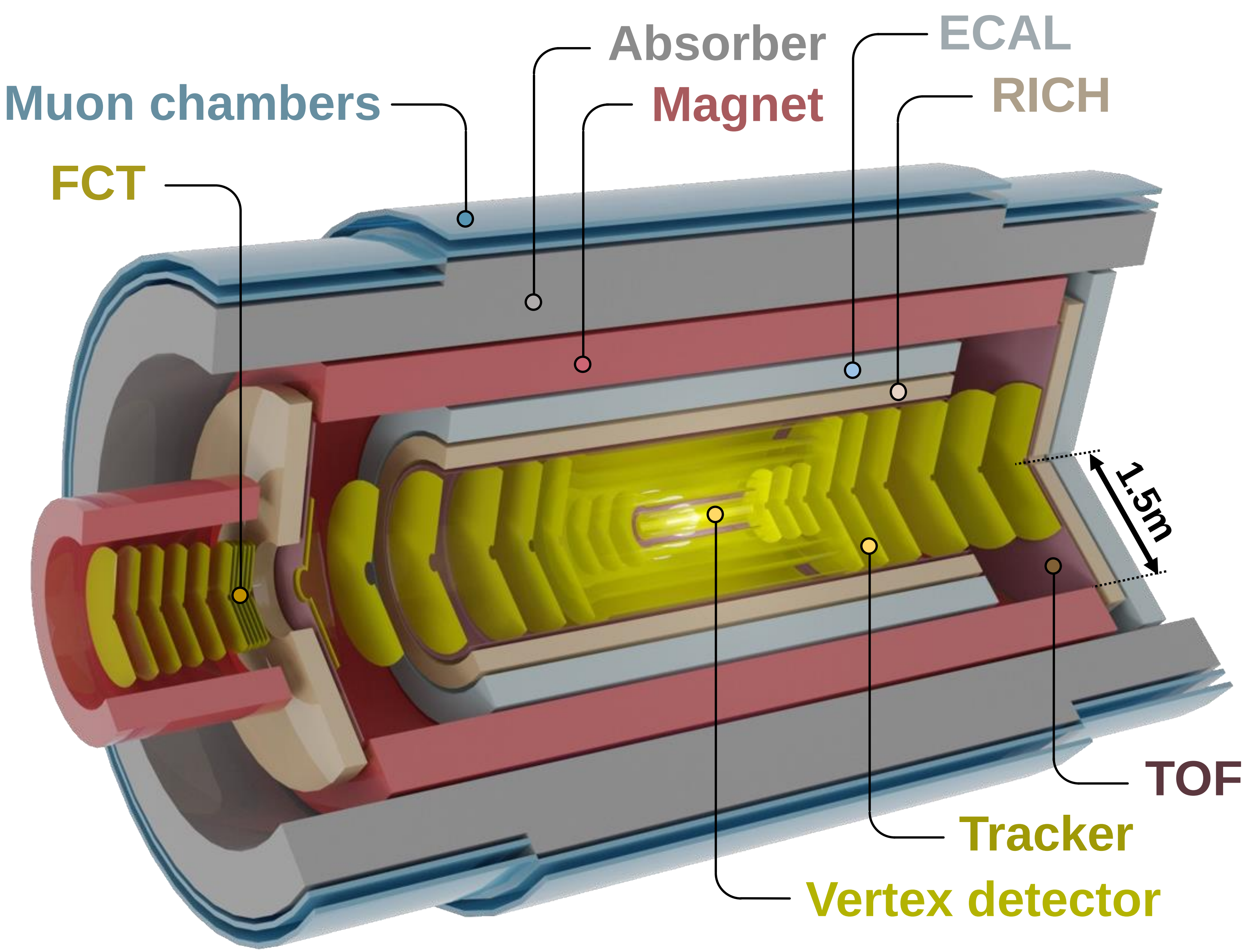
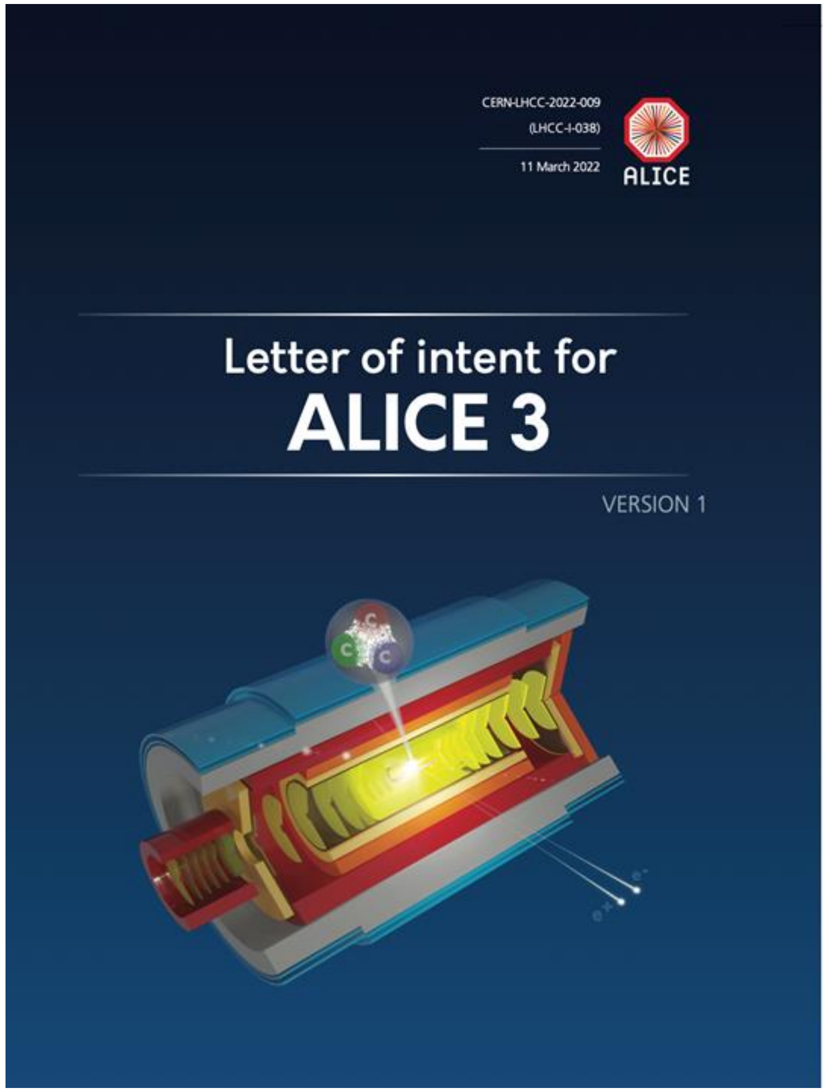
ALICE 3 – The Final Frontier ?

R. Bellwied (University of Houston)





CERN-LHCC-2022-009
(LHCC-I-038)
11 March 2022

ALICE

Letter of intent for
ALICE 3

VERSION 1

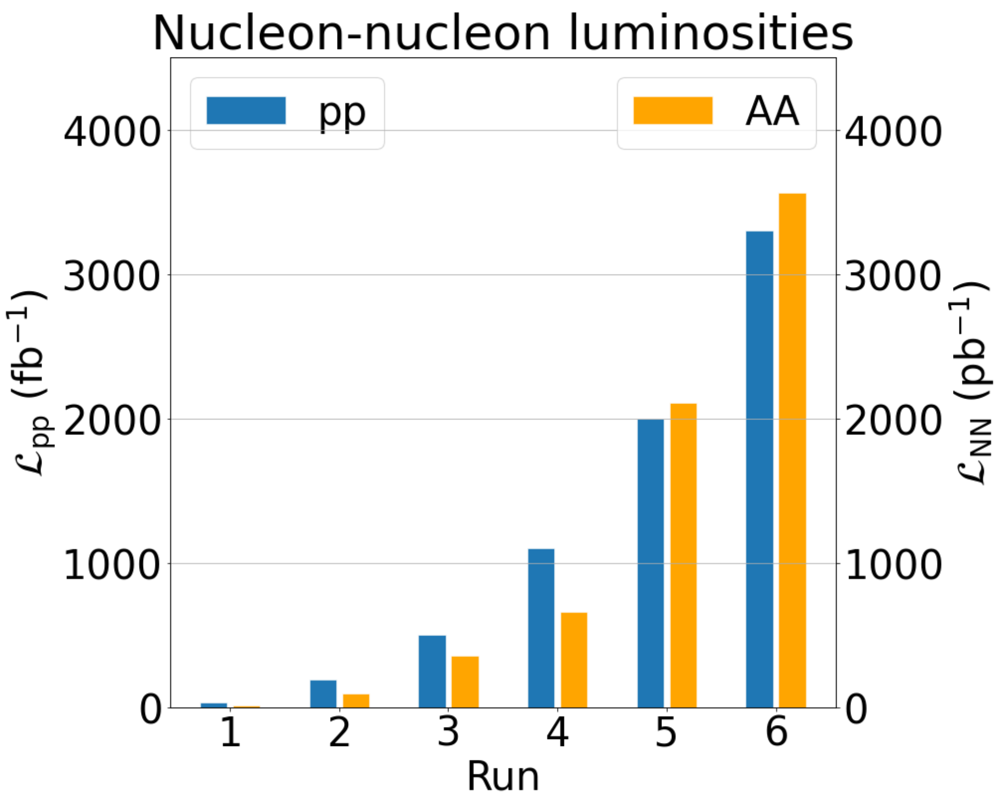
Reference: ALICE 3 Letter of Intent
(arXiv:2211.02491)

WWND 2023 – Feb.5-10,2023, Puerto Vallarta, Mexico

LHC Program

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
~1-2·10^{27} cm^{-2} s^{-1}



Run 5 → higher luminosities for ions

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

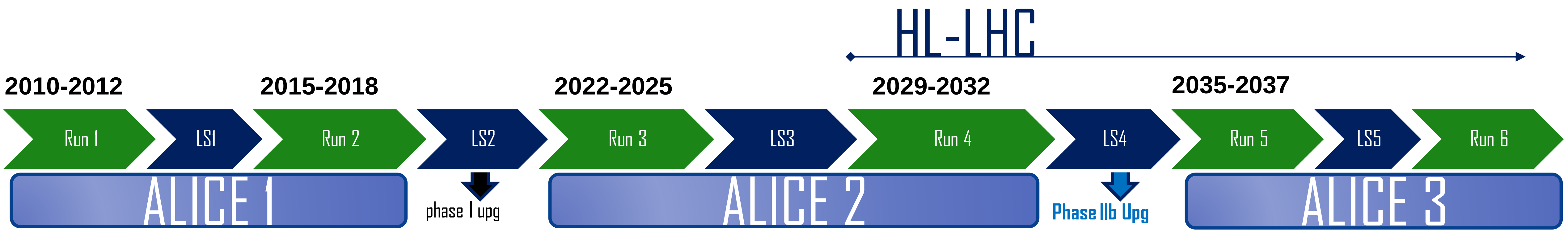
Run 4 → HL-LHC

- push pp luminosity to 4·10^{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

ALICE 3 Timeline



HL-LHC

2010-2012 Run 1
LS1
2015-2018 Run 2
LS2
2022-2025 Run 3
LS3
2029-2032 Run 4
LS4
2035-2037 Run 5
LS5
Run 6

ALICE 1
phase I upg
ALICE 2
Phase IIb Upg
ALICE 3

2023 – 2025: selection of technologies, small-scale proof of concept prototypes (~25% of R&D funds)

2026 – 2027: large-scale engineered prototypes (~75% of R&D funds) ➪ **Technical Design Reports**

2028 – 2030: construction and testing

2031 – 2032: contingency

2033 – 2034: installation and commissioning

2035 – 2042: physics campaign

Heavy-ion physics at the LHC in Run 3/4 (high T, low μB, large heavy flavor & jet yields)

- **Nuclear PDFs**
  ⟶ Ultra-peripheral collisions, pA
- **QGP evolution from early phase onwards: temperature, chiral symmetry restoration, …**
  ⟶ precision measurements of dilepton spectra
- **Quenching** and **connection to collectivity in small systems**
  ⟶ systematic measurements of different collision systems
- **Onset of collective behaviour**
  ⟶ high-multiplicity pp collisions, intermediate systems (pA, OO)
- **Transport properties and thermalisation in the QGP**
  ⟶ precision measurements of heavy-flavour probes
- **Transition of partons from the QGP to hadrons**
  ⟶ charmed baryons, exotic states
- **Many more opportunities**
  ⟶ BSM searches,…….

… beyond Run 4

- **Early stages**: temperature of QGP before hadronisation
  - Dilepton and photon production, elliptic flow
  - Electric conductivity of the QGP
- **Chiral symmetry** restoration: $\rho - a_1$ mixing
- **Heavy flavour diffusion and thermalisation in the QGP**
  - Beauty and charm flow
  - Charm hadron correlations
- **Jet quenching with HFQ correlations**
- **Hadronization**, final state interactions in heavy-ion collisions
  - Multi-charm baryons: thermal processes/quark recombination
  - Quarkonia and exotic mesons: dissociation and regeneration
- **Structure of exotic hadrons**
  - Momentum correlations (femtoscopy)
  - Production yields – dissociation in final state scattering
  - Decay studies in ultra-peripheral collisions
  - New nuclear states including charm
- **Ultra-soft photons**
- **BSM searches**: ALPs, dark photons, long-lived particles

My topics for today:

