Verhandlungen der Deutschen Physikalischen Gesellschaft e.V.

ALICE upgrades and physics prospects

DPG Spring Meeting,
Köln, 10-14 March 2025

Andrea Dainese (INFN Padova)
on behalf of the ALICE Collaboration

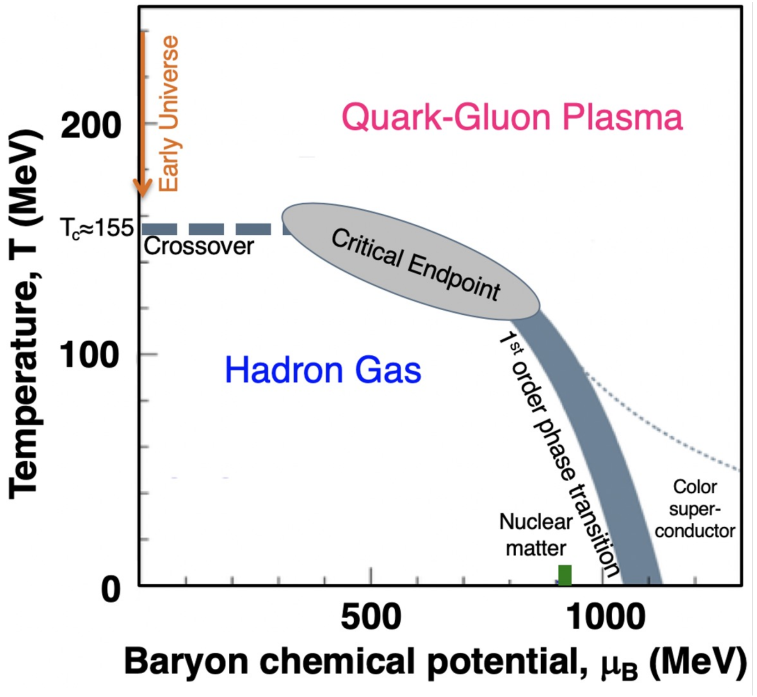
INFN PADOVA
Istituto Nazionale di Fisica Nucleare
Sezione di Padova

Hans Gutbrod (1942-2025)

Among the founders of Relativistic Heavy Ion Physics and of the ALICE Collaboration

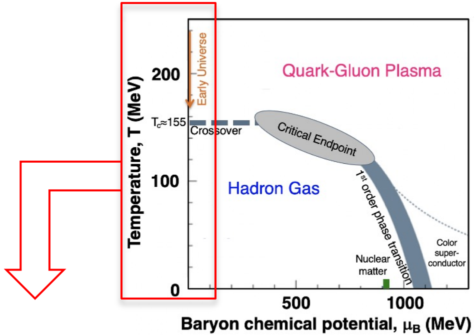
Strongly-interacting matter in extreme conditions: the Quark-Gluon Plasma

- At high energy density ε → phase transition to the QGP
    - Colour confinement removed
    - Chiral symmetry approx. restored

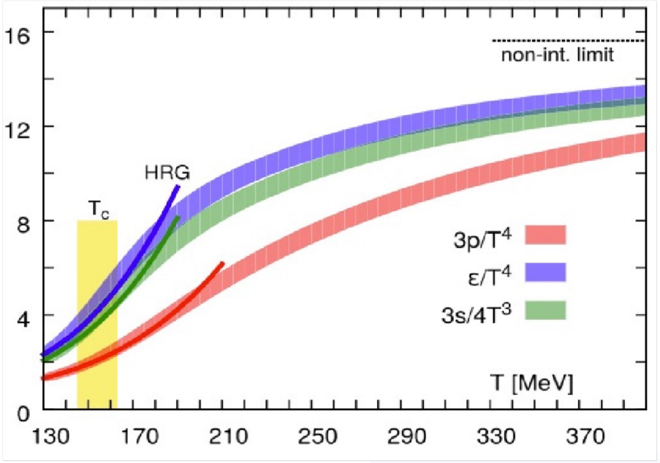


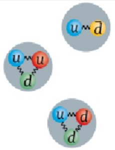
Strongly-interacting matter in extreme conditions: the Quark-Gluon Plasma

- At high energy density ε → phase transition to the QGP
  - Colour confinement removed
  - Chiral symmetry approx. restored
- Lattice QCD:
  - ε_c ~1 GeV/fm^3 (T_c~155 MeV ~10^{12} K at μ_B=0)
  - Transition is a crossover at low μ_B



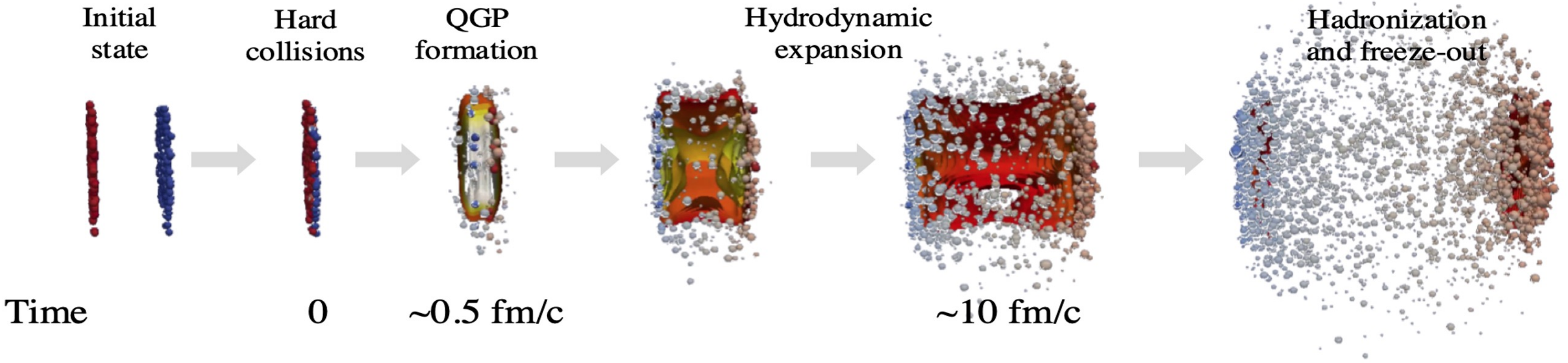
[PRD 90 094503 (2014)]





QGP study in heavy-ion collisions

High-energy nucleus-nucleus → **large ε & T** (>> ε_c, T_c) over **large volume** (~ 10 fm^3)



Visualization by J.E. Bernhard, arXiv:1804.06469

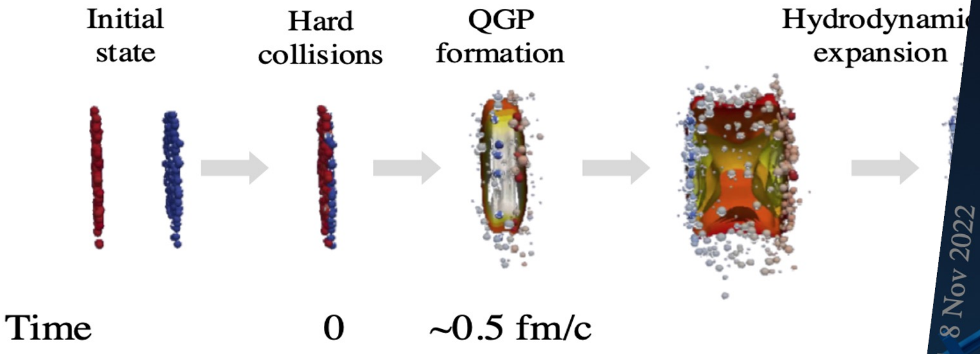
The QGP as seen at the LHC:

Energy density > 10 GeV/fm^3
Colour charge deconfined
Strong energy loss for hard partons

Expands hydro-dynamically like a very-low viscosity liquid
Hadronizes as in thermal equilibrium

QGP study in heavy-ion collisions

High-energy nucleus-nucleus → large ε & T (>> ...fm^3)



The QGP as seen at

Energy density > 10 GeV/fm^3
Colour charge deconfined
Strong energy loss for hard partons

...ium

Major (expected) open questions after the 2020s

- Initial state of heavy-ion collisions: is the gluon density reaching saturation at small x?

→ Direct probes of small-x initial gluon PDF: forward-rapidity photons

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

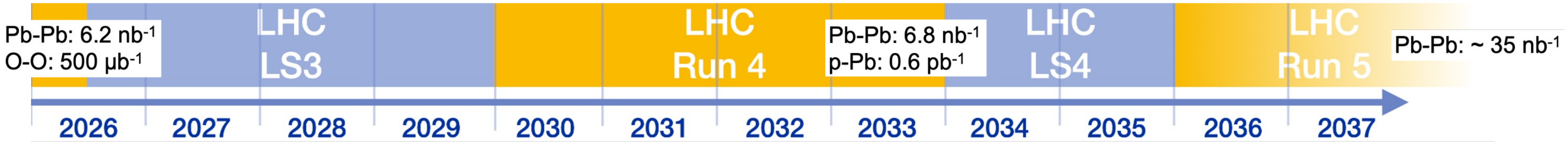
→ Systematic measurement of (multi-)charm hadrons

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

→ Precision measurements of dileptons

- QCD chiral phase structure → fluctuations of conserved charges
- Nature of exotic charm hadrons → charm hadron-hadron correlations

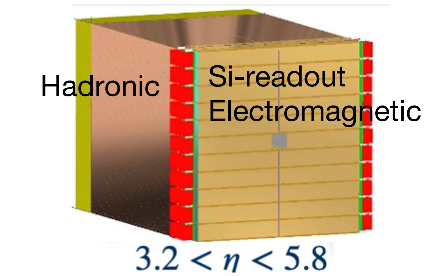
Timeline of ALICE upgrades



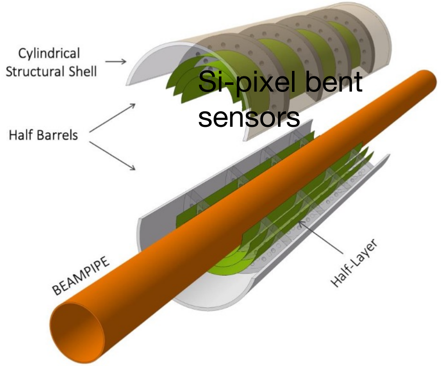
FoCal & ITS3

- Specific upgrades in LS3 (2026-29)
- TDRs approved in March 2024
- Moving towards "production" phase

FoCal TDR: CERN-LHCC-2024-004

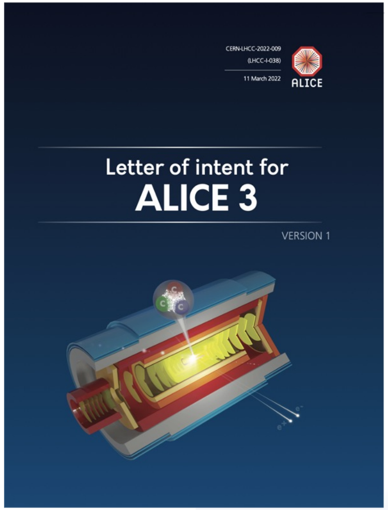


ITS3 TDR: CERN-LHCC-2024-003



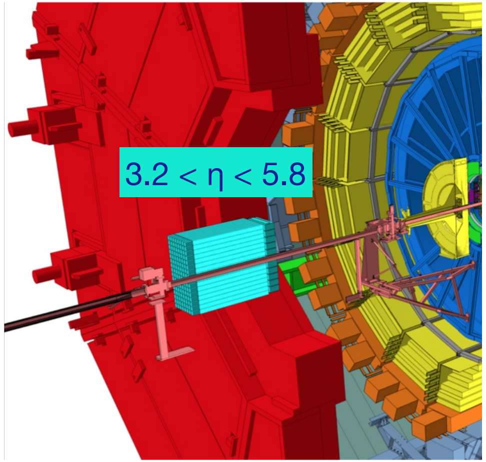
ALICE 3

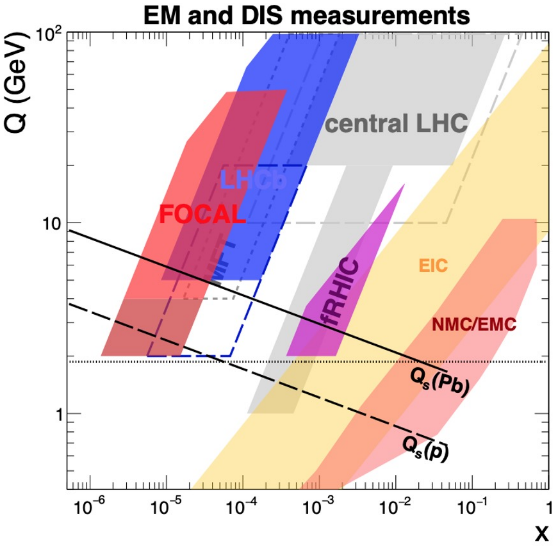
- New detector in LS4 (2034-35)
- LoI reviewed in 2022



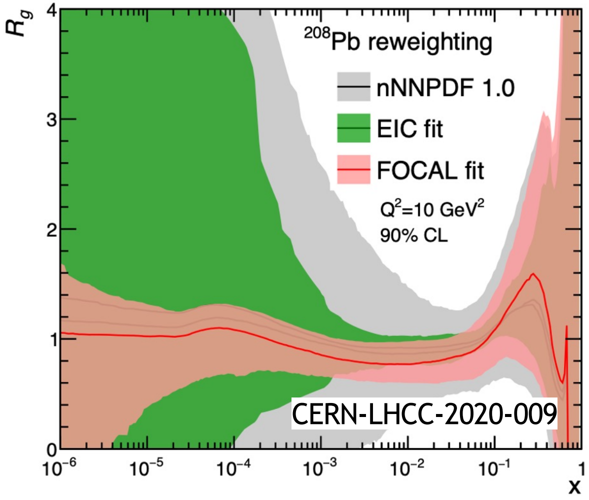
CERN-LHCC-2022-009

Forward Calorimeter (FoCal)





Impact on shadowing factor of Pb gluons



- Main goal: direct photon detection in p-Pb to probe gluon density in Pb down to $x{\sim}10^{-6}$, well below saturation scale Q_S
- and much more: correlations, jets, J/ψ in hadronic and UPC collisions
- Unique programme, complementary to LHCb, ATLAS/CMS and EIC coverage; EM probes (photons) complementary to hadronic ones (e.g. charm)

