The 10th Annual
Large Hadron Collider Physics Conference
May 16-21, 2022

2022 LHCP TAIPEI ONLINE

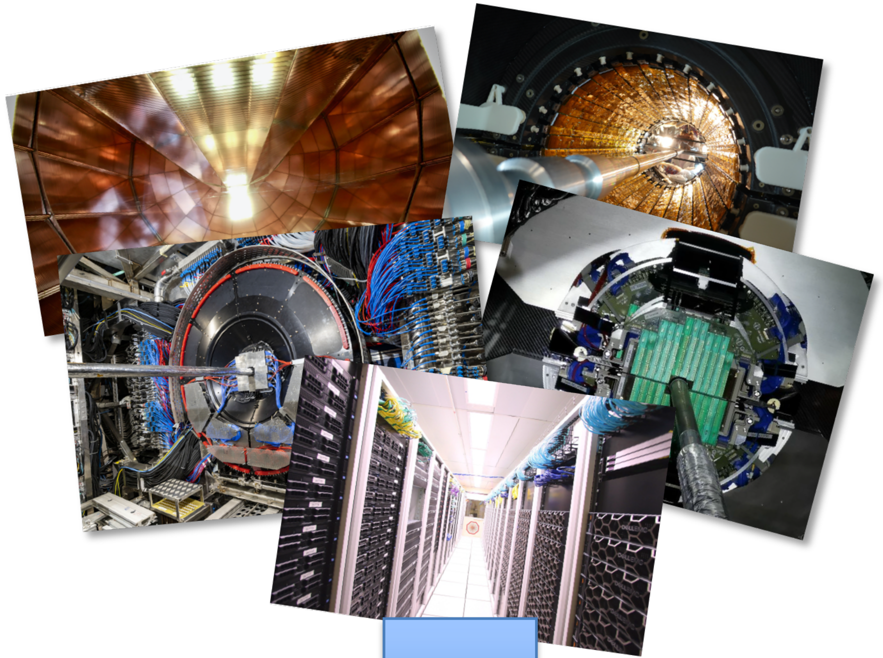
ALICE Upgrades

Antonio Uras
IP2I - Lyon – CNRS/IN2P3
on behalf of the ALICE Collaboration

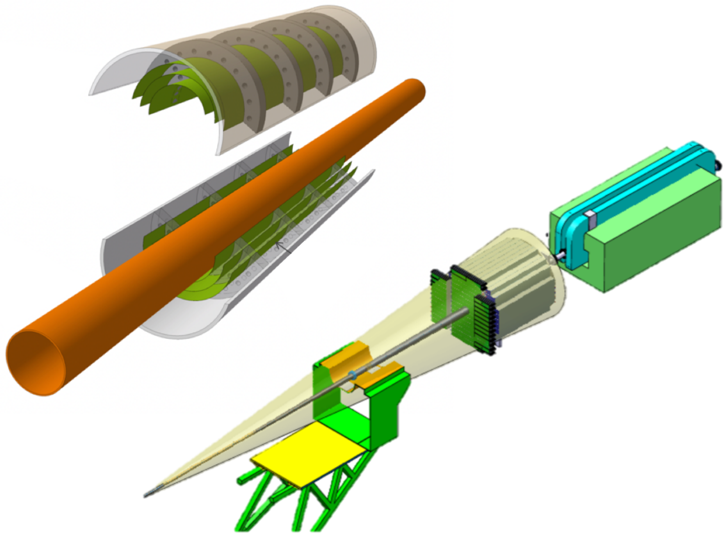
ALICE

ALICE Upgrade Timeline

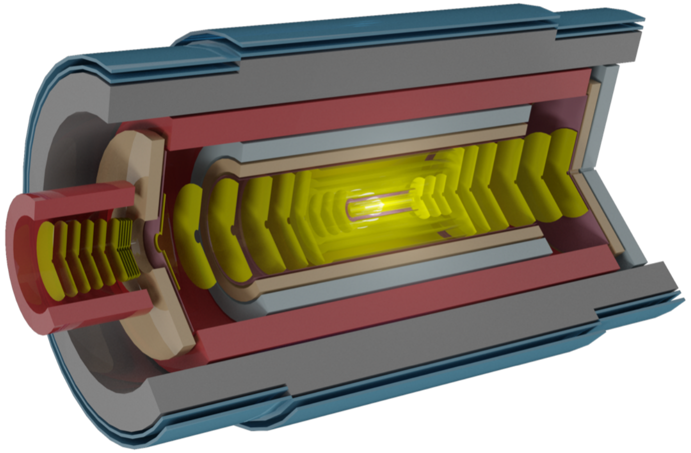
LS2: ITS2, MFT, TPC, FIT, O²

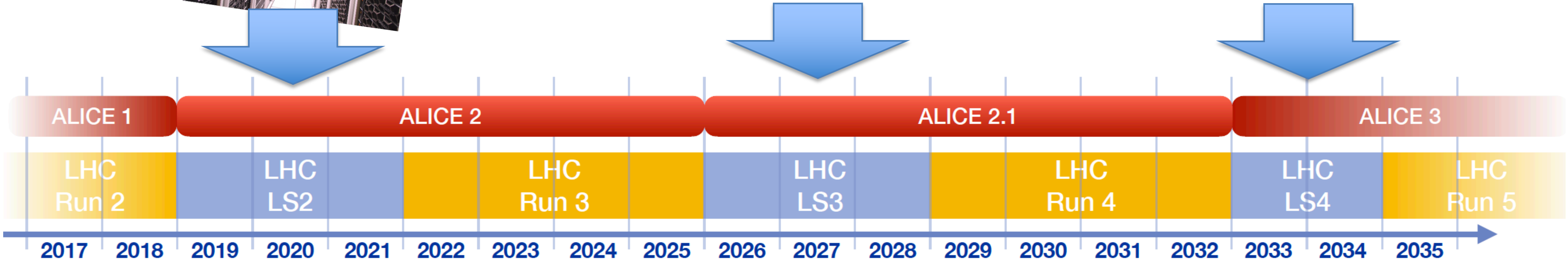


LS3: ITS3, FoCal



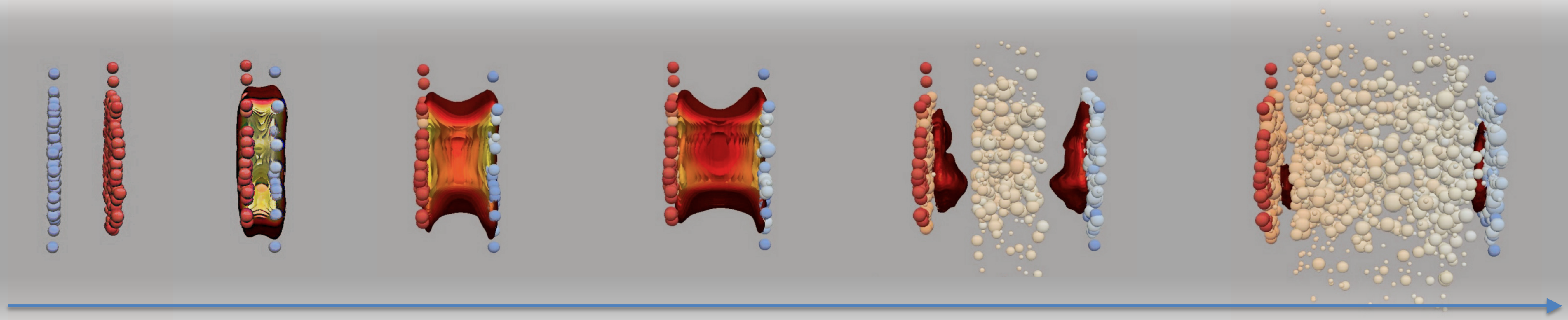
LS4: ALICE 3





ALICE Physics Program: Current and Future Challenges

- **How is the equilibrium phase reached?**
- **What are the properties of the deconfined phase?** Viscosity, electromagnetic emission, diffusion coefficients for heavy quarks? Can they be estimated by the available theoretical models?
- **How do hadrons emerge from the deconfined phase?**
- **Is QGP produced in collisions involving a small number of nucleons?**

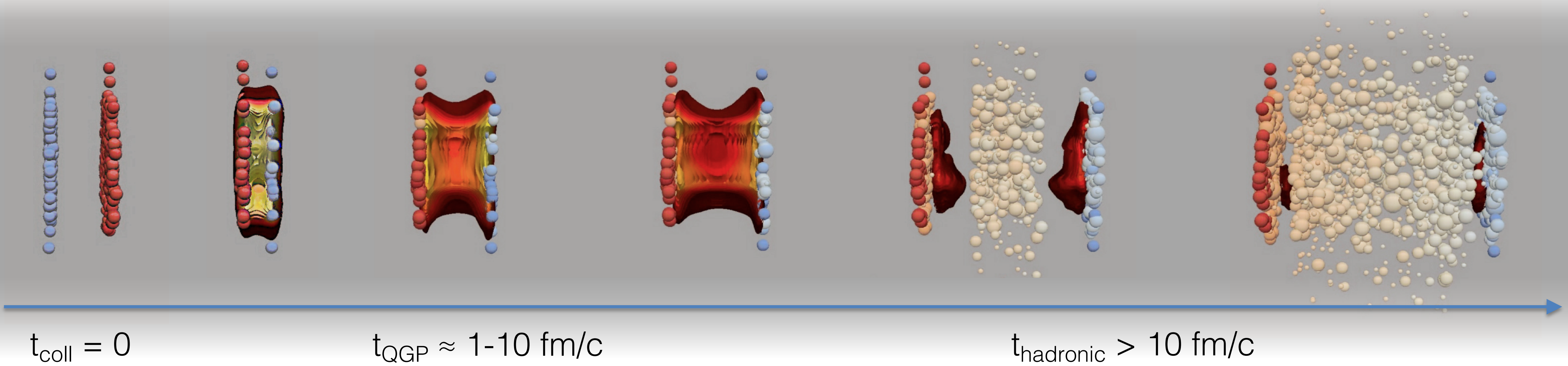


$t_{coll} = 0$ $t_{QGP} \approx$ 1-10 fm/c $t_{hadronic} >$ 10 fm/c

ALICE Physics Program: Current and Future Challenges

- **Two main physics items driving the ALICE experimental approach:**
  - **Transport and hadronization of heavy flavors in the medium:** differential measurements of HF hadron production (suppression, enhancement, flow…) down to vanishing p_T
  - **Electromagnetic radiation from the medium:** dilepton measurements below J/ψ mass, down to zero p_T, to map the evolution of the collision

➡ Light and high-granularity detector + continuous readout to access untriggerable probes with high S/B



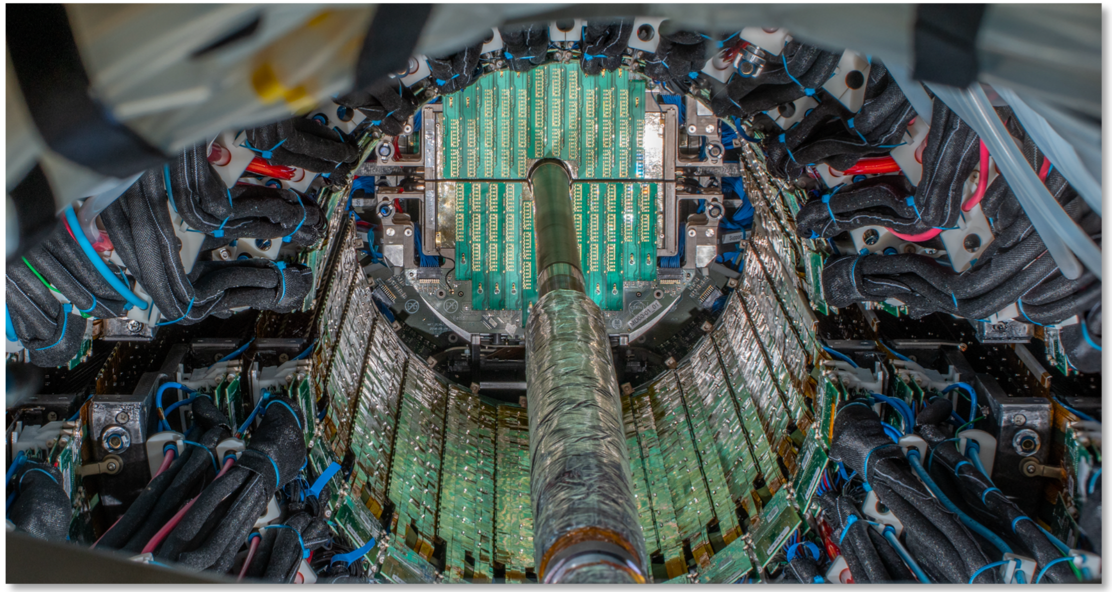
ALICE 2: Ready for Run 3

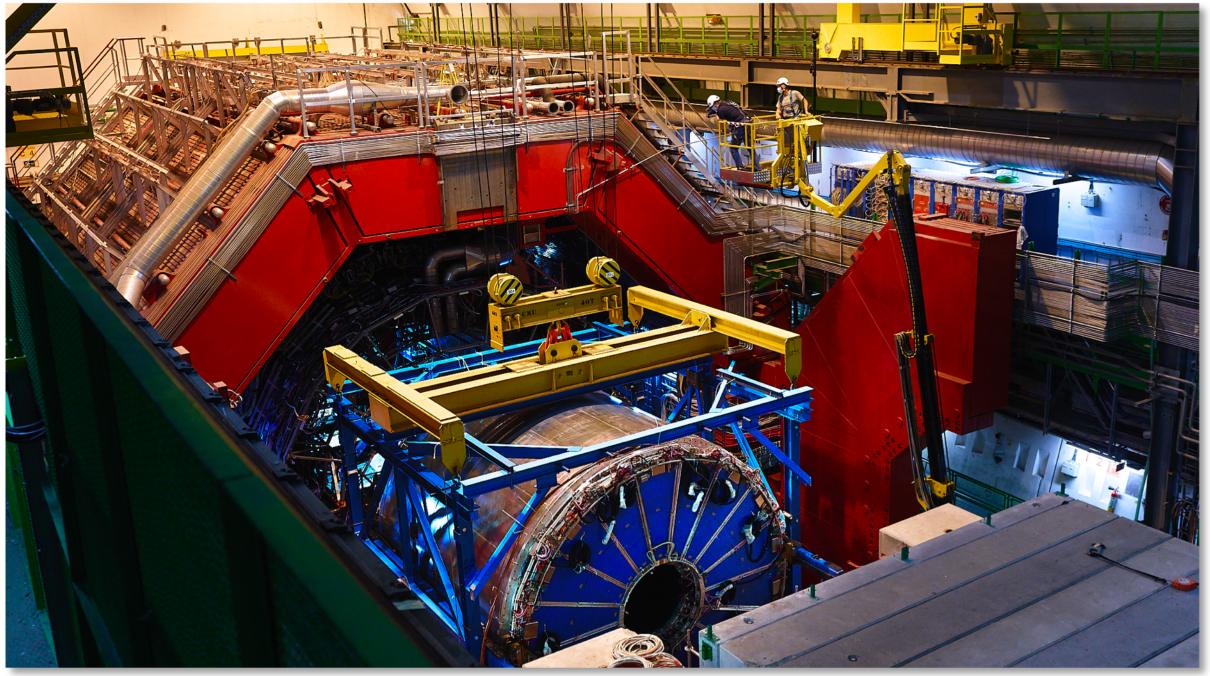
New, large area (10 m^2) Inner Tracking System based on the CMOS chip ALPIDE

Main goal: improving tracking performance, namely at low p_T

Stefania Beolè, **Mon 3.15 PM**

- 0.3% X_0 per layer in the inner most 3 layers (light mechanical structure) + spatial resolution *o*(5 μm)
- Extended coverage, now including forward rapidity

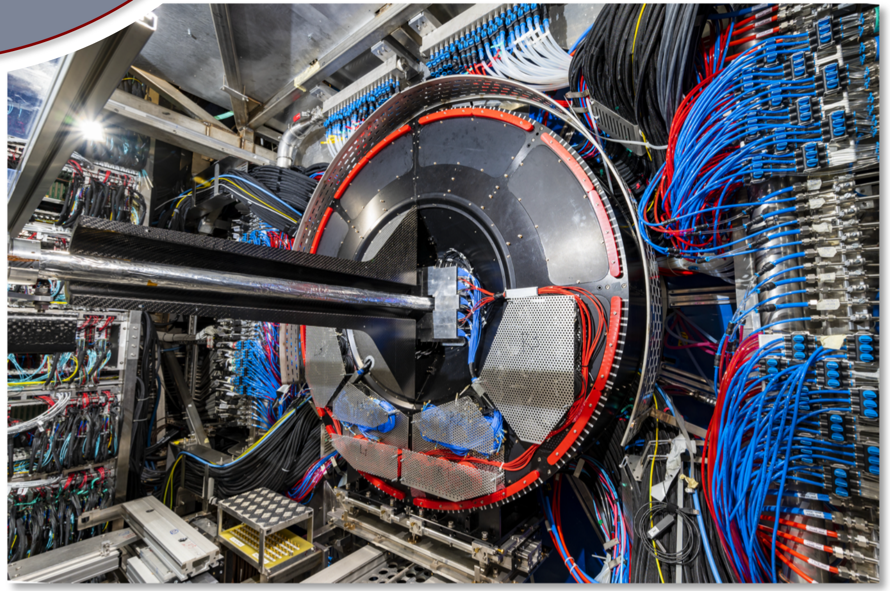




TPC Upgrade

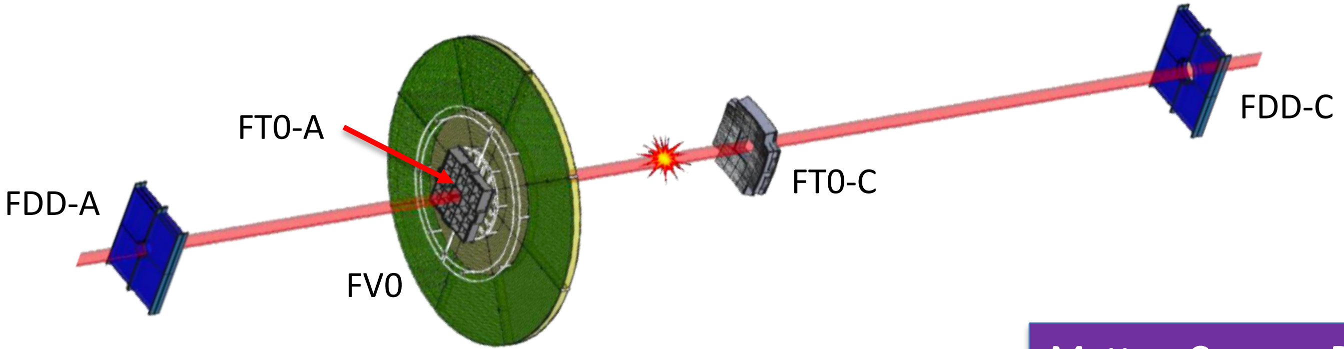
- Replacement of the MWPC-based readout by GEM detectors, allowing for TPC operation in continuous mode
- Space-charge distortions minimized, preserving PID capabilities

