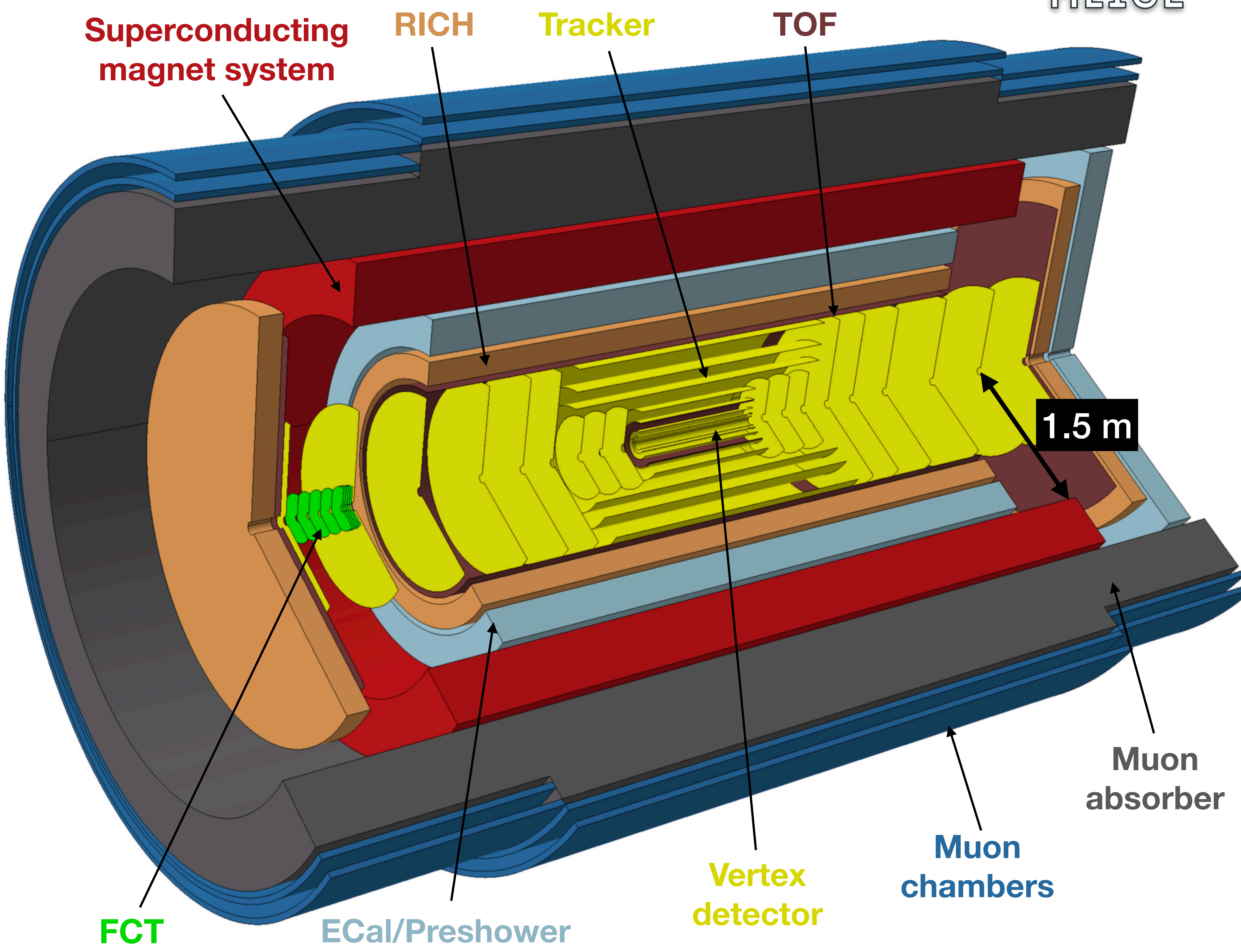
ALICE 3

physics motivation and detector concept



Terzo Incontro di
Fisica con Ioni Pesanti
alle Alte Energie

November 25 - 26, 2021

Jochen Klein (CERN)
for the ALICE Collaboration

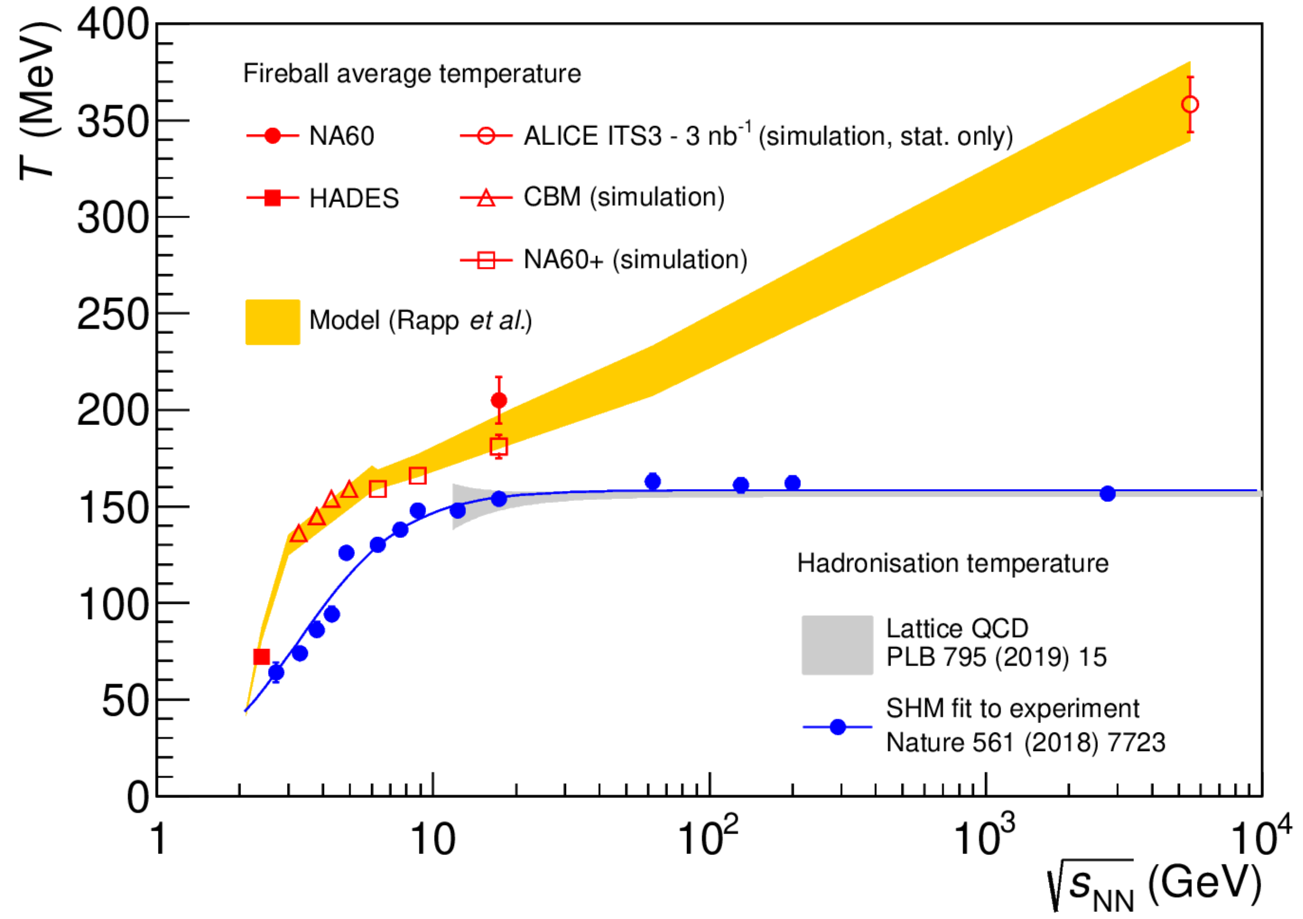
Context

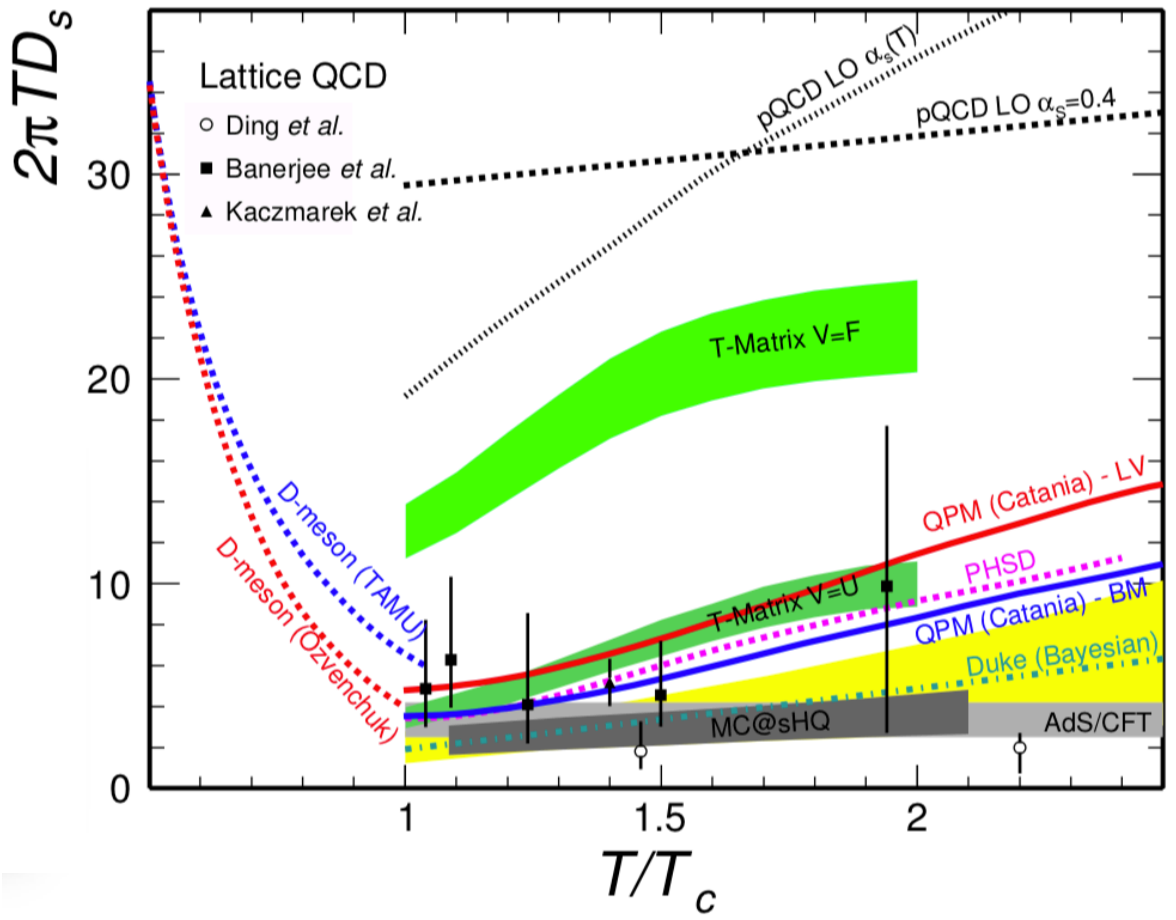
- Idea for **next-generation heavy-ion programme** for Run 5 and 6 at the LHC developed within ALICE in the course of 2018/19
  - Discussed at the **heavy-ion town meeting** (CERN, October 2018)
  - Expression of Interest submitted as input to the **European Strategy for Particle Physics Update** (Granada, 2019)
- Further development of detector concept and physics studies within ALICE
  - **ALICE 3 workshops** in October 2020, June 2021, October 2021
- **Letter of Intent** prepared over the course of 2021
  - **LHCC review** started in October 2021

Initiative supported by **EPPSU**

ALICE 3 physics

- **Early stages**: temperature of QGP before hadronisation
  - Dilepton and photon production, elliptic flow
  - Electric conductivity of the QGP
- **Chiral symmetry** restoration: $\rho - a_1$ mixing
- **Heavy flavour diffusion and thermalisation in the QGP**
  - Beauty and charm flow
  - Charm hadron correlations
- **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
- Ultra-soft photons: experimental test of Low's theorem
- BSM searches: ALPs, dark photons





