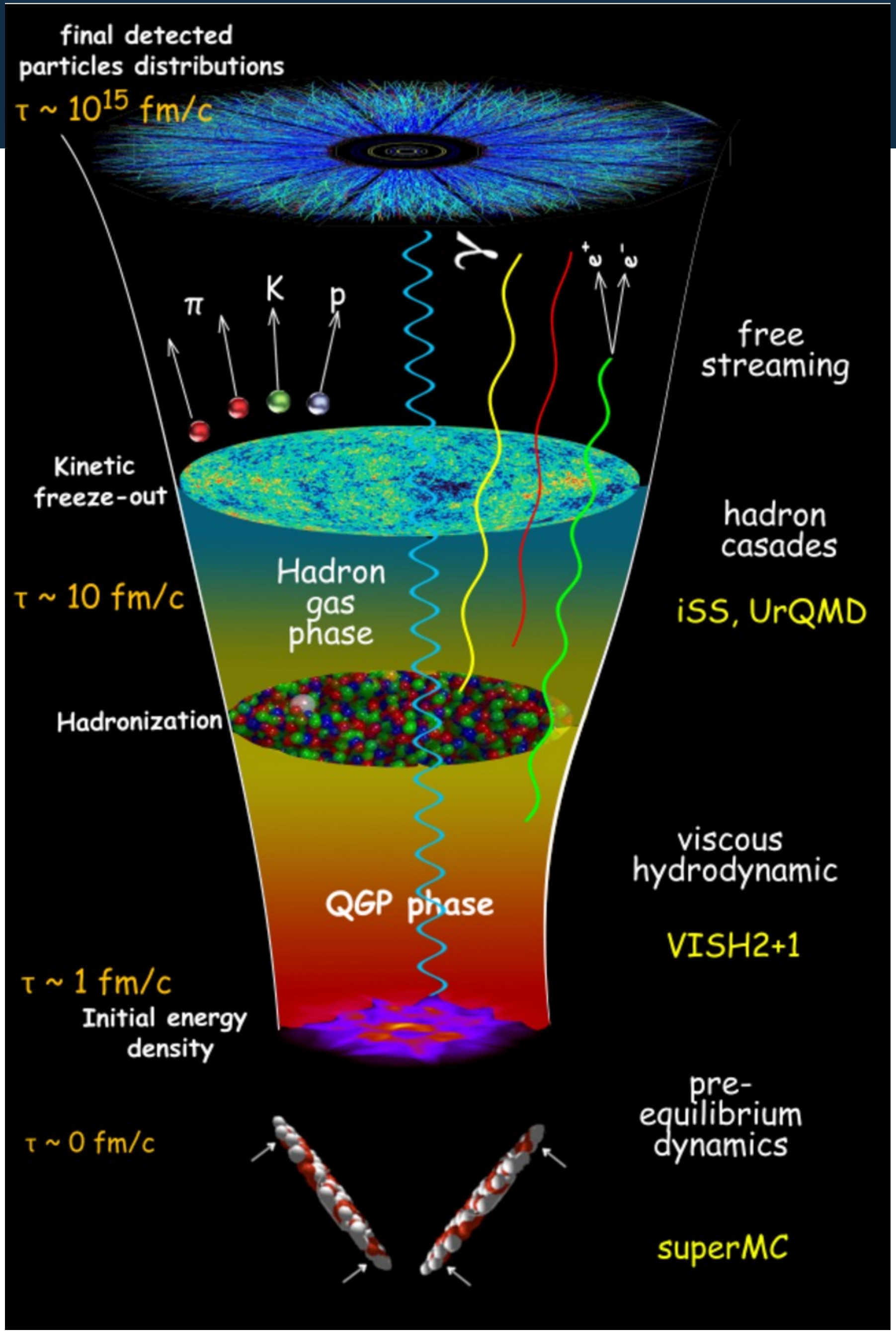
Overview on ALICE highlights

Mario Rodríguez
Facultad de Ciencias Físico Matemáticas, BUAP (México)
09.07.2024



time

Particles towards the detectors

Hadron gas

Hydrodynamic evolution

Deconfinement of quarks and gluons

Extremely large temperature

Feb 10, 2000:

"...The data provide evidence for colour deconfinement in the early collision stage and for a collective explosion of the collision fireball in its late stages. The new state of matter exhibits many of the characteristic features of the theoretically predicted Quark-Gluon Plasma."

.....

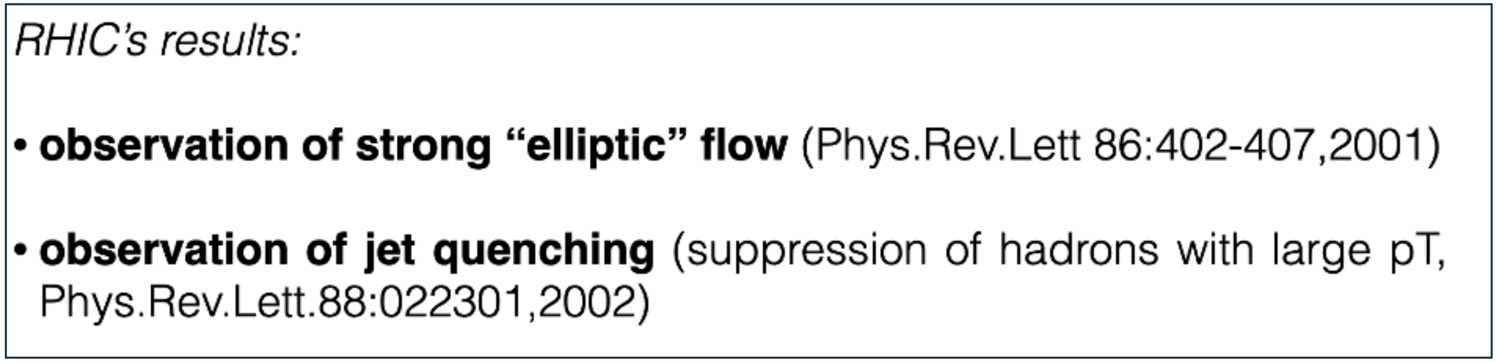
" The higher energies of RHIC and LHC are needed to complete the picture and provide a full characterization of the Quark-Gluon Plasma."

Feb 10, 2000:

"...The data provide evidence for colour deconfinement in the early collision stage and for a collective explosion of the collision fireball in its late stages. The new state of matter exhibits many of the characteristic features of the theoretically predicted Quark-Gluon Plasma."

.....

" The higher energies of RHIC and LHC are needed to complete the picture and provide a full characterization of the Quark-Gluon Plasma."



RHIC's results:

- **observation of strong "elliptic" flow** (Phys.Rev.Lett 86:402-407,2001)
- **observation of jet quenching** (suppression of hadrons with large pT, Phys.Rev.Lett.88:022301,2002)

Signatures of the QGP formation

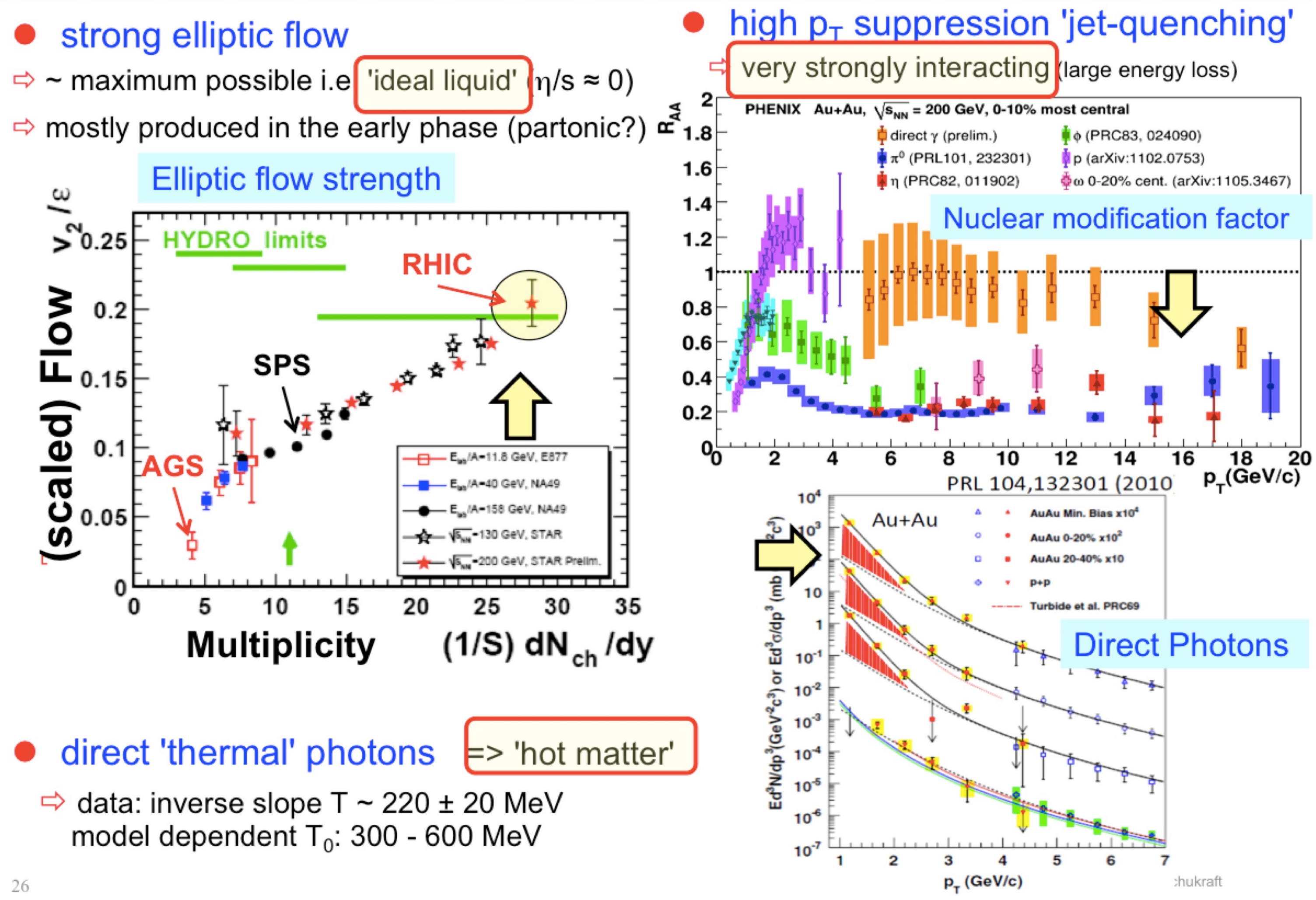
Some signatures of the QGP in Heavy-ion collisions:

- **Collective flow**: radial and anisotropic
- **Long-range angular correlations** (hydrodynamical evolution of the medium)
- **Suppression of high pT hadrons** (energy loss of partons in the medium)
- **Enhancement of thermal photons and dileptons** due to the emission from the plasma

Signatures of the QGP formation

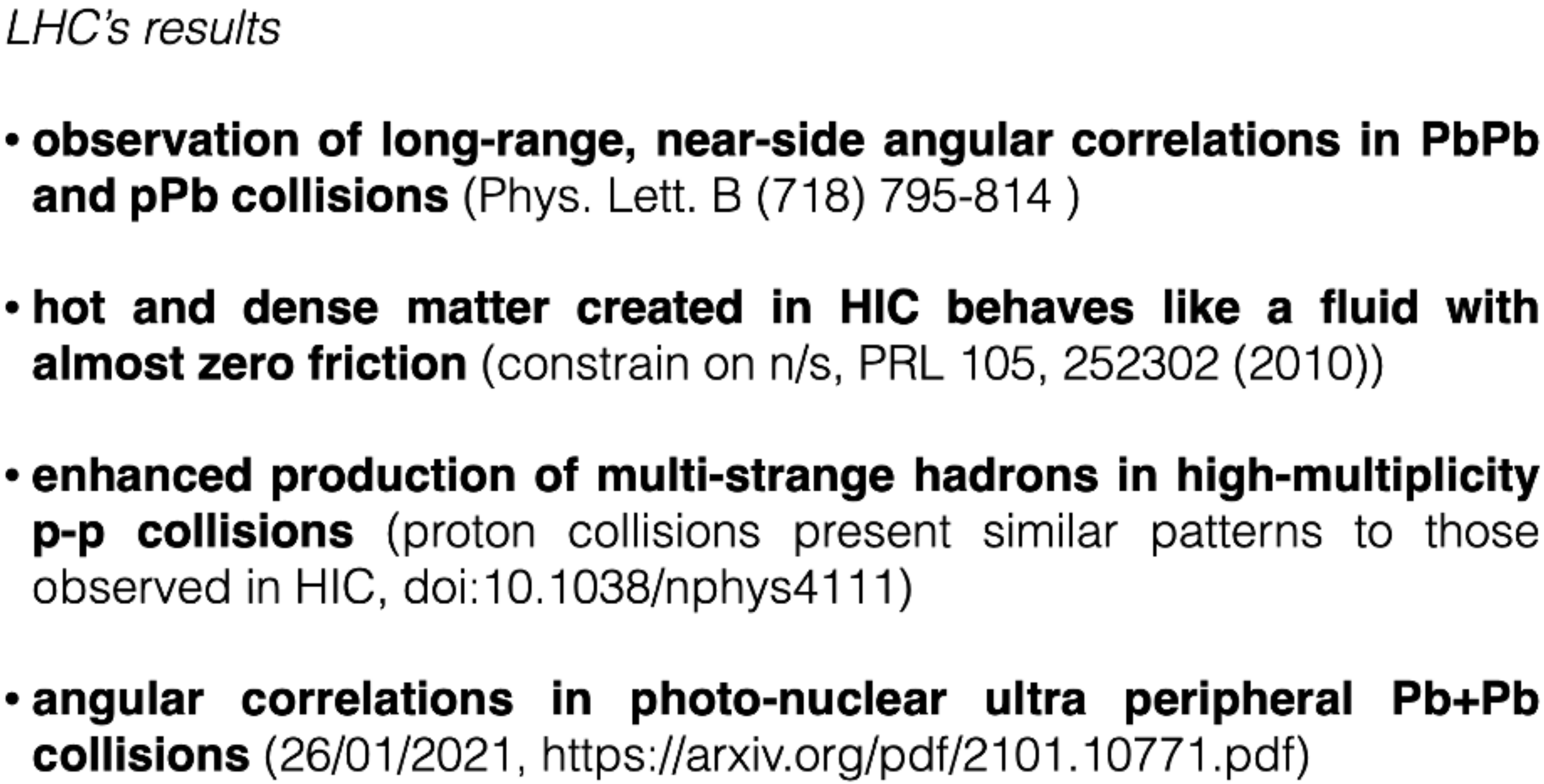
Some signatures of the QGP in Heavy-ion collisions:

- **Collective flow**: radial and anisotropic
- **Long-range angular correlations** (hydrodynamical evolution of the medium)
- **Suppression of high pT hadrons** (energy loss of partons in the medium)
- **Enhancement of thermal photons and dileptons** due to the emission from the plasma



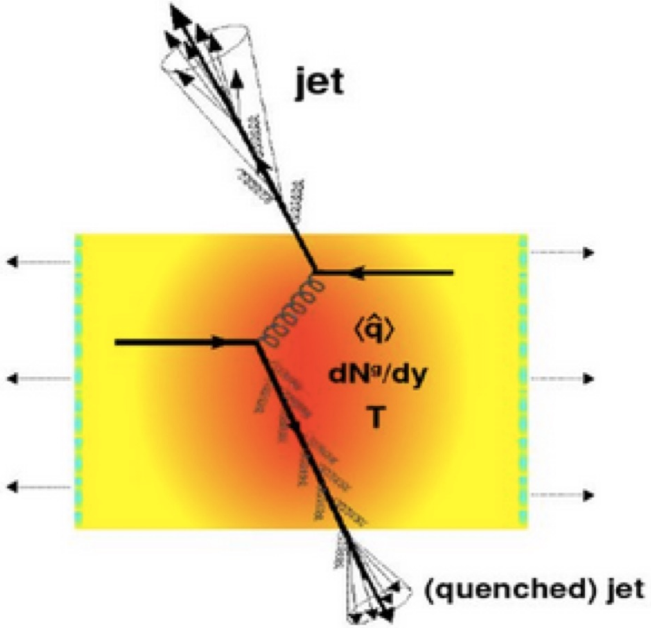
- strong elliptic flow
  - ⇨ ~ maximum possible i.e 'ideal liquid' ($\eta/s \approx 0$)
  - ⇨ mostly produced in the early phase (partonic?)
- high p_T suppression 'jet-quenching'
  - ⇨ very strongly interacting (large energy loss)
- direct 'thermal' photons => 'hot matter'
  - ⇨ data: inverse slope T ~ 220 ± 20 MeV
    model dependent T_0: 300 - 600 MeV

LHC results



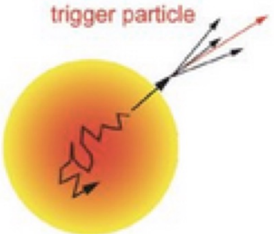
LHC's results

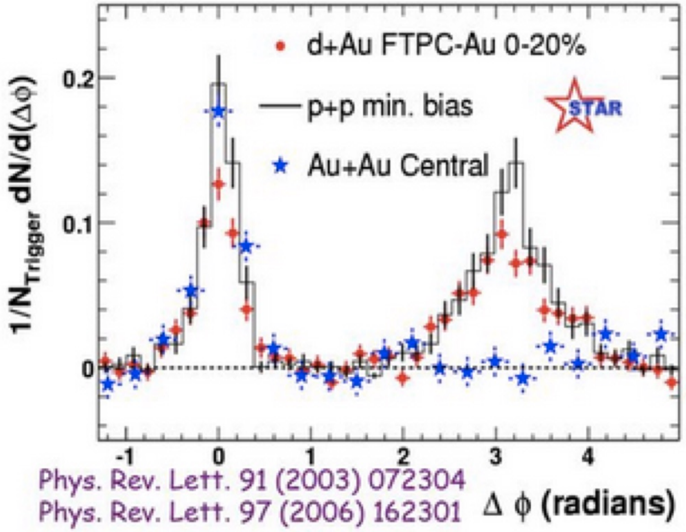
- **observation of long-range, near-side angular correlations in PbPb and pPb collisions** (Phys. Lett. B (718) 795-814)
- **hot and dense matter created in HIC behaves like a fluid with almost zero friction** (constrain on n/s, PRL 105, 252302 (2010))
- **enhanced production of multi-strange hadrons in high-multiplicity p-p collisions** (proton collisions present similar patterns to those observed in HIC, doi:10.1038/nphys4111)
- **angular correlations in photo-nuclear ultra peripheral Pb+Pb collisions** (26/01/2021, https://arxiv.org/pdf/2101.10771.pdf)



Jet-quenching
(Bjorken, 1982)

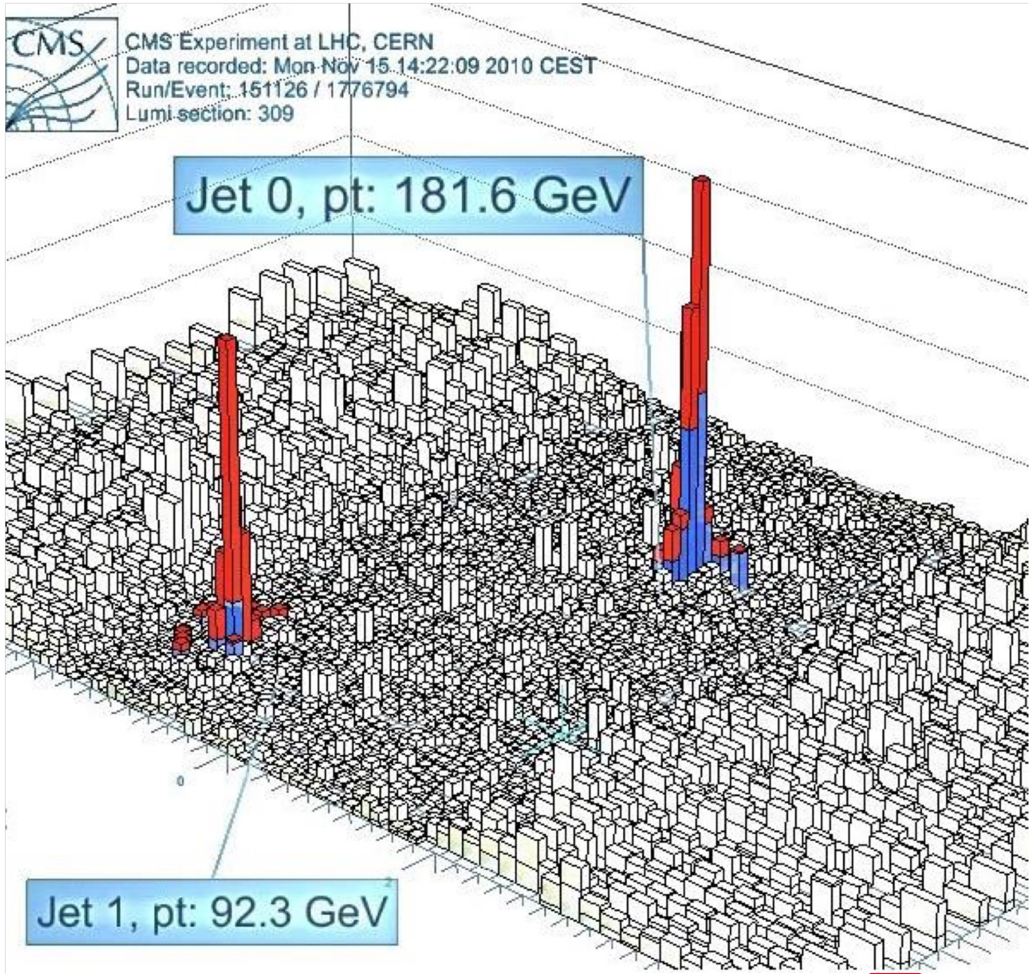
$4 < p_T^{trig} < 6$ GeV/c
$p_T^{assoc} > 2$ GeV/c





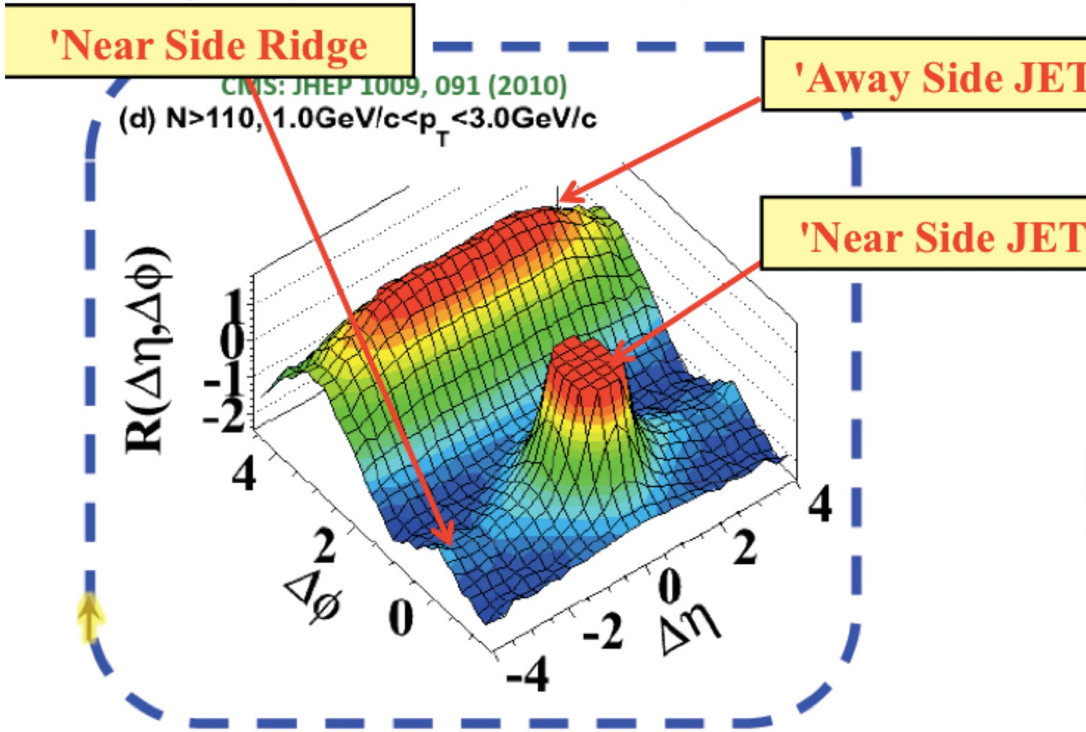
Phys. Rev. Lett. 91 (2003) 072304
Phys. Rev. Lett. 97 (2006) 162301

Indication of **jet quenching**:
Suppression of high p_T particles



Discovery

- The first LHC Discovery (pp, Sept 2010)
  - ⇨ long range rapidity 'ridge' in 2-particle correlations
    - ✪ visible in the highest multiplicity pp collisions
    - ✪ arguably still the most unexpected LHC discovery



CMS: JHEP 1009, 091 (2010)

Particles That Flock: Strange Synchronization Behavior at the Large Hadron Collider

Scientific American, February (2011)

Scientists at the Large Hadron Collider are trying to solve a puzzle of their own making: why particles sometimes fly in sync

If we are here today it is because we didn't succeed to kill it.

We have therefore submitted the paper to expose our findings to the scrutiny of the scientific community at large.

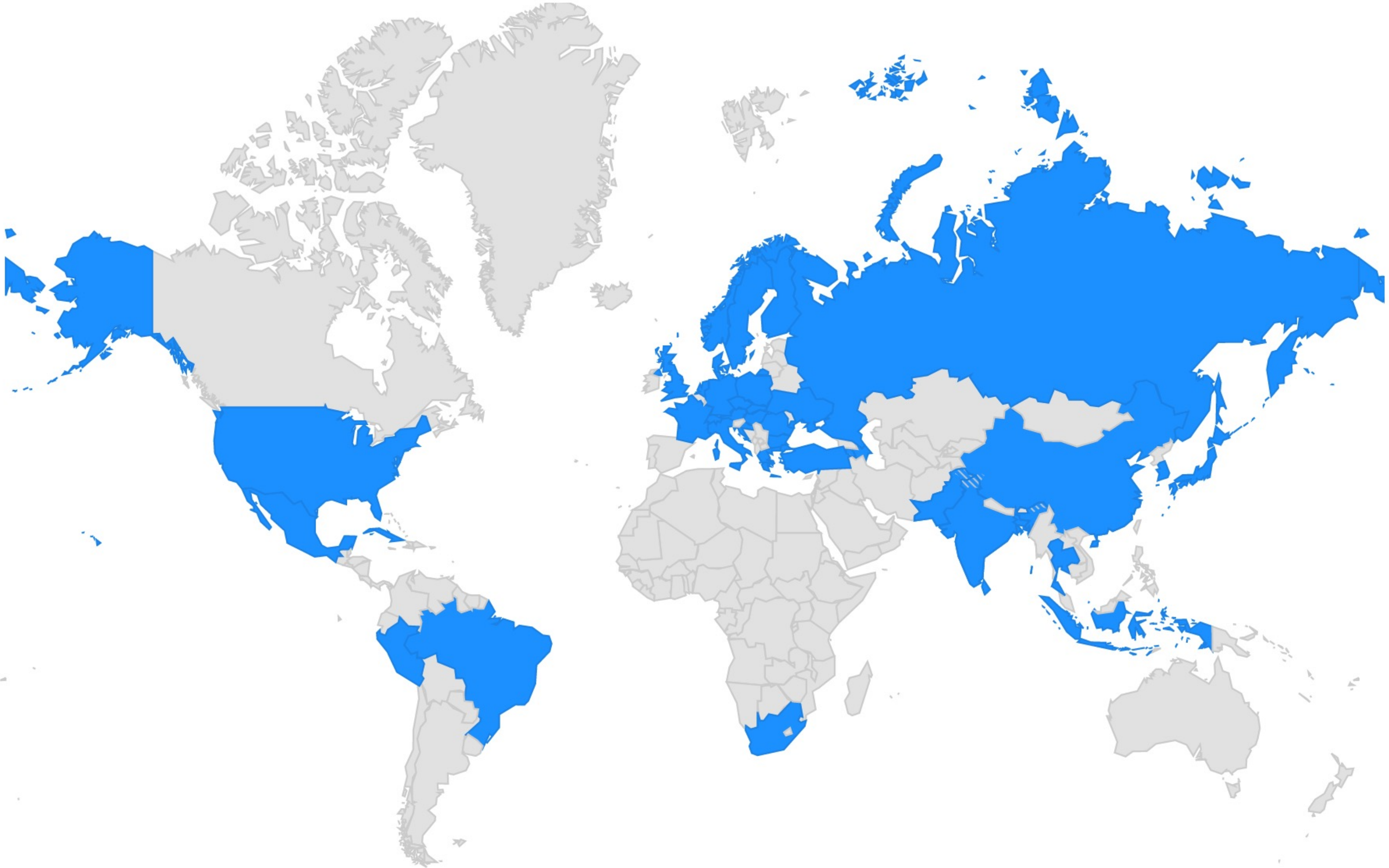
G. Tonelli, CERN/INFN/UNIPI *CERN LPCC/EP/PP SEMINAR* *September, 21 2010*

29

Dec. 2013 Kyoto J. Schukraft

ALICE Collaboration

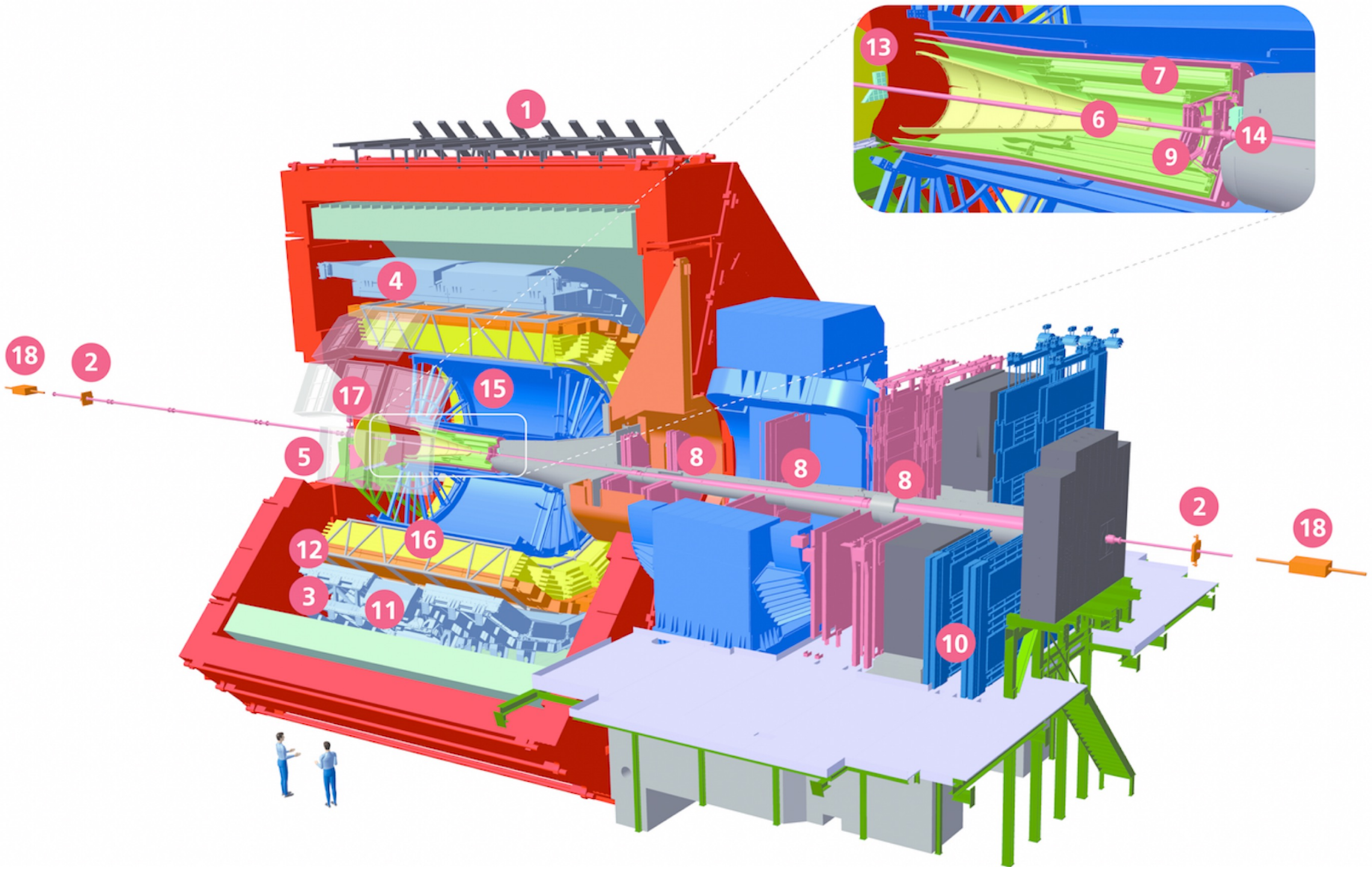
40 countries, 169 institutes, 2006 members



ALICE main goals

- ALICE is optimized to study the collisions of nuclei at the ultra-relativistic energies provided by the LHC.
- The aim is to study the physics of strongly interacting matter at the highest energy densities reached so far in the laboratory. In such conditions, an extreme phase of matter - called the quark-gluon plasma (QGP) - is formed
- The ALICE detector was specifically designed to study the QGP created at LHC energies.