ALICE 2: Ready for Run 3



Fast-interaction Trigger system

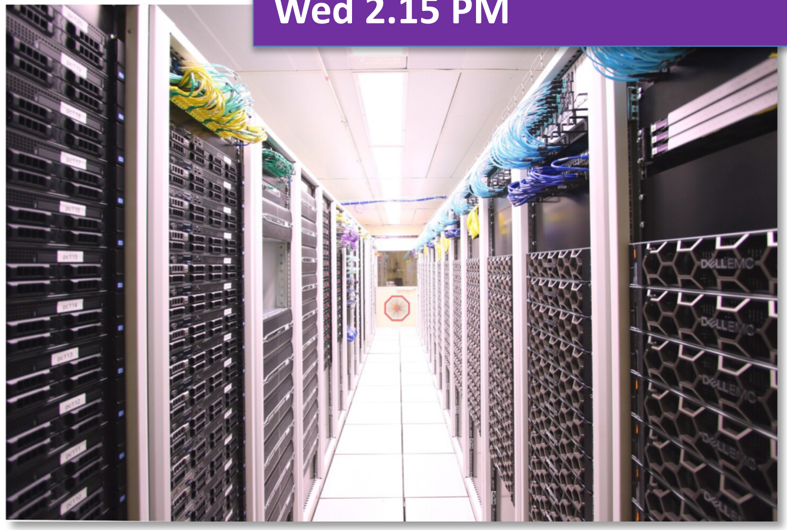
- Timing signal for TOF with high resolution (13 ps FT0; 200 ps FV0)
- Centrality, luminosity and event plane determination



Matteo Concas, Paul Buehler
Wed 2.15 PM

New Readout and Online-Offline (O^2) System

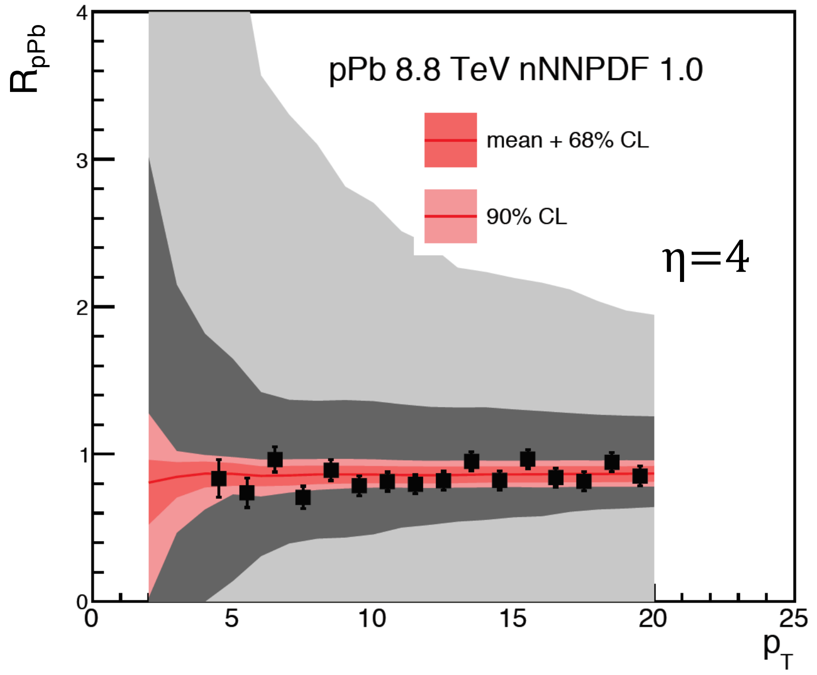
- **Upgraded readout for several detectors (incresed interaction rate)**
- **Synchronous processing:**
  - First Level Processors (FLP): 200 nodes, reading detectors at up to **3 TB/s**
  - GPU-based Event Processing Nodes (EPN): 250 nodes reading FLP output at **0.5 TB/s**
  - Compressed time frames from EPN output at **0.1 TB/s**, feeding asynchronous processing and physics analyses

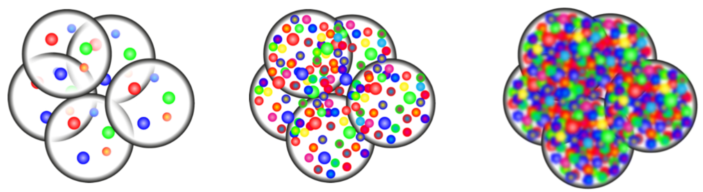


Towards Run 4: FoCal

Forward physics at LHC provides an opportunity to study the low-x region

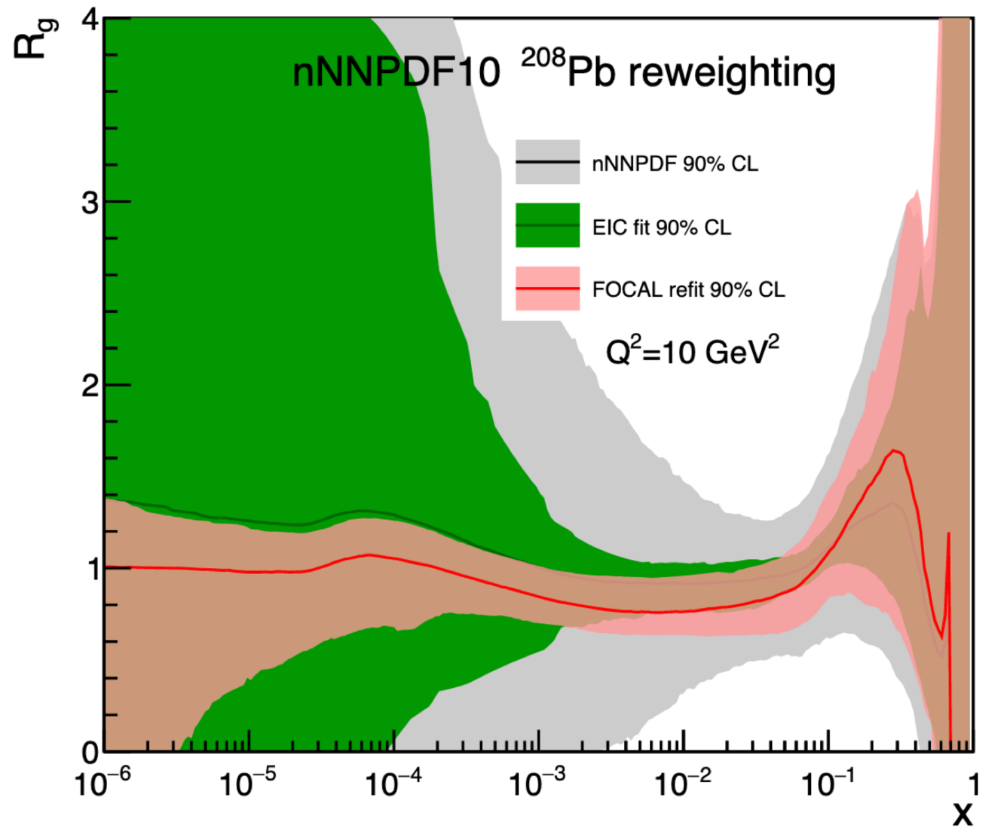
- Access to non-linear QCD mechanisms: investigate the onset of possible of gluon saturation (CGC)
- Quantify and constrain modifications of gluon (n)PDFs at small-x and Q^2
- Direct photons provide a more direct access to the low-x region (10^{-5})
  - No fragmentation function
  - No final-state effects



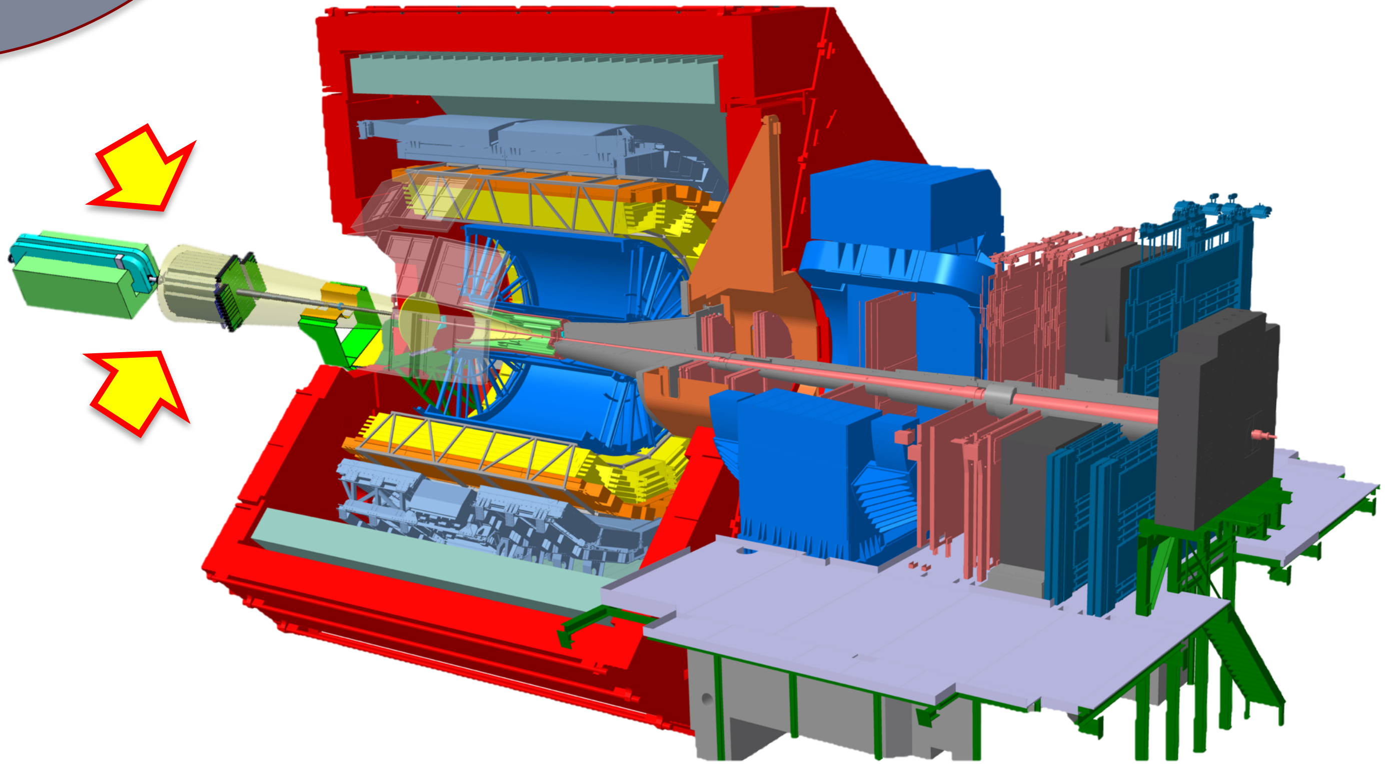


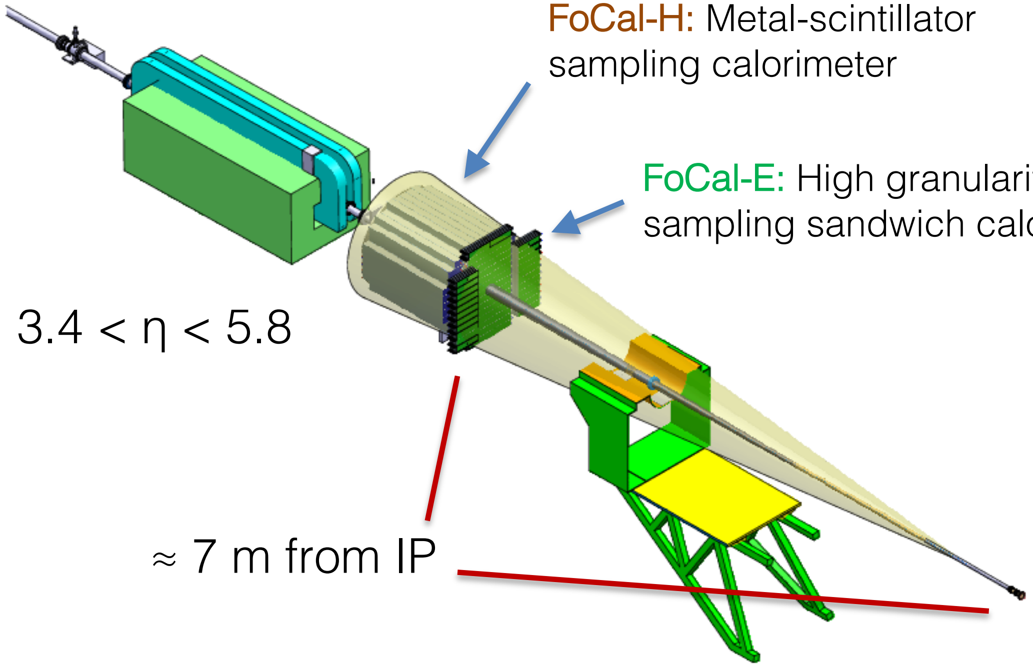
Projected uncertainties of the measurement and its impact on the PDF

arXiv:1909.05338



Towards Run 4: FoCal



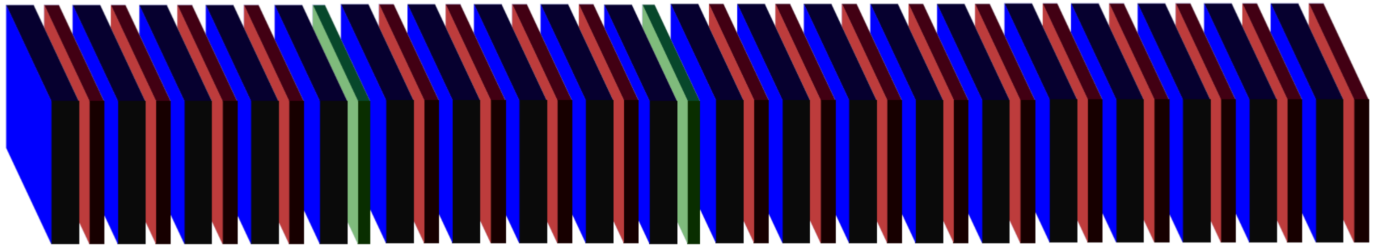


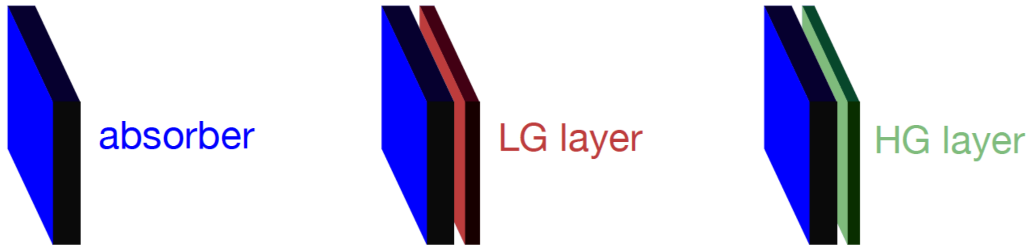
Novel calorimetry design enabling to achieve better performance for direct photon measurements:

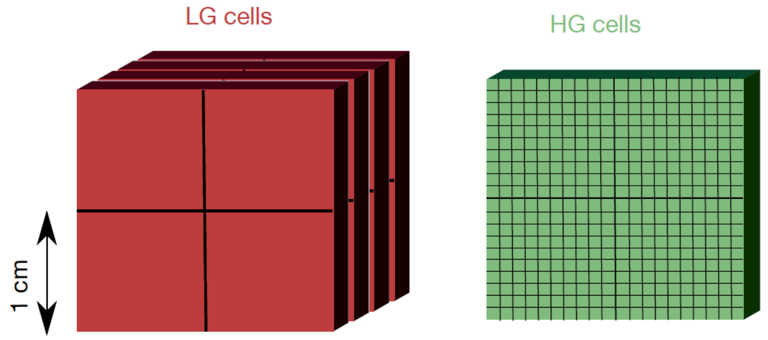
- Energy resolution ≈ 1% + position resolution ≈ 1 mm
- Combined rejection based on invariant mass and shower shape analysis, and isolation
- Signal to background ratio > 0.1 for p_T > 4 GeV/c

FoCal-E

- Test beam at SPS in summer 2021 with 4 different energies (20/40/60/80 GeV)
- Electron peak visible in all energies, described well in MC simulations



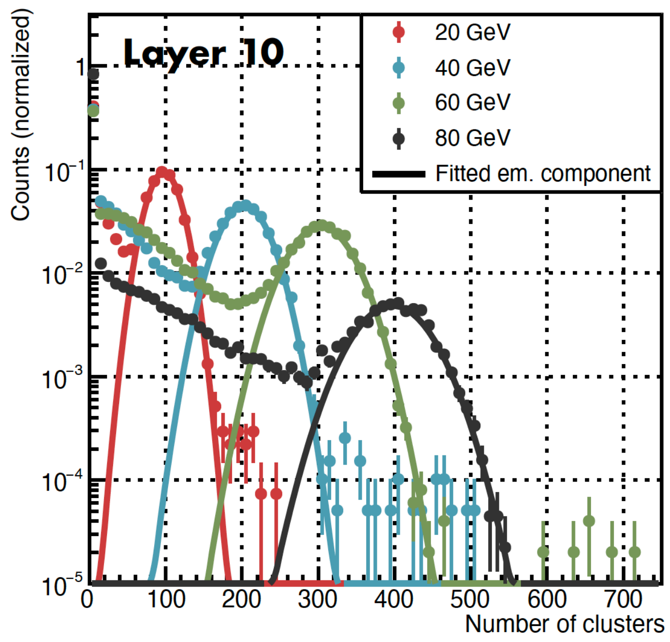


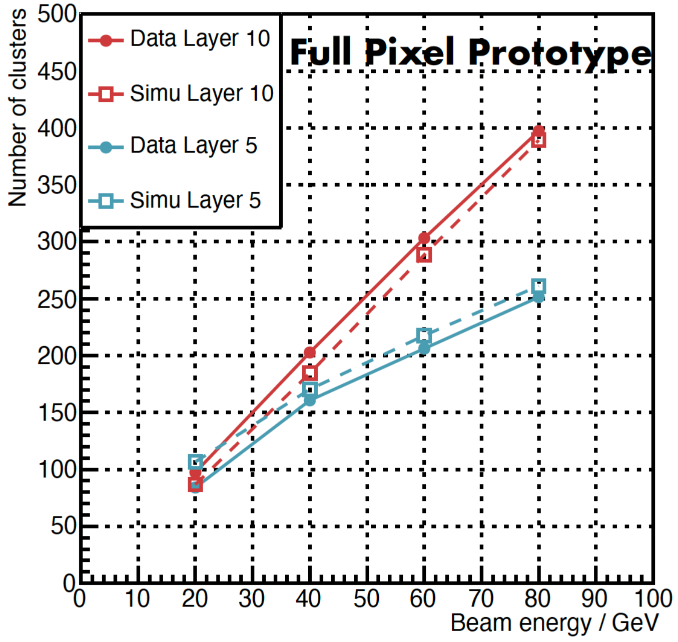


Radiator: 3.5 mm W (≈ 1 X_0)

Low Granularity: 1 × 1 cm², analogue readout

High Granularity: 30 × 30 μm² pixel, digital readout (ALPIDE)



