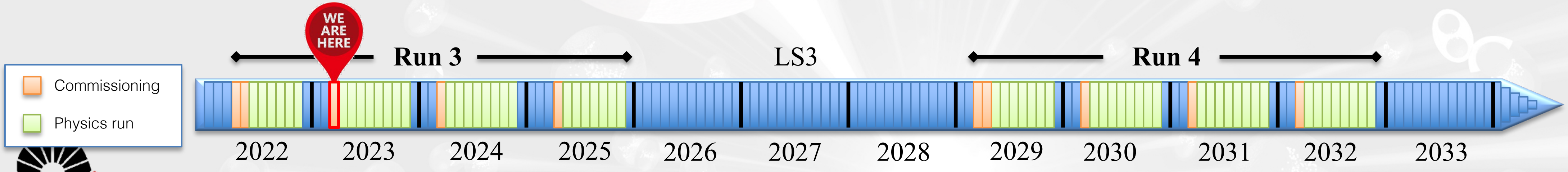
Heavy-ion physics at the LHC beyond Run 4

David Dobrigkeit Chinellato

Hard Probes 2023 - 30th March 2022

Setting the stage for Run 5+6: the Run 3+4 programme

disclaimer: this slide only mentions a few highlights!



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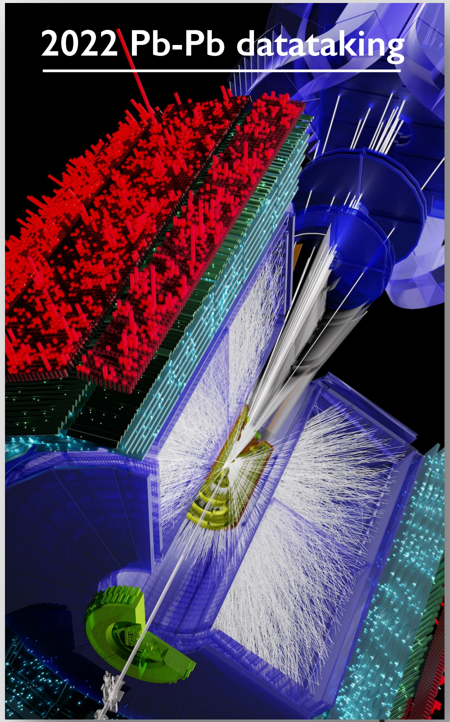
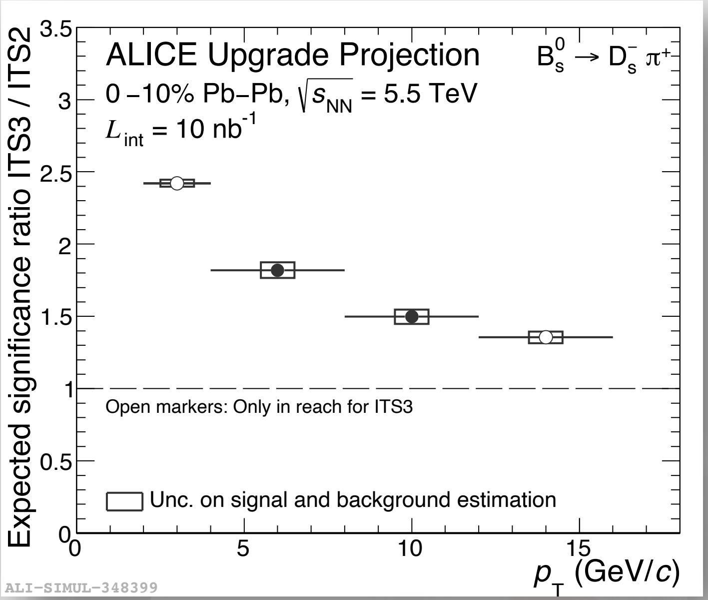
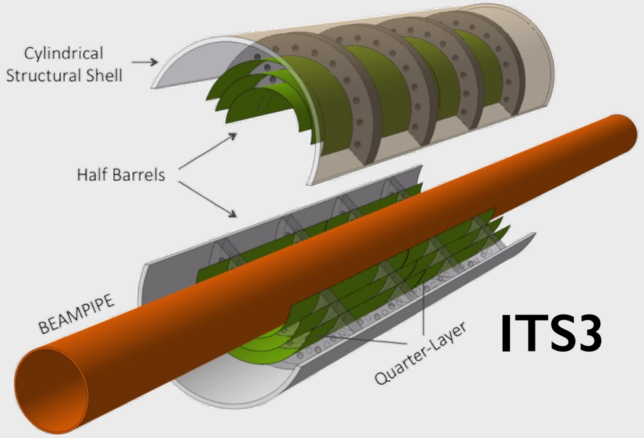
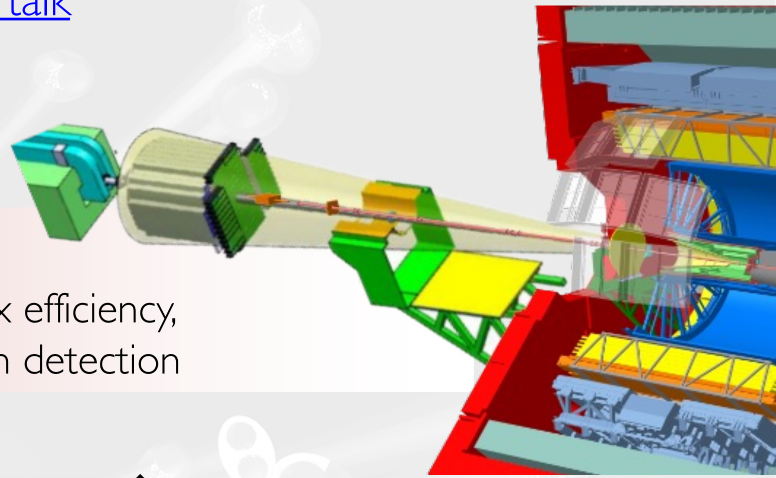




ITS3: See Jory Sonneveld's talk
Tuesday 15:40

FoCal: See Tatsuya Chujo's talk
Tuesday 15:20

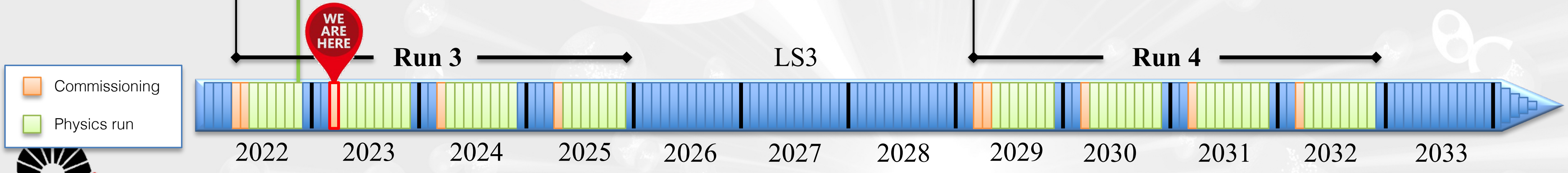




Gem-based TPC, ITS2, software upgrade
Low-pT single HF, high-mult pp/p-Pb, nuclei production up to A = 4, hadronic interactions

ITS3, FoCal
3x tracking precision, 2x efficiency, forward (direct) photon detection

ALICE



FoCal

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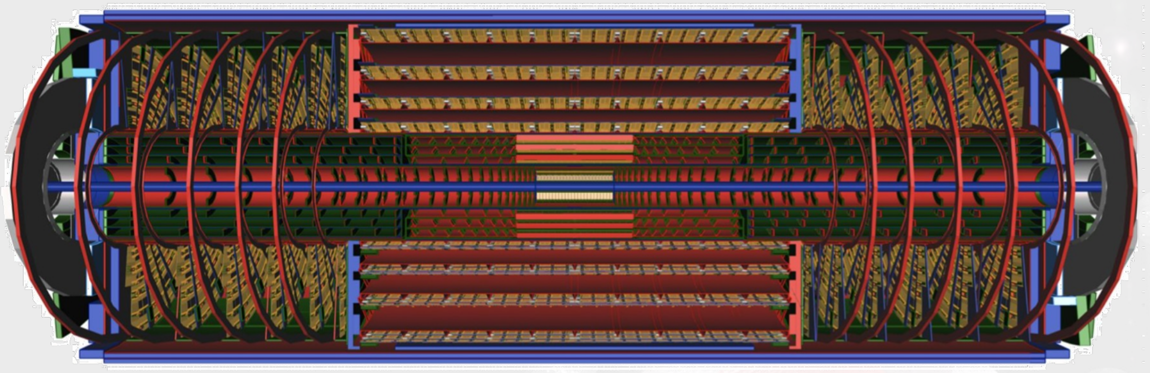
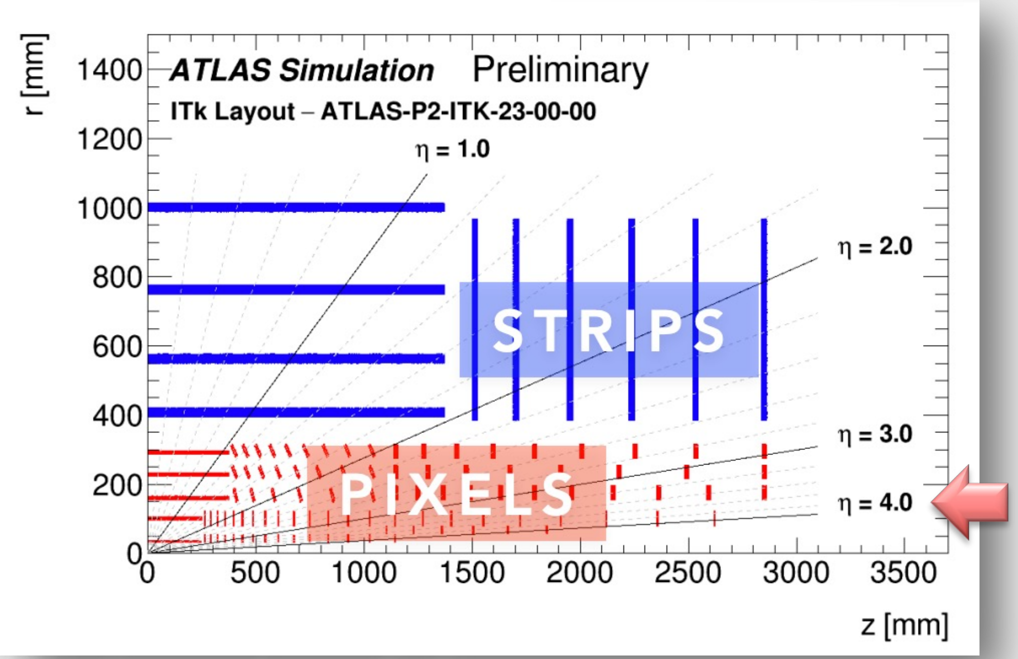




ATLAS EXPERIMENT

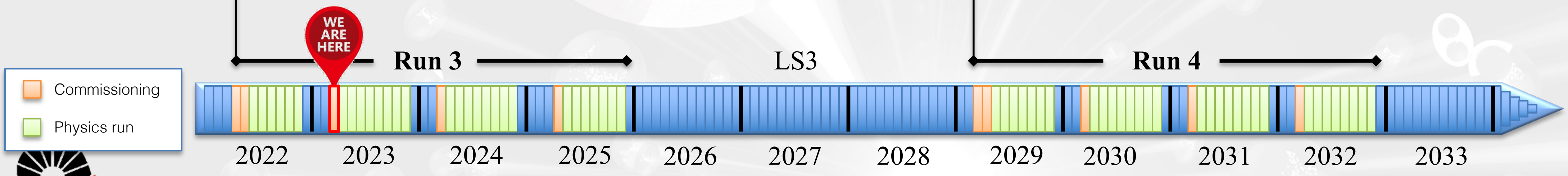
ZDC upgrade, RPD

Higher-luminosity-enabled centrality determination, reaction plane determination

ITk, HGTD, HL-ZDC

Silicon-based inner tracker with wide η coverage

High-granularity timing detector (forward): TOF



Setting the stage for Run 5+6: the Run 3+4 programme

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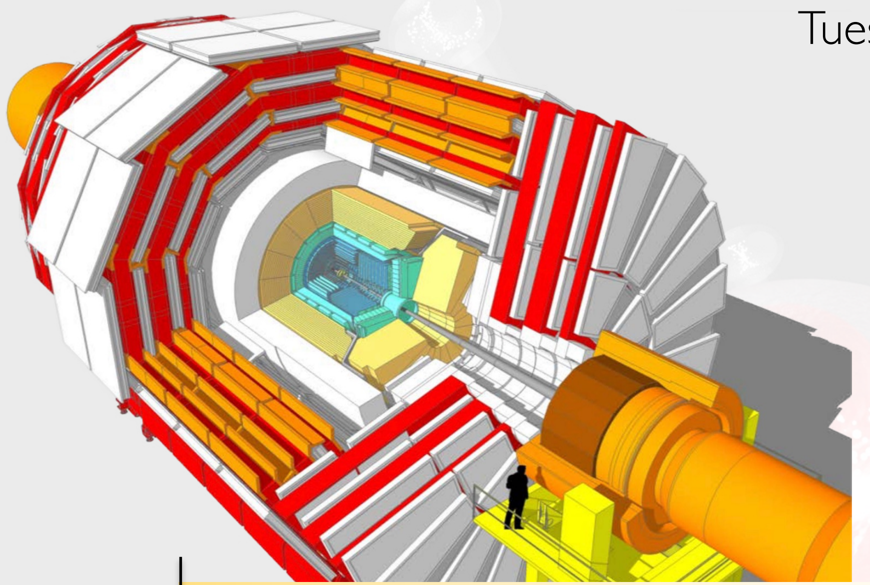
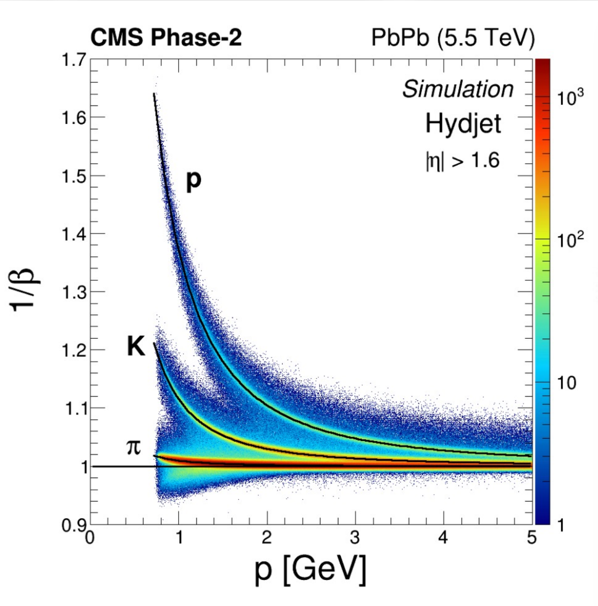
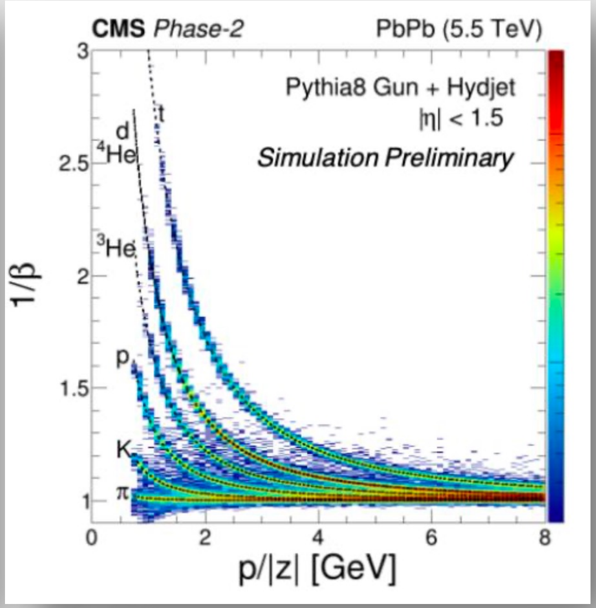
See <u>Yen-Jie Lee's talk</u>
Tuesday 14:00

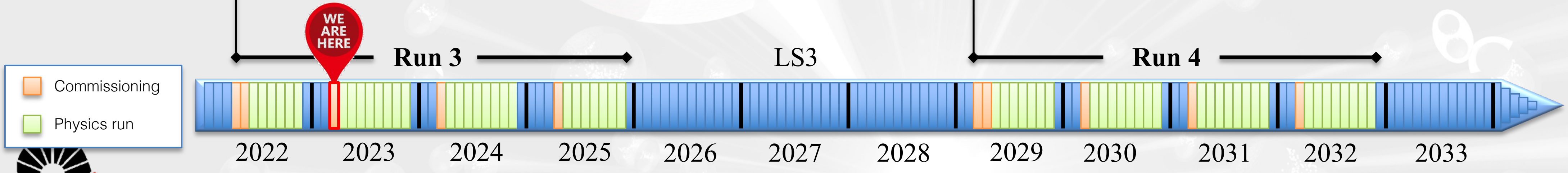






Inner tracker, HCal, Forward muon system
Increased bandwidth, larger MB statistics

MTD, phase 2 tracker upgrade
|η| < 4, π/K/p/nuclei PID, collectivity, HF diffusion, collectivity and hadronization



