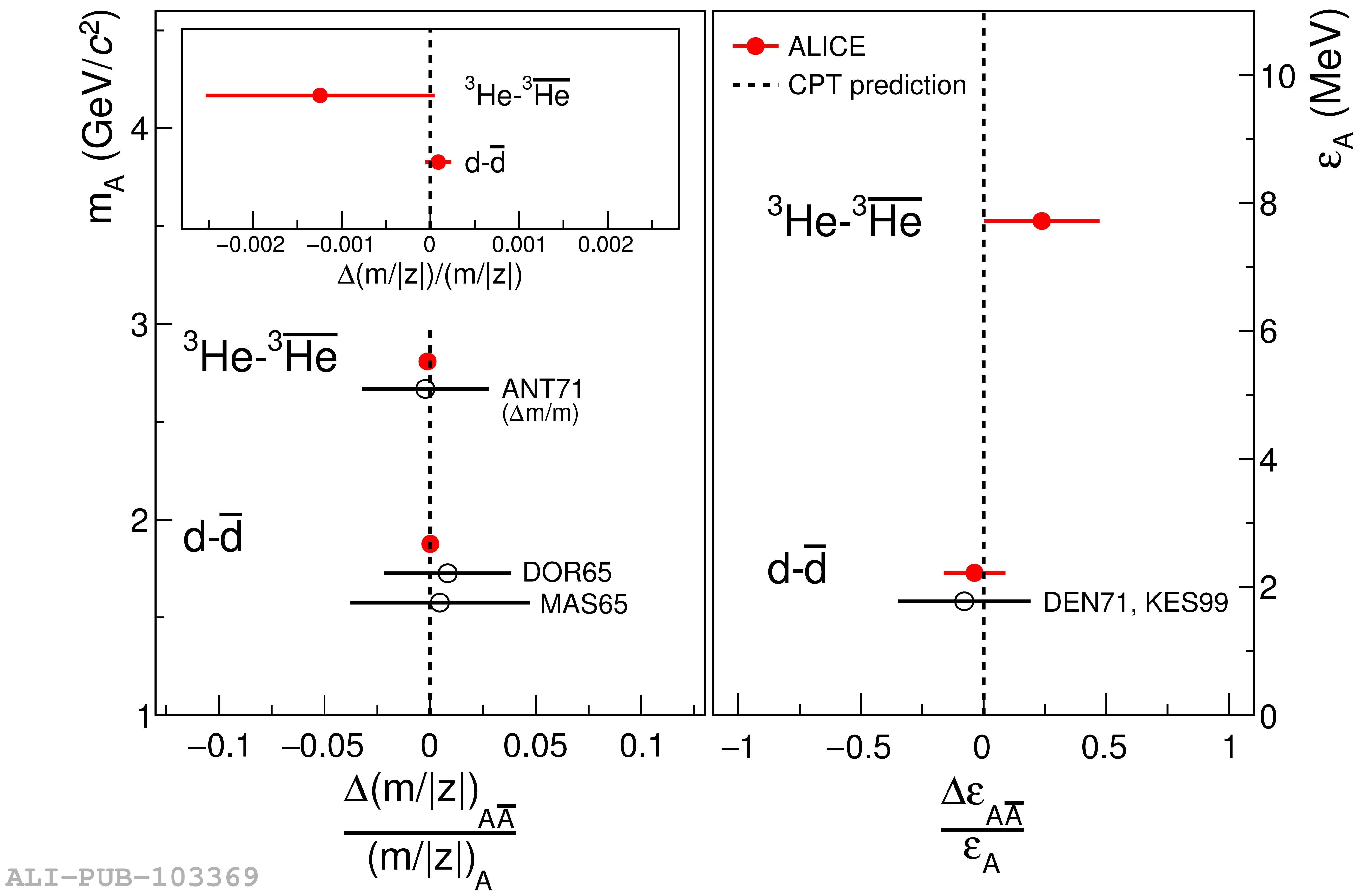
ALICE Collaboration: *Enhanced production of multi-strange hadrons in high-multiplicity proton–proton collisions.* **Nature Physics** 13, 535–539 (2017). https://doi.org/10.1038/nphys4111

ALICE impact in Nuclear Physics: CPT invariance in N-N interactions

- CPT invariance: a fundamental symmetry of the nature: all physics laws are the same when we change at the same time the charge (C), space (P) and time (T). As a consequence: **masses of the particles and antiparticles should be the same**.
- ALICE: The most precise measurement of the antinuclei masses so far. ALICE took advantage of:
  - matter and antimatter are produced at LHC in equal amounts
  - nuclei and antinuclei are produced in high amounts in heavy ion collisions
  - excellent particle identification for low momenta - a strong advantage of ALICE at the LHC



ALICE impact in Nuclear Physics: CPT invariance in N-N interactions

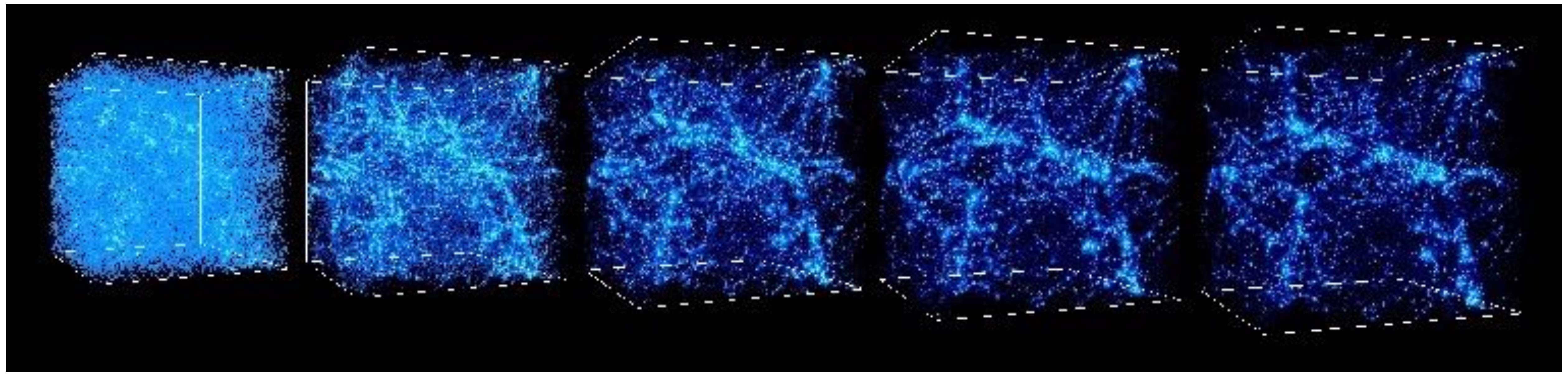


ALICE Collaboration: *Precision measurement of the mass difference between light nuclei and anti-nuclei.* **Nature Physics**, 11, 811–814 (2015). https://doi.org/10.1038/nphys3432

ALICE contribution to Cosmology: complementary measurements for a possible discovery of Dark Matter

Dark Matter (DM)

Matter which contributes to 23% of the total mass-energy of the Universe. It does not interact electromagnetically nor by strong force. Only gravitational observations are available so far.



Dark matter played an important role at Universe evolution - "gravitational skeleton" for the stars and galaxies formation.

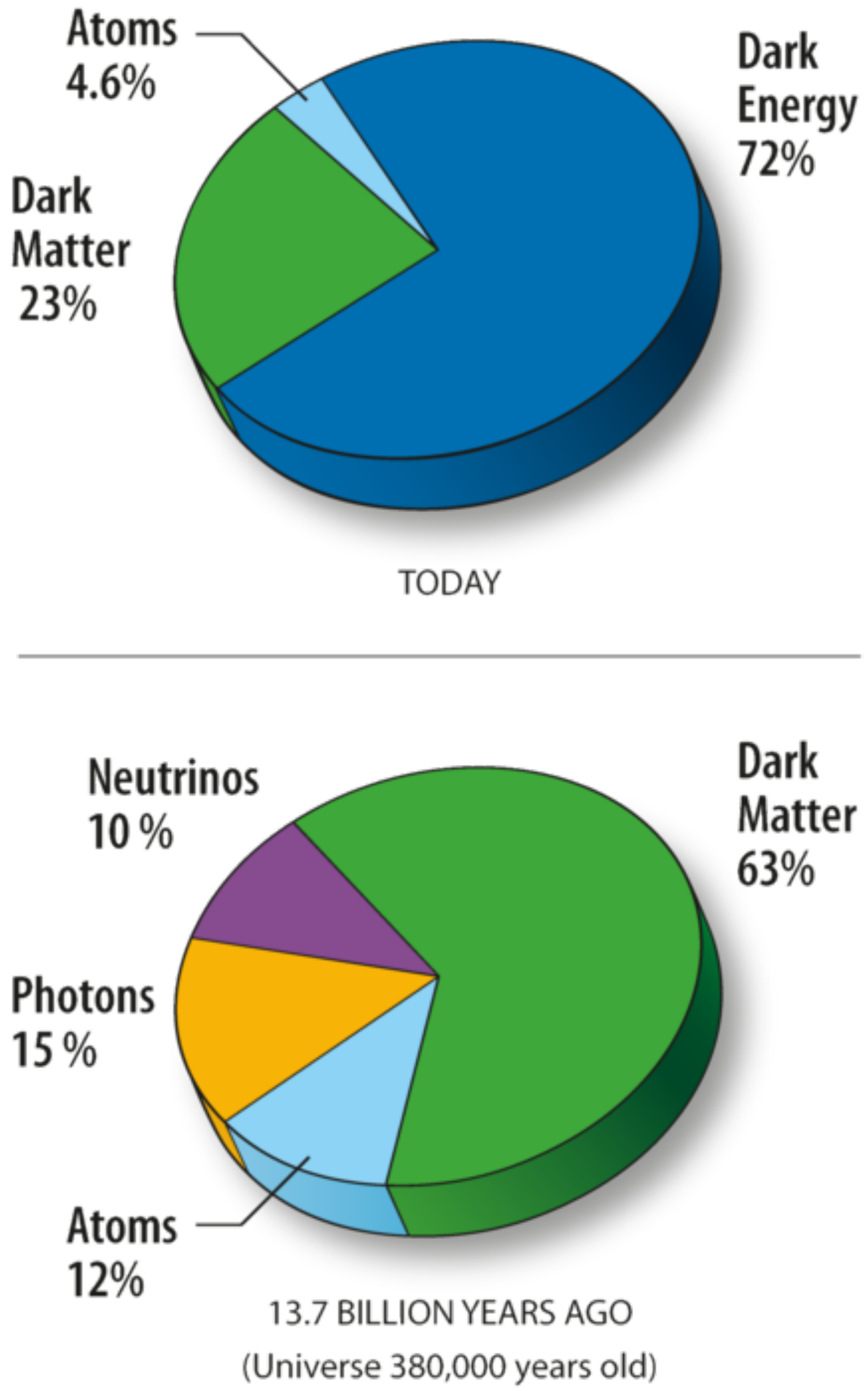


Fig.: https://en.wikipedia.org/wiki/Dark_energy

ALICE contribution to Cosmology: complementary measurements for a possible discovery of Dark Matter

