ALICE

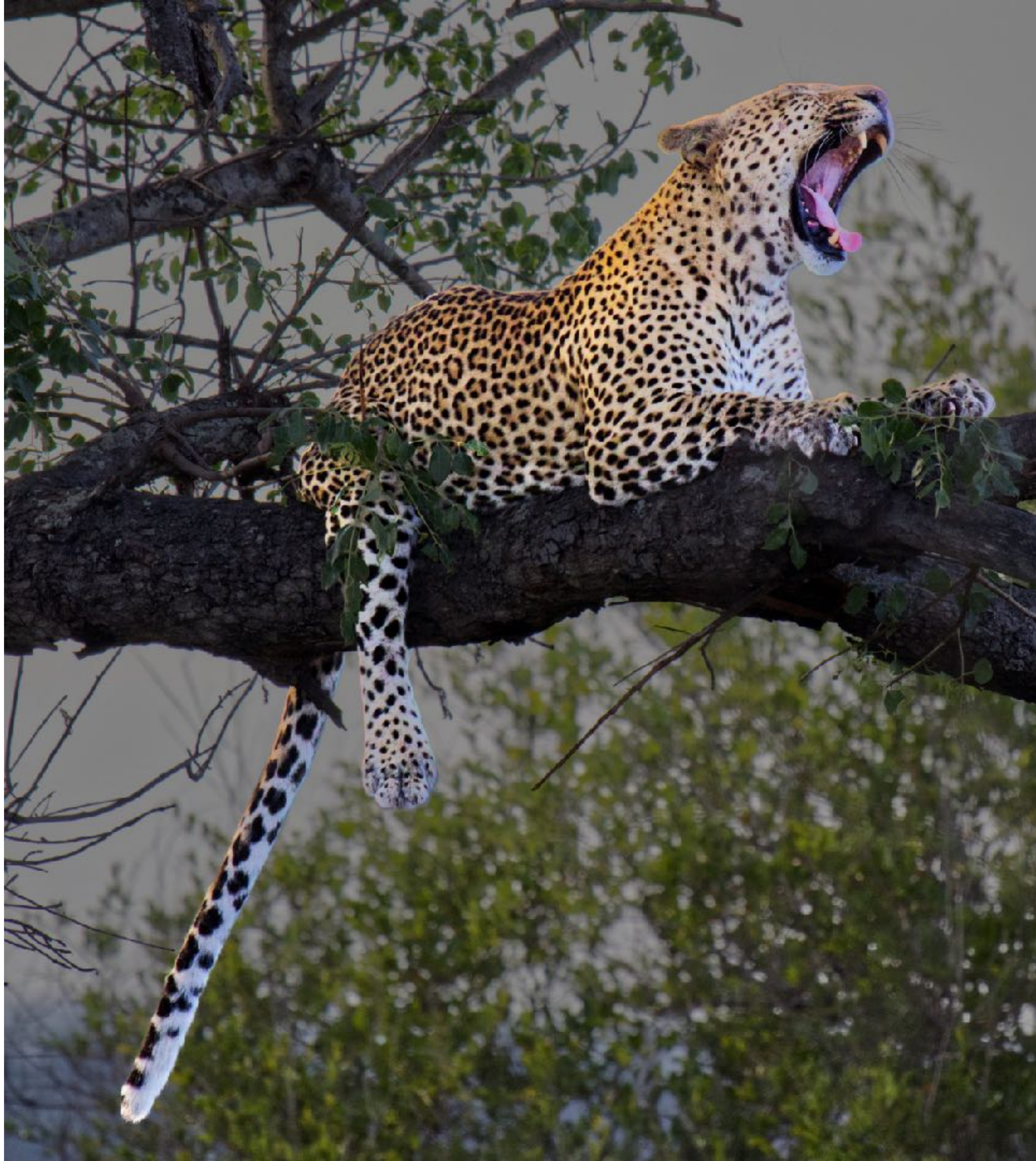
ALICE upgrades

perspectives for heavy-ion physics at the LHC

Kruger 2022
Discovery Physics at the LHC

December 6, 2022

Jochen Klein (CERN)
for the ALICE Collaboration



Outline

- **High-luminosity era for heavy-ions era at the LHC**
  - prospects for luminosity
  - experimental programmes
- **ALICE 2 (Run 3 & 4)**
  - detector upgrades
  - physics projections
- **ALICE 3: next-generation upgrade**
  - requirements and detector concept
  - physics performance and prospects

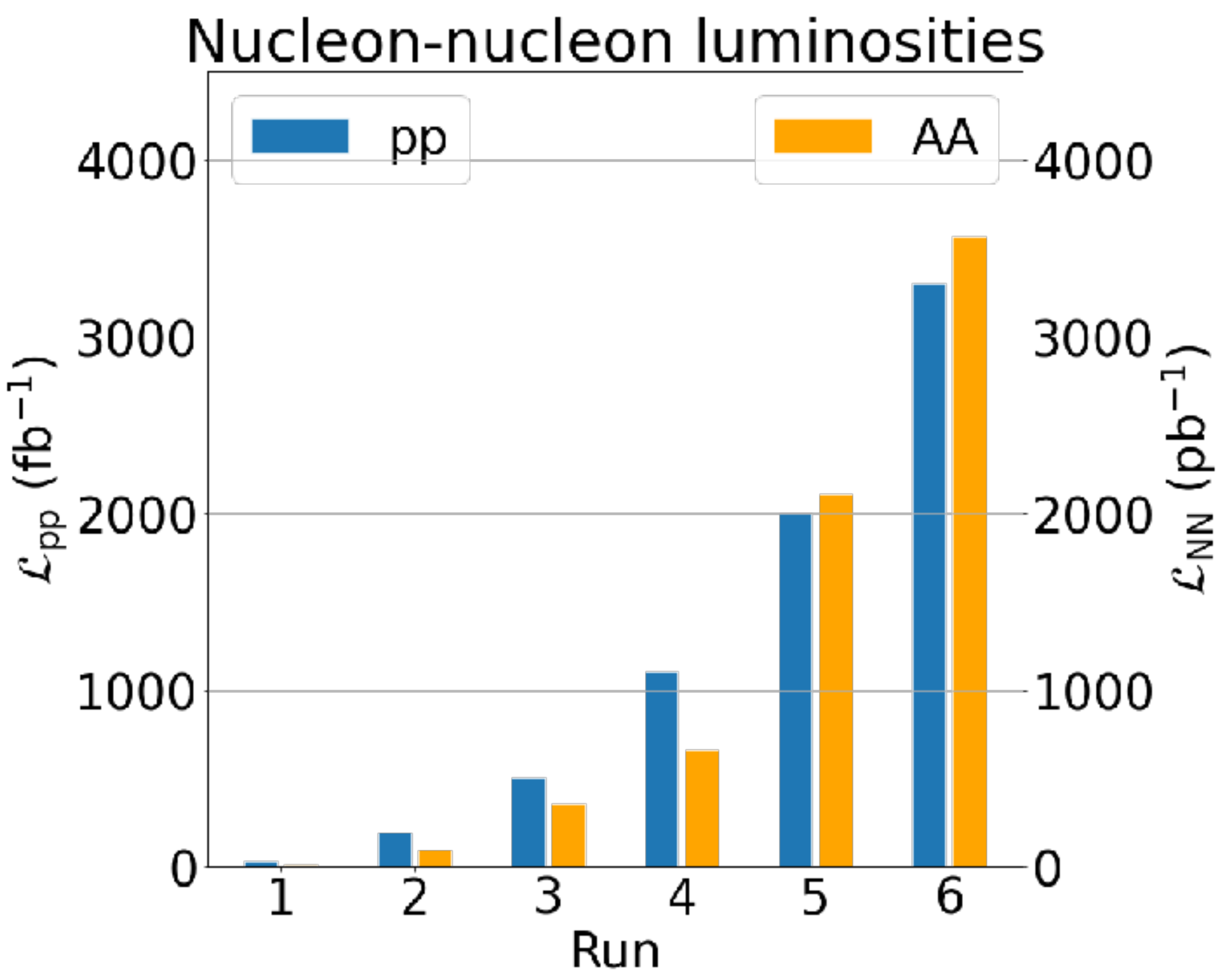
Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
2009 - 2013	2015 - 2018	2022 - 2025	2029 - 2032	2035 - …	

LHC programme

Collision systems

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

Pb-Pb luminosity limited by LHC ~1-2·10^{27} cm^{-2} s^{-1}



Run 5 → higher luminosities for ions

- mitigate space charge effects (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 (~7·10^{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

LHC experiments

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

High luminosity for ions (Run 3 – Run 4)

HL-LHC (Run 4 – Run 6)

Higher luminosities for ions (Run 5 – Run 6)

	Run 1 – Run 2	Run 3	Run 4	Run 5 – Run 6
ALICE	ALICE 1	ALICE 2 upgrade	ALICE 2.1 upgrade	ALICE 3 phase IIb upgrades
LHCb	LHCb	LHCb upgrade I(a)	LHCb upgrade Ib	LHCb phase IIb upgrades
ATLAS	ATLAS	ATLAS phase I upgrades	ATLAS phase II upgrades	
CMS	CMS (Run 1 – Run 2, first part)	CMS phase I upgrades (end of Run 2 – Run 3)	CMS phase II upgrades	

→ evolution of LHC and the experiments

intermediate upgrade | major upgrade

ALICE upgrades

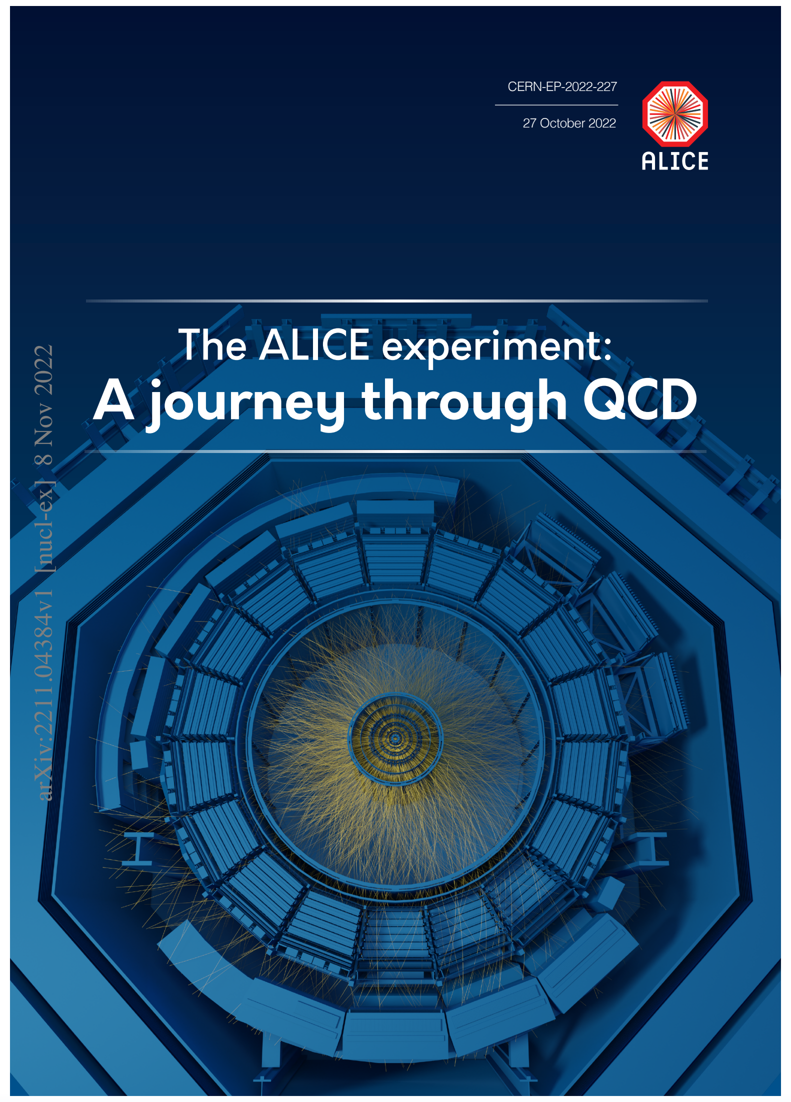
	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Collision systems	pp, pPb, Pb-Pb	pp, pPb, Xe-Xe, Pb-Pb	pp, pO, OO, pPb, Pb-Pb	pp, pPb, Pb-Pb	pp, pA?, AA	pp, pA?, AA
LHC schedule	Run 1 2009 - 2013	Run 2 2015 - 2018	Run 3 2022 - 2025	Run 4 2029 - 2032	Run 5	Run 6

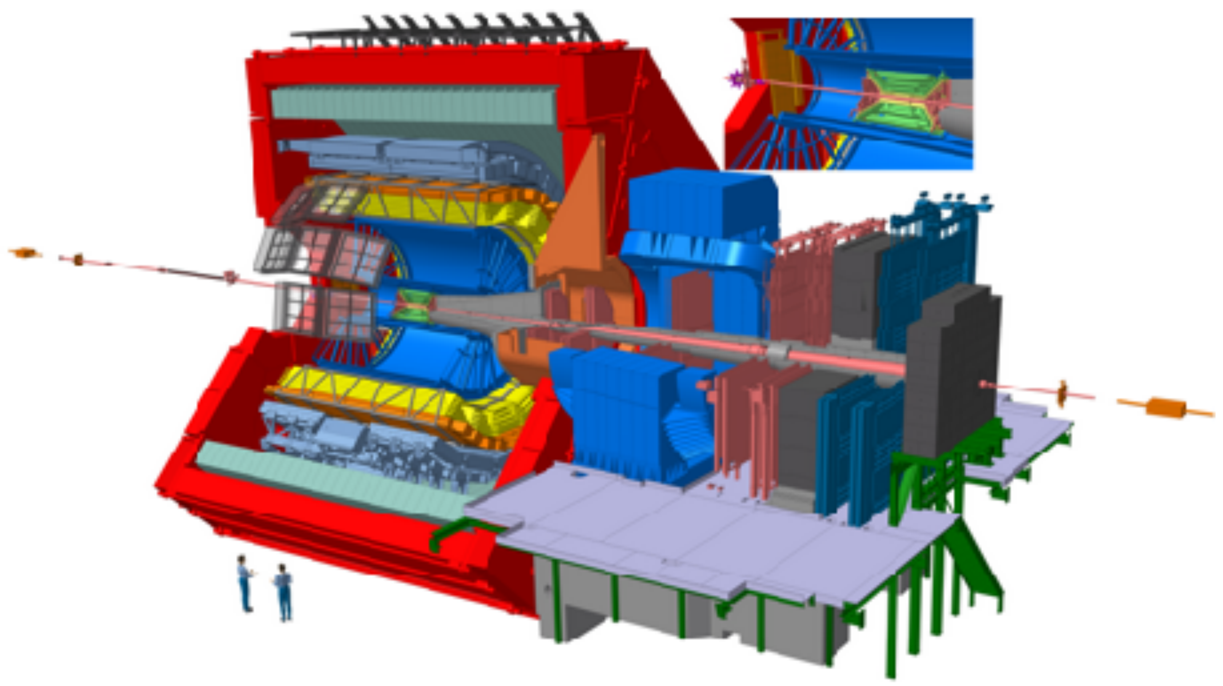
High luminosity for ions

HL-LHC

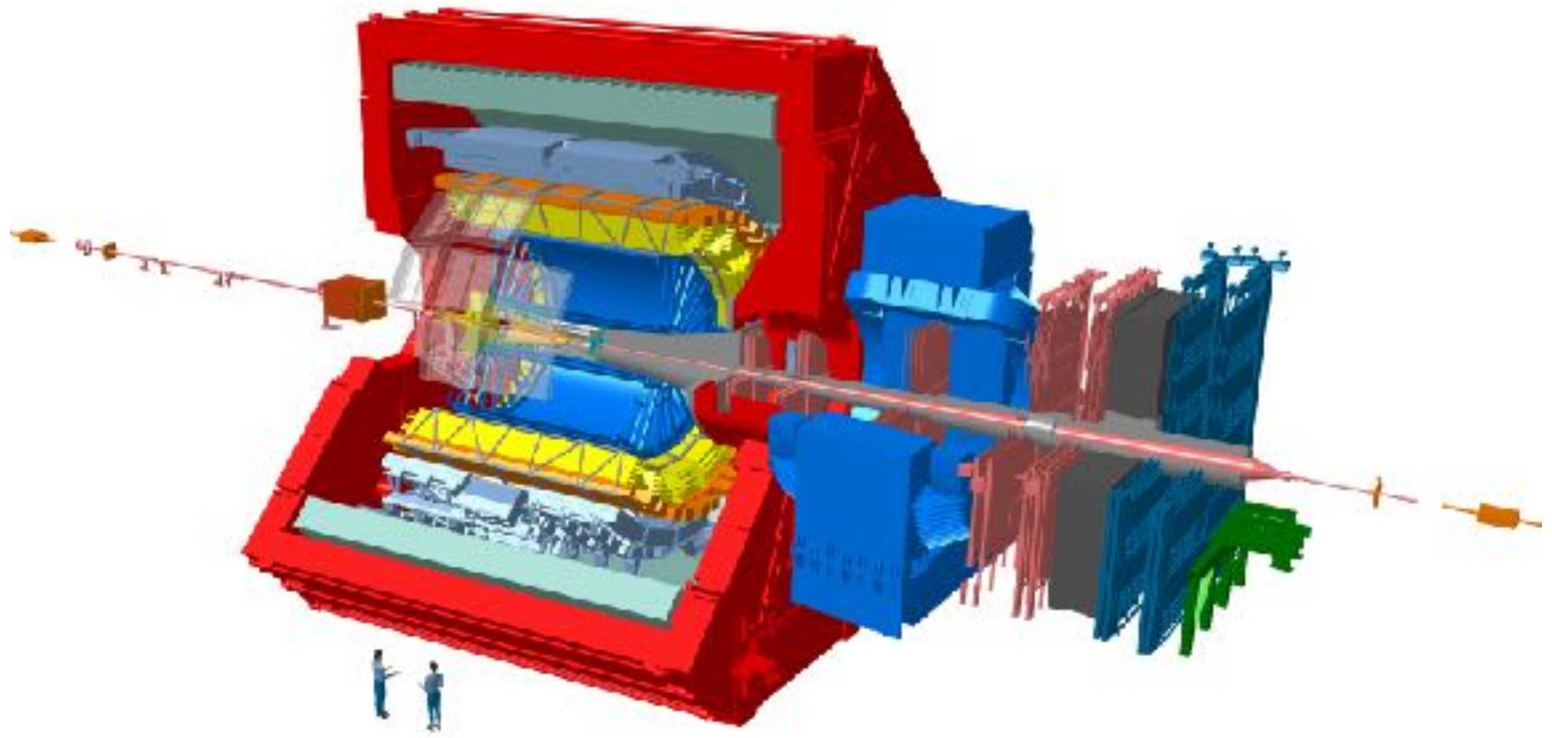
Higher luminosities for ions

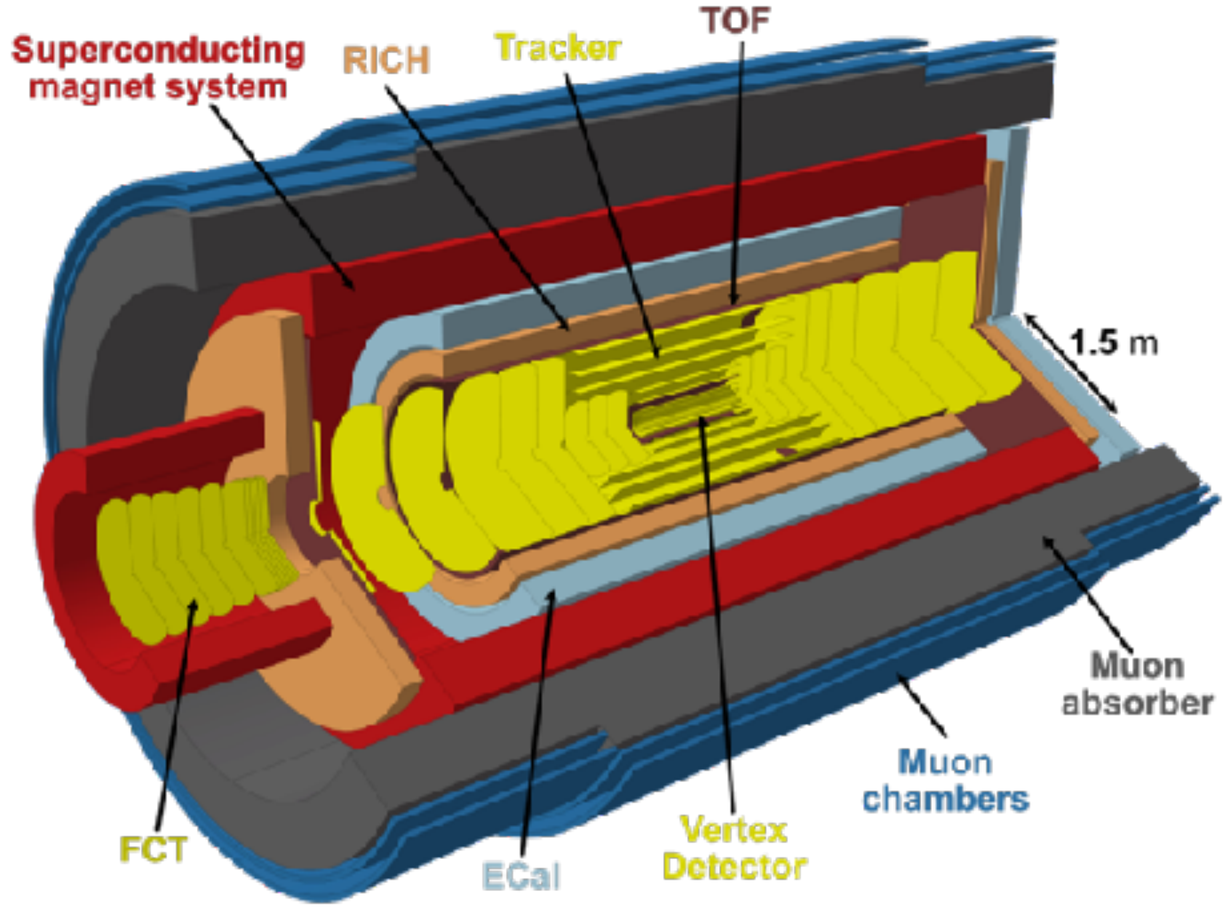
ALICE	ALICE 1	ALICE 2 upgrade	ALICE 2.1 upgrade	ALICE 3 phase IIb upgrades





→ F. Antinori
→ arXiv:2211.04384





intermediate upgrade | major upgrade

ALICE 2

- High interaction rate: 50 kHz Pb-Pb, 1 MHz pp
  → **no gating of TPC with limited ion backflow**

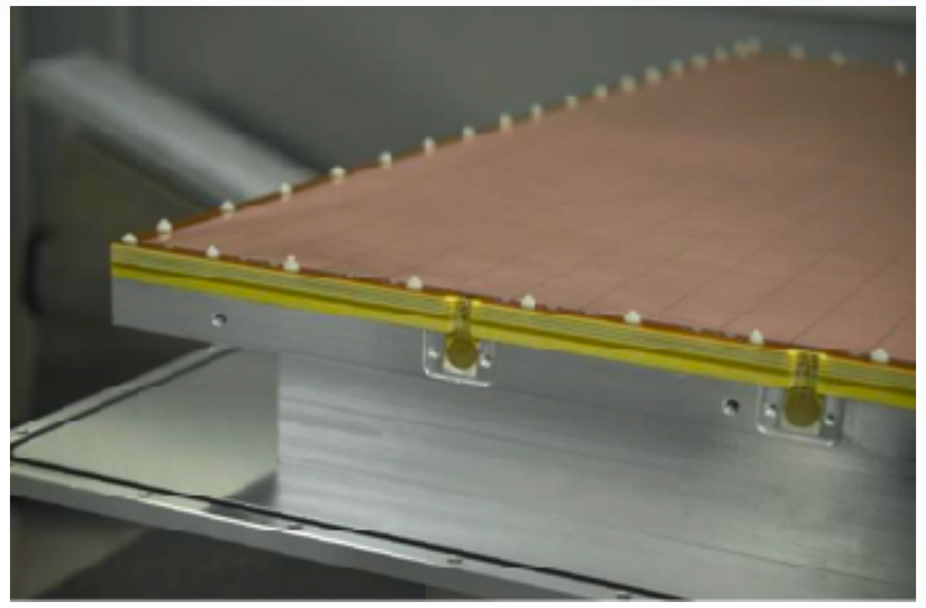
- Reconstruction of heavy-flavour decay vertices
  → **improve pointing resolution**

- Large statistics of untriggerable probes
  → **continuous readout**

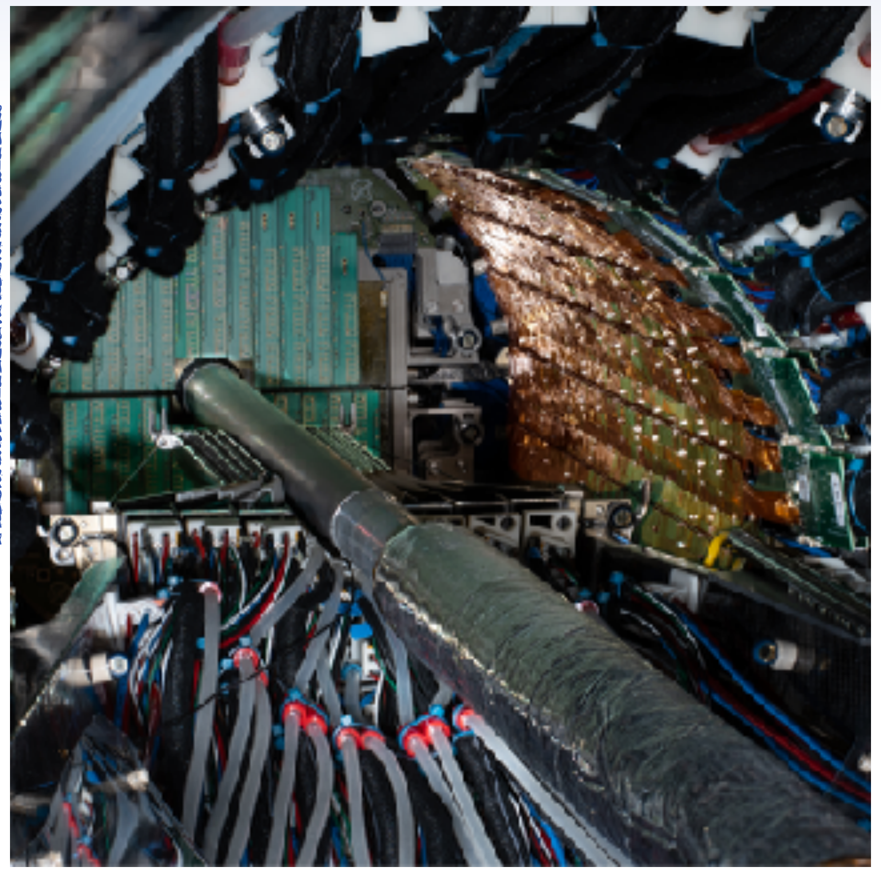
- Skimming based on reconstructed events
  → **online reconstruction**

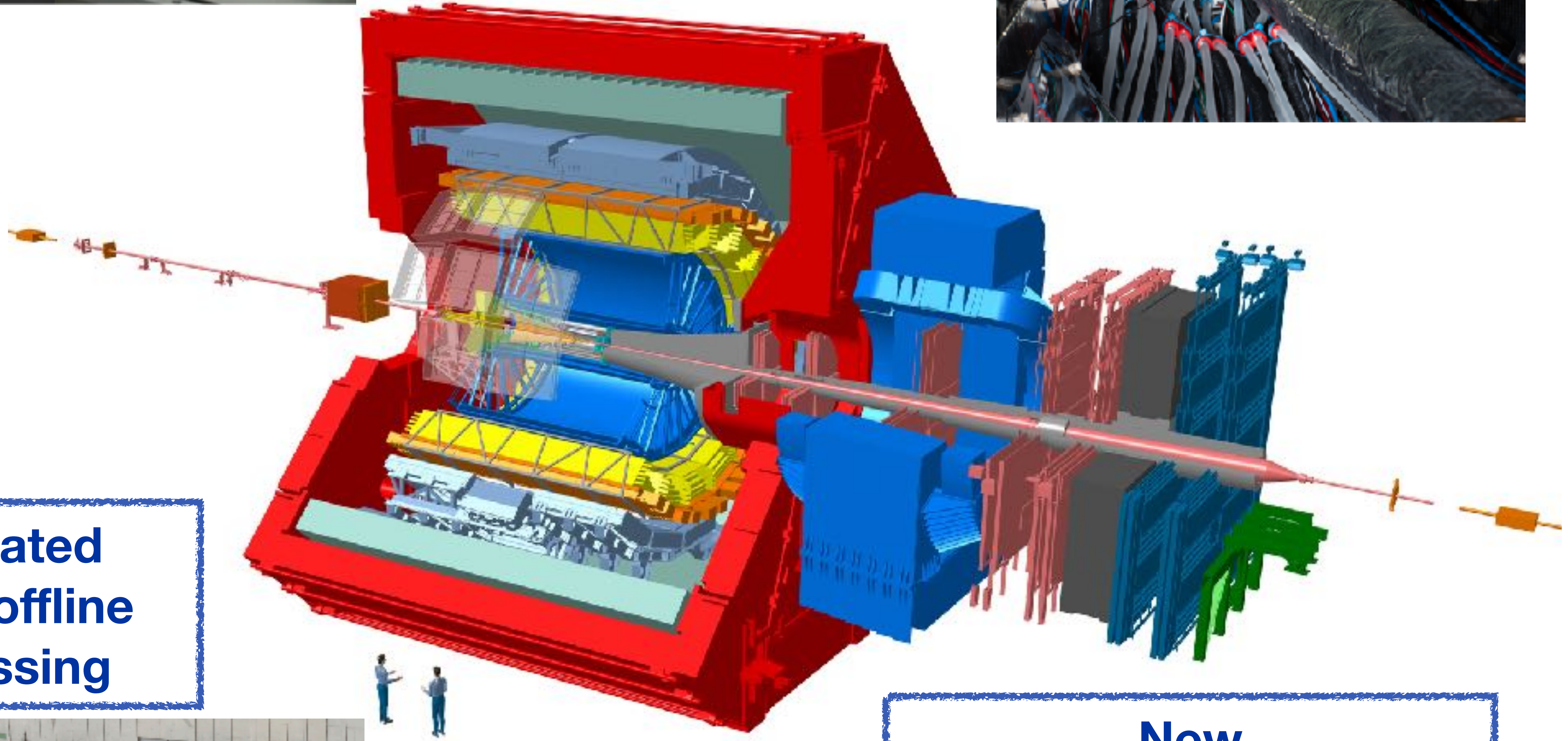
Consolidation and readout upgrade of all subsystems

GEM-based Time Projection Chamber



MAPS-based Inner Tracking System and Muon Forward Tracker





Integrated online/offline processing

New Fast Interaction Trigger

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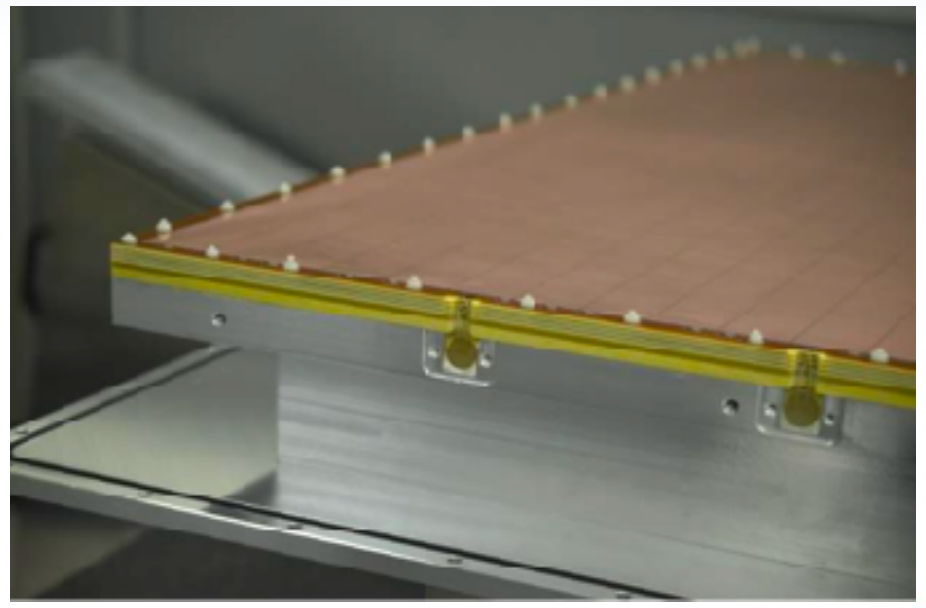
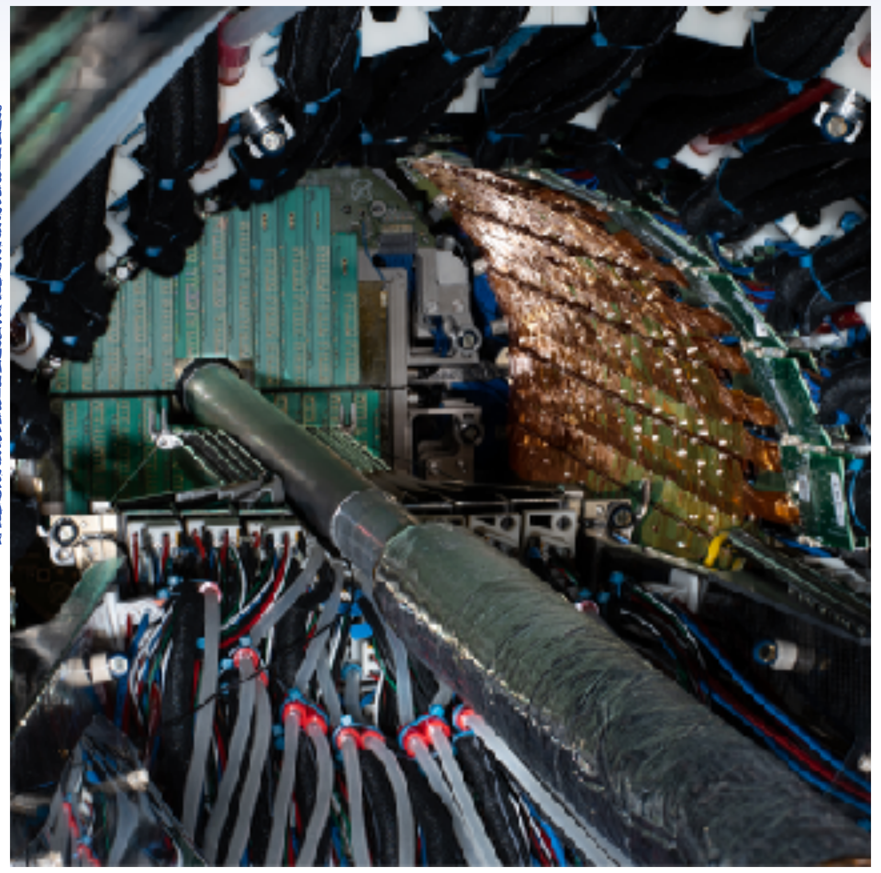
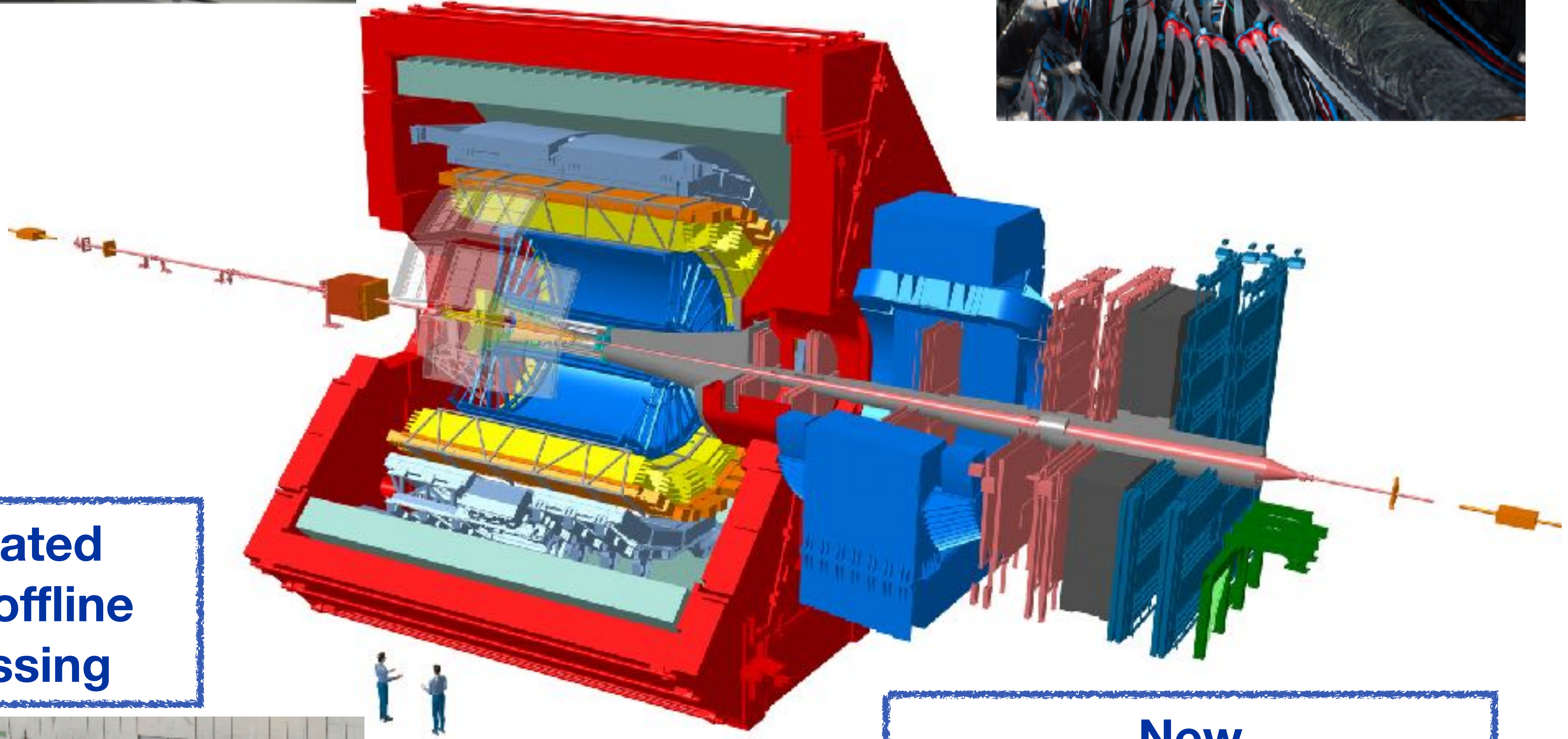


MAPS-based Inner Tracking System and Muon Forward Tracker





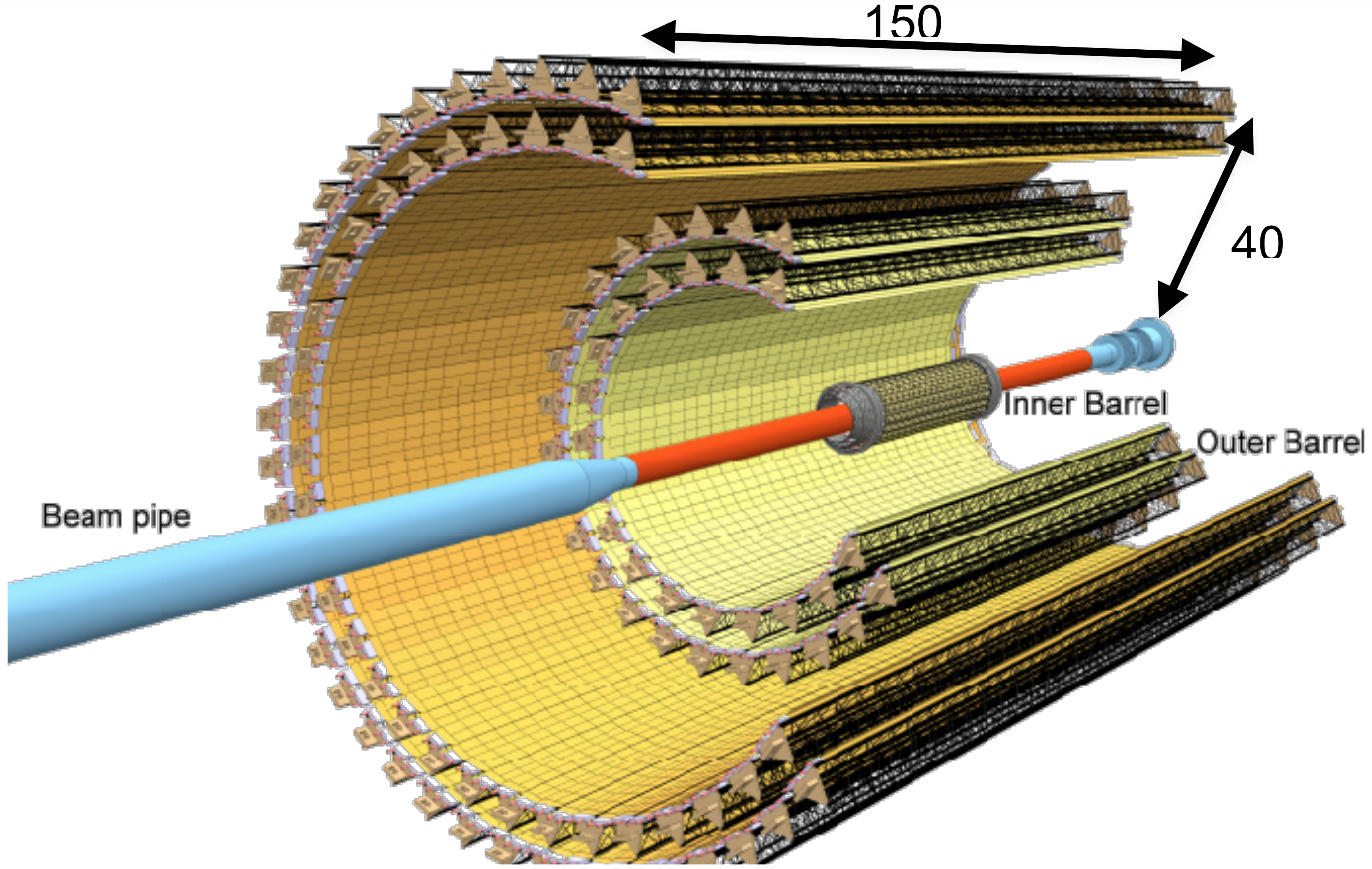
Integrated online/offline processing

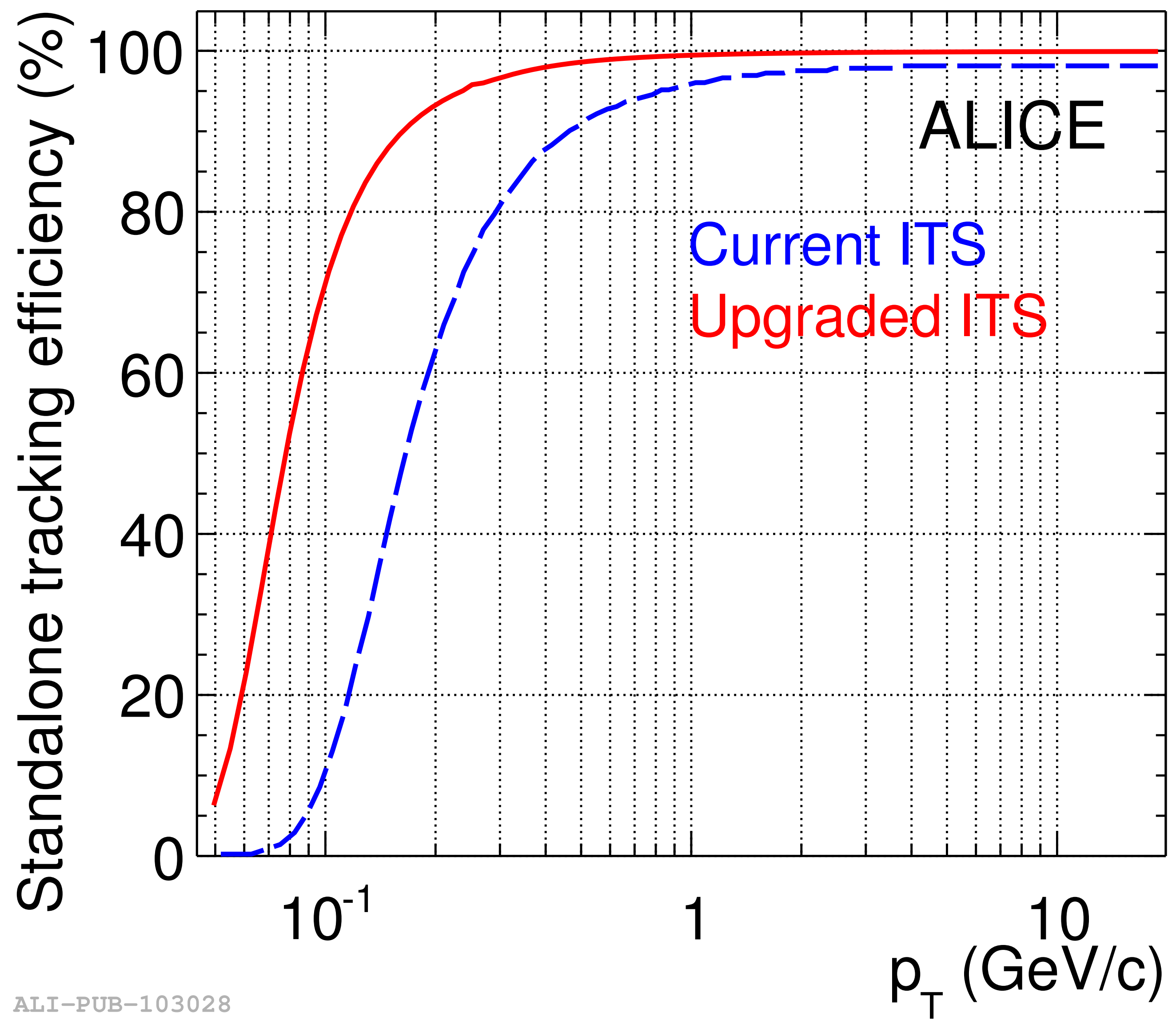
New Fast Interaction Trigger

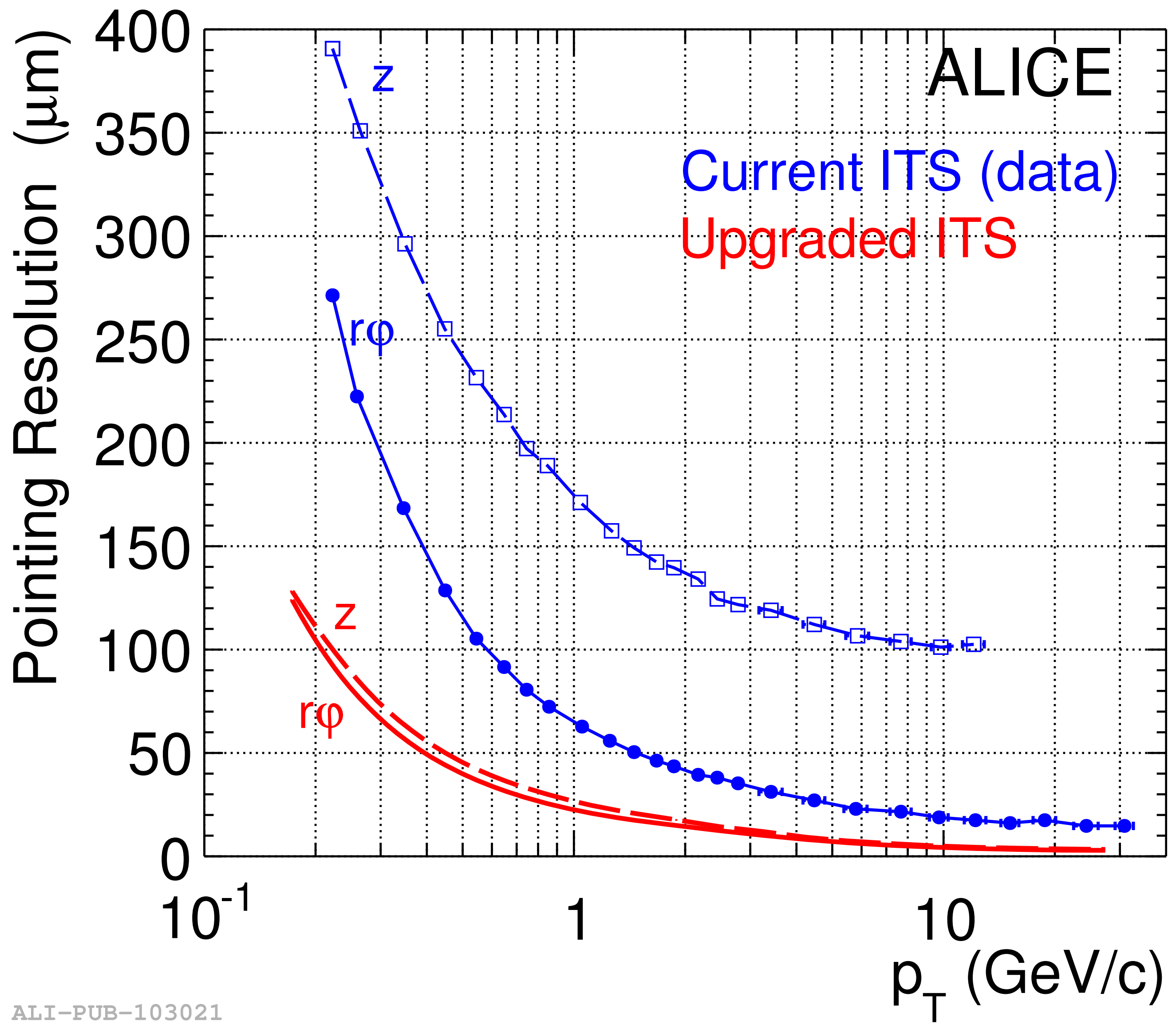
Inner Tracking System (ITS2)

- **Requirements**
  - improve pointing resolution by a factor ~3 in rφ, ~5 in *z*
  - improve efficiency and resolution at low p_T
  - increase readout rates 100 kHz Pb-Pb, 1 MHz pp
- **Concept**
  - smaller and thinner beampipe first layer: 39 mm → 23 mm
  - reduce material of detection layers ~1.14 % → ~0.35 % X_0 (per inner layer)
  - increase position resolution 11 x 100 μm² → 5 x 5 μm²
  - Monolithic Active Pixel Sensors
  - 7 layers arranged in inner (3), middle (2), outer (2) layers

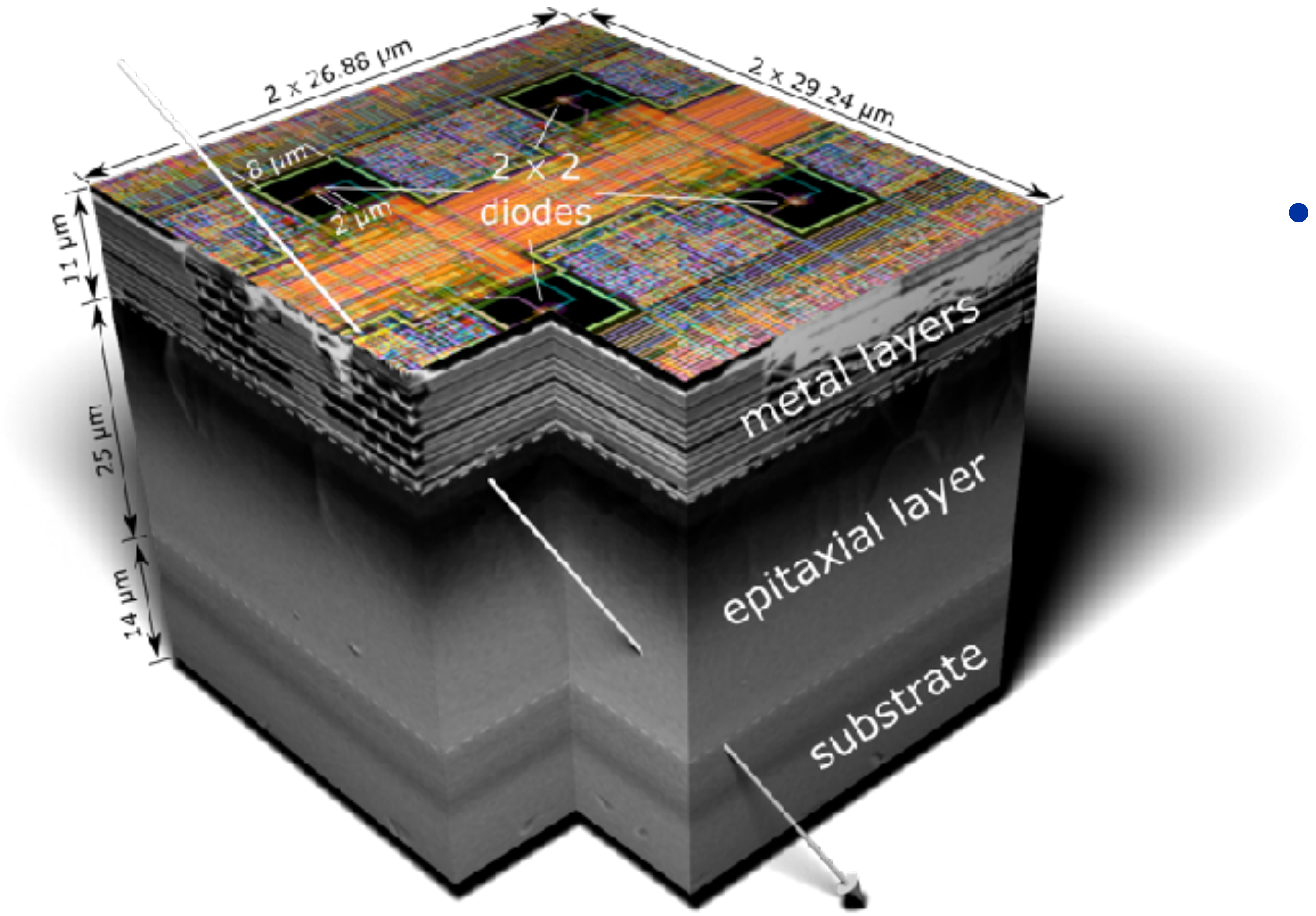
Improved resolution, reduced material, faster readout





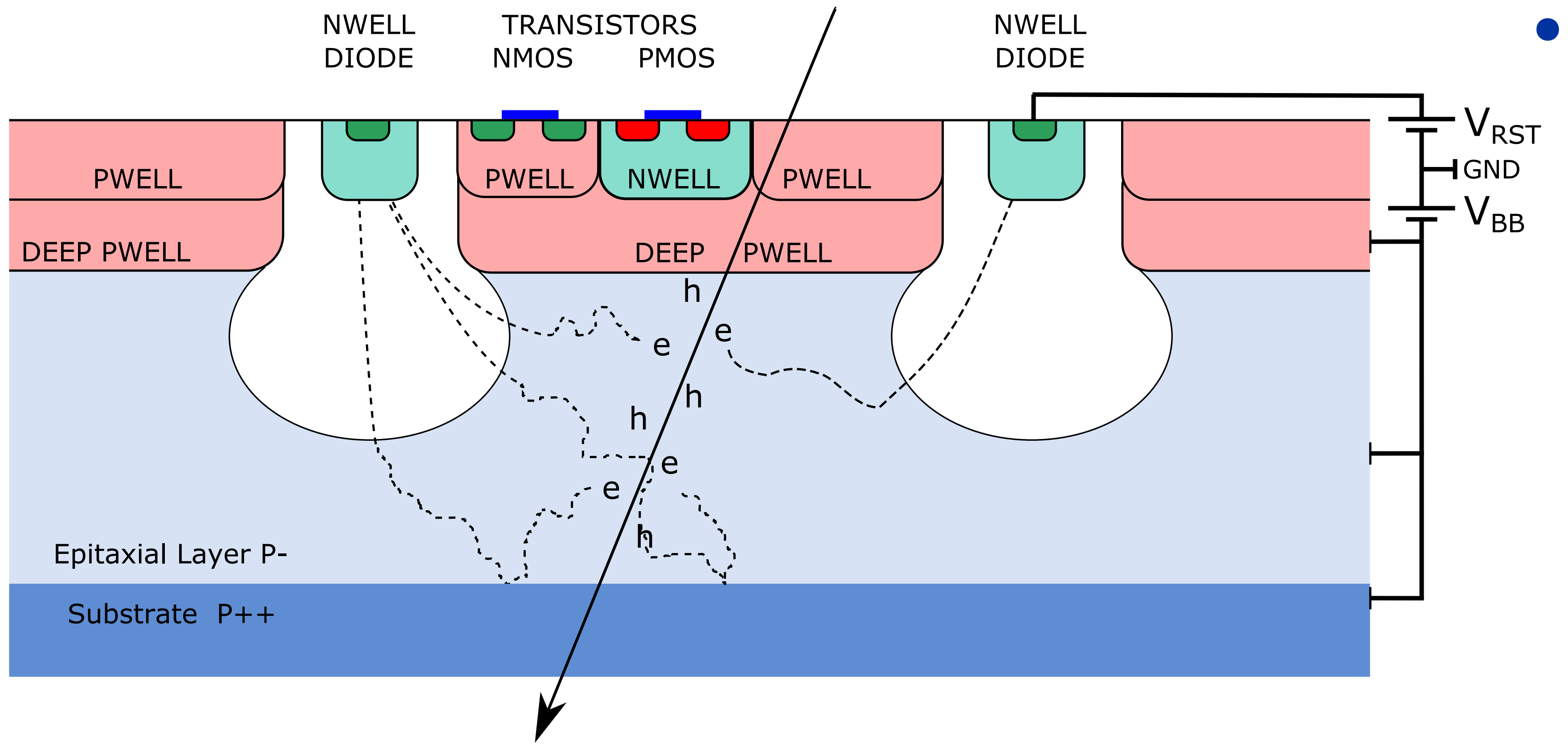


ALICE Pixel Detector (ALPIDE)



ALICE ITS2 development

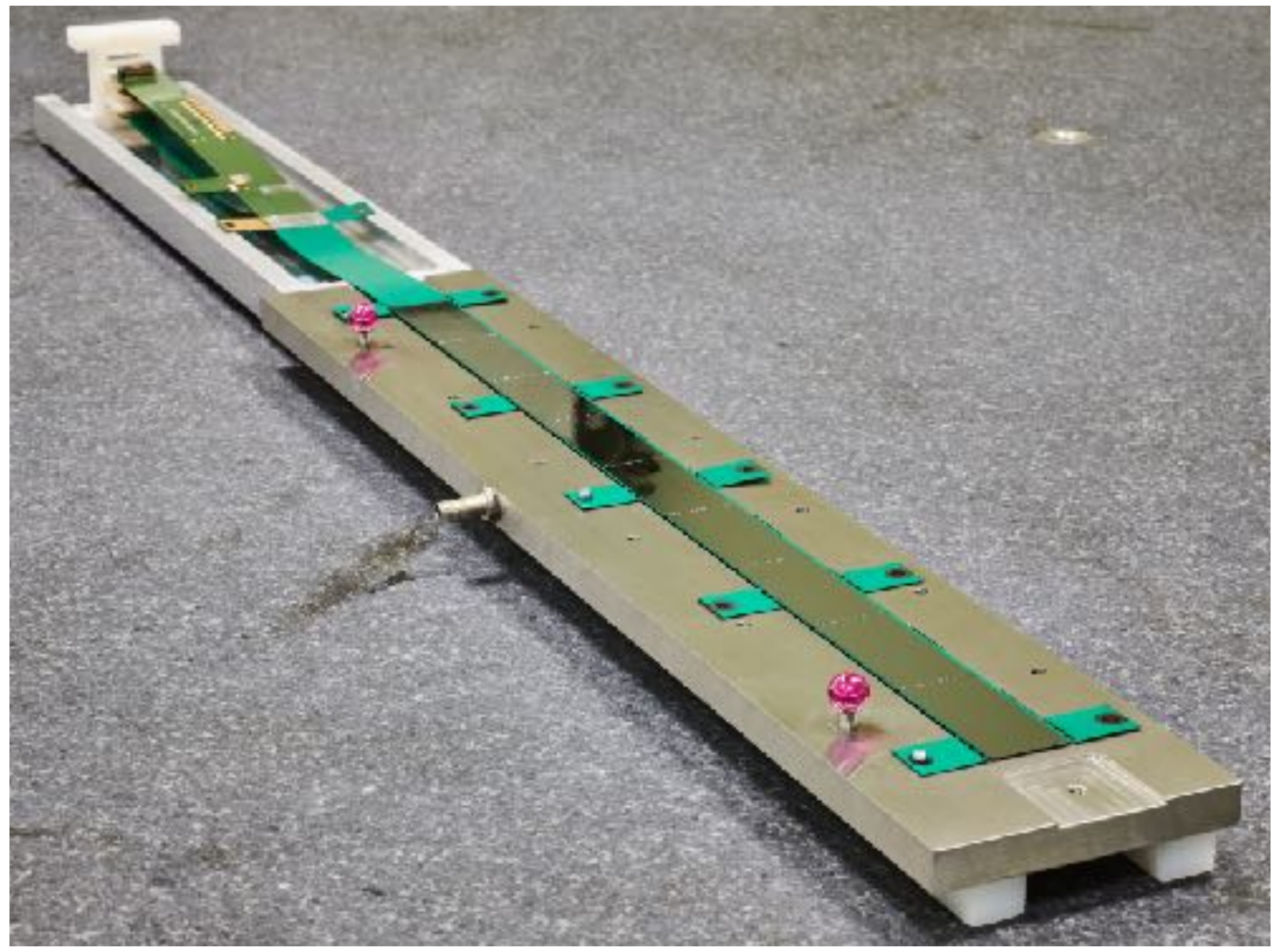
- **Technology**
  - TowerJazz 180 nm CMOS Imaging Process
  - high-resistivity (> 1kΩ cm) p-type epitaxial layer on p-type substrate
  - small n-well diode (2 µm diameter) → low capacitance (~fF)
  - reverse bias voltage (-6 V $< V_{BB} <$ 0 V) to substrate
    to increase depletion zone around NWELL collection diode
  - deep PWELL shields NWELL of PMOS transistors

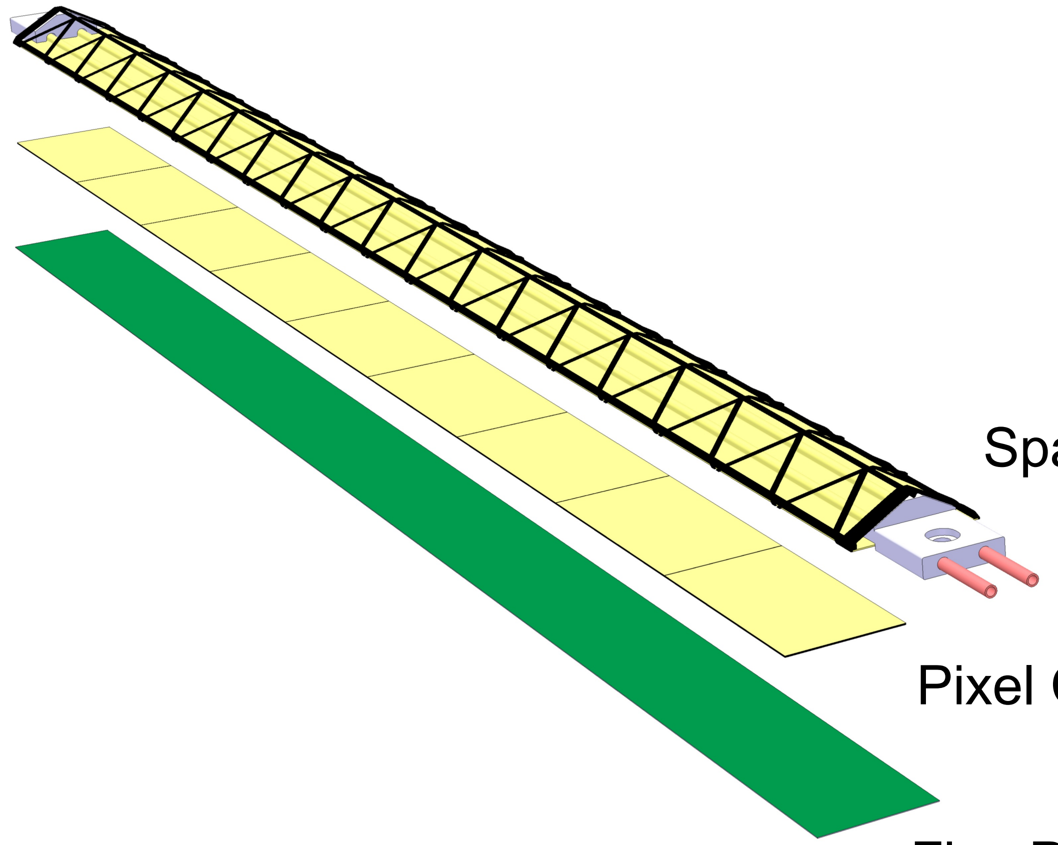


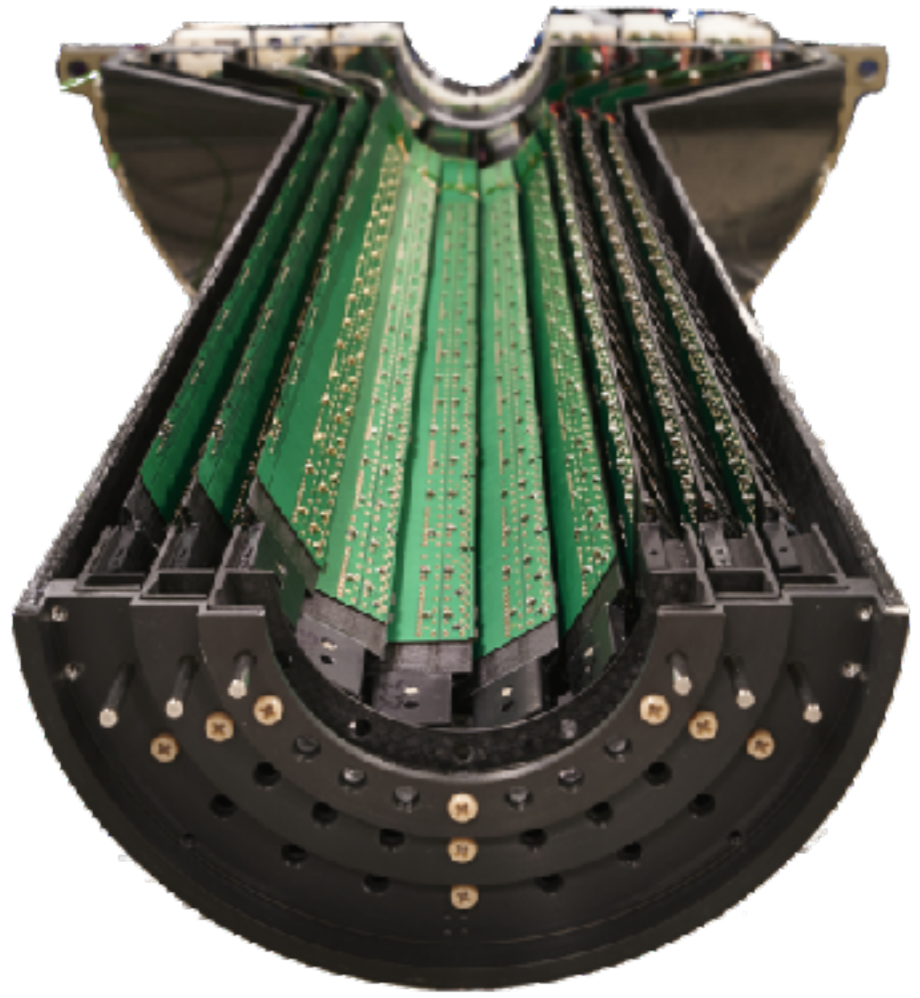
- **Key features**
  - in-pixel amplification and shaping,
    discrimination and Multiple-Event Buffers (MEB)
  - in-matrix data sparsification
  - on-chip high-speed link (up to 1.2 Gbps)
  - low total power consumption < 40 mW/cm2