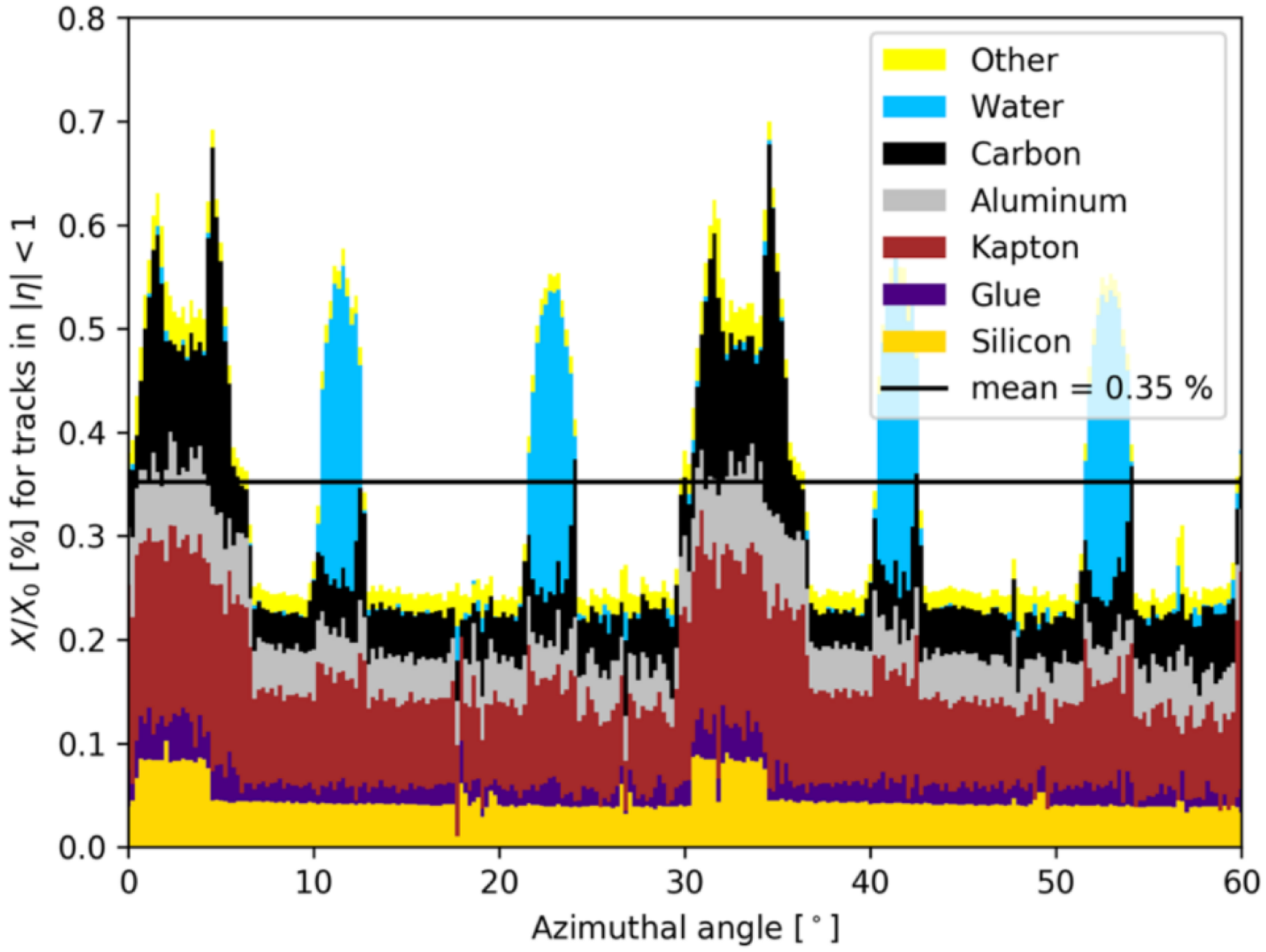


Towards Run 4: ITS3, a truly Cylindrical Inner Tracker

ITS3: replacing the 3 innermost layers of ITS2 with a next-generation vertex detector based on truly cylindrical layers (bent, wafer-scale CMOS sensors)

Stefania Beolè, **Mon 3.15 PM**

- **Pointing resolution** $\propto r_0 \cdot \sqrt{x/X_0}$
- Silicon only contributes to 15 % of the material budget for the ITS2 layers
- Pointing resolution can be improved by removing material in the first layers
  - Move from water to air cooling
  - Integrate power and data on chip
  - Self-supporting structure
- **Enhanced precision in the identification of HF signals, and rejection of displaced background for prompt signals (e.g. low-mass dielectrons)**



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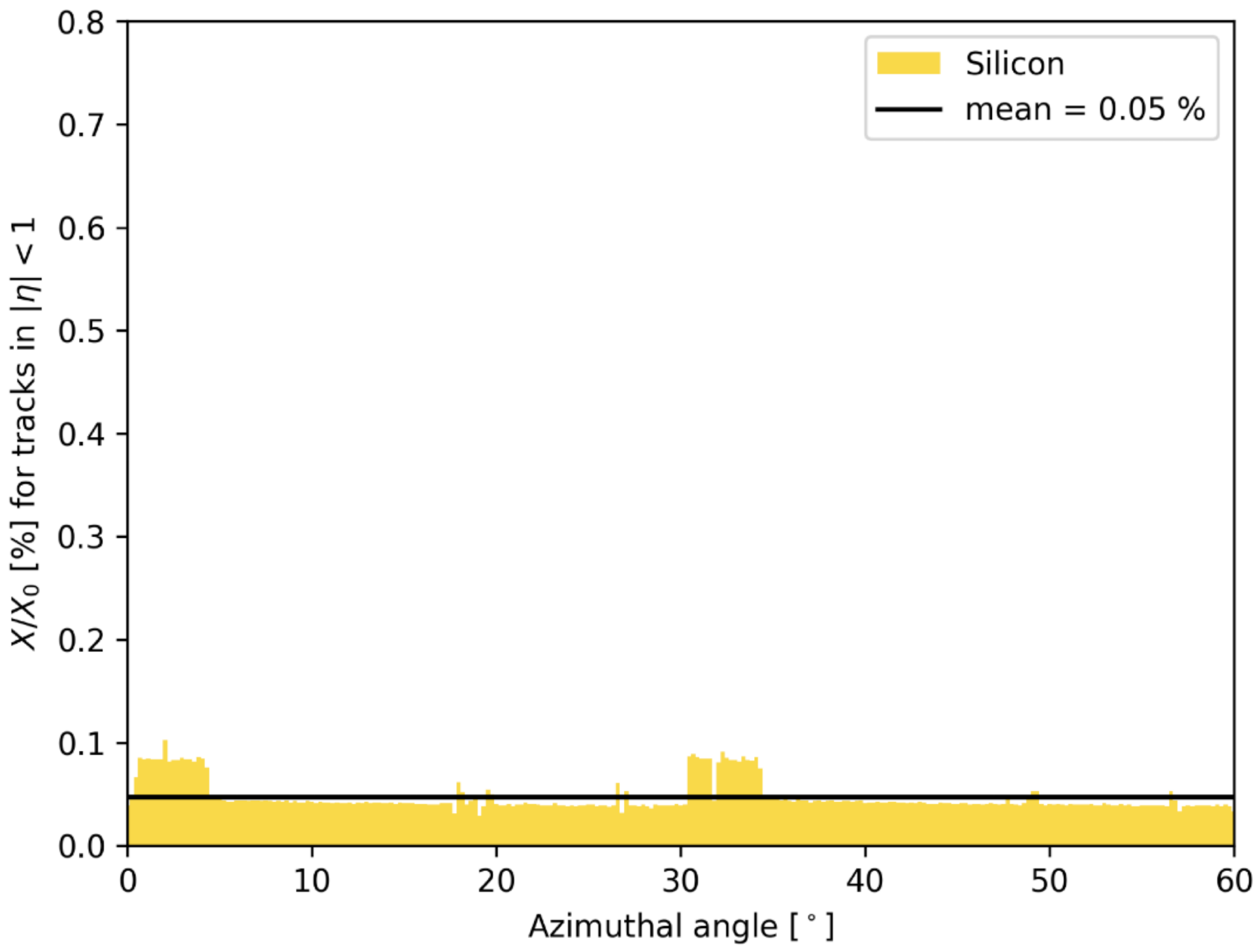
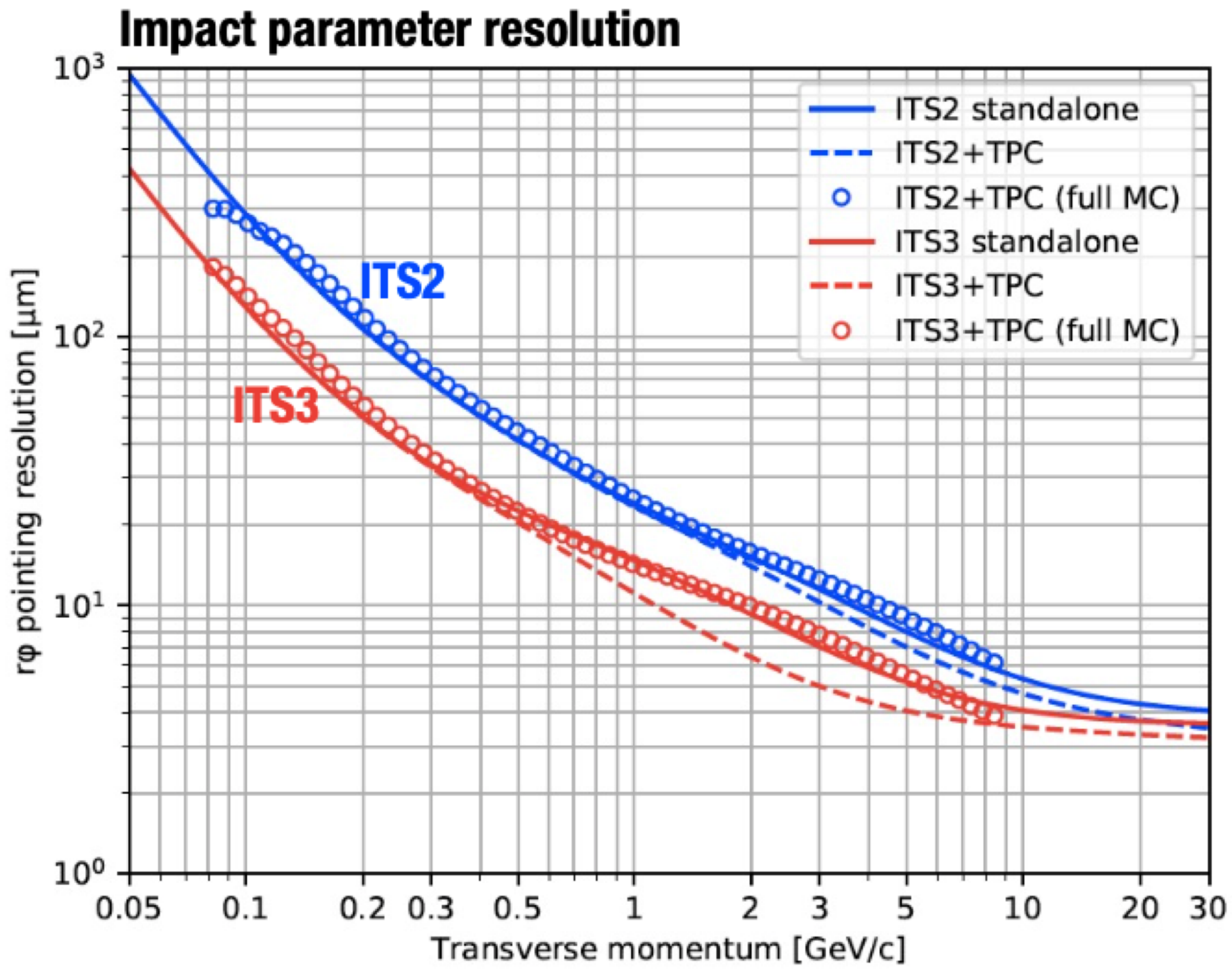
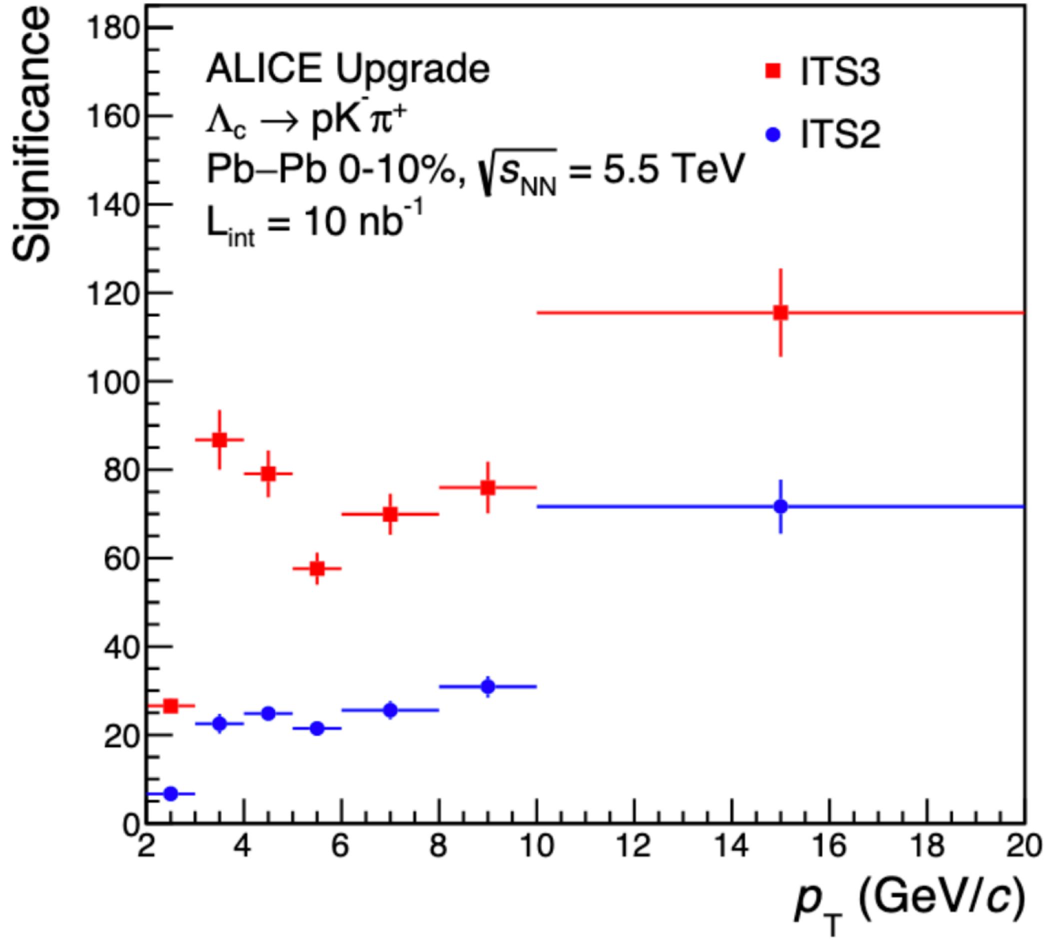


ITS3 design will allow to get closer to the IP w.r.t. ITS2: innermost layer from 22 mm to 18 mm (beam pipe to be replaced around the IP) → **further improvement in the vertex resolution**





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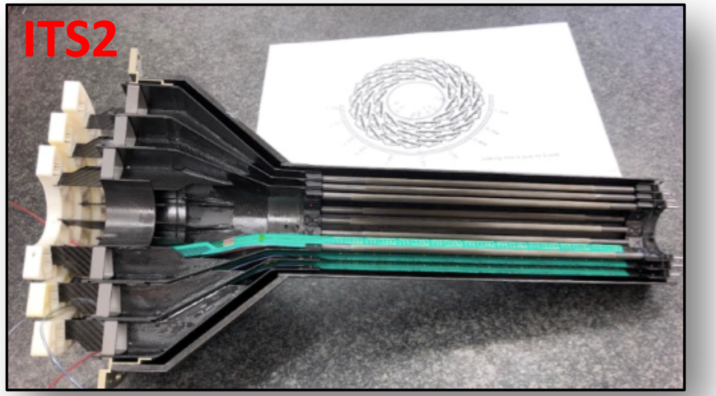
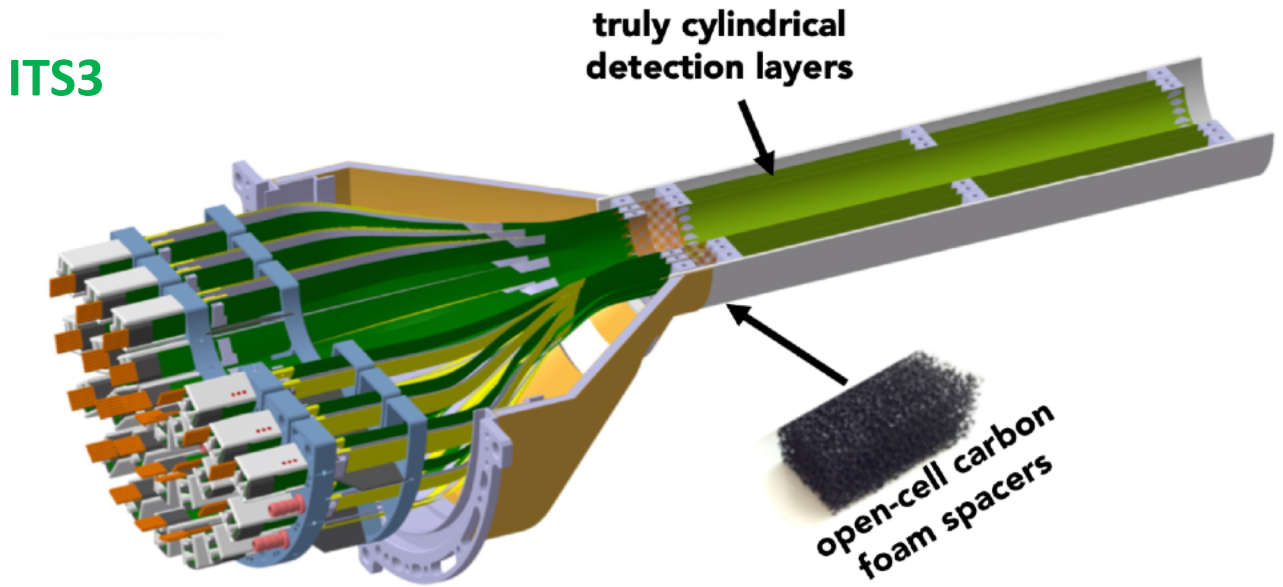
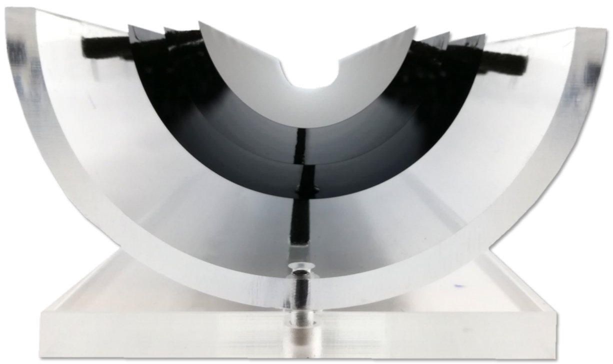




ITS3 Concept

- 280 mm long sensor ASICs out of 300 mm long stitched wafers (2 halves × 3 layers)
- 20-40 μm (0.02 - 0.04% X_0), bent shape with R = 18/24/30 mm
- Carbon foam rib to hold ASICs in place + air cooling



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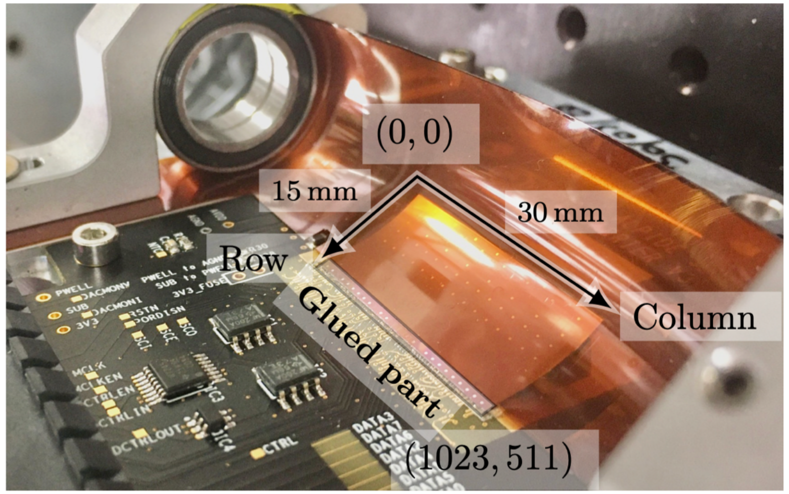
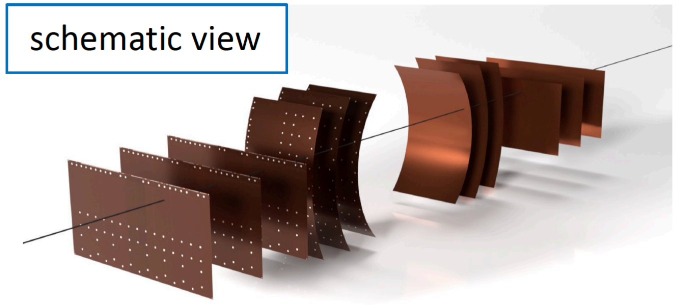