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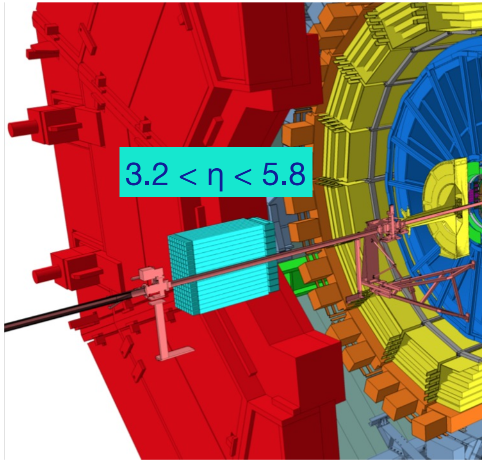
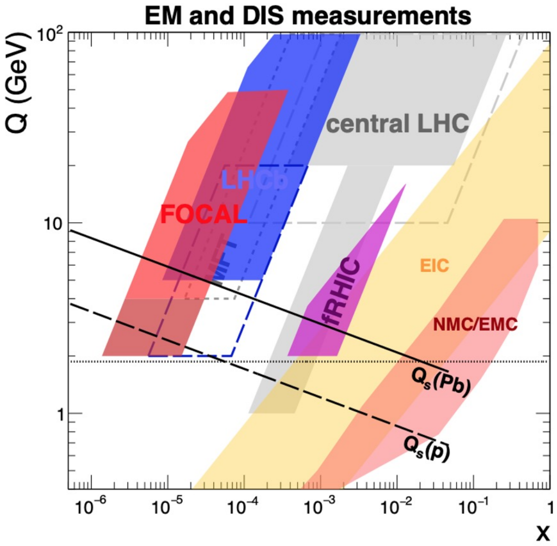
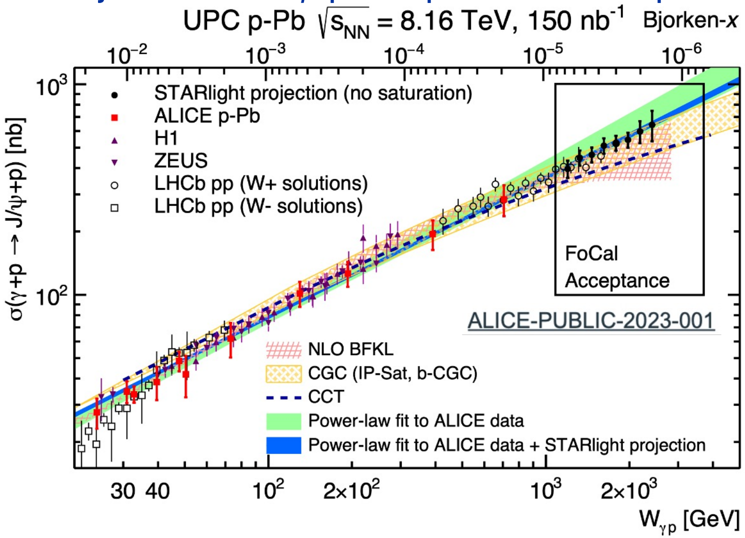




Projection of J/ψ photoproduction in p-Pb



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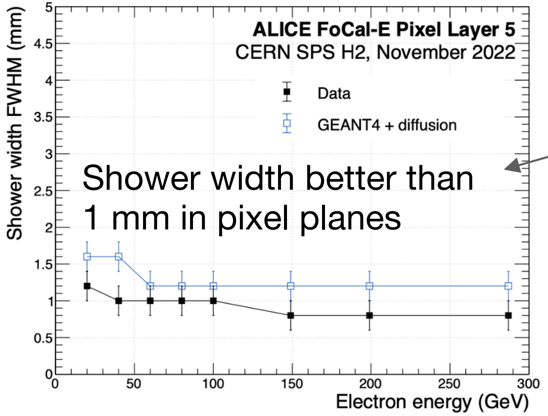
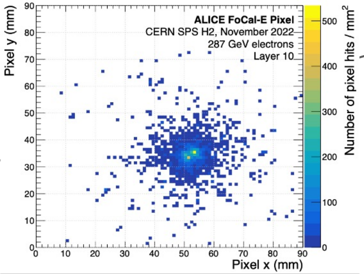
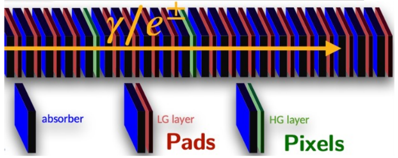
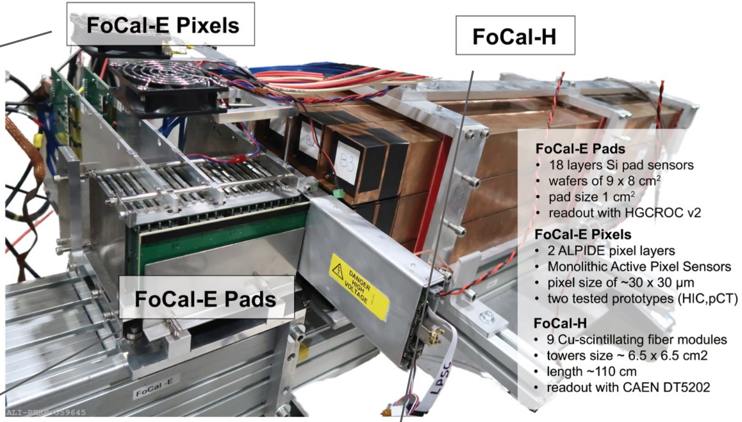
FoCal prototype performance

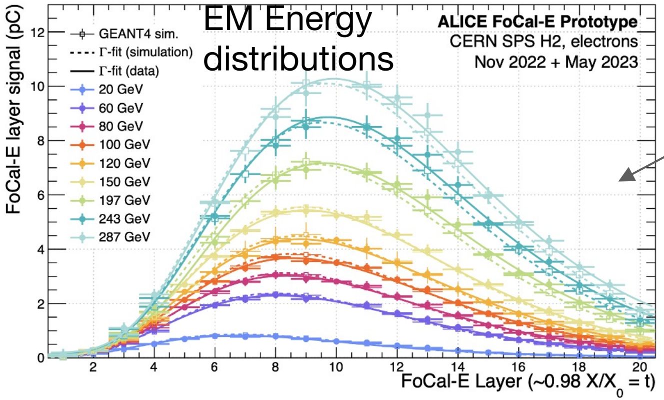
FoCal test beam paper: https://arxiv.org/abs/2311.07413

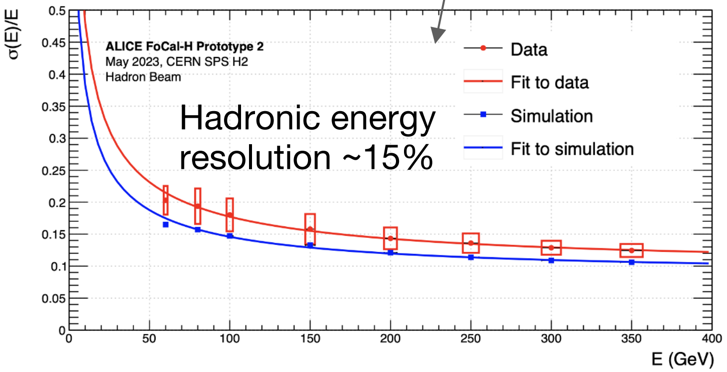






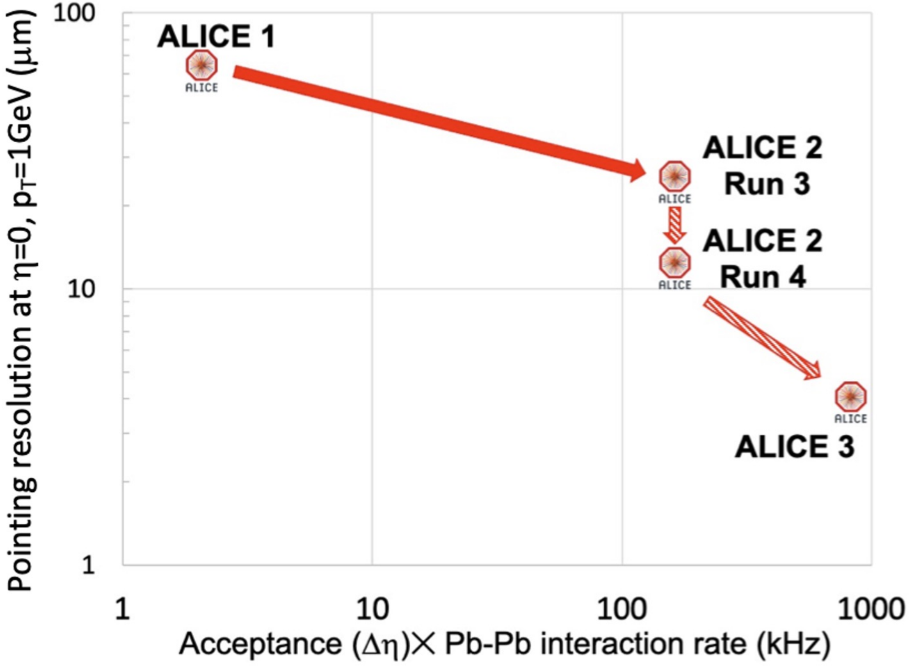






ALICE tracking+PID: upgrade strategy

Large steps in pointing precision and "effective acceptance"



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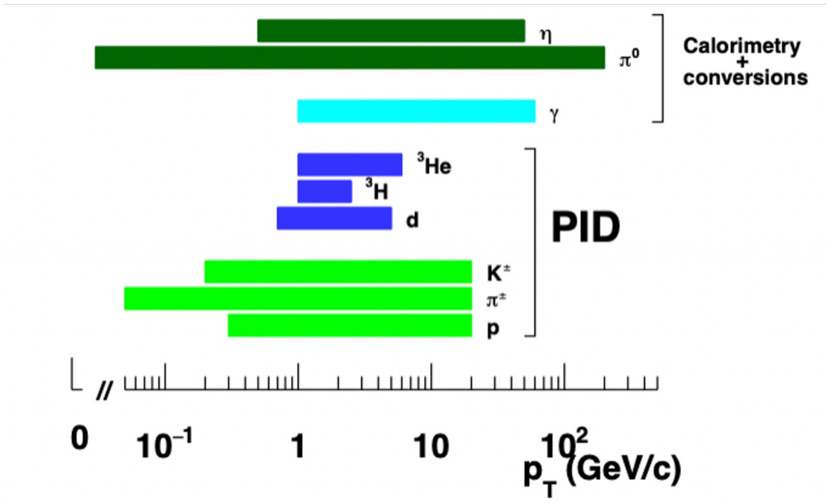
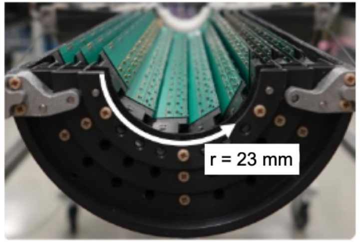
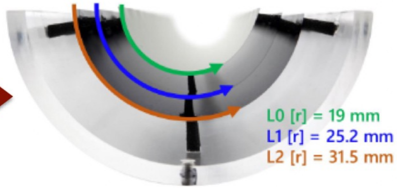
Keep/strengthen ALICE unique reach in particle identification



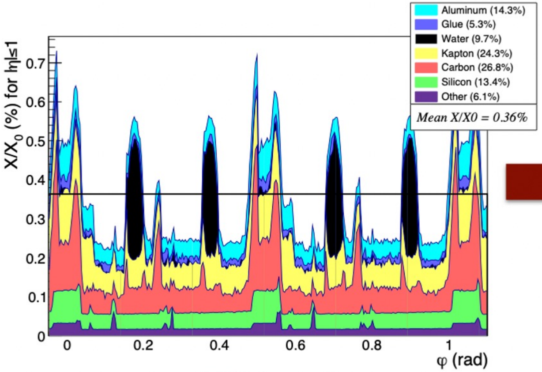
ITS3, a cylindrical pixel barrel



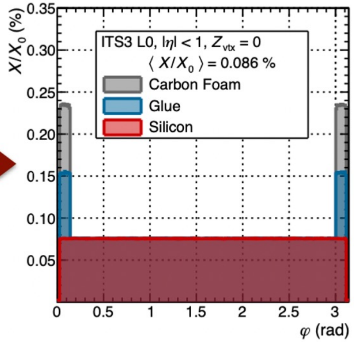
ITS2 Inner Barrel



ITS3 Engineering Model 1

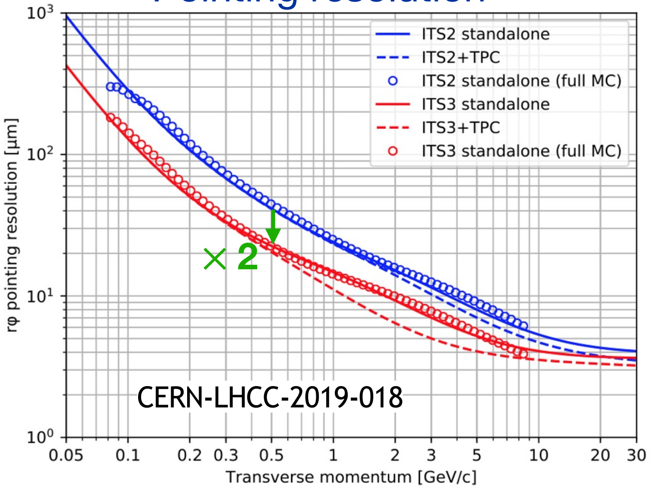


ITS2 Layer 0



ITS3 Layer 0

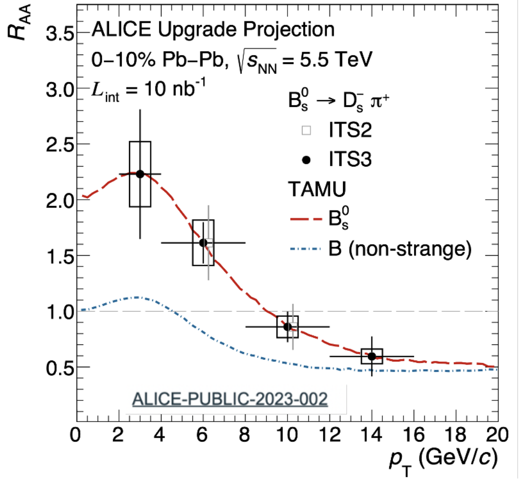
Pointing resolution



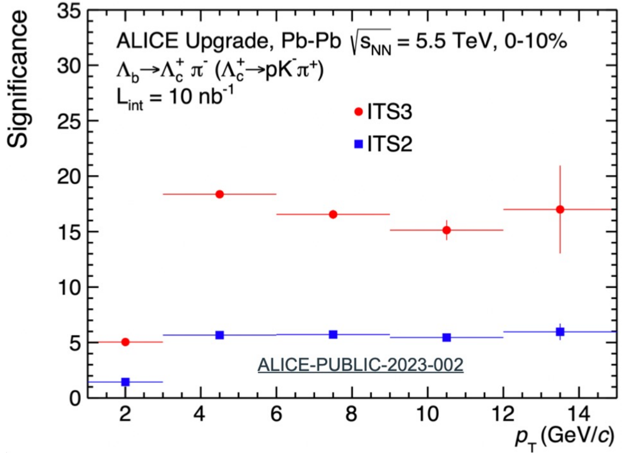
- Detection layers closer to the interaction point, r_{inner}: 23 → 19 mm
- Reduced beam pipe diameter, r_{pipe}: 18 → 16 mm
- Reduced thickness (~ no supporting structures, air cooling), x/X_0: 0.36% → 0.09%

