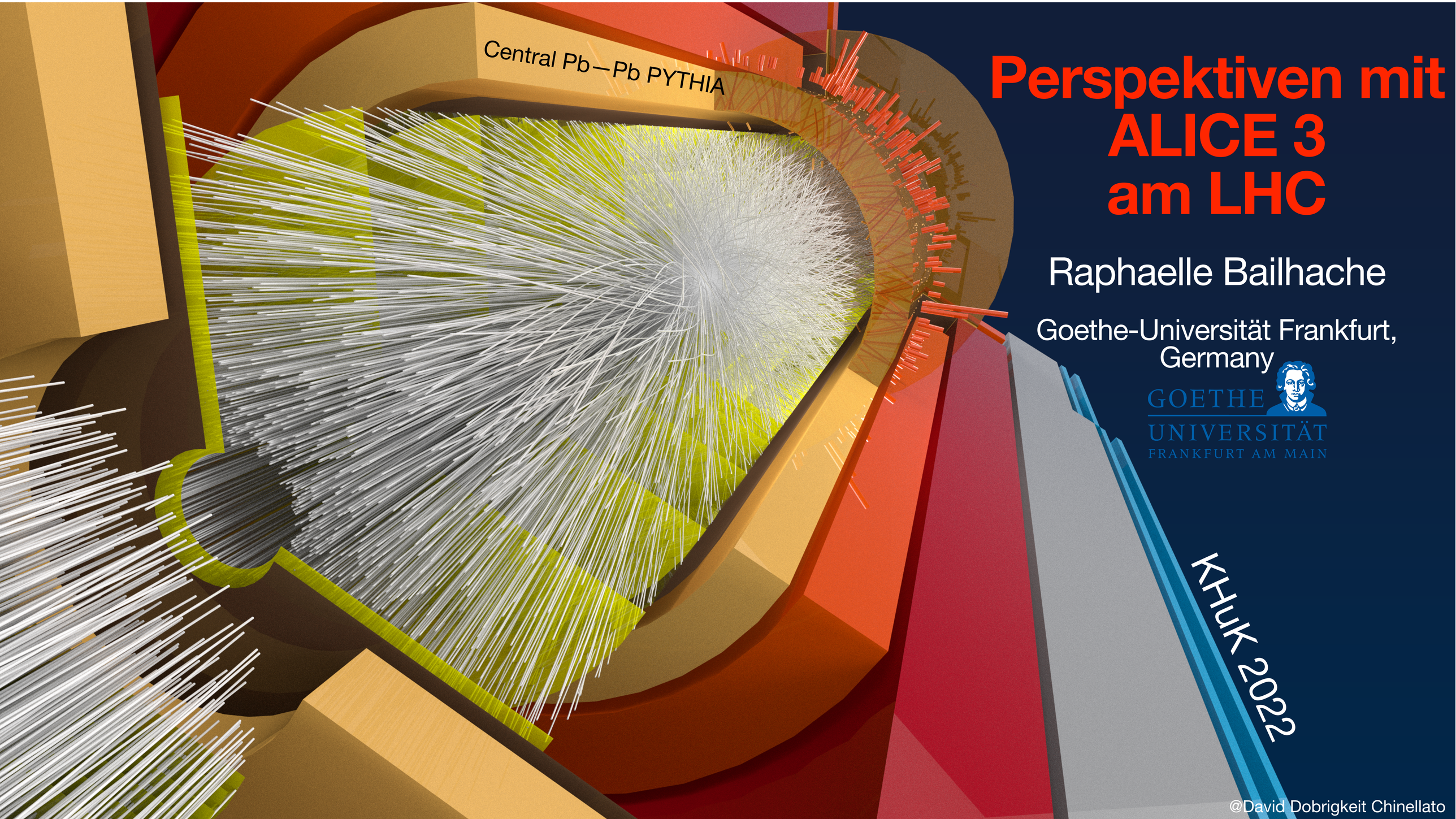


Perspektiven mit ALICE 3 am LHC

Raphaelle Bailhache

Goethe-Universität Frankfurt, Germany

KHuK 2022

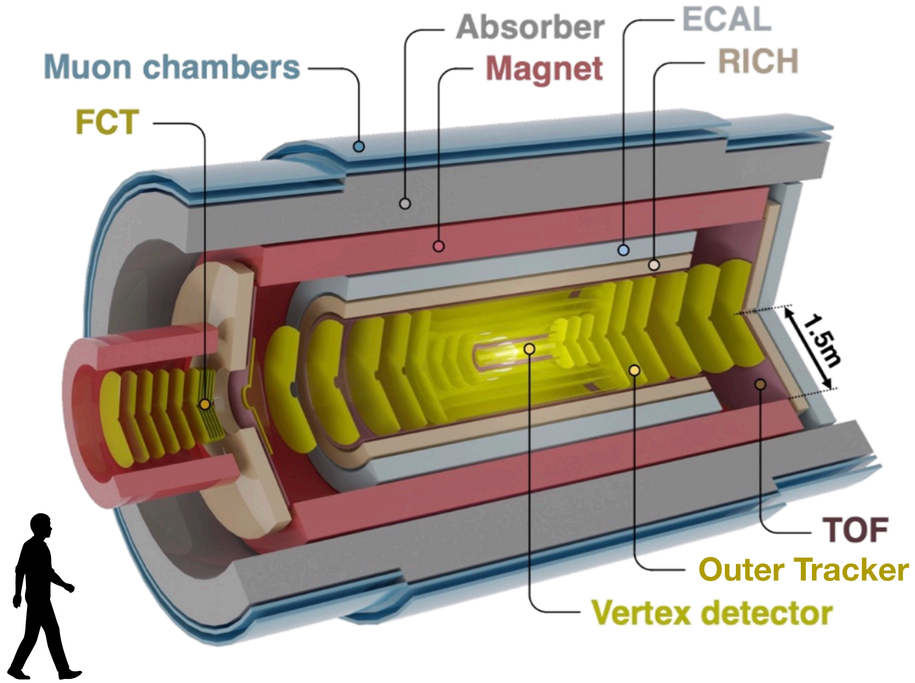
@David Dobrigkeit Chinellato

ALICE timeline

High luminosity for ions | HL-LHC | Higher luminosities for ions

Run 1 2009 - 2013	Run 2 2015 - 2018	Run 3 2022 - 2025	Run 4 2029 - 2032	Run 5	Run 6
ALICE 1		ALICE 2	ALICE 2.1 upgrade	ALICE 3 upgrade	

See talk of Yvonne Pachmayer



Exploit the high luminosity potential of the LHC !
Address remaining fundamental questions

ALICE 3

→ First ideas at Heavy-Ion town meeting 2018 D.Adamova et al. ArXiv:1902.01211

→ **Letter of Intent: March 2022** ALICE CERN-LHCC-2022-009

- Recommended by the LHCC
- Strong German contribution
- Broad interest expressed by the international community

→ **Next step: scoping document (end of 2023)**

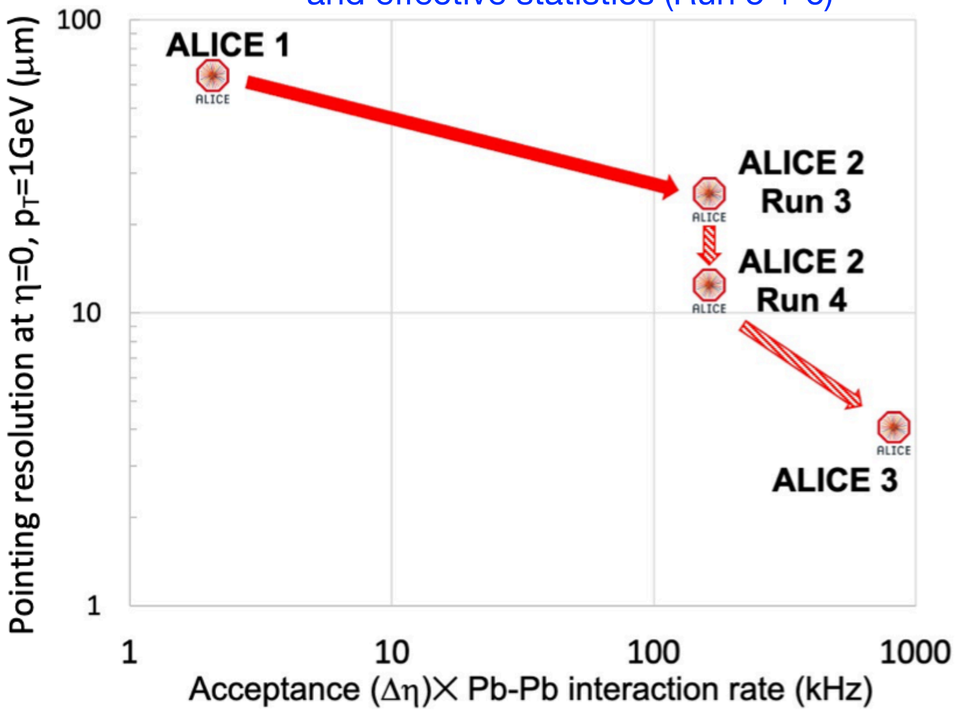
- First funding scheme

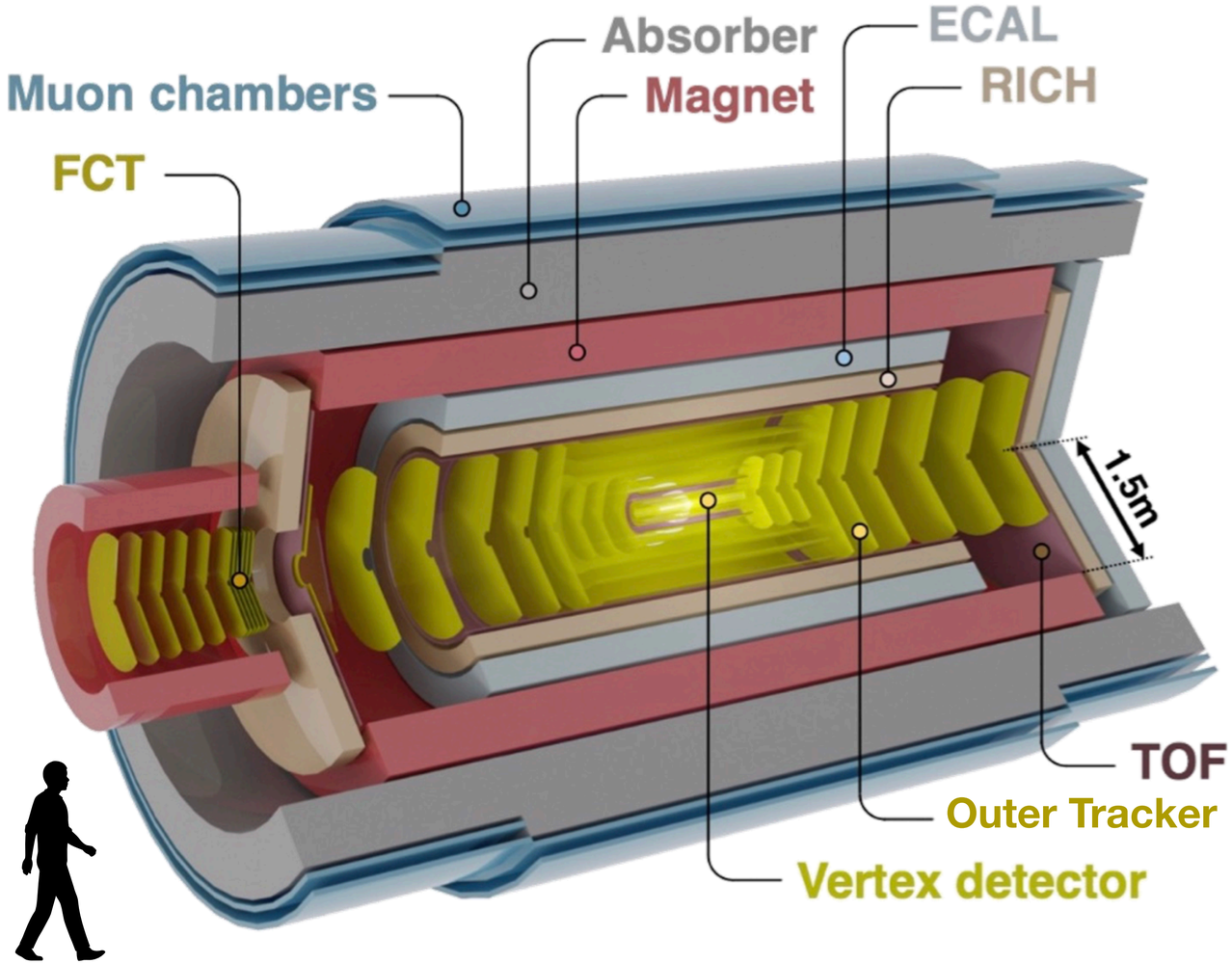
Major upgrade | Intermediate upgrade | New detector

ALICE 3

- Compact all-silicon tracker with high-resolution vertex detector
  - First layer at 5mm (ALICE 2 Run 4: 18 mm)
- Particle identification $\gamma, e^{\pm}, \mu^{\pm}, K^{\pm}, \pi^{\pm}$
  - Over large acceptance ($-4 < \eta < 4$)
  - Down to very low p_T

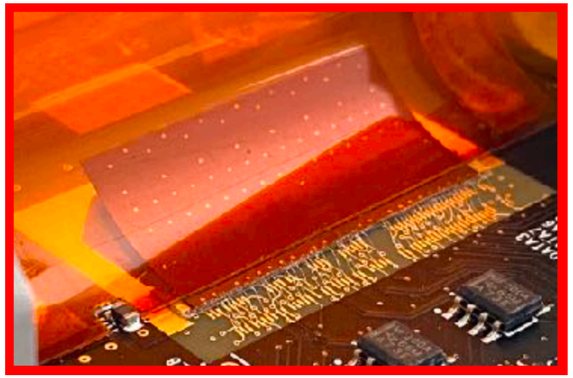
Improved pointing resolution
and effective statistics (Run 5 + 6)





D.Adamova et al. ArXiv:1902.01211
ALICE CERN-LHCC-2022-009

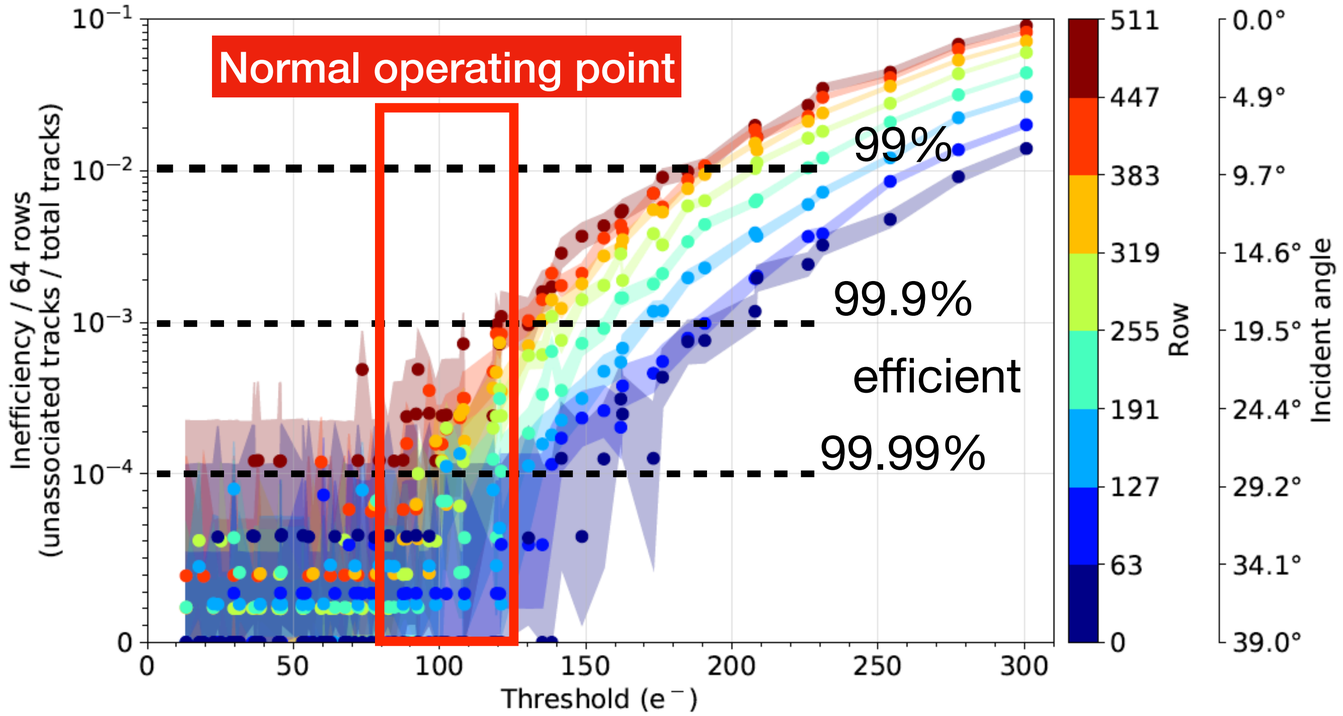
Super-light vertex detector



Need latest silicon technologies being developed by ALICE !
Curved wafer-scale ultra-thin (< 50 μm) silicon sensors

- Perfectly cylindrical layers
  with Tower Partners Semiconductor 65 nm
- No need of big support structures
  → Reduce material budget by $O(10)$
- Verified that it works !
  with Desy testbeam facility

Technology relevant for other fields…..



