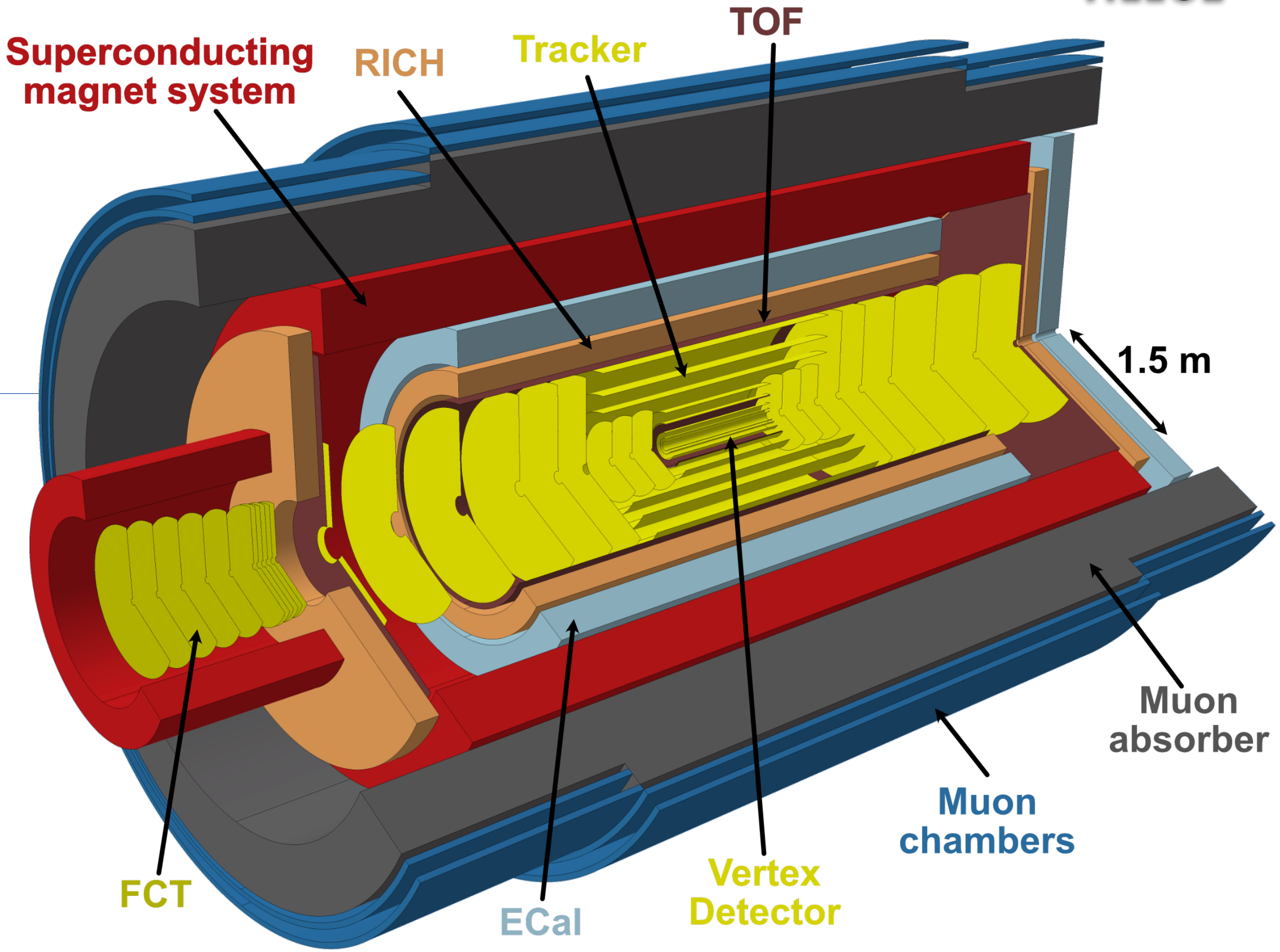
ALICE 3

a next-generation heavy-ion experiment for LHC Run 5 and beyond



Science Coffee
Lund

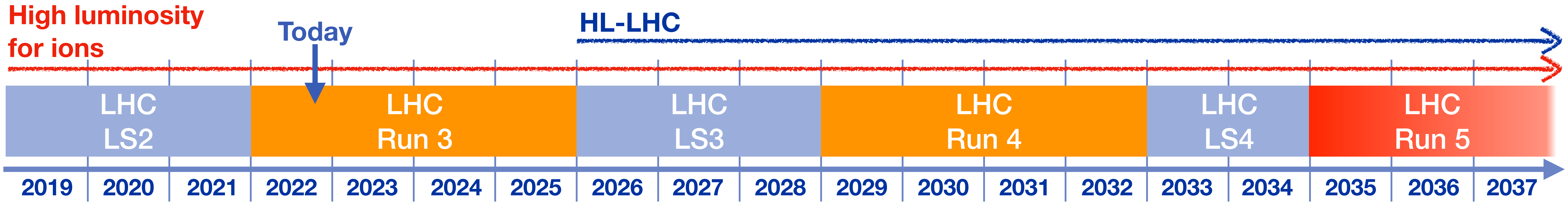
October 4, 2022

Jochen Klein (CERN)

Outline

- **High-luminosity era of the LHC**
  - LHC programme
  - ALICE 2 (Run 3 and 4)
- **Heavy-ion physics at the LHC**
  - programme for Run 3 and 4
  - remaining questions beyond Run 4
- **Next-generation upgrade**
  → ALICE 3 for Run 5 & 6
  - detector concept
  - physics performance

European Particle Physics Strategy Update recommends **full exploitation of the LHC**, incl. heavy-ion programme

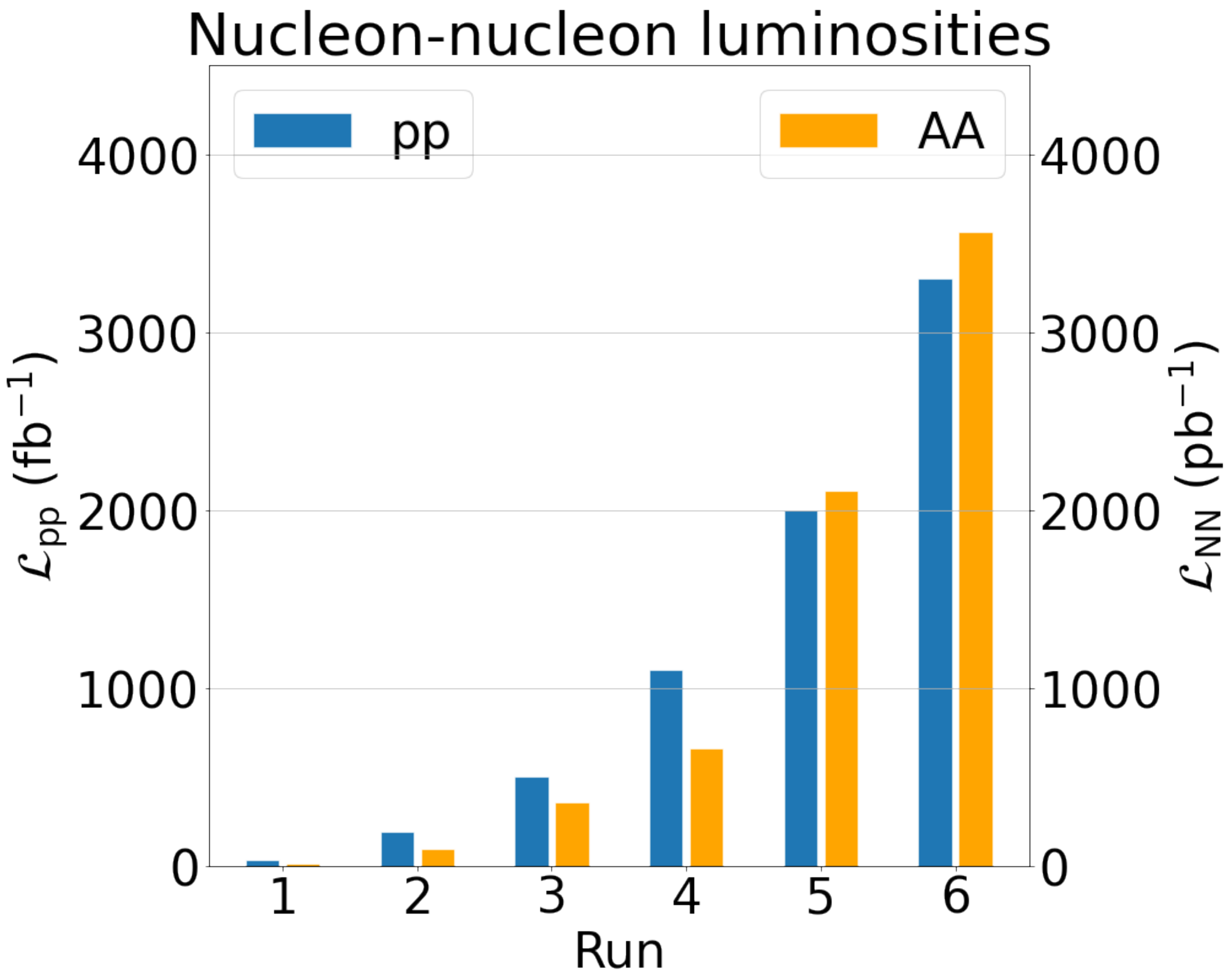


LHC programme

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

Pb-Pb luminosity limited by LHC
~$1\text{-}2 \cdot 10^{27}$ 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 $4 \cdot 10^{34}$ cm^{-2} s^{-1}

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

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

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	2009 - 2013	2015 - 2018	2022 - 2025	2029 - 2032		

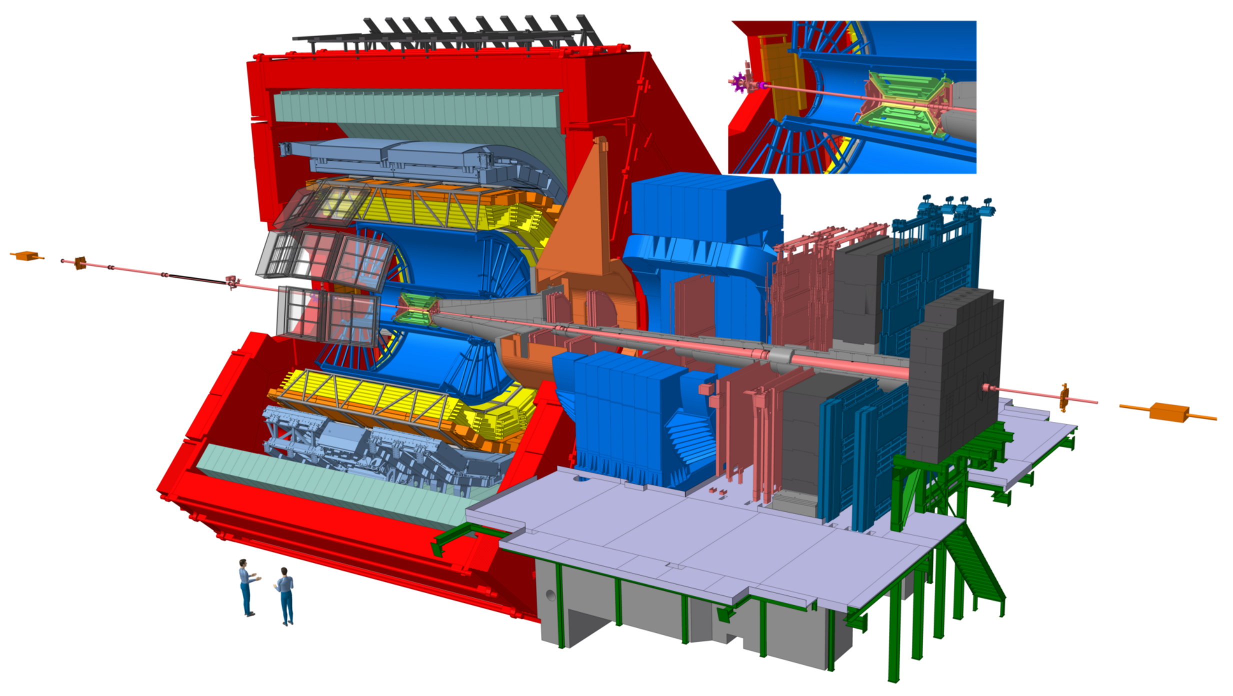
High luminosity for ions

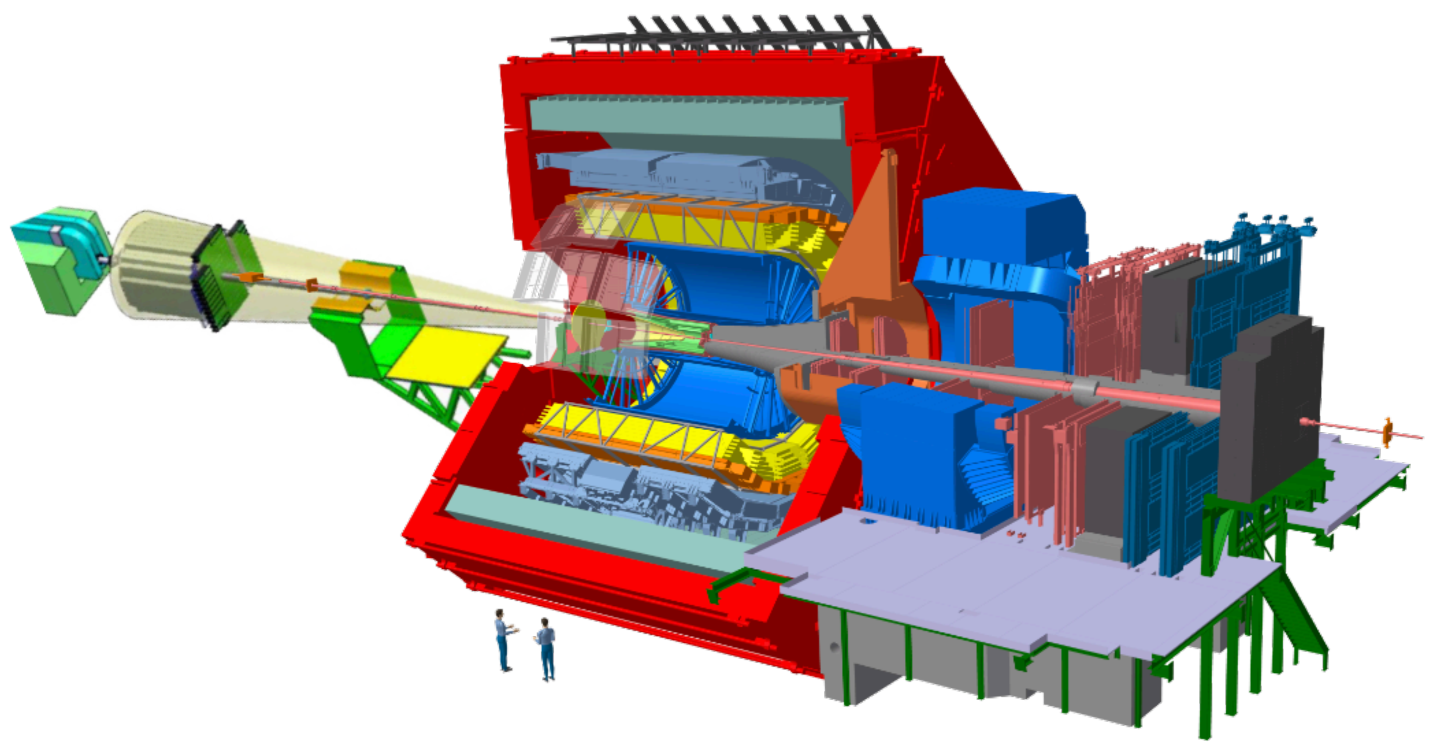
HL-LHC

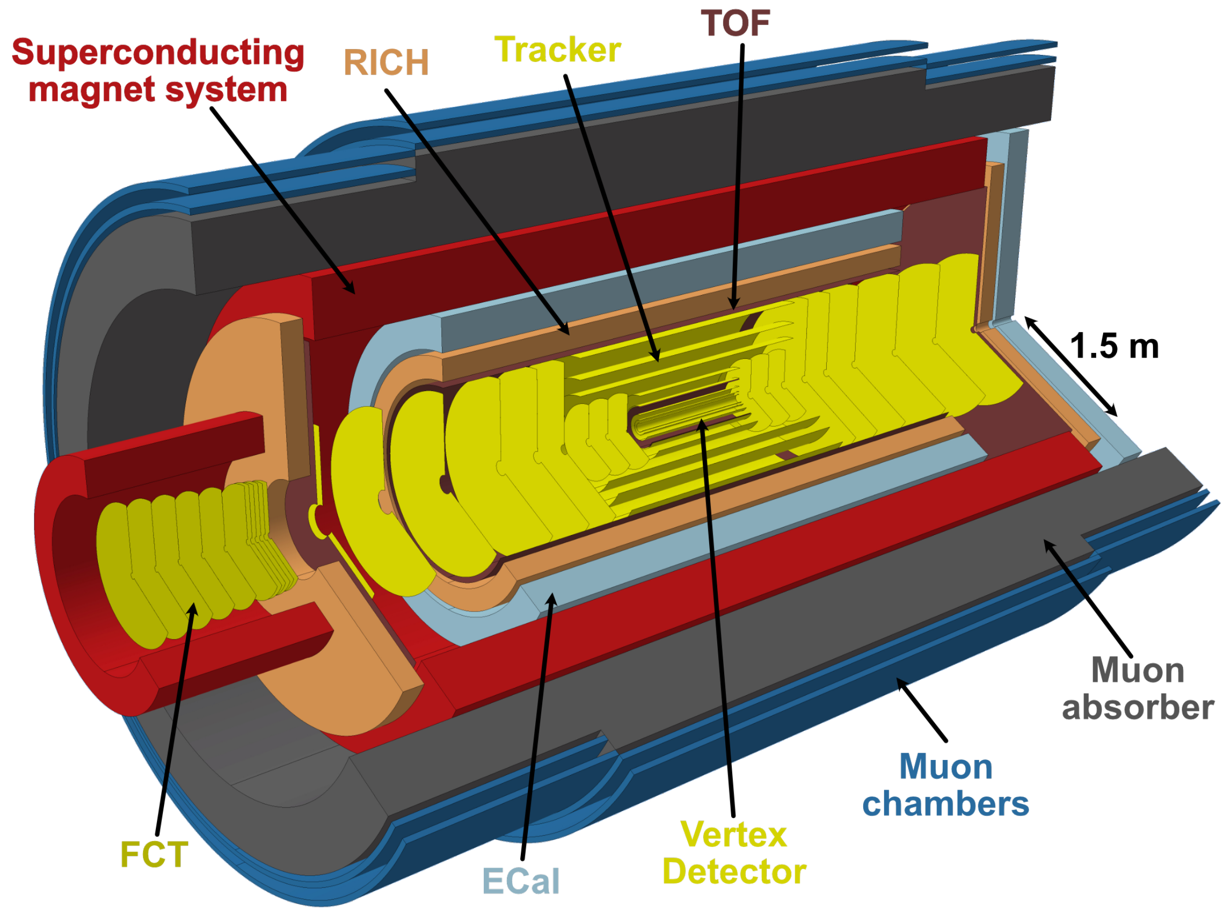
Higher luminosities for ions

ALICE

ALICE 1	ALICE 2	ALICE 2.1	ALICE 3







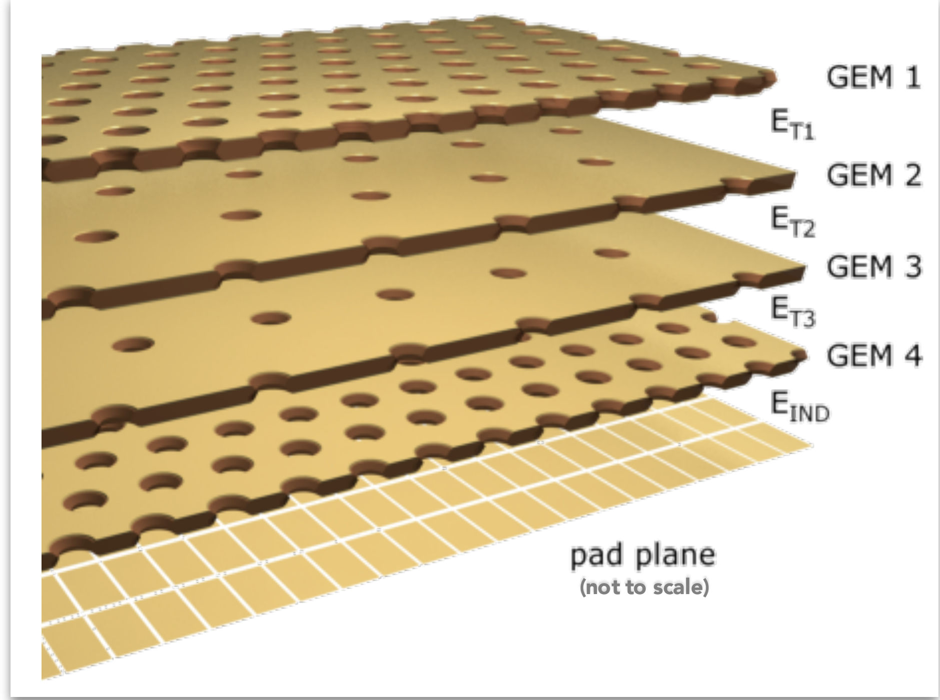
intermediate upgrade

major upgrade

ALICE 2

Time Projection Chamber

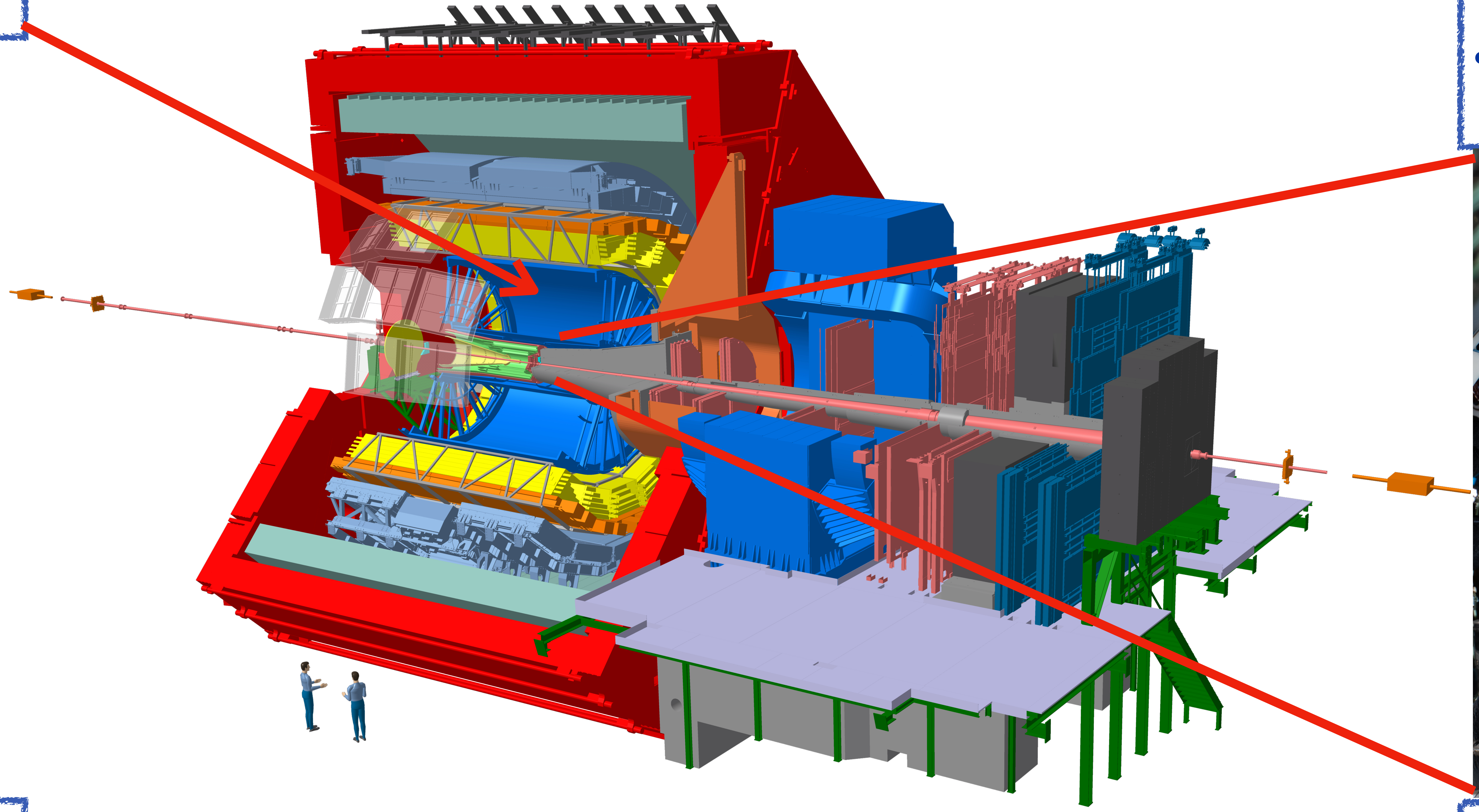
- new readout chambers: MWPC → GEM



Consolidation and readout upgrade of all subsystems

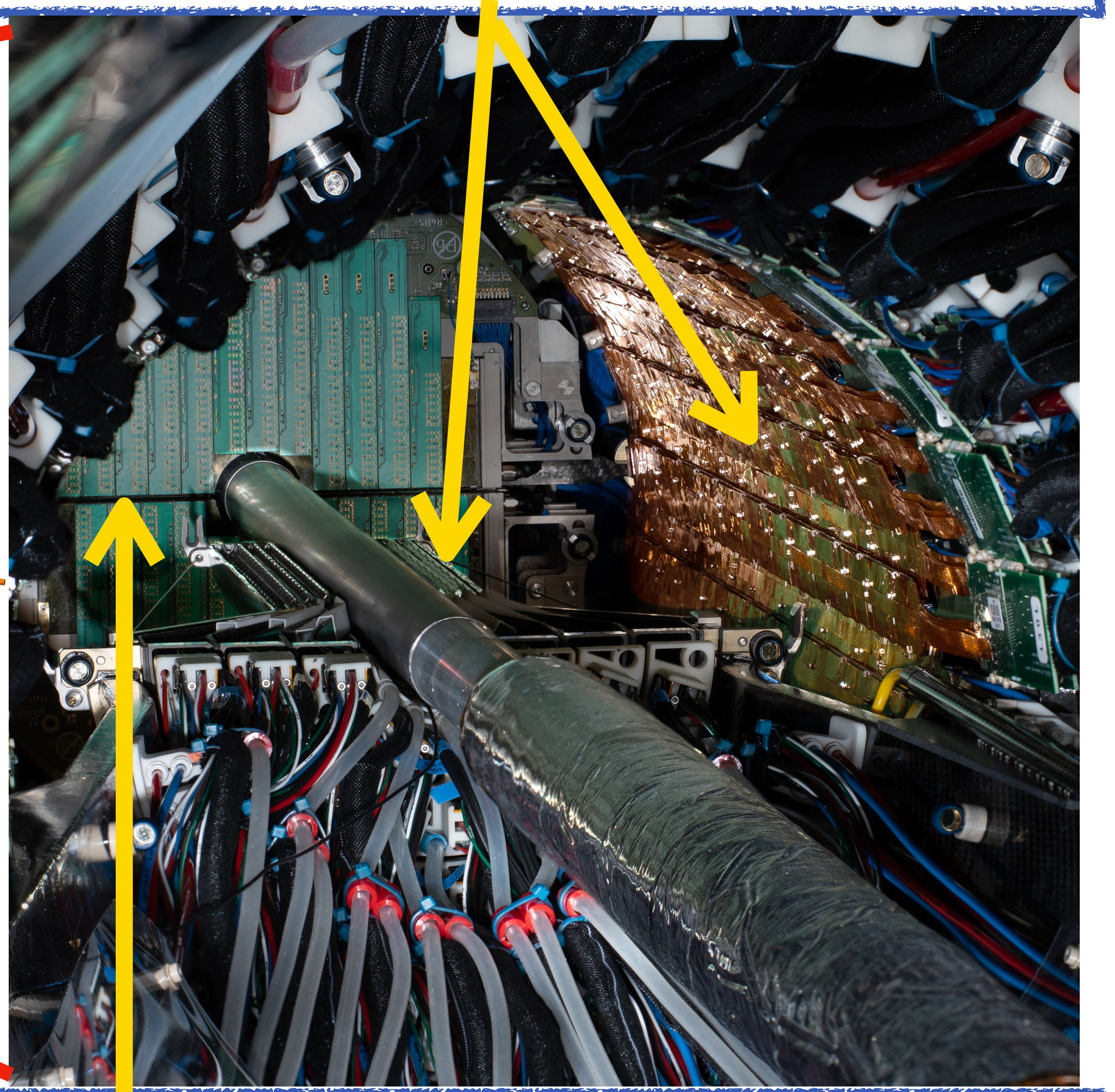
Fast Interaction Trigger

- new detectors



Inner Tracking System

- **3 + 2 + 2 layers of MAPS (~10 m²)**
- improved vertexing at higher rates



Integrated on-/off-line system

- continuous readout
- GPU-based reconstruction parallel with data taking
- online event selection

➡ **Continuous readout** with Pb-Pb @ 50 kHz
➡ **Better vertexing**

Muon Forward Tracker

- MAPS-based tracker installed
- vertexing in forward acceptance (muon arm)

