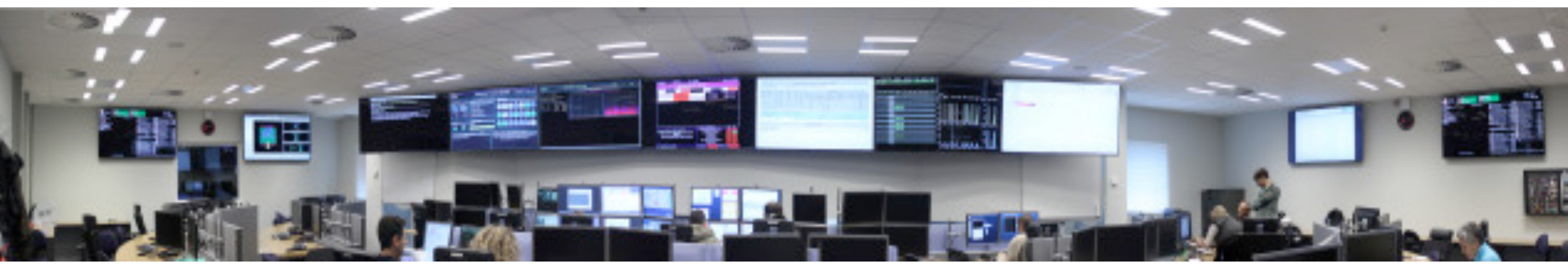
Recent Highlights on Hadron Collisions with ALICE at the LHC



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Scientific Session at JINR, Dubna, dedicated to the 300th anniversary of the Russian Academy of Sciences

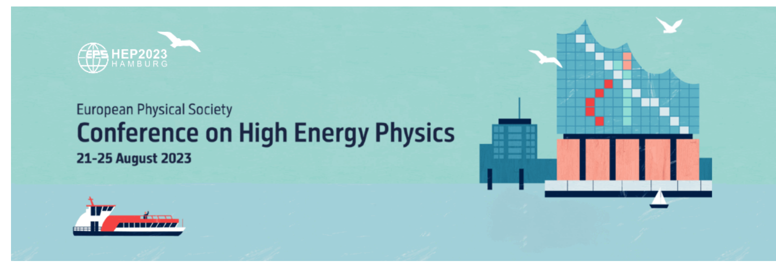
Dubna, Russia, 04.04.2024, 15:30-15:50

Supported by Saint Petersburg State University, project ID: 95413904

A wealth of ALICE results in 2023 at major conferences, among them:

Quark Matter 2023 conference,
3–9 Sept 2023, Houston, Texas, 77010, USA
1 plenary talk
- 30 parallel talks
- 60 posters

European Physical Society Conference on High Energy Physics (EPS-HEP) 2023
Germany, Hamburg, (2023-08-21 - 2023-08-25) -- 27 talks



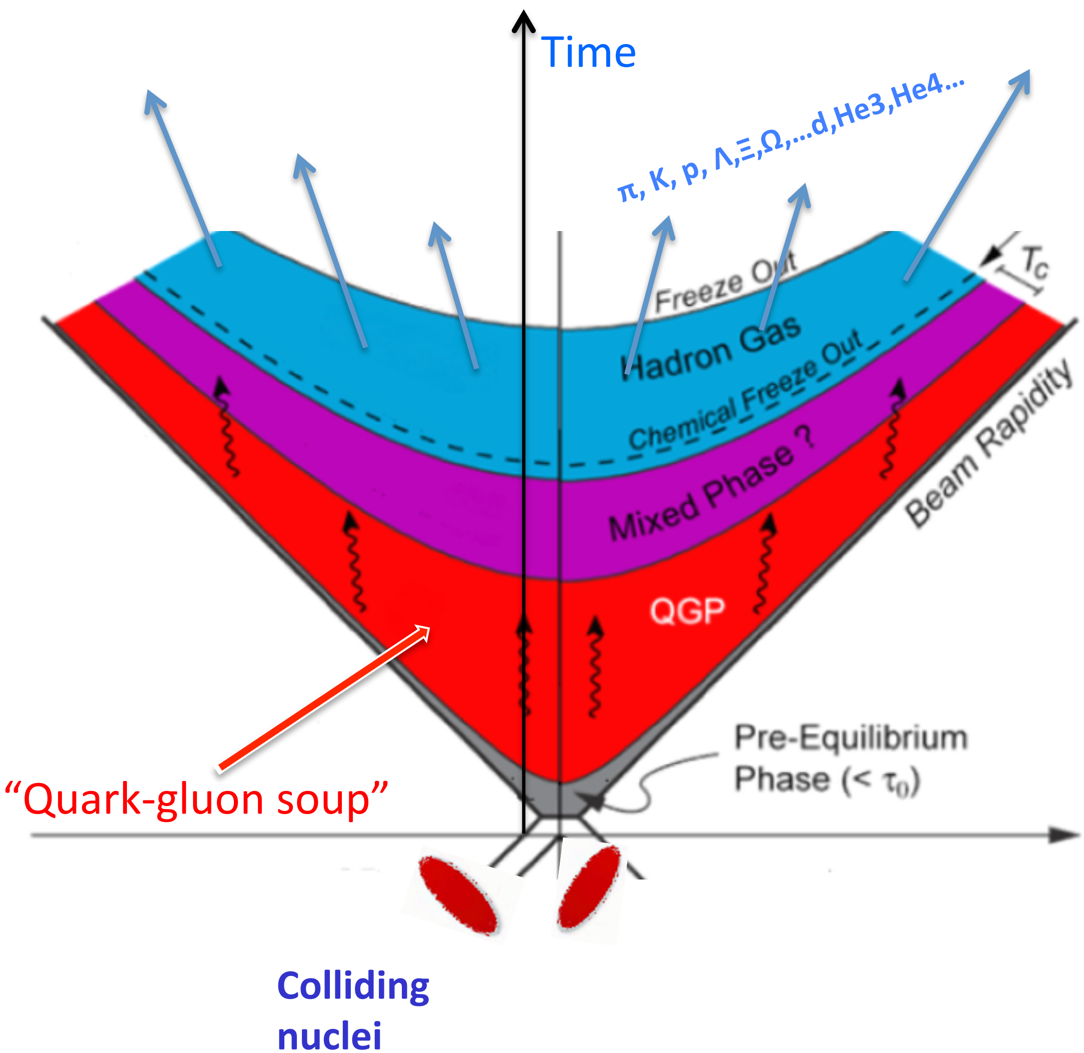
The 7th International Conference on the Initial Stages of High-Energy Nuclear Collisions: Initial Stages 2023
Copenhagen, Denmark, (2023-06-19 - 2023-06-23) -- 2 plenary talk + 1 flash plenary, 10 parallel session talks, 13 posters

- See also "The ALICE experiment. A journey through QCD" , arXiv:2211.04384
- So, this talk is focused only on just few topics:

Layout of this talk

- Introduction.
- Some exotica: 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, p-Pb and Pb–Pb collisions at midrapidity
  - ✧Charm in pp, p-Pb and Pb-Pb collisions
- Two-body scattering involving strange and charm hyperons
- Run 3 data taking, performance and the 1st results
- ALICE @LHC Schedule and challenges for Run 4

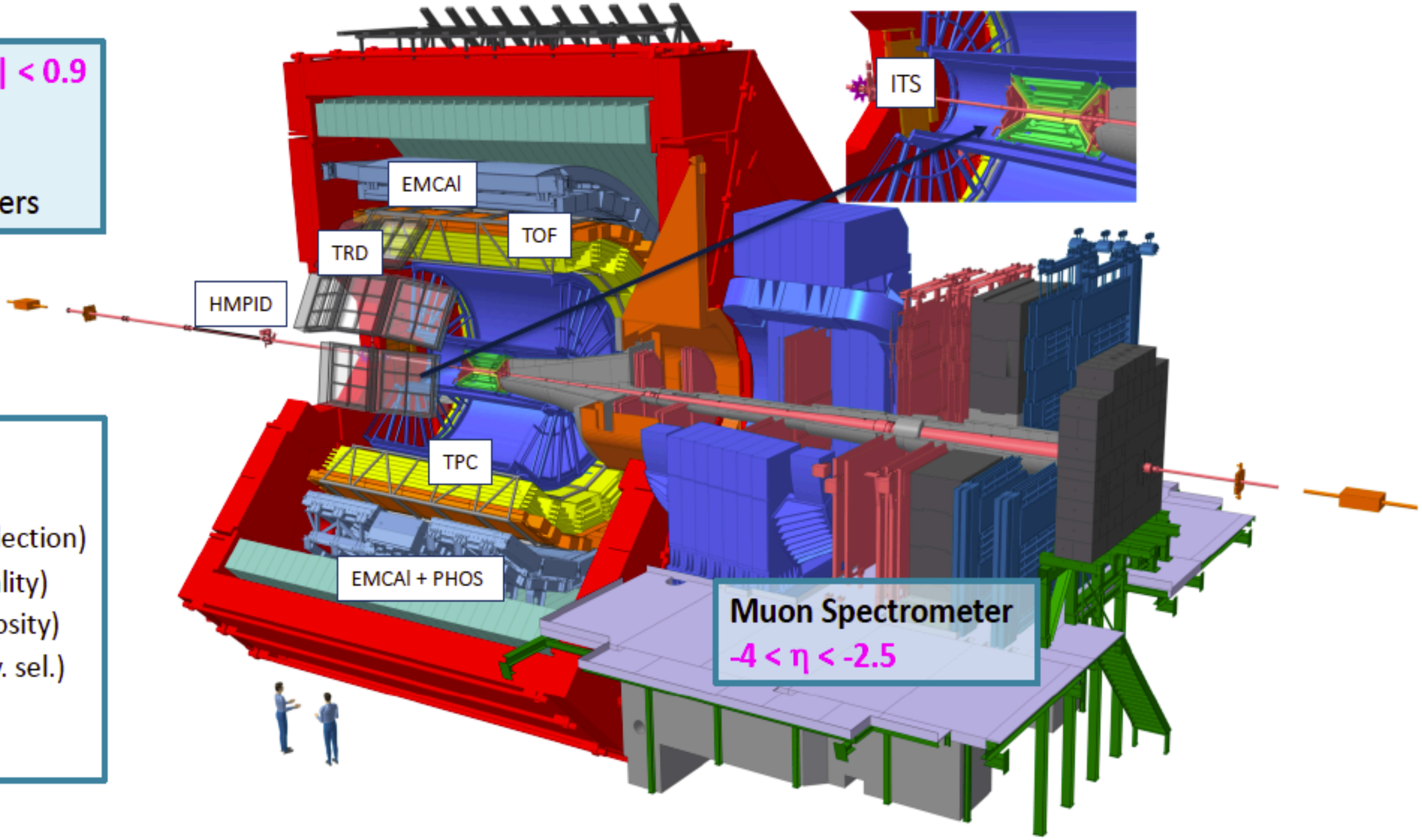
Space-time stages of nucleus-nucleus collision



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

ALICE in Run 1 and Run 2 in 2009-2018

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 in Run 1 and Run 2 in 2009-2018

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

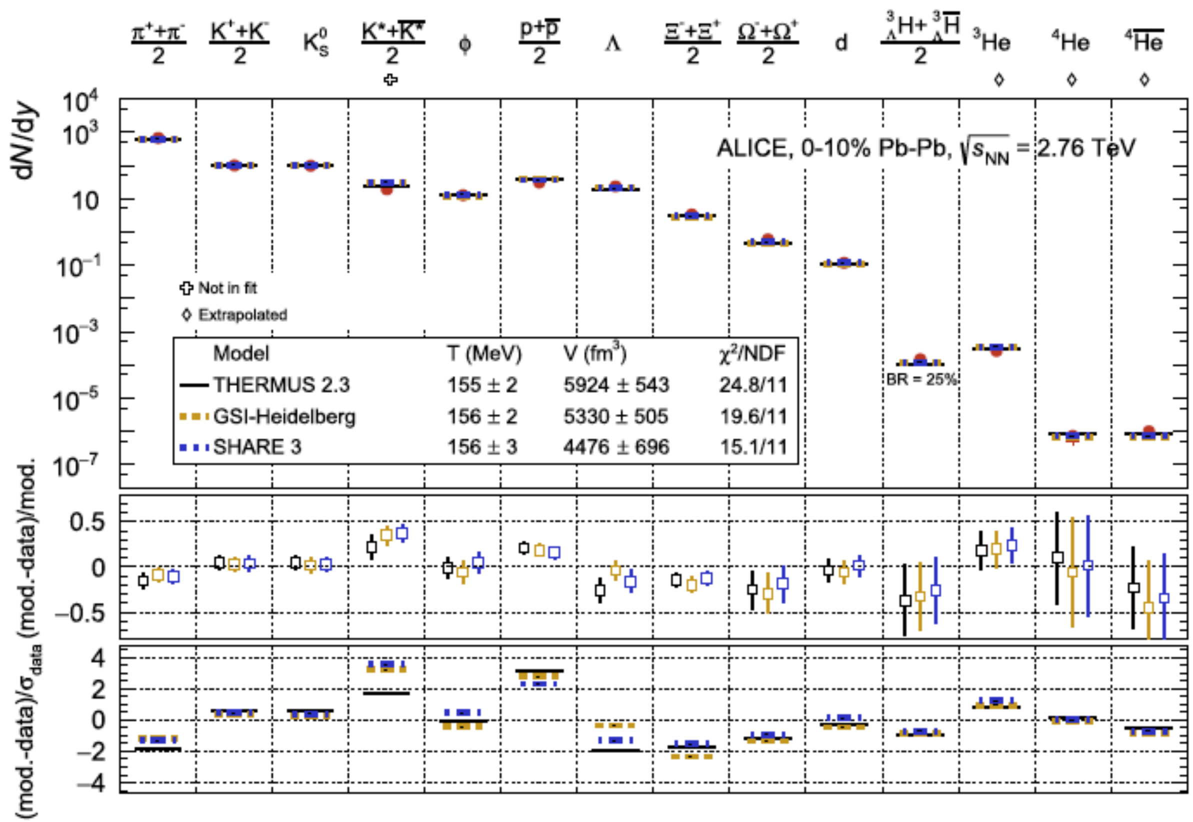
- **ALICE Collaboration: 40 countries, 169 institutes, 1977 members**
- **Publications: total 475**

✓ Some exotica:

QGP and formation

of light (anti) (hyper) nuclei

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



Pb–Pb collisions

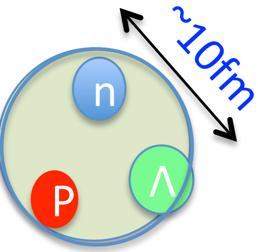
- $^4\overline{He}$ is the heaviest antinucleus observed
- What is the mechanism of light (anti)nuclei and (anti)hypernuclei production in hadron collisions?
- Statistical hadronisation model (SHM)[2] vs. Coalescence?

