ALICE — Status, Highlights, Future

Kai Schweda (GSI)
on behalf of the ALICE Collaboration

OUTLINE

① introduction

② selected physics highlights

③ present status for Run 3

④ future

INTRODUCTION

Early universe governed by **phase transitions** of fundamental **quantum fields**

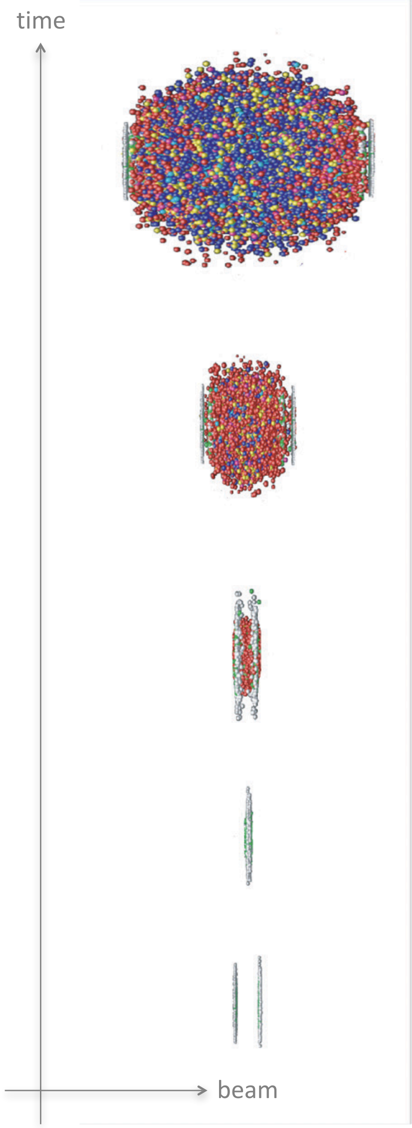
QCD parton-hadron transition at high temperature **accessible** in **collisions** of heavy nuclei at highest energies

→ Probe **QCD** as genuine **multi-particle theory**

→ Relate **collective phenomena** to **fundamental interactions** in QCD

Source: Michael Turner, *National Geographic (1996)*

COLLISION HISTORY



particles freely streaming to detector

collective expansion /
bulk production - hadronization

thermalization - quark-gluon plasma
interactions within QCD-medium

hard-probes generation, c,b - quarks

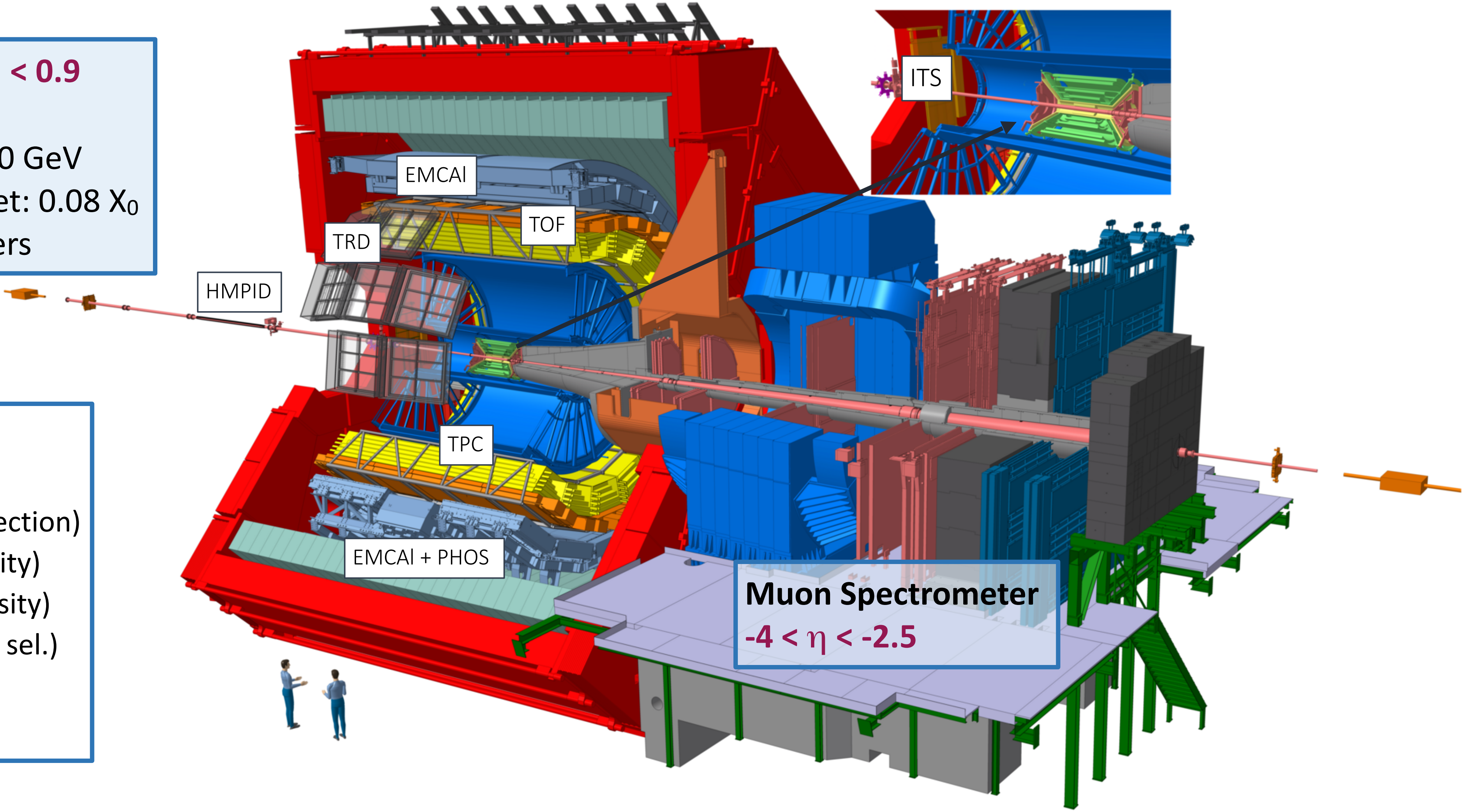
initial state

- Light flavour production
- Nuclei and antinculei
- Heavy flavour production
- Quarkonia
- Photons, low-mass dileptons
- Jets

THE LARGE HADRON COLLIDER

ALICE 1 (2009 - 2018): RUN 1 & 2

Central Barrel $|\eta| < 0.9$
- Tracking
- PID, p = 0.1 - 20 GeV
- Material budget: 0.08 X_0
- EM-Calorimeters



ACORDE (cosmics)

Forward detectors:
- AD (diffraction selection)
- V0 (trigger, centrality)
- T0 (timing, luminosity)
- ZDC (centrality, ev. sel.)
- FMD (N_{ch})
- PMD ($N\gamma$, Nch)

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

ALICE

THE ALICE COLLABORATION

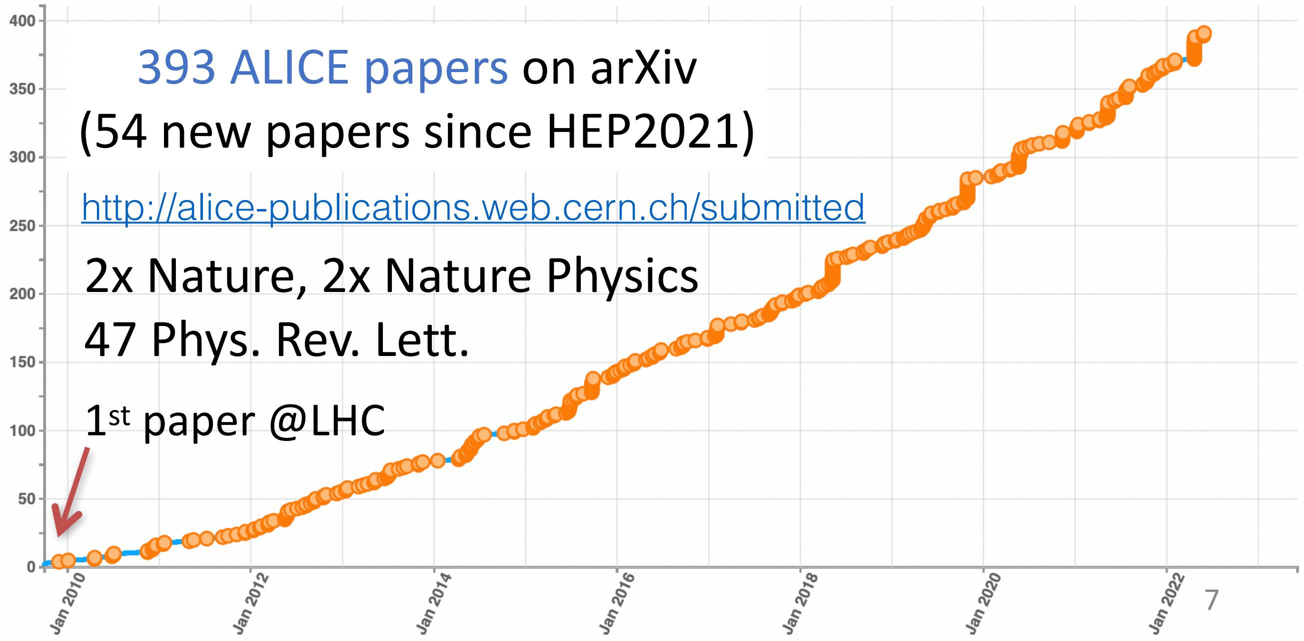
40 countries, 173 institutes

2008 members, 1046 scientific authors

384 doctoral students

Run 1 | Run 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}



393 ALICE papers on arXiv

(54 new papers since HEP2021)

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

2x Nature, 2x Nature Physics

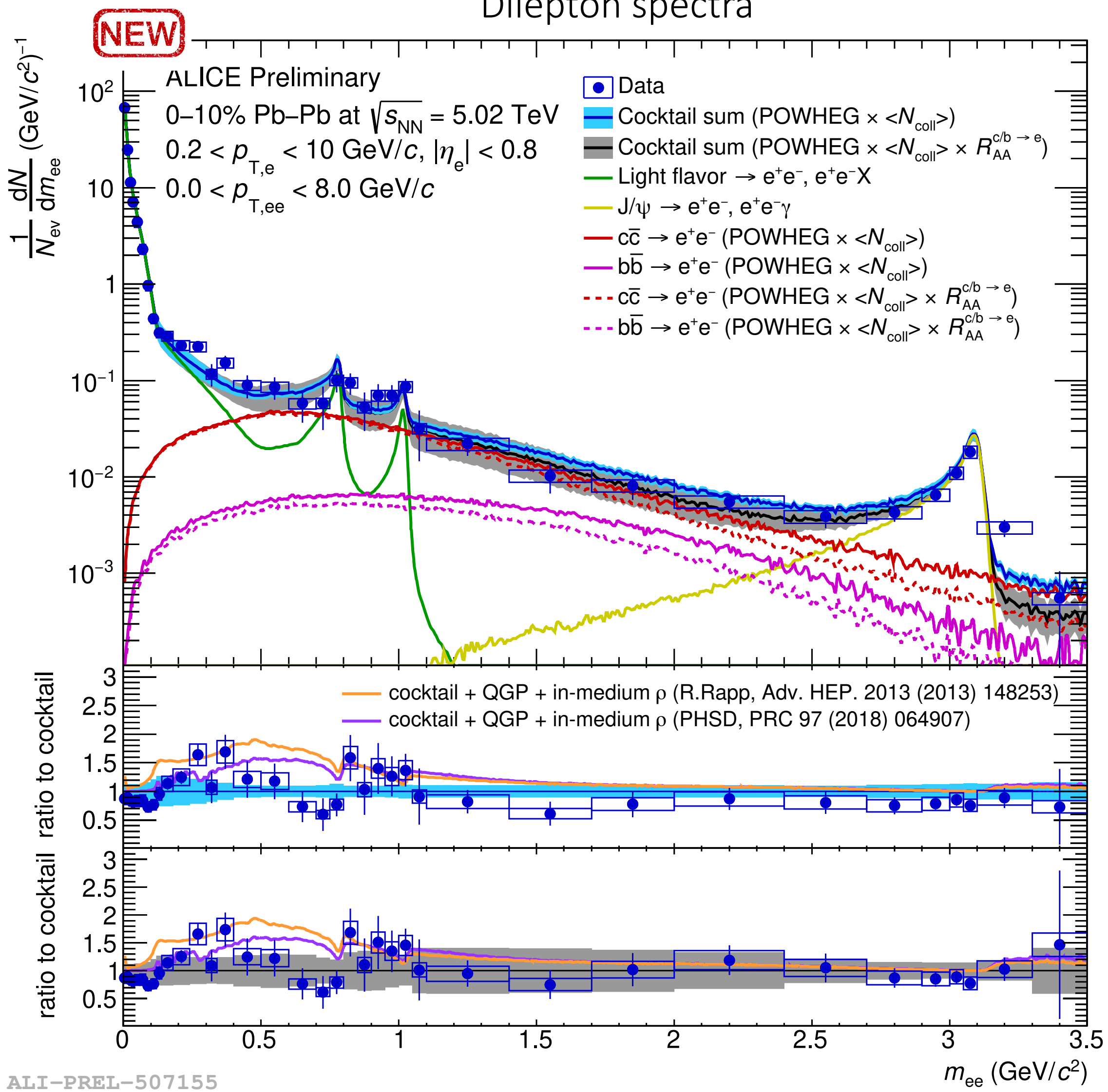
47 Phys. Rev. Lett.

1st paper @LHC

QGP THERMAL EMISSION - VIRTUAL PHOTONS

- new measurement of direct γ in Pb-Pb at 5.02 TeV
- hint for excess at low m_{ee}
- consistent with thermal radiation from the medium
- extract direct photon spectrum at (m_{ee} < 0.4 GeV)

Dilepton spectra



higher precision for real (and virtual) γ in Run 3: better vertexing, lower material budget and larger data sample

QGP THERMAL EMISSION - DIRECT PHOTONS

- Virtual γ (from dileptons) method, 0-10% centrality
- Real γ (photon conversion method), other centralities

$$\gamma + Z \rightarrow e^+ + e^- + Z$$

Intermediate p_T ($p_T \lesssim$ 4 GeV/c) – "thermal" photons

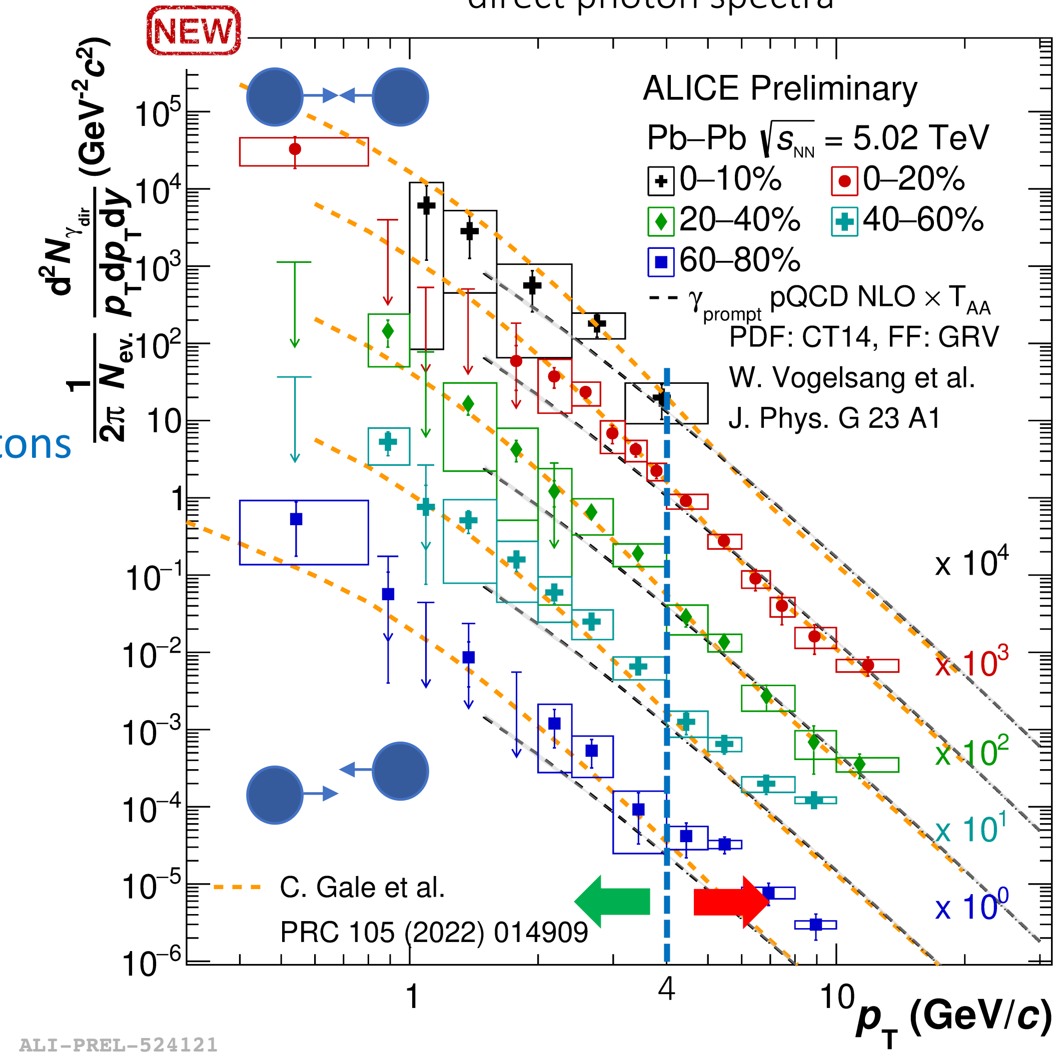
- consistent with model with pre-equilibrium and thermal photons

