Physics cases and plans for the ALICE 3 detector at LHC

ALICE

Nikhef

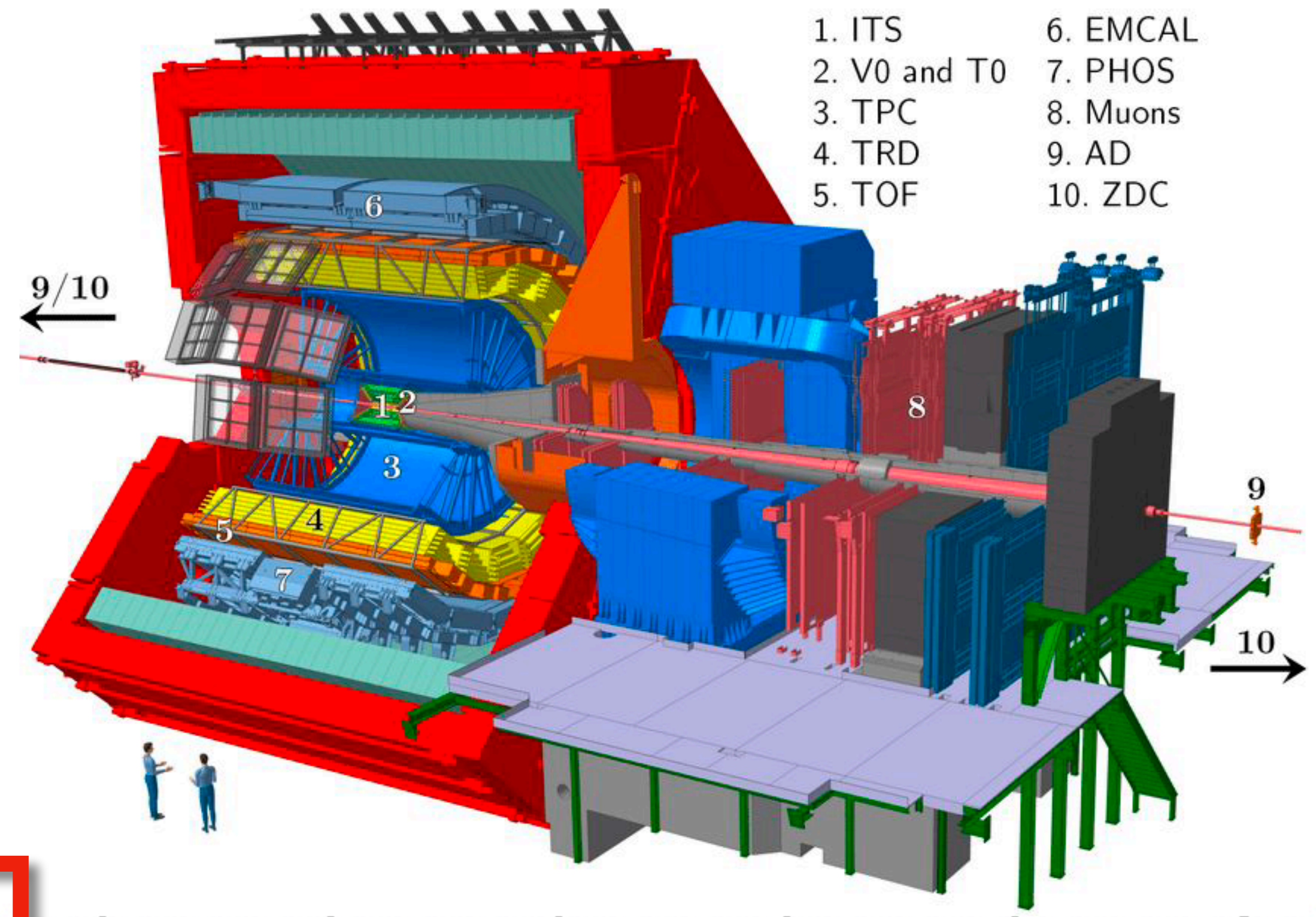
Alessandro Grelli

On behalf of the ALICE Collaboration

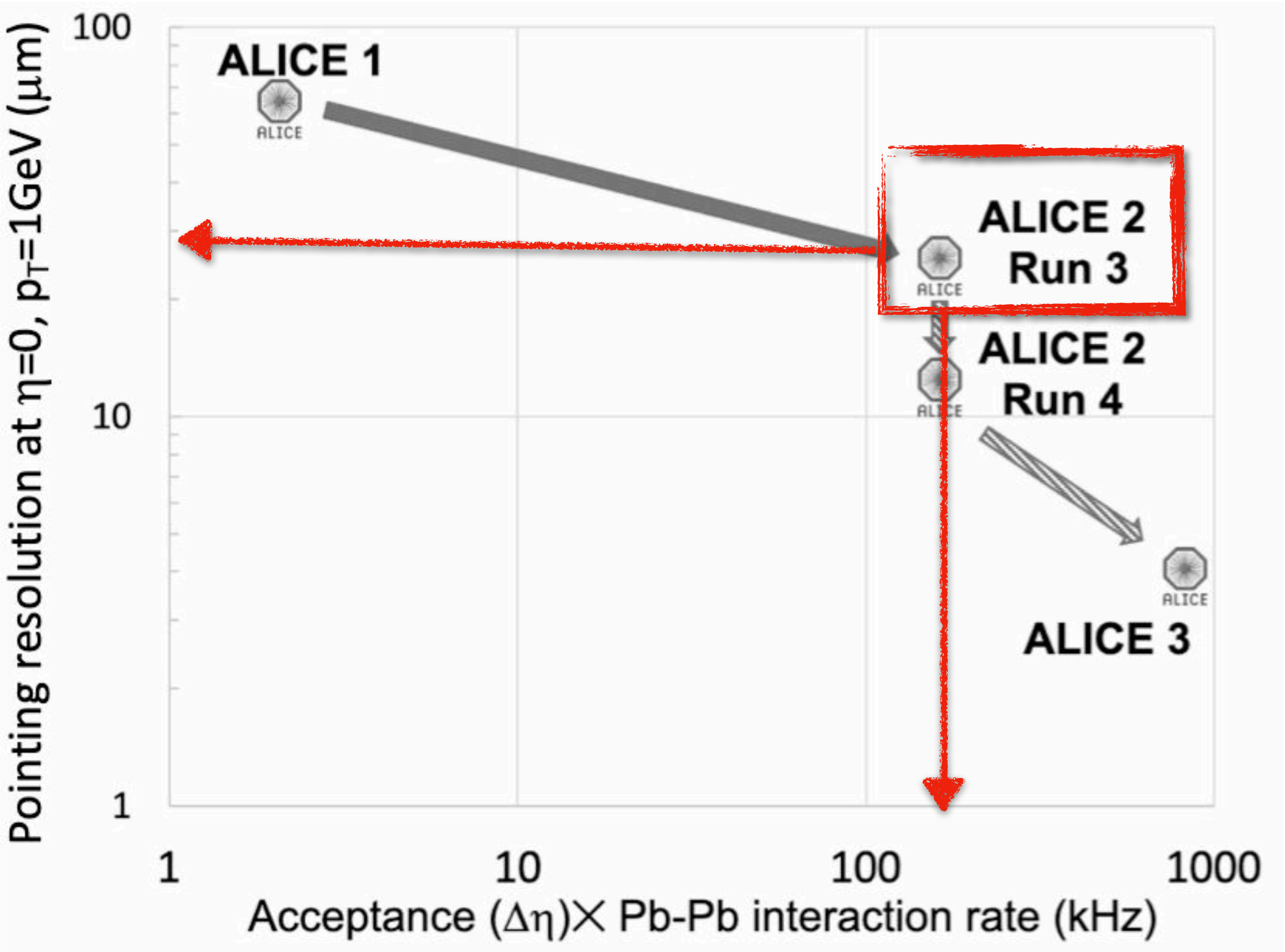
ALICE in LHC Run 3

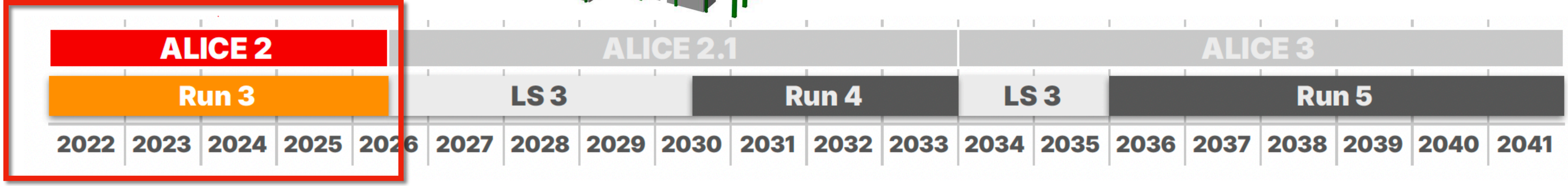
ALICE 2

- High granularity pixel tracker based on MAPS technology
- Continuous readout (TPC,TOF, Muon)
- Low material budget



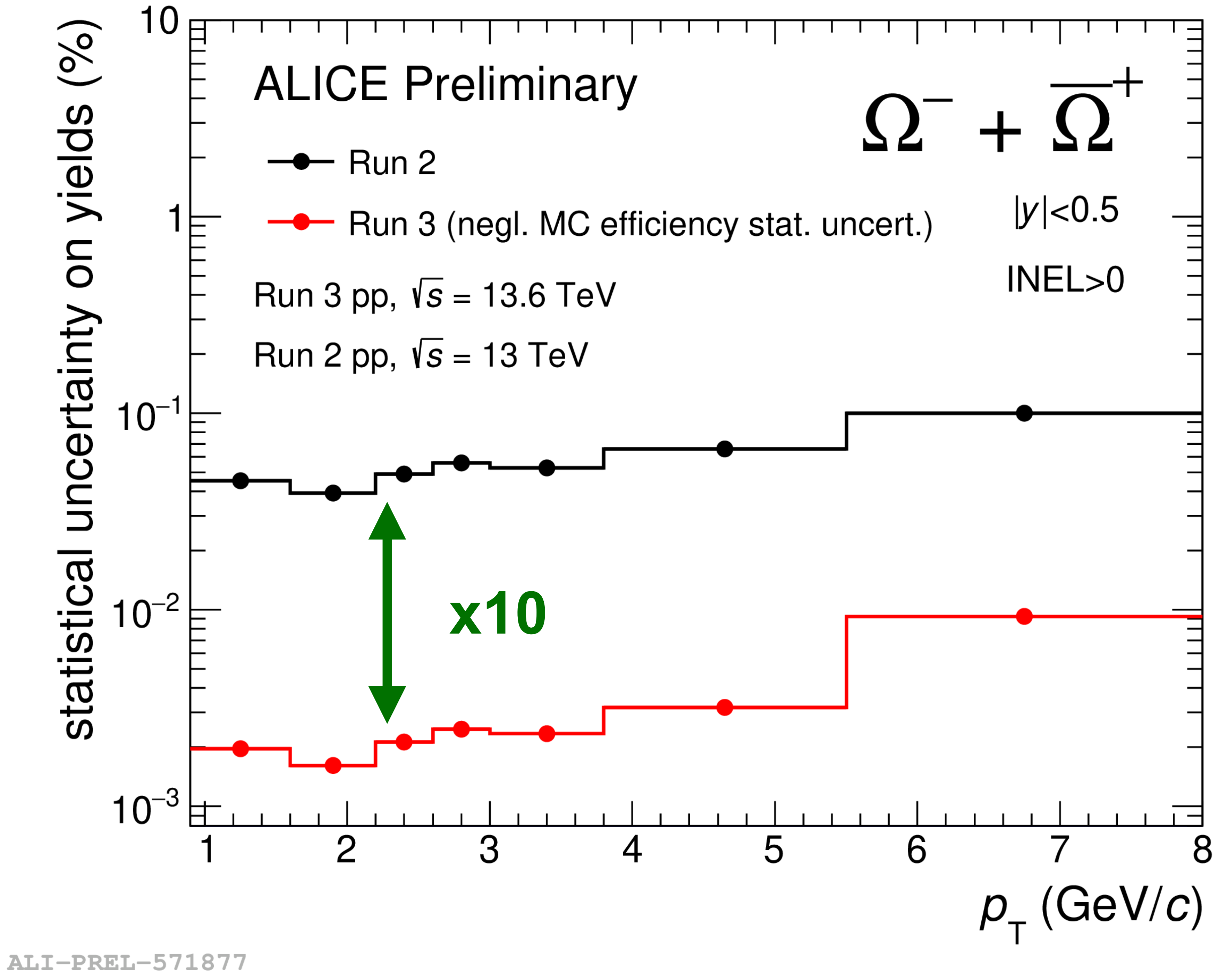
Pb-Pb: 6.5 nb^{-1}
O-O: 500 μb^{-1}

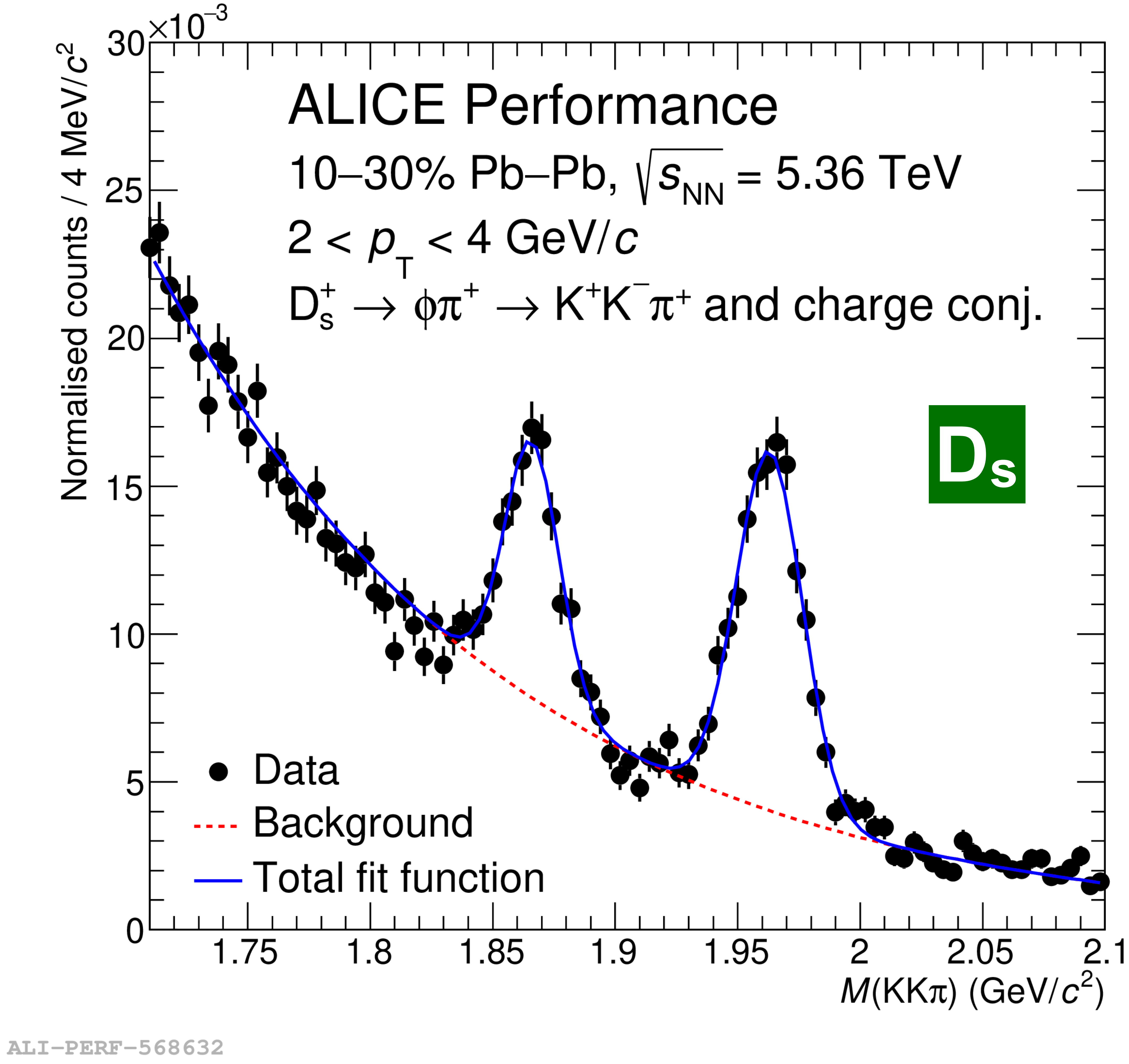




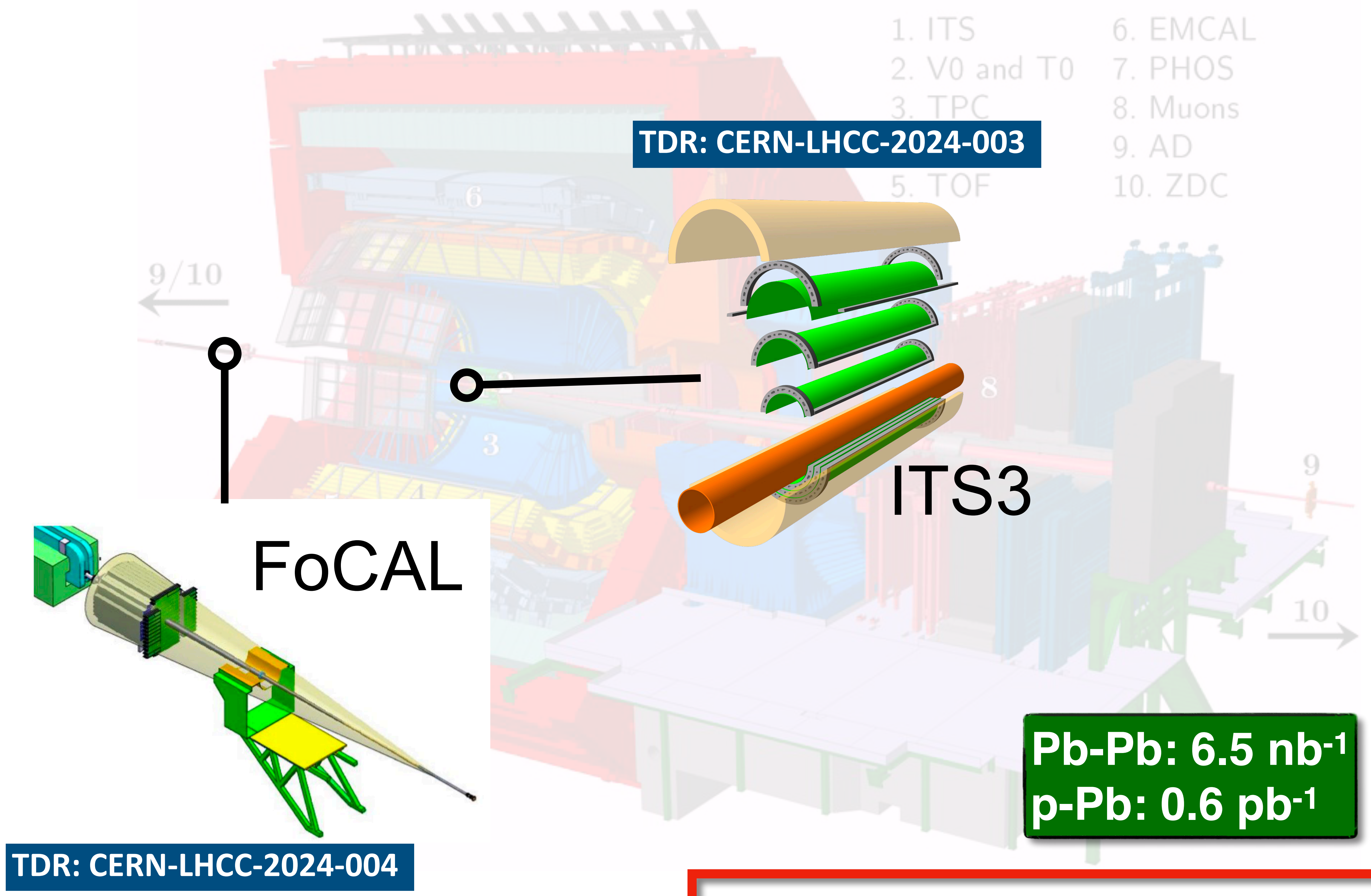
ALICE in LHC Run 3

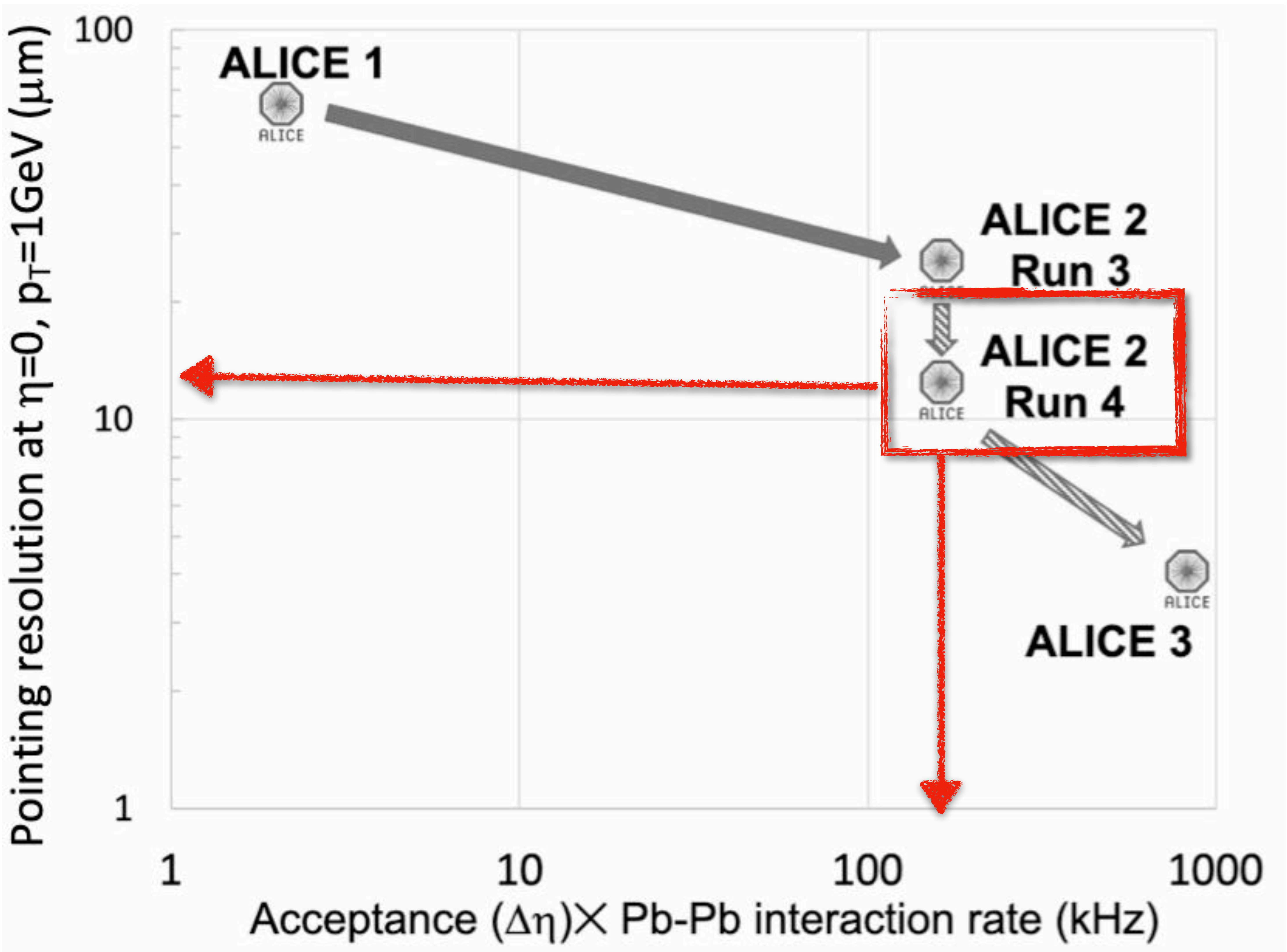
- Integrated Pb-Pb luminosity in line with expectations
- Observables statistical uncertainty largely improved

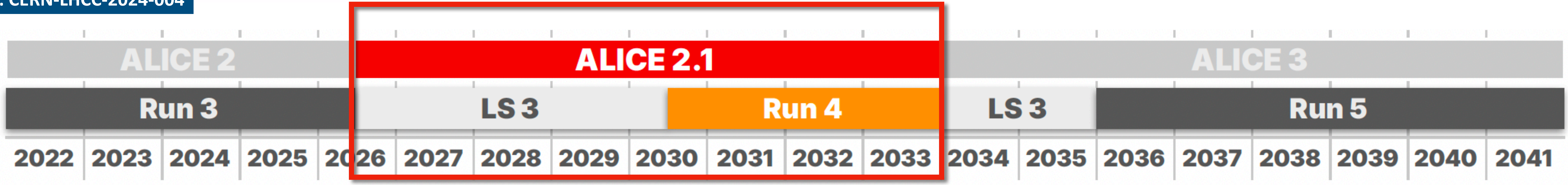




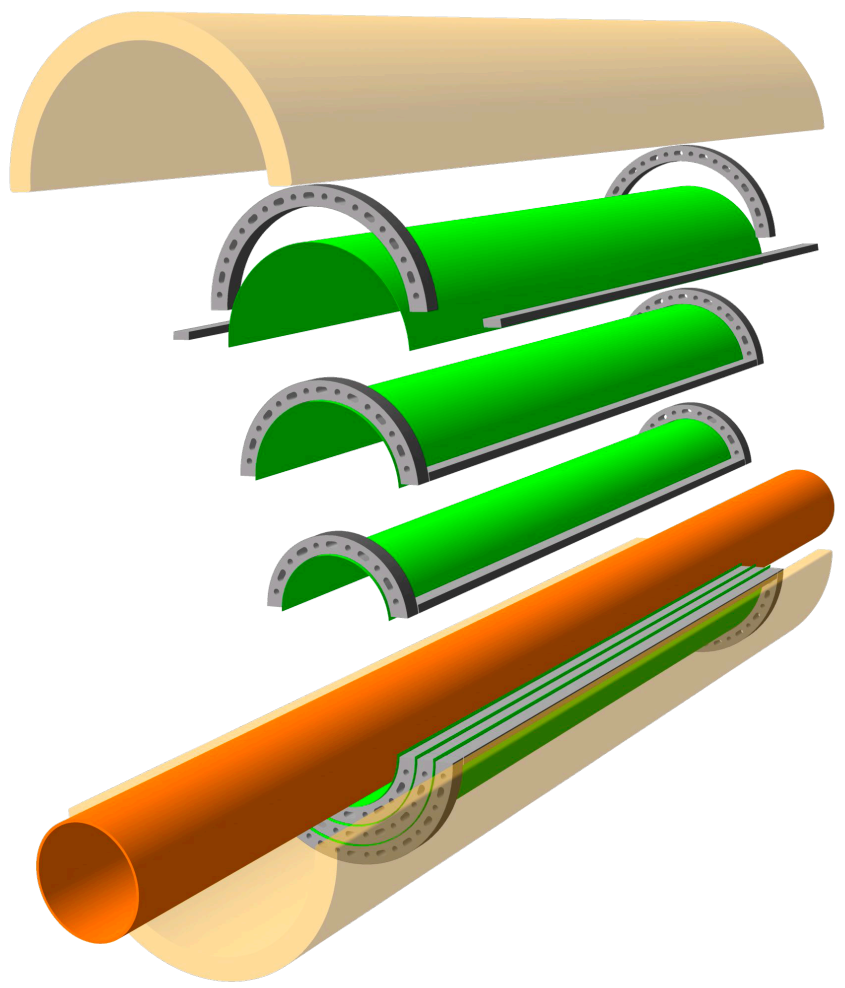
ALICE 2.1: ITS3 & FoCAL

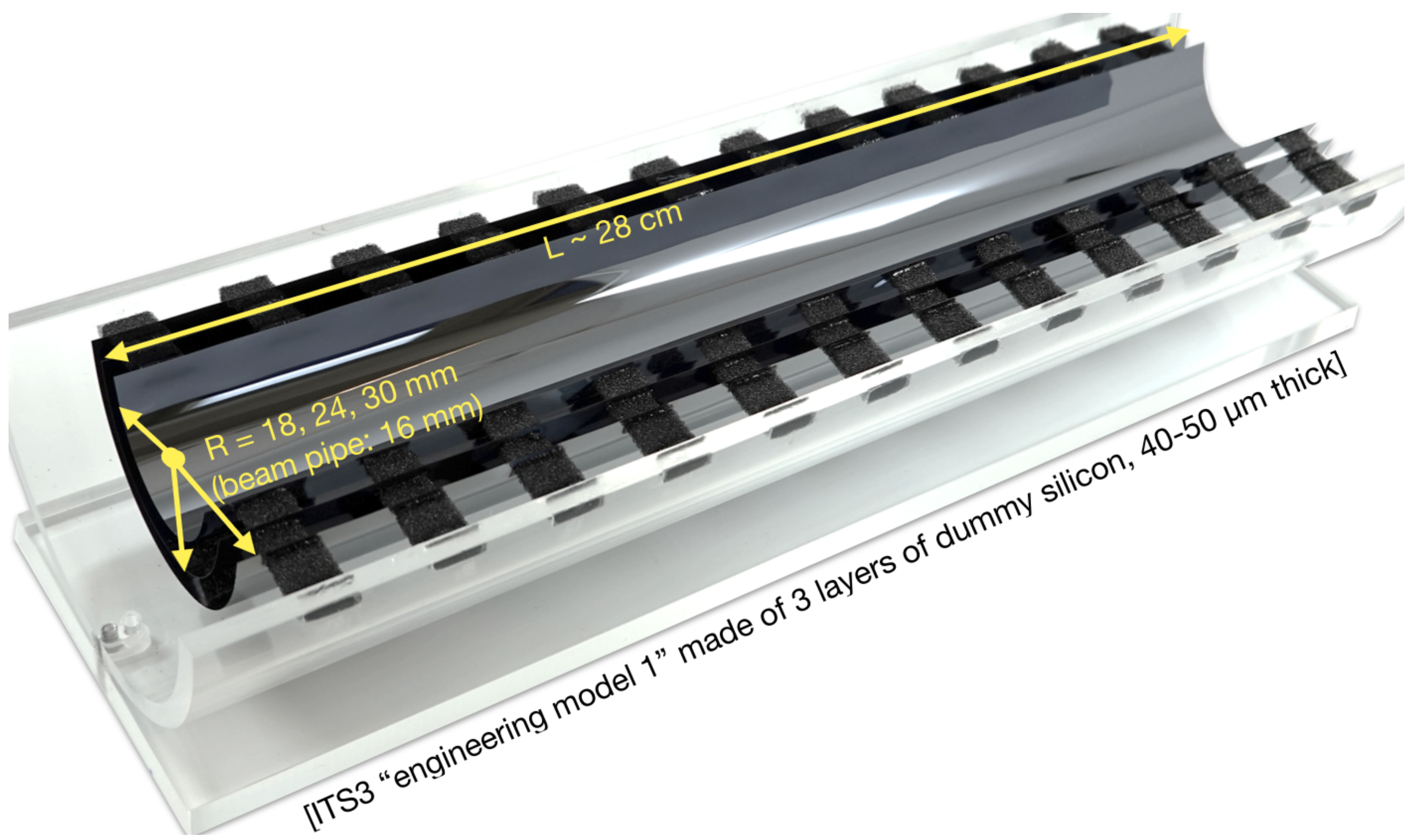


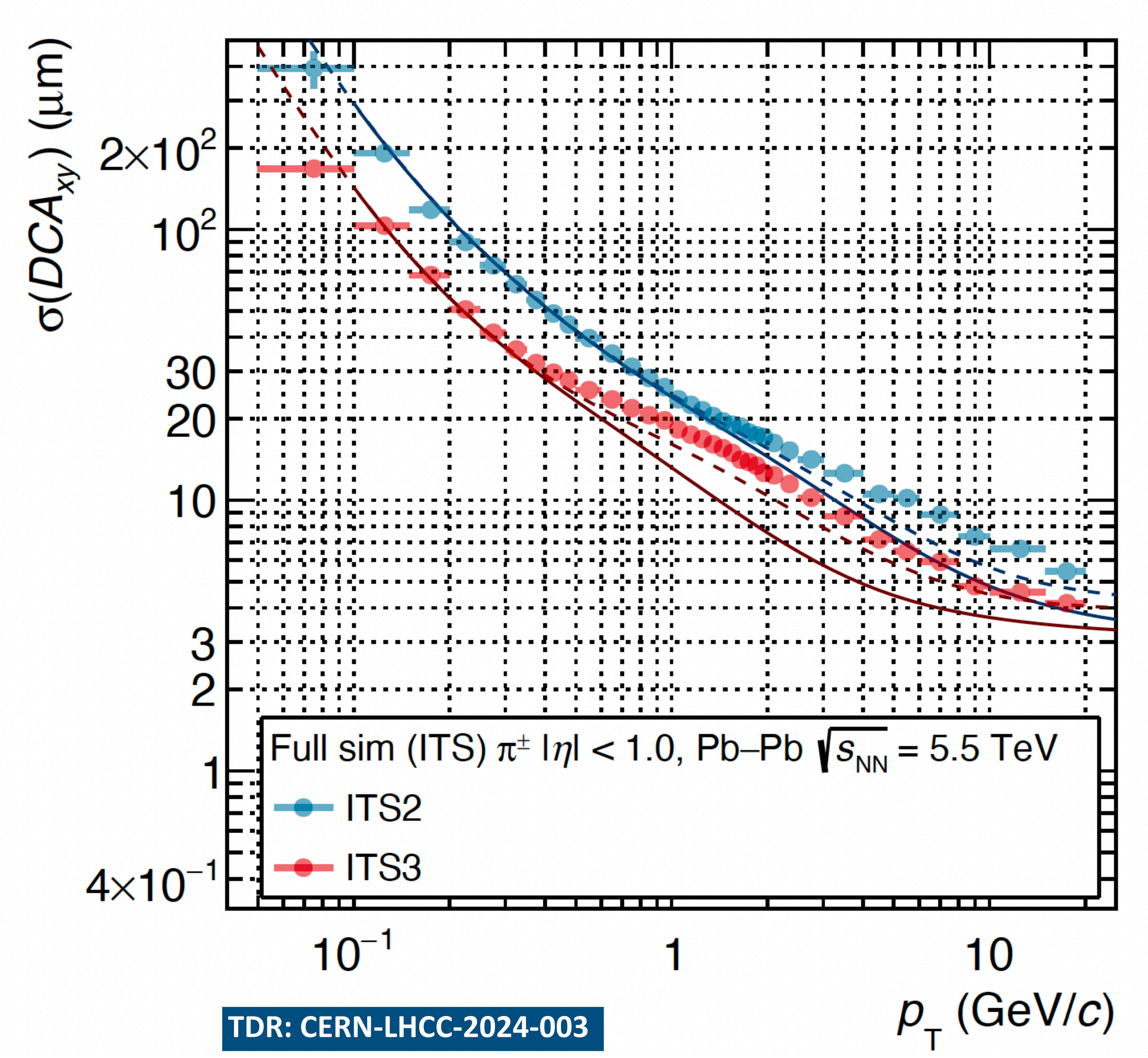




Inner Tracking System: ITS3





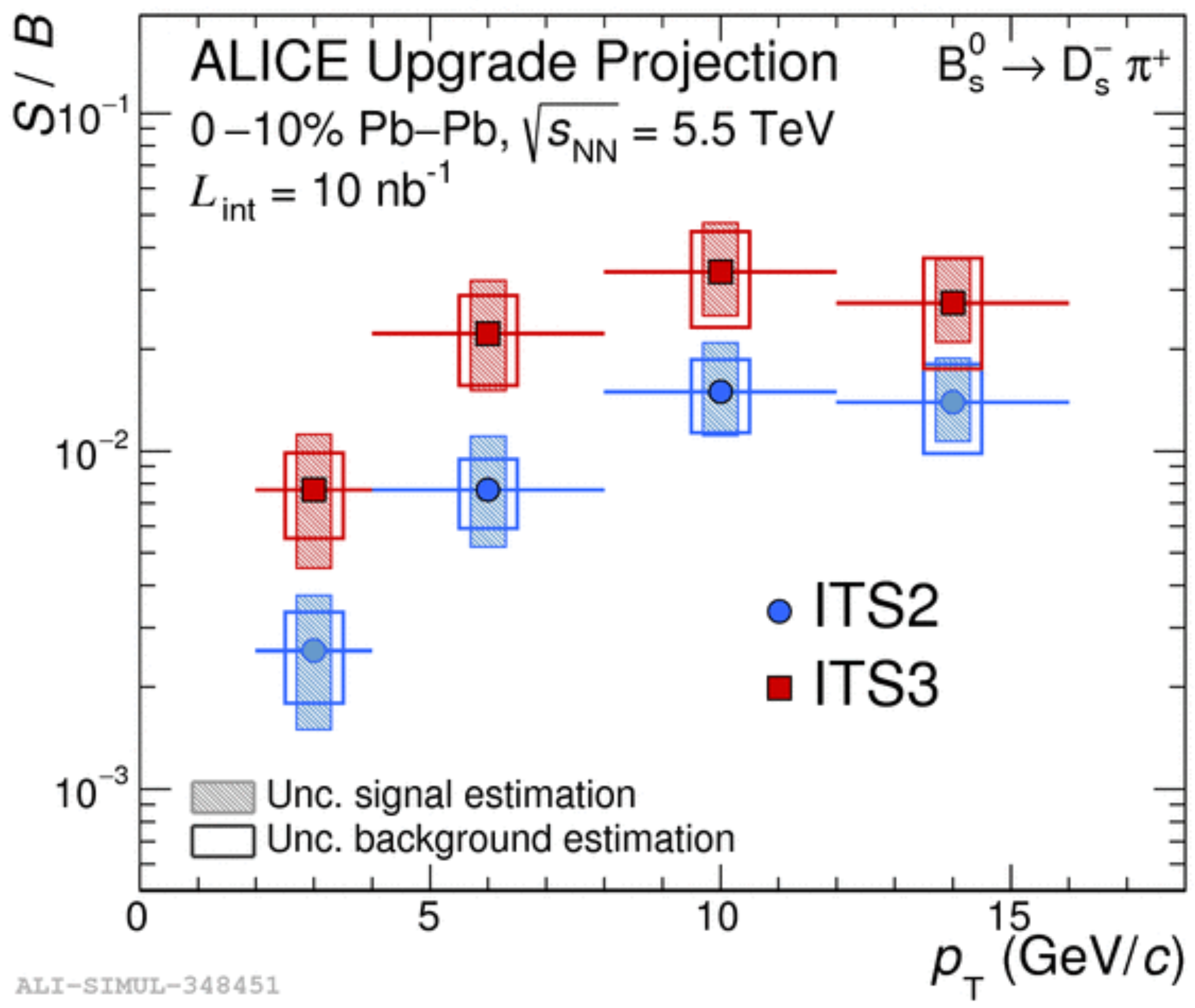


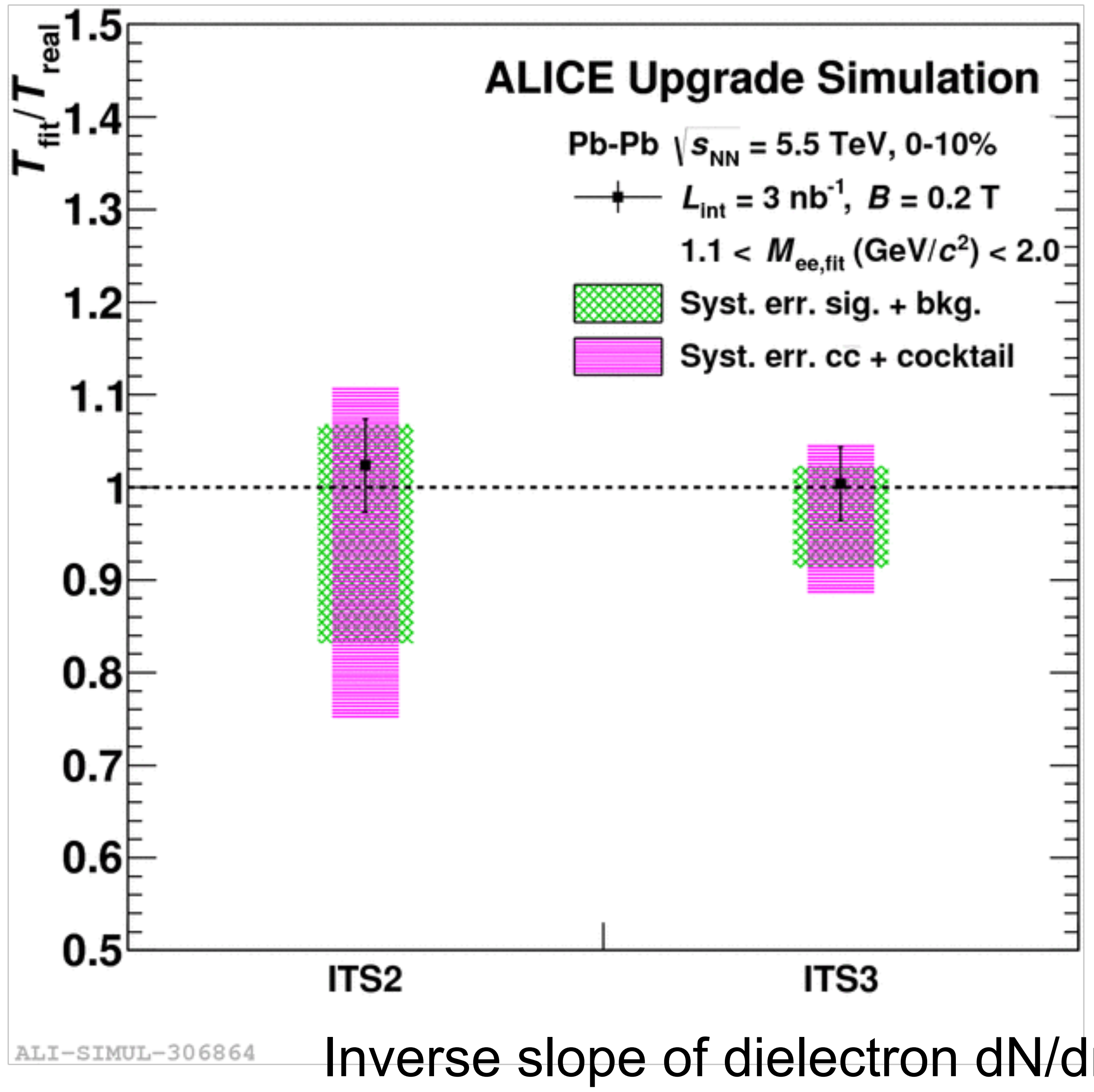
- Replacement of 3 innermost layers of the current ALICE silicon tracker
- Curved wafer-scale ultra-thin silicon sensors
  - Truly cylindrical layers
  - Low power, air cooling
  - Material budget at 0.07 X_0 per layer
- **Enhance ALICE low p_T tracking, solid baseline for R&D towards ALICE 3**

ALICE @ LHC Run 4

- Precision era for many standard observables (e.g R_{AA} and v_2). In addition:

  - Advances on medium effects and **hadrochemistry** of single charm
  - **thermal radiation** from the quark-gluon plasma
  - Advances on **collectivity** from small to large systems





Inverse slope of dielectron dN/dm_{ee}

- Many more questions will remain open!