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

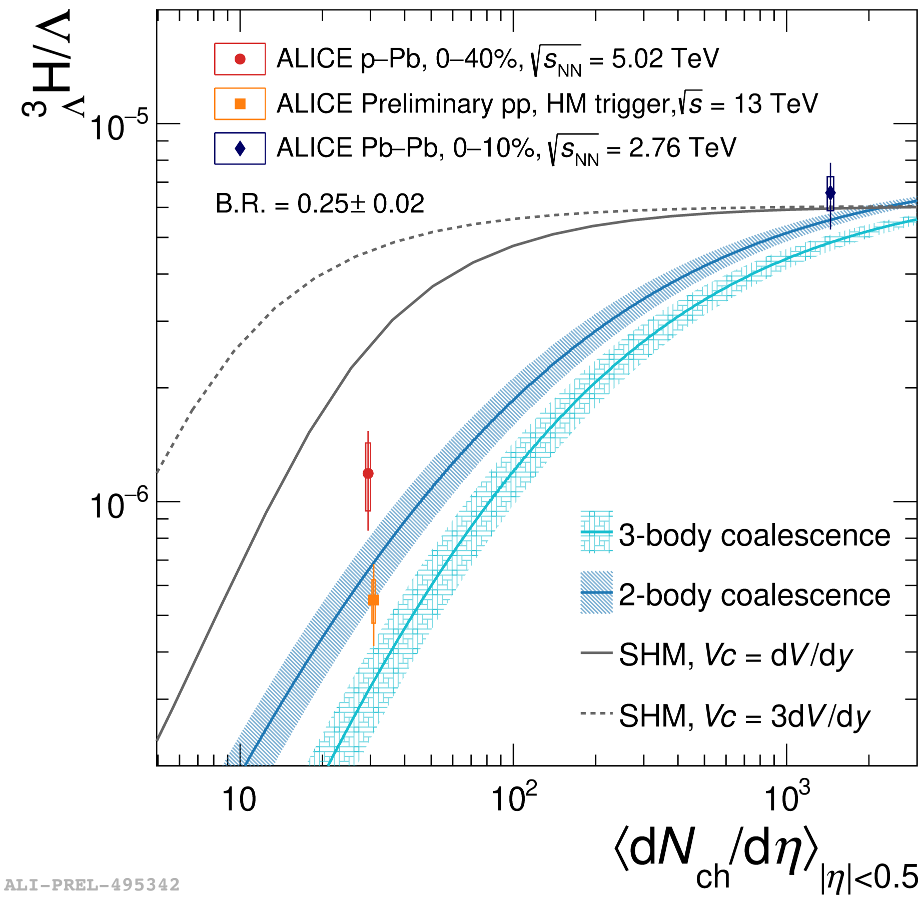
[2] A.Andronic, P.Braun-Munzinger,R. Redlich, J.Stachel, Nature 561 (2018) 321

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



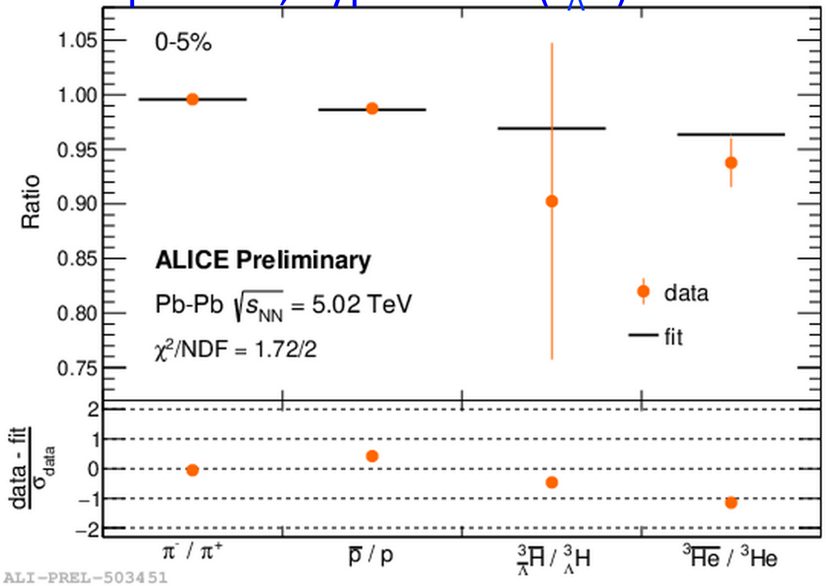
- The 1st measurement in p–Pb collisions at the LHC of hypertriton, reconstructed via the decay channel $^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$
  - The lightest hypernucleus (p,n, Λ) (mass ≈ 2.991 GeV/c^2)
  - The binding energy : **B_{Λ} ≈ 130 keV**
- **Fragile but surviving at chemical freeze-out 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 – it is expected in the upcoming LHC Run 3 with the upgraded ALICE

New!

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

ALICE
A JOURNEY OF DISCOVERY

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



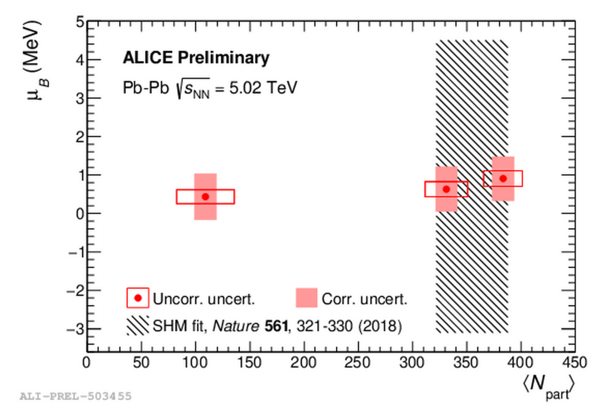
Fit using the relation obtained from SHM.

- 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

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
  - Most precise measurement in Pb-Pb at LHC



✓Jets in QGP medium

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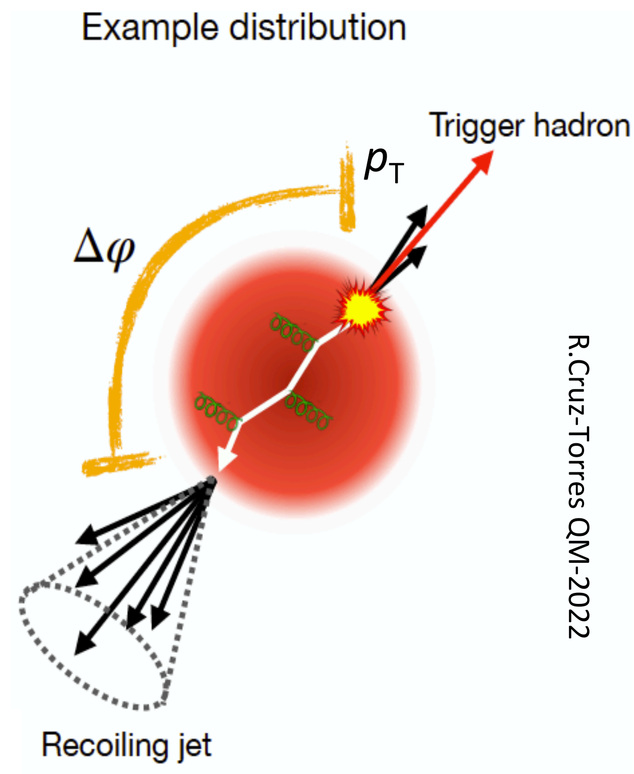
Jets as probes
for the study of the deconfined matter

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)- th**e azimuthal correlation between the trigger hadron and recoil jet

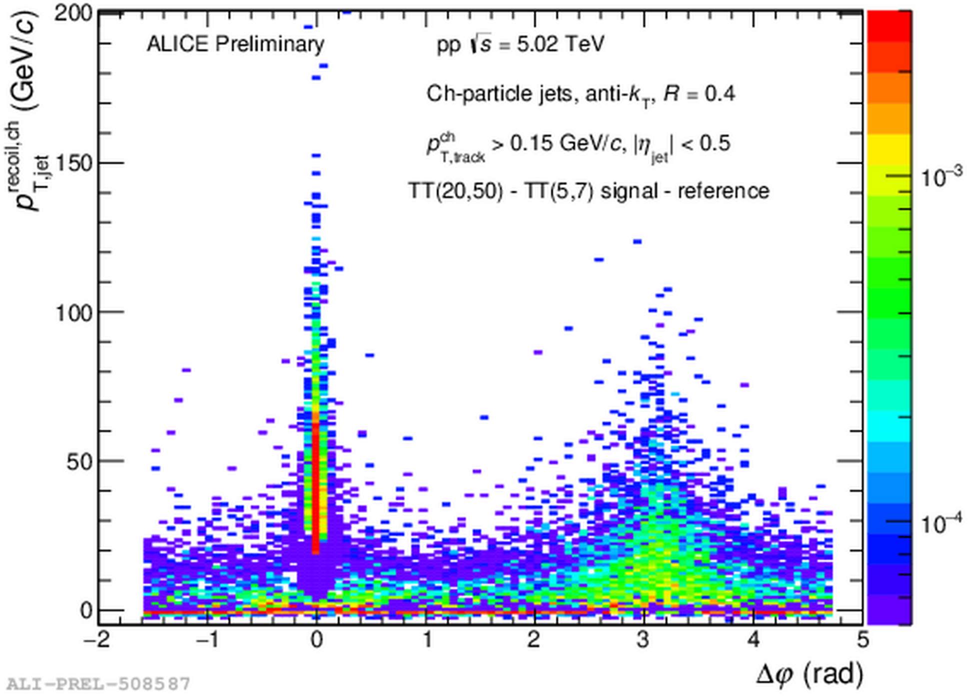
$$\Delta_{recoil}(p_T, \Delta\phi) = \frac{1}{N_{trig}} \frac{d^2 N_{jet}}{dp^{ch}_{T,jet} d\Delta\phi}\bigg|_{TT_{sig}} - c \cdot \frac{1}{N_{trig}} \frac{d^2 N_{jet}}{dp^{ch}_{T,jet} d\Delta\phi}\bigg|_{TT_{ref}}.$$

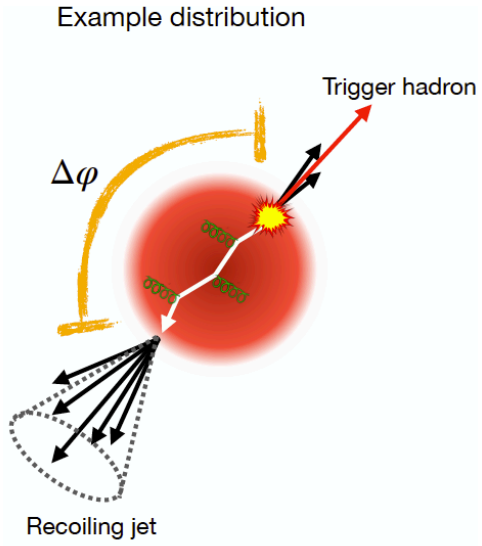
New!