ALICE setup in Run 1 & 2



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

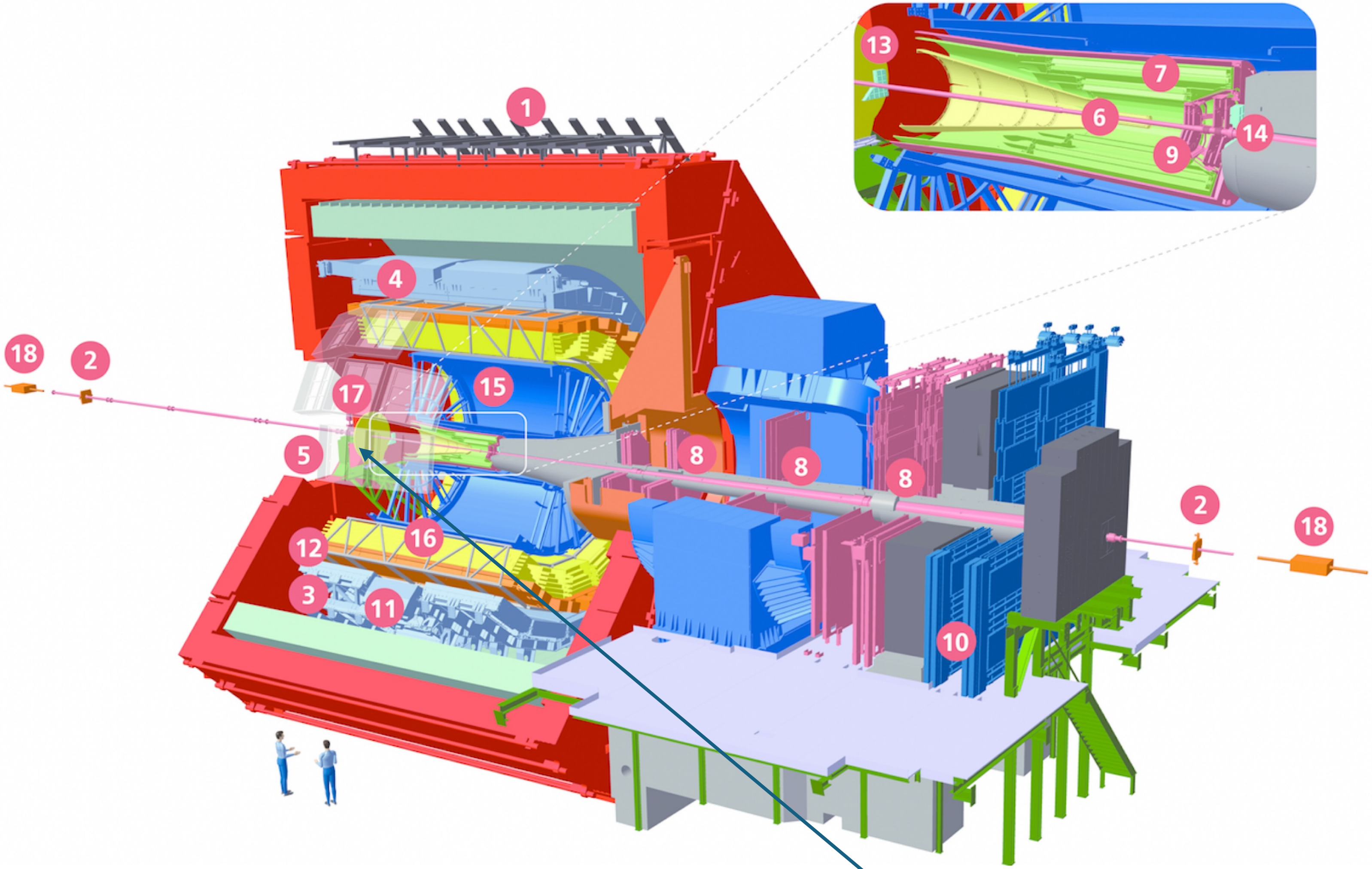
15 **TPC** | Time Projection Chamber

16 **TRD** | Transition Radiation Detector

17 **V0+** | Vzero + Detector

18 **ZDC** | Zero Degree Calorimeter

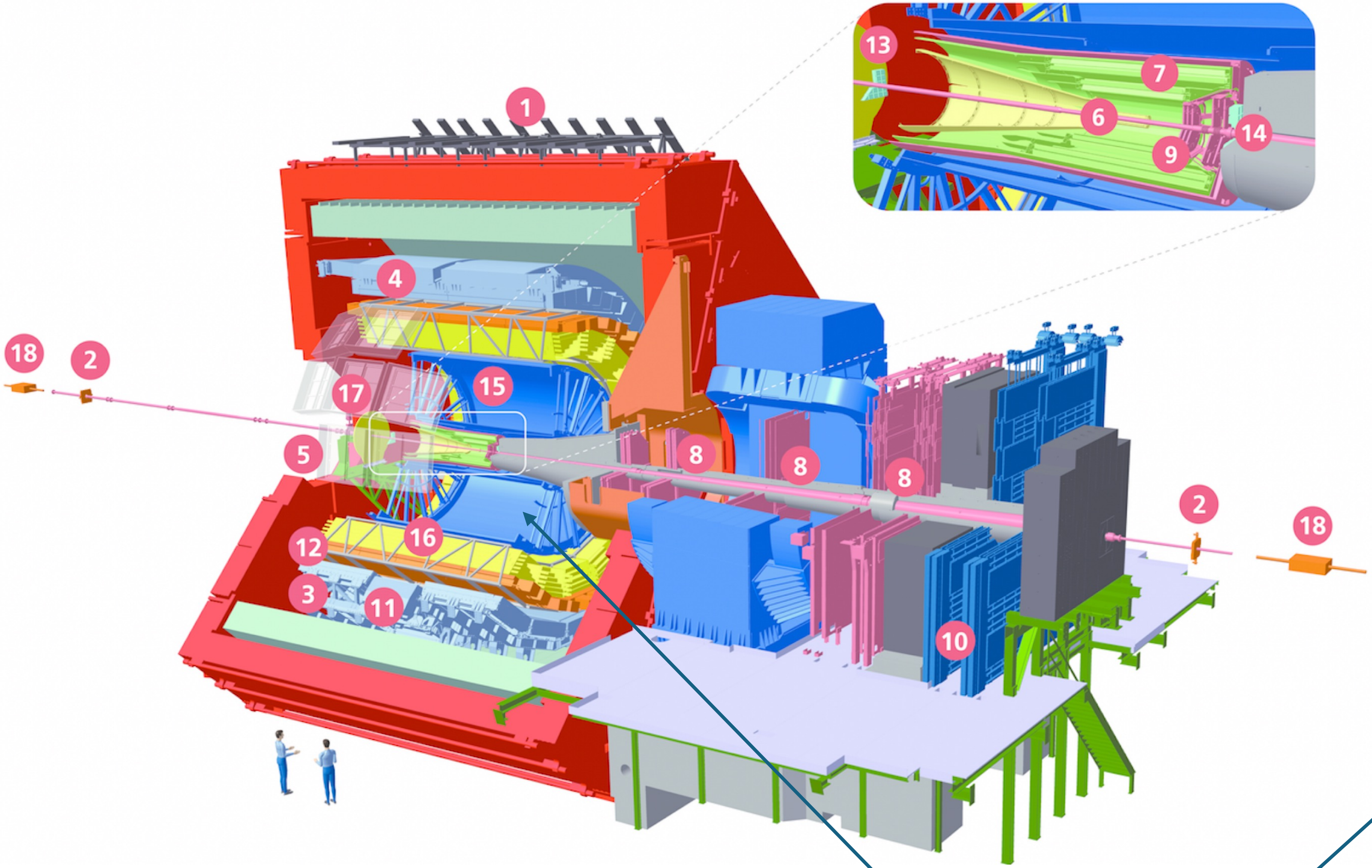
ALICE setup in Run 1 & 2



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

MB & centrality trigger
$2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta < 1.7$ (V0C)

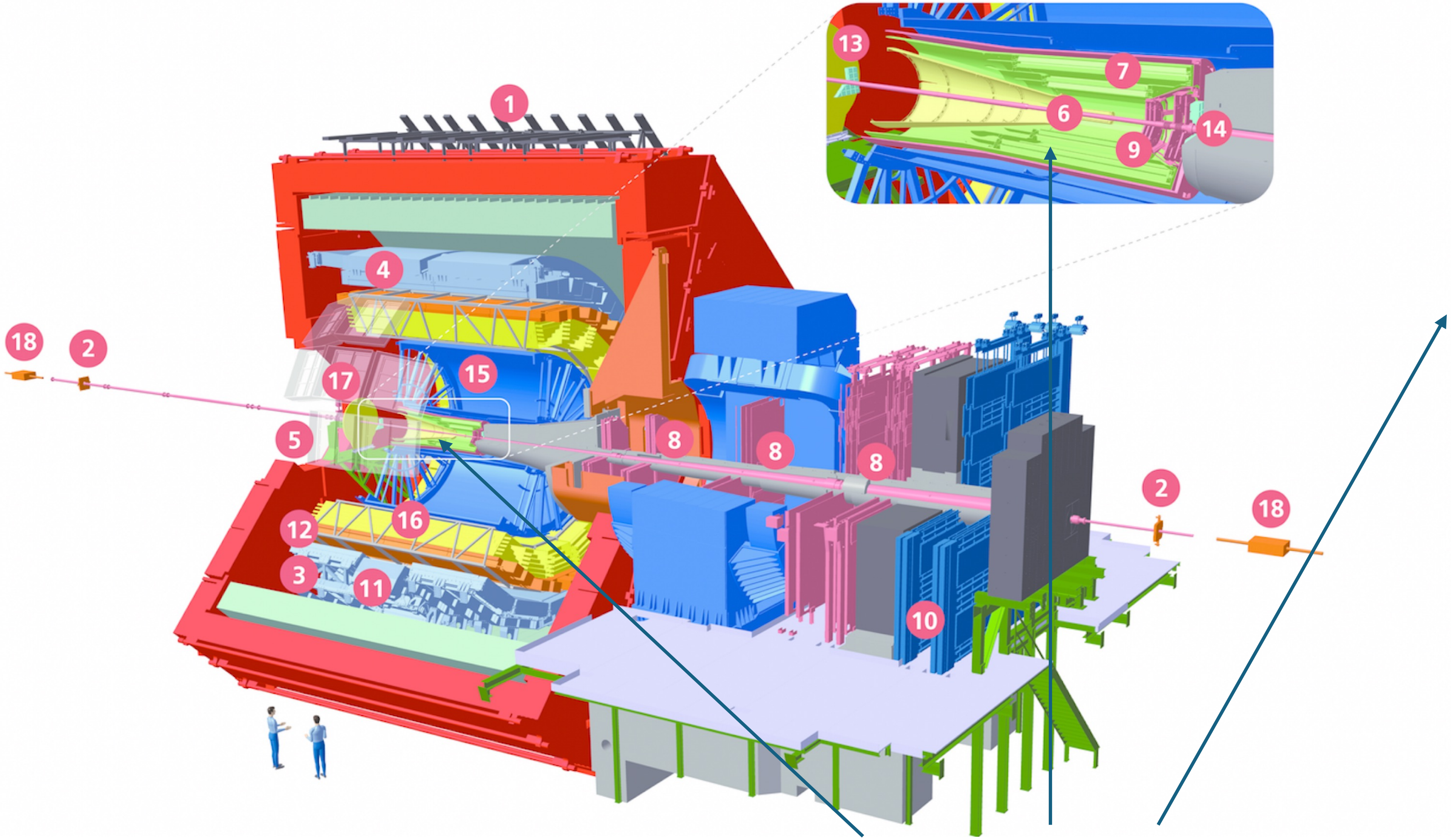
ALICE setup in Run 1 & 2



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

Tracking & ID (dE/dx)
$|\eta| < 0.9$

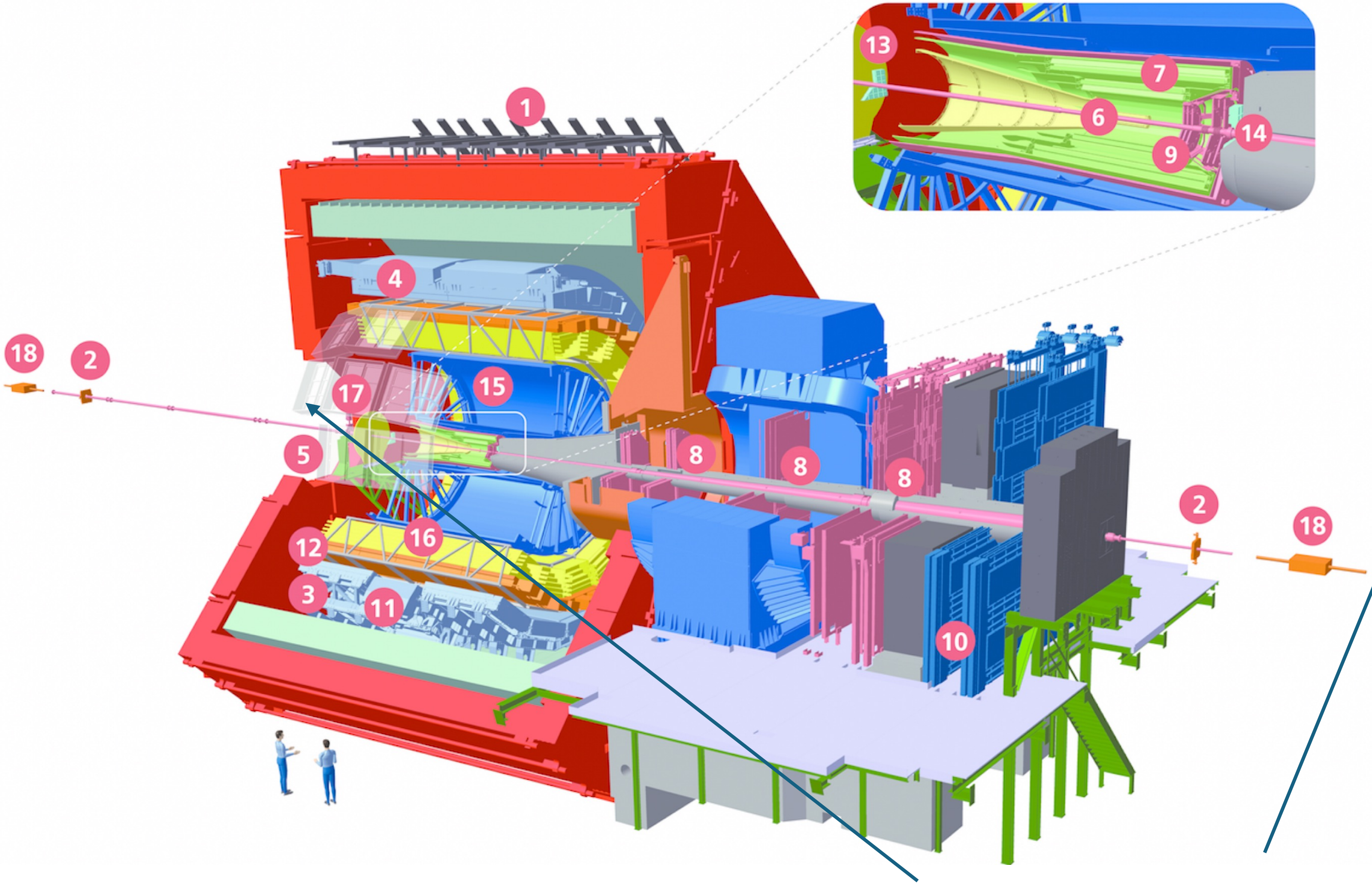
ALICE setup in Run 1 & 2



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

Primary & secondary vertices, tracking
$|\eta| < 0.9$

ALICE setup in Run 1 & 2

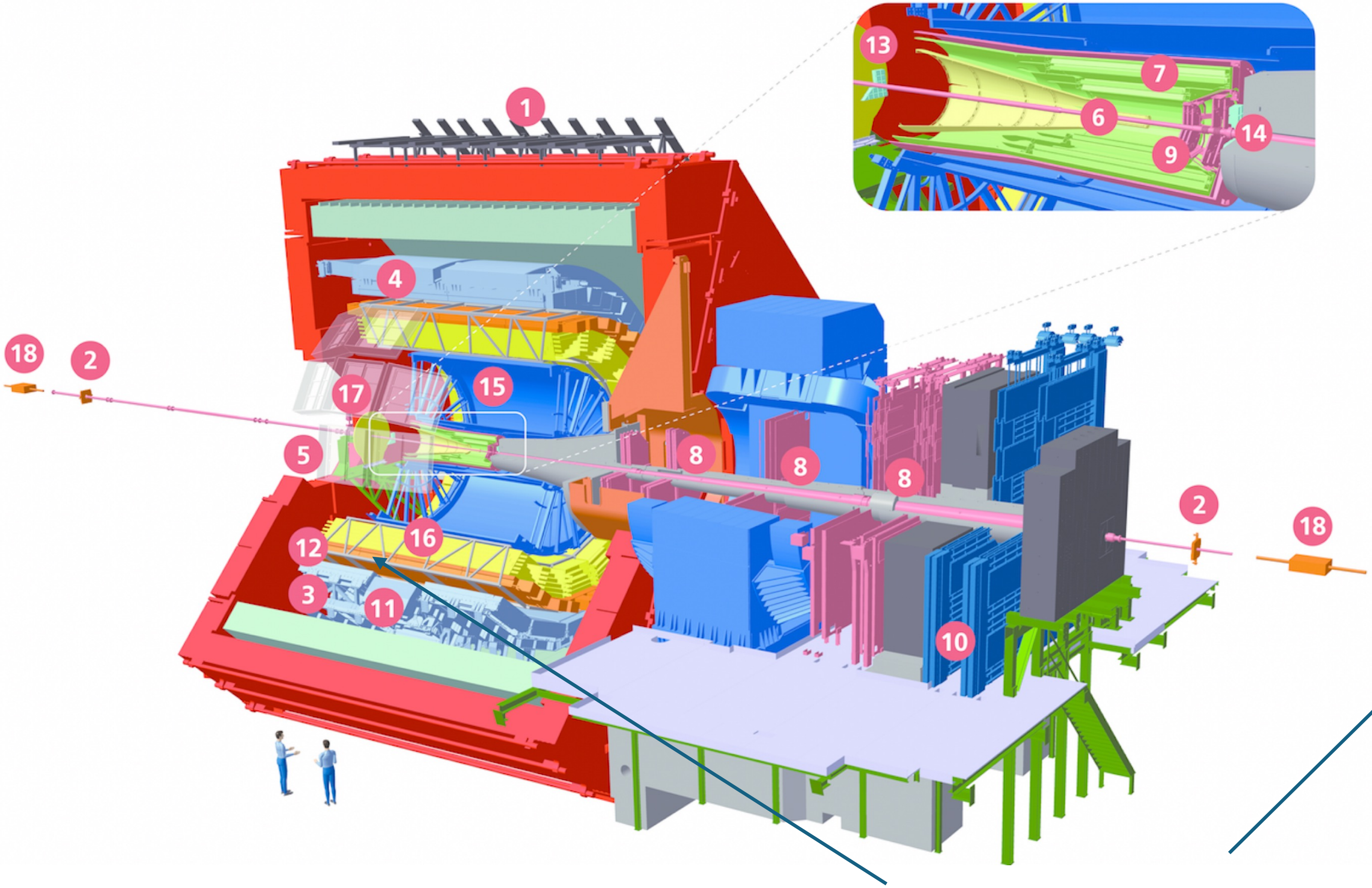


1	**ACORDE**	ALICE Cosmic Rays Detector
2	**AD**	ALICE Diffractive Detector
3	**DCal**	Di-jet Calorimeter
4	**EMCal**	Electromagnetic Calorimeter
5	**HMPID**	High Momentum Particle Identification Detector
6	**ITS-IB**	Inner Tracking System - Inner Barrel
7	**ITS-OB**	Inner Tracking System - Outer Barrel
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

PID for high momentum charged particles

$|\eta| < 0.6$, 57.6^0 azimuth

ALICE setup in Run 1 & 2



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

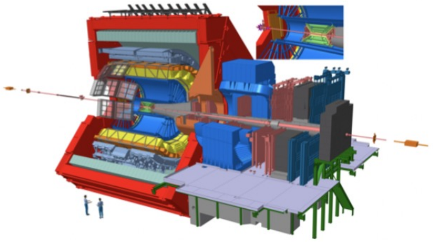
PID using the time of flight of charged particles

$|\eta| < 0.9$

ALICE

Time line / Outline

ALICE 1



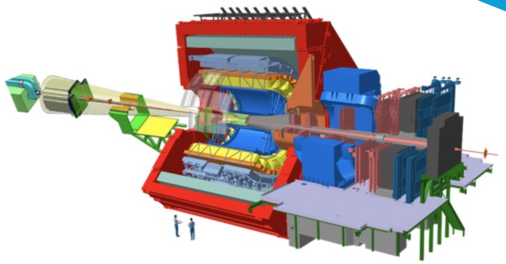
Run 1 (2009-2013) →pp, pPb and PbPb

Run 2 (2015-2018) → pp, pPb, XeXe and PbPb

We are here

09.07.2024

ALICE 2



Run 3 (2022-2025)
pp, pPb, pO, OO and PbPb

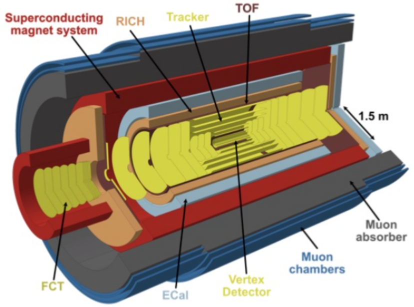
High luminosity for ions

ALICE 2.1

Run 4 (2029-2032)
pp, pPb, and PbPb

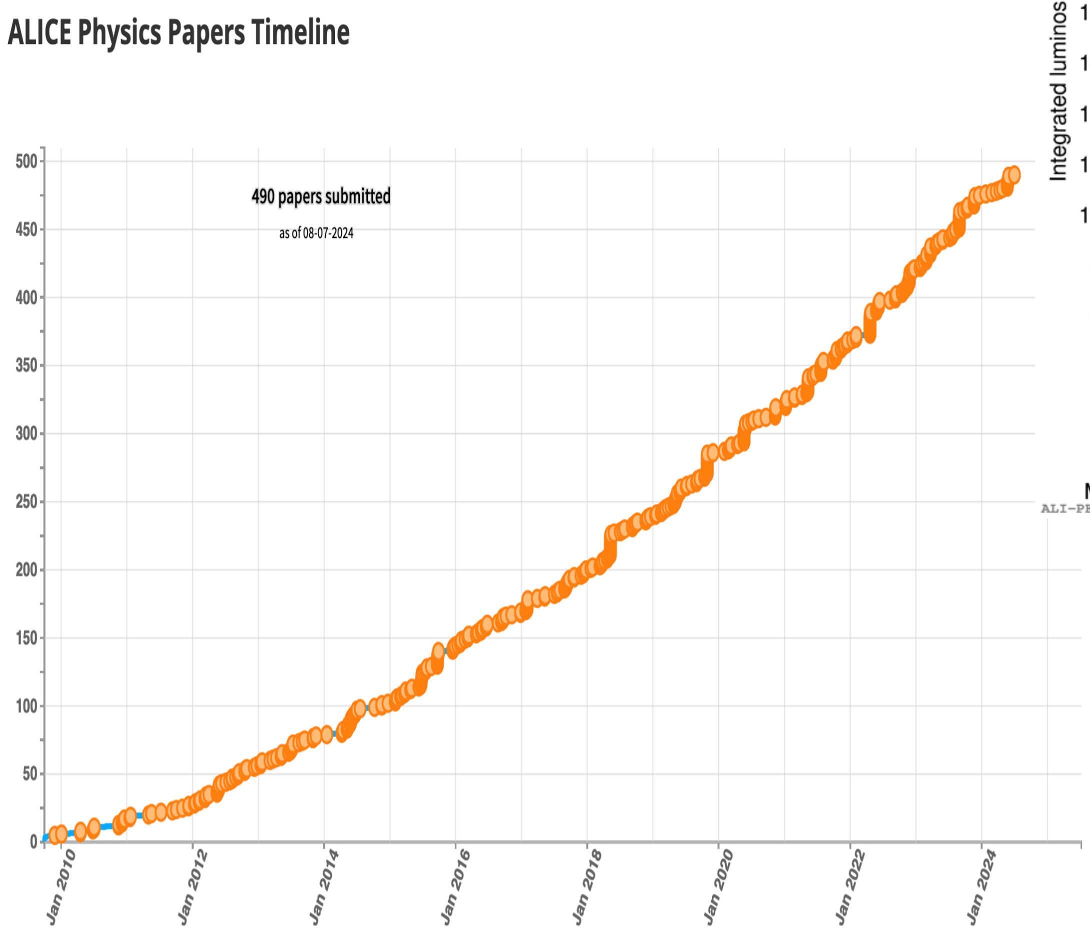
HL-LHC

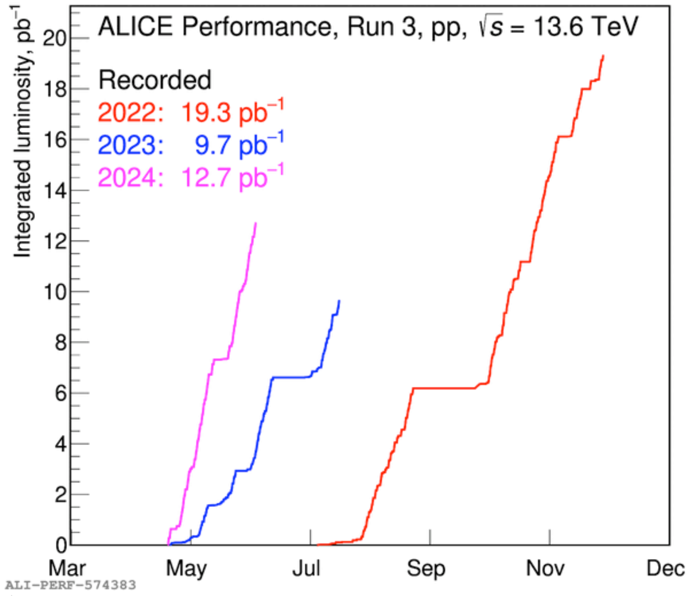
ALICE 3

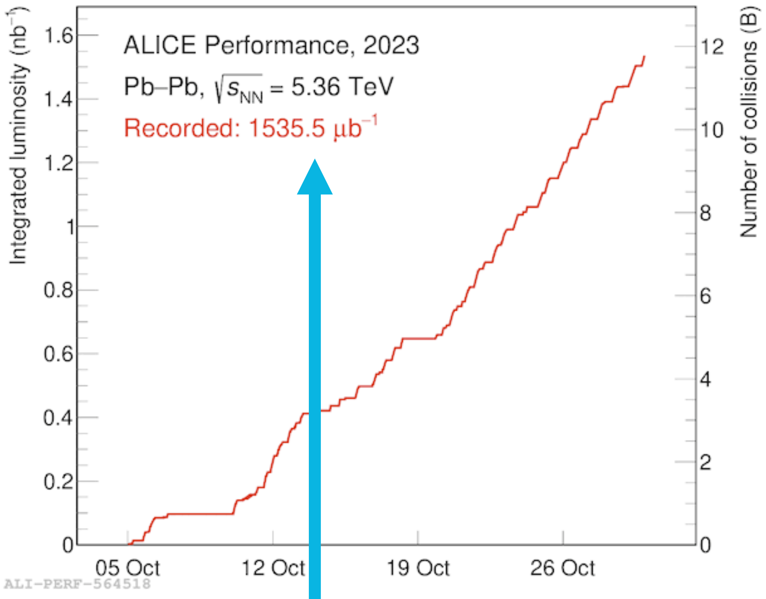


Run 5 (2035 -)
pp, pPb? and PbPb

ALICE publications and collected data


ALICE Physics Papers Timeline





System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010, 2011 2015, 2018	2.76 5.02	~75 μb^{-1} ~800 μb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	~15 nb^{-1} ~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013	0.9, 2.76, 7, 8	~200 mb^{-1}, ~100 nb^{-1} ~1.5 pb^{-1}, ~2.5 pb^{-1}
	2015, 2017	5.02	~1.3 pb^{-1}
	2015-2018	13	~36 pb^{-1}

Run 1 Run 2

2009-2018

Last year we almost doubled the integrated luminosity w.r.t. runs 1 & 2.

