Physics Prospects for ALICE in Run 5 and Beyond

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ALICE

Introduction

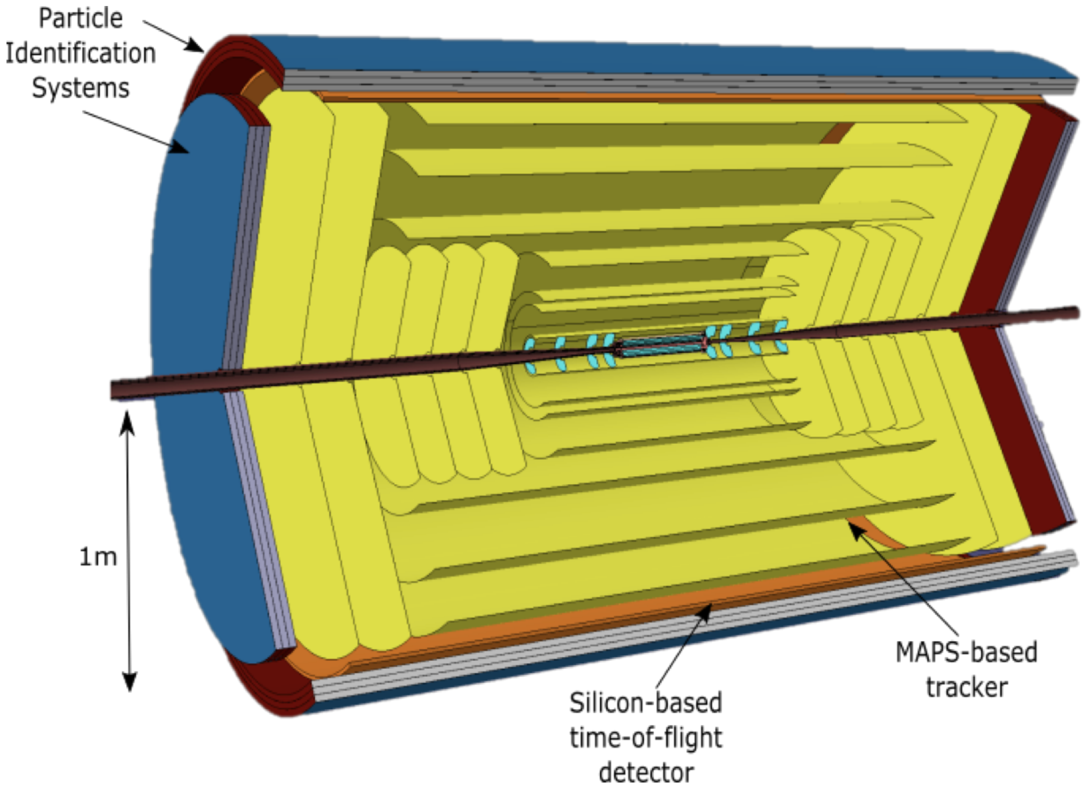
ALICE 3: new dedicated heavy-ion experiment at the LHC, replacing ALICE starting of Run 5: hadronization mechanisms in the medium, QGP transport properties, access to the pre-equilibrium phase

- **Discussed at the heavy-ion town meeting** (CERN, Oct 2018)

https://arxiv.org/abs/1902.01211

- **Expression of Interest** submitted as input to the European Particle Physics Strategy Update (Granada, May 2019)