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





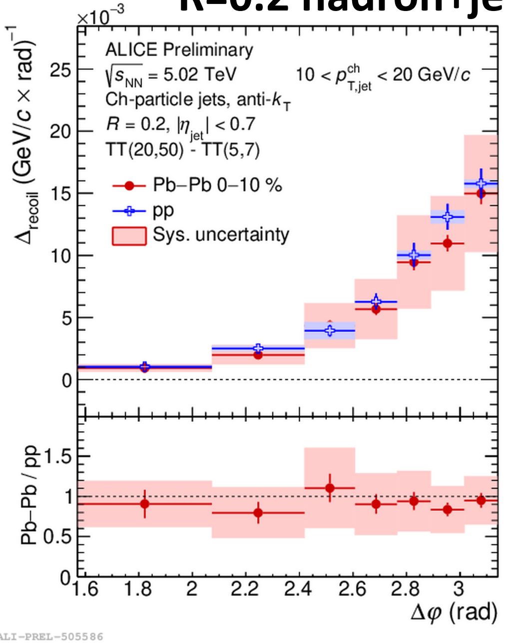
R.Cruz-Torres QM-2022

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

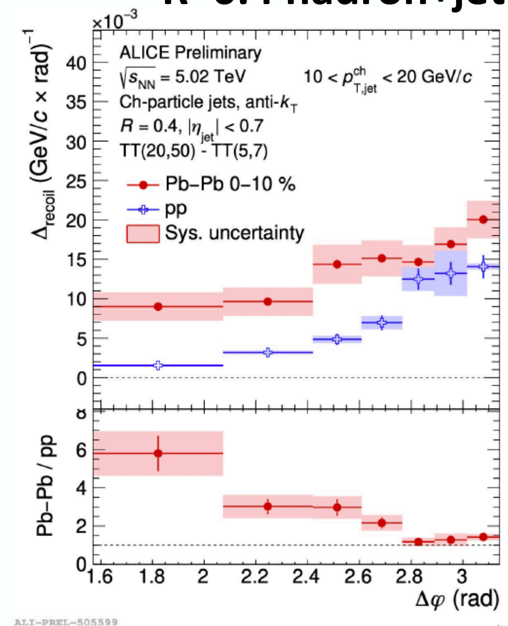
New!

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

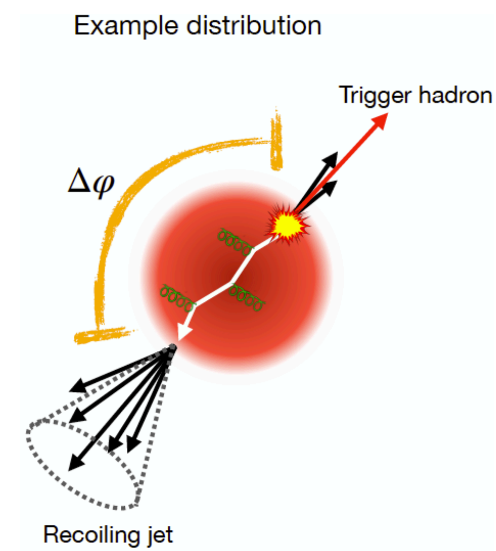
R=0.2 hadron+jet



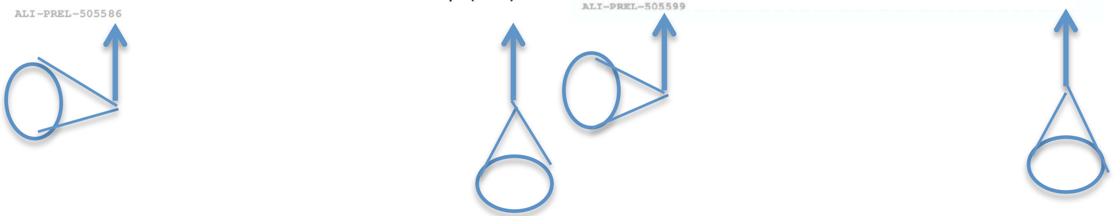
R=0.4 hadron+jet



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.

✓ Strangeness and charm

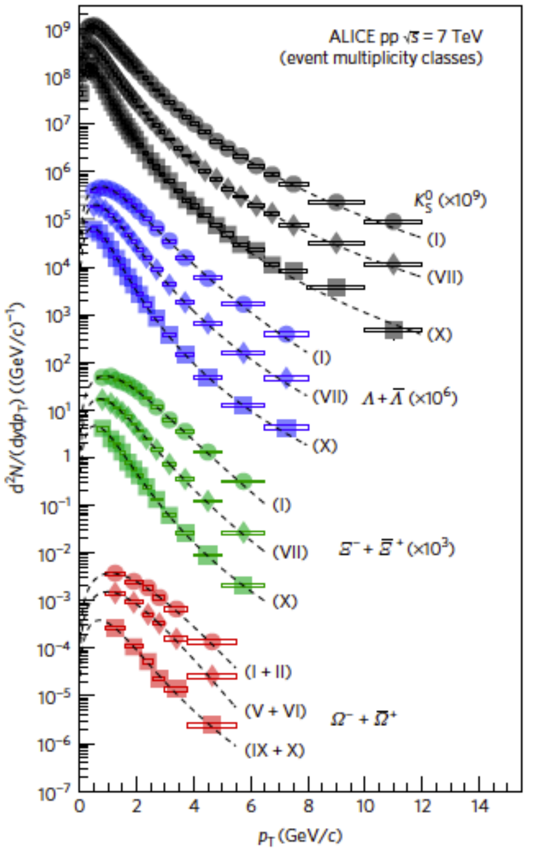
in collisions of large and small systems

✧ **Strangeness in *pp, p-Pb and Pb–Pb* collisions at midrapidity**

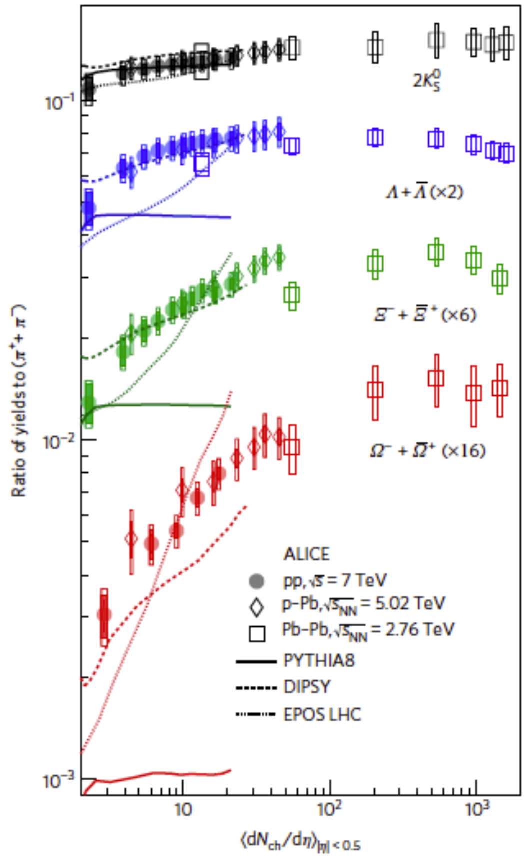
Enhanced production of multi-strange particles in high-multiplicity pp, p–Pb and Pb-Pb collisions

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

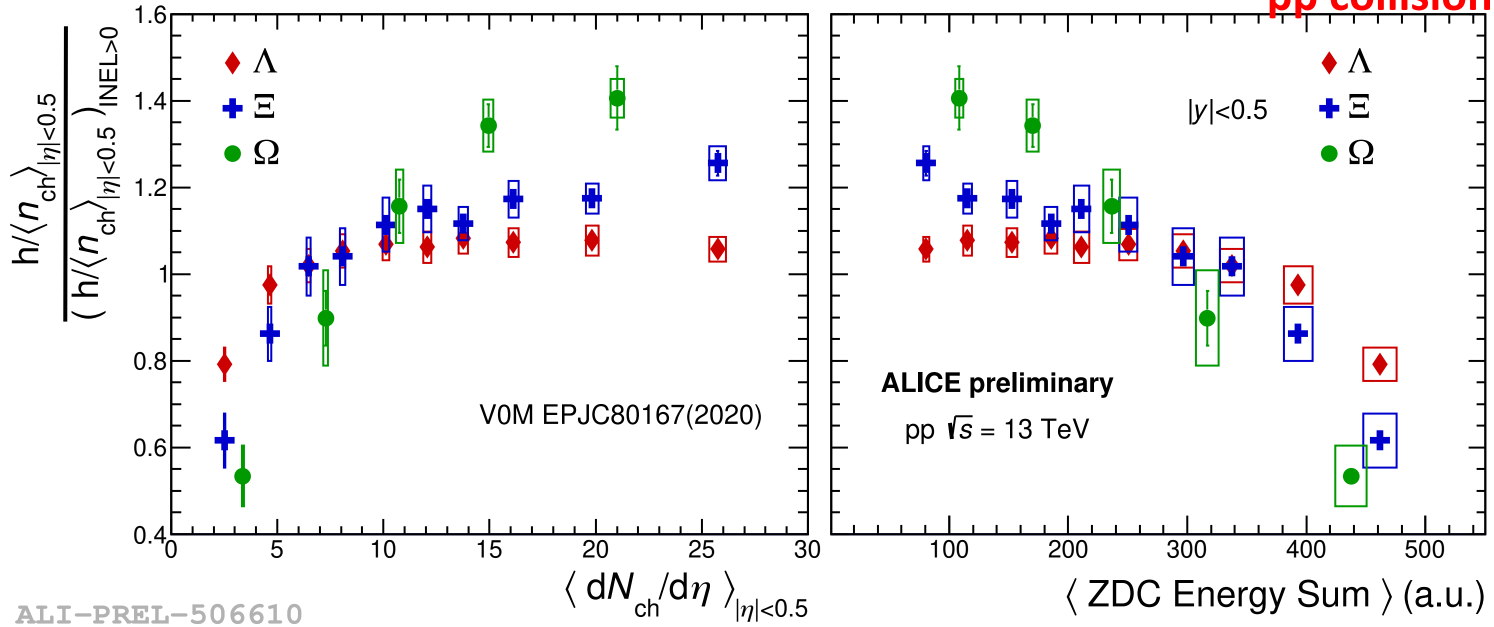
- The enhancement is larger for particles with larger strangeness content
- No dependence on the LHC collision energy

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

New!

Strangeness at midrapidity vs multiplicity and effective energy

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)

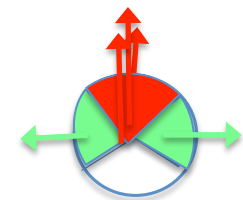
- Yields of multistrange baryons are anticorrelated with the forward energy, measured by ZDC
- Correlated with the effective energy available in the event for particle production
- Role of the initial stages and number of partonic collisions (MPI) in strangeness production?

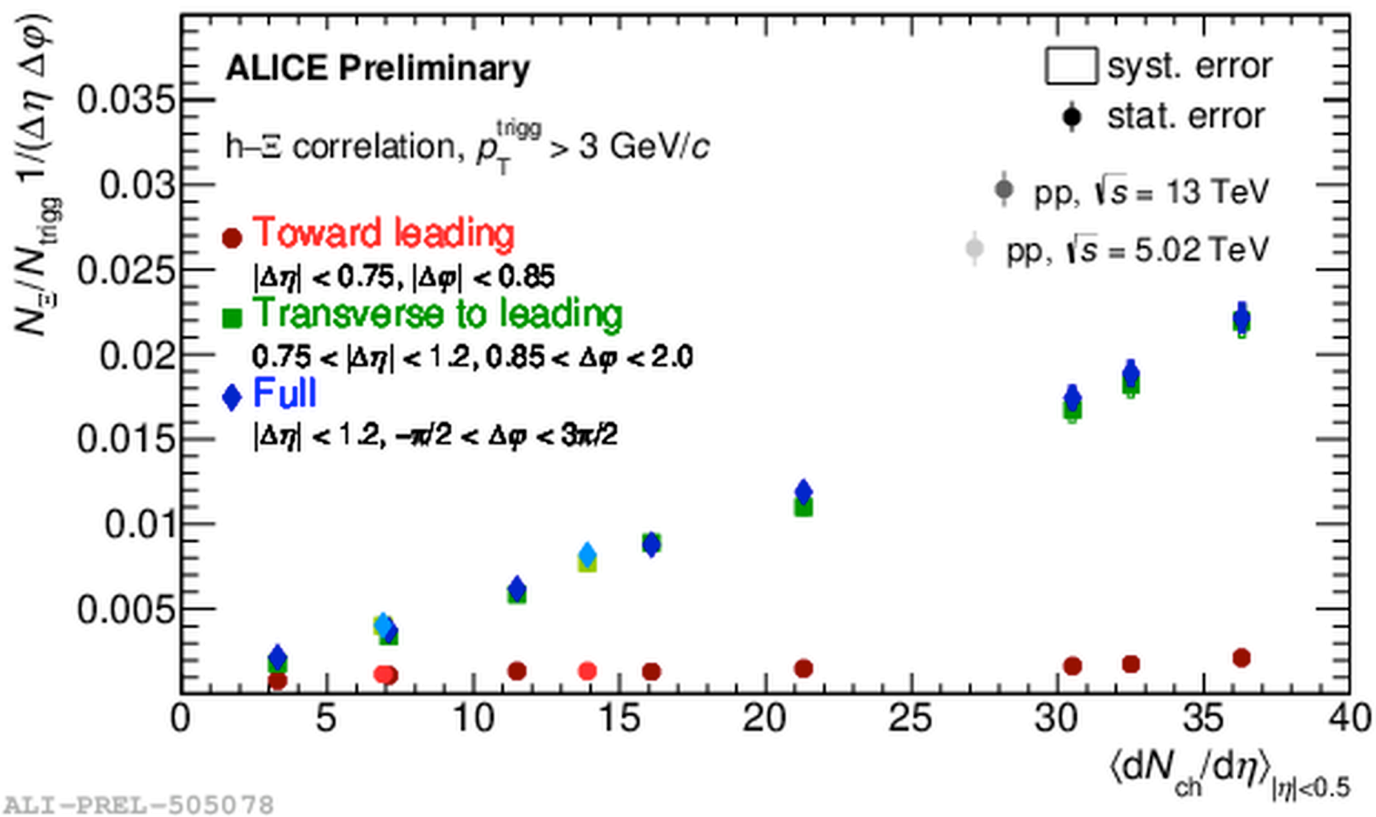
New!