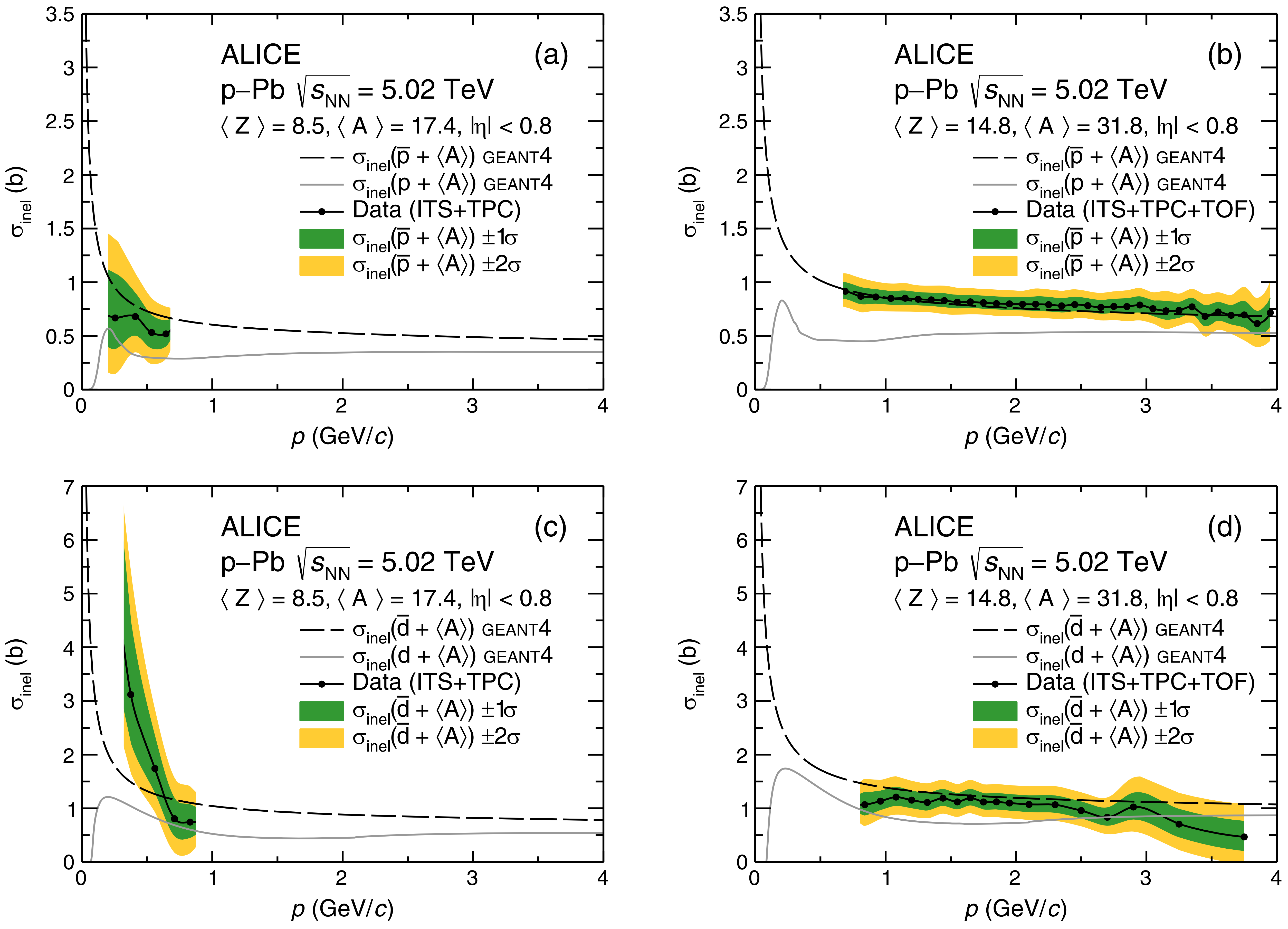
3 ways how to search for DM (if it is in a form of fundamental particles):

1. directly, e.g. at LHC (ATLAS and CMS)
2. by scattering of DM particles on nuclei
3. via annihilation or weak decay of DM particles to ordinary matter particles, as in AMS experiment - one of the promising signatures could be a production of antinuclei, which should be higher than a **background production in cosmic rays** (ALICE!)

Fig.: https://en.wikipedia.org/wiki/Alpha_Magnetic_Spectrometer

ALICE contribution to Cosmology: complementary measurements for a possible discovery of Dark Matter

ALICE contribution: an estimation of antinuclei production in proton-proton collisions (proxy for cosmic ray interactions within the interstellar medium) and an estimation of the cross section of the light antinuclei on nuclei.



ALICE Collaboration: *Measurement of the Low-Energy Antideuteron Inelastic Cross Section,* **Physical Review Letters** 125, 162001 (2020), doi: 10.1103/PhysRevLett.125.162001

ALICE Collaboration: *(Anti-)deuteron production in pp collisions at √s = 13 TeV*, **Eur. Phys. J. C** (2020) 80:889 https://doi.org/10.1140/epjc/s10052-020-8256-4

ALICE impact in Astrophysics: hyperon matter in neutron stars cores

- the state equation for neutron stars depends on cross section knowledge of the nucleons and hyperons (strange baryons)
- cross sections are measured in the scattering experiments
- the scattering experiments can be easily set up with more-or-less stable particles containing up and down quarks (e.g. protons, neutrons or pions)
- the scattering experiments with strange baryons (a. k. a. hyperons - Y) are impossible to realise (due to unstability and very low production)
- femtoscopy - a method which can measure the interactions of two particles