High p_T ($p_T \gtrsim$ 5 GeV/c) – prompt photons

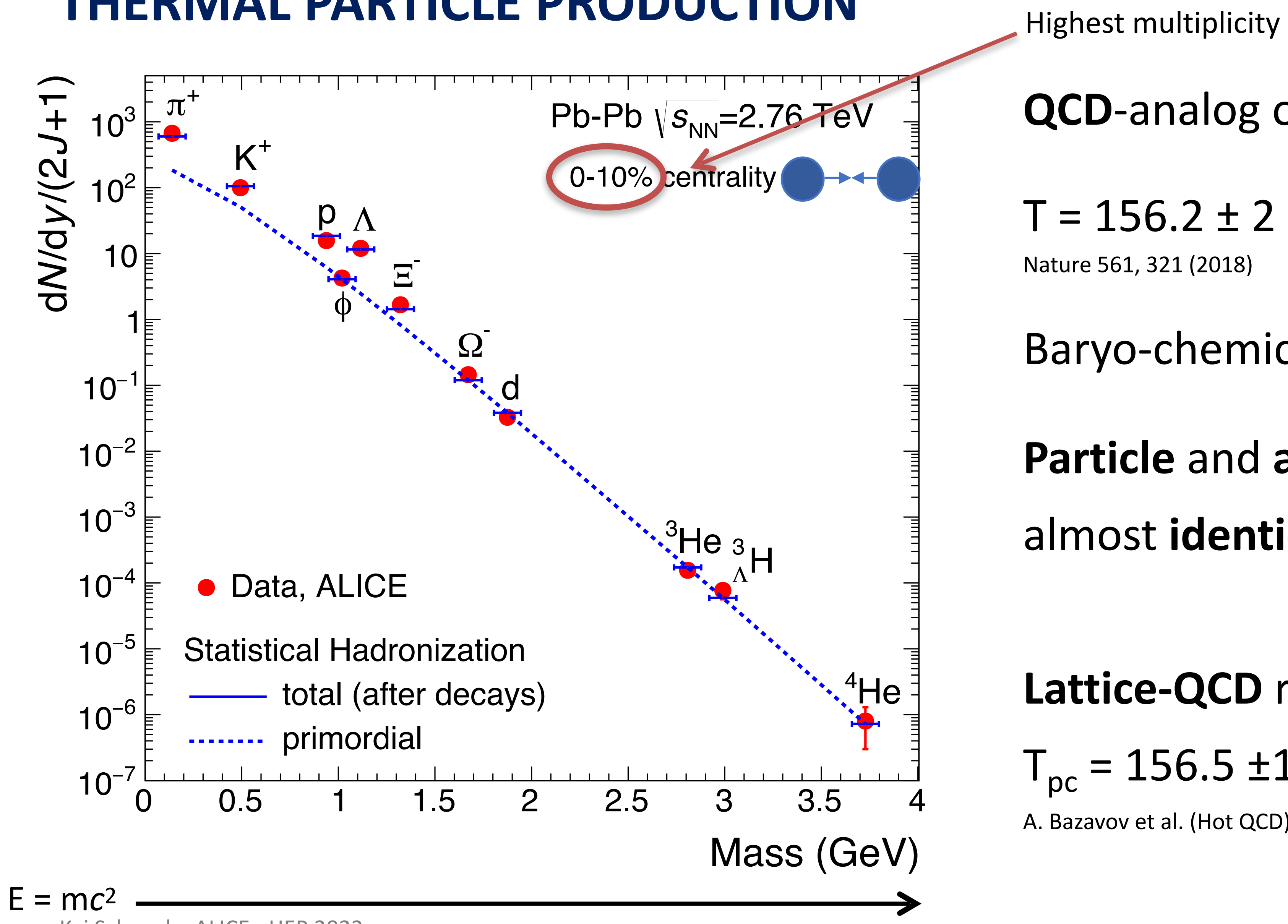
- consistent with pQCD expectations
- NLO pQCD, N_{coll} scaling, PDF modification

higher precision for real (and virtual) γ in Run 3:
better vertexing, lower material budget and larger data sample

direct photon spectra



THERMAL PARTICLE PRODUCTION



QCD-analog of **Planck spectrum**

T = 156.2 ± 2 MeV

Nature 561, 321 (2018)

Baryo-chemical potential $\mu_B \approx 0$

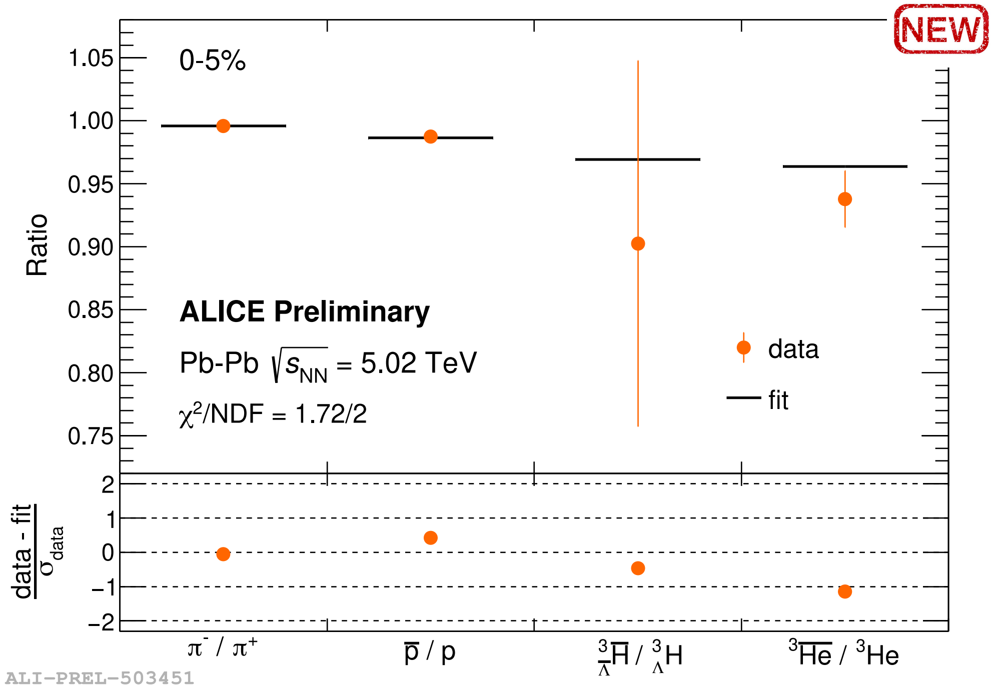
Particle and **antiparticles** created at almost **identical yields**

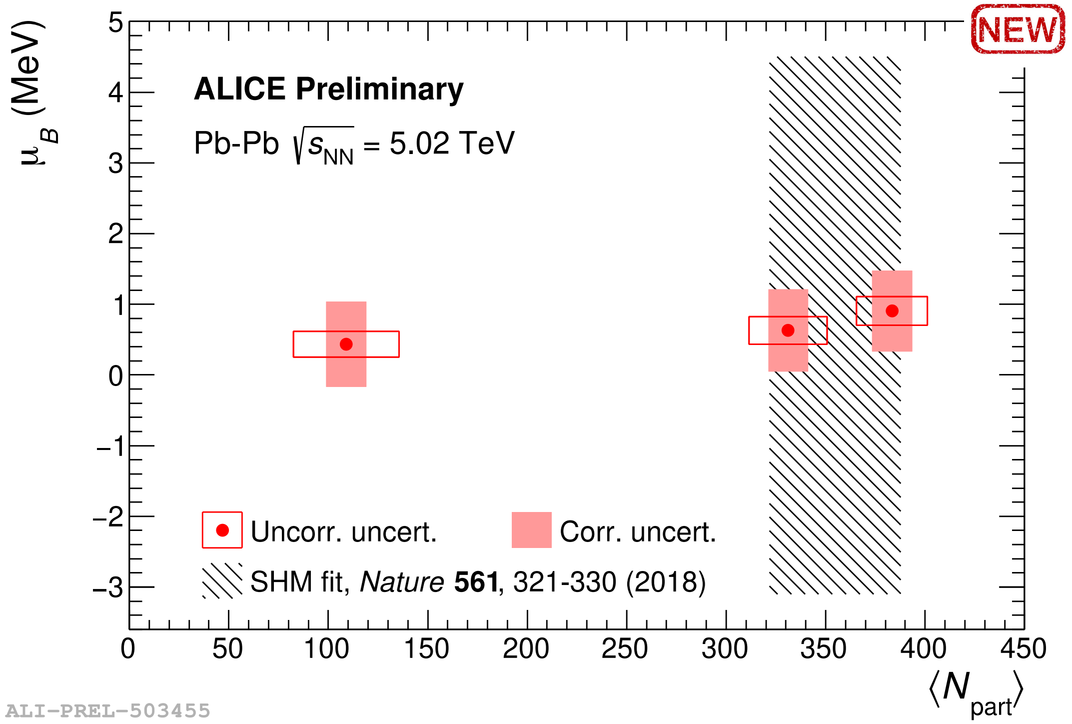
Lattice-QCD results **agree**

T_{pc} = 156.5 ±1.5 MeV

A. Bazavov et al. (Hot QCD) arXiv:1812.08235

QUANTIFYING ANTIMATTER-MATTER IMBALANCE AT THE LHC





Baryo-chemical potential μ_B, by fitting $\bar{h}/h$ (1)

$$\frac{\bar{h}}{h} \propto exp\left[-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T} - 2I_3\frac{\mu_{I_3}}{T}\right]$$

(1) *J. Cleymans et al., Phys. Rec. C 74, (2006) 034903*

With $T = 156.2 \pm 2$ MeV

Most precise measurement at the LHC

thanks to the cancellation of uncertainties in the ratios

➪ ~6 x improvement wrt previous estimation(2)

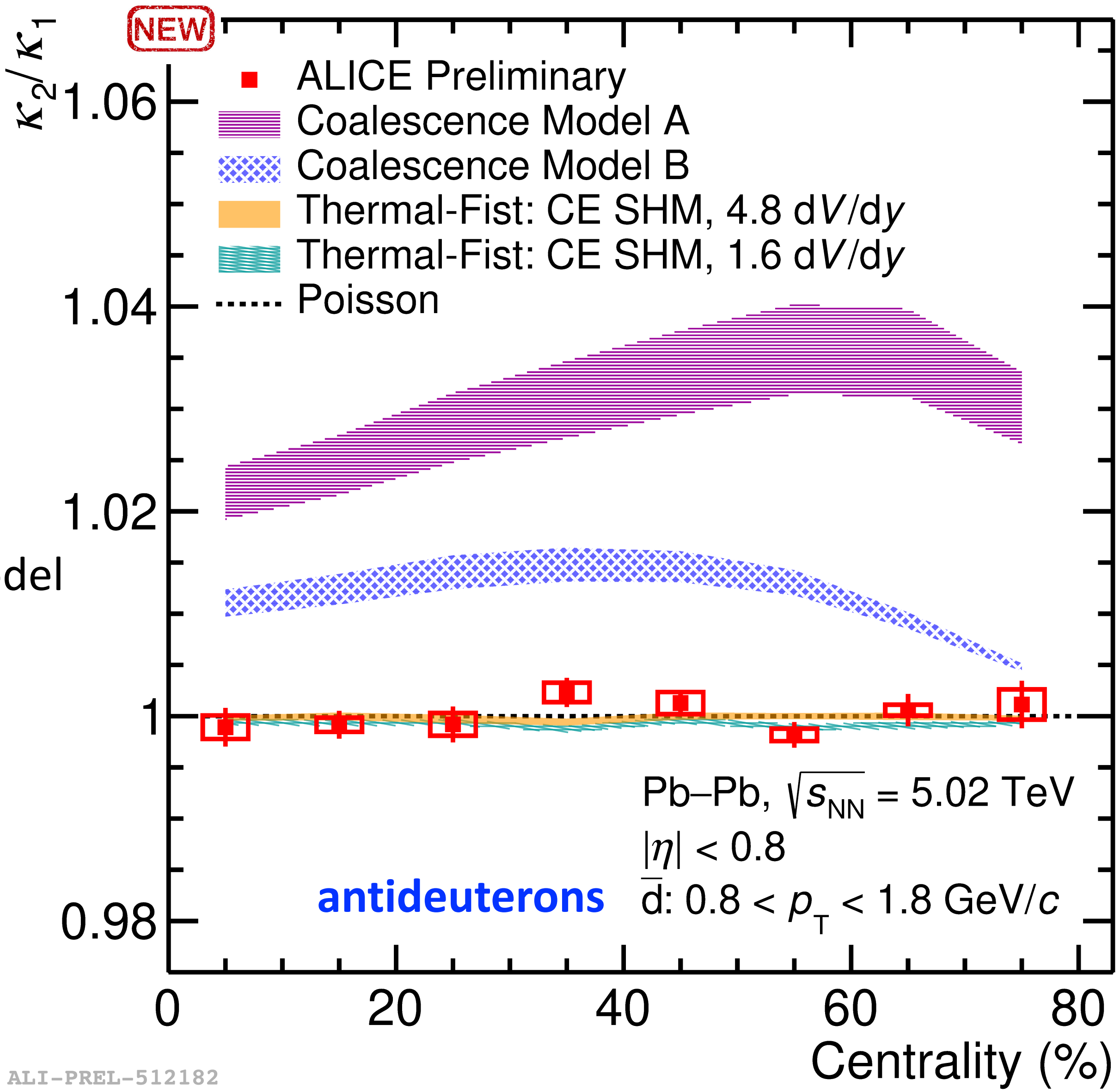
(2) *A. Andronic et al., Nature 561, 321-330 (2018),*

ANTIMATTER SYNTHESIS BEYOND THE AVERAGE: ANTIDEUTERONS

New observables based on event-by-event fluctuations to distinguish statistical hadronisation and hadron coalescence

$$\frac{\kappa_2}{\kappa_1} = \frac{\langle (n - \langle n \rangle)^2 \rangle}{\langle n \rangle}$$