NIM-A 1028, 2022, 166280

ALICE 3 detector concept

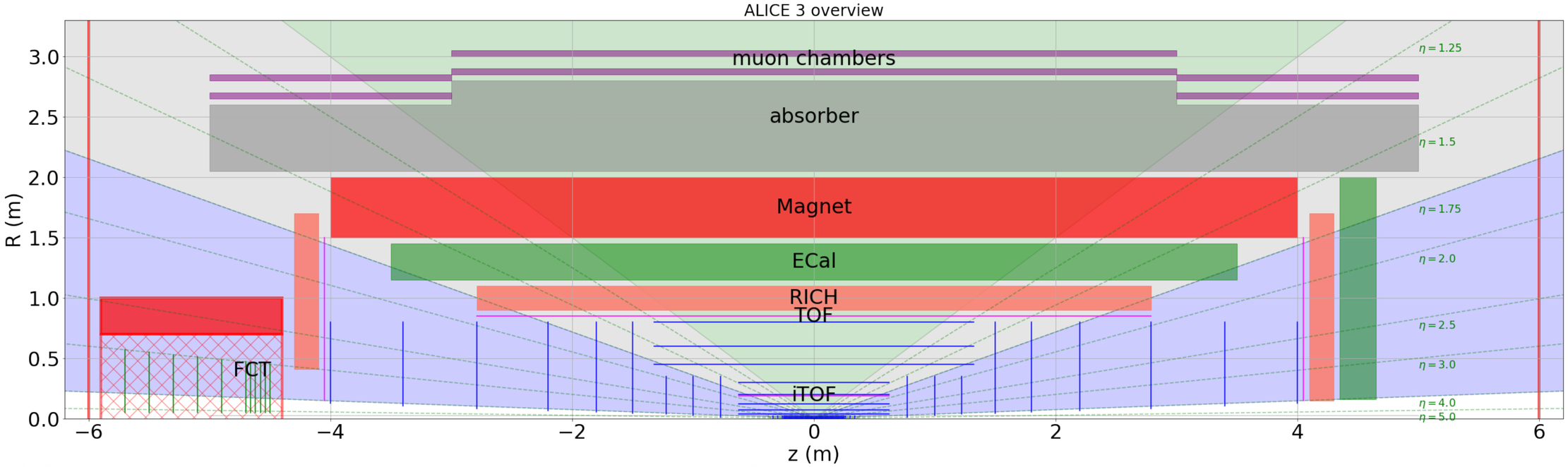
- **Vertex tracker: excellent pointing resolution**
  Needed for heavy-flavour (rejection/reconstruction)
  - **Vertex detector** (3 first layers/disks)
    Retractable IRIS tracker inside of the beam pipe
  - **Outer tracker** (8 layers/ 2x9 disks)

- **Time-of-Flight and Ring-Cherenkov detectors**
  - Hadron identification for heavy-flavour hadron decays, and net-baryon measurements
  - Electron identification (with ECal) for e^+e^-

- **Electromagnetic calorimeter + Photon conversion method**
  γ detection for P-wave quarkonia, γ radiation, jets

- **Muon identification**
  J/ψ detection for P-wave quarkonia, exotic hadrons

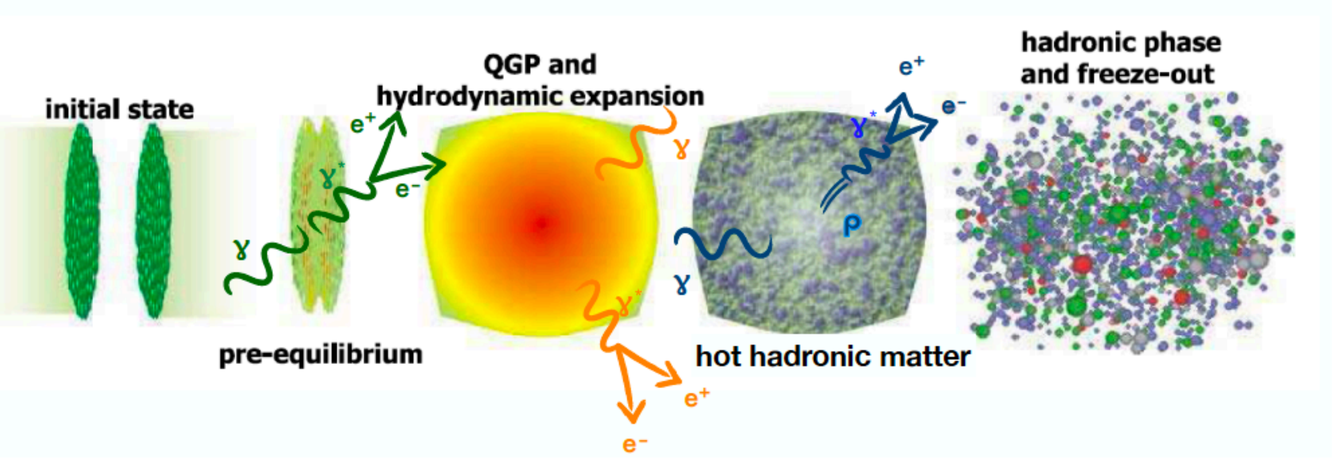
- **Forward Conversion Tracker**
  Ultra-soft photons



ALICE CERN-LHCC-2022-009

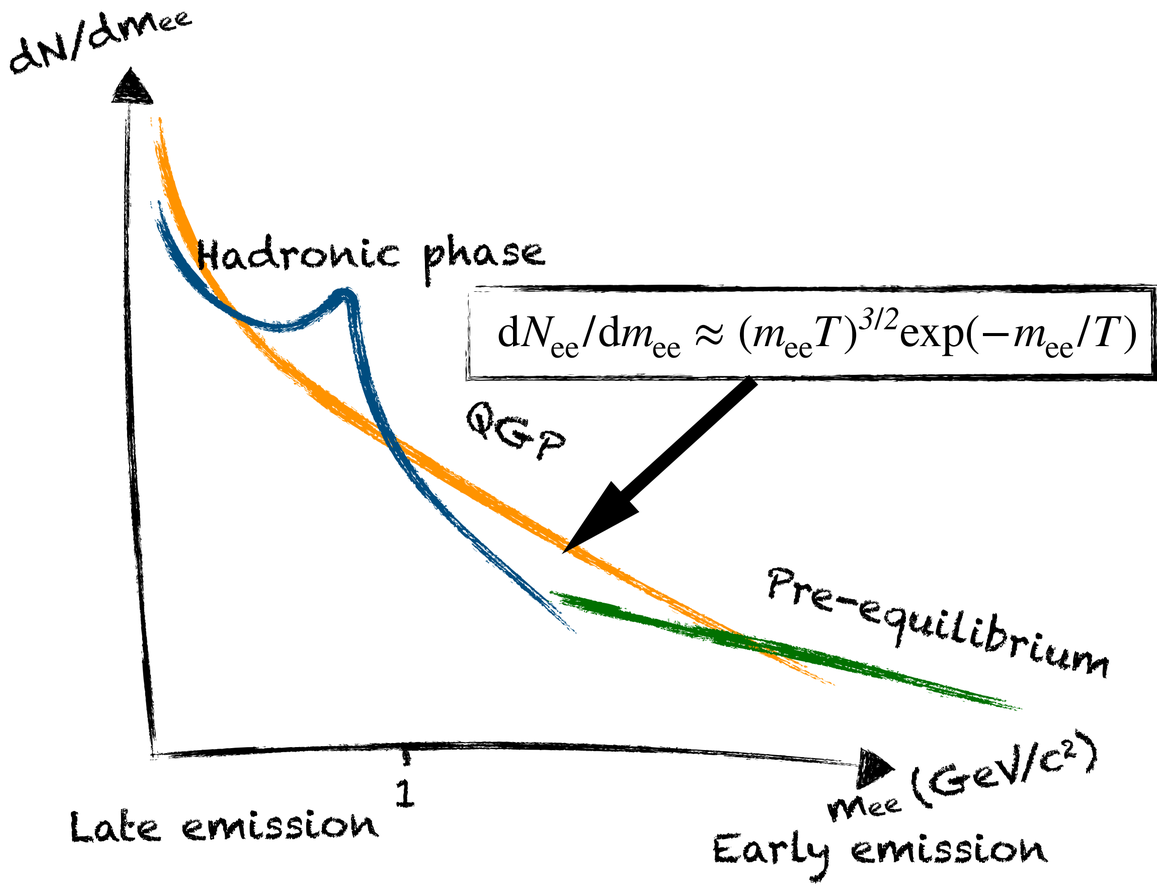
Selected physics topics
Electromagnetic radiation

All ideas proposed by German groups !



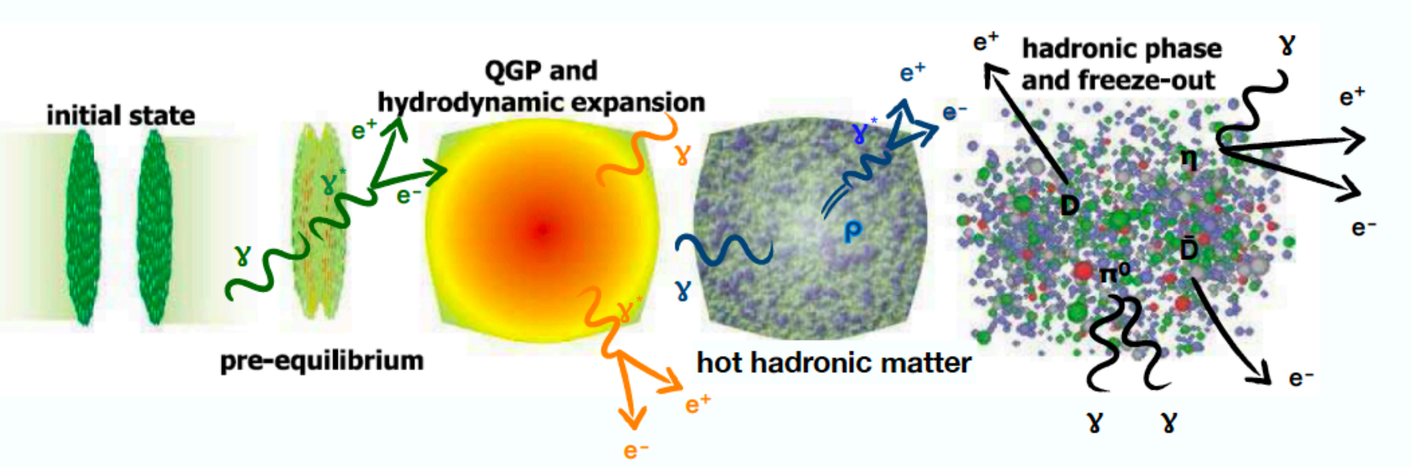
Thermal radiation from the QGP
→ Access to early average QGP temperature

