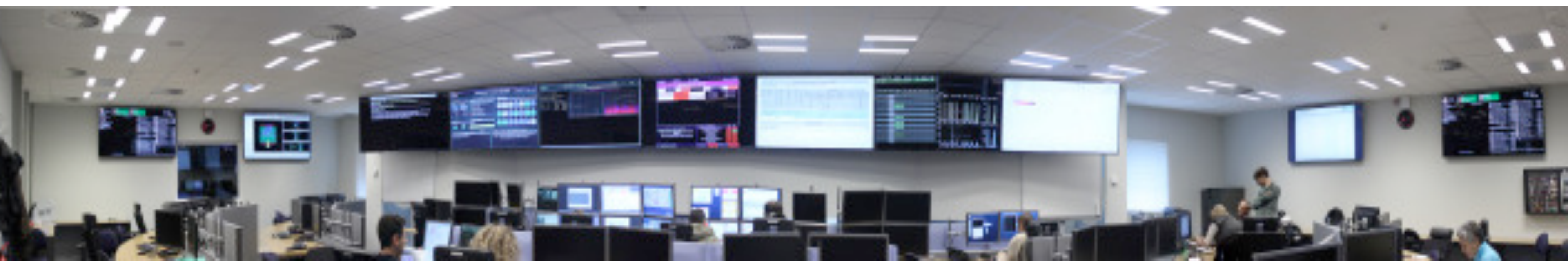
SOME HIGHLIGHTS OF RESEARCH ON HEAVY ION COLLISIONS BY ALICE AT LHC



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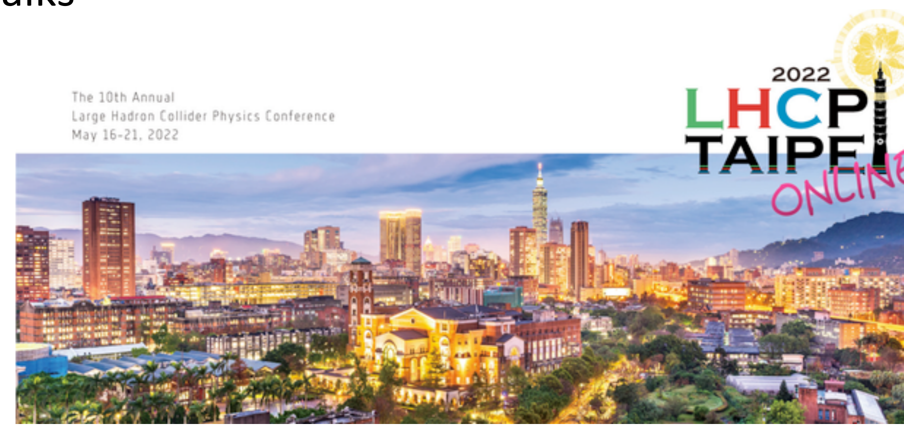
LXXII International Conference "NUCLEUS–2022: Fundamental problems and applications"
Moscow, Russia, 2022-07-11 - 2022-07-16

A wealth of ALICE results at major conferences in spring/summer 2022:

Quark Matter 2022 conference (4-10 April 2022):
- 1 plenary talk
- 35 parallel talks
- 84 posters



Large Hadron Collider Physics conference (16-21 May 2022):
- 6 plenary talks
- 17 parallel talks
- 10 posters

SQM 2022
The 20th International Conference on Strangeness in Quark Matter
13-17 June 2022 Busan, Republic of Korea

SQM 2022 conference (13-17 June 2022):
2 plenary, 26 parallel, 9 posters

ICHEP 2022 conference (06-13 July 2022):
1 plenary, 39 parallel, 13 posters

Layout of this talk

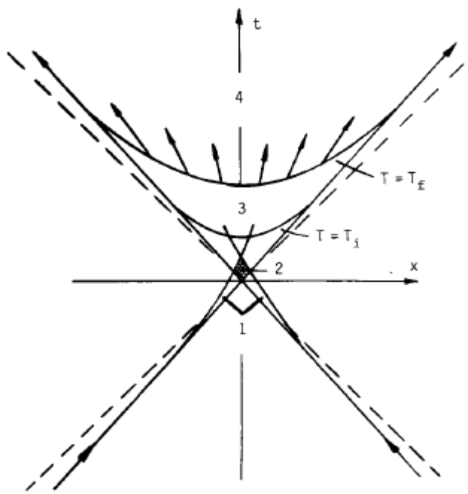
- Introduction.
- QGP and formation of light (anti) (hyper) nuclei
- Jets in QGP medium
- Strangeness and charm in collisions of large and small systems
    - Strangeness in pp collisions at midrapidity
    - Charm in pp, p-Pb and Pb-Pb collisions
    - Two-body scattering involving *strange* and *charm* hyperons
- Flow of identified particles in small systems
- ALICE @LHC Schedule

”Relativistic heavy ion physics“- why ?: a bit of history

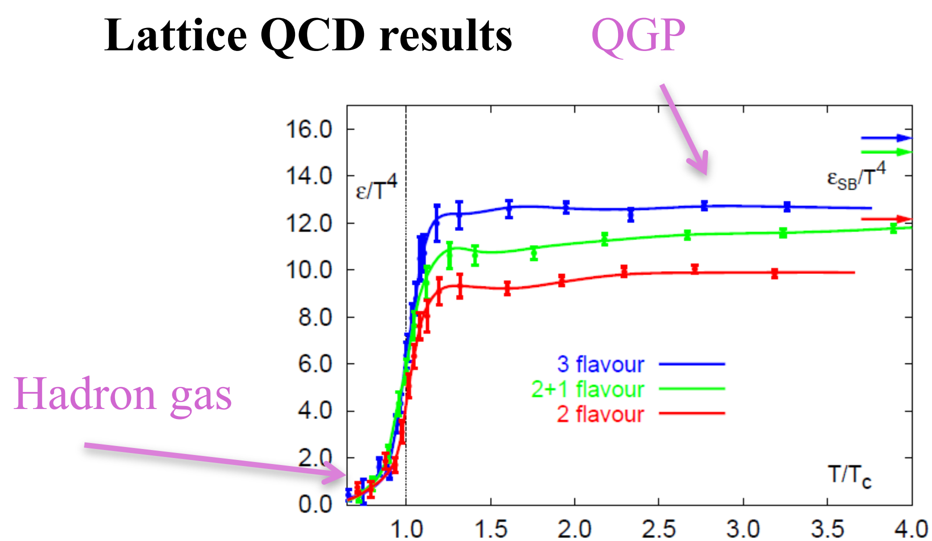
Cabibbo, N. & Parisi, G. , Exponential hadronic spectrum and quark liberation. Phys. Lett. B 59, 67–69 (1975).

Collins, J. C. & Perry, M. J. Superdense matter: neutrons or asymptotically free quarks? Phys. Rev. Lett.34, 1353–1356 (1975).

E.V.Shuryak, Quark-gluon plasma and hadronic production of leptons, photons and psions, Phys. Lett. *B78* (*1978*) *150.*



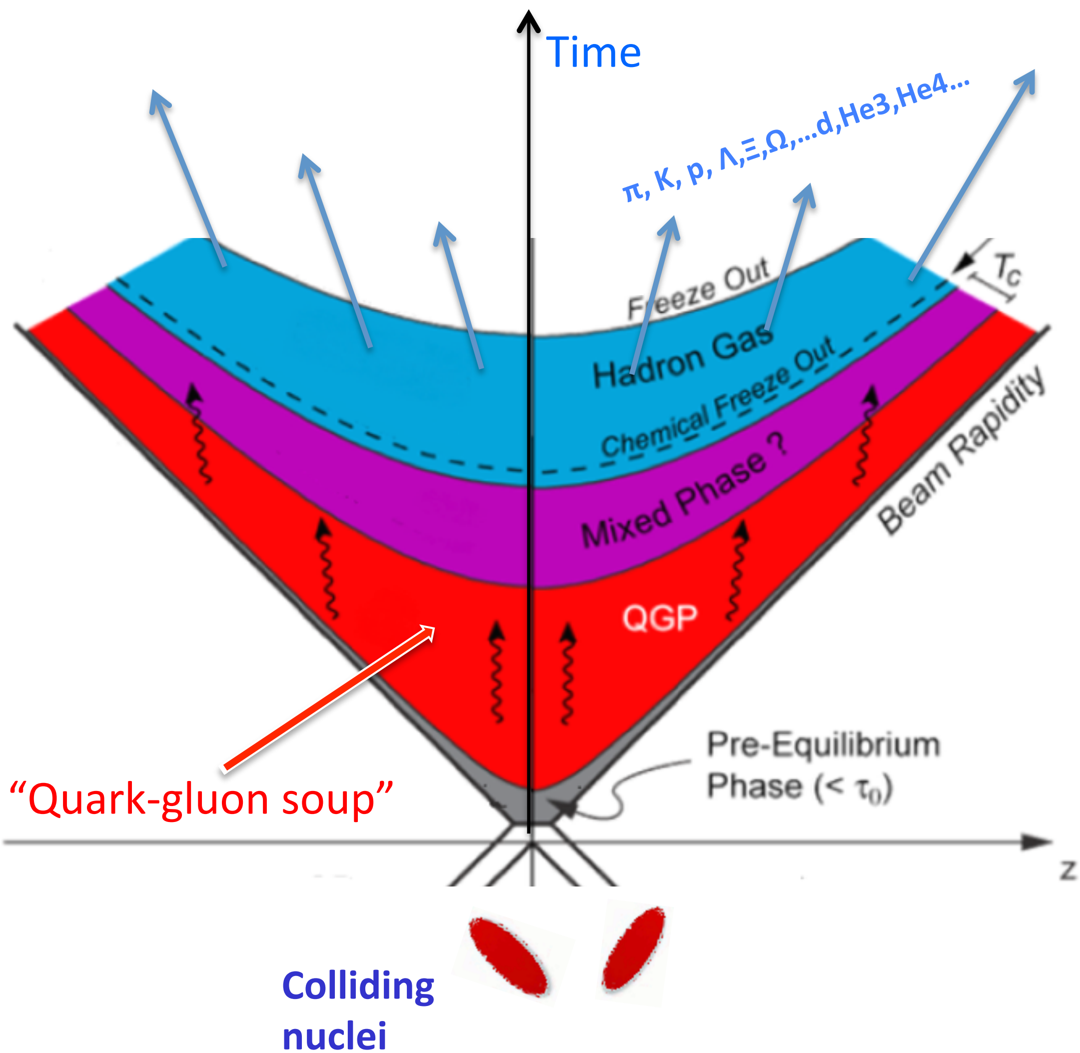
E.V.Shuryak, Phys. Lett. *B78* (*1978*) *150*



F. Karsch, Lect. Notes Phys. 583 (2002) 209

➢ *Early expectations: QGP* like an ideal gas of quarks and gluons

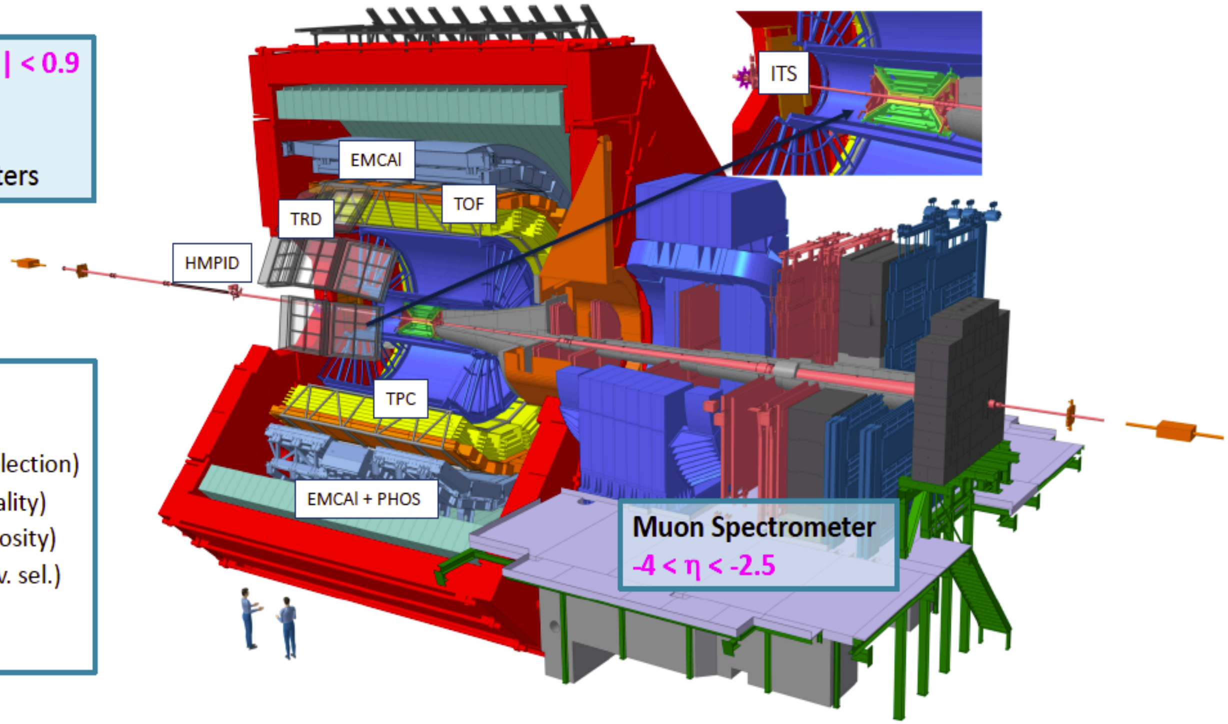
Space-time stages of nucleus-nucleus collision



- ➢ Pre-equilibrium phase
  $\tau_{eq} < 0.5$ fm/c
- ➢ QGP medium
  - Almost perfect liquid: $\eta/s \sim 0.1$
  - Temperature: ~300 MeV from the photon spectrum inverse slope
  - Large volume: ~5000 fm^3
  - Mean life time: $\tau \sim 10$ fm/c
  - Energy density (in central Pb-Pb collisions at 5.02 TeV): ≈20 GeV/fm^3 ($\gg \varepsilon_{crit} \approx 1$ GeV/fm^3)
- ➢ Mixed phase
- ➢ Chemical freeze-out:
  particle composition is fixed at $T_{ch} \sim 155$ MeV
- ➢ Thermal freeze-out:
  particle p_T spectra are fixed at $T_{tfo} \sim 100$ MeV

ALICE in Run 1 and Run 2

Central Barrel $|\eta| < 0.9$
- Tracking
- PID
- EM-Calorimeters



ACORDE (cosmics)

Forward detectors:
- AD (diffraction selection)
- V0 (trigger, centrality)
- V0 (timing, luminosity)
- ZDC (centrality, ev. sel.)
- FMD (N_{ch})
- PMD ($N\gamma$, Nch)

- ALICE is optimized for Heavy-Ion Physics - excellent tracking of low momenta particles
- Efficient registration of the hadrons, electrons, muons, and photons. produced in pp, p-Pb and Pb-Pb collisions at the LHC.