ITS2 integration

Inner Barrel





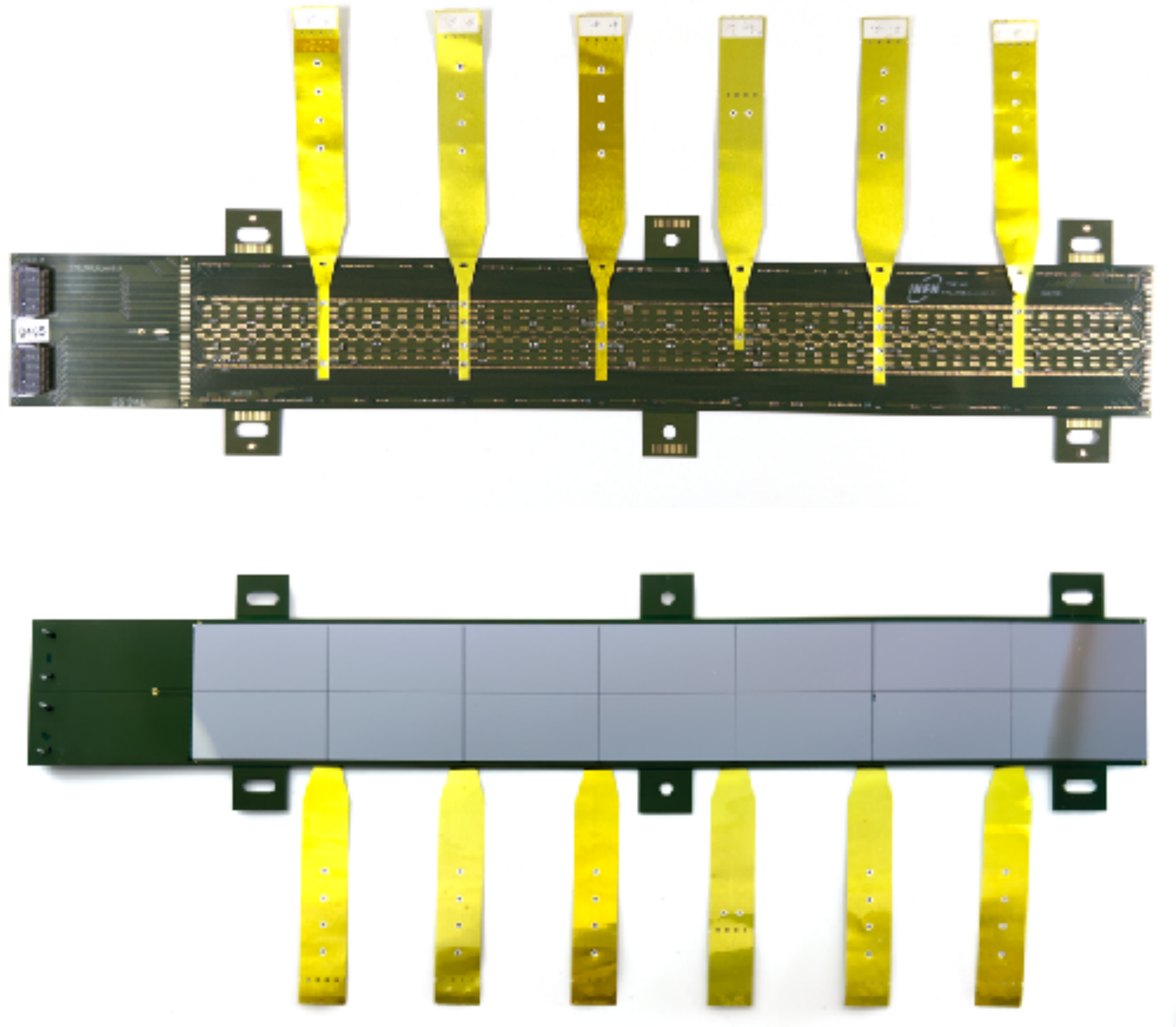


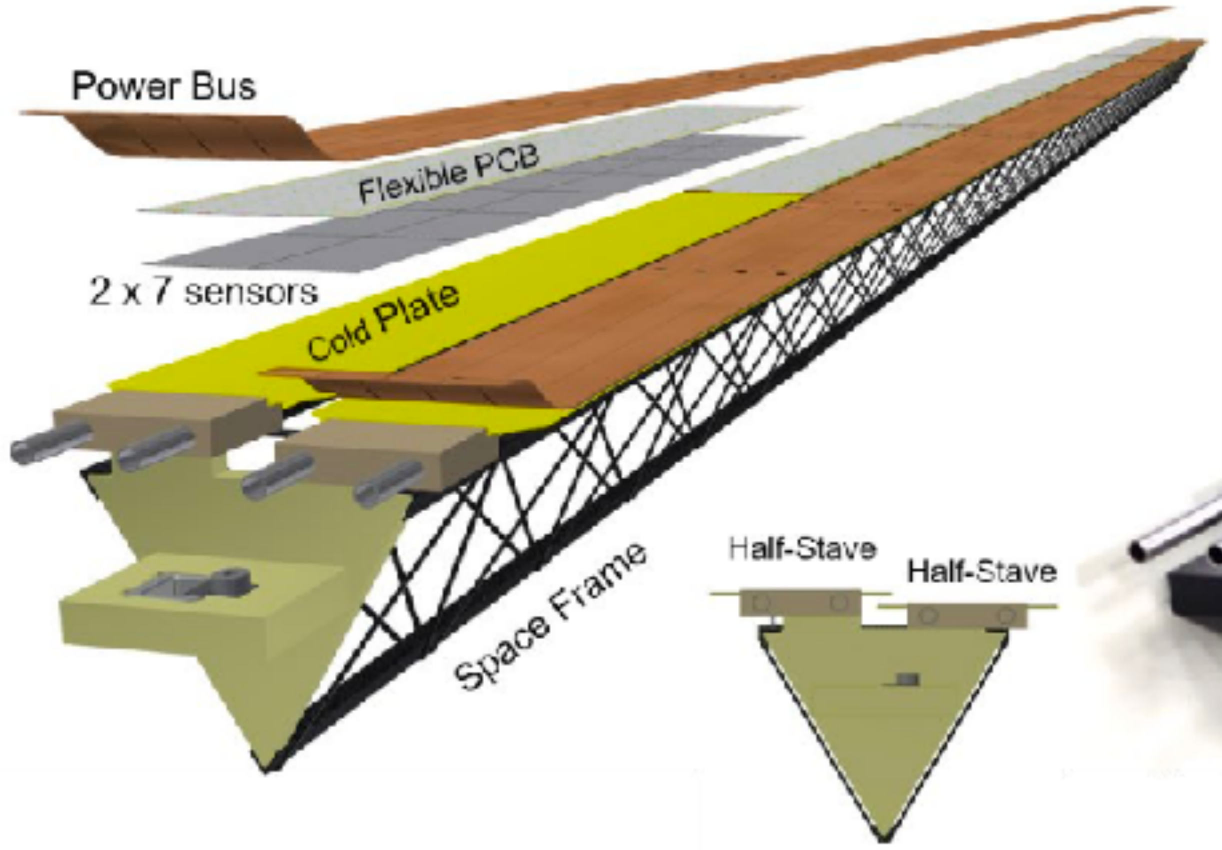
Module

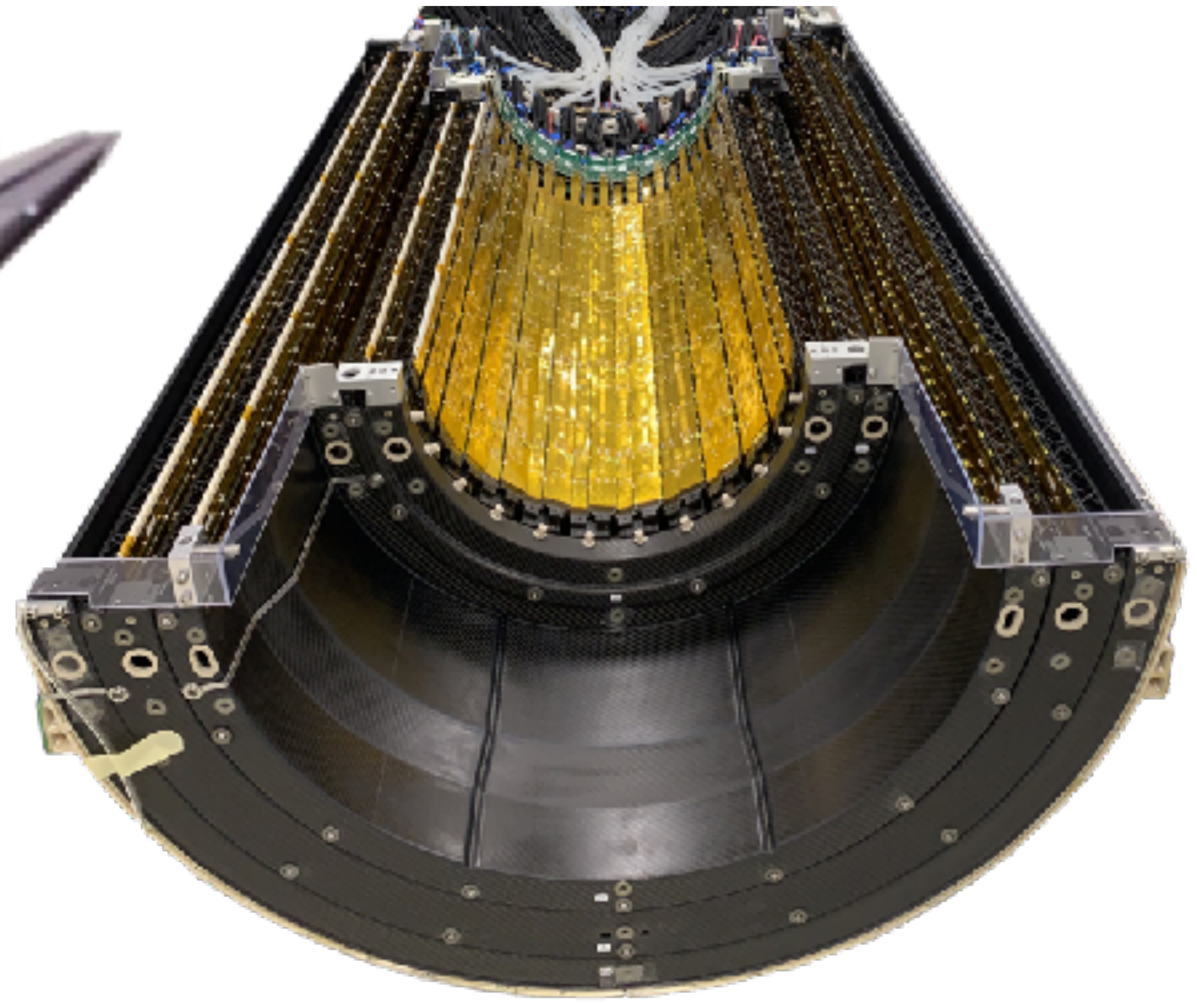
Stave

half-barrel

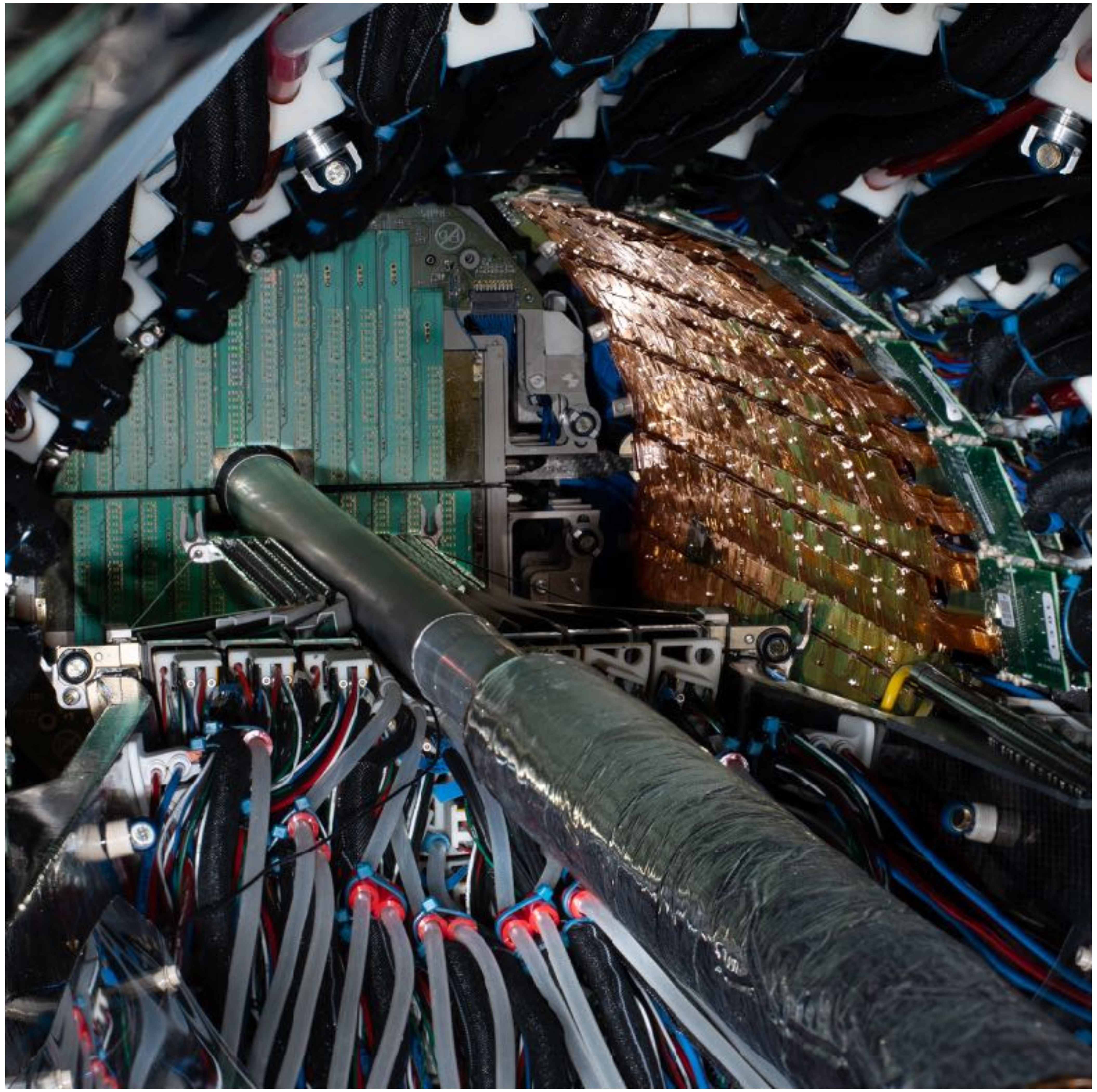
Outer Barrel

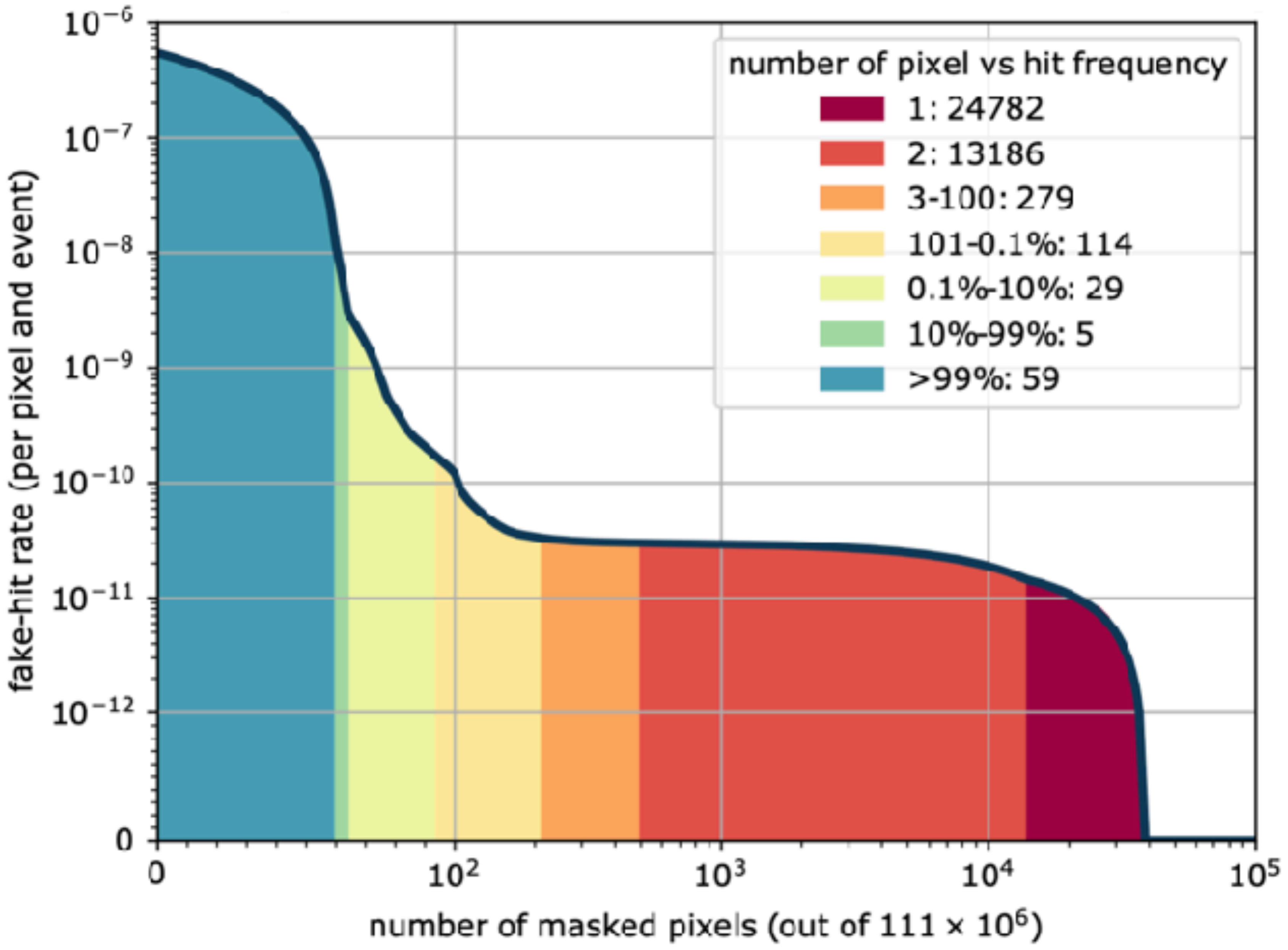


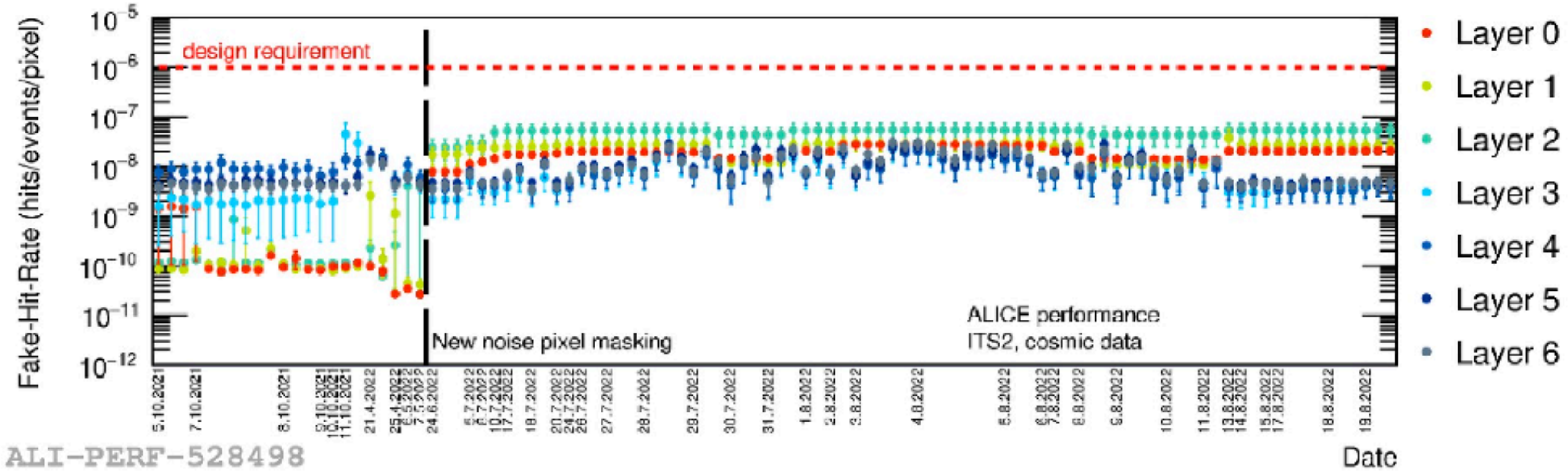




ITS2 installation

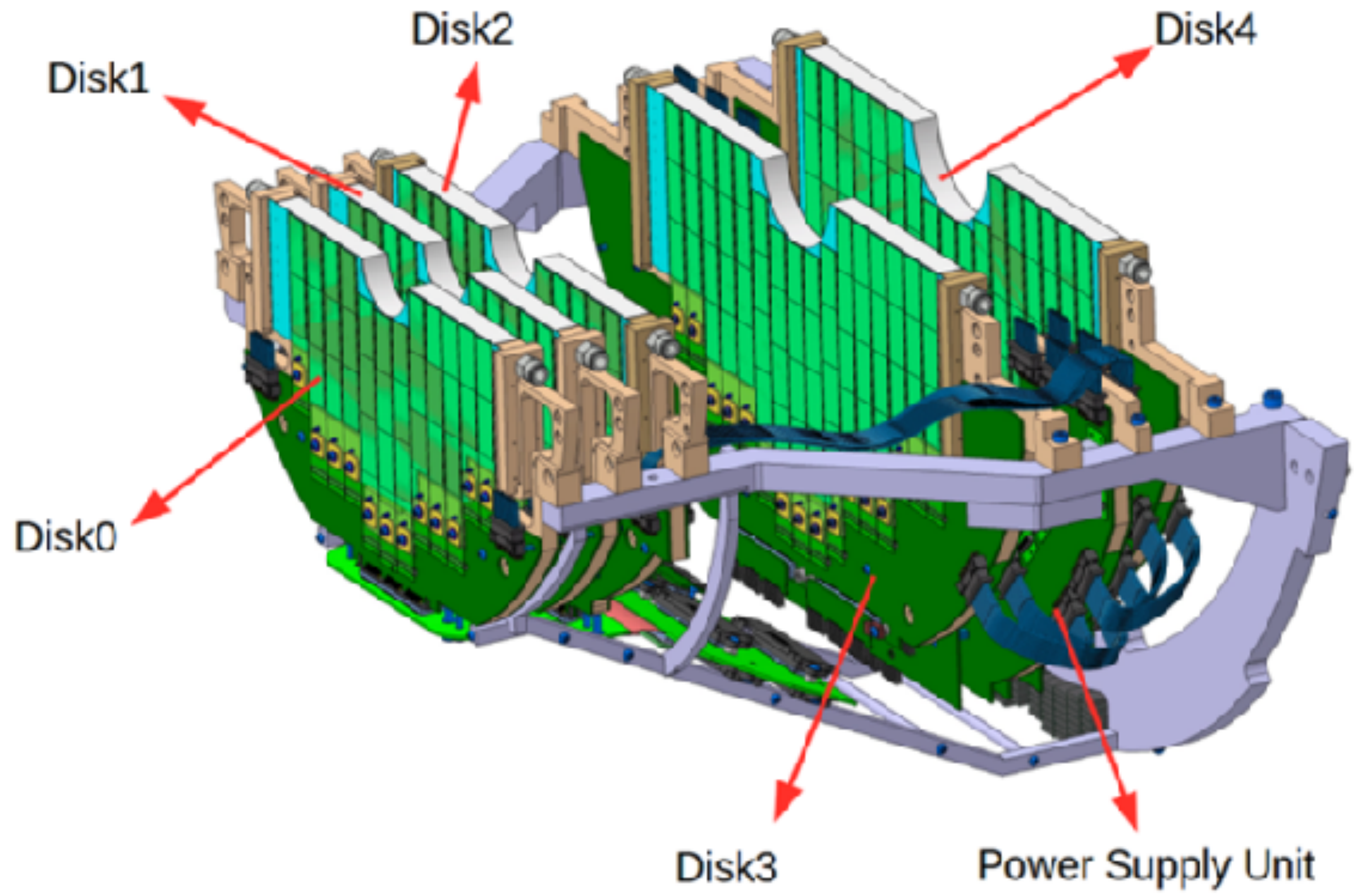


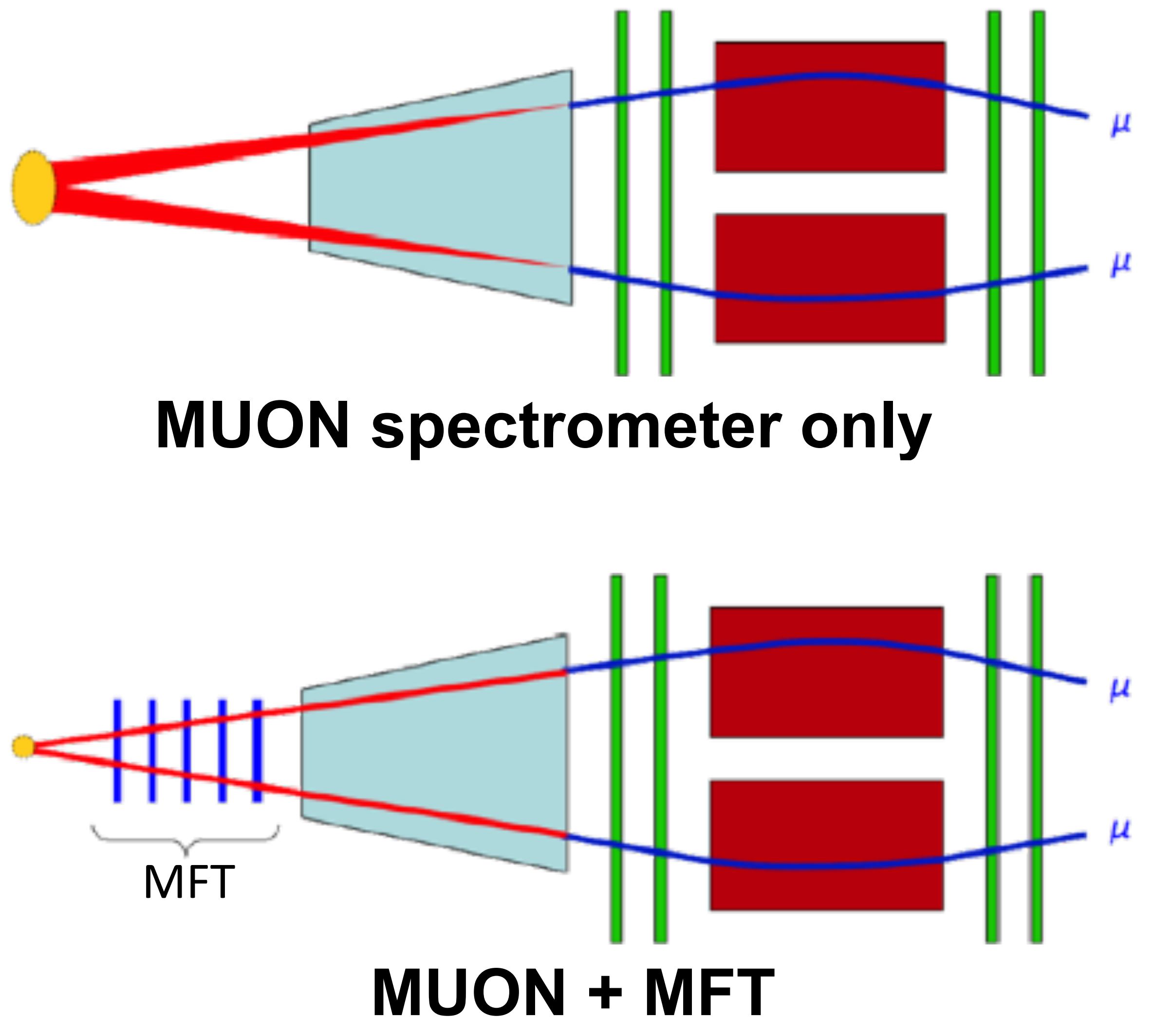


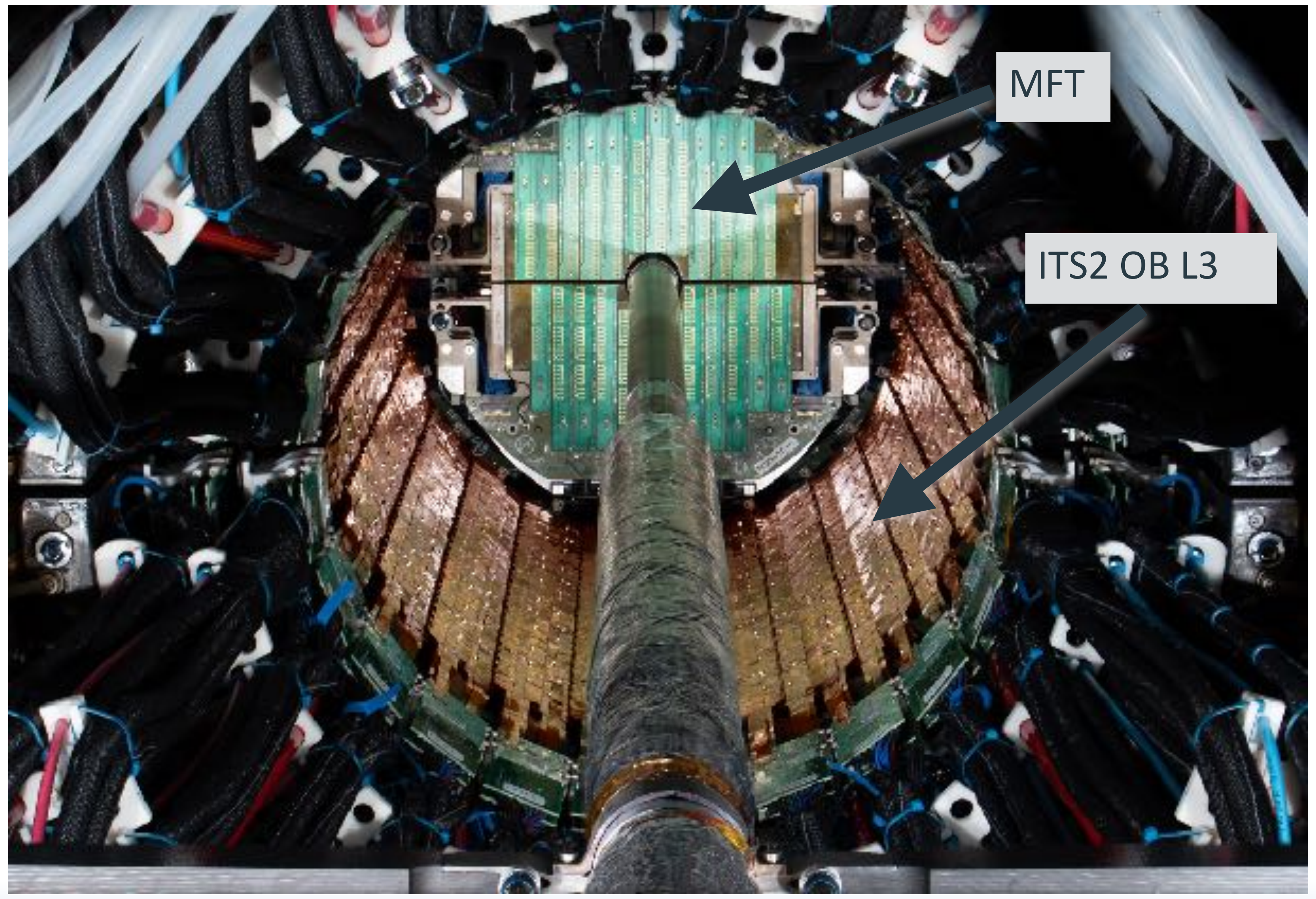


Muon Forward Tracker

- **Requirements**
  - propagate muon tracks to primary vertex (prompt vs. non-prompt)
  - handle high readout rates 100 kHz Pb-Pb, 1 MHz pp
  - < 300 krad, < 2 x 10^{12} 1 MeV n_{eq}/cm^2
- **Concept**
  - ALPIDE as sensor (936 chips, 0.4 m^2)
  - 10 half-disks, 2 detection planes each ($2.5 < \eta < 3.6$)

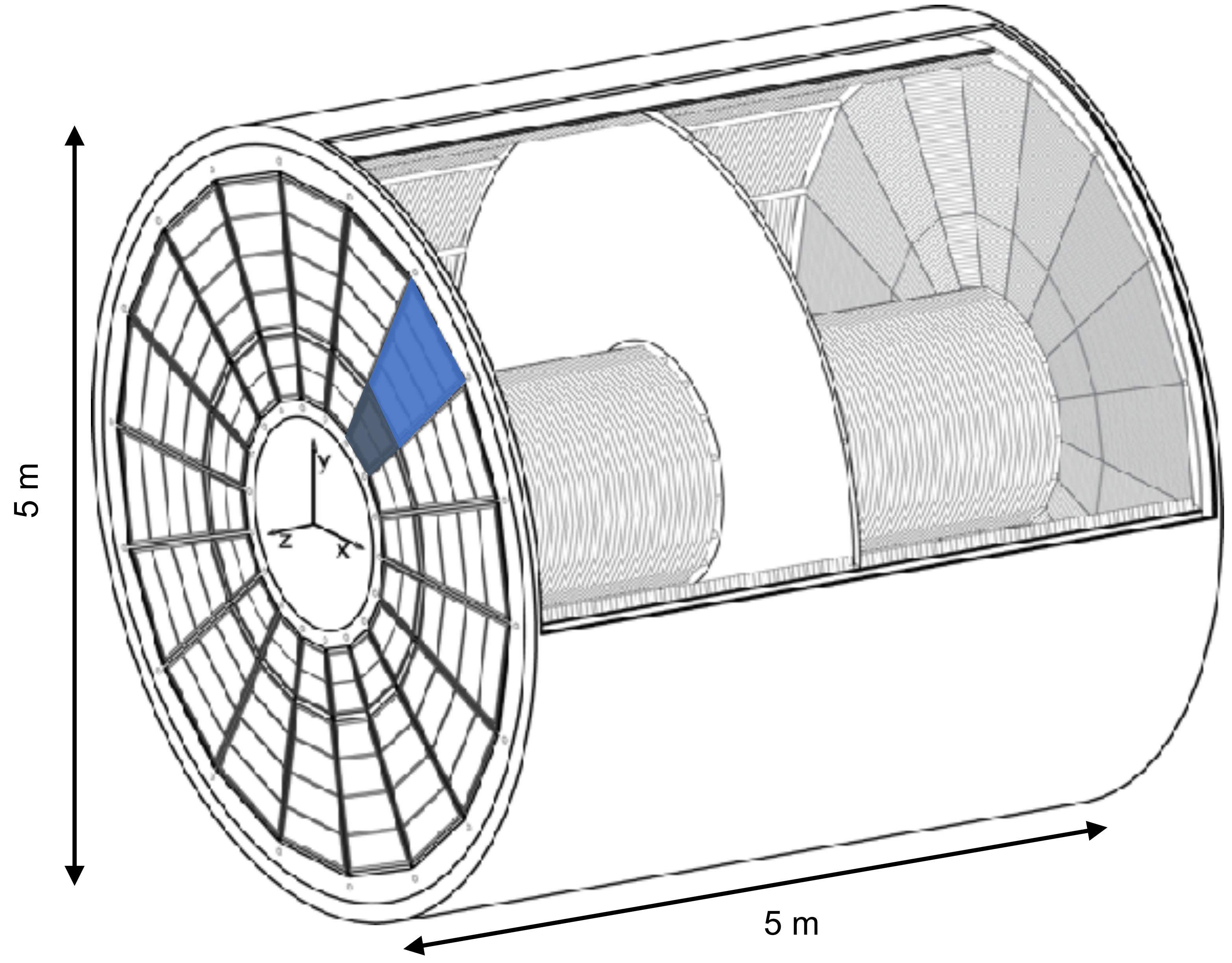




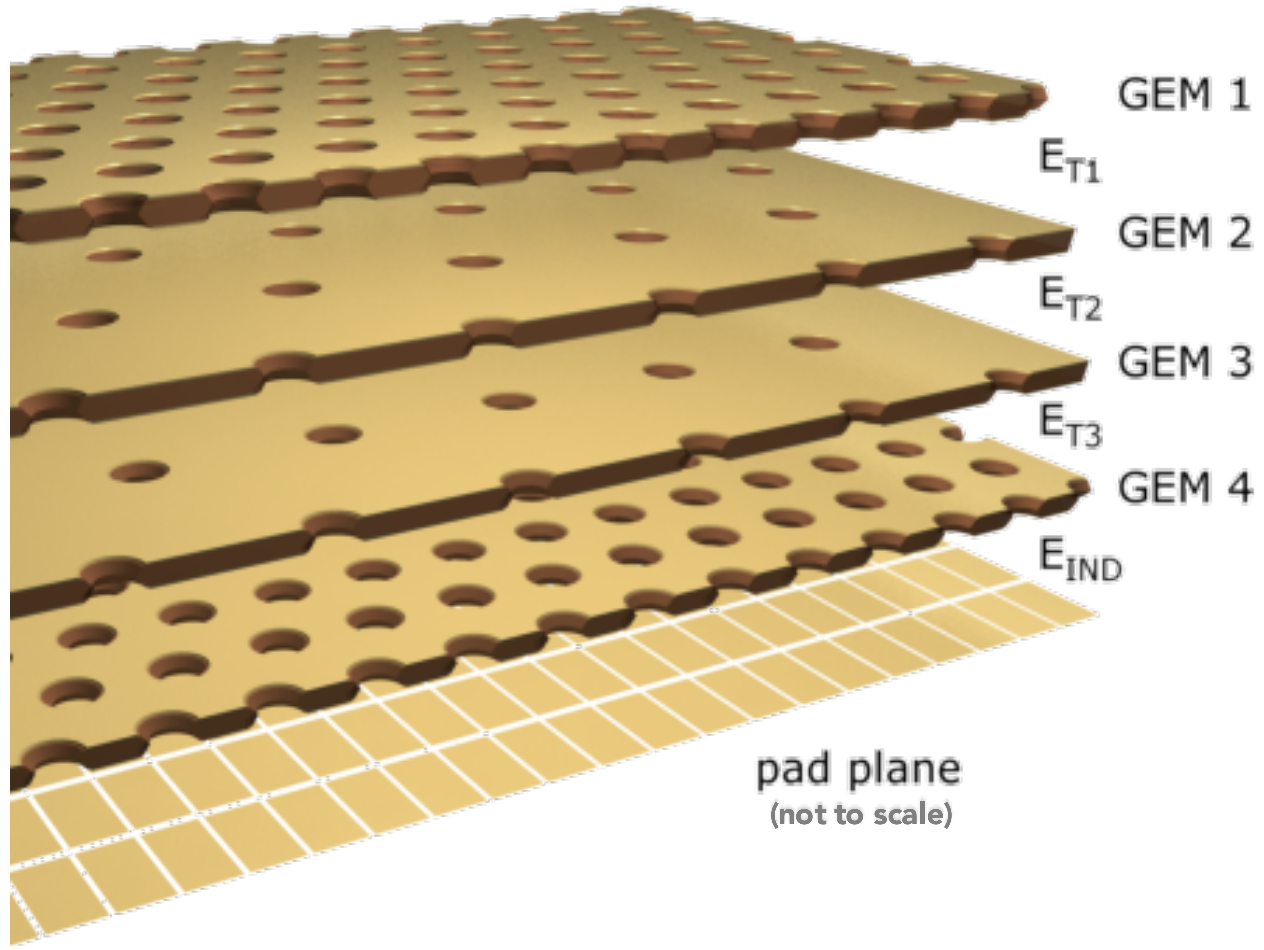


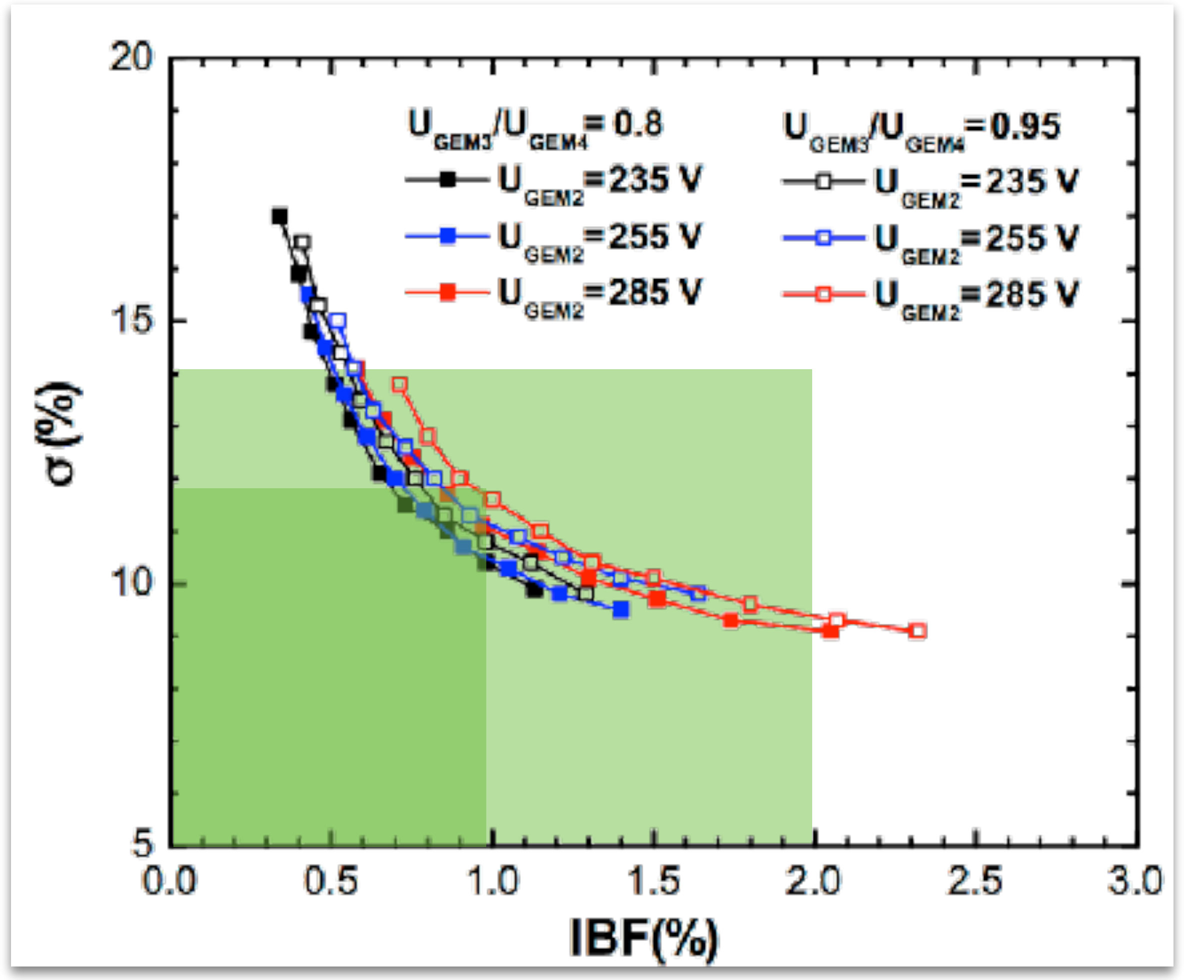
Time Projection Chamber

- **Requirements**
  - continuous readout
    → ion back-flow < 1 %
  - preserve particle identification performance
    → $\sigma_E /E < 12\%$ (^{55}Fe), nominal gain ≈ 2000
  - stable operation with Run 3 rates
    (50 kHz Pb-Pb, few MHz pp)

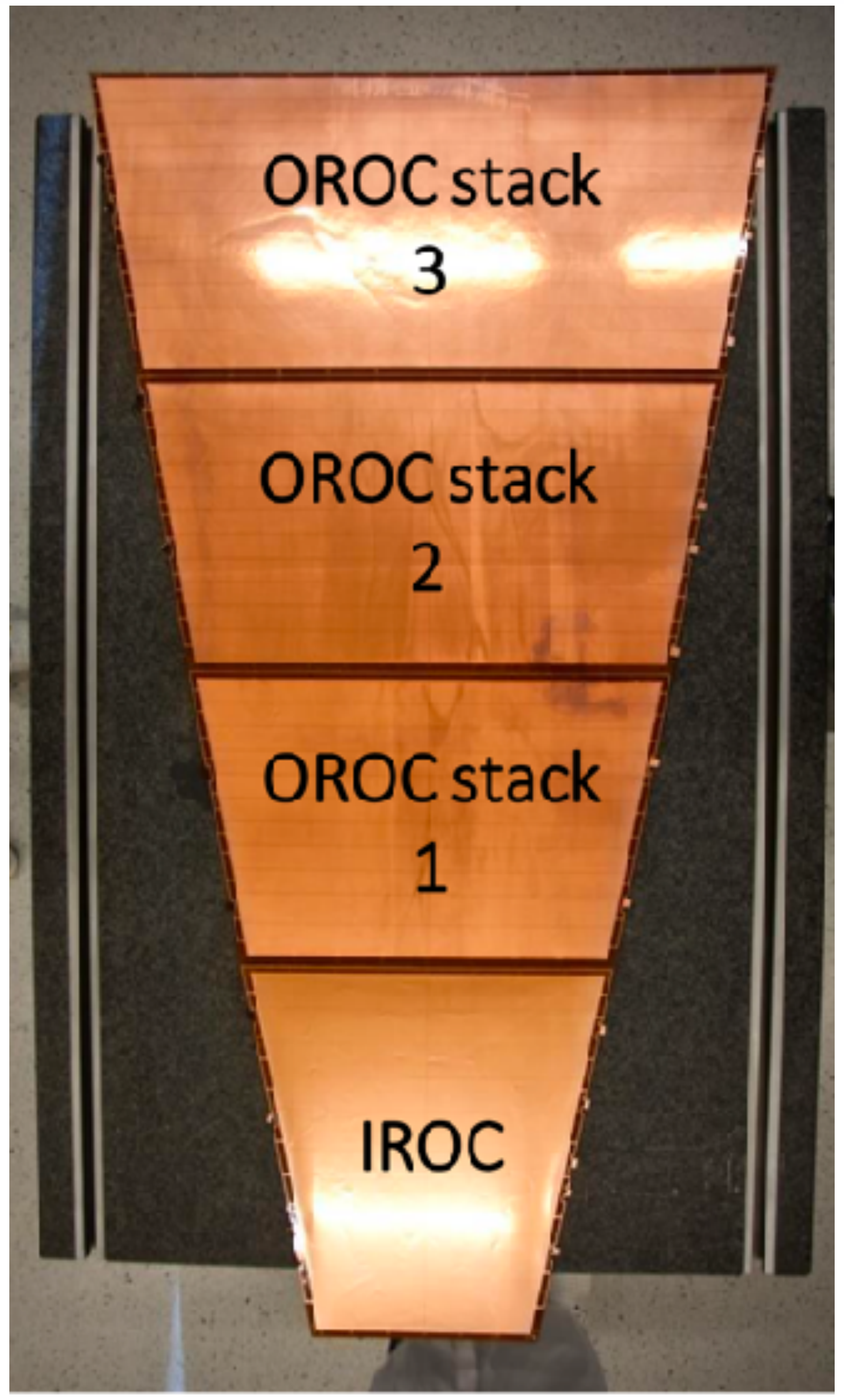


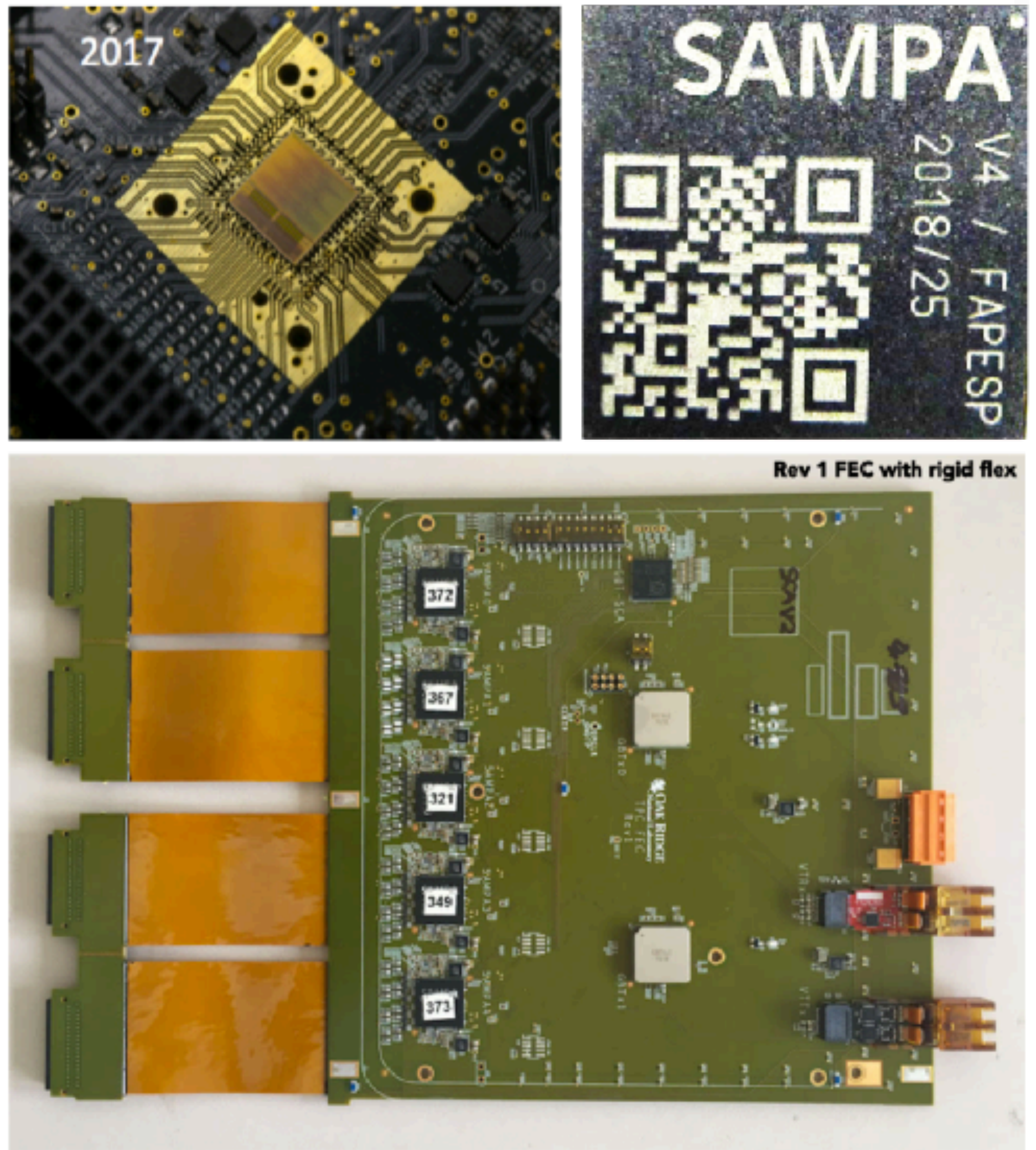
- **Concept**
  - Stack of 4 GEM foils with
    standard (140 μm) and large pitch (280 μm)
  - no gating grid
  - operation with $Ne\text{-}CO_2\text{-}N_2$ (90-10-5)

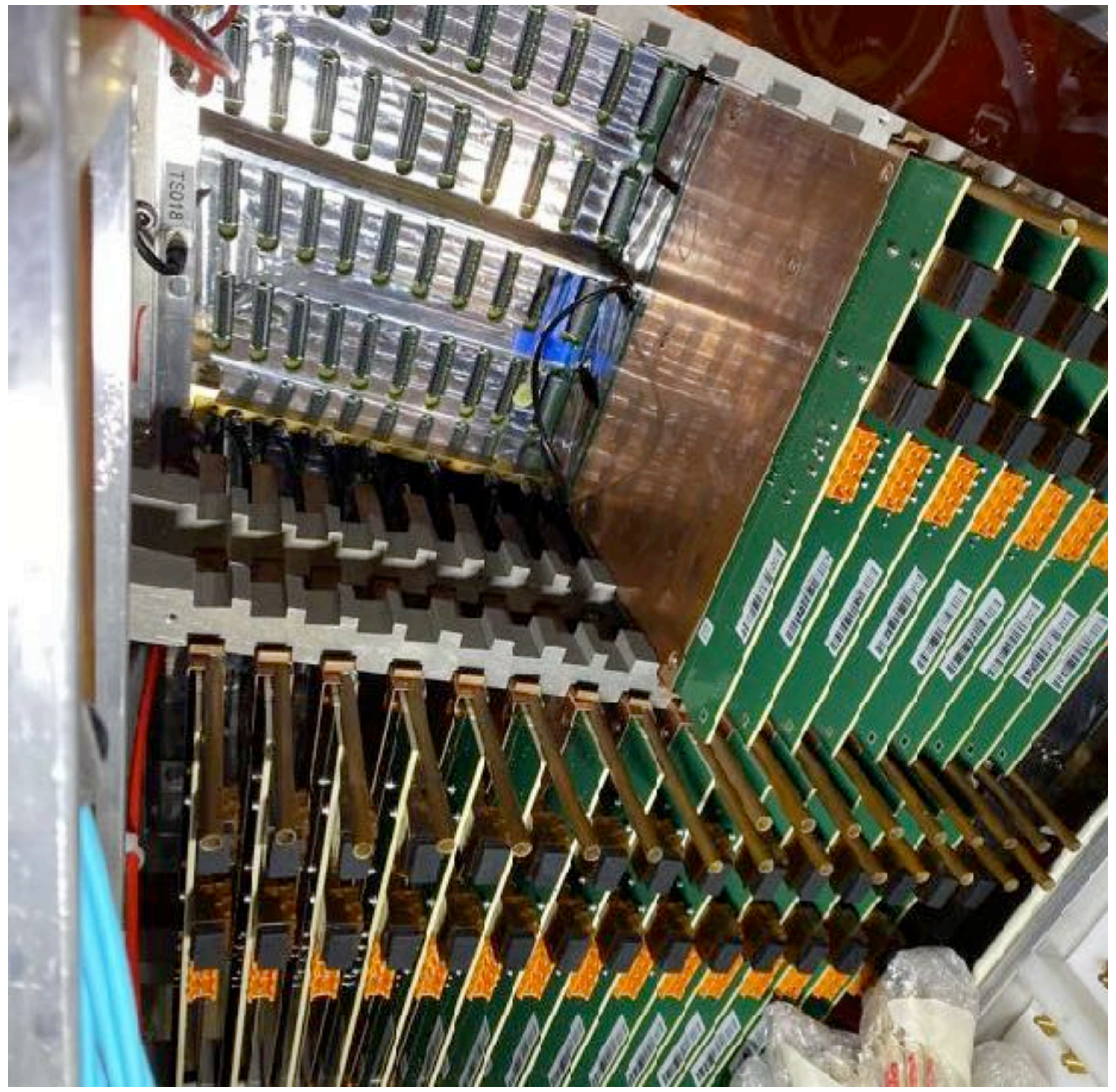




Readout chambers







- Large-size single-mask foils from CERN PCB workshop

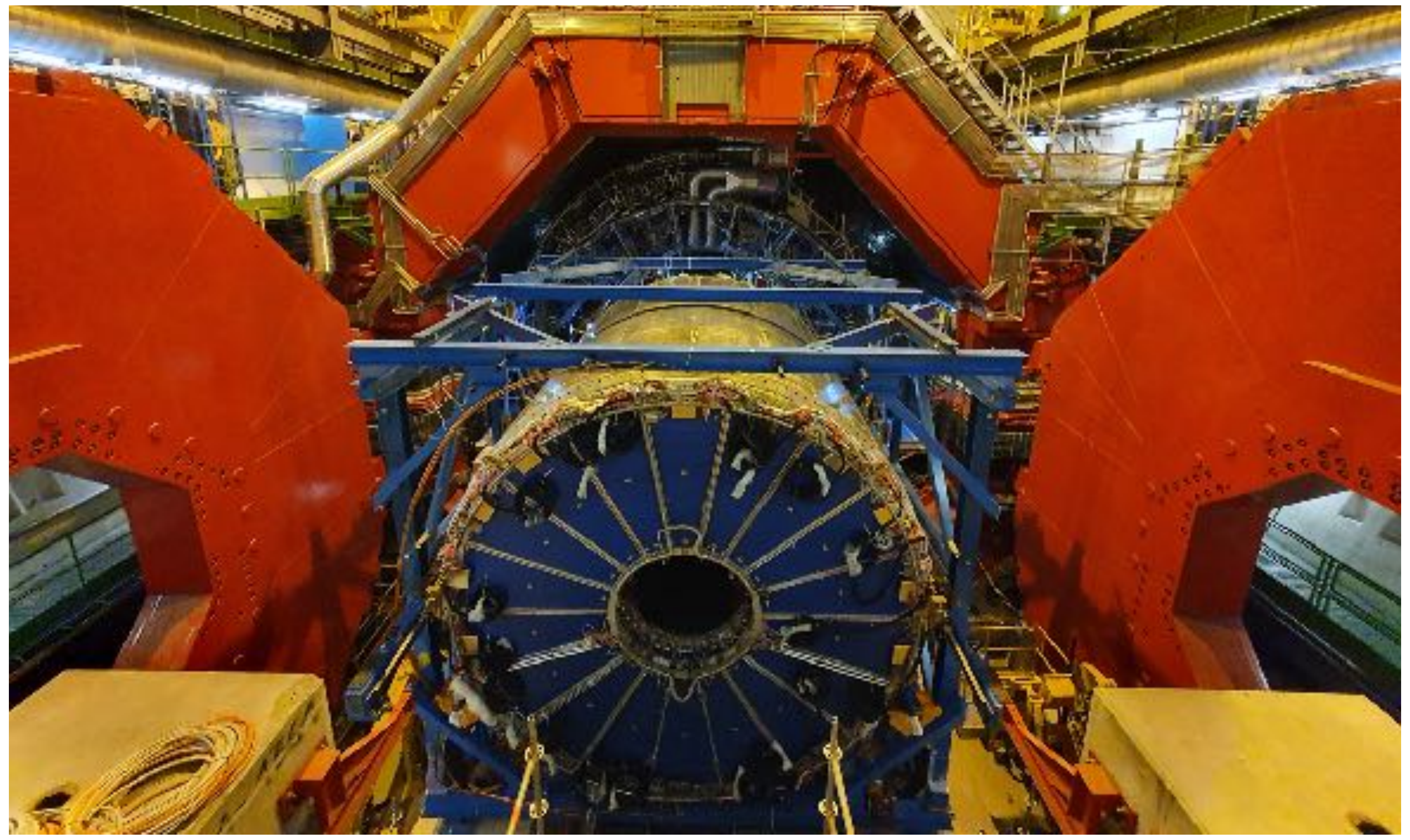
- SAMPA ASIC (130 nm TSMC CMOS)
  - Integrated Pre-Amp
  - Shaper (t_{peak}=160 ns)
  - 10-bit ADC

- 3276 Front-End Cards (FEC)
  - transmission of ADC data at 5 MHz through optical links