Chiral symmetry

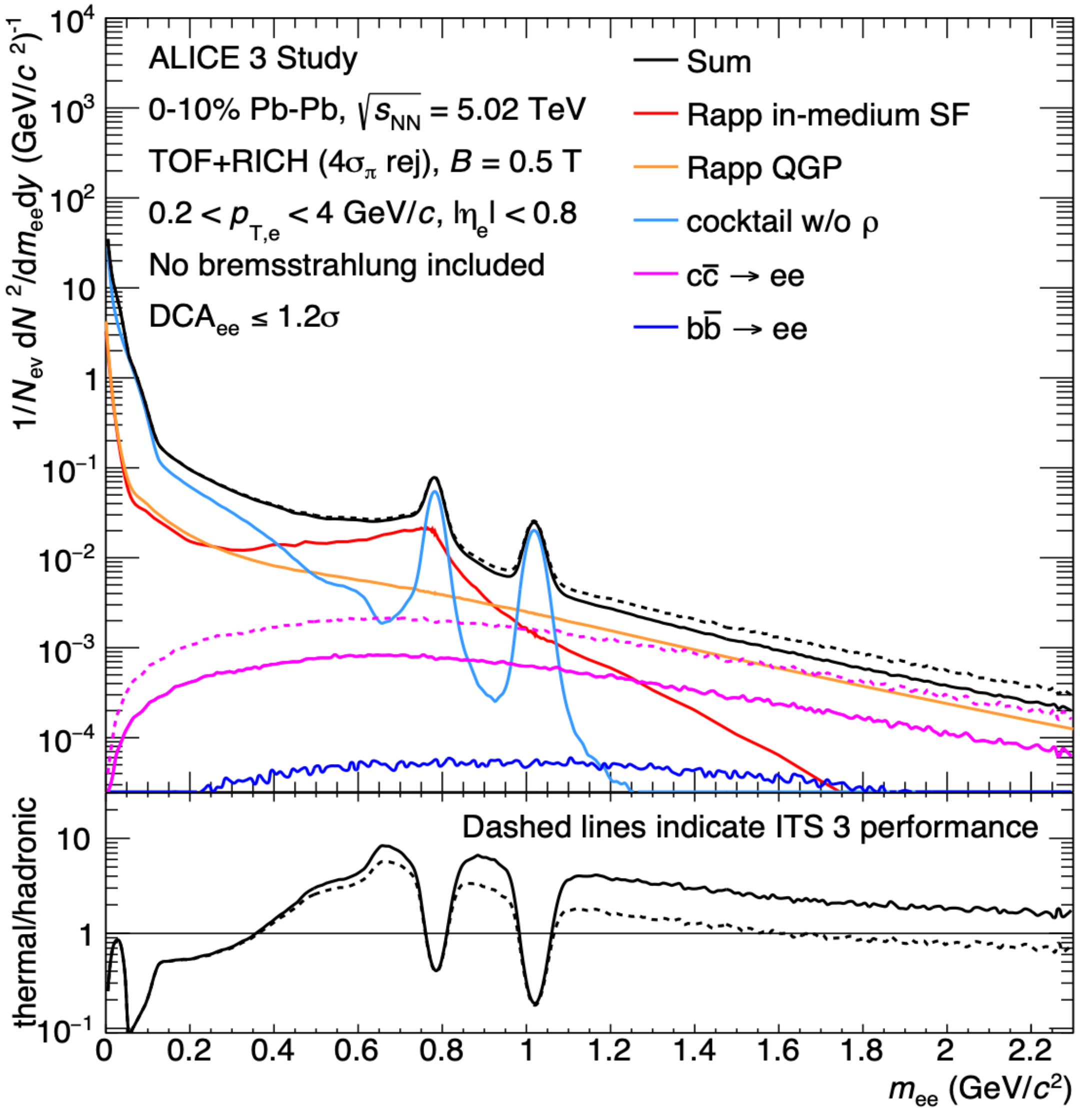
Heavy Flavor

Hadronization

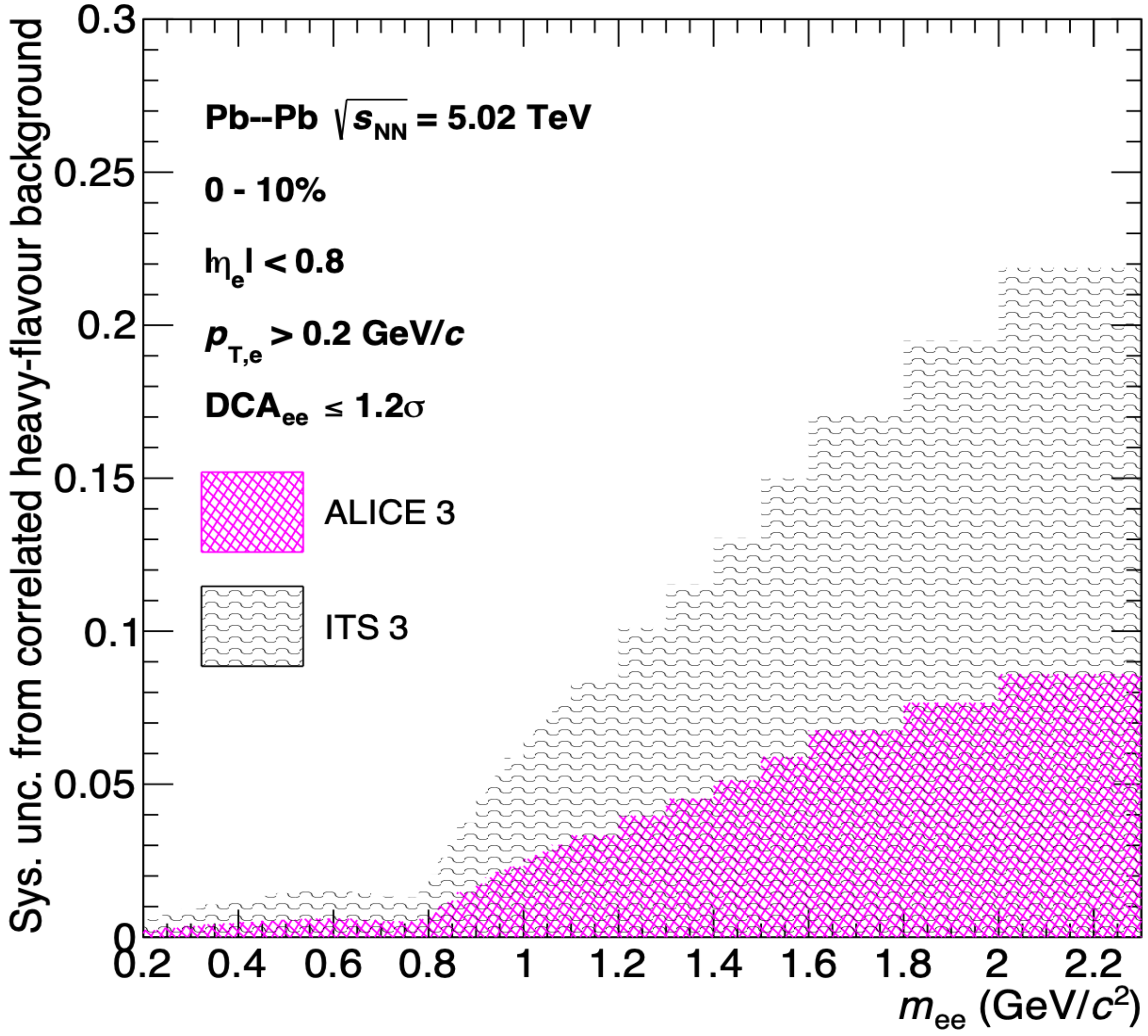
Forward physics

Di-electrons: chiral symmetry and thermal emission (measure parity partner mixing ($\rho - a_1$))

Correlated dielectron distribution



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

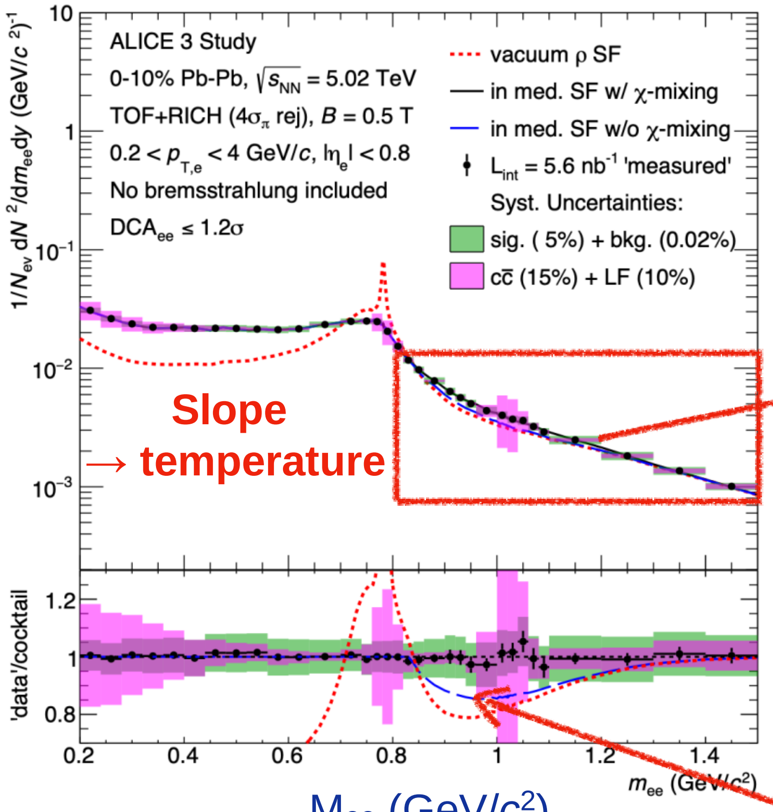
Time evolution and chiral symmetry

- **Understand time evolution and mechanisms of chiral symmetry restoration**
  → high-precision measurements of dileptons, also multi-differentially
  → further reduced material; excellent heavy-flavour rejection

[CERN-LPCC-2018-07]

Run 5 & 6

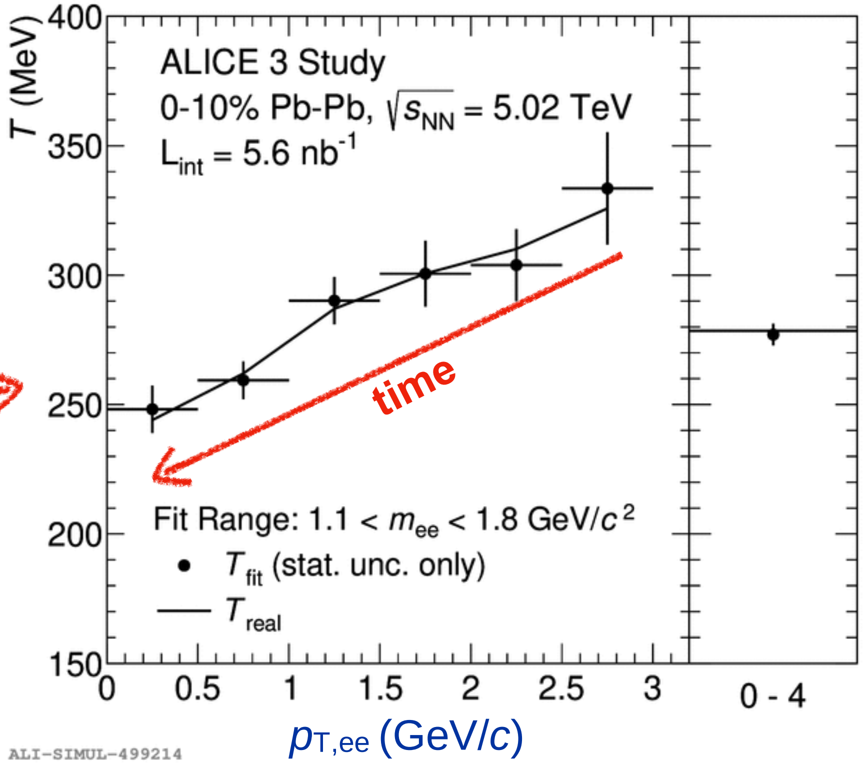
Invariant mass spectrum of dielectrons



Slope
→ temperature

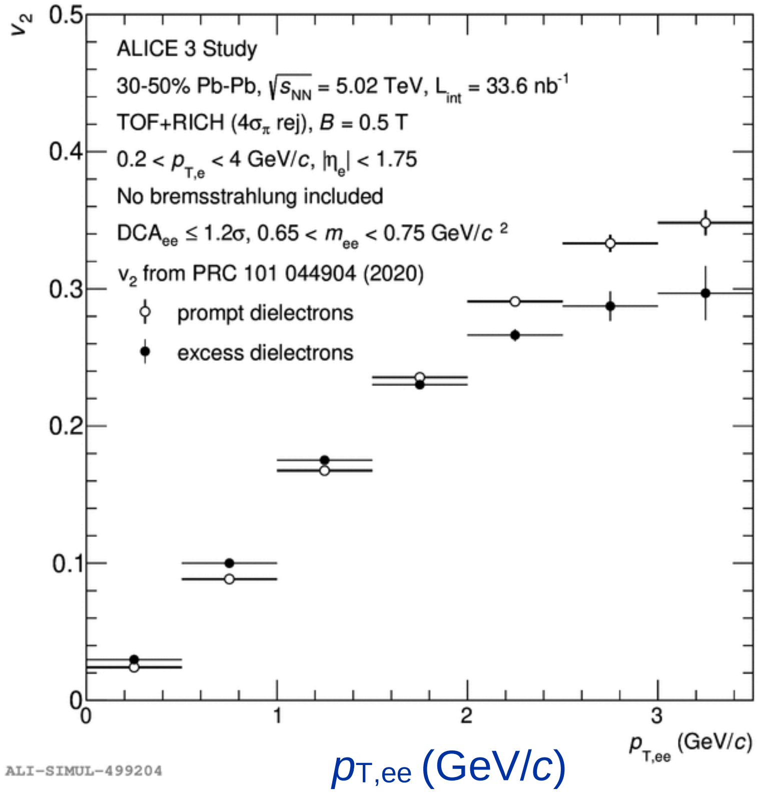
Only ALICE 3 precision

***T*($p_{T,ee}$)**
→ control on emission time



Without ρ-a$_1$ mixing
→ dip in thermal spectrum

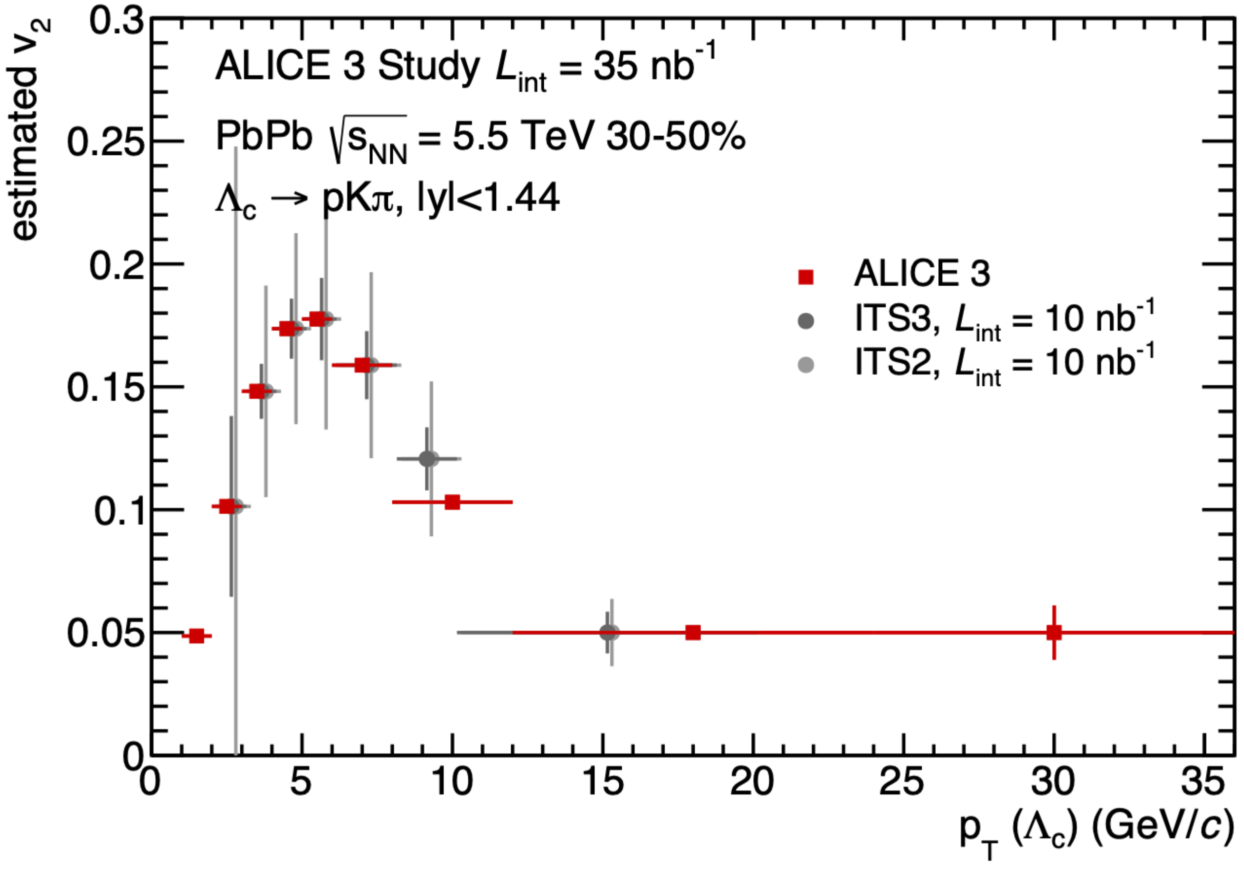
Dilepton v$_2$
→ temporal emission profile



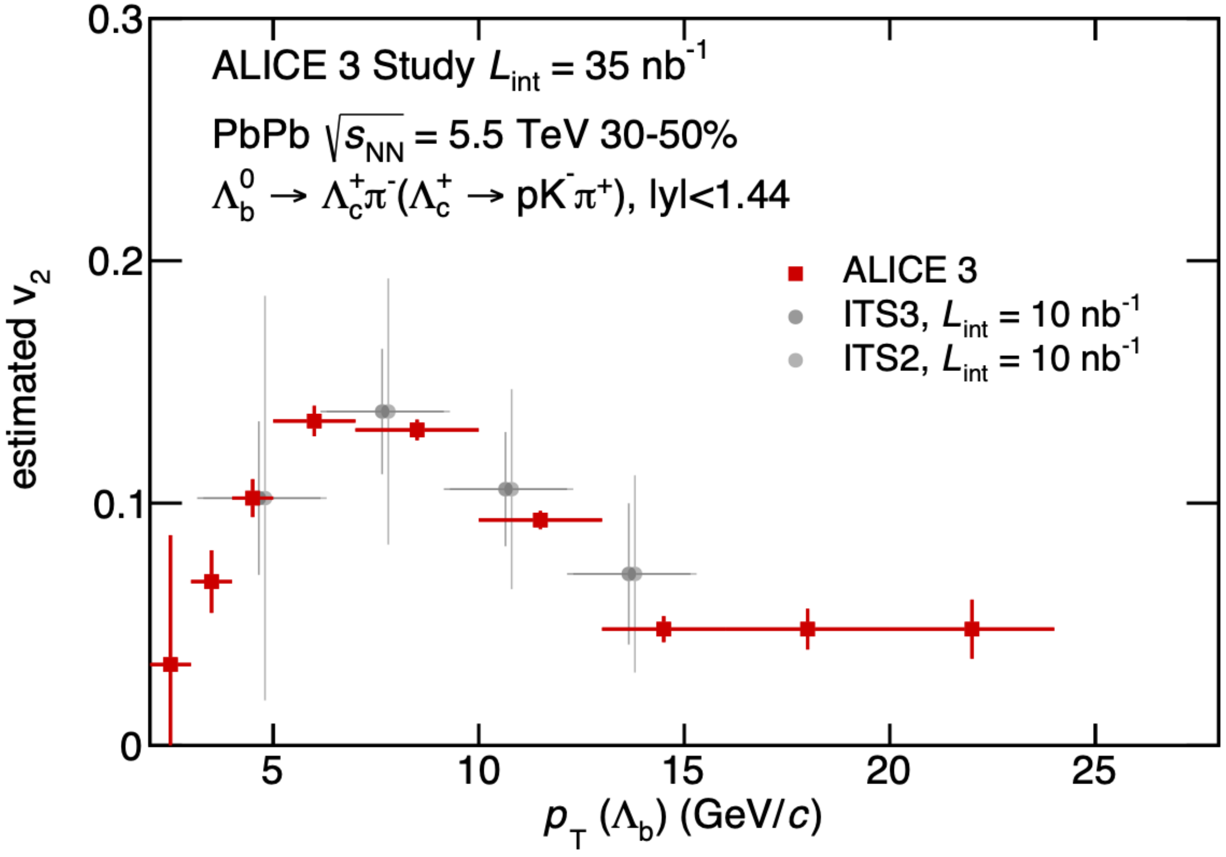
- **Additional parity partner measurement in strange baryon sector**
  → Ξ(1820)/Ξ(1530) – marginal in Run2, definitive in Run 4++