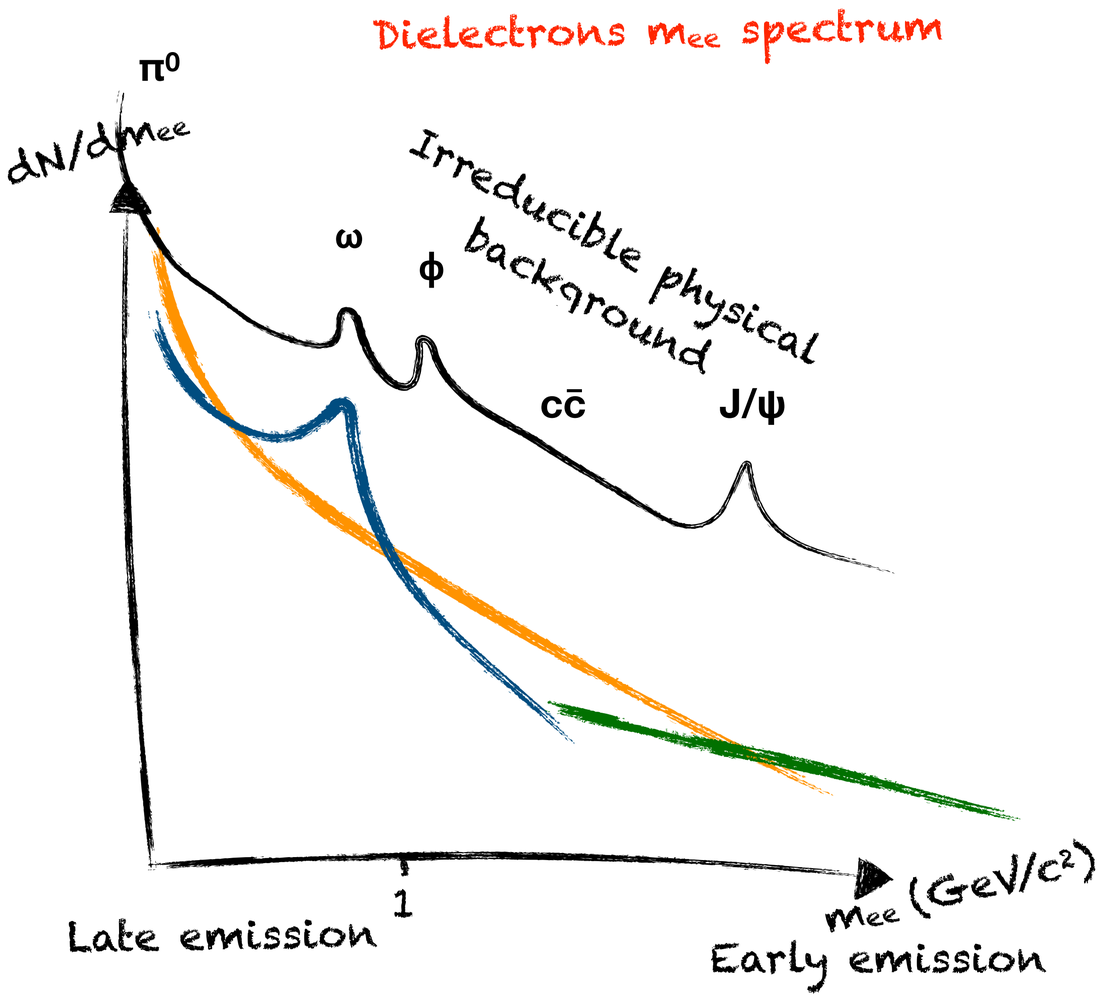
Dielectrons m_{ee} spectrum



$$dN_{ee}/dm_{ee} \approx (m_{ee}T)^{3/2}\exp(-m_{ee}/T)$$

Selected physics topics
Electromagnetic radiation



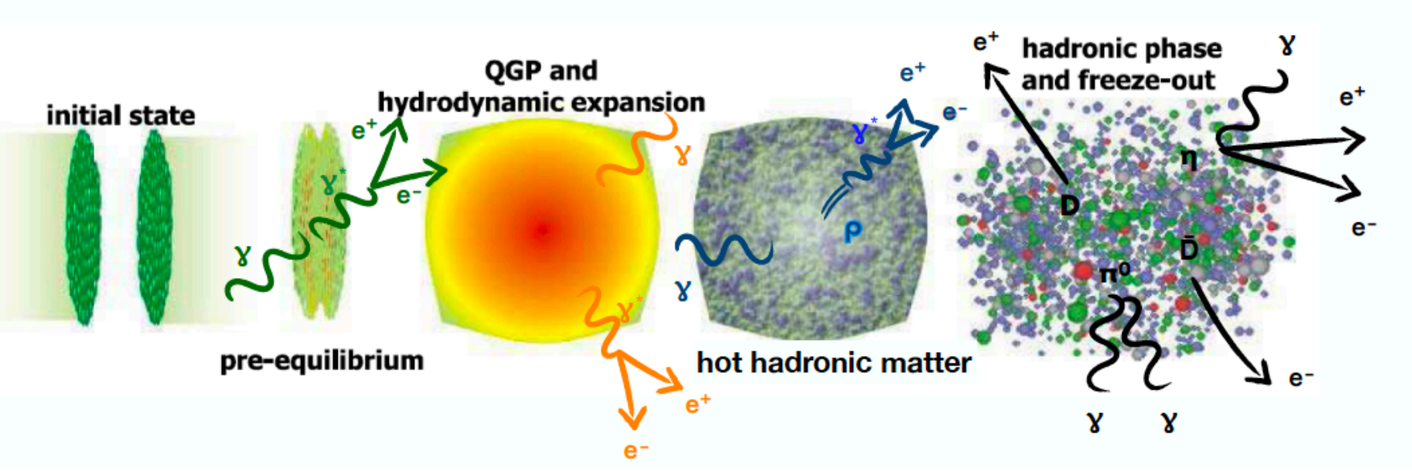


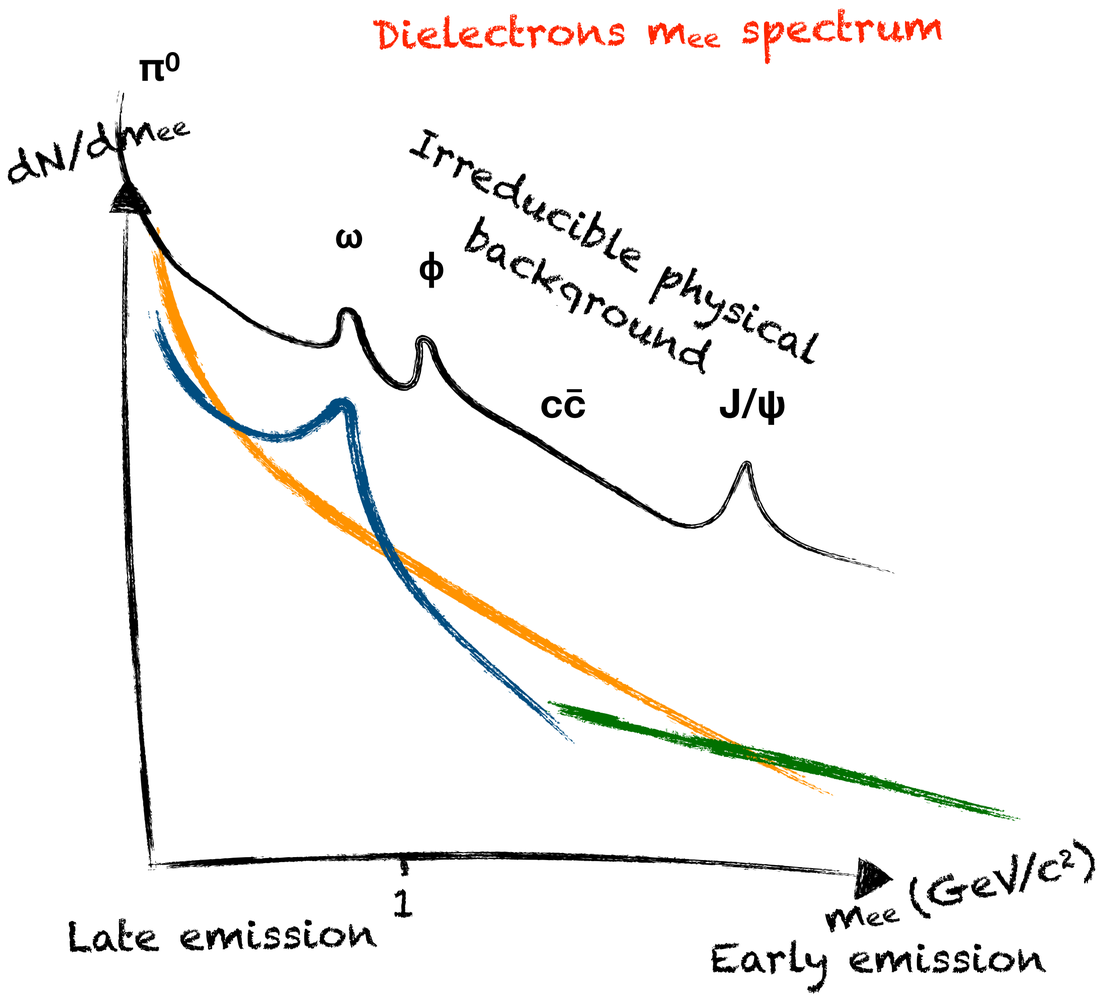
Thermal radiation from the QGP
→ Access to early average QGP temperature

Real challenge at LHC energies !

Large background from heavy-flavour hadron decays ($c\bar{c}$)
→ Very efficiently suppressed thanks to pointing resolution

Selected physics topics
Electromagnetic radiation





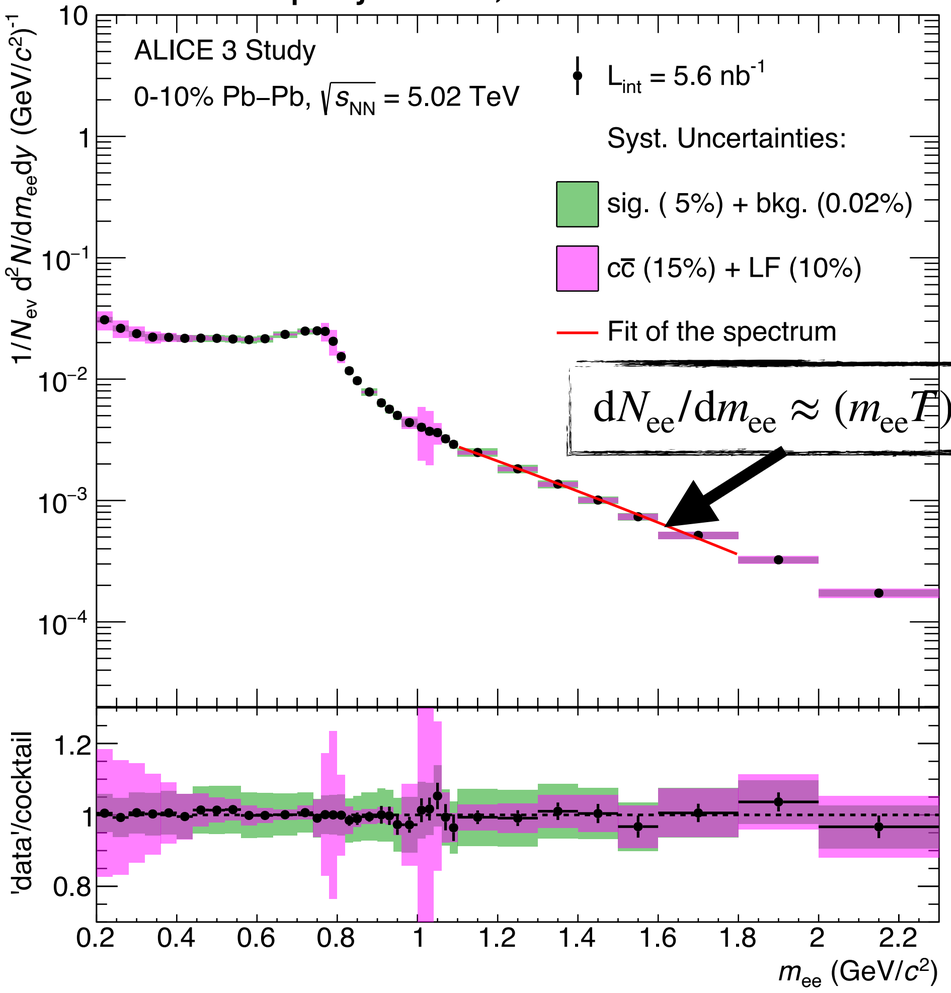
Thermal radiation from the QGP
→ Access to early average QGP temperature

Real challenge at LHC energies !

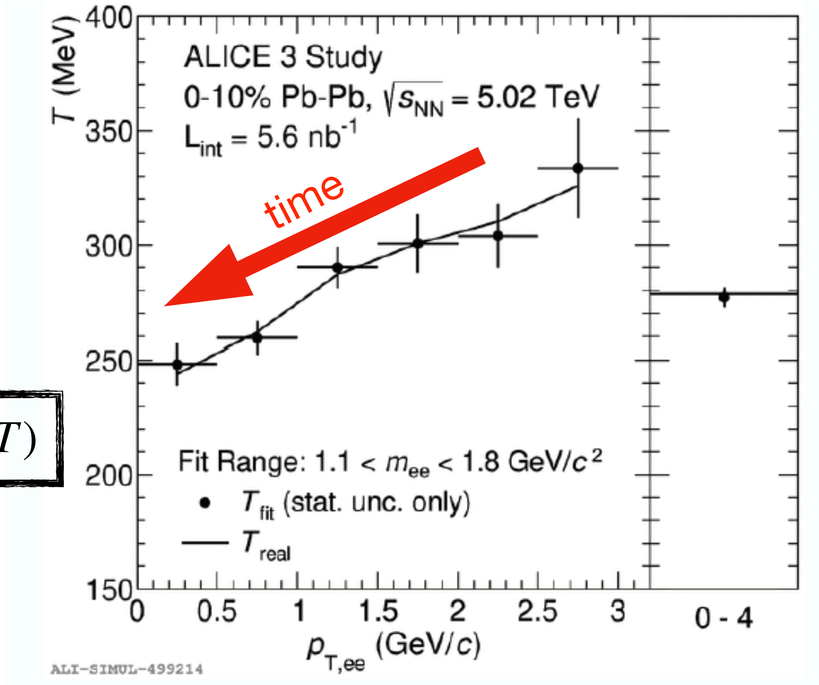
Large background from heavy-flavour hadron decays (c$\bar{c}$)
→ Very efficiently suppressed thanks to pointing resolution
Large combinatorial background
→ Very efficiently suppressed thanks to low p_{T} tracking + material budget

Selected physics topics
Electromagnetic radiation

Thermal dielectron m_{ee} spectrum
ALICE 3 projection, one month Pb—Pb



$$dN_{ee}/dm_{ee} \approx (m_{ee}T)^{3/2}\exp(-m_{ee}/T)$$



Fit of m_{ee} spectrum →Average temperature

New with ALICE 3: fit for different $p_{T,ee}$ windows

→ **Probe time dependence of fireball *T***
Not accessible before Run 5

Complementary measurements with real photons

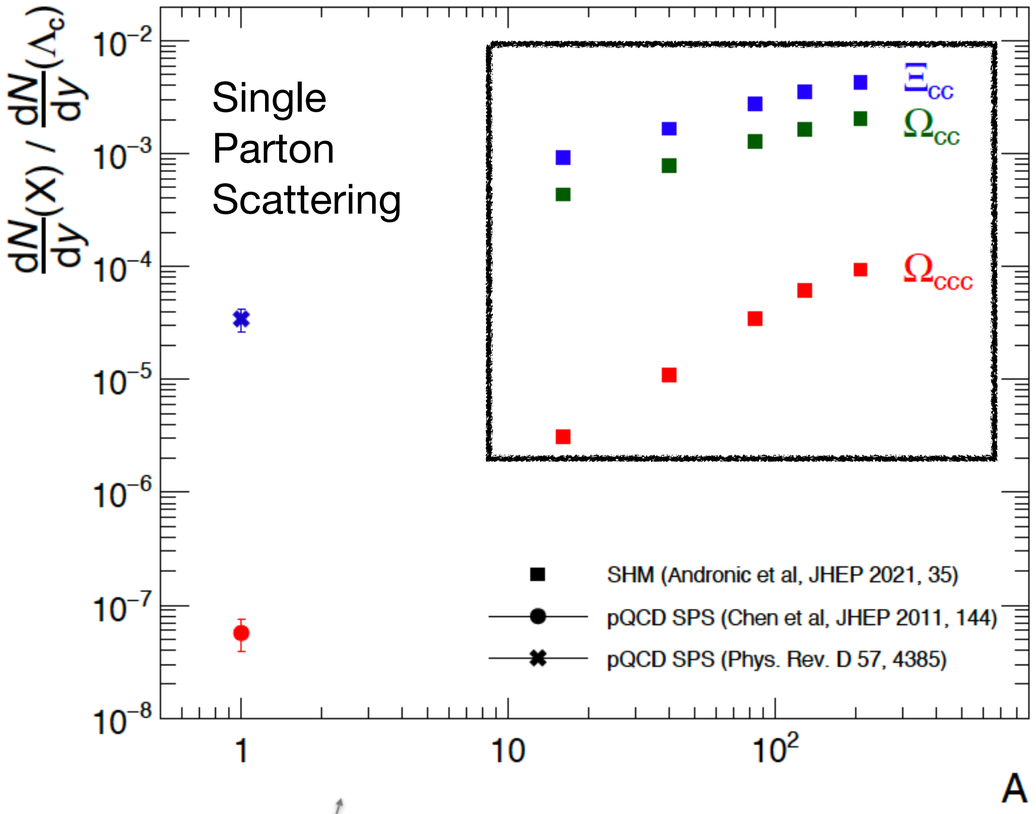
Selected physics topics
Deconfinement and hadronization

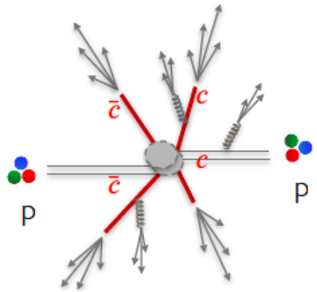
Until end of Run 4: single-charm hadron measurements
New with ALICE 3: multi-charm baryons

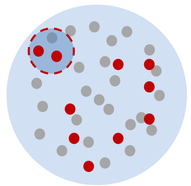
Unique probe of hadron formation !

- Require multiple charm quarks
- **In pp:** very small contribution from single parton scattering
- **In nuclear collisions:**
  High density of charm quarks
  → Much larger multi-charm population predicted by Statistical Hadronisation Model
  Determine the degree of thermalisation of c quarks

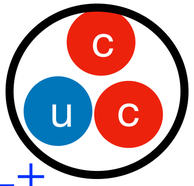
Nucleus-nucleus collisions







Selected physics topics
Multi-charm baryon reconstruction



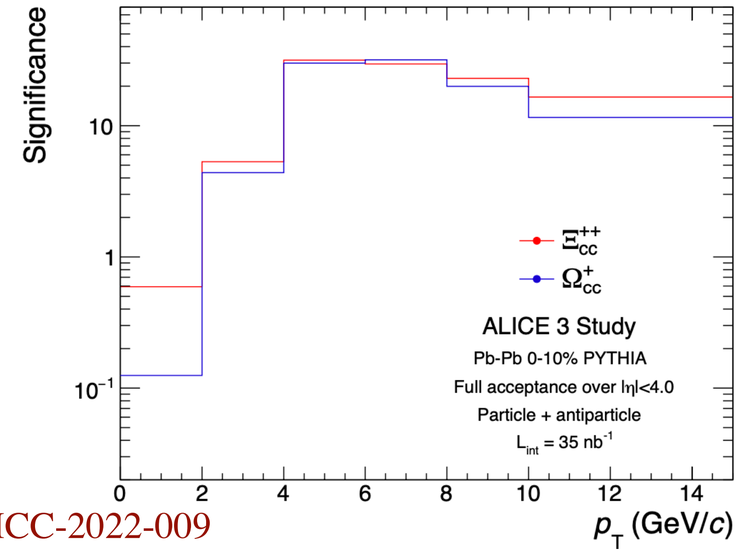
$$\Xi_{cc}^{++} \rightarrow \Xi_c^{+} + \pi^{+}$$
$$\Xi_c^{+} \rightarrow \Xi^{-} + 2\pi^{+}$$

First ALICE 3 tracking layer at 5 mm:

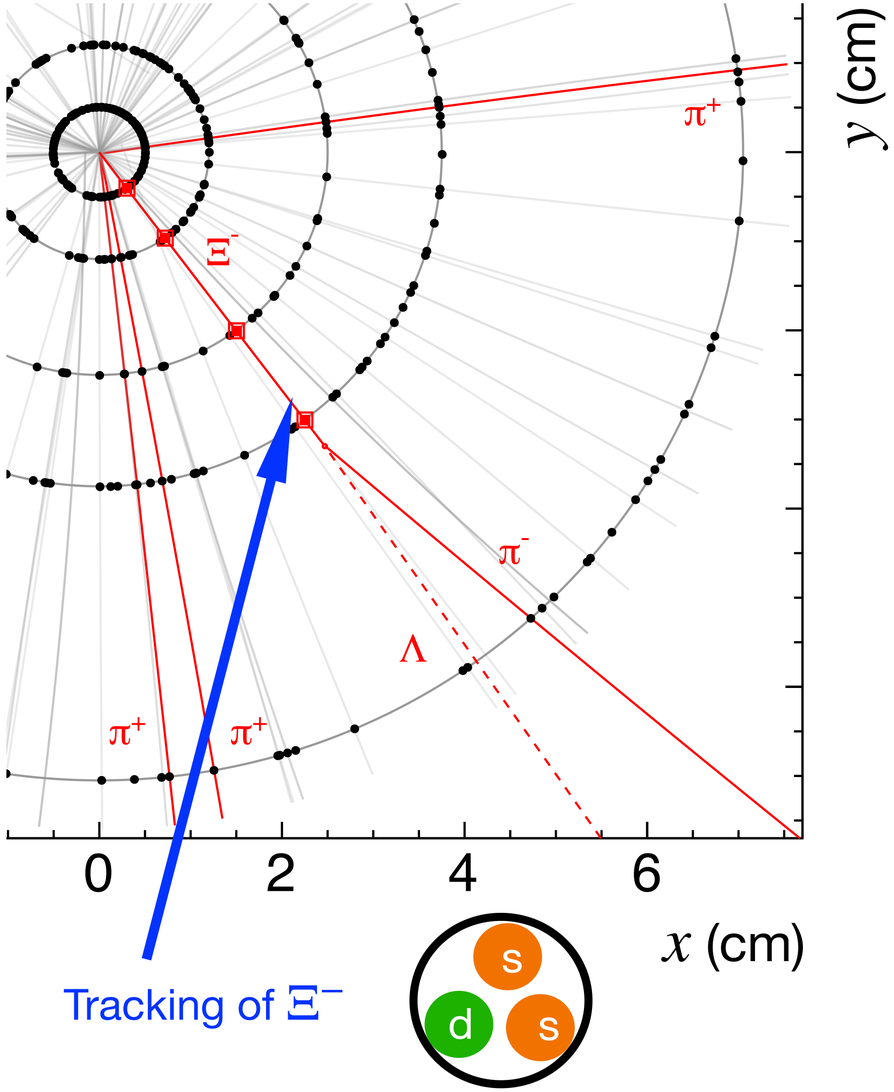
- Track strange baryon (Ξ^{-}) before it decays
- High selectivity thanks to pointing resolution of Ξ baryon