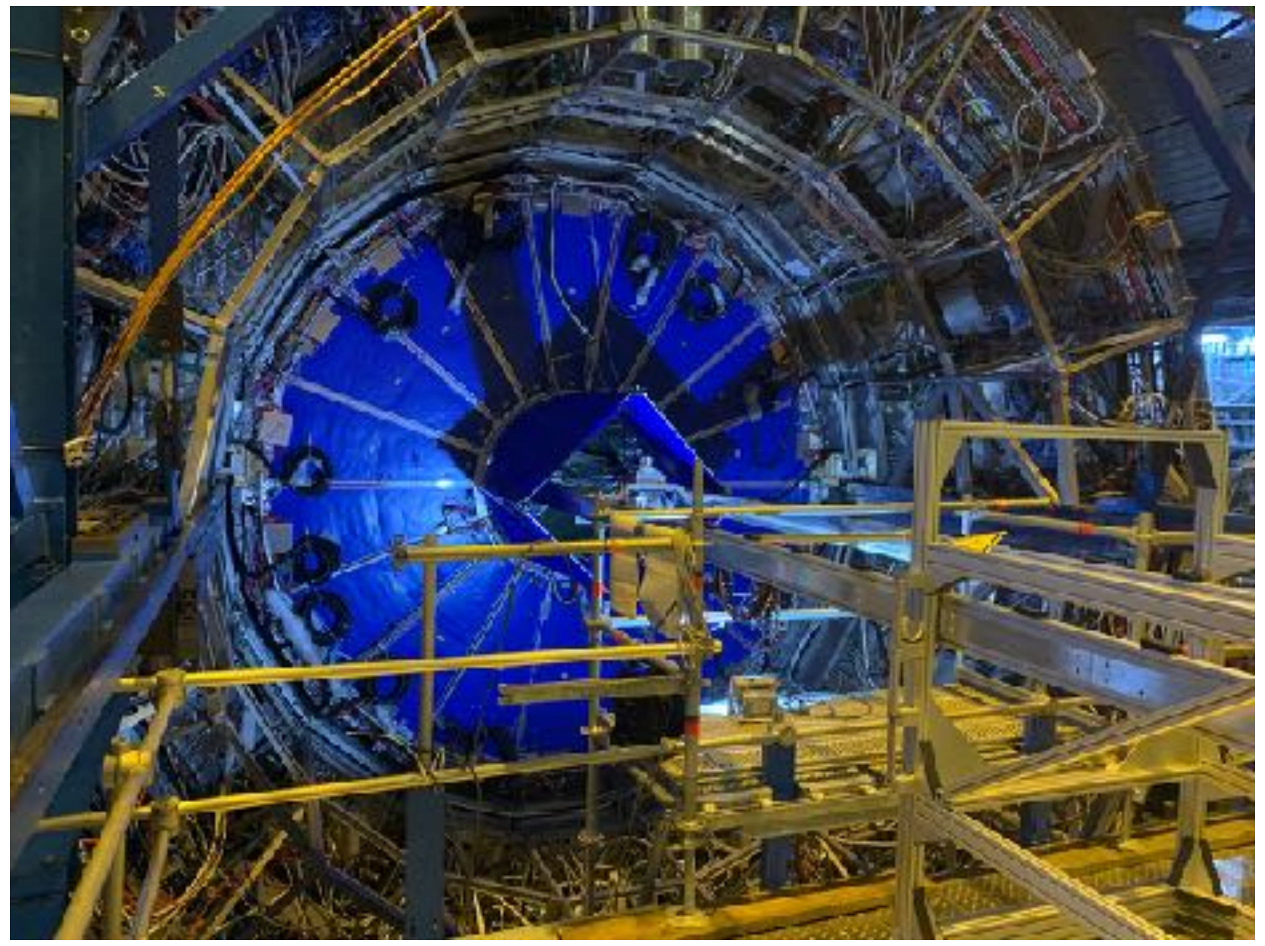
TPC installation

Transport

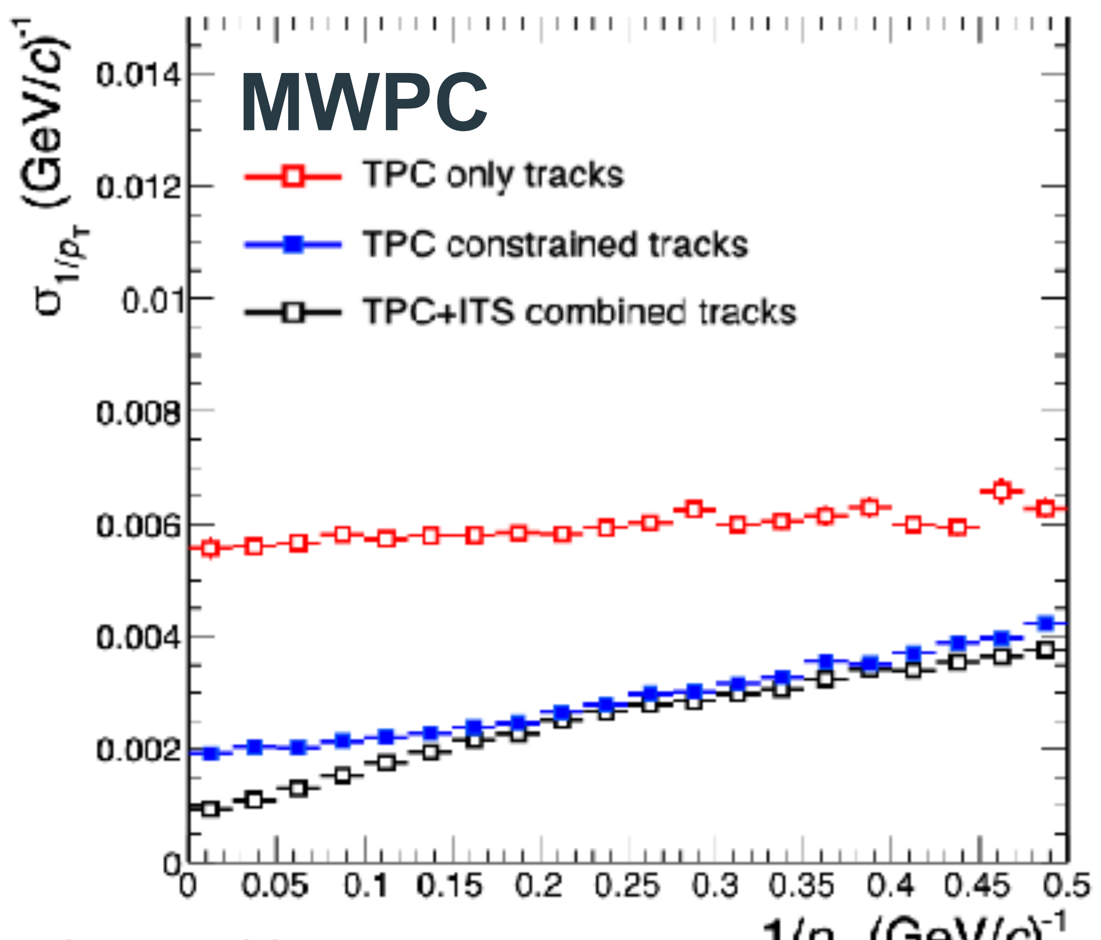
Lowering to cavern



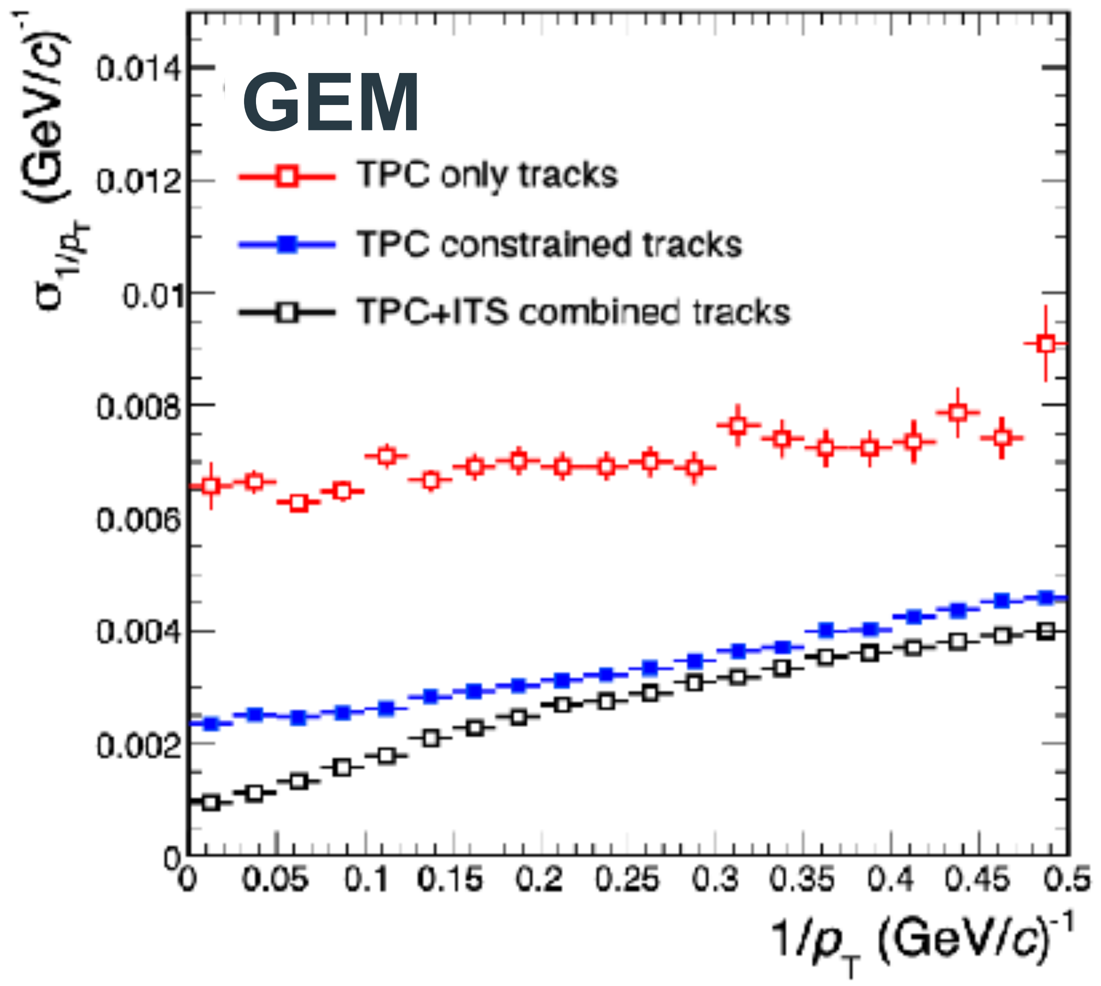
Insertion

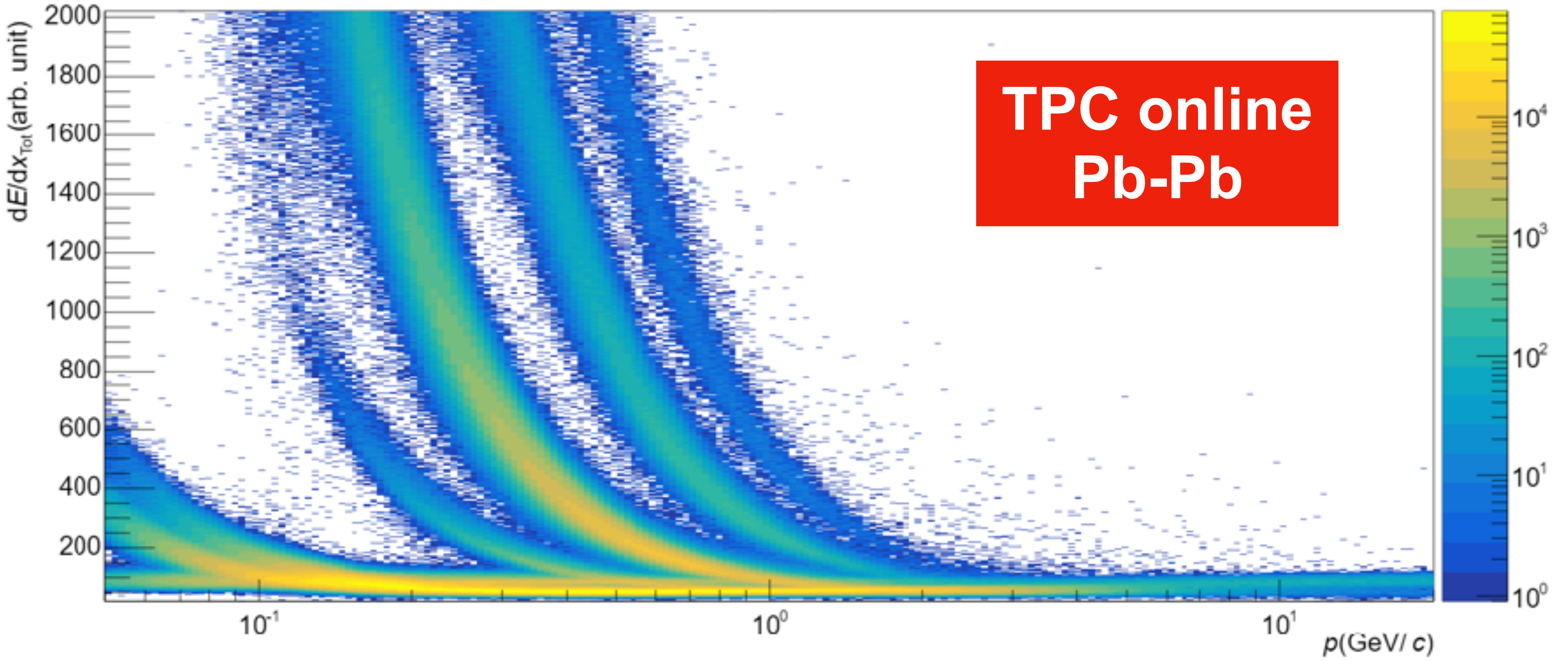


Final position



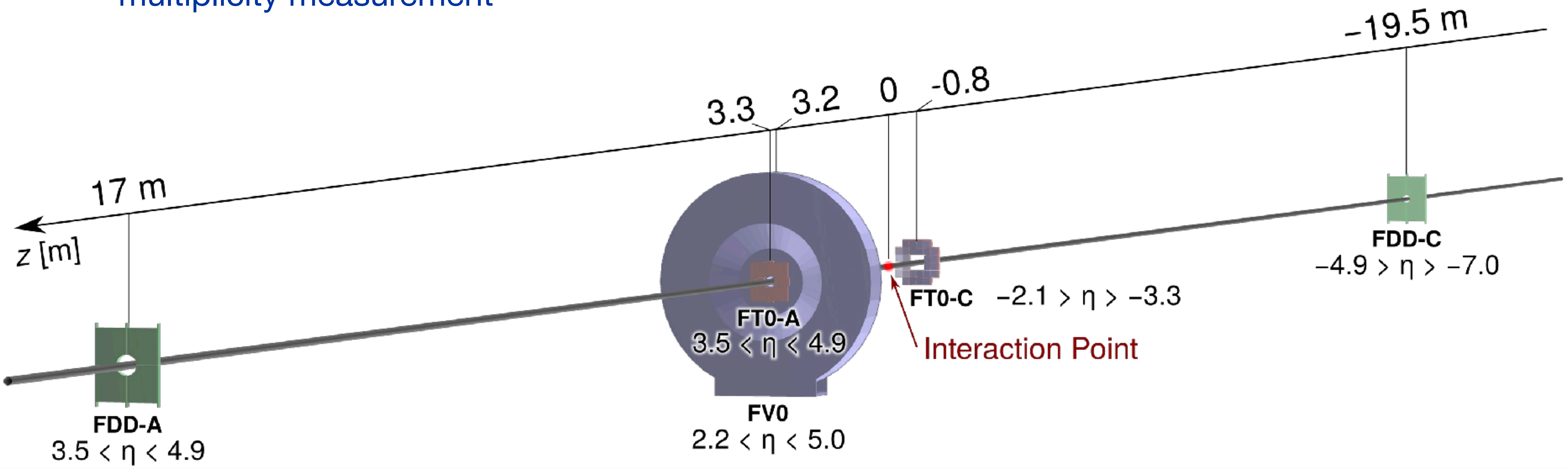
CERN-LHCC-2015-002





Fast Interaction Trigger

- **Requirements**
  - fast interaction trigger (latency < 425 ns)
  - collision time determination
  - luminosity monitoring
  - multiplicity measurement
- **Concept**
  - FT0: quartz radiators + MCP
  - FV0: scintillators. + clear fibres + PMT
  - FDD: scintillators + wavelength shifter + clear fibres + PMT



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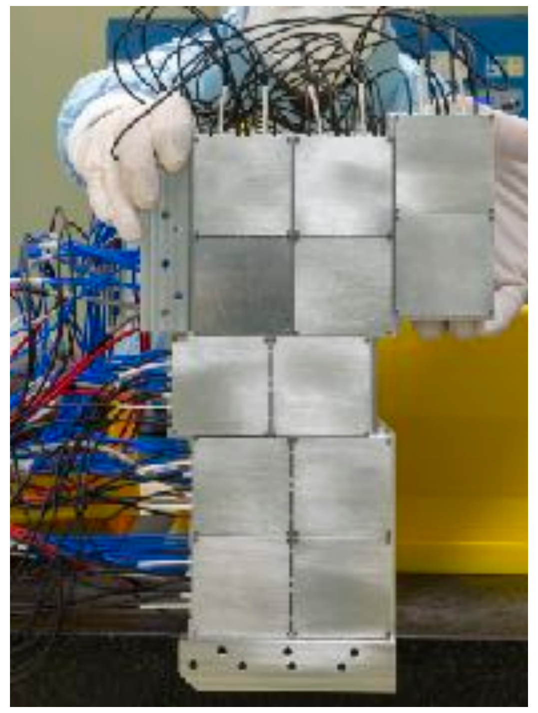
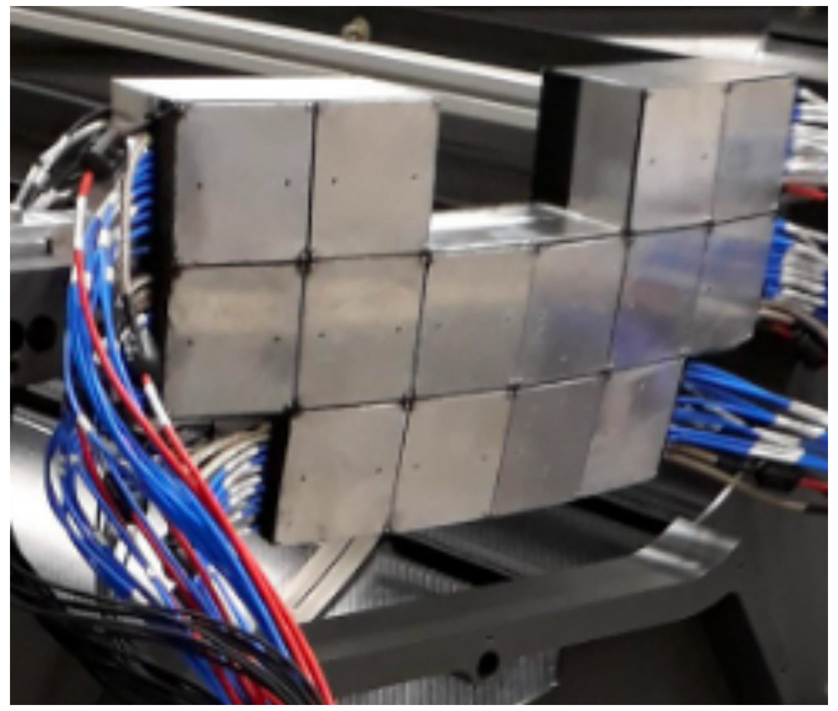
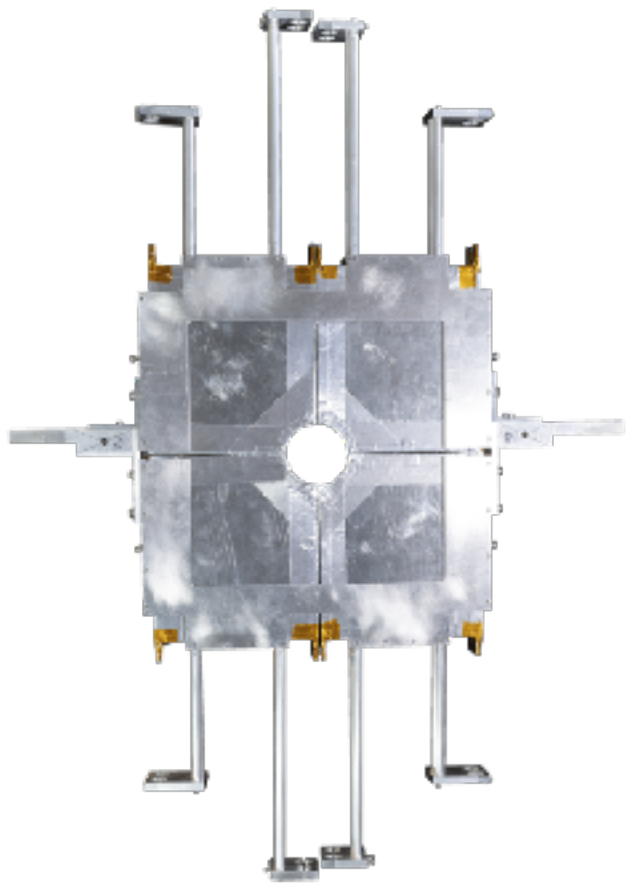
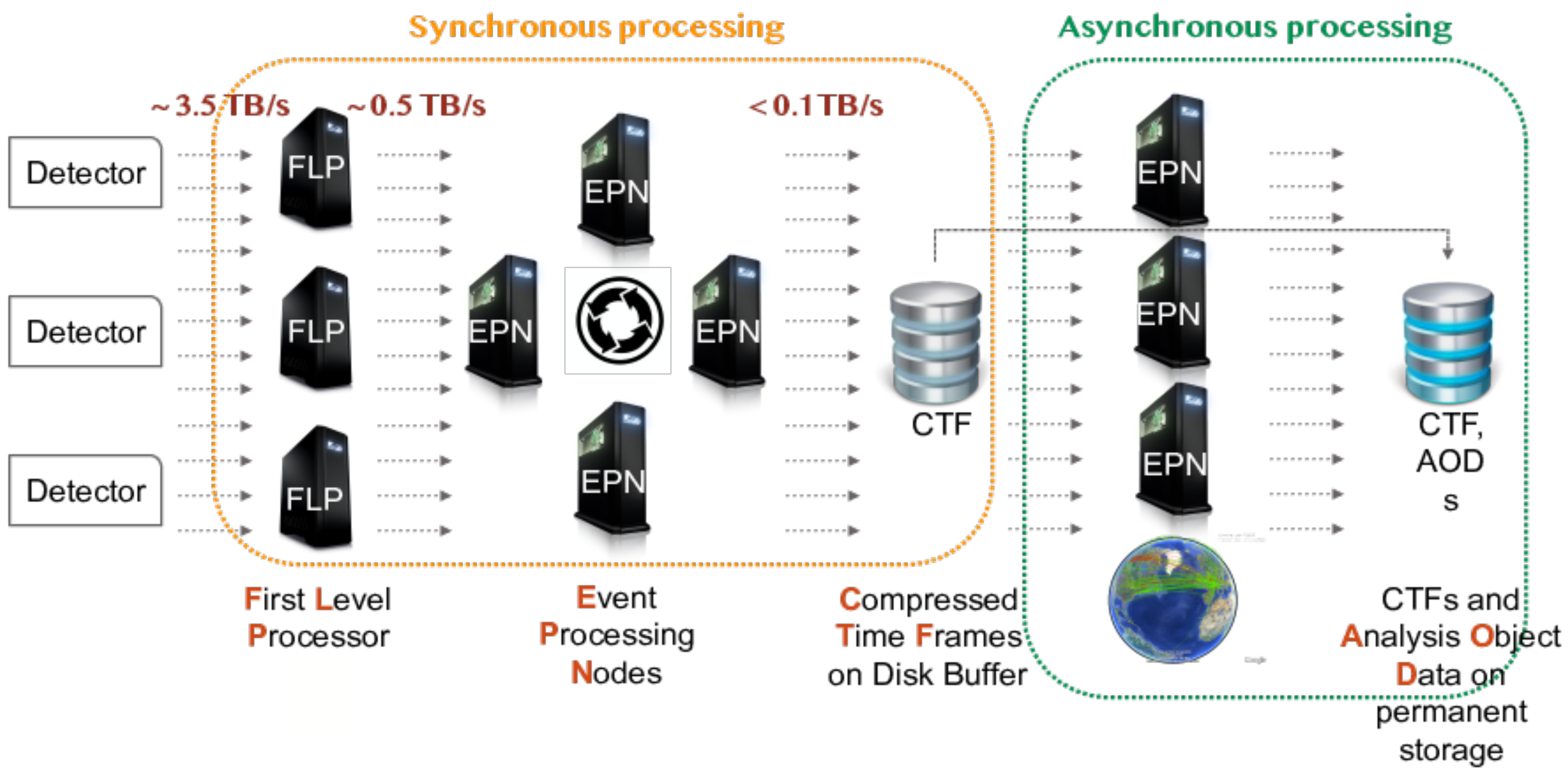
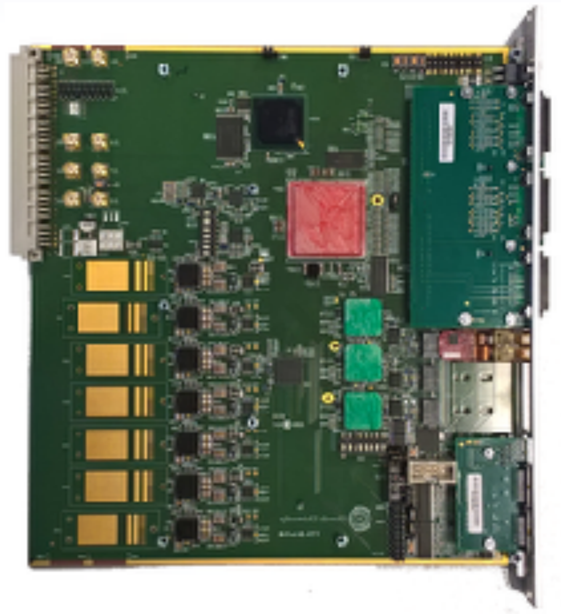


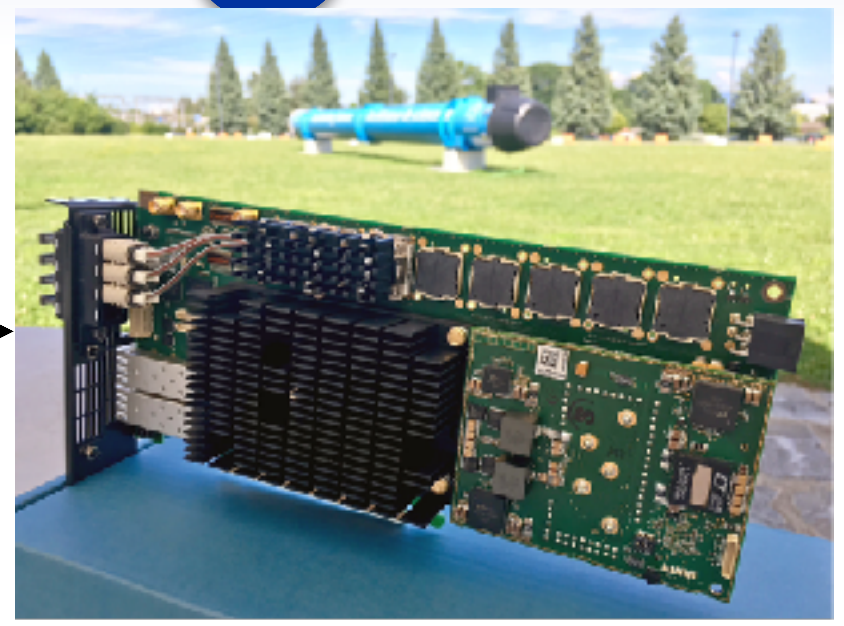
Online-offline processing

→ D. Rohr





Detector, e.g. RU

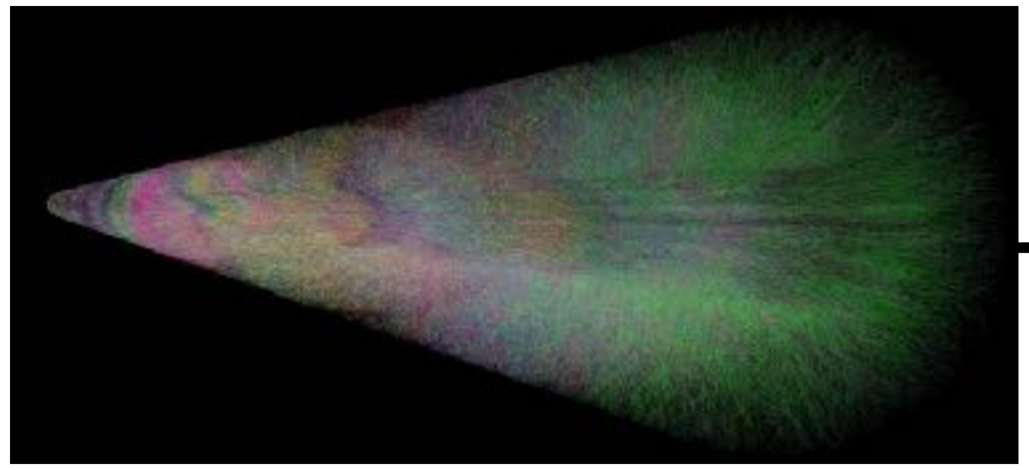


Common Readout Unit

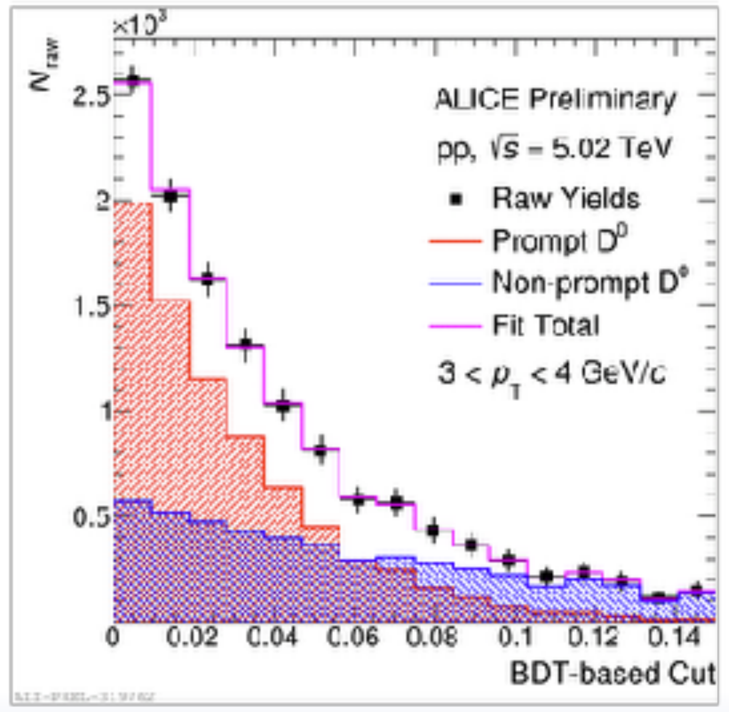
Event Processing Nodes

First Level Processors

- Zero suppression and building in First Level Processors
- Synchronous reconstruction pass in Event Processing Nodes
  - 2000 GPUs in 250 EPNs
- Asynchronous reconstruction pass on EPNs and WLCG (improved calibration)

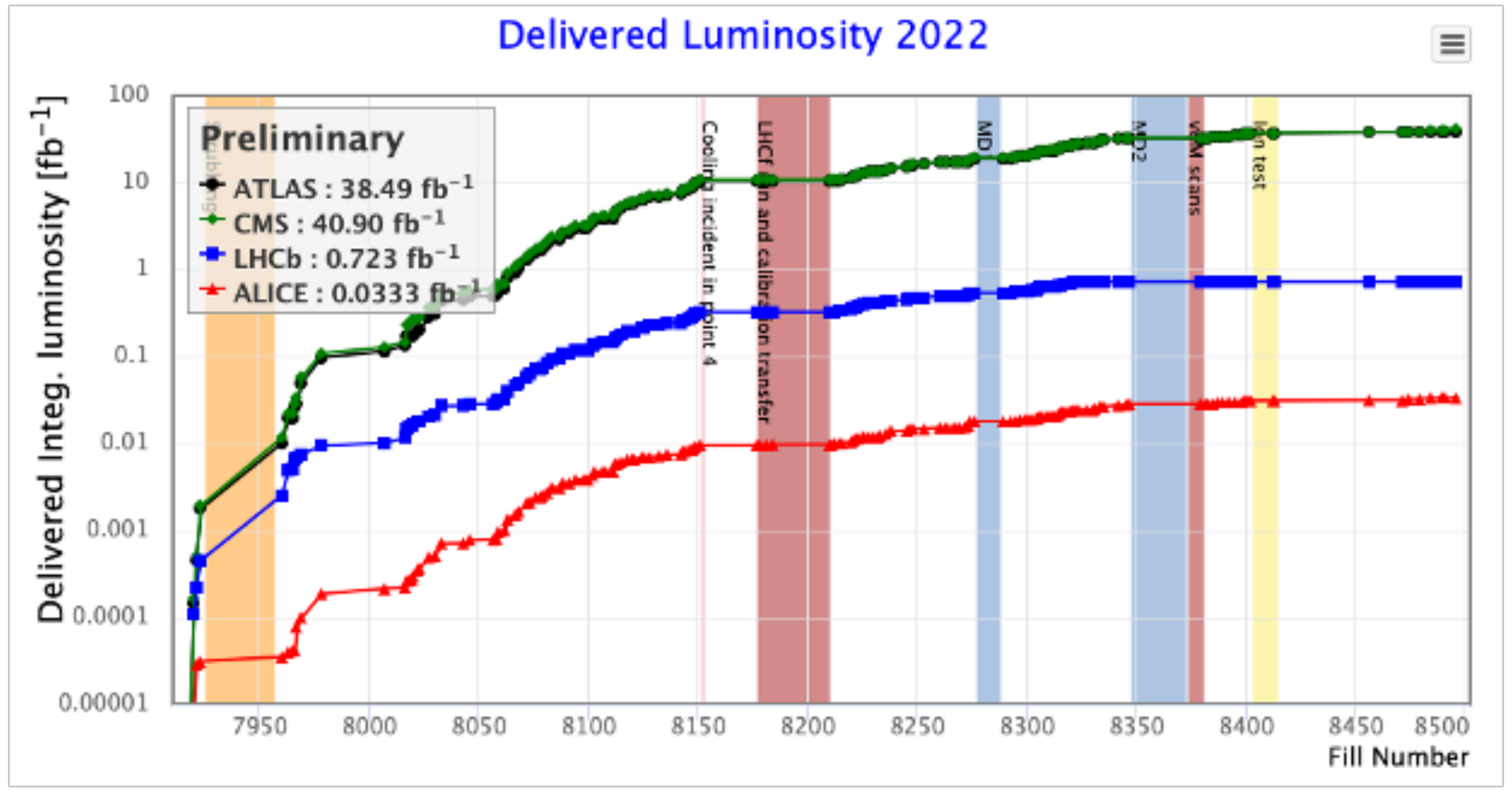


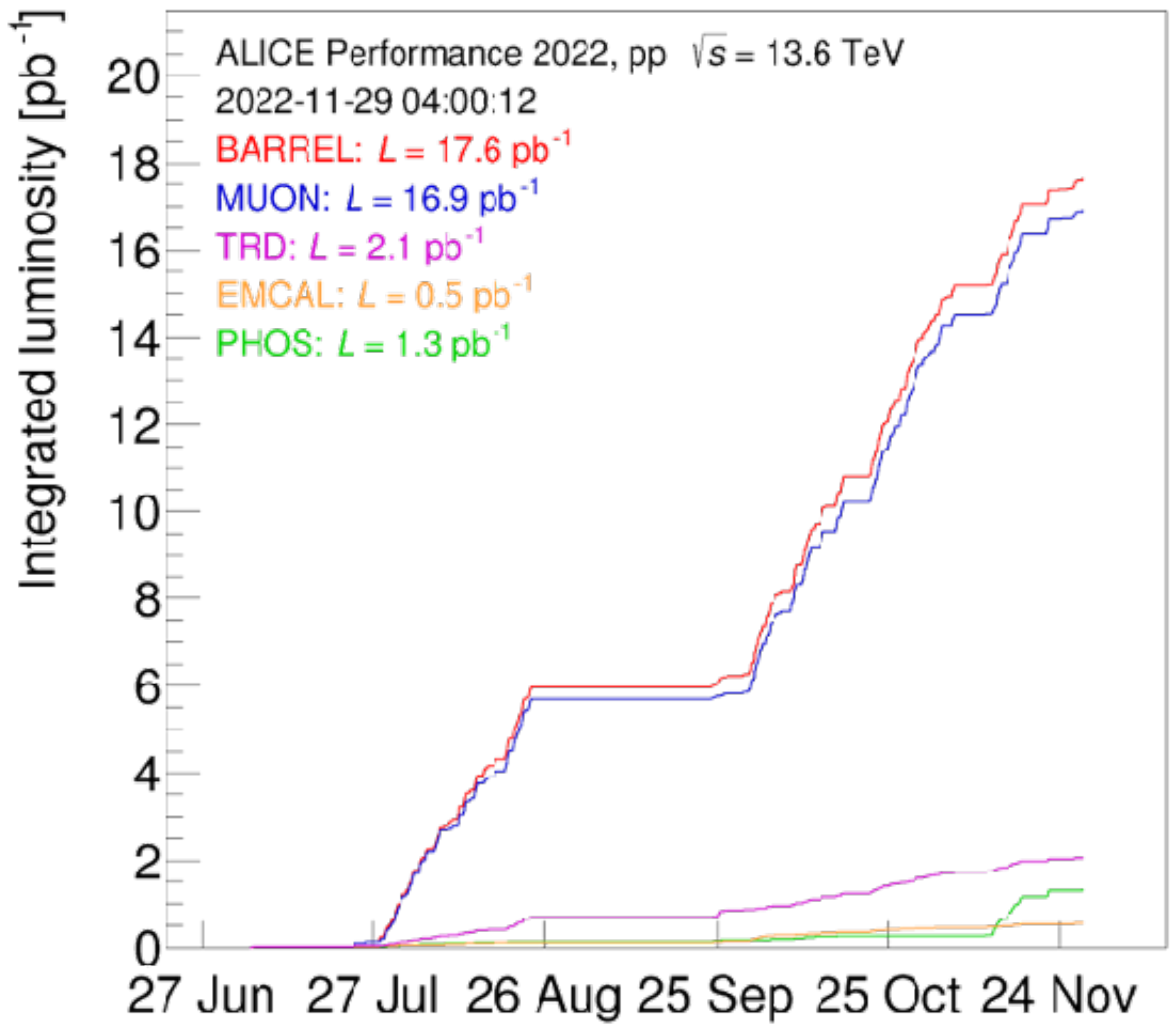
Events from continuous read-out

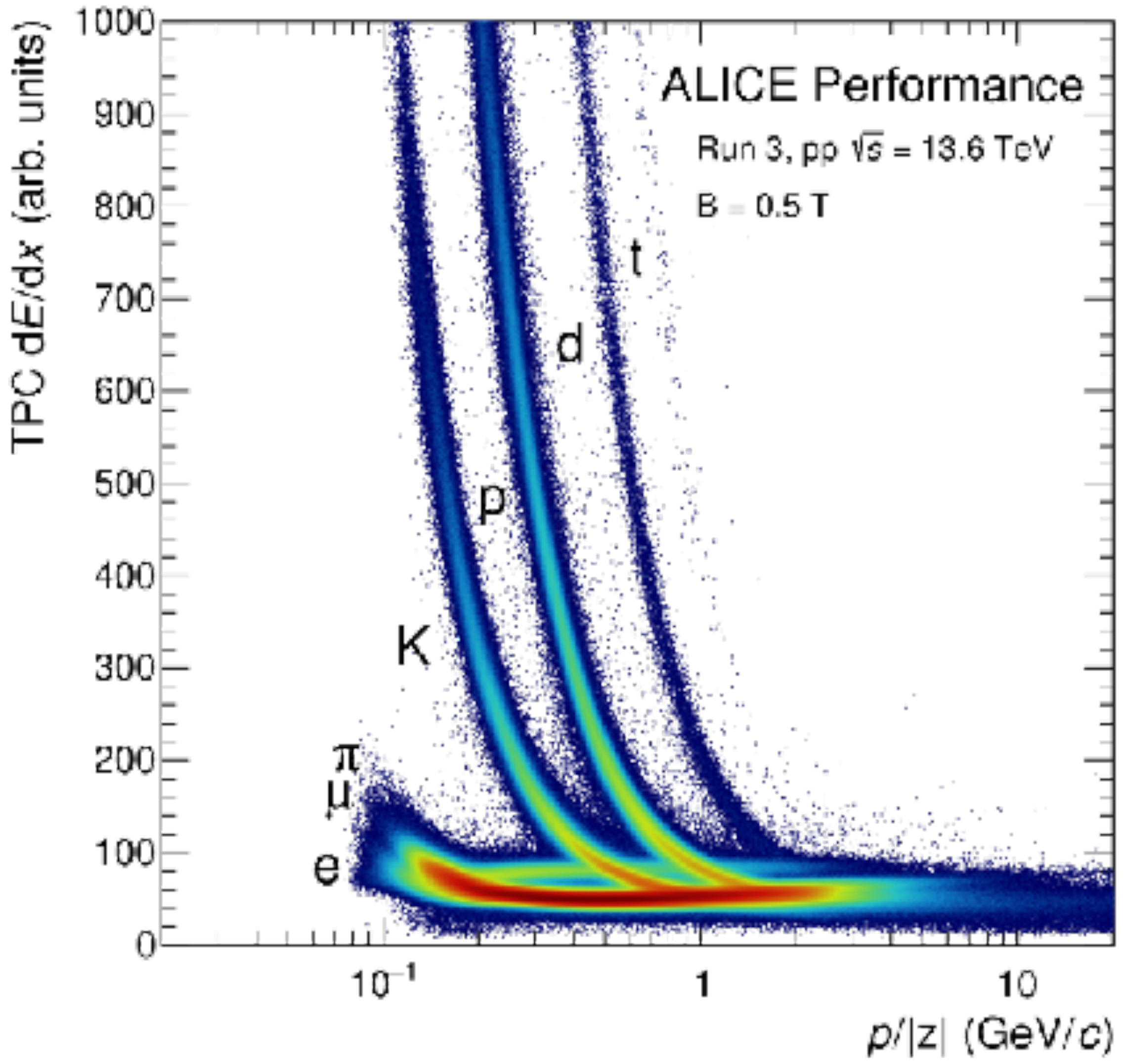


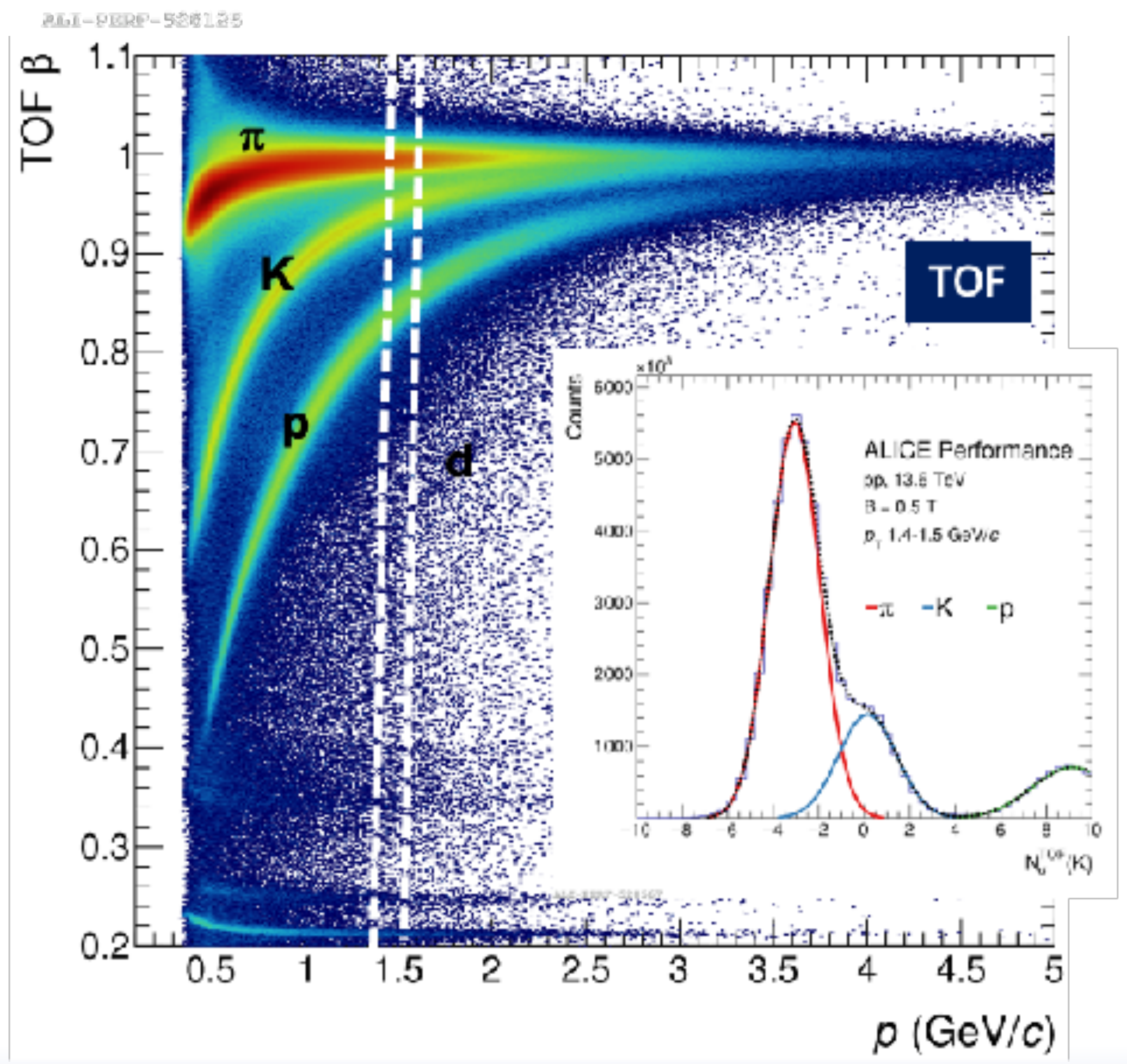
Data analysis

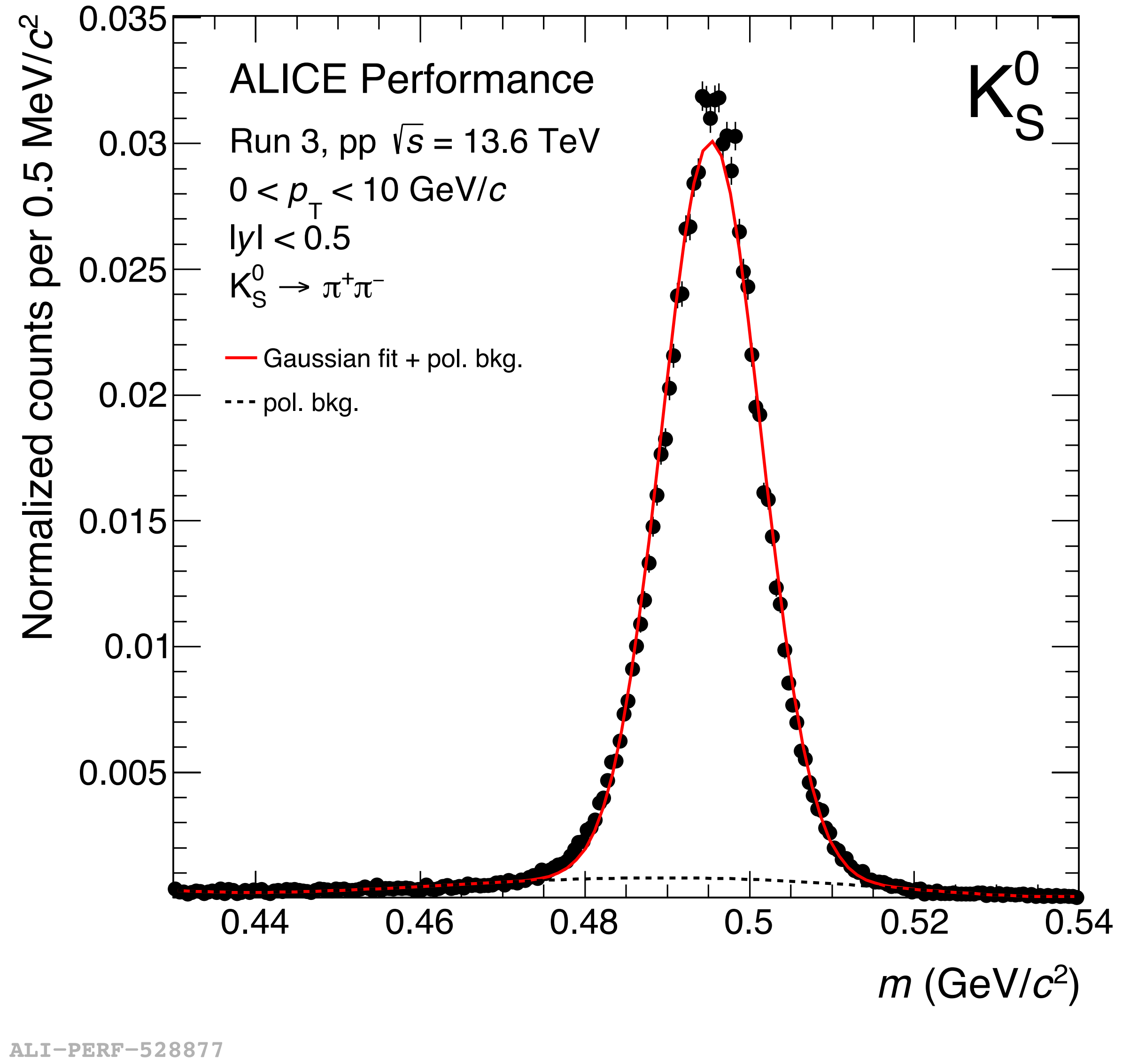
Run 3 pp

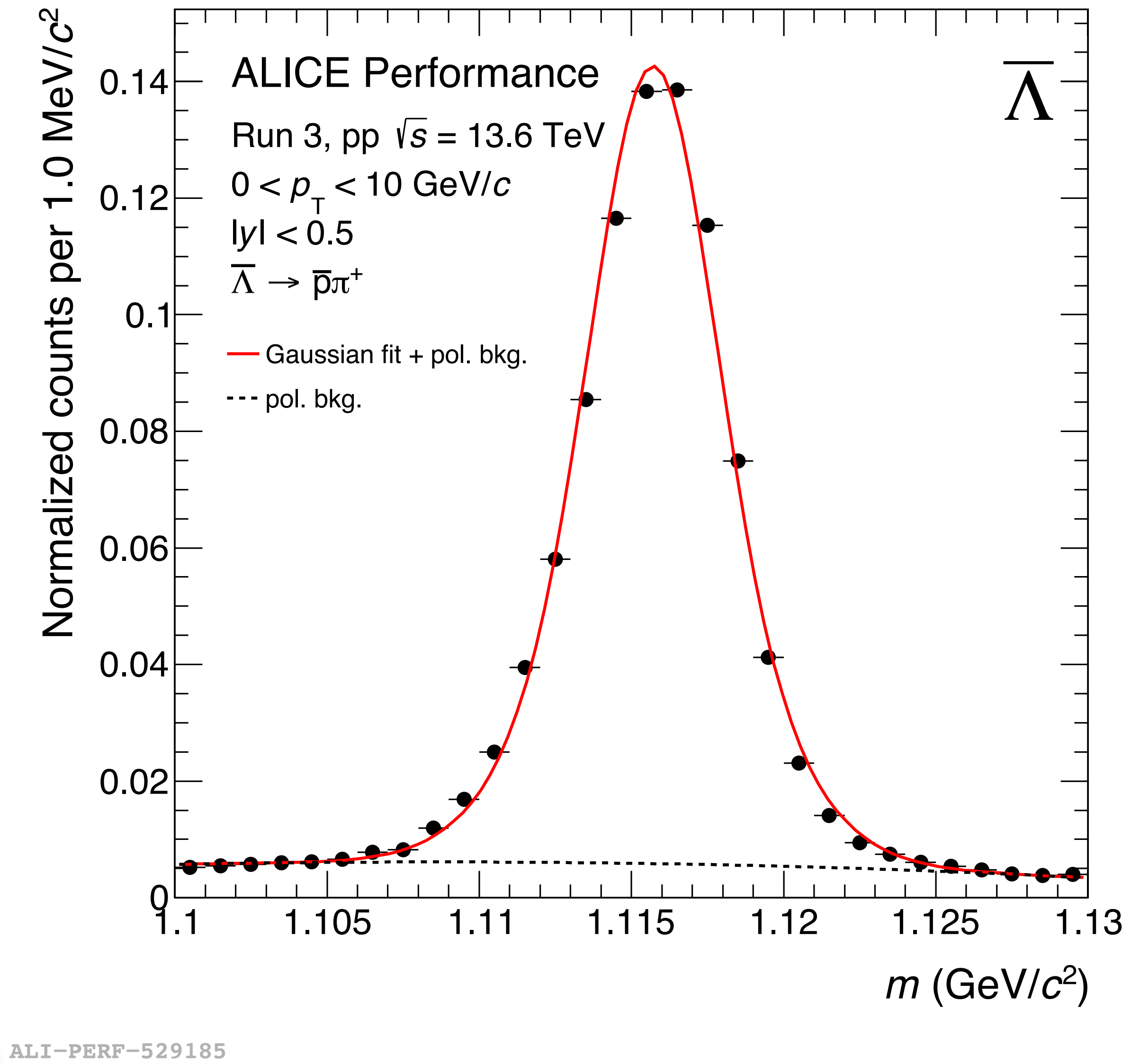

Delivered Luminosity 2022
Preliminary
ATLAS : 38.49 fb^{-1}
CMS : 40.90 fb^{-1}
LHCb : 0.723 fb^{-1}
ALICE : 0.0333 fb^{-1}
Delivered Integ. luminosity [fb^{-1}]
Fill Number


ALICE Performance 2022, pp $\sqrt{s}$ = 13.6 TeV
2022-11-29 04:00:12
BARREL: L = 17.6 pb^{-1}
MUON: L = 16.9 pb^{-1}
TRD: L = 2.1 pb^{-1}
EMCAL: L = 0.5 pb^{-1}
PHOS: L = 1.3 pb^{-1}
Integrated luminosity [pb^{-1}]
27 Jun 27 Jul 26 Aug 25 Sep 25 Oct 24 Nov

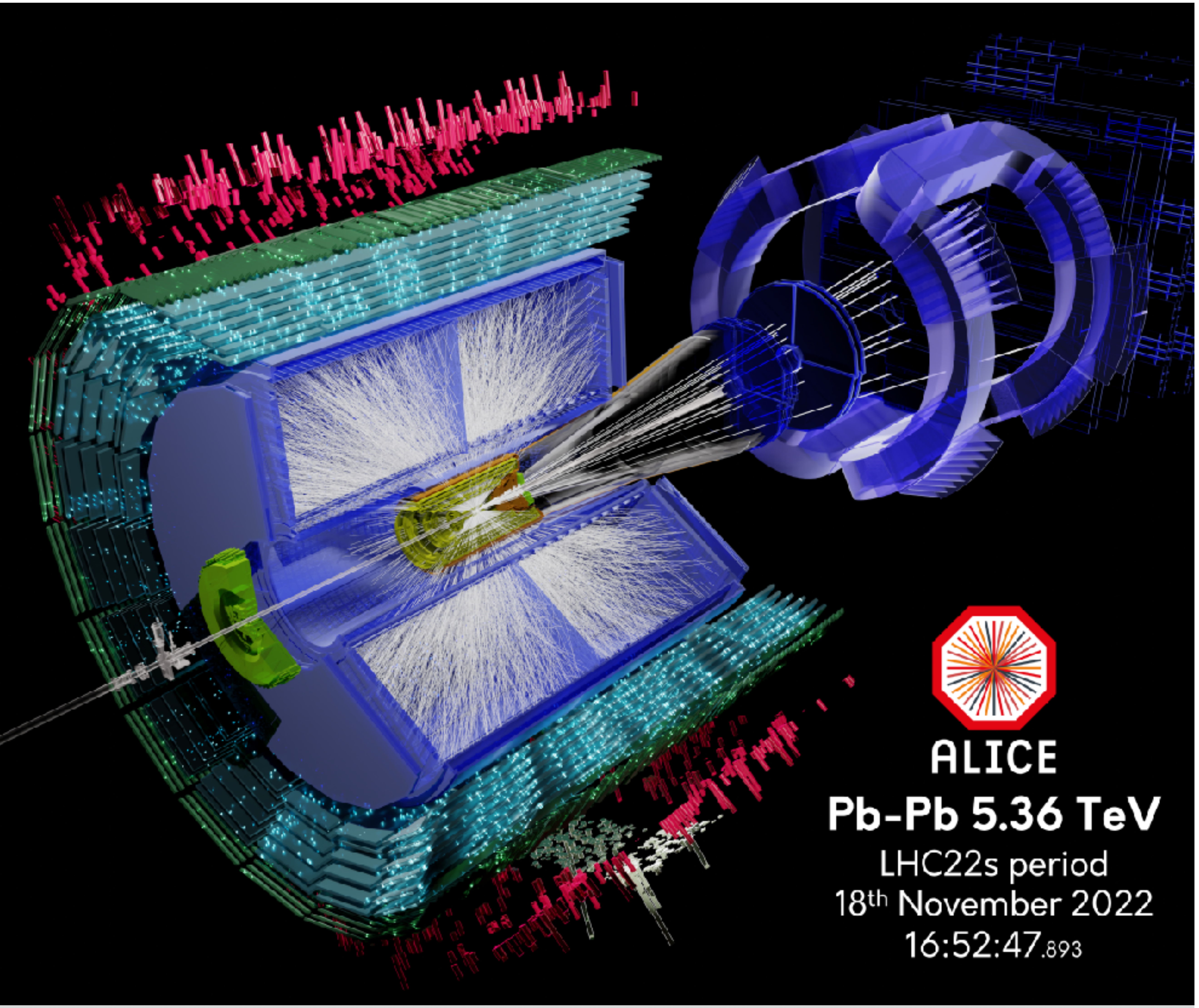

ALICE Performance
Run 3, pp $\sqrt{s}$ = 13.6 TeV
B = 0.5 T
TPC dE/dx (arb. units)
p/|z| (GeV/c)

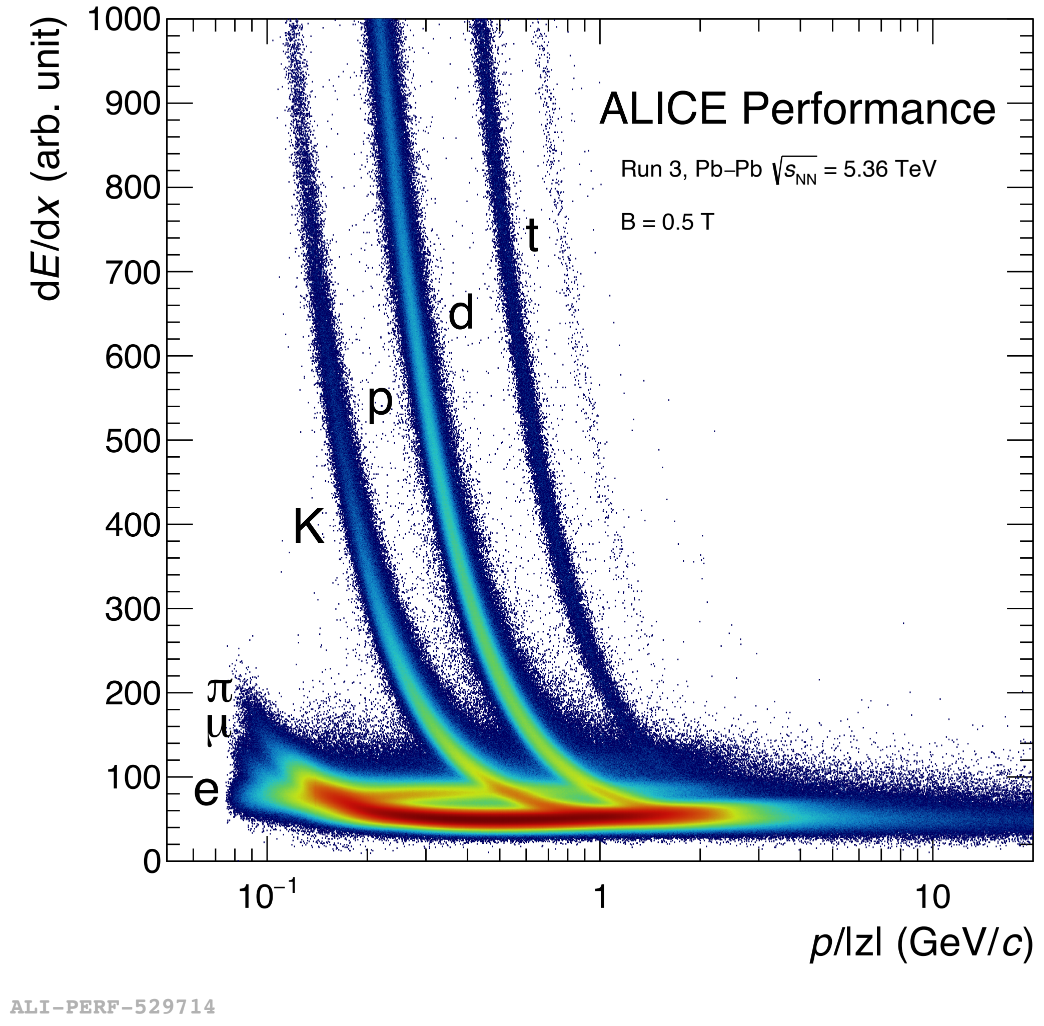

ALI-PERF-526125
TOF β
TOF
ALICE Performance
pp, 13.6 TeV
B = 0.5 T
p (GeV/c)

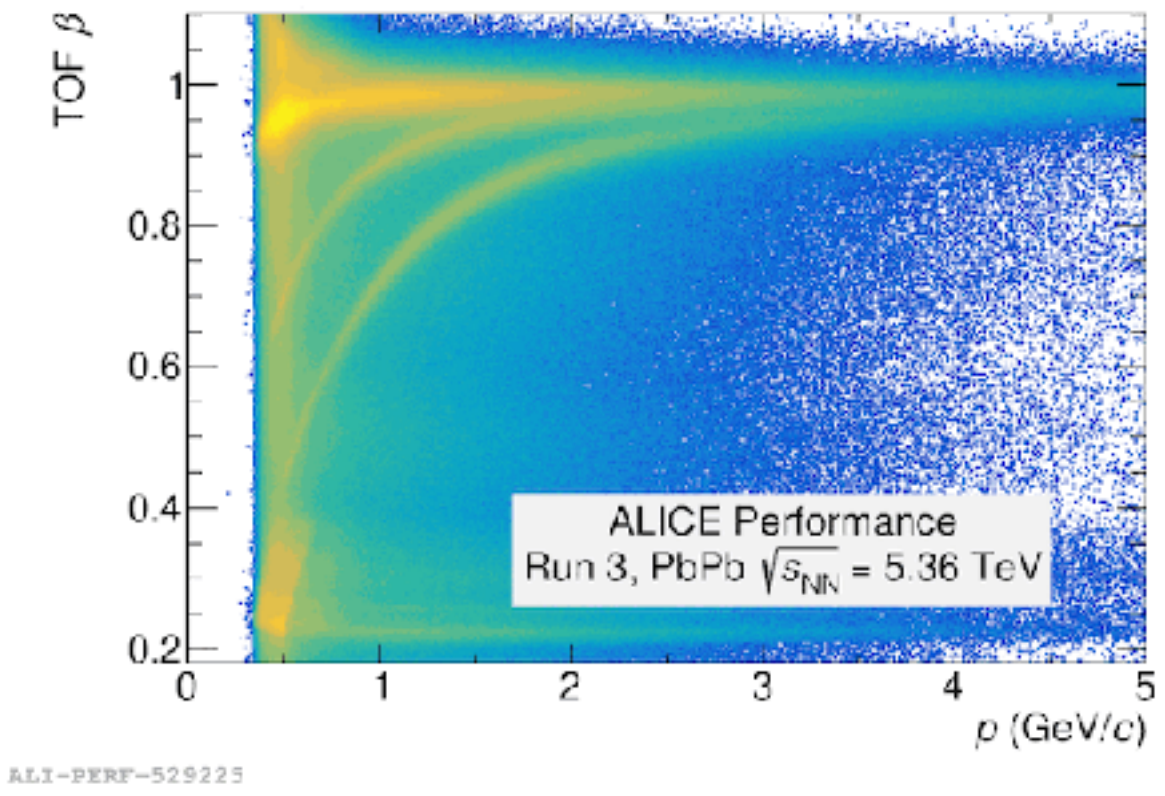

ALICE Performance
Run 3, pp $\sqrt{s}$ = 13.6 TeV
$0 < p_T < 10$ GeV/c
$|y| < 0.5$
$K^0_S \to \pi^+\pi^-$
Gaussian fit + pol. bkg.
pol. bkg.
Normalized counts per 0.5 MeV/c^2
m (GeV/c^2)
ALI-PERF-528877

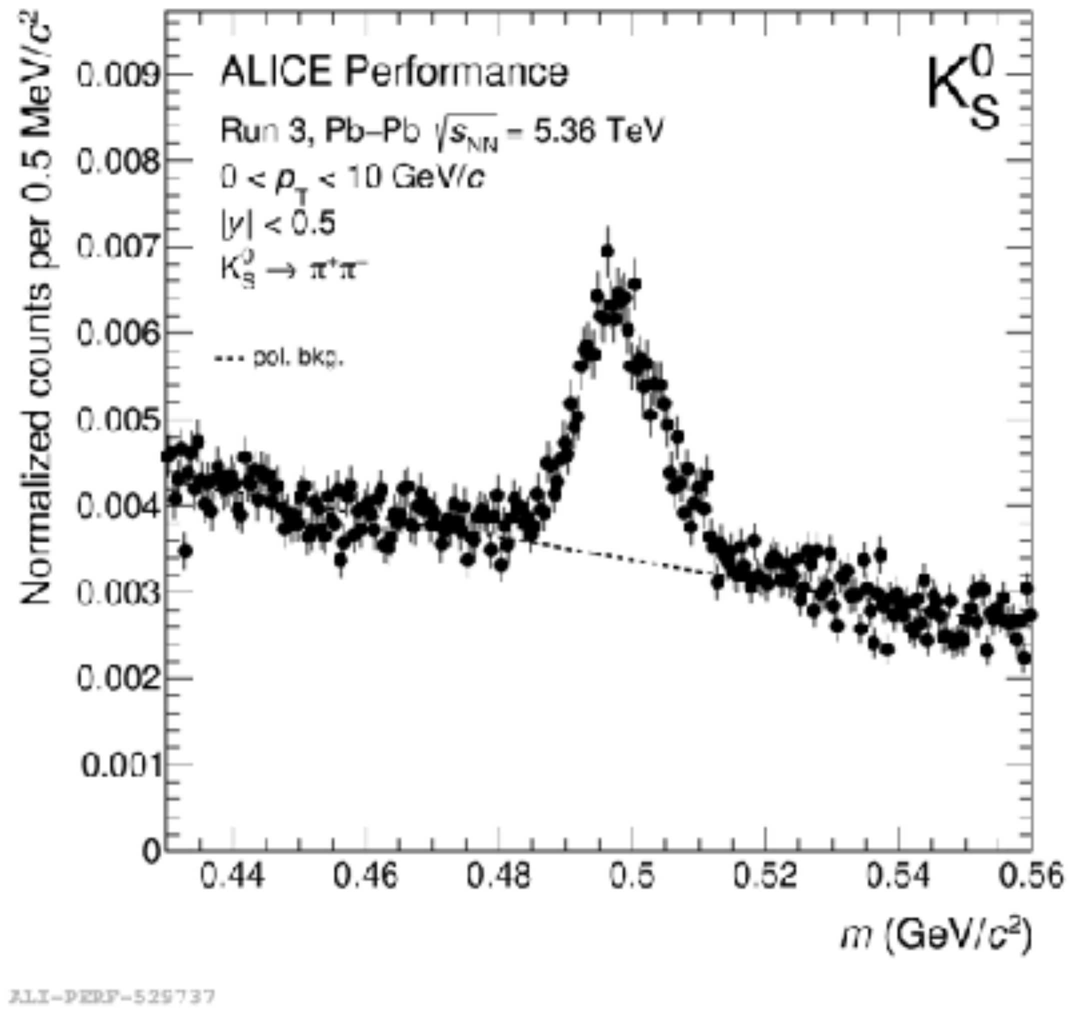

ALICE Performance
Run 3, pp $\sqrt{s}$ = 13.6 TeV
$0 < p_T < 10$ GeV/c
$|y| < 0.5$
$\overline{\Lambda} \to \overline{p}\pi^+$
Gaussian fit + pol. bkg.
pol. bkg.
Normalized counts per 1.0 MeV/c^2
m (GeV/c^2)
ALI-PERF-529185