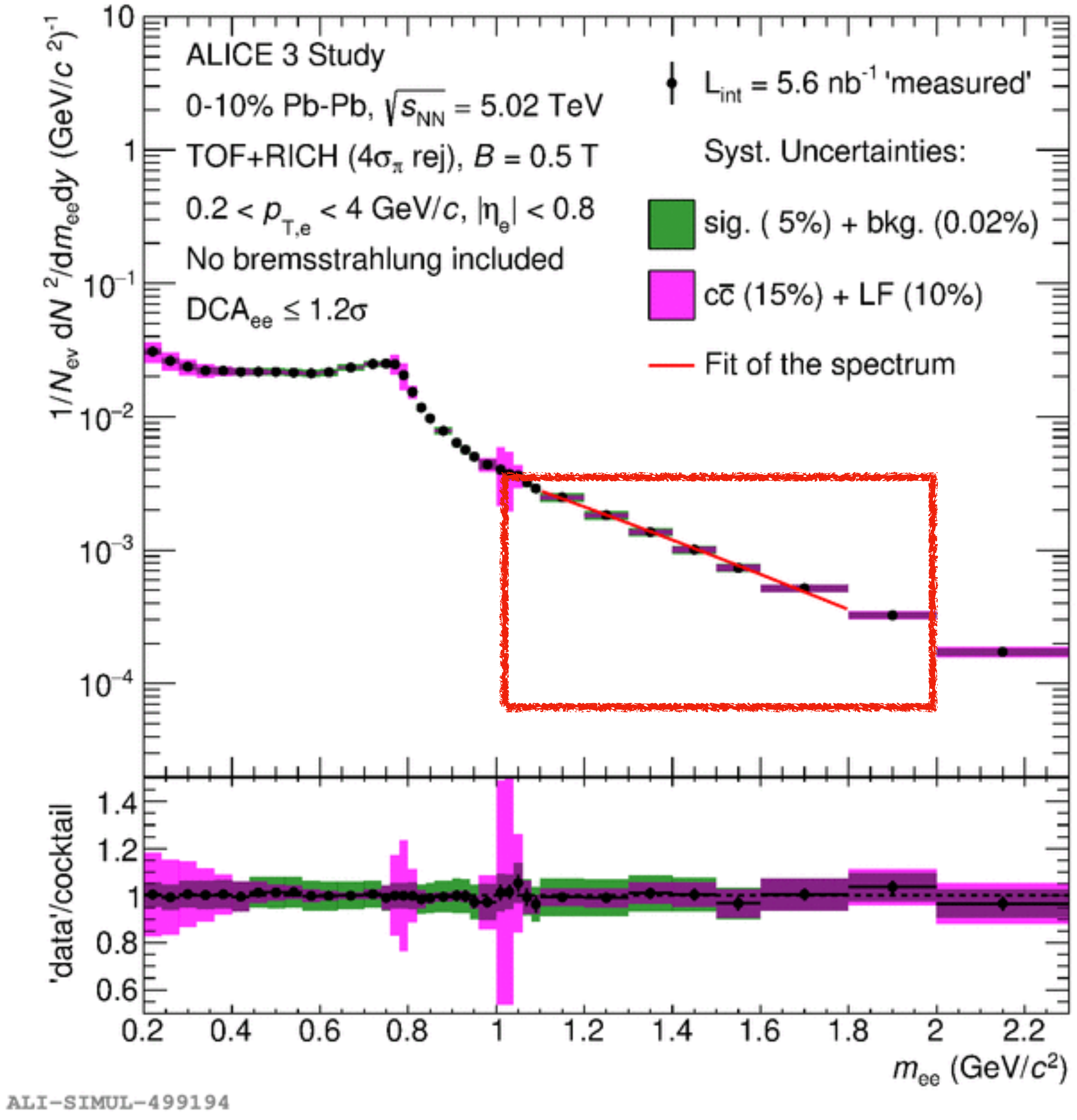
Ds: heavy quark diffusion coefficient

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

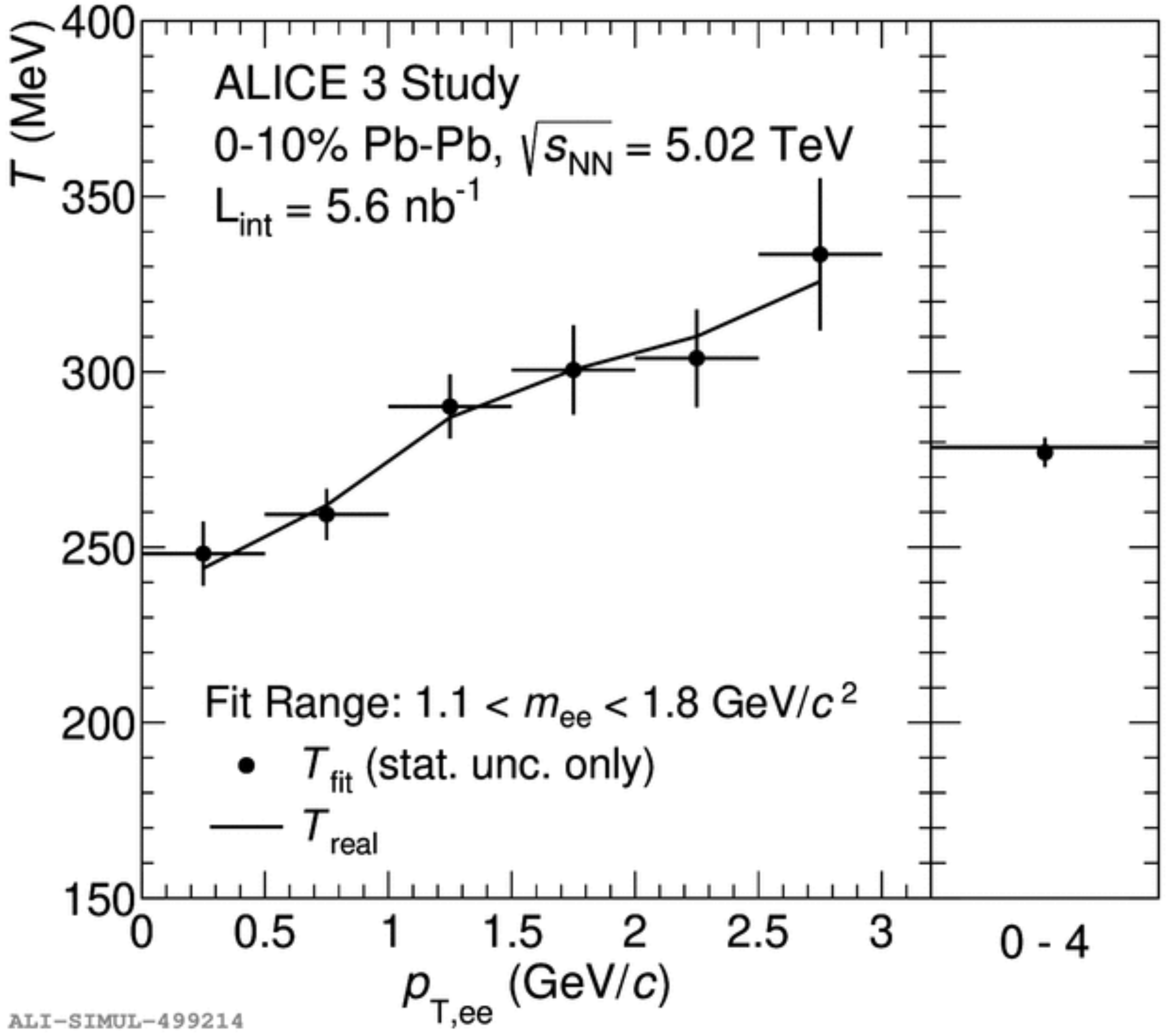
$$\tau_Q = (m_Q/T)\, D_s$$

QGP temperature

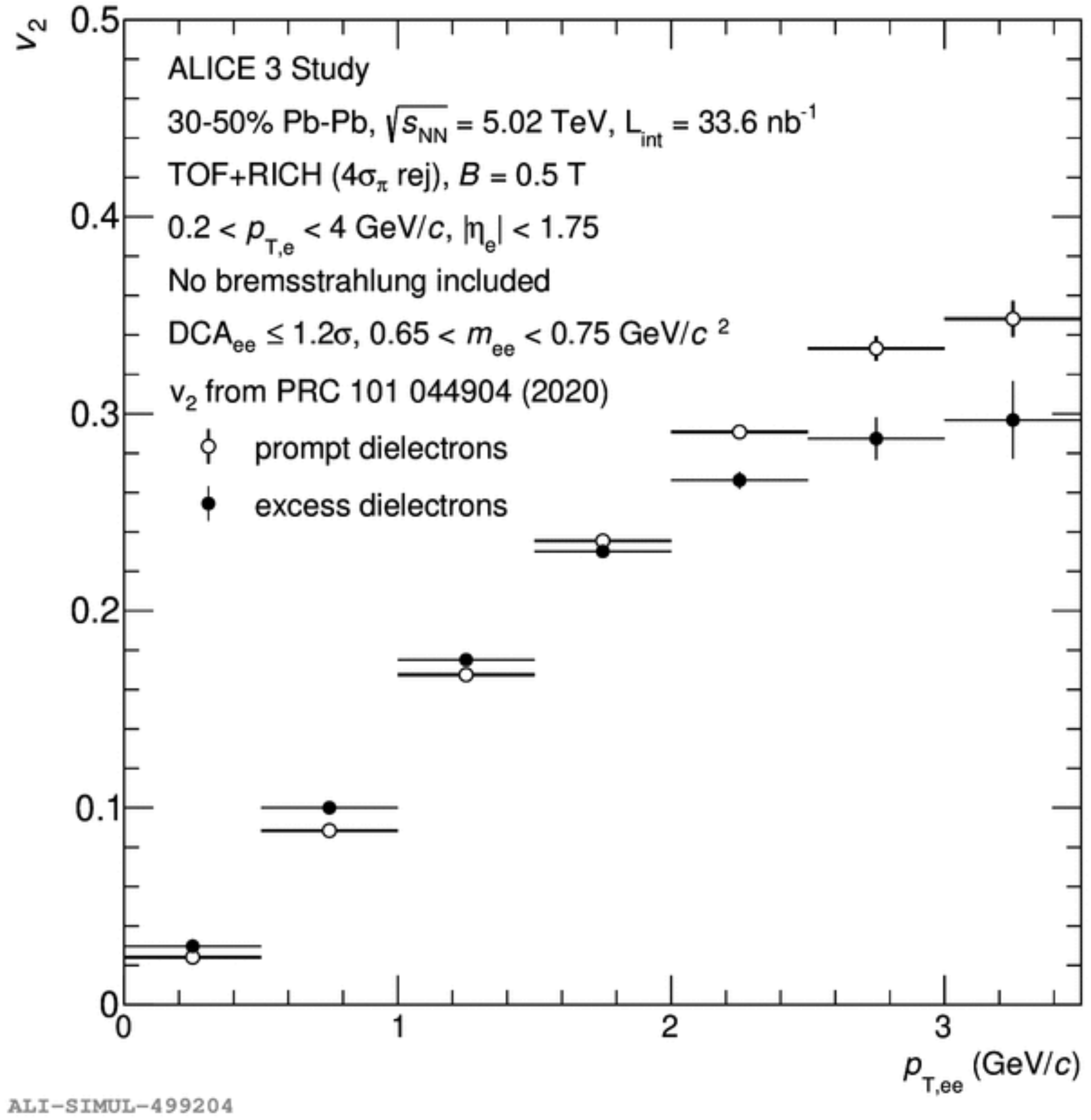
Di-lepton mass distribution



Temperature from slope (M_{ee})



Dielectron v_2

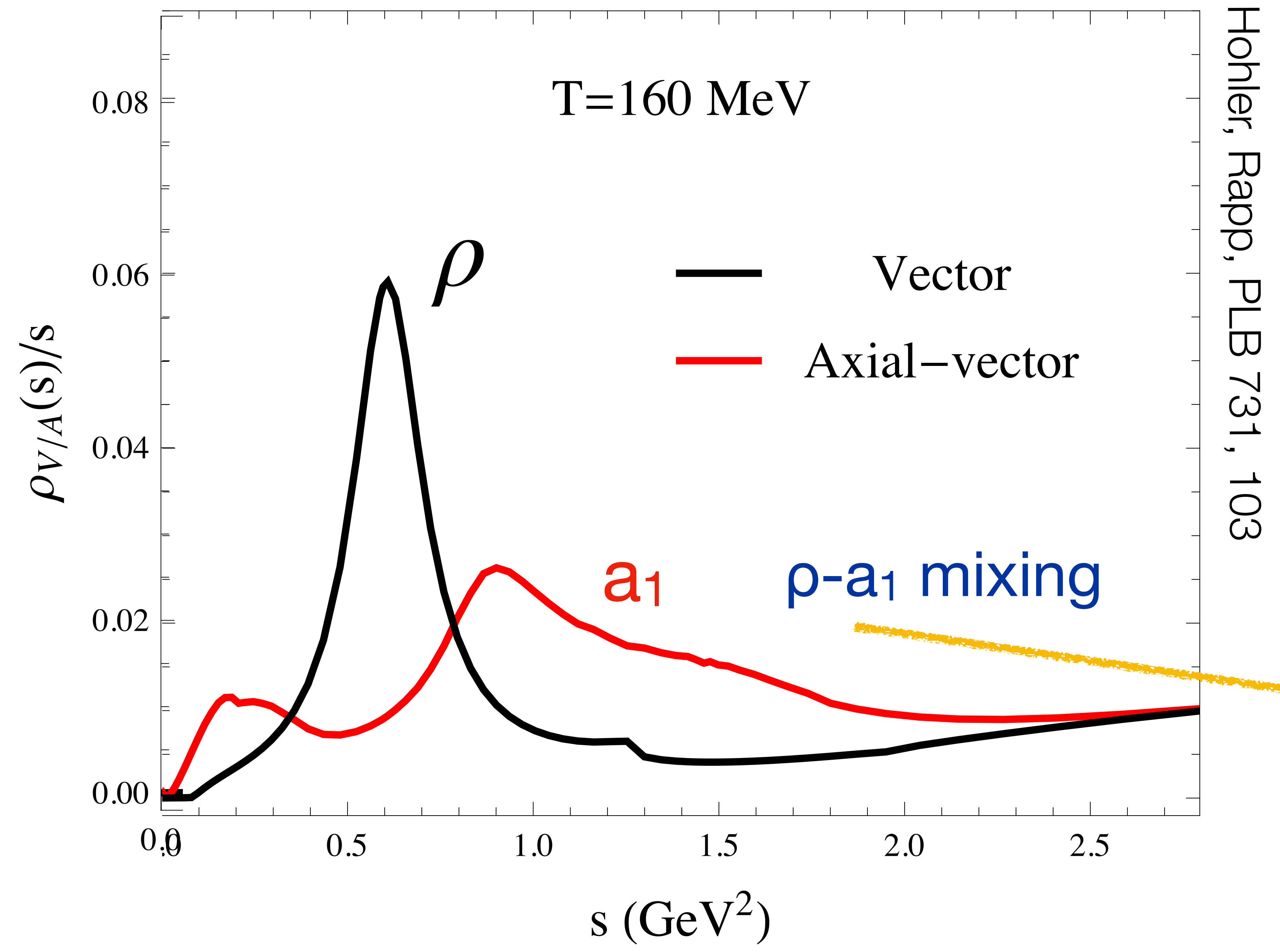


Extremely challenging
→ requiring precision of ALICE 3

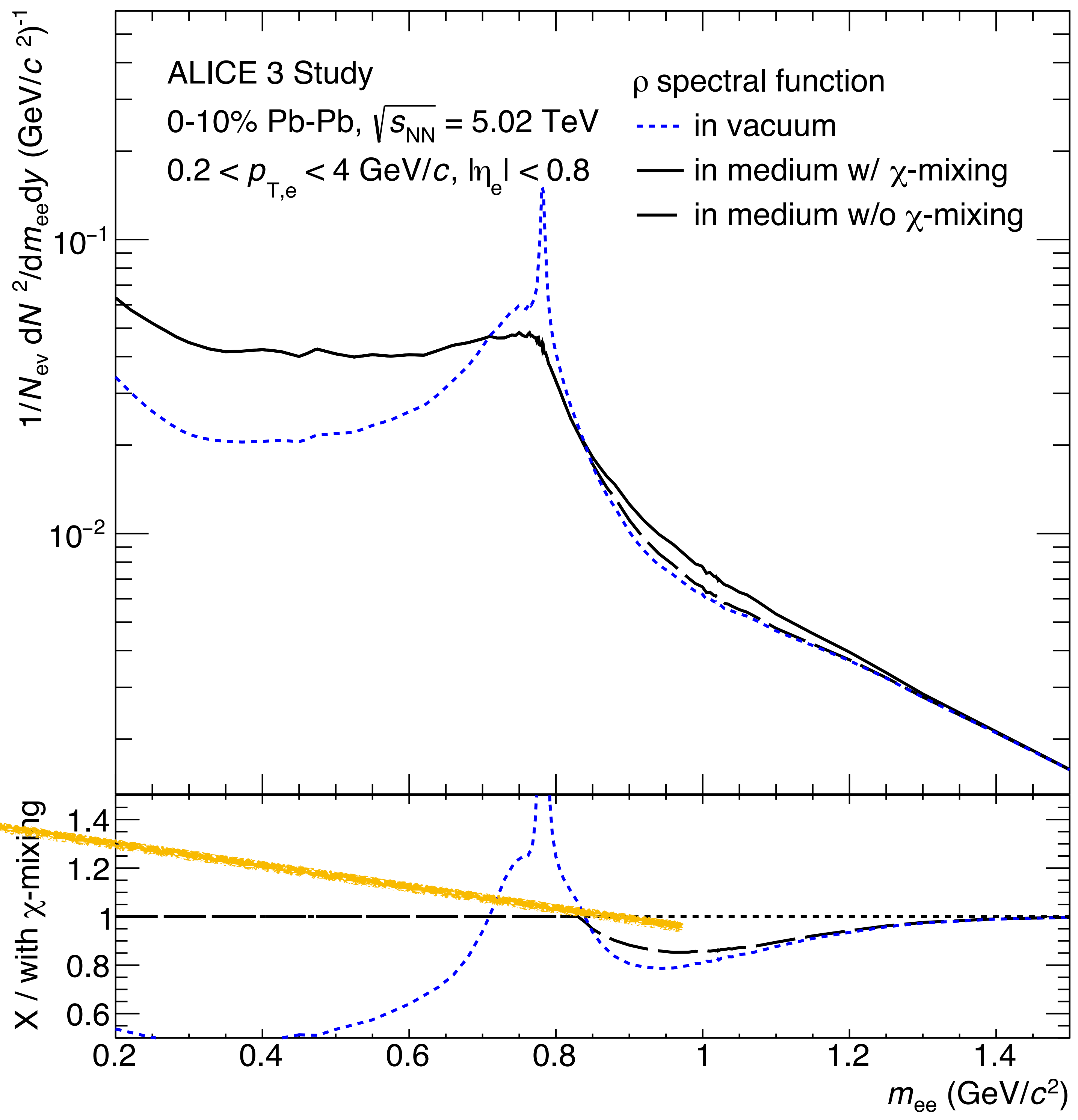
- Precision measurement of dielectrons as function of mass and p_T
- Excellent precision for dilepton v_2
  → time evolution of emission