Beyond LHC run 4

☑ What will remain open after LHC Run 4? .. and what we need to tackle it

- How to establish a firm connection between parton transport, collective phenomena and hadronisation?
  - Requires extension of the study of parton energy loss down to momenta typical of diffusion phenomena ➜ *Needs precision measurements of beauty quark*
- Do we understand hadron formation from deconfined QGP? ➜ *Needs multi charm hadrons, exotic hadrons*
- Complete picture of the temperature dependence of QGP bulk and shear viscosities? ➜ *heavy flavour would give just an average picture so we need multi-differential electromagnetic radiation*

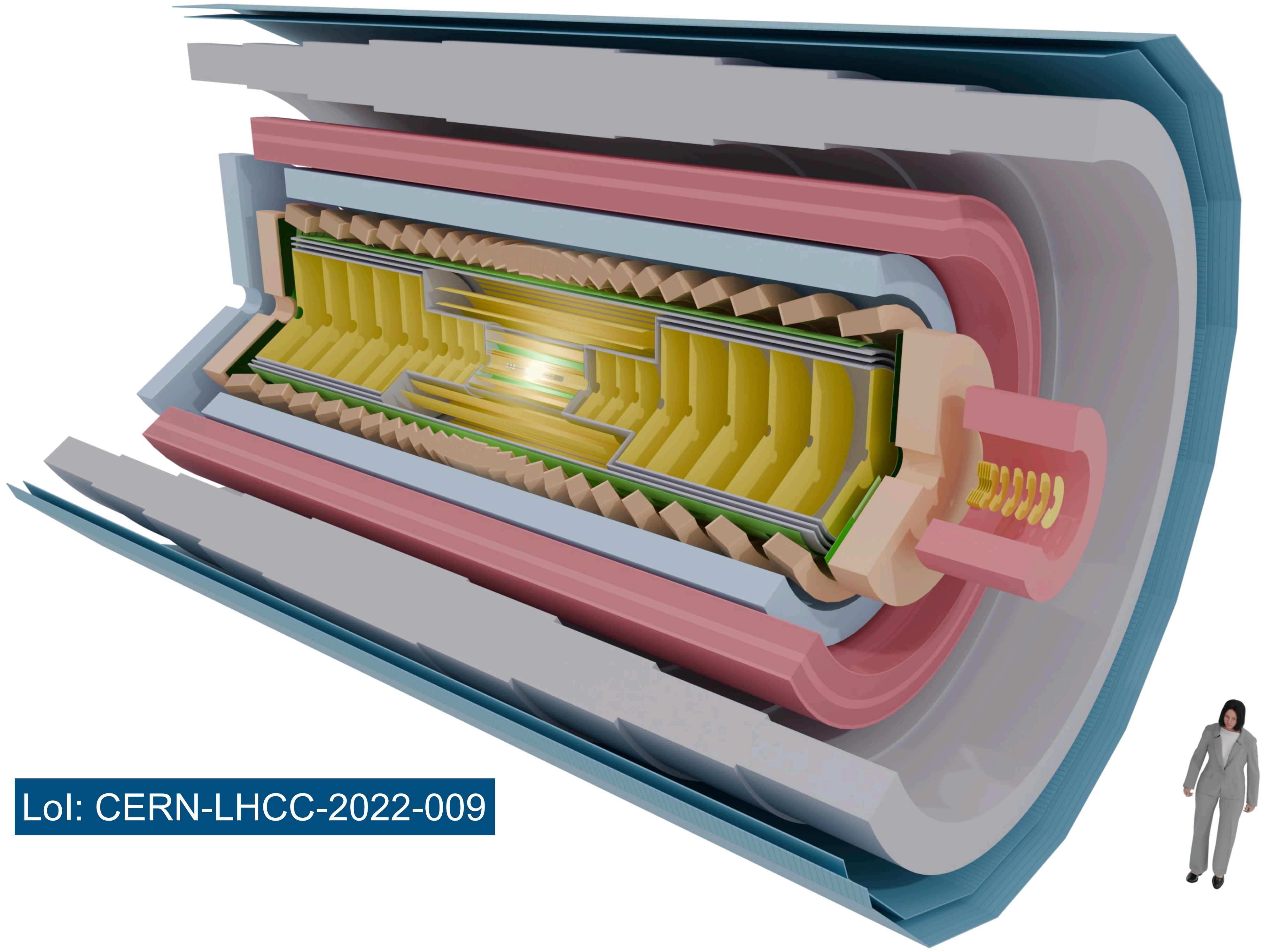
Beyond LHC run 4

☑ And much more:

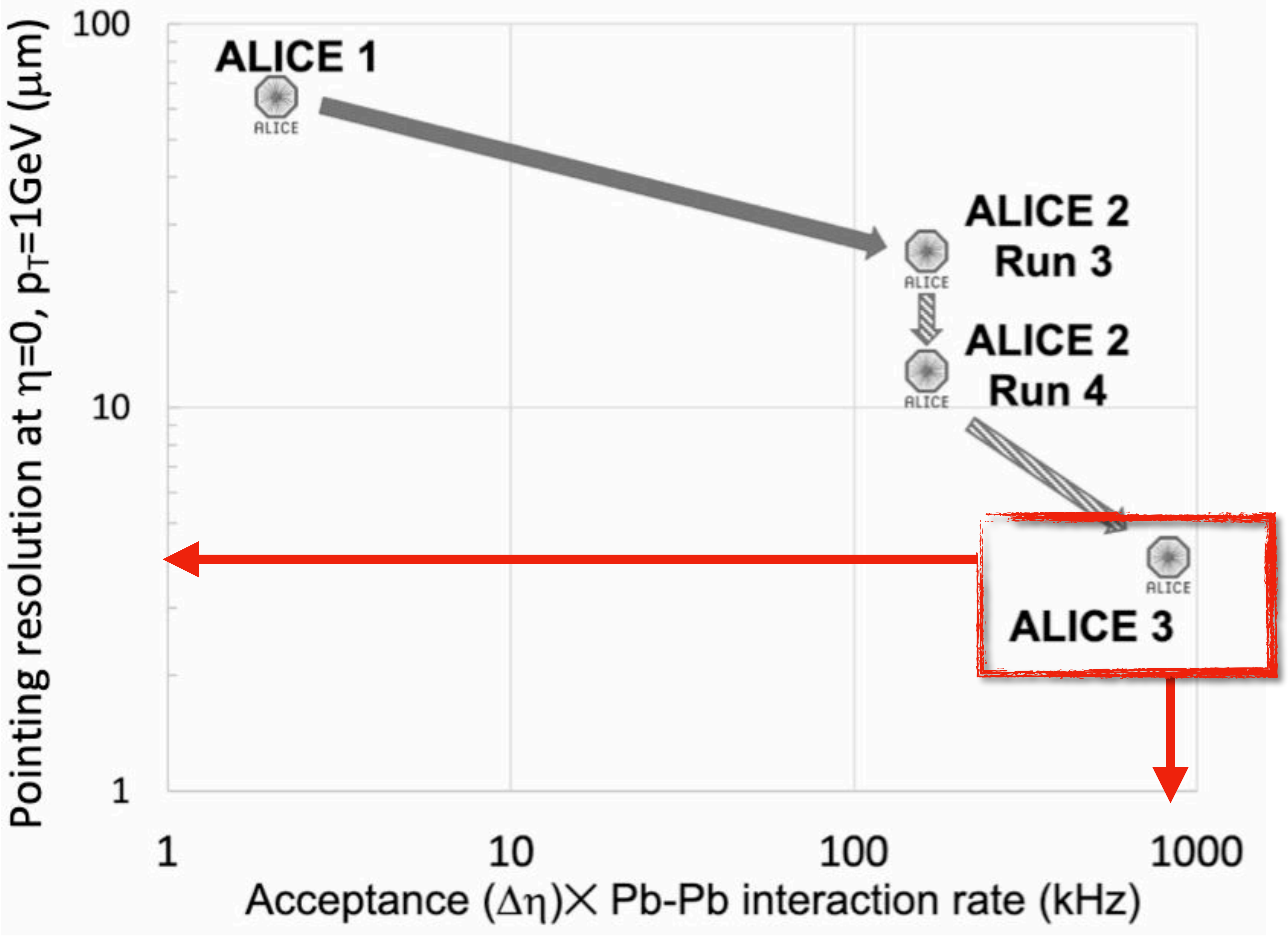
- Chiral symmetry restoration? ➜ *Needs precise measurement in the di-lepton sector*
- Origin of collectivity in small systems? ➜ *Needs large phase space, high data rate*
- What is the nature of the hadron-hadron potential in the charm sector? ➜ *Needs large phase space, high data rate*
- Can we push the studies of anti-hyper nuclei and investigate the possible existence of super nuclei? ➜ *High data rate, state-of-art tracking and particle identification*
- Physics Bejond Standard Model ➜ *High data rate, state-of-art tracking*

We need a large acceptance, fast and precise detector

Toward LHC Run 5: ALICE 3



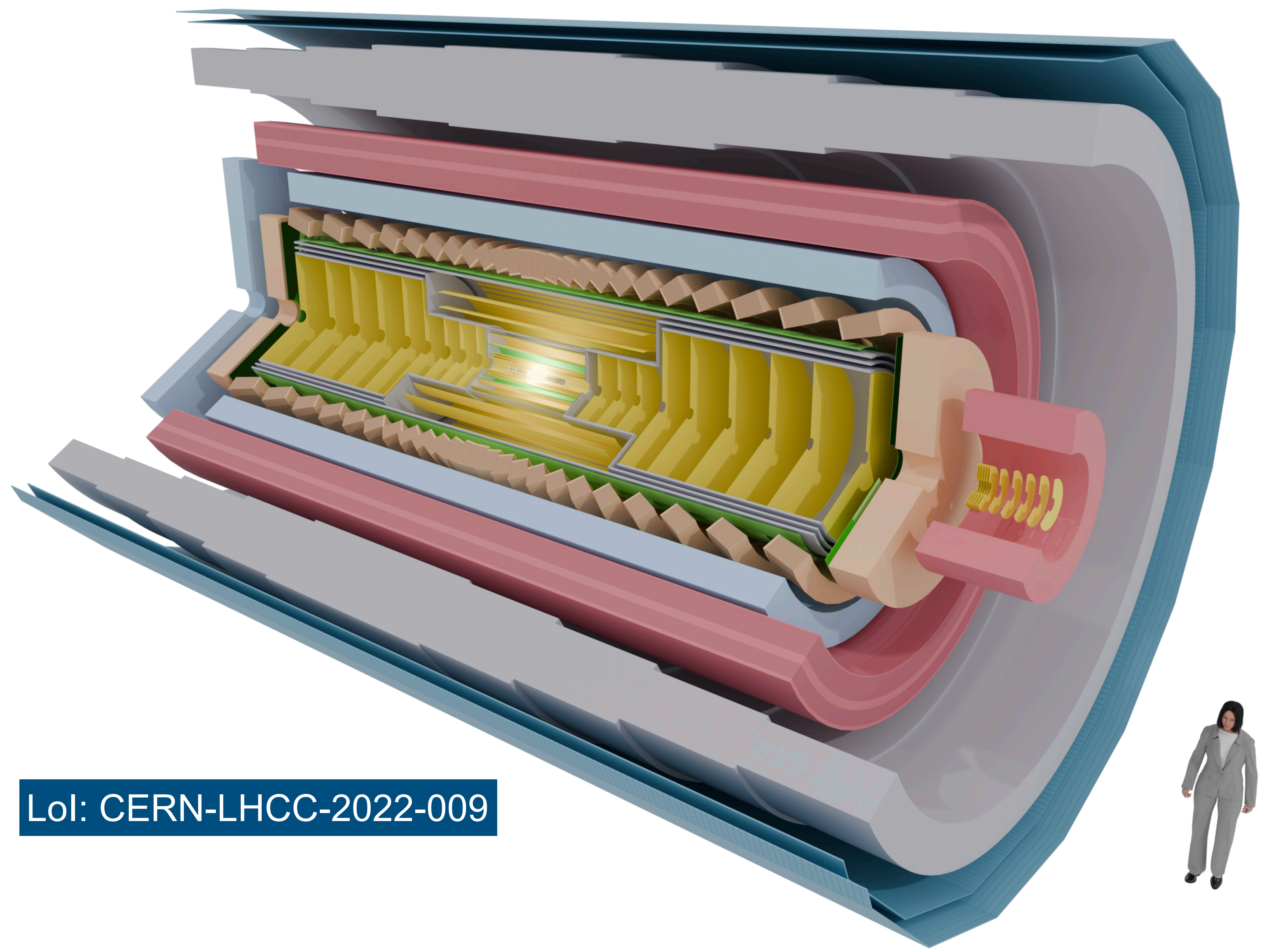
LoI: CERN-LHCC-2022-009

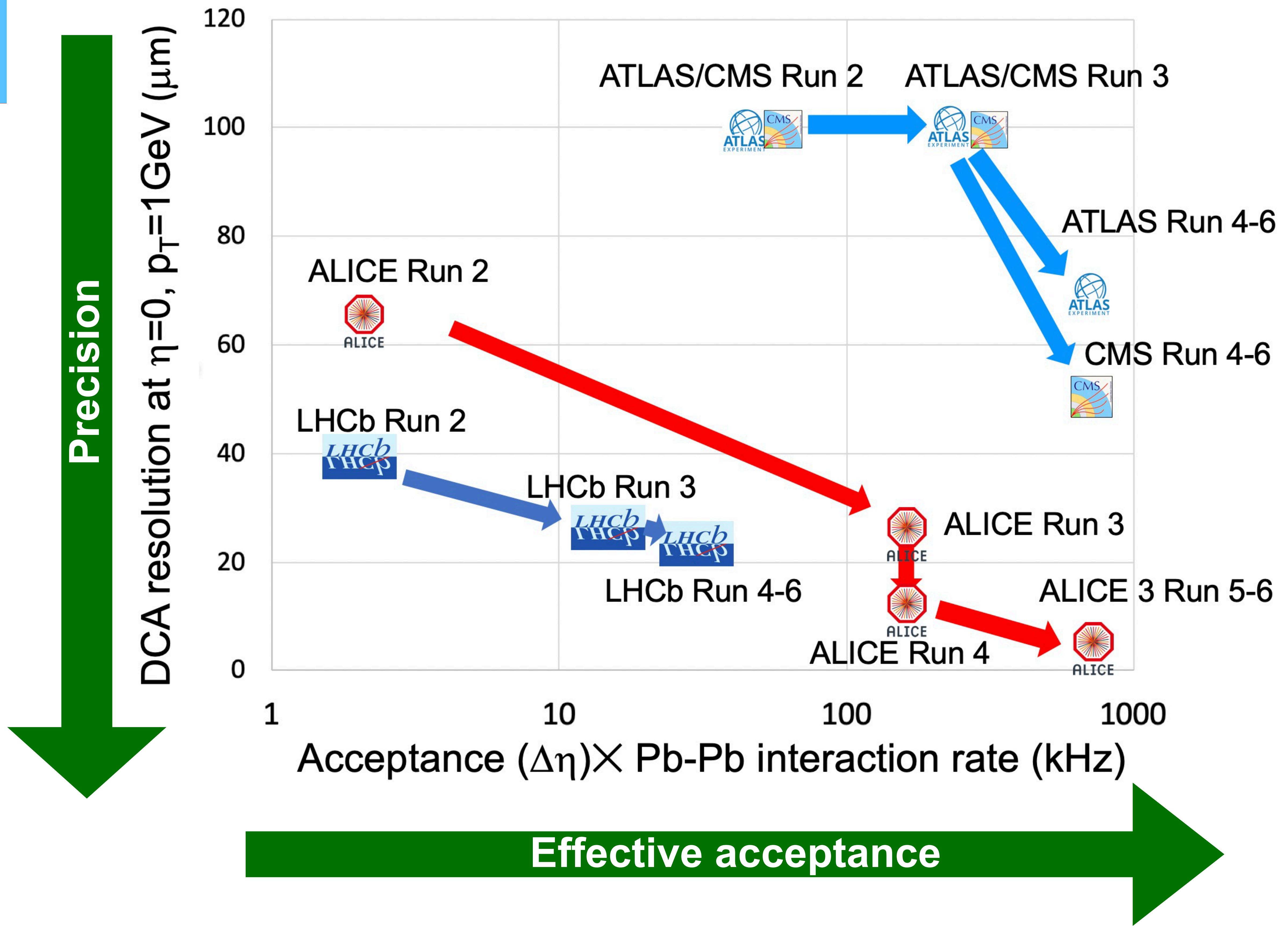


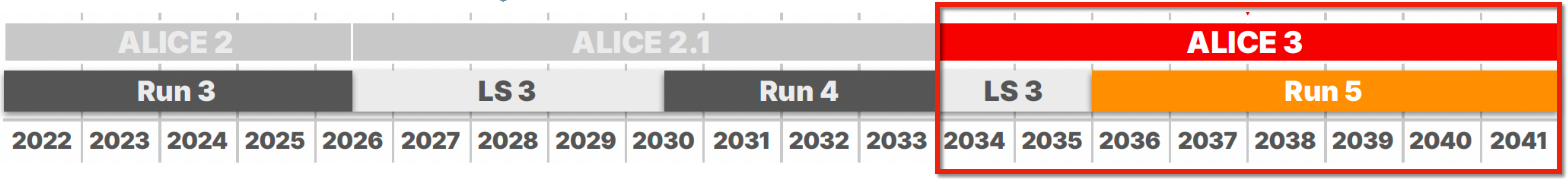
- ALICE 2 — Run 3
- ALICE 2.1 — LS 3, Run 4
- **ALICE 3** — LS 3, Run 5

2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 | 2039 | 2040 | 2041

Toward LHC Run 5: ALICE 3



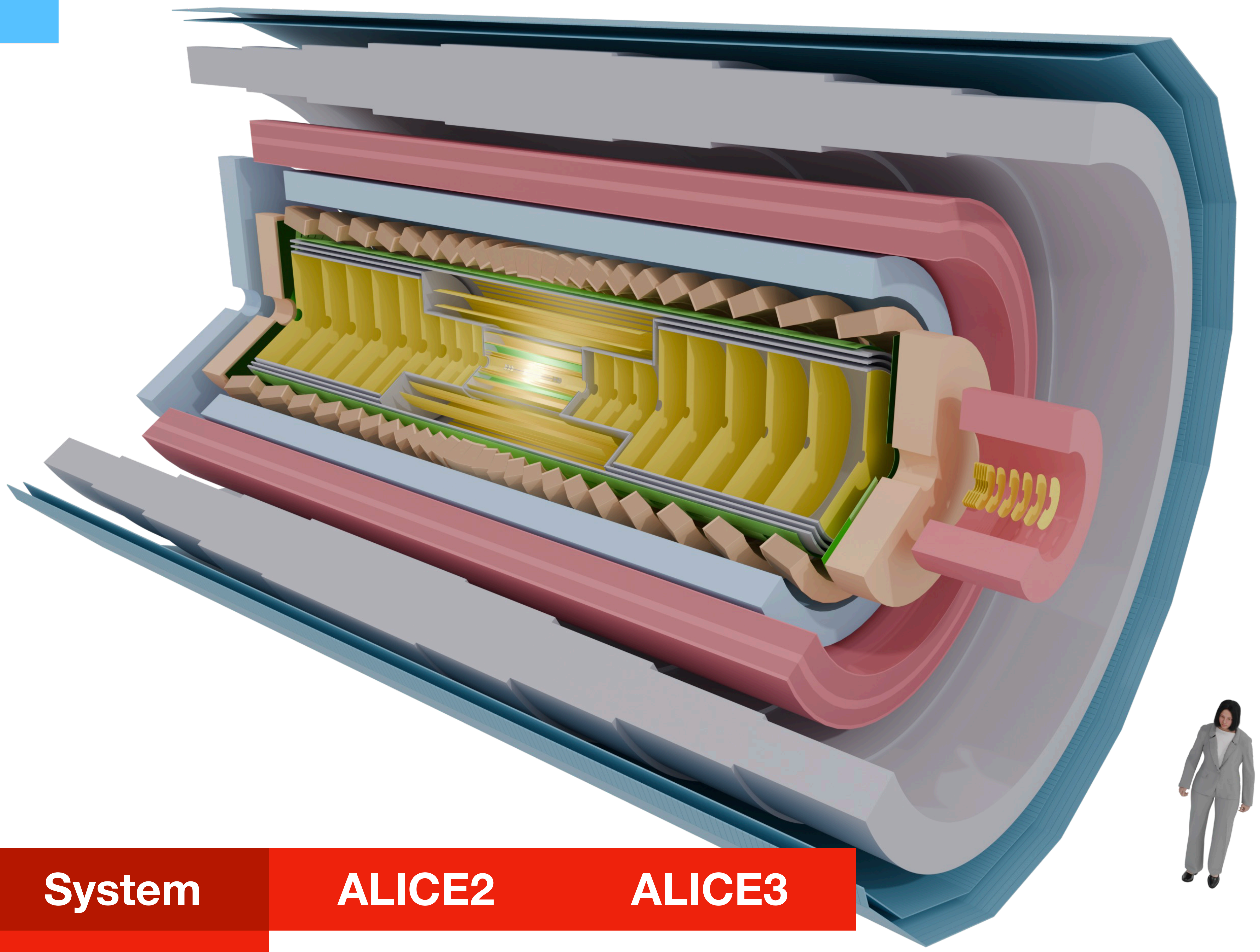




ALICE 3

☑ ALICE 3 in a nutshell:

- Compact (~2 x 8 m)
- Large acceptance, **|η|<4, p_T >0.04 GeV/*c***
- Superconducting magnet system
- Max field: B = 2 T (*0.5 T runs foreseen*)
- Continuous readout and online processing
- Pointing resolution ~3-4 µm and p_T resolution better than 1% @1 GeV/*c*
- Particle Identification (PID) in a wide range of momenta and |η|<4

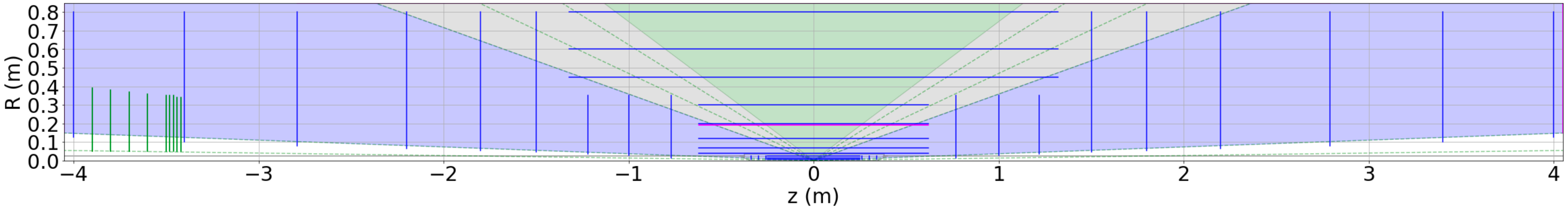


System	ALICE2	ALICE3
pp	1 MHz	24 MHz
Pb-Pb	50 kHz	~100-150 kHz

Max projected LHC luminosity

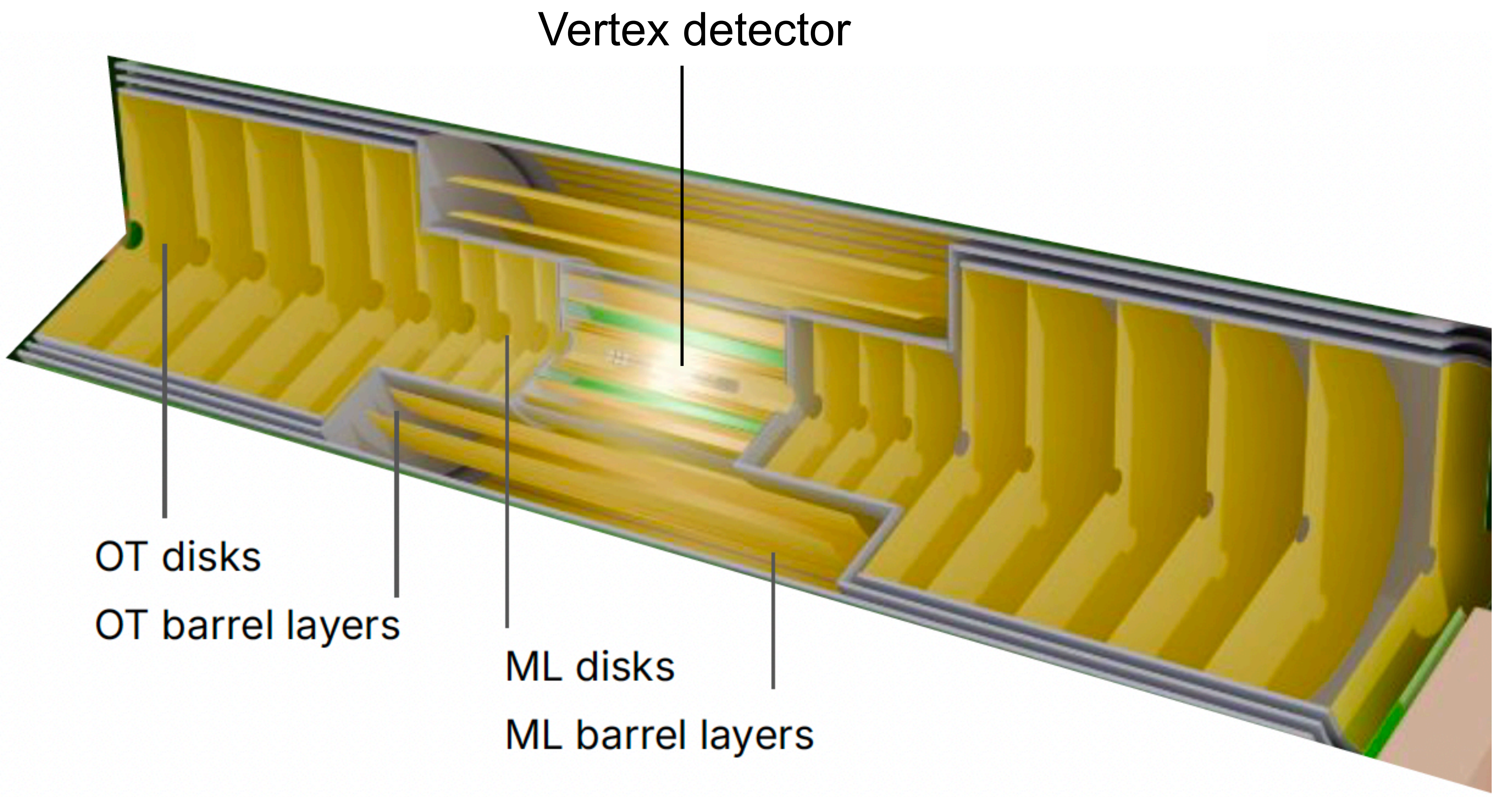
ALICE 3 silicon tracker

LoI: CERN-LHCC-2022-009



Layer	Material thickness (%X_0)	Intrinsic resolution (µm)	Barrel layers Length (±z) (cm)	Barrel layers Radius (r) (cm)	Forward discs Position ($\|z\|$) (cm)	Forward discs R_{in} (cm)	Forward discs R_{out} (cm)
0	0.1	2.5	50	0.50	26	0.50	3
1	0.1	2.5	50	1.20	30	0.50	3
2	0.1	2.5	50	2.50	34	0.50	3
3	1	10	124	3.75	77	5	35
4	1	10	124	7	100	5	35
5	1	10	124	12	122	5	35
6	1	10	124	20	150	5	80
7	1	10	124	30	180	5	80
8	1	10	264	45	220	5	80
9	1	10	264	60	279	5	80
10	1	10	264	80	340	5	80
11	1				400	5	80

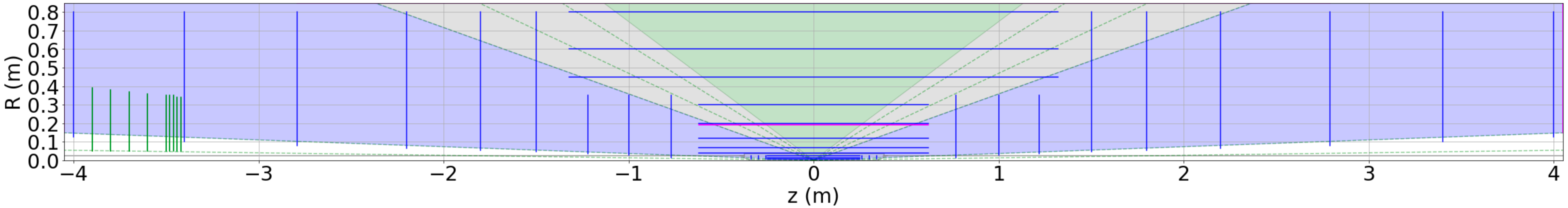
Table 8: Geometry and key specifications of the tracker.



ALICE 3 silicon tracker

LoI: CERN-LHCC-2022-009

11 layers, 12 disks



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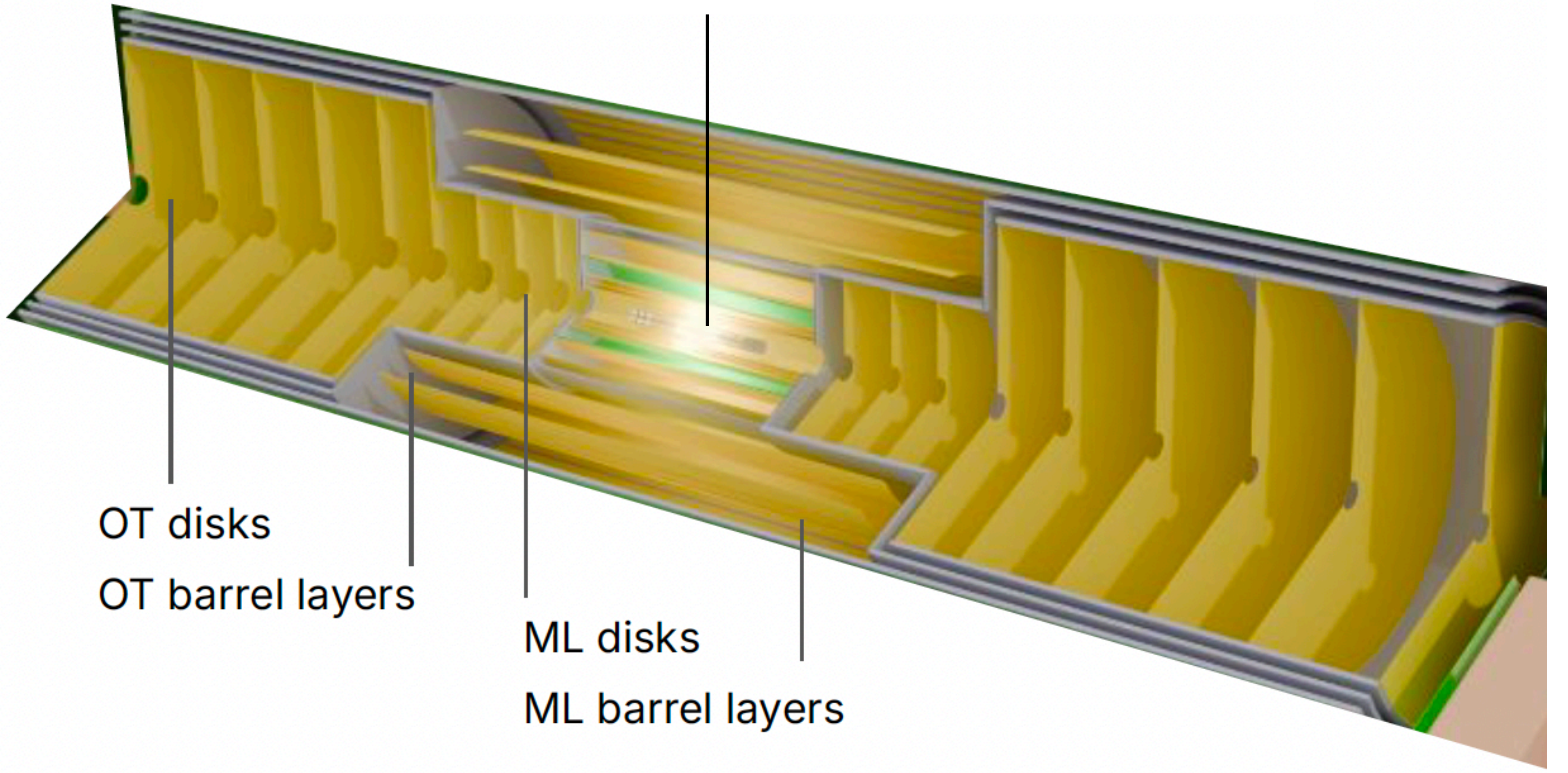

ALICE 3 silicon tracker

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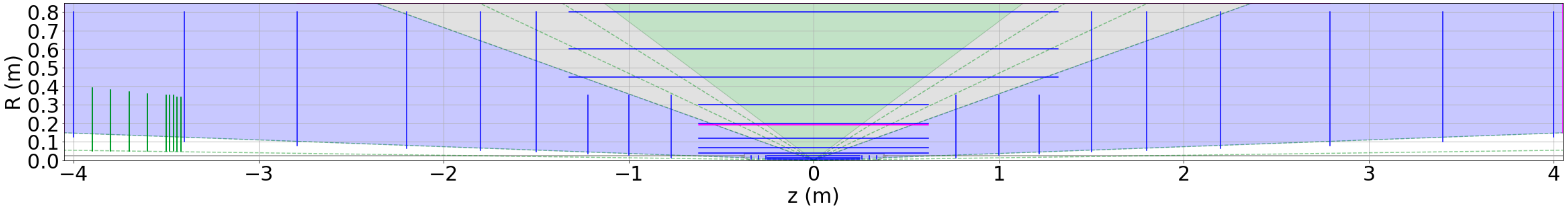