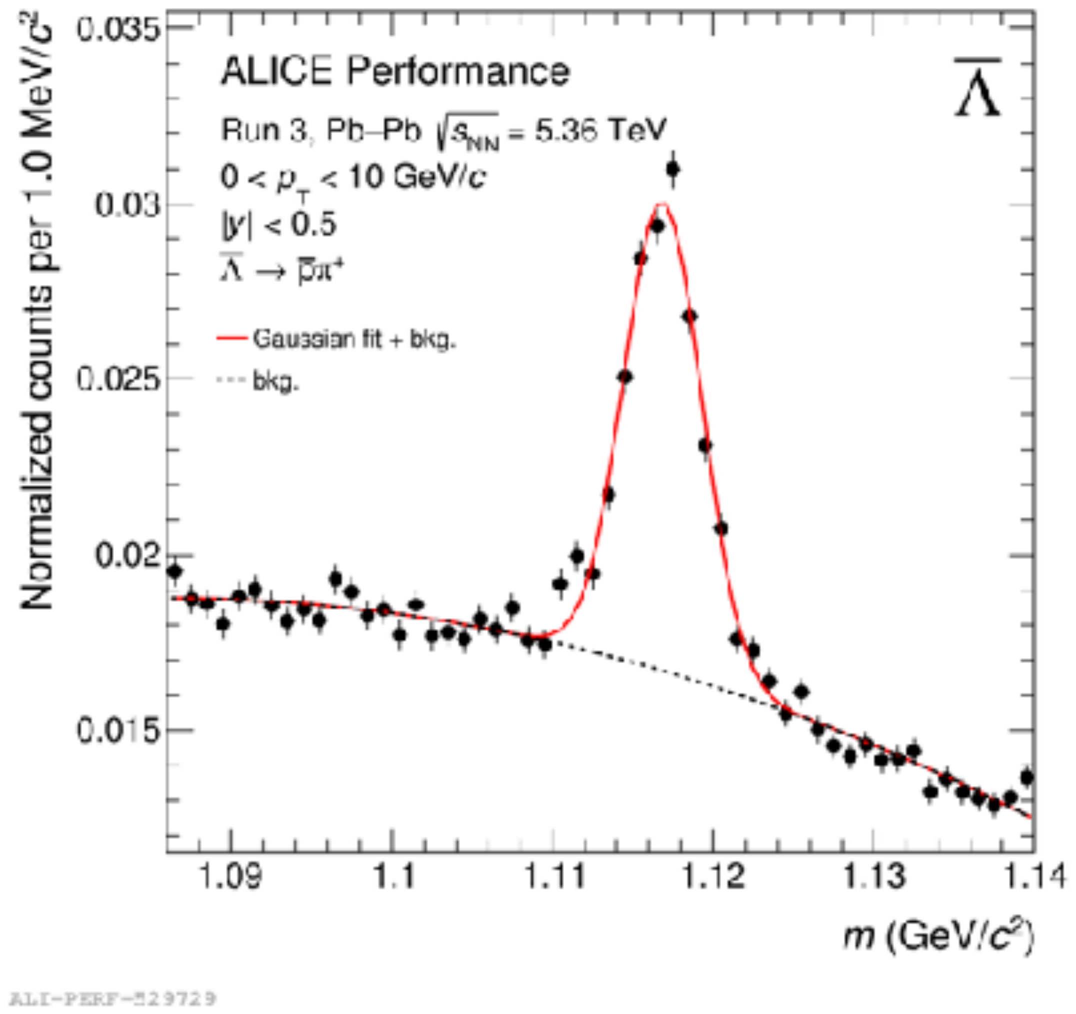
Run 3 Pb-Pb pilot







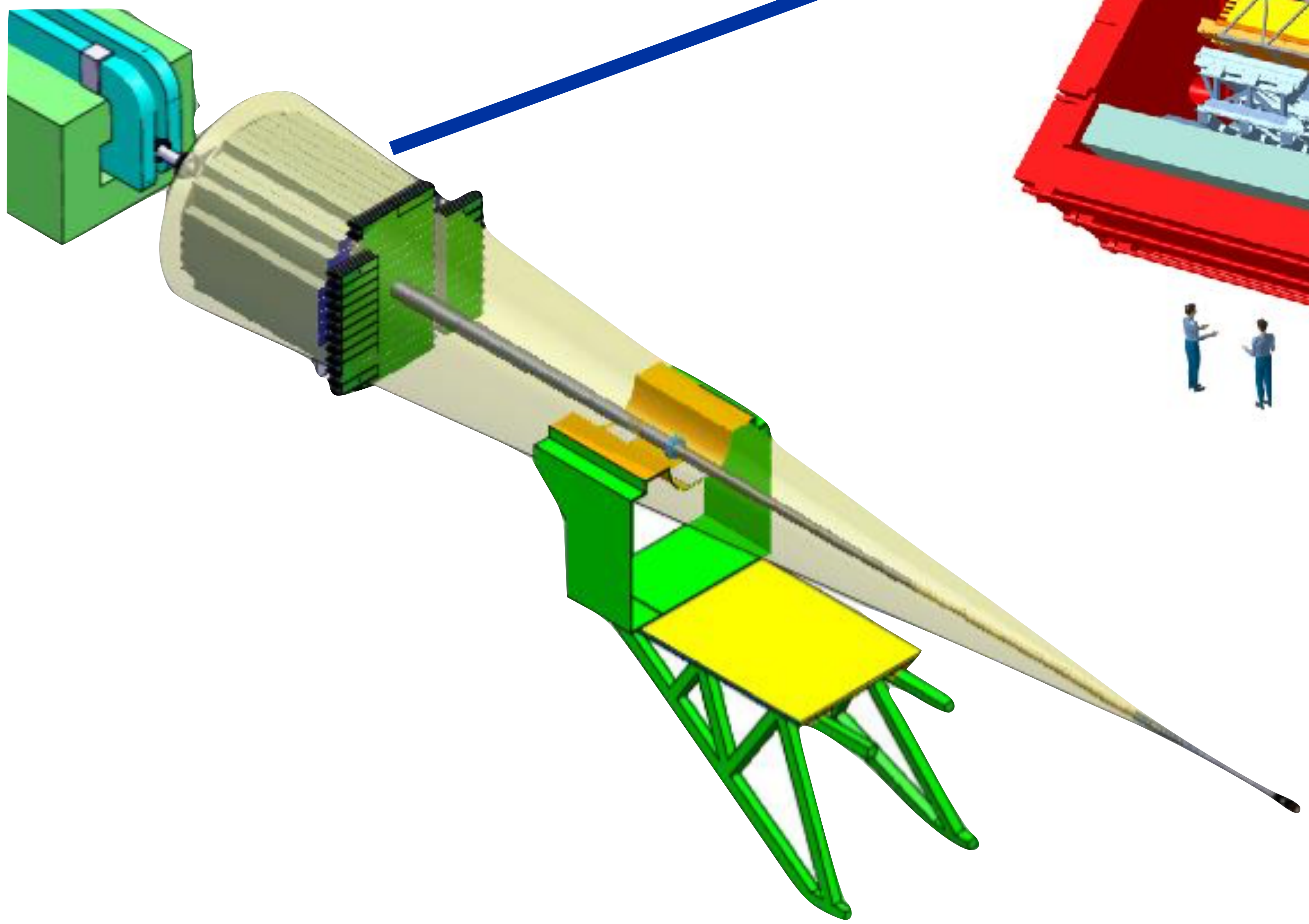


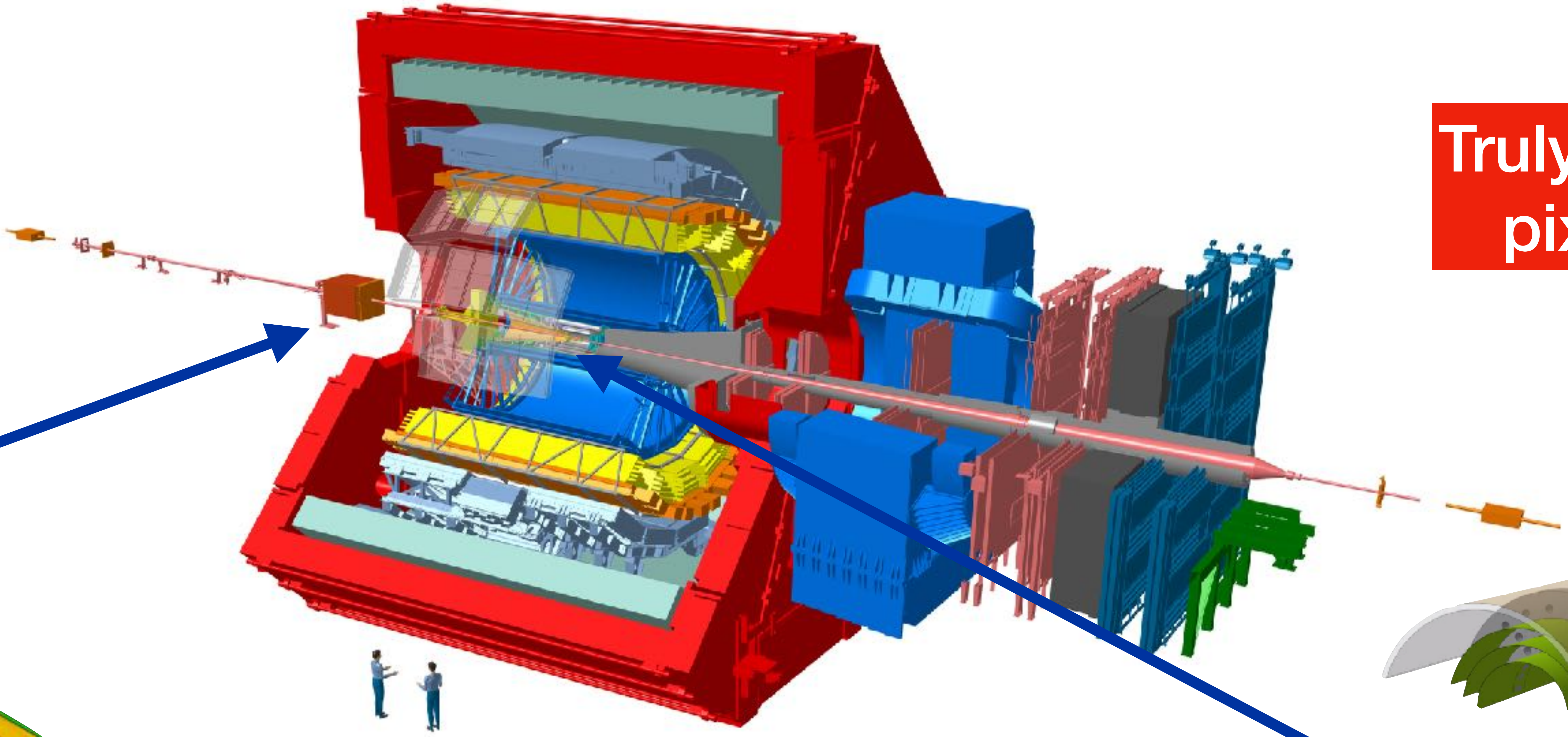


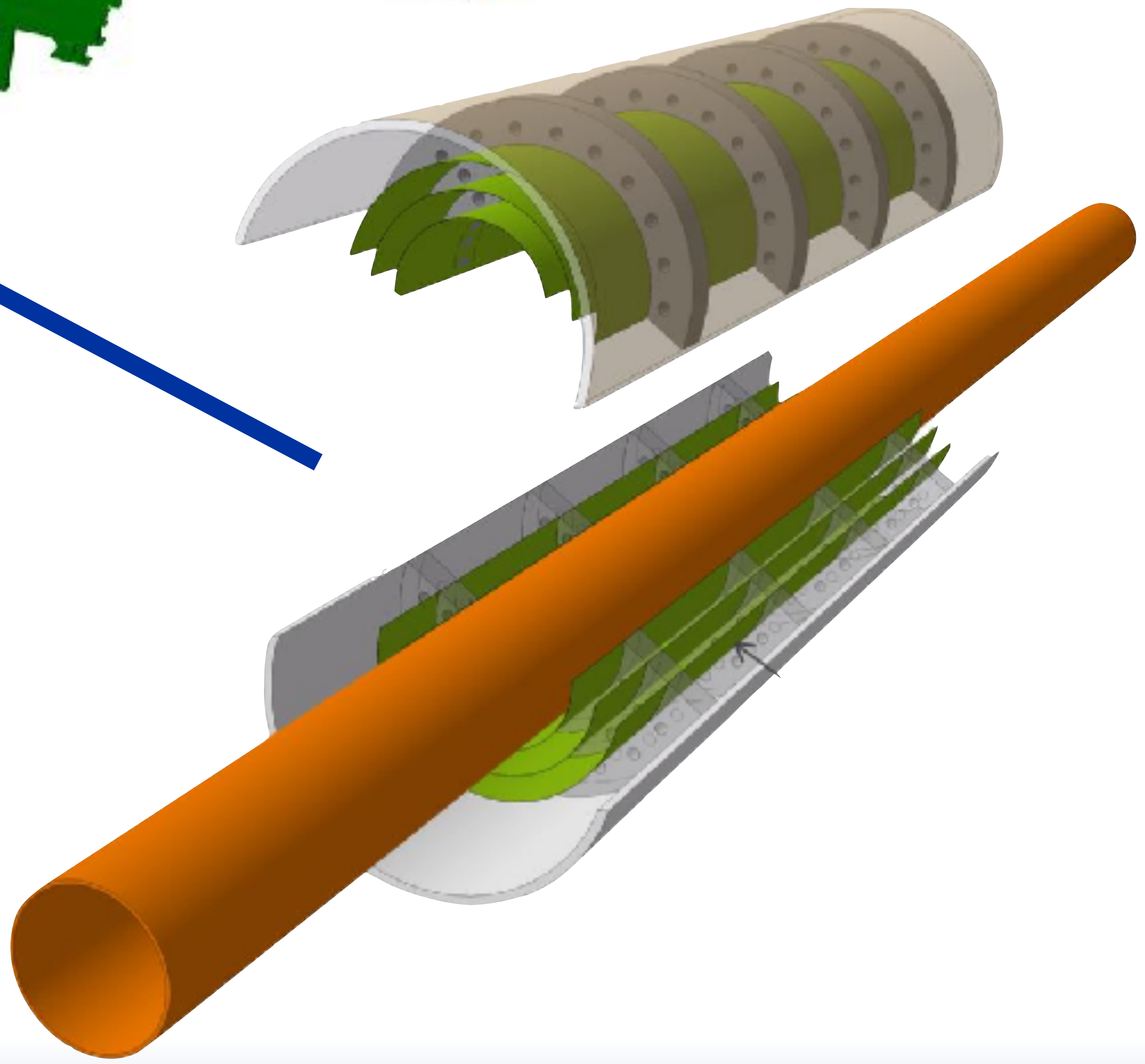
ALICE 2.1

New Forward Calorimeter

Truly cylindrical pixel layers

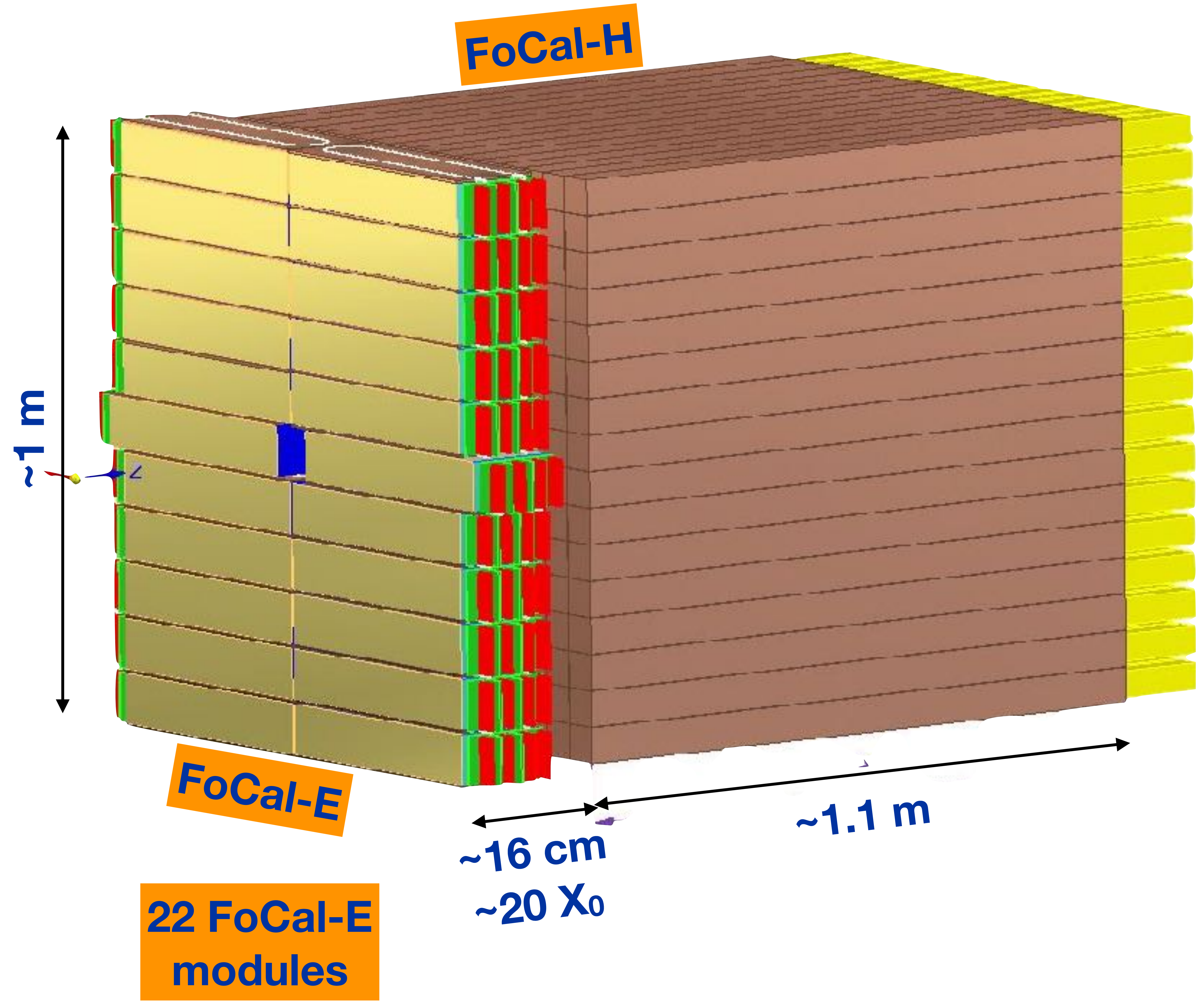






Forward Calorimeter (FoCal)

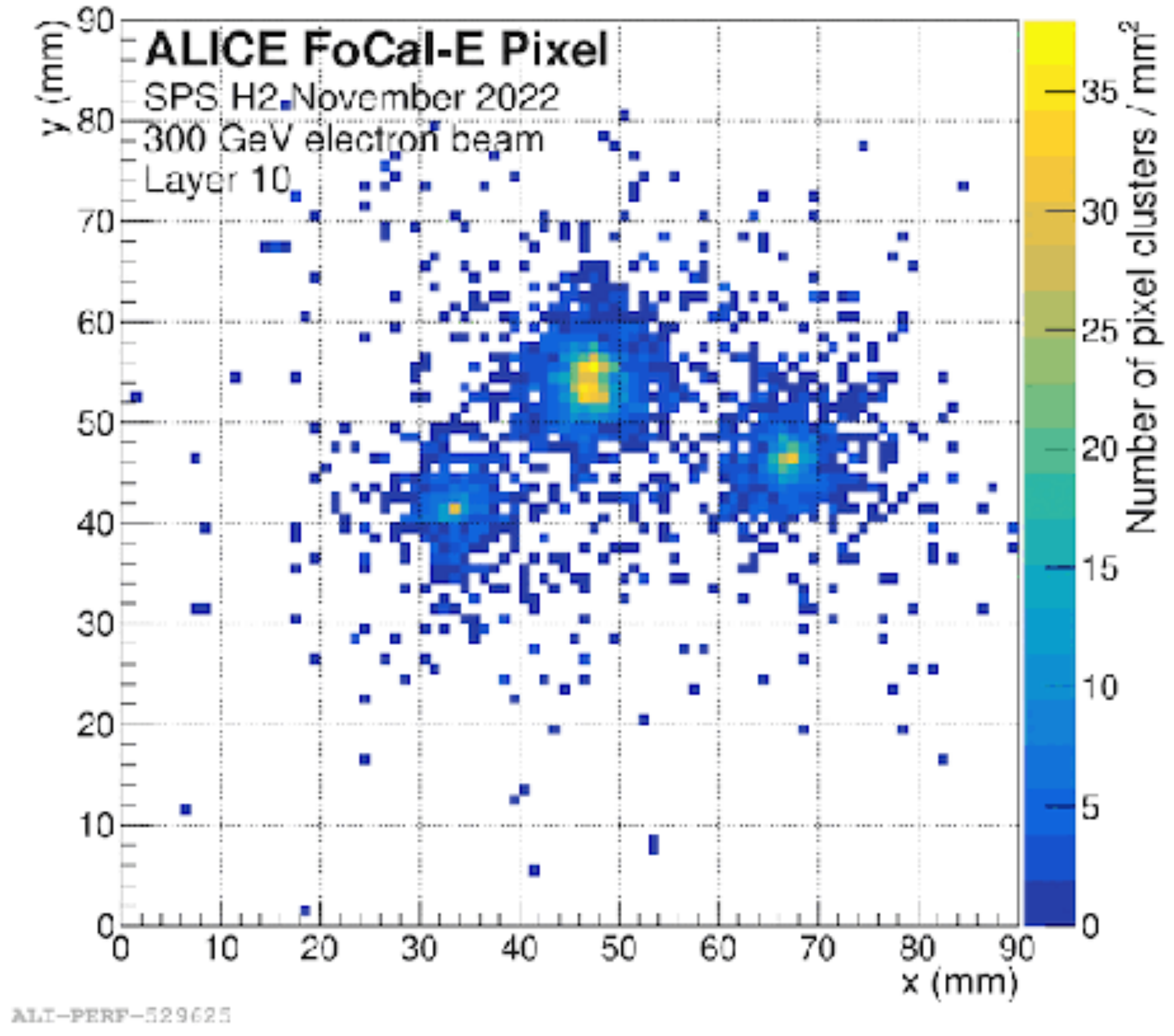
- **Objectives**
  - direct photon detection to probe gluon density at small *x*
  - forward π^0 in pp, pPb, PbPb
- **Requirements**
  - good two-photon separation
- **Concept**
  - forward coverage 3.4 < η < 5.8
  - highly granular ECal
  - conventional HCal

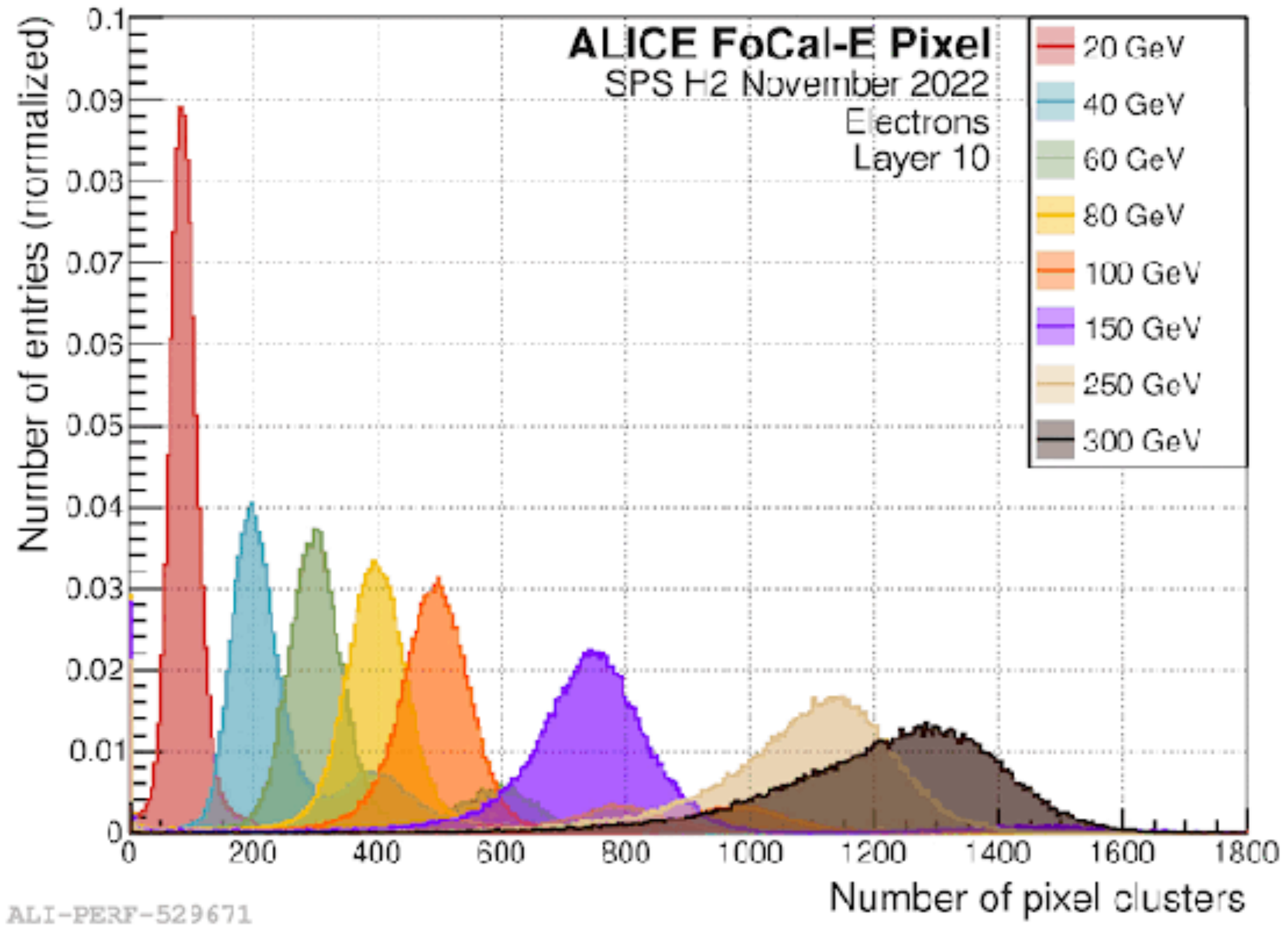


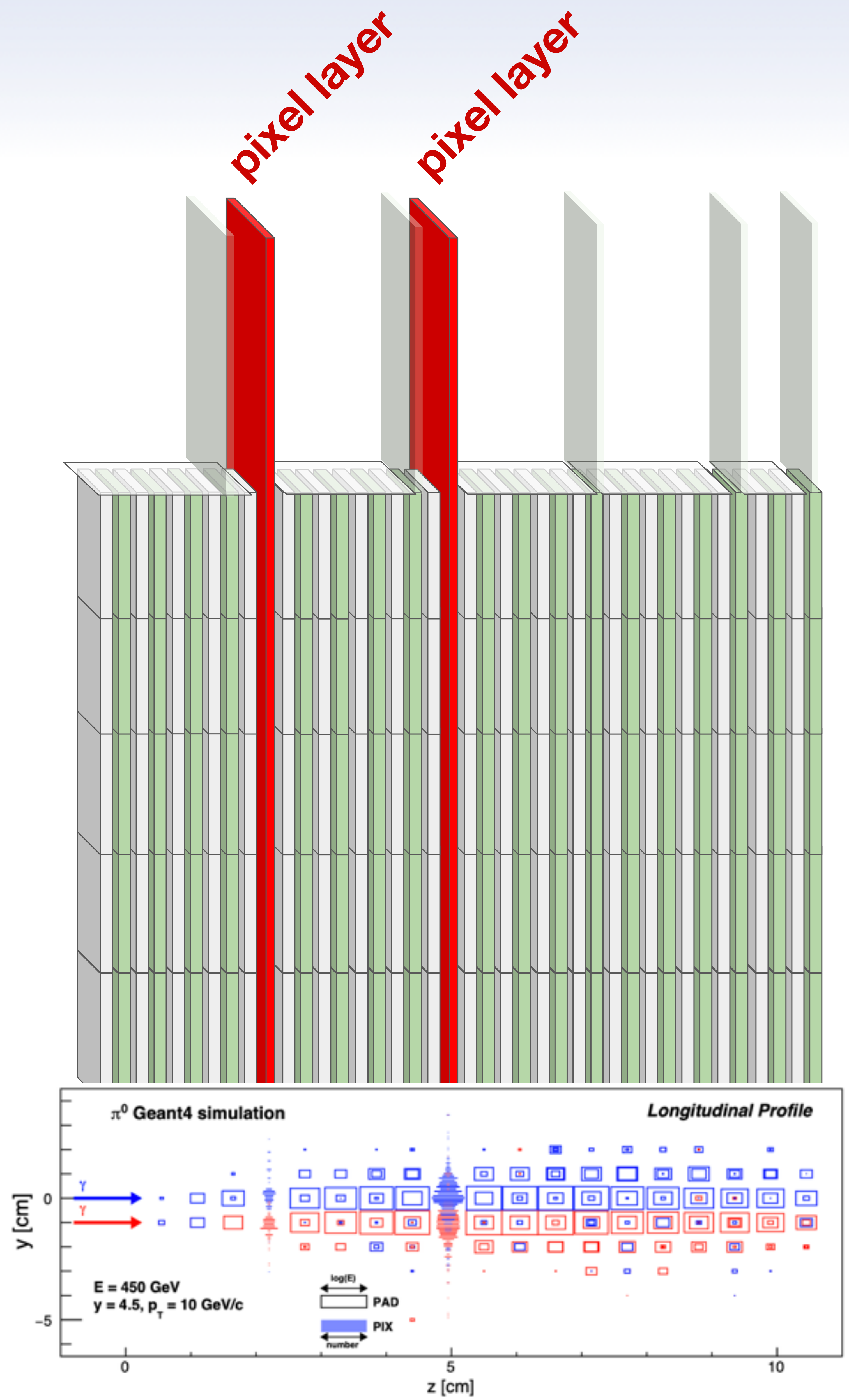
Letter-of-Intent: CERN-LHCC-2020-009

FoCal-E

- 22 modules each a stack of 20 layers (~20 X_0)
  - ~3.5 mm tungsten absorber (~1 X_0, $R_M \approx 1$ cm)
  - 18 layers of silicon pad sensors
  - 2 layers of silicon pixel sensors (ALPIDE)
- Prototype validated in test beam campaigns

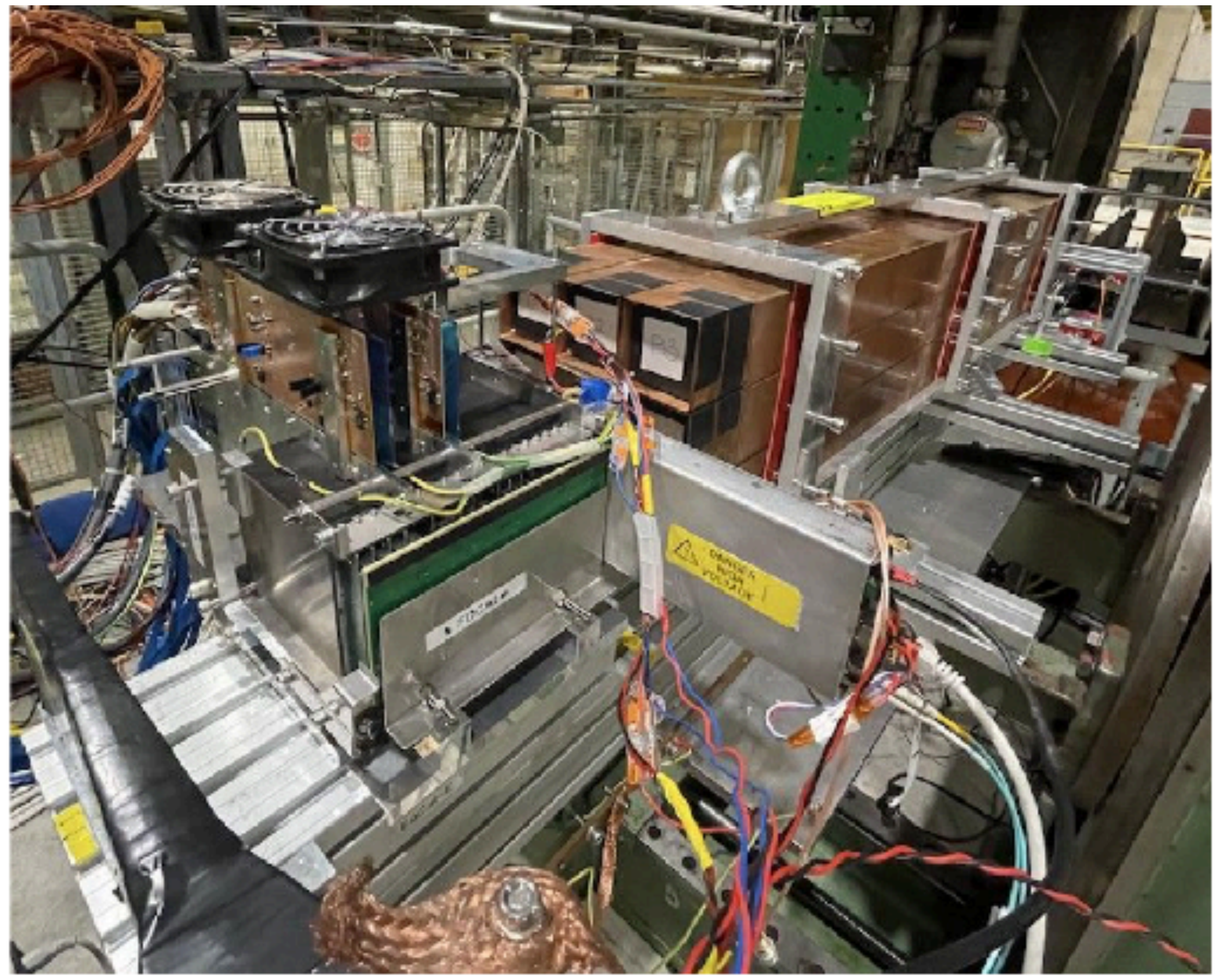


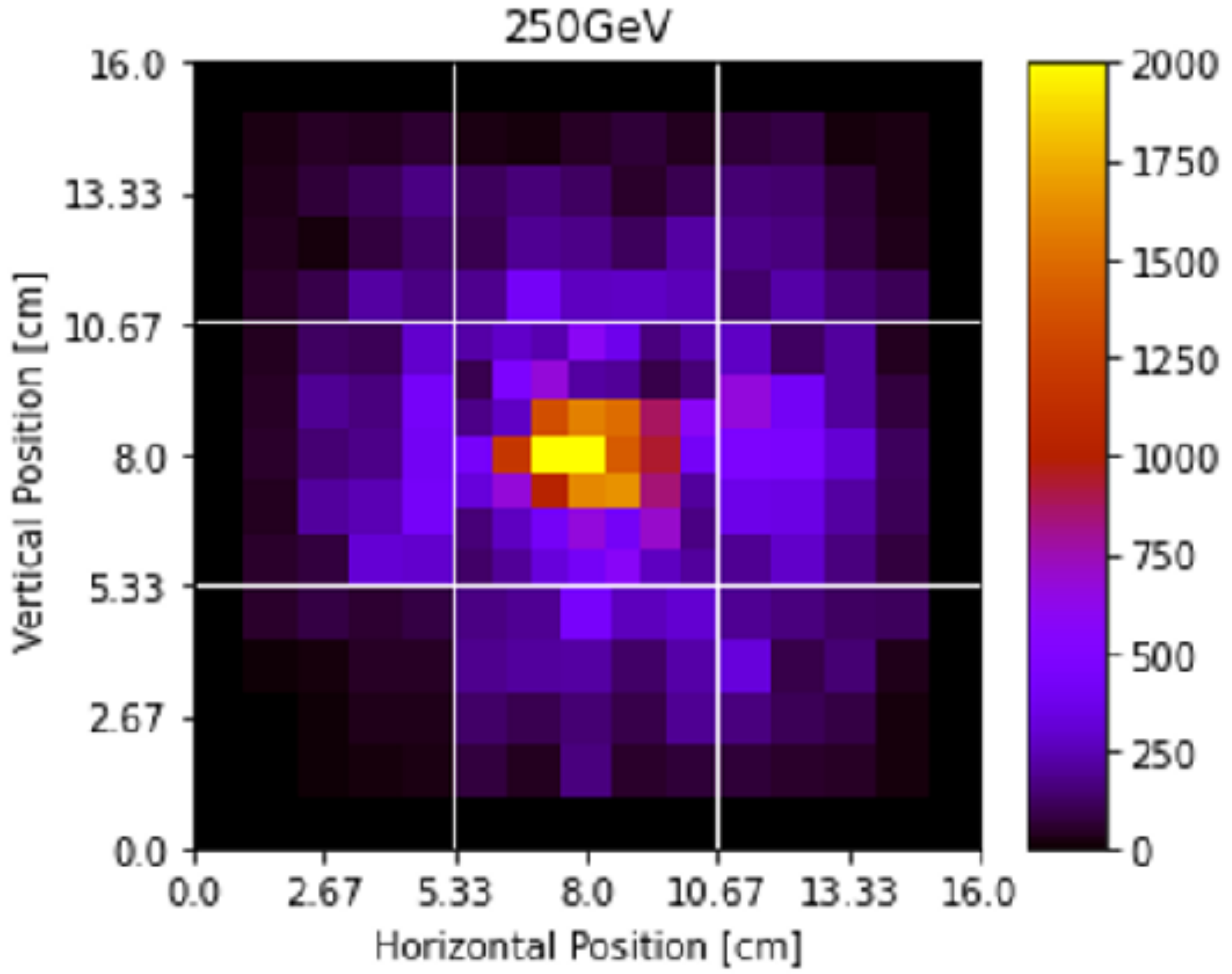


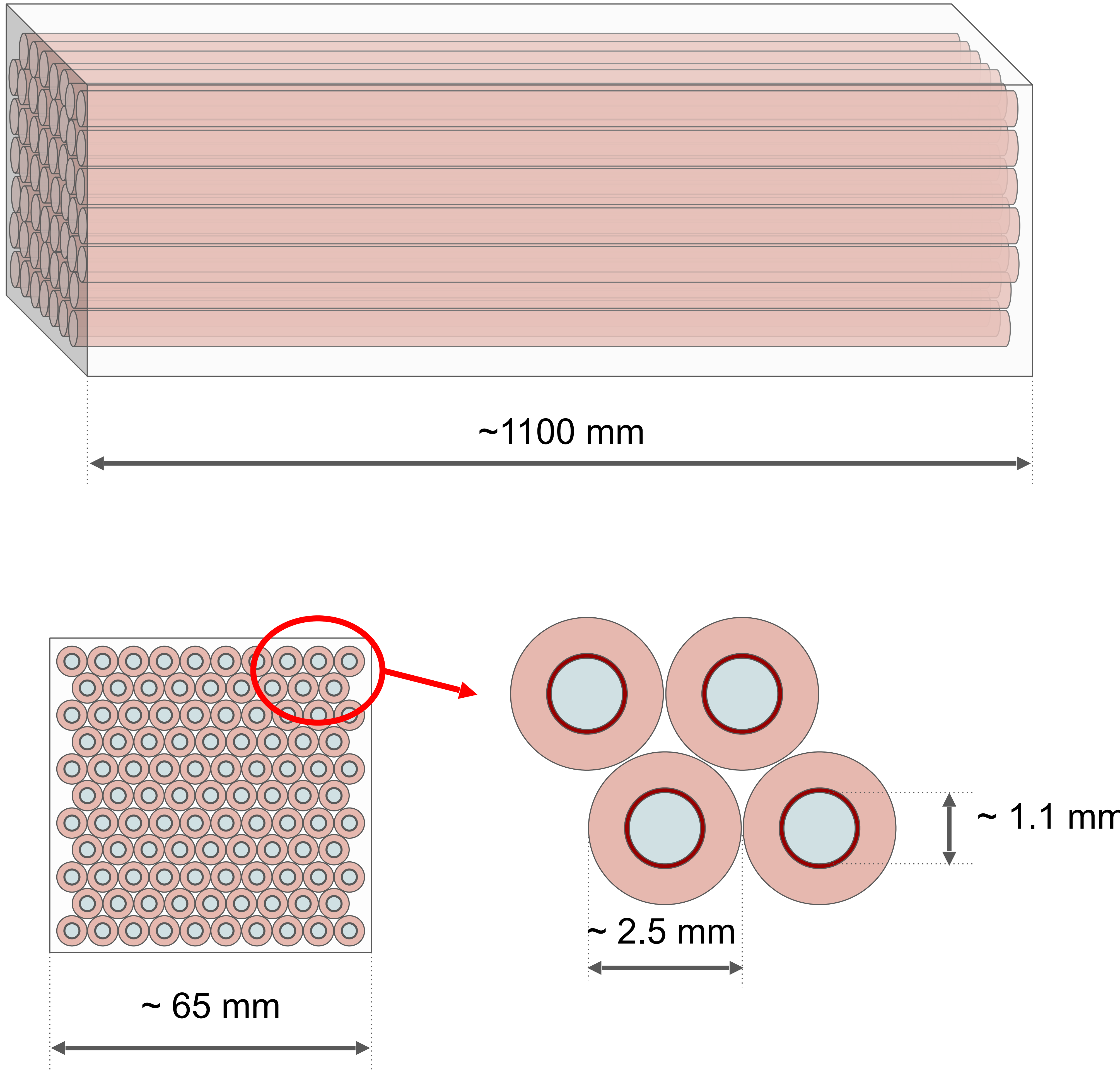


FoCal-H

- Array of copper tubes with BCF12 scintillating fibres
- Full tower prototype validated in test beam (Nov '22 @ SPS)

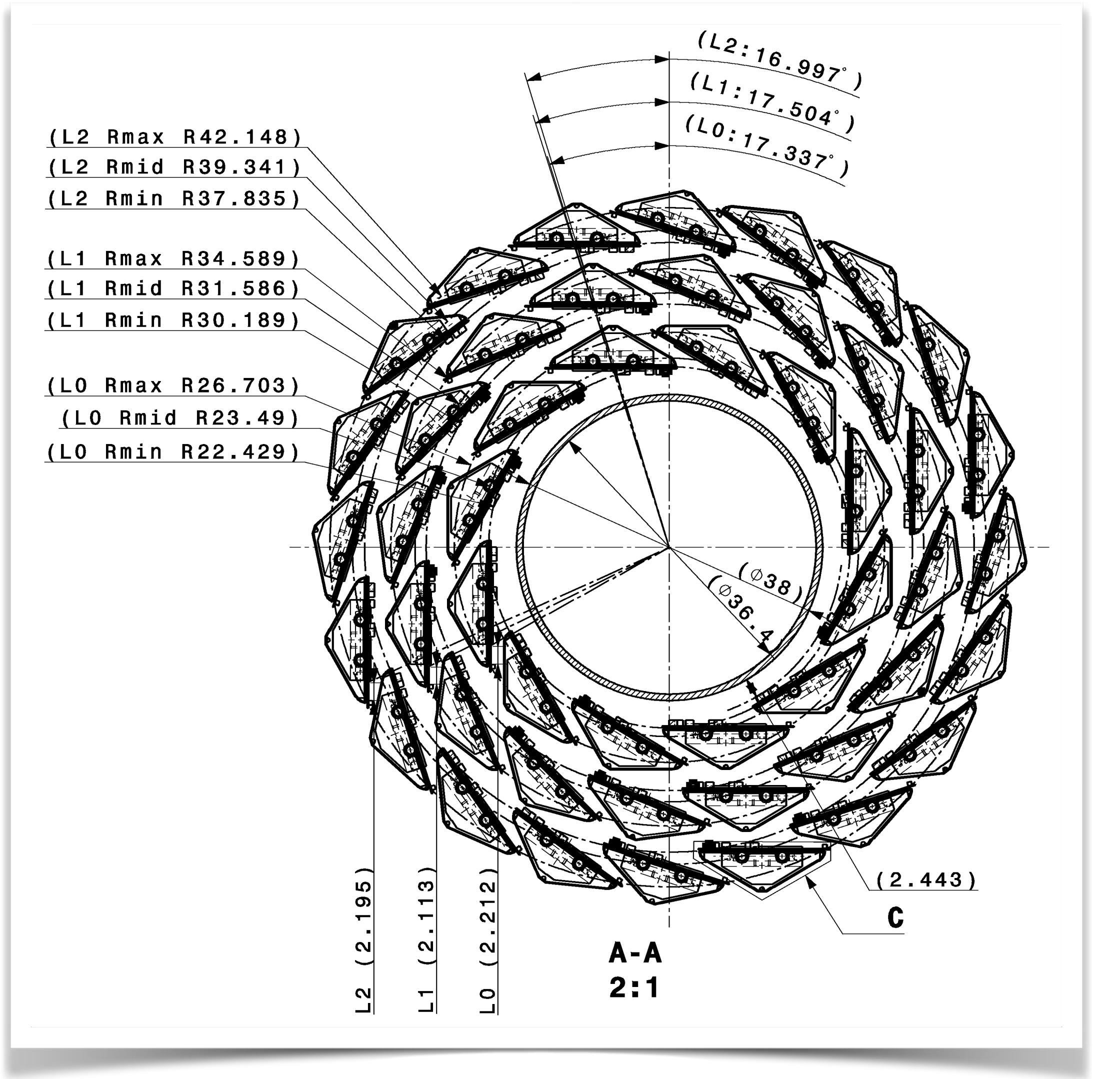


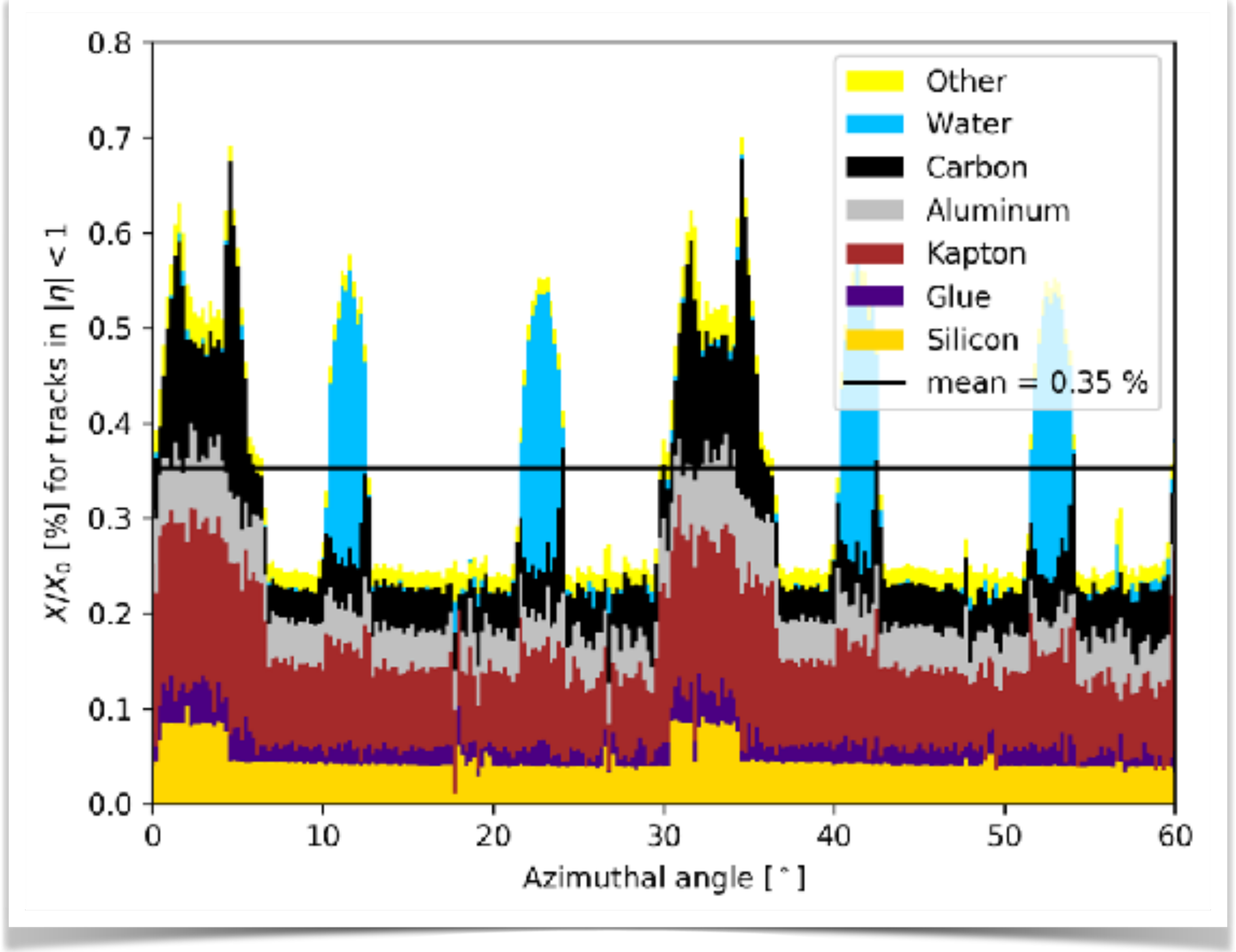




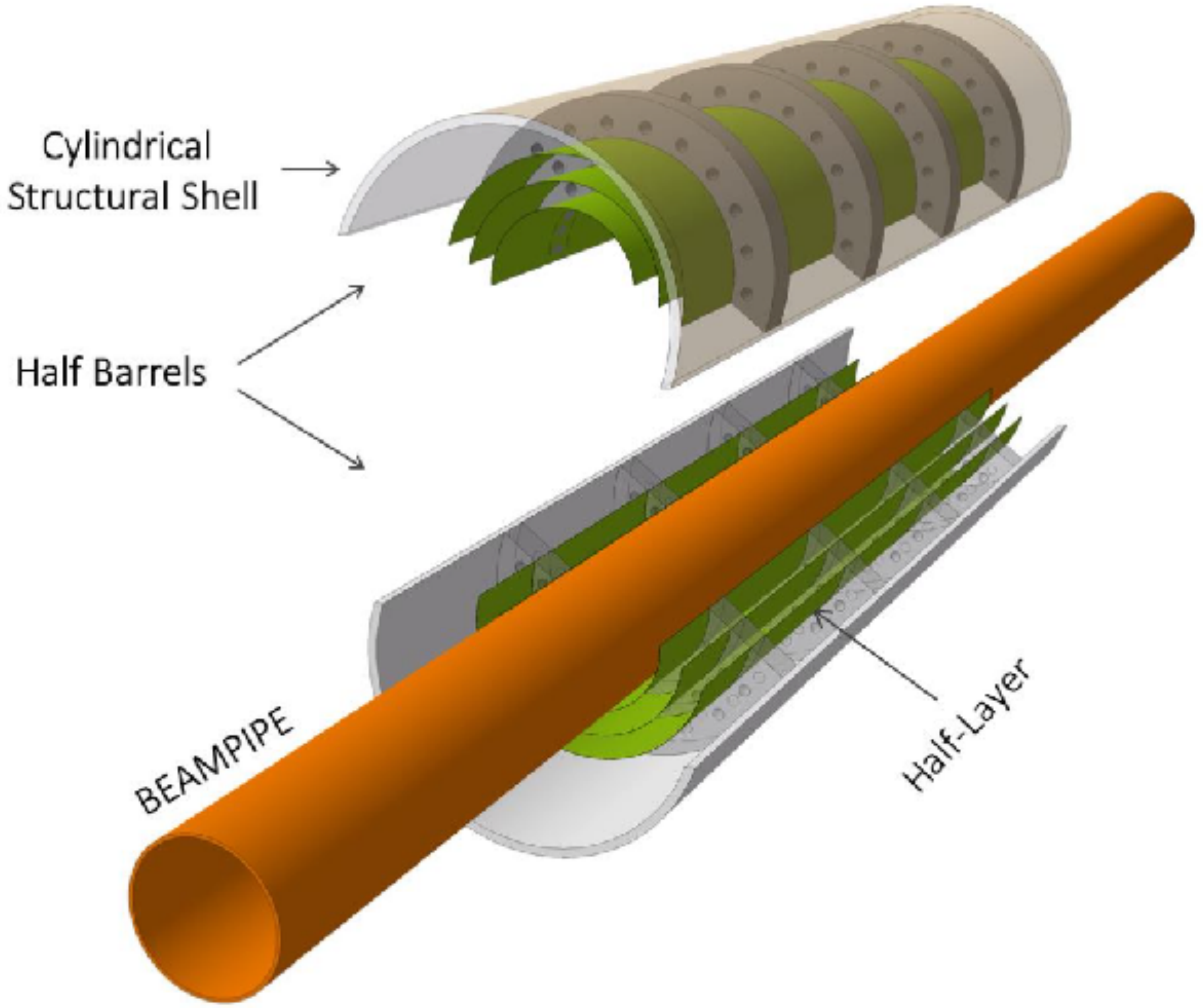
ITS3

ITS2





ITS3



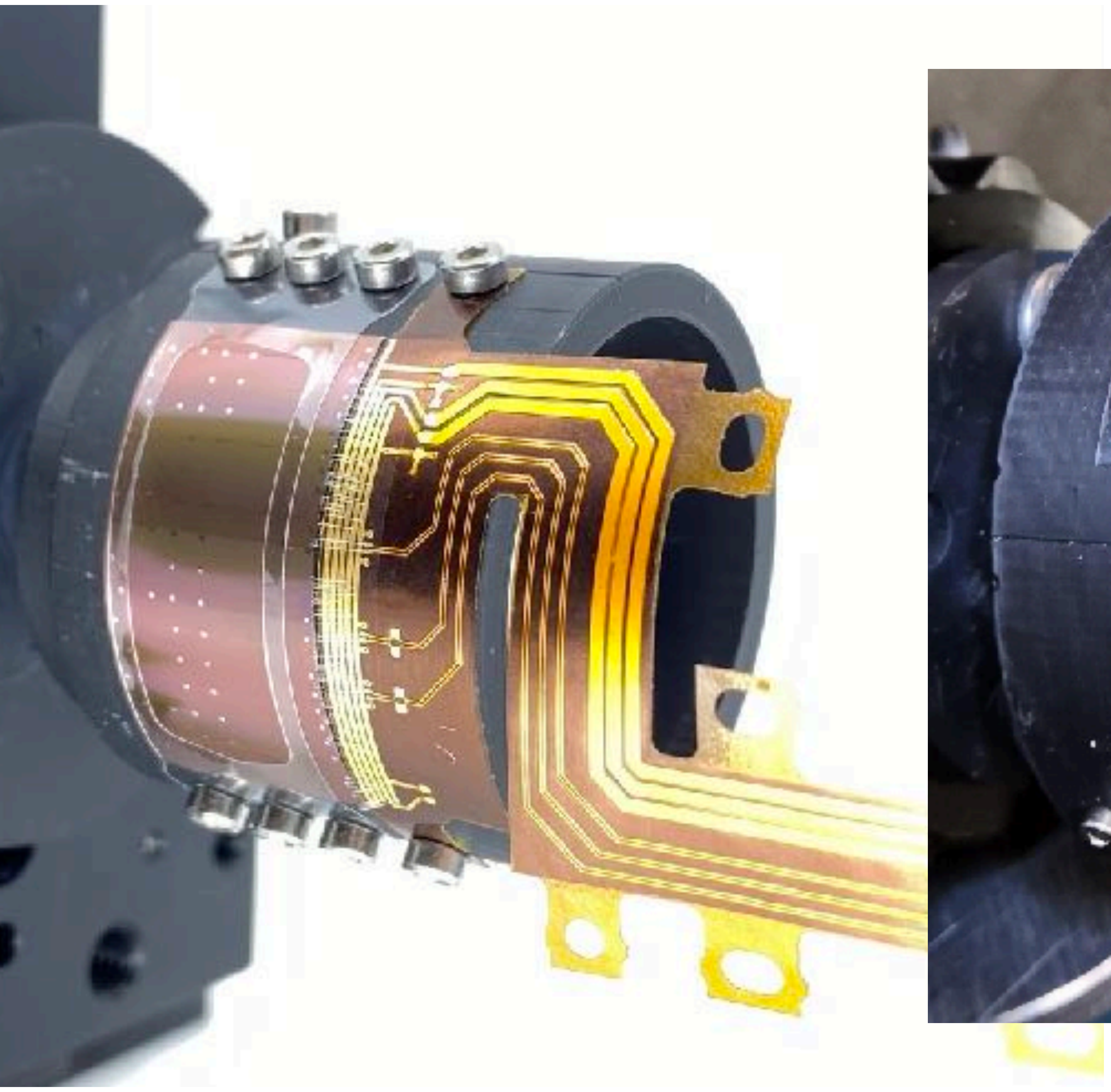
- **Improve vertexing performance** for:
  - Heavy flavour probes: charm baryons, beauty
  - low-mass dielectrons
- by
  - moving closer to the interaction point
  - reducing material budget

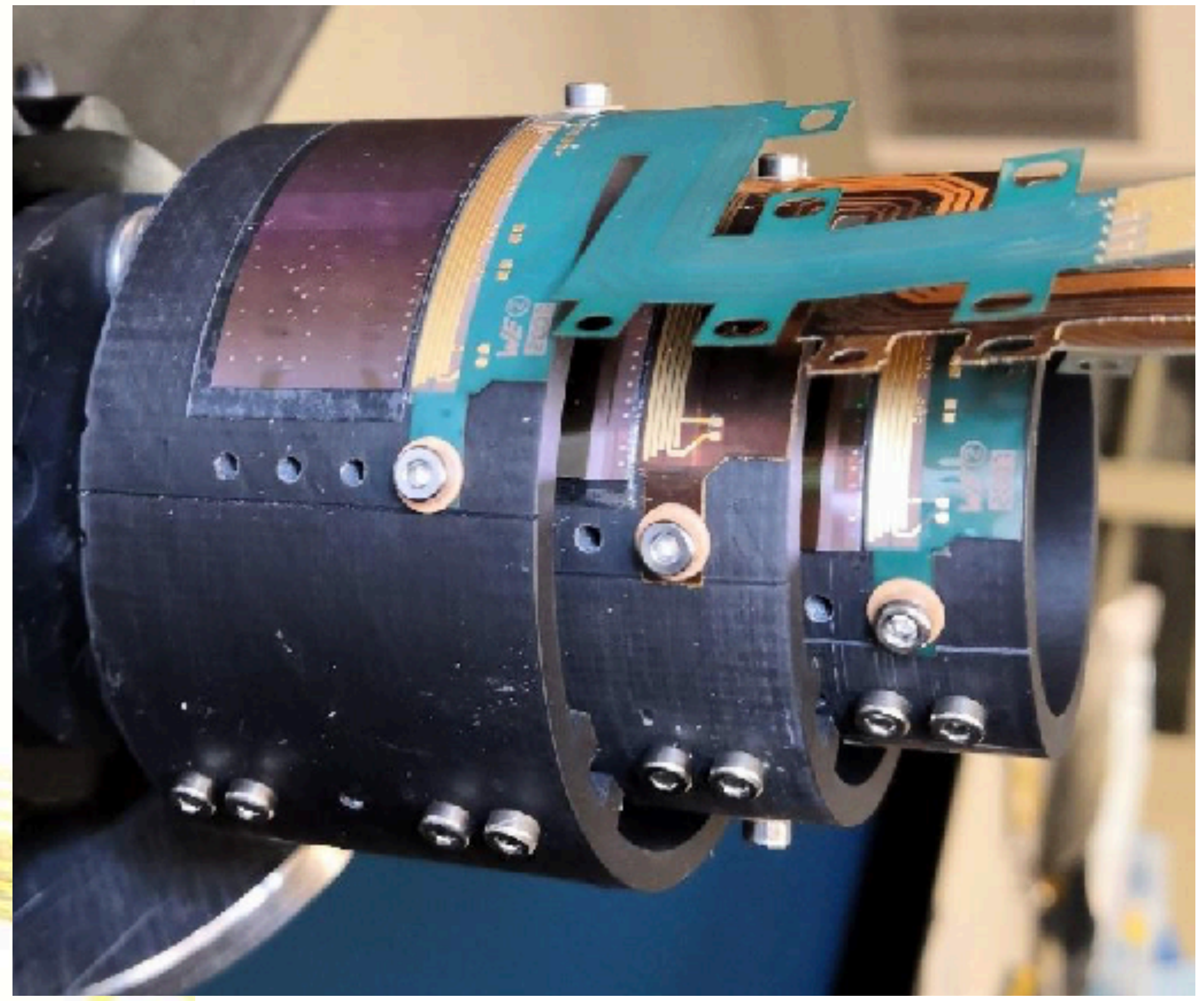
- Replace Inner Barrel with **truly cylindrical layers**
  - bending of silicon sensors → thinning, mechanics ✓
  - avoid support structures and services
    → air cooling ✓
  - power consumption, radiation hardness
    → sensor design in TPSCo 65 nm process ✓
  - wafer-scale sensors
    → development of stitched sensors

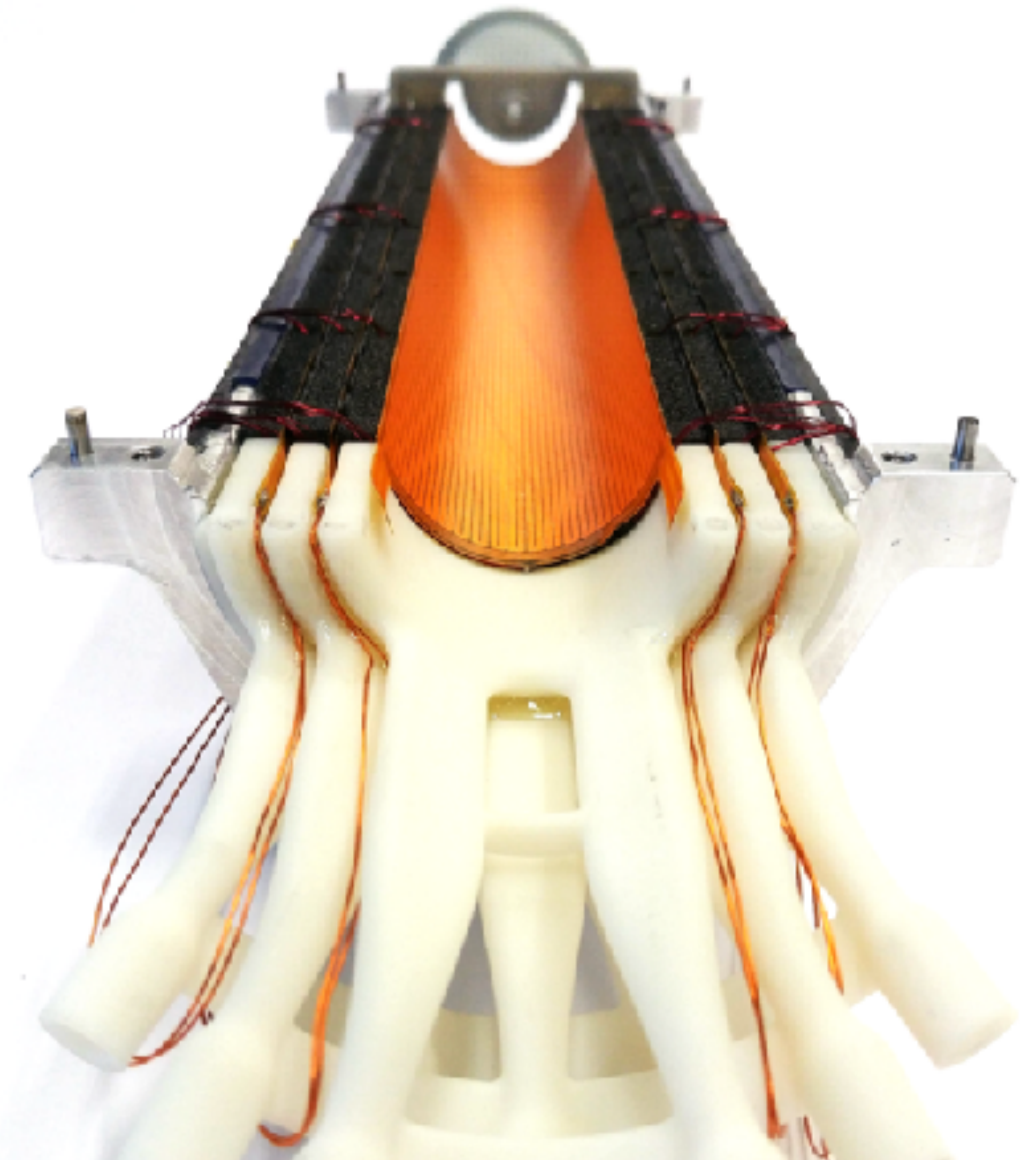
ITS3 - bent sensors

[arXiv:2105.13000]

- Functionality of 50 μm ALPIDEs bent to radii down to 1.8 cm demonstrated in beam tests at various facilities
- Handling and bending of wafer-scale sensors established
- Cooling concept demonstrated and being optimised





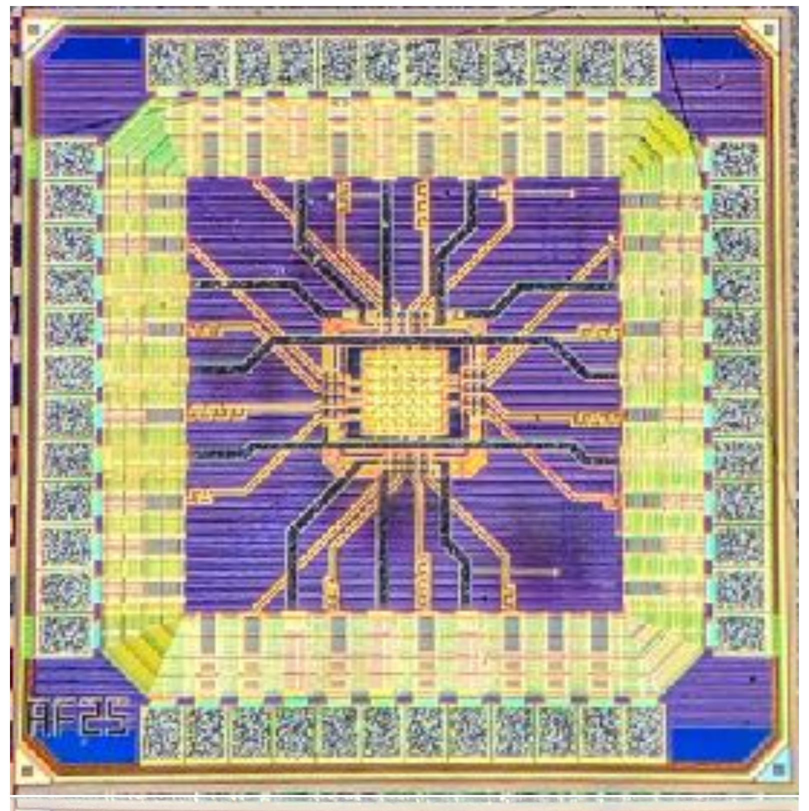


“bread board” model 3

ITS3 - sensor technology

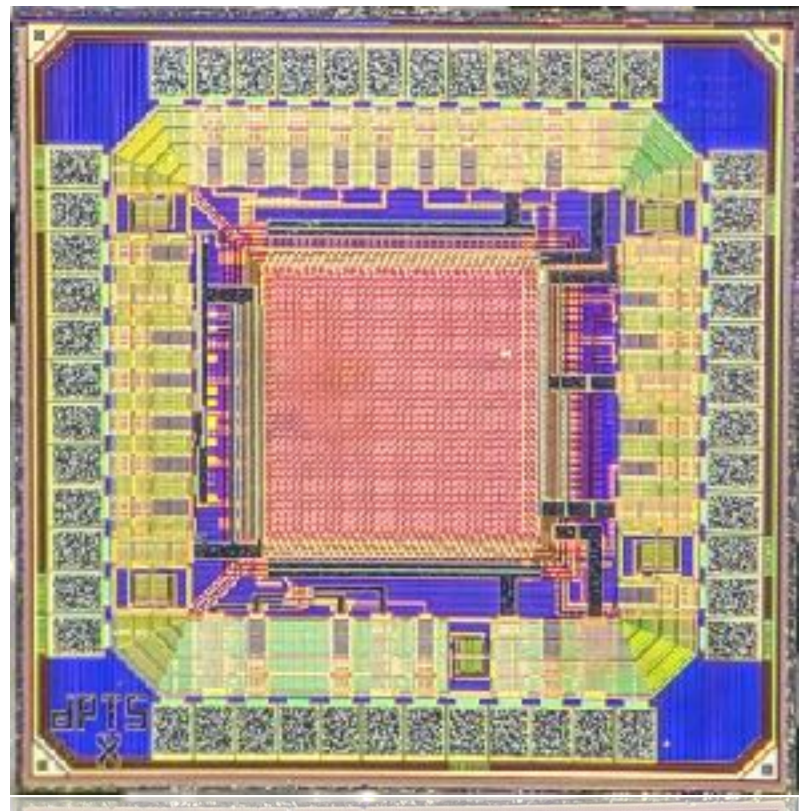
- Extensive R&D run with 55 different prototypes in TPSCo 65 nm process within ALICE ITS3 and CERN EP R&D
  - full functionality of digital front-end verified: 100% detection efficiency
  - even after 10^{15} 1 MeV n_{eq}/cm^2 (NIEL): >99% detection efficiency even at room temperature