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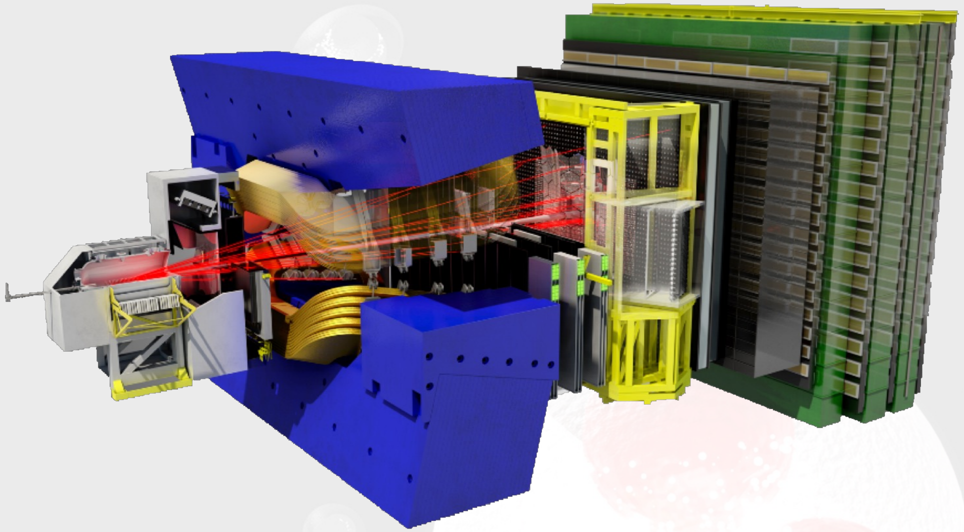
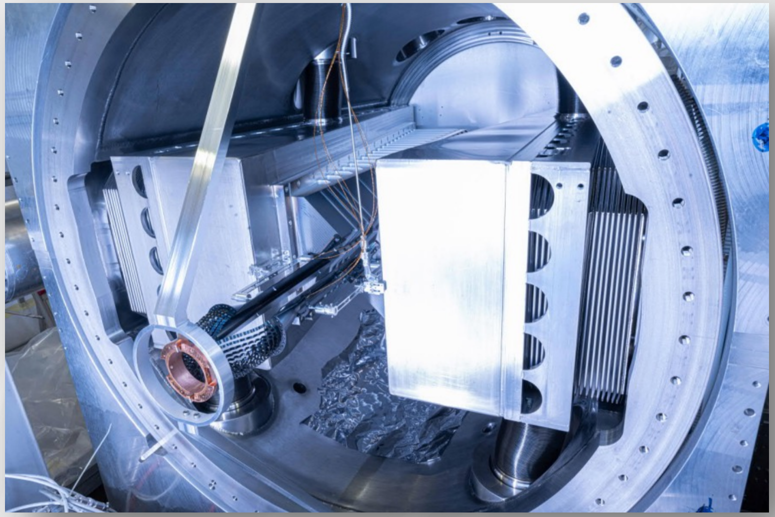


SMOG2: fixed-target, lighter ions

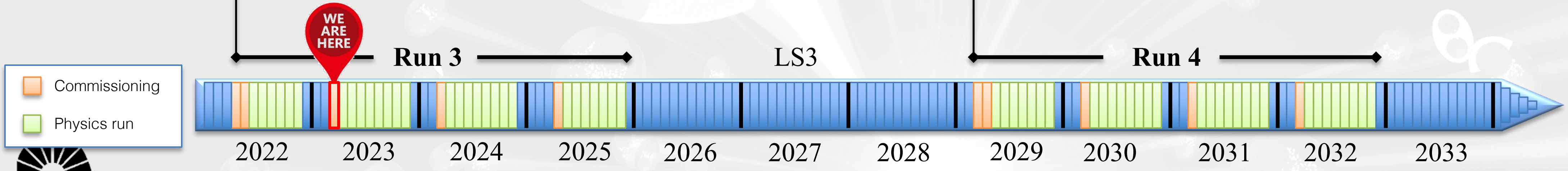


New VELO, SciFi, RICH upgrade

Improved tracking, 50 kHz Pb-Pb > 30% centrality

SciFi tracker upgrade

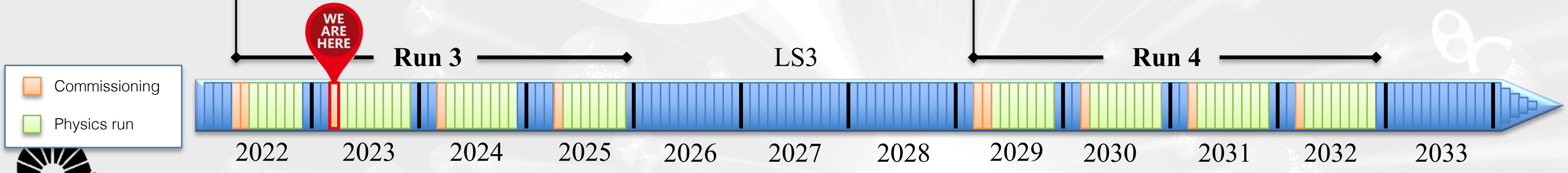
Further tracking improvement, lower momenta



A bright future ahead at the LHC: ALICE, ATLAS, CMS, LHCb

disclaimer: this slide only mentions a few highlights!

	Run 3	Run 4
ALICE	**Gem-based TPC, ITS2, software upgrade** Low-pT single HF, high-mult pp/p-Pb, nuclei production up to A = 4, hadronic interactions	**ITS3, FoCal** 3x tracking precision, 2x efficiency, forward (direct) photon detection
ATLAS EXPERIMENT	**ZDC upgrade, RPD** Higher-luminosity-enabled centrality determination, reaction plane determination	**ITk, HGTD, HL-ZDC** Silicon-based inner tracker with wide η coverage High-granularity timing detector (forward): TOF
CMS	**Inner tracker, HCal, Forward muon system** Increased bandwidth, larger MB statistics	**MTD, phase 2 tracker upgrade** $\|\eta\| < 4$, π/K/p/nuclei PID, collectivity, HF diffusion, collectivity and hadronization
LHCb	**New VELO, SciFi, RICH upgrade** Improved tracking, 50 kHz Pb-Pb > 30% centrality	**SciFi tracker upgrade** Further tracking improvement, lower momenta



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ALICE

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LHCb

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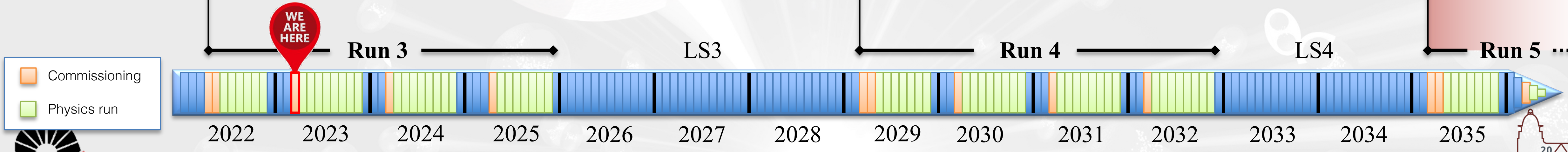
Further tracking improvement, lower momenta

The Future is Now

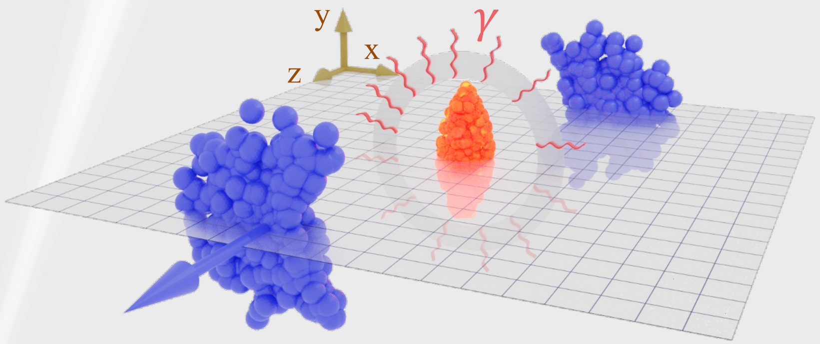
(This talk!)

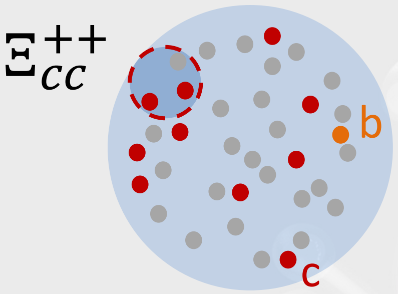


Heavy-ion physics in the 2030s

Thermal emission of the QGP as the system evolves

- More differential dilepton invariant mass spectrum
- Understand system evolution more directly
- Search for chiral symmetry restoration

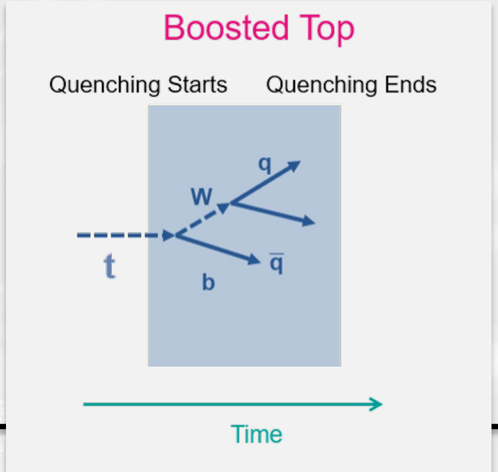




(Multi-)charm and beauty thermalisation and collectivity in the medium

- Full map of heavy-flavour yields, hadronization and collective behaviour
- Systematic, wide-p_T measurements from D^0 to Ξ_{cc}^{++}, Ω_{ccc}^{++}
- Precise correlations of $c\bar{c}$ pairs over wide acceptance

- **Delayed energy loss probing with boosted top: $t \rightarrow b + W \rightarrow q\bar{q}$**
- **Possibility to run with different ions**: p, O, Ar, Ca, Kr, In, Xe, Pb
- **Exotic, heavy-flavour states** formed in and out of medium
- **Correlations (HF, jet-Z, …) and net quantum number fluctuations**
- **Hadronic interactions** of heavy-flavour hadrons



LHCb Upgrades for Run 5

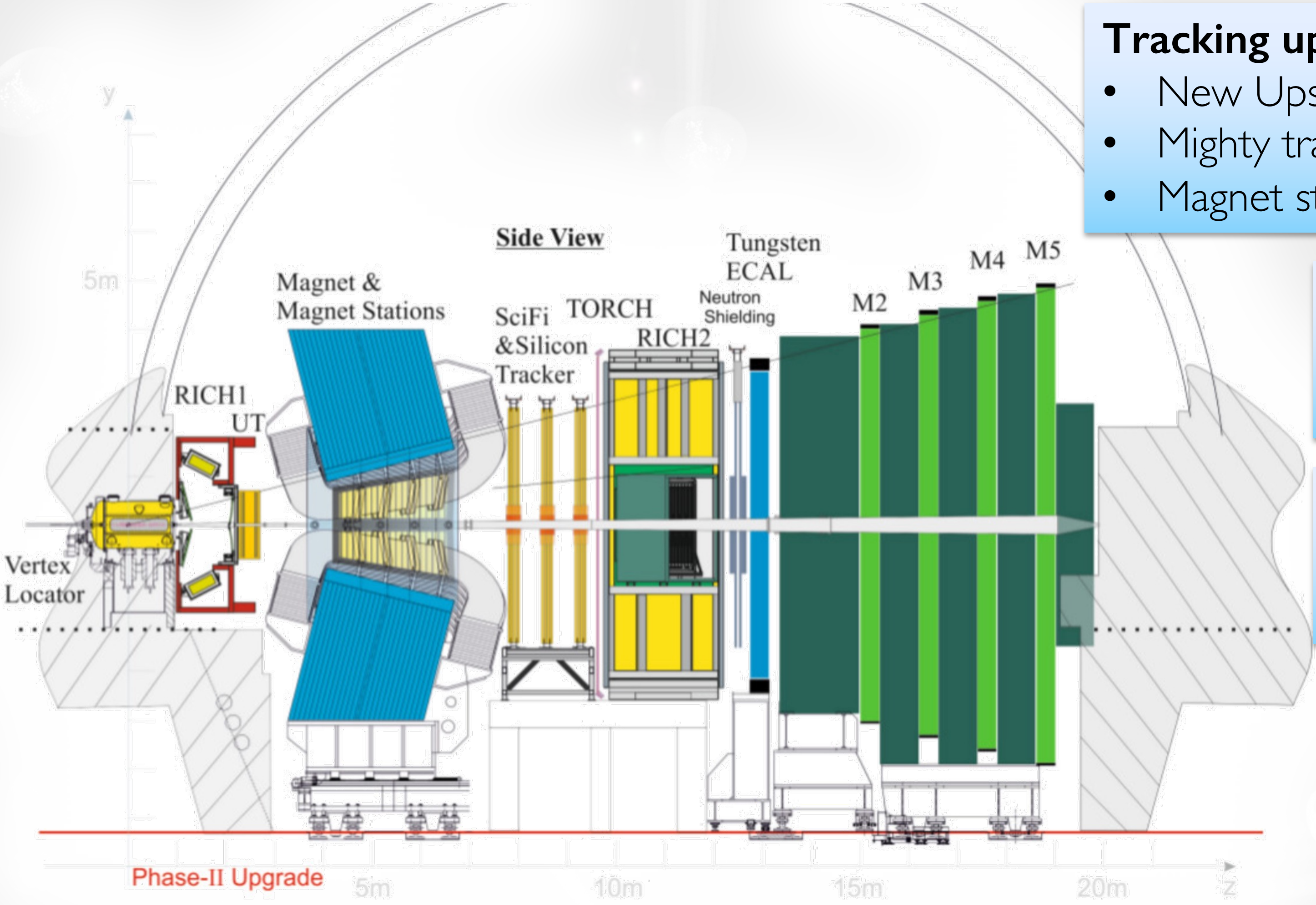
[CERN-LHCC-2021-012]

RICH
- RICH1 and RICH2
- With precision timing

TORCH
- Time-of-flight wall
- Precision timing

New VErtex LOcator
- Precision timing

Fixed target
- Extension with polarised gas target, solid target



Tracking upgrade
- New Upstream Tracker (timing)
- Mighty tracker (SciFi+silicon)
- Magnet stations for lower p_T

Muon stations
- M2 – M5
- Additional shielding

Calorimeters
- SPACAL or Shashlik
- Precision timing

- **No centrality limitation in Pb-Pb**
- **Excellent vertexing capabilities**

LHCb Physics in Run 5

- Detector with phase II upgrades will be able to cope with heavy-ion multiplicities
- Unique forward coverage gives access
  to many observables of interest for heavy-ion physics, e.g.
  - **Quarkonium and open heavy flavour**
    - $\Psi(2S)$, Υ
    - open charm and beauty mesons down to $p_T = 0$
    - P wave charmonium states, also for fixed target
  - **Dileptons and photons**
    - dilepton spectrum in di-muon channel in the rho mass region
    - real photons through conversions
  - **Nuclear PDFs and saturation**
    - low-x regime of QCD

[CERN-LHCC-2021-012]

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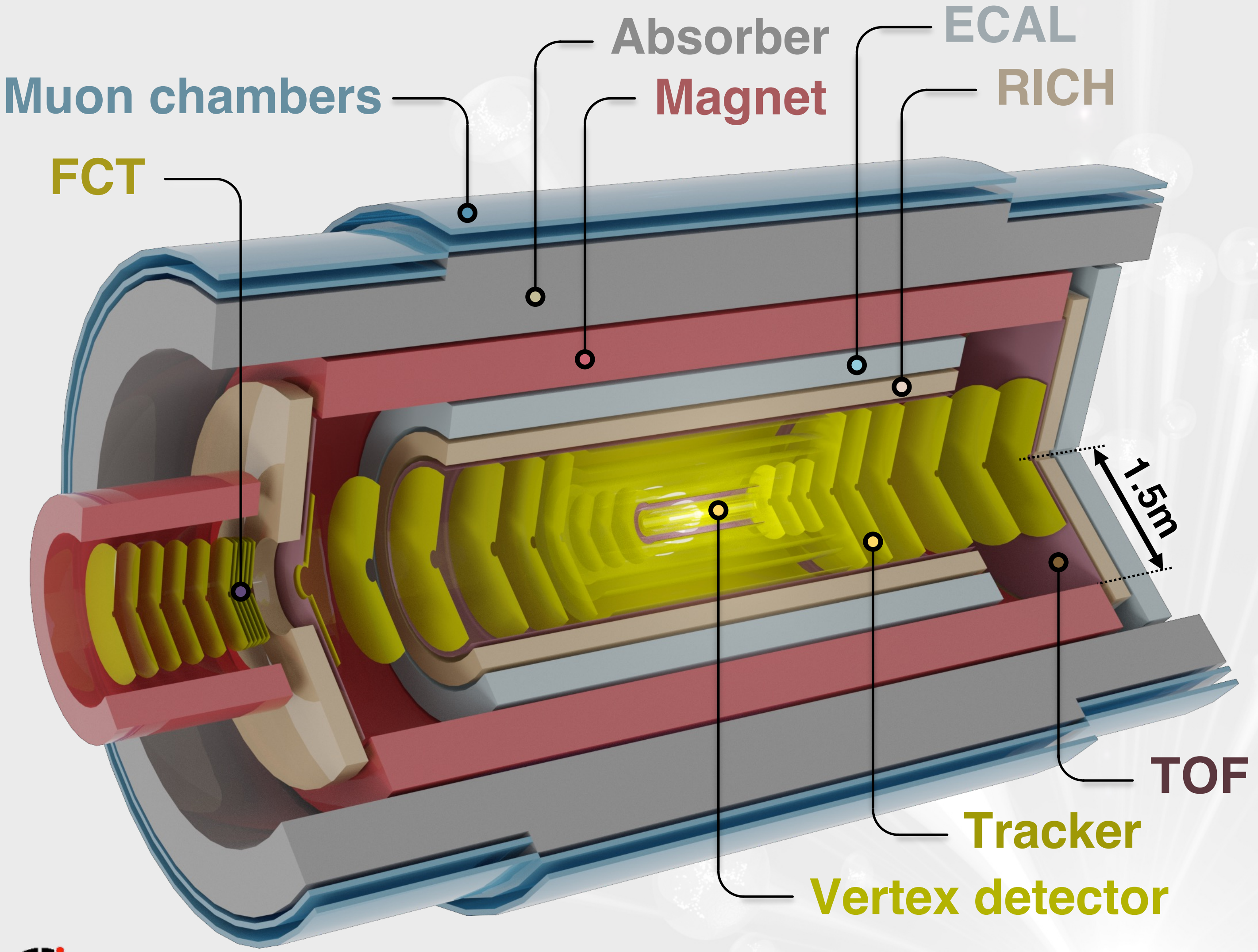
ALICE 3: a next-generation experiment for the 2030s



- **All-silicon, large-acceptance, low-p_T tracker**
  - High rate: 5x bigger luminosity, exploit LHC
  - Momentum precision of $\sigma_p/p \sim 1\%$
  - $\sim 10\%\ X_0$ overall material budget
- **State-of-the-art particle identification**
  - Silicon-based TOF and RICH
  - Muon identification
- **Very high vertexing precision**
  - First layer at 5 mm from interaction point
  - Impact parameter resolution:
    - ~10 µm at p_T ~200 MeV/c
    - ~3 µm at p_T > 1 GeV/c