ITS3, a cylindrical pixel barrel

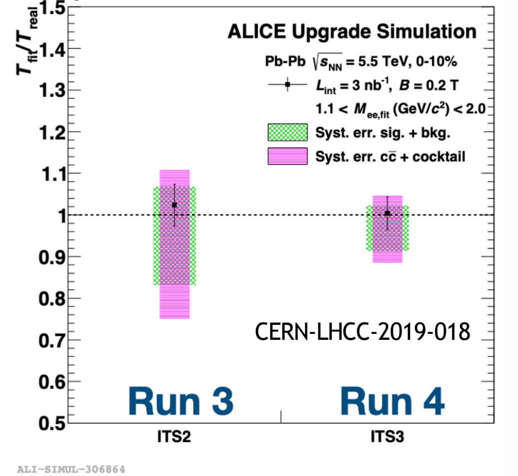
Nuclear modification of B_s in Pb-Pb



Significance of Λ_b

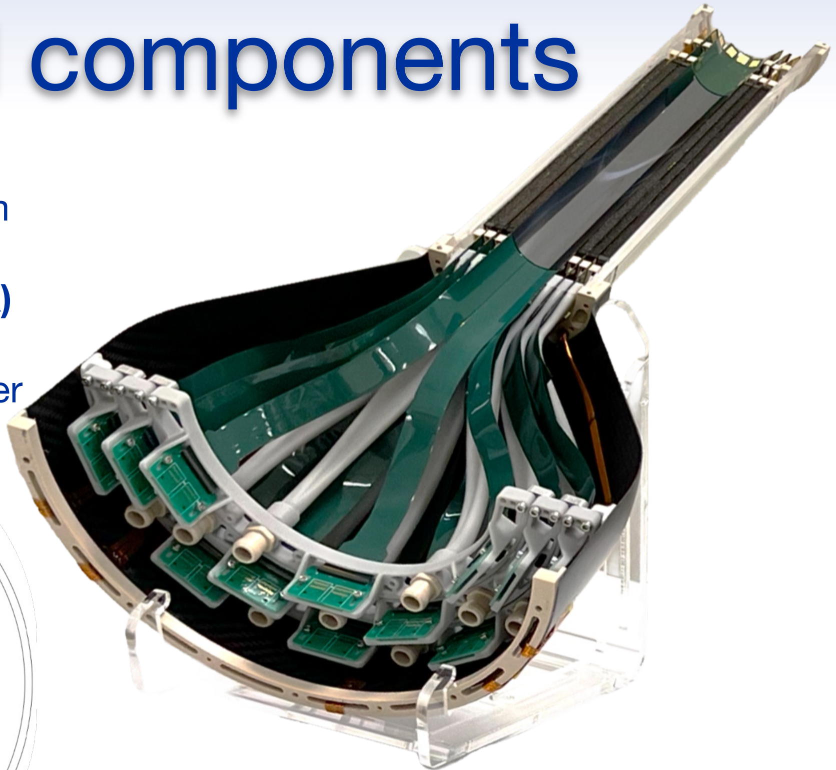


Inverse slope T of thermal e^+e^- dN/dM



- Improve vertexing performance and reduce backgrounds for:
  - Heavy-flavour hadrons → interaction of heavy quarks in QGP
  - Low-mass dielectrons → thermal radiation from QGP

ITS3: towards final components

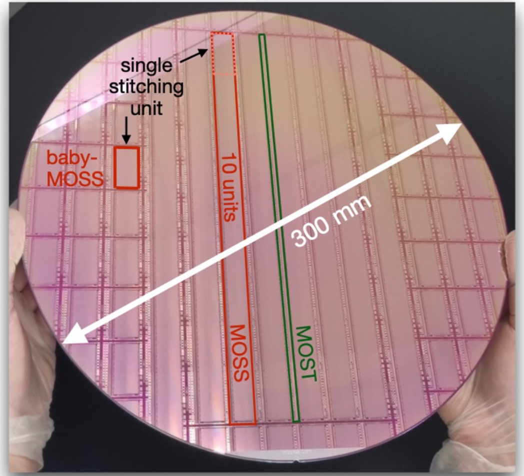


Pixel sensor Engineering Run 1

- Monolithic Stitched Sensor (MOSS): 259x14 mm^2 x50 μm
- Extensively tested and validated

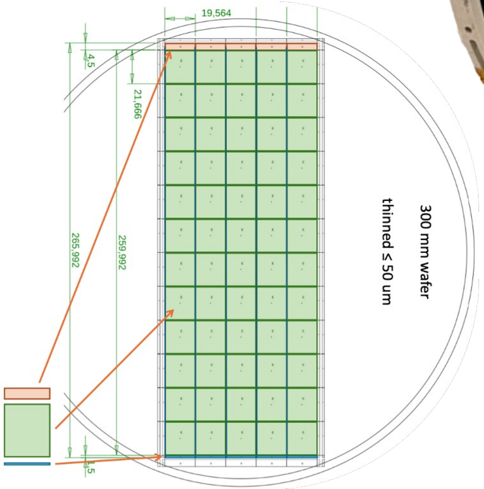
Preparation of Engineering Run 2, for final sensor (MOSAIX)

- Stitched in both directions: 259x105 mm^2 x50 μm
- Final verification ongoing; expected delivery after summer



Engineering Run 1 wafer with various dies

Monolithic Stitched Sensor (MOSS)



Large participation in R&D by ALICE-Germany

Engineering Model 3

- All three layers, with dummy sensors
- Mechanical support structure (carbon foam longerons and spacers)
- FPCs integrated on both sides

ALICE 3 concept

➡ Novel and innovative detector concept

- Compact and lightweight all-pixel tracker
- Retractable vertex detector
- Extensive particle identification TOF, RICH, MID
- Large acceptance $|\eta|<4$
- Superconducting solenoid magnet B= 2 T
- Continuous read-out and online processing

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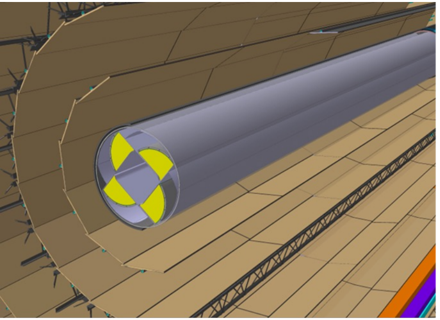

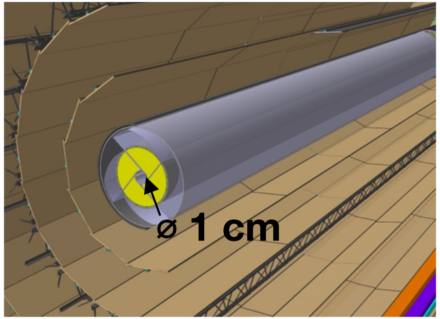

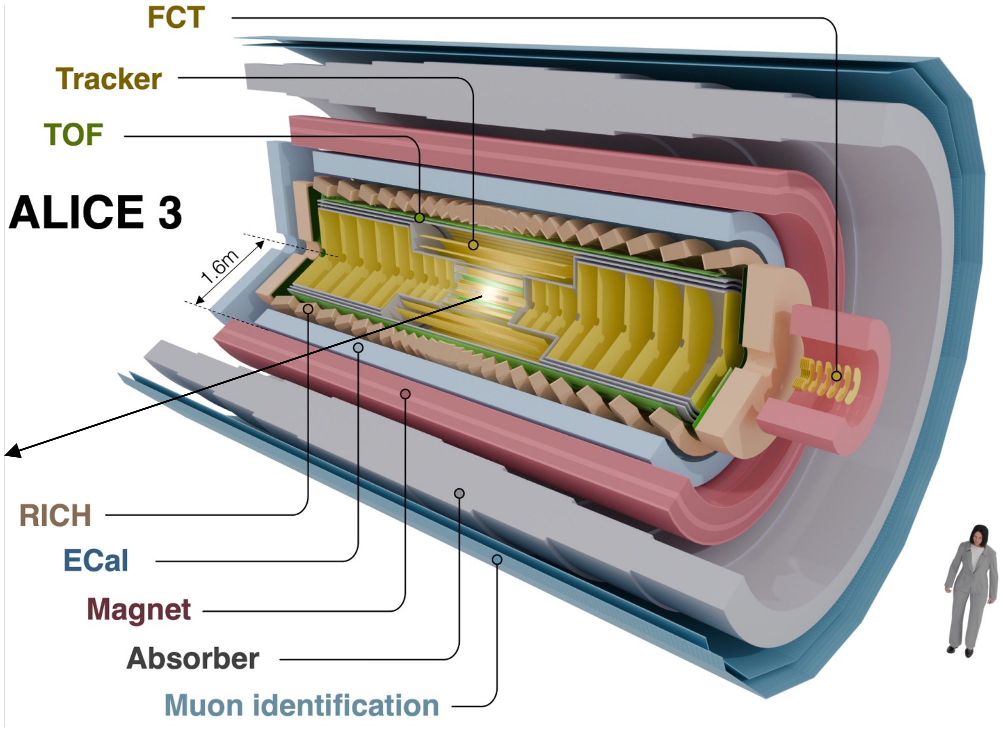

Main ALICE 3 physics goals

- **Access to temperature as function of time**
  - ➟ high-precision di-electron mass spectra, p_T dependence, elliptic flow
- **Understanding thermalisation in the QGP**
  - ➟ direct access to charm diffusion: D-Dbar azimuthal correlations
  - ➟ degree of thermalisation of beauty: high-precision beauty measurements
  - ➟ approach to chemical equilibrium: multi-charm hadrons
- **Fundamental aspects of the QCD phase transition**
  - ➟ net-baryon and net-charm fluctuations
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  - ➟ hadron-hadron interaction potentials
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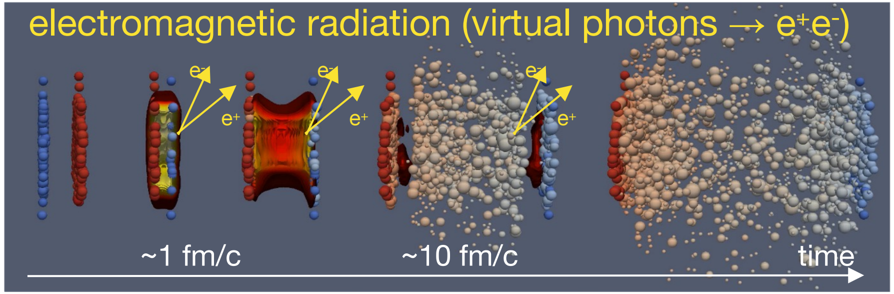

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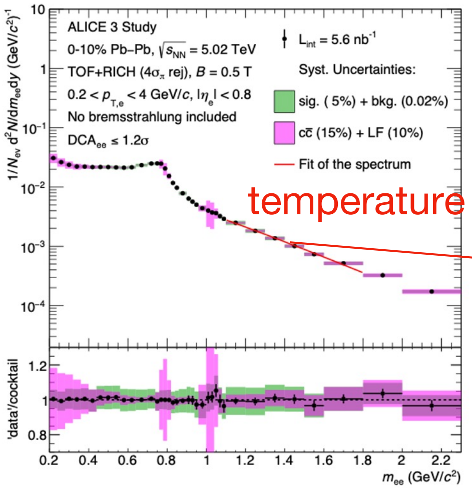

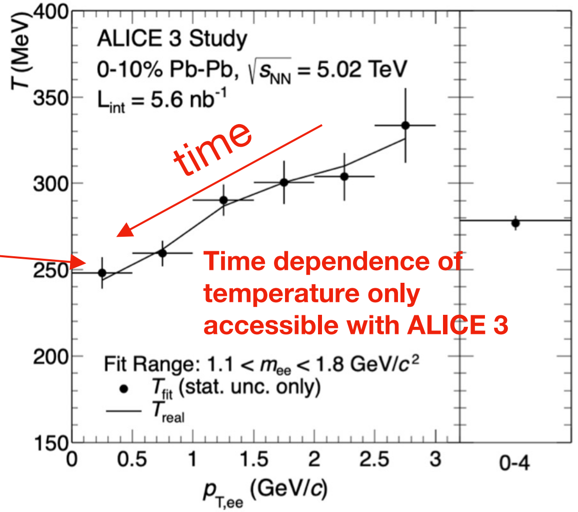

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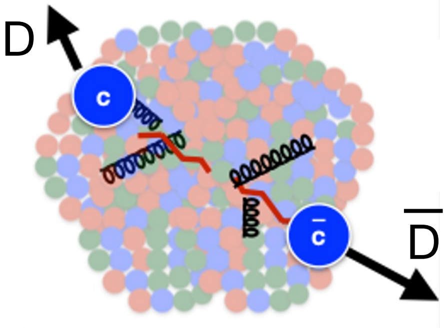

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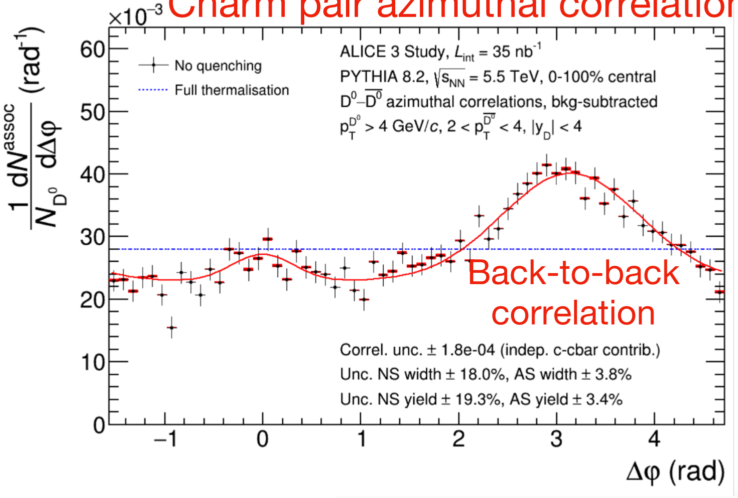
Charm pair azimuthal correlation



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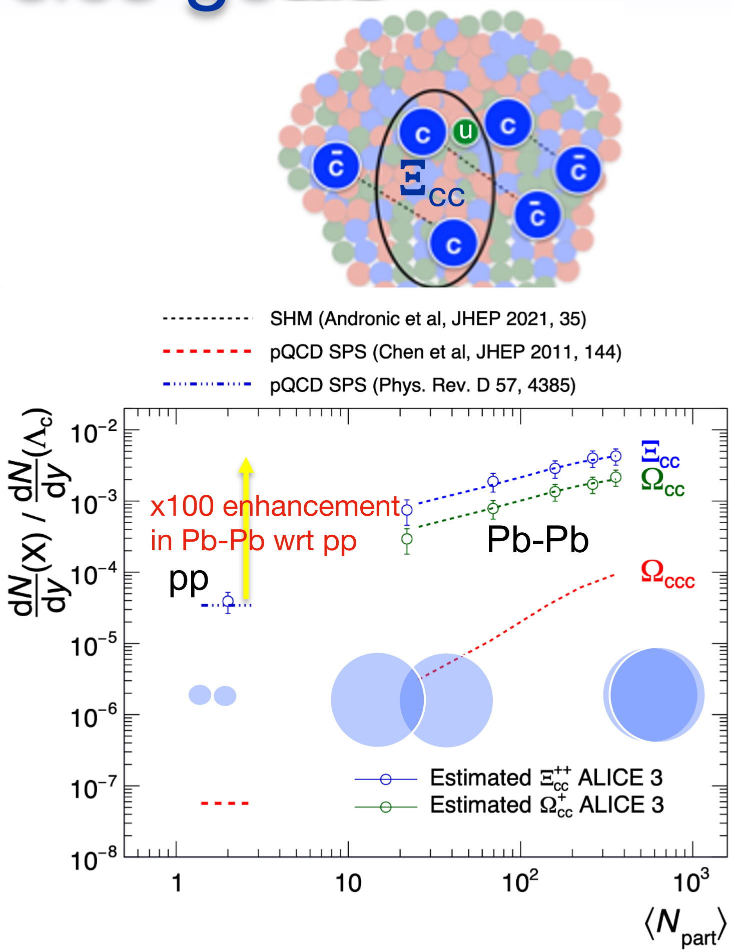

