A Large Ion Collider Experiment

Highlights and perspectives from ALICE

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on behalf of the ALICE Collaboration

https://alice-collaboration.web.cern.ch

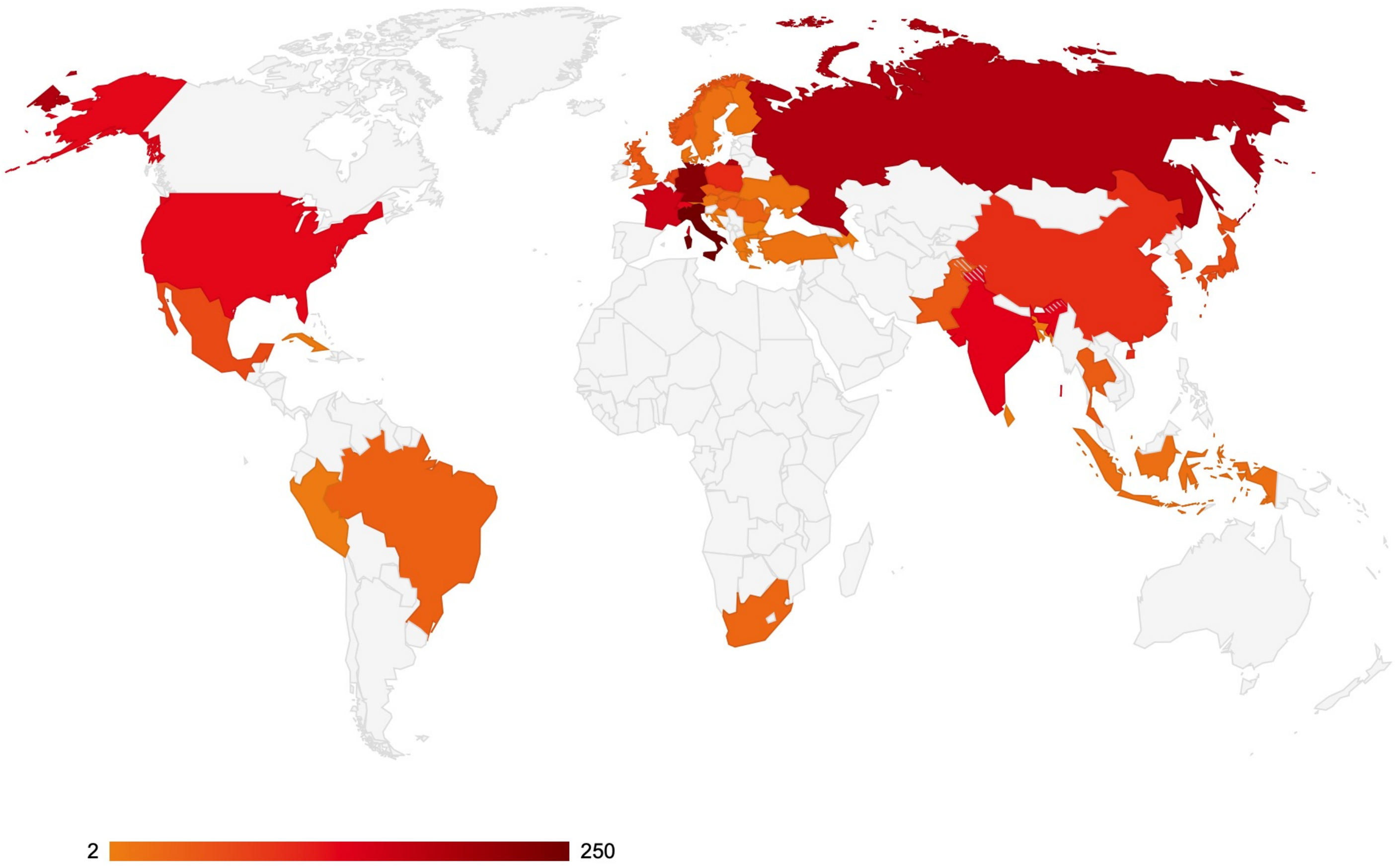
LISHEP 2021 – Session C

6-8 July 2021, virtual

Outline

1. Introduction
2. A few physics highlights
3. Upgrade activities for Run 3
4. Future perspectives

The ALICE Collaboration



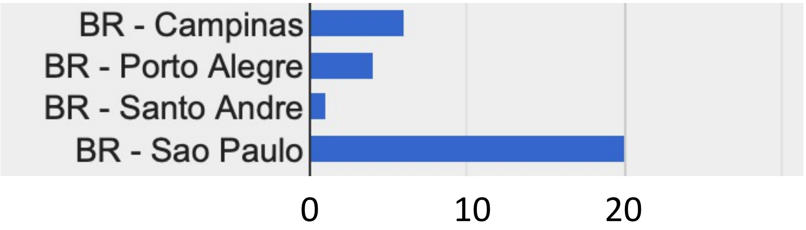
42 Countries, 173 Institutes

1946 Members

about **1000 signing authors**

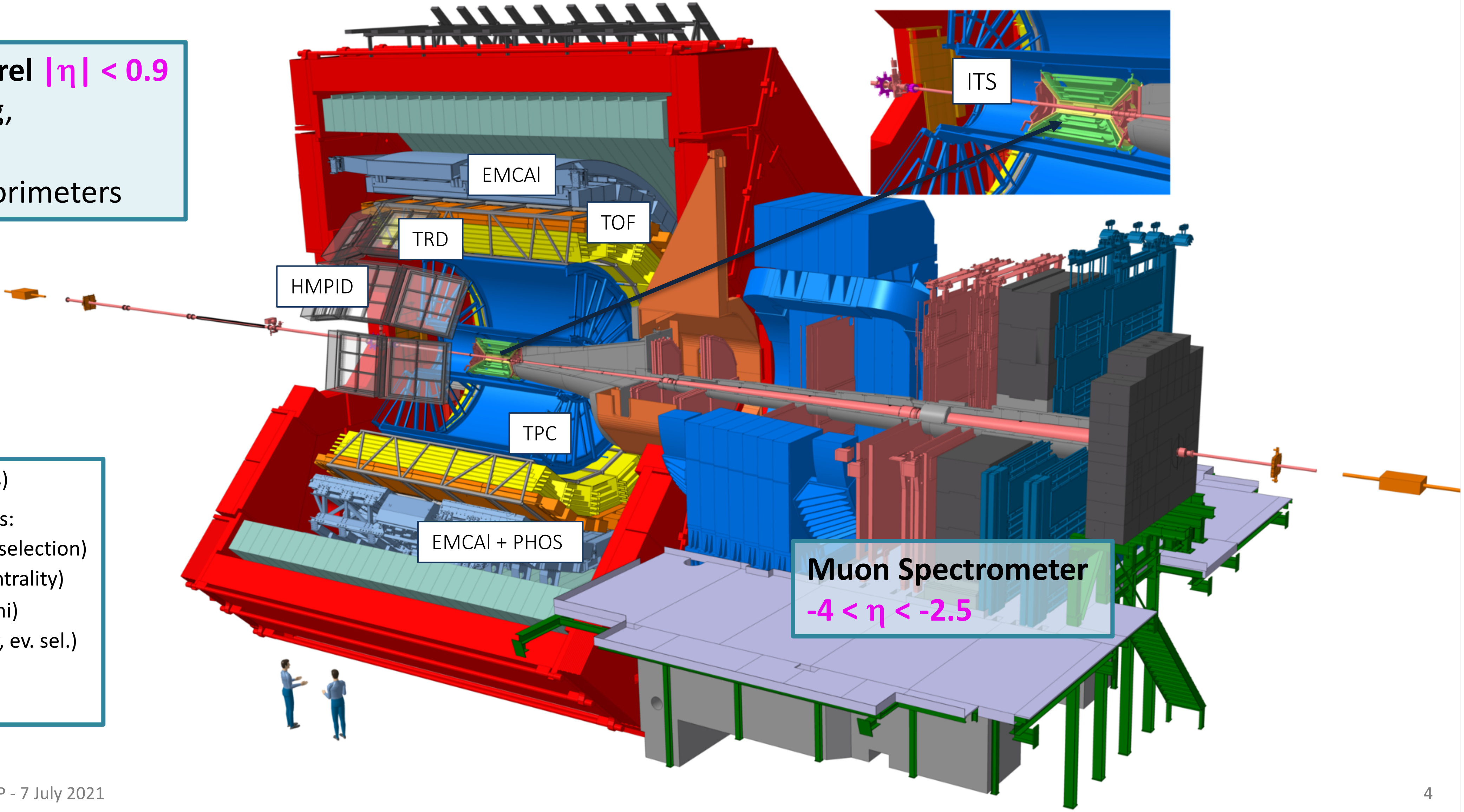
Brazil in ALICE

- **30** members
- **11** Ph.D. scientists
- **15** authors



The ALICE detector (version 1: Run 1 + Run 2)

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



ACORDE (cosmics)

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

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

ALICE data taking and publications

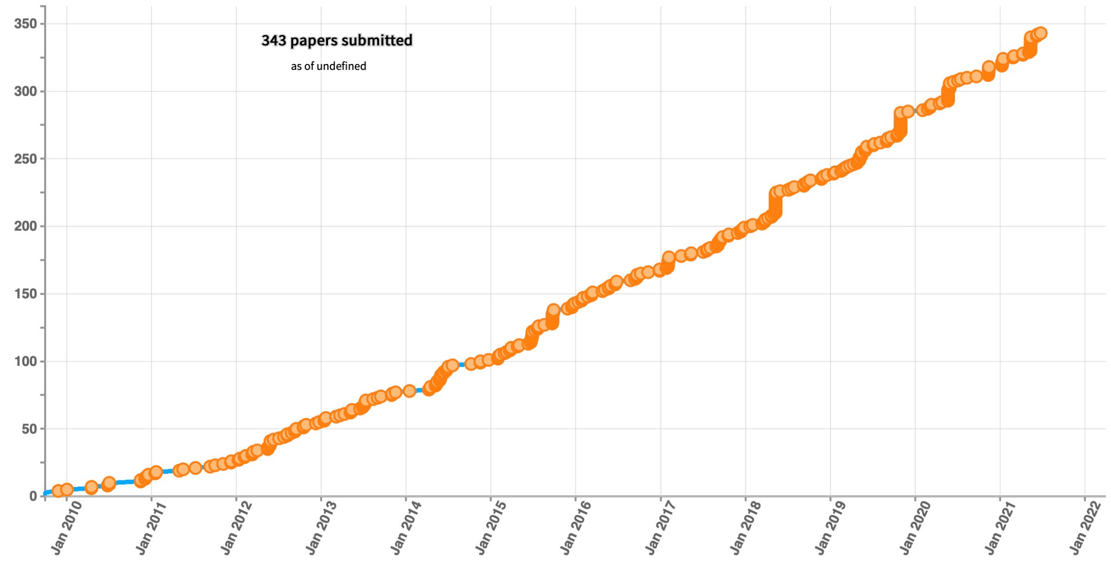
Run 1 (2009 – 2013) LS1 **Run 2** (2015 – 2018) **LS2** **Run 3** (2022 – 2024) LS3 **Run 4** (2027 – 2029)

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 mb^{-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

343 ALICE papers on arXiv so far



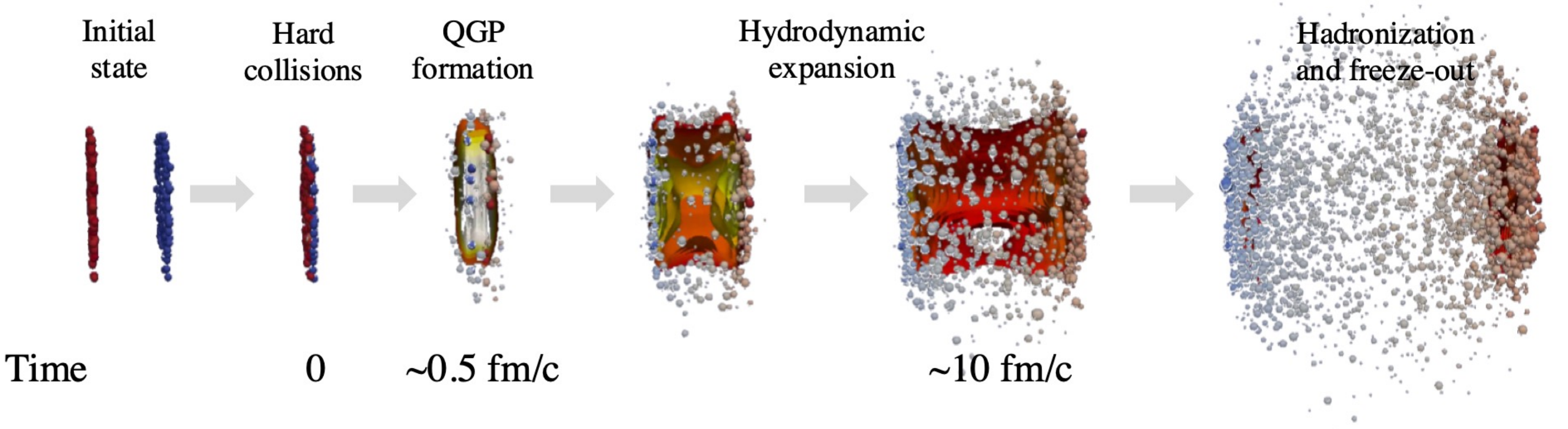
http://alice-publications.web.cern.ch/submitted

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 $\varepsilon > 15$ GeV/fm^3) & **large volume** (~5000 fm^3)



Visualization by J.E. Bernhard, arXiv:1804.06469

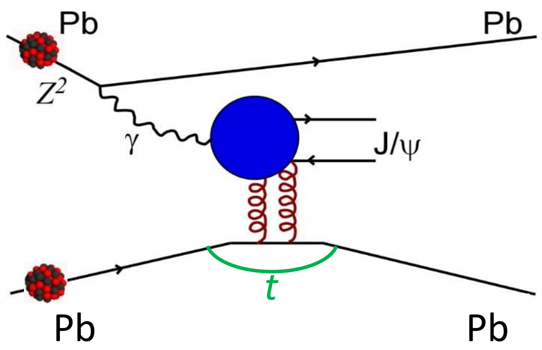
Study the time evolution of the collision

