

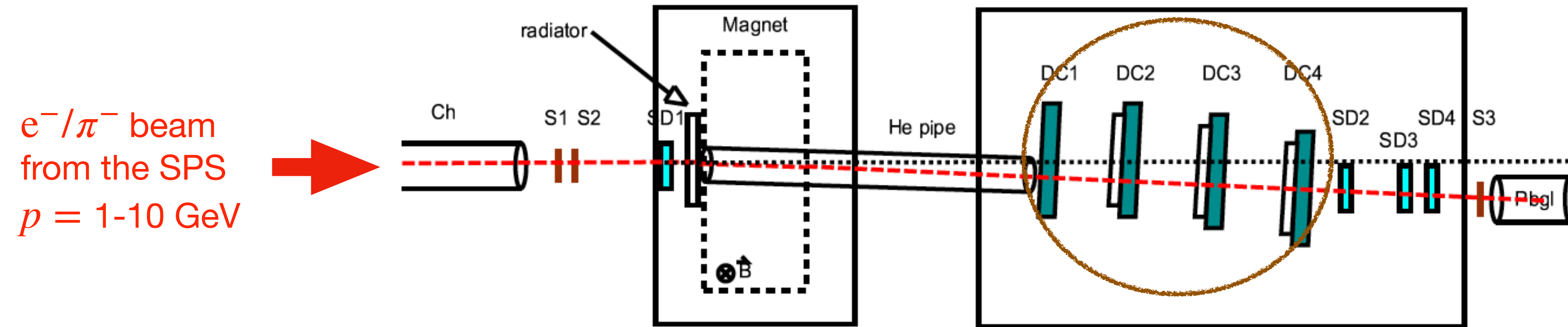
# As close as possible to the Big Bang: dilepton with ALICE 3

Raphaëlle Bailhache

Goethe-Universität Frankfurt am Main, Germany

# My first contact with electrons (and PBM !)

Testbeam of the ALICE Transition Radiation Detector prototypes at CERN in 2004



S1-S3. : three scintillator detectors for triggering

SD1-SD4: four silicon detectors as position reference

Ch and Pbgl: a Cherenkov detector and a lead glass calorimeter to identify independently the  $e^-$  and  $\pi^-$

DC1-DC4: four prototypes ALICE TRD chambers with and without radiators

# My first contact with electrons (and PBM !)

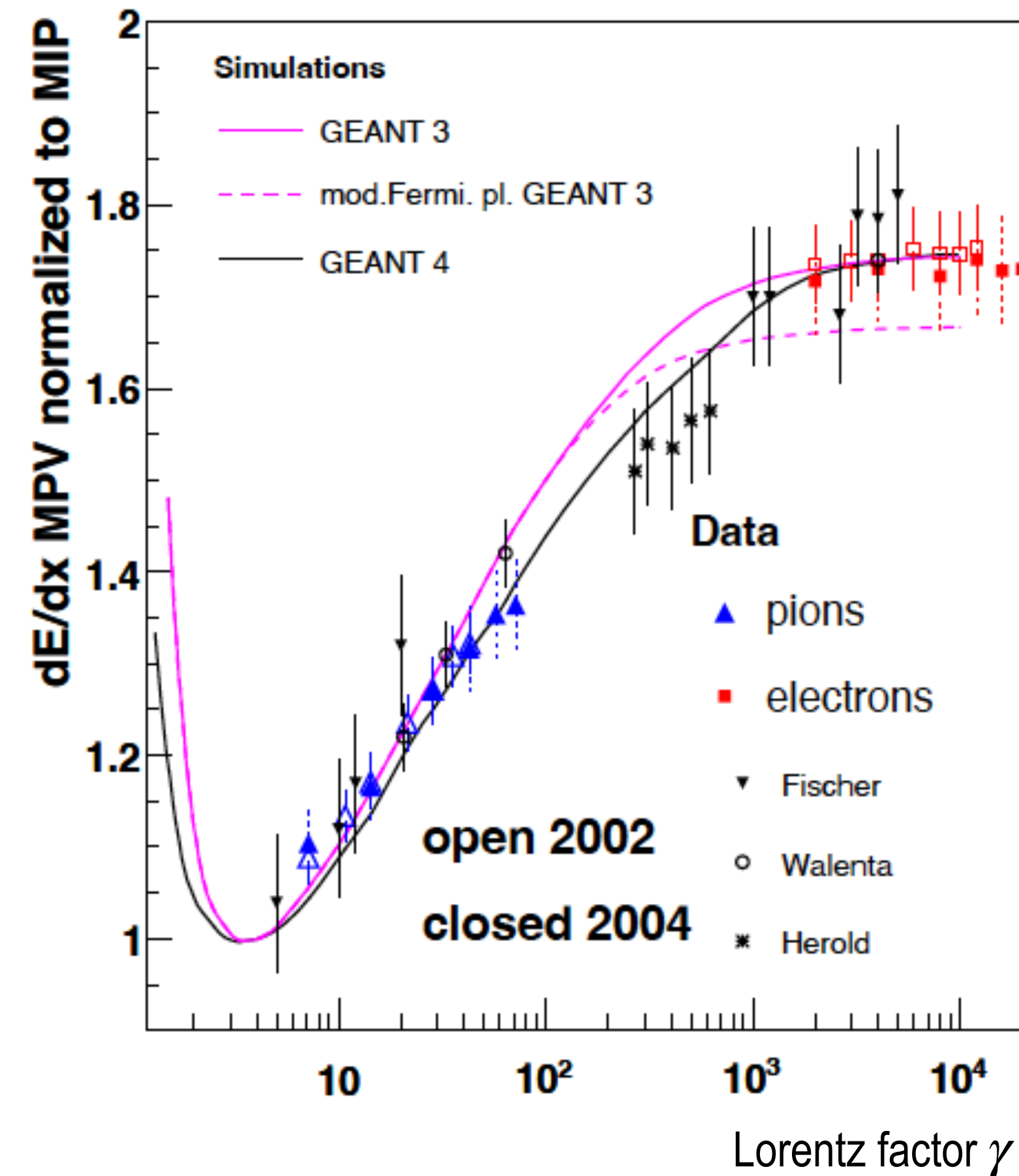
Testbeam of the ALICE Transition Radiation Detector prototypes at CERN in 2004

My diploma thesis. R. Bailhache et al.,  
Nucl. Instr. Meth. A563, 310-313, 2006.

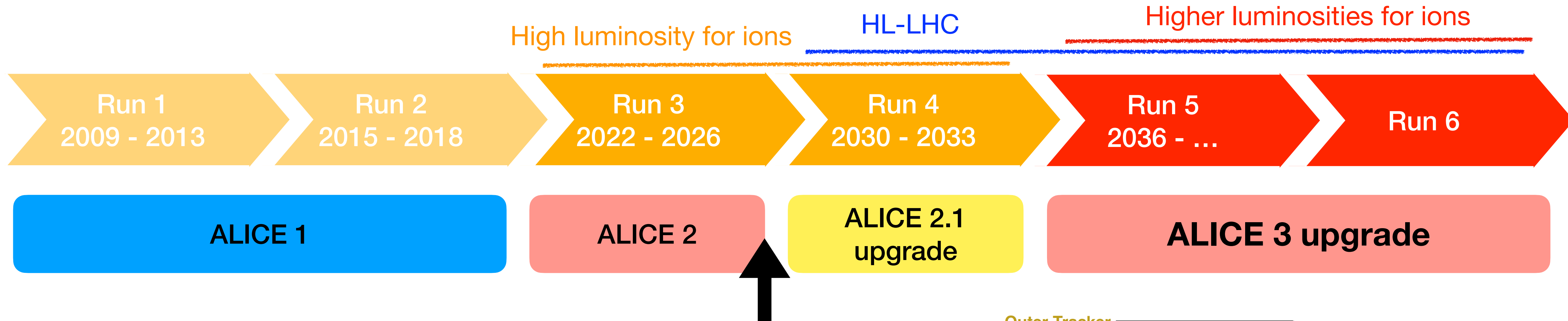
## One of the results:

Without the radiator, measurement of the most probable energy loss for  $\pi^-$  and  $e^-$  via ionisation in the Xe/CO<sub>2</sub>(15%) gas of the chambers

...and the beginning of an adventure



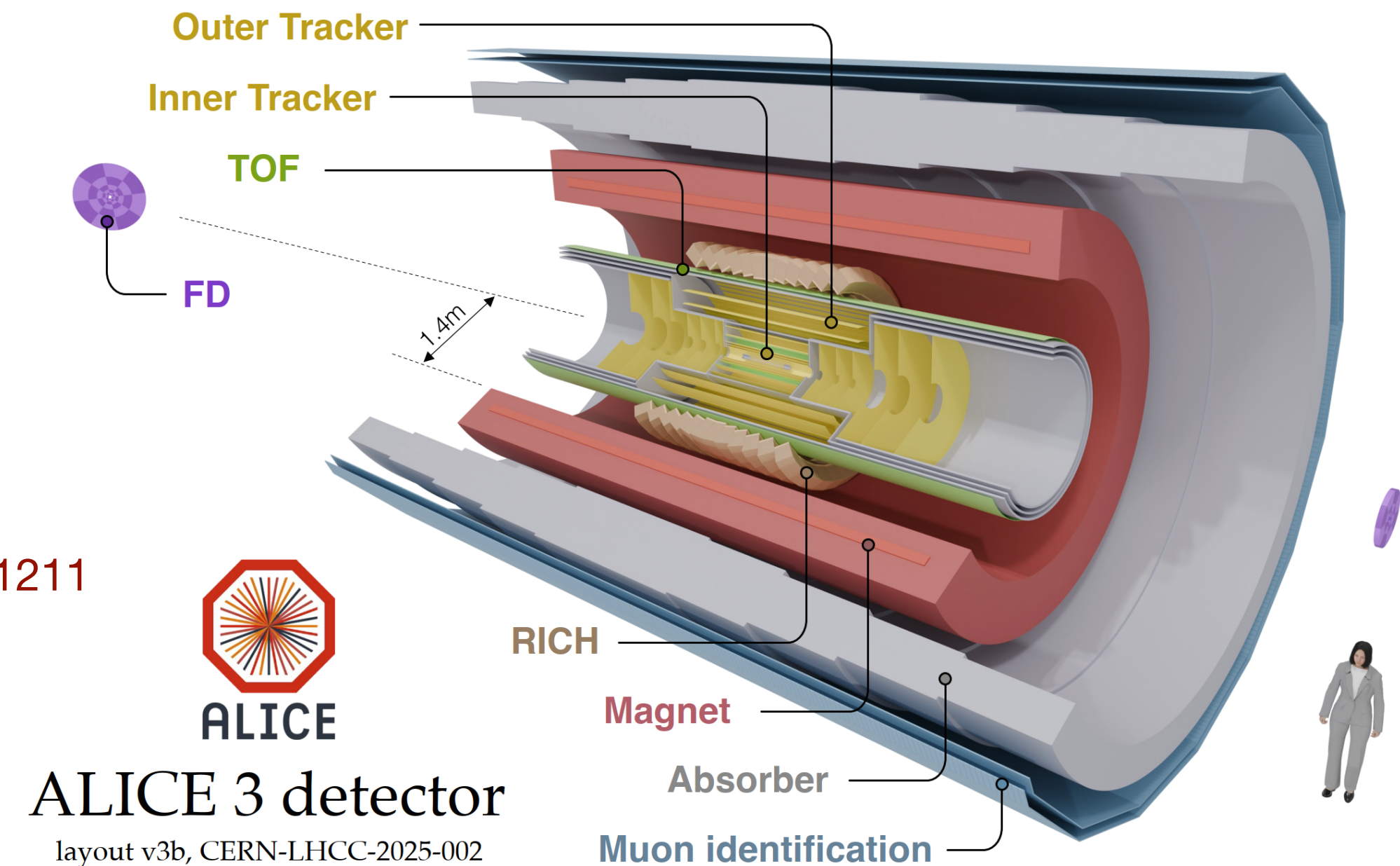
# ALICE timeline



## Beyond Run 4 (focus of this talk):

Address fundamental questions still open:

- First ideas at Heavy-Ion town meeting 2018 [D.Adamova et al. ArXiv:1902.01211](#)
- Letter of Intent for **ALICE 3**: 2022 [CERN-LHCC-2022-009](#)
- Scoping document of **ALICE 3**: 2025 [CERN-LHCC-2025-002](#)

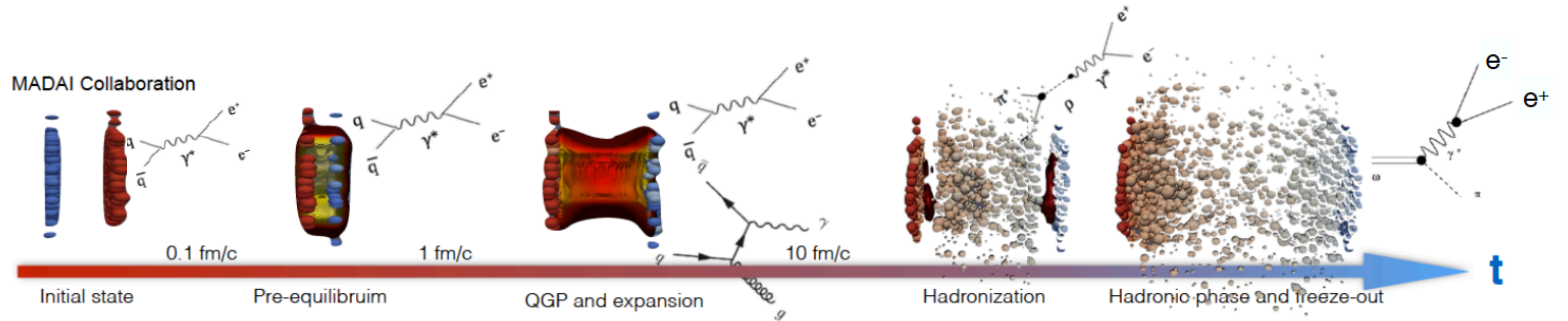


**ALICE**  
**ALICE 3 detector**  
layout v3b, CERN-LHCC-2025-002

Intermediate upgrade

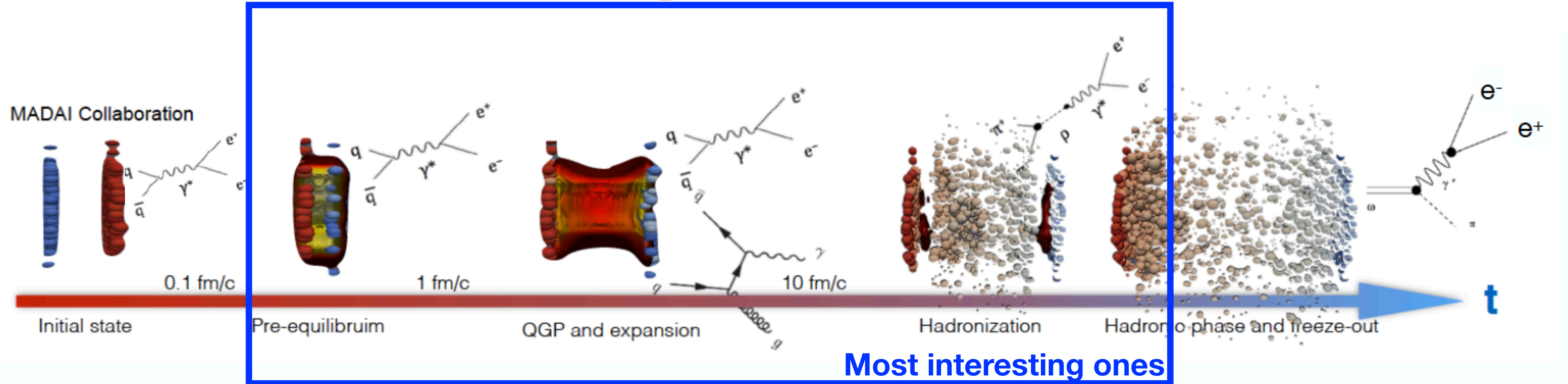
Major upgrade

# Motivations for dilepton measurements



Dileptons produced at (almost) all stages of the heavy-ion collision with negligible final-state interactions  
→ Carry information from the whole space-time evolution of the system

# Motivations for dilepton measurements

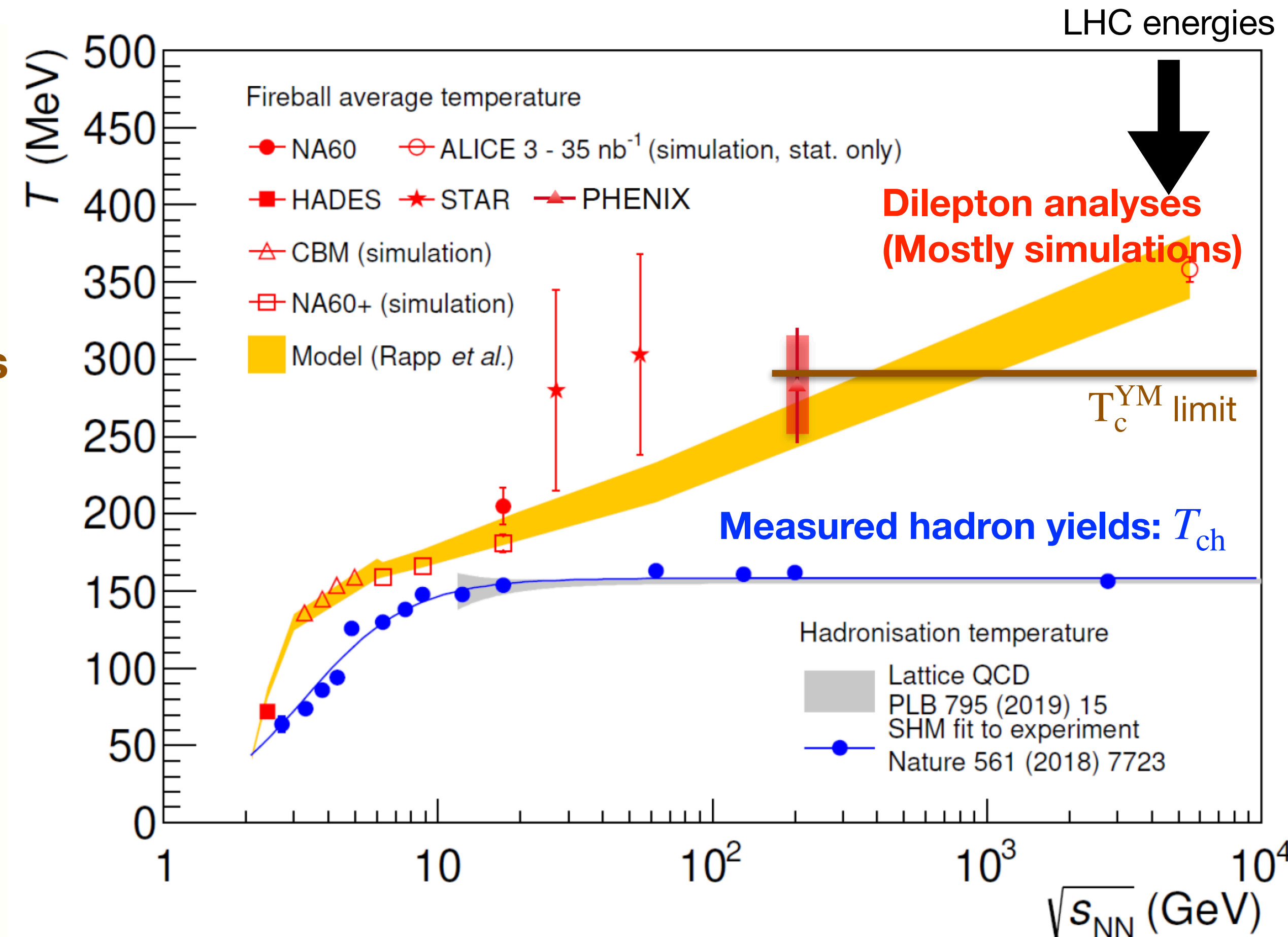


- **Pre-equilibrium phase:** radiation before the hydrodynamic phase  $\rightarrow$  kinetic and chemical equilibration time
- **Quark-Gluon-Plasma:** thermal radiation from the QGP  $\rightarrow$  temperature
- **Hadronic phase:** modified spectral function of  $\rho$  mesons produced in the hot medium  $\rightarrow$  chiral symmetry

Different contributions **can be disentangled using the invariant mass:** larger  $m_{l^+l^-} \rightarrow l^+l^-$  emitted earlier

# Goals for Run 3 + 4

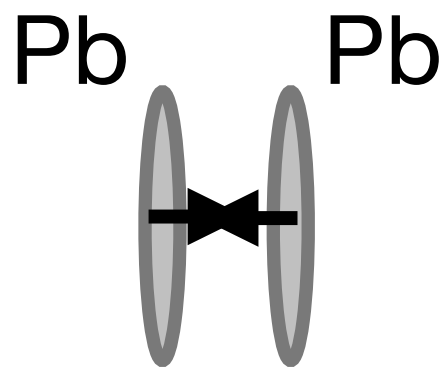
- First temperature measurements of the thermalised QGP  
→ First answer if this temperature
  - **Increases from RHIC to LHC**
  - **Or saturates due to the needed presence of quarks in the medium to produce  $l^+l^-$**
- Patterns indicative of chiral symmetry restoration
- First flow measurements



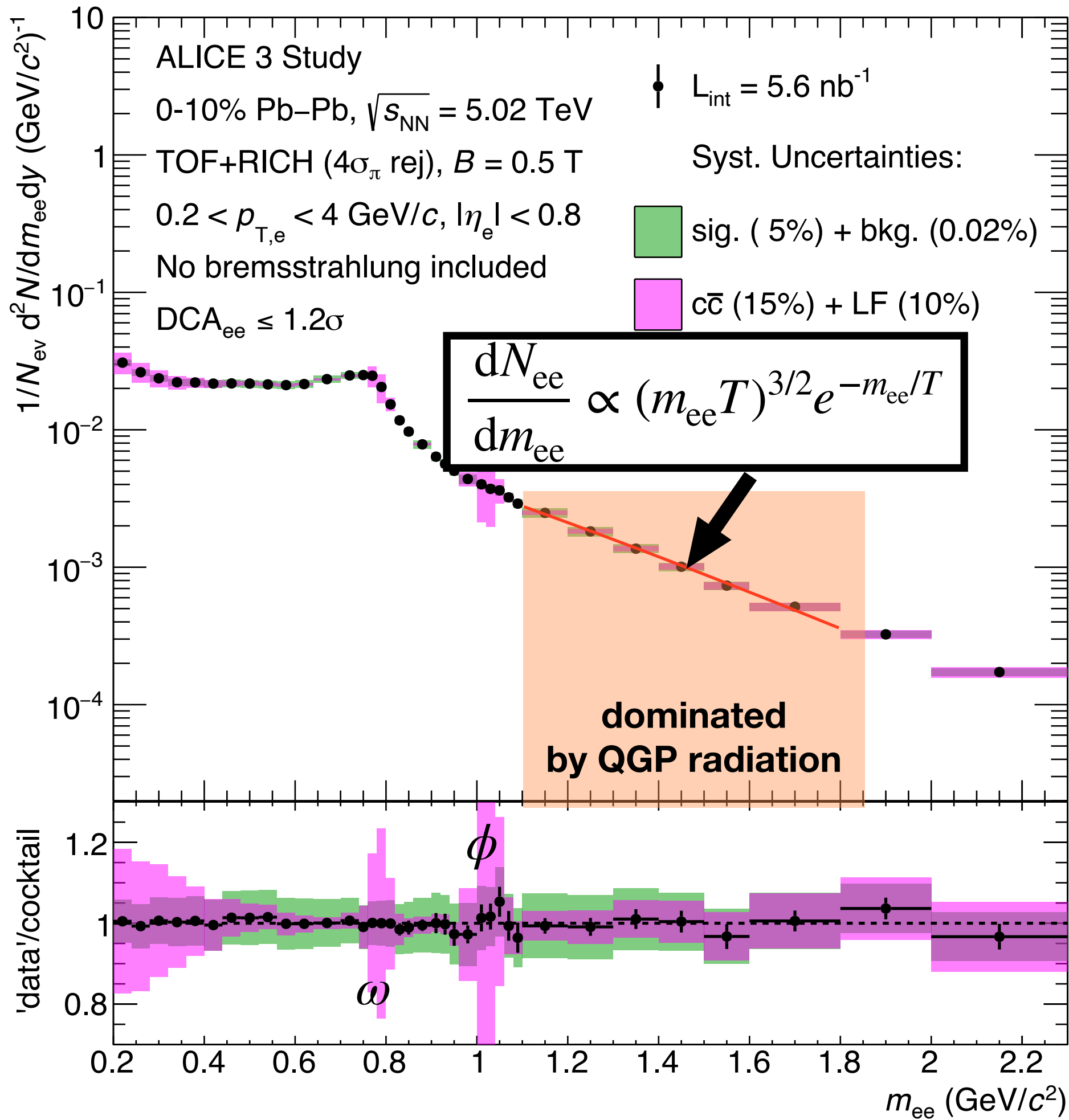
Established model at SPS, RHIC energies:  
 R. Rapp, Adv. High Energy Phys. 2013 (2013) 148253  
 P.M Hohler and R. Rapp, Phys. Lett. B 731 (2014) 103  
 Alternative idea:  
 H. Stoecker et al., arXiv:2603.24219  
 S. Borsanyio et al., Phys. Rev. D 105 (2022) 074513