Cumulant ratio favors the statistical hadronisation model over naive coalescence



ANTIMATTER SYNTHESIS BEYOND THE AVERAGE

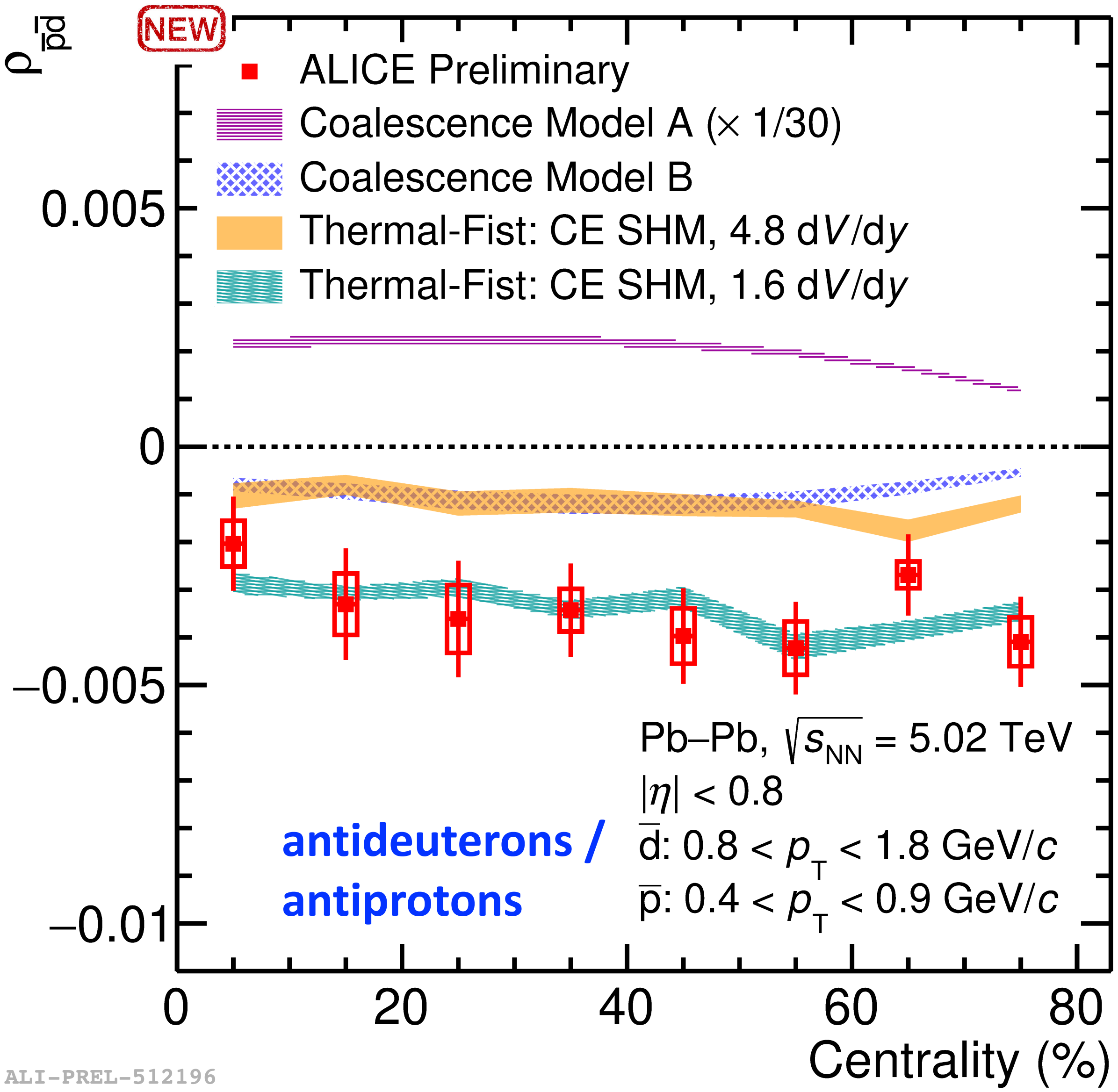
https://arxiv.org/abs/2204.10166

Cumulant ratio well described by SHM

$$\rho_{\bar{p}\bar{d}} = \frac{\langle (n_{\bar{d}} - \langle n_{\bar{d}} \rangle)(n_{\bar{p}} - \langle n_{\bar{p}} \rangle) \rangle}{\sqrt{\kappa_{2\bar{d}}\kappa_{2\bar{p}}}}$$

- Correlation between antiprotons and antideuterons constrains the correlation volume for baryon number
- agrees with results for yields of nuclei & antinuclei
- Different from results for yields of protons & antiprotons and fluctuations

However: more sophisticated coalescence model including Poissonian fluctuations matches data, arXiv:2204.10879

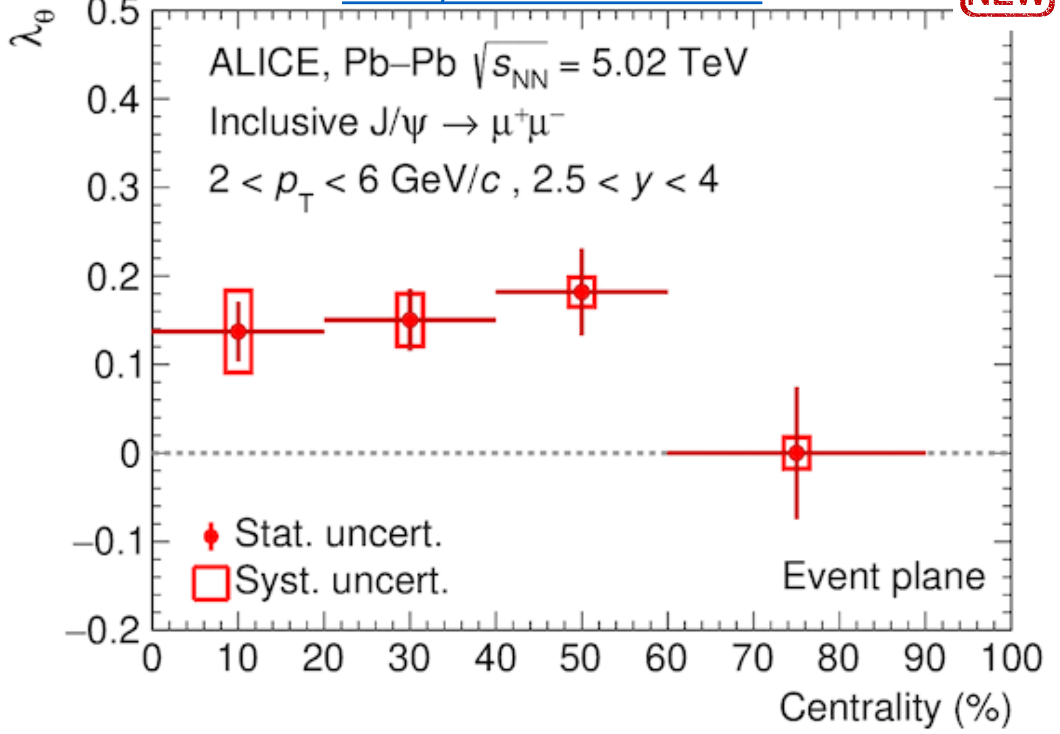


POLARIZATION OF J/ψ IN PB-PB COLLISIONS

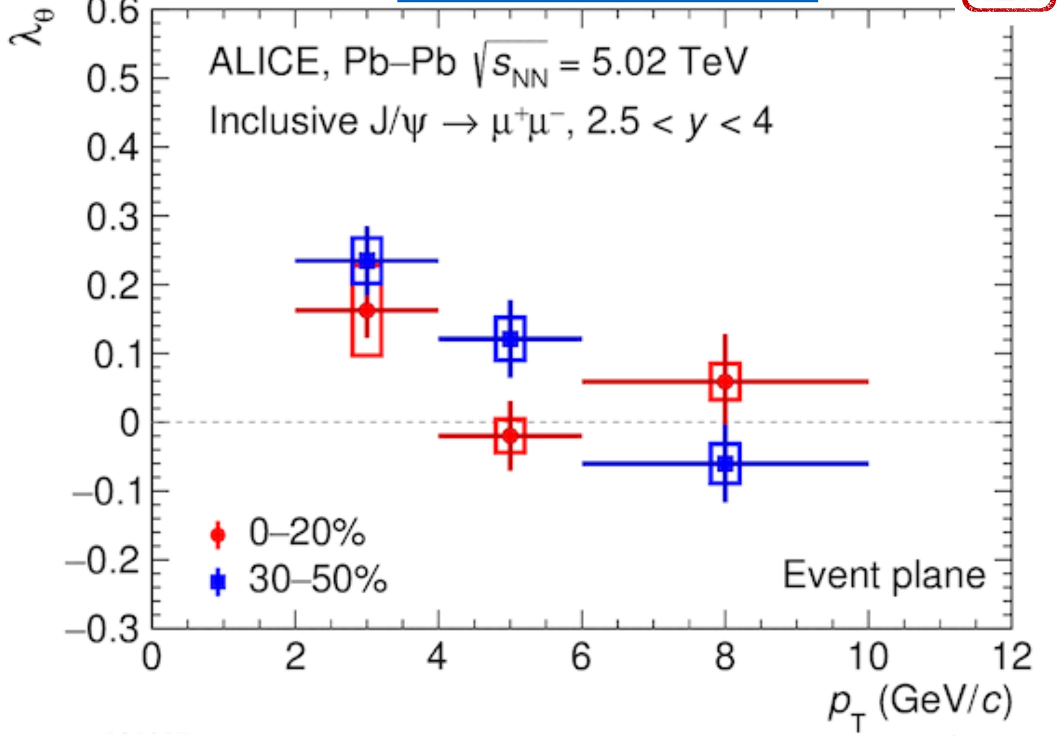
$$W(\theta) \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta \cos^2\theta\right)$$

polar angular distribution of dilepton decay

ALICE, arXiv:2204.10171 NEW

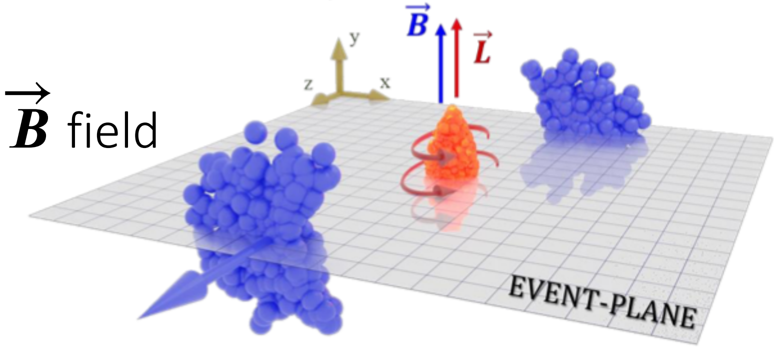


ALICE, arXiv:2204.10171 NEW



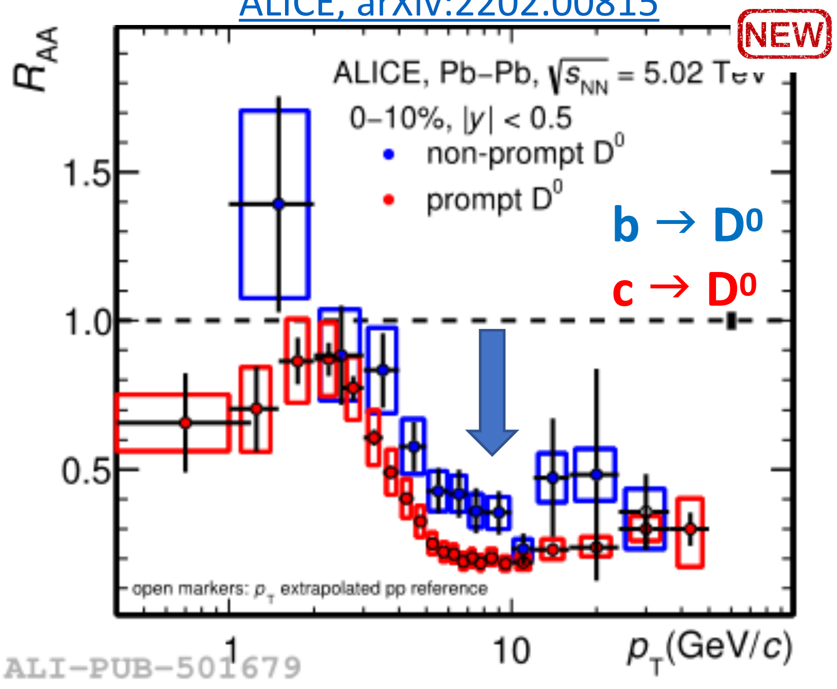
- Clear signal observed by ALICE
- Increase towards lower p_T (reaching **3.9**σ) disfavours effects due to early $\vec{B}$ field
- Link to QGP vorticity and spin-orbit coupling?