ALICE's contribution so far

CERN-EP-2022-227

27 October 2022

ALICE

Accepted for publication in EPJC

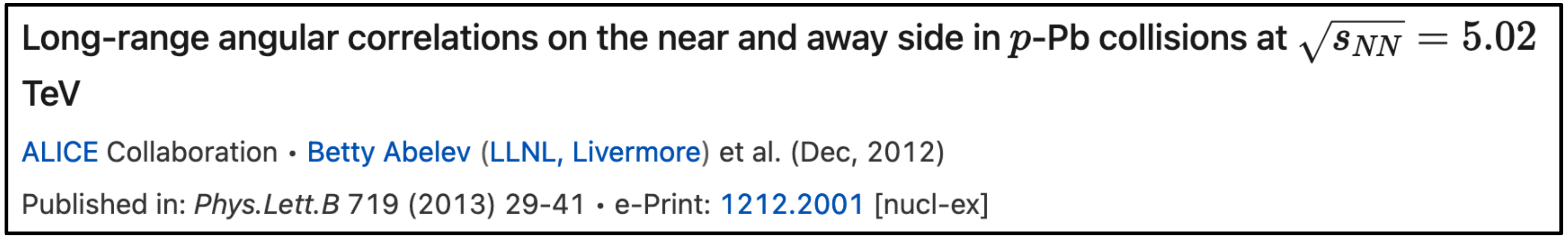
The ALICE experiment:
A journey through QCD

arXiv:2211.04384v1 [nucl-ex] 8 Nov 2022

Elliptic flow of charged particles in Pb-Pb collisions at 2.76 TeV

ALICE Collaboration • K Aamodt (Bergen U.) et al. (Nov, 2010)

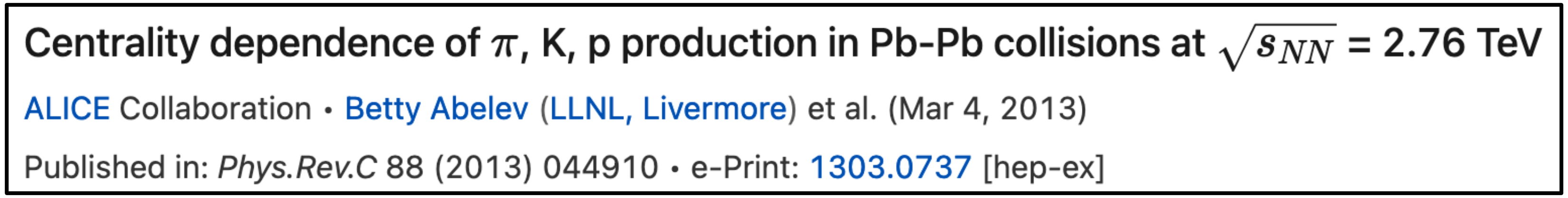
Published in: *Phys.Rev.Lett.* 105 (2010) 252302 • e-Print: 1011.3914 [nucl-ex]



Long-range angular correlations on the near and away side in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

ALICE Collaboration • Betty Abelev (LLNL, Livermore) et al. (Dec, 2012)

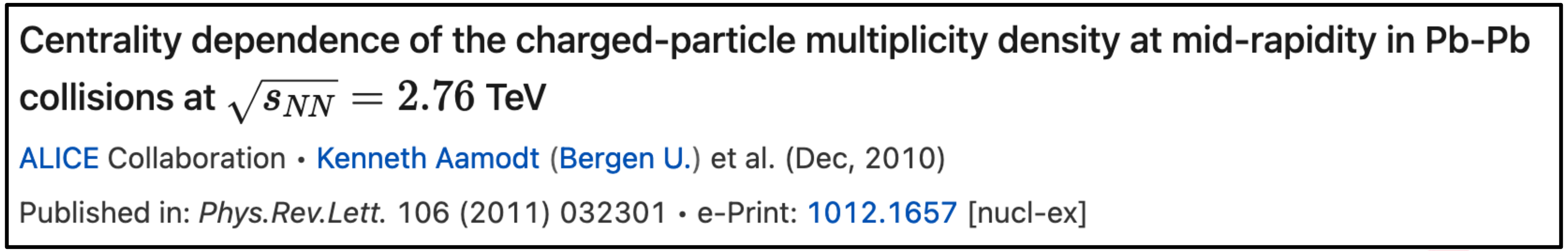
Published in: *Phys.Lett.B* 719 (2013) 29-41 • e-Print: 1212.2001 [nucl-ex]



Centrality dependence of π, K, p production in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

ALICE Collaboration • Betty Abelev (LLNL, Livermore) et al. (Mar 4, 2013)

Published in: *Phys.Rev.C* 88 (2013) 044910 • e-Print: 1303.0737 [hep-ex]



Centrality dependence of the charged-particle multiplicity density at mid-rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

ALICE Collaboration • Kenneth Aamodt (Bergen U.) et al. (Dec, 2010)

Published in: *Phys.Rev.Lett.* 106 (2011) 032301 • e-Print: 1012.1657 [nucl-ex]

ALICE's contribution so far

CERN-EP-2022-227

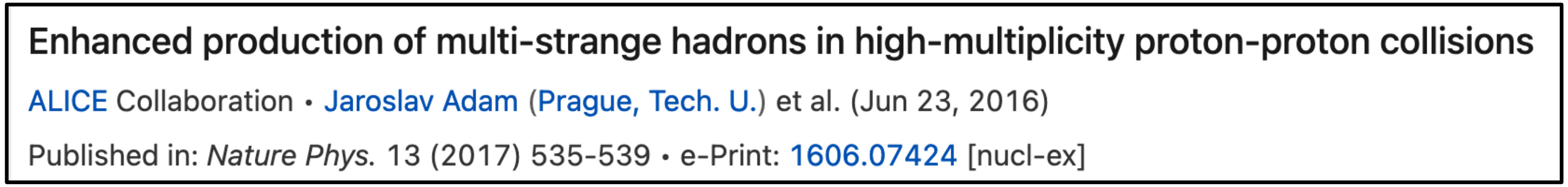
27 October 2022

ALICE

Accepted for publication in EPJC

The ALICE experiment:
A journey through QCD

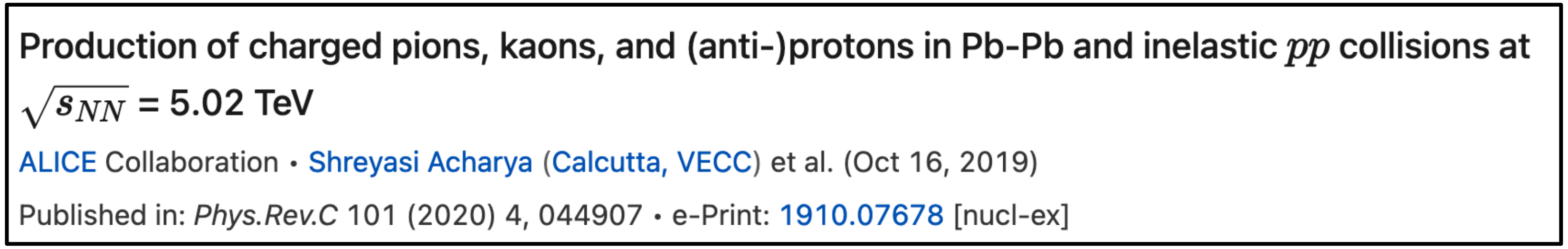
arXiv:2211.04384v1 [nucl-ex] 8 Nov 2022



Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions

ALICE Collaboration • Jaroslav Adam (Prague, Tech. U.) et al. (Jun 23, 2016)

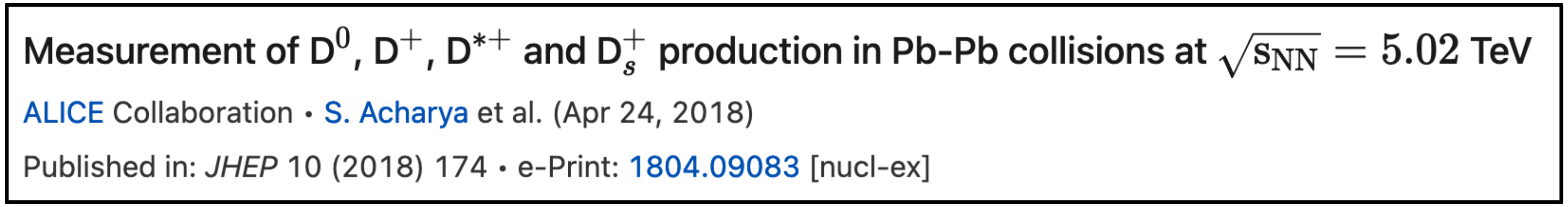
Published in: *Nature Phys.* 13 (2017) 535-539 • e-Print: 1606.07424 [nucl-ex]



Production of charged pions, kaons, and (anti-)protons in Pb-Pb and inelastic pp collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

ALICE Collaboration • Shreyasi Acharya (Calcutta, VECC) et al. (Oct 16, 2019)

Published in: *Phys.Rev.C* 101 (2020) 4, 044907 • e-Print: 1910.07678 [nucl-ex]



Measurement of D^0, D^+, D^{*+} and D_s^+ production in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

ALICE Collaboration • S. Acharya et al. (Apr 24, 2018)

Published in: *JHEP* 10 (2018) 174 • e-Print: 1804.09083 [nucl-ex]

Multiplicity dependence of (multi-)strange hadron production in proton-proton collisions at $\sqrt{s}$ = 13 TeV

ALICE Collaboration • Shreyasi Acharya (Calcutta, VECC) et al. (Aug 5, 2019)

ALICE

ALICE’s contribution so far

CERN-EP-2022-227

27 October 2022

ALICE

arXiv:2211.04384v1 [nucl-ex] 8 Nov 2022

Accepted for publication in EPJC

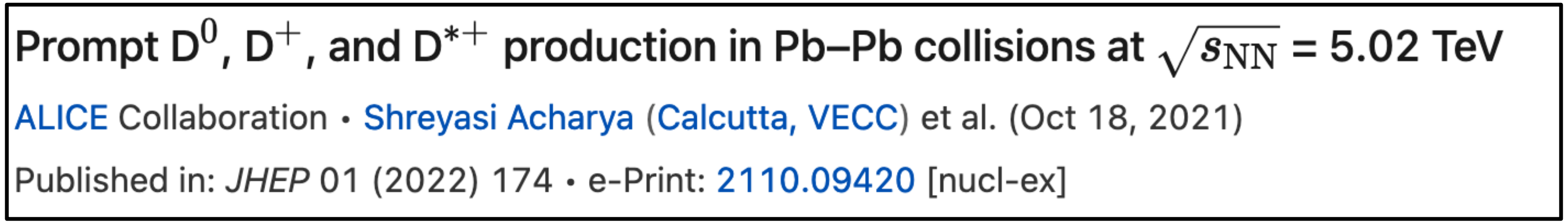
The ALICE experiment:

A journey through QCD

Measurement of anti-^{3}He nuclei absorption in matter and impact on their propagation in the Galaxy

ALICE Collaboration • Shreyasi Acharya (Calcutta, VECC) et al. (Feb 3, 2022)

Published in: *Nature Phys.* 19 (2023) 1, 61-71 • e-Print: 2202.01549 [nucl-ex]



Prompt D^0, D^+, and D^{*+} production in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

ALICE Collaboration • Shreyasi Acharya (Calcutta, VECC) et al. (Oct 18, 2021)

Published in: *JHEP* 01 (2022) 174 • e-Print: 2110.09420 [nucl-ex]

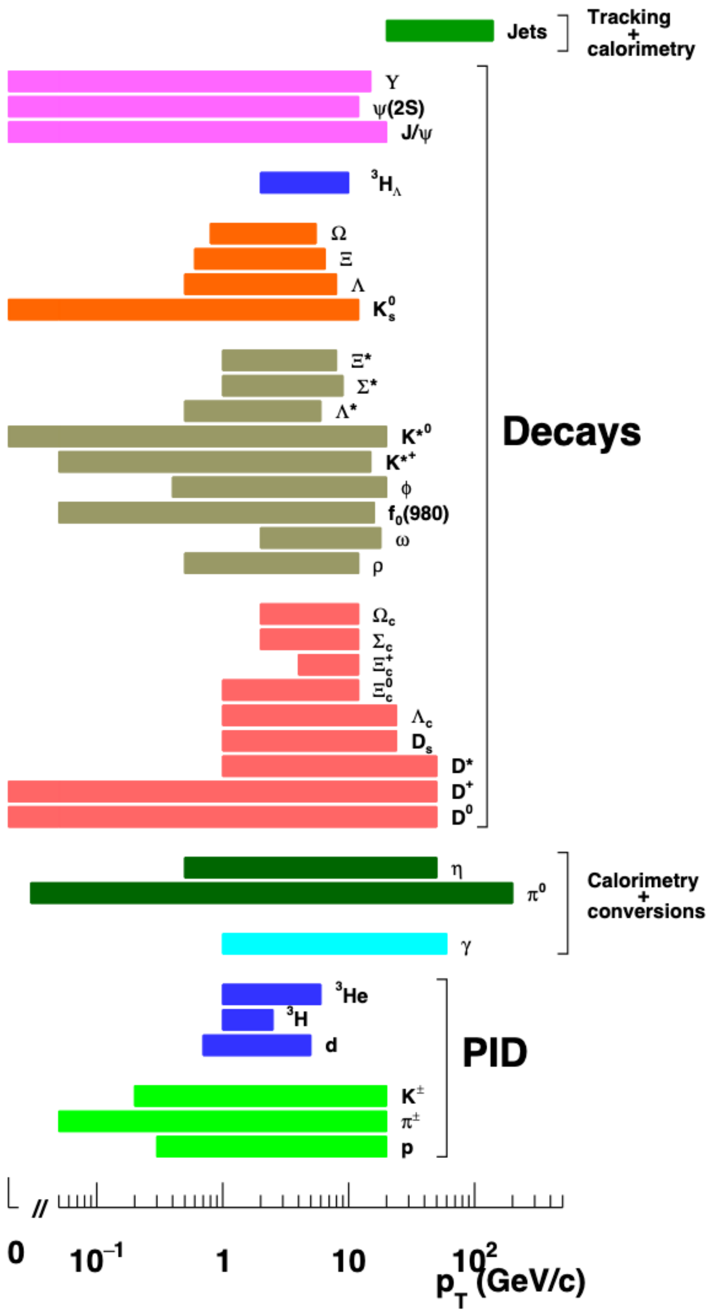
Study of cosmic ray events with high muon multiplicity using the ALICE detector at the CERN Large Hadron Collider

ALICE Collaboration • Jaroslav Adam (Prague, Tech. U.) et al. (Jul 27, 2015)

Published in: *JCAP* 01 (2016) 032 • e-Print: 1507.07577 [astro-ph.HE]

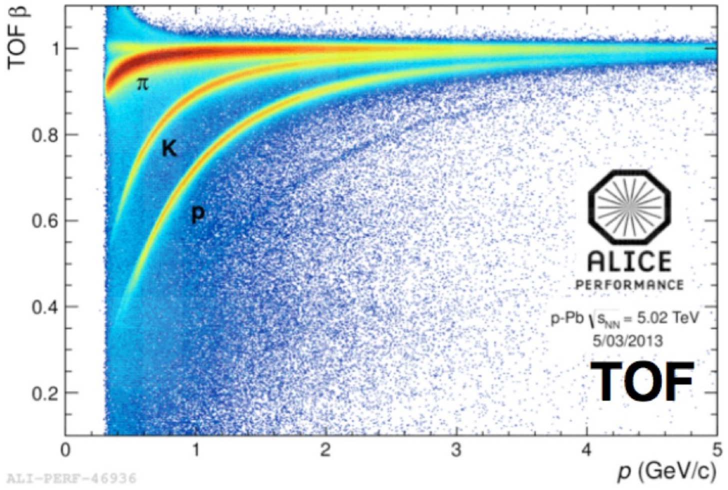
ALICE's contribution so far

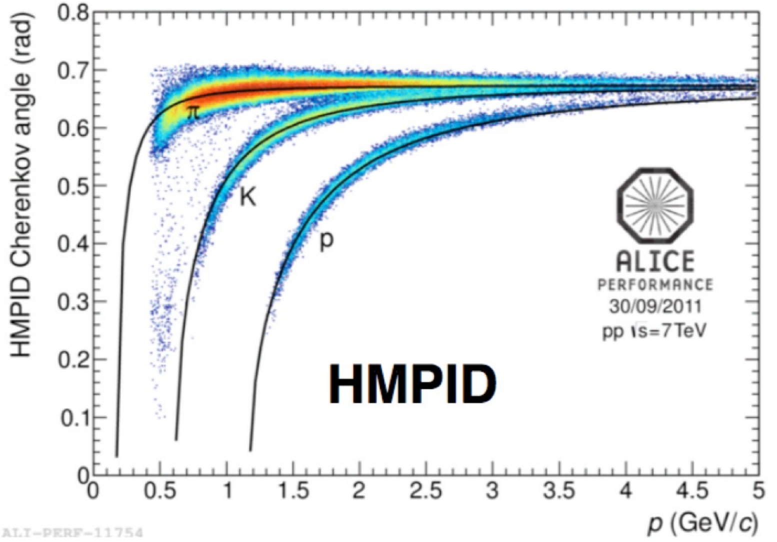
- What does the Standard Model have to say about the plausibility of the existence of the QGP?
- Are there emergent phenomena that arise from high density QCD?
- Does the QGP behave as a gas or a liquid? How quickly does it expand?
- What happens to the QGP when it is excited by the presence of large momentum/mass quarks or gluons?
- How do QGP constituents react to the enormous electromagnetic fields created by heavy-ion collisions?
- Are the extremely high energies at the LHC sufficient for the formation of the QGP in proton–proton collisions? (small systems)
- How do the hadrons that emerge in the dense medium after the transition from QGP to normal matter interact between themselves?
- What can we learn from these studies regarding the properties of the extremities in the Universe, such as the core of neutron stars?

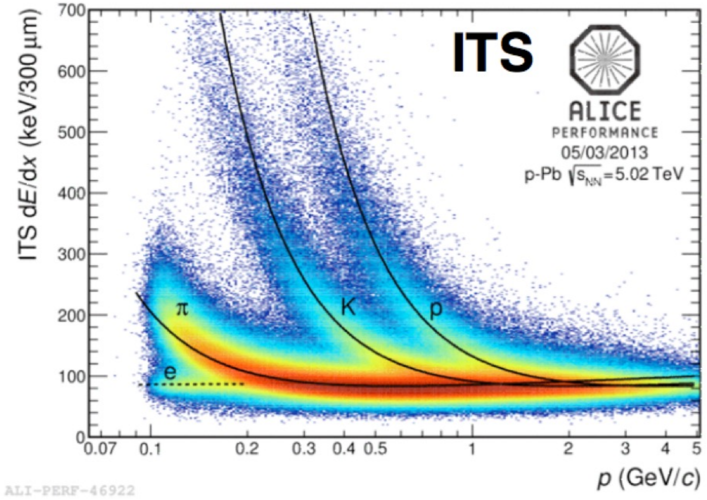


Particle identification with ALICE

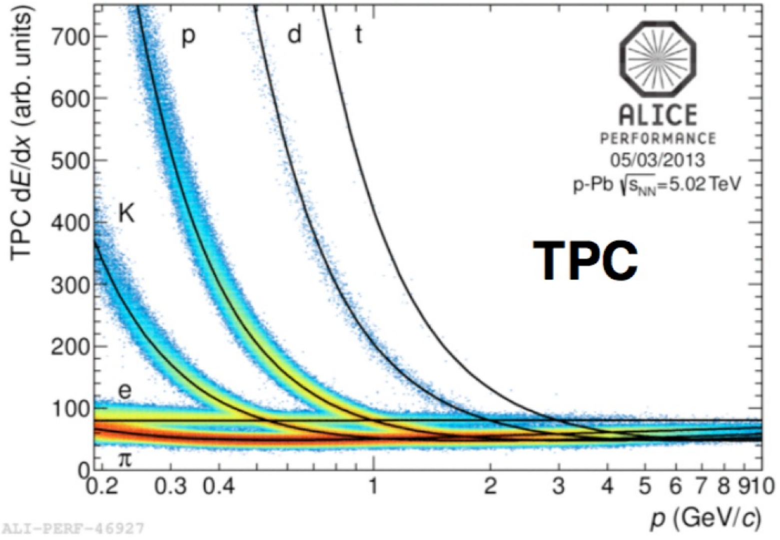
ALICE has excellent tracking and PID capabilities







Several PID methods are used in ALICE.

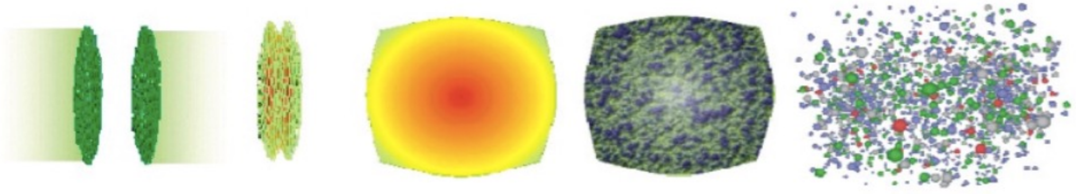


ALICE’s results on elliptic flow

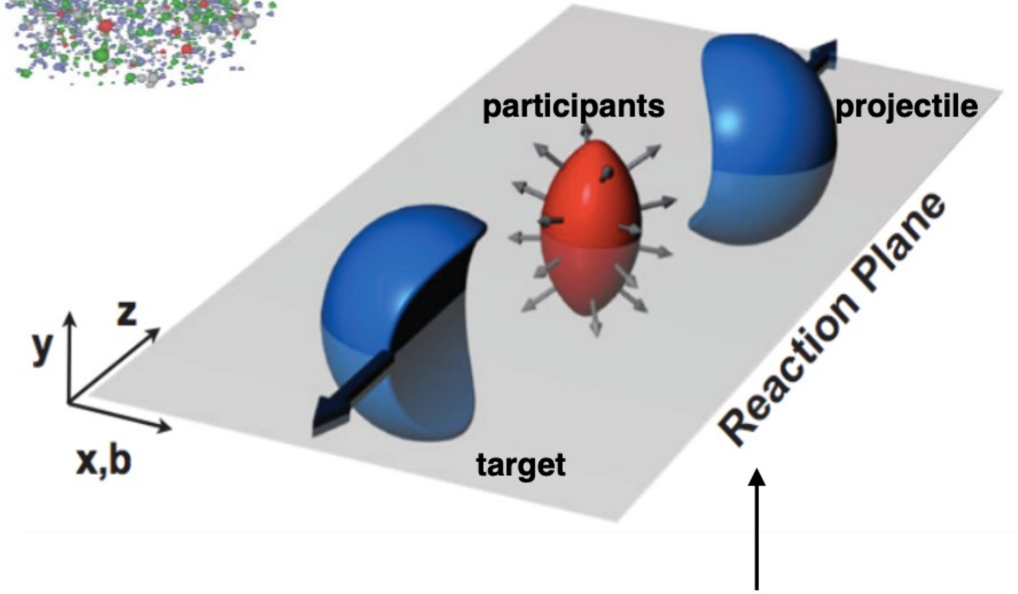
The azimuthal dependence for the particle yield can be written in the form of a Fourier series:

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_R)]\right)$$

E: energy of the particle
p: momentum
p_t: transverse momentum
ϕ: azimuthal angle
ψ_R: reaction plane angle
v_n: differential flow (v_1, directed flow and v_2 elliptic flow)

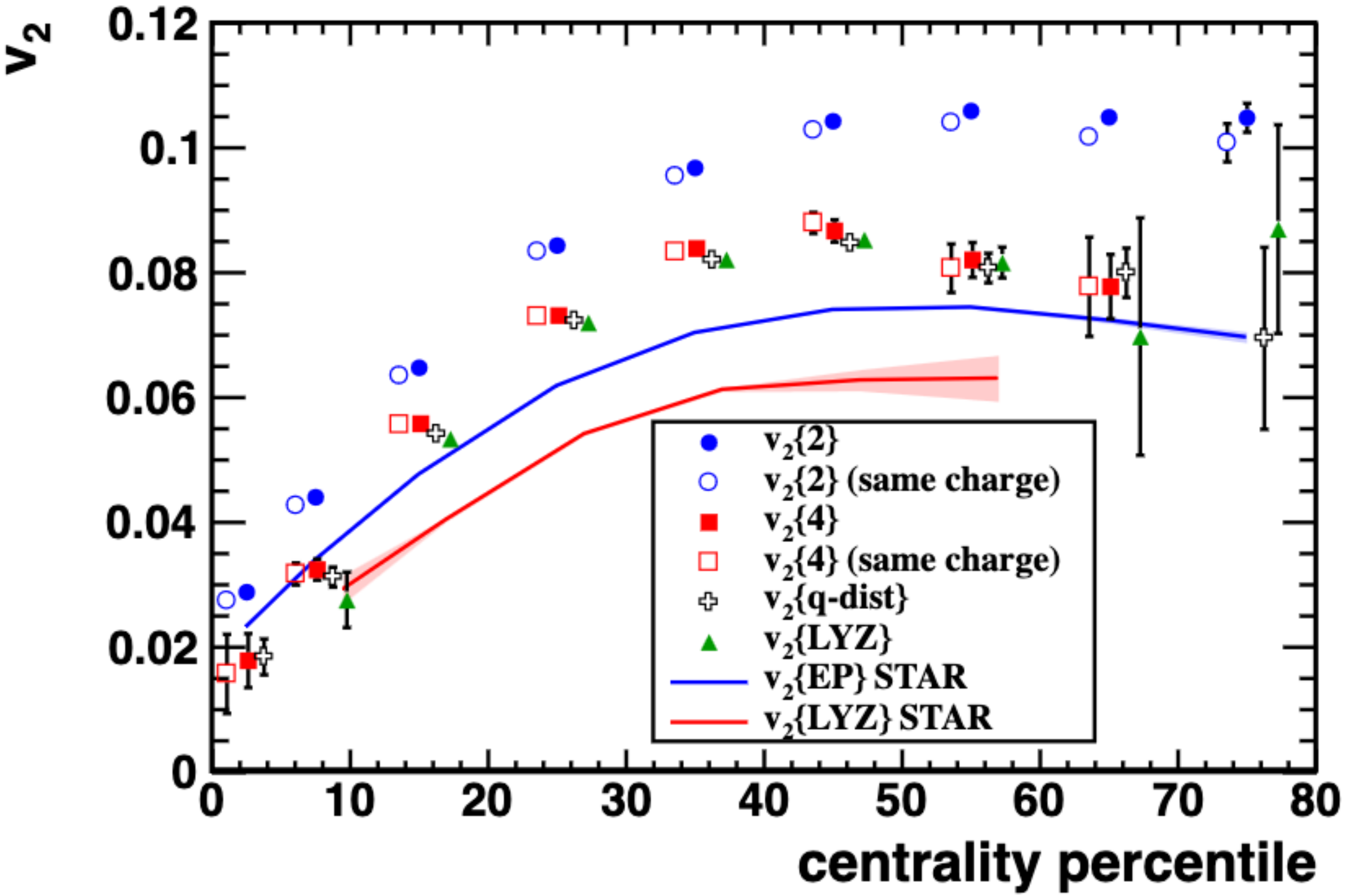


- Flow provides information on the equation state and the transport properties of matter created in a heavy-ion collision.
- Azimuthal anisotropy in particle production is the clearest experimental signature of collective flow.
- Elliptic flow depends on the ratio of shear viscosity to entropy ratio: η/s.
- Measurements of elliptic flow at RHIC revealed that hot and dense matter created in the collision there flows as a good fluid (almost no friction)



defined by the beam axis *z* and the impact parameter direction

ALICE’s results on elliptic flow

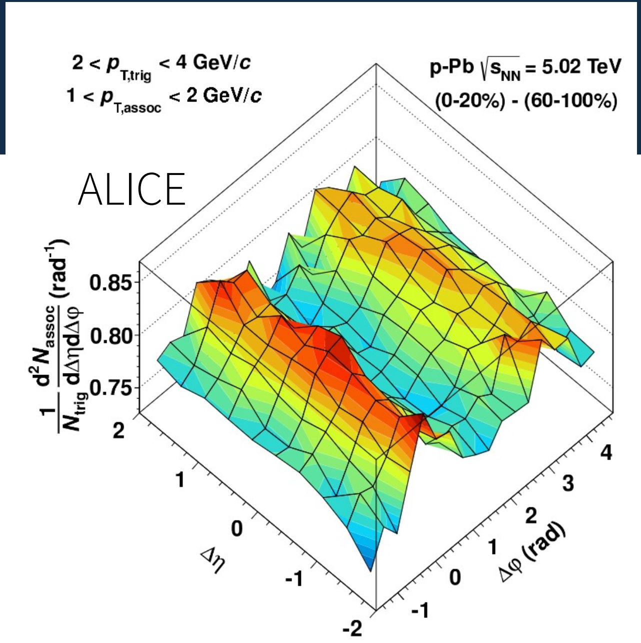


Phys.Rev.Lett. 105 (2010) 252302

The measurements from ALICE show that the elliptic flow of charged particles increases by about 30% compared with flow measured at RHIC at 0.2 TeV.

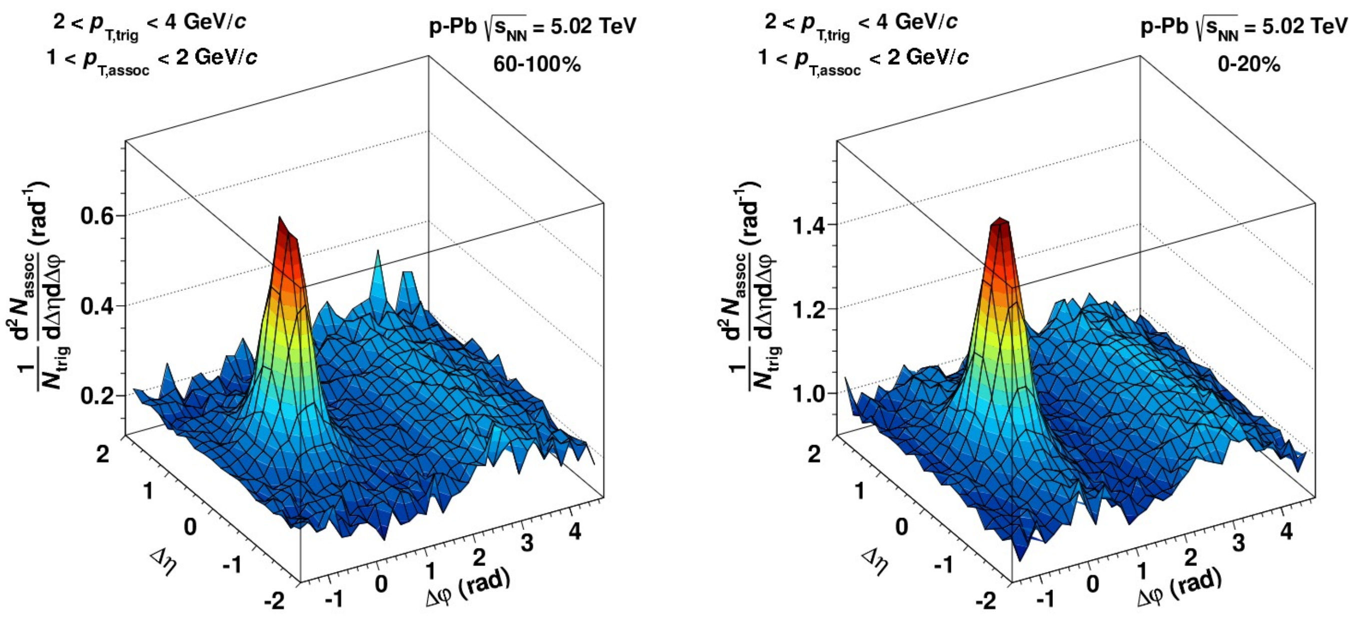
This result indicates that the hot and dense matter created in HIC behaves like a fluid with almost zero friction → strong constraint on the temperature dependence of η/s.