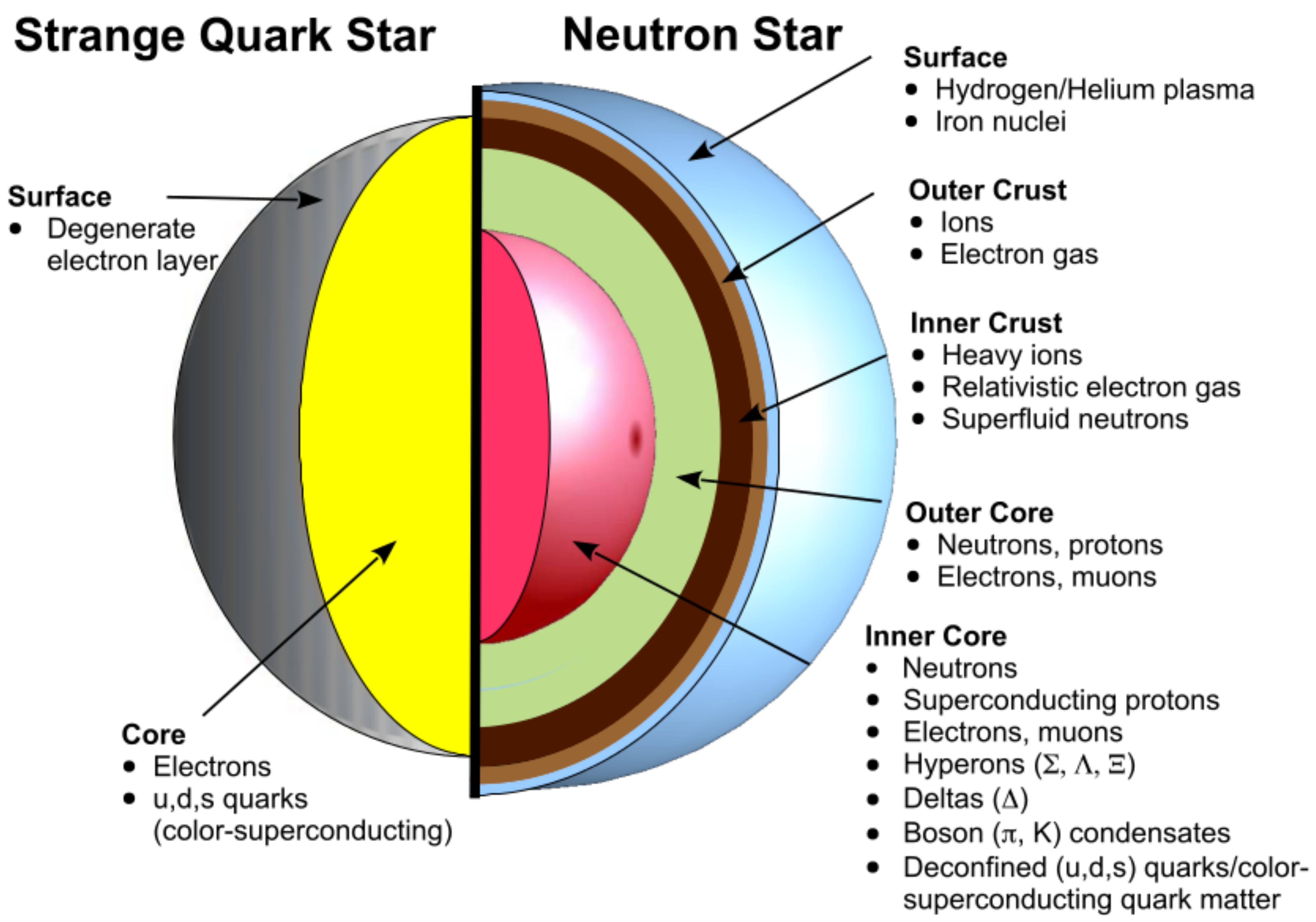
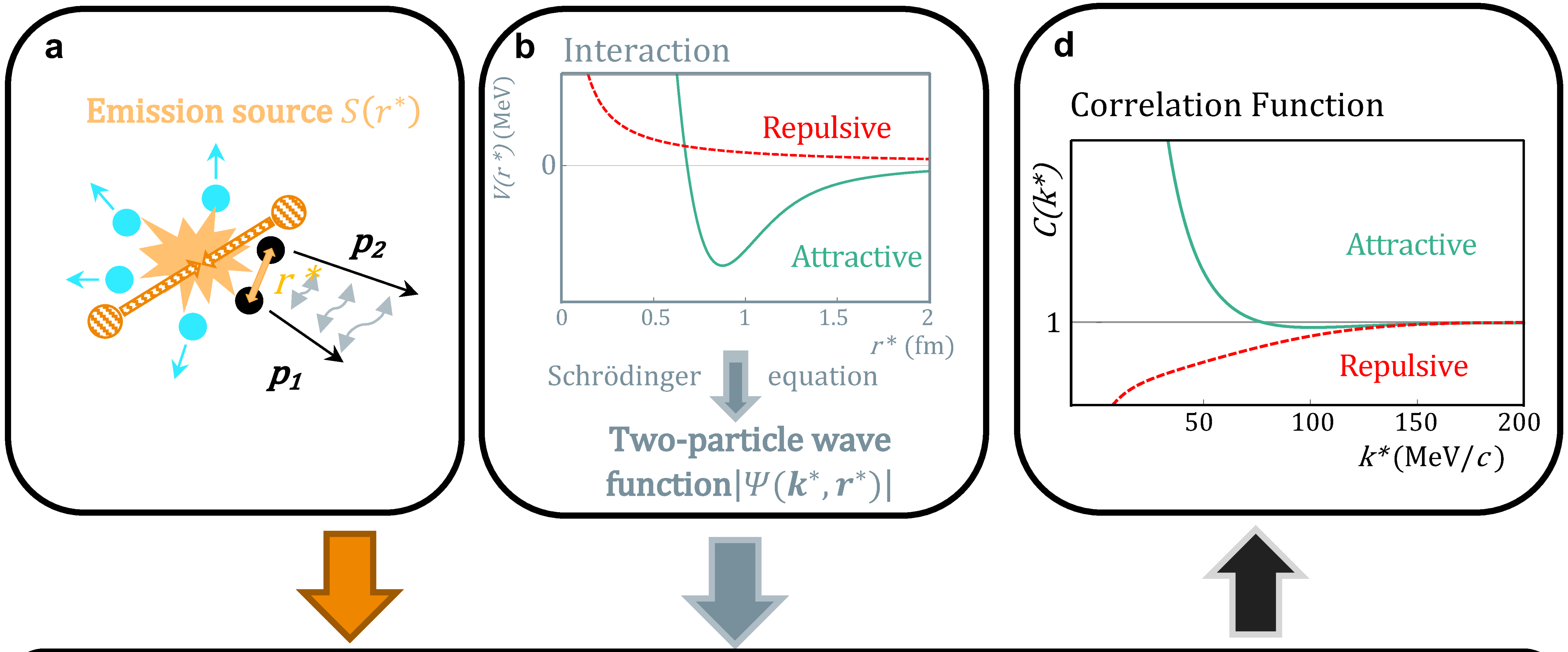


Fig.: https://astrobites.org/2014/08/11/peeling-apart-a-neutron-star/

ALICE impact in Astrophysics: hyperon matter in neutron stars cores

Method: particle correlations in momentum space a.k.a. femtoscopy

- source emitting particles interact elastically via strong interaction
- attractive force can indicate possible bound states



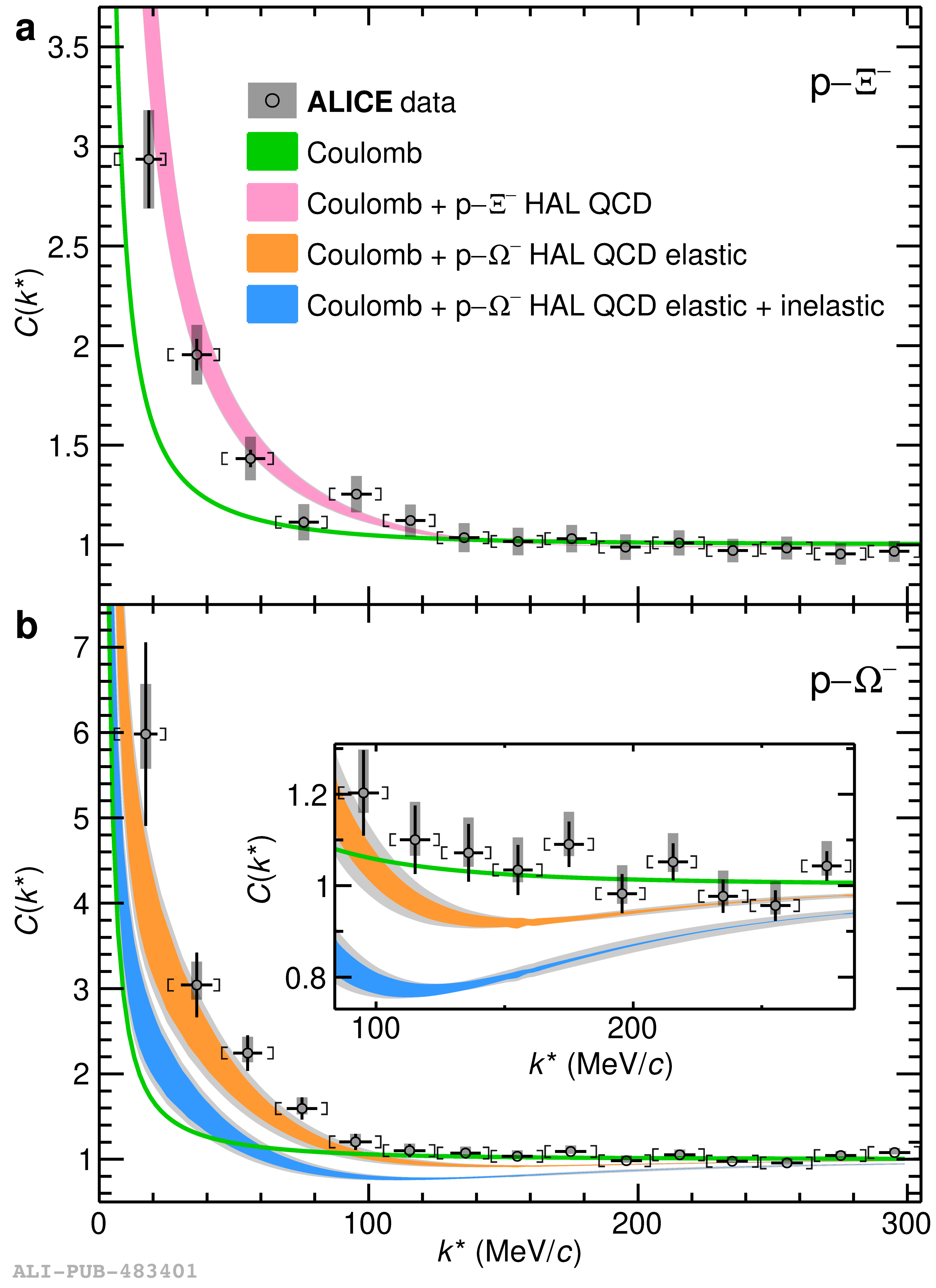
c

$$C(k^*) = \int S(r^*) \; |\Psi(\boldsymbol{k}^*, \boldsymbol{r}^*)|^2 \, d^3r^* = \xi(k^*) \cdot \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$

ALI-PUB-483391

ALICE impact in Astrophysics: hyperon matter in neutron stars cores

- an exact knowledge about a character of Y-N and Y-Y has important consequences on neutron star physics
- the hyperons in the cores of the neutron stars - their existence and amounts depend on interactions with nucleons
- a full exploitation of the method in LHC Run 3 and Run 4

