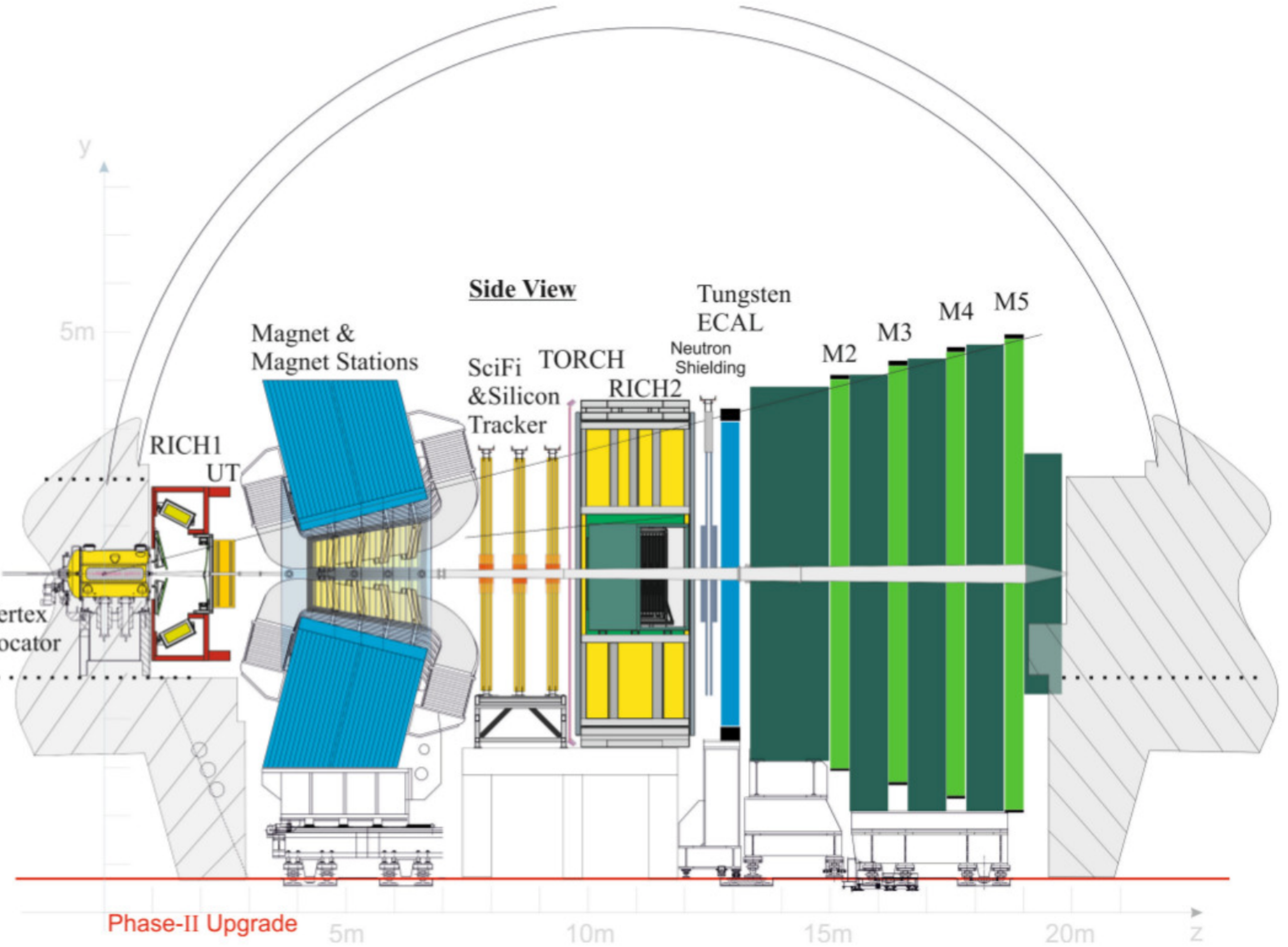
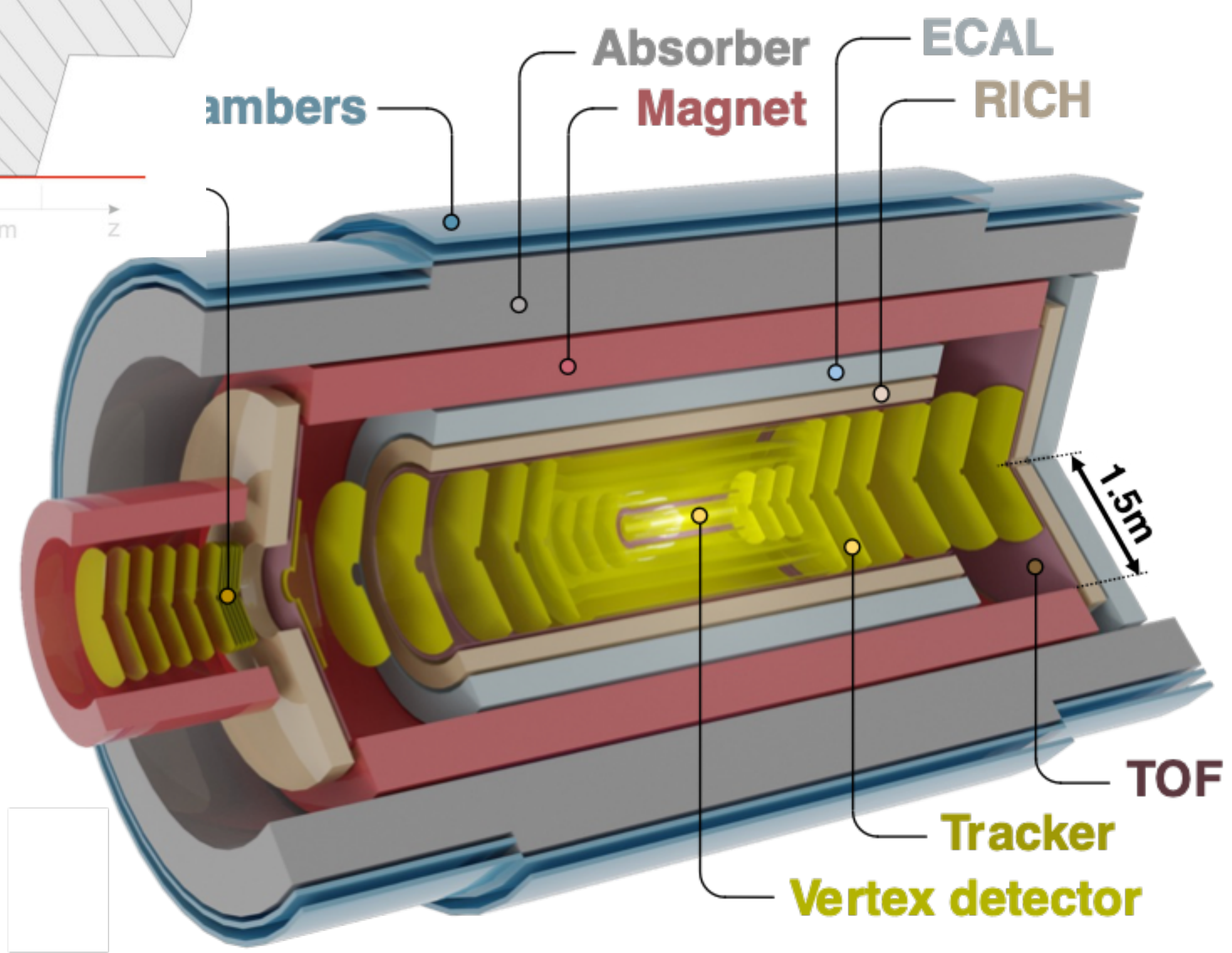
LHC upgrades for heavy-ions for Run 5 and beyond (with a focus on ALICE 3)





Gian Michele Innocenti (CERN)

Luciano Musa (CERN)

With material from C. Parkes and J. Klein

Upgrade programs of LHC experiments

intermediate upgrade | major upgrade

	Run 1 and 2 (2009-2018)	Run 3 (2022-2025)	Run 4 (2029-2032)	Run 5 and 6 (2034-2040)
ATLAS EXPERIMENT	ATLAS	ATLAS phase I upgrades	ATLAS phase II upgrades	
CMS	CMS	CMS phase I upgrades	CMS phase II upgrades	
LHCb	LHCb	LHCb upgrade I(a)	LHCb upgrade Ib	LHCb upgrade II
ALICE	ALICE 1	ALICE 2 upgrade	ALICE 2.1 upgrade	ALICE 3 upgrade

→ LHCb will implement a vast upgrade of its detector apparatus
→ ALICE will be replaced by a brand new detector, ALICE3

J. Klein, Quark Matter 2022

LHCb Phase II upgrade for Run 5 and 6

TDR LHCb Upgrade Phase II
C. Parkes, ECFA 2022

LHCb upgrade II for Run 5 and 6

→ peak luminosity in pp collisions of $1.5 \cdot 10^{34}$ cm^{-2} s^{-1} with sizeable increase in radiation load ($6*10$ n_{eq}/cm^2)

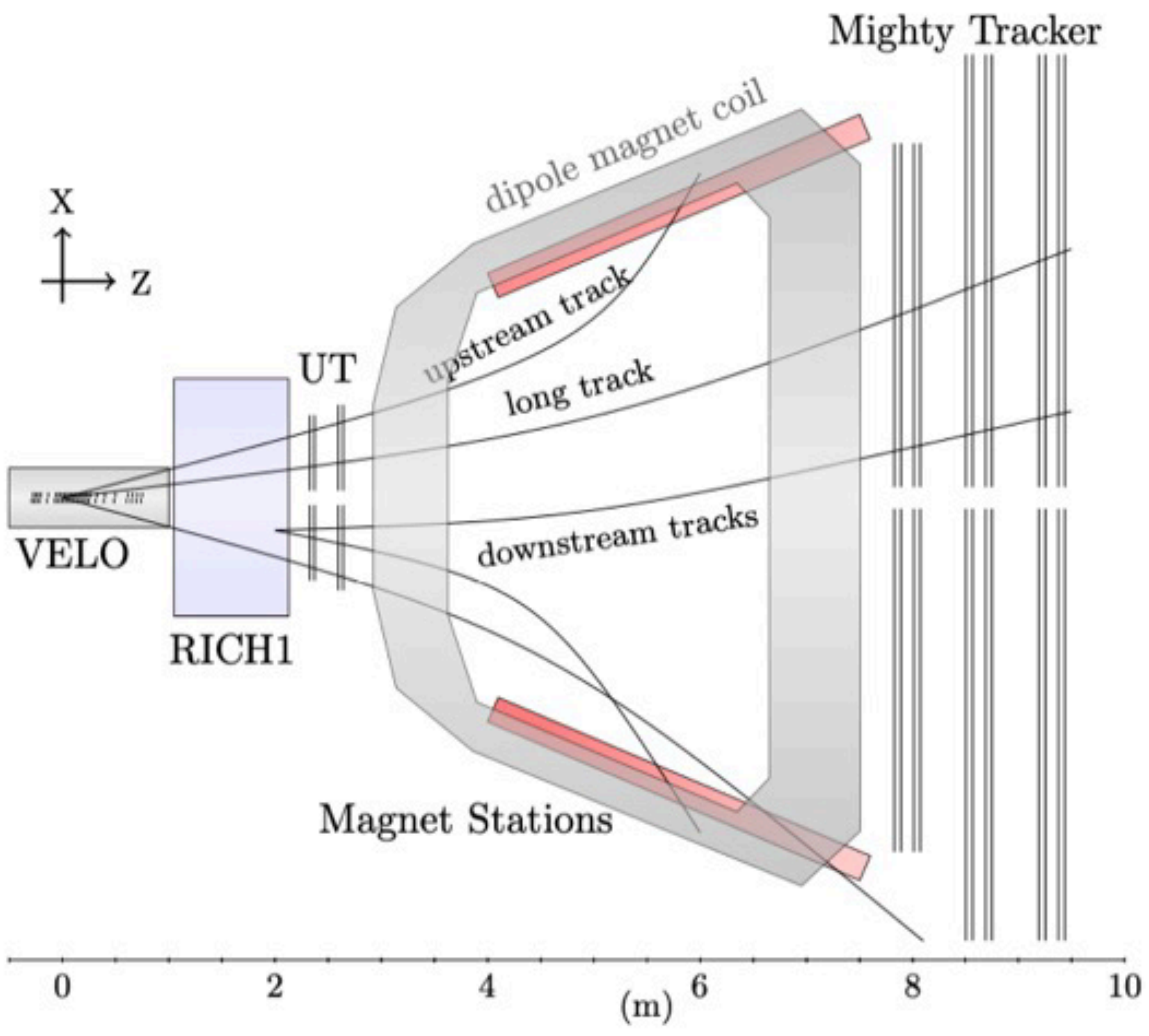
→ will allow LHCb to exploit its unique kinematic coverage also in central heavy-ion collisions

VELO:
- increased granularity and radiation hardness

→ 4D tracking (with timing info) to "preserve" Run3/4 performance)

Upstream Tracker (UT) and Mighty tracker (MT)
- high-granularity silicon pixels and scintillating fibres

→ increased low-p_T capabilities



Online/offline data processing:

→ towards 200 TB/s of data throughput

LHCb upgrade II for Run 5 and 6

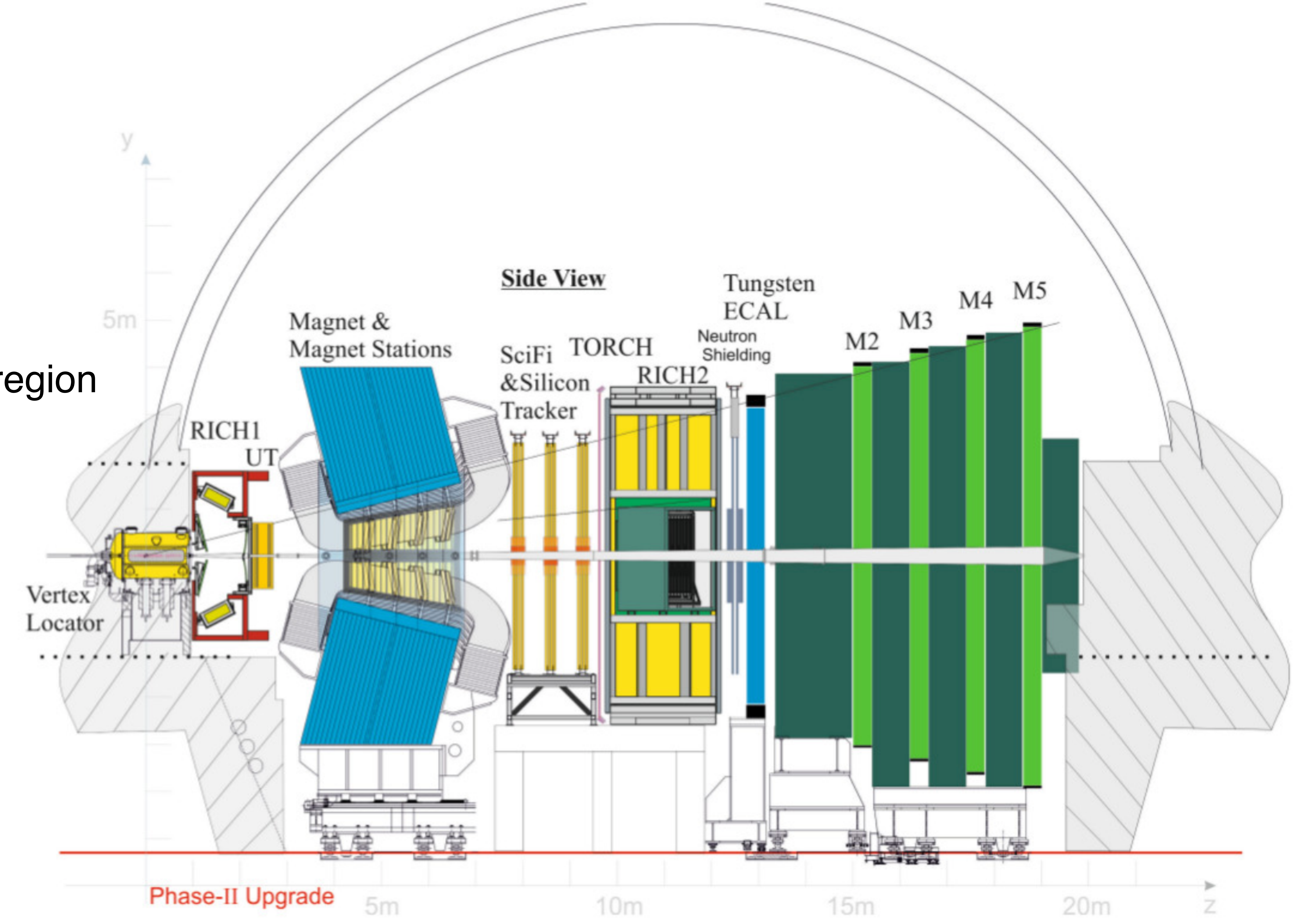
→ peak luminosity in pp collisions of $1.5 \cdot 10^{34}$ cm^{-2} s^{-1} with sizeable increase in radiation load (6*10 n_{eq} /cm^2)