Heavy-flavour transport in QGP

Λ_c v_2 performance



Λ_b v_2 performance

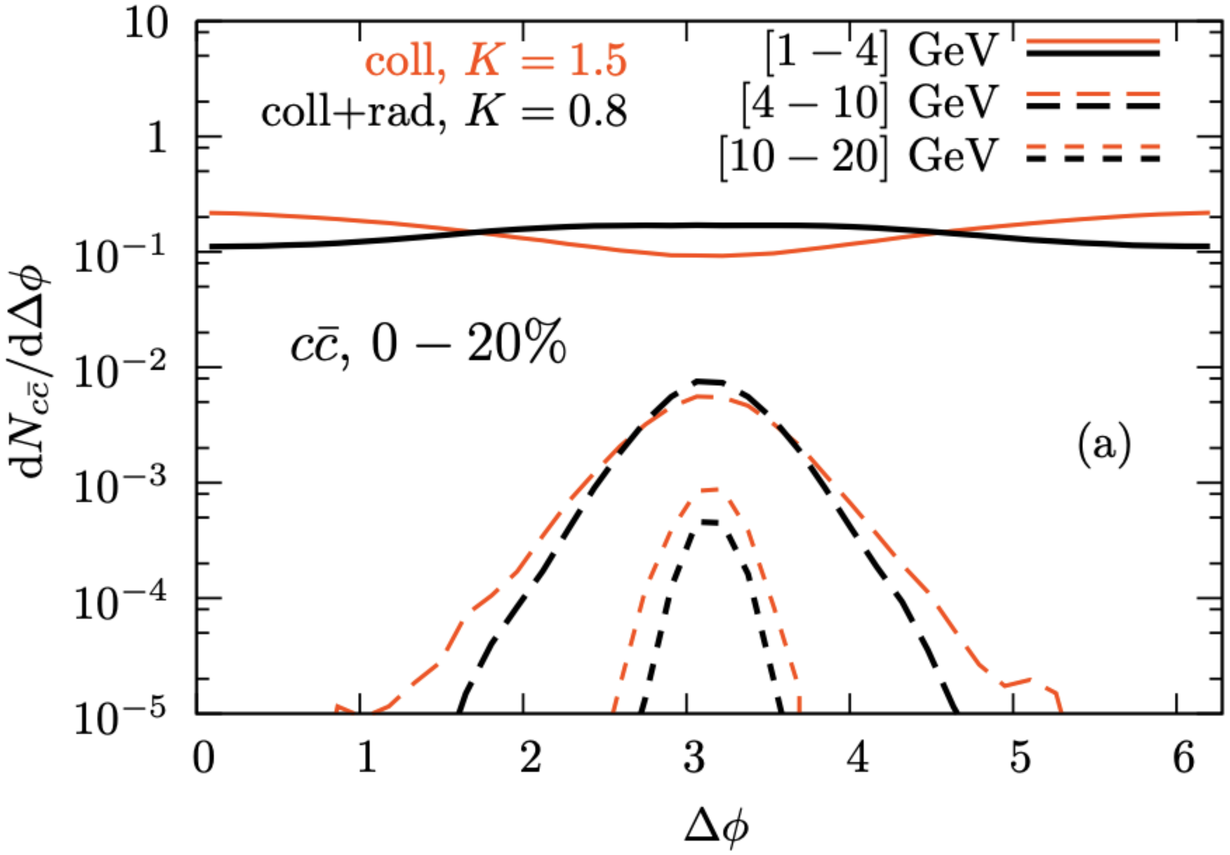


- **Heavy quarks: access to quark transport at hadron level**
  - Expect beauty thermalisation slower than charm – smaller v_2
- **Need ALICE 3 performance (pointing resolution, acceptance) for precision measurement of e.g. Λ_c and Λ_b v_2**

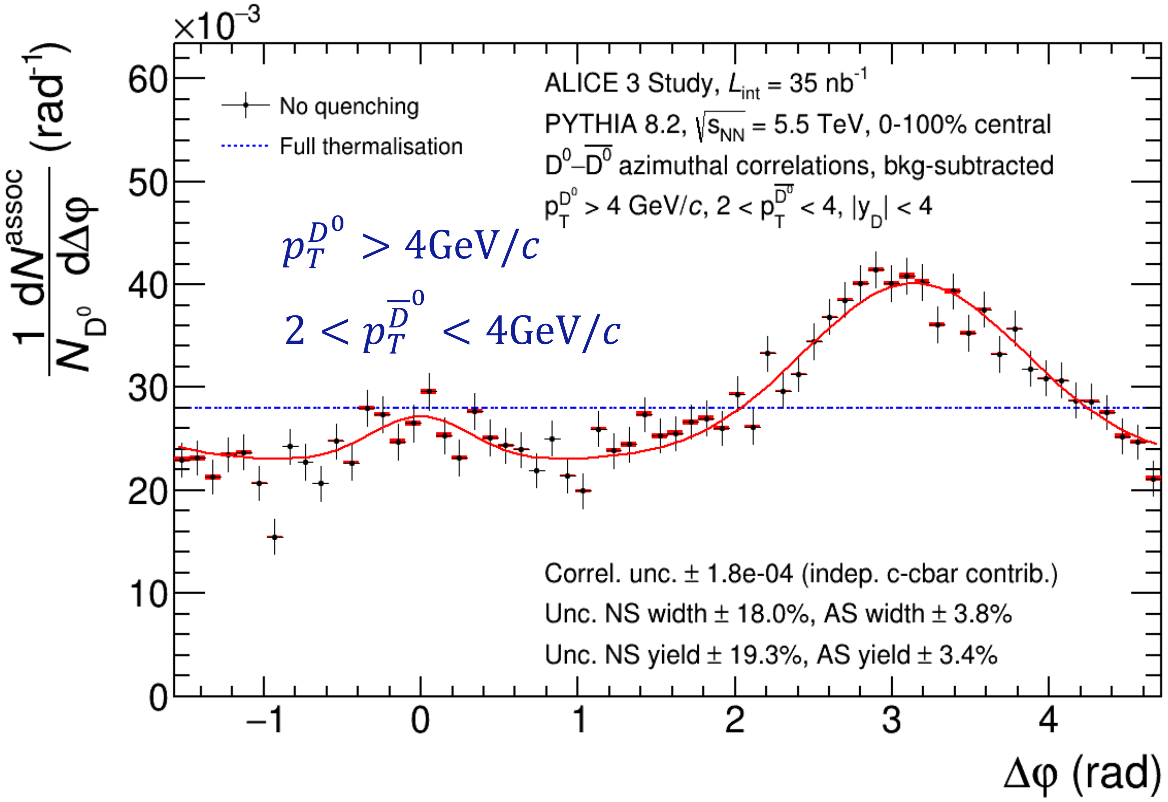
D-Dbar azimuthal correlations

Charm azimuthal correlations

M Nahrgang et al, [PRC 90, 024907]()



ALICE 3 projection: $D\overline{D}$ correlations

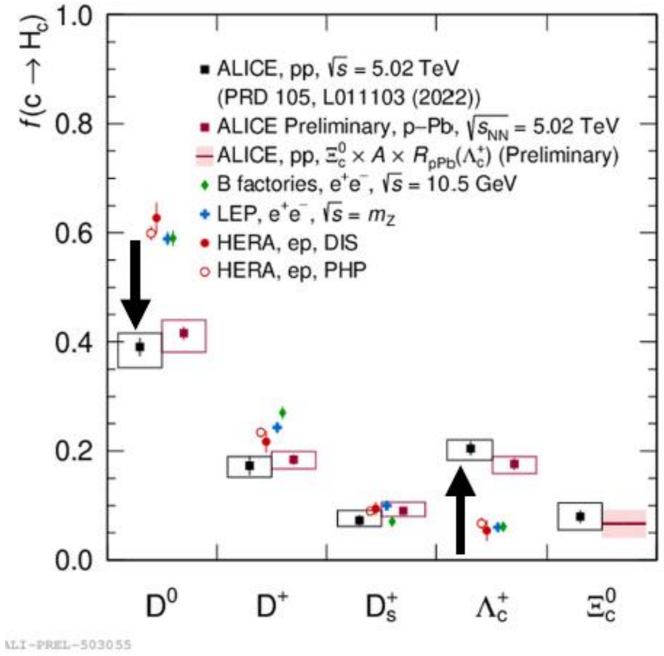


- **Angular decorrelation directly probes QGP scattering**
  - Signal strongest at low p_T
- Very challenging measurement:
  need good purity, efficiency and η coverage
  → **heavy-ion measurement only possible with ALICE 3**

Flavor dependent hadronization studies at the LHC

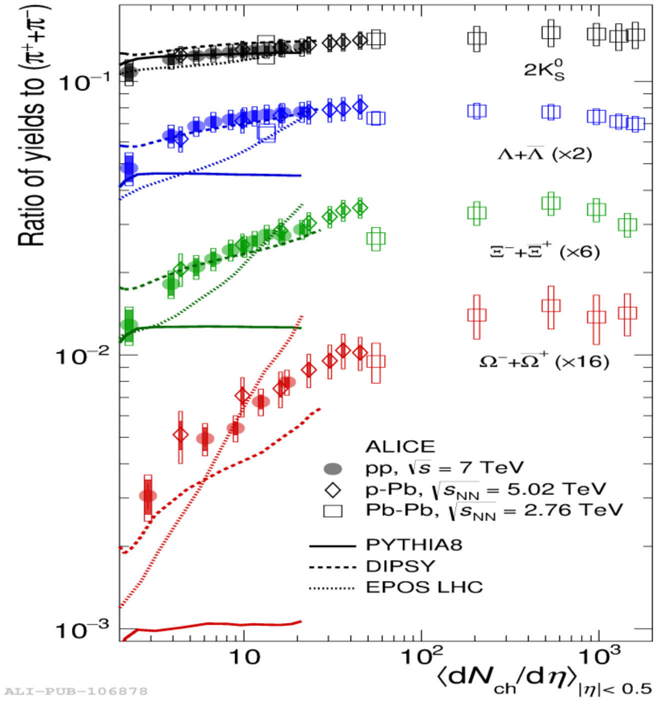
Small systems discoveries: significant impact on hadronization modeling

Non-universality of charm fragmentation



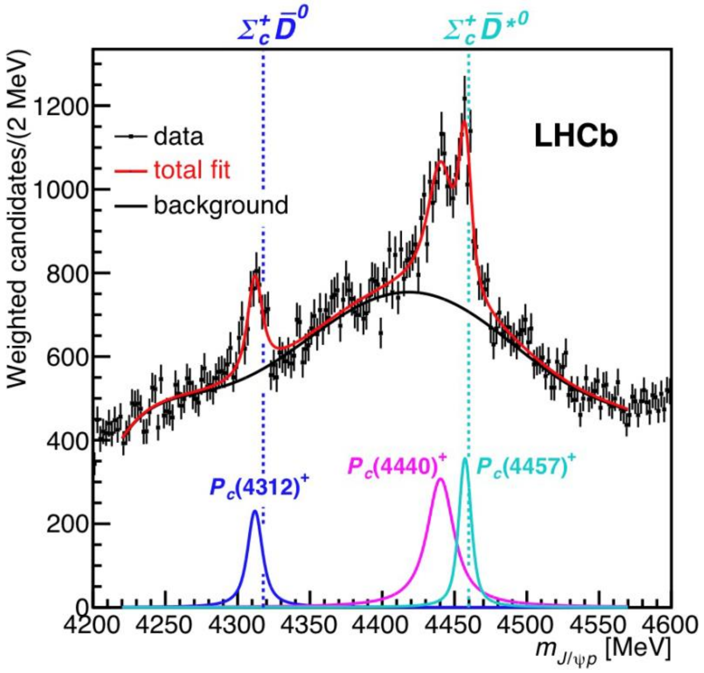
ALICE, Phys.Rev.D 105, L011103(2022)

Strangeness enhancement as function of centrality



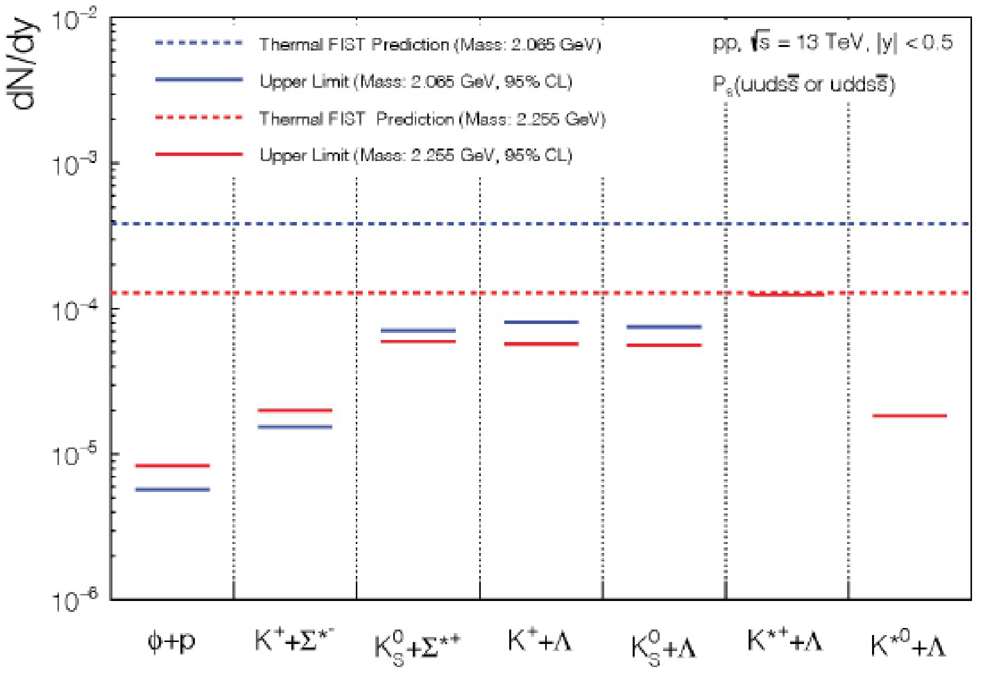
ALICE, Nature Physics 13, 535 (2017)

Multi-quark states in charm sector



ALICE preliminary

No multi-quark states in strange sector



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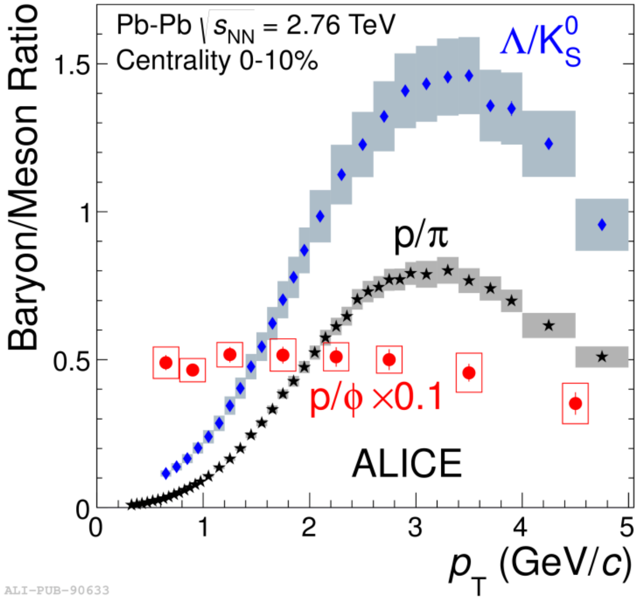
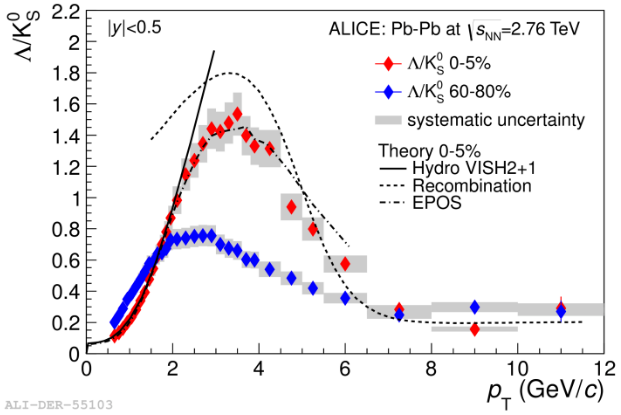
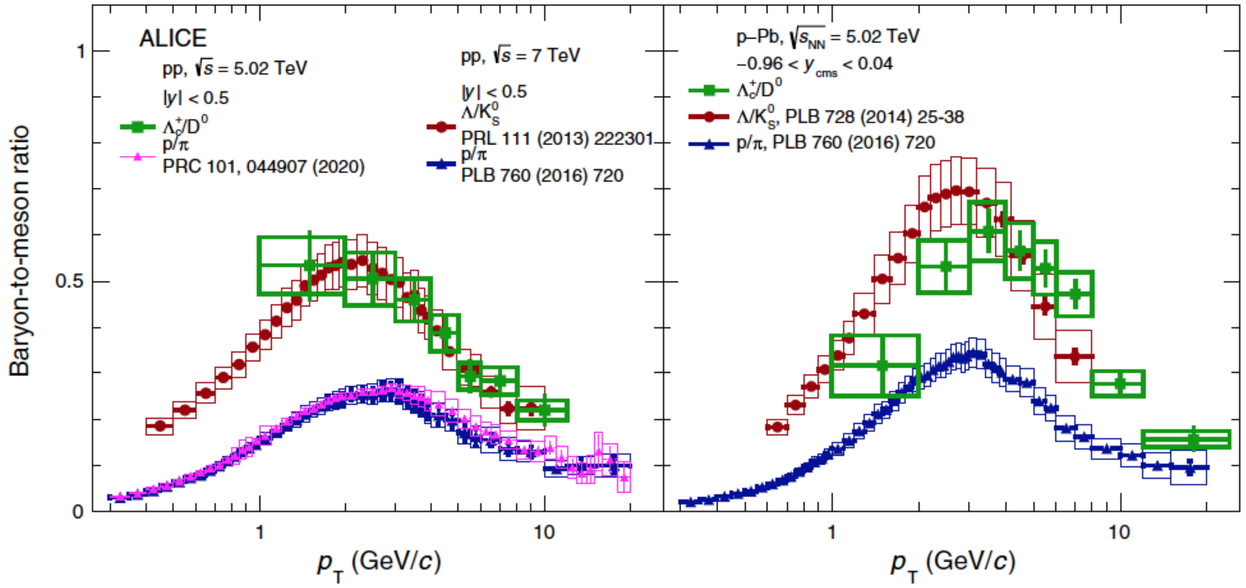
Large systems discoveries:

Comparable B/M pattern for all flavors and system sizes (magnitude changes as f(flavor & system size))

