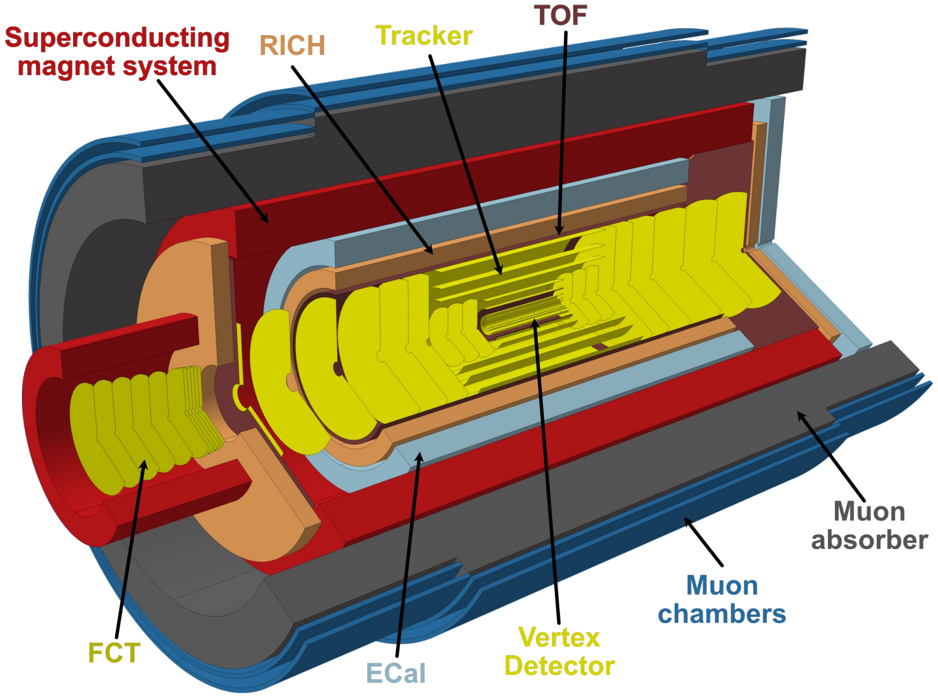
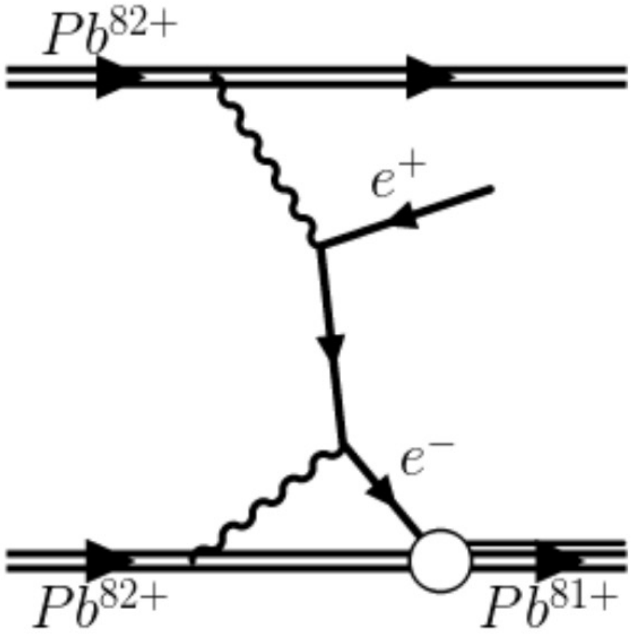
The nuclear program beyond LHC Run 4





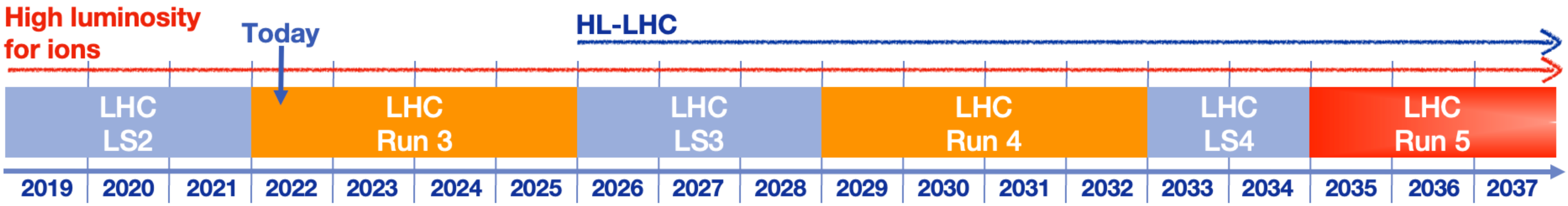
Alexander Kalweit (CERN)

Deciphering nuclear phenomenology across energy scales, 23rd September 2022

The long term LHC schedule (1)

Many thanks to M. v. Leeuwen & J. Klein for providing most of the slides for this talk!

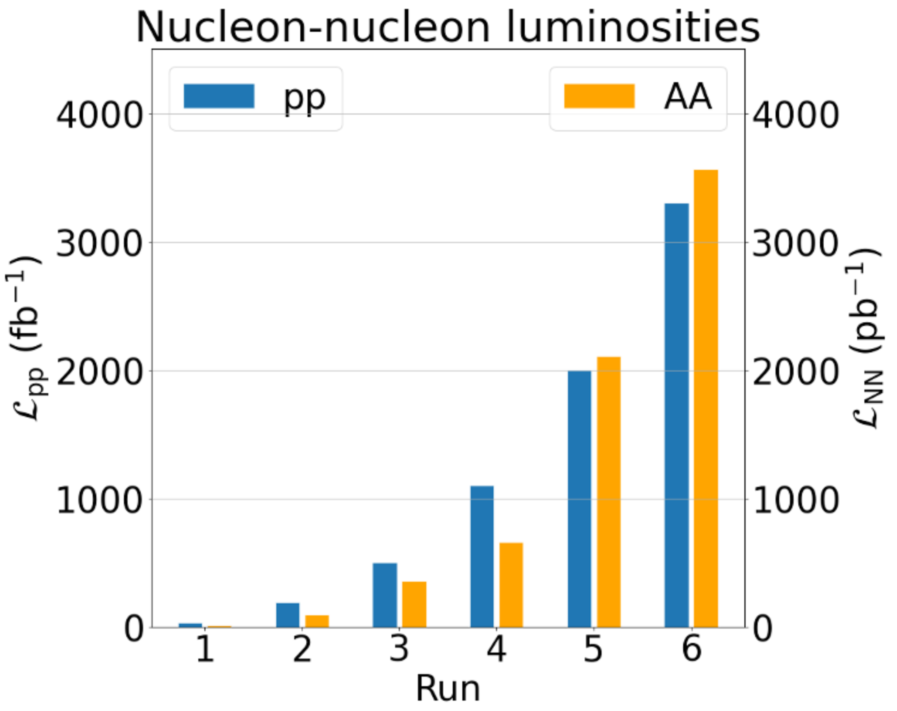
- The European strategy for particle physics recommends the full exploitation the LHC including its heavy-ion program.
- A new era for heavy-ion physics at the LHC is about to start: the completion of the ALICE upgrades in LS2 (ALICE 2) together with high intensity Pb-ion running will allow to collect 100x the min bias statistics with respect to Run 1 & 2 at unprecedented precision.
- For the pp community, the big game changer will come in 2029 with the High Luminosity LHC operation (HL-LHC) after the completion of the Phase II upgrades in ATLAS and CMS.



The long term LHC schedule (2)

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	Run 1 2009 - 2013	Run 2 2015 - 2018	Run 3 2022 - 2025	Run 4 2029 - 2032	Run 5	Run 6

Pb-Pb luminosity limited by LHC
~1-2x10^{27} cm^{-2} s^{-1}



Run 5 → higher luminosities for ions

- mitigate SC effects in SPS & LEIR, e.g. with lighter species

Run 4 → HL-LHC

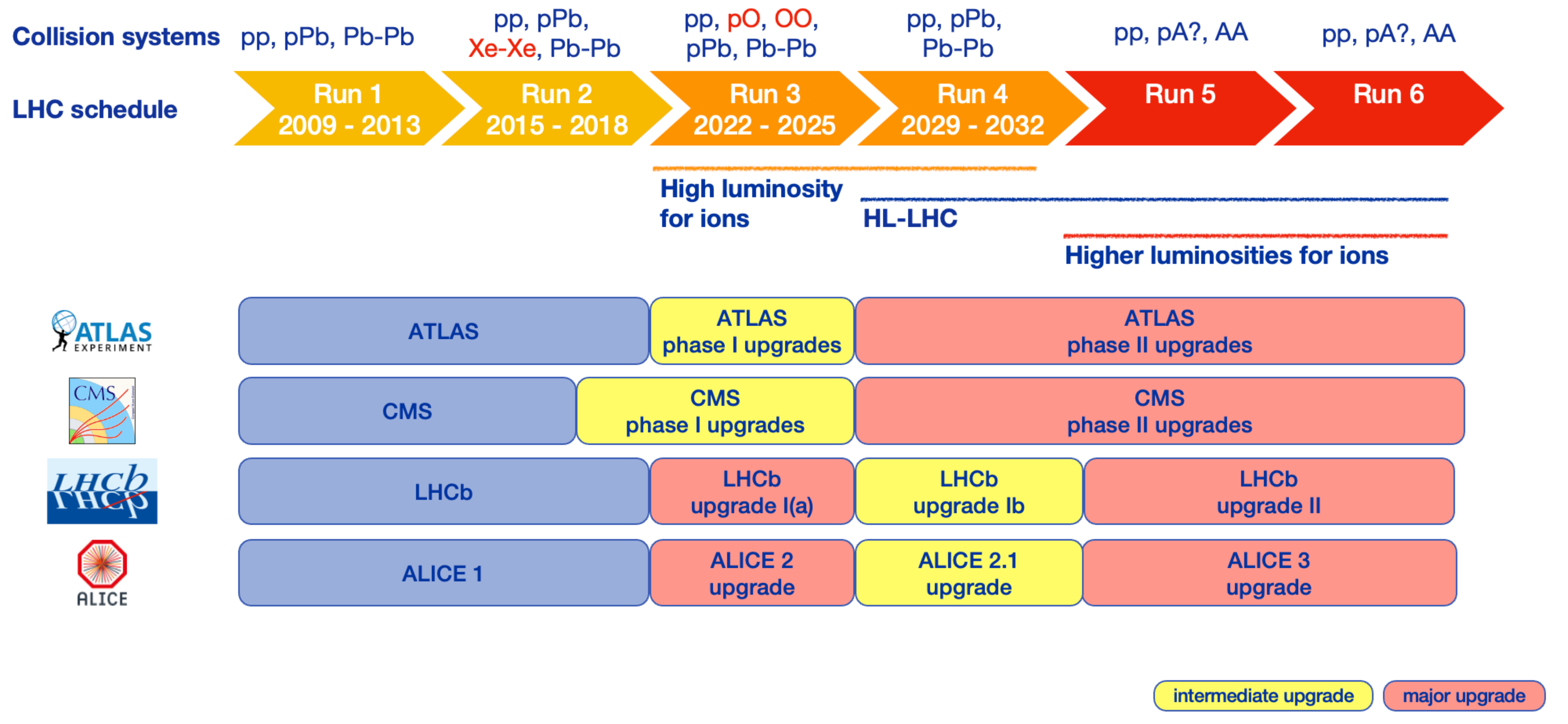
- push pp luminosity to 4x10^{34} cm^{-2} s^{-1}

Run 3 → high luminosity for ions (~7x10^{27} cm^{-2} s^{-1}) and **OO**

- improved collimation systems
  - ➞ lifted limitation in the LHC from bound-free pair production
  - ➞ ion luminosities now limited by bunch intensities from injectors

[slide from J. Klein, QM 2022]

Evolution of LHC experiments



[slide from J. Klein, QM 2022]

Heavy-ion running in LHC Run 5 & 6

- **Baseline approach for heavy-ion program**
  - maximize statistics for rare probes
    ➝ identify species best suited for physics program
  - 6 running years with 1 month / year with that species
- Complemented with high-rate **pp running** (3 fb^{-1} / year) at 14 TeV
- Consider **special runs** (pp reference, small systems),
  also based on insights from Run 3 & 4

[https://indico.cern.ch/event/1078695/]