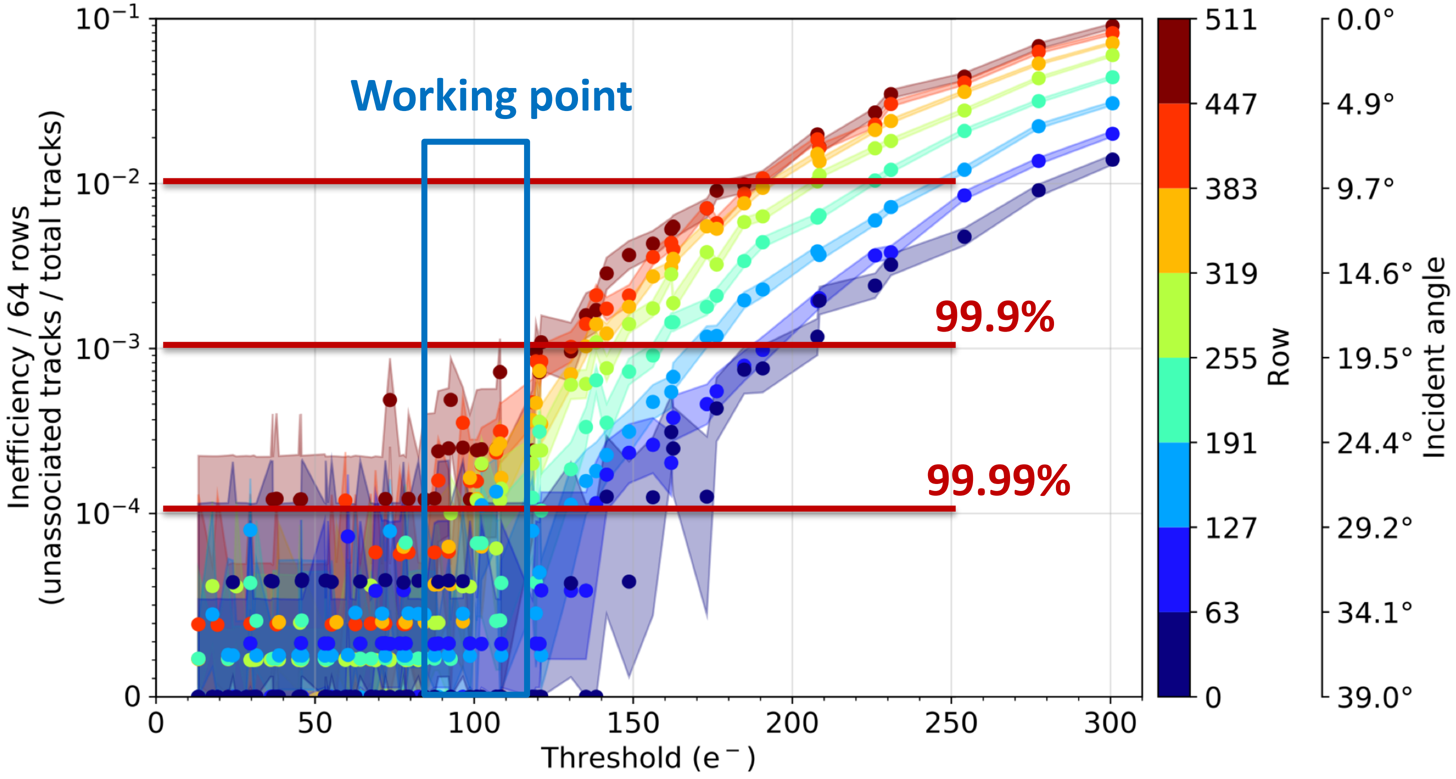
(https://doi.org/10.1016/j.nima.2021.166280)

ALPIDE telescope used for the tests

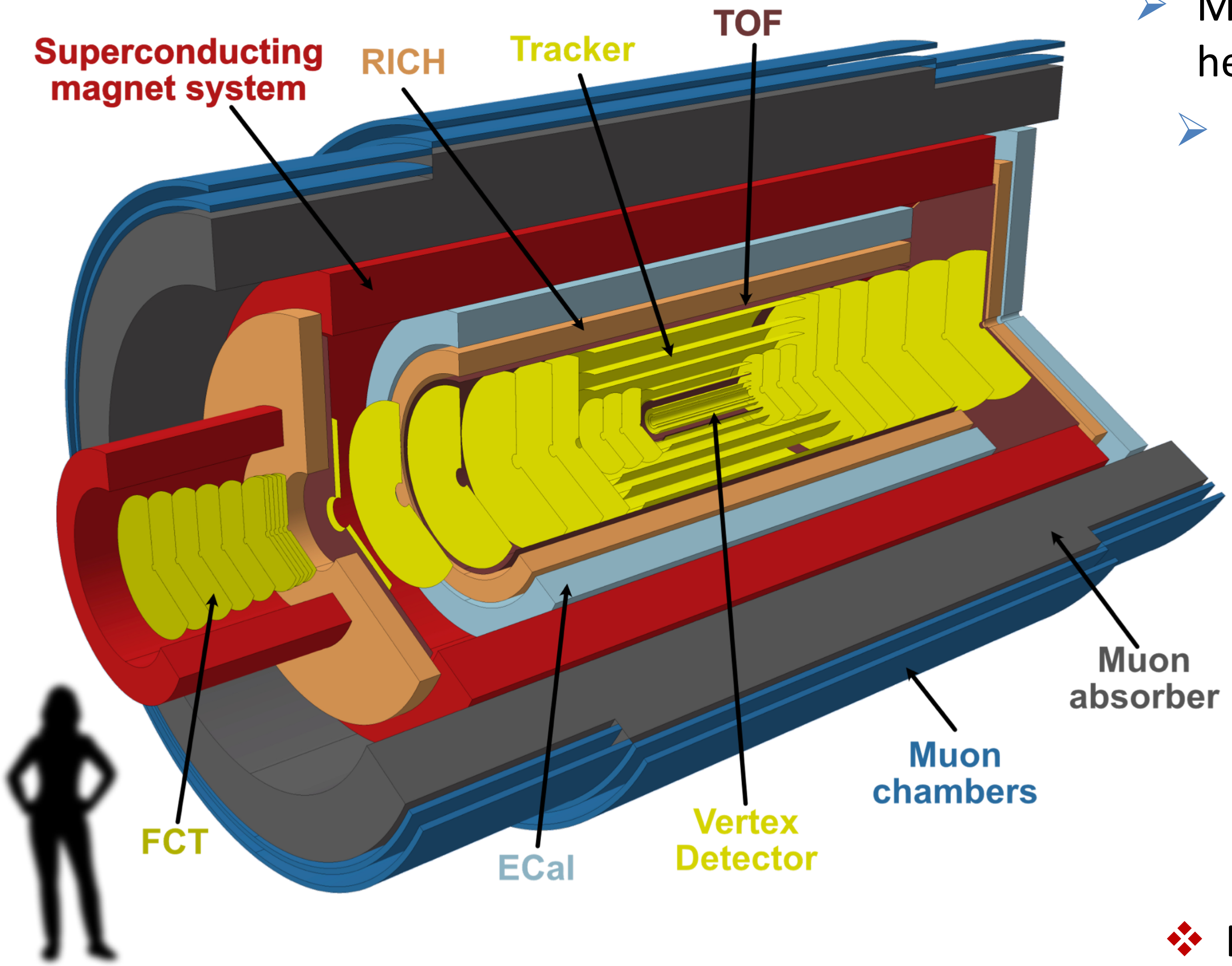
- Bent ALPIDE efficiency > 99.9%
- Digital pixel test structure efficiency > 99 %

Major milestones have been passed:

- Full-size mechanical integration prototypes
- Air cooling concept verified
- Bending of thinned sensors verified
- Tower Jazz 65 nm technology qualified
- Efficiency of building blocks and pixel matrices
- Beam characterisation of pixel sensor



ALICE 3: a new experiment for Run 5 and beyond



Selected physics case (CERN-LHCC-2022-009):

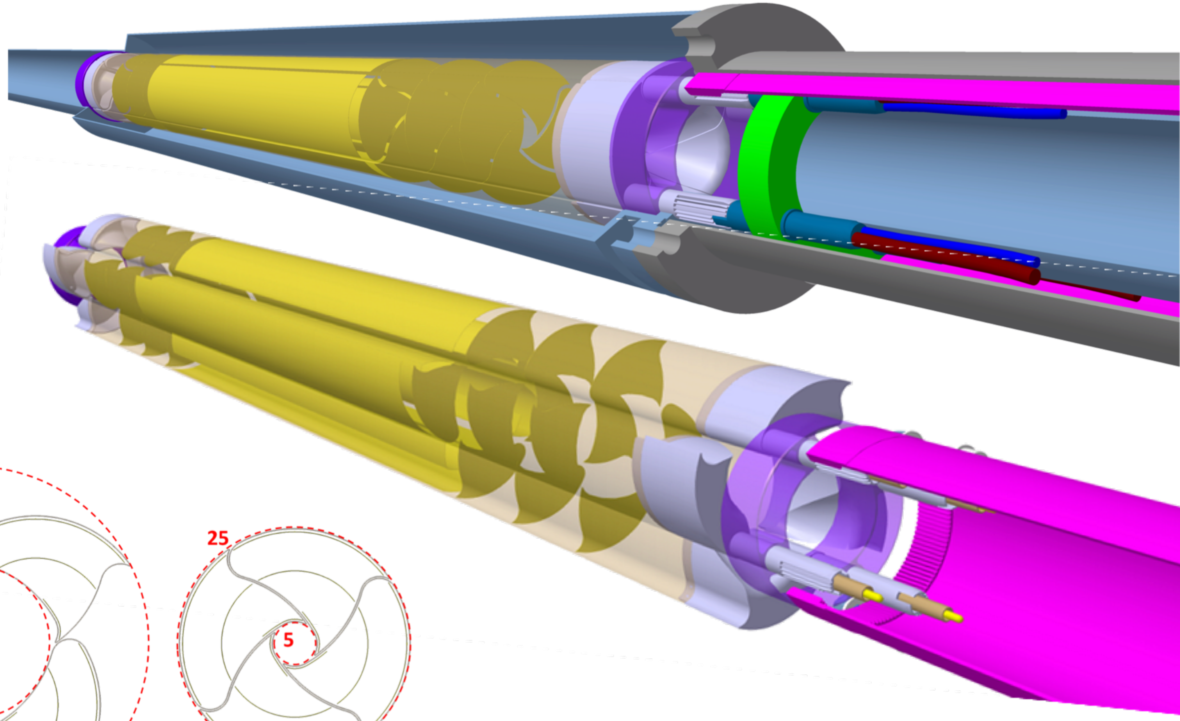
- Microscopic mechanisms of in-medium energy loss of heavy quarks
- HF hadronization mechanisms
- Non-conventional hadronic structures
- Dilepton production: temperature of the QGP and pre-equilibrium phase
- Ultra-soft photons, BSM searches, …

Laura Fabbietti, **Mon 5 PM**

- **Compact and ultra-light all-silicon tracker with large acceptance and high-resolution vertex detector**
- **Superconducting magnet system**
- **Particle identification down to vanishing p_T over 8 units of pseudorapidity**
- **Fast readout and online processing**

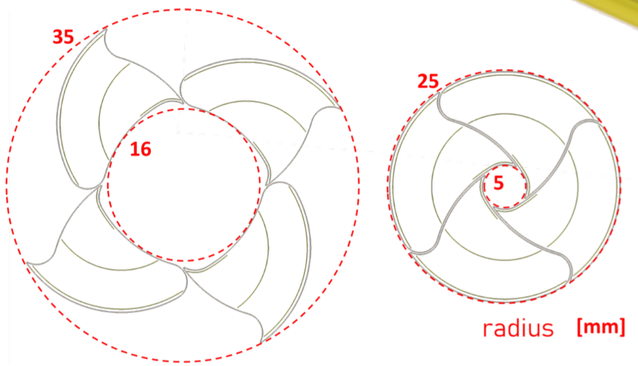
ALICE 3: Vertex Detector and Outer Tracker

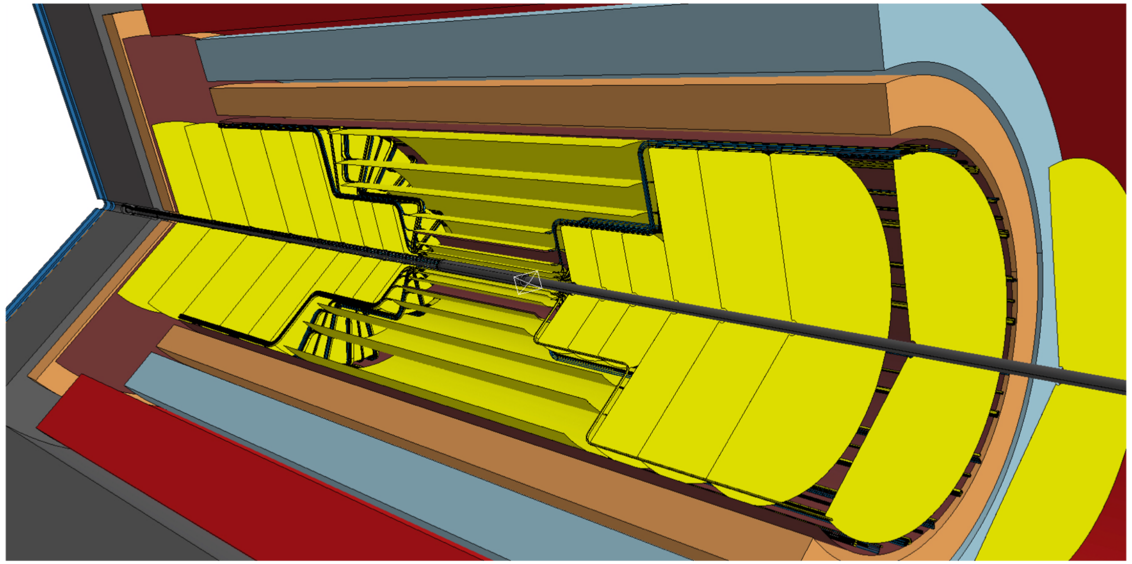
Stefania Beolè, **Mon 3.15 PM**



Vertexing layers

- Wafer-sized, bent MAPS (leveraging on ITS3 activities)
- Rotary petals for secondary vacuum (thin walls to minimise material)
- R&D on mechanics, cooling, radiation tolerance





Outer Tracker

- MAPS on modules on water-cooled carbon-fibre cold plate
- Carbon-fibre space frame for mechanical support
- **R&D challenges** on powering scheme and industrialisation

ALICE 3: PID Strategy

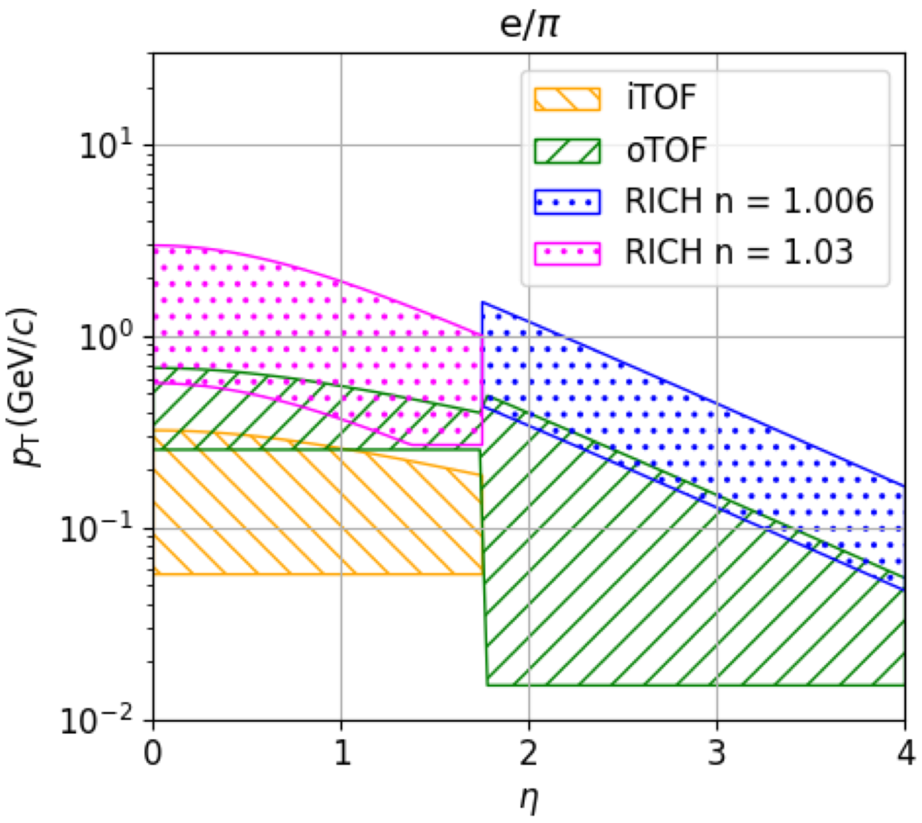
TOF detector: PID at low momenta

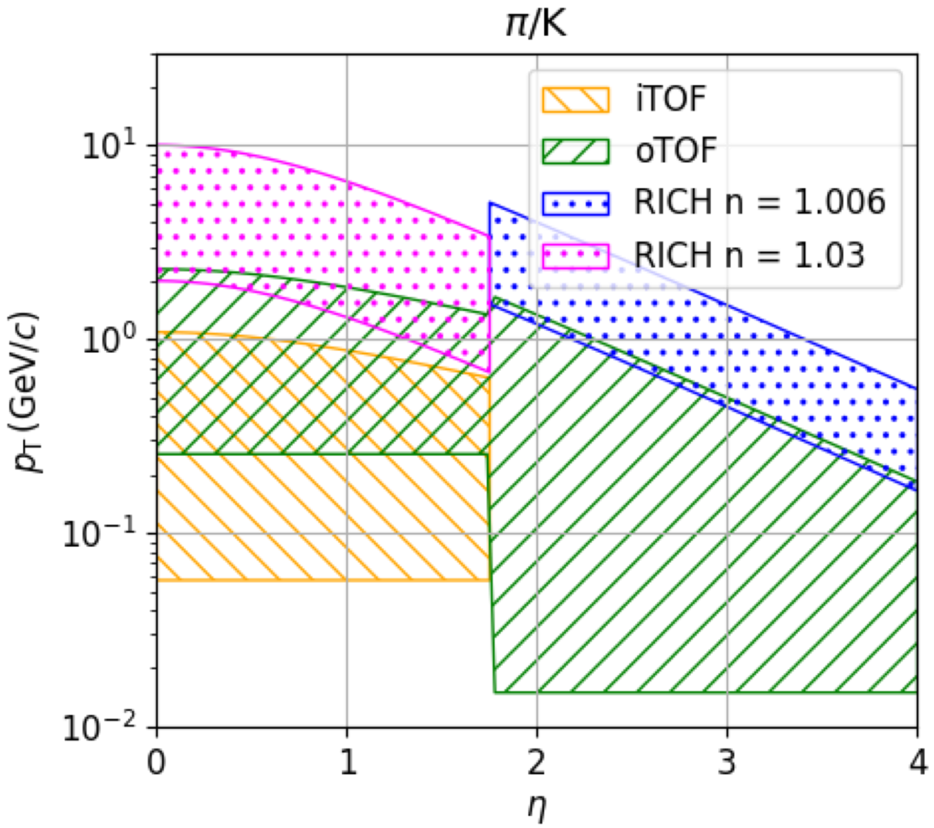
- TOF resolution ≈ 20 ps achievable with silicon timing sensors (R&D needed)
- Barrel TOF at R ≈ 19 cm and R ≈ 85 cm + forward TOF at z ≈ 405 cm

+ muon identifier
+ ECal...