Strangeness production in jets and out of jets

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

Ξ vs. multiplicity





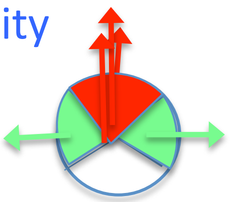
Near-side jet,
out-of-jet
and full yield of Ξ
vs. multiplicity

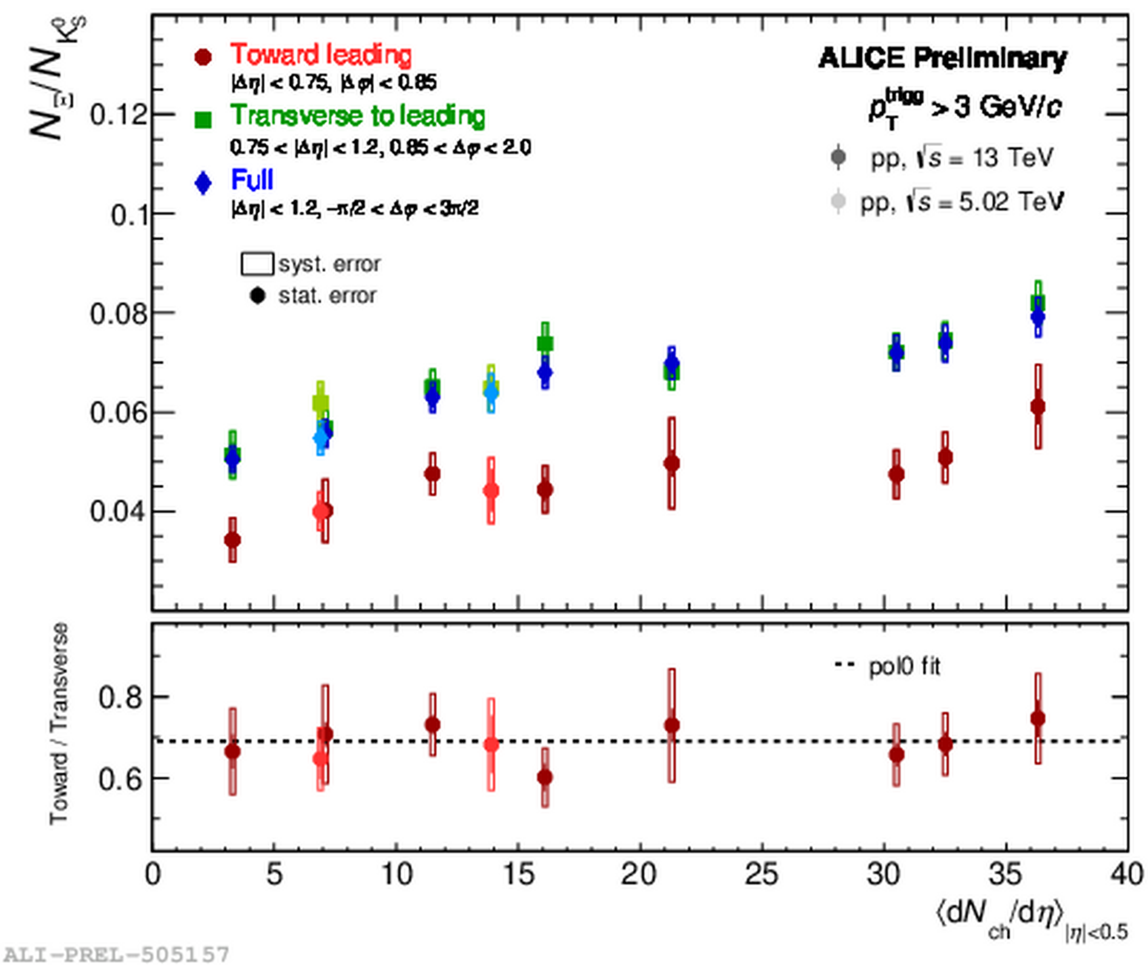
- **For Ξ mesons the near-side leading jet yield is practically flat with multiplicity**
- **Linear growth** of Ξ yield with multiplicity **in transverse** to leading

New!

Strangeness production in jets and out of jets

Ξ/K^0_s ratios vs. multiplicity





Near-side jet, out-of-jet and inclusive Ξ/K^0s yield ratios vs. multiplicity of charged particles

➢ **A week dependence on multiplicity in both cases**

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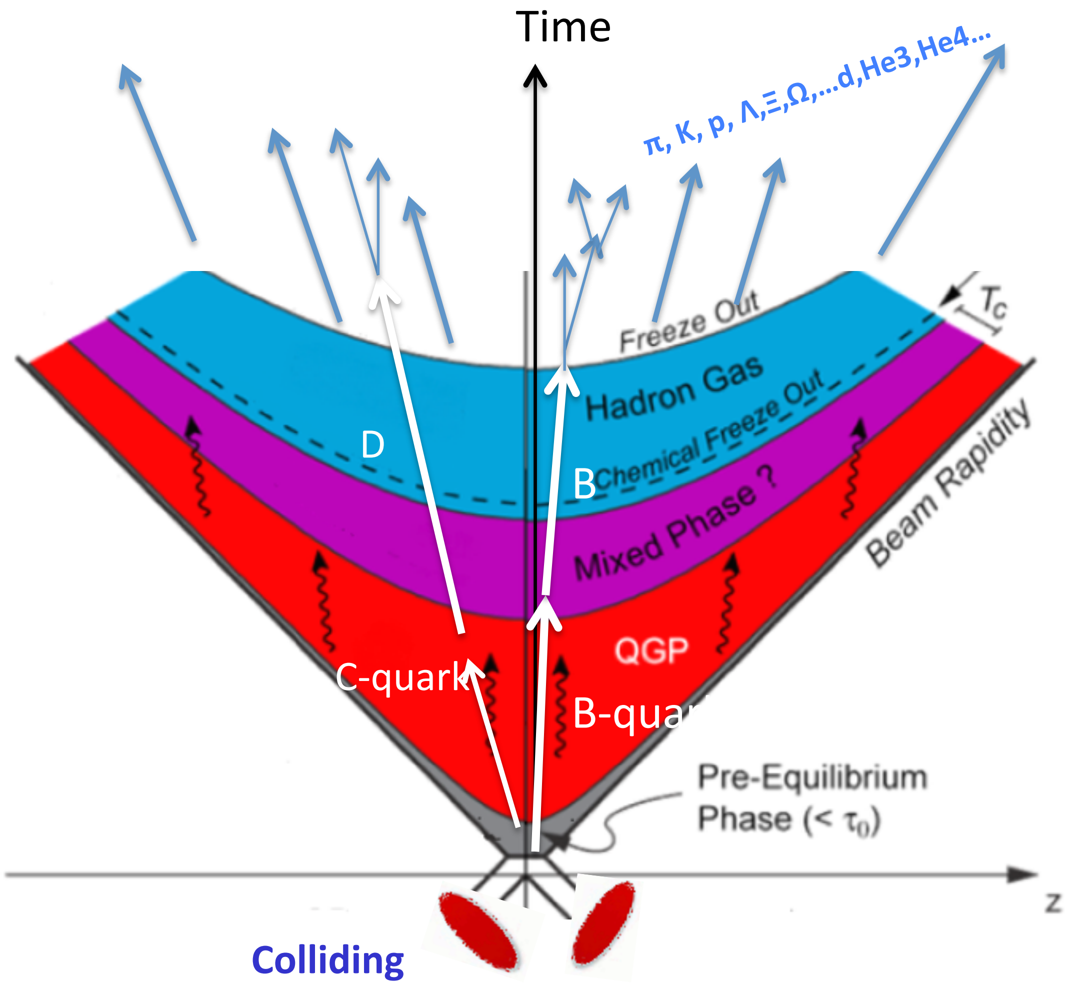
✓ Strangeness and charm

in collisions of large and small systems

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

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



Why open heavy flavour is interesting?

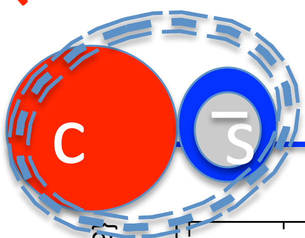
- ✓ Production is relevant to early stages of collision
- ✓ Theoretical calculation of production in perturbative QCD
- ✓ Transport of c-quark through the medium: collisions and radiative e-losses ?
- ✓ Hadronisation mechanism?

Charm measurements in ALICE:

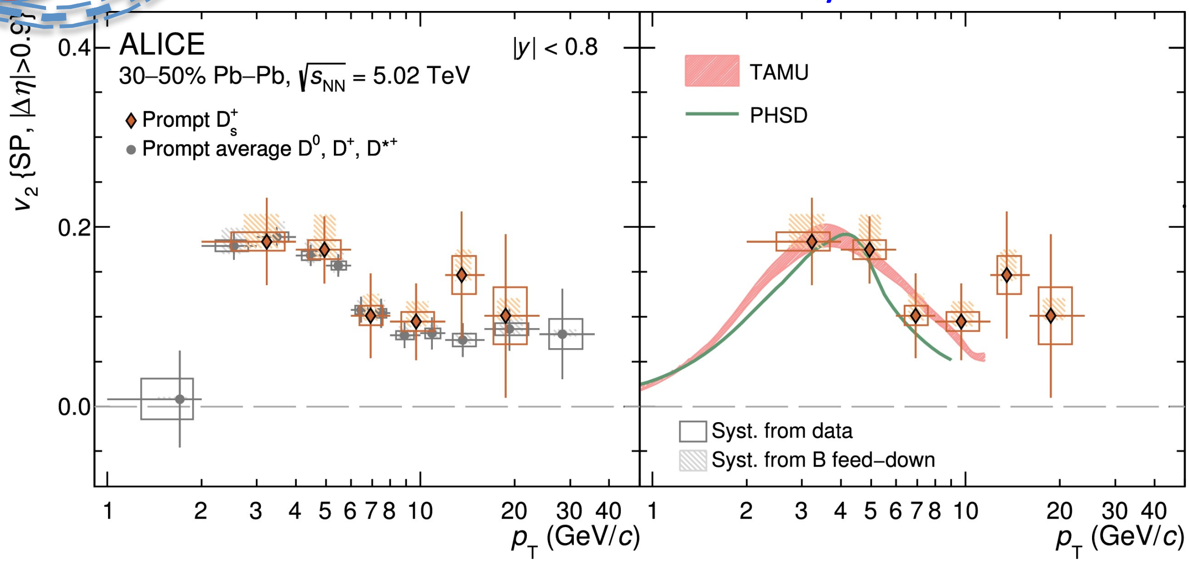
D-mesons (D^0, D^+,D_s^+, D^*) and charm baryons (Λ_c^+, Σ_c^{++}, Σ_c^+, Σ_c^0, Ξ_c^+, Ξ_c^0, Ξ_c ,Ω_c^0)

New!

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



Physics Letters B 827 (2022)



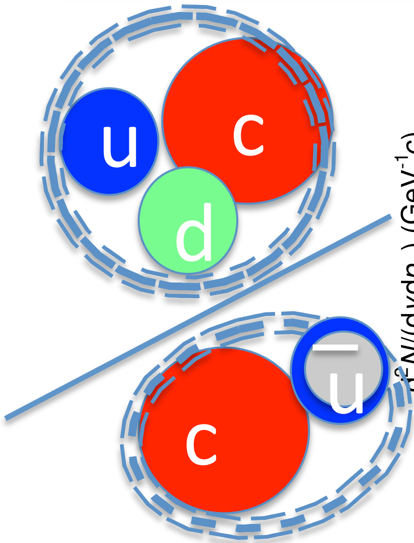
Pb–Pb collisions

- 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

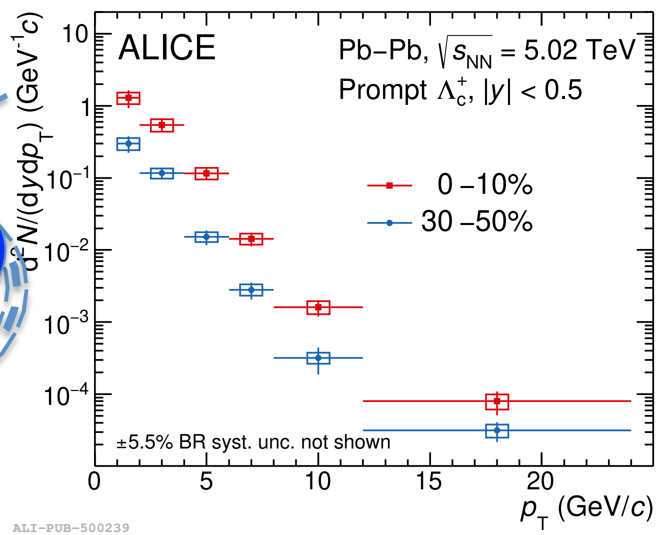
New!

