A Large Ion Collider Experiment

ALICE physics highlights and perspectives

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20th Lomonosov Conference

Moscow, 19 - 25 August 2021

ALICE

Outline

① Introduction

② Physics highlights

③ Preparations for Run 3

④ Future perspectives

ALICE

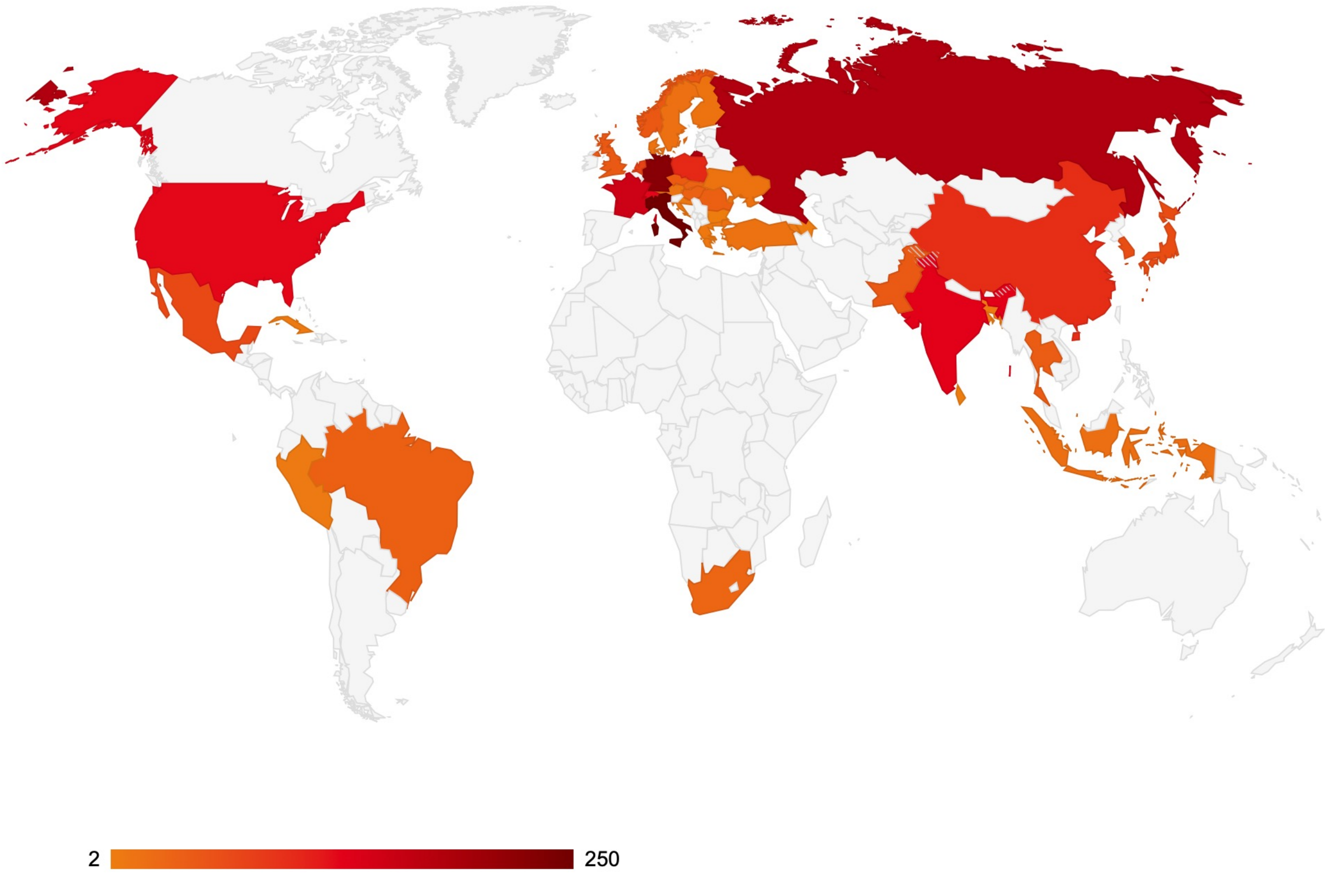
Outline

1. Introduction
2. Physics highlights
3. Preparations for Run 3
4. Future perspectives

Other ALICE talks at this conference

Igor Altsybeev	*Overview of recent ALICE results on particle correlations and fluctuations*	19.08.A ✓
Tatiana Karavicheva	*ALICE upgrade overview for Run 3 and 4 at the CERN LHC*	19.08.A ✓
Dmitry Blau	*Overview of direct photon and neutral mesons measurements with ALICE at the LHC*	23.08.C
Viktor Riabov	*Recent results on light flavor hadron production in the ALICE experiment at the LHC*	23.08.C
Valeri Pozdniakov	*Recent results on ultra-peripheral collision studies with ALICE at LHC*	23.08.C
Artem Isakov	*Analysis of b jets production in p--Pb and pp at $\sqrt{s_{NN}}$ = 5 TeV with ALICE*	23.08.C

The ALICE Collaboration



42 Countries, 173 Institutes

1946 Members

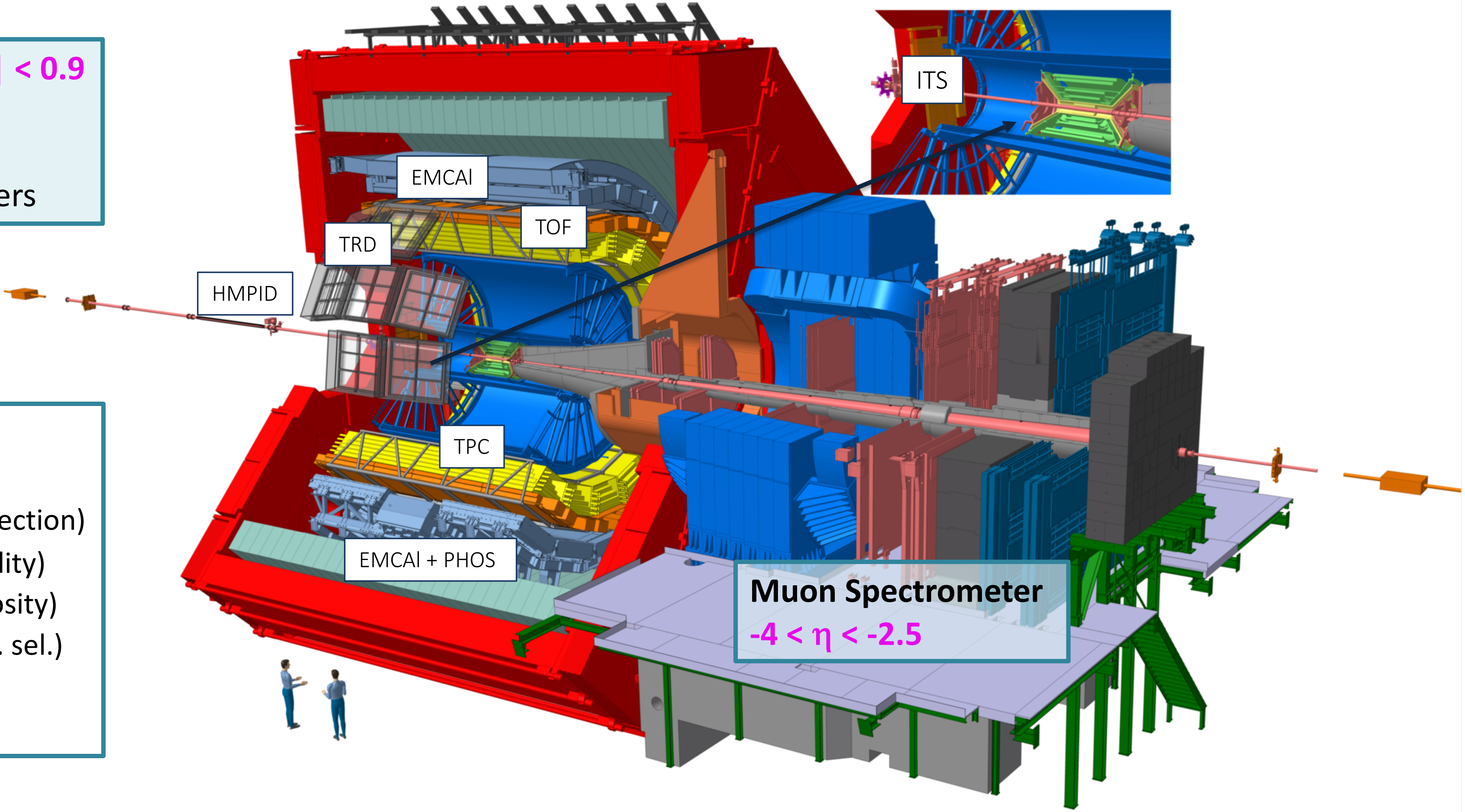
about **1000 signing authors**

Russia in ALICE

- 174 members
- **94** authors
- **39** Ph.D. scientists

The ALICE detector (version 1: Run 1 + 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)

Muon Spectrometer
$-4 < \eta < -2.5$

ALICE

ALICE data taking and publications

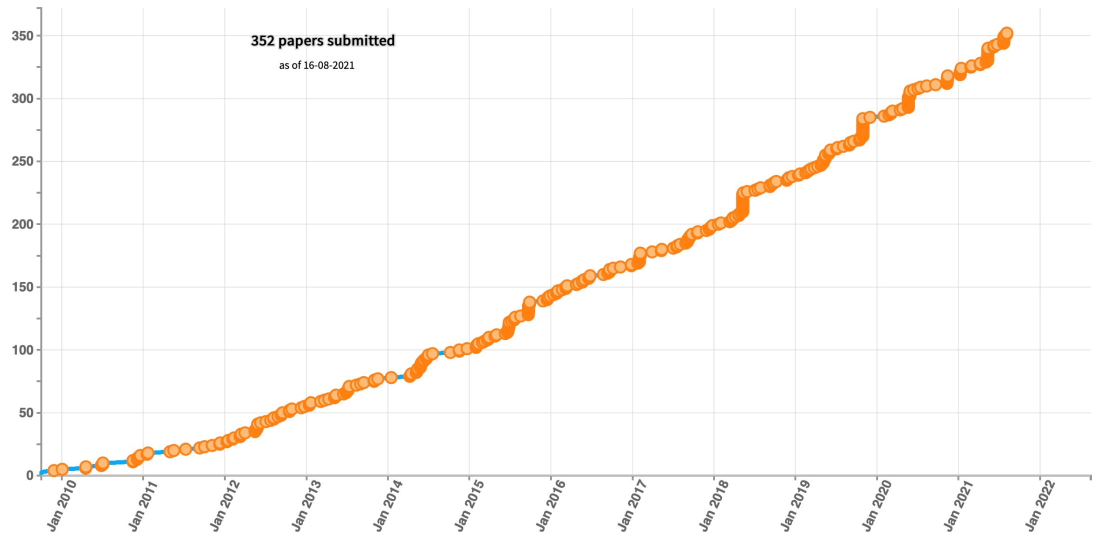
Run 1 (2009 – 2013) LS1 **Run 2** (2015 – 2018) **LS2** **Run 3** (2022 – 2024) LS3 **Run 4** (2027 – 2029)