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

➪

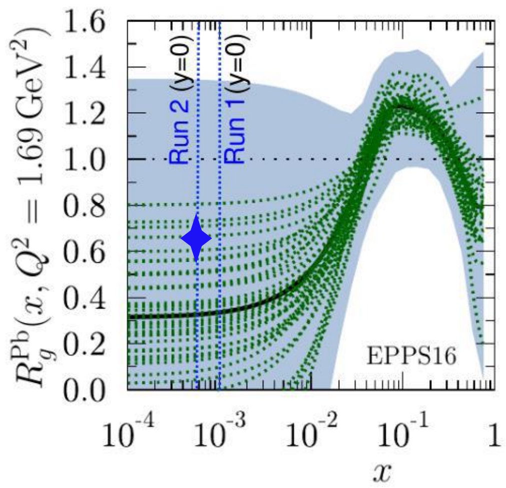
- Light flavour (including light-nuceli) production
- Heavy flavour production
- Quarkonia
- Photons, low-mass dileptons
- Jets
- Ultra Peripheral Collisions

Coherent J/ψ photoproduction in Pb-Pb Ultra Peripheral Collisions



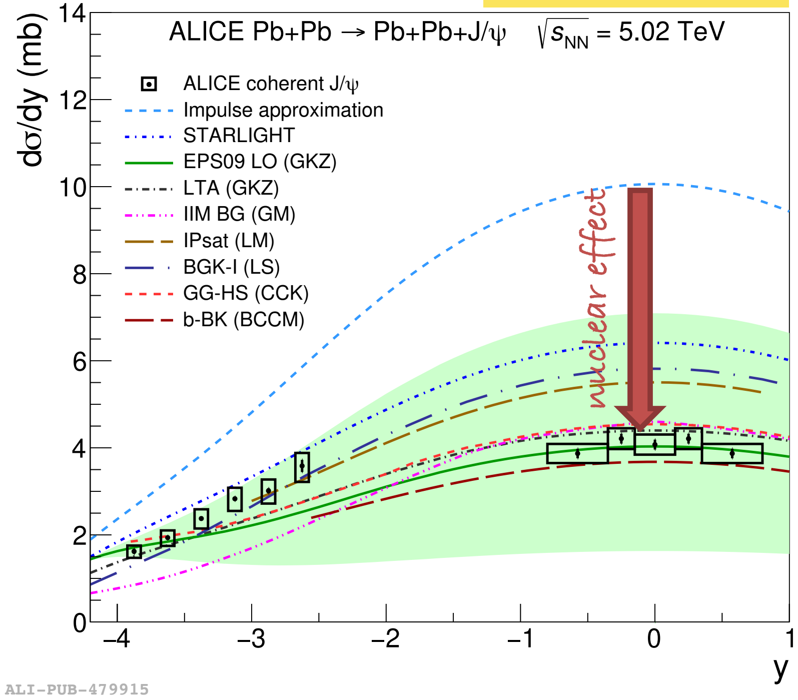
$$\left.\frac{d\sigma_{\gamma A\to J/\psi A}}{dt}\right|_{t=0} = \frac{M^3_{J/\psi}\Gamma_{ee}\pi^3\alpha_s^2(Q^2)}{48\alpha_{em}Q^8}\left[xg_A(x,Q^2)\right]^2$$

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

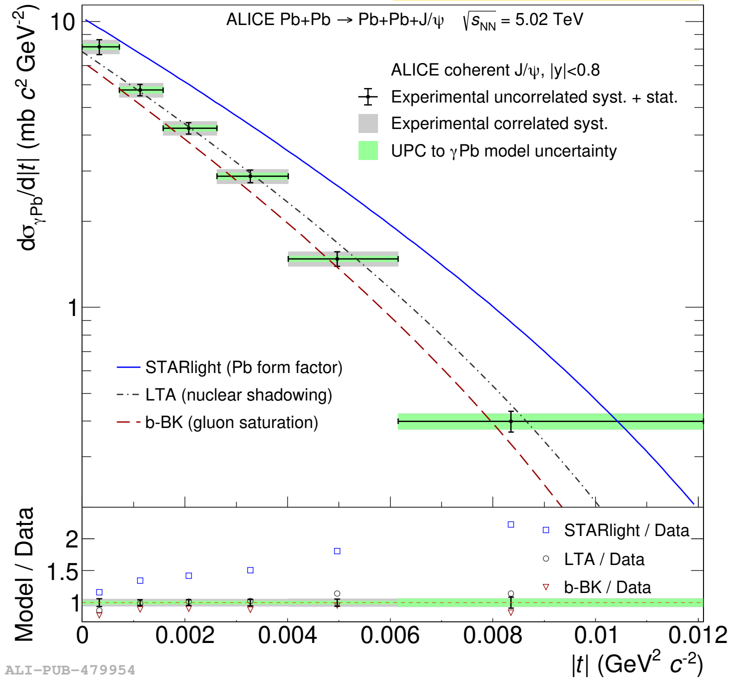


$$R_g^A(x,Q^2) = \frac{g_A(x,Q^2)}{Ag_p(x,Q^2)}$$

arXiv:2101.04577



arXiv:2101.04623



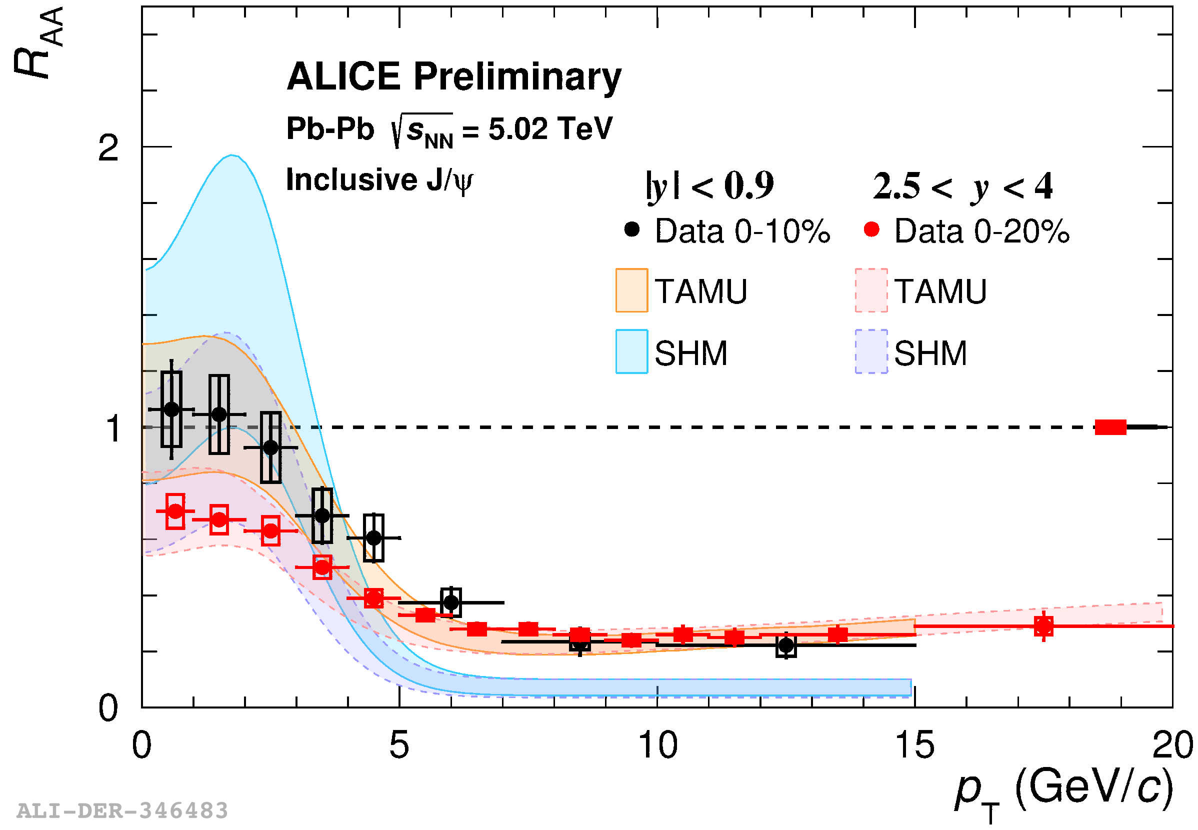
$|t| \approx p_T^2$

New measurment probing low-x gluon nuclear PDFs

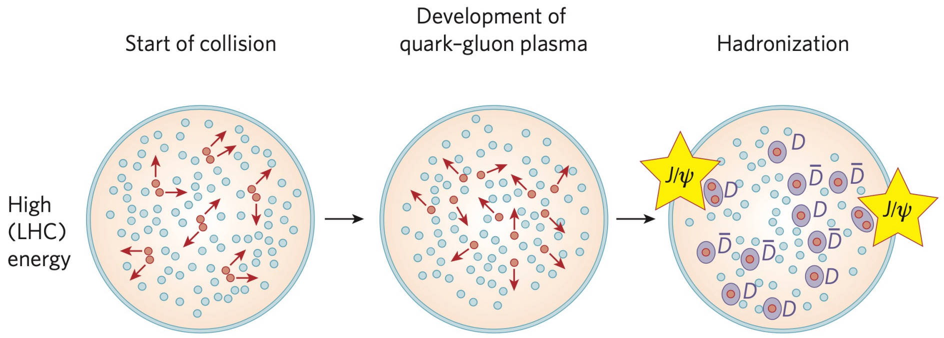
- Comparison with the impulse approximation (no nuclear effects) allows for extraction of the gluon shadowing factor: $\mathbf{R_g \sim 0.65}$ **at** $\mathbf{x \sim 10^{-3}}$
- **First measurement** of t-dependence: sensitive to transverse gluon distribution

J/ψ production in Pb-Pb collisions

PLB 805 (2020) 135434



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



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

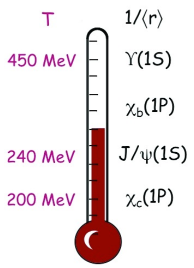
- At low p_T, modification decreases from **forward** to **central** rapidity
- reflects rapidity dependence of the $c\bar{c}$ cross-section (⇨ regeneration probability)

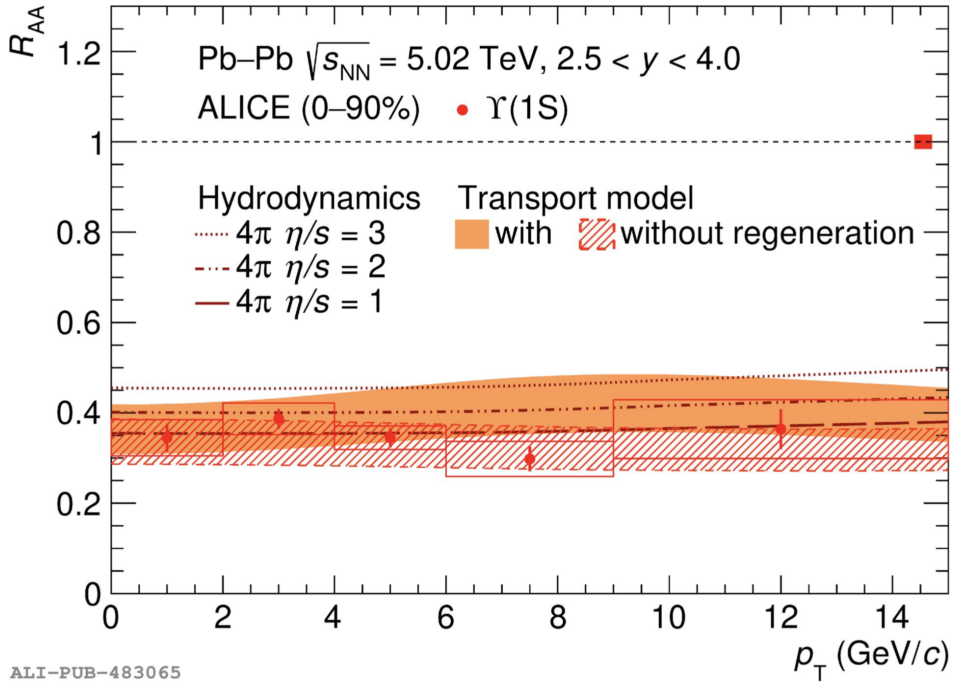
Suppression of bottomonia in Pb-Pb collisions

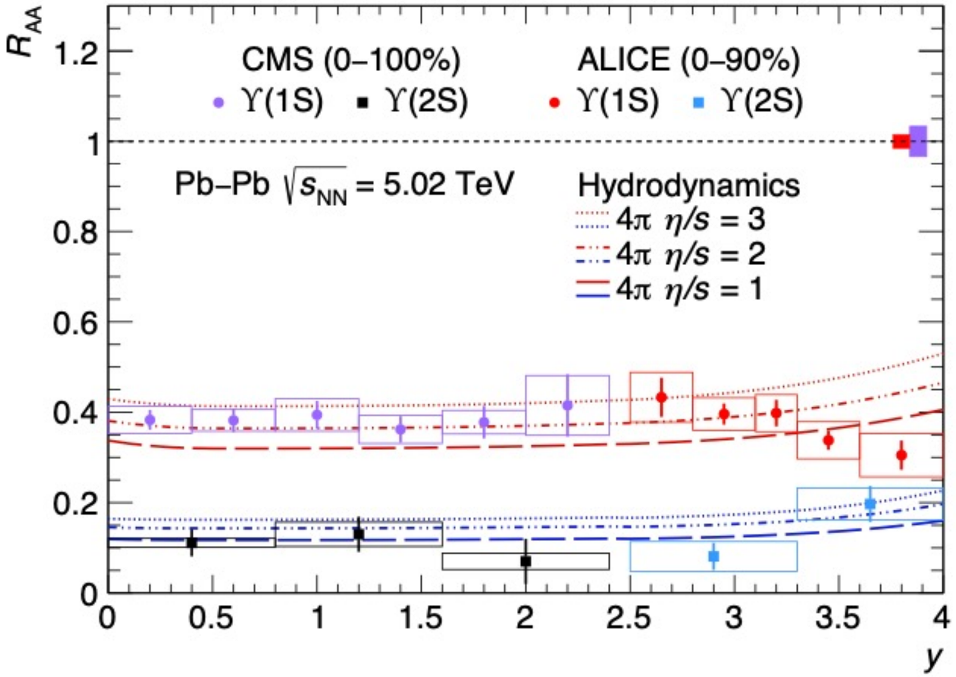
arXiv:2011.05758 **[nucl-ex]**

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

0.05 0.55 0.65 1.1 GeV



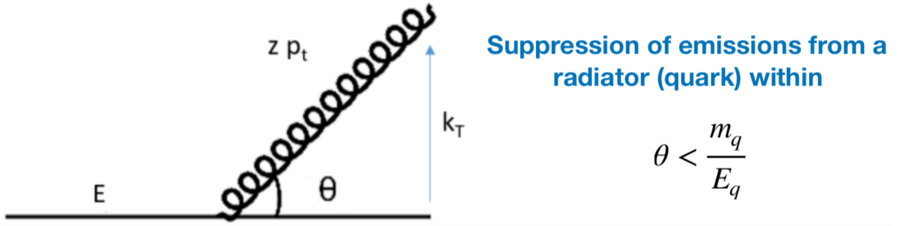




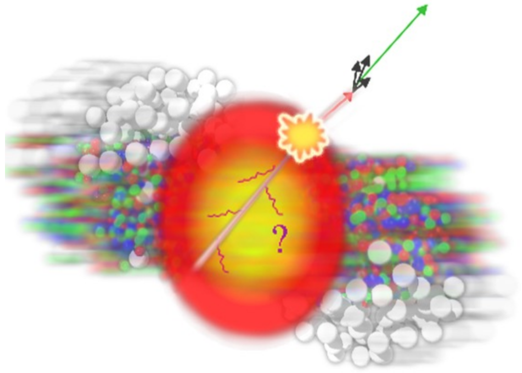
- Screening induces a strong suppression of Y production, which is flat vs p_T ⇨ recombination effects small
- Y(2S) (**first time!**) at forward rapidity - a suppression stronger wrt Y(1S) consistent with lower binding energy