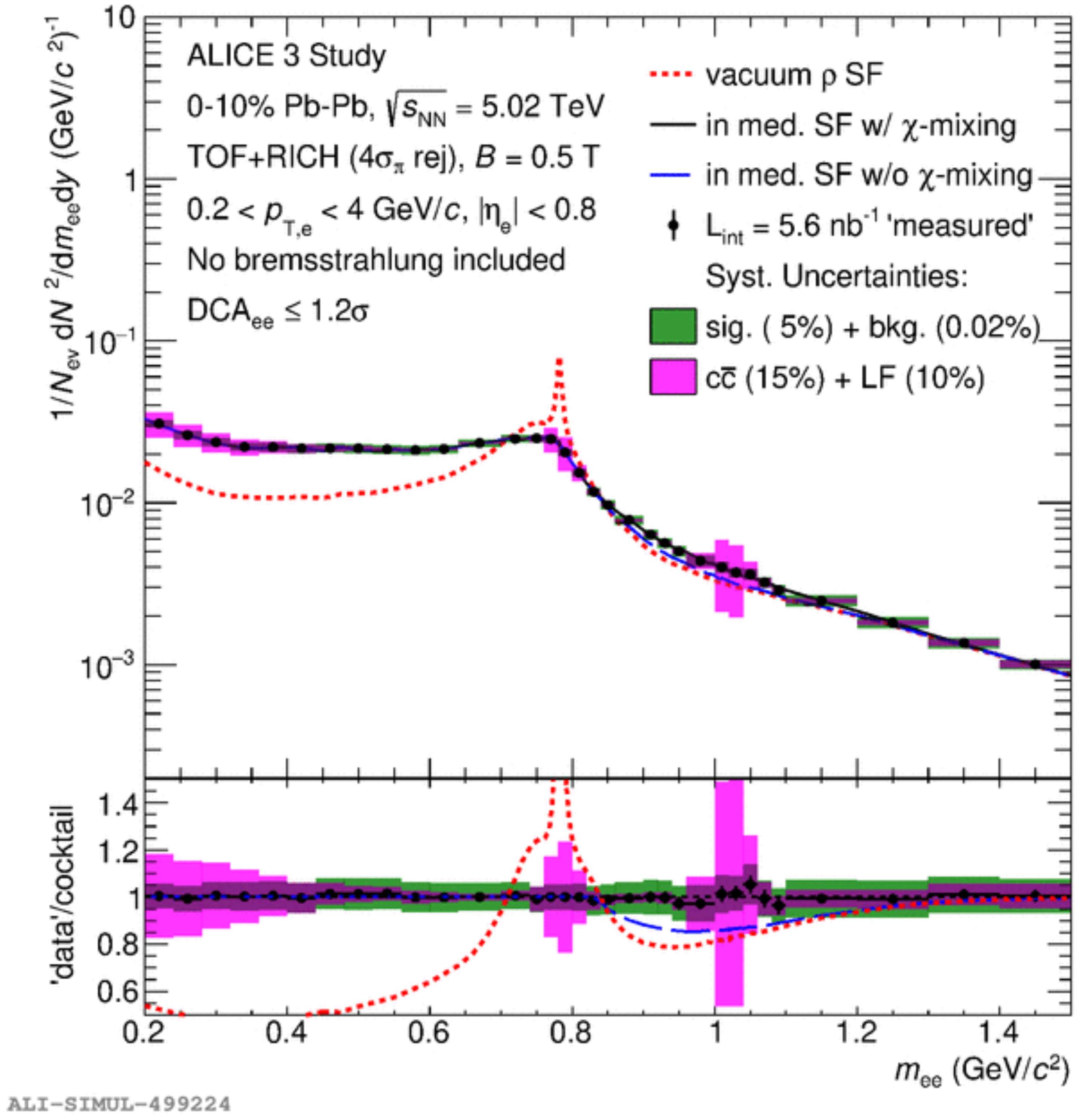
Chiral symmetry restoration

Spectral function at T = 160 MeV



Dilepton mass distribution





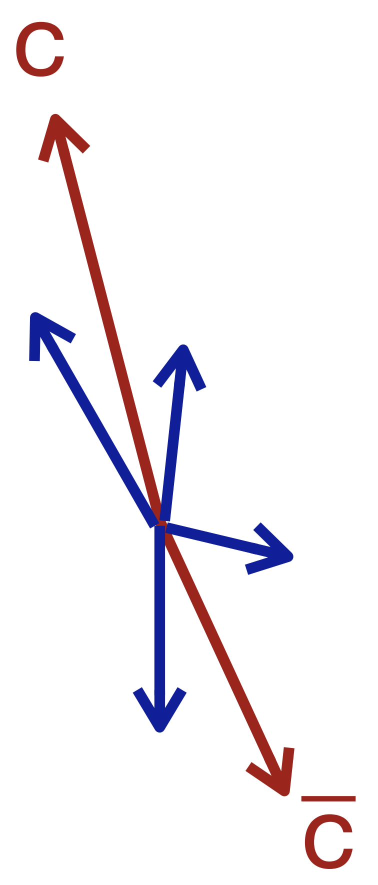
- Chiral symmetry breaking generates hadron masses
- **Unique window on ρ-a_1 mixing**
  - Requires **large precision** dilepton measurement in mass range **0.8 - 1.2 GeV/c^2**

Extremely challenging
→ requiring precision of ALICE 3

Heavy-quark propagation

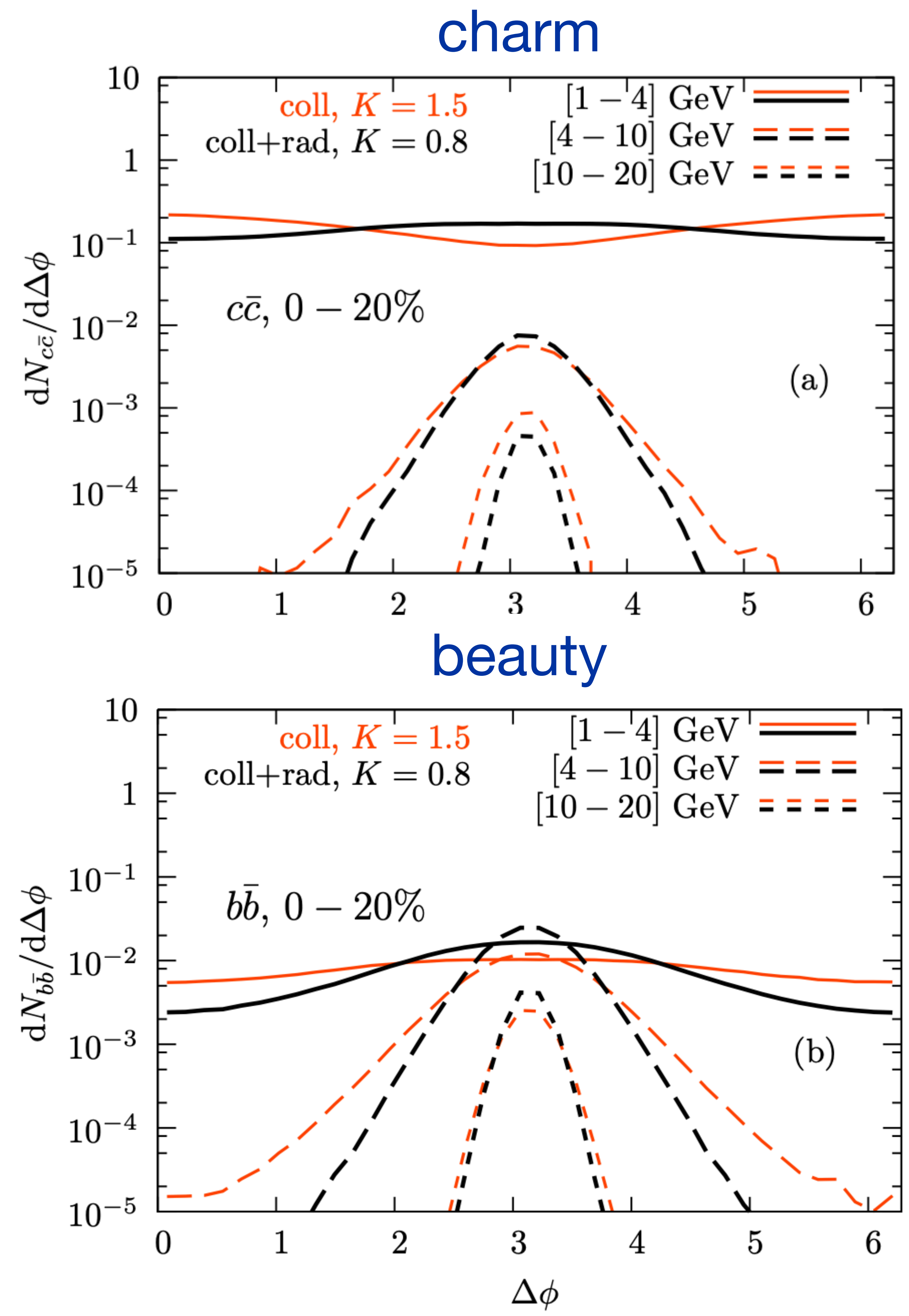
$$\langle r^2 \rangle = 6\, D_s\, t$$

heavy quark diffusion
⇒ collisional broadening



$$\hat{q} = \frac{\langle q_\perp^2 \rangle}{\lambda}$$

$\hat{q}$: semi-hard scattering
⇒ radiative energy loss



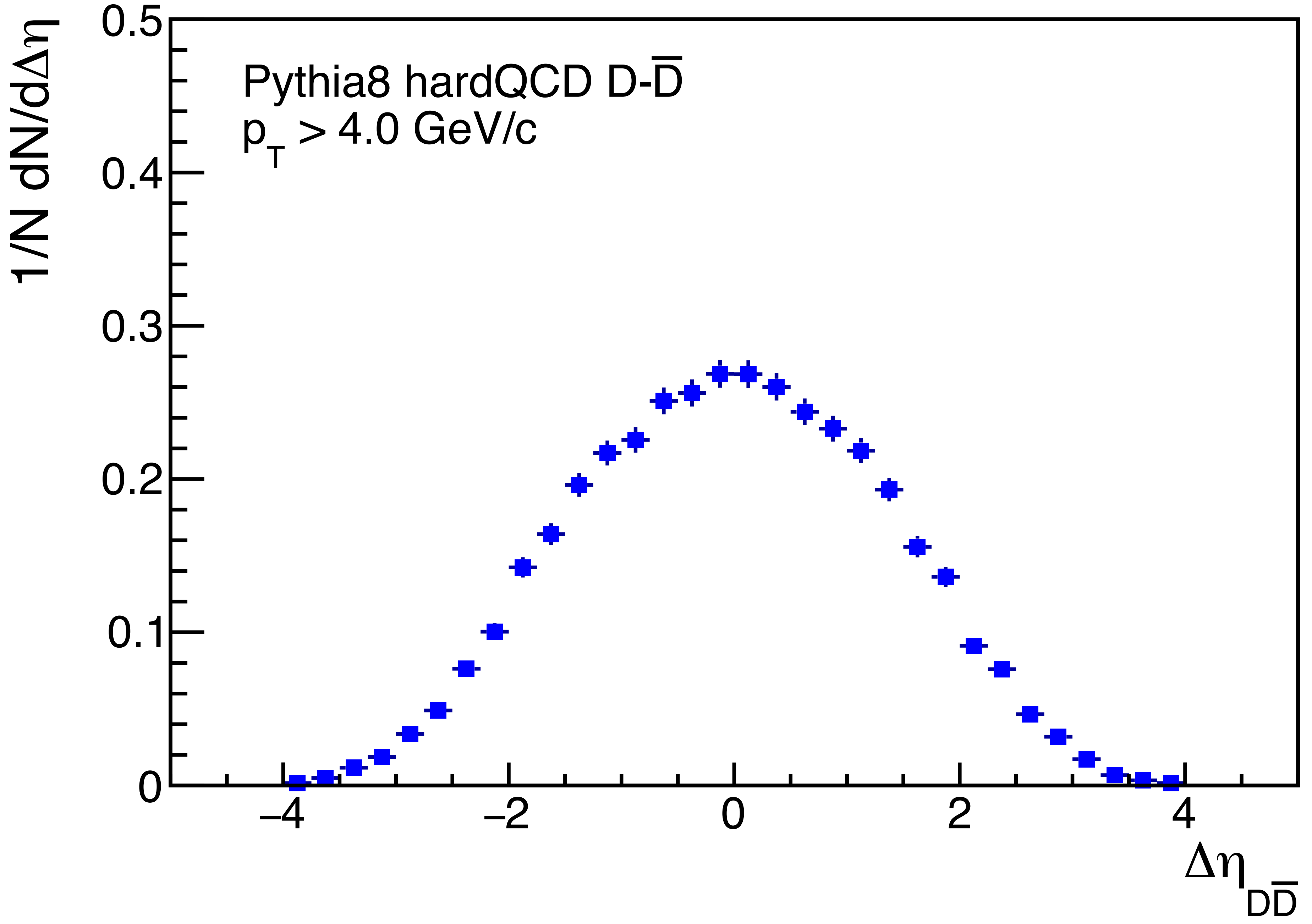
M Nahrgang et al, PRC 90, 024907

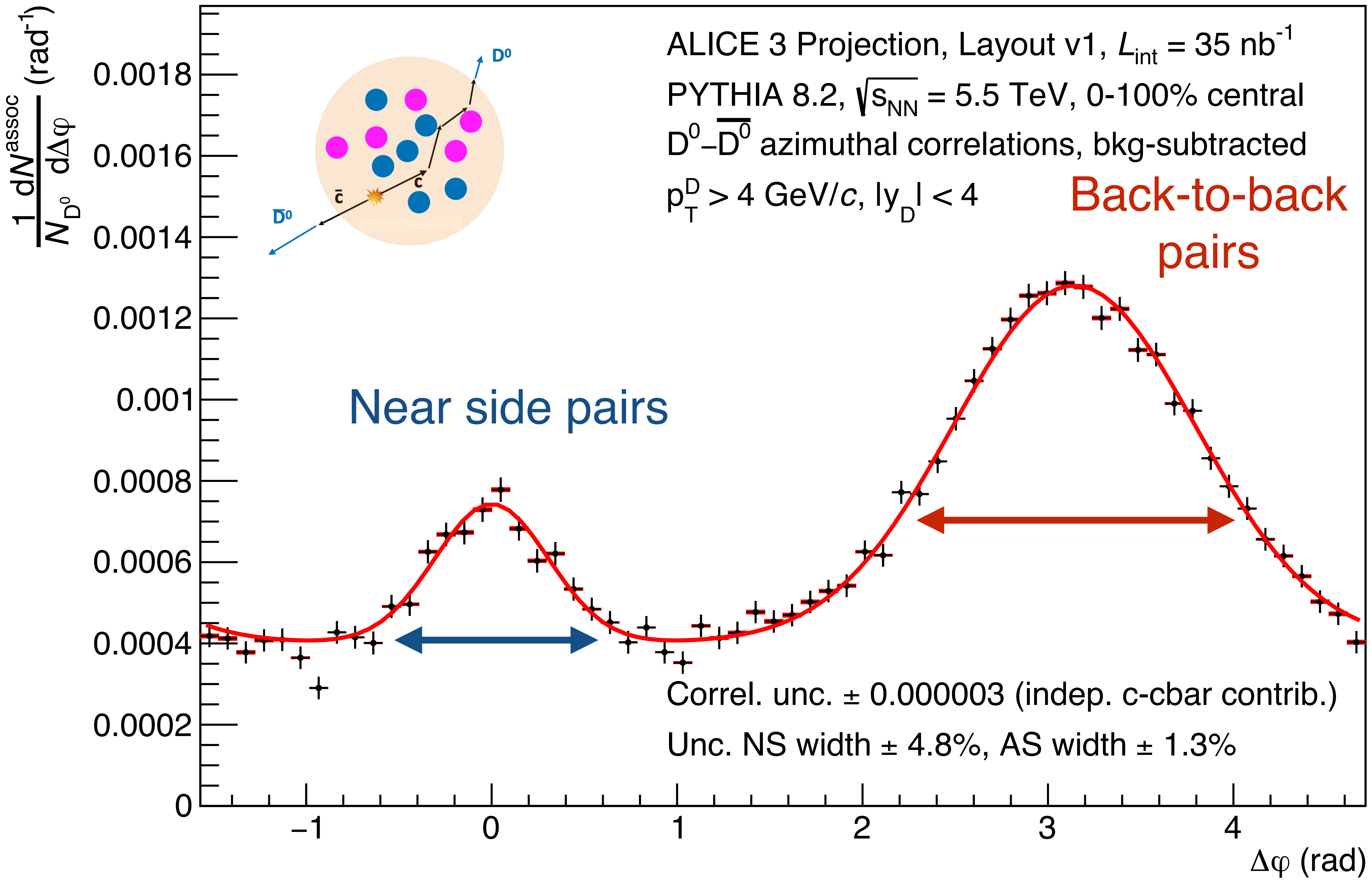
- Azimuthal correlations between DD̄, BB̄ pairs
  - **Direct access** to interactions with QGP, momentum diffusion, in particular at low p_T
- **Complementary to heavy-flavour flow**
  - Angular distributions sensitive to **interaction mechanism**, nature of scattering centers