← ALICE I → ← ALICE 2 →

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

352 ALICE papers on arXiv so far



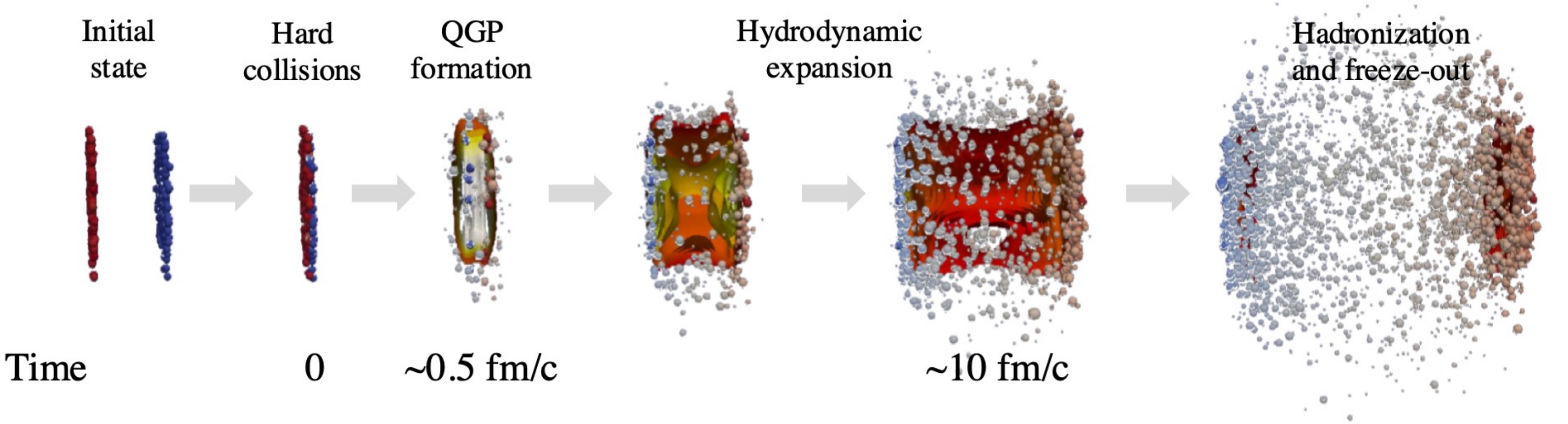
http://alice-publications.web.cern.ch/submitted

A few physics highlights

… focus on new results

Focal point of the experiment: characterize the QGP

- Explore the deconfined phase of QCD matter ⇨ quark-gluon plasma
- LHC Pb-Pb ⇨ large energy density (initial ε > 15 GeV/fm^3) & large volume (~5000 fm^3)



Visualization by J.E. Bernhard, arXiv:1804.06469

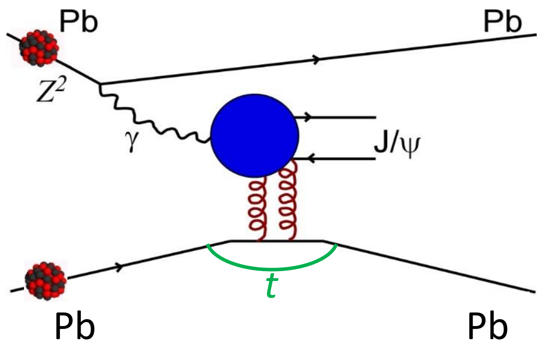
Study the time evolution of the collision

- Initial stage
- Macroscopic properties
- Colour deconfinement
- Parton interactions
- Expansion dynamics
- Hadronic phase

⇨

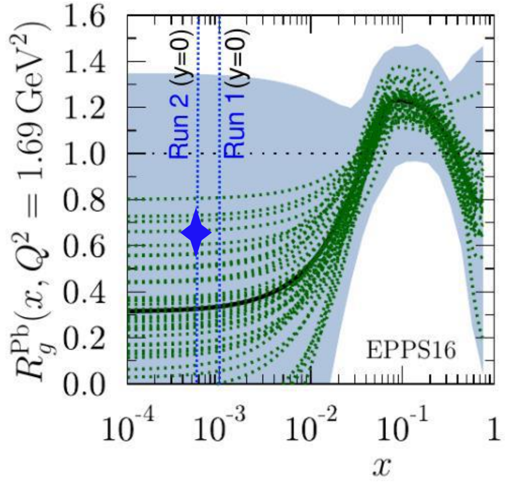
- Light flavour (including light-nuclei) production
- Heavy flavour production
- Quarkonia
- Photons, low-mass dileptons
- Jets
- Ultra Peripheral Collisions

Coherent J/ψ photoproduction in Pb-Pb ultra peripheral collisions



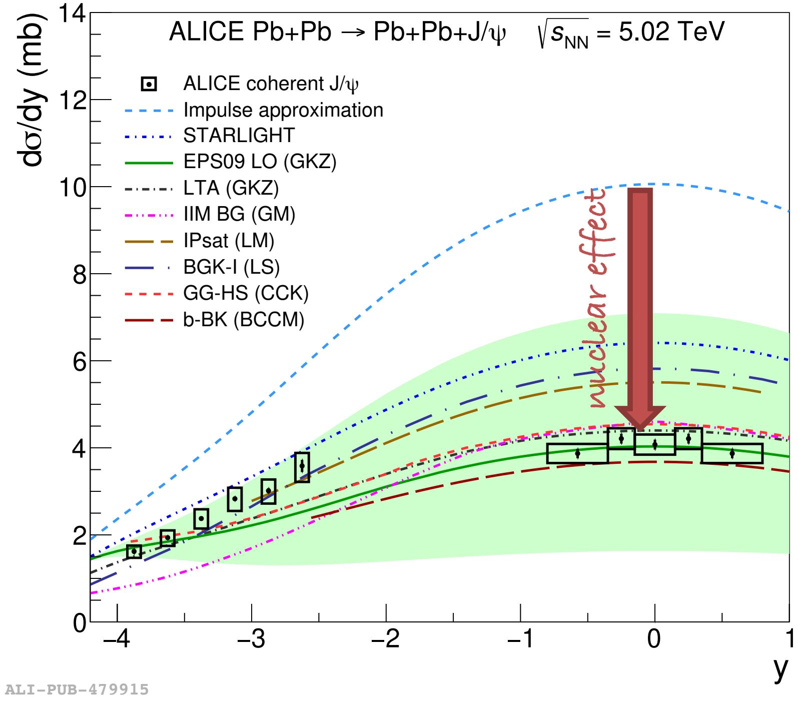
$$\left.\frac{d\sigma_{\gamma A\to J/\psi A}}{dt}\right|_{t=0} = \frac{M^3_{J/\psi}\Gamma_{ee}\pi^3\alpha_s^2(Q^2)}{48\alpha_{em}Q^8}\left[xg_A(x,Q^2)\right]^2$$

Eskola et. al., EPJC 77 (2017) 163

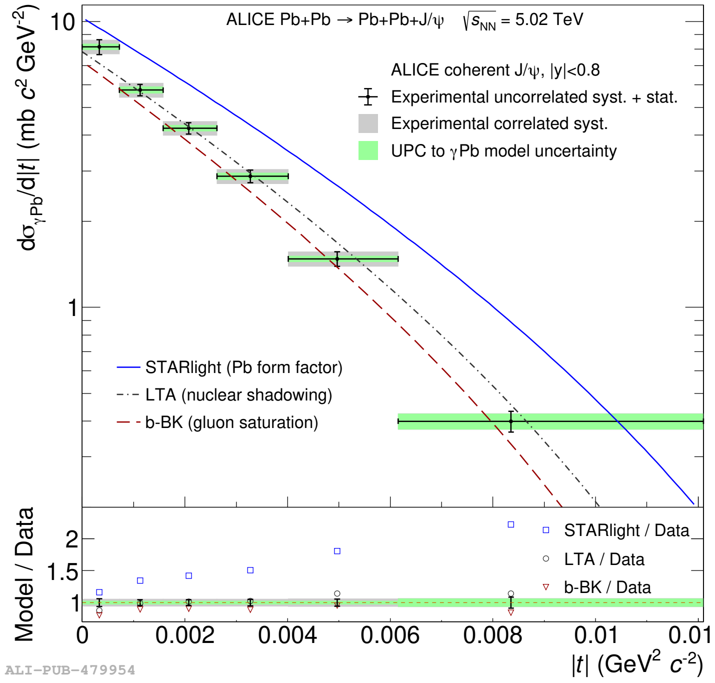


$$R_g^A(x,Q^2) = \frac{g_A(x,Q^2)}{Ag_p(x,Q^2)}$$

arXiv:2101.04577



arXiv:2101.04623



$|t| \approx p_T^2$

New measurment probing low-x gluon nuclear PDFs

- Comparison with the impulse approximation (no nuclear effects) allows for extraction of the gluon shadowing factor: **$R_g \sim 0.65$ at $x \sim 10^{-3}$**
- **First measurement** of t-dependence: sensitive to transverse gluon distribution

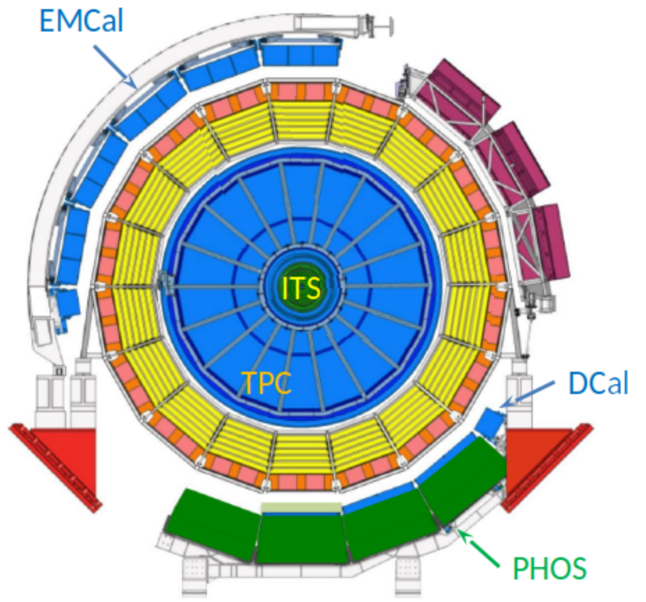
talk V. Posdniakov

Neutral pion spectra over 3 orders of magnitude in p_T

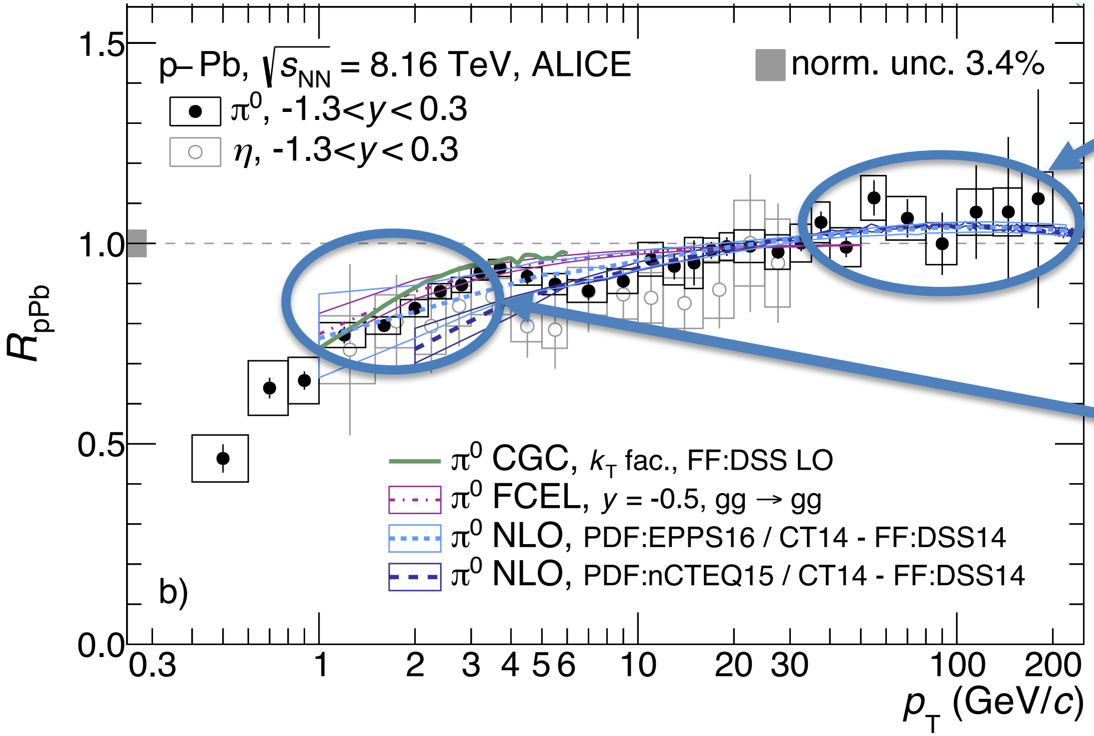
Neutral pions measured from p_T = 0.3 to 200 GeV/c, with photon conversion and EM calorimeters

- p-Pb collisions: nuclear modification of parton distribution functions:

  ⇨ **Low p_T**: Rp-Pb < 1 due to nuclear shadowing **High p_T**: no significant modification



arXiv:2104.03116

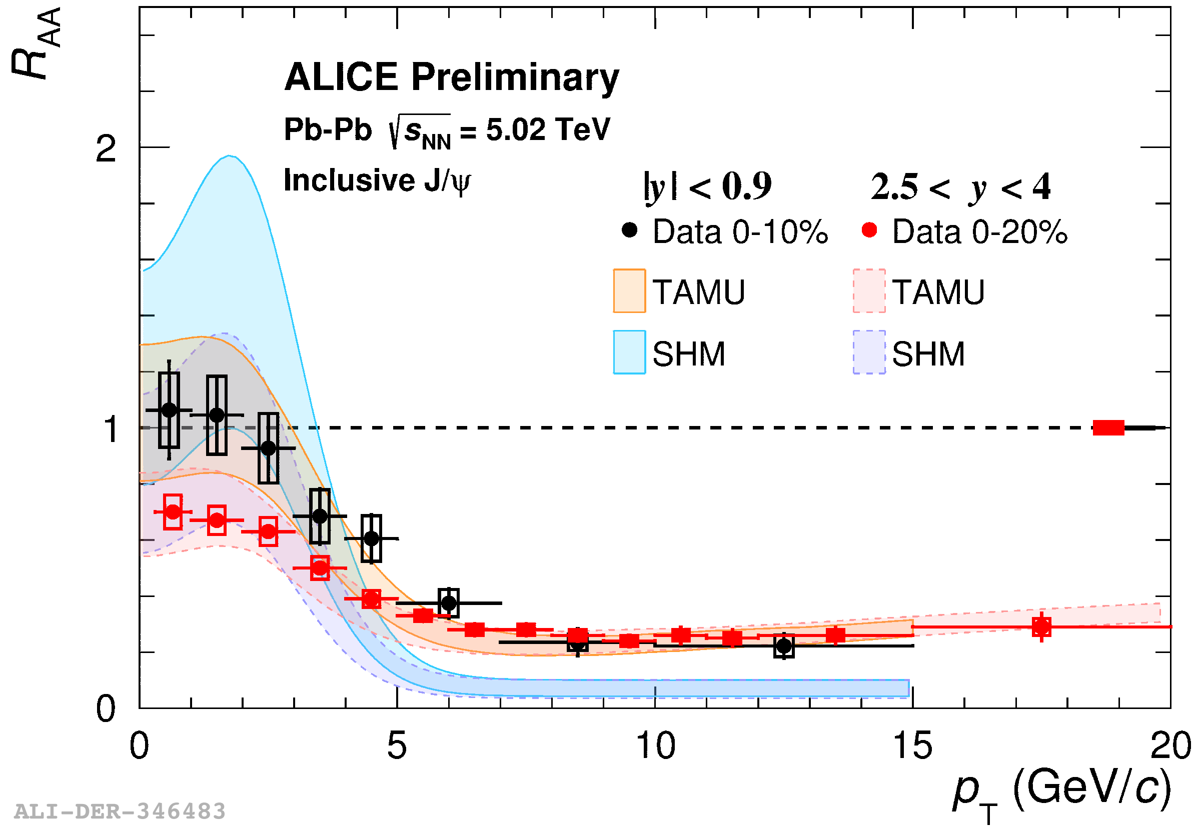


$R_{p\text{-}Pb}$ = 1 for no nuclear effects in p-Pb collisions

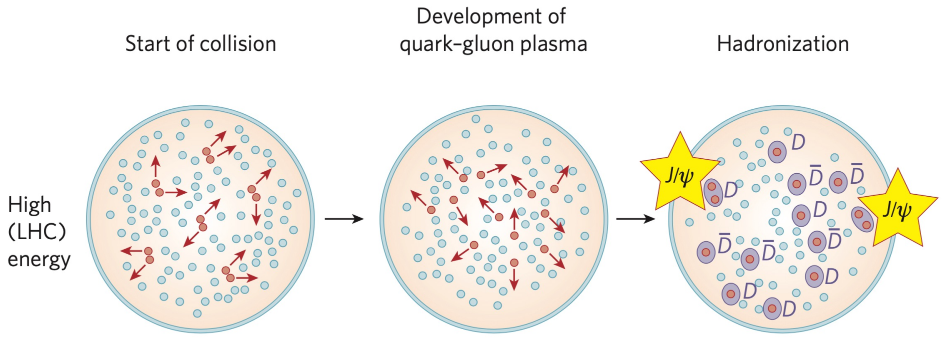
Sensitivity to nuclear shadowing / parton saturation at low momentum

talk D. Blau

J/ψ dissociation and (re)generation at the LHC



$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dp_T|_{PbPb}}{dN/dp_T|_{pp}}$$



Cartoon from [Nature 448, 302–309(2007)]

J/ψ suppression reduced at low p_T

$c\bar{c}$ regeneration counterbalances the suppression by screening in the QGP

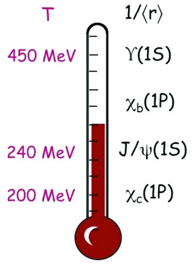
- At low p_T , modification decreases from **forward** to **central** rapidity
- reflects rapidity dependence of the $c\bar{c}$ cross-section (⇨ regeneration probability)

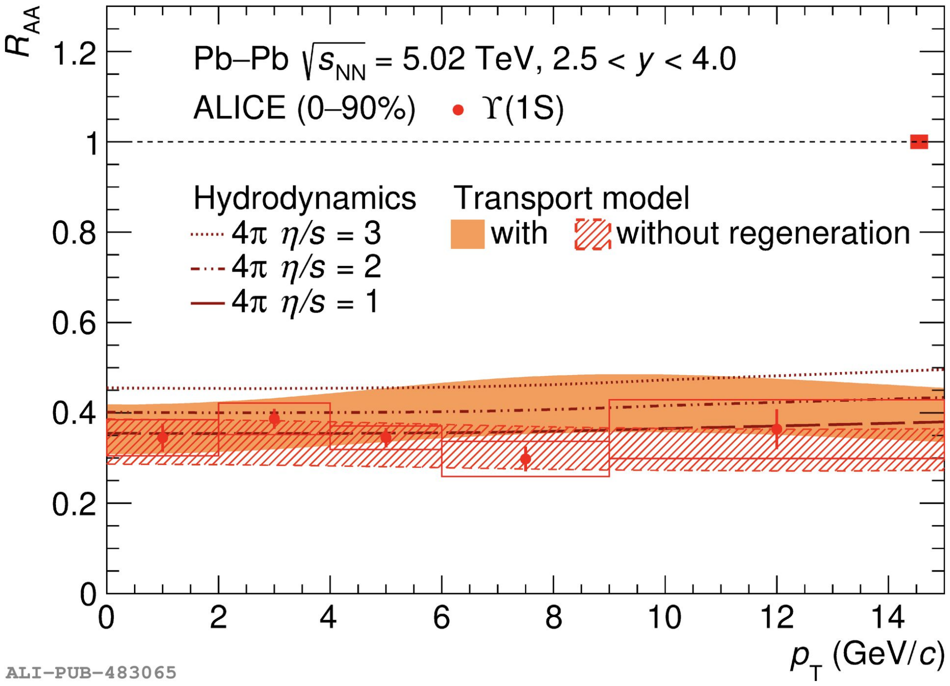
Suppression of bottomonia in Pb-Pb collisions

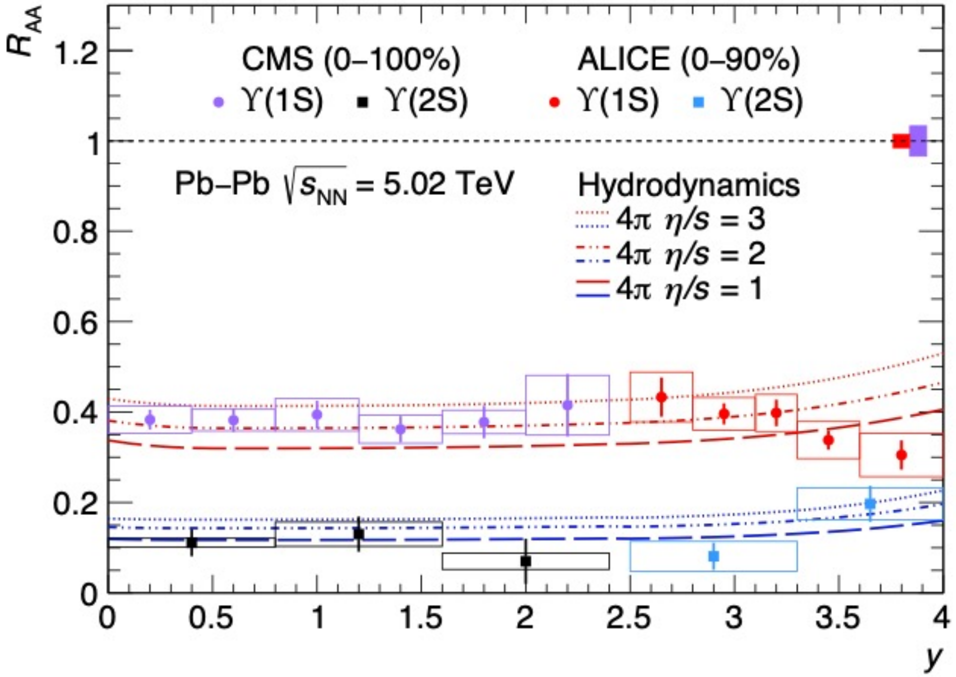
arXiv:2011.05758

Varying the binding energy: ψ(2S) < Υ(2S) < J/ψ < Υ(1S)

0.05 0.55 0.65 1.1 GeV







- Screening induces a strong suppression of Υ production, which is flat vs p_T ⇨ recombination effects small
- Υ(2S) (**first time!**) at forward rapidity - a suppression stronger wrt Υ(1S) consistent with lower binding energy
- Hint of a decrease of the RAA at large rapidity not described by models

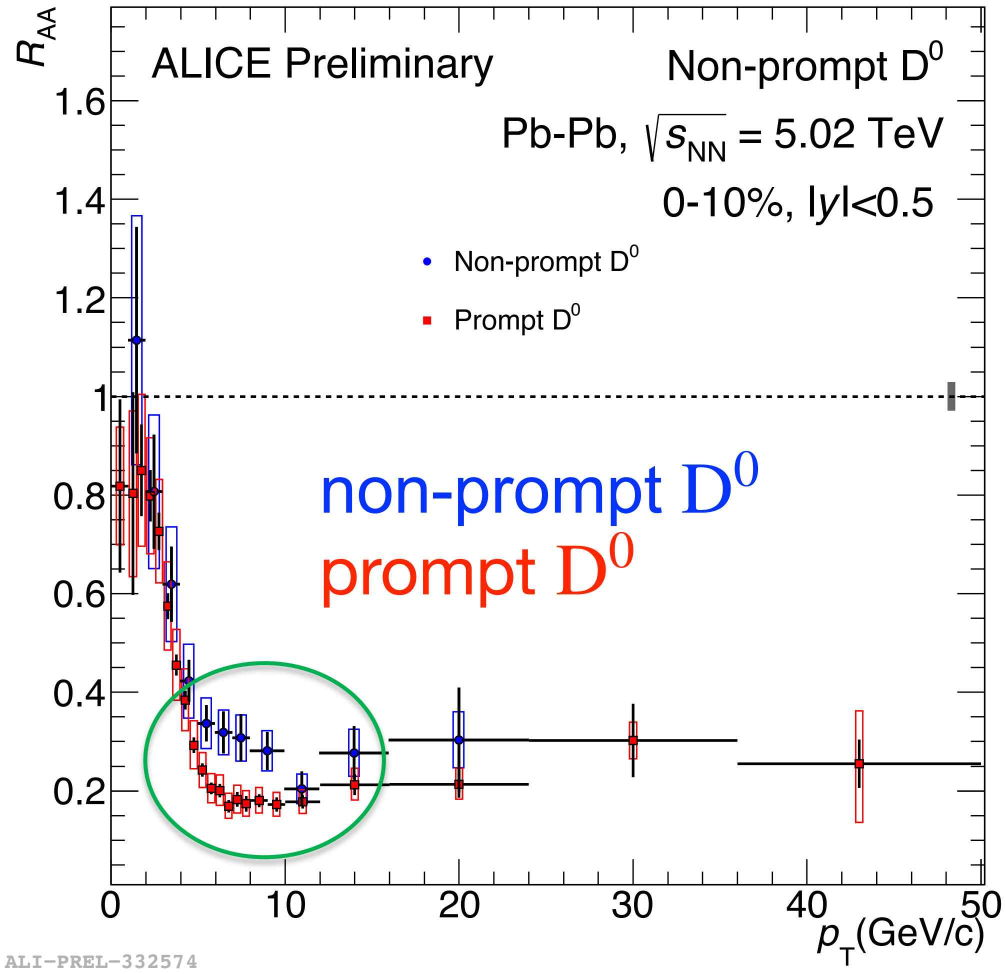
Energy loss and hadronization of c and b quarks in the QGP (1)