Constraining hadronization mechanisms with Λ^{+}_{c}/D^{0} production ratios

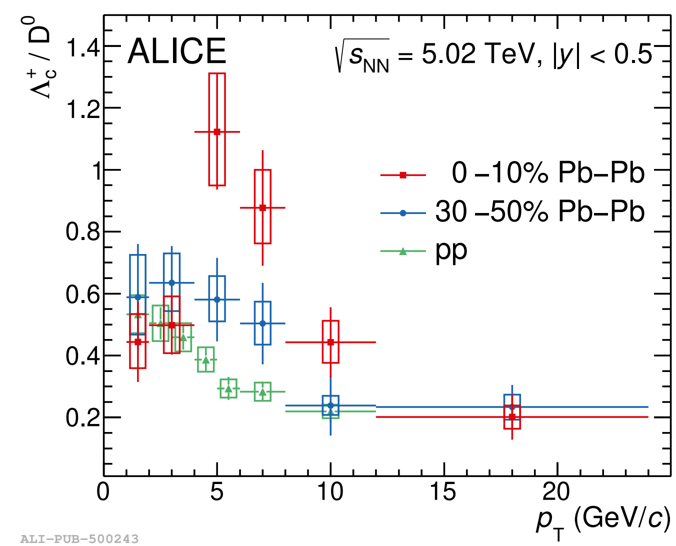
pp and Pb–Pb collisions



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.

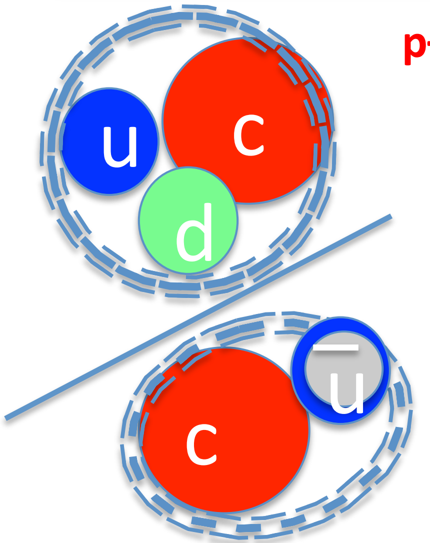
The Λ^{+}_{c}/D^{0} ratio in central and mid-central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV compared with the results obtained from pp collisions [1]

➢ Λ^{+}_{c}/D^{0} - ratio is sensitive to hadronisation mechanism

[1] ALICE Collaboration, S. Acharya et al.,Phys. Rev. C 104 (2021) 054905.

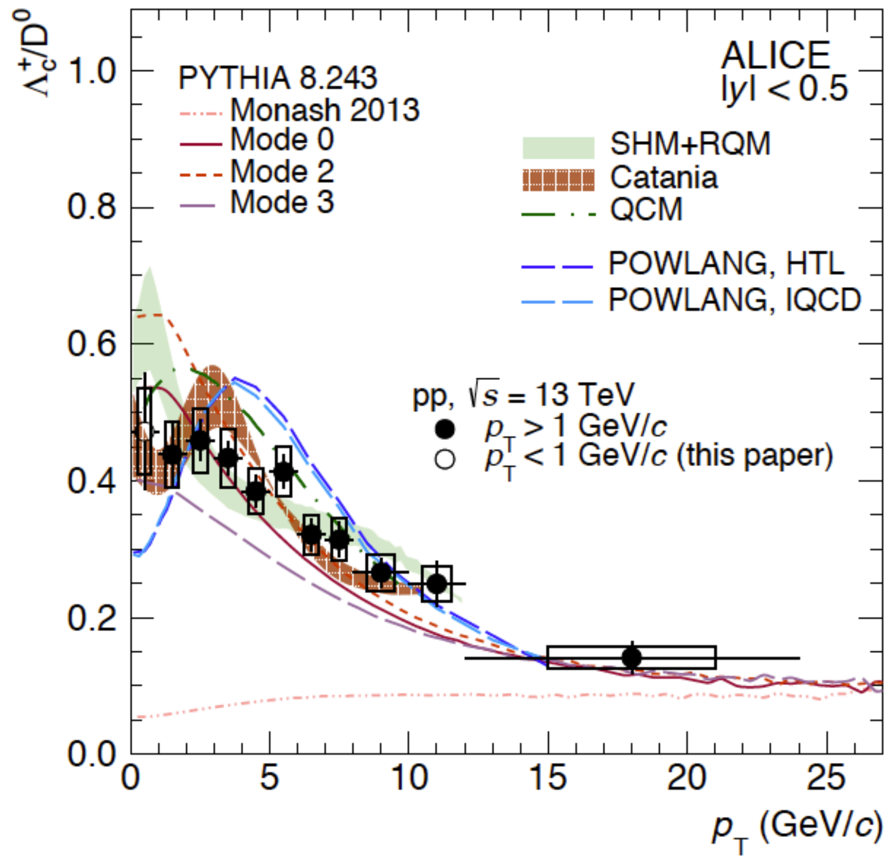
New!

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



p–p collisions

The Λ^+_c/D^0 ratio as a function of p_T
Is measured in p--p collisions
at 7 TeV (Run1), 5.02 TeV (Run2) and at 13 TeV .
Is also measured in in p-Pb collisions at 5.02 TeV (Run2) and compared with models.



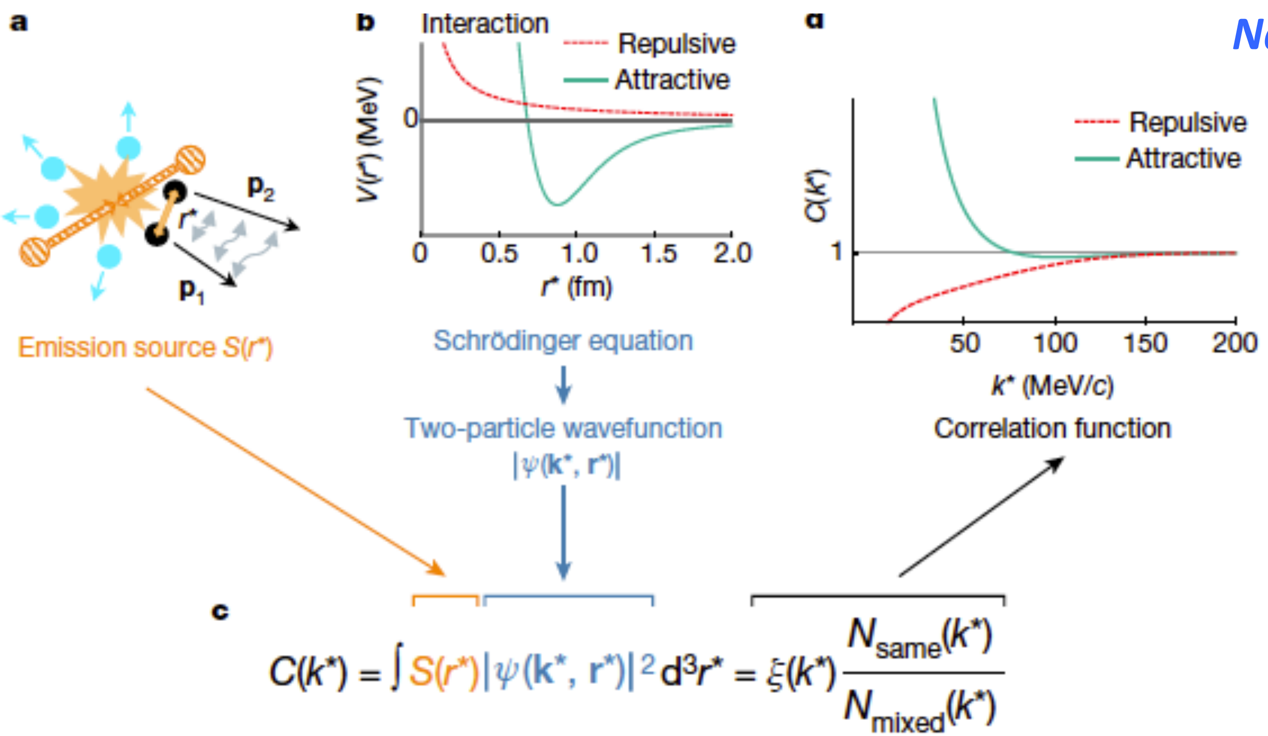
- Behavior is similar to Pb—Pb case
- Λ^+_c/D^0 - ratio is sensitive to hadronisation mechanism
- So far, standard hadronization models fail to reproduce the baryon enhancement[1].

[1] ALICE Collaboration, JHEP 12 (2023) 086. https://arxiv.org/abs/2308.04877,

✓ Two-body scattering involving strange and charm hyperons

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

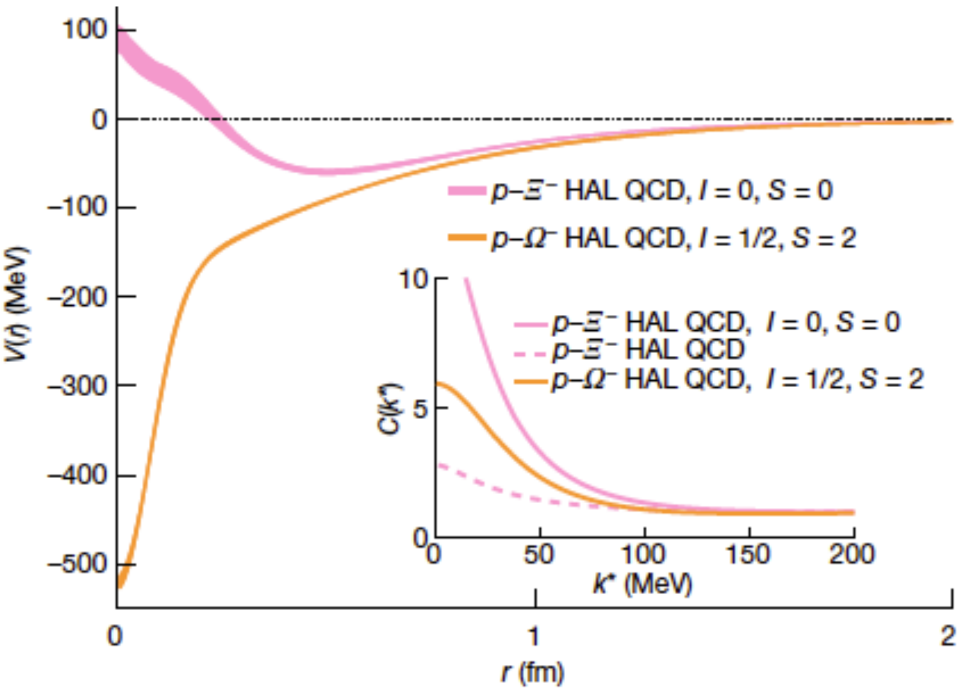
***Nature* 588, 232–238 (2020)**

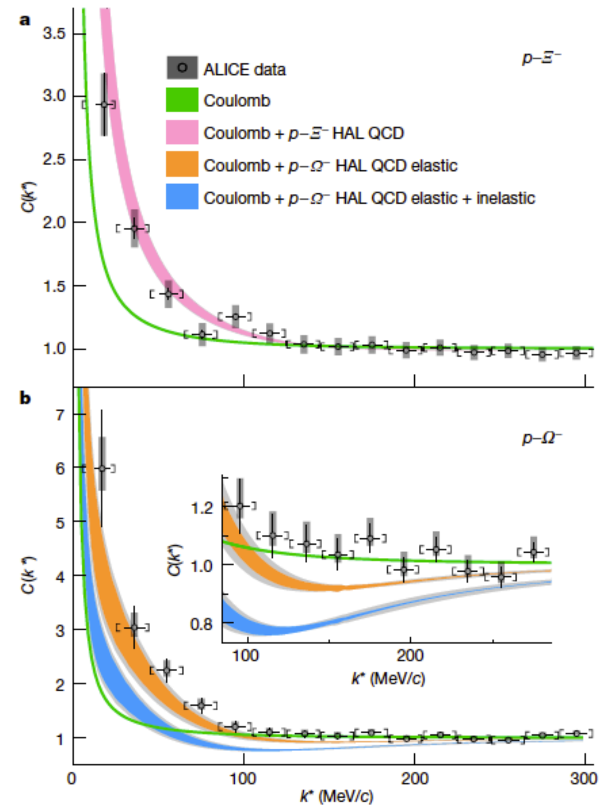


- Absence of interaction C(k*) = 1
- Attractive potential C(k*) > 1
- Repulsive potential C(k*) < 1
- Bound-state formation C(k*) <> 1

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

***Nature* 588, 232–238 (2020)**





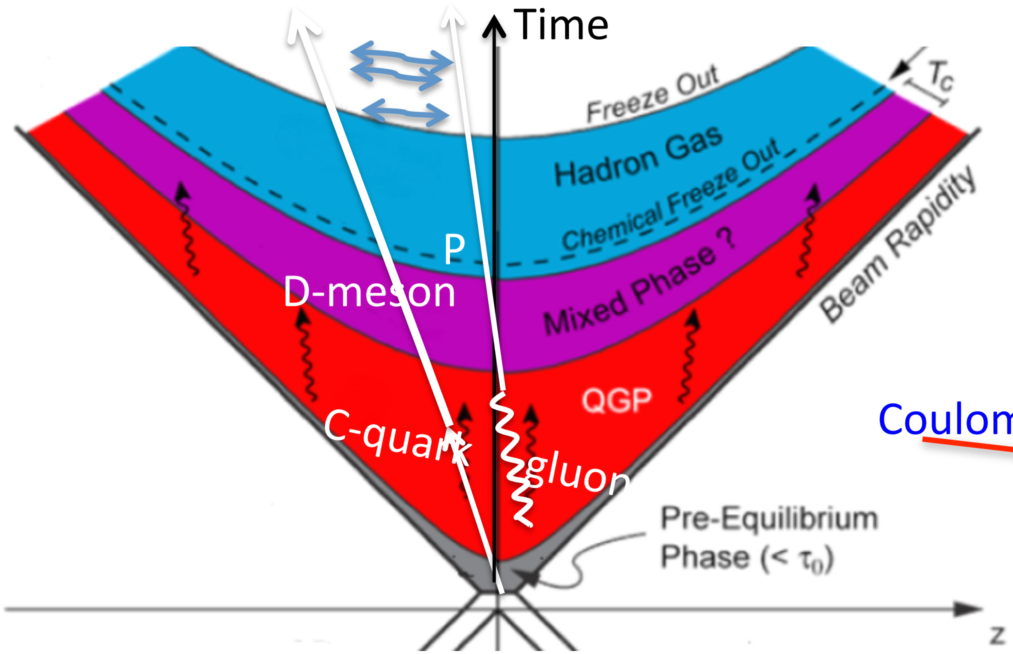
Potentials for the p-Ξ⁻ and p-Ω⁻ interactions predicted by the HAL QCD collaboration.