Nucleon-nucleon luminosity: $\mathcal{L}_{NN} = A^2 \cdot \mathcal{L}_{AA}$

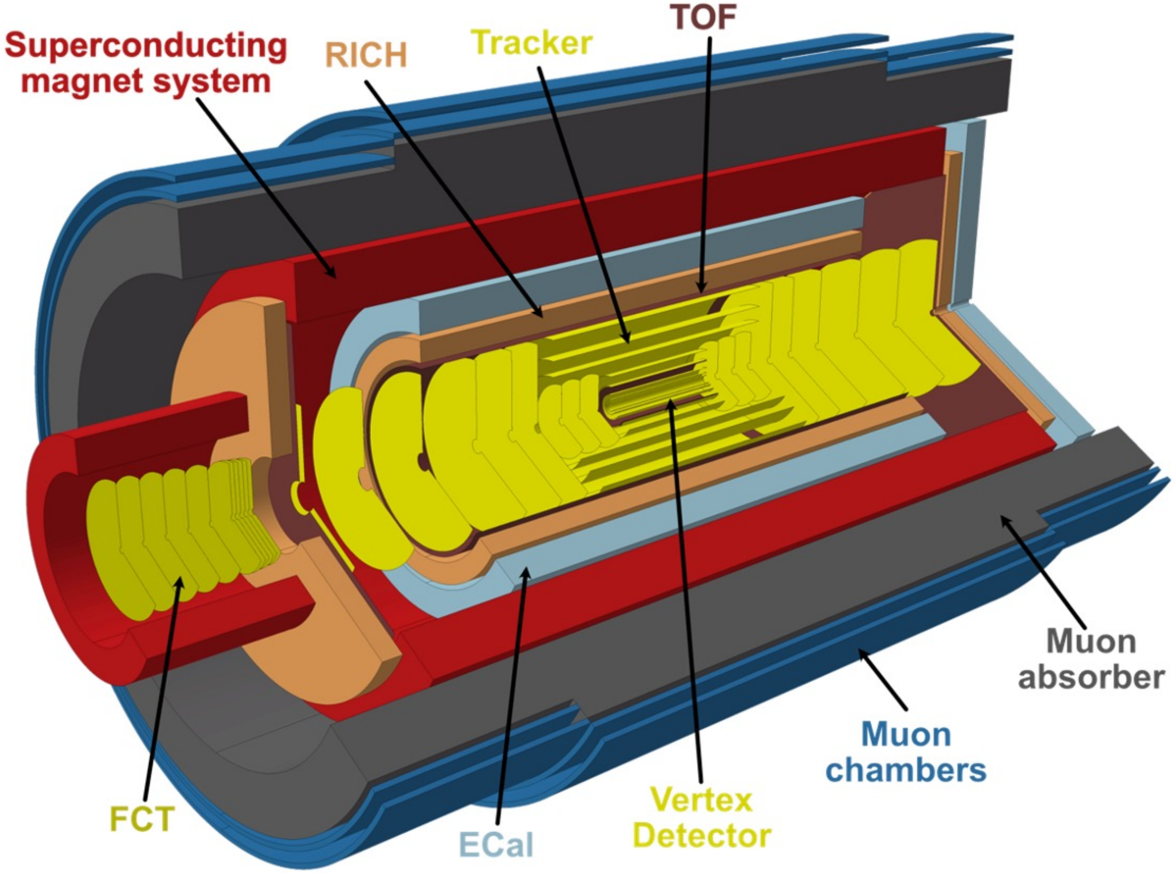
optimistic scenario	O-O	Ar-Ar	Ca-Ca	Kr-Kr	In-In	Xe-Xe	Pb-Pb
$\langle L_{AA} \rangle$ (cm^{-2} s^{-1})	$9.5 \cdot 10^{29}$	$2.0 \cdot 10^{29}$	$1.9 \cdot 10^{29}$	$5.0 \cdot 10^{28}$	$2.3 \cdot 10^{28}$	$1.6 \cdot 10^{28}$	$3.3 \cdot 10^{27}$
$\langle L_{NN} \rangle$ (cm^{-2} s^{-1})	$2.4 \cdot 10^{32}$	$3.3 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$2.6 \cdot 10^{32}$	$1.4 \cdot 10^{32}$
$\mathcal{L}_{AA}$ (nb^{-1} / month)	$1.6 \cdot 10^{3}$	$3.4 \cdot 10^{2}$	$3.1 \cdot 10^{2}$	$8.4 \cdot 10^{1}$	$3.9 \cdot 10^{1}$	$2.6 \cdot 10^{1}$	$5.6 \cdot 10^{0}$
$\mathcal{L}_{NN}$ (pb^{-1} / month)	409	550	500	510	512	434	242

Strength of QGP effects (e.g. charm abundance, quenching, also background) →

ALICE 3:
the dedicated heavy-ion experiment for LHC Run 5 & 6

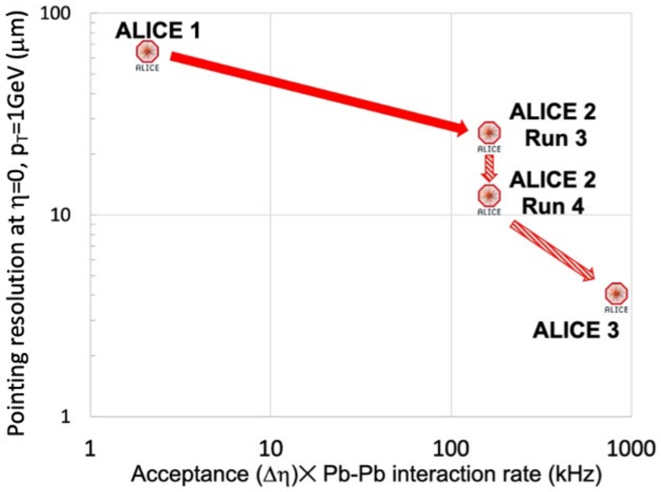
ALICE 3 detector concept

- Compact all-silicon tracker
  with high-resolution vertex detector
- Superconducting magnet system
- Particle Identification over large acceptance:
  muons, electrons, hadrons, photons
- Fast read-out and online processing



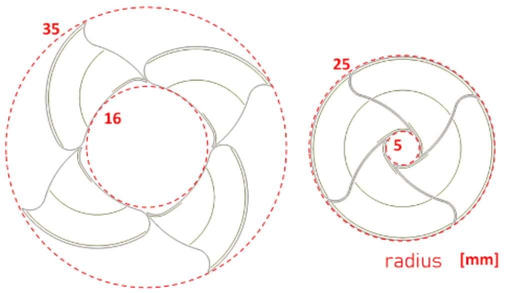
For LHC Run 5 & 6

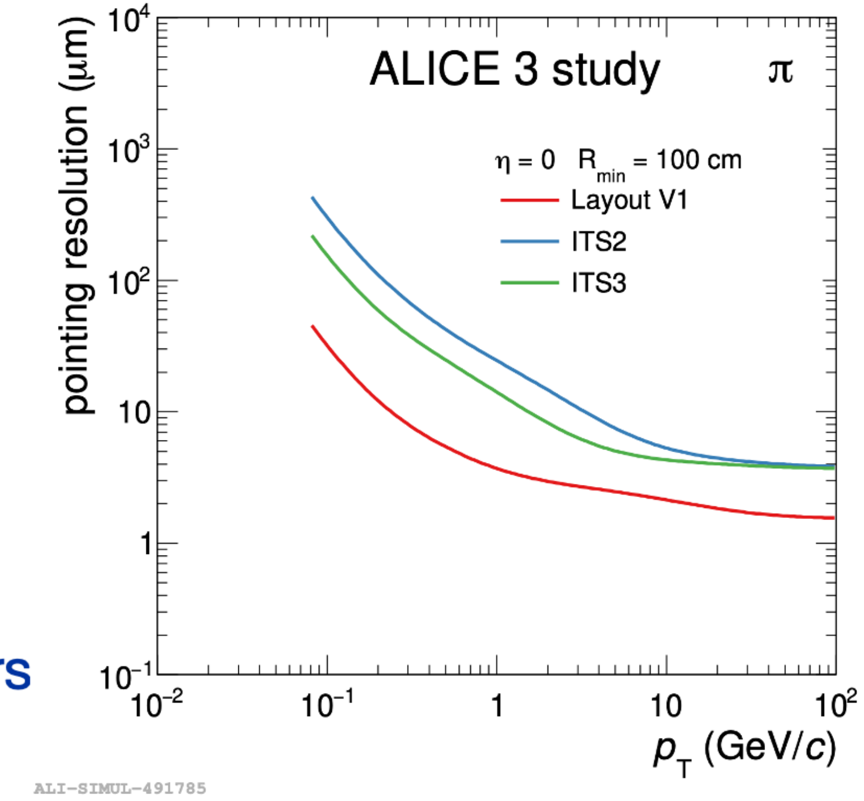
Improvement of pointing resolution and effective statistics



Vertexing

- **Pointing resolution** $\propto r_0 \cdot \sqrt{x/X_0}$
  (multiple scattering regime)
  ➟ 10 µm @ p_T = 200 MeV/c
  - radius and material of first layer crucial
  - minimal radius given by required aperture:
    R ≈ 5 mm at top energy,
    R ≈ 15 mm at injection energy
    → **retractable vertex detector**
- **3 layers within beam pipe** (in secondary vacuum)
  at radii of 5 - 25 mm
  - wafer-sized, bent Monolithic Active Pixel Sensors
  - σ_{pos} ~2.5 µm → 10 µm pixel pitch
  - 1 ‰ X_0 per layer

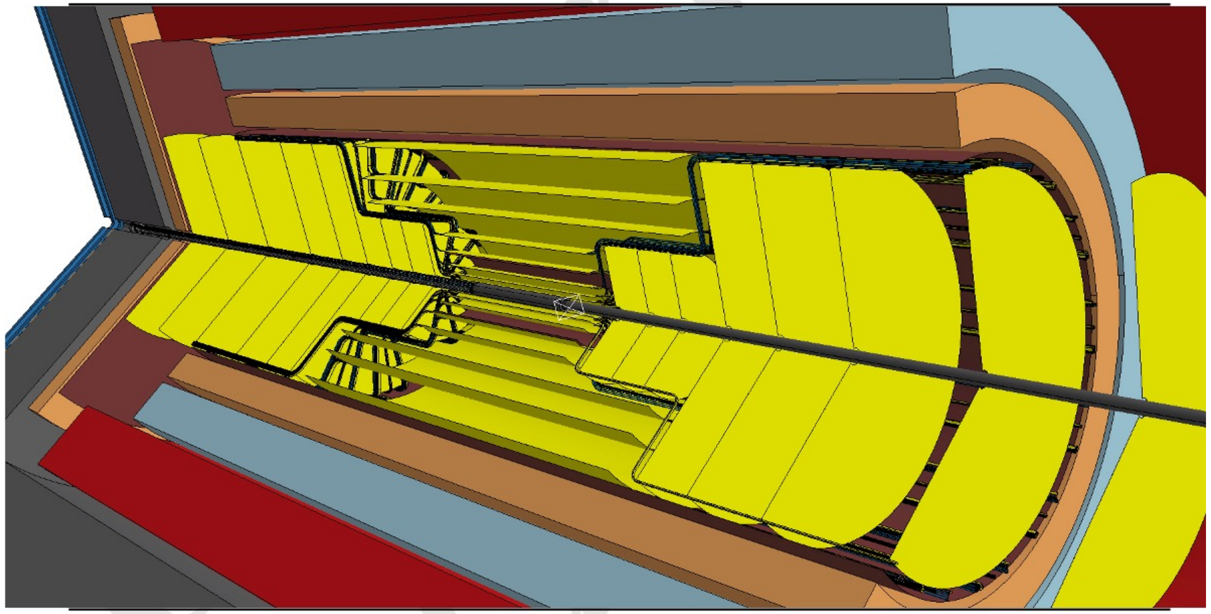


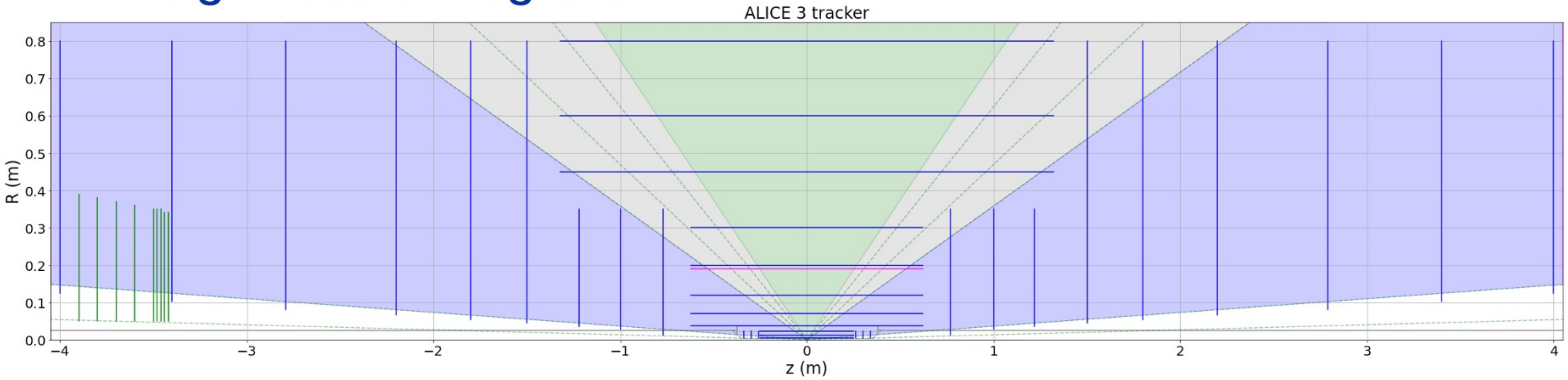


5x better than ALICE 2.1 (ITS3 + TPC)
→ e.g. S/B ~10x for D^0

Outer tracker

- MAPS on modules on water-cooled carbon-fibre cold plate
- carbon-fibre space frame for mechanical support
- **R&D programme** on
  - powering scheme (→ material)
  - design for industrialisation, e.g. module integration



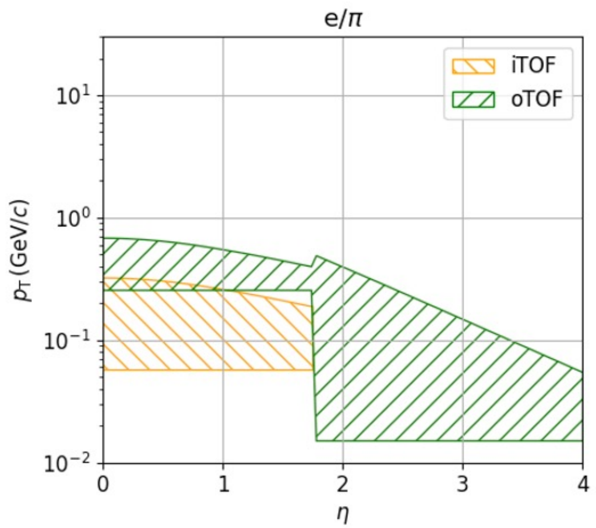


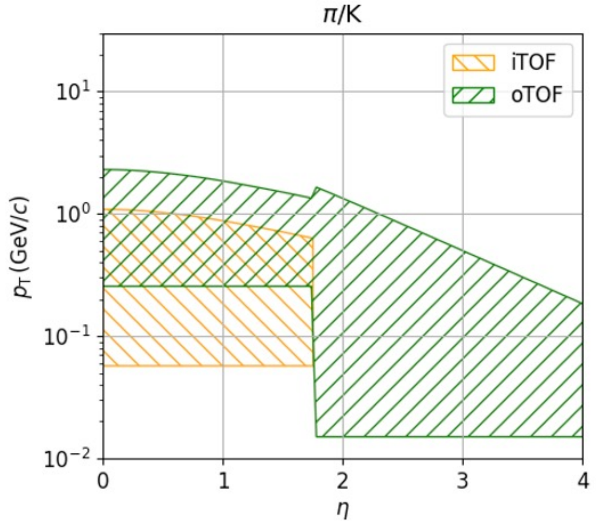
Total silicon surface ~60 m^2

Time of flight

- **Separation power** $\propto \dfrac{L}{\sigma_{\text{tof}}}$
  - distance and time resolution crucial
  - larger radius results in lower p_T bound
- **2 barrel + 1 forward TOF layers**
  - outer TOF at R ≈ 85 cm
  - inner TOF at R ≈ 19 cm
  - forward TOF at z ≈ 405 cm
- **Silicon timing sensors** ($\sigma_{TOF} \approx$ 20 ps)
  - **R&D programme** on
    monolithic CMOS sensors with integrated gain layer