Enables a rich physics programme!
→ in what follows: a few highlights

See Alessandro Grelli's talk, Tuesday 14:20

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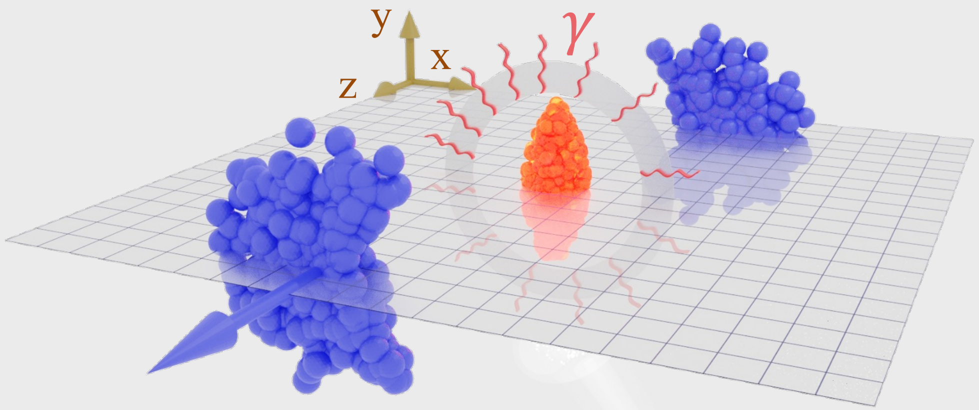
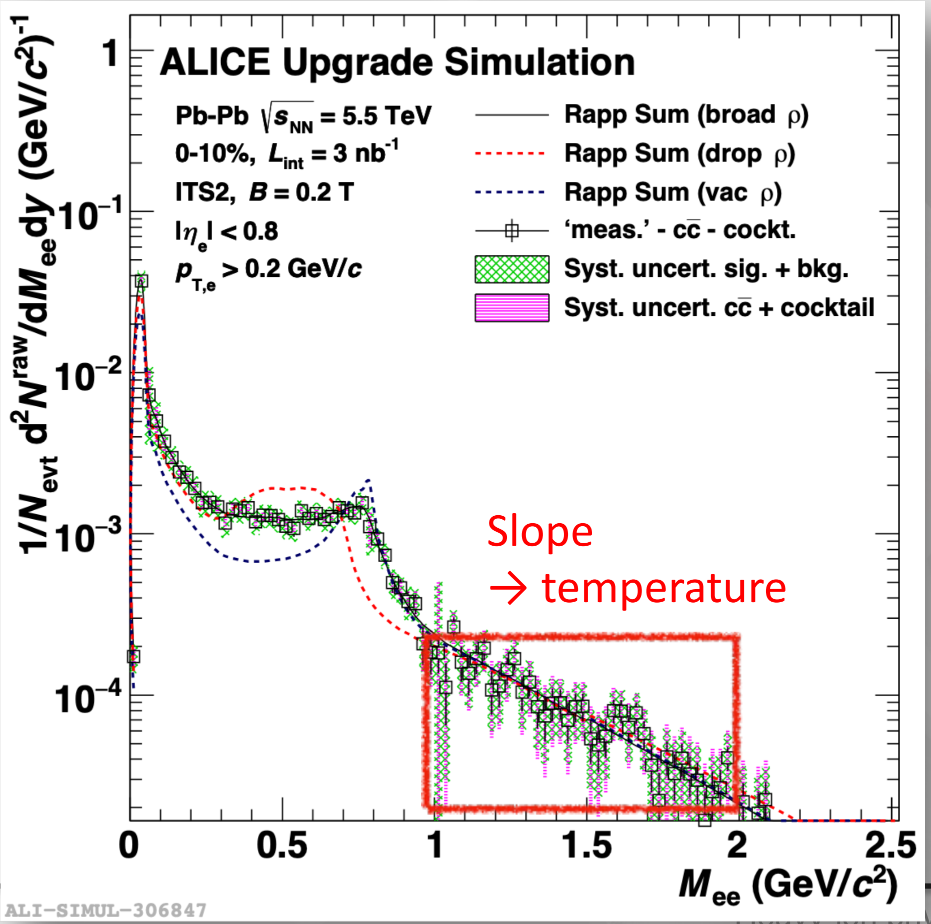
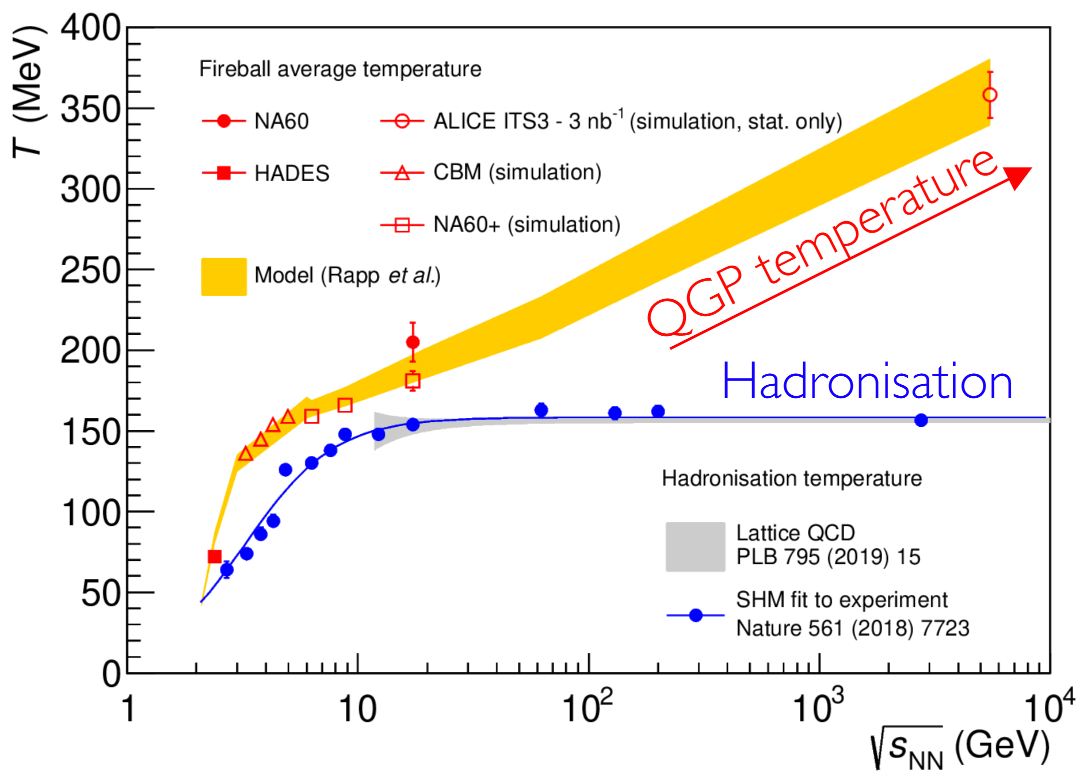


Thermal emission of the QGP in Runs 3+4 with dileptons

[CERN-LPCC-2018-07]





T. Galatyuk, https://github.com/tgalatyuk/QCD_caloric_curve

Runs 3+4: time-averaged QGP temperature

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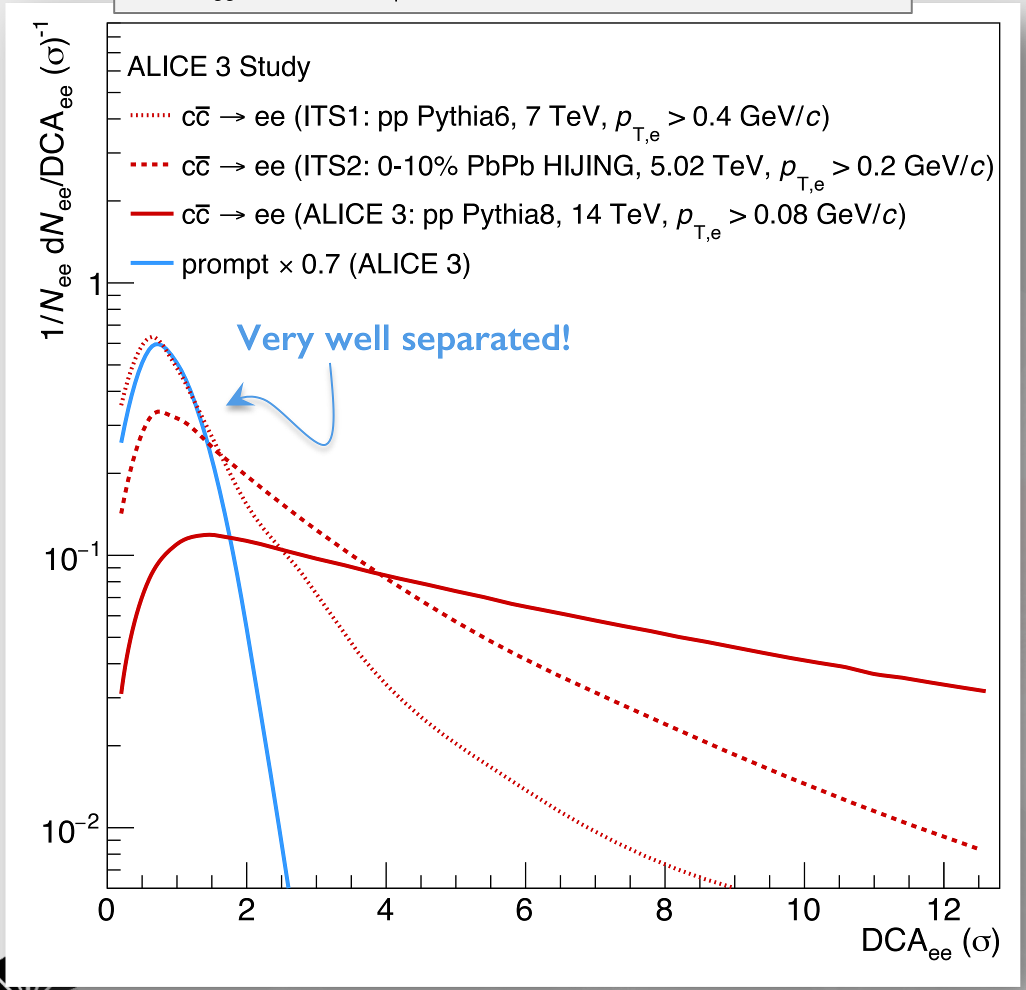
Dileptons as a QGP thermometer in Runs 5+6

DCA_{ee}: Sum of squares of normalized DCAs to PV



High-precision tracking

- 1st layer at R = 5mm

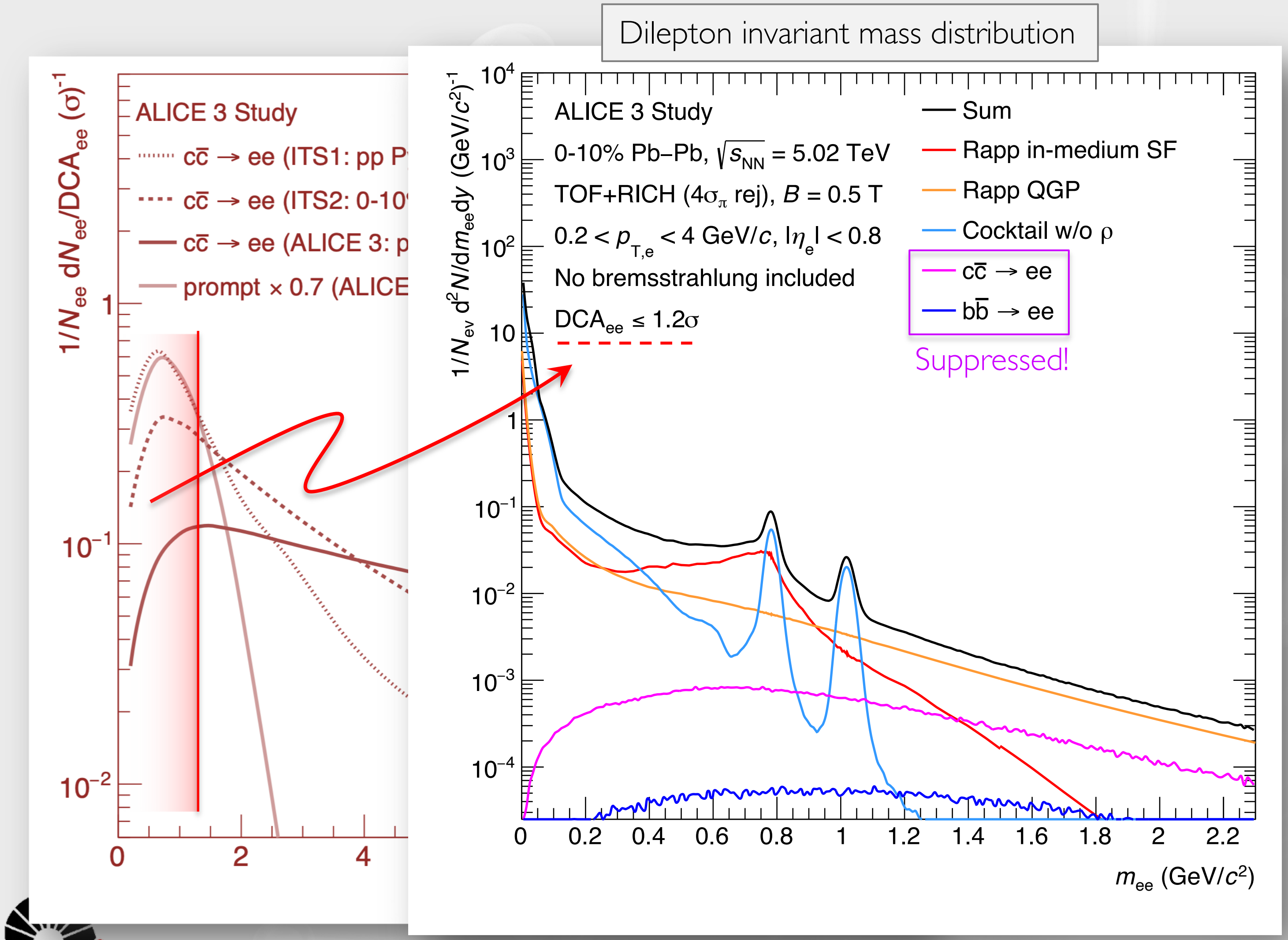
Electron Identification

- Time-of-flight (TOF) via silicon
- Ring-imaging Cherenkov (RICH)
- Electromagnetic Calorimeter

Unprecedented HF rejection and low-p_T electron ID

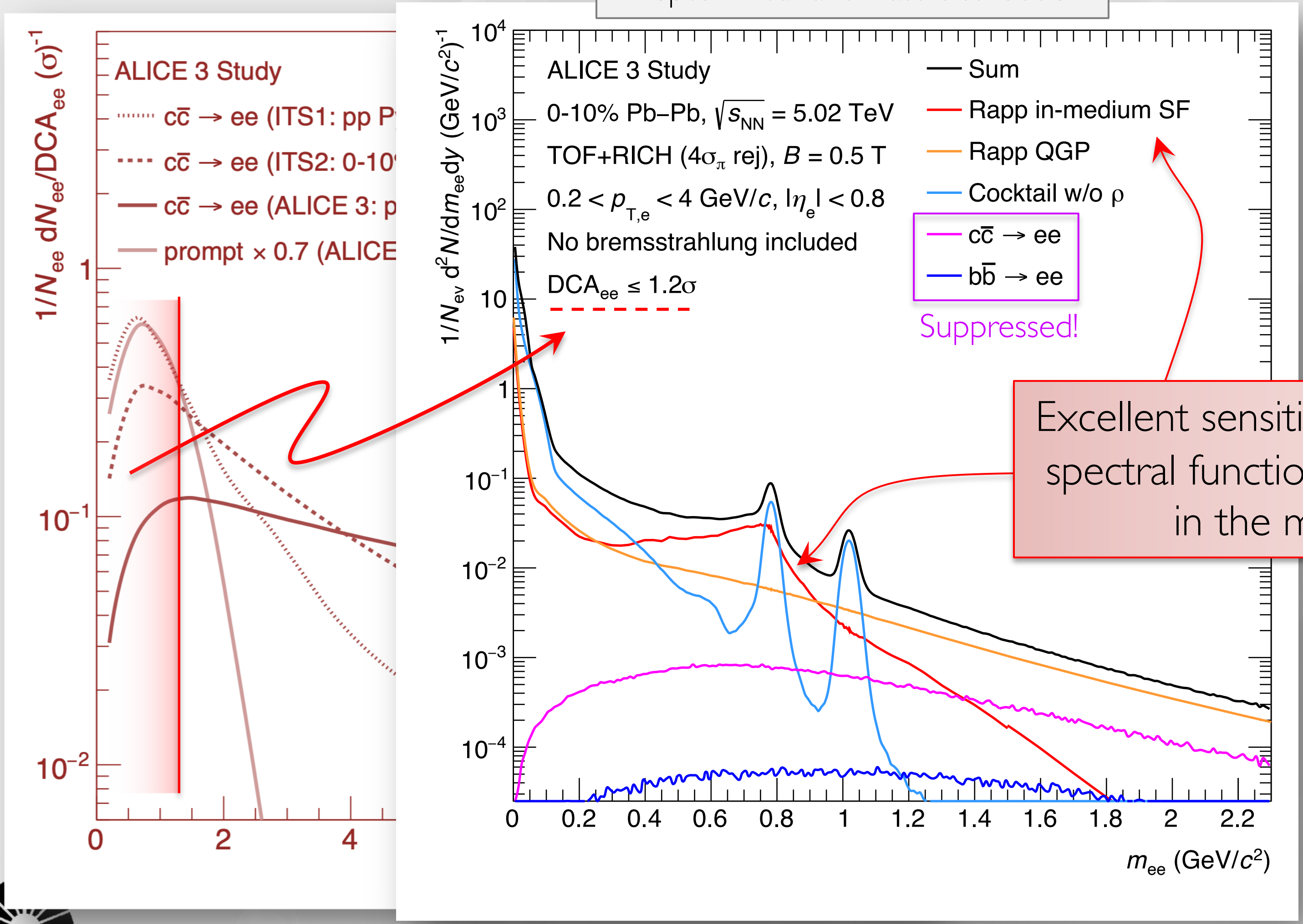
- DCA_{ee}: separation of e^+e^- pairs and HF daughters
  - ALICE 3: extreme performance!
  - Sets the stage: the ultimate dielectron experiment

Dileptons as a QGP thermometer in Runs 5+6



Dileptons as a QGP thermometer in Runs 5+6

Dilepton invariant mass distribution



Excellent sensitivity to $\rho^0(770)$ spectral function modification in the medium