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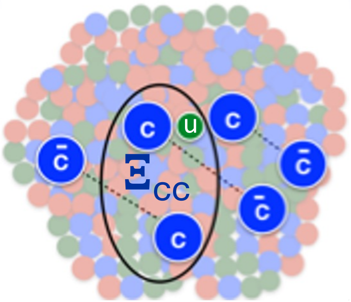

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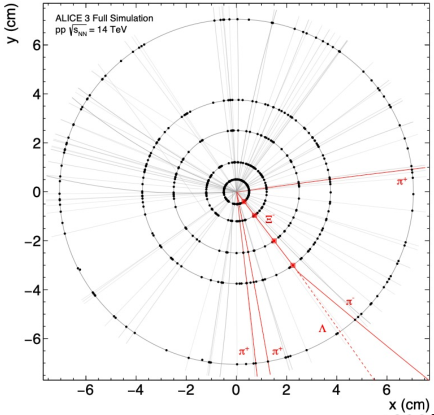

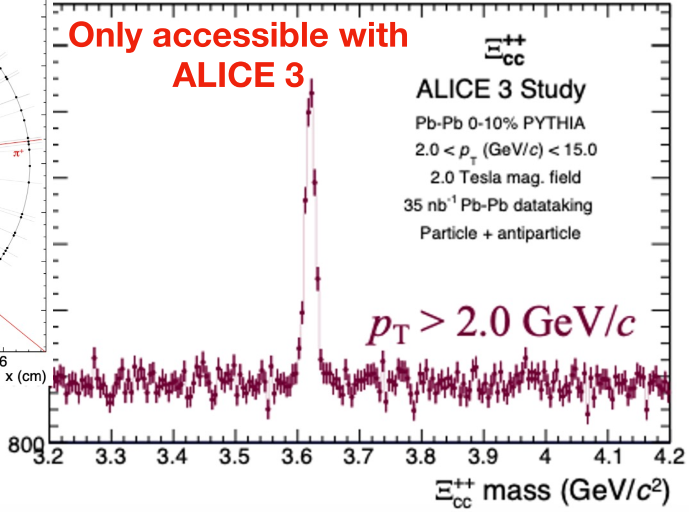

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Inprint of chiral symmetry restoration in ρ mass shape

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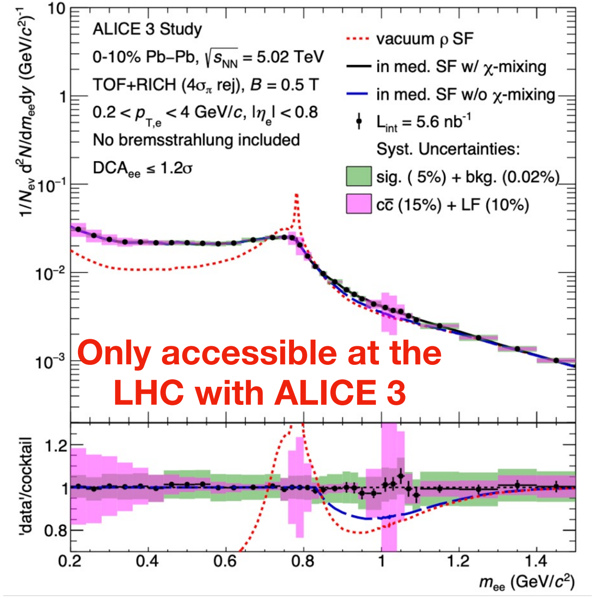

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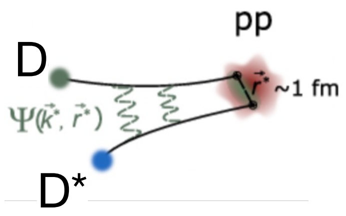

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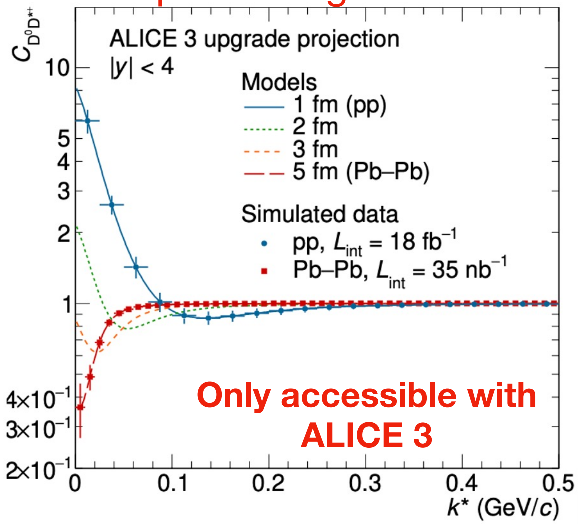
Charm pair strong interaction



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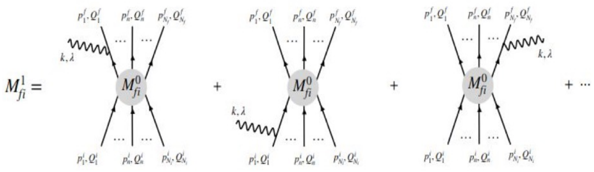
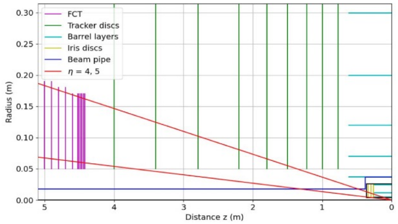
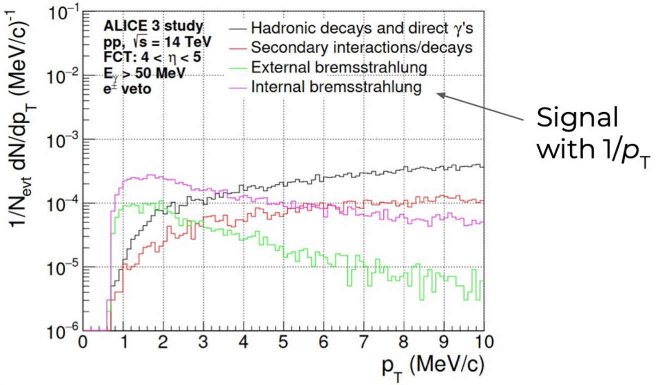
  - ➟ approach to chemical equilibrium: multi-charm hadrons
- **Fundamental aspects of the QCD phase transition**
  - ➟ net-baryon and net-charm fluctuations
  - ➟ mechanism of chiral symmetry restoration in the QGP: di-electron mass spectrum
- **Laboratory for hadron and fundamental physics**
  - ➟ hadron-hadron interaction potentials
  - ➟ conclusive test of Low's theorem





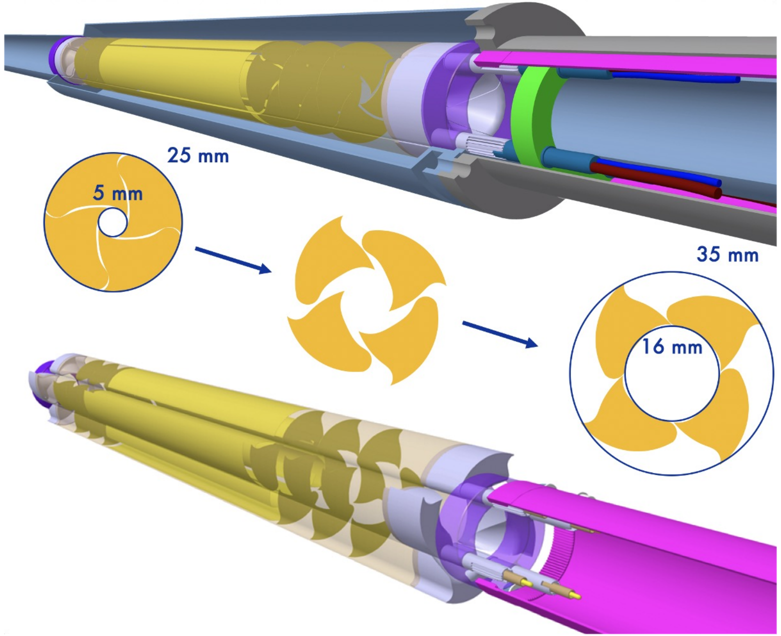
Low's theorem: internal photon radiation ~$1/p_T$

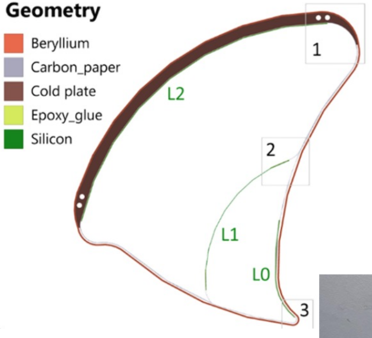


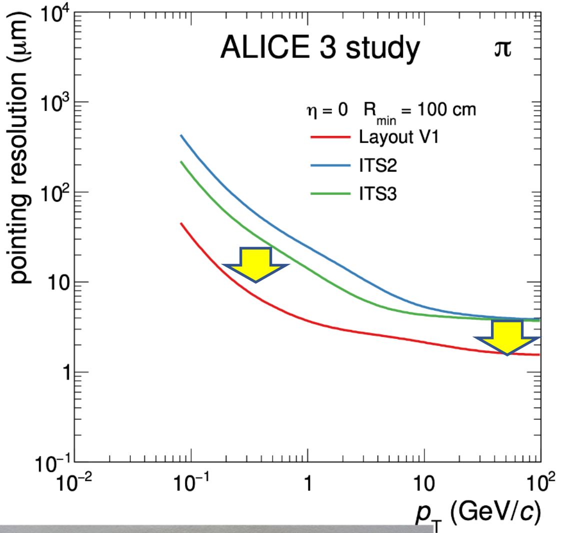
p_T ~ MeV photons only accessible with FCT at ALICE 3

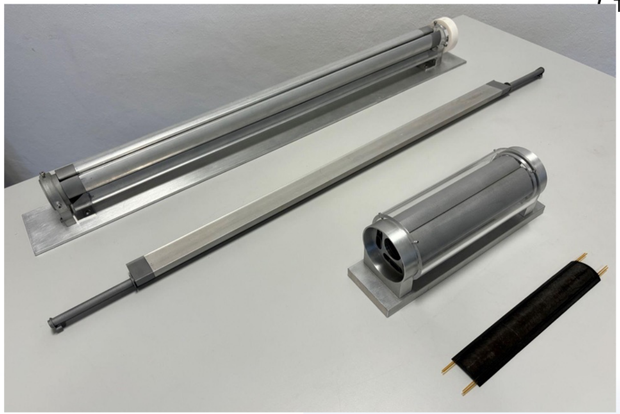
Vertex Detector concept and R&D

- Retractable vertex detector inside beam pipe (Iris)
- Target specifications for pixel sensor: 10x10 μm^2 pixels, <50 μm thickness, NIEL: ~10^{16} 1 MeV n_{eq}/cm^2

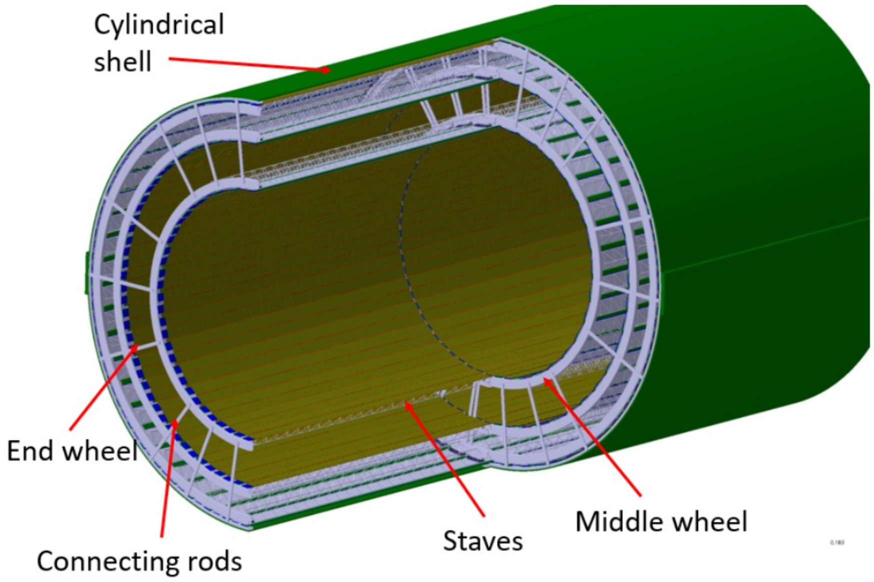






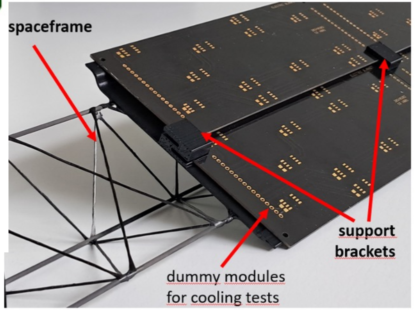


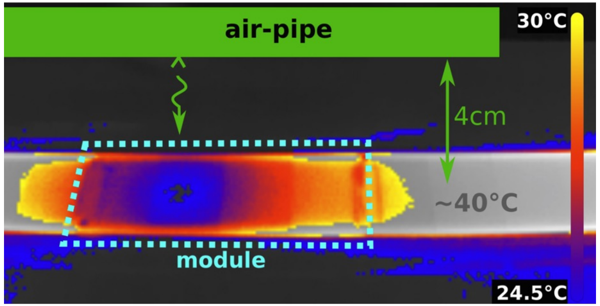
Outer Tracker layout and R&D



60 m² silicon pixel detector

- large coverage: 8 pseudorapidity units
- compact: $R_{out} \approx 80$ cm, $z_{out} \approx \pm 400$ cm
- high-spatial resolution: $\sigma_{pos} \approx 10\ \mu m$
  → pixel size ~ $50 \times 50\ \mu m^2$
- low material budget: x/X_0 ~ 1% per layer
- low power density: ≈ 20 mW/cm²