→ will allow LHCb to exploit its unique kinematic coverage <u>also in central heavy-ion collisions</u>

Quarkonium and open heavy flavour:
- Ψ(2S), Υ
- open charm and beauty mesons down to $p_T = 0$
- P wave charmonium states, also for fixed target

Dileptons and photons:
- dilepton spectrum in di-muon channel in the ρ mass region
- real photons through conversions

Nuclear PDFs and saturation:
- low-x regime of QCD

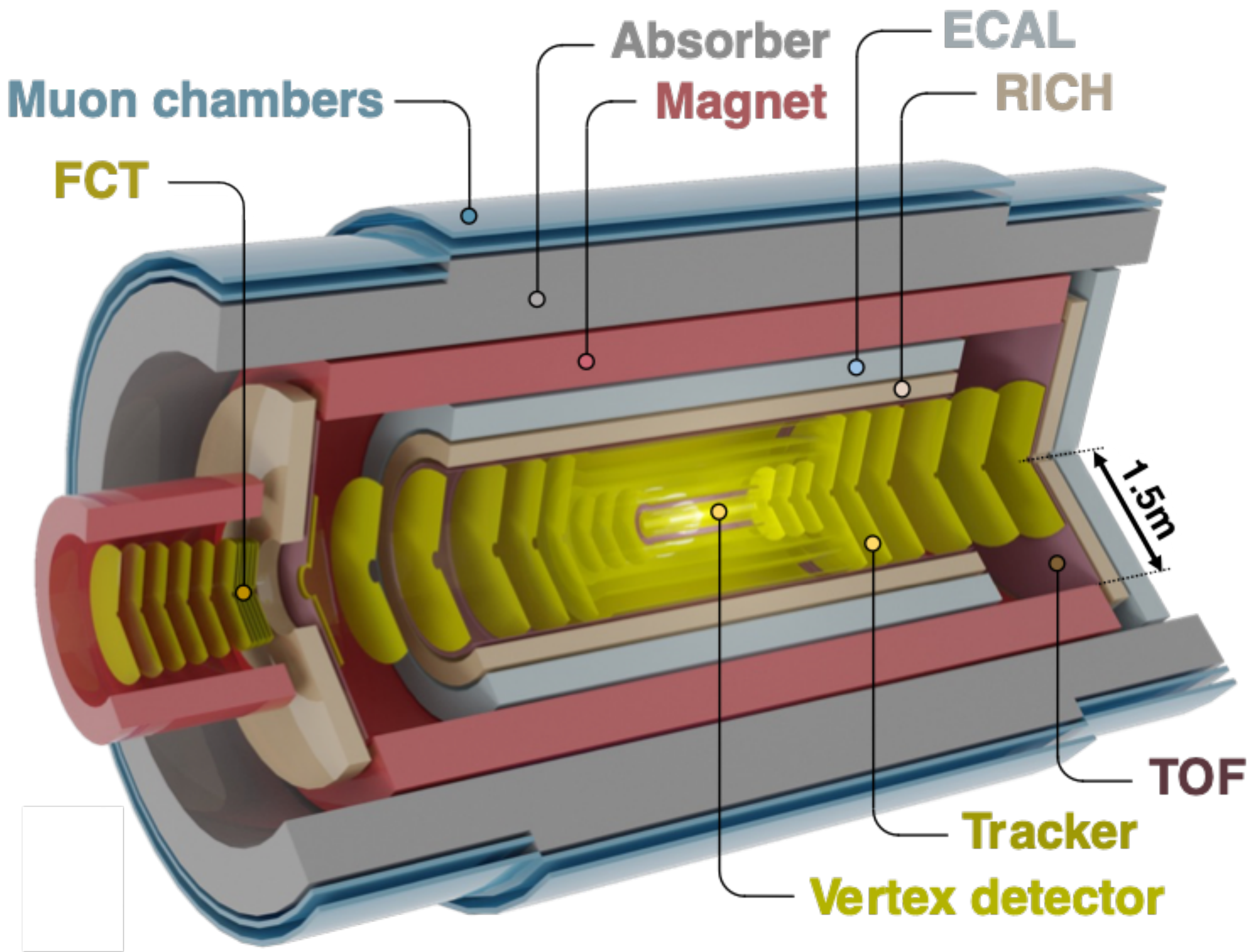


ALICE 3 for Run 5 and 6: physics goals and performance

ALICE 3 Letter of Intent, CERN-LHCC-2022-009, arXiv:2211.02491
LoI submitted in October ’21
Review concluded in March ’22

ALICE 3: A new heavy-ion experiment for the '30

ALICE 3: A high-rate, high-resolution, large coverage **(|η|<4)** heavy-ion experiment for **Run 5 and 6**



- 35 nb^{-1} of PbPb **(or ArAr/KrKr?)** minimum bias
- 18 fb^{-1} of pp minimum bias

High resolution tracker + Time-of-Flight and RICH
over 8 pseudorapidity units

"Low-p_T" muon detector:
→ accessing J/ψ down to pT=0

Calorimetry:
- Electromagnetic calorimeter (1.5 < η < 4)
- Prospects for HCAL being discussed

ALICE 3: A new heavy-ion experiment for the ‘30

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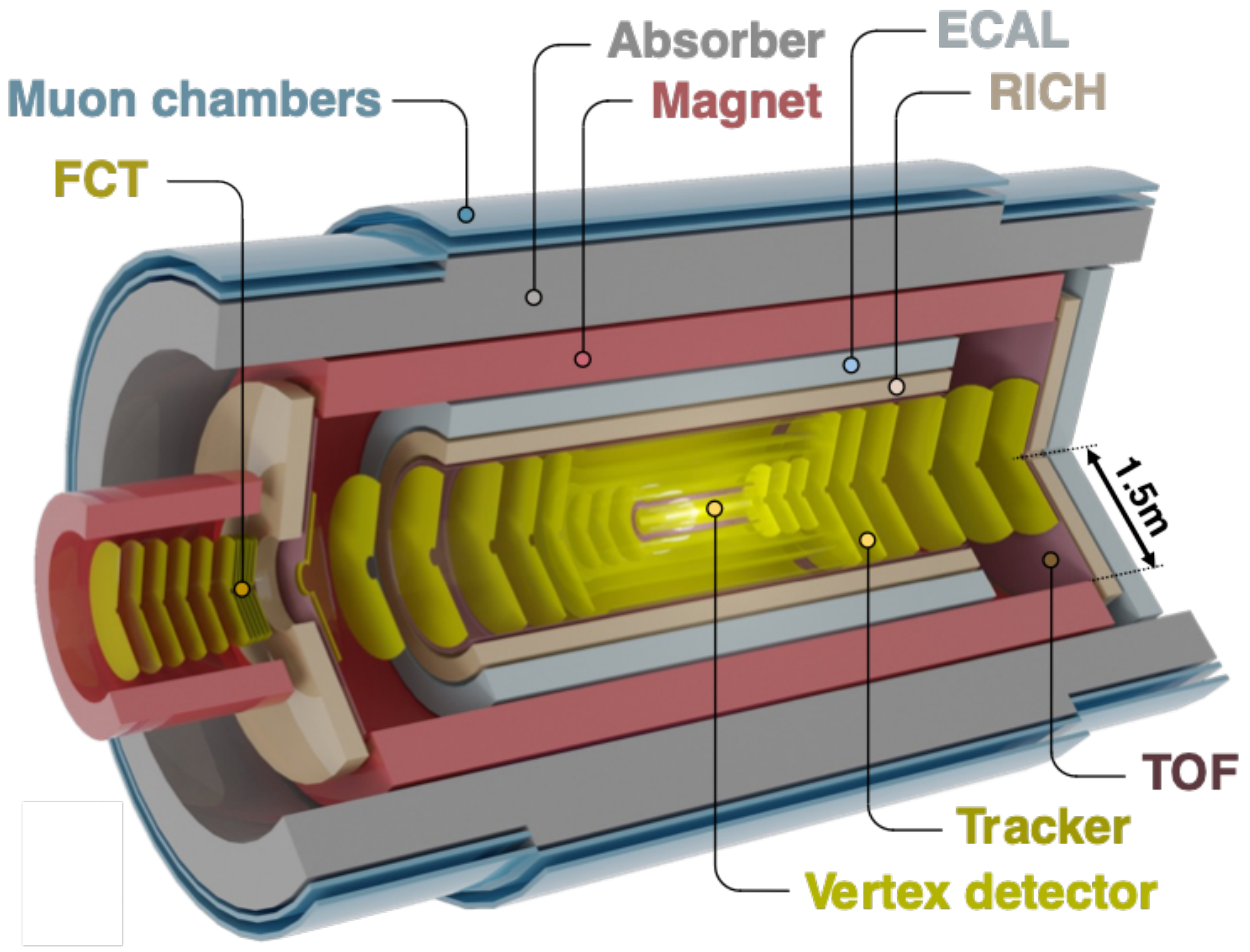
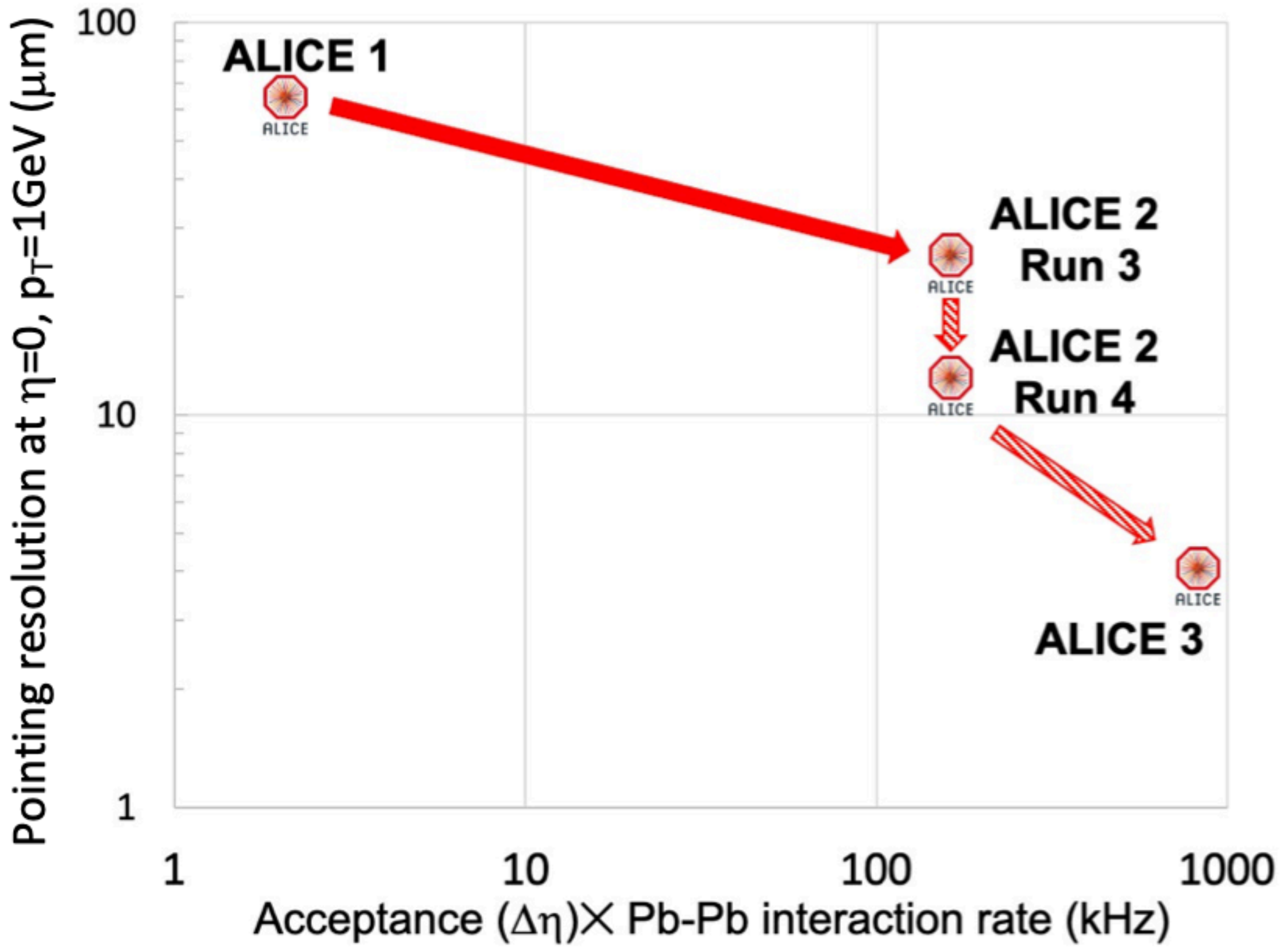
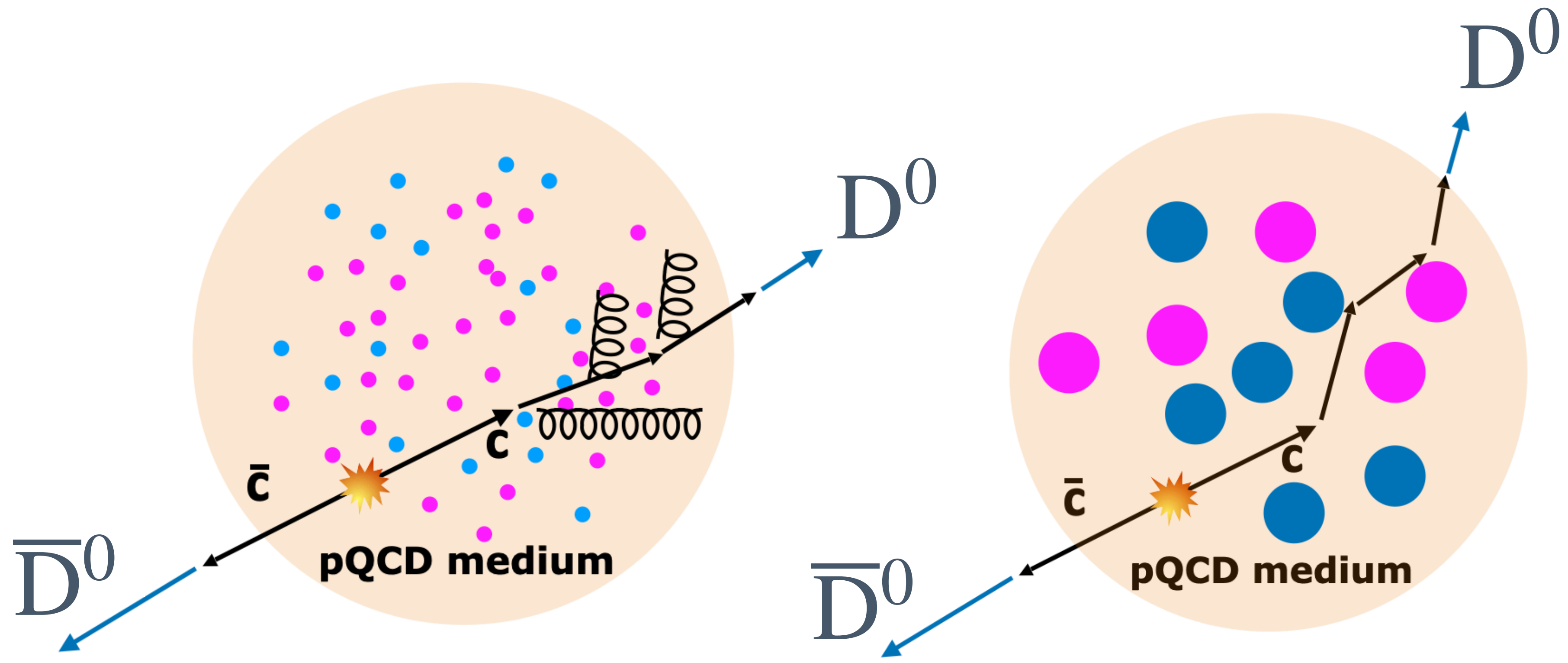