→ **Unique experimental access with ALICE 3 in Pb—Pb collisions**

Expected significance for Ξ_{cc}^{++} , Ω_{cc}^{+} in Pb—Pb

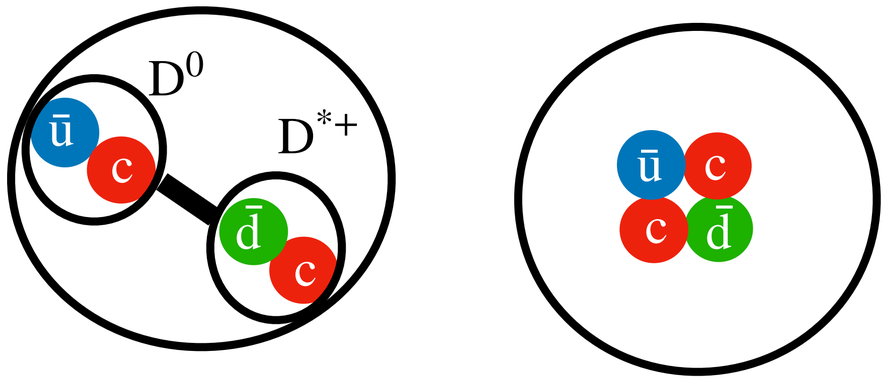


One reconstructed Ξ_{cc}^{++} decay in the ALICE 3 tracker



Selected physics topics
Nature of exotic bound states

T_{cc}^{+} discovered
in July 2021 by LHCb CERN-EP-2021-165



Distinguish between the two cases using two particle momentum correlation

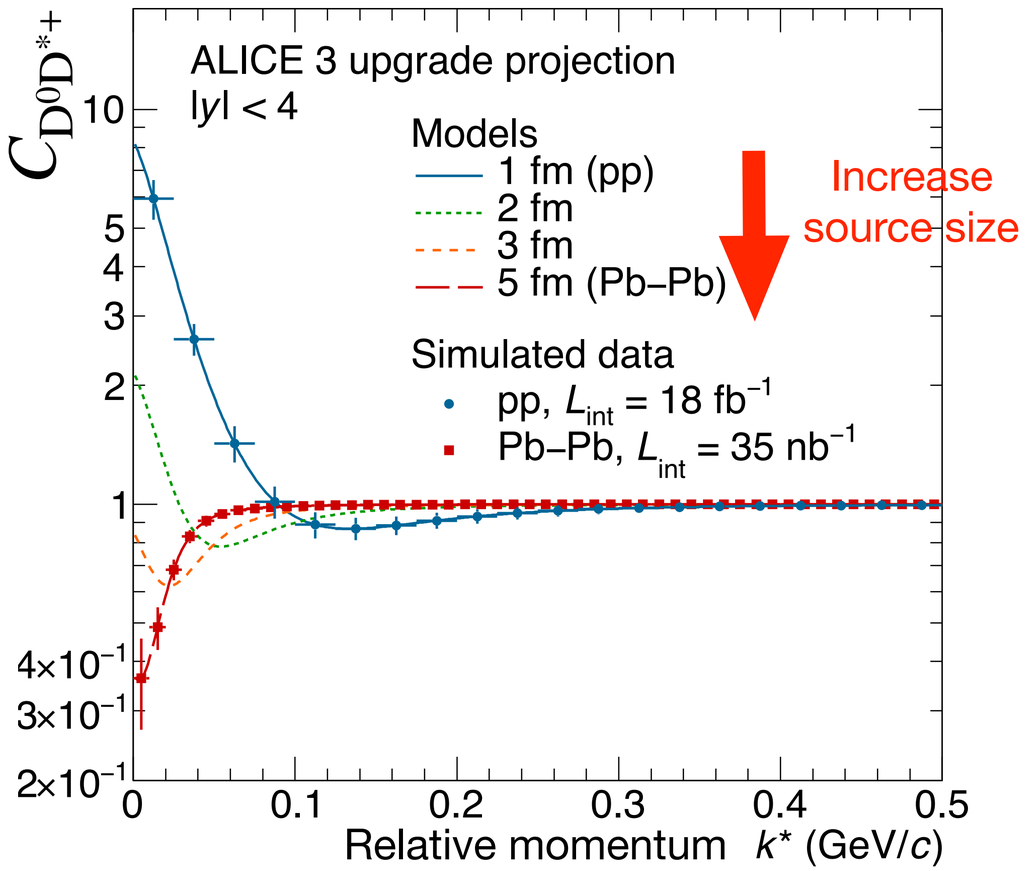
$$C(k^*) = \int d^3r^* S(r^*) |\Psi(k^*, r^*)|^2$$

connected to source function/size and two-particle wave function

Behaviour of $C(k^*)$ → Get information on interaction potential

Possible with ALICE 3 thanks to pointing resolution + large acceptance

Projection for D^0D^{*+} momentum correlation



$$k^* = 1/2\,|\mathbf{p}^*_{D^0} - \mathbf{p}^*_{D^{*+}}|$$

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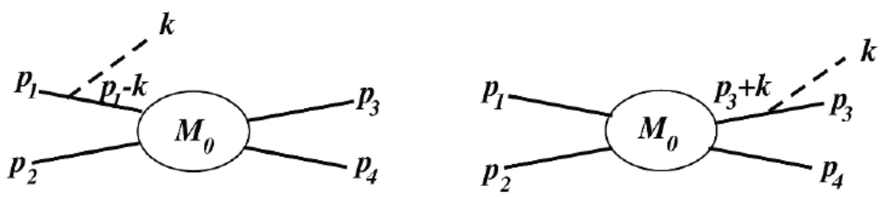
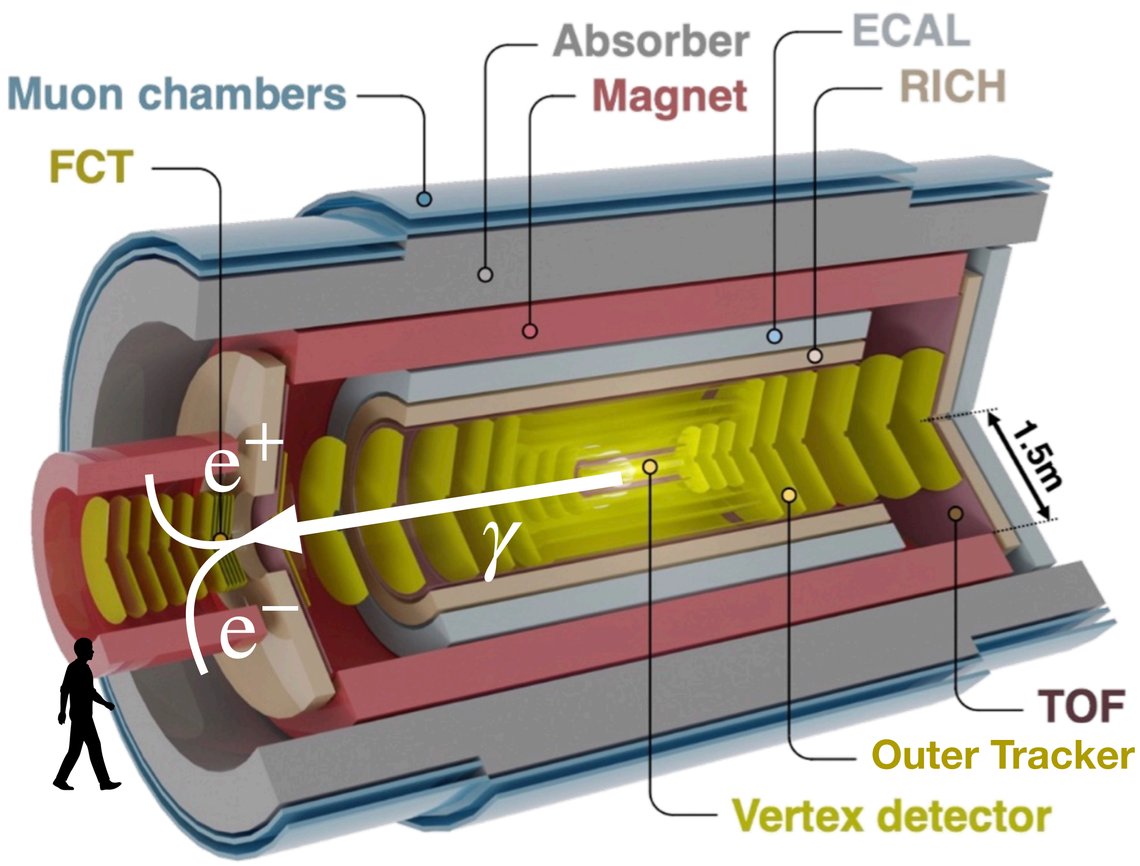
Selected physics topics
Ultra-soft γ production

$p_1+p_2 \rightarrow p_3+p_4+k.$



γ produced via inner bremsstrahlung

- **Not understood**
  - Cross section computable with Low-theorem
  - **Large excess observed at lower** $\sqrt{s}$ in association with hadrons
- **Systematic study proposed with ALICE 3**
  - Dedicated Forward Conversion Tracker
  - Measurements planned in different colliding systems:
    - $\mathrm{pp} \rightarrow \mathrm{pp}\pi^+\pi^-\gamma$
    - $\mathrm{pp} \rightarrow \mathrm{pp}J/\psi\gamma \rightarrow \mathrm{pp}\mathrm{e}^+\mathrm{e}^-\gamma$ ($\approx$ purely leptonic final state)
    - Inclusive pp collisions (for $\neq$ charged particle multiplicity)



Forward Conversion Tracker (FCT, $3 \leq \eta \leq 5$)
Measure γs with $1 \leq p_{\mathrm{T}} \leq$ 10 MeV/c

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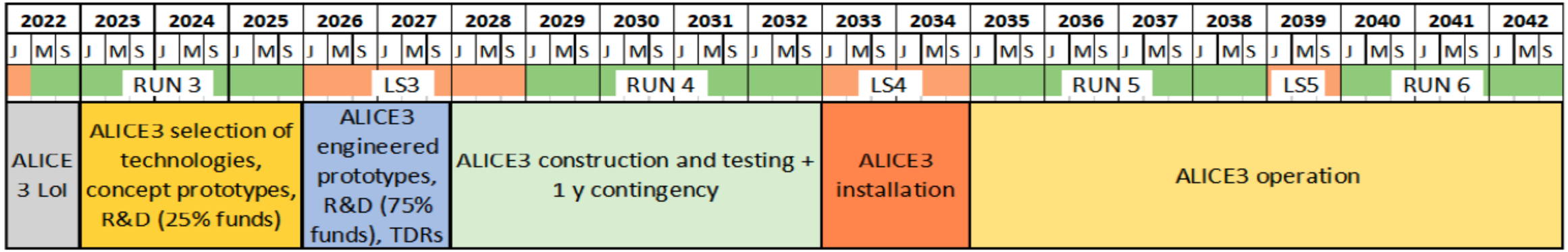
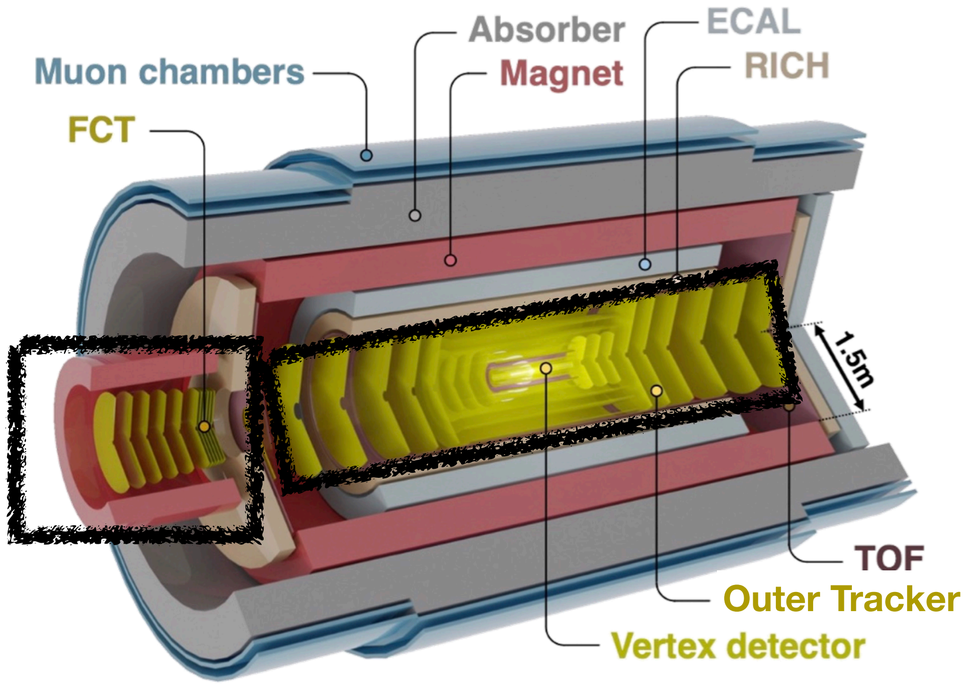
ALICE 3 timeline



Planned contributions in Germany:

→ Outer Tracker

→ Forward Conversion Tracker



German ALICE teams

FSP ALICE
Erforschung von Universum und Materie

Bundesministerium für Bildung und Forschung

- Uni Bonn. Bernhard Ketzer
- Uni Frankfurt (Physics) Harald Appelshäuser, Henner Büsching
- Uni Frankfurt (Comp. Sc.). Thorsten Kollegger, Volker Lindenstruth
- Uni Heidelberg Johanna Stachel
- TU München Laura Fabbietti
- Uni Münster Anton Andronic

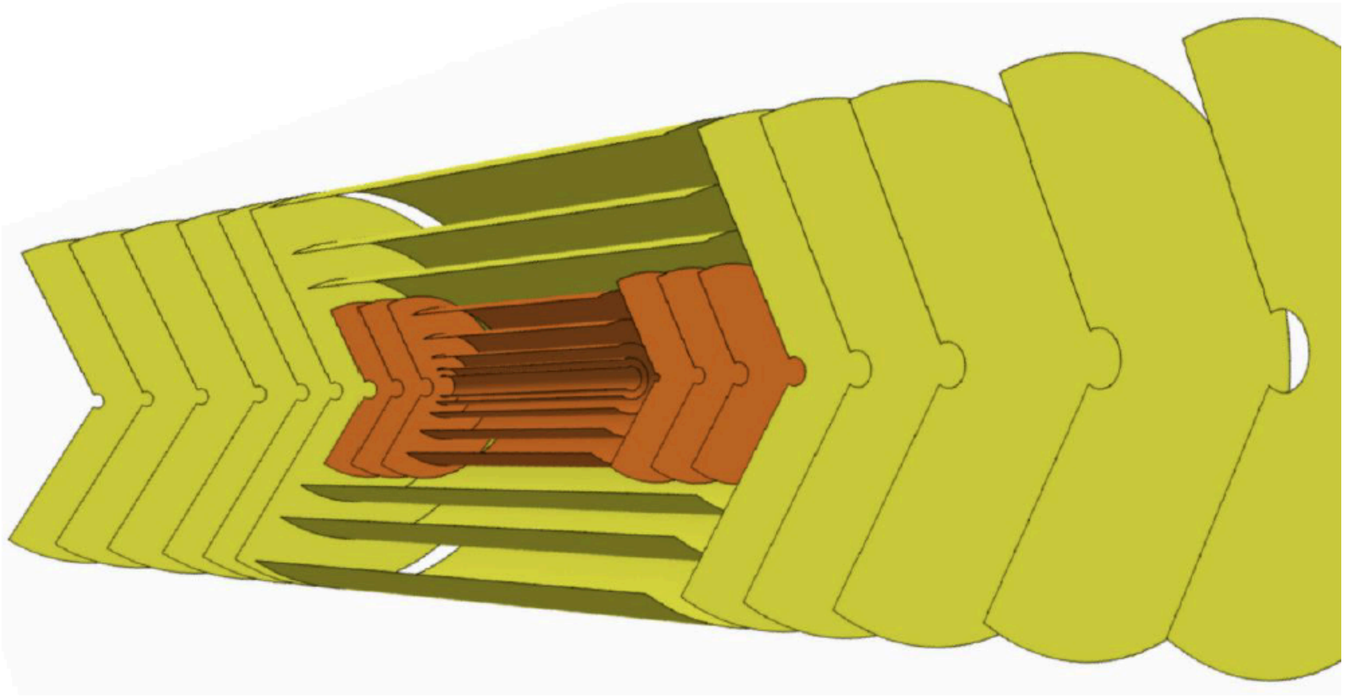
- GSI Silvia Masciocchi

HELMHOLTZ

Outer Tracker

- MAPS-based tracker
- 60 m² active surface
  → module needs to be industrialised