ALICE data in Runs 1,2 in 2=09-2018

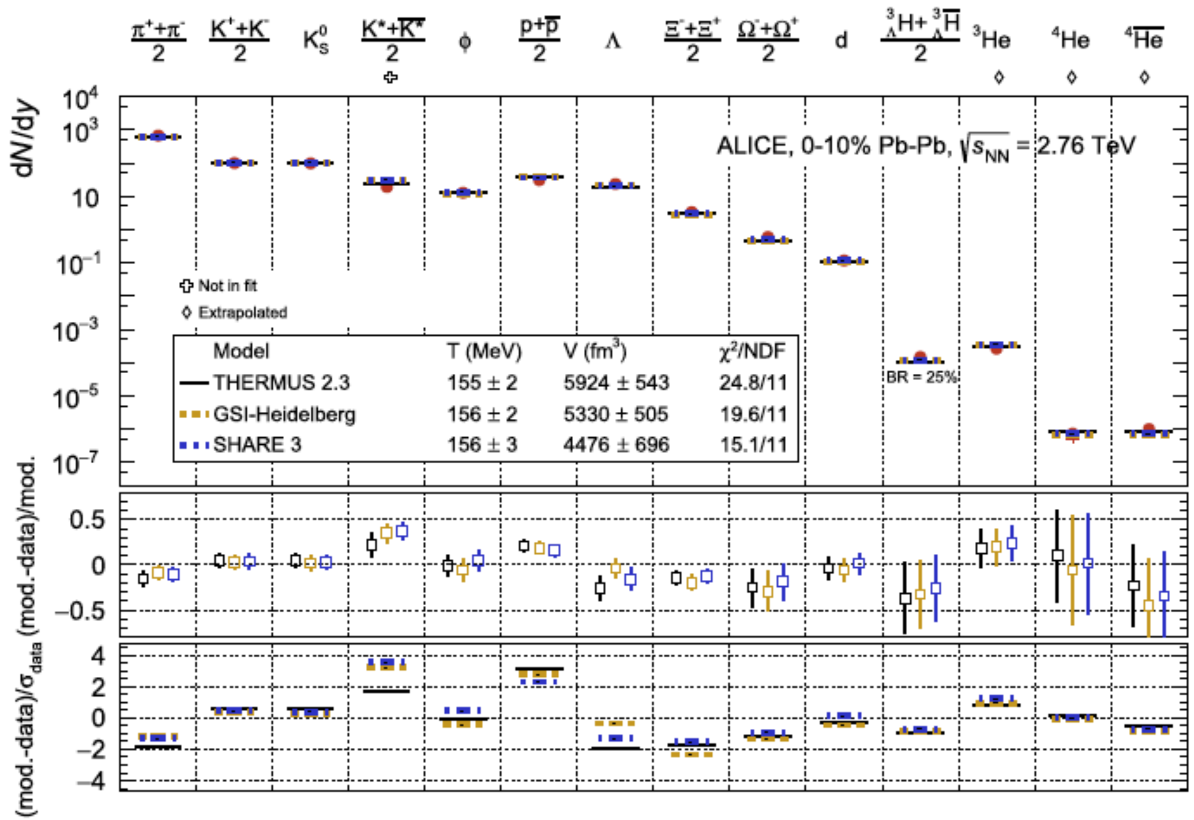
System	Year(s)	$\sqrt{s_{NN}}$ (TeV)	L_{int}
Pb-Pb	2010, 2011 2015, 2018	2.76 5.02	~75 μb^{-1} ~800 μb^{-1}
Xe-Xe	2017	5.44	~0.3 μb^{-1}
p-Pb	2013 2016	5.02 5.02, 8.16	~15 nb^{-1} ~3 nb^{-1}, ~25 nb^{-1}
pp	2009-2013 2015, 2017 2015-2018	0.9, 2.76, 7, 8 5.02 13	~200 mb^{-1}, ~100 nb^{-1} ~1.5 pb^{-1},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

Run 1 Run 2

- **ALICE Collaboration: 40 countries, 173 institutes, 2027 members**
  Publications: total > 390

✓ QGP and formation of light (anti) (hyper) nuclei

Formation of light (anti) (hyper) nuclei in central Pb-Pb collision at $\sqrt{s_{NN}}$=2.76 TeV



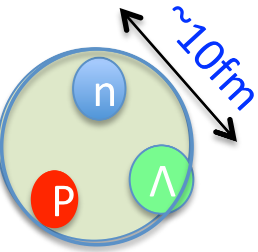
Pb–Pb collisions

- $^4\overline{He}$ is the heaviest antinucleus observed
- What is the mechanism of light (anti)nuclei and (anti)hypernuclei production in hadron collisions?
- Statistical hadronisation model (SHM)[2] vs. Coalescence?

Thermal-model fits to the p_T-integrated yields of many hadron species measured in ALICE[1]

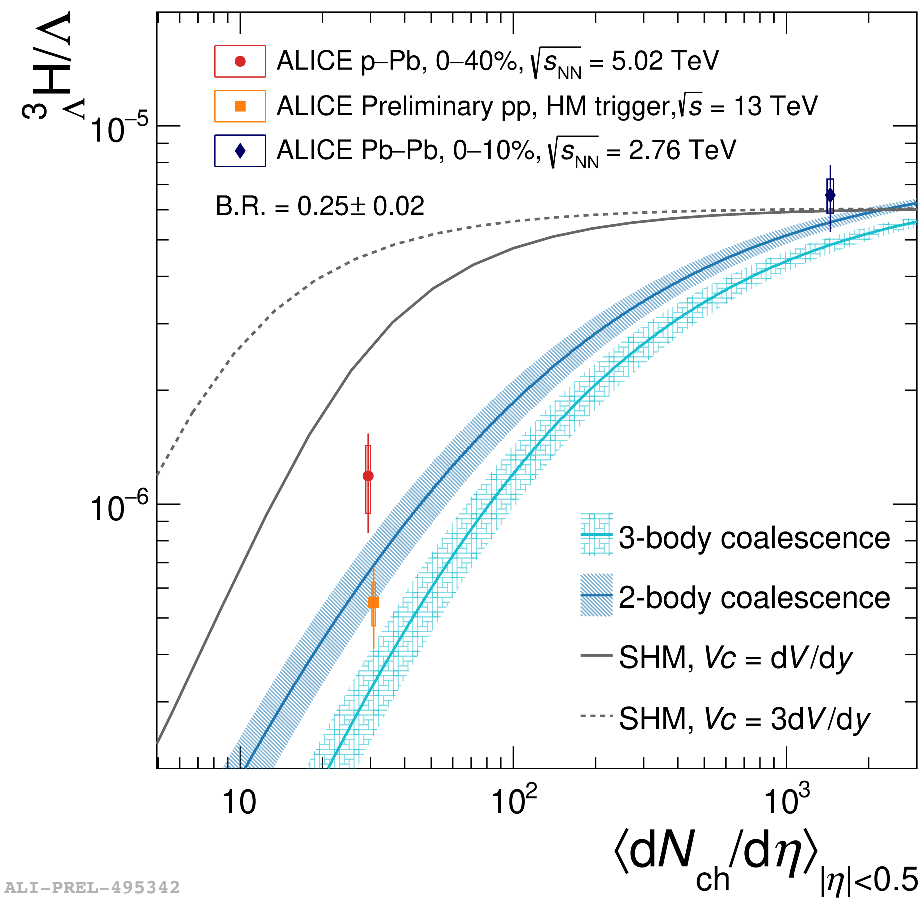
[1] ALICE Collab., Nucl. Phys. A 971 1 (2018) 1-20
[2] NATURE, (2 0 1 8) vol. 561, 321-325

Formation of light (anti) (hyper) nuclei in pp, p--Pb and Pb--Pb collisions: hypertriton



pp, p-Pb and Pb–Pb collisions

arXiv:2107.10627



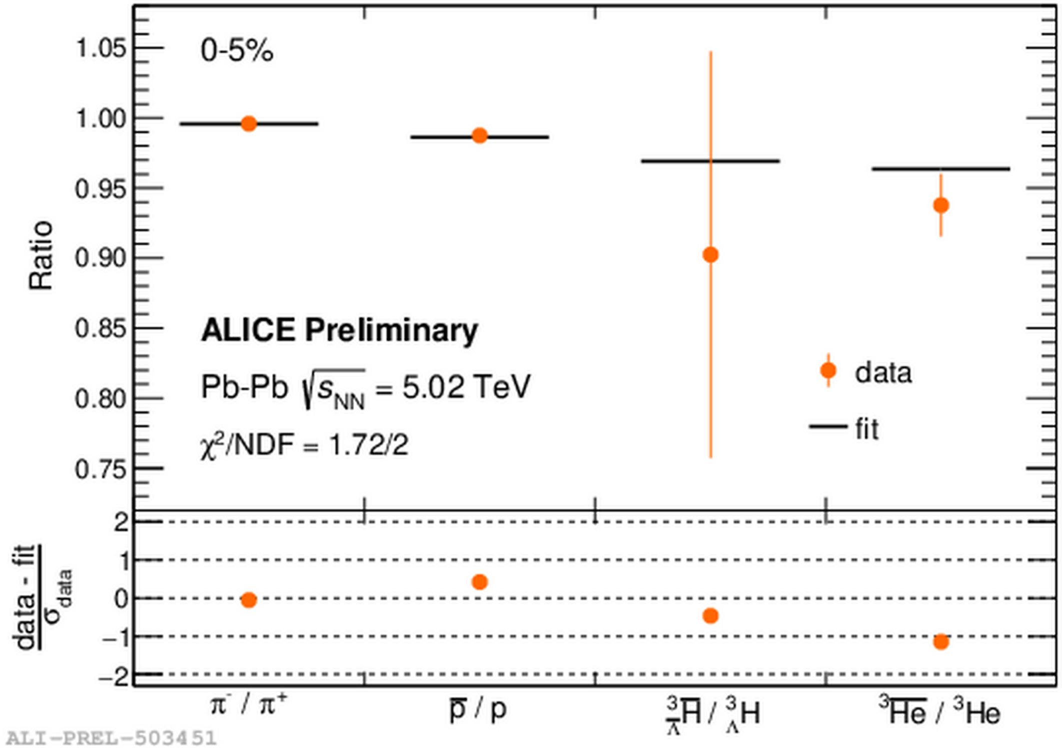
- The 1[st] measurement in p–Pb collisions at the LHC of hypertriton, reconstructed via the decay channel ${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$
  - The lightest hypernucleus (p,n, Λ) (mass ≈ 2.991 GeV/c^2)
  - The binding energy : B_Λ ≈ 130 keV
- **Fragile but surviving at chemical freeze-out temperature T_{ch} = 156 MeV ?**
- Important to discriminate between nucleosynthesis mechanisms in dense and hot environments
- Results are currently in favour of coalescence
- Improved statistics – is expected in the upcoming LHC Run 3 with the upgraded ALICE
- Search of Σ^0–hypernuclei: talk by Alexander Borissov at this conference,12 July 2022, 12:30

New!

Formation of light (anti) (hyper) nuclei in Pb--Pb collisions: antimatter-over-matter ratios

Antiparticle-to-particle ratios of charged pions, protons, hypertriton ($^{3}_{\Lambda}H$) and ^{3}He

Pb–Pb collisions, $\sqrt{s_{NN}}$=5.02 TeV



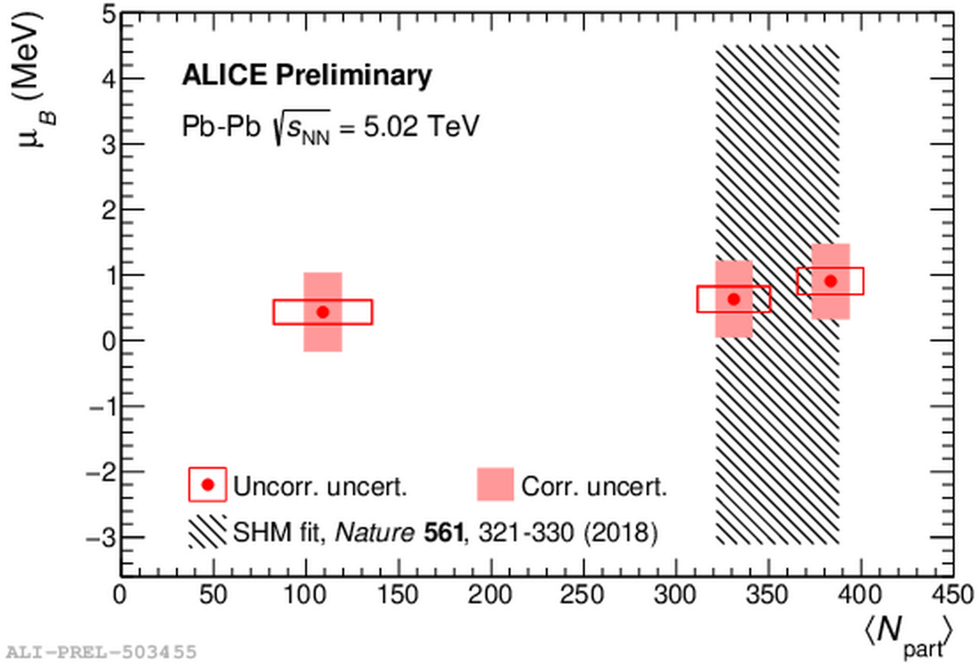
- T = 156.5 ± 1.5 MeV, fixed from the Statistical Hadronisation Model (SHM) [A. Andronic et al., Nature 561, (2018) 321]
- Measurement of baryon chemical potential μ_B

Fit using the relation obtained from SHM.

New!