# Beyond 2033

- Temperature measurements of the thermalised QGP
  - Differential measurements with ALICE 3 ( $m_{ee}, p_{T,ee}$ )
  - Probe time dependence

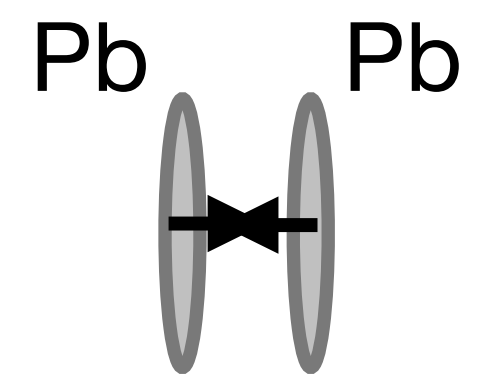


Simulated excess  $m_{ee}$  spectrum with ALICE 3



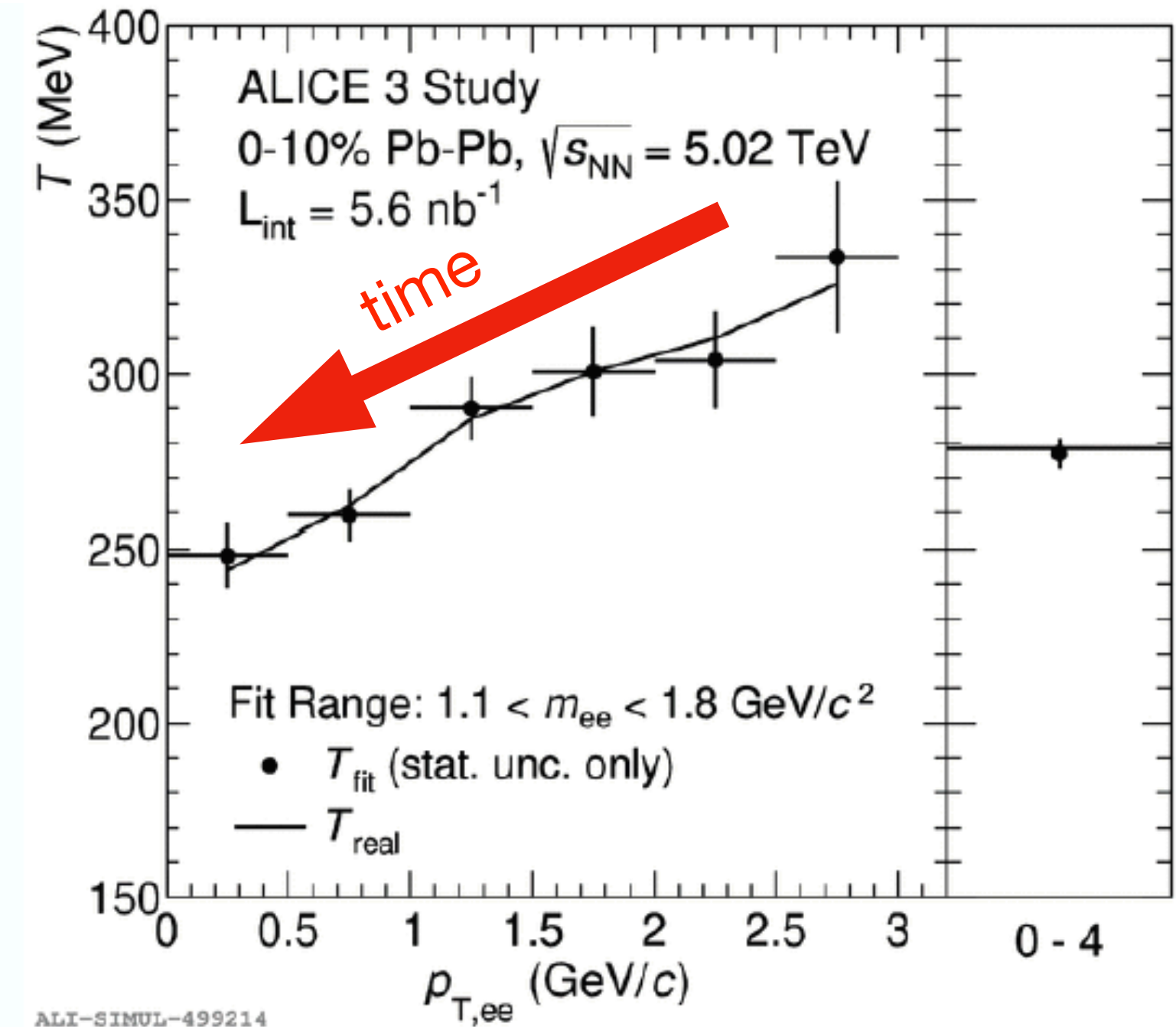
ALICE 3 Letter-of-Intent CERN-LHCC-2022-009

# Beyond 2033



Simulated measurements with ALICE 3

- Temperature measurements of the thermalised QGP
  - Differential measurements with ALICE 3 ( $m_{ee}, p_{T,ee}$ )
  - Probe time dependence

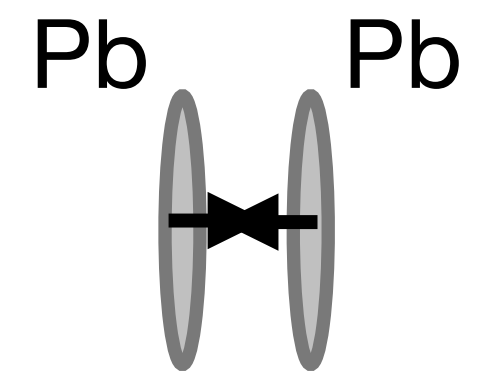


Fit of  $m_{ee}$  spectrum → Average temperature

Fit for different  $p_{T,ee}$  → Probe time dependence of  $T$

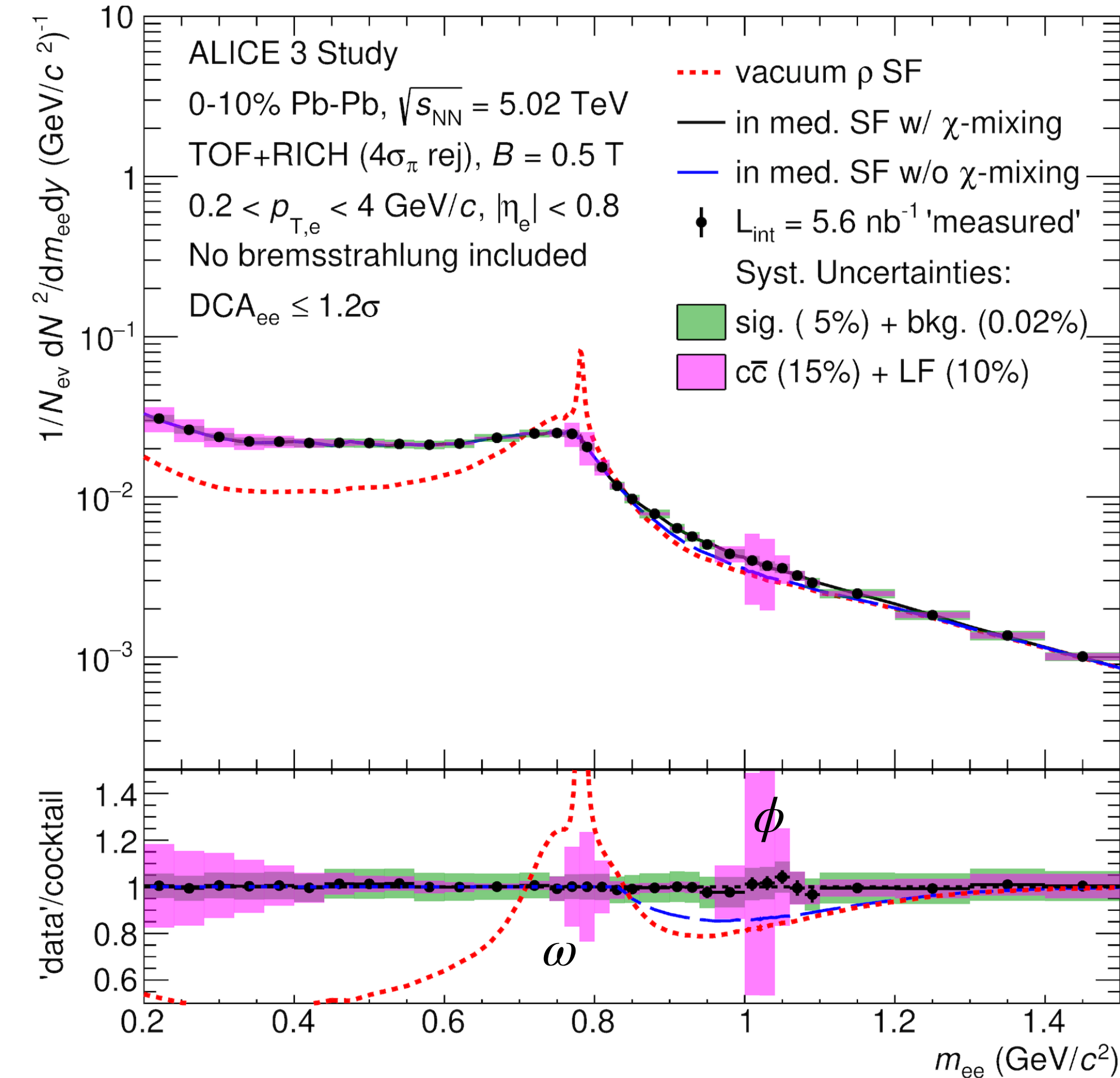
ALICE 3 Letter-of-Intent CERN-LHCC-2022-009

# Beyond 2033



- Temperature measurements of the thermalised QGP
  - Differential measurements with ALICE 3 ( $m_{ee}, p_{T,ee}$ )
  - Probe time dependence
- Study in detail mechanisms of chiral symmetry restoration
  - Precision measurement of  $\rho$  spectral function of a large  $m_{ee}$  range
  - Sensitive among others to  $\rho - a_1$  chiral mixing
- Differential measurements to establish the origin of  $1^+1^-$ 
  - $p_{T,ee}$  (or  $m_{T,ee}$ ) sensitive to radial flow
  - Elliptic flow
  - Polarisation sensitive to production mechanisms

## Simulated excess $m_{ee}$ spectrum with ALICE 3



ALI-SIMUL-498140

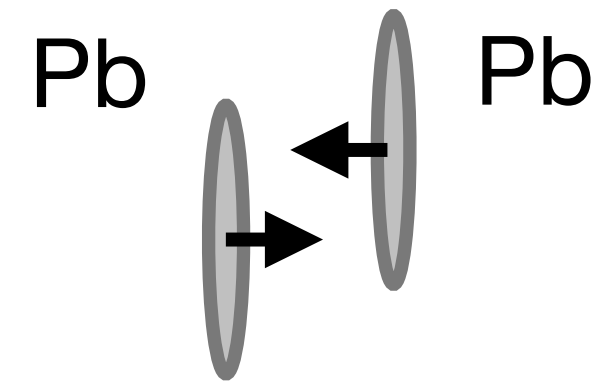
P.M Hohler and R. Rapp, Phys. Lett. B 731 (2014) 103

R. Rapp private communication

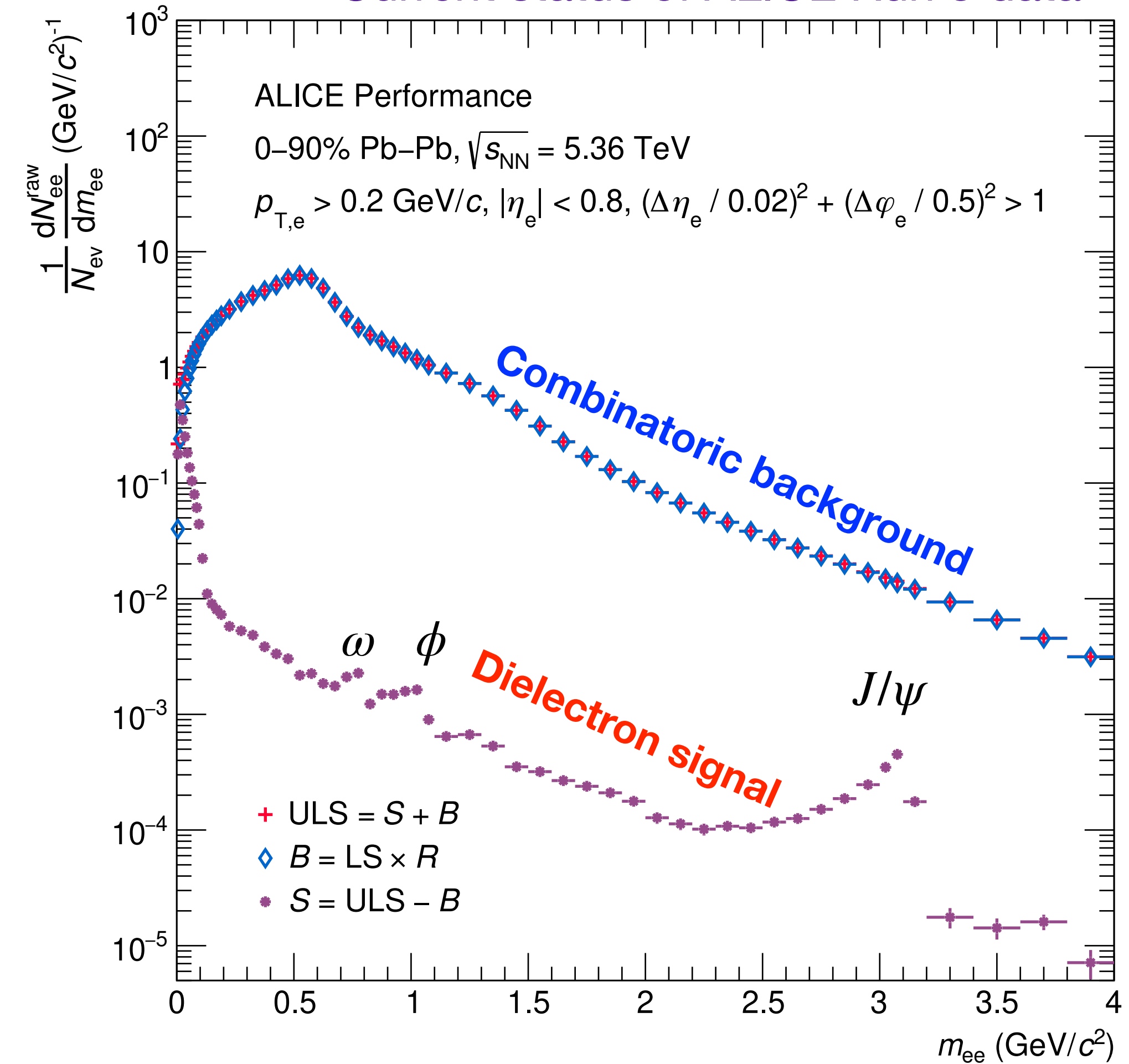
ALICE 3 Letter-of-Intent CERN-LHCC-2022-009

# The challenges

- Small production cross sections
  - Internal conversion probability of  $\gamma^*$  around  $10^{-2}$
  - $10^2$  more hadrons
- Need high readout rates capabilities
- Need very high quality electron/muon identification capabilities
- Large combinatoric background
  - Need low  $p_T$  tracking and particle identification capabilities
  - Need uniform ( $2\pi$  azimuthal) coverage



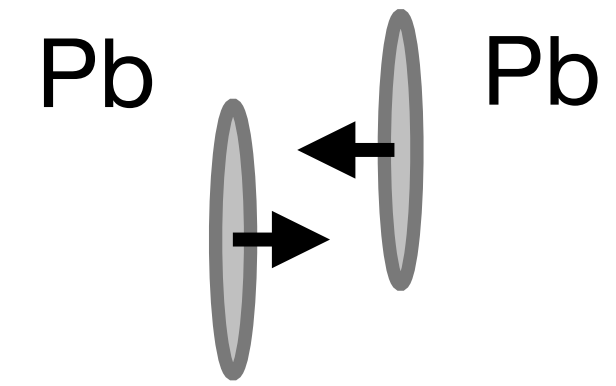
Current status of ALICE Run 3 data



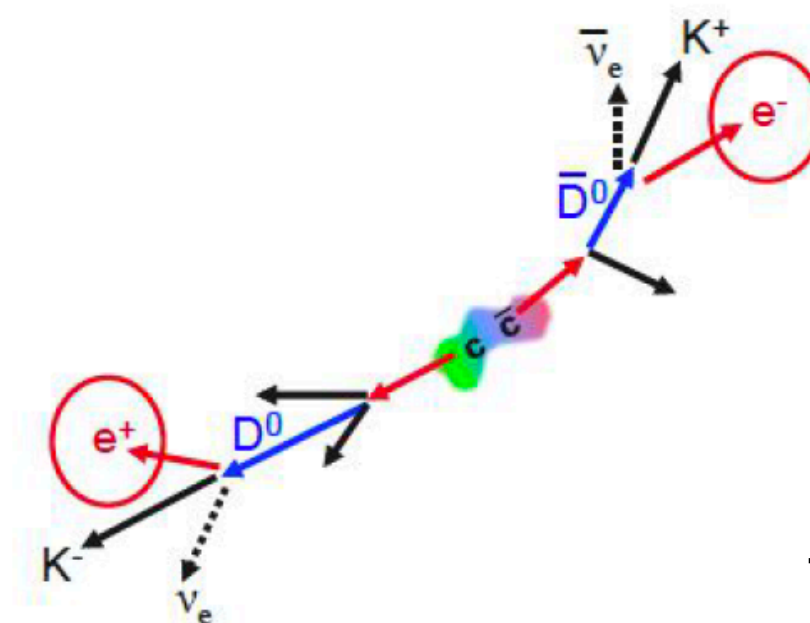
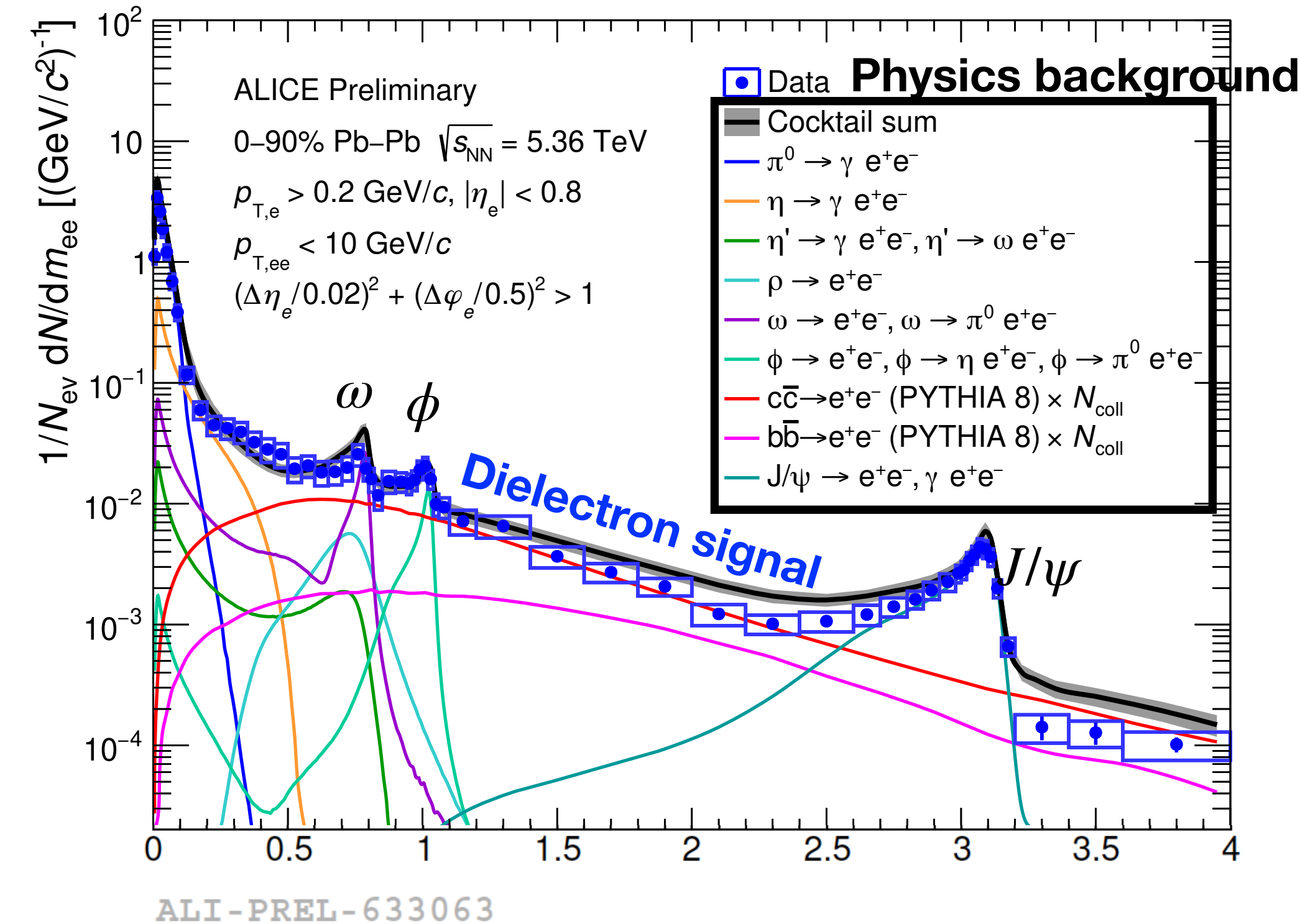
ALI-PERF-633197

# The challenges

- Small production cross sections
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 → Need high readout rates capabilities  
 → Need very high quality electron/muon identification capabilities
- Large combinatoric background
  - Need low  $p_T$  tracking and particle identification capabilities
  - Need uniform ( $2\pi$  azimuthal) coverage
- Very large physics background from hadronic decays in particular heavy-flavour hadron decays
  - Need very good pointing resolution to handle it