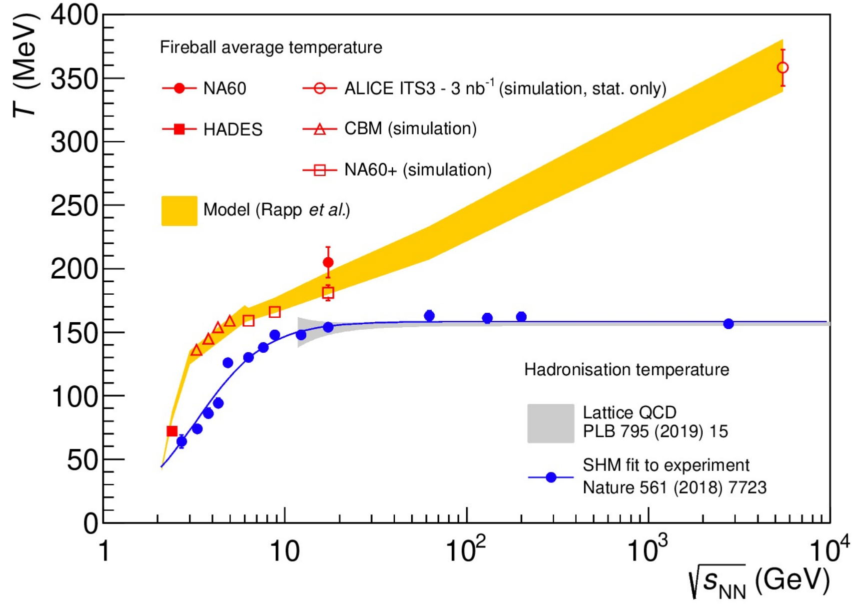
In this presentation >>> Selected material from the preliminary discussions on the **ALICE 3 physics goals and scientific opportunities**, and the **detector concept**



see also talks by C. Lippman, G. Contin, S. Bufalino

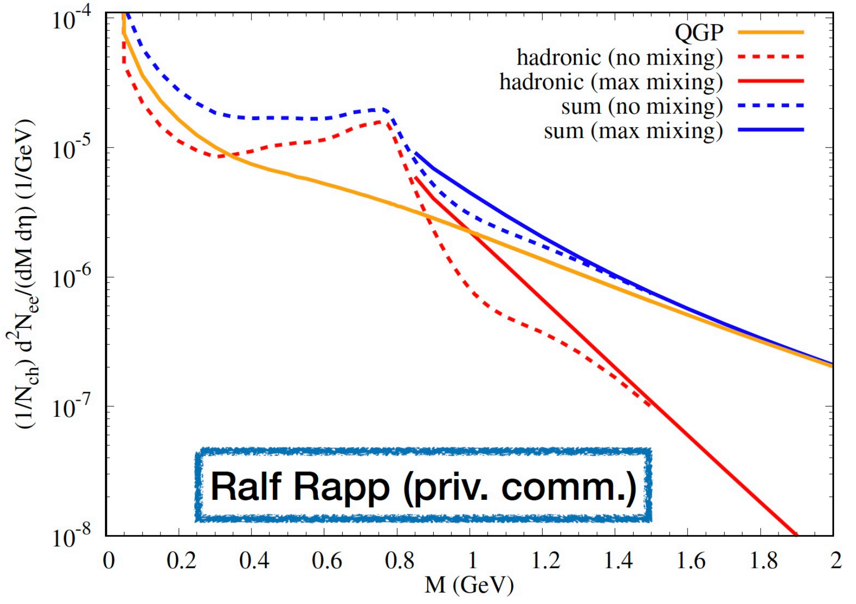
Thermal Radiation and Chiral Symmetry Restoration