Formation of light (anti) (hyper) nuclei in Pb--Pb collisions: antimatter-over-matter ratios

Pb–Pb collisions, $\sqrt{s_{NN}}$=5.02 TeV



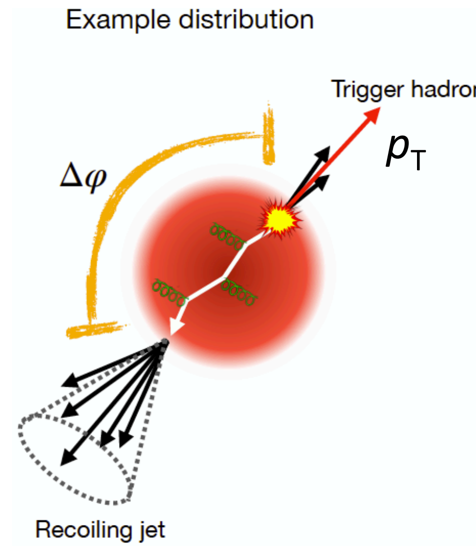
- Most precise measurement in Pb-Pb at LHC
- Small but non-zero μ_B at LHC

- The analysis will be extended to antimatter-over-matter ratios for strange baryons, such as Λ, Ξ and Ω

✓Jets in QGP medium

Jets as probes for the study of the deconfined matter

Charged-particle jets recoiling from a high-p_T trigger hadron



R.Cruz-Torres QM-2022

- **Observables for recoil jets:**
- Signal Trigger Track (**TT_{sig}**) -- interval 20 to 50 GeV/c *(labeled as TT20,50)*
- Reference Trigger Track (**TT_{ref}**) -- interval 5 to 7 GeV/c *(labeled as TT5,7)*
- **Δ_{recoil} (p_T, Δϕ)- the** azimuthal correlation between the trigger hadron and recoil jet

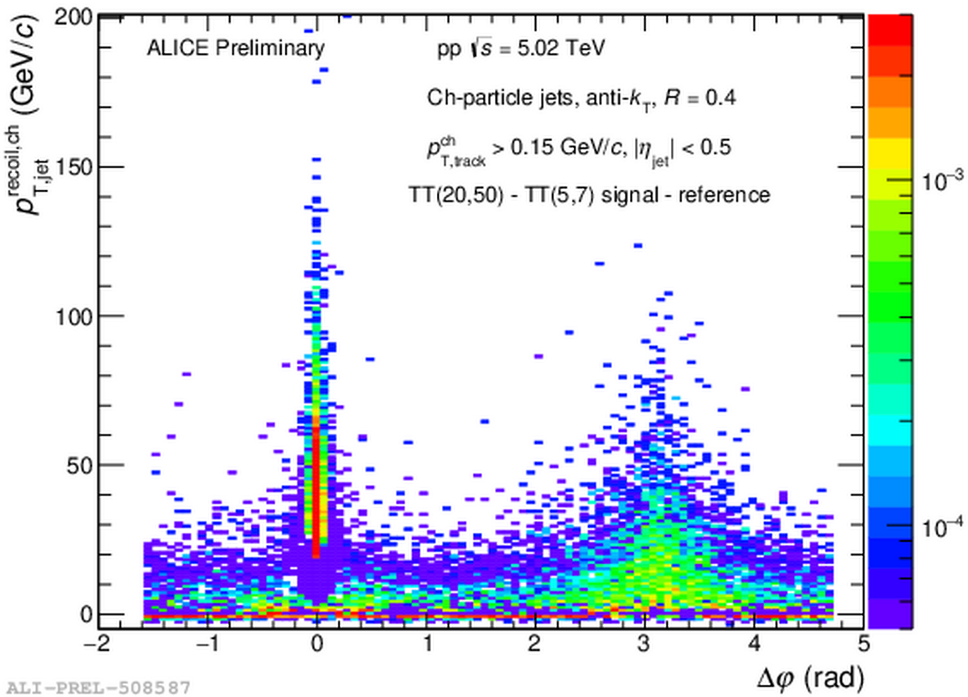
$$\Delta_{recoil}(pT, \Delta\phi) = \frac{1}{N_{trig}} \frac{d^2 N_{jet}}{dp^{ch}_{T,jet} d\Delta\phi}\bigg|_{TT_{sig}} - c \cdot \frac{1}{N_{trig}} \frac{d^2 N_{jet}}{dp^{ch}_{T,jet} d\Delta\phi}\bigg|_{TT_{ref.}}$$

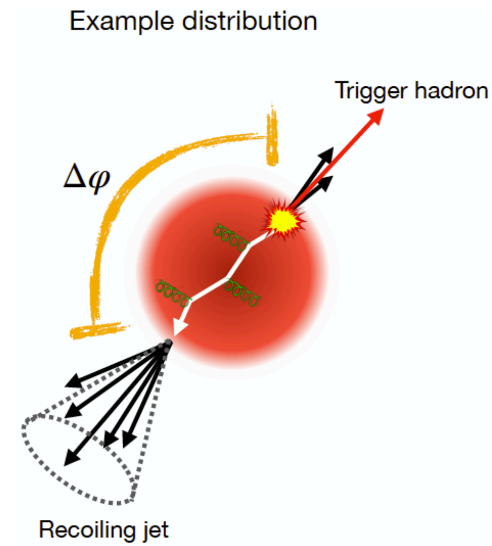
New!

Jets in QGP medium: modification of the angular structure of recoil jets

pp and Pb–Pb collisions

Measurement of the semi-inclusive hadron+jet distributions





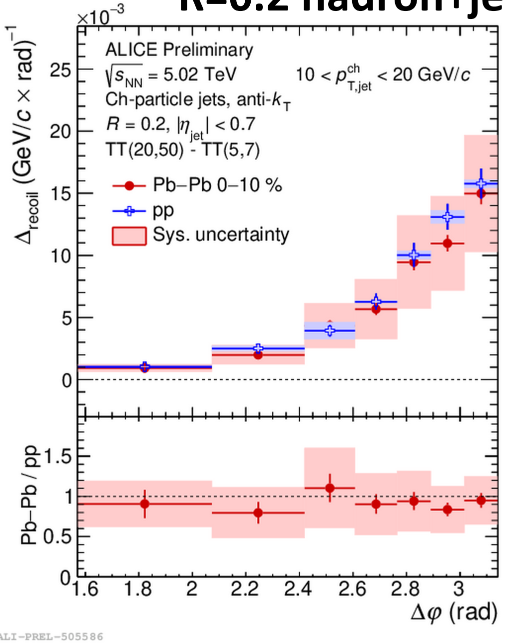
R.Cruz-Torres QM-2022

- Modification of $\Delta\phi$ distribution for recoil jets
- Medium-induced gluon radiation vs. multiple-scattering-like intra-jet?

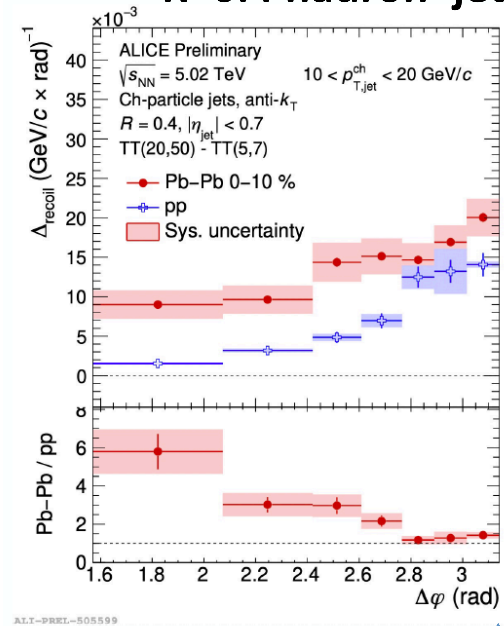
New!

Jets in QGP medium: modification of the angular structure of recoil jets

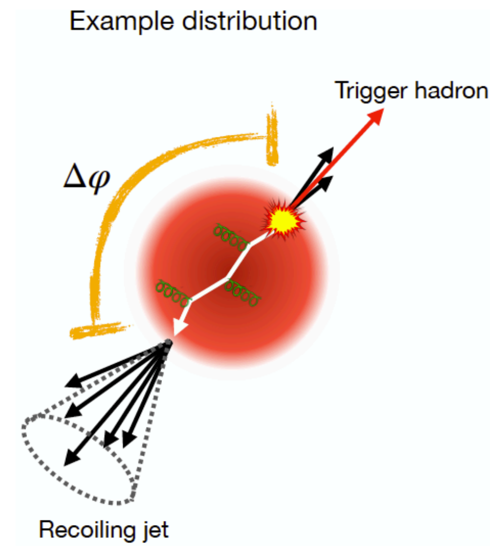
R=0.2 hadron+jet



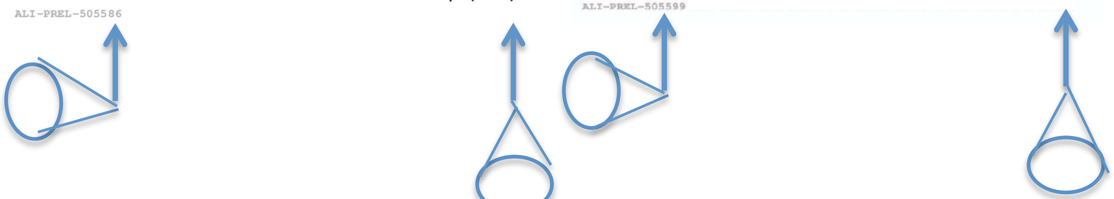
R=0.4 hadron+jet



pp and Pb–Pb collisions



R.Cruz-Torres QM-2022



- **Modification of $\Delta\varphi$ distribution for recoil jets**

- At high p_T , the Pb–Pb and pp shapes are consistent within uncertainties.

- At low p_T (R=0.4), a significant azimuthal (in Δϕ) broadening is seen in Pb–Pb collisions with respect to pp collisions.

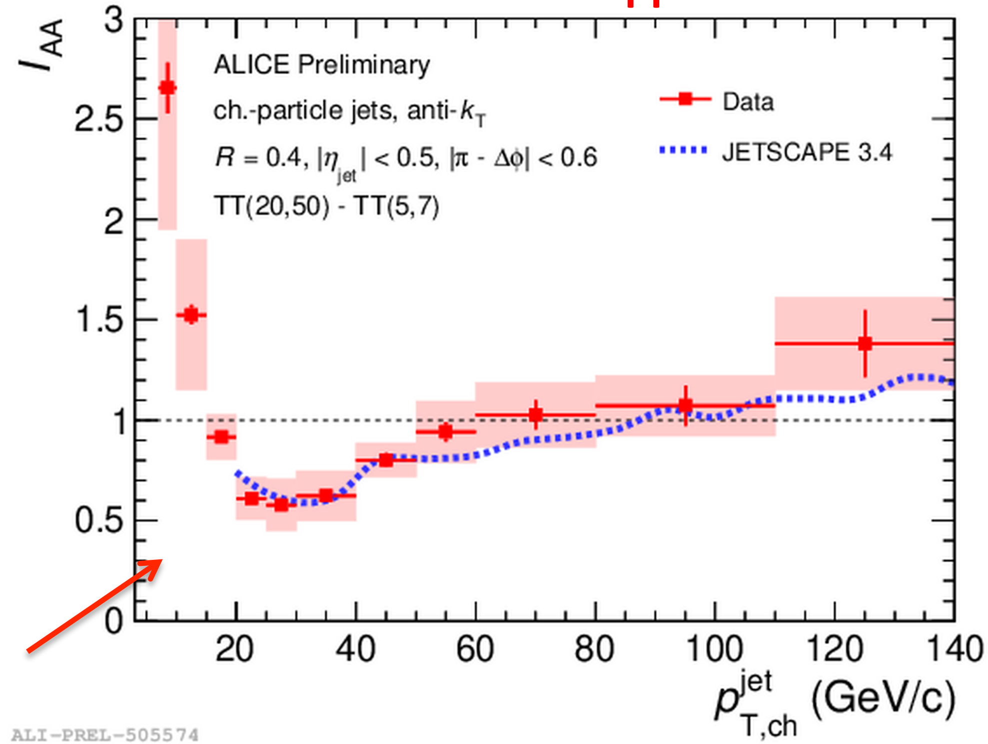
New!

Jets in QGP medium: modification of the angular structure of recoil charge particle jets

pp and Pb–Pb collisions

$$I_{AA} = \frac{\Delta_{recoil}(Pb - Pb)}{\Delta_{recoil}(pp)}$$

- Jet energy is redistributed in HI collisions?
- Low jet momenta region: energy recovery?



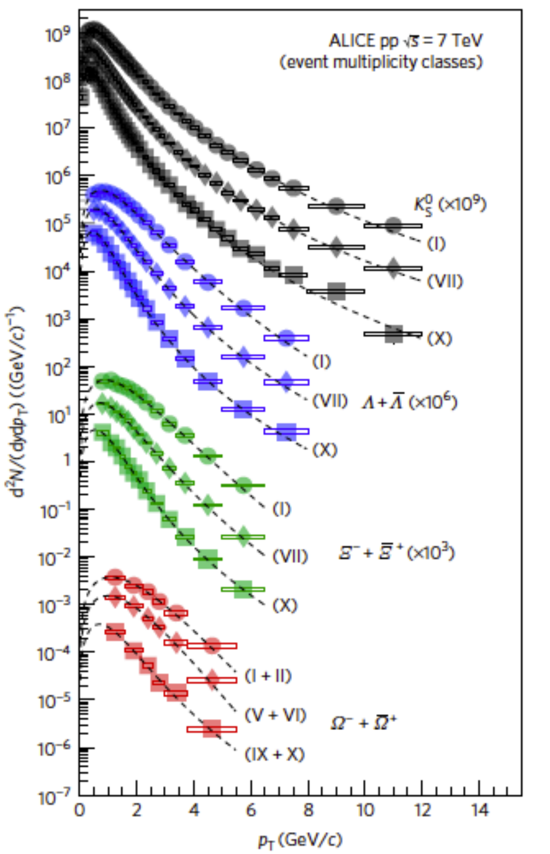
R=0.4 hadron+jet I_{AA} distribution vs. $p_{T,ch}^{jet}$ in 0-10% Pb-Pb collisions over pp collisions at $\sqrt{s_{NN}}$=5.02 TeV

✓Strangeness in hadronic collisions

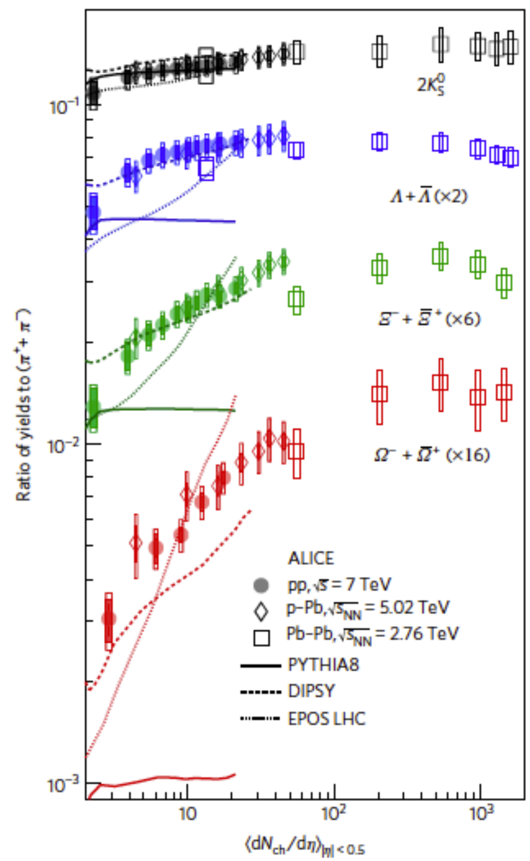
Enhanced production of multi-strange particles in high-multiplicity pp, p–Pb and Pb-Pb collisions

Nature Physics 13,535–539 (2017)

p_T-differential yields



p_T-integrated yield ratios to pions ($\pi^+ + \pi^-$) as a function of $\langle dN_{ch}/d\eta \rangle$ measured in $|y| < 0.5$.



pp, p-Pb and Pb–Pb collisions

- The enhancement is larger for particles with larger strangeness content
- No dependence on the LHC collision energy

- Striking similarities in strangeness production for large and small systems
- Origin of strangeness enhancement?