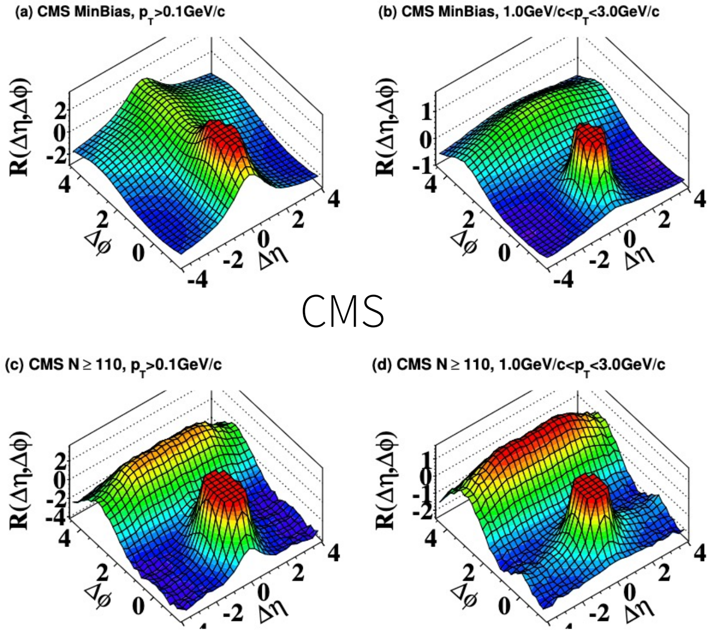
ALICE's results on elliptic flow



[Phys.Lett.B 719 (2013) 29-41]

ALICE

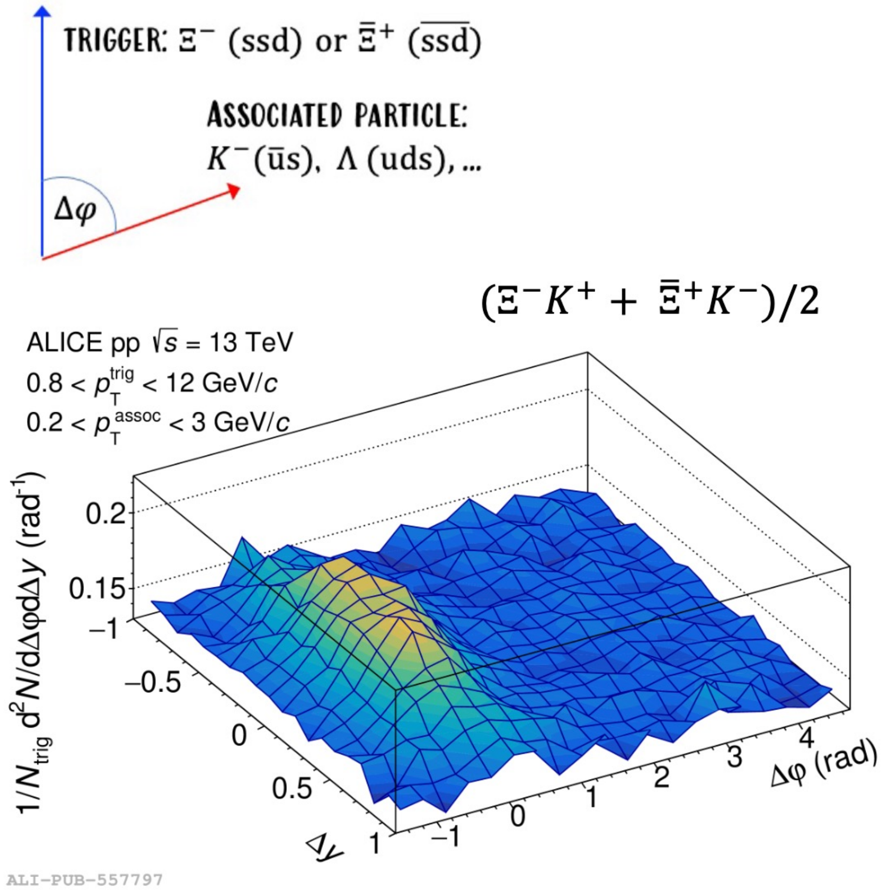


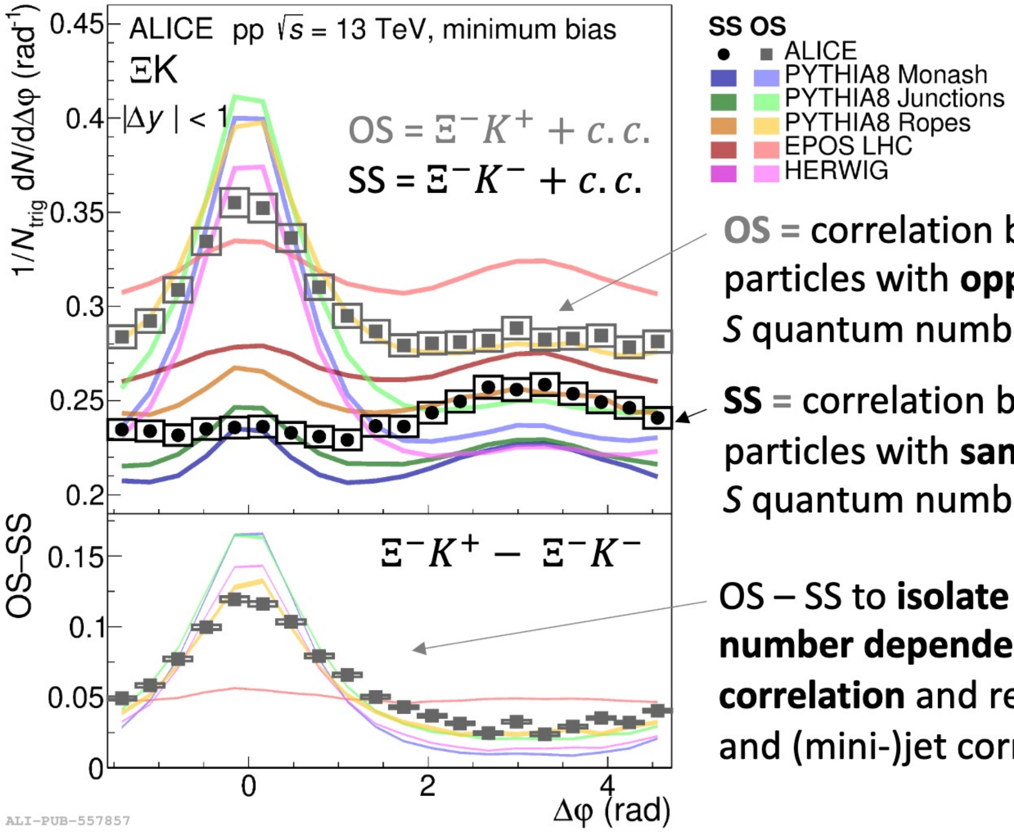


Azimuthal correlations in high-multiplicity pPb collisions exhibit a long-range structure at the near side (Δϕ ≈ 0). This ridge-like structure is qualitatively similar to that observed in pp collisions at √s = 7 TeV ([JHEP 09 (2010) 091]) and in AA collisions over a broad range of center-of-mass energies

ALICE’s results on elliptic flow

Angular correlations of strange hadrons





https://indico.in2p3.fr/event/29792/contributions/137156/attachments/85074/127269/SQM2024_ChiaraDeMartin.pdf

OS = correlation between particles with **opposite-sign** S quantum number

SS = correlation between particles with **same-sign** S quantum number

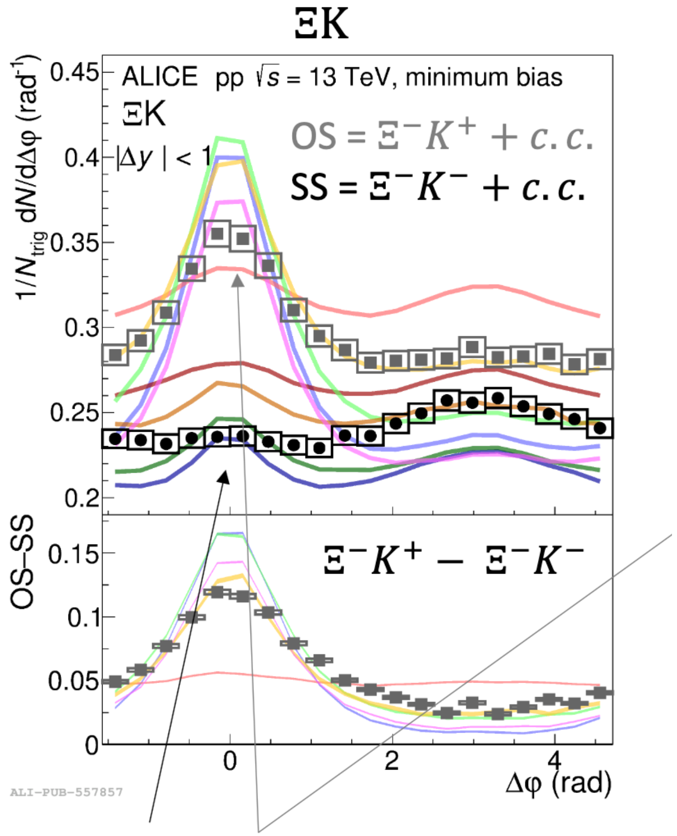
From SQM 2024

OS – SS to **isolate quantum-number dependent correlation** and remove flow and (mini-)jet correlations

arXiv:2308.16706

ALICE’s results on elliptic flow

Balancing of strangeness quantum number



OS correlation attributed to $s\bar{s}$ pair
No SS near-side peak (no shared $q\bar{q}$)

Can correlations help distinguish between the phenomenological models capable of predicting strangeness enhancement (SE) in pp collisions?

co.in2p3.fr/event
tributions/13715
nts/85074/1272
24_ChiaraDeMart

PYTHIA8 (string hadronization model)
→ predicts SE if ropes/junctions are included

HERWIG (cluster hadronization model)
→ qualitatively predicts SE with baryonic ropes mechanism

→ **$s\bar{s}$** are produced in pairs and remain **correlated** in final state

From SQM 2024

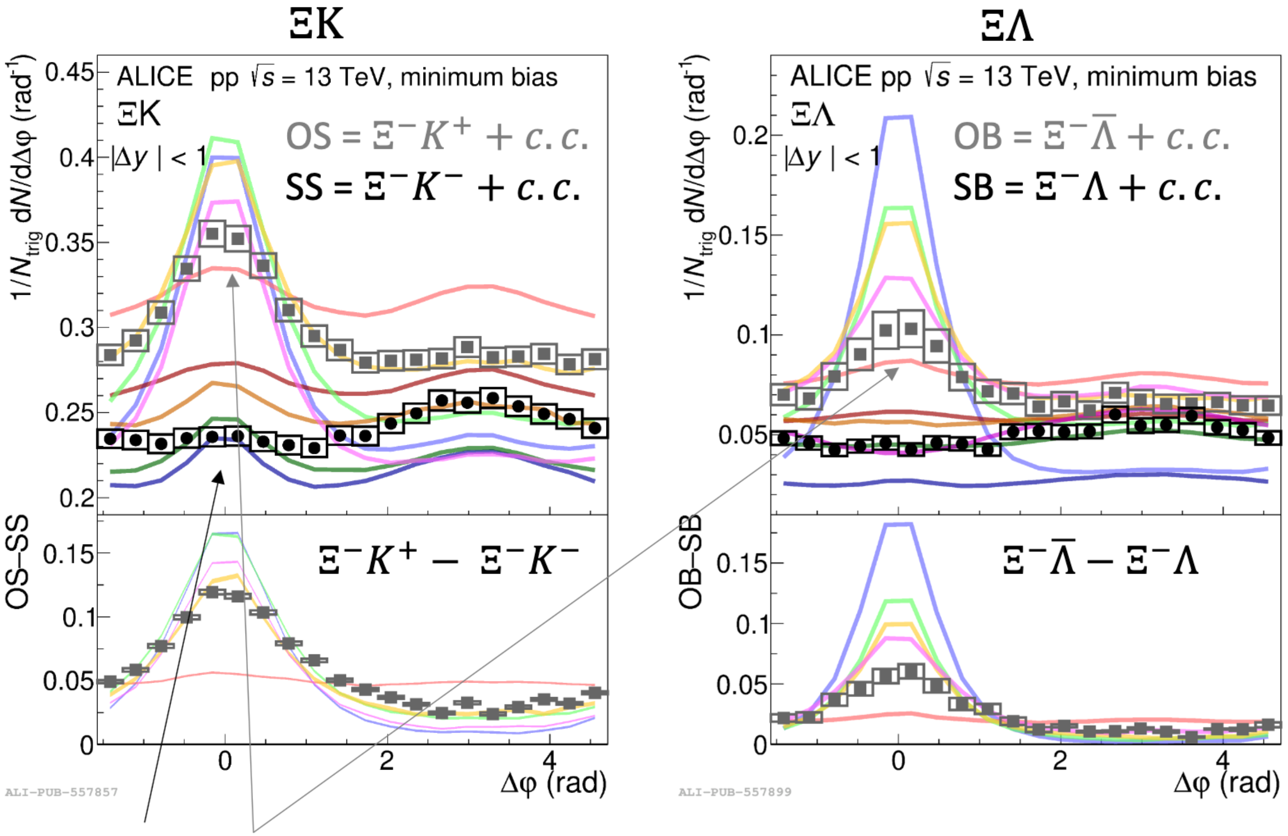
EPOS LHC (core-corona model)
→ describes SE as an increase of the “core” part (thermalised medium with global strangeness conservation) wrt “corona”(string-breaking)

→ **decorrelation of s quarks**

🟪 🟪 HERWIG

ALICE’s results on elliptic flow

Balancing of strangeness quantum number



OS correlation attributed to $s\bar{s}$ pair

No SS near-side peak (no shared $q\bar{q}$)

PYTHIA8 and HERWIG predict narrower and taller near-side (NS) peaks
→ **effects of string breaking too large**

PYTHIA8 with ropes and junctions provide better description than Monash
→ **diquark breaking mechanism is not enough** to describe the data

EPOS LHC predicts broader NS peaks
→ consequence of **decorrelation**

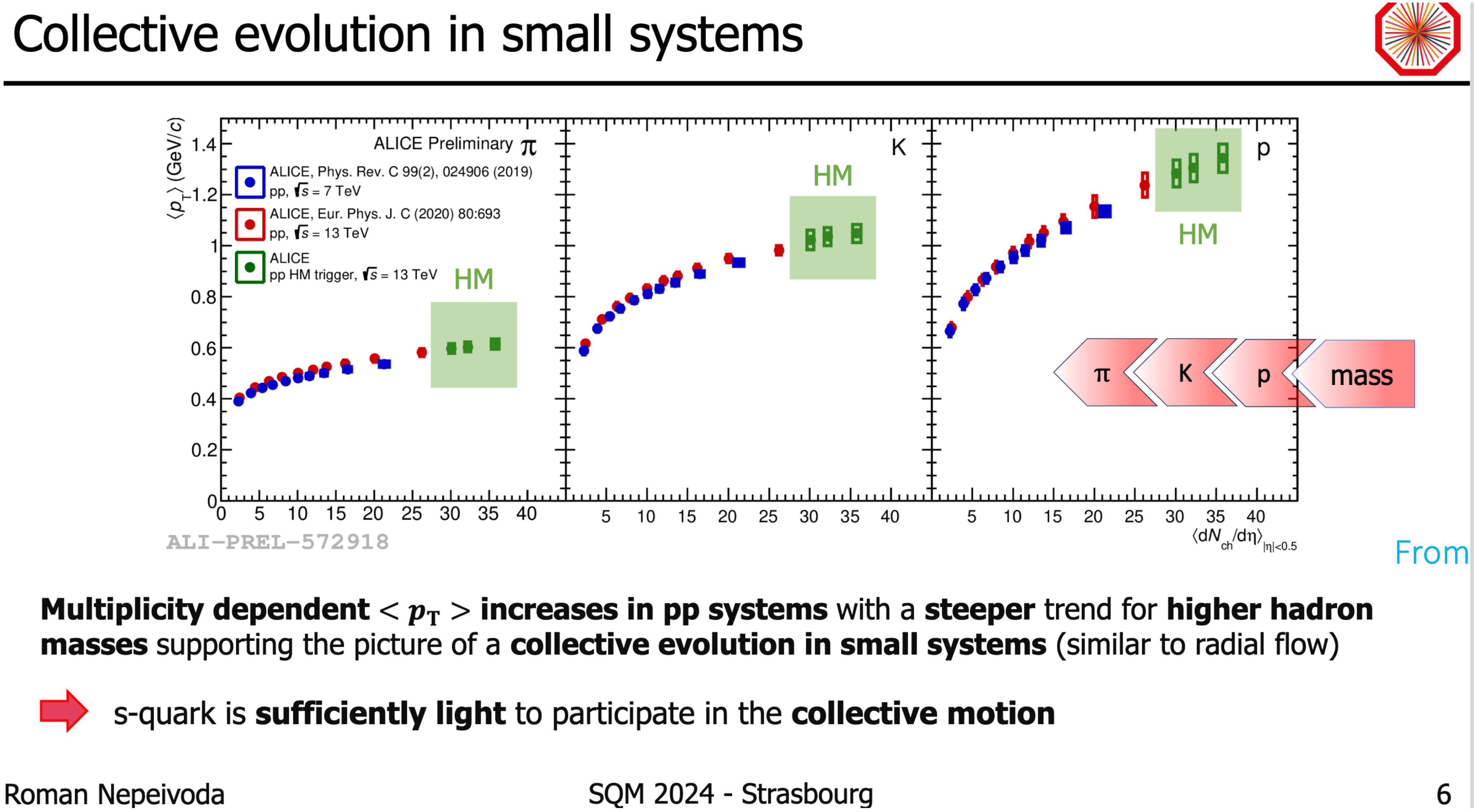
https://indico.in2p3.fr/event/29792/contributions/137156/attachments/85074/127269/SQM2024_ChiaraDeMartin.pdf

From SQM 2024

SS	OS	
●	■	ALICE
🟦	🟦	PYTHIA8 Monash
🟩	🟩	PYTHIA8 Junctions
🟧	🟨	PYTHIA8 Ropes
🟥	🟥	EPOS LHC
🟪	🟪	HERWIG

arXiv:2308.16706

ALICE’s results on elliptic flow



Collective evolution in small systems

Multiplicity dependent $< p_T >$ **increases in pp systems** with a **steeper** trend for **higher hadron masses** supporting the picture of a **collective evolution in small systems** (similar to radial flow)

➡ s-quark is **sufficiently light** to participate in the **collective motion**

Roman Nepeivoda SQM 2024 - Strasbourg 6

From SQM 2024

https://indico.in2p3.fr/event/29792/contributions/137150/attachments/85201/127462/systemSizeStrangeness_SQM_NR.pdf

ALICE's results on strangeness

Strangeness originally proposed as a signature of QGP

→ Enhanced production of strangeness in lead-lead collisions is considered as a signature of quark-gluon plasma (QGP)

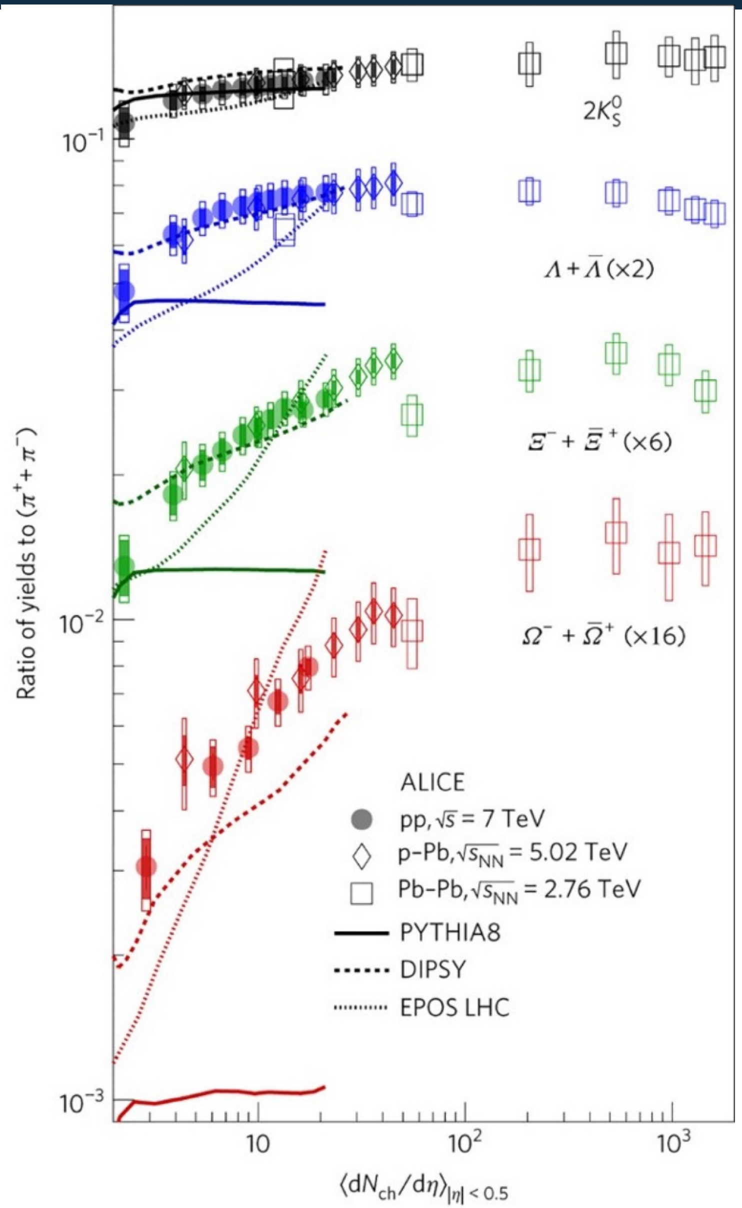
→ not expected in pp collisions

ALICE’s results on strangeness

Strangeness originally proposed as a signature of QGP

→ Enhanced production of strangeness in lead-lead collisions is considered as a signature of quark-gluon plasma (QGP)

→ not expected in pp collisions



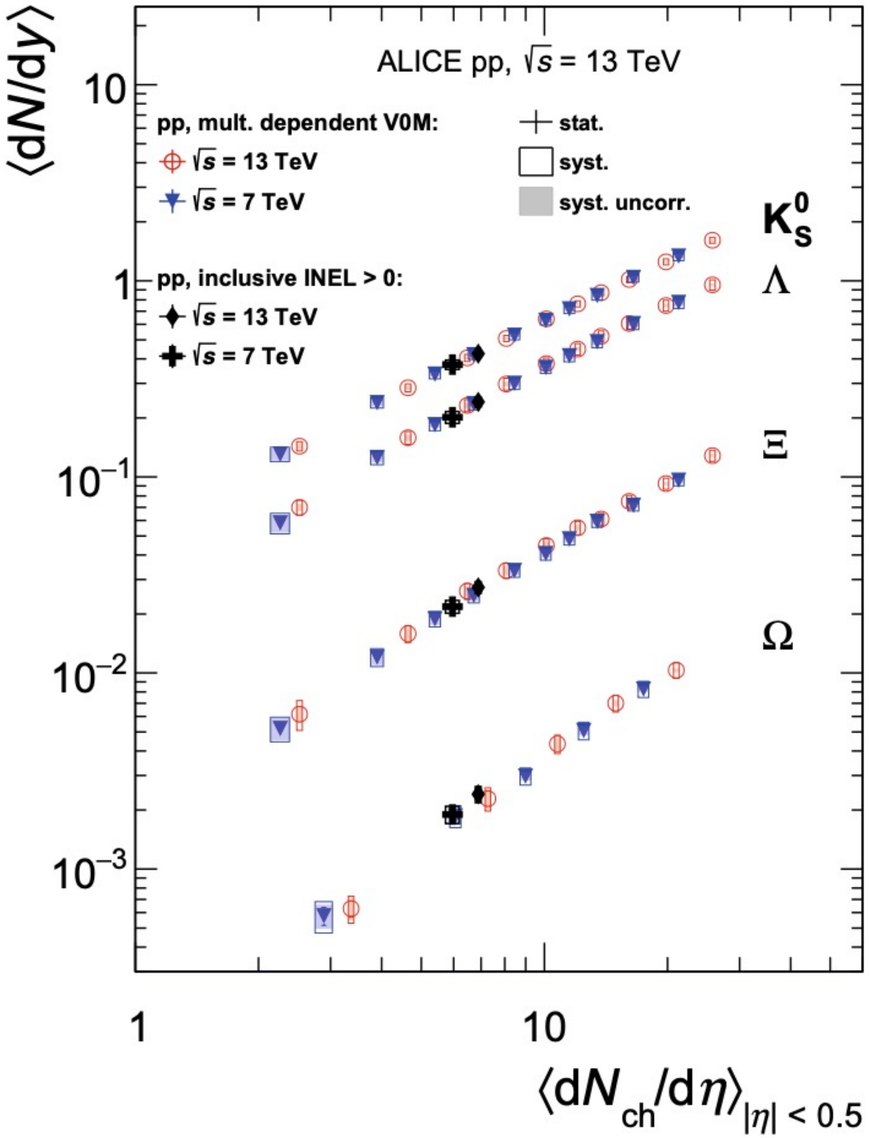
ALICE’s results on strangeness

Strangeness originally proposed as a signature of QGP

→ Enhanced production of strangeness in lead-lead collisions is considered as a signature of quark-gluon plasma (QGP)

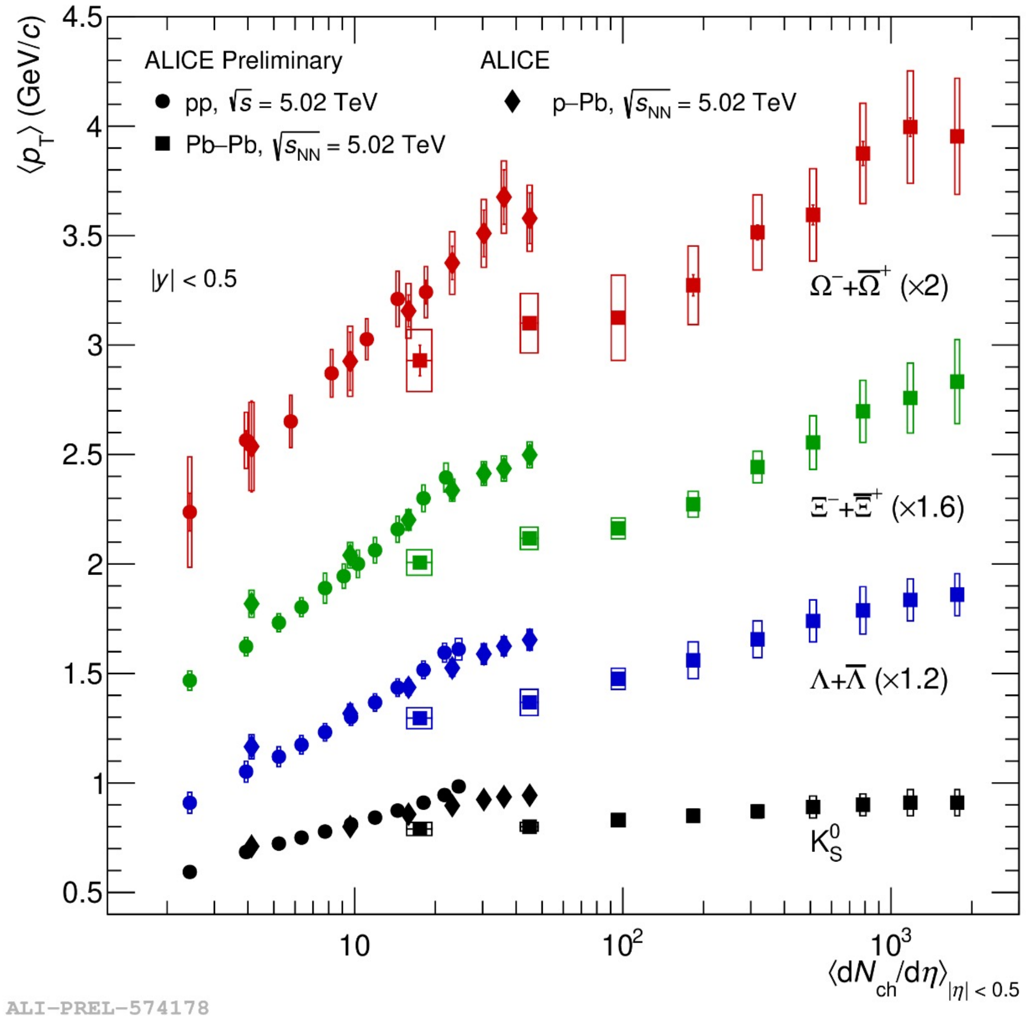
→ not expected in pp collisions

- the yields of strange hadrons increase with the charged particle multiplicity following a power law behaviour
- the trend is the same at 7 TeV and 13 TeV
- the abundance of strange hadrons depends on the local charged particle density and turns out to be invariant with the collision energy,



ALICE, Eur.Phys.J.C 80, 167 (2020)

Multiplicity dependent $< p_T >$ of strange particles



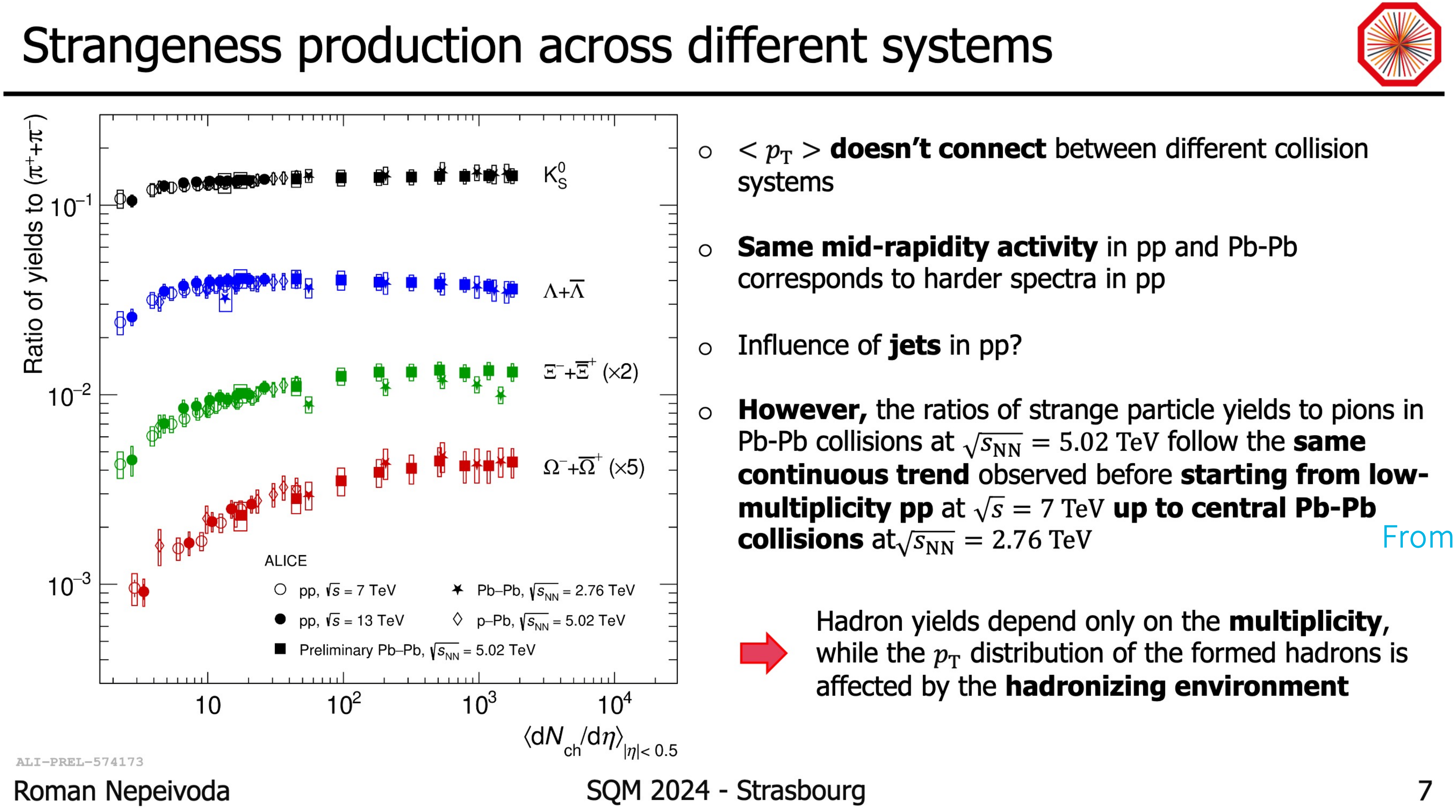
- $< p_T >$ **doesn't connect** between different collision systems
- **Same mid-rapidity activity** in pp and Pb-Pb corresponds to harder spectra in pp
- Influence of **jets** in pp?