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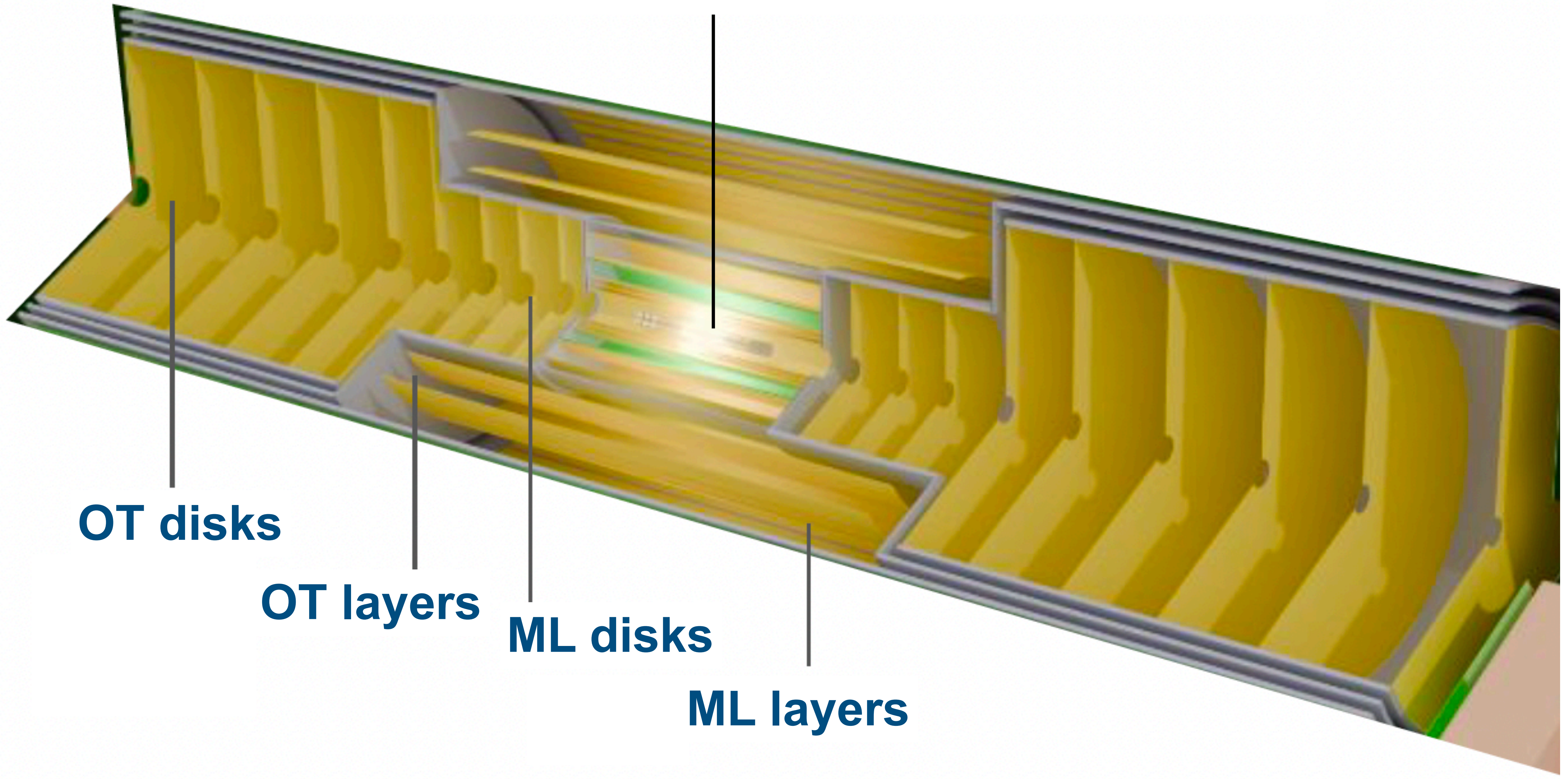
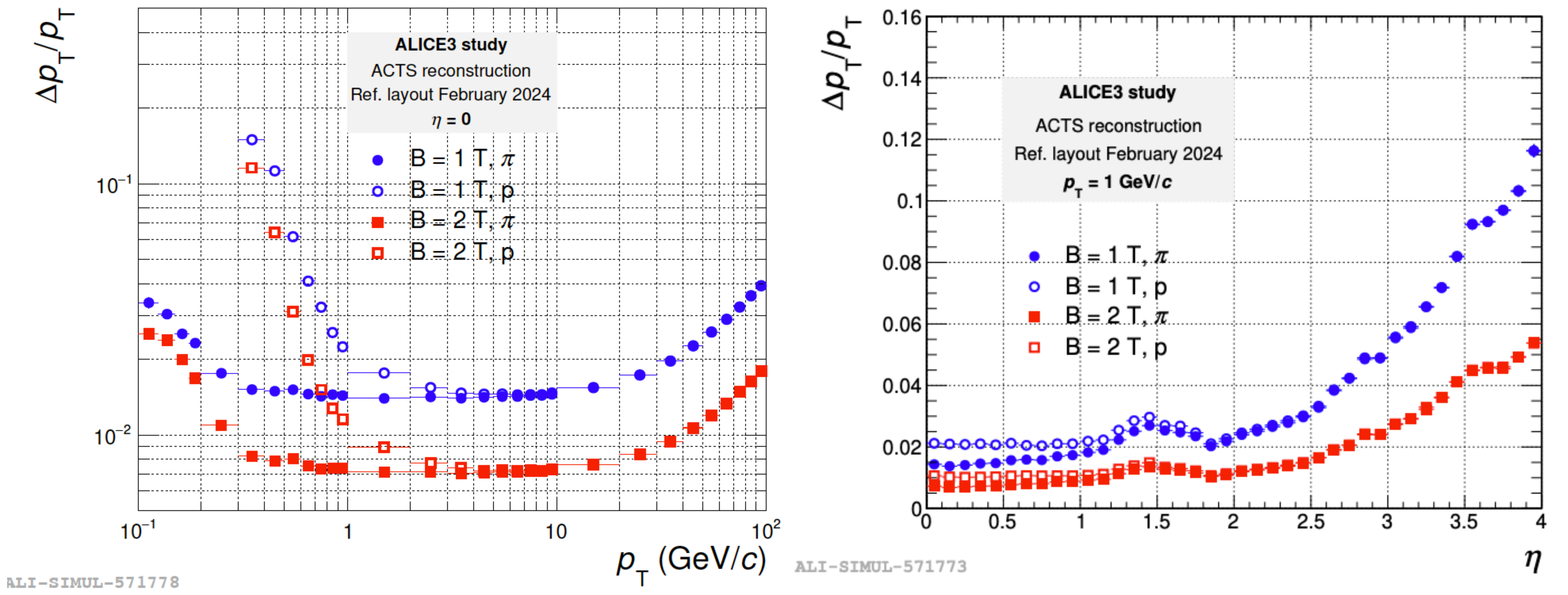
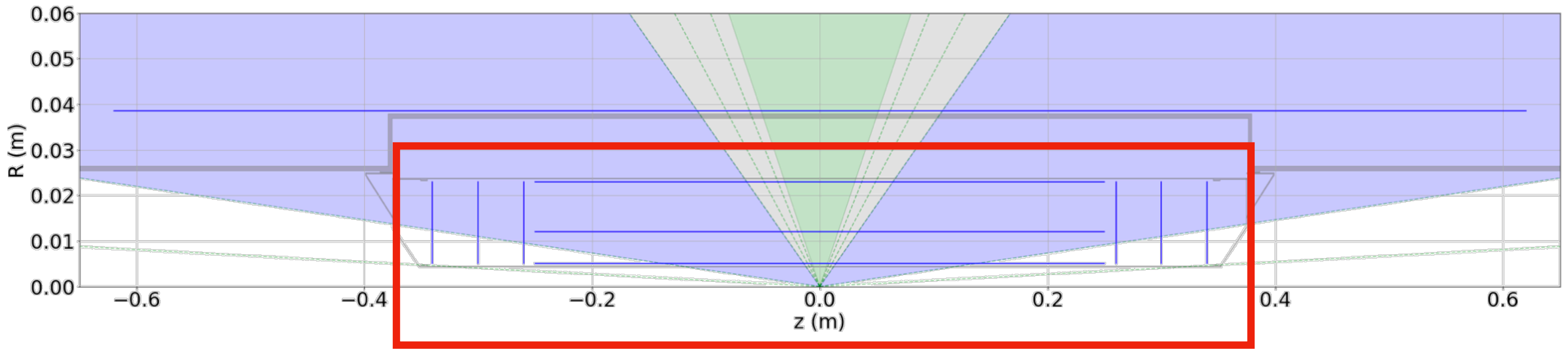


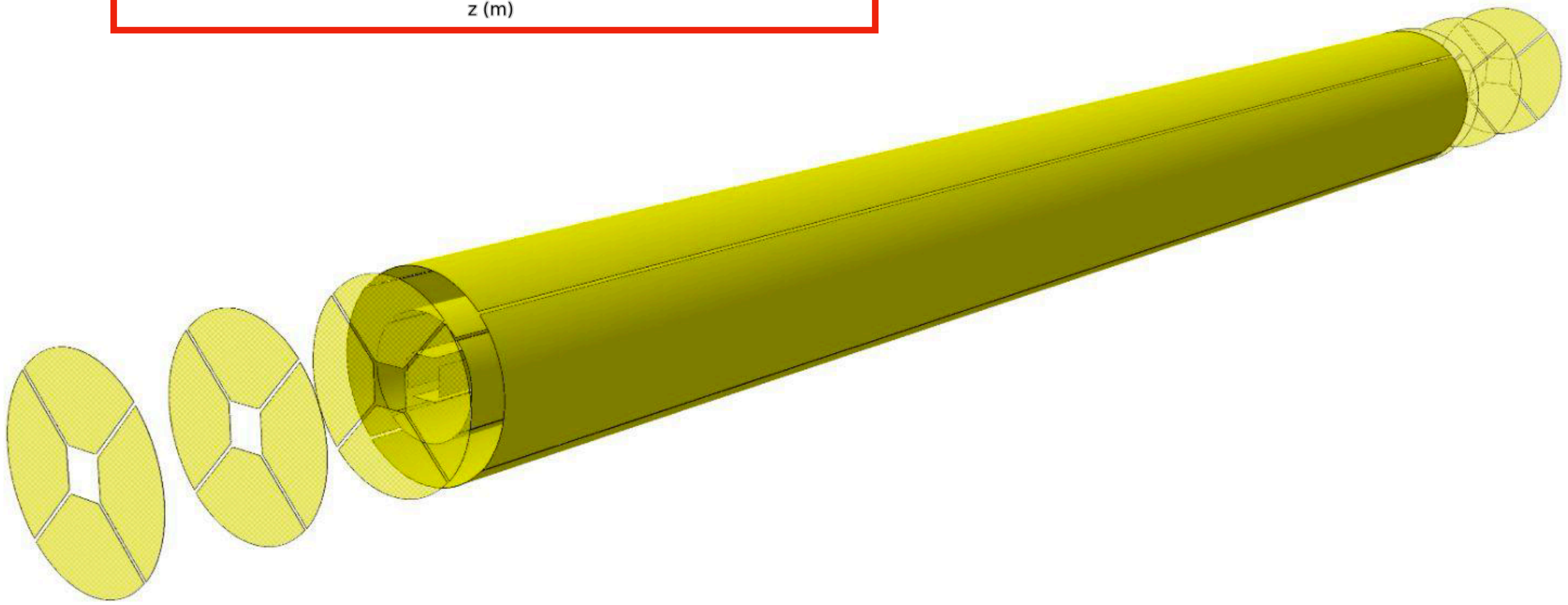
Momentum resolution



- **With 2T field**: p_T resolution for pions ≈ 0.7% at p_T ~ 1 GeV/c and central rapidity, better than 1% till ~ |η| ≤1

Vertex detector



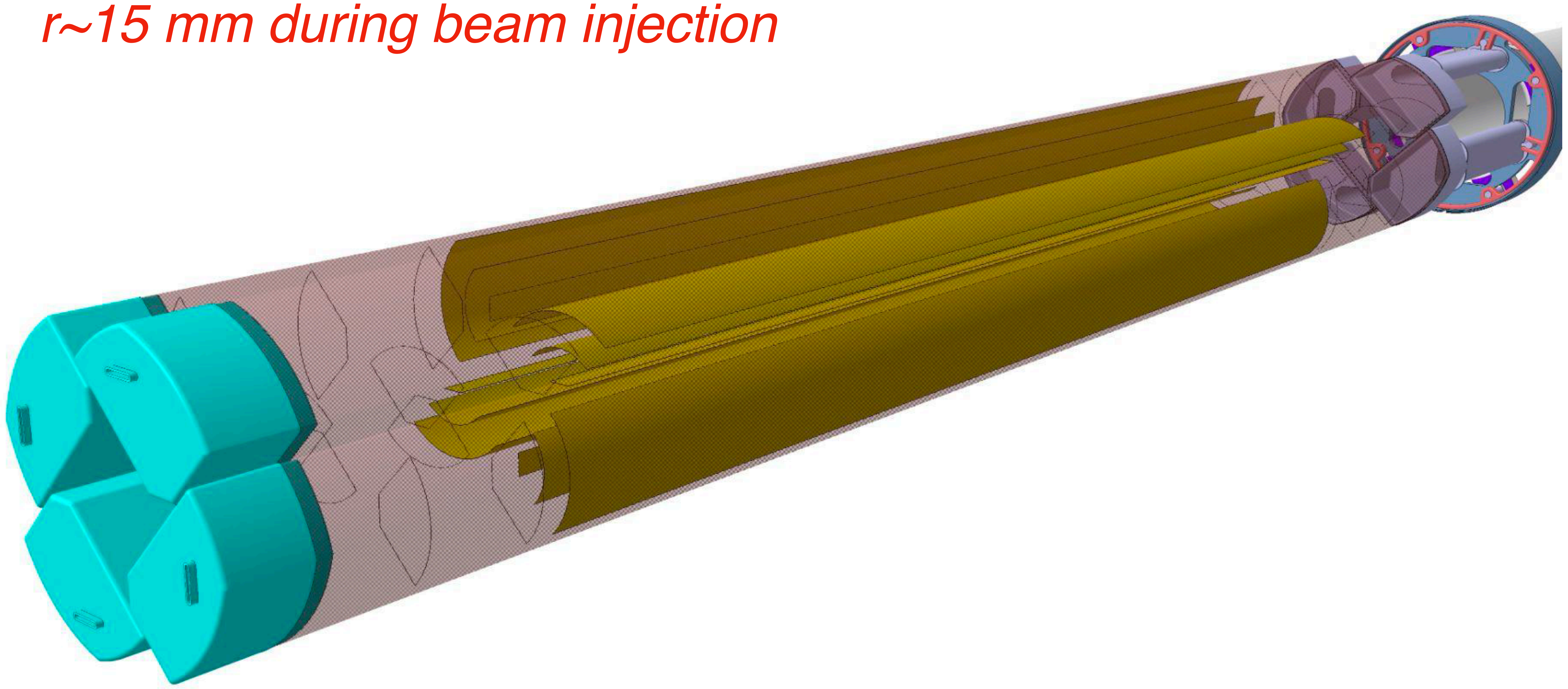


- In vacuum, *retractable,* tracker (**3 layers + 6 disks**): In closed position the first layer will be at **5 mm** from the beam
- **Wafer-size sensors based on CMOS Active Pixel Sensors (MAPS) technology**
- Pixel pitch of about 10 µm and **~0.1% X_0/layer**

- The maximum radiation load per operational year will be about **1.5 10^{15} 1 MeV n_{eq}/cm^2**
- Cooling on the outer surface of the 3rd layer (microchannel) while the layer 0 and 1 cooled via conduction on the petals

Vertex detector

Distance from interaction point:
r~15 mm during beam injection



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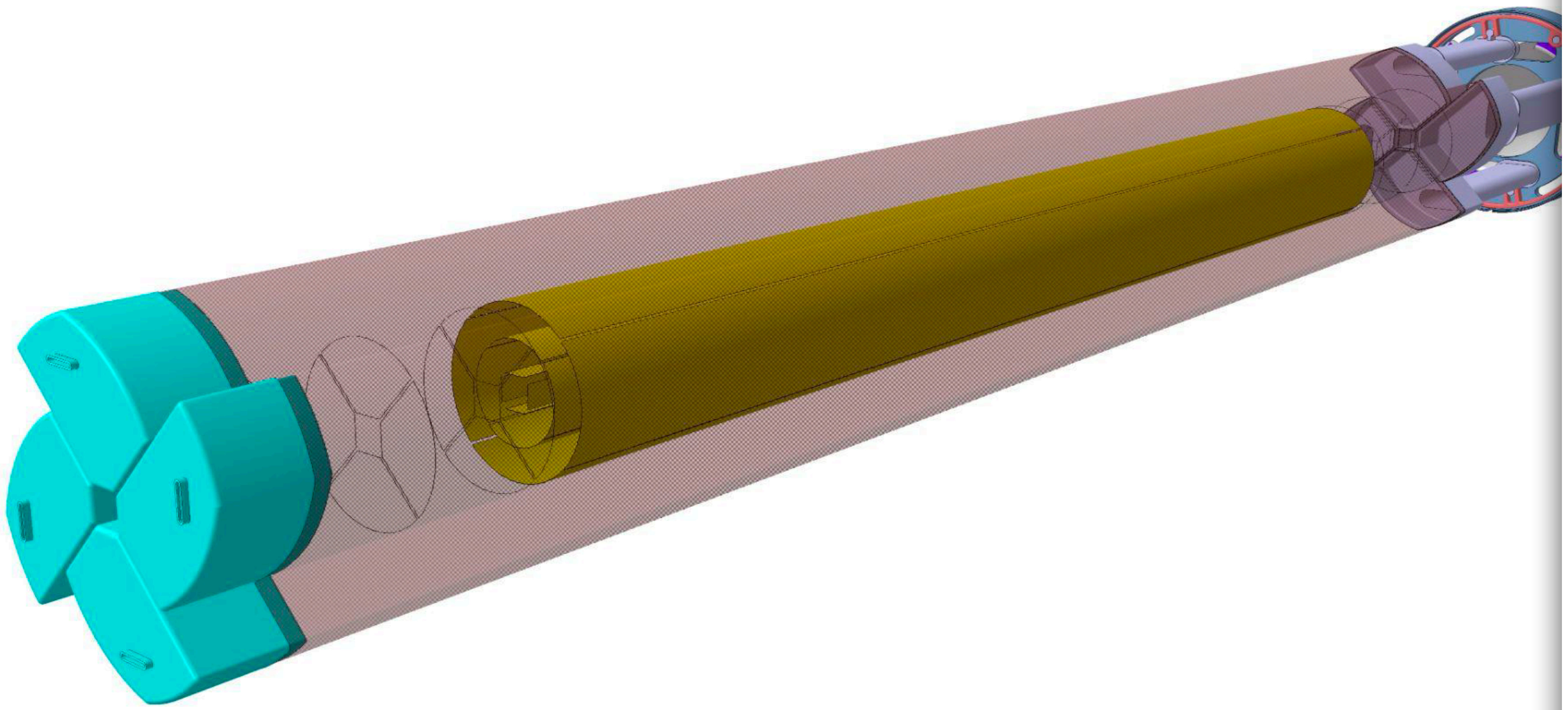
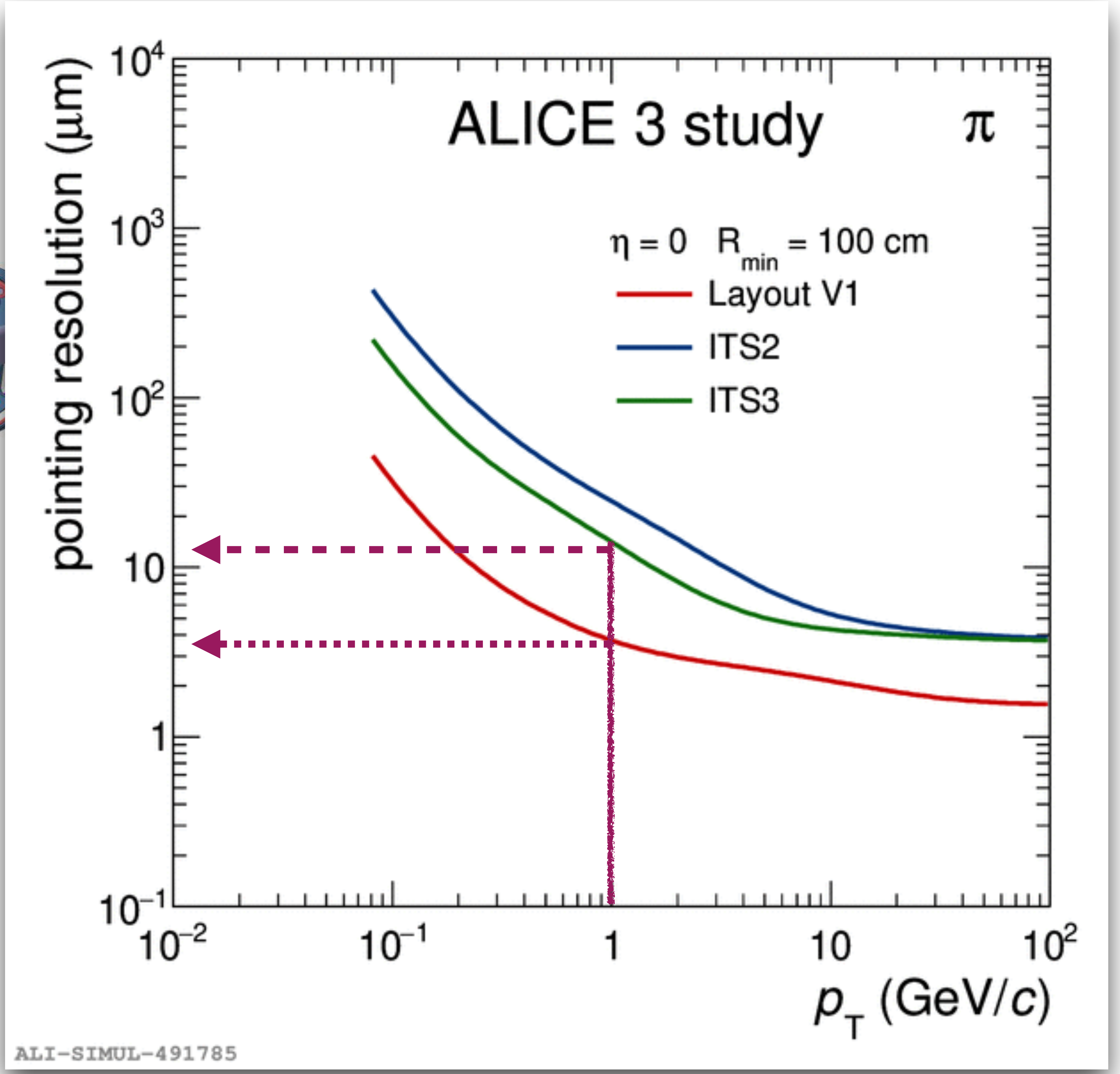
- Cooling on the outer surface of the 3rd layer (microchannel) while the layer 0 and 1 cooled via conduction on the petals

Vertex detector

LoI: CERN-LHCC-2022-009

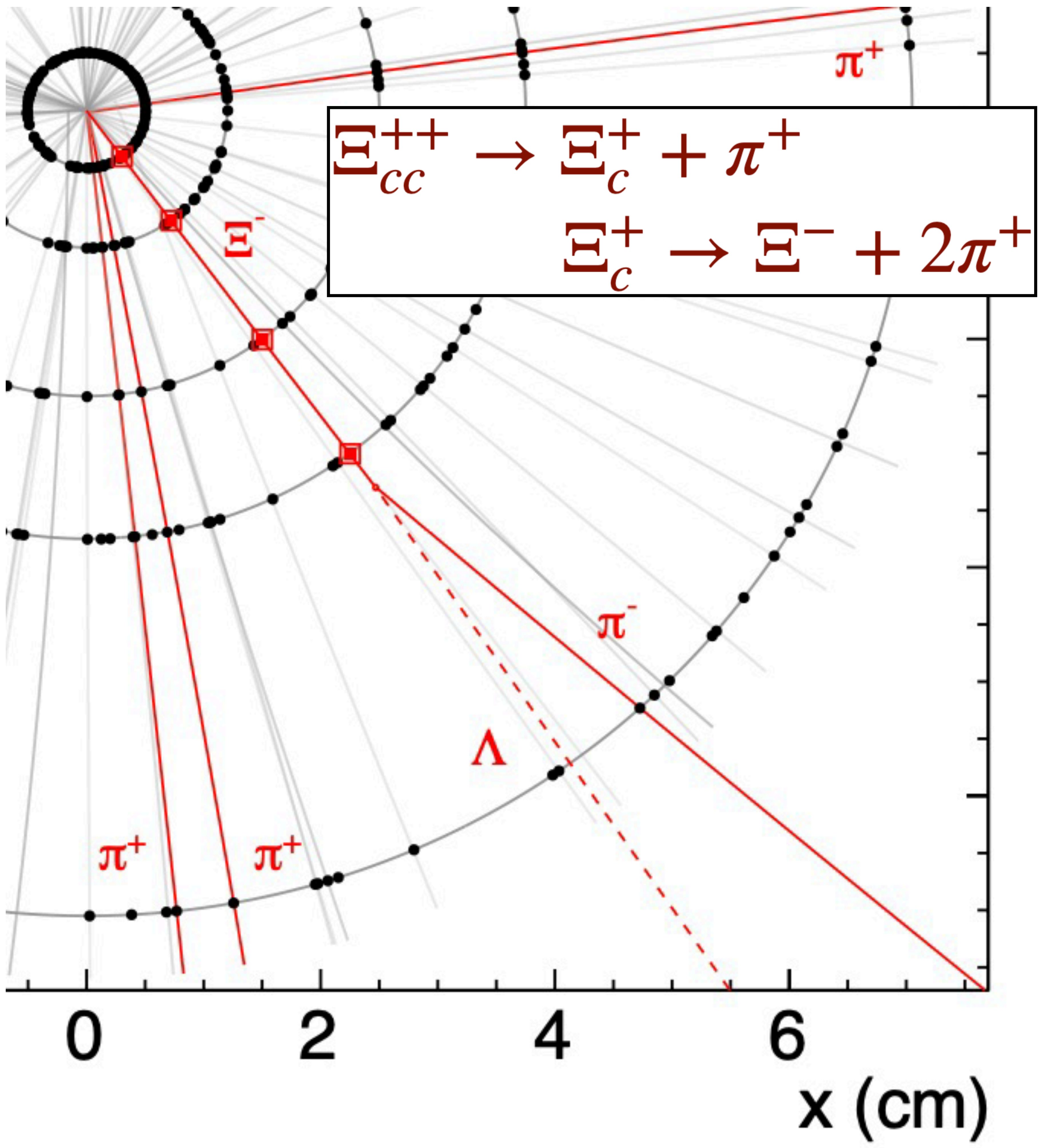
Distance from interaction point:
r~5 mm during stable beam



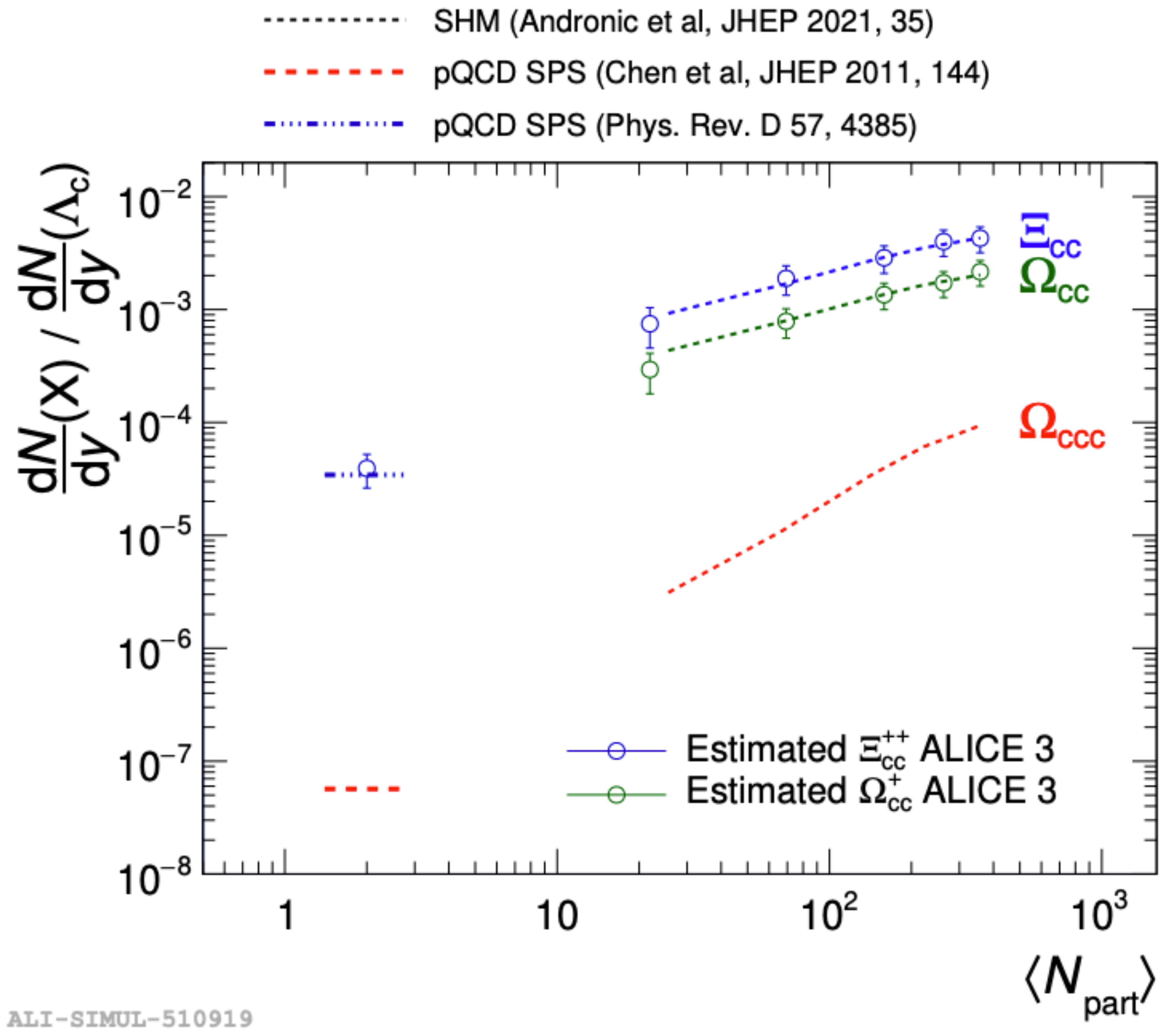


- 5 times better pointing resolution at ~1GeV/*c* with respect ALICE2.1
- **<u>Several R&D challenges:</u>** secondary vacuum, services, radiation load …

Strangness tracking

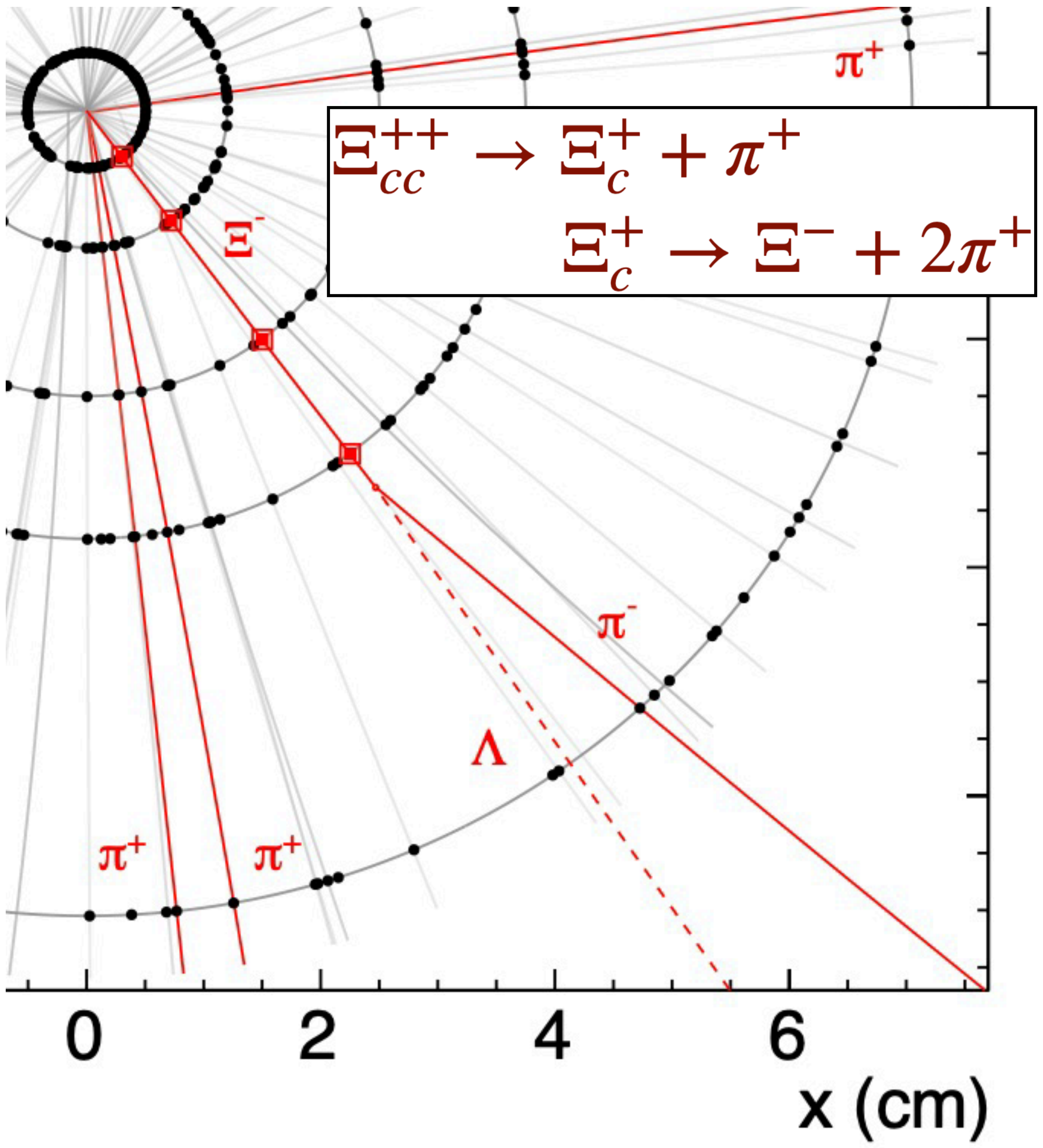


- **<u>Track strange particles in the vertex detector before their (weak) decay</u>**
- Full reconstruction of decay topology tracking charged strange decaying hadrons
- **Unique experimental access to multicharm hadrons with ALICE 3 in Pb-Pb collisions**

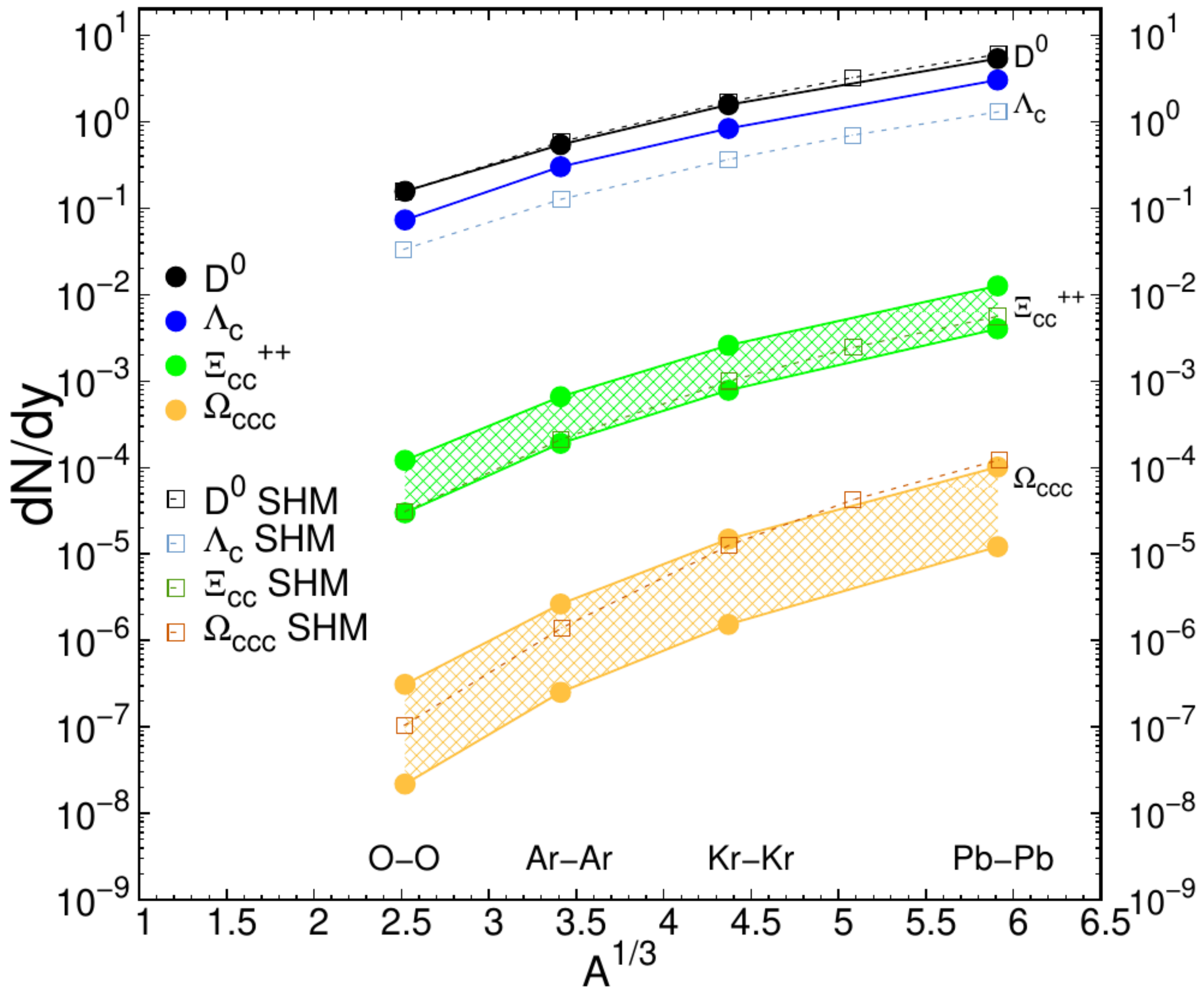


Strangness tracking

- **Track strange particles in the vertex detector before their (weak) decay**
- Full reconstruction of decay topology tracking charged strange decaying hadrons
- **Combined with centrality dependence or possible lighter ion runs**

