arXiv:2211.02491

ALICE 3 - A new horizon for QCD

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RHIC-BES seminar series, June 27th 2023

UNIVERSITY OF HOUSTON

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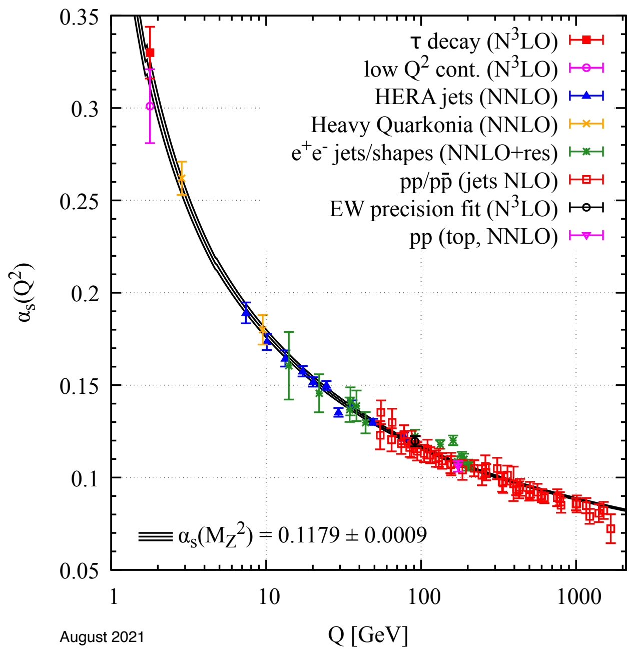
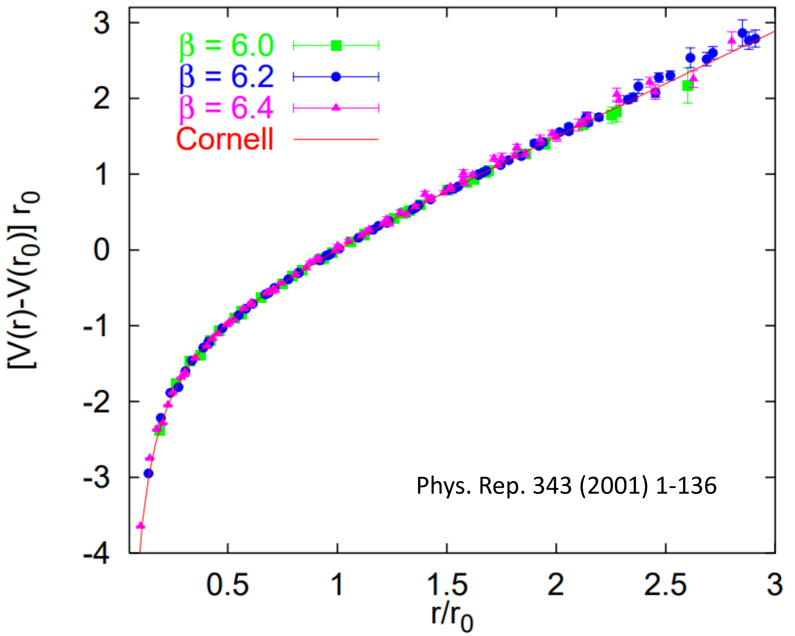
Hallmarks of Quantum Chromodynamics (QCD)

2004 Nobel Prize





2008 Nobel Prize

Asymptotic freedom

Vanishing of strong force at high energy

Confinement

Quarks are never alone

Chiral symmetry breaking

Origin of 95% of observable mass in universe

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Unlocking the QCD Lagrangian

$$\mathcal{L}_{\mathrm{QCD}} = \sum_{q=u,d,s,\ldots} \overline{\psi}_{qi}(x)\left[(i\gamma_\mu D^\mu)_{ij} - m_q\delta_{ij}\right]\Psi_{qj}(x) - \frac{1}{4}F^a_{\mu\nu}(x)F^{\mu\nu\,a}(x)$$

Can be **approximated in high energy limit** - perturbative QCD

✓ E.g. Running of strong coupling α_s, cross sections of hard processes

Can be **partially solved in low energy limit** - Lattice QCD

✓ E.g. QCD potential at large distances, mass of hadrons

Untractable for **dynamical low energy processes**

✓ E.g. Space-time structure of hadron/nuclear structure, hadron formation..

Q momentum exchange

High energy

$Q \gg \lambda_{QCD}$ = 200 MeV

Low energy

$Q \sim \lambda_{QCD}$

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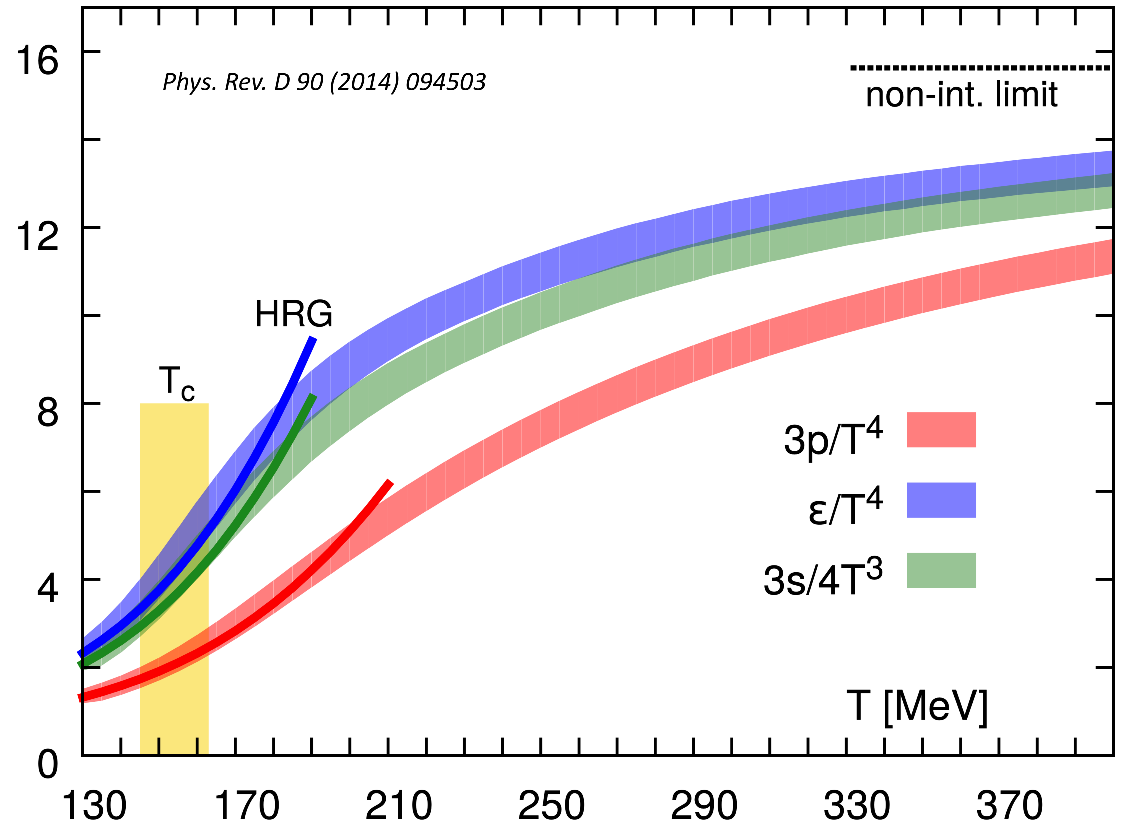
Emergence of the Quark-Gluon Plasma

Lattice QCD predicts **rapid change in hadronic thermodynamic properties** around T_c=156 MeV of many-body system



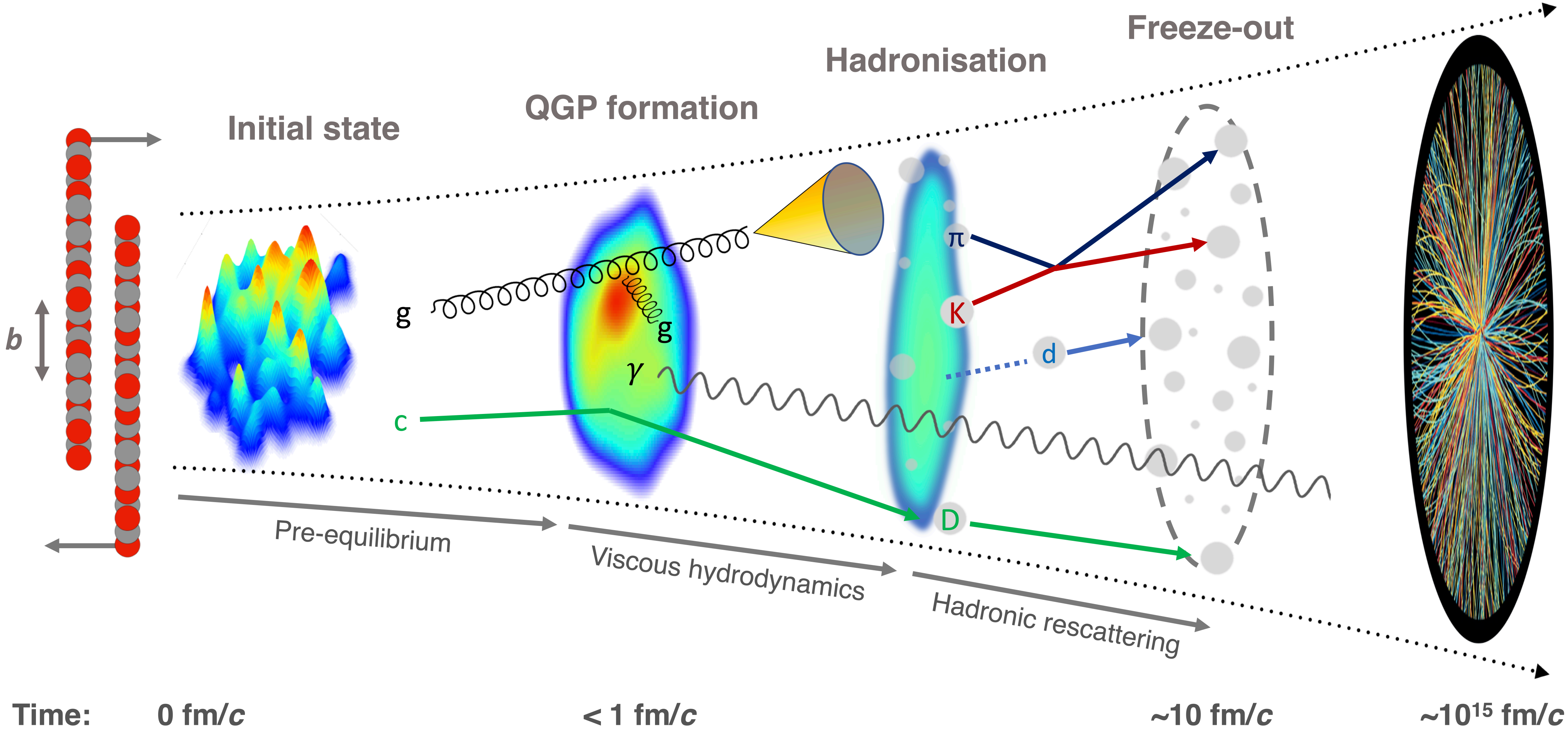
Formation of **Quark-Gluon Plasma (QGP)**

✓ Quarks & gluons no longer confined

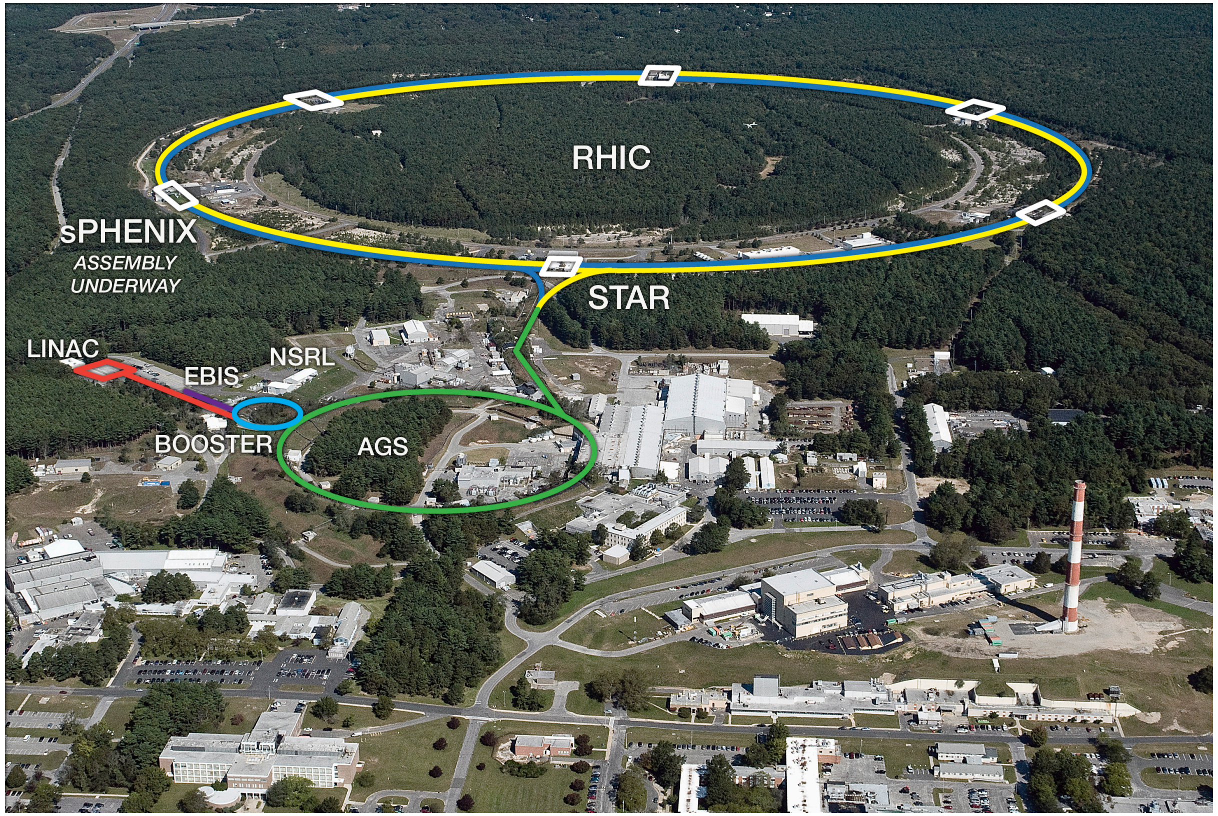
Crossover phase transition for matter-antimatter symmetric system

✓ Accompanied by **Chiral Symmetry Restoration**

"Standard Model" of Heavy-Ion collisions



Machines that collide heavy-ions



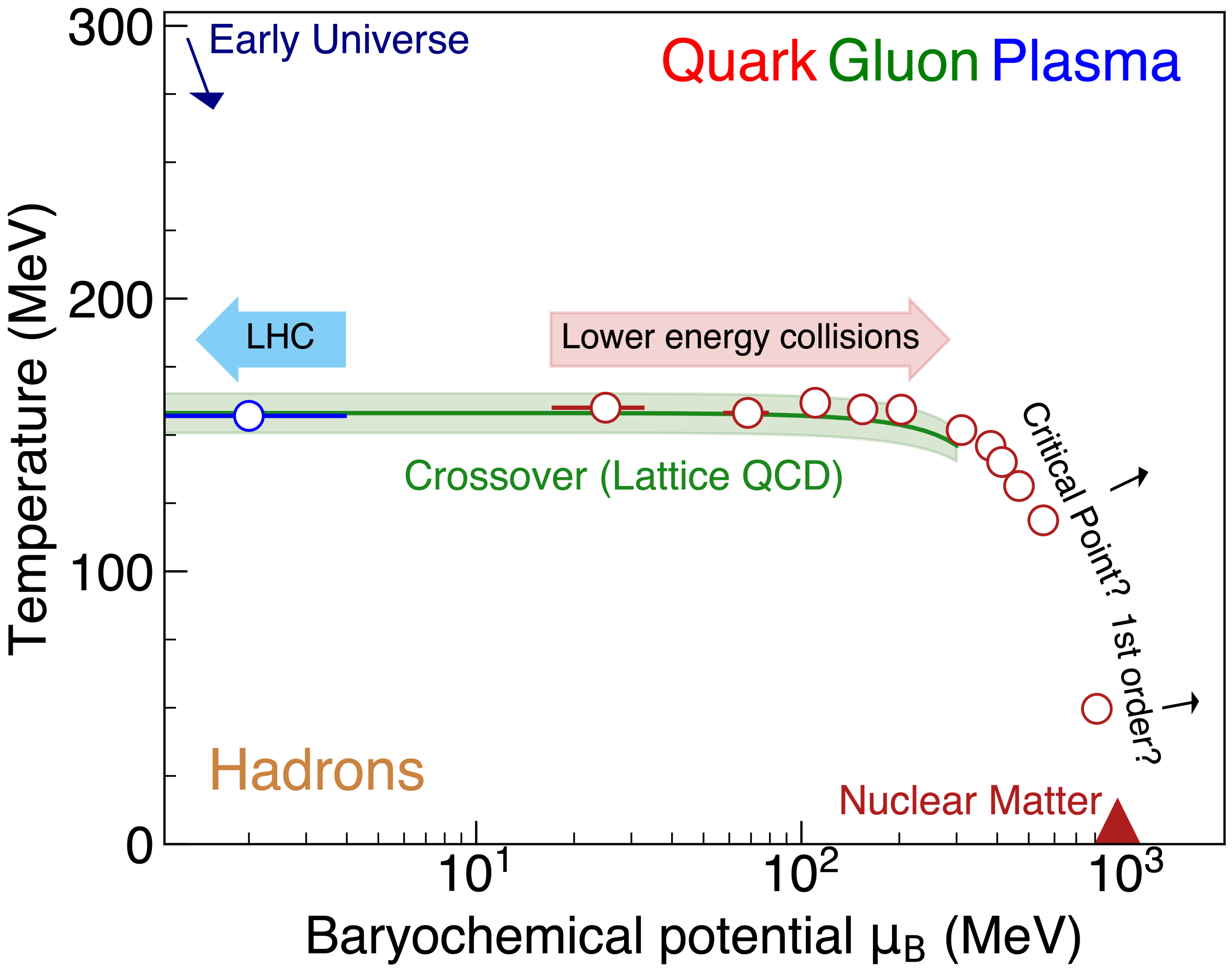
Relativistic Heavy-Ion Collider (RHIC)