Need large statistics, large purity for D (B) mesons, large η coverage

$D^0\bar{D}^0$ correlations

Rapidity-difference between D and D̄





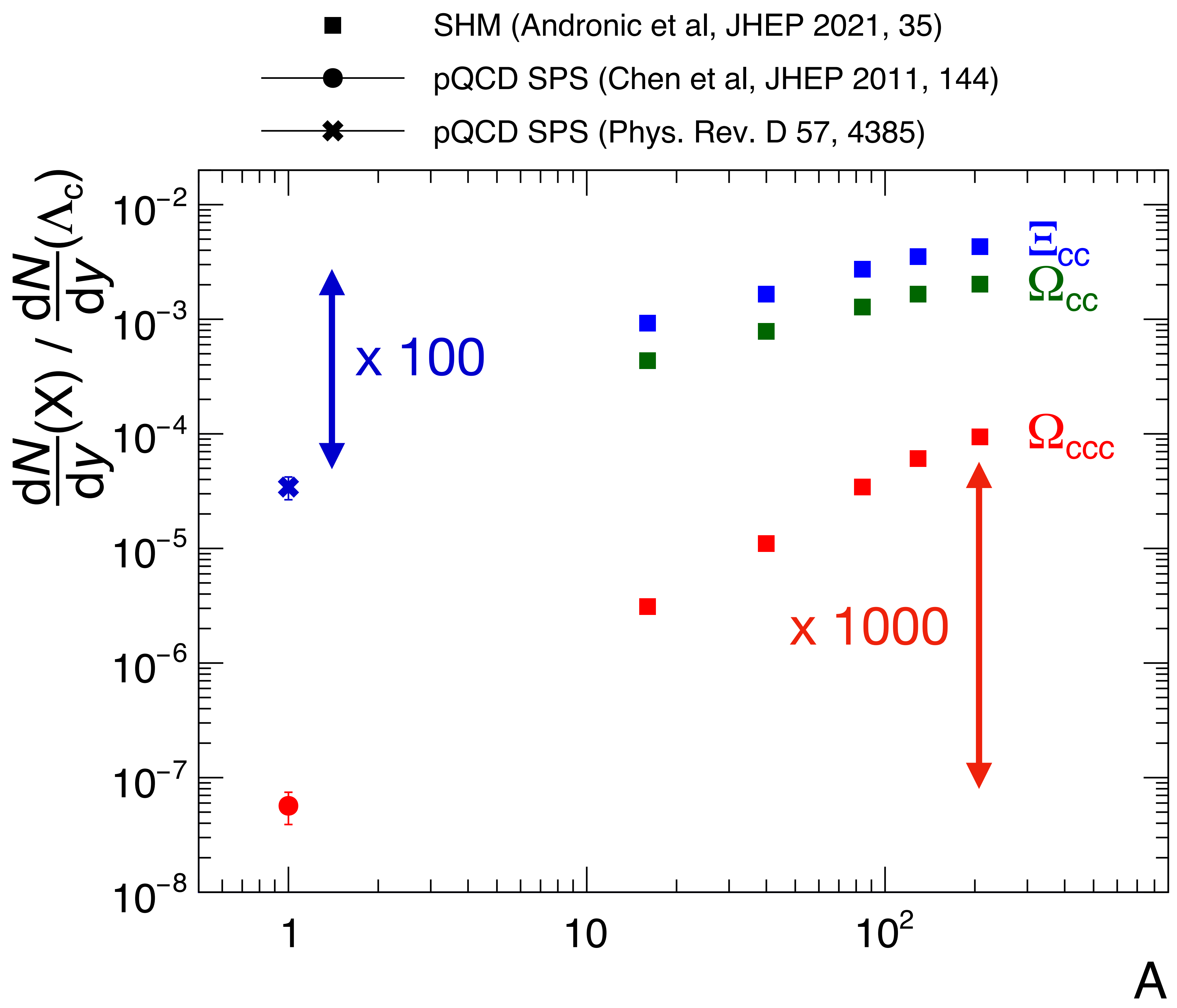
Requires reconstruction of D mesons over large rapidity

Low background: high precision

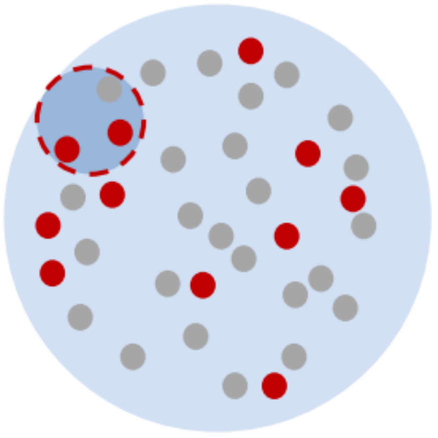
→ **unique sensitivity to broadening of $c\bar{c}$ pairs**

Hadronisation: multicharm states

- **Multi-charm baryons**: unique probe of hadron formation
  - Requires **production of multiple charm quarks**
  - Single-scattering contribution very small (unlike e.g. J/ψ)
- Statistical hadronisation model:
  very large enhancement in AA
  - Specific relation between yields: g_c^n for *n*-charm states
  - How is thermalisation approached microscopically?
- Systematic measurement of multiple states
  to test thermalisation and hadronisation
  - Dependence on flavour, hadron size, binding energy, etc

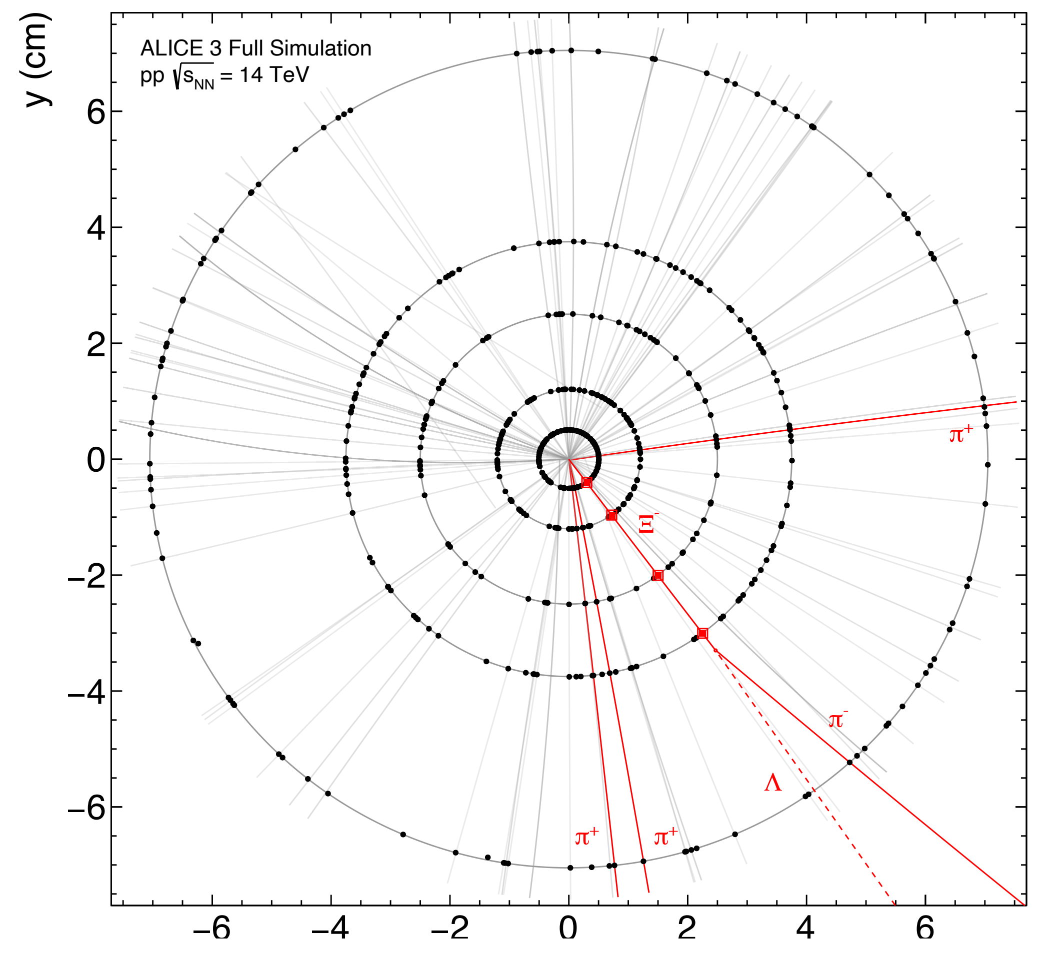


Single and double-charm baryons: Λ_c, Ξ_c, Ξ_{cc}, Ω_{cc}
Multi-flavour mesons: B_c, D_s, B_s, ...
Tightly/weakly bound states J/ψ, $\chi_{c1}(3872)$, T_{cc}^+
Large mass light flavour particles: nuclei

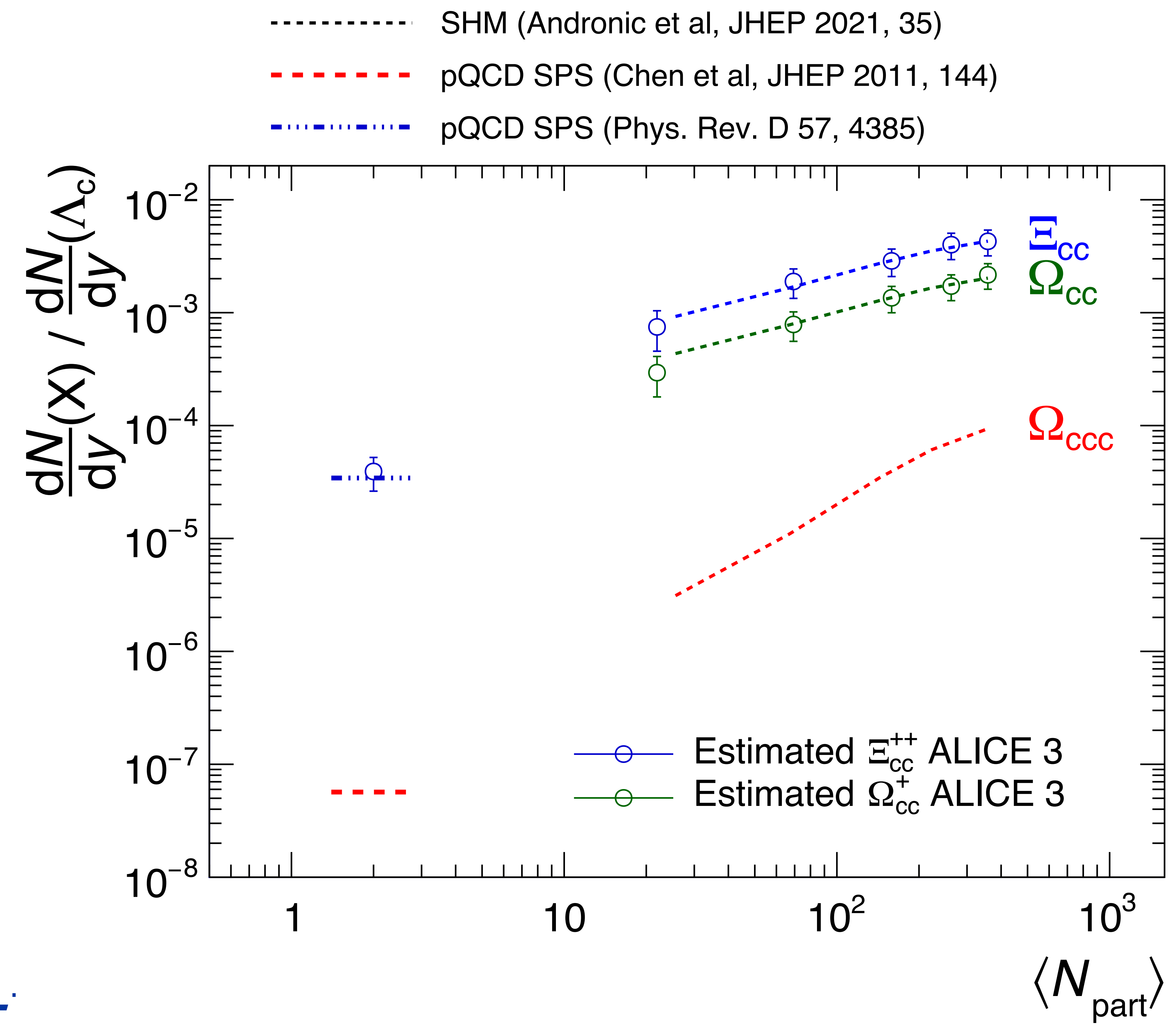


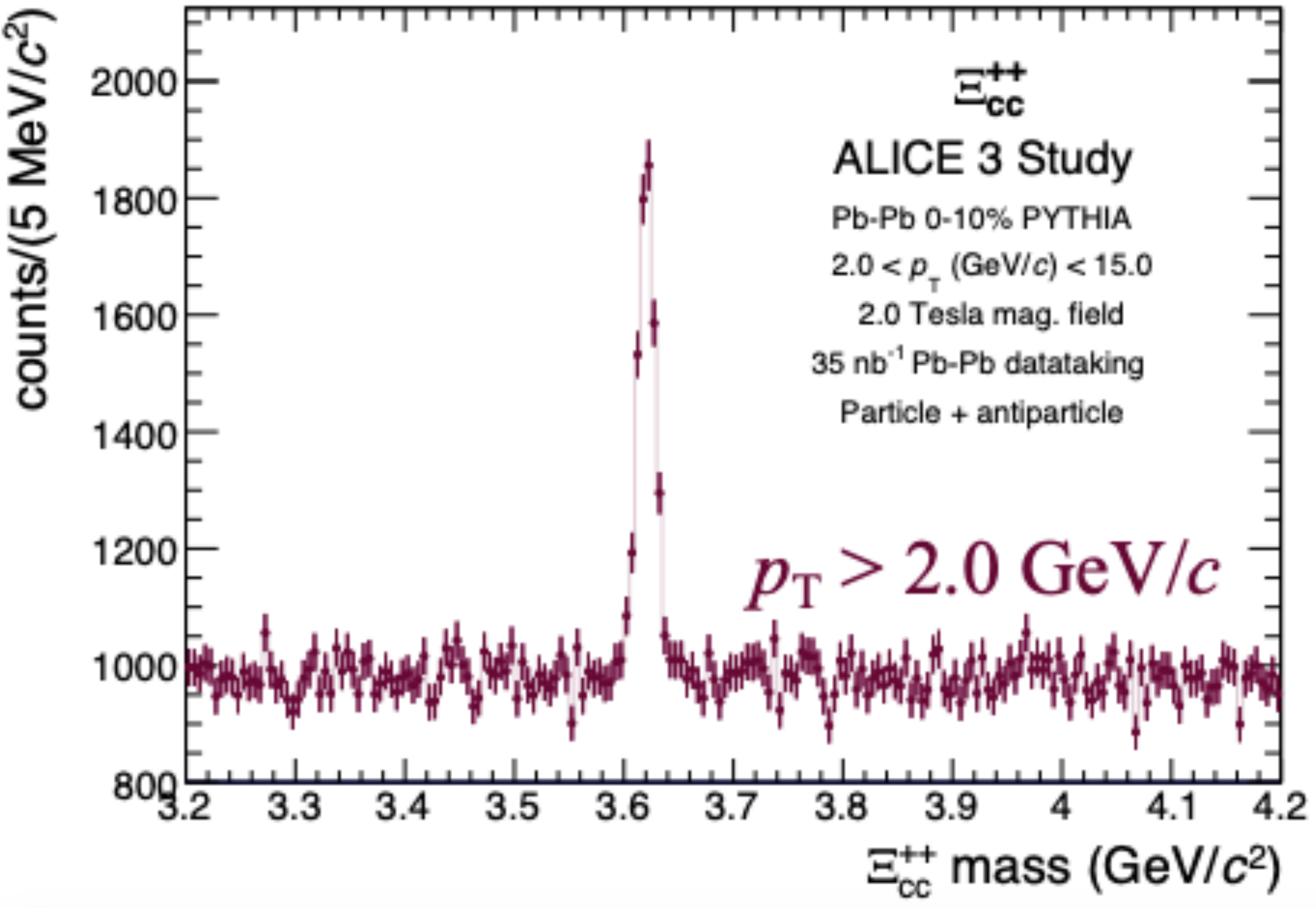
Need large samples, excellent pointing resolution, particle identification

Multi-charm baryons



New technique: strangeness tracking with Ξ baryon
→ high selectivity



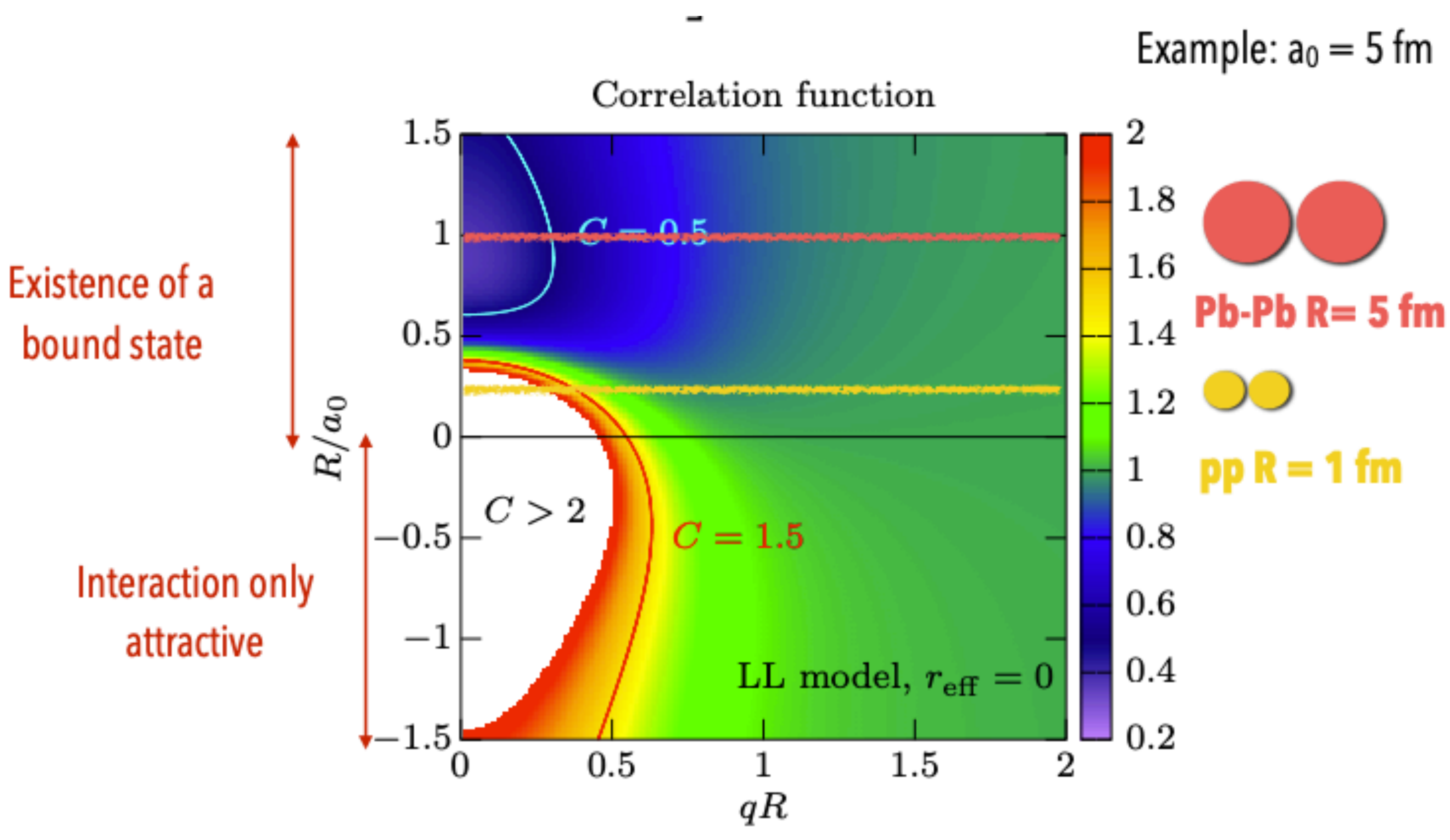


$$\Xi_{cc}^{+} \to \Xi_{c}^{+} + \pi^{+}$$
$$\Xi_{c}^{+} \to \Xi^{-} + 2\pi$$

Multi-charm baryons vs system size
→ new insights in thermalisation and hadronisation dynamics