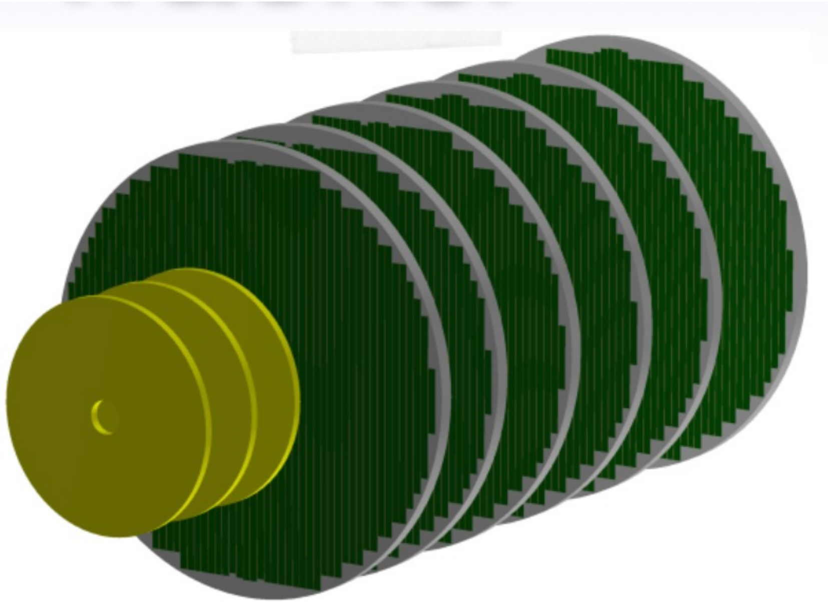


R&D focuses on:

- sensor design
- concept of module based on industry-standard processes for assembly
- lightweight mechanics & cooling options (air and water)

Leading R&D contributions by ALICE-Germany

Outer Tracker layout and R&D



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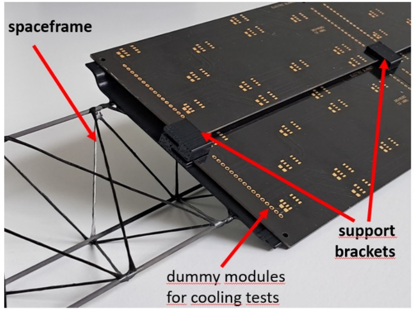
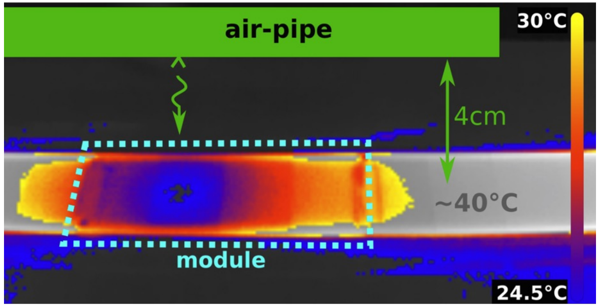


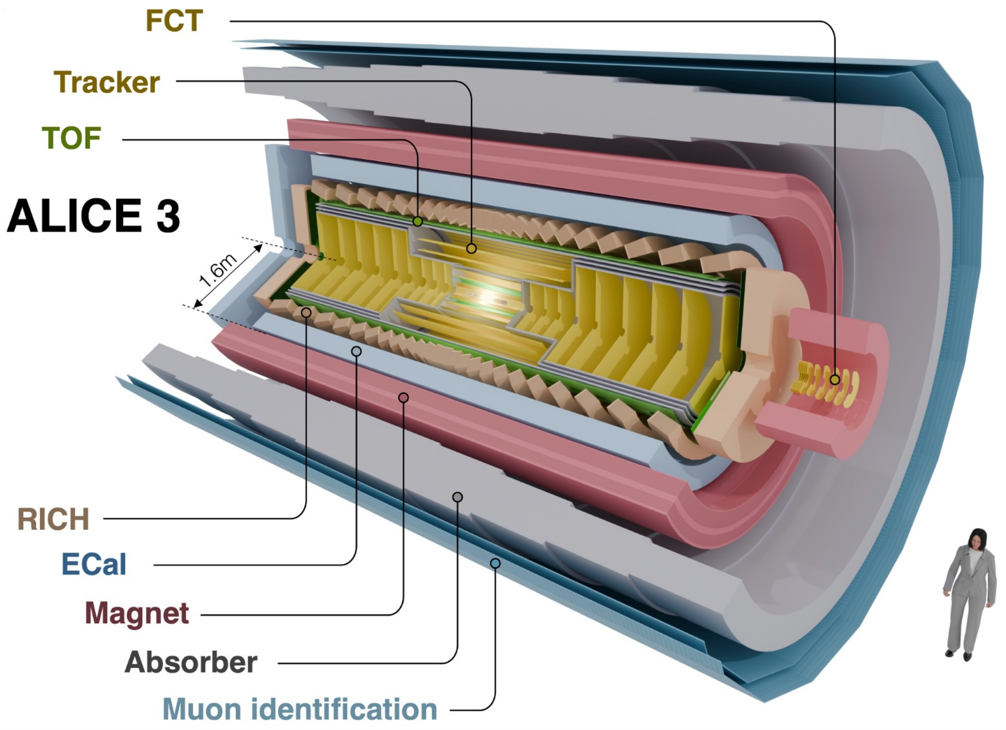


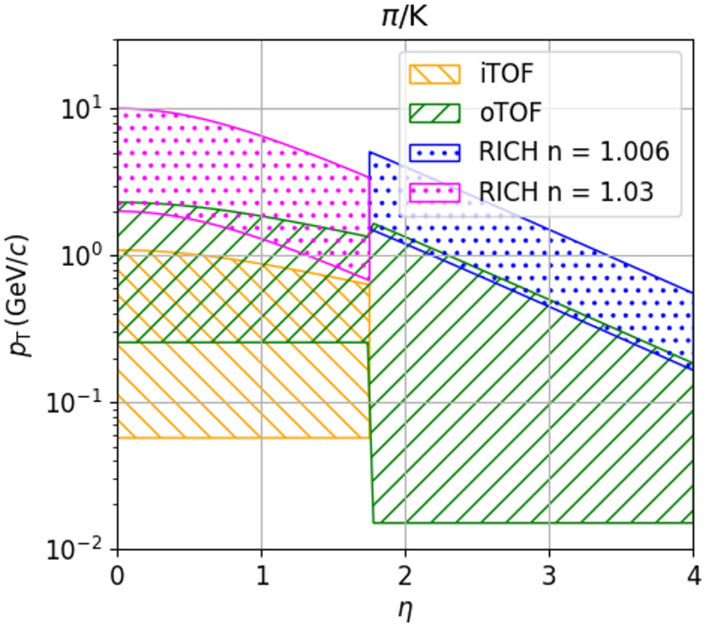
R&D focuses on:

- sensor design
- concept of module based on industry-standard processes for assembly
- lightweight mechanics & cooling options (air and water)

Electron and hadron ID requirements

e, π, K, p separation with **TOF + RICH** detectors, with specifications σ_t = 20 ps, σ_θ = 1.5 mrad





Silicon Time of Flight

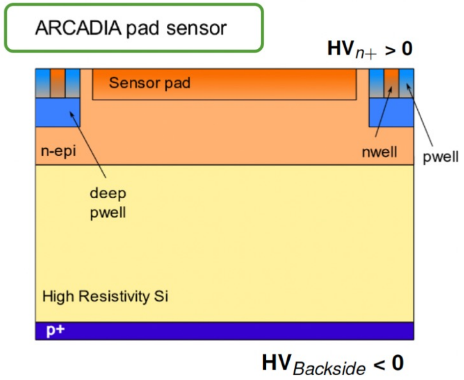
Barrel TOF ($|\eta| < 2$)

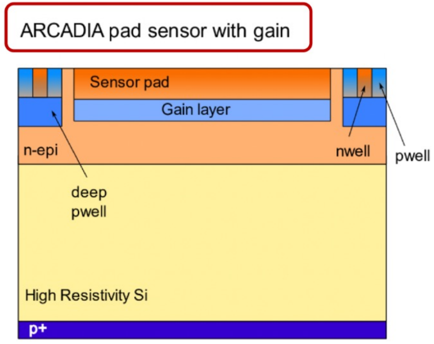
- Outer TOF: radius = 85 cm, pitch = 5 mm
- Inner TOF: radius = 19 cm, pitch = 1 mm

Forward TOF disks ($2 < |\eta| < 4$)

- Radial size = 15-100 cm, pitch = 1 mm

Target time resolution: 20 ps



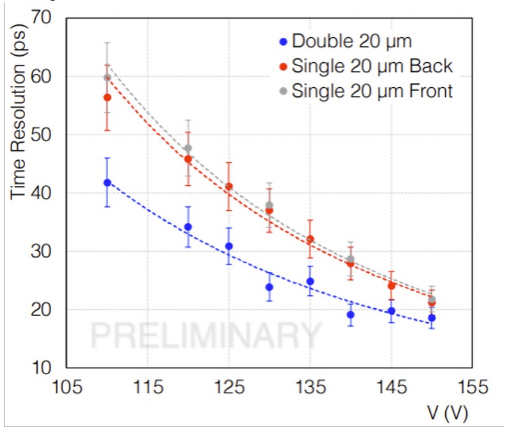


Two R&D lines in ALICE:

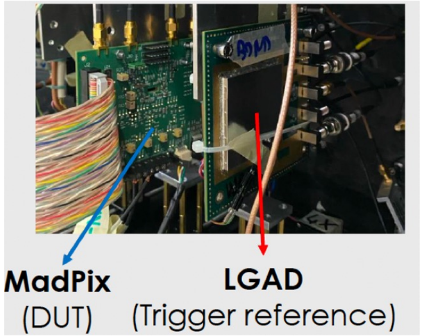
- **Hybrid LGADs**: R&D with thin sensors
  → close to target time resolution in test beams

- **CMOS LGAD (baseline):**
  → single chip with sensor and readout
  → significant cost reduction
  → first prototypes, test beams, optimisation

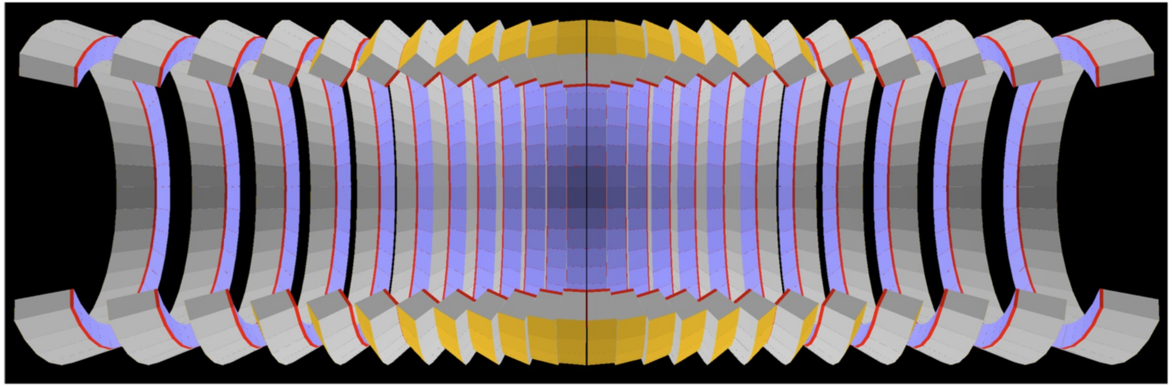
Hybrid LGAD time resolution



CMOS-LGAD (MadPix)



RICH with Si photon sensors

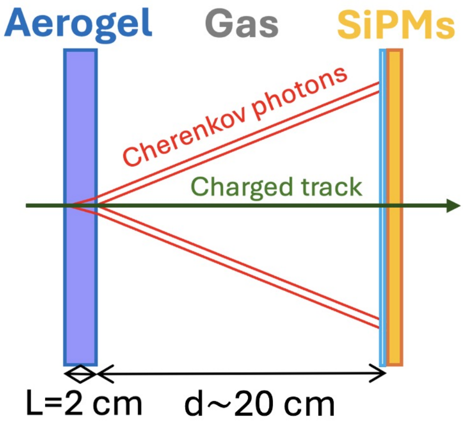


Barrel RICH (|η| < 2)

- radius= 0.9m, length= 5.6m
- photon detection area = 39 m^2
- readout cell size = 2 x 2 mm^2

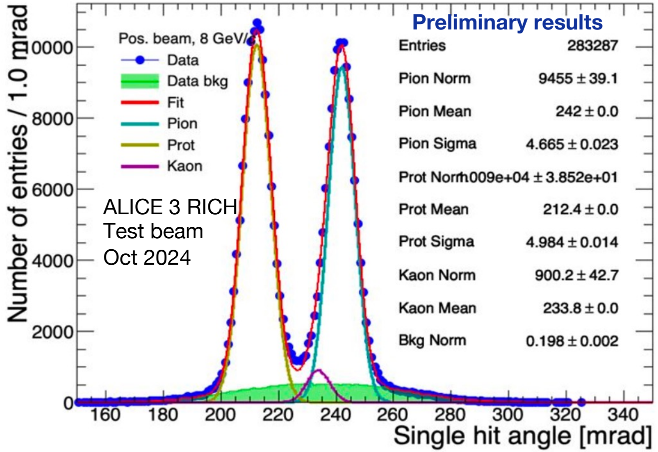
Forward RICH (2 < |η| < 4)

- photon detection area = 14 m^2

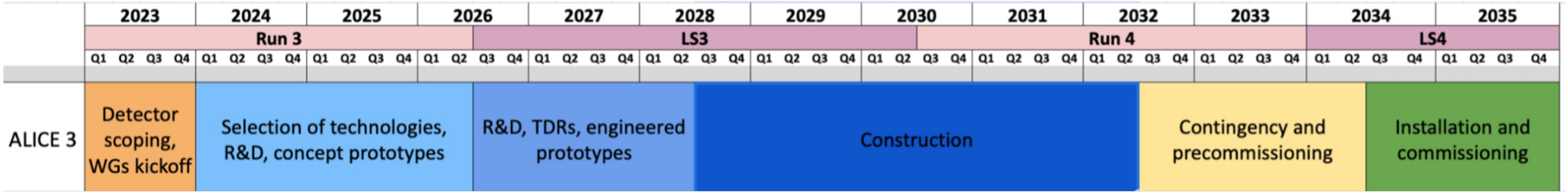


Target Cherenkov angle resolution achieved in test beam with small detector prototype

R&D focuses on choice of SiPM, radiation tolerance and cooling



ALICE 3 timeline



2022: **Letter of Intent reviewed by LHCC → very strong support**

2023 – 2025: **detector scoping, resource planning, sensors selection, small-scale prototypes**

2026 – 2027: **large-scale engineered prototypes → Technical Design Reports**

2028 – 2031: **construction and assembly**

2032 – 2033: **contingency and pre-commissioning**

2034 – 2035: **Long Shutdown 4 - installation and commissioning**

2036 – 2041: **physics campaign, Pb-Pb ~35 nb^{-1}, pp ~ 18 fb^{-1}**

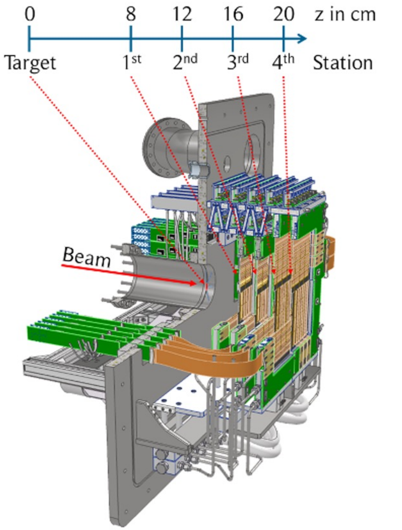
ALICE R&D synergies

- ALICE has pioneered Si MAPS R&D for 10-15 years (ALPIDE, ITS3, air cooling)
- ALICE 3 now drives:
  - further innovation in MAPS (low material, time res., large area, modularity and automation)
  - novel R&D for PID detectors (Si timing, radiation tolerant SiPM)
- This matches ECFA R&D Roadmap towards FCC-ee detectors, but also upgrades and new experiments in nuclear and HI physics (CBM, R^3B, NA60+)