Total silicon surface ~45 m^2

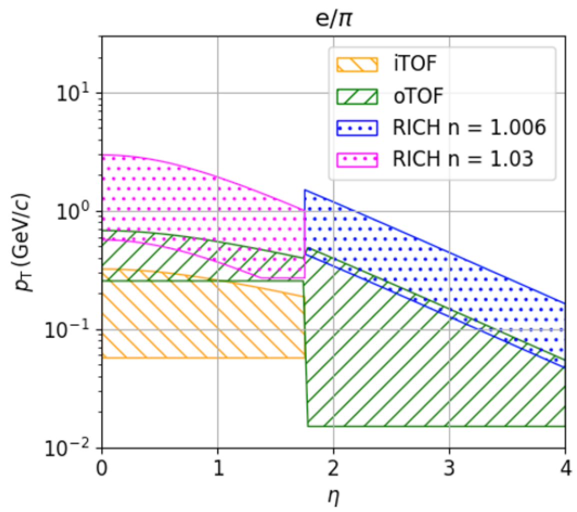


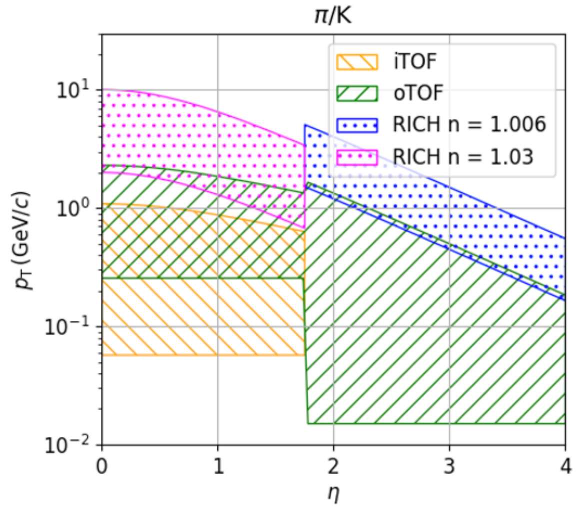


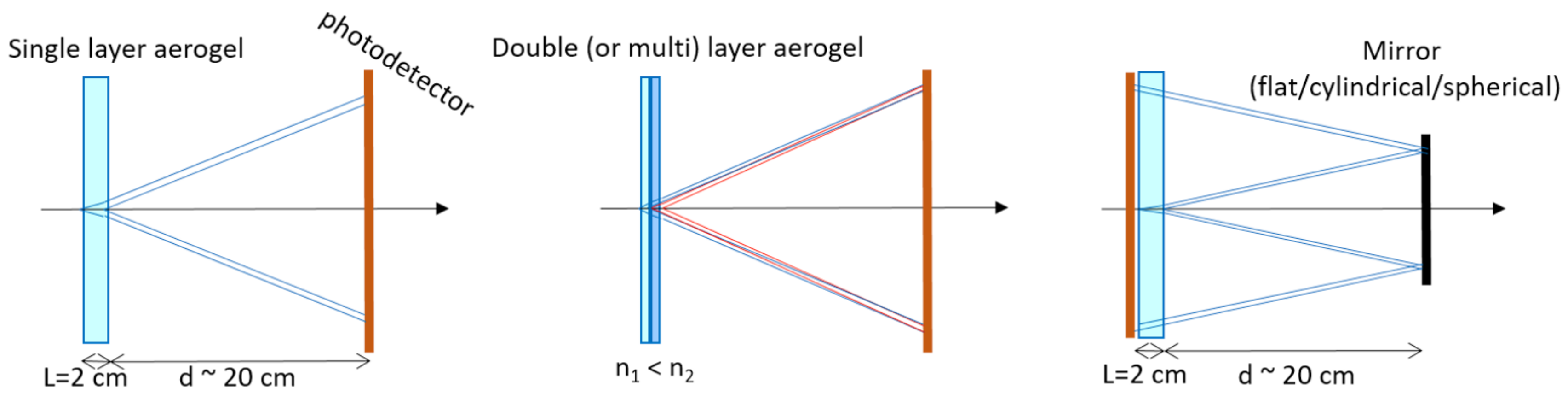
Ring-imaging Cherenkov

- **Extend PID reach of outer TOF to higher p_T → Cherenkov**
  - **aerogel radiator**
    to ensure continuous coverage from TOF
    → refractive index n = 1.03 (barrel)
    → refractive index n = 1.006 (forward)
  - **silicon photon sensors**
    - **R&D programme** on monolithic photon sensors

Total SiPM surface ~60 m²







Electromagnetic calorimeter

- **Large acceptance ECal**
  → sampling calorimeter (à la ALICE EMCal/DCal):
  O(100) layers (1 mm Pb + 1.5 mm plastic scintillator)
- **Additional high energy resolution segment** at mid-rapidity
  → $PbWO_4$-based (à la ALICE PHOS)

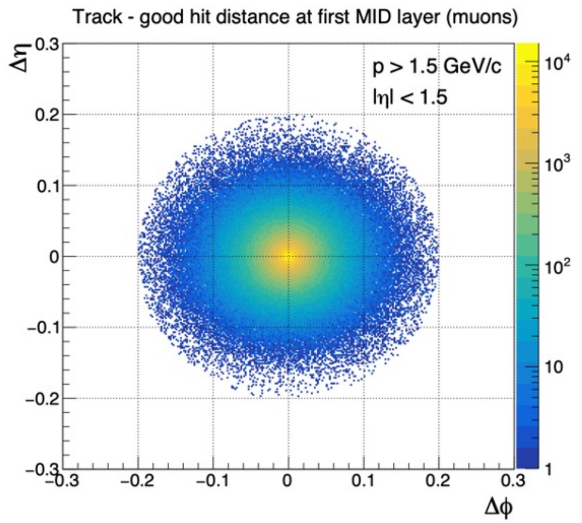
Established technologies

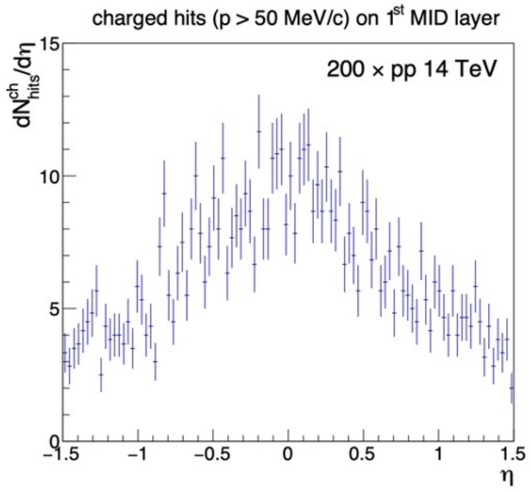
ECal module	Barrel sampling	Endcap sampling	Barrel high-precision
acceptance	$\Delta\varphi = 2\pi$, $\|\eta\| < 1.5$	$\Delta\varphi = 2\pi$, $1.5 < \eta < 4$	$\Delta\varphi = 2\pi$, $\|\eta\| < 0.33$
geometry	$R_{in} = 1.15$ m, $\|z\| < 2.7$ m	$0.16 < R < 1.8$ m, $z = 4.35$ m	$R_{in} = 1.15$ m, $\|z\| < 0.64$ m
technology	sampling Pb + scint.	sampling Pb + scint.	$PbWO_4$ crystals
cell size	30×30 mm^2	40×40 mm^2	22×22 mm^2
no. of channels	30 000	6 000	20 000
energy range	$0.1 < E < 100$ GeV	$0.1 < E < 250$ GeV	$0.01 < E < 100$ GeV

Muon identifier

- **Hadron absorber**
  - ~70 cm non-magnetic steel
- **Muon chambers**
  - search spot for muons ~0.1 x 0.1 (eta x phi)
    → ~5 x 5 cm^2 cell size
  - matching demonstrated with 2 layers
    of muon chambers
    - scintillator bars
    - wave-length shifting fibres
    - SiPM read-out

Established technologies



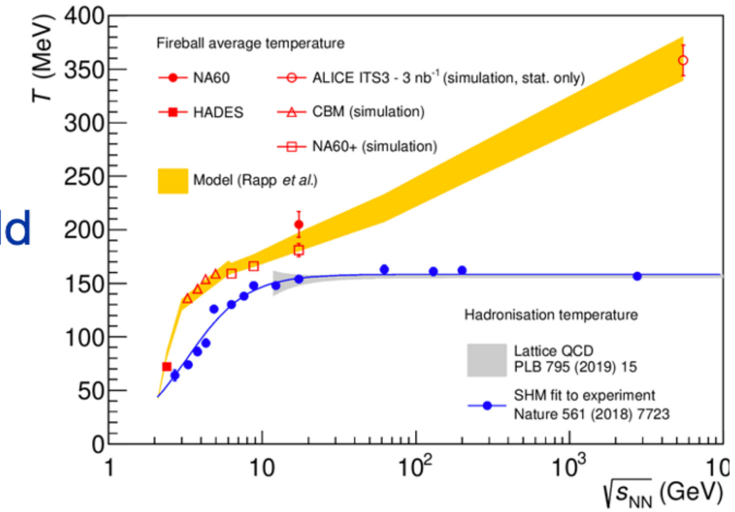


Electromagnetic radiation

- Access to precise QGP temperature
  - First measurements in Run 3 and 4
- **ALICE 3**: access time evolution and flow field (‘photon puzzle’)
  - Dilepton v_2 vs mass and p_T
  - Double-differential spectra: T vs mass, p_T
- **ALICE 3**: high precision in ρ-a_1 mixing region
- Complementary measurements with photons

Need:
- excellent electron ID (hadron rejection),
- low-mass detector (conversion bkg),
- excellent pointing resolution (HF decay bkg)

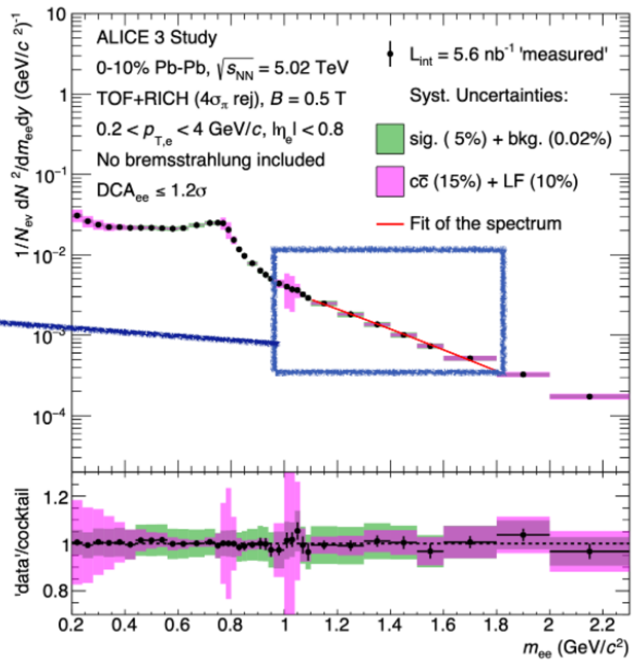
Photon detection: conversions + ECAL



T vs energy

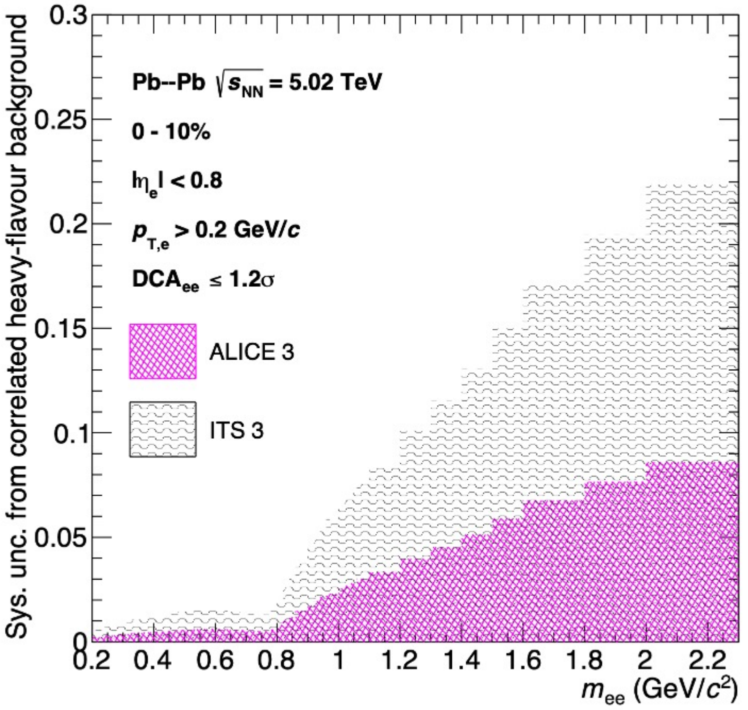
Direct measure of temperature

Dielectron mass



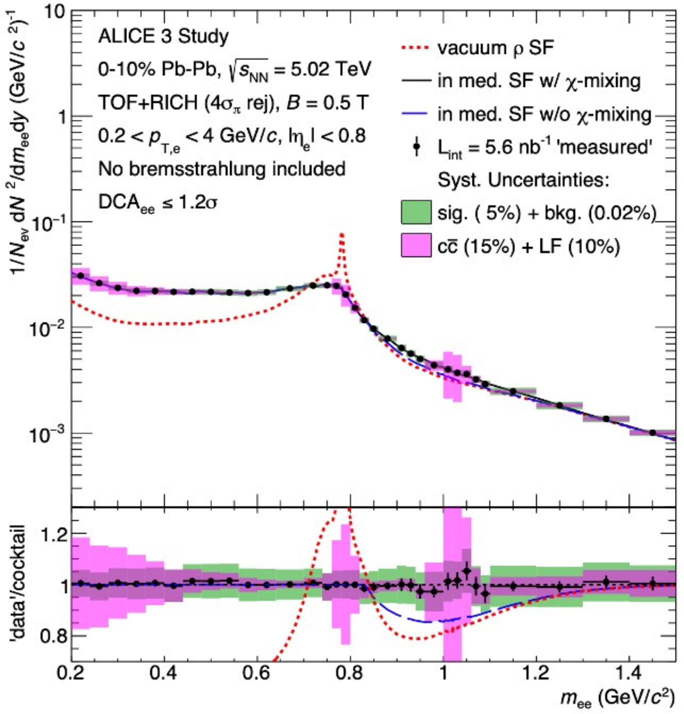
Dielectrons: chiral symmetry and thermal emission