⇨ Interpretation needs further theory studies

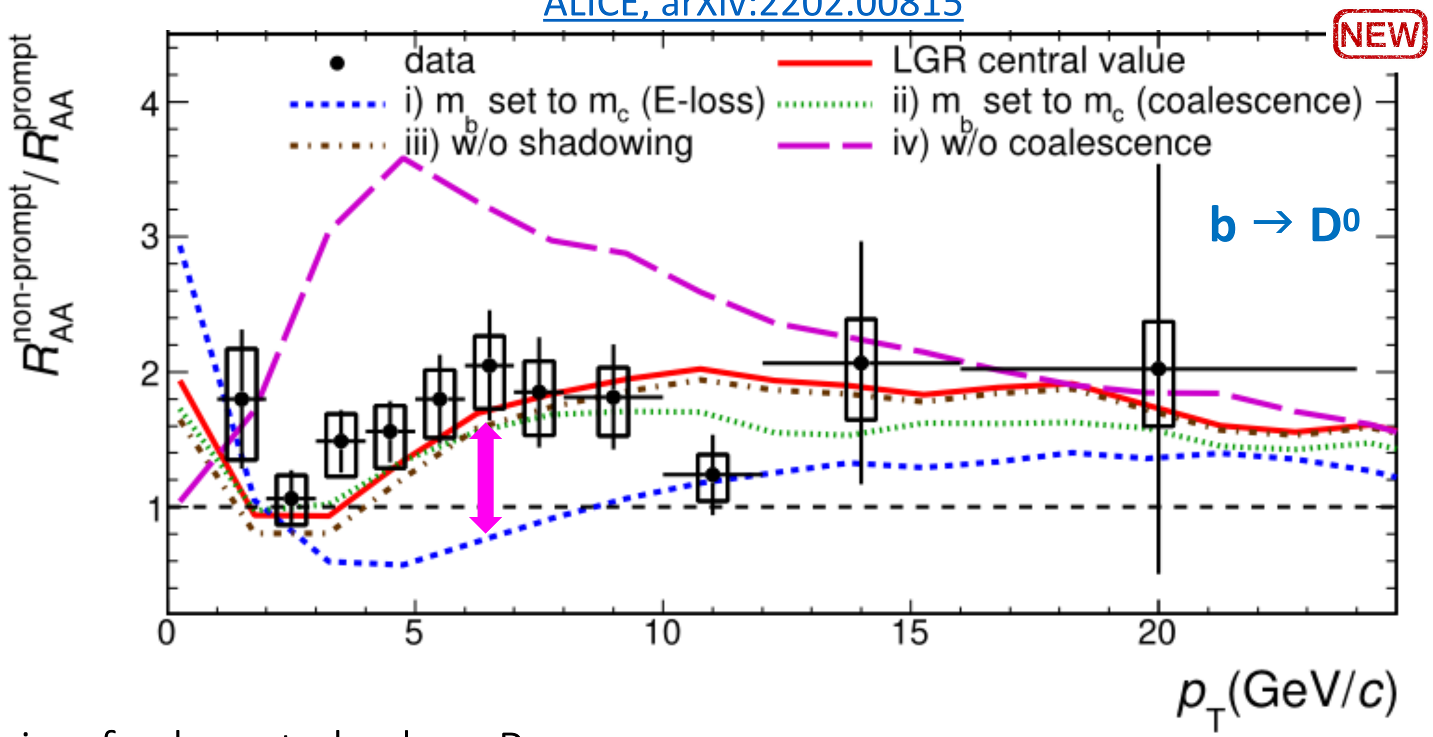


ENERGY LOSS OF CHARM AND BEAUTY IN THE QUARK-GLUON PLASMA

ALICE, arXiv:2202.00815

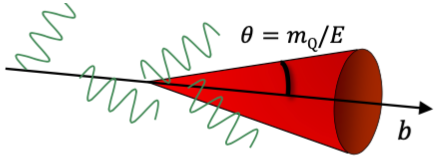


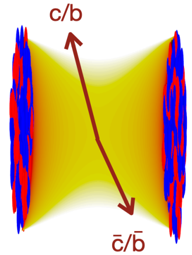
ALICE, arXiv:2202.00815



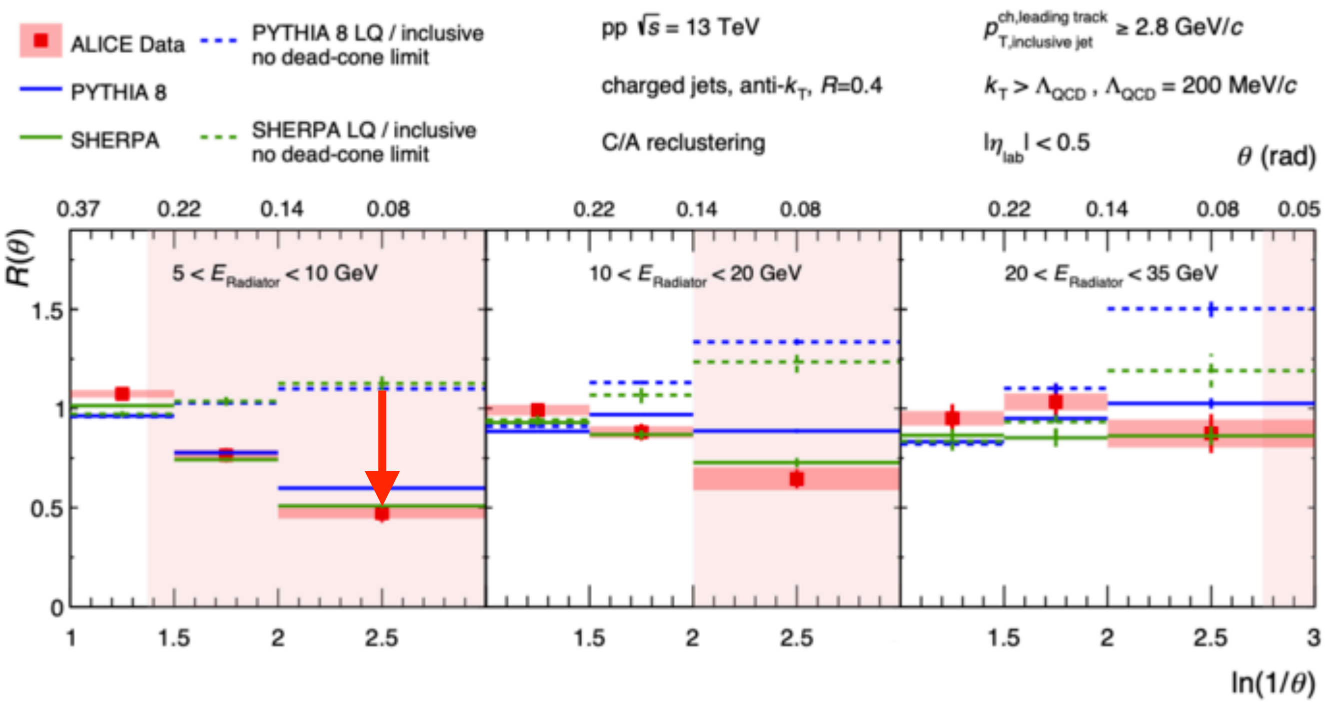
- Unprecedented access to the low p_T region for beauty hadron R_{AA}
- Data well described by models that include collisional and radiative energy loss and recombination
- R_{AA} less suppressed for beauty (non-prompt D mesons) than for charm (prompt D mesons)

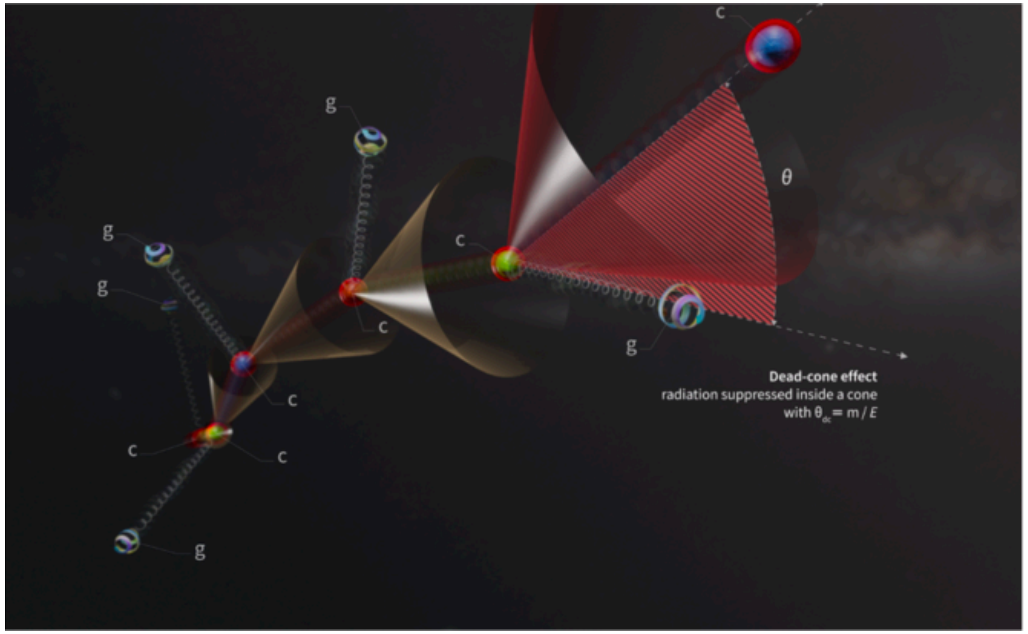
⇨ Mass-dependent energy loss by gluon radiation (dead cone effect)





FIRST DIRECT OBSERVATION OF THE DEAD CONE



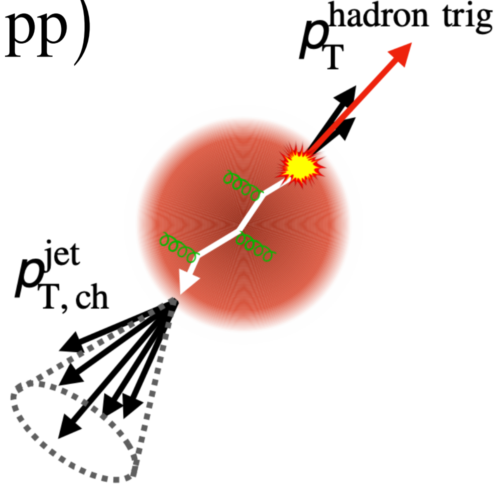


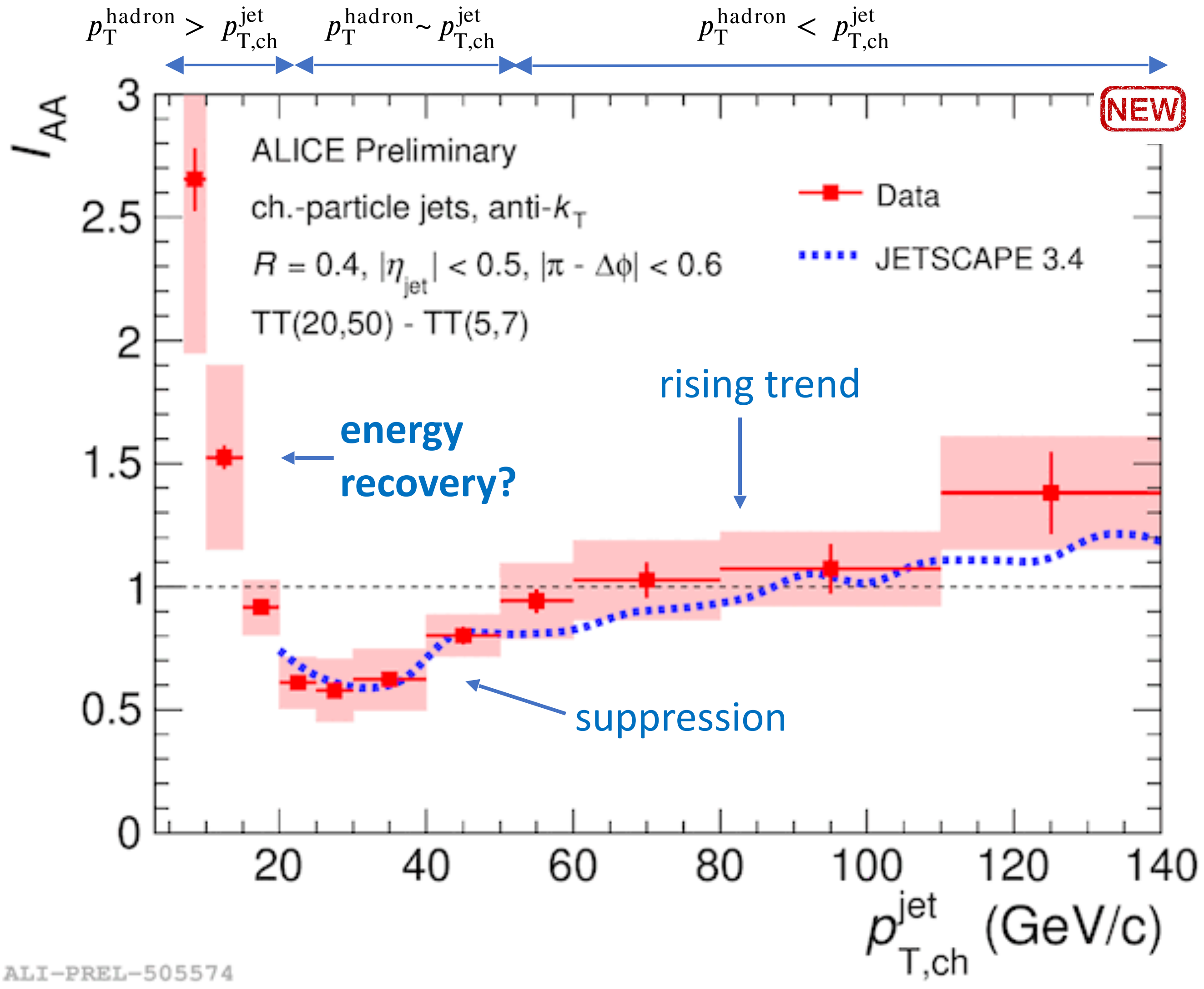
Nature 605 (2022) 7910, 440

- **Dead cone**: a **fundamental** effect in **QCD**
- **Suppression** of **gluon radiation** at **small angles**
- Depending on **particle mass**, $\theta_C = m_Q/E$, **decreases with increasing energy**

JET QUENCHING: ENERGY REDISTRIBUTION

$$I_{AA} \equiv \frac{\Delta_{\mathrm{recoil}}\left(\mathrm{Pb-Pb}\right)}{\Delta_{\mathrm{recoil}}\left(\mathrm{pp}\right)}$$





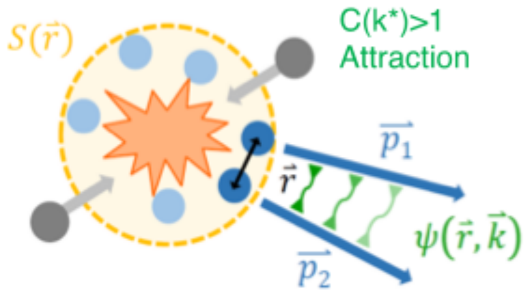
JETSCAPE prediction in agreement with measurement

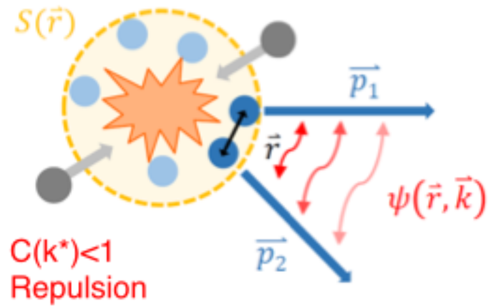
Hint of **energy recovery at low jet momenta**

ALICE

STRONG INTERACTION BETWEEN CHARMED AND LIGHT HADRONS

First study of two body scattering involving charmed hadrons from momentum correlations at femtometer distances





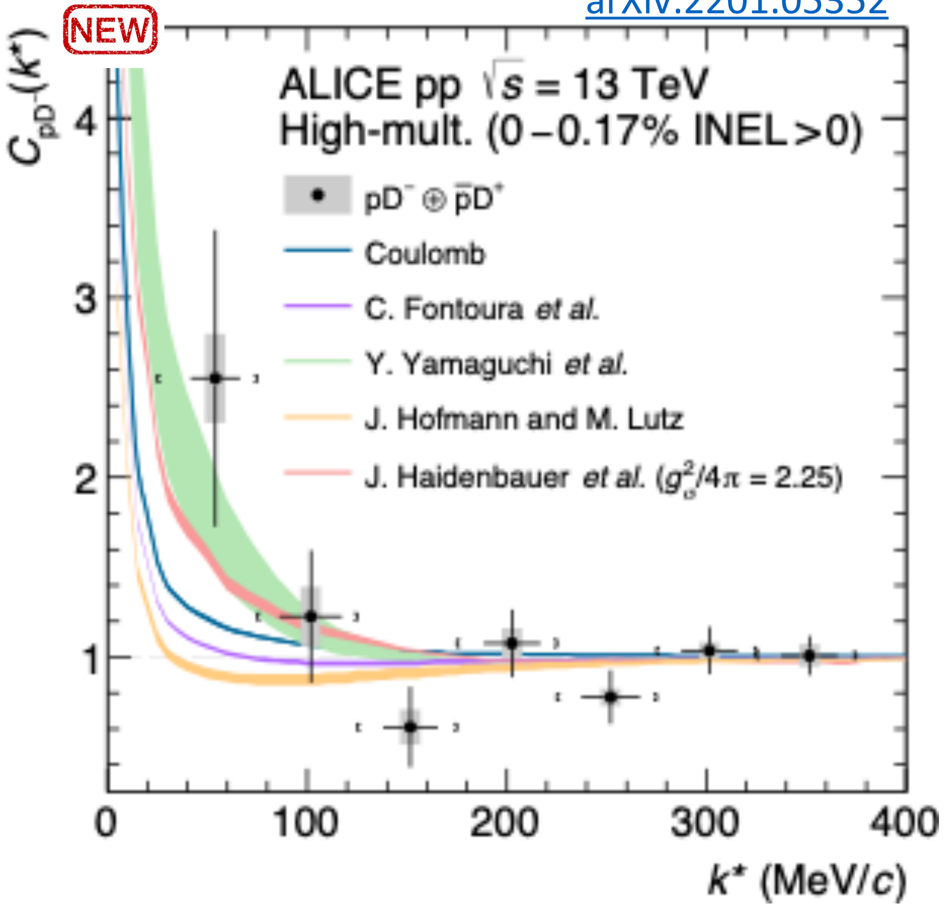
Experiment | Theory

$$C(\vec{k}^*) = \mathcal{N}\frac{N^{\mathrm{pairs}}_{\mathrm{same}}(k^*)}{N^{\mathrm{pairs}}_{\mathrm{mixed}}(k^*)} = \int S(\vec{r}^*)\,|\psi(\vec{k}^*,\vec{r}^*)|^2\,\mathrm{d}^3r^*$$