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

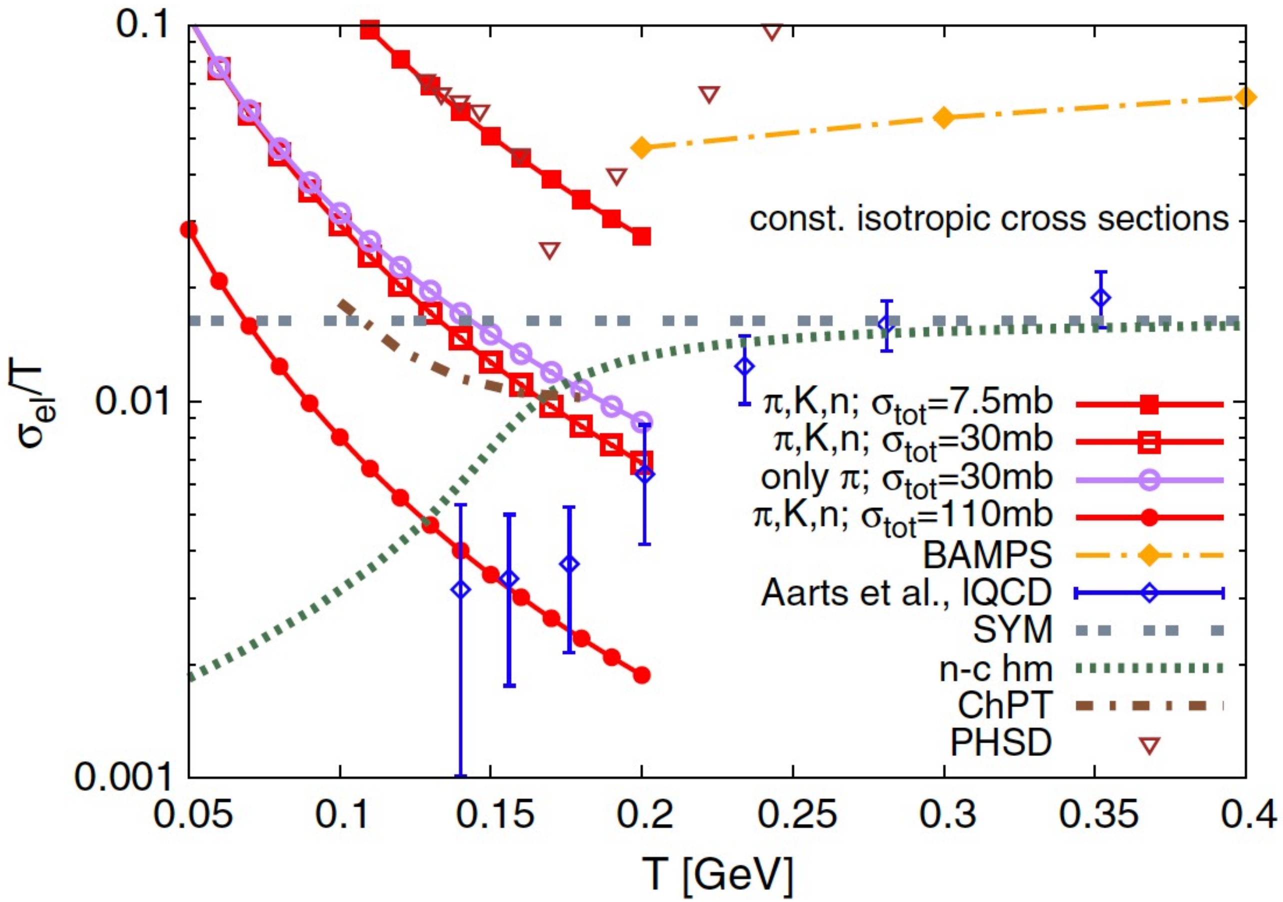
- Effect on **ρ-a$_1$ mixing** on the dilepton mass spectrum above ϕ peak
- In-medium broadening of narrow vector resonances?



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 ($p_T^{\gamma} \ll p_T^{hadrons} \approx$ 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

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

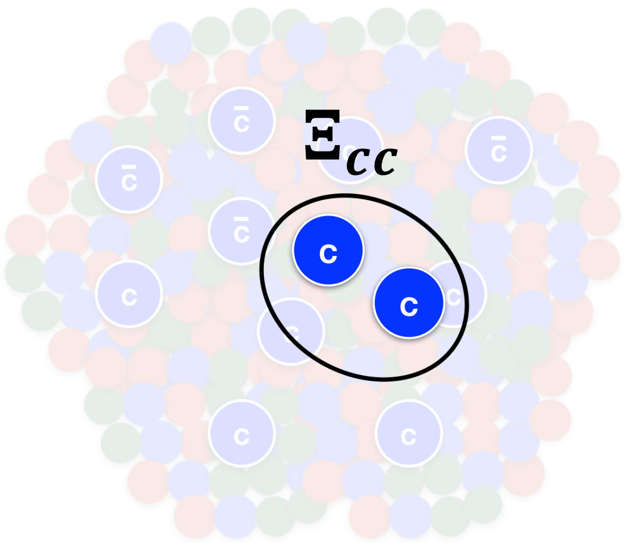
- **Soft photon puzzle:** nearly every measurement shows factor 2–5 enhancement w.r.t. Low's theorem predictions. **Proposed explanations:** cold quark-gluon plasma, quark synchrotron radiation, string fragmentation. Handle to investigate fundamental non-perturbative properties of QCD