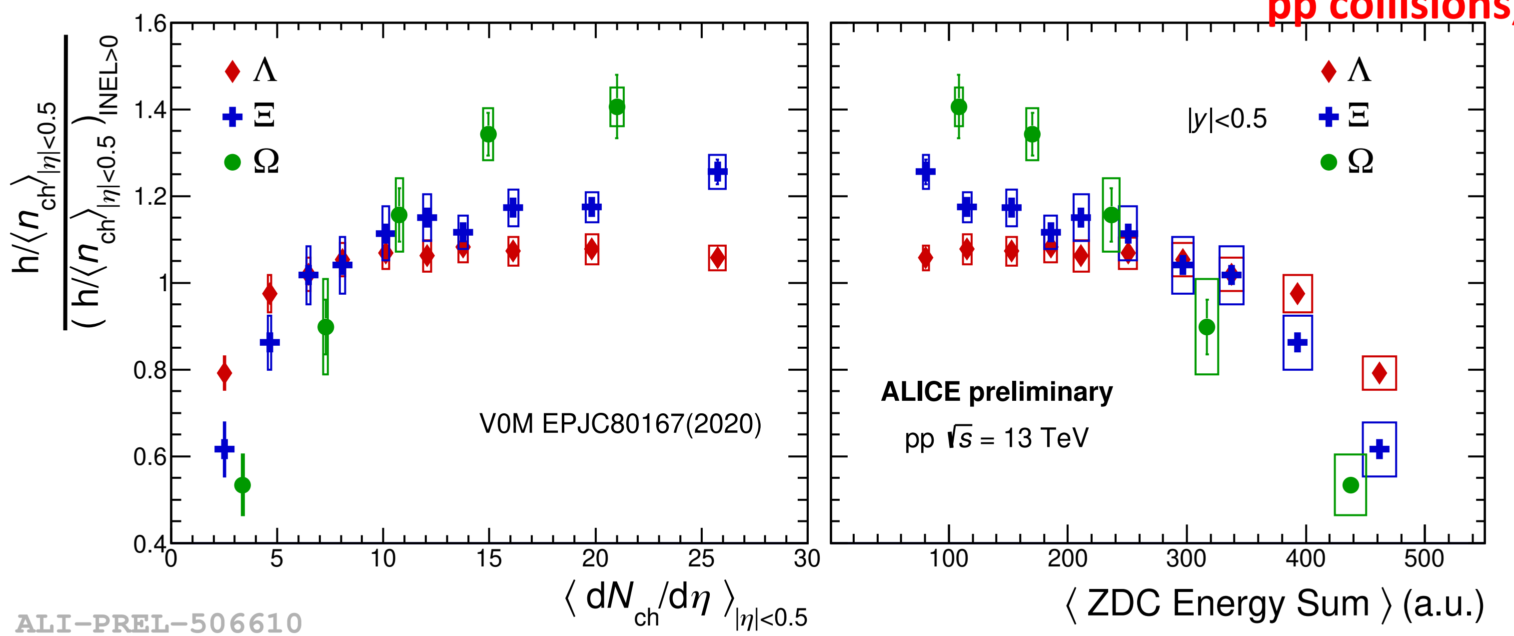
New!

Strangeness at midrapidity vs multiplicity and efficient energy

ALICE

A JOURNEY OF DISCOVERY

pp collisions, 13 TeV



Λ: (uds)
Ξ: (dss)
Ω: (sss)

- Λ, Ξ and Ω production vs midrapidity multiplicity -(left) and vs. energy deposited in ALICE's Zero Degree Calorimeters (ZDC) −(right)

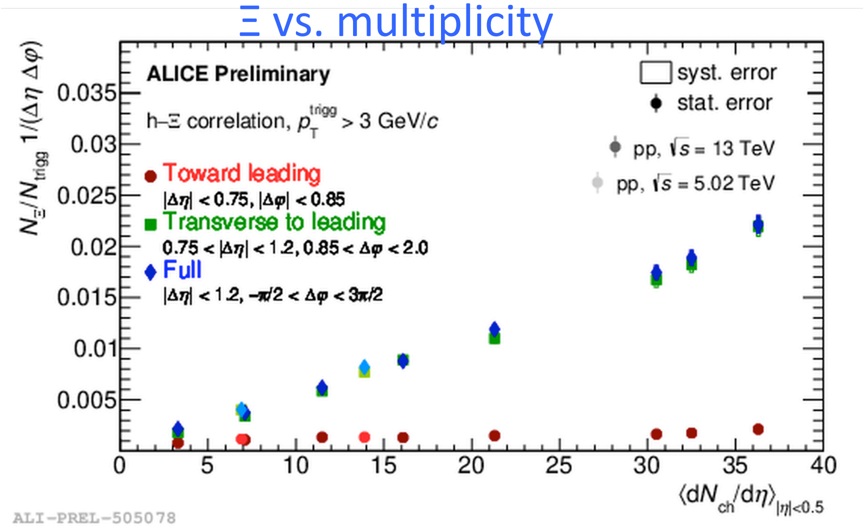
- Yields of multistrange baryons are anticorrelated with the forward energy, measured by ZDC
- Correlated with the effective energy available in the event for particle production
- Role of the initial stages and number of partonic collisions (MPI) in strangeness production?

New!

Strangeness production in jets and out of jets

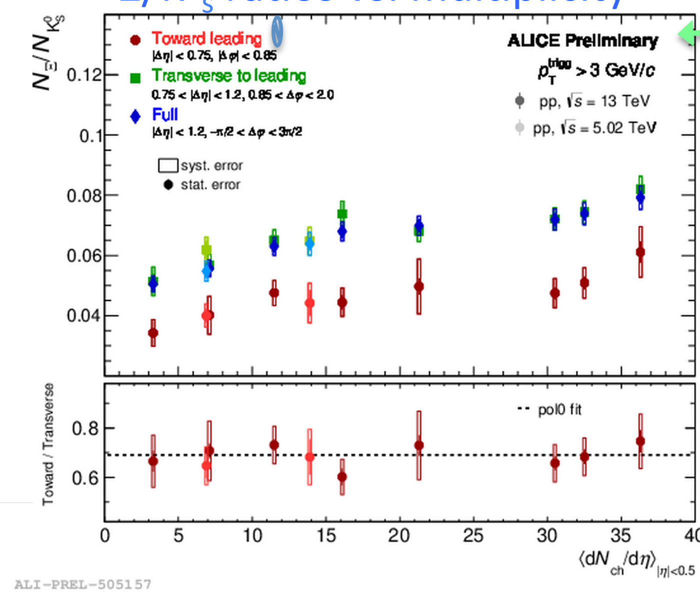
pp collisions at √s=13 TeV and √s =5.02 TeV

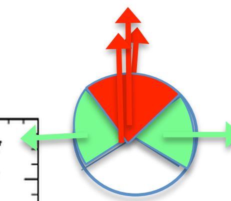
Ξ vs. multiplicity



Near-side jet, out-of-jet and full yield of Ξ vs. multiplicity of charged particles produced at midrapidity

Ξ/K^0_s ratios vs. multiplicity



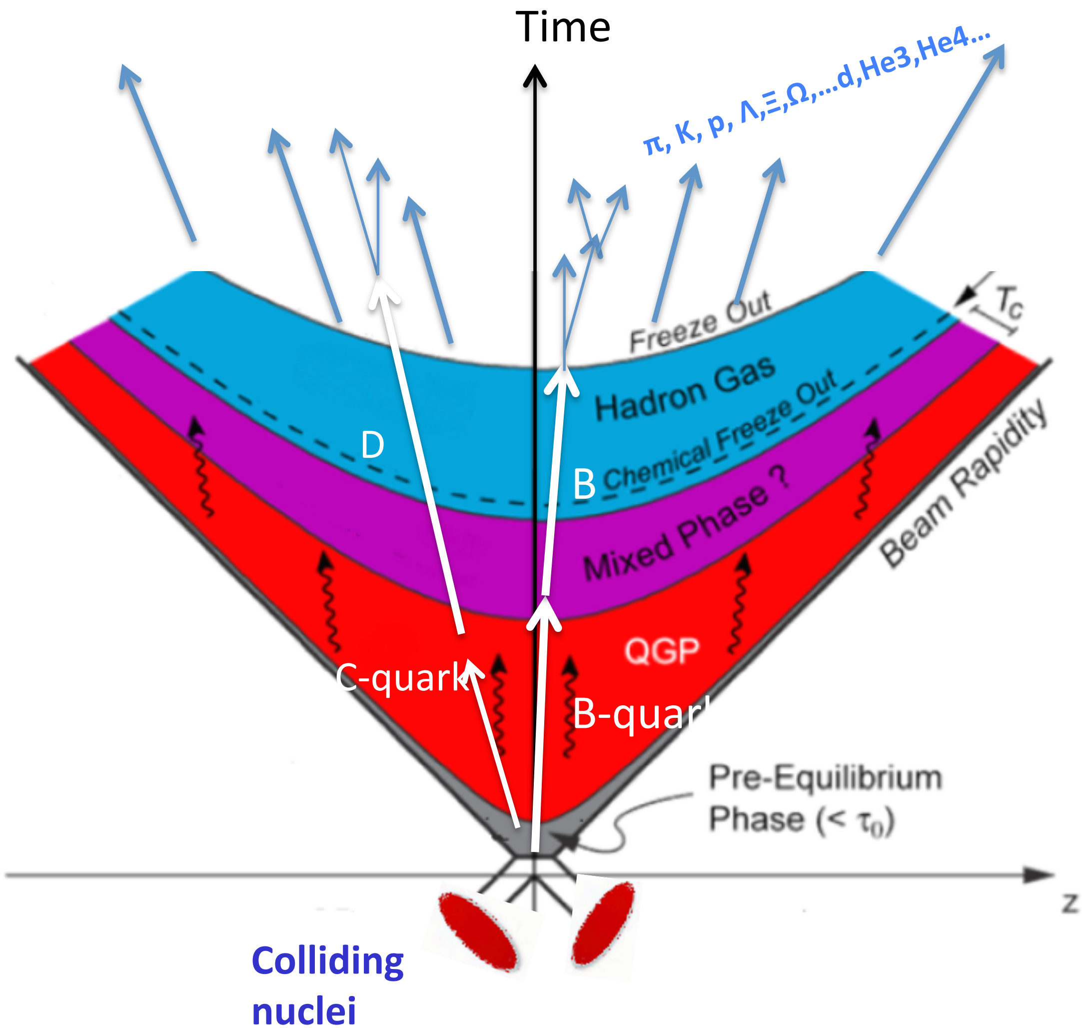


Near-side jet, out-of-jet and inclusive Ξ/K0s yield ratios vs. multiplicity of charged particles

- For Ξ mesons **the near-side leading jet yield is practically flat with multiplicity**
- **Linear growth** of Ξ yield with multiplicity **in transverse to leading**

✓ Charm in pp, p-Pb and Pb-Pb collisions

Charm in pp, p-Pb and Pb-Pb collisions



Why open heavy flavour is interesting?

- ✓ Production is relevant to early collision stages
- ✓ Theoretical calculation of production in perturbative QCD
- ✓ Transport of c-quark through the medium: collisions and radiative e-losses ?
- ✓ Hadronisation mechanism?

Charm measurements in ALICE:

$D^0 \rightarrow K^- \pi^+$

$D^+ \rightarrow K^- \pi^+ \pi^+$

$D_s^+ \rightarrow \phi\, \pi^+ \rightarrow K^+ K^- \pi^+$

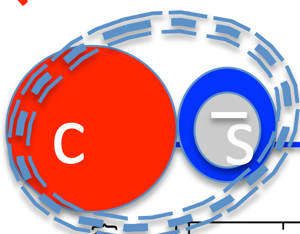
$D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$

$\Lambda_c^+ \rightarrow K_s^0\, p \rightarrow \pi^+ \pi^- p$

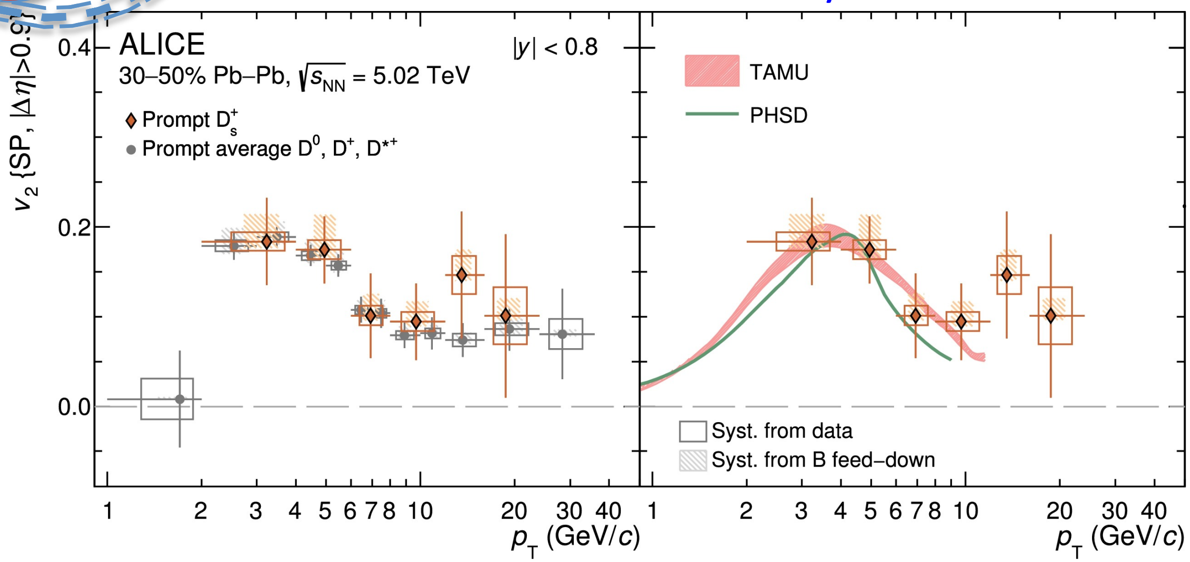
$c \rightarrow \mu^\pm X$ (with muon spectrometer)

Flow of prompt D_s^+-mesons in Pb-Pb collisions

New!



Physics Letters B 827 (2022)



Pb–Pb collisions

- For prompt D^+_s mesons v_2 is compatible with that of non-strange D mesons
- Charm participates in collective expansion/motion: noticeable elliptic flow is in line with TAMU and PHSD models with charm-quark coalescence
- Future data samples will be collected in Run 3 extended to lower p_T with the upgraded ALICE detector

New!