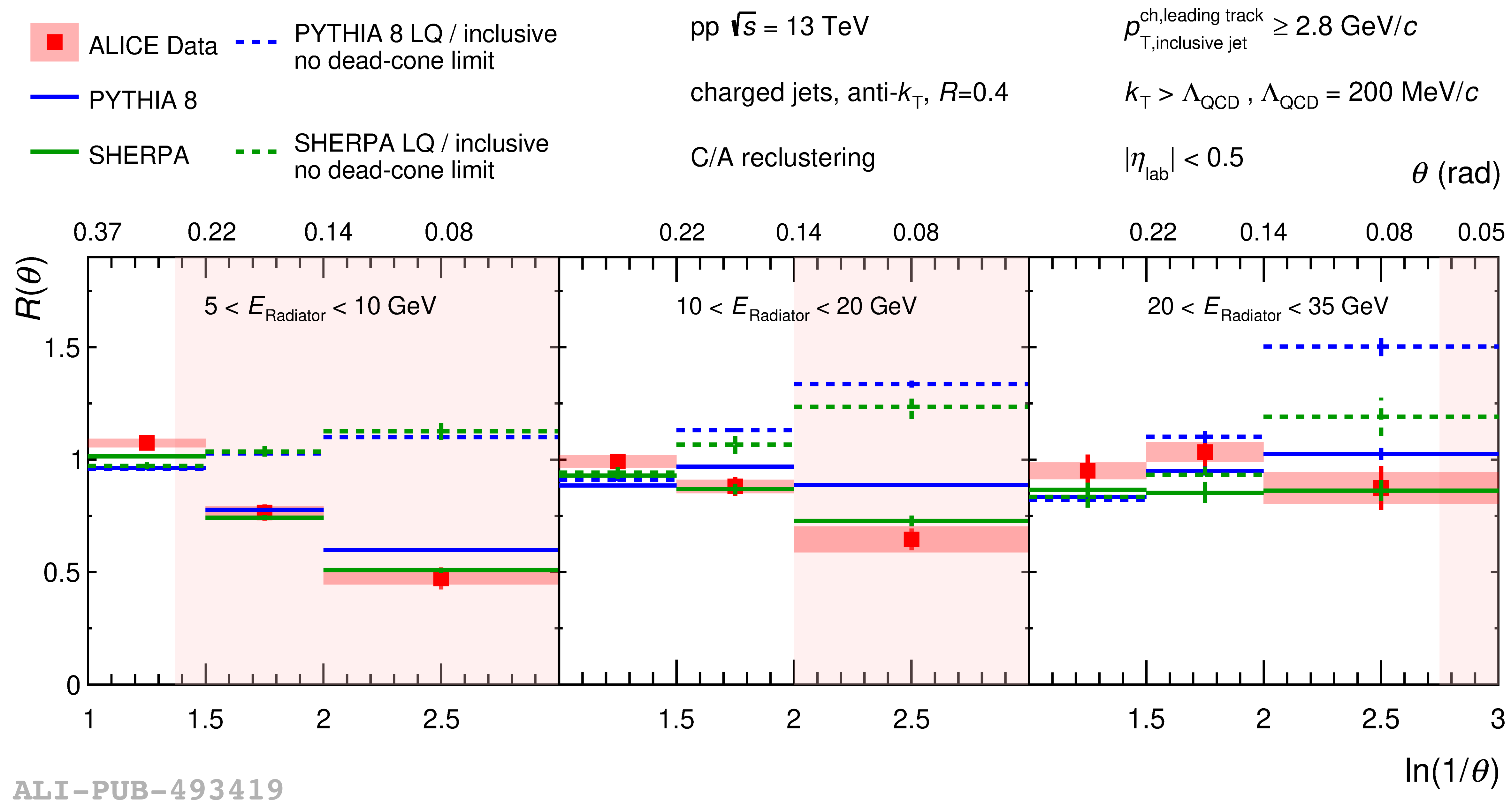


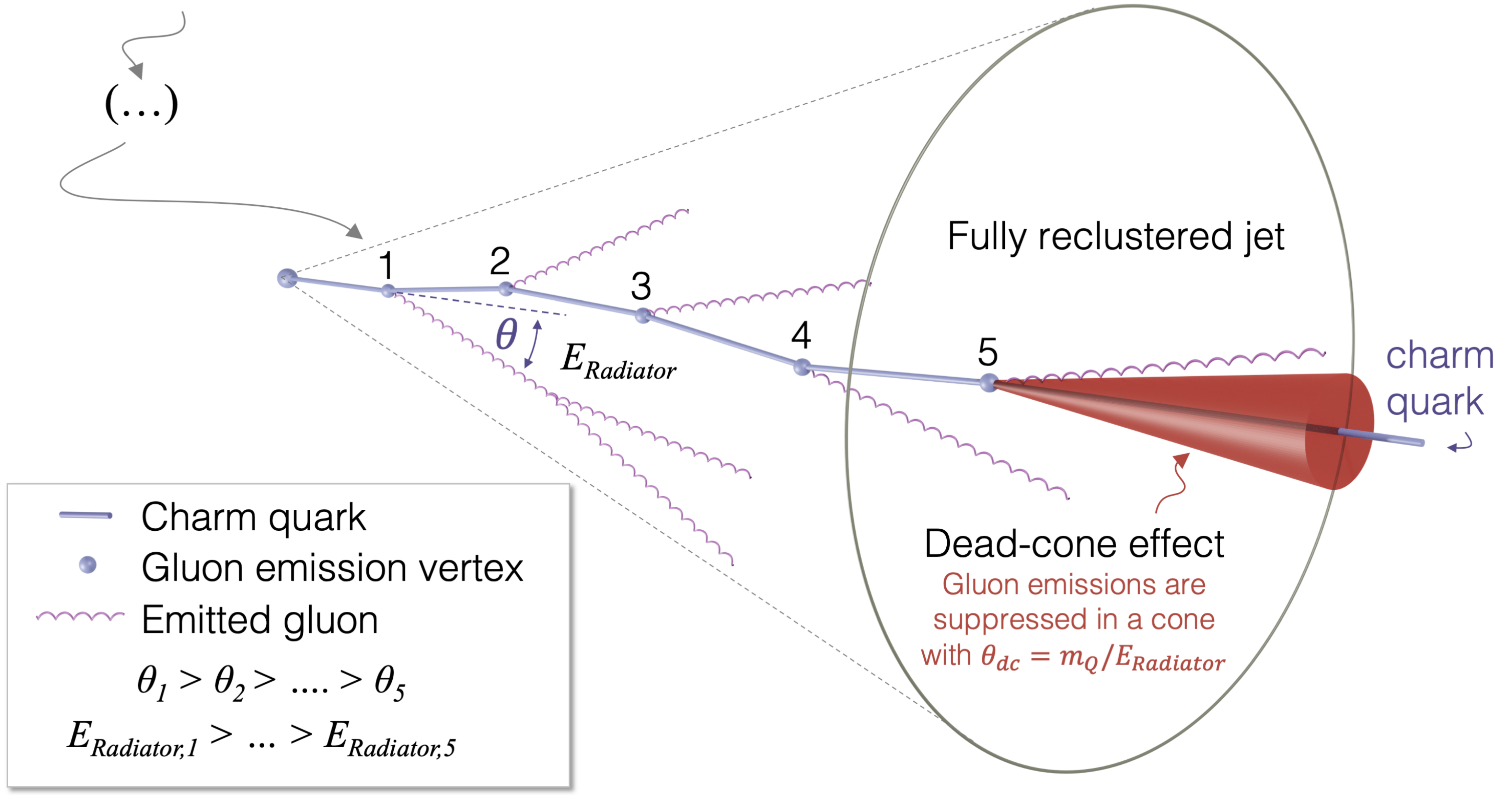
ALICE Collaboration: *Unveiling the strong interaction among hadrons at the LHC*, **Nature** 588, 232–238 (2020). https://doi.org/10.1038/s41586-020-3001-6

Dead cone effect observed - ALICE contribution to QCD

- it is a part of the space (cone), where the gluon bremstrahlung is supressed
- the size of the cone is proportional to mass-over-energy of the quark which emits gluons
- direct experimental observation of the heavy quark mass!

ALICE Collaboration: *Direct observation of the dead-cone effect in quantum chromodynamics,* **Nature** 605, 440–446 (2022). https://doi.org/10.1038/s41586-022-04572-w