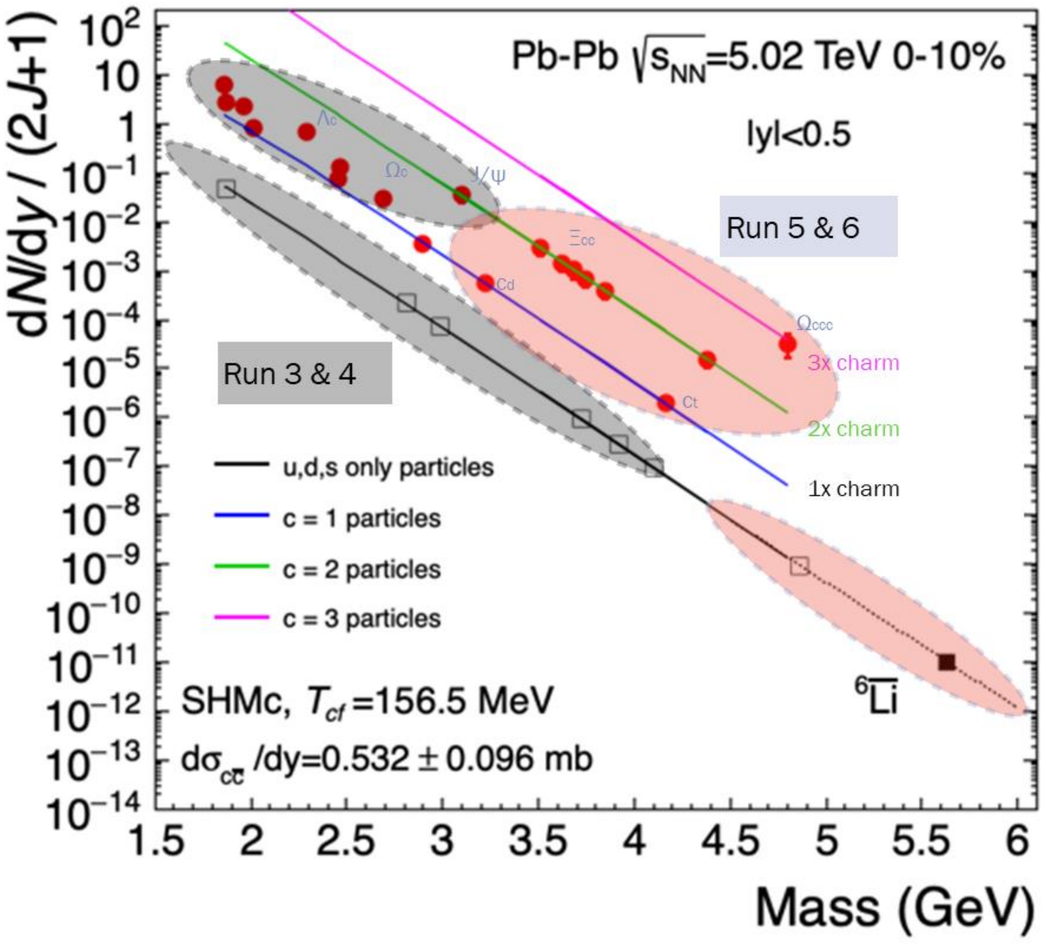






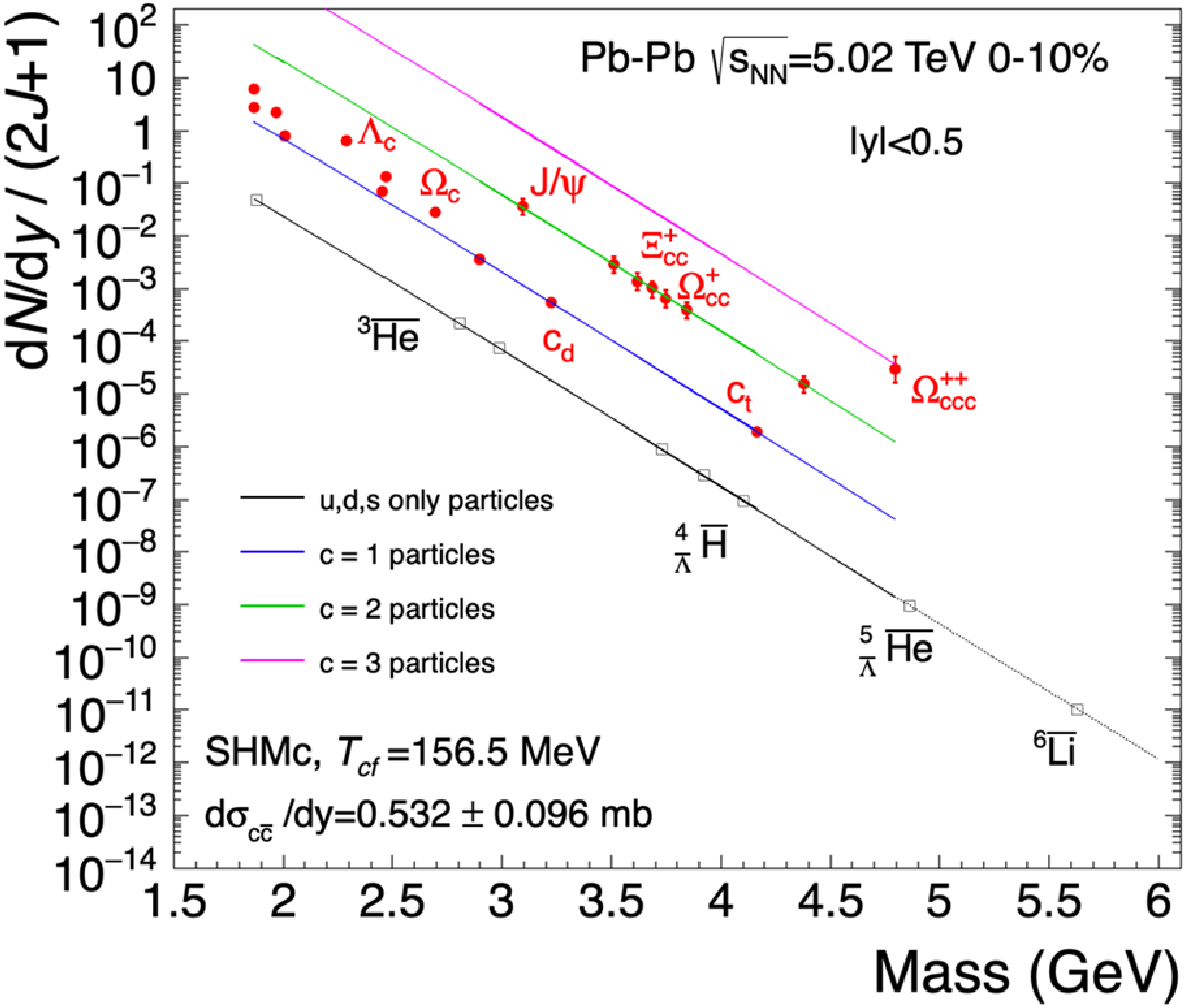
ALICE, Phys.Rev.C91, 024609 (2015)   ALICE, Phys. Rev.Lett. 111,22301 (2013)   ALICE, Phys. Rev. Lett. 127, 202301 (2021)

Program for ALICE Runs 3-6



What can ALICE 3 contribute to hadron formation

- **Light flavor nuclei**
- **Multi quark states**
- **Multi-charm baryons**: unique probe of hadron formation
  - Require **production of multiple charm quarks**
  - Very large enhancements in SHM
  - Unique sensitivity to **thermalisation and hadronisation dynamics**



Significant questions to be answered: - *role of entanglement in initial/final state, fragmentation/coalescence,*

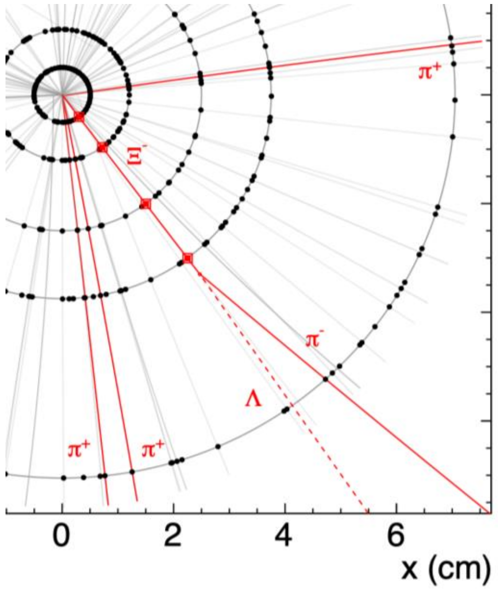
- *flavor dependent formation models in quark and hadronic state,*

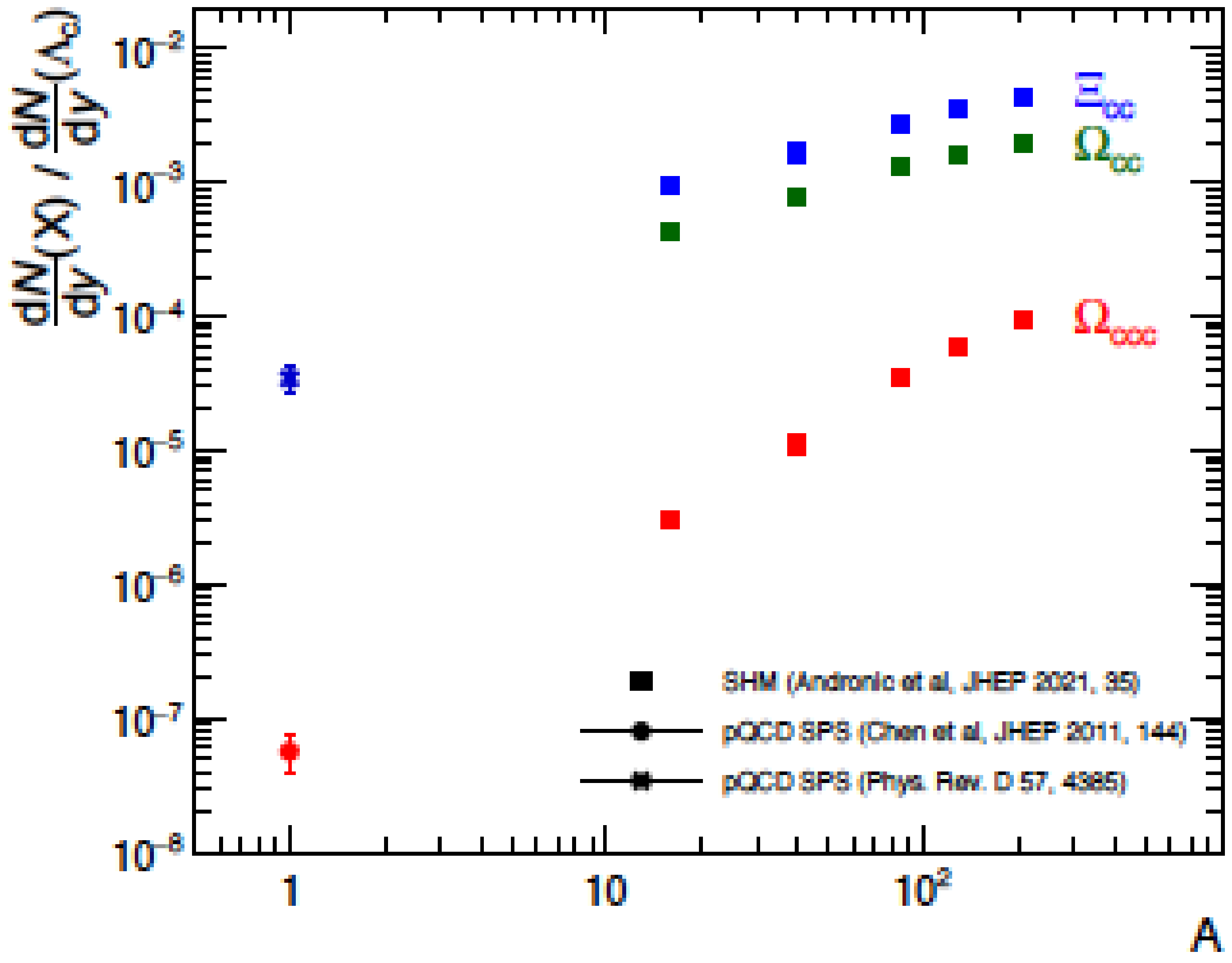
- *probability of hypermatter in high T and ρ systems*