From SQM 2024

https://indico.in2p3.fr/event/29792/contributions/137150/attachments/85201/127462/systemSizeStrangeness_SQM_NR.pdf

Roman Nepeivoda SQM 2024 - Strasbourg 7

https://indico.in2p3.fr/event/29792/contributions/137150/attachments/85201/127462/systemSizeStrangeness_SQM_NR.pdf



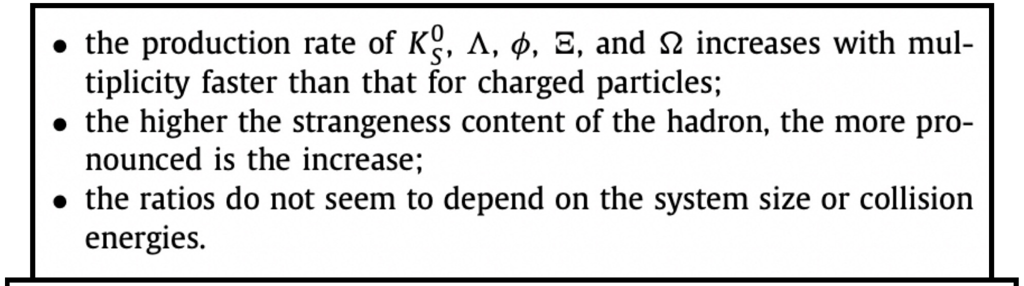
Strangeness production across different systems

- $< p_T >$ **doesn't connect** between different collision systems
- **Same mid-rapidity activity** in pp and Pb-Pb corresponds to harder spectra in pp
- Influence of **jets** in pp?
- **However,** the ratios of strange particle yields to pions in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV follow the **same continuous trend** observed before **starting from low-multiplicity pp** at $\sqrt{s} = 7$ TeV **up to central Pb-Pb collisions** at $\sqrt{s_{NN}} = 2.76$ TeV

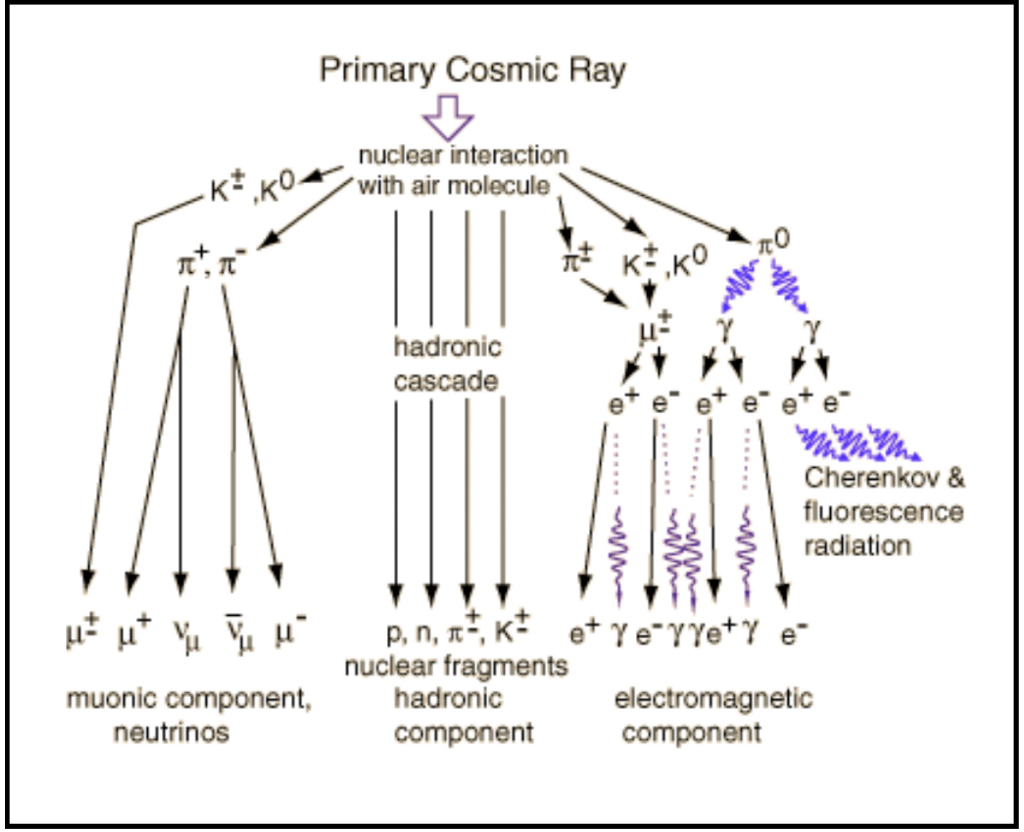
➡ Hadron yields depend only on the **multiplicity**, while the p_T distribution of the formed hadrons is affected by the **hadronizing environment**

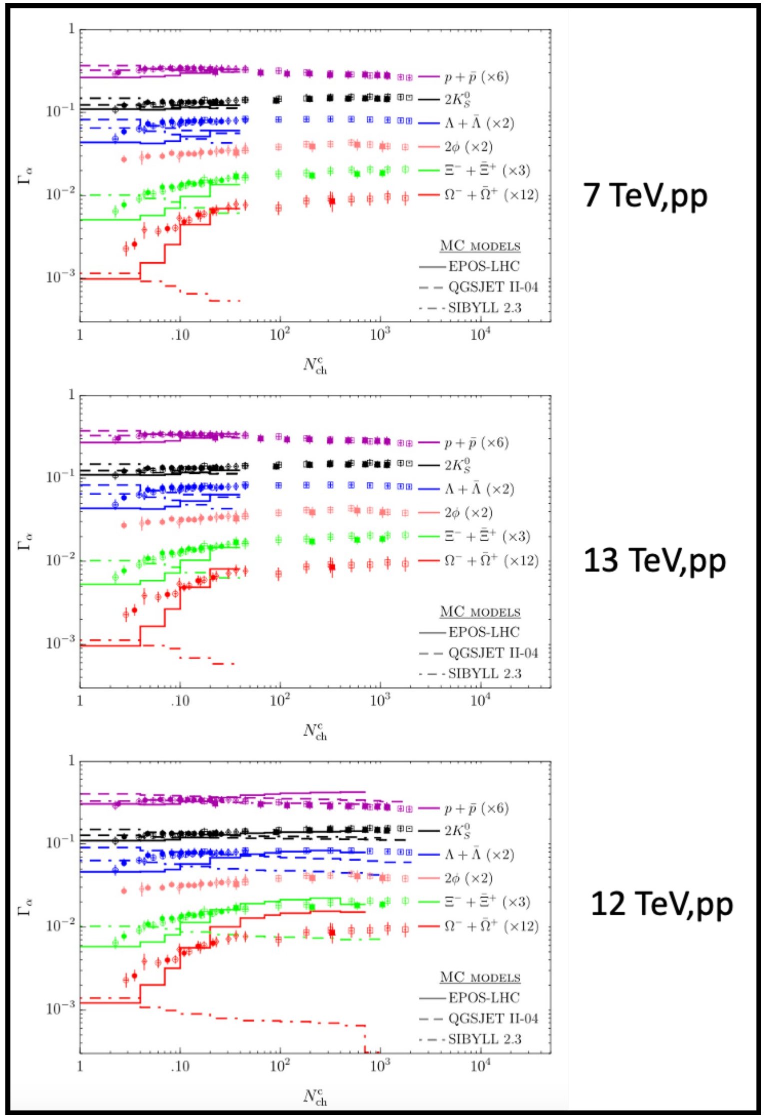
Roman Nepeivoda SQM 2024 - Strasbourg 7

From SQM 2024



- the production rate of K^0_S, Λ, ϕ, Ξ, and Ω increases with multiplicity faster than that for charged particles;
- the higher the strangeness content of the hadron, the more pronounced is the increase;
- the ratios do not seem to depend on the system size or collision energies.





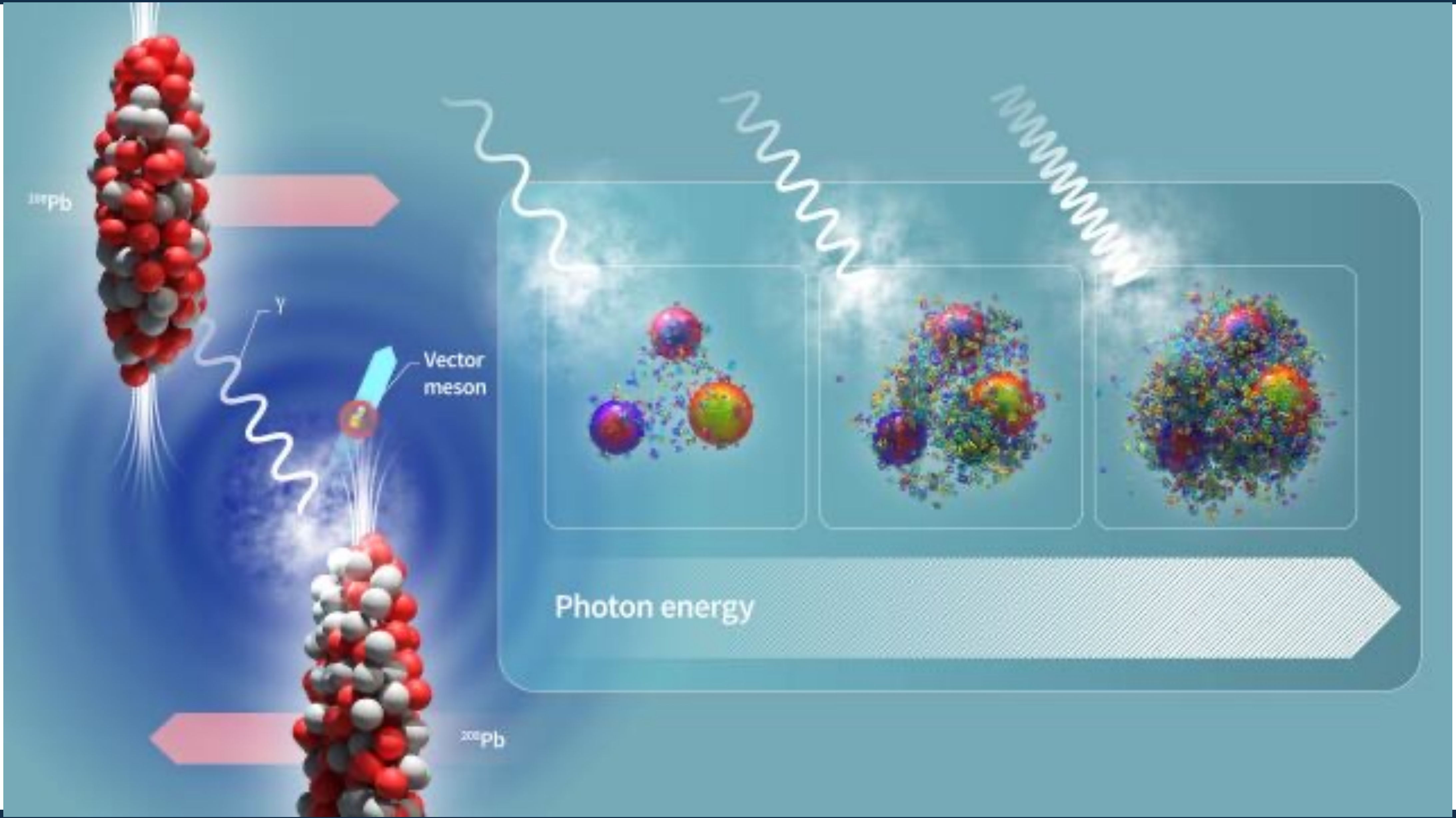
7 TeV,pp

13 TeV,pp

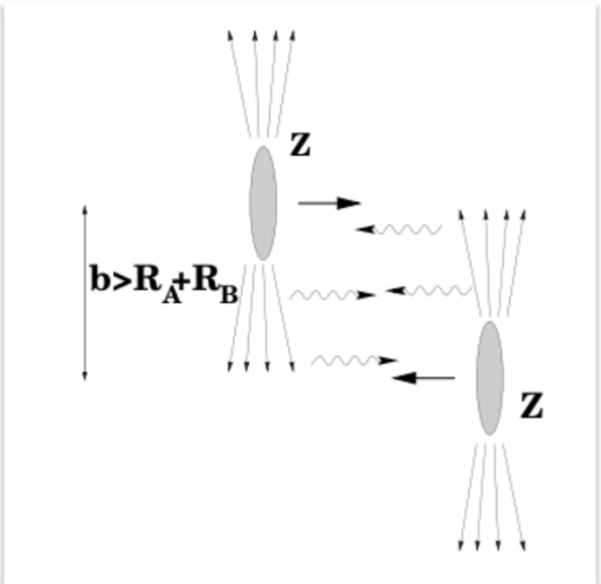
12 TeV,pp

Anchordoqui L. et al, Physics Letters B, Volume 810, 10 November 2020, 135837

ALICE’s UPC



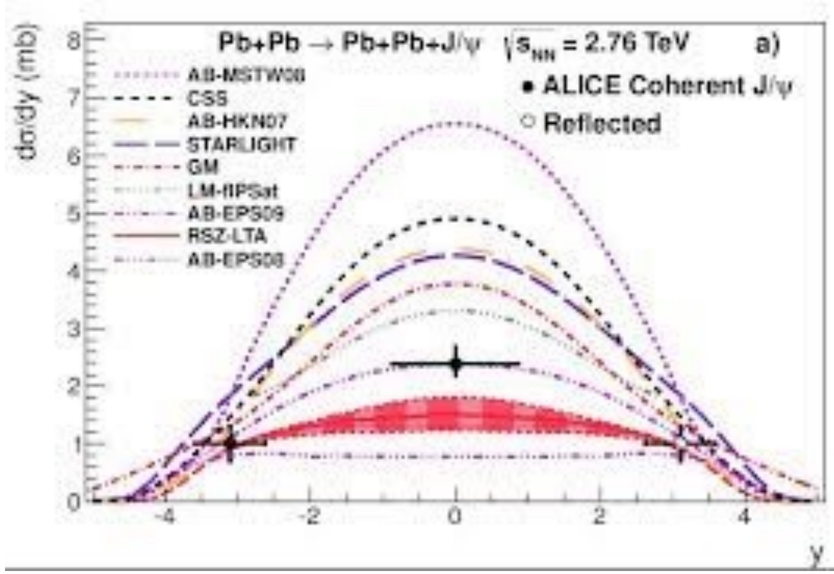
ALICE’s UPC



- The photo production of vector mesons can be studied in ultra peripheral collisions (UPC) at LHC.
- UPC occurs if b > R_A+R_B —> the photons and nuclei can interact in several ways.
- Hadronic interactions are suppressed: only interactions mediated by the strong electromagnetic field behaving as a flux of virtual photons possible.
- LHC is used as a photon collider.

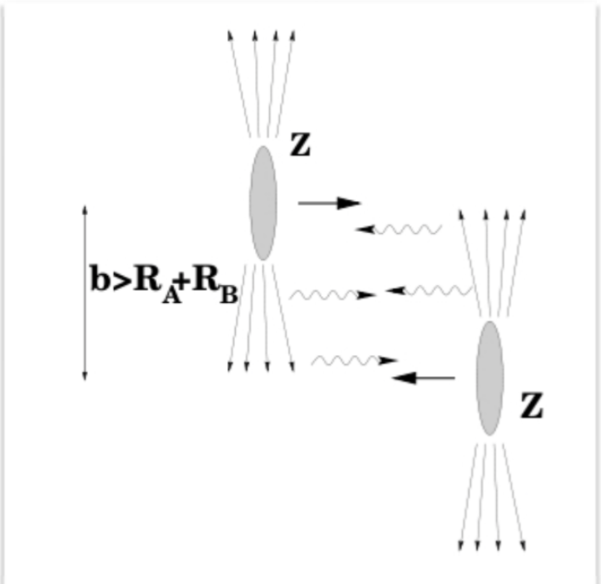
he AB-MSTW08 model, which assumes that the forward scattering cross section scales with the number of nucleons squared, disagrees with the measurement, both for the value of the cross section and for the ratio of the two rapidity intervals, and is strongly disfavoured. STARLIGHT deviates by nearly three standard deviations in the cross section and is also disfavoured. Best agreement is found with models which include nuclear gluon shadowing consistent with the EPS09 or EPS08 parameterizations

- Coherent process: photon interacts with the entire ion (all nucleons). In most of the cases there are not neutron emission (80%)
- Incoherent process: the photon interacts with single nucleon (most of the times the target nucleus dissociates)



Physics Letters B
Volume 718, Issues 4–5, 29 January 2013, Pages 1273-1283

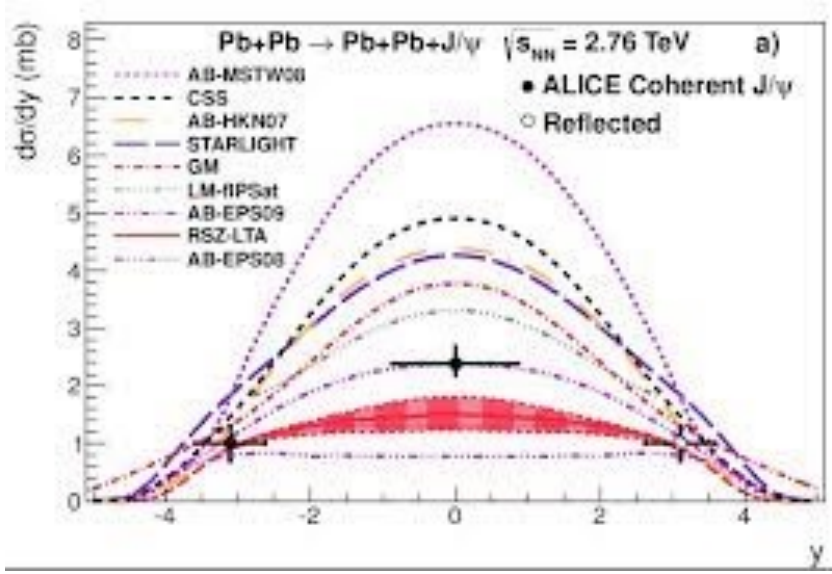
ALICE’s UPC



- The photo production of vector mesons can be studied in ultra peripheral collisions (UPC) at LHC.
- UPC occurs if b > $R_A + R_B$ —> the photons and nuclei can interact in several ways.
- Hadronic interactions are suppressed: only interactions mediated by the strong electromagnetic field behaving as a flux of virtual photons possible.
- LHC is used as a photon collider.

he AB-MSTW08 model, which assumes that the forward scattering cross section scales with the number of nucleons squared, disagrees with the measurement, both for the value of the cross section and for the ratio of the two rapidity intervals, and is strongly disfavoured. STARLIGHT deviates by nearly three standard deviations in the cross section and is also disfavoured. Best agreement is found with models which include nuclear gluon shadowing consistent with the EPS09 or EPS08 parameterizations

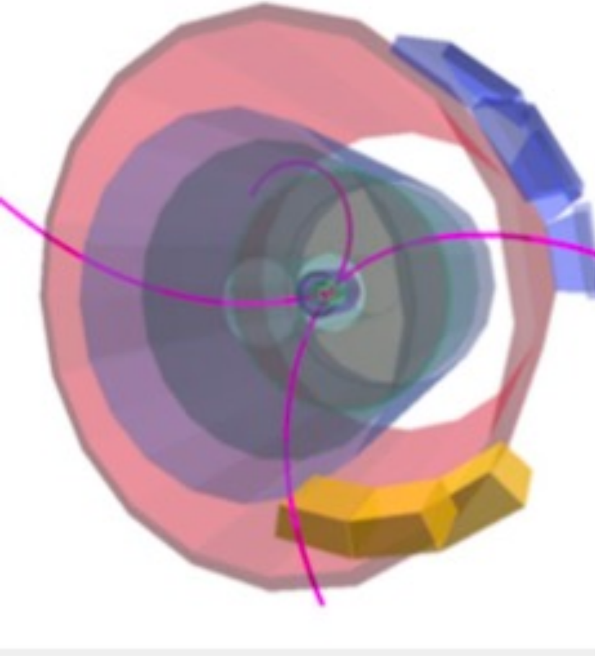
- Coherent process: photon interacts with the entire ion (all nucleons). In most of the cases there are not neutron emission (80%)
- Incoherent process: the photon interacts with single nucleon (most of the times the target nucleus dissociates)

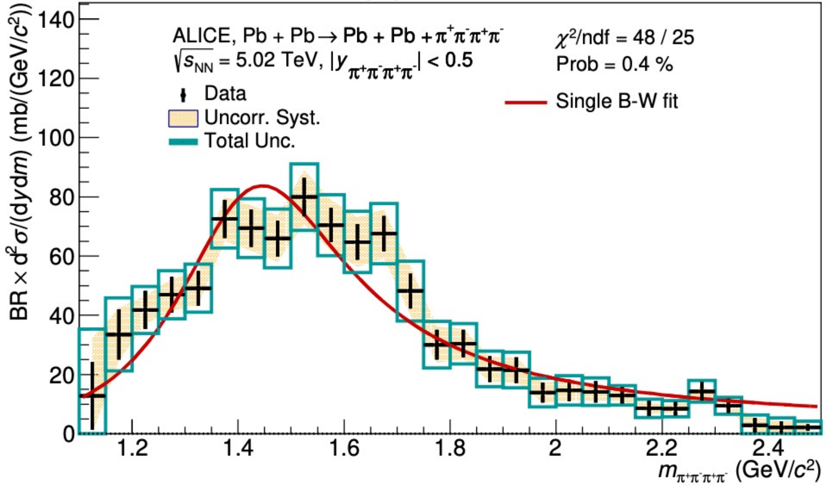


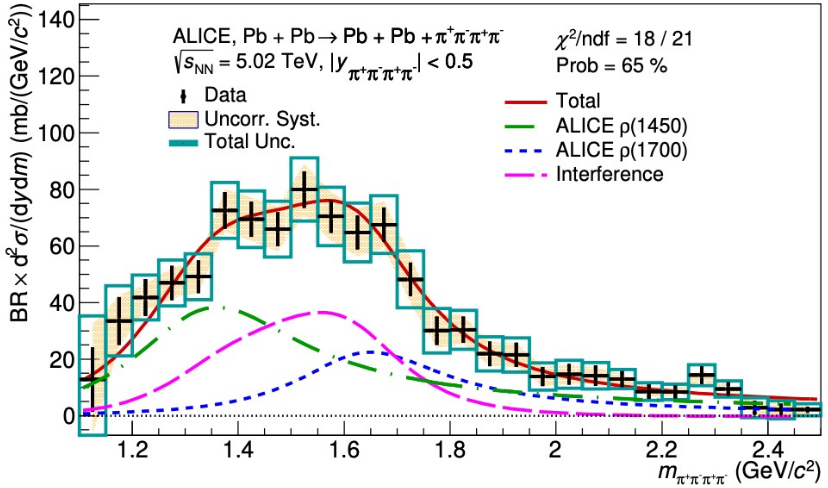
Physics Letters B
Volume 718, Issues 4–5, 29 January 2013, Pages 1273-1283

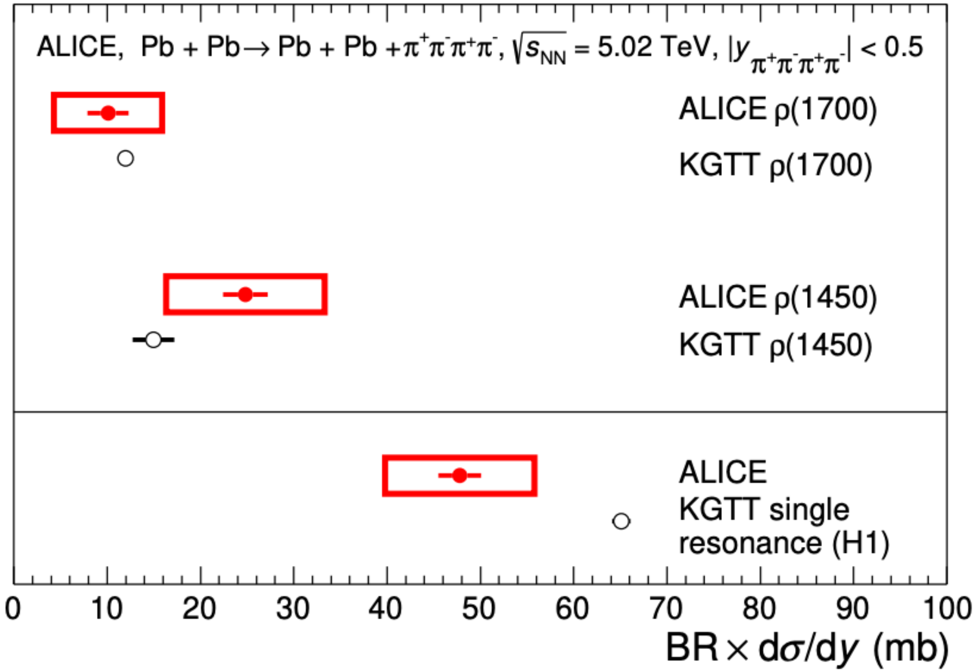
Four pion photo-production

https://arxiv.org/pdf/2404.07542 , to apper in PLB



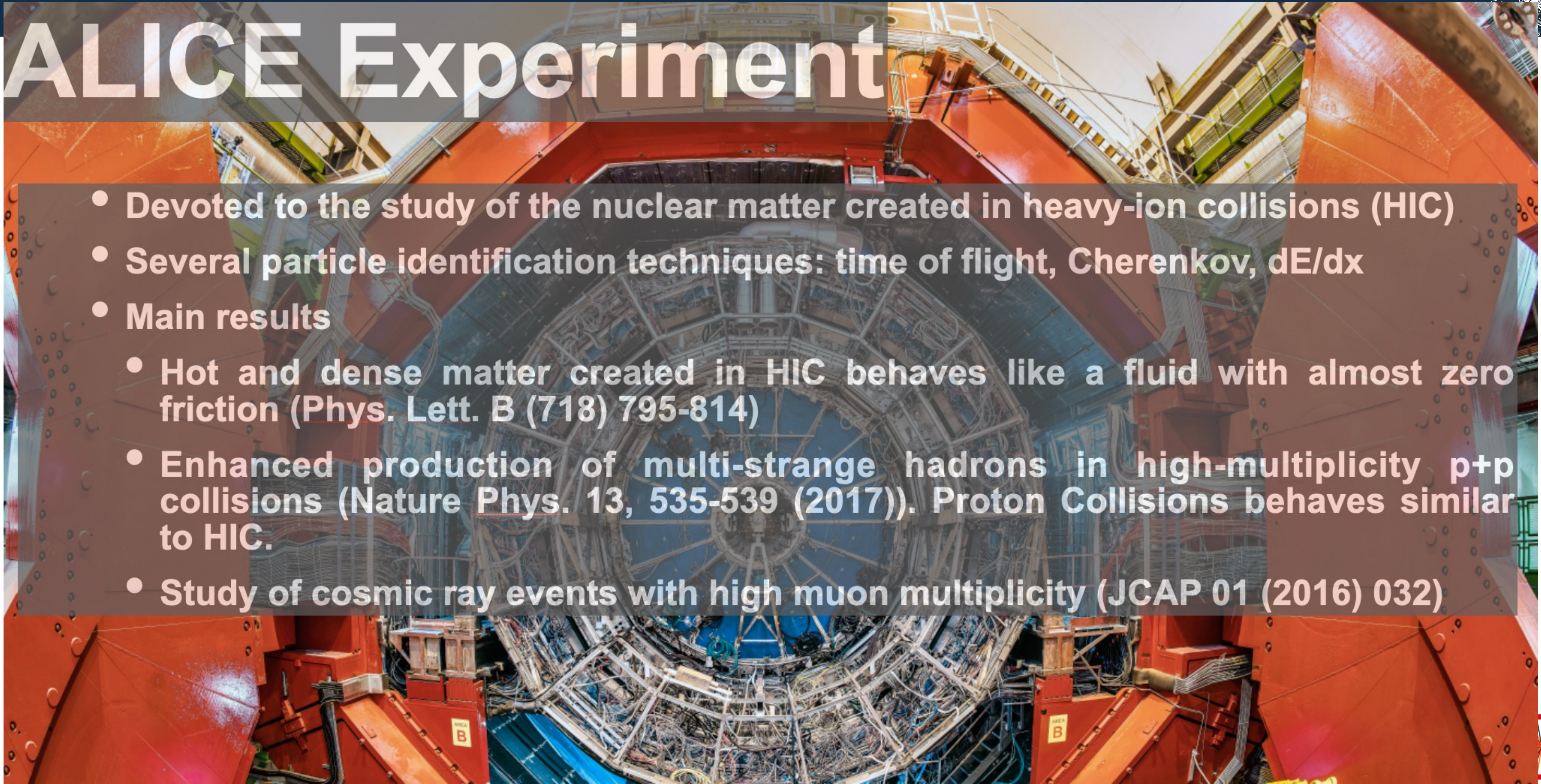




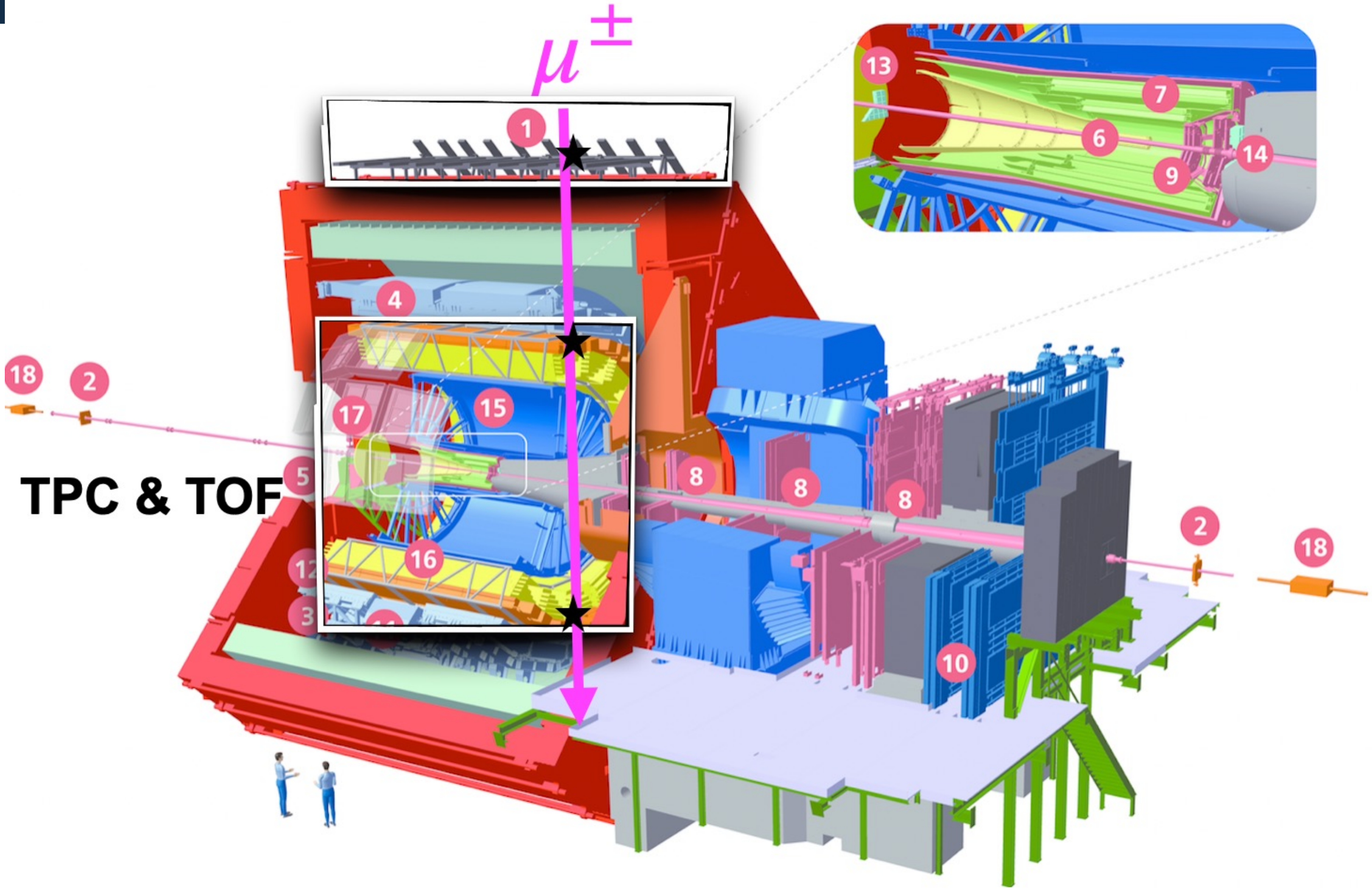


The $\pi^+\pi^-\pi^+\pi^-$ invariant mass distribution is best described by the fit assuming two excited resonances, **ρ(1450)** and **ρ(1700),** and the interference term between them