Less suppression for (non-prompt) D mesons from B decays than prompt D mesons

- Quarks and gluons lose energy while traversing the QGP (**R_{AA} < 1**)
- Energy loss predicted to depend on QGP density, but also on quark mass
- "Dead cone effect" reduces gluon radiation for high-mass quarks

radiation suppressed for $\theta_C < m_Q/E$

- Also note: first measurement of D meson production down to zero p_T in Pb-Pb
- More precise measurement with new ITS in Run 3

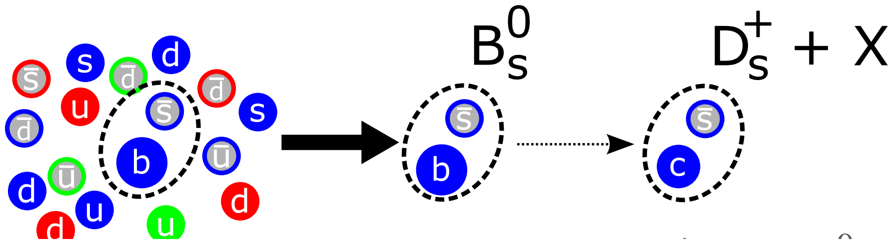


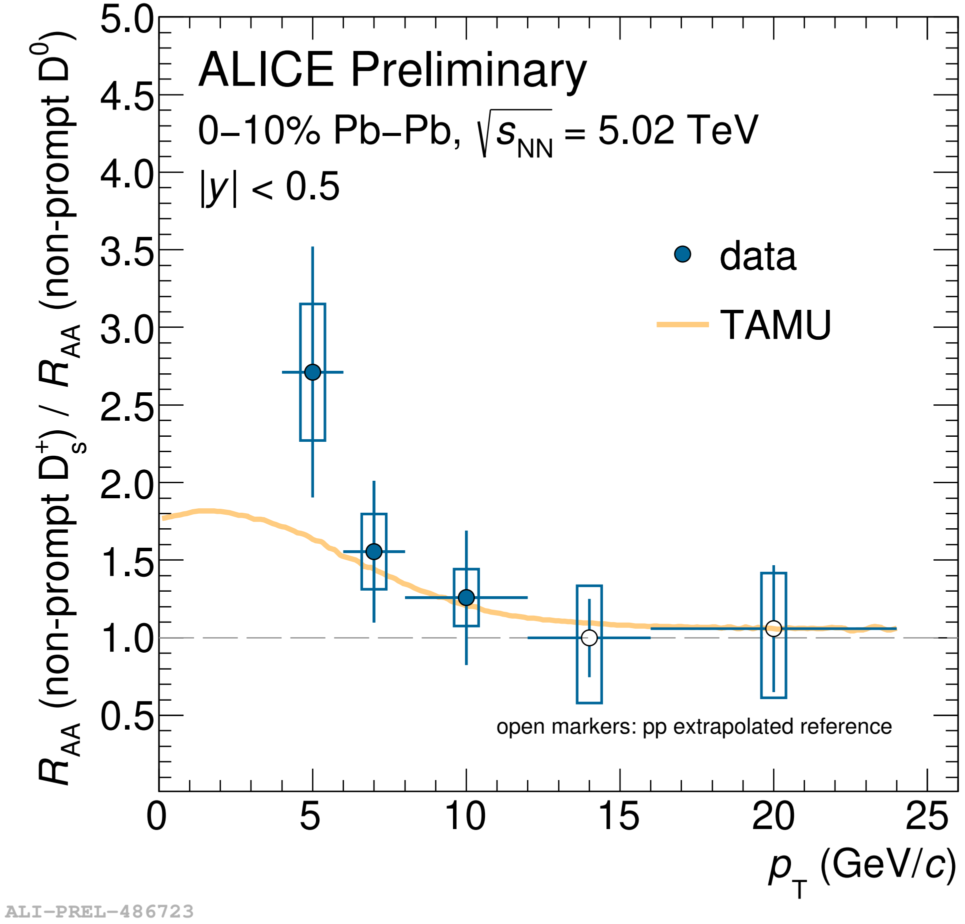
Energy loss and hadronization of c and b quarks in the QGP (3)

R_{AA}(non-prompt D^{+}_{s}) > R_{AA}(non-prompt D^0) consistent with coalescence picture

- non-prompt D^{+}_{S} less suppressed than non-prompt D^0 at low p_T

- enhanced production of B^{0}_{s} from beauty hadronization via coalescence (50% of D^{+}_{s} from B^{0}_{s})



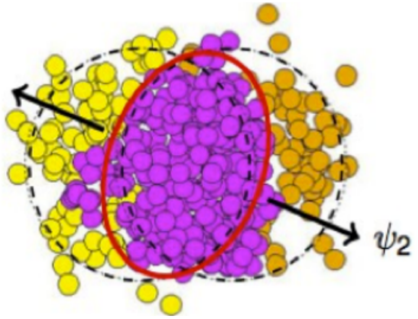


QGP expansion: collective flow of hadrons

Flow of identified hadrons in Xe-Xe collisions … similar to Pb-Pb collisions

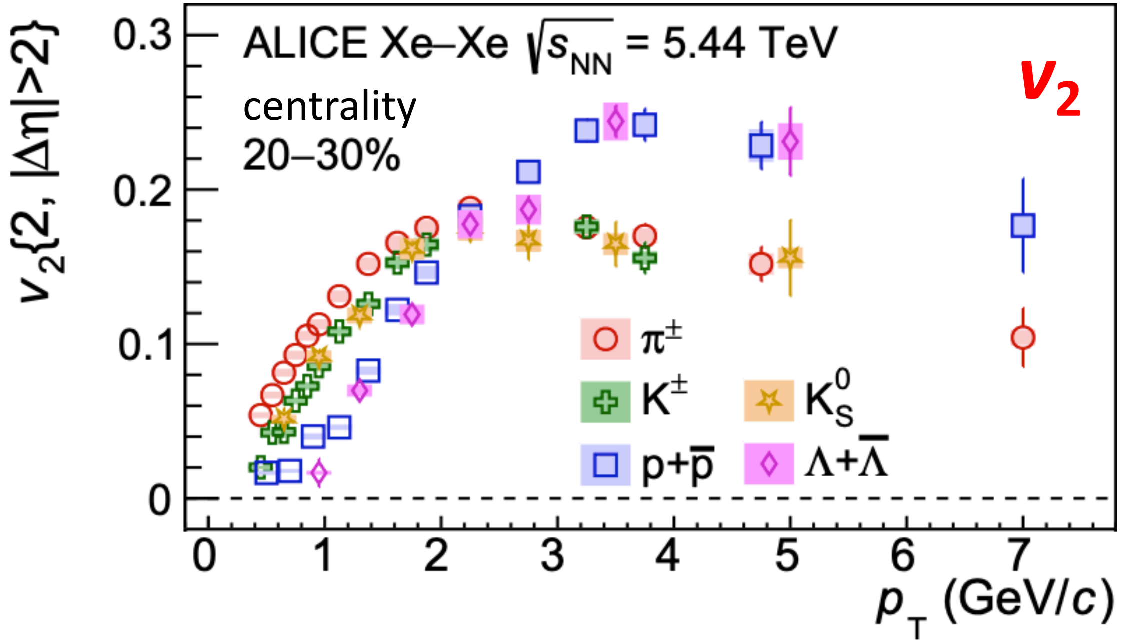
Geometrical elliptical shape → azimuthal modulation in momentum distributions

$$\frac{dN}{Nd\phi} = 1 + 2v_2 \cos\left(2(\phi - \Psi_{RP})\right) + \ldots$$ higher harmonics (v_3 , v_4 , …)



V_2 – elliptic flow reflects the almond-shaped **geometry** of the interaction volume

https://arxiv.org/abs/2107.10592



p_T < 2-3 GeV/c - **clear "mass ordering"**
from collective dynamics during hydro expansion
(heavier hadrons shifted to higher p_T by radial flow)

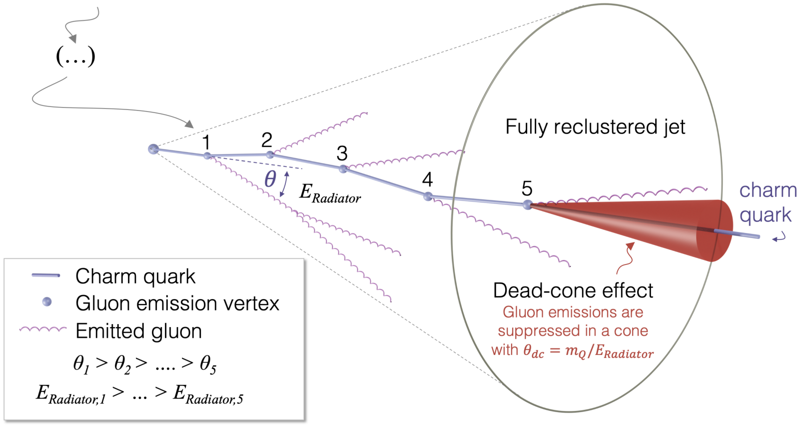
3 < p_T < 8-10 GeV/c - **baryons flow more than mesons**
consistent with hadronisation by coalescence

Evolution with p_T and centrality **similar to Pb-Pb collisions**

talk I. Altsybeev

Direct observation of the dead-cone effect in QCD

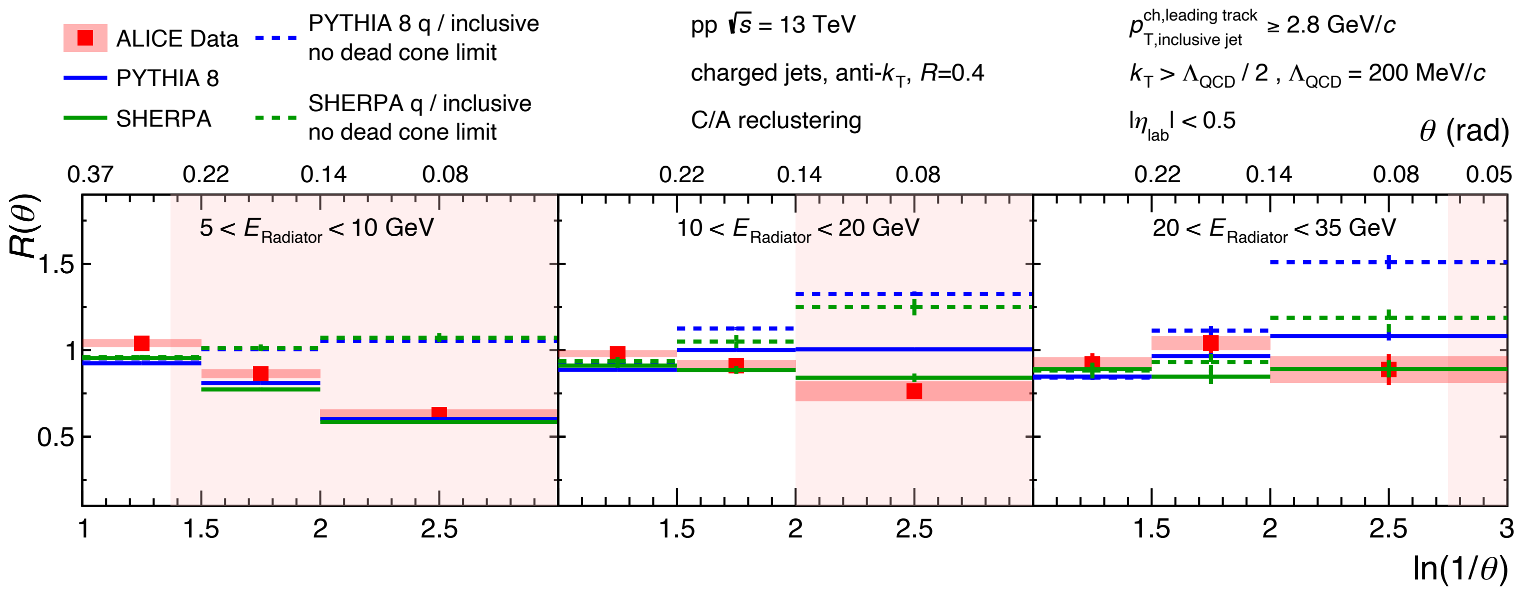
by measuring D^0-meson tagged jets in hadronic collisions (pp 13 TeV)