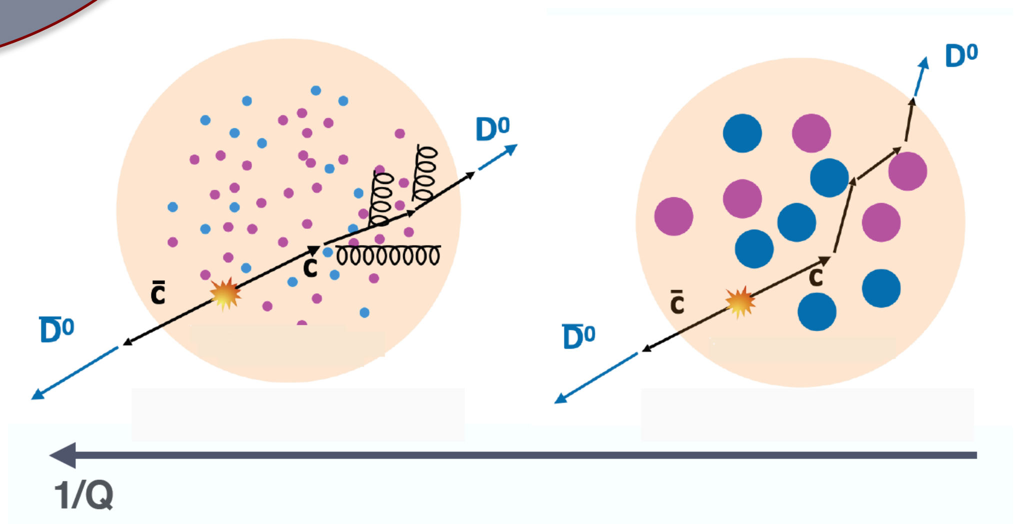
RICH detector:

- Extend PID reach of outer TOF to higher p_T
- R ≈ 120 cm, 50 ps time resolution
- Aerogel radiator + SiPM readout
- Refractive index n = 1.03 (barrel) and 1.006 (forward)





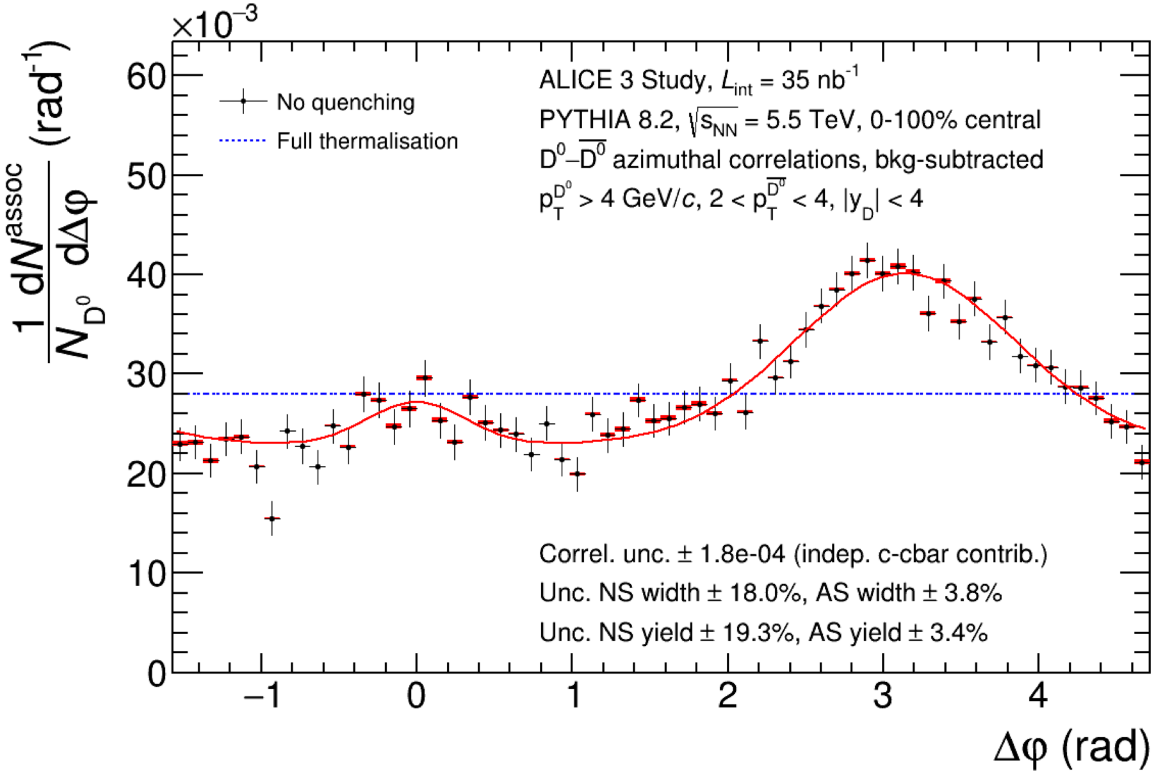
ALICE 3: HF Transport in the QGP



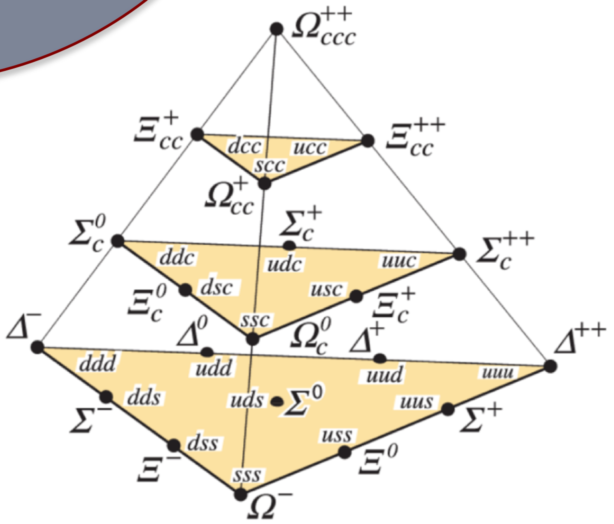
Goal: measure angular (de)correlations — direct probe of HF interaction with the QGP

- Very challenging measurement: need good purity, efficiency and η coverage
- Heavy-ion measurement at low p_T only possible with ALICE 3

- Insight on the relative importance of the **different energy loss mechanisms** as a function of p_T
- Shed light on the quasi-particle nature of the QGP at different momentum scales
- In the limit of **full thermalisation**, the flight direction of the charm quarks would be **fully randomized**, and no remnant of the initial correlation would be visible



ALICE 3: HF Hadronization in the QGP



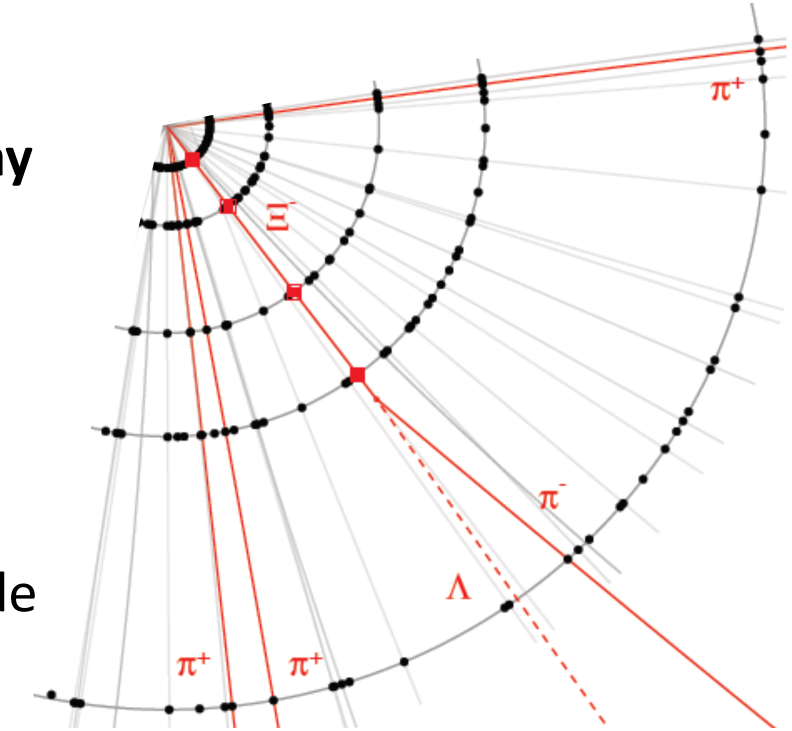
- Multi-charm baryons (almost pure coalescence hadrons) → **discrimination power on the role of the various hadronization mechanisms**
- In heavy-ion collisions at the LHC, large increase of multi-HF baryons (≈ 1000) expected via coalescence **with charm quarks from different hard scatterings (N_c ≈ 100 in central Pb-Pb)**

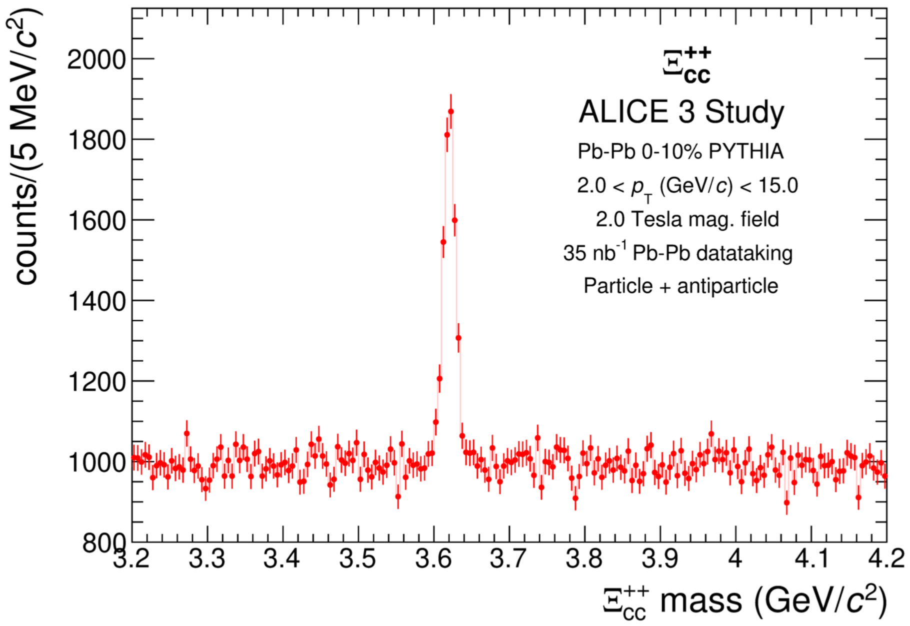
David Chinellato, Mon 3.15 PM

- Challenging **reconstruction of decay cascades, e.g.**

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

Strangeness tracking: detecting the strangeness part of the cascade in the innermost tracking layers

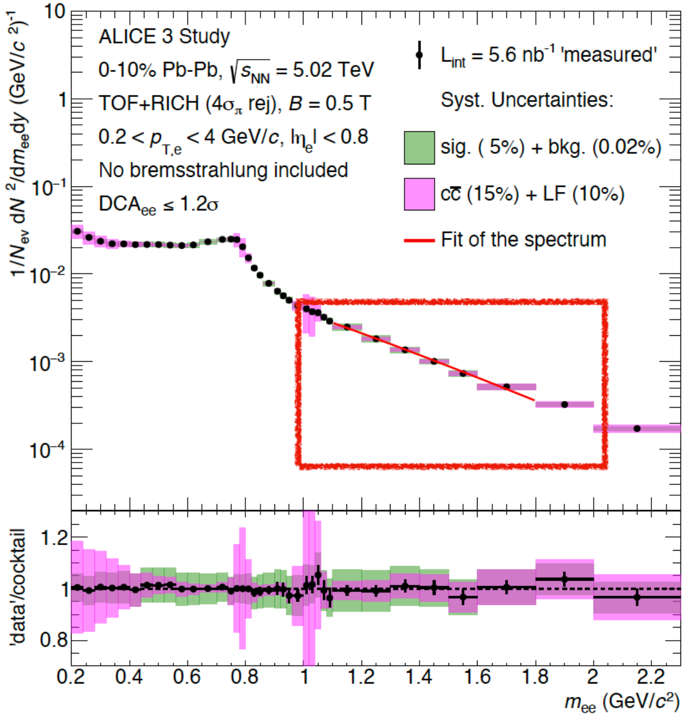




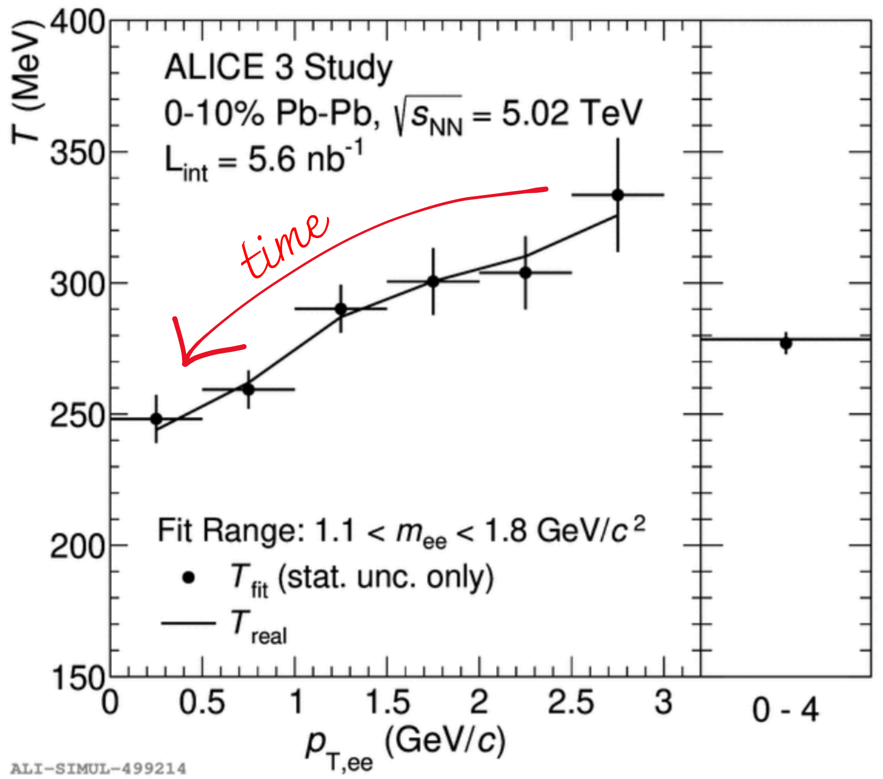
ALICE 3: EM Radiation from the QGP

- **Precision measurement of dielectrons as function of mass and p_T**
- Excellent precision for dilepton v_2 vs p_T in different mass ranges → time evolution of emission
- Improved pointing resolution → significant reduction of charm contribution and associated uncertainty: unique opportunity at the LHC

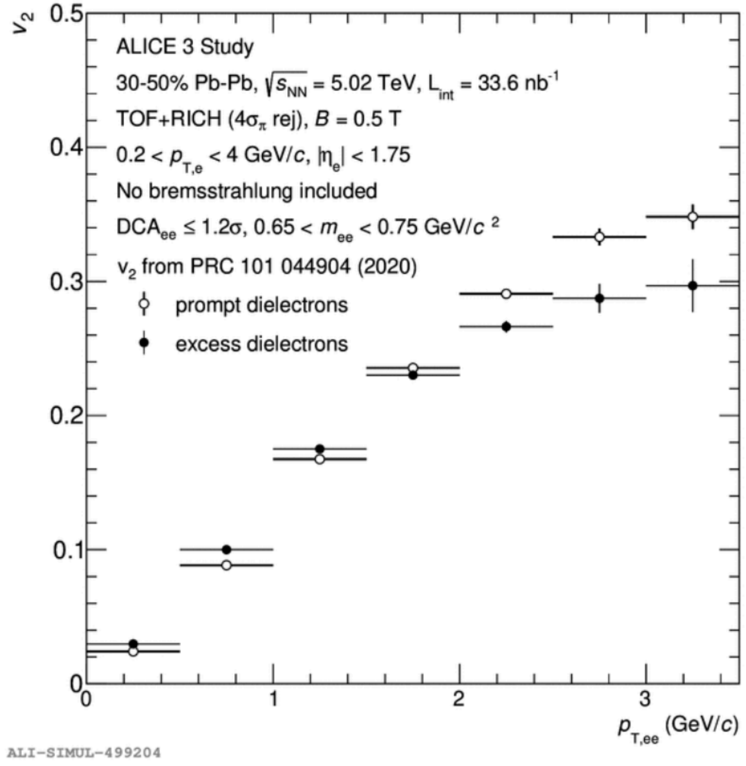
Dielectron mass distribution



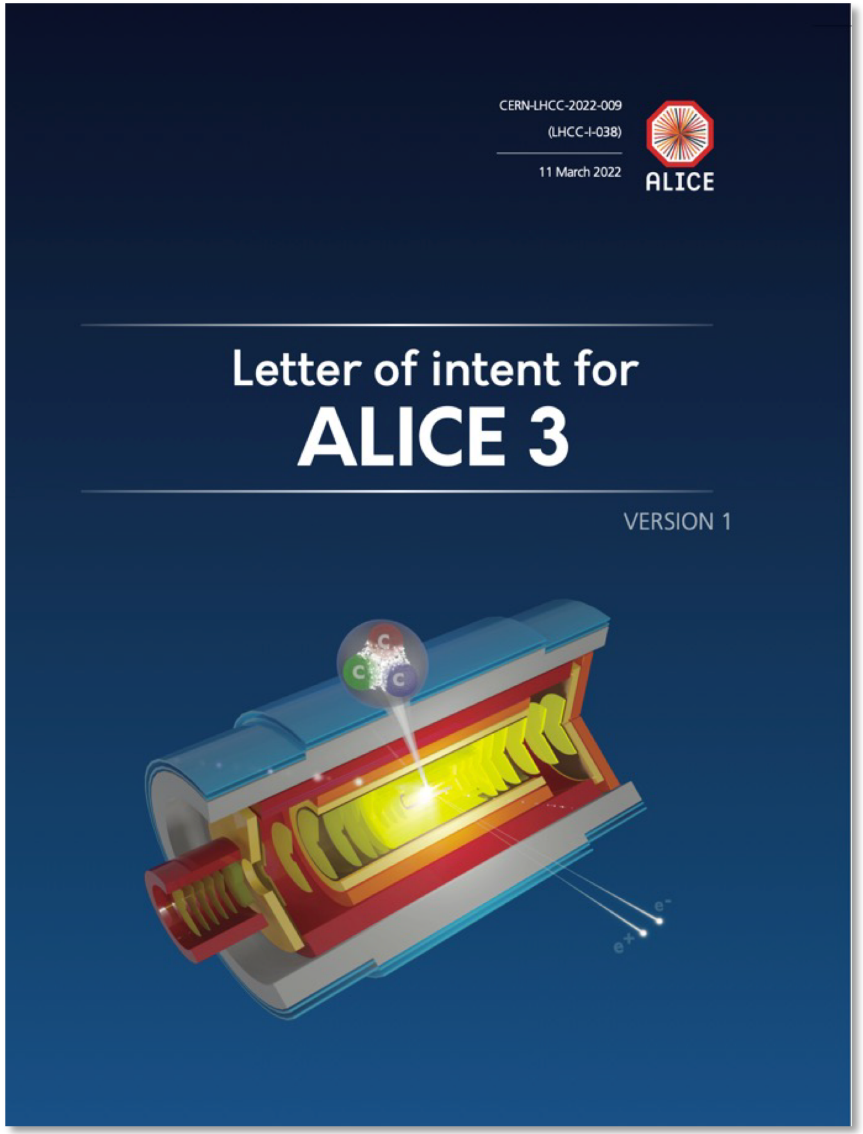
Temperature from slope (M_{ee})