Constraining hadronization mechanisms with Λ^+_c/D^0 production ratios

ALICE
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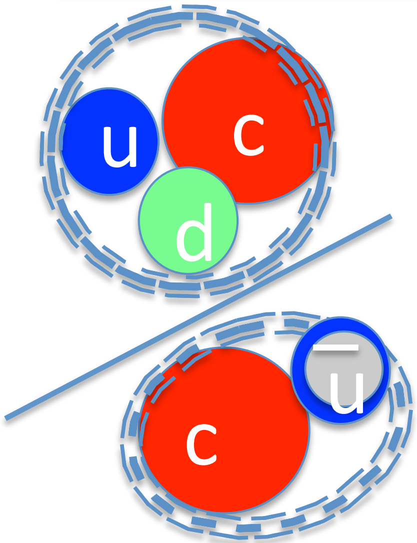
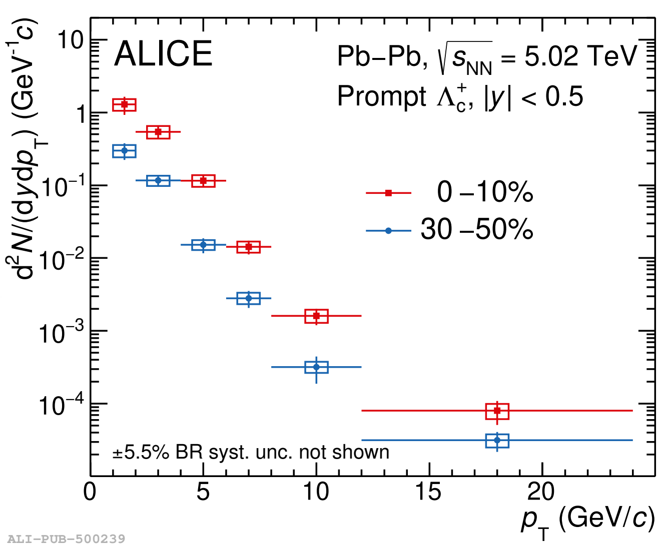
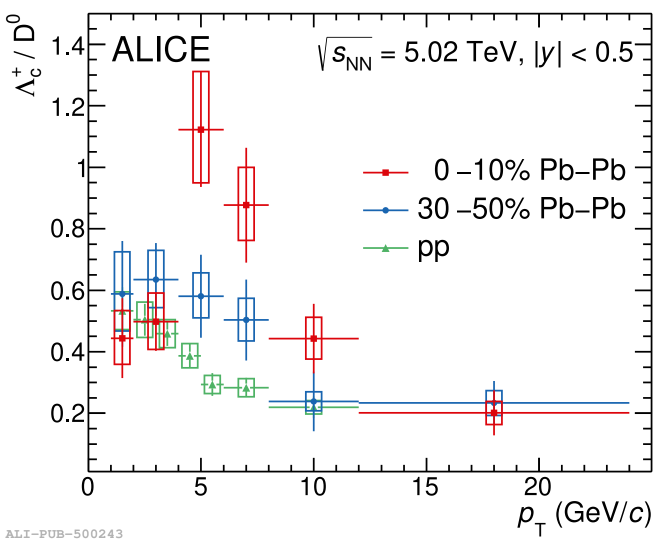
pp and Pb–Pb collisions



Prompt Λ^+_c



Λ^+_c/D^0



The p_T-differential production yields of prompt Λ^+_c in central (0–10%) and mid-central (30–50%) Pb–Pb collisions at √sNN = 5.02 TeV.

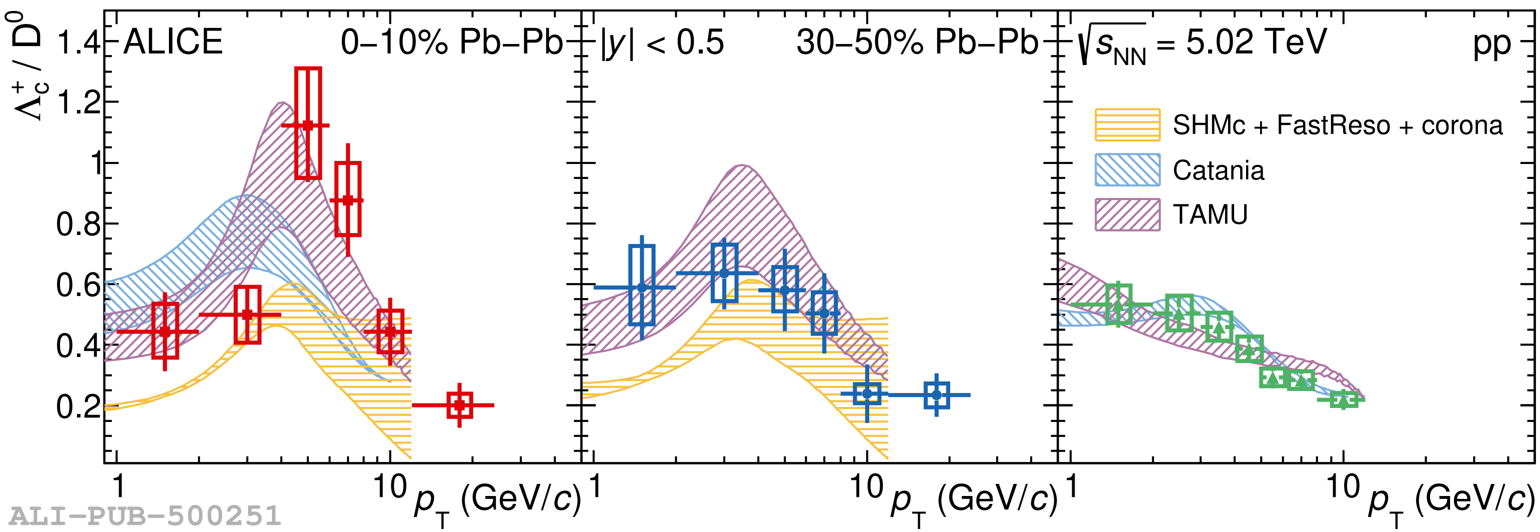
The Λ^+_c/D^0 ratio in central and mid-central Pb–Pb collisions at √sNN = 5.02 TeV compared with the results obtained from pp collisions [10, 11]

- Λ^+_c/D^0 - ratio is sensitive to hadronisation mechanism

New!

Constraining hadronization mechanisms with Λ^+_c/D^0 production ratios

pp and Pb–Pb collisions



Different theoretical calculations:

TAMU, PRL 124, 042301 (2020) arXiv:1905.0921

Catania, PRC 96, 044905 (2017) arXiv: 1712.00730.

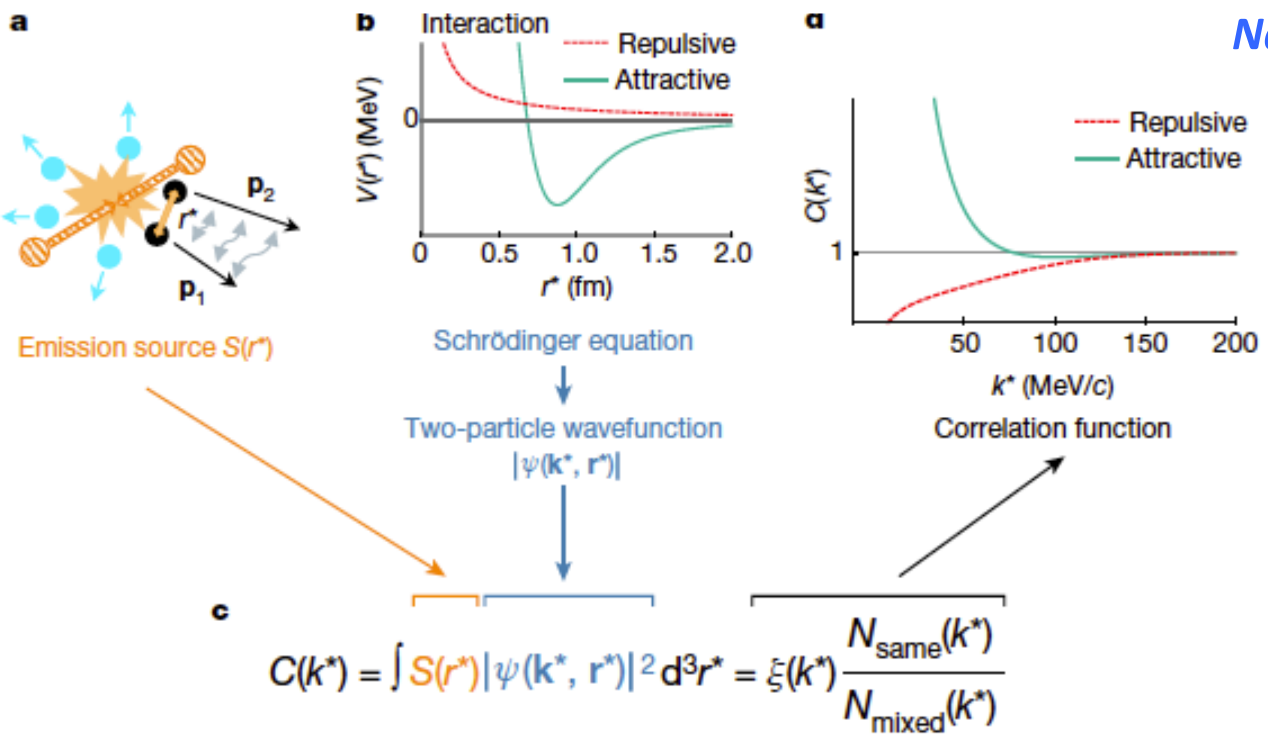
SHMc, HEP 07 (2021) 035 arXiv:2104.12754

- The Λ^+_c/D^0 ratio is enhanced in central Pb-Pb collisions with respect to the pp measurement **for 4 < p_T < 8 GeV/c**
- It is described by theoretical calculations that include hadronisation via both coalescence and charm quark fragmentation mechanisms.
- However, no enhancement with multiplicity for p_T integrated Λc /D. Is it due to radial flow? arXiv:2112.08156 and arXiv:2111.11948

✓ Two-body scattering involving *strange* and *charm* hyperons

Two-body scattering and study of strong interaction involving *strange* hyperons

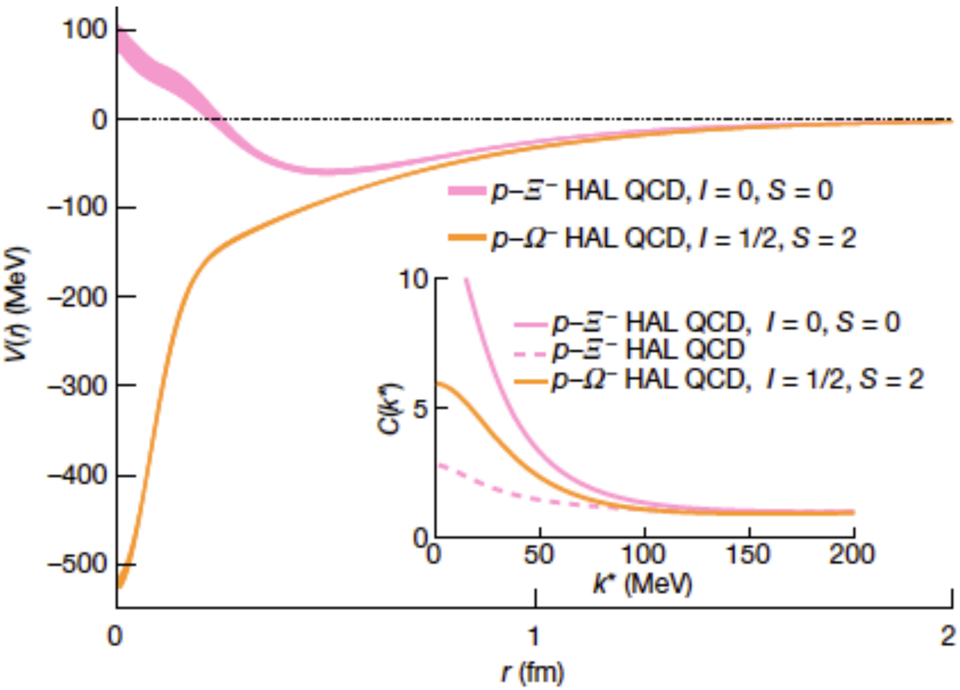
***Nature* 588, 232–238 (2020)**

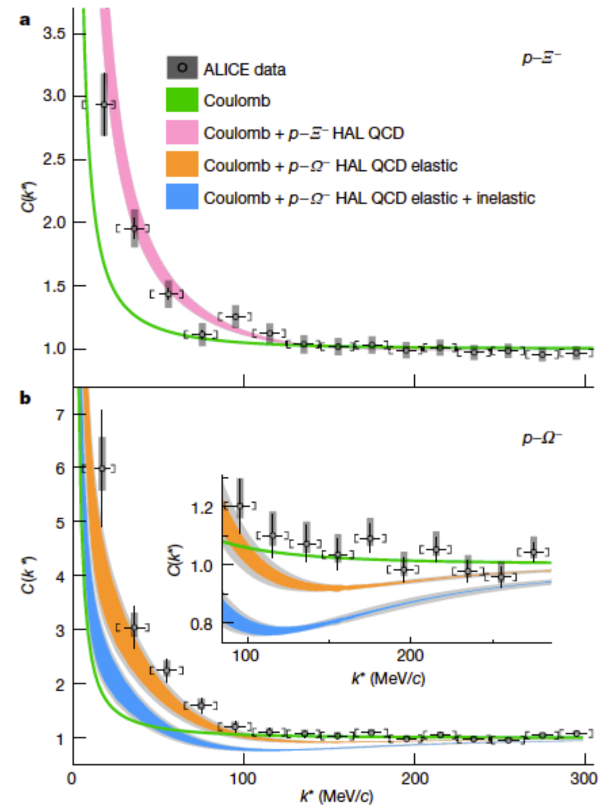


- ➢Absence of interaction C(k*) = 1
- ➢Attractive potential C(k*) > 1
- ➢Repulsive potential C(k*) < 1
- ➢Bound-state formation C(k*) <> 1

Two-body scattering and study of strong interaction involving ***strange*** hyperons

Nature **588, 232–238 (2020)**





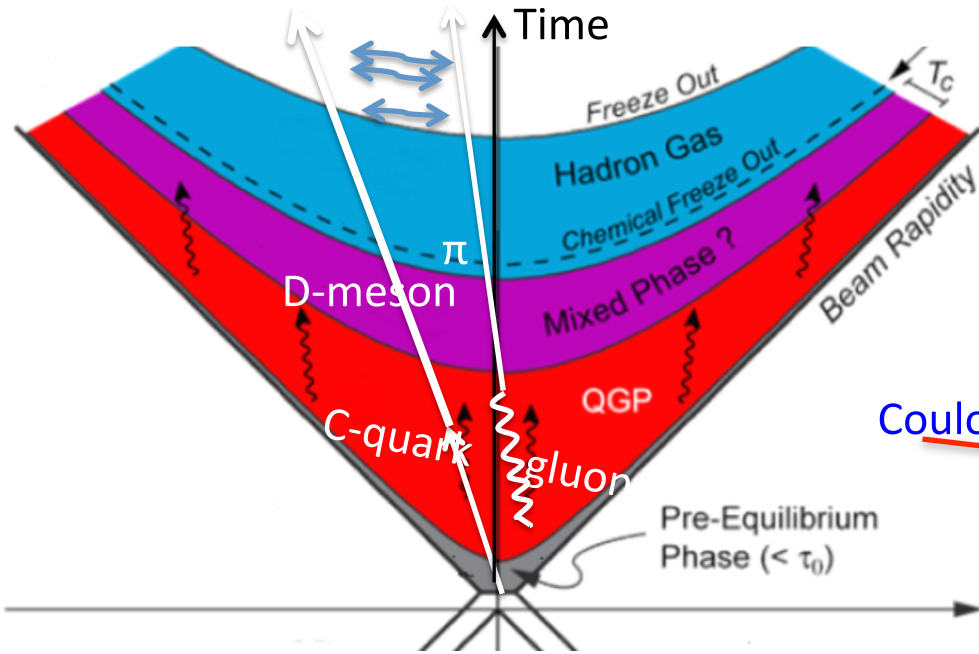
Potentials for the p-Ξ⁻ and p-Ω⁻ interactions predicted by the HAL QCD collaboration.