Follow a heavy quark through the primary Lund Plane & suppress hadronization effects/non pert. (at small K_T)

Ratio of the splitting angle (θ) distributions for D^0-meson tagged jets and inclusive jets, in bins of $E_{radiator}$

$$R(\theta) = \frac{1}{N^{D^0\,\text{jets}}} \frac{dn^{D^0\,\text{jets}}}{d\ln(1/\theta)} \Bigg/ \frac{1}{N^{\text{inclusive jets}}} \frac{dn^{\text{inclusive jets}}}{d\ln(1/\theta)} \Bigg|_{k_T, E_{\text{Radiator}}}$$



Radiation suppressed in the expected angular region (shaded)

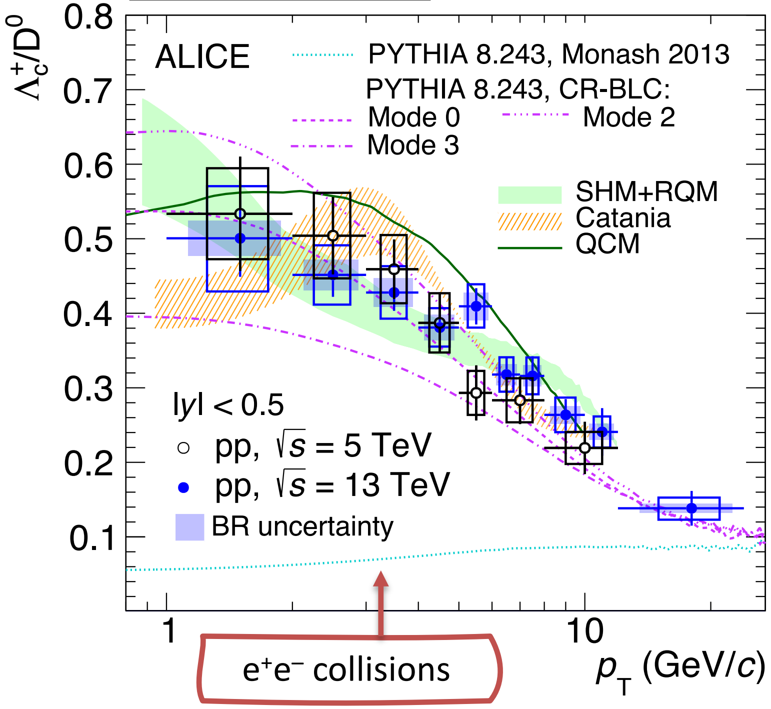
Suppression lifted as $mass_Q$ << $E_{radiator}$

[arXiv: 2106.05713](https://arxiv.org/abs/2106.05713) [nucl-ex]

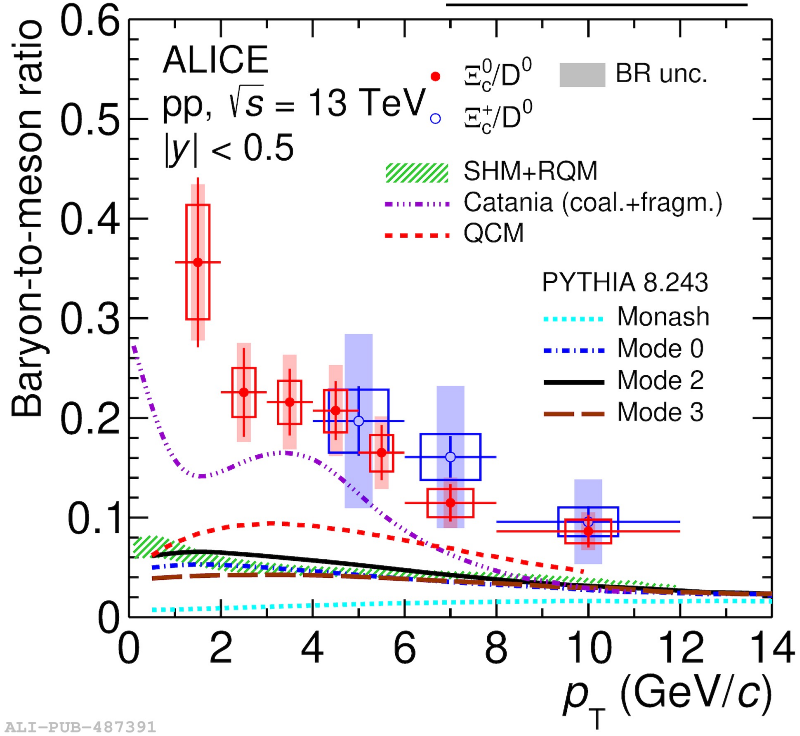
Charm baryon/meson measurements in pp collisions

Charm hadronization differs at the LHC

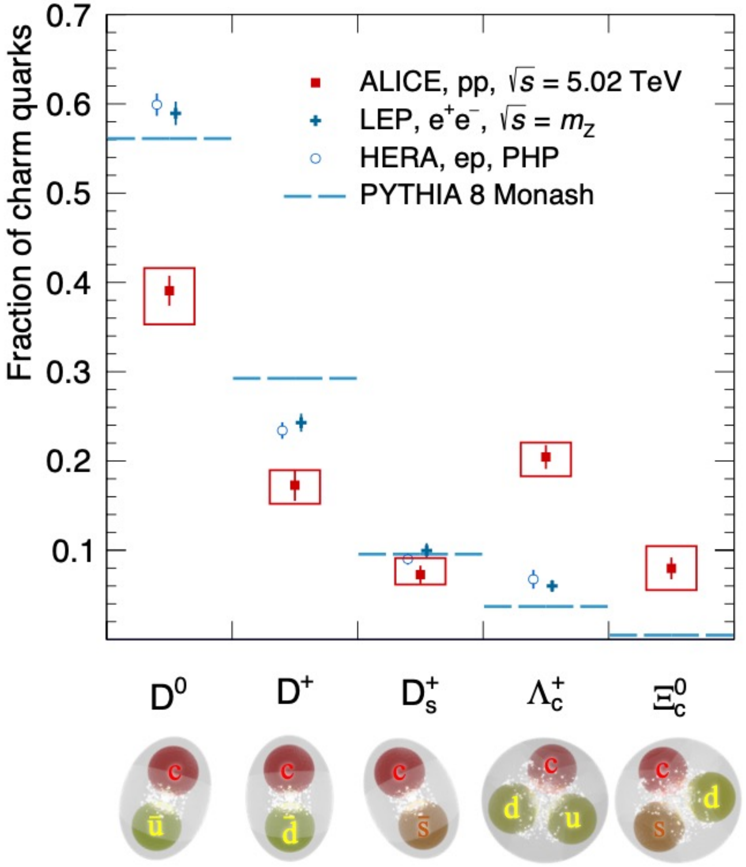
arXiv:2011.06078 arXiv:2106.08278



arXiv:2105.05187



arXiv:2105.06335

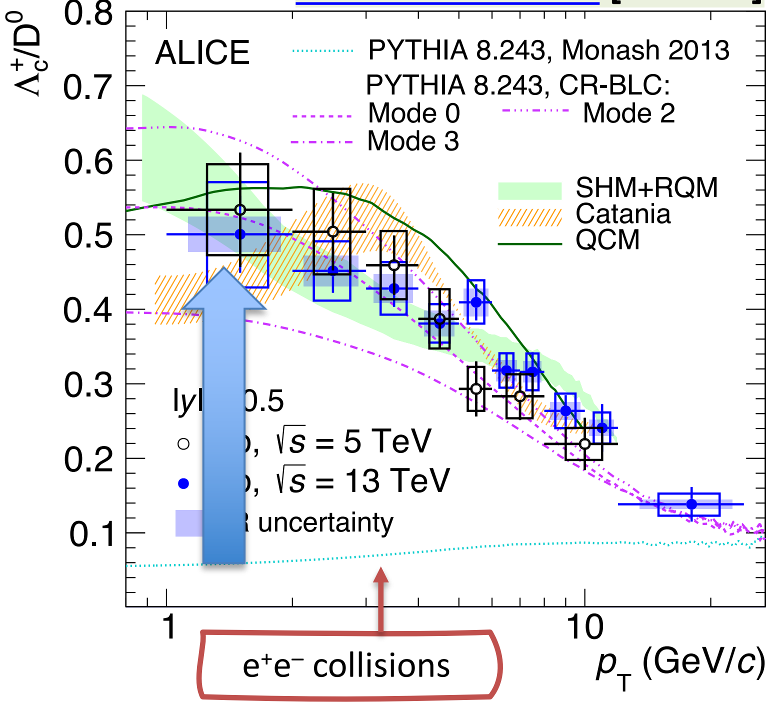


- unique measurements (at low-momenta) of Λ_c (also Ξ_c and Ω_c)
- cross section (fragmentation fraction) larger than expected (ee and ep)

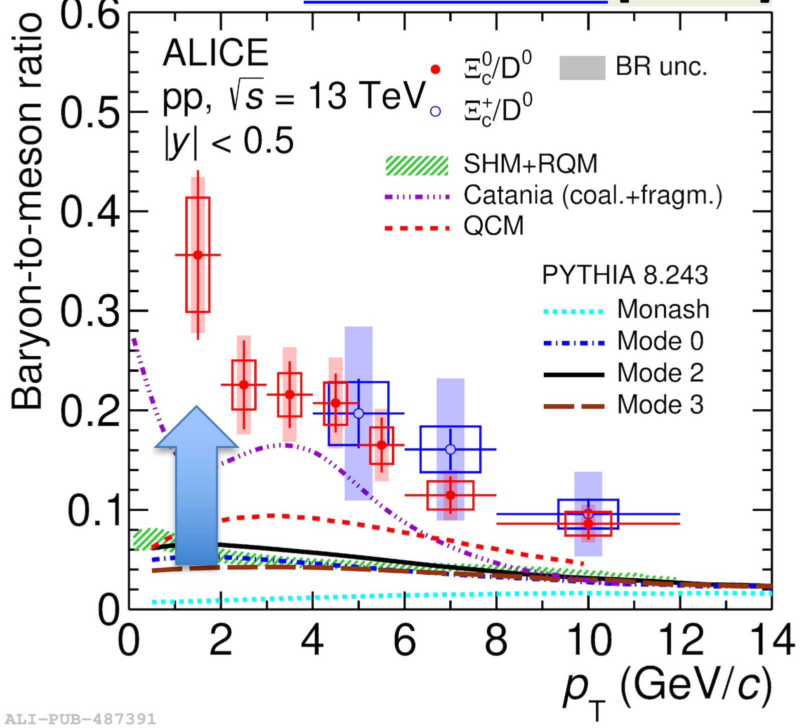
Charm baryon/meson measurements in pp collisions

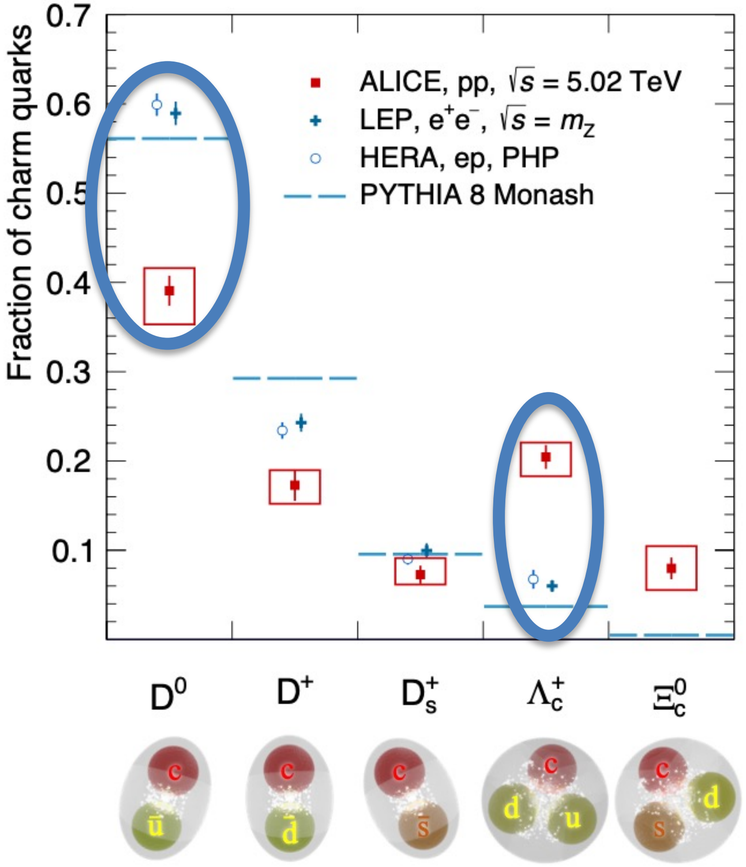
Charm hadronization differs at the LHC

arXiv:2011.06078 [nucl-ex]



arXiv:2105.05187 [nucl-ex]