CBM Si sensors upgrade options:

- upgrade MVD with next generation MAPS
- possible addition of timing silicon layers (LGADs, SPADs)
- forward silicon tracker (fragments ID inside the beampipe)

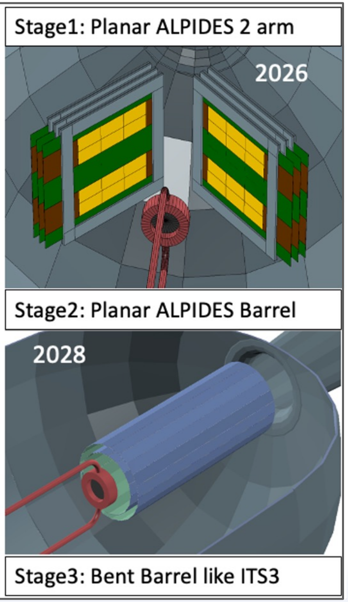
(courtesy P. Gasik)



Target Recoil Tracker

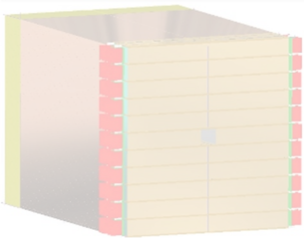
for R^3B at FAIR

(courtesy R. Gernhäuser)

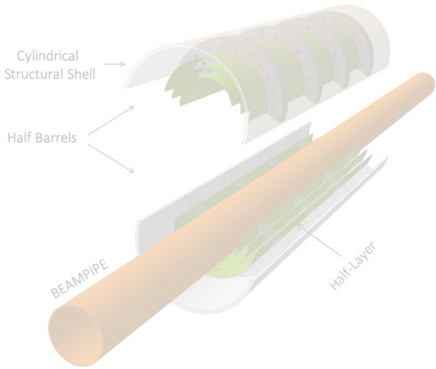


Summary

- The ALICE collaboration actively pursues future upgrades: **this is crucial to fully exploit the wonderful LHC performance as HI collider**
- **LS3 "small-scale" upgrades ITS3 and FoCal entering production phase**
  - Marvels of technology with very strong physics impact
- **ALICE 3 needed for ultimate QGP and QCD studies with heavy quarks, dielectrons, and much more**
  - Targets large increase, x3-5, in: pointing resol., acceptance (with PID), rate capabilities
  - Based on frontier Si-based sensors, with strong benefit for future HEP/NP experiments
- **Important phase in 2024-2026: R&D towards TDRs**
  - New collaborators interested in physics and sensor R&D are welcome!



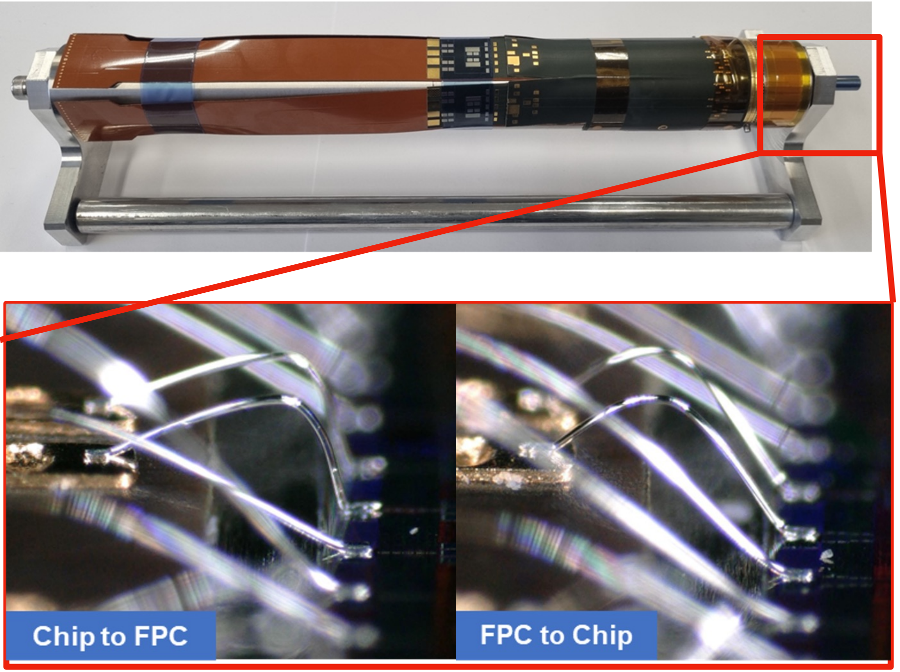
Thanks for your attention!



ITS3 recent highlights

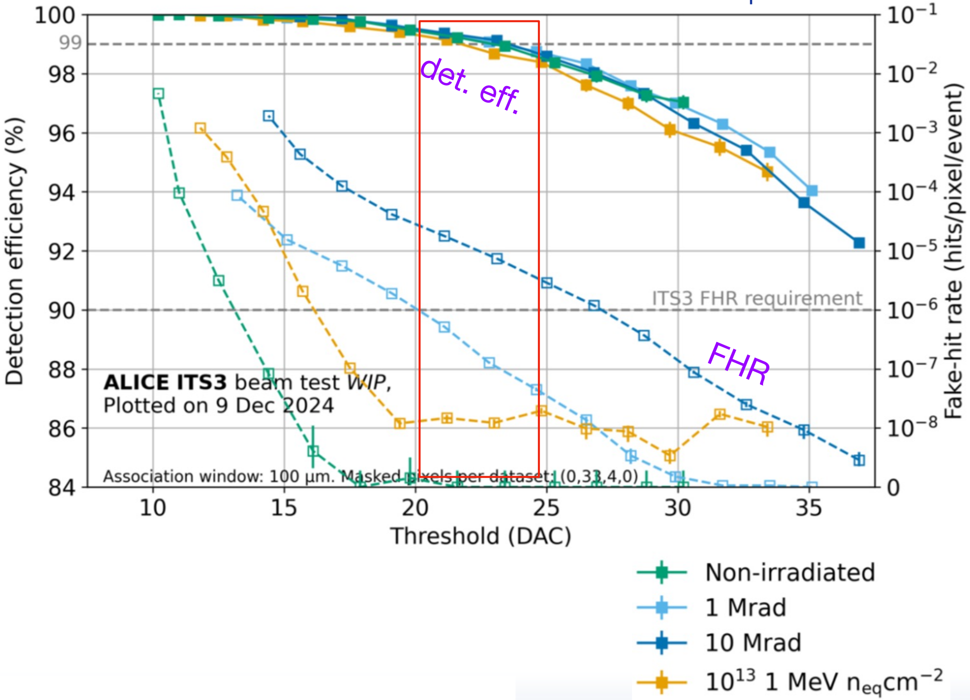
MOSAIX FPC A side Layer 0 (R=19 mm)

- wire-bonding tests of curved components (FPC and sensor) on cylindrical support



MOSS stitched prototype performance after irradiation

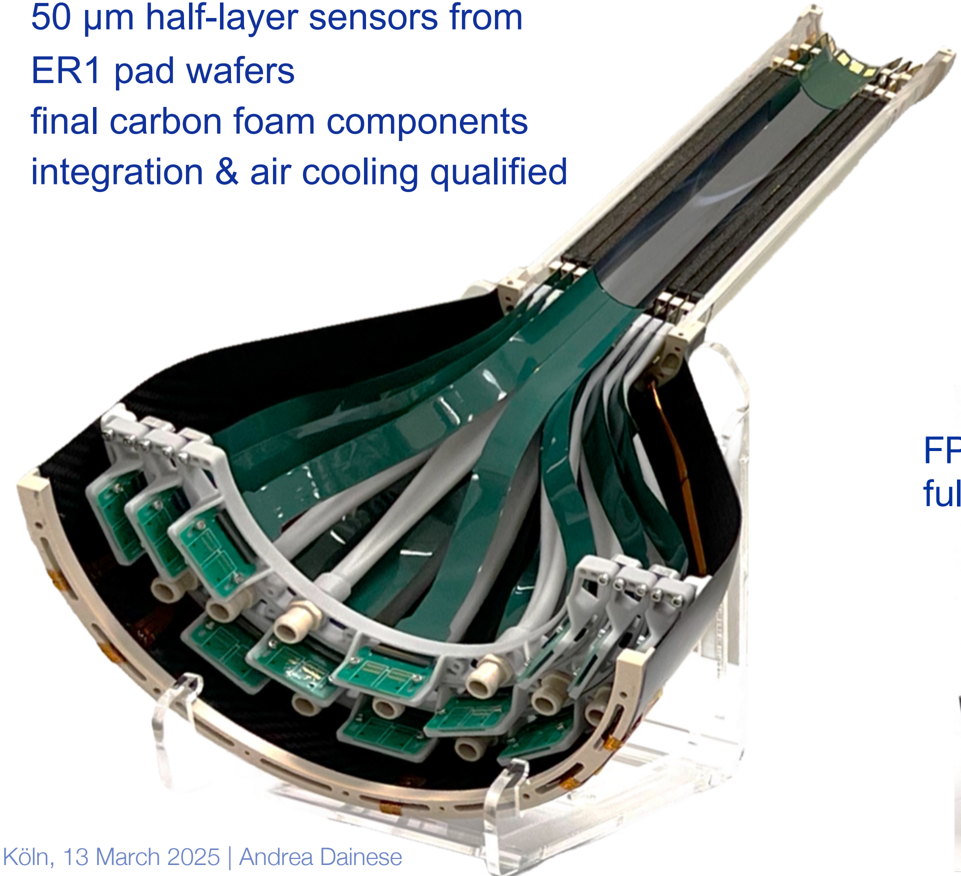
- large operational margin even beyond specs (TID 400 krad, NIEL 4×10^{12} 1 MeV n_{eq} cm^{-2})



ITS3 recent highlights

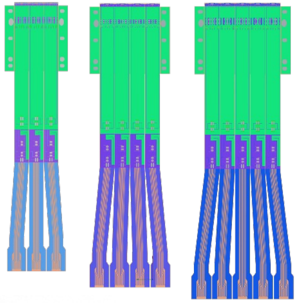
ITS3 Engineering Model 3

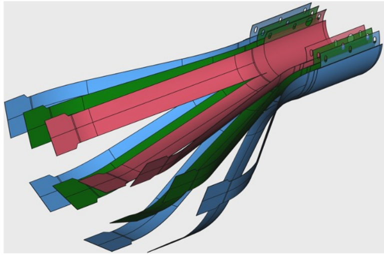
- 50 µm half-layer sensors from ER1 pad wafers
- final carbon foam components
- integration & air cooling qualified



FPC assembly design for MOSAIX (ER2)

One specific FPC per each layer





FPC A side, full size, fully functional

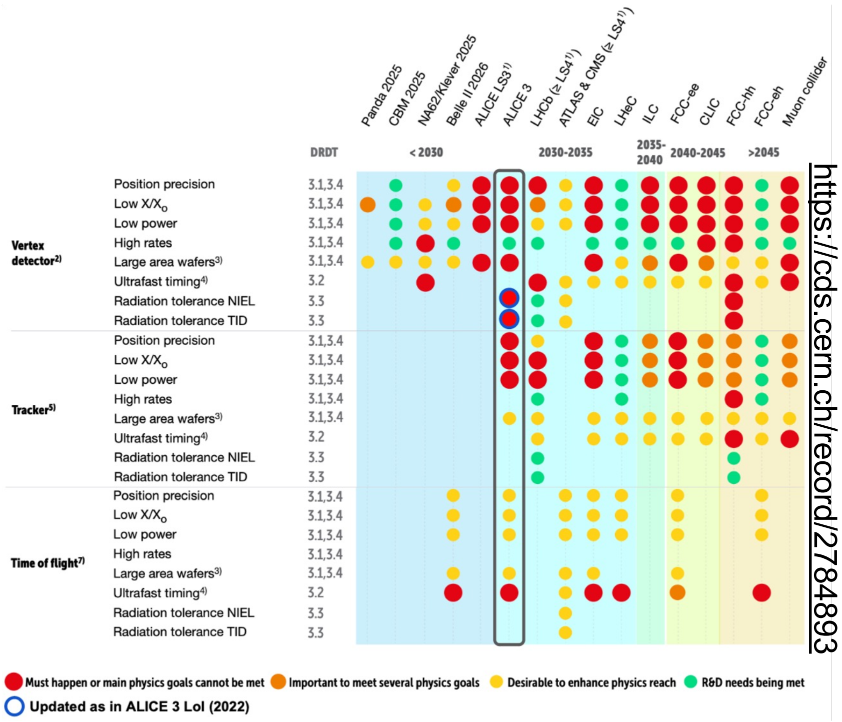
ALICE R&D paves the way for future HEP experiments

ALICE 3 and FCC-ee det. have similar pixel vertex specs:

	ITS3	ALICE 3 VTX	FCC-ee
Single point resolution (μm)	5	2.5	3
Time resolution (ns RMS)	2000	100	20
In-pixel hit rate (Hz)	54	94	few 100
Fake-hit rate (/pixel/event)	10^{-7}	10^{-7}	
Power consumption (mW / cm^2)	35	70	50
Particle hit density (MHz/cm^2)	8.5	94	200
NIEL (1 MeV n_{eq})	4×10^{12}	1×10^{16}	10^{14} (per year)
TID (Mrad)	0.3	300	10 (per year)
Material budget (% X_0/layer)	0.09	0.1	˜0.3
Pixel size (μm)	20	10	15-20

ECFA DRD Roadmap:

→ R&D for ALICE upgrades covers a significant part of the long-term strategic R&D lines defined by ECFA



https://cds.cern.ch/record/2784893

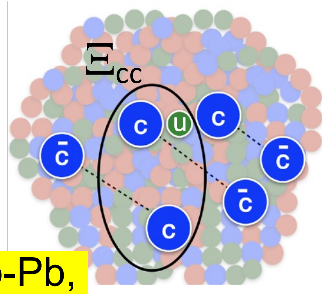
ALICE 3: physics vs detector matrix

Physics goals		*Subsystems and specifications*							
Observable	***Uniqueness***	**Magnet**	**IT**	**OT**	**TOF**	**RICH**	**ECAL**	**MID**	**FCT**
Multi-charm baryons	Observation of multi-charm baryons in AA collisions	**B = 1-2 T**	**σ ~2.5 μm** **R_{in}= 5 mm** **x/X_0~0.1%** **$\|\eta\|<4$**	**σ ~10 μm** **R_{out} > 65 cm** **x/X_0~1%** **$\|\eta\|<4$**	**Outer/Forward** **σ ~ 20 ps**	Barrel **Forward**			
D-Dbar correlations	Angular de-correlation of soft charm	**B = 1-2 T**	"	"	**Outer/Forward** **σ ~ 20 ps**	Barrel **Forward**			
Beauty mesons and baryons	Precision of 0.01 on elliptic flow	**B = 1-2 T**	"	"	**Outer** **σ ~ 20 ps**	Barrel **Forward**		$\|\eta\|<1.3$	
Quarkonia, χ_{c1}(3872)	Measurement at low p_T and central rap.	**B = 1-2 T**	**$\|\eta\|<1.3$**	**$\|\eta\|<1.3$**			Pb/Scintillator	**$\|\eta\|<1.3$**	
$\chi_{c1,2}$	P-wave charmonia in AA collisions	**B = 1-2 T**	**$\|\eta\|<1.3$**	**$\|\eta\|<1.3$**	Outer σ ~ 20 ps	Barrel	Crystals segment	**$\|\eta\|<1.3$**	
Di-leptons (T, flow, χ-symm)	Time-evolution of thermal radiation; chiral symm. at μ_B=0	**B = 0.5-1 T**	**σ ~2.5 μm** **R_{in}= 5 mm** **x/X_0~0.1%** **$\|\eta\|<2$**	**$\|\eta\|<2$**	**Inner/Outer** **σ ~ 20 ps**	**Barrel**		$\|\eta\|<1.3$	
Net-baryon fluctuations	6th order net-proton cumulants	**B = 1-2 T**	**$\|\eta\|<4$**	**$\|\eta\| < 4$**	**Outer/Forward** **σ ~ 20 ps**	**Forward**			
Photon-jet, full jets	High-precision low-p_T, large-R jet modification						**Pb/Scintillator barrel/endcap**		
Hadronic physics (femtoscopy, nuclei)	Charm-charm hadronic inter.; observation of charm-nuclei; (hyper)nuclei with A = 5 and 6	**B = 1-2 T**	**σ ~2.5 μm** **R_{in}= 5 mm** **x/X_0~0.1%** **$\|\eta\|<4$**	**σ ~10 μm** **R_{out} > 65 cm** **x/X_0~1%** **$\|\eta\|<4$**	**Outer/Forward** **σ ~ 20 ps**	Barrel **Forward**			
Searches in $\gamma\gamma$ in UPCs	ALPs m>0.1GeV and low coupling	**B = 1-2 T**	$\|\eta\|<4$	$\|\eta\|<4$	Inner/Outer/ Forward σ ~ 20 ps	Barrel/Forward	**Pb/Scintillator barrel/endcap**		
Ultrasoft photons	Validity and limits of Low theorem	**Small dipole** **B ~ 0.25 T**							**$4 < \eta < 5$** **x/X_0~1%**

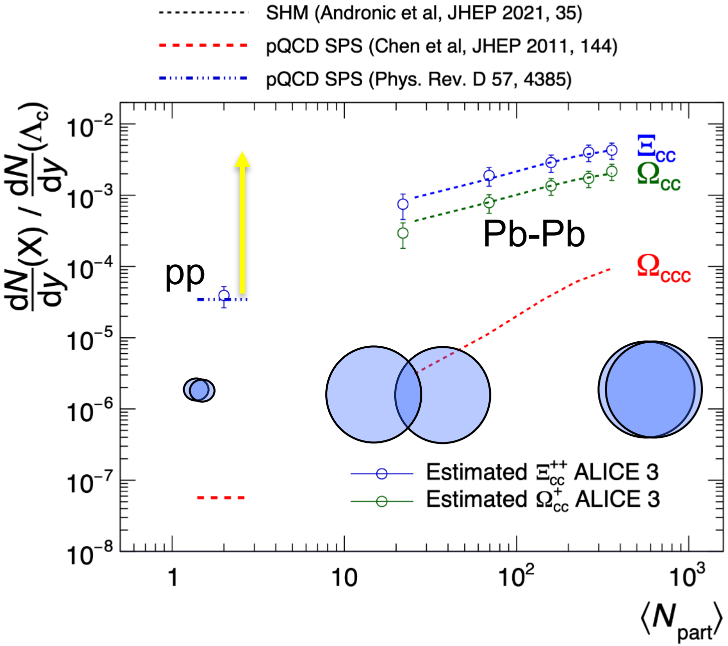
ALICE 3: multi-charm hadron formation

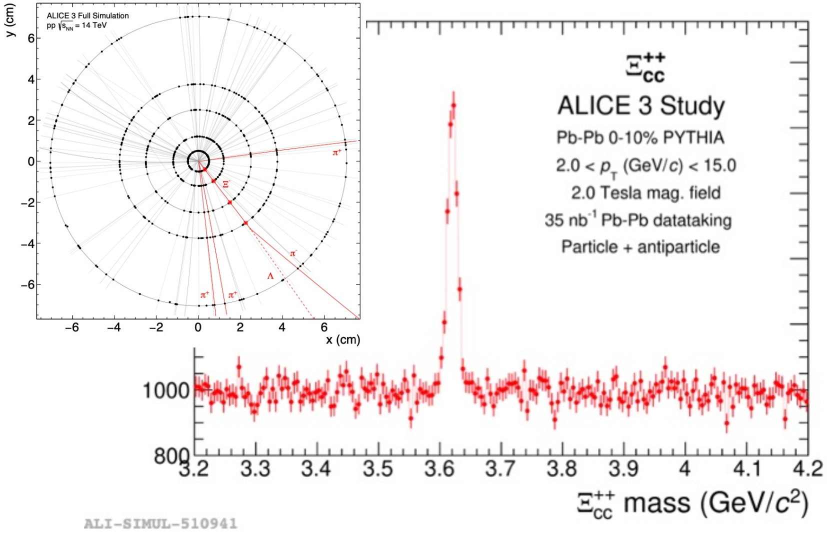
Multi-charm baryons: unique probe of hadron formation

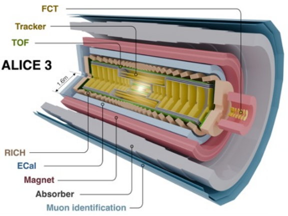
- requires recombination of multiple charm quarks
- negligible same-scattering production (unlike e.g. J/ψ)



x100-1000 enhancement in Pb-Pb, sensitive to degree of thermalisation





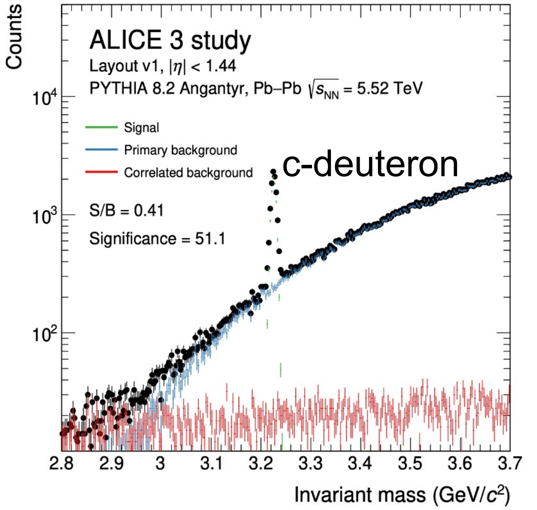


ALICE 3: a unique instrument at the HL-LHC

→ beyond QGP physics: new windows not accessible otherwise

Hadronic physics

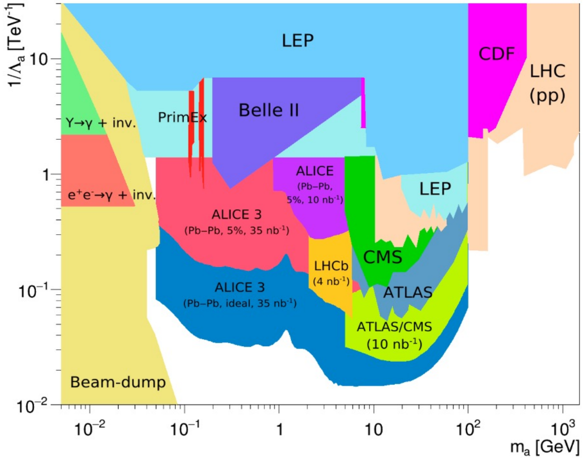
→ e.g. charm-nuclei (nuclei with charm-baryons)



+ femtoscopy, exotic hadrons, photoproduction, …

BSM searches

→ e.g. axion-like particles (ALPs) in photon-photon collisions (UPC Pb-Pb)



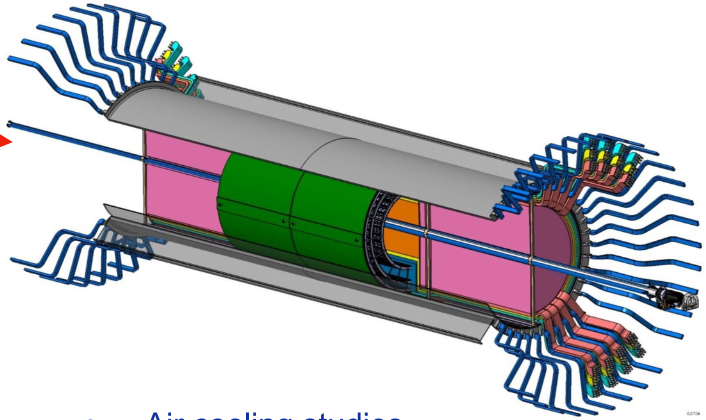
→ unique access to region $0.1 < m_a < 2$ GeV

+ dark photons, light-by-light, …

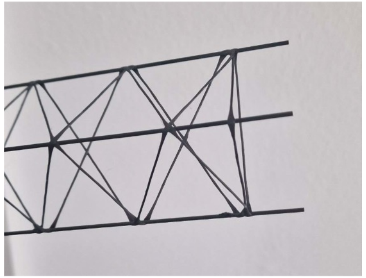
R&D for Outer Tracker

Barrel layout and design:

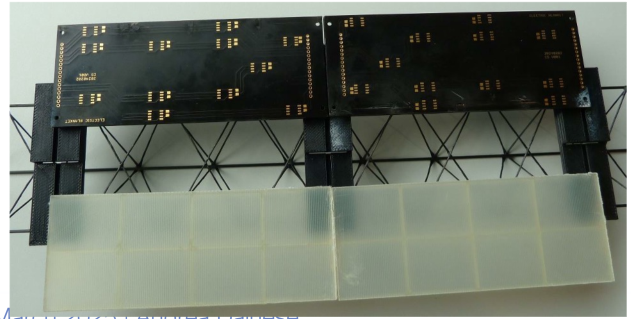
- Study compatibility with the different detector volumes
- Study of interfaces and integration of services



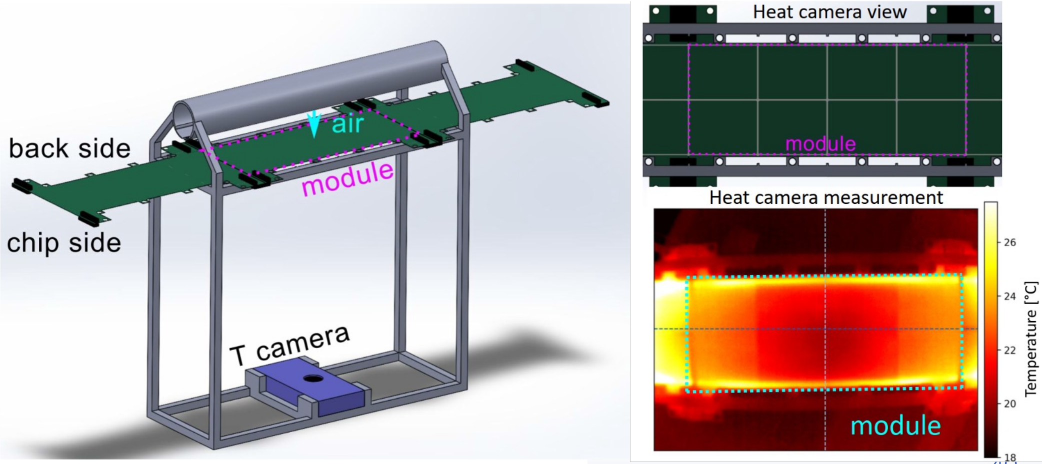
- Stave carbon spaceframes prototype (similar to CBM STS)



- Module fixation and assembly procedure

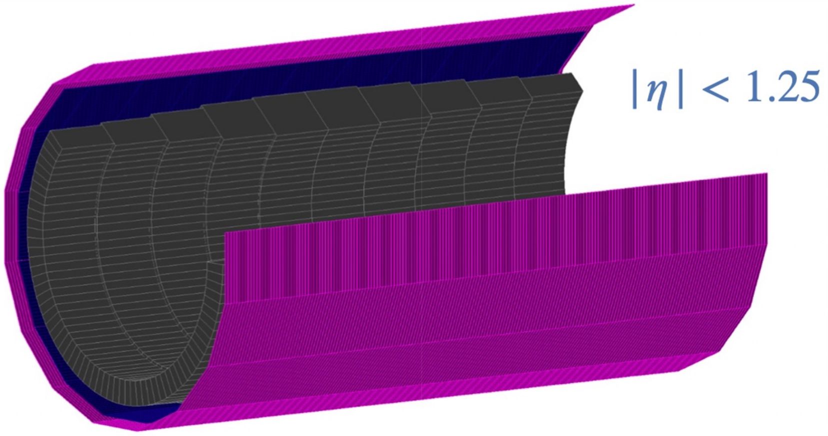


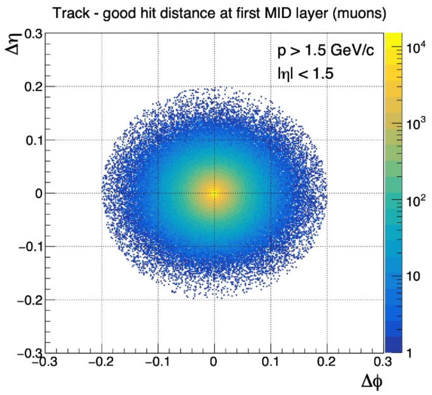
- Air cooling studies



Muon Identifier

- **Necessary for quarkonium to dimuons**
- **Hadron absorber** outside the magnet
  - ~70 cm of 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 with SiPM read-out
    - resistive plate chambers
    - multi-wire proportional chambers

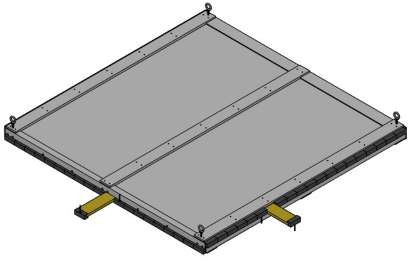


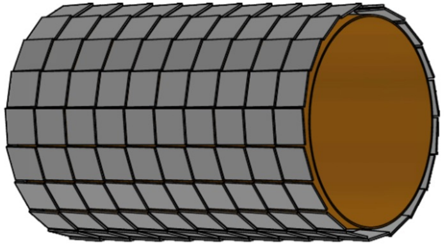


R&D for Muon ID detector

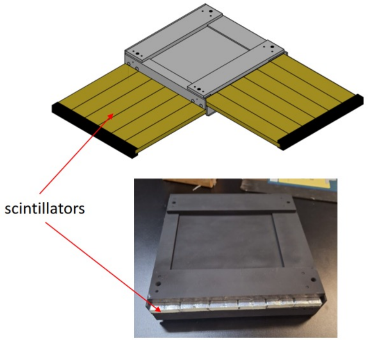
1x1 m^2 module design and barrel layout:

- Module mechanics, detailed scintillators and SiPM integration
- Arrangement in barrel, services integration