Physics goals: making heavy-flavor physics "light"

Covered in this talk

- Interactions with the QGP of highly energetic quarks and gluons
- quark thermalization and equilibration
- mechanisms of hadron formation in QCD?
- → **multi-charm hadrons and heavy-flavour correlations**



- QGP temperature throughout its space-time evolution
- **mechanisms of chiral symmetry restoration** in the QGP?
- mechanisms of **hadron formation in QCD?**
- → **precise measurements of low-mass dileptons**

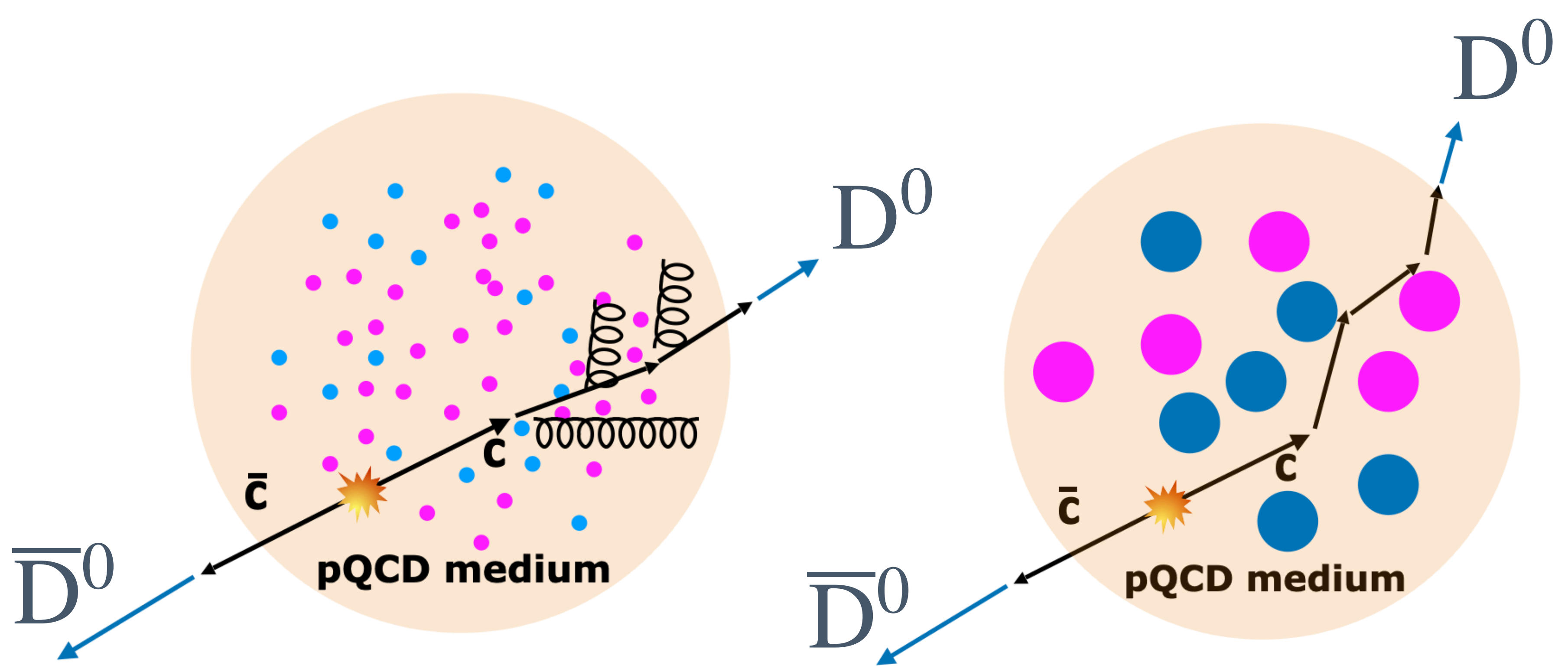
- QCD chiral phase structure → **fluctuations of conserved charges**
- Hadronic interaction potential → **hadron-hadron correlations**
- Formation of nuclei, hyper-nuclei and super nuclei

See arXiv:2211.02491 for a complete description

Heavy-flavour correlations in HI collisions

M. Nahrgang, et al. arXiv:1305.3823
S. Cao et al., Phys. Rev. C 92, 054909 (2015)
T. Stavreva et al., JHEP vol. 2013, 72 (2013)

"Rutherford-like" experiment with $D^0\overline{D}^0$ correlations

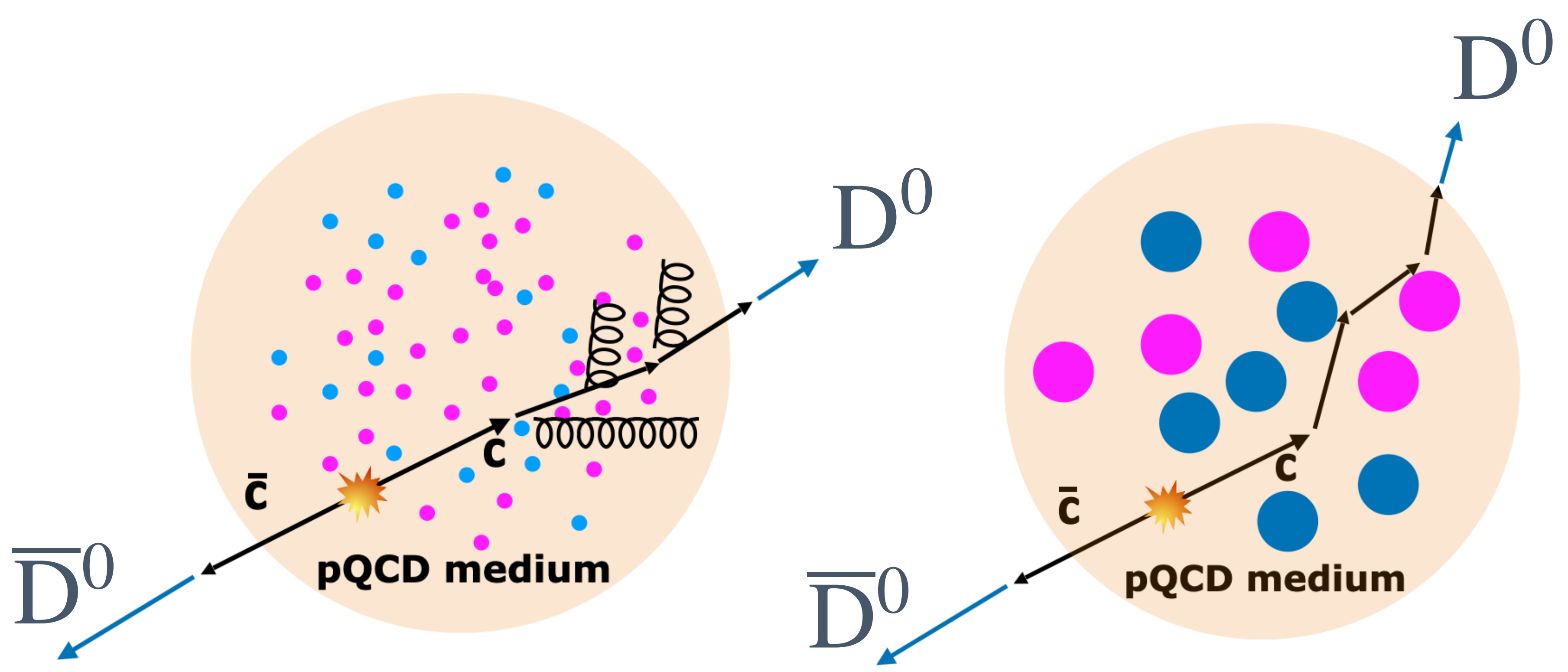


→ partonic "structure" of the hot medium

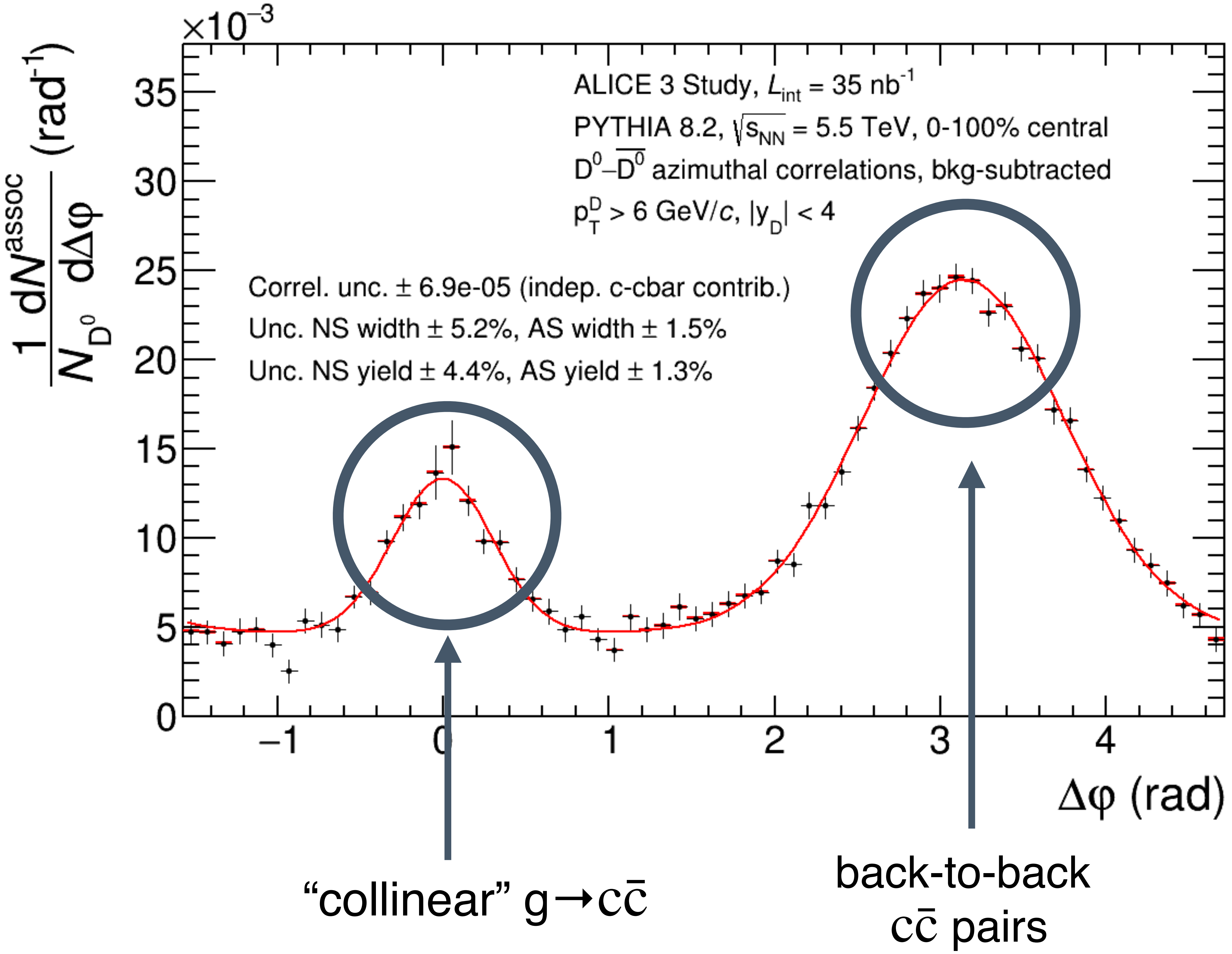
→ **Tracking and vertexing with μm-accuracy over |η|<4**
→ superconducting magnet with forward dipoles
→ Hadron PID from low (TOF) to high p_T (Cherenkov)

Heavy-flavour correlations in HI collisions

"Rutherford-like" experiment with $D^0\overline{D}^0$ correlations



→ partonic "structure" of the hot medium



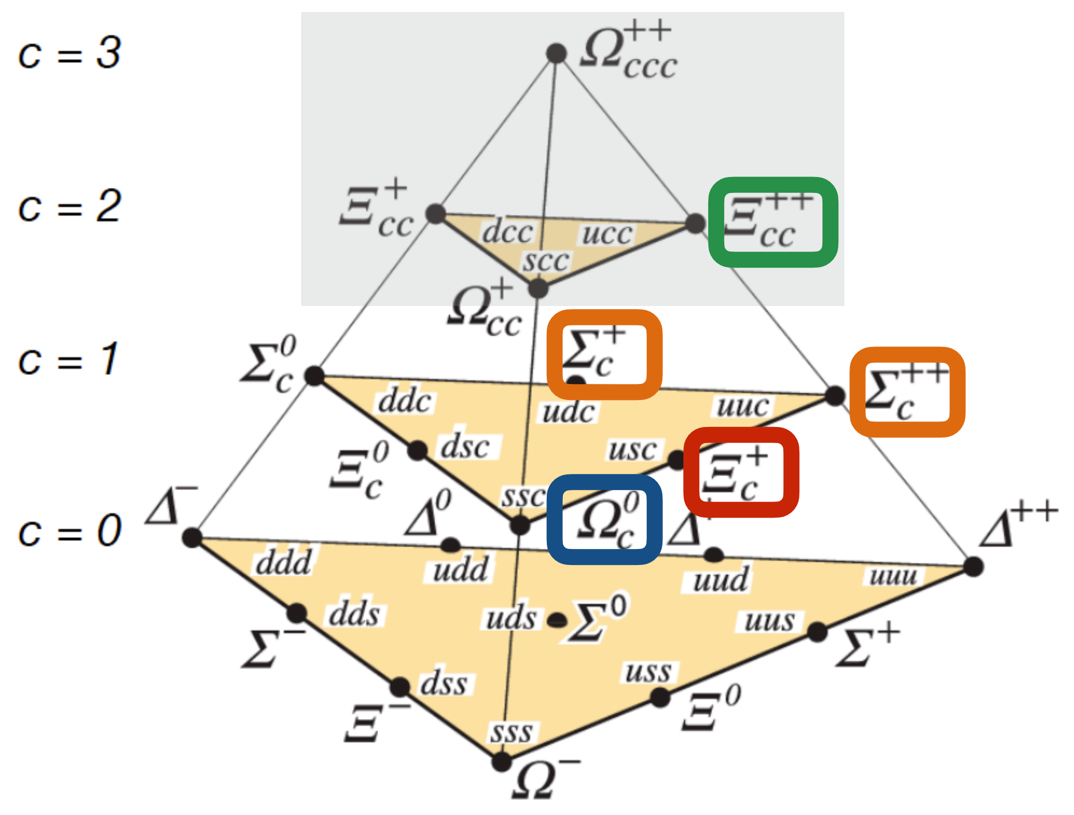
→ **Tracking and vertexing with μm-accuracy over |η|<4**
→ superconducting magnet with forward dipoles
→ Hadron PID from low (TOF) to high p_T (Cherenkov)