→ 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)**

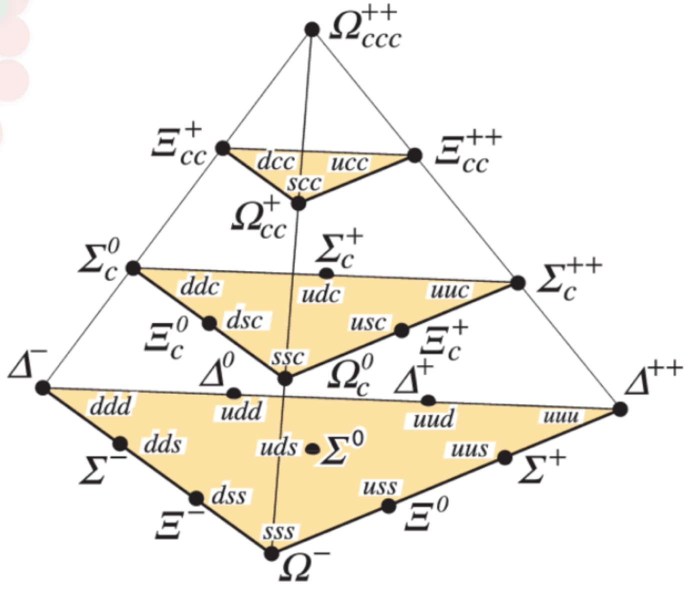
Multi-charm baryons are almost pure coalescence particles: (potentially) large discrimination power on the role of the various hadronization mechanisms



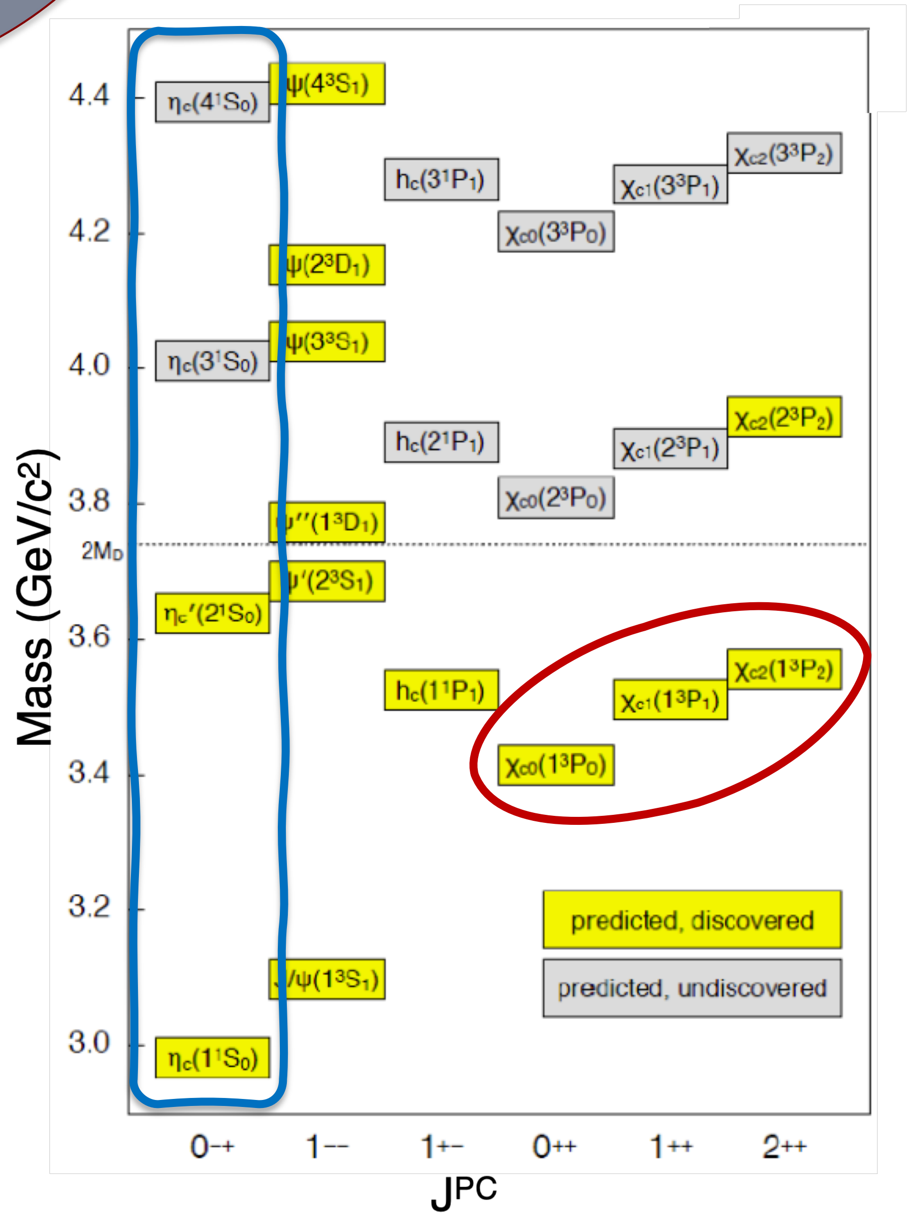
Ω_{cc} and Ω_{ccc} not yet observed. Ω_{ccc} may only be accessible in heavy-ion collisions