$\vec{k}^* \equiv$ relative momentum in the rest frame

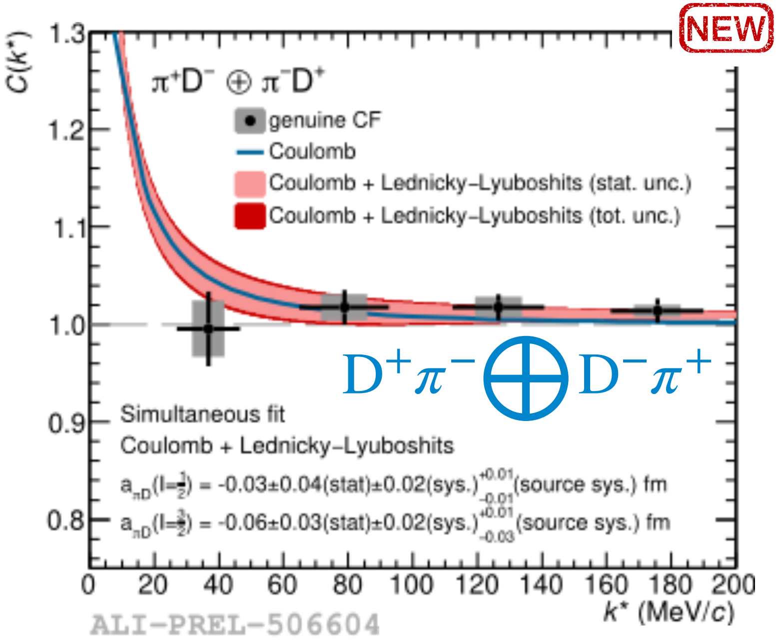
Koonin-Pratt equation, M.Lisa, S. Pratt et al., Ann.Rev.Nucl.Part.Sci. 55 (2005) 357-402

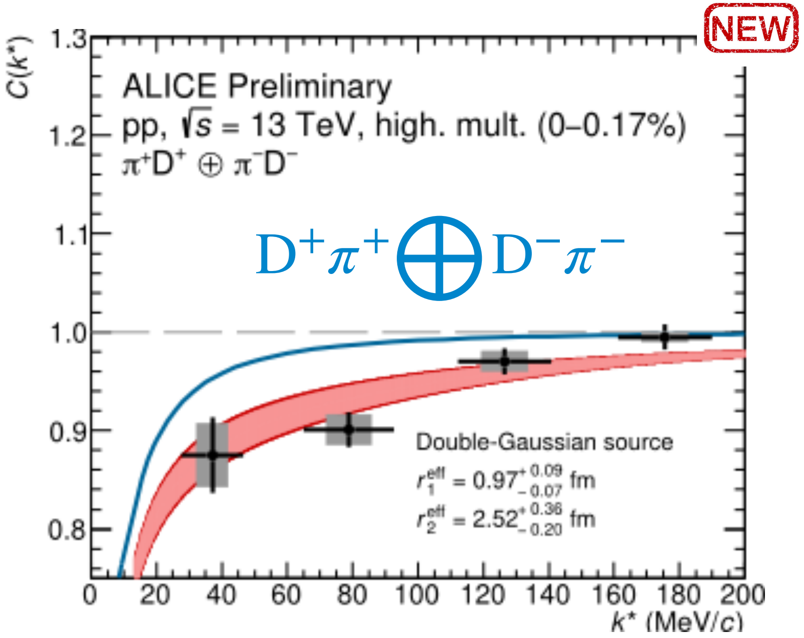
arXiv:2201.05352

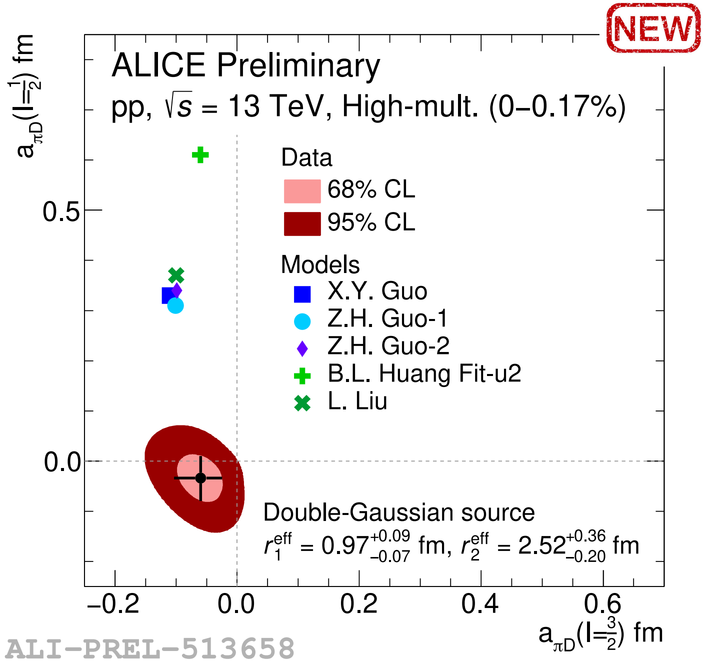


Data compatible with Coulomb only interaction,
but comparison slightly improved when also considering attractive strong interaction

STRONG INTERACTION BETWEEN CHARM AND LIGHT HADRONS







Dπ correlation function suggests a deviation from the Coulomb baseline

- Simultaneous fit to same sign and opposite sign correlations to study the isospin dependence

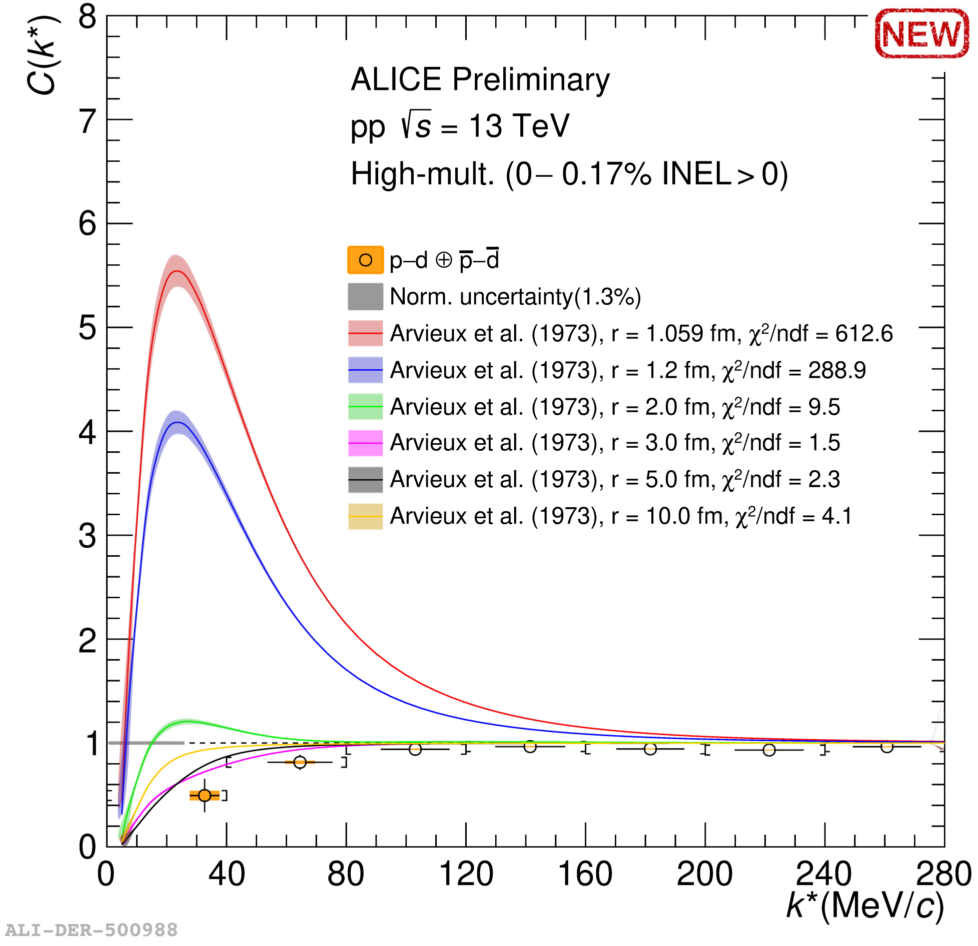
π^+D^+: I = 3/2 channel

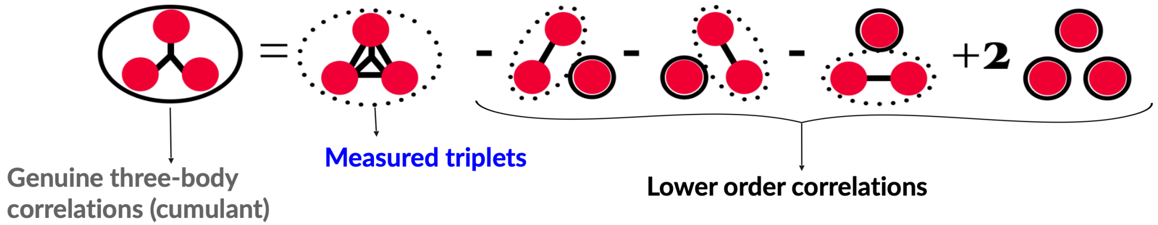
π^+D^-: I = 3/2 (33%), I=1/2 (66%)

Scattering parameters extracted are lower than lattice QCD expectations

- Suggest a small rescattering of D mesons in the hadronic phase of HI collisions

STRONG INTERACTION FOR 3-BODY AND DEUTERON-PROTON





- ALICE is pioneering new methods to explore the three body interactions
- first measurement of the genuine three-body $NN\overline{K}$ interactions via cumulants
  - three-body effects are found to be not significant in ppK^- systems
  - first measurement of proton-deuteron interaction via correlations at the LHC
  - model fits the data only for large source radii

GOODBYE ALICE 1, HELLO ALICE 2 !

ALICE UPGRADE
FOR RUN 3 (2022 - 2025)

> Improve tracking resolution at low p_T

x50 statistics increase for most observables

⇩

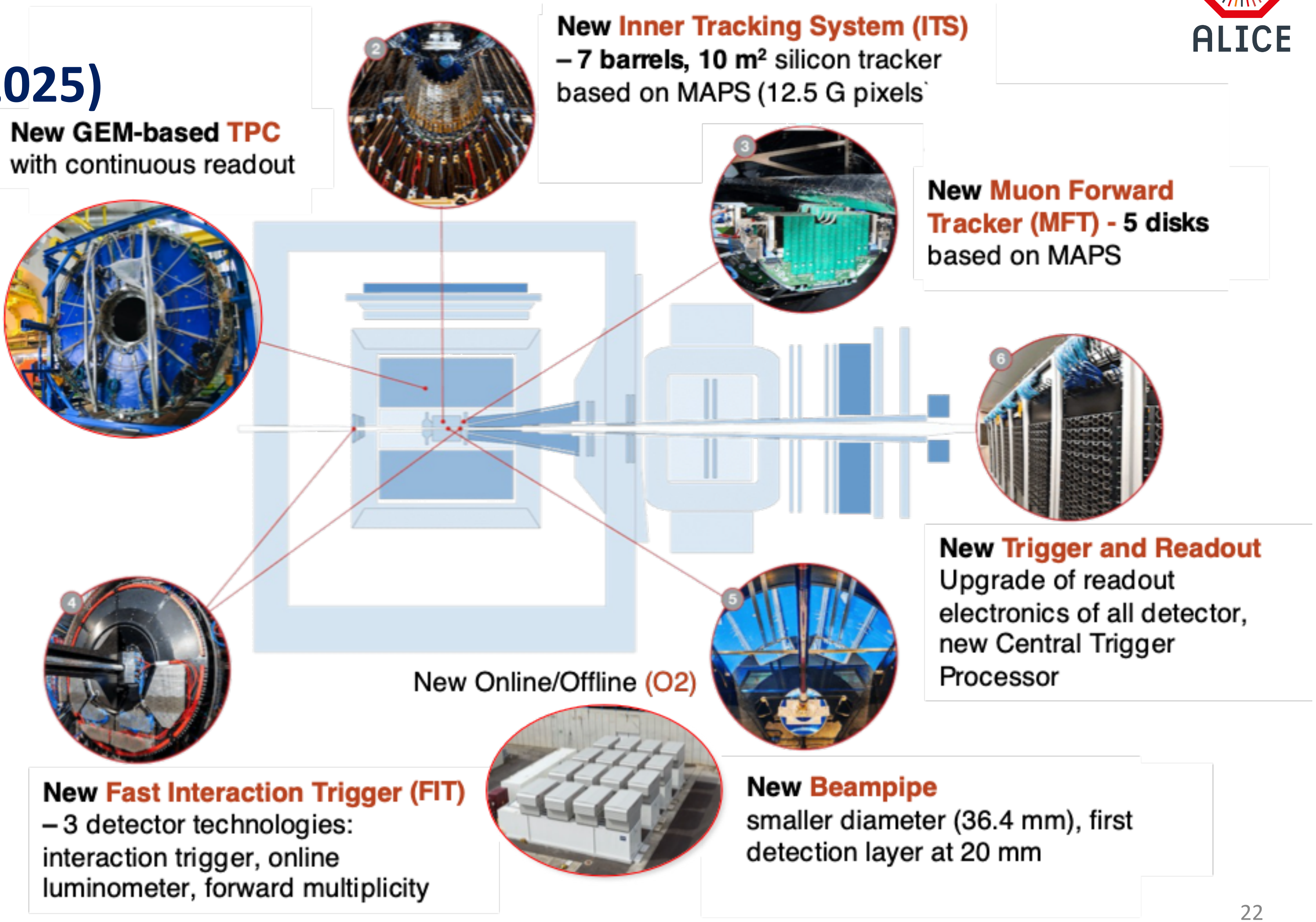
Run 3+4: **13 nb^{-1} Pb-Pb**

50 kHz (Pb-Pb), ≈ 1 MHz (pp)

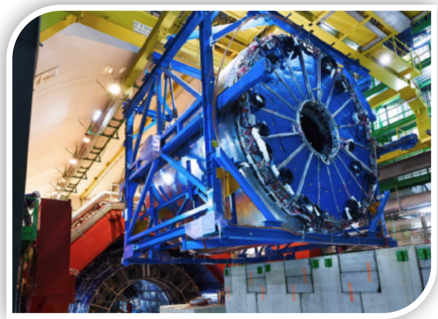
online reconstruction

all events to storage!