  ITS2 = the largest MAPS detector at the moment
  10 m², 5 institutes busy for 3-5 years
- Low material budget (1% X_0 per layer)
  → Reducing power consumption critical
- 10 μm position resolution
  (Not too stringent - choice of larger pixels to reduce power)



Layer	Material thickness ($\%X_0$)	Intrinsic resolution (μm)	Barrel layers Length ($\pm z$) (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

Current version (ALICE 3 LoI)

ALICE CERN-LHCC-2022-009

Forward Conversion Tracker

Current version (ALICE 3 LoI)

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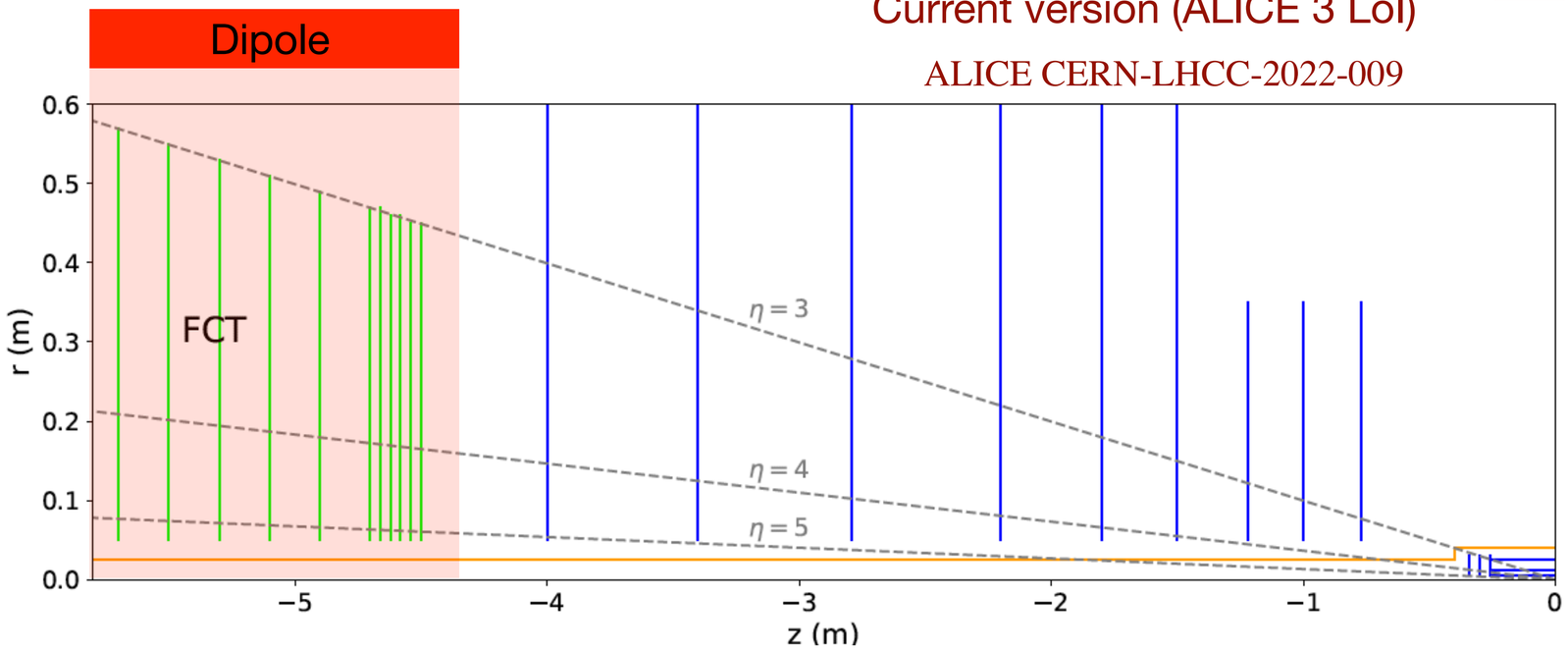
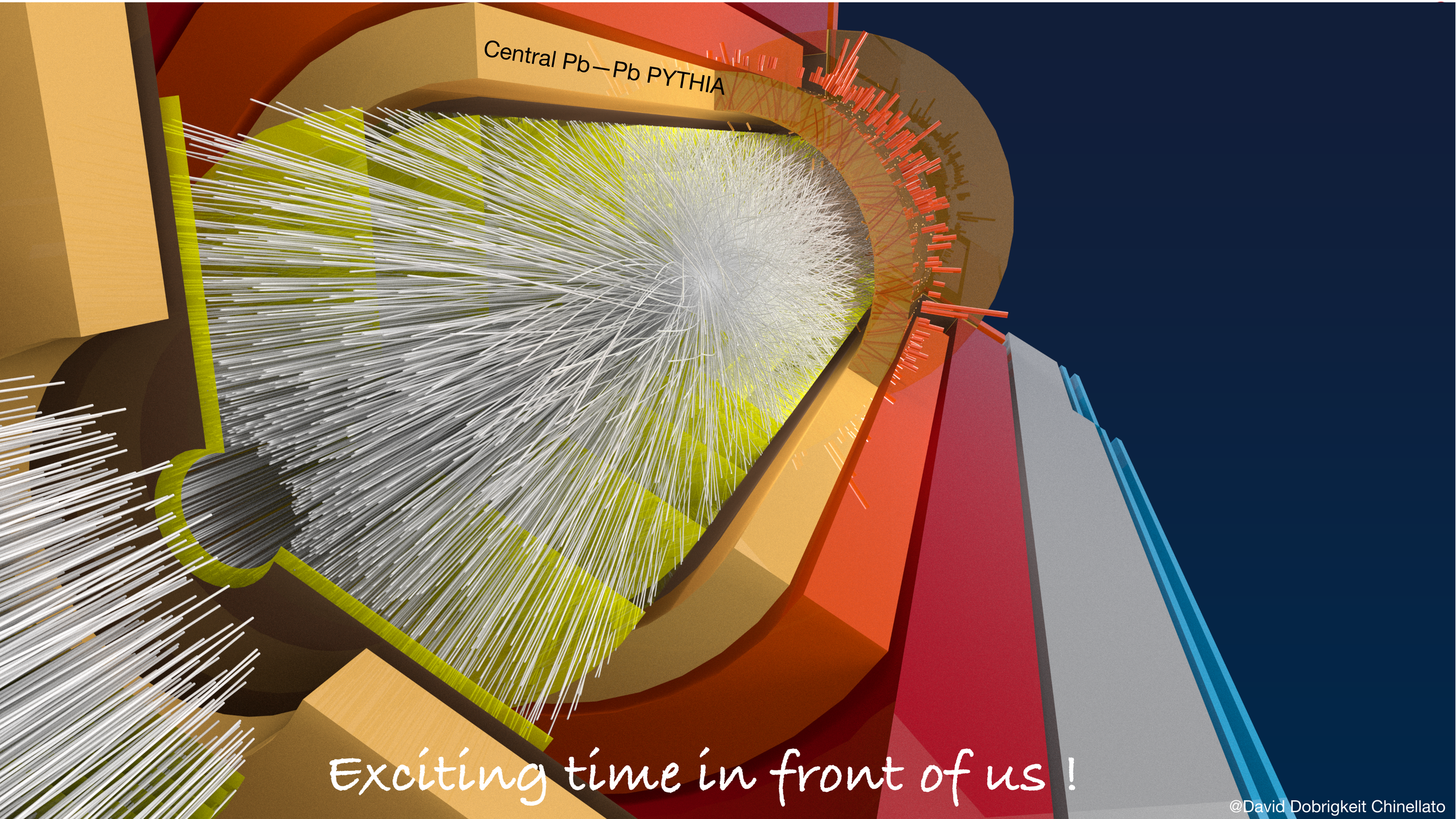


- Thin tracking disks to cover $3 < \eta < 5$
  - Few ‰ of a radiation length per layer
  - Position resolution < 10 μm
- In a dipole magnet ($B_y \approx 0.3$T)
- R&D programme on:
  - Minimisation of material in front of FCT
  - Large area, thin disks
  - Operational conditions

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

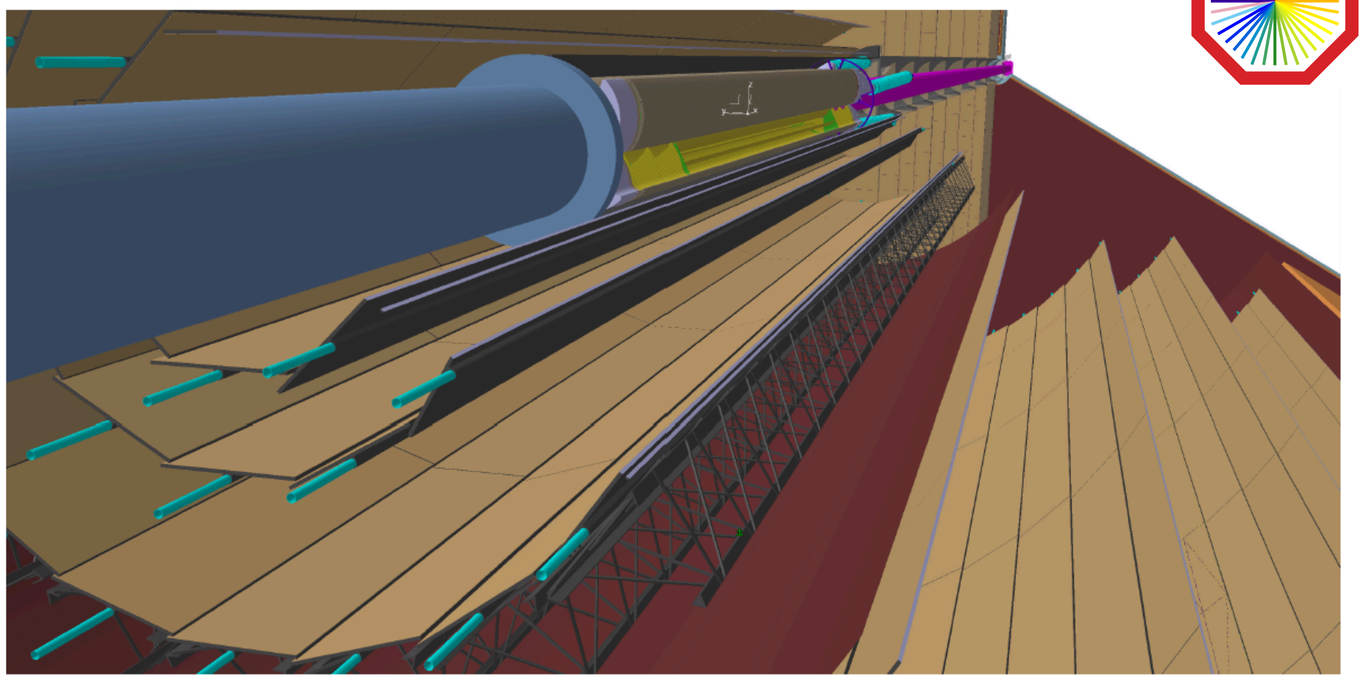

Central Pb—Pb PYTHIA
Exciting time in front of us !
@David Dobrigkeit Chinellato

Back-up

Outer Tracker

Main building blocks

- Modules:
  - Sensors interconnected and bonded to a high thermal conductive substrate
  - Assembled in staves structures
- Support elements:
  - Mechanical support, alignment, cooling, electrical connectivity



ALICE CERN-LHCC-2022-009

ALICE 3 tracker environment

- Hit density decreases by $\mathcal{O}(10^4)$ from layer 0 to 10
- Bandwidth dominated by the vertex detector
- Noise performance critical for the outer most layers

					Hit Rate		Bandwidth				Radiation tolerance	
	Layer	Radius (cm)	Surface (cm^2)	Pixels (10^6)	Hit Rate ($10^6/cm^2/s$)	Hit Rate (10^9/layer/s)	Hits (Gbit/s)	Noise (Gbit/s)	Total (Gbit/s)	Power (W)	NIEL (1 MeV n_{eq}/cm^2)	TID (Mrad)
Outer Tracker	3	3.8	0.29	120	1.7	1.8	28	0.7	79	175	1.6×10^{14}	5
	4	7	0.55	220	0.48	1.2	18	1.4	43	131	4.6×10^{13}	1.5
	5	12	0.94	370	0.16	0.8	13	2.4	27	224	1.6×10^{13}	0.5
	6	20	1.6	620	0.058	0.6	9.9	4.0	19	374	5.6×10^{12}	0.2
	7	30	2.3	930	0.026	0.5	7.9	6.0	16	561	2.5×10^{12}	0.08
	8	45	7.5	3000	0.012	0.6	9.6	19.1	33	1792	1.1×10^{12}	0.04
	9	60	10.0	4000	6.5×10^{-3}	0.5	8.2	25.5	36	2389	6.3×10^{11}	0.02
	10	80	13.3	5300	3.7×10^{-3}	0.4	6.8	34.0	42	3185	3.5×10^{11}	0.01

- Radiation load: 50 months of 24 MHz pp interactions
- Bandwidth: 16 bit/hit, single pixel clusters
- Fake-hit rate: 10^{-8} / pixel / event at 40 MHz readout rate

Current version (ALICE 3 LoI)

Outer Tracker

ALICE 3 Vertex Detector and Outer Tracker — in numbers

	Vertex Detector		Outer Tracker		ITS3	ITS2
Pixel size (μm^2)	÷ 9	$O(10 \times 10)$	• 2.8	$O(50 \times 50)$	$O(20 \times 20)$	$O(30 \times 30)$
Position resolution (μm)	÷ 2	2.5	• 2	10	5	5
Time resolution (ns RMS)	÷ 10	100	÷ 10	100	100* / O(1000)	O(1000)
Shaping time (ns RMS)	÷ 25	200	÷ 25	200	200* / O(5000)	O(5000)
Fake-hit rate (/ pixel / event)	≈	$< 10^{-8}$	≈	$< 10^{-8}$	$<10^{-7}$	$<< 10^{-6}$
Power consumption (mW / cm^2)	+ 75%	70	67%	20	20 (pixel matrix)	40 / 30**
Particle hit density (MHz / cm^2)	• 20	94	÷ 100	0.06	8.5	5
Non-Ionising Energy Loss (1 MeV n_{eq} / cm^2)	• 3000	1×10^{16}	• 100	2×10^{14}	3×10^{12}	3×10^{12}
Total Ionising Dose (Mrad)	• 1000	300	• 20	5	0.3	0.3