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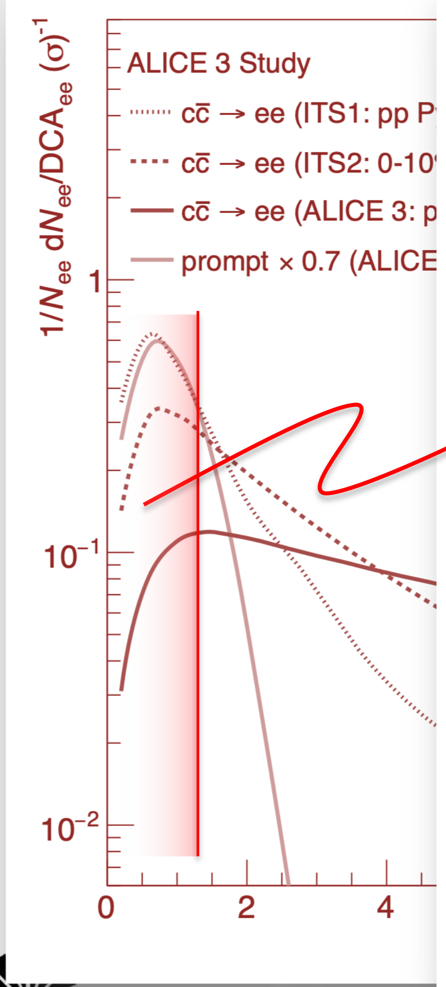
Dileptons as a QGP thermometer in Runs 5+6



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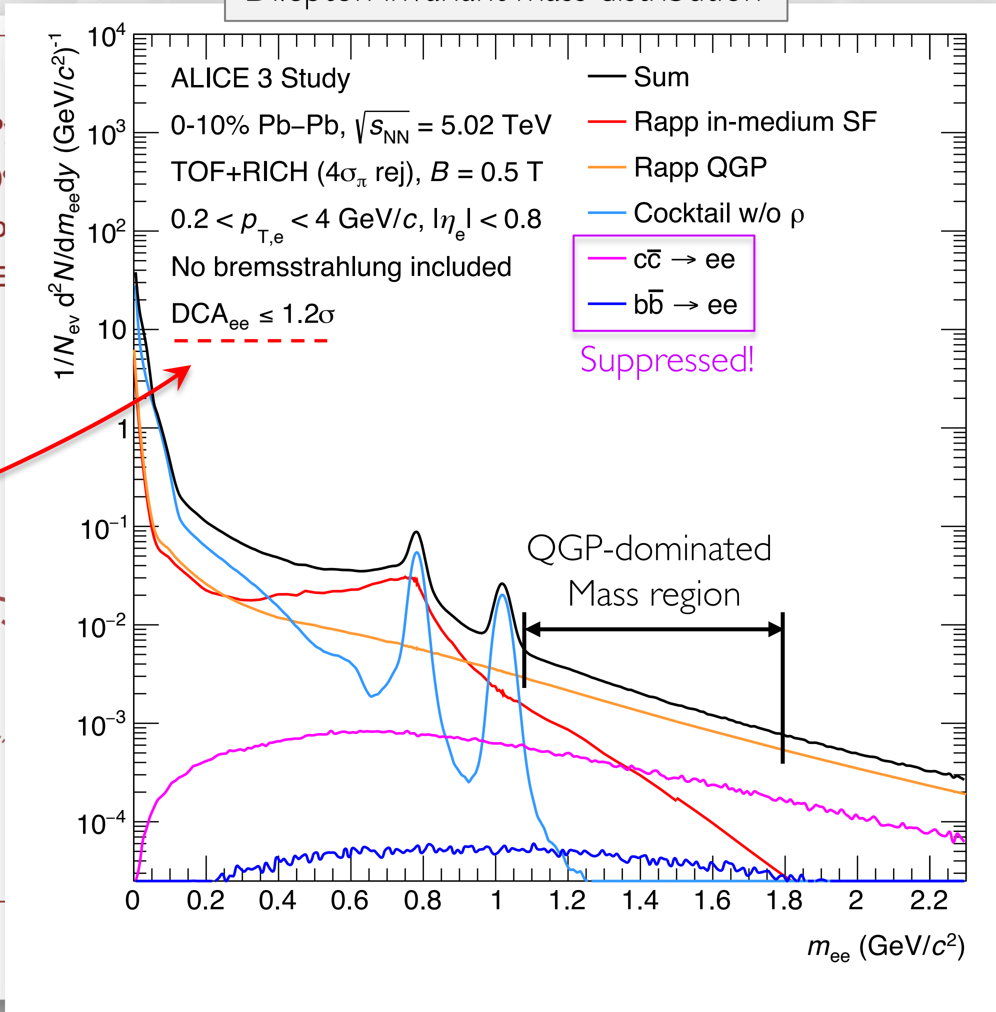

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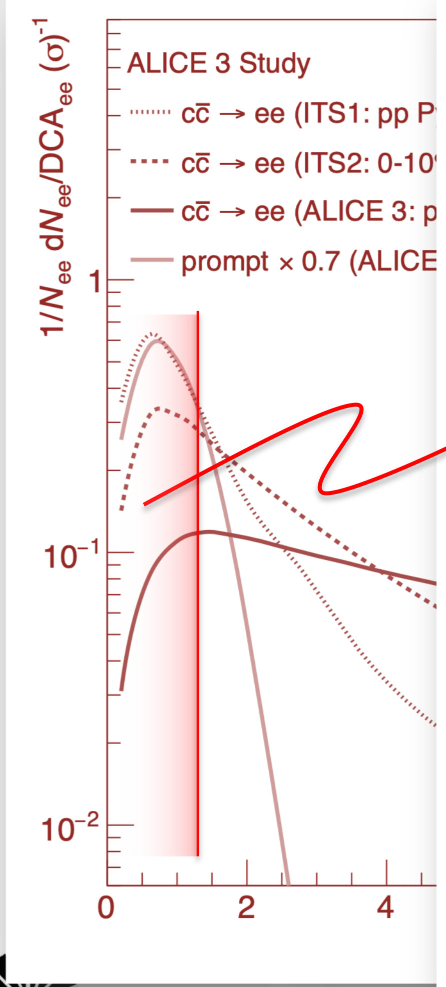
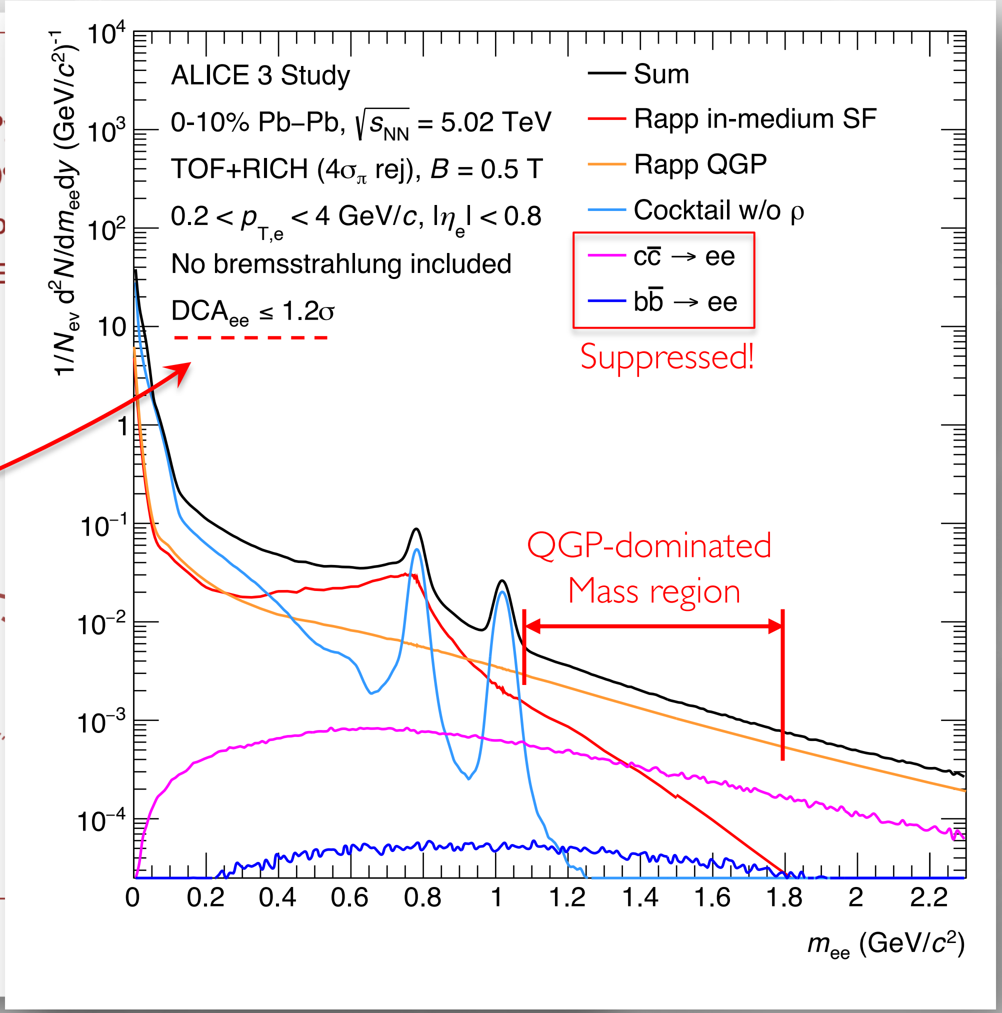
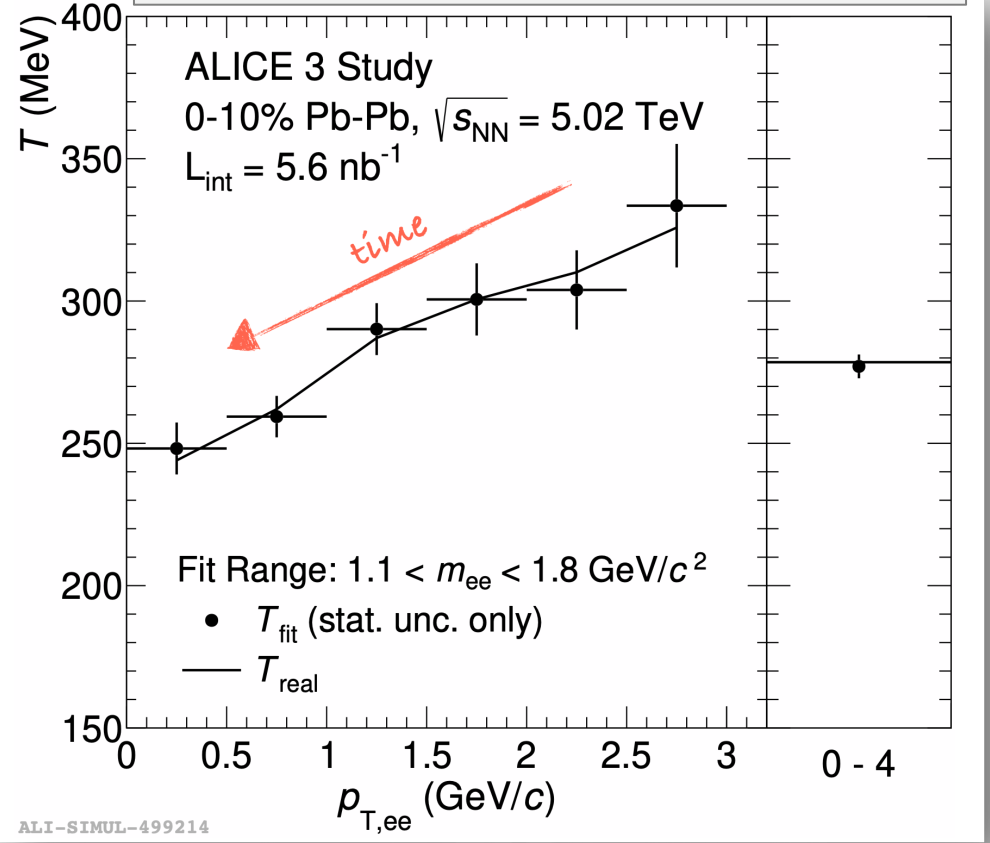




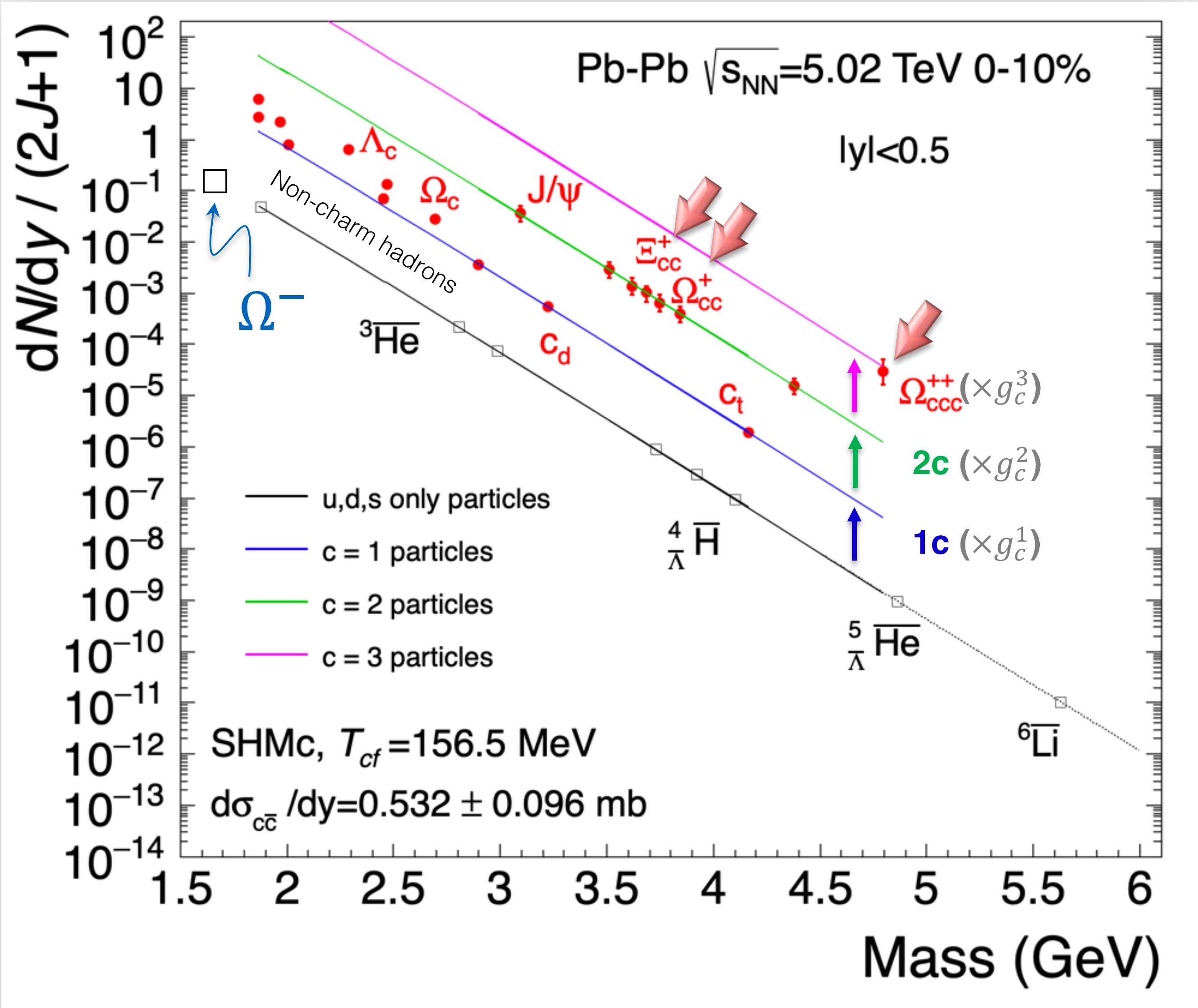
$p_{T,ee}$-differential mass slope in QGP-dominated region



Differential analysis in $p_{T,ee}$:

- Unique opportunity to probe system evolution!

Multi-charm thermalisation: Ξ_{cc}^{++}, Ω_{cc}^{+} and Ω_{ccc}^{++}



- u, d, s-hadrons: mass exponential hierarchy, dominated by quarks created at phase boundary (e.g. Ω^-)
  - Realm of classical strangeness studies
- Charm: still an exponential with mass (thermalised yields) but exponential displaced by charm fugacity g_c^n [1,2]
  - SHMc: g_c provides information about mechanisms
  - Due to large, fixed N_{charm}: game changer
  - Strongest for multi-charm: extreme sensitivity
    - Very large centrality dependence
  - Complete charm thermalization not a given

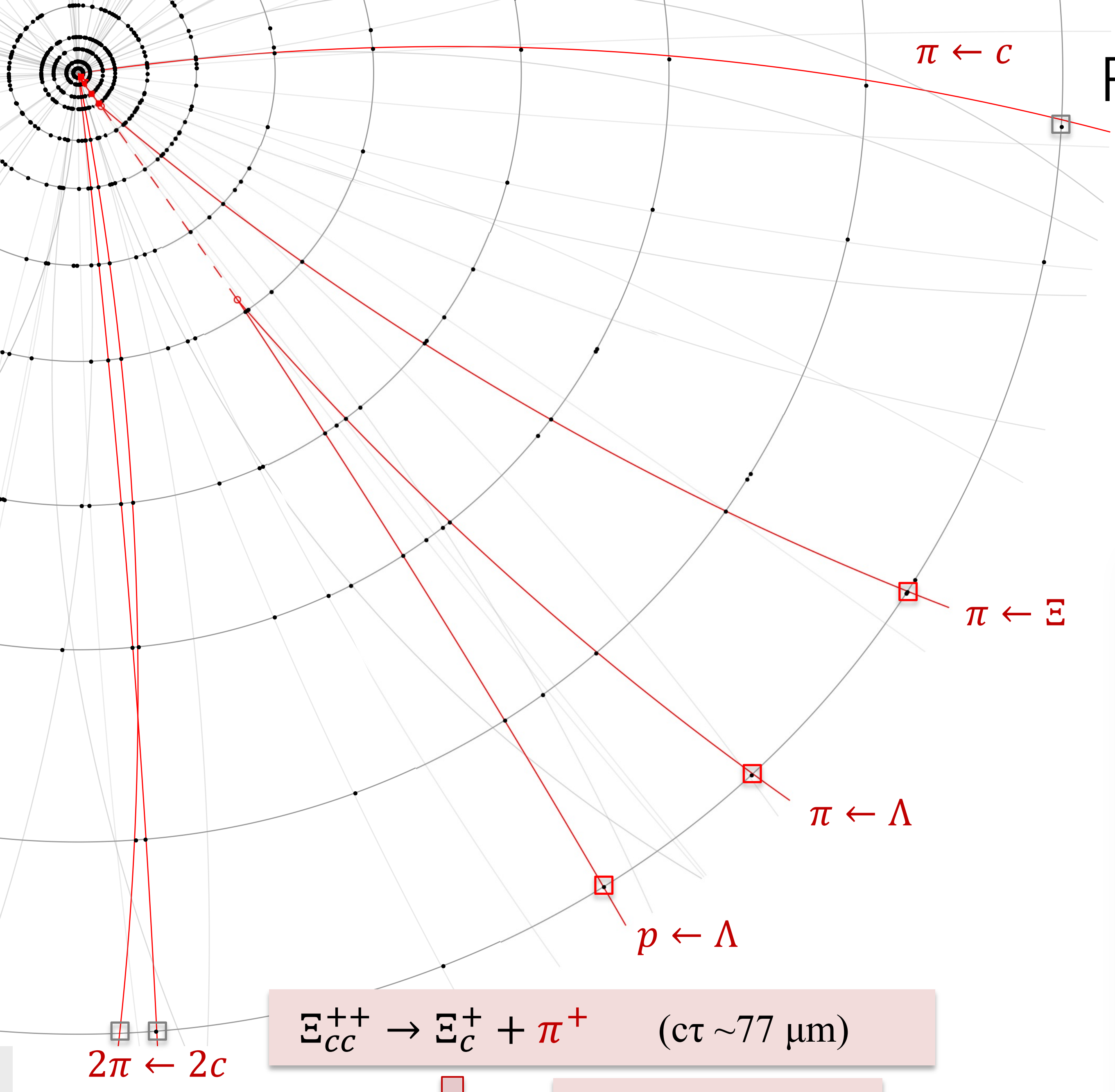
$\Xi_{cc}^{++} \rightarrow \Xi_c^{+} + \pi^{+}$ (cτ ~77 μm)