APTS



- **matrix:** 6x6 pixels
- **readout:** direct analog readout of central 4x4
- **pitch:** 10, 15, 20, 25 µm

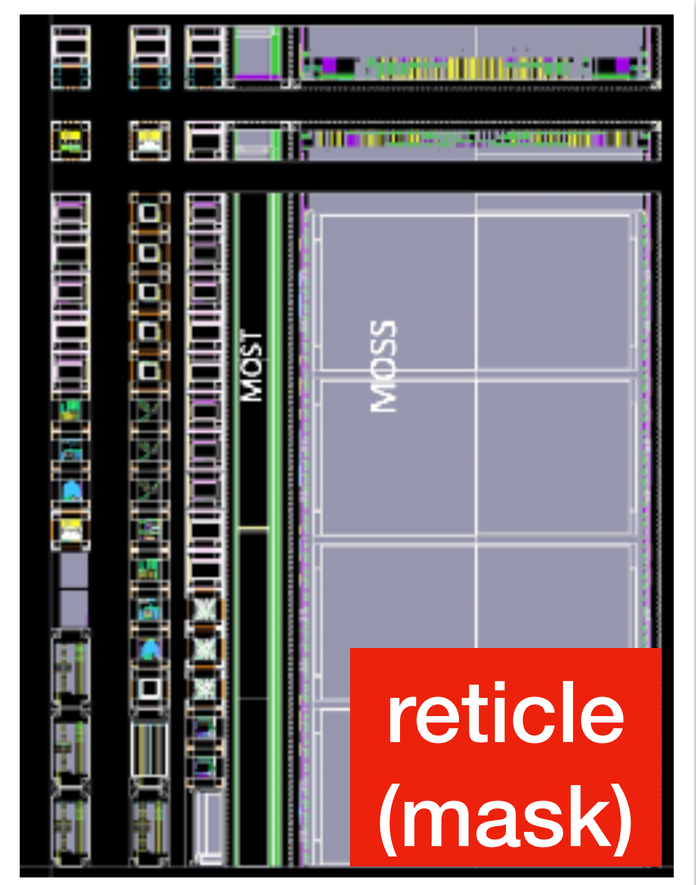
DPTS

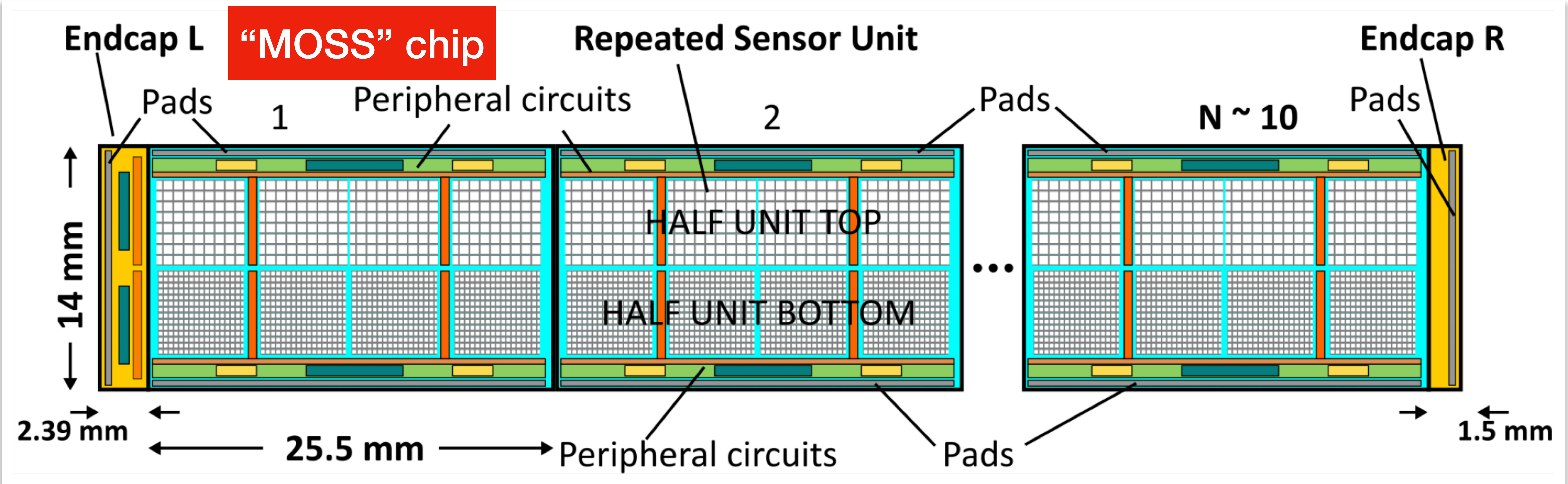


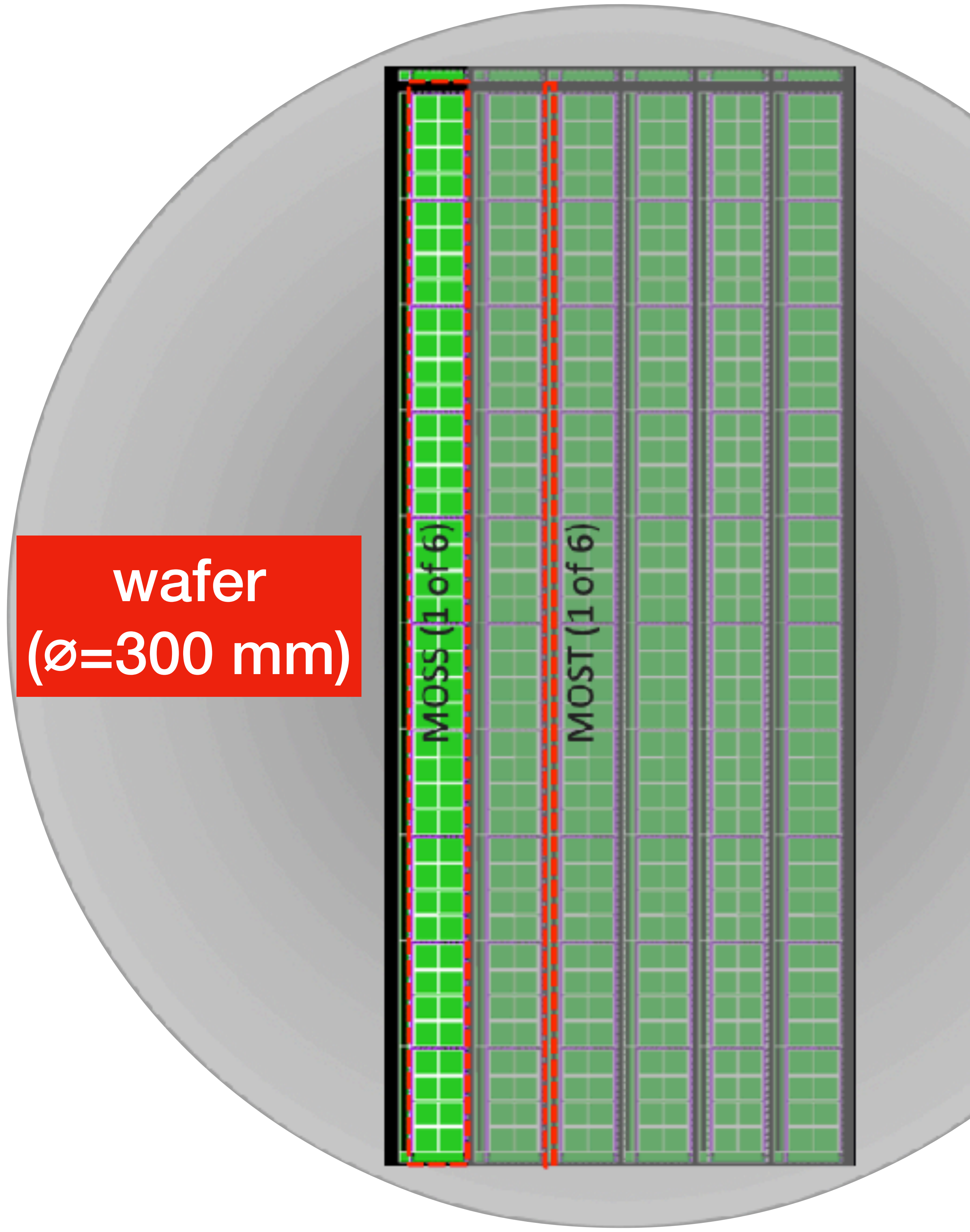
- **matrix:** 32x32 pixels
- **readout:** async. digital with ToT
- **pitch:** 15 µm

ITS3 - stitched sensors

- First engineering run with stitched digital pixels submitted
  - sensor unit repeated along a stripe, readout circuitry in the endcaps
  - processed wafers expected back mid 2023 (final milestone for TDR)







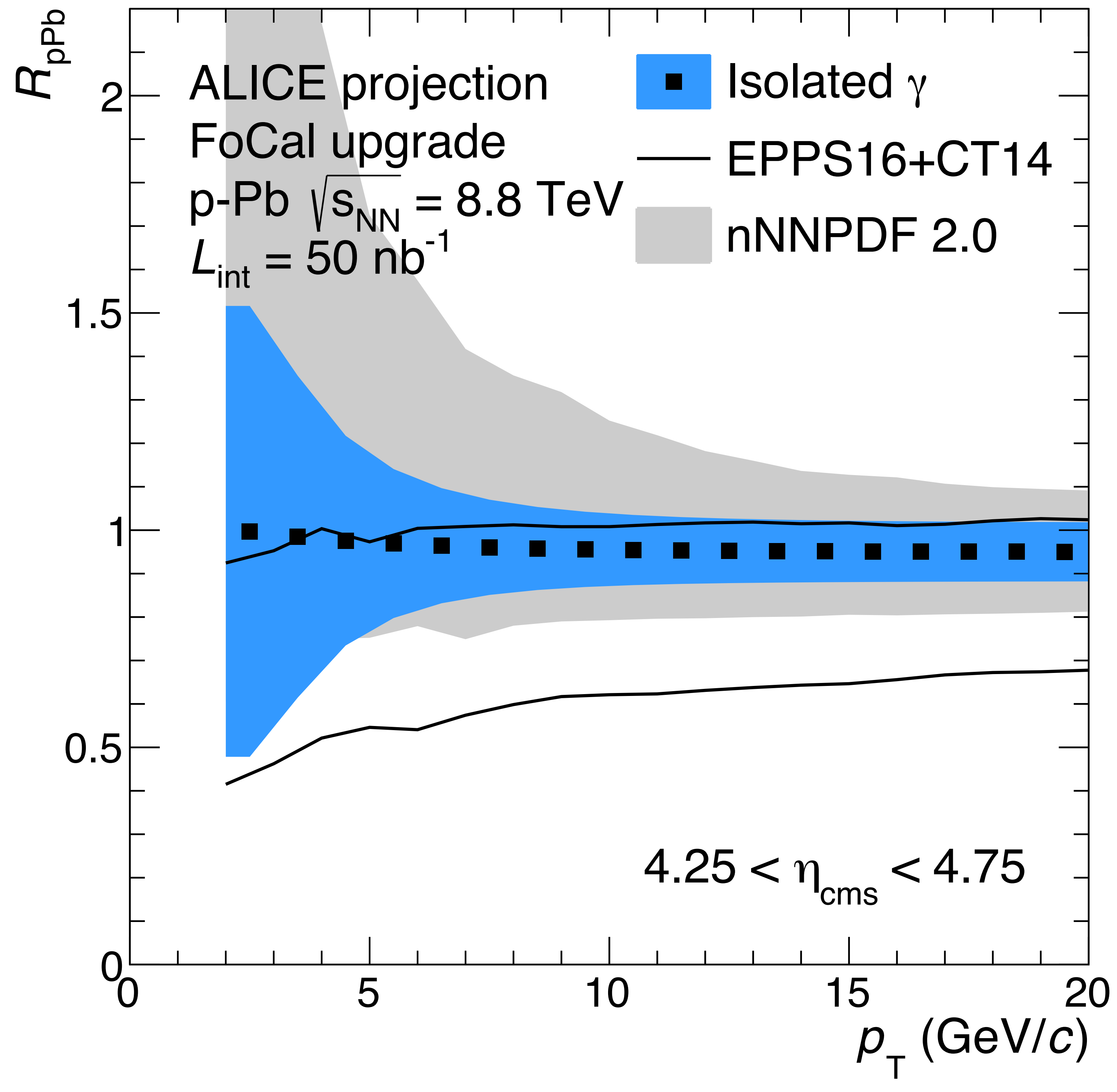
Prospects for Run 3 & 4

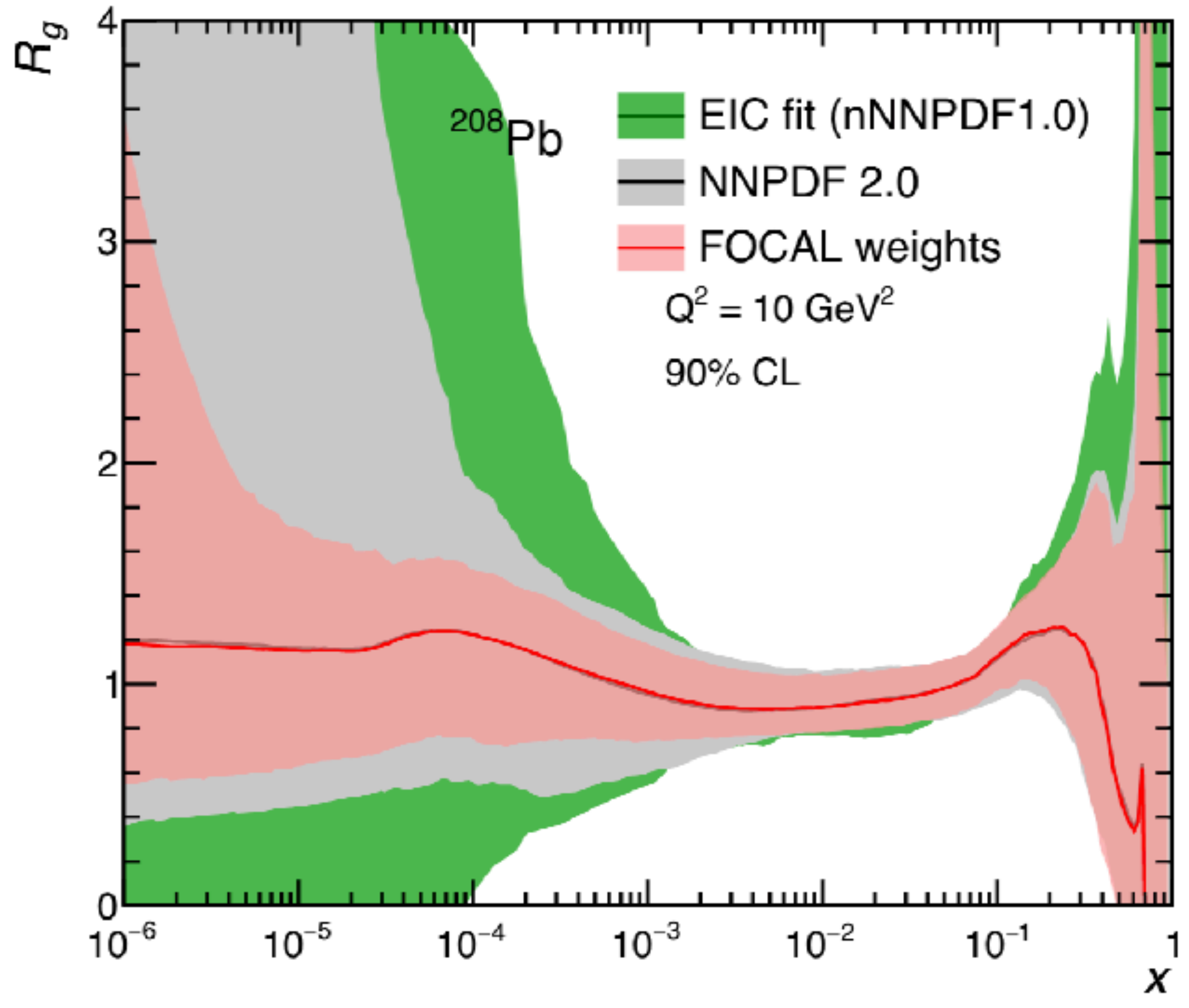
- **Runs 3 & 4 will allow new measurements and bring new insights, e.g.**
  - nuclear PDFs
  - thermal radiation
  - heavy-flavour transport
  - emergence of collectivity from small to large systems

Understanding of QGP will remain incomplete after Run 3 and 4

Nuclear PDFs

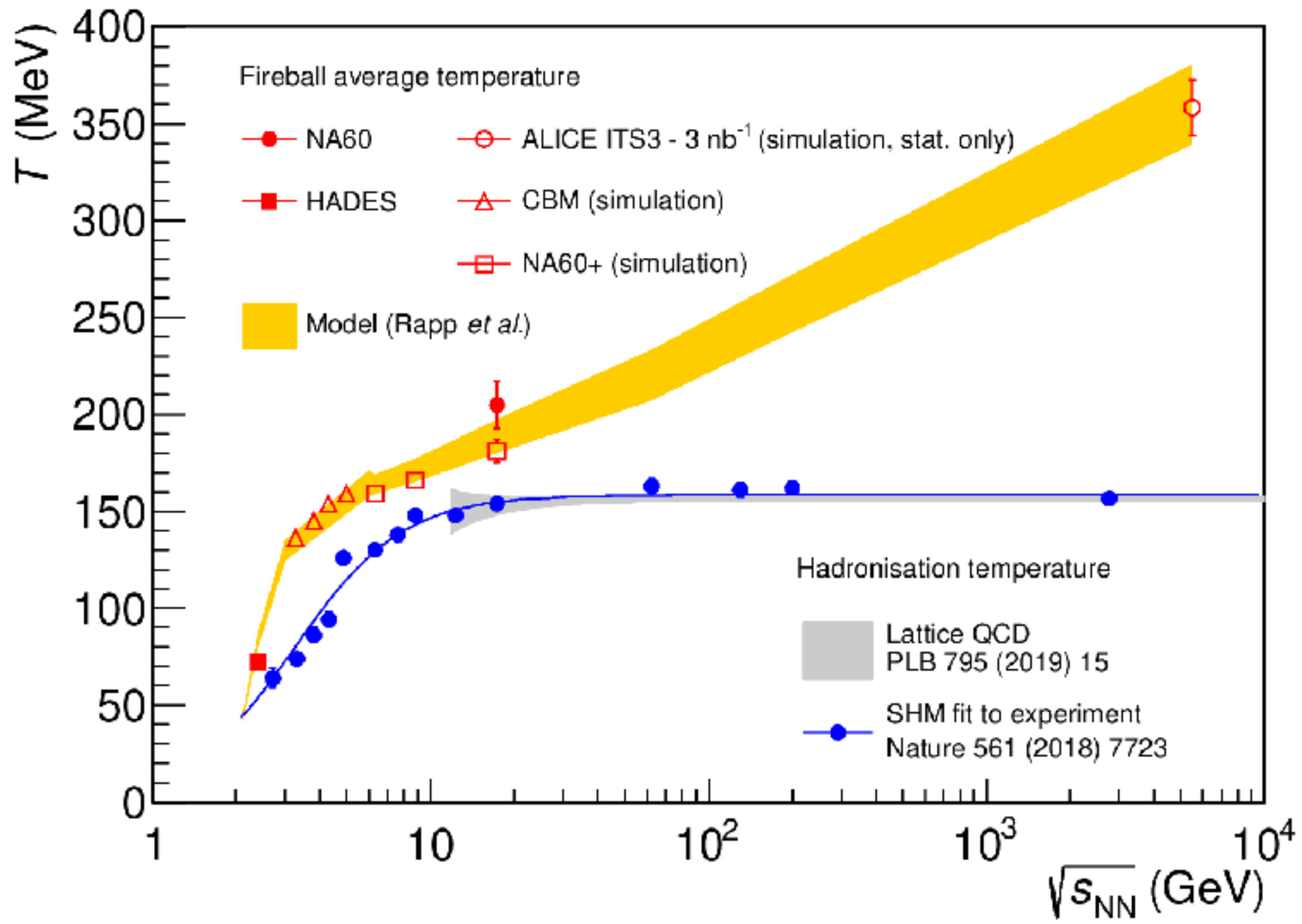
- **Constrain gluon densities down to low *x***
  → measurements of isolated photons in p-Pb collisions
  → FoCal

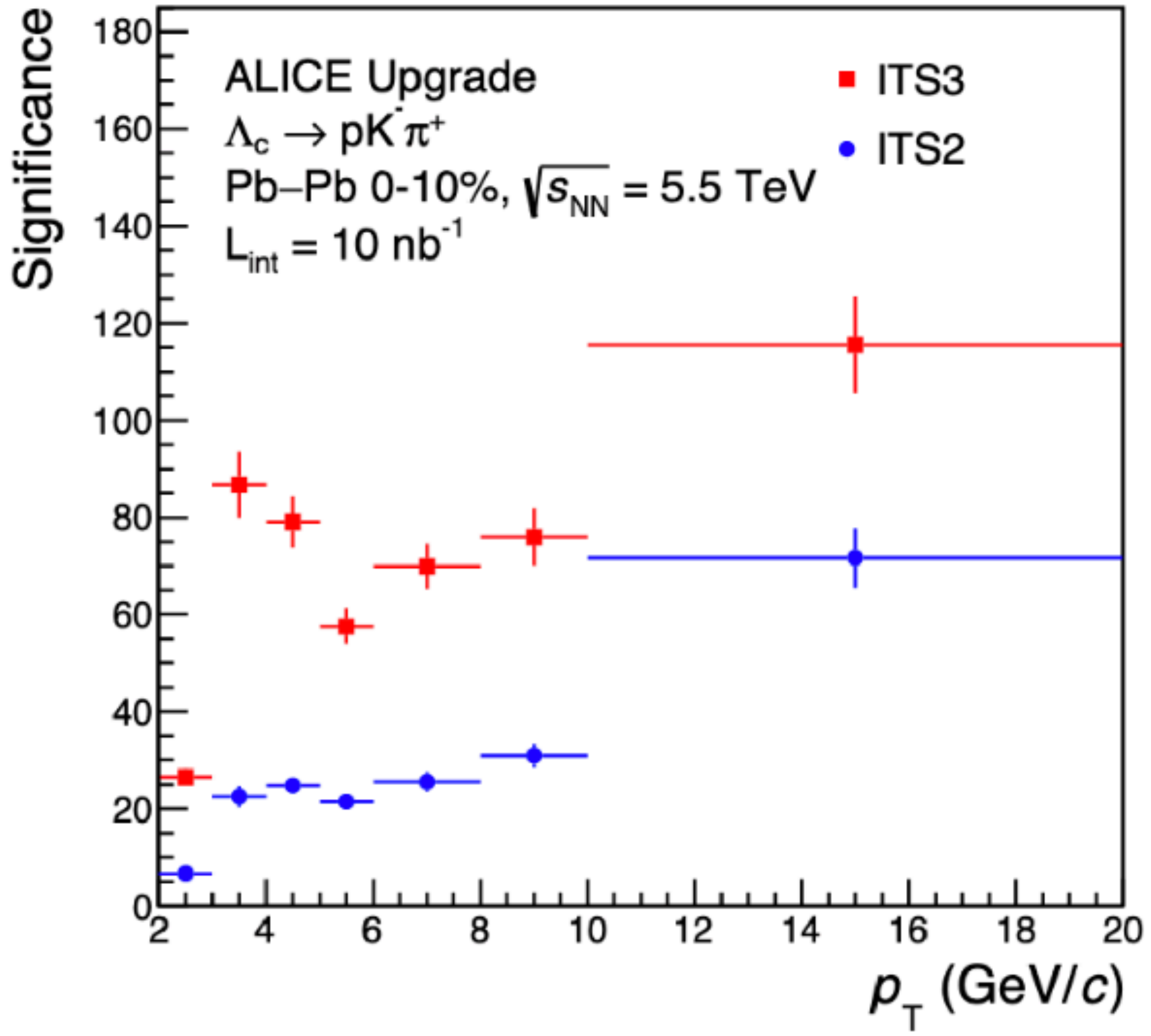




Thermal radiation

- **Measure temperature of plasma phase at LHC energies**
  → measurements of direct photons and dileptons
  → statistics; reduced, well-known material; heavy-flavour rejection

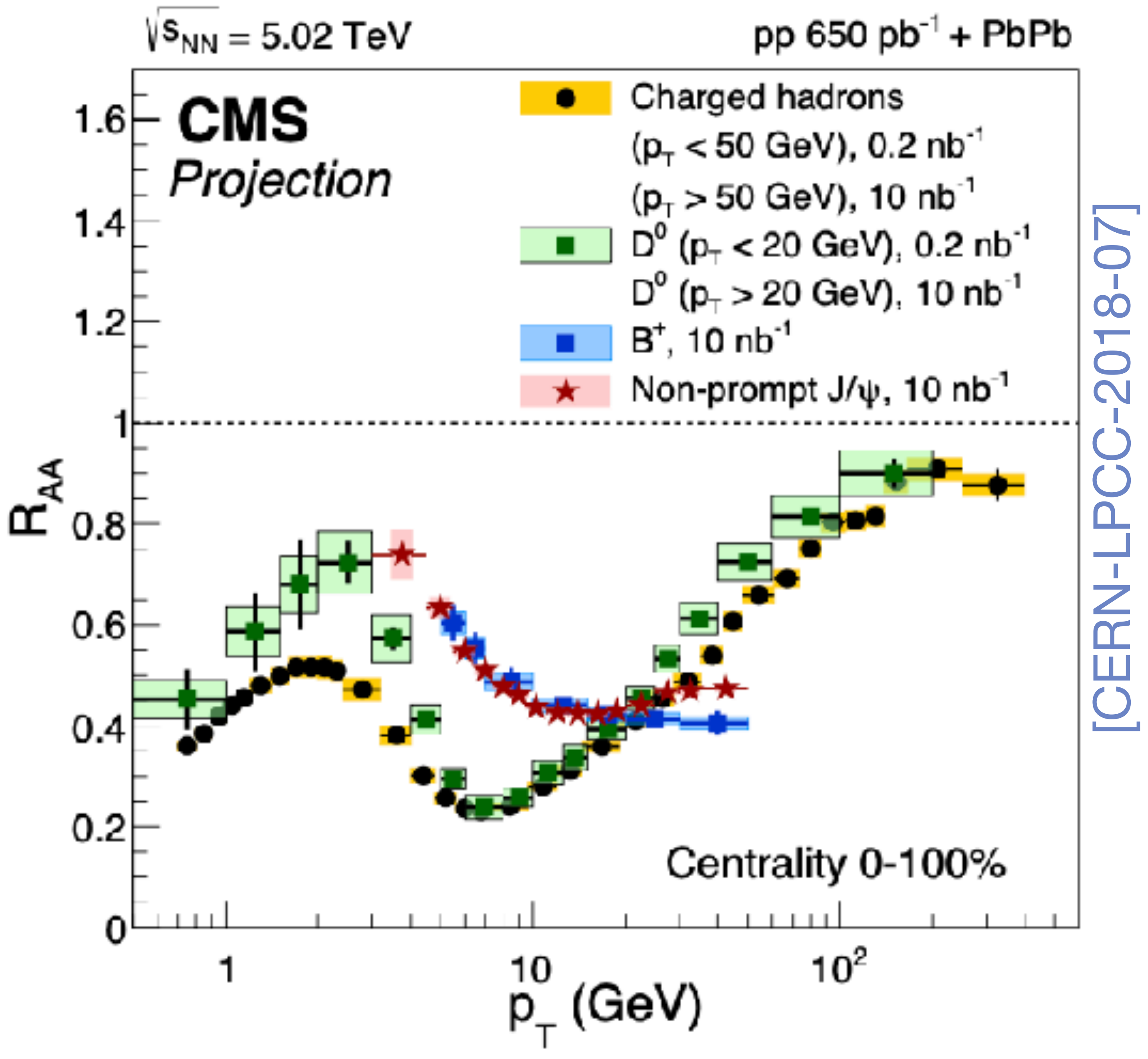




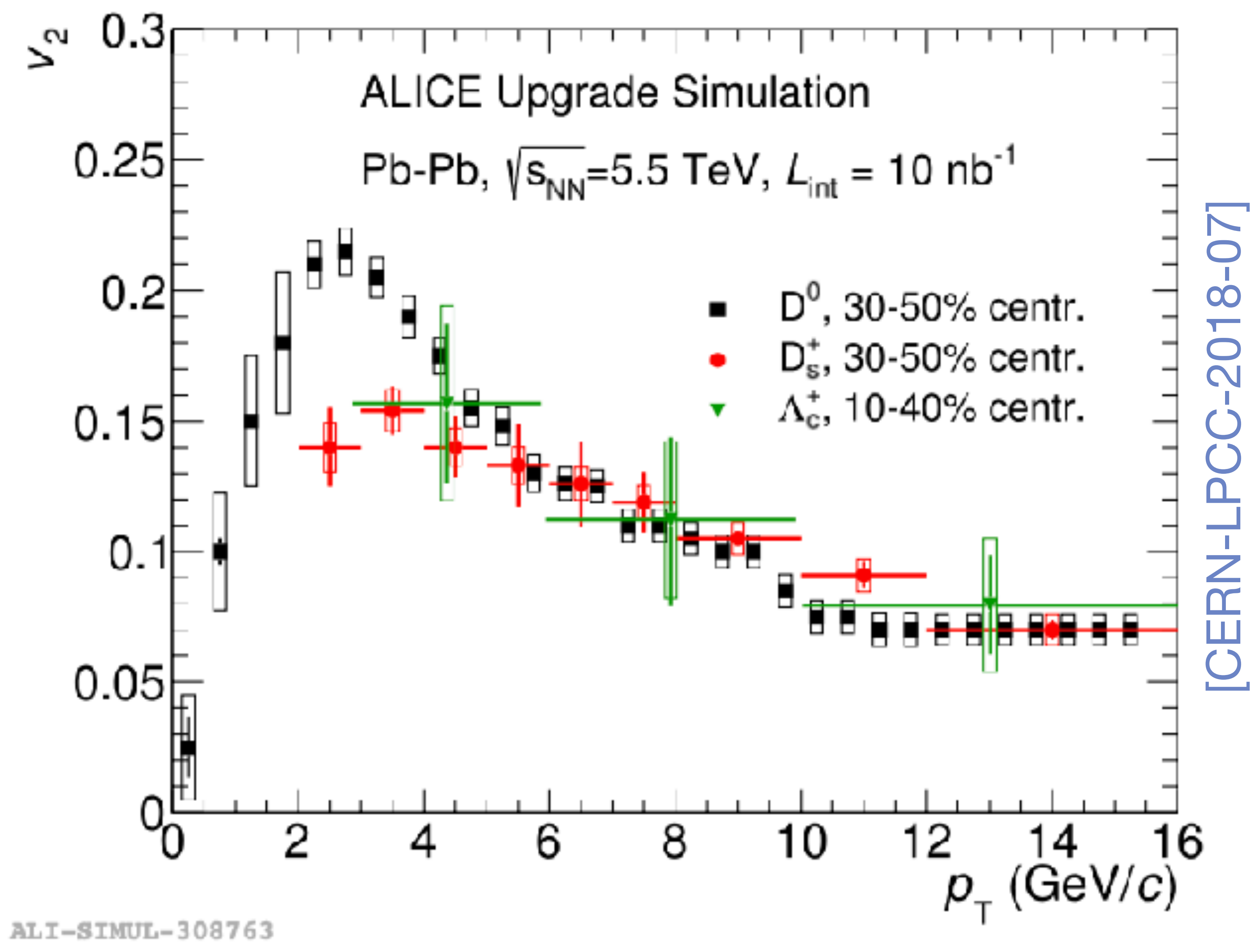
Heavy-flavour transport

- **Measure spatial diffusion coefficient in the QGP**
  → precision measurements of R_{AA} and v_2 for charm
  → statistics and vertexing

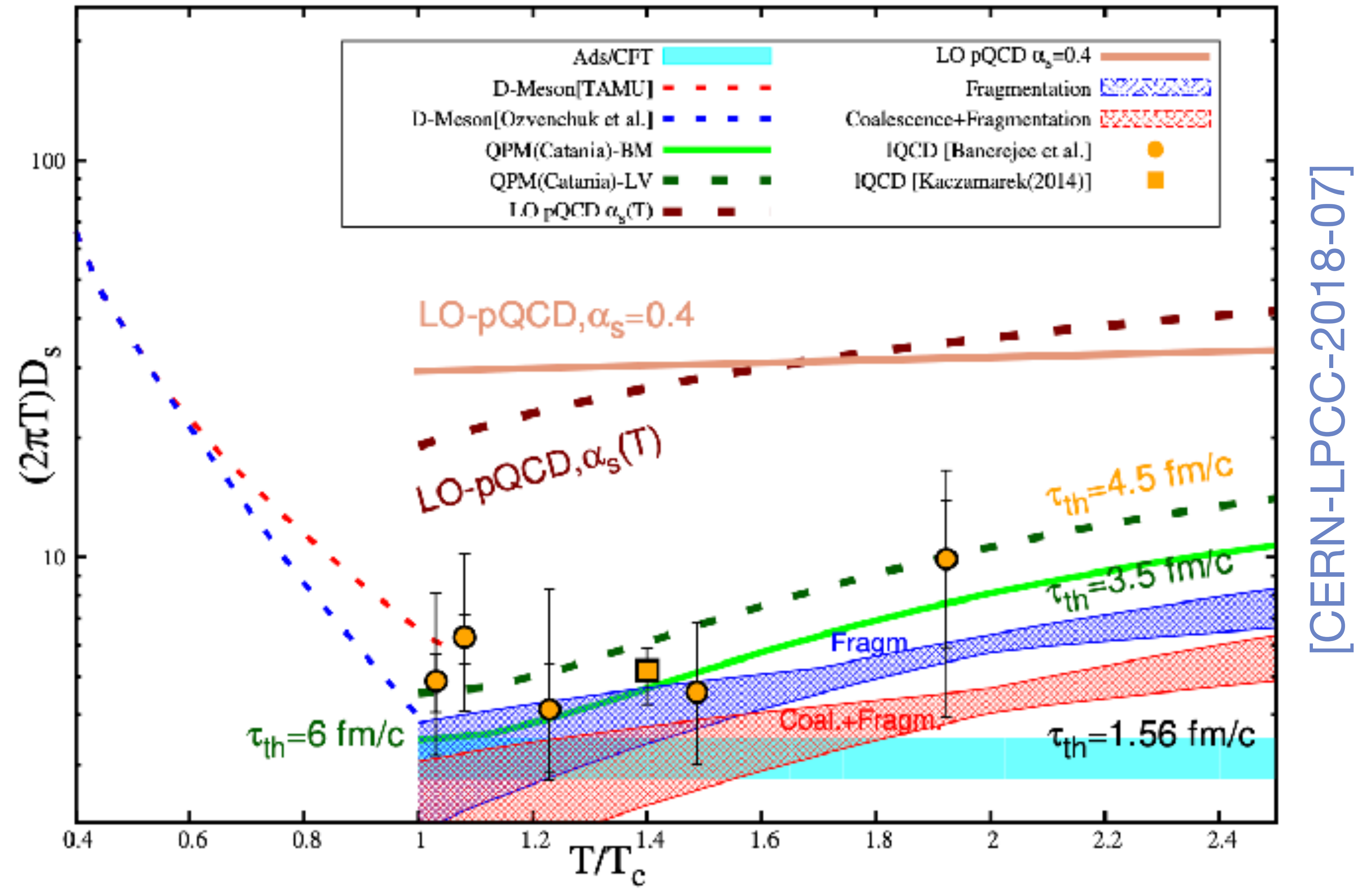
Precise R_{AA} for c and b mesons



v_2 for charm hadrons

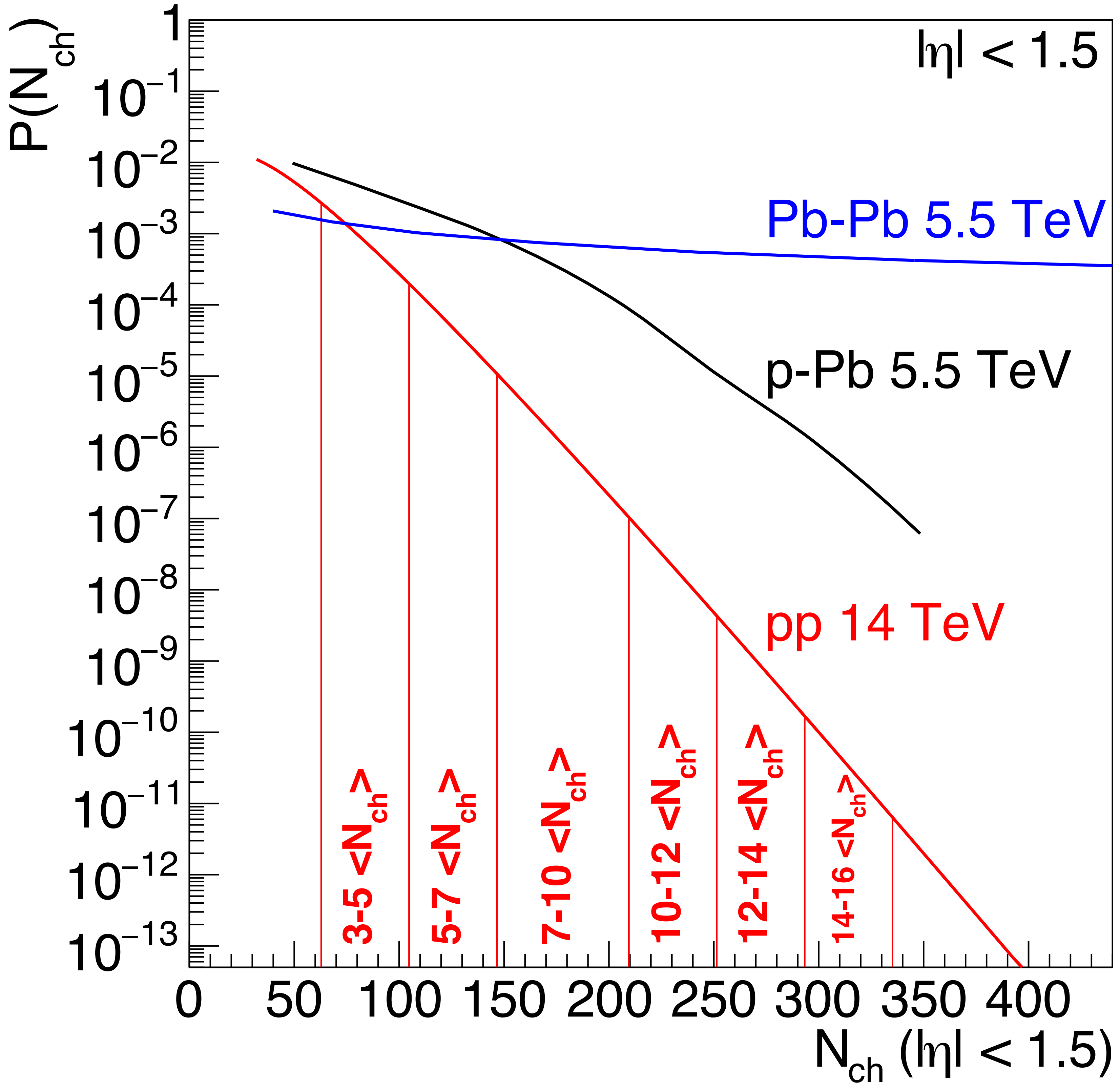


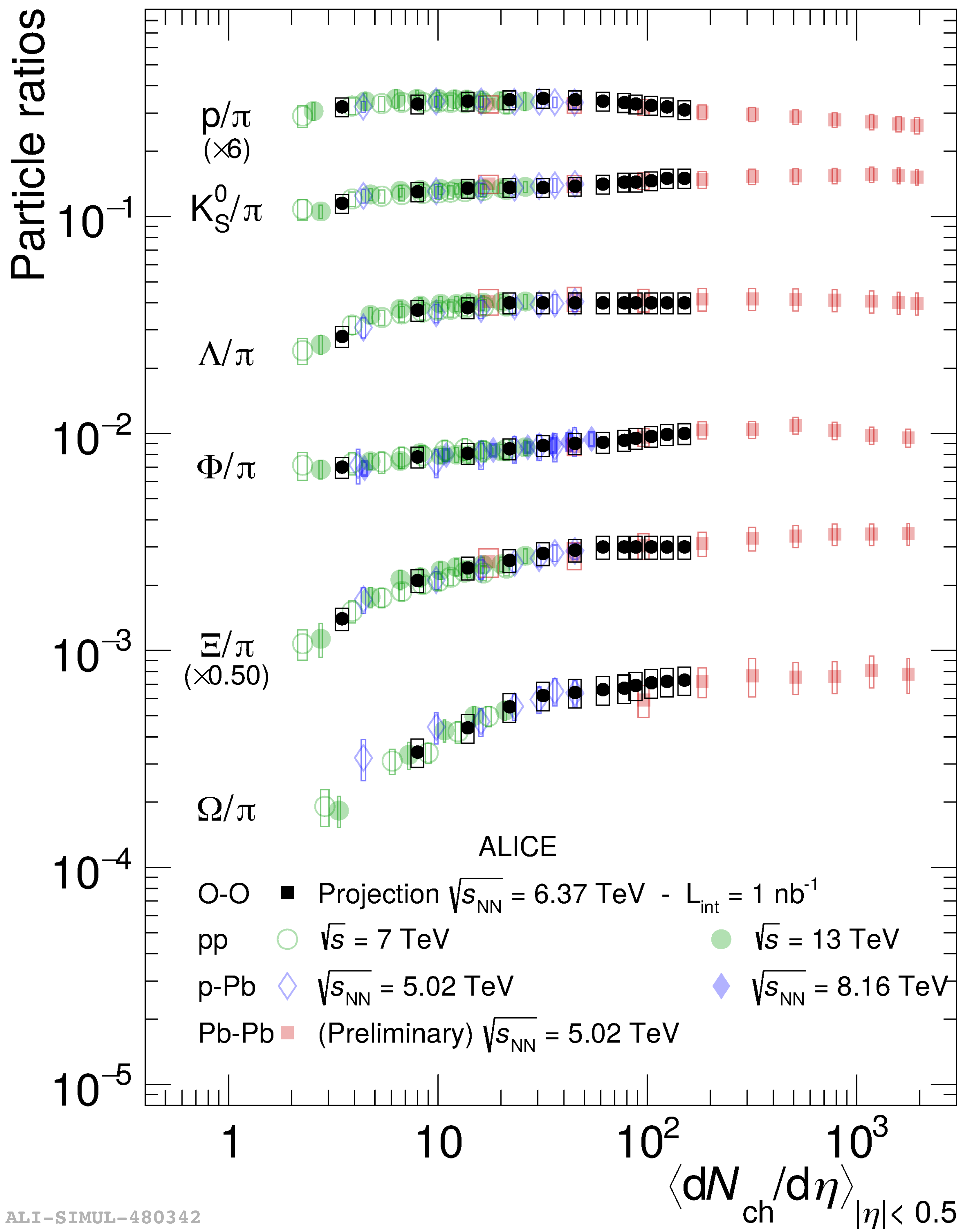
R_{AA} and v_2 → D_s



Small systems

- **Understand evolution from small to large systems**
  → systematic measurements of flow and particle production
  → large high-multiplicity pp sample, new collision systems



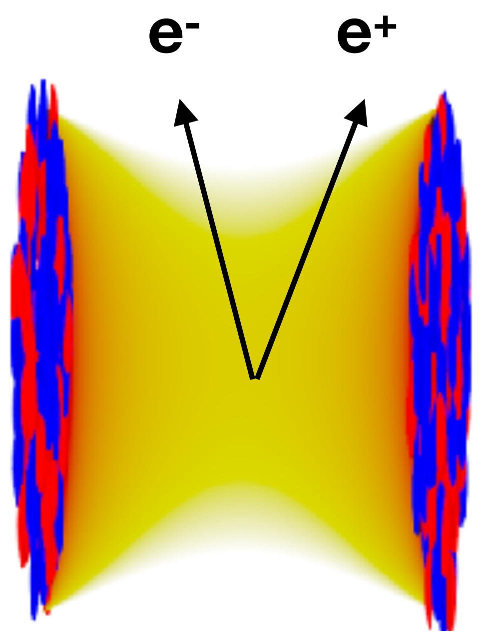


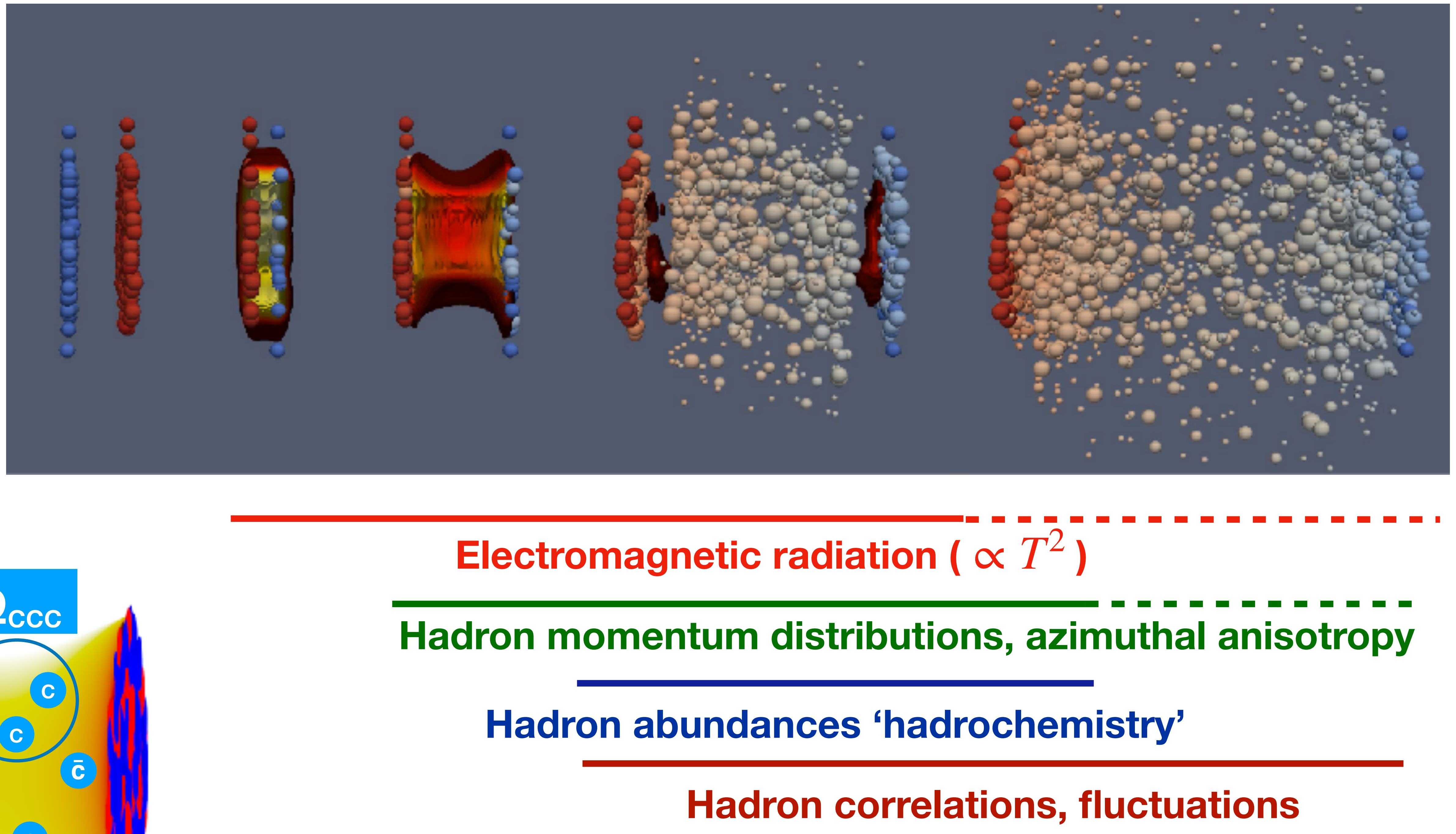
Questions beyond Run 4

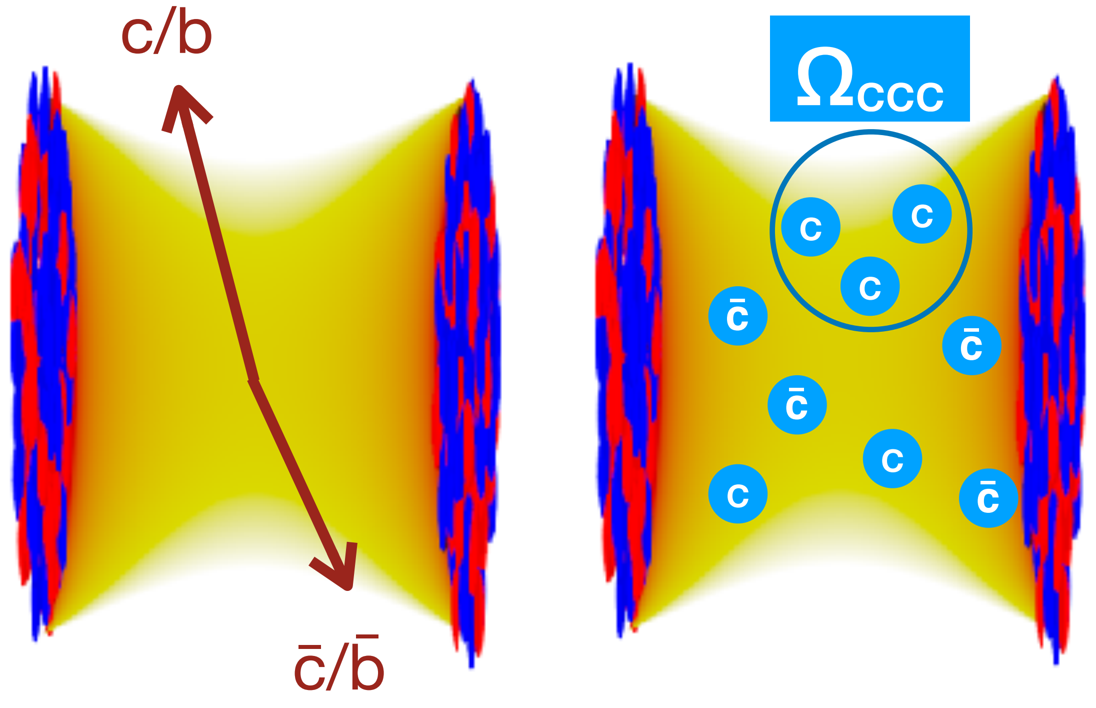
- **Fundamental questions will remain open** after LHC Run 3 & 4
  → next-generation heavy-ion programme for LHC Run 5 & 6
  - What is the nature of interactions between highly energetic quarks and gluons and the quark-gluon plasma?
  - To what extent do quarks of different mass reach thermal equilibrium?
  - How do quarks and gluons transition to hadrons as the quark-gluon plasma cools down?
  - What are the mechanisms for the restoration of chiral symmetry in the quark-gluon plasma?
- **Heavy-ion programme for Run 5 & 6 opens many more opportunities**

Measurements beyond Run 4

- Further progress relies on
  - **precision measurements of dileptons**
    - ➡ evolution of the quark gluon plasma
    - ➡ mechanisms of chiral symmetry restoration in the quark-gluon plasma
  - **systematic measurements of (multi-)heavy-flavoured hadrons**
    - ➡ transport properties in the quark-gluon plasma
    - ➡ mechanisms of hadronisation from the quark-gluon plasma
  - **hadron correlations**
    - ➡ interaction potentials
    - ➡ fluctuations
  - …

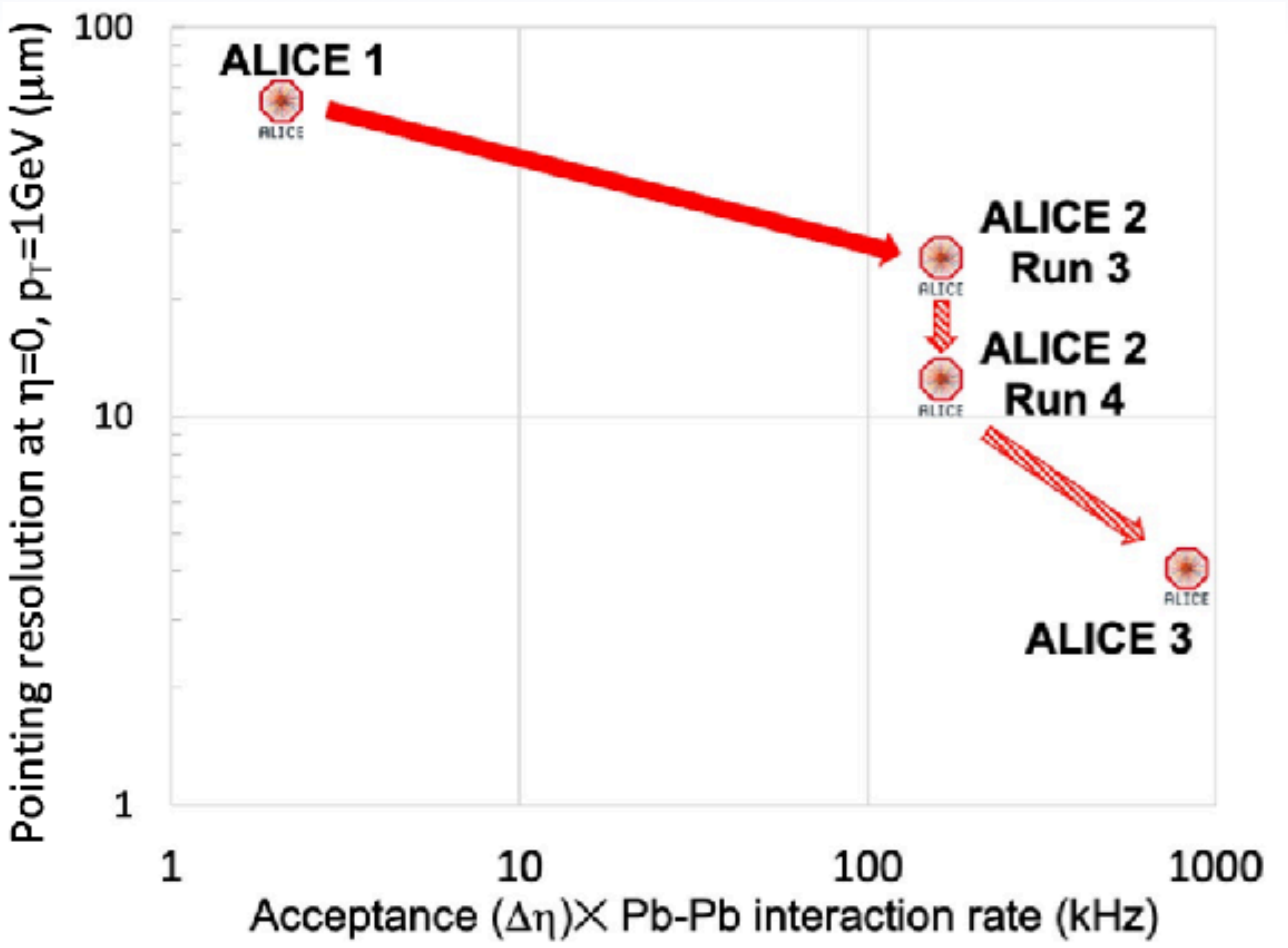






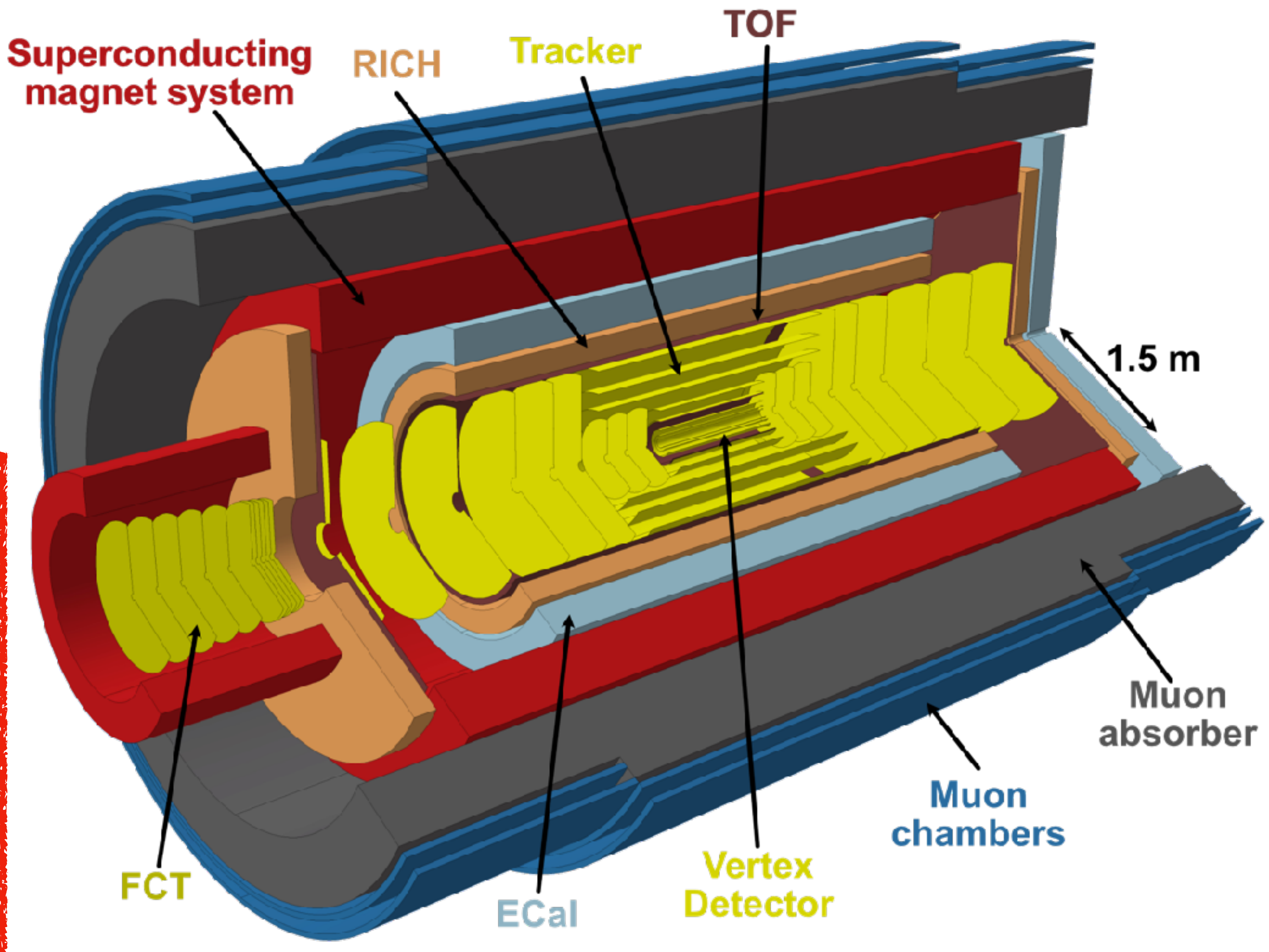
Heavy-ion collisions exhibit rich phenomenology
and give access to many more topics,
e.g. collective effects, BSM searches, …

ALICE 3



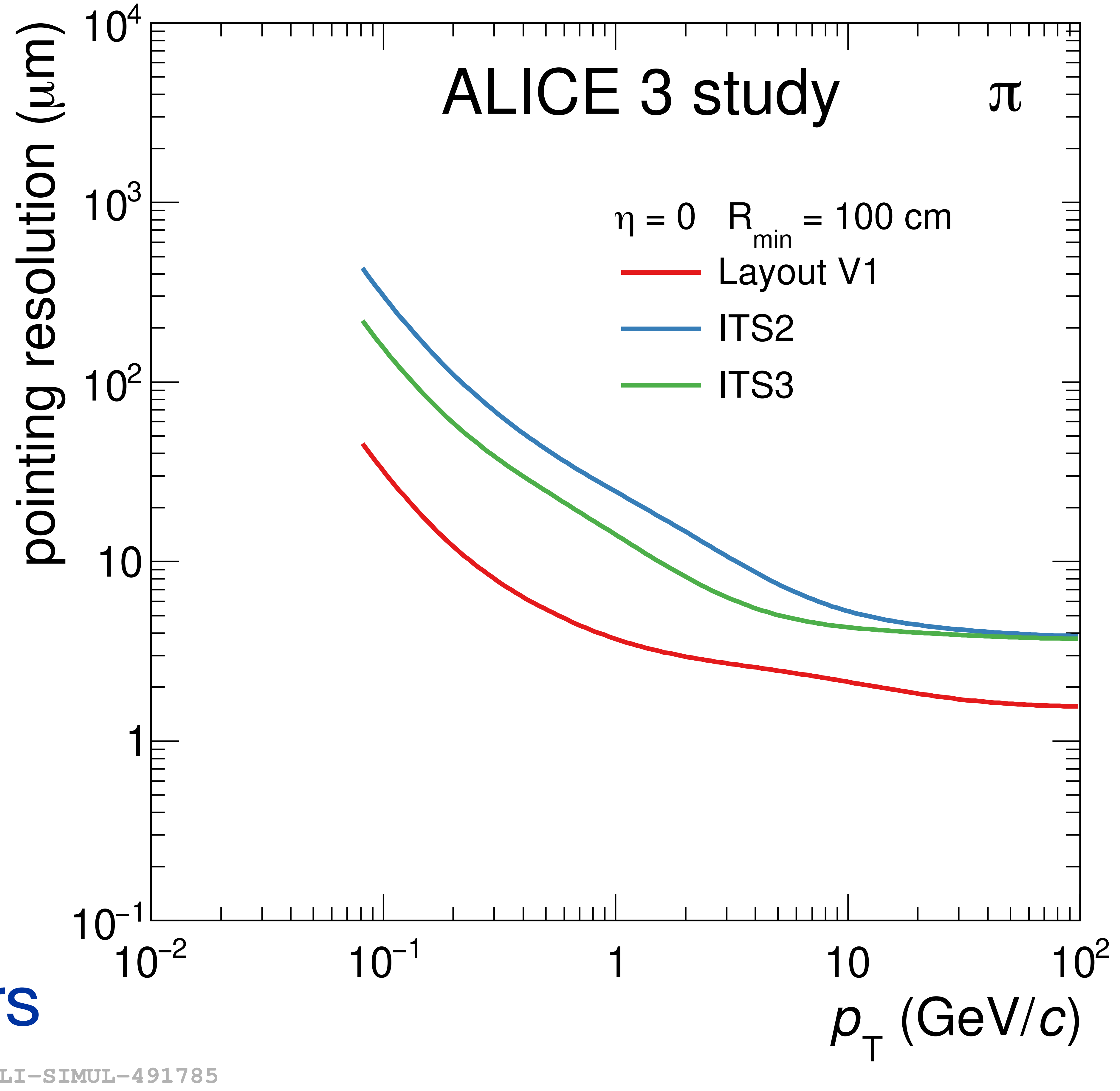
Novel and innovative detector concept

- Compact and lightweight all-silicon tracker
- Retractable vertex detector
- Extensive particle identification
- Large acceptance
- Superconducting magnet system
- Continuous read-out and online processing



Vertexing

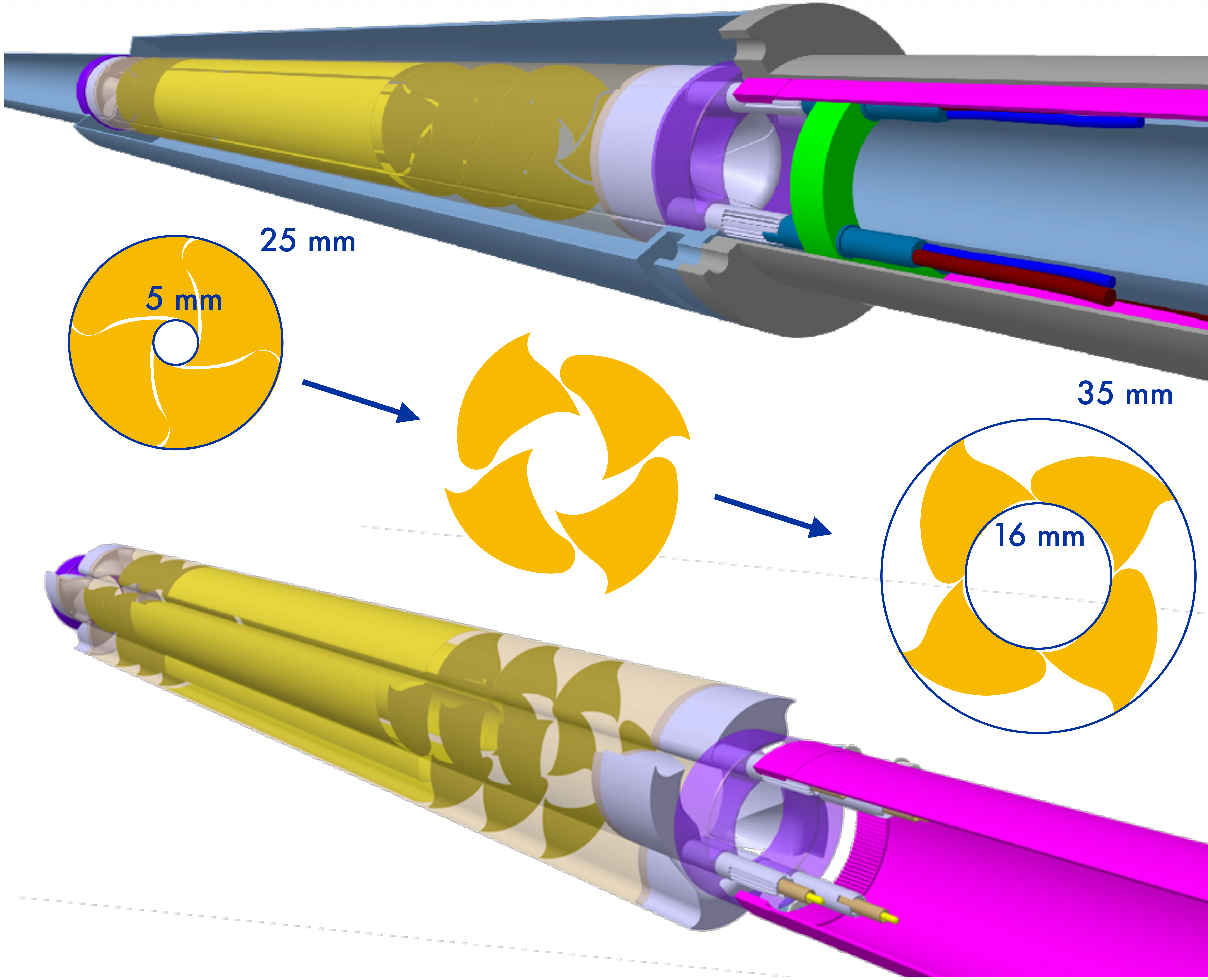
- **Pointing resolution** $\propto r_0 \cdot \sqrt{x/X_0}$ (multiple scattering regime)
  ➟ 10 µm @ p_T = 200 MeV/*c*
  - radius and material of first layer crucial
  - minimal radius given by required aperture:
    R ≈ 5 mm at top energy,
    R ≈ 15 mm at injection energy
    → **retractable vertex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