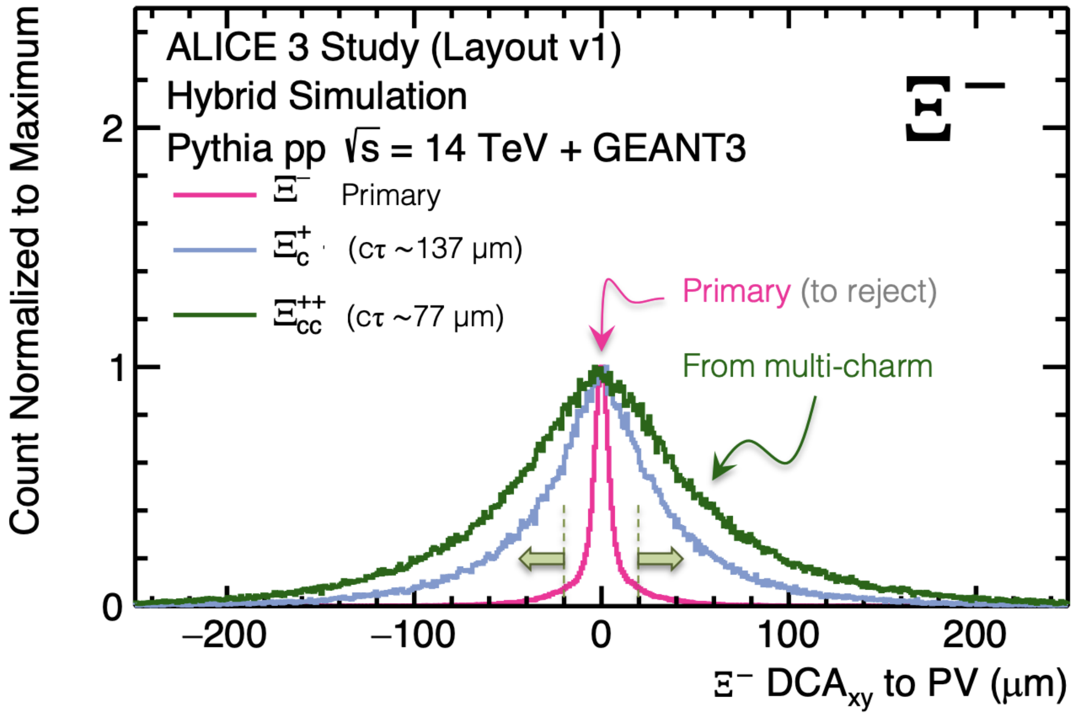
Multi-charm baryons

New technique: strangeness tracking

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



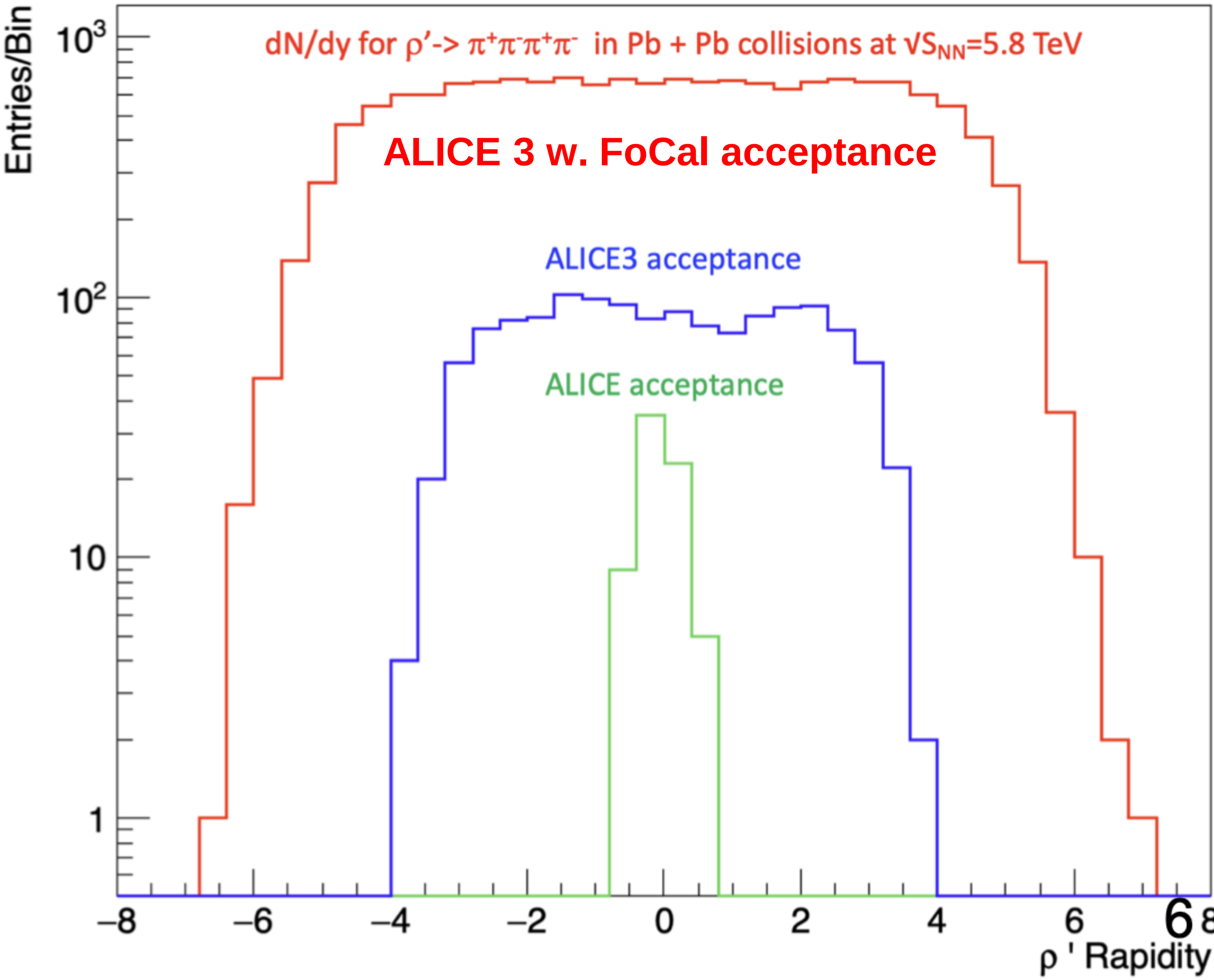




Pointing of Ξ baryon provides high selectivity

Ultraperipheral collisions

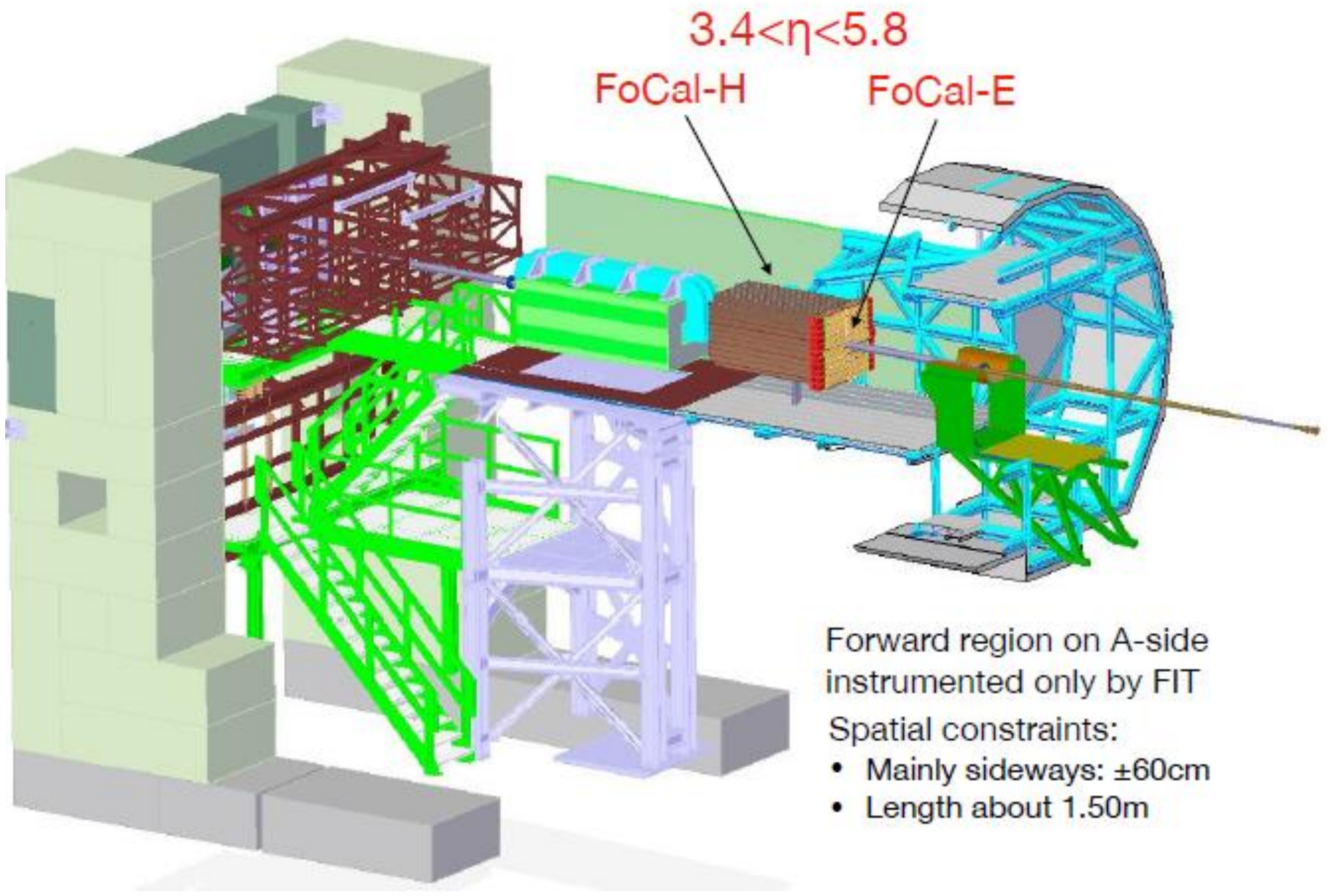
- Most studied UPC final states are simple: J/psi -> e+e-, ρ-> π+π-, etc. but need to see these charged particles + "Nothing else"
- "Nothing else" requires large angular acceptance & low pT coverage
- Example: distinguish low p_T $\{\pi^+\pi^-\pi^0\}$ from higher p_T $\{\pi^+\pi^-\}$
- Almost all UPC channels have 1 or 2 (depending on process) rapidity gaps
- **Wide rapidity coverage is important**; charged + neutrals are important



Wider rapidity range -> wider $\sqrt{s_{\gamma N}}$ energy range

- Huge win for complex final states
  - D^0D^0bar, b-mesons, 6-prongs etc.

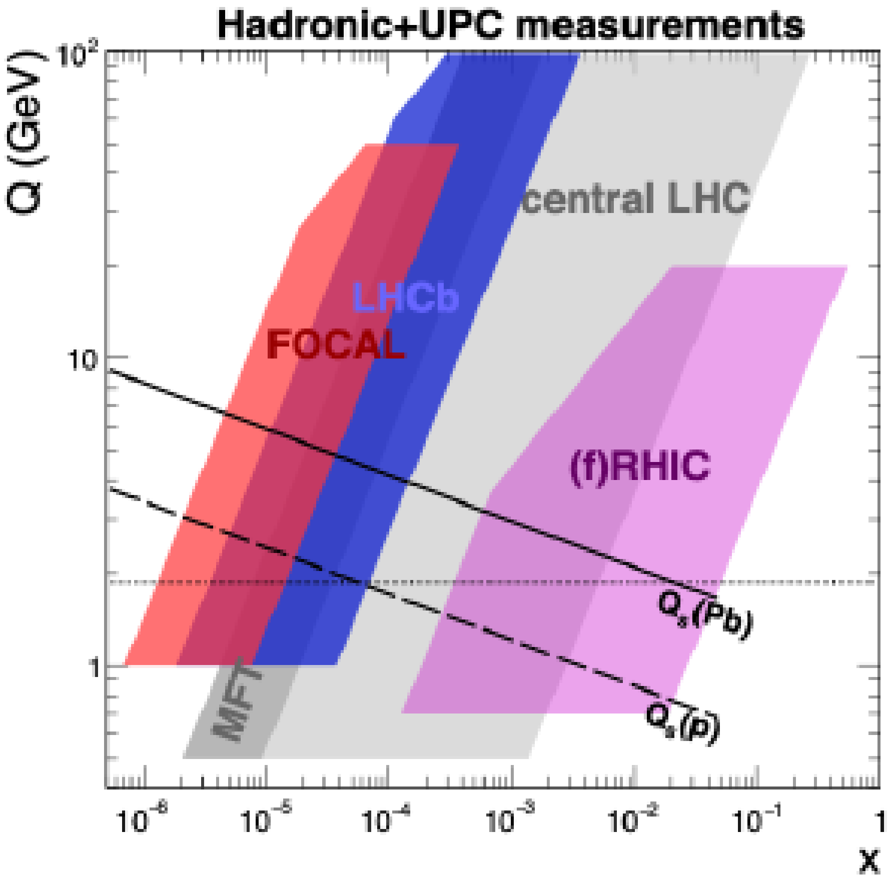
Icing on the cake: a Forward calorimeter (FoCal)



Forward region on A-side instrumented only by FIT

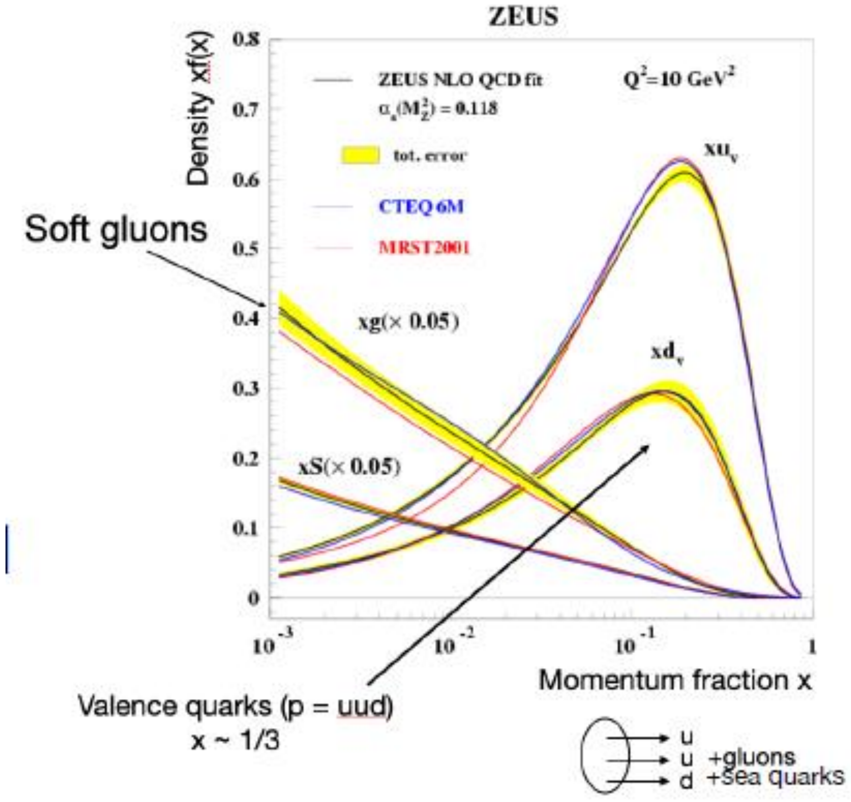
Spatial constraints:

- Mainly sideways: ±60cm
- Length about 1.50m

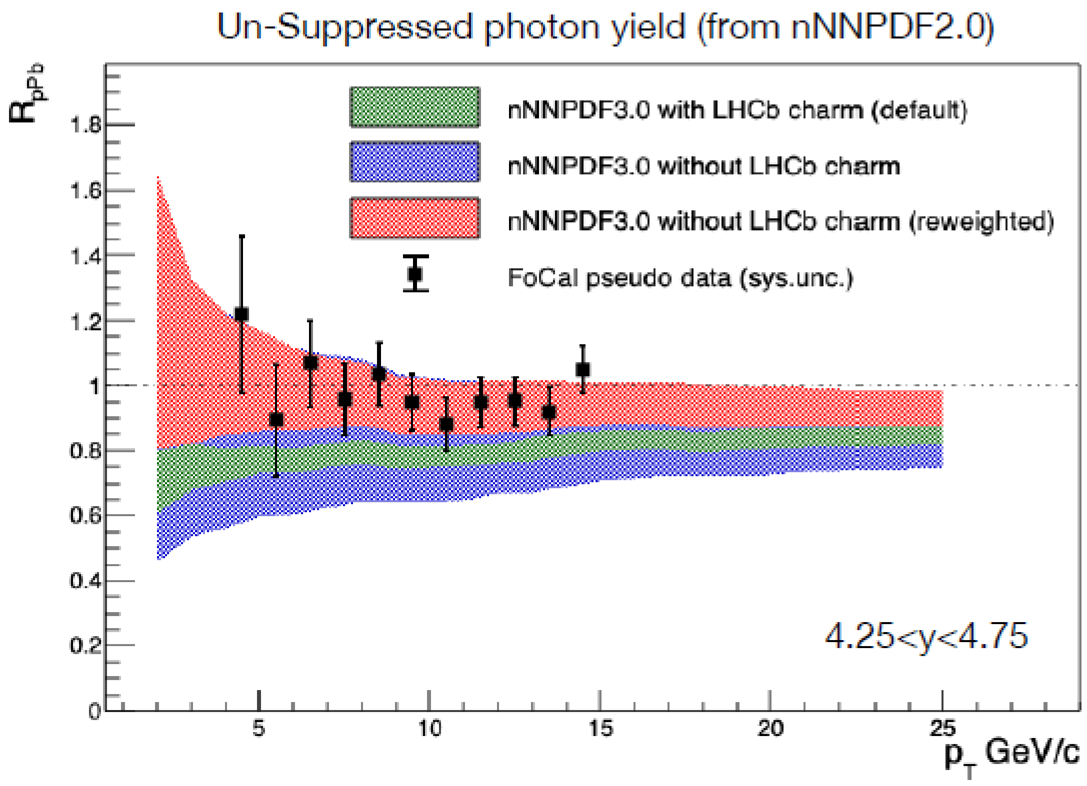


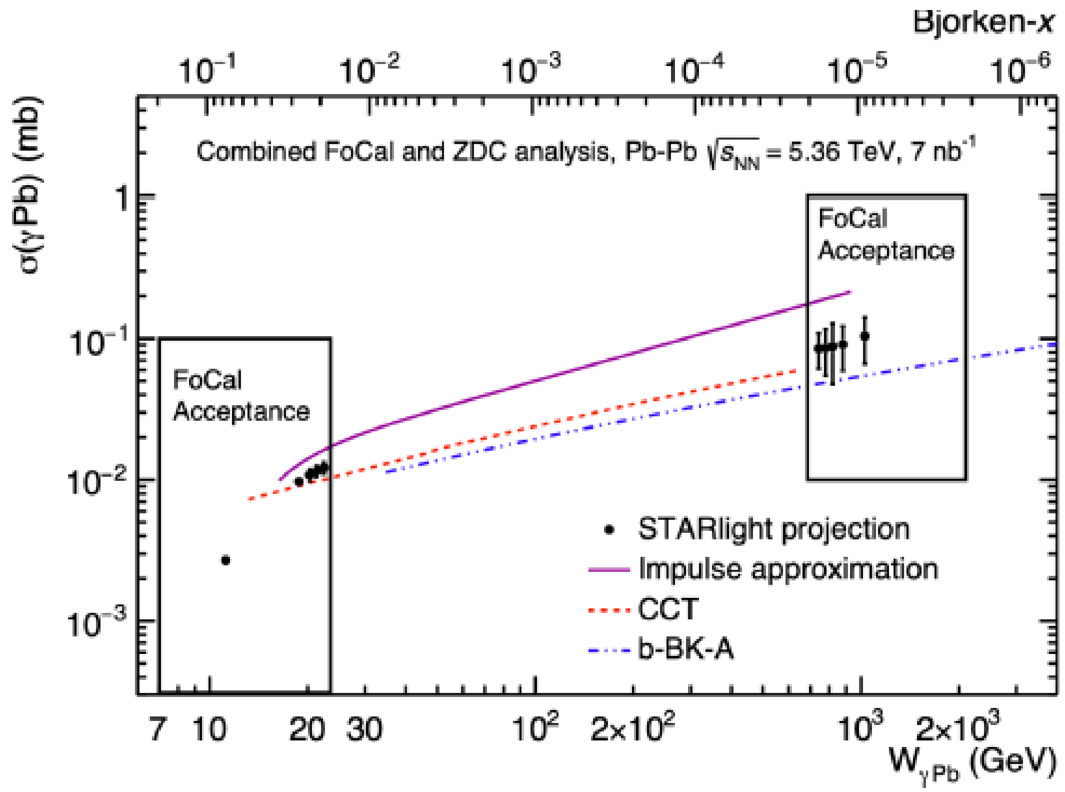
Letter-of-Intent: CERN-LHCC-2020-009

- Low x-measurements in the region of gluon domination
- **Wide rapidity coverage is important**; charged + neutrals are important
- PID somewhat important

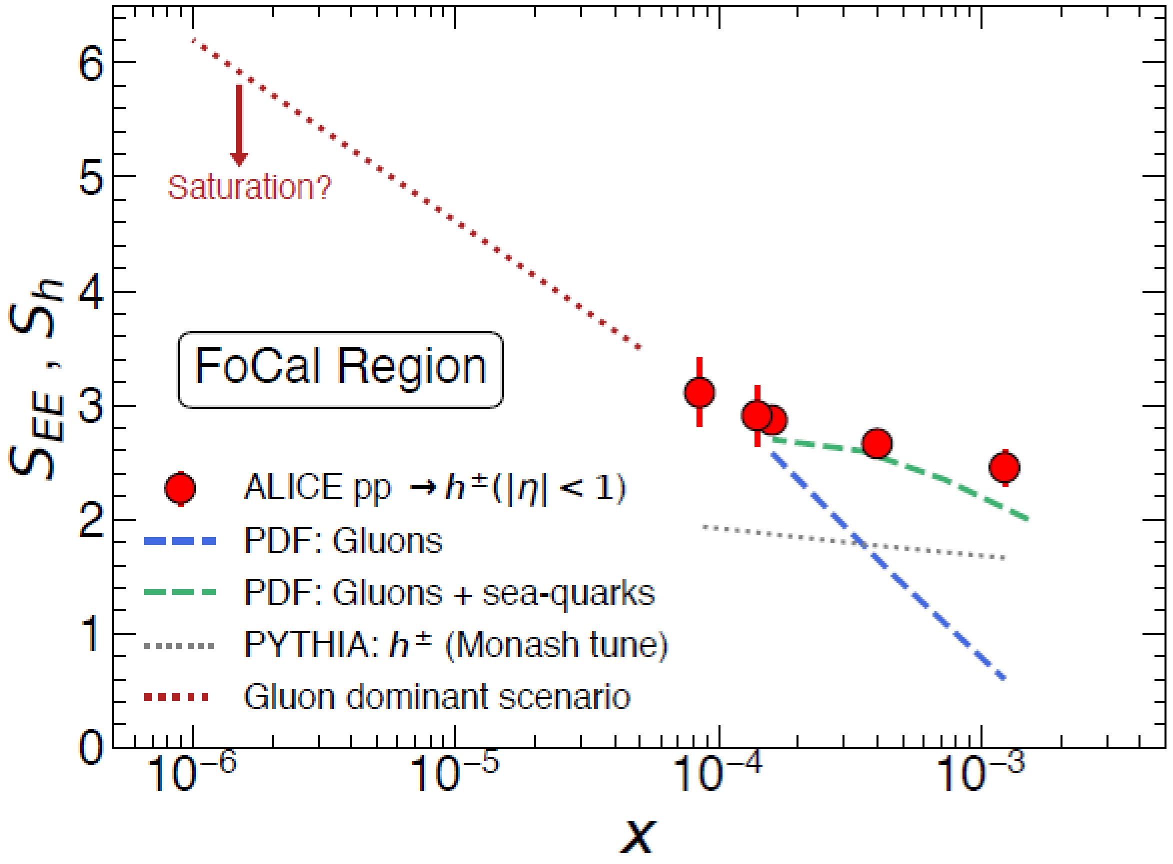


Saturation and Entanglement (FoCal Physics)