ALICE 3: unique experimental access in Pb-Pb collisions

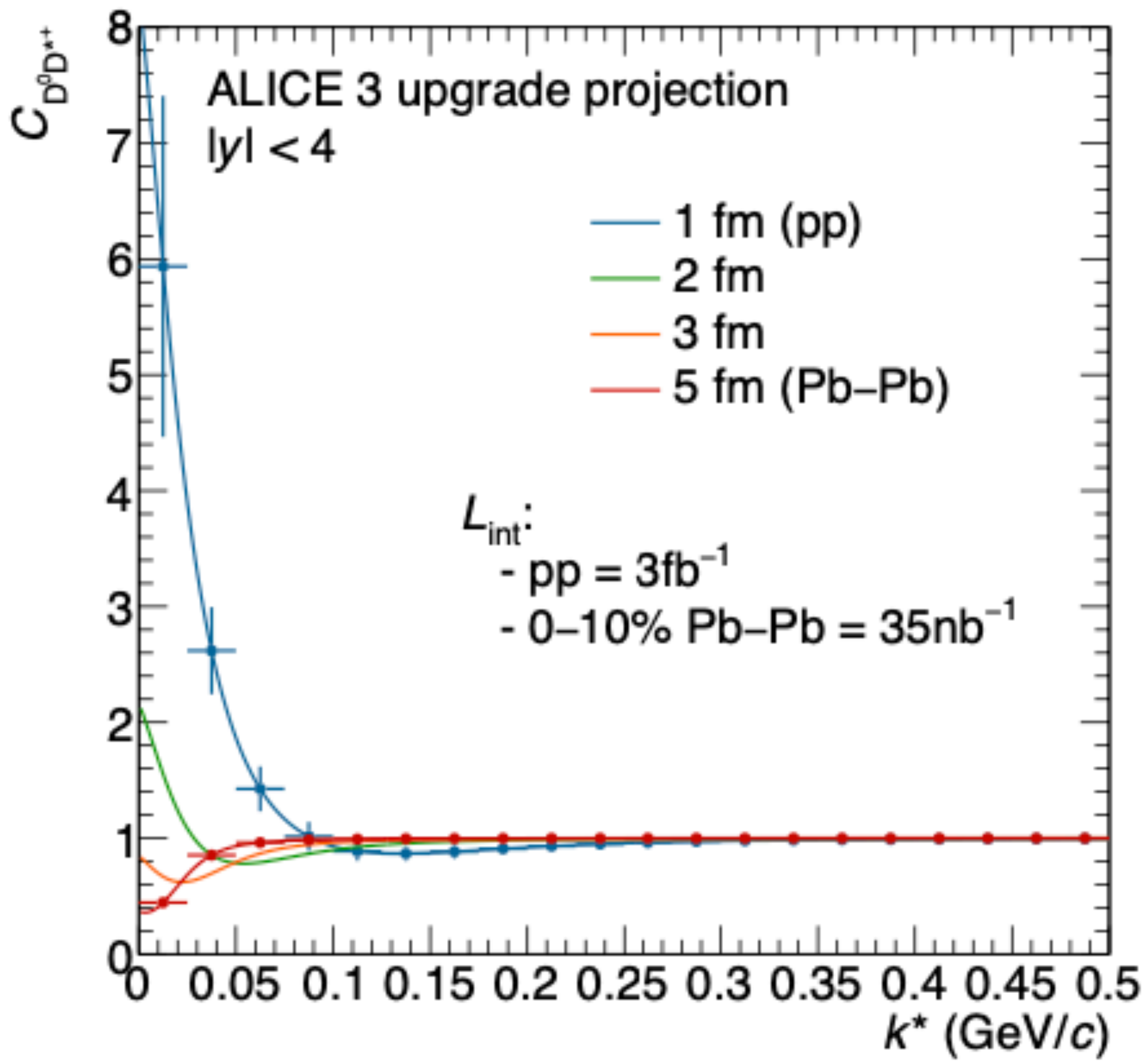
Nature of exotic states



Y. Kamiya et al. arXiv:2108.09644v1

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

DD* momentum correlation



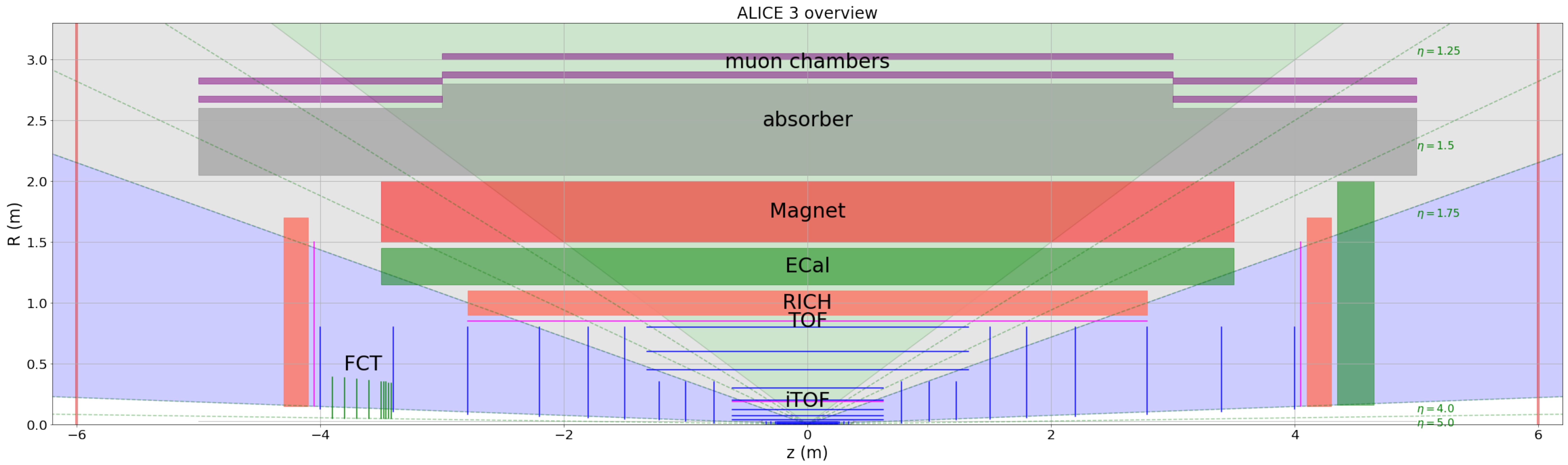
- Characteristic sign-change between pp and Pb-Pb in case of bound T_{cc} state
- Effect clearly visible within experiment precision

Observables

- **Heavy-flavour hadrons** ($p_T \rightarrow 0$, $|\eta| < 4$)
  - vertexing (decay chain)
  - tracking (inv. mass resolution)
  - hadron ID (background suppression)
- **Dielectrons** (p_T ~0.1 - 3 GeV/c, M_{ee} ~0.1 - 4 GeV/c^2)
  - vertexing (HF background suppression)
  - tracking (inv. mass resolution)
  - electron ID
- **Photons** (100 MeV/c - 50 GeV/c, wide η range)
  - electromagnetic calorimetry
- **Quarkonia and Exotica** ($p_T \rightarrow 0$)
  - muon ID
- **Ultrasoft photons** (p_T = 1 - 50 MeV/c)
  - dedicated forward detector
- **Nuclei**
  - identification of z > 1 particles

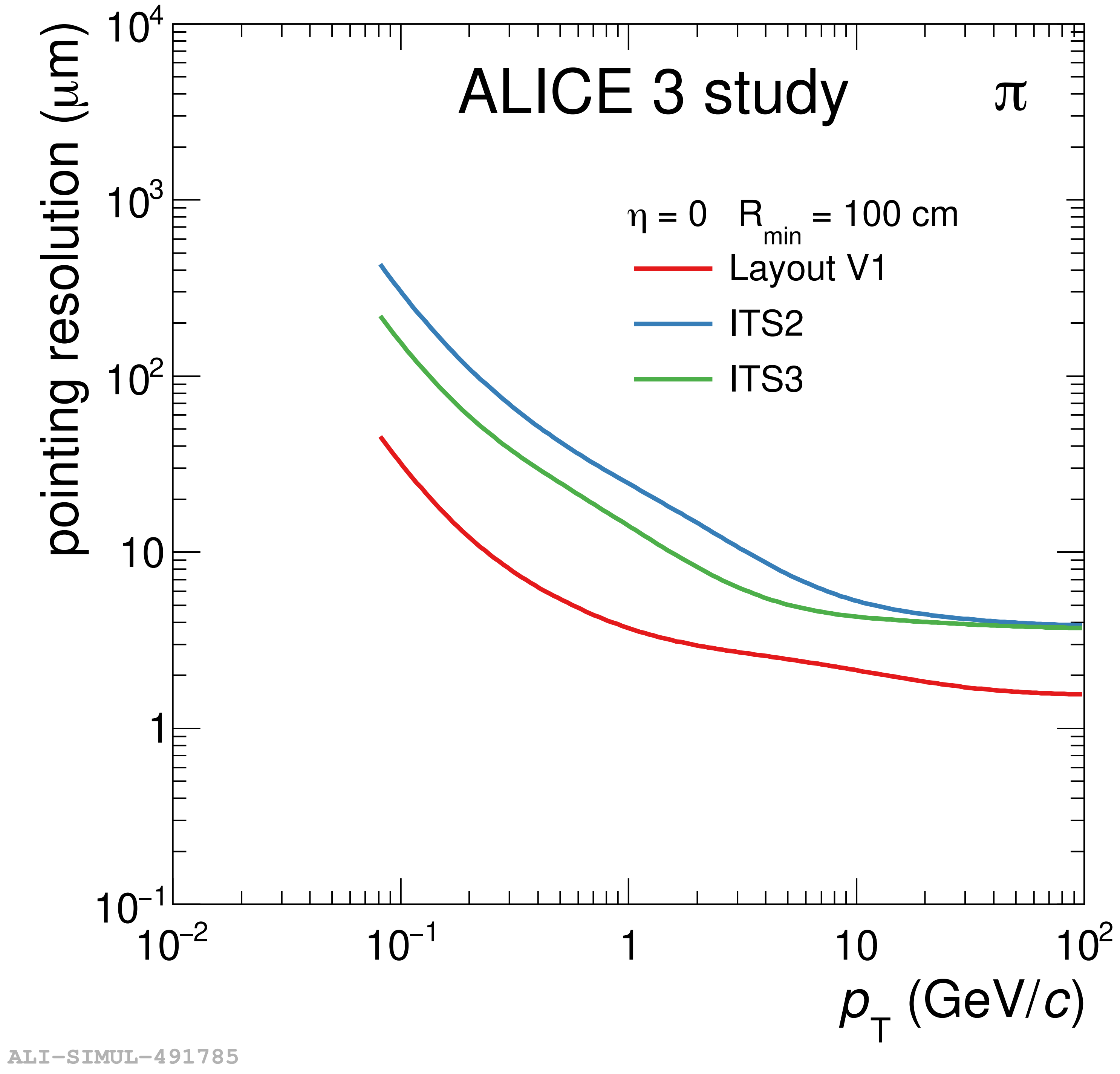
Key requirements

- Tracking over large rapidity range
- Excellent vertexing
- Excellent particle identification
- High rate



Vertexing

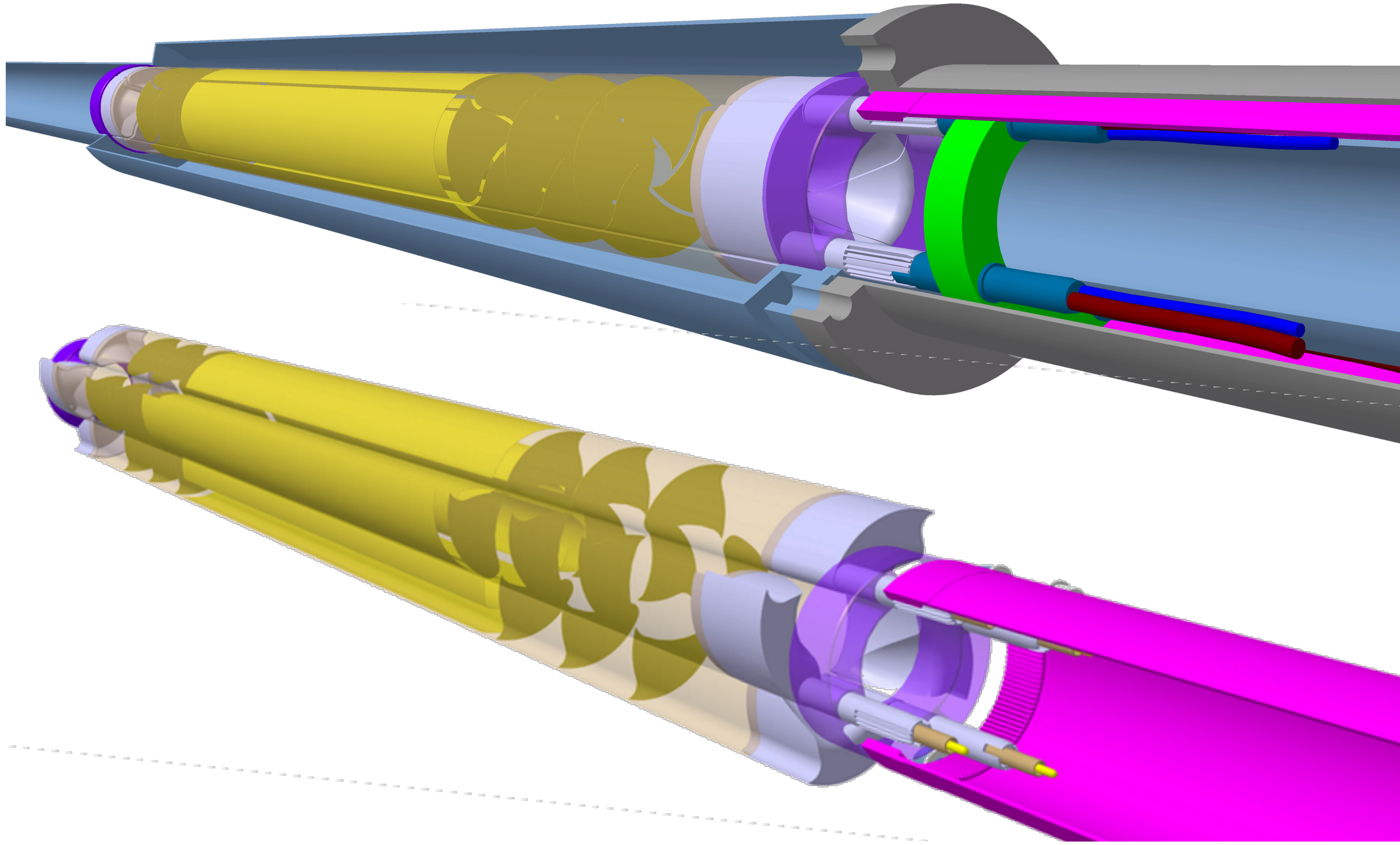
- **Pointing resolution** $\propto r_0 \cdot \sqrt{x/X_0}$ (multiple scattering regime)
  ➟ 10 µm @ p_T = 200 MeV/*c*
  - radius and material of first layer crucial
  - minimal radius given by required aperture:
    R ≈ 5 mm at top energy,
    R ≈ 15 mm at injection energy
    → **retractable vertex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