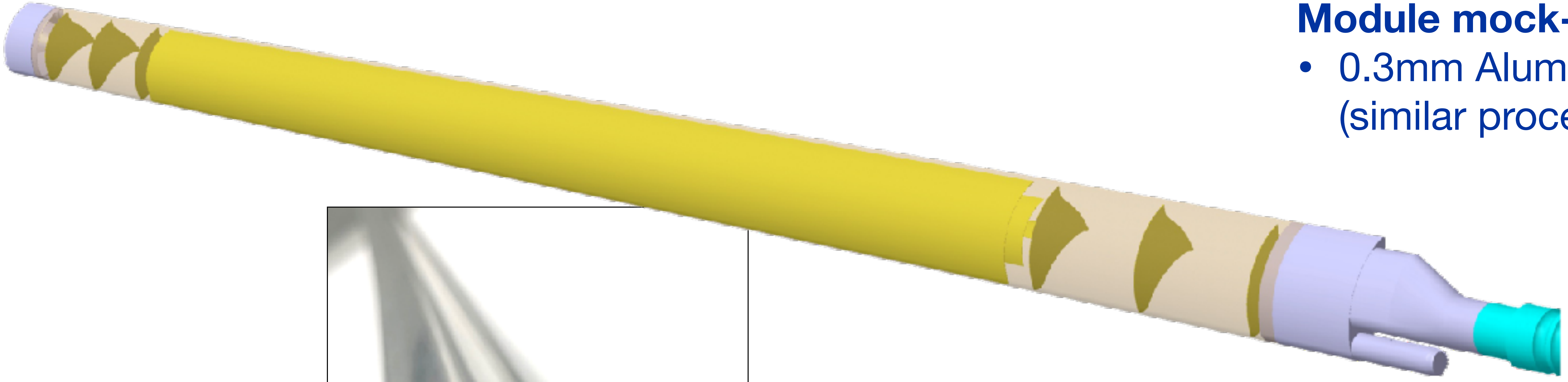
5x better than ALICE 2.1 (ITS3 + TPC)

Vertex Detector

- **Conceptual study**
  - wafer-sized, bent MAPS (leveraging on ITS3 activities)
  - rotary petals for sensors and secondary vacuum
  - matching of petals to beam pipe parameters
  - feed-throughs for power, cooling, data
- **R&D challenges** on mechanics, cooling, radiation tolerance



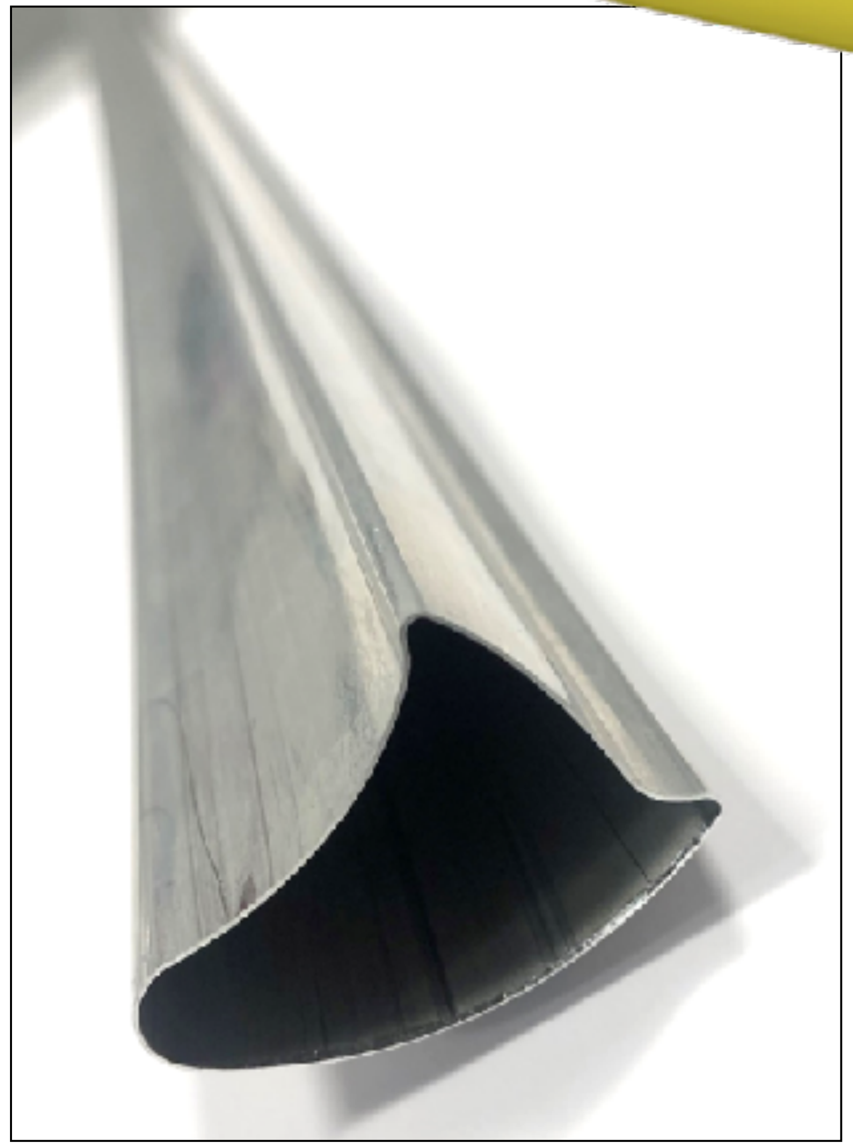
Vertex detector (mechanics)

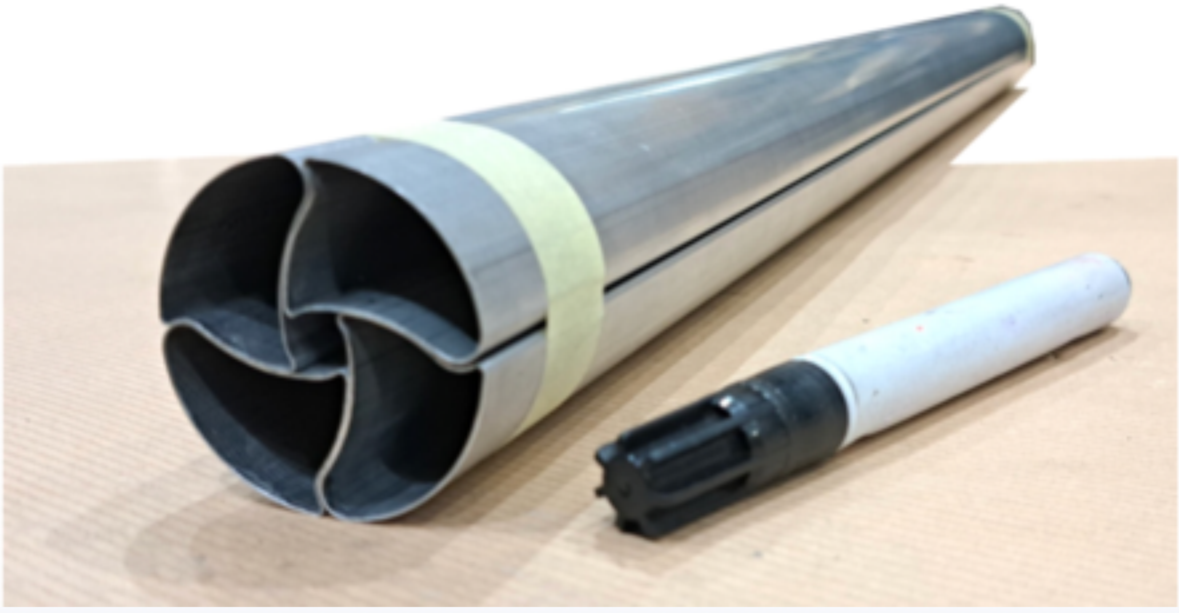


Module mock-up

- 0.3mm Aluminum foil welded and formed (similar process done at CERN with Al bellow 0.2 mm - R&D)

extruded aluminium (procedure also used in beampipe)



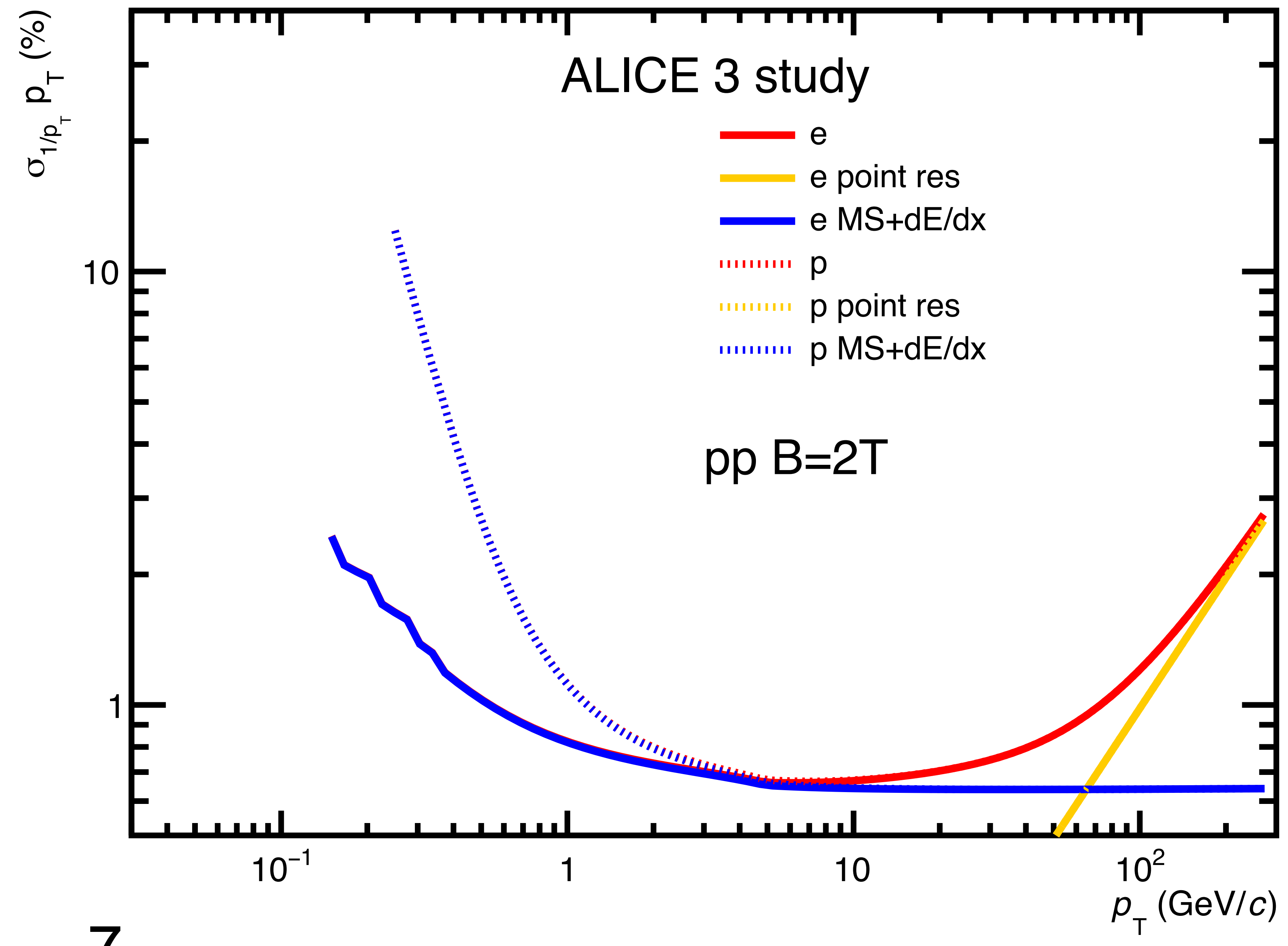


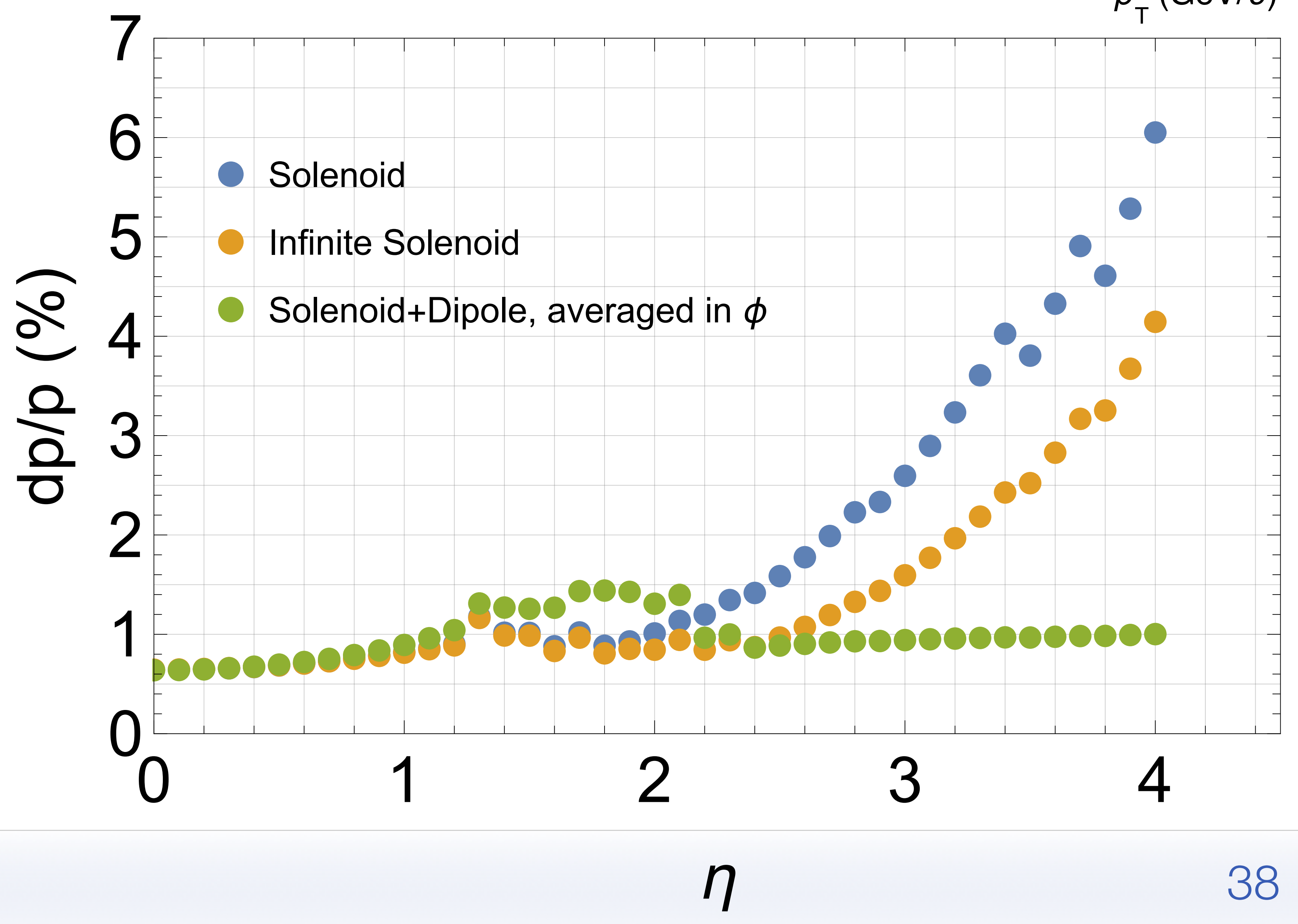
3d-printed aluminum

Tracking

- **Relative p_T resolution** $\propto \dfrac{\sqrt{x/X_0}}{B \cdot L}$
  (limited by multiple scattering)
  ➡ ~1 % up to η = 4
  - integrated magnetic field crucial
  - overall material budget critical

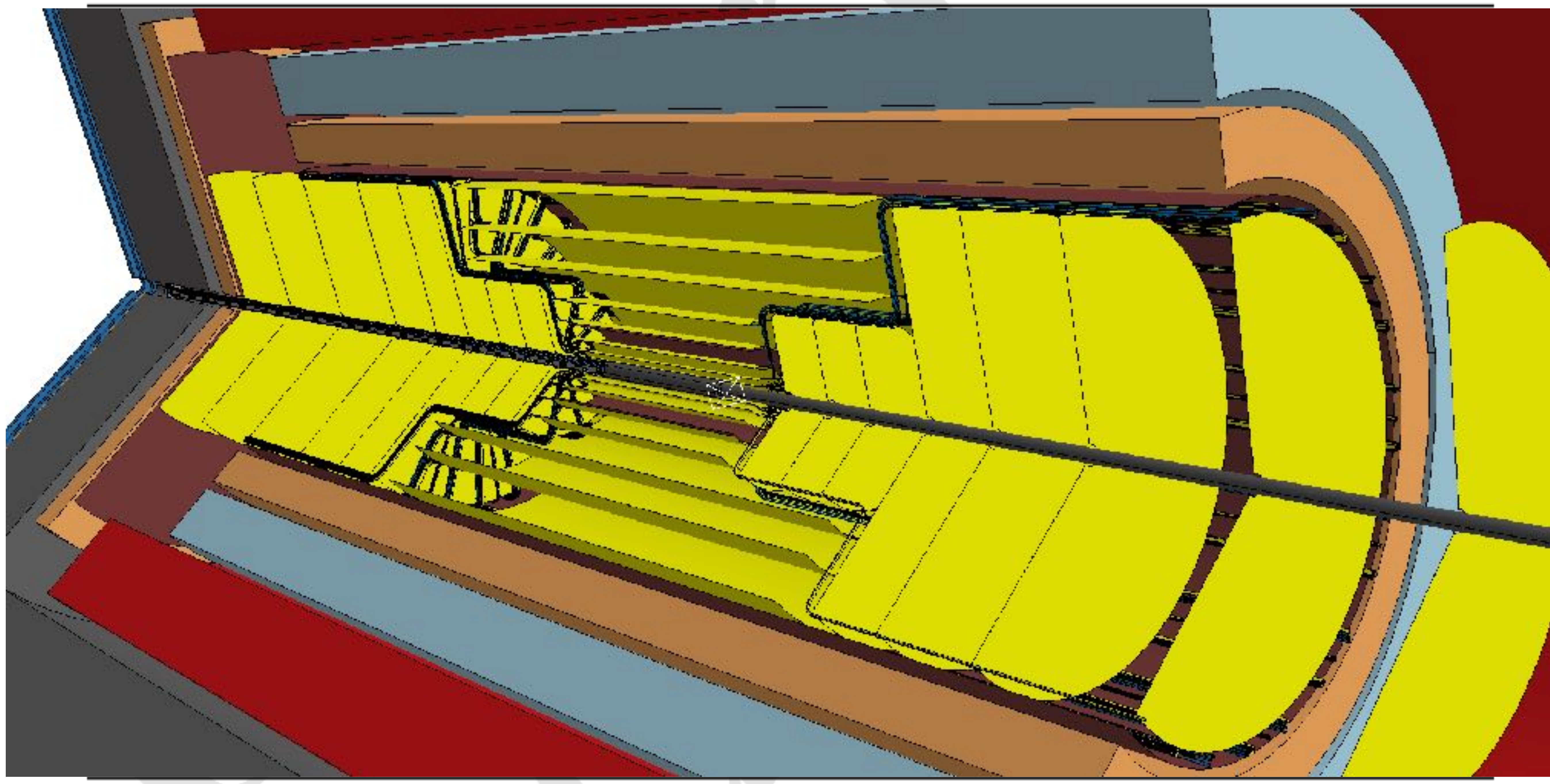
- **~11 tracking layers (barrel + disks)**
  - MAPS
  - σ_{pos} ~10 µm → 50 µm pixel pitch
  - R_{out} ≈ 80 cm and L ≈ 4 m (→ magnetic field integral ~1 Tm)
  - timing resolution ~100 ns (→ reduce mismatch probability)
  - material ~1 % X_0 / layer → overall X/X_0 = ~10 %

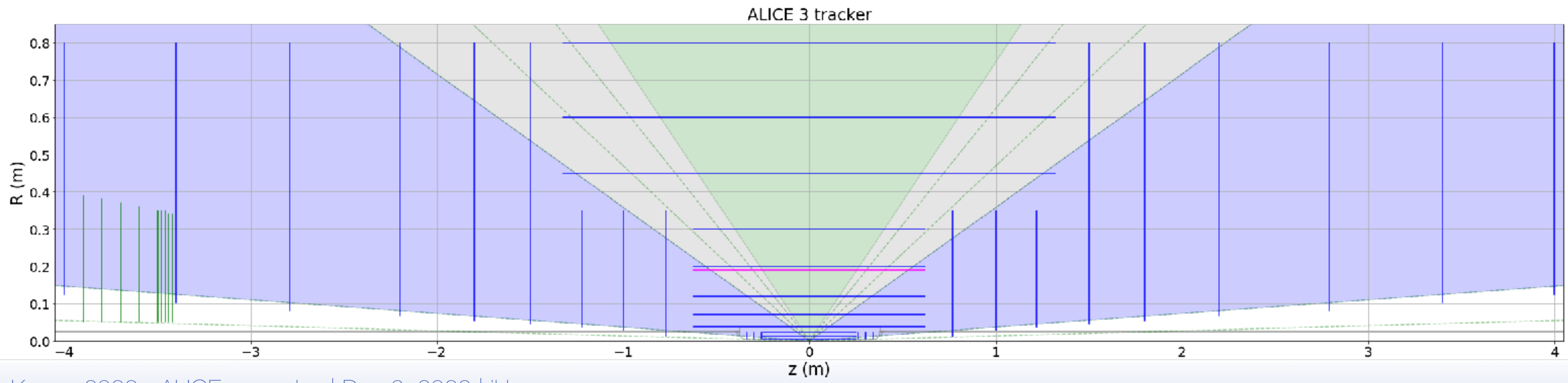




Outer Tracker

- MAPS on modules on water-cooled carbon-fibre cold plate
- carbon-fibre space frame for mechanical support
- **R&D challenges** on
  - powering scheme (→ material)
  - industrialisation



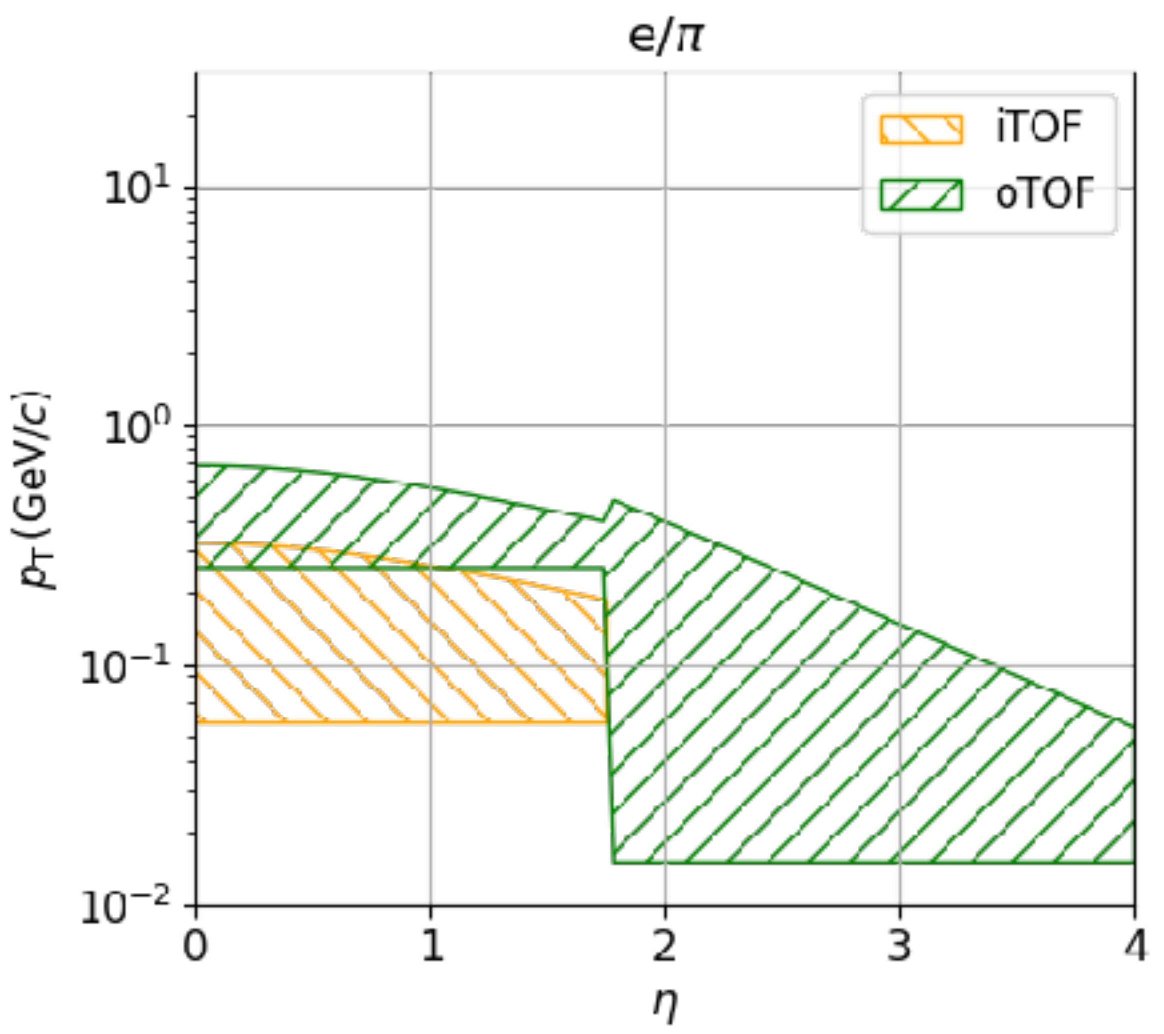


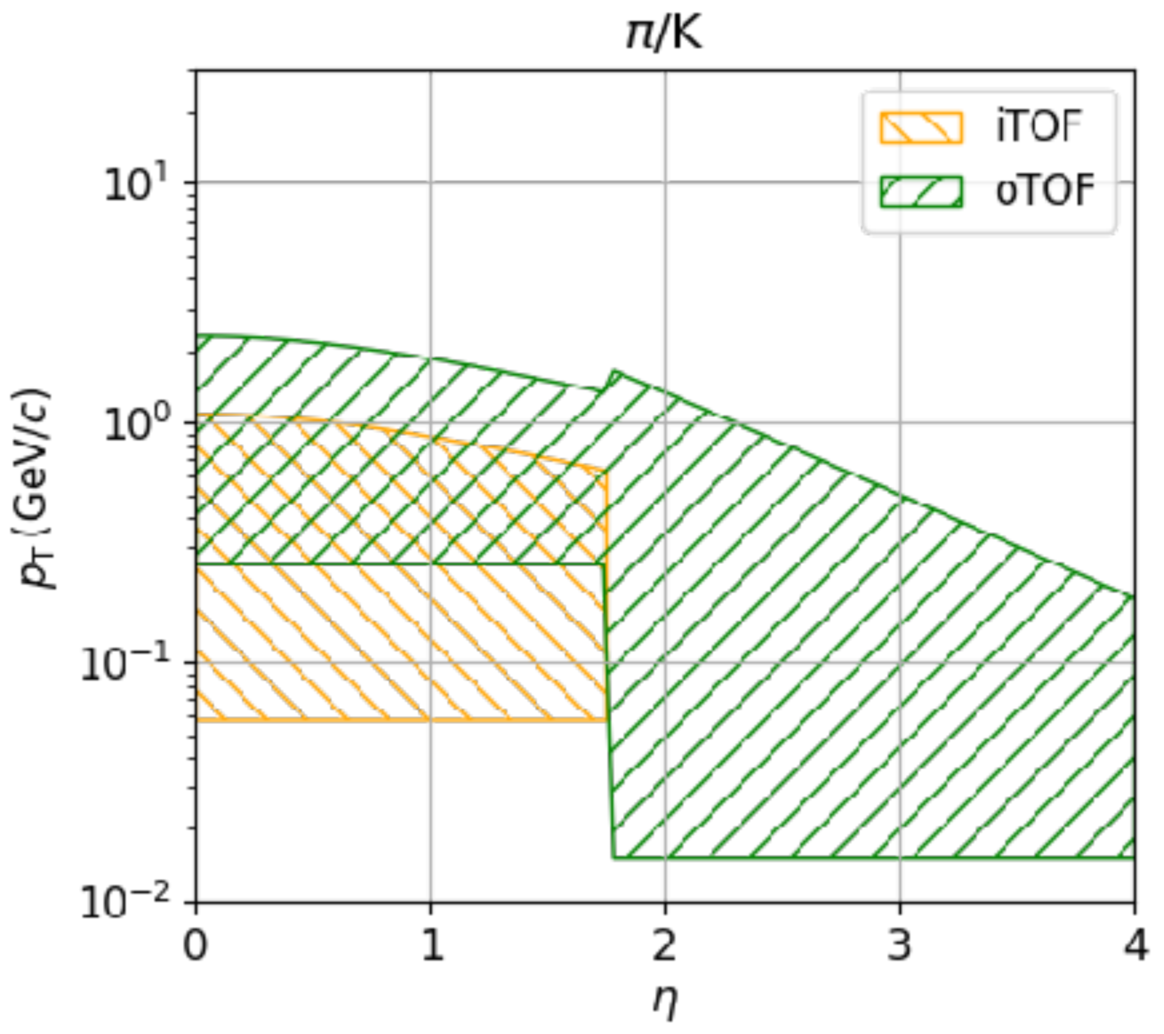
Total silicon surface ~60 m²

Time of flight

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

Total silicon surface ~45 m²

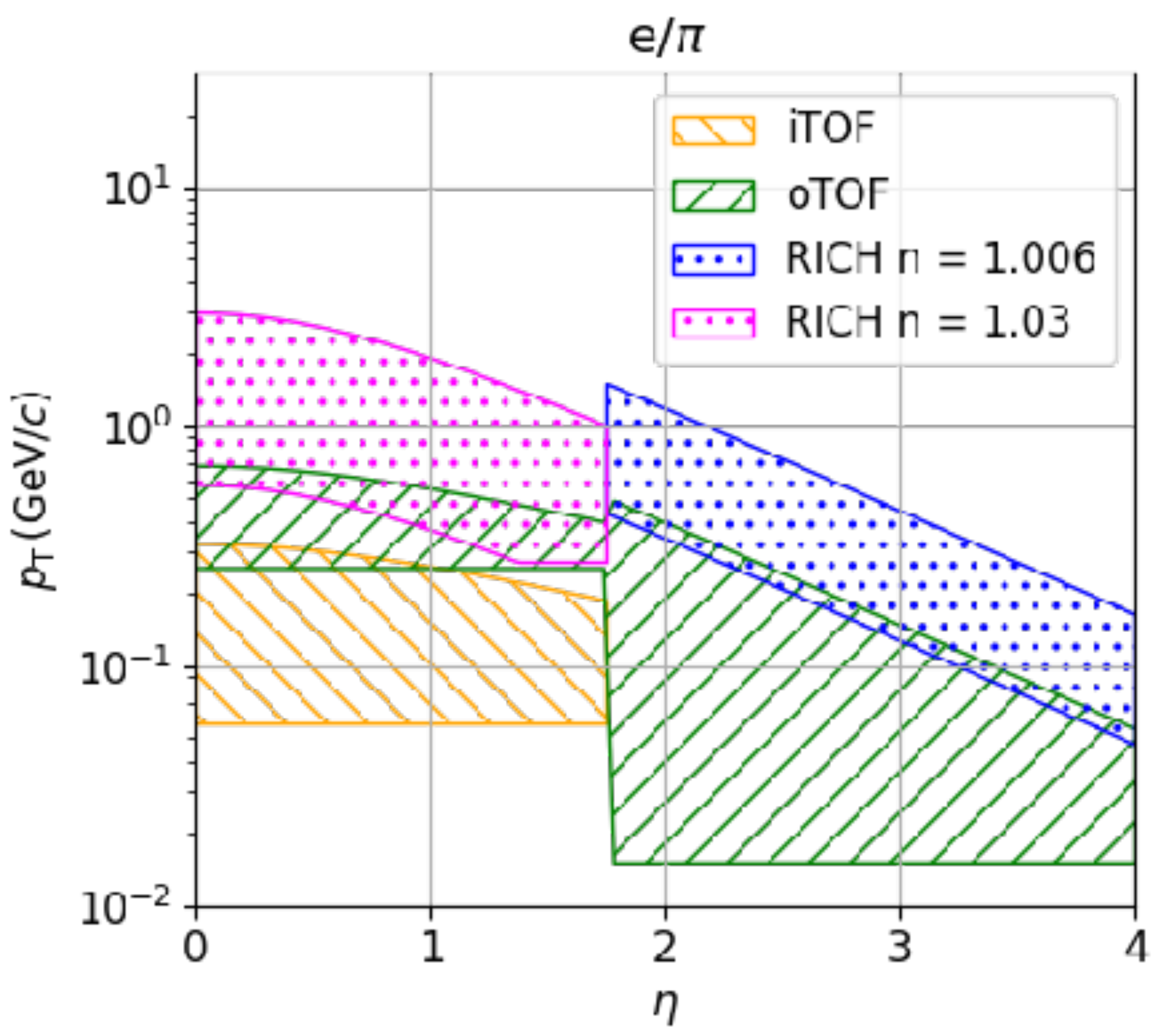


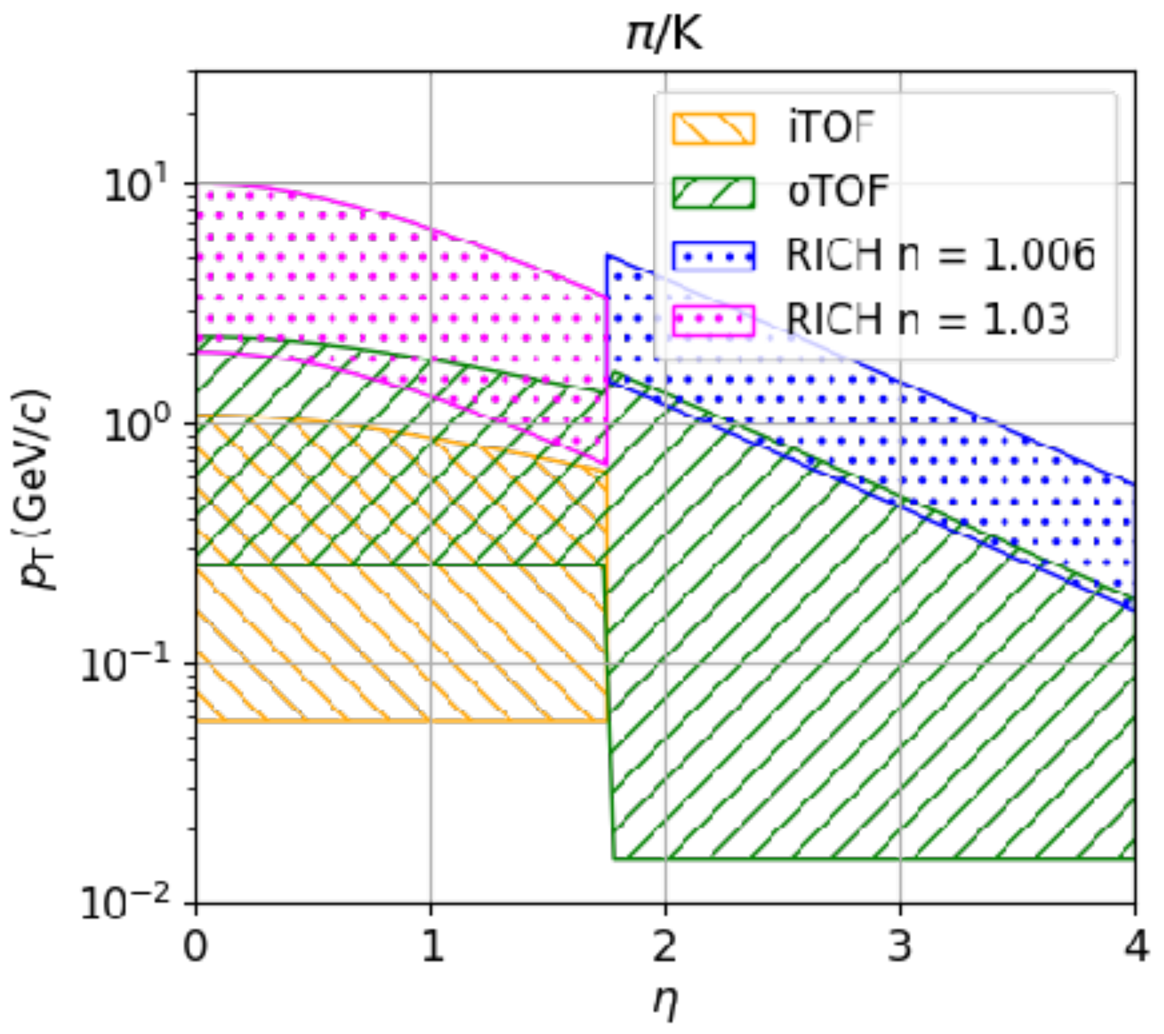


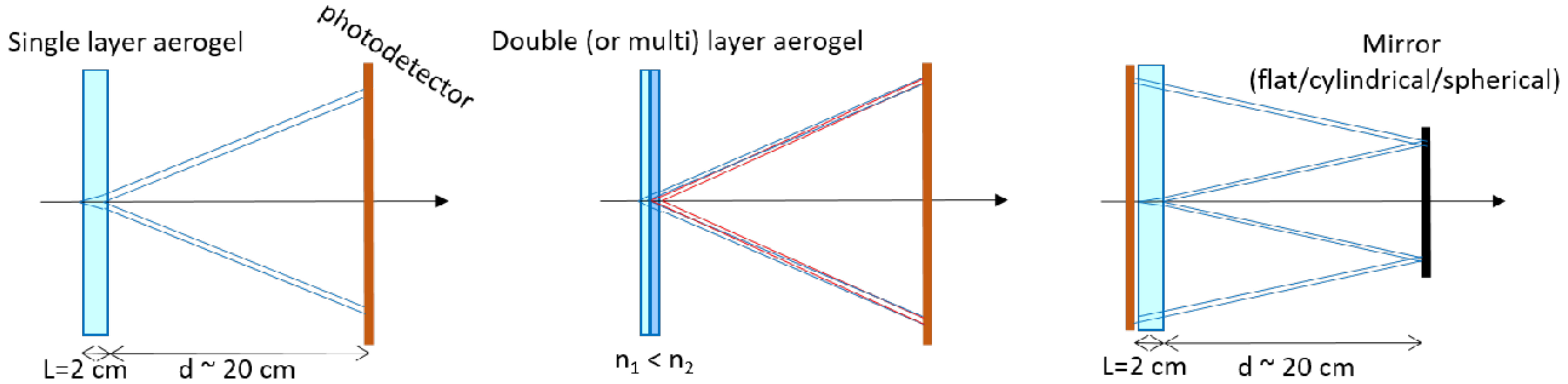
Ring-Imaging Cherenkov

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

Total SiPM surface ~60 m²





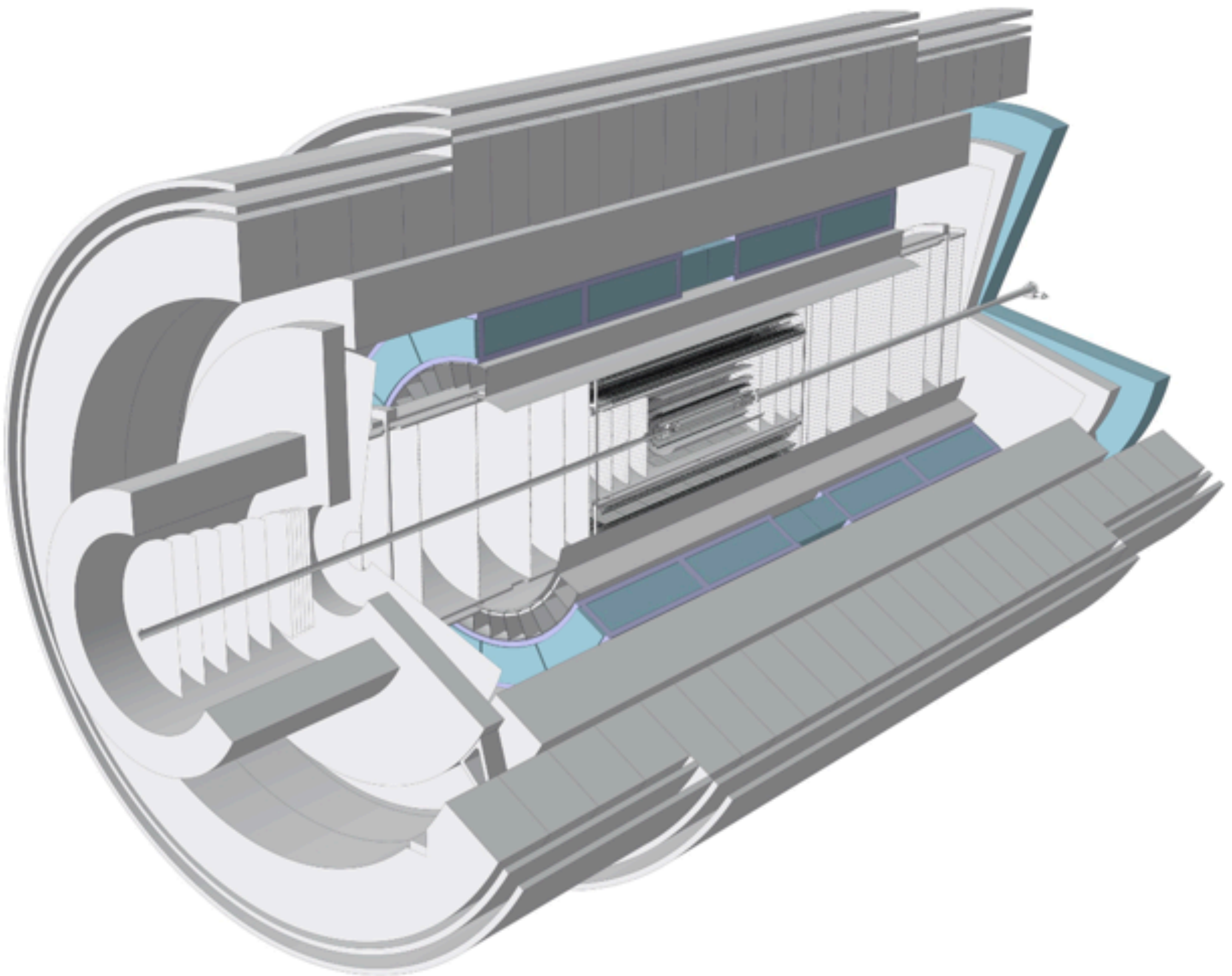


Electromagnetic calorimeter

- **Large acceptance calorimeter**
  → sampling calorimeter (à la EMCal/DCal):
  e.g. O(100) layers (1 mm Pb + 1.5 mm plastic scintillator)

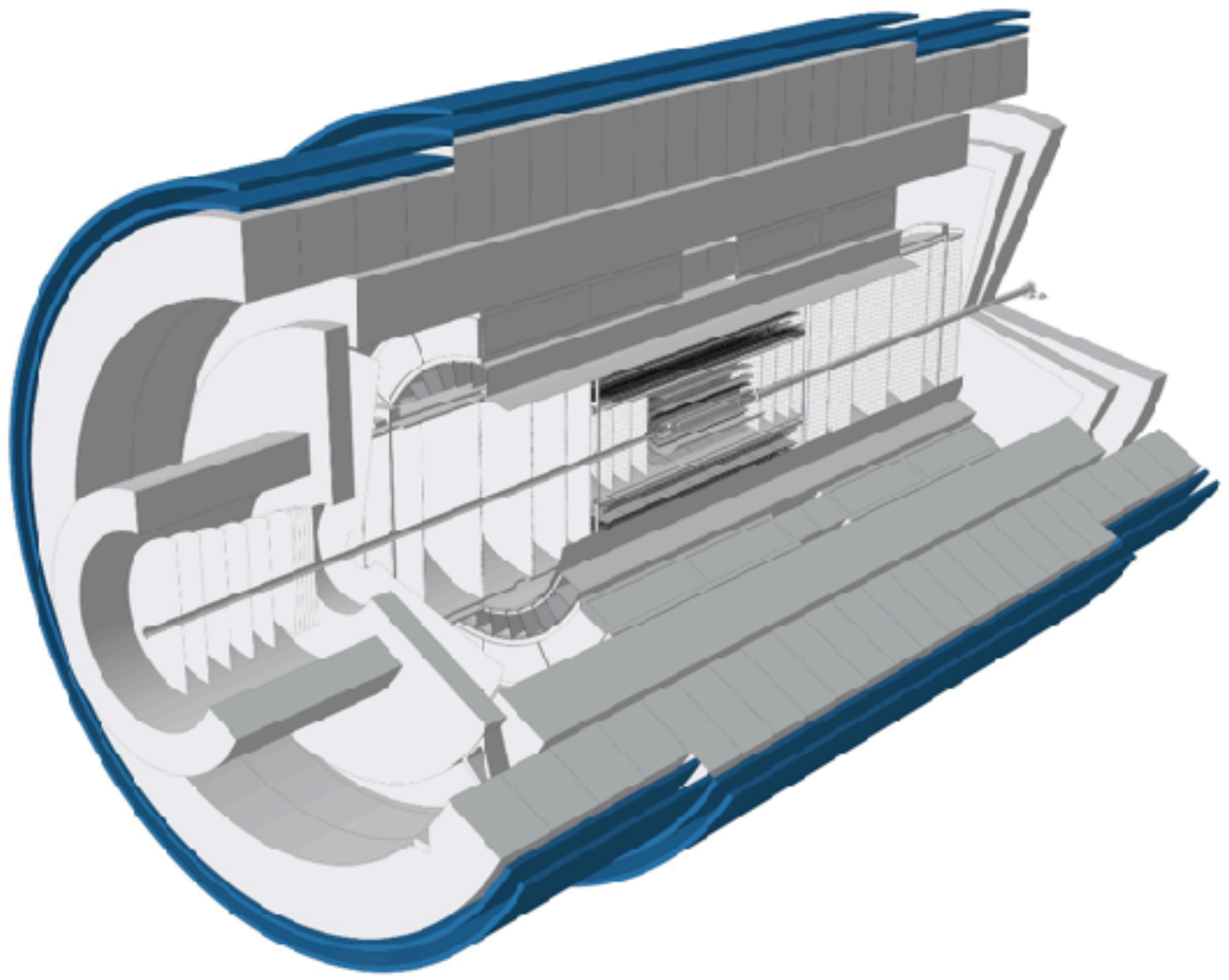
- **Additional high energy resolution segment** at midrapidity or forward
  → $PbWO_4$-based

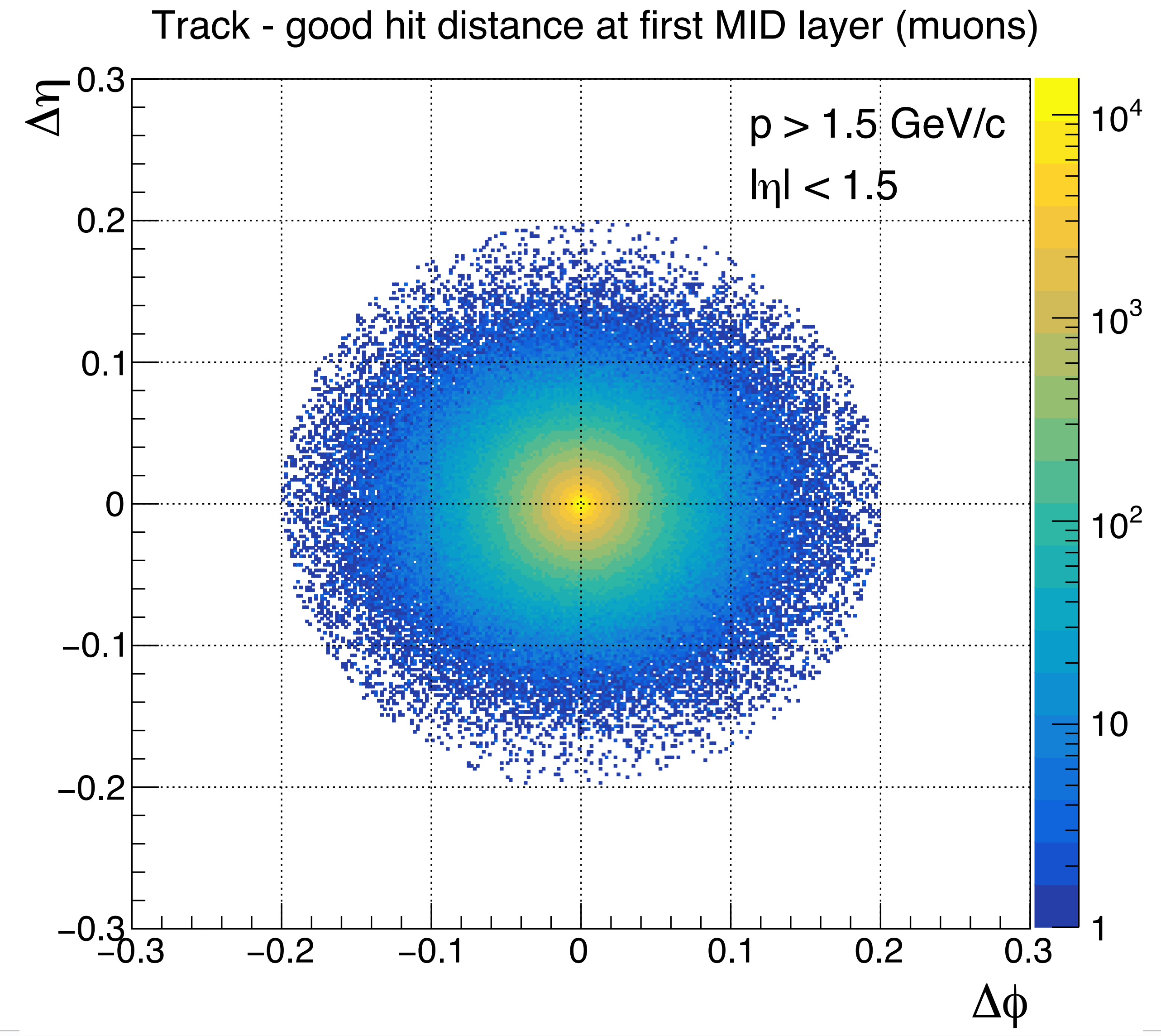
ECal module	Barrel sampling	Endcap sampling	Barrel high-precision
acceptance	$\Delta\varphi = 2\pi$, $\lvert\eta\rvert < 1.5$	$\Delta\varphi = 2\pi$, $1.5 < \eta < 4$	$\Delta\varphi = 2\pi$, $\lvert\eta\rvert < 0.33$
geometry	$R_{in} = 1.15$ m, $\lvert z\rvert < 2.7$ m	$0.16 < R < 1.8$ m, $z = 4.35$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



Muon ID

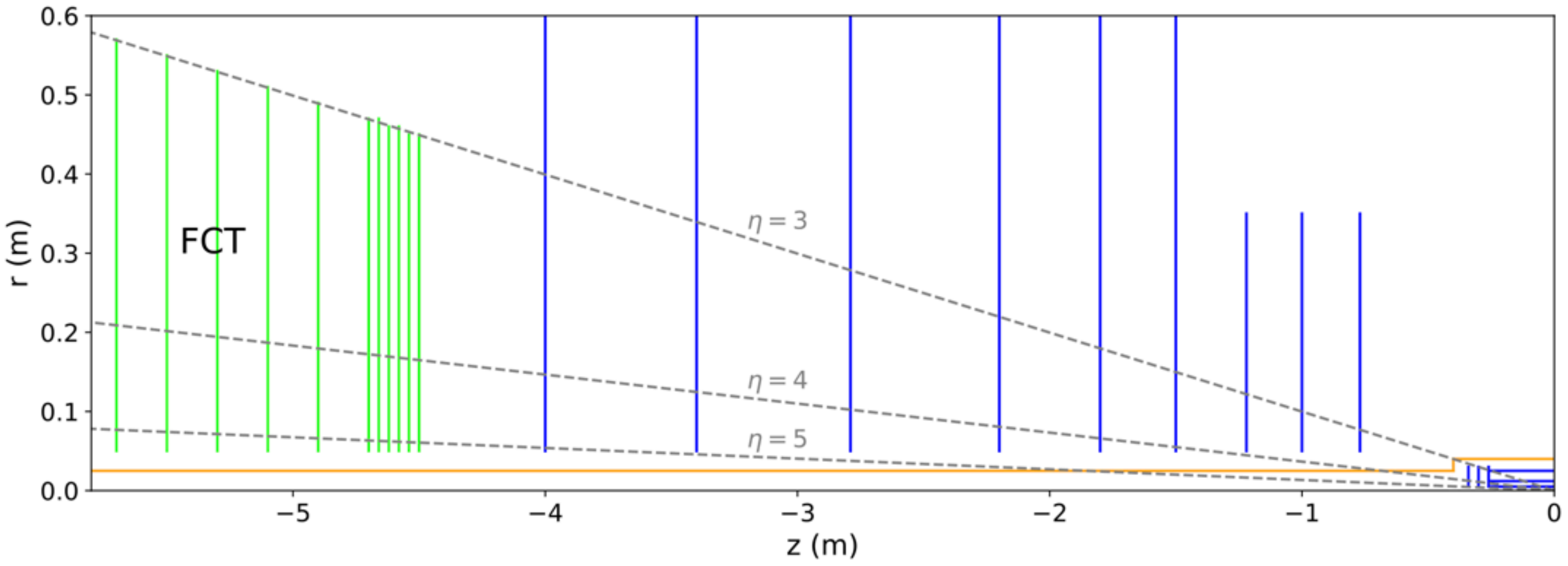
- **Hadron absorber** outside of the magnet
  - ~70 cm non-magnetic steel
- **Muon chambers**
  - search spot for muons ~0.1 x 0.1 (eta x phi) → ~5 x 5 cm² cell size
  - matching demonstrated with 2 layers of muon chambers
    - scintillator bars with SiPM read-out
    - resistive plate chambers





Forward conversion tracker

- **Thin tracking disks** to cover $3 < \eta < 5$
  - few ‰ of a radiation length per layer
  - position resolution < 10 µm
- **Research & Development**
  - Large area, thin disks
  - Minimisation of material in front of FCT
  - Operational conditions

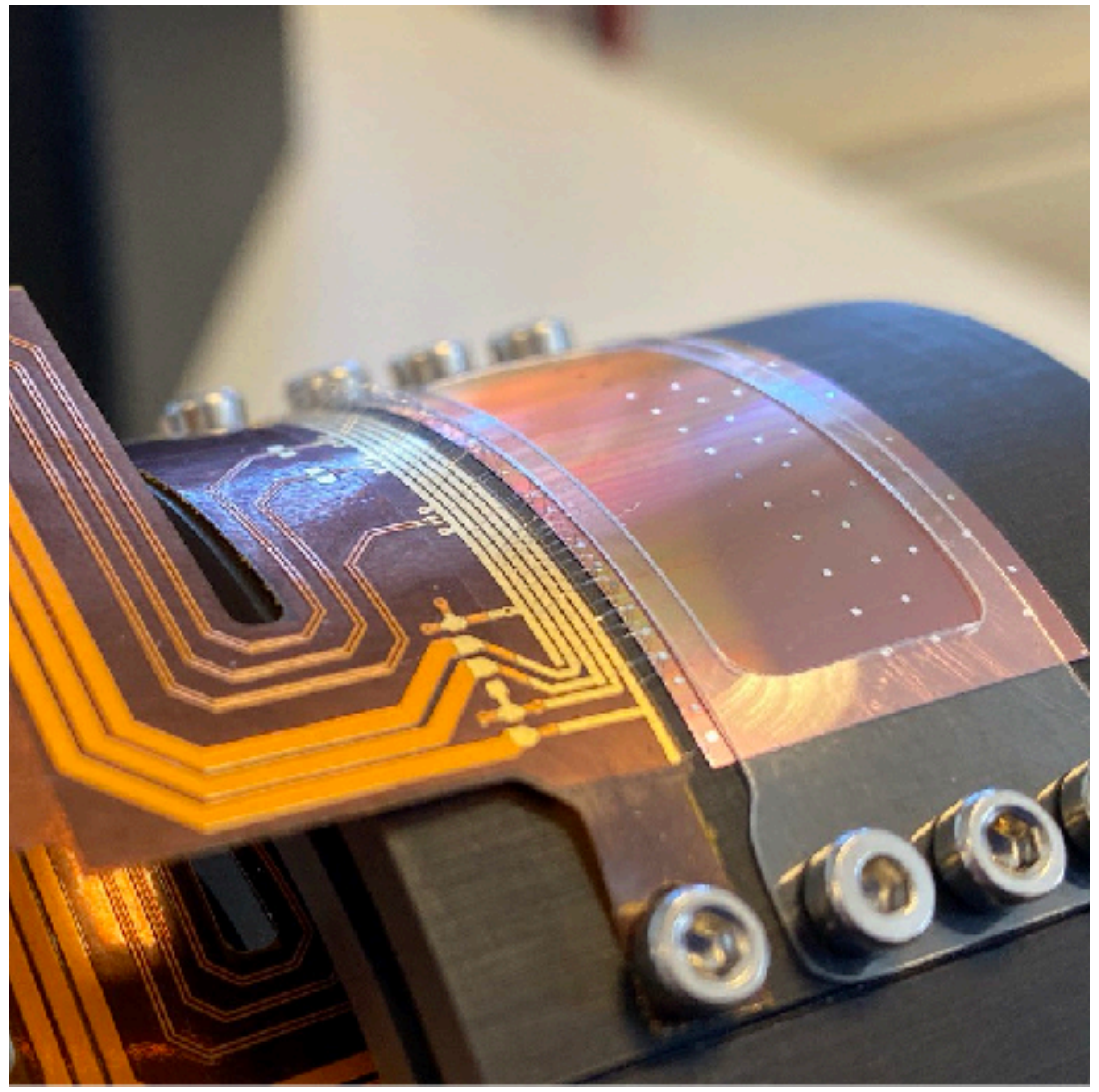


Layer	z (m)	r_{min} (m)	r_{max} (m)
0	−4.50	0.05	0.45
1	−4.54	0.05	0.45
2	−4.58	0.05	0.46
3	−4.62	0.05	0.46
4	−4.66	0.05	0.47
5	−4.70	0.05	0.47
6	−4.90	0.05	0.49
7	−5.10	0.05	0.51
8	−5.30	0.05	0.53
9	−5.50	0.05	0.55
10	−5.70	0.05	0.57

ALICE

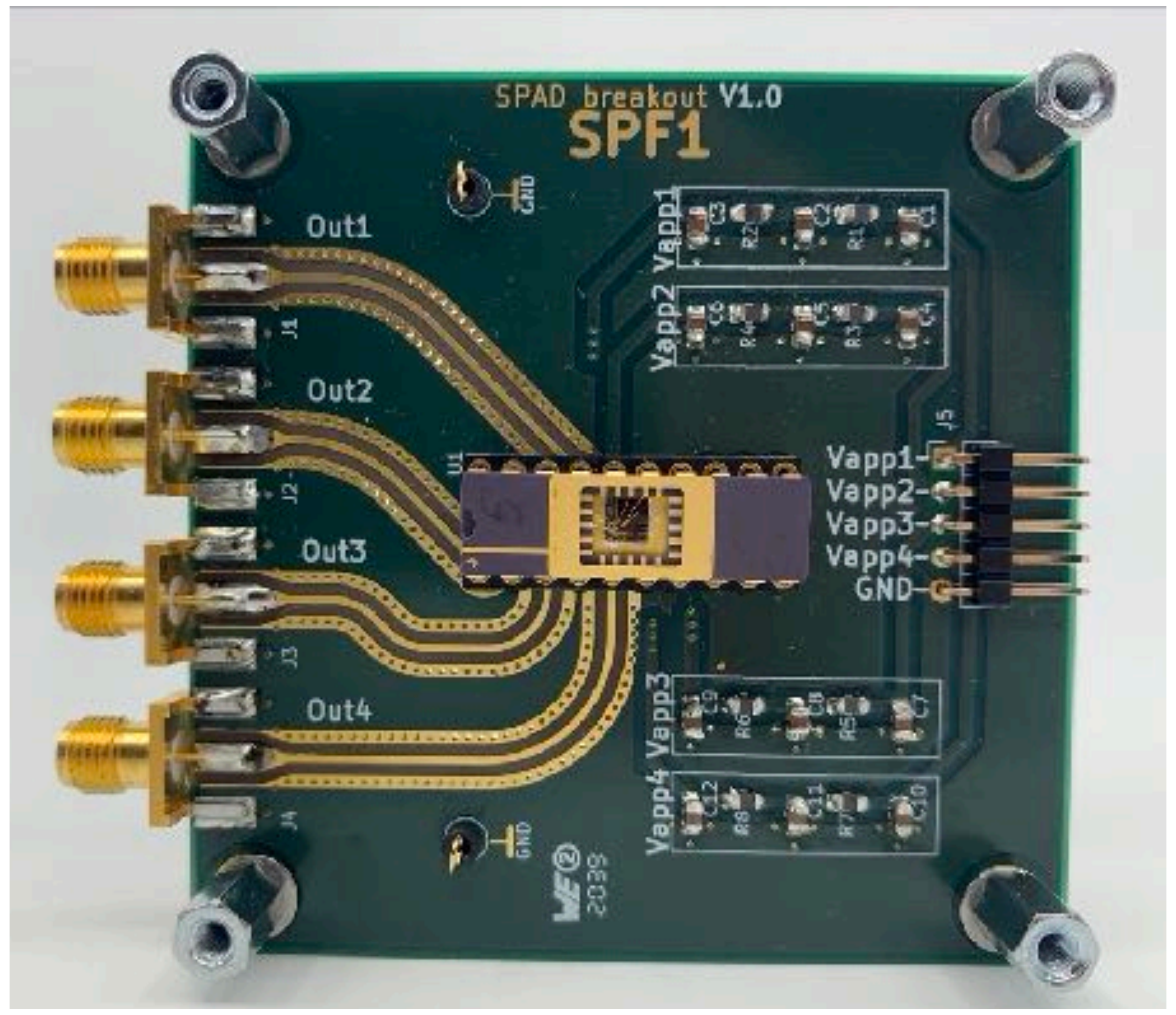
Strategic R&D

- **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
    → first tests in beam
  - monolithic timing sensors
    → implement gain layer
- **Photon sensors**
  - monolithic SiPMs
    → integrate read-out
- **Detector mechanics and cooling**
  - mechanics for operation in beam pipe
    → establish compatible with LHC beam
  - minimisation of material in the active volume
    → micro-channel cooling