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

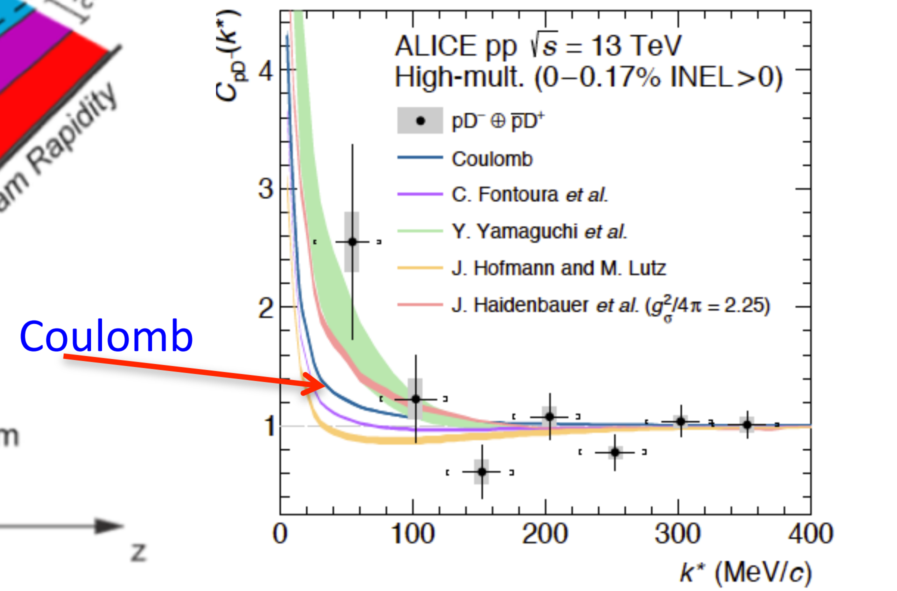
- Important input for the equation of state of neutron stars

New!

Two-body scattering involving *charm* hadrons



***pp* collisions**
Phys.Rev.D 106 (2022) 052010, 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

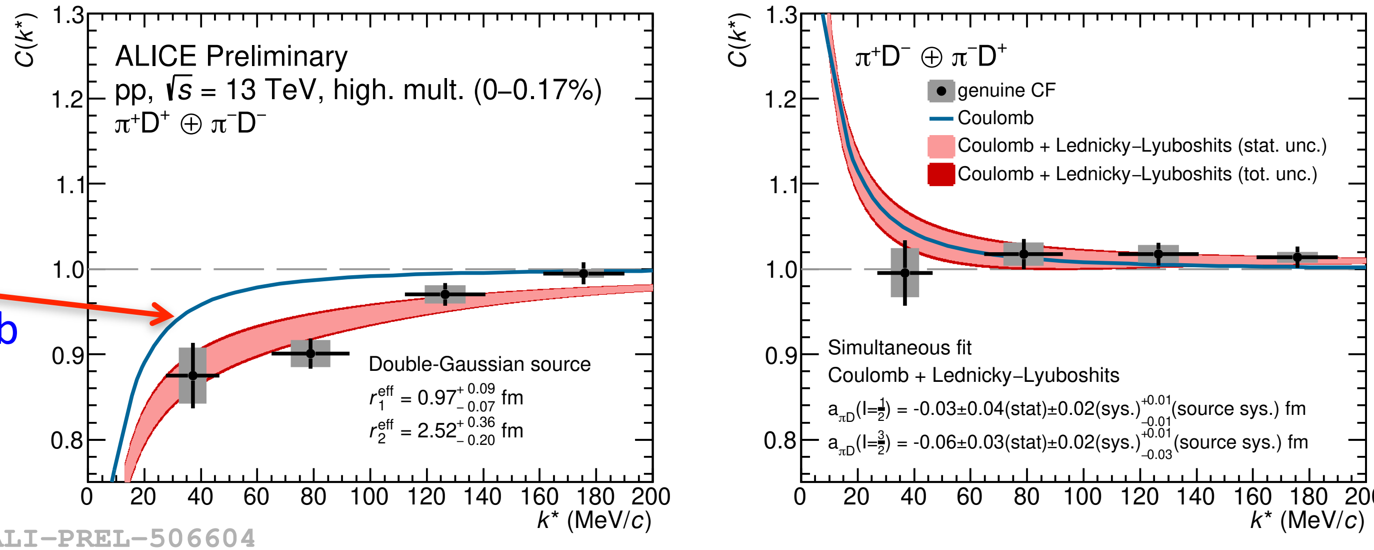
New!

Two-body scattering involving *charm* hadrons

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

pp collisions

Coulomb



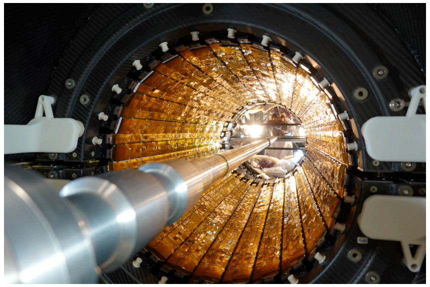
D-π femtoscopy in high multiplicity pp collisions at √s=13 TeV

- 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**

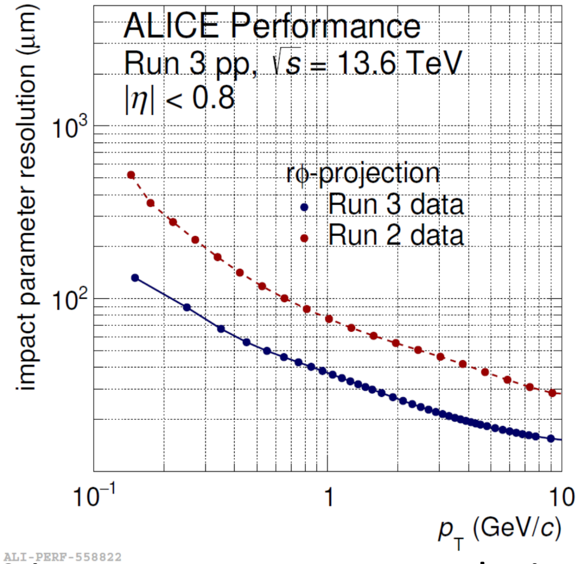
✓ Run 3 data taking, performance

and the 1st results

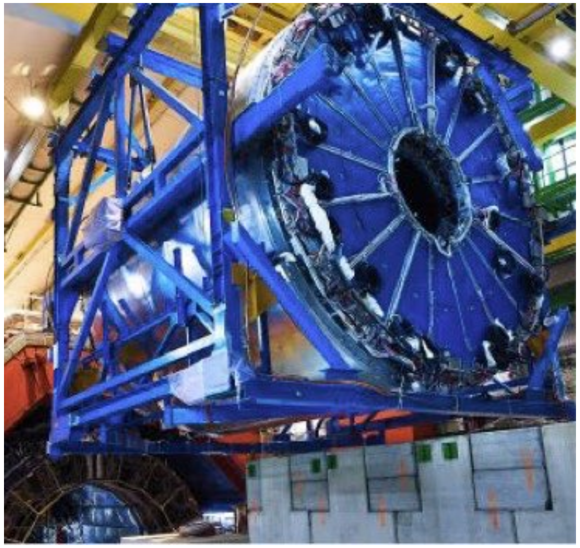
ALICE upgrade for Run 3: Inner Tracking System (ITS2) and GEM TPC



ITS 2 - the new Inner Tracking System (26 May, 2021)



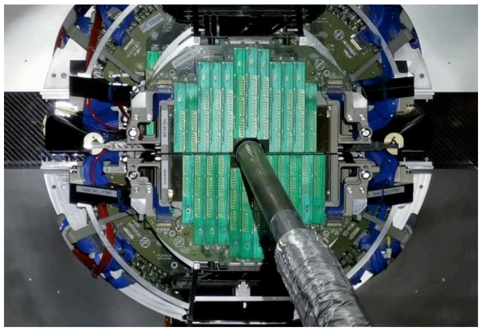
ITS impact parameter resolution

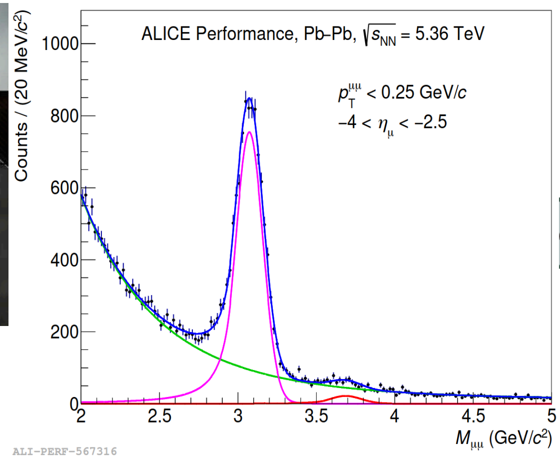


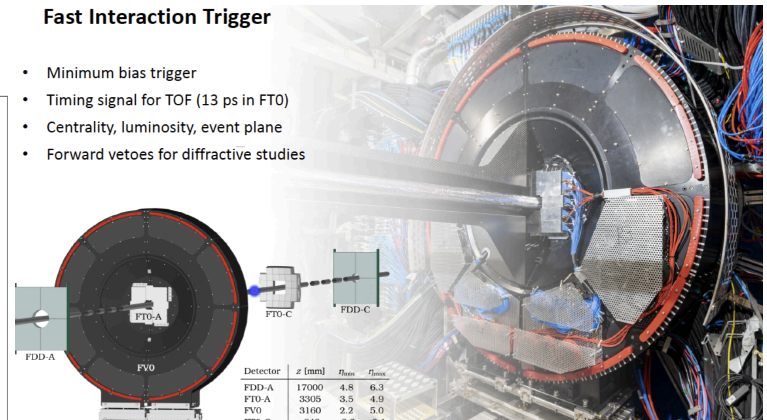
- ITS 2 is the largest pixel detector ever built in CMOS (MAPS) technology: 12,5 Gpixel camera of ~10 m^2 area.
- High tracking precision and vertex resolution,
- Fast readout
- Closer to the IP: first layer at ≈22 mm
- Smaller pixels: 28 x 29 μm^2
- Lower material budget of the Inner Barrel: 0.35% X_0

- TPC with new Gas Electron Multiplier (GEM) technology
- New electronics (SAMPA),
- continuous readout

Pixel Muon Forward Tracker (MFT) and Fast Interaction Trigger (FIT)

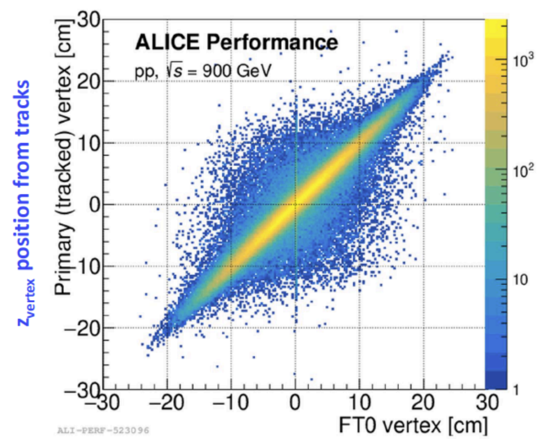






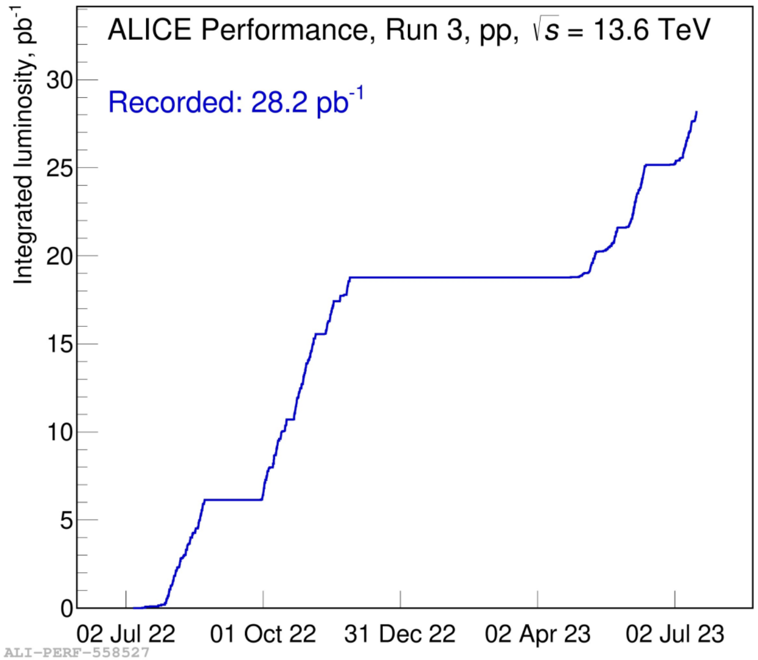
- ➢ The new Muon Forward Tracker, one of ALICE's main subdetectors, was installed in the cavern in December 2020
- ➢ Substantial increase in pseudorapidity coverage for ALICE
- ➢ High pointing resolution for muon tracking