Brookhaven National Lab (BNL), New York

Large Hadron Collider (LHC)

CERN, Geneva, Switzerland

The QCD Phase Diagram



QGP produced at LHC has **highest temperatures** and **largest matter-antimatter symmetry**

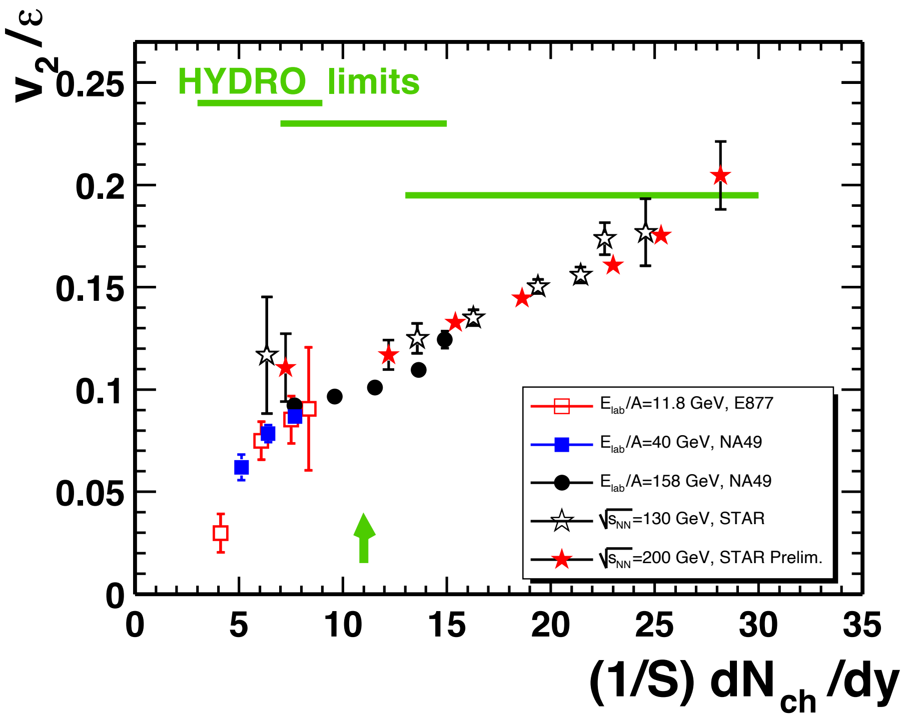
✓ Early universe in this state ~10^{-6} seconds after big bang

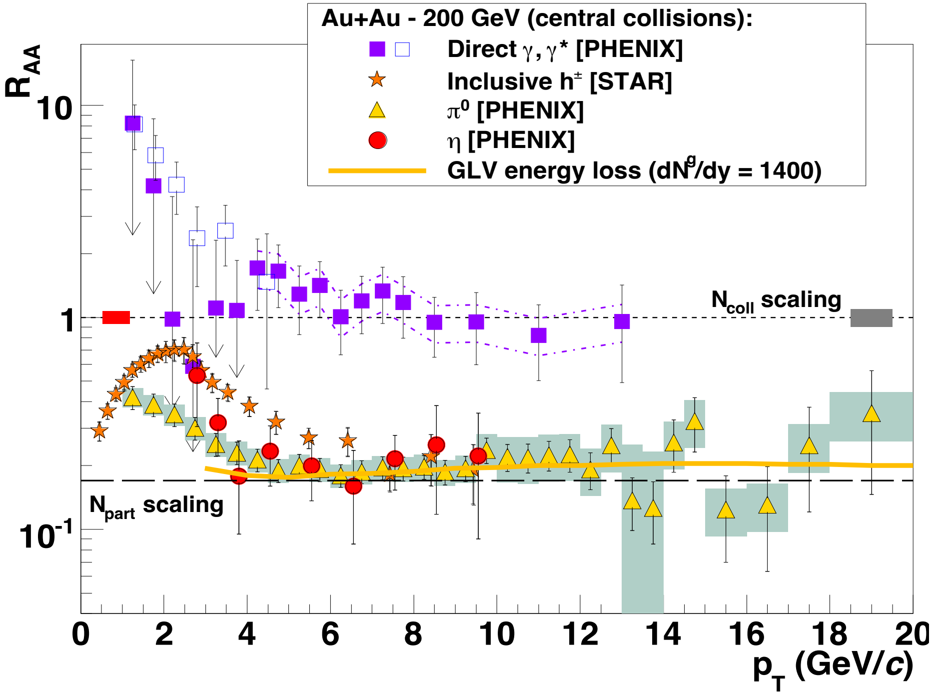
Ongoing dedicated high energy program at RHIC

✓ STAR and new sPHENIX detector

Lower energies at SPS (CERN), RHIC, FAIR, NICA search for **QCD critical point** and **thresholds of QGP** formation

Major QGP discoveries at RHIC (2000s)





[RHIC Scientists Serve Up 'Perfect' Liquid]

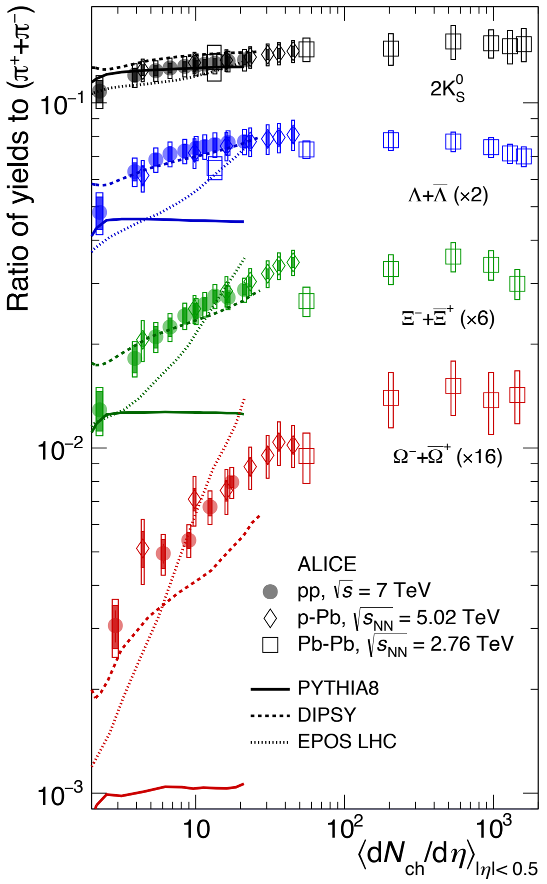
Perfect liquid

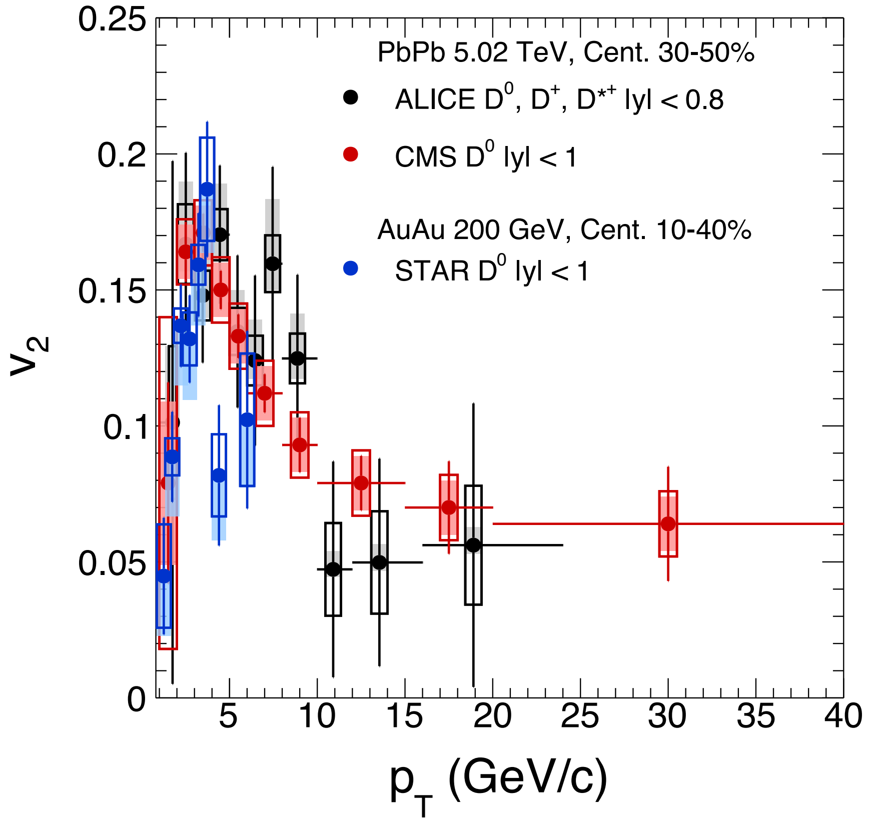
Elliptic flow achieves hydrodynamic limit

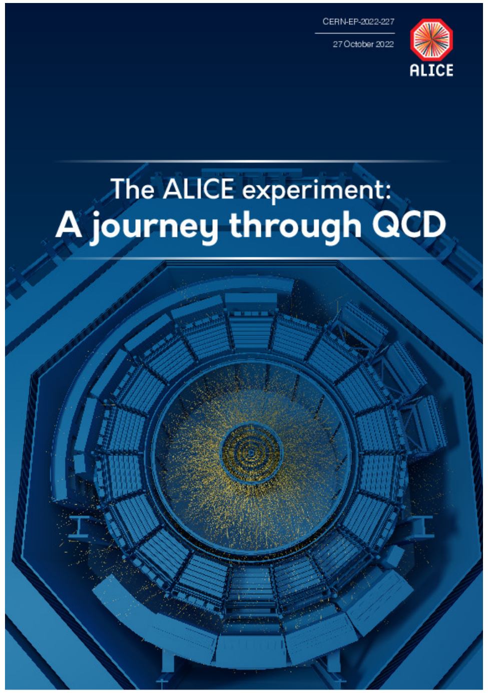
High-momentum hadron suppression

Partons lose energy in the QGP

QGP discoveries at RHIC and LHC (2010s)







[ALICE Review Paper]

QGP is everywhere?

Small systems exhibit QGP behavior

Charm flow and quenching

Heavy quarks couple with QGP medium

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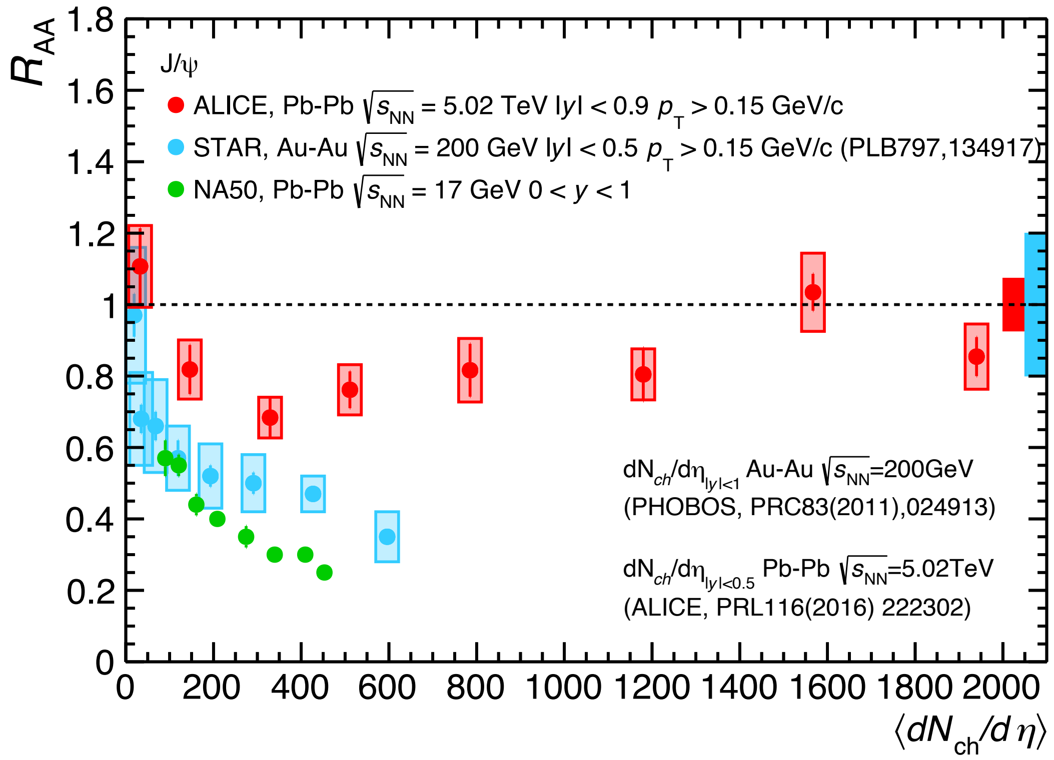
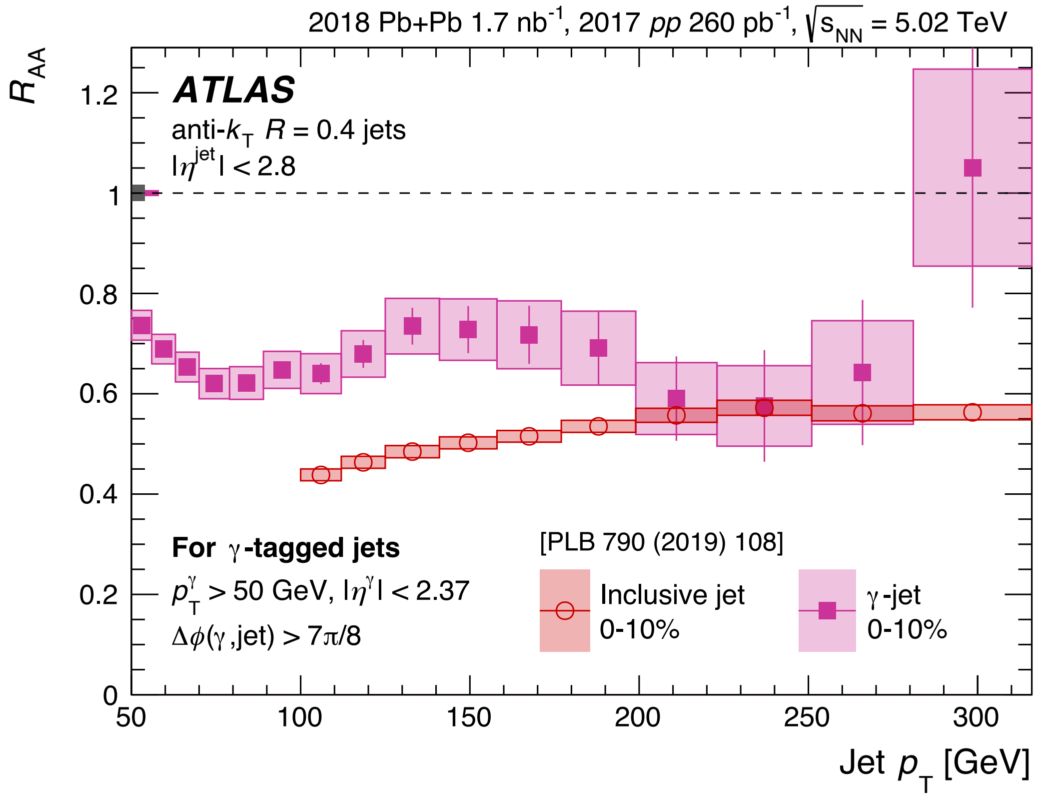
Unique QGP studies at the LHC

arXiv:2303.10090

arXiv:2211.04384





Charmonium

Regeneration evidence of deconfinement

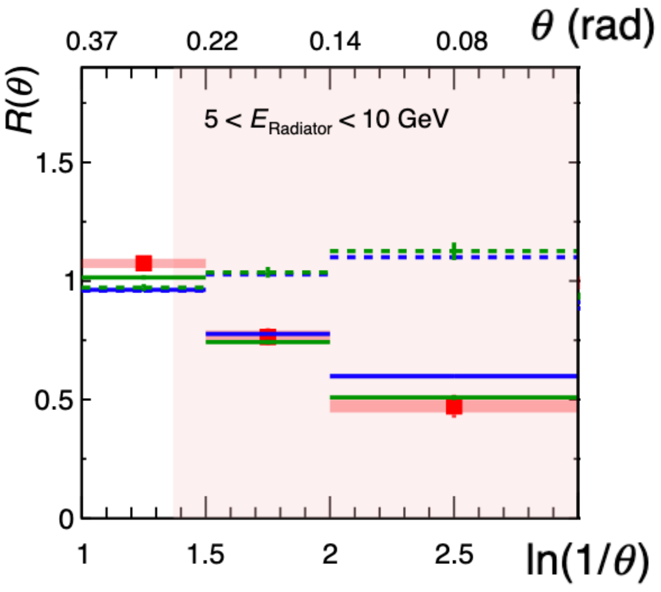
Full jet reconstruction over widest kinematics

Probes of microscopic QGP structure at various scales

Unravelling few-body QCD

[Charm hadronisation differs at the LHC]

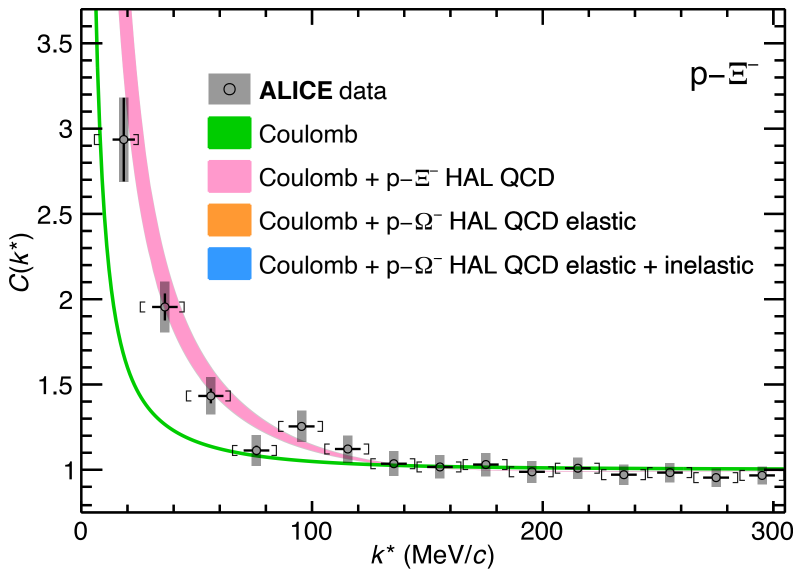
[Dead-cone effect exposed by ALICE]