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

[1] ALICE 3 letter of intent
[2] JHEP **07** (2021) 035
[3] Andronic et al, QM2022

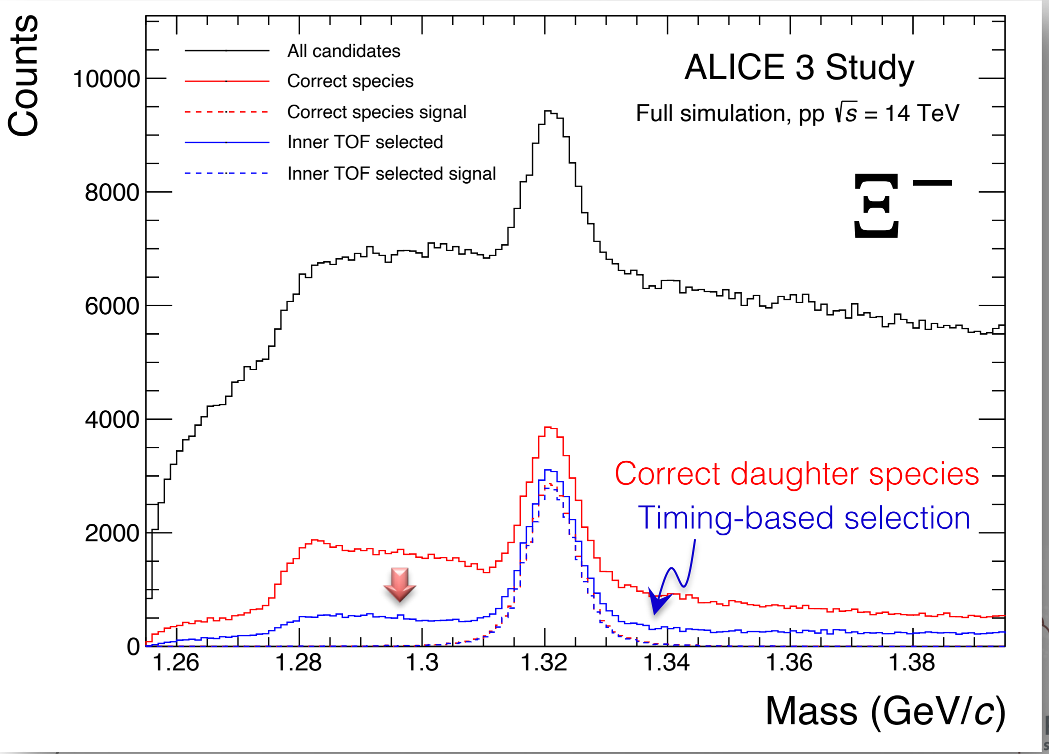
Reconstructing strange baryons in ALICE 3: Ξ^- and Ω^-

- TOF identification for Ξ decay products
  - Primary pions and protons arrive earlier than those from Ξ: heavy particles travel slower
- Don't just select π and p…
  - …select π and p which arrived late!



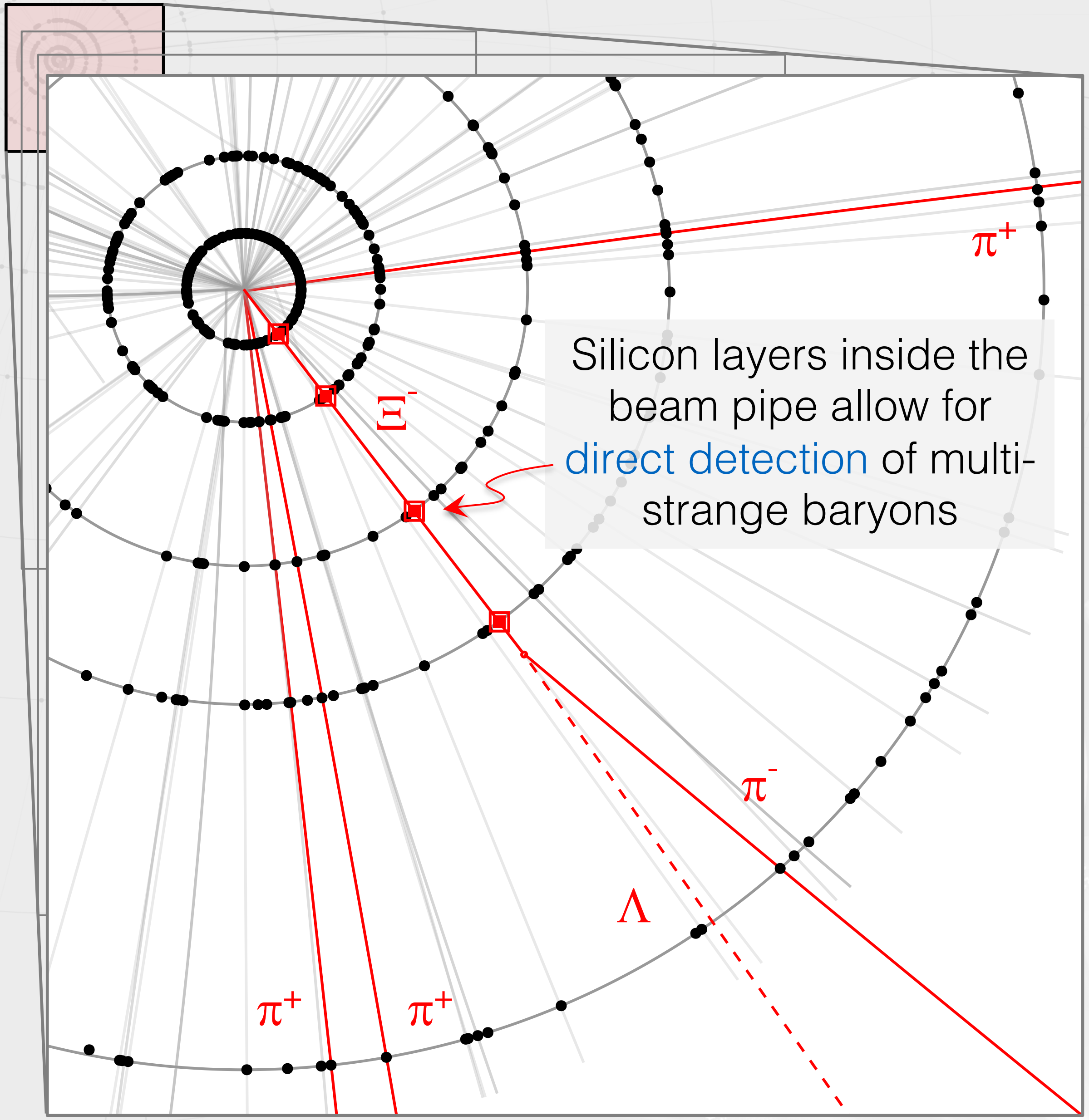
$$\Xi_{cc}^{++} \rightarrow \Xi_c^+ + \pi^+ \qquad (c\tau \sim 77\ \mu\text{m})$$

$$\Xi_c^+ \rightarrow \Xi^- + 2\pi^+$$



A crucial tool:

Strangeness tracking in ALICE 3



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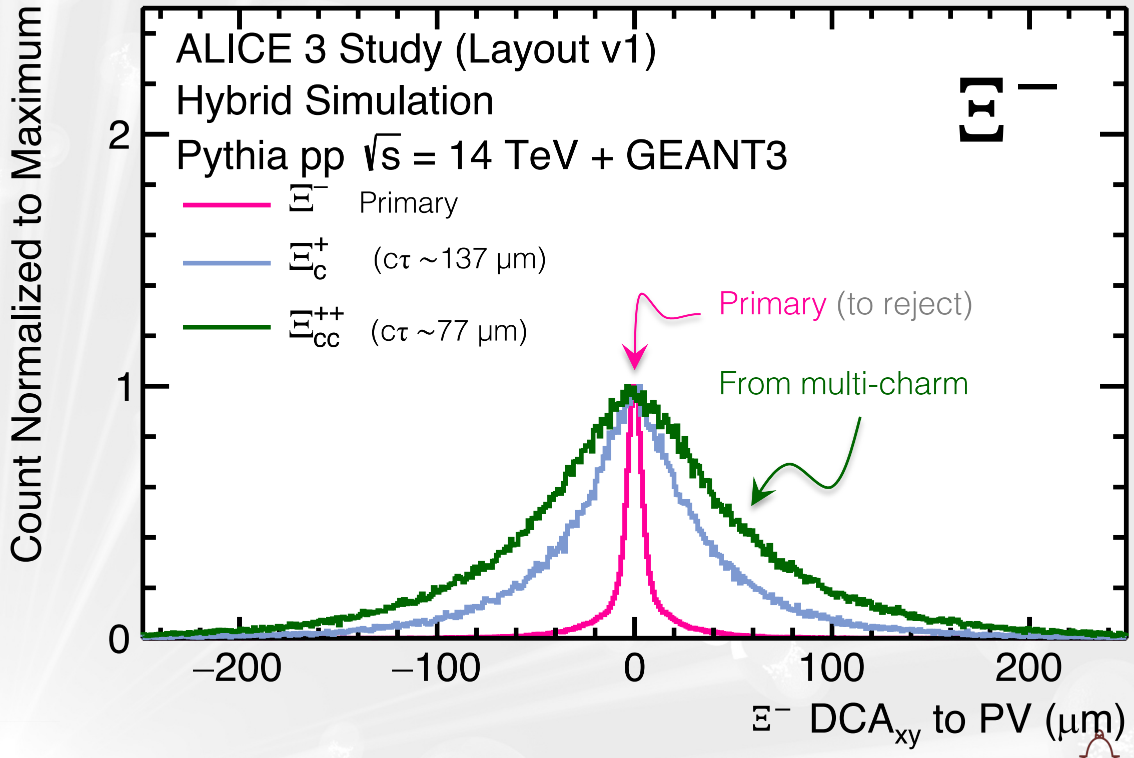

+ Timing information: select strange decay daughters within population of particles of the same species

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A crucial tool:

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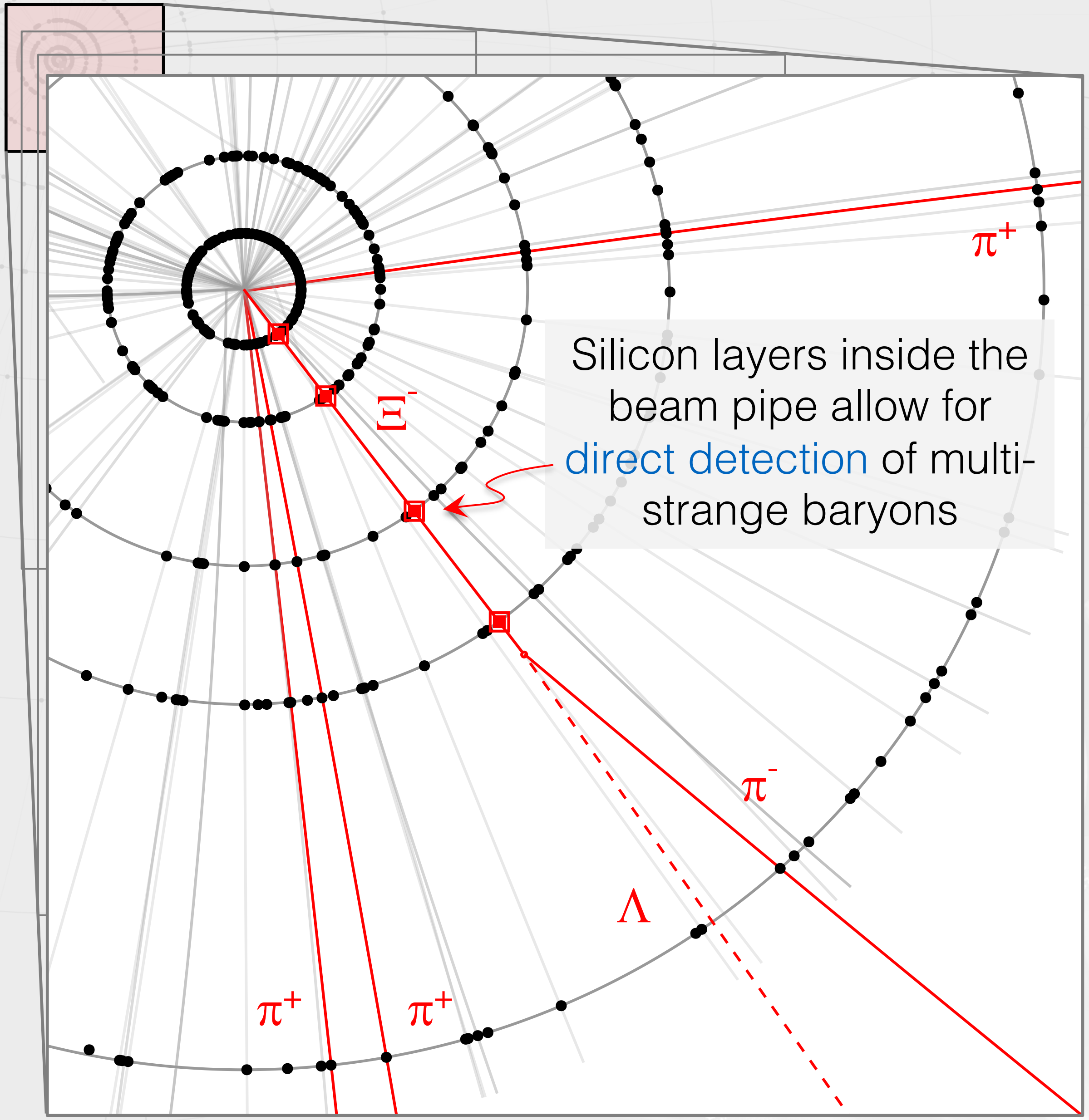

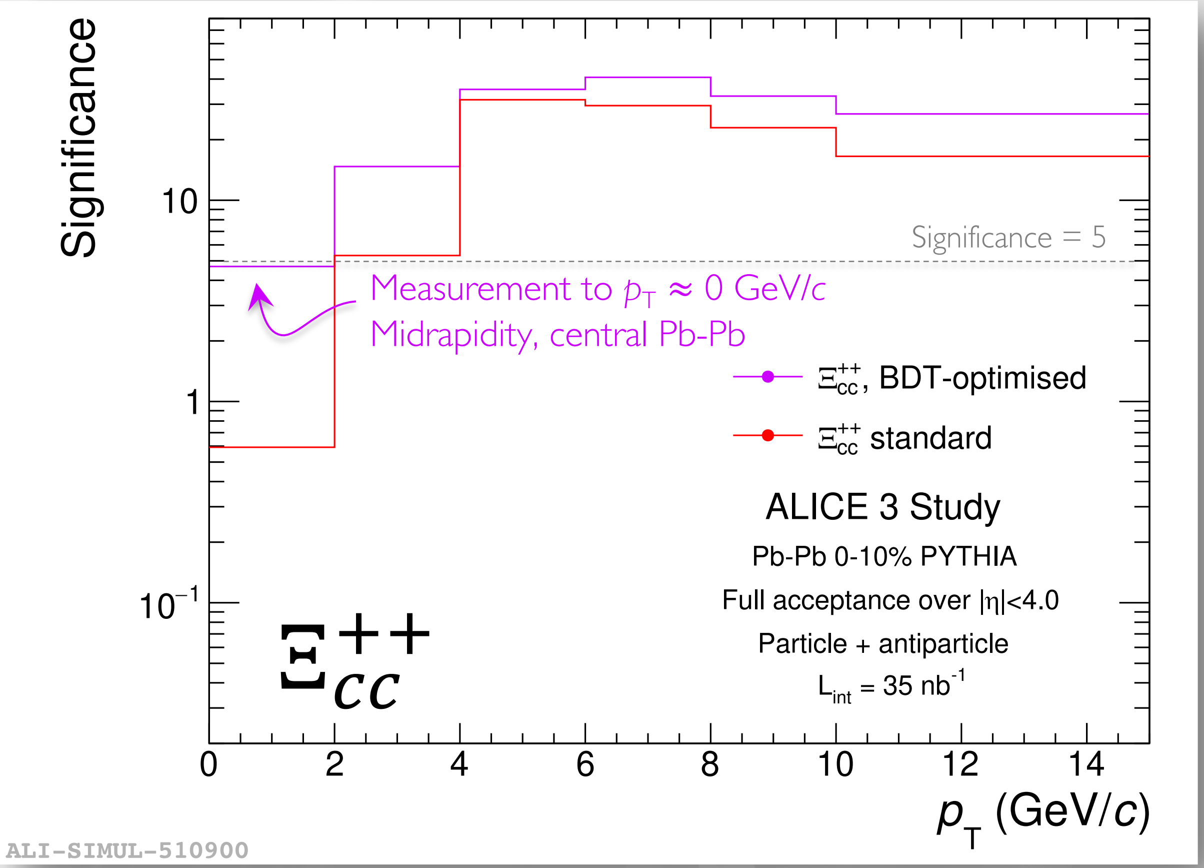

Expected Ξ_{cc}^{++} significance with 35 nb^{-1} of Pb-Pb data collected with ALICE 3

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A crucial tool:

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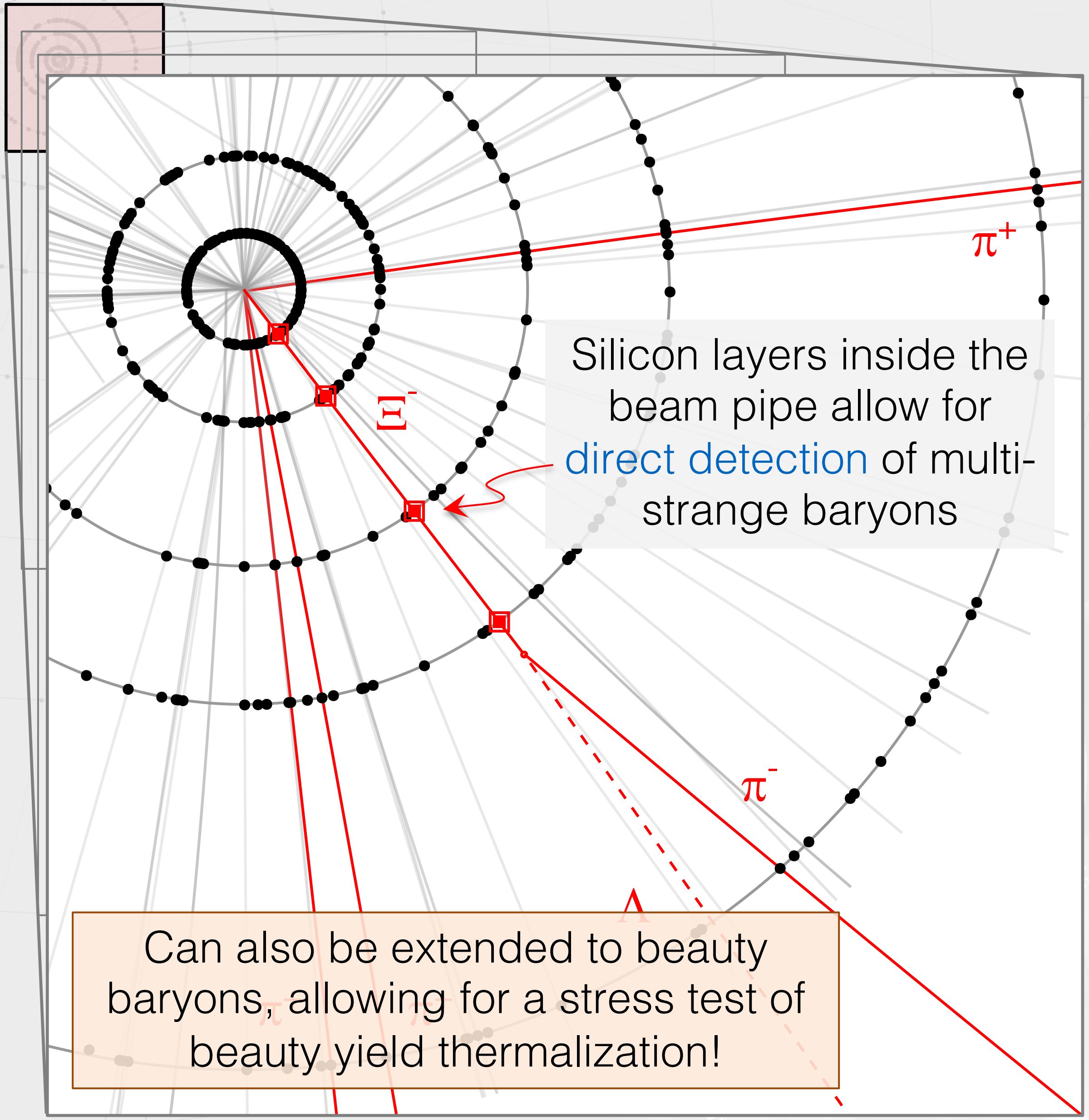
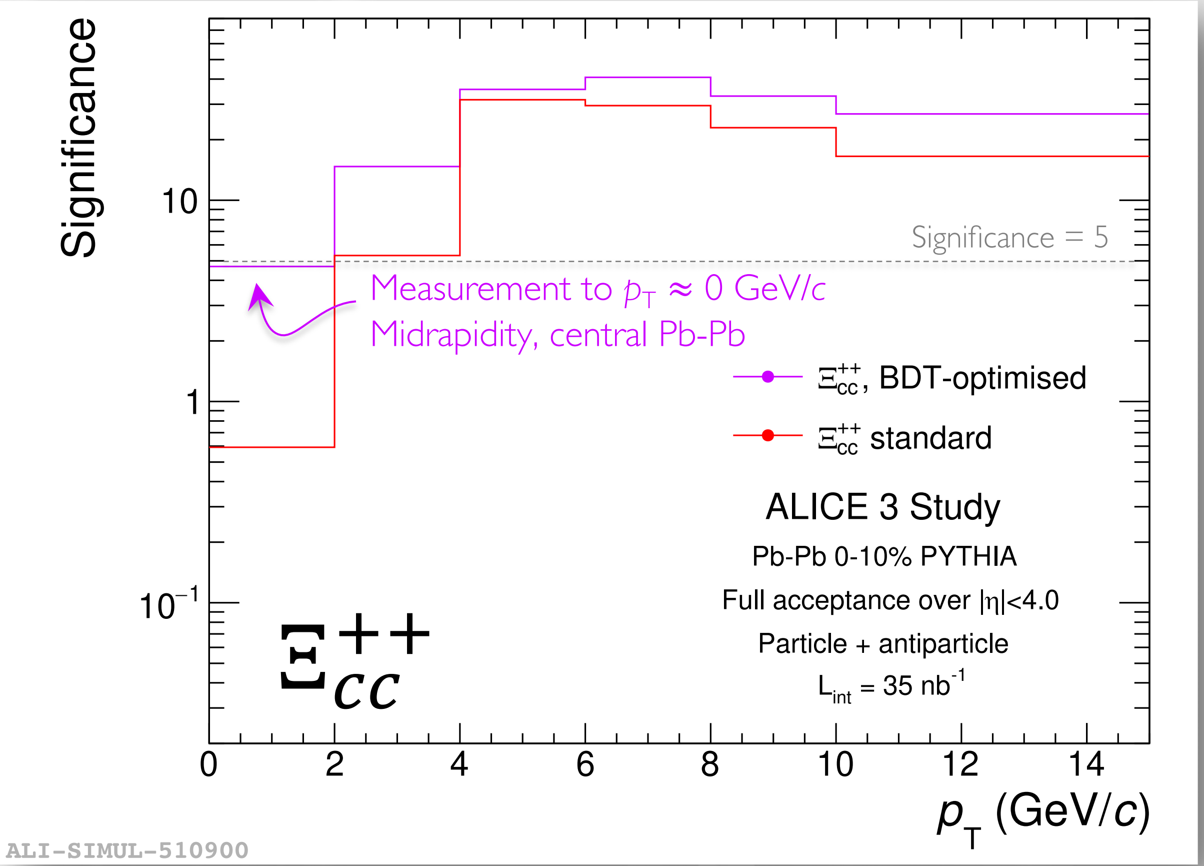


Silicon layers inside the beam pipe allow for direct detection of multi-strange baryons

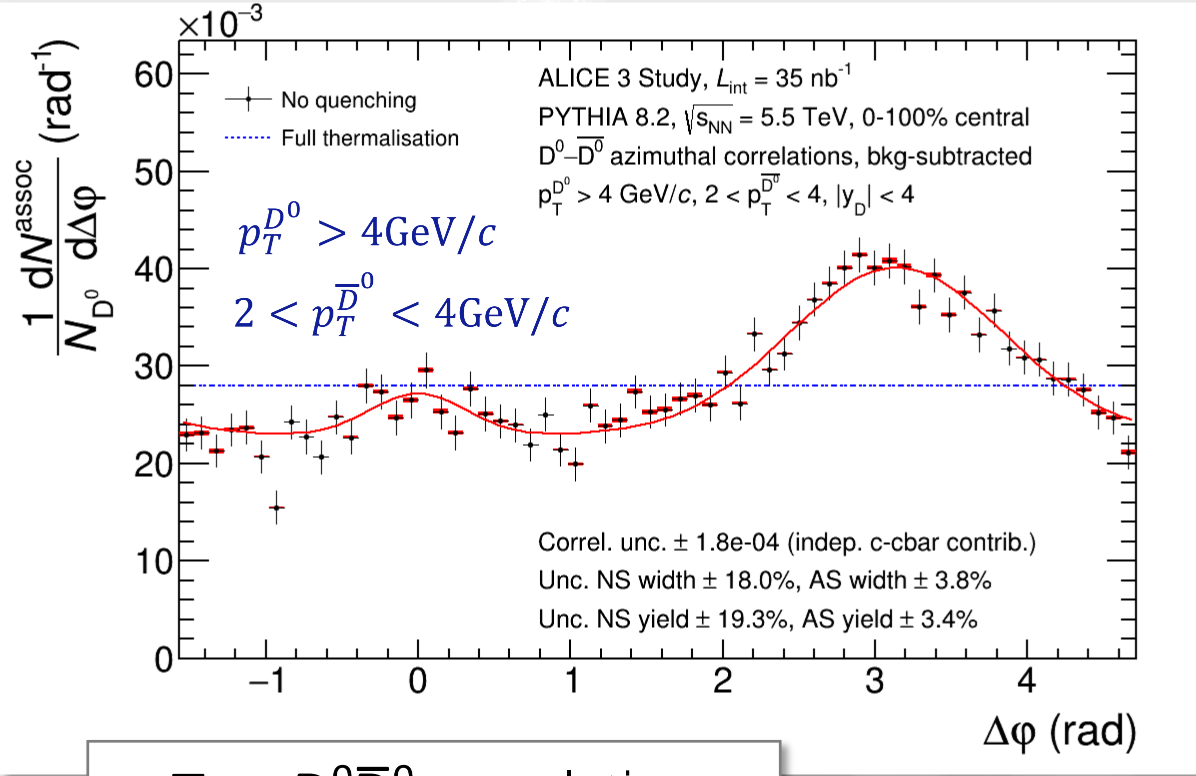
Can also be extended to beauty baryons, allowing for a stress test of beauty yield thermalization!



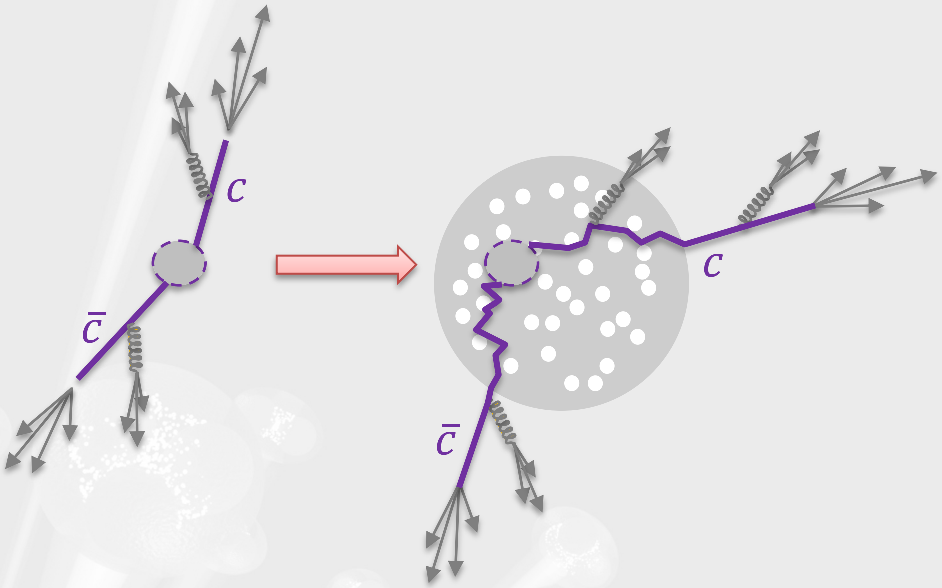
Expected Ξ_{cc}^{++} significance with 35 nb^{-1} of Pb-Pb data collected with ALICE 3

+ Timing information: select strange decay daughters within population of particles of the same species

Direct measurement of $c\bar{c}$ (de-)correlation in the medium



$c\bar{c} \rightarrow D^0\overline{D}^0$ correlations



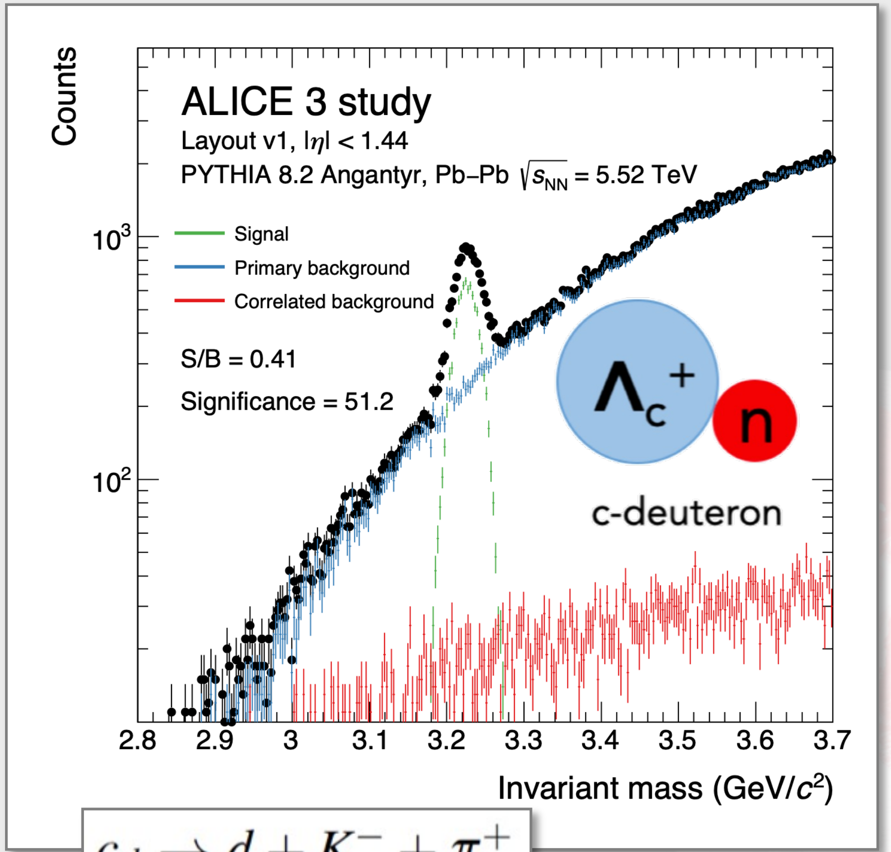
Angular decorrelation directly probes QGP scattering

- Brownian motion of charm in the plasma
- Collisional vs radiative energy losses
- Signal strongest at low p_T

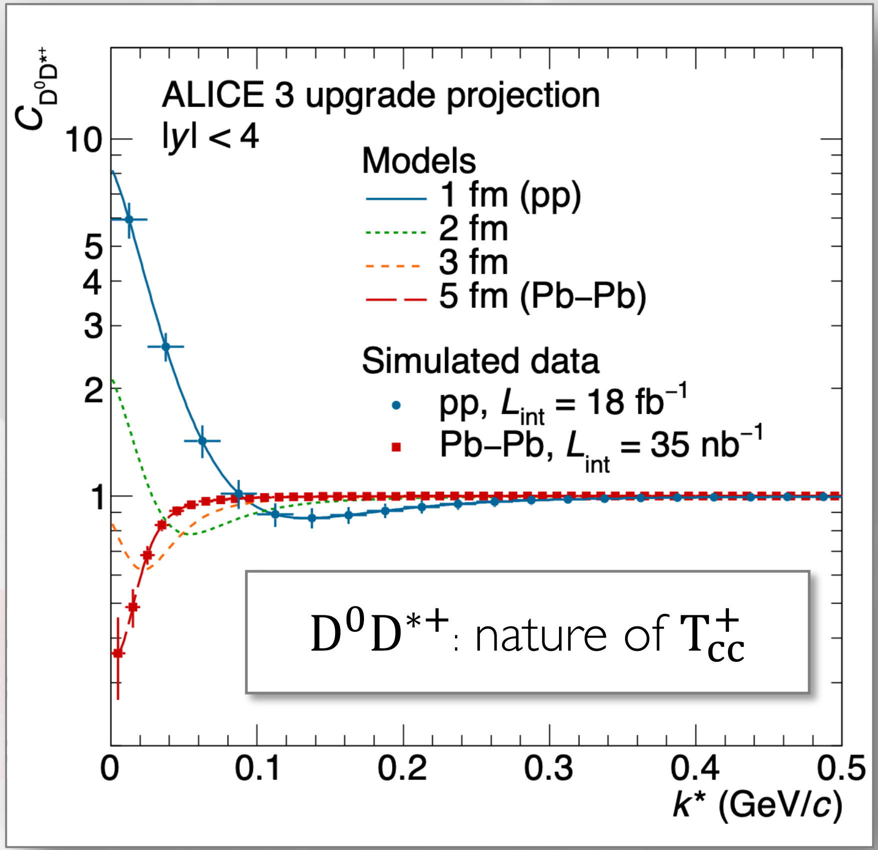
Very challenging measurement:

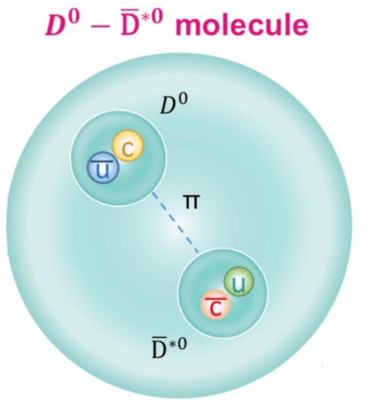
- need good purity, efficiency and η coverage
- HI measurement only possible with ALICE 3

Hadronic physics in Runs 5+6



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



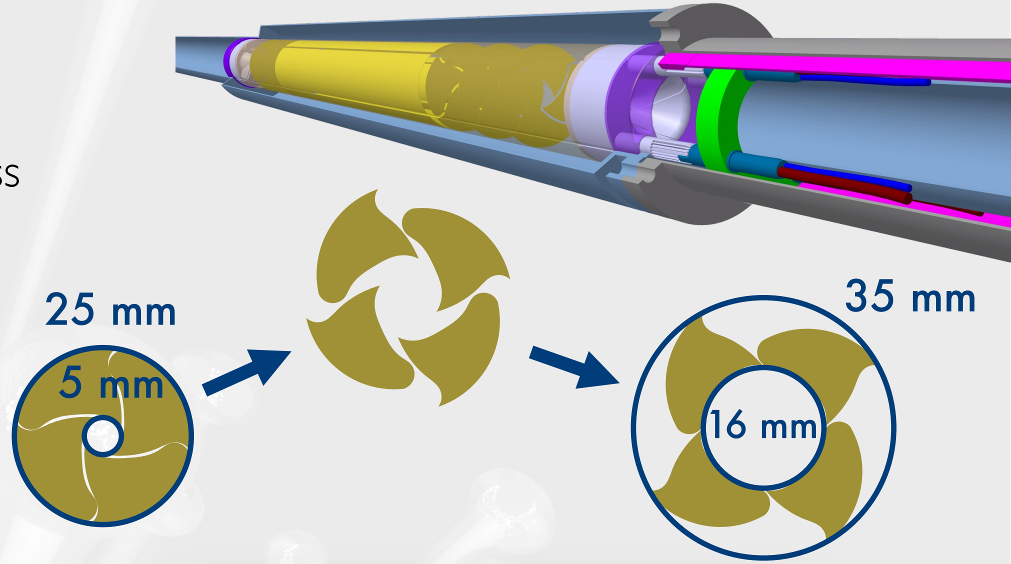


r_{molecule} as large as 5 fm

- First observation of a charmed nucleus feasible

- Direct measurement of the $D^0 D^{*+}$ interaction
- Nature of charmed exotica: molecular, tetraquark