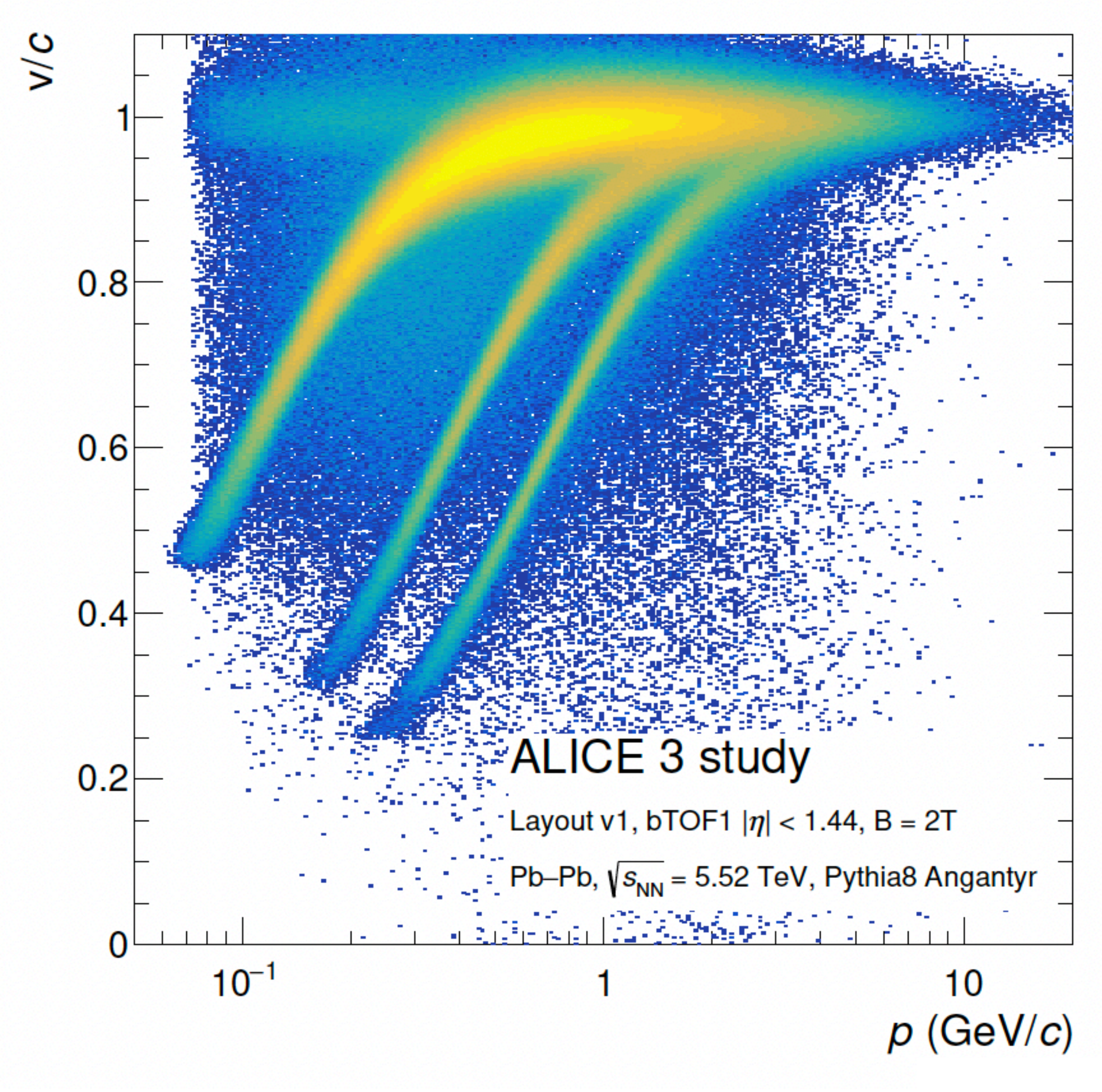


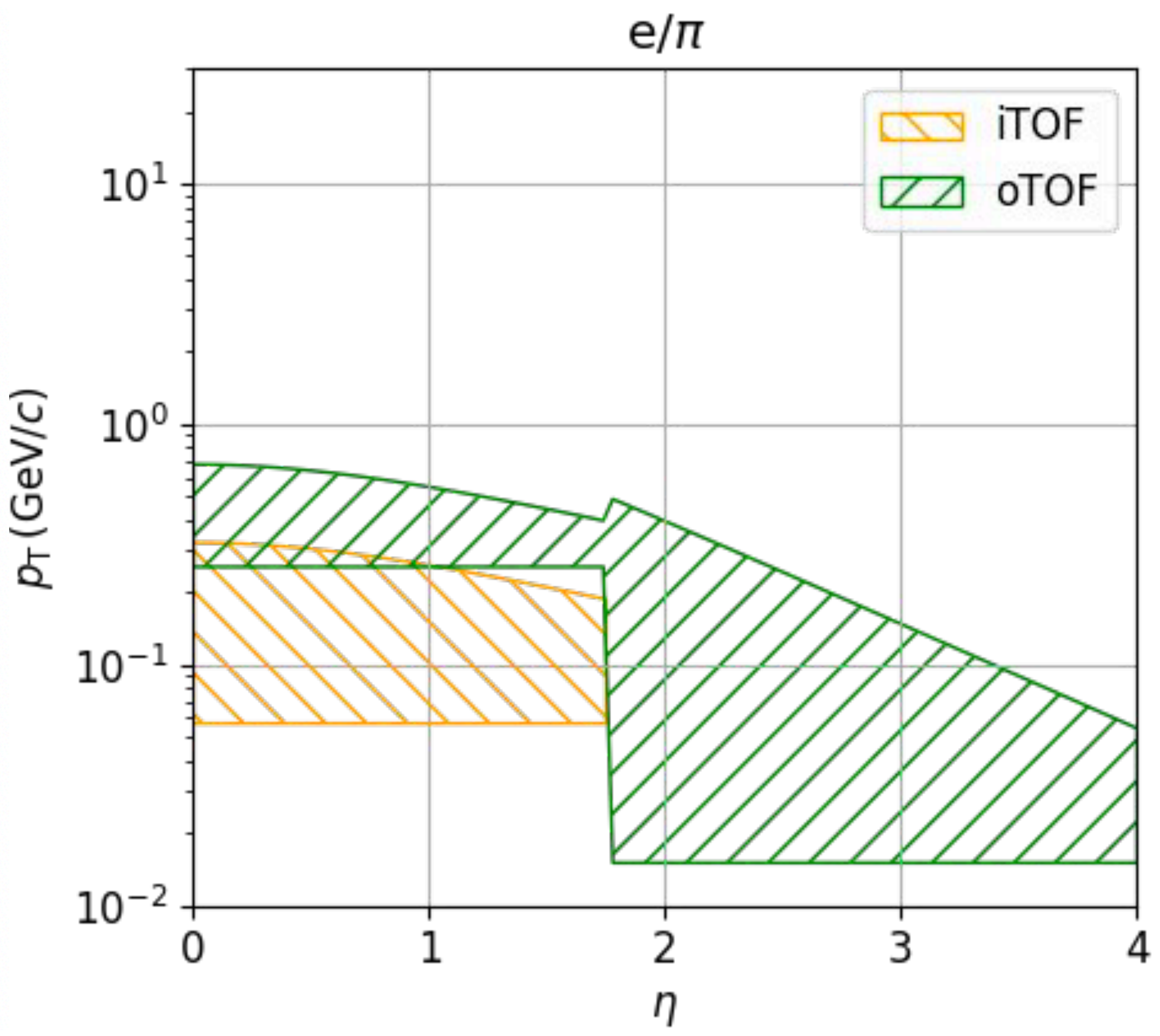
A. Andronic et al., JHEP07 (2021) 035

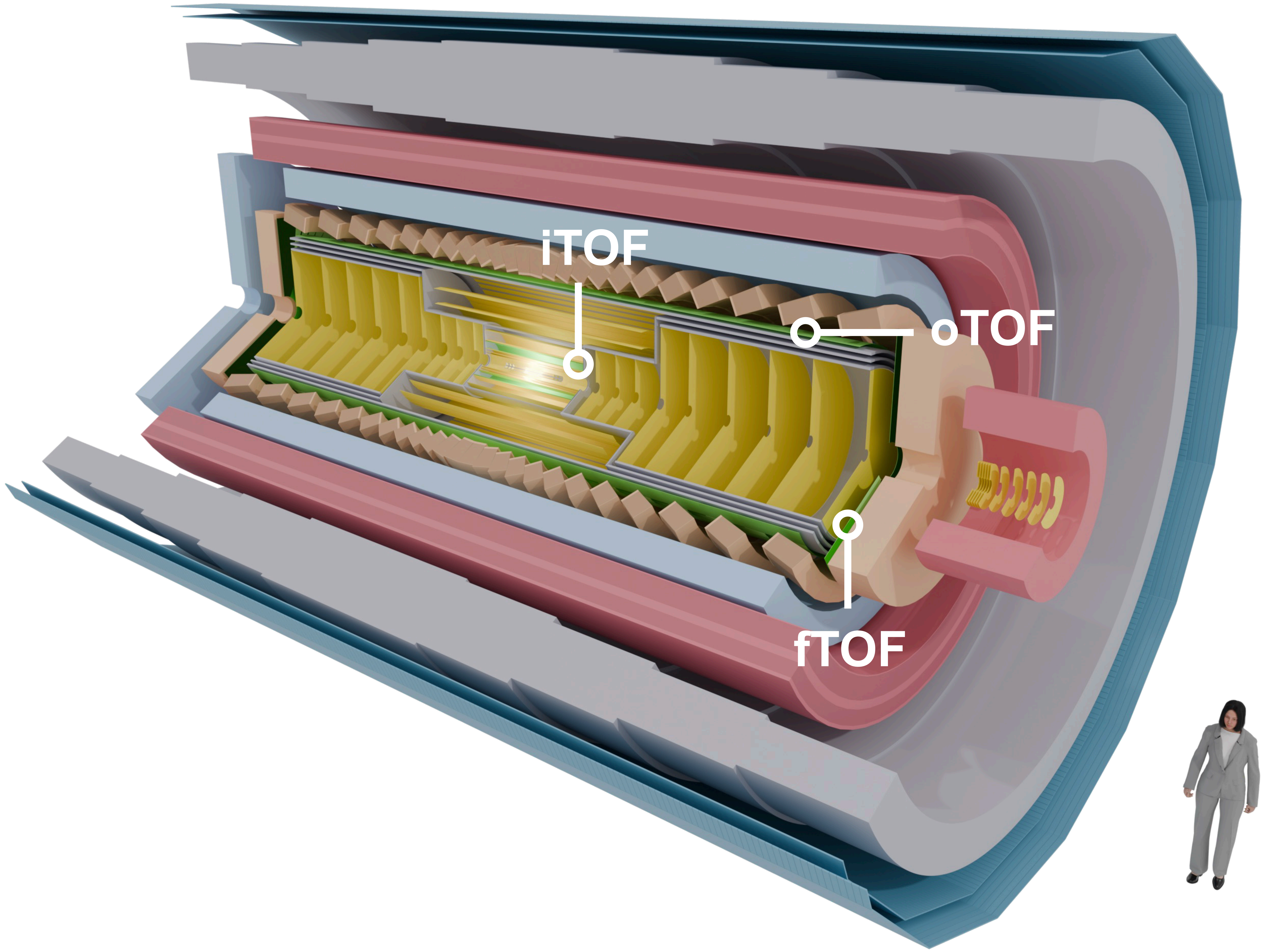


Nikhef

Particle Identification: TOF



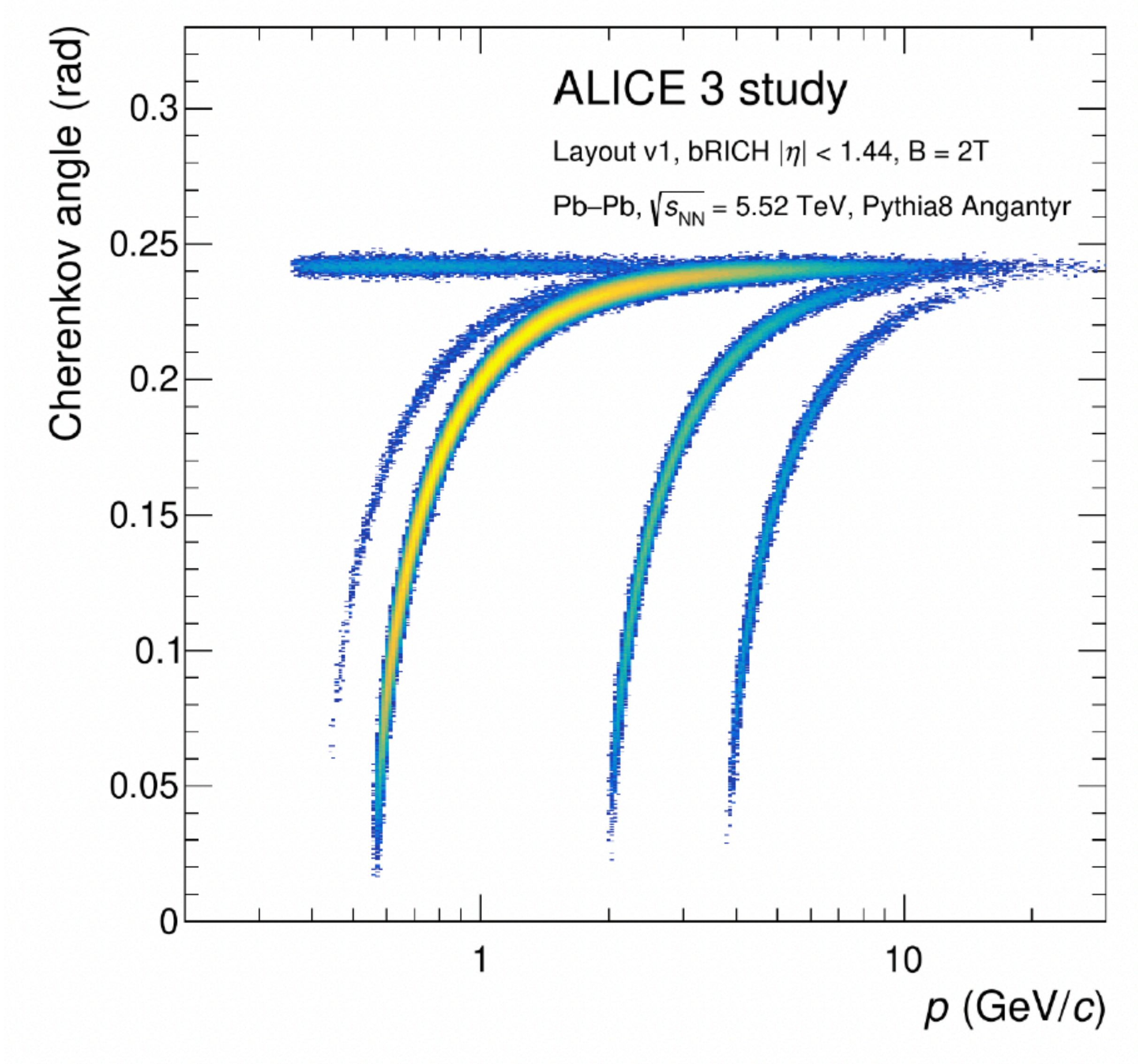


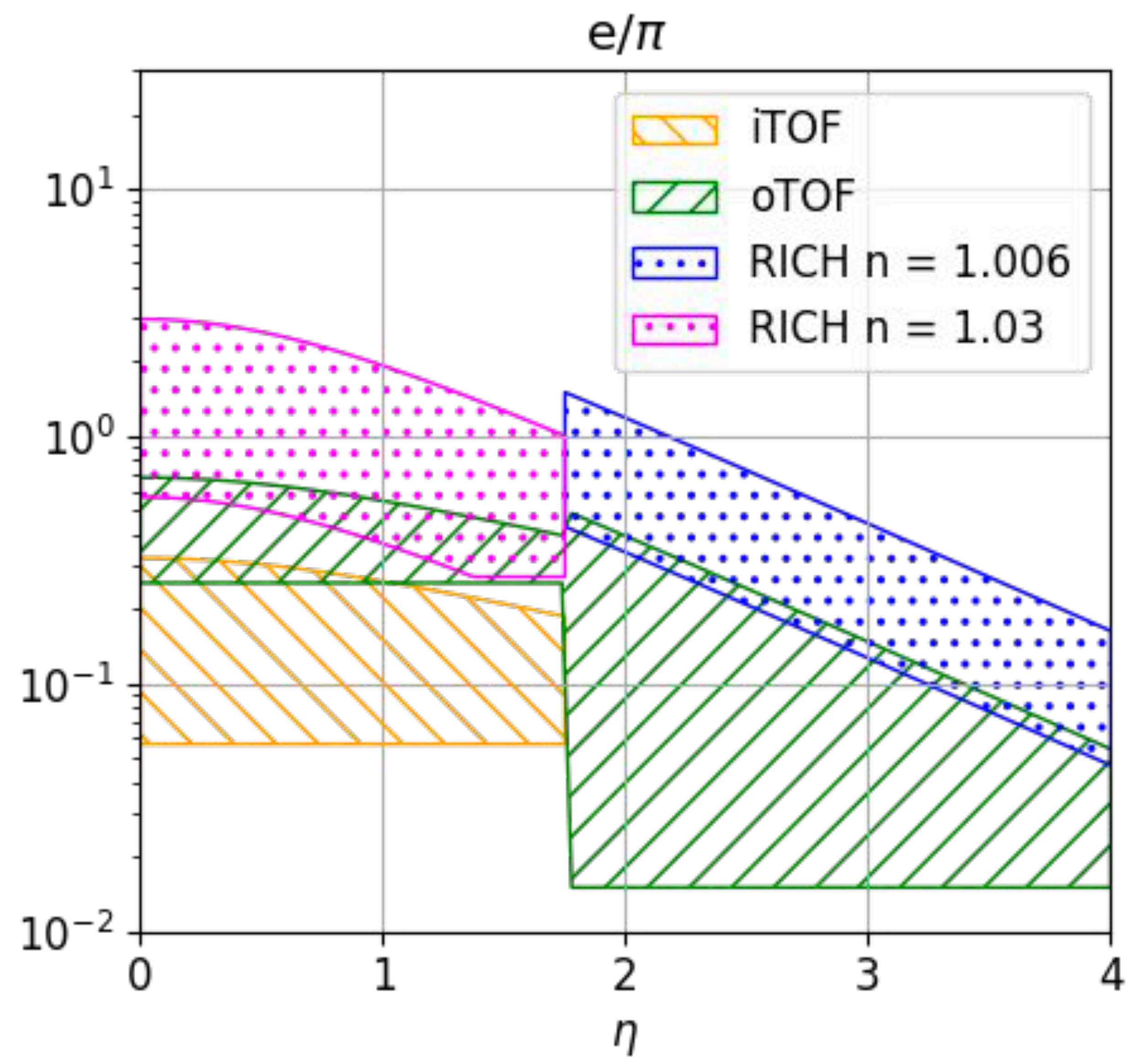


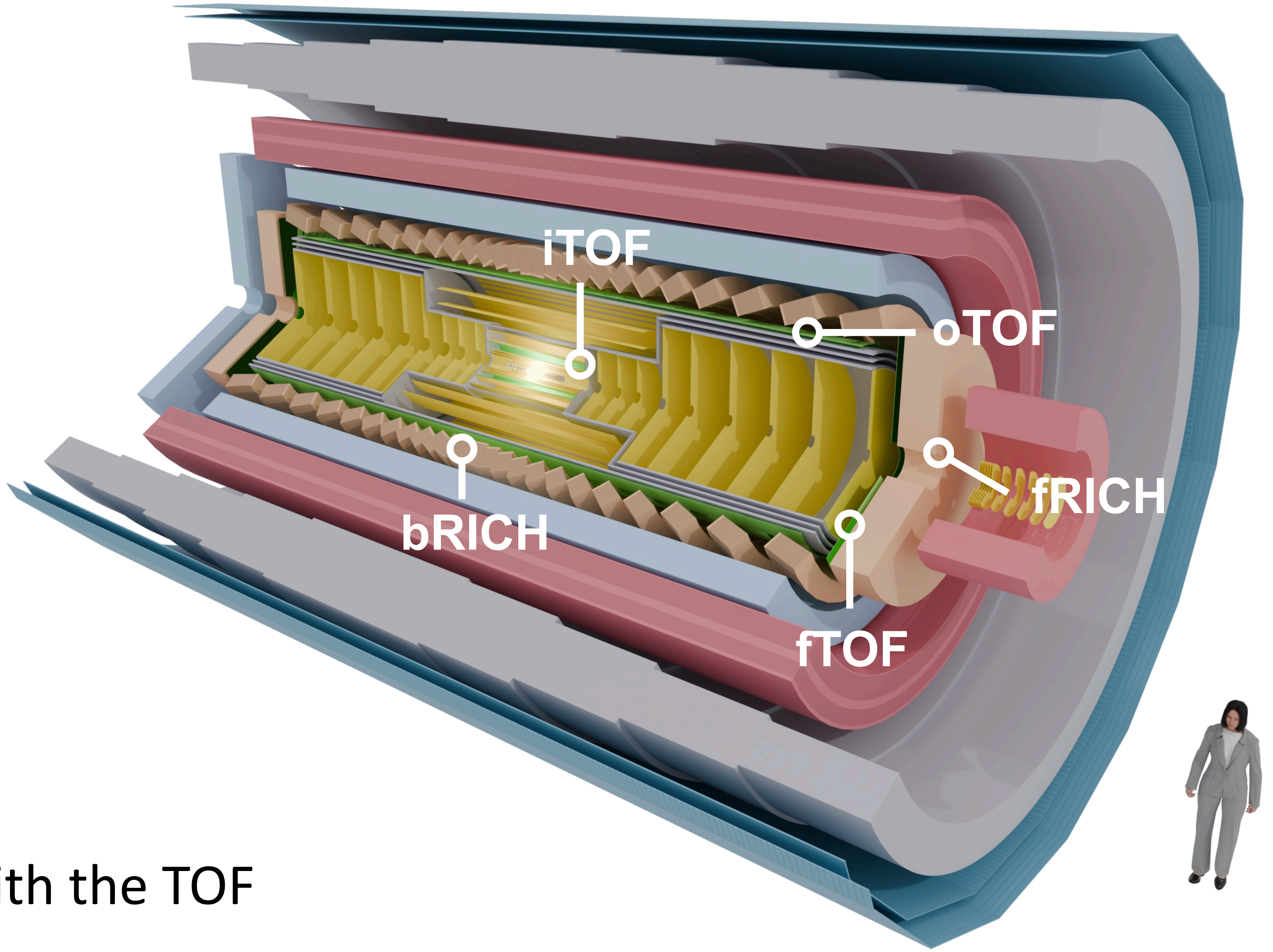
- Two barrel layers and one forward layer
  - Outer TOF (oTOF) at r≈85cm
  - Inner TOF (iTOF) at r≈19cm
  - Forward TOF (fTOF) at z≈405cm
- Silicon sensors with σ_{TOF} ≈ 20ps

Particle Identification:RICH

RICH: Complement PID reach of outer TOF to higher p_T with Cherenkov detector





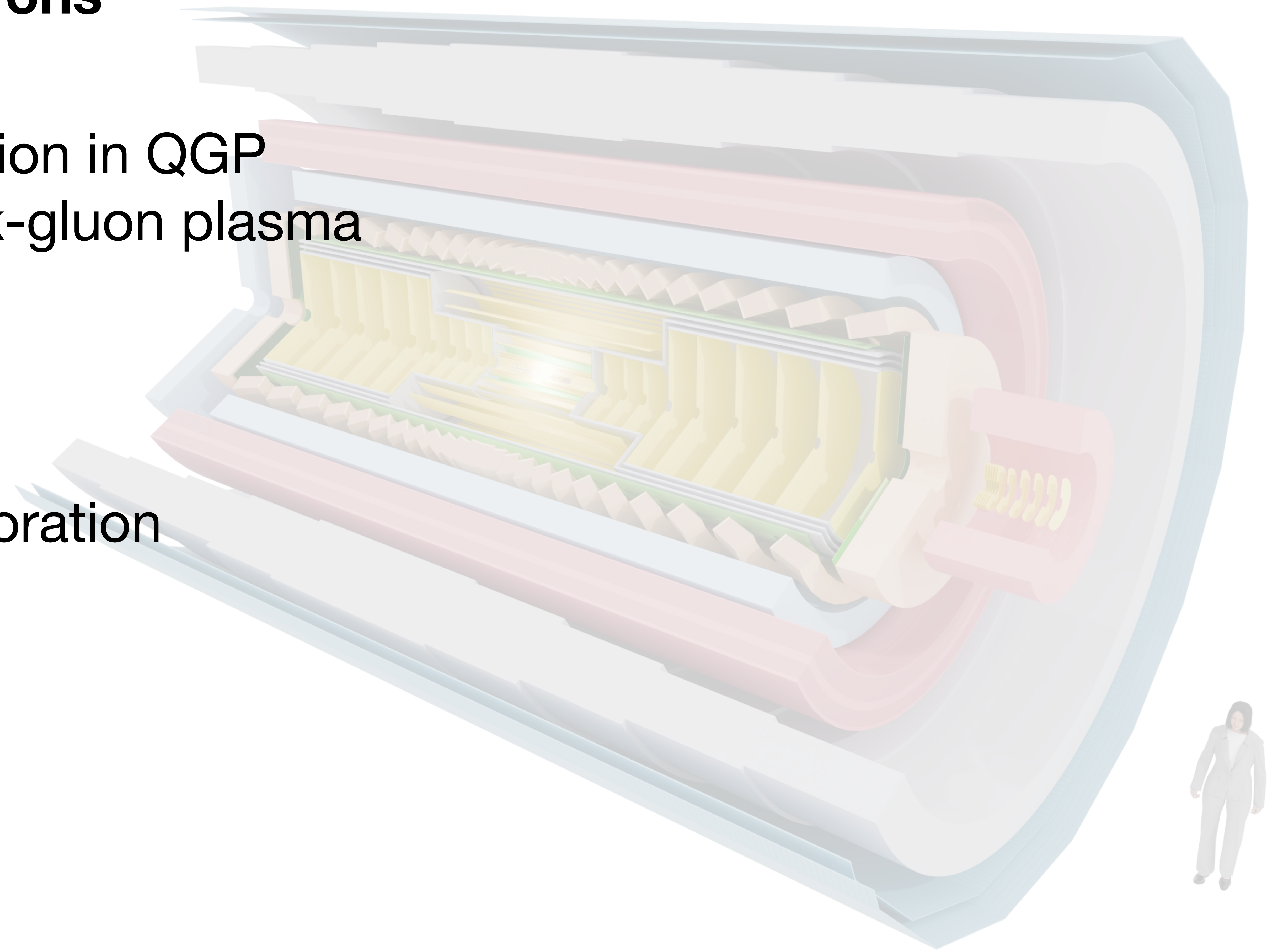


- Aerogel radiator:
  - Refractive index n = 1.03 in the barrel
  - Refractive index n = 1.006 at forward
- Design aimed to ensure continuous coverage with the TOF system

ALICE 3 measurements (a selection)

Measurements of (multi-)heavy-flavoured hadrons

- parton propagation mechanisms in QGP
- study equilibration of heavy quark and diffusion in QGP
- mechanisms of hadronisation from the quark-gluon plasma



Precision measurements of dileptons

- accessing QGP evolution
- mechanisms of chiral symmetry (partial) restoration

Hadron correlations and fluctuations

- interaction potentials and charmed-nuclei

Beyond Standard Model

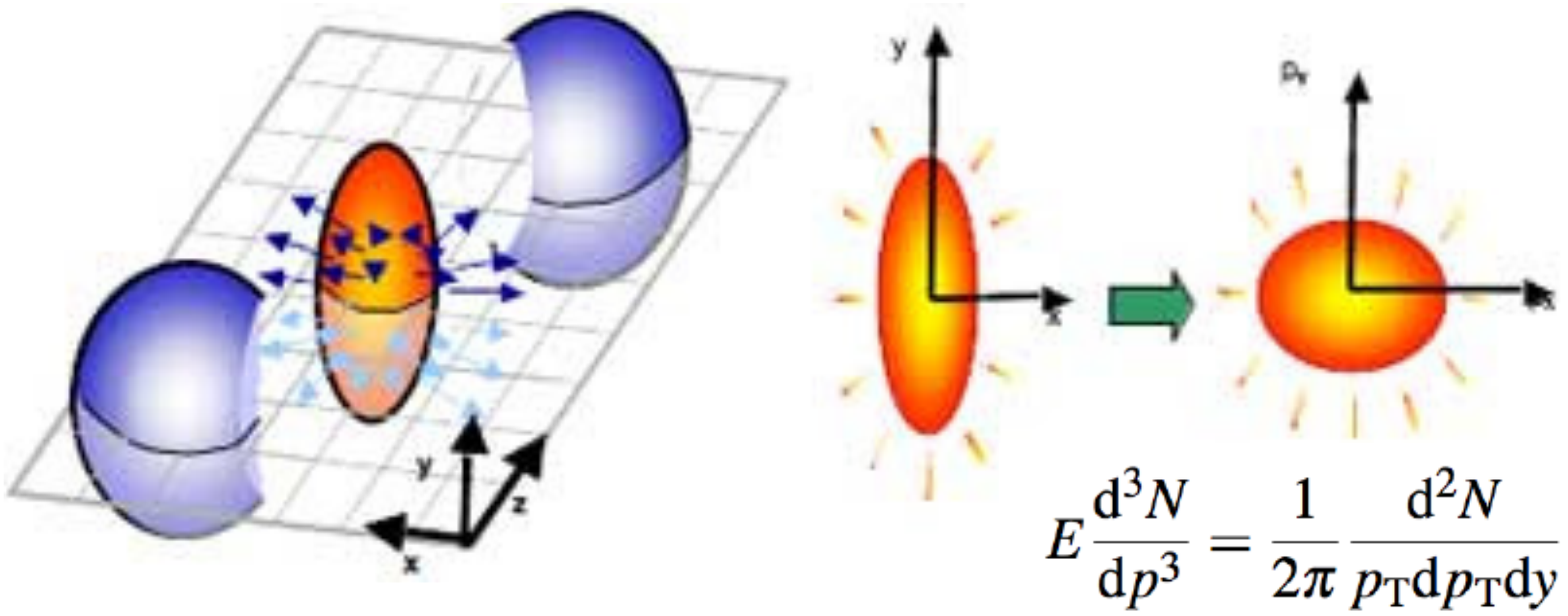
- Input for Dark Matter searches in space
- Axion-like particles

Heavy quark thermalisation

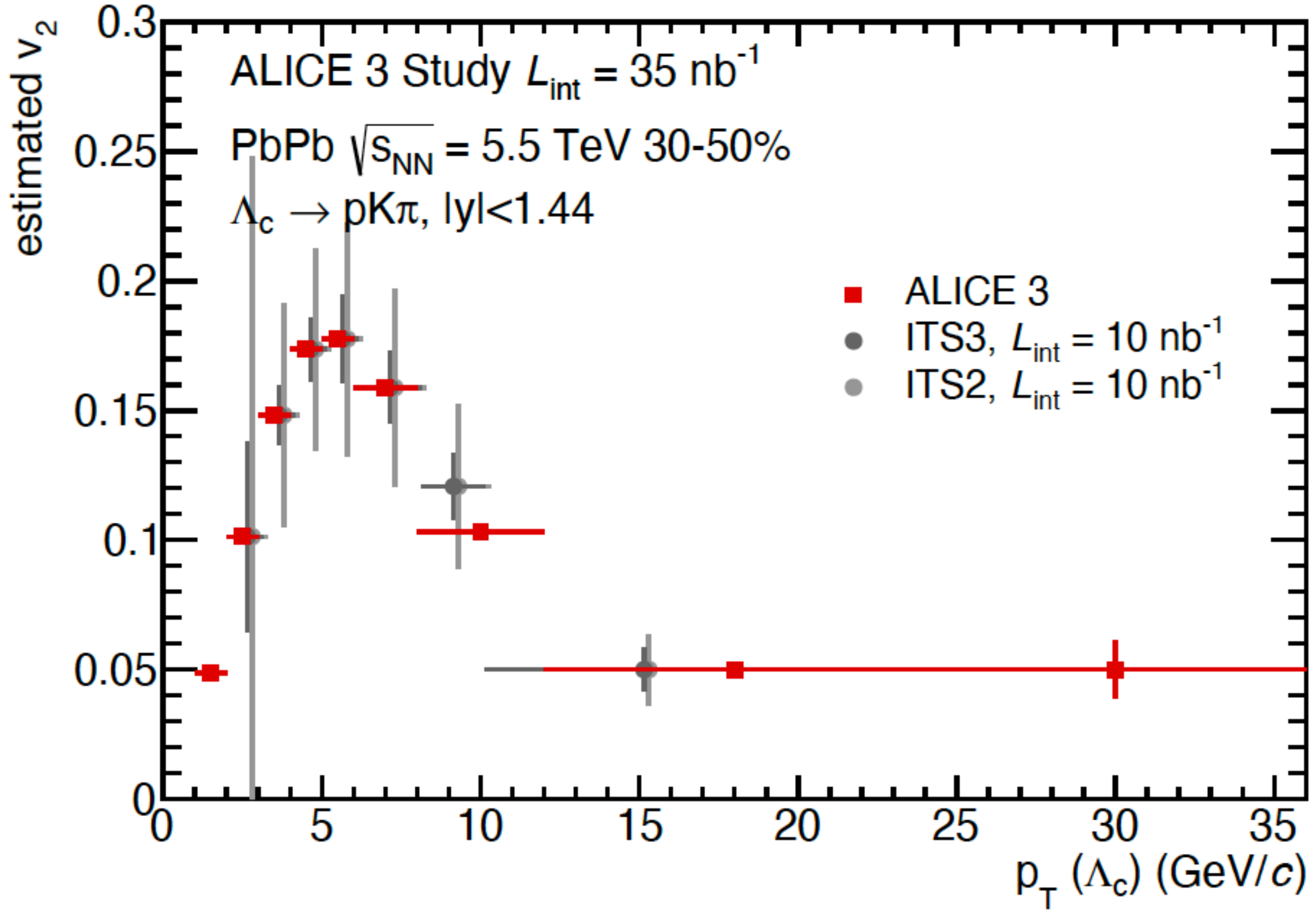
$$\langle r^2 \rangle = 6\, D_s\, t$$ Heavy-quark diffusion coefficient D_s

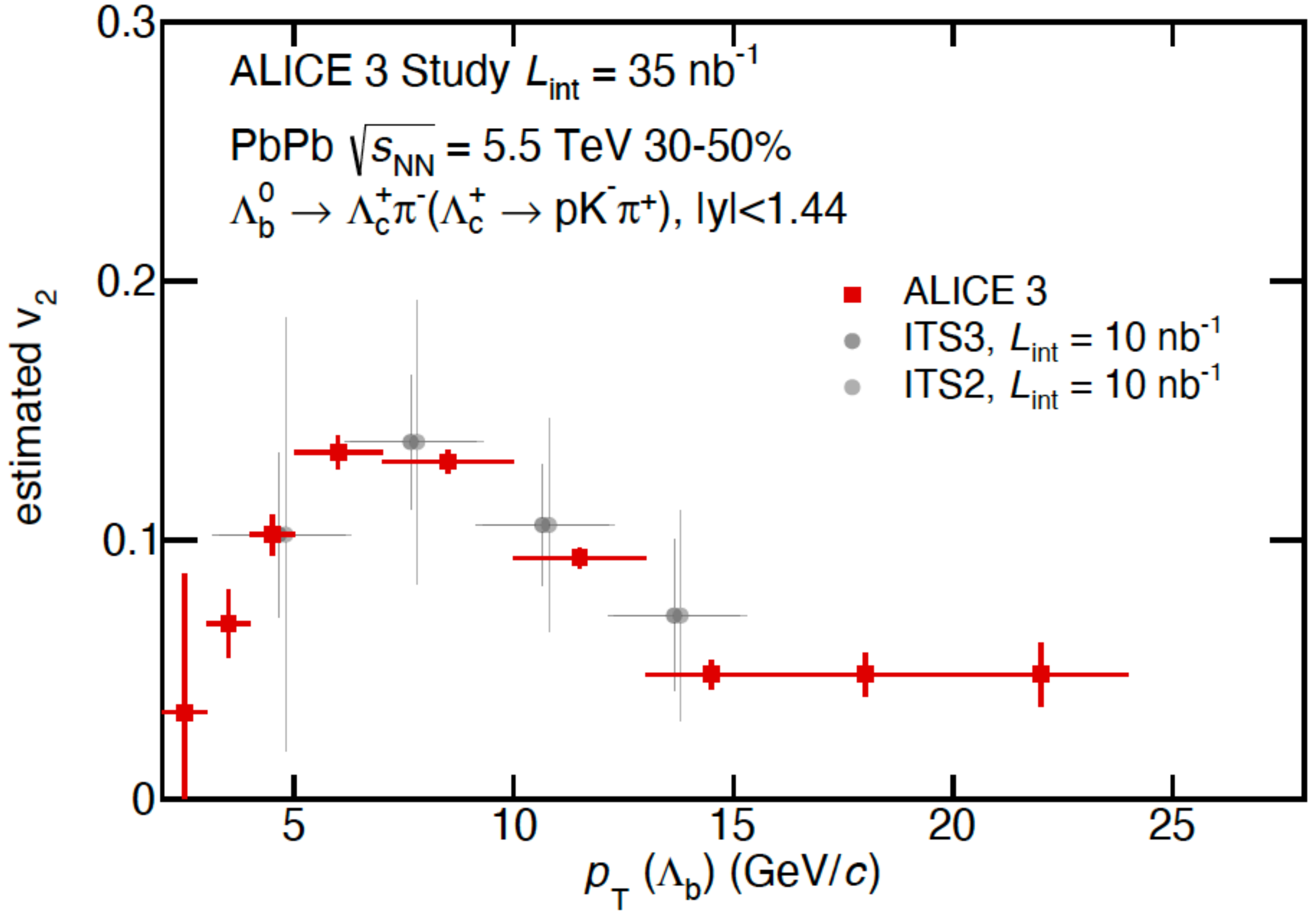
$$\tau_Q = (m_Q/T)\, D_s$$ Relaxation time

- **Interactions - diffusion lead to thermalisation** of heavy quarks:
  - Large charm v_2 close to full thermalisation?
  - Expected weaker beauty thermalisation
    $\Longrightarrow$ smaller v_2 if compared with charm. Is beauty v_2>0?