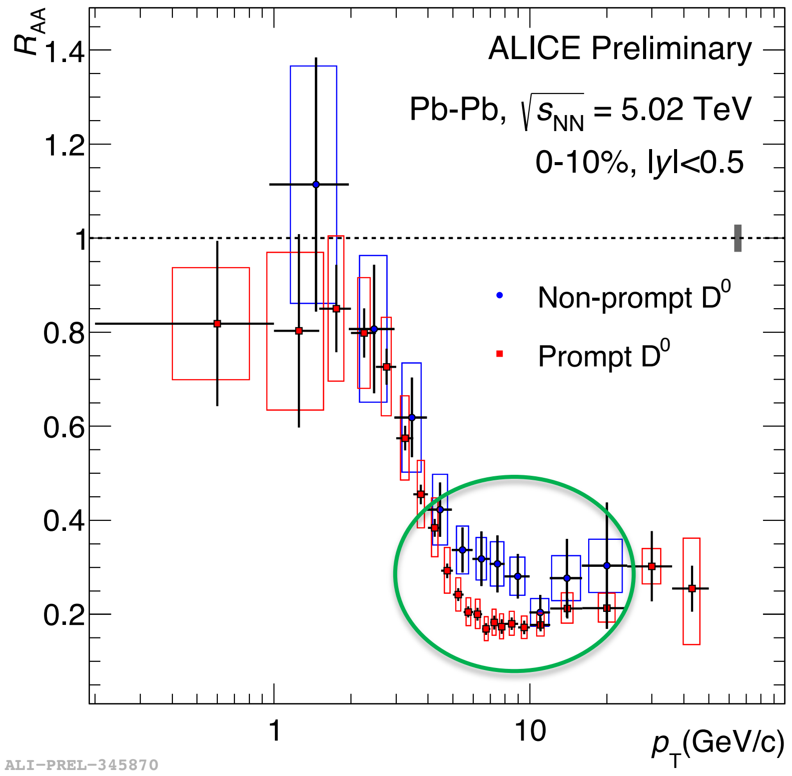
Energy loss of c and b quarks in the QGP

- **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



- Less suppression for (non-prompt) D mesons from B decays than prompt D mesons
- Also note: first measurement of D meson production down to zero p_T in Pb-Pb
- Preparing precise measurement with new ITS in Run 3

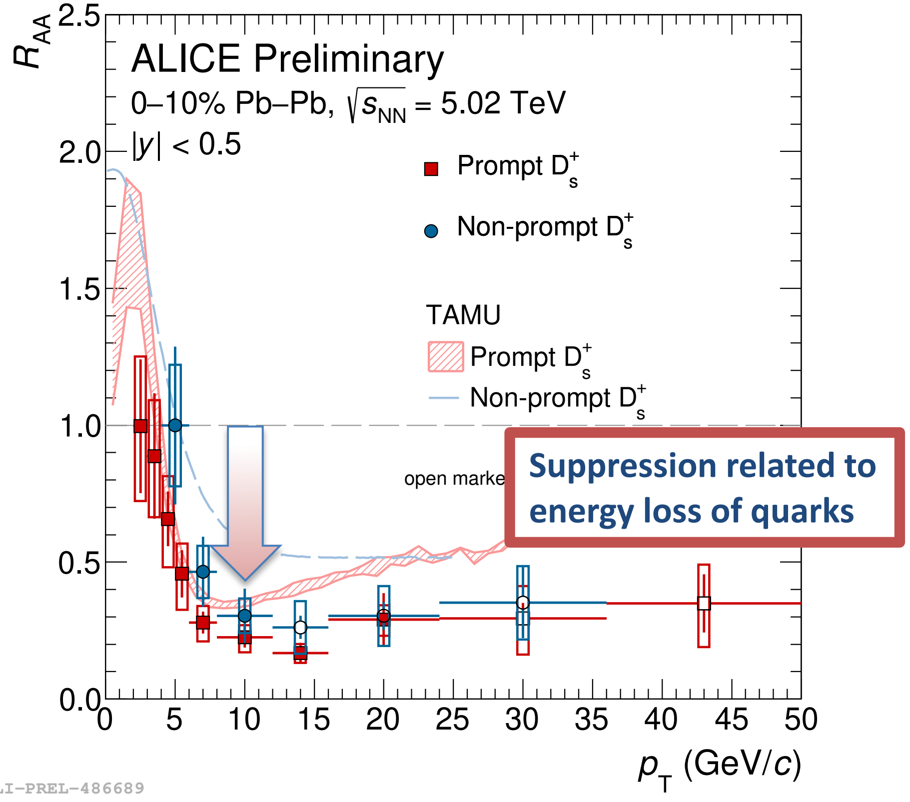


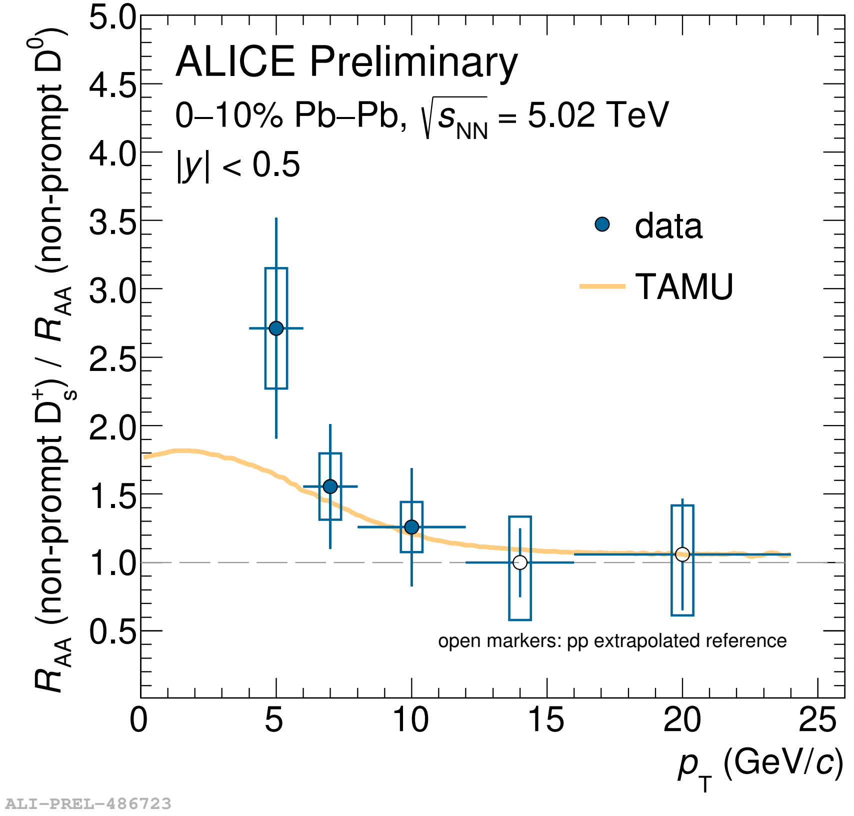


Studying hadronization mechanism in Pb-Pb collisions

Expectation: beauty looses less energy in QGP as compared to lighter charm (dead-cone effect)

R_{AA} = yield in AA per NN / yield in pp **R_{AA} = 1 at high p_T ⇔ no nuclear effects**





TAMU
PRL **124**, 042301

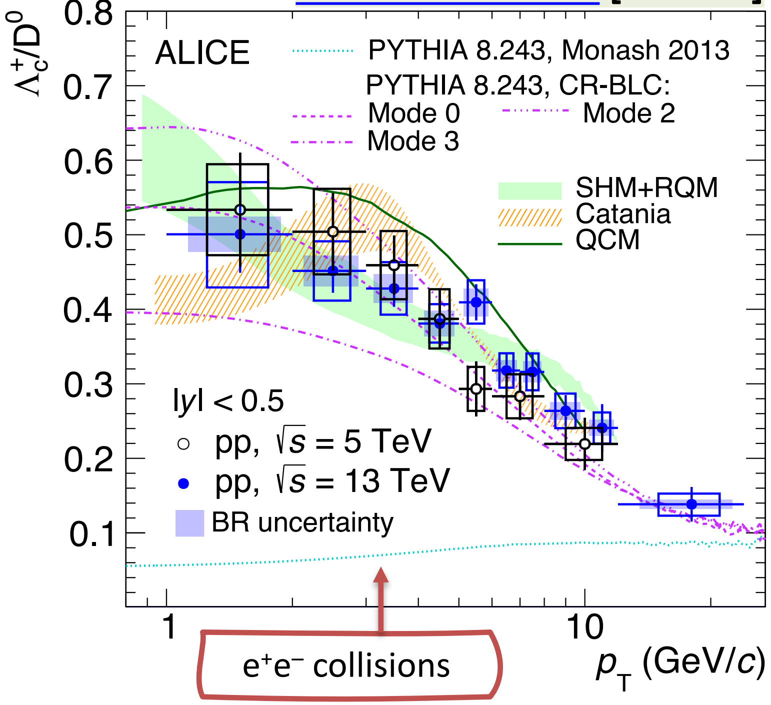
Two observations: **1)** hint **R_{AA}(non-prompt D^+_s) > R_{AA}(prompt D^+_s)** and **2) R_{AA} (non-prompt D^+_s) > R_{AA} (non-prompt D^0)**

- Consistent with $m_b > m_c$ and coalescence
- Enhanced production of B^0_s from beauty hadronization via coalescence (50% of D^+_s from B^0_s)

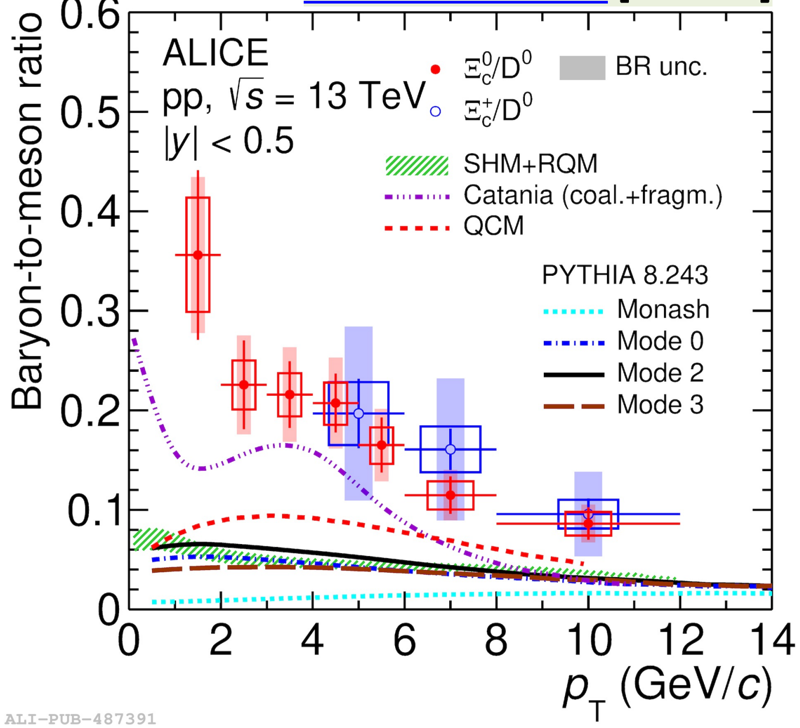
Charm baryon/meson measurments in pp collisions

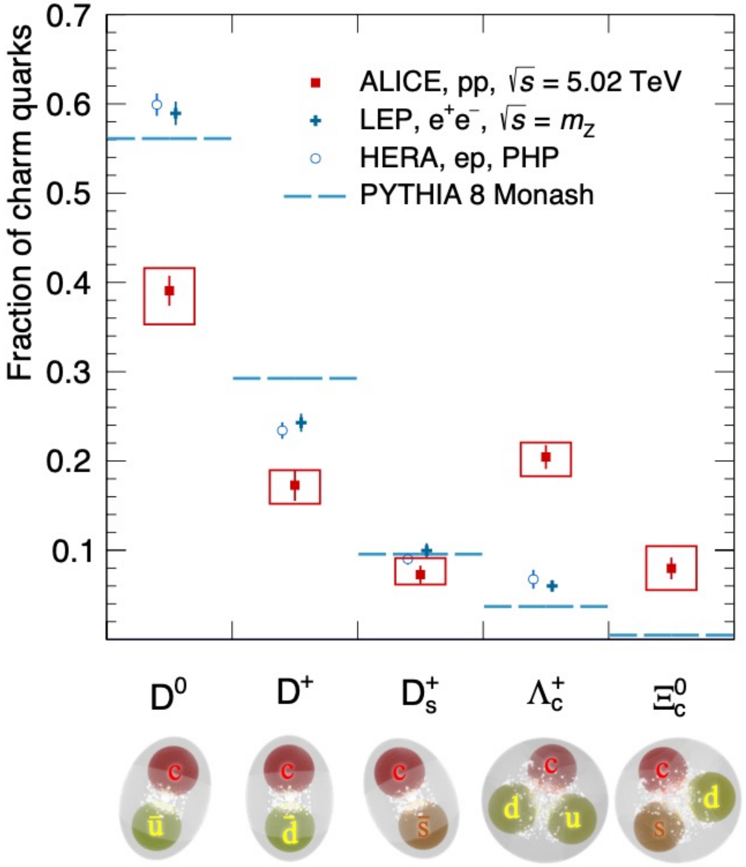
Charm hadronization differs at the LHC

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)