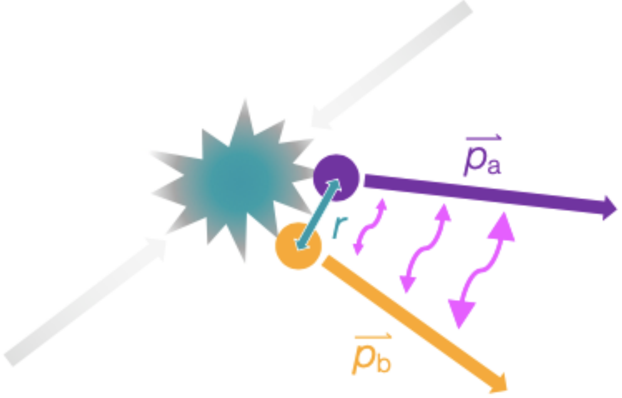


- unique measurements (at low-momenta) of Λ_c (also Ξ_c and Ω_c)
- cross section (fragmentation fraction) larger than expected (ee and ep)

Strong interaction between hadrons

Correlation function sensitive to interaction potential

talk I. Altsybeev



1. Fix source geometry
2. **Measure correlation fct. C(k^*)**

→ **study the strong interaction**

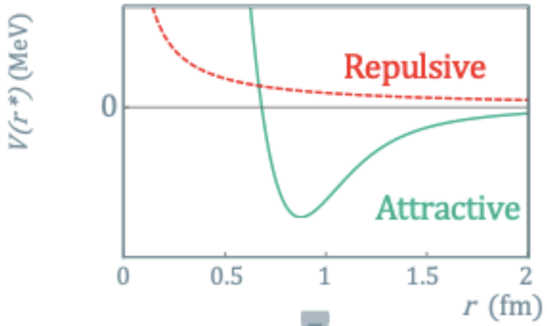
$$C(k^*) = \int S(r)\ \left|\psi(\vec{k}^*,\vec{r})\right|^2 d^3r$$

Emission source   Two-particle wave function

Source parametrisation

Gaussian source

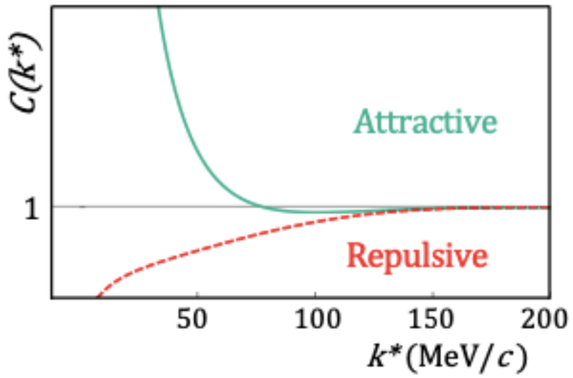
Interacting potential



Schrödinger equation**

Two-particle wave function $|\Psi(k^*,r)|$

Correlation function



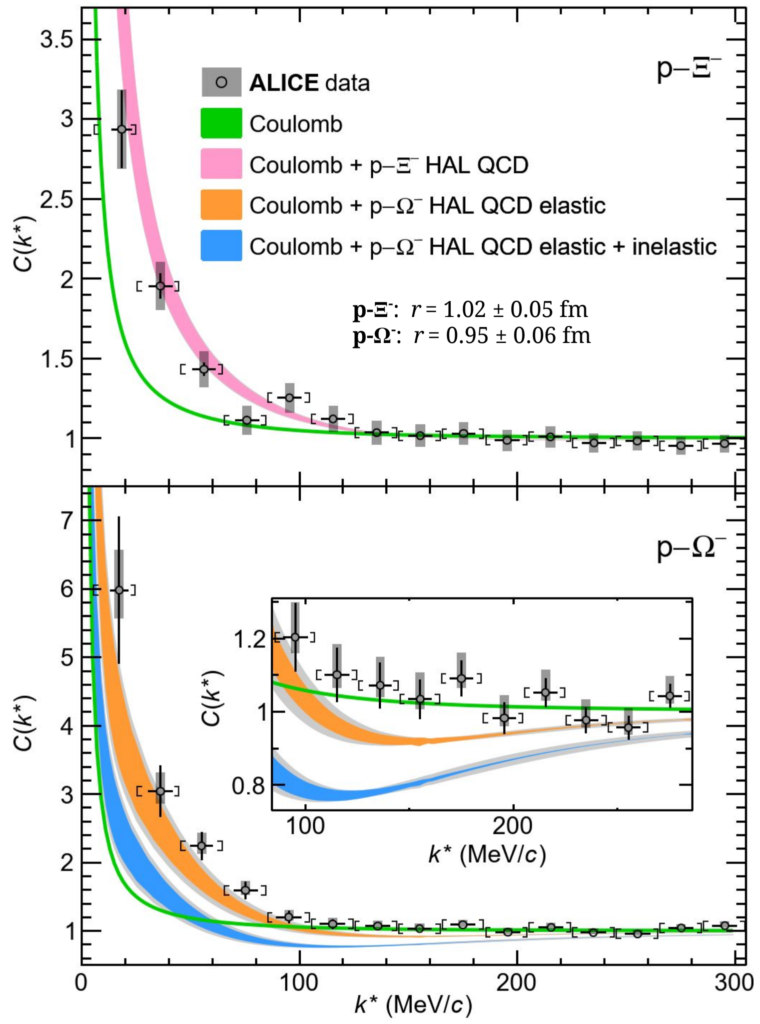
Strong interaction between hadrons

ALICE measurements on topic

Phys. Rev. C 99 (2019) 024001	p-p, p-Λ, Λ–Λ (pp)
Phys. Lett. B 797 (2019) 134822	Λ–Λ (p-Pb)
Phys. Rev. Lett. 123 (2019) 112002	p-Ξ^- (p-Pb)
Phys. Rev. Lett. 124 (2020) 092301	p-K (pp)
Phys. Letters B 805 (2020) 135419	p-Σ (pp)
Phys. Lett. B 811 (2020) 135849	source size in pp
Nature 588 (2020) 232-238	**p-Ω (pp)**
arXiv:2104.04427	NΛ – NΣ (pp)
arXiv: 2105.05578	p-ϕ (pp)
arXiv:2105.05683	**K-p (Pb-Pb)**
arXiv:2105.05190	p-/p, p-/Λ, Λ–/Λ (pp)

"Unveiling the strong interaction among stable and unstable"

Nature 588 (2020) 232-238



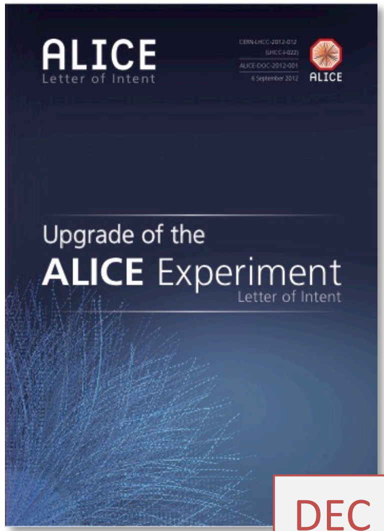
Proton-hyperon (p-Y) strong interaction poorly known

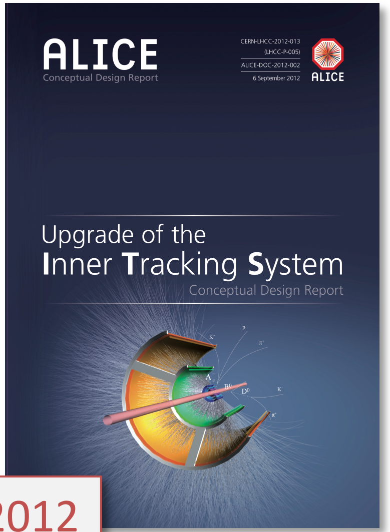
precise measurement of strong interaction for p-Ξ^- and p-Ω^-

- direct comparison to lattice QCD
- p-Ξ^- important for the EoS of neutron stars (which contain hyperon-rich matter)

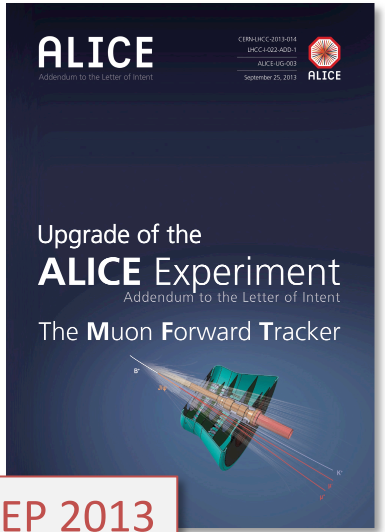
Upgrade activities for Run 3 and Run 4
ALICE version 2.0

ALICE Detector Version 2.0 (Upgrades for Run 3+)



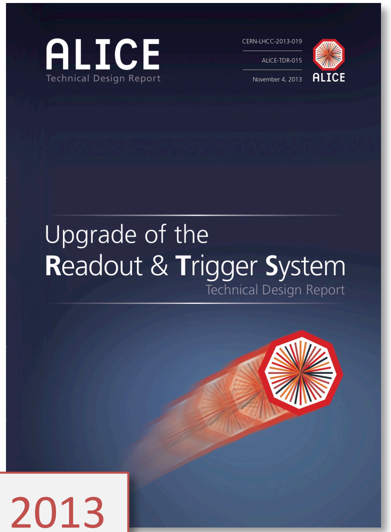


DEC 2012

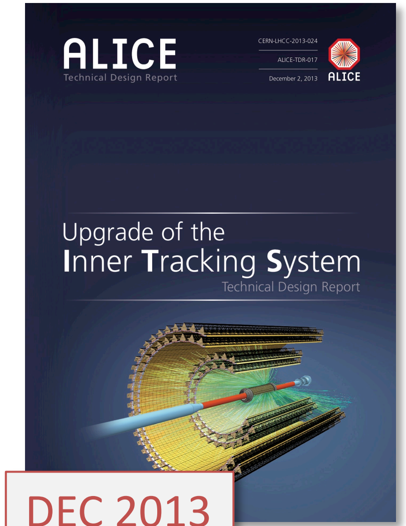


SEP 2013

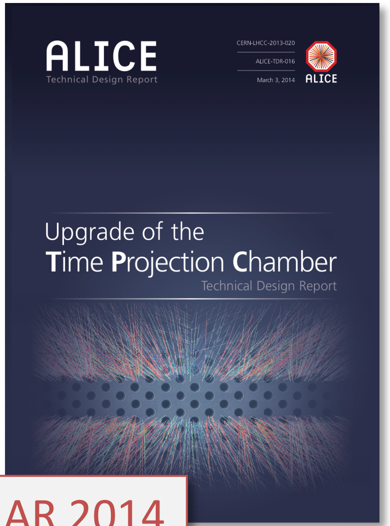
- From LoI to last TDR: 2013 – 2015 ✓
- Construction: 2016 – 2019 ✓
- Installation: 2020 – 2021 ✓
- Global commissioning: ongoing