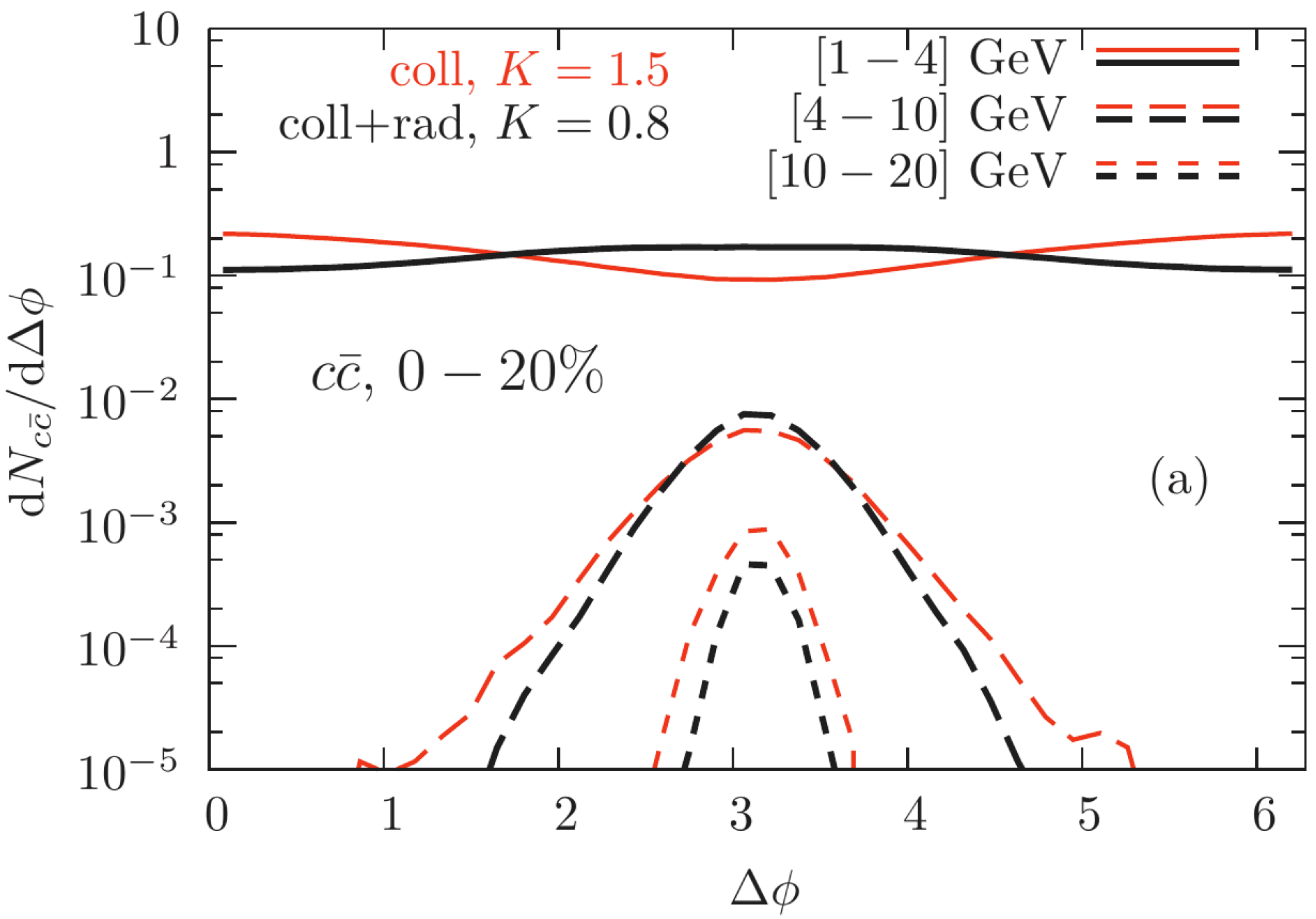


$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+2\sum_{n=1}^{\infty} v_n \cos[n(\varphi-\Psi_n)]\right)$$





Heavy quark propagation



Nahrgang et al. PRC90 024907

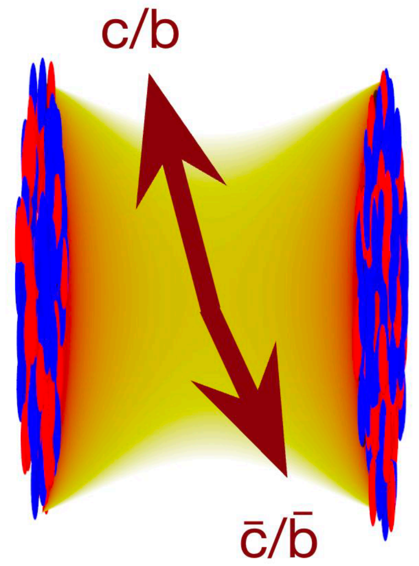
- Azimuthal angular correlation of charm quark accessed via D meson pairs
- Directly probe heavy quark transport in QGP
  - sensitive to energy loss and thermalisation degree

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

Heavy-quark diffusion
→ collisional broadening

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

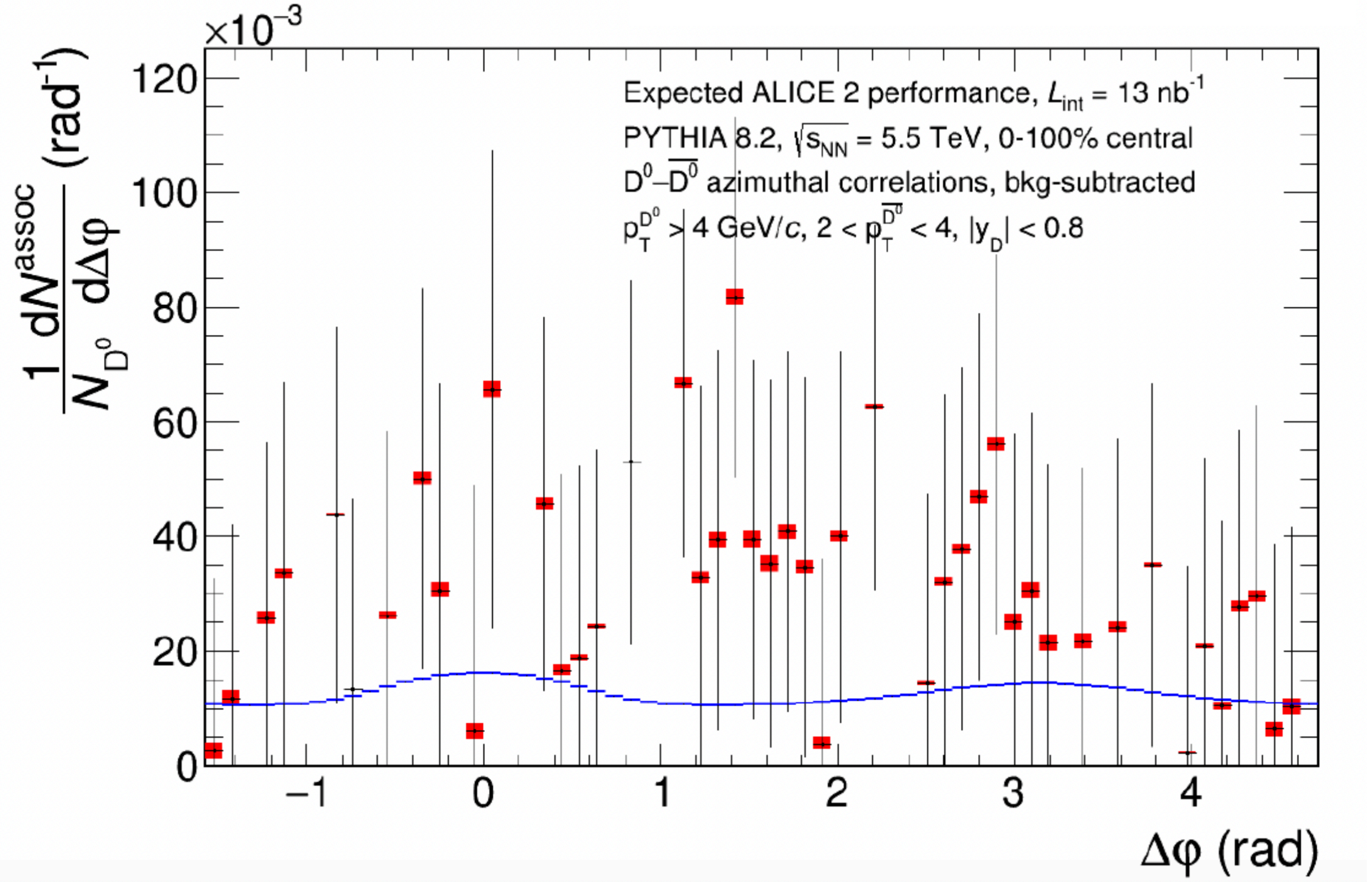
Semi-hard scattering
→ radiative energy loss



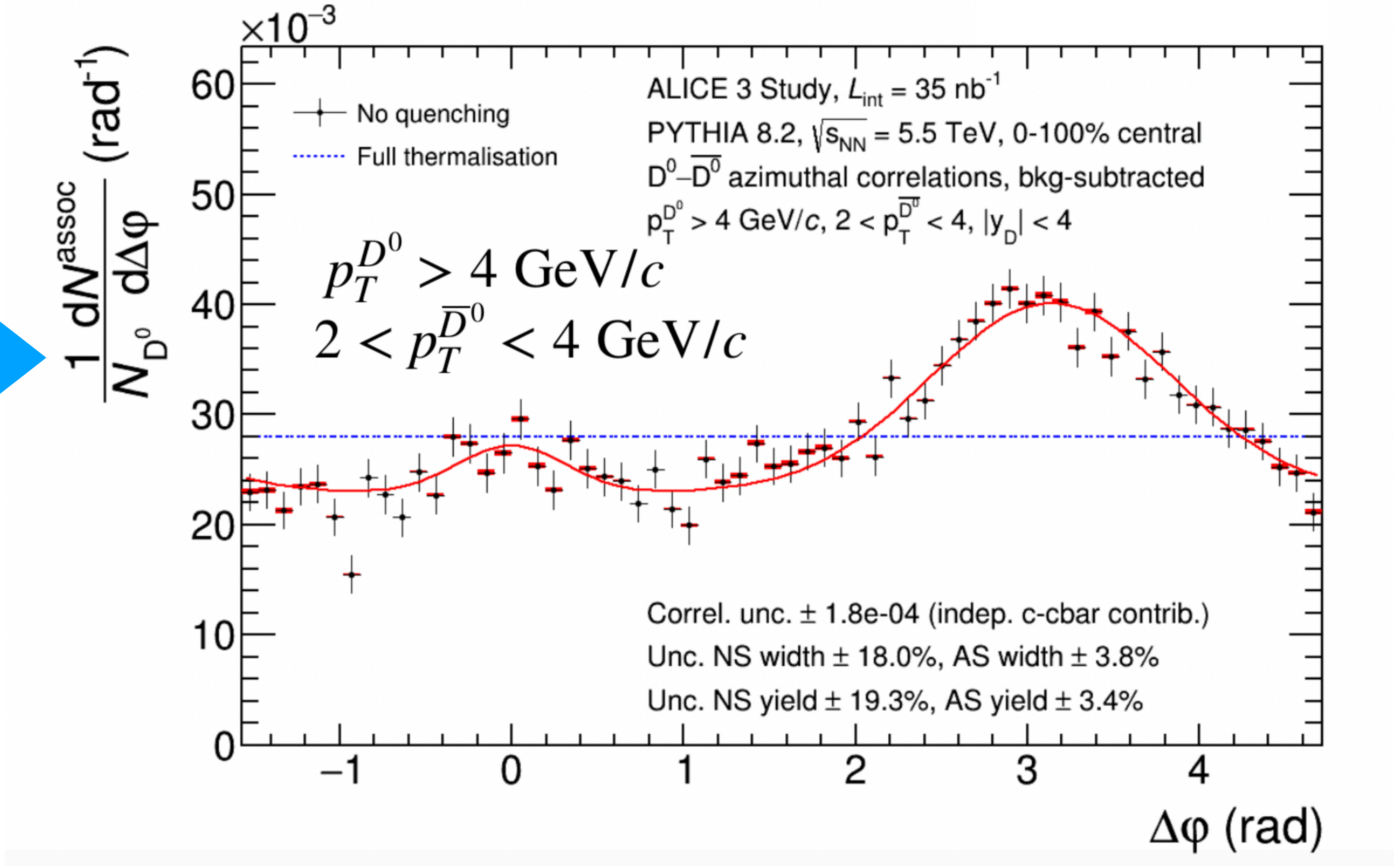
- Signal stronger at low p_T and advantages from large η-coverage -> **unique to ALICE 3**

Heavy quark propagation

ALICE: run3+4 projections

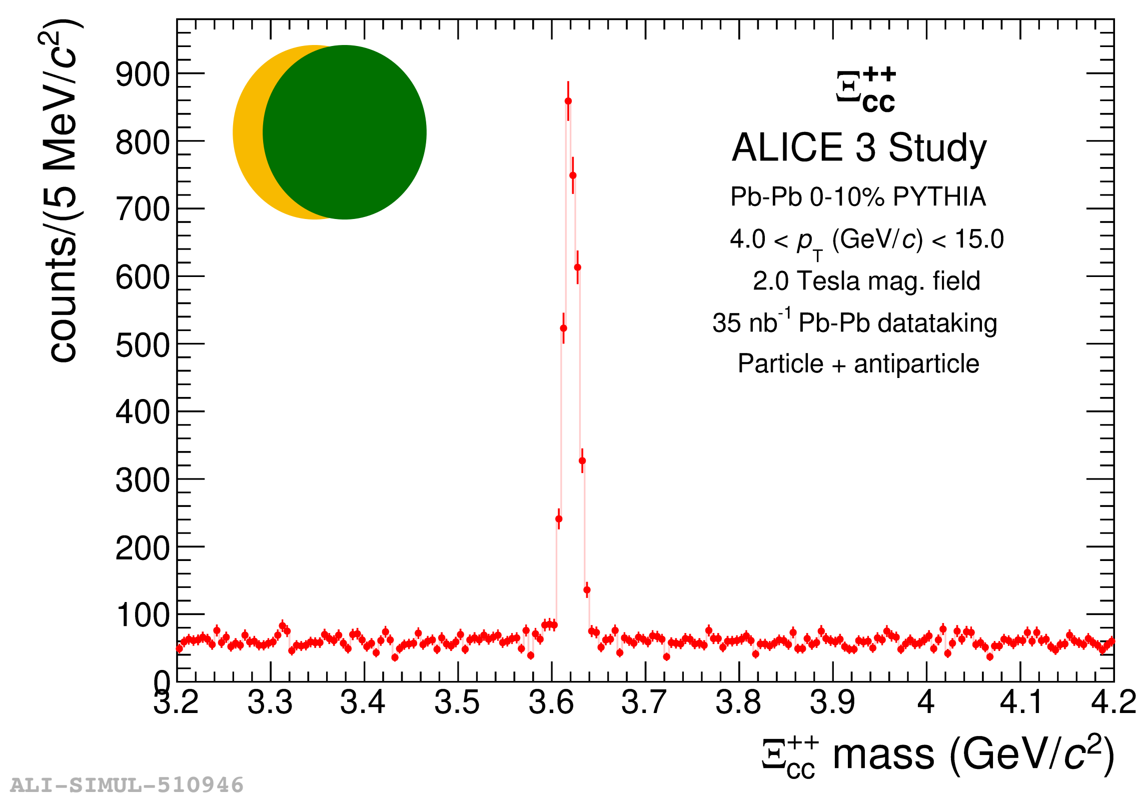


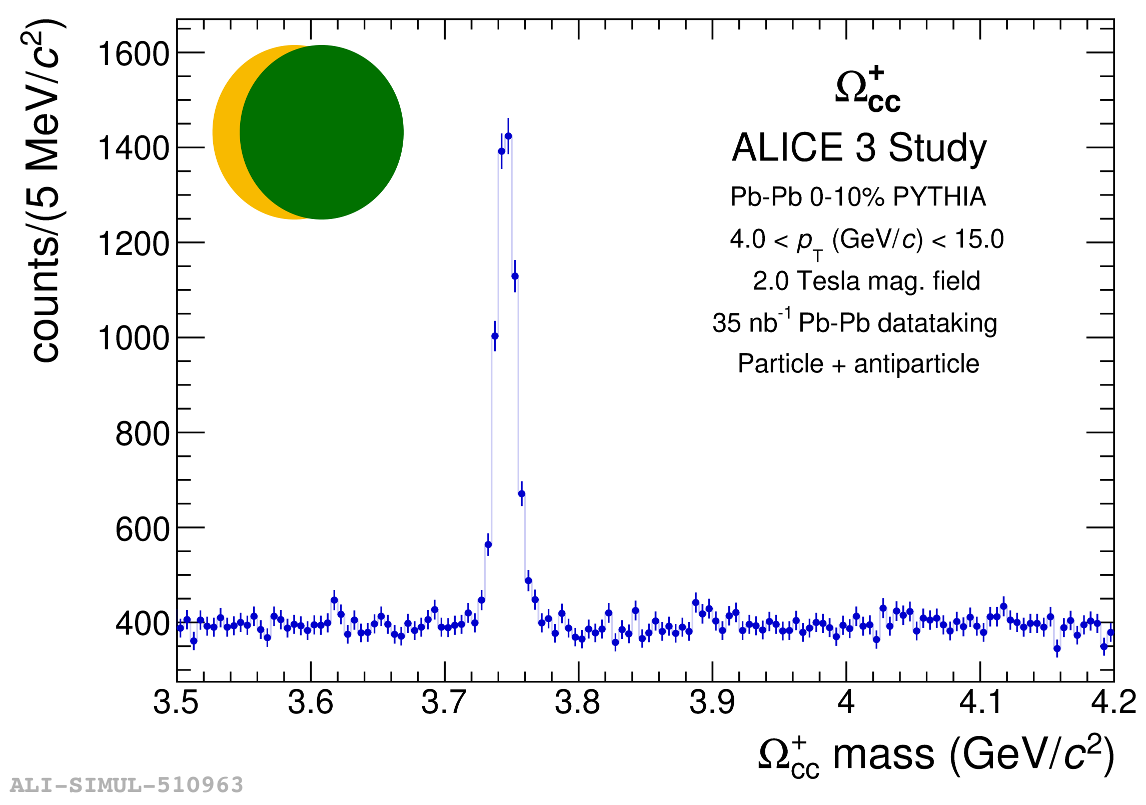
ALICE3: projections

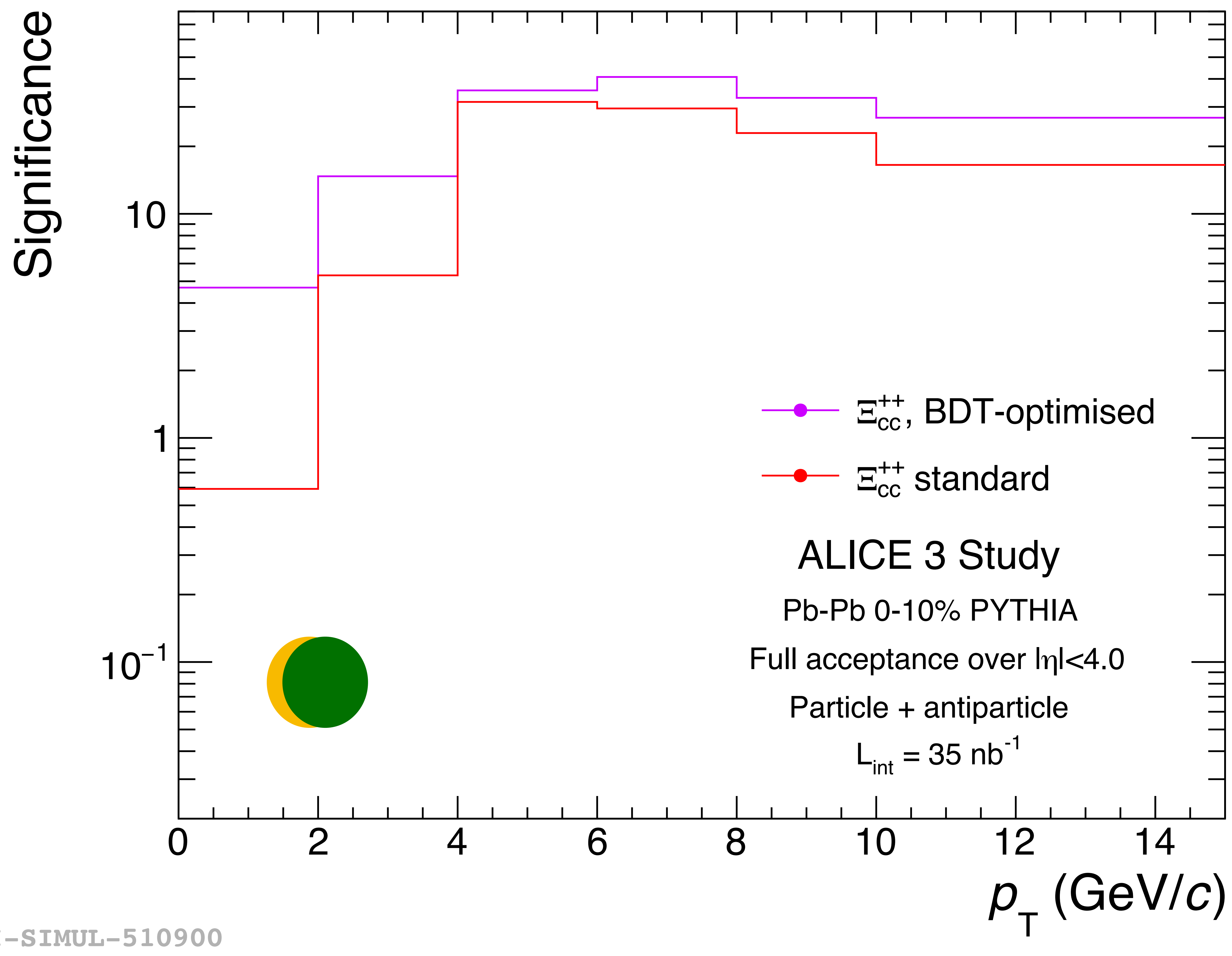


Multi-charm baryons

- Ξ_{cc}^{++} reconstructed in the channel:
  $\Xi_{cc}^{++} \rightarrow \Xi_c^+\pi^+ \rightarrow \Xi^-\pi^+\pi^+\pi^+$
- Ω_{cc}^{+} reconstructed in the channel:
  $\Omega_{cc}^{+} \rightarrow \Omega_c^0\pi^+ \rightarrow \Omega^-\pi^+\pi^+$
- Predicted enhancement by order of magnitude in the case of hadronisation from QGP







Multi-charm baryons

- Ξ_{cc}^{++} reconstructed in the channel:

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

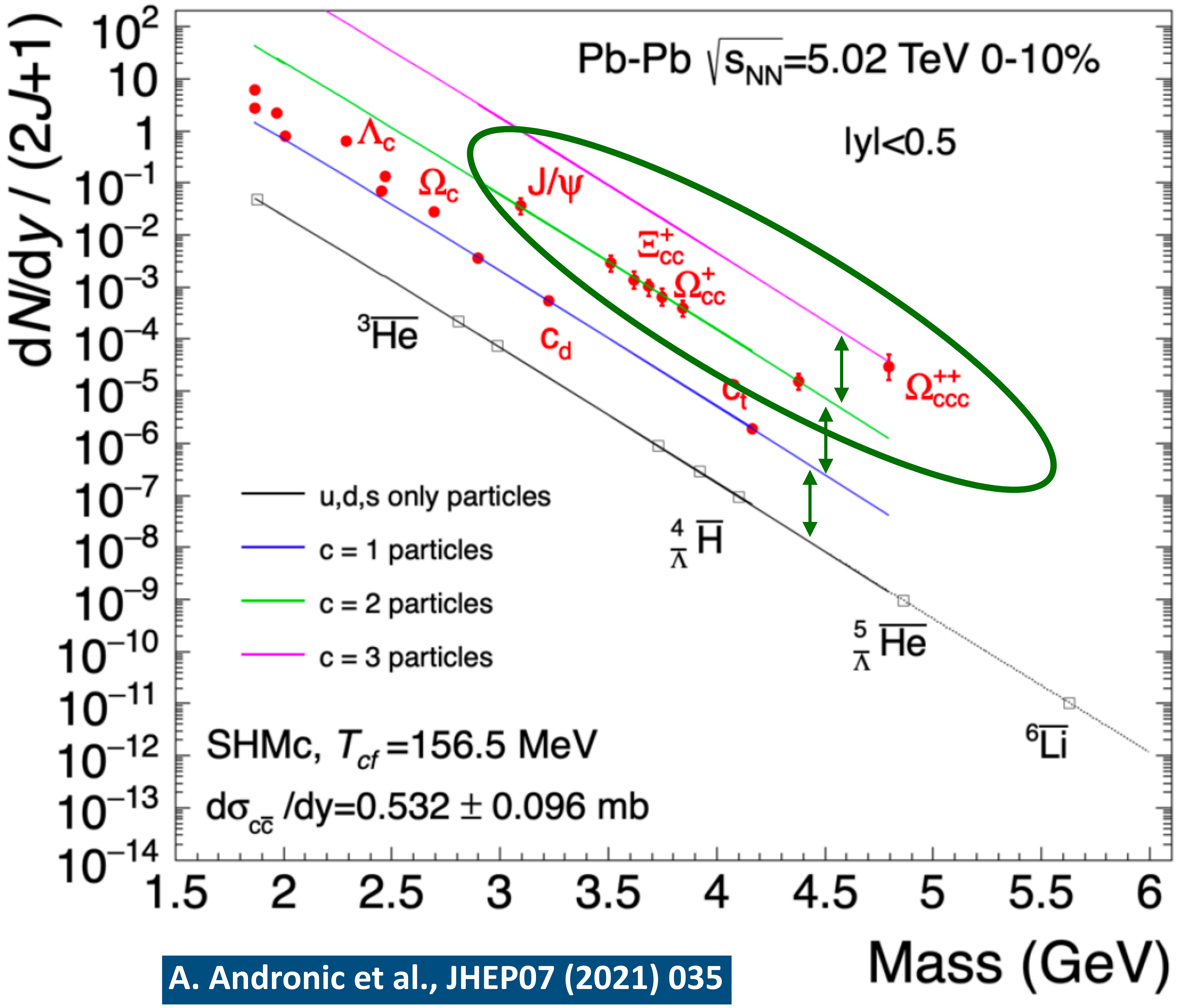
- Ω_{cc}^{+} reconstructed in the channel:

  $\Omega_{cc}^{+} \rightarrow \Omega_c^0 \pi^+ \rightarrow \Omega^- \pi^+ \pi^+$

- Predicted enhancement by order of magnitude in the case of hadronisation from QGP

In statistical hadronisation model emergence of a unique pattern, due to g_c^n and mass hierarchy

$\Rightarrow$ testing ground for deconfinement

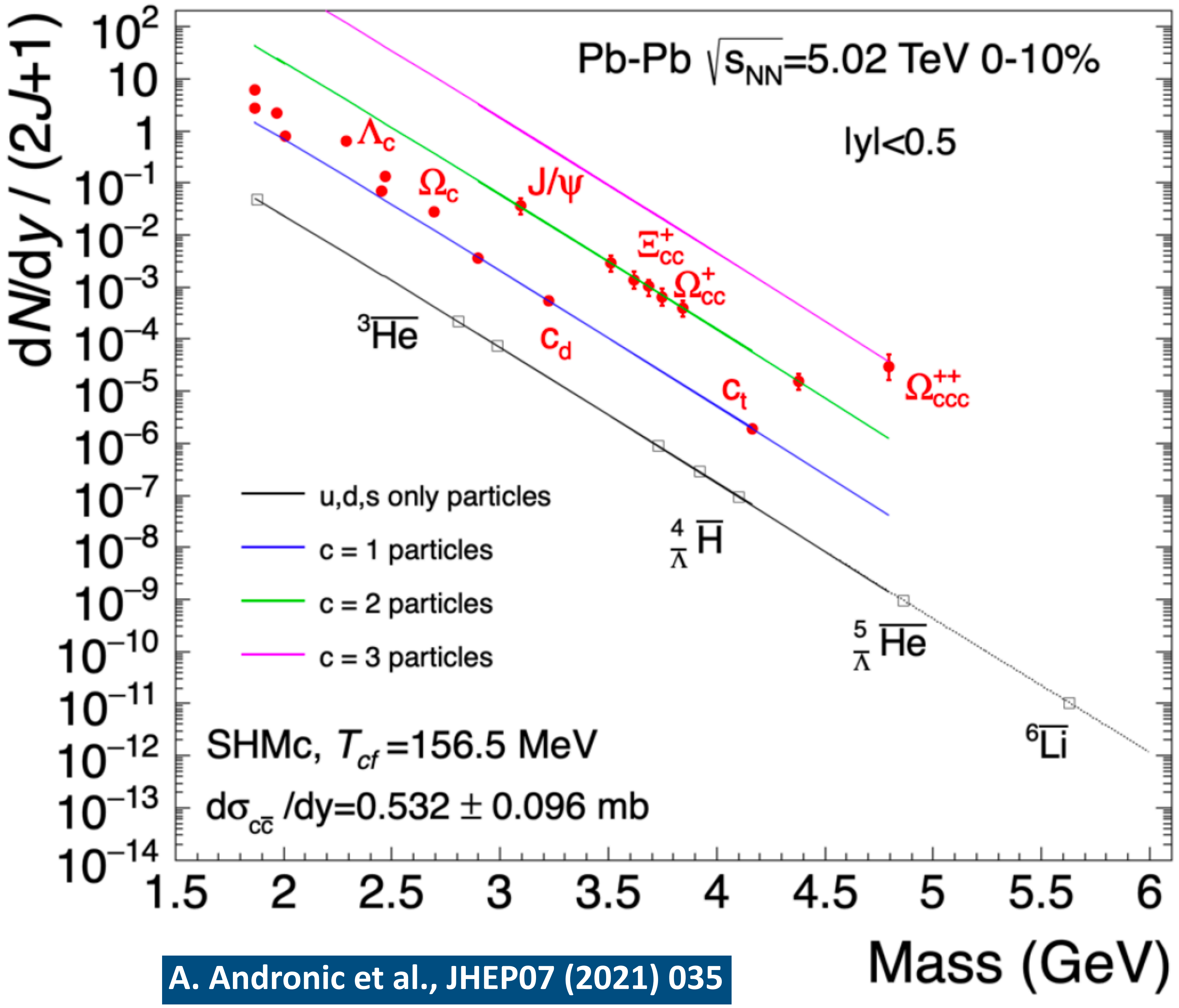


A. Andronic et al., JHEP07 (2021) 035

LoI: CERN-LHCC-2022-009

Nuclei

- ALICE 3 can shed light on the sector of hyperon-nucleon and charmed-baryon nucleon interactions.
- Anti-hyper nuclei with A>5 as $^{5}_{\bar{\Lambda}}\overline{\mathrm{He}}$ or $^{6}\overline{\mathrm{Li}}$ yet to be discovered
- ALICE 3 apparatus well suited for the study of $^{4}_{\Lambda}$He or $^{5}_{\Lambda}$He of interest as baseline for the study of multi-charm baryon production in QGP
- Discovery potential for super-nulei (?) like c-deuteron, c-triton and c-^{3}He.

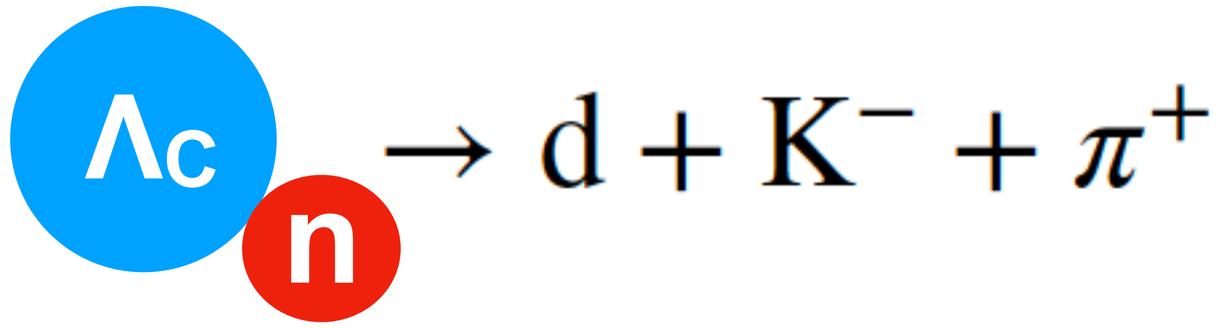


A. Andronic et al., JHEP07 (2021) 035

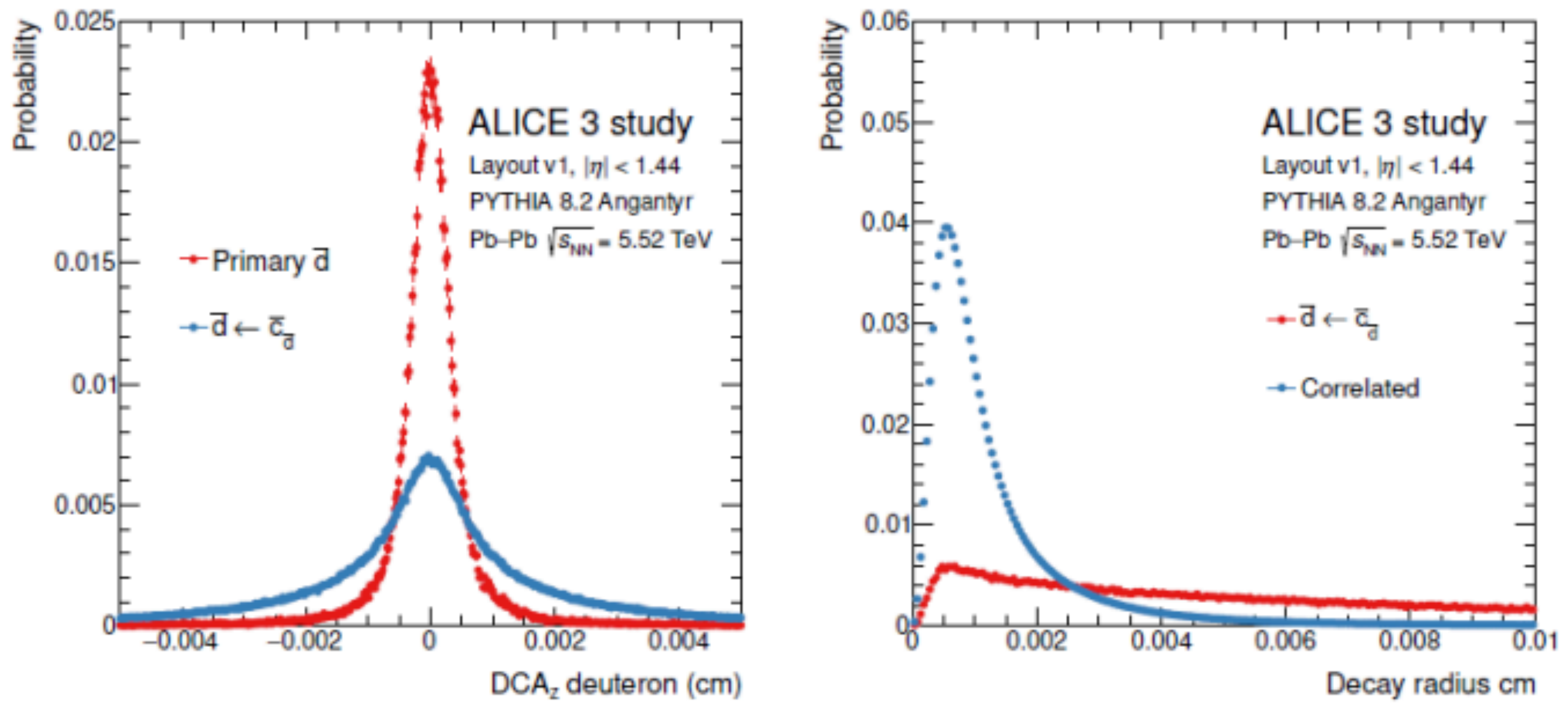
LoI: CERN-LHCC-2022-009

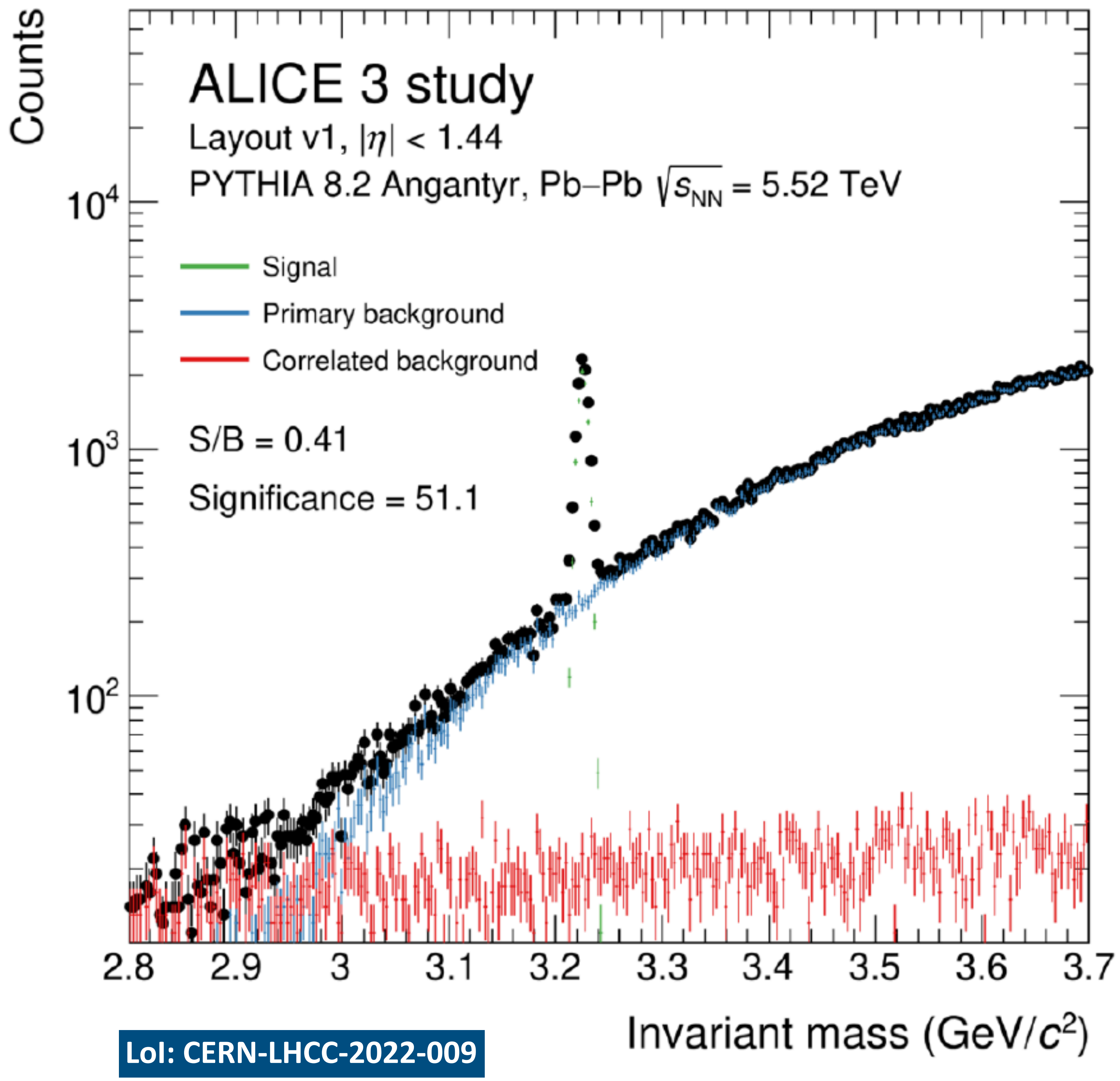
Super-nuclei

- Discovery potential for super-nulei (?) like c-deuteron, c-triton and c-^{3}He.