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

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



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)**

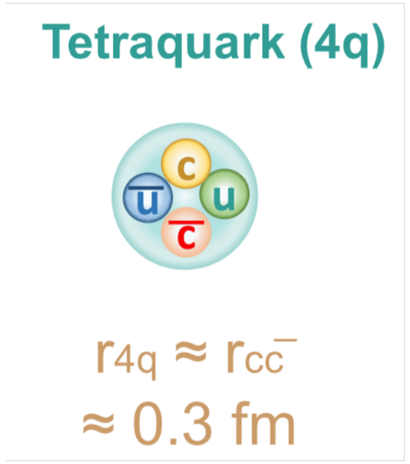
Pseudoscalar η_c states

- 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)

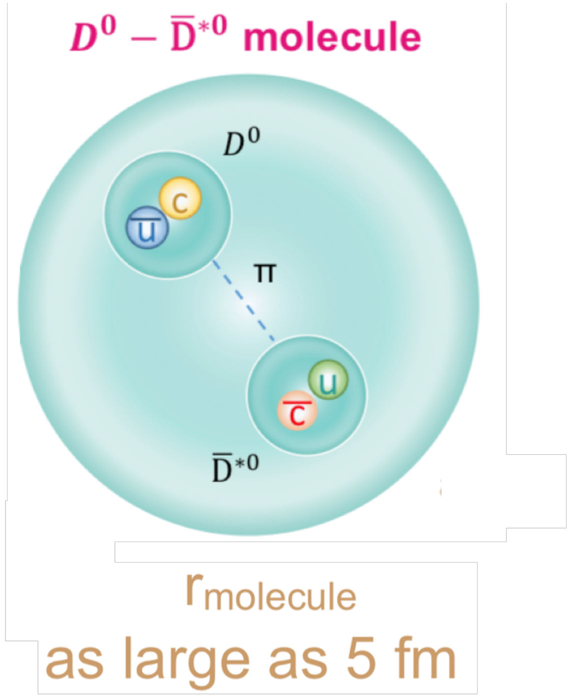