NOV 2013

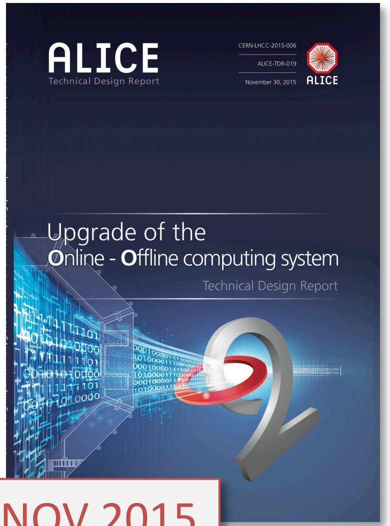


DEC 2013



MAR 2014

MAY 2015



NOV 2015

ALICE Detector Version 2.0 (Upgrades for Run 3+)

talk T. Karavicheva

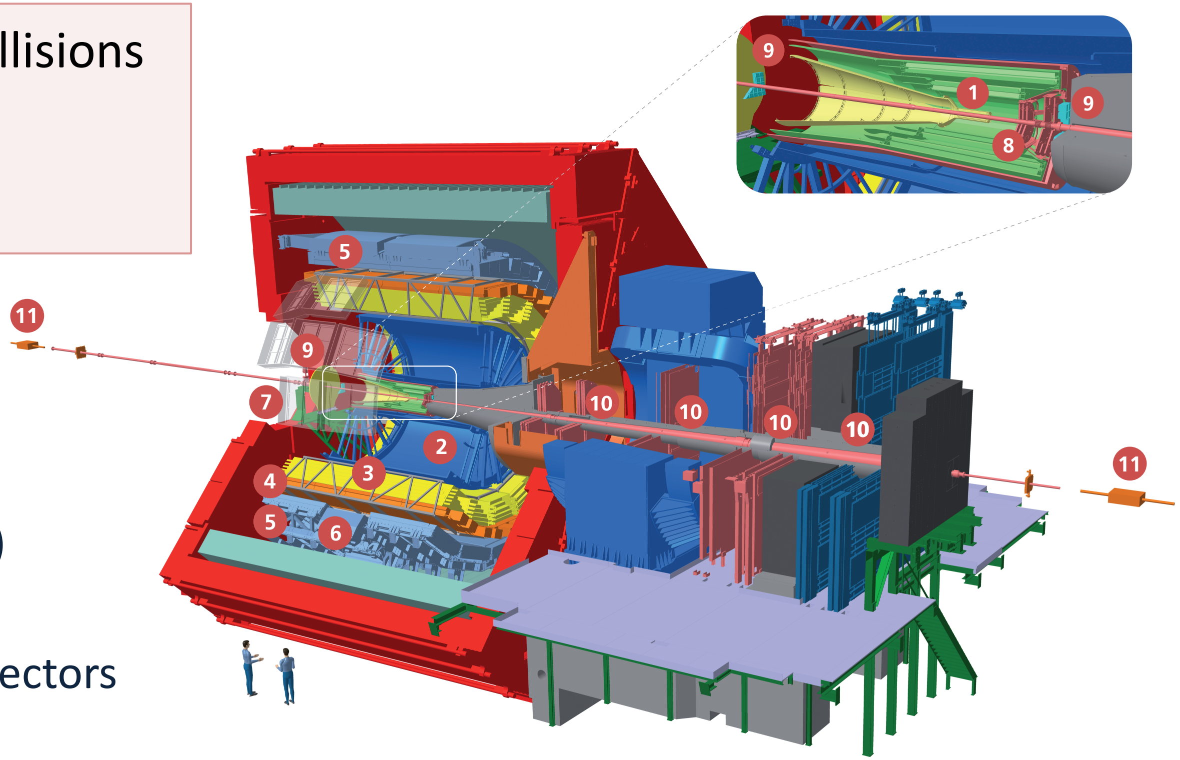
Runs 1 and 2: 1 nb^{-1} of Pb-Pb collisions

Interaction rate ~8 kHz

readout rate ≈ 1 kHz

LS2 upgrade

- New TPC R/O planes
- New silicon tracker (ITS & MFT)
- New Fast Interaction Trigger (FIT)
- New Online/Offline system (**O2**)
- Upgrade readout of all other detectors



1 ITS | Inner Tracking System
2 TPC | Time Projection Chamber
3 TRD | Transition Radiation Detector
4 TOF | Time Of Flight
5 EMCal | Electromagnetic Calorimeter
6 PHOS / CPV | Photon Spectrometer
7 HMPID | High Momentum Particle Identification Detector
8 MFT | Muon Forward Tracker
9 FIT | Fast Interaction Trigger
10 Muon Spectrometer
11 ZDC | Zero Degree Calorimeter

> Improve tracking resolution at low p_T

x50 statistics increase for most observables

Run 3+Run 4: **13 nb^{-1} of Pb-Pb collisions**

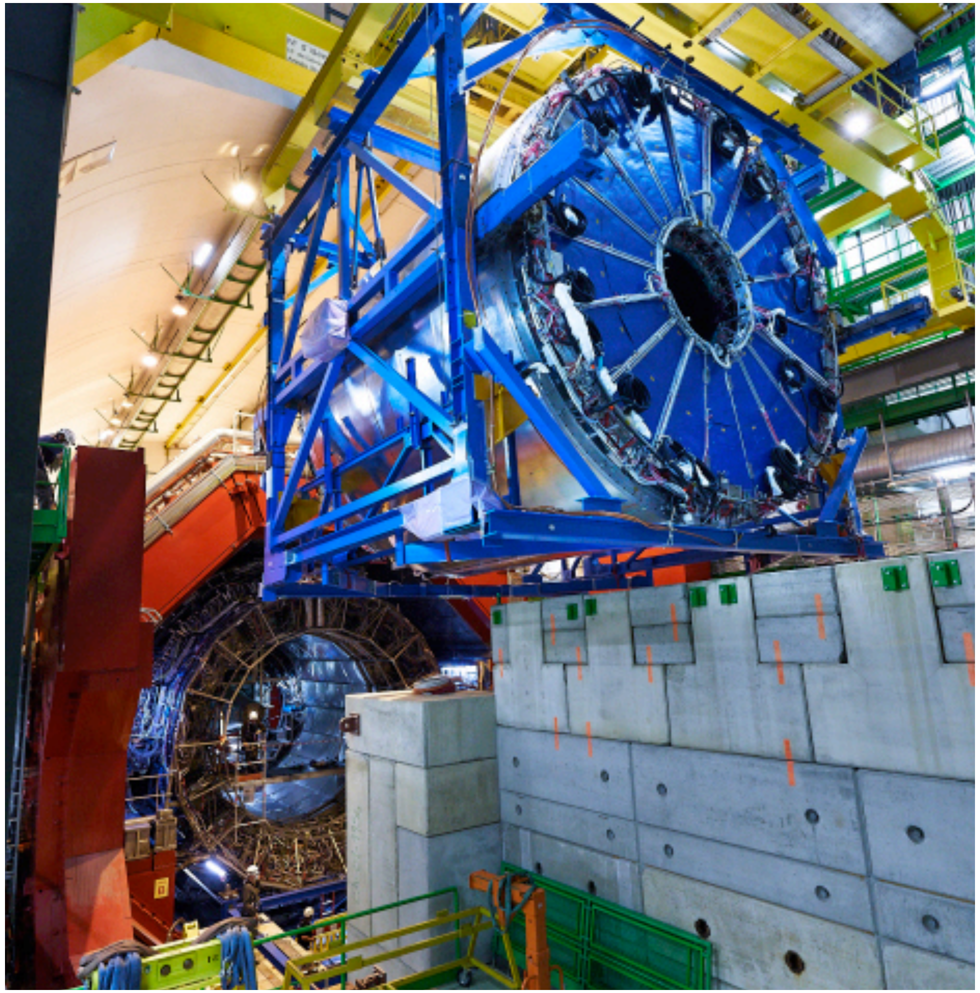
readout rate ≈ 50 kHz (Pb-Pb), ≈ 1 MHz (pp)

online reconstruction : all events to storage!

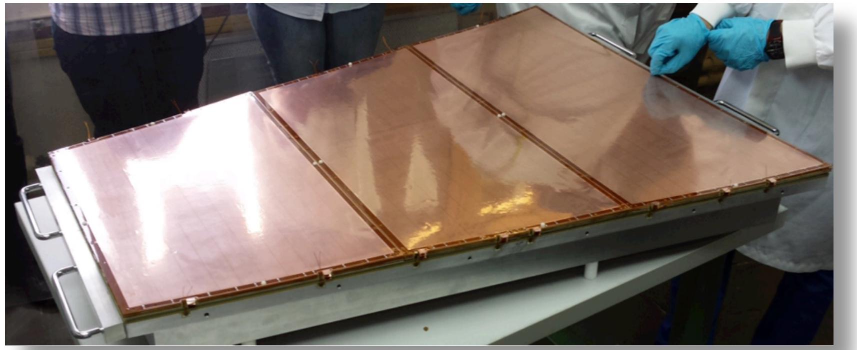
TPC Upgrade for continuous readout

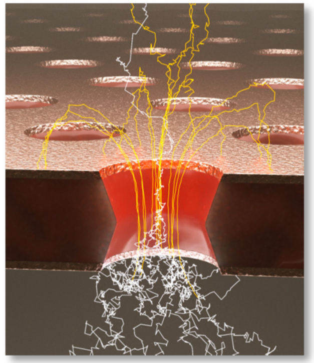
Goal: TPC continuous readout (➪ no gating grid)

Solution: Replace MWPC with 4-GEMs



100 m² single-mask foils GEM production



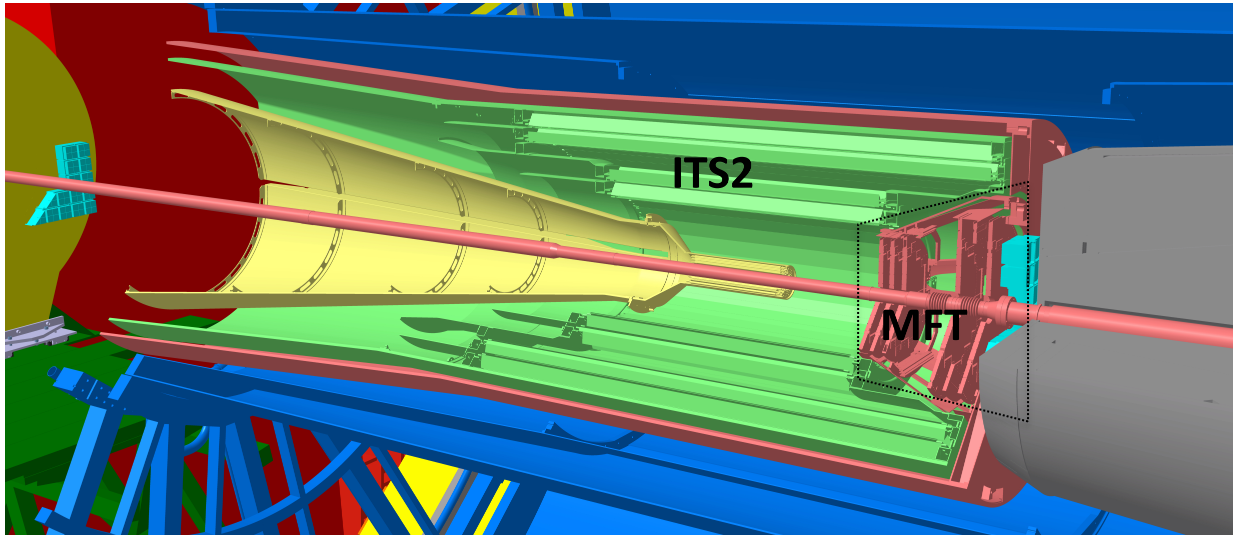


Read Out Chamber

➪ GEM provides ion backflow suppression to **< 1%**

➪ 524 000 pads readout continuously ➪ **3.4 TByte/sec**

New Inner Tracking System and Muon Froward Tracker

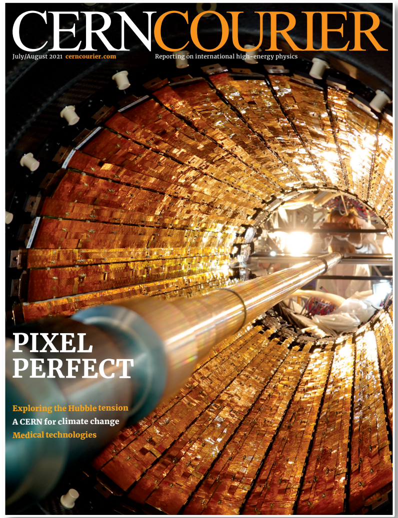


Inner Tracking System upgrade (ITS2)