Unique technologies

→ also relevant for
LHC, FAIR, EIC, FCC, …

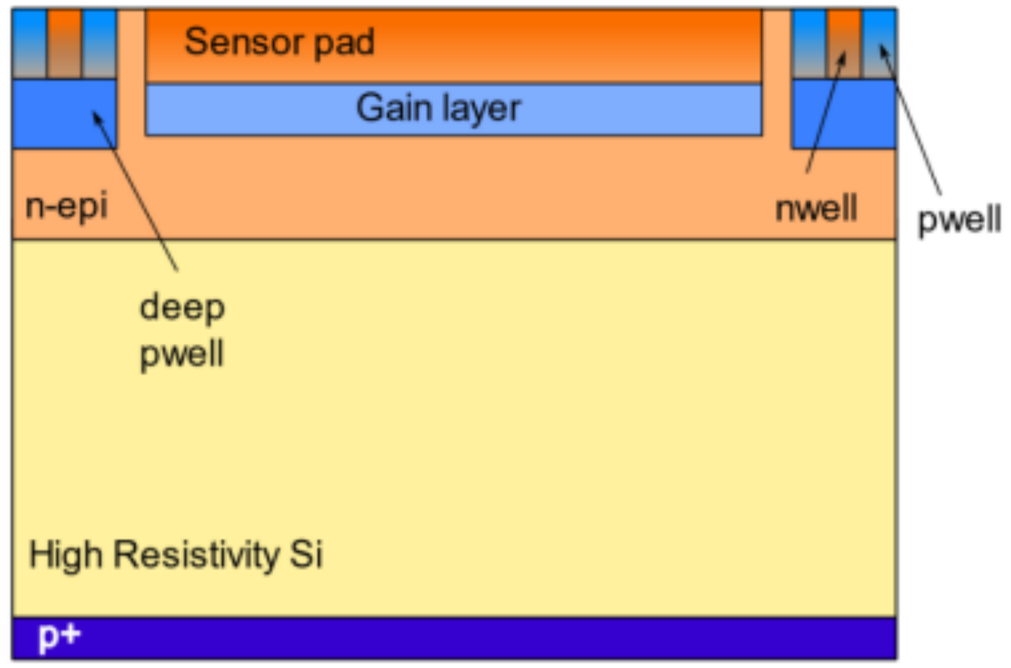


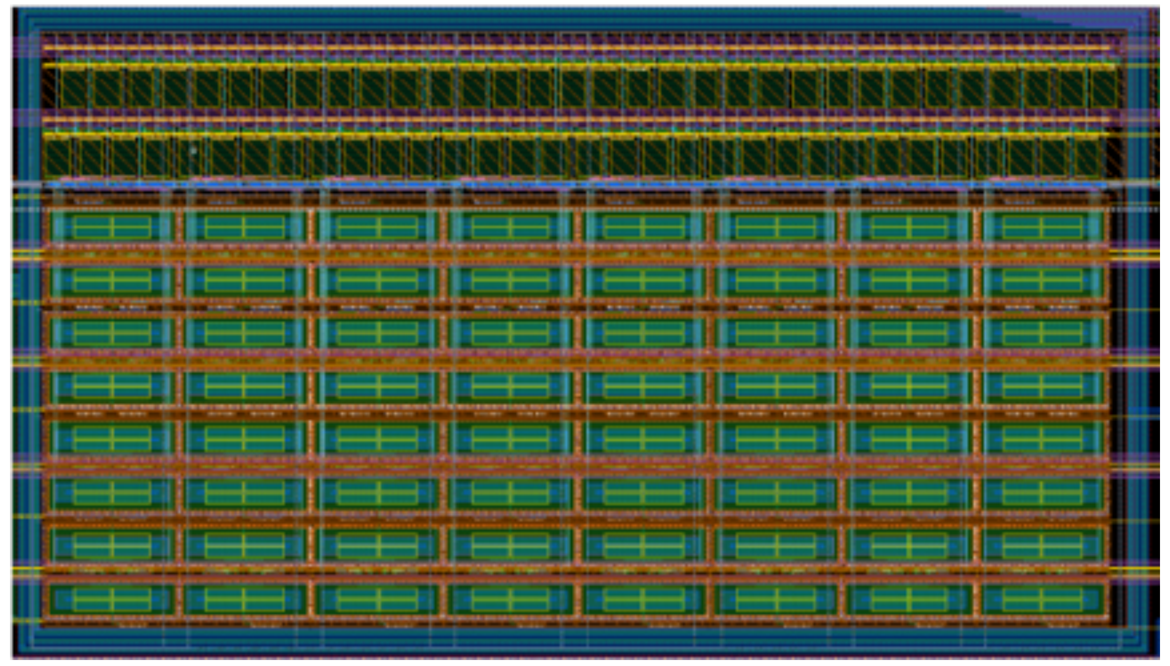
Recent R&D

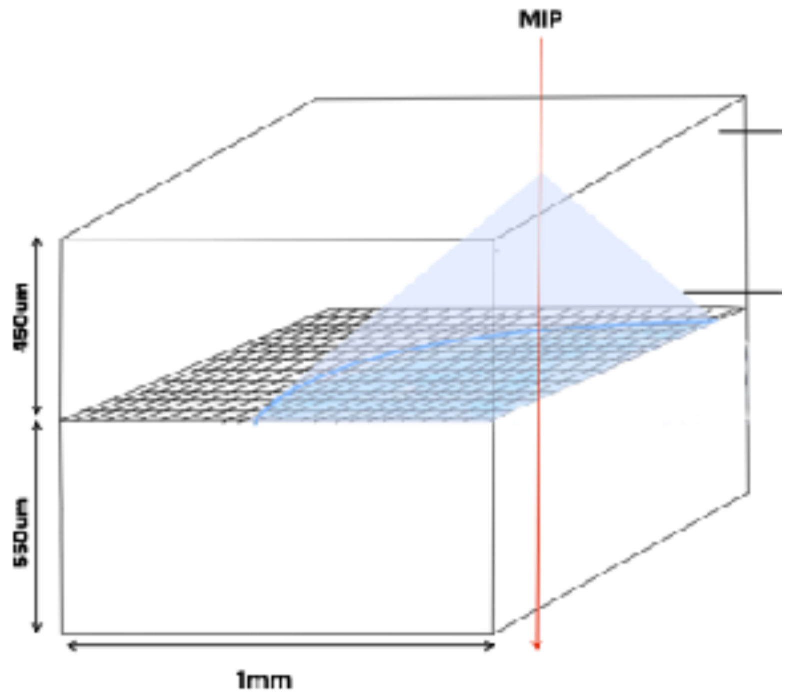
- **Monolithic pixels sensors**
  → see ITS3

- **Monolithic timing sensor**
  - demonstrator with gain layer submitted to L-foundry process
  - sensors expected back in January

- **SiPMs for charged particle detection**
  - characterisation in beam tests
  - Cherenkov radiation in protection layer
  - multiple hits improve time resolution

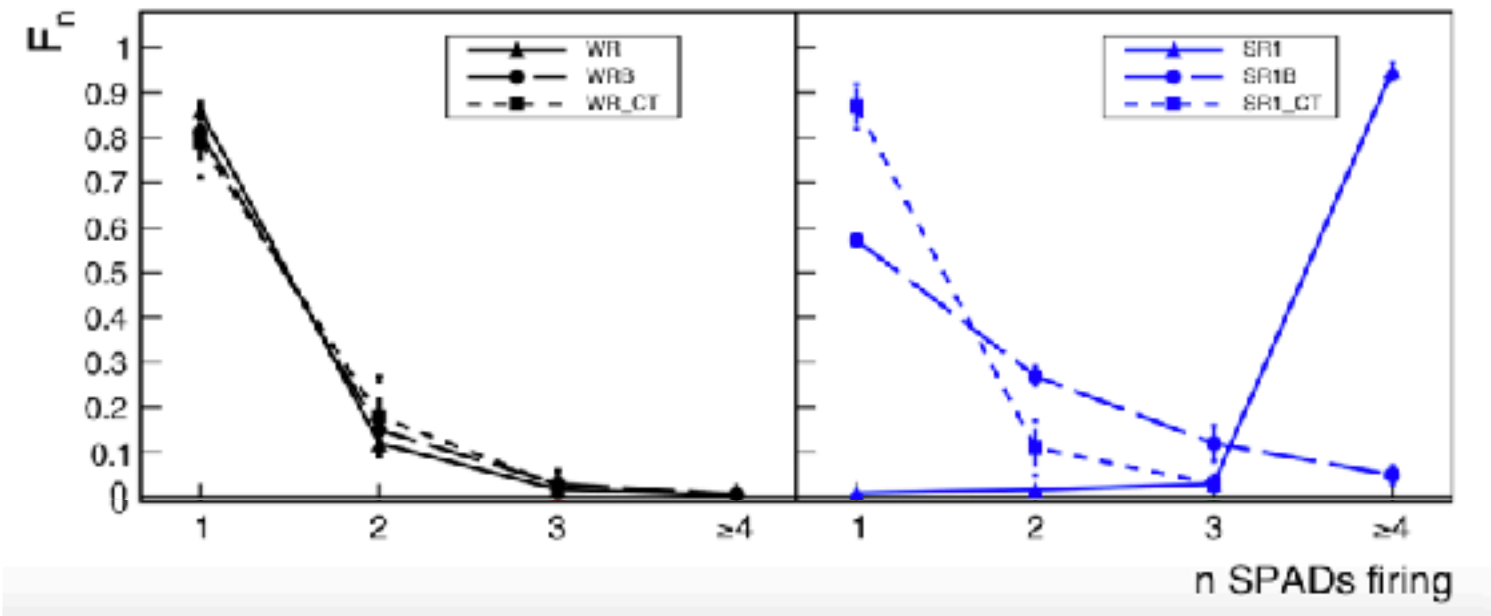






Cluster size distribution

No protection layer   With protection layer



With protection layer, front-side beam shows large clusters

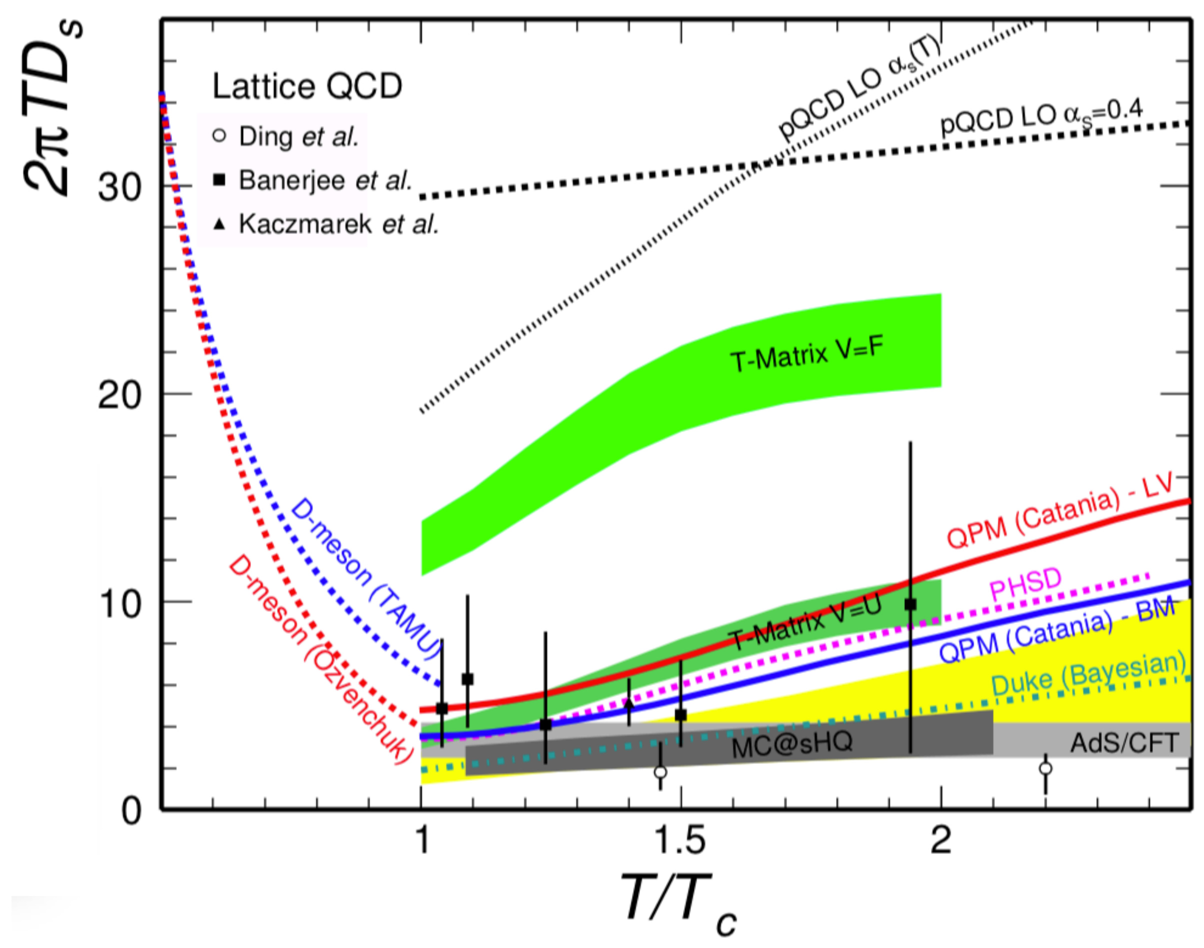
Physics programme

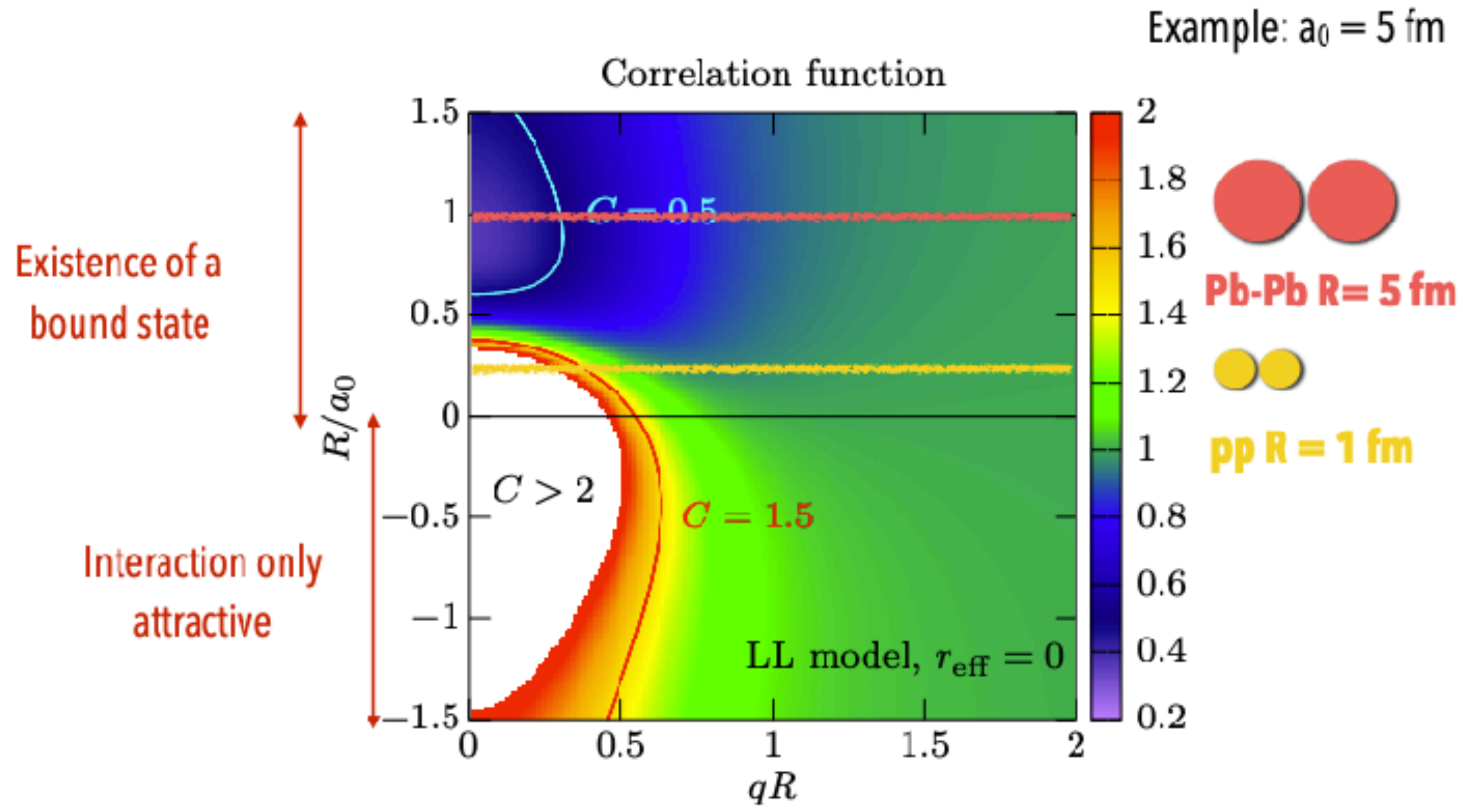
- **Early stages**: temperature of QGP before hadronisation
  - Di-lepton and photon production, elliptic flow
  - Electric conductivity of the QGP
- **Chiral symmetry** restoration: $\rho - a_1$ mixing
- **Heavy flavour diffusion and thermalisation in the QGP**
  - Beauty and charm flow
  - Charm hadron correlations
- **Hadronisation**, final state interactions in heavy-ion collisions
  - Multi-charm baryon production: 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**: charm nuclei
- **Susceptibilities**
- **Ultra-soft photons**: experimental test of Low's theorem
- **BSM searches**: ALPs, dark photons
- …

D_s: heavy quark diffusion coefficient

$$\langle r^2 \rangle = 6\ D_s\ t$$

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





Y. Kamiya et al. arXiv:2108.09644v1

[CERN-LHCC-2022-009]

Time evolution & 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

Invariant mass spectrum of dielectrons

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

Dilepton v_2 → temporal emission profile

Without ρ-a₁ mixing
→ dip in thermal spectrum

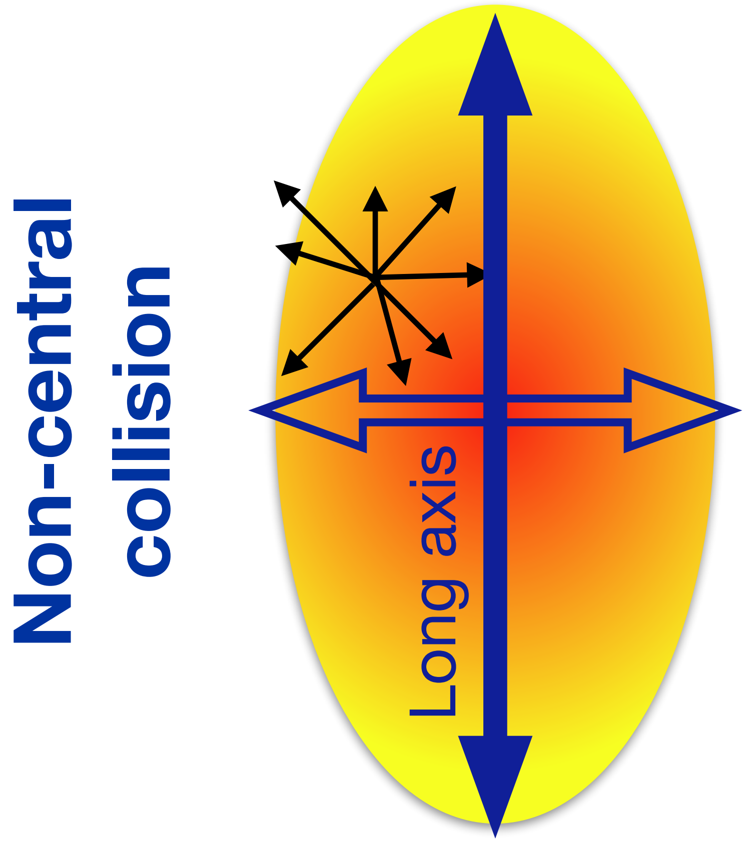
Heavy flavour transport

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

relaxation time

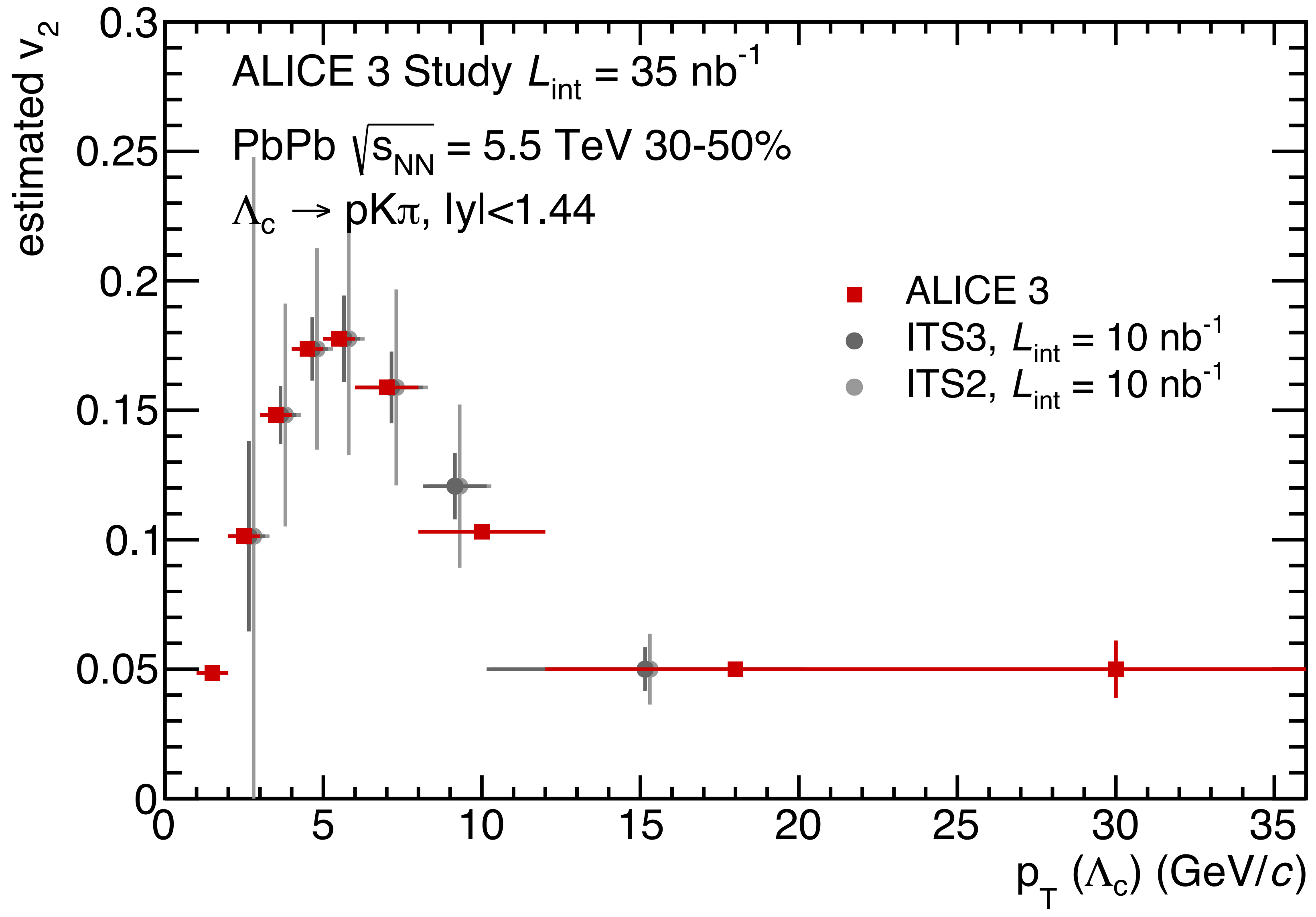
$$\tau_Q = (m_Q/T)\, D_s$$

Interactions with the plasma generate azimuthal anisotropy v_2:

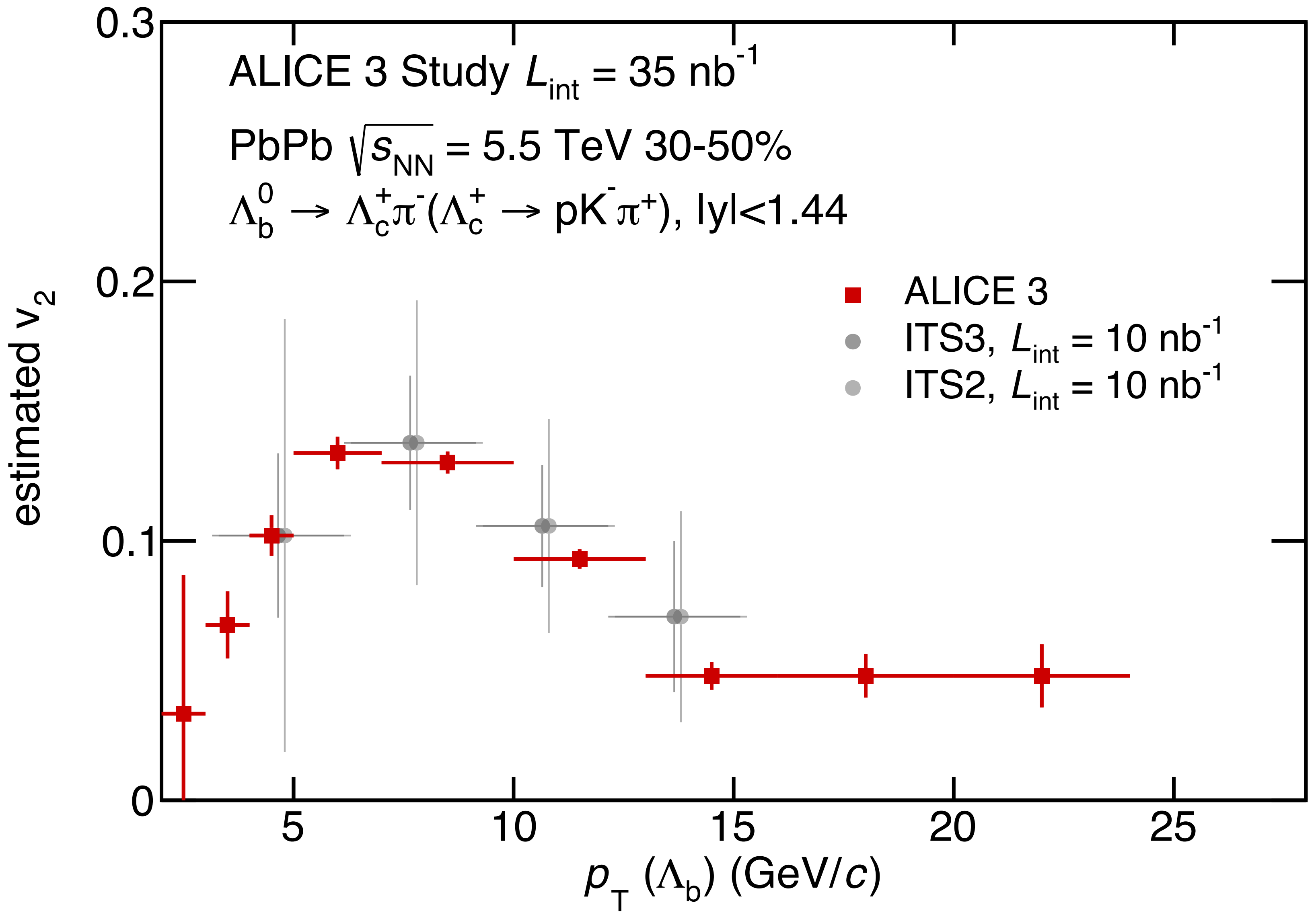


$$\frac{dN}{d\phi} \propto 1 + 2\, v_2 \cos 2(\varphi - \psi)$$

Λ_c v_2 performance



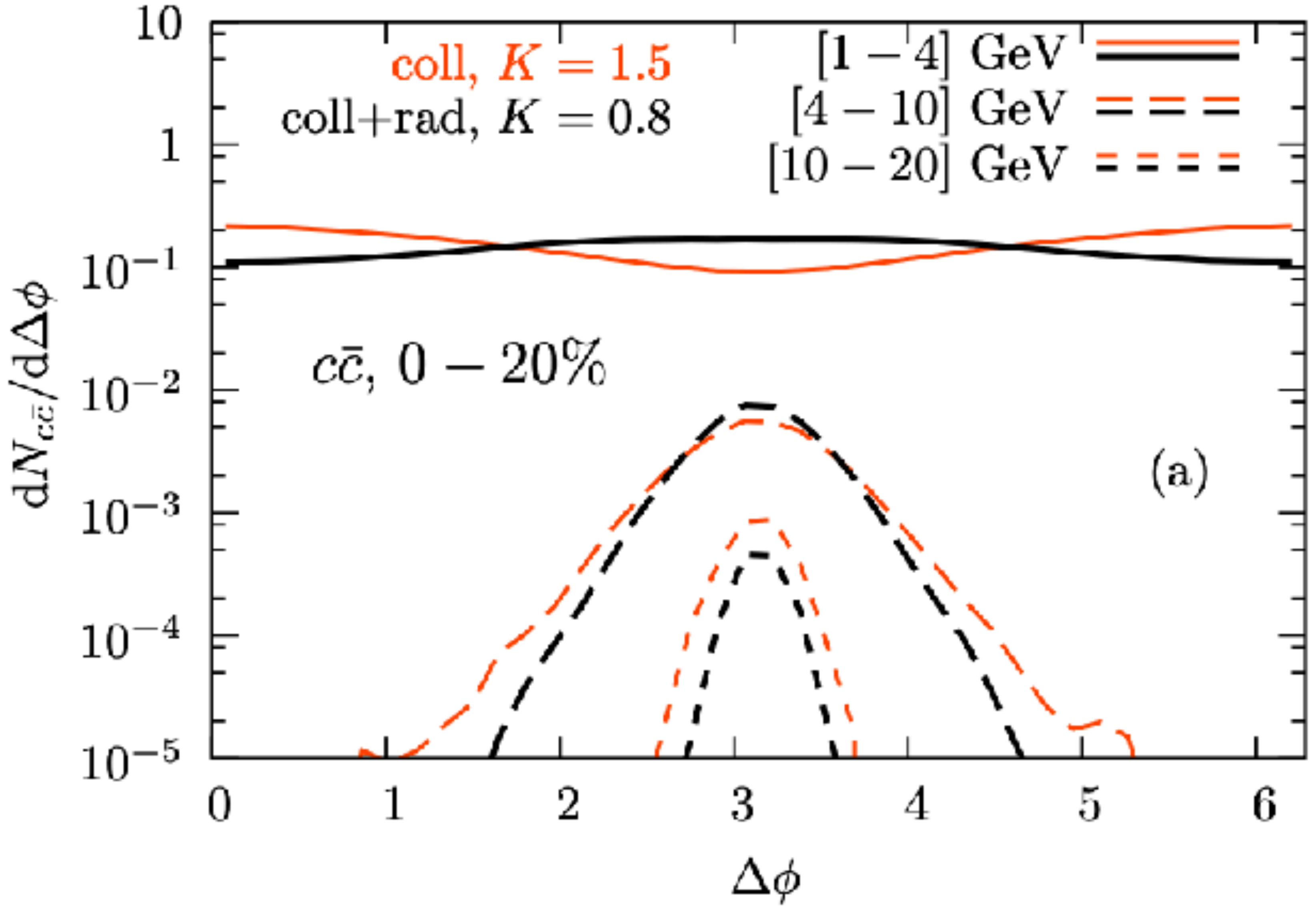
Λ_b v_2 performance



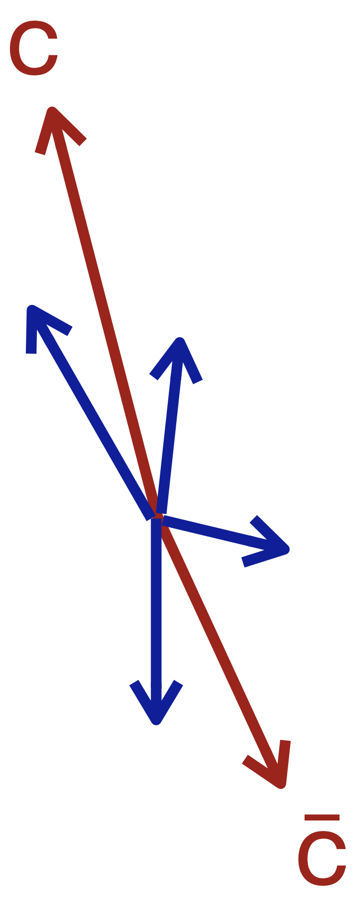
$D\bar{D}$ azimuthal correlations

- **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

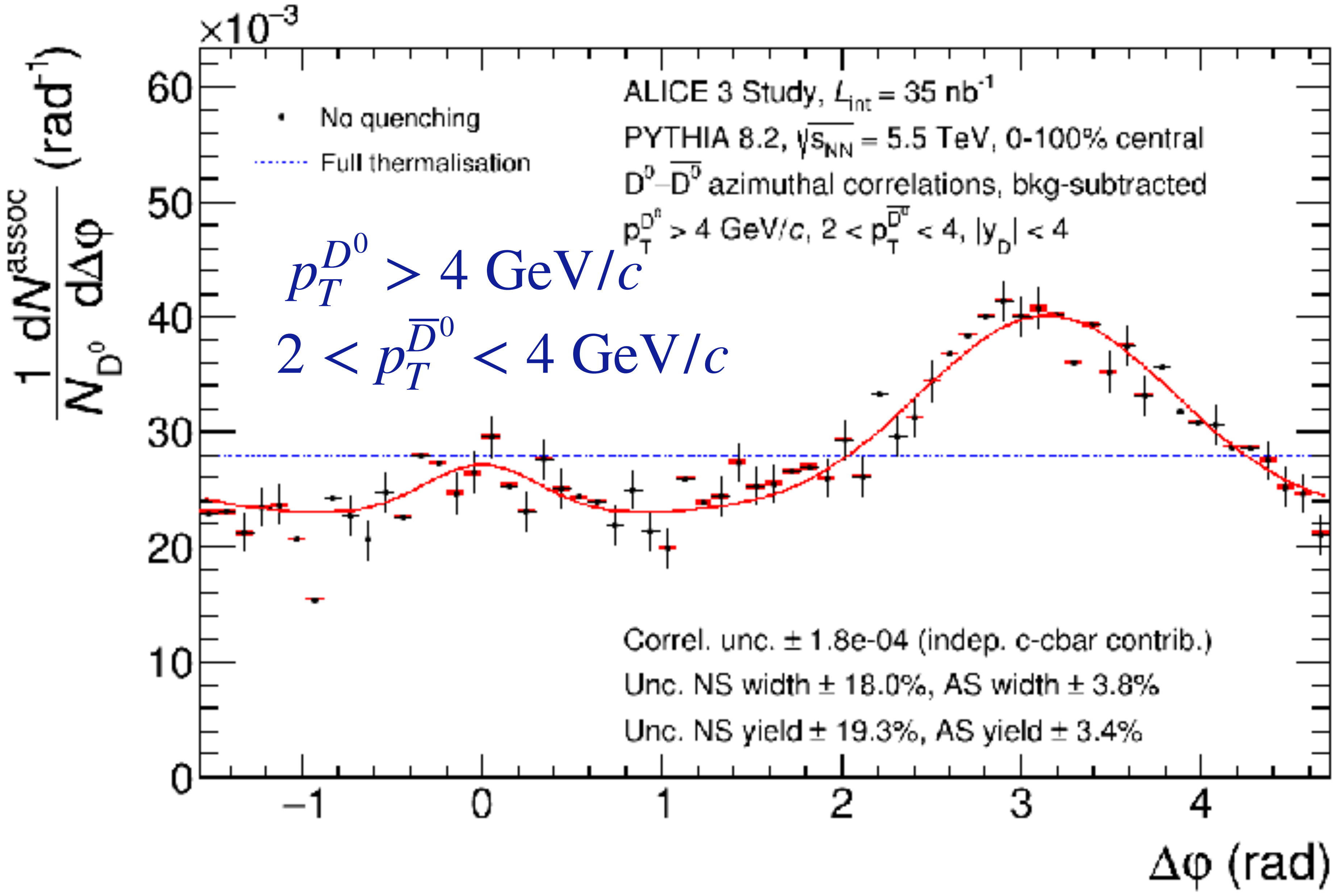
Charm azimuthal correlations



M Nahrgang et al, PRC 90, 024907



ALICE 3 projection: $\mathrm{D\bar{D}}$ correlations

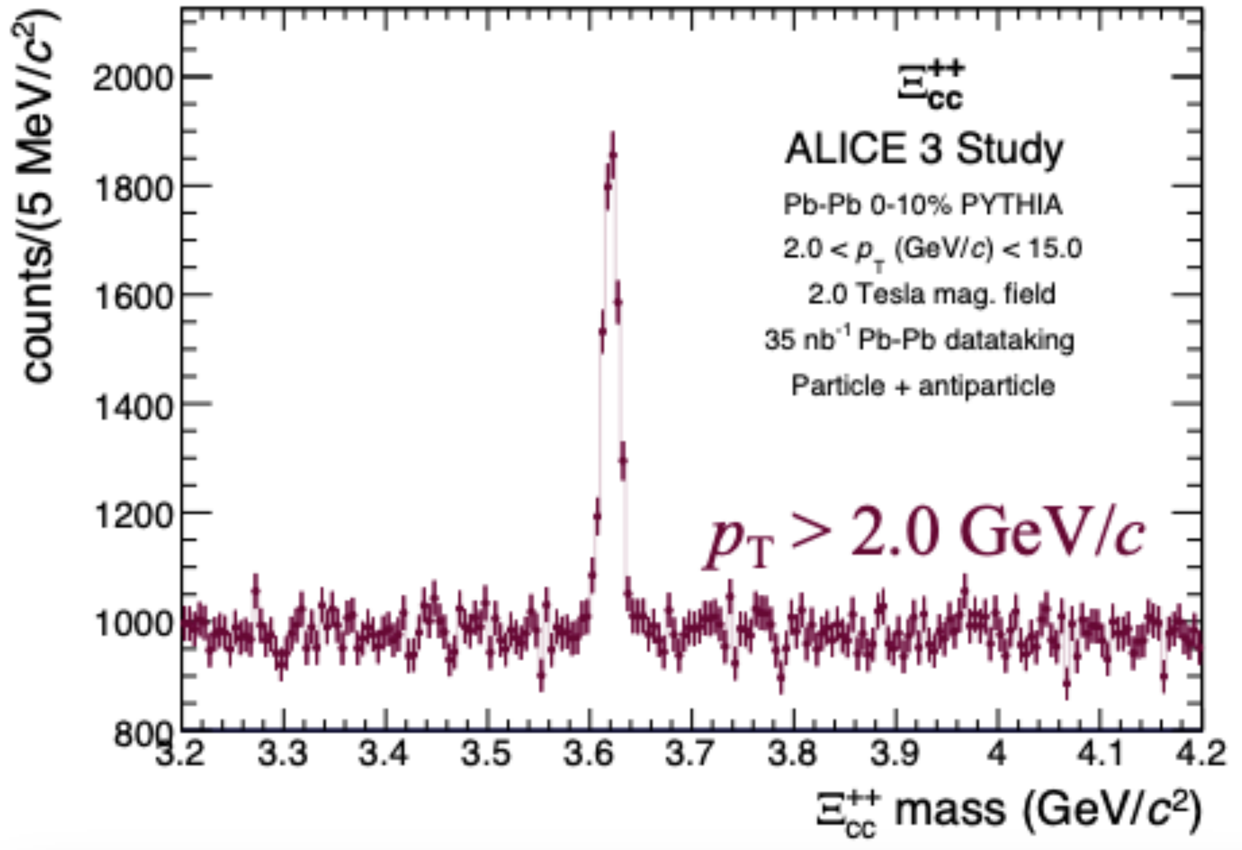


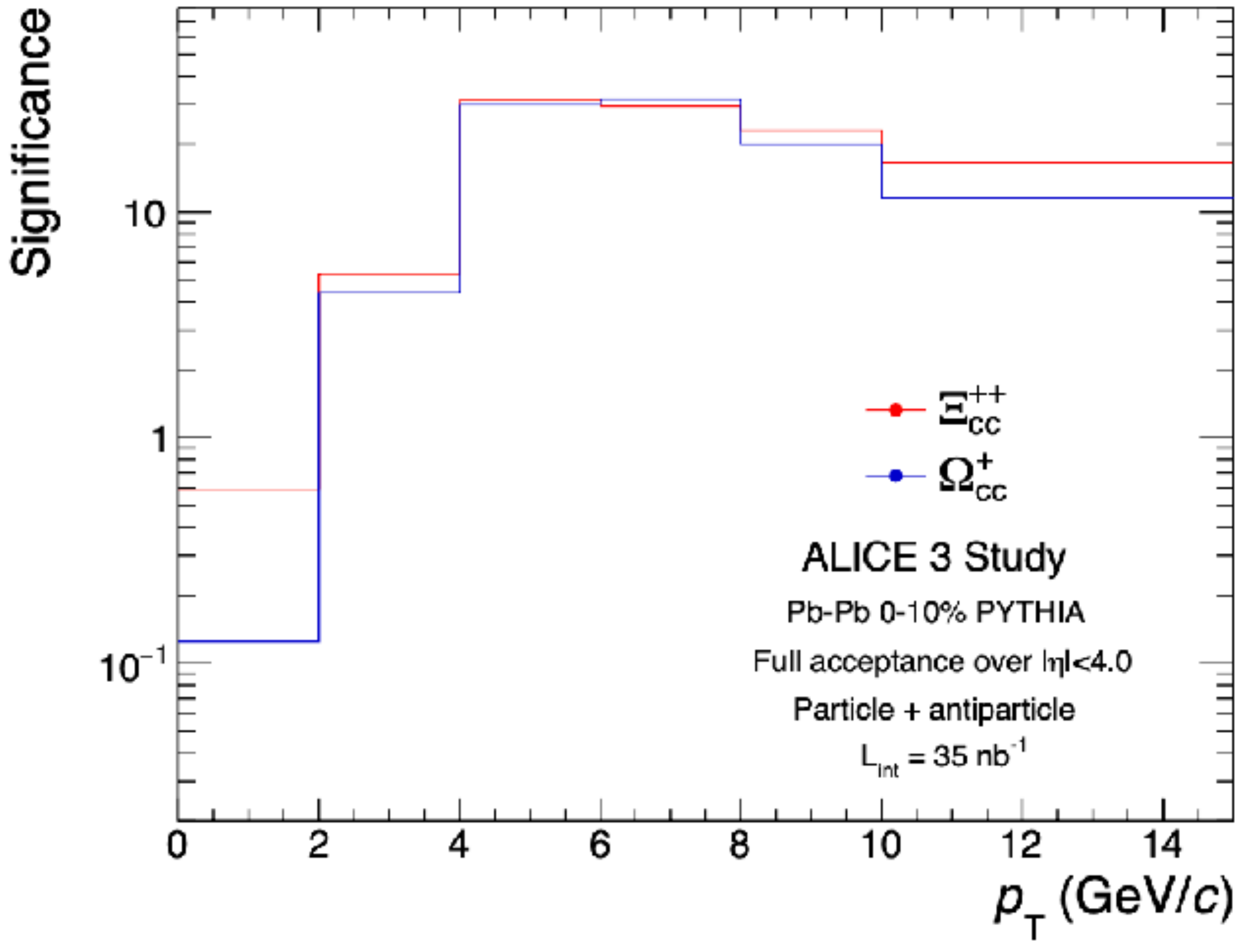
Multi-charm baryons

→ P. Braun-Munzinger

- **Expected enhancement of multi-charm states provides high sensitivity to equilibration**
  → systematic measurement of hadron yields
  → luminosity, acceptance, vertexing, PID, strangeness tracking

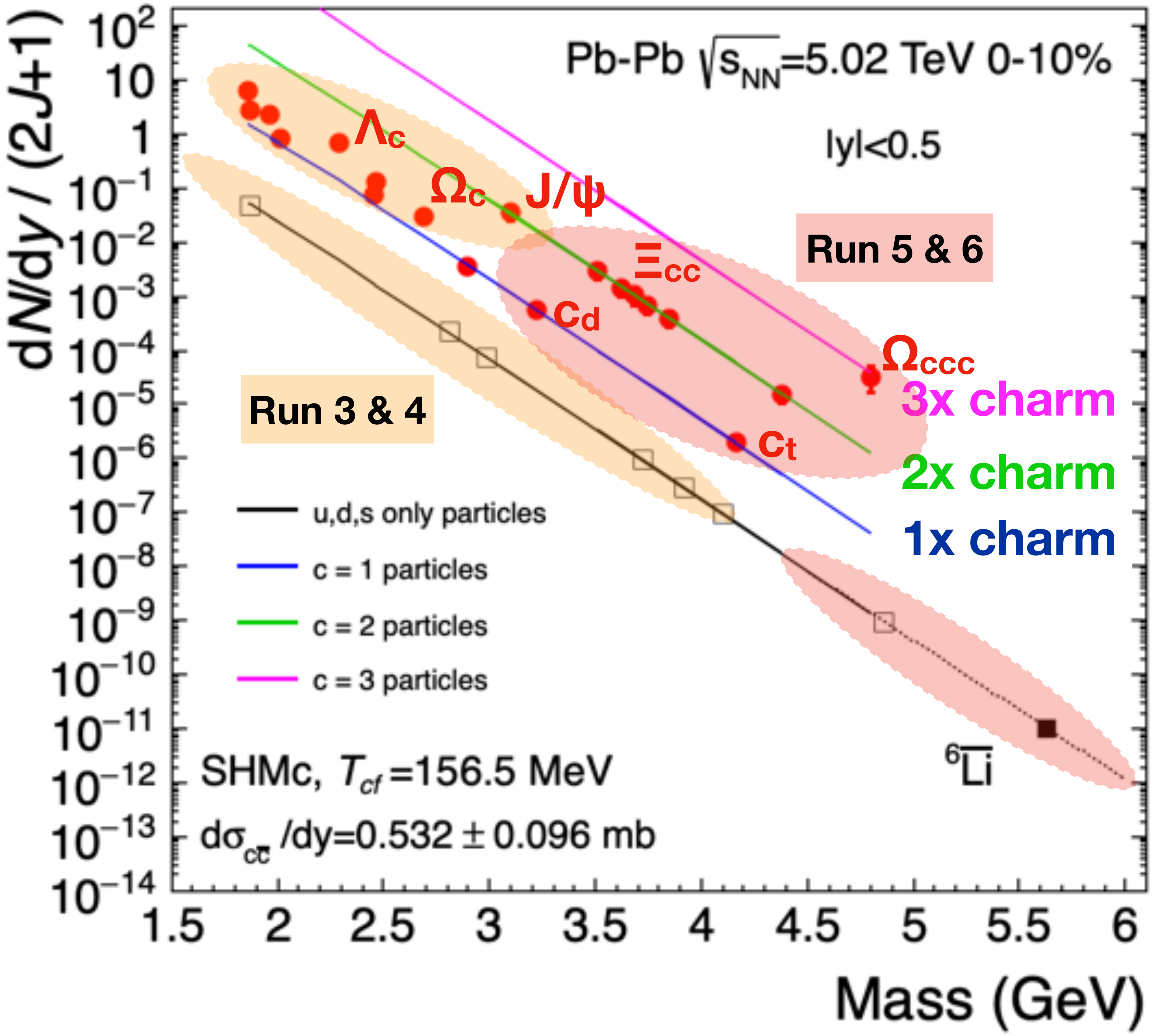
$$\Xi_{cc}^{+} \rightarrow \Xi_{c}^{+} + \pi^{+}$$
$$\Xi_{c}^{+} \rightarrow \Xi^{-} + 2\pi^{+}$$





[CERN-LHCC-2022-009]

Hadron yields in statistical hadronisation model



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

Timeline of upgrades

ALICE 2

ITS3 FoCal ALICE 3

Letter of Intent

ALICE 2

ITS3
FoCal

ALICE 3

Technical Design Report

ALICE 2

ITS3
FoCal

ALICE 3

construction

ALICE 1 | ALICE 2 | ALICE 2.1 | ALICE 3

LHC Run 1 | LHC LS1 | LHC Run 2 | LHC LS2 | LHC Run 3 | LHC LS3 | LHC Run 4 | LHC LS4 | LHC Run 5

2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035

Conclusions

- LHC has entered the **era of high luminosity for heavy ions**
- **ALICE 2 completed** in time and on budget
  - data taking with pp and Pb-Pb collisions successfully started
  - excellent prospects for new results with Run 3 and 4
- **ALICE 3 is needed** to address remaining questions
  - **properties of the QGP** and much more:
  - **innovative detector concept** with R&D activities in several strategic areas

Thank you for your attention

… in a great place of searches and discoveries!



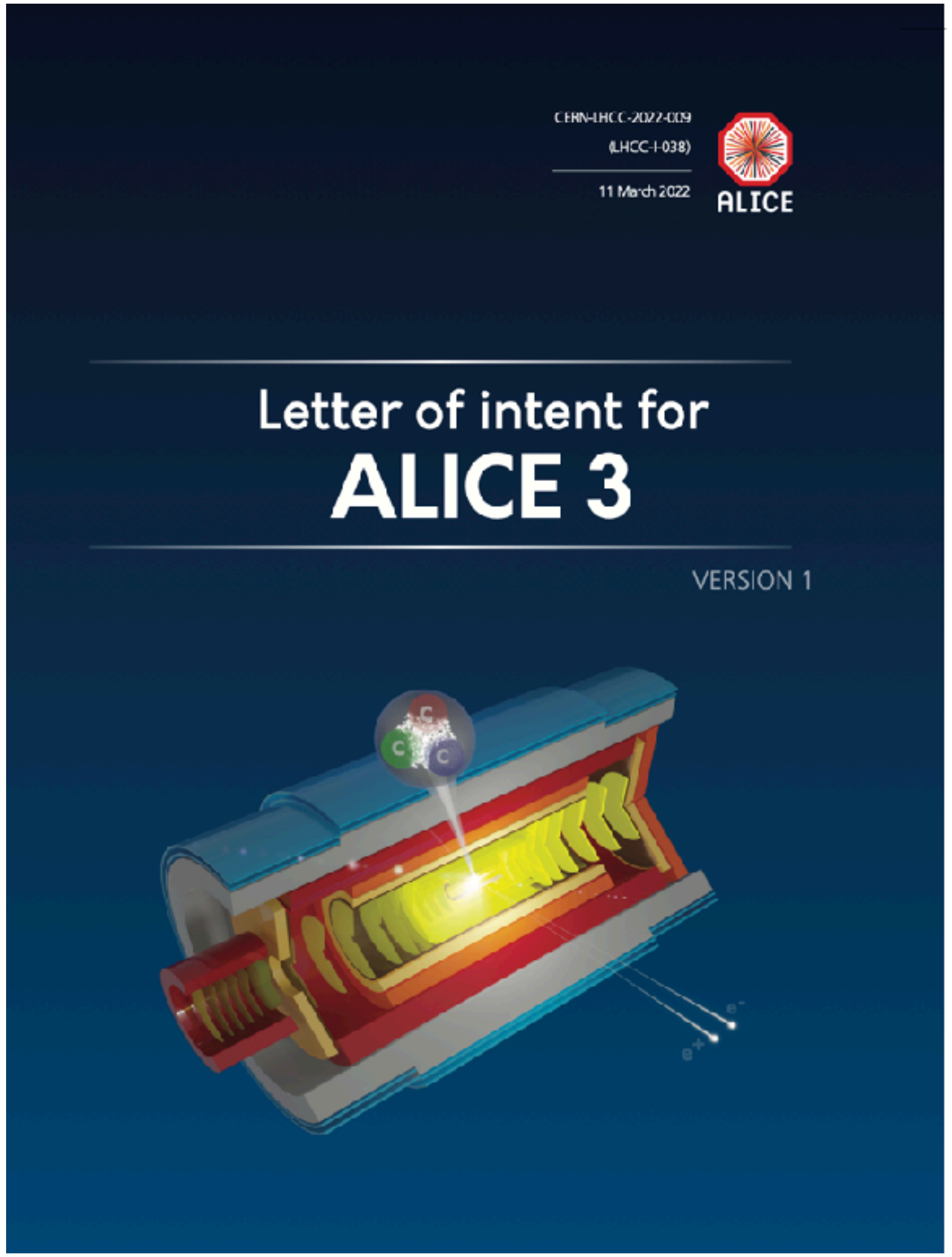


Backup

Status and planning

- **Physics case and detector concept**
developed in the course of 2020-2021 → **Letter of Intent**
  - **endorsed by Collaboration Board** in January 2022
  - **LHCC** review concluded in March 2022
→ **very positive evaluation** [LHCC-149]
    - Exciting physics program
    - Detector well matched with physics program and strategically interesting R&D opportunities
  - **R&D activities** have started

- **Timeline**
  - **2023-25**: selection of technologies,
small-scale proof of concept prototypes
  - **2026-27**: large-scale engineered prototypes
→ Technical Design Reports
  - **2028-30**: construction and testing
  - **2031-32**: contingency
  - **2033-34**: Preparation of cavern and installation of ALICE 3



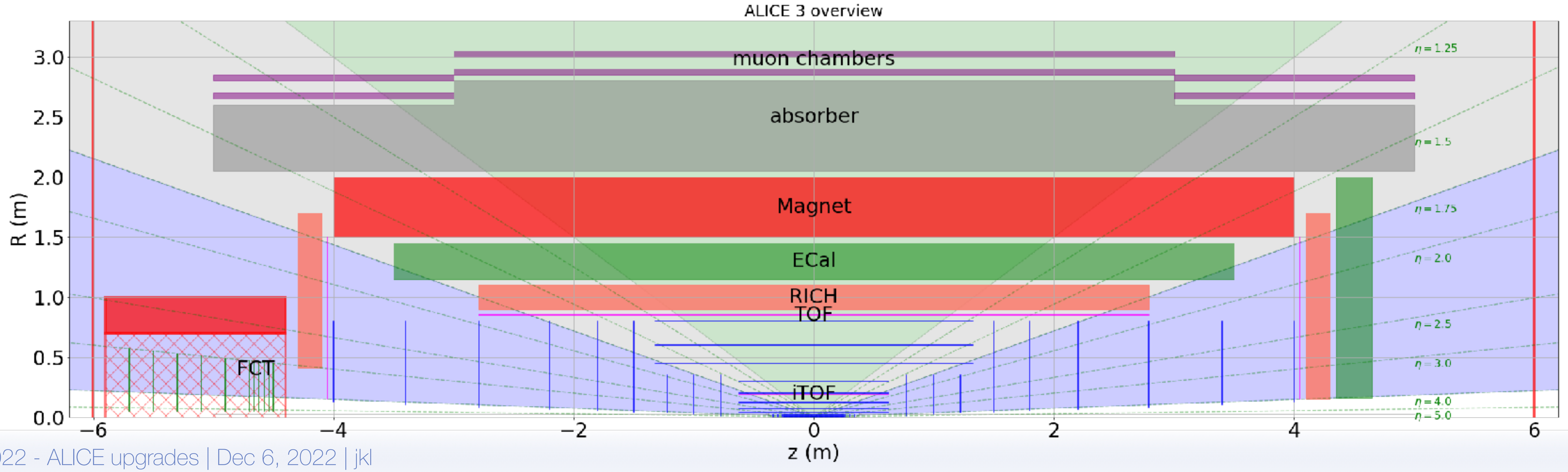
[CERN-LHCC-2022-009]
[arXiv:2211.02491]

Detector requirements

Component	Observables	$\vert\eta\vert < 1.75$ (barrel)	$1.75 < \vert\eta\vert < 4$ (forward)	Detectors
Vertexing	Multi-charm baryons, dielectrons	**Best possible DCA resolution, $\sigma_{DCA} \approx 10$ μm at 200 MeV/c**	**Best possible DCA resolution, $\sigma_{DCA} \approx 30$ μm at 200 MeV/c**	Retractable silicon pixel tracker: $\sigma_{pos} \approx 2.5$ μm, $R_{in} \approx 5$ 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: $\sigma_{pos} \approx 10$ μm, $R_{out} \approx 80$ 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: $L \approx 70$ 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 silicon pixel sensors

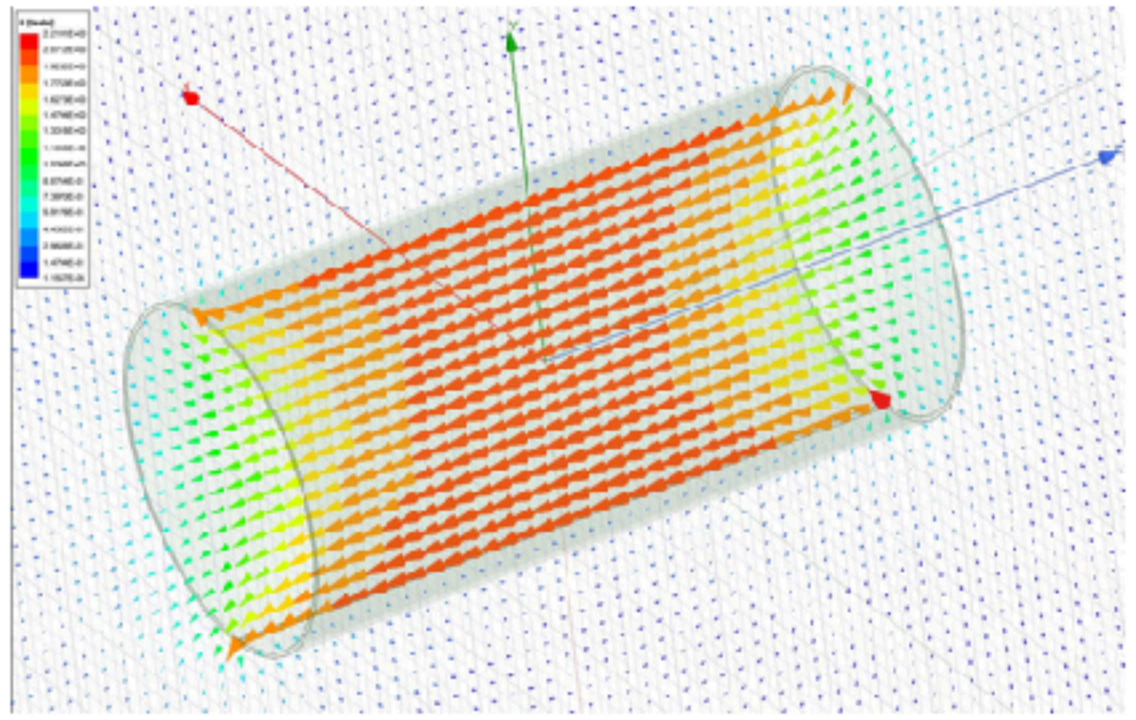
Probes and detector

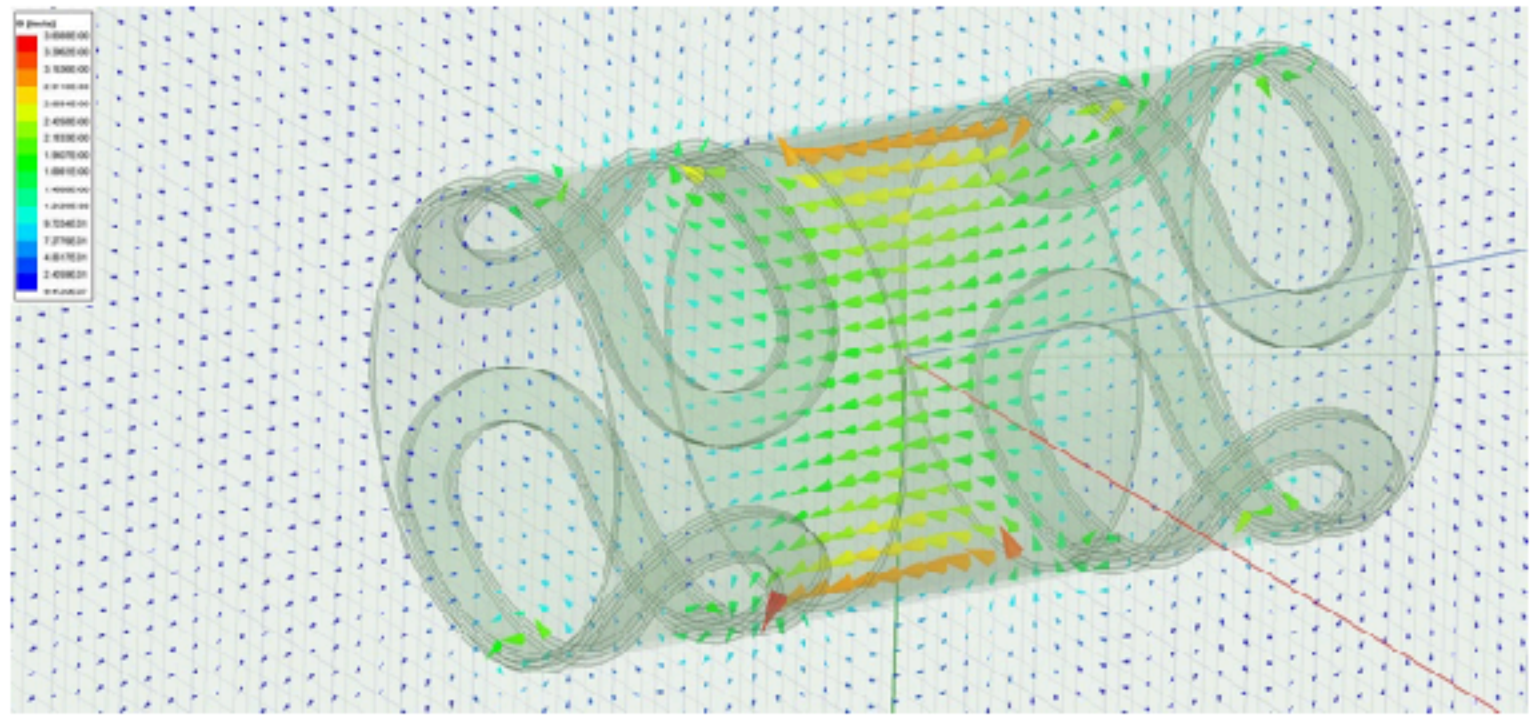
- **Heavy-flavour hadrons** ($p_T \to 0$, wide η range)
  ➟ vertexing, tracking, hadron ID
- **Dileptons** (p_T ~0.1 - 3 GeV/c, M_{ee} ~0.1 - 4 GeV/c^2)
  ➟ vertexing, tracking, lepton ID
- **Photons (100 MeV/c - 50 GeV/c, wide η range)**
  ➟ electromagnetic calorimetry
- **Quarkonia and Exotica ($p_T \to 0$)**
  ➟ muon ID
- **Jets**
  ➟ tracking and calorimetry, hadron ID
- **Ultrasoft photons (p_T = 1 - 50 MeV/c)**
  ➟ dedicated forward detector
- **Nuclei**
  ➟ identification of $z > 1$ particles

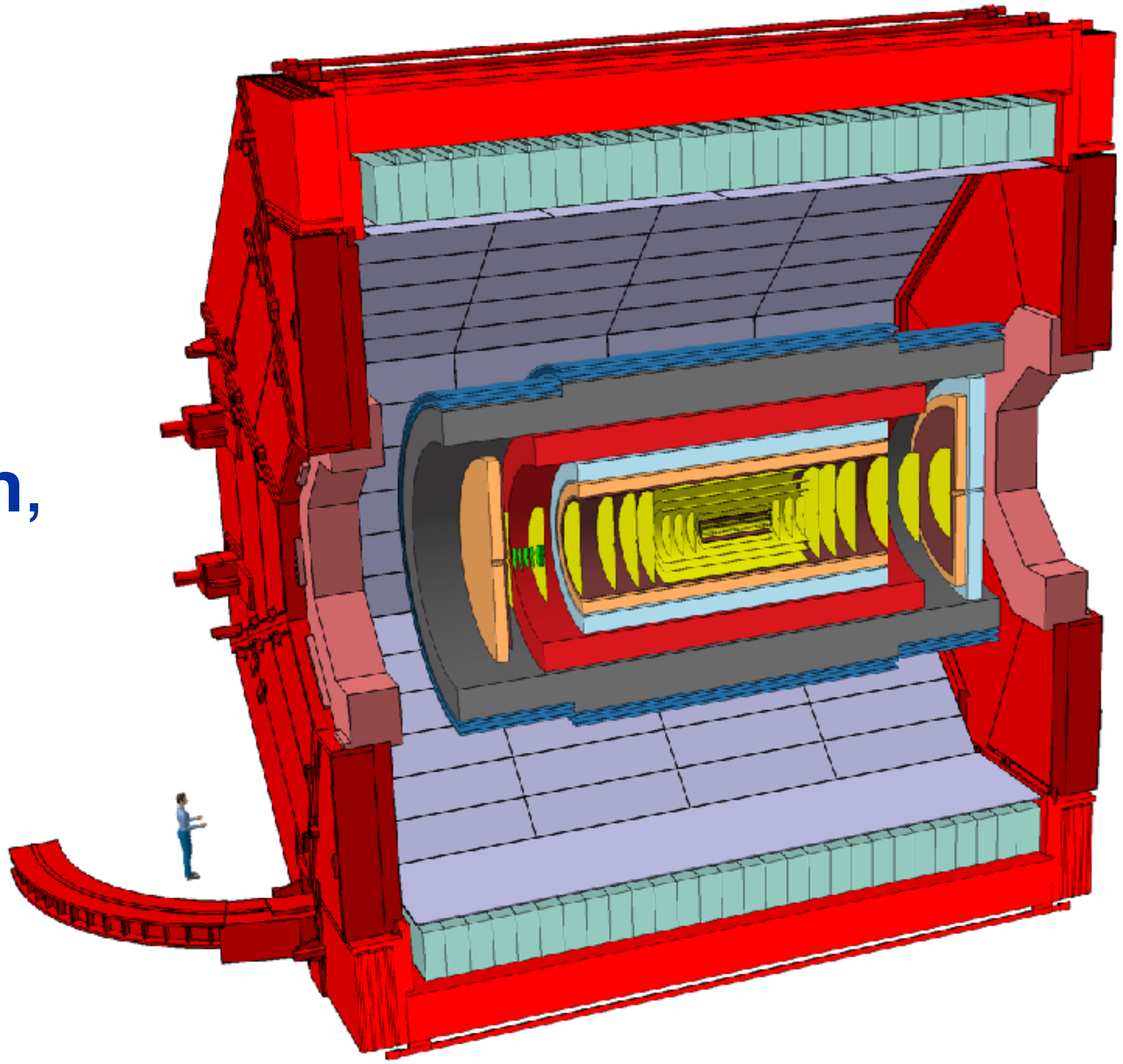


Integration

- **Installation of ALICE 3 around nominal IP2**
  - L3 magnet can remain,
    ALICE 3 to be installed inside
- **Cryostat of ~8 m length, free bore radius 1.5 m,**
  magnetic field configuration to be optimised