Heavy-Flavor Exotica

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



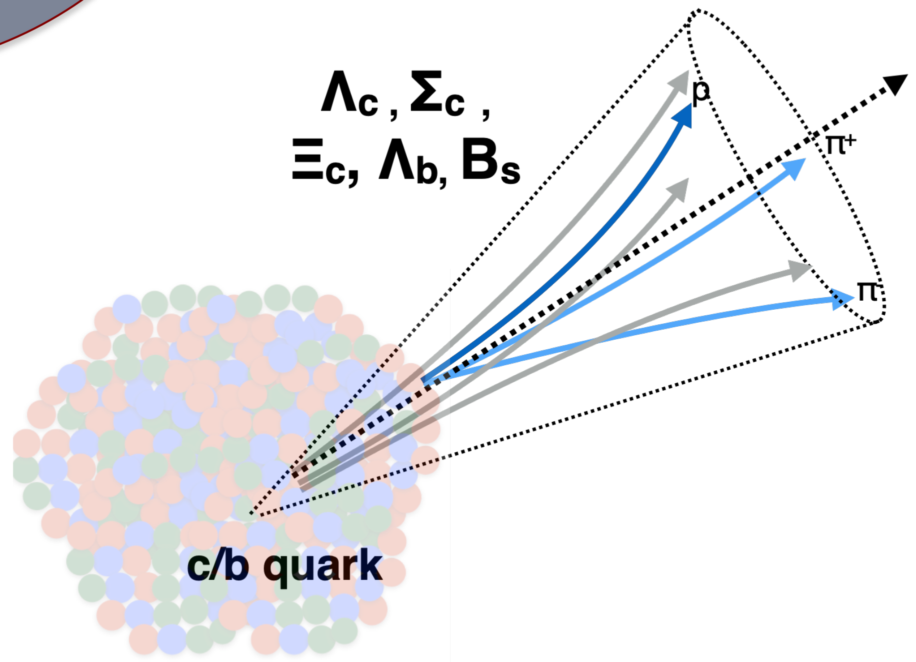
VS



- 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**

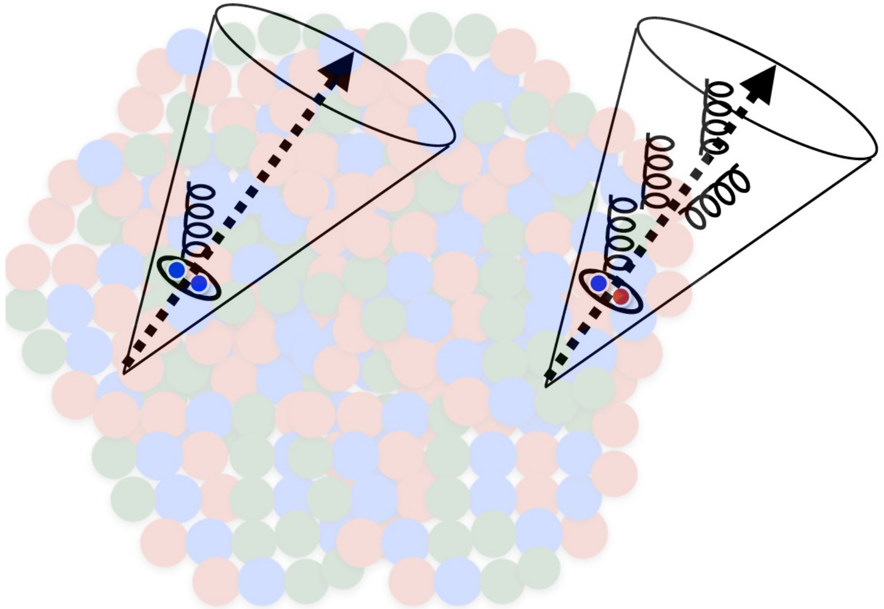
Low-p_T reach crucial for a full characterization of the hadronization mechanism