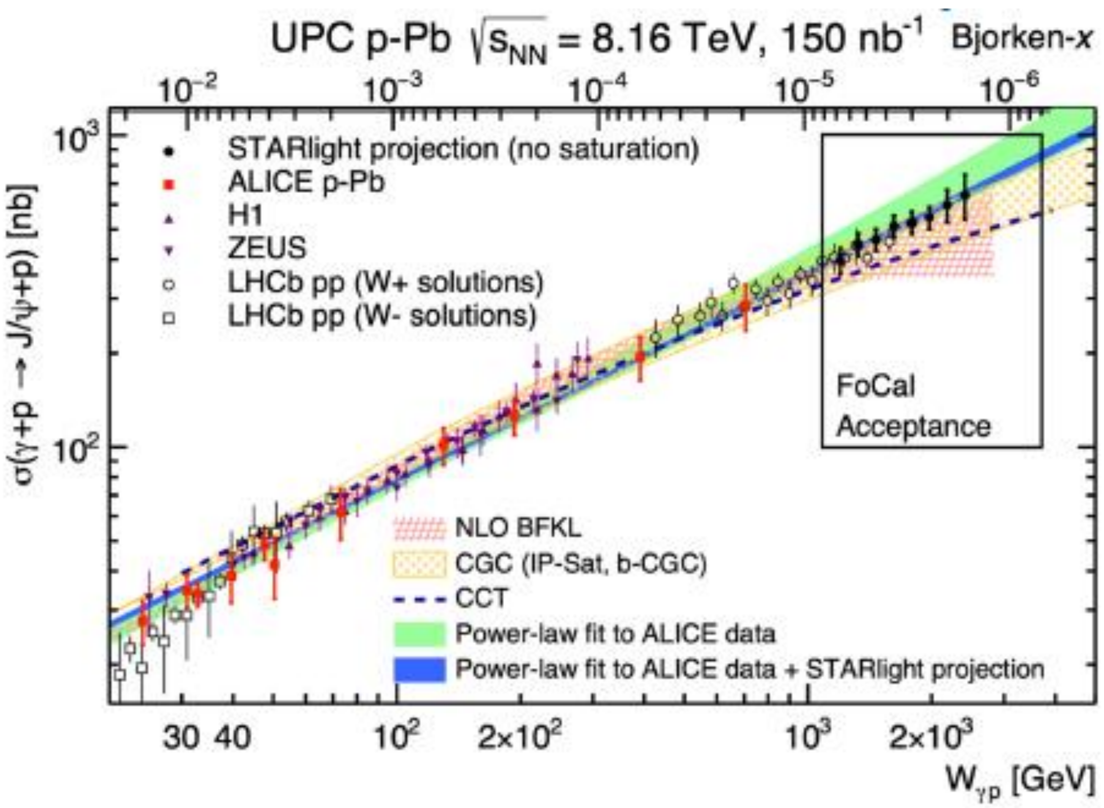


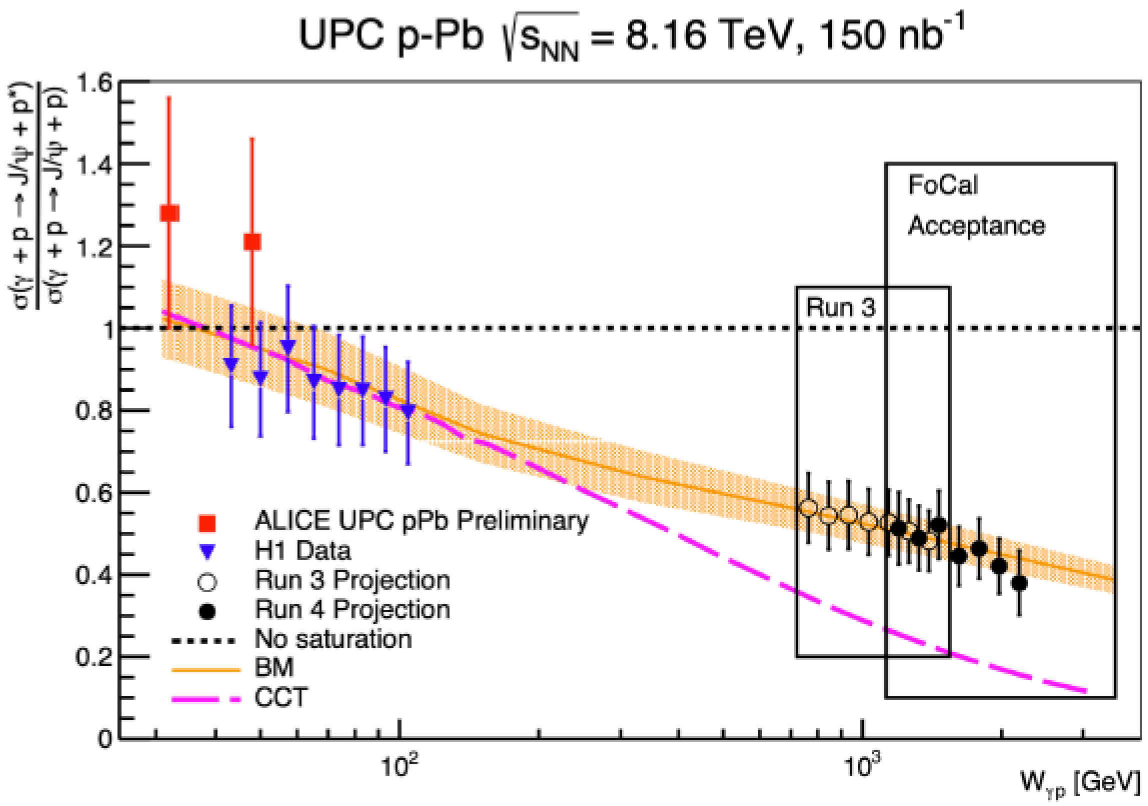


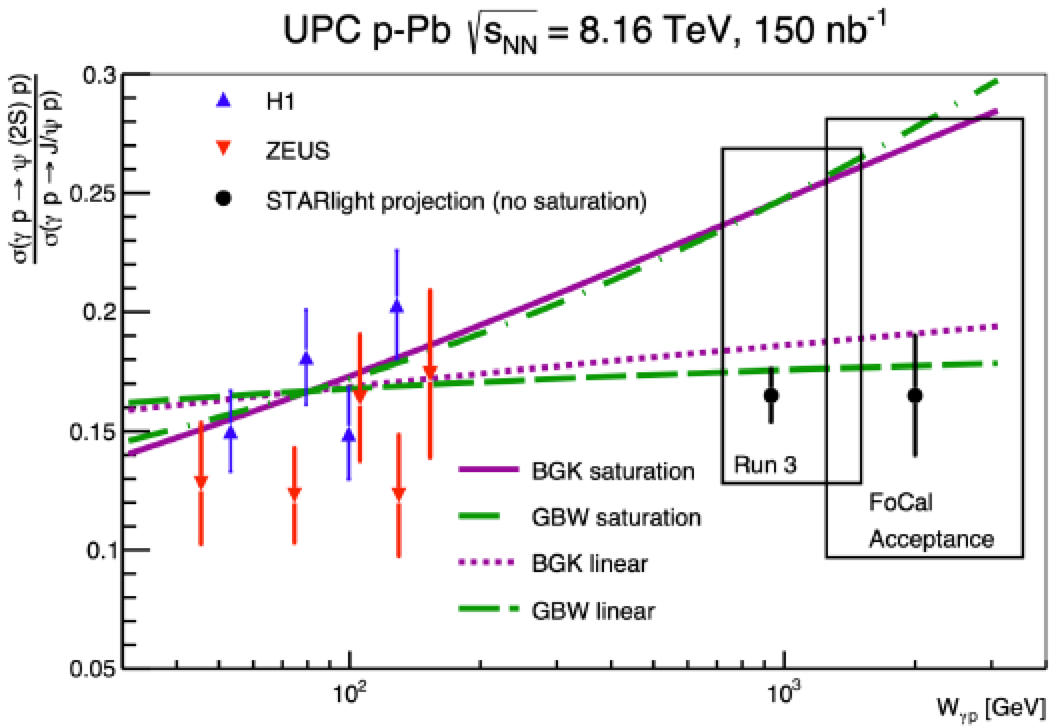
- Unique program utilizing photons and neutral pions in forward direction for:
    - Gluon saturation measurements
    - UPC measurements
    - Entanglement measurements



UPC Measurements in pPb in the FoCal

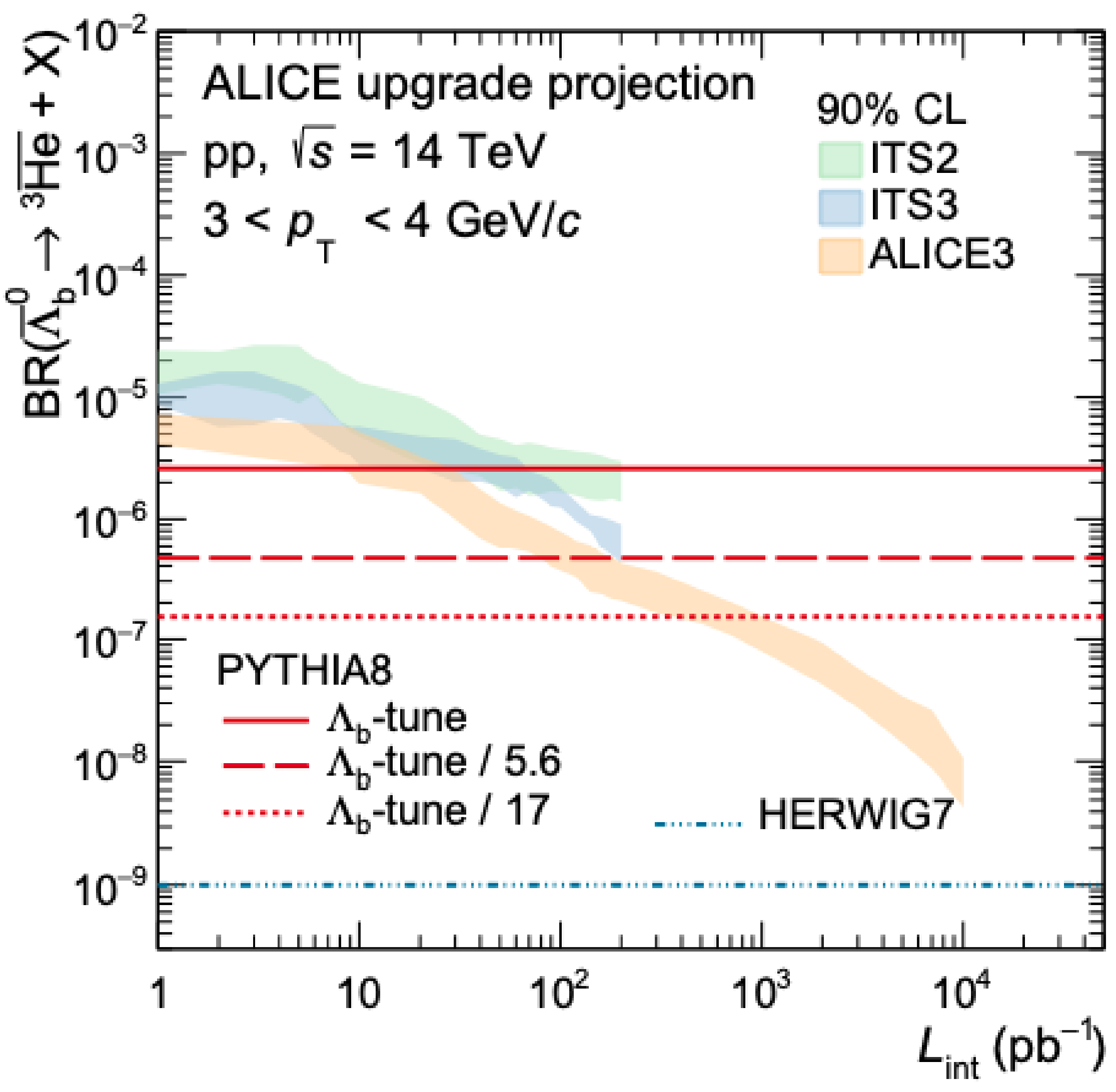




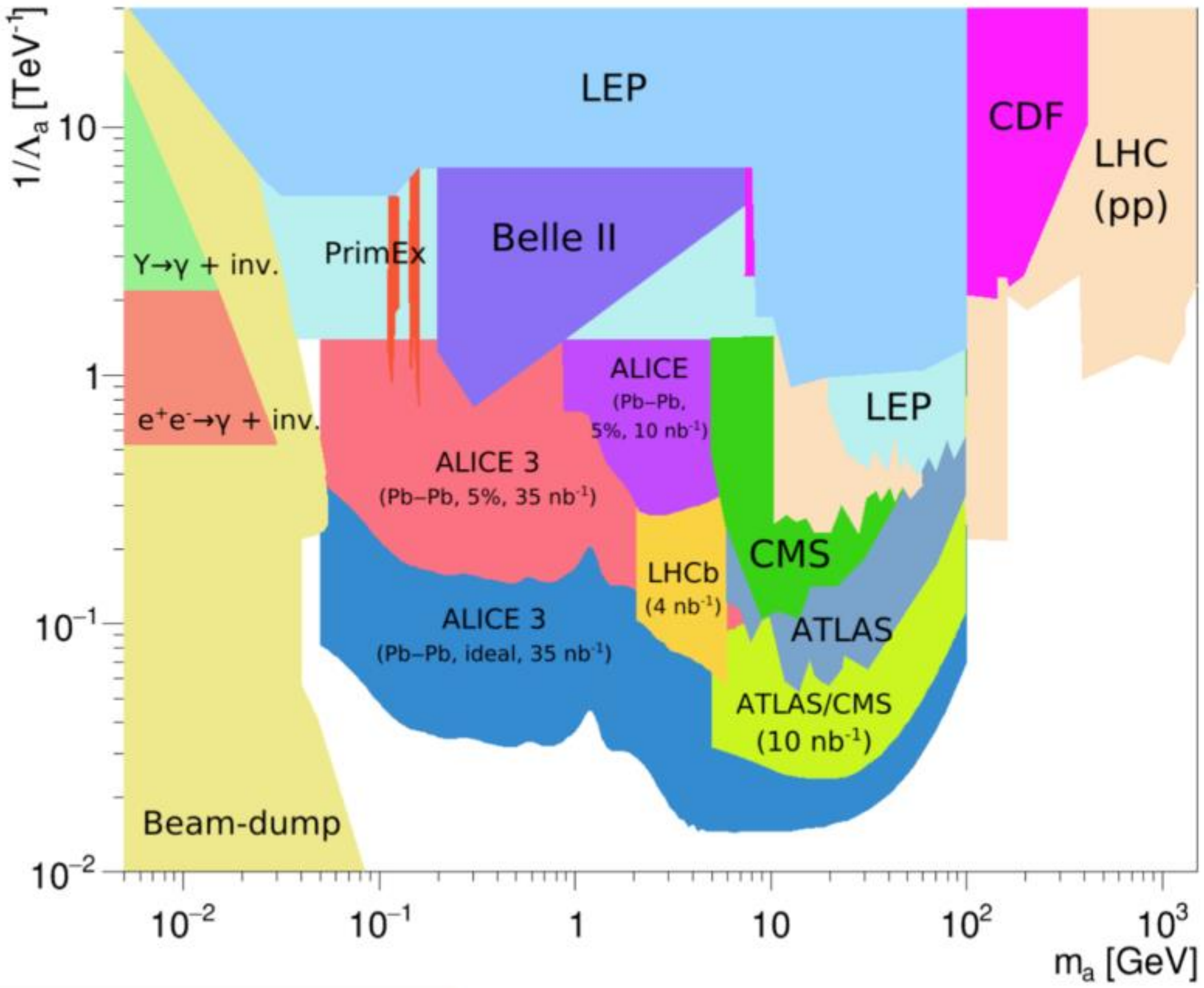


- UPC measurements in pPb focus on heavy quark states to determine magnitude of gluon saturation

BSM – ALP, Dark Matter searches



- Limits on axion-like particles



- Limits on axion-like particles (complementary to other exp.)