- Closer to the IP: first layer at ≈22 mm
- Smaller pixels: 28 x 29 μm^2
- Lower material budget: 0.35% X_0

⇨ improved pointing resolution (**x 3**)

⇨ Improved tracking efficieny at low p_T



Based on MAPS technology (ALPIDE)

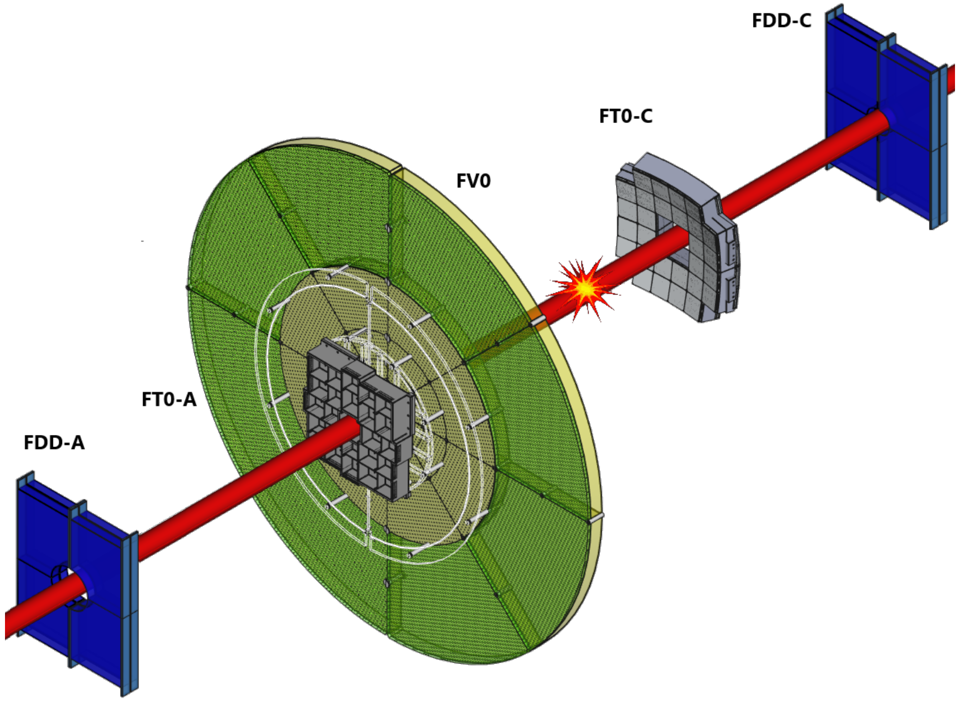
- **10 m²** active silicon area
- **12.5 G-pixels**
- **50 μm** thin sensor
- Spatial resolution **~5µm**
- Max particle rate ~ **100 MHz /cm²**

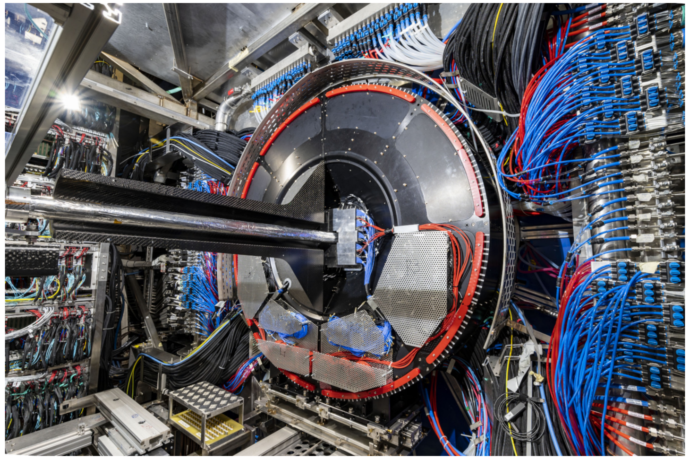
New Muon Forward Tracker (MFT)

- New forward vertex detector upstream muon absorber

⇨ improved muon pointing resolution

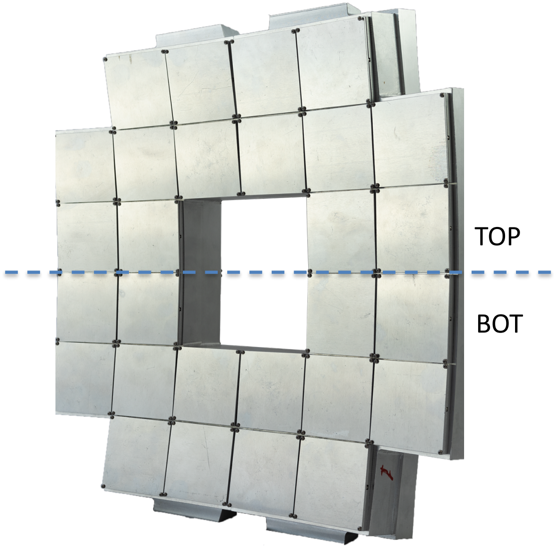
The (new) Fast Interaction Trigger (FIT)





FT0-A + FV0

FT0-C



Fast Interaction Trigger

- Minimum Bias and centrality selection
- Rejection of beam/gas events

Collision time for Time-Of-Flight particle ID

Multiplicity → Centrality and **Event Plane**

FT0 Cherenkov array

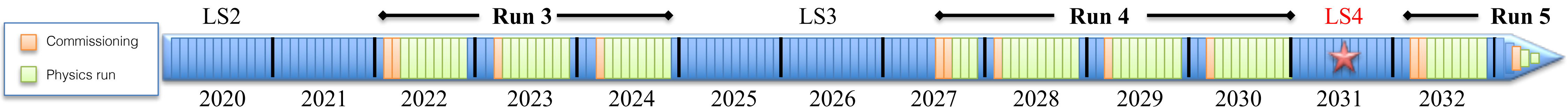
Based on quartz Cherenkov radiators

Modified Planacon MCP-PMTs

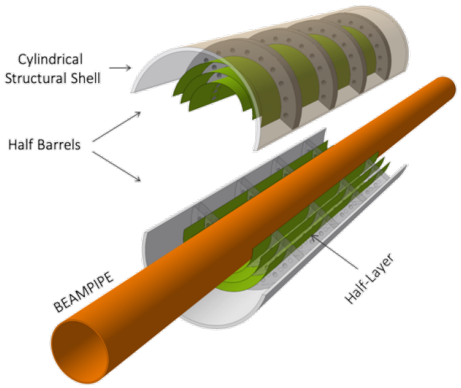
Excellent time resolution:

- **< 50 ps** for single channels @ 1 MIP
- **7 ps** achieved with higher amplitudes or multi-channel average

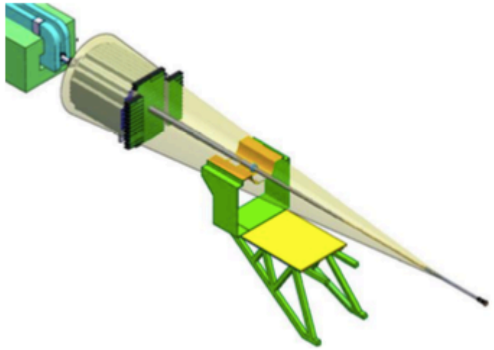
Perspectives: upgrades for Run 4, ALICE 3 for Run 5



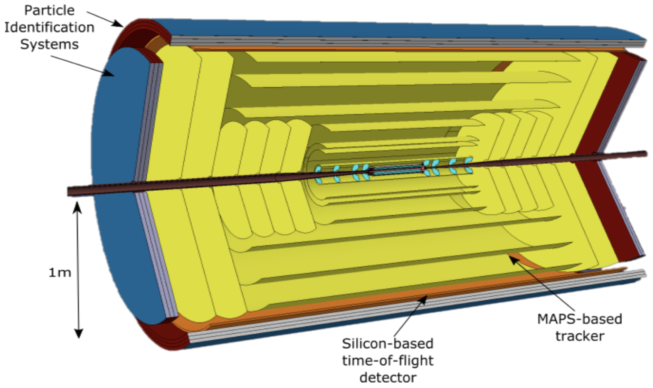
ITS3



FoCal



ALICE 3



ITS3: wafer-scale, ultra-thin, bent MAPS
improvement in the measurement of low p_T charm and beauty hadrons and low-mass dielectrons

LoI: CERN-LHCC-2019-018

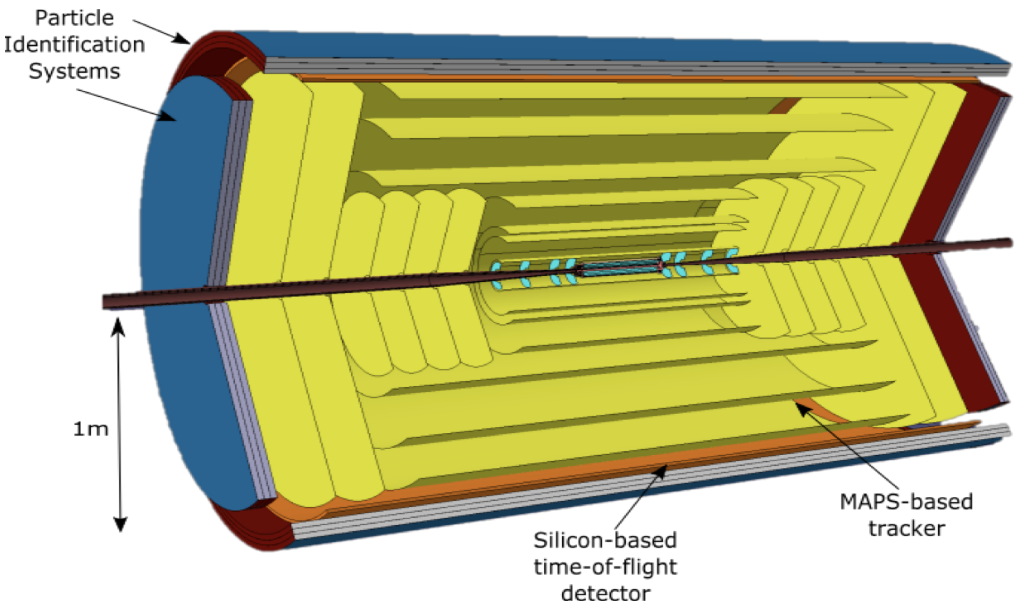
FoCal: forward EM calo with Si readout
for isolated γ measurement in $3.4 < \eta < 5.8$ in p-Pb

LoI ALICE-PUBLIC-2019-005

ALICE 3: a new dedicated heavy-ion detector for Run 5+ (> 2030)

Novel measurements of electromagnetic and hadronic probes of the QGP at very low momenta

⇨ mechanism of hadron formation in the QGP, QGP transport properties, QGP electrical conductivity, QGP radiation and access to the pre-hydrodynamization phase, Chiral Symmetry restoration, …

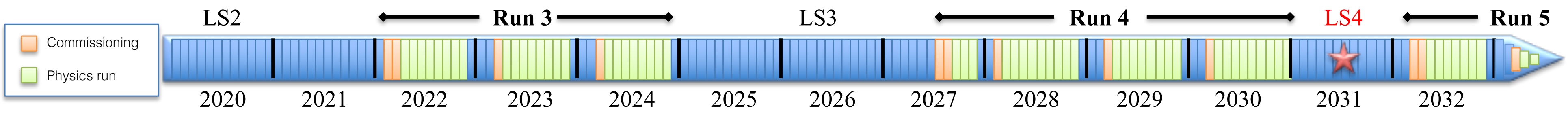


Expression of Interest arXiv:1902.01211

Also submitted as input to the European Strategy for Particle Physics Update (Granada, May 2019)

Timeline

- Conceptual studies ongoing 2019-2021
- Public workshop in October 2021
- Submit a LoI to the LHCC by 2021
- Construction and installation by LS4



Conclusions

A wealth of results based on full Run 2 samples offer:

- Detailed insights into **QGP workings and properties**
- plus a broader and **rich QCD programme**:
    - pQCD, hadron structure, formation of hadrons and nuclei

Underway and coming up:

- Major upgrade for Run 3 on track (ALICE v. 2.0)
- In preparation: ITS3, FoCal for Run 4 (ALICE v. 2.1)
- Plans for next generation dedicated HI experiment for Run 5+ (ALICE v. 3.0)