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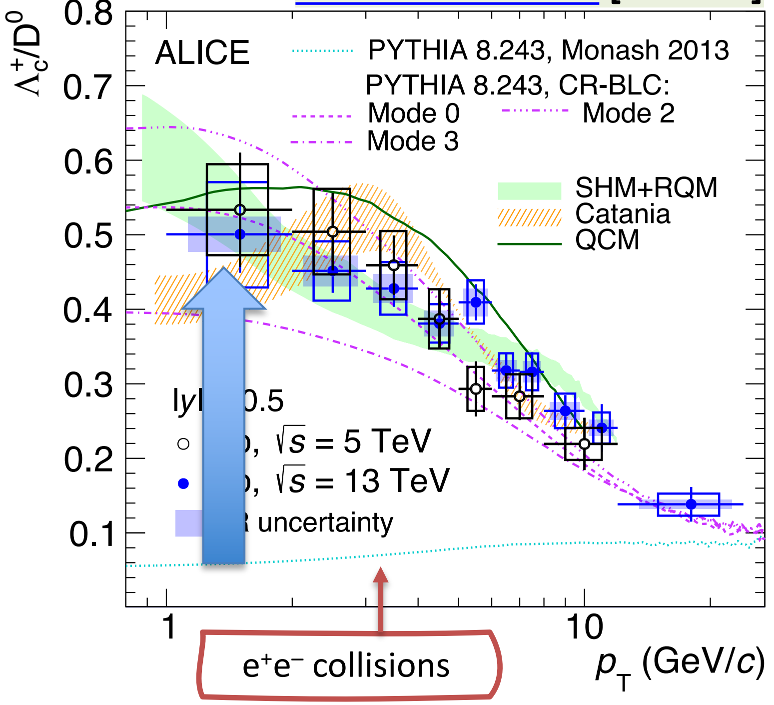

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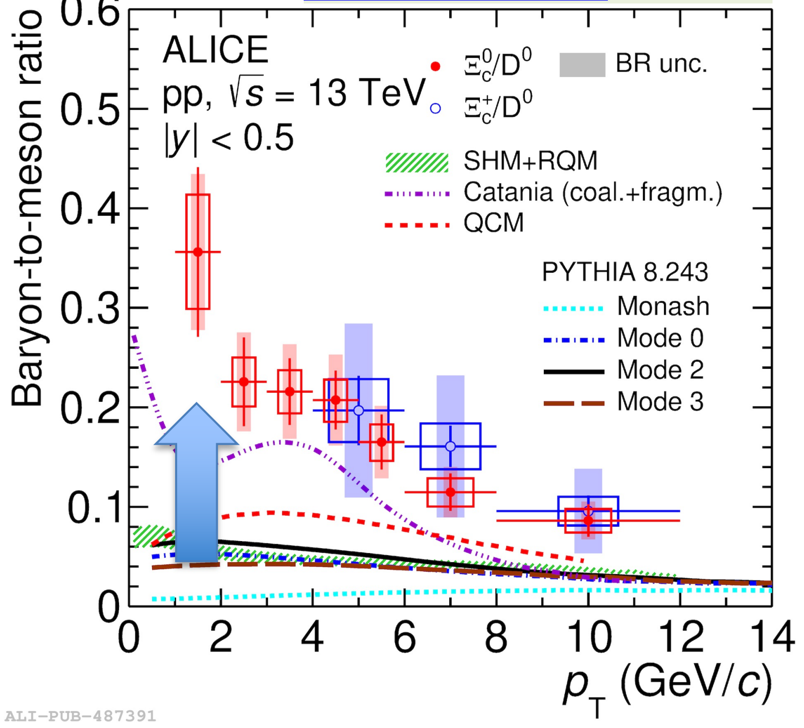
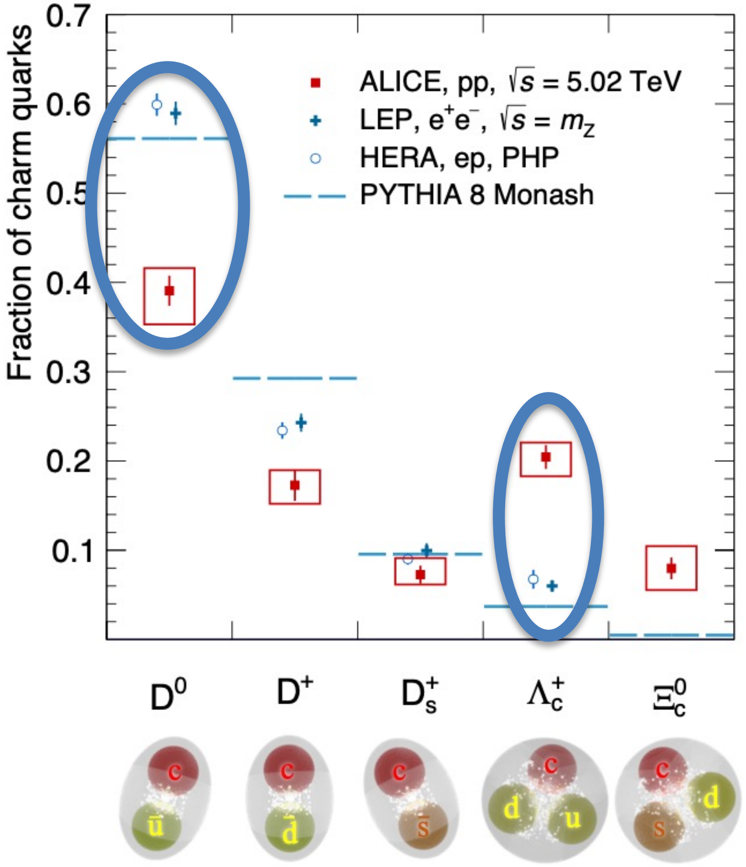




- unique measurements (at low-momenta) of Λ_c (also Ξ_c and Ω_c)
- cross section (fragmentation fraction) larger than expected (ee and ep)

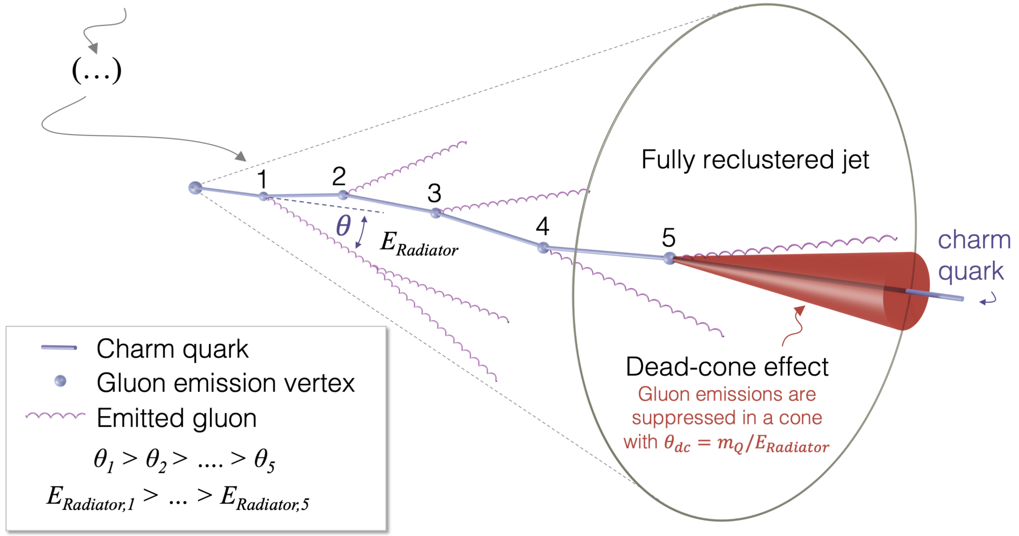
Measuring the dead-cone in radiation off of a heavy quark

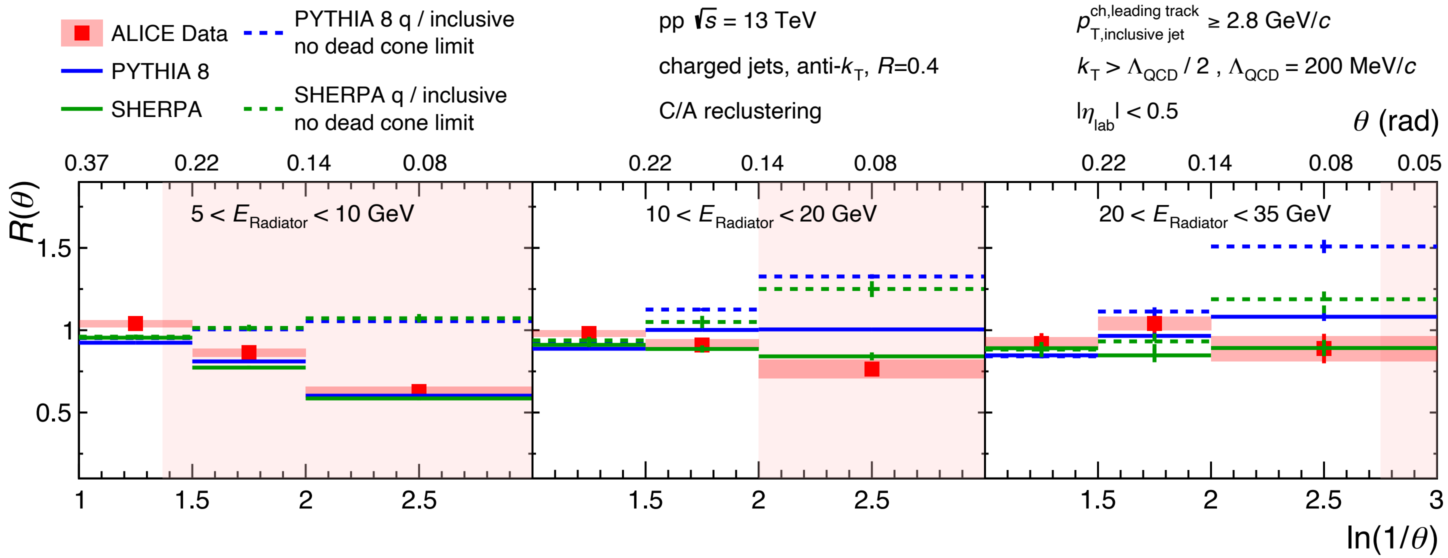
Follow a heavy quarks through the primary Lund Plane & suppress hadronization effects/non pert. (at samll K_T)

Expectation: radiation suppressed for $\theta_c < m_Q/E$

arXiv: 2106.05713 [nucl-ex]

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



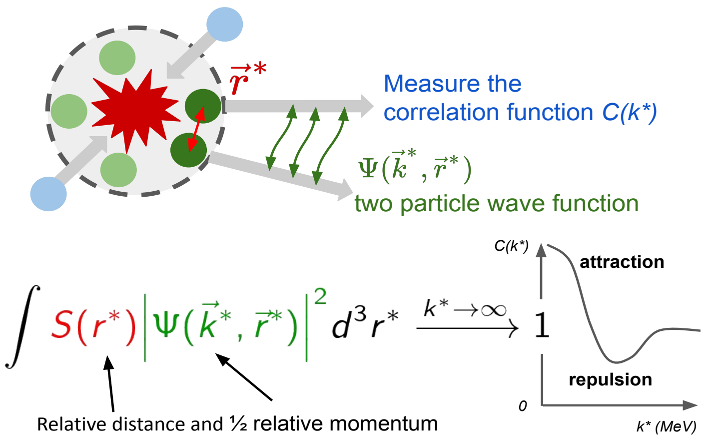


New ALICE measurement for D-tagged jets (R < 1)

- Radiation suppressed in the expected angular region (shaded)
- Suppression lifted as $mass_Q << E_{radiator}$

QCD interaction among hadrons

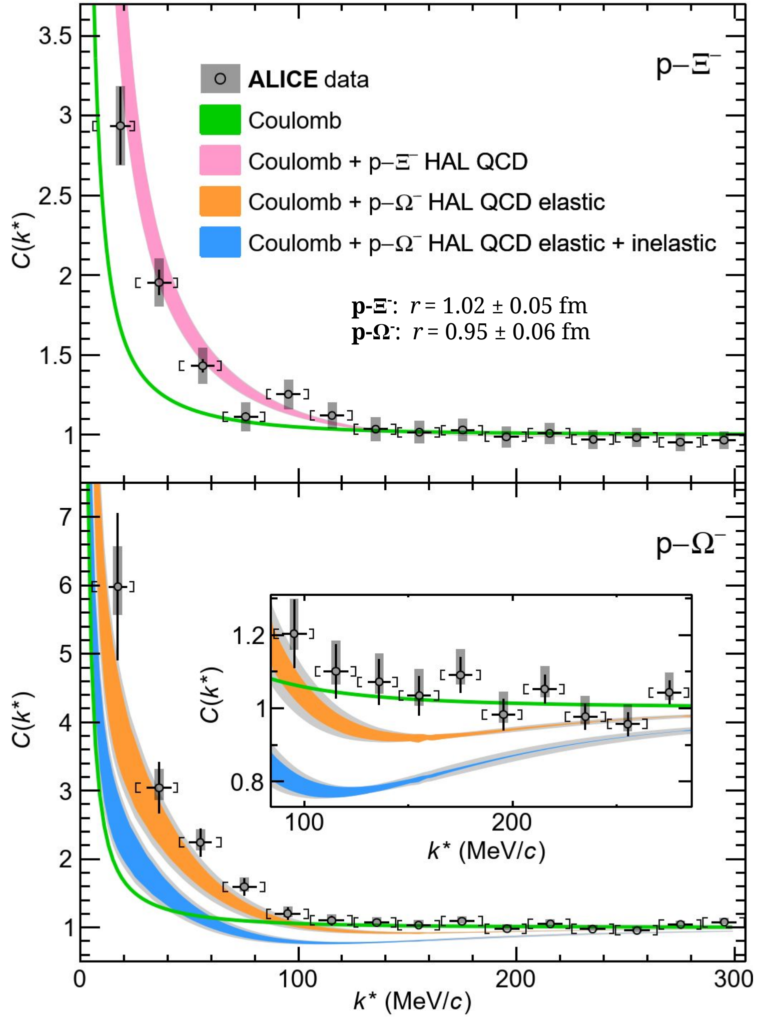
"Unveiling the strong interaction among stable and unstable
Nature 588 (2020) 232-238



$$C(k^*) = \int S(r^*) \left|\Psi(\vec{k}^*, \vec{r}^*)\right|^2 d^3 r^* \xrightarrow{k^* \to \infty} 1$$

Relative distance and ½ relative momentum evaluated in the pair rest frame

Measure C(k*), fix S(r), study the interaction. *Phys. Lett. B 811 (2020) 135849*



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

- Measured in ALICE: momentum correlation of proton-hyperon pairs from a source of known size
- precise measurment of strong interaction for p-Ξ^- and p-Ω^-
  - direct comparison to lattice QCD
  - p-Ξ^- important for neutron star EoS