Detector requirements from observables

- **Heavy-flavour hadrons ($p_{\mathrm{T}} \longrightarrow 0$, wide η range)**

  → vertexing, tracking, hadron ID
- **Jets**
  - **tracking, calorimetry, hadron ID**
- **Ultrasoft photons (pT=1-50 MeV)**
  - **dedicated forward detector**
- **Nuclei**
  - **PID of Z>1**
- **Dileptons (p_{T} ~0.1 - 3 GeV/c, M_{ee} ~0.1 - 4 GeV/c^2)**

  → vertexing, tracking, lepton ID
- **Photons (100 MeV/c - 50 GeV/c, wide η range)**

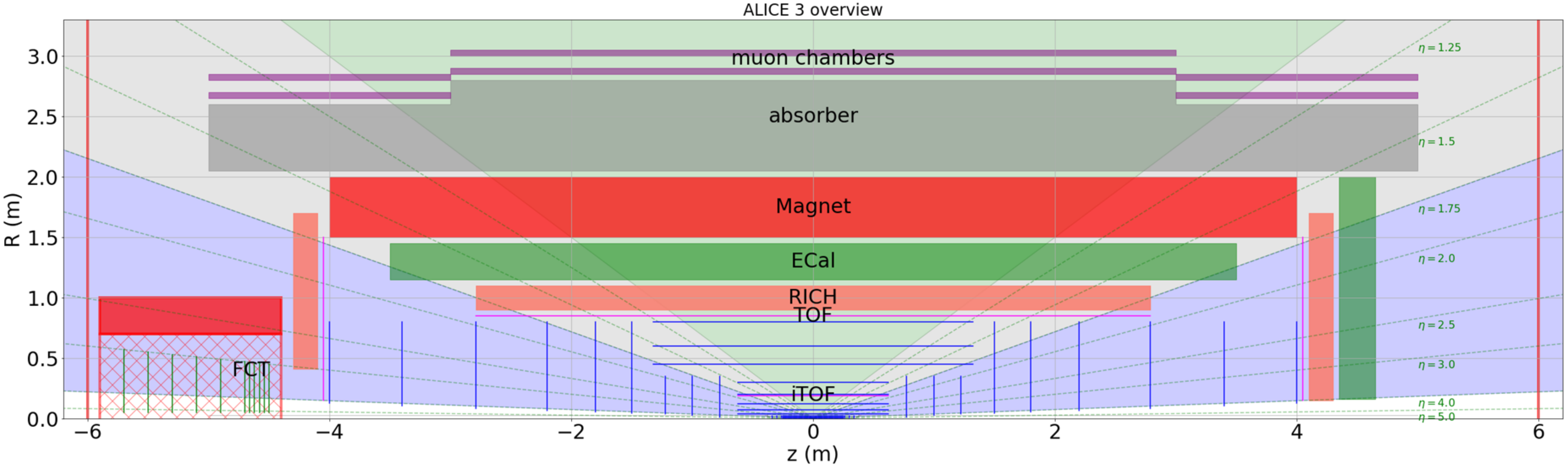
  → electromagnetic calorimetry
- **Quarkonia and Exotica ($p_{\mathrm{T}} \longrightarrow 0$)**

  → muon ID

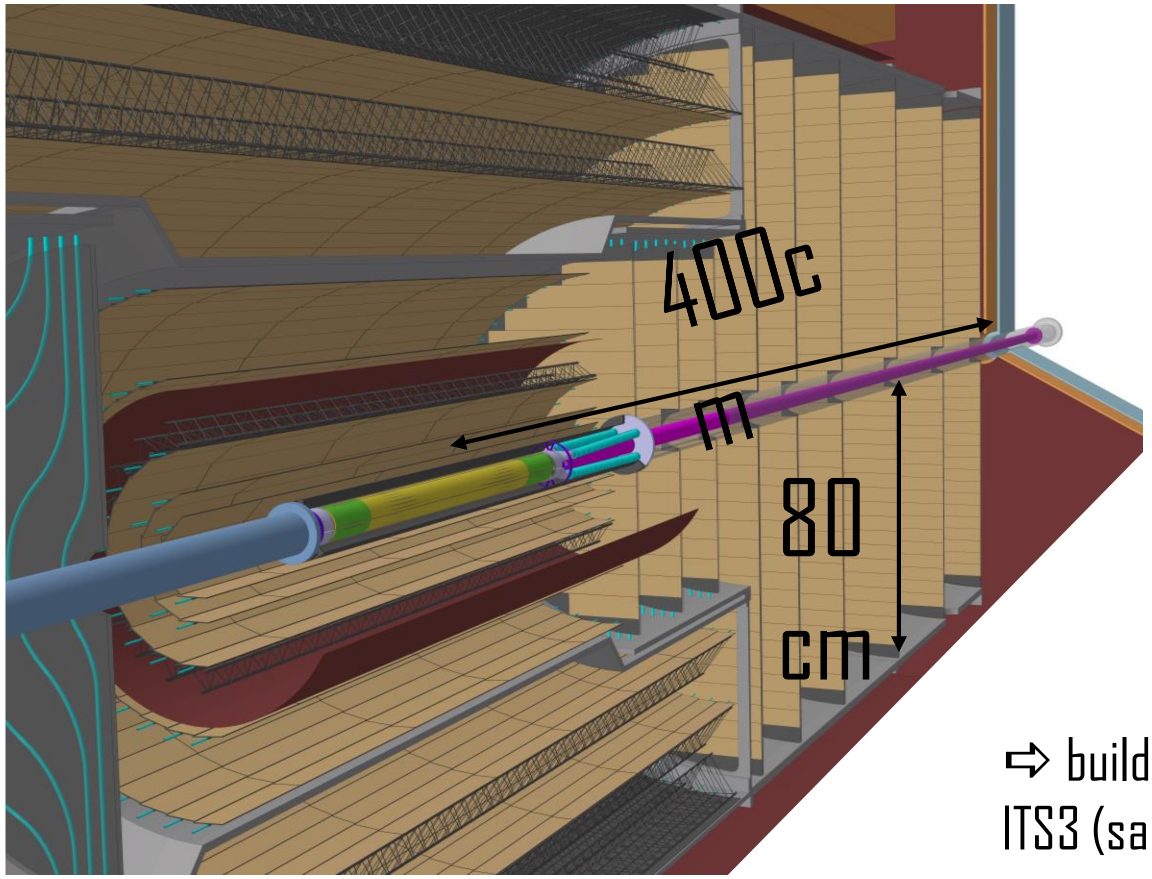
Detector requirements

Component	Observables	$\|\eta\| < 1.75$ (barrel)	$1.75 < \|\eta\| < 4$ (forward)	Detectors
Vertexing	Multi-charm baryons, dielectrons	Best possible DCA resolution, $\sigma_{DCA} \approx 10\ \mu m$ at 200 MeV/c	Best possible DCA resolution, $\sigma_{DCA} \approx 30\ \mu m$ at 200 MeV/c	Retractable silicon pixel tracker: 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	σ_{p_T} / p_T ~1-2 %		Silicon pixel tracker: $\sigma_{pos} \approx 10\ \mu m$, $R_{out} \approx 80$ cm, $X/X_0 \approx 1\%$ / layer
Hadron ID	Multi-charm baryons	π/K/p separation up to a few GeV/c		Time of flight: $\sigma_{tof} \approx 20$ ps RICH: aerogel, $\sigma_\theta \approx 1.5$ 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: aerogel, $\sigma_\theta \approx 1.5$ mrad possibly preshower detector
Muon ID	Quarkonia, $\chi_{c1}(3872)$	reconstruction of J/Ψ at rest, i.e. muons from 1.5 GeV/c		steel absorber: L ≈ 70 cm muon detectors
Electromagnetic calorimetry	Photons, jets	large acceptance		Pb-Sci calorimeter
	χ_c	high-resolution segment		$PbWO_4$ calorimeter
Ultrasoft photon detection	Ultra-soft photons		measurement of photons in p_T range 1 - 50 MeV/c	Forward Conversion Tracker based on Tracker based on silicon pixel sensors sensors

ALICE 3 overview



The Heart –
60 m^2 Silicon Pixel Detector inside a 2 T solenoid

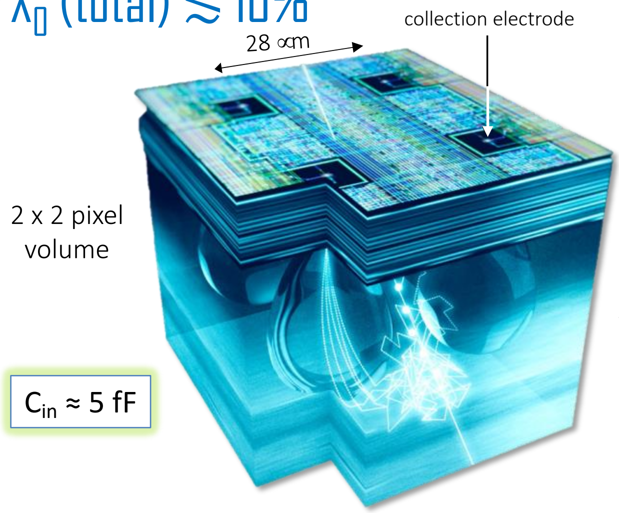


60 m^2 silicon pixel detector

based on CMOS Active Pixel Sensor (APS) technology

- large coverage: $\pm 4\eta$
- compact: $R_{out} \approx 80$ cm, $z_{out} \approx \pm 400$ cm
- high-spatial resolution: $\sigma_{pos} \approx 5\mu m$ (req. $< 10\mu m$)
- very low material budget: X/X_0 (total) $\lesssim 10\%$
- low power: ≈ 20 mW/cm^2

⇨ build on experience with ITS2 and ITS3 (same CMOS process)



Artistic view of a SEM picture of ALPIDE cross section

R&D focusses on

- module (O(10 x 10 cm^2)) concept based on industry-standard processes for assembly and testing
- services: reduce (eliminate) interdependency between modules (⇨ replacement of single modules)

Inside the Heart: A Curved Vertexing Tracker

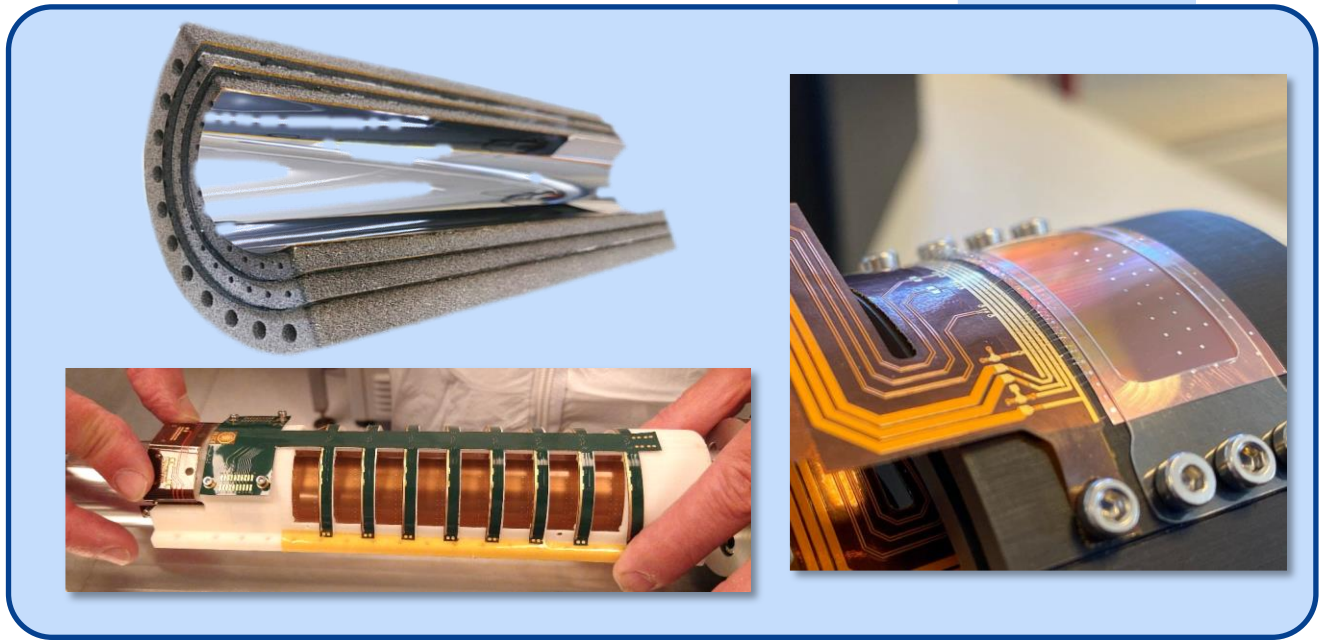
Pointing resolution $\propto r_0 \cdot \sqrt{x/X_0}$ multiple scattering regime ➟ 10 µm @ p_T = 200 MeV/*c*

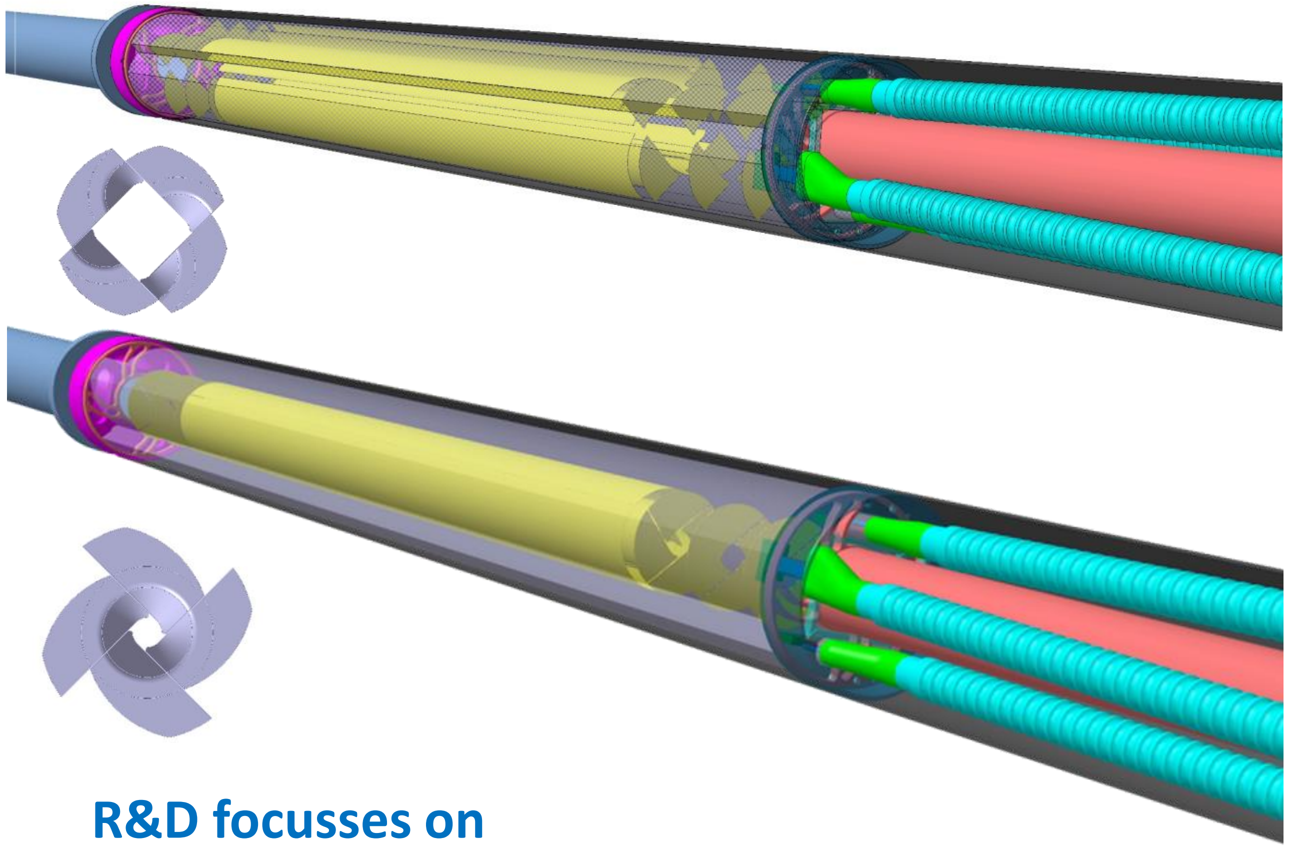
Ultimate performance

wafer-size, ultra-thin, curved, CMOS APS sensor

- 5mm radial distance from interaction point (inside beampipe, retractable configuration)
- unprecedented spatial resolution: $\sigma_{pos} \approx 2.5$ µm
- … and material budget ≈ 0.1% X_0 / layer

ITS3 R&D





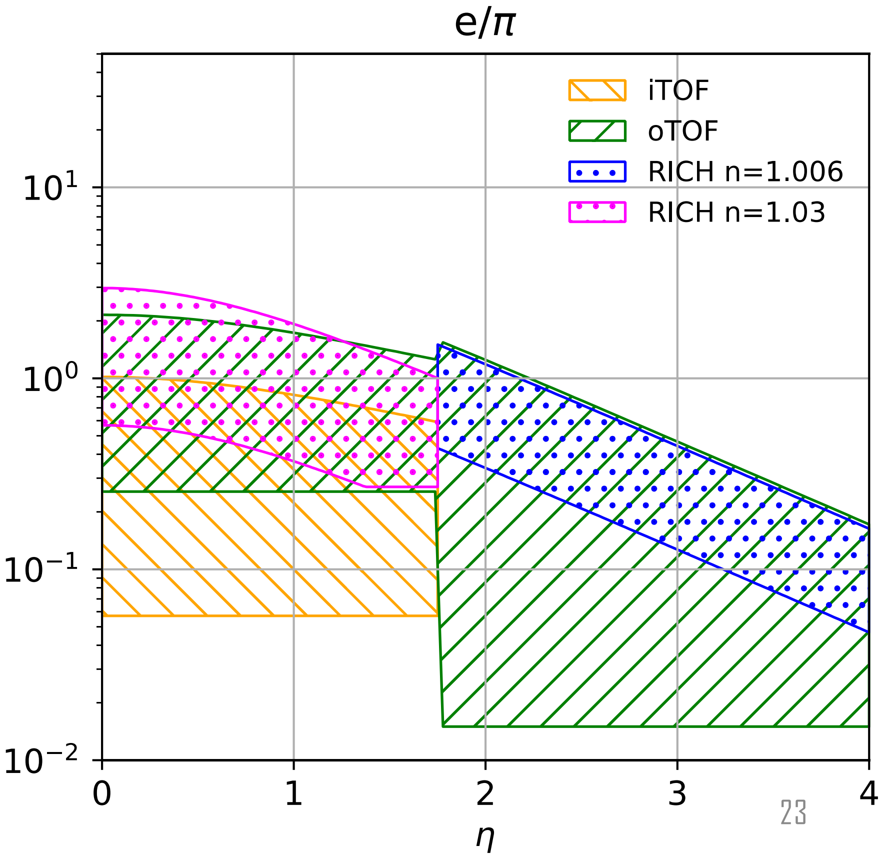
R&D focusses on

- wafers-sized, curved sensors (**same as for ITS3**)
- **advanced mechanics and cooling for integration inside beampipe** (rotary petals, matching beampipe parameters, feed-through for services)