QCD Dead-cone effect

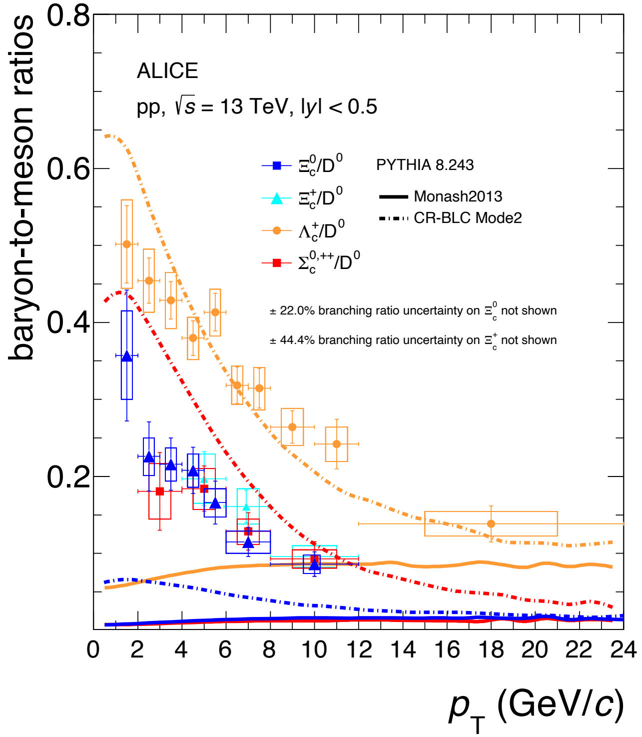
Radiation from charm quarks suppressed

[Neutron stars go under the LHC microscope]



Hyperon interactions attractive

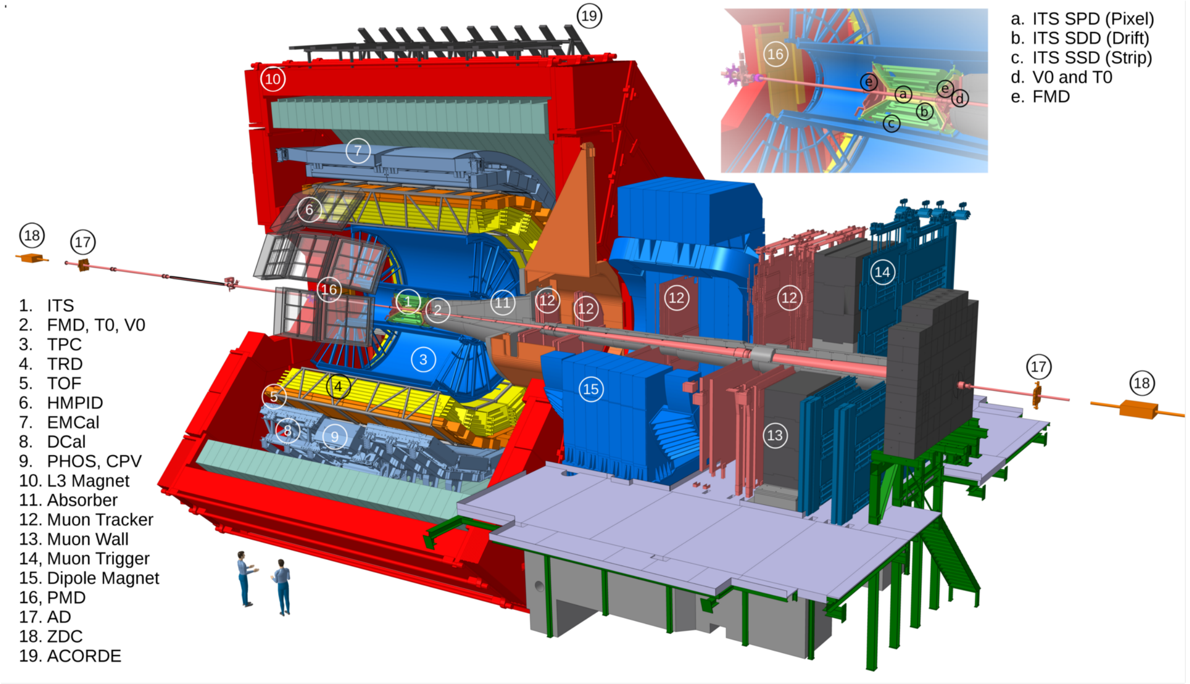
Implications for neutron star equation of state

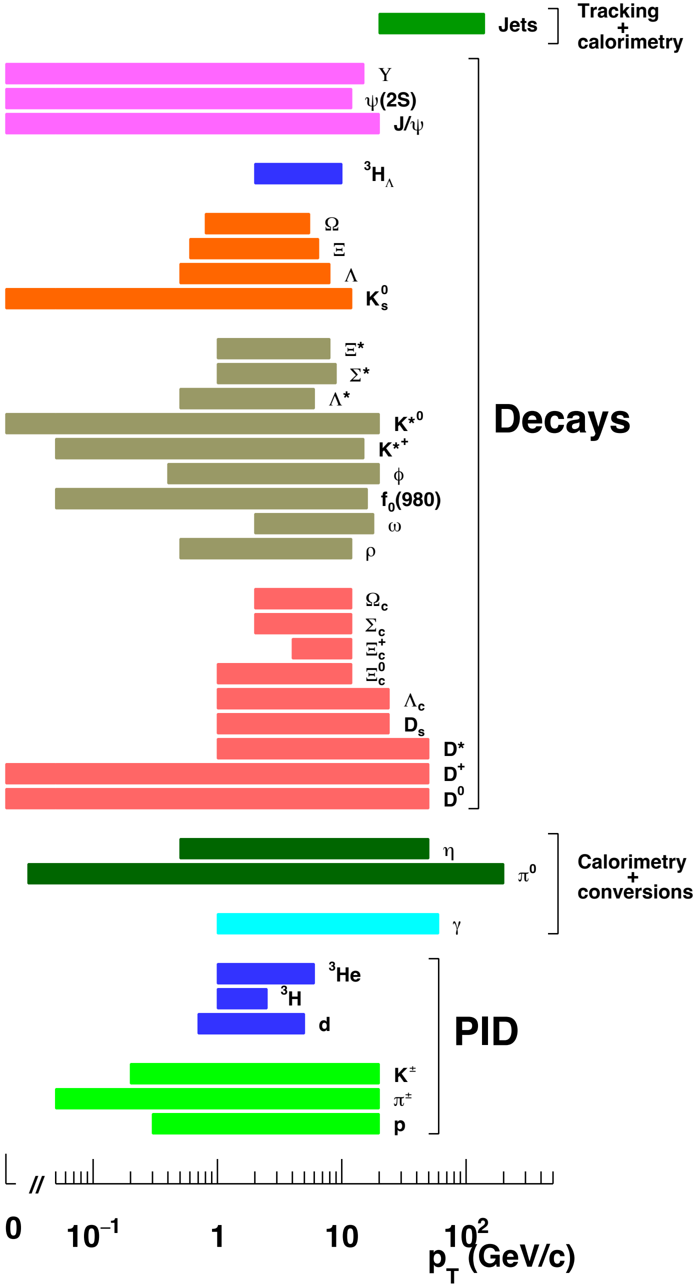


Non-universal hadron production

Charmed baryons favored in proton collisions wrt electron

The ALICE detector (2010s)





Broad momentum acceptance probes all aspects of **QGP behaviour**

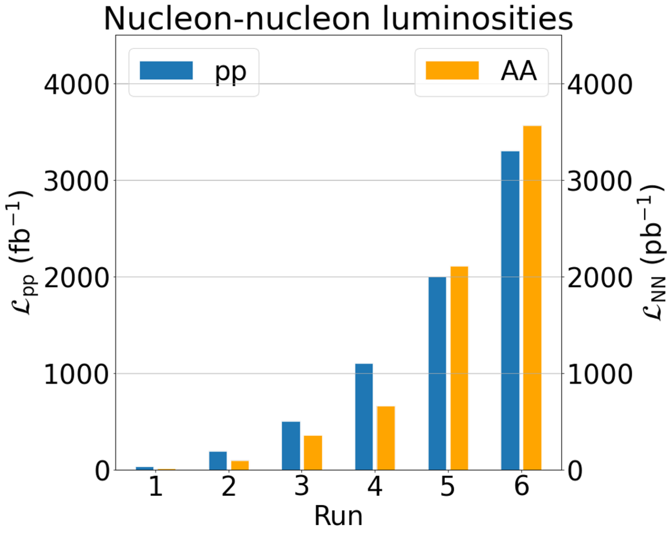
✓ World leading **particle identification**

Looking ahead at the LHC

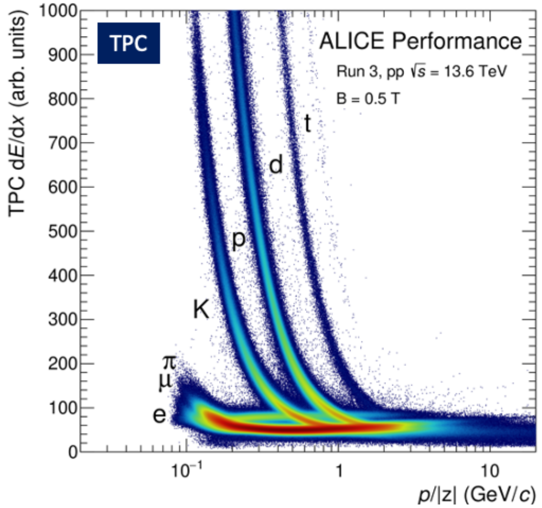
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Collision systems	pp, pPb, Pb-Pb	pp, pPb, Xe-Xe, Pb-Pb	pp, pO, OO, pPb, Pb-Pb	pp, pPb, Pb-Pb	pp, pA?, AA	pp, pA?, AA
LHC schedule	2009 - 2013	2015 - 2018	2022 - 2025	2029 - 2032		

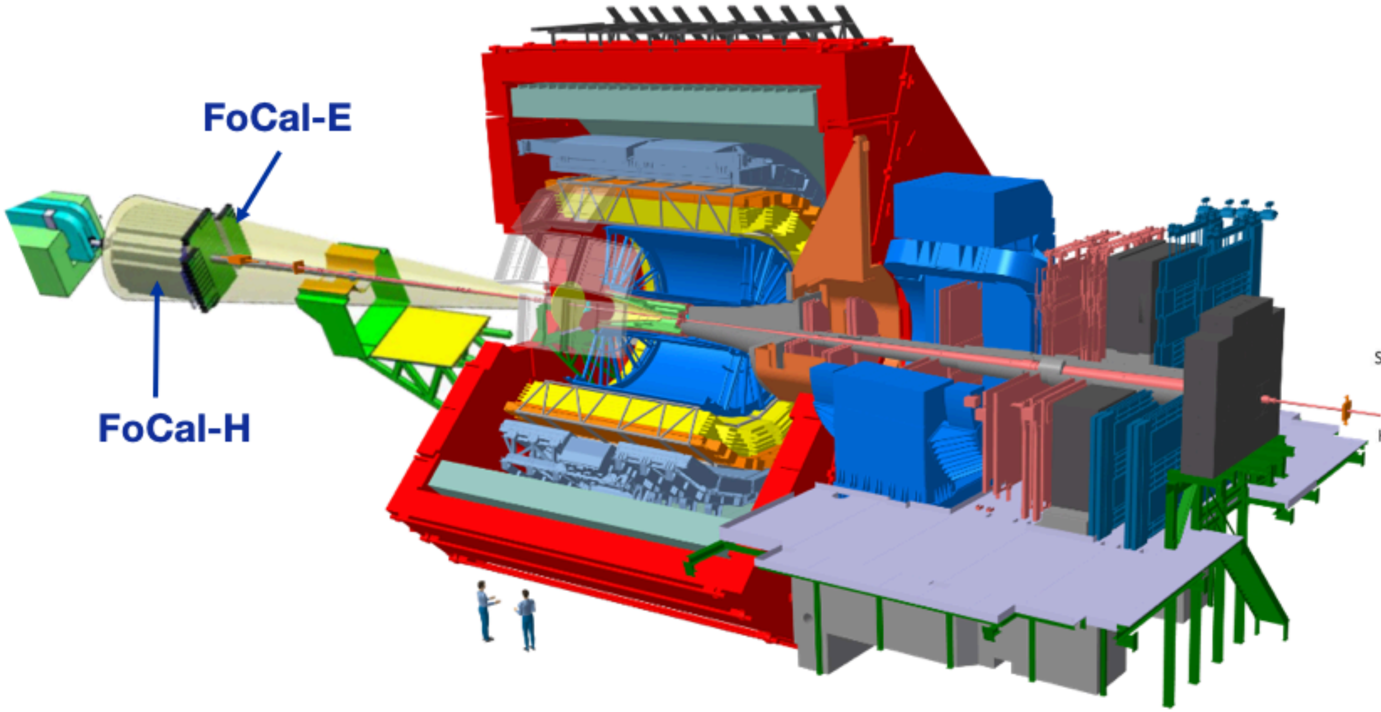
Experiment	Runs 1–2	Run 3	Run 4	Runs 5–6
ATLAS	ATLAS	ATLAS phase I upgrades	ATLAS phase II upgrades	
CMS	CMS	CMS phase I upgrades (from Run 2)	CMS phase II upgrades	
LHCb	LHCb	LHCb upgrade I(a)	LHCb upgrade Ib	LHCb upgrade II
ALICE	ALICE 1	ALICE 2 upgrade	ALICE 2.1 upgrade	ALICE 3 upgrade

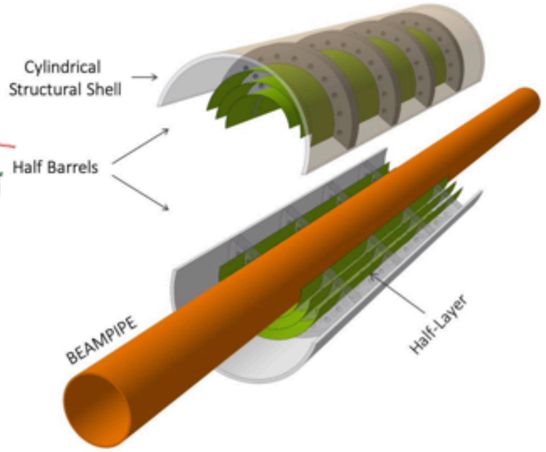
intermediate upgrade | major upgrade



ALICE 2 in the 2020s







Recent upgrades to TPC, ITS and new MFT for Run 3 (and many others). New FoCal and ITS3 in Run 4

- ✓ **Precision era** for jet, heavy-flavor and electromagnetic probes in **large & small systems**
- ✓ Deeper explorations of **proton/nuclear structure** and **rare hadron interactions**

ALICE 3 - A next generation heavy-ion detector

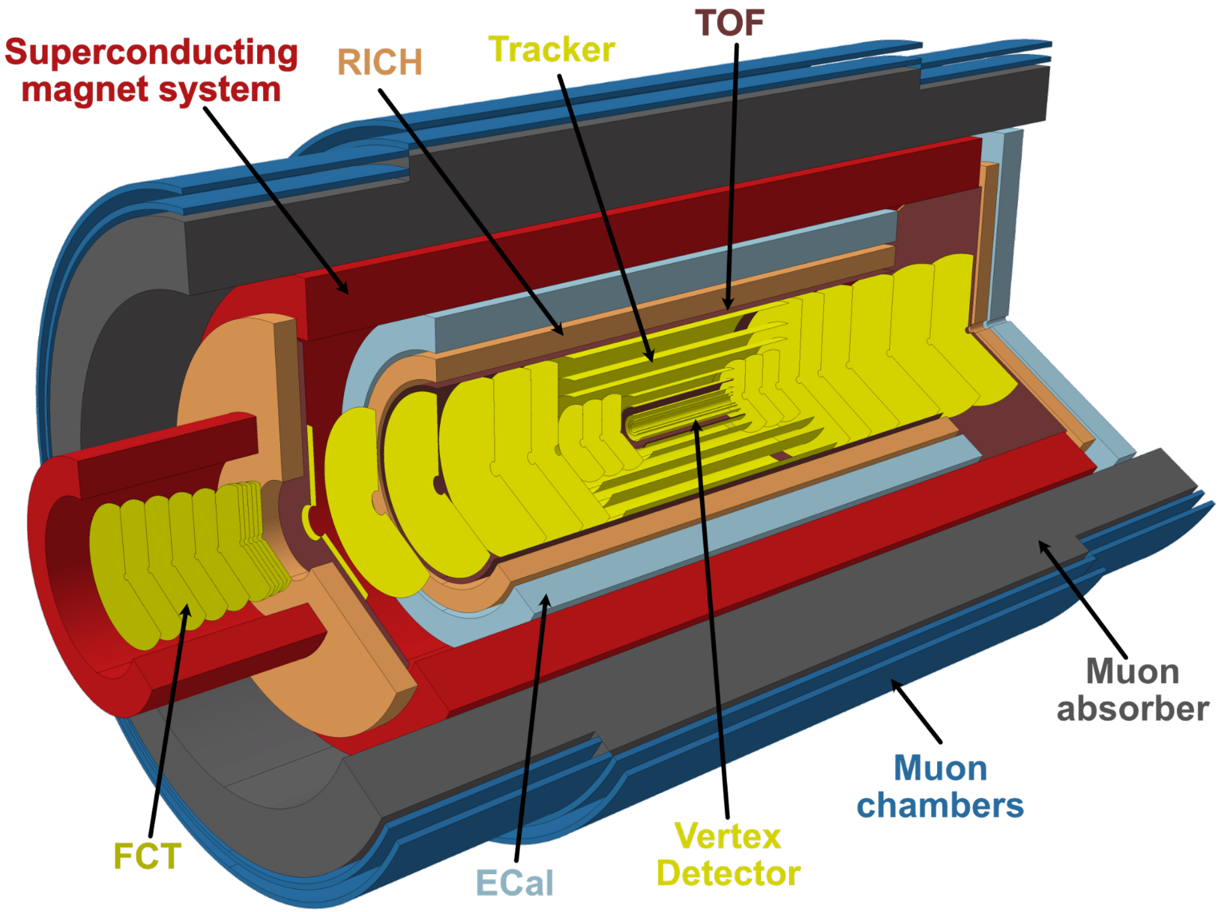
Compact all-silicon tracker with high-resolution vertex detector and **extremely low material budget**

Superconducting magnet system up with B=2 T

Particle Identification over large acceptance: muons, electrons, hadrons, photons at $|\eta| < 4$

Fast read-out and online processing.