Quarkonia and HF Hadrons in Jets

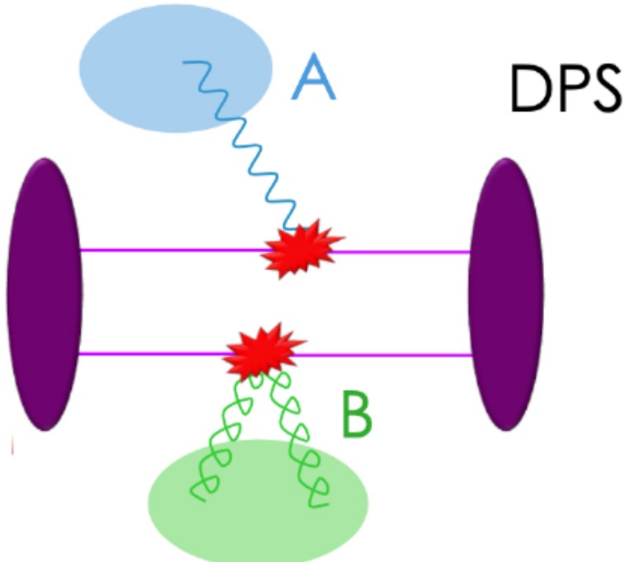


- **Direct measurement of the fragmentation patterns** of charmed/beauty mesons and baryons
- **Jets provide energy and direction scale** for the fragmentation process: proxy for initial HF quark direction and energy

- **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

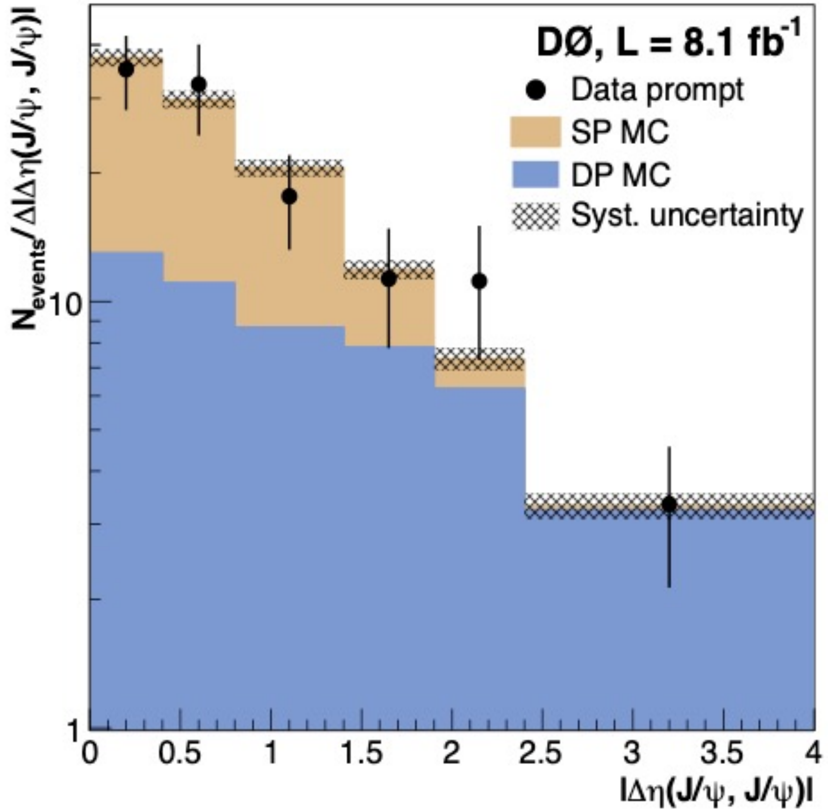


➡ Low-p_T reach needed for a complete picture of the fragmentation functions



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)