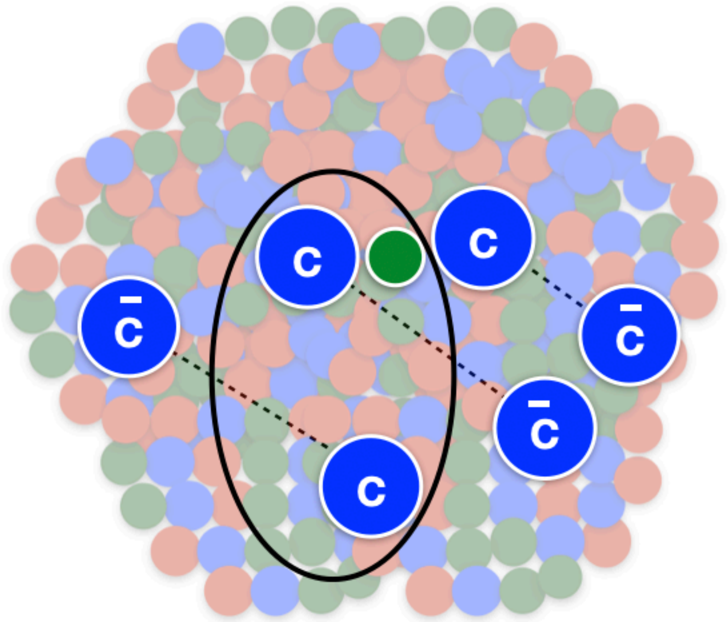
Multi heavy-quark hadrons

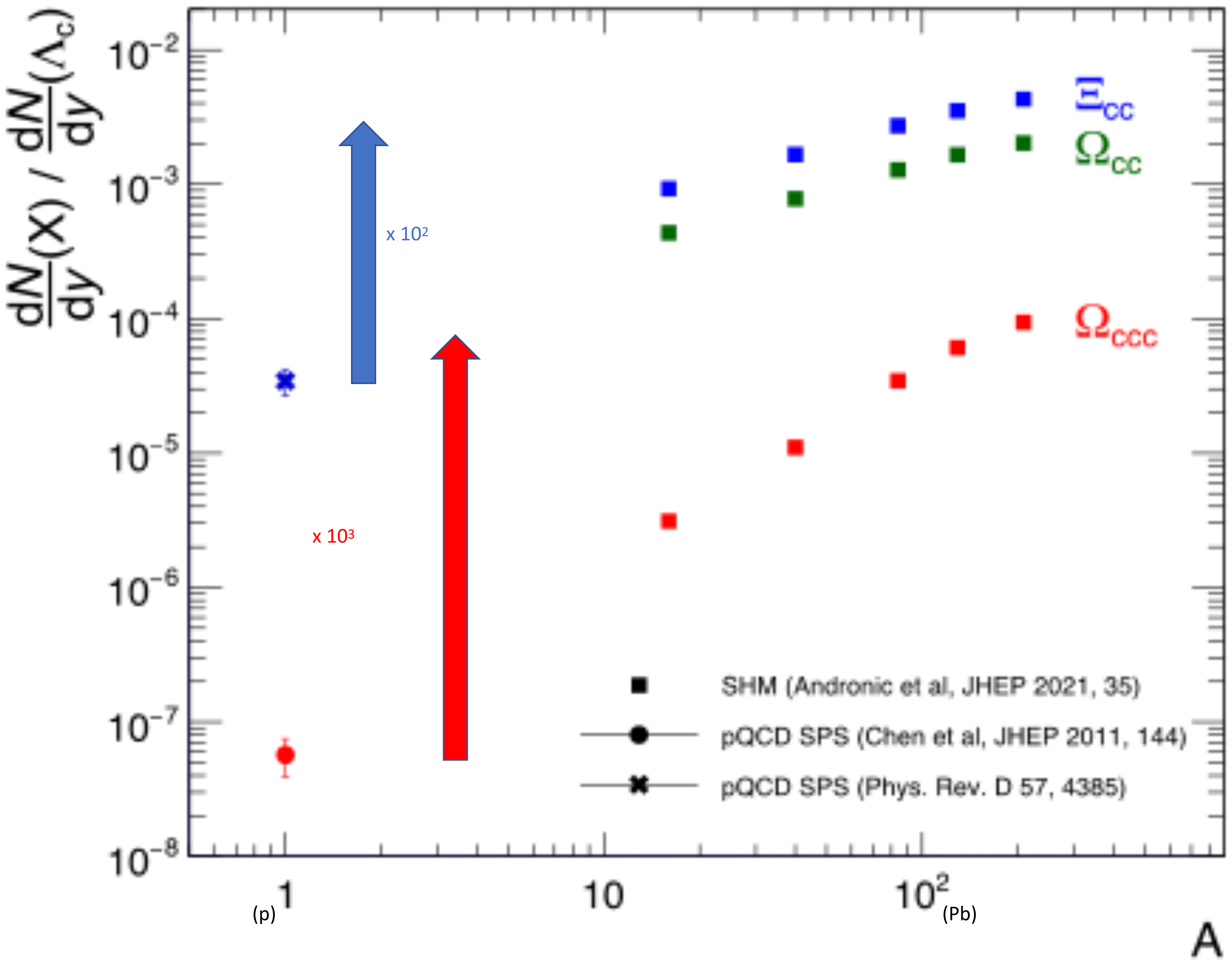
ALICE: arXiv.2011.06078
Beccatini: Phys. Rev. Lett. 95 (2005) 022301
SHMC: arXiv.2104.12754
G. Chen et al., Phys. Rev. D 89, 074020 (2014)

- Negligible same-scattering production
- In presence of hadron production from uncorrelated charm quarks
  → Large enhancement (up to x100) w.r.t. in-vacuum hadronization

double-c
(~fb^{-1} region)



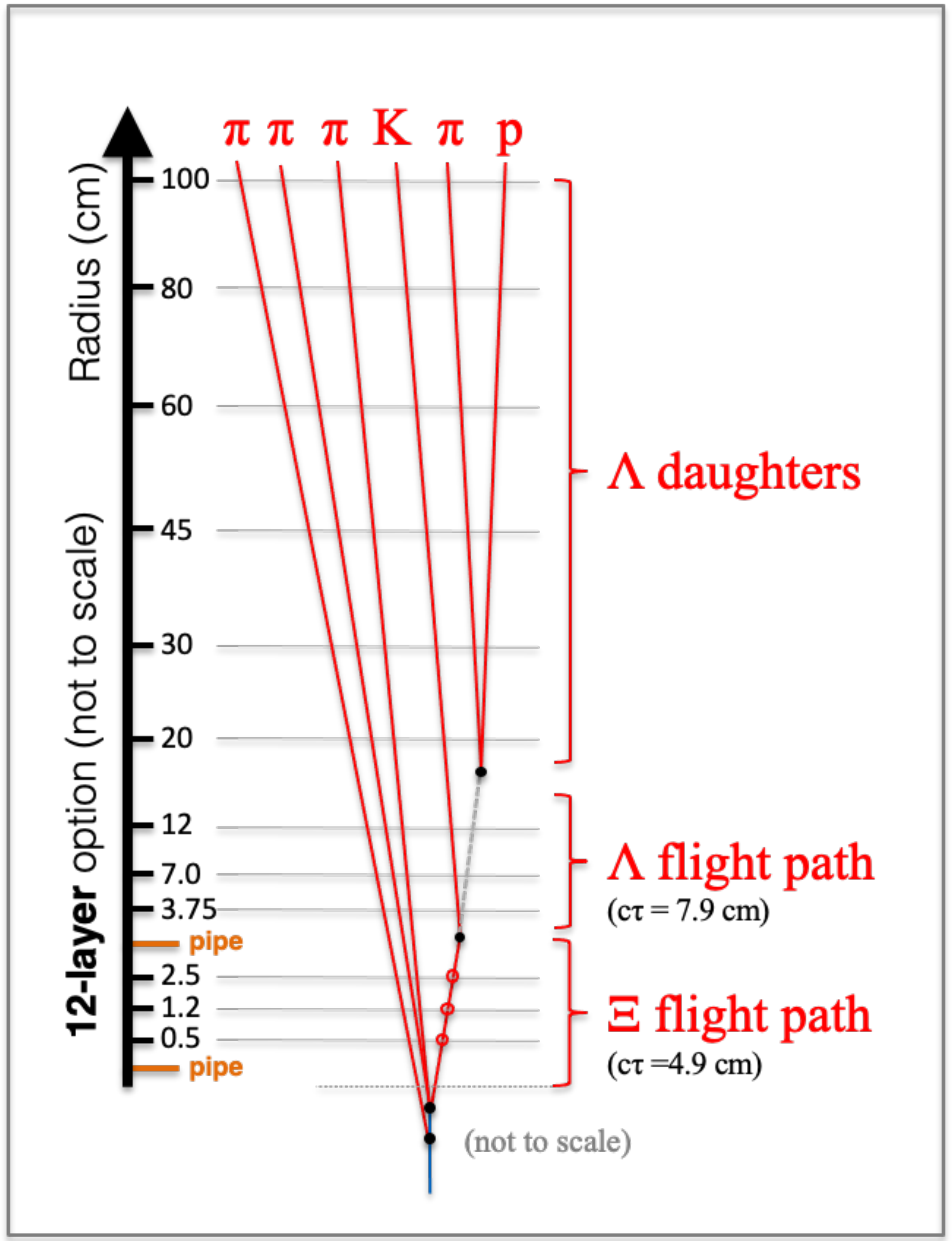




→ Extreme benchmarks for mechanisms of hadronization beyond "leading color" in small and large systems

→ **connection between "equilibrium" properties of charm quarks and hadronization modifications?**

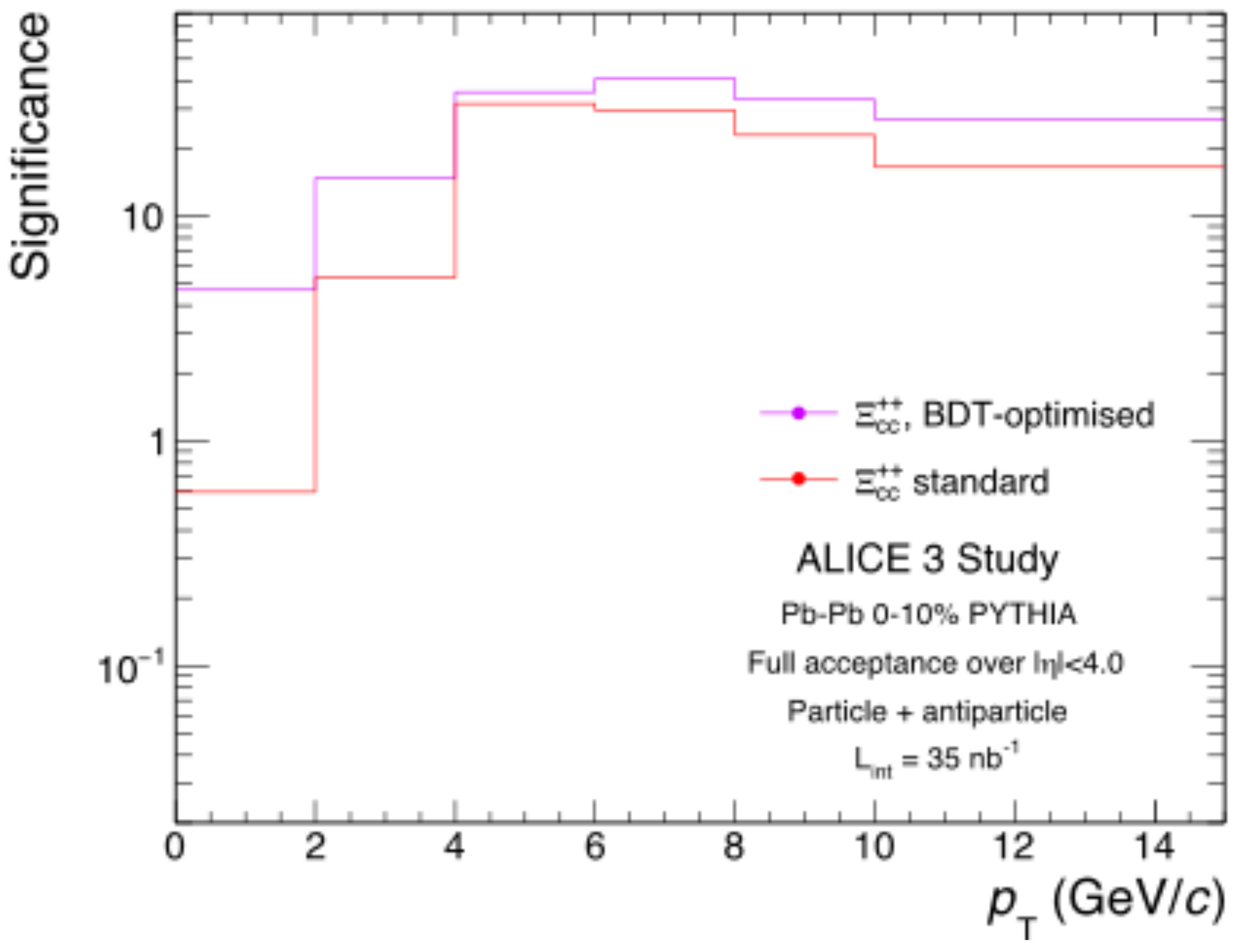
Multi heavy-quark hadrons



$\Xi^{++}_{cc} \rightarrow \Xi^{+}_{c} + \pi^{+}$ ($c\tau \approx$ 76 μm)

$\Xi^{+}_{c} \rightarrow \Xi^{-} + 2\pi^{+}$ ($c\tau \approx$ 132 μm)

$\Xi^{-} \rightarrow \Lambda + K^{-}$



High-resolution layers close to the beam pipe:

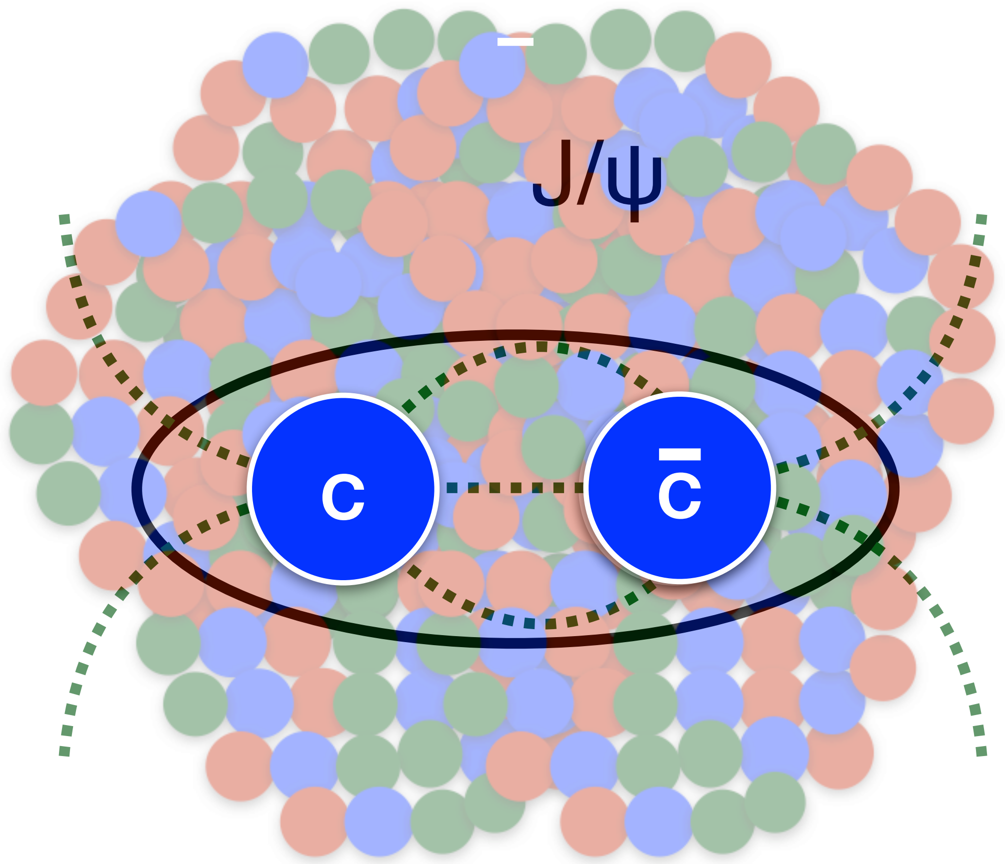
→"track strange baryons" before they decay

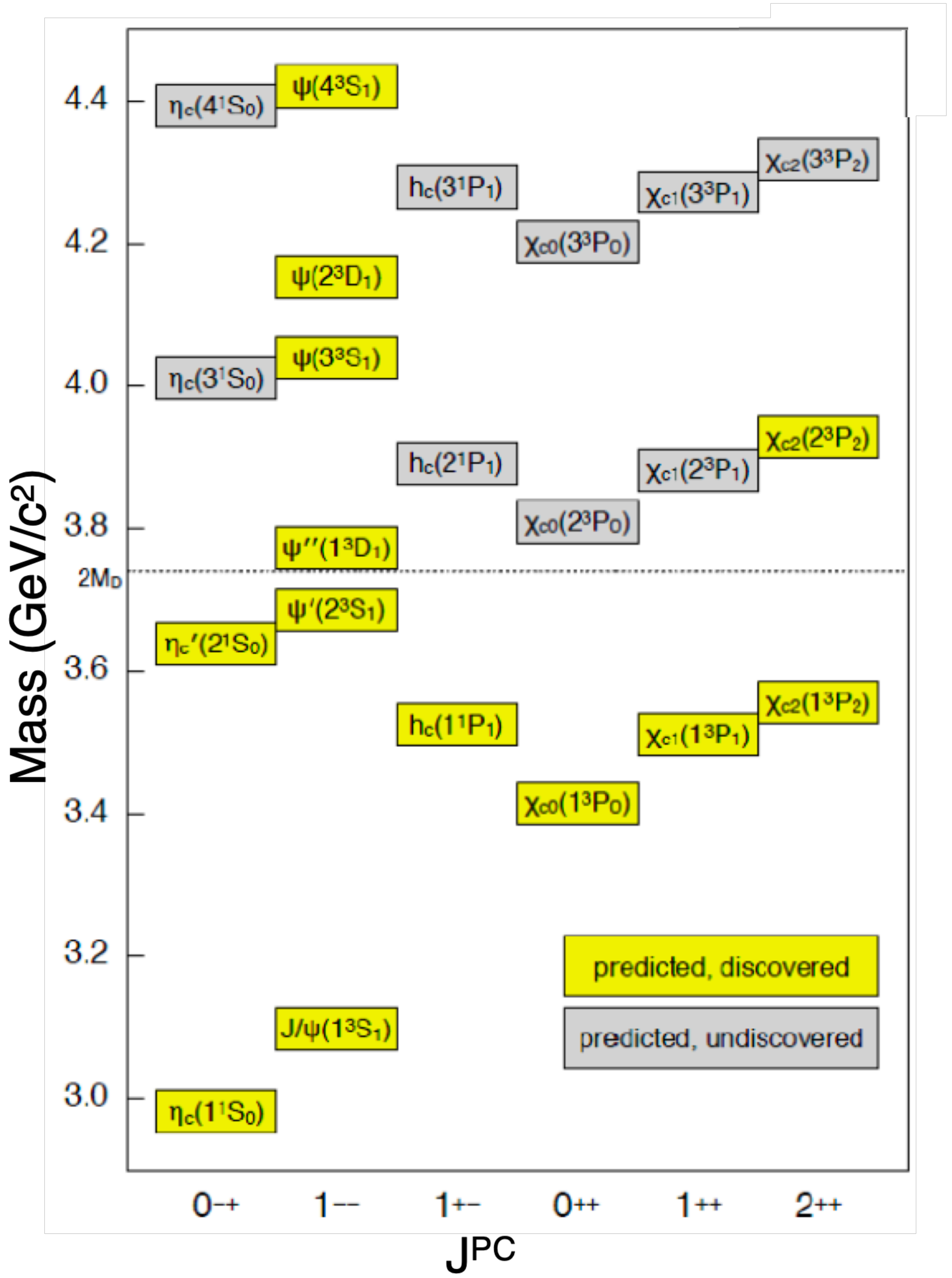
- strong improvement in selection accuracy
- large reduction of combinatorial background

Ξ^{++}_{cc} and Ω_{cc} measurable in central PbPb collisions down to low p_T

"New" bound-states in heavy-ions

Strong push from the theoretical community to measure more states with different quantum number properties





Pseudo-scalars (η_c)

- never measured in HI collisions

χ_c and $\chi_b \rightarrow J/\psi+\gamma$ (L=1):

- different bound-state stability and sensitivity to thermal fluctuations
  → **significant discrepancies among different theoretical predictions**

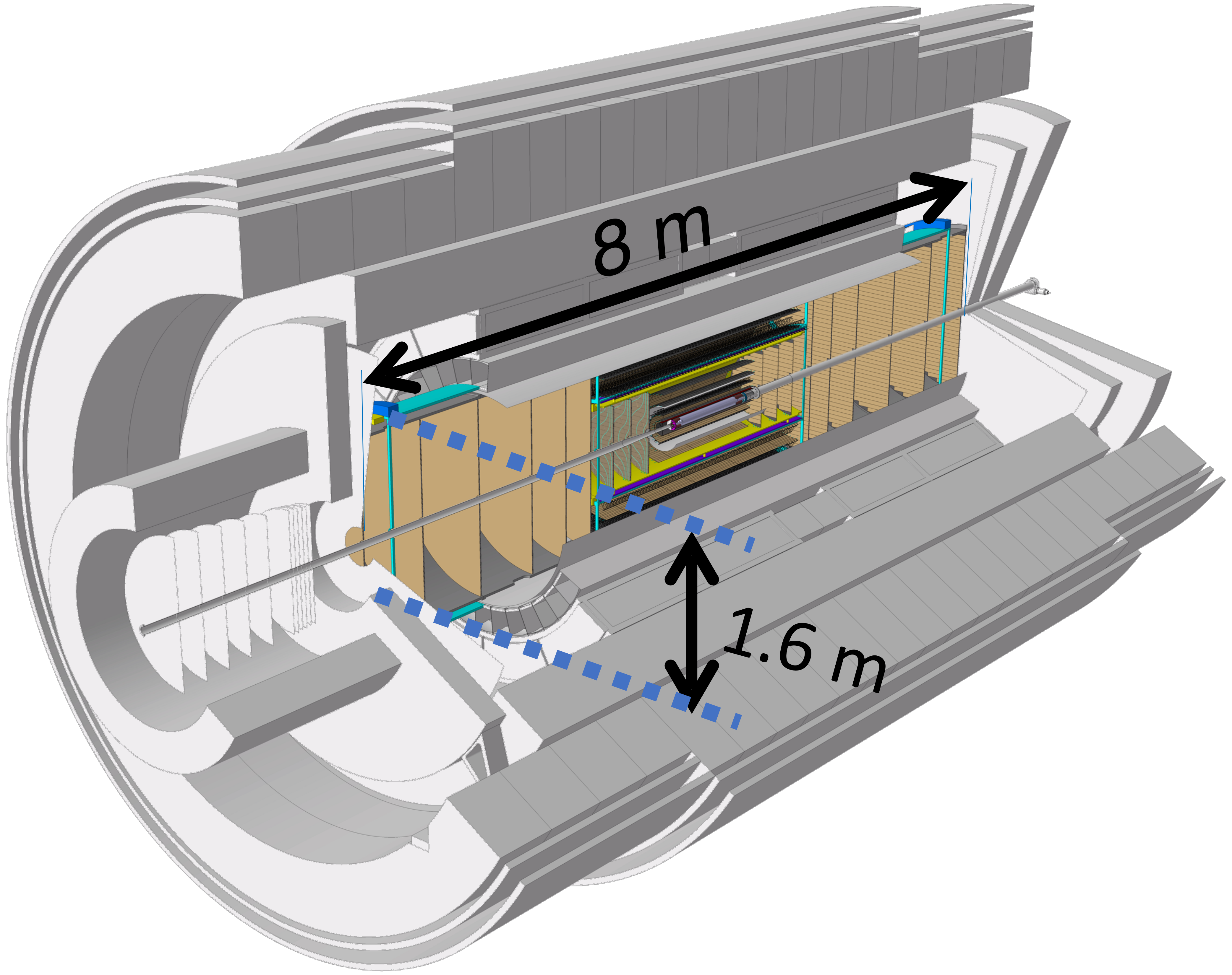
- Photon reconstruction down to ~ 0.5 GeV with good resolution:
- J/ψ and Y reconstruction **down to low p_T**

A focus on the ALICE 3 tracking system

ALICE ITS3 Letter of Intent: ALICE-PUBLIC-2018-013
ALICE ITS3, arXiv.2105.13000
ALICE ITS3, arXiv.2212.08621