Raw data rate: 3.5 TB/s —> 100 GB/s to tape



INSTALLATION OF NEW AND UPGRADED DETECTORS



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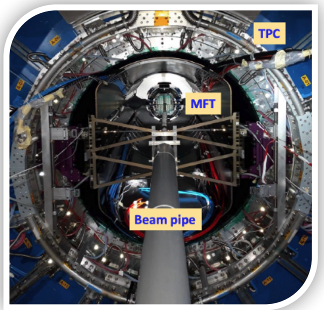

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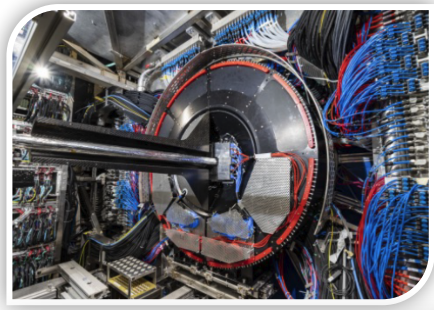

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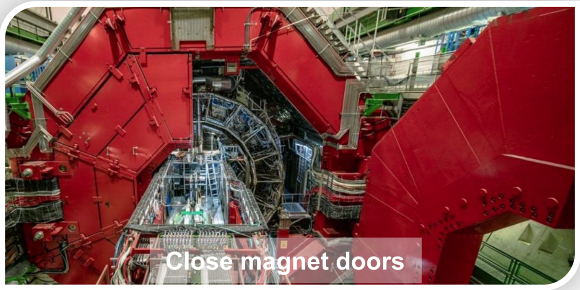

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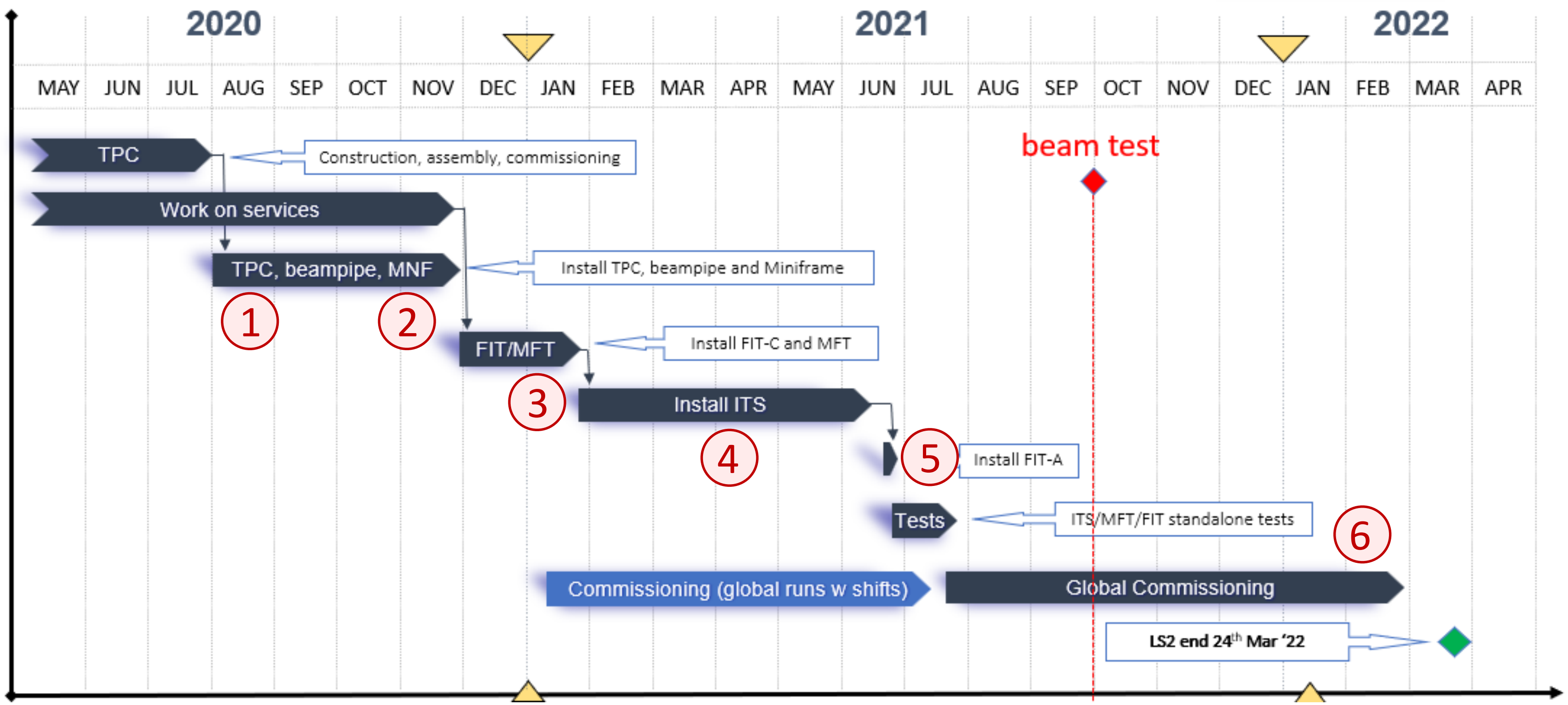
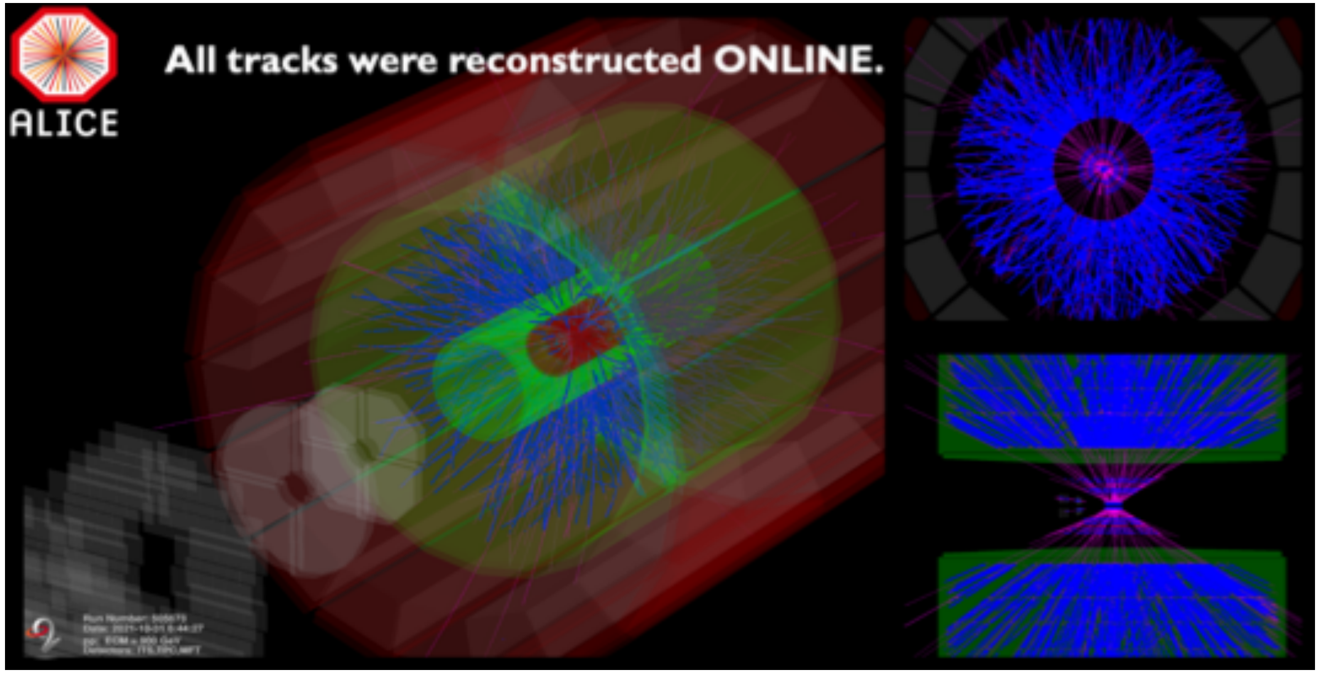


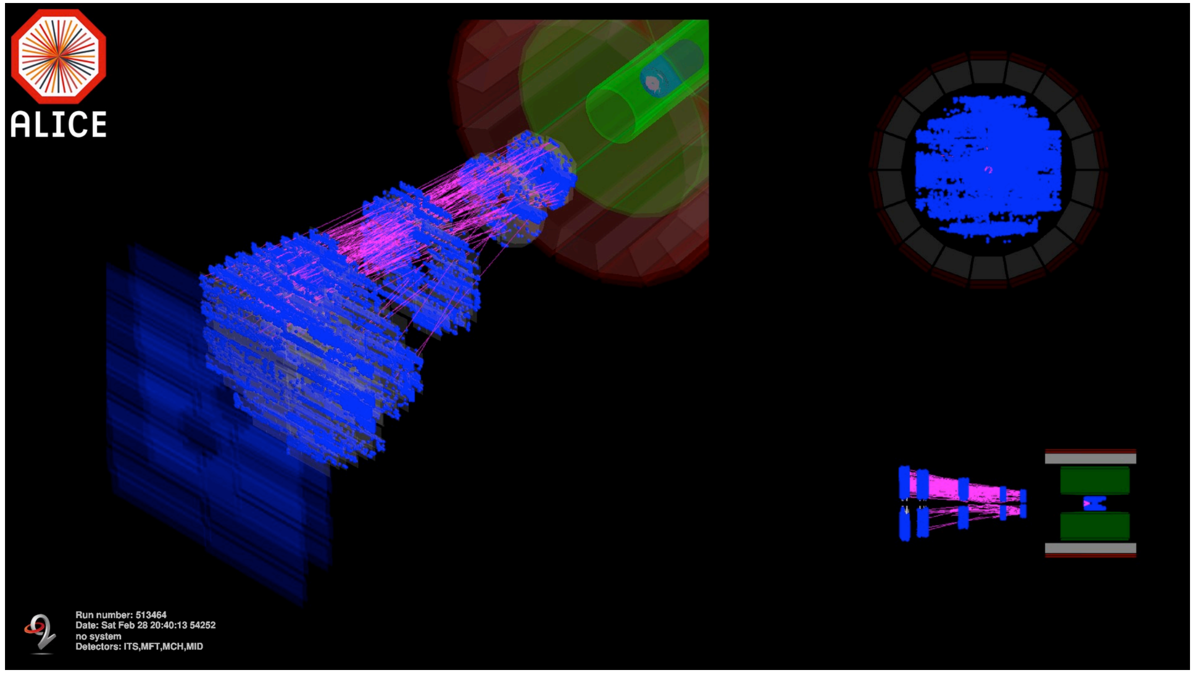
FIRST COLLISIONS IN RUN 3

ALICE

proton-proton collisions from the pilot beam October 2021

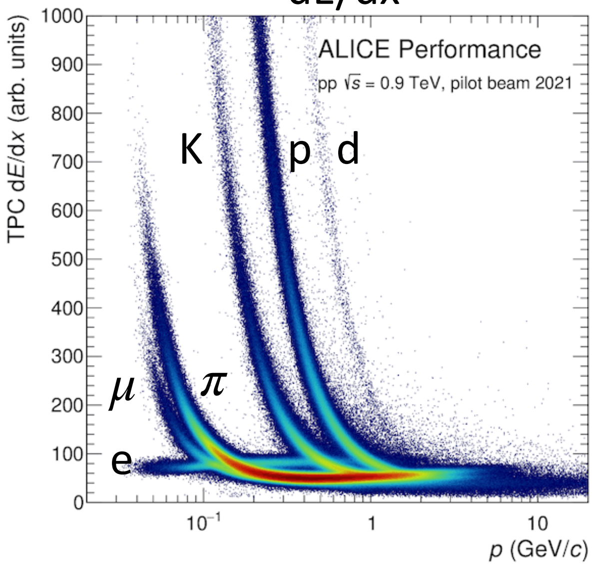


Muon splash events from TED beam shots - April 2022

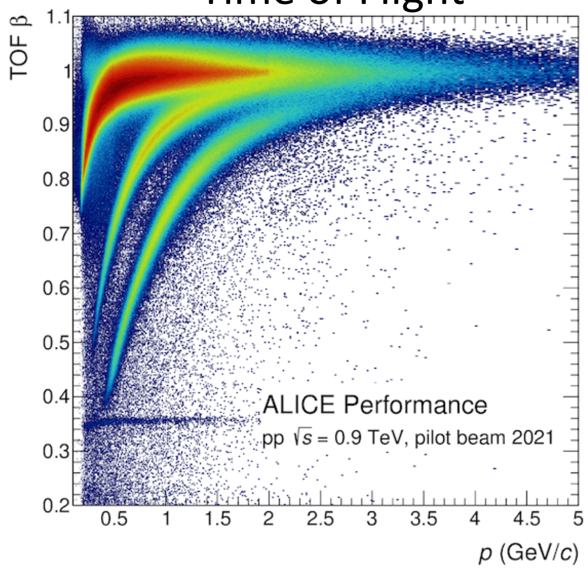


PILOT BEAM RESULTS (OCTOBER 2021)

dE/dx

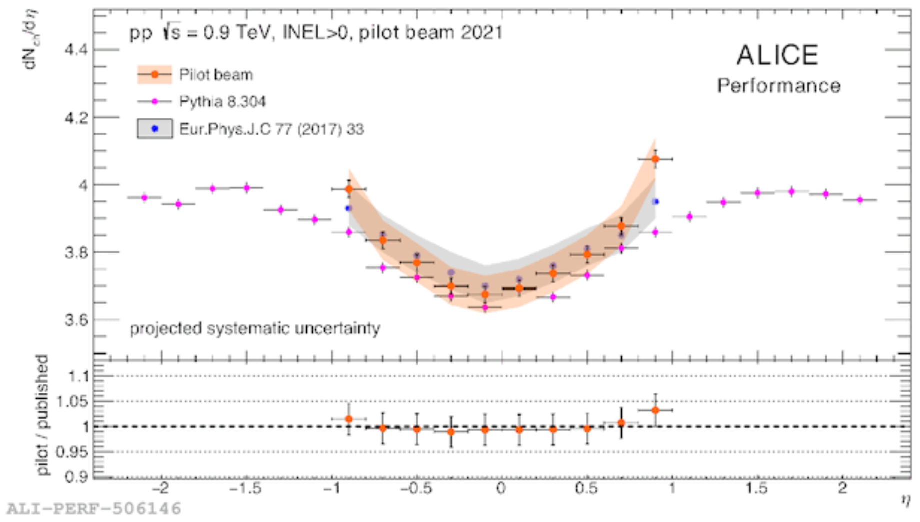


Time of Flight

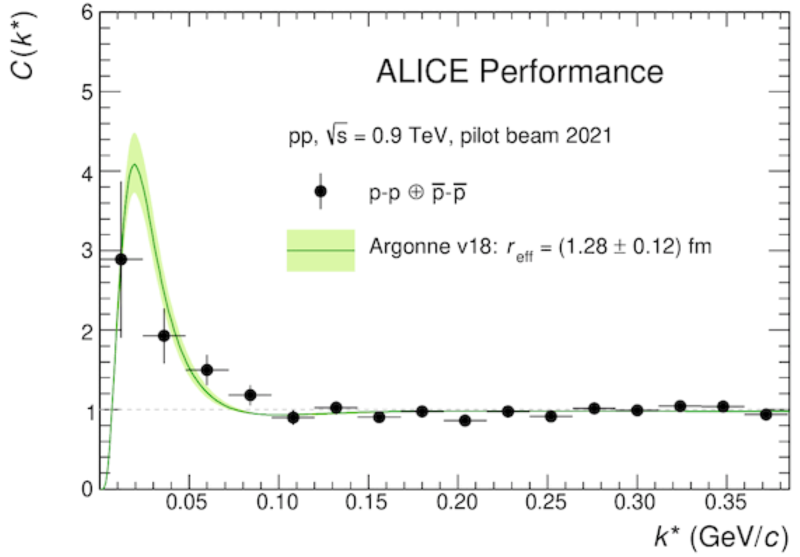


PID capabilities fully available

Measured $dN_{ch}/d\eta$ compatible with previous results

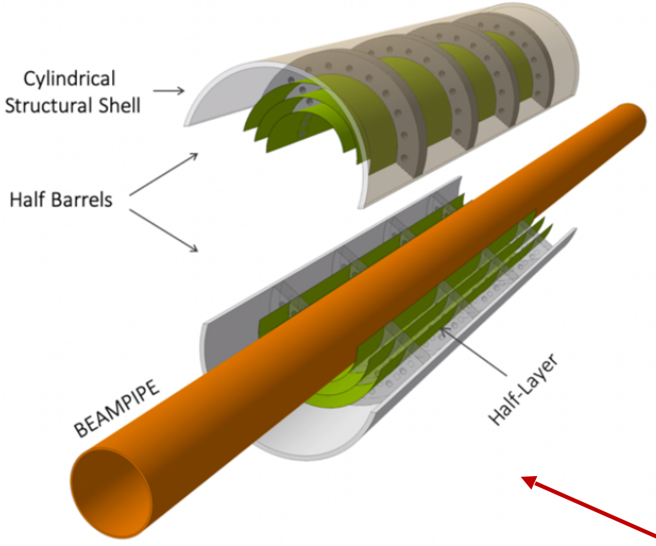


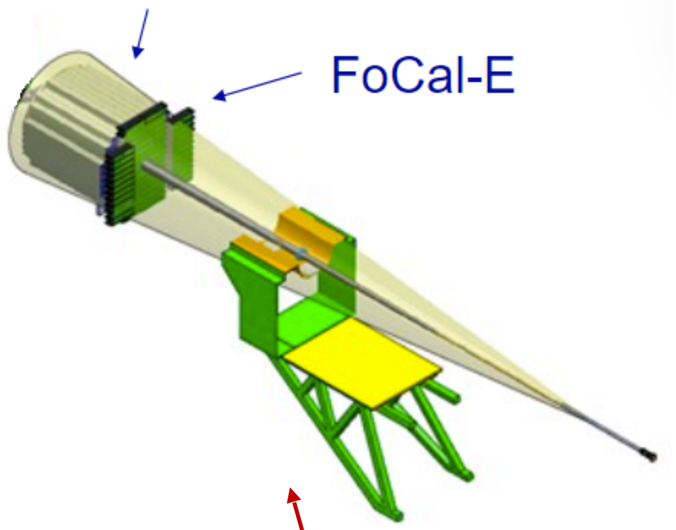
First look at the p-p momentum correlation function