If c-deuteron is bound and weakly decaying we can discover it:
Significance 51 with 1 month Pb-Pb ~ 5.6 nb^{-1}





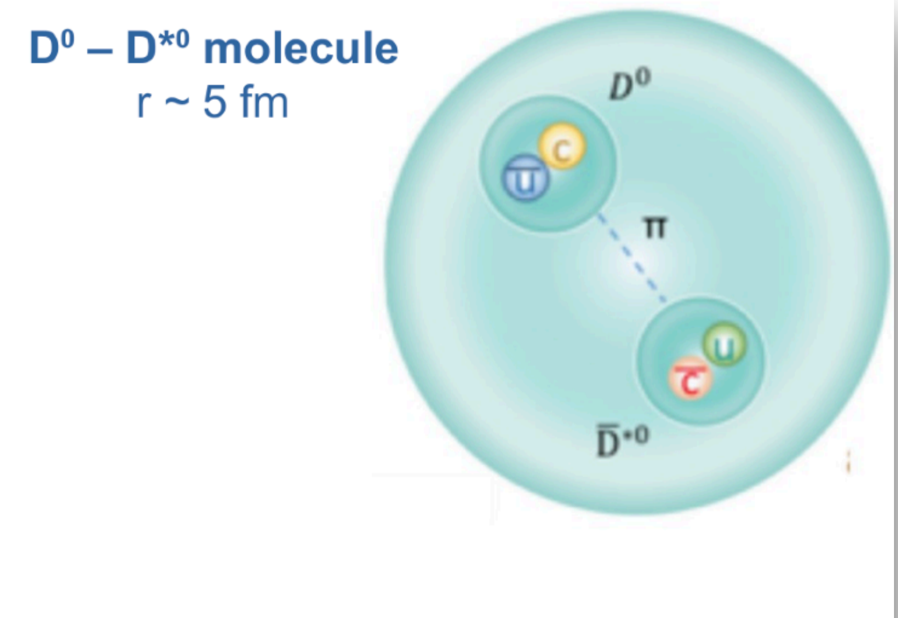
LoI: CERN-LHCC-2022-009

c-triton abundance factor >300 lower, resulting in a factor 18 loss in significance. Still in reach with full ALICE 3 Pb-Pb data sample (35 nb^{-1})

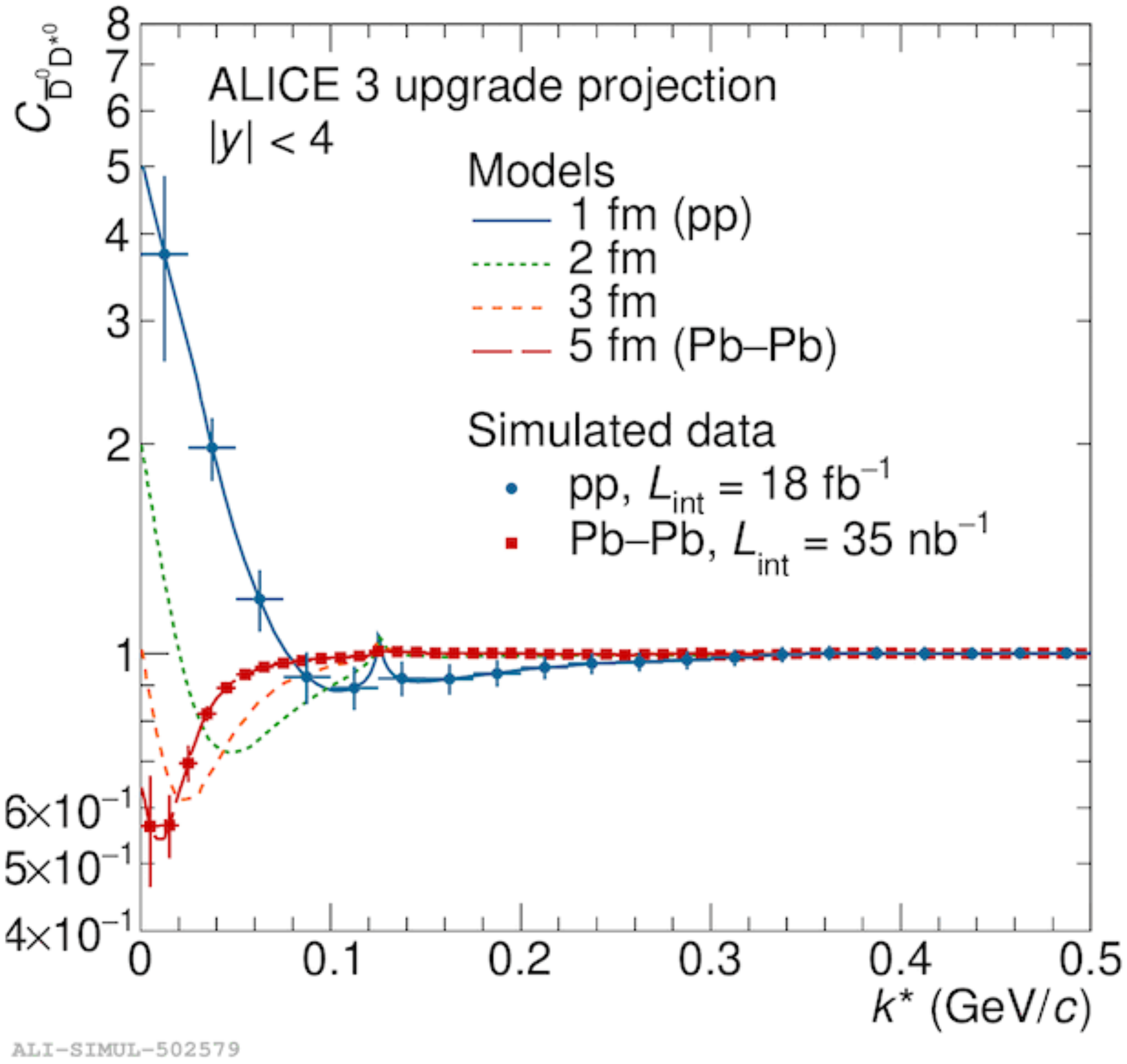
Charm hadron molecules

- D-D momentum correlations accessible via two-particle femtoscopy measurements
- Unique tests of long range strong interaction with rare hadrons
- Investigation of molecular nature of exotic states

Kamiya, Y., Hyodo, T. & Ohnishi, Eur. Phys. J. A 58, 131 (2022)

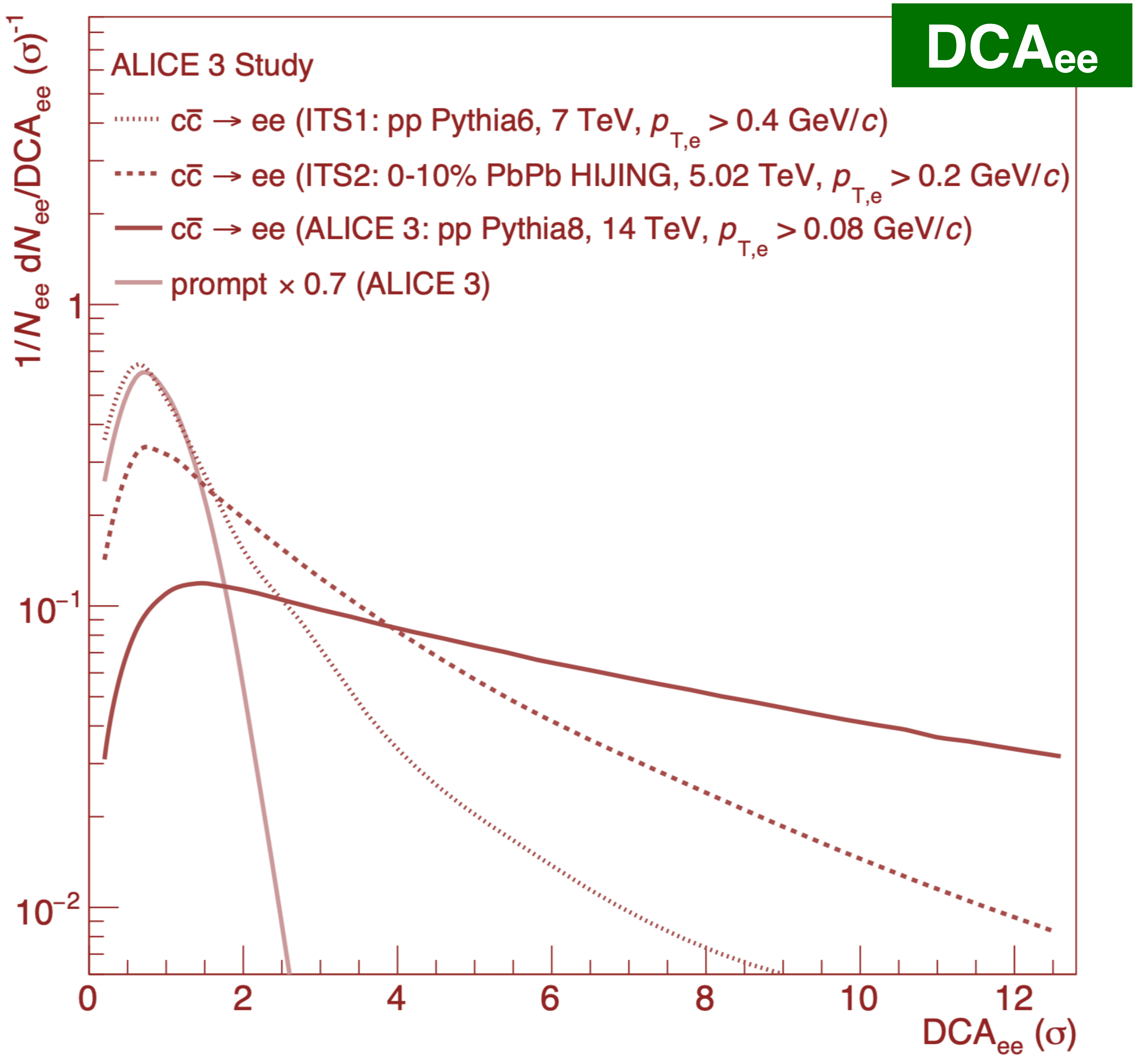


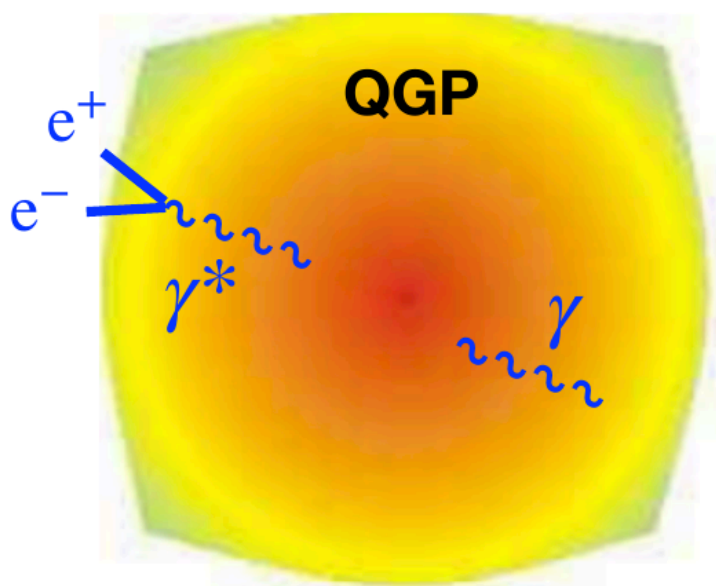
$D^0 - D^{*0}$ correlation femtoscopy



LoI: CERN-LHCC-2022-009

Thermal radiation





Electromagnetic radiation

- Access to QGP temperature before hadronisation

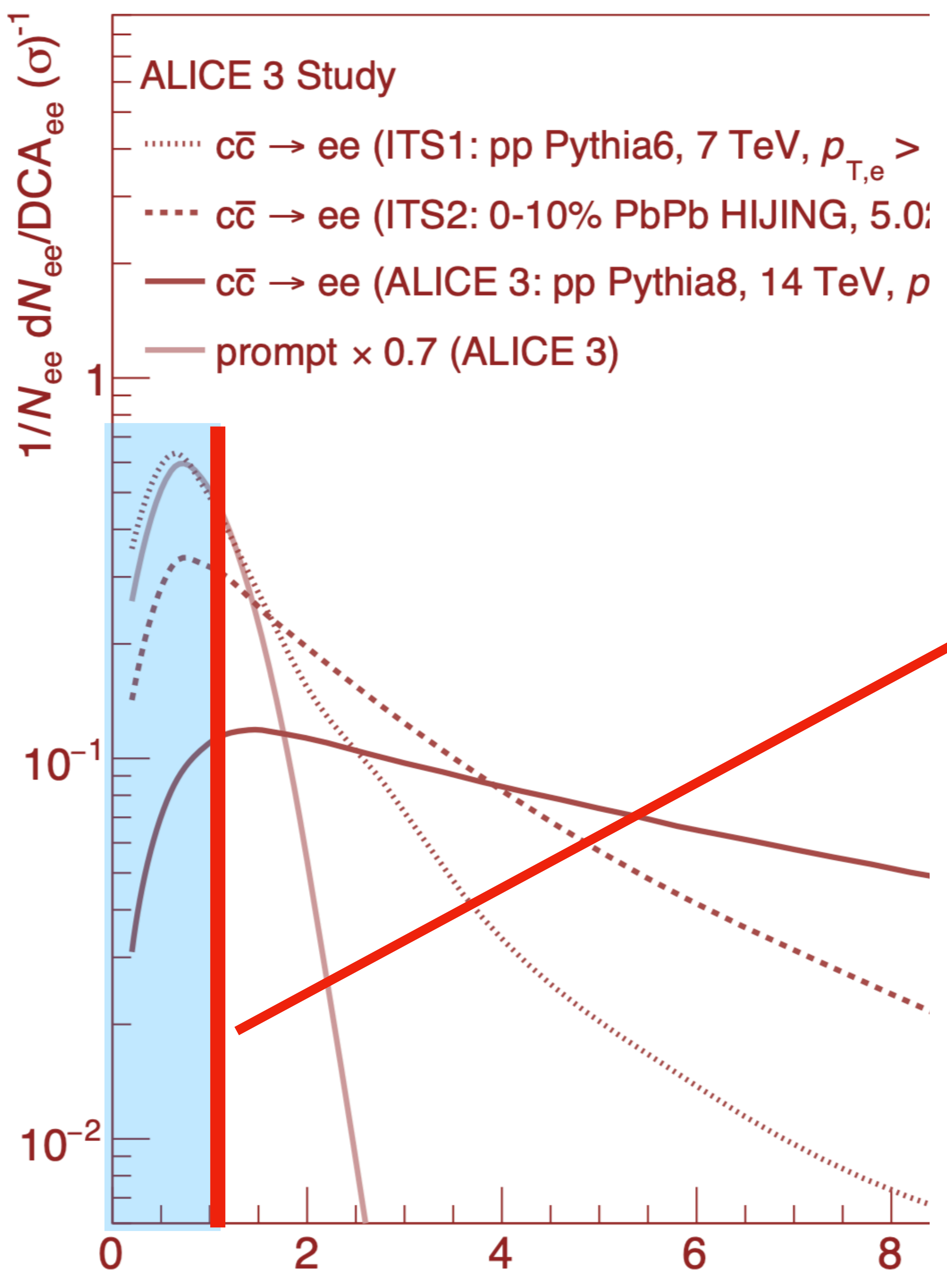
Electron Identification

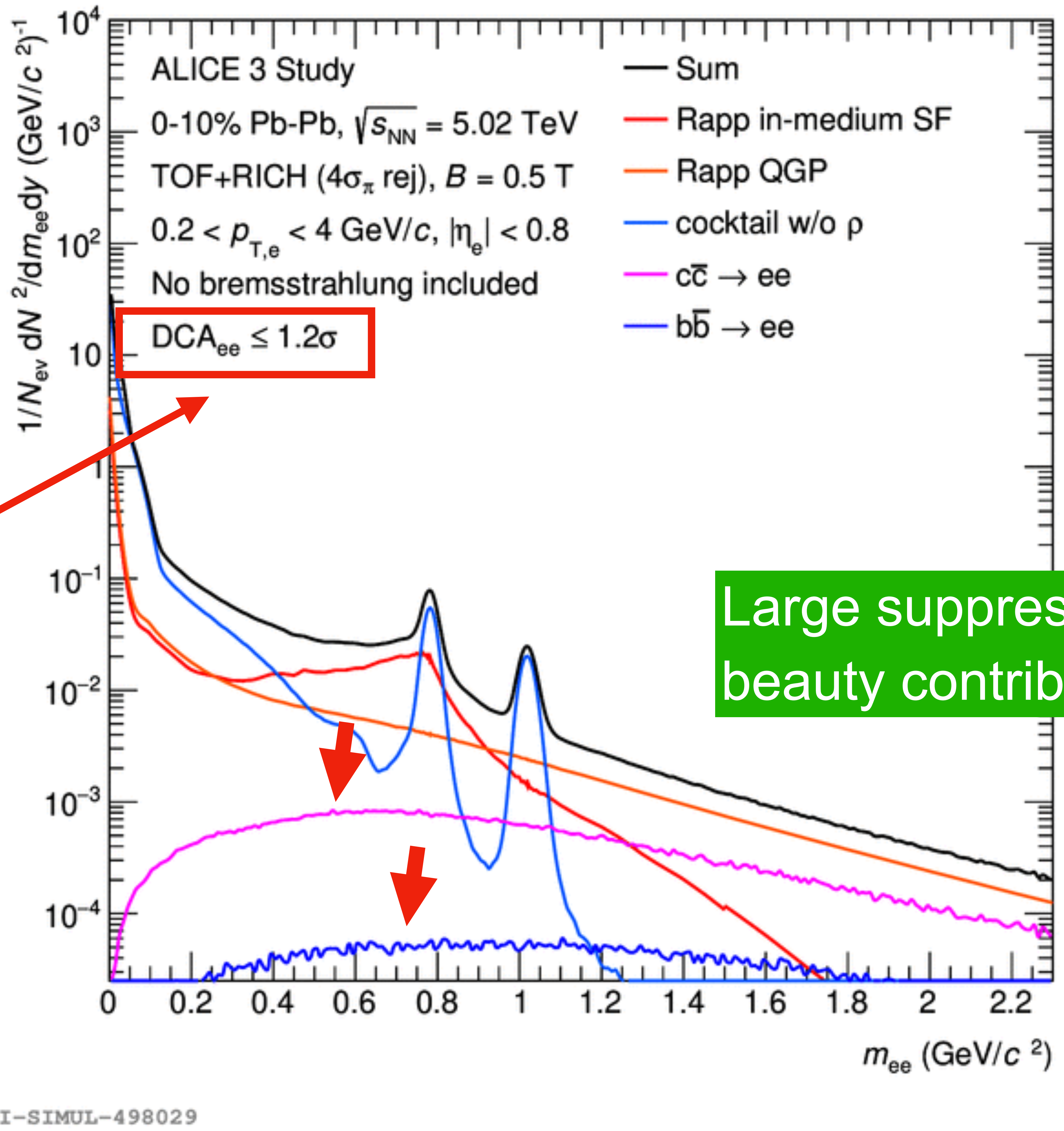
- Time-of-flight (TOF) via silicon
- Ring-imaging Cherenkov (RICH)
- Electromagnetic Calorimeter

HF rejection and low-p_T electron ID

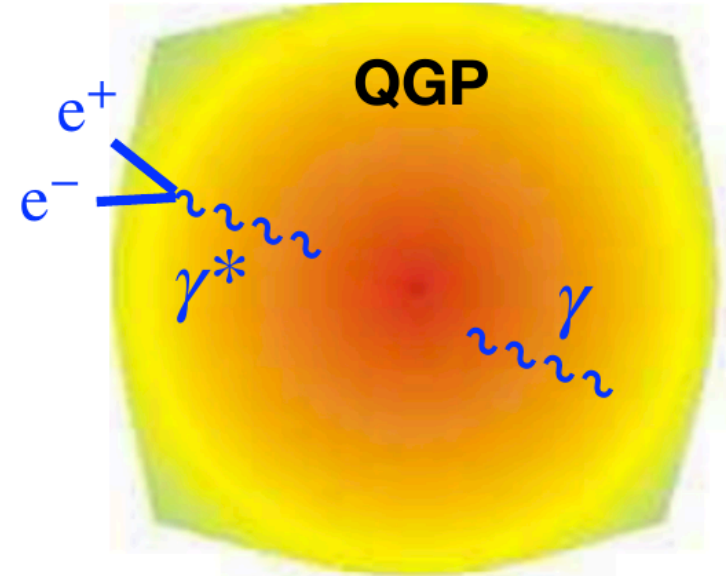
- DCA_{ee}: separation of e^+e^- pairs and HF daughters
- **ALICE 3: superior pointing resolution**

Thermal radiation

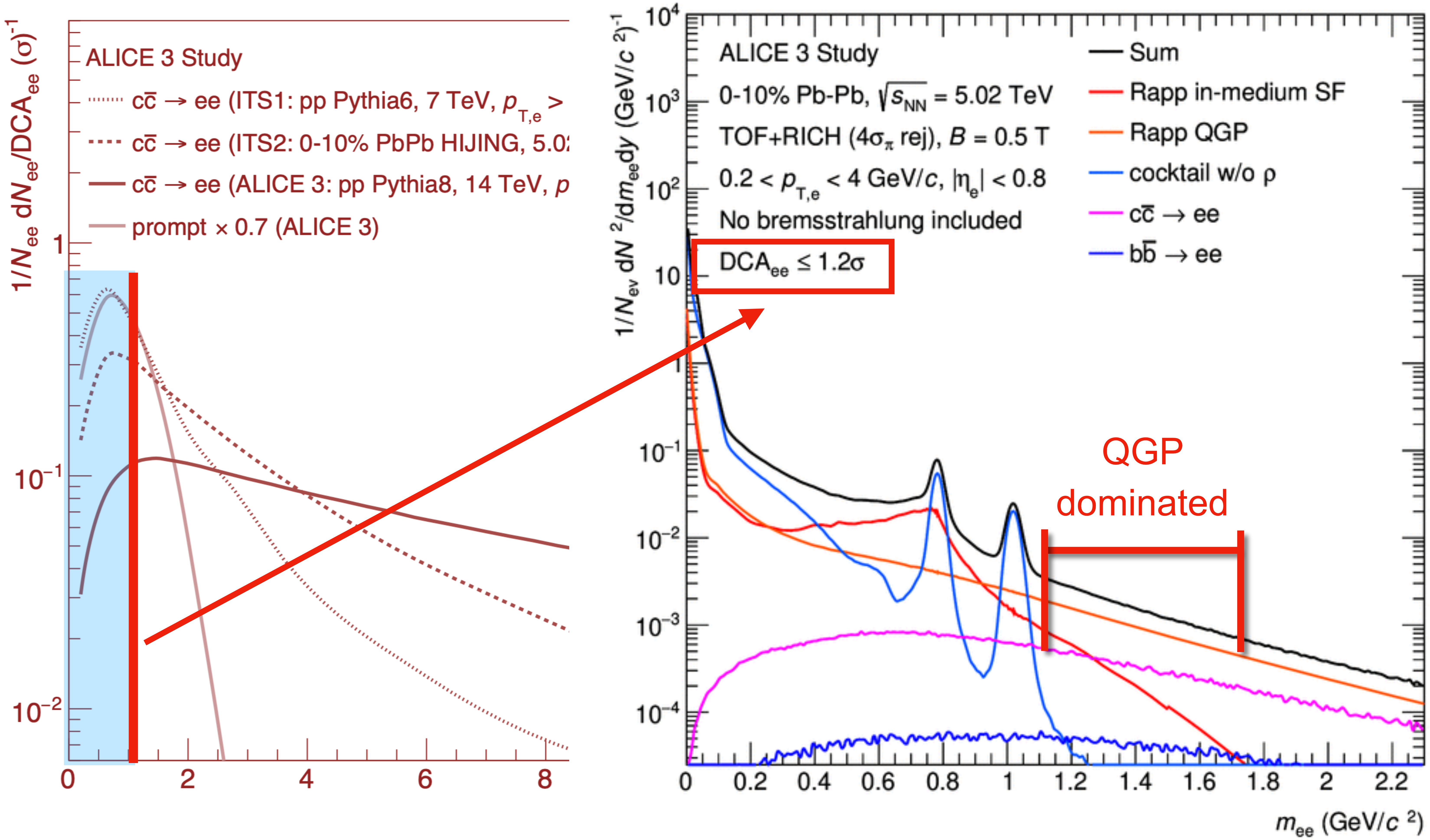




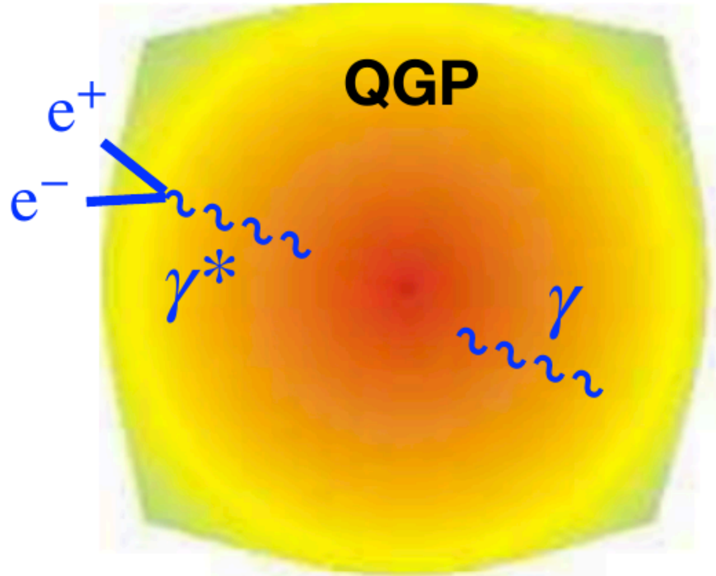
Large suppression of charm and beauty contributions