RICH and TOF for Particle Identification

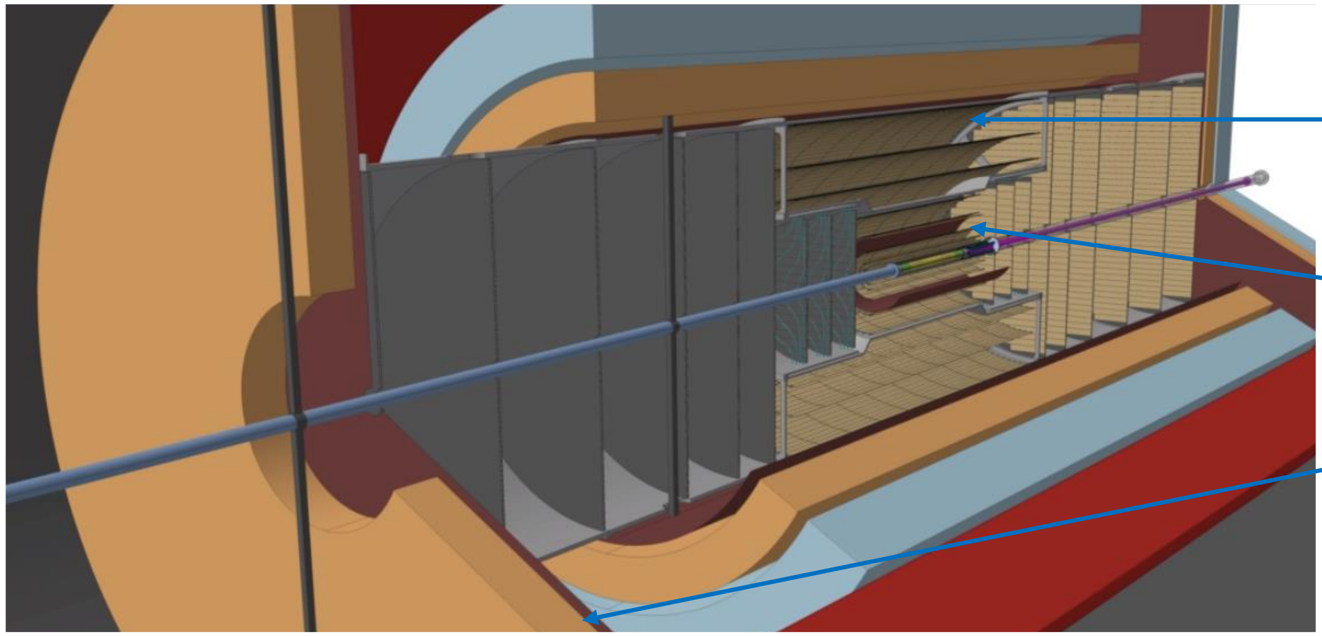
- Refine forward PID detector setup
- Evaluate impact of RICH and TOF separately (scoping)
    - Refine overlap/transition region
- Muon identification
    - refined simulation with detector material, absorber, and matching
- Evaluate performance of ECAL for electron ID
    - for quarkonia
    - for thermal radiation

e/π separation vs η, p_T



Example study: improve TOF resolution to cover electron ID up to 1.5 GeV
would need 2 ps TOF resolution ⇒ need multiple technologies to cover range

Time Of Flight



Barrel TOF ($|\eta| < 1.75$)

- Outer TOF radius = 85cm
  surface: 30m^2, pitch: 5 mm
- Inner TOF, radius = 19 cm
  surface: 1.5m^2, pitch: 1 mm

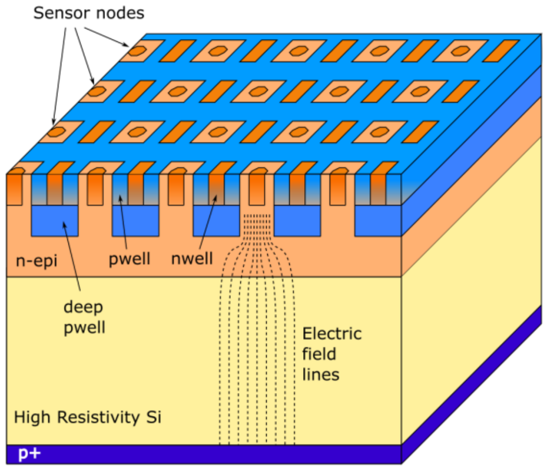
Forward TOF ($1.75 < |\eta| < 4$)

- Inner radius = 15 cm, Outer radius = 150 cm
  surface = 14m^2, pitch = 1mm to 5mm

Two R&D lines

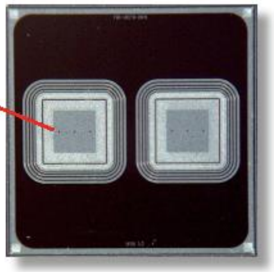
- **CMOS LGAD (baseline):** main R&D line in ALICE
  - ➪ integration of sensor and readout in a single chip
  - ➪ easier system integration and significant cost reduction
- **Conventional LGADs (fallback)**: R&D line in ALICE with very thin sensors

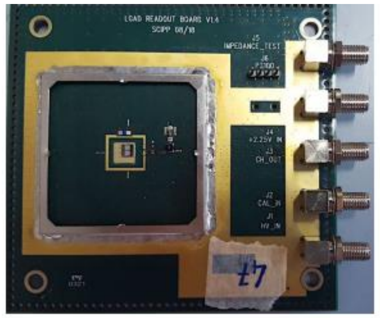
$\sigma_{TOF} \lesssim 20$ps



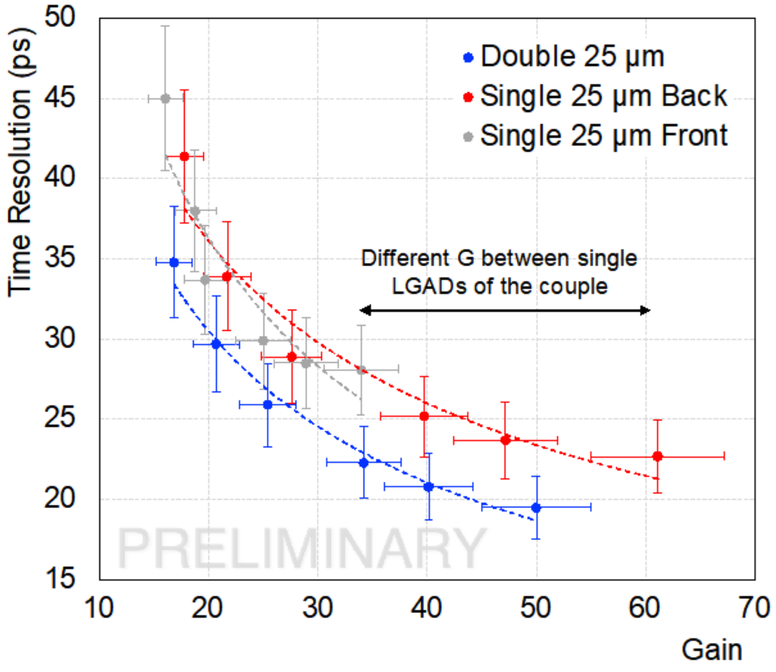
First very thin LGAD prototypes produced by FBK

25 µm and 35 µm-thick FBK single channel
Area = 1x1 mm^2

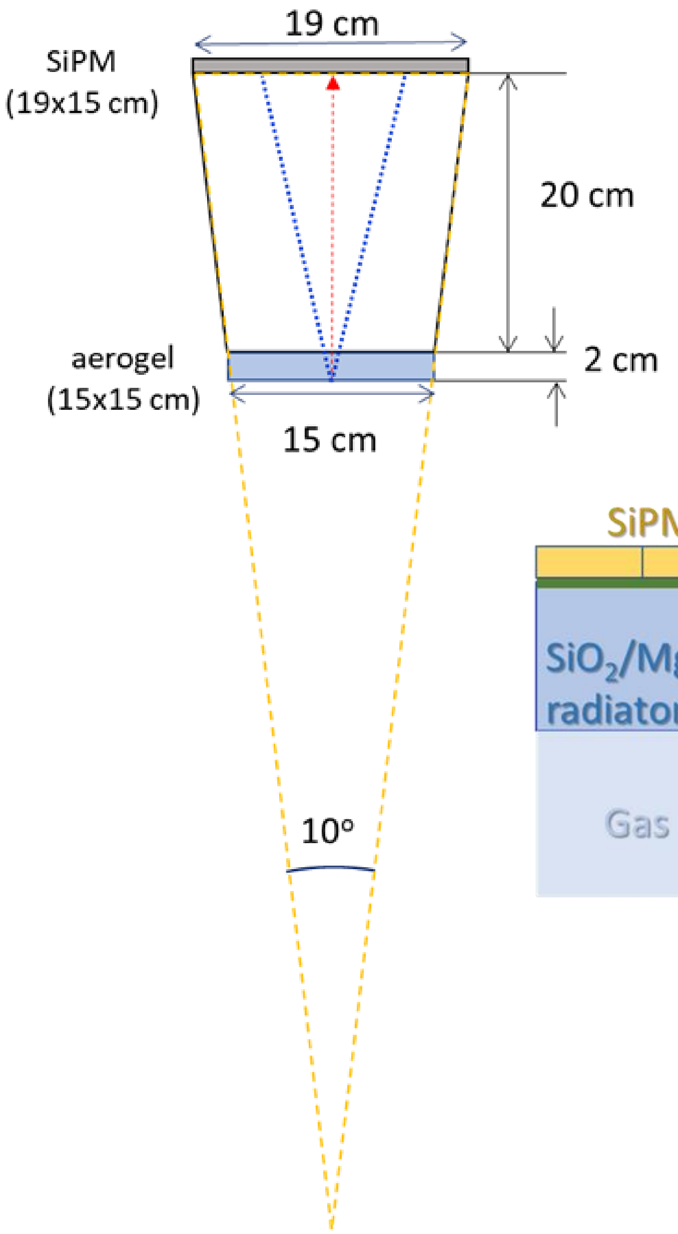




+ Second stage external amplifier ($G_{amplifier}$ ~ 11-14)

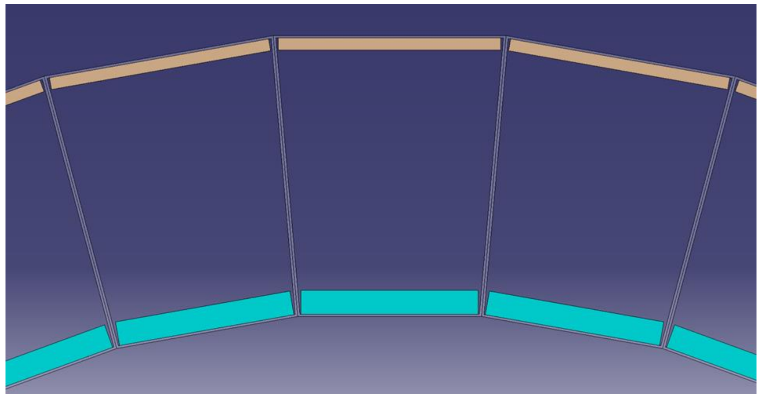


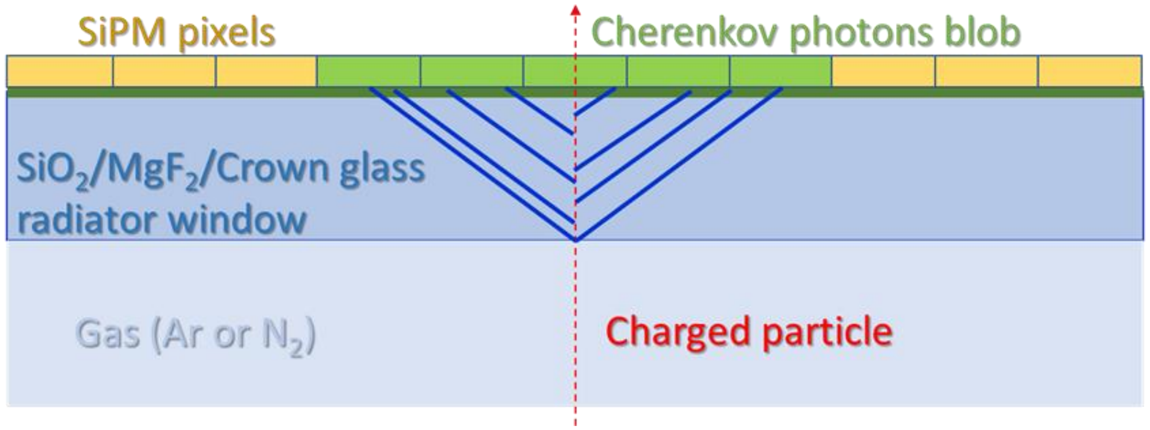
PID: RICH + TOF combined in a single detector?

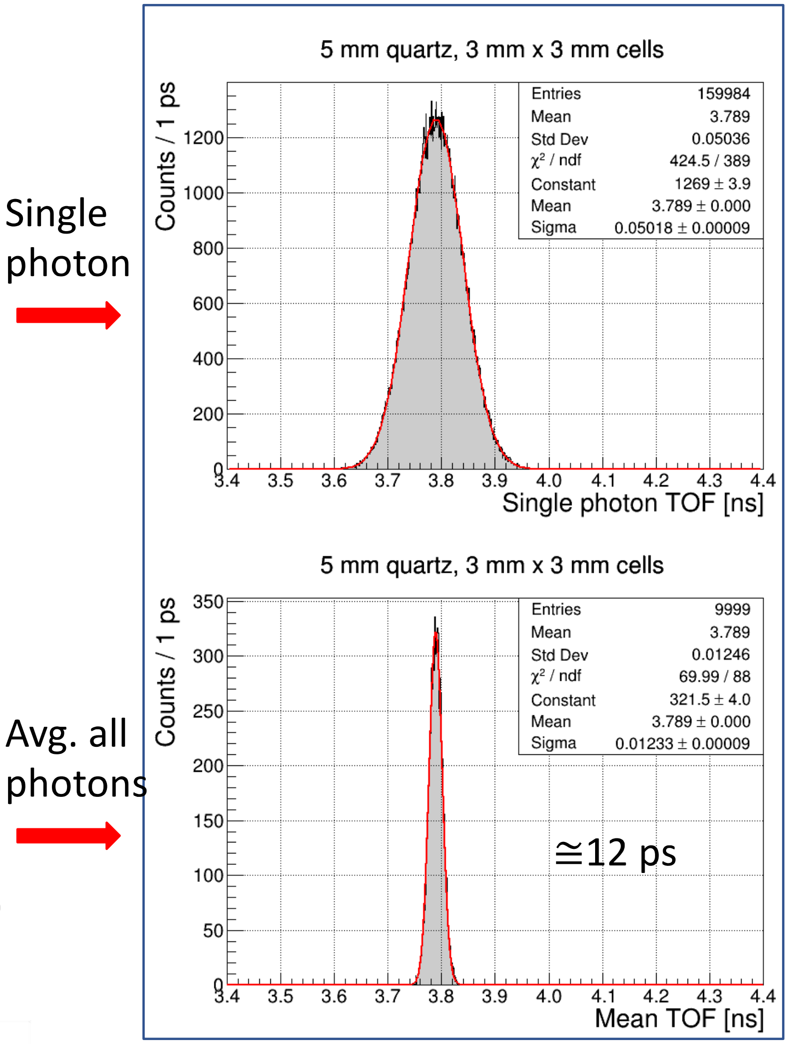


TOF measurement in RICH SiPM layer

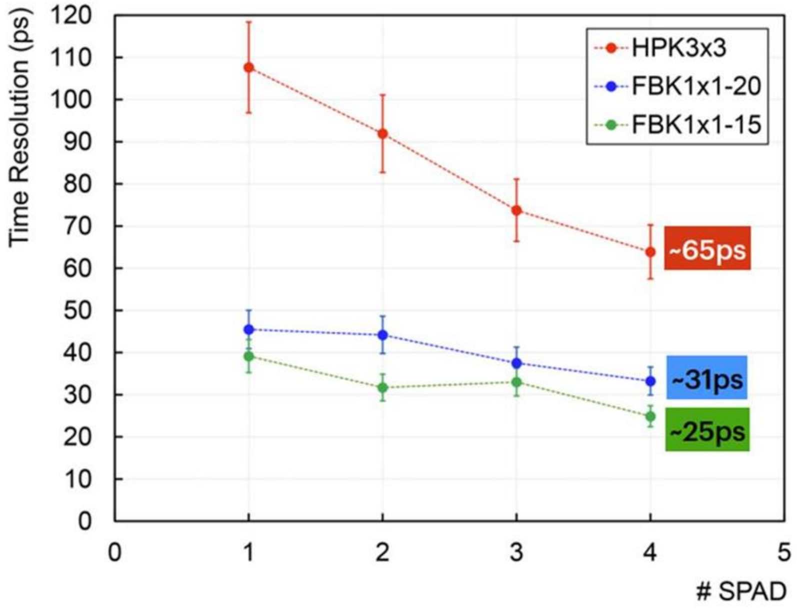
- Radiator window in front of photosensor (w/o gap)
- Time information from Cherenkov photon cluster surrounding the MIP







Results obtained in previous tests with a very thin radiator layer (sensor passivation layer)



Summary

ALICE 3

- Utilize the LHC-HL to measure new signals in heavy-ions
- Ultimate precision for QGP properties (+ nuclei structure, BSM physics, …)

- New technologies – compelling R&D program for applications beyond ALICE
- R&D – areas open for common effort / synergies (e.g. EIC)

- New interest, members, collaborators are most welcome!