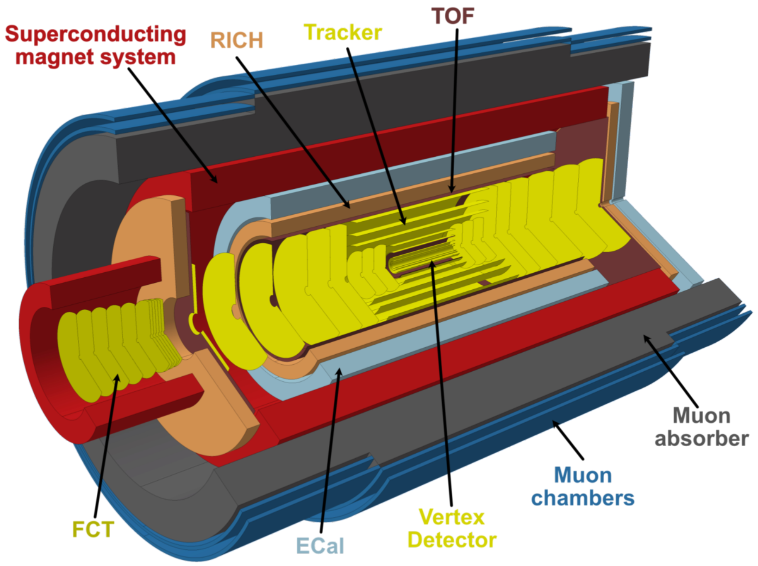
FUTURE UPGRADES

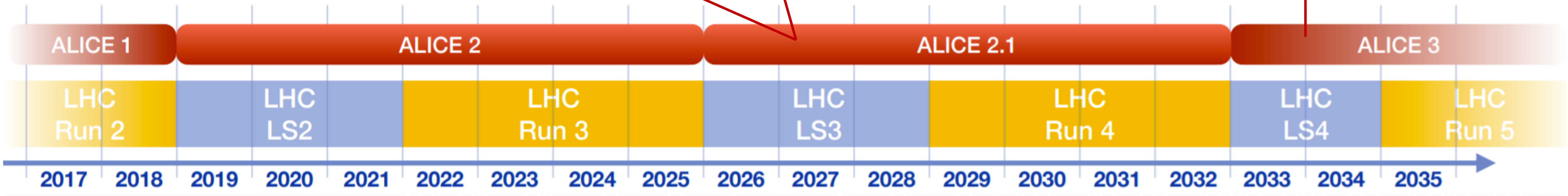
ITS3





ALICE 3

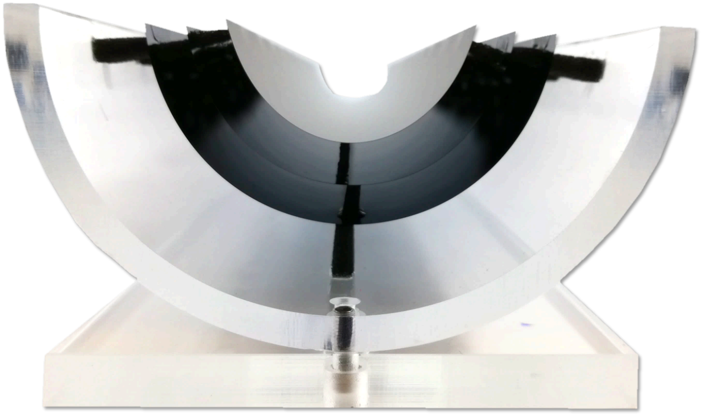




ITS3: A NEW THINNER INNER TRACKER FOR RUN 4 (2029 - 2032)

LoI: CERN-LHCC-2019-018

Replace beam pipe and three inner layers of ITS2 (1st layer @ 18 mm)

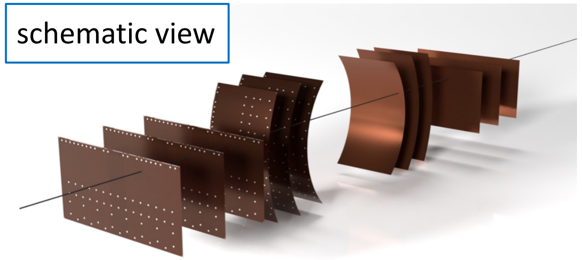


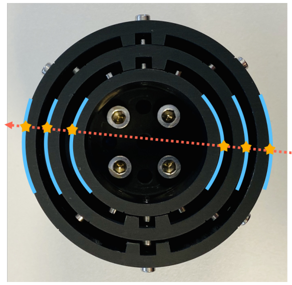
wafer-scale MAPS sensors curled around beam pipe

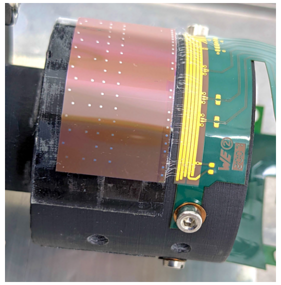
- **~6x** less material budget
- **2x** tracking precision and efficiency at low p_T

Curved pixel sensors (ALPIDE) extensively validated at in-beam tests (https://doi.org/10.1016/j.nima.2021.166280)

schematic view



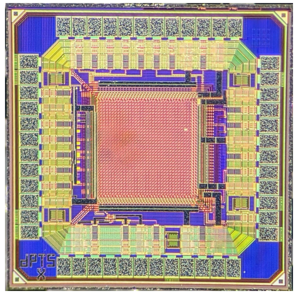




Full-size prototype of half-layers (unprocessed silicon)

Good progress on mechanical, electrical and thermal studies using ITS2 or dummy silicon wafers

First prototype sensors using 65 nm process showed excellent performance!



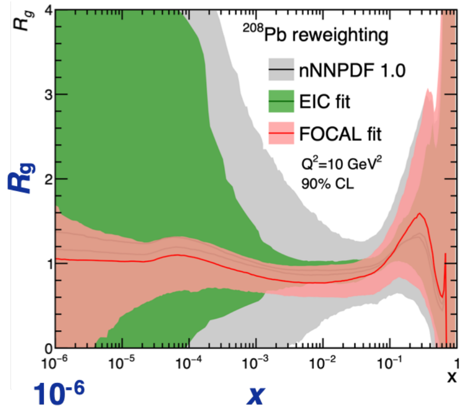
First wafer-scale pixels sensor ready for fabrication (26 cm x 1.4 cm)

FoCal: new detector in preparation for Run 4

LoI ALICE-PUBLIC-2019-005

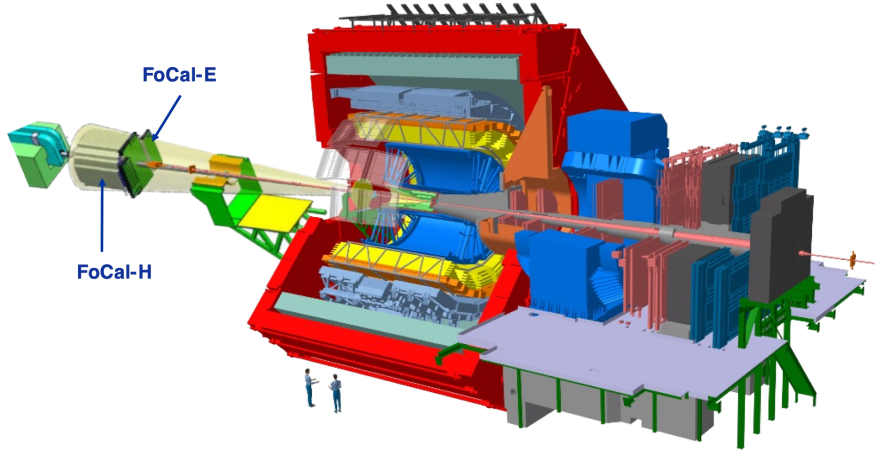
FoCal: forward electromagnetic + hadronic calorimeter

- **FoCal-E**: high-granularity Si-W sampling calorimeter for **direct γ** and π_0
- **FoCal-H**: metal-scintillator sampling hcal for **photon isolation** and **jets**



Main goal: study saturation/shadowing at low-x with direct photons in pp and p-Pb

Impact on gluon nuclear PDFs: present nNNPDF, w/ FoCal pseudodata, w/EIC pseudodata



Test beam in 2021

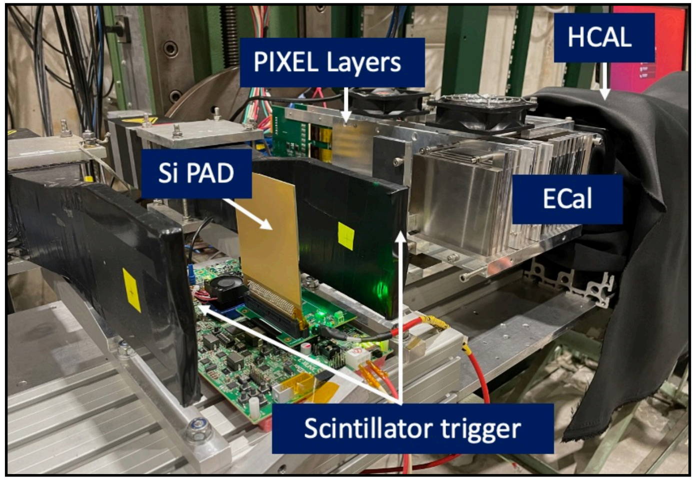
- **FoCal-E**: 2 pixel (ALPIDE) layers, 1 pad layer
- **FoCal-H**: complete prototype, commercial readout system
- Full-pixel prototype: **EPICAL-2**

Main activity in 2022

- Preparation of full demonstrator for test beam in Sep/Oct

HCAL prototype

SPS Test beam Sep/Oct

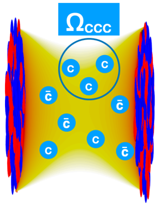


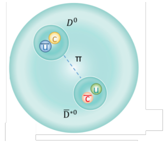
ALICE 3 - a next-generation heavy-ion detector for LHC Run 5 & 6

Key physics questions and drivers

- Nature of **interactions with the QGP** of highly energetic quarks and gluons
- To what extent do quarks of different mass reach **thermal equilibrium** ?
- What are the **mechanisms of hadron formation** in QCD?

➪ Systematic measurement of (multi-)charm hadrons

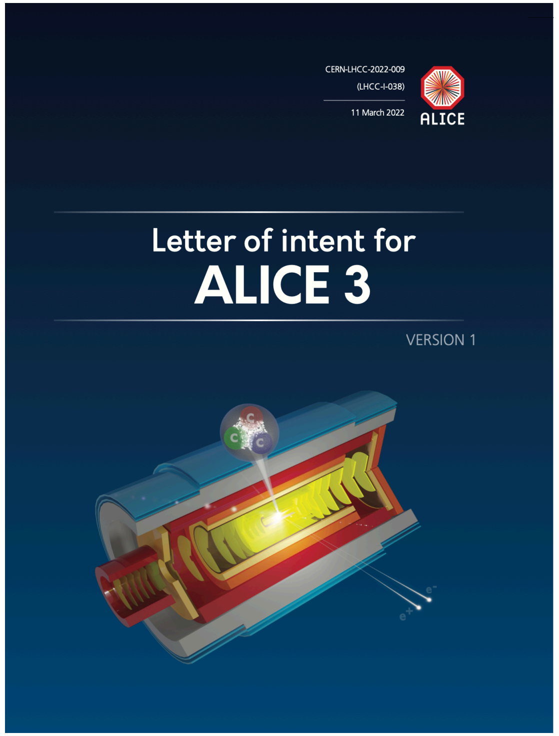




- QGP **temperature** throughout its temporal evolution
- What are the mechanisms of **chiral symmetry restoration** in the QGP?

➪ Precision measurements of dileptons

- QCD chiral phase structure (➪ fluctuations of conserved charges)
- Hadron interaction potential (➪ hadron-hadron correlations)
- ….



Letter of Intent: CERN-LHCC-2022-009

LHCC review completed in March

planned for installation in LS4

''a roadmap for exciting heavy-ion physics in 2035"

"ALICE 3 detector concept […] is well matched to the proposed, ambitious physics program''

ALICE 3 DETECTOR

Compact all-silicon tracker
→ clean separation of signal and background

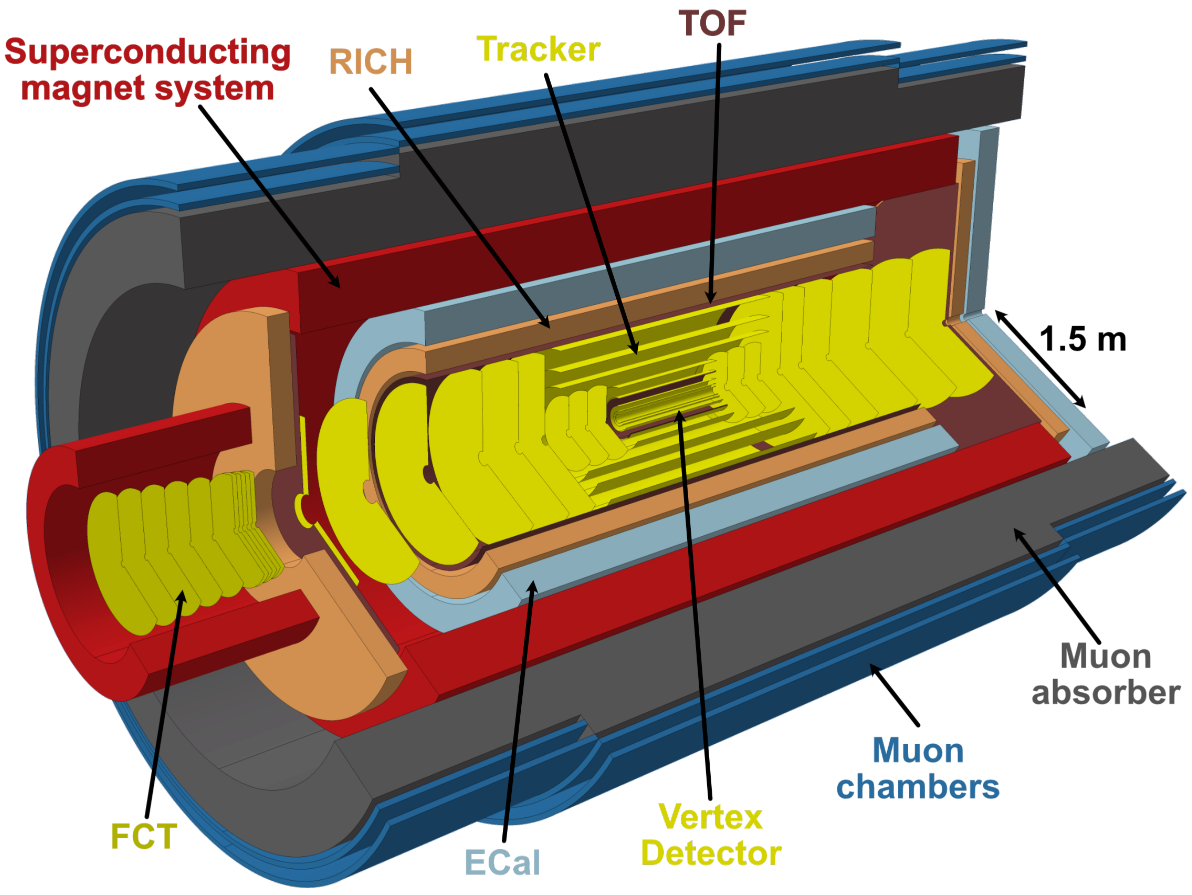
Vertex detector with excellent pointing resolution
→ clean reconstruction of decay chains