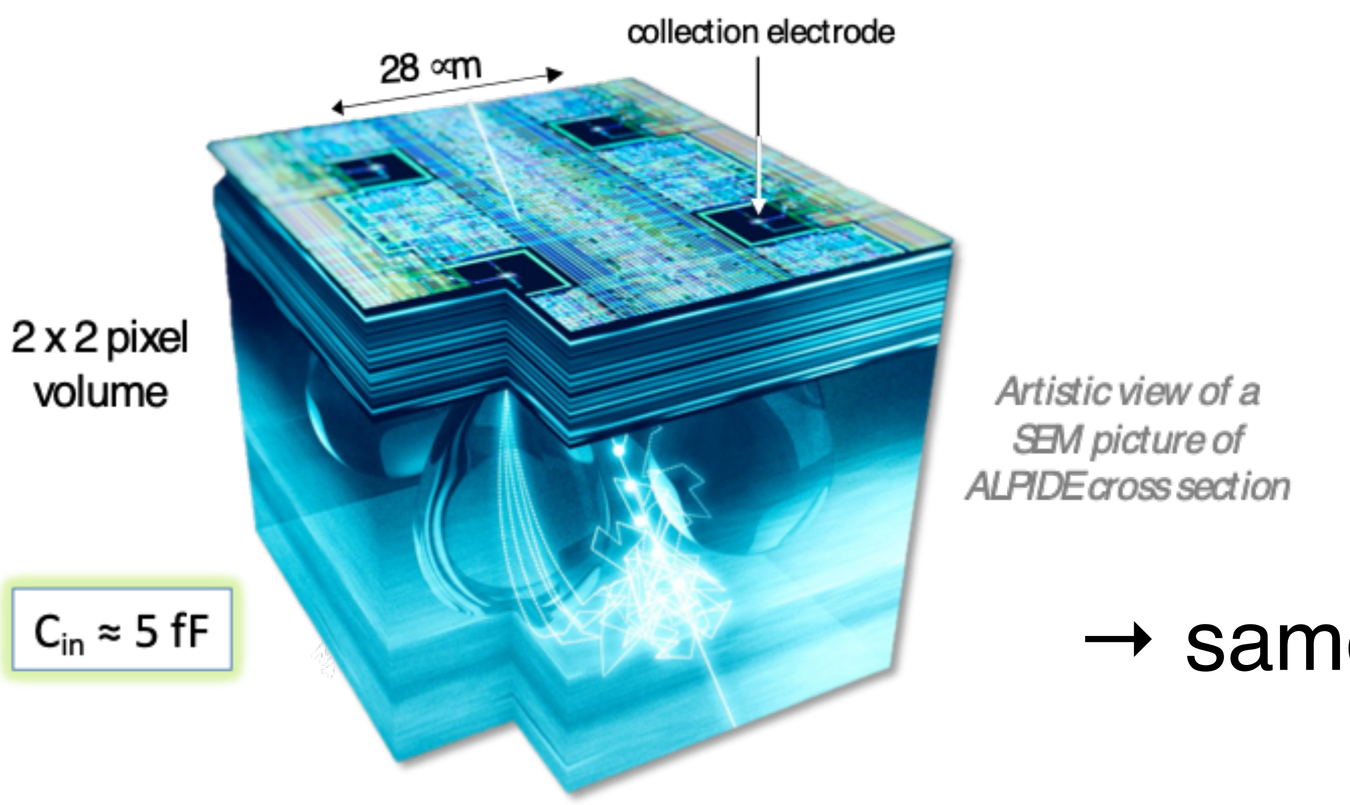
L. Musa, ICPAQGP, VECC, 2023

The ALICE 3 outer tracker



60 m² silicon pixel detector
based on CMOS Active Pixel Sensor (APS) technology

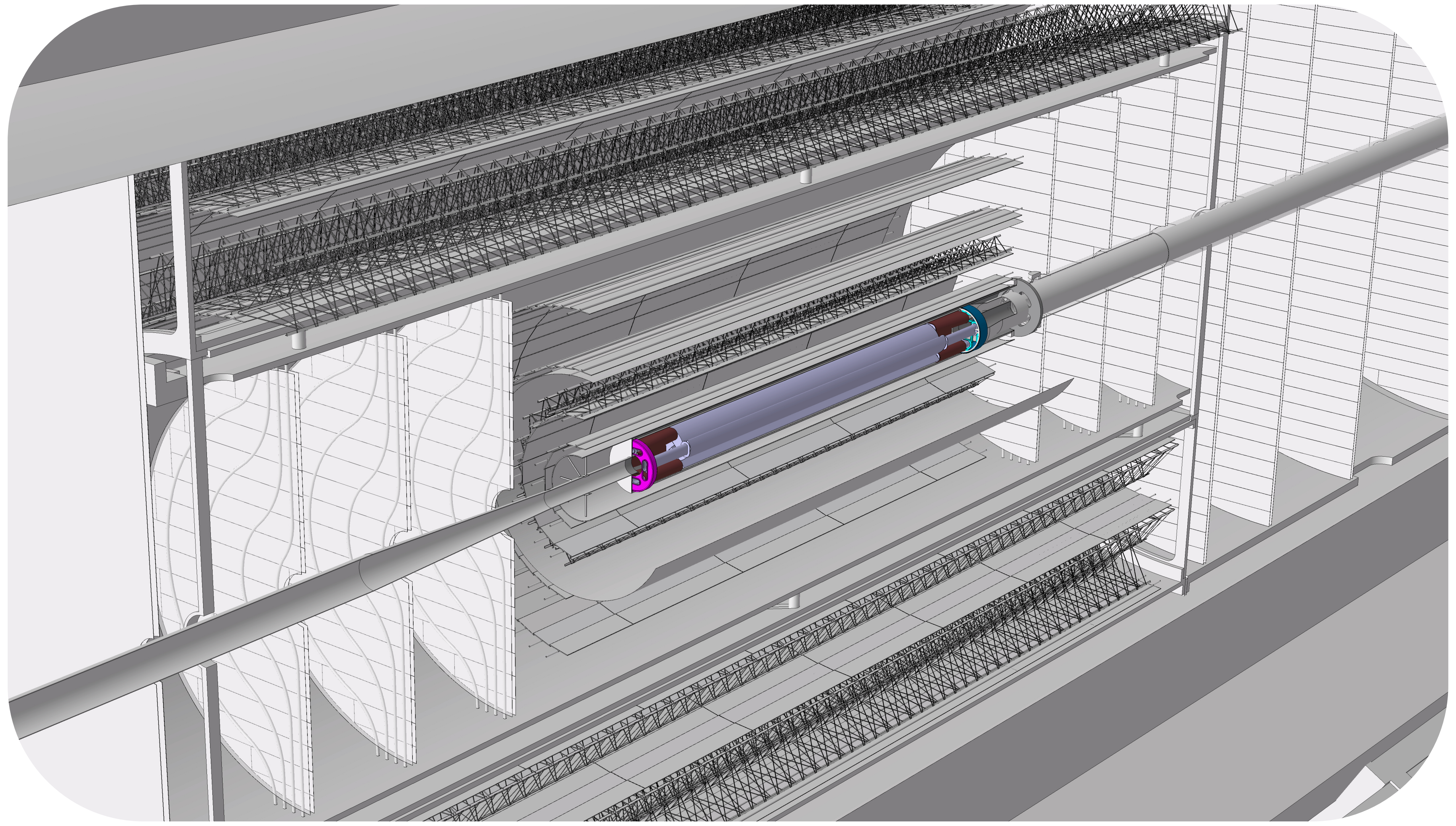
- large coverage: ±4η
- high-spatial resolution: $\sigma_{pos} \approx 5\mu m$
- very low material budget: X/X_0 (total) $\lesssim 10\%$
- low power: ≈ 20 mW/cm²



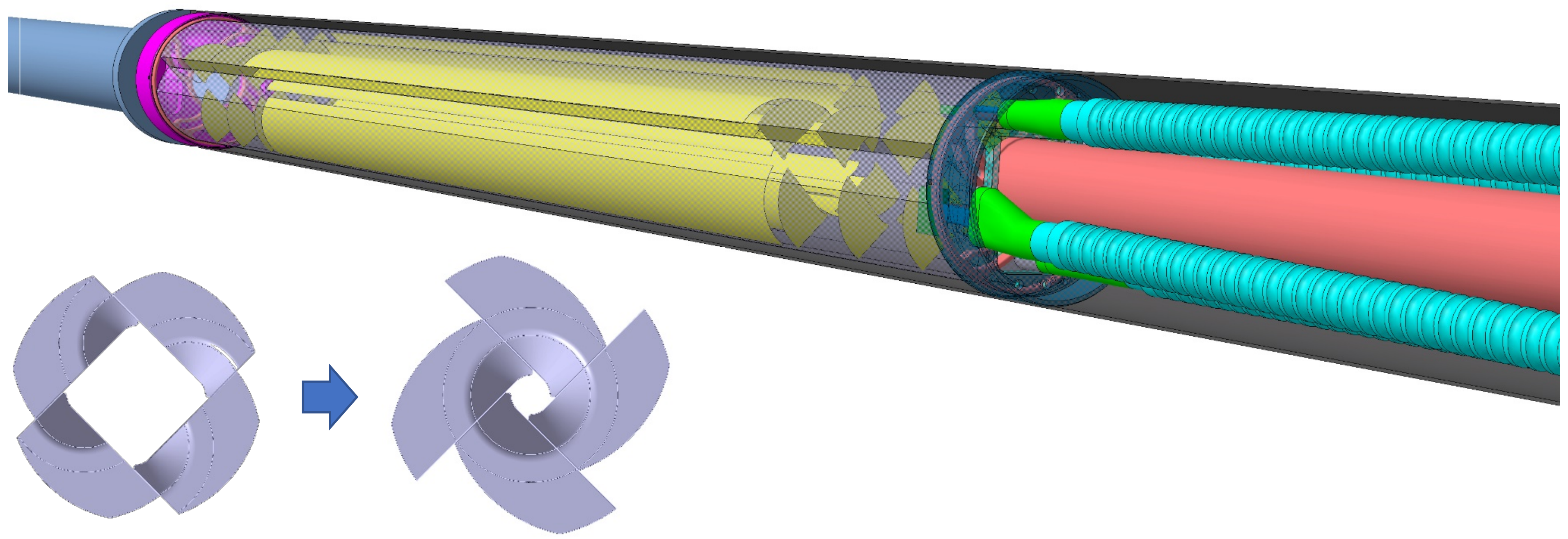
→ same CMOS process of the ITS2/3

R&D will focus on:
- module concept based on industry-standard processes for assembly and testing
- services: reduce (eliminate) interdependency between modules (replacement of single modules)

The ALICE 3 vertex detector



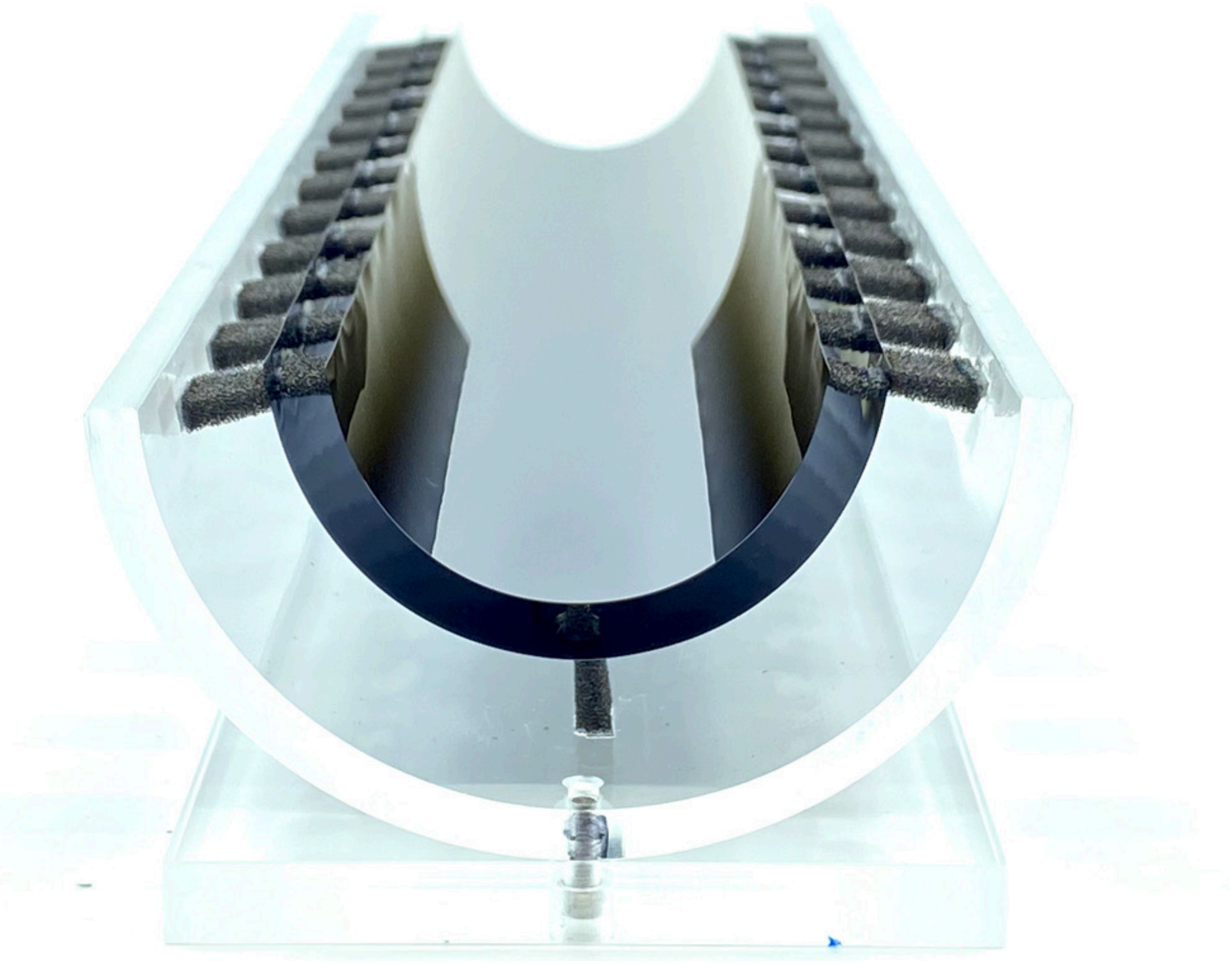
IRIS concept:
→ retractable vertex detector concept inside beampipe
→ rotary petals in a secondary vacuum



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

R&D will focus on:
- wafers-sized, curved sensor technology (relying on the ITS3 R&D)
- advanced mechanics for operations inside the beampipe and cooling for integration inside beampipe

A new pixel technology at the core of the ALICE 3 vertexer



Prototype for the ITS3 upgrade

Ultra-light ("massless") sensors based on CMOS technology (< 0.05 X_0)

- large sensors **with "stitching" techniques**
- **"bendable" when thinned** below ~20-40 µm

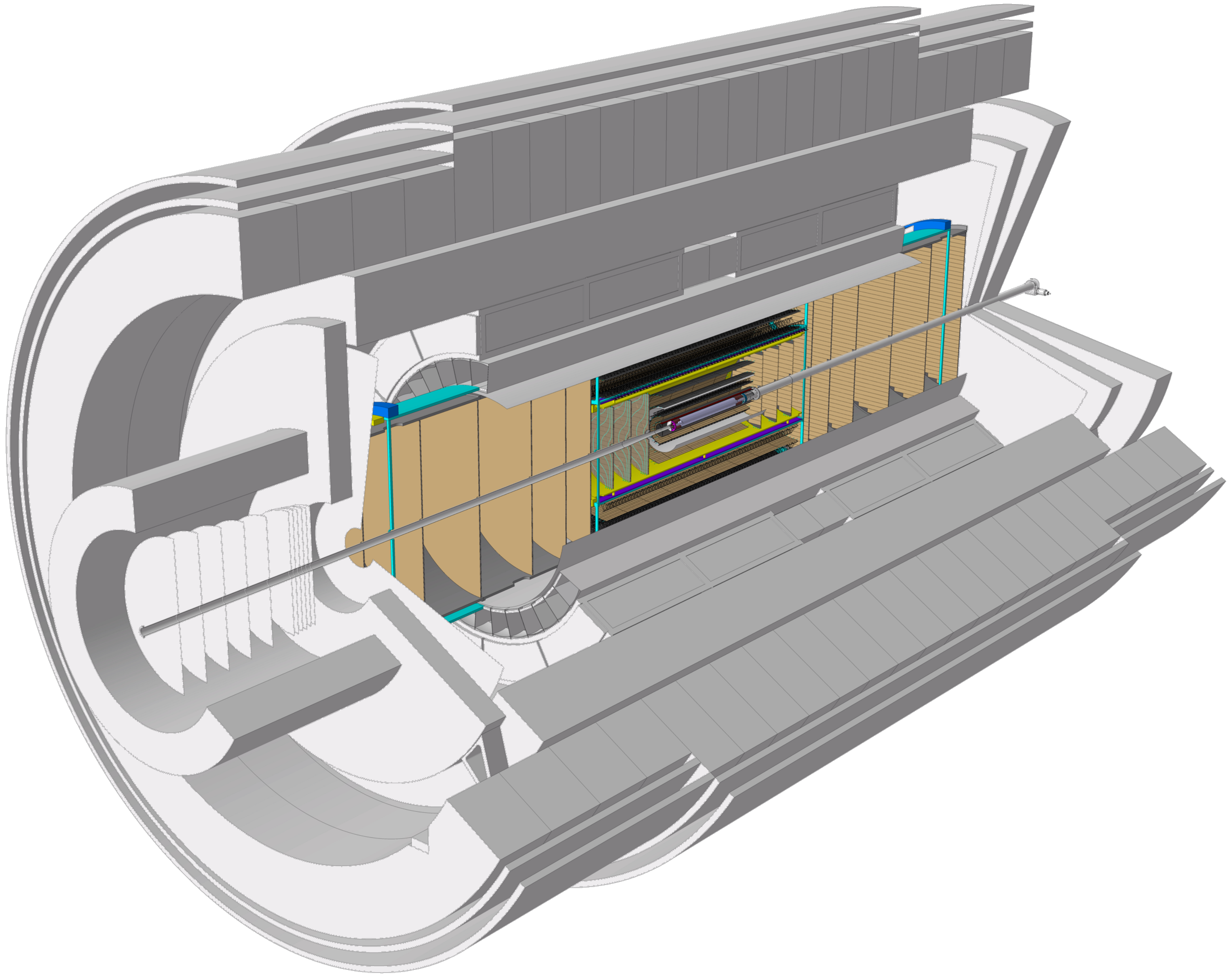
↓

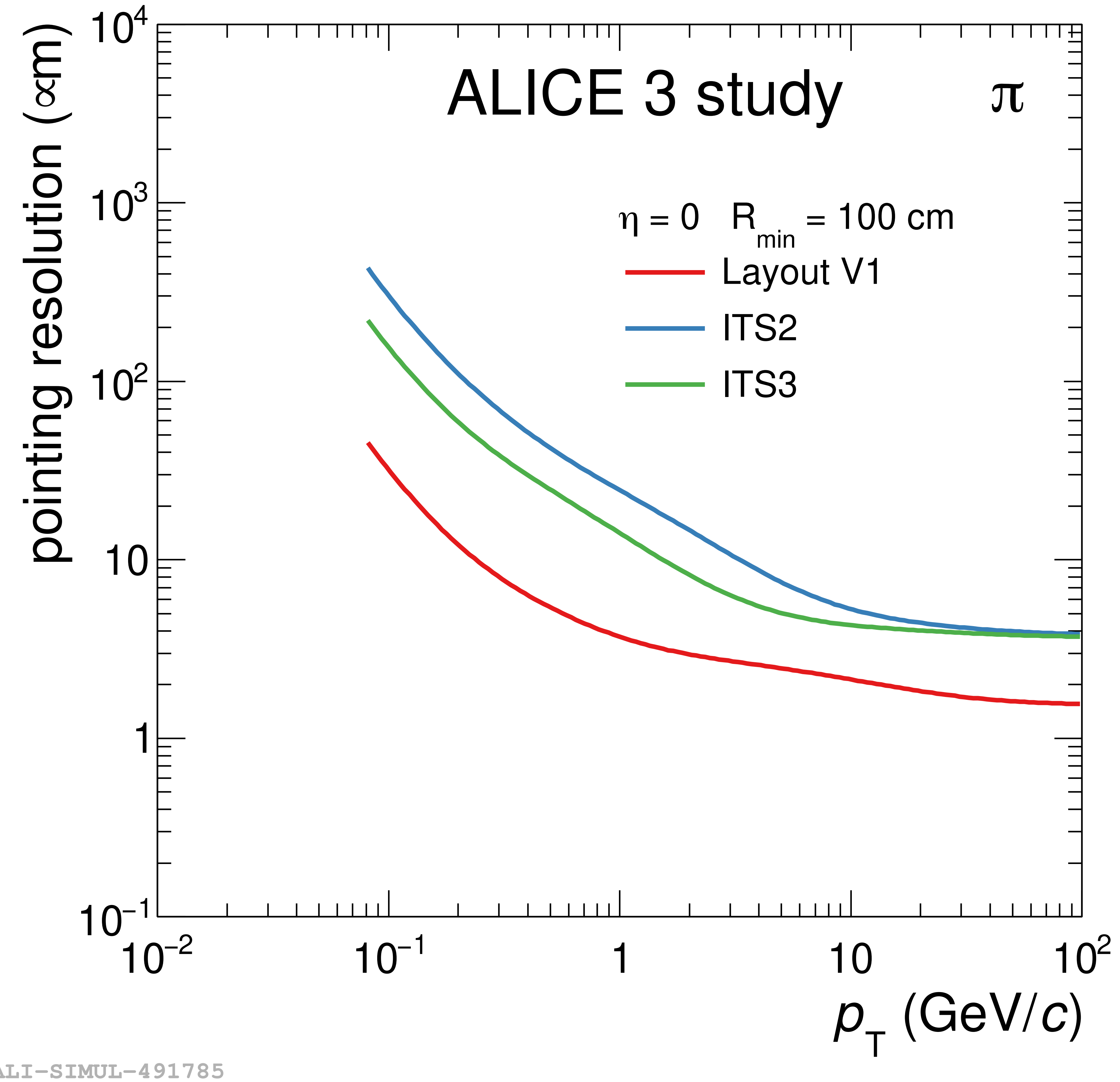
unprecedented impact parameter resolution for heavy-flavour physics