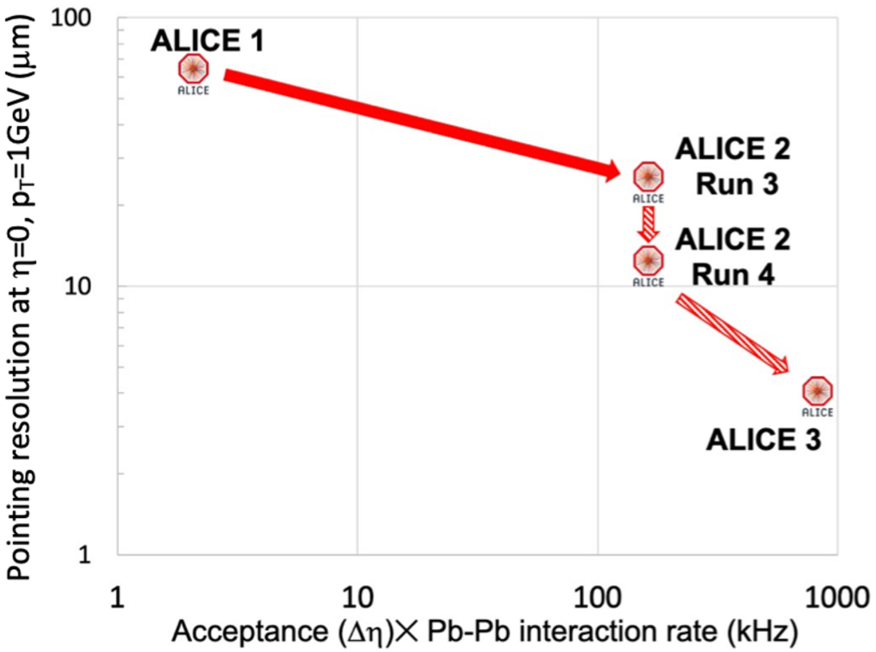
✓ **Starts taking data in 2035**

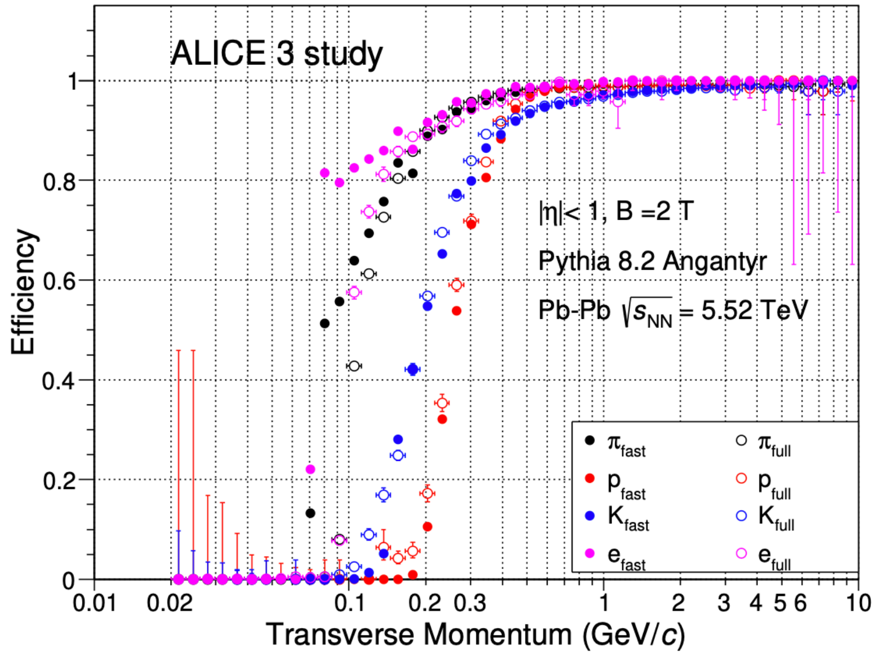


arXiv:2211.02491

ALICE 3 - Expected Luminosities & Performance

System	$\mathscr{L}^{\text{month}}$	$\mathscr{L}^{\text{Run5+6}}$
pp	0.5 fb^{-1}	18 fb^{-1}
pp reference	100 pb^{-1}	200 pb^{-1}
A–A		
Xe–Xe	26 nb^{-1}	156 nb^{-1}
Pb–Pb	5.6 nb^{-1}	33.6 nb^{-1}





Will collect **all ion luminosity provided by LHC** - 100s billions of A-A events!

✓Factor 3 improvement in pointing resolution compared to ALICE in Run 4

✓Momentum resolution 1-2% over broad **0.1 < p_T < 100 GeV/c** and **|η| < 4** ranges

ALICE 3 - Vertex detector and inner tracking

Pointing resolution (σ_{DCA}) of tracks to vertex **few µm** at 1 GeV/c

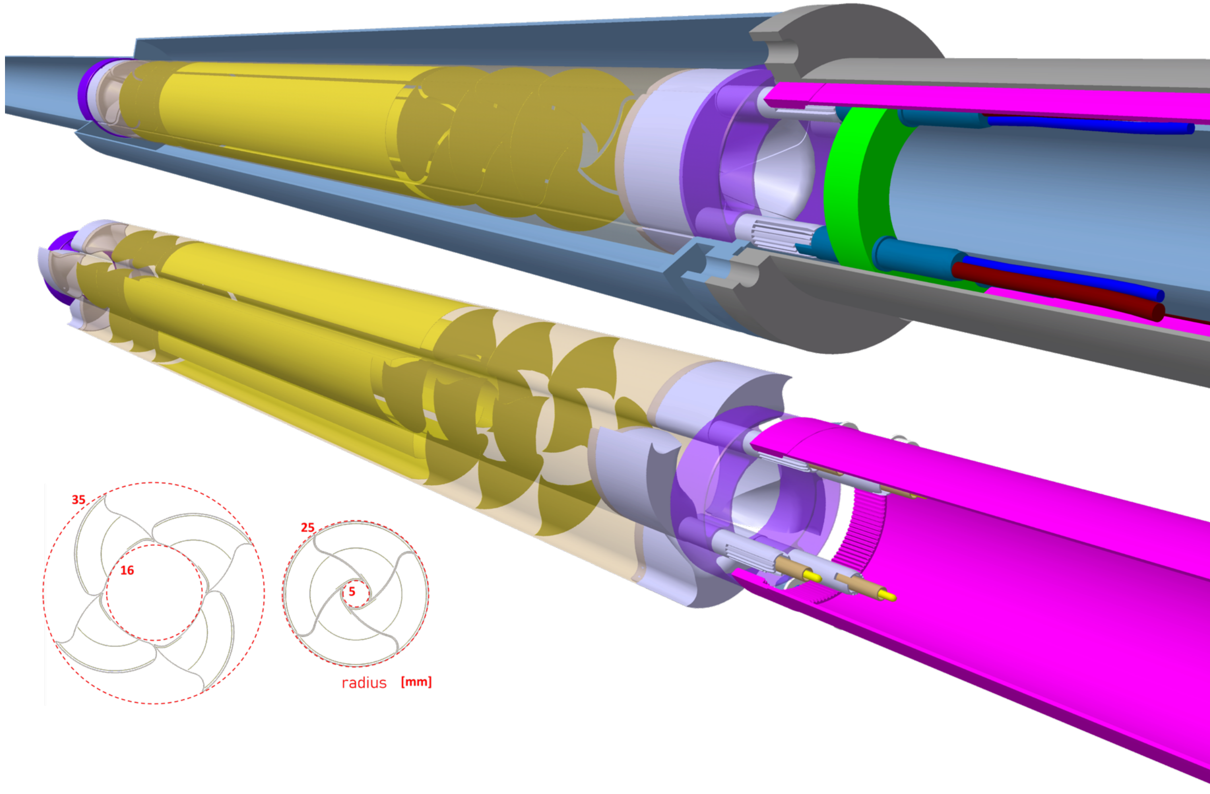
Achieved by placing retractable vertex detector 5 mm (r_0) away from beam

Vertex detector has **3 tracker layers**

✓ Material thickness (X) 0.1% of radiation length (X_0)

✓ CMOS Monolithic Active Pixel Sensors (MAPS): curved, thin, large-area, low power

✓ Intrinsic resolution 2.5 µm



$$\sigma_{DCA} \propto r_0 \cdot \sqrt{X/X_0 \cdot \cosh\eta} \cdot \frac{1}{p}.$$

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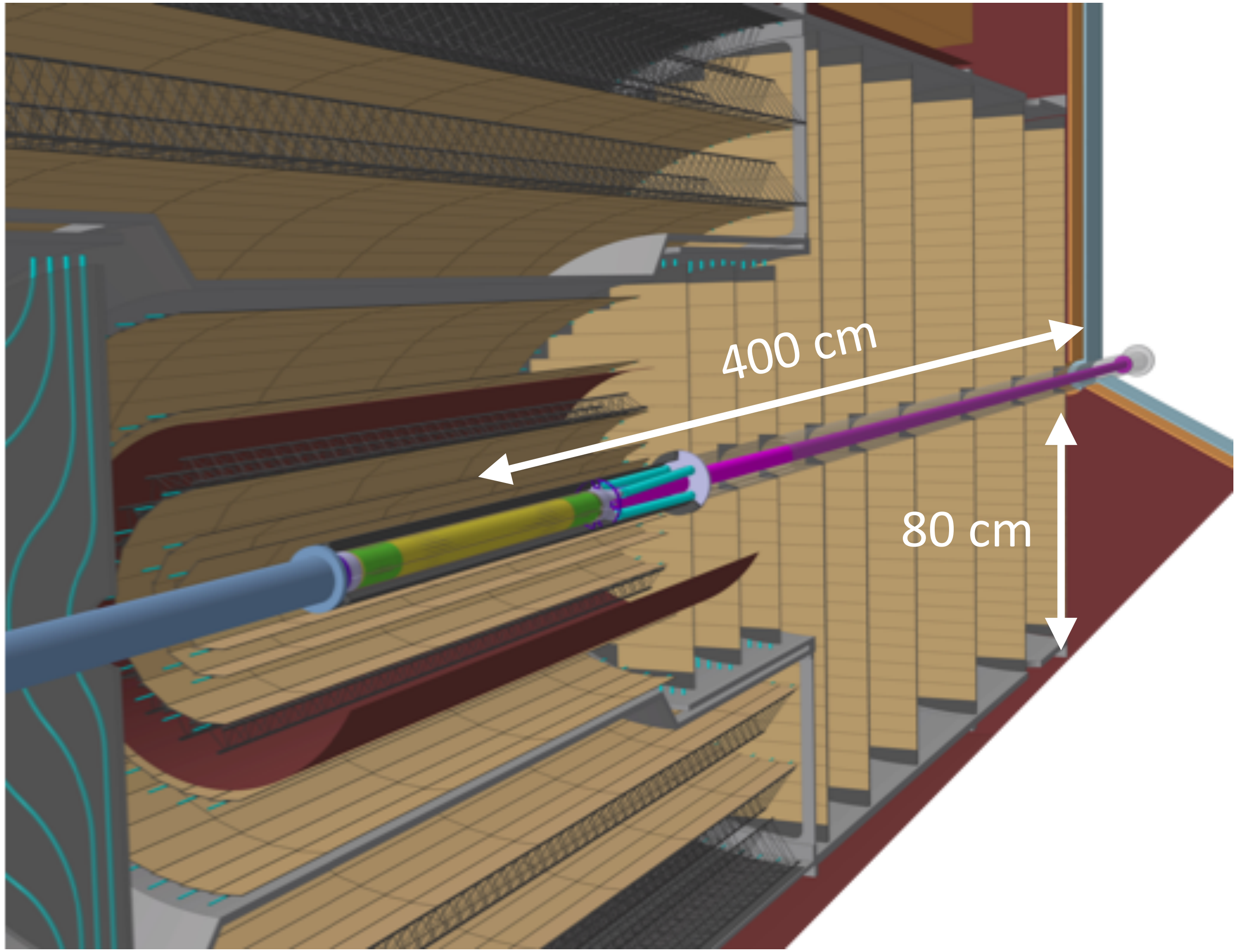
ALICE 3 - Outer tracker



60 m² silicon pixel detector

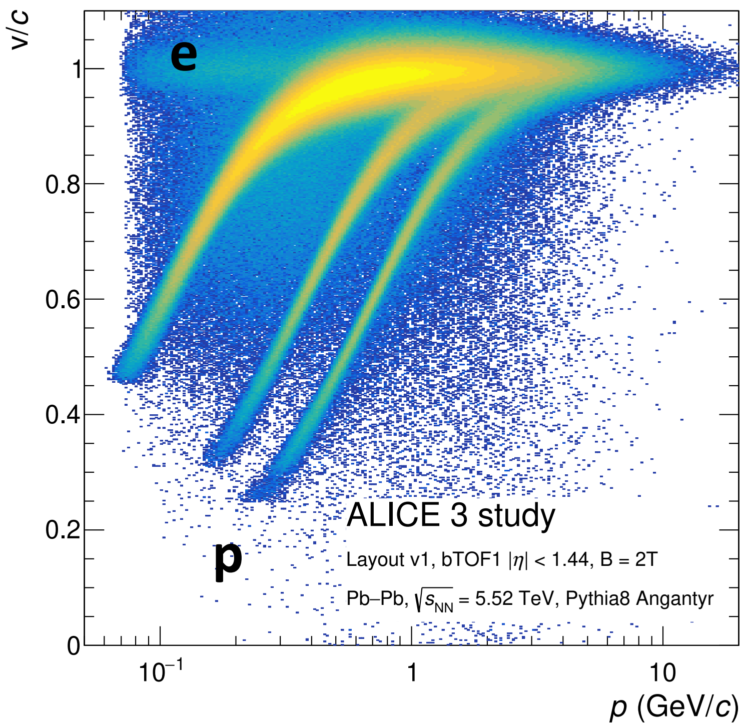
Outer tracker compact and has **8 barrel layers, 9 forward discs**

- ✓ R_{out} = 80 cm, z_{out} ± 400 cm
- ✓ Pixel size ~ 50x50 μm²
- ✓ Pixel resolution ~10 μm
- ✓ X/X_0 ~ 1%

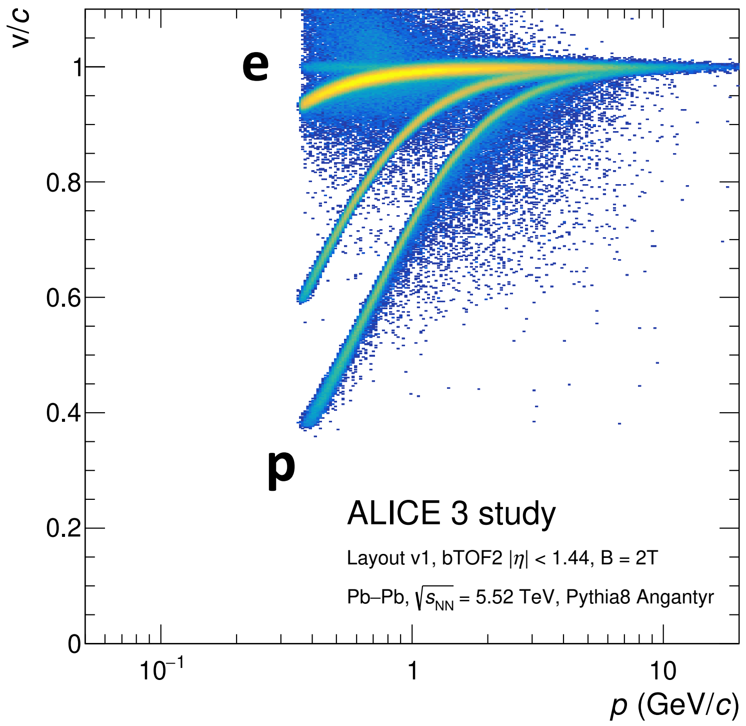
Both inner and outer trackers will build on on **experience with ITS2 and ITS3**

ALICE 3 - Particle Identification

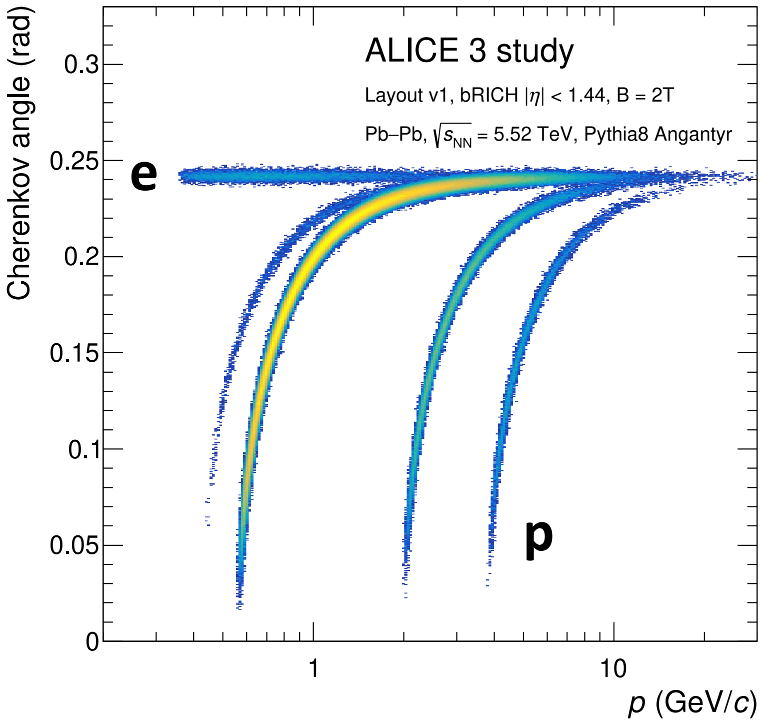
Inner TOF, R = 20 cm



Outer TOF, R = 85 cm



RICH, R =90cm



e, π, K, p separation with TOF + RICH detectors, with specifications $\sigma_{time} < 20$ ps, $\sigma_{\theta} < 1.5$ mrad