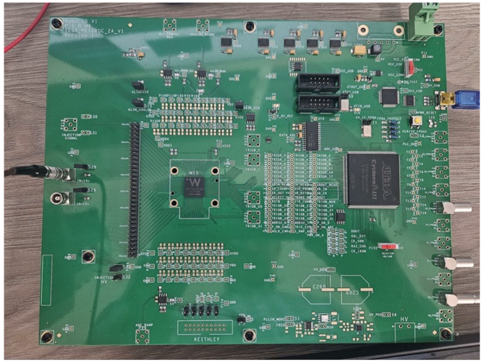


25x25 cm^2 prototype



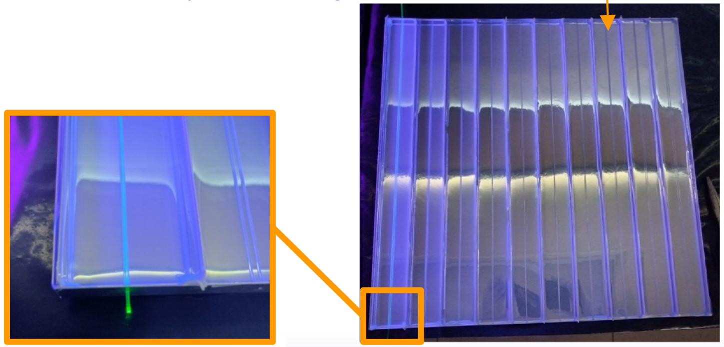
Front-End Card preliminary design

- First prototypes available

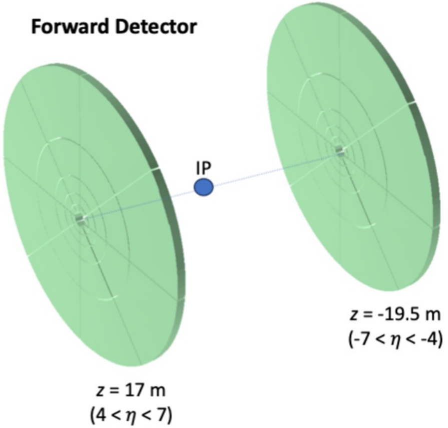


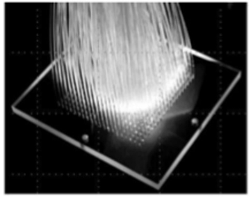
Testbeam in Oct 24 of Scintillators/SiPM and MWPC prototypes using final size iron absorber:

- First test of scintillator casted directly in container
- Analysis in progress



Forward Detectors





Two segmented scintillator disks for charged particle detection at $4 < |\eta| < 7$:

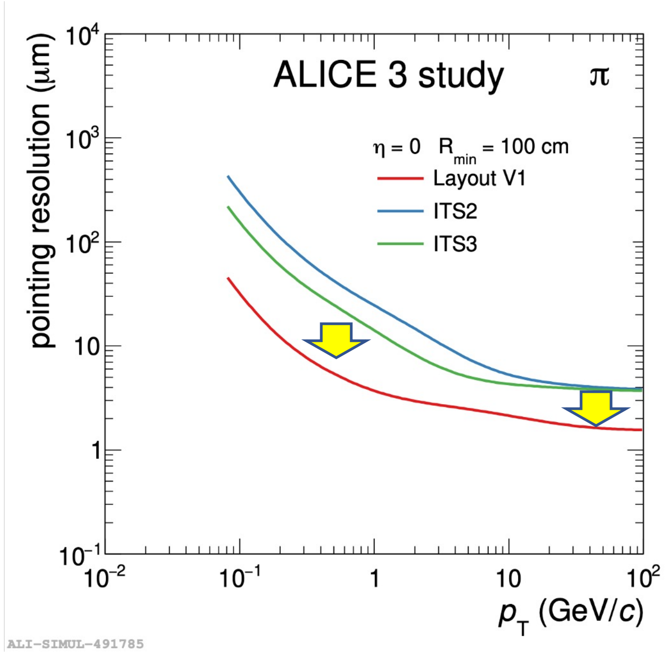
- event characterization
- vetoing for diffraction and UPC measurements

Baseline layout: Eljen scintillators and fine-mesh PMT

R&D will mainly focus on:

- different scintillators (PEN/PET)
- alternative photon detectors: SiPM or LAPPD

Inner Tracker and Vertex Detector



Pointing resolution ~ few μm at ~1 GeV/*c*

→ critical for heavy-flavour and dielectron measurements

Requires pushing the frontiers in many respects:

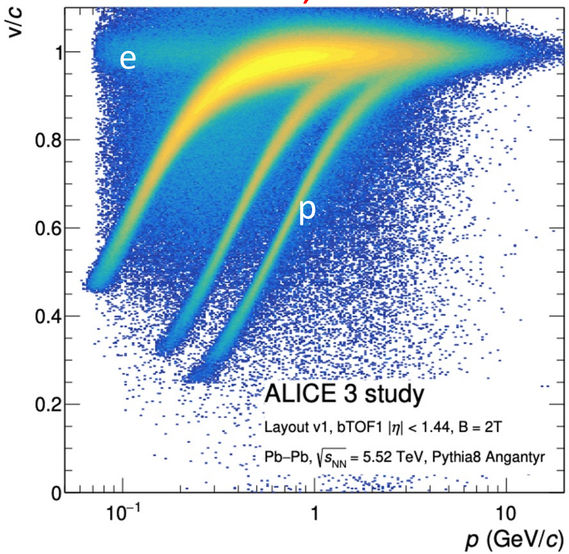
- spatial resolution: $\sigma_{pos} \approx 2.5\ \mu m$
  → pixel size ~ $10 \times 10\ \mu m^2$
- material budget ≈ 0.1% of X_0 per layer
- 5 mm radial distance from interaction point
  → has to be inside beampipe
  → ~$1.5\ 10^{15}$ 1 MeV n_{eq} / cm^2 per operational year

Frontier R&D on CMOS Monolithic Active Pixel Sensors (MAPS): curved, thin, large-area, low power
→ build on experience with ITS2 and ITS3

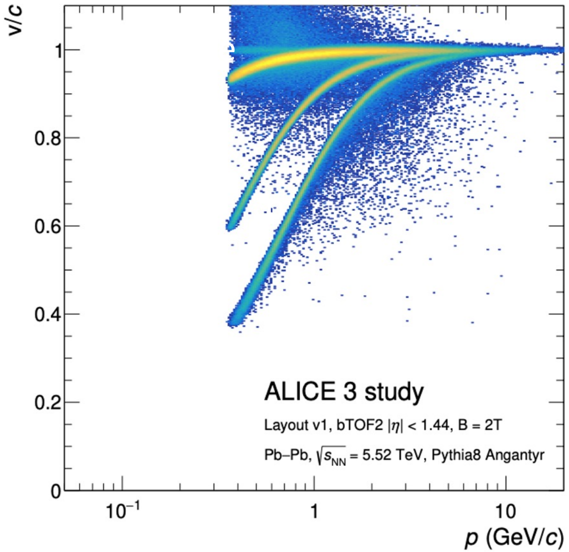
Electron and hadron ID requirements

e, π, K, p separation with **TOF + RICH** detectors, with specifications σ_t = 20 ps, σ_θ = 1.5 mrad

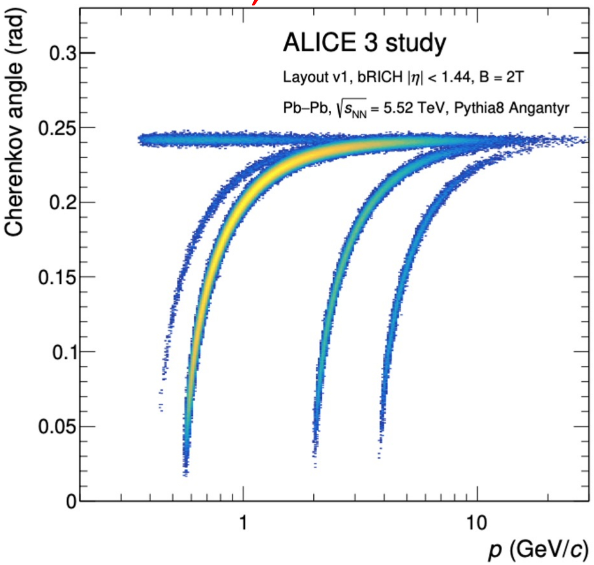
Inner TOF, R = 20 cm



Outer TOF, R = 85 cm



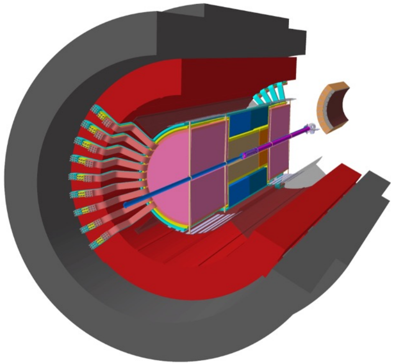
RICH, R = 90 cm



+ endcap TOF and RICH

ALICE 3: integration studies

1)



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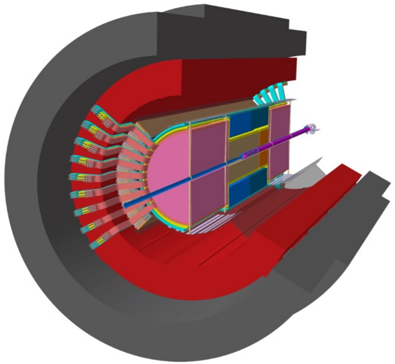

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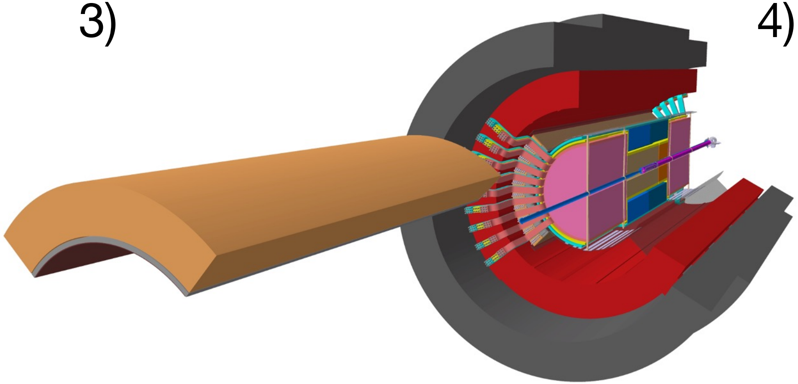

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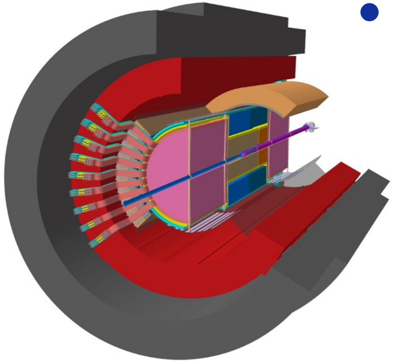
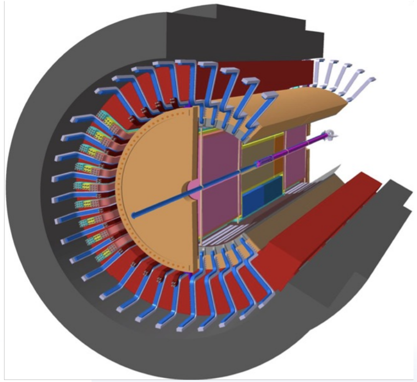
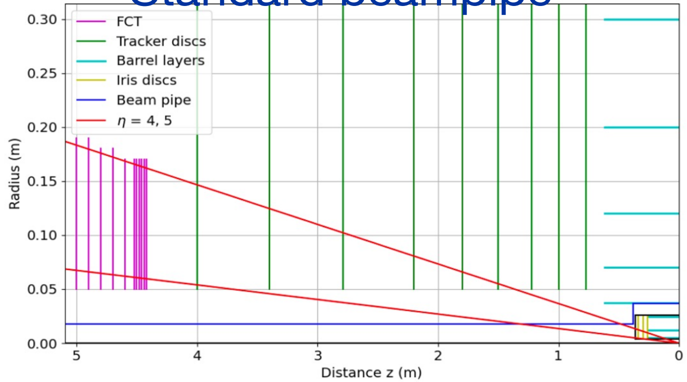


- Study of integration scheme with alternating services
- Enables modular and independent installation of: tracker endcaps, RICH and TOF barrels, RICH and TOF endcaps
- Improves contingency in LS4 schedule

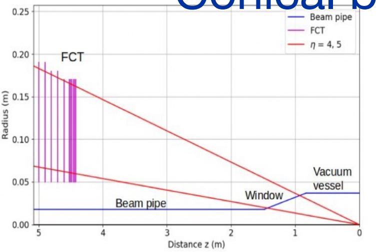


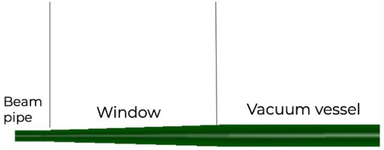
FCT studies

Standard beampipe

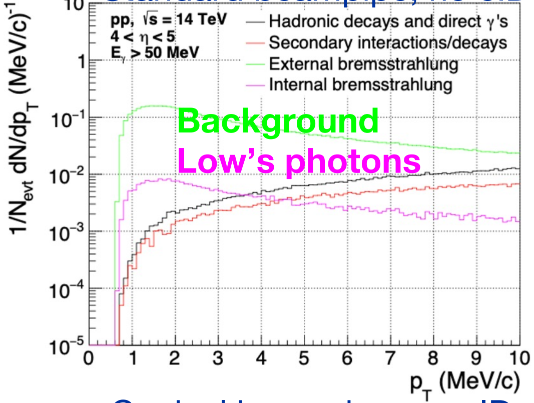


Conical beampipe

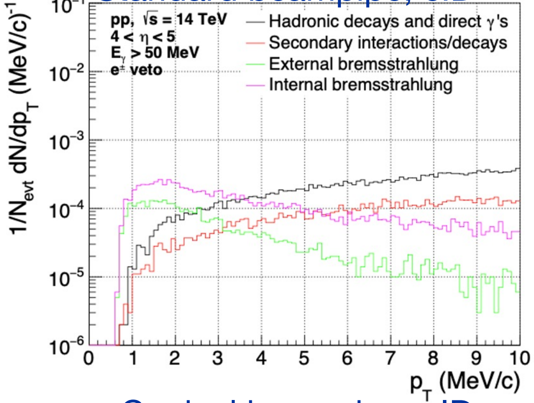




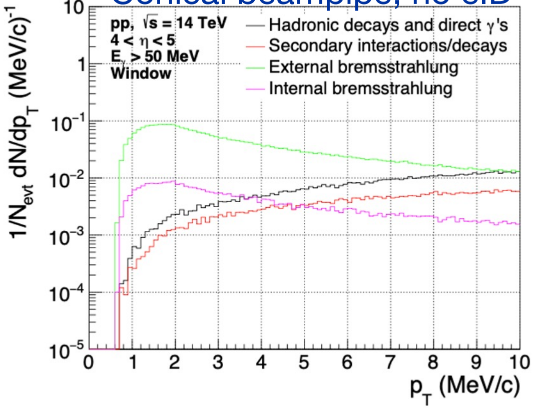
Standard beampipe, no eID



Standard beampipe, eID



Conical beampipe, no eID



Conical beampipe, eID