Current status of ALICE Run 3 data

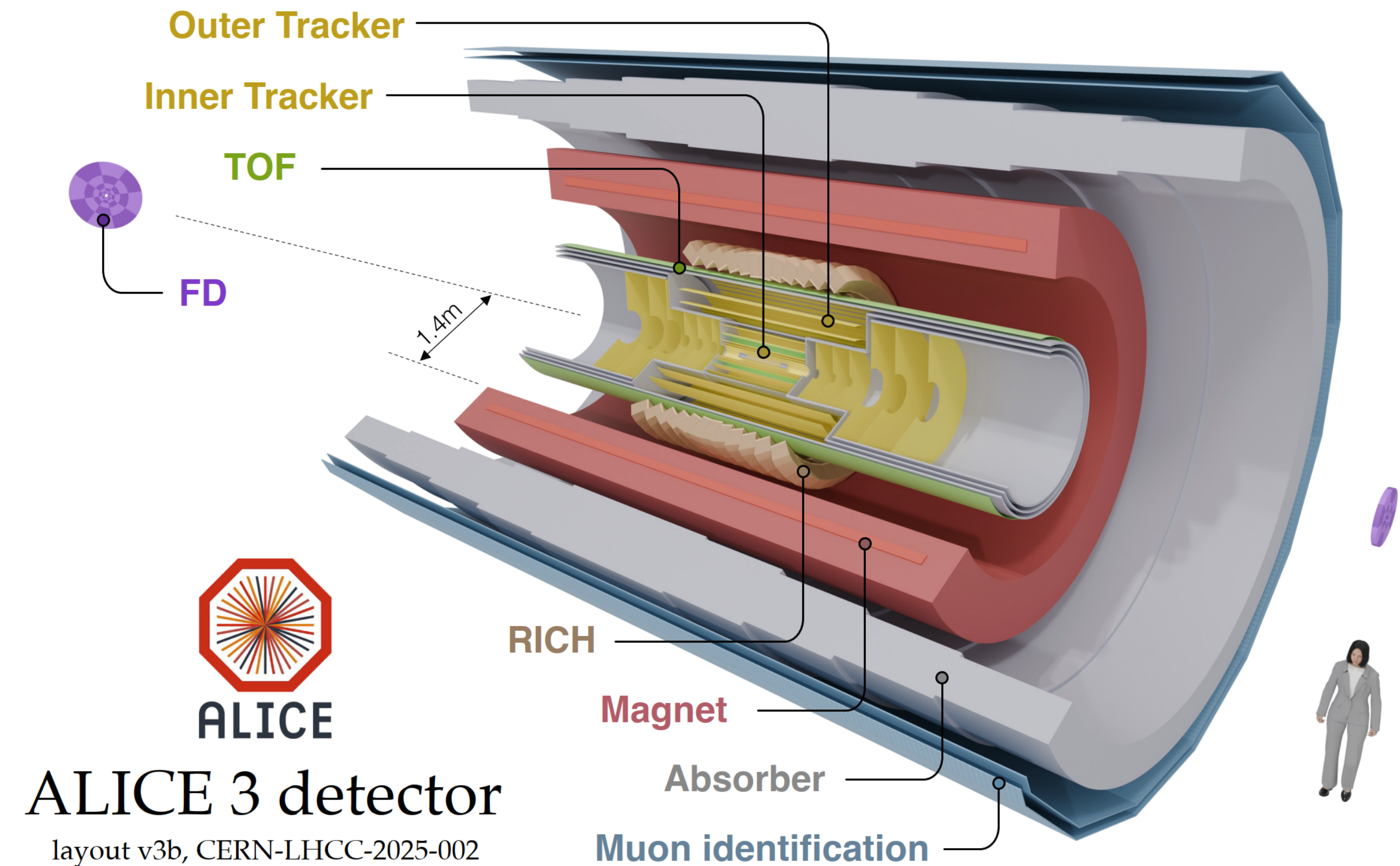


$$c\bar{c} \rightarrow e^+e^-$$

$c\tau \approx 150$  (450)  $\mu\text{m}$   
for charm (beauty) hadrons

# ALICE 3 detector concept

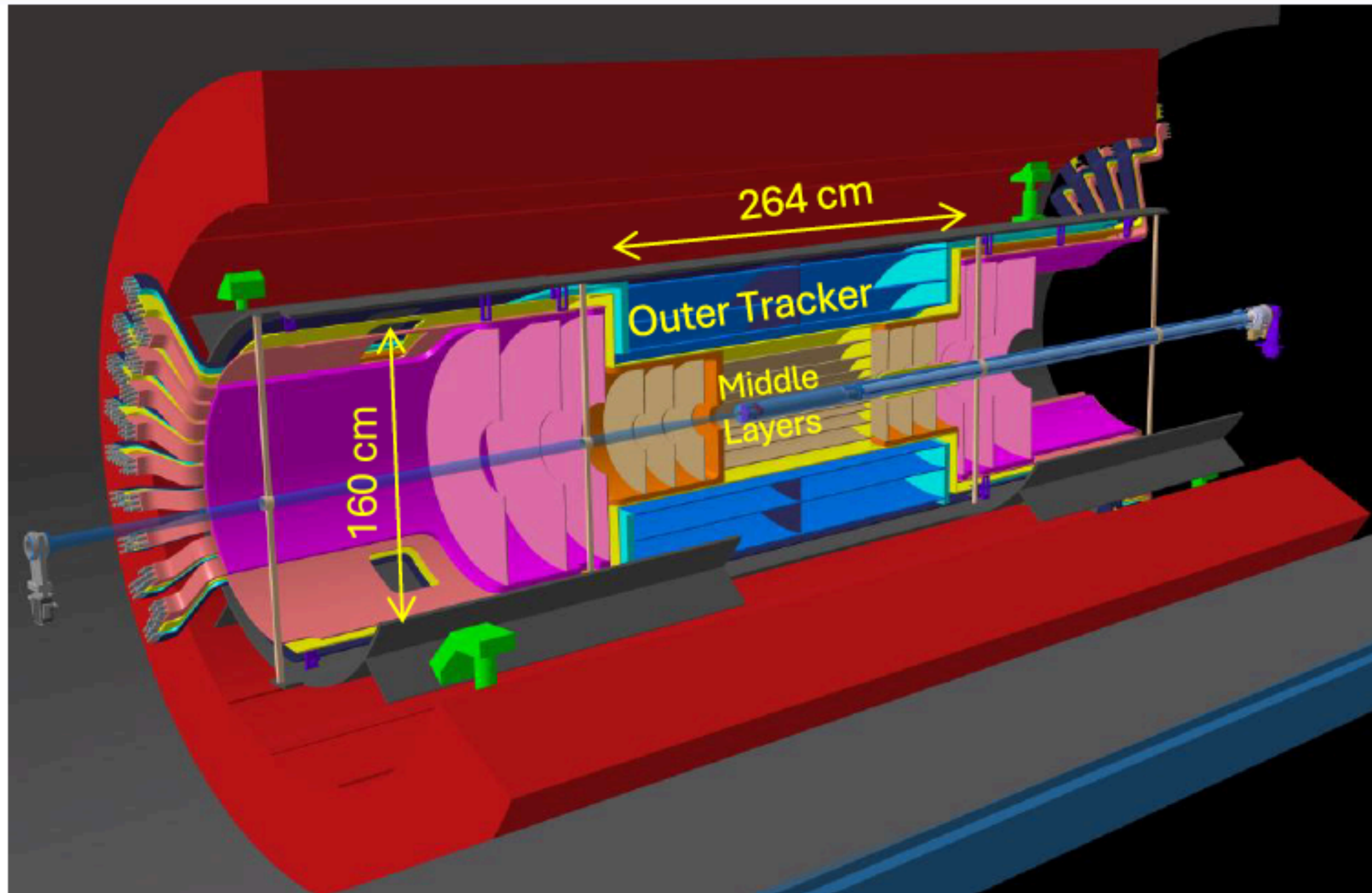
- Compact all-silicon tracker
- Retractable vertex detector with very good pointing resolution
- Particle identification  $\gamma, e^\pm, \mu^\pm, K^\pm, \pi^\pm$  down to low  $p_T$
- Superconducting solenoid,  $B = 2T$  + low B field runs
- Continuous read-out and online processing with high-rate capabilities



| Interaction rates | ALICE Run 3, 4 | ALICE 3  |
|-------------------|----------------|----------|
| pp                | 500 kHz-1 MHz  | 24 MHz   |
| Pb-Pb             | 50 kHz         | 100* kHz |

\*current HL-LHC projection

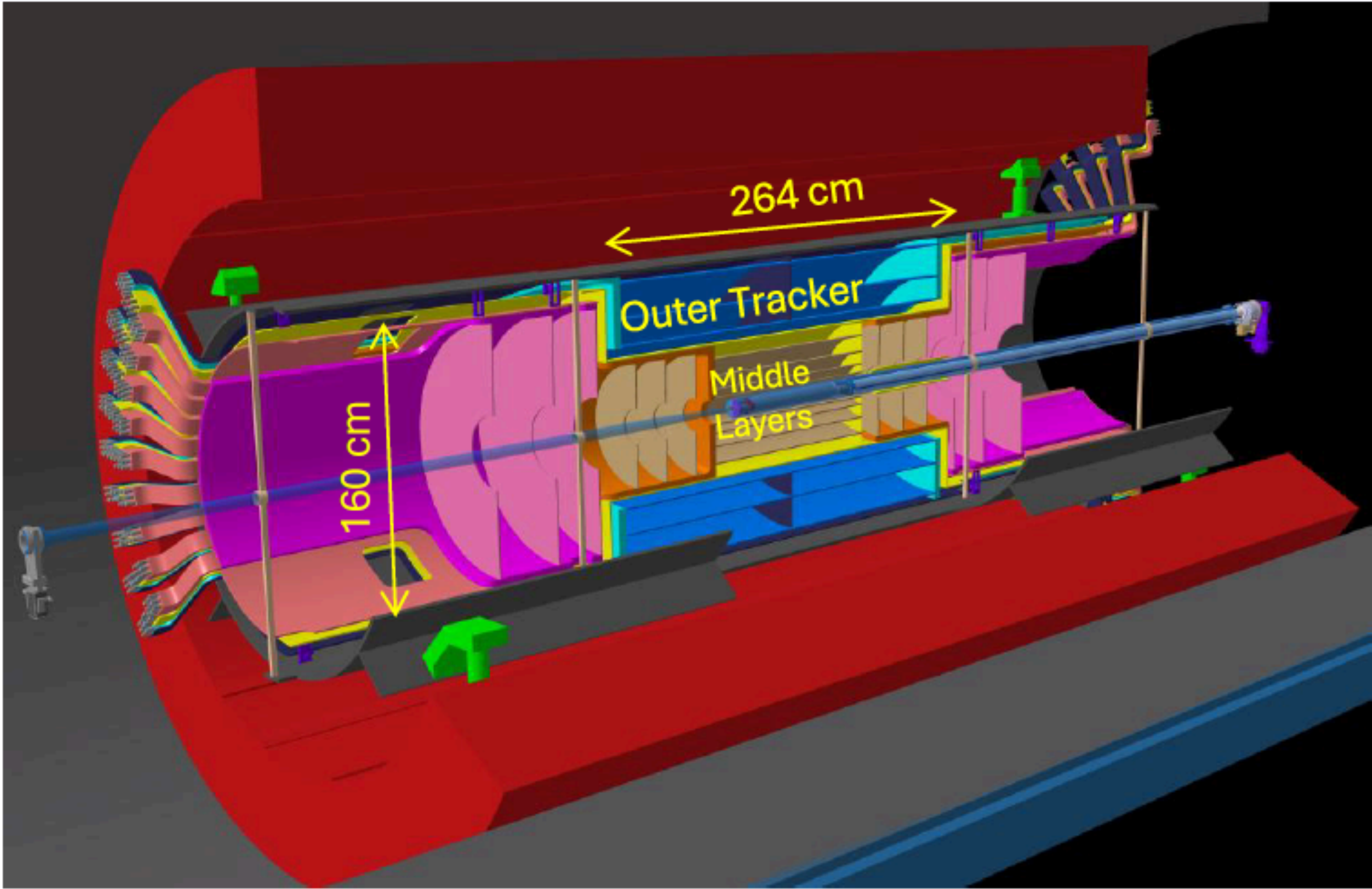
# Tracker



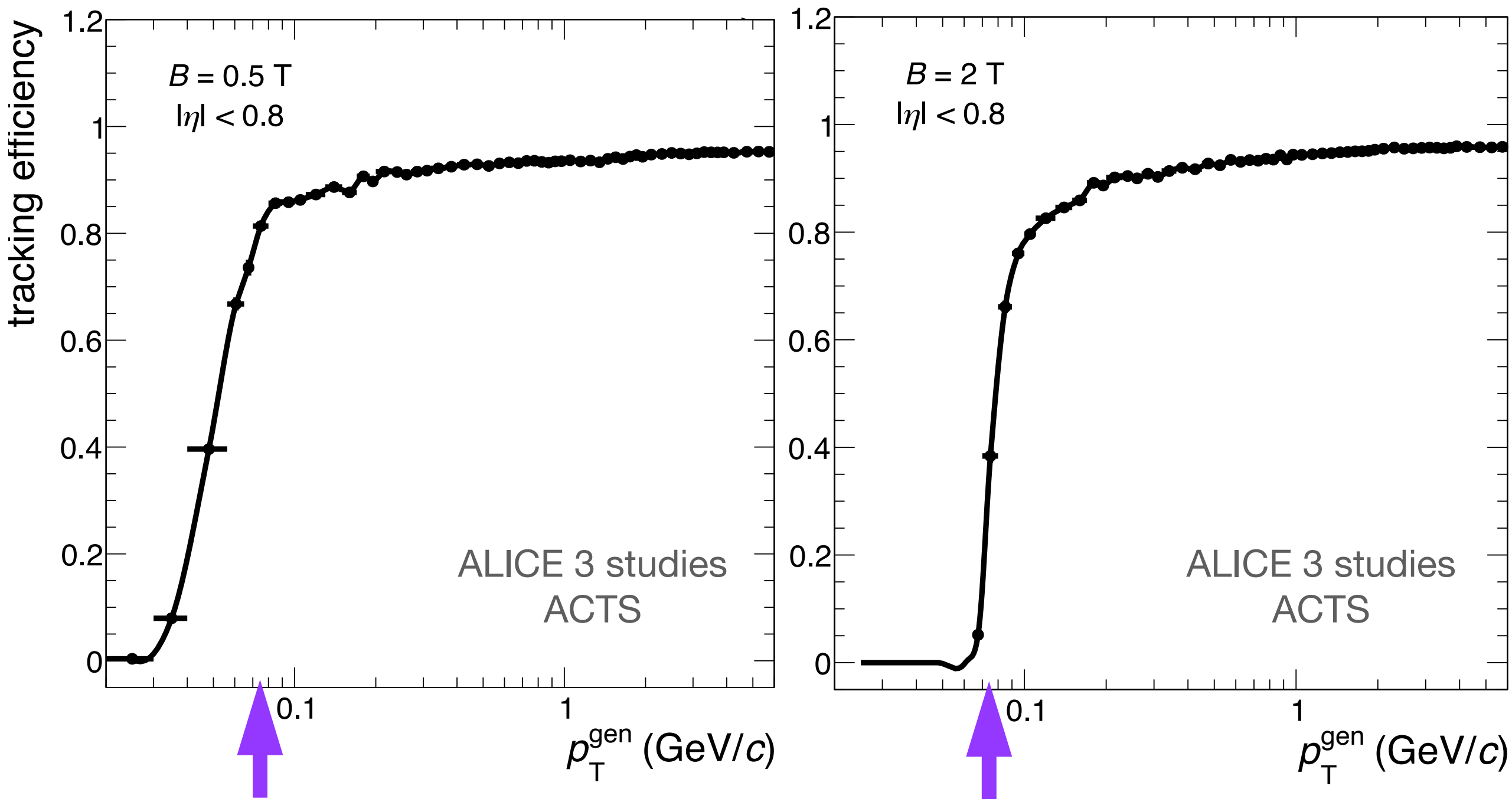
Very large Monolithic Active Pixel Sensor-based tracker !

- $47 \text{ m}^2, \pm 2.5 \eta$
- At mid rapidity:
  - 3 Outer layers at radius of 45, 60 and 80 cm
  - 5 middle layers at radius of 7, 9, 12, 20 and 30 cm
- Low material budget (for a silicon tracker):  $\sim 1\% X_0/\text{layer}$
- Time resolution: 100 ns, low power: 20 mW/cm<sup>2</sup>
- Main R&D challenge: its size
  - Power consumption and distribution
  - Module design for industrial production

# Tracker



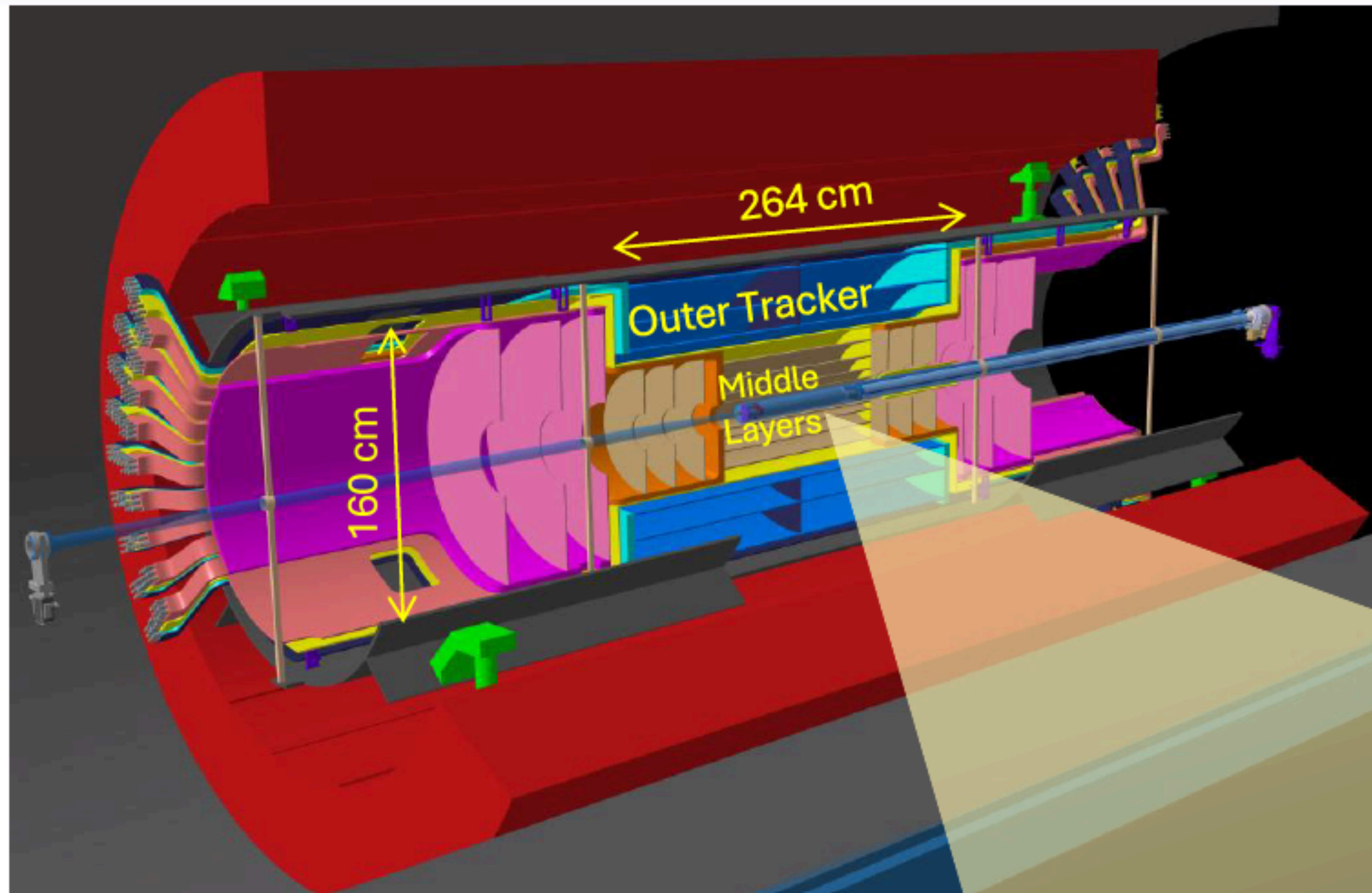
Tracking efficiency for electrons to reach at least the 7th layers



| Detector | Radius (m) | $p_{T,\text{min}}$ threshold (GeV/c) |         |
|----------|------------|--------------------------------------|---------|
|          |            | B = 0.5 T                            | B = 2 T |
| iTOF     | 0.21       | 0.02                                 | 0.06    |

→ Current ALICE goes down to  $\sim 0.075$  GeV/c with low B field runs

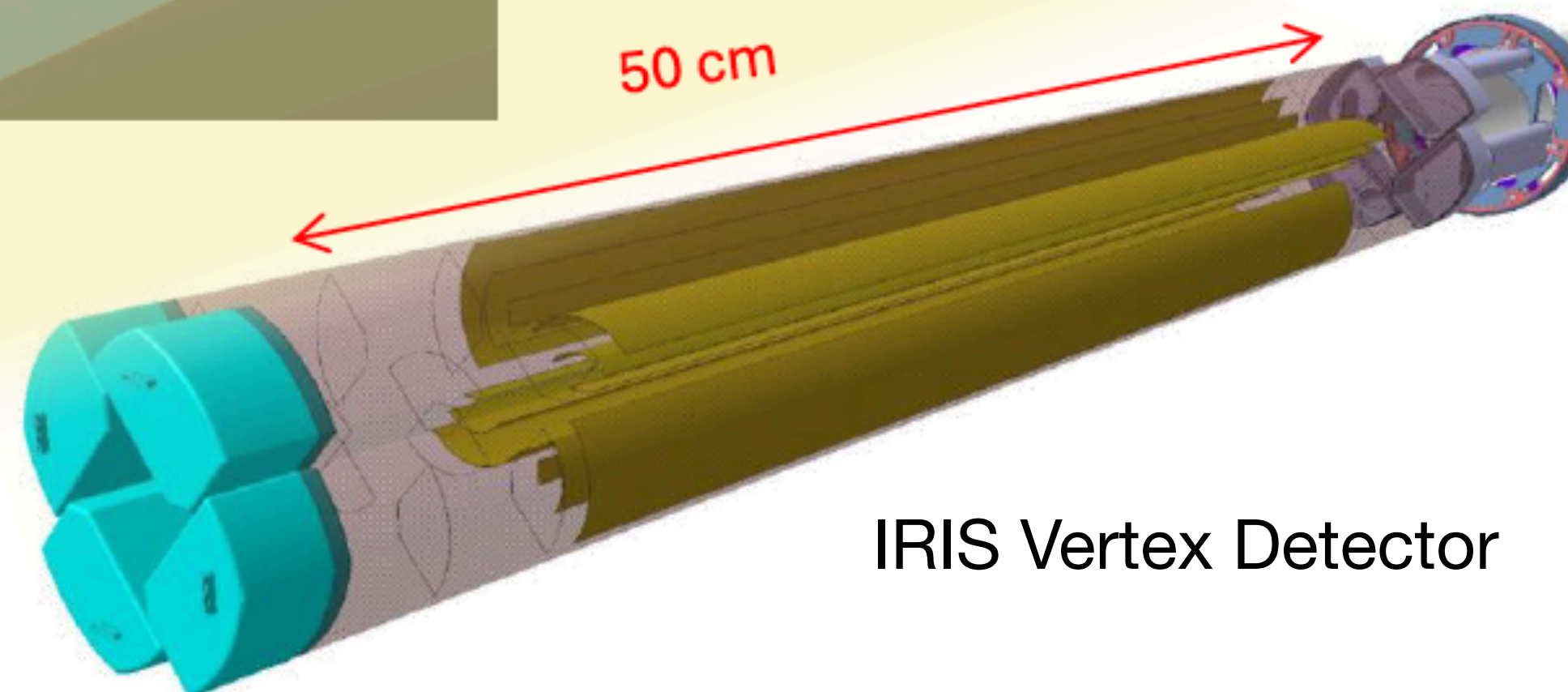
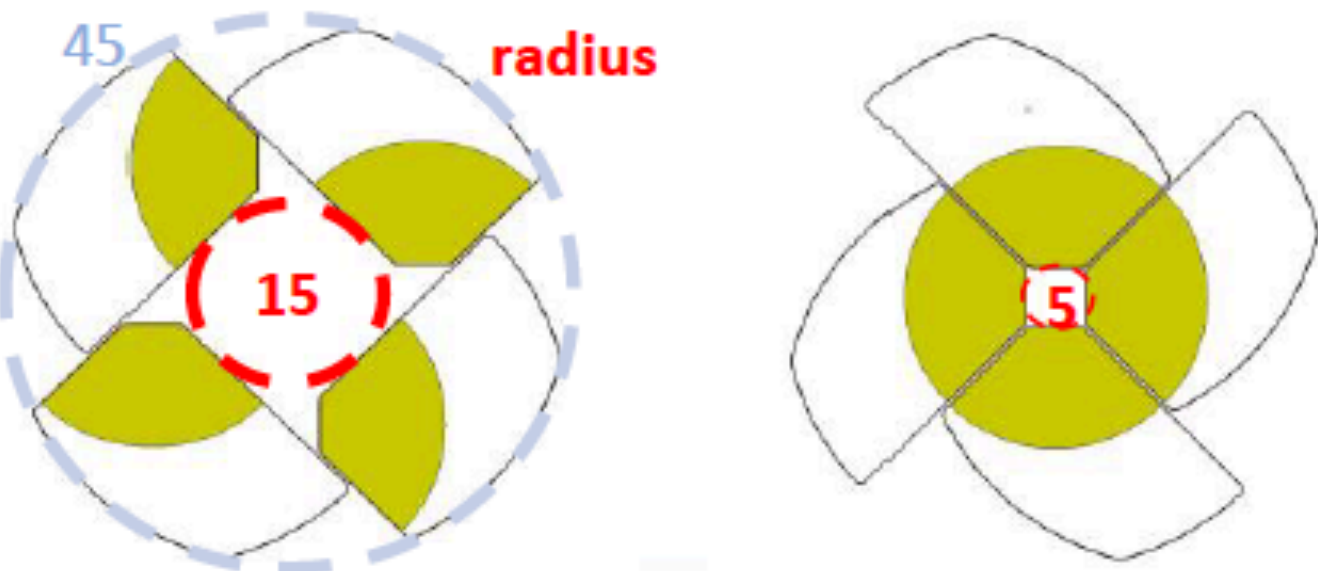
# Vertex detector



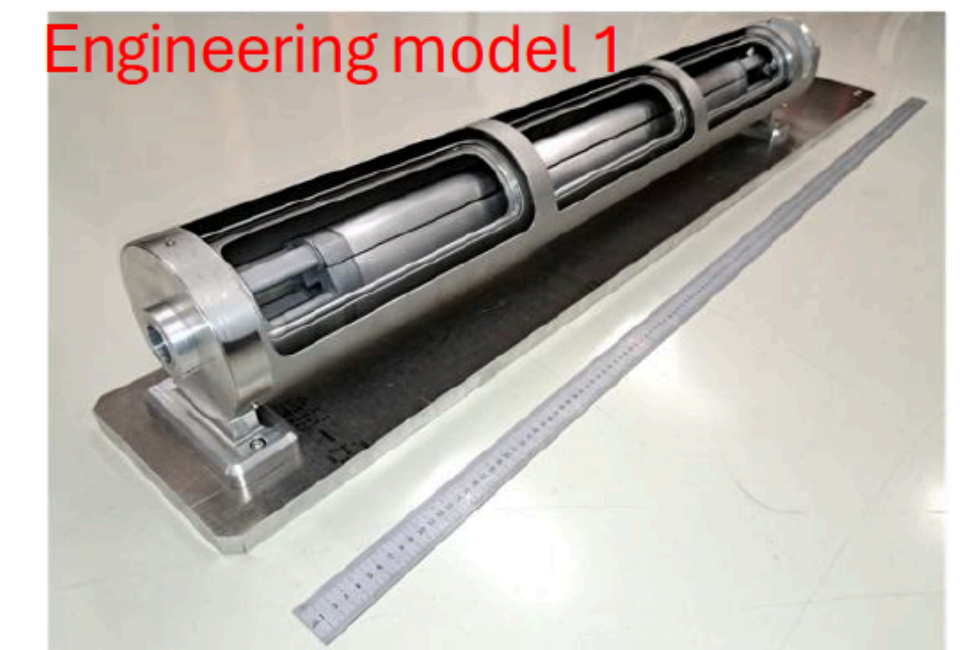
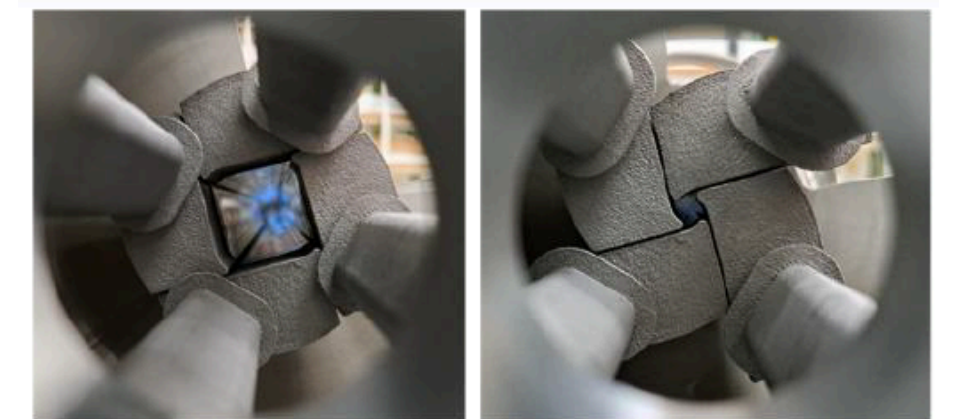
Wafer-scale, truly cylindrical Monolithic Active Pixel Sensor