And it works! as proven by dedicated test beams after irradiation (ITS3 prototype)

ALICE ITS3 Letter of Intent: ALICE-PUBLIC-2018-013
ALICE ITS3, arXiv.2105.13000
ALICE ITS3, arXiv.2212.08621

The ALICE 3 tracking resolution



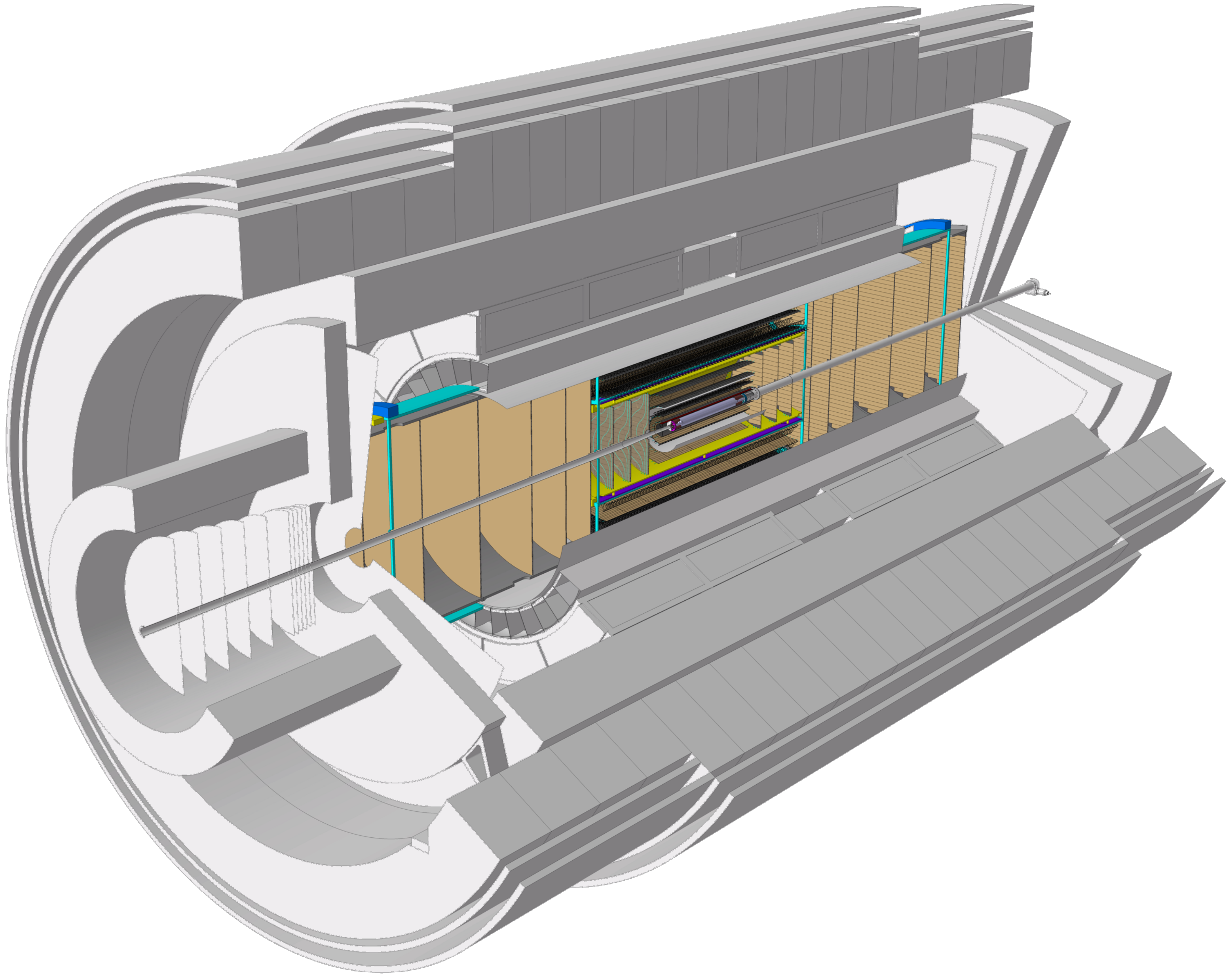


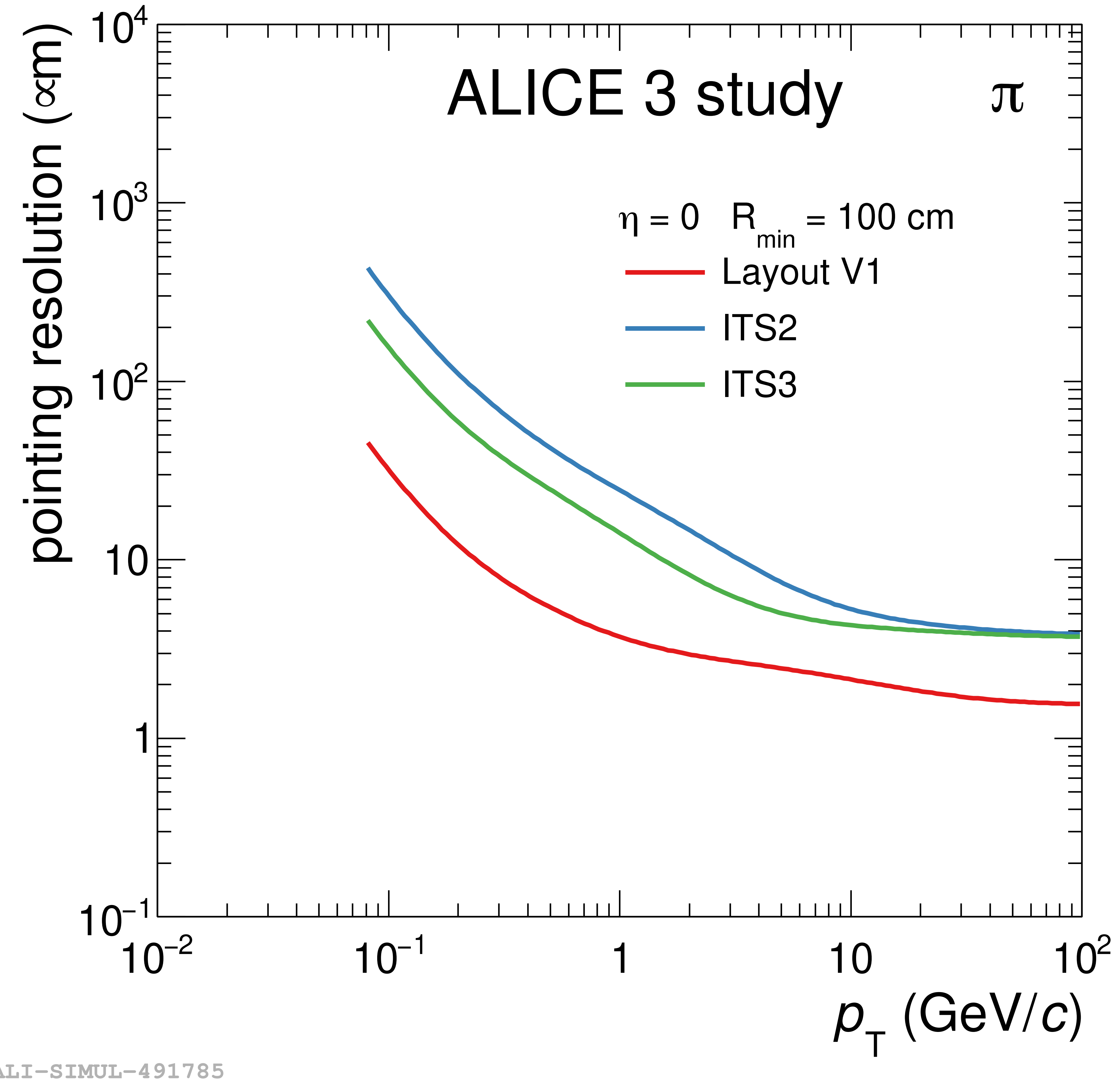
ALI-SIMUL-491785

- **DCA resolution** ~ few µm at ~1 GeV
- Secondary vertex resolution ~ 3-4 µm at low p_T

→ **critical for multiple-HF measurements**

The ALICE 3 tracking resolution



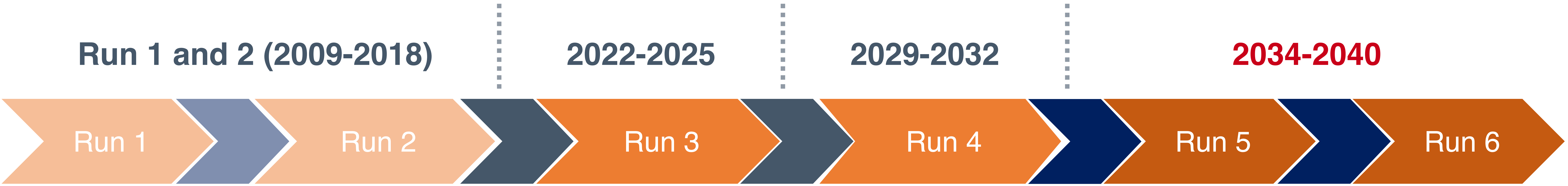


J.D. Bjorken, AIP Conference Proceedings 132, 390 (1985)

J.D. Bjorken in a 1985 paper on Ξ_{cc} and Ω_{ccc} measurements:

My guess for the resolution requirement is (ideally) a few microns(!!) in the transverse direction and perhaps 200 microns in the longitudinal.

ALICE 3 tentative timeline



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

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

2028 – 2030: construction and testing

2031 – 2032: contingency

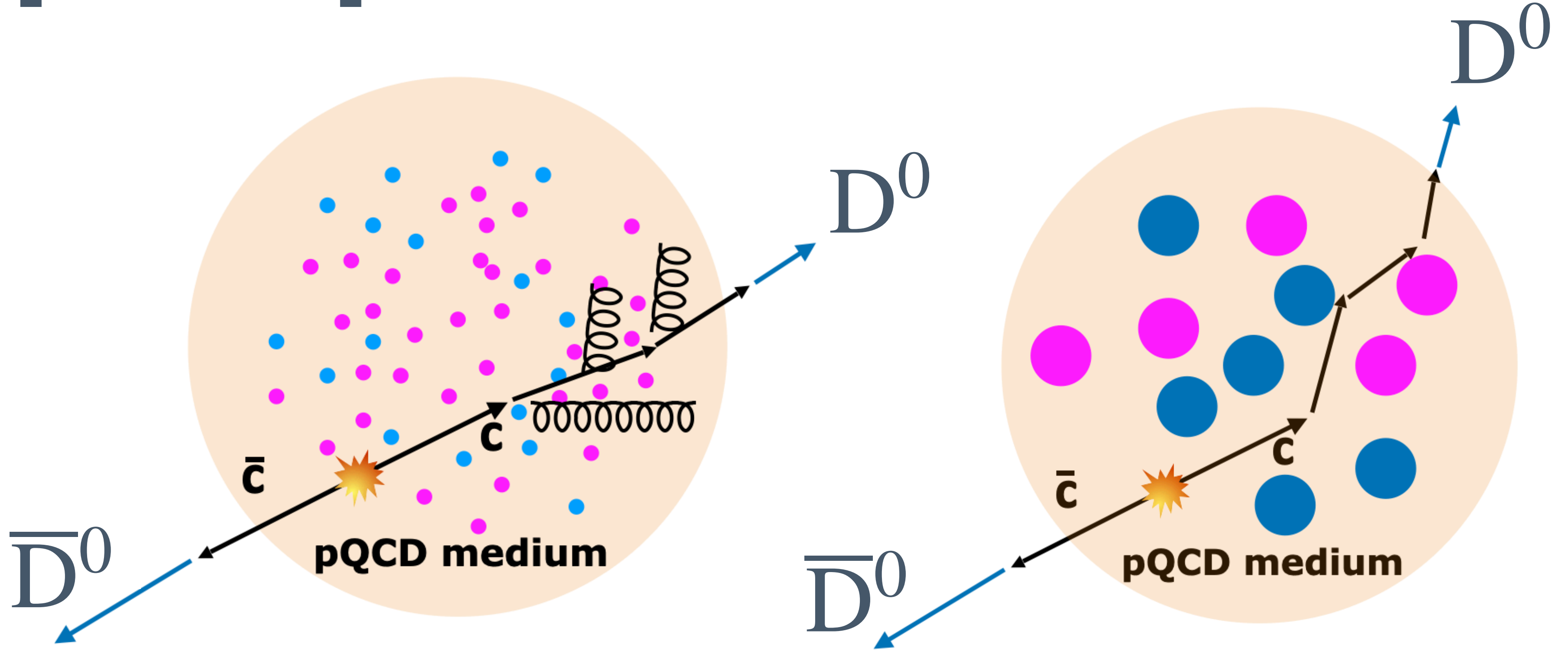
2033 – 2034: installation and commissioning