ALICE 2.1

Time Projection Chamber

- new readout chambers: **MWPC → GEM**

Consolidation and readout upgrade of all subsystems

Fast Interaction Trigger

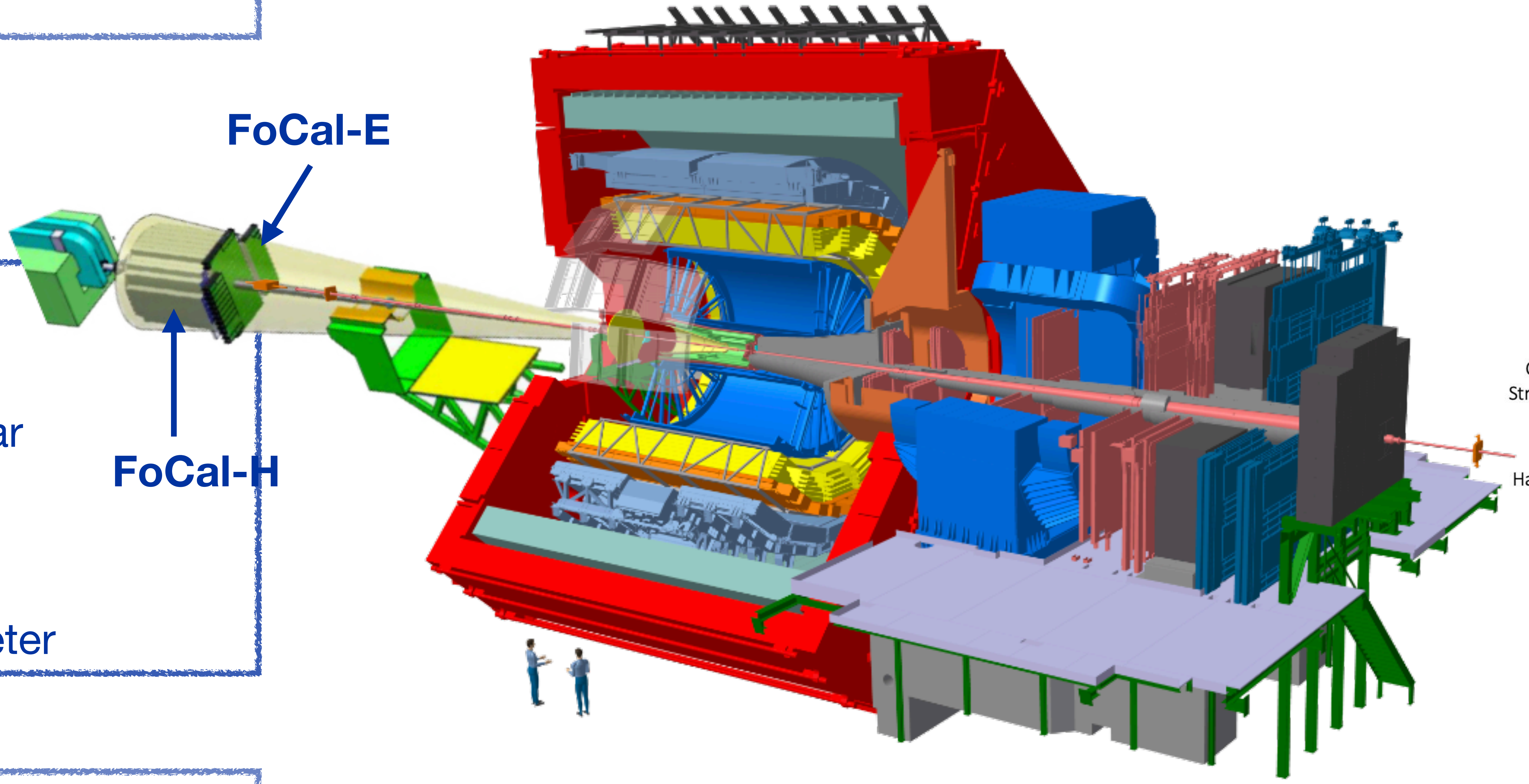
- new detectors

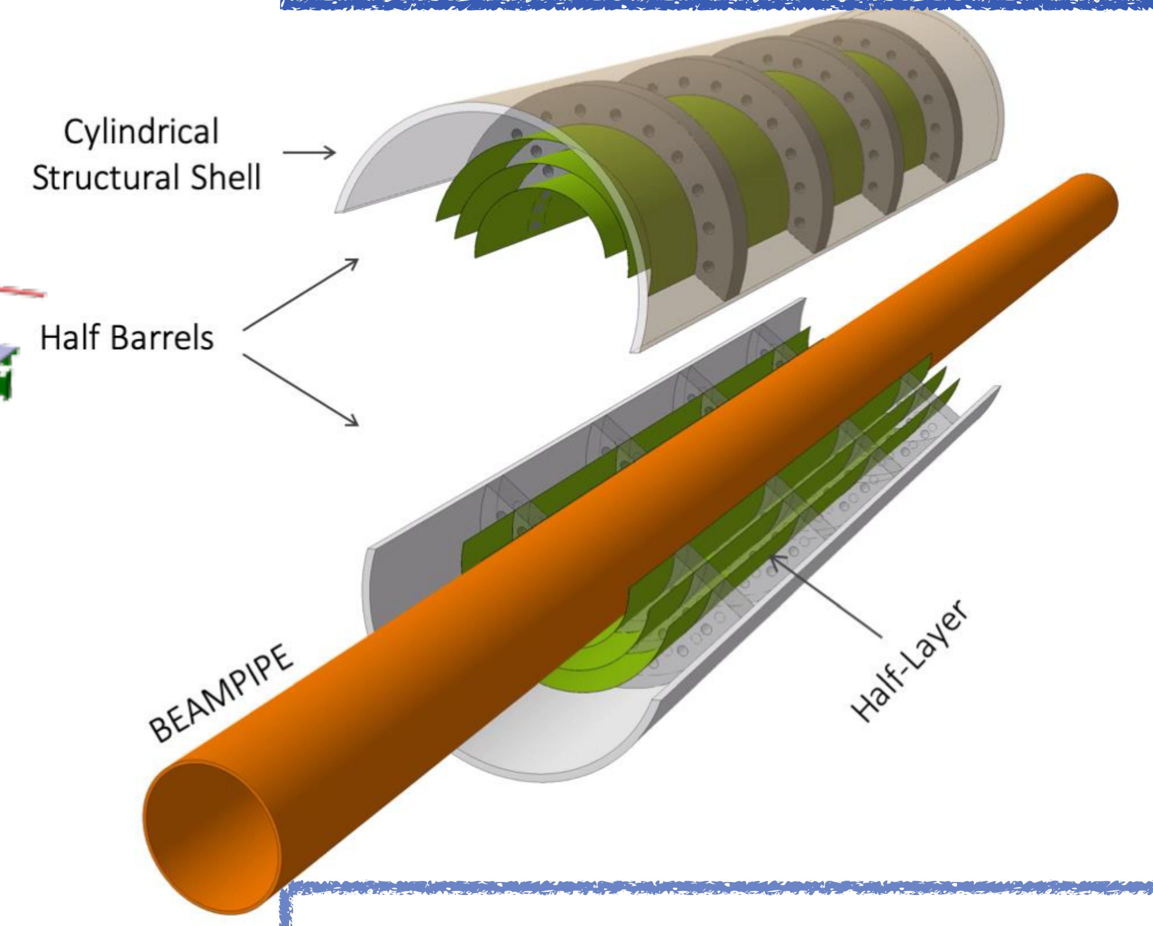
Inner Tracking System

- **3 + 2 + 2 layers of MAPS (~10 m²)**
- improved vertexing at higher rates
- **ITS3 → Bent, wafer-scale monolithic pixel sensors for 3 innermost layers**

FoCal

- **FoCal-E**: Si-W high-granular elm. calorimeter
- **FoCal-H**: Cu-fibre hadronic calorimeter





Integrated on-/off-line system

- **continuous readout**
- **GPU-based reconstruction** parallel with data taking
- online event selection

➡ **Continuous readout** with Pb-Pb @ 50 kHz
➡ **Better vertexing**
➡ **Measurement of isolated photons**

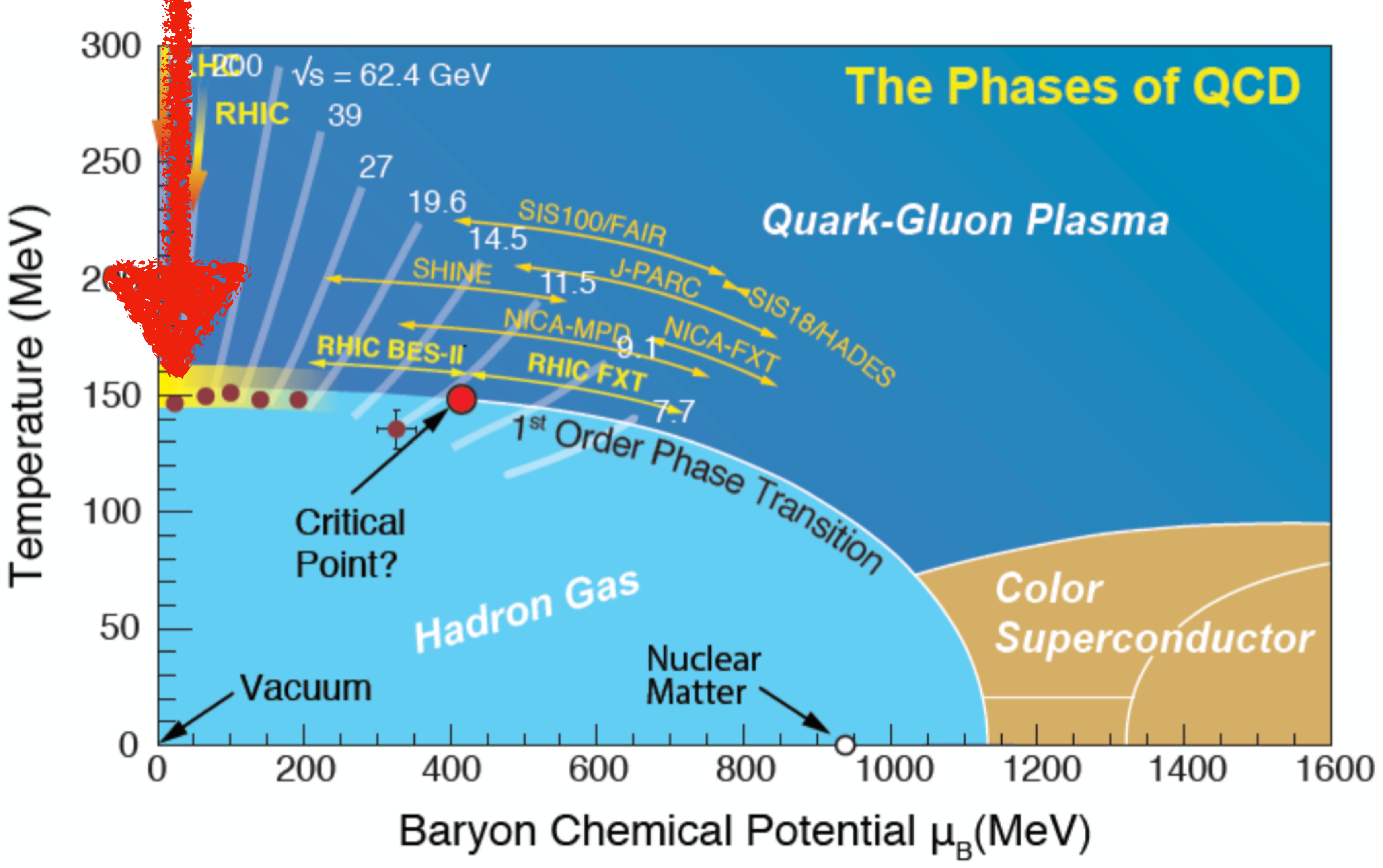
Muon Forward Tracker

- **MAPS-based tracker** installed
- vertexing in forward acceptance (muon arm)

Heavy-ion physics at the LHC

LHC for heavy-ion physics

- **Unique potential**
  → high T, low μ_B, large HF yields
- **Progress enabled** by
  - increased **luminosity**
  - improved **detector performance**, e.g. vertexing, acceptance

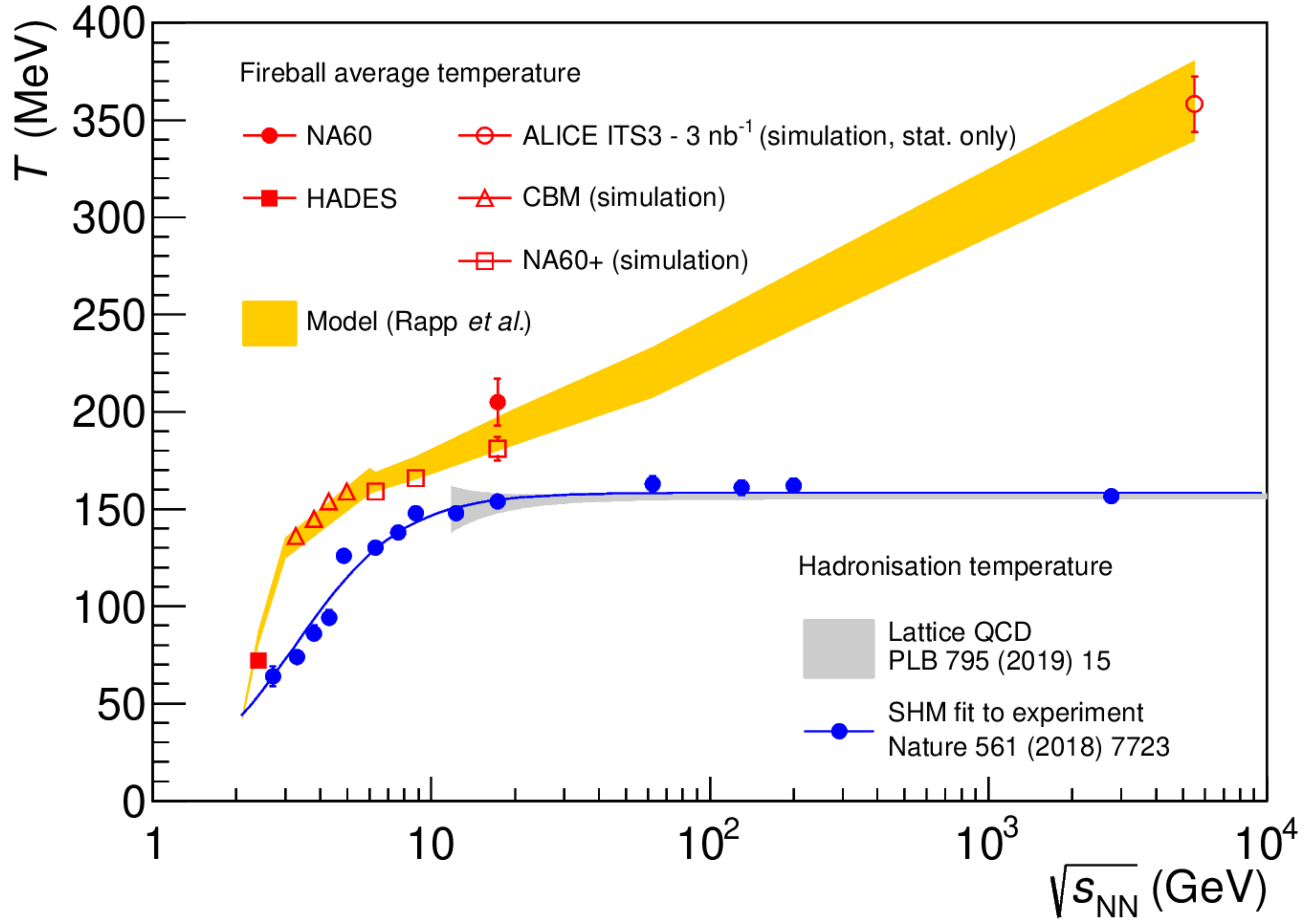


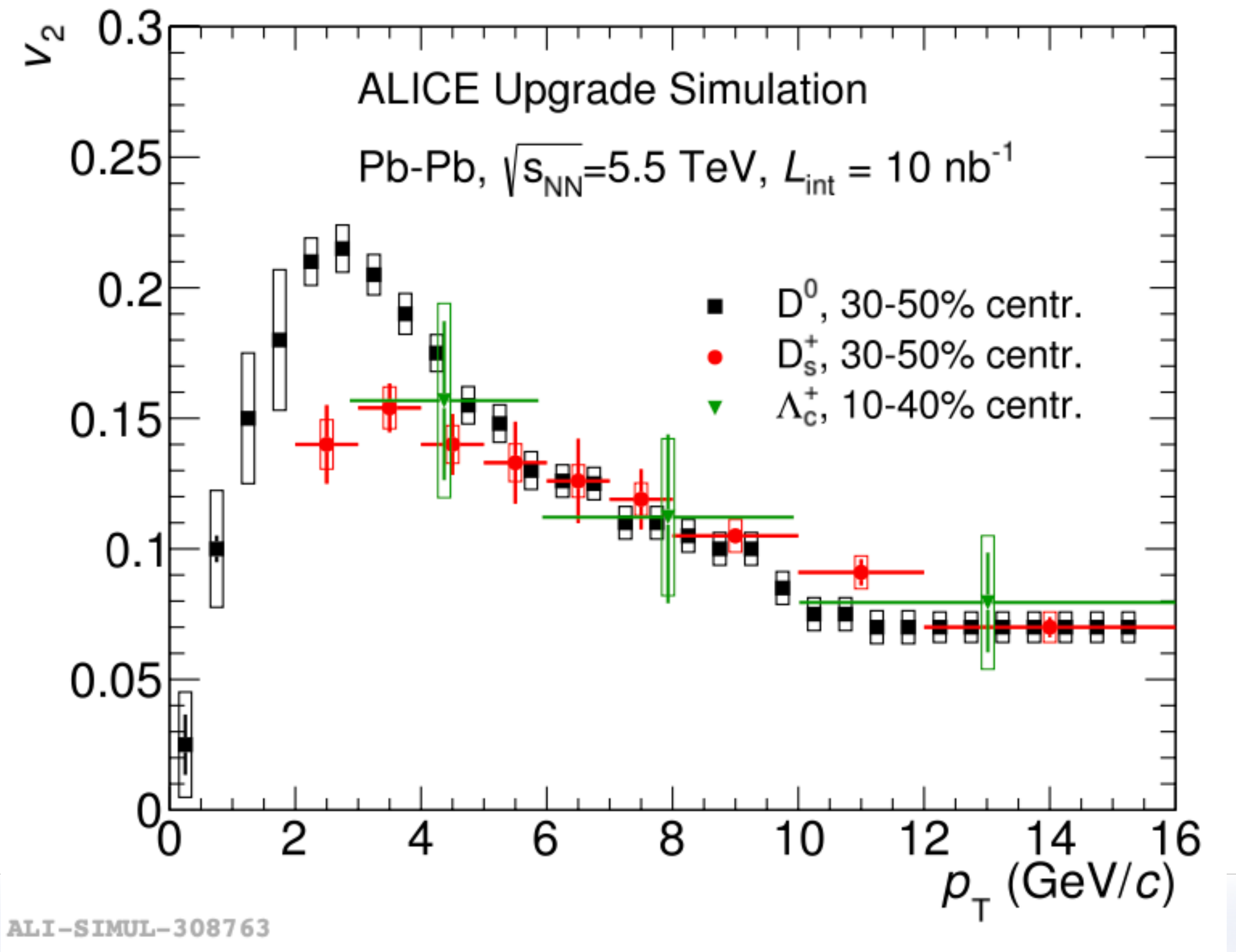
- **QGP evolution from early phase onwards: temperature, chiral symmetry restoration, …**
  → precision measurements of dilepton spectra
- **Transport properties and thermalisation in the QGP**
  → precision measurements of heavy-flavour probes
- **Transition of partons from the QGP to hadrons**
  →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

Prospects for Run 3 & 4

- **Runs 3 and 4 will bring new insights**, e.g.
  - time-averaged thermal radiation from the quark-gluon plasma
  - medium effects and hadrochemistry of single charm
  - collectivity from small to large systems
  - jet substructure

Understanding of QGP will remain incomplete after Run 3 and 4



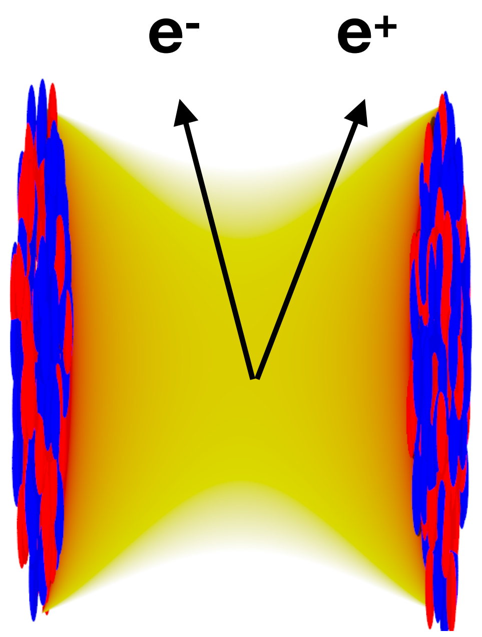


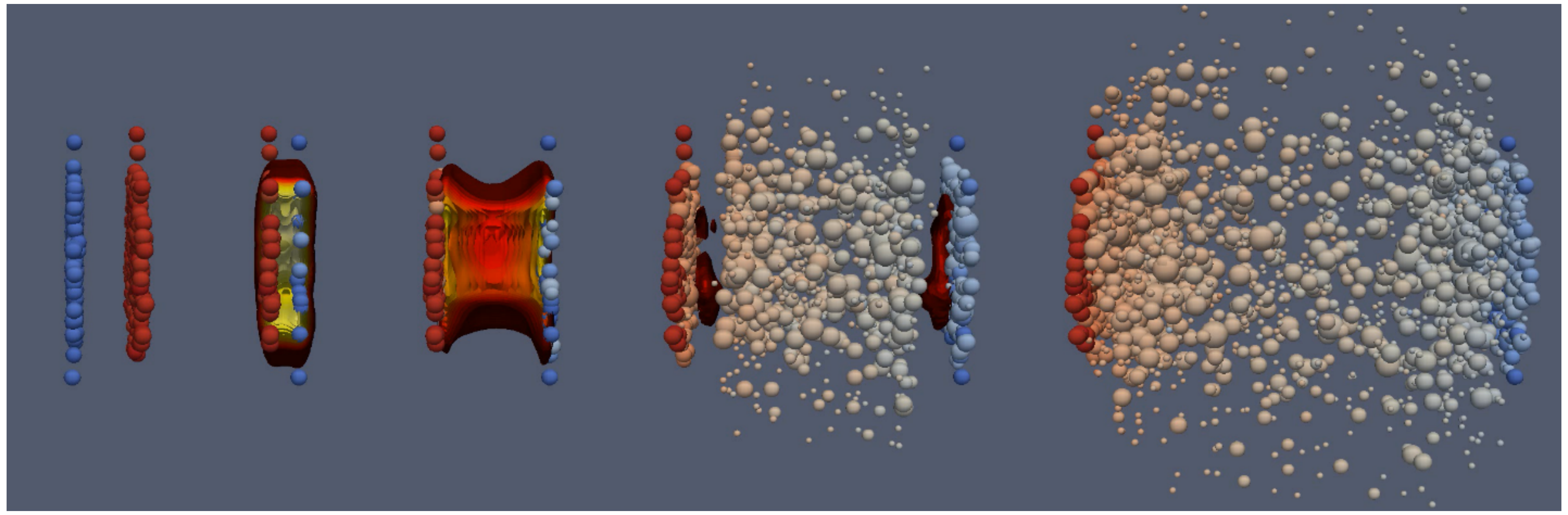
Questions beyond Run 4

- **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?
  - Does the production of ultra-soft photons deviate from Low's theorem?

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
  - …



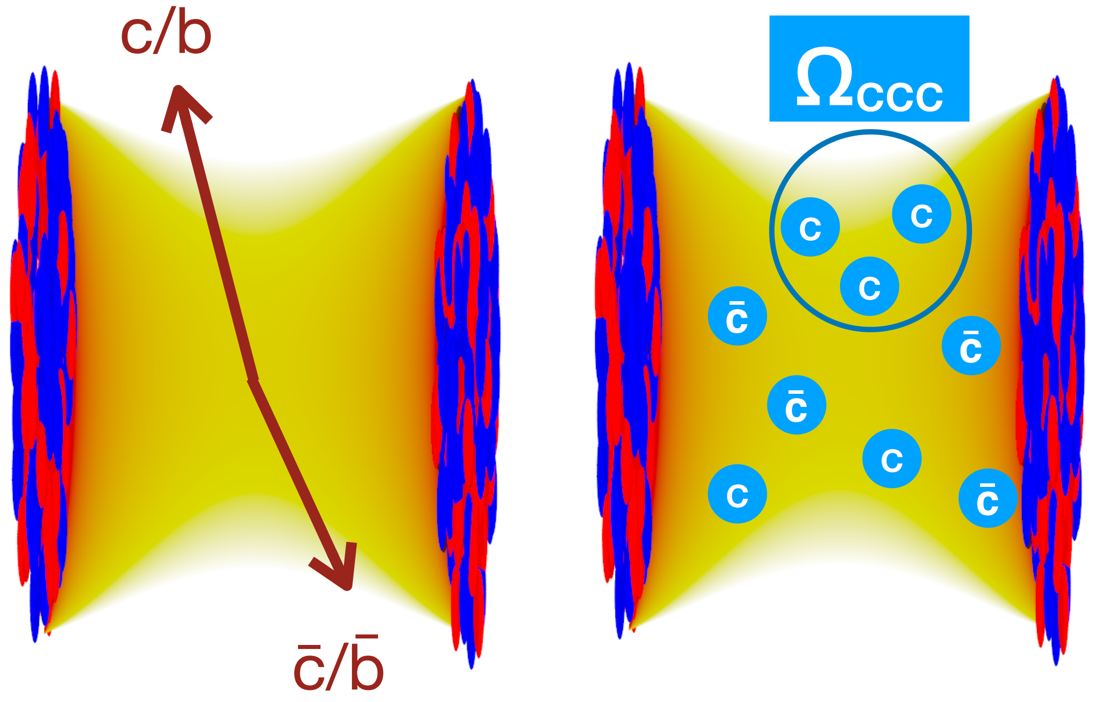


Electromagnetic radiation ($\propto T^2$)

Hadron momentum distributions, azimuthal anisotropy

Hadron abundances 'hadrochemistry'

Hadron correlations, fluctuations



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

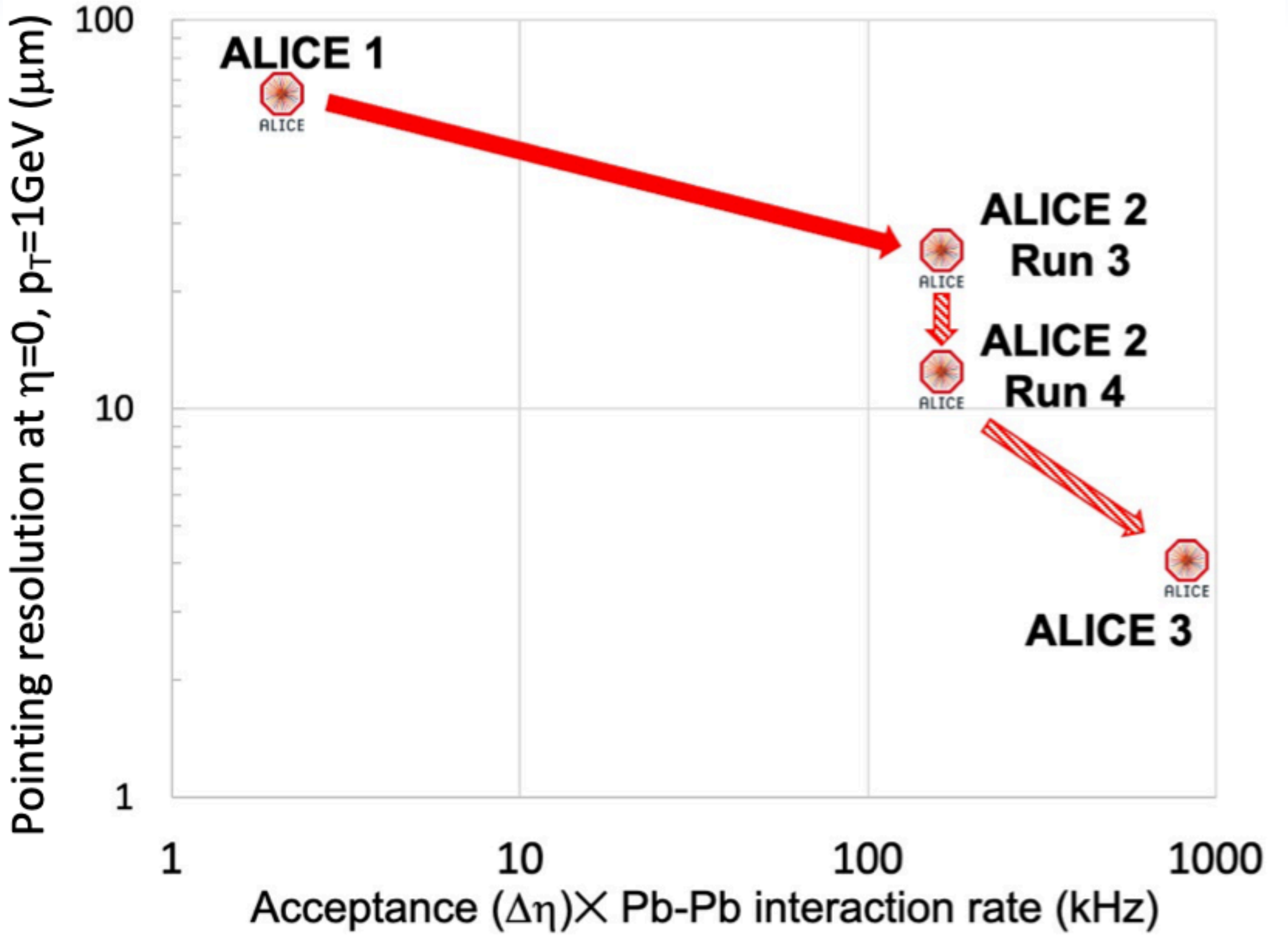
Probes

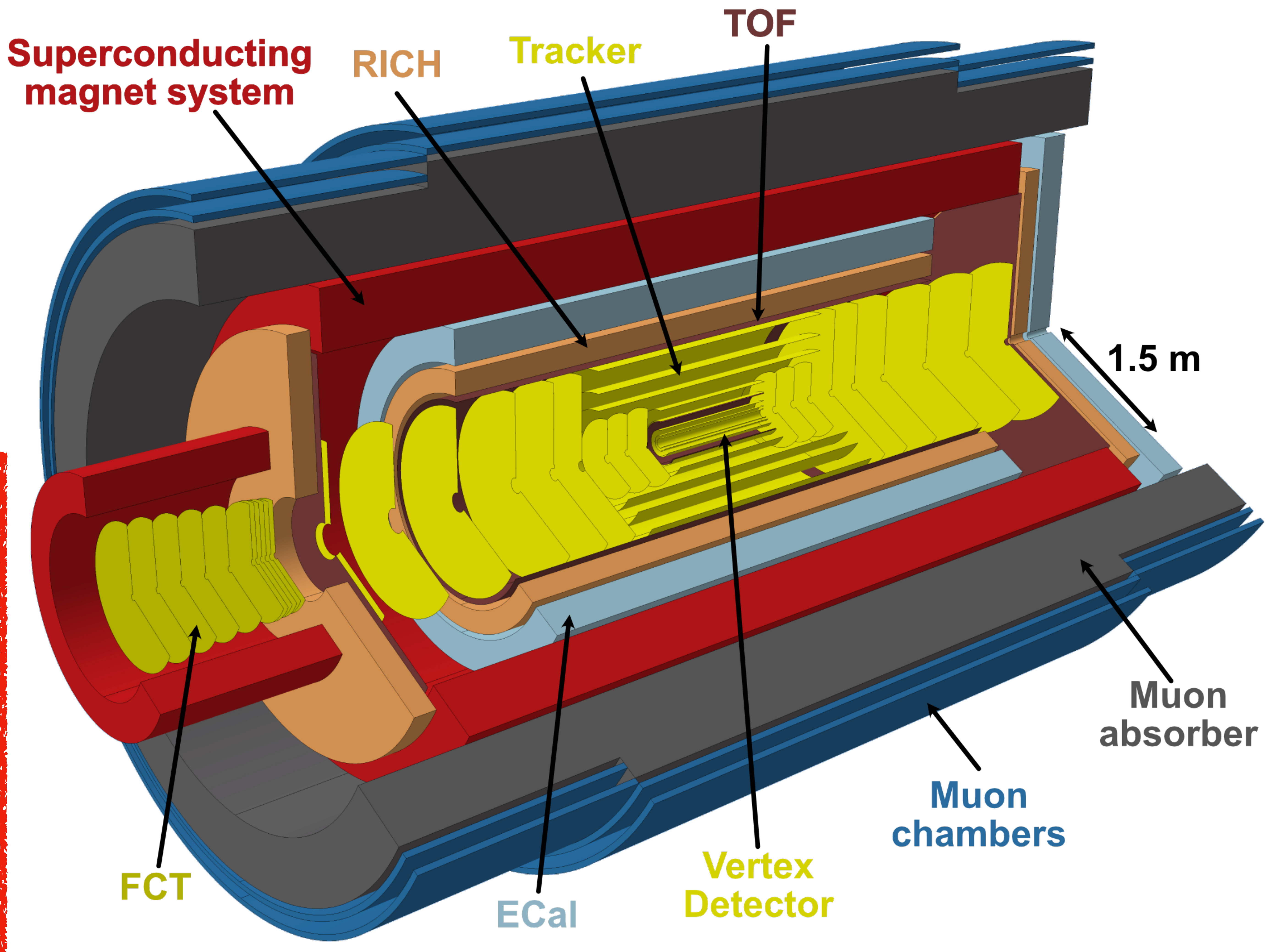
- **Heavy-flavour hadrons** ($p_T \rightarrow 0$, wide η range)
  ➟ vertexing, tracking, hadron ID
- **Dileptons** (p_T ~0.1 - 3 GeV/c, M_{ee} ~0.1 - 4 GeV/c^2)
  ➟ vertexing, tracking, lepton ID
- **Photons (100 MeV/c - 50 GeV/c, wide η range)**
  ➟ electromagnetic calorimetry
- **Quarkonia and Exotica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