ALICE (3) in wonderland: making it all happen



Silicon pixel sensors

- thinning and bending of silicon sensors: expand on experience with ITS3
- exploration of new CMOS processes: first in-beam tests with 65 nm process
- modularisation and industrialisation

Silicon timing sensors

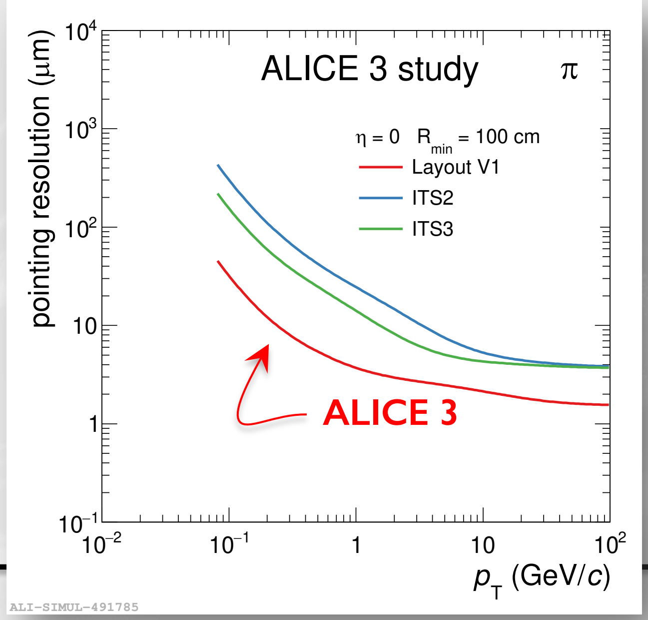
- characterisation of SPADs/SiPMs/LGADs → first tests in beam
- monolithic timing sensors → implement gain layer
- Target performance: 20 ps time resolution

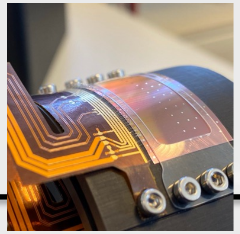
Photon sensors

- monolithic SiPMs → integrate read-out

Detector mechanics and cooling

- mechanics for operation in beam pipe → establish compatibility with LHC beam
- minimisation of material in the active volume → micro-channel cooling





Strategic R&D: synergies among experiments

A bright heavy-ion physics programme at the LHC even beyond this decade!

Heavy-flavour thermalisation and collectivity

- Heavy-flavour correlations and diffusion
- (Multi-)charm and beauty yields to zero p_T
- Precise collectivity measurements
- Charmed nuclei production
- Exotica production and binding nature

Thermal emission via dilepton measurements

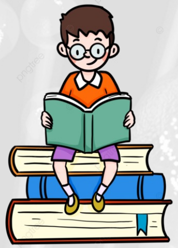
- Differential temperature measurements
- Assess system evolution more directly

Hadronic interactions programme

- Now including charm hadrons

Insights of system evolution: boosted *t*

…and much more!



Further reading:

ALICE 3 letter of intent

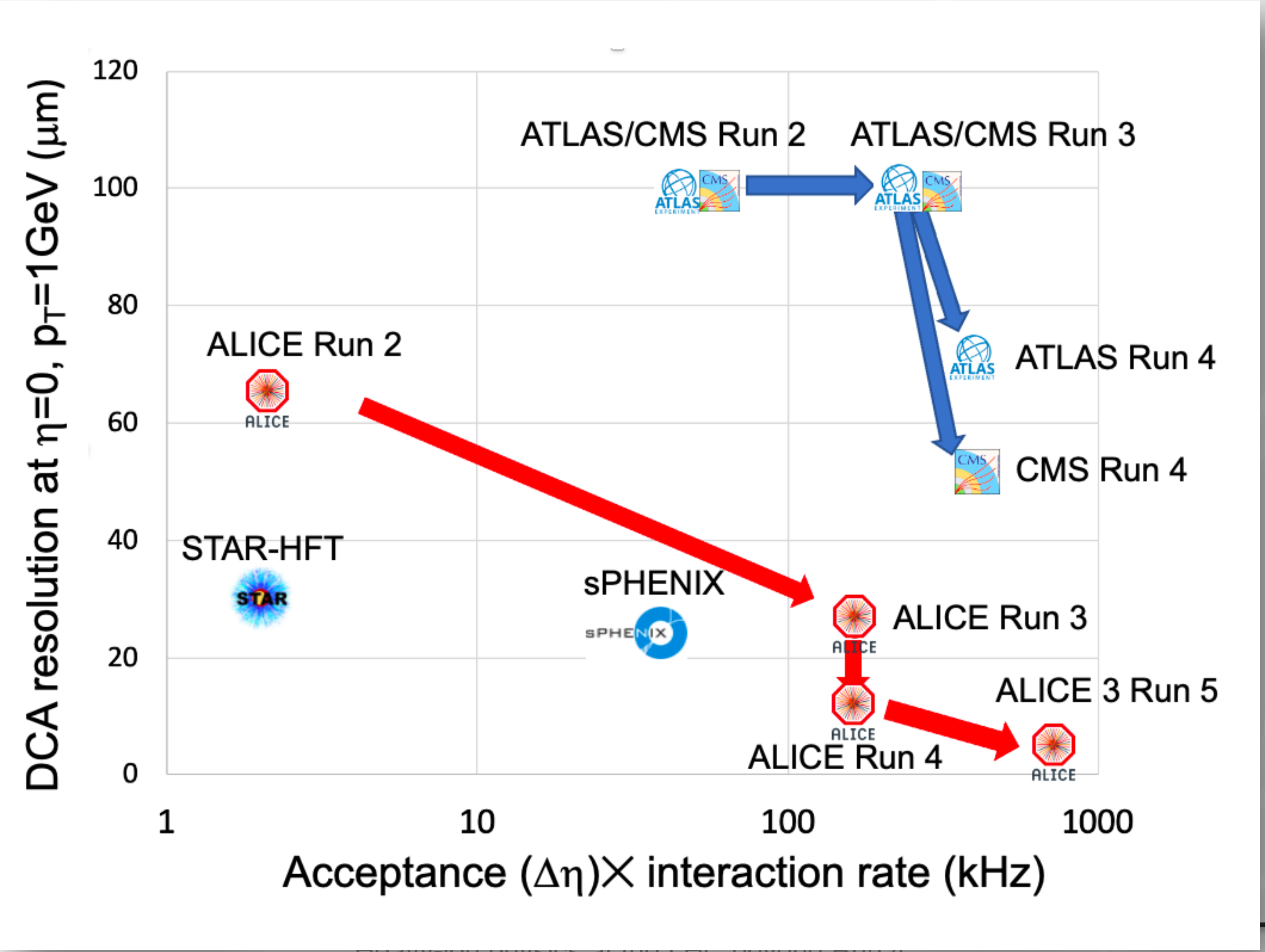
ATLAS phase II upgrades (Run 4)

CMS phase II upgrades (Run 4)

LHCb phase II upgrades

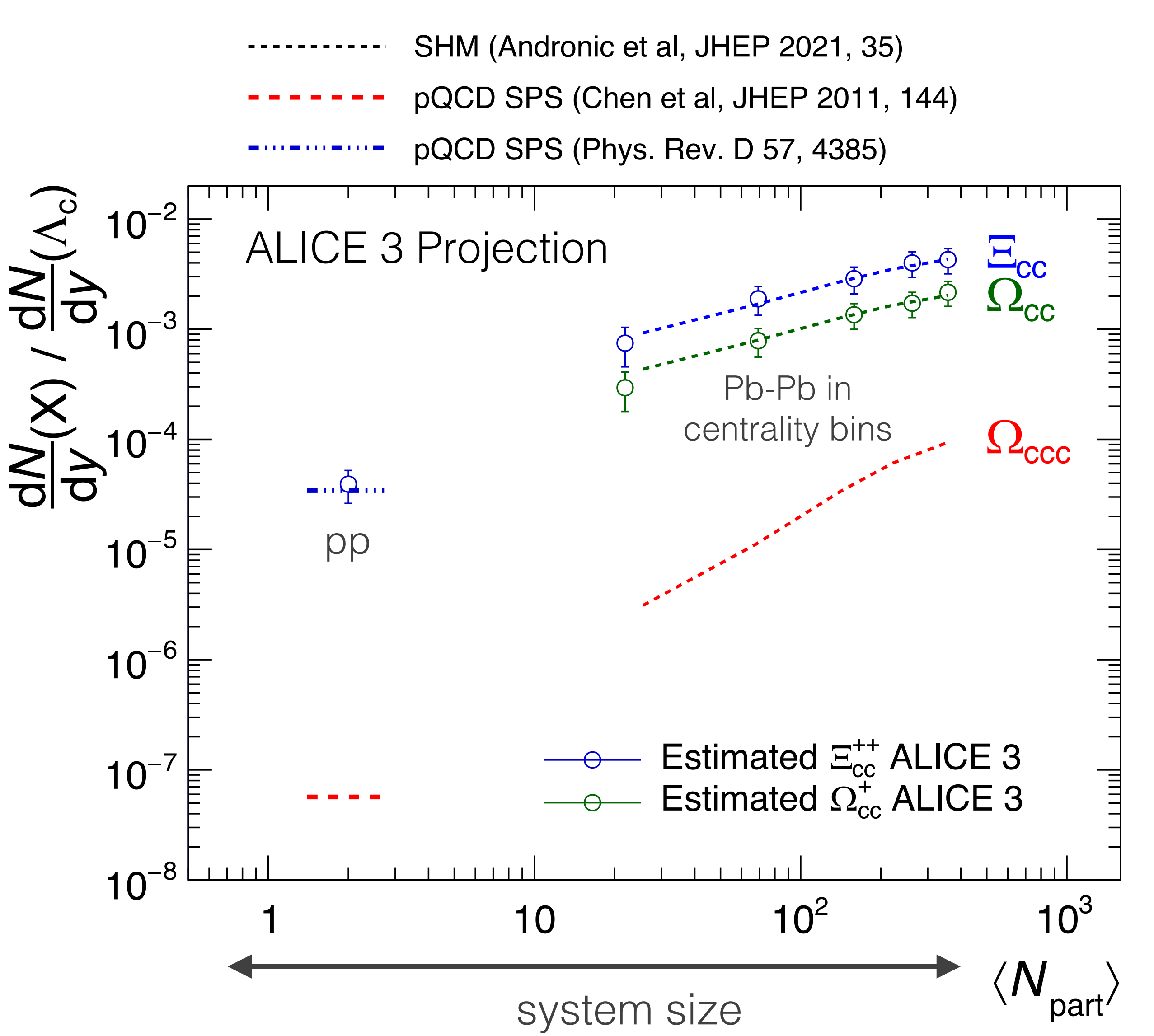

Thank you!
URKNALL
UNTERWEGS

Tracking precision and data rate competitiveness



The future: ALICE 3 multi-charm results

- Precise multi-charm baryon measurements spanning system size:
  - centrality selection
  - different collision systems: Kr-Kr, Ar-Ar, …
- Very high sensitivity: measurement feasible even in low (e.g. SPS in pp) yield scenarios
- The ultimate challenge: Ω_{ccc}^{++}
  - Depends on unknown branching ratios
  - Depends on unknown lifetimes
  - Detector capable, but huge integrated luminosity is a necessity
    - semi-leptonic channels
    - non-prompt Ω_{cc}^{+}

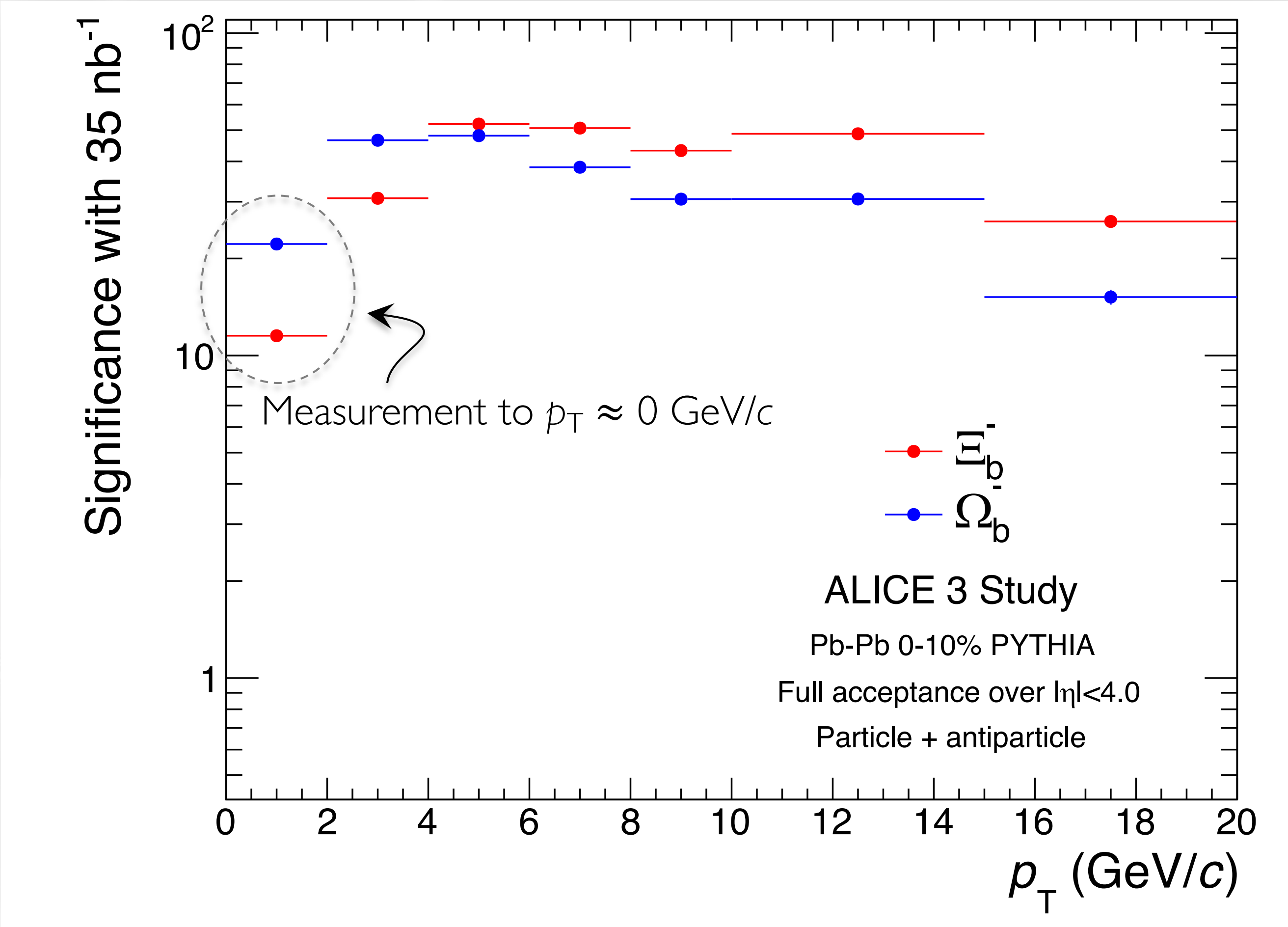


Quantity	pp	O–O	Ar–Ar	Ca–Ca	Kr–Kr	In–In	Xe–Xe	Pb–Pb
$\sqrt{s_{NN}}$ (TeV)	14.00	7.00	6.30	7.00	6.46	5.97	5.86	5.52
L_{AA} ($cm^{-2}s^{-1}$)	3.0×10^{32}	1.5×10^{30}	3.2×10^{29}	2.8×10^{29}	8.5×10^{28}	5.0×10^{28}	3.3×10^{28}	1.2×10^{28}
$\langle L_{AA} \rangle$ ($cm^{-2}s^{-1}$)	3.0×10^{32}	9.5×10^{29}	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%).