* goal, not crucial, like not possible due to power budget

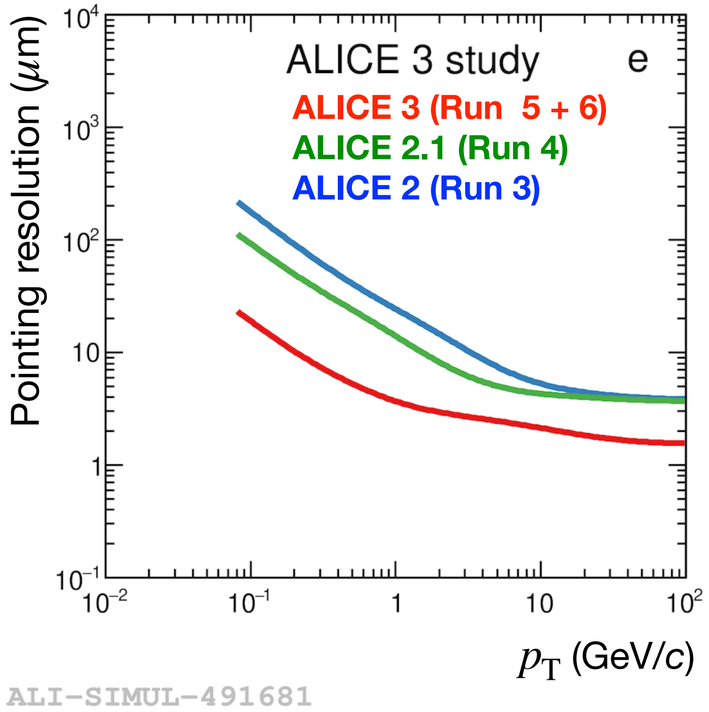
** Innermost layers / outer layers

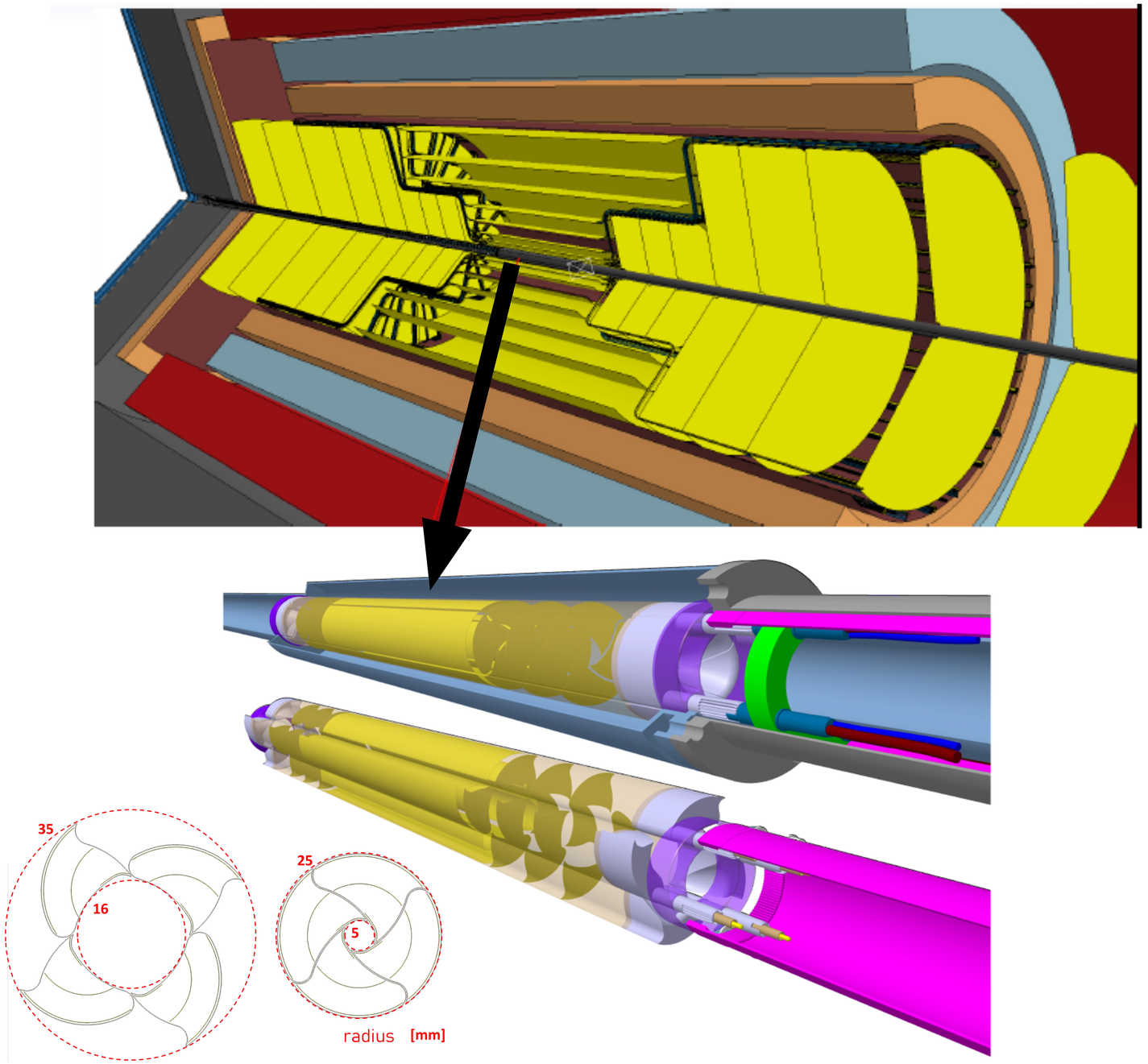
Improving performance concerning all aspects

Vertex Detector and Outer Tracker need different optimisation

Vertex detector

- Larger/longer MAPS-based tracker than for ALICE 2
- Position of first layer at mid-rapidity:
  r = **5 mm** (ALICE 2.1: 18 mm; ALICE 2: 22mm)
- Achieved with a retractable vertex detector inside of the beam pipe in secondary vacuum





ALICE 3 core cost

System	Technology	Cost (MCHF)
Tracker	MAPS	30.5
TOF	Monolithic LGADs	14.8
	Hybrid LGADs[6]	26.4
RICH	Aerogel and monolithic SiPMs	20.9
	Aerogel, analogue SiPMs + readout[6]	34.0
ECal	Pb-scintillator + $PbWO_4$	17.0
MID	Steel absorber, scintillator bars, SiPMs	7.0
FCT	MAPS (solenoid + separate magnet)	5.3
	MAPS (solenoid + dipoles)	2.3
Magnet system	Superconducting solenoid + FCT magnet	25.0
	Superconducting solenoid and dipoles	40.0
Computing	Data acquisition and processing	6.0
Common items	Beampipe, infrastructure, engineering	15.0
Total		141.5

Luminosity

System	$\mathscr{L}^{\text{month}}$	$\mathscr{L}^{\text{Run5+6}}$
pp	$0.5\,\text{fb}^{-1}$	$18\,\text{fb}^{-1}$
pp reference	$100\,\text{pb}^{-1}$	$200\,\text{pb}^{-1}$
A–A		
Xe–Xe	$26\,\text{nb}^{-1}$	$156\,\text{nb}^{-1}$
Pb–Pb	$5.6\,\text{nb}^{-1}$	$33.6\,\text{nb}^{-1}$

Table 2: Integrated luminosities for different collision systems

Integrated luminosity for Run 3+4

200 pb^{-1} at 13.6 TeV with high-multiplicity and rare probe selection

13 nb^{-1} with Pb—Pb

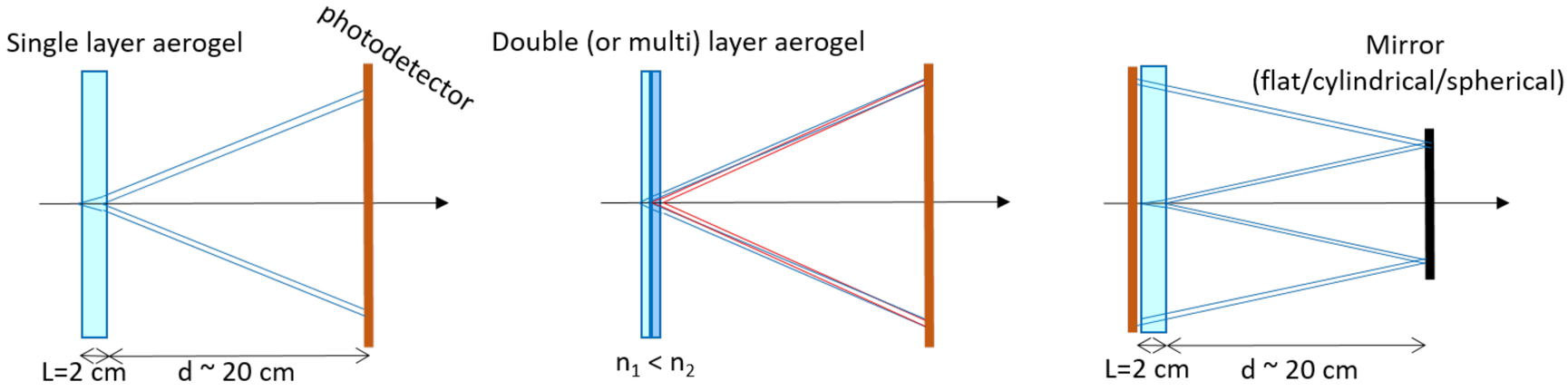
Time-of-Flight

- **Separation power** $\propto \frac{L}{\sigma_{\mathrm{tof}}}$
  - distance and time resolution crucial
- **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** ($\sigma_{TOF} \approx 20$ ps)
  - Total silicon surface ~45 m^2
  - **R&D programme** on
    monolithic CMOS sensors with integrated gain layer

Ring-Imaging Cherenkov

Extend PID reach of outer TOF to higher p_T
➟ Cherenkov

- 2 cm thick **aerogel radiator**
  to ensure continuous coverage from TOF
  → refractive index n = 1.03 (barrel)
  → refractive index n = 1.006 (forward)
- **Silicon photon detection layer at 20 cm from the radiator:**
  - Total SiPM surface ~60 m^2
  - **R&D programme** on monolithic photon sensors
- Cherenkov angular resolution ≈ 1.5 mrad
- Cherenkov emission threshold determines low p_T reach



Electromagnetic calorimeter

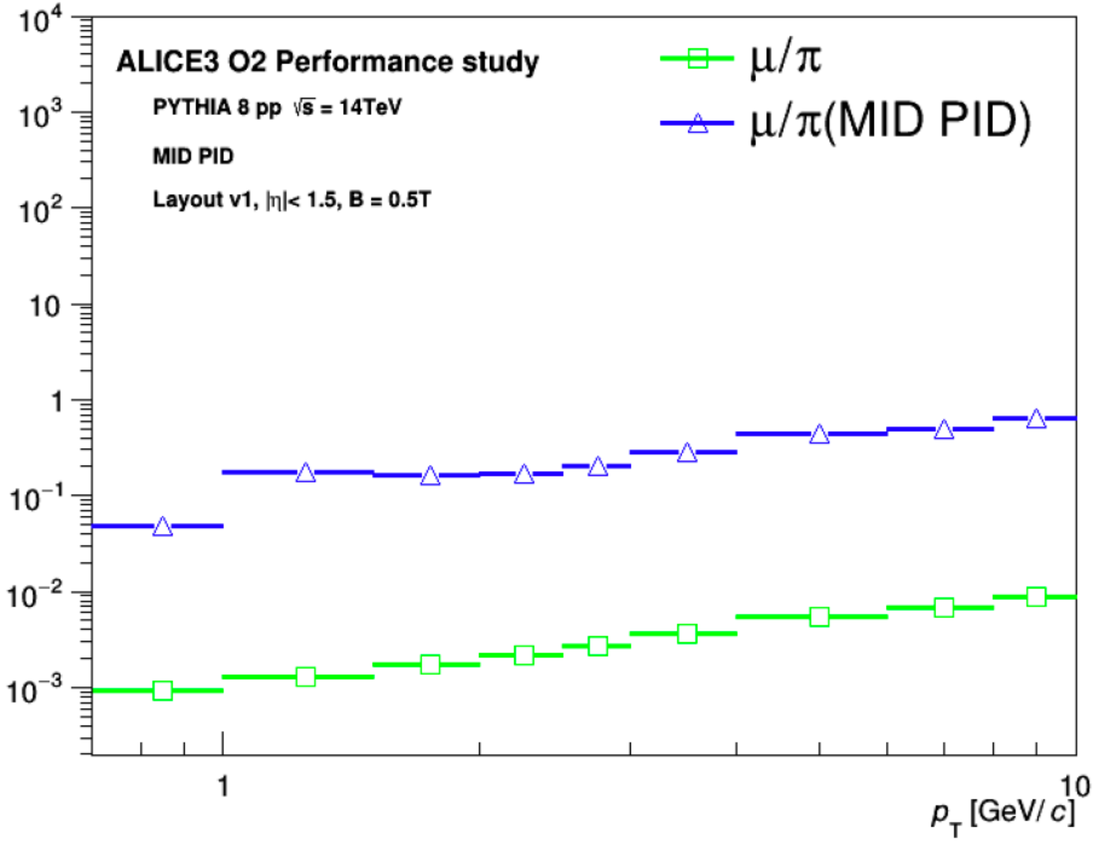
- **Large acceptance ECal**
  → sampling calorimeter (à la ALICE EMCal/DCal):
  O(100) layers (1 mm Pb + 1.5 mm plastic scintillator)

- **Additional high energy resolution segment** at mid-rapidity
  → $PbWO_4$-based (à la ALICE PHOS)

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 Identifier

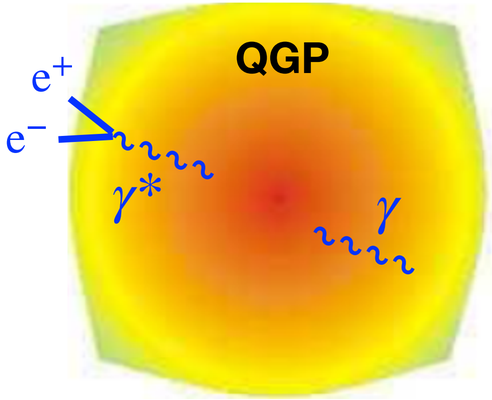
- **Hadron absorber**
  - ~70 cm non-magnetic steel
- **Muon chambers**
  - search spot for muons ~0.1 x 0.1 (eta x phi)
    → ~5 x 5 cm^2 cell size
  - matching demonstrated with 2 layers of muon chambers
    - scintillator bars
    - Equipped with wave-length shifting fibres
    - Read-out with SiPM



Outer Tracker: German R&D interests

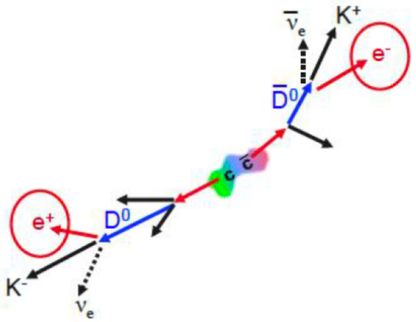
	Module develop-ment	Module production	Sensor develop-ment	Module/ Sensor Characte-rization	Powering	Readout	Mecha-nics	Cooling	Detector Control	Simu-lations
Uni Bonn	X			X			X			
Uni Frankfurt (phys.)				X	X	X		X		X
Uni Frankfurt (comp. sci.)						X				
Uni Heidelberg	X	X	X	X	X		X			X
TU München			X	X		X				X
Uni Münster		X		X			X	X		X
GSI	X	X	X	X			X	X		X

Electromagnetic radiation

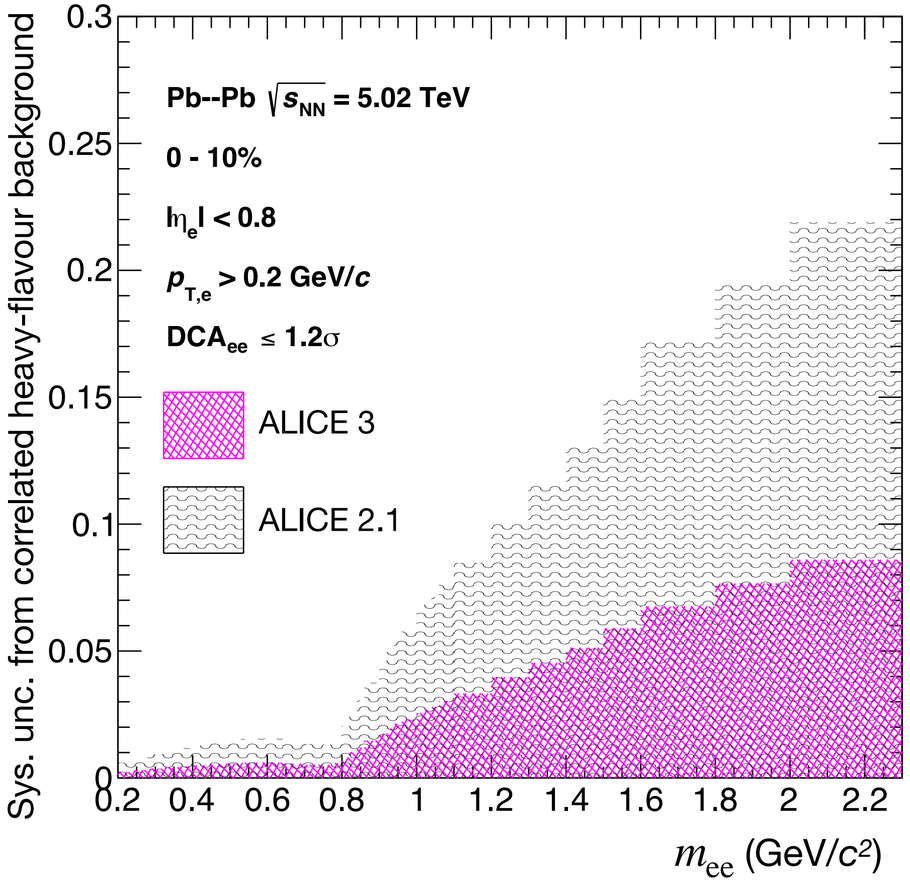


Averaged temperature T of the QGP using thermal dielectron m_{ee} spectrum at $m_{\mathrm{ee}} > 1.1$ GeV/c^2