ALICE on topic
pΛ, pK, pΞ^-, pΩ, pΣ^0, $\Lambda\Lambda$, pp

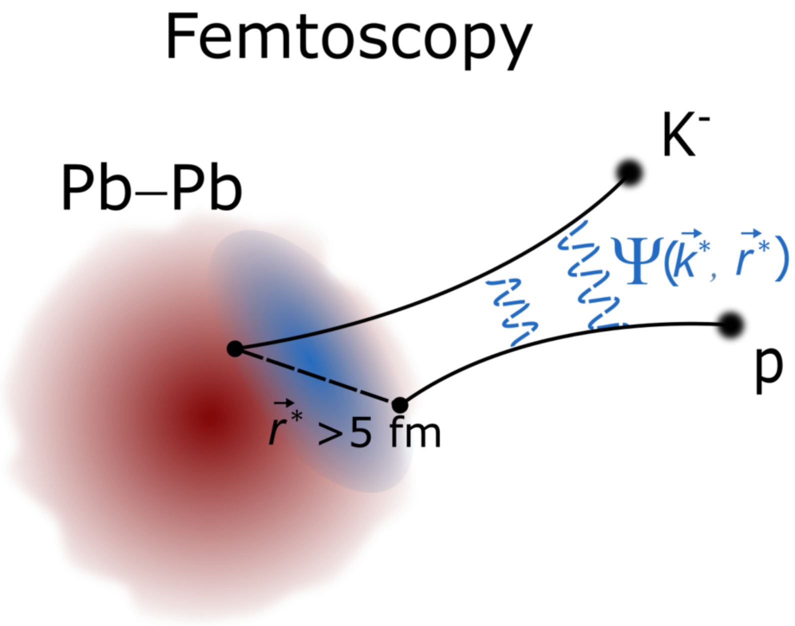
Phys. Rev. C 99 (2019) 024001
Phys. Rev. Lett> 124 (2020) 092301
Nature 588 (2020) 232-238
Phys. Rev. Lett. 123 (2019) 112002
Phys. Letters B 805 (2020) 135419
Phys. Lett. B 797 (2019) 134822
Phys. Lett. B 797 (2019) 134822
Phys. Lett. B 811 (2020) 135849

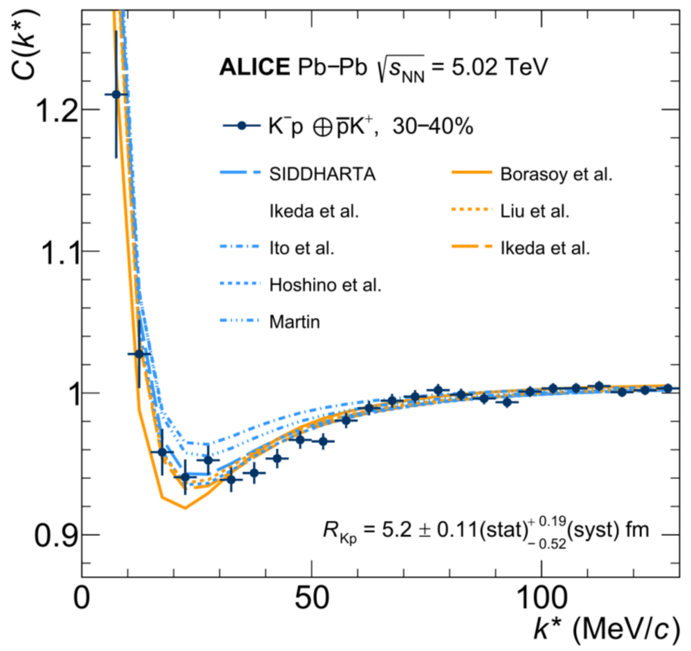
Strong force at work – hadron interactions

Use Pb-Pb to measure interaction as function of distance

arXiv:2105.05683 **[nucl-ex]**

K⁻- p correlations in Pb-Pb collisions





Femtoscopy

- Small systems (pp) r*~1 fm – sensitive to inelastic channels
- Large systems (Pb-Pb) r*> 3 fm – only elastic channels. ⇨ **Alternative to scattering experiments; exotic atoms**

Upgrade activties for Run 3 and Run 4
ALICE version 2.0

ALICE Detector Version 2.0 (Upgrades for Run 3+)

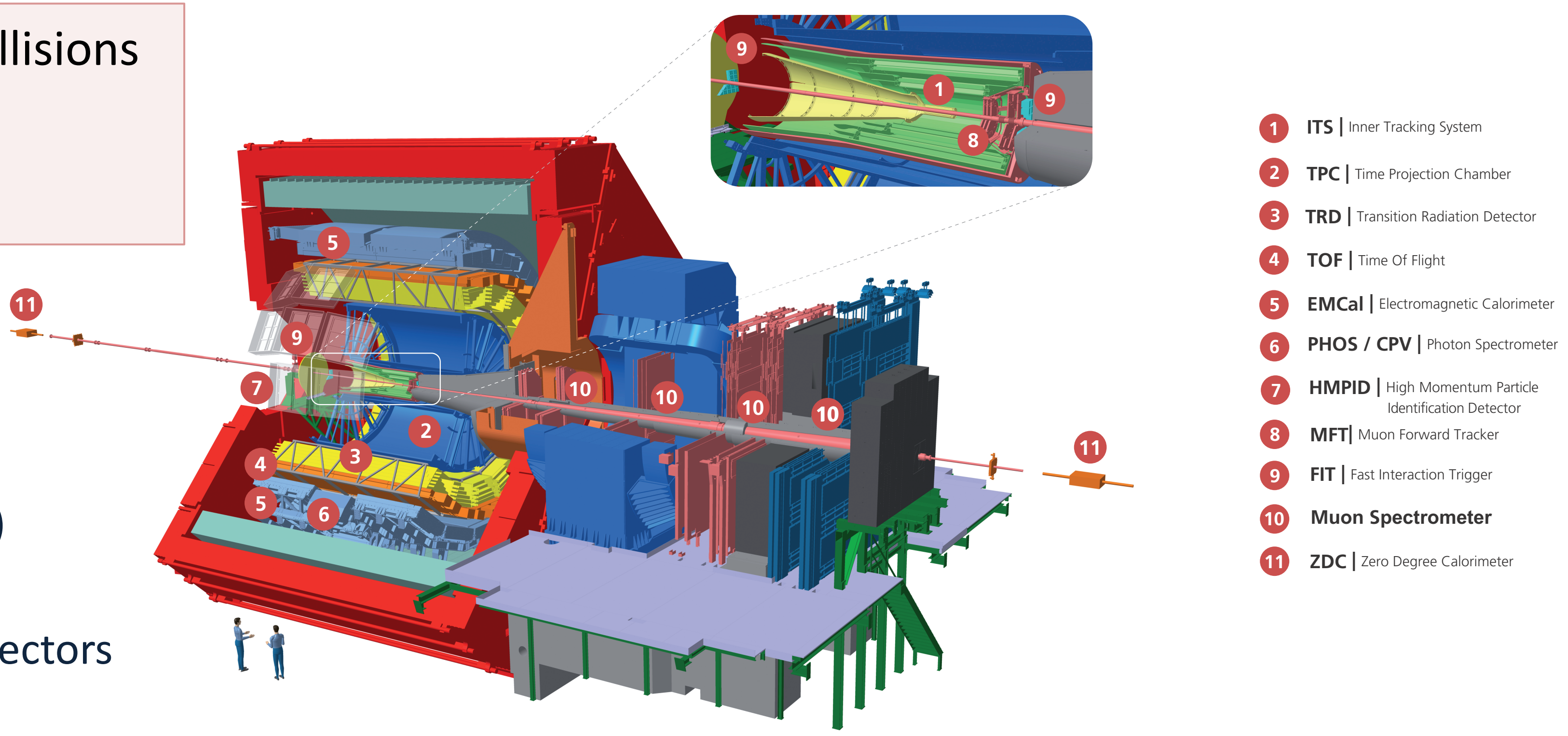
Runs 1 and 2: 1 nb^{-1} of Pb-Pb collisions

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



> Improve tracking resolution at low p_T

x50 statistics increase for most observables

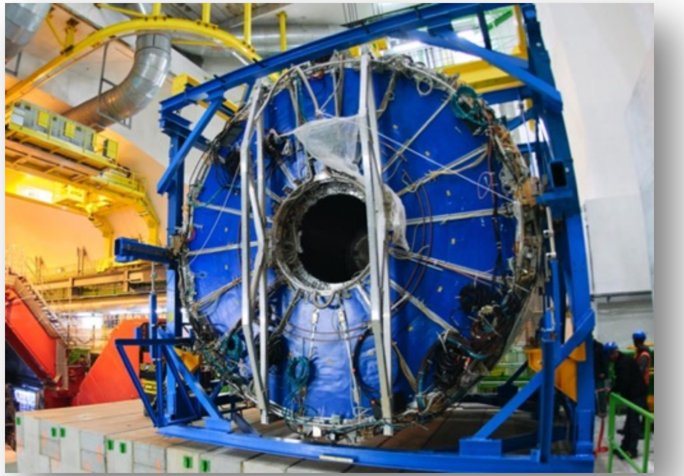
Run 3+Run 4: **13 nb^{-1} of Pb-Pb collisions**

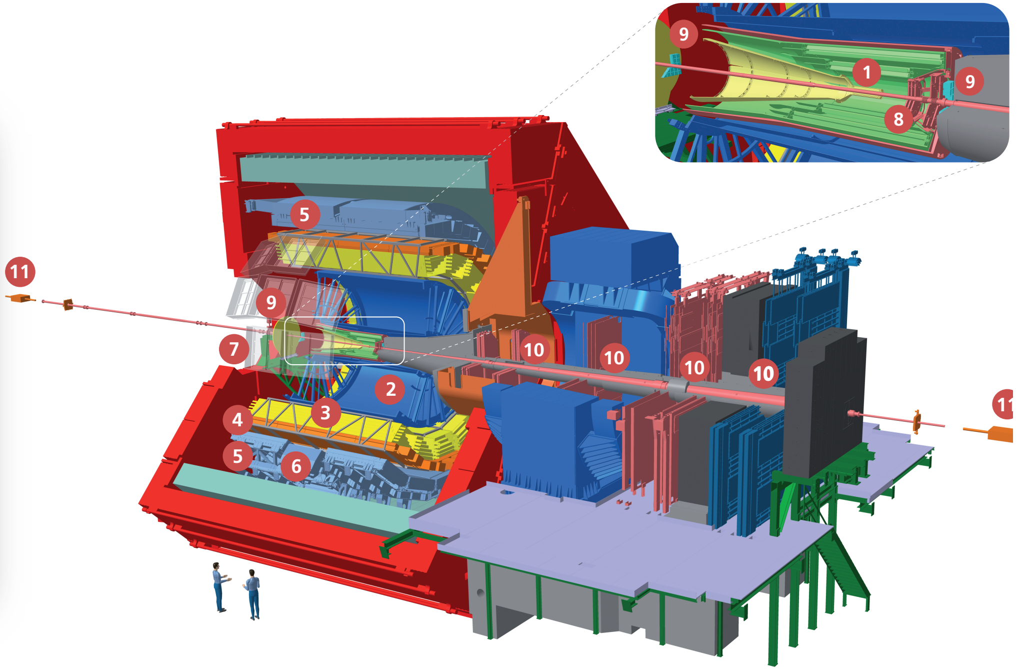
readout rate ≈ 50 kHz (Pb-Pb), ≈ 1 MHz (pp)

online reconstruction : all events to storage!

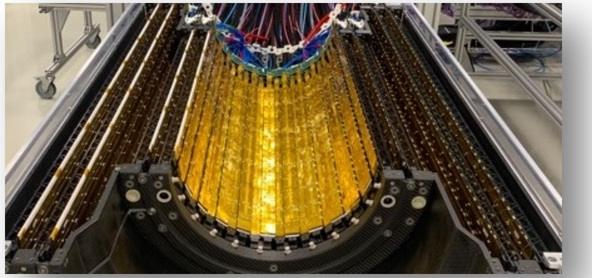
ALICE Detector Version 2.0 (Upgrades for Run 3+)

GEM-based TPC readout

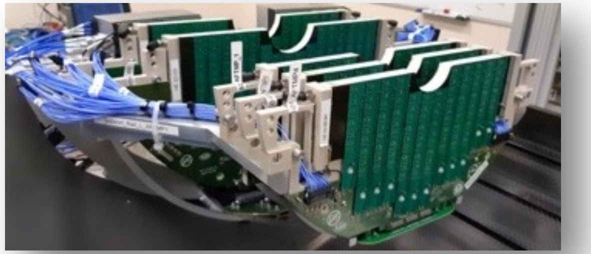




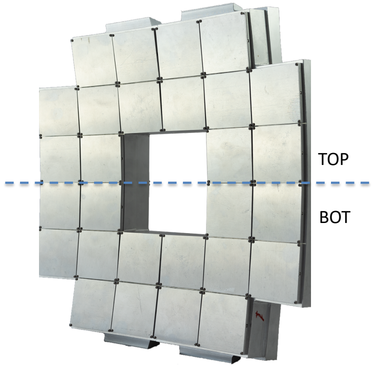
Monolithic-pixel - ITS2



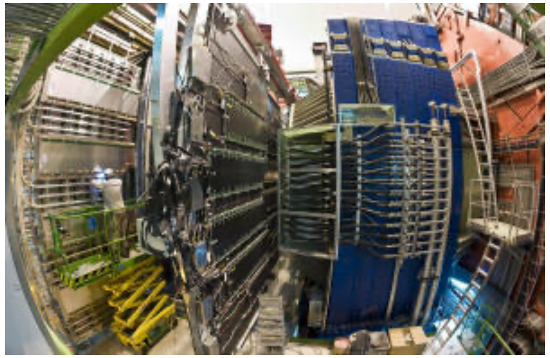
Pixel Muon Forward Tracker (MFT)



Fast Interaction Trigger FIT

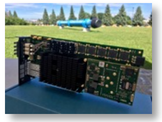


Muon Spectrometer



New Central Trigger Processor (CTP)