Relative syst uncertainty from HF decay bkg



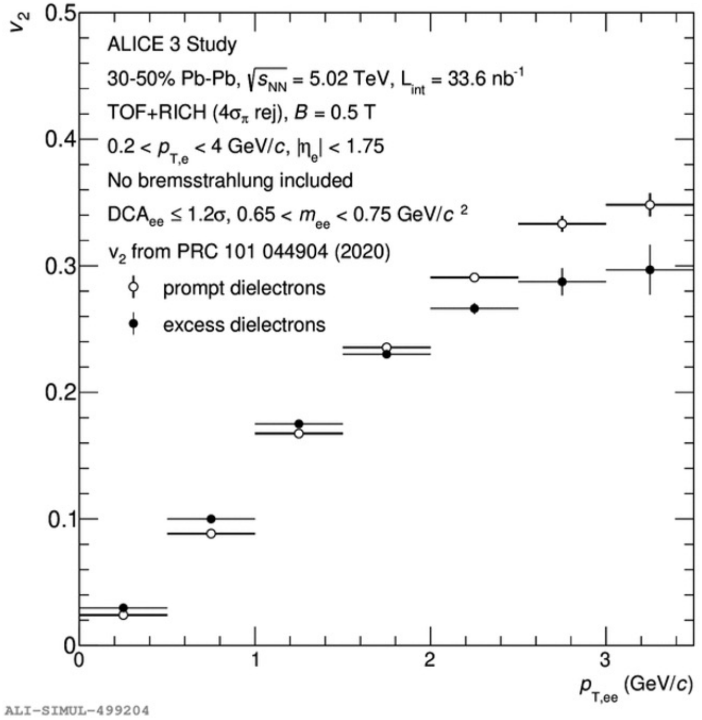
- HF decays produce correlated background
- Large for $m_{ee} \gtrsim 1 \mathrm{GeV}/c^2$
- Can be effectively suppressed in ALICE 3

ALICE 3 mass spectrum



High precision:
access $\rho - a_1$ mixing

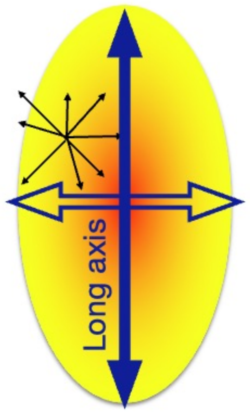
Dielectron v2



Excellent precision for dilepton v_2 vs p_T in different mass ranges
→ **time evolution of emission**

Heavy flavour transport

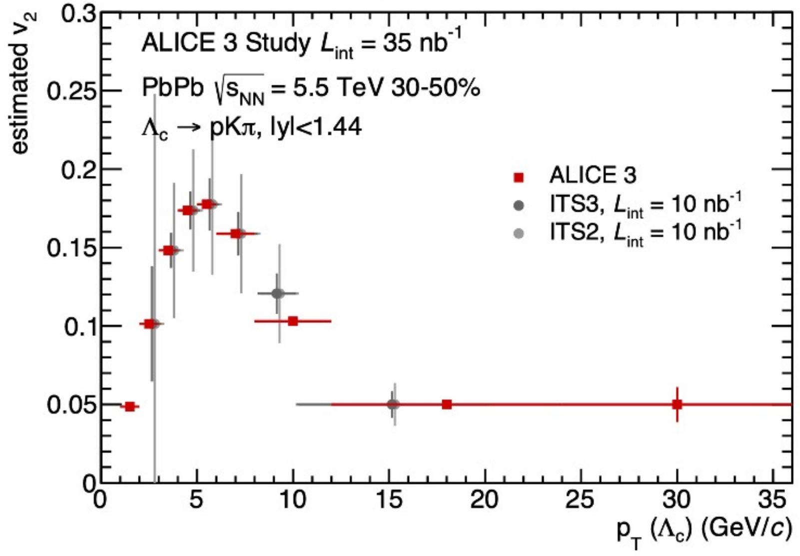
Non-central collision



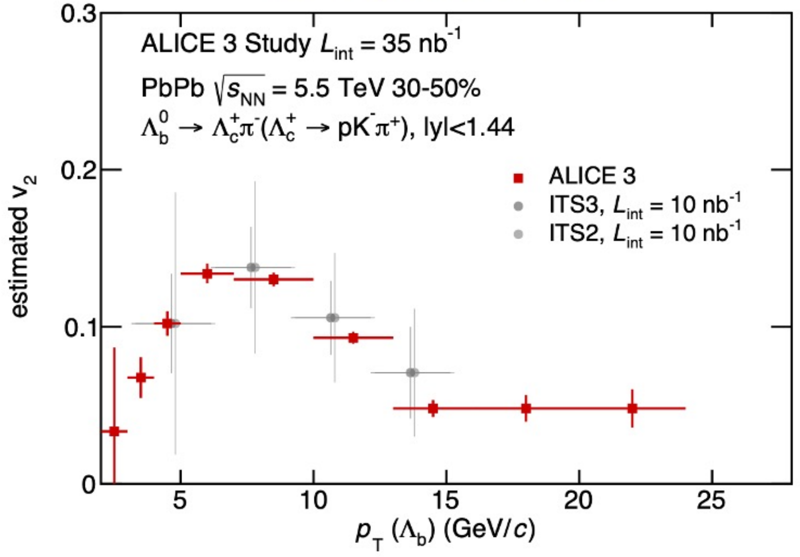
Interactions with the plasma generate azimuthal anisotropy v_2:

$$\frac{dN}{d\phi} \propto 1 + 2v_2\cos2(\varphi - \psi)$$

Λ_c v_2 performance



Λ_b v_2 performance

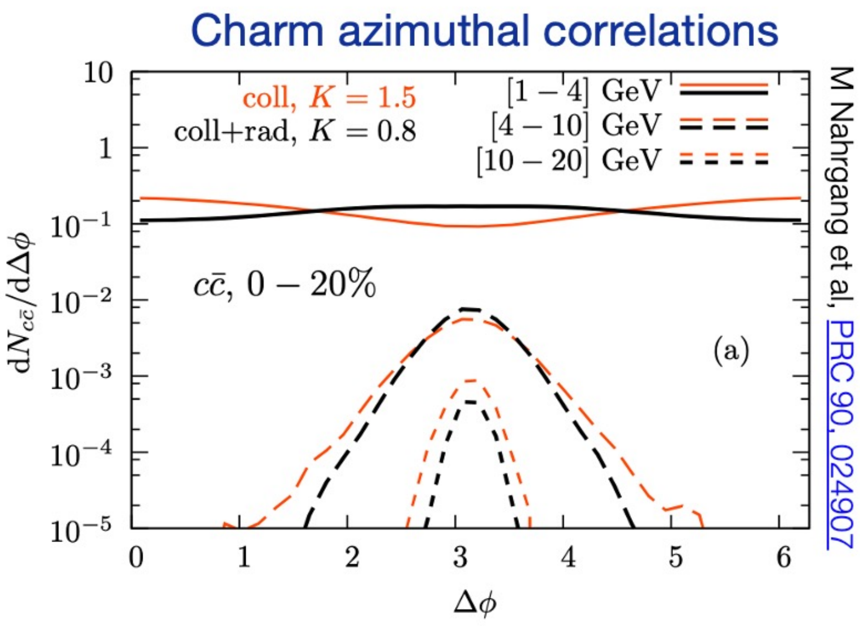


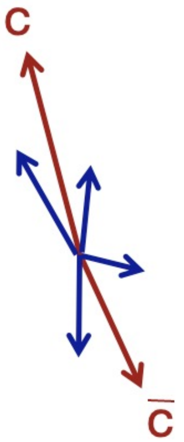
- **Heavy quarks: access to quark transport at hadron level**
  - Expect beauty thermalisation slower than charm — smaller v_2
- Need ALICE 3 performance (pointing resolution, acceptance) for precision measurement of e.g. Λ_c and Λ_b v_2

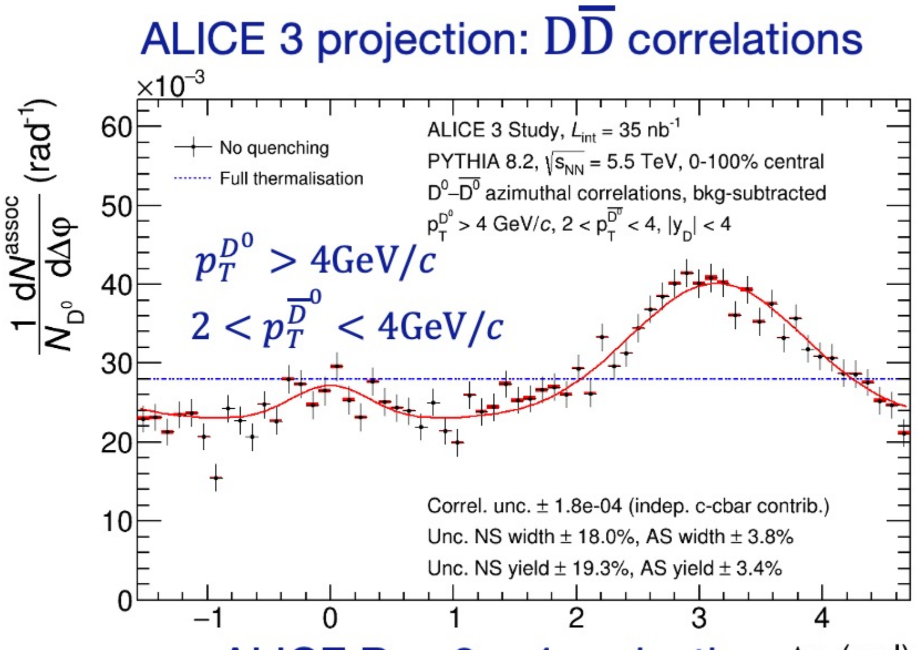
relaxation time

$$\tau_Q = (m_Q/T)D_s$$

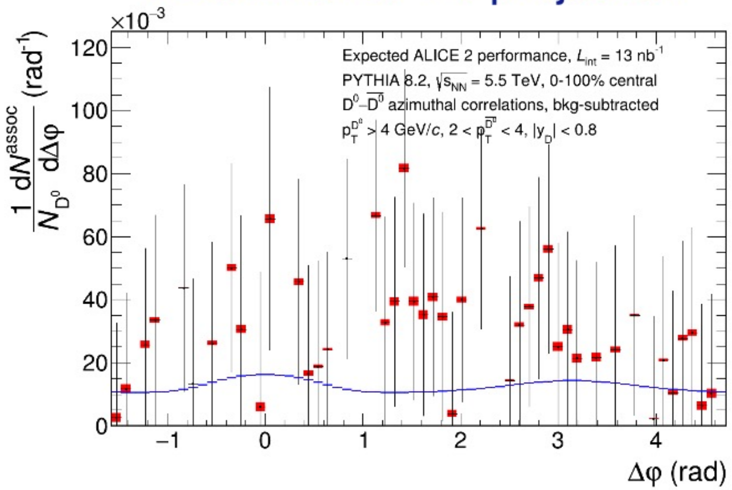
DDbar azimuthal correlations







ALICE Run 3 + 4 projection



- **Angular decorrelation directly probes QGP scattering**
  - Signal strongest at low p_T
- Very challenging measurement:
  need good purity, efficiency and η coverage
  → heavy-ion measurement only possible with ALICE 3

Hadron formation

- **Multi-charm baryons**: unique probe of hadron formation
  - Require **production of multiple charm quarks**
  - Single-scattering contribution very small (unlike e.g. J/ψ)
- Statistical hadronisation model: **very large enhancement** in AA
  - Charm out of equilibrium: yields scale with g_c^n for n-charm states
  - How is thermalisation approached microscopically?