✓Endcap TOF and RICH for full η coverage

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Full ALICE 3 detector requirements

Component	Observables	Barrel ($\|\eta\| < 1.75$)	Forward ($1.75 < \|\eta\| < 4$)	Detectors
Vertexing	(Multi-)charm baryons, dielectrons	Best possible DCA resolution, $\sigma_{DCA} \approx 10\,\mu m$ at $p_T = 200\,MeV/c$, $\eta = 0$	Best possible DCA resolution, $\sigma_{DCA} \approx 30\,\mu m$ at $p_T = 200\,MeV/c$, $\eta = 3$	retractable Si-pixel tracker: $\sigma_{pos} \approx 2.5\,\mu m$, $R_{in} \approx 5\,mm$, $X/X_0 \approx 0.1\,\%$ for first layer
Tracking	(Multi-)charm baryons, dielectrons, photons ...	$\sigma_{p_T}/p_T \approx 1--2\,\%$		Silicon pixel tracker: $\sigma_{pos} \approx 10\,\mu m$, $R_{out} \approx 80\,cm$, $L \approx \pm 4\,m$ $X/X_0 \approx 1\,\%$ per layer
Hadron ID	(Multi-)charm baryons	$\pi/K/p$ separation up to a few GeV/c		Time of flight: $\sigma_{tof} \approx 20\,ps$ RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,mrad$
Electron ID	Dielectrons, quarkonia, $\chi_{c1}(3872)$	pion rejection by 1000x up to 2–3 GeV/c		Time of flight: $\sigma_{tof} \approx 20\,ps$ RICH: $n \approx 1.006 - 1.03$, $\sigma_\theta \approx 1.5\,mrad$
Muon ID	Quarkonia, $\chi_{c1}(3872)$	reconstruction of J/ψ at rest, i.e. muons from $p_T \sim 1.5\,GeV/c$ at $\eta = 0$		steel absorber: $L \approx 70\,cm$ muon detectors
ECal	Photons, jets	large acceptance		Pb-Sci sampling calorimeter
ECal	χ_c	high-resolution segment		$PbWO_4$ calorimeter
Soft photon detection	Ultra-soft photons		measurement of photons in p_T range 1–50 MeV/c	Forward conversion tracker based on silicon pixel tracker

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ALICE 3 Planning

2022: Letter of Intent reviewed by LHCC → Very strong support

2023-25: Selection of technologies, small-scale proof of concept prototypes

2026-27: Large-scale engineered prototypes → Technical Design Reports

2028-31: Construction and testing

2032: Contingency

2033-34: Preparation of cavern and installation

2035-41: Run 5 and 6 ALICE 3 physics campaign

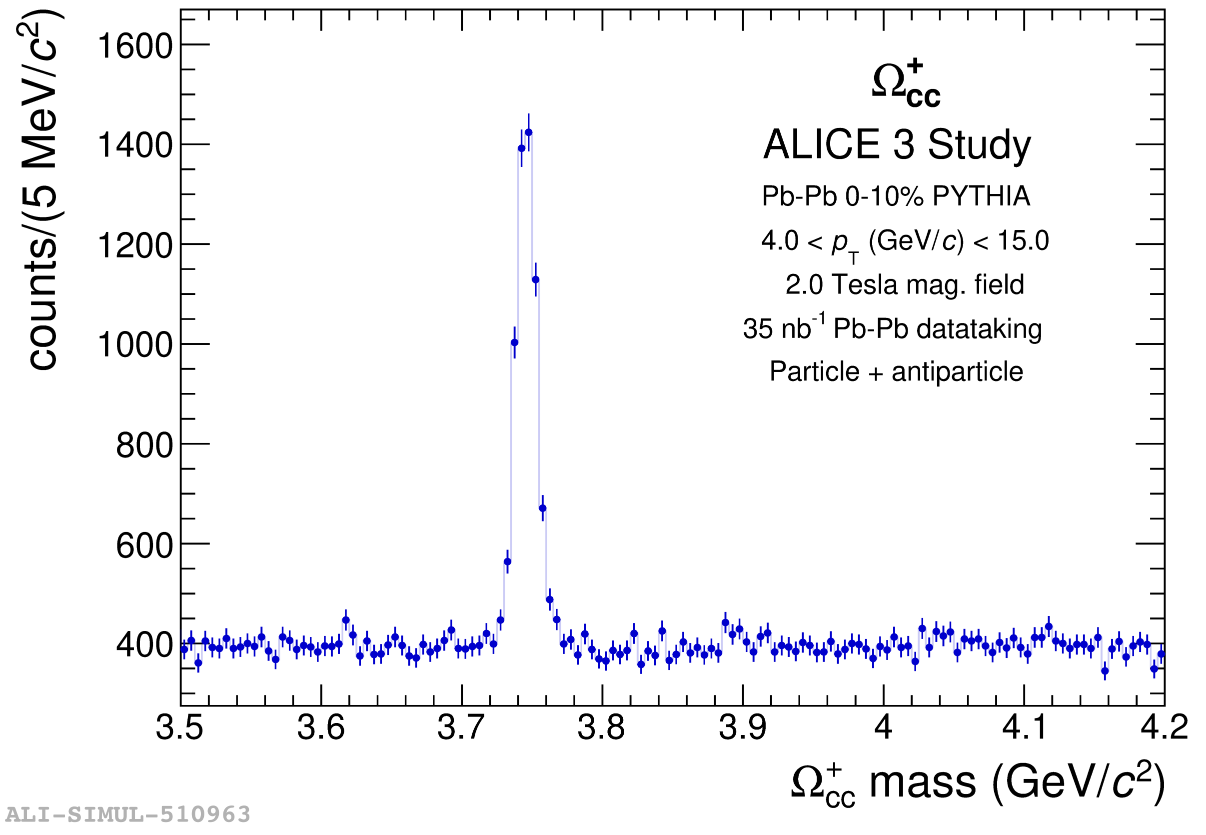
Some physics topics explored with ALICE 3

Can we **learn more** about the **QGP**?

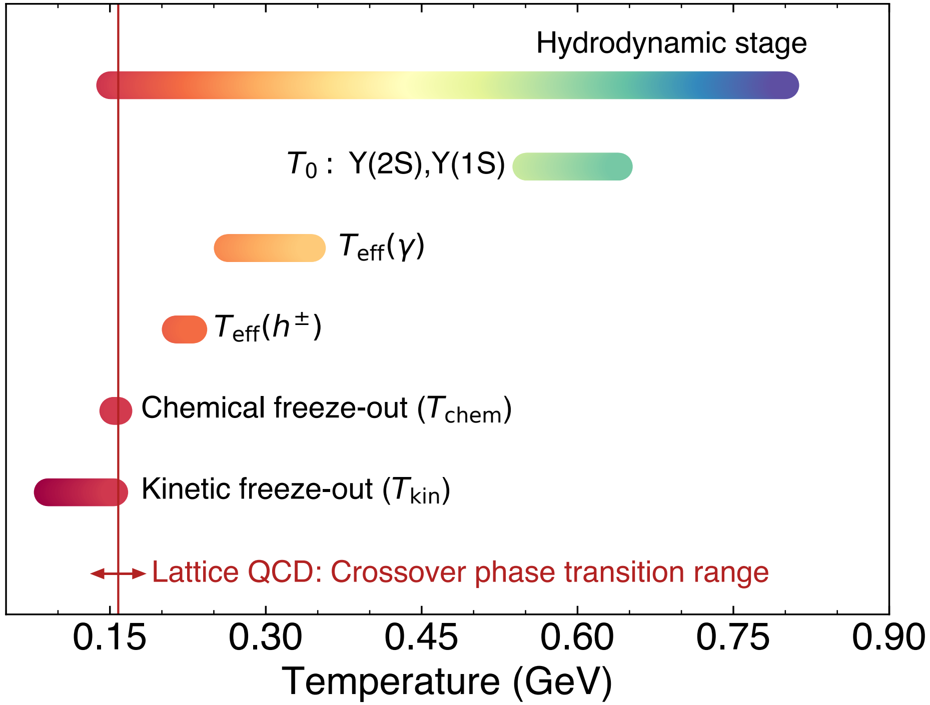
Have we **exhausted** our tests of **fundament QCD**?

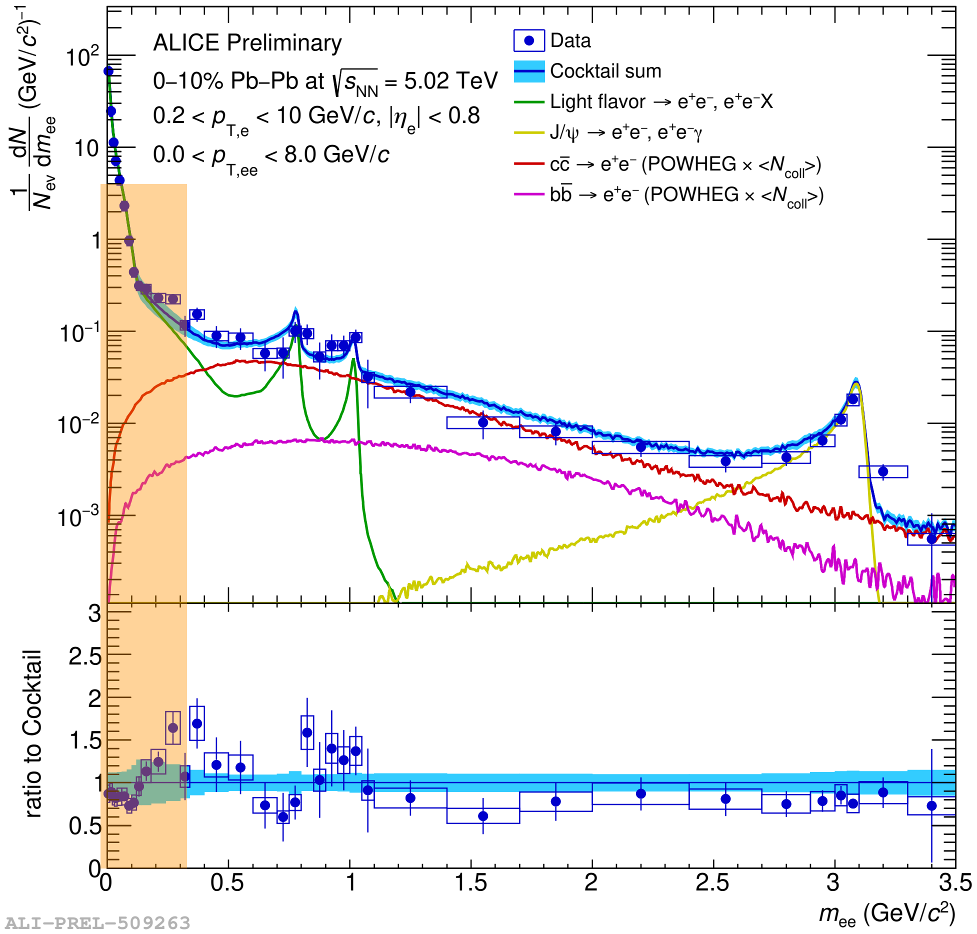
Is there more can we explore regarding **hadronization and hadronic interactions**?

Can we contribute to **Beyond Standard Model searches**?



Temperature of the QGP



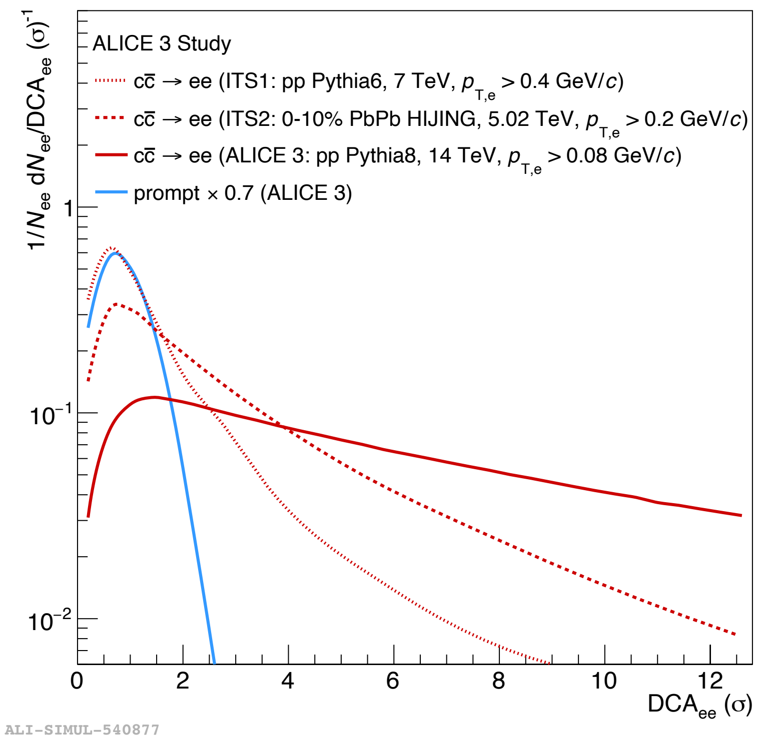


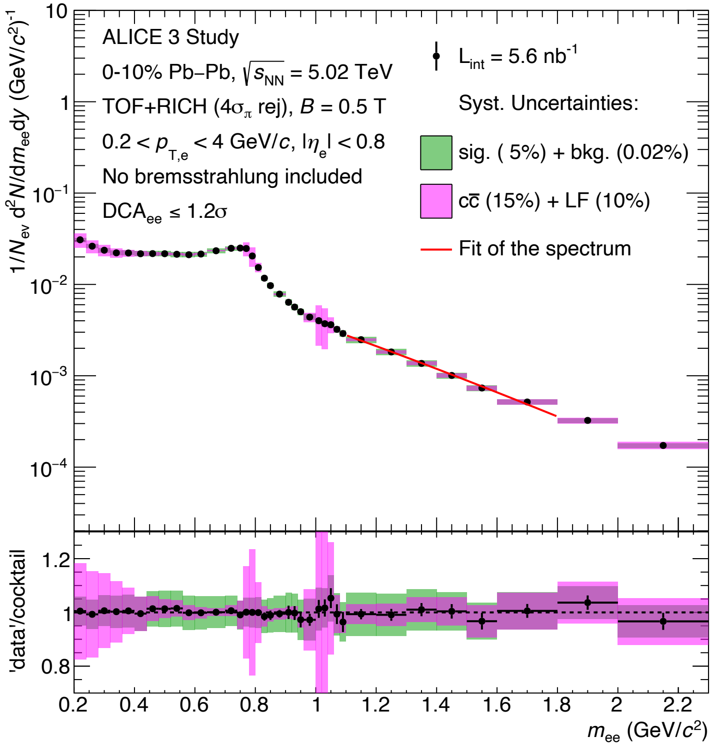
Vast majority of **QGP temperature** estimates from **models** constrained by data

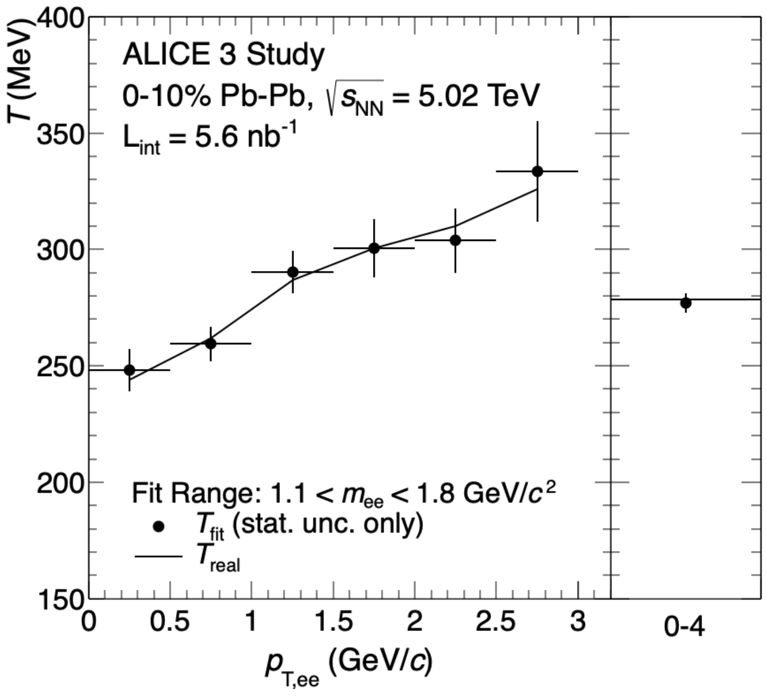
✓ **Photons direct probe** from data, but blue-shifted as QGP is expanding

✓ **Di-electrons best temperature probe** as Lorentz invariant → Very challenging experimentally

Thermal radiation from di-electrons in ALICE 3







Very clean **separation of prompt and heavy-flavor** electrons

✓ **Direct QGP temperatures** from **slope** of intermediate **di-electron invariant mass spectrum**