Particle identification
→ background suppression

Large acceptance, $-4 < \eta < 4$, $p_T > 0.02$ GeV
→ statistics and correlations

Superconducting magnet system
→ effective provision of required magnetic field

Continuous readout and online processing
→ large data sample to access rare signals



⇨ novel detector concept based on innovative technologies relevant for future HEP experiments

CONCLUSIONS

The wealth and breadth of results achieved in Run 1 and 2 offer

- detailed insights into **QGP properties**
  - e.g. macroscopic and fluid-dynamic properties, heavy quark interaction, jet modification;
- plus a broader **programme**
  - pQCD, interaction between hadrons, formation of nuclei and antinuclei, …

ALICE completed the Phase I upgrade … and is now **ready for Run 3** with significantly enhanced capabilities

Future

- In preparation for Run 4: **ITS3** and **FoCal**, R&D on track
- **ALICE 3 LoI** (phase II upgrade, installation in LS4) endorsed by LHCC

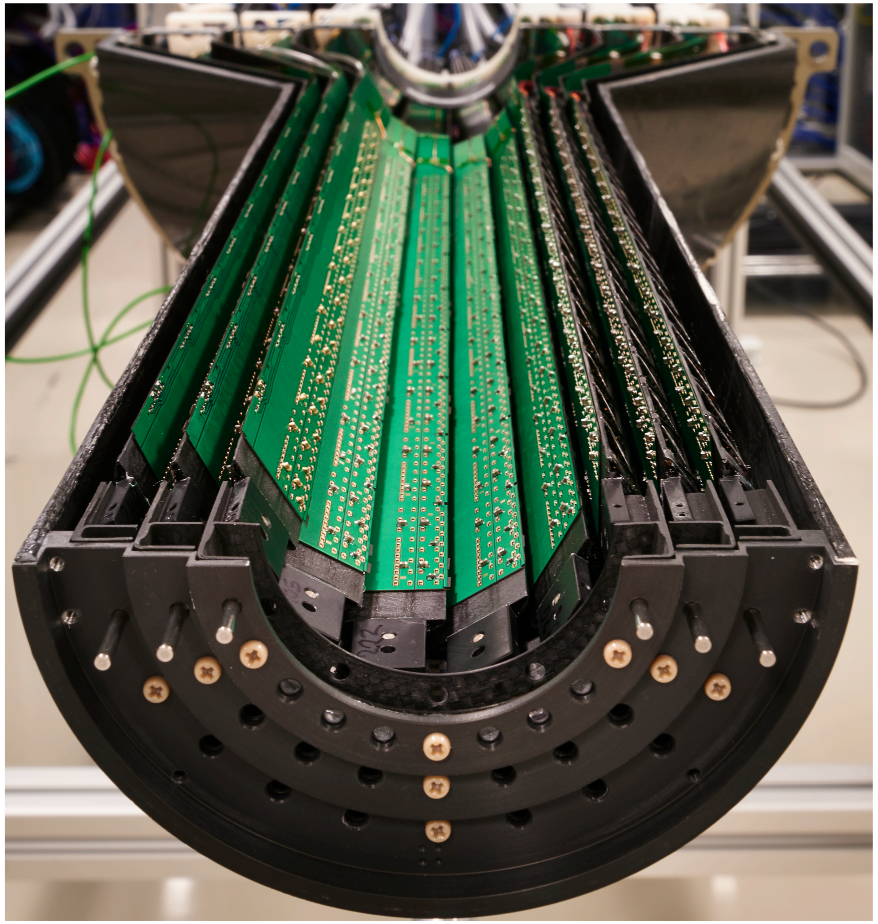
⇨ Moving forward to the R&D phase

BACKUP

ALICE

ITS3 - PREPARATION FOR RUN 4

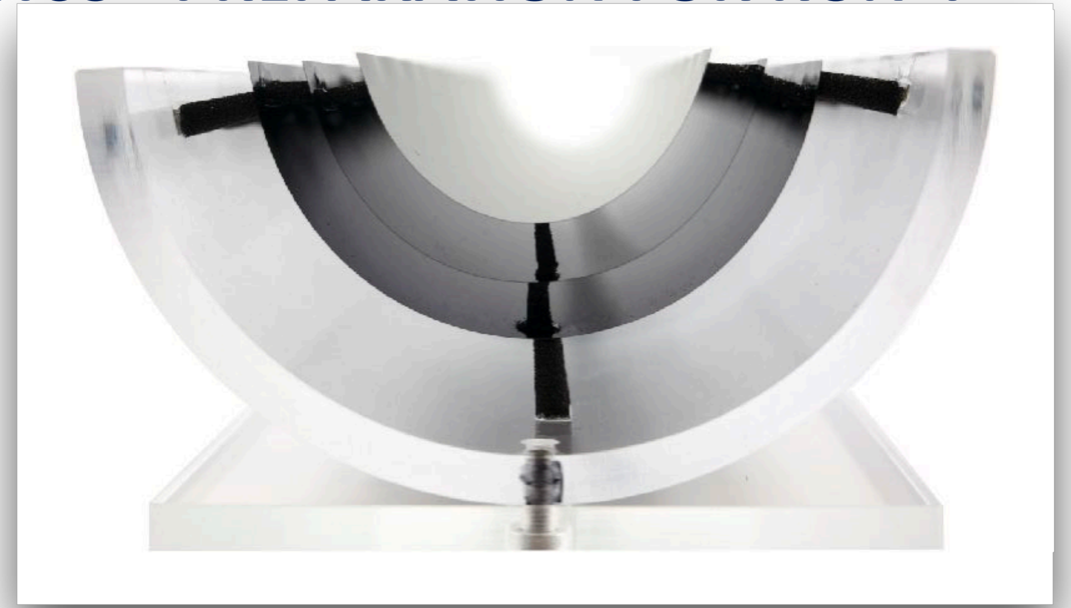
by employing wafer-scale, bent sensors



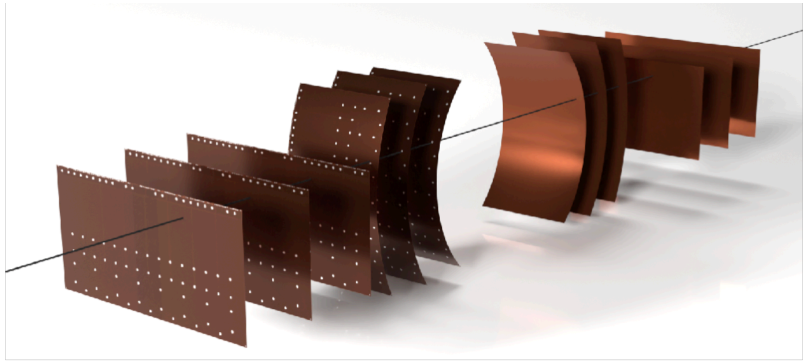
TDR planned for mid 2023

CERN-LHCC-2019-018

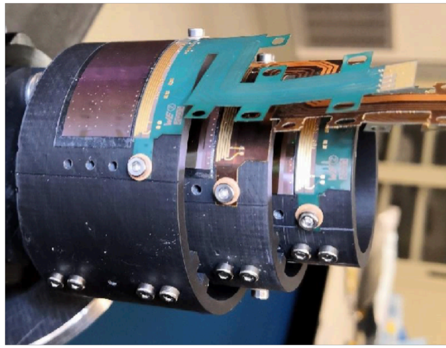
ITS3 - PREPARATION FOR RUN 4



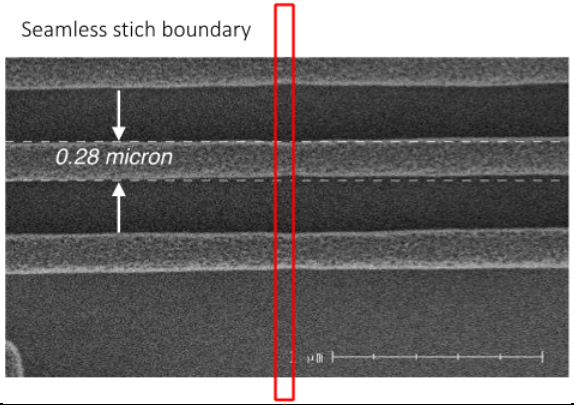
bending silicon chips thinned down to 30-50μm



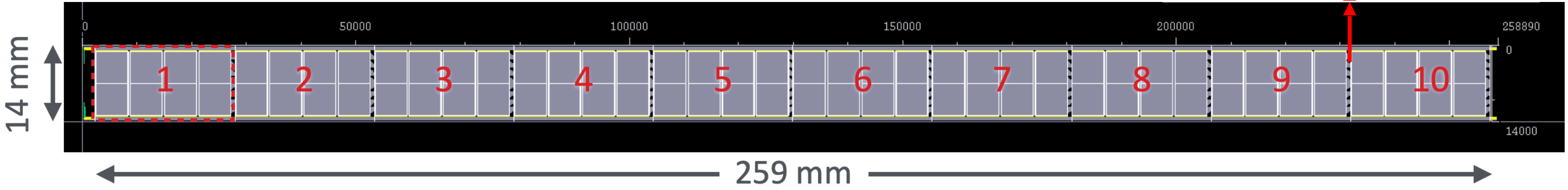
Schematic view μITS3 test beam setup



Picture of the μITS3

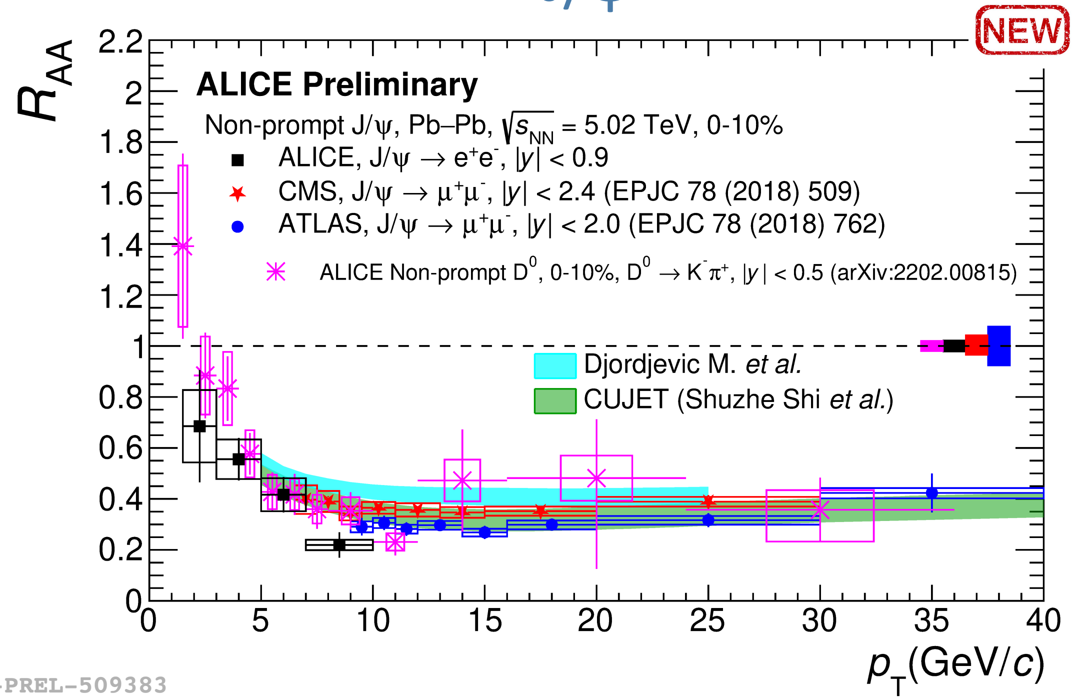


ITS3 — large-scale stitched prototype

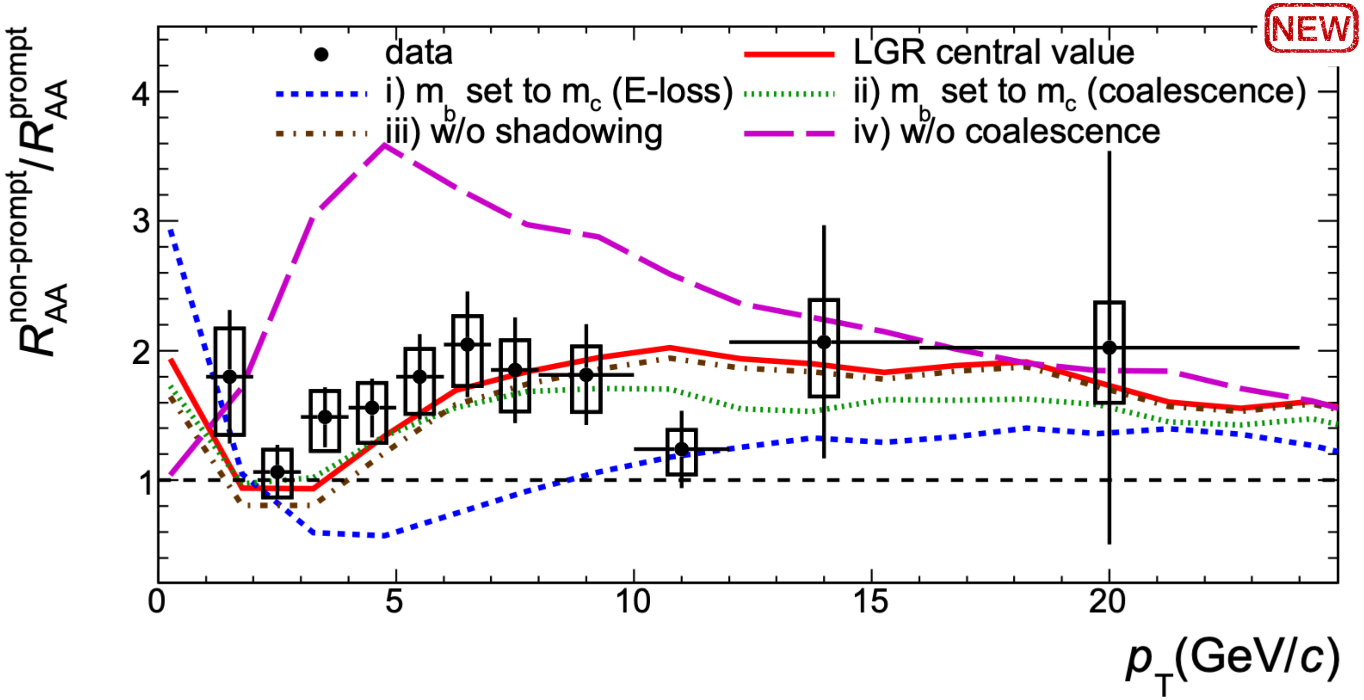


MODIFICATION OF J/Ψ AND D MESON YIELDS FROM BEAUTY DECAYS

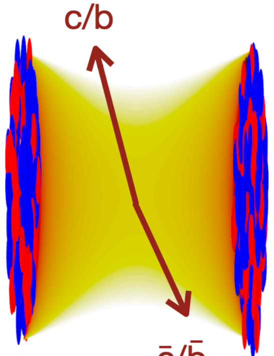
J/ψ



D0 arXiv:2202.00815



Unprecedented access to the low p_T region for beauty hadron R_{AA} through the me



of non-prompt J/ψ and D meson

R_{AA}(non-prompt)/R_{AA}(prompt) larger than unity for p_T > 5 GeV/c

Model description requires mass-dependent energy loss and coalescence