- Heavy-flavour decays produce correlated backgr
- Large for $m_{ee} \gtrsim 1\,\mathrm{GeV}/c^2$
- **Can be effectively suppressed with ALICE 3**
  Thanks to excellent pointing resolution



Relative systematic uncertainties
from correlated heavy-flavour background



R. Rapp, Adv. High Energy Phys. 2013 (2013) 148253
P.M Hohler and R. Rapp, Phys. Lett. B 731 (2014) 103
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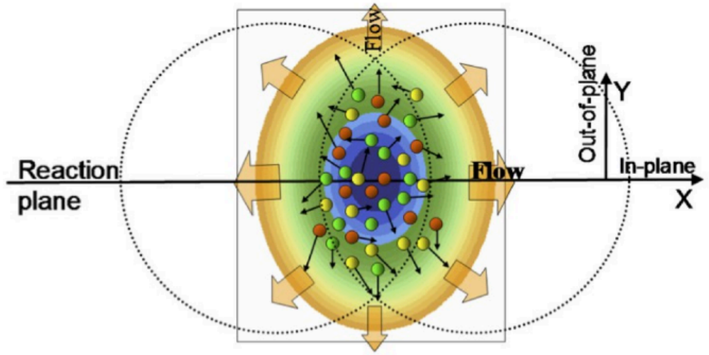
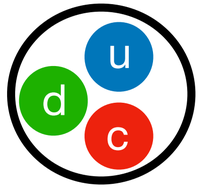
Heavy-quark transport

Non-central collision

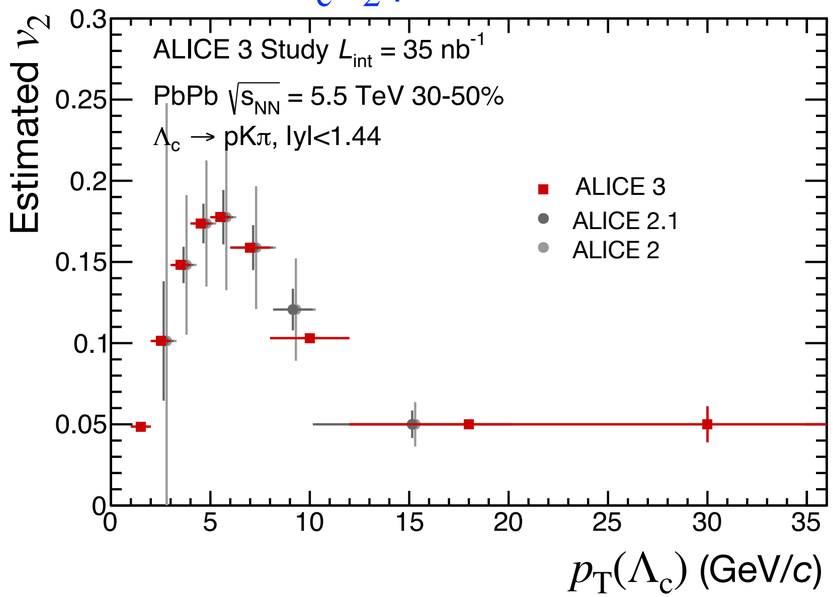


Interactions with the plasma generate azimuthal anisotropy v_2:

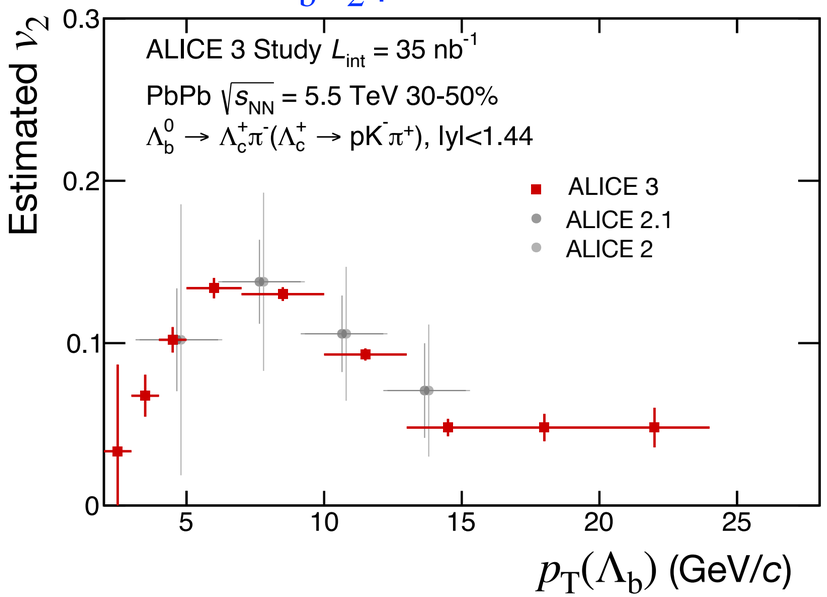
$$\frac{dN}{d\phi} \propto 1 + 2\, v_2 \cos 2(\varphi - \psi)$$



Λ_c v_2 performance



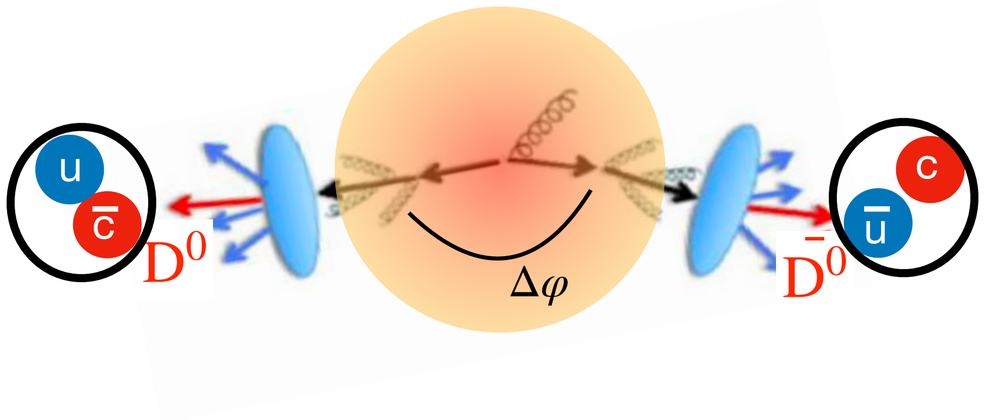
Λ_b v_2 performance



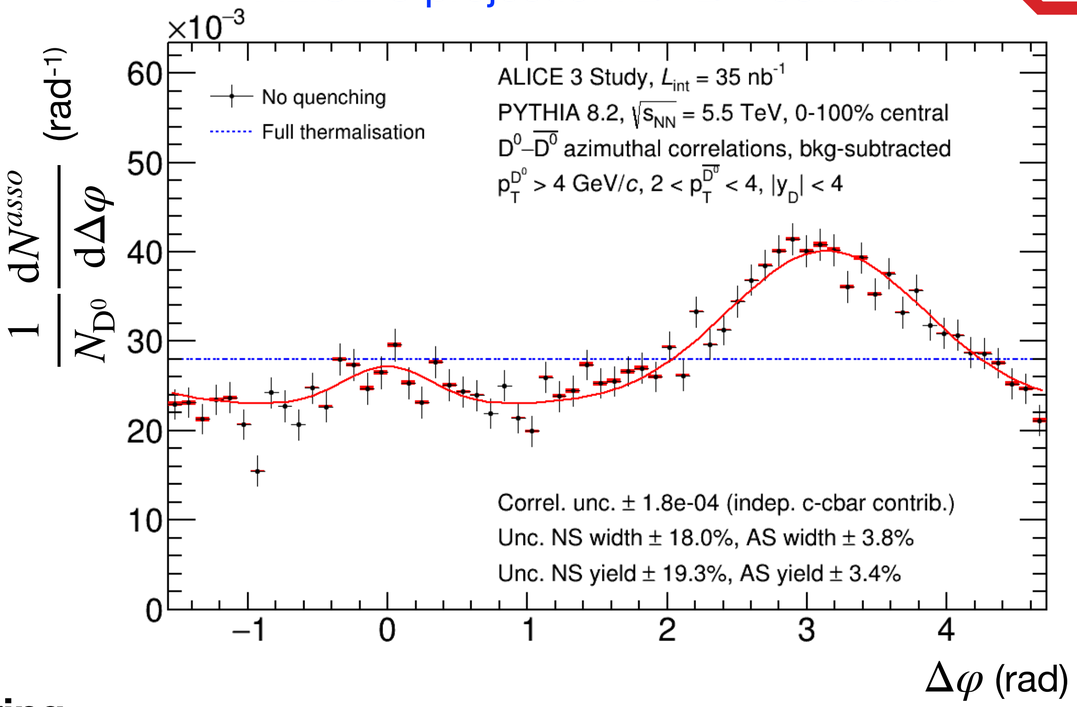
- Access to **(heavy-)quark transport properties in the QGP** at hadron level
  - Precise R_{AA} and v_2 measurements of charm and beauty hadrons down to low p_T → **diffusion coefficients D_s**
  - Expect beauty thermalisation slower than charm → smaller v_2

→ **Need ALICE 3 performance (pointing resolution, acceptance) for precise measurements down to low p_T**

Heavy-quark correlations



ALICE 3 projection: $D^0\bar{D}^0$ correlation

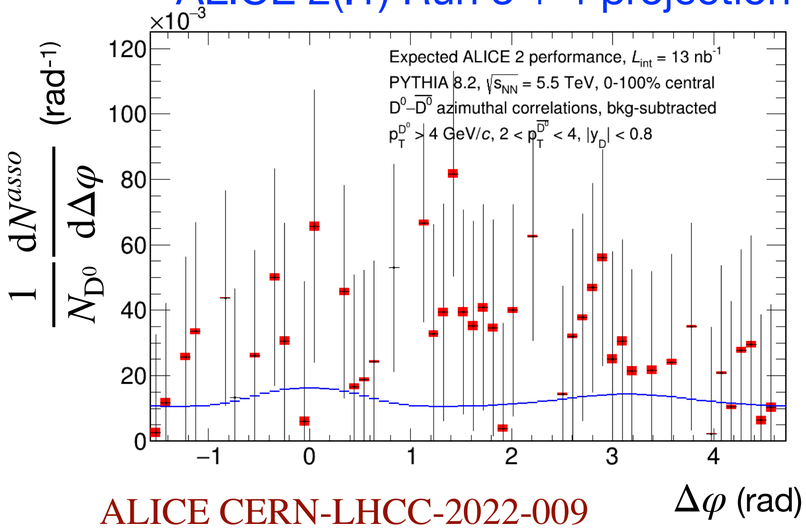


Angular decorrelation of heavy-flavour hadrons → **probe QGP scattering**

- Sensitive to energy loss mechanisms, degree of thermalisation
- Strongest signal at low p_{T}
- Require high purity, efficiency and large η coverage

→ **Heavy-ion measurement only possible with ALICE 3**

ALICE 2(.1) Run 3 + 4 projection



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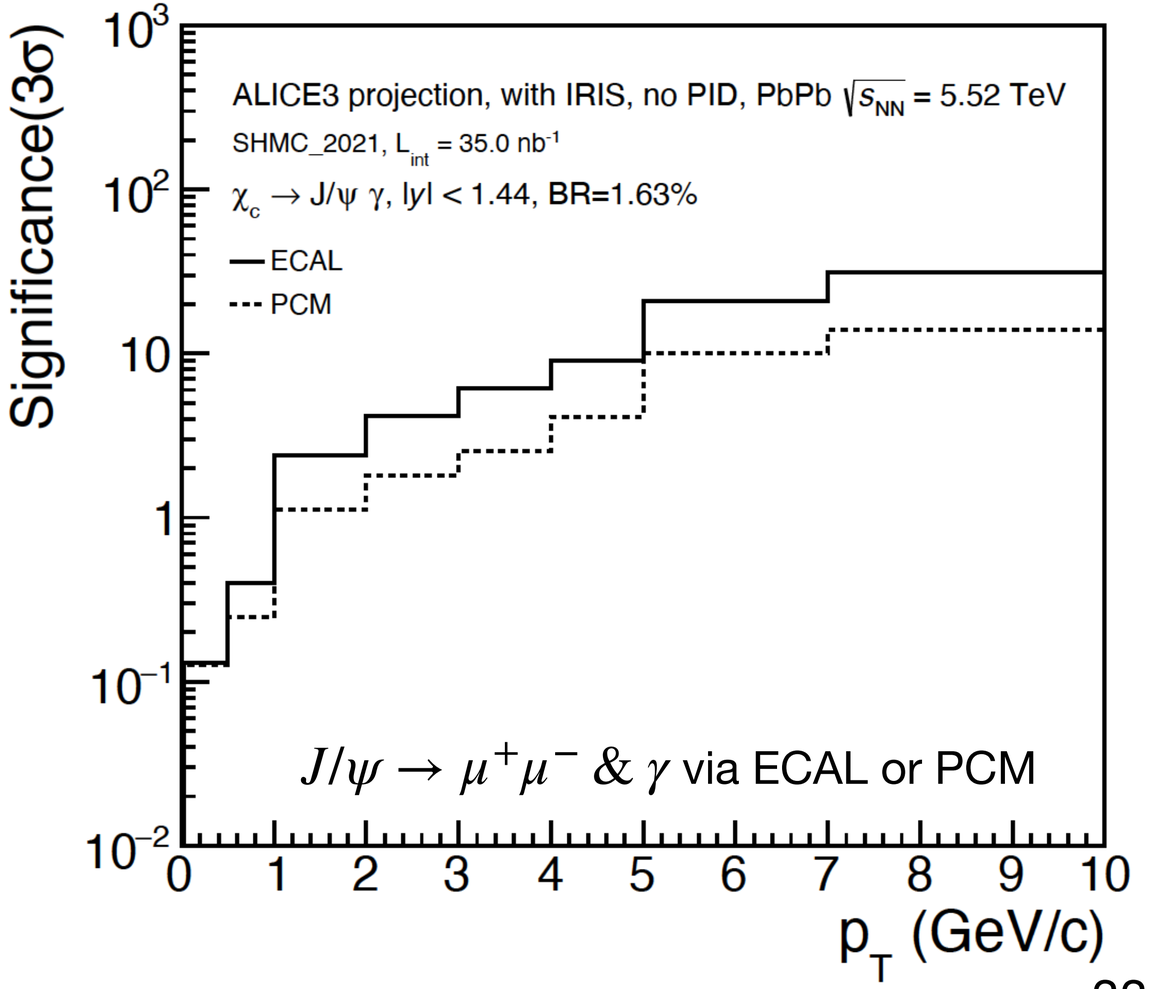
Other bound states: quarkonia

- Explore new states:
  - P-wave (L=1) states χ_c, χ_b
  - Pseudoscalar (L=0) states η_c, η_b
- Melting temperature depends on angular momentum…
- Measurement of χ_c, χ_b →Test theory