Qualitative steps needed in detector performance and statistics

→ next-generation heavy-ion experiment

ALICE 3





Novel and innovative detector concept

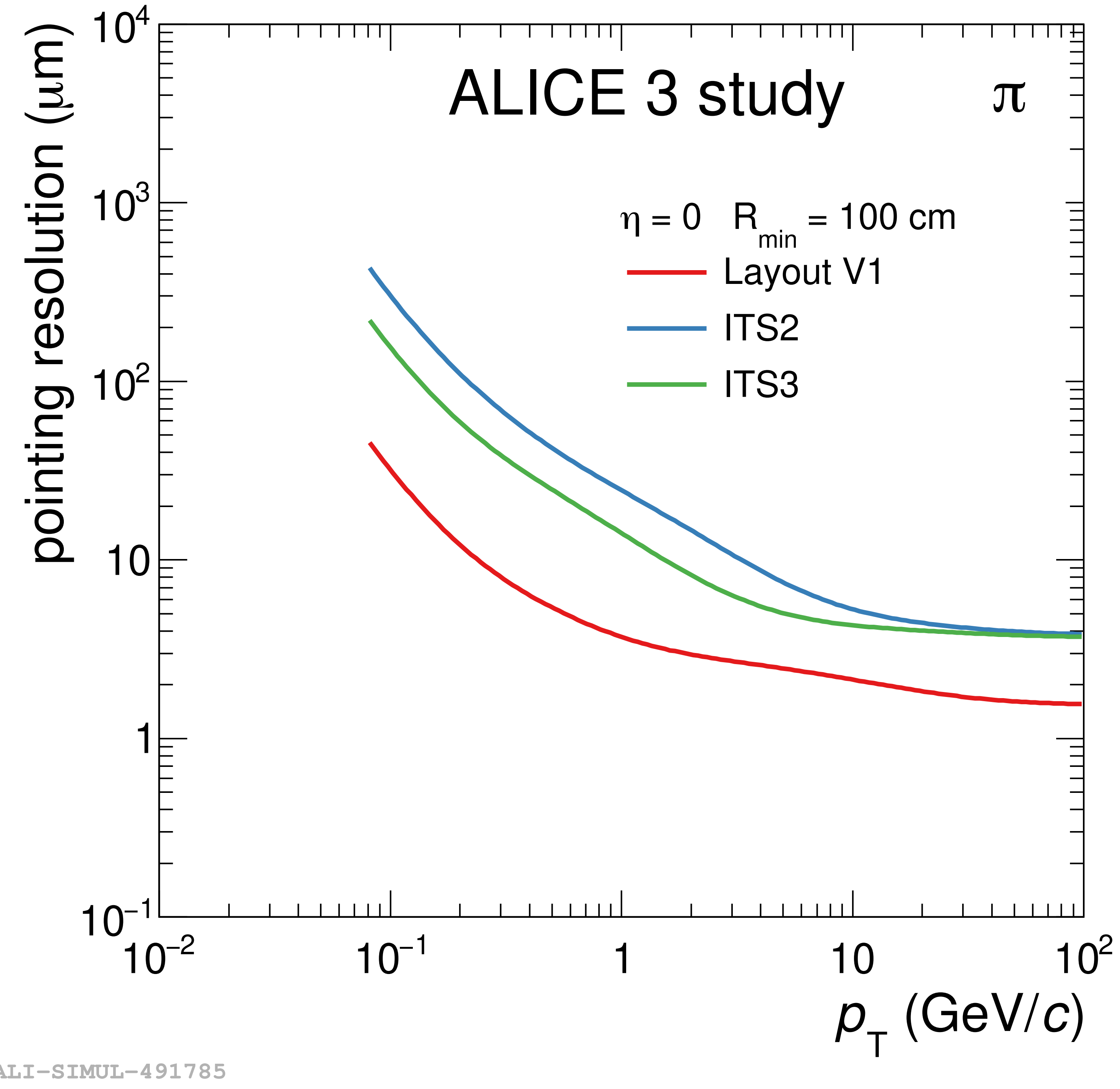
- Compact and lightweight all-silicon tracker
- Retractable vertex detector
- Particle identification systems
- Large acceptance
- Superconducting magnet system
- Continuous read-out and online processing

Detector requirements

Component	Observables	$|\eta| < 1.75$ (barrel)	$1.75 < |\eta| < 4$ (forward)	Detectors
Vertexing	Multi-charm baryons, dielectrons	**Best possible DCA resolution, $\sigma_{DCA} \approx 10$ 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 ≈ 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

Vertexing

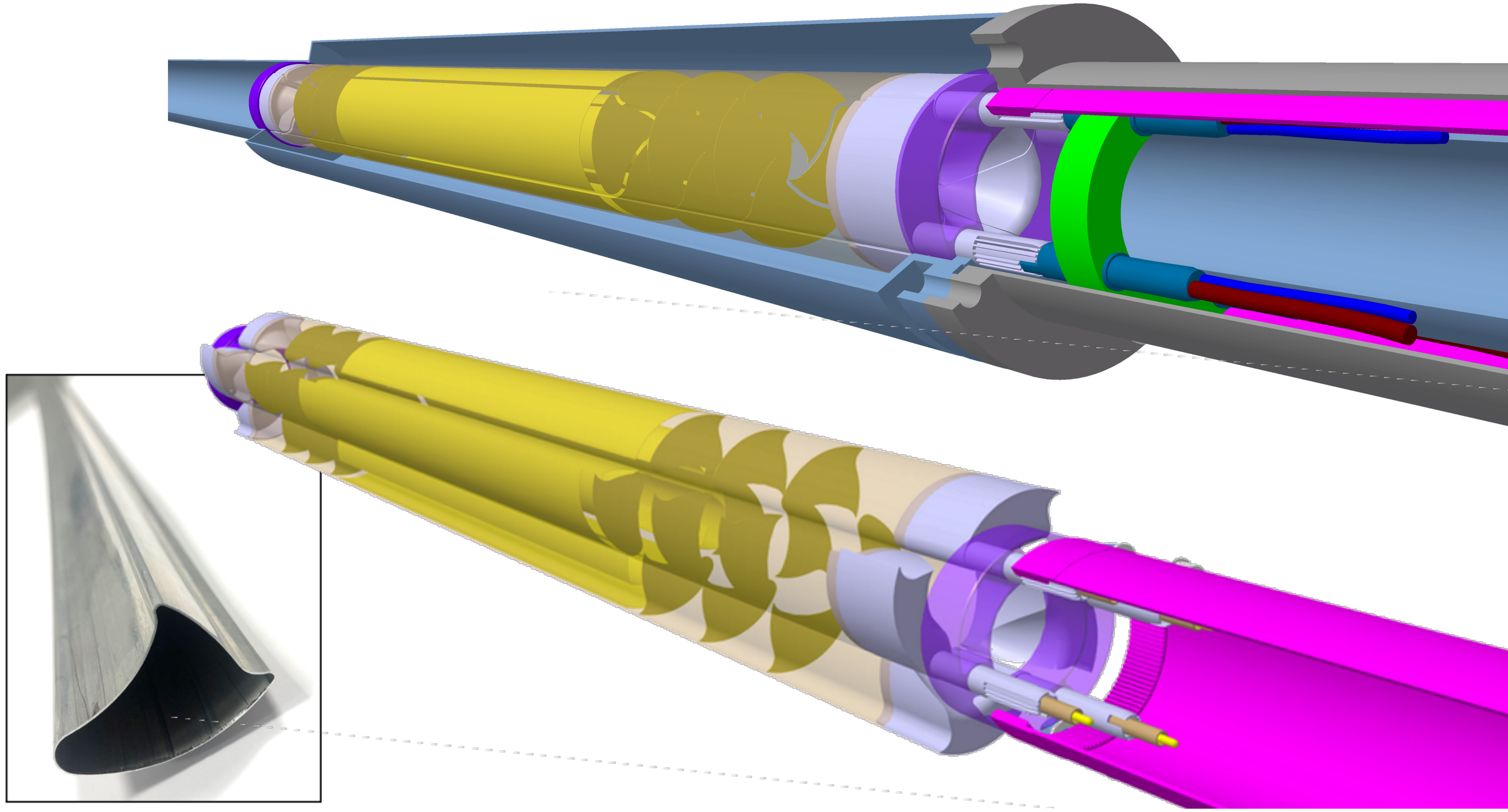
- **Pointing resolution** $\propto r_0 \cdot \sqrt{x/X_0}$
  (multiple scattering regime)
  ➡ 10 µm @ p_T = 200 MeV/c
  - radius and material of first layer crucial
  - minimal radius given by required aperture:
    R ≈ 5 mm at top energy,
    R ≈ 15 mm at injection energy
    → **retractable vertex 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

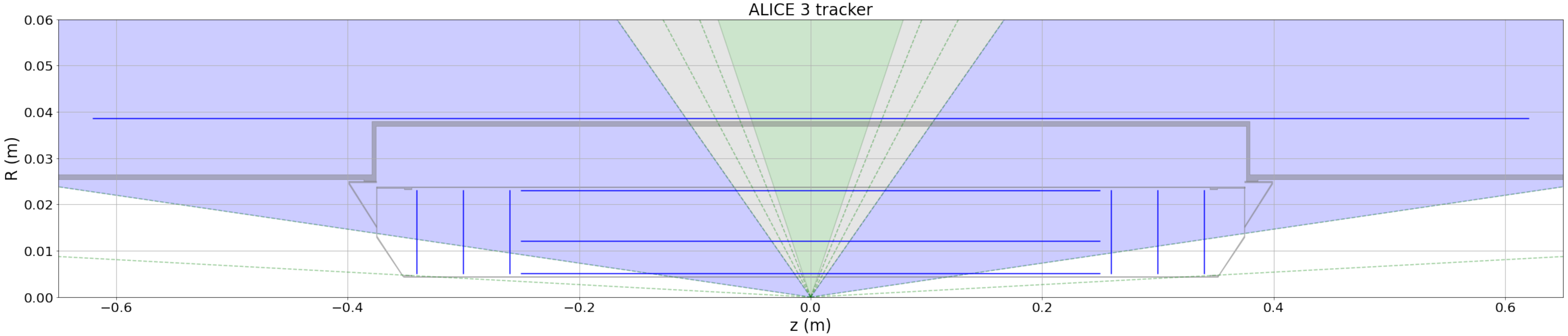


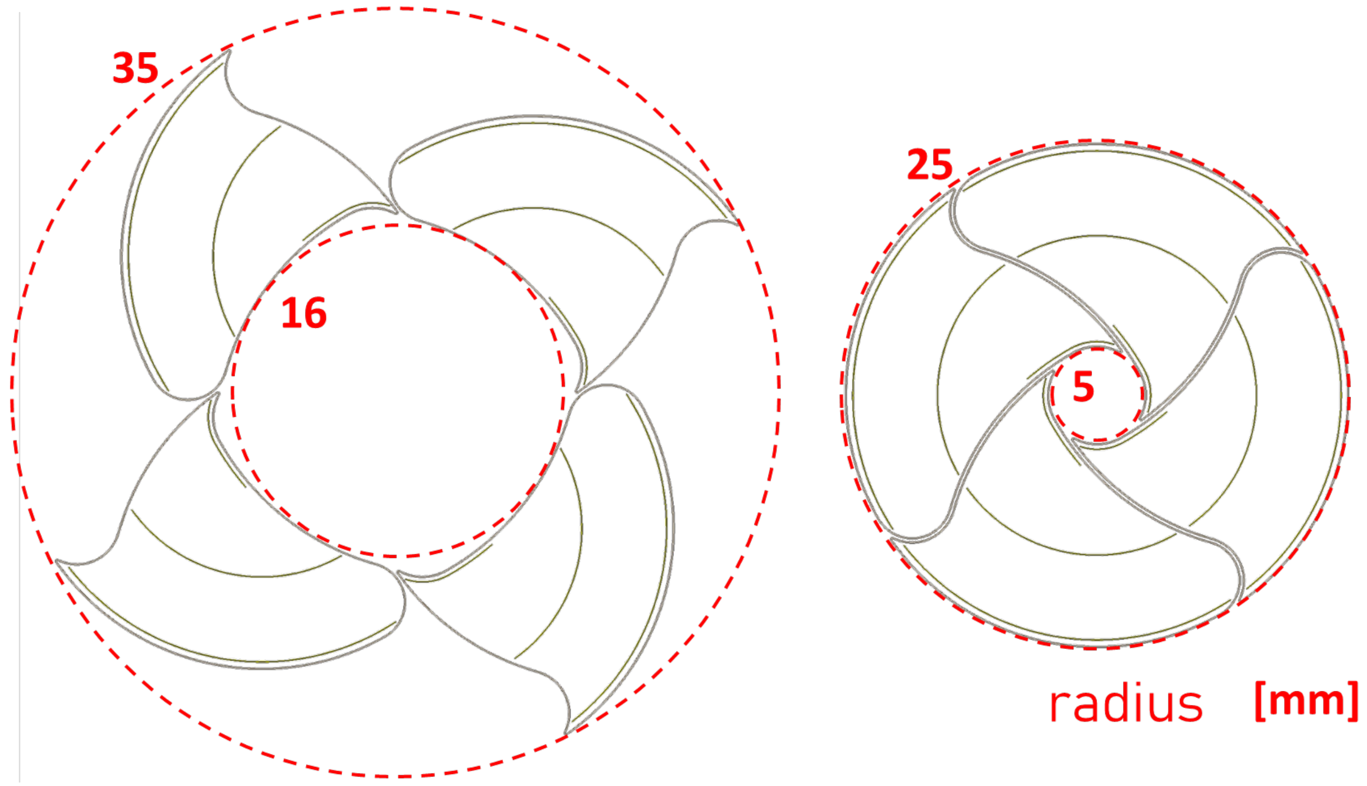
5x better than ALICE 2.1
(ITS3 + TPC)

Vertex Detector

- **Conceptual study**
  - wafer-sized, bent MAPS (leveraging on ITS3 activities)
  - rotary petals for secondary vacuum (thin walls to minimise material)
  - matching to beampipe parameters (impedance, aperture, …)
  - feed-throughs for power, cooling, data
- **R&D challenges** on mechanics, cooling, radiation tolerance

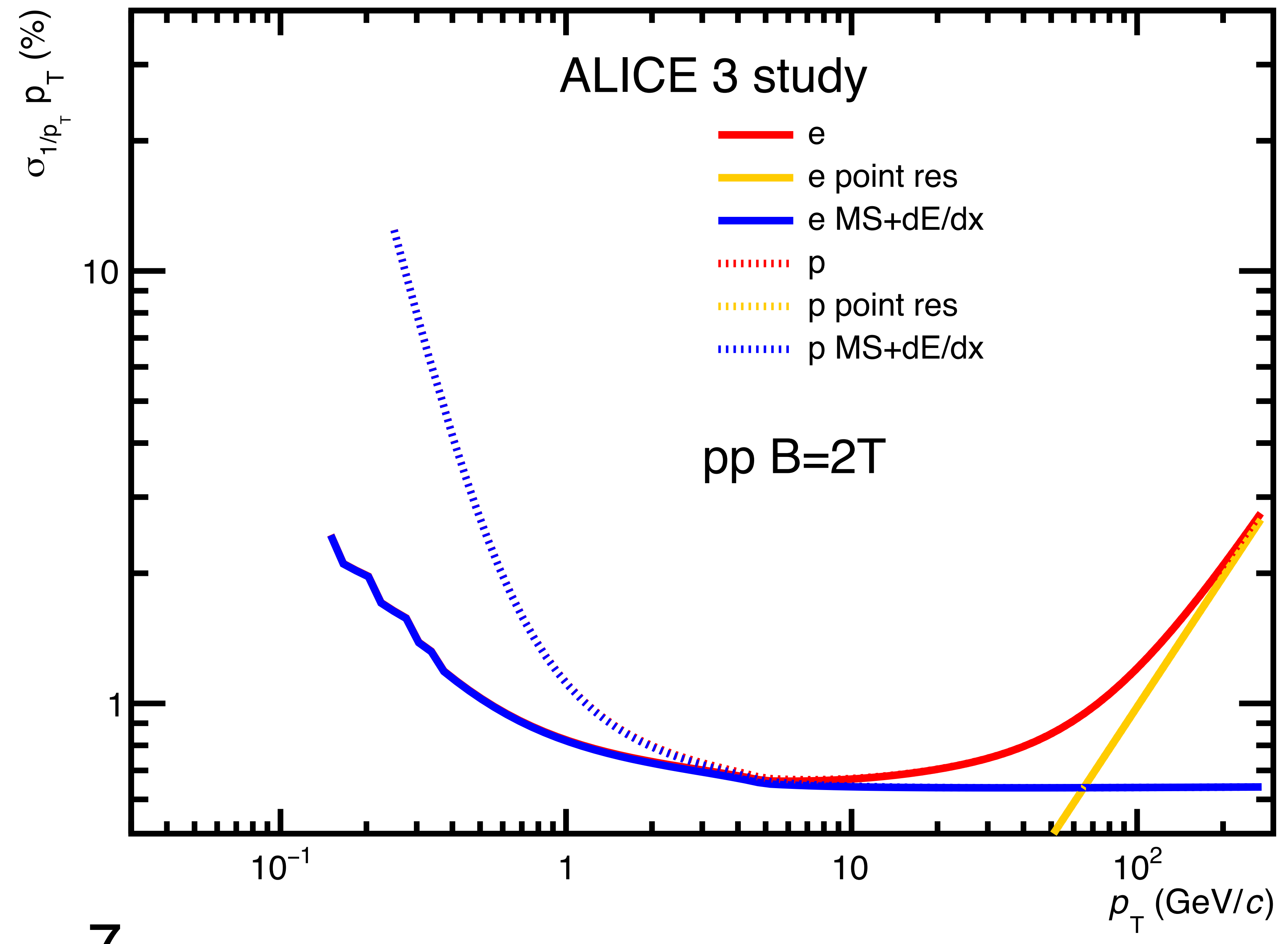


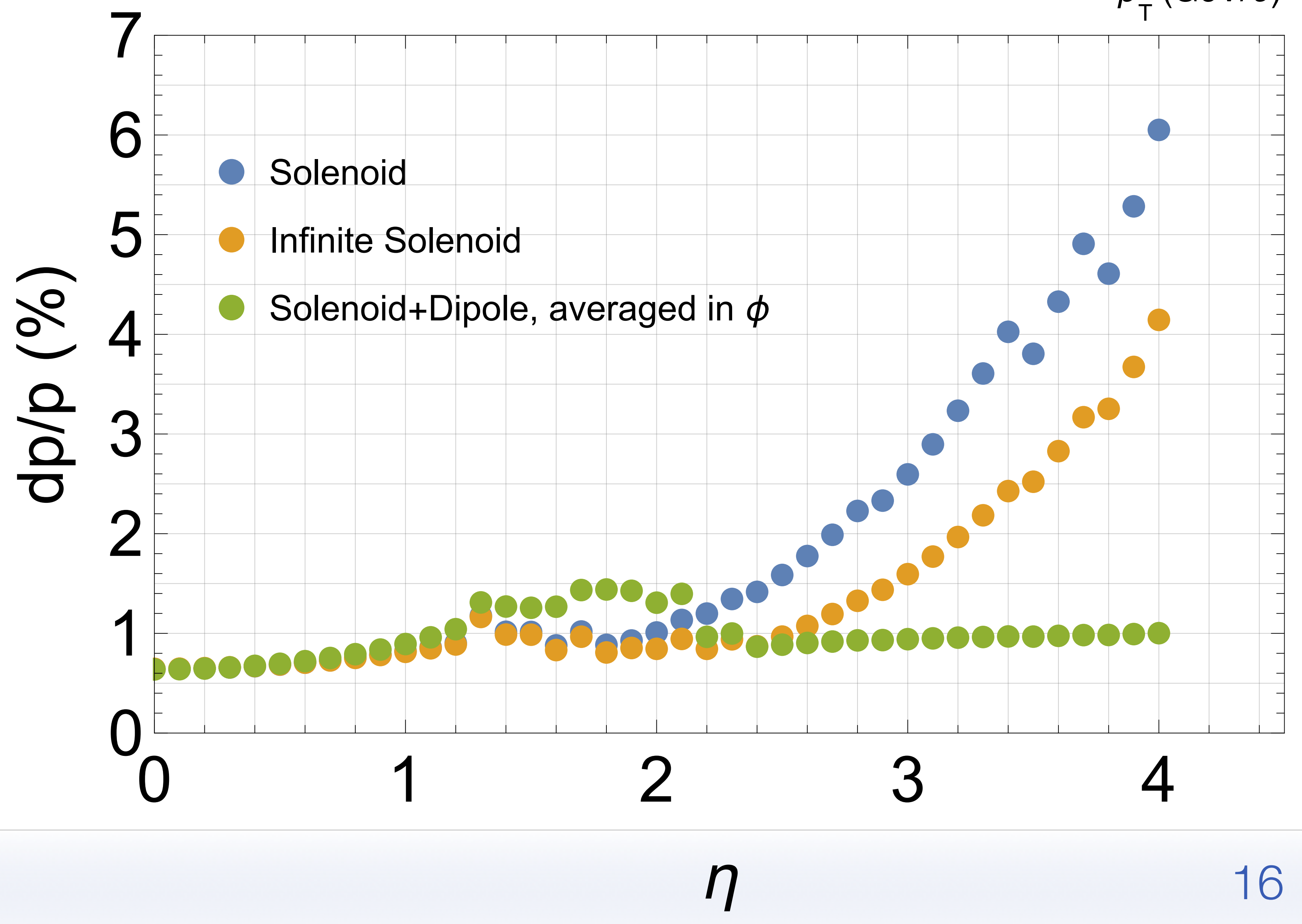




Tracking

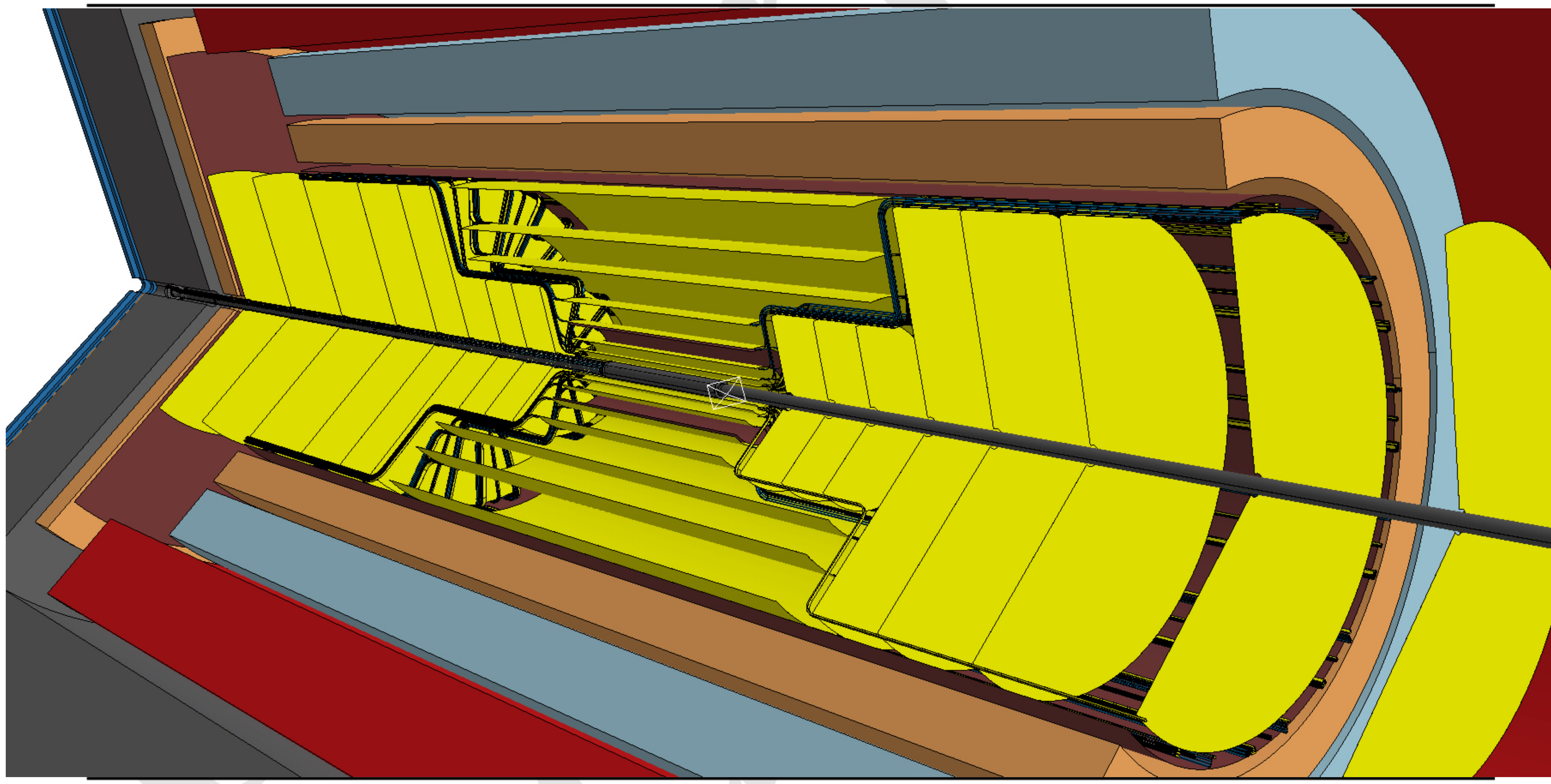
- **Relative p_T resolution** $\propto \dfrac{\sqrt{x/X_0}}{B \cdot L}$
  (limited by multiple scattering)
  ➟ ~1 % up to η = 4
  - integrated magnetic field crucial
  - overall material budget critical
- **~11 tracking layers (barrel + disks)**
  - MAPS
  - σ_{pos} ~10 µm → 50 µm pixel pitch
  - R_{out} ≈ 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 %