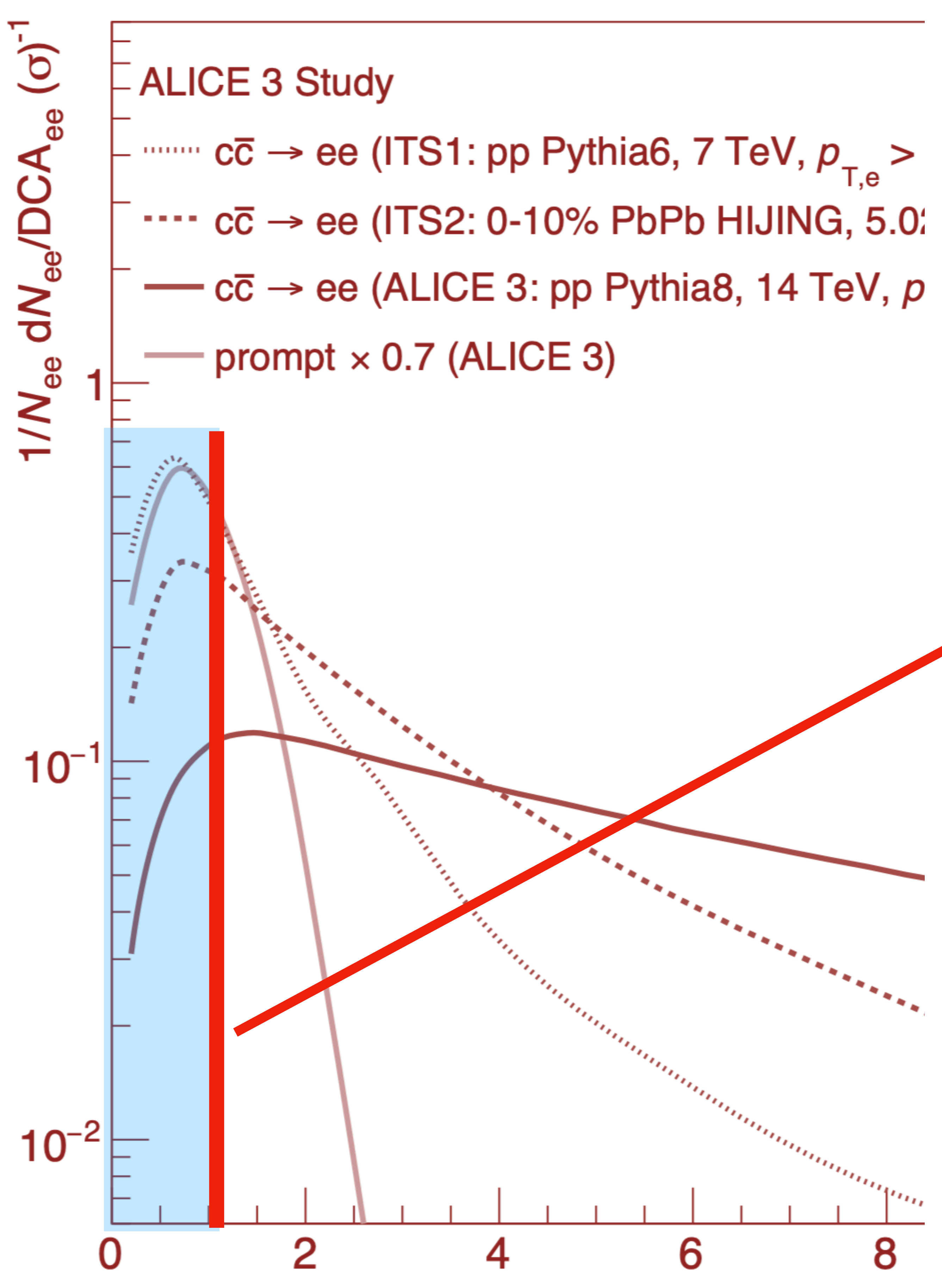
Thermal radiation

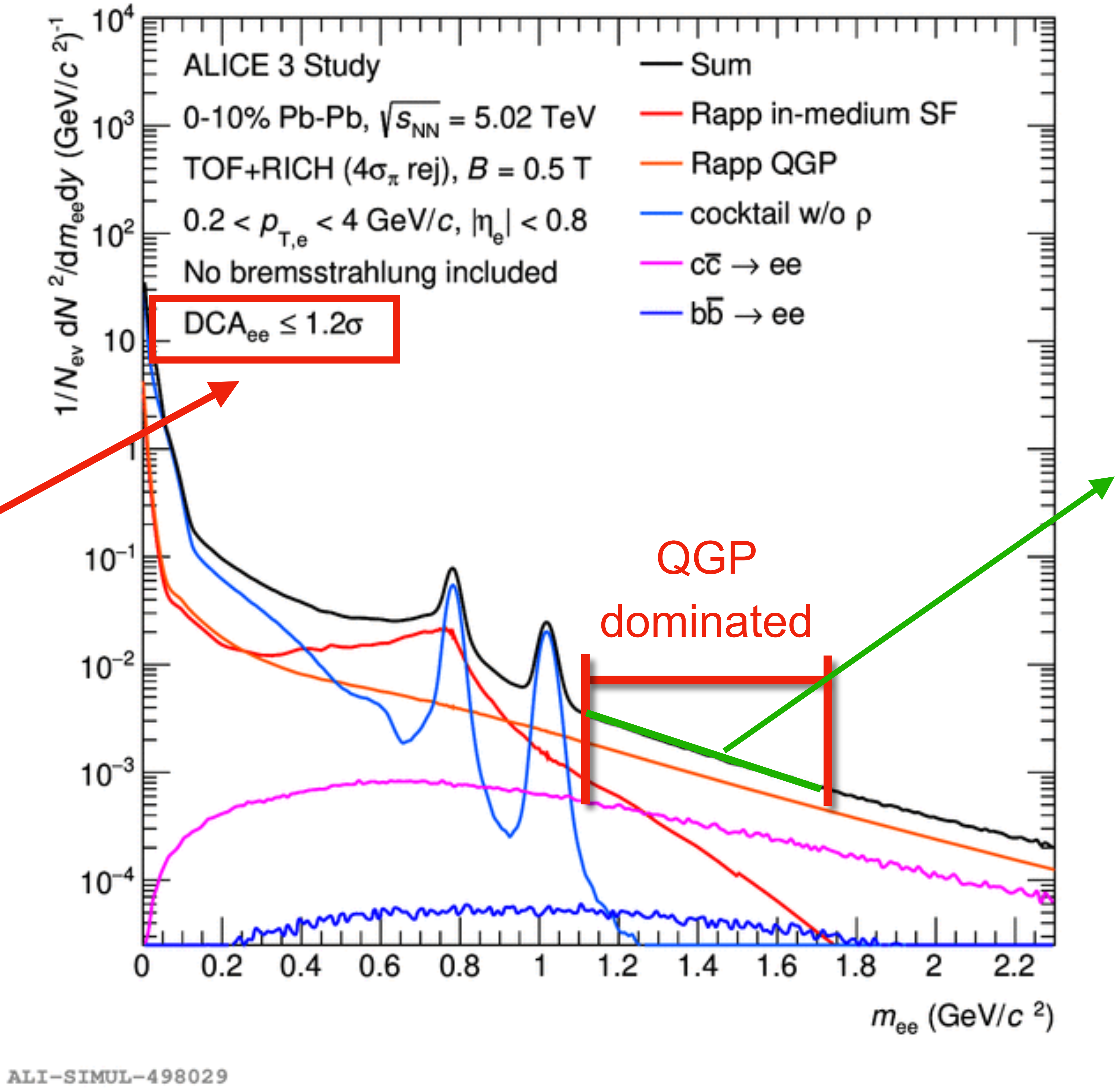


ALI-SIMUL-498029

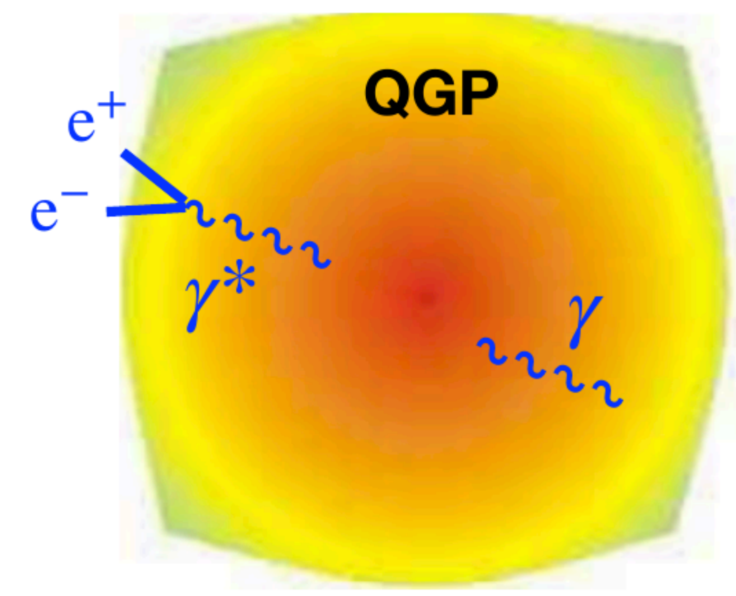


Thermal radiation

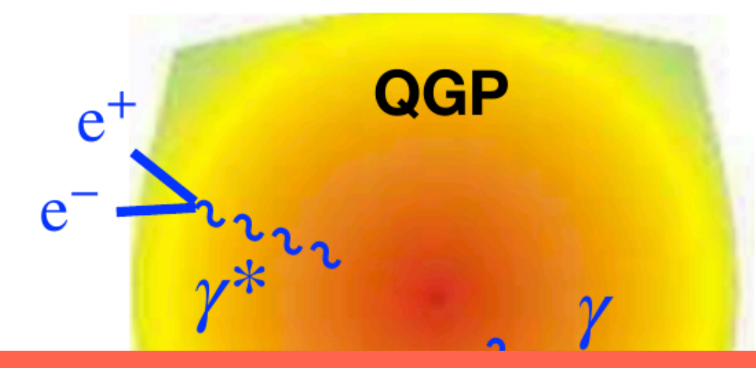


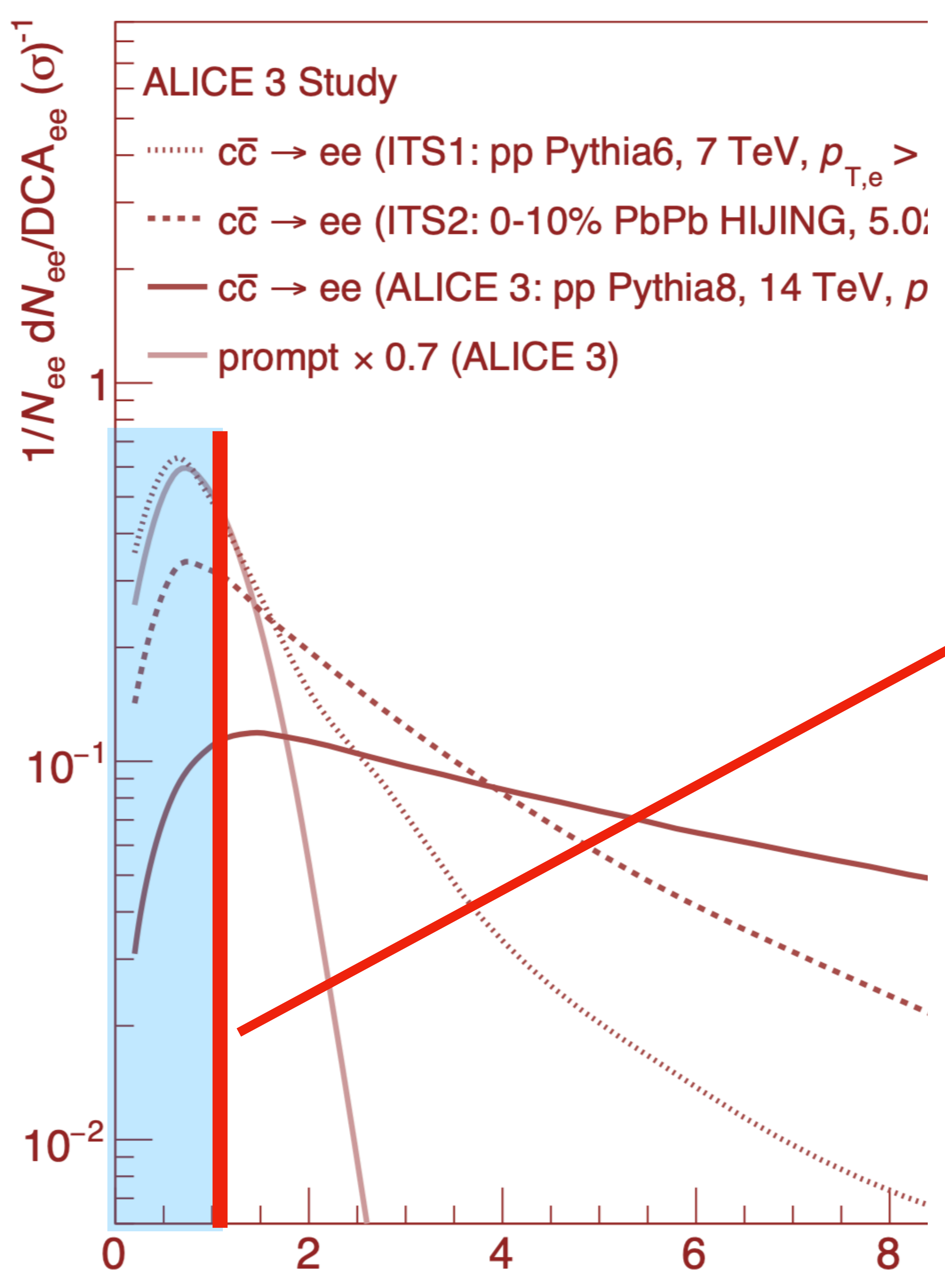


$$\frac{dN_{ee}}{dm_{ee}} \propto (m_{ee}T)^{3/2} e^{-m_{ee}/T}$$

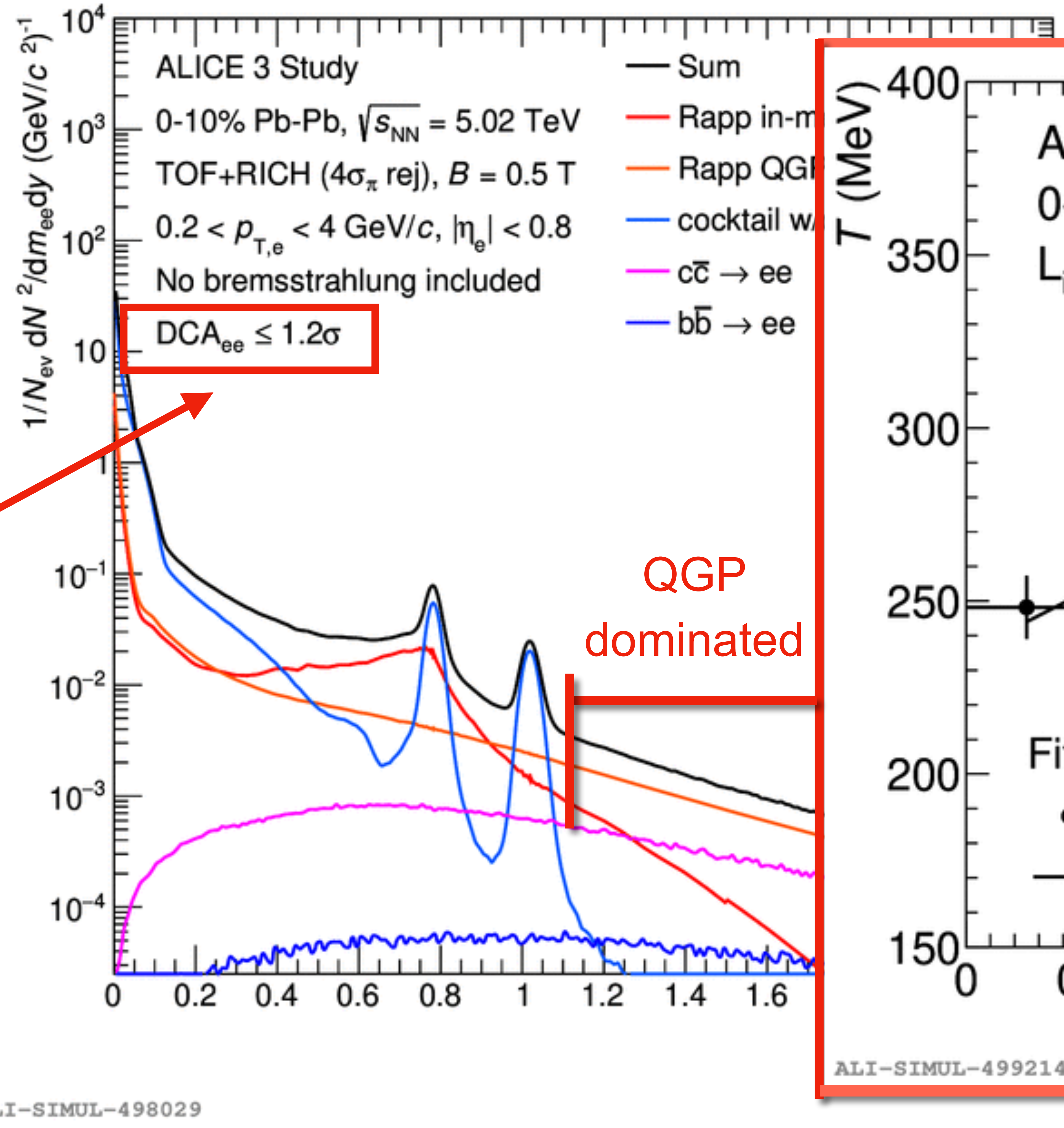


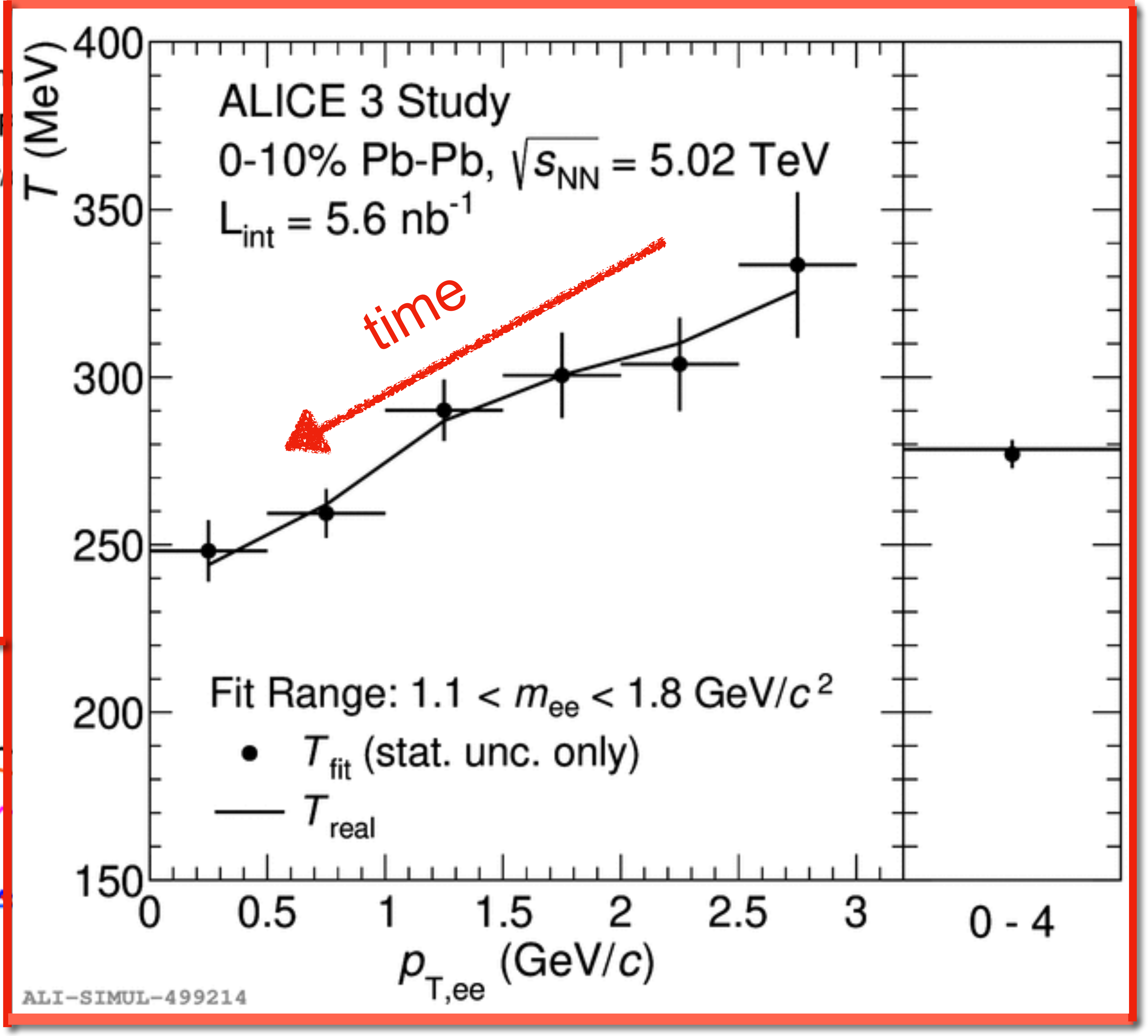
Thermal radiation



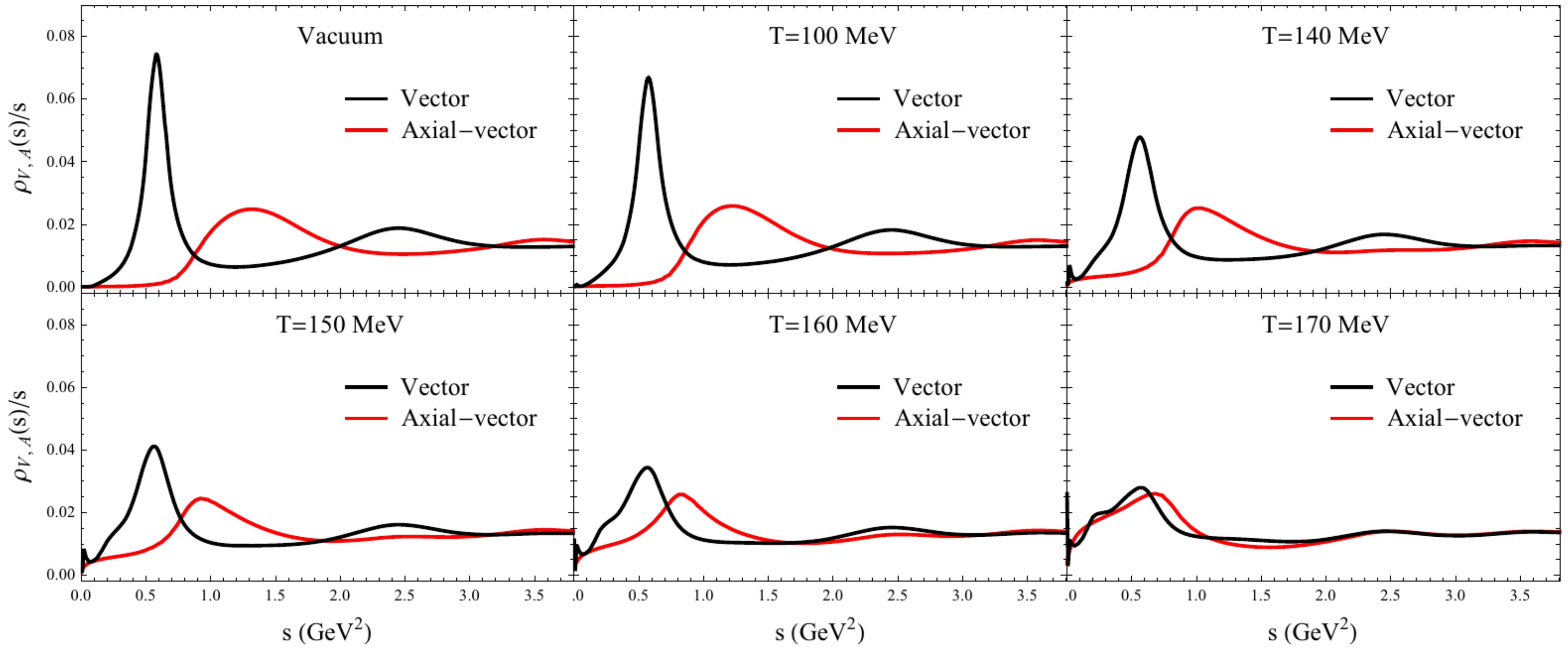


LoI: CERN-LHCC-2022-009

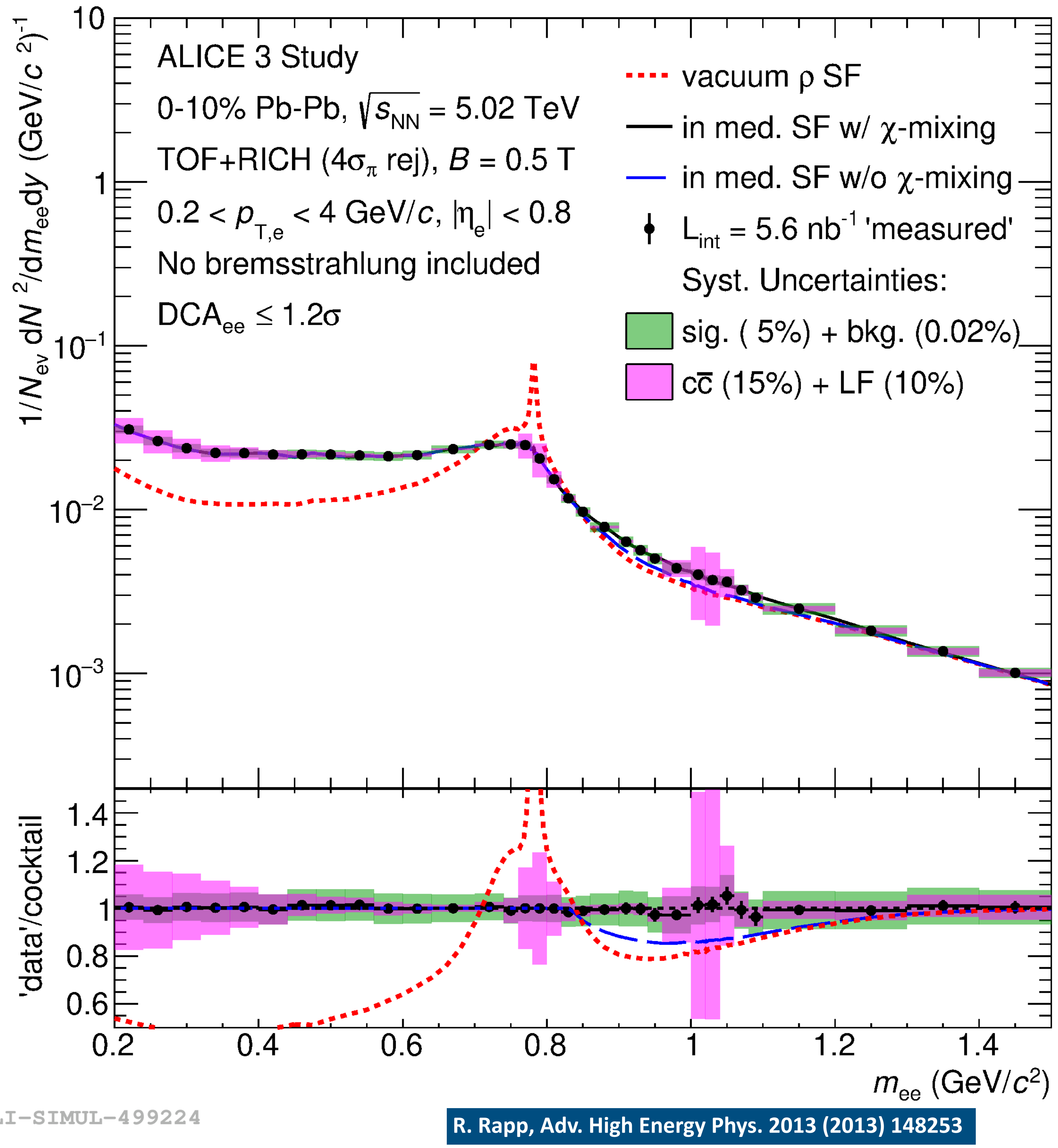




Chiral symmetry



P. M. Hohler – R. Rapp, Phys. Lett. B731 (2014) 103



R. Rapp, Adv. High Energy Phys. 2013 (2013) 148253

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

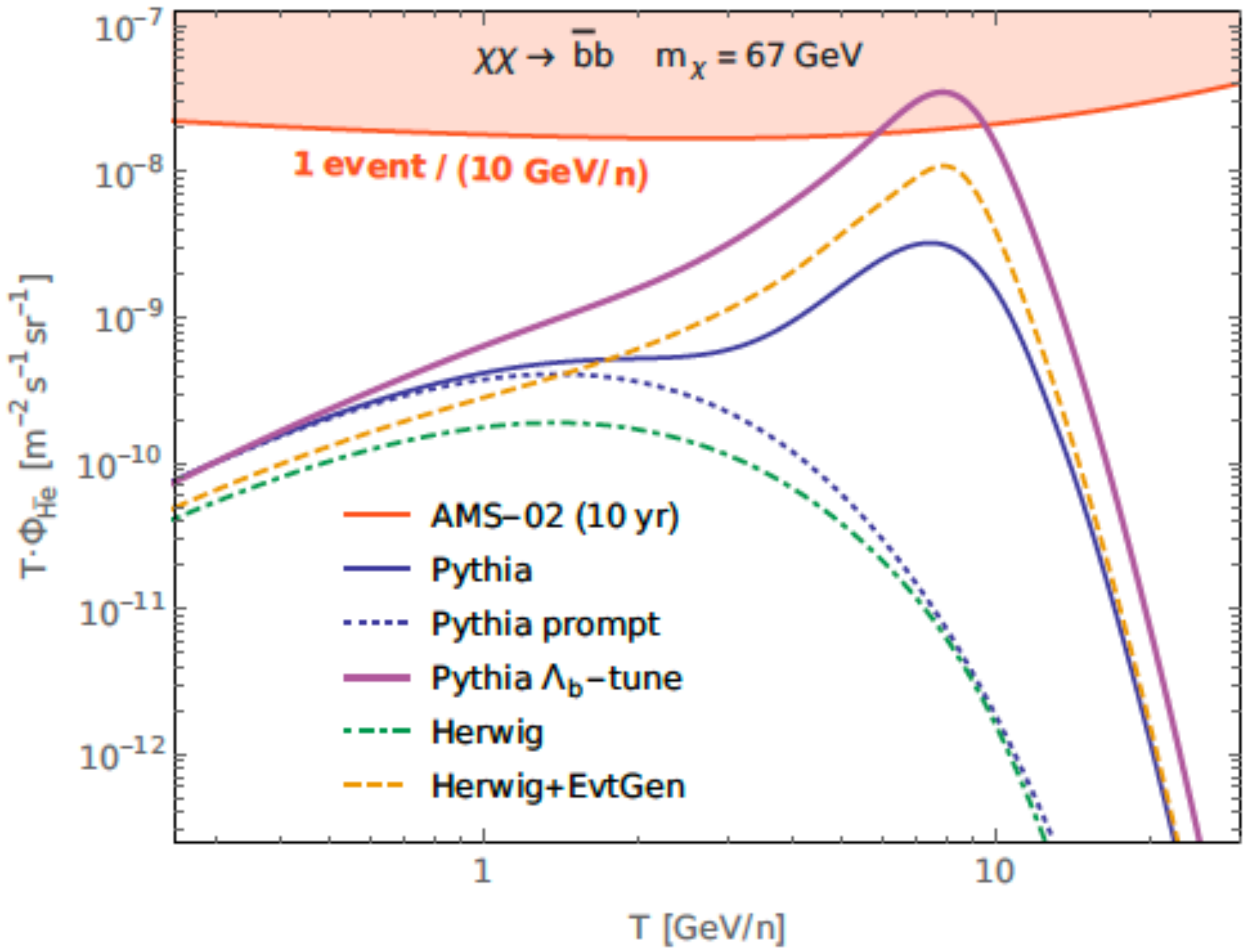
- Spectral function of low mass dielectrons determined with **6-8% unc.** in the region **$0.4 \leq m_{ee} \leq 1.3$ GeV/c^2**
- Chiral **mixing of ρ^0 and a_1 produces a 20-25% modification of the ρ^0 spectral function** (**$0.8 \leq m_{ee} \leq 1.2$ GeV/c^2**)
- ALICE 3 can observe chiral mixing effect and together with more differential measurements (di-electrons v_2) constraint the modification of a_1 spectral function

Dark Matter

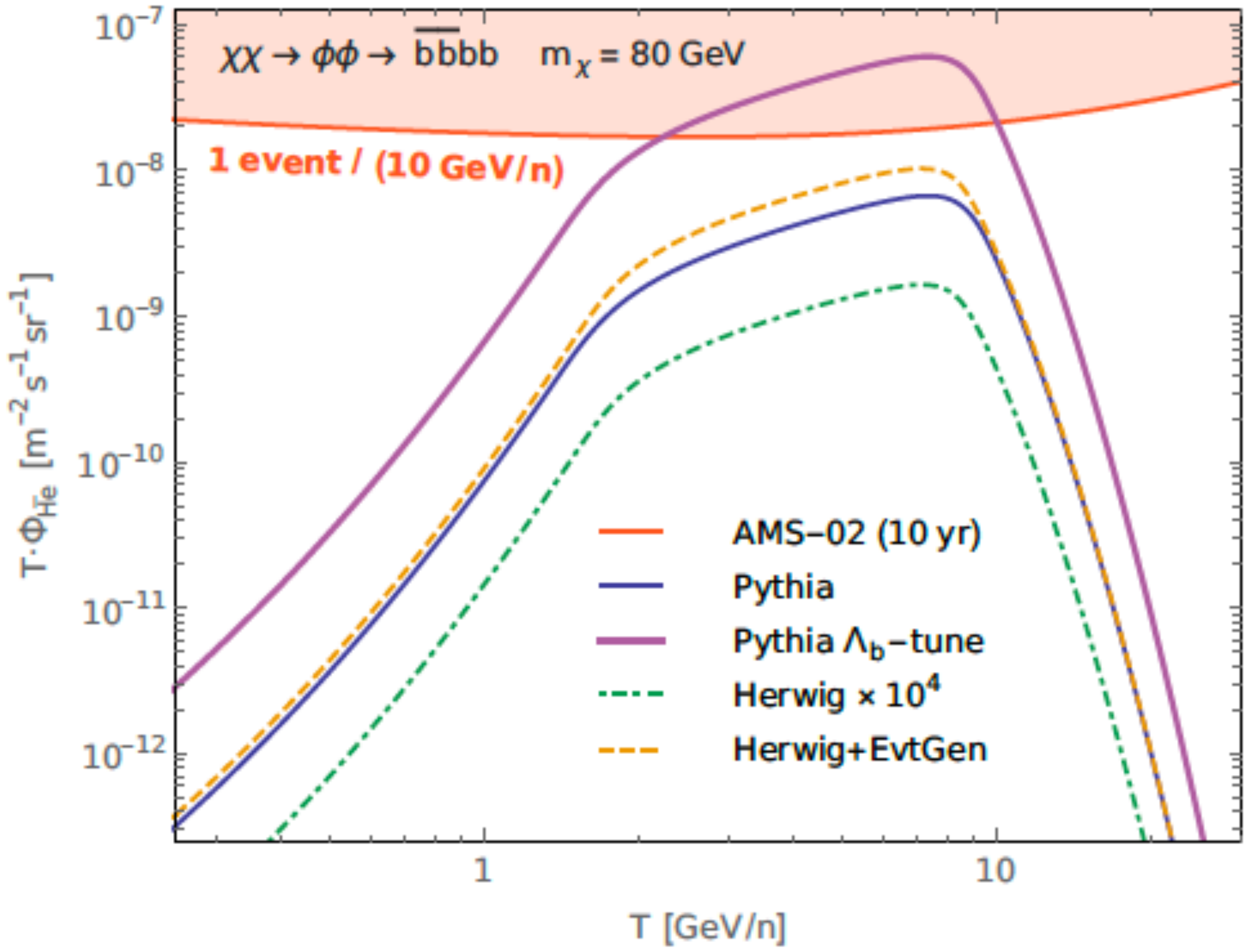
- **Anti-nuclei from b quarks:**
  - Recent AMS discovery of cosmic-ray anti-nuclei (Anti-^{3}He) can be a signature of the dark matter

$$\chi\chi \rightarrow b\bar{b} \rightarrow \overline{\Lambda}_b^0 + X \rightarrow {}^3\overline{\mathrm{He}} + X$$

  - Anti-^{3}He from Λ_b decays from dark matter annihilation would lead to an enhanced flux of anti-^{3}He near earth.
  - ALICE 3 well positioned (together with LHCb) to impose constraints on branching ratio from Λ_b decays.



M. Winkler, T. Linden PRL 126 (2021)



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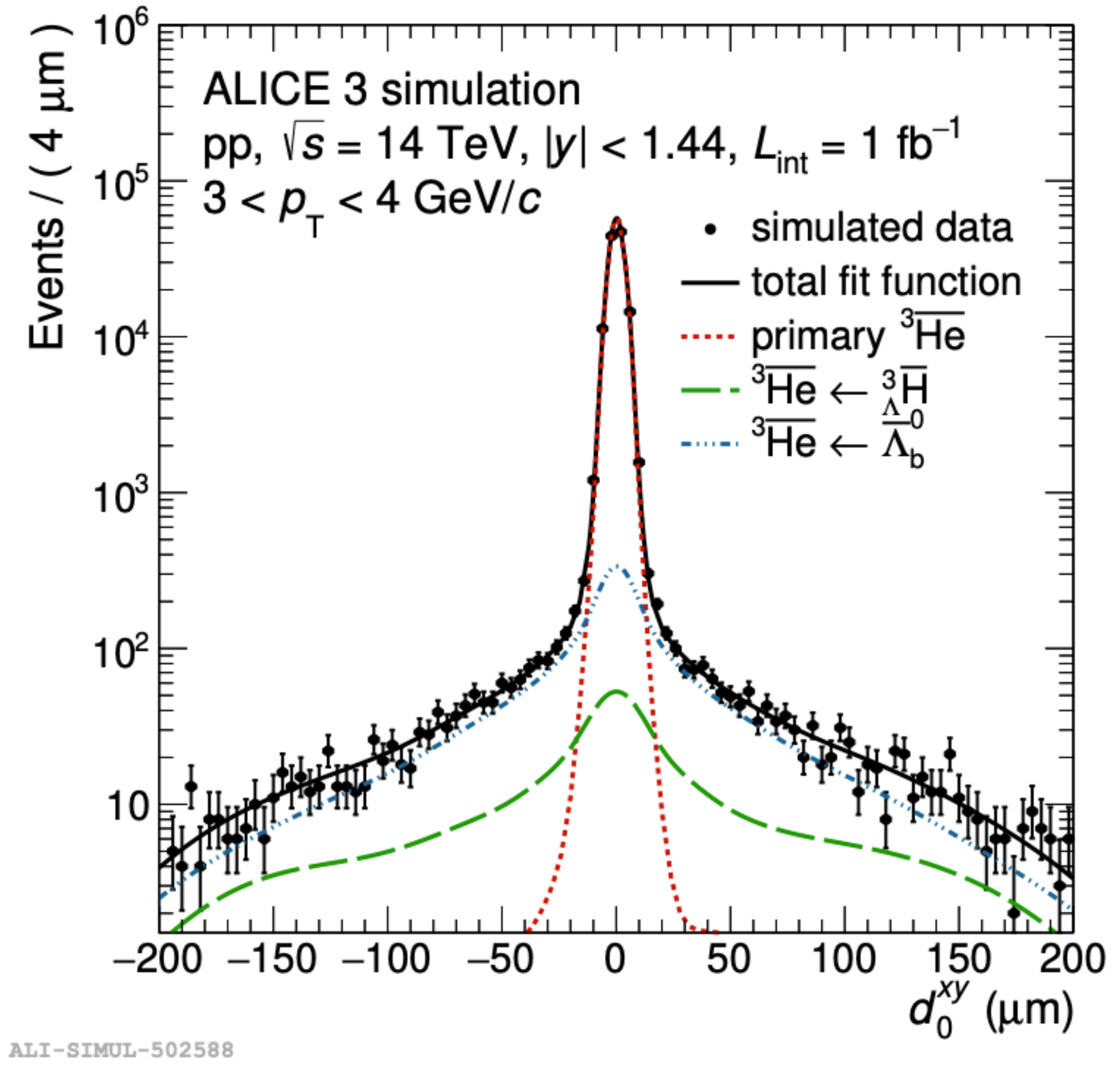
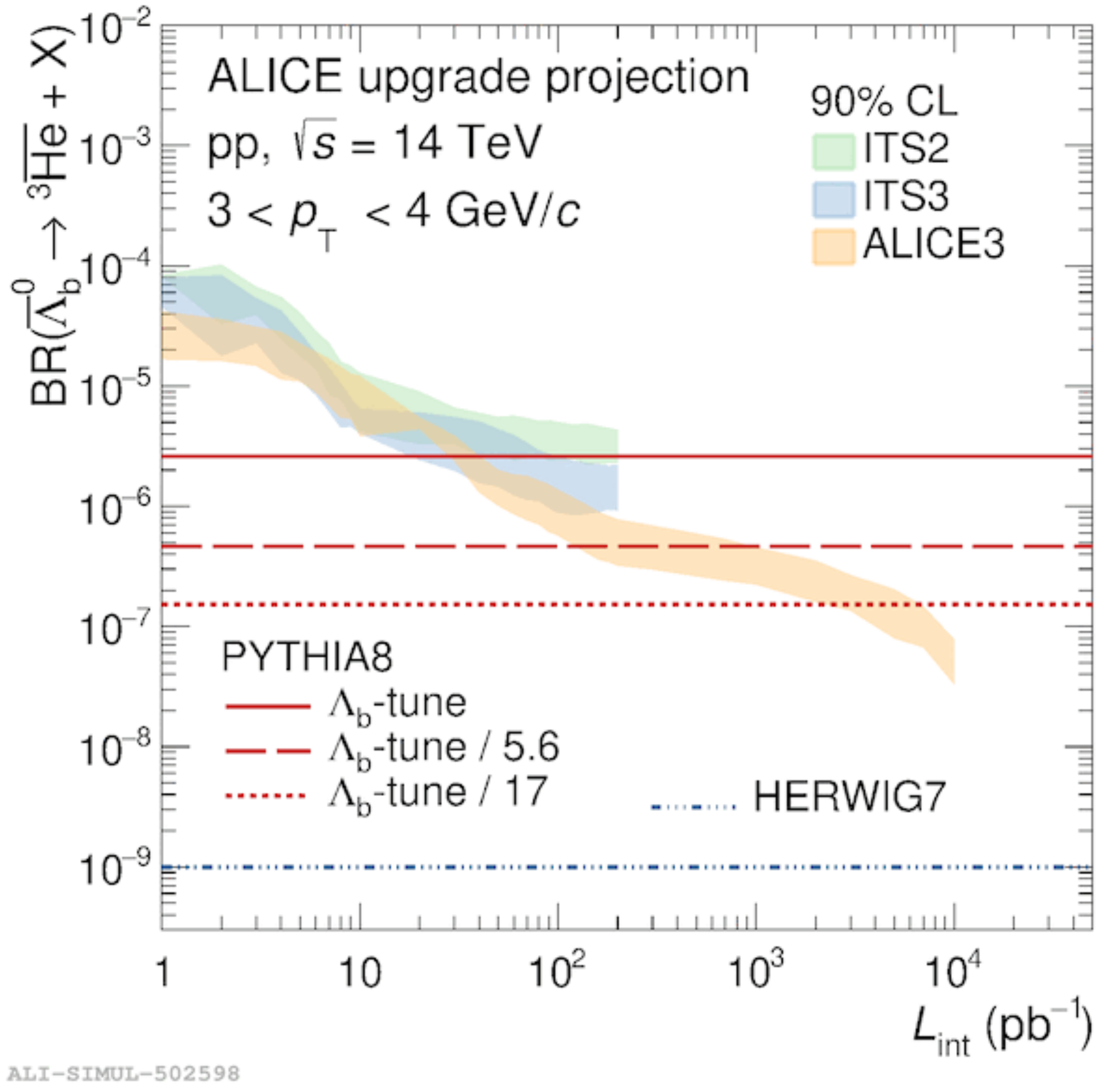




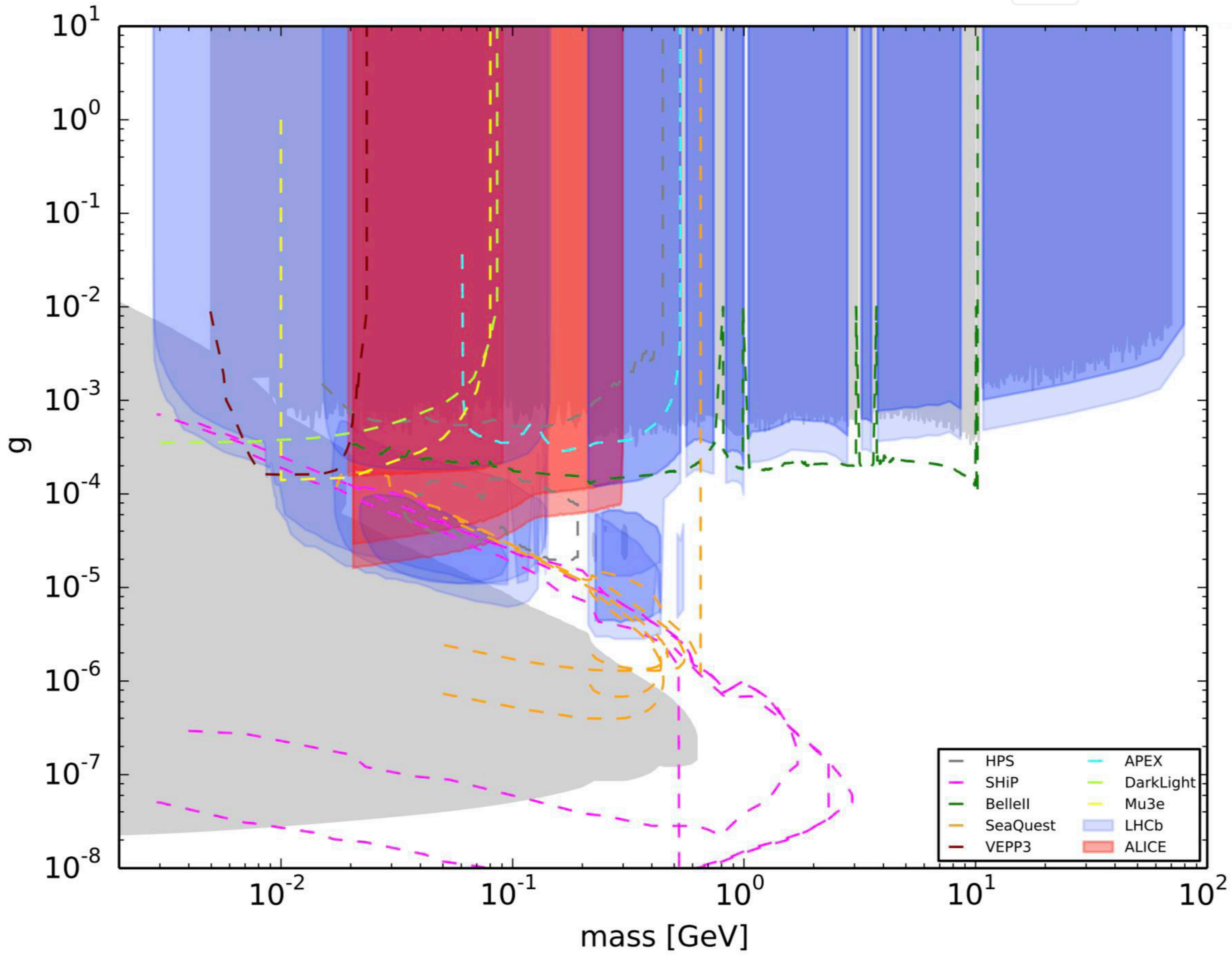
LoI: CERN-LHCC-2022-009

Dark Photons

- **Theorised Extra-U(1) gauge bosons. Hints:**
  - Antiproton spectrum (AMS) and positron excess in cosmic ray (PAMELA, FERMI, AMS)
  - Muon anomalous magnetic moment
- **ALICE 3 future searches:**
  - Displacement searches (M<20 MeV)
  - Final-state radiation, Drell-Yan and thermal rad (M>1 GeV)
  - Meson Decays (*π^0, η, Φ Dalitz decays D^{*0}, radiative J/ψ and Υ decays*)

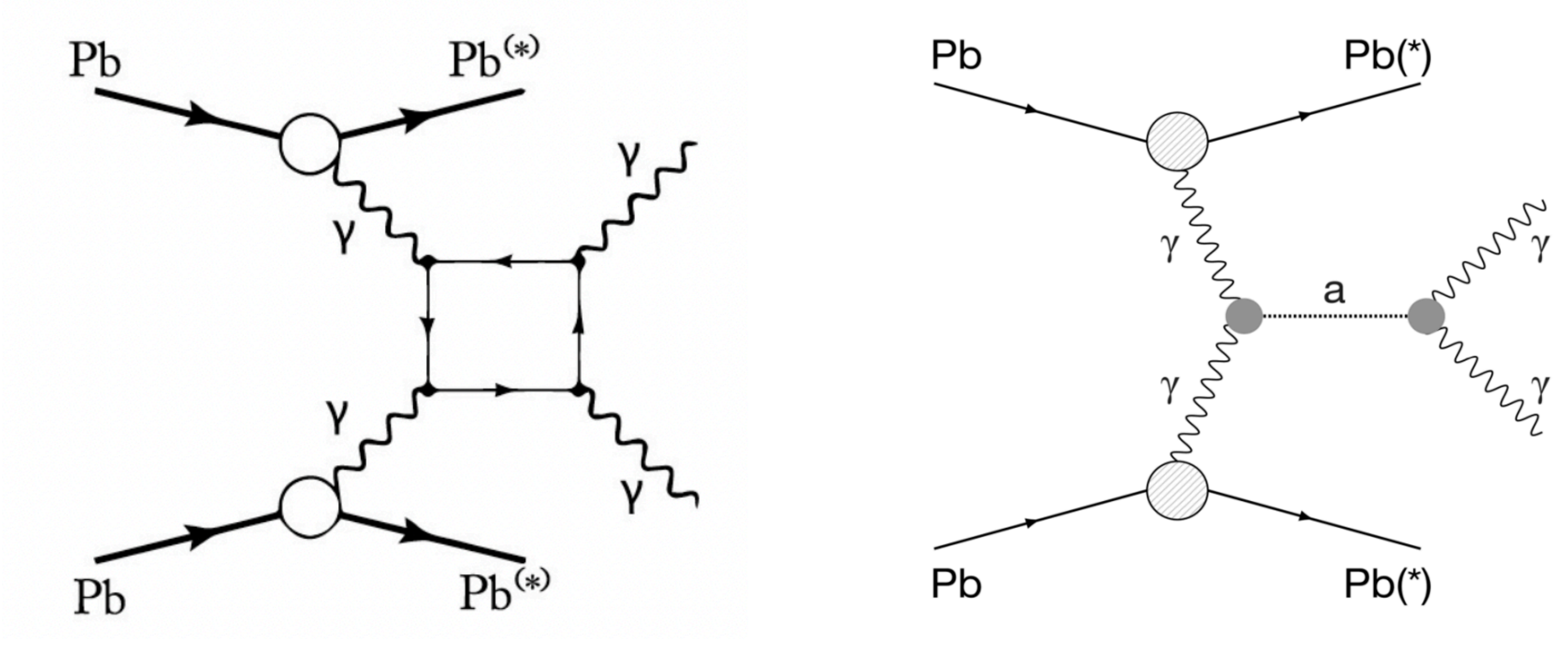
Phys. Rev. Lett. 116, 251803

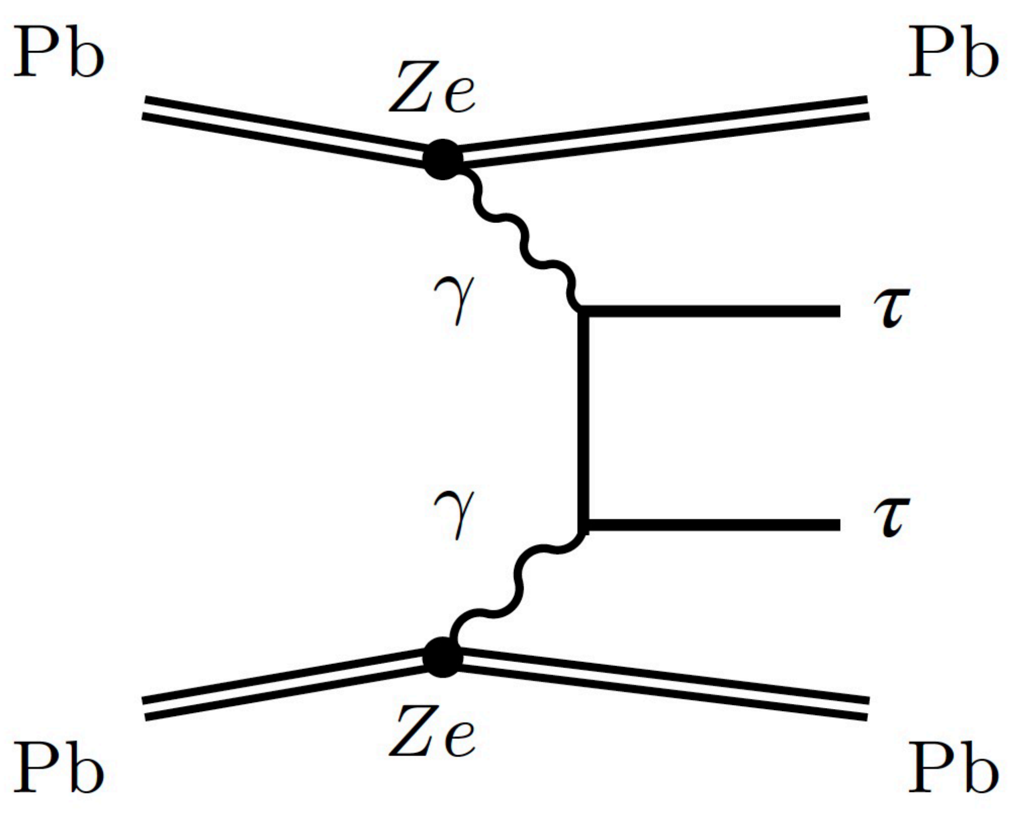
darkcast

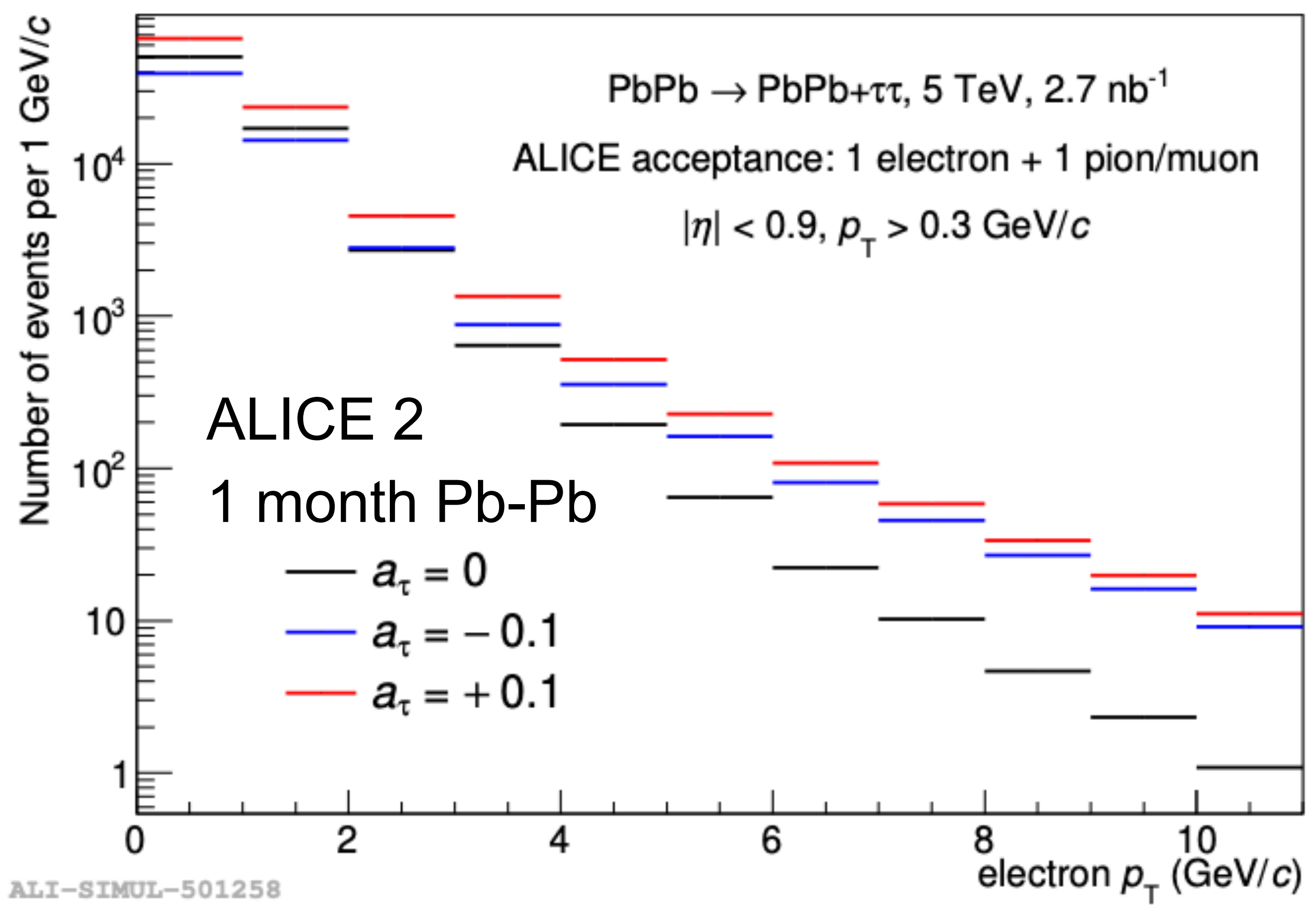


BSM searches in UPCs

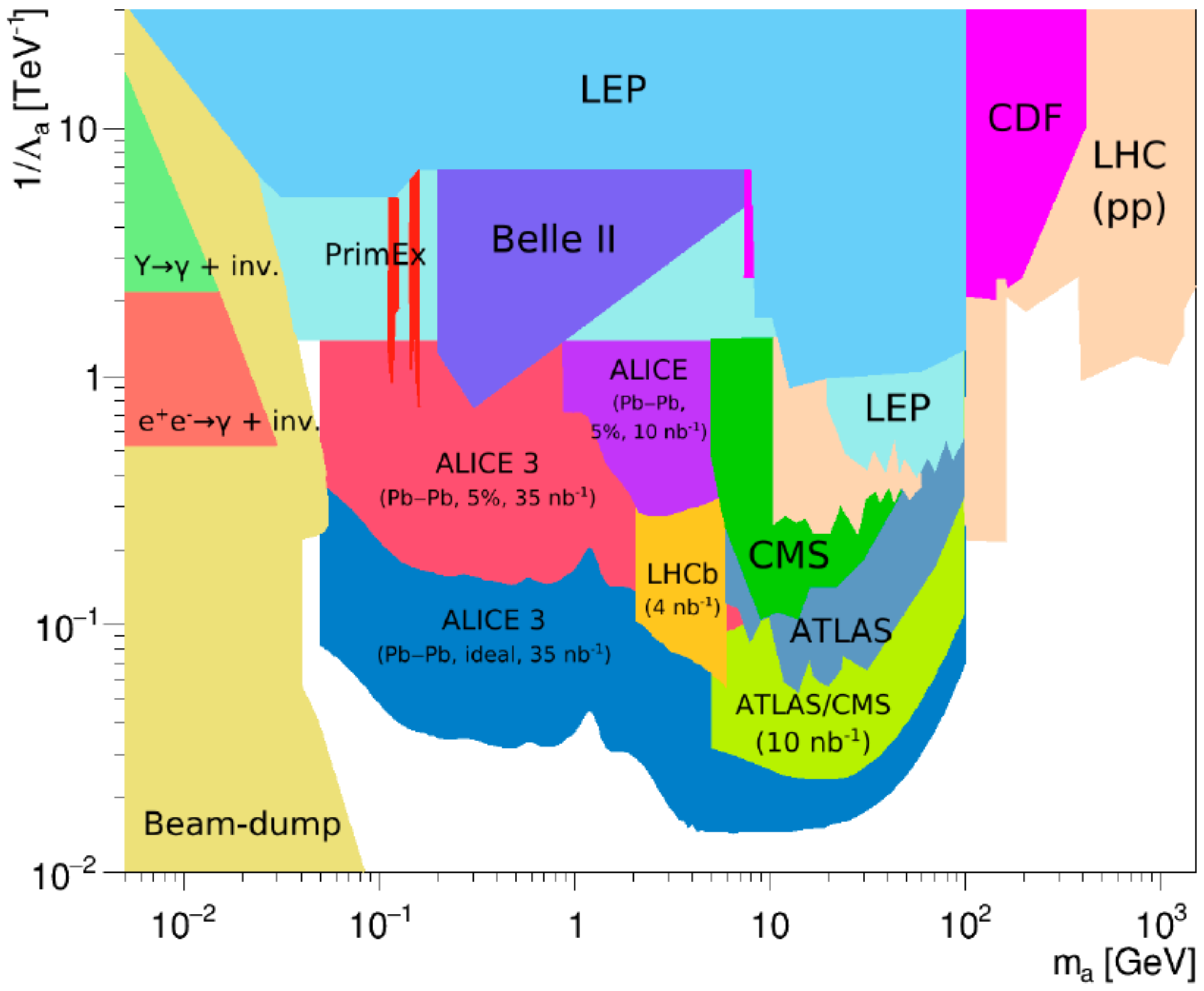
- Ultra peripheral collisions (UPC) clean environment plus large enhancement of γγ rate (~10^7)
  - **Searches of BSM particle coupling to photons**: modification of light-by-light scattering rates from virtual corrections from heavy particles (magnetic monopoles, vector-like fermions, dark particles)
  - **a_τ (τ anomalous magnetic moment)** measurements and possible deviation from SM by looking to 1 electron + 1 pion events in UPC. Low-p_T reach and larger acceptance of ALICE 3 will improve ALICE 2 sensitivity keeping unique low-p_T access compared to ATLAS/CMS