Dielectron v_2



ALICE 3: Costs and Planning



- **2023-25**: selection of technologies, small-scale proof of concept prototypes (≈ 25% of R&D funds)
- **2026-27**: large-scale engineered prototypes (≈ 75% of R&D funds) → Technical Design Reports
- **2028-31**: construction and testing
- **2032**: contingency
- **2033-34**: Preparation of the cavern and installation of ALICE 3

CERN-LHCC-2022-009

Summary

Evgeny Kryshen,
Mon 5 PM

- **ALICE LS2 upgrade program successfully accomplished:** detector ready to take data in Run 3 with a new inner tracking system, a new TPC readout, and a new data acquisition system

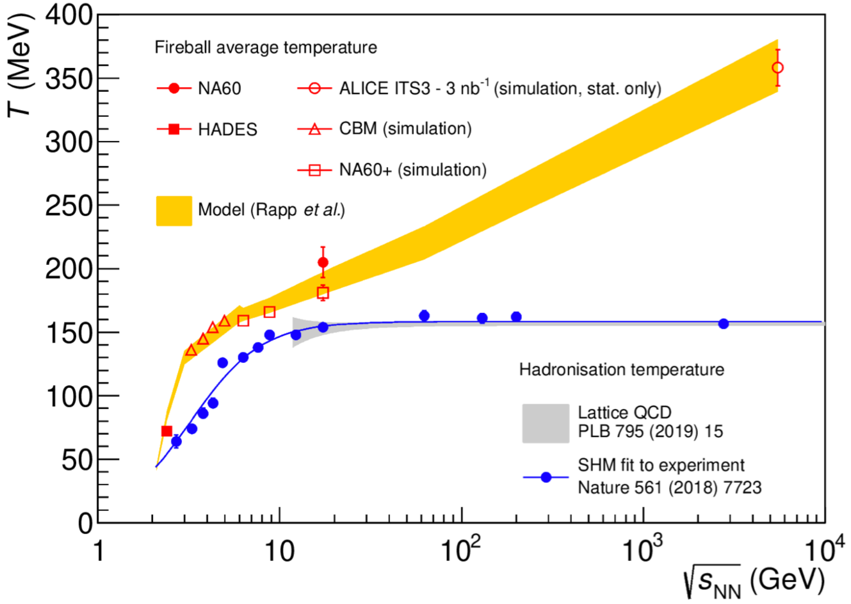
- **ALICE LS3 upgrade program under finalization: next-generation vertex detector with truly cylindrical layers (ITS3), forward calorimeter (FoCal). Significant R&D progress:**
  - Operation of bent silicon sensors in test beams
  - Demonstration of FoCal concept in test beams
  - Complete prototype under construction

- **ALICE LS4 upgrade program already well defined:** Letter of Intent of the ALICE 3 proposal recently reviewed by LHCC → CERN-LHCC-2022-009. **Recommendation to proceed with R&D programme**

Backup Slides

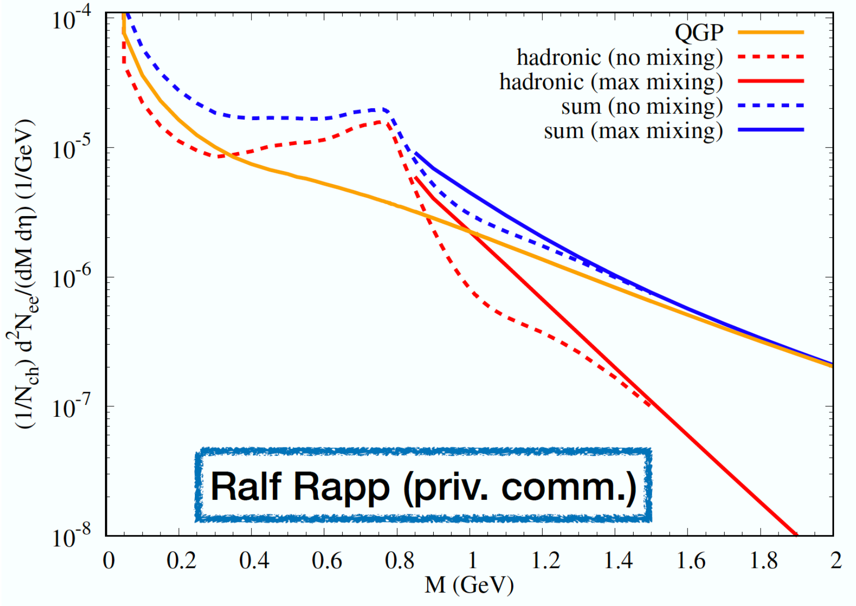
Thermal Radiation and Chiral Symmetry Restoration

Precision temperature measurement with uncertainties comparable to low-energy experiments?



Effects of chiral symmetry restoration, predicted by QCD, can be studied at the LHC at vanishing μ_B

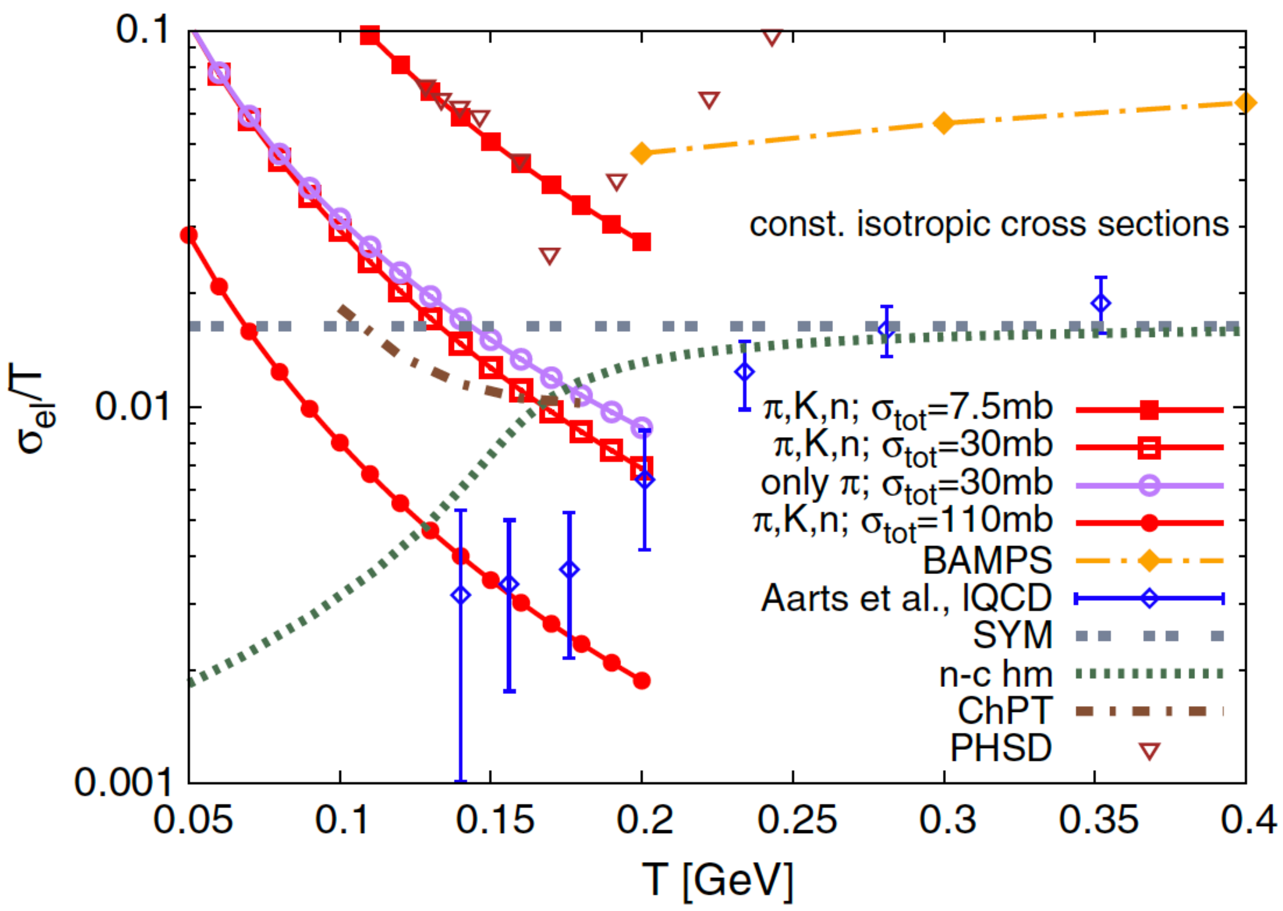
- Effect on **ρ-a$_1$ mixing** on the dilepton mass spectrum above ϕ peak
- In-medium broadening of narrow vector resonances?



Measurement of pre-equilibrium dileptons through multi-differential (p_T, flow, polarization, DCA) measurements: **fireball chronometer**

Dilepton Spectra and Electric Conductivity

- **Electric conductivity, or electric charge diffusion coefficient:** response of an equilibrated relativistic gas of electrically charged particles, upon the influence of a small, static, electric field



- **Lower and upper limits of thermal dilepton production spectra connected to QGP conductivity:** spectra can be exploited to constrain predictions on the QGP electric conductivity

Precise data are needed to challenge theoretical models on the estimation of the diffusion coefficients of the strongly interacting QGP

Phys. Rev. D 93, 096012 (2016)

Soft Photons: Testing Low's Theorem

- **Soft photons ($p_T^{\gamma} \ll p_T^{hadrons}$ ≈ 300-500 MeV)** can be produced at any stage of hadronic collisions, with no specific constraints in their number by conservation laws

- **Low's theorem:** QCD prediction providing a precise relation between very soft photon and inclusive hadron production

$$\frac{dN_\gamma}{d^3k} = \frac{\alpha}{2\pi k_0} \int d^3p_1 d^3p_2 d^3p_3 \ldots d^3p_N \sum_{i,j=1}^{N} \eta_i \eta_j e_i e_j \frac{-(p_i \cdot p_j)}{(p_i \cdot k)(p_j \cdot k)} \frac{dN_{\text{hadrons}}}{d^3p_1 d^3p_2 d^3p_3 \ldots d^3p_N}$$

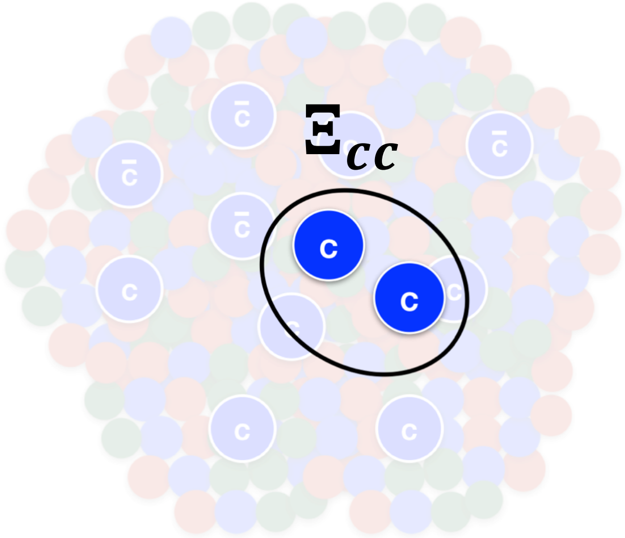
- **Soft photon puzzle:** nearly every measurement shows factor 2–5 enhancement w.r.t. Low's theorem predictions. **Proposed explanations:** cold quark-gluon plasma, quark synchrotron radiation, string fragmentation. Handle to investigate fundamental non-perturbative properties of QCD

→ Ultra-light converter-tracker + calorimeter at forward η should allow measuring soft photons down to $p_T \approx 10$ MeV (possibly exploiting HBT analysis techniques)

Multi-HF Baryons

- In heavy-ion collisions, large increase of multi-HF baryons (≈ 1000) expected via coalescence **with charm quarks from different hard scatterings ($N_c \approx 100$ in central Pb-Pb)**

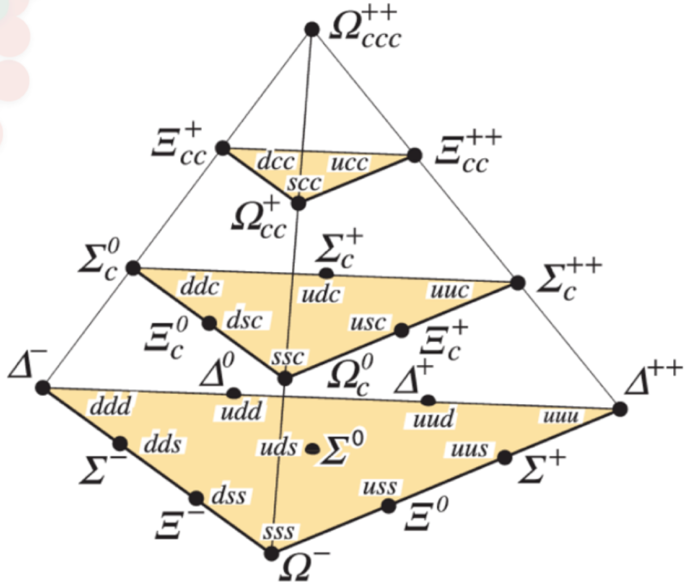
Multi-charm baryons are almost pure coalescence particles: (potentially) large discrimination power on the role of the various hadronization mechanisms



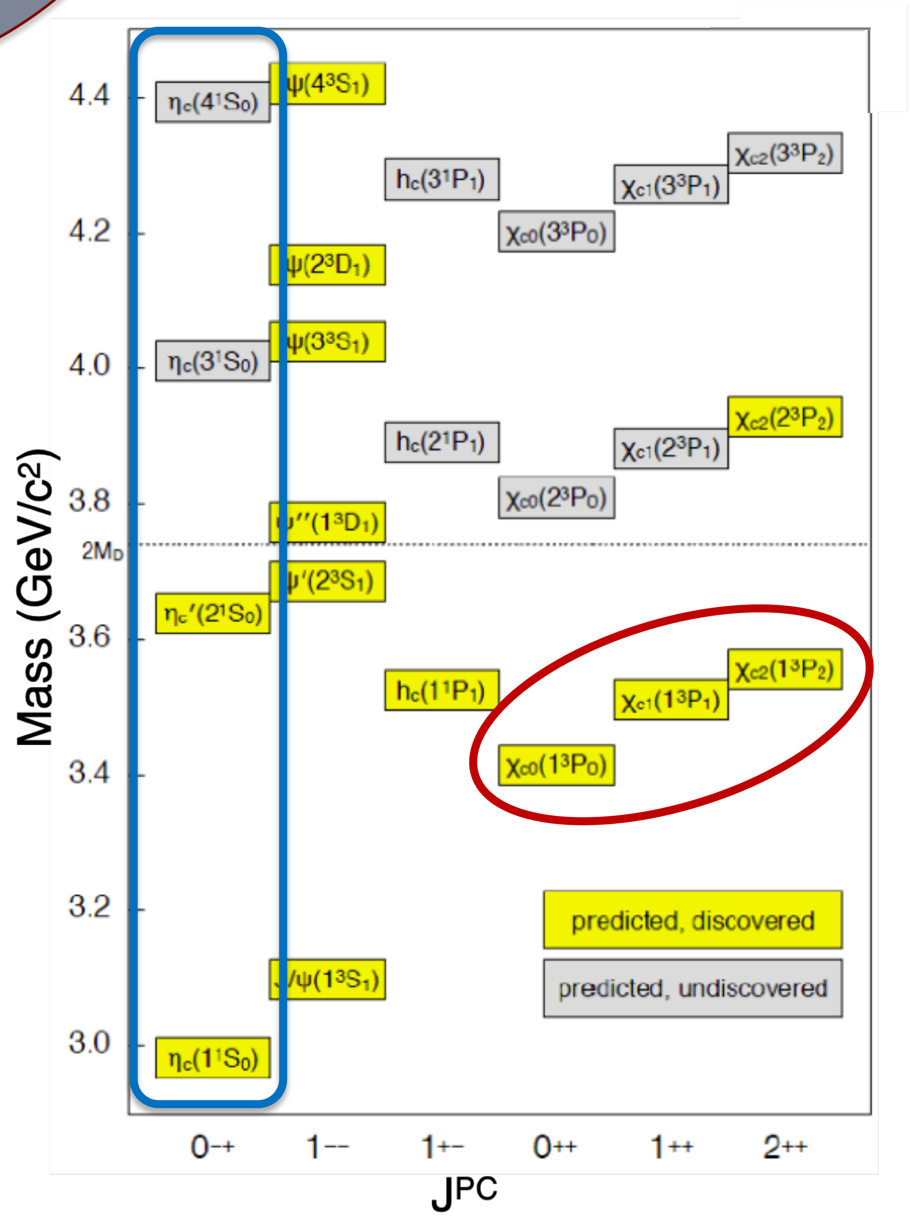
Ω_{cc} and Ω_{ccc} not yet observed. Ω_{ccc} may only be accessible in heavy-ion collisions

Establish clean **reconstruction of decay cascade,** exploiting state-of-the-art vertexing and tracking

$$\Omega_{ccc}^{++} \rightarrow \Omega_{cc}^{+} + \pi^{+}$$
$$\Omega_{cc}^{+} \rightarrow \Omega_{c}^{0} + \pi^{+}$$
$$\Omega_{c}^{0} \rightarrow \Omega^{-} + \pi^{+}$$
$$\Omega^{-} \rightarrow \Lambda + K^{-}$$
$$\Lambda \rightarrow p + \pi^{-}$$



Quarkonium Measurements



Complete spectroscopy of states in the QGP → study **direct** exclusive quarkonium production by subtraction of the feed-down components

χ_c states:

- Binding energy in between J/ψ and ψ(2S)
- Sizable feed-down contribution to J/ψ
- **Most promising decay mode: $\chi_c \rightarrow$ J/ψ γ (γ measured with calorimetry and/or pair conversion)**

Pseudoscalar η_c states

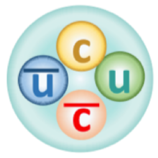
- Similar behaviour in the QGP w.r.t. vector states e.g. J/ψ
- Factorisation approach + heavy-quark spin symmetry assumption allows for the simultaneous treatment of J/ψ and η_c(1S)

Heavy-Flavor Exotica

Hadrons with more than 3 valence quarks for which we don't have a complete understanding of their nature: e.g. X(3872)

- **Detailed and differential study in heavy-ion collisions proposed as a tool to indirectly constrain its nature:** production yield in the dense QCD environment could be largely influenced by its inner structure