[Phys.Lett. B 792, 284–289 (2019); Nucl.Phys. A 998, 121737 (2020)].

- Important input for the equation of state of neutron stars

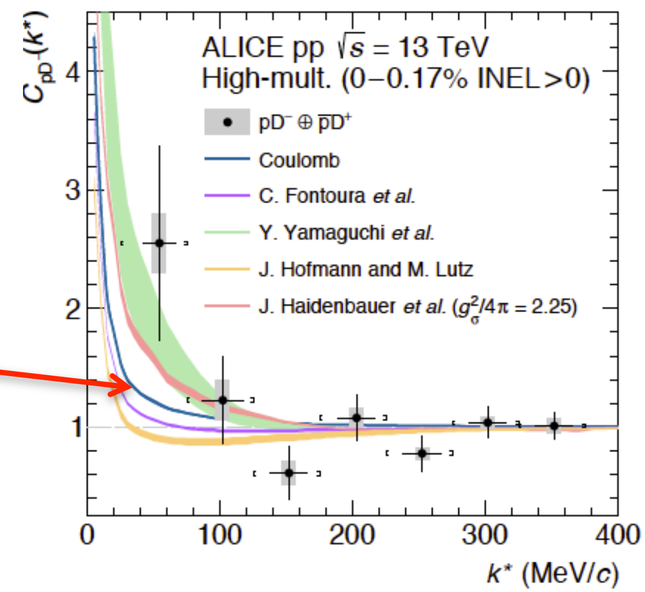
New!

Two-body scattering involving *charm* hadrons



pp collisions

arxiv:2201.05352



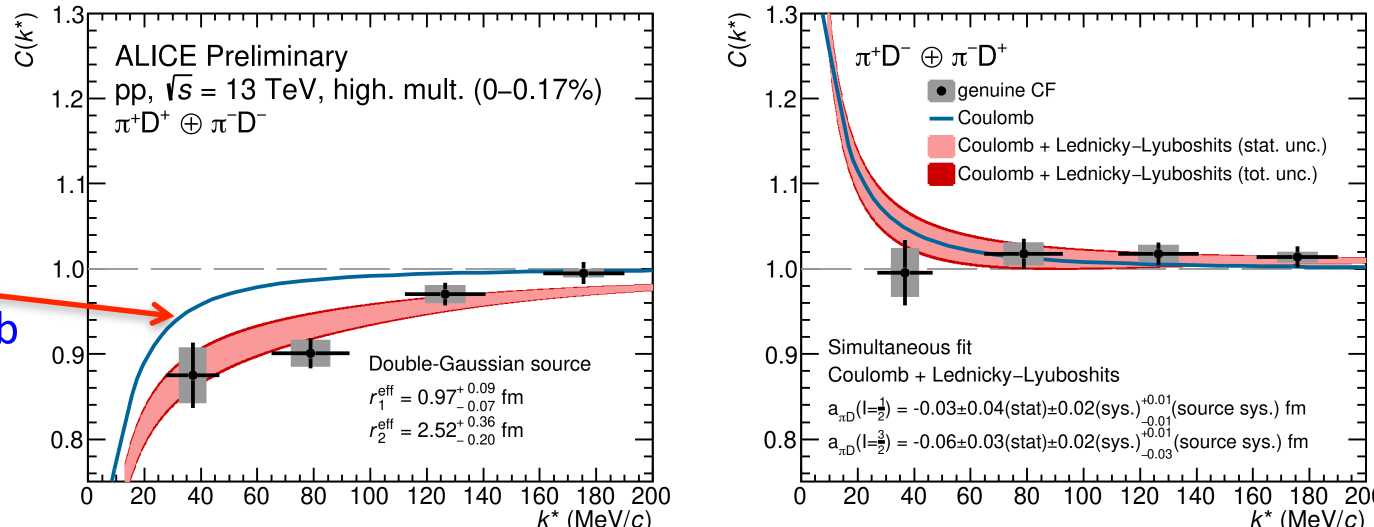
- The data are compatible with the Coulomb-only interaction hypothesis within (1.1–1.5) σ.
- The scattering parameters of charm hadrons with non-charm hadrons are important for models based on charm-quark transport in the expanding QGP
- Precision studies during the LHC Runs 3 and 4 are planned with 10 times increased statistics

New!

Two-body scattering involving *charm* hadrons

$\pi^+D^+ \oplus \pi^-D^-$ $\quad$ $\pi^+D^- \oplus \pi^-D^+$

pp collisions



Coulomb

ALI-PREL-506604

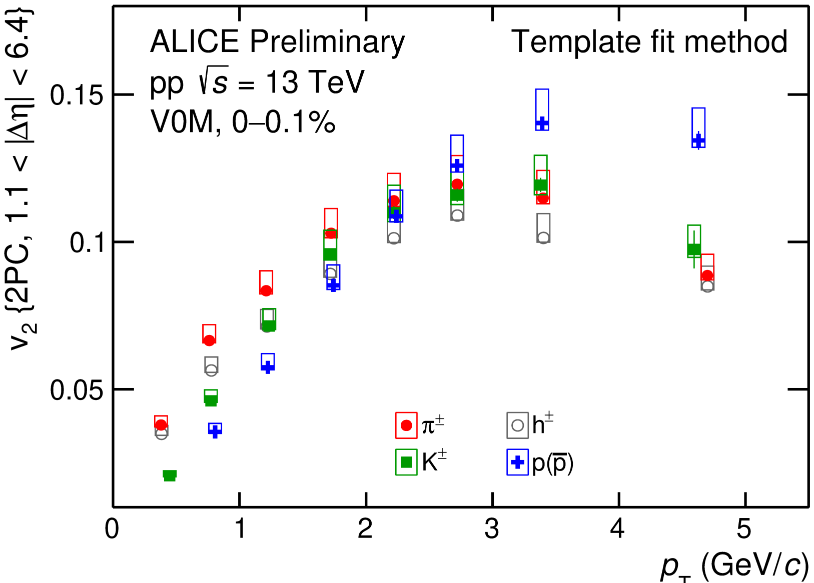
D-π femtoscopy in high multiplicity pp collisions at √s=13 TeV

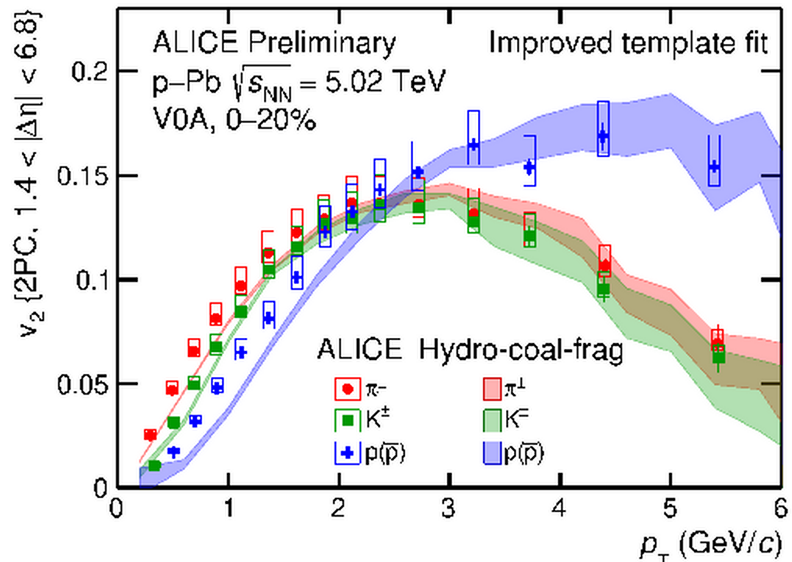
- The first studies of residual strong interaction between charm and light hadrons performed with Run 2 data
- Some deviation from the Coulomb baseline, indication on a shallow repulsive potential (left)
- **Significant improvement is foreseen with Run 3 data**

✓ Flow of identified particles in pp and p-Pb collisions

New! Flow of identified particles in pp and p-Pb collisions

pp and p-Pb collisions





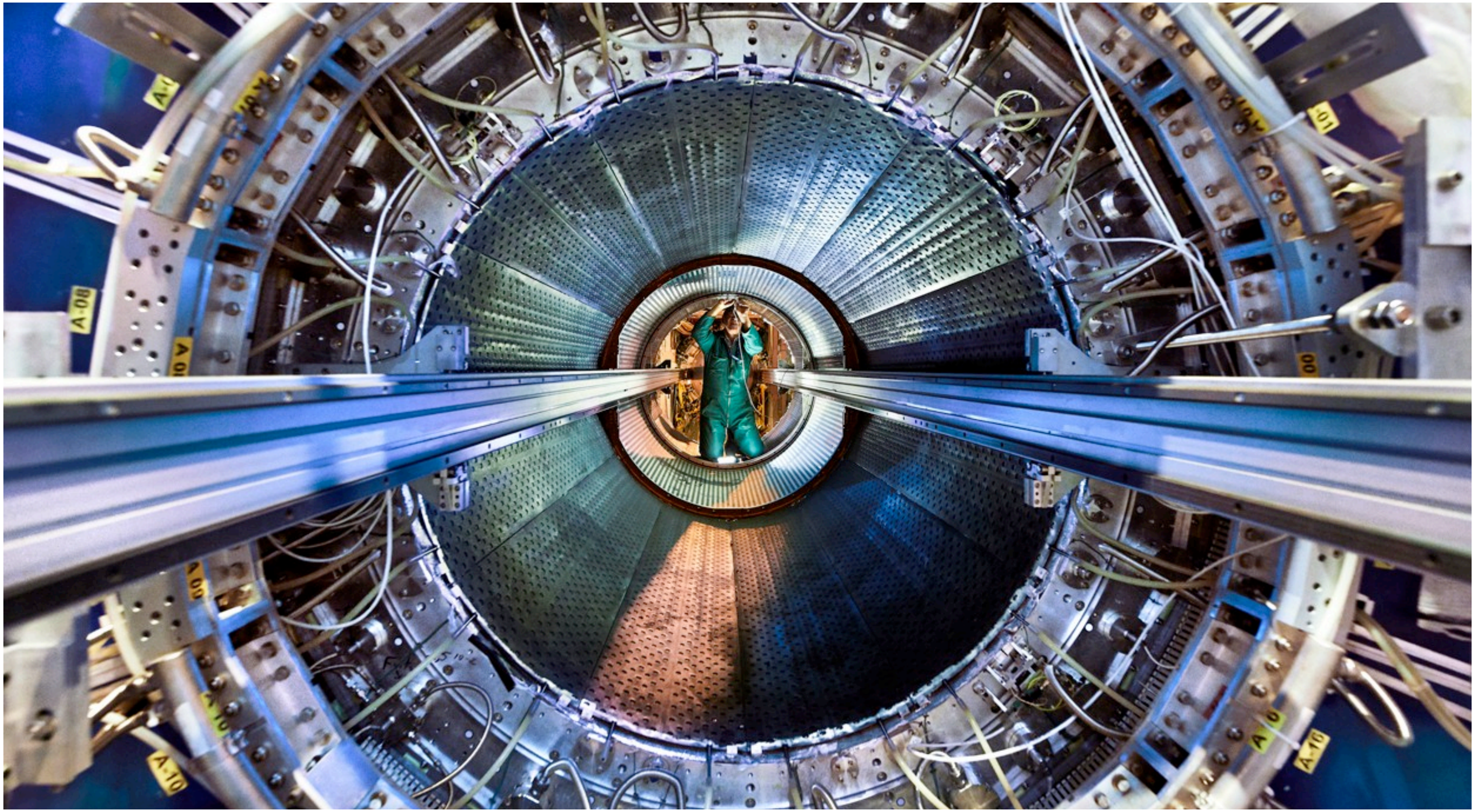
v_2 in High Multiplicity pp collisions with h, pi, K, p

- Collective effects in small systems
- Baryon-meson splitting - both in High Multiplicity pp and in p-Pb collisions
- Partonic flow + coalescence + fragmenation?

Hydro-coal-frag model
from Phys. Rev. Lett. 125, 072301 (2020)