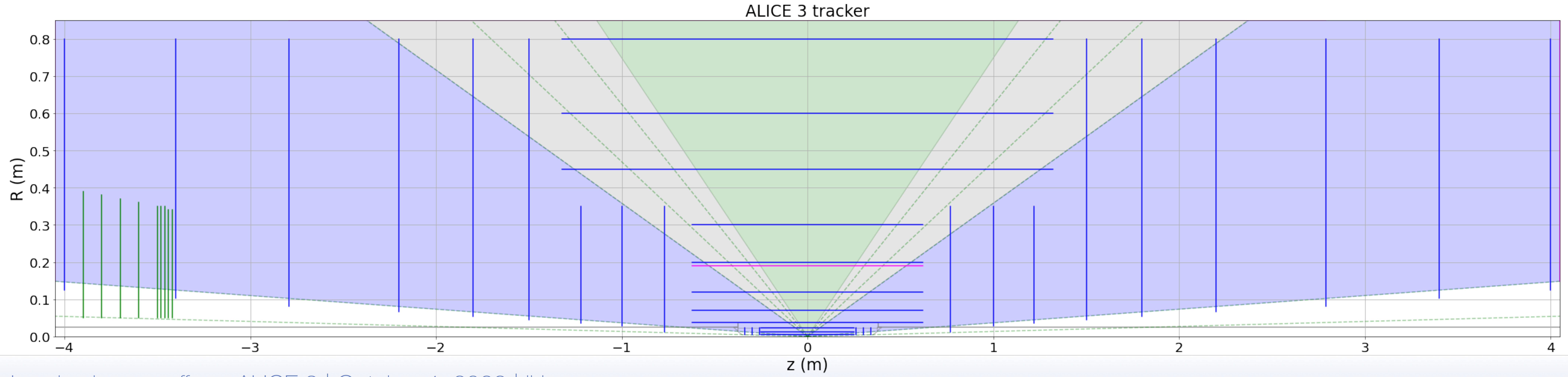




Outer Tracker

- 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

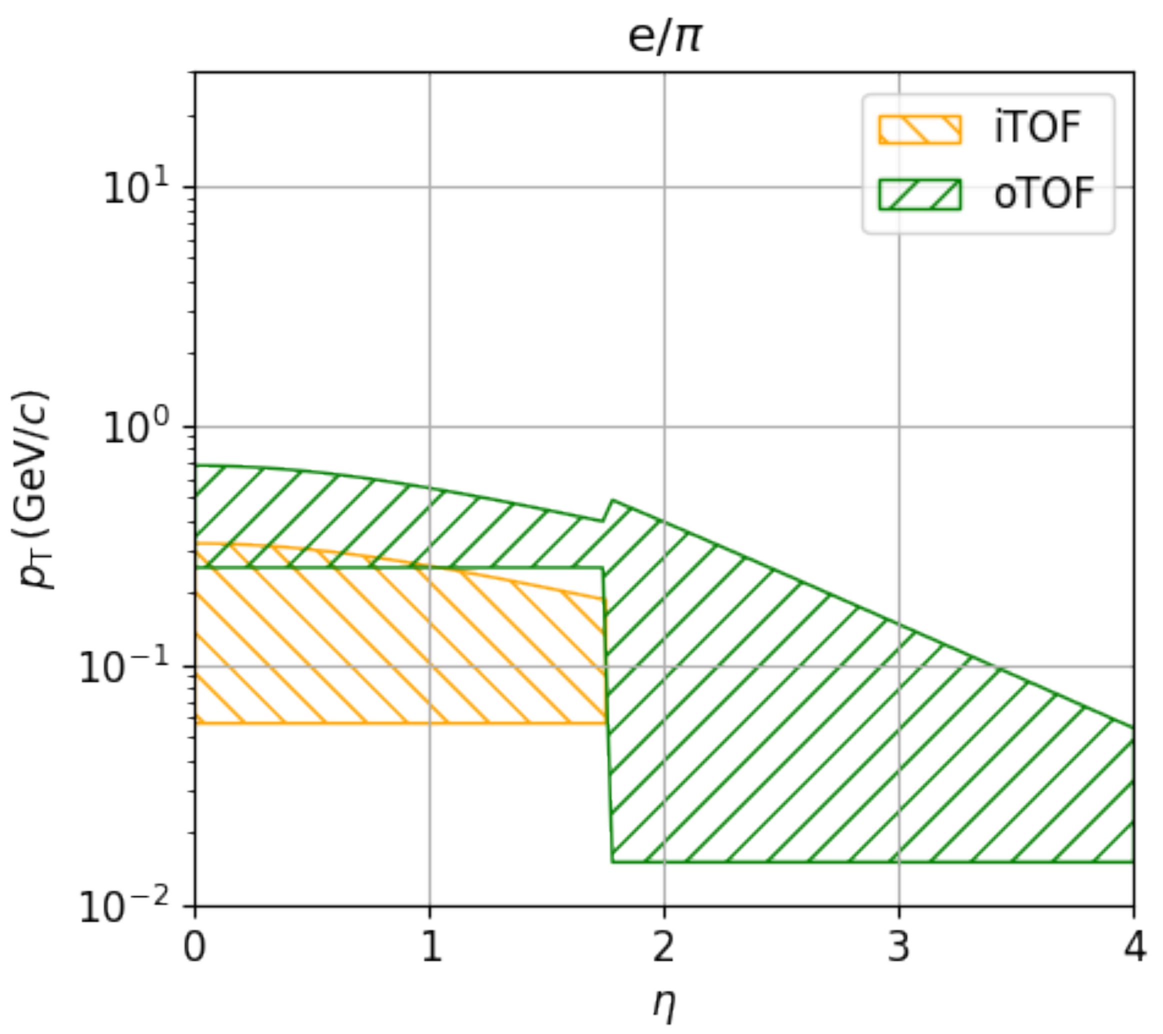




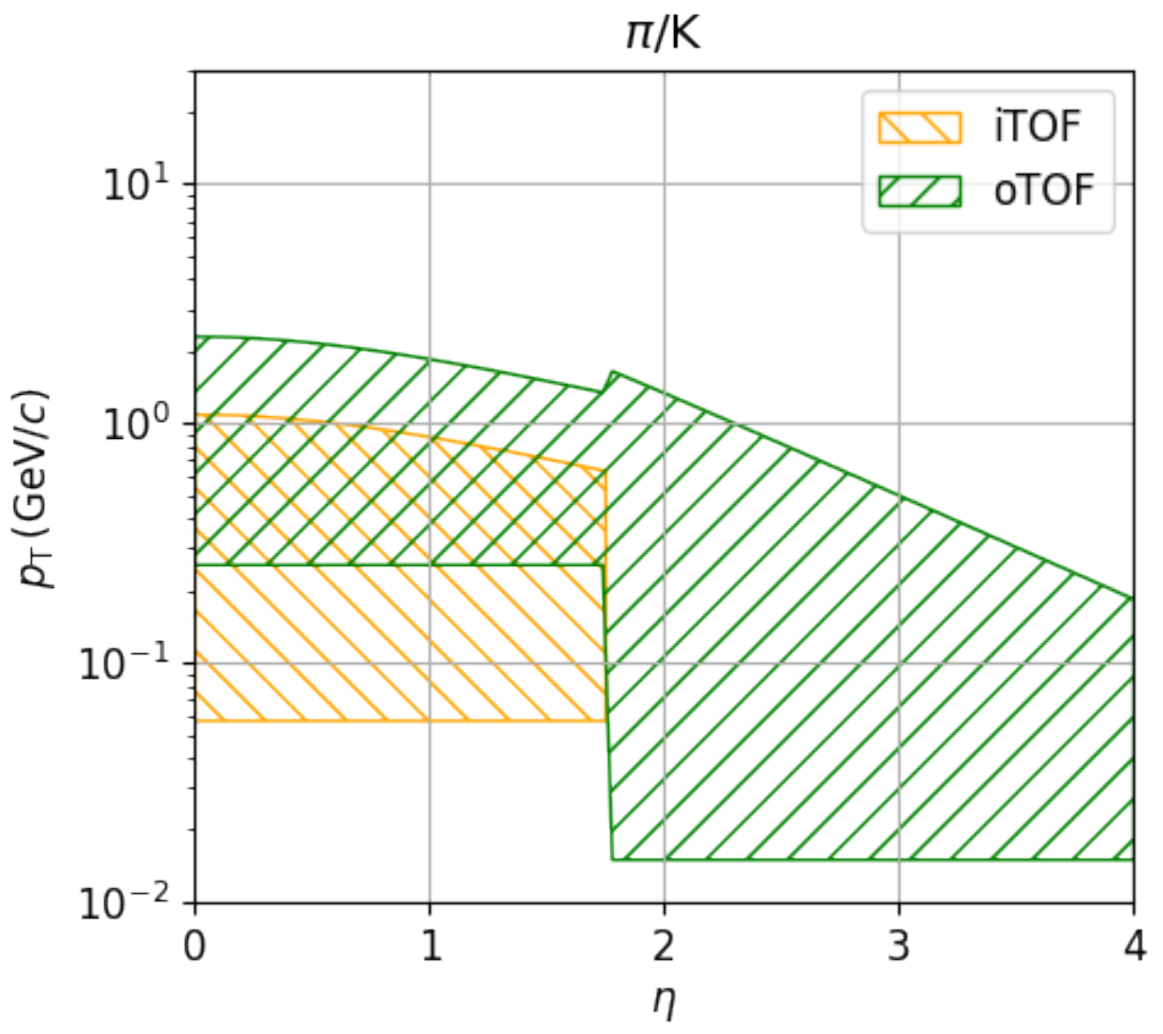
Total silicon surface ~60 m²

Time of flight

- **Separation power** $\propto \dfrac{L}{\sigma_{\rm tof}}$
  - 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** ($\sigma_{\rm TOF}$ ≈ 20 ps)
  - R&D on monolithic CMOS sensors with integrated gain layer



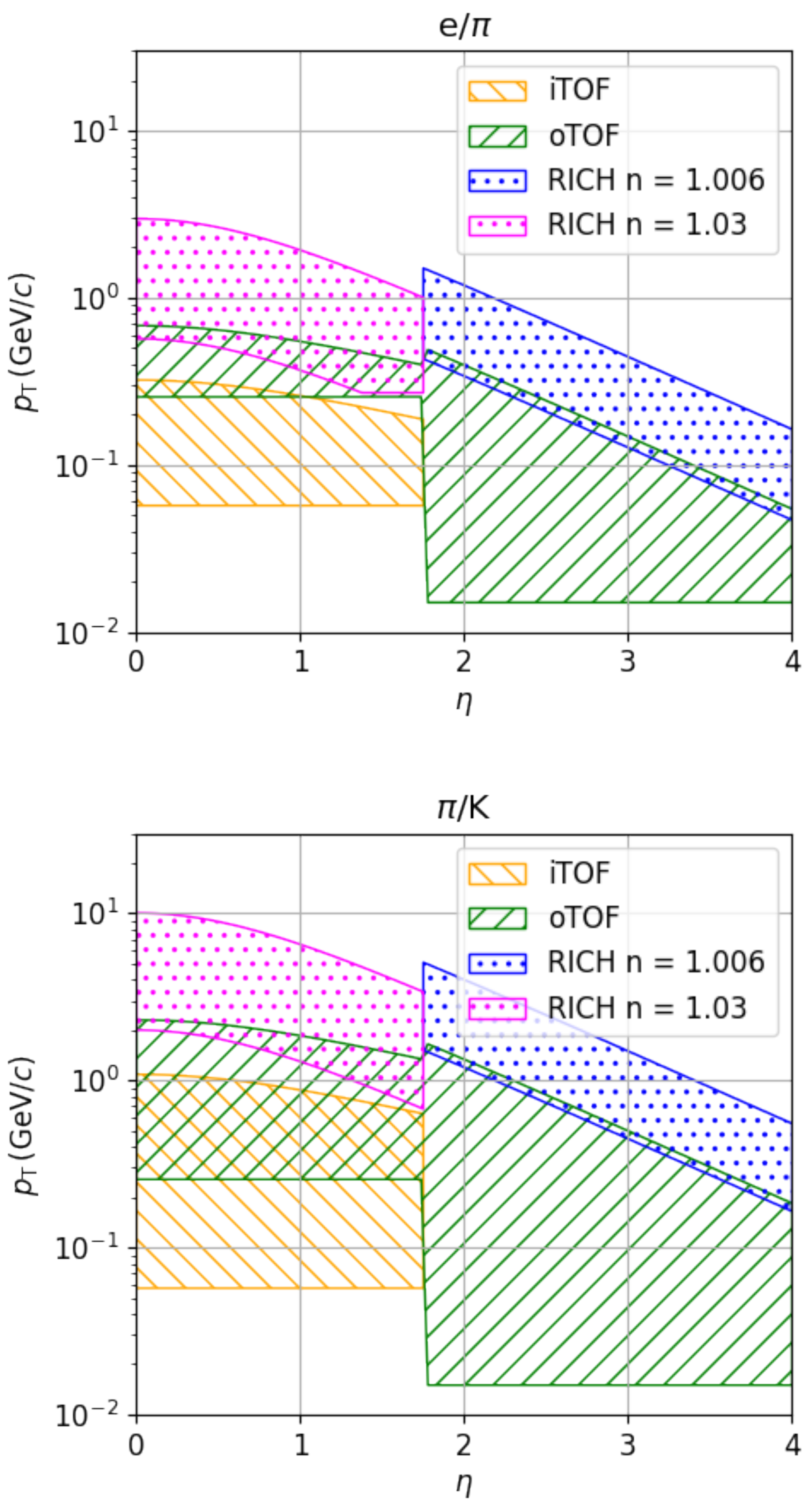
Total silicon surface ~45 m²

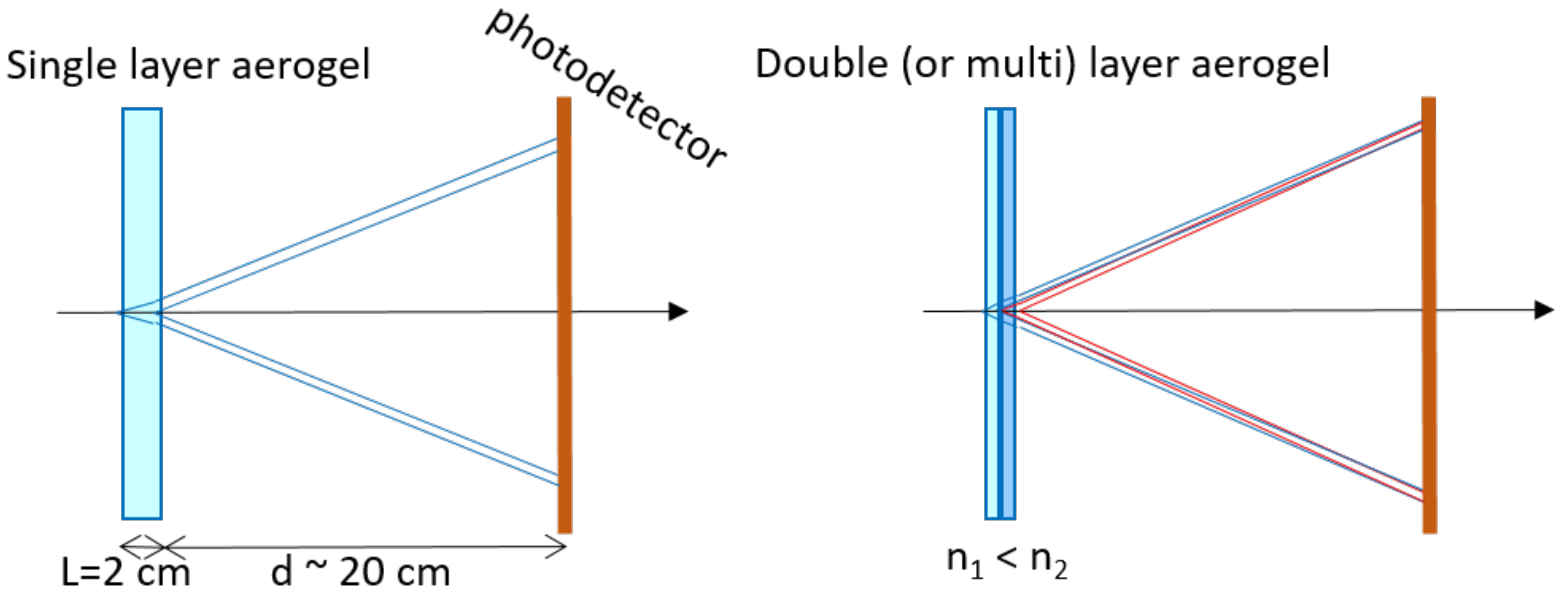


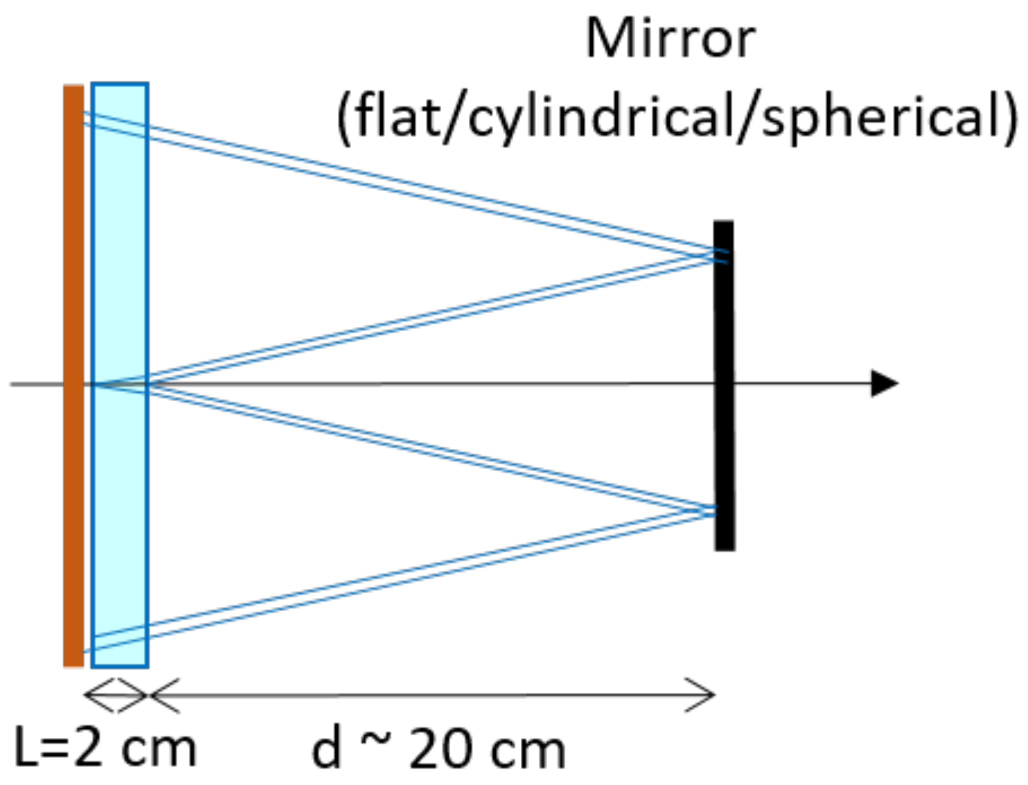
Ring-Imaging Cherenkov

- **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







Elm. calorimeter

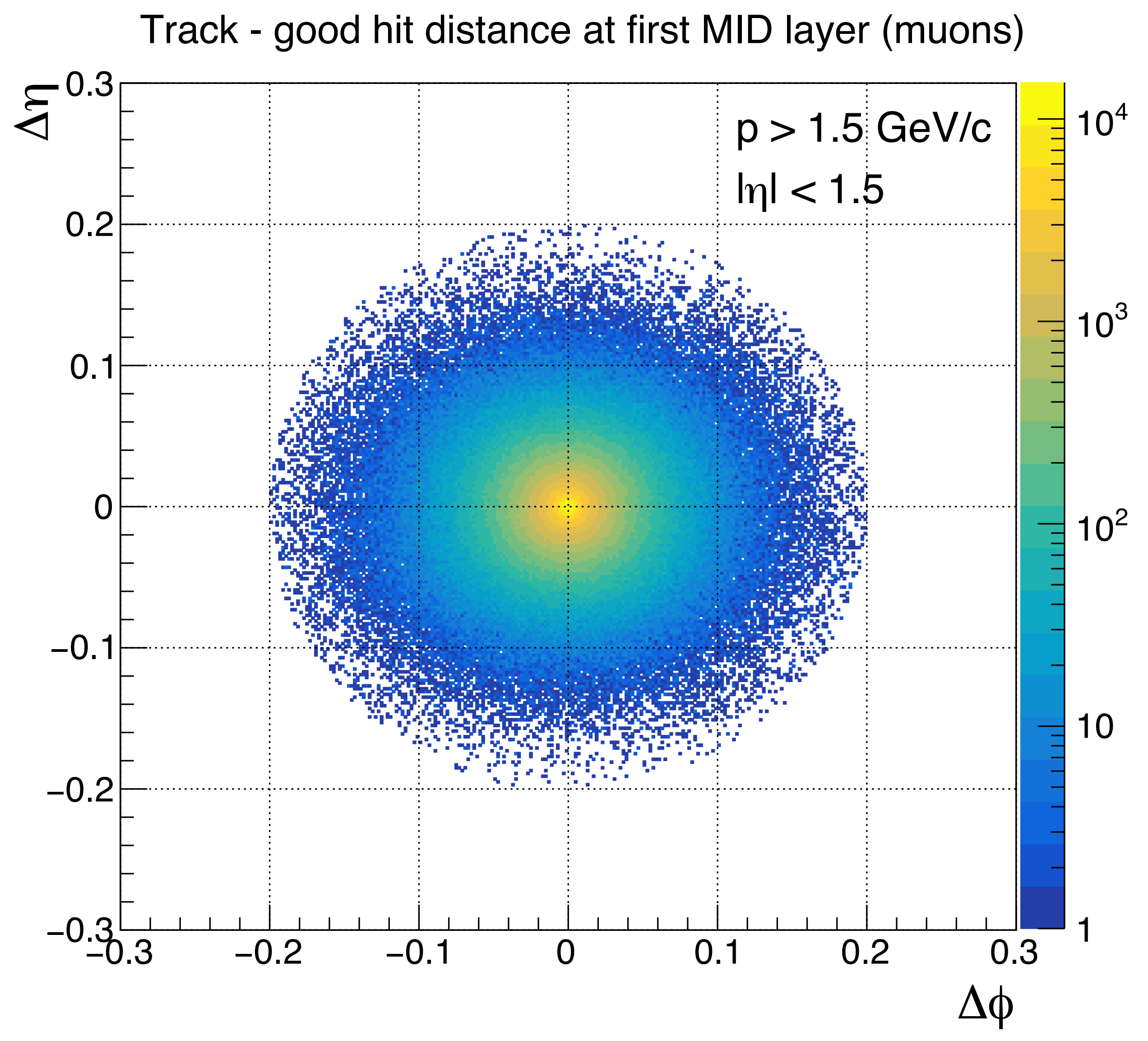
- **Large acceptance ECal**
  → sampling calorimeter (à la EMCal/DCal):
  e.g. O(100) layers (1 mm Pb + 1.5 mm plastic scintillator)

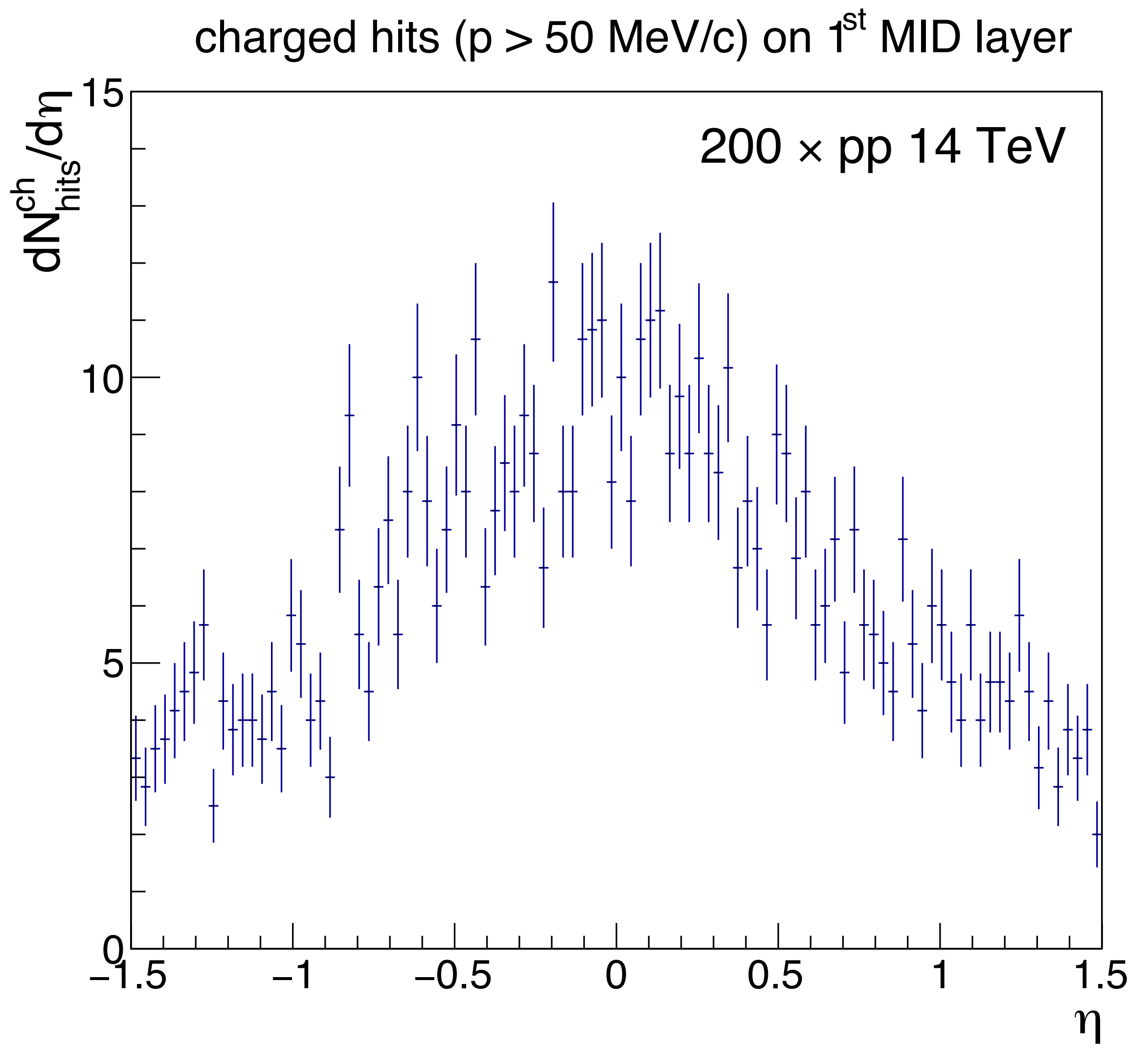
- **Additional high energy resolution segment** at midrapidity or forward
  → $PbWO_4$-based

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

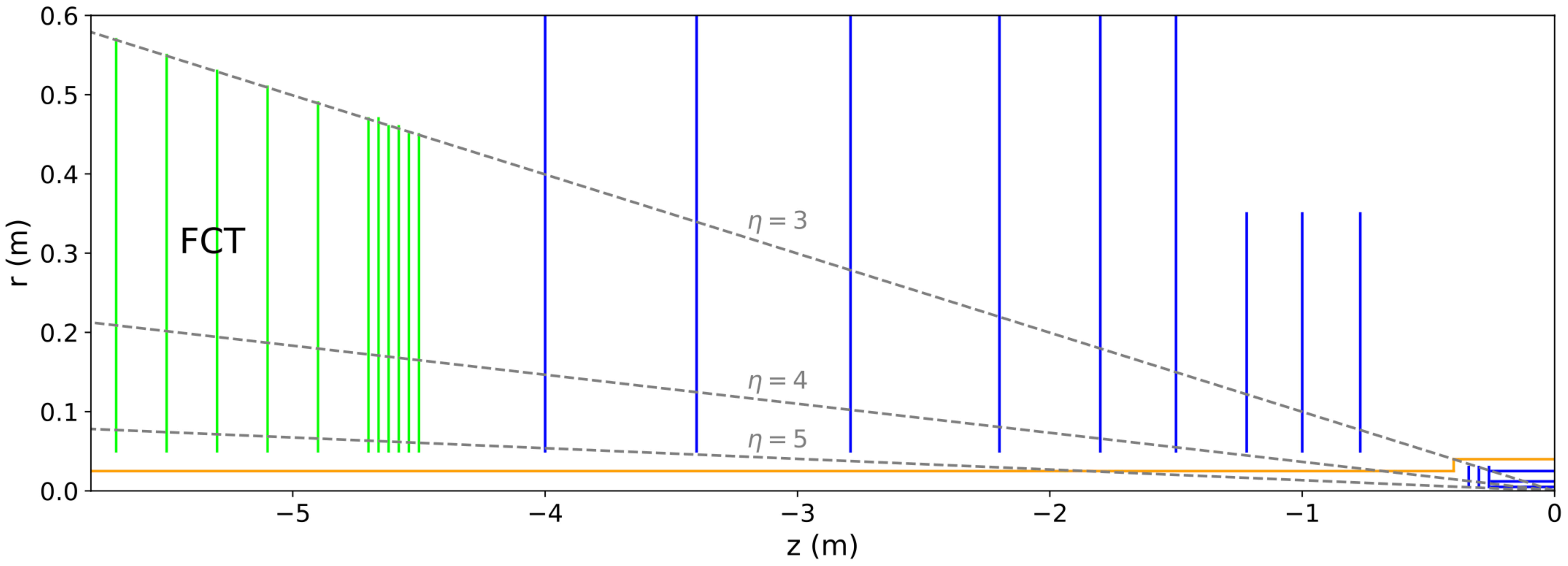
- **Hadron absorber** outside of the magnet
  - ~70 cm non-magnetic steel
- **Muon chambers**
  - search spot for muons ~0.1 x 0.1 (eta x phi) → ~5 x 5 cm² cell size
  - matching demonstrated with 2 layers of muon chambers
    - scintillator bars with SiPM read-out
    - resistive plate chambers





Forward conversion tracker

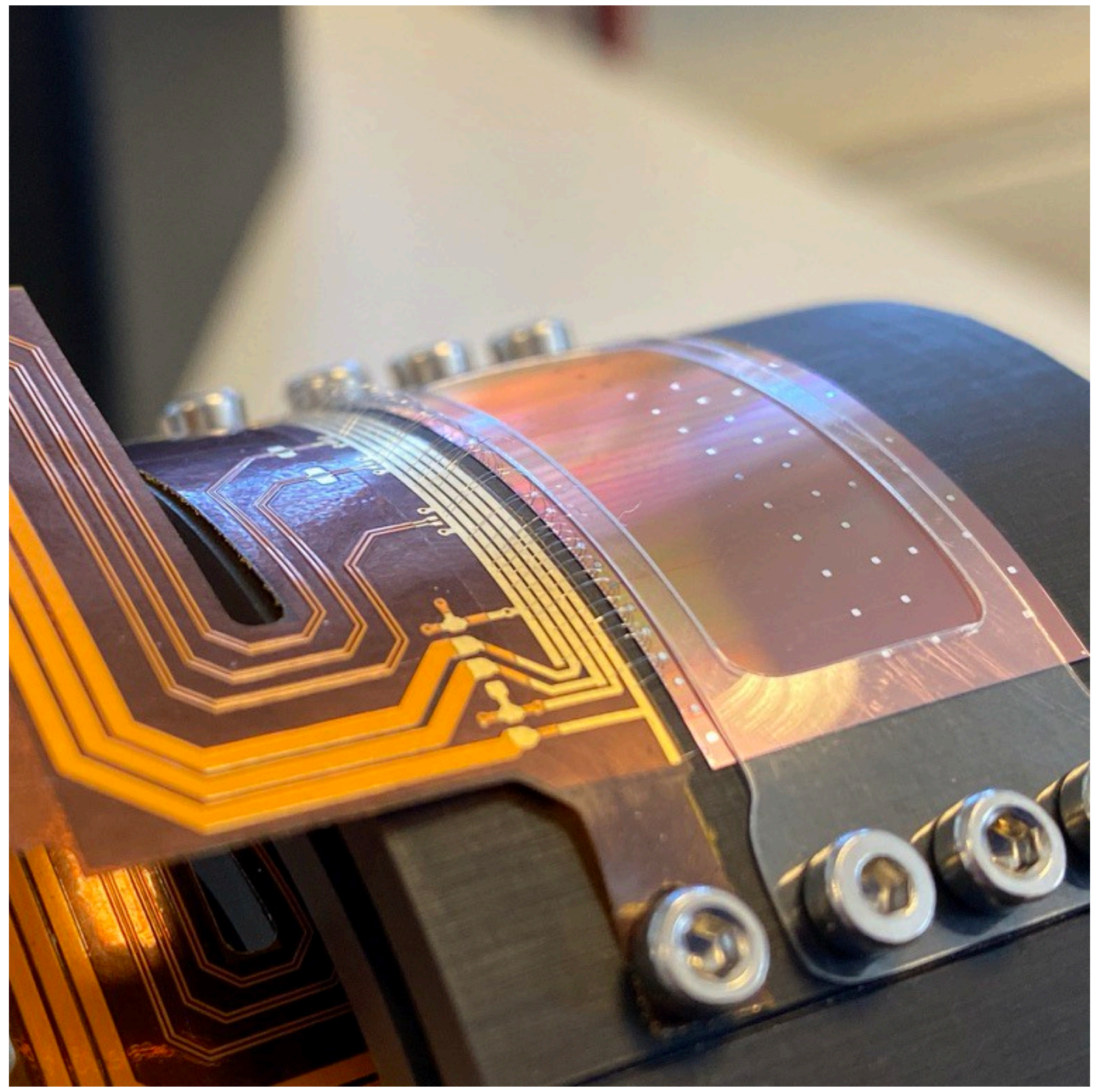
- **Thin tracking disks**
  to cover 3 < η < 5
  - few ‰ of a radiation length per layer
  - position resolution < 10 µm
- **Research & Development**
  - Large area, thin disks
  - Minimisation of material in front of FCT
  - Operational conditions