**Require muon identification down to 1.5 GeV/*c*
+ photon detection**

$\chi_c \to J/\psi + \gamma$ significance in Pb—Pb
six years of running



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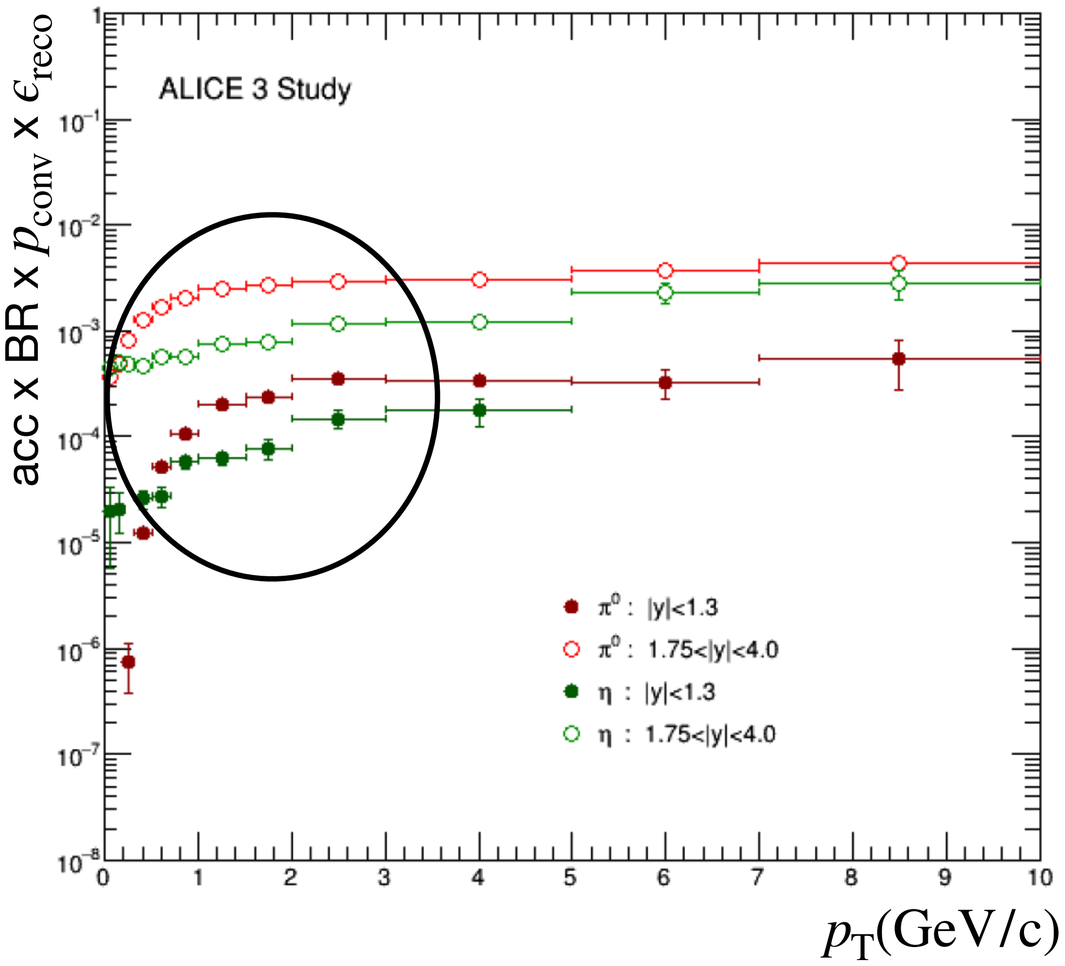
Measurement of η (and π^0) down to p_T = 0

- p_T spectrum of direct photons
  → **Alternative method of *T* determination**
  with different systematic uncertainties

- Main background: π^0, η decays:
  Can be measured down to very low p_T for $1.75 < \eta < 4$
  Not possible with ALICE 2

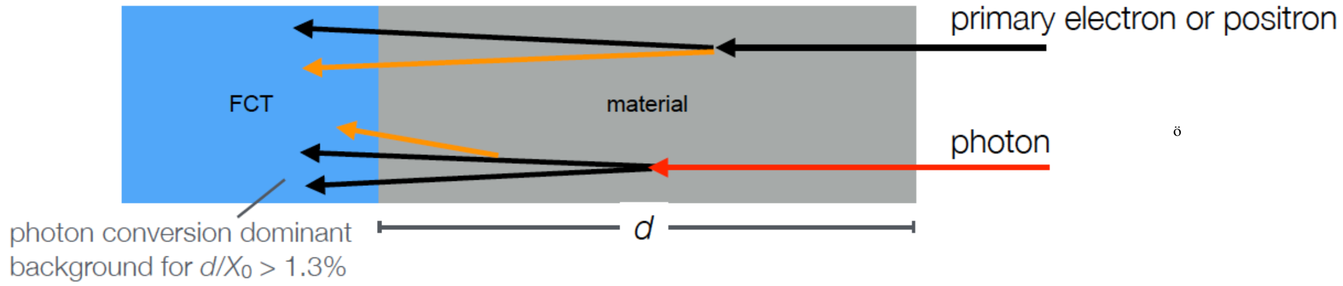
Significant reduction of uncertainties expected

Acceptance for
$\eta \to \gamma\gamma$ with $p_\gamma > 100\,\mathrm{MeV}/c$



Ultra-soft γ in inclusive pp collisions

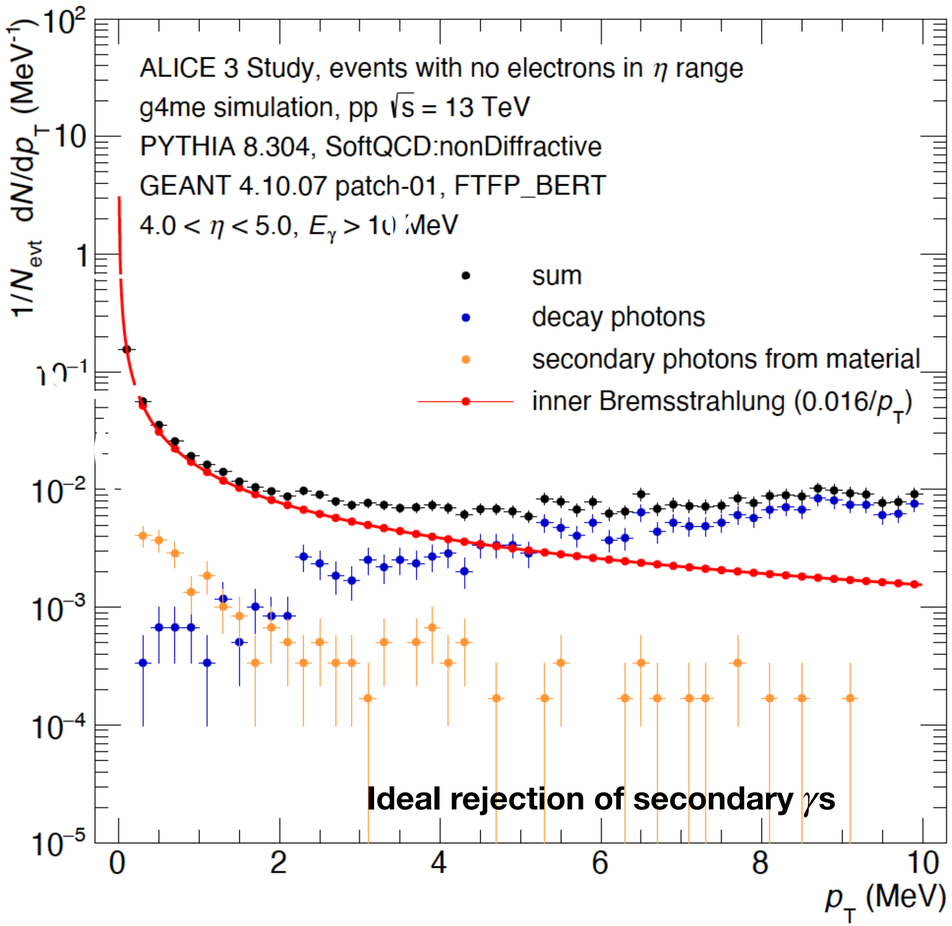
- **Signal:** inner Bremsstrahlung
- Background:
  - Decay photons ($\pi^0 \rightarrow \gamma\gamma$)
  - Secondary photons from material



→Minimize material in front of FCT

→ Develop strategy to reject events with $e^{\pm}$ in the FCT η acceptance (here ideal case)

Inclusive pp collisions at $\sqrt{s} = 13$ TeV
Expected yields for signal and backgrounds



→ **Expect 20% uncertainties in all planned reactions**
Complementary ultra-soft e^+e^- measurements (lower p_T than ALICE 2)

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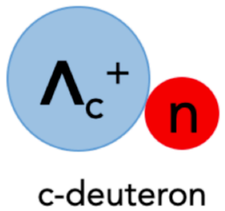
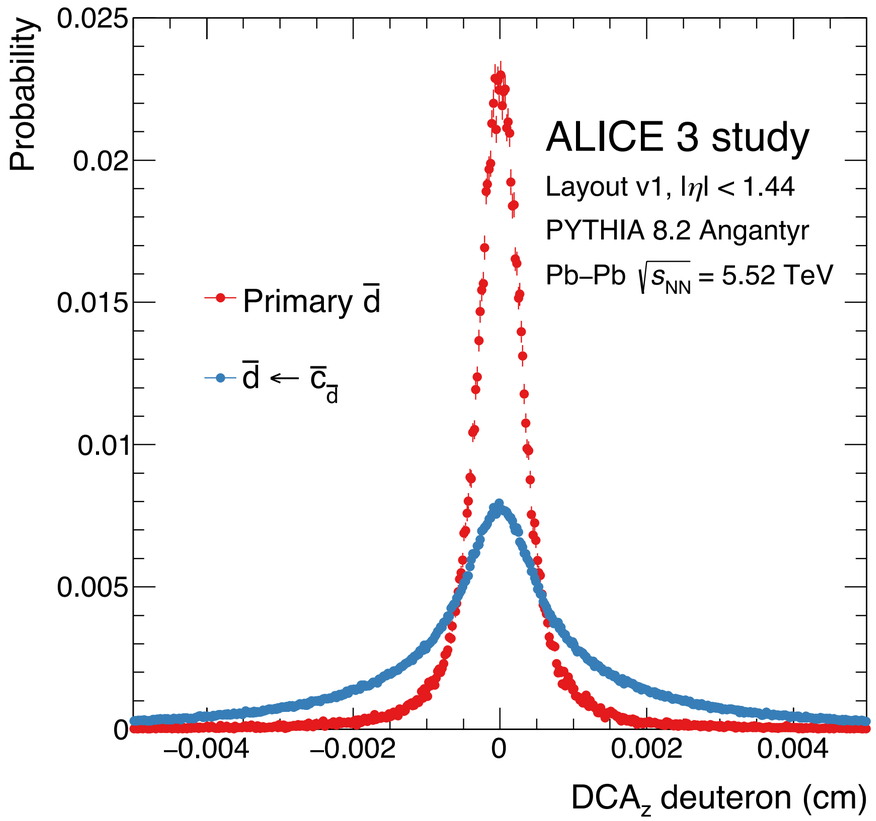
Nuclear states: charm-deuteron



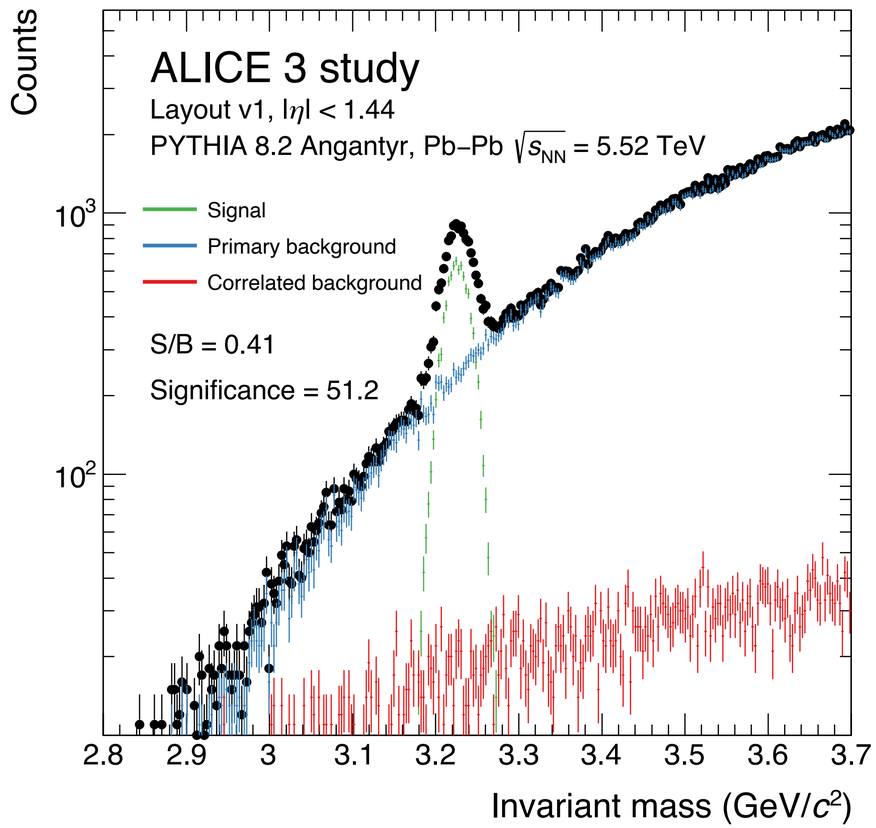
Study with the decay channel:
$c_d \rightarrow d + K^- + \pi^+$

Assumed yield predicted by
Statistic Hadronisation Model

Impact parameter distribution



Invariant mass distribution
in minimum-bias Pb—Pb collisions
On month data taking



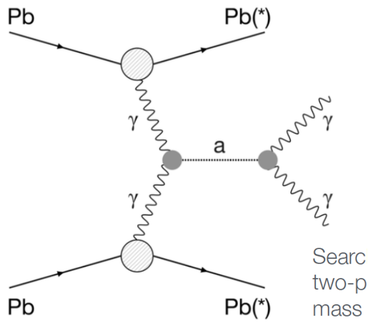
Unique sensitivity to undiscovered charm-nuclei:

- For c-deuteron: reach significance of 50 for one month Pb—Pb fully integrated (centrality, p_T, η)
- For c-triton ($\Lambda_c nn$): 2.5 significance for one month Pb—Pb fully integrated

Beyond QGP physics

- **Axion-like particles (ALPs)** = elementary pseudoscalar particles appearing in many BSM extensions as Goldstone bosons (Dark matter candidates/mediators)

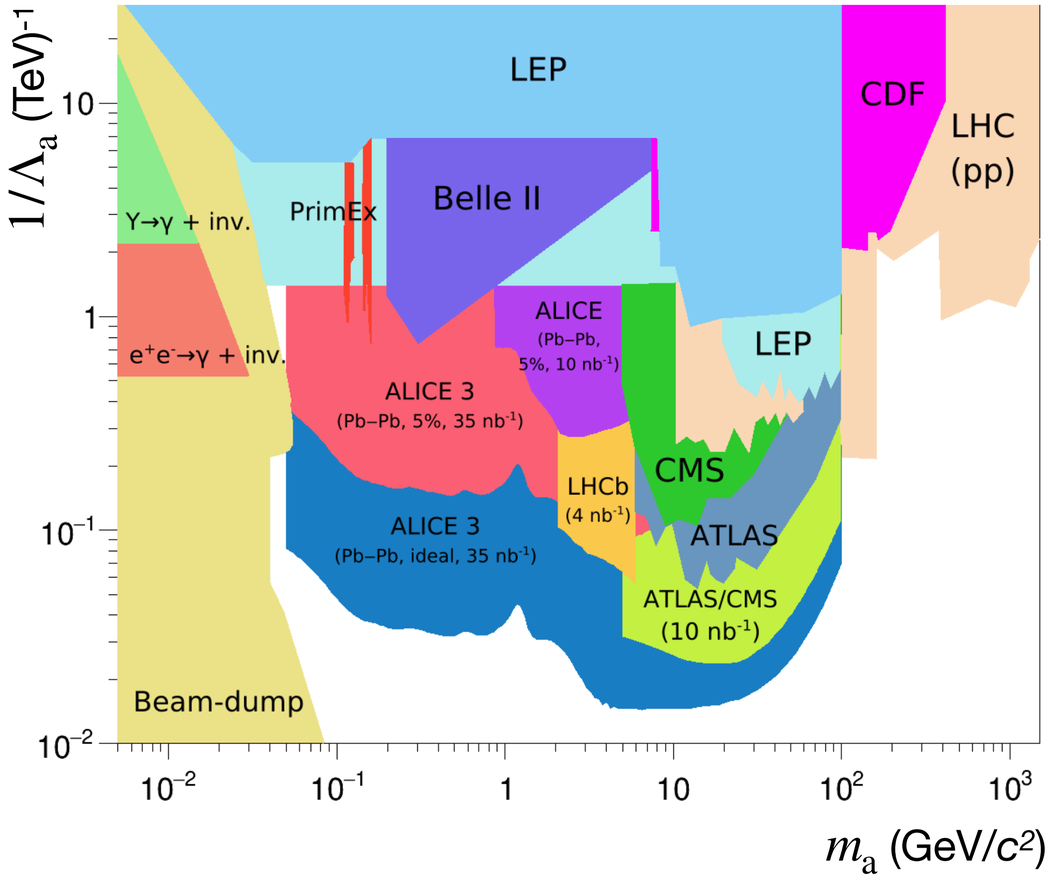
- **Search for ALPs in ultra-peripheral collisions**



Look for peak in the two-photon invariant mass spectrum
Background considered: $\pi^0\pi^0$ photo-production, light-by-light scattering

- **With ALICE 3 take advantage of:**
  - Large rapidity coverage $|\eta| \leq 4$
  - Capability to measure γ down to small E ($E \geq$ 50-100 MeV)

ALP search: expected sensitivity
as a function of m_a and ALP-γ coupling $1/\Lambda_a$



Existing limits from ATLAS, JHEP 03, 243 (2021)
Projections for ATLAS/CMS from PRL 118 (2017), 171801
Projections for LHCb from Goncalves et al. EPJC 81 (2021), 522

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