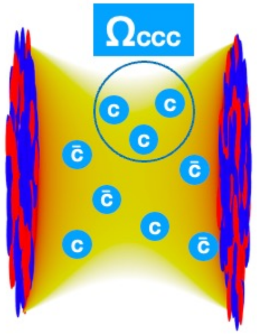
Measure additional states to test physical picture:

Single and double-charm baryons: Λ_c, Ξ_c, Ξ_{cc}, Ω_{cc}

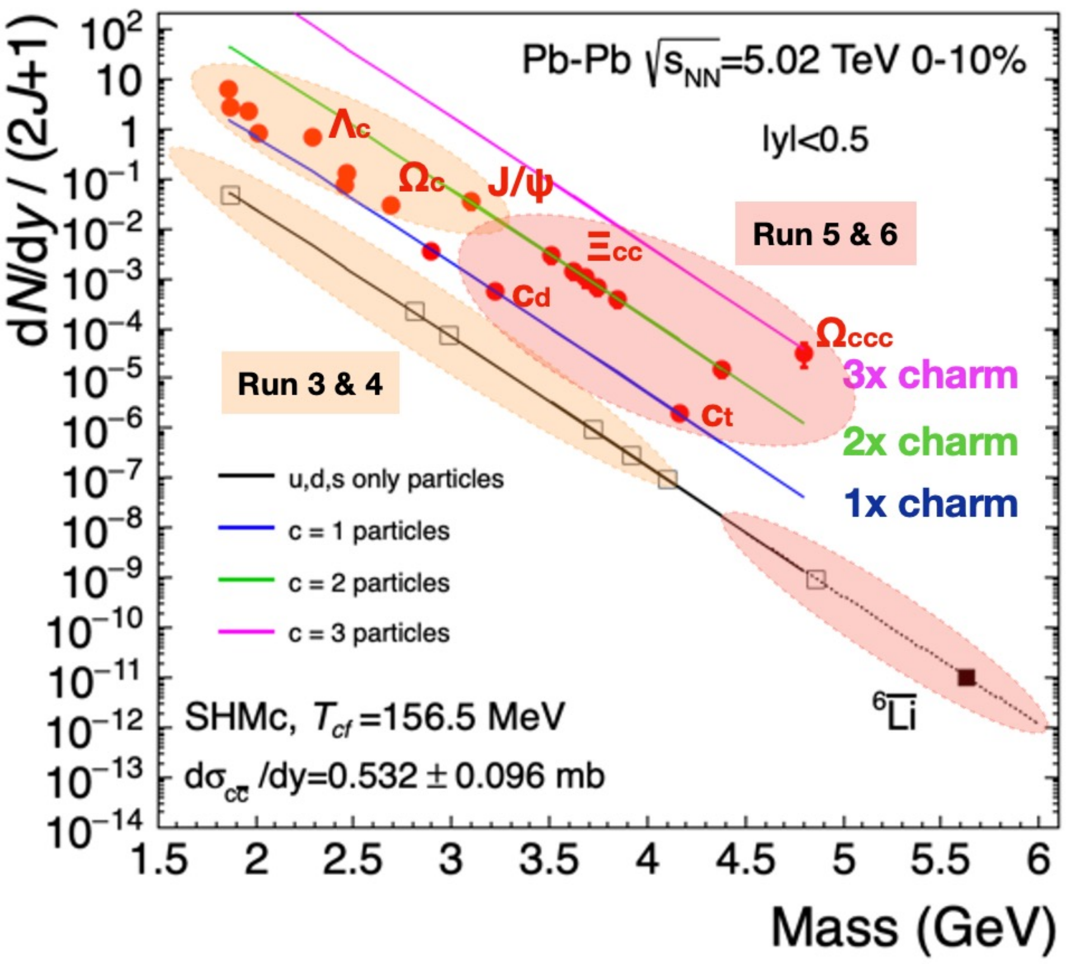
Multi-flavour mesons: B_c, D_s, B_s, ...

Tightly/weakly bound states J/ψ, $\chi_{c1}(3872)$, T_{cc}^+

Large mass light flavour particles: nuclei

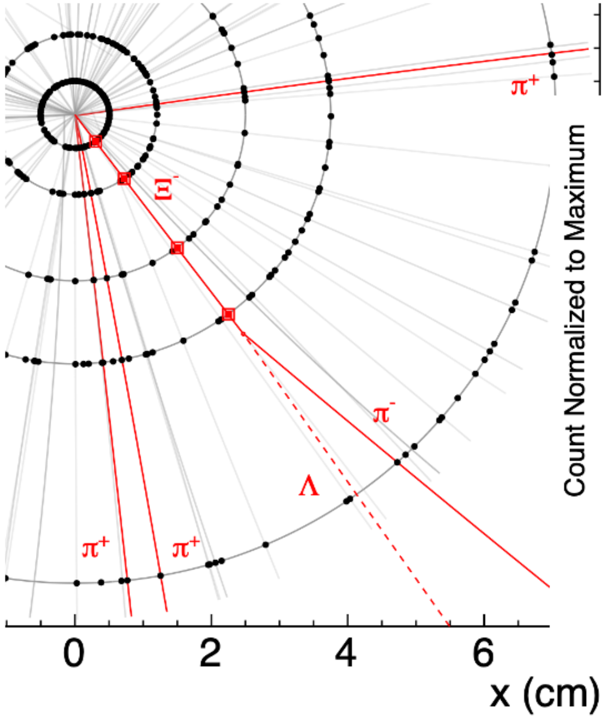


Hadron yields in statistical hadronisation model

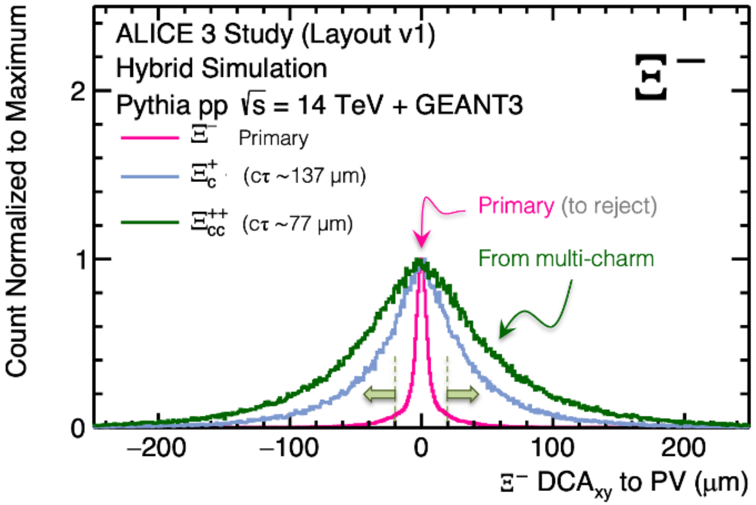


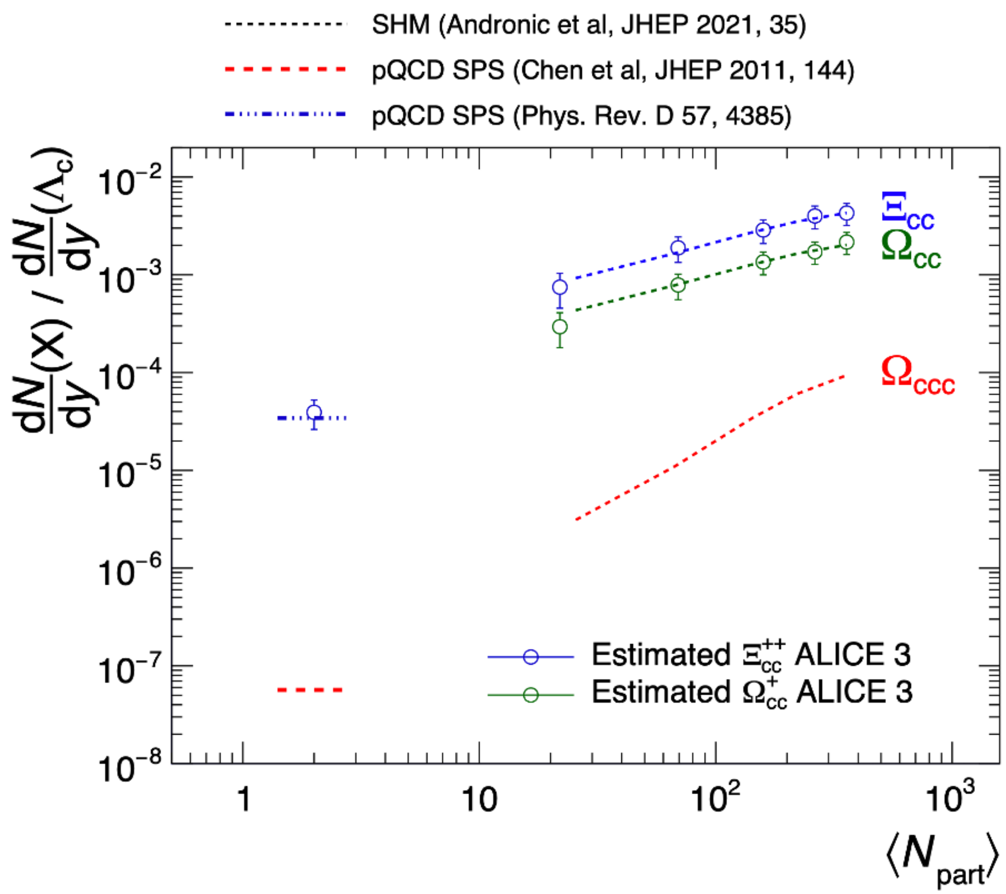
Multi-charm baryons

New technique: strangeness tracking



Impact parameter of Ξ





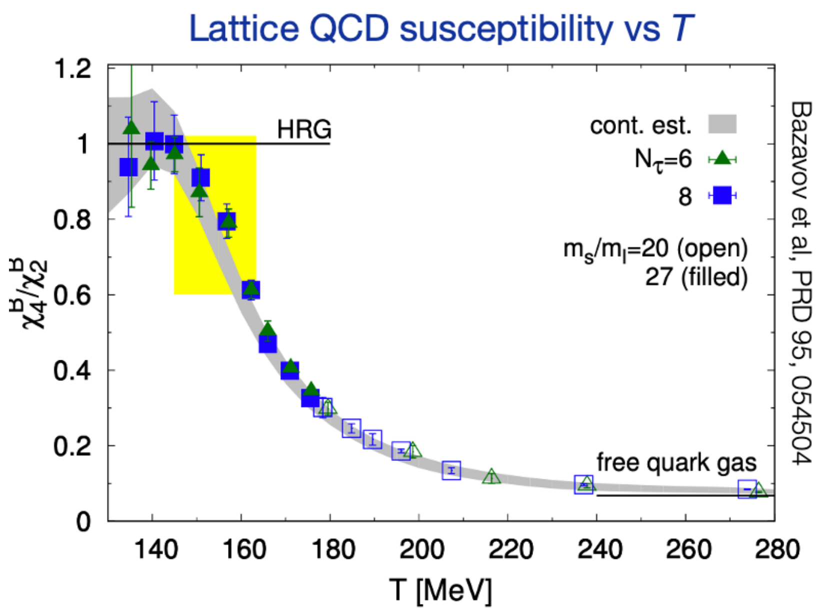
Pointing of Ξ baryon provides high selectivity

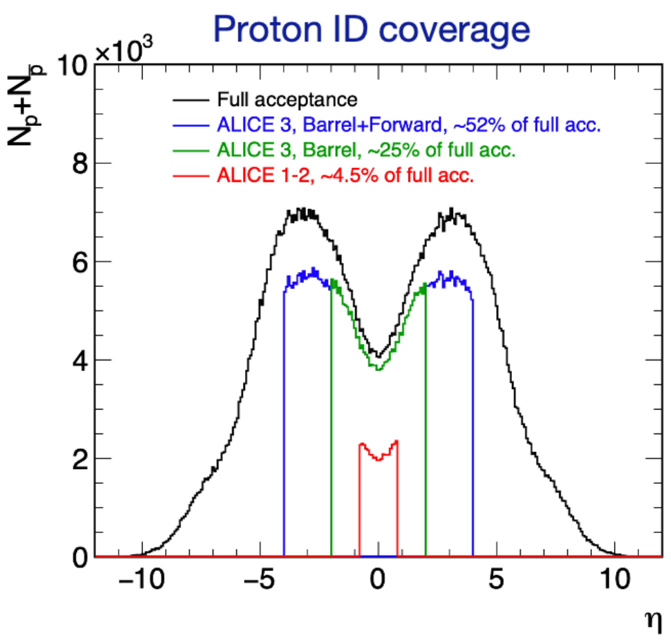
$\Xi_{cc}^{++} \rightarrow \Xi_c^{+} + \pi^{+}$ $\quad$ $\Xi_c^{+} \rightarrow \Xi^{-} + 2\pi^{+}$

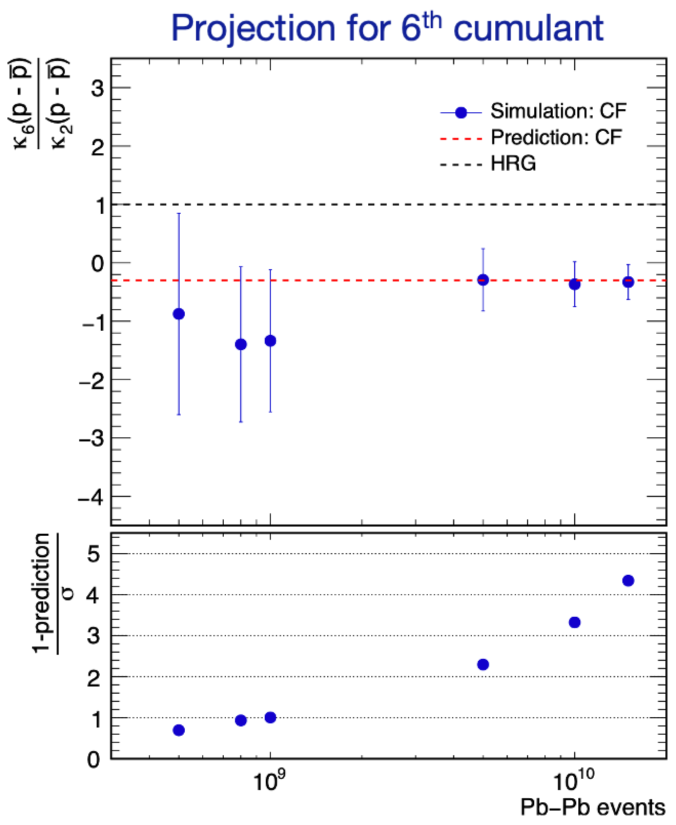
Large enhancements: unique sensitivity to **thermalisation and hadronisation dynamics**