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

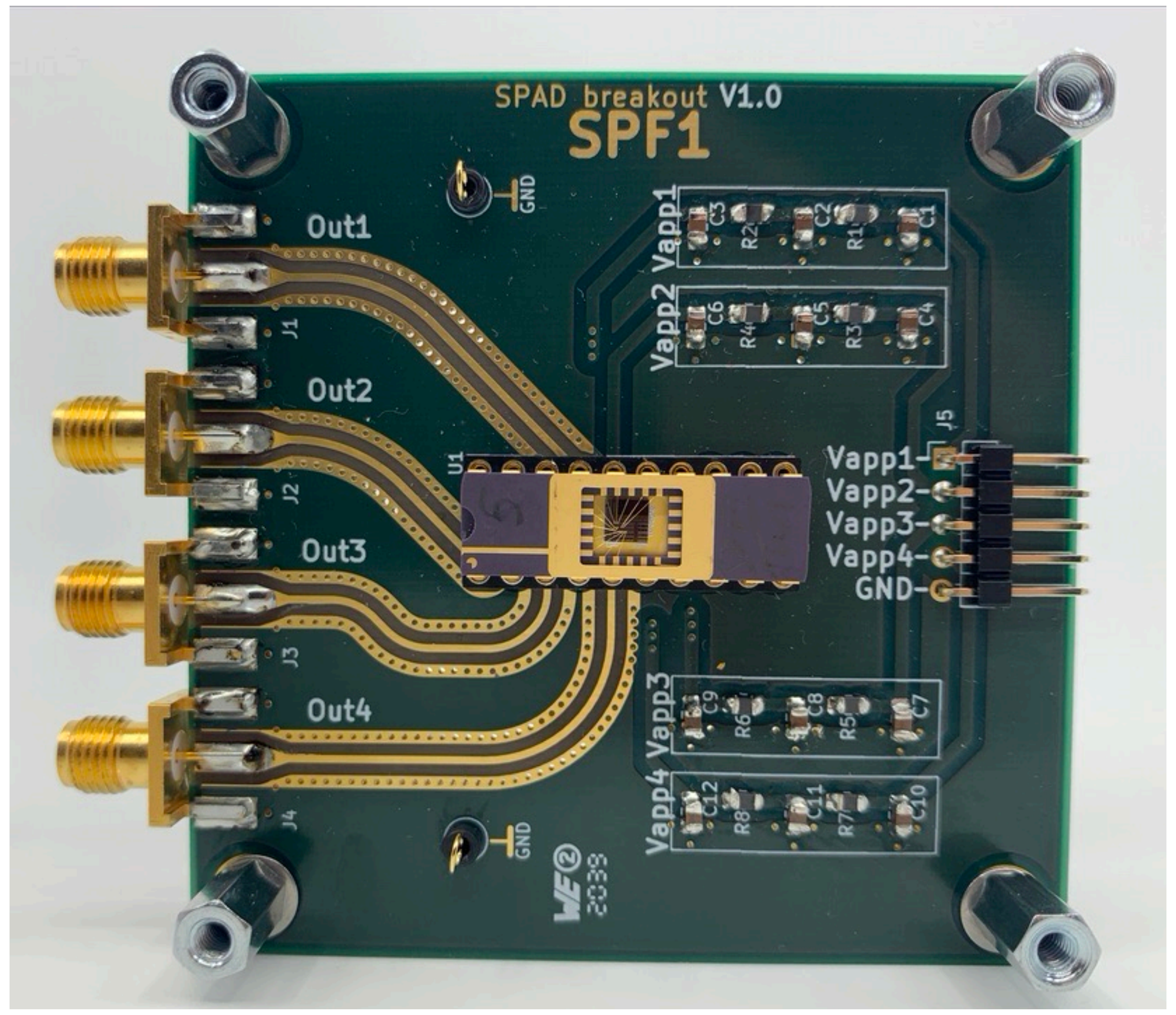
Strategic R&D

- **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 and relevant technologies

➝ Synergies with LHC, FAIR, EIC, …



Physics programme

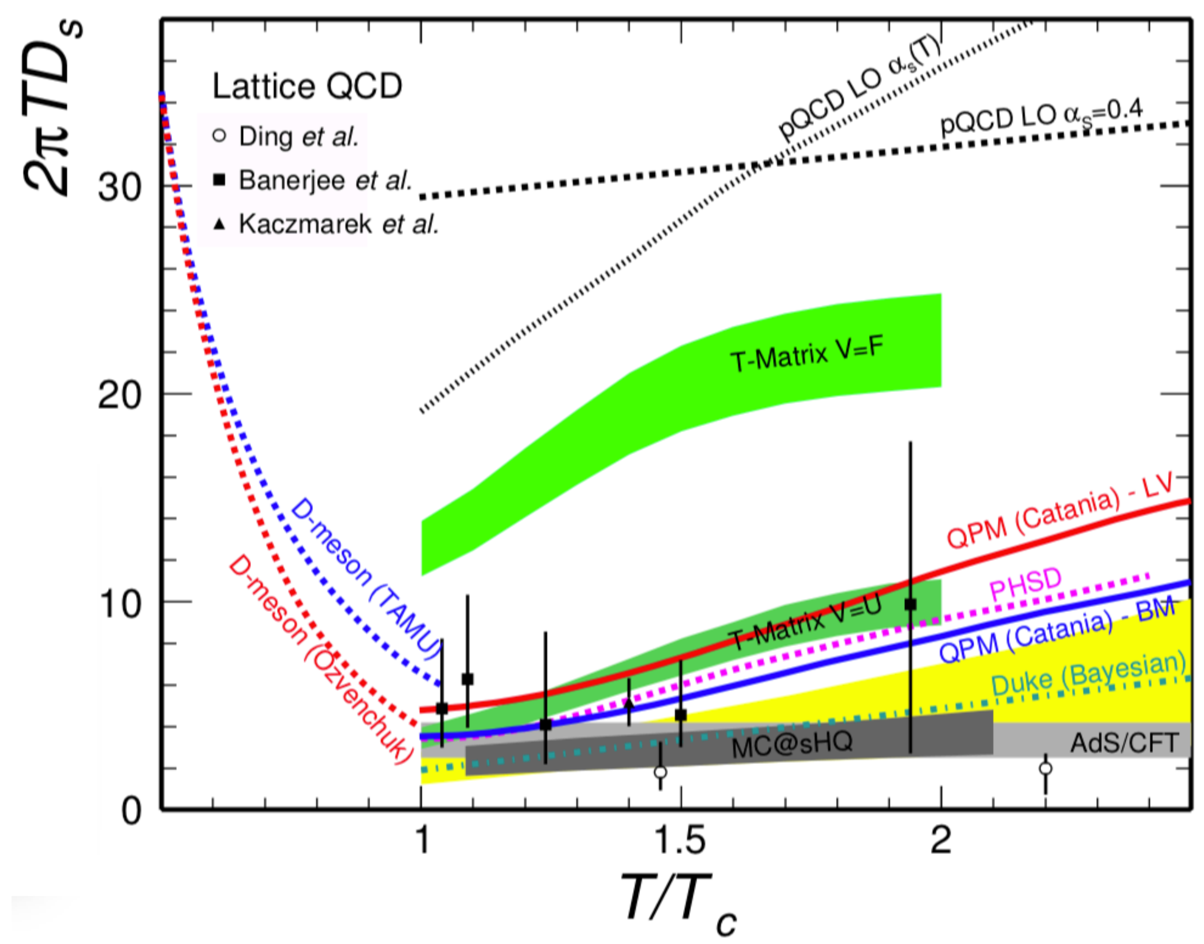
- **Early stages**: temperature of QGP before hadronisation
  - Di-lepton and photon production, elliptic flow
  - Electric conductivity of the QGP
- **Chiral symmetry** restoration: $\rho - a_1$ mixing
- **Heavy flavour diffusion and thermalisation in the QGP**
  - Beauty and charm flow
  - Charm hadron 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
- …

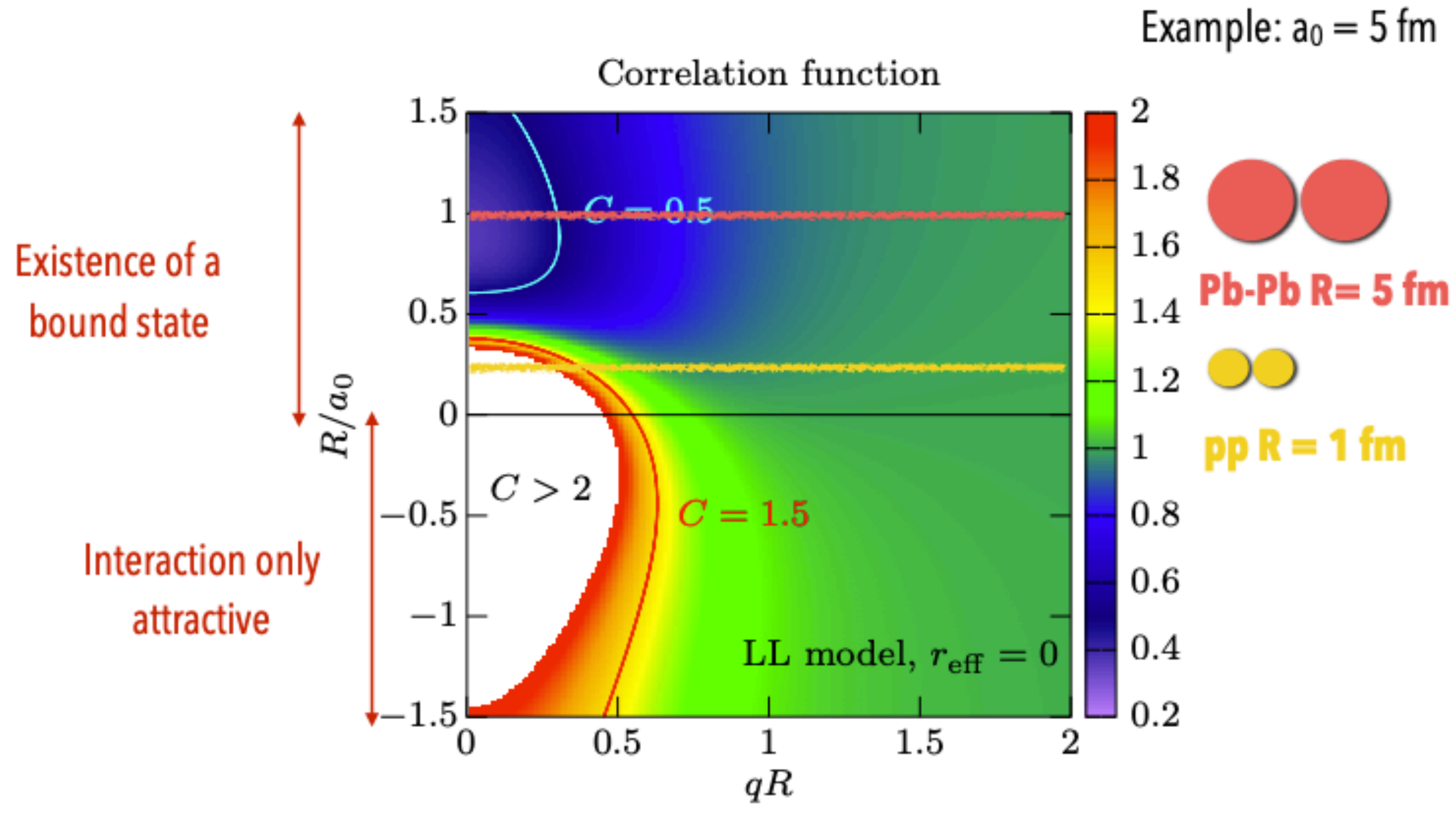
[CERN-LHCC-2022-009]

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

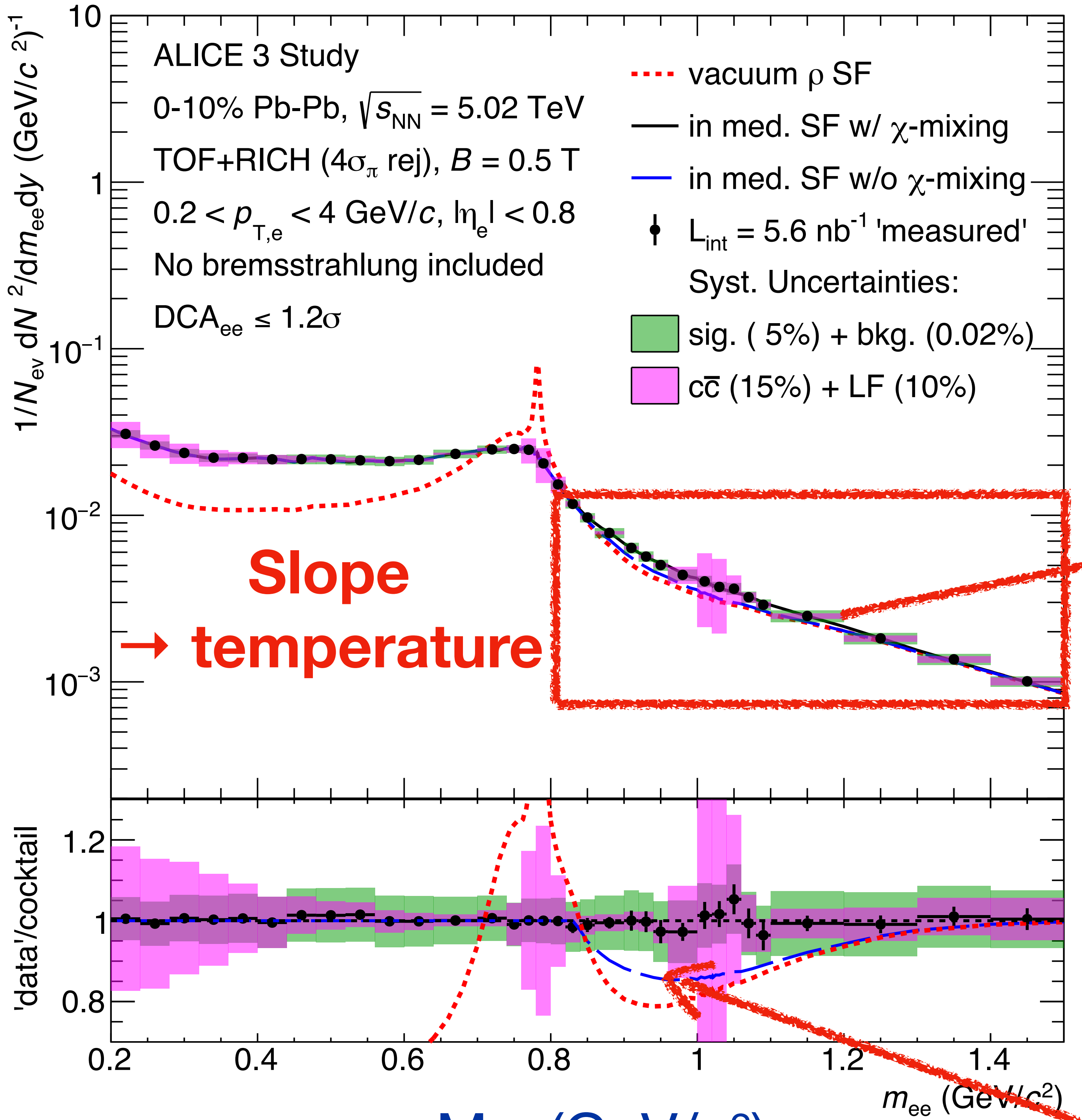
Time evolution & chiral symmetry

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

[CERN-LPCC-2018-07]

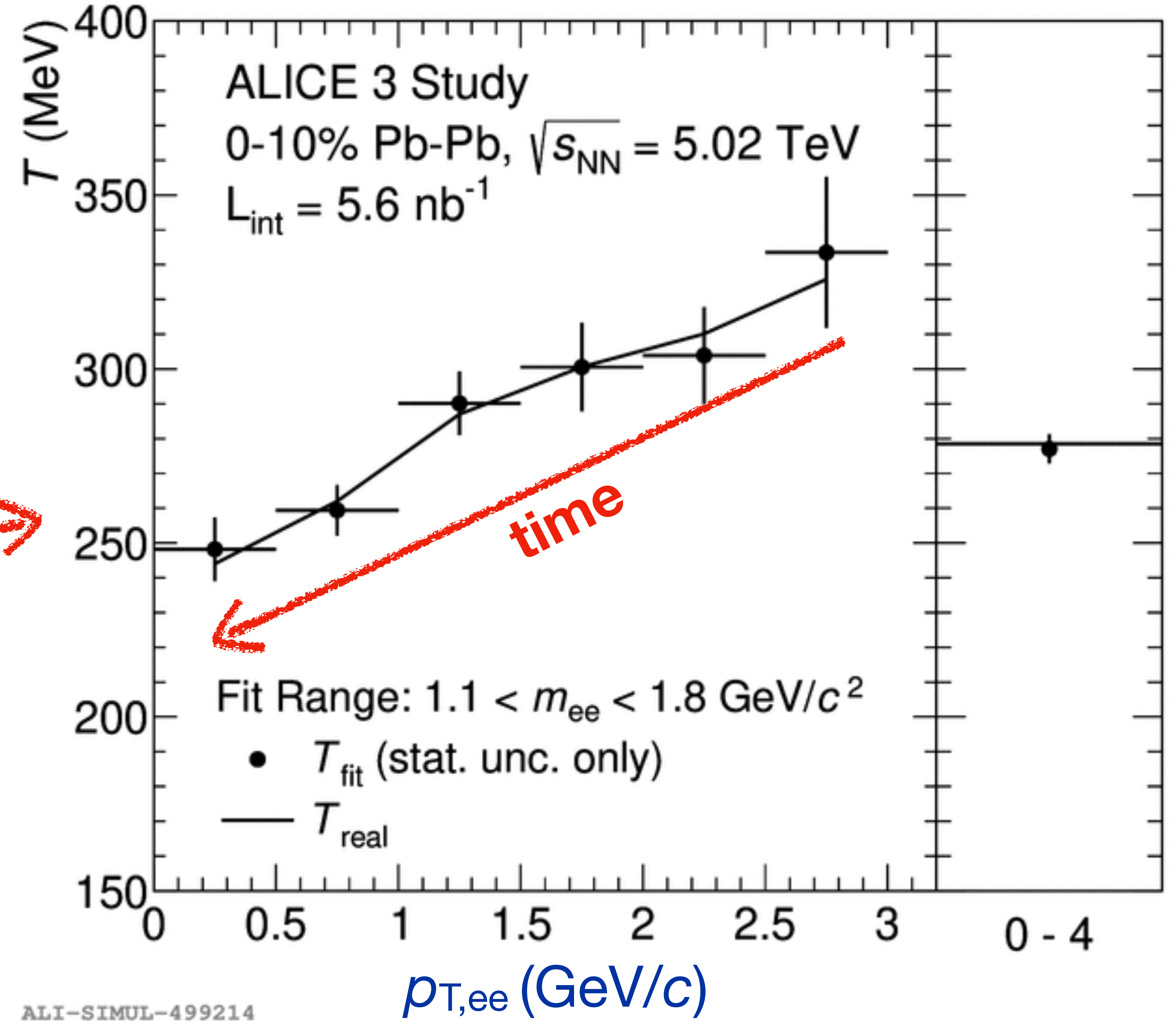
Run 5 & 6

Invariant mass spectrum of dielectrons



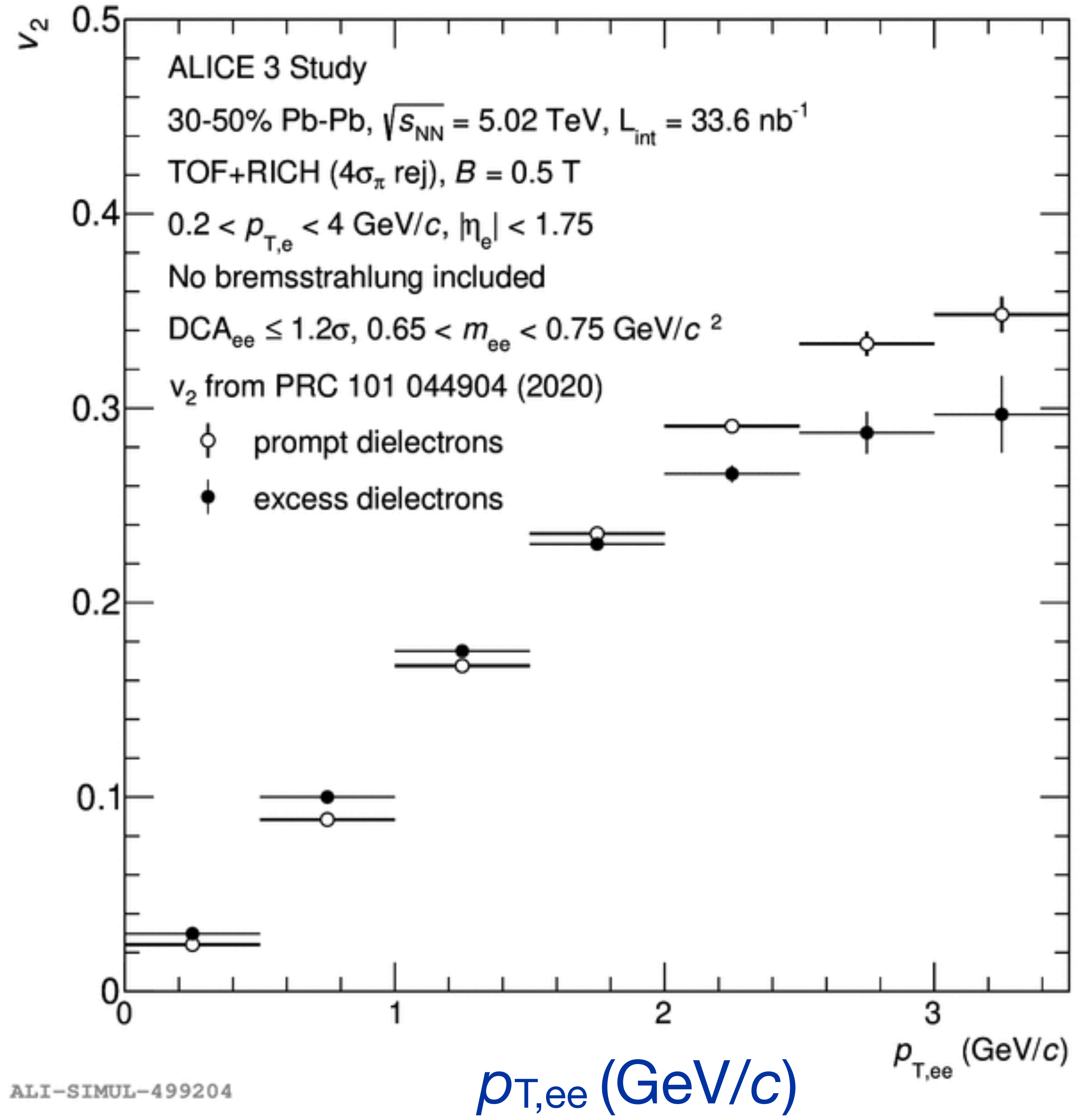
M_{ee} (GeV/c^2)

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



$p_{T,ee}$ (GeV/c)

Dilepton v_2
→ temporal emission profile

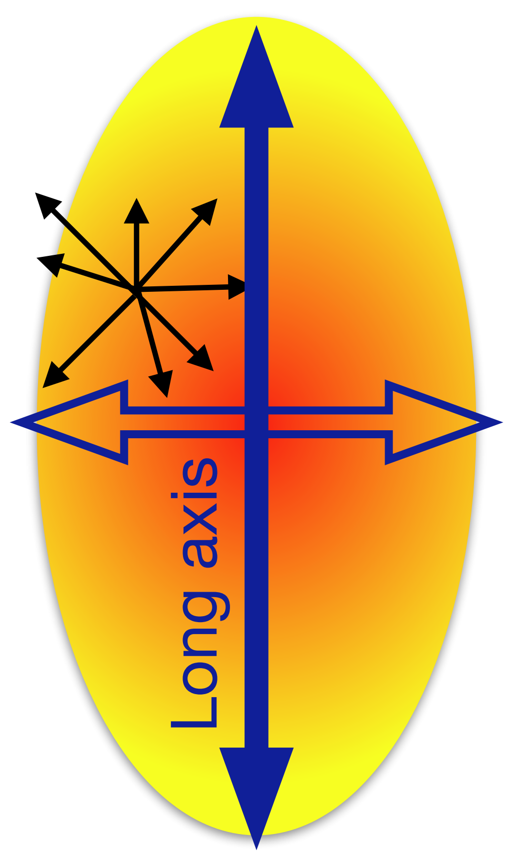


$p_{T,ee}$ (GeV/c)

Without ρ-a_1 mixing
→ dip in thermal spectrum

Heavy flavour transport

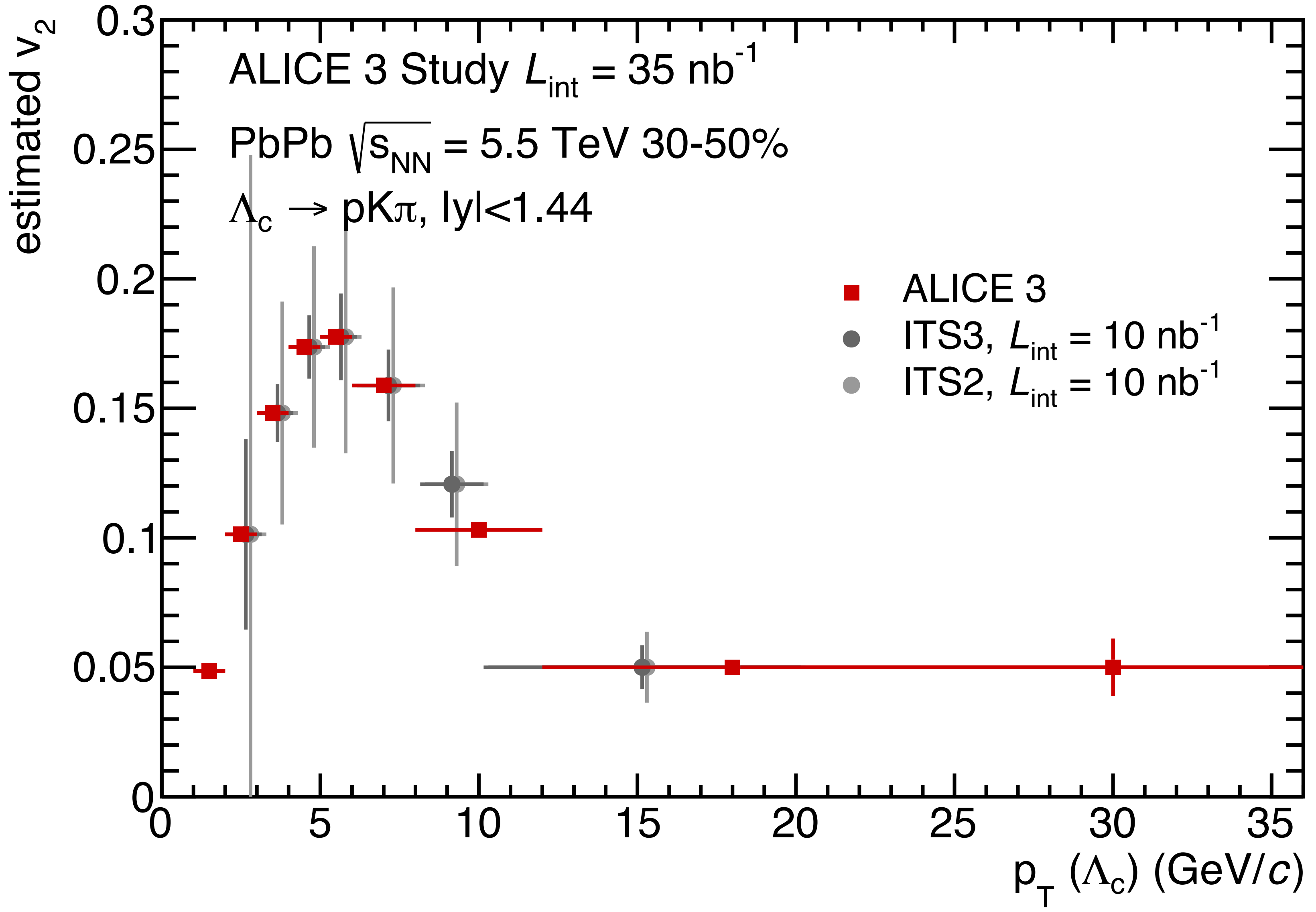
Non-central collision



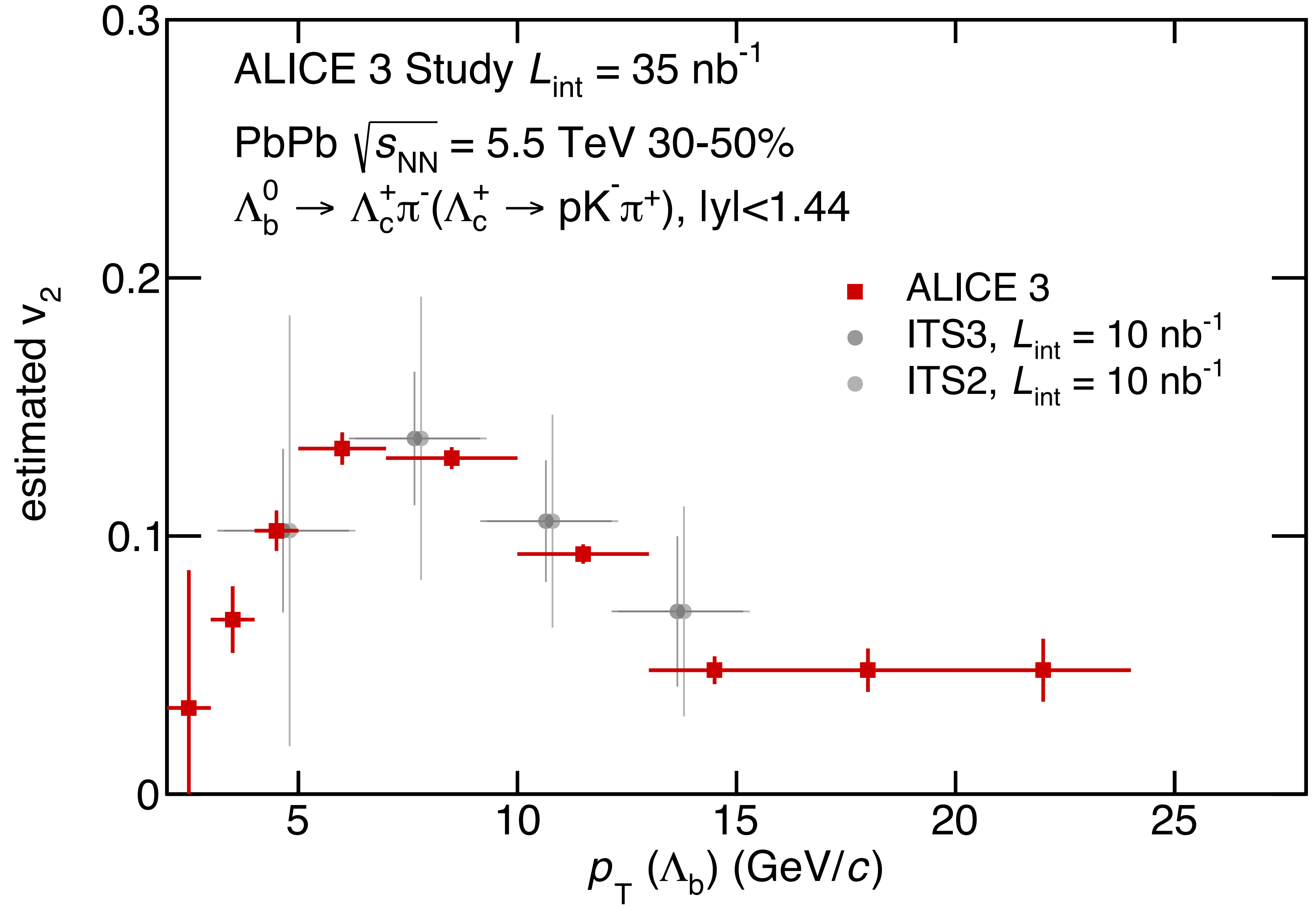
Interactions with the plasma generate azimuthal anisotropy v_2:

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

Λ_c v_2 performance



Λ_b v_2 performance



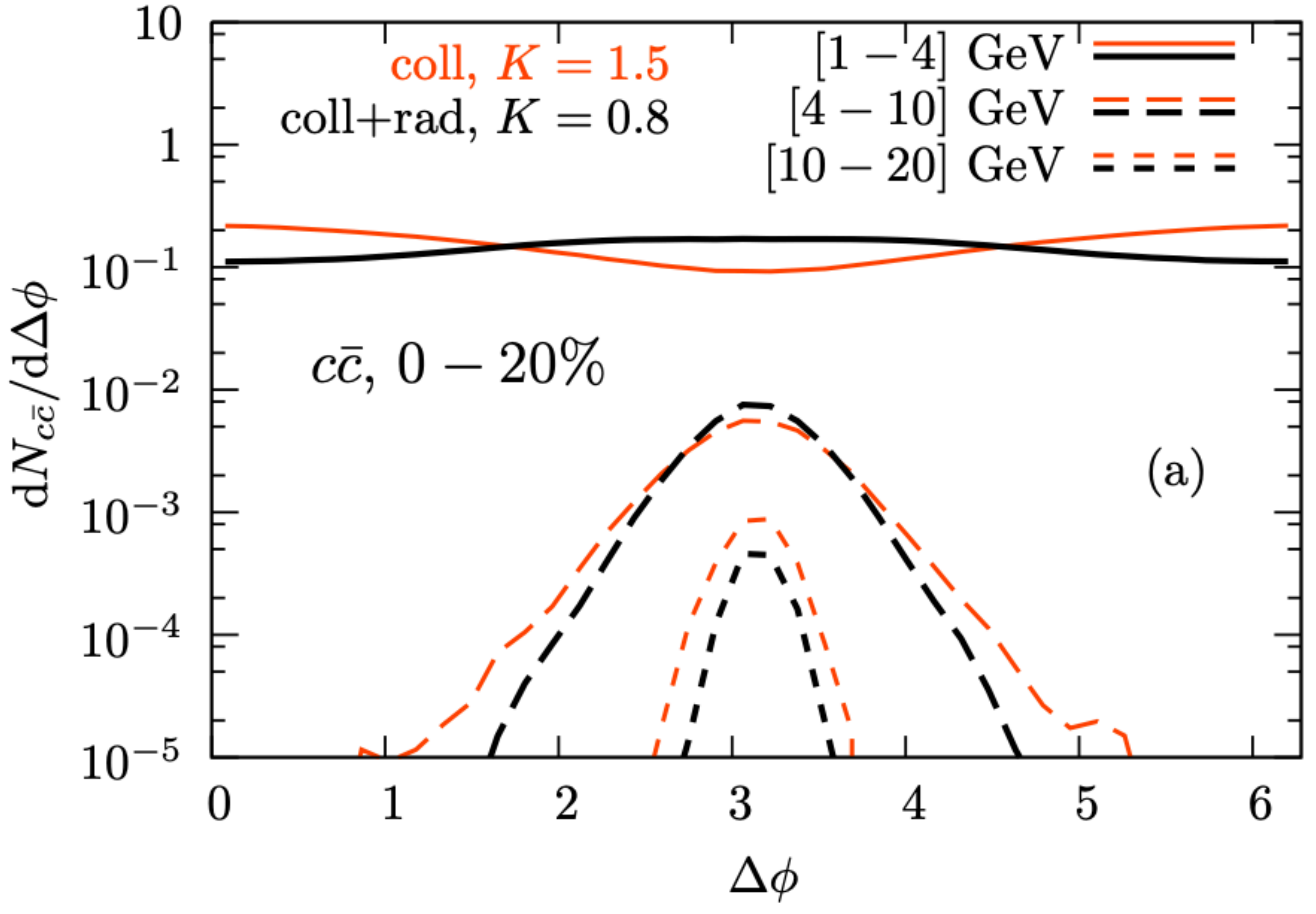
- **Heavy quarks: access to quark transport at hadron level**
  - Expect beauty thermalisation slower than charm — smaller v_2
- Need ALICE 3 performance (pointing resolution, acceptance) for precision measurement of e.g. Λ_c and Λ_b v_2

relaxation time

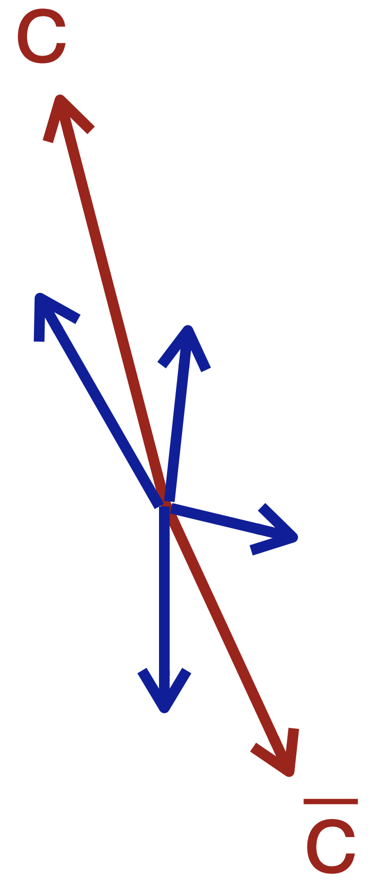
$$\tau_Q = (m_Q/T)\,D_s$$

DD̄ azimuthal correlations

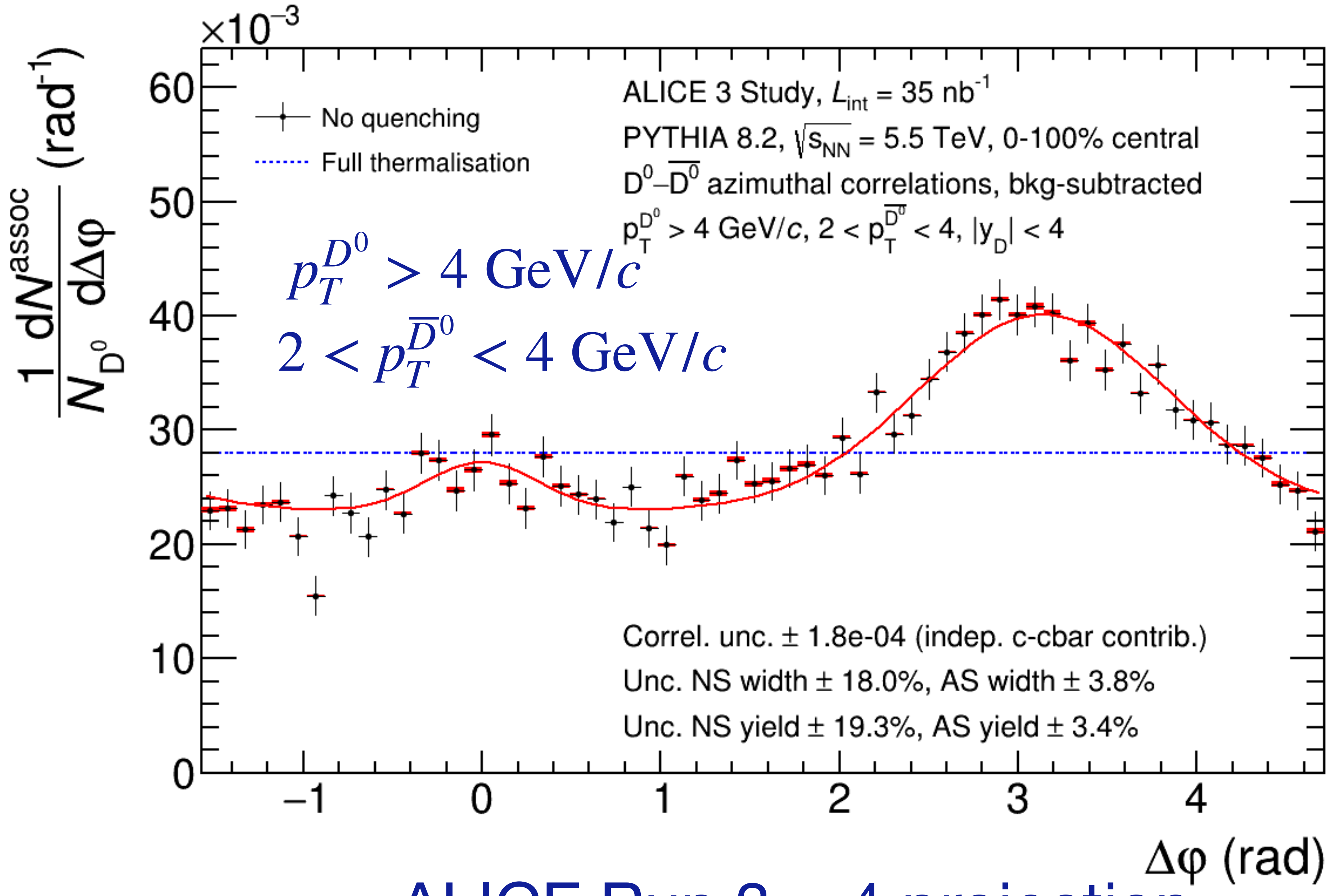
Charm azimuthal correlations



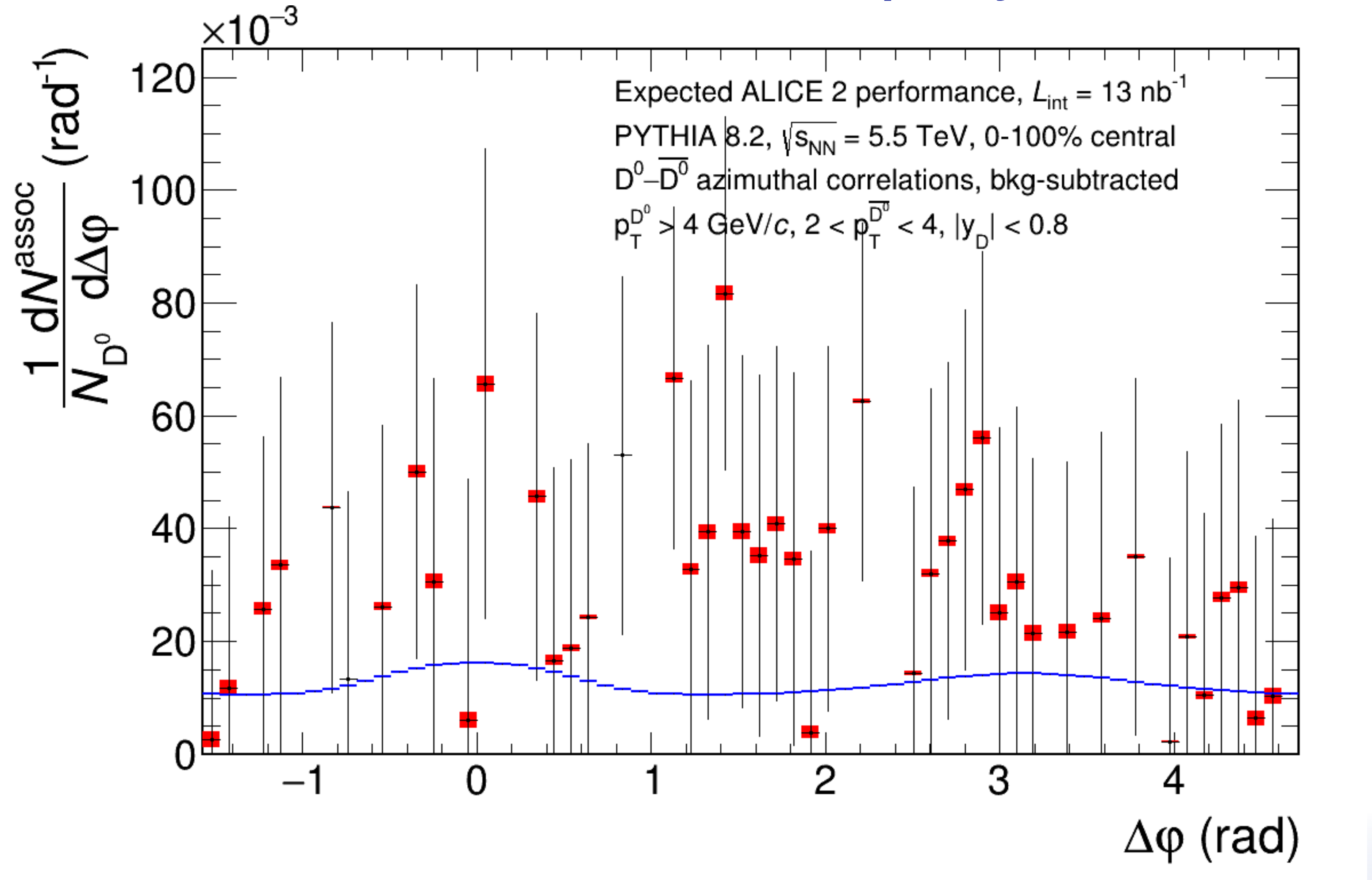
M Nahrgang et al, PRC 90, 024907



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



ALICE Run 3 + 4 projection

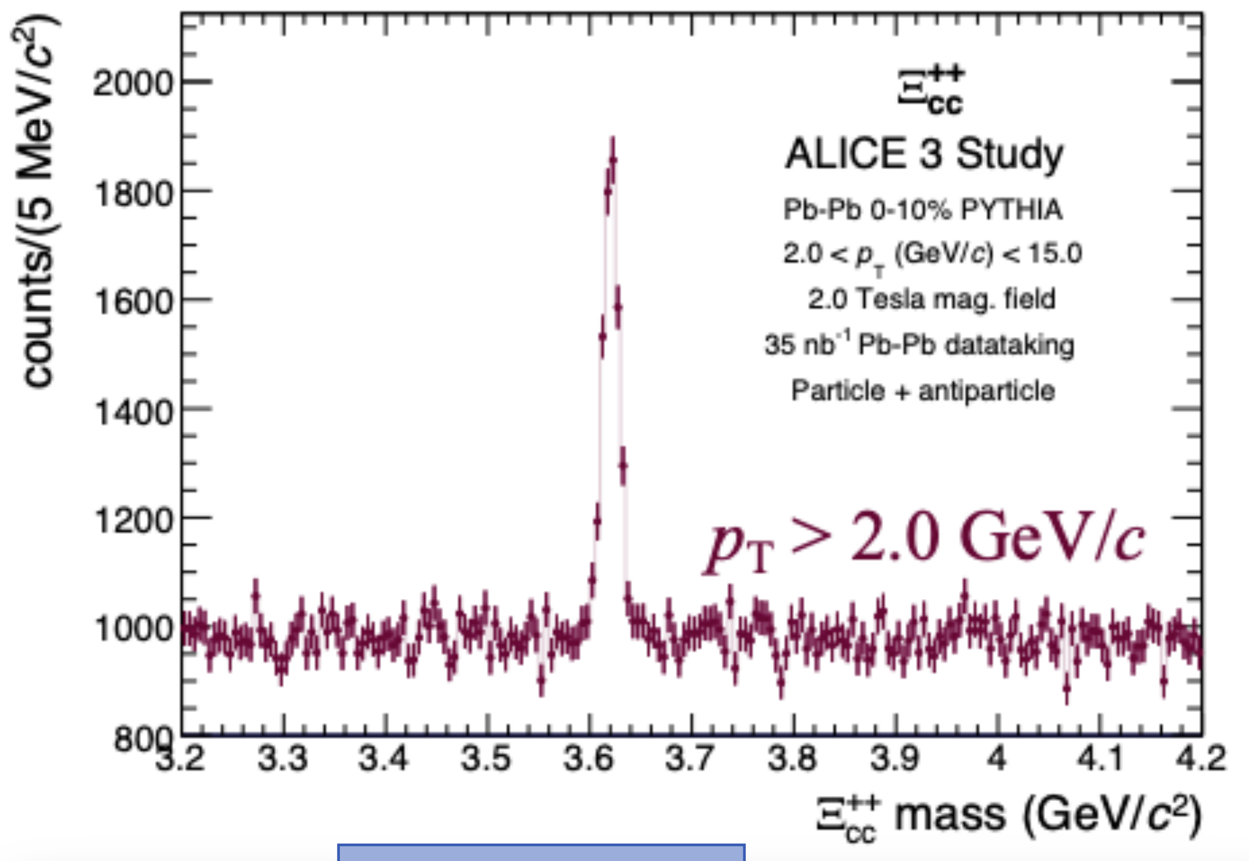


- **Angular decorrelation directly probes QGP scattering**
  - Signal strongest at low p_T
- Very challenging measurement:
  need good purity, efficiency and η coverage
  → heavy-ion measurement only possible with ALICE 3

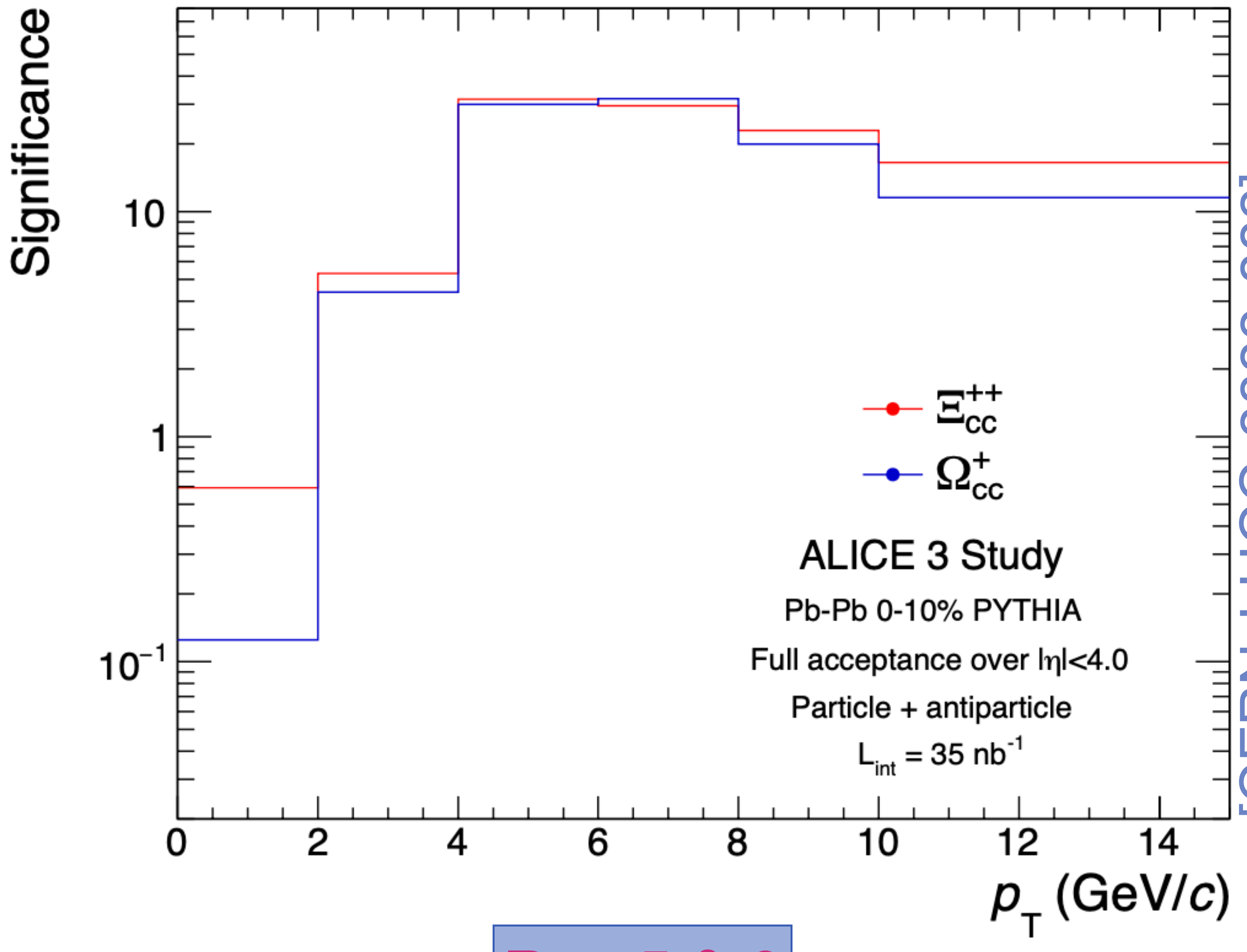
Multi-charm baryons

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

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



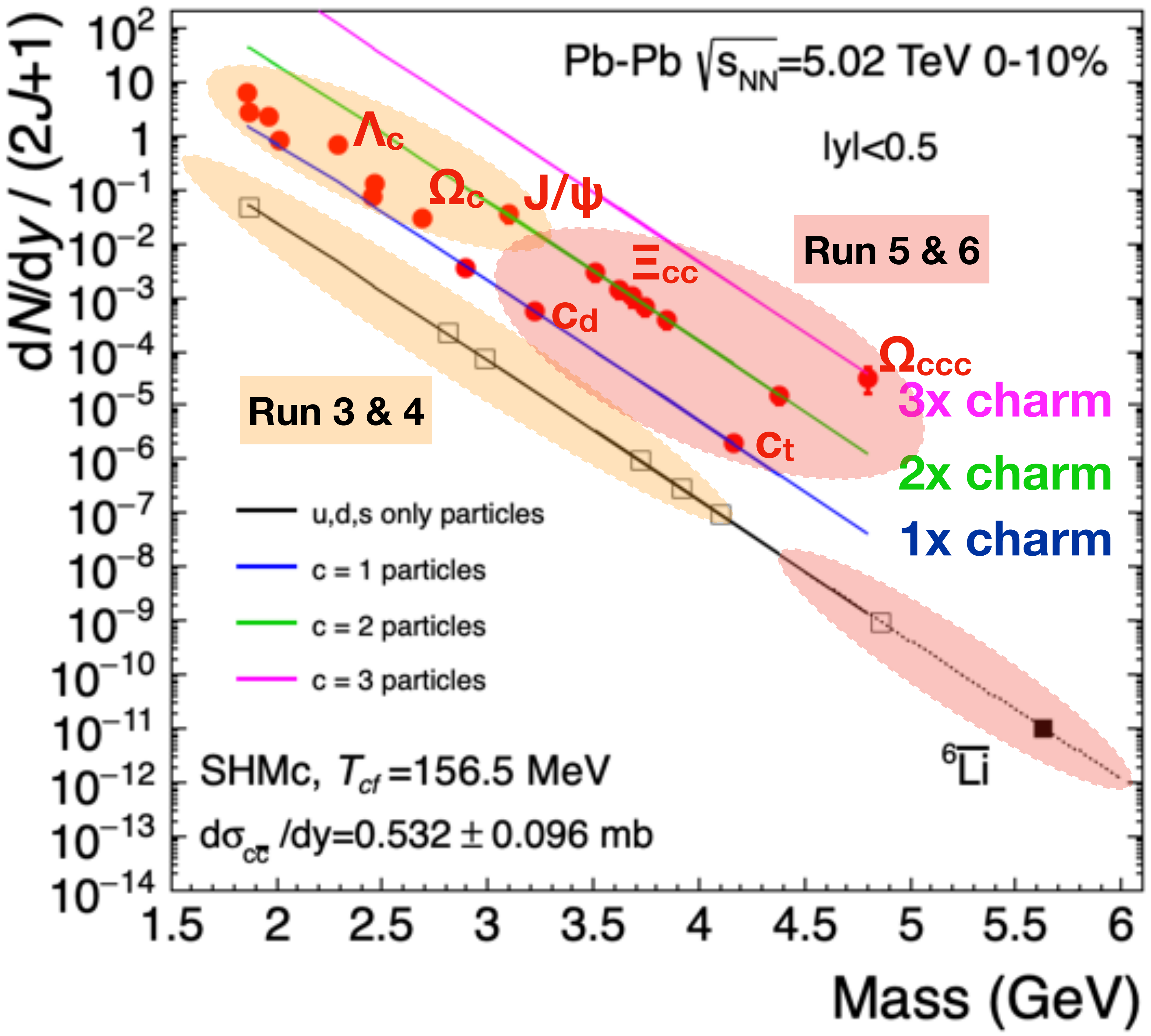
Run 5 & 6



[CERN-LHCC-2022-009]

Run 5 & 6

Hadron yields in statistical hadronisation model

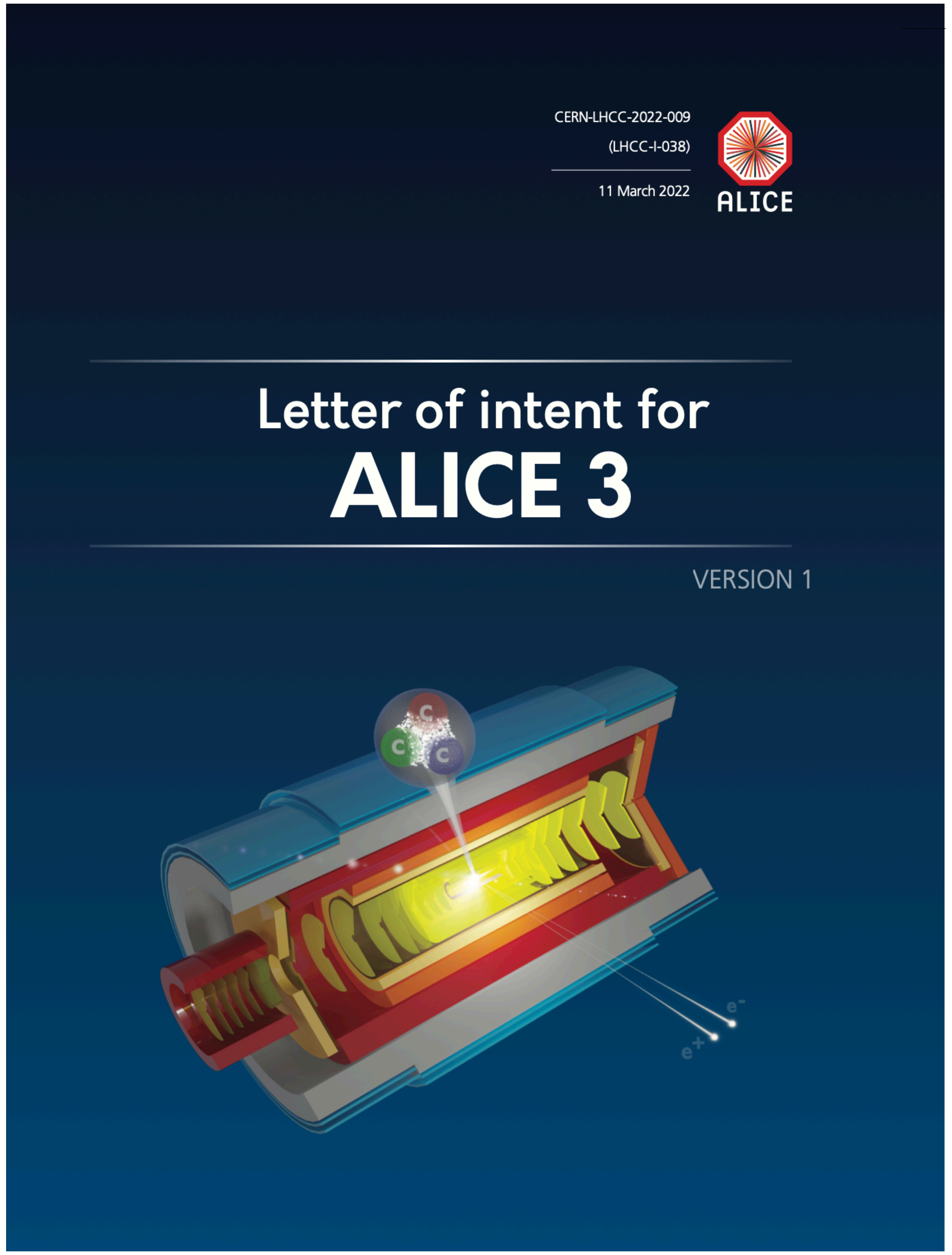


[A. Andronic et al., JHEP 07 (2021) 035]

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
  - **2028-31**: construction and testing
  - **2032**: contingency
  - **2033-34**: Preparation of cavern and installation of ALICE 3



[CERN-LHCC-2022-009]

Conclusions

- **ALICE 3 is needed** to unravel the properties of the quark-gluon plasma
  - Thermal radiation and chiral symmetry restoration
  - Hadronisation and nature of hadronic states
  - and much more …
- **Innovative detector concept**
  to meet the requirements for the ALICE 3 physics programme
  - building on experience with technologies pioneered in ALICE
  - requiring R&D activities in several strategic areas

Thank you for your attention!