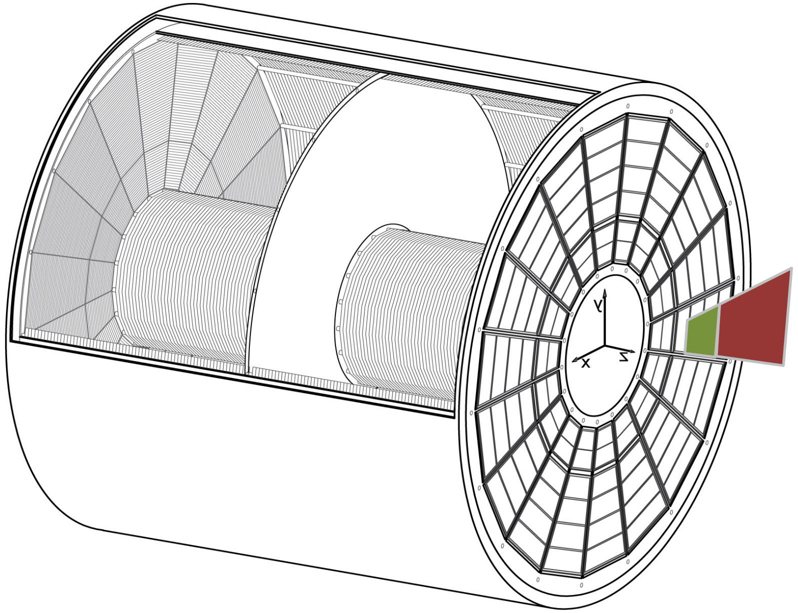
Upgrade of R/O for EMCal, PHOS, TRD, HMPID, ZDC



New Online/Offline (O2)

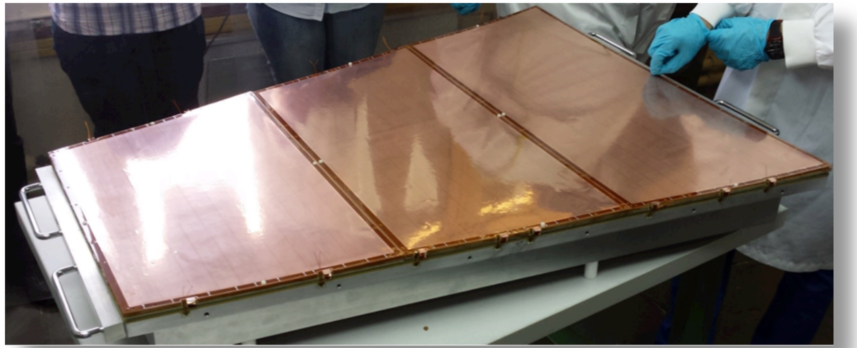
TPC Upgrade for continuous readout

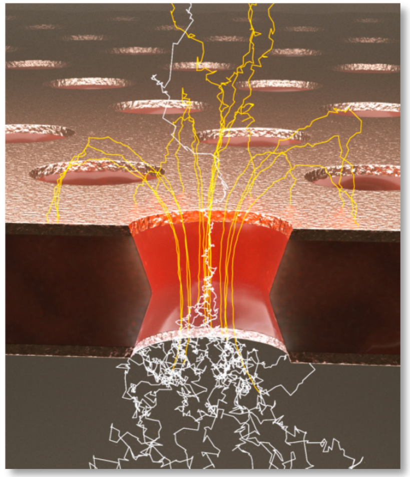
Goal: operate TPC at 50 kHz (⇨ no gating grid) **Solution:** Replace MWPC with 4-GEMs

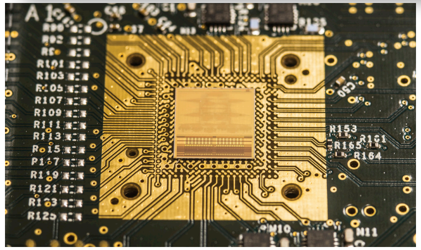


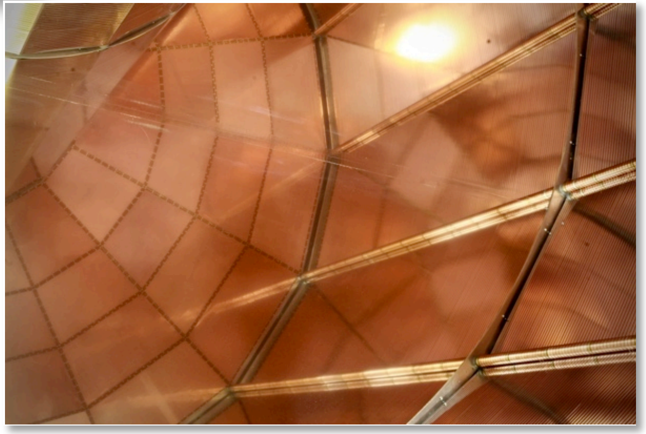
100 m² single-mask foils GEM production

Read Out Chamber









***SAMPA**: developed by the University of São Paulo (USP), the University of Campinas (Unicamp) and the Technological Institute of Aeronautics (ITS)*

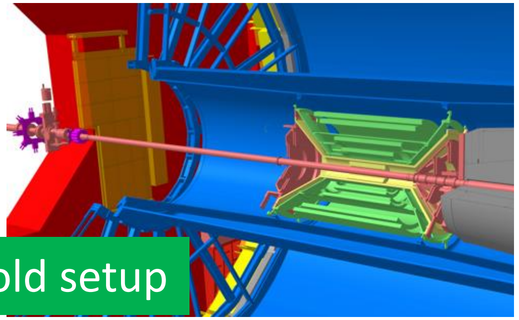
⇨ GEM provides ion backflow suppression to **< 1%**

⇨ 524 000 pads readout continuously

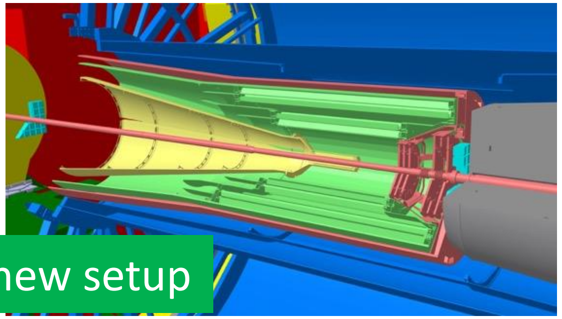
⇨ **3.4 TByte/sec**

ALICE

Inner Tracking System Upgrade



6 layers (39mm < r < 440mm)
$-1 \leq \eta \leq 1$



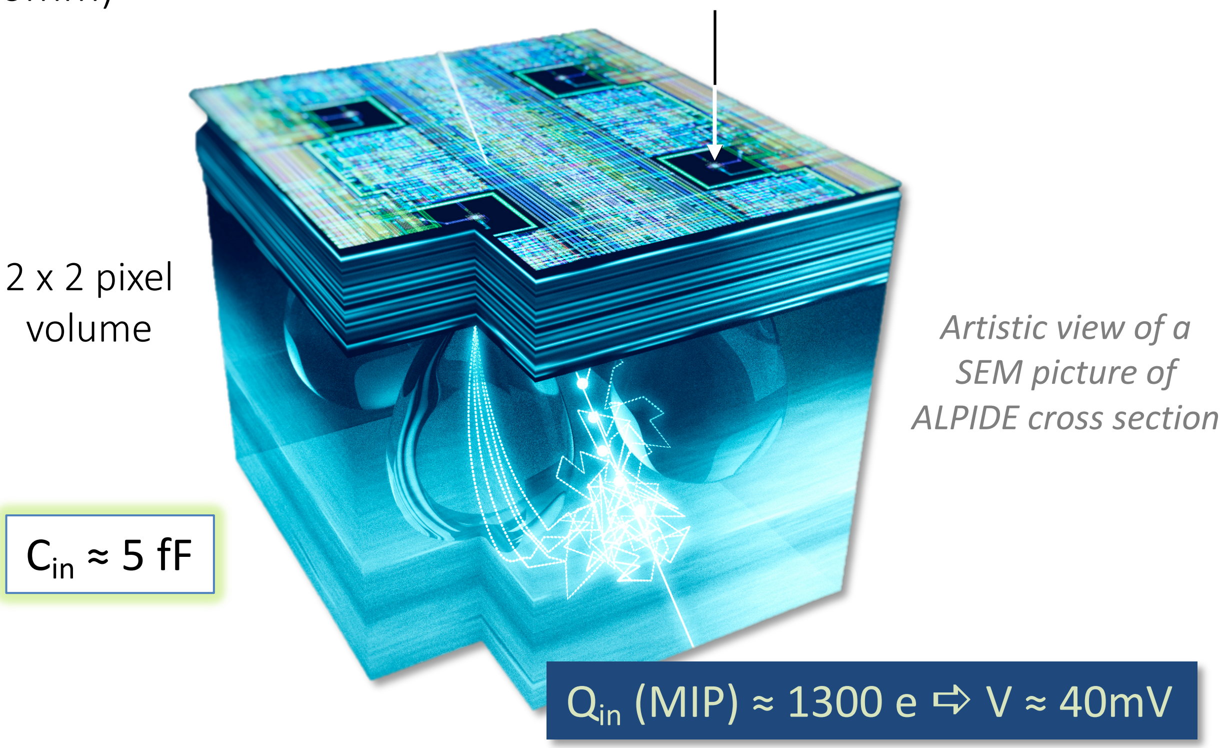
7 layers (22mm < r < 400mm)
$-1.3 \leq \eta \leq 1.3$

Motivations and goals

- Improved vertex and tracking precision
  ⇨ closer to IP, smaller pixels, less material
- Faster readout (x 100)

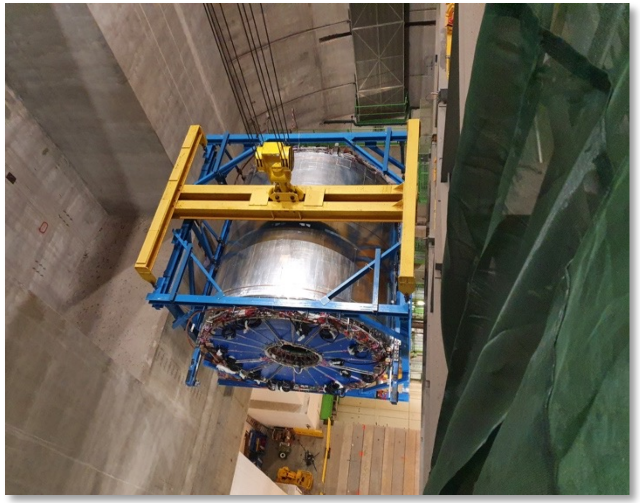
Based on novel MAPS technology (ALPIDE)

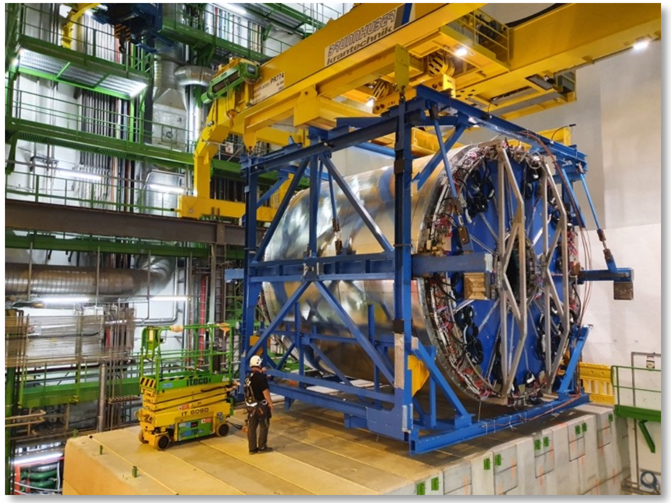
- 10 m^2 active silicon area (12.5 G-pixels)
- Spatial resolution ~5µm
- Max particle rate ~ 100MHz /cm^2 (w/o pile-up)
- Fake hit rate: < 1Hz/cm^2
- X/X_0 (first three layers): 0.35%

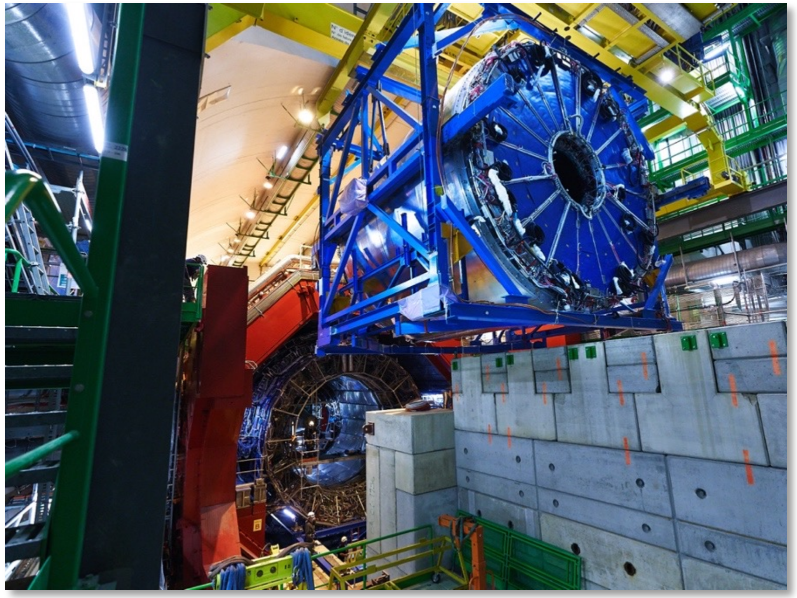


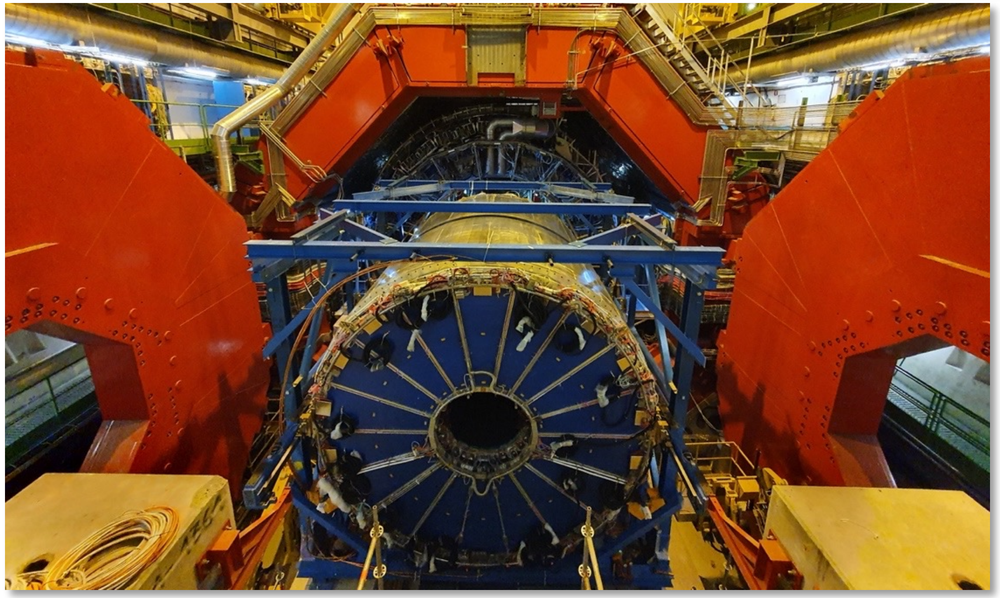
Artistic view of a SEM picture of ALPIDE cross section