✓ **ALICE LS2 Upgrade**

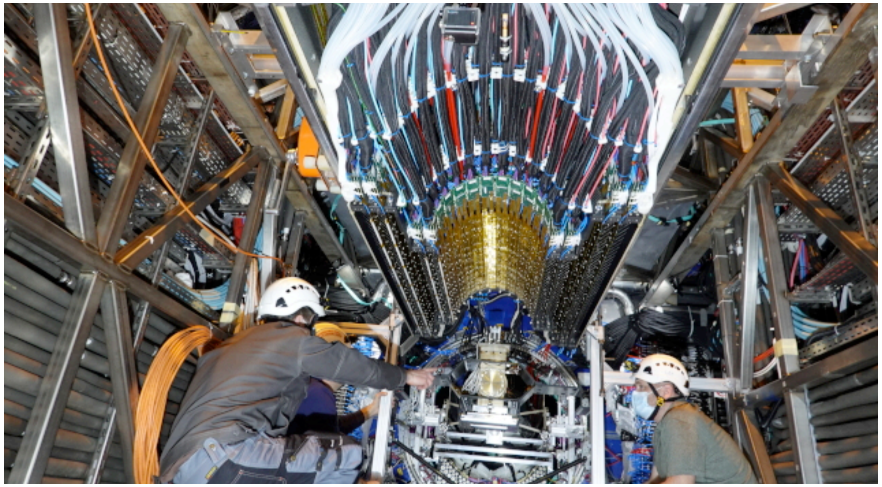
ALICE LS2 Upgrade is completed



Credit: Maximilien Brice, Julien Marius Ordan/CERN

ALICE upgrade:
Inner Tracking System (ITS2) for Run 3

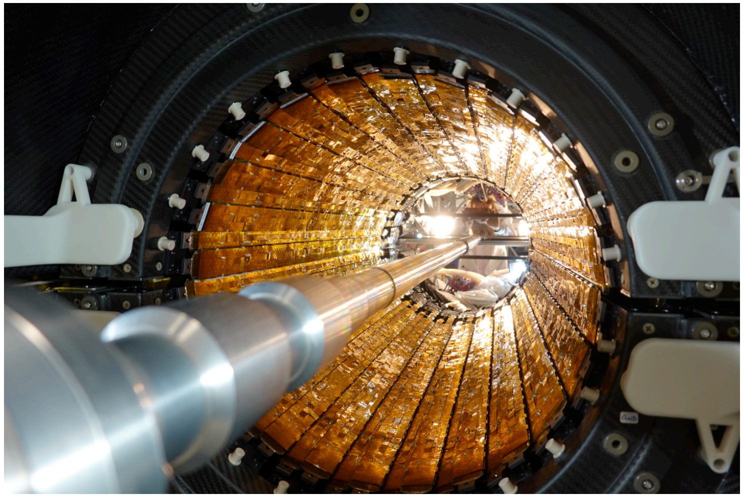
26 May, 2021



ALICE, the new Inner Tracking System

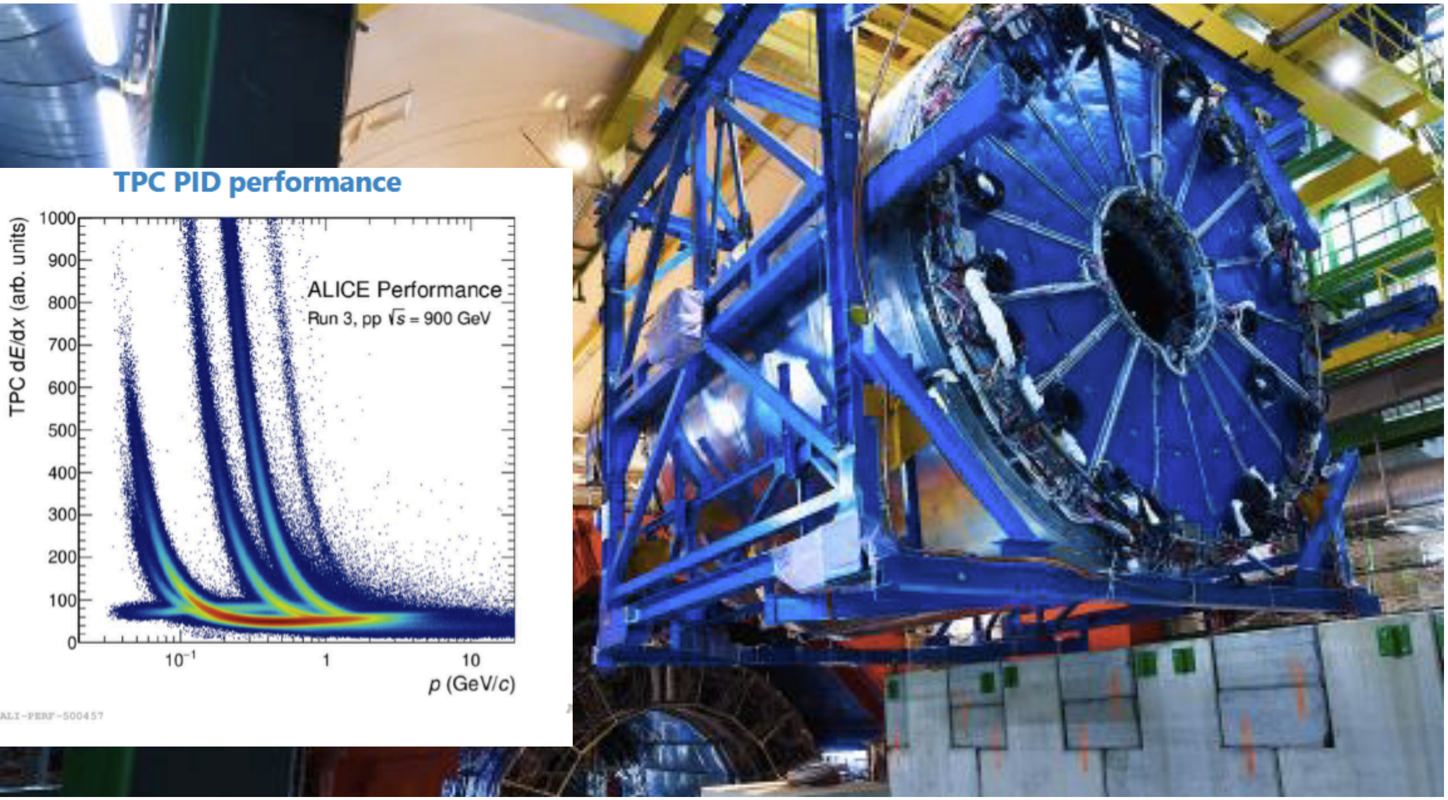
Installation of the Outer Barrel of the new ITS. (Image: CERN)

ITS2 in the process of installation



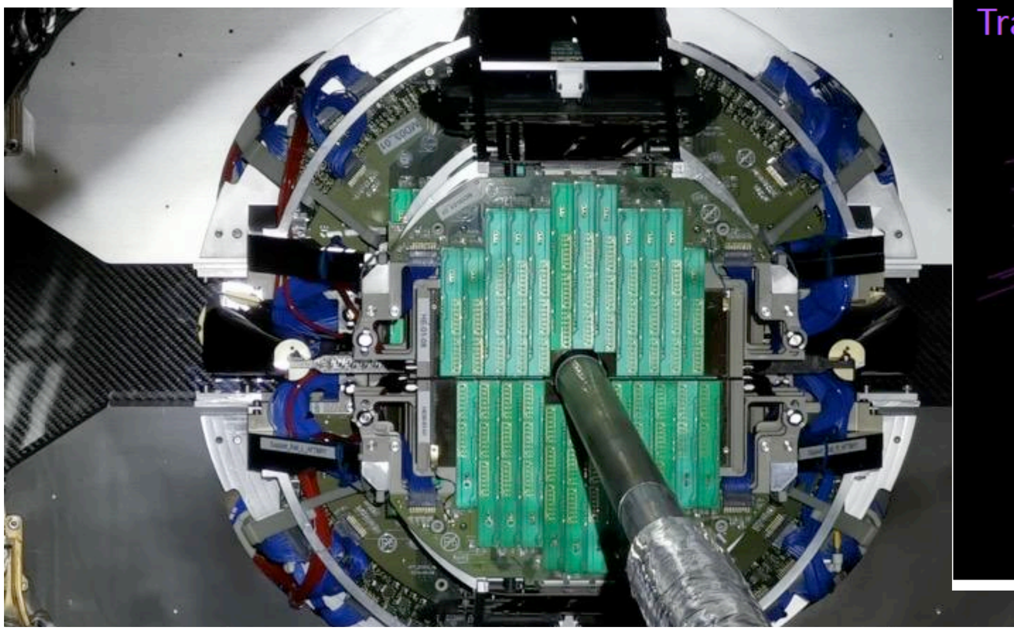
- The new ITS is the largest pixel detector ever built in CMOS Monolithic Active Pixel Sensor (MAPS) technology: 12,5 Gpixel camera of ~10 m^2 of active silicon area.
- High tracking precision and vertex resolution, fast readout
- Closer to the IP: first layer at ≈22 mm
- Smaller pixels: 28 x 29 μm^2
- Lower material budget of the Inner Barrel: 0.35% X_0

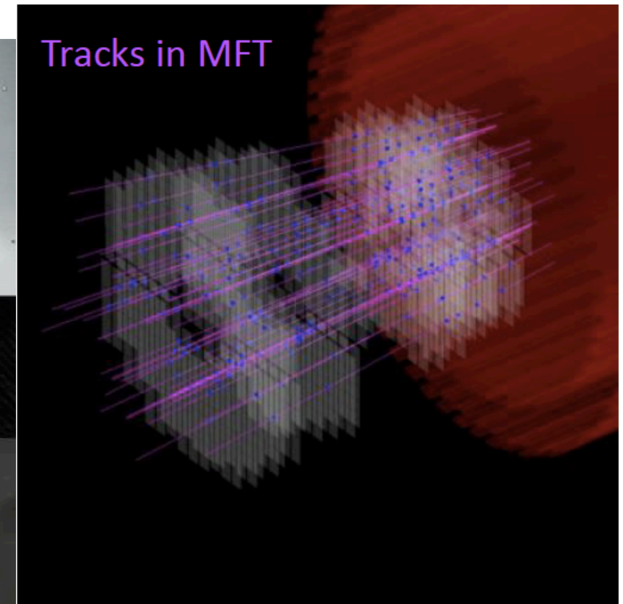
GEM TPC in the pilot beam in October 2021



- Photo: Installation of the TPC
- TPC with new Gas Electron Multiplier (GEM) technology
- New electronics (SAMPA),
- continuous readout

Pixel Muon Forward Tracker (MFT) in the pilot beam in October 2021





- The new Muon Forward Tracker, one of ALICE's main subdetectors, was installed in the cavern in December 2020

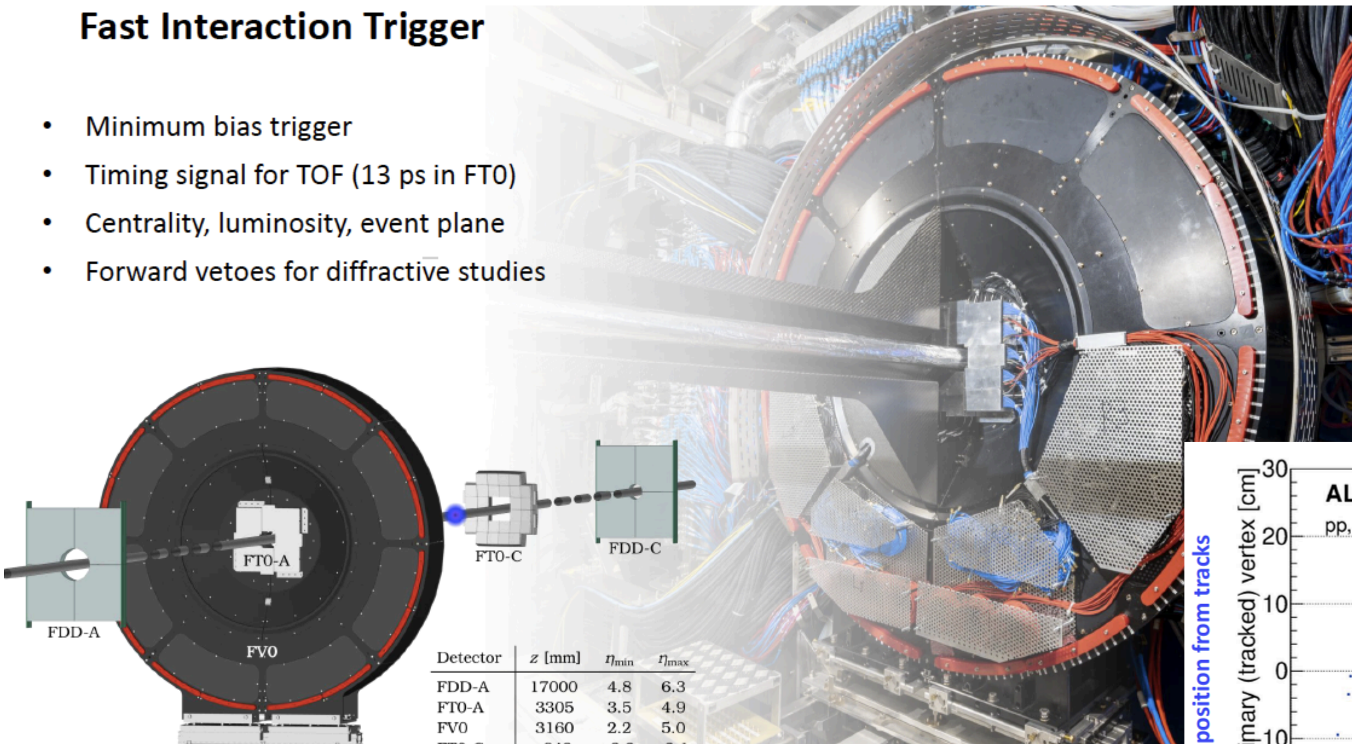
. Good performance of the new MFT in the pilot beam

- Substantial increase in pseudorapidity coverage for ALICE
- High pointing resolution for muon tracking

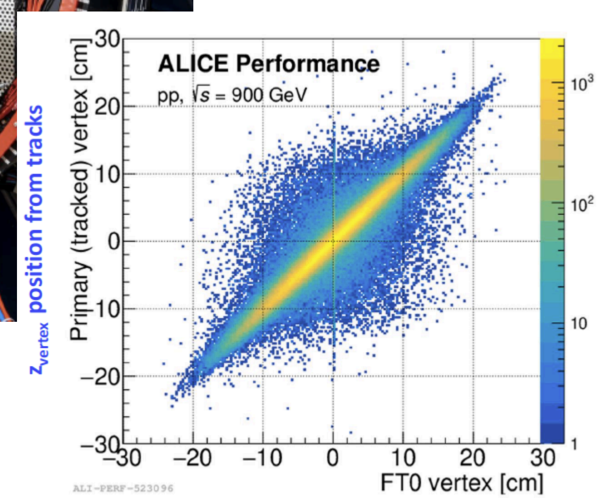
Fast Interaction Trigger (FIT) in October 2021 run

Fast Interaction Trigger

- Minimum bias trigger
- Timing signal for TOF (13 ps in FT0)
- Centrality, luminosity, event plane
- Forward vetoes for diffractive studies



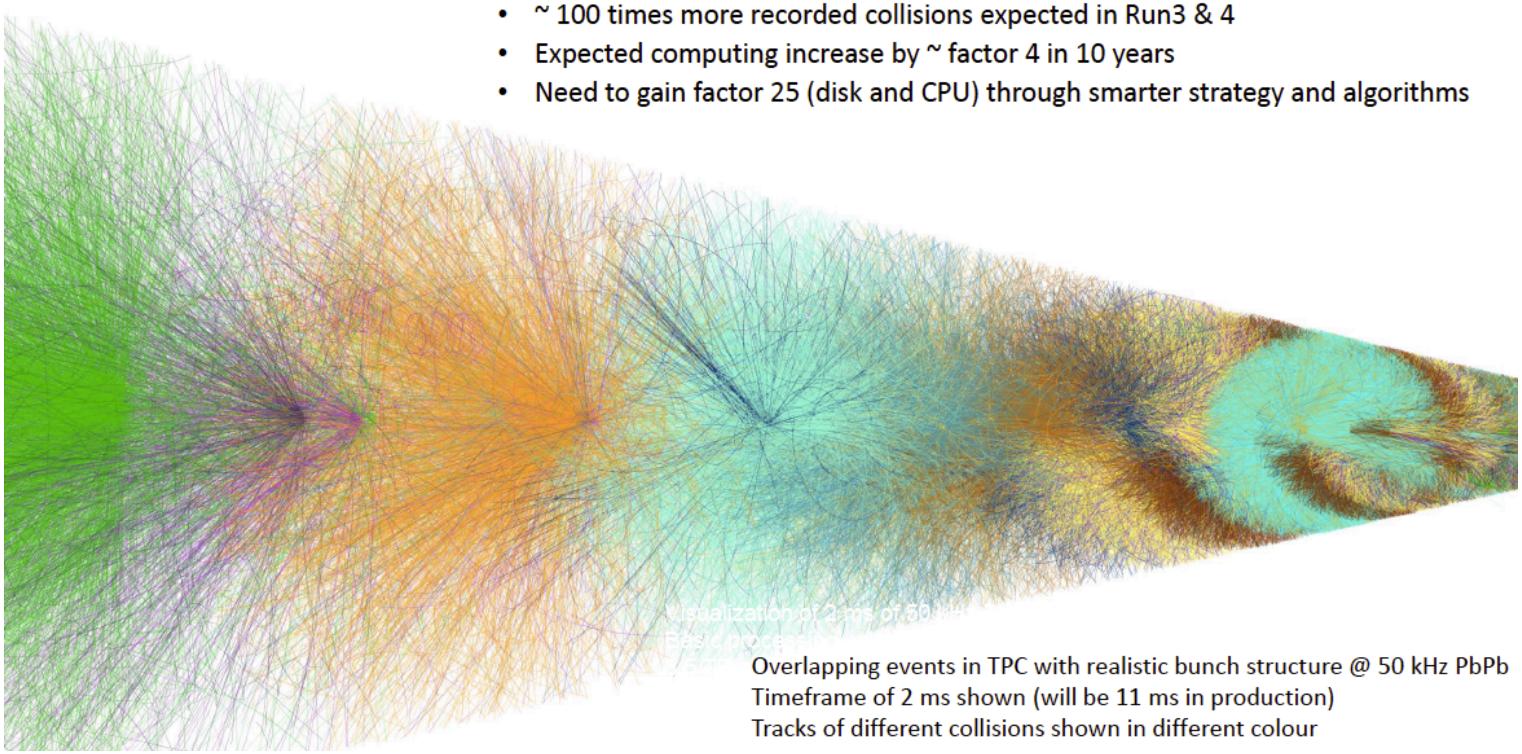
Detector	z [mm]	η_{min}	η_{max}
FDD-A	17000	4.8	6.3
FT0-A	3305	3.5	4.9
FV0	3160	2.2	5.0
FT0-C	-843	-3.3	-2.1



z_{vertex} position based on FT0 timing

ALICE upgrade for Runs 3 and 4: Integrated Online-Offline System (O^2)