- Radial distance from interaction point: 5 mm (Inside beampipe, retractable configuration)
- Unprecedented pointing resolution
- Ultra-light, material budget  $\approx 0.1\% X_0/\text{layer}$
- Time resolution: 100 ns, low power: 70 mW/cm<sup>2</sup>

Pushes the technology on many fronts

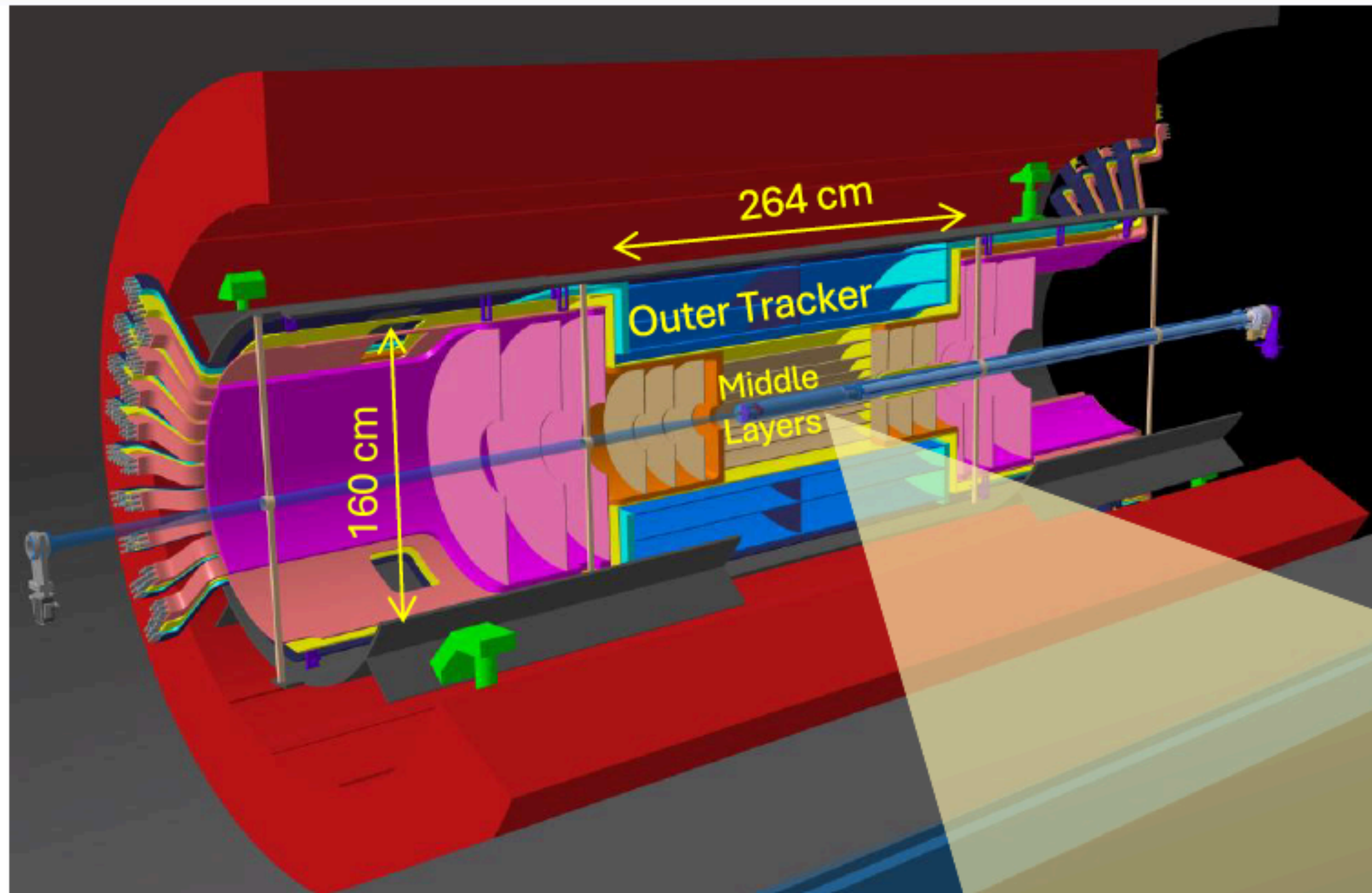


IRIS Vertex Detector



Full scale IRIS prototype for mechanical tests

# Vertex detector

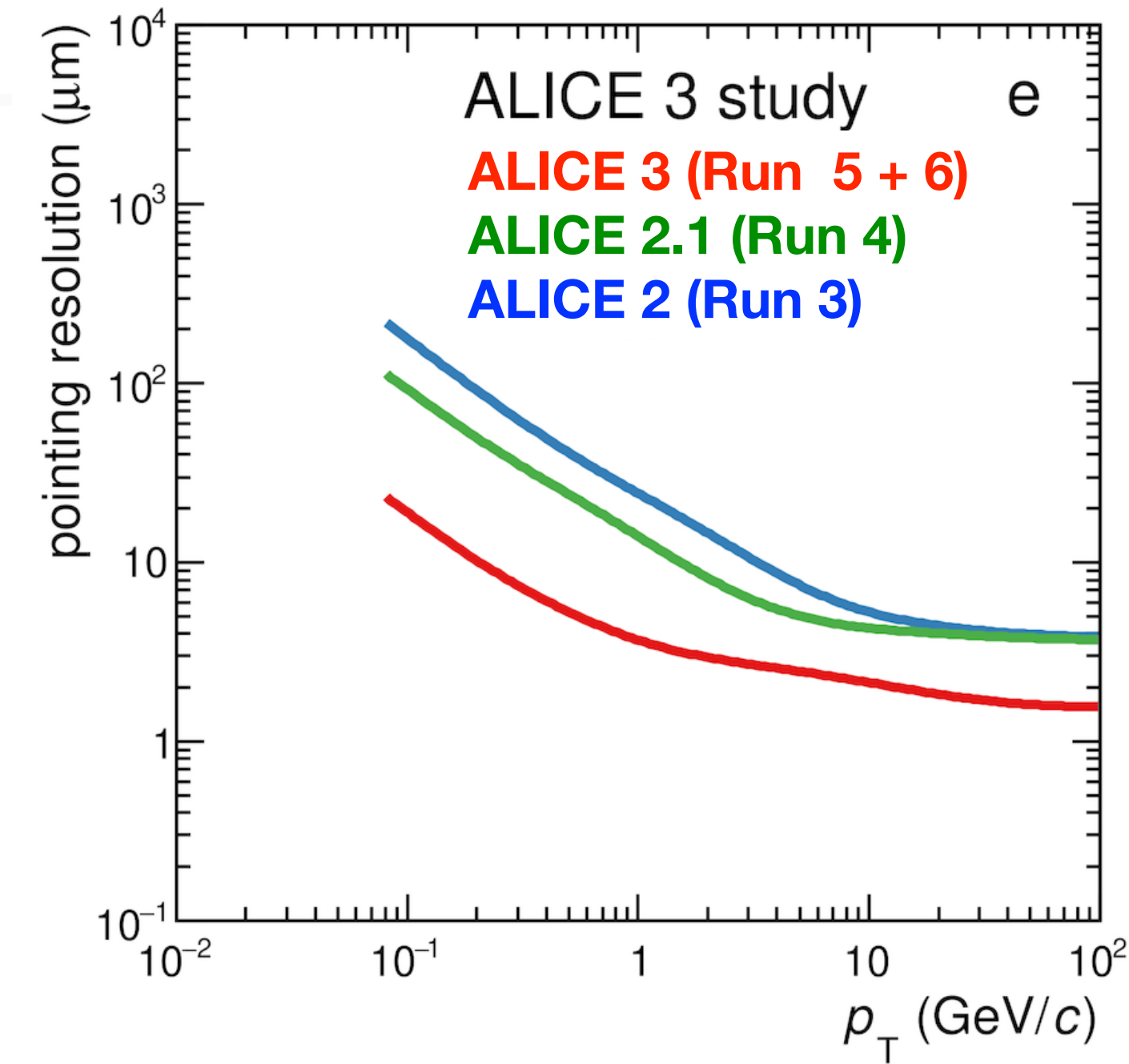


Position of first layer at  $\eta = 0$

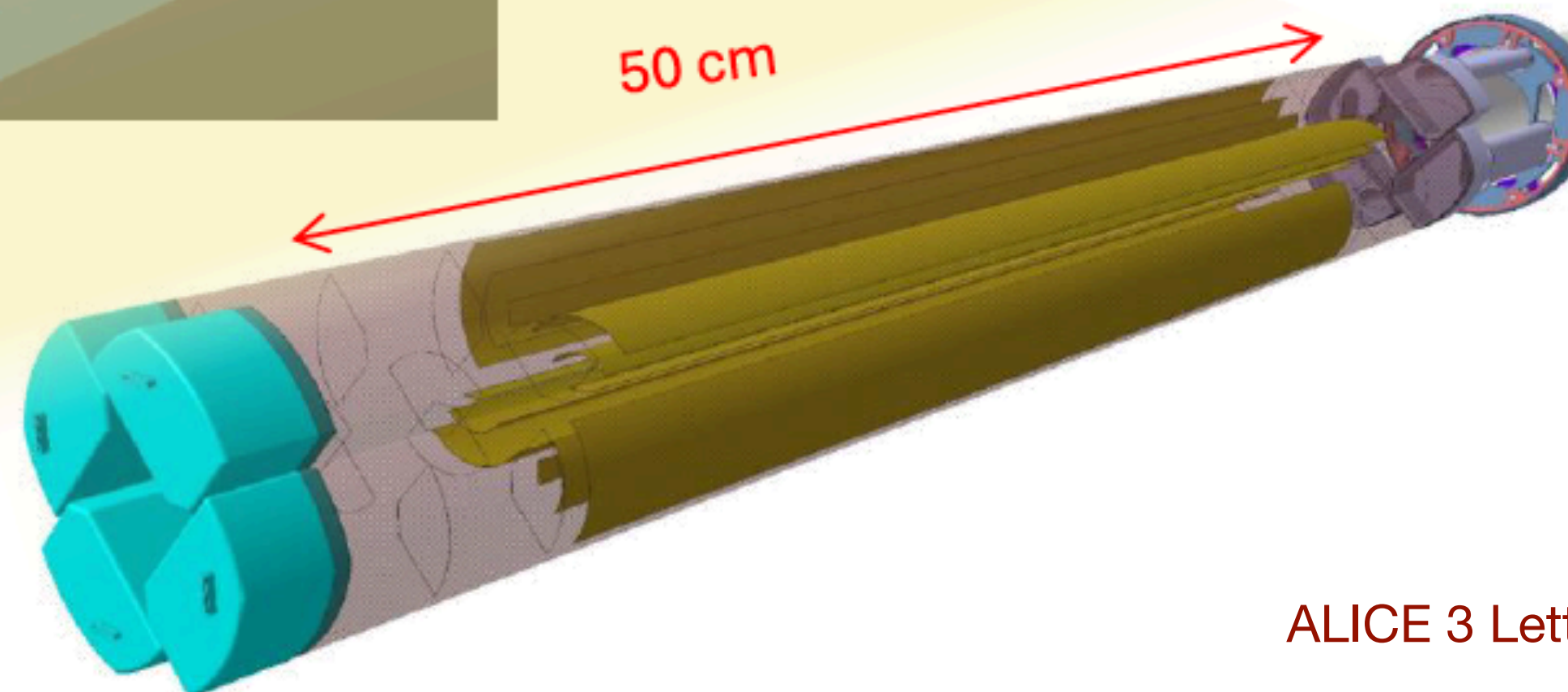
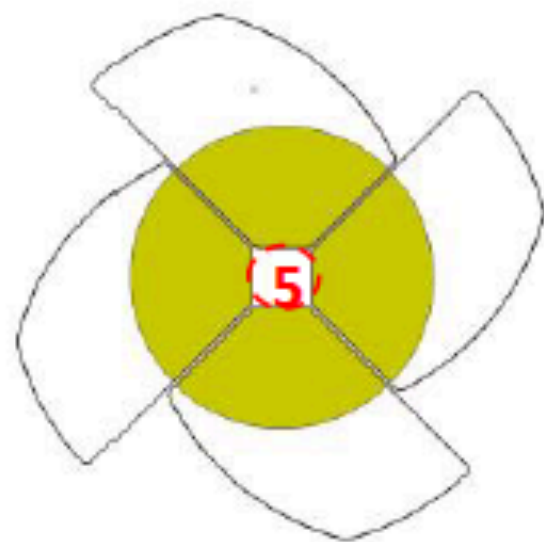
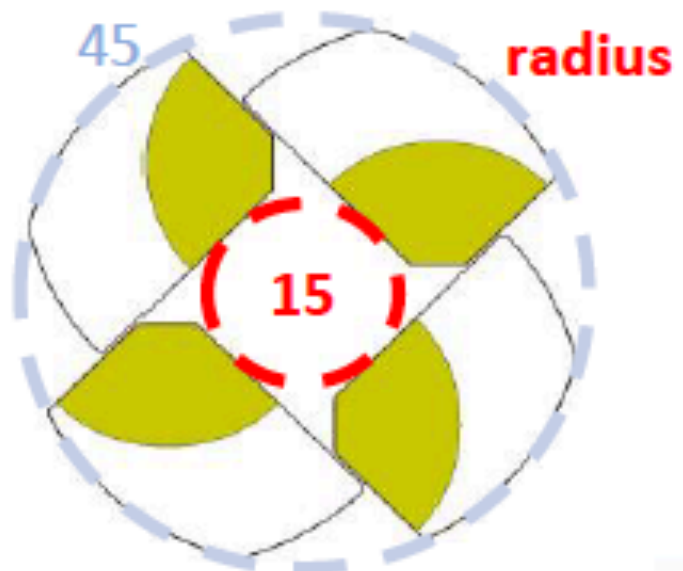
- $r = 5$  mm
- $r = 18$  mm (ALICE Run 4)
- $r = 22$  mm (ALICE Run 3)

→ Very good pointing resolution

Game changer for dileptons !

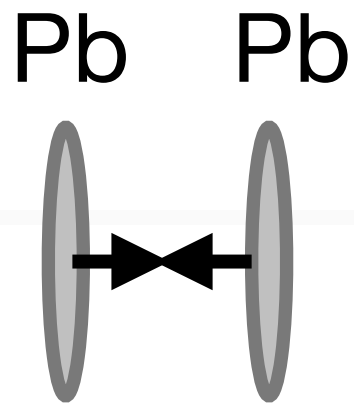
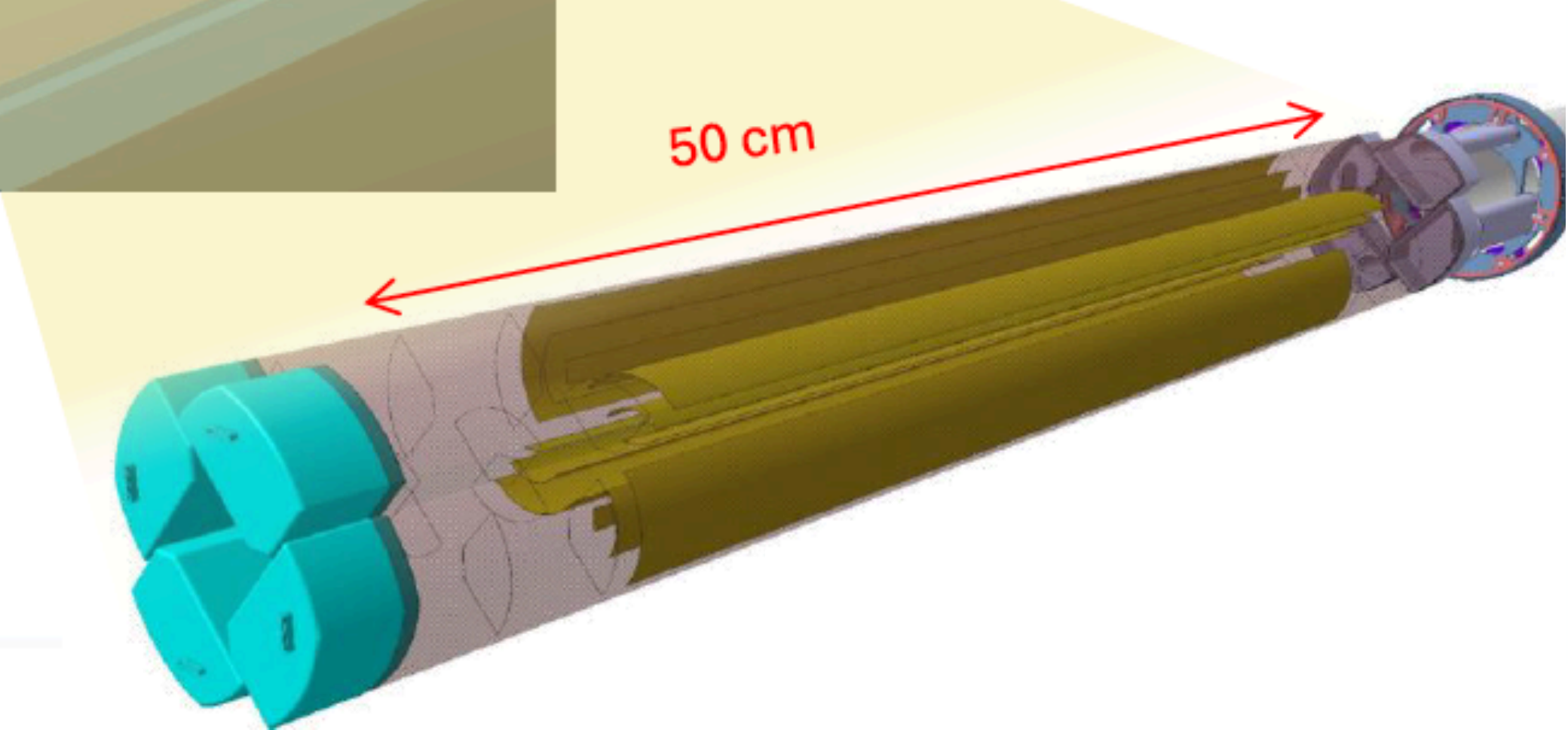
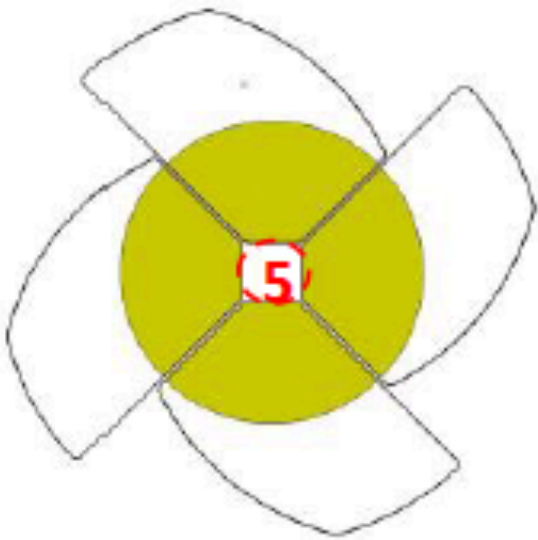
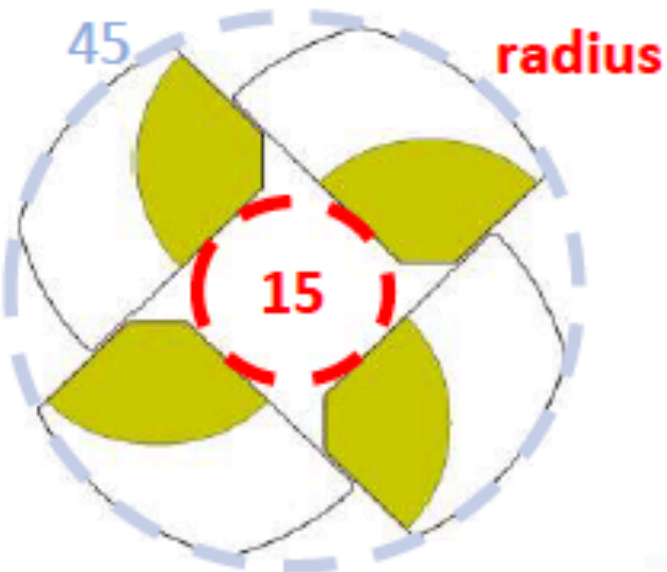
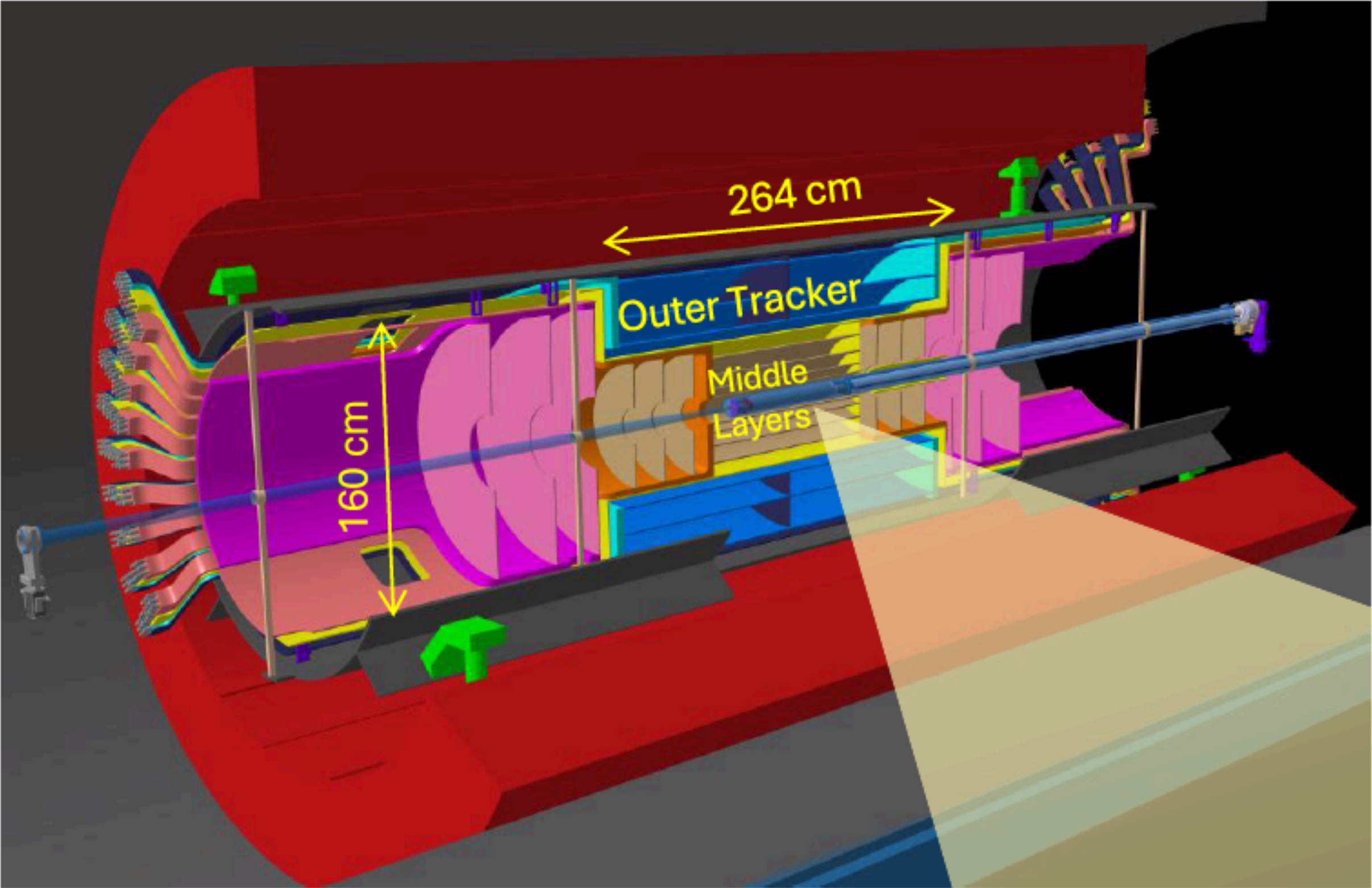