ALICE 3: unique experimental access in Pb-Pb collisions

Net-proton fluctuations





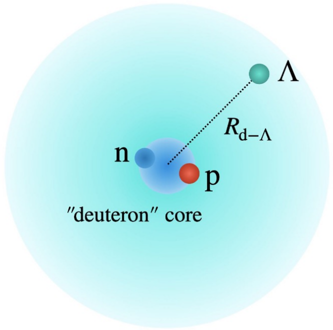


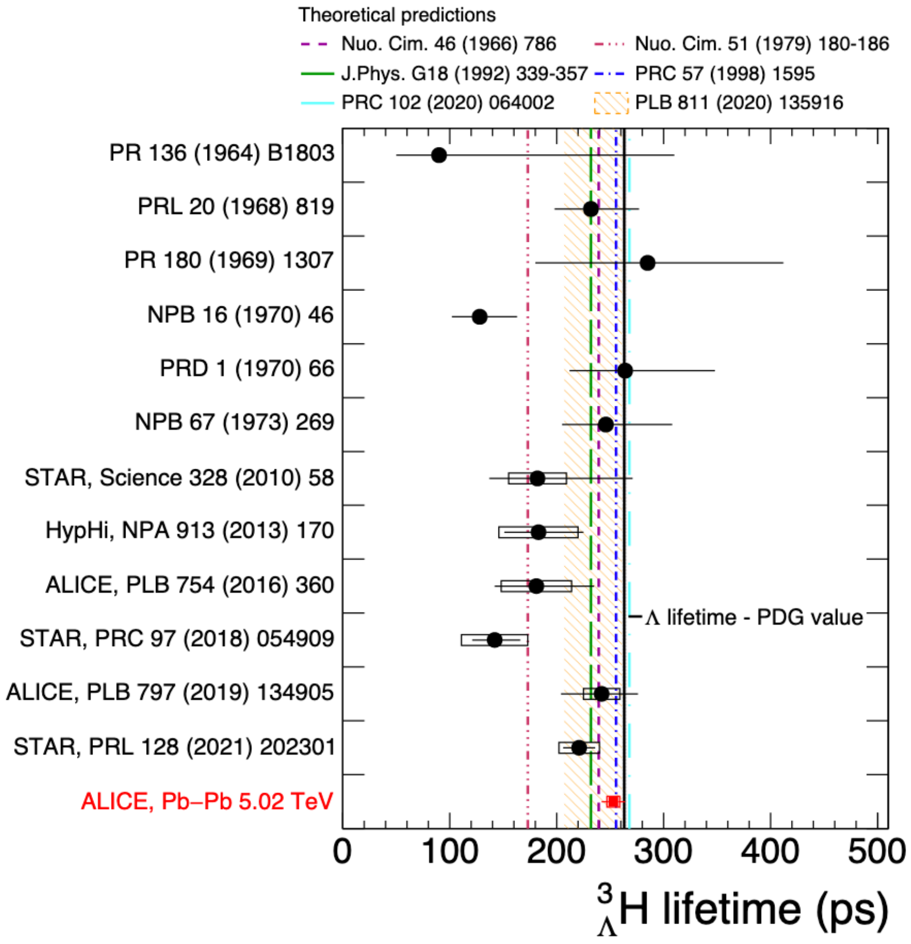
- Baryon number susceptibility of QGP: calculable with lattice QCD
- Accessible via net-proton number fluctuations: cumulants κ_n
- 4σ observation in reach with ALICE 3

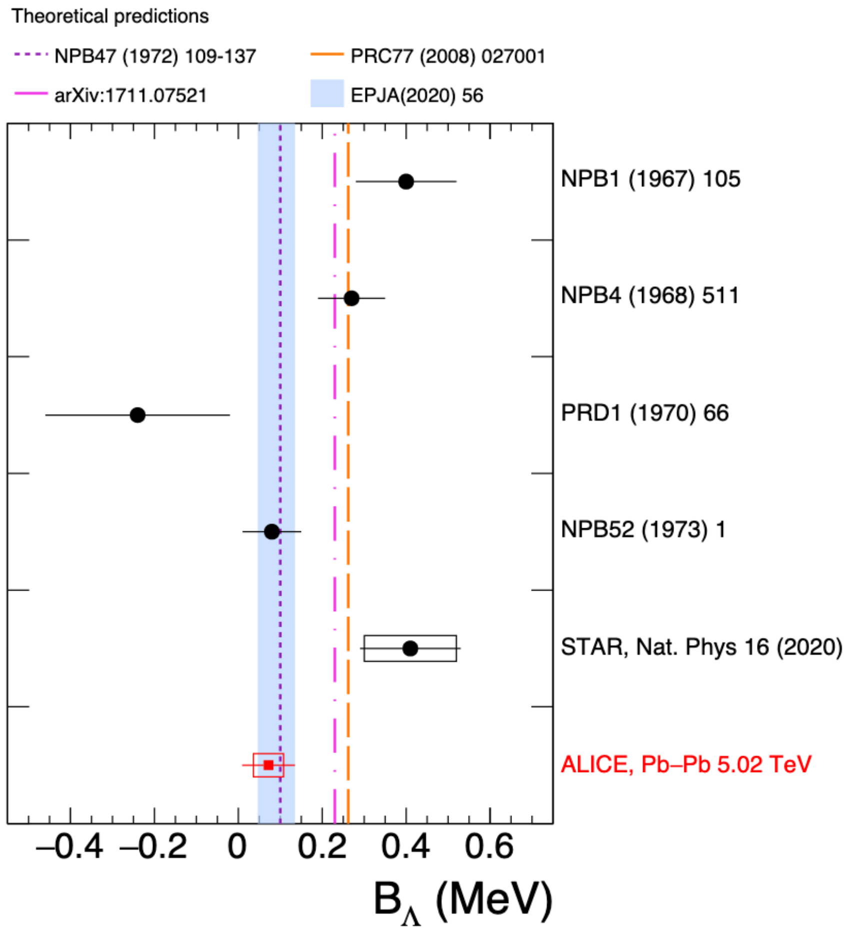
$$\chi_n = \frac{\partial(p/T^4)}{\partial(\mu_B/T)^n} = \frac{\kappa_n}{T^3}$$

ALICE 3:
so much more than
“traditional” heavy-ion physics

Hypertriton lifetime and binding energy







→ Most precise measurements are done at the LHC and not at dedicated low energy facilities!

[ALICE, arXiv:2209.07360]

Hypertriton production and its size

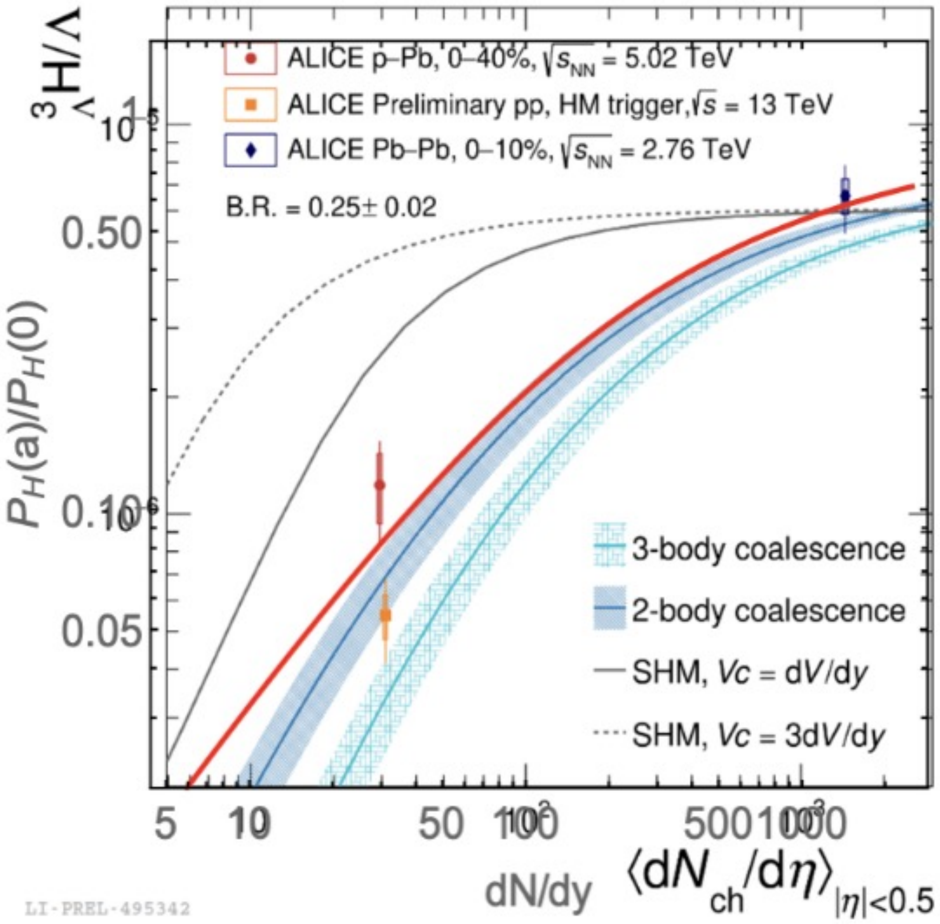
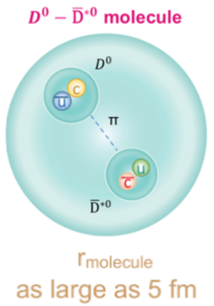
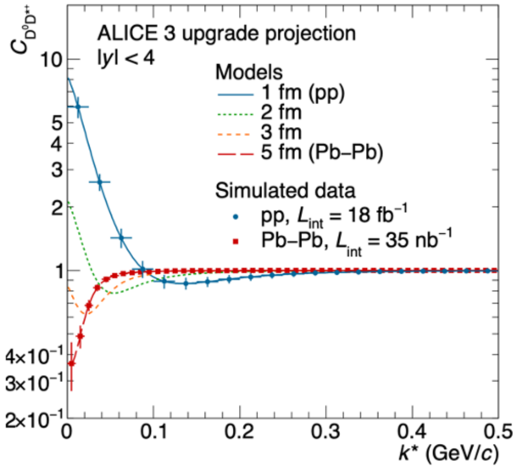


Figure 2. Yield ratio $^3_\Lambda$H/Λ as a function of $dN_{ch}/d\eta$ measured in Pb+Pb, p+Pb, and p+p collisions at LHC. The red curve shows the prediction for the SHM with size correction, Eq. (2). The curves with uncertainty bands show the predictions of coalescence models. The solid and dotted curves show the predictions of the SHM with strangeness neutrality for two different values of the strangeness correlation volume V_C.

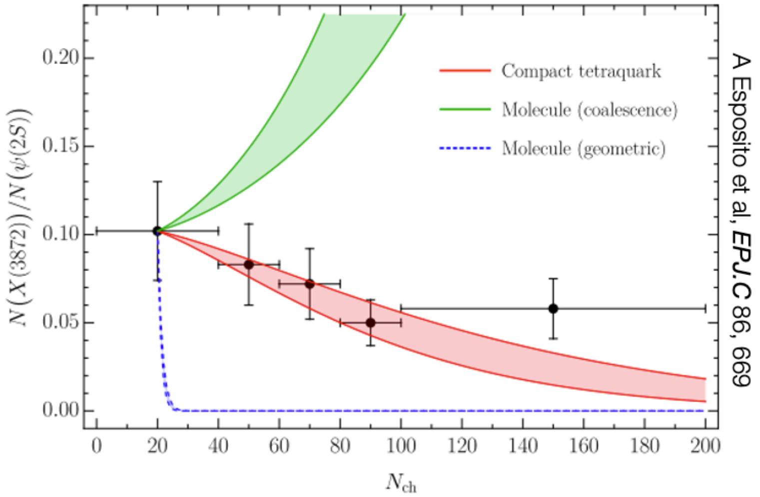
Exotic bound states

$D^0 D^{*+}$: nature of T_{cc}^{+}

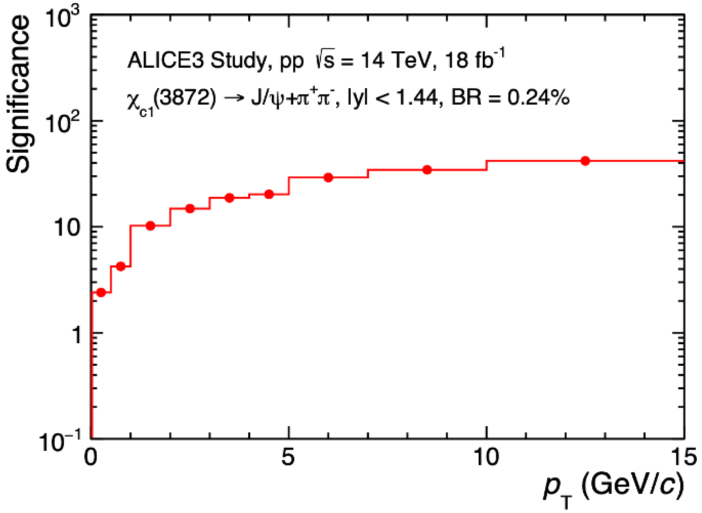




Dissociation and regeneration vs multiplicity



$\chi_{c1}(3872)$ significance (pp)



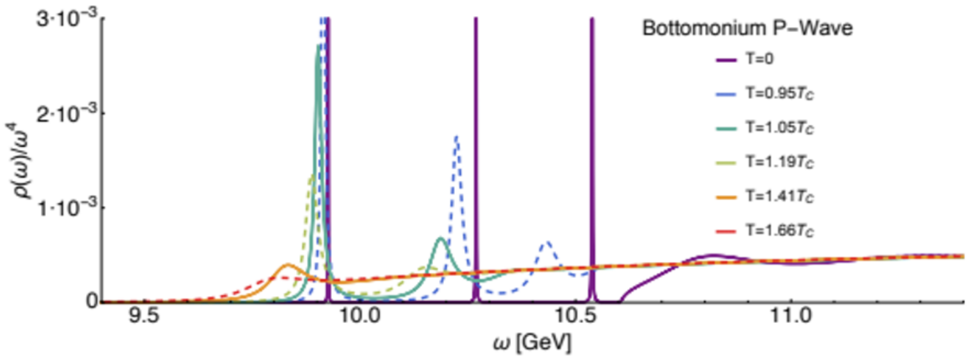
Requires:
muon ID down to 1.5 GeV/*c*

- Exotic states: $\chi_{c1}(3872)$, T_{cc}^{+}, …
  - Include double charm states, potentially weakly-bound states
  - **Investigate structure** with femtoscopic momentum correlations
  - Understand **dissociation and regeneration in QGP**

→ A new way of thinking! Use a system size scan from pp to heavy-ion collisions to elucidate the structure of exotic bound states!