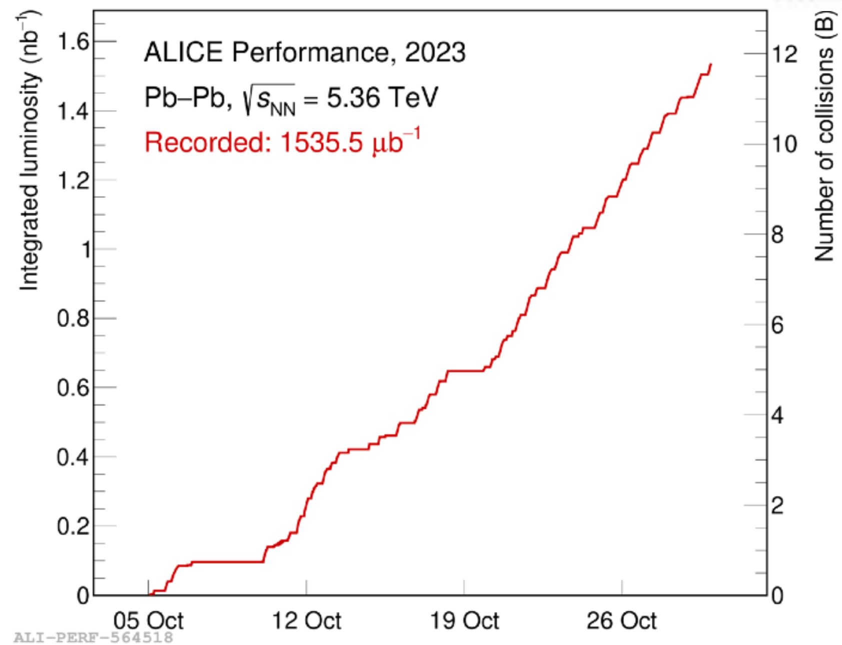
J/ψ signal extraction
di-muon spectra
in Pb-Pb UPCs at 5.36 TeV



z_{vertex} position based on FT0 timing

ALICE Data taking in Run 3



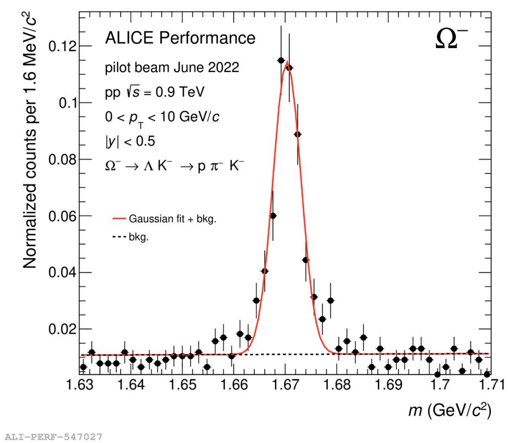


Run 3 (2022 - now)

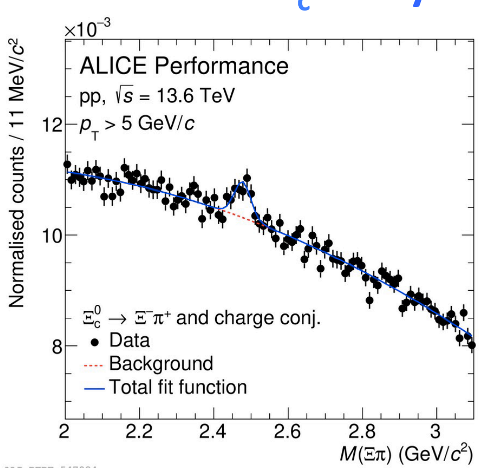
- 2022 pp: 19.3/pb or 1000 billion minimum bias collisions
- 2023 pp: 9.7/pb or 500 billion minimum bias collisions
  (~800 larger sample compared to Run 1-2)
- 2023 Pb-Pb: 1.5/nb or 12 billion minimum bias collisions
  (x40 larger minimum bias sample compared to Run 1-2)

The 1st results in Run 3: Ω and open heavy flavor in *pp* at √s=13.6 TeV

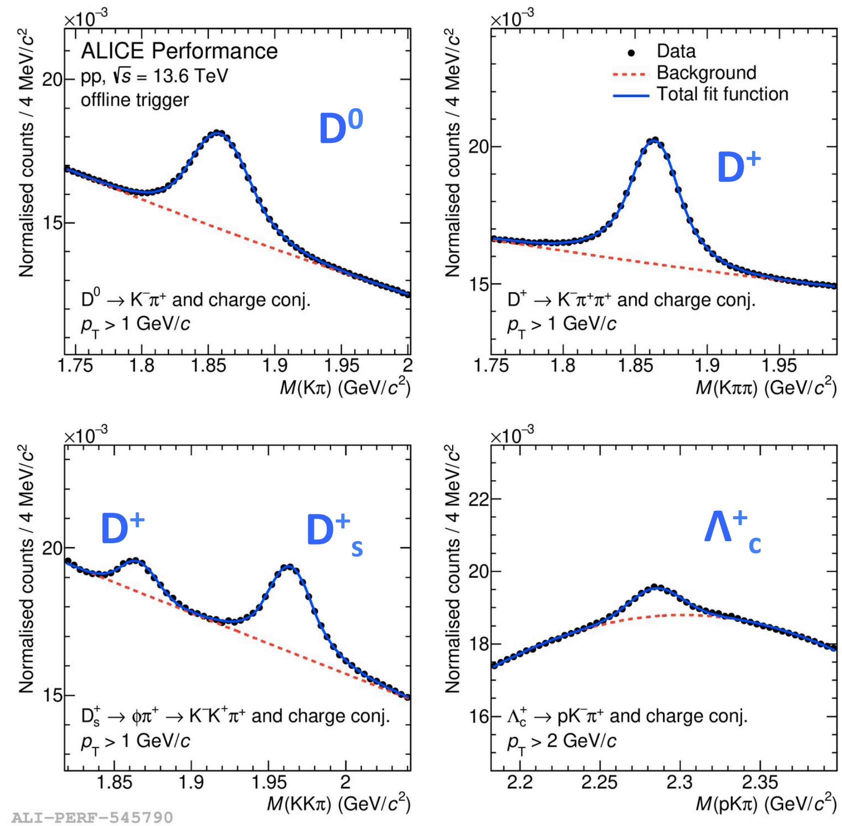
- **First Ω⁻ baryon yields**



- **First Ξ^0_c baryon yields**



- **D^0, D^+, D^+_s, and Λ^+_c signals obtained from the HF software trigger in *pp* collisions at √s=13.6 TeV**

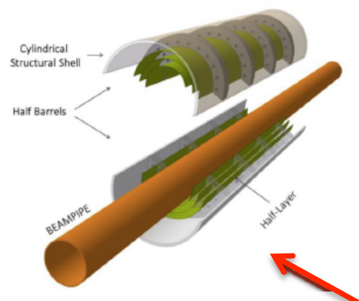


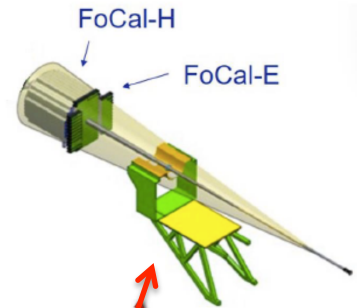
ALICE @LHC Schedule

ALICE LS2 Upgrade finished

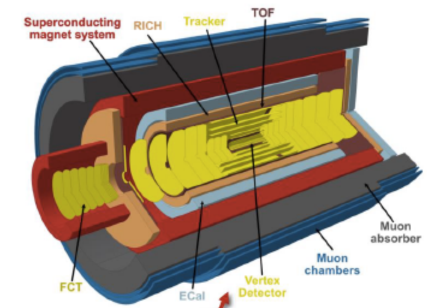
Today

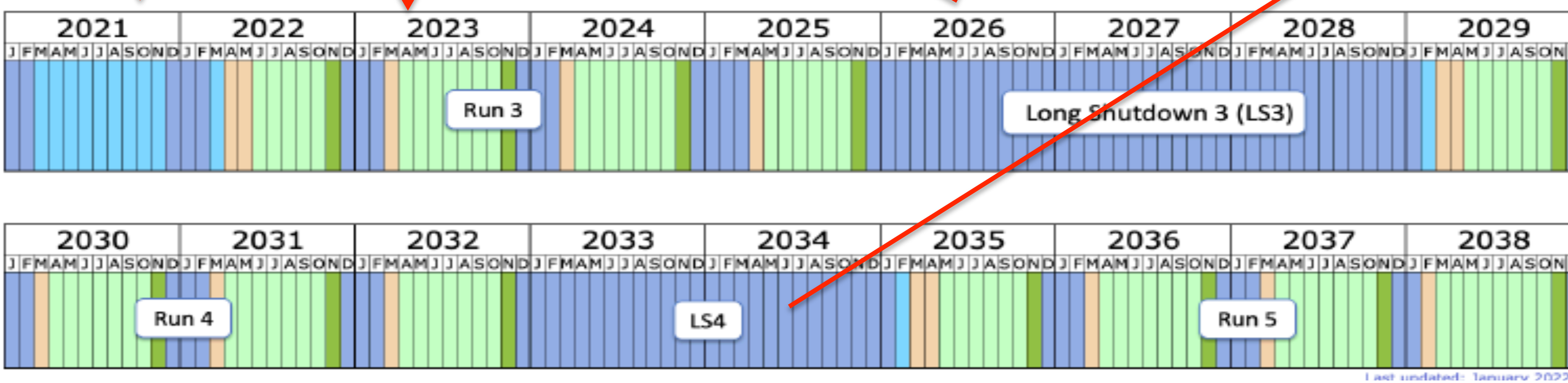
ALICE LS3 Upgrade





ALICE LS4 Upgrade ALICE 3

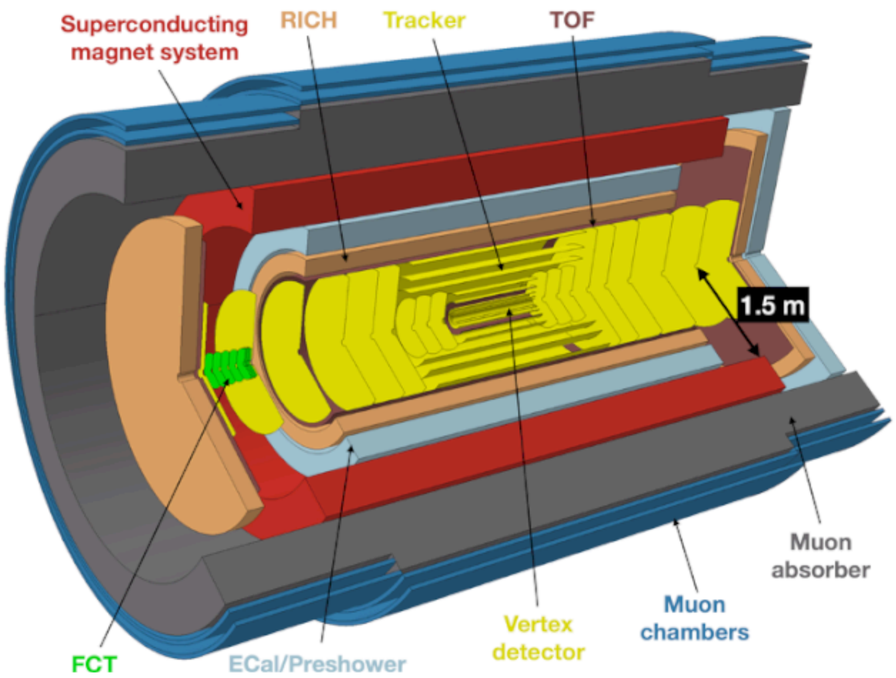




ALICE 3 in Run 5

expected > 2035

- ALICE 3 -- a completely new experiment, fast with precise tracking and timing.
- A large-acceptance (|η|<4), 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
  - ✧ Long-range correlation studies
  - ✧ Searches beyond-the-Standard-Model