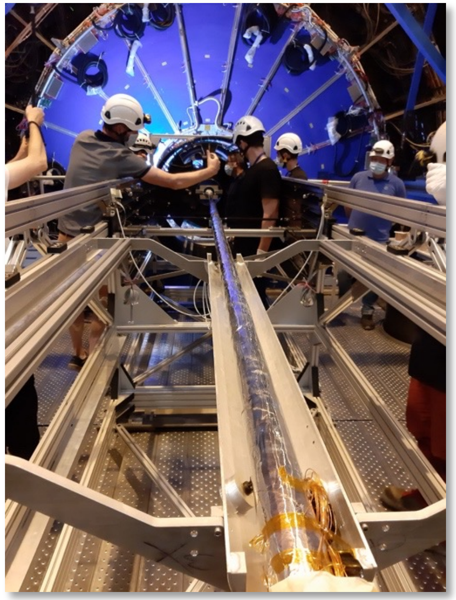
TPC reinstallation in the ALICE cavern (August 2020)





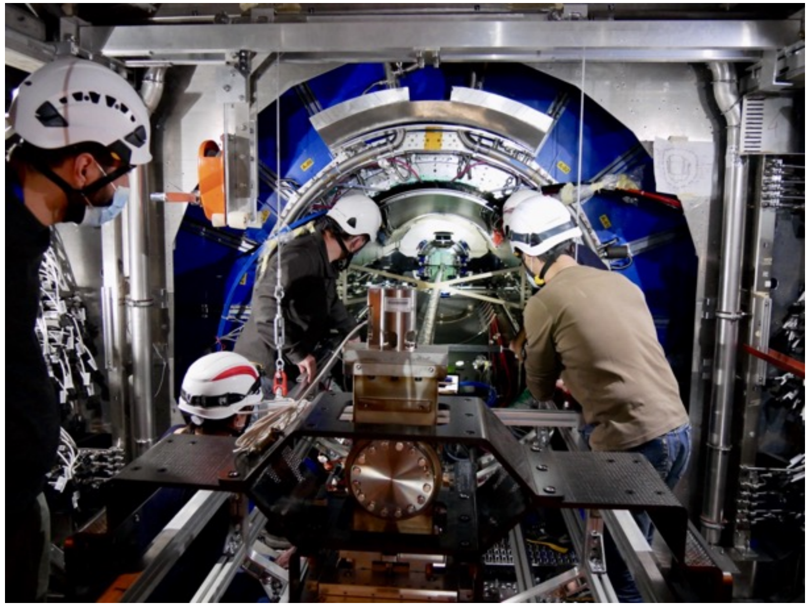


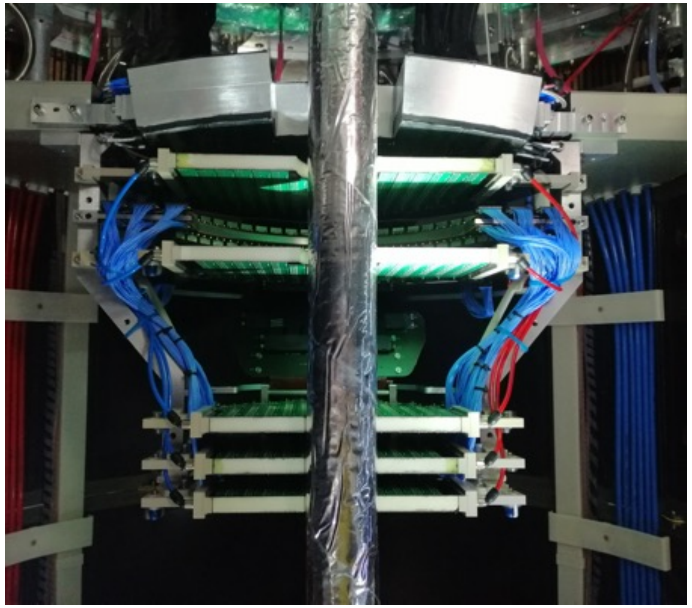


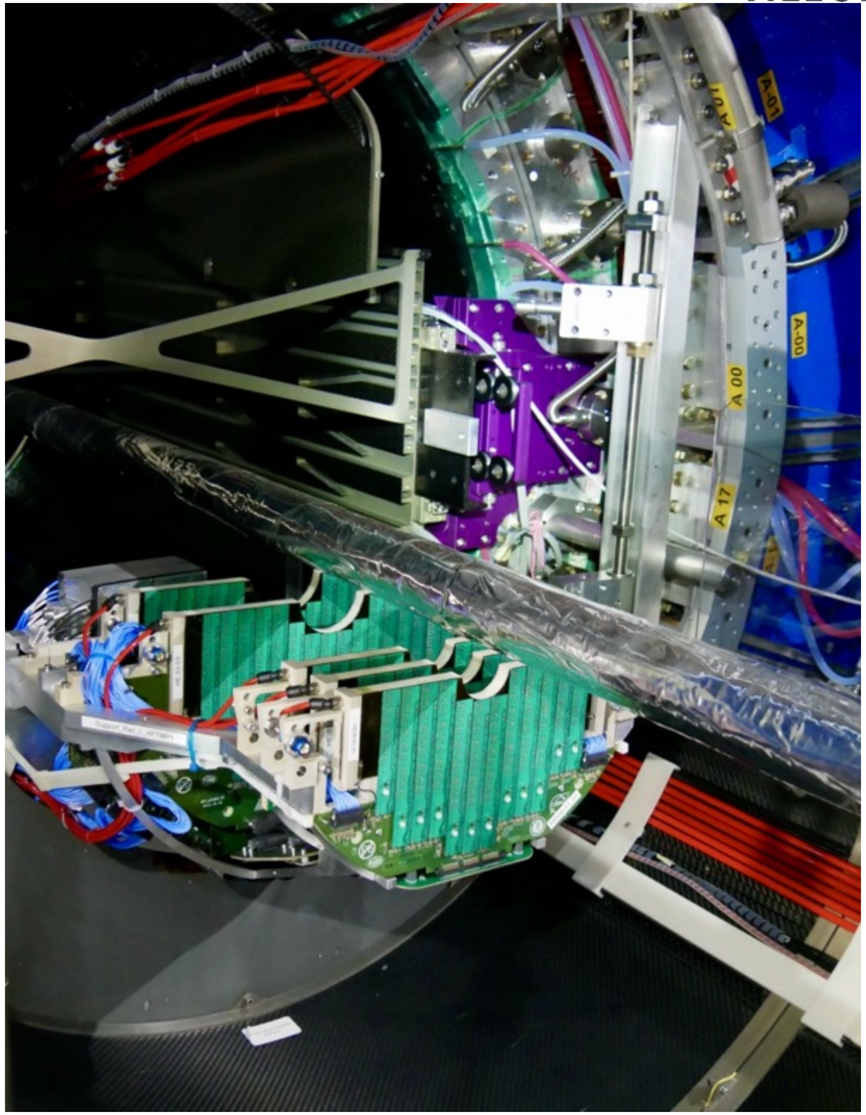


ALICE

MFT and FIT/C Installation - Dec 2020

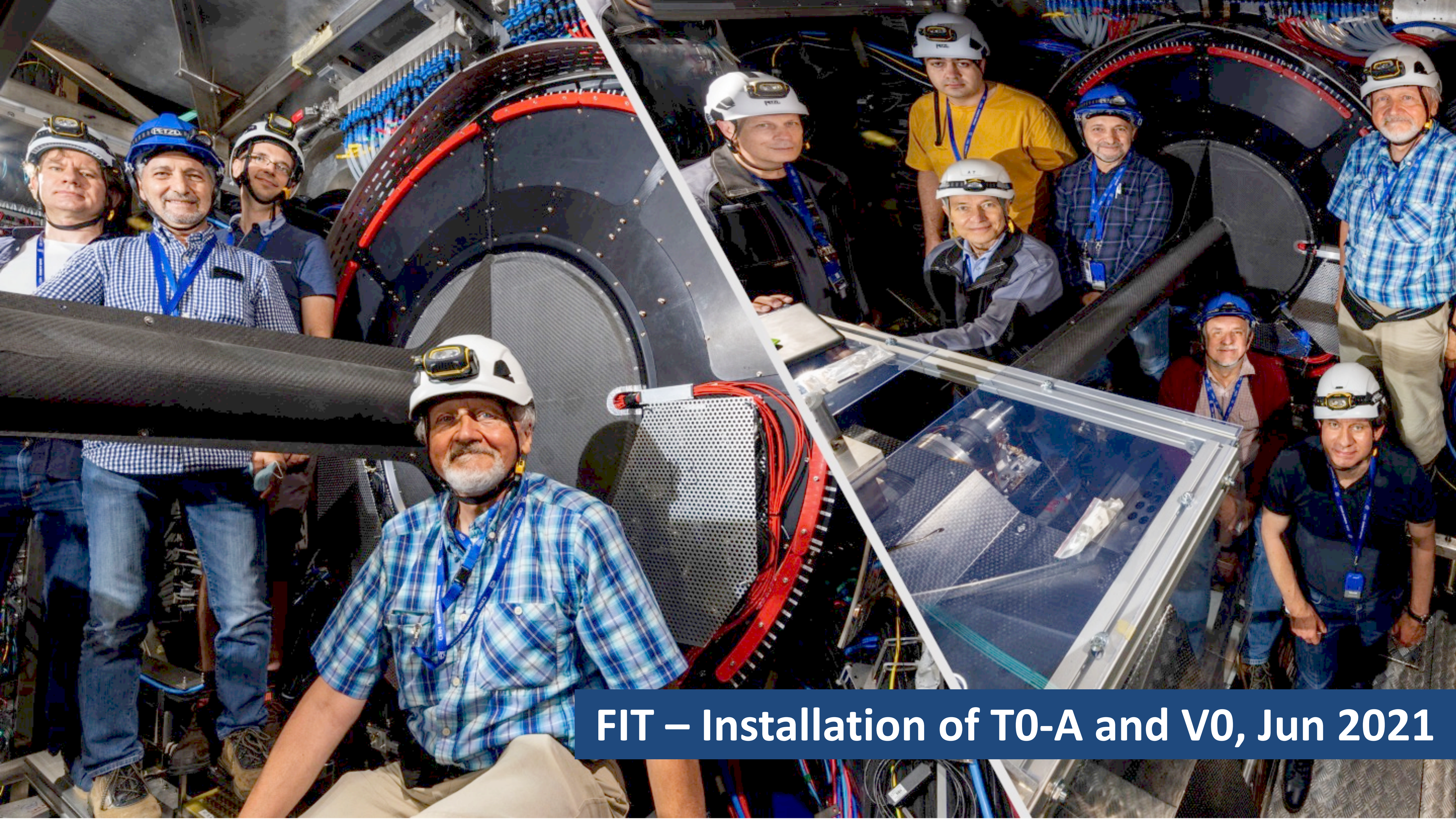






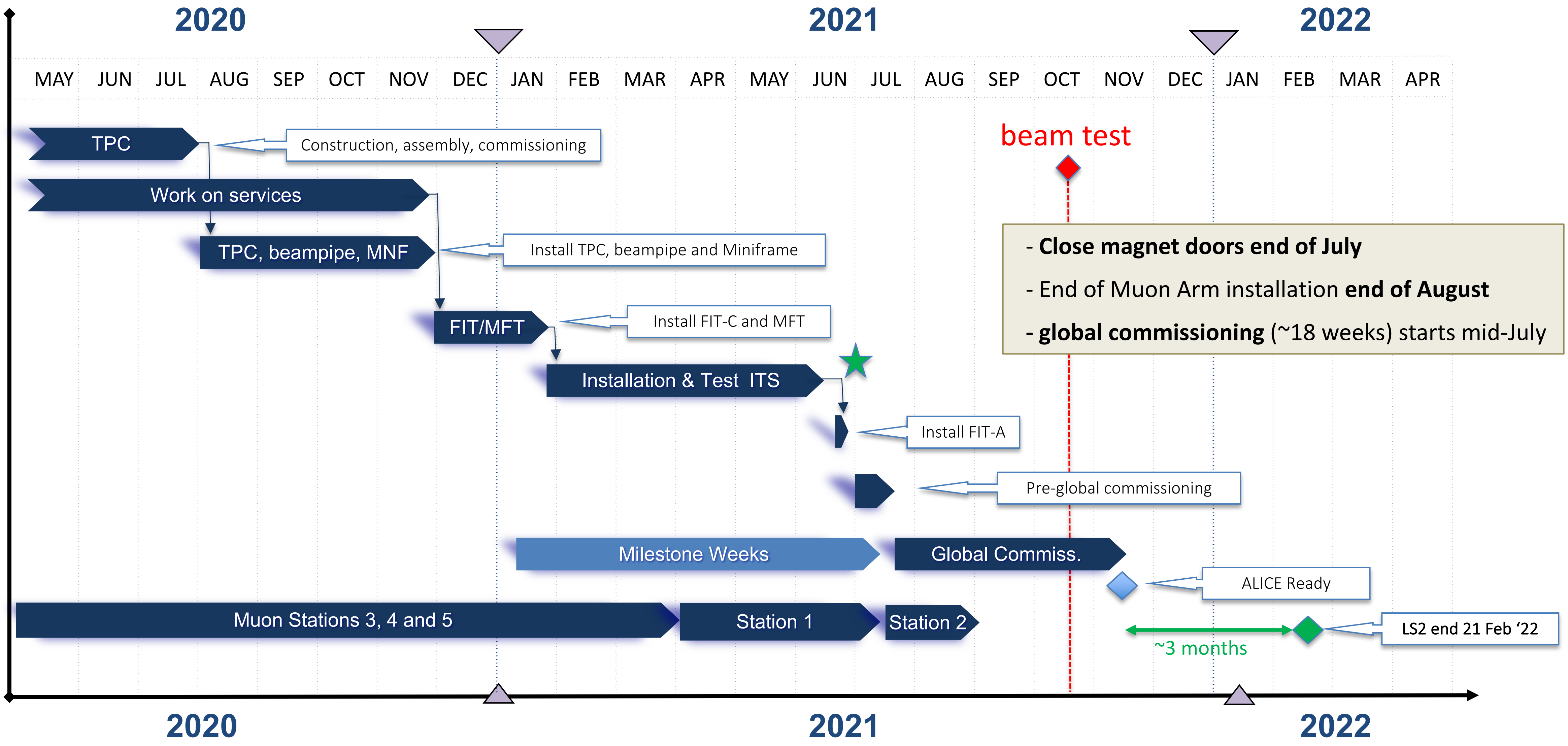
O2 - EPN server delivery (Dec 2020) and Installation (Jan 2021)