Backup

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

HL-LHC

Higher luminosities for ions

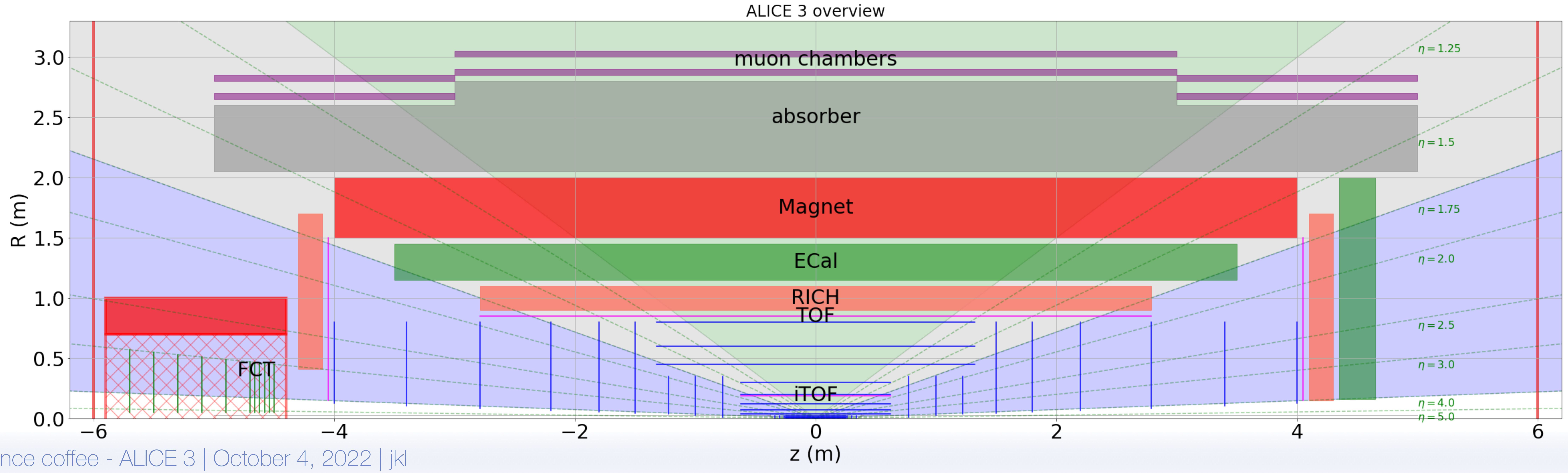
Experiment			
ATLAS	ATLAS	ATLAS phase I upgrades	ATLAS phase II upgrades
CMS	CMS	CMS phase I upgrades	CMS phase II upgrades
LHCb	LHCb	LHCb upgrade I(a)	LHCb upgrade Ib	LHCb phase IIb upgrades
ALICE	ALICE 1	ALICE 2 upgrade	ALICE 2.1 upgrade	ALICE 3 phase IIb upgrades

→ evolution of LHC and the experiments

intermediate upgrade | major upgrade

Probes and detector

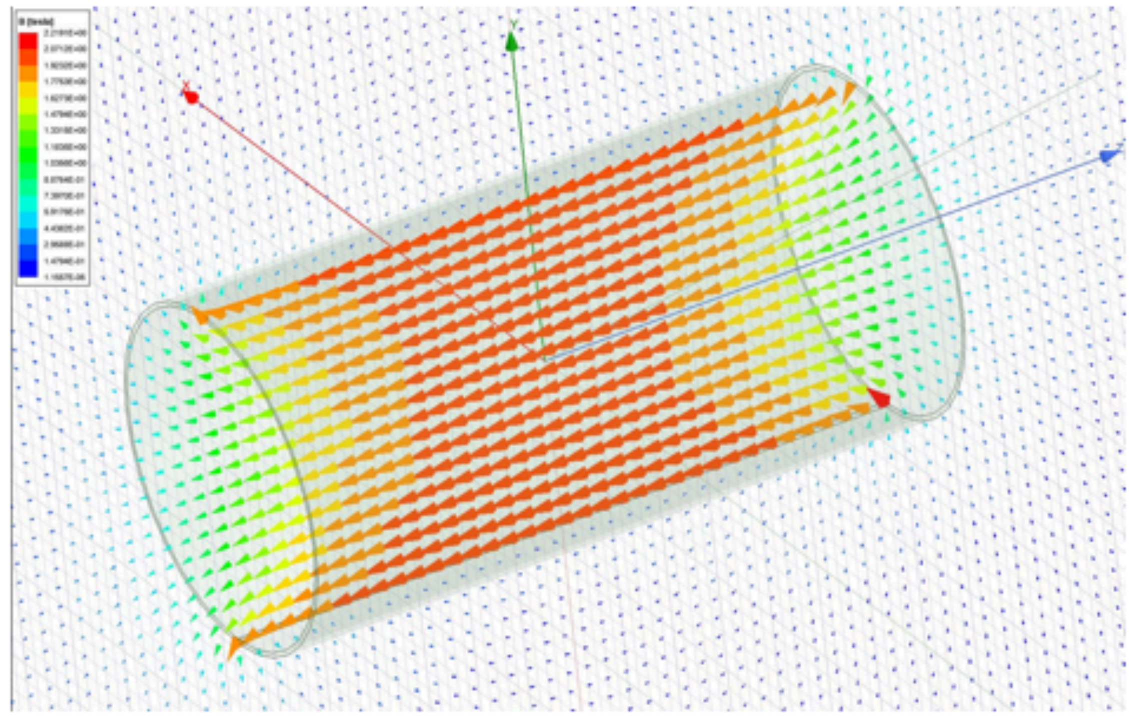
- **Heavy-flavour hadrons** ($p_T \rightarrow 0$, wide η range)
  ➟ vertexing, tracking, hadron ID
- **Dileptons** (p_T ~0.1 - 3 GeV/c, M_{ee} ~0.1 - 4 GeV/c^2)
  ➟ vertexing, tracking, lepton ID
- **Photons (100 MeV/c - 50 GeV/c, wide η range)**
  ➟ electromagnetic calorimetry
- **Quarkonia and Exotica ($p_T \rightarrow 0$)**
  ➟ 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

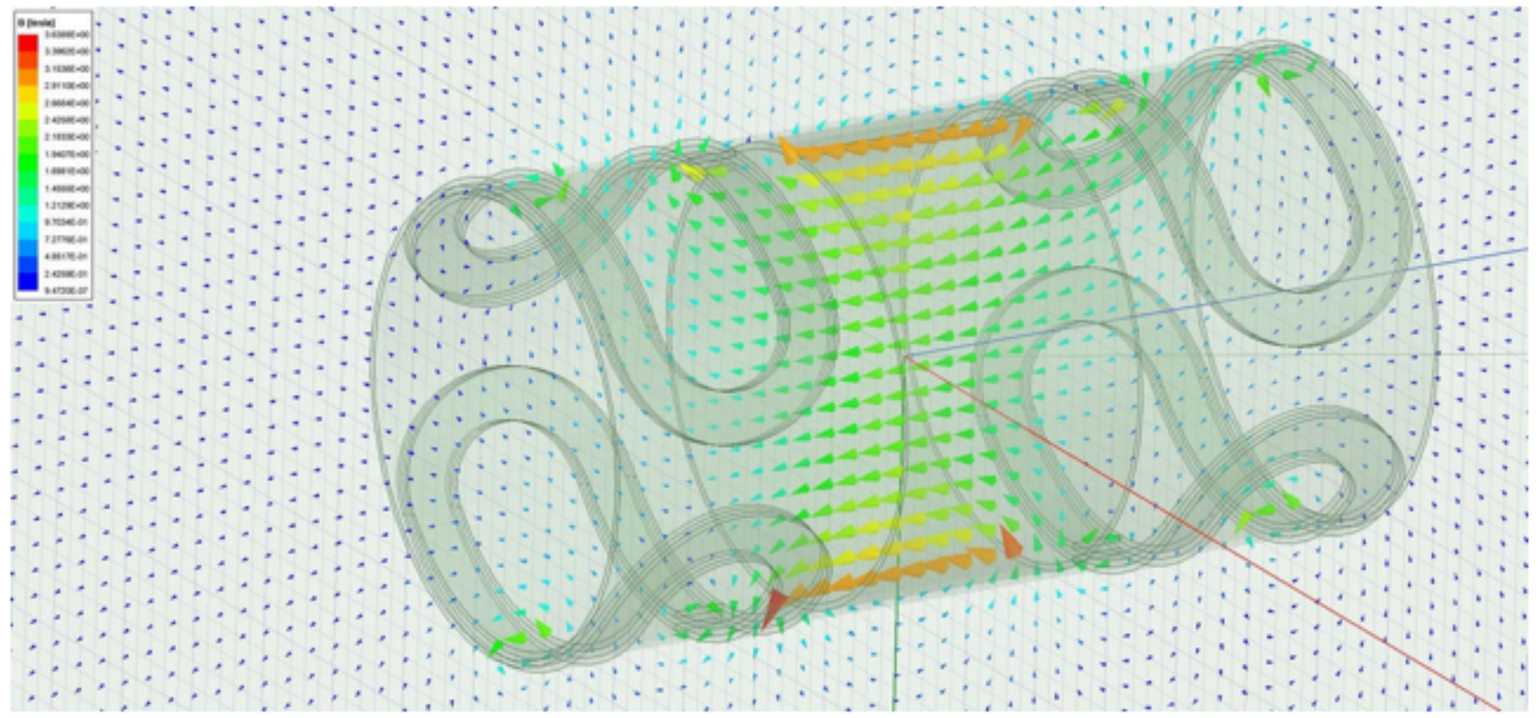


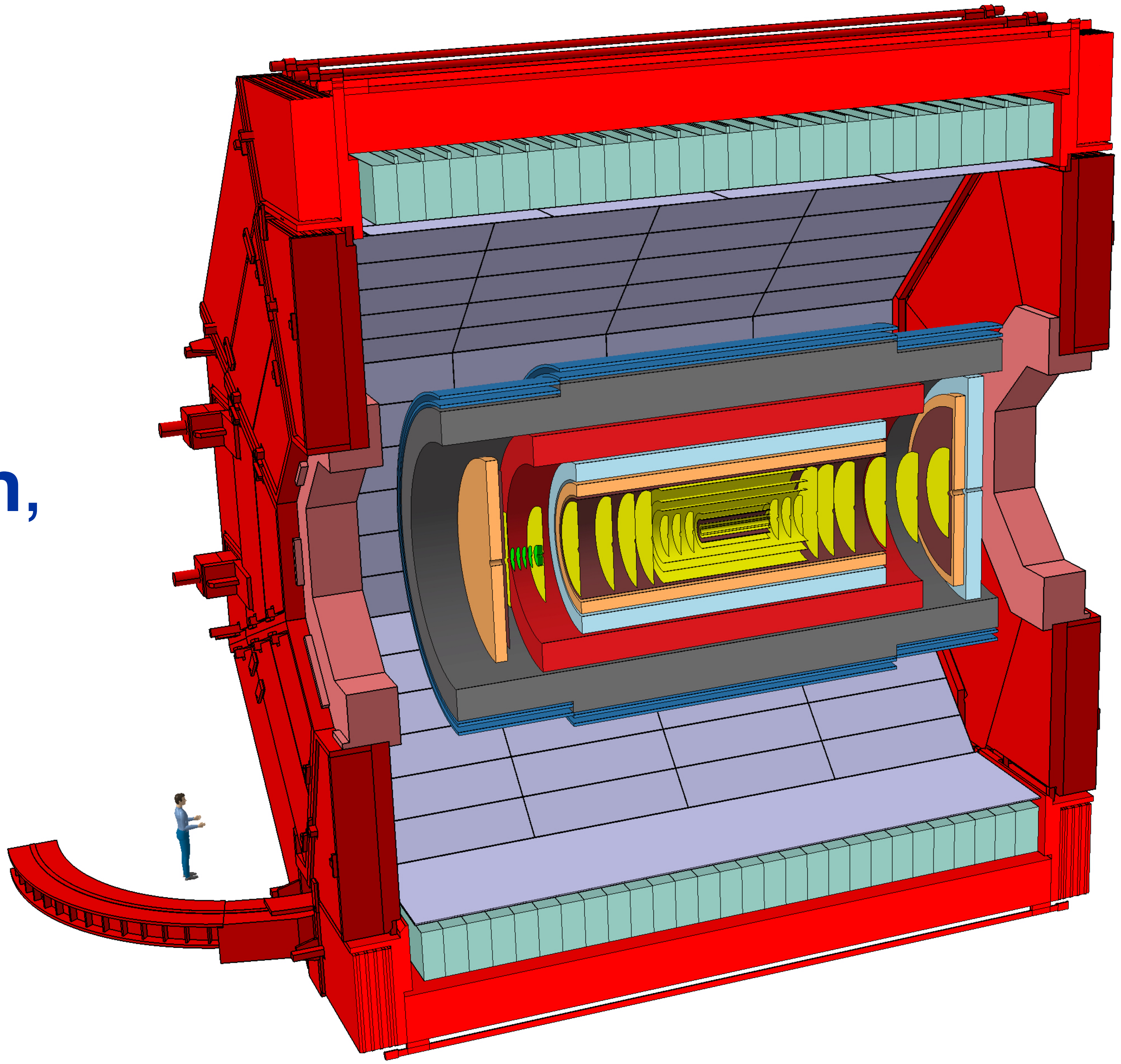
Integration

- **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

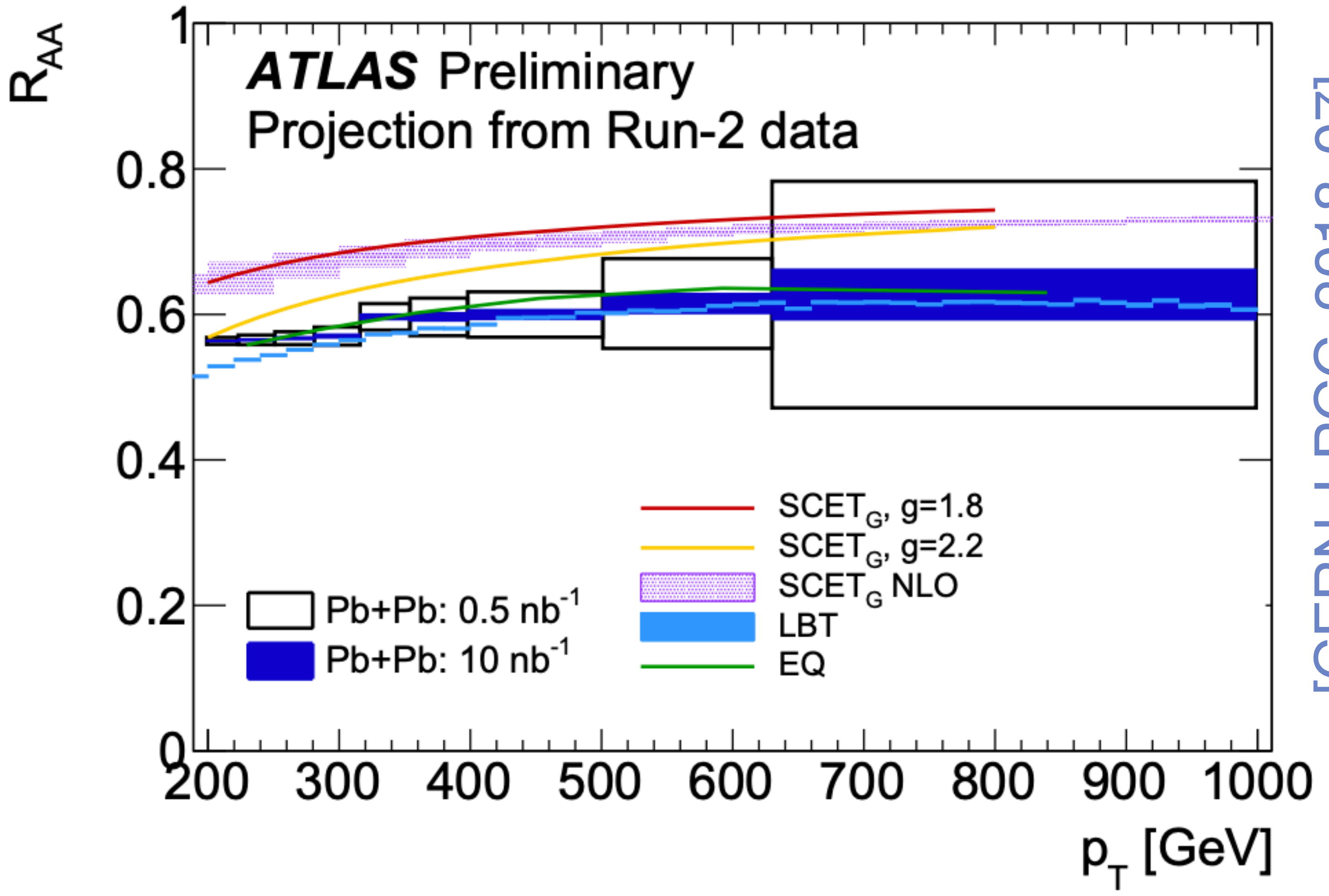
- Design to handle available heavy-ion luminosities, with current estimates hit rates similar across collision systems
- **First layer at 5 mm** → challenging hit rates and radiation load: **~1.5 10^{15} 1 MeV n_{eq} / cm^2** per operational year (comparable to first layer in ATLAS/CMS)
- Moderate hit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



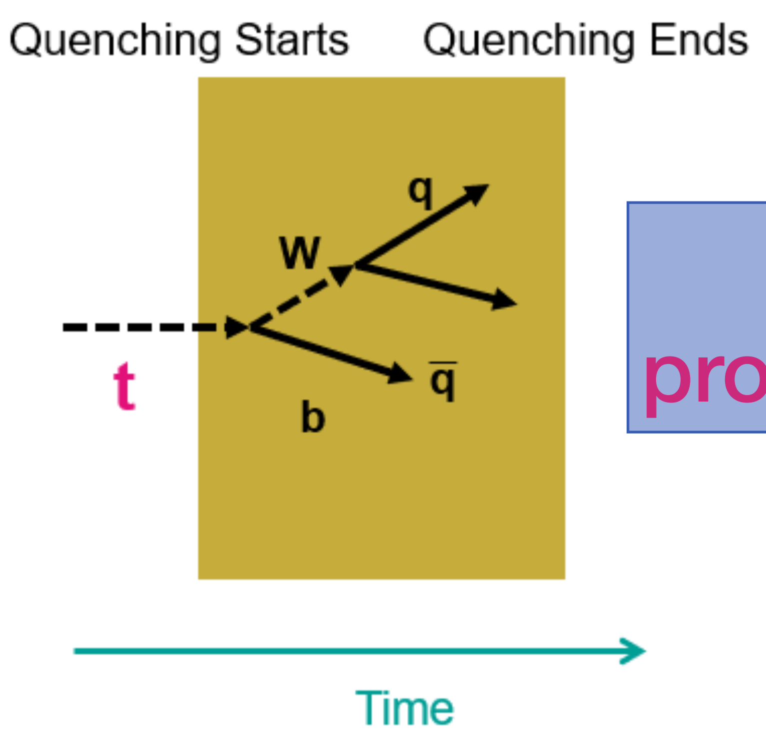
[CERN-LPCC-2018-07]

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

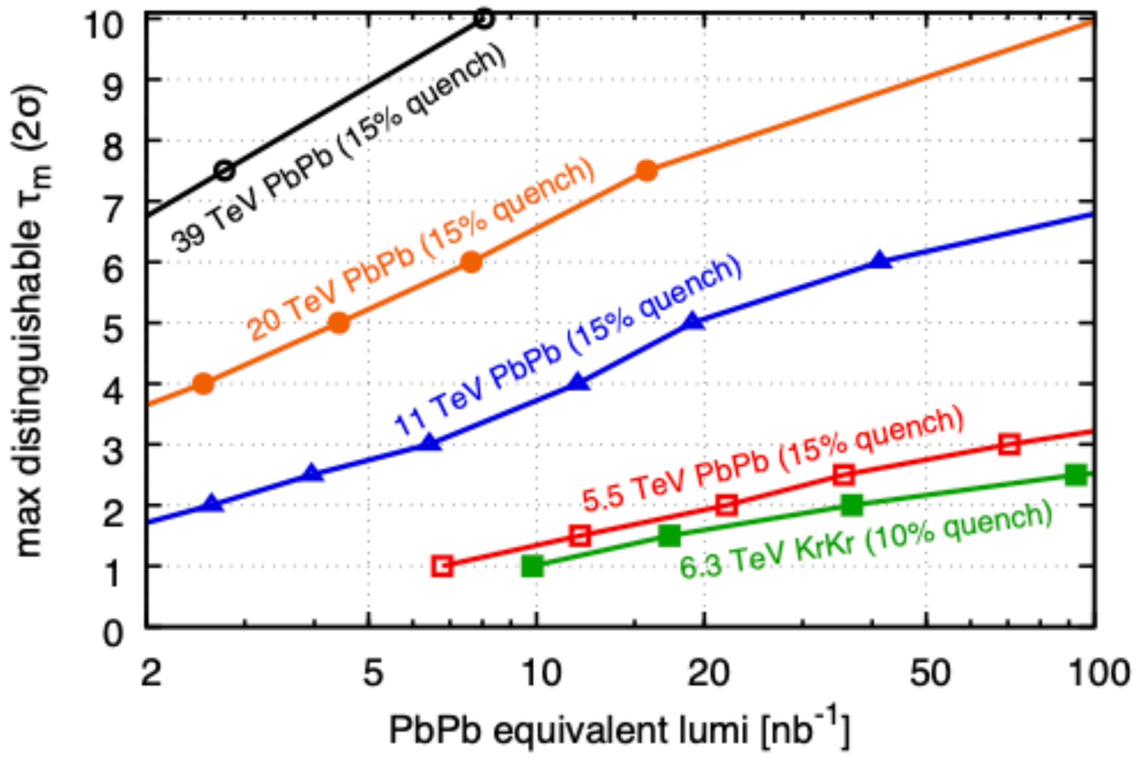
Run 3 & 4

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

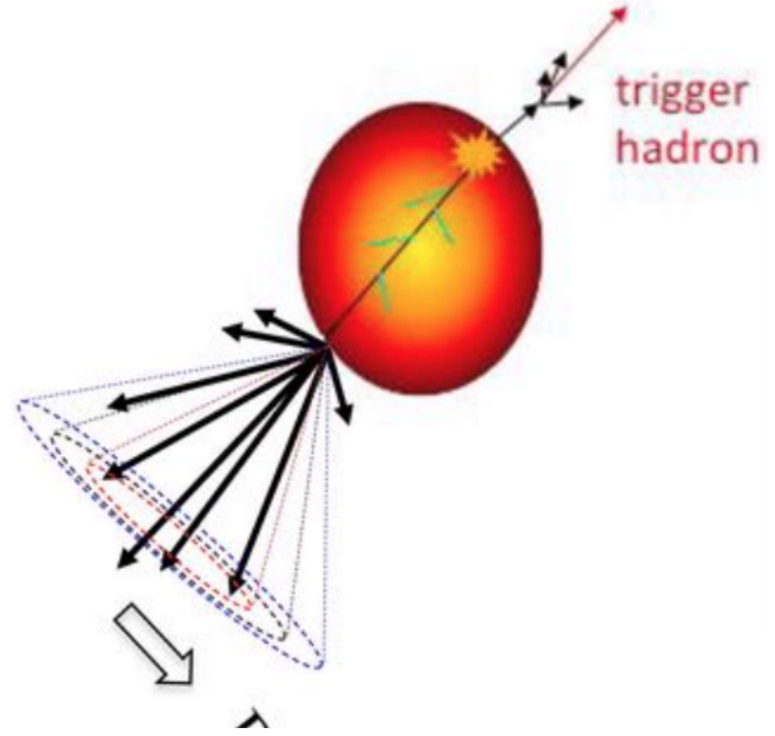
Boosted Top



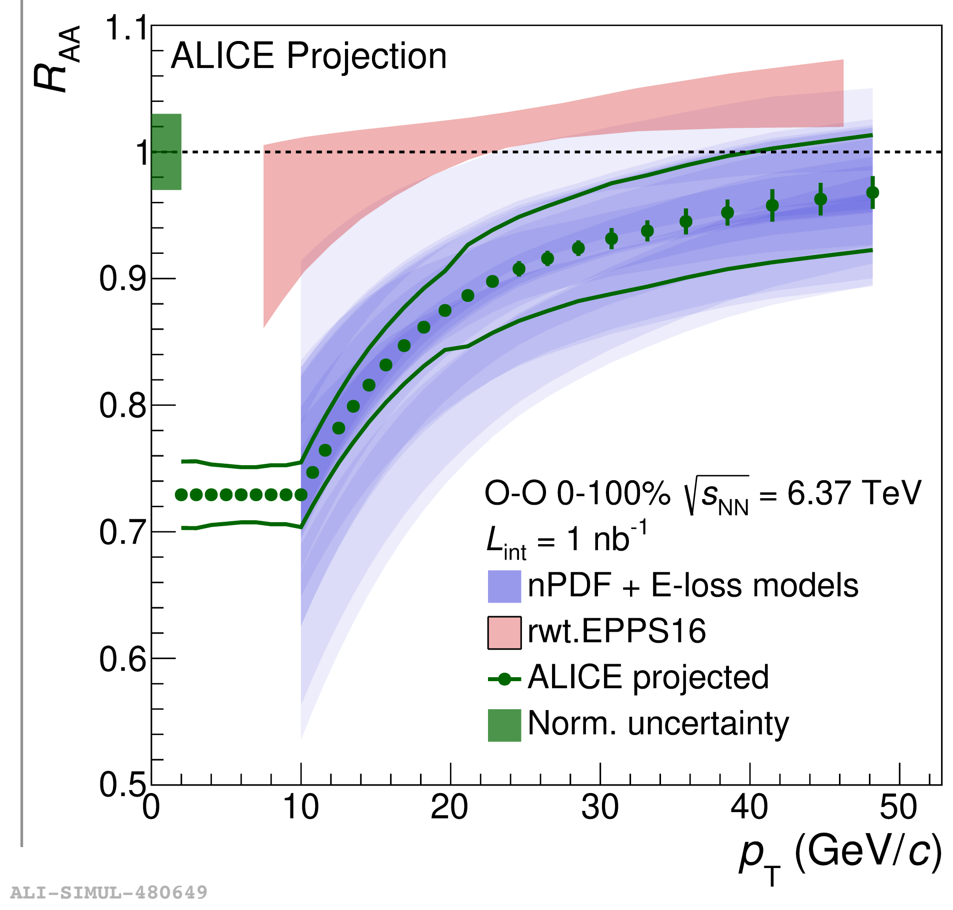
Run 3 & 4:
proof of concept



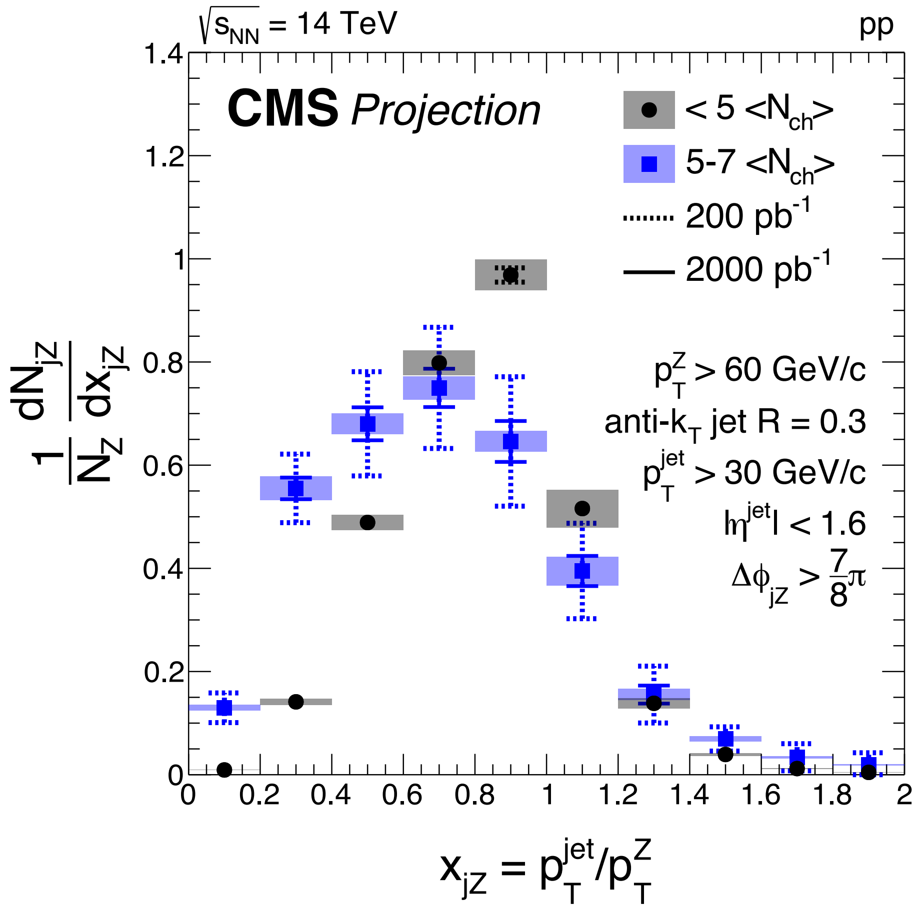
Limits on quenching in small systems



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**

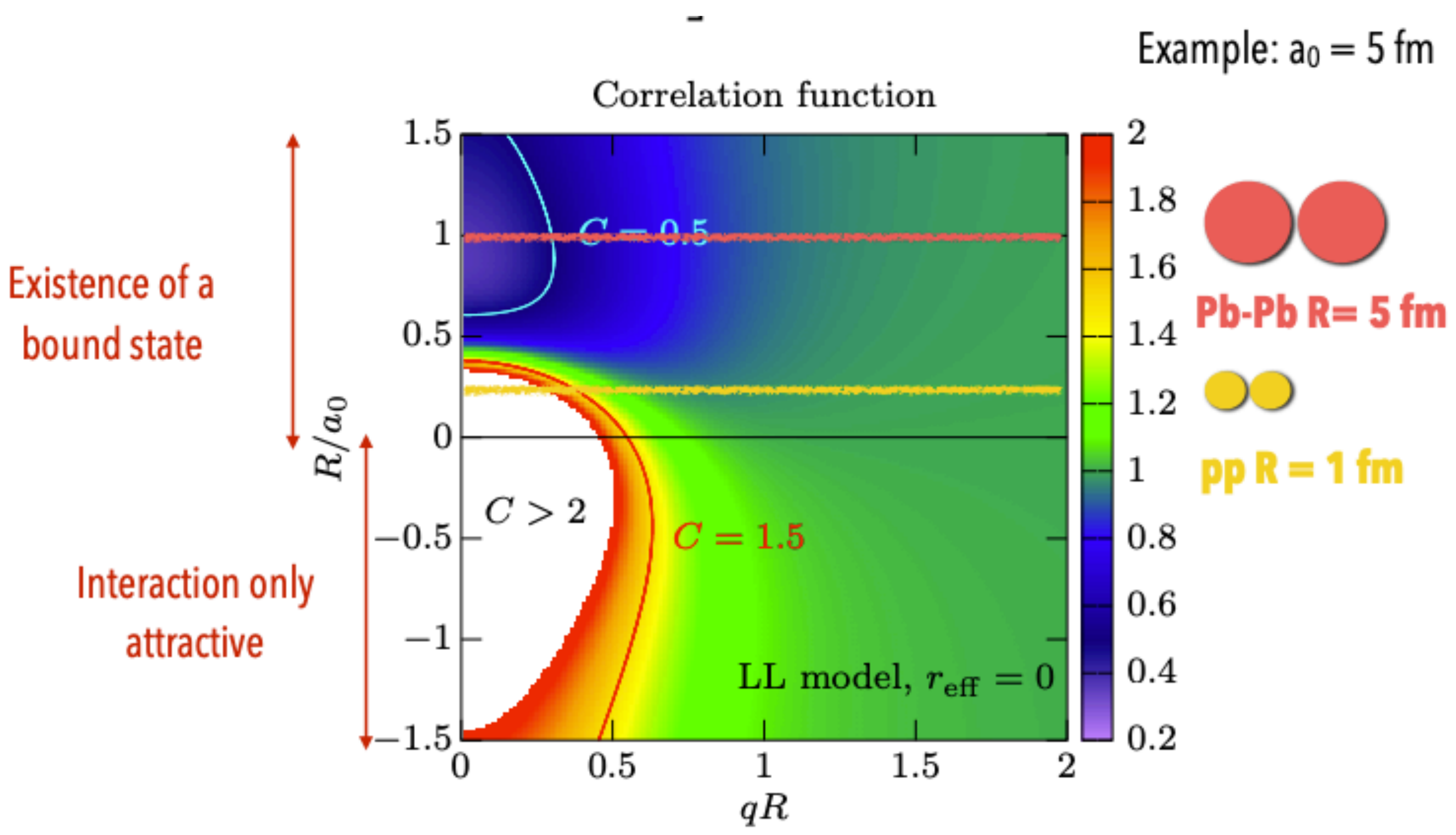


[ALICE-PUBLIC-2021-004]