ALICE Experiment

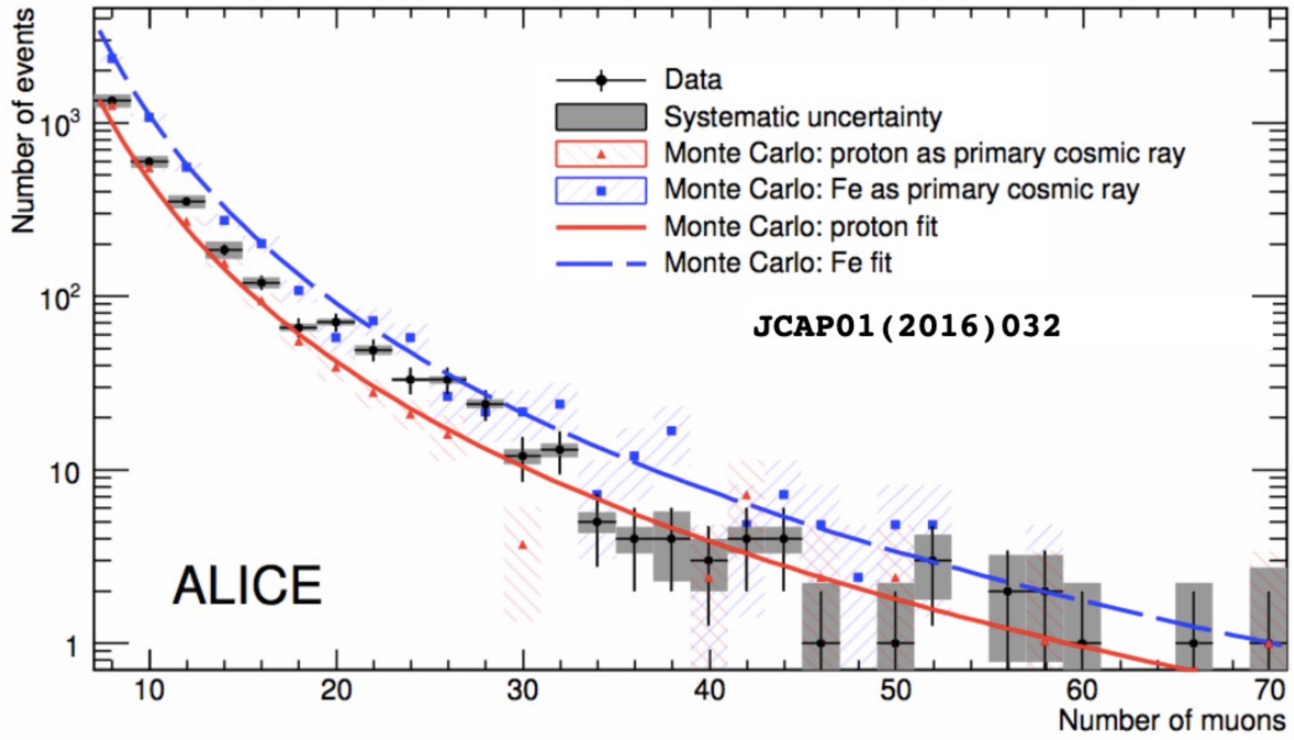


- Devoted to the study of the nuclear matter created in heavy-ion collisions (HIC)
- Several particle identification techniques: time of flight, Cherenkov, dE/dx
- Main results
  - Hot and dense matter created in HIC behaves like a fluid with almost zero friction (Phys. Lett. B (718) 795-814)
  - Enhanced production of multi-strange hadrons in high-multiplicity p+p collisions (Nature Phys. 13, 535-539 (2017)). Proton Collisions behaves similar to HIC.
  - Study of cosmic ray events with high muon multiplicity (JCAP 01 (2016) 032)

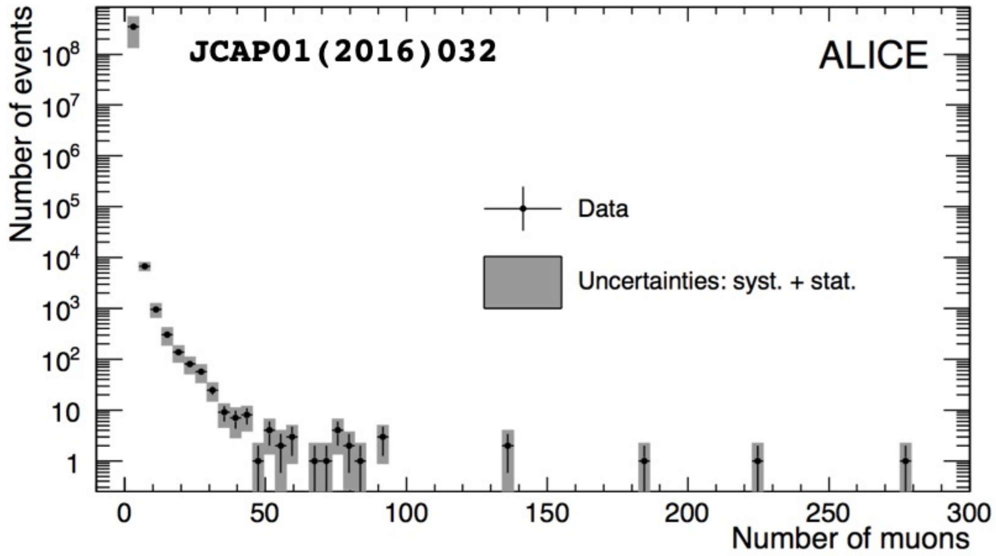


① **ACORDE** | ALICE Cosmic Rays Detector
② **AD** | ALICE Diffractive Detector
③ **DCal** | Di-jet Calorimeter
④ **EMCal** | Electromagnetic Calorimeter
⑤ **HMPID** | High Momentum Particle Identification Detector
⑥ **ITS-IB** | Inner Tracking System - Inner Barre
⑦ **ITS-OB** | Inner Tracking System - Outer Barr
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’s results on multi-muon events



ALICE results on Cosmic Ray Physics



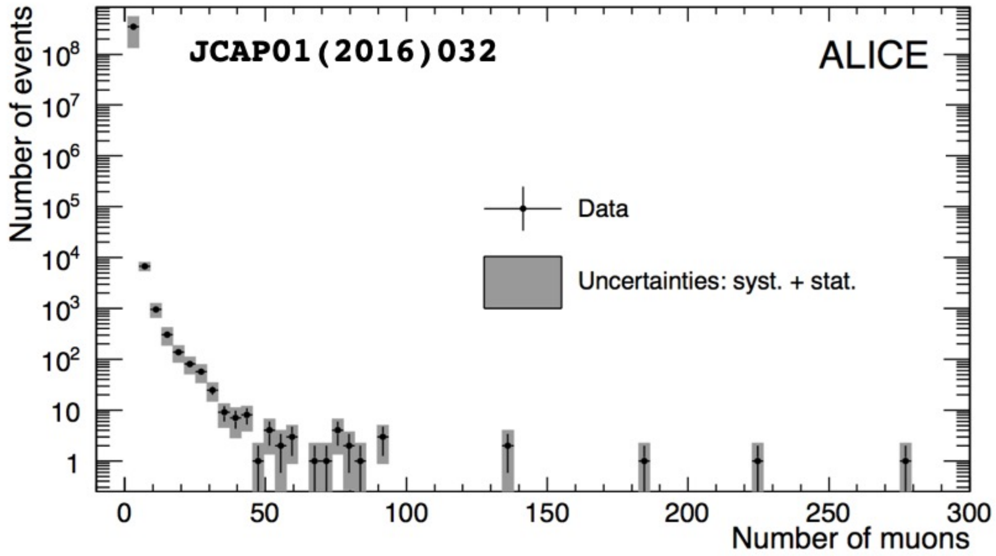
We find a smooth distribution up to #μ < 70 and 5 events with more than 100 atmospheric muons (HMM)

ALICE's results on multi-muon events

HMM events	CORSIKA 6990 QGSJET II-03 proton	 iron	CORSIKA 7350 QGSJET II-04 proton	 iron	Data
Period [days per event]	15.5	8.6	11.6	6.0	6.2
Rate [$\times 10^{-6}$ Hz]	0.8	1.3	1.0	1.9	1.9
Uncertainty (%) (syst + stat)	13	16	8	20	49

- Pure **iron** sample simulated with **QGSJET II-04** model reproduces HMM event rate in close agreement with the measured value.
- Independent of the version model, the rate of HMM events with pure proton cosmic-ray composition is more difficult to reproduce.
- This result is compatible with recent measurements which suggest that the composition of the primary cosmic-ray spectrum with energies larger than 10^{16} eV is dominated by heavier elements: Phys. Rev. Lett. **107** (2011) 171104.

ALICE results on Cosmic Ray Physics

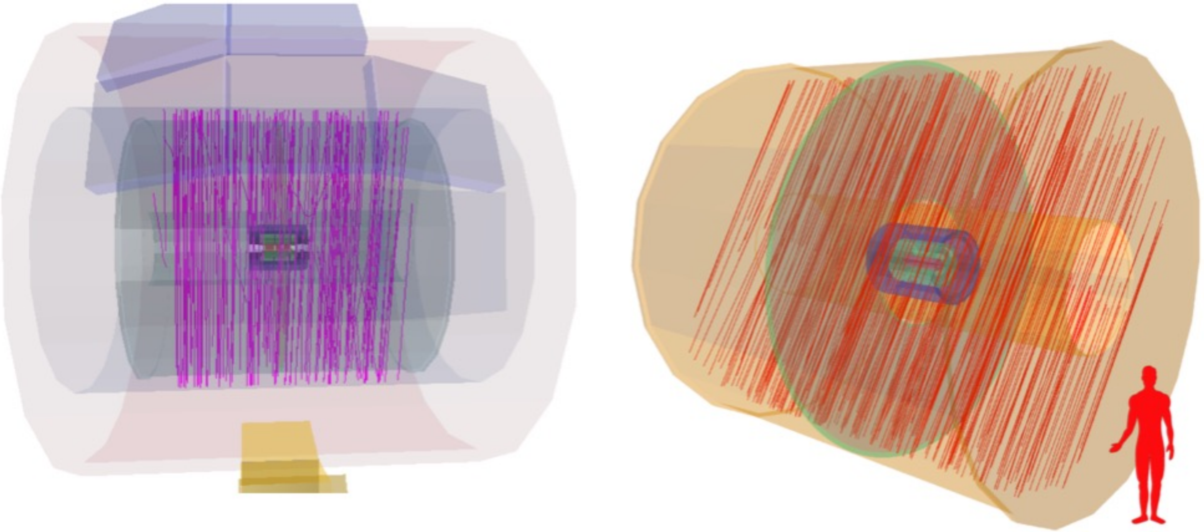


We find a smooth distribution up to #μ < 70 and 5 events with more than 100 atmospheric muons (HMM)

ALICE’s results on multi-muon events

- In 30.8 days (Run 1 data), ALICE collected 5 events with more than 100 muons.
- In ALICE’s cosmic paper, we reported that the frequency of such kind of events can be reproduced with the QGSJET II-04 hadronic interaction model (tuned with LHC data).
- These events are originated due to EAS from primary cosmic rays whose composition is dominated by a heavy component (Fe) with energies larger than 10^{16} eV.
- The core of the EAS is located very close from the ALICE at LHC with a zenith angles less than 50 degrees.
- This result may put significant constraints on alternative, more exotic, production mechanisms (e.g. QGP in cosmic ray showers Astropart.Phys.17:355-365,2002).

JCAP01(2016)032

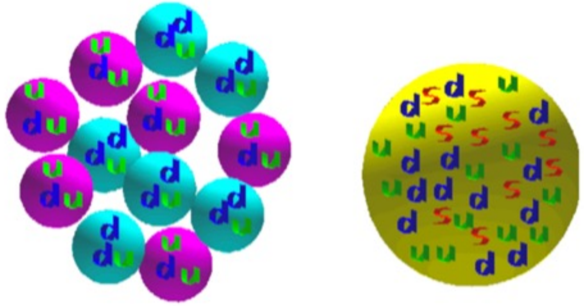


ALICE’s results on multi-muon events

The ALICE results on high muon multiplicity events motivated some theoretical work: ApJ 839, 31 (2017)

Strange quark matter

Roughly equal numbers of u, d, s quarks in a single ‘bag’ of cold hadronic matter.



Nucleus (^{12}C)
Z=6, A=12
Z/A = 0.5

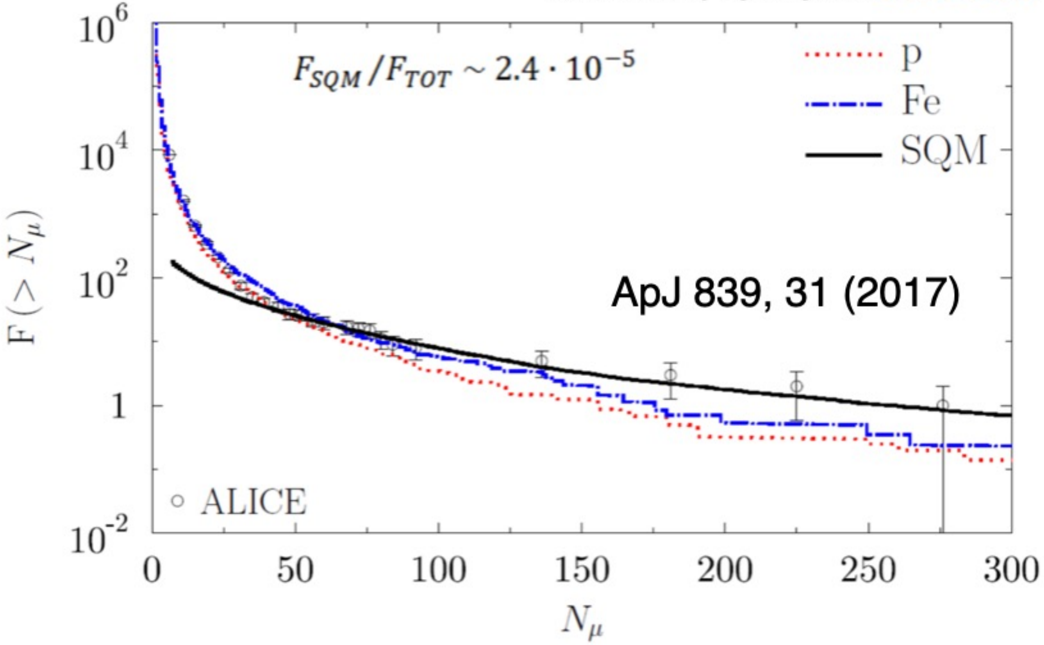
Strangelet*
A=12 (36 quarks)
Z/A = 0.083

From Maciej Rybczyński, ISMD 2017

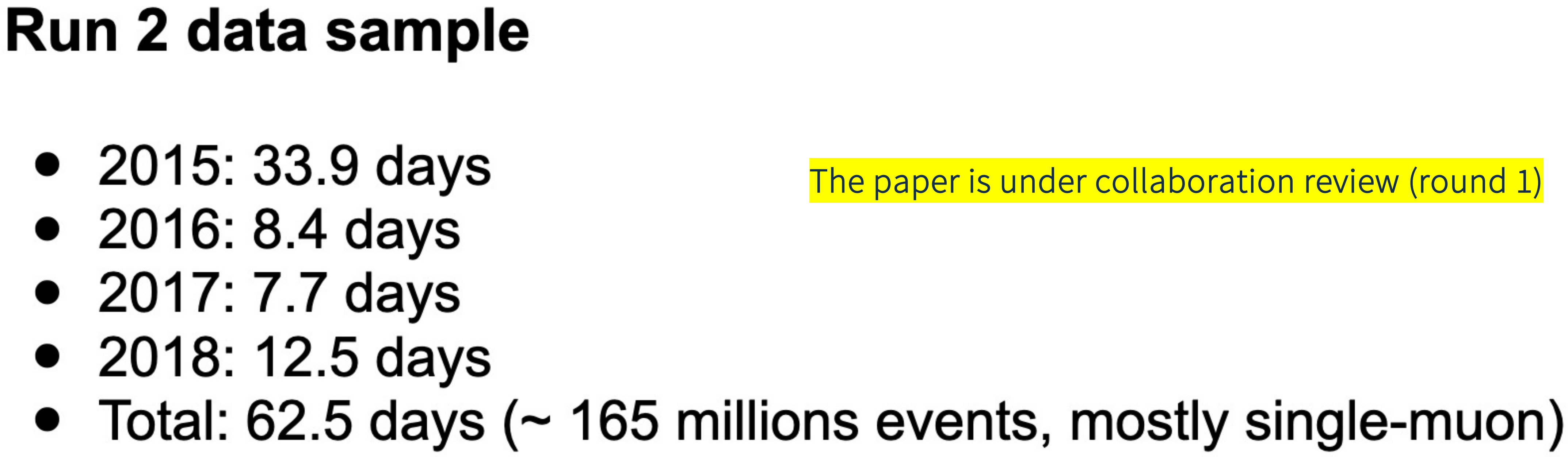
*small lump of Strange Quark Matter

High multiplicity muon bundles from strange quark matter

From Maciej Rybczyński, ISMD 2017



Integral multiplicity distribution of muons for the ALICE data (circles) published in JCAP 01 (2016) 032. Monte Carlo simulations for primary protons (dotted line); iron nuclei (dashed dot line) and primary strangelets with mass A taken from the $A^{-7.5}$ distribution (full line) with abundance of the order of $2 \cdot 10^{-5}$ of the total primary flux.

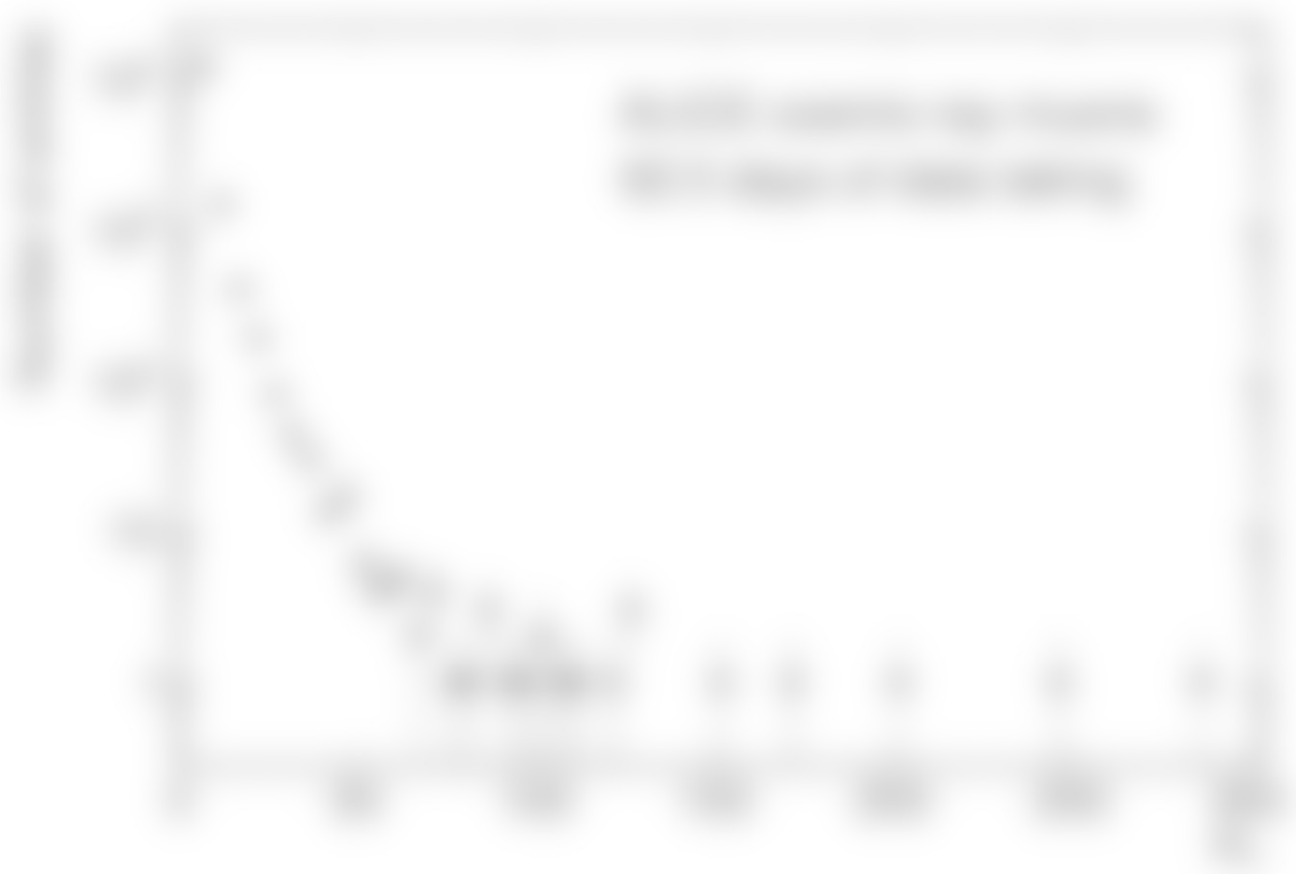


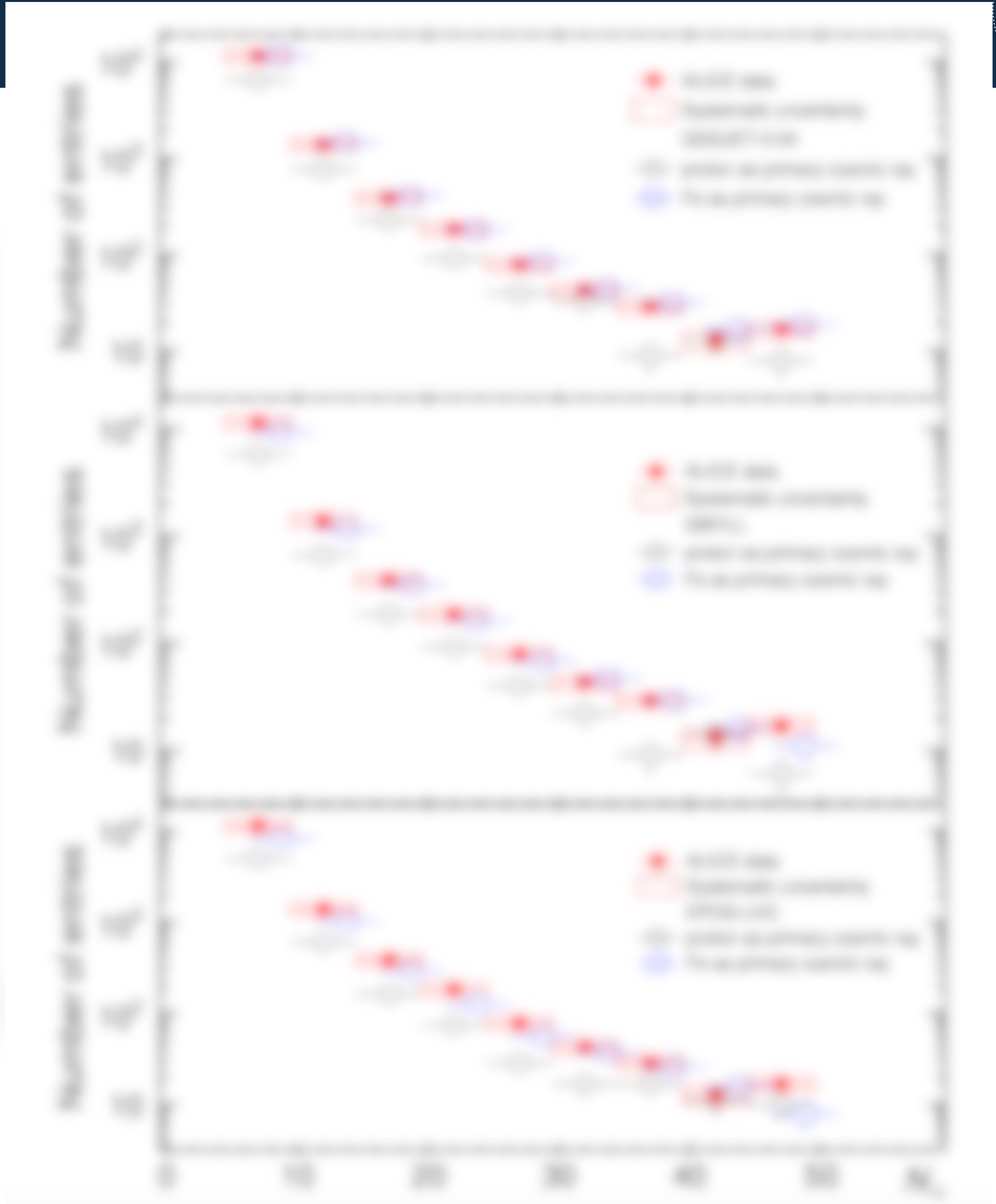
Run 2 data sample

- 2015: 33.9 days
- 2016: 8.4 days
- 2017: 7.7 days
- 2018: 12.5 days
- Total: 62.5 days (~ 165 millions events, mostly single-muon)

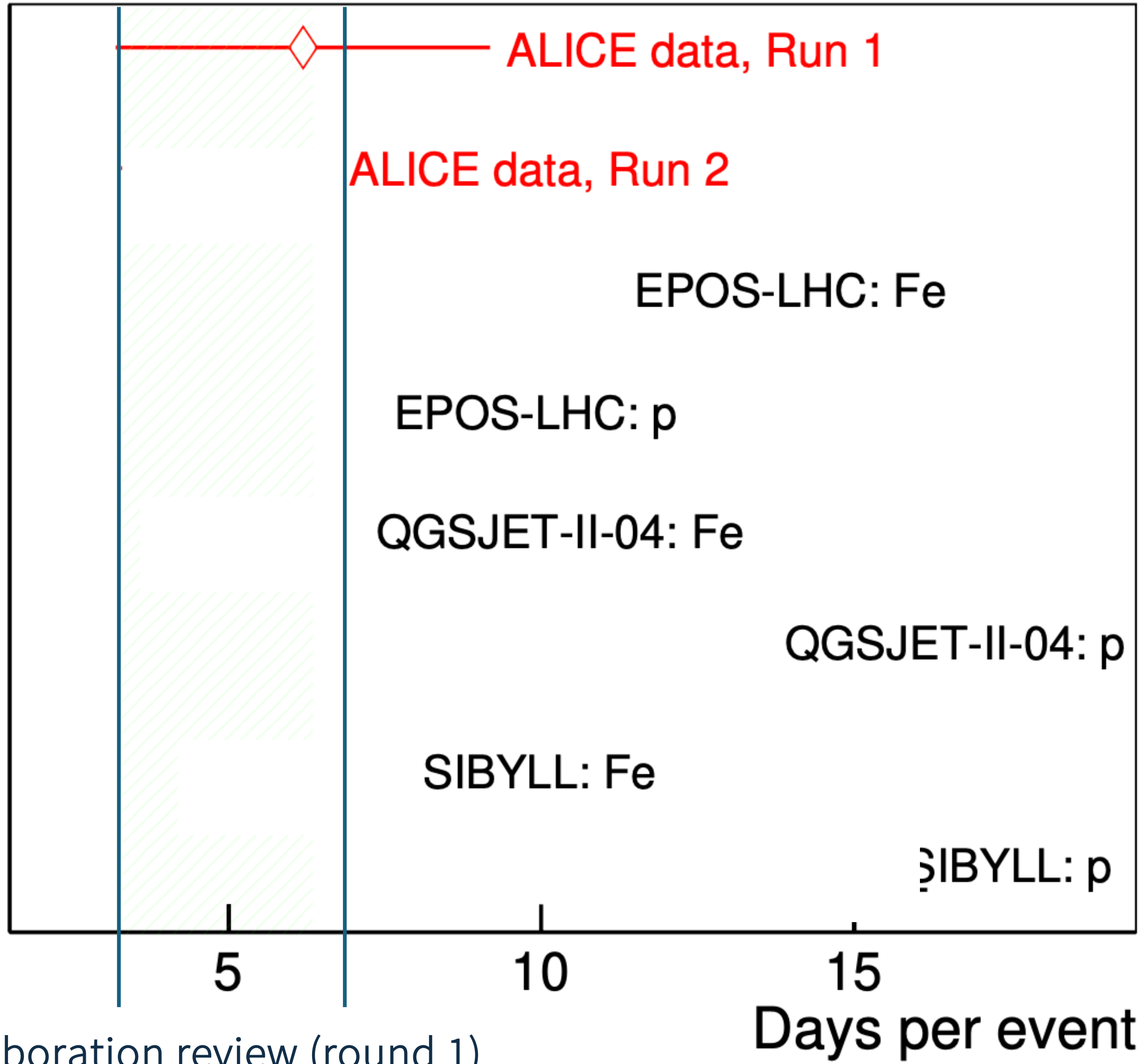
The paper is under collaboration review (round 1)

A comparison with the predictions given by EPOS-LHC, SIBYLL and QGSJET-II-04 was done with the new ALICE data





The paper is under collaboration review (round 1)

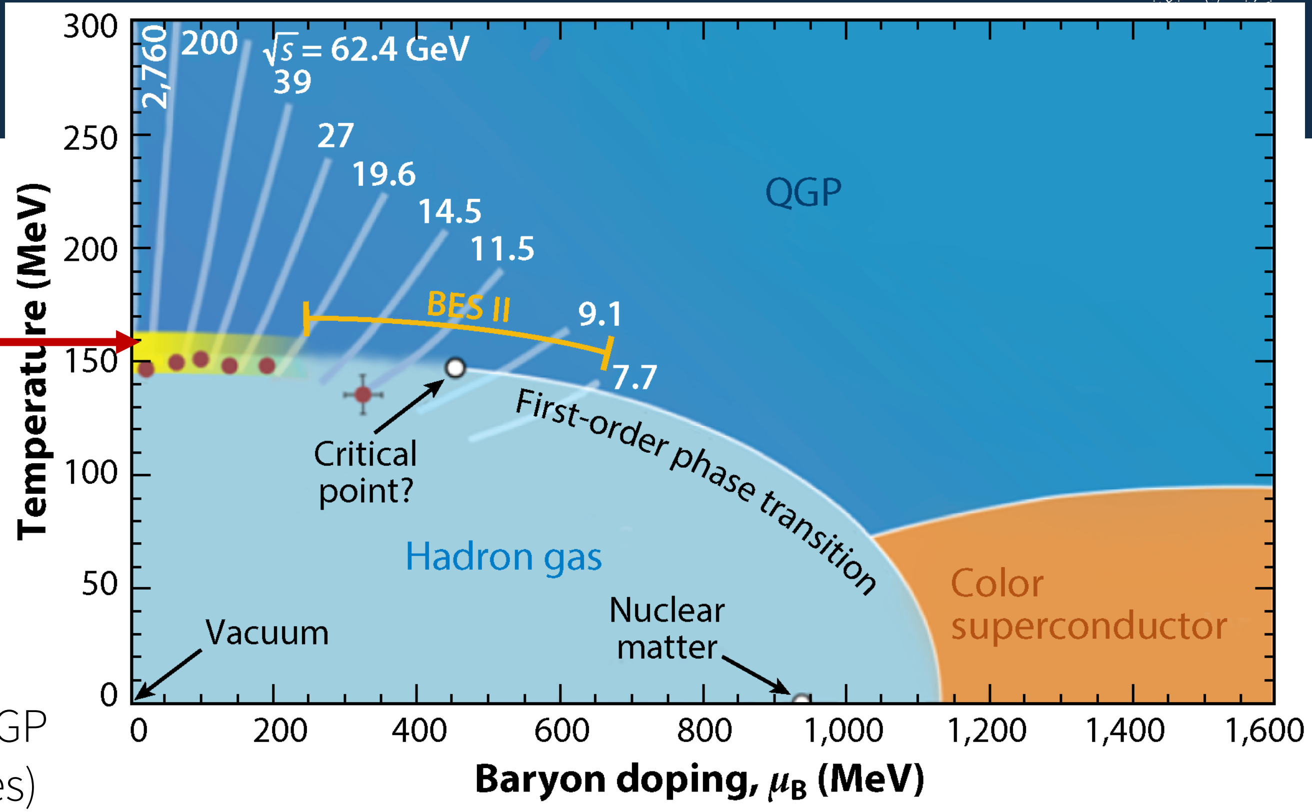


The paper is under collaboration review (round 1)