May 2021 - ITS fully installed



FIT – Installation of T0-A and V0, Jun 2021

ALICE LS2 Schedule



- **Close magnet doors end of July**
- End of Muon Arm installation **end of August**
- **global commissioning** (~18 weeks) starts mid-July

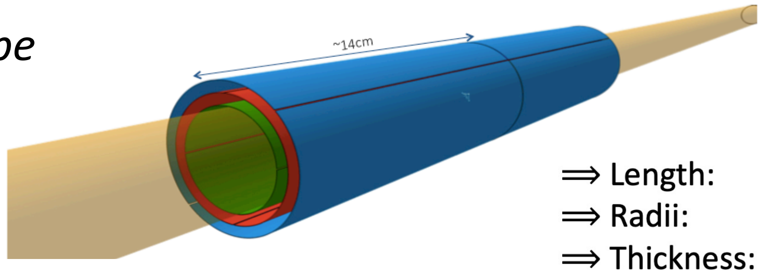
Perspectives

LS3 upgrades, ALICE 3 for Run 5

Enhancing vertexing – Inner Tracker 3 for Run 4

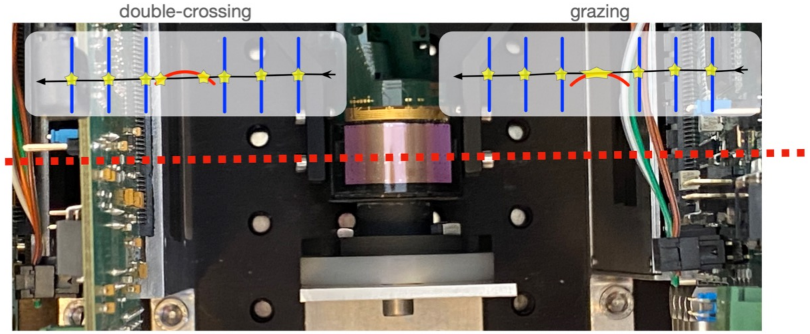
ITS3: Ultrathin wafer-scale MAPS – detector curled 'onto' the beam pipe

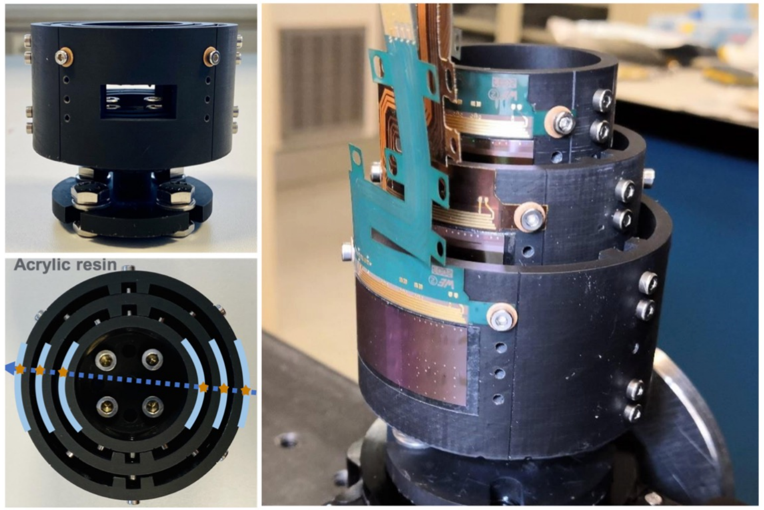
[LoI - CERN-LHCC-2019-018 ; LHCC-I-034]

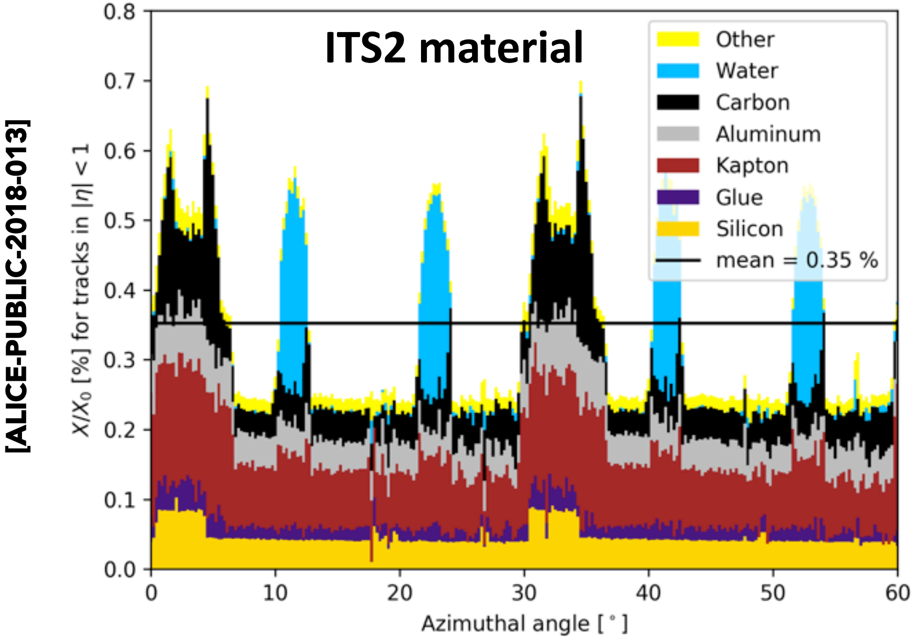


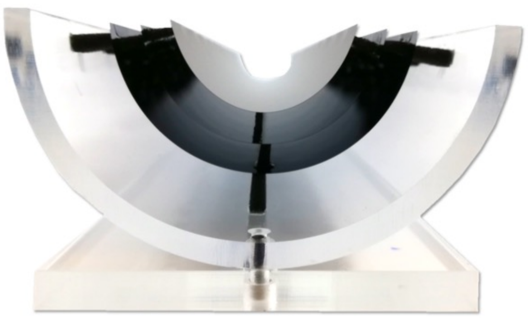
- ⟹ Length: 24 cm
- ⟹ Radii: 18, 24, 30 mm
- ⟹ Thickness: 50, 40, 40 µm

in-beam performance of bent MAPS [arXiv:2105.13000] **[physics.ins-det]**









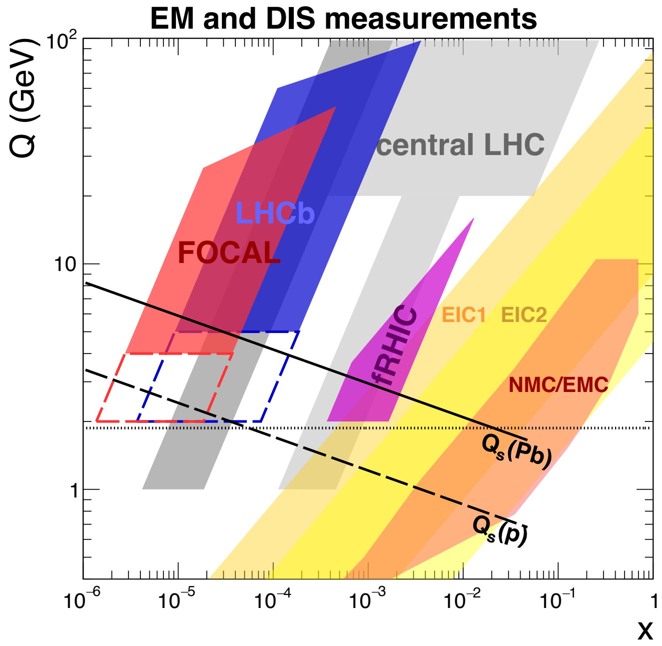
ITS3: keep silicon 'only'!

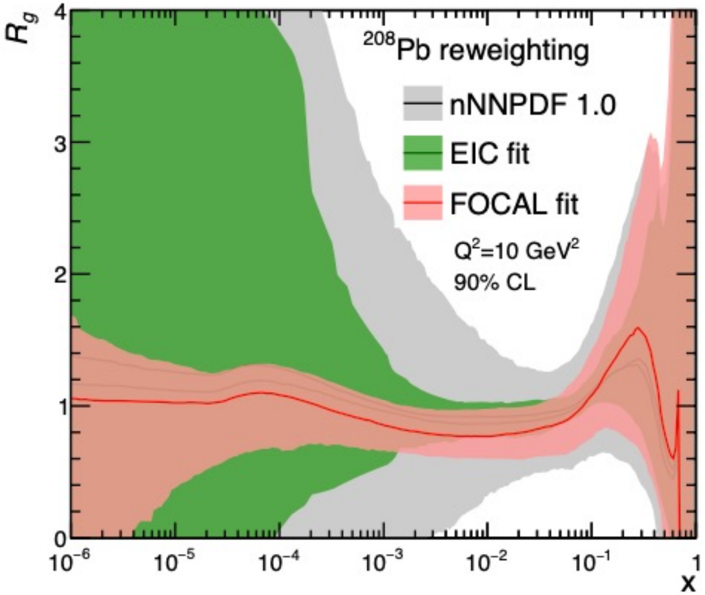
… remove cooling, PCBs, mechanical support ⇨ ultra-light inner layers

ALICE

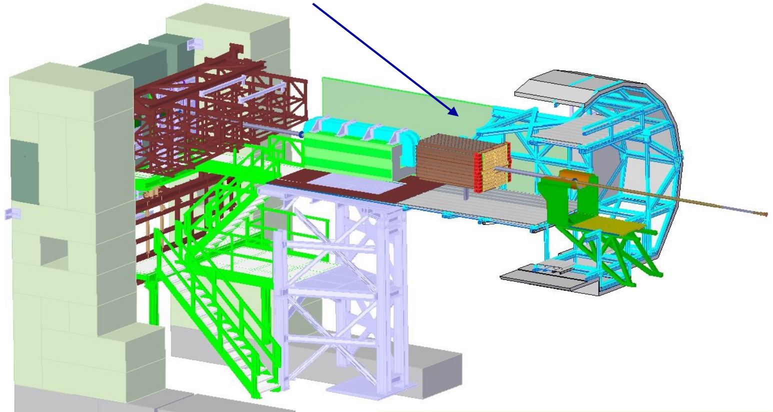
Glue at smallest-x ever – FoCal for Run 4

Nuclear modification of gluon distributions with photons, but also jets (di-jets), J/ψ (Υ) in UPC, W, Z, ….



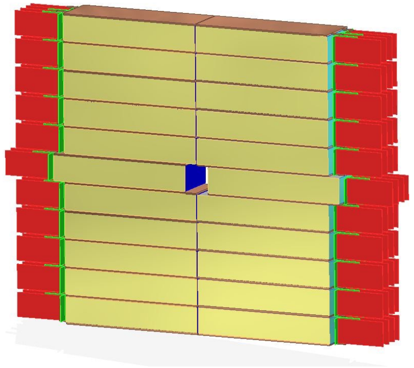


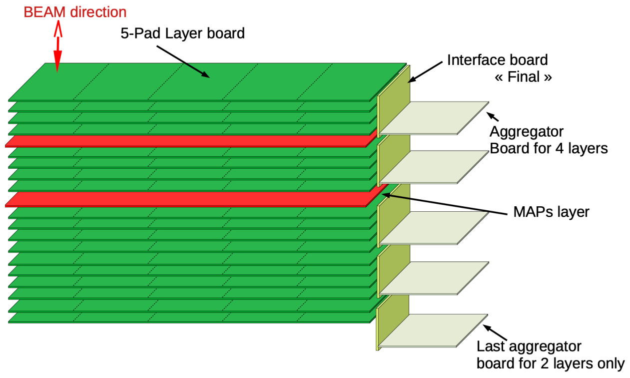
7 m from IP, 3.4 < η < 5.8



LoI: CERN-LHCC-2020-009

FoCal-E: 22 modules





Detector concept

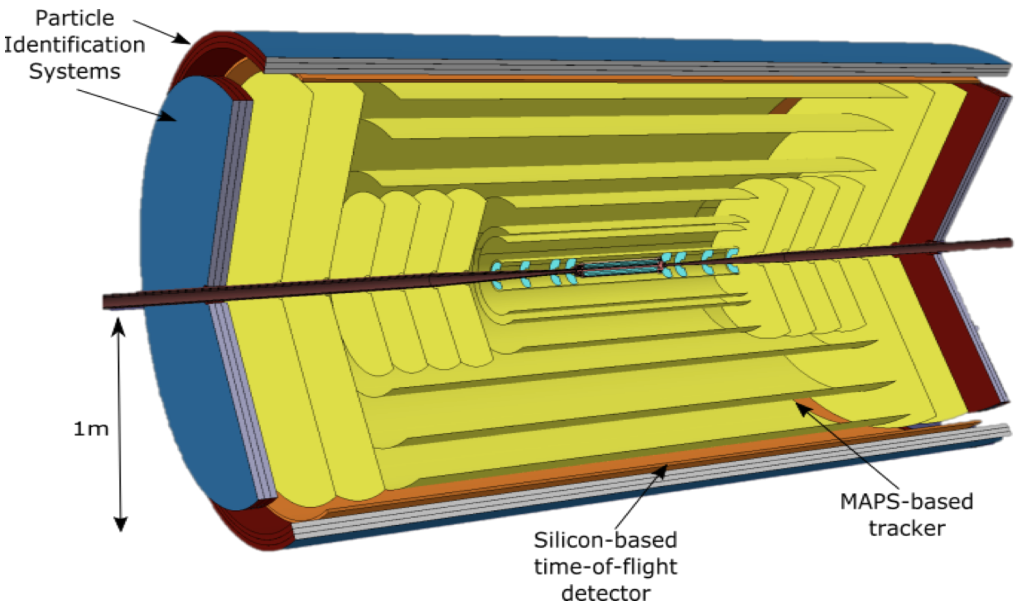
FoCal-E: high-granularity ($\approx 1\ mm^2$) Si-W sampling sandwich calorimeter for photons and π^0

FoCal-H: conventional sampling calorimeter for photon isolation

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, …

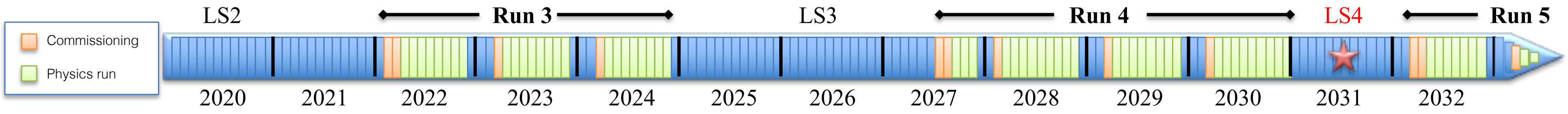


Expression of Interest arXiv:1902.01211

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



ALICE

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 2.1)
- Plans for next generation dedicated HI experiment for Run 5+ (ALICE 3.0)