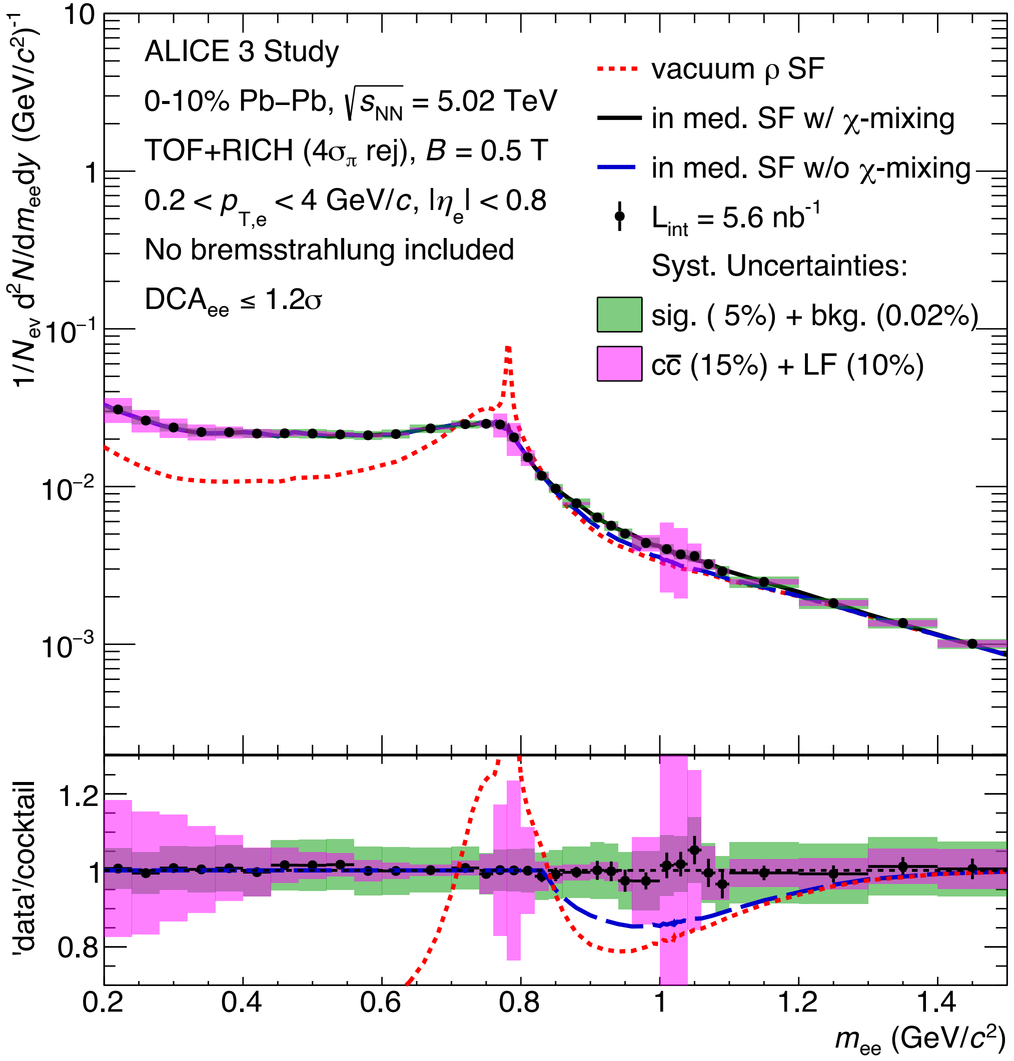
✓ Increasing electron p_T probes earlier times → **Evolution of QGP temperature**

Searches for Chiral Symmetry Restoration

Long sought after evidence of QGP formation

Fundamental feature of high temperature **Lattice QCD**

Onset of exponential at m_{ee} ~ 1 GeV/c²
indicative of **Chiral Symmetry Restoration**
$\rho - a_1$ mixing



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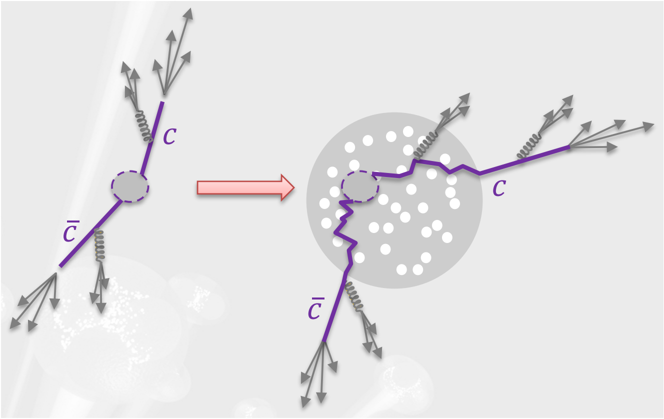
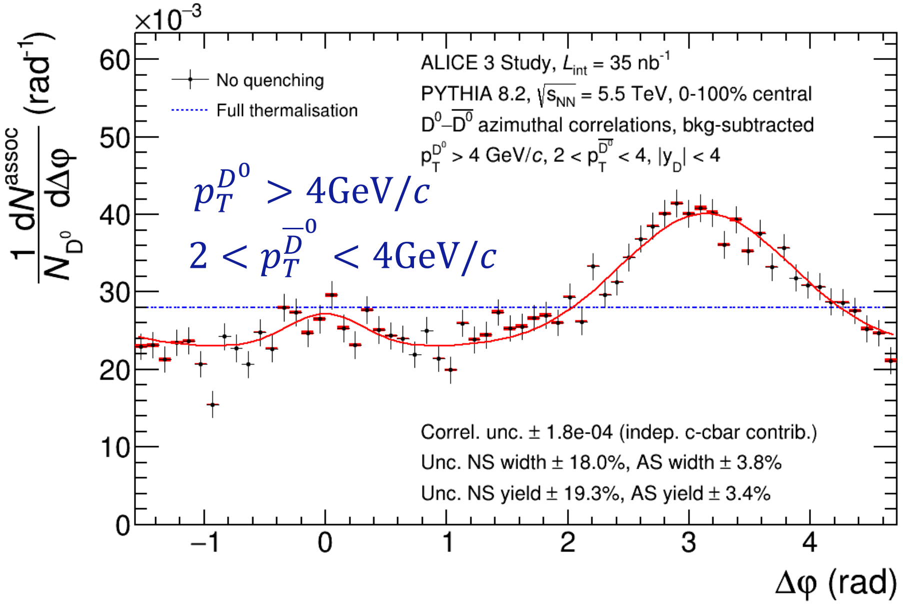
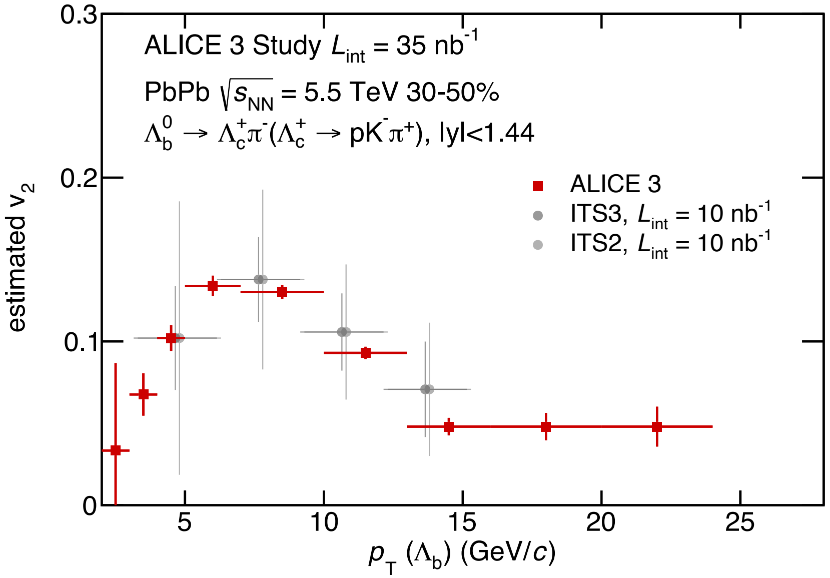
Heavy-flavor interactions in QGP



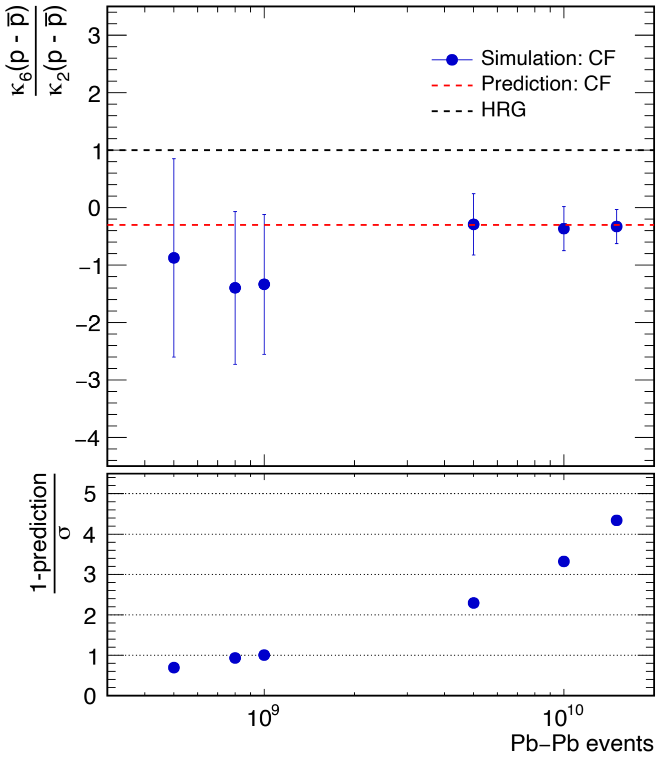


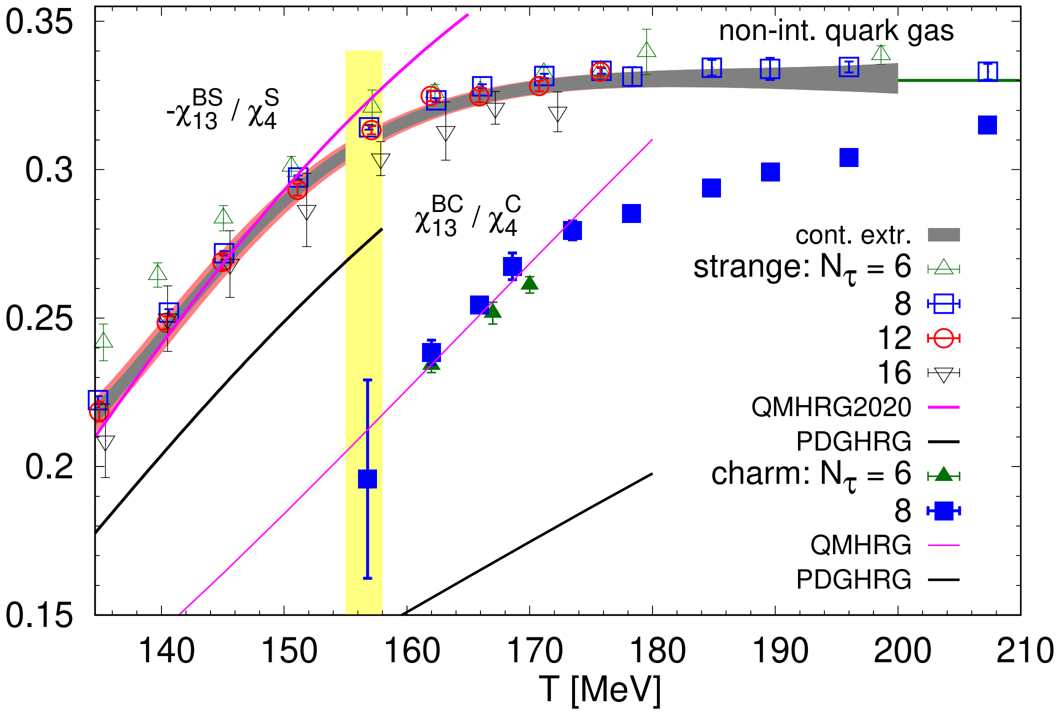


Two-particle **D⁰ correlations** probe microscopic **QGP charm diffusion directly**

Beauty flow provides best constraints on **bottom quark diffusion** & limits on QGP equilibration

New tests of Lattice QCD during QGP transition



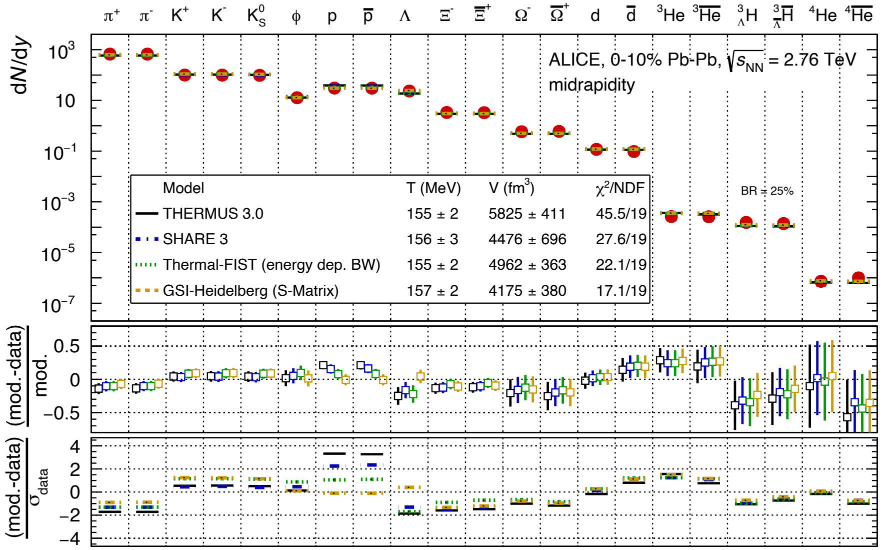


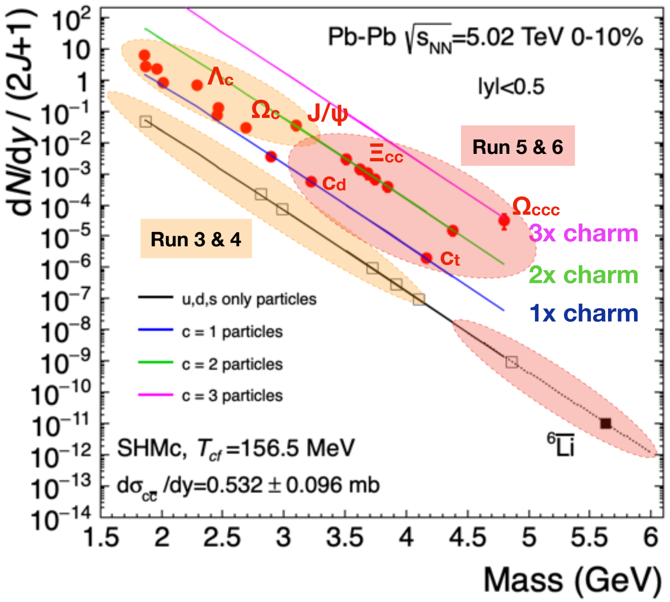
Measured **fluctuations of net-quantum numbers** explore **chiral features of cross-over transition**

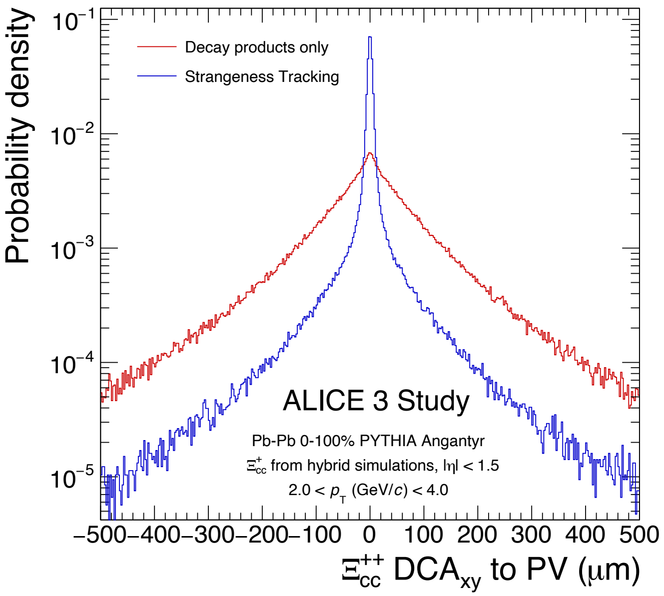
✓ Increased precision of high order net baryon fluctuations and strangeness/charm being explored

✓ Become accessible for the first time

Multi-charm baryon production in ALICE 3





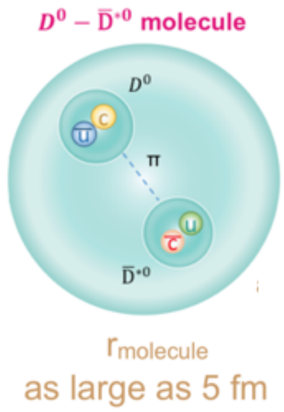


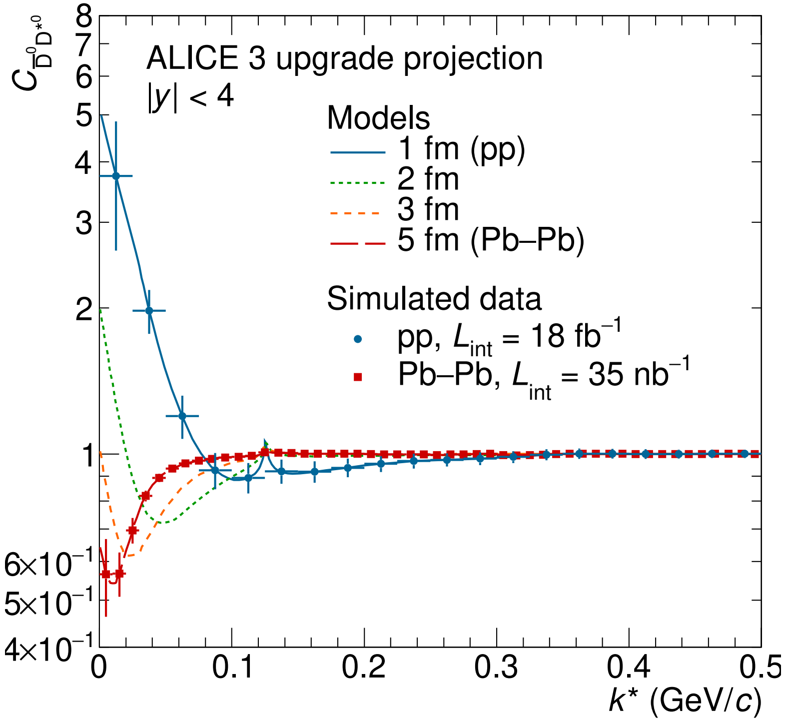
Statistical Hadronization → Example of **emergent behavior in QCD**