Running scenario

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

new ideas under study, e.g. charge states and bunch splitting

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

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

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

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

Rates and radiation

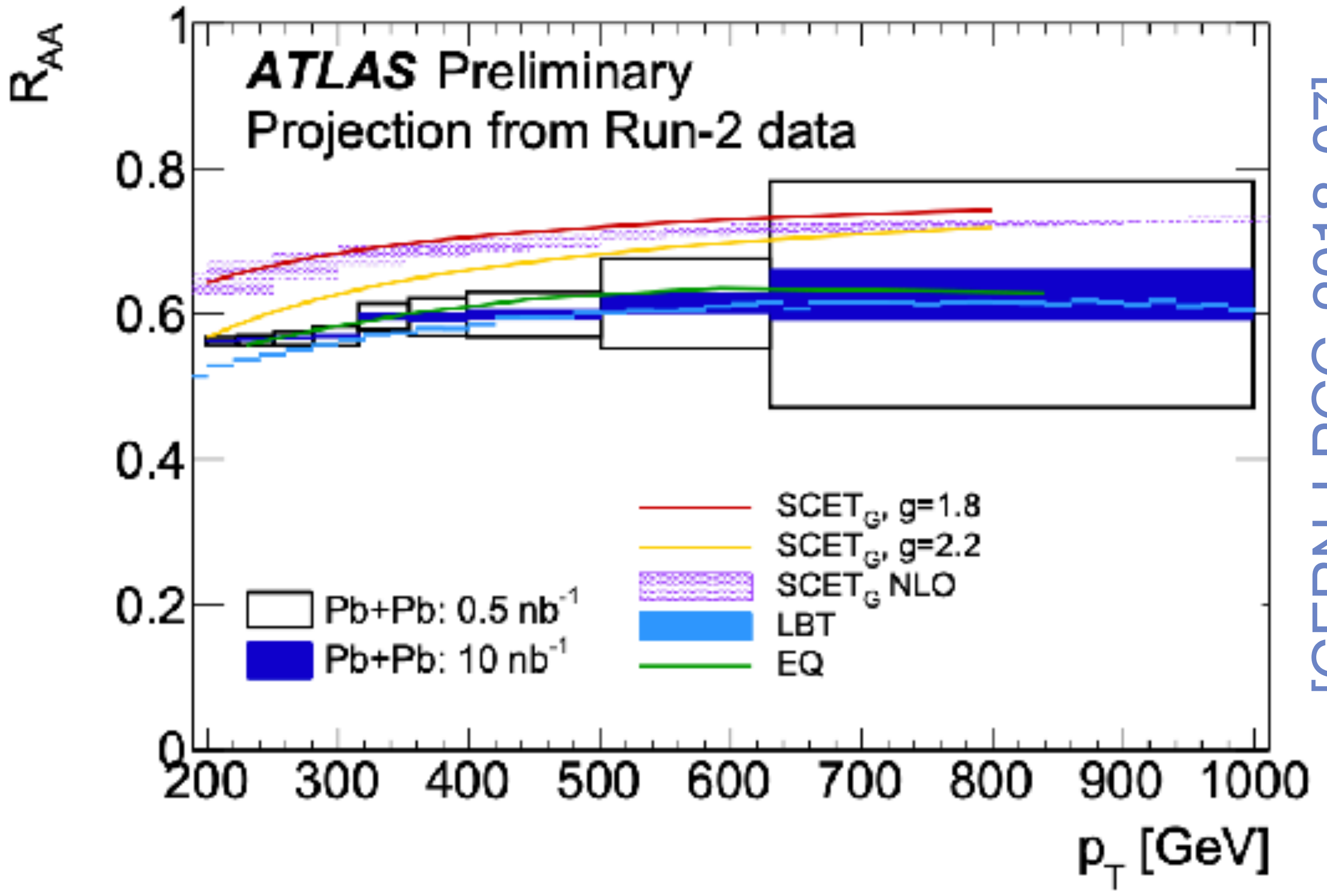
- Design to handle available heavy-ion luminosities,
  with current estimates hit rates similar across collision systems
- **First layer at 5 mm** → challenging hit rates and radiation load:
  ~1.5 10^{15} 1 MeV n_{eq} / cm^2 per operational year (comparable to first layer in ATLAS/CMS)
- Moderate hit rates and radiation load in other layers,
  already at R = 20 cm (inner TOF) down to ~10^{12} 1 MeV n_{eq} / cm^2 per operational year

		pp	Ar-Ar	Kr-Kr	Xe-Xe	Pb-Pb
	L_{AA} (cm^{-2} s^{-1})	$3.0 \cdot 10^{32}$	$3.2 \cdot 10^{29}$	$8.5 \cdot 10^{28}$	$3.3 \cdot 10^{28}$	$1.2 \cdot 10^{28}$
	$\langle L_{AA} \rangle$ (cm^{-2} s^{-1})	$3.0 \cdot 10^{32}$	$2.0 \cdot 10^{29}$	$5.0 \cdot 10^{28}$	$1.6 \cdot 10^{28}$	$3.3 \cdot 10^{27}$
R = 0.5 cm	R_{hit} (cm^{-2} s^{-1})	$9.4 \cdot 10^{7}$	$6.9 \cdot 10^{7}$	$5.3 \cdot 10^{7}$	$4.6 \cdot 10^{7}$	$3.5 \cdot 10^{7}$
	NIEL (1 MeV n_{eq} / cm^2 / month)	$1.8 \cdot 10^{14}$	$8.6 \cdot 10^{13}$	$6.0 \cdot 10^{13}$	$4.1 \cdot 10^{13}$	$1.9 \cdot 10^{13}$
	TID (Rad / m)	$5.8 \cdot 10^{6}$	$2.8 \cdot 10^{6}$	$1.9 \cdot 10^{6}$	$1.3 \cdot 10^{6}$	$6.1 \cdot 10^{5}$
R = 20 cm	R_{hit} (cm^{-2} s^{-1})	$5.9 \cdot 10^{4}$	$4.3 \cdot 10^{4}$	$3.3 \cdot 10^{4}$	$2.8 \cdot 10^{4}$	$2.2 \cdot 10^{4}$
	NIEL (1 MeV n_{eq} / cm^2 / month)	$1.1 \cdot 10^{11}$	$5.4 \cdot 10^{10}$	$3.7 \cdot 10^{10}$	$2.6 \cdot 10^{10}$	$1.2 \cdot 10^{10}$
	TID (Rad / m)	$3.6 \cdot 10^{3}$	$1.7 \cdot 10^{3}$	$1.2 \cdot 10^{3}$	$8.2 \cdot 10^{2}$	$3.8 \cdot 10^{2}$
R = 100 cm	R_{hit} (cm^{-2} s^{-1})	$2.4 \cdot 10^{3}$	$1.7 \cdot 10^{3}$	$1.3 \cdot 10^{3}$	$1.1 \cdot 10^{3}$	$8.8 \cdot 10^{2}$
	NIEL (1 MeV n_{eq} / cm^2 / month)	$4.5 \cdot 10^{9}$	$2.1 \cdot 10^{9}$	$1.5 \cdot 10^{9}$	$1.0 \cdot 10^{9}$	$4.7 \cdot 10^{8}$
	TID (Rad / m)	$1.4 \cdot 10^{2}$	$6.9 \cdot 10^{1}$	$4.8 \cdot 10^{1}$	$3.3 \cdot 10^{1}$	$1.5 \cdot 10^{1}$

Quenching

- **Understand mass and time dependence as well as onset in small systems**
  → precision measurements, also with new probes and in intermediate systems
  → statistics and new collision systems (OO, pO, also high-multiplicity pp)

Precise jet R_{AA} up to high p_T

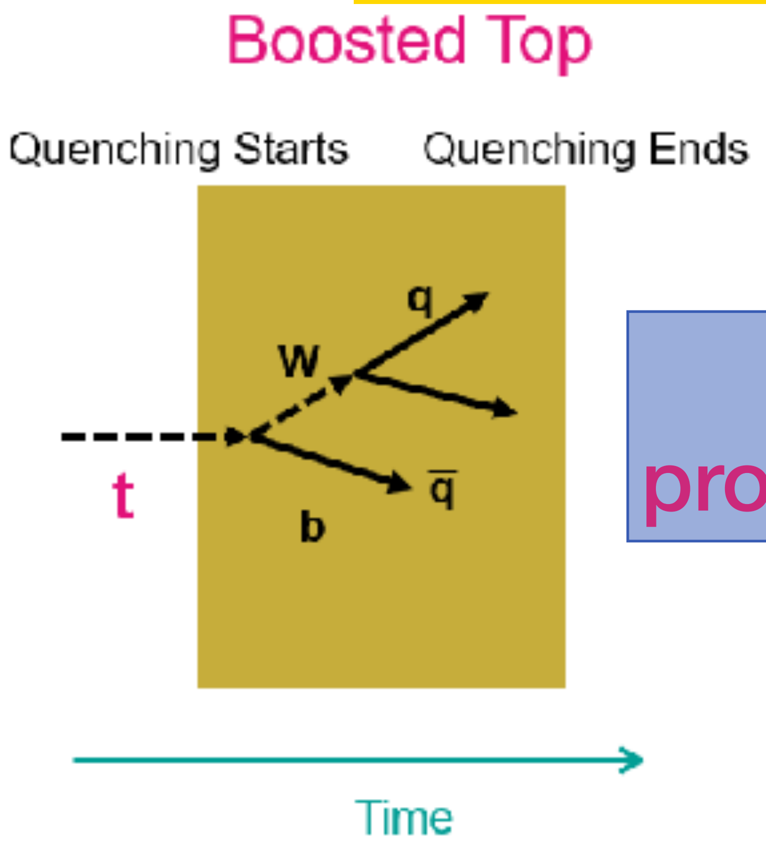


[CERN-LPCC-2018-07]

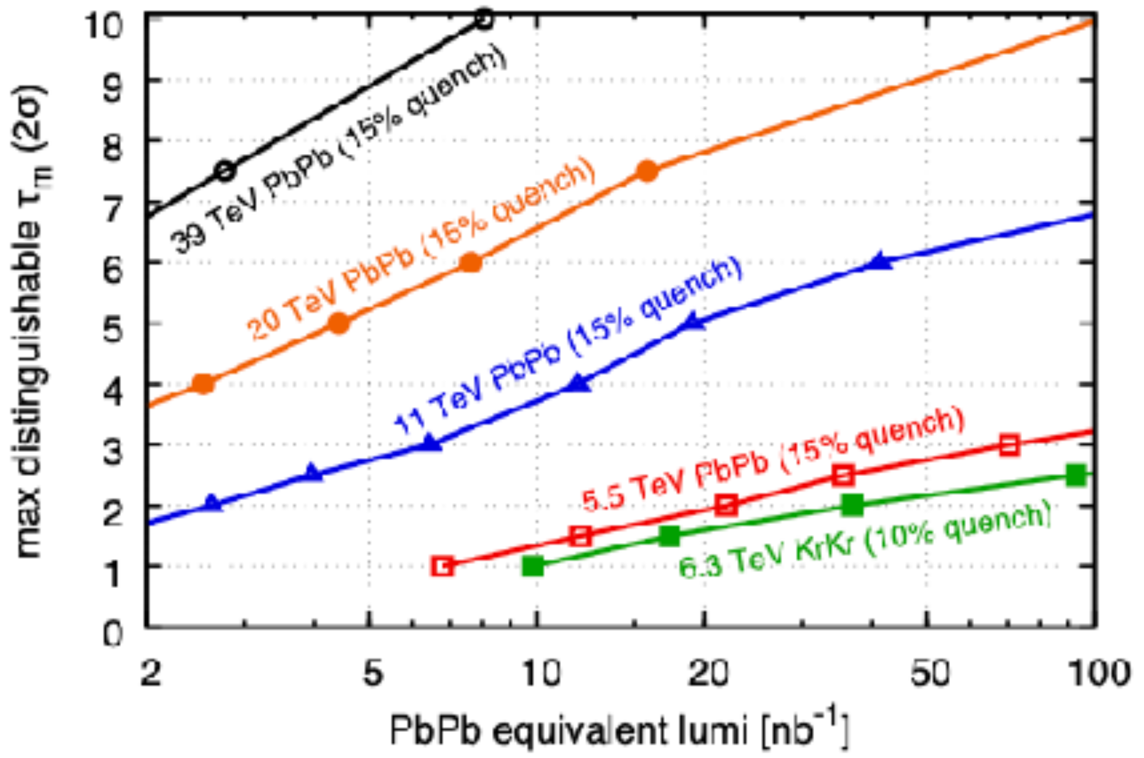
large samples allow us to look at tagged jets, substructure, …

Run 3 & 4

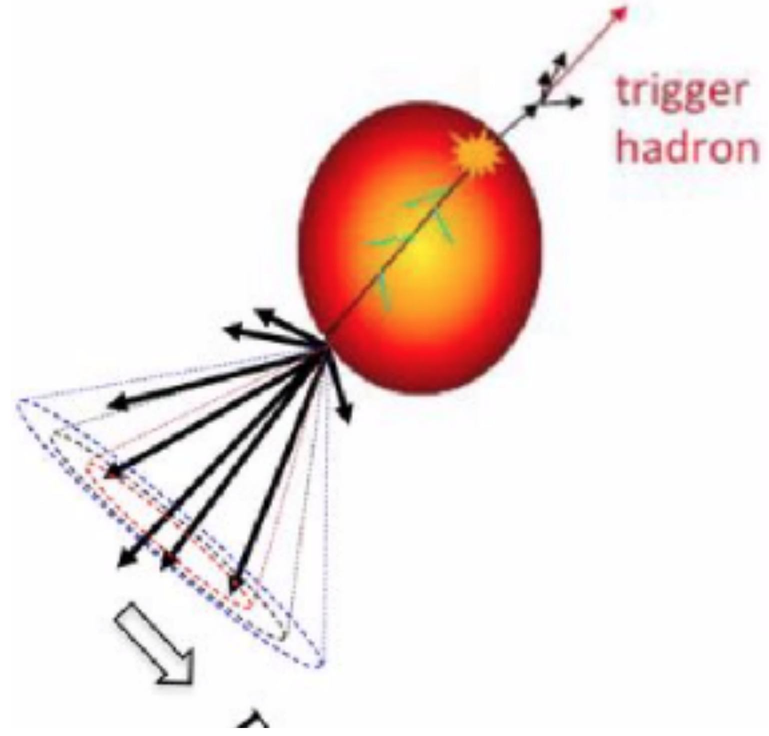
$t \to b + W \to q\bar{q}$
→ probe medium after τ_m



Run 3 & 4:
proof of concept

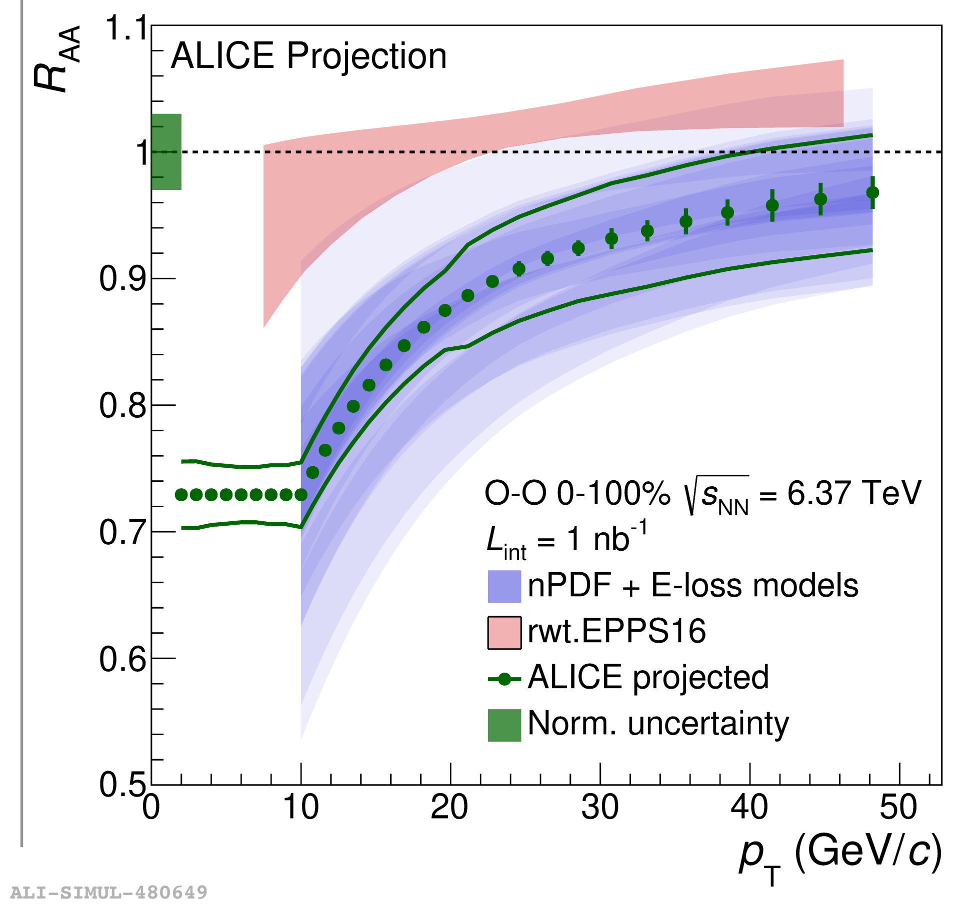


Limits on quenching in small systems



Limits for energy shift out of R = 0.4 cone:

- **pp (7-10 ⟨N_{ch}⟩): 70 MeV/c**
- **pp (10-12 ⟨N_{ch}⟩): 600 MeV/c**
- **OO: 150 MeV/c**



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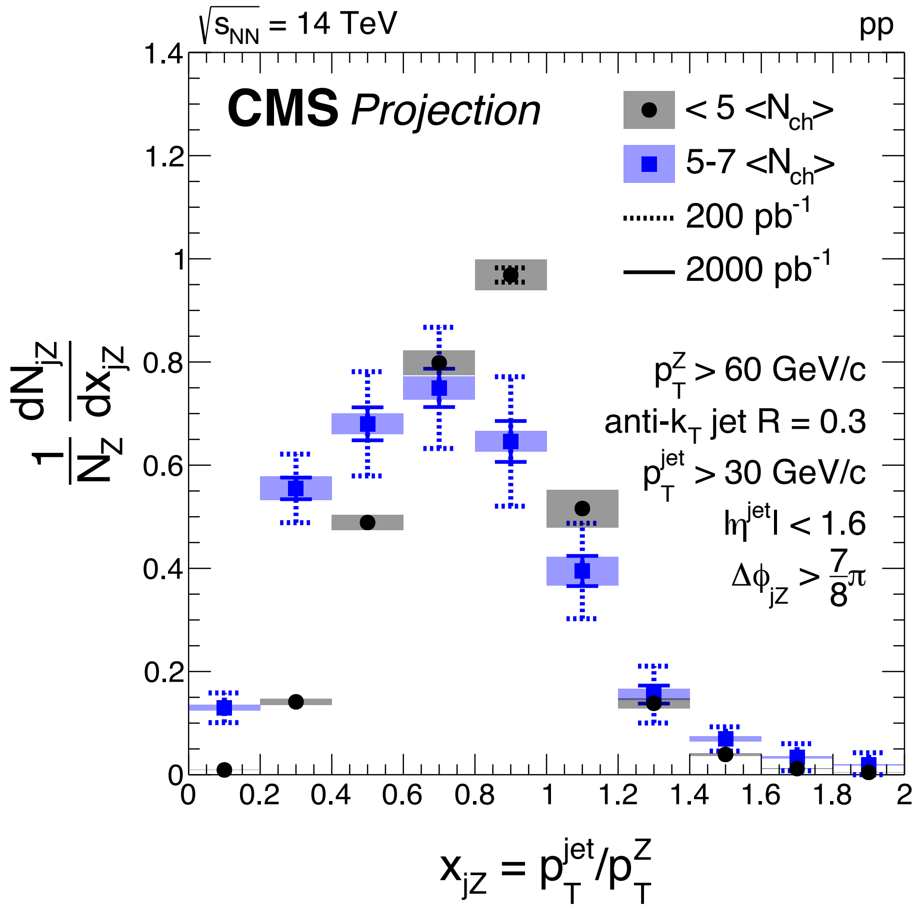
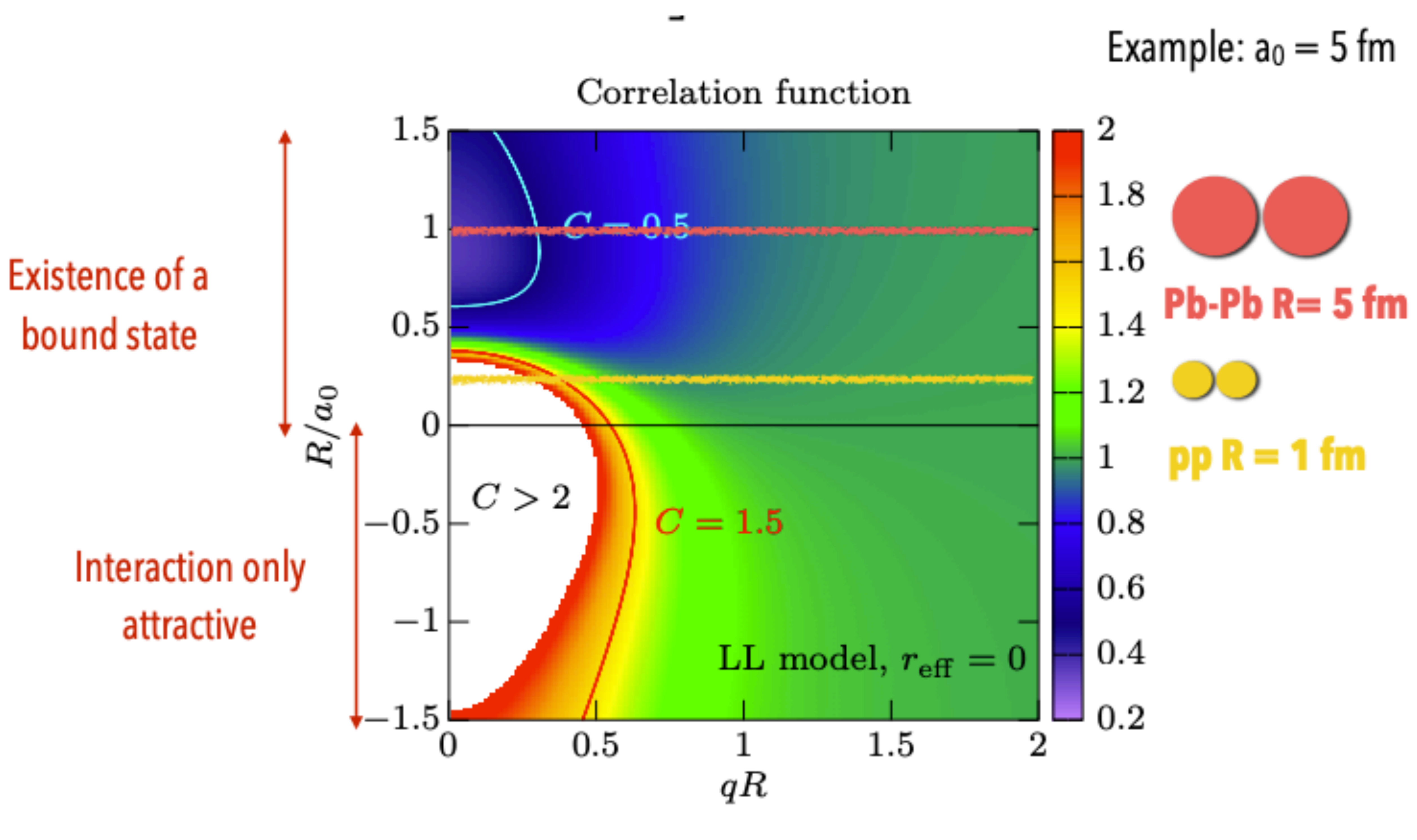


Run 3 (pp HM, OO, p-Pb)

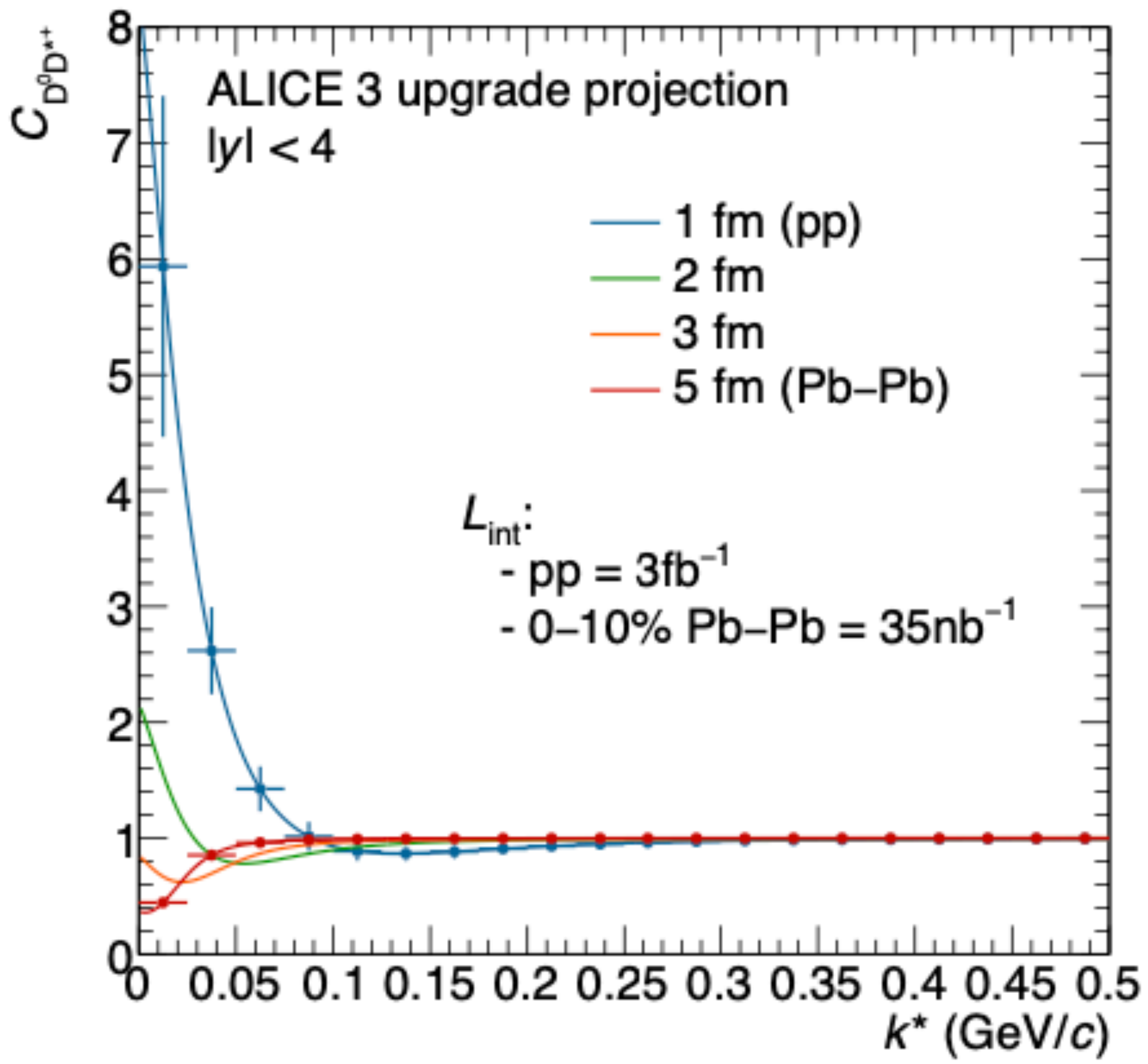
Nature of exotic states



Y. Kamiya et al. arXiv:2108.09644v1

- Study interaction between hadrons trough momentum correlation
- Carries information about existence of bound states

DD* momentum correlation

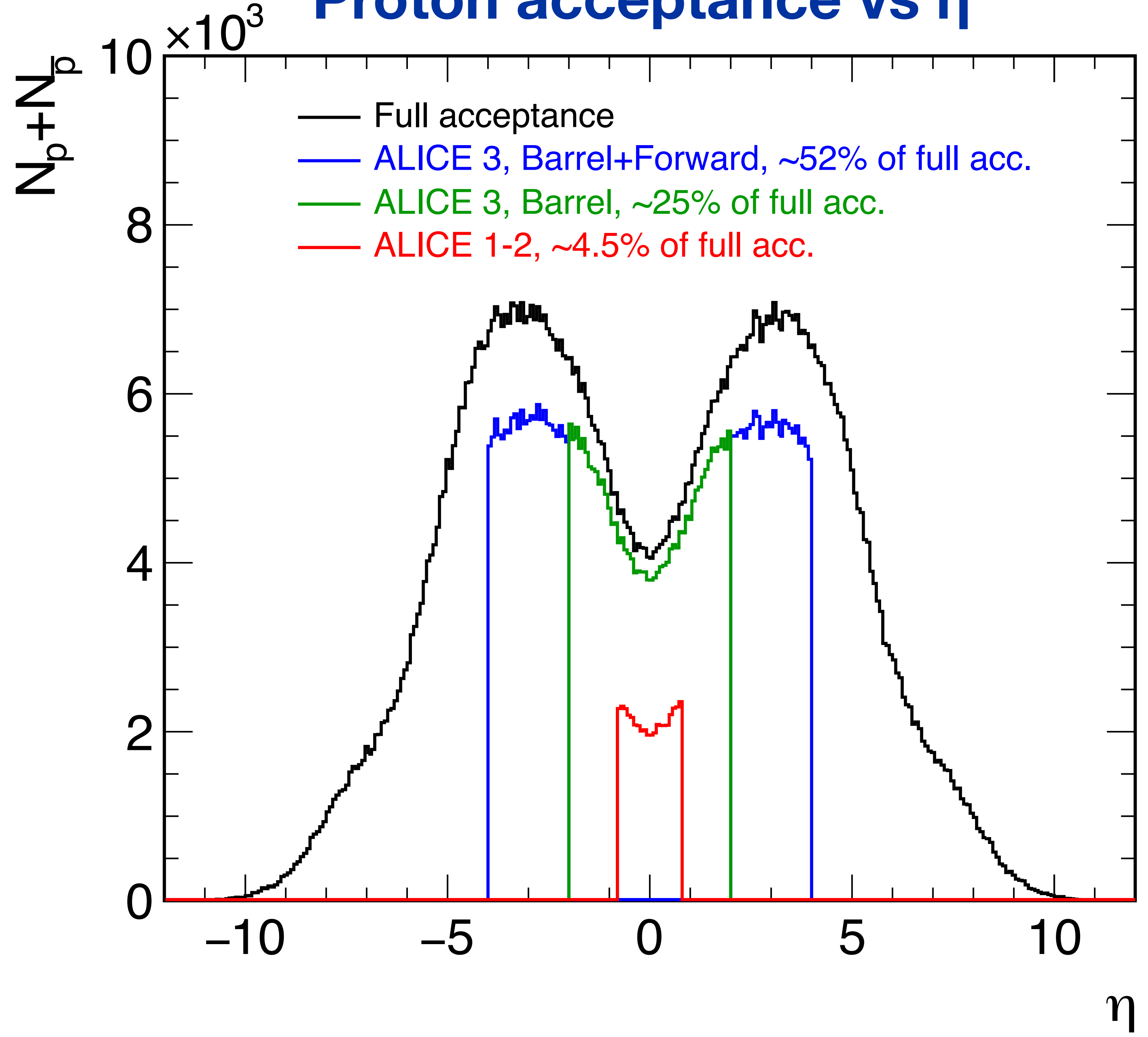


- Characteristic sign-change between pp and Pb-Pb in case of bound T_{cc} state
- Effect clearly visible within experiment precision

Susceptibilities

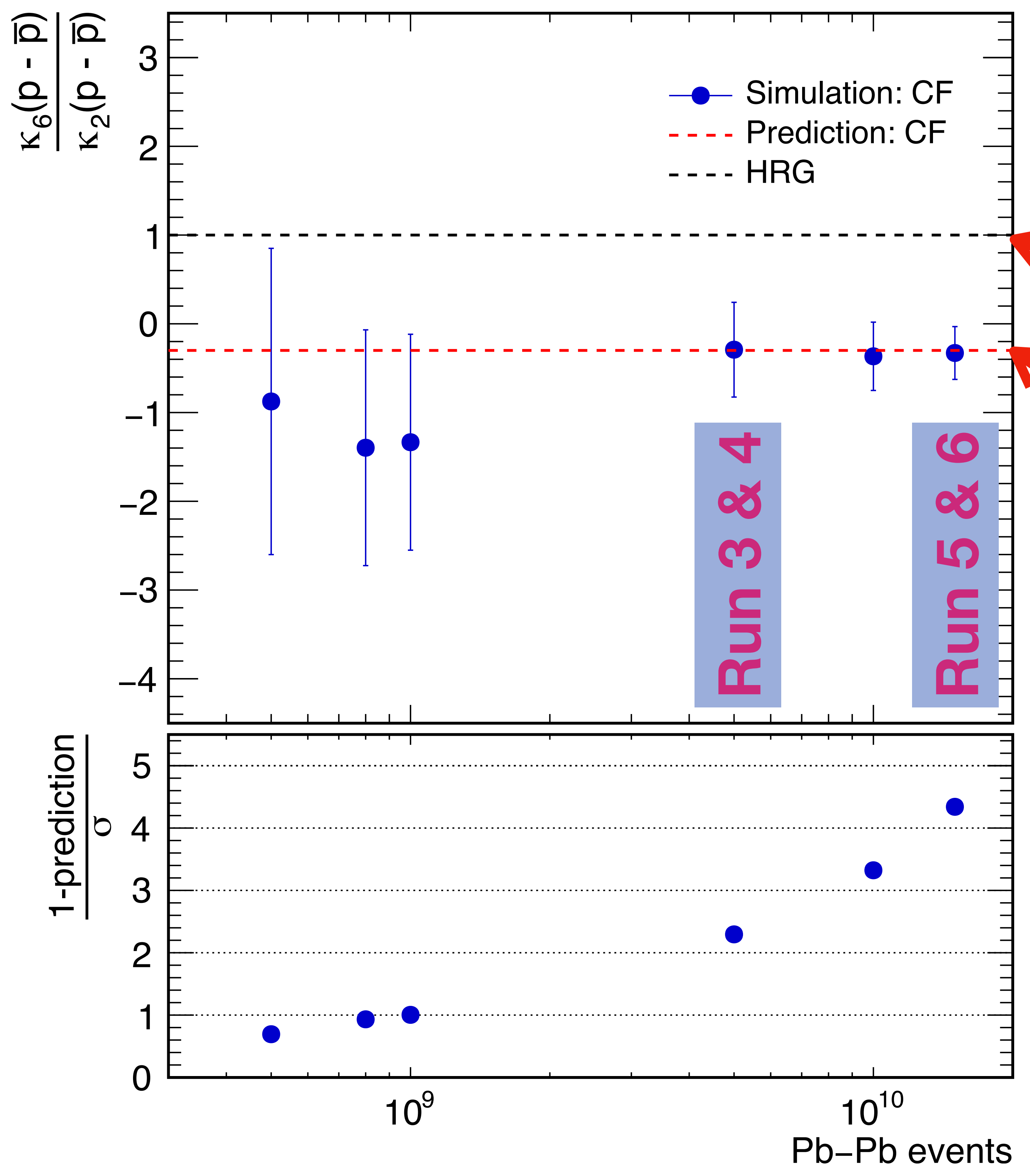
- **Comparison of critical behaviour with lattice QCD predictions**
  → measurements of net-baryon fluctuations (cumulants κ_n)
  → excellent particle identification over large acceptance

Proton acceptance vs η

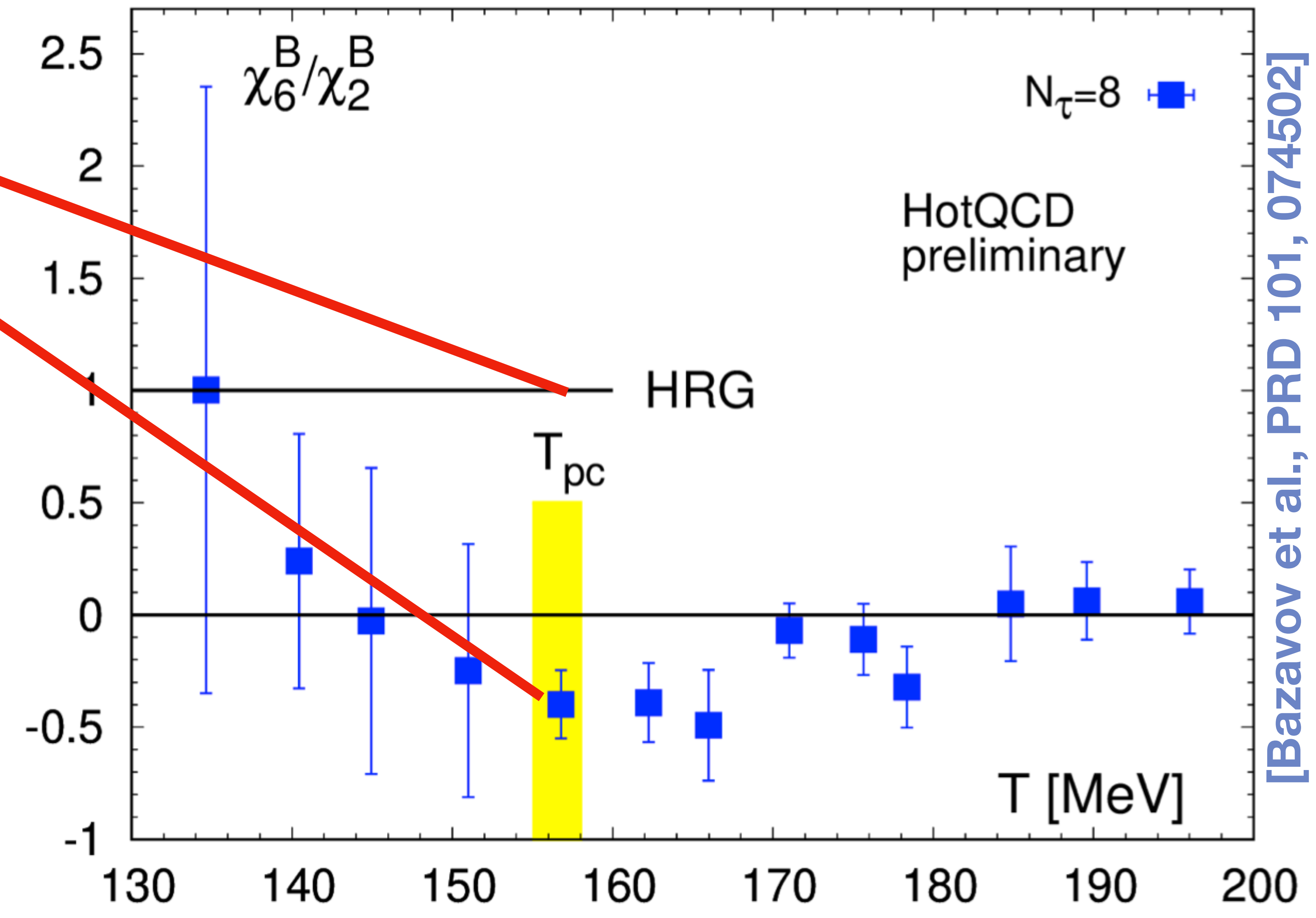


Run 3 & 4: limited Eff. x Acc.
Run 5 & 6: large Eff. x Acc.

Projection for 6th cumulant



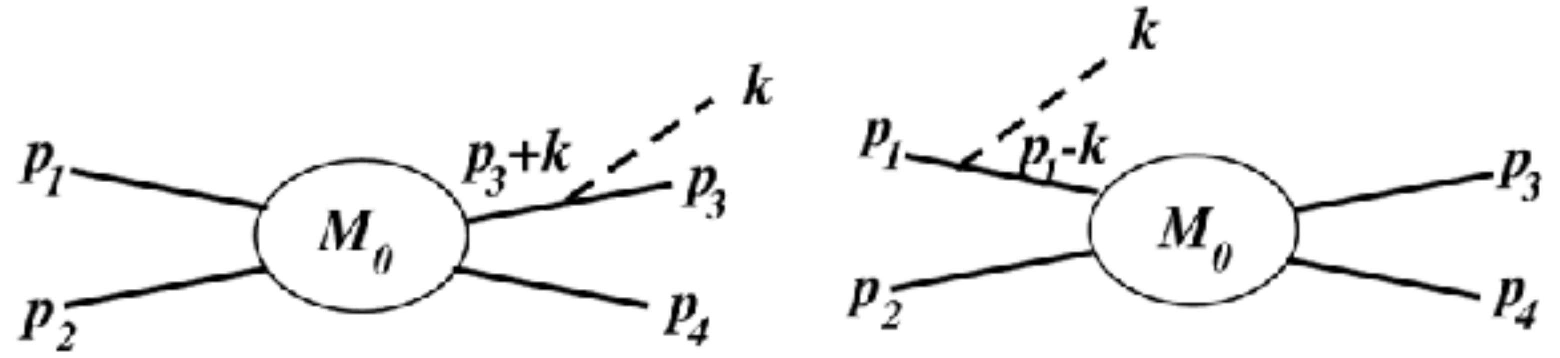
Predictions from lattice QCD



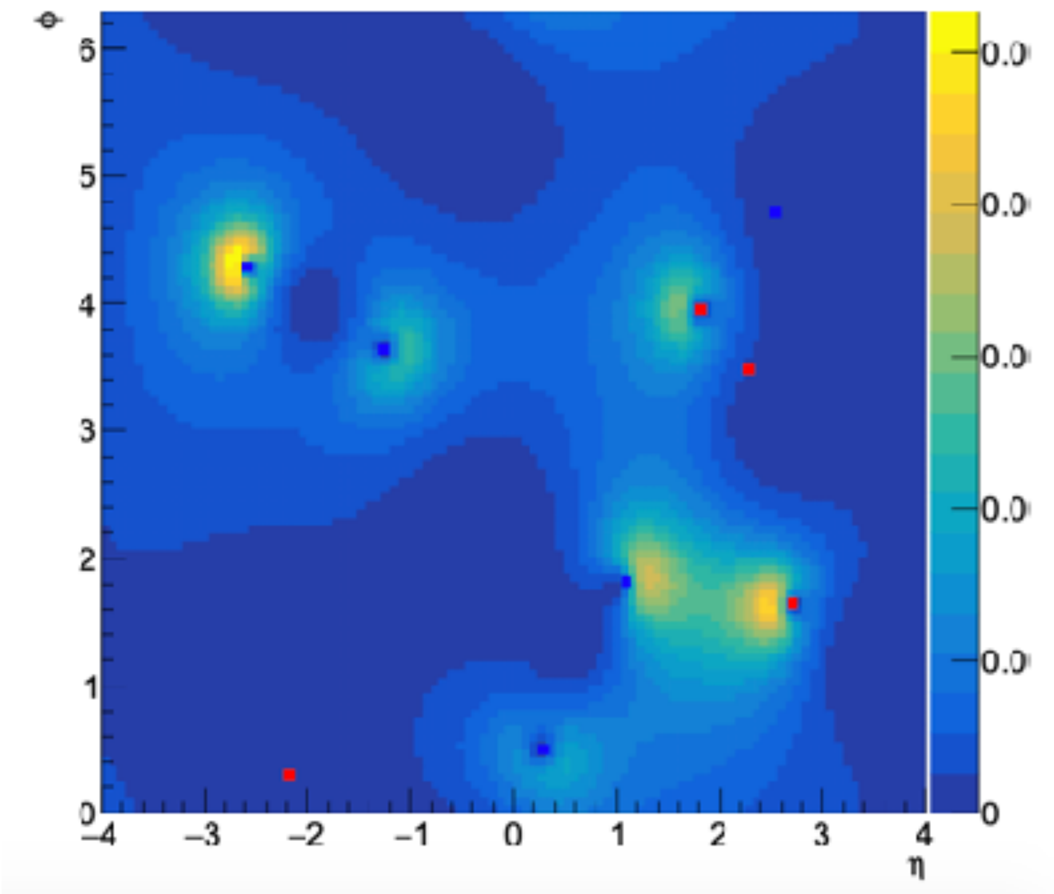
Low’s theorem — soft photons

- **Low’s theorem:** production of soft photons linked to charged final state (not to “blob”)

$$\frac{\mathrm{d}N^{\gamma}}{\mathrm{d}^3\vec{k}} = \frac{\alpha}{(2\pi)^2}\frac{-1}{E_{gamma}}\int\left(\mathrm{d}^3\vec{p}_1\ldots\mathrm{d}^3\vec{p}_N\right)\left(\sum_{\mathrm{Particle}\ i}\frac{\eta_i e_i P_i}{P_i K}\right)^2\frac{\mathrm{d}N^{\mathrm{H}}}{\mathrm{d}^3\vec{p}_1\ldots\mathrm{d}^3\vec{p}_N}$$

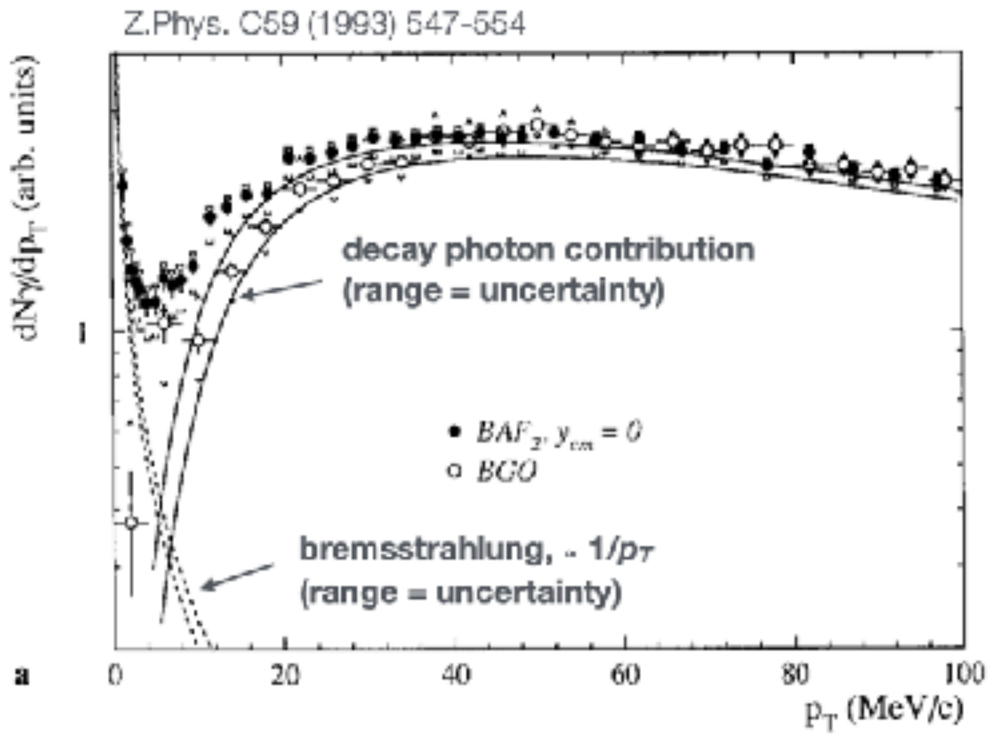


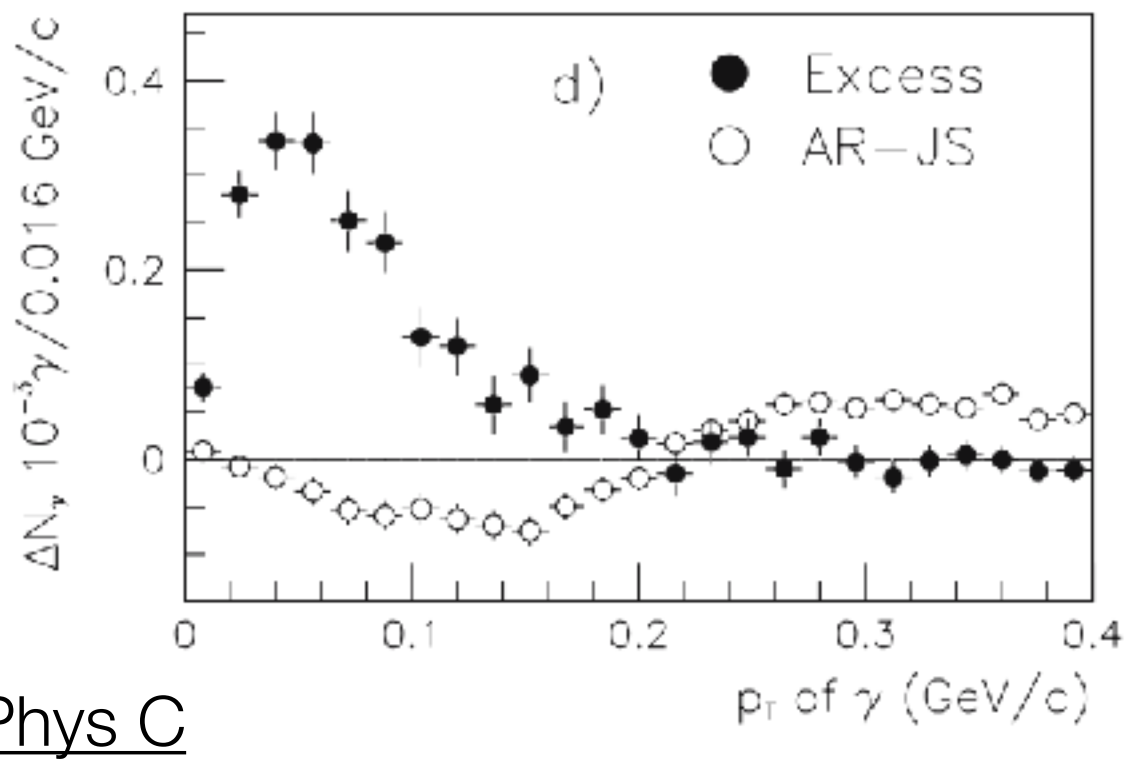
Single event photon emission



- Observational question: **Photon excess in association with hadrons** seen in previous experiments (not in $e^+e^- \rightarrow \mu^+\mu^-$)

Rapidity distribution signal and decay





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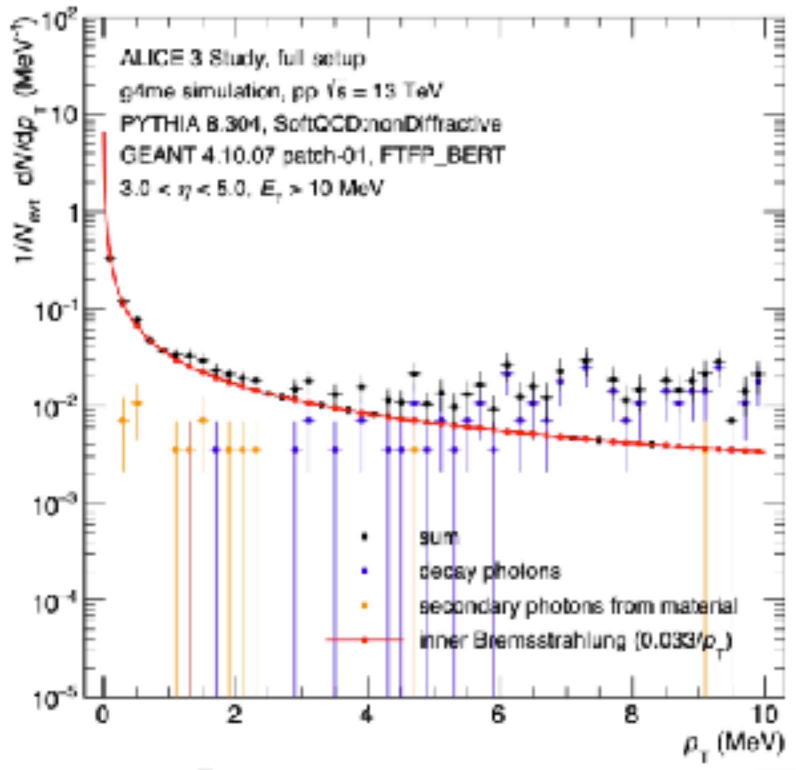
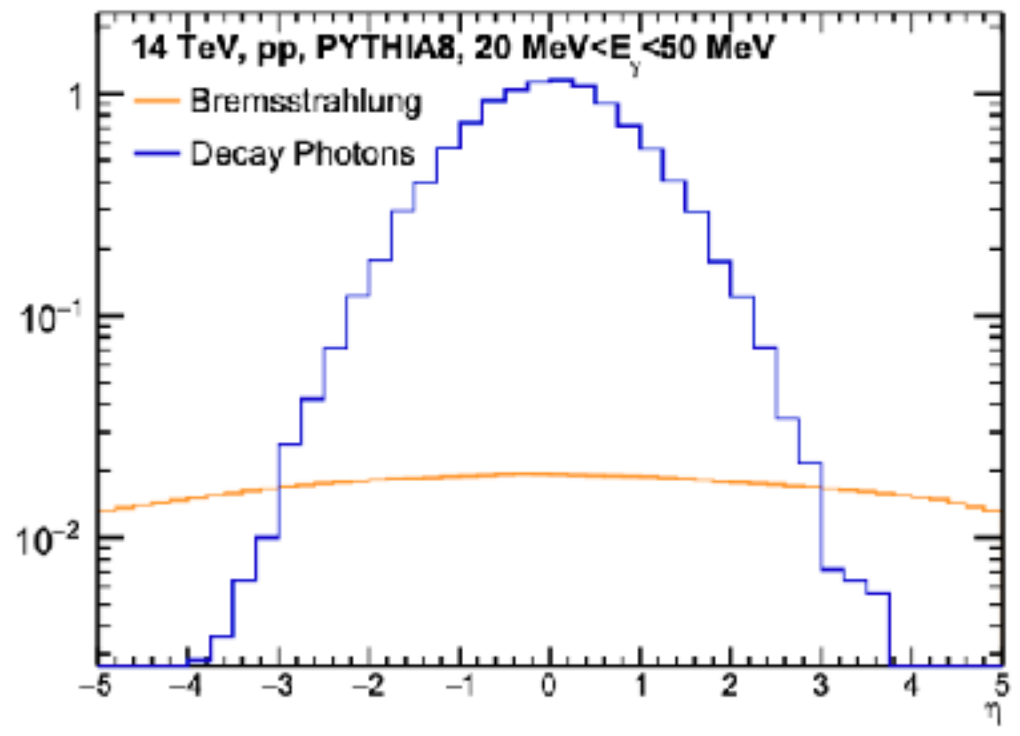
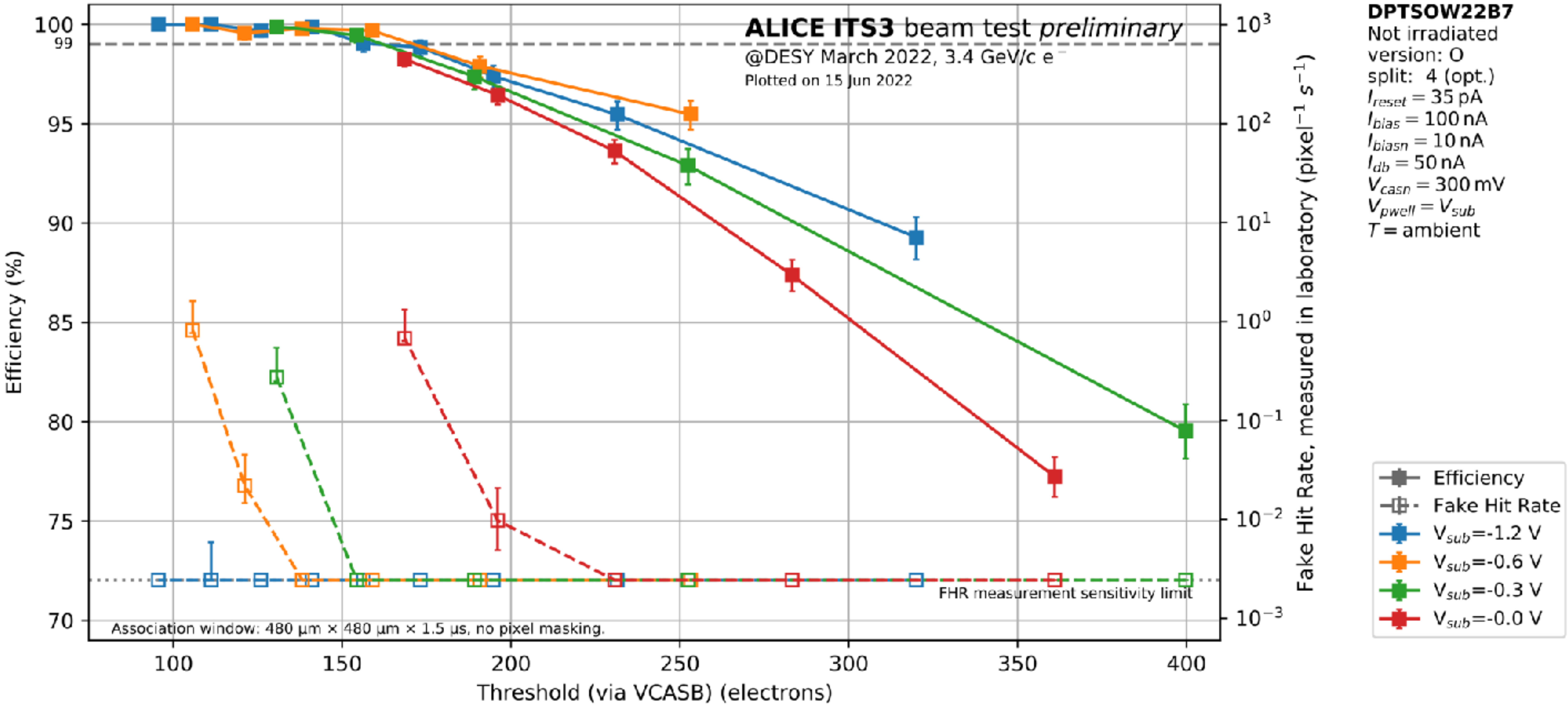


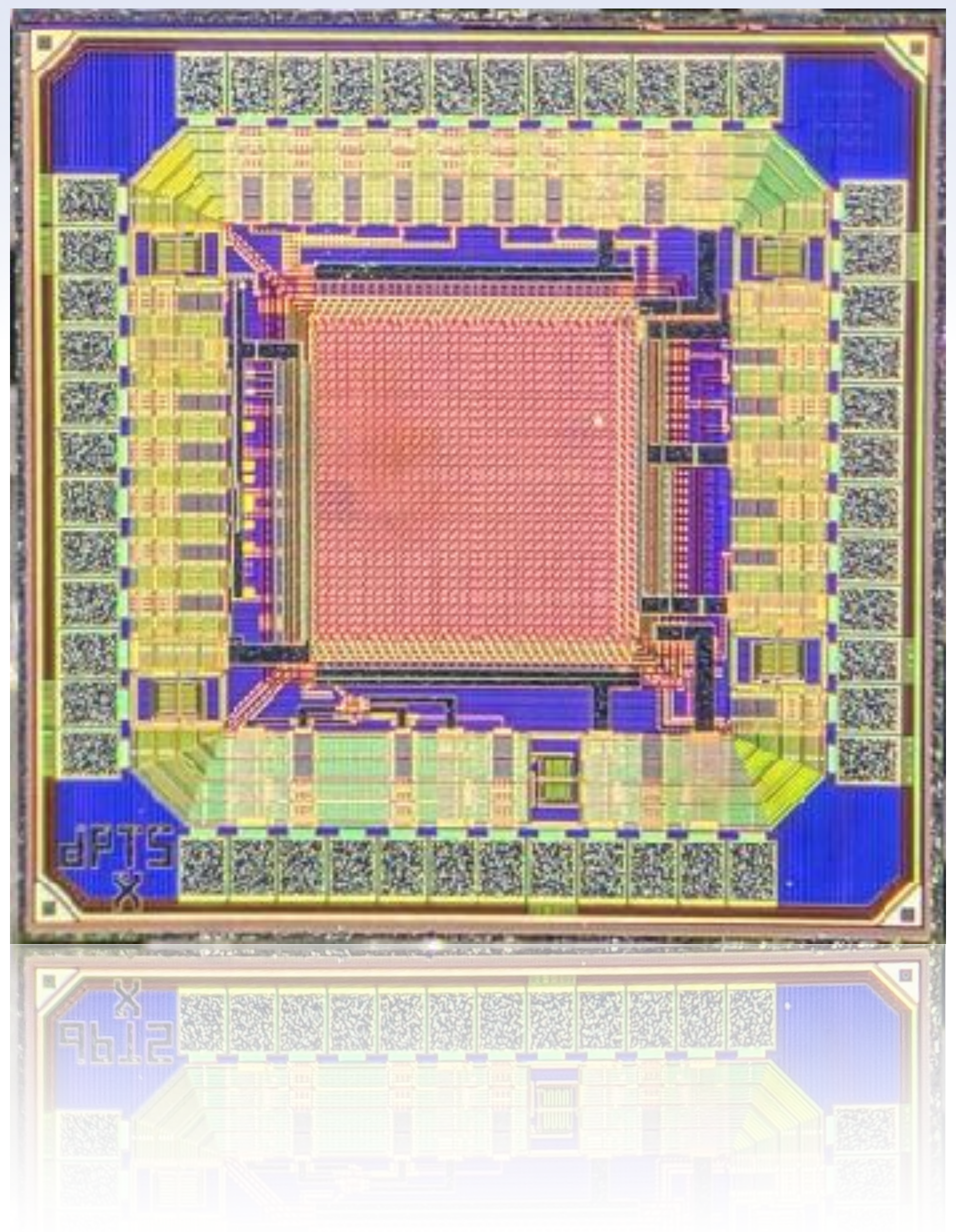


Observable: (ultra-)soft photons (p_T < 50 MeV/*c*) at forward rapidity

S/B best at large rapidity, very low p_T

ITS3 - sensors

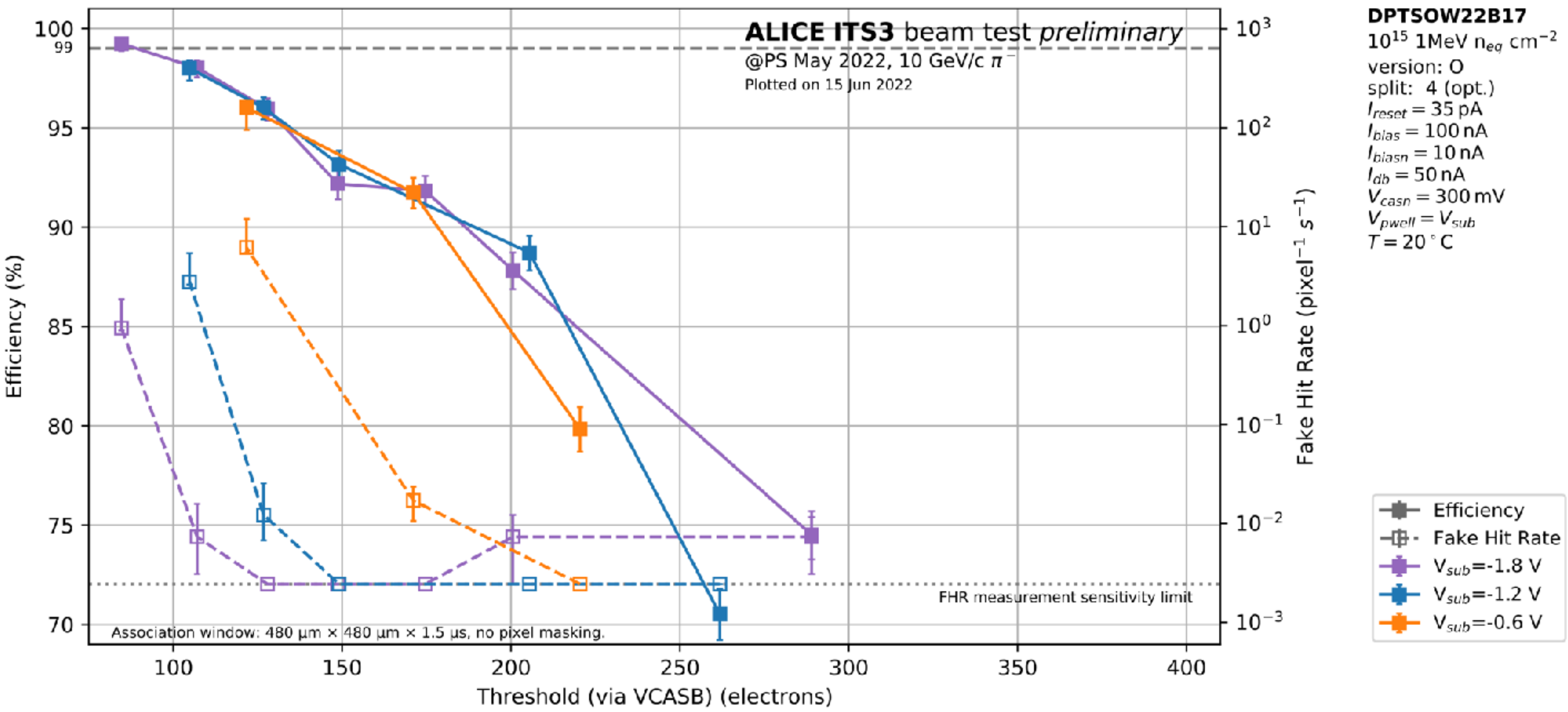


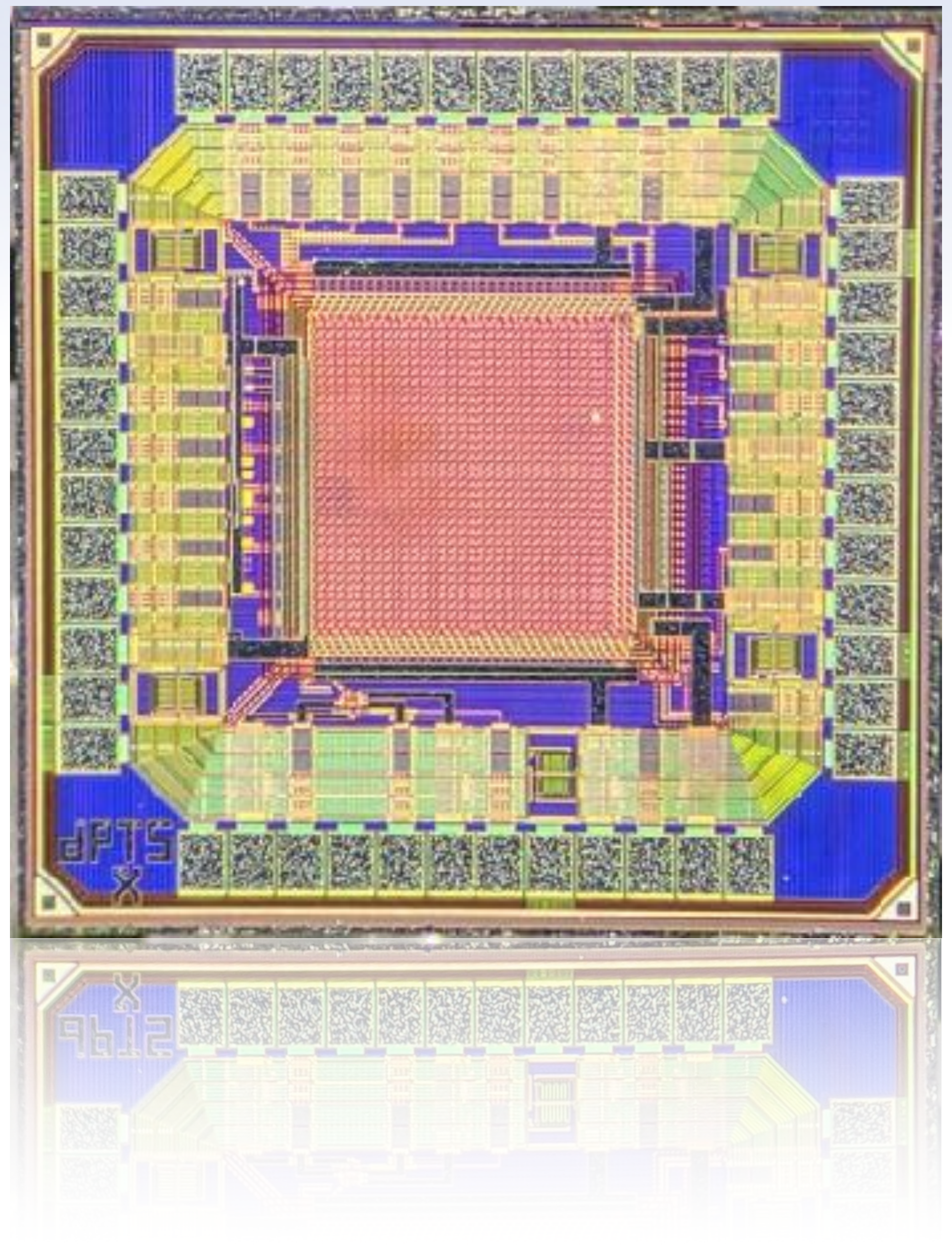


TPSCo 65 nm digital pixel test structure (from MLR1 run)

- Full functionality of digital front-end verified in silicon
- 100% detection efficiency easily achieved

ITS3 - sensors





TPSCo 65 nm digital pixel test structure (from MLR1 run)

- Even after 10^{15} 1 MeV n_{eq}/cm^2 (NIEL), >99% detection efficieny
- NB: at +20°C