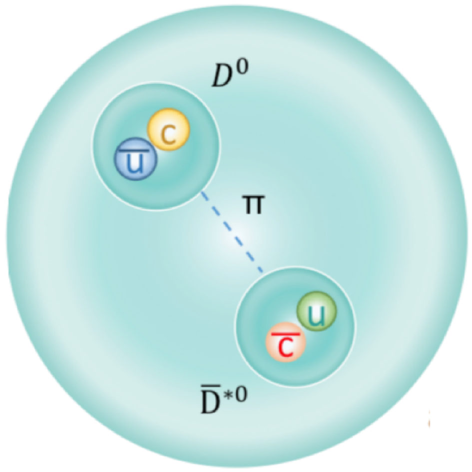
Tetraquark (4q)



$r_{4q} \approx r_{c\bar{c}}$
≈ 0.3 fm

VS

$D^0 - \bar{D}^{*0}$ molecule

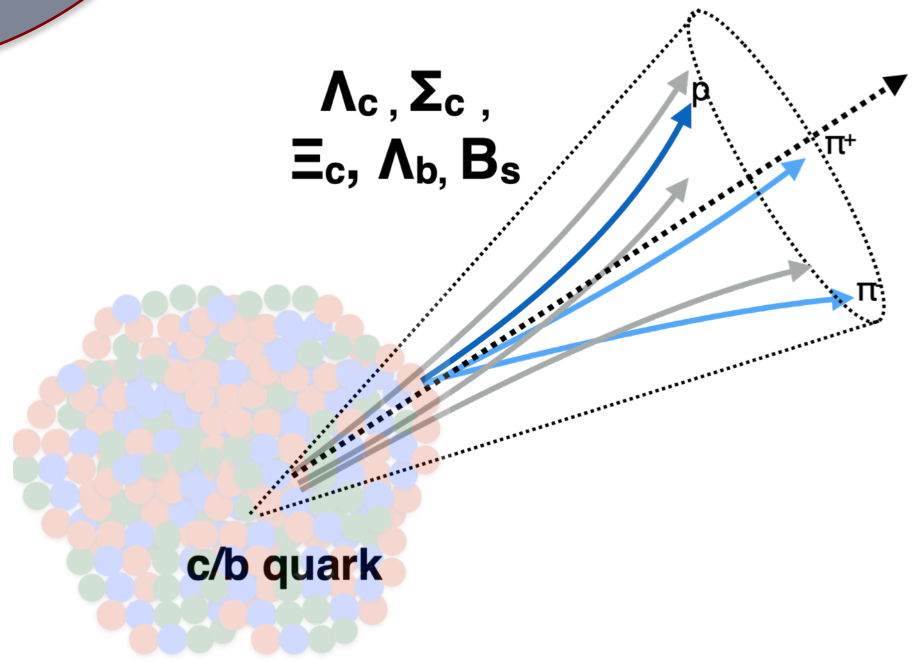


$r_{molecule}$
as large as 5 fm

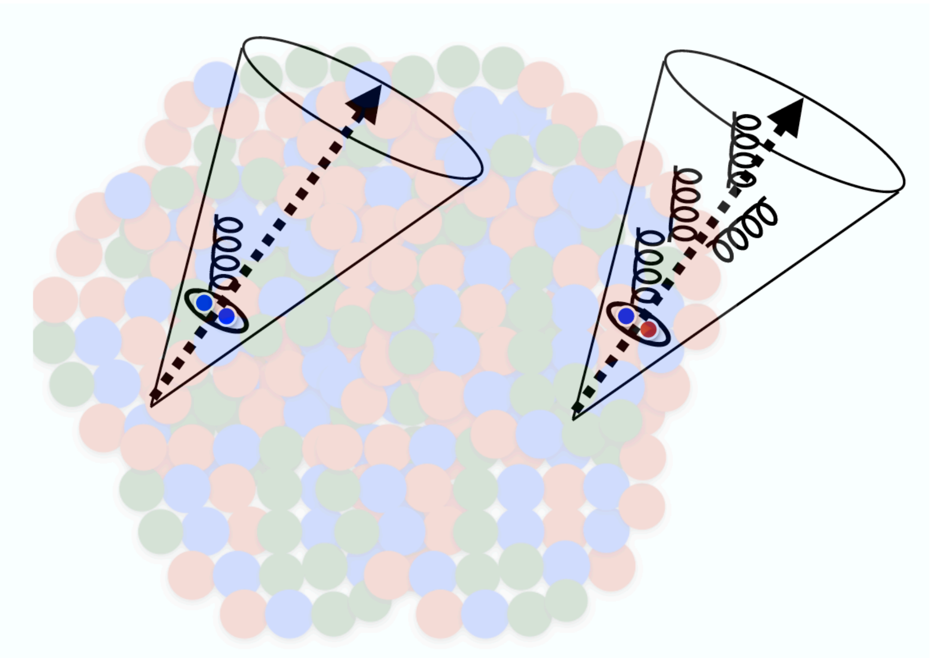
- If the mystery of its nature is addressed by the end of Run 4 we will have a **new, tuned tool to study HF hadronization in the QGP**

Low-p_T reach crucial for a full characterization of the hadronization mechanism

Quarkonia and HF Hadrons in Jets



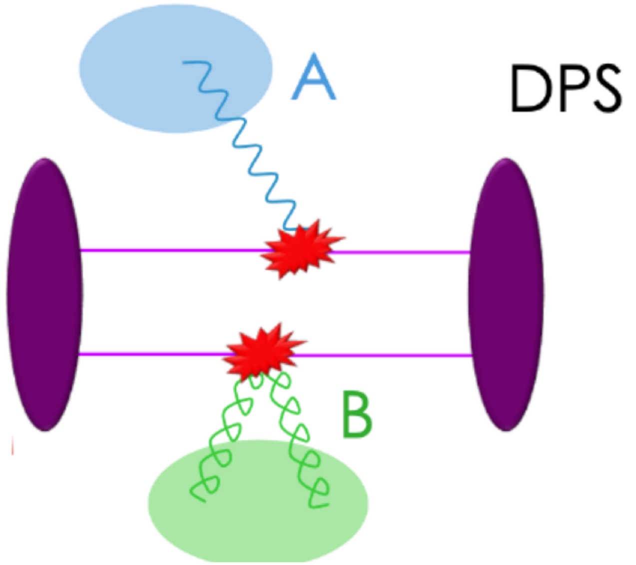
- **Direct measurement of the fragmentation patterns** of charmed/beauty mesons and baryons
- **Jets provide energy and direction scale** for the fragmentation process: proxy for initial HF quark direction and energy



- **Studying the fragmentation shower of quarkonium and open HF inside jets in AA collisions:** new insights into the properties of in-medium propagation of quarkonium states inside the QGP

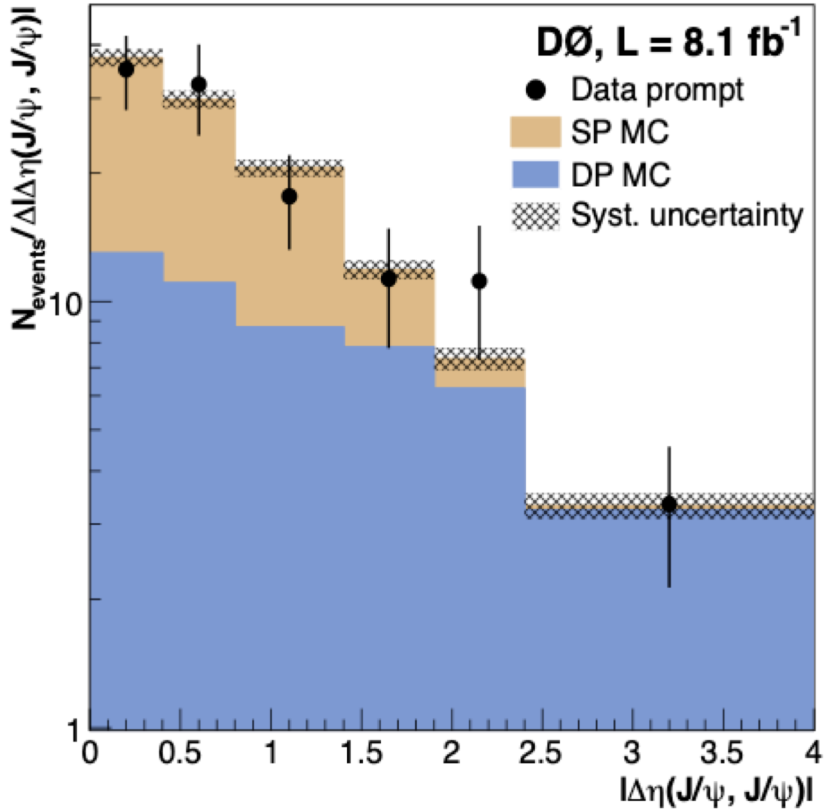
➡ Low-p_T reach needed for a complete picture of the fragmentation functions

Double Parton Scattering: Quarkonia and Open HF



Measurements of the production of quarkonia "in association" with another final state particle

Double parton scattering: two independent scatterings in one pp/pA collision



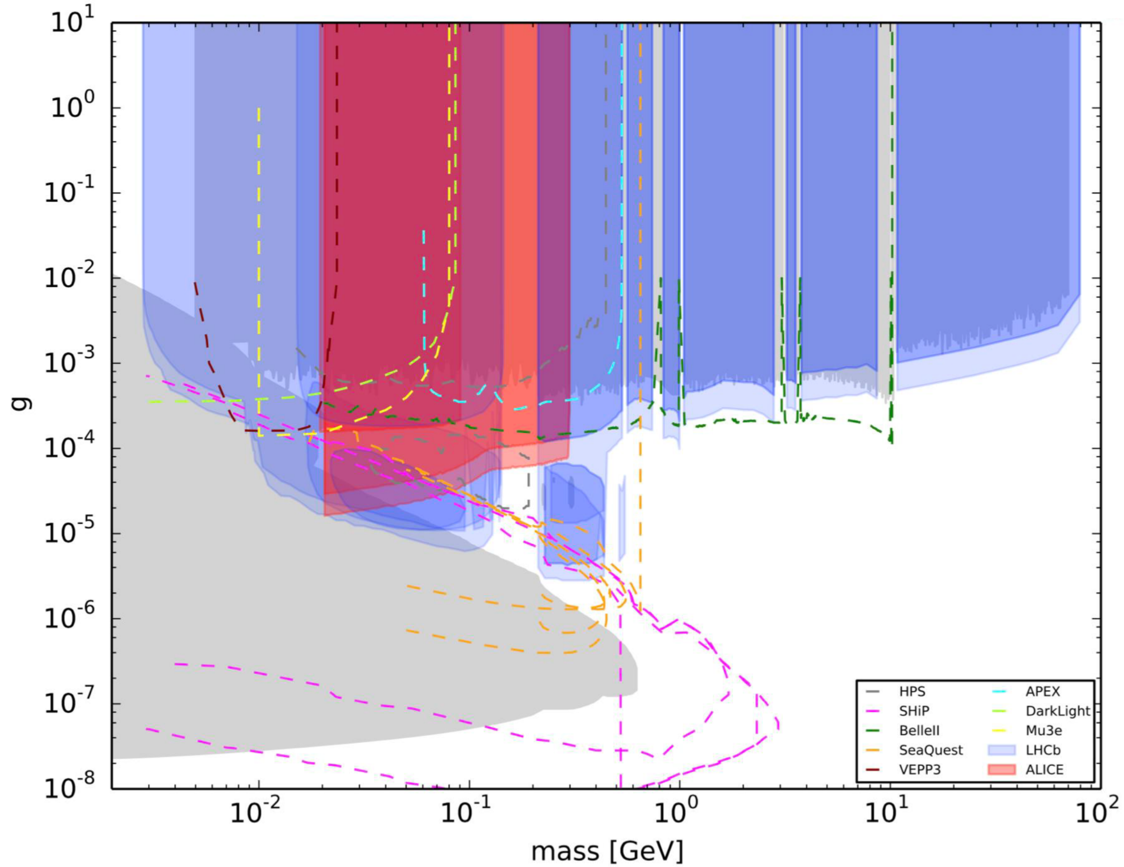
Phys. Rev. D 90, 111101(R)

- **Powerful probe to study** factorization of hard processes in hadronic collisions, and transverse parton densities in nucleons and nuclei
- **DPS events characterized by large pseudorapidity gap between the two hadrons: → At large Δη pure DPS "environment"**

Dark Photons

Dark Photons: hypothetical extra-U(1) gauge bosons, motivated by:

- Antiproton spectrum and positron excess in cosmic ray observations
- Muon anomalous magnetic moment



Phys. Rev. Lett. 116, 251803 + ALICE projections

Possible channels in ALICE 3:

- Meson decays such as π^0, η, ϕ Dalitz decays, D^{*0} decays, radiative J/ψ and Υ decays
- **Final-state radiation, Drell-Yan, thermal rad. for M >1 GeV**
- Displaced searches (M < 20 MeV)

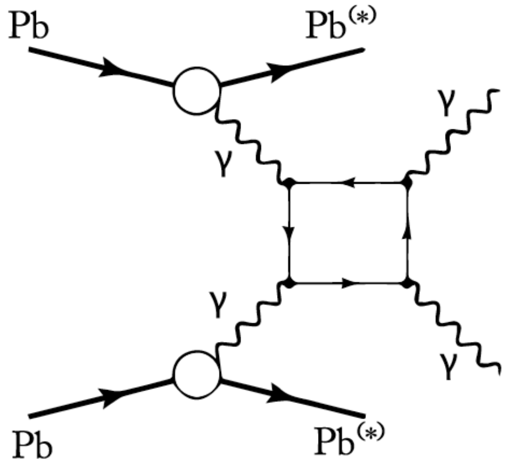
Requirements for ALICE 3

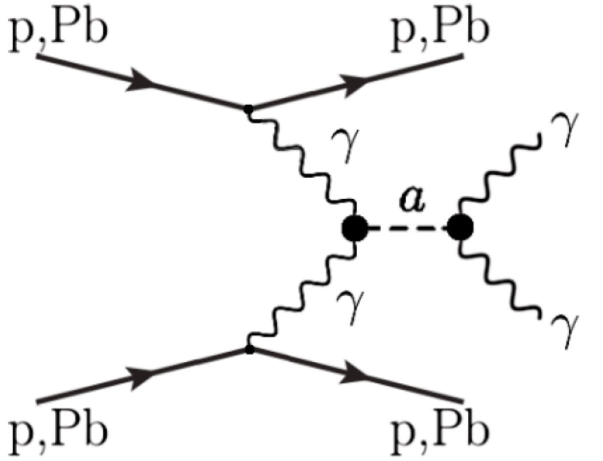
- Good electron ID capability for wide momentum range (low momenta from π^0 Dalitz decays to high momenta from DY and thermal dielectrons)
- High-rate capability and in-bunch pileup separation + good vertexing to separate thermal dielectrons and HF pairs

BSM Searches in Ultra-Peripheral Collisions

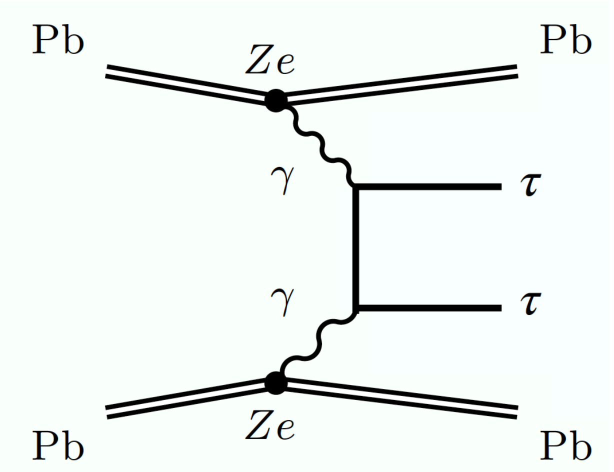
Ultra-peripheral heavy-ion collisions (UPC): clean environment + huge $Z^4 \approx 5 \cdot 10^7$ enhanced gamma+gamma rate w.r.t. pp

- **Searches of BSM particle coupling predominantly to photons:** modifications of the light-by-light scattering rates from virtual corrections from heavy particles (magnetic monopoles, vector-like fermions, dark sector particles)





- **Precision measurements of EM couplings of SM particles:** anomalous magnetic moment (g-2) of the tau



➡ **Challenge for ALICE 3:** acceptance for tau and light-by-light scattering down to low p_T?

ALICE 3: Costs and Planning

System	Technology	Cost (MCHF)
Tracker	MAPS	30.5
TOF	Monolithic timing sensors (integrated gain layer)	14.8
	Hybrid LGADs	26.4
RICH	Aerogel and monolithic SiPMs	20.9
	Aerogel, analog SiPMs + read-out	34.0
ECal	Pb-Sci sampling and $PbWO_4$	17.0
Muon ID	Steel absorber, scintillator bars, SiPMs	7.0
FCT	MAPS (solenoid and dipoles)	2.3
	MAPS (solenoid and separate dipole for FCT)	5.3
Magnets	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		**141.4**

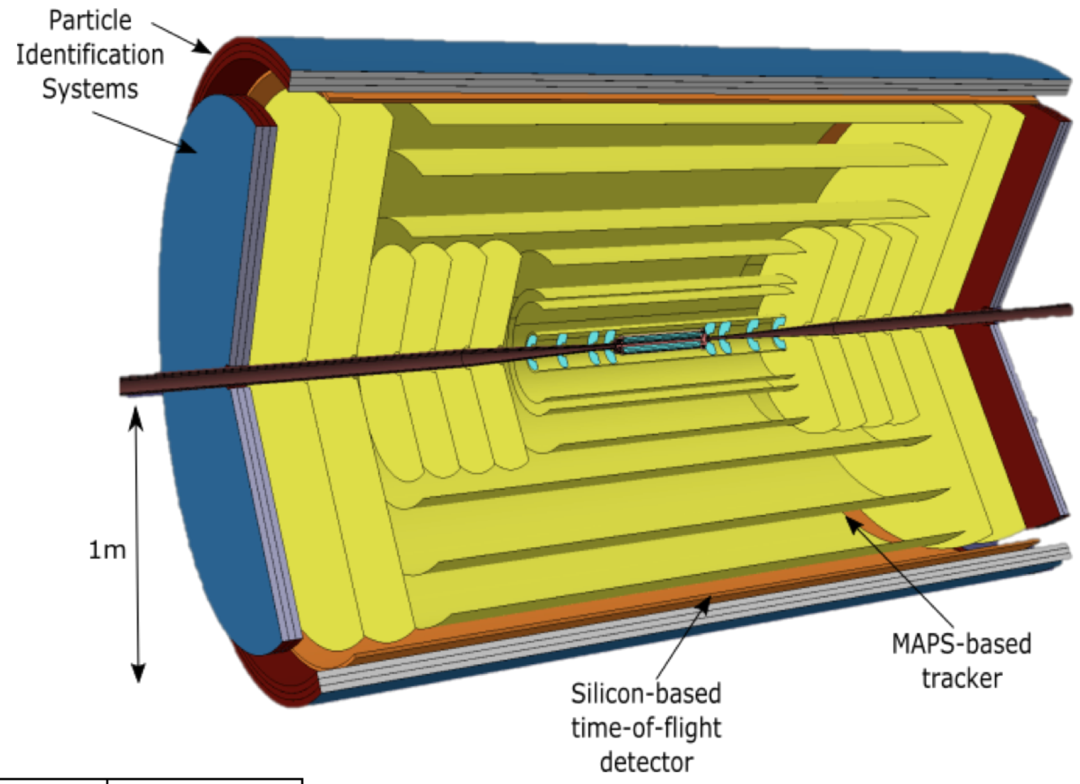
- Core cost
- No R&D
- No man power

- **2023-25**: selection of technologies, small-scale proof of concept prototypes
- **2026-27**: large-scale engineered prototypes → Technical Design Reports
- **2028-31**: construction and testing
- **2032**: contingency
- **2033-34**: Preparation of cavern and installation of ALICE 3