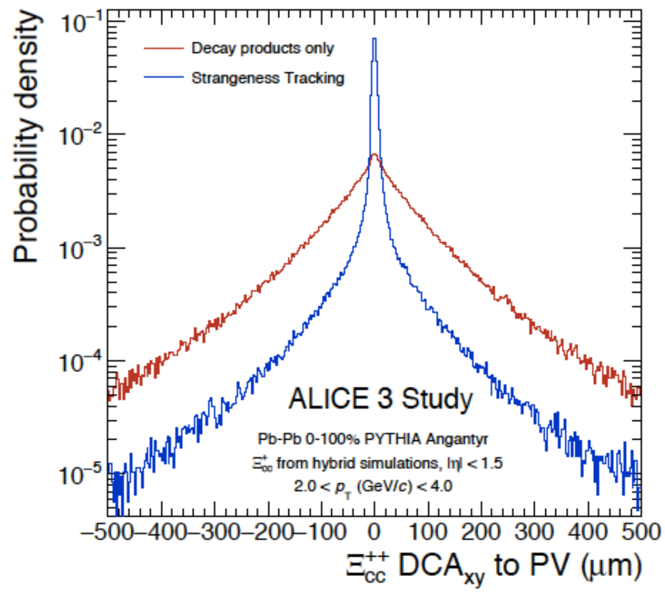
Letter of Intent for ALICE 3
https://cds.cern.ch/record/2803563/files/2211.02491.pdf

Beauty and multi-charm studies with ALICE 3

Particle	Mass (GeV/c)	$c\tau$ (μm)	Decay Channel	Branching Ratio (%)
Ω_{cc}^{+}	3.746	50 (assumed)	$\Omega_c^0 + \pi^+$	5.0 (assumed)
Ω_c^0	2.695	80	$\Omega^- + \pi^+$	5.0 (assumed)
Ξ_{cc}^{++}	3.621	76	$\Xi_c^+ + \pi^+$	5.0 (assumed)
Ξ_c^+	2.468	137	$\Xi^- + 2\pi^+$	(2.86 ± 1.27)
Ξ_c^+	2.468	137	$\mathrm{p} + \mathrm{K}^- + \pi^+$	$(6.2 \pm 3.0)10^{-3}$

Table 6: Particles and decay channels used in the reconstruction of the Ξ_{cc}^{++} and Ω_{cc}^{+} analyses using strangeness tracking. Values from [227]. Where no measurement is available, a branching ratio of 5% is assumed.

arXiv:2211.02491



- Measurements of the multi-charm baryons are a central part of the ALICE 3 physics
- Challenge: small life time cτ and BR

- Effective reconstruction using strangeness tracking : example for

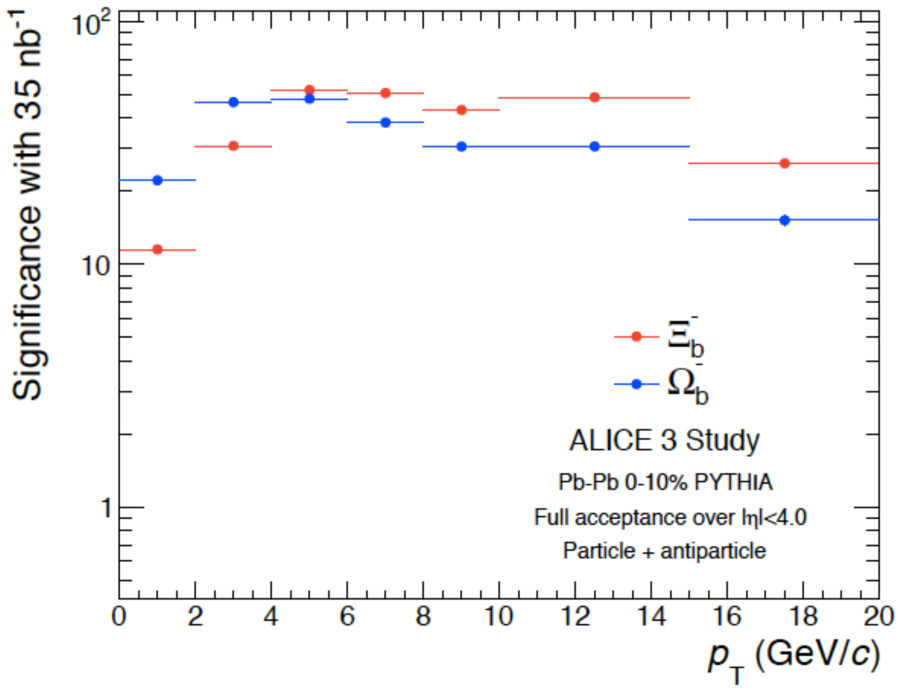
$$\Xi_{cc}^{++} \to \Xi_c^+ + \pi^+ \to \Xi^- + 3\pi^+ \quad \text{and} \quad \Omega_{cc}^{+} \to \Omega_c^0 + \pi^+ \to \Omega^- + 2\pi^+.$$

See Section 3.2.1.3 in *arXiv:2211.02491*

Beauty hadrons Ξ^-_b and Ω^-_b with ALICE 3

$$\Xi_b^- \rightarrow \Xi_c^0 + \pi^- \rightarrow \Xi^- + \pi^+ + \pi^-$$

$$\Omega_b^- \rightarrow \Omega_c^0 + \pi^- \rightarrow \Omega^- + \pi^+ + \pi^-$$



- Masses of Ξ^-_b and Ω^-_b are assumed to be 5,797 GeV/c2 and 6.046, respectively, as measured by the LHCb.
- BR are unknown so far (<5%)
- Large life time cτ ~ 500 μm --- it is beneficial for background discrimination

See in *arXiv:2211.02491*

Summary

1. Production of loosely bound light (anti)(hyper)nuclei --Still puzzling.
2. Progress in results on the medium induced effects on strange and charm particle yields and on the shape of jets
3. Studies of the residual strong interaction between strange, charm, and light hadrons
   - The new physics lab
   - 10 times increased statistics during the LHC Runs 3 and 4

4. The intriguing similarities in collision of small systems and in heavy-ion collisions are still to be investigated.

5. Run 3 has started successfully:

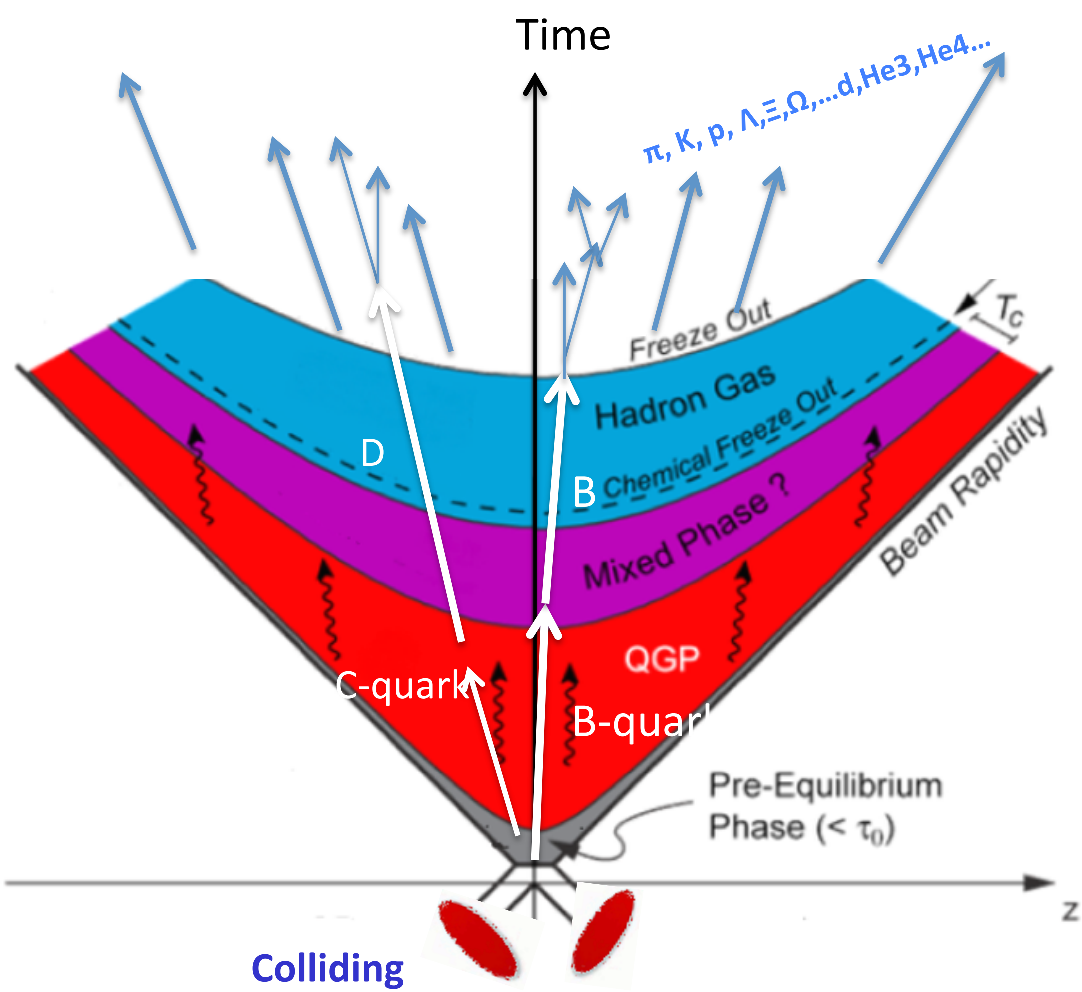
- New tracking detectors and higher pointing resolution
- Higher counting rate and the extended rapidity coverage
- Better muon measurements in the forward arm

7. Future upgrades are in progress for Run 4: ITS3 and FoCal

8. ALICE 3 with a completely new detector in Run 5 will be focused on rare processes of multi-charm and beauty baryon production aimed at the precise evaluation of the QGP properties.

Back-up

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:

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

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

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

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

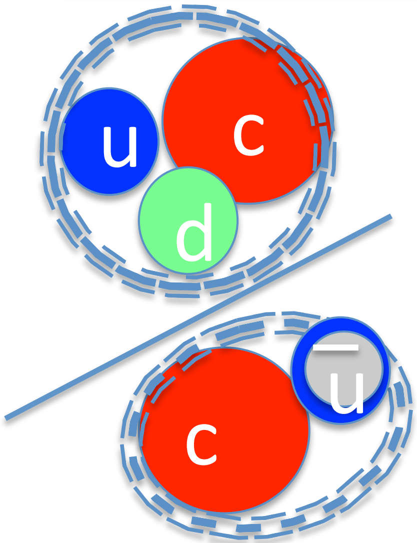
$\Lambda_c^+ \rightarrow K_s^0 p \rightarrow \pi^+ \pi^- p$

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

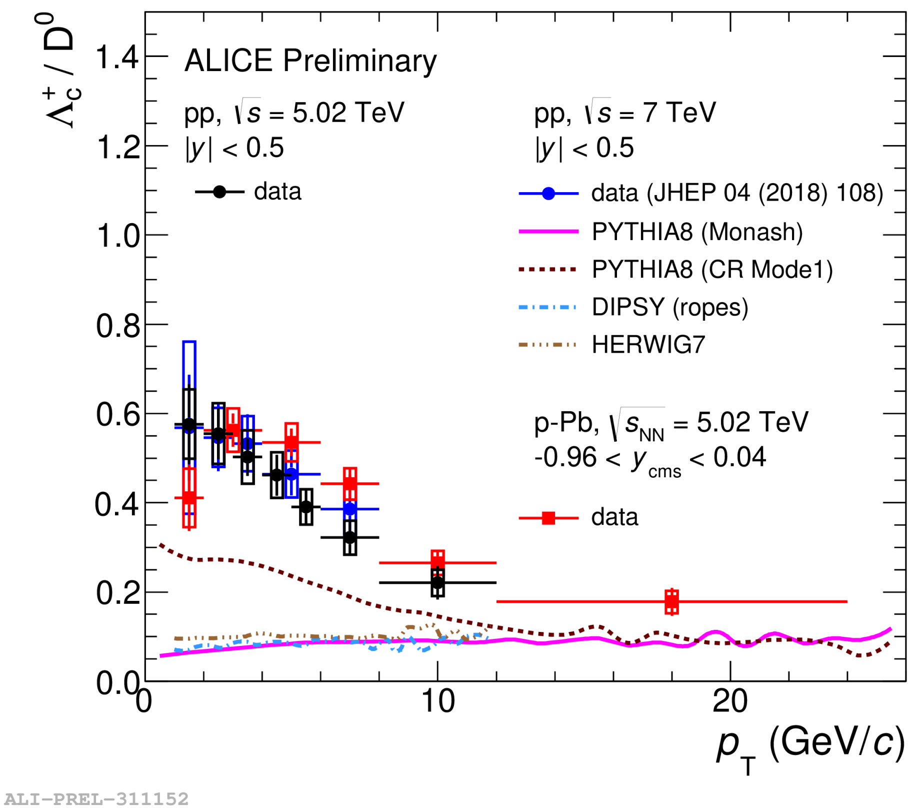
New!

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

p–p and p–Pb collisions



Λ^+_c/D^0



The Λ^+_c/D^0 ratio as a function of p_T measured in pp collisions at 7 TeV (Run1) and 5.02 TeV (Run2) and 13 TeV and in p-Pb collisions at 5.02 TeV (Run2) compared with models.

- Similar beavior
- Λ^+_c/D^0 - ratio is sensitive to hadronisation mechanism
- So far, standard hadronization models fail to reproduce the baryon enhancement