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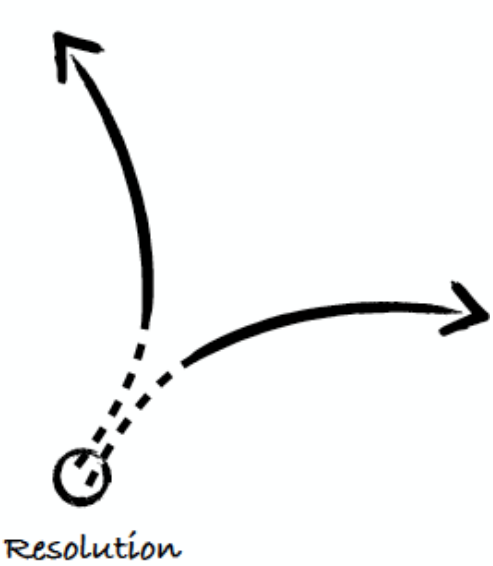
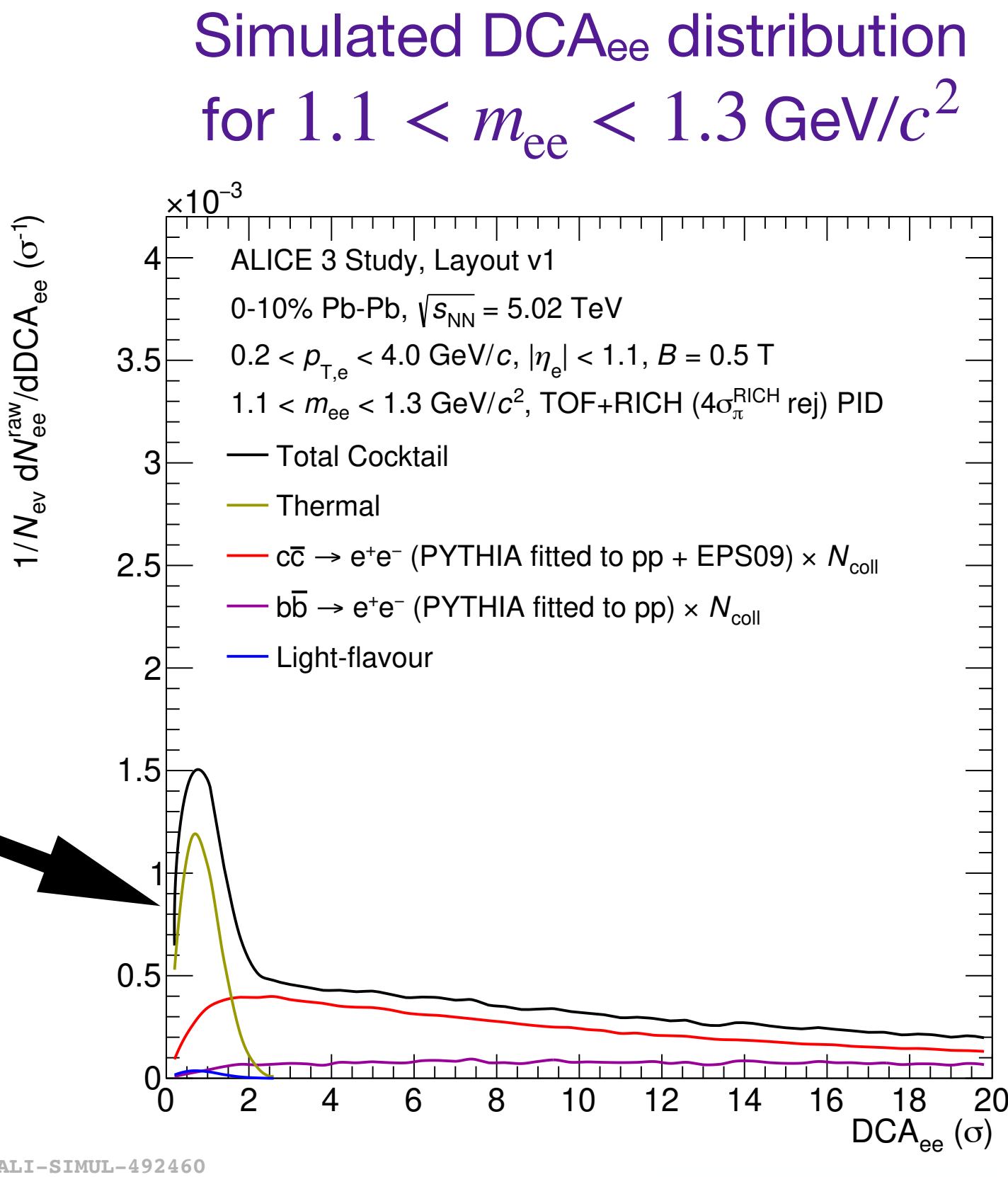


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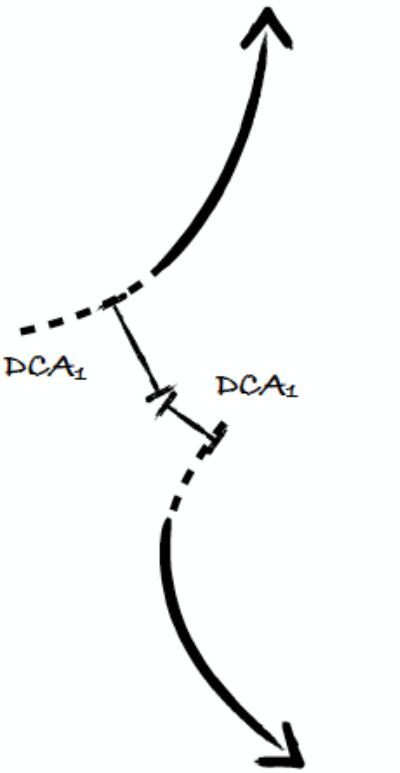
# Vertex detector



Thermal radiation would be seen as a clear peak at small  $DCA_{ee}$

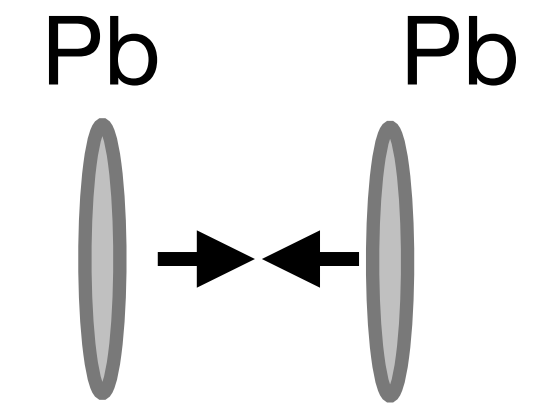


Prompt

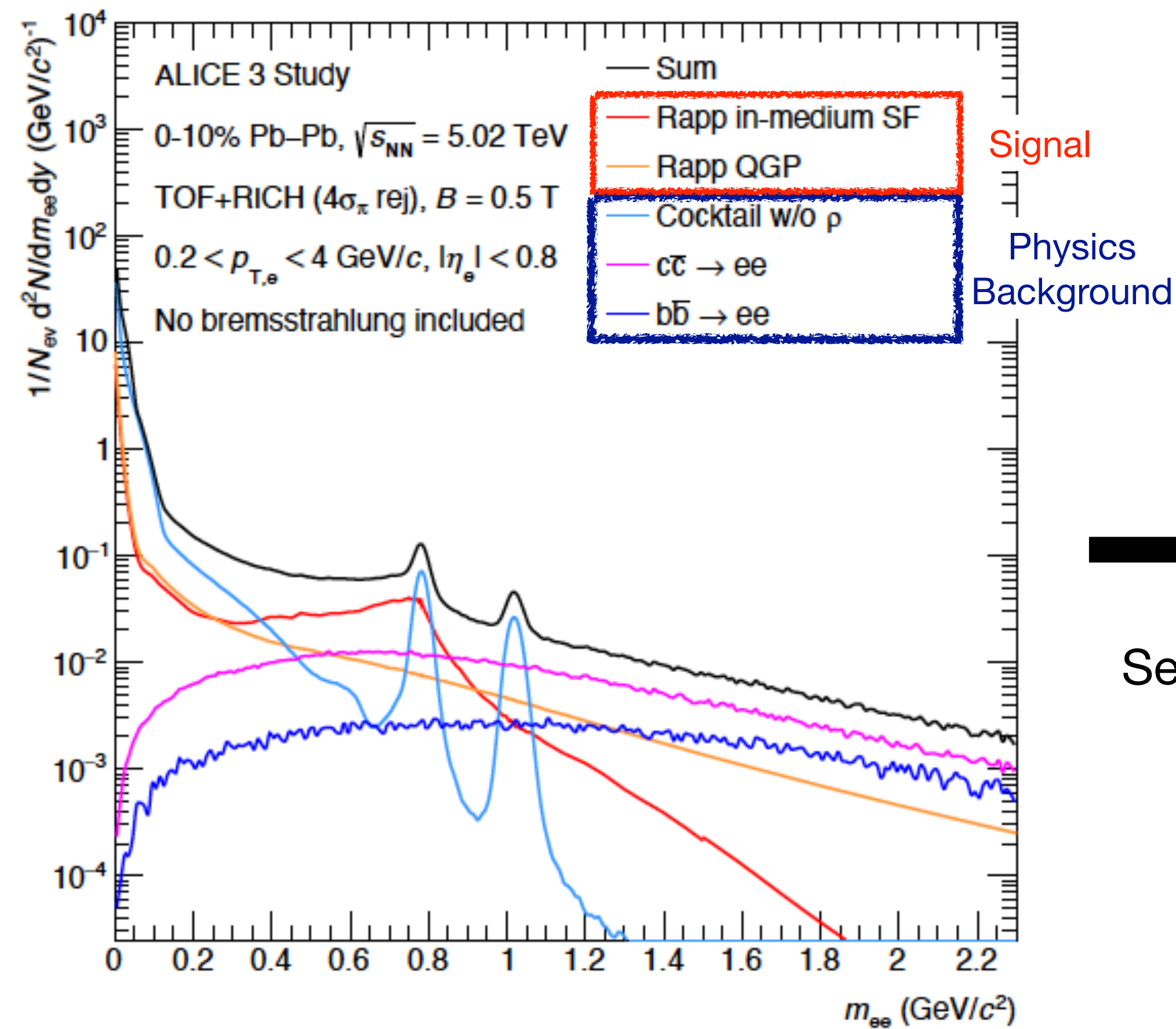


non-prompt  
(Heavy-flavour)

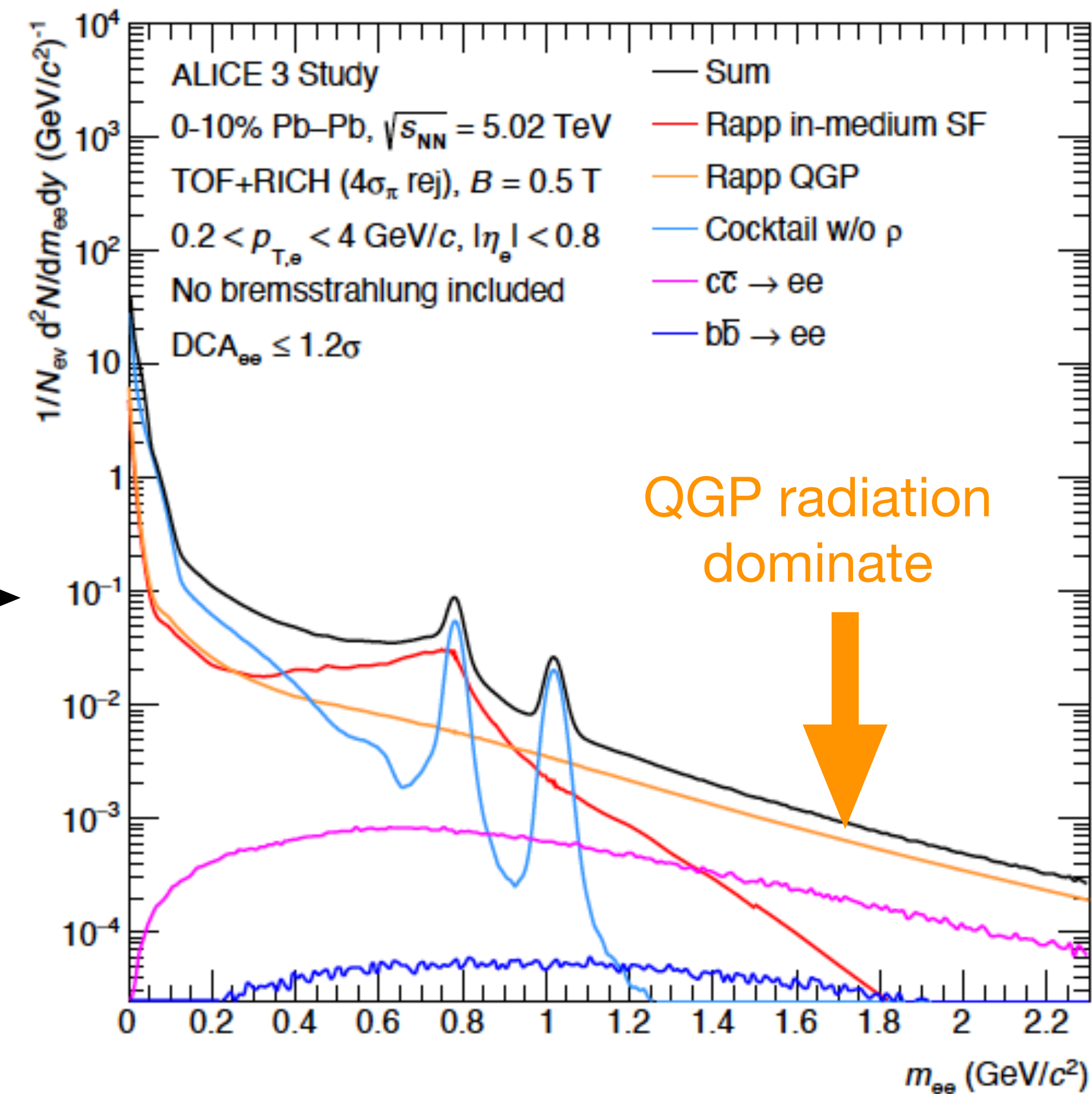
# Handle on heavy-flavour background



Simulated raw dielectron spectra with ALICE 3

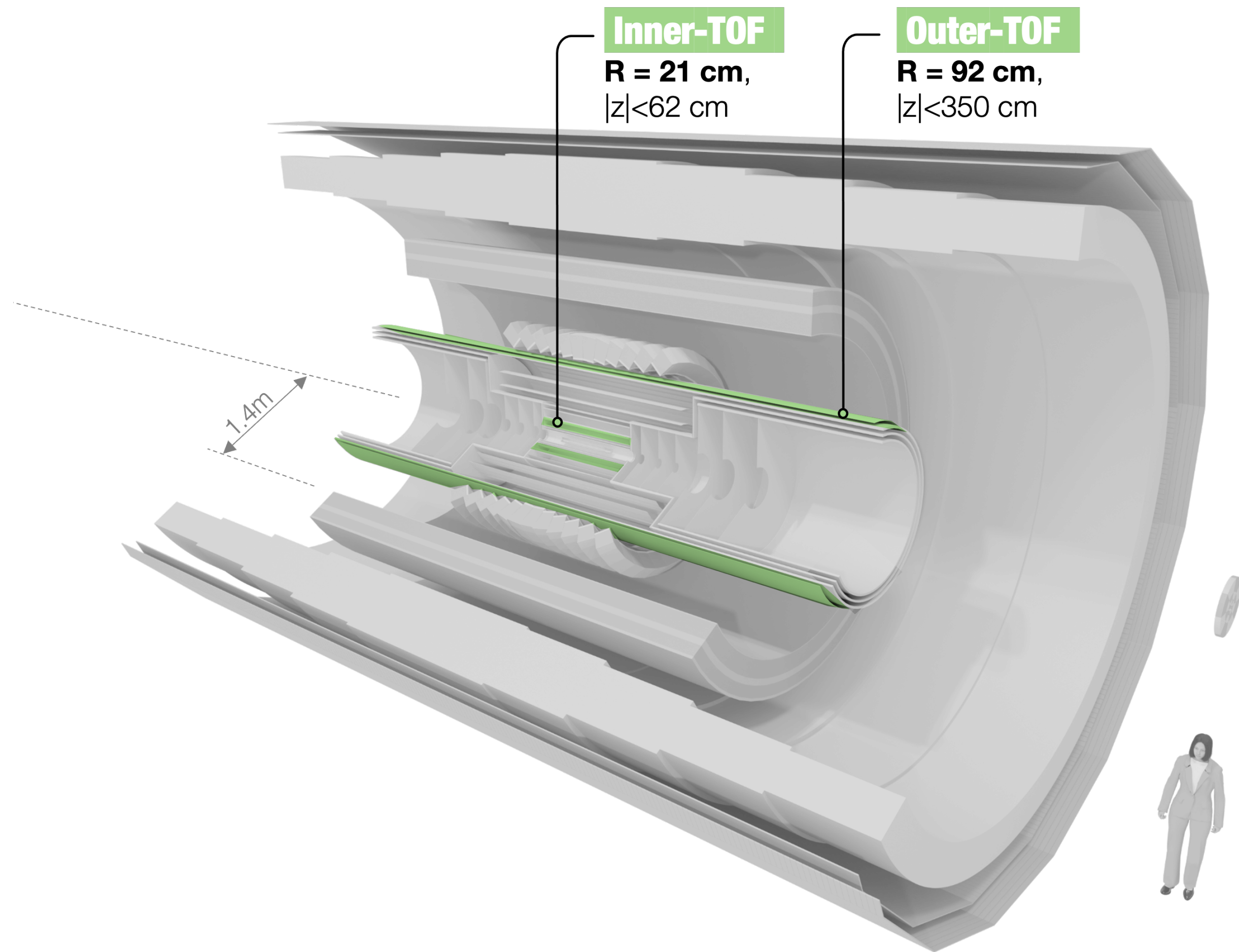


Select prompt pairs



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# Electron Identification



Very precise measurement of the particle time-of-flight

- Monolithic CMOS-LGAD (Complementary Metal-Oxide-Semiconductor Low-Gain Avalanche Diode)

Silicon particle detector with:

- internal signal amplification in the sensor
- readout circuits built on the same piece of silicon

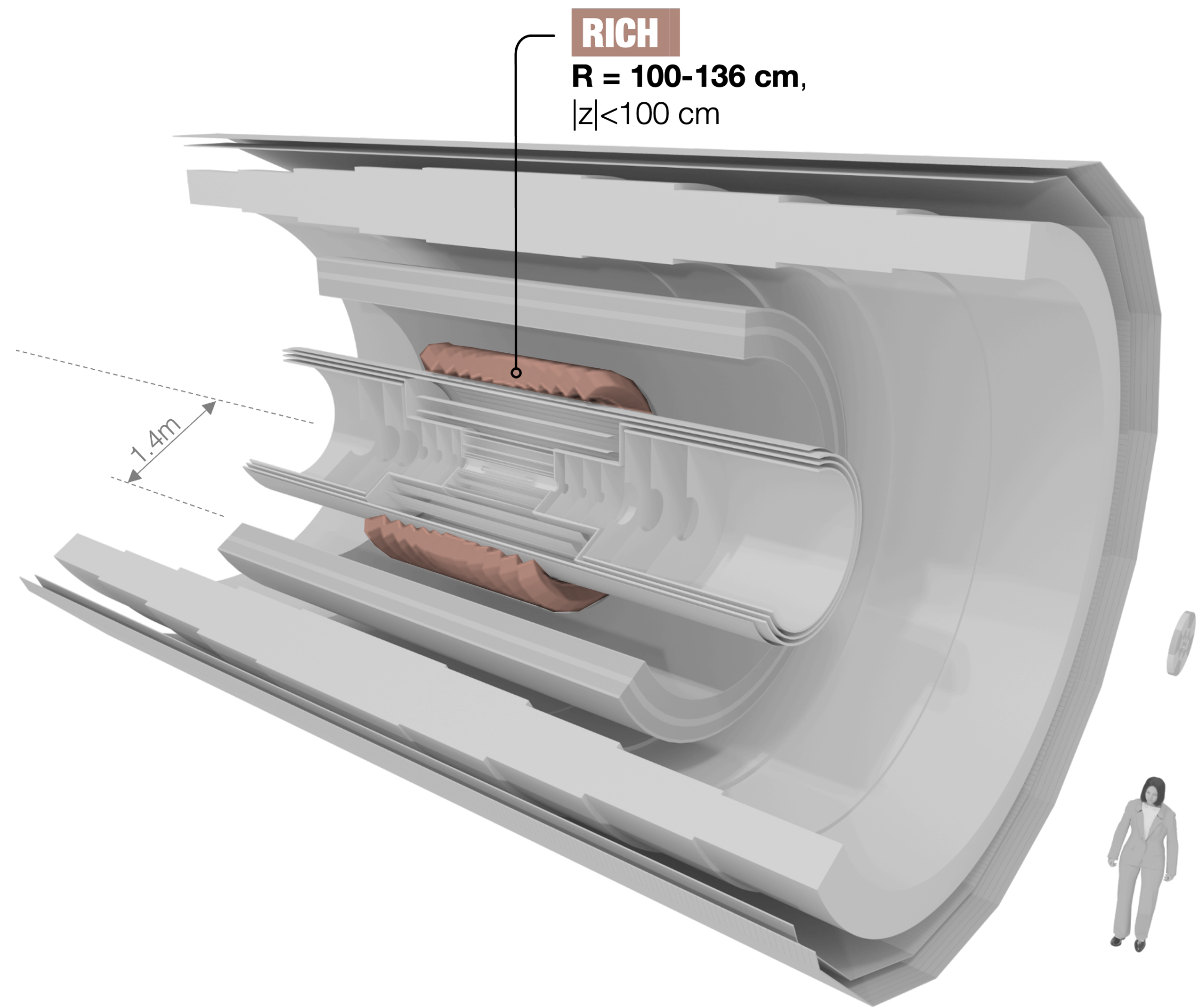
→ Ultra-Fast Timing

- Time resolution of the sensor:  $\sigma_t = 20 \text{ ps}$   
→ Particle separation power  $\propto \frac{R}{\sigma_t}$
- $39 \text{ m}^2$  area coverage,  $\pm 2.0 \eta$
- Material budget  $X/X_0 \sim 1\text{-}3\%$

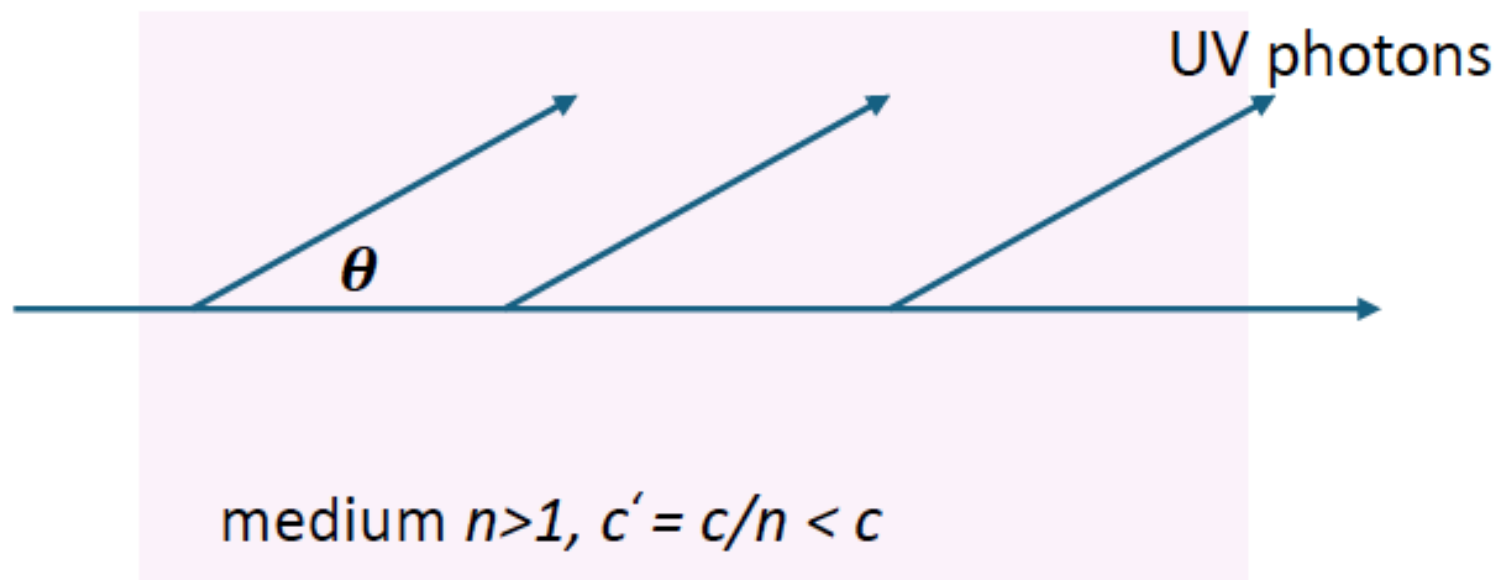
Main R&D challenge:

- Time resolution at system level
- Large area

# Electron Identification



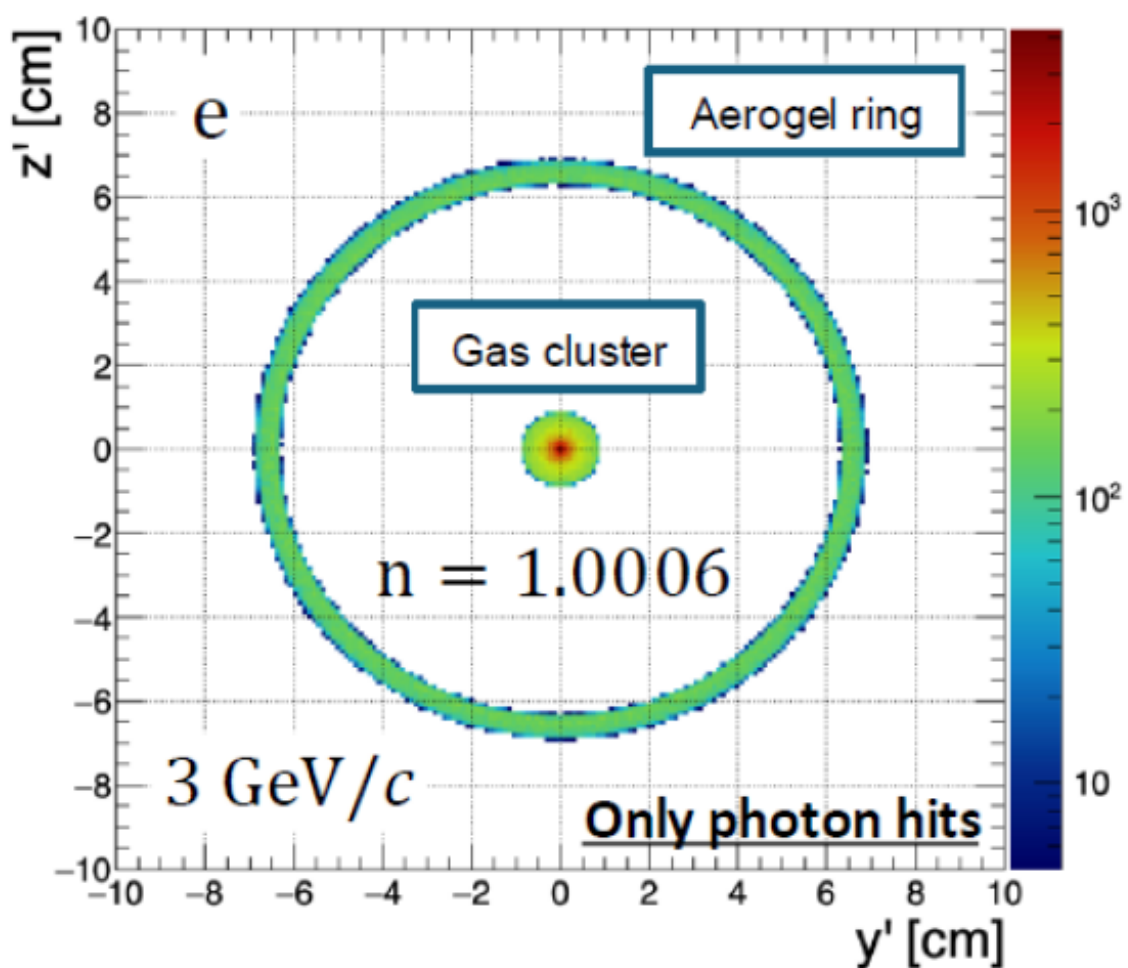
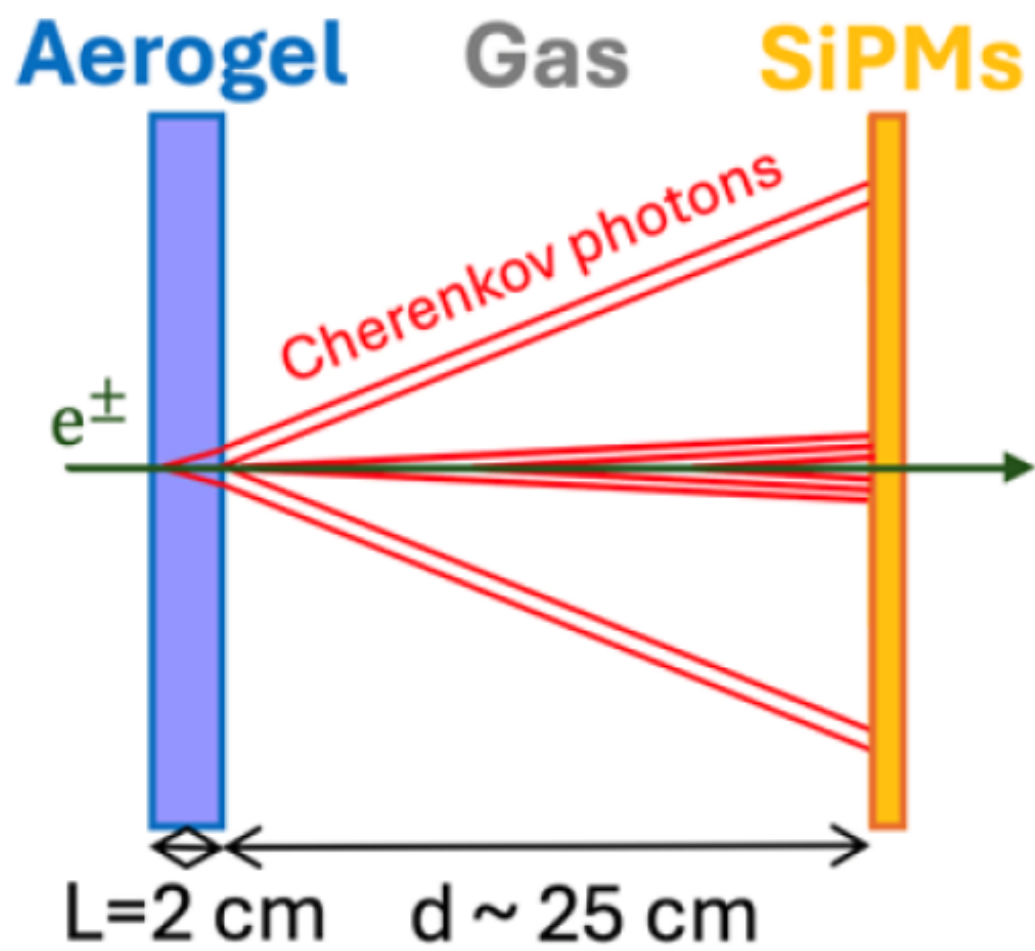
Measurement of cherenkov photons



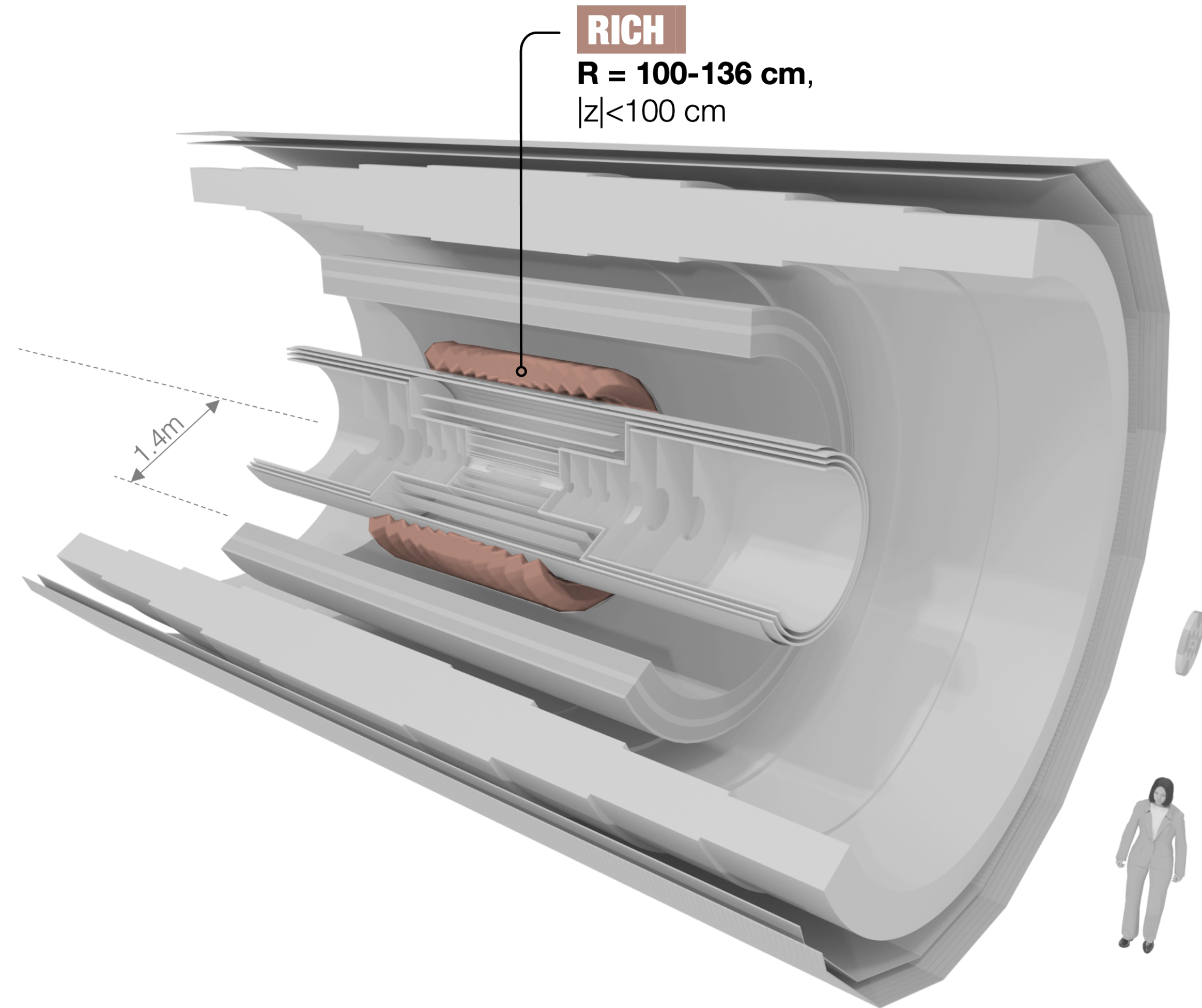
for charged particle with  $\beta \geq \frac{1}{n}$ ,  $\cos(\theta) = \frac{1}{\beta n}$

One module with two radiators:

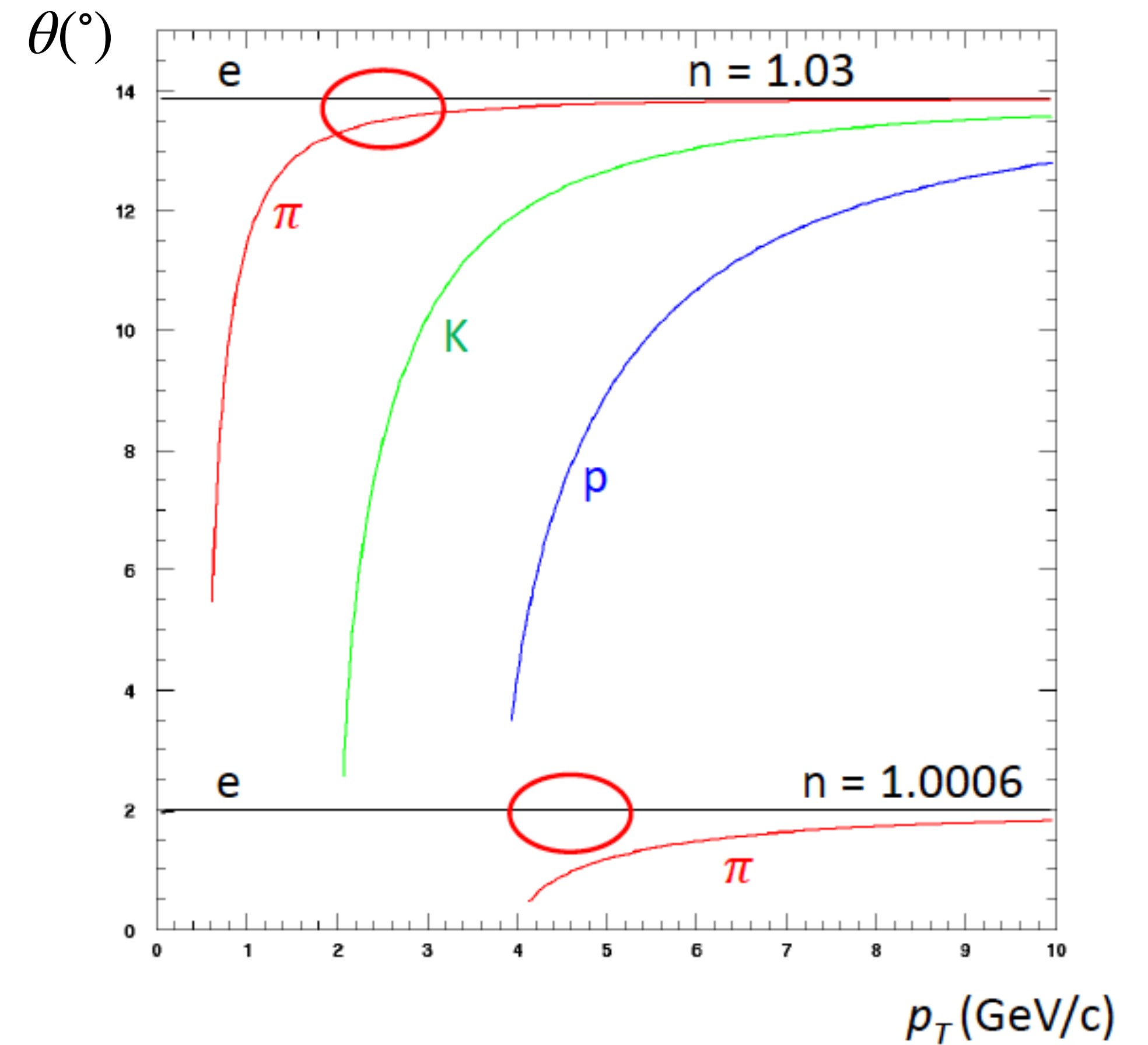
- Aerogel  $n = 1.03$
- Gas CO<sub>2</sub>  $n = 1.0006$



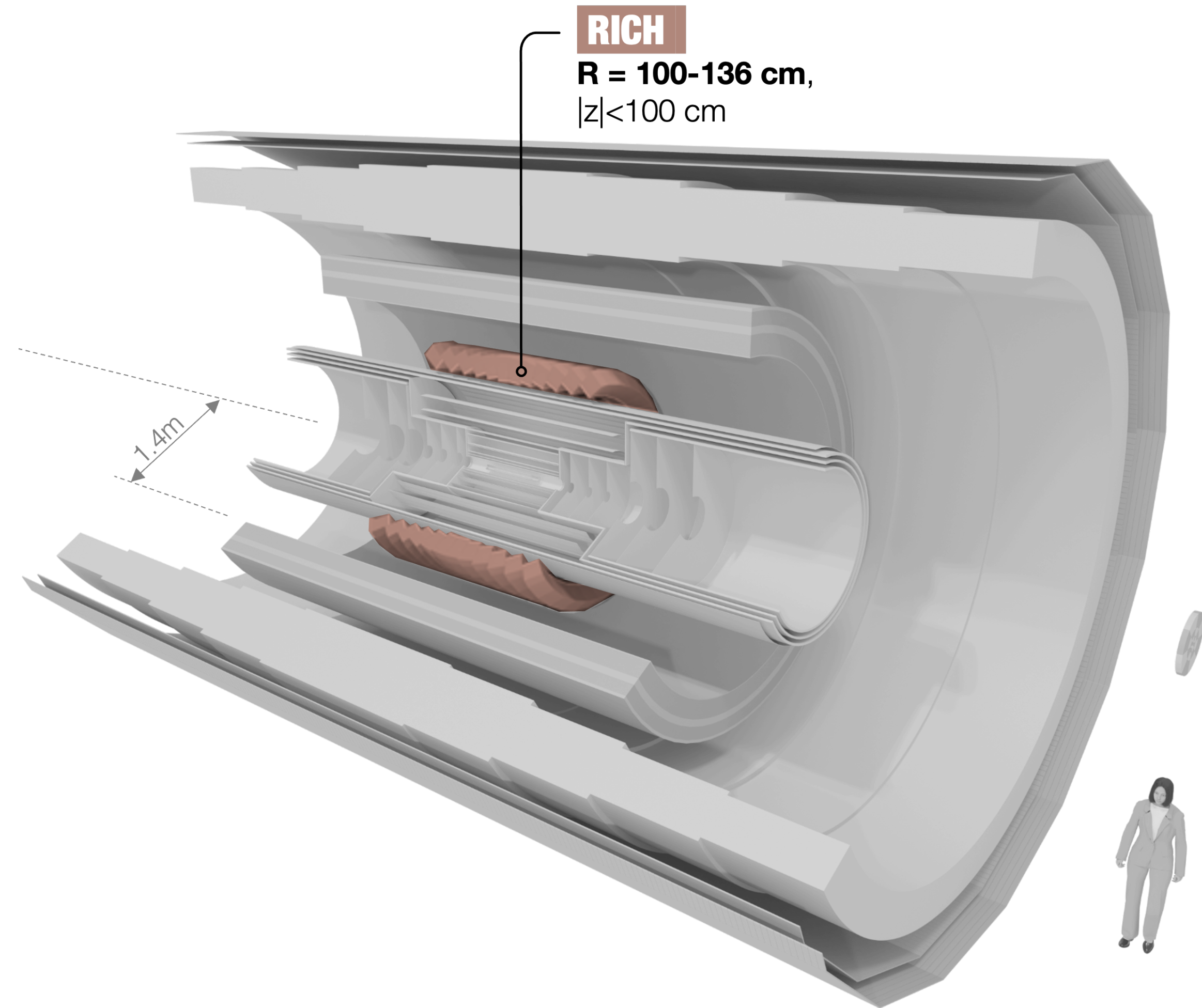
# Electron Identification



Measurement of cherenkov photons



# Electron Identification



Measurement of cherenkov photons

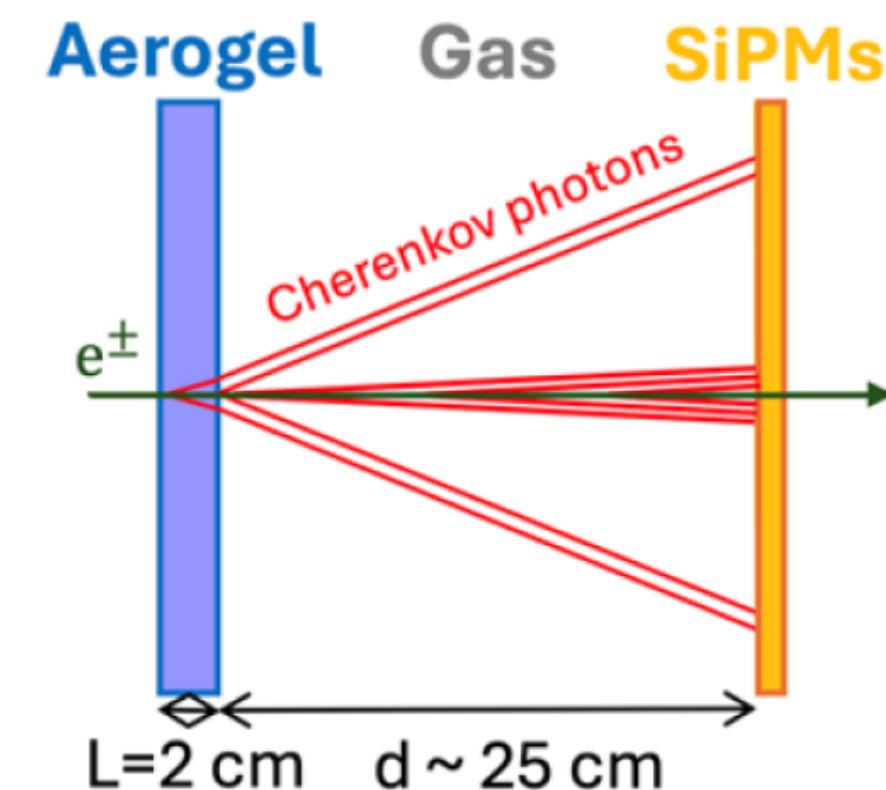
- 10.4 m<sup>2</sup> area coverage,  $\pm 0.8 \eta$
- Photo-detector: Silicon-Photomultiplier (SiPM)
- Cherenkov angle resolution 1.5 mrad

Main R&D challenge:

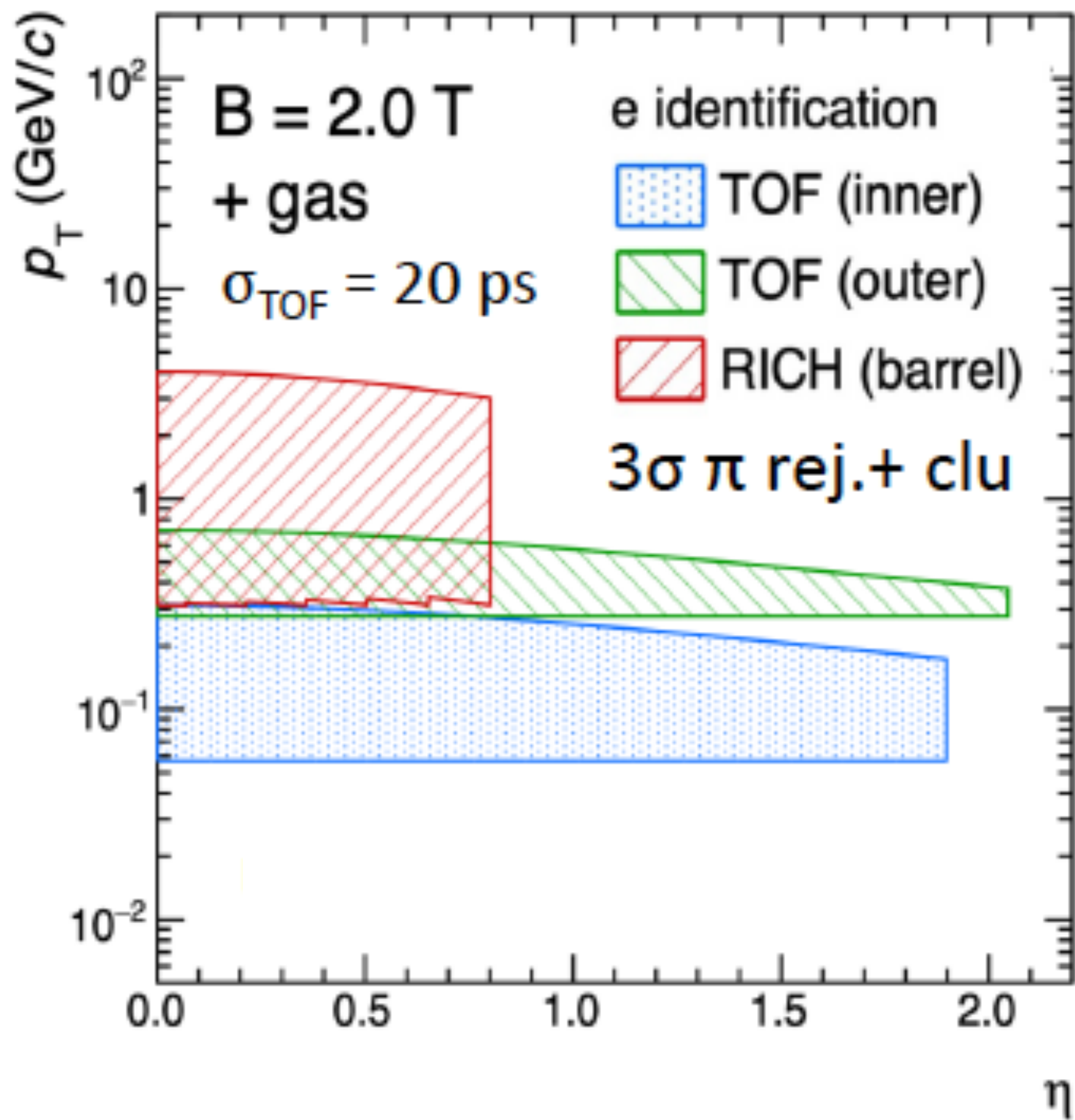
Radiation tolerance of SiPMs

Dark Count Rate DCR < 1 MHz/mm<sup>2</sup>

To achieve this, CO<sub>2</sub> cooling by -40°C and annealing



# Electron Identification



For  $B = 2 \text{ T}$ :

- Minimum  $p_T$ 
  - Defined by the curvature of the tracks in the magnetic field
  - Minimum  $p_T$  to reach a given radius:

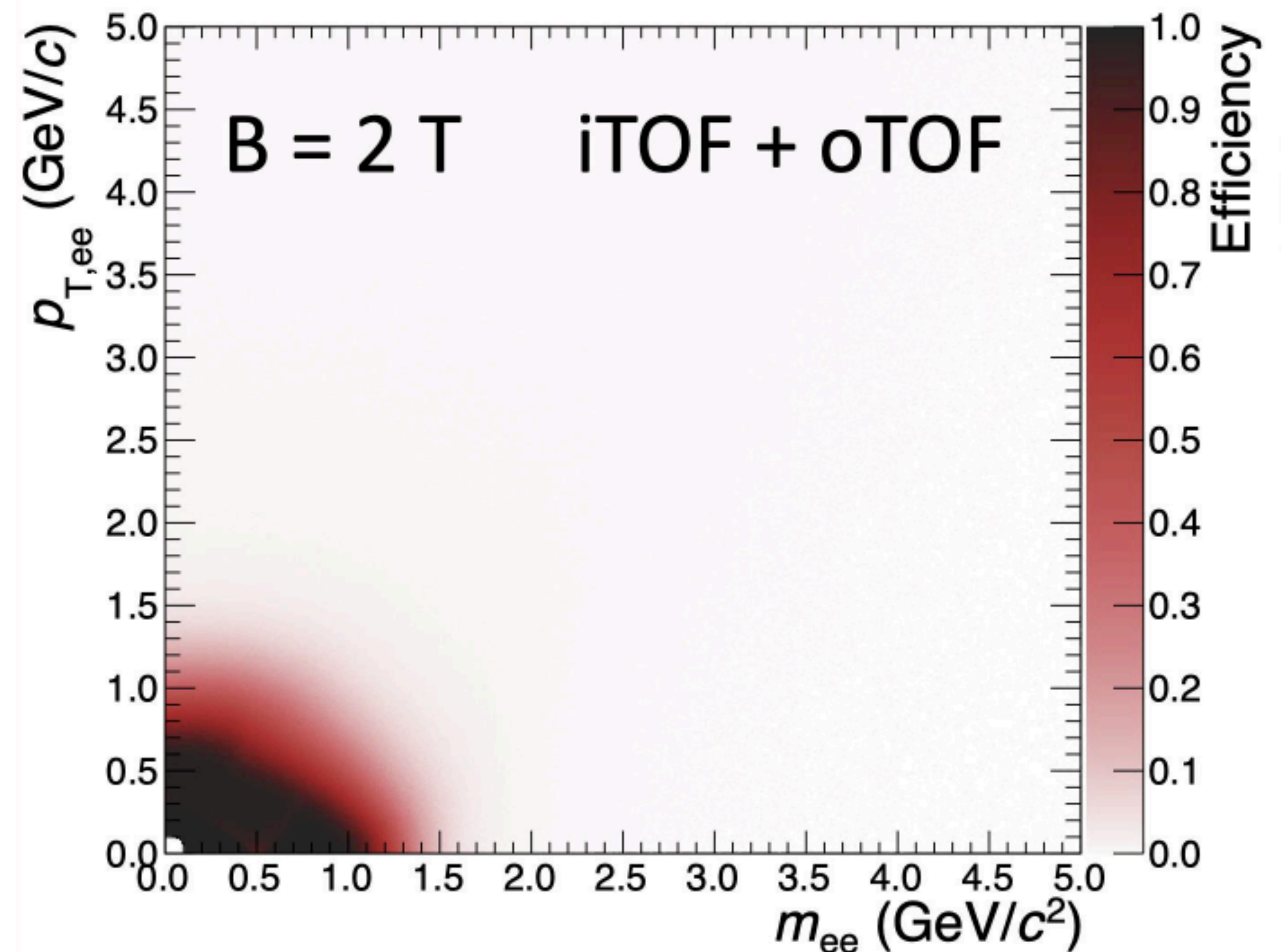
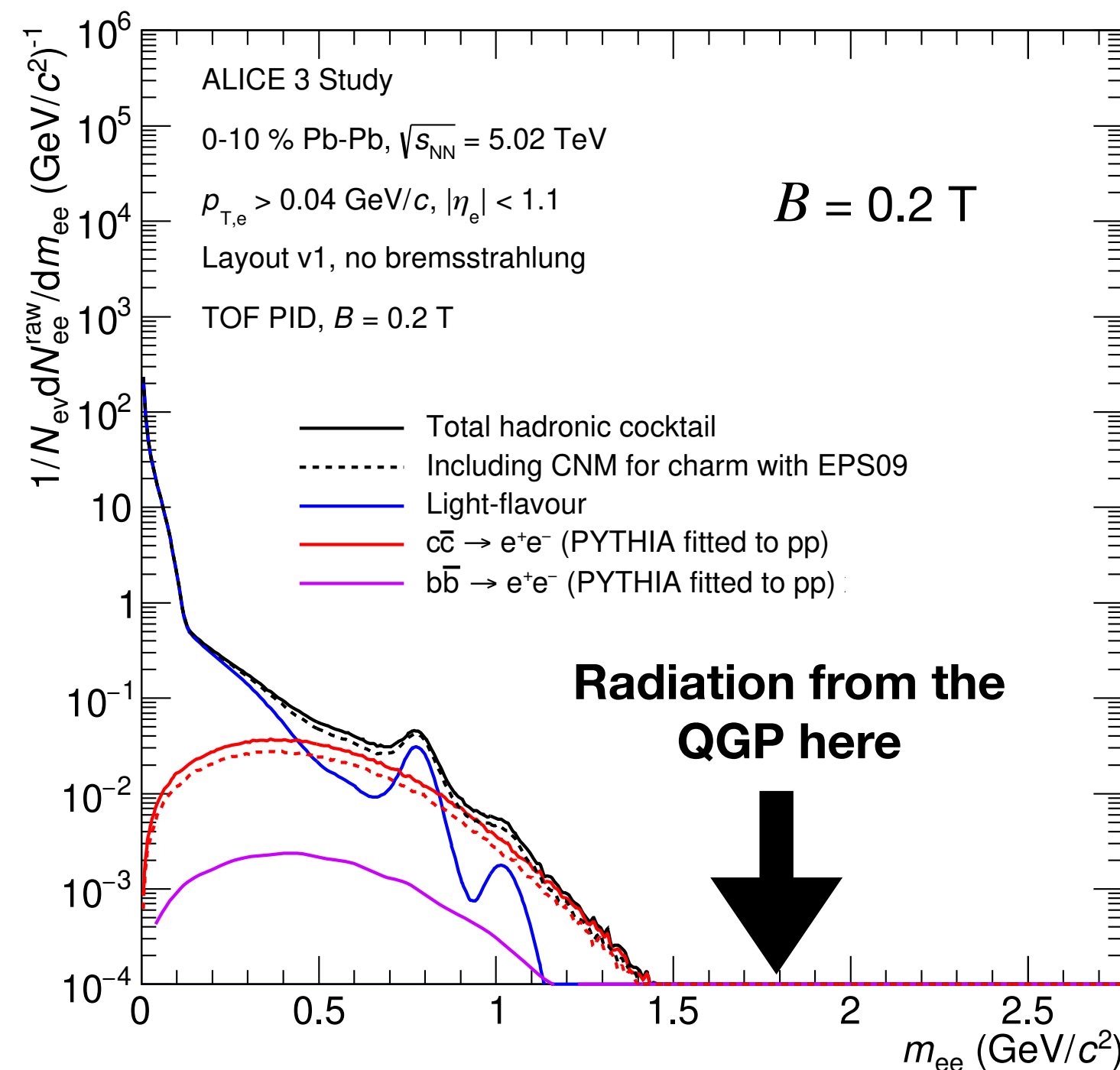
| Detector | Radius (m) | $p_{T,\text{min}}$ threshold (GeV/c) |                   |
|----------|------------|--------------------------------------|-------------------|
|          |            | $B = 0.5 \text{ T}$                  | $B = 2 \text{ T}$ |
| iTOF     | 0.21       | 0.02                                 | 0.06              |
| oTOF     | 0.92       | 0.07                                 | 0.28              |
| RICH     | 1.2        | 0.09                                 | 0.36              |

- Maximum  $p_T$  defined by the detector resolution (time-of-flight, cherenkov angle) depending on momentum (not  $B$ )

Current ALICE goes down to  $p_T \sim 0.075 \text{ GeV/c}$  with low  $B$  field runs

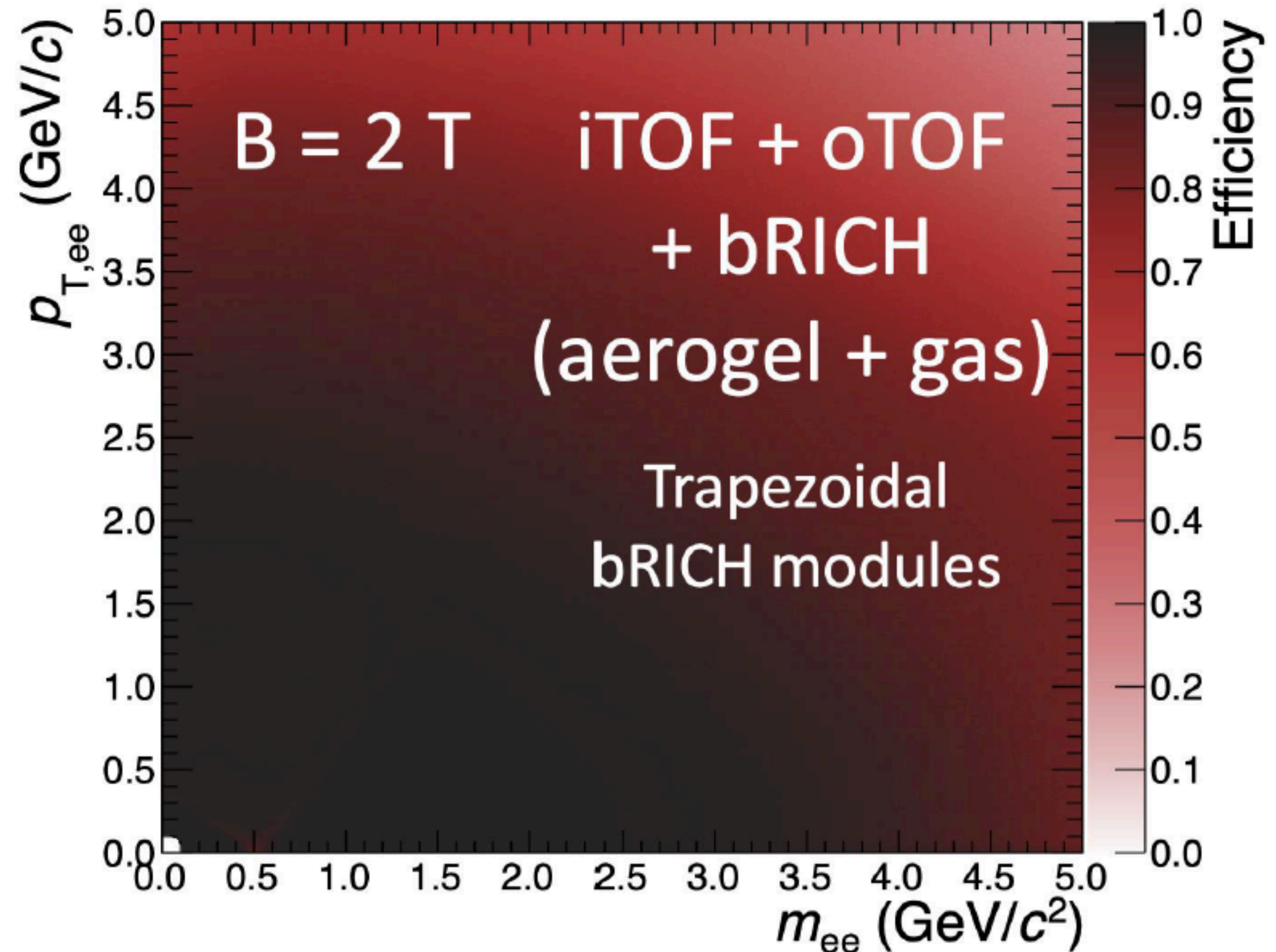
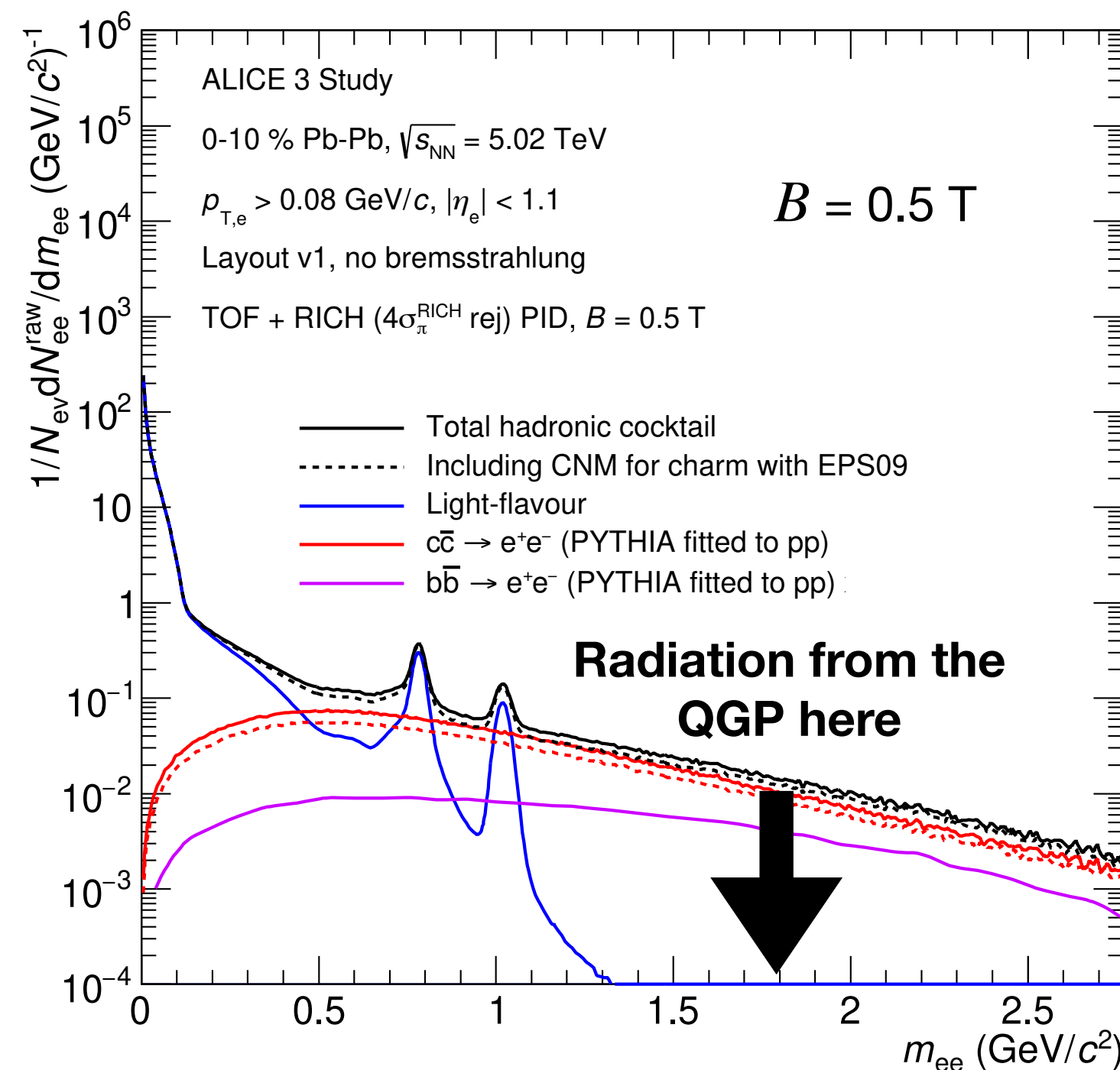
# TOF detectors alone

With only TOF detectors can not go above  $m_{ee} \approx m_\phi$   
 → Need the RICH detector for dielectrons !

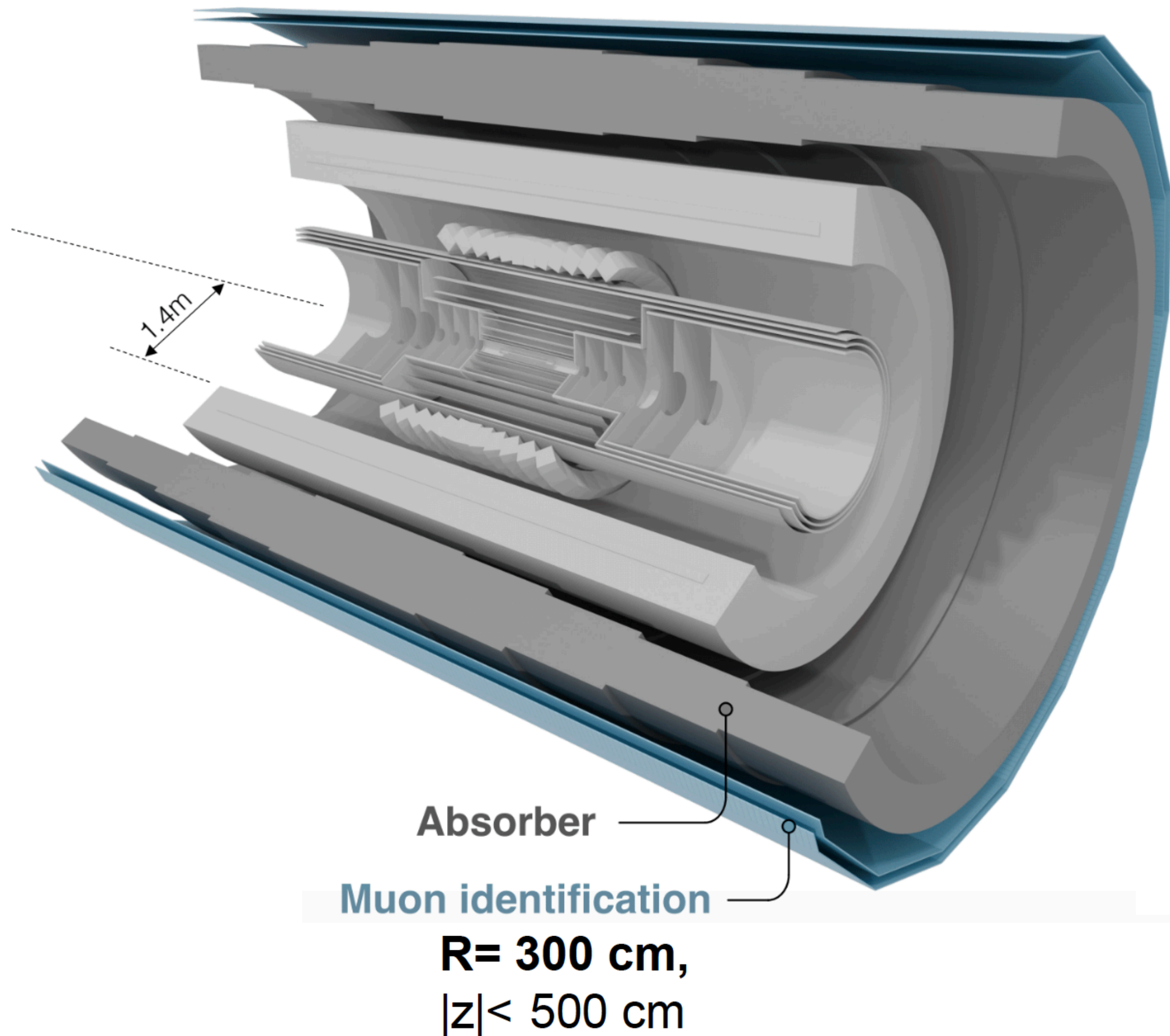


# RICH detector mandatory

With only TOF detectors can not go above  $m_{ee} \approx m_\phi$   
 → Need the RICH detector for dielectrons !



# Muon Identification



Muon chambers outside of the superconducting magnet

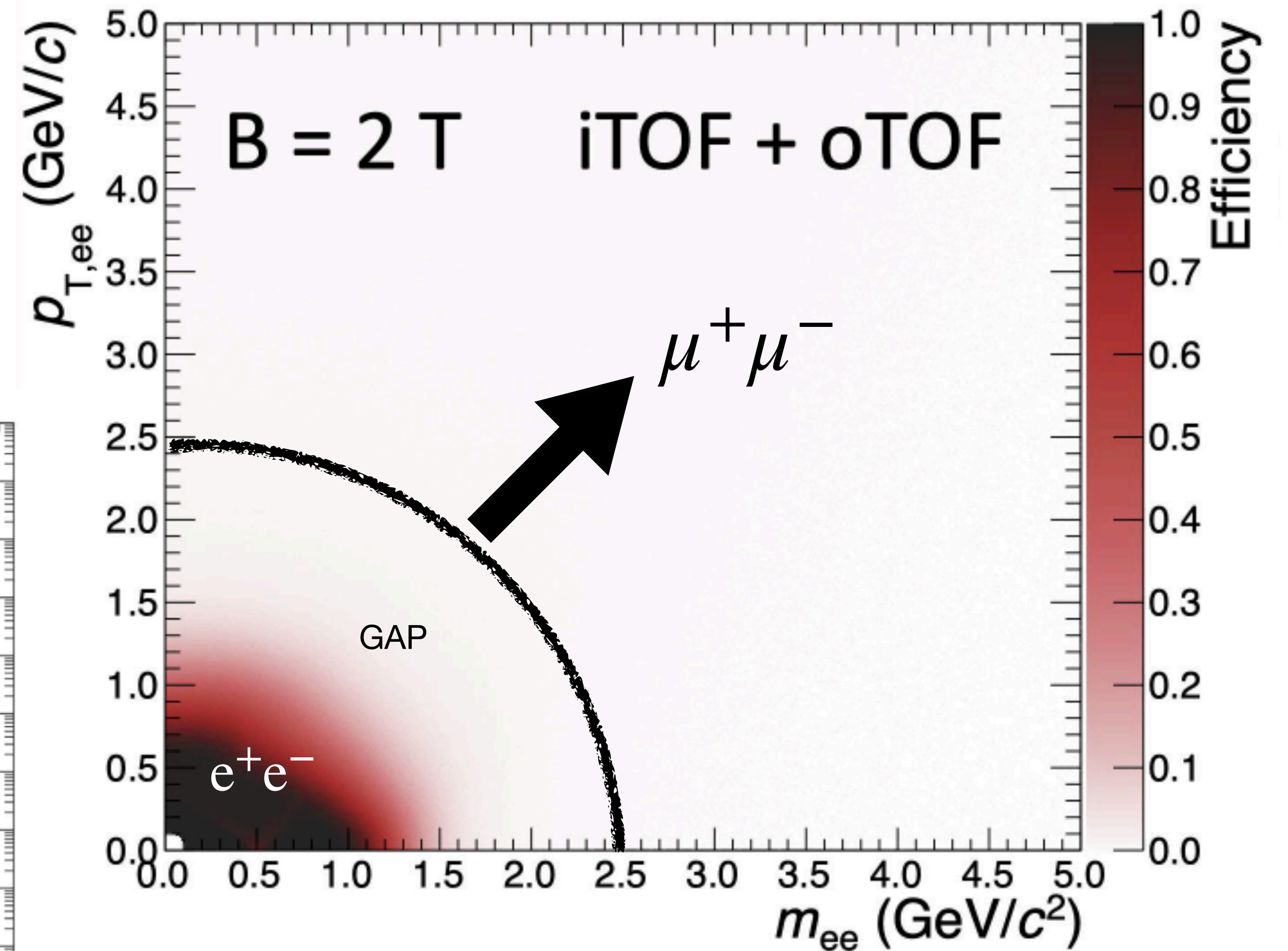
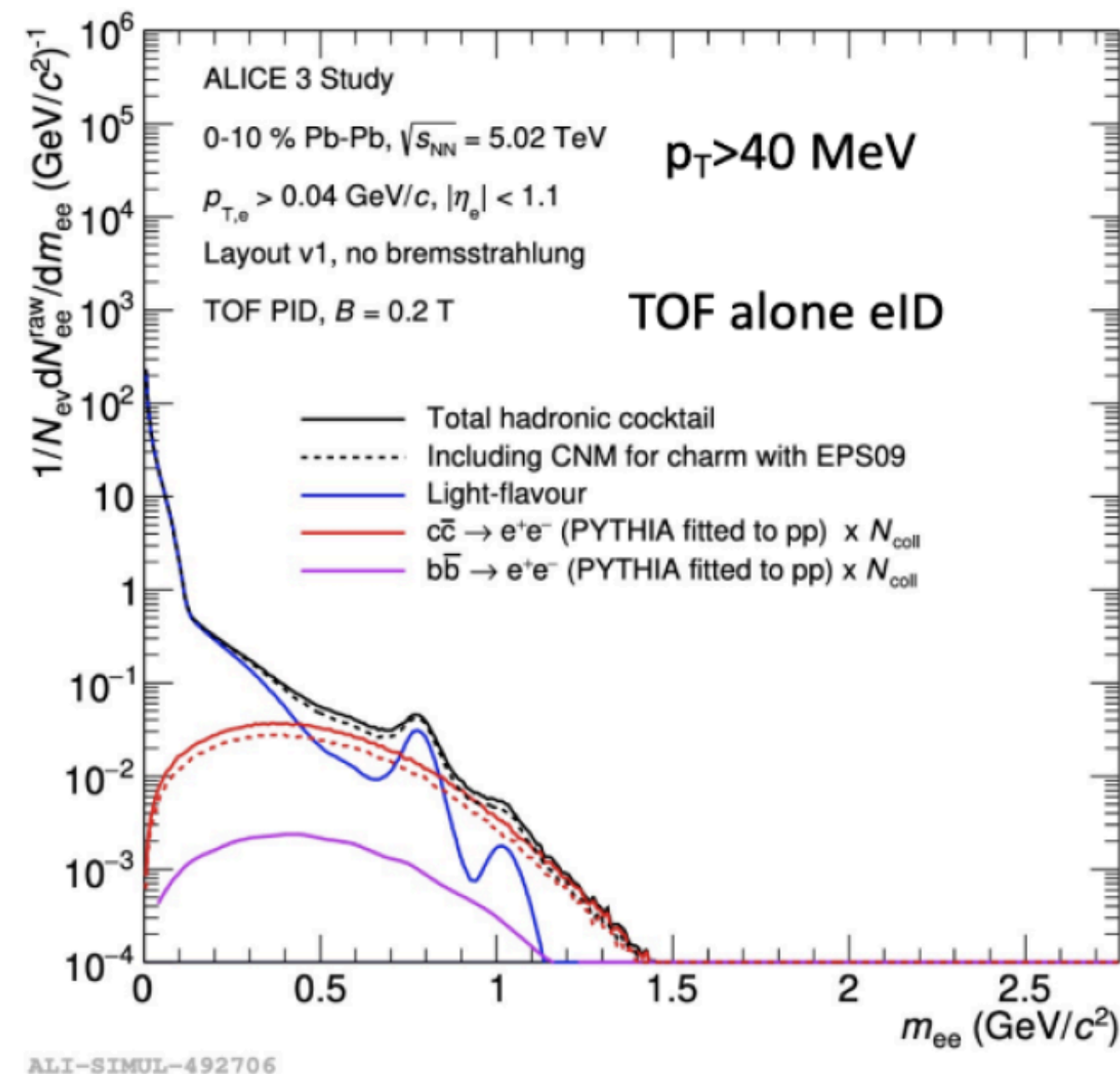
- 190 m<sup>2</sup> area coverage
- Standard magnetic steel absorber
- Double layer of crossed scintillator bars coupled to Silicon Photomultiplier via wavelength conversion fibers
- Alternative option: multiwire proportional chambers

R&D focused on:

- Selection of scintillator material
- Absorber geometry optimization

# TOF detectors alone

With only TOF detectors can not go above  $m_{ee} \approx m_\phi$   
 → Need the RICH detector for dielectrons !