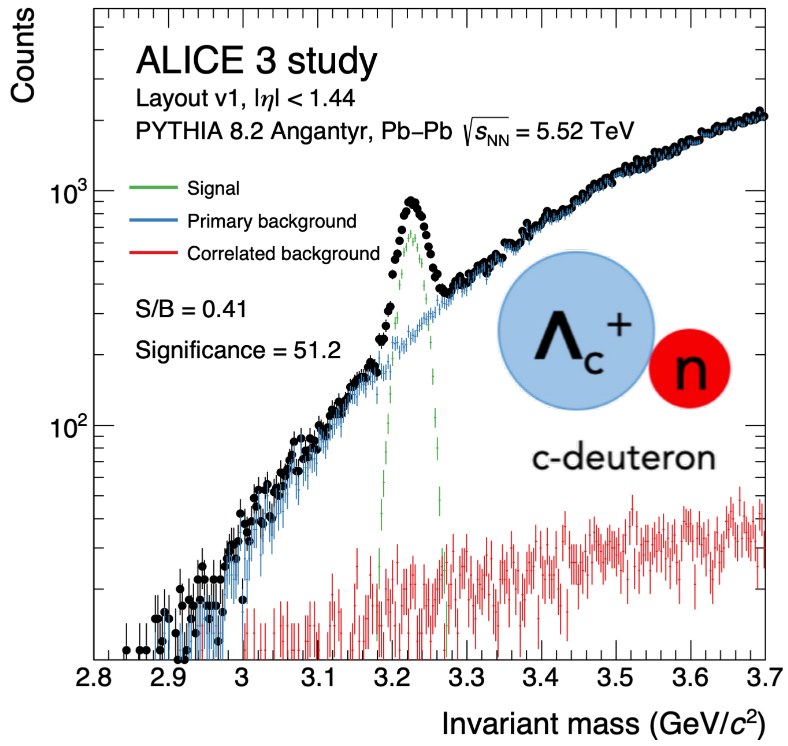
✓ Almost all light flavor hadrons/nuclei yields described by **thermal model** with few parameters

✓ **Open question for charmed hadrons** → unique tests with multi-charmed baryons

Hadronic interactions and exotic nuclei



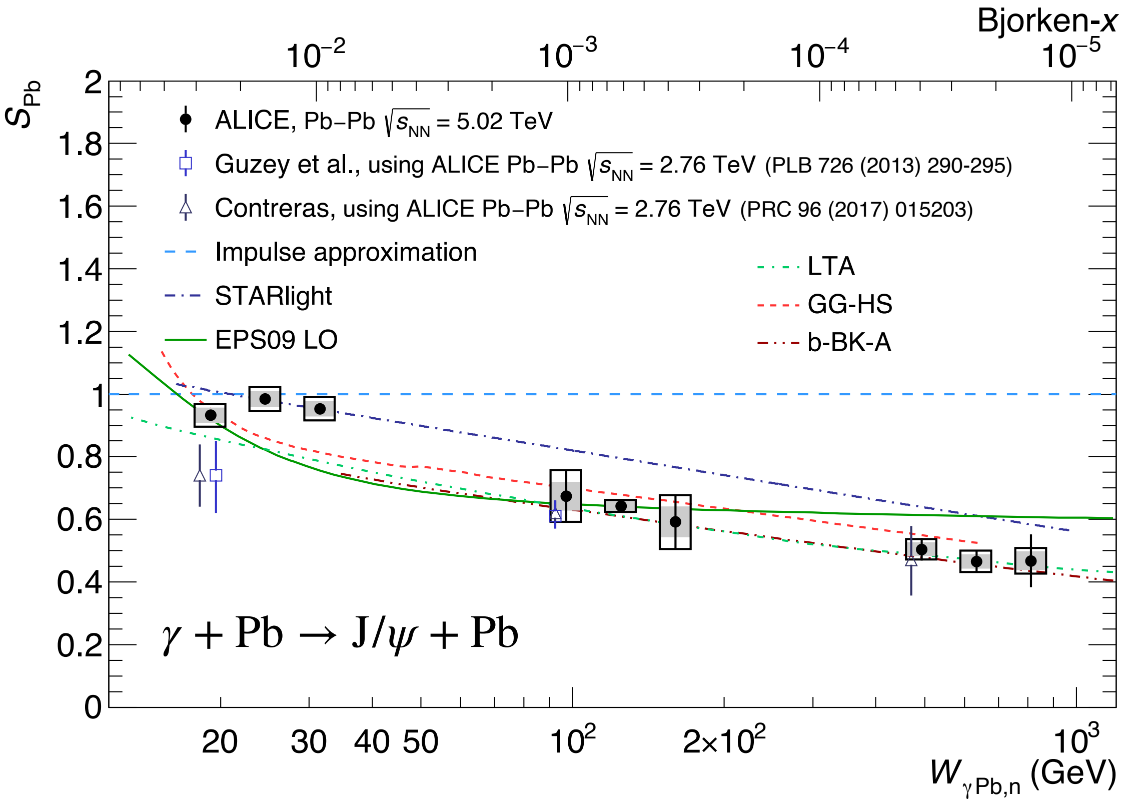




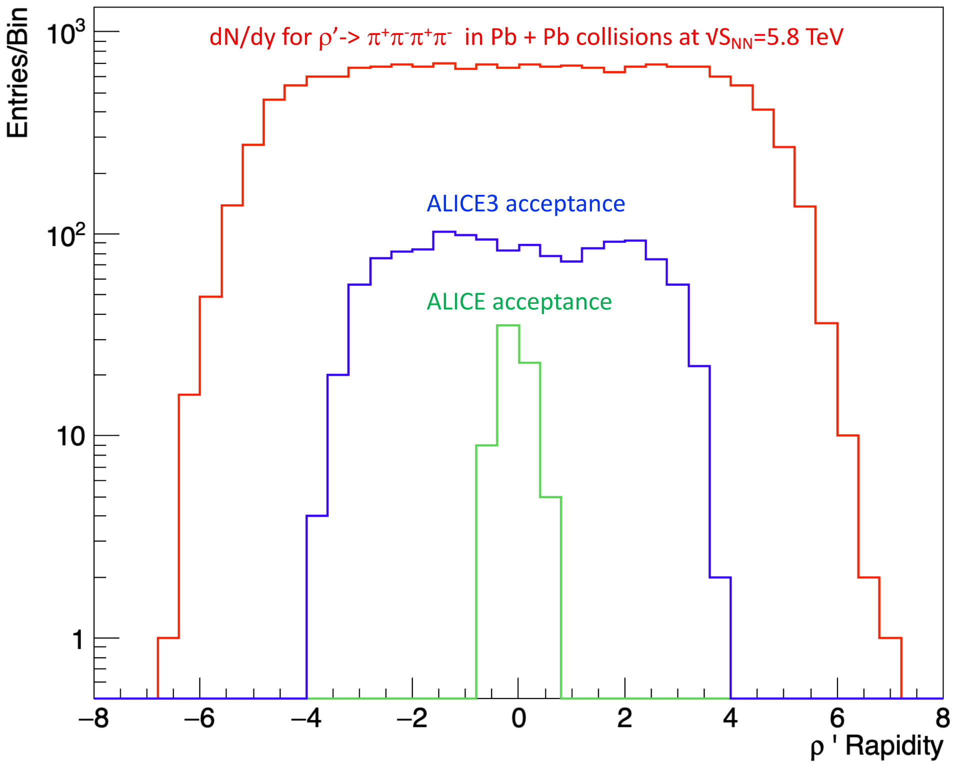
Two particle **D^0** femto correlations can be used to explore formation of **D^0 molecules**

- ✓ Candidate for structure of **exotic T_{cc} hadron**
- ✓ First observation of a **charmed nucleus feasible**

Ultra peripheral collisions (UPCs)



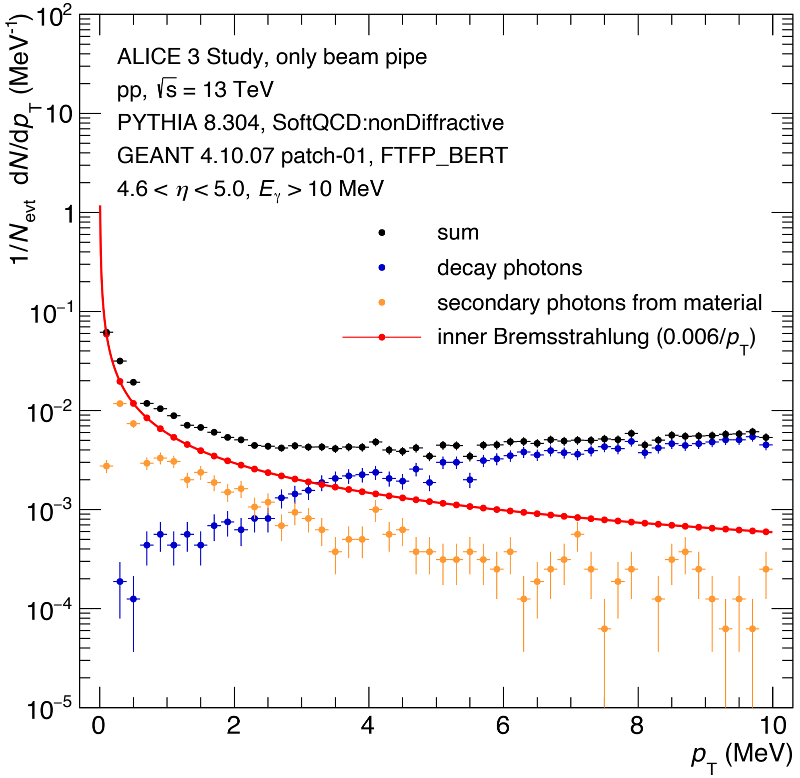
$\gamma + \mathrm{A} \rightarrow \rho' + \mathrm{A}$

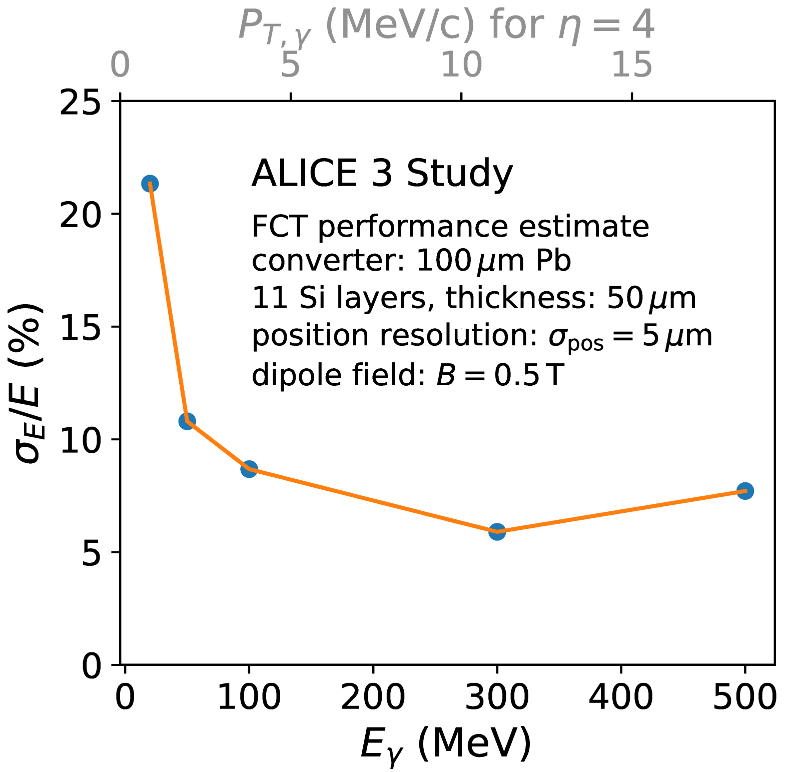


UPCs have emerged as an extremely powerful tool to explore cold nuclear matter (and much more)

- ✓ ALICE 3 provides excellent coverage and reconstruction of complex excited ρ states
- ✓ Hopes to resolve question **whether ρ' is one state or two** (2π & 4π decays)

Ultra soft photon production





Forward Conversion Tracker used to measure ultra-soft photons (few MeV) at forward rapidity (η ~4)

✓ Low's theorem can be used to test **infrared limits of quantum field theories**

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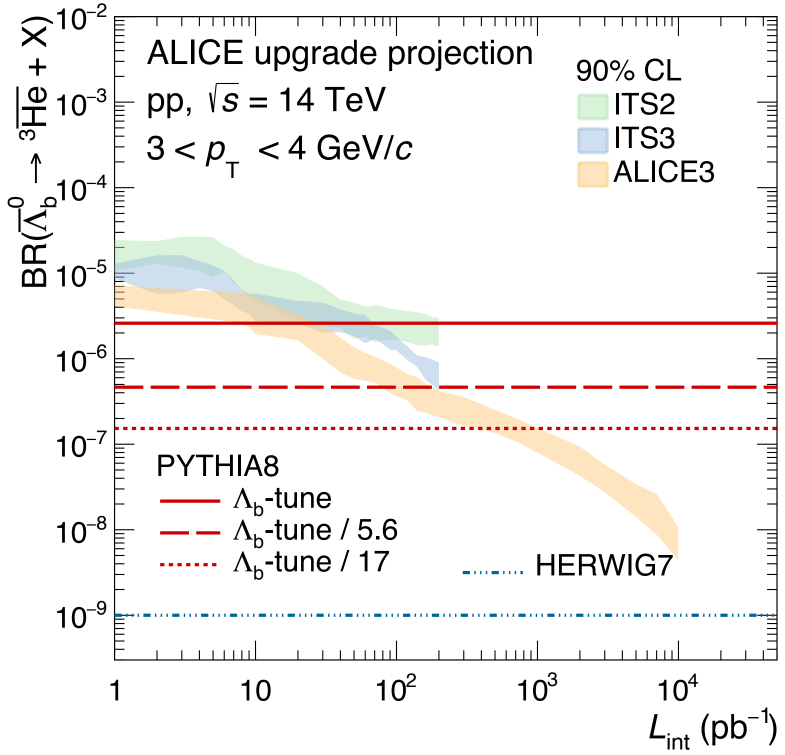
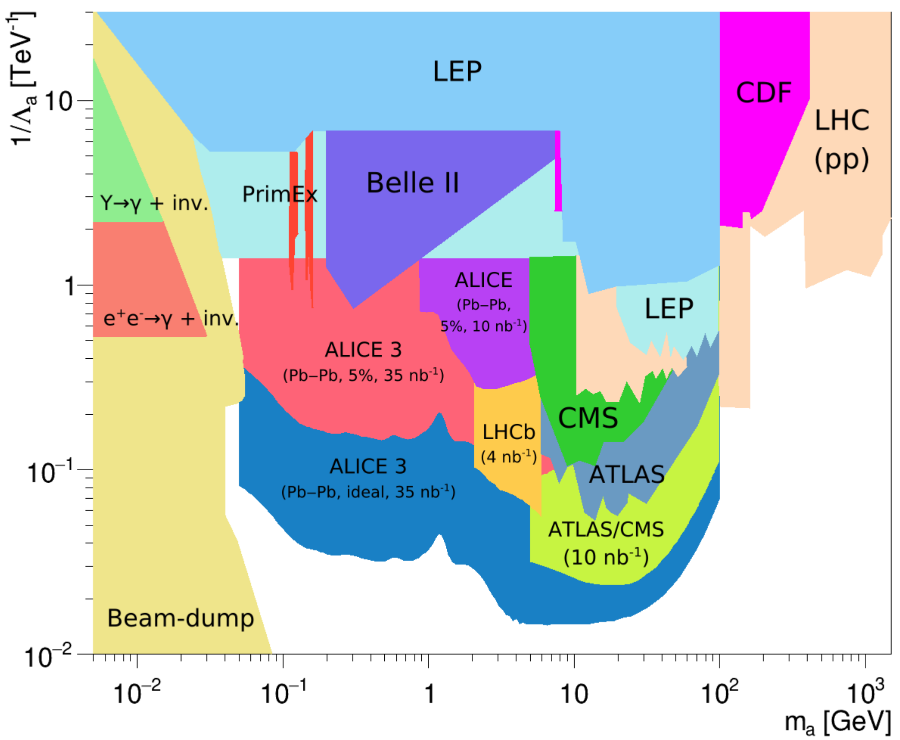
Beyond Standard Model searches





Recent AMS discovery of O(10) **anti-helium nuclei** might be signal of **dark matter production**

- ✓ Excellent constraints on branching ratio from **beauty baryon decay**
- ✓ **Light by light scattering** via UPCs provide **competitive limits on axion searches**

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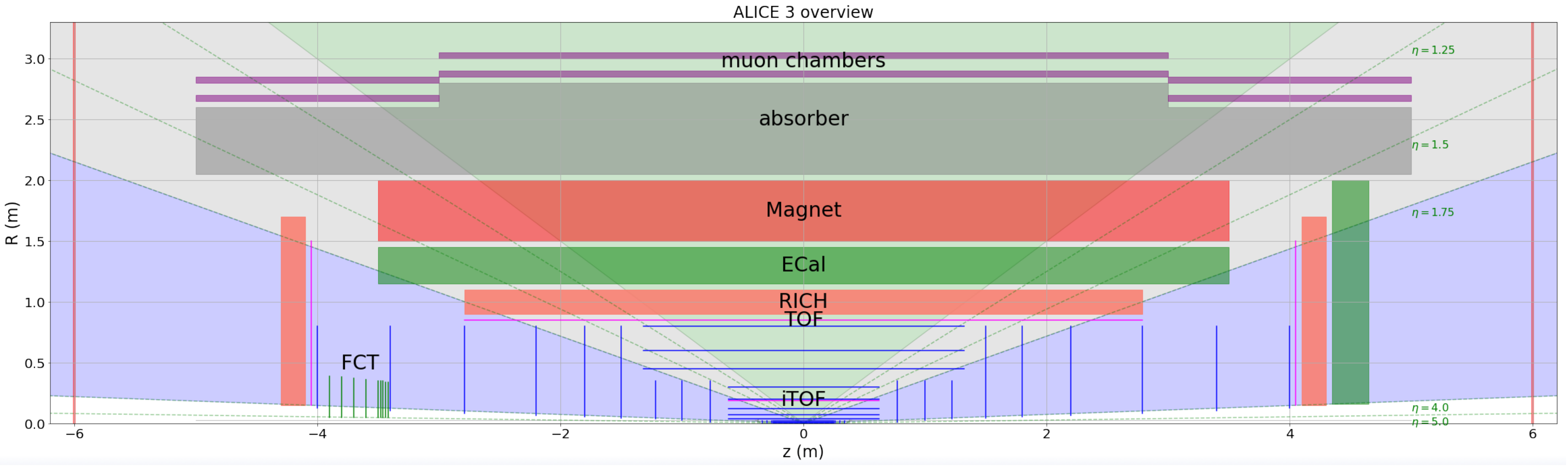
More physics topics opportunities with ALICE 3



See ALICE-USA white paper for more ideas!