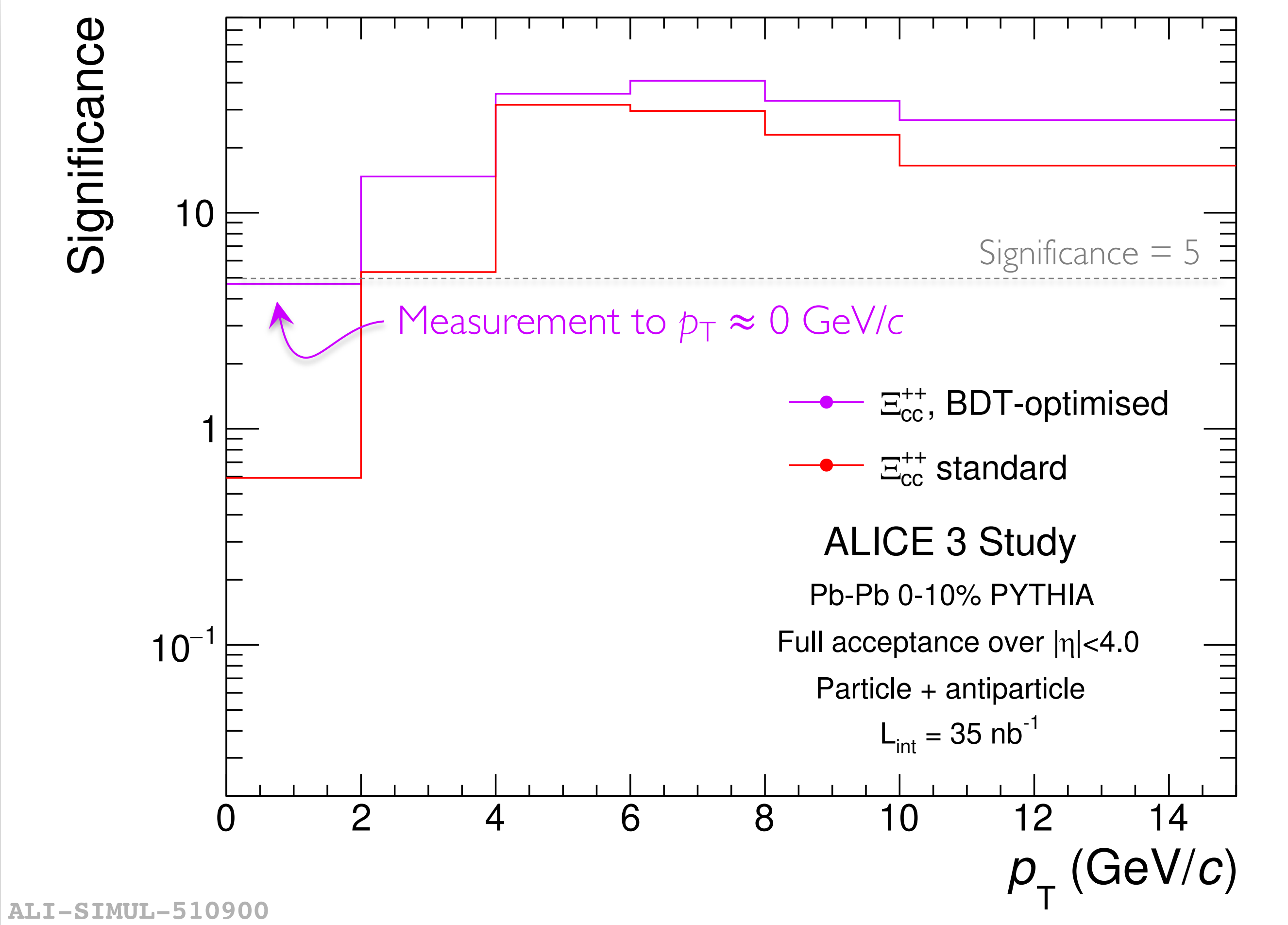
Ξ_b^- and Ω_b^- significance in 0-10% Pb-Pb collisions

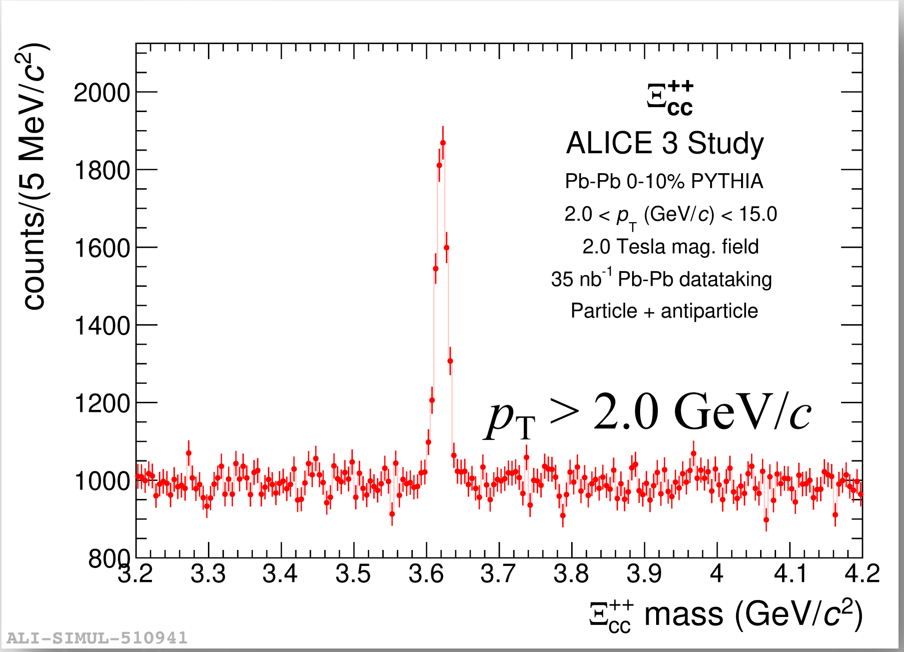
- Expected integrated lumi. of Pb-Pb collisions: 35 nb^{-1}
- Theoretical input:
  - GSI/Heidelberg yields [1],
  - PYTHIA mode 2 p_T distributions
- Significance: peaks at ~50
  - Goes to zero momentum
- Fundamental piece of information for measuring the exponential curve of beauty thermalization
  - Full thermalization may not be achieved → important measurement!

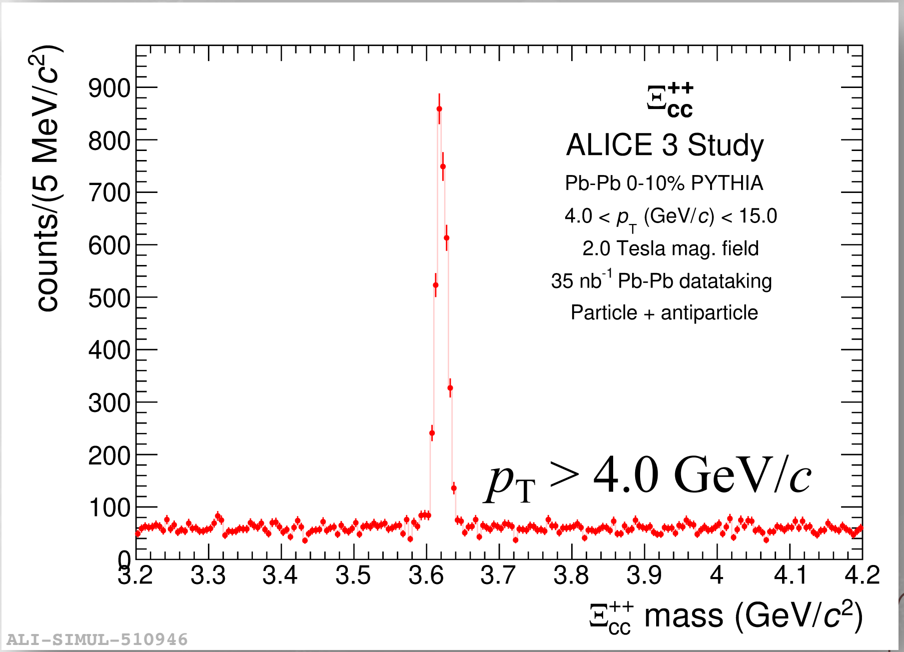


[1] Andronic, A., Braun-Munzinger, P., Köhler, M.K. et al., J. High Energ. Phys. 2021, 35 (2021).

Ξ_{cc}^{++}: A taste of analysis



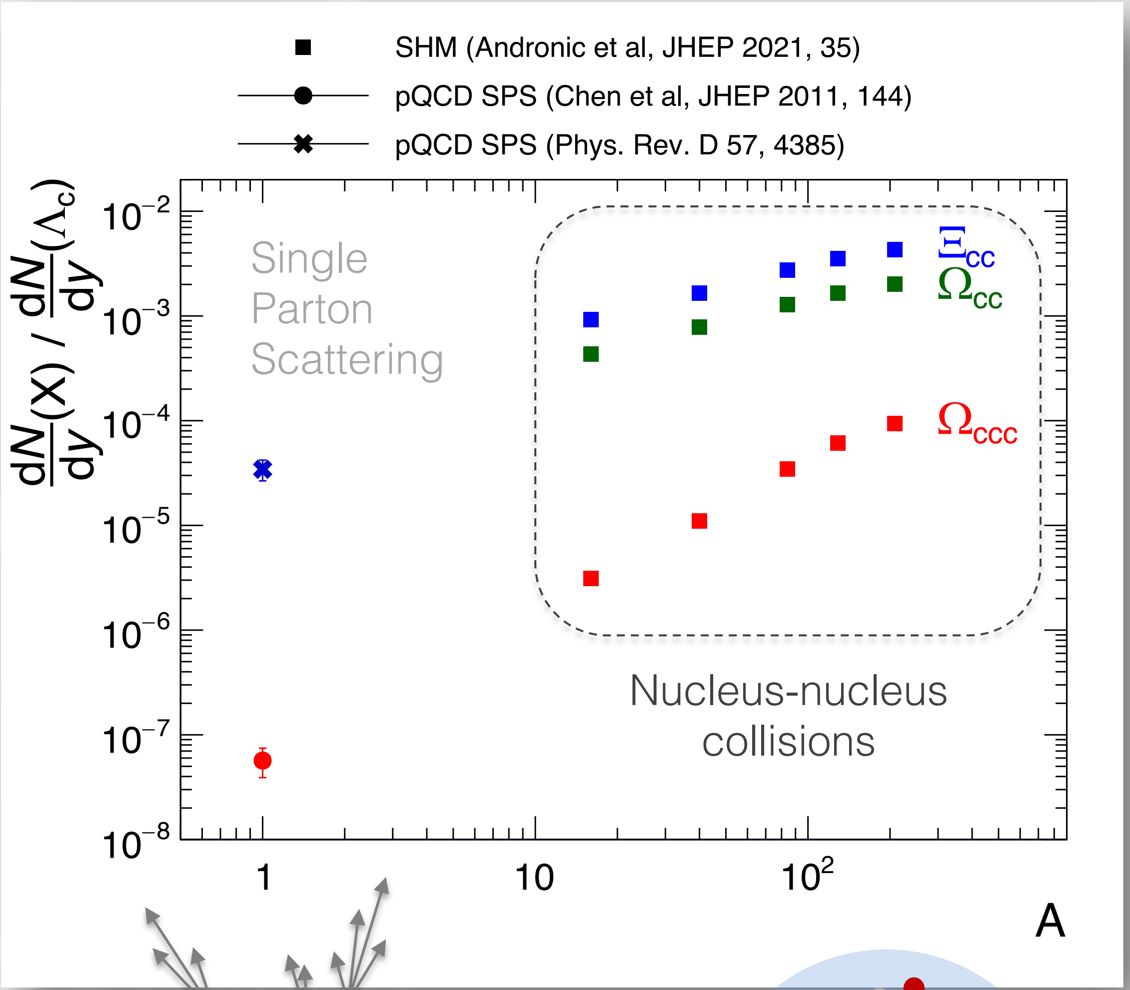


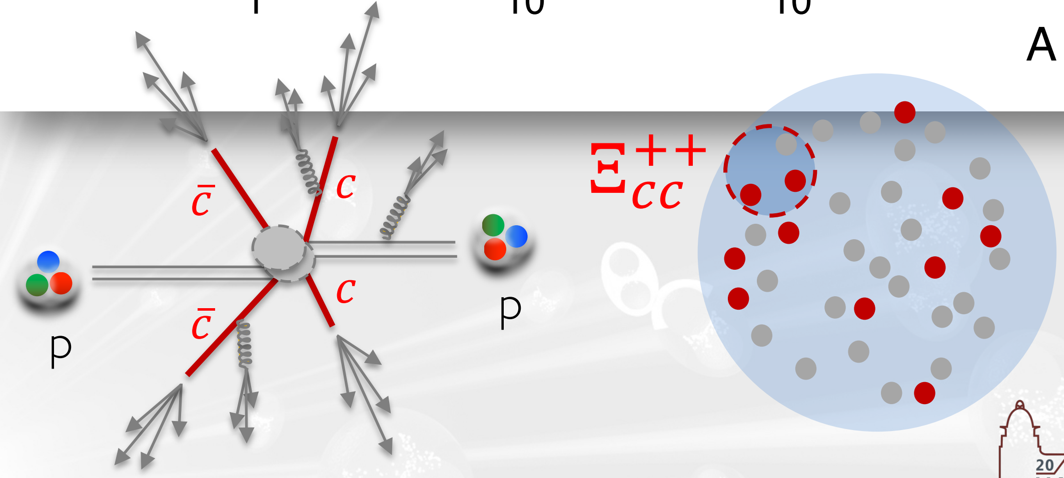


Expected Ξ_{cc}^{++} invariant mass distributions with 35 nb^{-1} of Pb-Pb data collected with ALICE 3

Multi-charm baryons: from low to high density QCD

- Formation of Ξ_{cc}^{++}, Ω_{cc}^{+}, Ω_{ccc}^{++}: extremely unlikely in single parton scattering (unlike e.g. J/ψ)
- Multi-parton interactions and multi-charm: multiple charm quarks combine into hadrons
- In nuclear collisions:
  - High density of charm quarks leads to much larger multi-charm population
  - Described by SHM (g_c) and coalescence
  - Enormous dynamic effect!



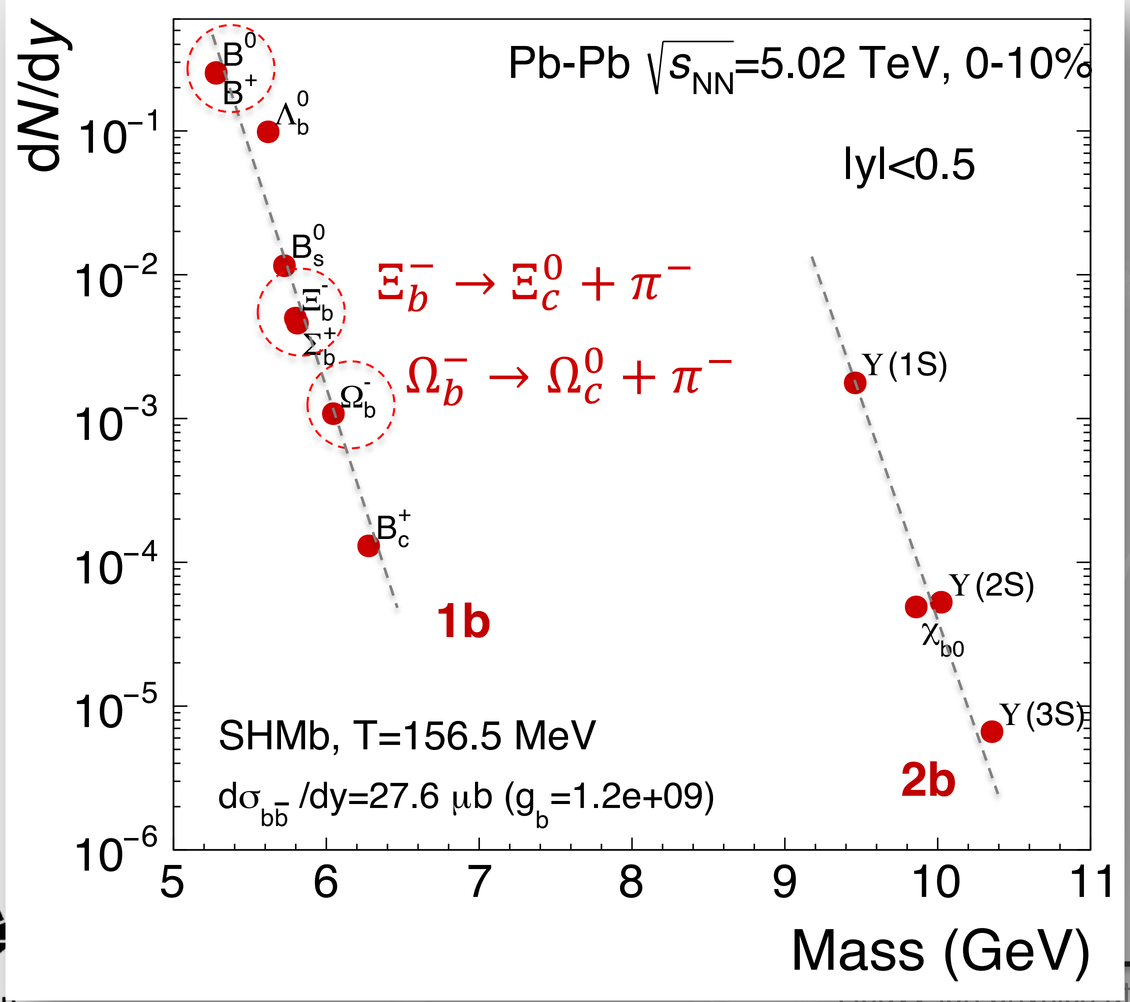


$$\Xi_{cc}^{++} \rightarrow \Xi_c^{+} + \pi^{+} \quad (c\tau \sim 77\ \mu m)$$

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

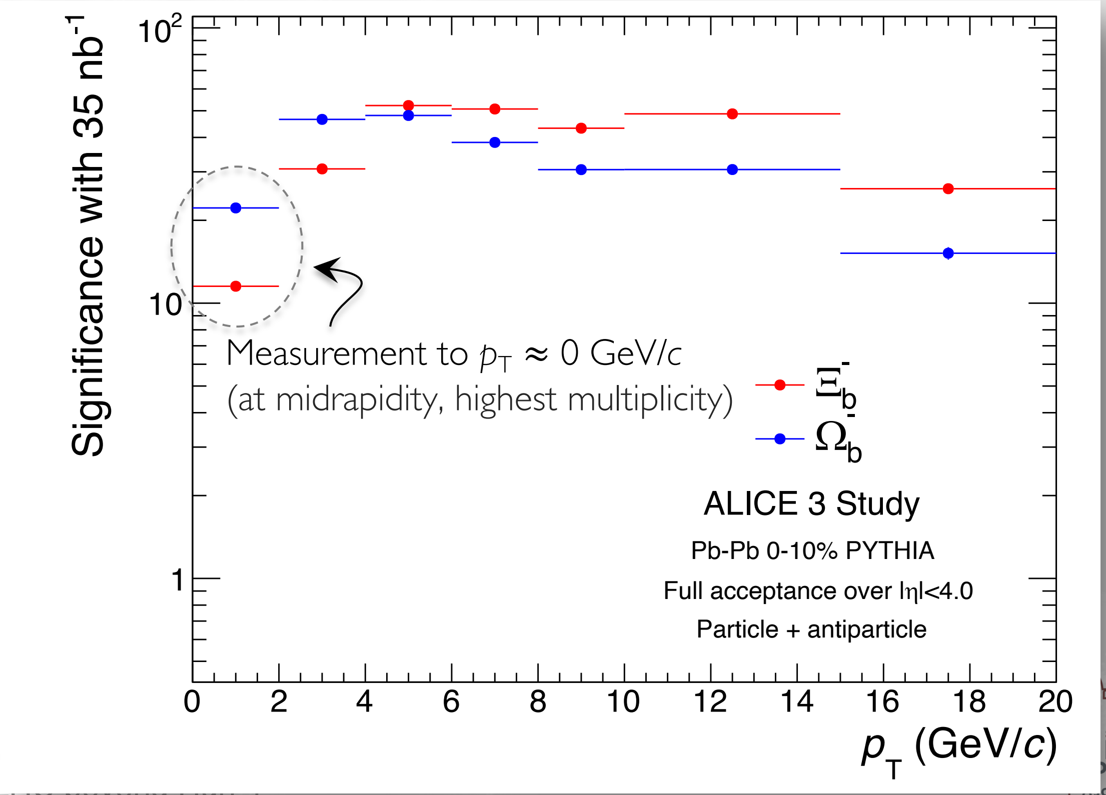
Beauty thermalization and Ξ_b^-, Ω_b^- via strangeness tracking

Prediction from SHMb



Motivation for going to beauty:

- Determine the degree of (incomplete?) beauty thermalization in nucleus-nucleus collisions
- Determine beauty quark diffusion coefficient



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