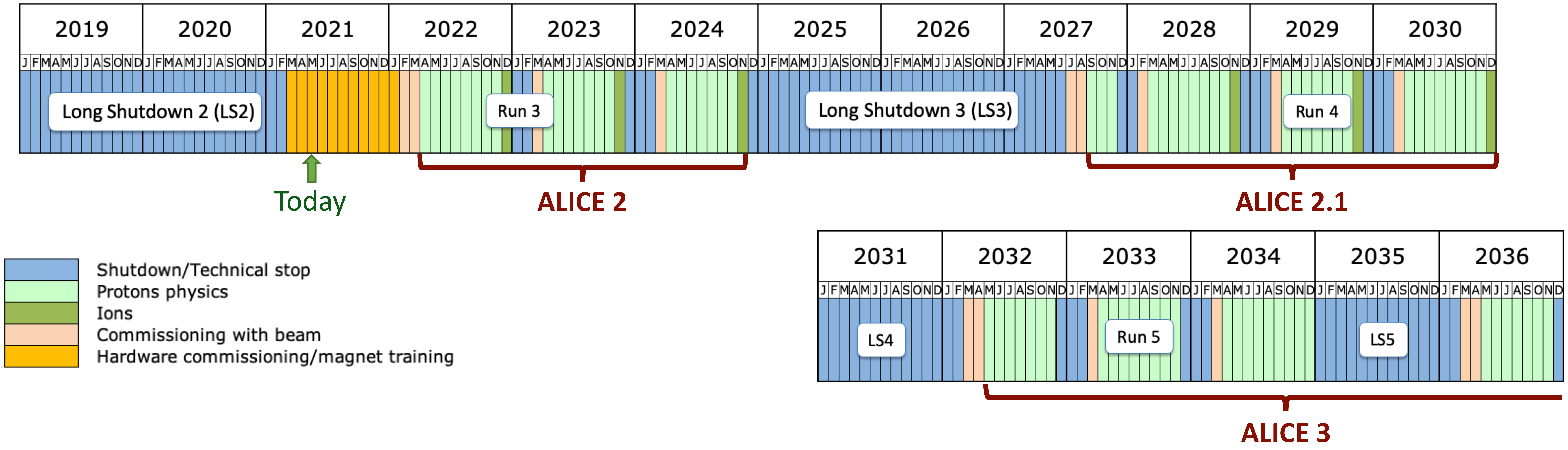




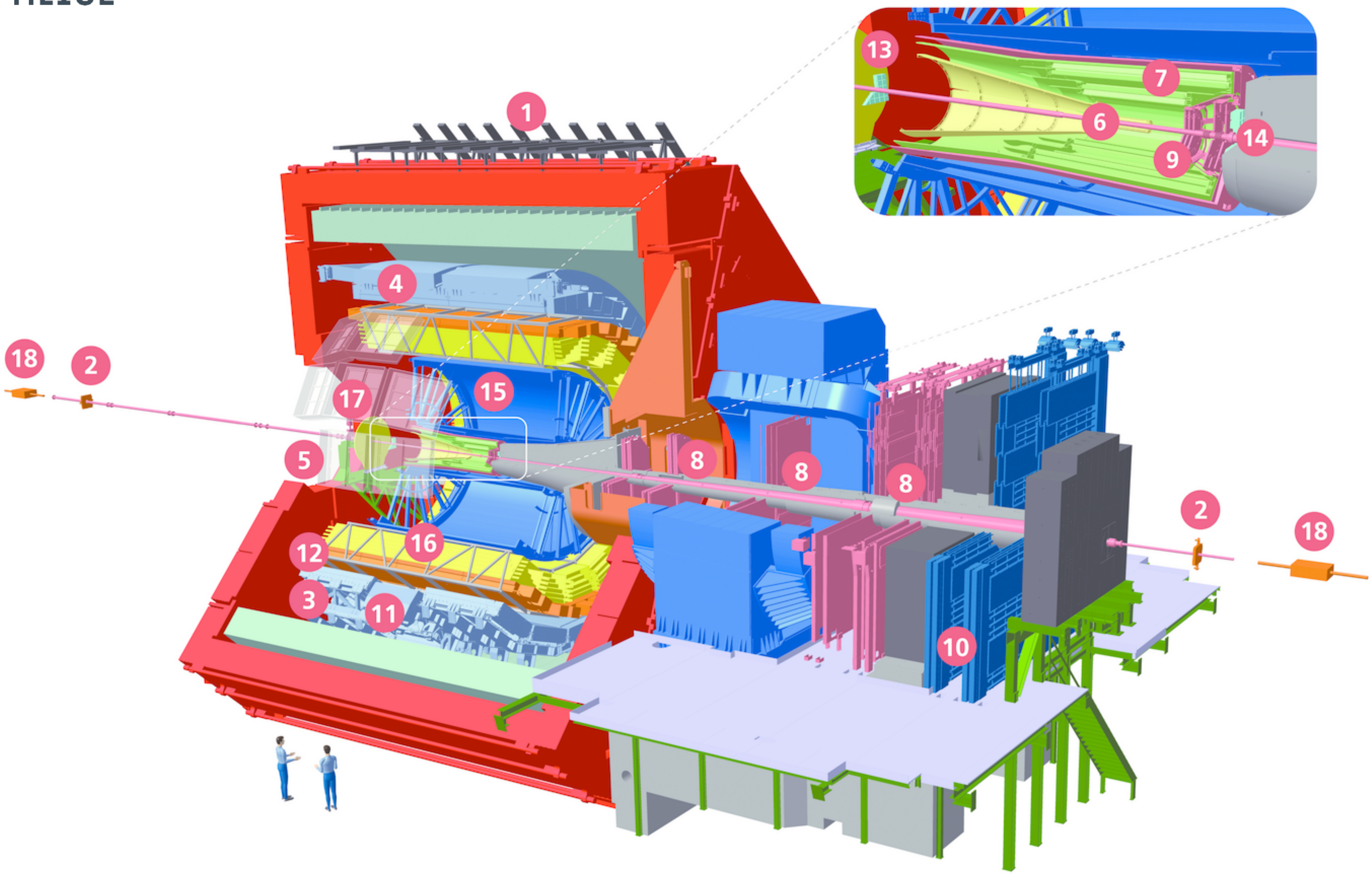
LHC lifetime cycle

LHC cycles:

- Run - collider on
- Long Shutdown (LS) - collider off



ALICE version 2.0 - Run 3

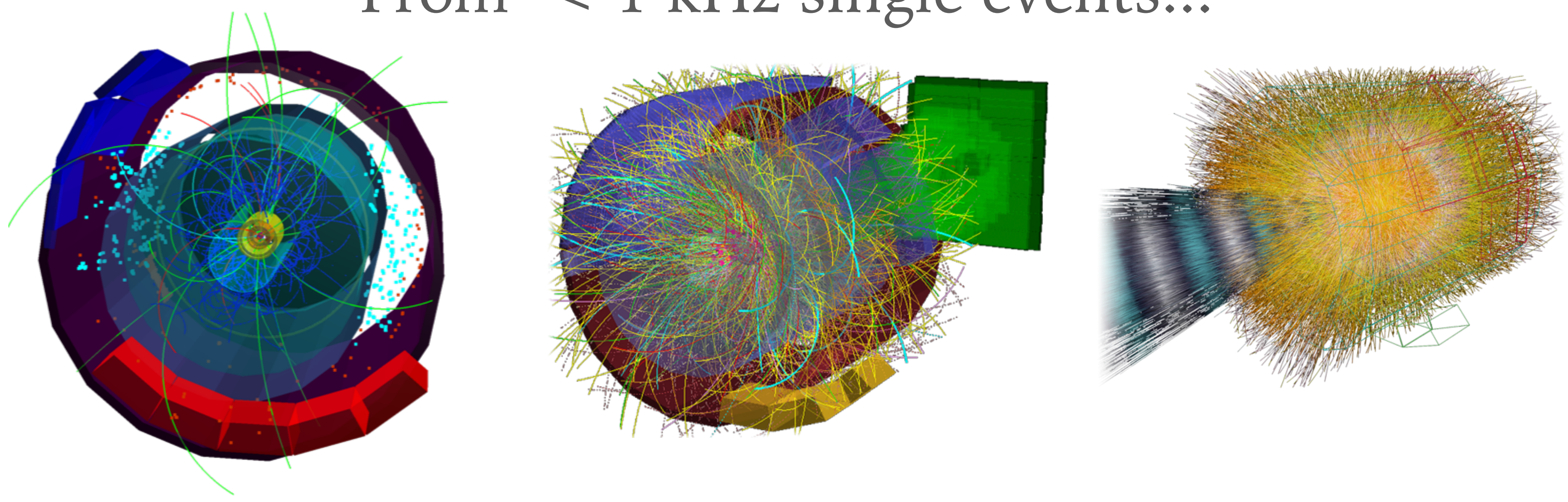


1. **ACORDE** | ALICE Cosmic Rays Detector
2. **AD** | ALICE Diffractive Detector
3. **DCal** | Di-jet Calorimeter
4. **EMCal** | Electromagnetic Calorimeter
5. **HMPID** | High Momentum Particle Identification Detector
6. **ITS-IB** | Inner Tracking System - Inner Barrel
7. **ITS-OB** | Inner Tracking System - Outer Barrel
8. **MCH** | Muon Tracking Chambers
9. **MFT** | Muon Forward Tracker
10. **MID** | Muon Identifier
11. **PHOS / CPV** | Photon Spectrometer
12. **TOF** | Time Of Flight
13. **T0+A** | Tzero + A
14. **T0+C** | Tzero + C
15. **TPC** | Time Projection Chamber
16. **TRD** | Transition Radiation Detector
17. **V0+** | Vzero + Detector
18. **ZDC** | Zero Degree Calorimeter

ALICE version 2.0 - Run 3

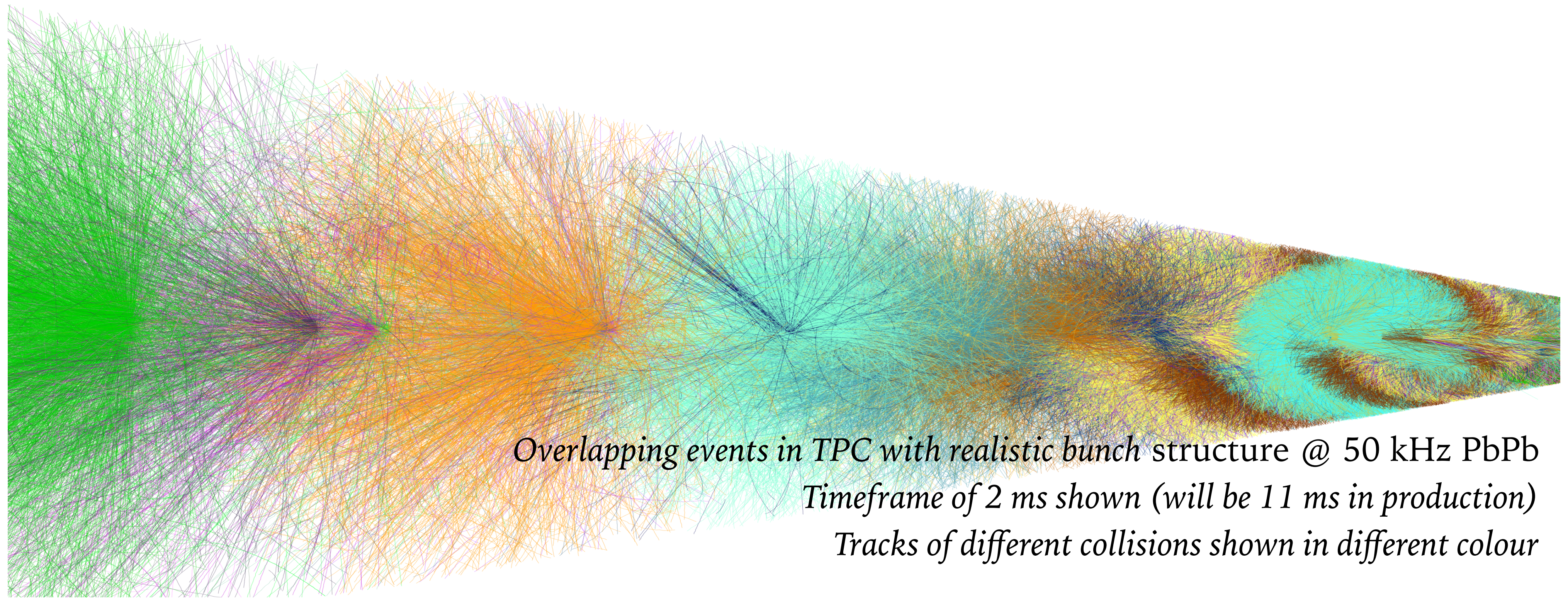
- 50kHz in Pb-Pb (in Run1/2 ~1kHz) => 50-100 times more statistics
- physics focused on interaction of QGP environment with heavy quarks, not yet discovered hadrons with heavy quarks, nuclei and antinuclei production and their interaction with environment
- significant detector inovation: higher granularity, material reduction, closer to interaction point
- completely changed philosophy for data analysis (a new software framework O^2)
- 100-times more events with the new philosophy would require only 4 times more computing resources

From < 1 kHz single events...



pp *pPb* *PbPb*

...to 50 kHz of continuous readout data.