Large η and p_{T} acceptance + excellent PID enable (for example):

- ✓ **Heavy-flavor jet correlations** or **photon-heavy-flavor jet correlations** with unprecedented purity at low transverse momentum scales
- ✓ Two-particle correlations with **large $\Delta\eta$ to probe early time dynamics and diffusion**

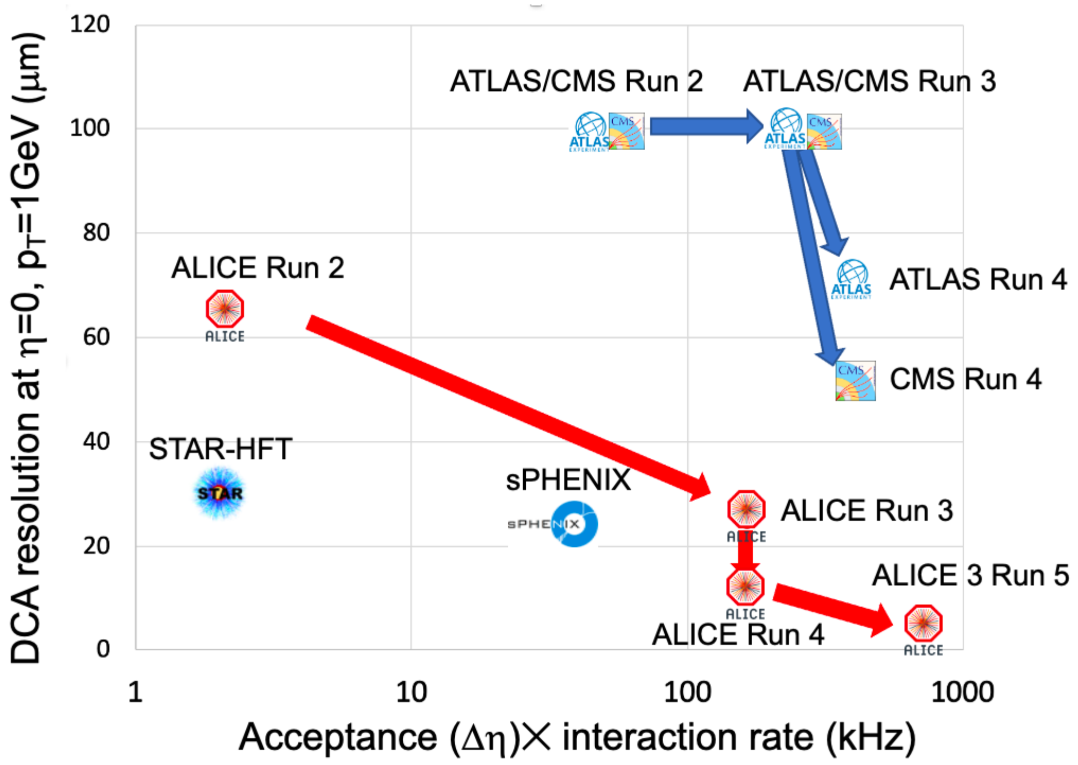
Summary

ALICE 3 opens **new era of discovery potential and precision in QCD**

Designed by heavy-ion physicists for heavy-ion physics

✓ Extremely versatile setup allows for **very broad physics program within and beyond QCD**

Continues hugely successful endeavor of pushing the **world's most powerful microscopes to new limits**

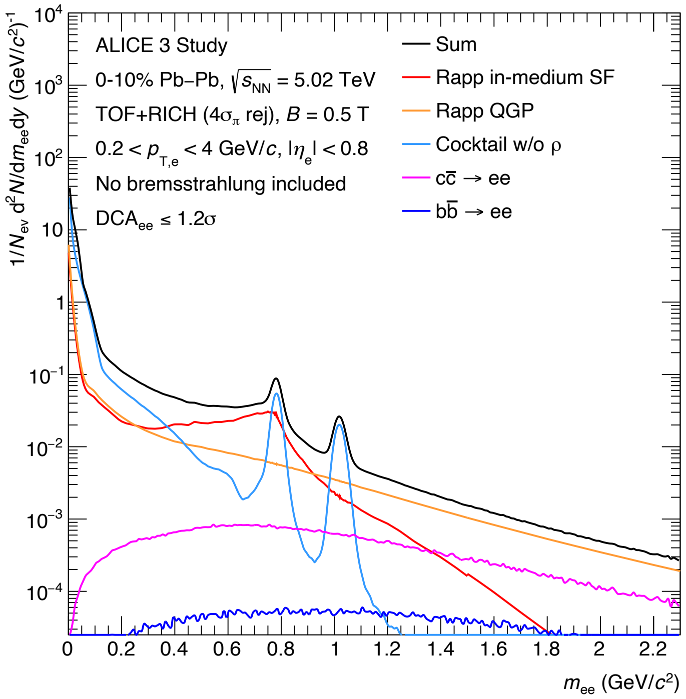


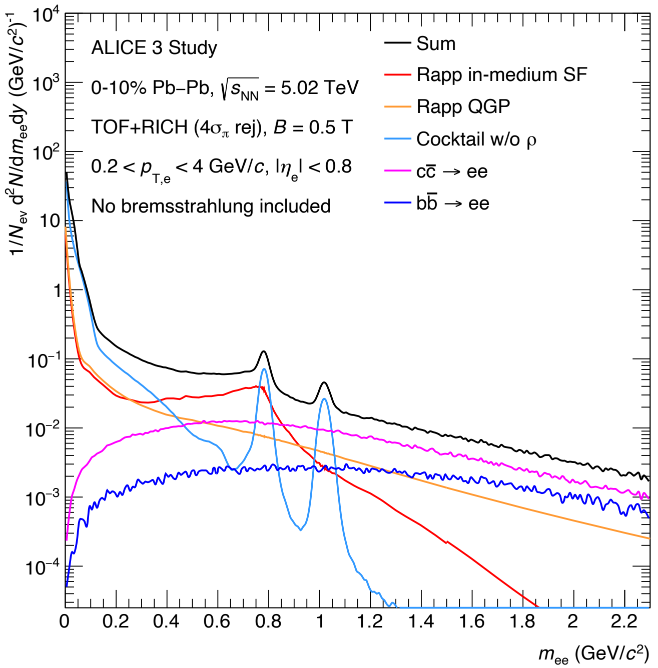
Quantity	pp	O–O	Ar–Ar	Ca–Ca	Kr–Kr	In–In	Xe–Xe	Pb–Pb
$\sqrt{s_{NN}}$ (TeV)	14.00	7.00	6.30	7.00	6.46	5.97	5.86	5.52
L_{AA} ($cm^{-2}s^{-1}$)	3.0×10^{32}	1.5×10^{30}	3.2×10^{29}	2.8×10^{29}	8.5×10^{28}	5.0×10^{28}	3.3×10^{28}	1.2×10^{28}
$\langle L_{AA} \rangle$ ($cm^{-2}s^{-1}$)	3.0×10^{32}	9.5×10^{29}	2.0×10^{29}	1.9×10^{29}	5.0×10^{28}	2.3×10^{28}	1.6×10^{28}	3.3×10^{27}
$\mathscr{L}_{AA}^{month}$ (nb^{-1})	5.1×10^{5}	1.6×10^{3}	3.4×10^{2}	3.1×10^{2}	8.4×10^{1}	3.9×10^{1}	2.6×10^{1}	5.6
$\mathscr{L}_{NN}^{month}$ (pb^{-1})	505	409	550	500	510	512	434	242
R_{max} (kHz)	24 000	2169	821	734	344	260	187	93
μ	1.2	0.21	0.08	0.07	0.03	0.03	0.02	0.01
$dN_{ch}/d\eta$ (MB)	7	70	151	152	275	400	434	682
				at $R = 0.5$ cm				
R_{hit} (MHz/cm^2)	94	85	69	62	53	58	46	35
NIEL (1 MeV n_{eq}/cm^2)	1.8×10^{14}	1.0×10^{14}	8.6×10^{13}	7.9×10^{13}	6.0×10^{13}	3.3×10^{13}	4.1×10^{13}	1.9×10^{13}
TID (Rad)	5.8×10^{6}	3.2×10^{6}	2.8×10^{6}	2.5×10^{6}	1.9×10^{6}	1.1×10^{6}	1.3×10^{6}	6.1×10^{5}
				at $R = 100$ cm				
R_{hit} (kHz/cm^2)	2.4	2.1	1.7	1.6	1.3	1.0	1.1	0.9
NIEL (1 MeV n_{eq}/cm^2)	4.9×10^{9}	2.5×10^{9}	2.1×10^{9}	2.0×10^{9}	1.5×10^{9}	8.3×10^{8}	1.0×10^{9}	4.7×10^{8}
TID (Rad)	1.4×10^{2}	8.0×10^{1}	6.9×10^{1}	6.3×10^{1}	4.8×10^{1}	2.7×10^{1}	3.3×10^{1}	1.5×10^{1}

Table 1: Projected LHC performance: For various collision systems, we list the peak luminosity L_{AA}, the average luminosity $\langle L_{AA} \rangle$, the luminosity integrated per month of operation $\mathscr{L}_{AA}^{month}$, also rescaled to the nucleon–nucleon luminosity $\mathscr{L}_{NN}^{month}$ (multiplying by A^2). Furthermore, we list the maximum interaction rate R_{max}, the minimum bias (MB) charged particle pseudorapidity density $dN/d\eta$, and the interaction probability μ per bunch crossing. For the radii 0.5 cm and 1 m, we also list the particle fluence, the non-ionising energy loss, and the total ionising dose per operational month (assuming a running efficiency of 65%).

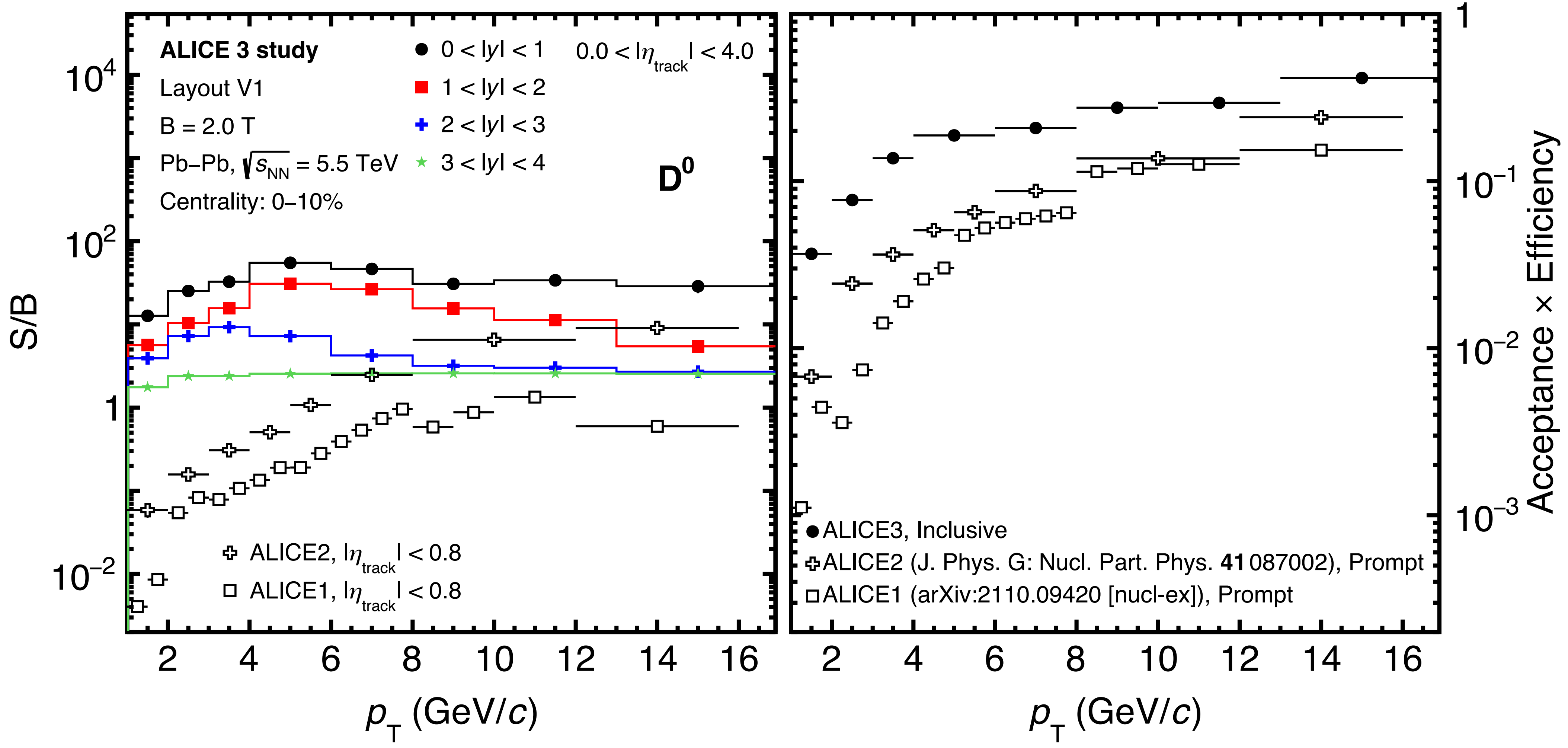
Backup - Kinematics and di-electrons

Observables	Kinematic range
Heavy-flavour hadrons	$p_T \to 0$, $\|\eta\| < 4$
Dielectrons	$p_T \approx 0.05$ to $3\,\mathrm{GeV}/c$, $M_{ee} \approx 0.05$ to $4\,\mathrm{GeV}/c^2$
Photons	$p_T \approx 0.1$ to $50\,\mathrm{GeV}/c$, $-2 < \eta < 4$
Quarkonia and exotica	$p_T \to 0$, $\|\eta\| < 1.75$
Ultrasoft photons	$p_T \approx 1$ to $50\,\mathrm{MeV}/c$, $3 < \eta < 5$
Nuclei	$p_T \to 0$, $\|\eta\| < 4$





Backup - D meson



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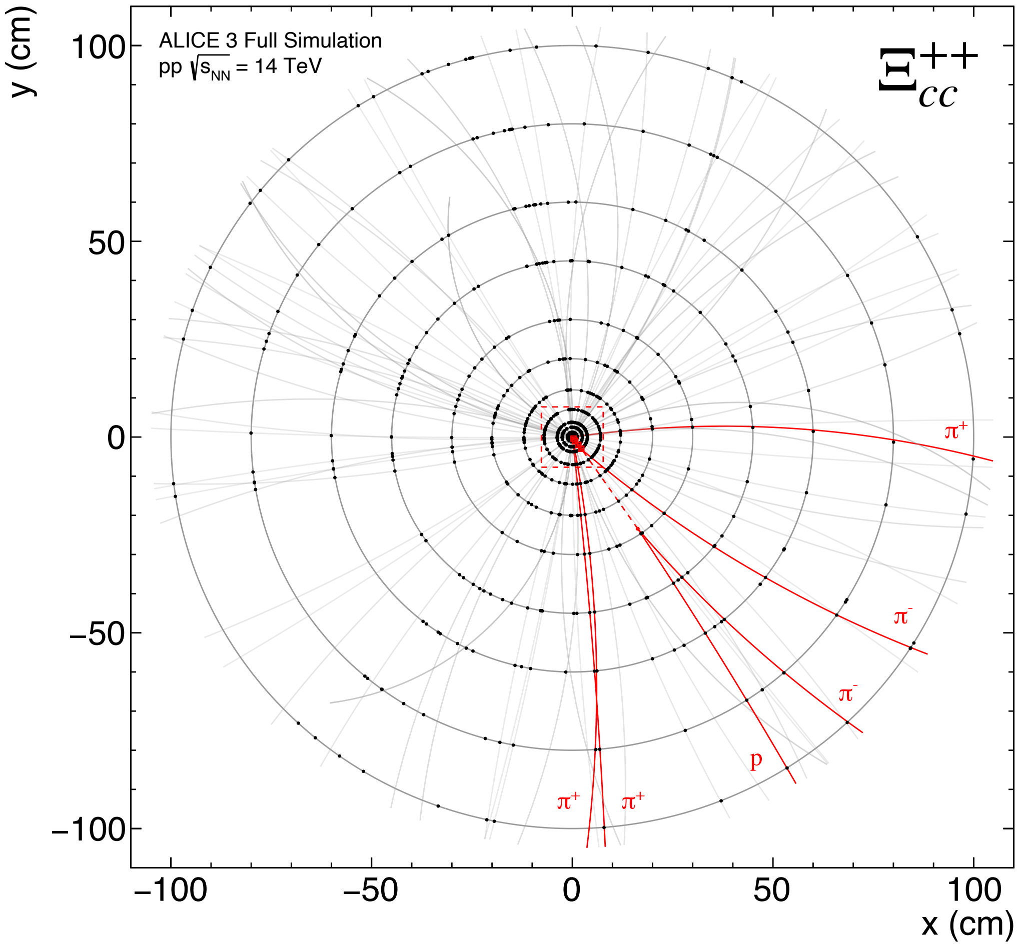
Backup - Multi-charm baryons

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	$p + K^- + \pi^+$	$(6.2 \pm 3.0)10^{-3}$

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.



Backup - Multi-charm baryons