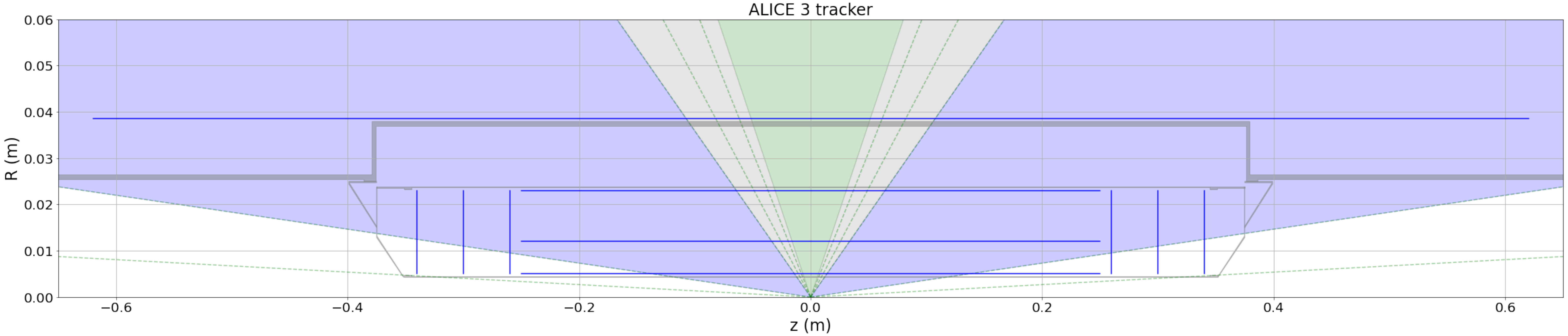


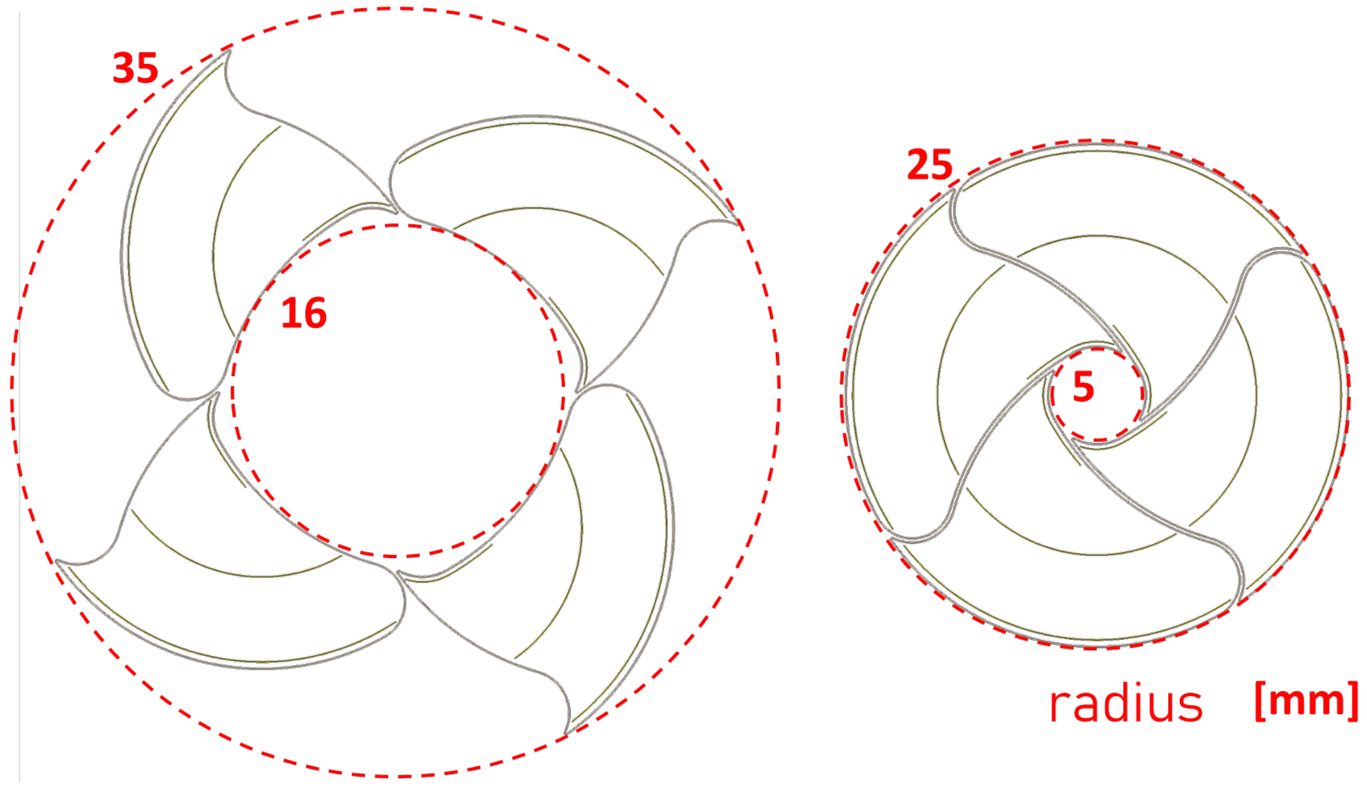
5x better than ALICE 2.1 (ITS3 + TPC)

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



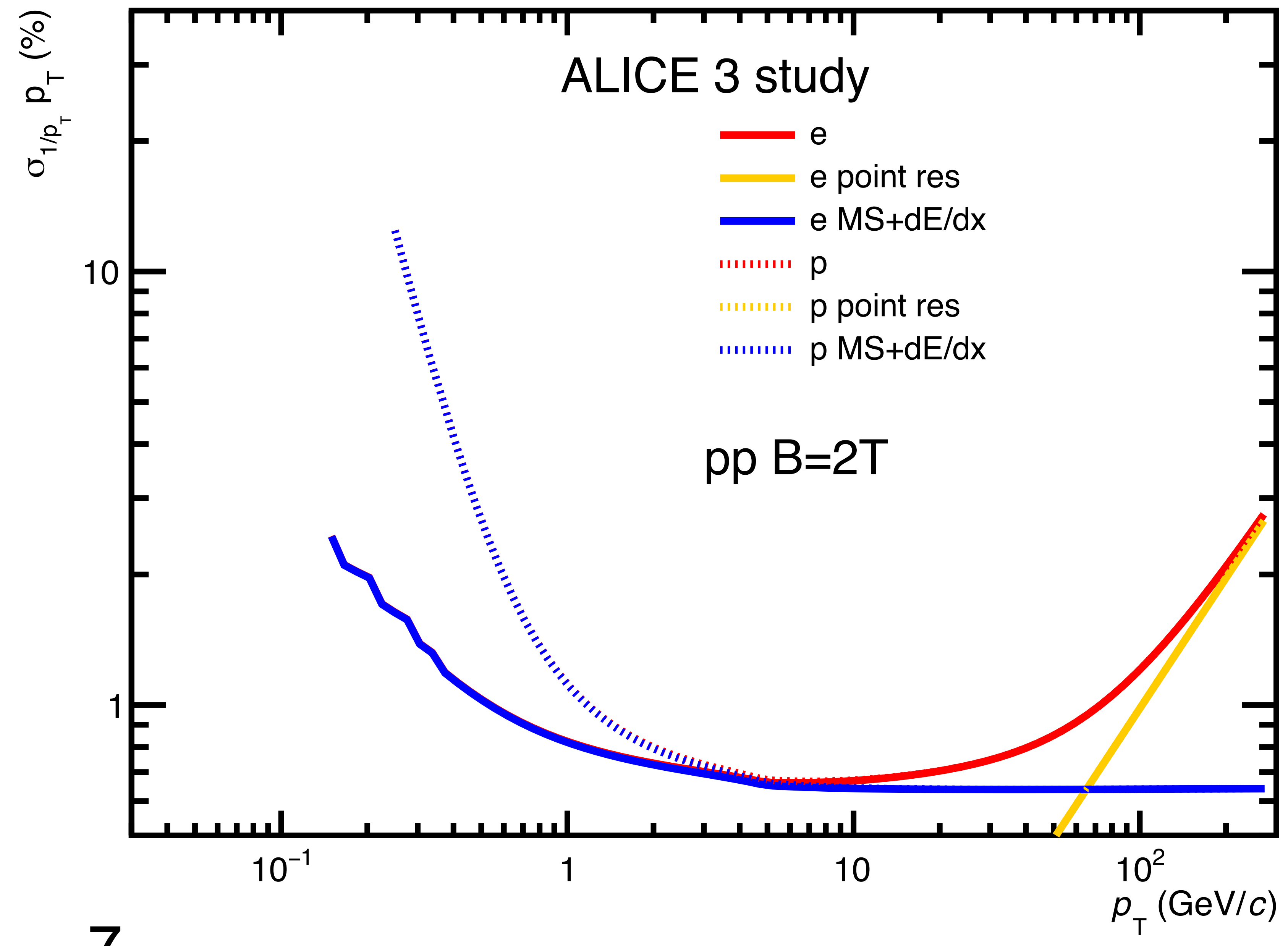


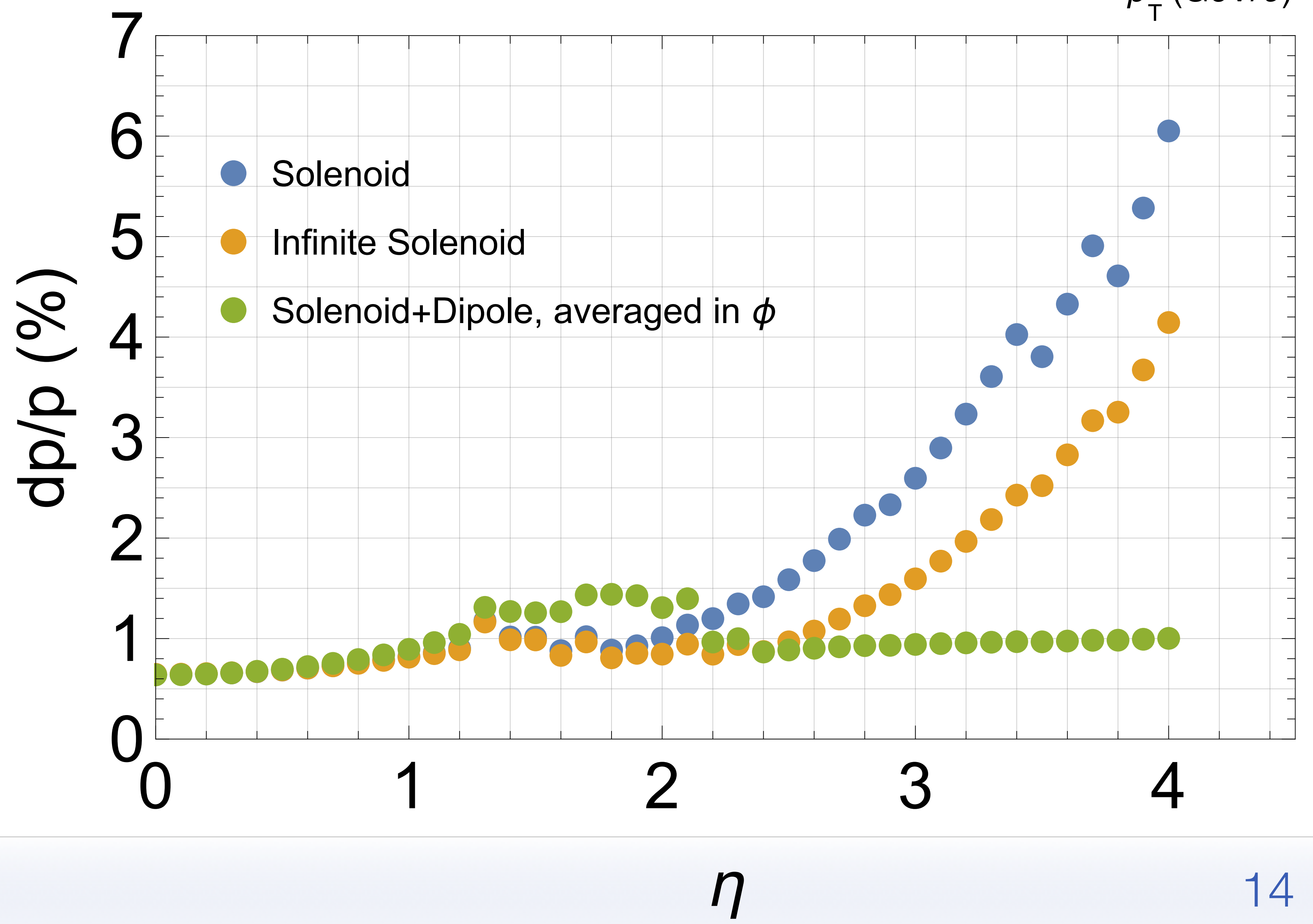


Tracking

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

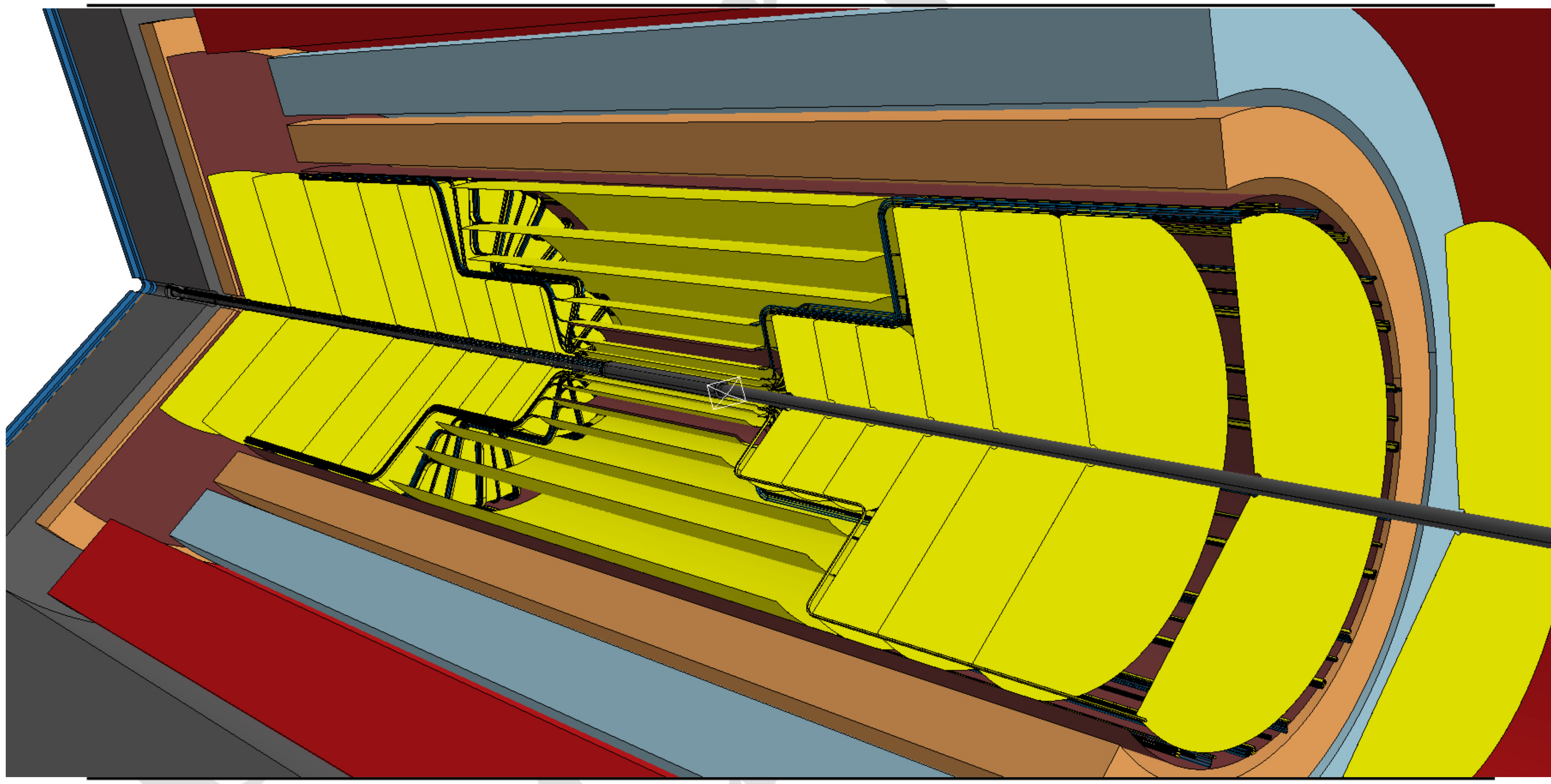
- **~11 tracking layers (barrel + disks)**
  - MAPS
  - σ_{pos} ~10 µm → 50 µm pixel pitch
  - R_{out} ≈ 80 cm and L ≈ 4 m (→ magnetic field integral ~1 Tm)
  - timing resolution ~100 ns (→ reduce mismatch probability)
  - material ~1 % X_0 / layer → overall X/X_0 = ~10 %