ALICE3

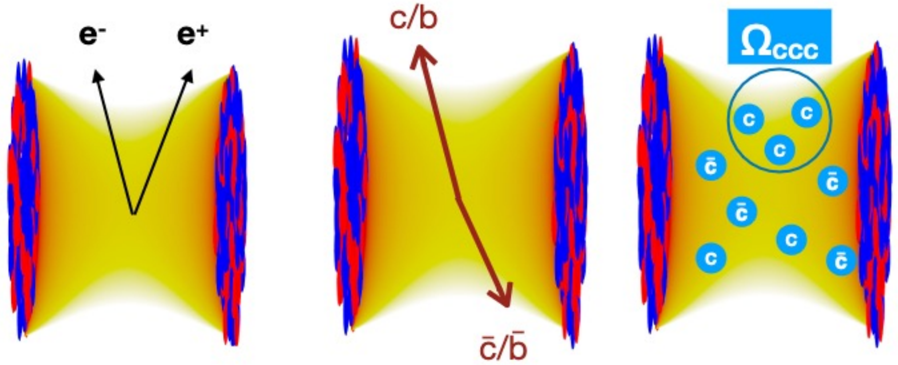
LHC conditions for heavy ions:

- High Temperature
- Low chemical potential
- Large heavy-flavor yields



Heavy ion physics at the LHC

- Precision measurements of dilepton spectra (QGP evolution) and heavy-flavour probes (transport properties)
- Charmed baryons and exotic states (transition from QPG to hadrons)
- Systematic measurements of different collision sytems (collectivity in small systems)
- High-multiplicity pp collisions and intermediate systems (pO, OO) → onset of collective behaviour

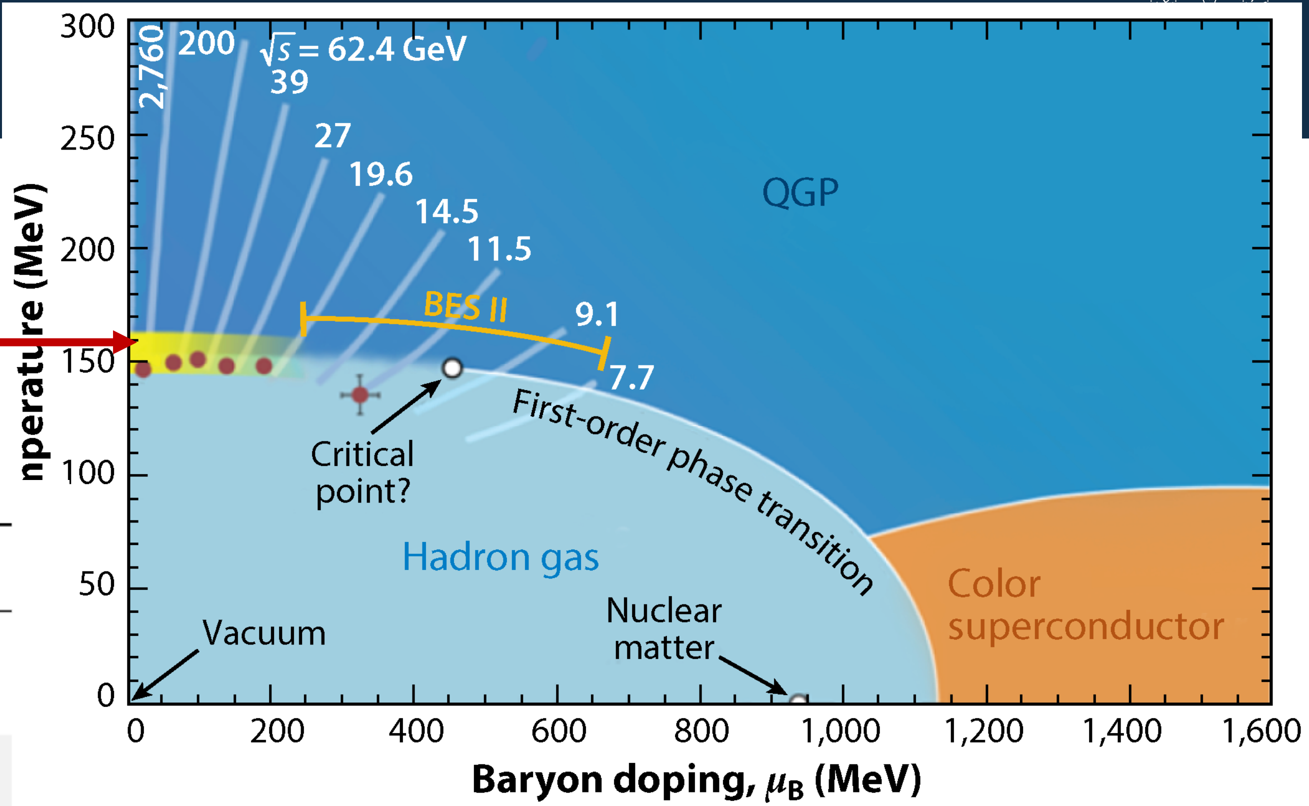


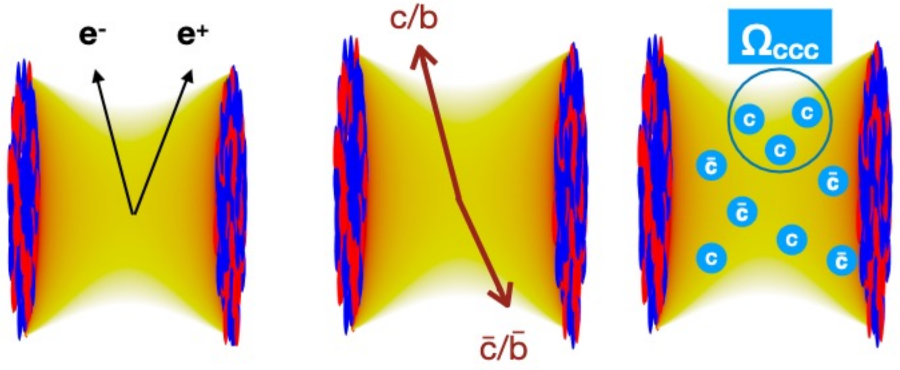
ALICE3

LHC conditions for heavy ions:

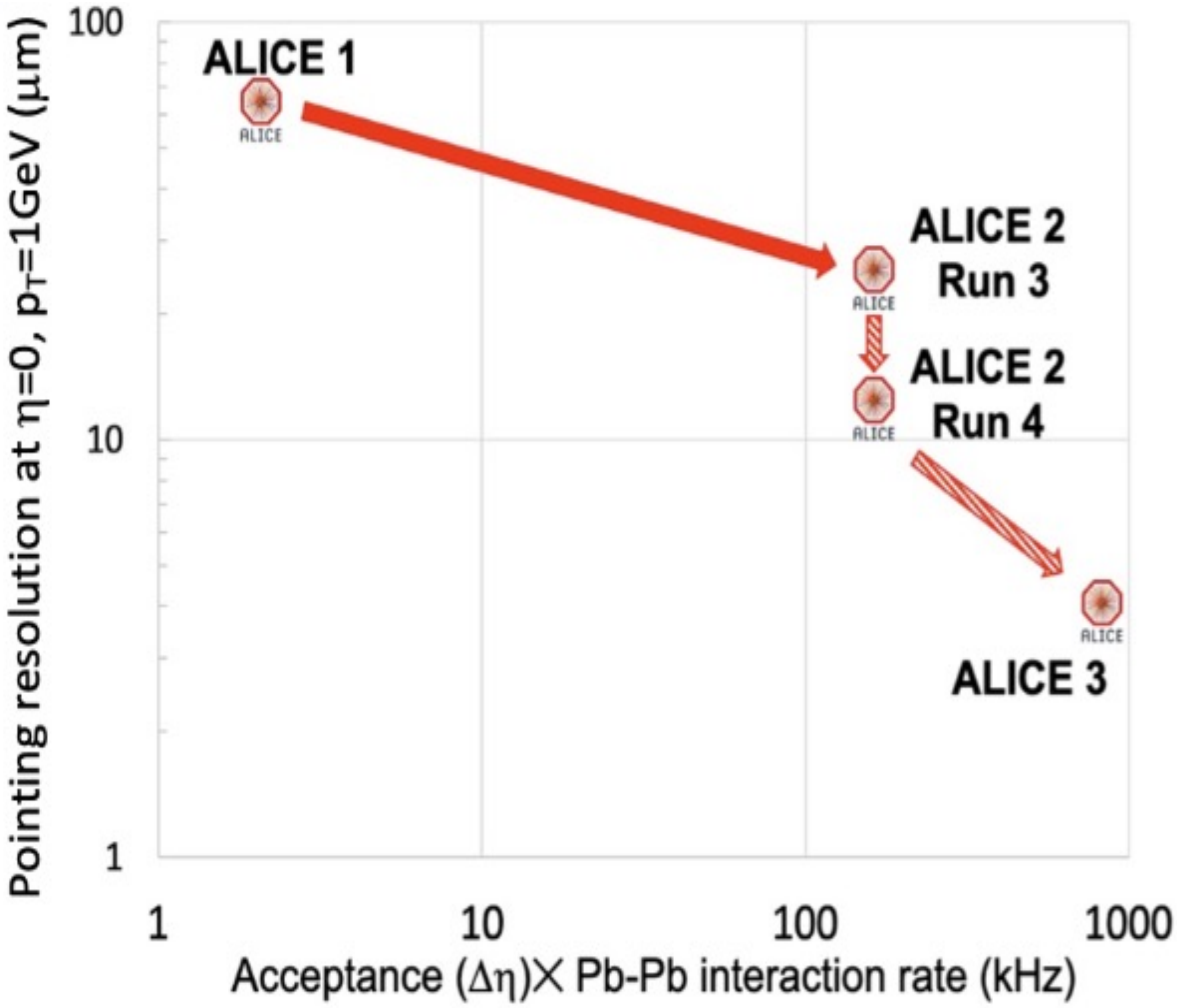
- High Temperature
- Low chemical potential
- Large heavy-flavor yields

Observables	**Kinematic range**
Heavy-flavour hadrons	$p_T \to 0$, $\lvert\eta\rvert < 4$
Dielectrons	$p_T \approx 0.05$ to $3\,\mathrm{GeV}/c$, $M_{ee} \approx 0.05$ to $4\,\mathrm{GeV}/c^2$
Photons	$p_T \approx 0.1$ to $50\,\mathrm{GeV}/c$, $-2 < \eta < 4$
Quarkonia and exotica	$p_T \to 0$, $\lvert\eta\rvert < 1.75$
Ultrasoft photons	$p_T \approx 1$ to $50\,\mathrm{MeV}/c$, $3 < \eta < 5$
Nuclei	$p_T \to 0$, $\lvert\eta\rvert < 4$

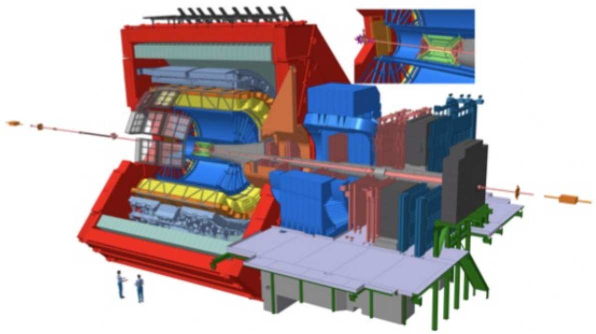




ALICE3

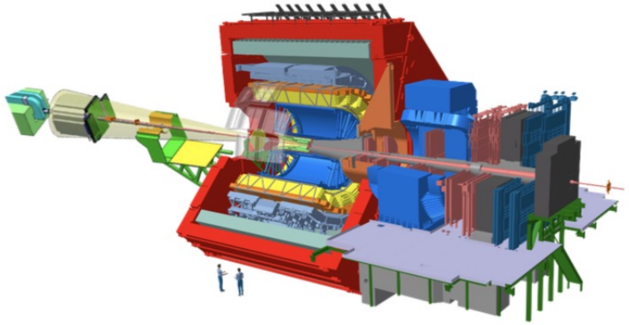


ALICE 1

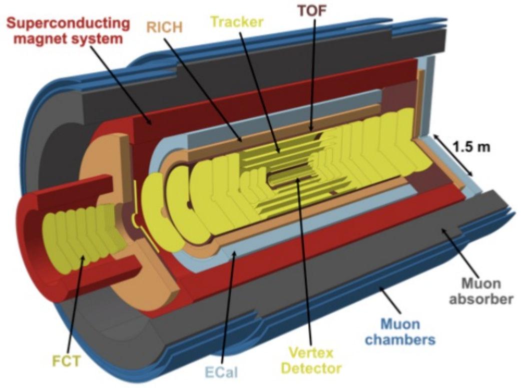


ALICE 2

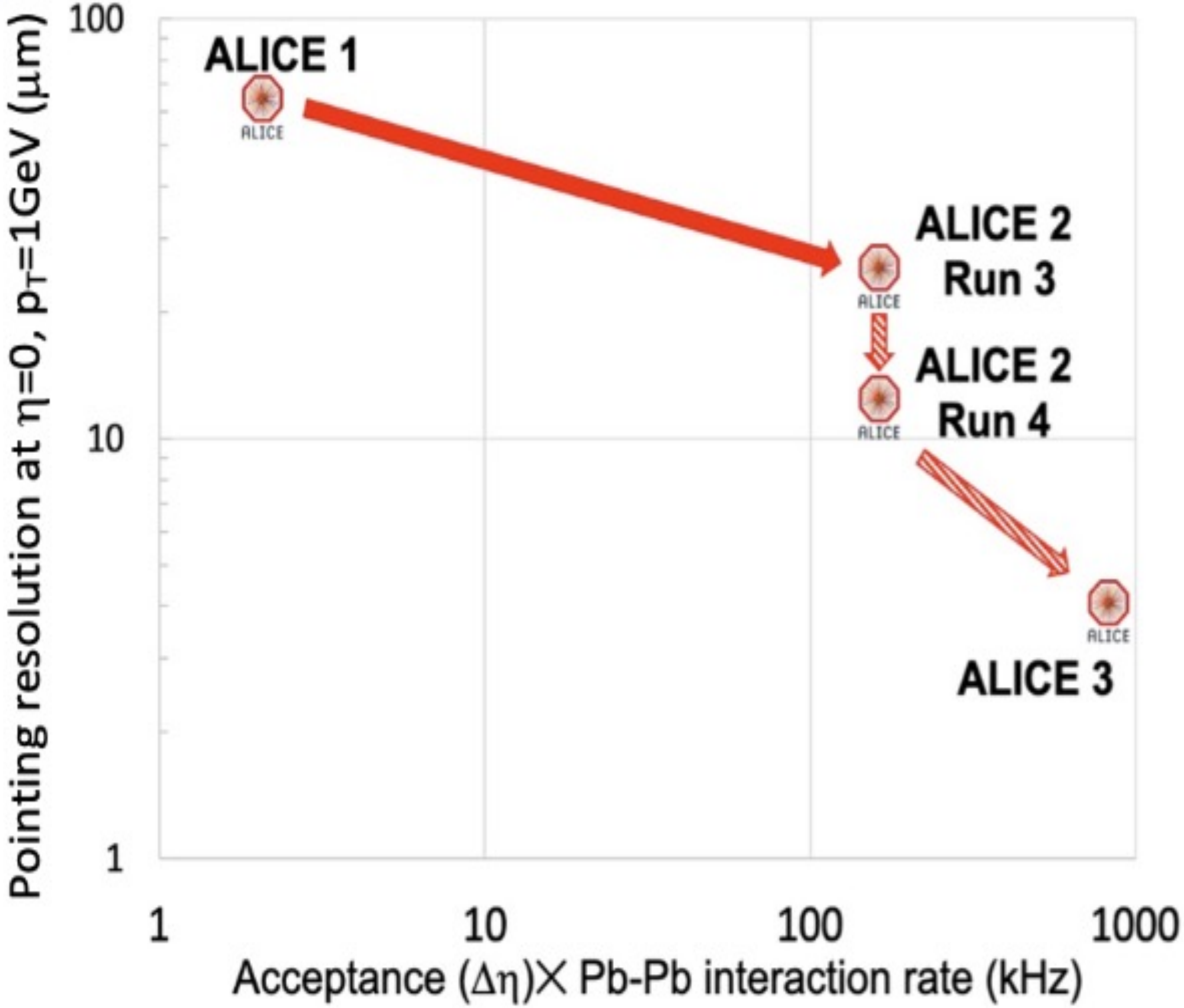
ALICE 2.1



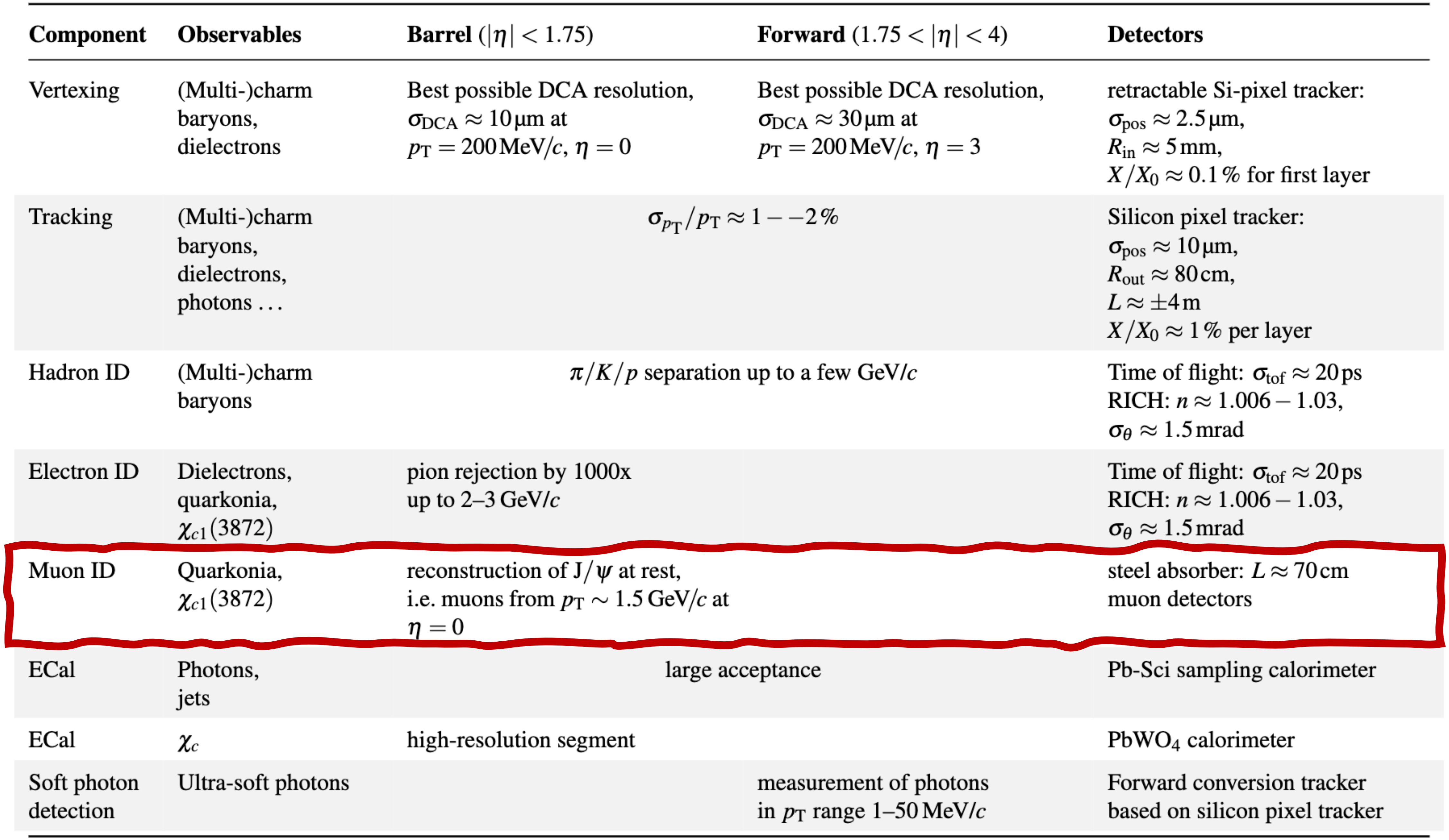
ALICE 3



ALICE3

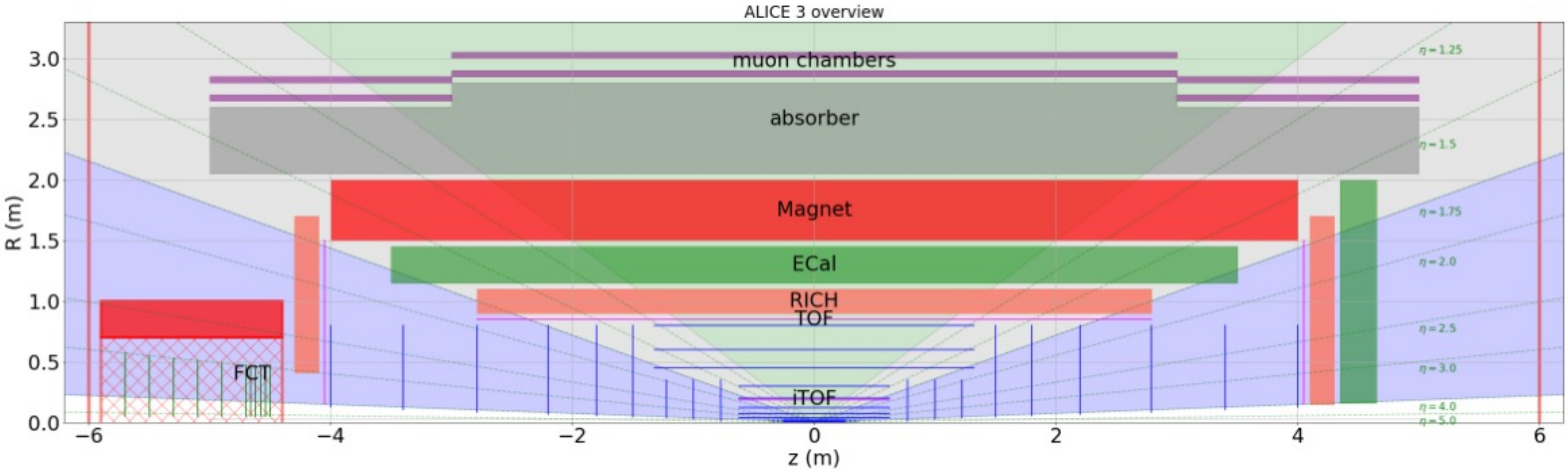


System	$\mathscr{L}^{\text{month}}$	$\mathscr{L}^{\text{Run5+6}}$
pp	$0.5\,\text{fb}^{-1}$	$18\,\text{fb}^{-1}$
pp reference	$100\,\text{pb}^{-1}$	$200\,\text{pb}^{-1}$
A–A		
Xe–Xe	$26\,\text{nb}^{-1}$	$156\,\text{nb}^{-1}$
Pb–Pb	$5.6\,\text{nb}^{-1}$	$33.6\,\text{nb}^{-1}$

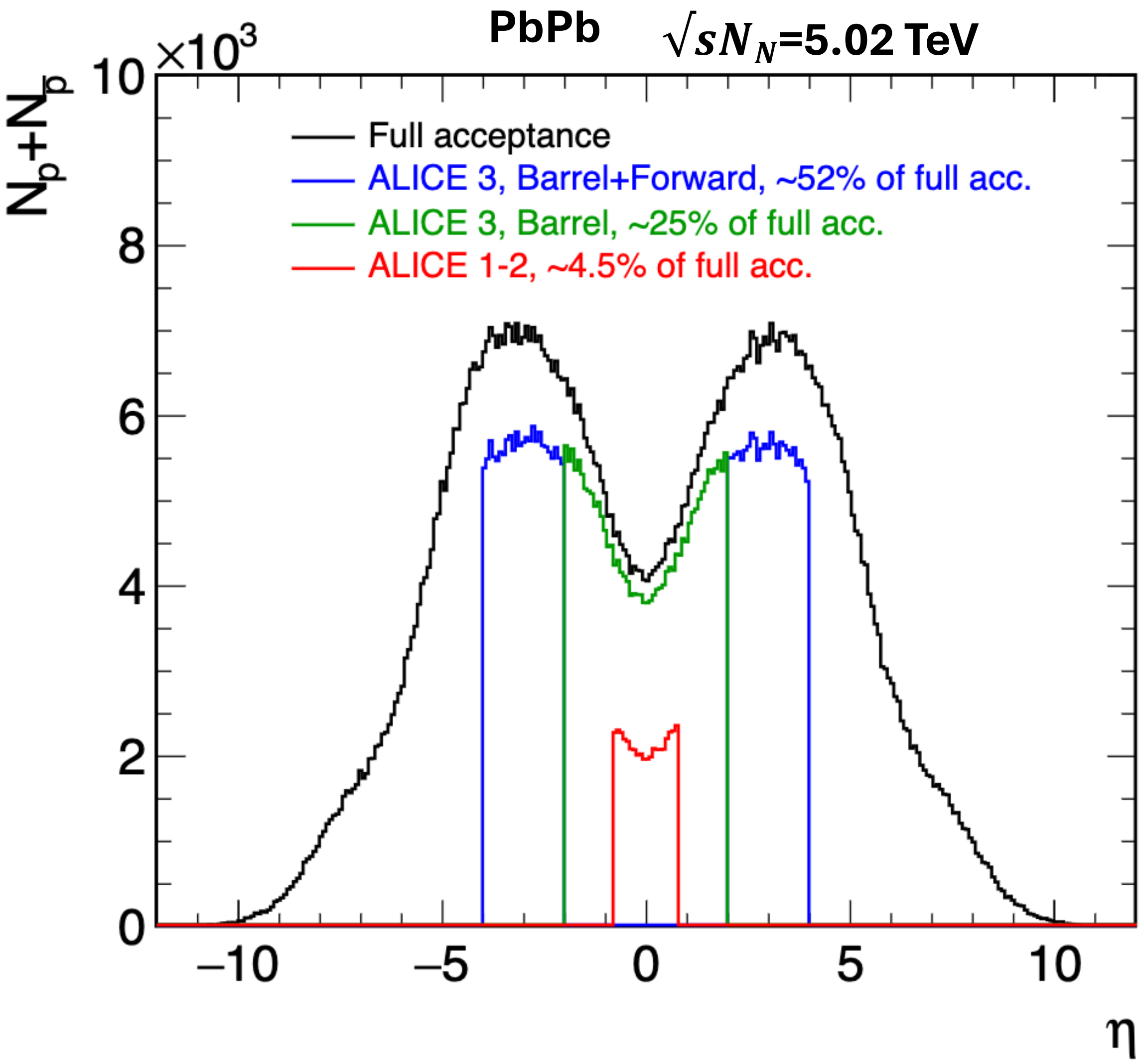


Component	Observables	Barrel ($\lvert\eta\rvert < 1.75$)	Forward ($1.75 < \lvert\eta\rvert < 4$)	Detectors
Vertexing	(Multi-)charm baryons, dielectrons	Best possible DCA resolution, $\sigma_{\mathrm{DCA}} \approx 10\,\mu\mathrm{m}$ at $p_{\mathrm{T}} = 200\,\mathrm{MeV}/c$, $\eta = 0$	Best possible DCA resolution, $\sigma_{\mathrm{DCA}} \approx 30\,\mu\mathrm{m}$ at $p_{\mathrm{T}} = 200\,\mathrm{MeV}/c$, $\eta = 3$	retractable Si-pixel tracker: $\sigma_{\mathrm{pos}} \approx 2.5\,\mu\mathrm{m}$, $R_{\mathrm{in}} \approx 5\,\mathrm{mm}$, $X/X_0 \approx 0.1\,\%$ for first layer
Tracking	(Multi-)charm baryons, dielectrons, photons ...	$\sigma_{p_{\mathrm{T}}}/p_{\mathrm{T}} \approx 1 - -2\,\%$		Silicon pixel tracker: $\sigma_{\mathrm{pos}} \approx 10\,\mu\mathrm{m}$, $R_{\mathrm{out}} \approx 80\,\mathrm{cm}$, $L \approx \pm 4\,\mathrm{m}$ $X/X_0 \approx 1\,\%$ per layer
Hadron ID	(Multi-)charm baryons	$\pi/K/p$ separation up to a few GeV/c		Time of flight: $\sigma_{\mathrm{tof}} \approx 20\,\mathrm{ps}$ RICH: $n \approx 1.006 - 1.03$, $\sigma_{\theta} \approx 1.5\,\mathrm{mrad}$
Electron ID	Dielectrons, quarkonia, $\chi_{c1}(3872)$	pion rejection by 1000x up to 2–3 GeV/c		Time of flight: $\sigma_{\mathrm{tof}} \approx 20\,\mathrm{ps}$ RICH: $n \approx 1.006 - 1.03$, $\sigma_{\theta} \approx 1.5\,\mathrm{mrad}$
Muon ID	Quarkonia, $\chi_{c1}(3872)$	reconstruction of J/ψ at rest, i.e. muons from $p_{\mathrm{T}} \sim 1.5\,\mathrm{GeV}/c$ at $\eta = 0$		steel absorber: $L \approx 70\,\mathrm{cm}$ muon detectors
ECal	Photons, jets	large acceptance		Pb-Sci sampling calorimeter
ECal	χ_c	high-resolution segment		$\mathrm{PbWO_4}$ calorimeter
Soft photon detection	Ultra-soft photons		measurement of photons in p_{T} range 1–50 MeV/c	Forward conversion tracker based on silicon pixel tracker

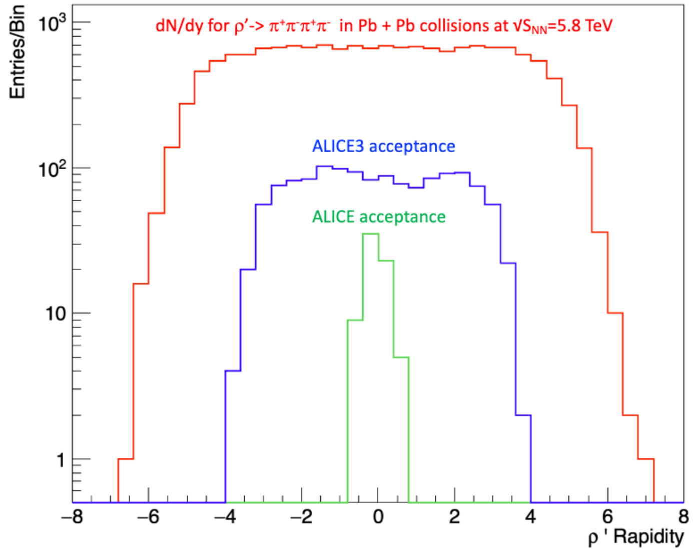
ALICE3

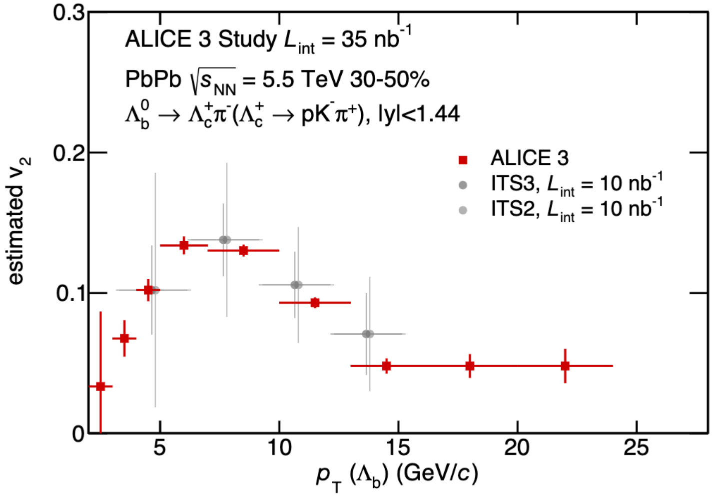

ALICE 3 overview
muon chambers
absorber
Magnet
ECal
RICH
TOF
iTOF
FCT
η=1.25
η=1.5
η=1.75
η=2.0
η=2.5
η=3.0
η=4.0
η=5.0
R (m)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−6
−4
−2
0
2
4
6
z (m)