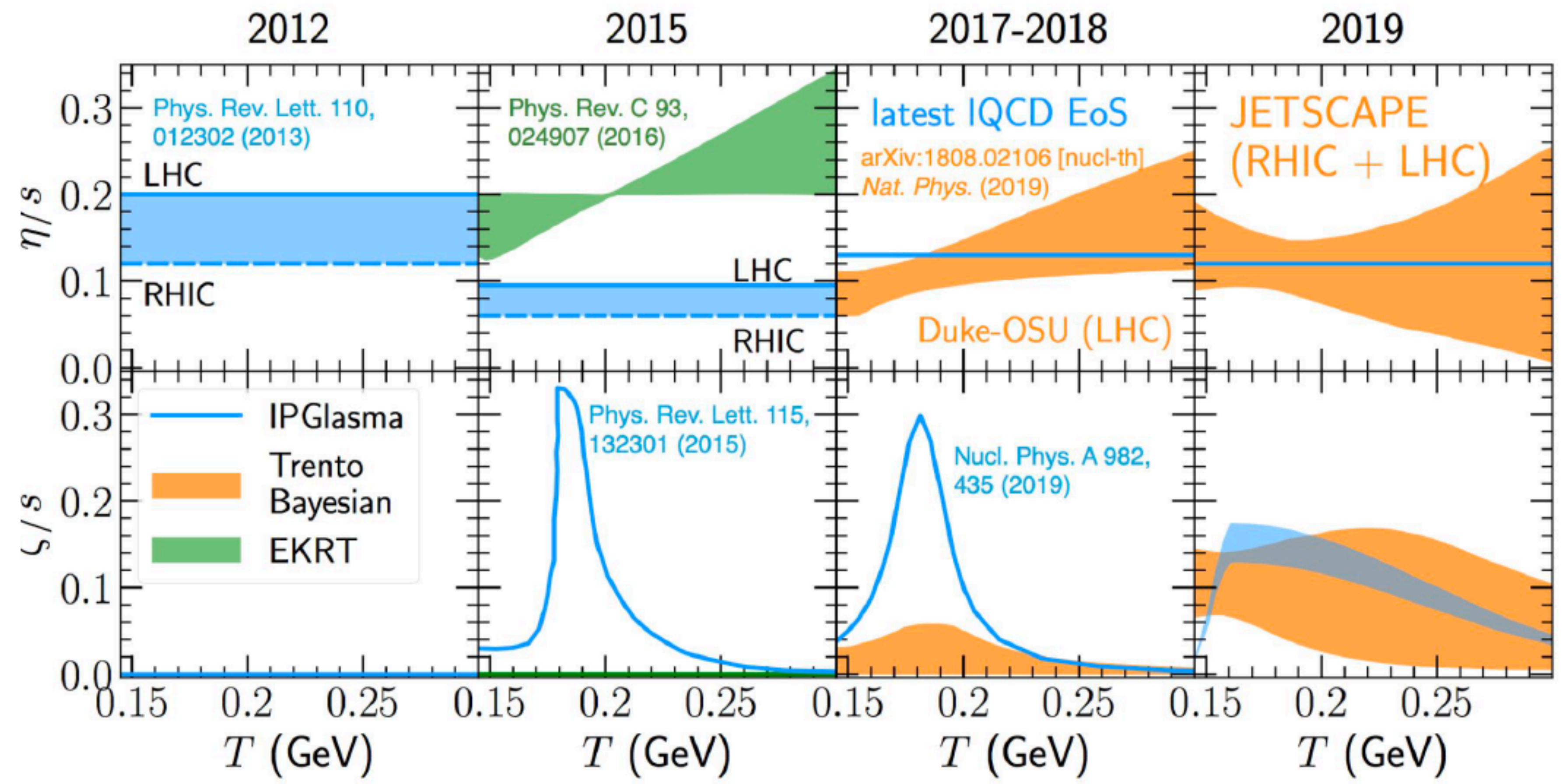
BSM searches in UPCs

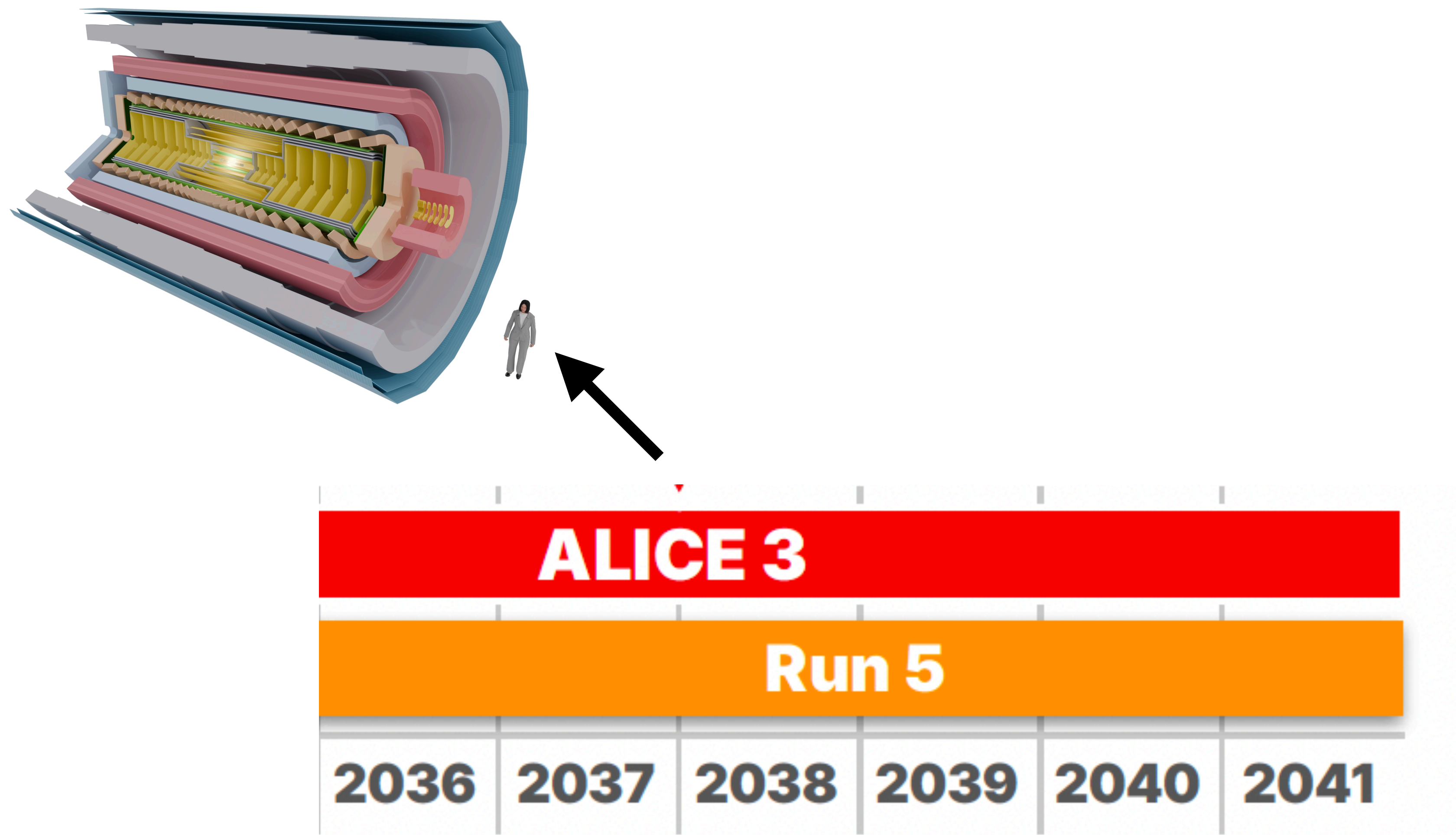


LoI: CERN-LHCC-2022-009

- Ultra-peripheral collisions (UPCs) are dominated by photon-photon and photon-nucleus interactions. Provide for a clean environment for axion-like particles (APL) studies
- Searches via **$\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$** process. Signal would be visible as a peak in the diphoton mass distribution
- Performance on the estimated production cross-section given as mass and recast limit in the plane (**$m_a, 1/\Lambda_a$**)

Concluding





- We come a long way in the study of QCD in extreme conditions since the starting of LHC but several question marks remain.
- These questions can be addressed with a new apparatus with x3-5 increase in pointing precision, acceptance and rate capability.
- ALICE 3 will allow exploiting the full power of heavy-ion collisions for QGP characterisation and open a window in BSM searches in such system.

Thanks!

Nikhef

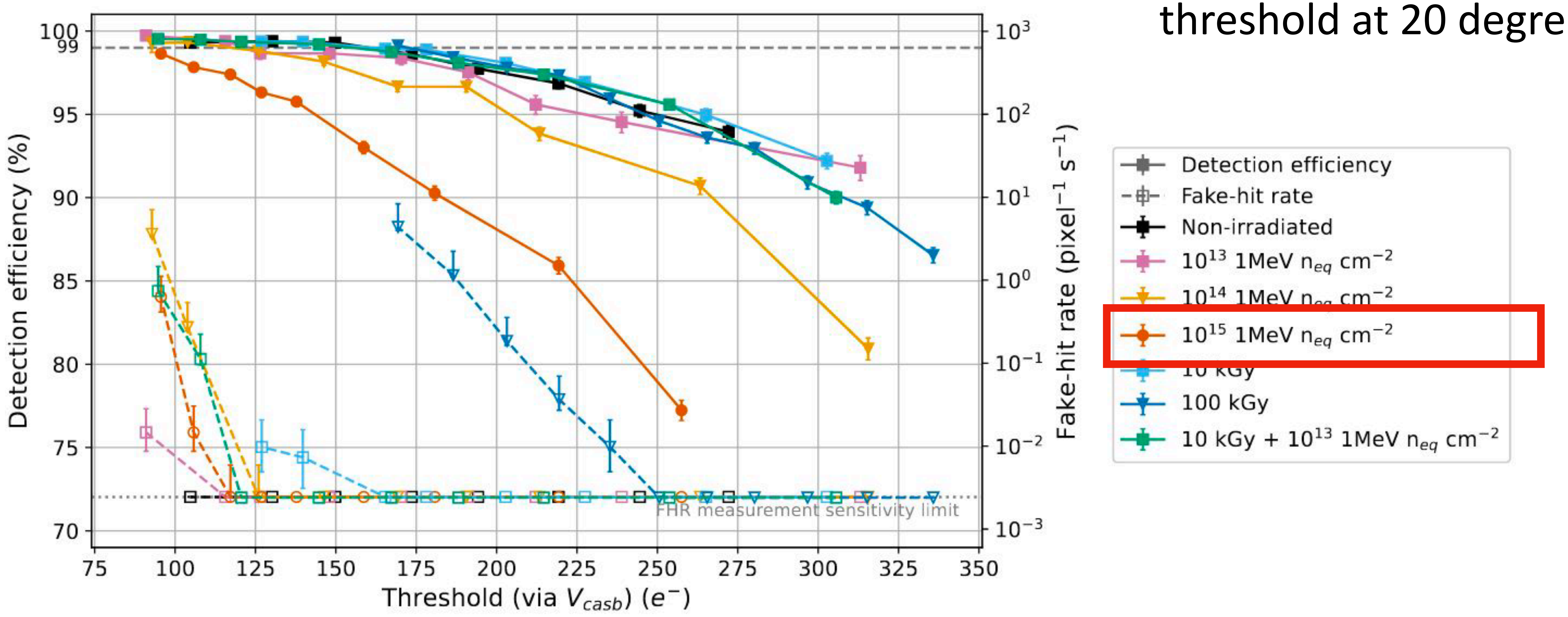
LHC machine performance

Quantity	pp	O–O	Ar–Ar	Ca–Ca	Kr–Kr	In–In	Xe–Xe	Pb–Pb
$\sqrt{s_{NN}}$ (TeV)	14.00	7.00	6.30	7.00	6.46	5.97	5.86	5.52
L_{AA} ($cm^{-2}s^{-1}$)	3.0×10^{32}	1.5×10^{30}	3.2×10^{29}	2.8×10^{29}	8.5×10^{28}	5.0×10^{28}	3.3×10^{28}	1.2×10^{28}
$\langle L_{AA}\rangle$ ($cm^{-2}s^{-1}$)	3.0×10^{32}	9.5×10^{29}	2.0×10^{29}	1.9×10^{29}	5.0×10^{28}	2.3×10^{28}	1.6×10^{28}	3.3×10^{27}
$\mathscr{L}_{AA}^{month}$ (nb^{-1})	5.1×10^{5}	1.6×10^{3}	3.4×10^{2}	3.1×10^{2}	8.4×10^{1}	3.9×10^{1}	2.6×10^{1}	5.6
$\mathscr{L}_{NN}^{month}$ (pb^{-1})	505	409	550	500	510	512	434	242
R_{max} (kHz)	24 000	2169	821	734	344	260	187	93
μ	1.2	0.21	0.08	0.07	0.03	0.03	0.02	0.01
$dN_{ch}/d\eta$ (MB)	7	70	151	152	275	400	434	682
	at $R = 0.5$ cm							
R_{hit} (MHz/cm^2)	94	85	69	62	53	58	46	35
NIEL (1 MeV n_{eq}/cm^2)	1.8×10^{14}	1.0×10^{14}	8.6×10^{13}	7.9×10^{13}	6.0×10^{13}	3.3×10^{13}	4.1×10^{13}	1.9×10^{13}
TID (Rad)	5.8×10^{6}	3.2×10^{6}	2.8×10^{6}	2.5×10^{6}	1.9×10^{6}	1.1×10^{6}	1.3×10^{6}	6.1×10^{5}
	at $R = 100$ cm							
R_{hit} (kHz/cm^2)	2.4	2.1	1.7	1.6	1.3	1.0	1.1	0.9
NIEL (1 MeV n_{eq}/cm^2)	4.9×10^{9}	2.5×10^{9}	2.1×10^{9}	2.0×10^{9}	1.5×10^{9}	8.3×10^{8}	1.0×10^{9}	4.7×10^{8}
TID (Rad)	1.4×10^{2}	8.0×10^{1}	6.9×10^{1}	6.3×10^{1}	4.8×10^{1}	2.7×10^{1}	3.3×10^{1}	1.5×10^{1}

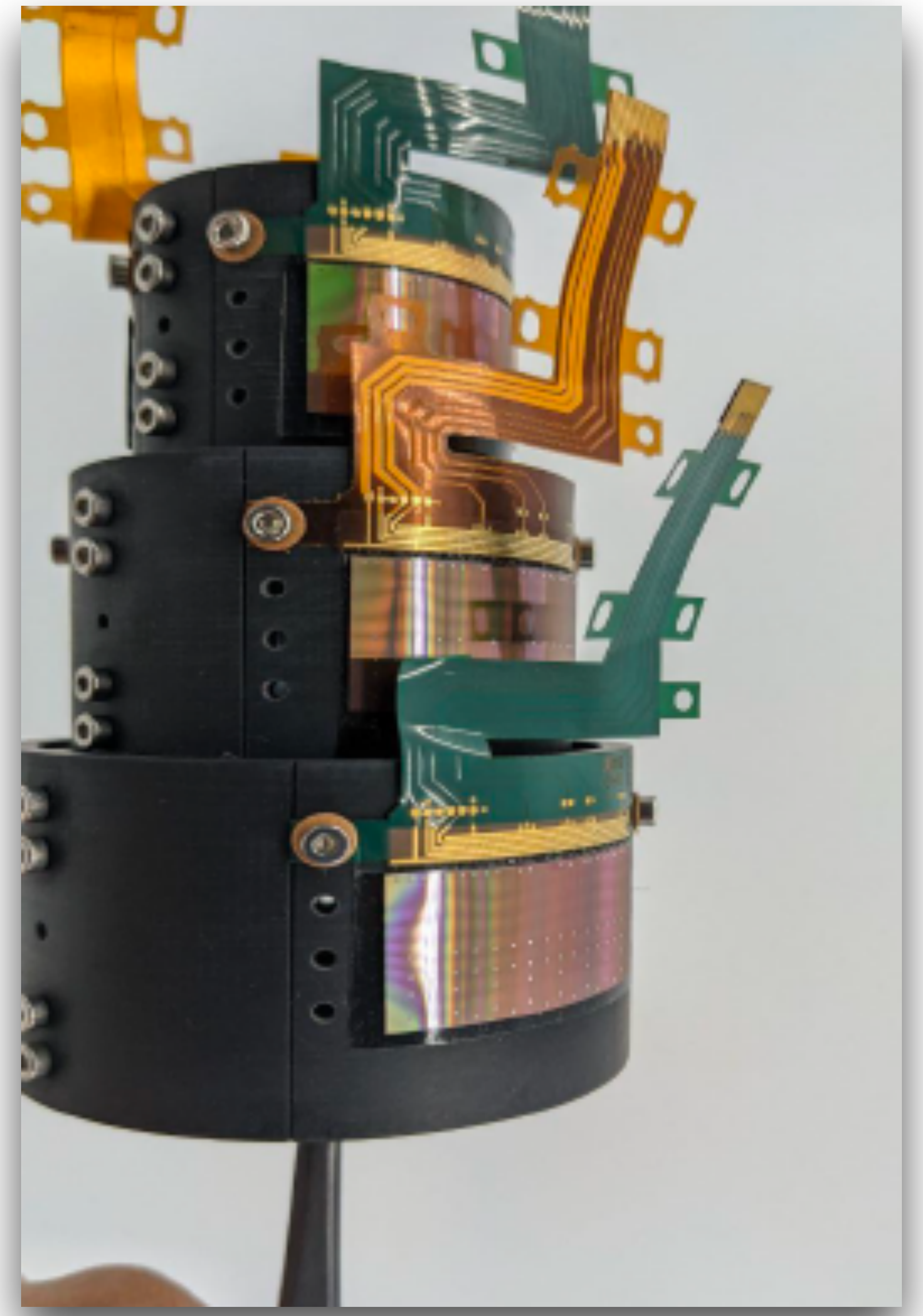
Table 1: Projected LHC performance: For various collision systems, we list the peak luminosity L_{AA}, the average luminosity $\langle L_{AA}\rangle$, the luminosity integrated per month of operation $\mathscr{L}_{AA}^{month}$, also rescaled to the nucleon–nucleon luminosity $\mathscr{L}_{NN}^{month}$ (multiplying by A^2). Furthermore, we list the maximum interaction rate R_{max}, the minimum bias (MB) charged particle pseudorapidity density $dN/d\eta$, and the interaction probability μ per bunch crossing. For the radii 0.5 cm and 1 m, we also list the particle fluence, the non-ionising energy loss, and the total ionising dose per operational month (assuming a running efficiency of 65%).

Toward ALICE3: Radiation hardness

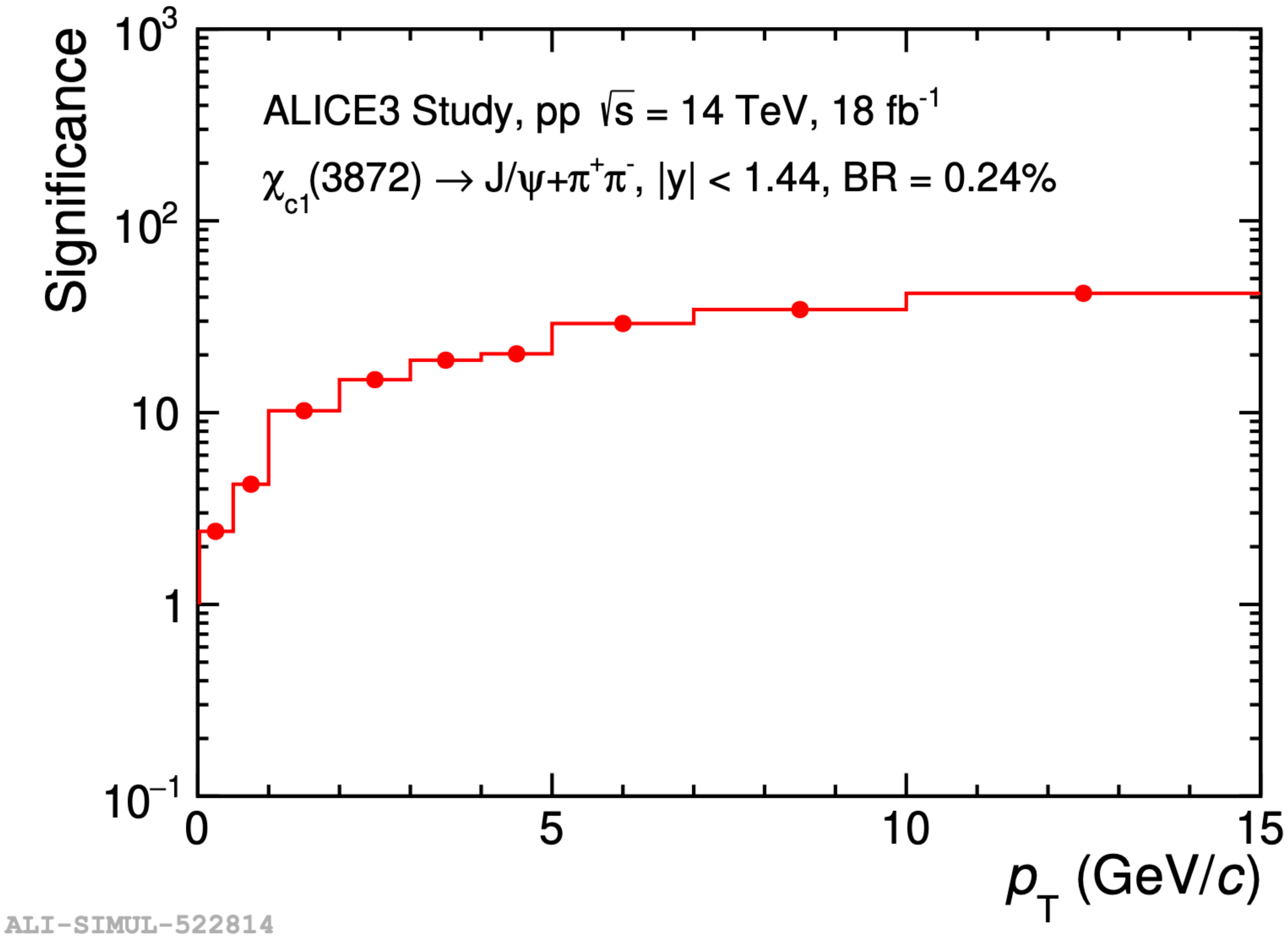
- Test structures (at room temperature) irradiated till **$1.5\ 10^{15}$ 1 MeV n_{eq}/cm^2**
- Still > 95% efficiency at intermediate low threshold at 20 degree celsius!



(b) Sensors irradiated to different levels.



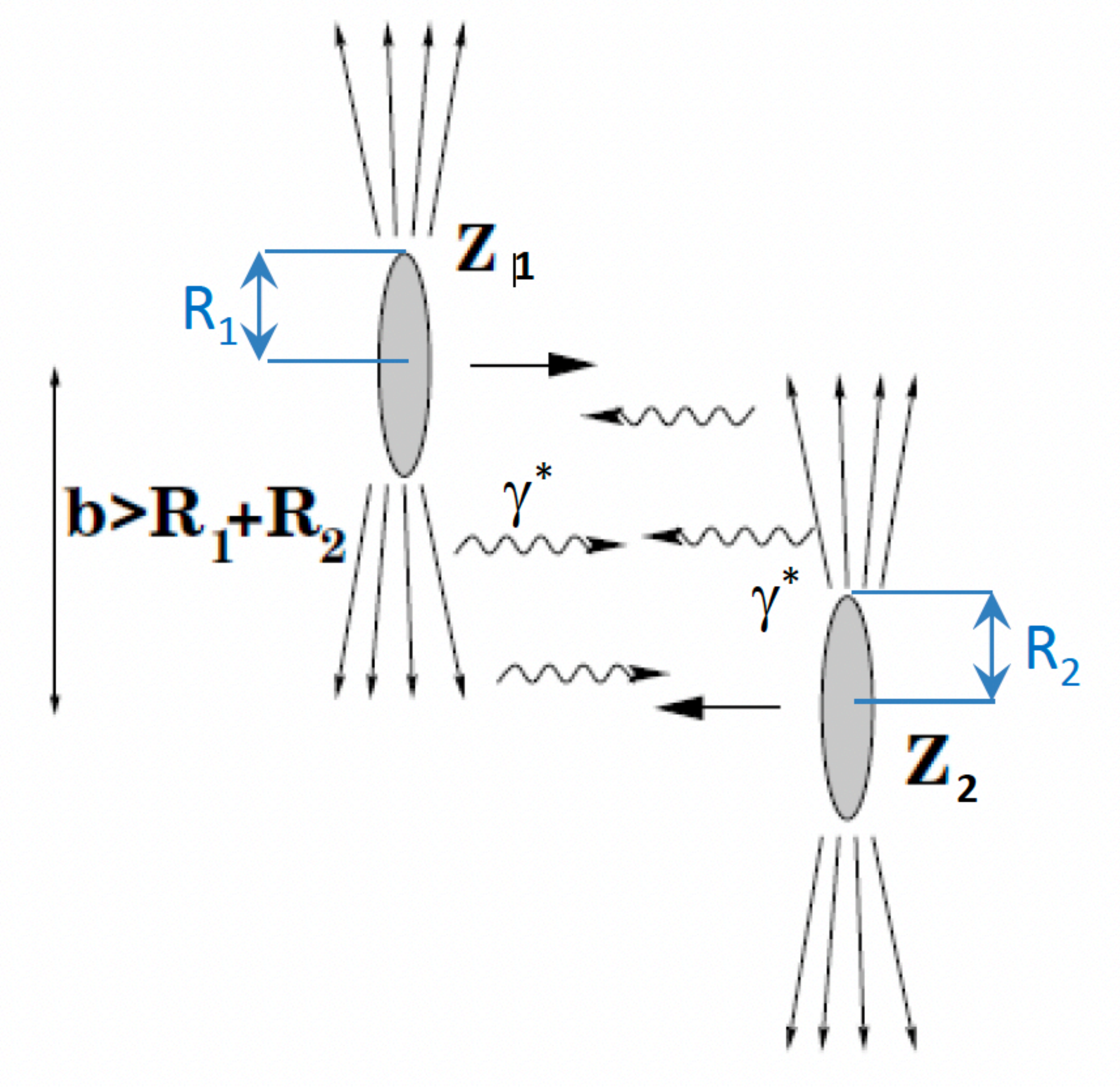
$X_{c1}(3872)$



Significance
ALICE3 Study, pp √s = 14 TeV, 18 fb⁻¹
χc1(3872) → J/ψ+π⁺π⁻, |y| < 1.44, BR = 0.24%
10³
10²
10
1
10⁻¹
0
5
10
15
pT (GeV/c)
ALI-SIMUL-522814

Ultra-preipheral collisions (UPC)

- Impact parameter $b > R1 + R2$
  - Hadronic interactions suppressed
- Photon induced reactions:
  - Well described in Weizsacker-Williams approximation
  - Photon flux Z^2 ($Z_{Pb} = 82$)
  - Large gamma-induced interaction cross-section
- Rapidity gap(s)



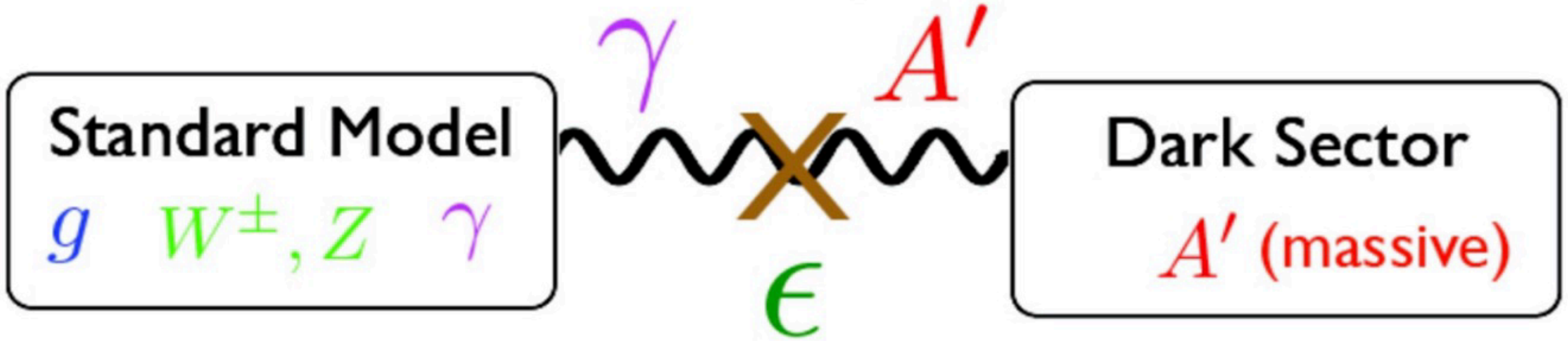
Dark Photons

$$L = L_{SM} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + m^2_{A'}A'_\mu A'^\mu + \frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu}$$

Standard Model Lagrangian

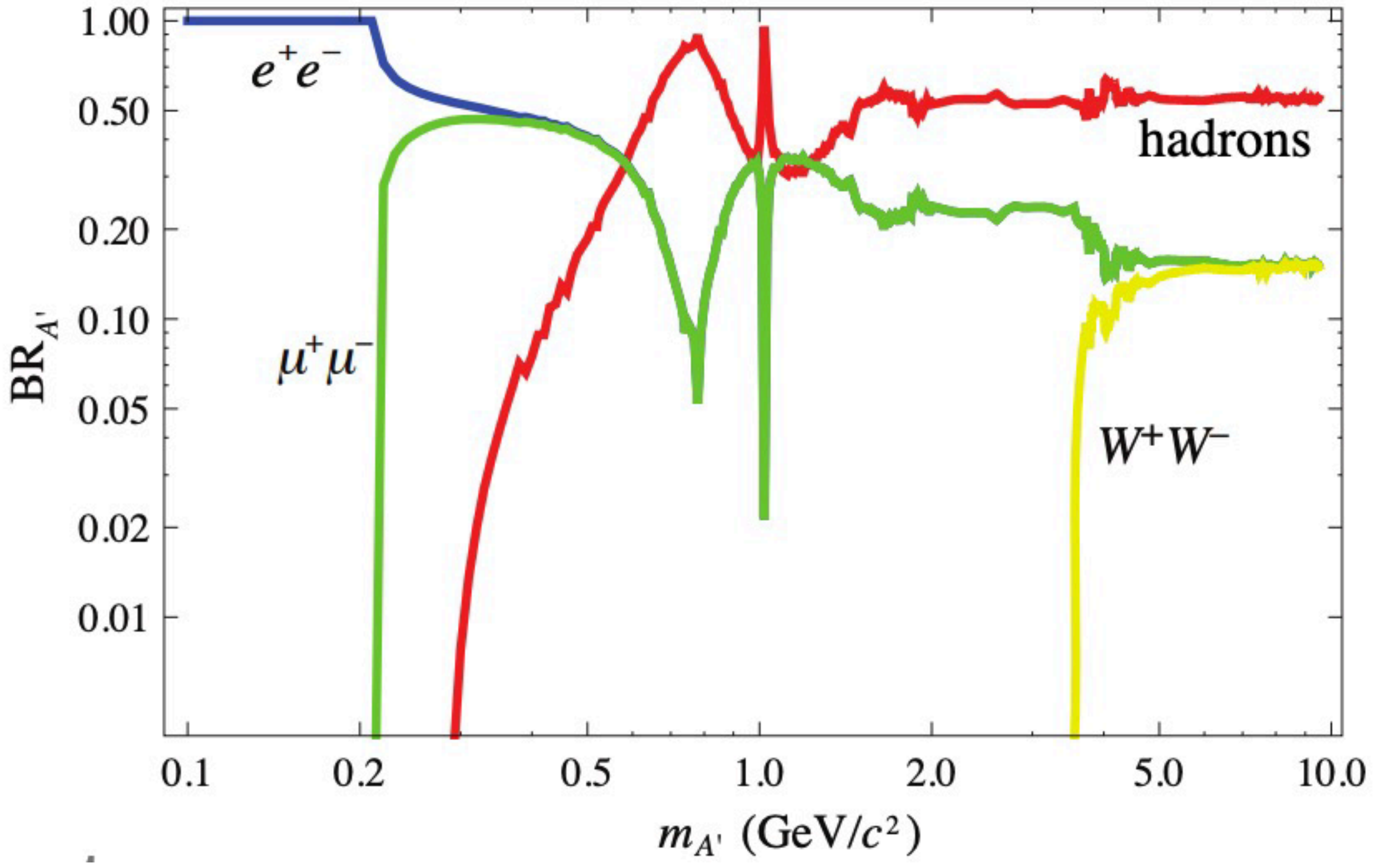
Additional U(1) symmetry describing the new force carried by a massive vector boson, ***the Dark photon A'***

Kinetic mixing term with the ***standard photon γ***

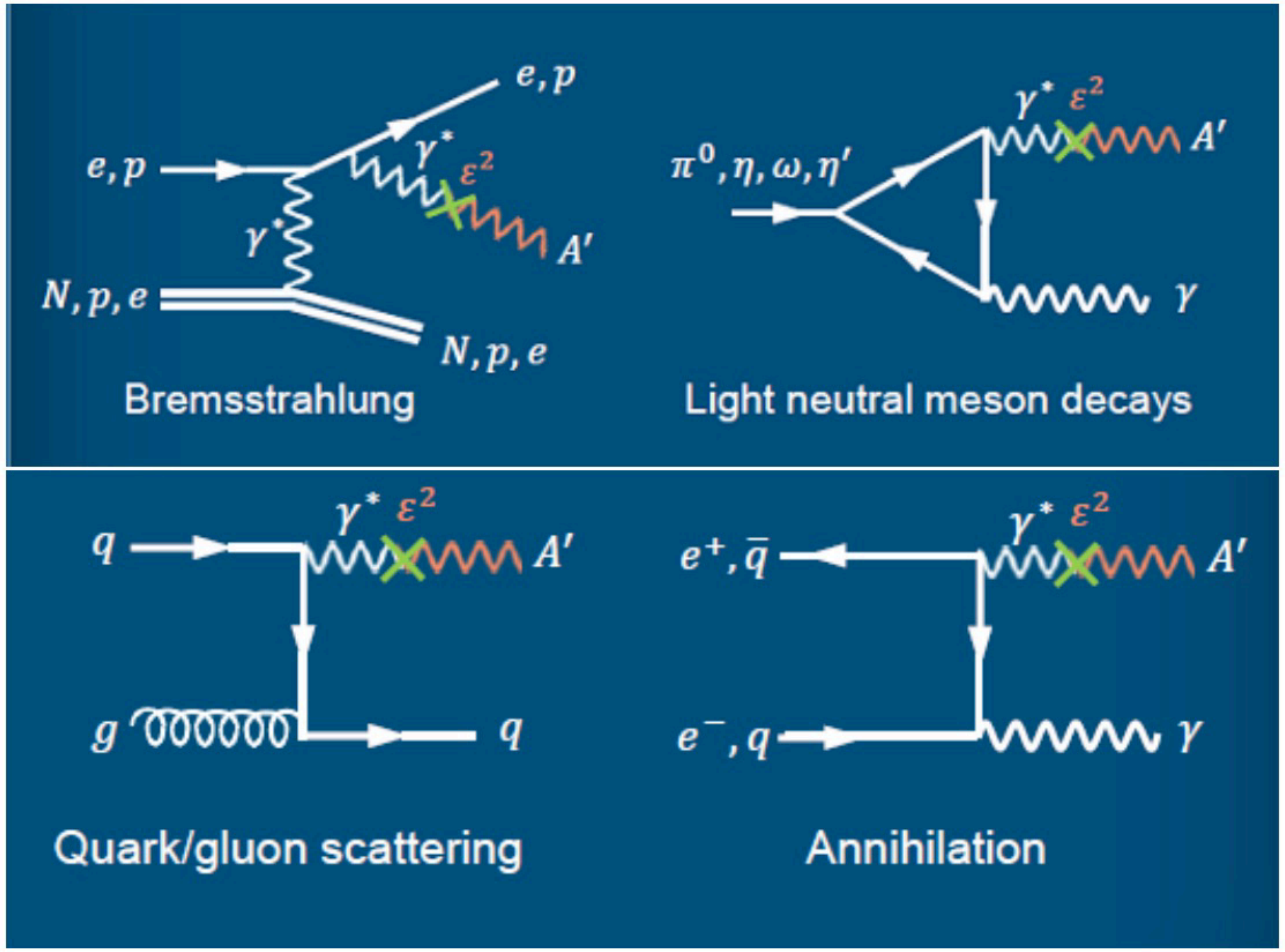


Dark Photons

A' visible decays assuming universal coupling εq (q = charge)



Gabriele Piperno - PANIC 2017



R. Jacobsson (CERN) LHC Operations Workshop, Evian, 2019

τ pair production

- τ pair photoproduction in Pb-Pb UPC cross section scales with Z^4
- Suppression by a factor $O(\alpha_{em}^2)$
- Photon induced reactions:
  - Well described in Weizsacker-Williams approximation
  - Photon flux Z^2 (Z_{Pb}= 82)
  - Large gamma-induced interaction cross-section
- Sensitive to anomalous magnetic moment $a_l = (g-2)_l/2$

a_τ: run 3+4 projections