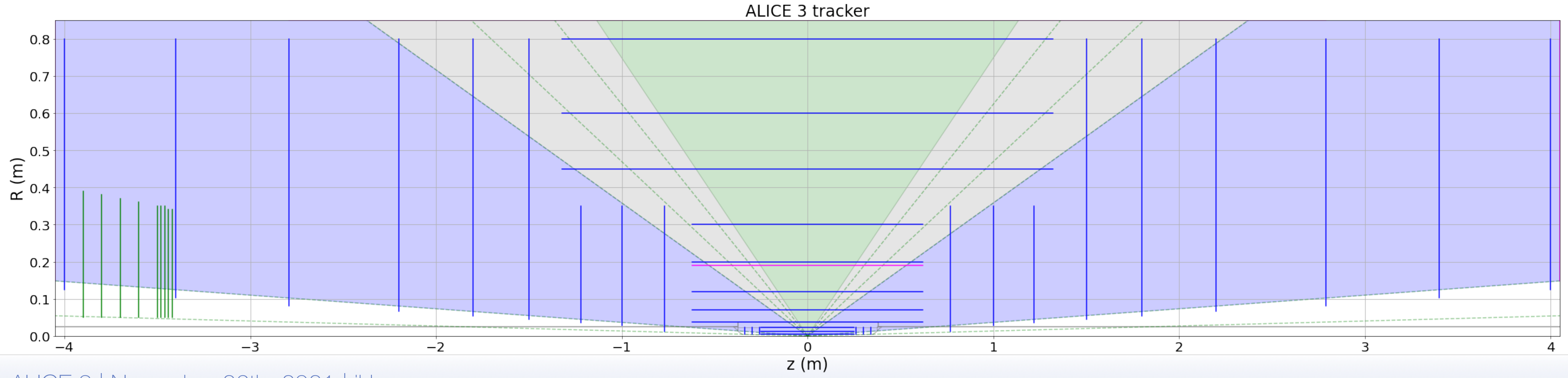




Outer Tracker

- 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

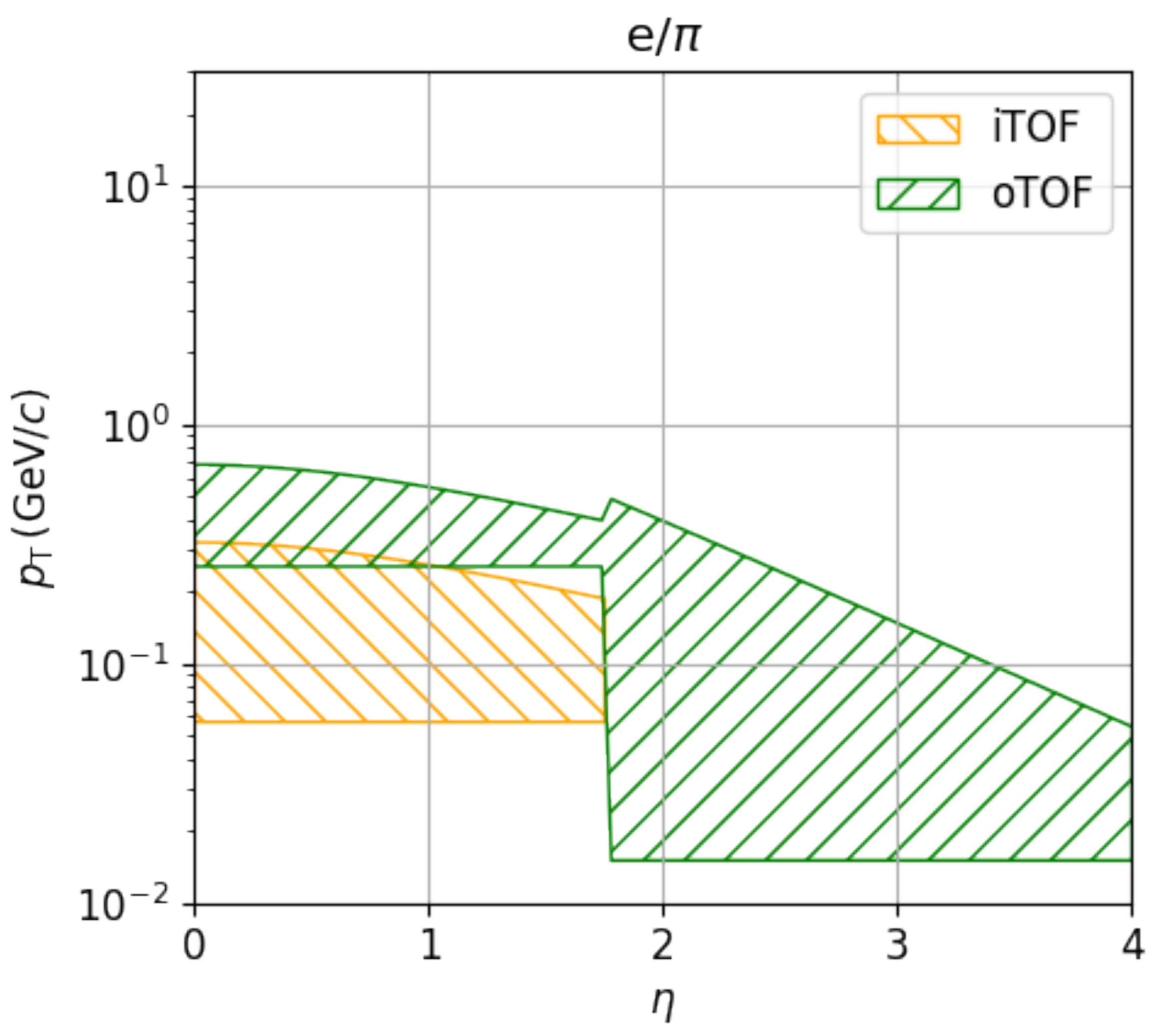


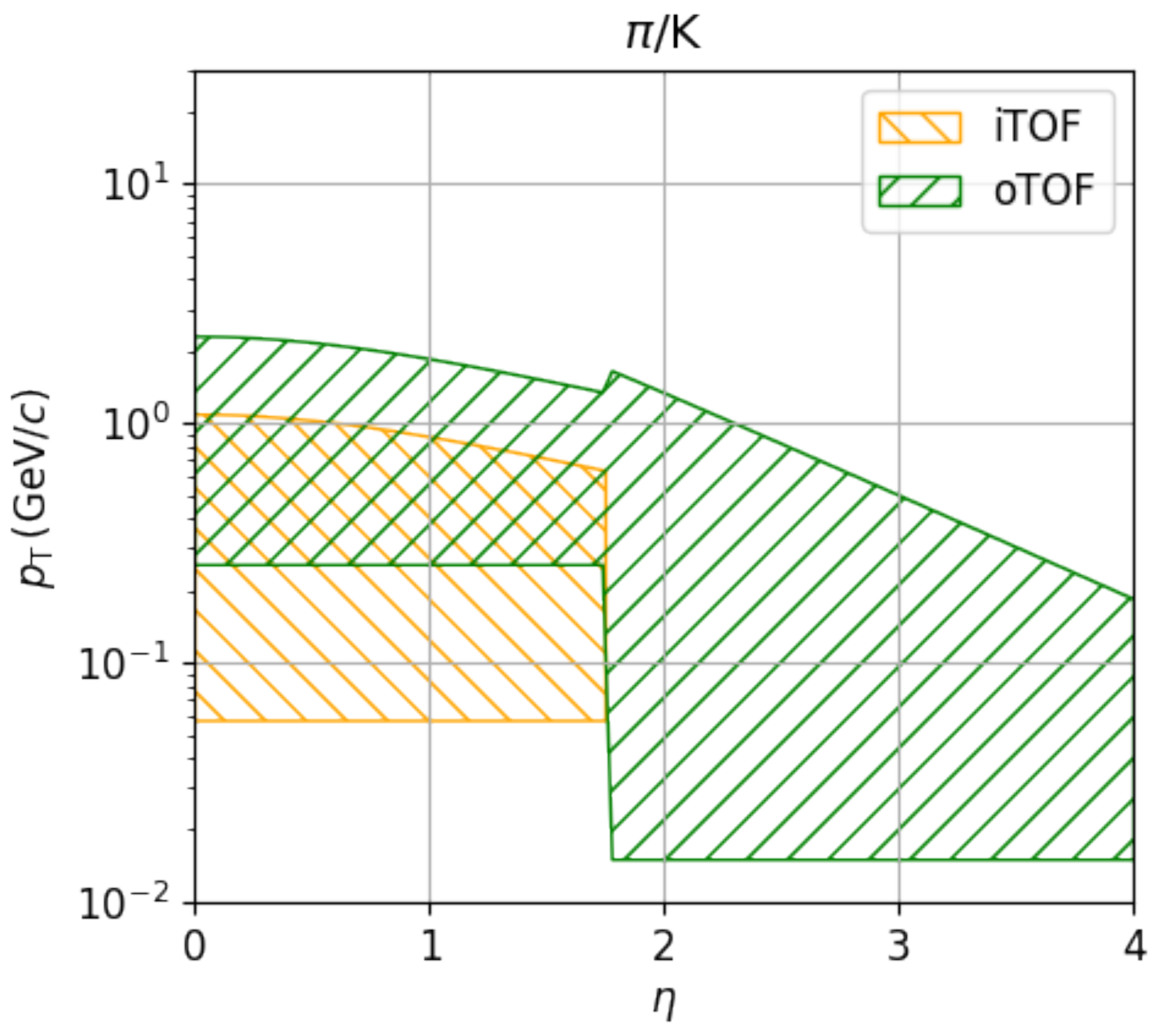


Total silicon surface ~60 m²

Time of Flight

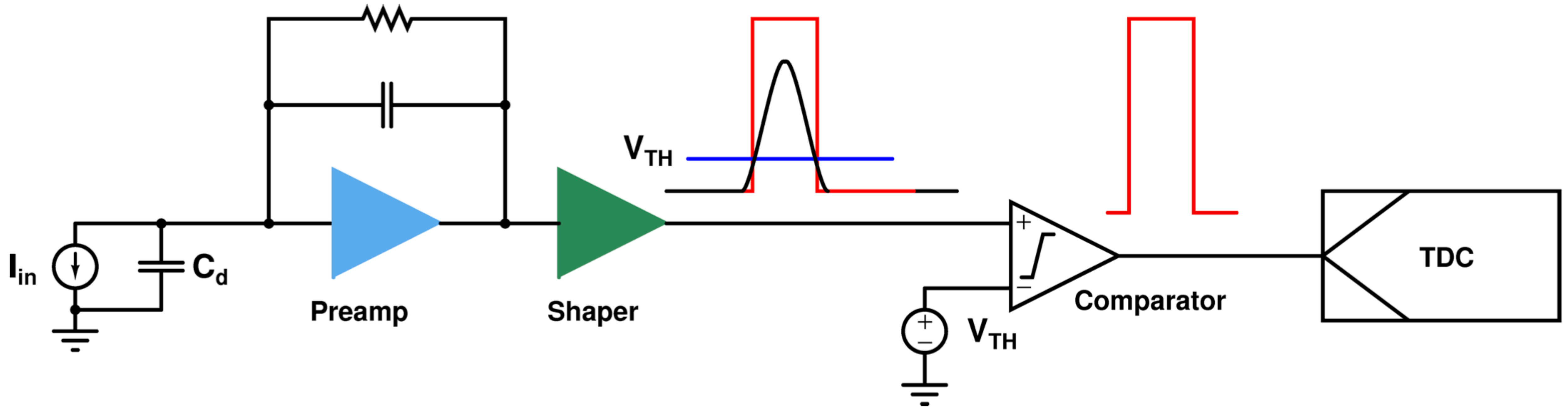
- **Separation power** $\propto \dfrac{L}{\sigma_{\text{tof}}}$
  - distance and time resolution crucial
  - larger radius results in lower p_T bound
- **2 barrel + 1 forward TOF layers**
  - TOF resolution $\sigma_{TOF} \approx 20$ ps based on silicon timing sensors
  - outer TOF at R ≈ 85 cm
  - inner TOF at R ≈ 19 cm
  - forward TOF at z ≈ 405 cm





TOF detector

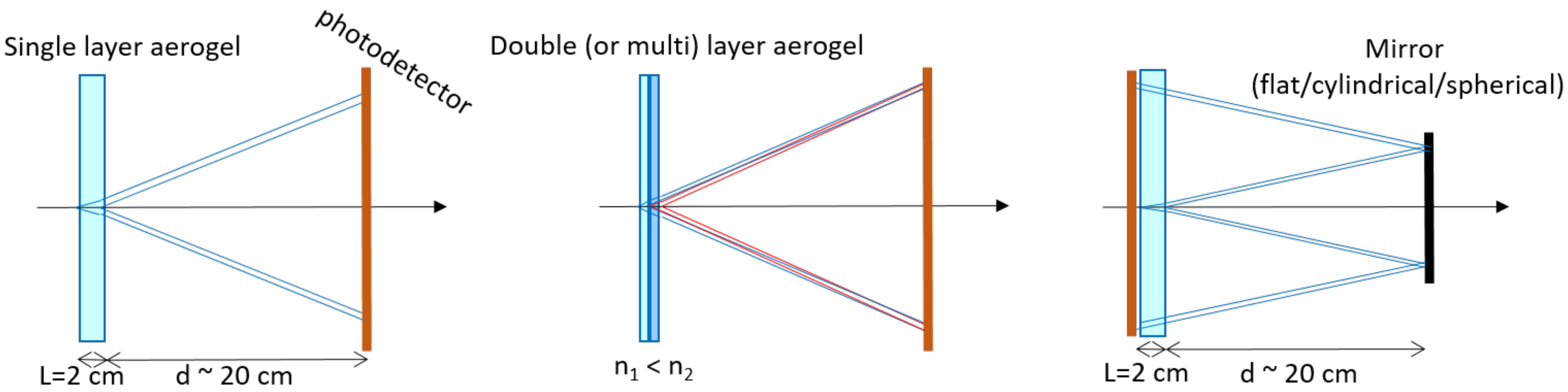
- **Sensor**
  - Low Gain Avalanche Diodes (LGAD)
    → established technology
    - requires separate read-out chip
  - **Monolithic timing sensors**
    → attractive solution
    - time resolution achievable
      with additional gain layer
  - Single Photon Avalanche Diodes (SPAD)
    → interesting in combination with
    photon detection for RICH
- **Front-end electronics and**
  Time to Digital Converter (leading edge and time over threshold)
  - engineering challenge