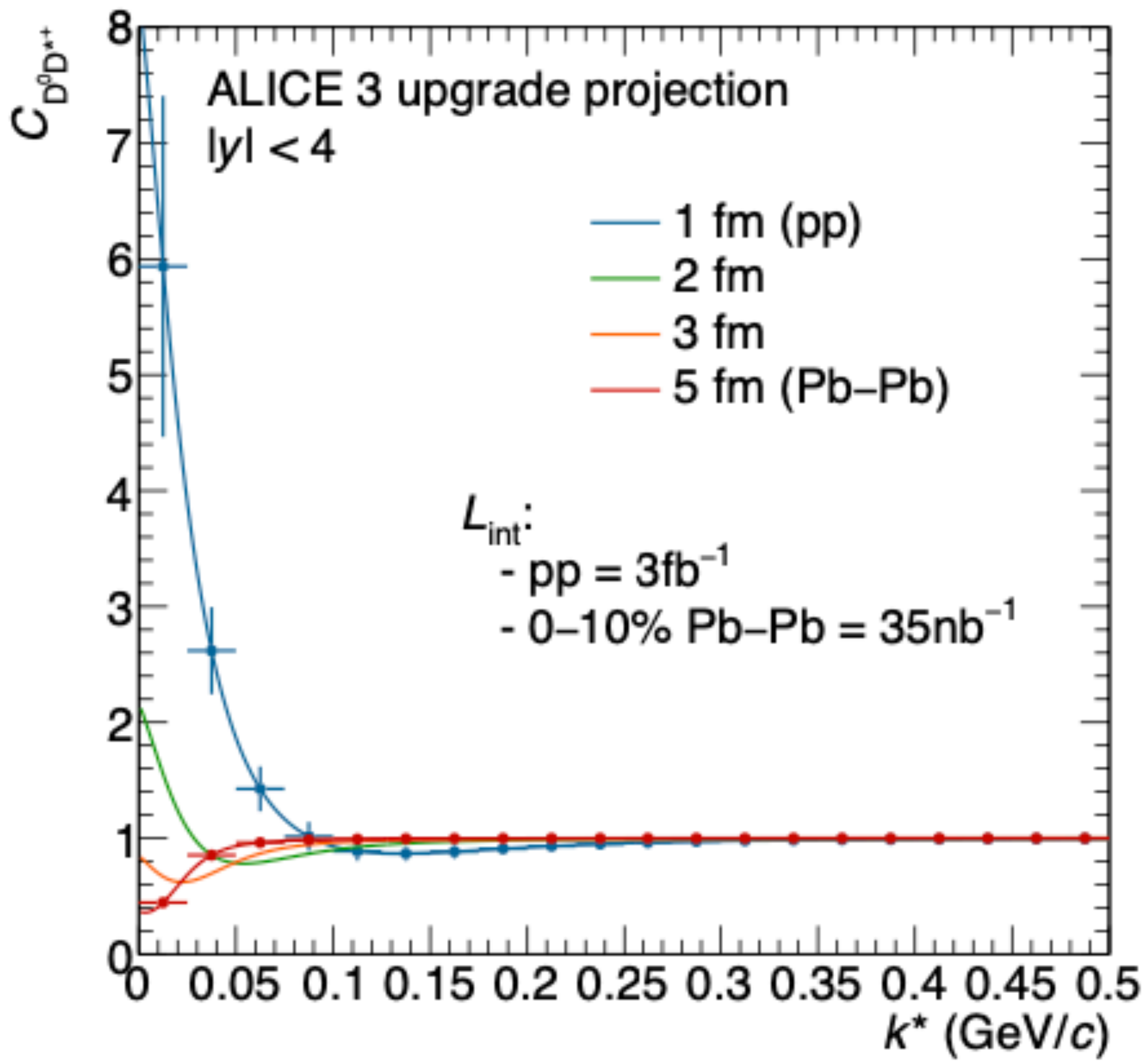
Run 3 (pp HM, OO, p-Pb)

Nature of exotic states



Y. Kamiya et al. arXiv:2108.09644v1

DD* momentum correlation



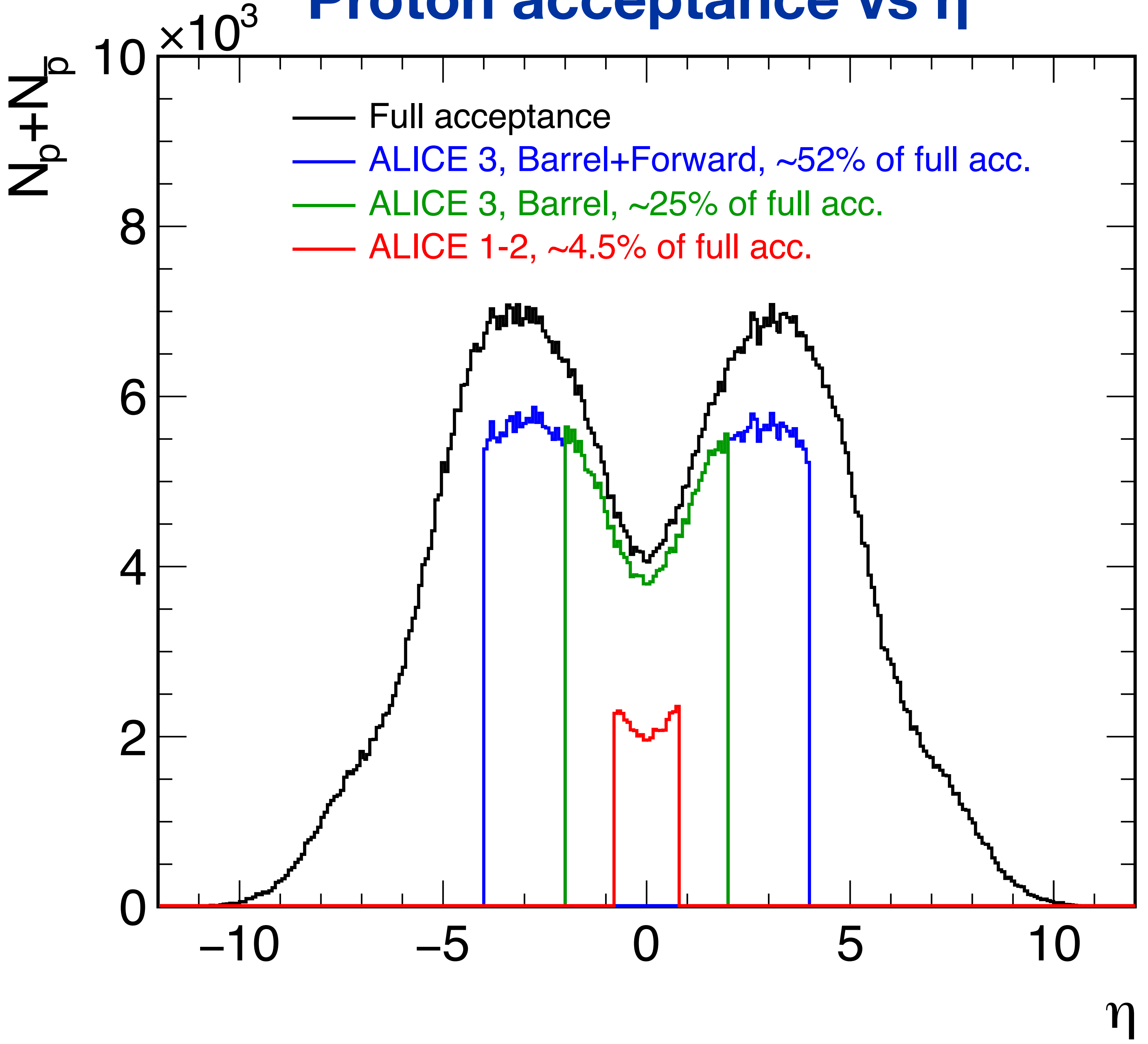
- Study interaction between hadrons trough momentum correlation
- Carries information about existence of bound states

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

Susceptibilities

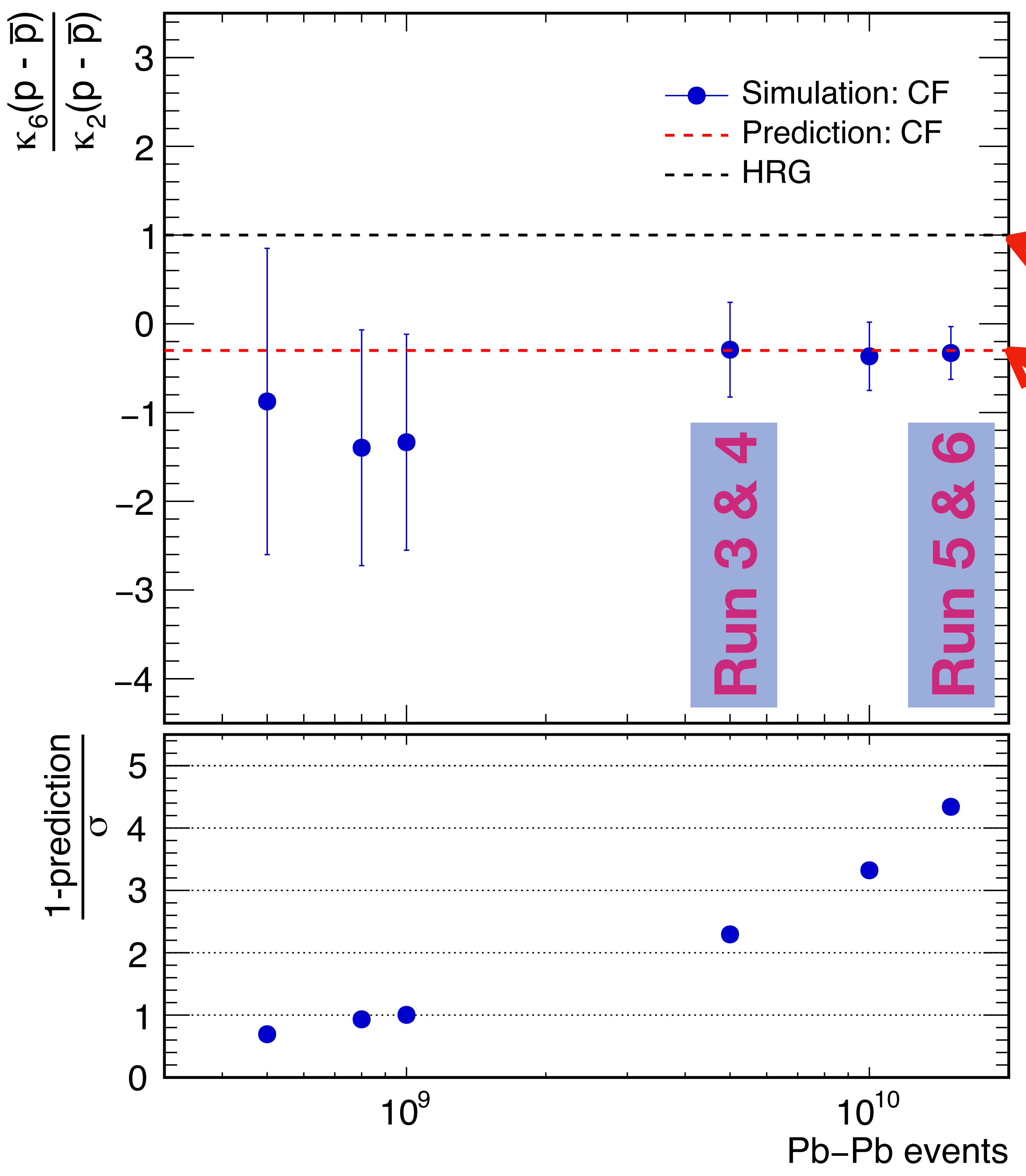
- **Comparison of critical behaviour with lattice QCD predictions**
  → measurements of net-baryon fluctuations (cumulants κ_n)
  → excellent particle identification over large acceptance

Proton acceptance vs η

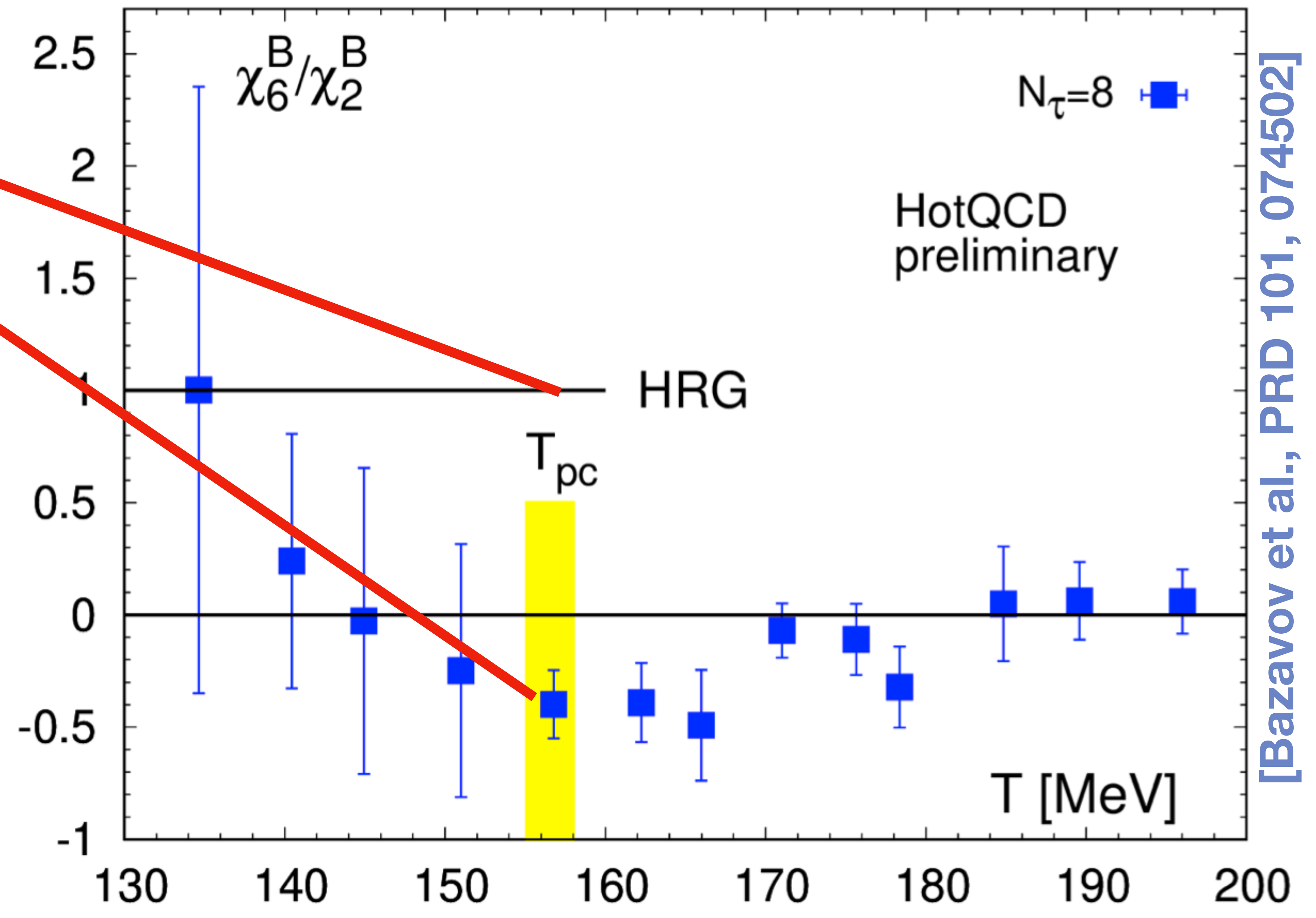


Run 3 & 4: limited Eff. x Acc.
Run 5 & 6: large Eff. x Acc.

Projection for 6th cumulant



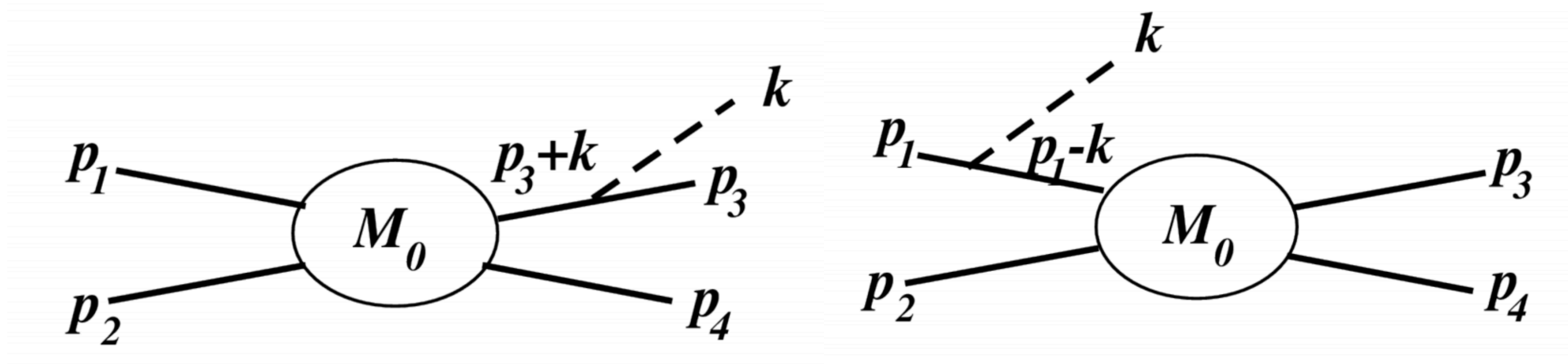
Predictions from lattice QCD



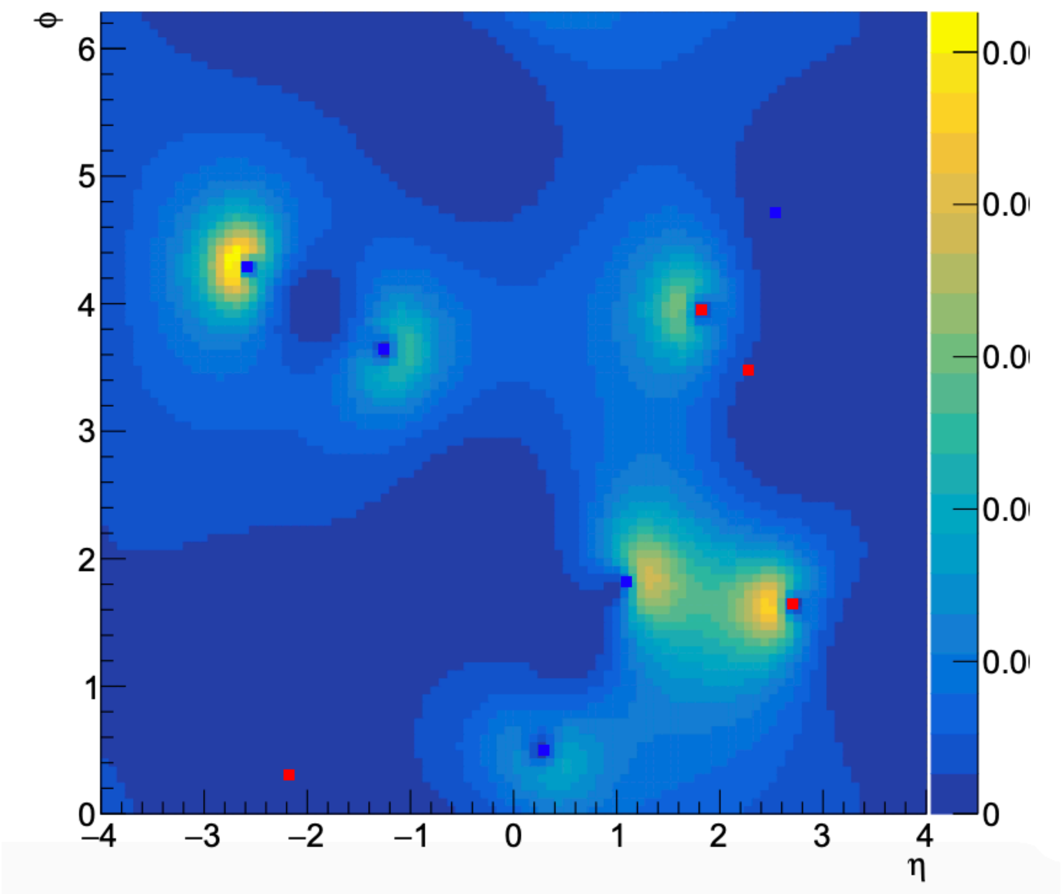
Low's theorem — soft photons

- **Low's theorem:** production of soft photons linked to charged final state (not to "blob")

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

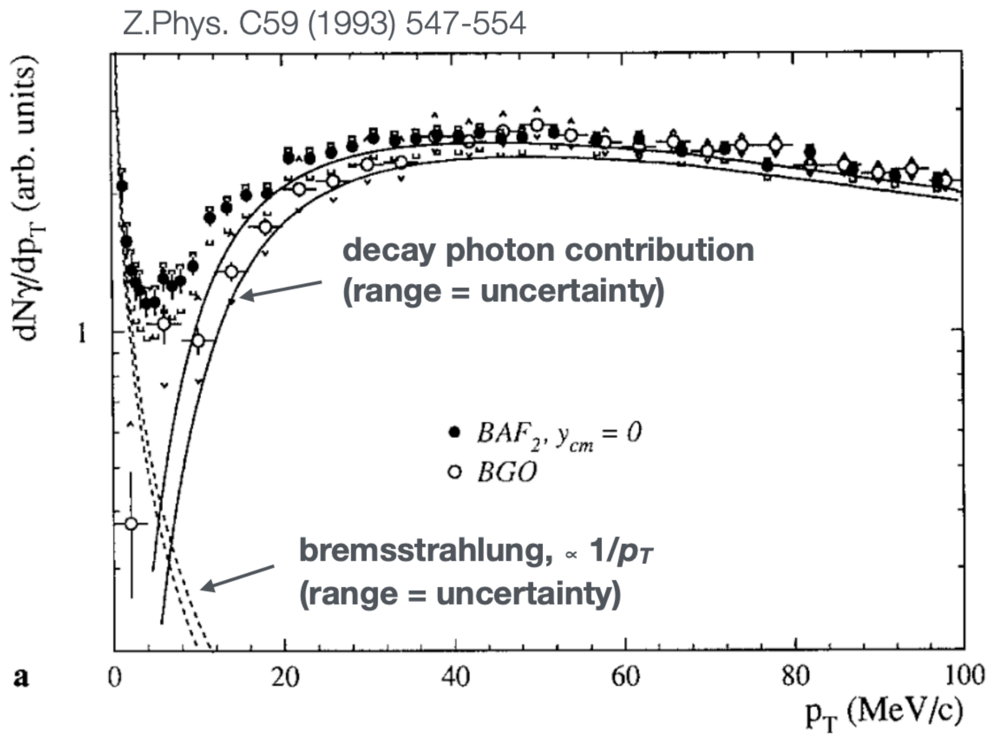


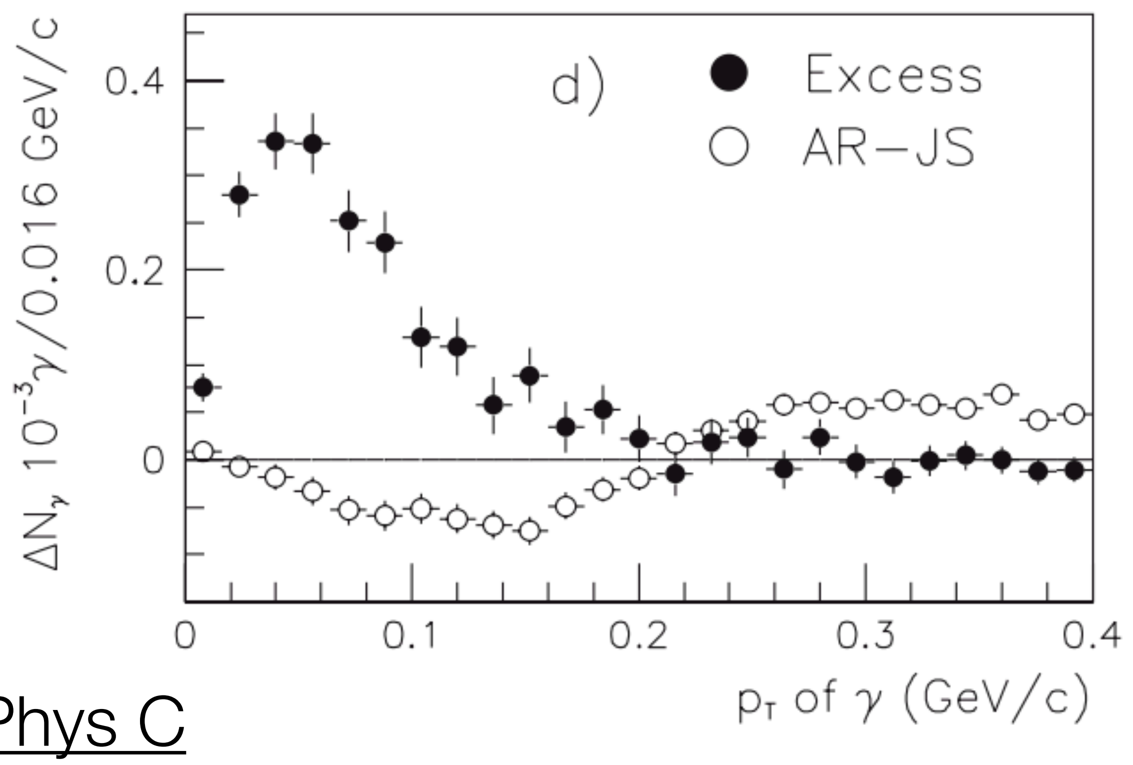
Single event photon emission



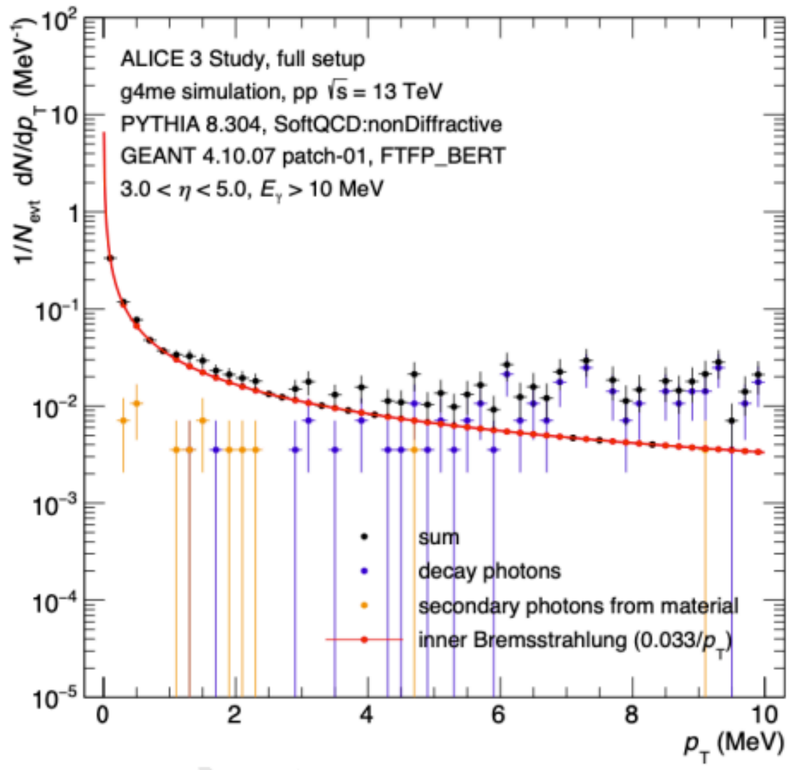
- Observational question: **Photon excess in association with hadrons** seen in previous experiments (not in $e^+e^- \to \mu^+\mu^-$)

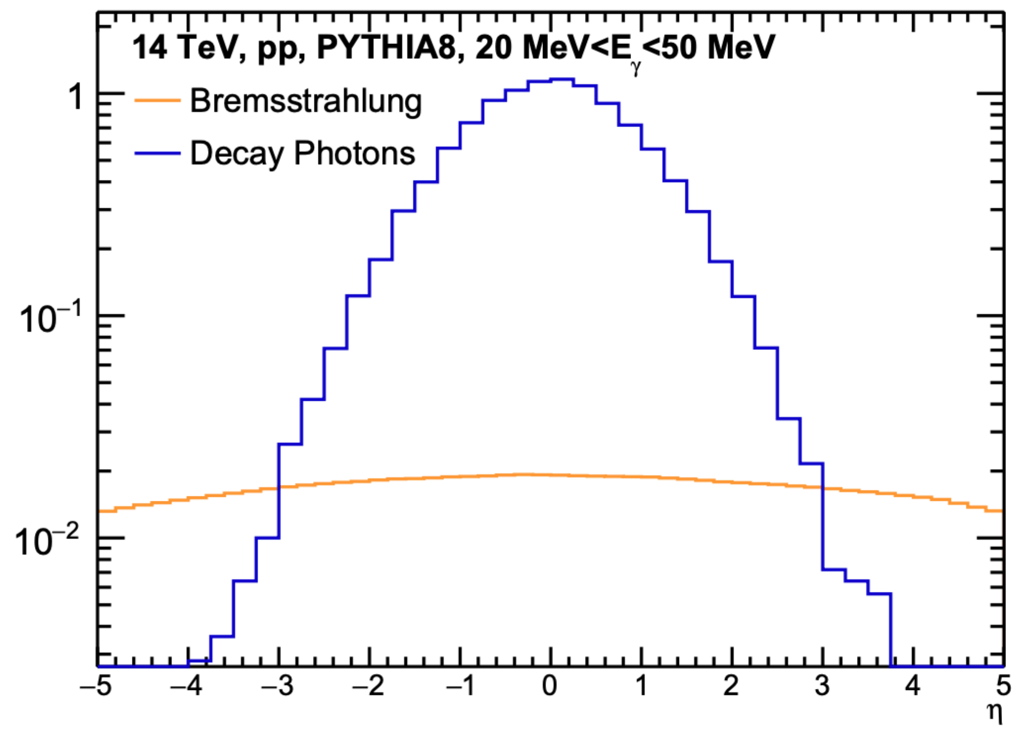
Rapidity distribution signal and decay





DELPHI, Z Phys C





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

S/B best at large rapidity, very low p_T