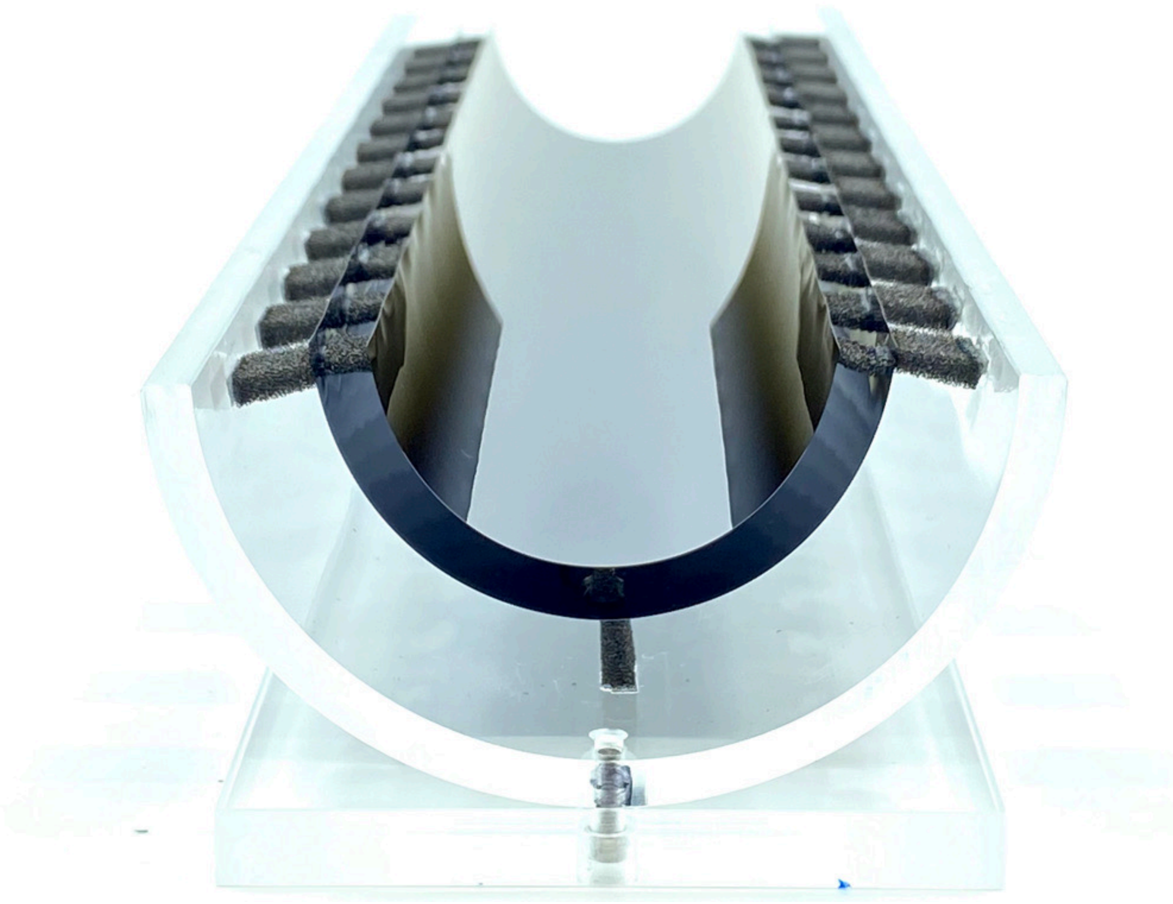
2035 – 2042: physics campaign

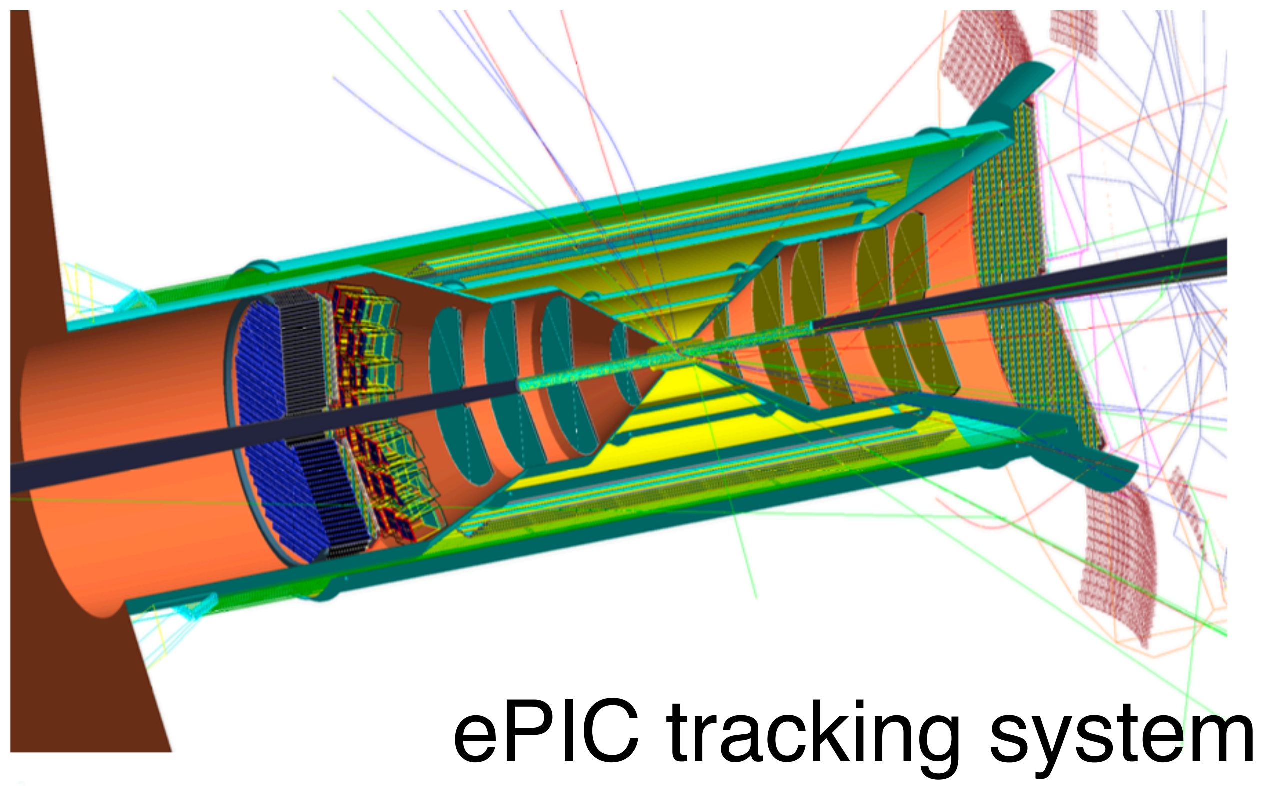
Preparation of **scoping document** (late 2023 early 2024)
- studies for scoping considerations
- refine R&D lines
- resource planning

Conclusions and (some) open questions

Heavy-ion program being extended till ~2040:
with high-resolution and high-rate experiments
→ microscopic description of in-medium dynamics
with rare HF hadrons, correlations, HF jets (more in the LoI)







ePIC tracking system
at the Electron-Ion Collider

Heavy-ion physics is driving the developments of new detector technologies
with big on future experimental programs

A relevant open question for Run 5 and 6 heavy-ion runs :
- which ion species to maximize the physics impact of Run 5 and 6?
- what is the smallest ions for quenching physics?

thank you for your attention!

BACKUP SLIDES

An overview of the LHC program: past and future

Run 4 → High-Luminosity LHC pp program

- pp luminosity to $4 \cdot 10^{34}$ cm^{-2} s^{-1}

Run 3 → high luminosity for ions (~$7 \cdot 10^{27}$ cm^{-2} s^{-1}) and OO

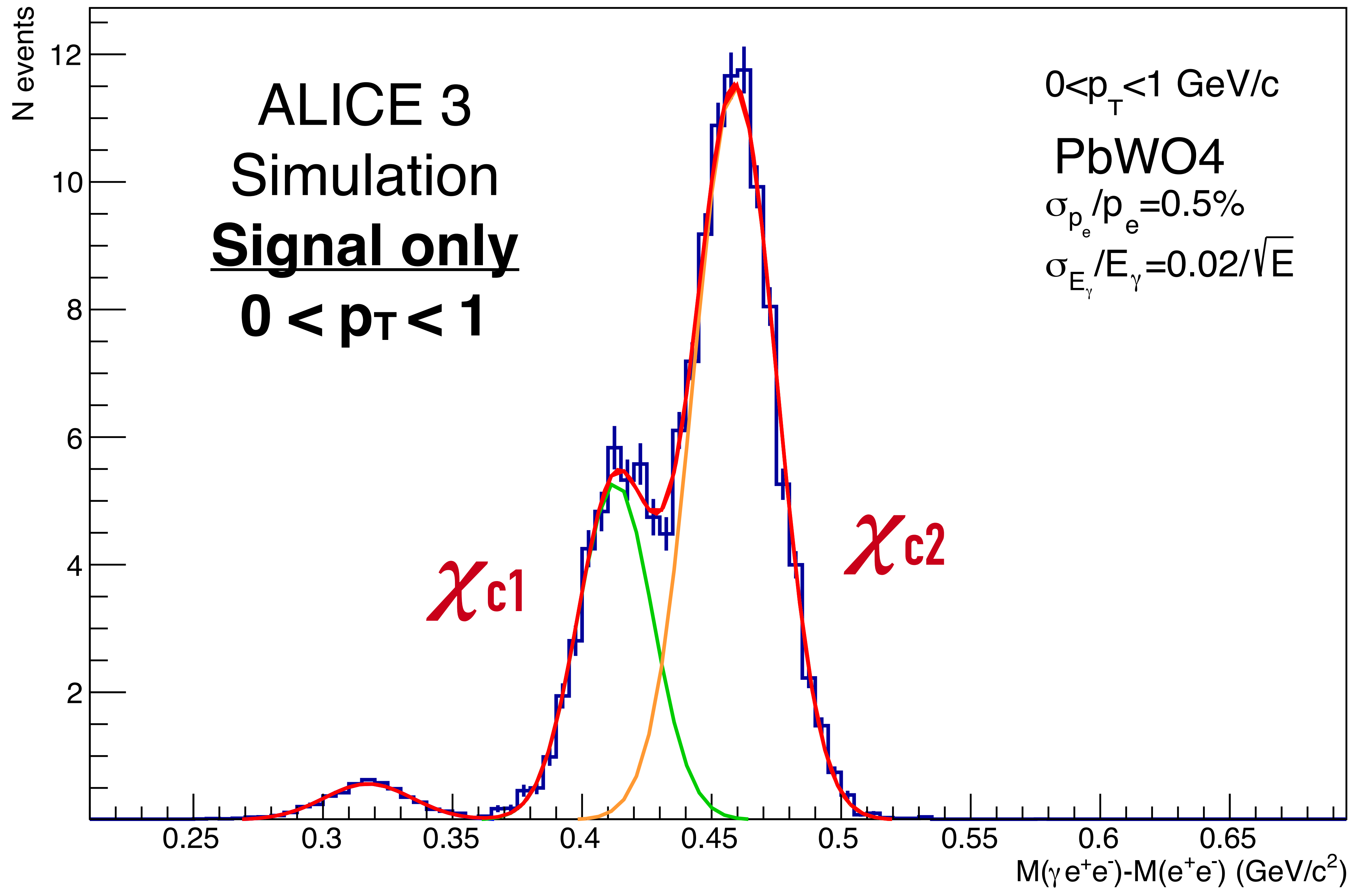
- improved collimation system
- lifted limitation in the LHC from bound-free pair production
- ion luminosities now limited by bunch intensities from injectors

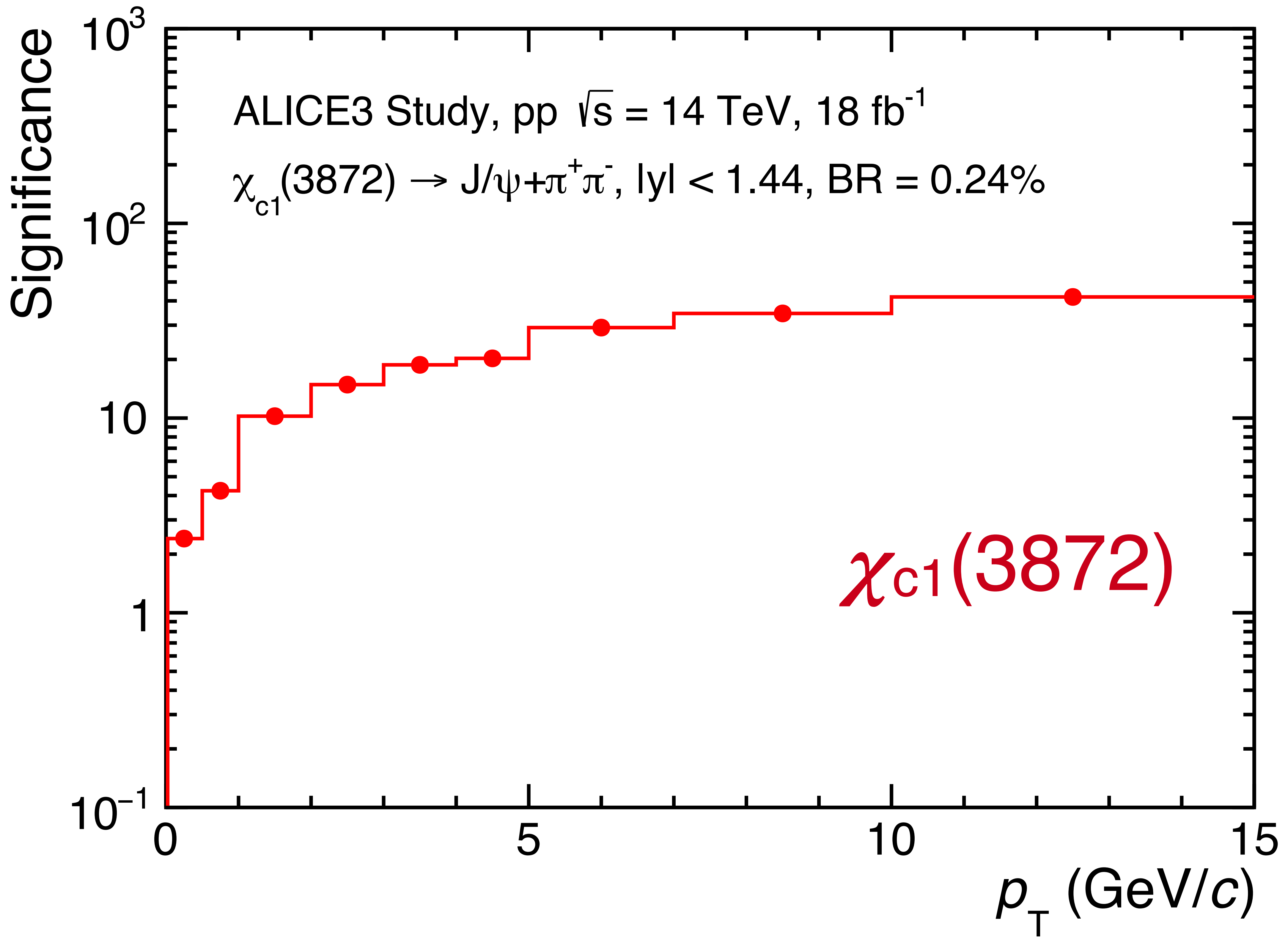
Run 5 → Higher luminosities for ions:

- mitigate space charge effects (SPS & LEIR) e.g. with **lighter species**

Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
pp, p-Pb Pb-Pb	pp, p-Pb Xe-Xe, Pb-Pb	pp, p-O, O-O p-Pb, Pb-Pb	pp, p-Pb Pb-Pb	pp, (p-A?) A-A	pp, (p-A?) A-A

$\chi_{c,b}$ and $\chi_{c1}(3872)$ states





Photon identification performed with ECAL:
- high-resolution crystals at mid rapidity (no boost)
- sampling calorimeter at more forward rapidities

χ_{c1}(3872) down to 0 GeV at central rapidity

→ unlock measurements of new bound states at low p_T also at central rapidity