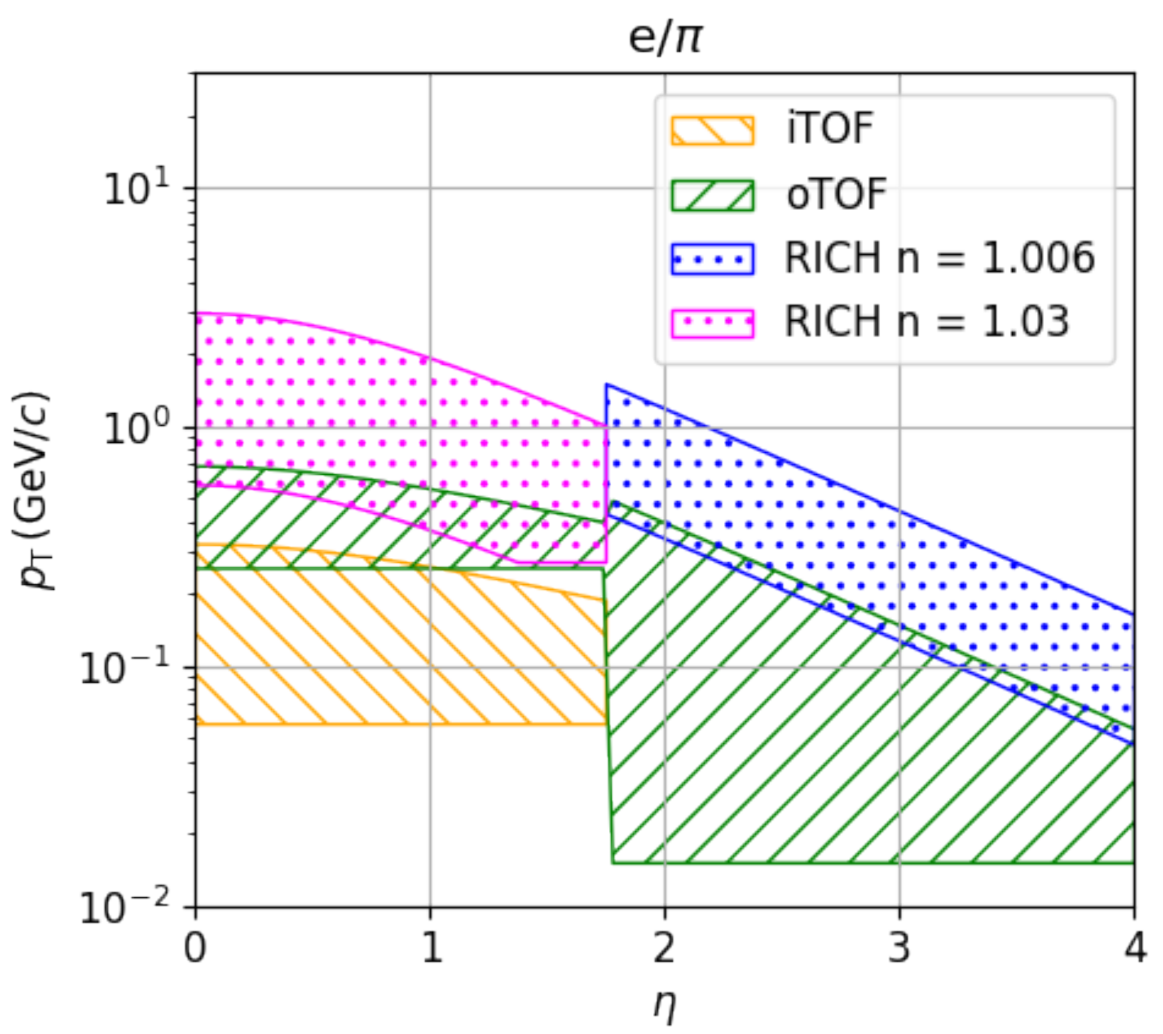


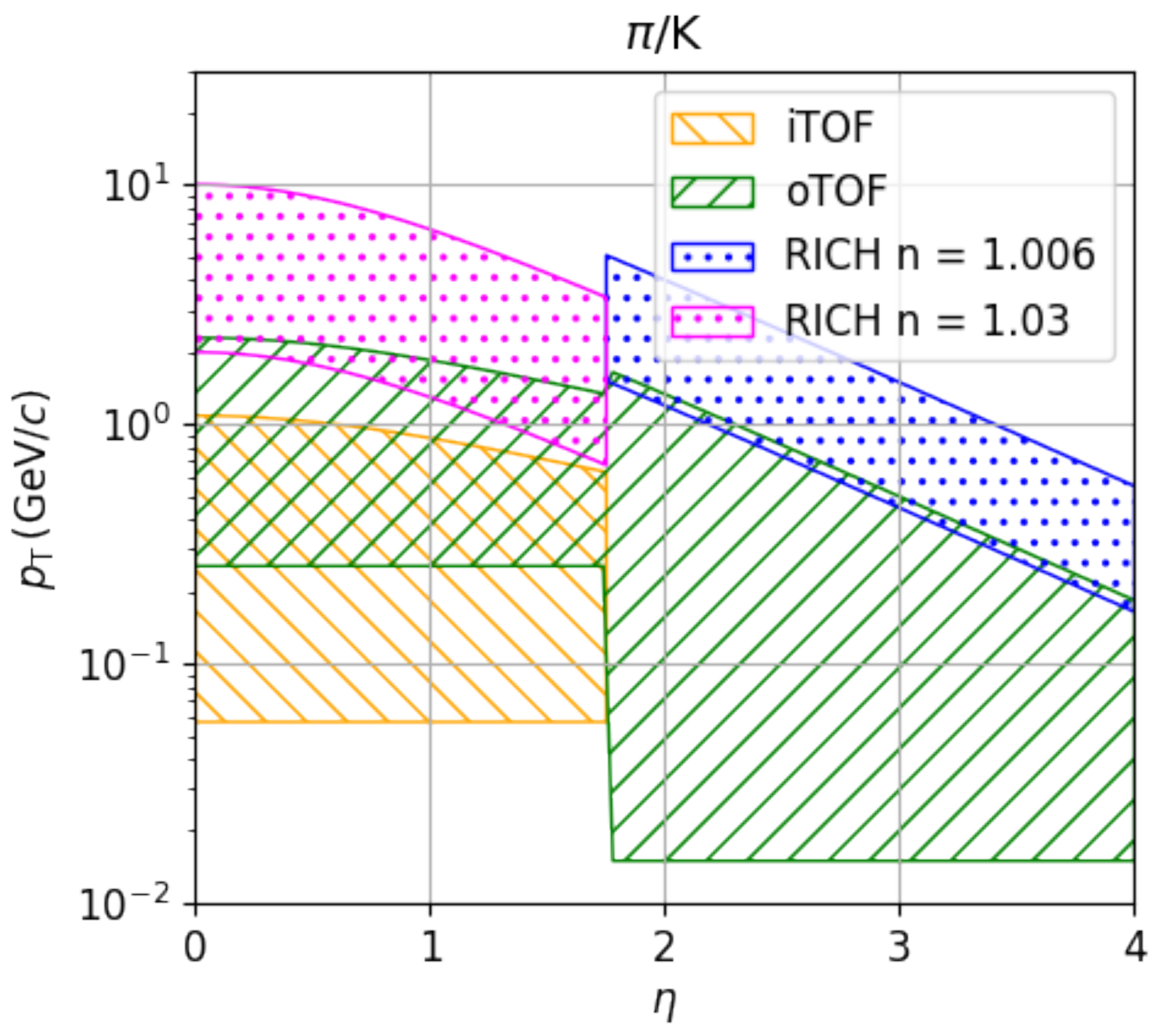
Total silicon surface ~45 m^2

RICH

- **Extend PID reach of outer TOF to higher p_T**
  ➟ Cherenkov
  - ensure continuous coverage from TOF
    → refractive index n = 1.03 (barrel)
    → refractive index n = 1.006 (forward)
  - aerogel radiator + photon detection layer







Technologies and R&D

- **Silicon Photomultipliers (SiPM)**
  → established technology, commercially available
  - limited area per device
  - requires separate front-end
  - high dark count rates

Total SiPM surface ~60 m^2

- **Monolithic sensors**
  → interesting in combination with charged particle timing measurement
  - requires significant R&D

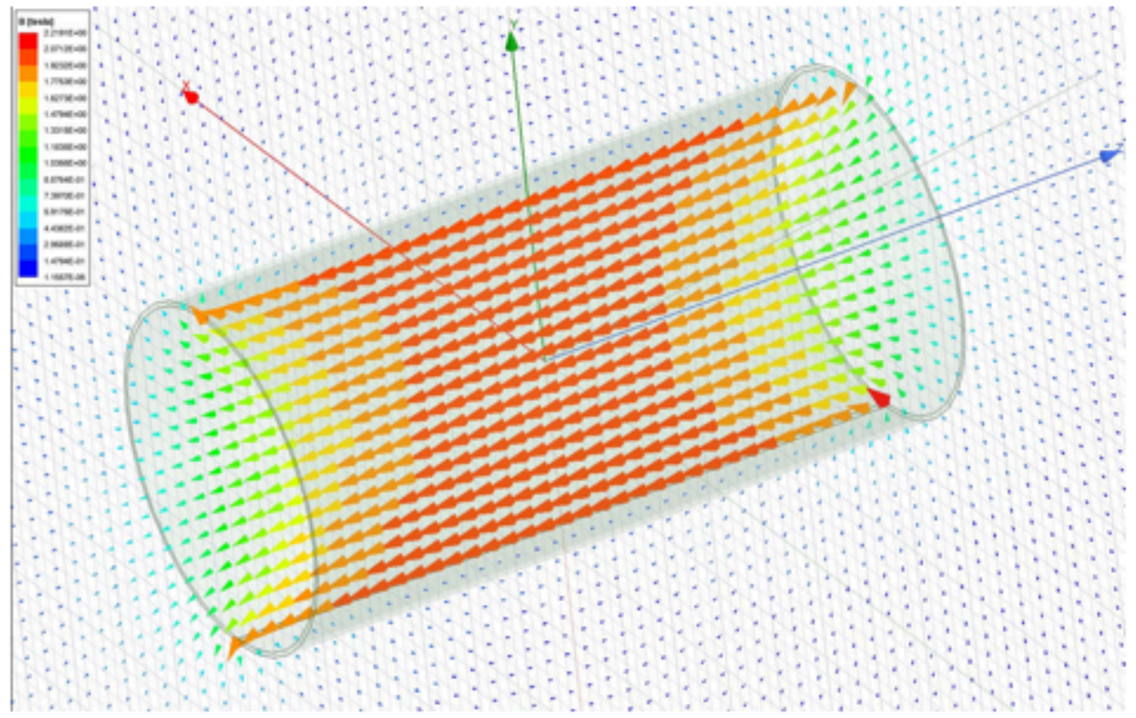
- **MCP-based solutions** (e.g. LAPPD)
  to be followed, suffer from magnetic field

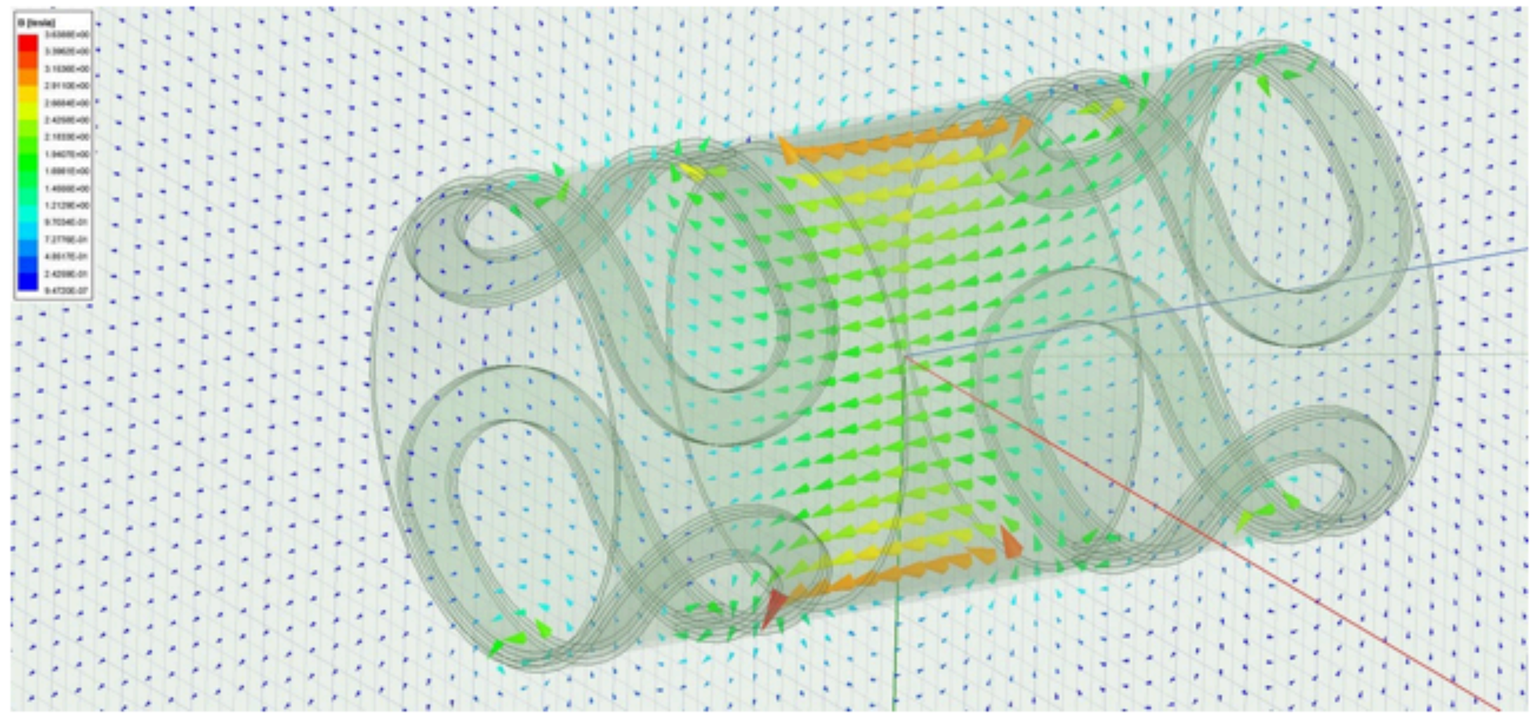
Requirements

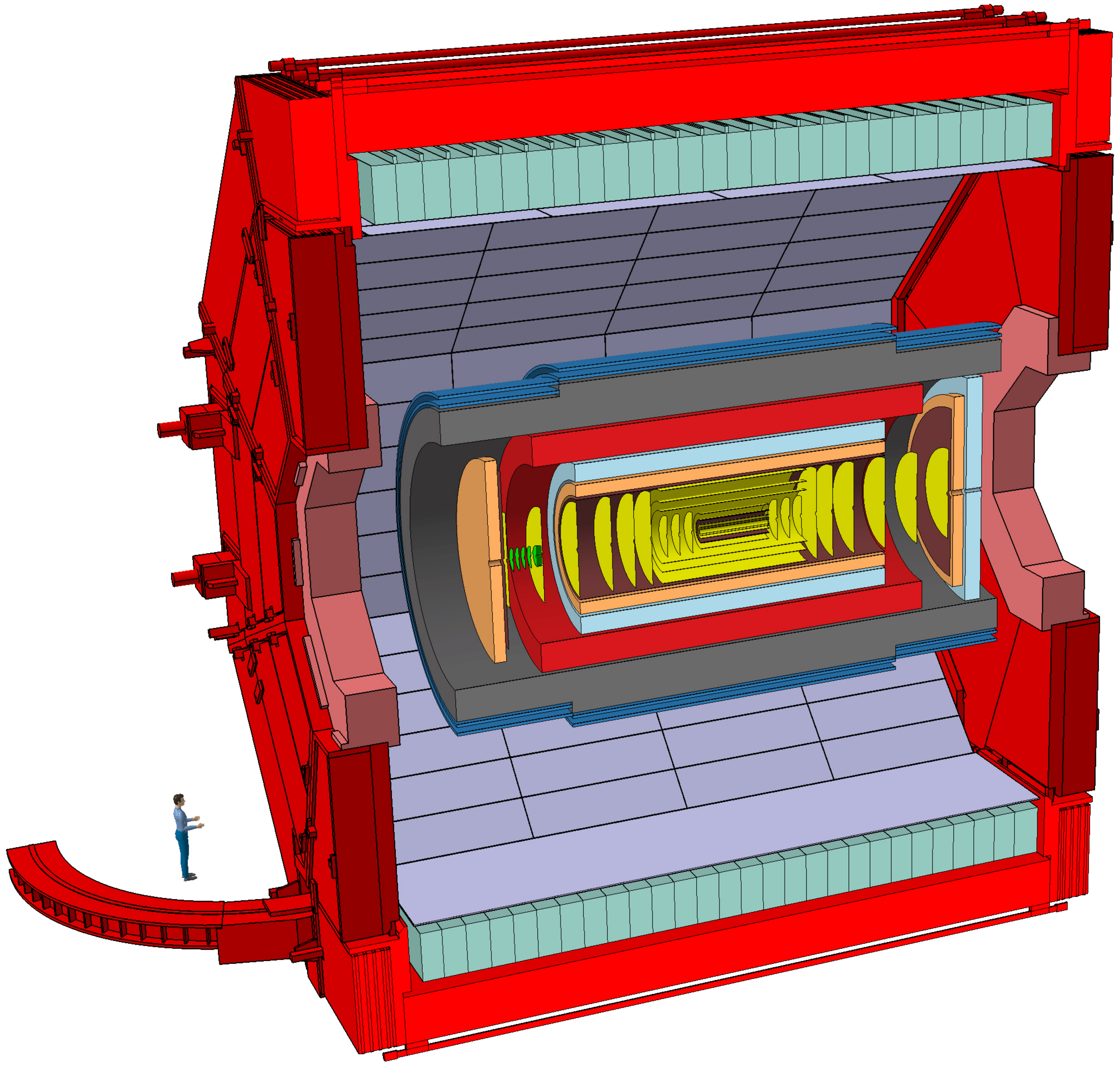
- PDE (visible light) > 40 - 50 %
- fill factor > 90 %
- time jitter < 100 ps
- total area O(50) m^2
- operation in magnetic field (up to 2 T)
- radiation load < 10^{12} 1 MeV n_{eq} / cm^2

Integration

- **Cryostat of 7 m length, free bore radius 1.5 m,** magnetic field configuration to be optimised
- **Installation of ALICE 3 around nominal IP2**
  - L3 magnet can remain, ALICE 3 to be installed inside







Conclusions

- **ALICE 3 is needed** to unravel the microscopic dynamics of the QGP
  - Properties of the QGP
  - Hadronisation and nature of hadronic states
  - Axion-like particles, ultra-soft photons, …
- **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!