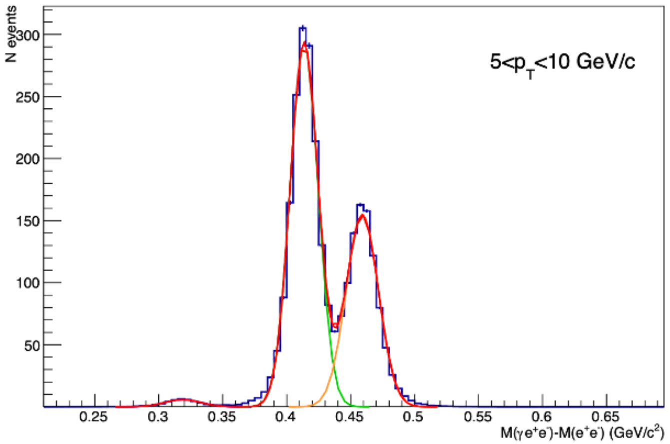
Other bound states: Quarkonia

Quarkonium spectral functions
Lattice QCD

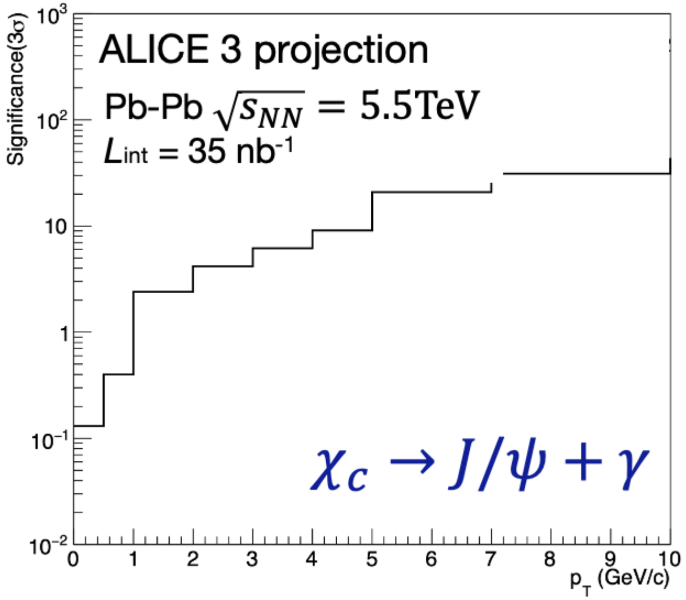


Burnier et al, *JHEP* 10 (2016) 032

χ_c with high-resolution ECAL



χ_c significance in Pb-Pb



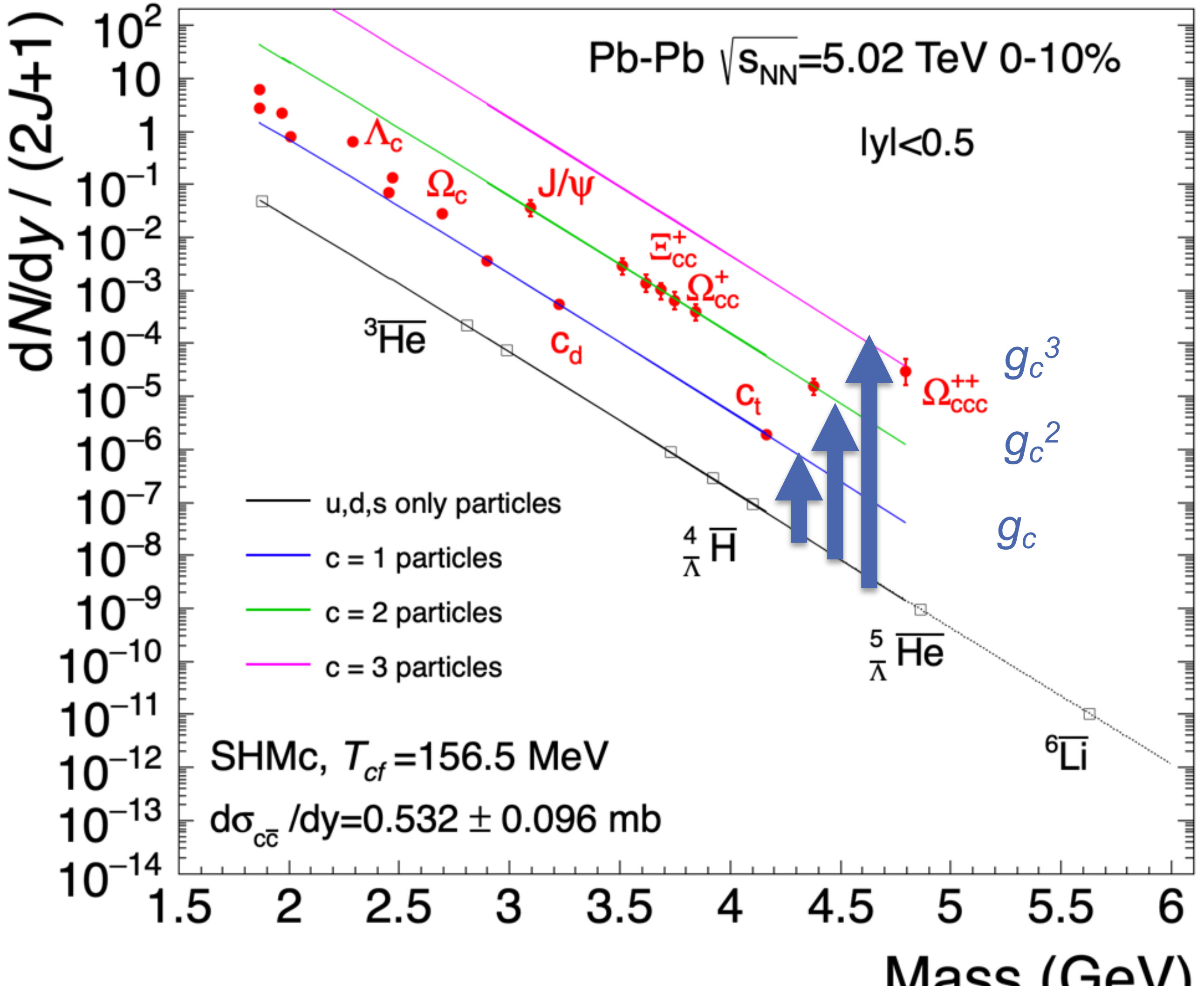
- Explore new states: P-wave and pseudoscalars
- Melting temperature depends on angular momentum
- Measurements of χ_c ; χ_b test theory
  - e.g. are there bound states above T_c?

Requires: muon ID down to 1.5 GeV/*c*, photon detection

Thermal production of charm particles

- Charm particle production rates are expected to be enhanced by the factor of the charm fugacity $g_c \approx 30$ (including charm nuclei).
- This makes multi-charm observable at LHC energies despite small branching ratios.
- Excellent synergy between charm and anti-nuclei physics: anti- and hyper-nuclei provide the baseline to measure g_c with multi-charm hadrons!

Predictions of statistical-thermal hadronization model



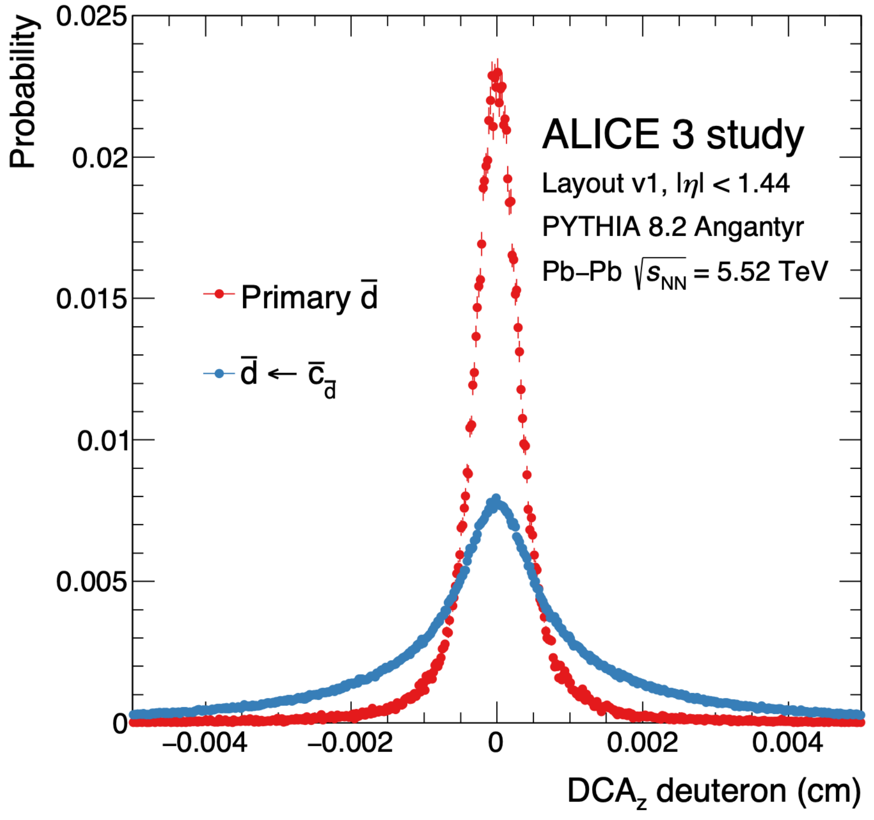
[A. Andronic *et al.*, *JHEP* 07 (2021) 035]

Charm nuclei: the c-deuteron

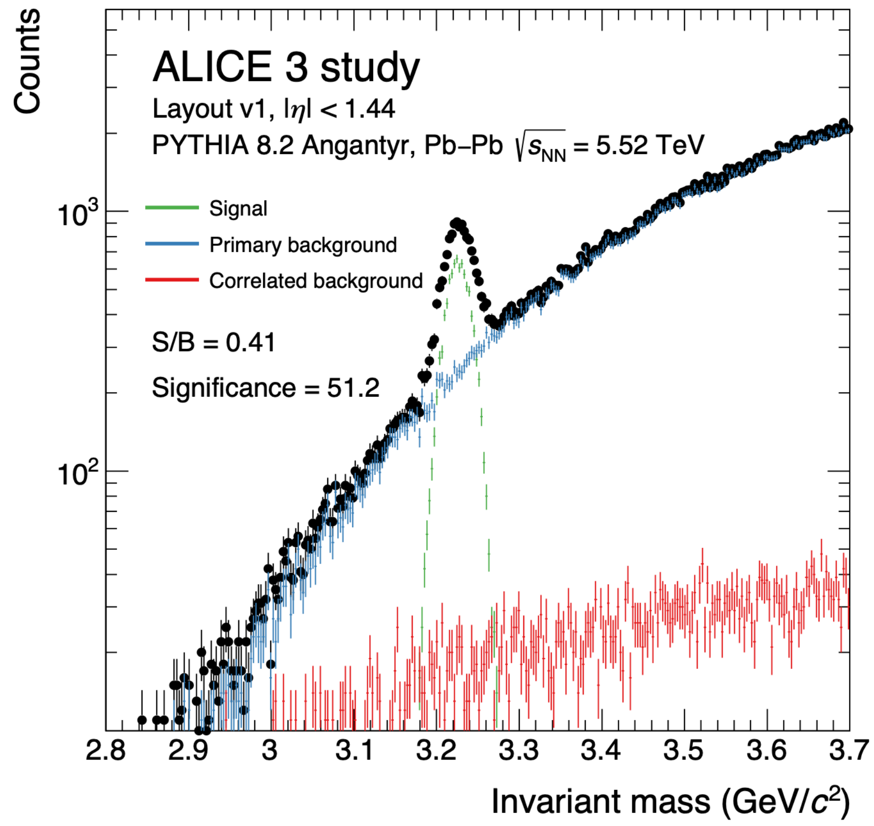
Decay channel:

$$c_d \to d + K^- + \pi^+$$

Impact parameter distributions



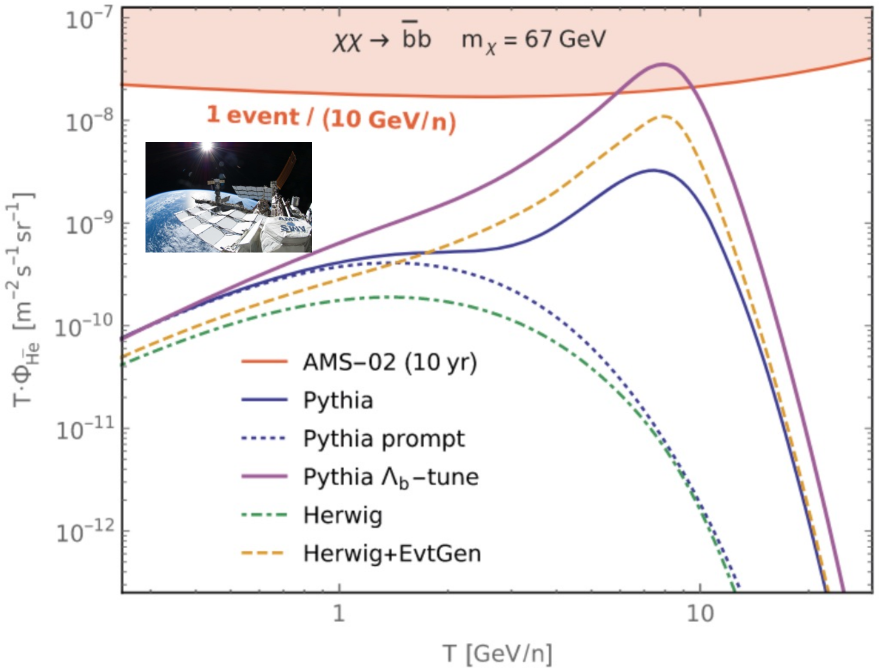
Invariant mass distribution



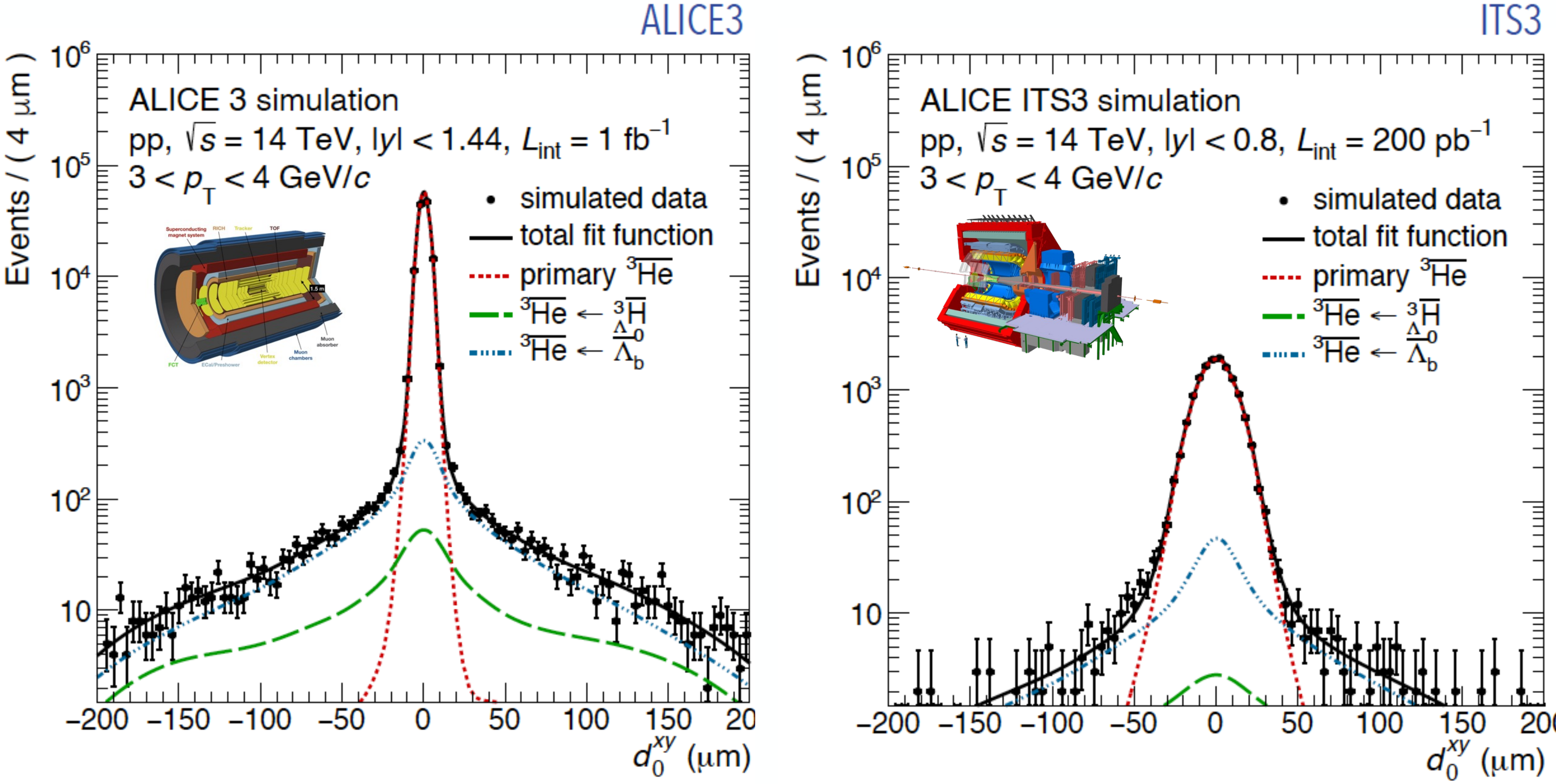
Unique sensitivity to undiscovered charm-nuclei:
charm-deuteron and higher nuclear states

Antinuclei production in b-quark decays (1)

$$\chi\chi \rightarrow b\bar{b} \rightarrow \overline{\Lambda}{}_b^0 + X \rightarrow {}^3\overline{\mathrm{He}} + X$$



[M. Winkler, T. Linden, PRL 126 (2021)]



[ALICE 3 Letter of Intent]

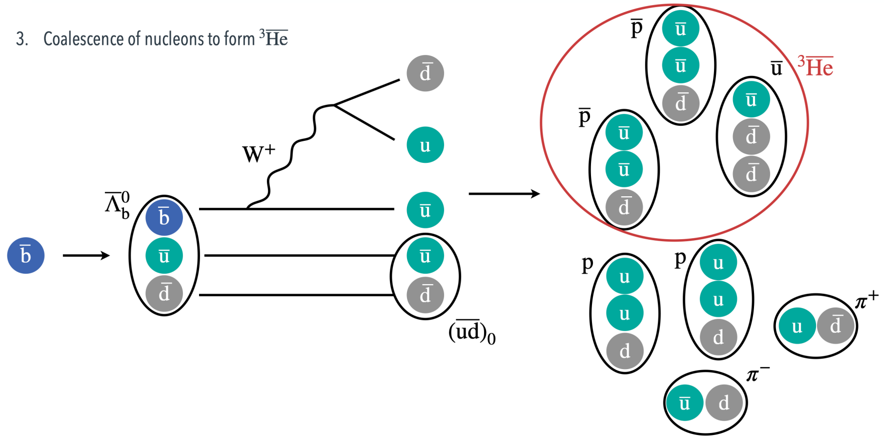
→ Anti-^{3}He originating from Λ_b decays from dark matter annihilation might lead to an enhanced flux of anti-^{3}He near earth.

→ Accelerator based experiments like ALICE are in the best position to determine the branching ratios of these rare decays.

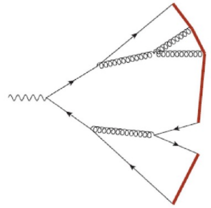
→ Precise dca-resolution of ALICE 3 is key to perform the measurement. First layer in beam-pipe removes all potential ambiguities from Moliere scattering that are difficult to simulate.

Antinuclei production in b-quark decays (2)

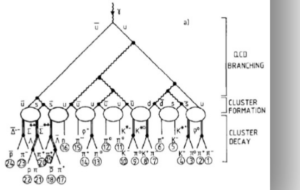
$$\chi\chi \rightarrow b\bar{b} \rightarrow \overline{\Lambda}_b^0 + X \rightarrow {}^3\overline{He} + X$$

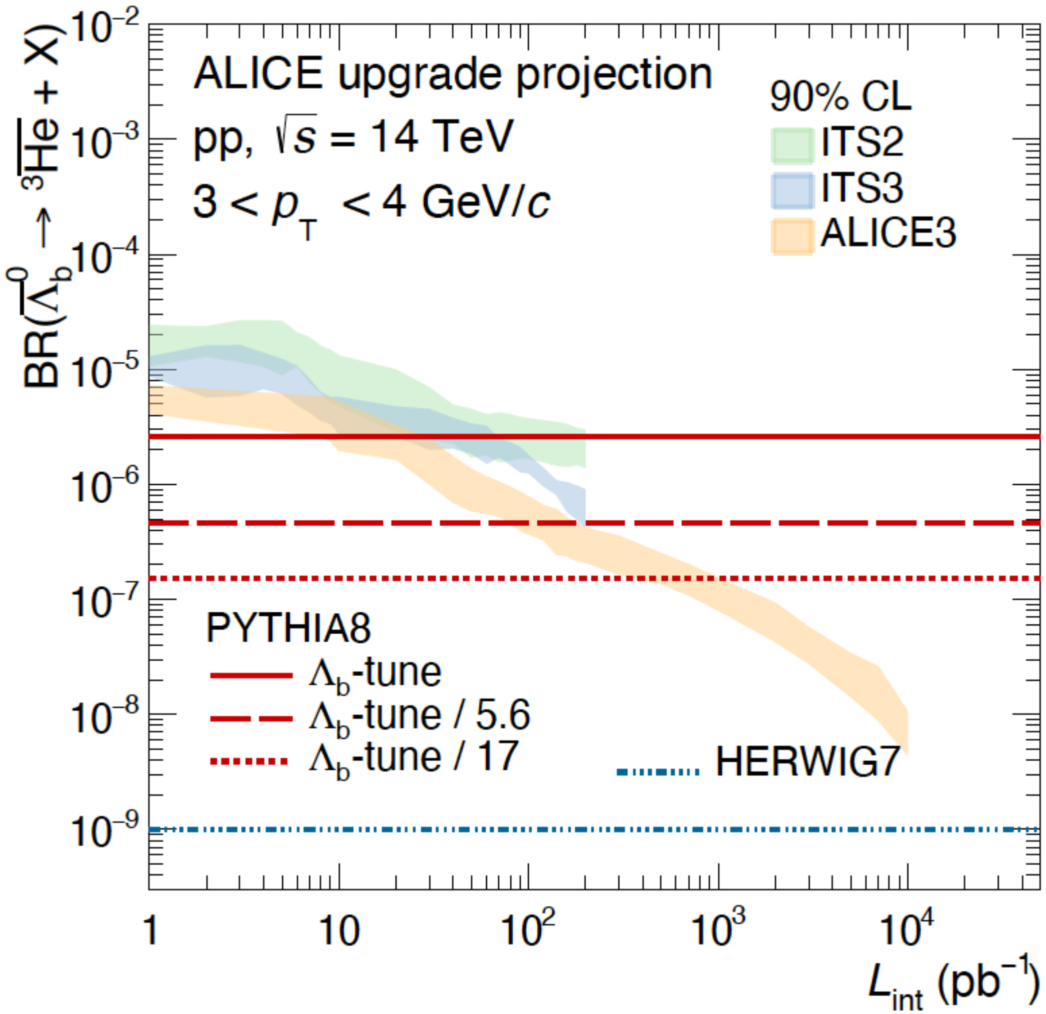


- **String fragmentation** (e.g. Lund model in PYTHIA)
  - Strings = colour-flux tubes between q and $\bar{q}$ end-points
  - Gluons represent kinks along the string
  - Strings break via vacuum-tunneling of (di)quark-anti(di)quark pairs



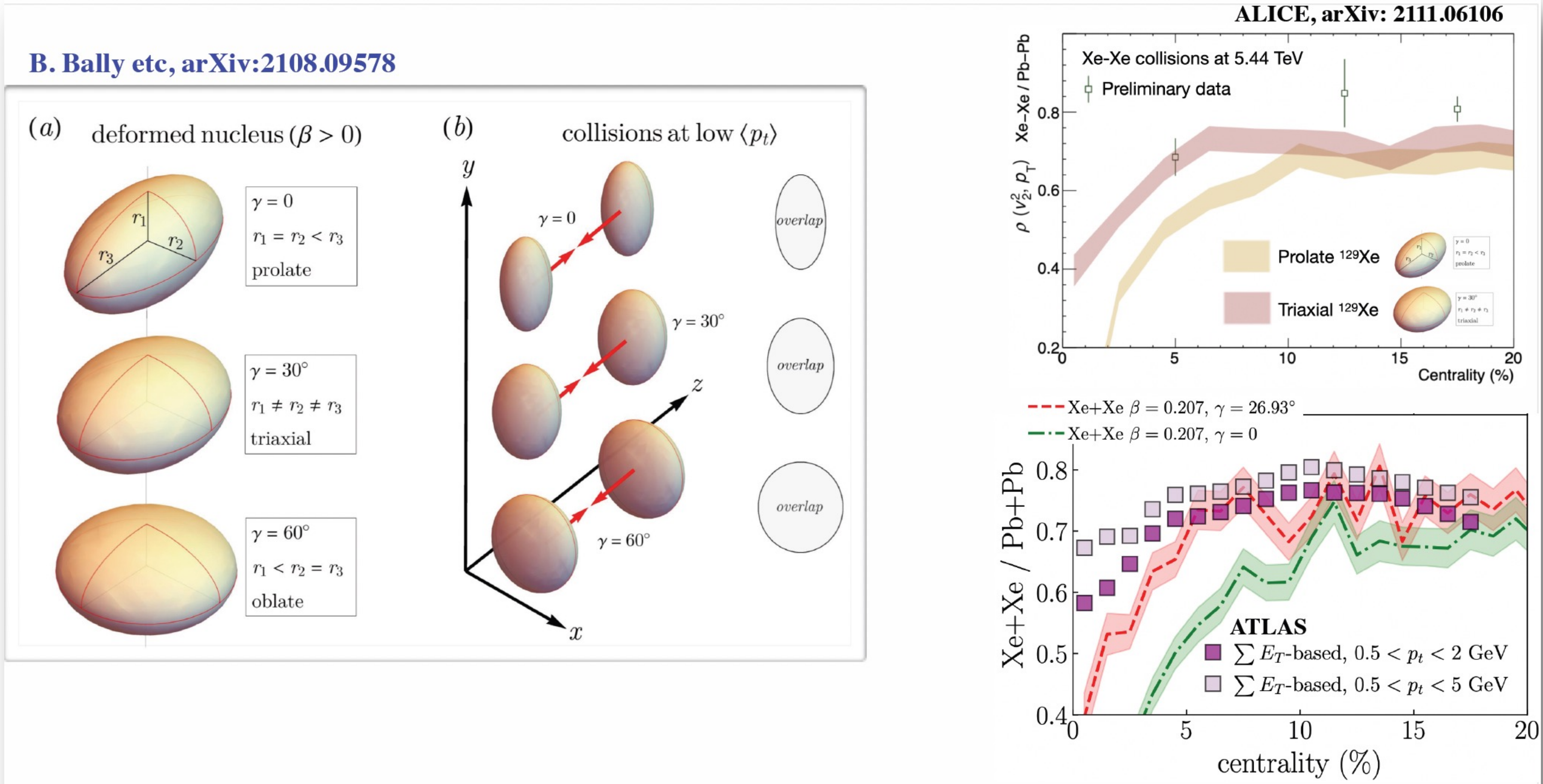
- **Cluster decay** in HERWIG
  - Shower evolved up to a softer scale
  - All gluons forced to split into $q\bar{q}$ pairs
  - Identify colour-singlet clusters of partons following color flow
  - Clusters decay into hadrons according to available phase space





After LHC Run 3 & 4, we will have understood the formation mechanisms of A < 5 anti- and hyper-nuclei from collisions, but will only **start to probe** their production in b-quark decays. Run 5 & 6 will provide the **definitive answer**.

Nuclear structure ?



❖ Better agreement between LHC data and calculations with γ = 26.93°

- Indication of triaxial structure of ^{129}Xe at high energy collisions at the LHC
- New connection of high-energy heavy-ion physics to low-energy nuclear (structure) physics

→ Thanks to Y. Zhou for providing the input!

Summary and conclusion

Summary and conclusion

- Keep one thing in mind: the LHC will be the only very high energy hadron-hadron collider for many many years to come.
- It is our duty to fully exploit it! It is the only place where a high energy heavy-ion program can be pursued in the foreseeable future.
- ALICE 3 offers a unique opportunity to fully complete the heavy-ion physics program at very high energies. This does not only include traditional heavy-ion physics topics, but also the new avenues discussed at this and similar workshops!

Thank you!

Planning

- **2023-25**: selection of technologies, small-scale proof of concept prototypes (~ 25% of R&D funds)
- **2026-27**: large-scale engineered prototypes (~75% of R&D funds) → Technical Design Reports
- **2028-31**: construction and testing
- **2032**: contingency
- **2033-34**: Preparation of cavern and installation of ALICE 3