ALICE3

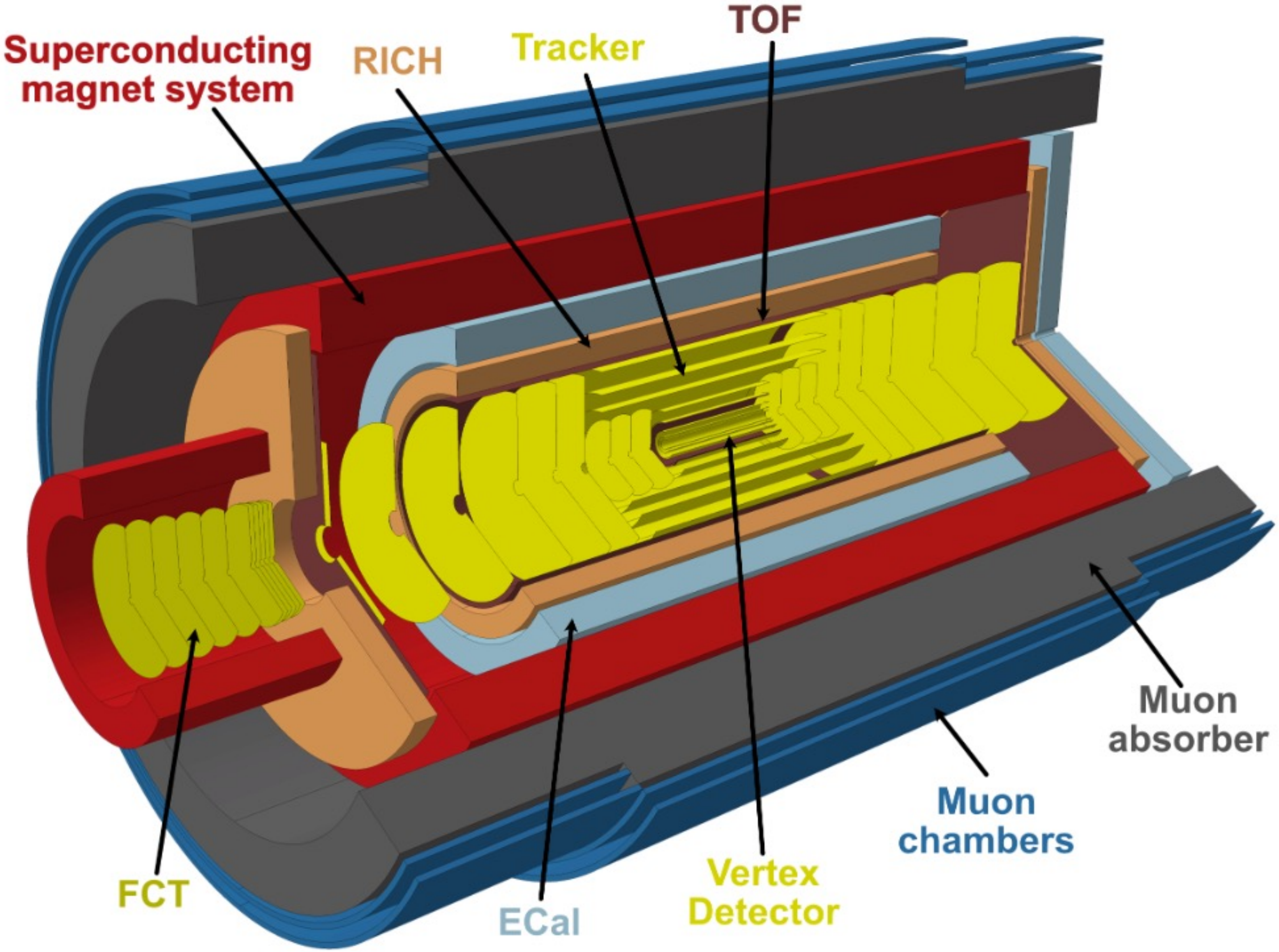


Ultra-peripheral (STARLIGHT) for $\rho' \rightarrow \pi^+\pi^-\pi^+\pi^-$

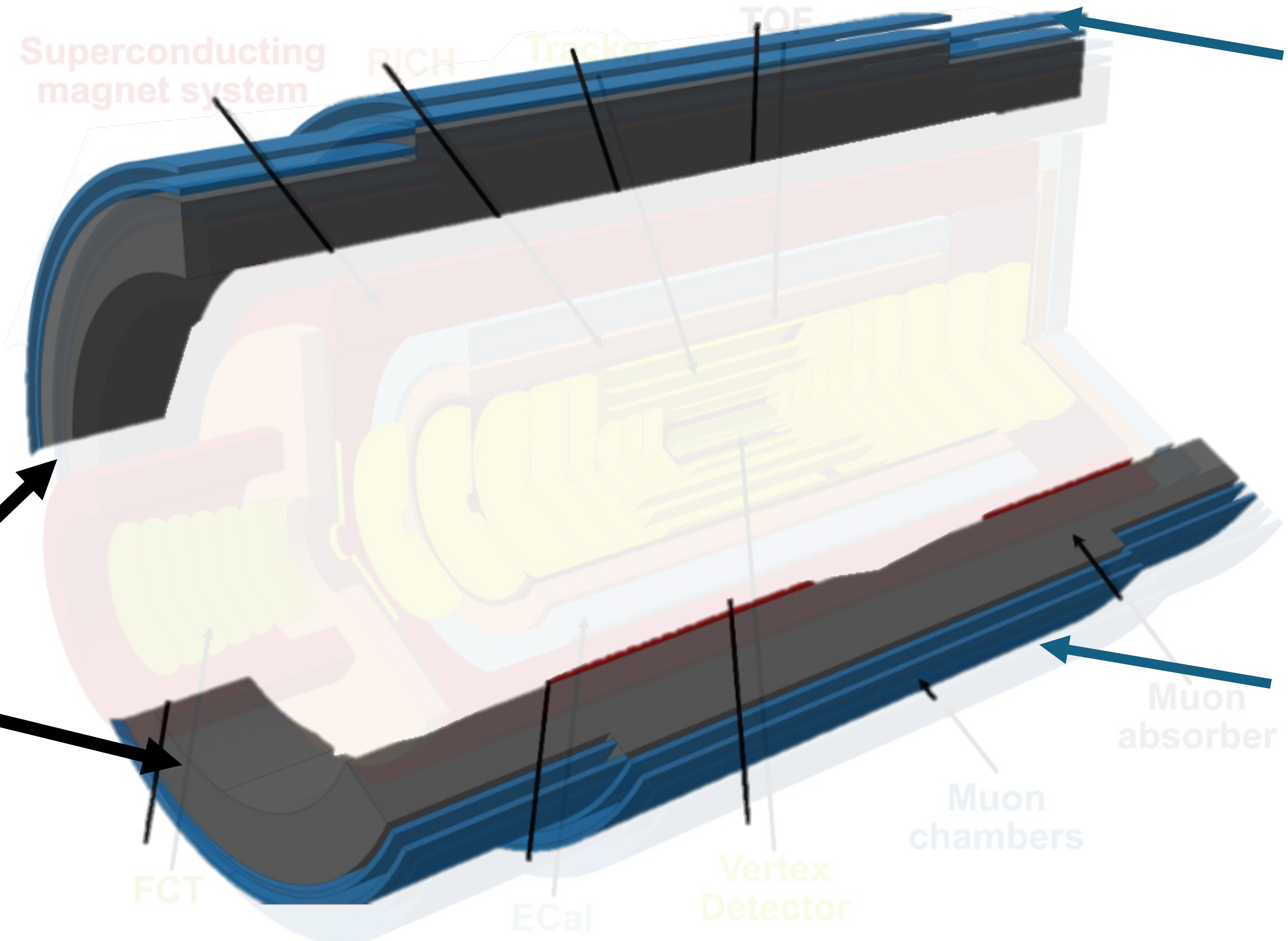




ALICE3 vs ALICE2


Superconducting magnet system
RICH
Tracker
TOF
Muon absorber
Muon chambers
Vertex Detector
ECal
FCT

MUON ID → MUON CHAMBERS + STEEL ABSORBER



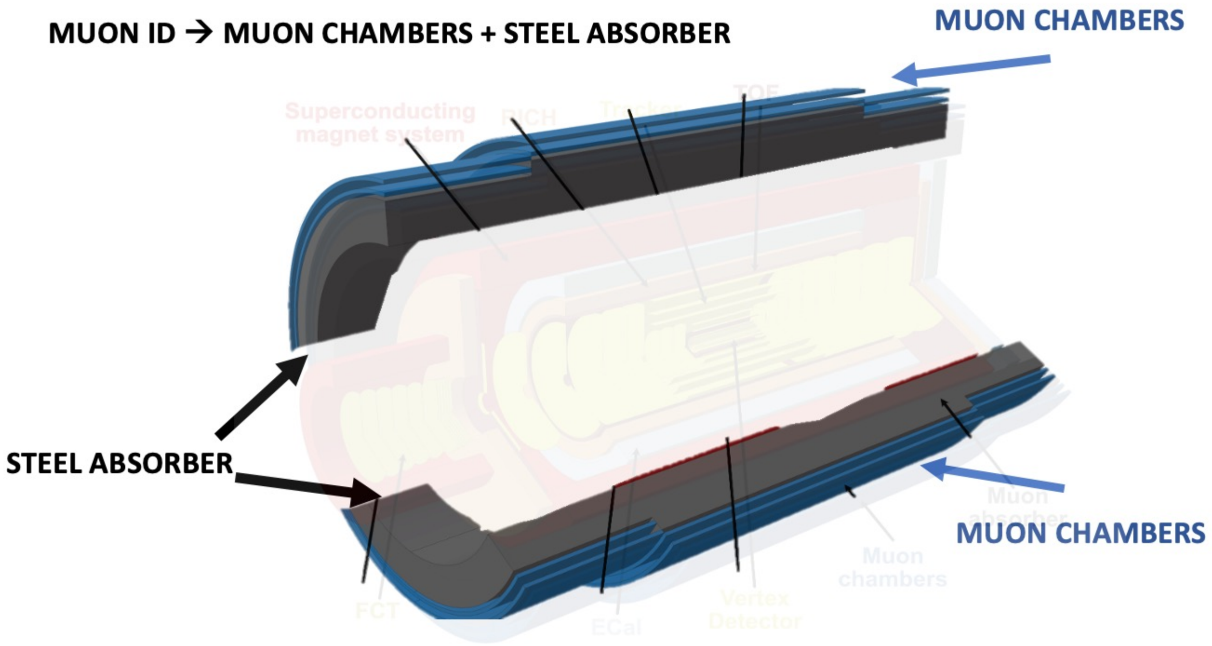
MUON CHAMBERS

STEEL ABSORBER

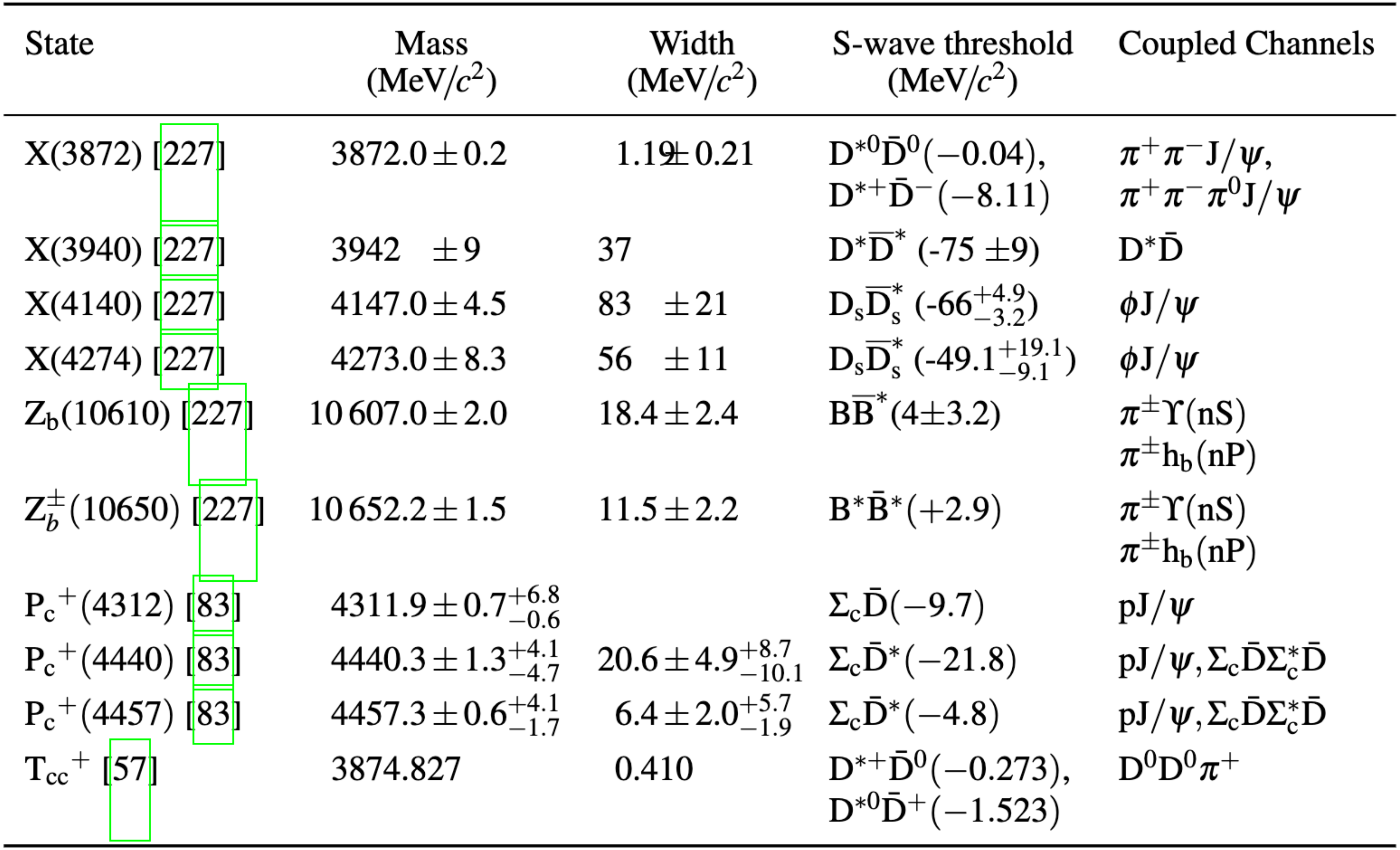
MUON CHAMBERS

MID DETECTOR

The goal of the muon identifier is the reconstruction of quarkonia (charmonia), down to pT = 0 in the muon channel, which complements the electron identification capabilities.

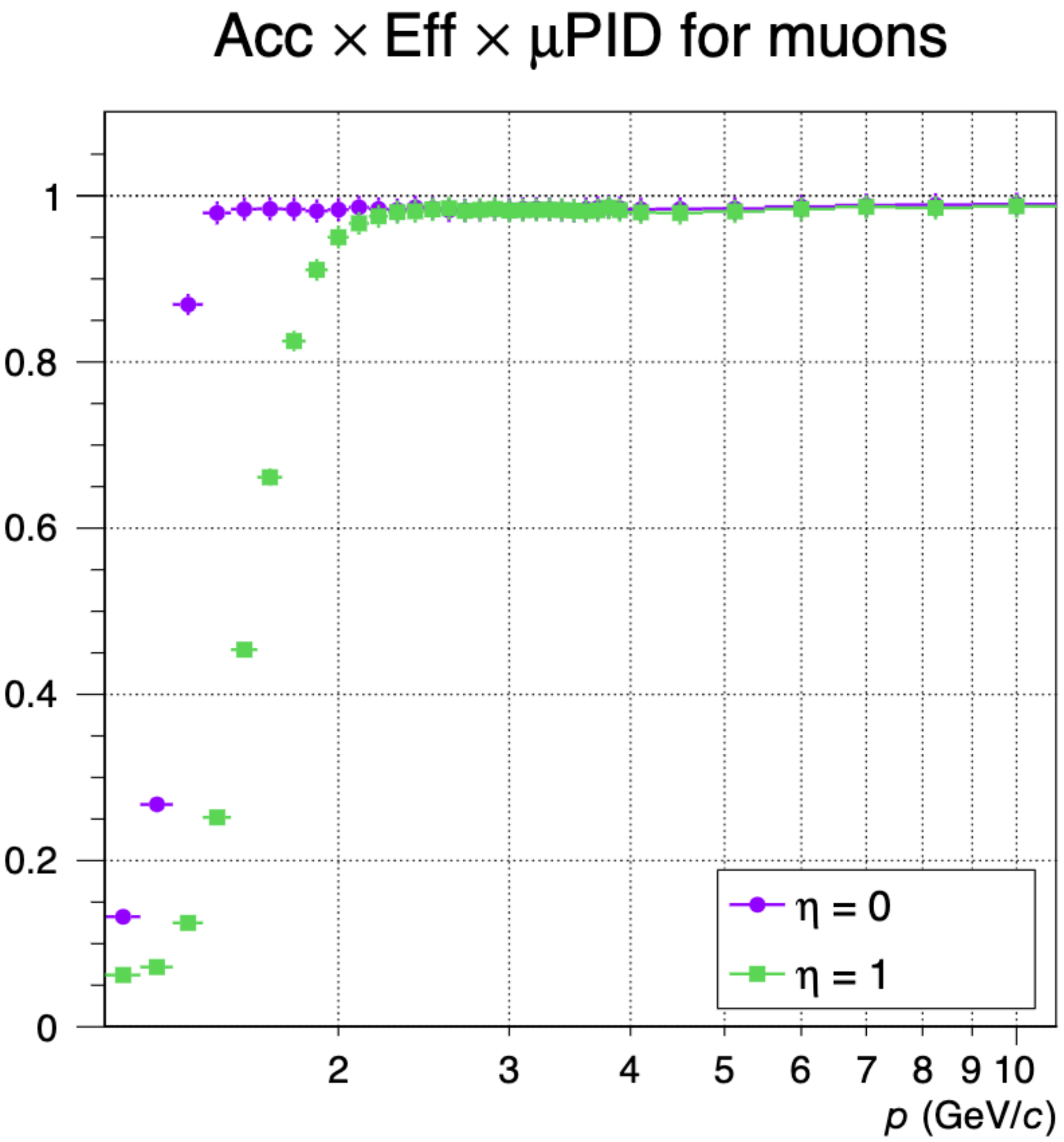


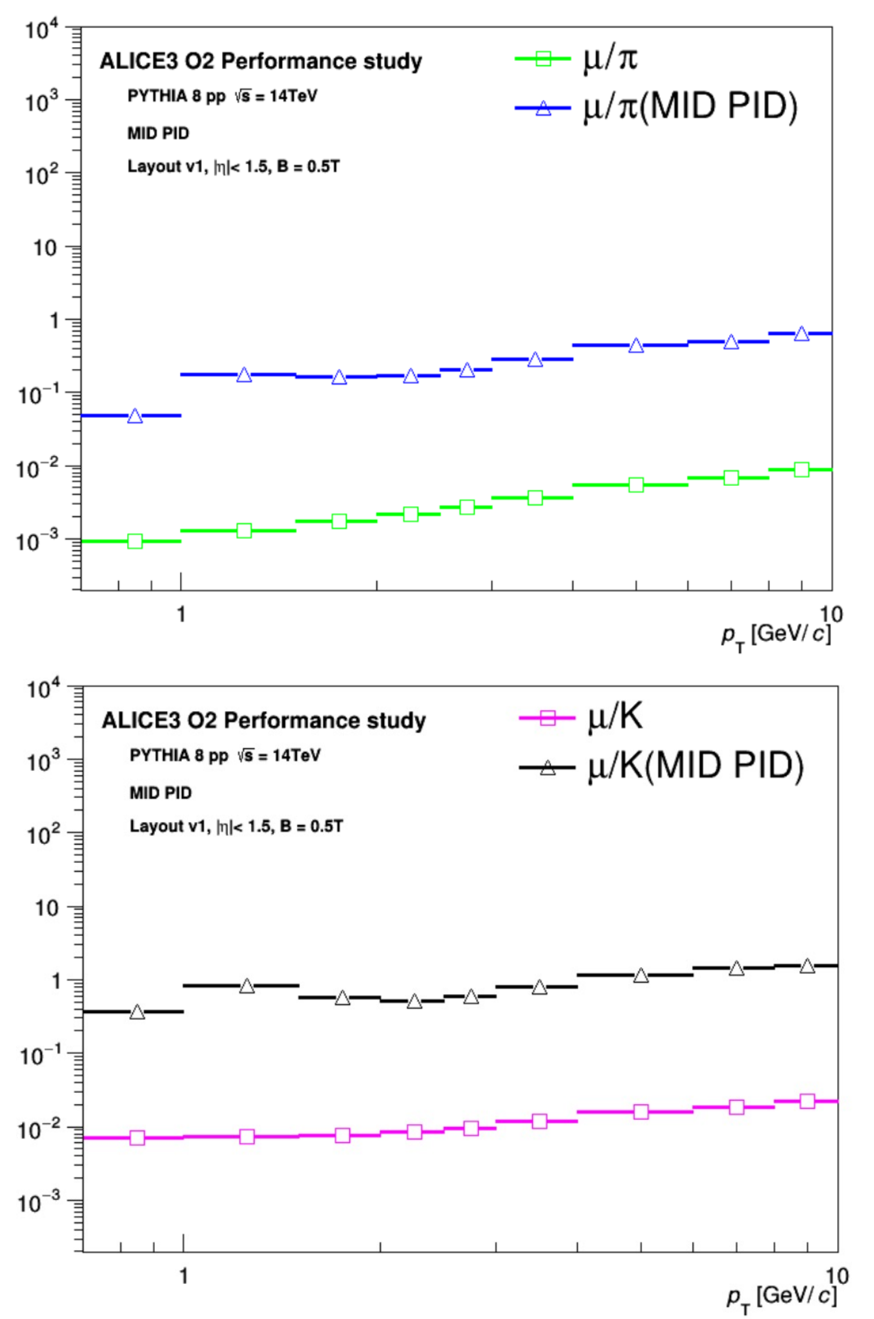
- MID will provide muon tagging for particles reconstructed in the tracker.
- It will be composed of chambers to track charged particles that pass through the hadron absorber of about 1kt.
- MID will ensure good efficiency for charmonia down to pT = 0 GeV/c → muons down to momenta of p ~ 1.5 GeV/c at $\eta \approx 0$
- Granularity of $\Delta\eta\Delta\phi = 0.02\times0.02$ for muon identification
- Two technologies *
    - RPC with a pad size between 50 mm and 60 mm → 40,000 channels.
    - To layers of plastic scintillator bars (5 cm wide with a 20 cm gap) equipped with wave-length shifting fibers + SiPM → 13,440 channels.



State	Mass (MeV/c^2)	Width (MeV/c^2)	S-wave threshold (MeV/c^2)	Coupled Channels
X(3872) [227]	3872.0 ± 0.2	1.19 ± 0.21	$D^{*0}\bar{D}^0(-0.04)$, $D^{*+}\bar{D}^-(-8.11)$	$\pi^+\pi^- J/\psi$, $\pi^+\pi^-\pi^0 J/\psi$
X(3940) [227]	$3942 \quad \pm 9$	37	$D^*\overline{D}^*$ (-75 ±9)	$D^*\bar{D}$
X(4140) [227]	4147.0 ± 4.5	$83 \quad \pm 21$	$D_s\overline{D}_s^*$ $(-66^{+4.9}_{-3.2})$	$\phi J/\psi$
X(4274) [227]	4273.0 ± 8.3	$56 \quad \pm 11$	$D_s\overline{D}_s^*$ $(-49.1^{+19.1}_{-9.1})$	$\phi J/\psi$
$Z_b(10610)$ [227]	$10\,607.0 \pm 2.0$	18.4 ± 2.4	$B\overline{B}^*(4 \pm 3.2)$	$\pi^\pm\Upsilon(nS)$ $\pi^\pm h_b(nP)$
$Z_b^\pm(10650)$ [227]	$10\,652.2 \pm 1.5$	11.5 ± 2.2	$B^*\bar{B}^*(+2.9)$	$\pi^\pm\Upsilon(nS)$ $\pi^\pm h_b(nP)$
$P_c{}^+(4312)$ [83]	$4311.9 \pm 0.7^{+6.8}_{-0.6}$		$\Sigma_c\bar{D}(-9.7)$	pJ/ψ
$P_c{}^+(4440)$ [83]	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	$\Sigma_c\bar{D}^*(-21.8)$	$pJ/\psi, \Sigma_c\bar{D}\Sigma_c^*\bar{D}$
$P_c{}^+(4457)$ [83]	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	$\Sigma_c\bar{D}^*(-4.8)$	$pJ/\psi, \Sigma_c\bar{D}\Sigma_c^*\bar{D}$
$T_{cc}{}^+$ [57]	3874.827	0.410	$D^{*+}\bar{D}^0(-0.273)$, $D^{*0}\bar{D}^+(-1.523)$	$D^0D^0\pi^+$

MID is found to be nearly 100 % efficient in identifying muons starting from pT ~ 1.5 GeV/c at **η** = 0





MID provides a pion and kaon rejection factors of 50–100

JINST

Published by IOP Publishing for Sissa Medialab

Received: *January 11, 2024*
Accepted: *February 16, 2024*
Published: *April 16, 2024*

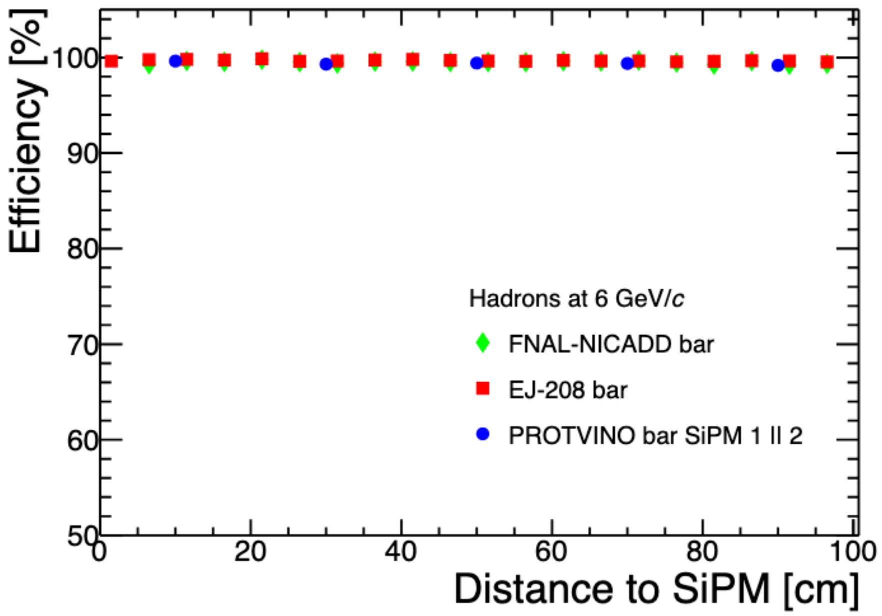
TECHNICAL REPORT

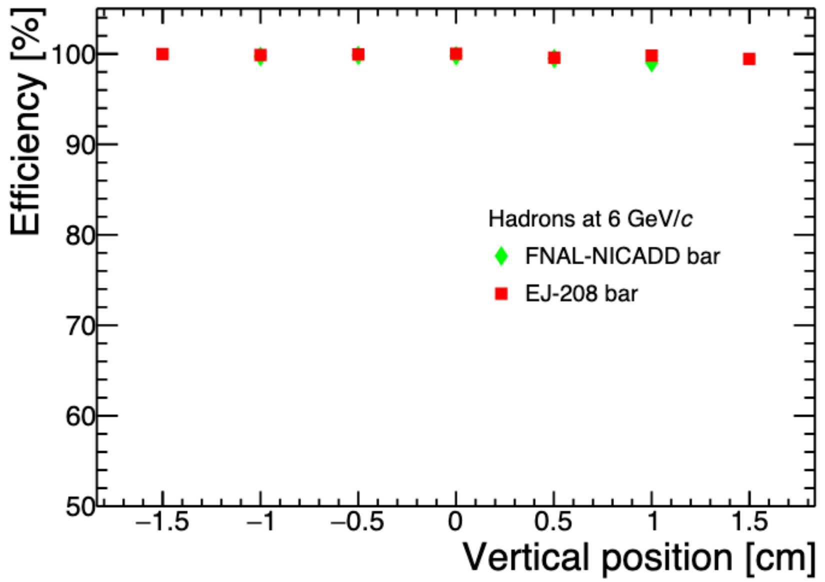
Characterisation of plastic scintillator paddles and lightweight MWPCs for the MID subsystem of ALICE 3

Ruben Alfaro,[a] **Mauricio Alvarado Hernández,**[b] **Gyula Bencédi**,[c]
Juan Carlos Cabanillas Noris,[d] **Marco Antonio Díaz Maldonado**,[b]
Carlos Duarte Galvan,[e] **Arturo Fernández Téllez**,[f] **Gergely Gábor Barnaföldi**,[c]
Ádám Gera,[c] **Varlen Grabsky**,[a] **Gergő Hamar**,[c] **Gerardo Herrera Corral,**[g]
Ildefonso León Monzón,[e] **Josué Martínez García,**[f] **Mario Iván Martínez Hernandez,**[f]
Jesús Eduardo Muñoz Méndez,[b] **Richárd Nagy**,[c] **Rafael Ángel Narcio Laveaga**,[d]
Antonio Ortiz,[b,*] **Mario Rodríguez-Cahuantzi**,[f] **Solangel Rojas Torres**,[h]
Timea Szollosova,[h] **Miguel Enrique Patiño Salazar,**[b] **Jared Pazarán García,**[b]
Hector David Regules Medel,[f] **Guillermo Tejeda Muñoz**,[f] **Paola Vargas Torres**,[b]
Dezső Varga,[c] **Róbert Vértesi**,[c] **Yael Antonio Vasquez Beltran**,[f]
Carlos Rafael Vázquez Villamar[b] **and Irandheny Yoval Pozos**[f]

[a]*Instituto de Física, Universidad Nacional Autónoma de México,*
Ciudad Universitaria, Mexico City, Mexico
[b]*Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México,*
Ciudad Universitaria, Mexico City, Mexico
[c]*HUN-REN Wigner Research Centre for Physics,*
Konkoly Thege Miklós 29–33, Budapest, Hungary
[d]*Instituto Tecnológico de Culiacán, Tecnológico Nacional de México,*
Juan de Dios Bátiz, Culiacán, Mexico
[e]*Universidad Autónoma de Sinaloa,*
Universitarios Oriente, Culiacán, Mexico
[f]*Facultad de Ciencias Físico Matemáticas, Benemérita Universidad Autónoma de Puebla,*
Av San Claudio, Puebla, Mexico
[g]*Centro de Investigación y Estudios Avanzados del IPN,*
Av Instituto Politécnico Nacional, Mexico City, Mexico
[h]*Czech Technical University in Prague,*
Brehova 7, Prague, Czech Republic

2024 JINST 19 T04006





Final comments

Locally correlated strangeness production in pp collisions overestimated by string breaking models and underestimated by models with thermalised medium

The ratios of strange particle yields to pions in Pb-Pb collisions at 5.02 TeV follow the same continuous trend observed before starting from low-multiplicity pp at s = 7 TeV up to central Pb-Pb collisions at 2.76 TeV

Hadron yields depend only on the multiplicity, while the average pT of the formed hadrons is affected by the hadronizing environment

Elliptic flow studies support the collective evolution in small systems

ALICE collected 62.5 days of data taking → comparison on muon multiplicity distribution with SIBYLL, EPOS-LHC and QGSJET-II-04 is finished. To be send to JCAP soon.

ALICE