- ~ 100 times more recorded collisions expected in Run3 & 4
- Expected computing increase by ~ factor 4 in 10 years
- Need to gain factor 25 (disk and CPU) through smarter strategy and algorithms

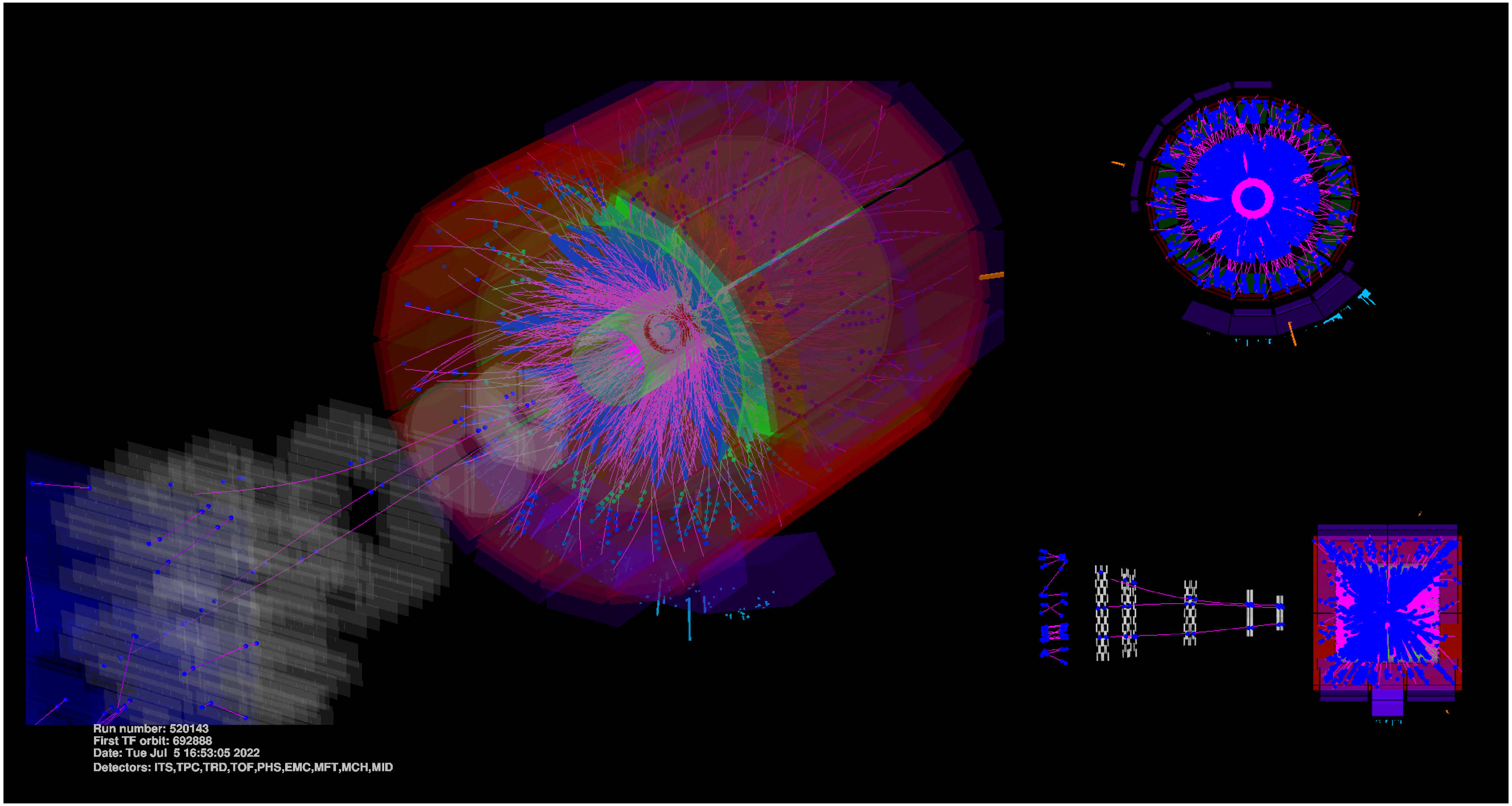


Overlapping events in TPC with realistic bunch structure @ 50 kHz PbPb
Timeframe of 2 ms shown (will be 11 ms in production)
Tracks of different collisions shown in different colour

- **Goal: record Pb-Pb collisions at 50 kHz (vs. 1 kHz in Runs 1 & 2)**
- **Collect 13 /nb in Runs 3&4 – gain factor 100 in statistics!**
- **Continuous readout**

The 5th of July 2022:
pp collisions at $\sqrt{s}$=13.6 TeV for the first time !

The 5th of July 2022, event display



Tracks from one time frame, 10 ms, about 100 pp interactions

✓ALICE @LHC Schedule

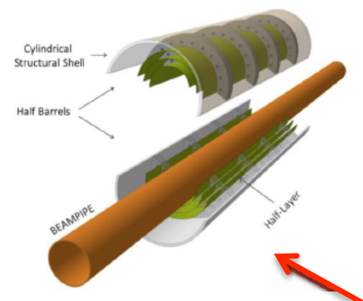
ALICE @LHC Schedule

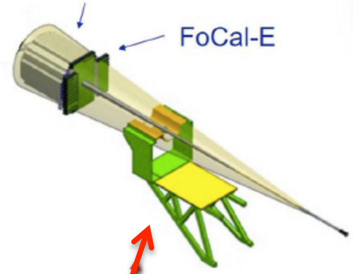
ALICE LS2 Upgrade finished

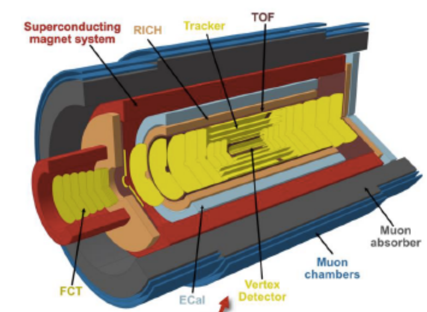
Today

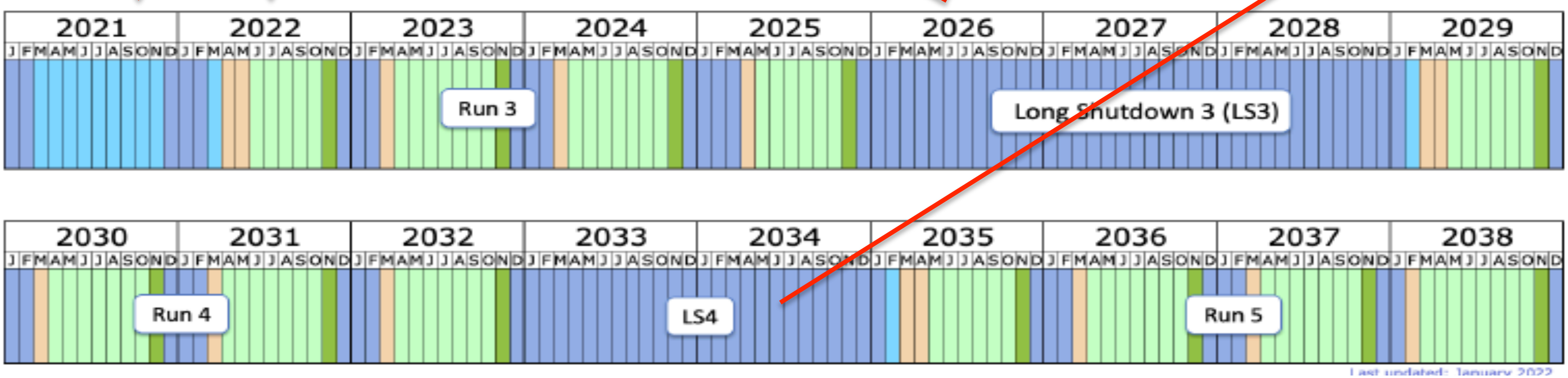
ALICE LS3 Upgrade

ALICE LS4 Upgrade ALICE 3



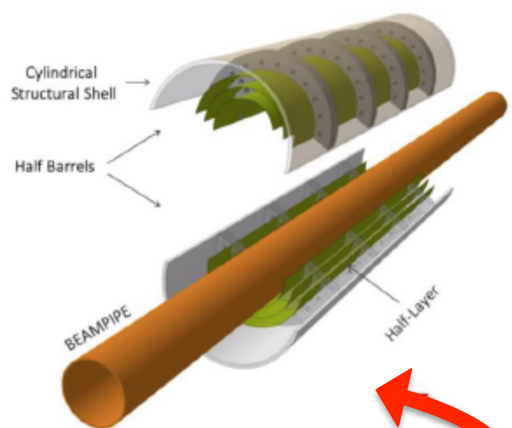


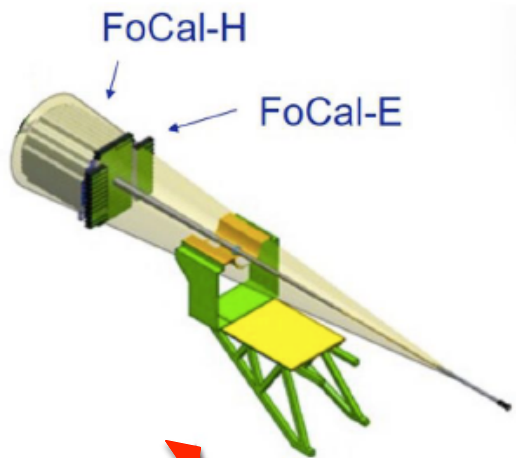




ALICE upgrade in 2026-2028: is under preparations

ITS3





- Large area, thin bent Si pixel MAPS sensors

ITS3

- Ultra-light, a truly-cylindrical Inner Barrel
- x3 less material
- Improves measurement of low p_T charm and beauty hadrons and low-mass dielectrons .

Forward Calorimeter

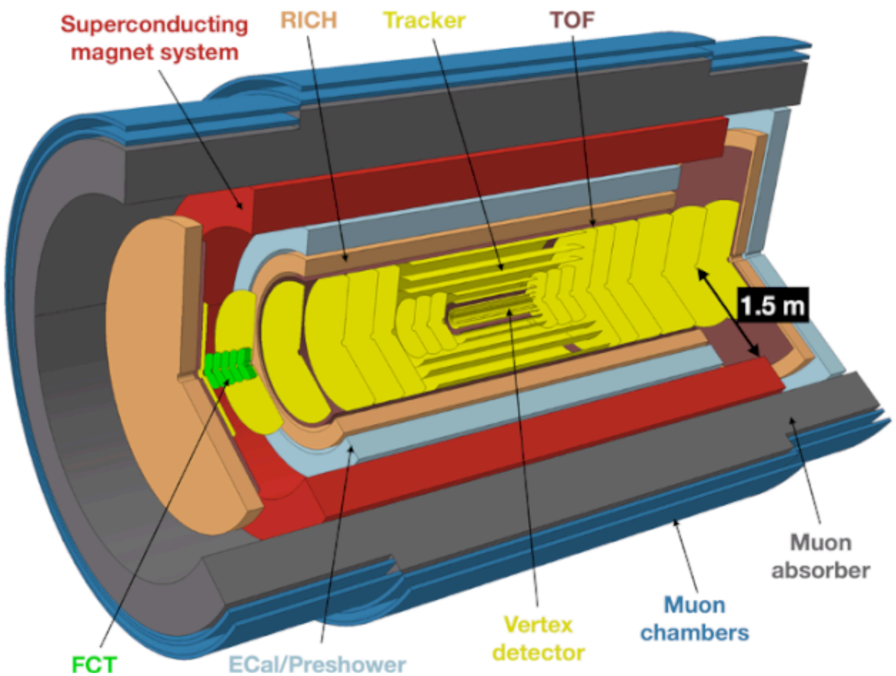
- high-granularity readout for direct photons at $3.2 < \eta < 5.8$
- to probe gluon density down to x ~ $5x10^{-6}$

[*LoI: CERN-LHCC-2019-018*]

ALICE 3 in Run 5

expected > 2031–?

- ALICE 3 -- a completely new experiment, fast with precise tracking and timing.
- A large-acceptance, ultra-low material budget, all-pixel silicon tracking system



- Future HI programme at the LHC:
  - ✧ Low-mass dileptons and soft hadrons (<50 MeV)
  - ✧ Evolution of QGP and chiral symmetry restoration
  - ✧ Exotic (multi-)heavy-flavoured hadrons, hadronisation mechanisms
  - ✧ Hadron correlations and interaction potentials
  - ✧ searches beyond-the-Standard-Model
  - ❖ see also talk at this conference by Yury Kharlov

Letter of Intent for ALICE 3 was reviewed by the LHCC in March 2022

THANK YOU FOR ATTENTION!

ALICE results at this conference "NUCLEUS–2022" :

who	talk	when
Sergey Kiselev	Hadronic resonance production with ALICE at the LHC	13 July 2022, 15:40
Gleb Romanenko	Femtoscopic analysis of identical charged kaons in Pb–Pb collisions at 5.02 TeV with ALICE –	13 July 2022, 15:20
Dmitry Blau	Direct photon and neutral meson production results from ALICE experiment	12 July 2022, 12:10
Dmitri Peresunko	Performance of the precise electromagnetic calorimeter ALICE/PHOS and upgrade plans	12 July 2022, 13:30
Alexander Borissov	Production of Sigma0 hyperon and search of Sigma0-hypernuclei at LHC with ALICE	12 July 2022, 12:30
Yury Kharlov	Probing the hot QCD matter via quarkonia at the next-generation heavy-ion experiment at LHC	12 July 2022, 13:10