# Summary and outlook

- An exciting time in front of us to allow unprecedented precision measurements
- Currently: critical phase where R&D and detectors need to be built
- Will define what we will really be able to measure....



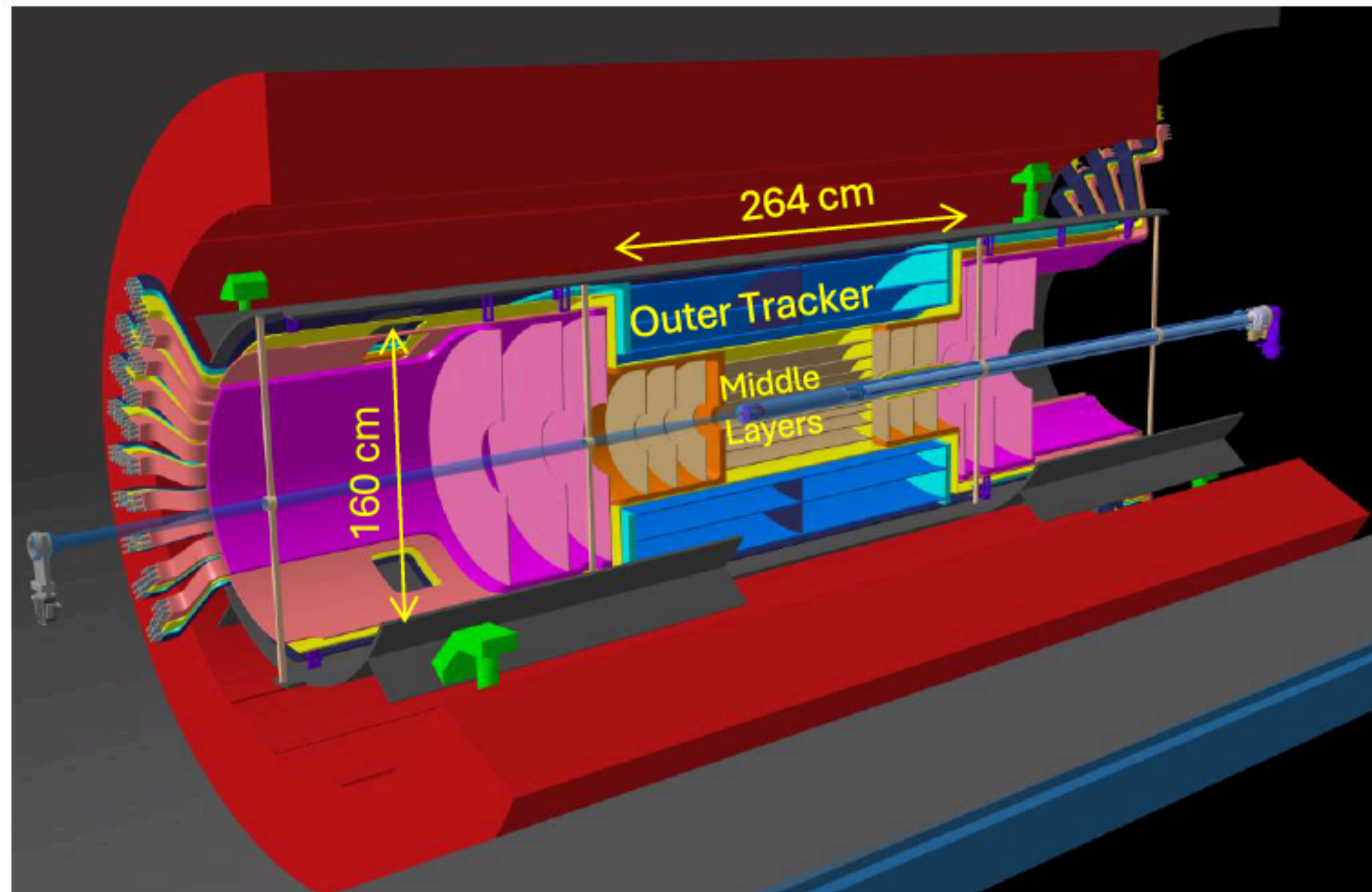
ALICE

ALICE 3 detector

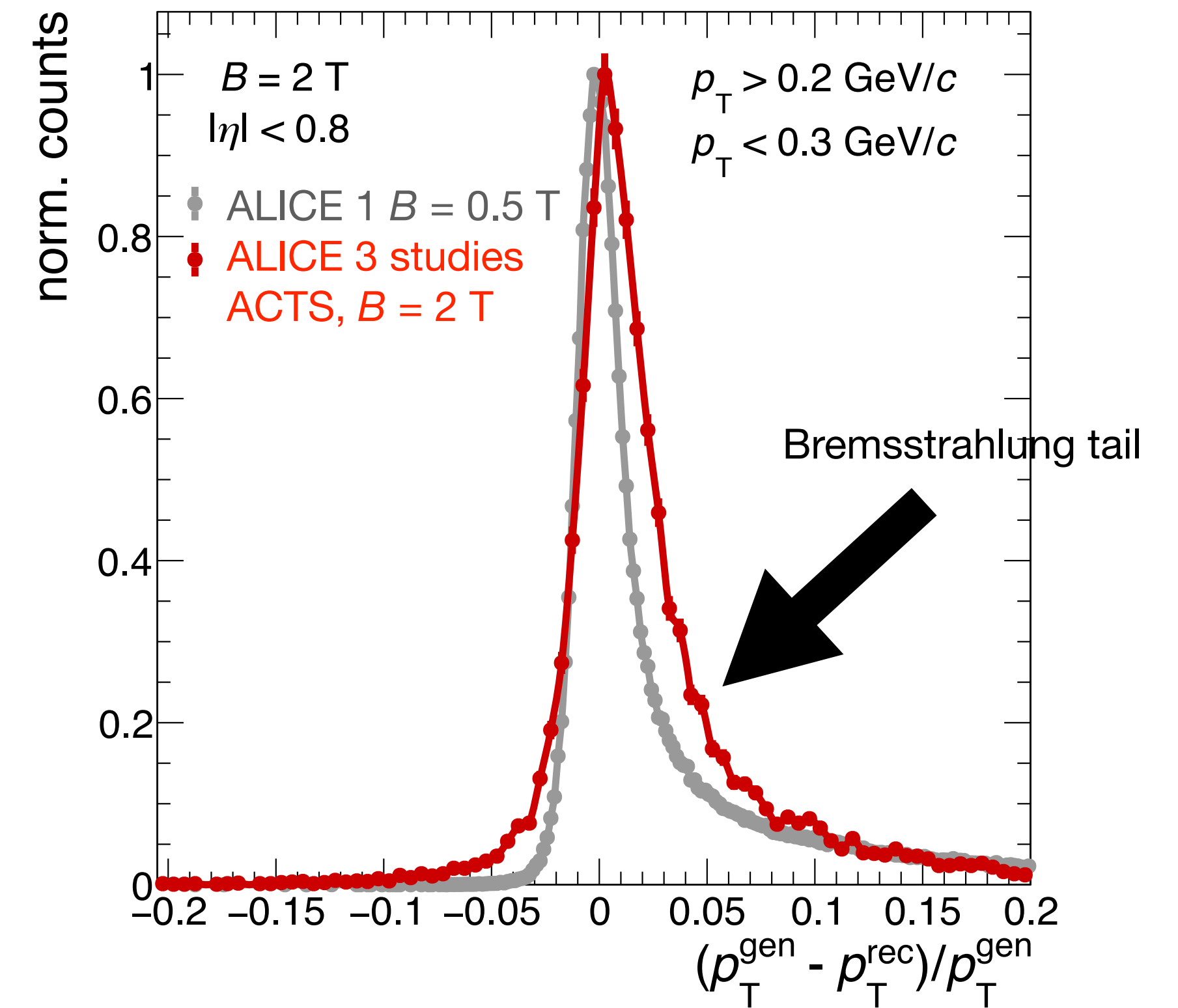
**Joyeux anniversaire Peter**

**Back-up**

# Tracker



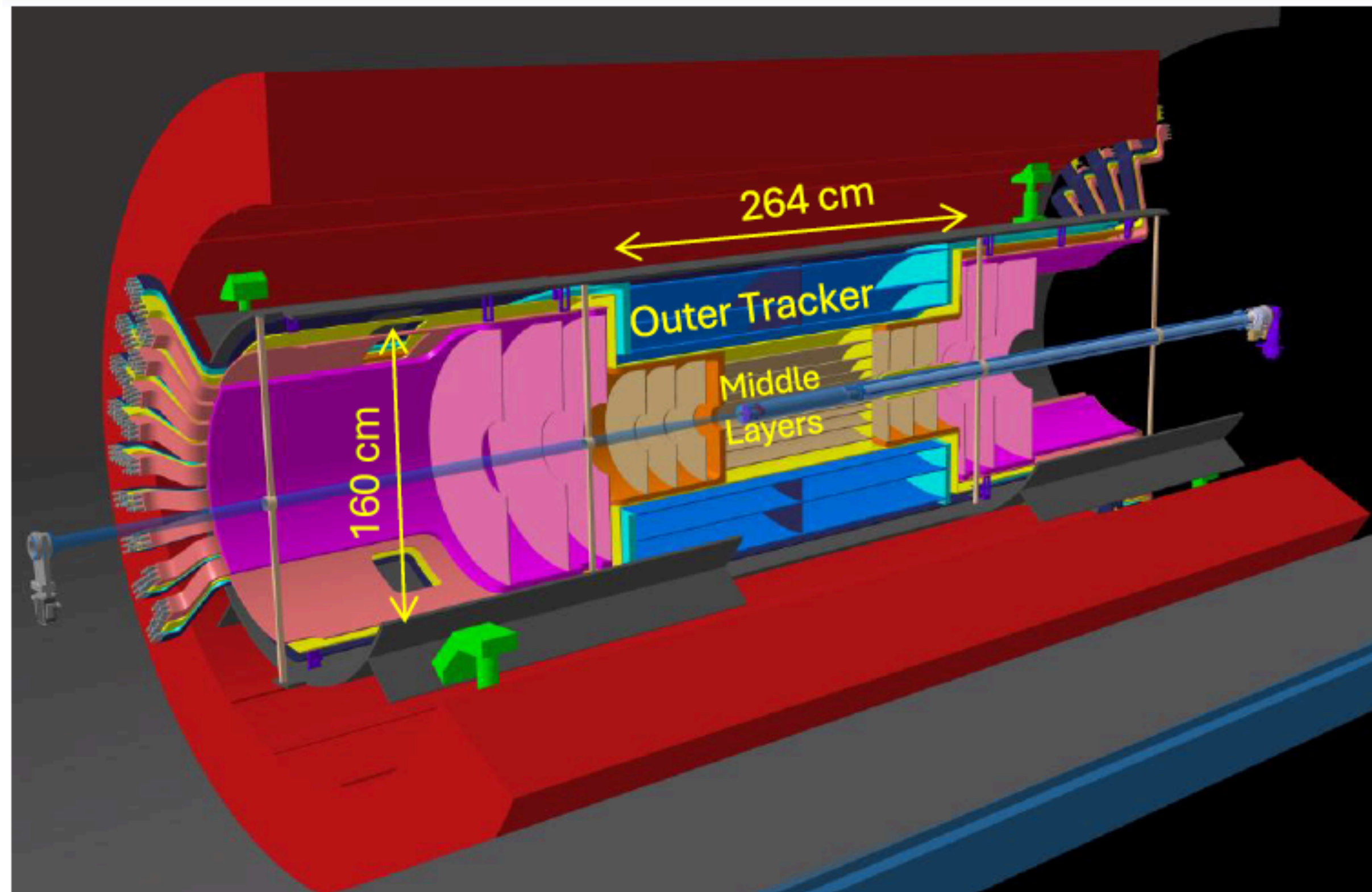
$p_T$  resolution



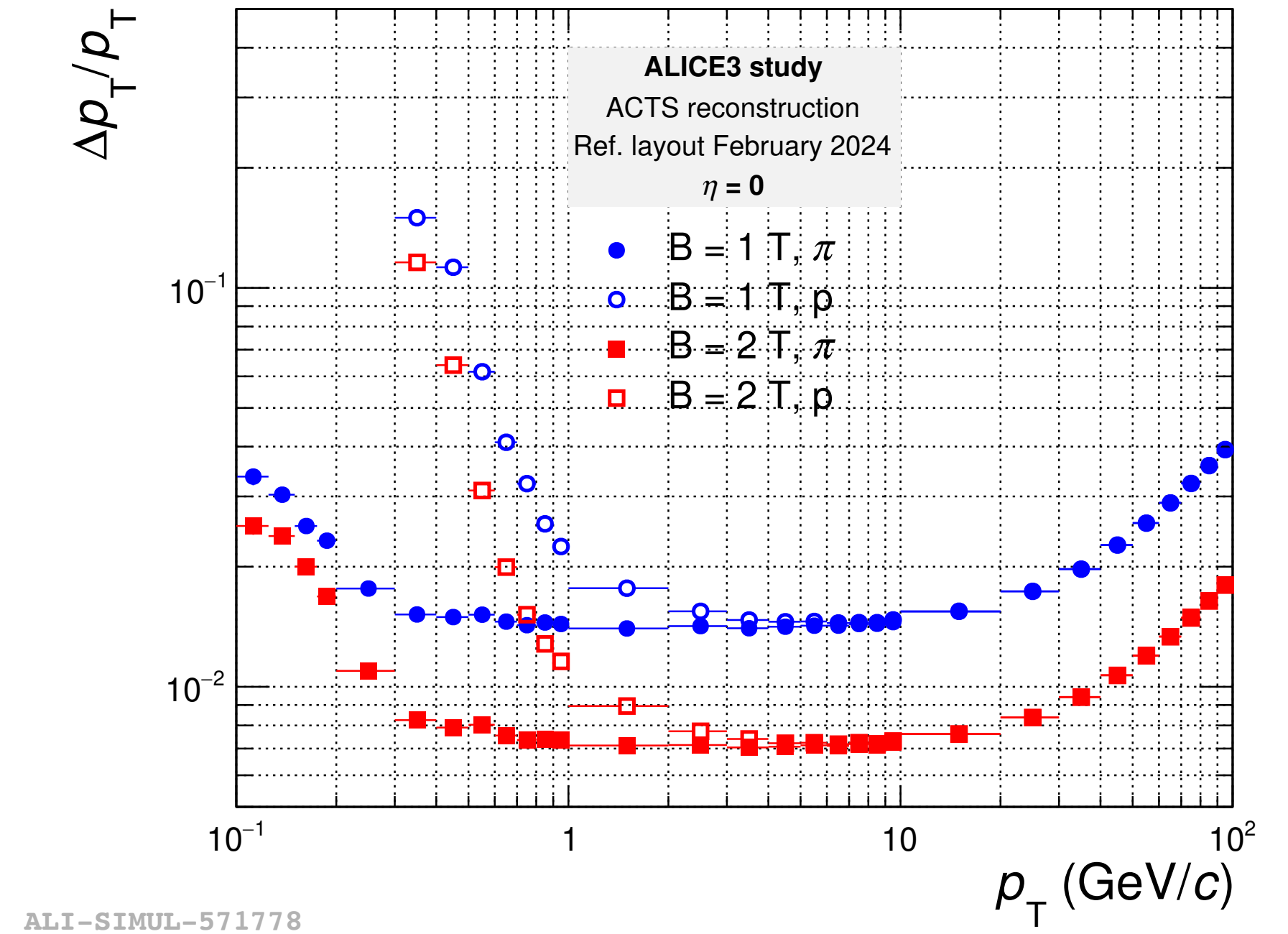
Below 2% for  $p_T > 0.2$  GeV/c ( $\pi^\pm$ ) and  $B = 1-2$  T

Electrons affected by Bremsstrahlung in the detector material  
 → Critical point for the ALICE 3 tracker

# Tracker



$p_T$  resolution



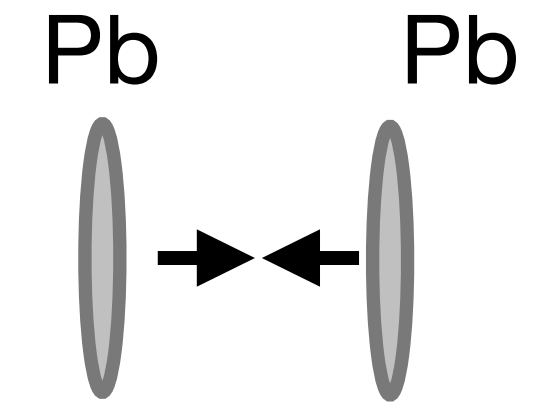
Below 2% for  $p_T > 0.2 \text{ GeV/c}$  and  $B = 1\text{-}2 \text{ T} \sim$  similar as ALICE

In addition: electrons affected by Bremsstrahlung in the detector material

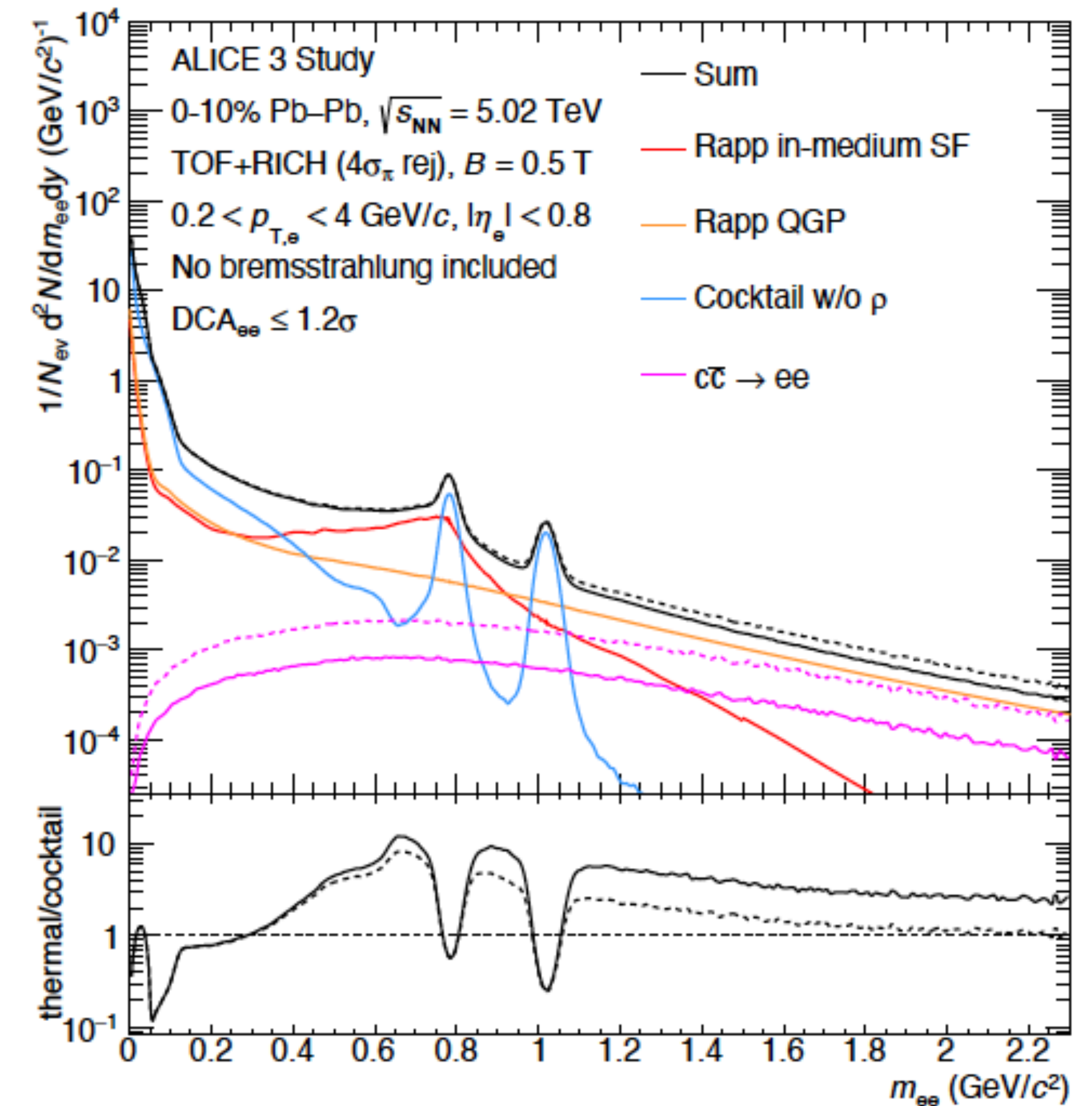
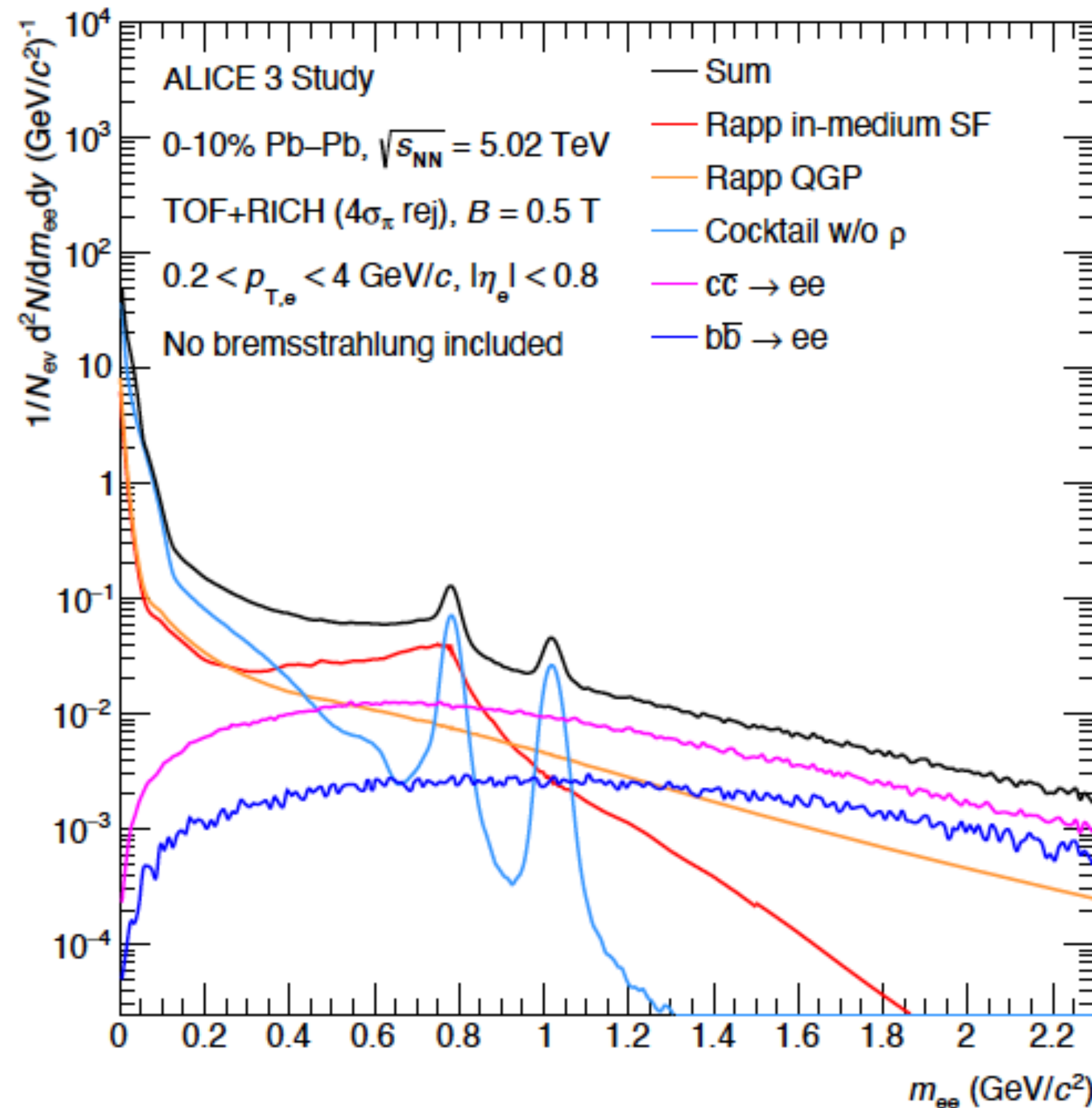
→ Reconstructed  $m_{ee}$  smaller than true  $m_{ee}$  (asymmetric tail)

→ Critical point for the ALICE 3 tracker

# Vertex detector



Could subtract/reject very efficiently the heavy-flavour hadron background



# Electron Identification