Detector Scenarios

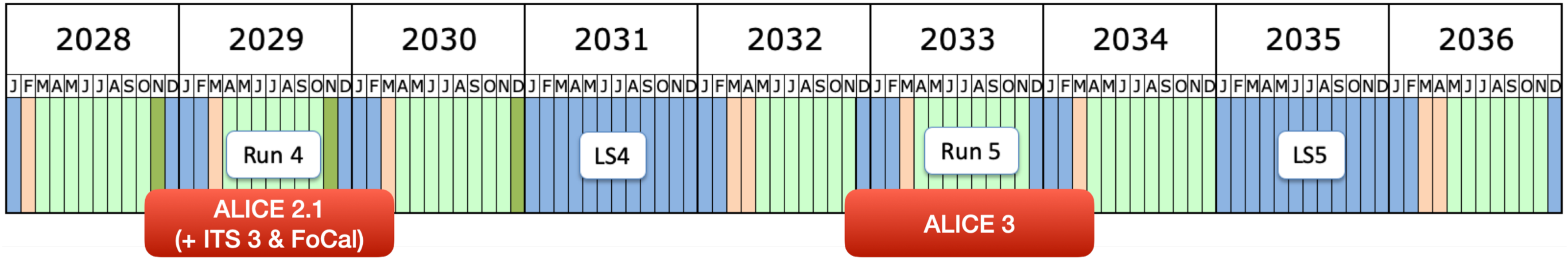
State-of-the art experiment optimized for “soft” physics from pp to Pb-Pb:

- Tracking and vertexing accuracy down to zero p_T
- Complete suite of PID detectors
- Large rapidity coverage
- Extreme acquisition rates for soft, untriggerable probes
- Unique vertexing capabilities



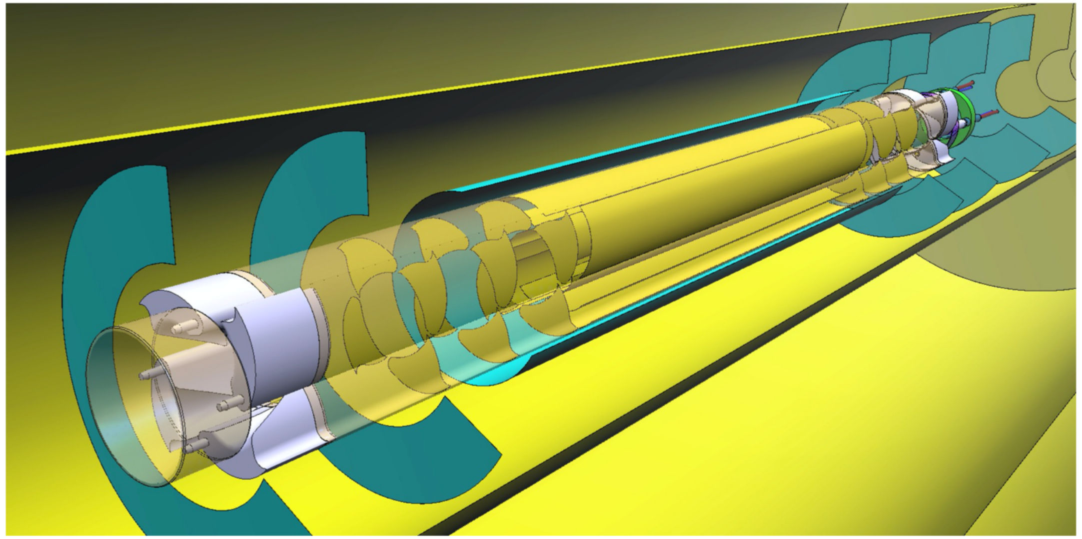
Important deadlines:

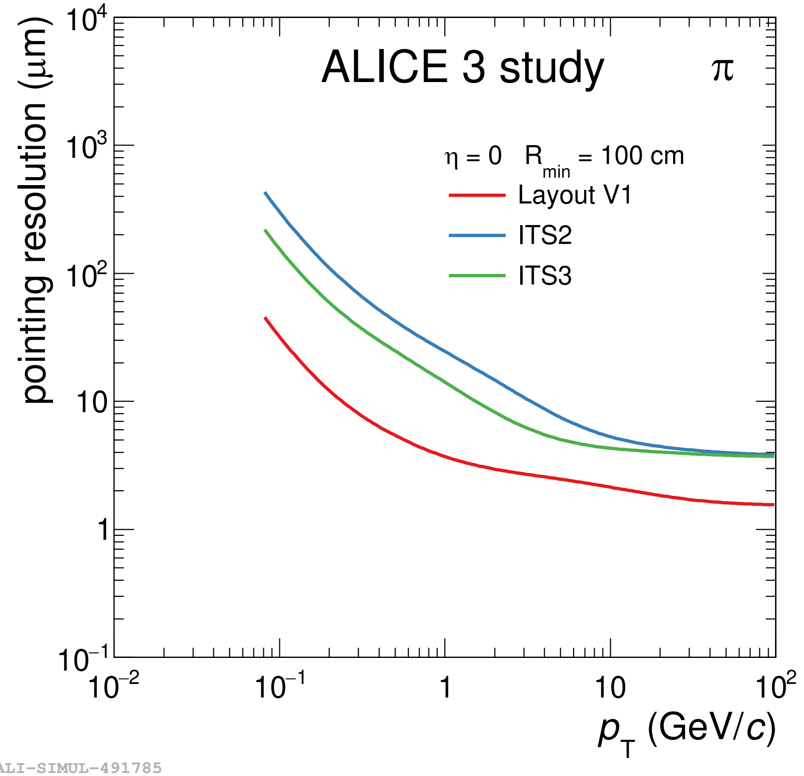
- Open ALICE 3 workshop in September/October
- End 2021: submission of the LoI to the LHCC



ALICE 3 will be equipped with a *o*(100 m²) tracker based on large, bended MAPS sensors

Retractable layers (IRIS) under study:
Getting closer to the interaction point during stable beam (R = 0.5, 1.2, 2.5 cm)





Ultra-light tracker:

≈ 0.05 % X_0 vertexing layers

≈ 0.5 % X_0 tracking layers

Large acceptance: |η| < 4.0, full azimuth down to very low p_T

Great potential for charm measurements

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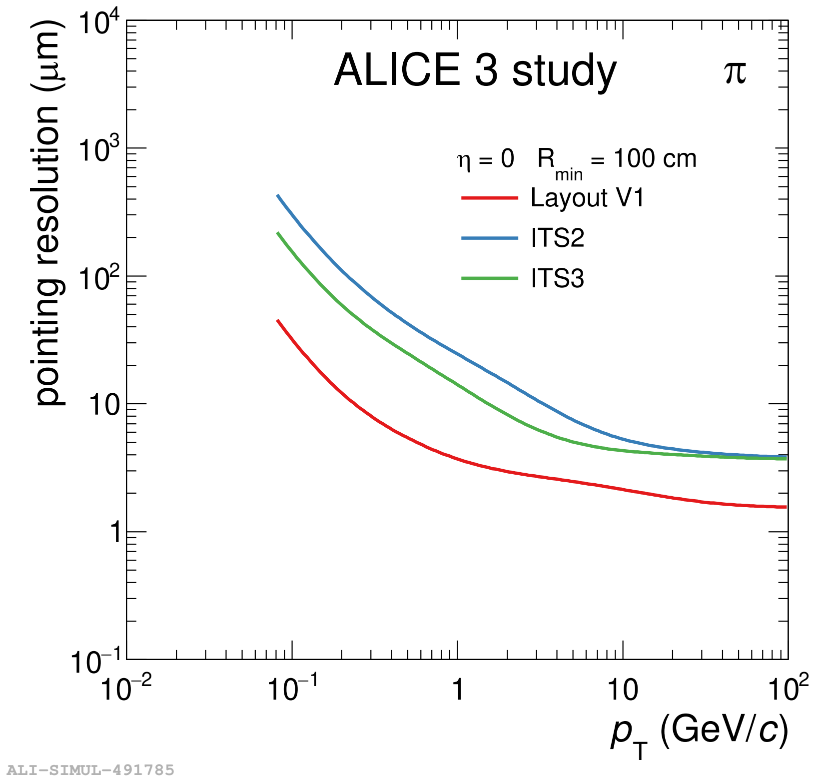

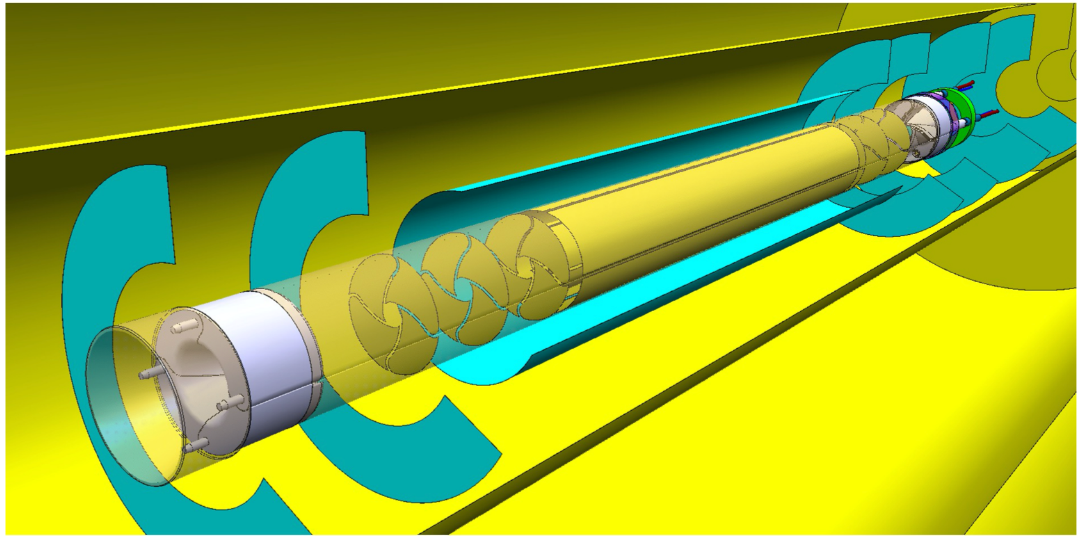

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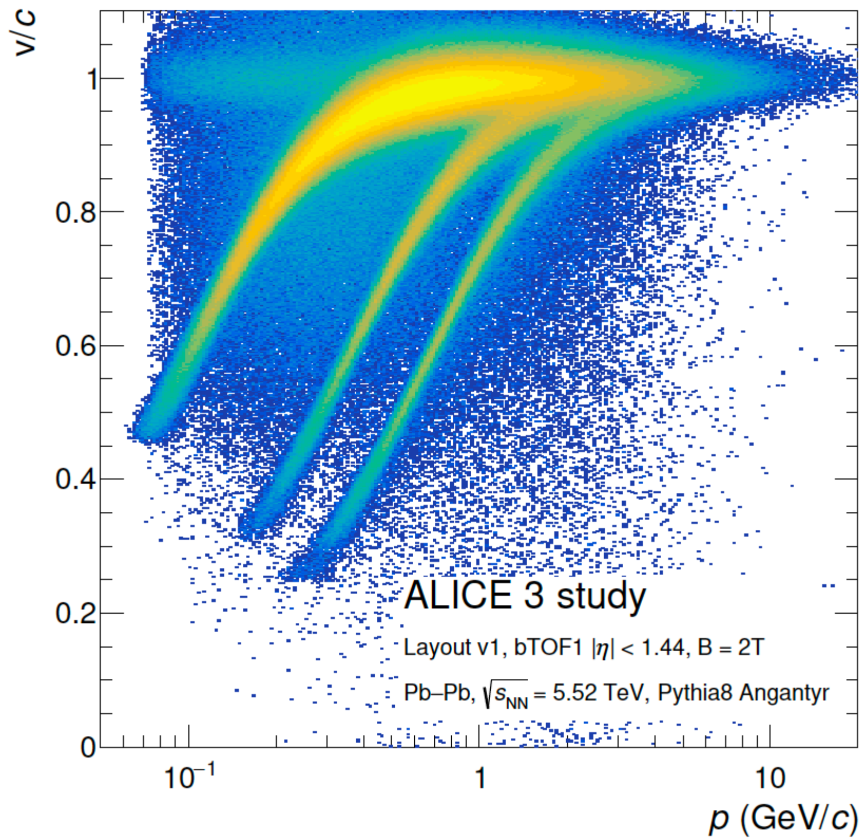
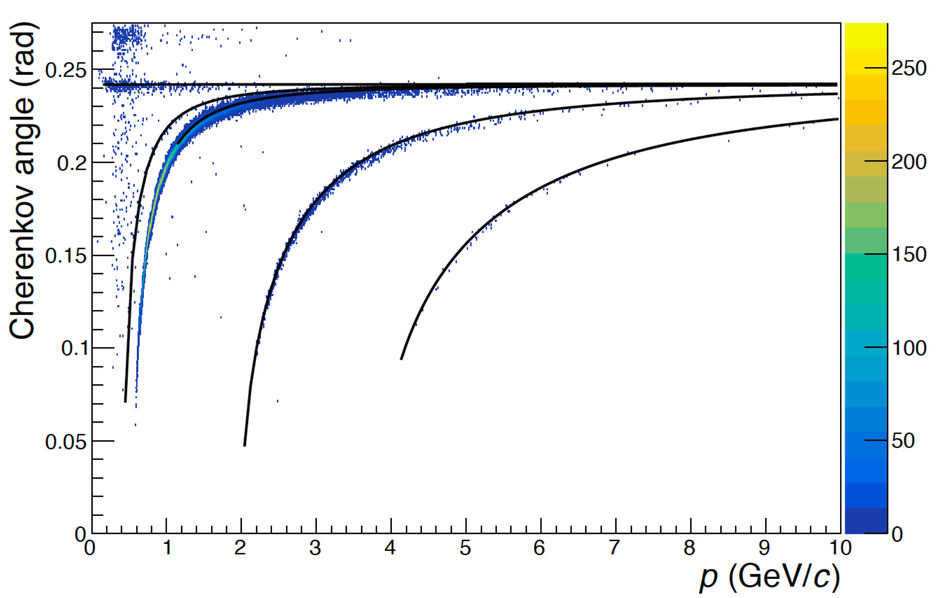
Great potential for charm measurements

ALICE 3: PID Strategy

TOF detector: PID at low momenta

- 2 barrel + 1 forward TOF layers
- TOF resolution ≈ 20 ps achievable with silicon timing sensors (R&D needed)
- Barrel TOF at R ≈ 19 cm and R ≈ 85 cm
- Forward TOF at z ≈ 405 cm





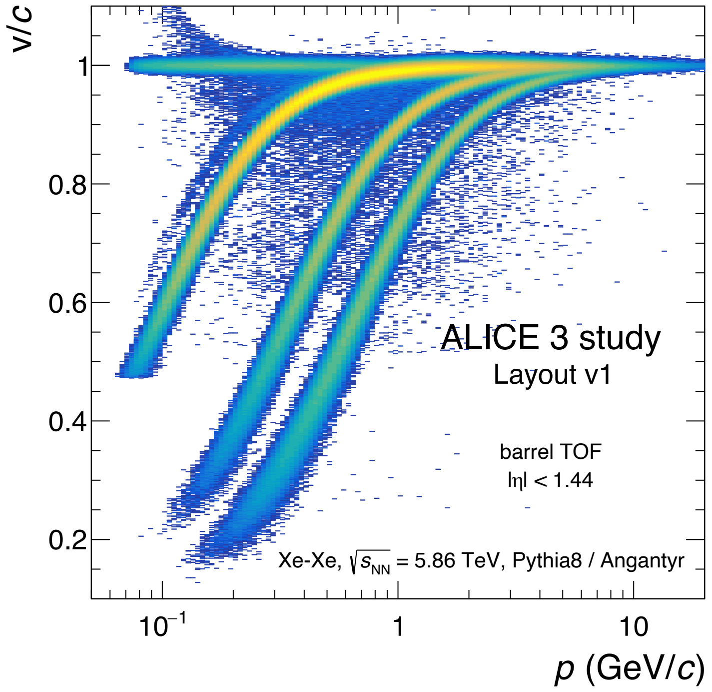
RICH detector:

- Extend PID reach of outer TOF to higher p_T
- Aerogel radiator + SiPM readout
- R ≈ 120 cm, 50 ps time res.

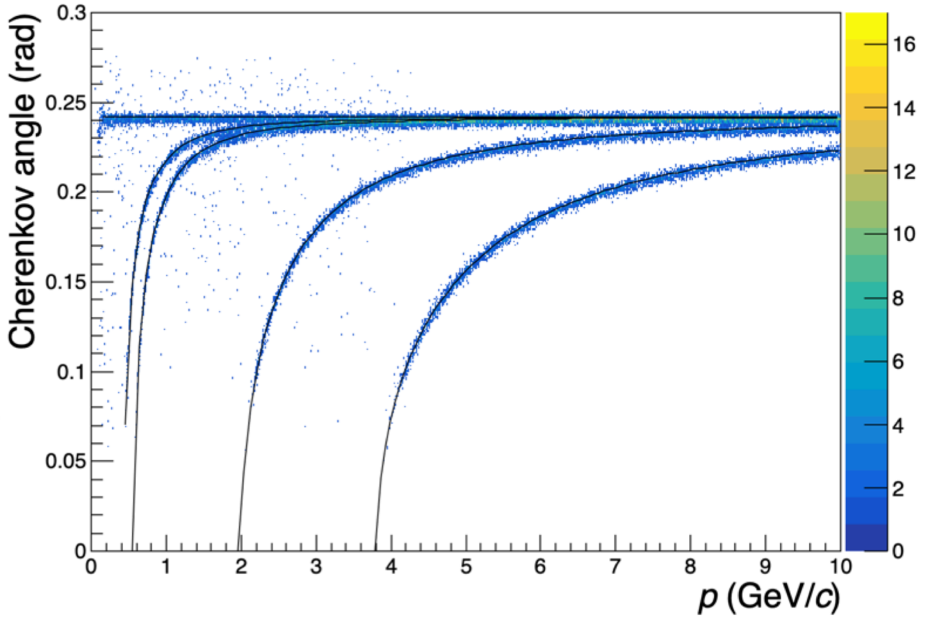
Detector Scenarios: PID

Several PID options and technologies under investigation (performance, costs…)

TOF detector outside the tracker:
R ≈ 100cm (+20cm?), σ = 20 ps



Aerogel-RICH detector:
R ≈ 120 cm, 50 ps time res.



- **Barrel ECAL:** E(photons) ≈ 0.1 GeV – 10/20 GeV, R ≈ 130 cm, $PbWO_4$ crystals
- **Forward conversion tracker:** photons down to $p_T \approx$ 10 MeV, 2.5 < η < 5
  → **Unique possibility to test soft theorems for photon production at the LHC**
- **MuonID:** muons down to $p_T \approx$ 1.5 GeV at $\eta = 0$, R ≈ 160 cm, GEM technology
  → **Unique possibility for charmonia down to zero p_T at $\eta = 0$ at the LHC**
- **Pixel Shower Detector** (radiator + high-granularity pixels) to improve electron ID

Summary and Conclusions

- **ALICE is preparing a next-generation heavy-ion experiment for LHC Run 5 and beyond:** access to novel measurements of electromagnetic and hadronic probes of the QGP at very low momenta

- **Physics goal: measurements** inaccessible in LHC Run 3+4 because of limitations in detector performance or available luminosity:
  - High-precision measurements of dielectron production
  - New measurements of quarkonium states, multi-charm baryons and exotica
  - Searches for signals of new physics beyond Standard Model

- **Performance studies and detector R&D plans are ongoing**
  - Physics cases and detector options explored by dedicated working groups, discussed in internal ALICE workshops
  - First ”open” workshop in September/October 2021, LoI to be submitted end of 2021