Overlapping events in TPC with realistic bunch structure @ 50 kHz PbPb
Timeframe of 2 ms shown (will be 11 ms in production)
Tracks of different collisions shown in different colour

Run 3 data flow

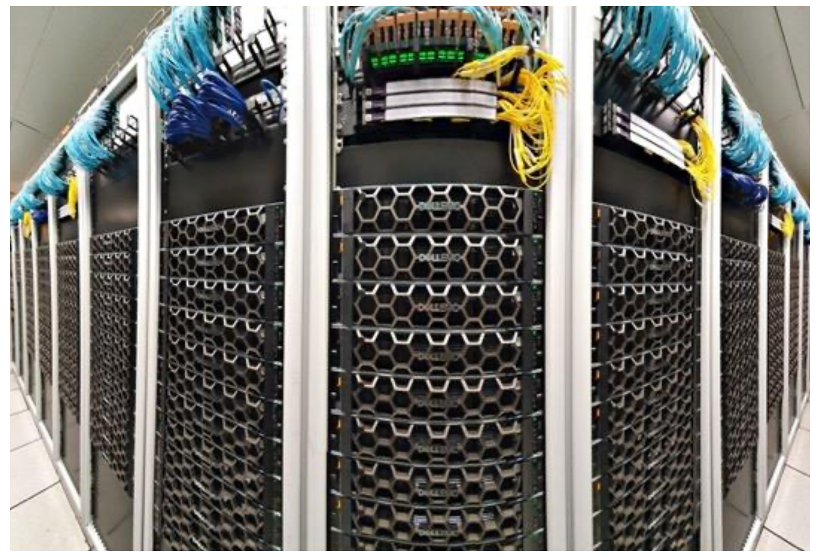
Detector

≳3TB/s
(~45GB/s in Run 2)

Readout

First Level Processor

FLP



192 nodes, 20 / 40 cores per node

up to 500 GB/s

Synchronous reconstruction (data reduction)

Event Processing Nodes

EPN

• • •

EPN

250 nodes
8 GPU and 64 CPU cores per node

*EPN input data quantum is the "**timeframe**": 11 ms of continuous readout data. ~10 GB*

up to 100 GB/s
(~10 GB/s in Run 2)

Compressed Time Frame (CTF)

On-site storage

80 PB
(1 PB in Run 2)

Asynchronous reconstruction (improved conditions)

EPN / Grid

EPN / Grid

EPN / Grid

Permanent storage

CTF, Analysis Object Data (AOD)

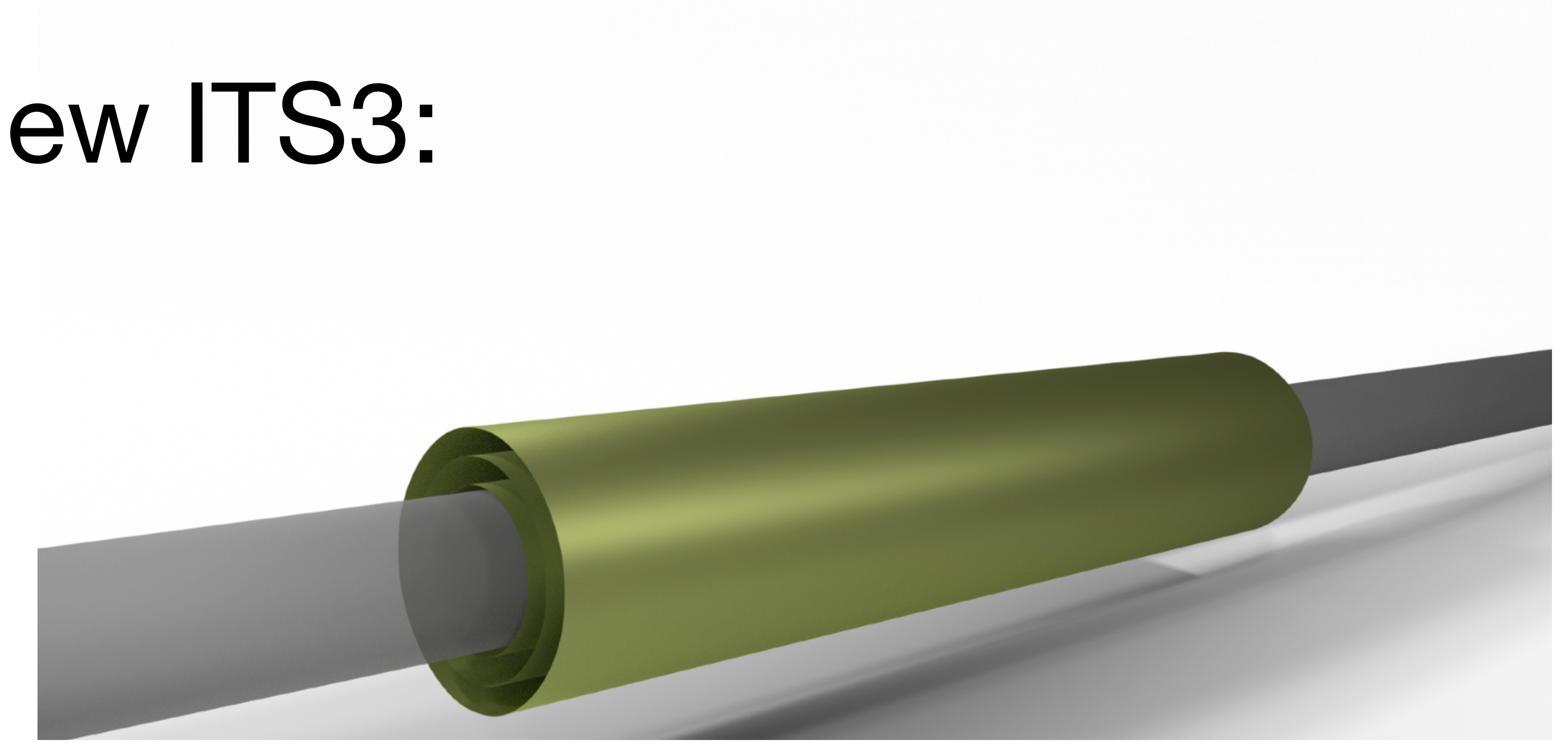
BEAM ON: data reduction

dátový tok

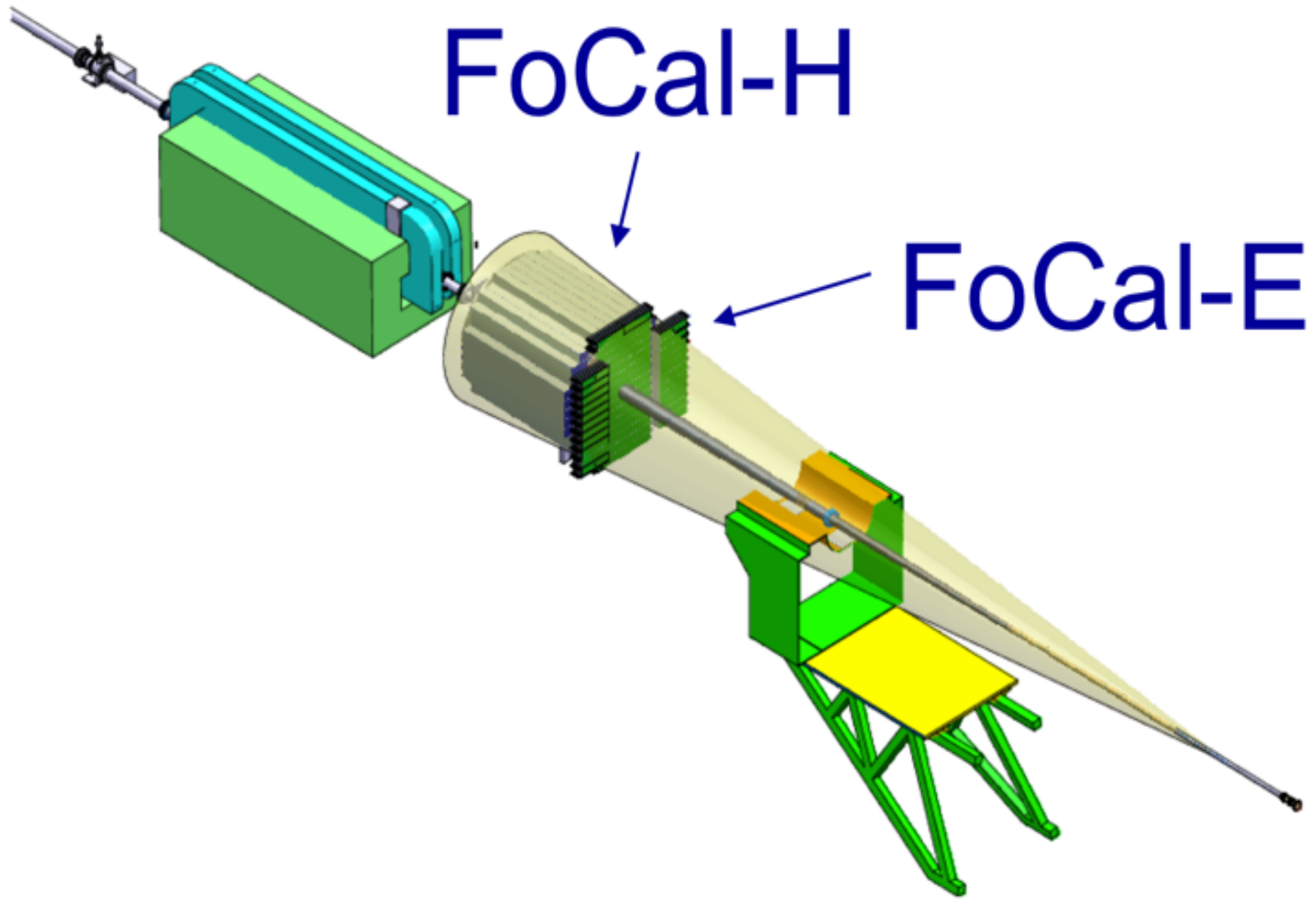
BEAM OFF: improved calibration

ALICE version 2.1 Run 4 (2028-2031) - HL-LHC

New ITS3:



FoCAL:



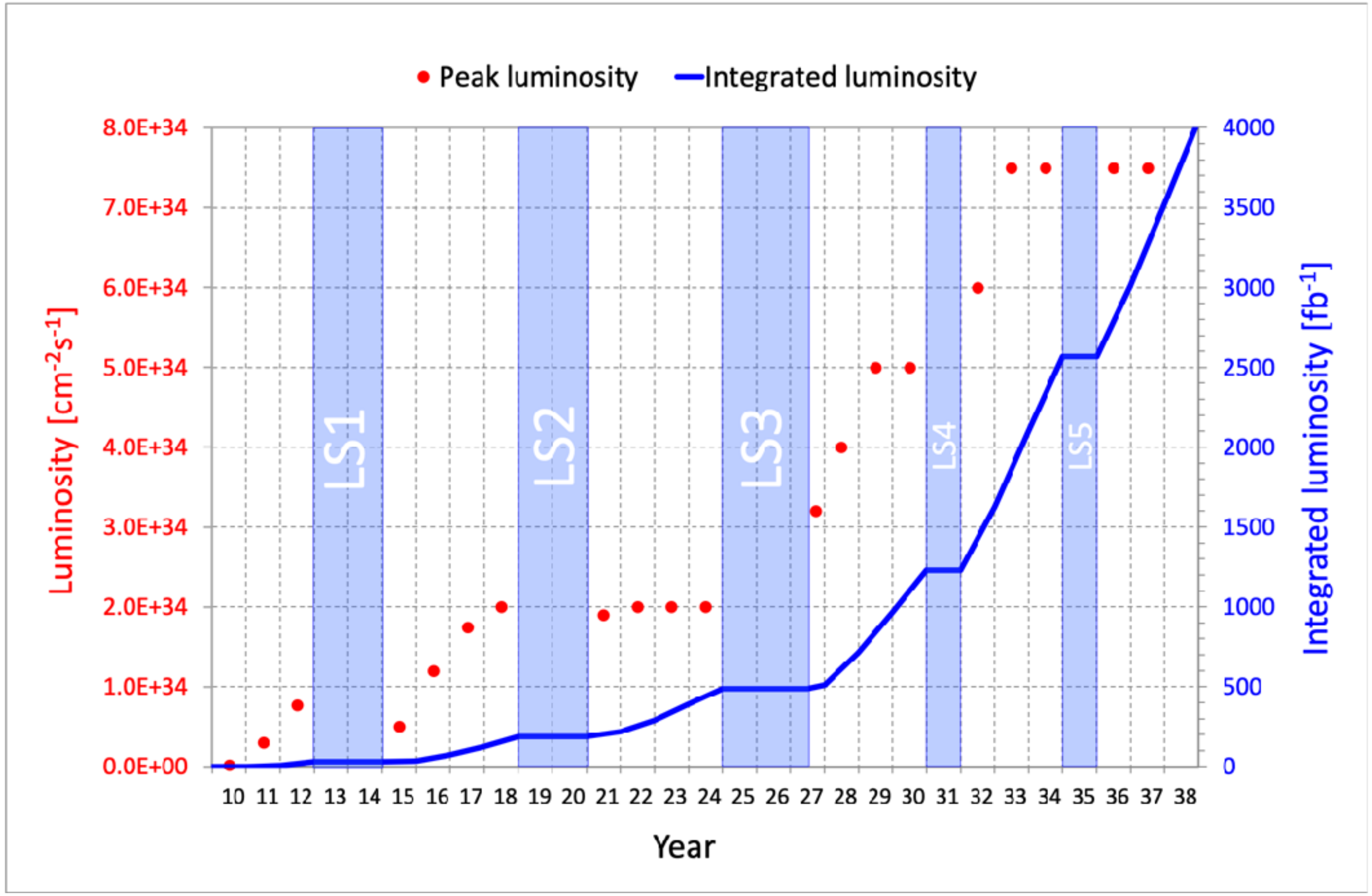
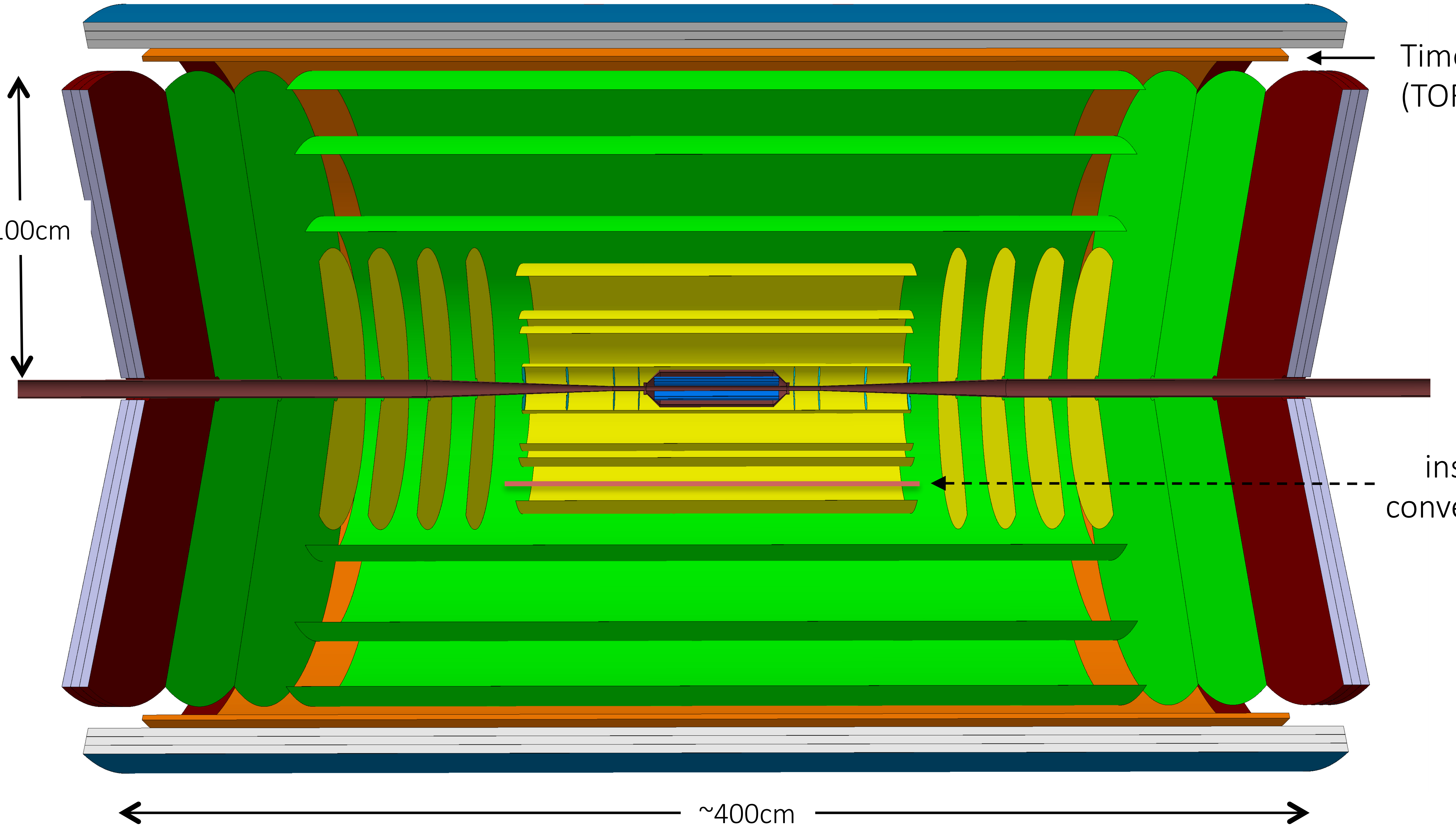


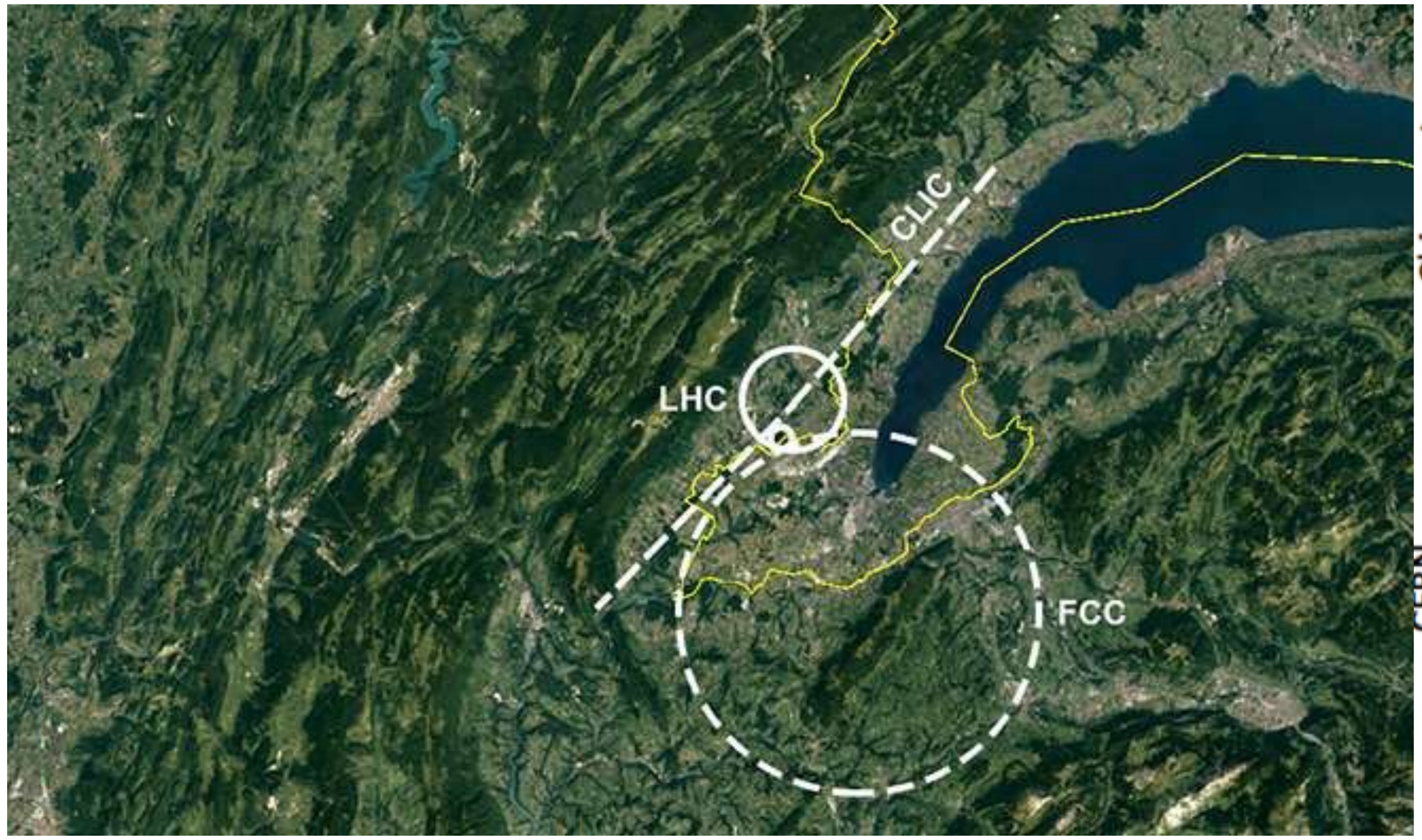
Fig.: https://lhc-commissioning.web.cern.ch/schedule/images/LHC-ultimate-lumi-projection.png

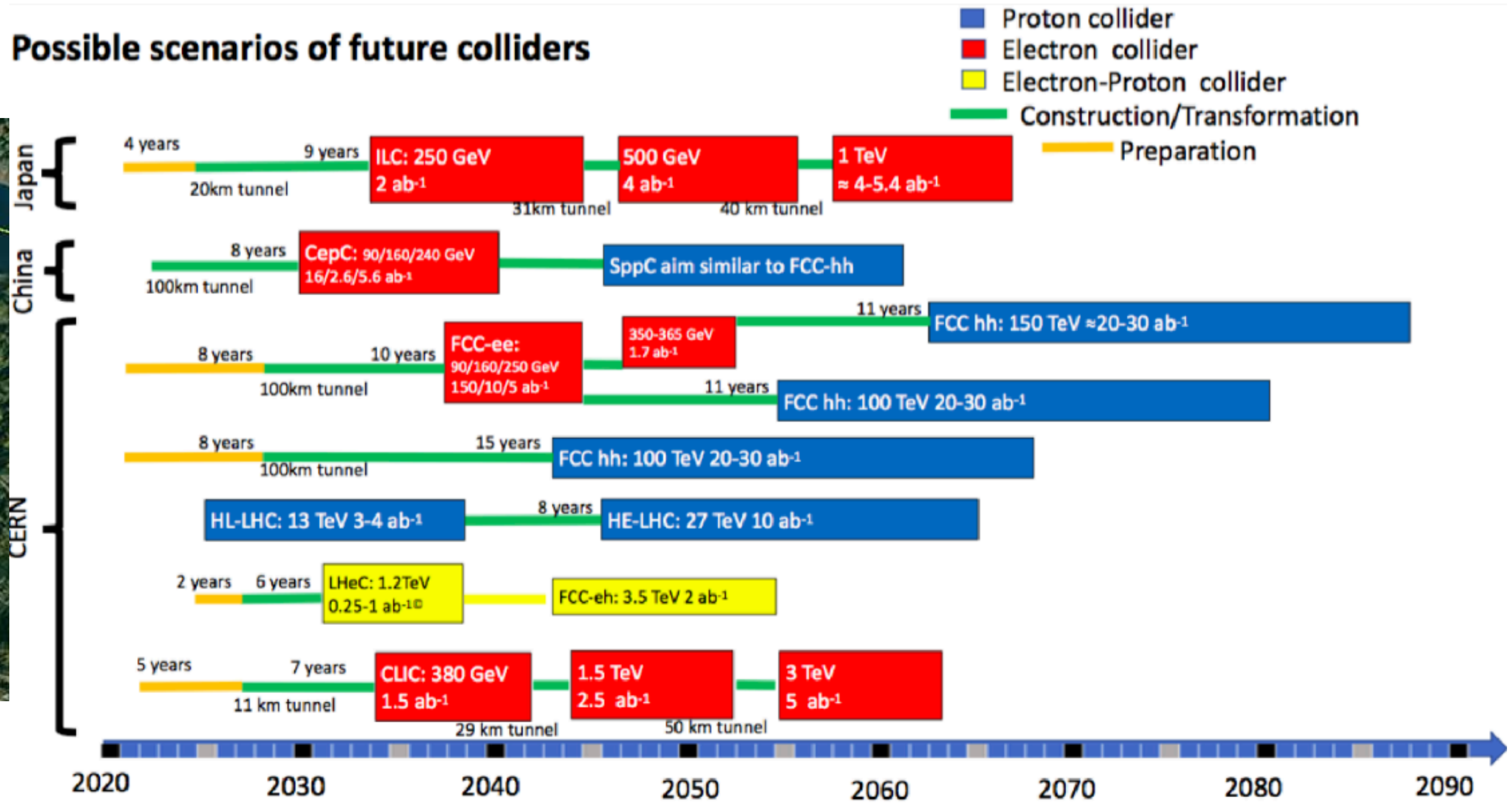
ALICE version 3.0 for Run 5 a Run 6 (2030+)



- 100-times more data than in Run3/4 => 10000-times higher statistics than so far
- the physics programme focused on rare effects connected with hadron formation in QGP, elektric conductivity in QGP, chiral symmetry restoration and so on
- Expression of Interest: arXiv:1902.01211 also a source for European Strategy for Particle Physics Update (Granada, May 2019)

Future after Run 6 ?



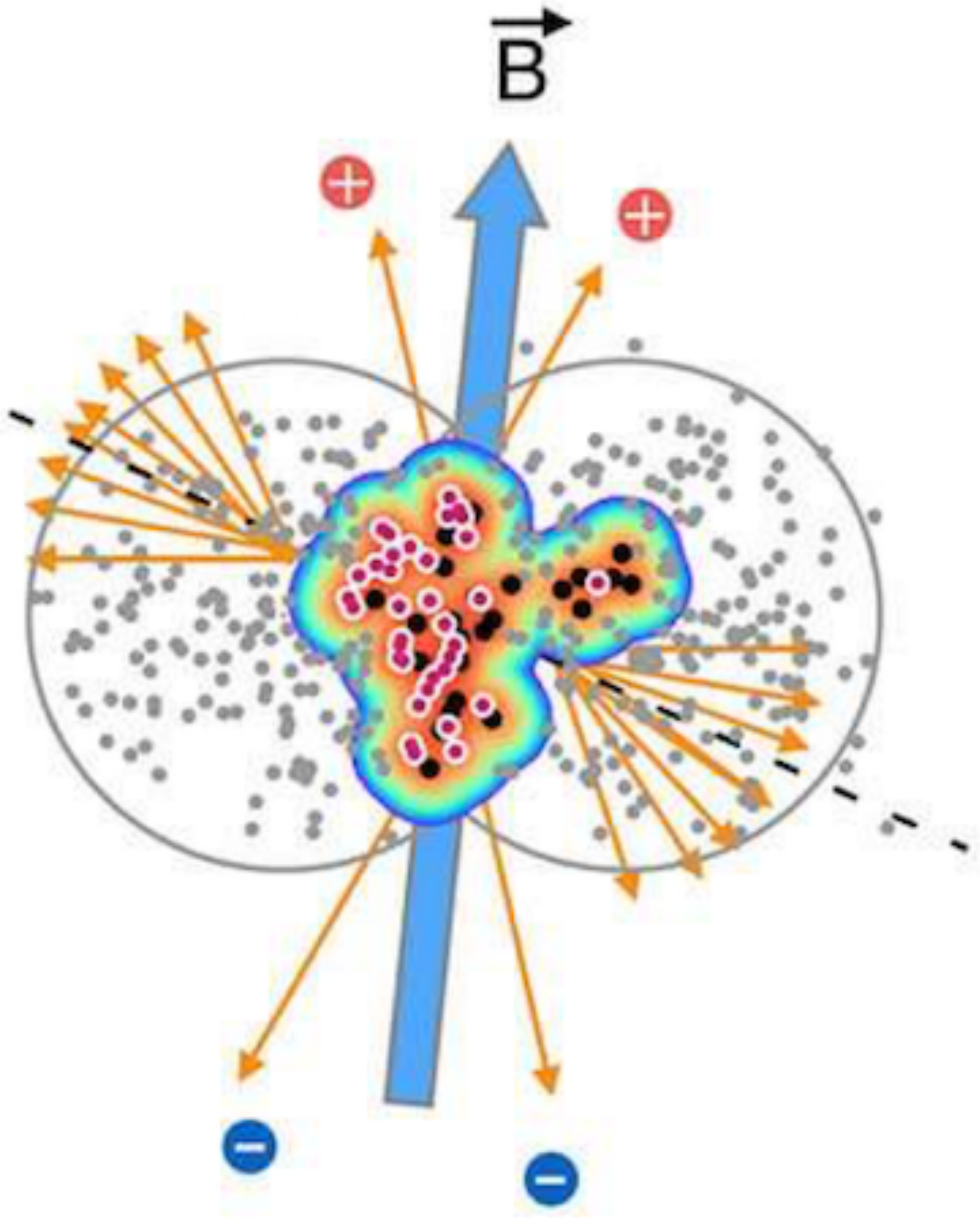


Summary

- ALICE - experiment and international collaboration at the biggest collider of the world
- QGP results: highest temperature, QGP in small systems?
- Interdisciplinary results: CPT invariance in antinuclei (**nuclear physics**), antideuteron production (**cosmology**), interactions with hyperons (**astrophysics**), confirmation of the dead cone effect (**particle physics**)
- Future of the experiment - near (Run 3 and Run 4) and far (Run 5 and Run 6)

Backup

Strongest magnetic field



- a collision of two lead nuclei (each has Q = 82) at ultrarelativistic velocities could generate extremely strong magnetic field of the order of 10^{14} –10^{15} T (1000-times more than regular magnetars)
- the field is generated by protons which did not participate in the collision (i.e. it is not head-on collision, there must be spectators)
- in the future (LHC Run 3 and Run 4) the electric conductivity of QGP could be studied