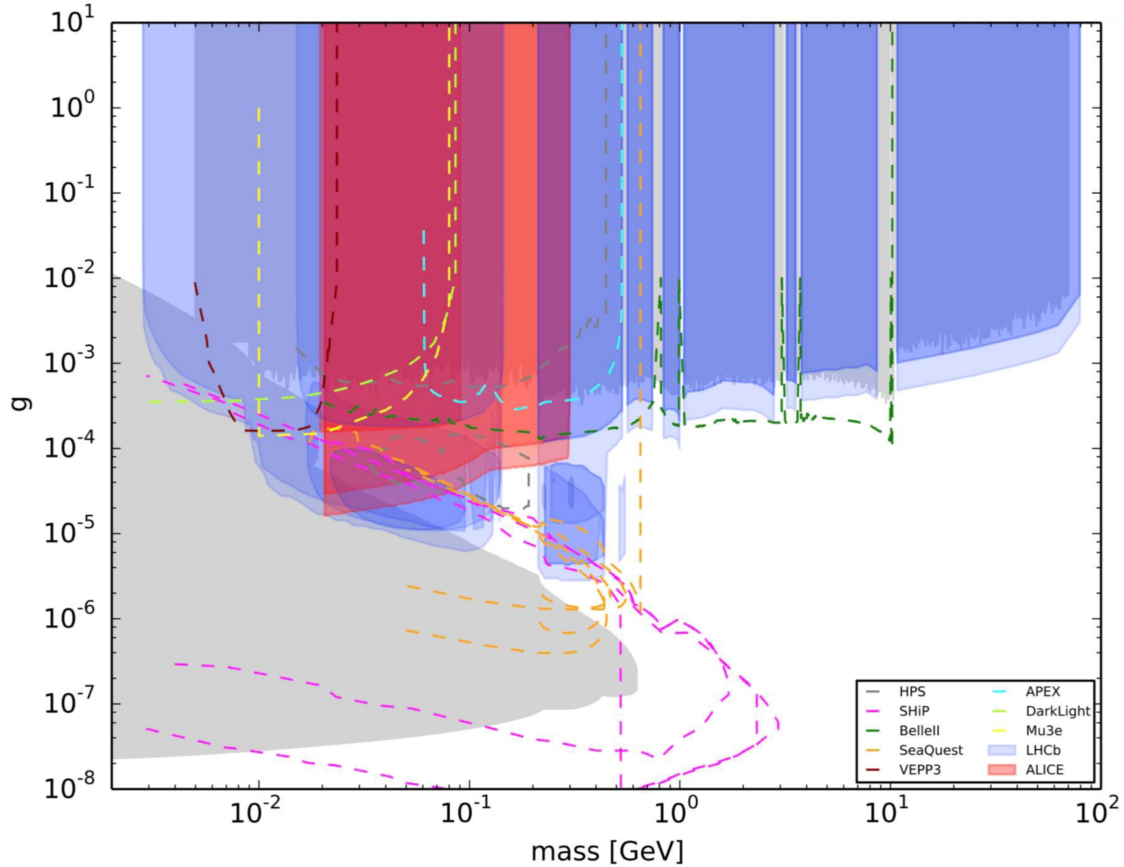
- **Powerful probe to study** factorization of hard processes in hadronic collisions, and transverse parton densities in nucleons and nuclei

- **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)

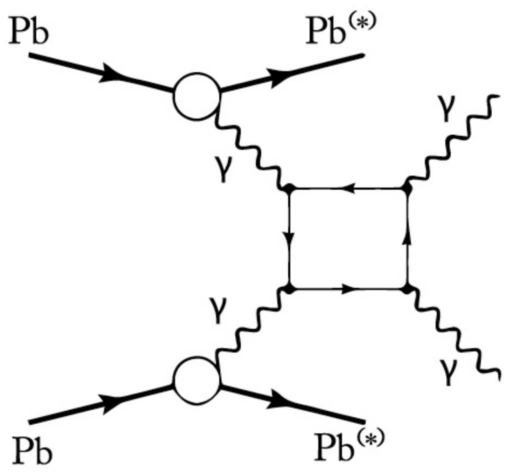
Requirements for ALICE 3

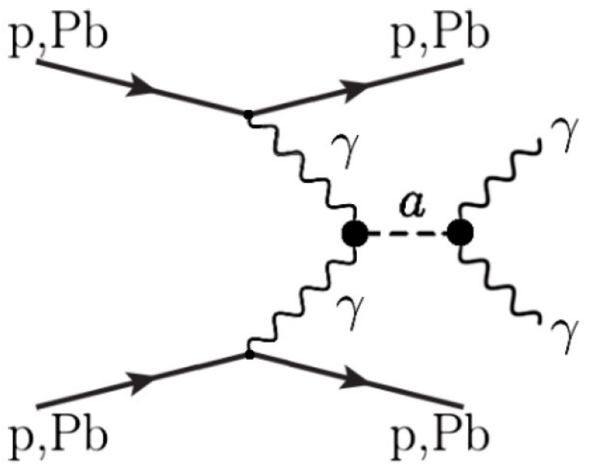
- Good electron ID capability for wide momentum range (low momenta from π^0 Dalitz decays to high momenta from DY and thermal dielectrons)
- High-rate capability and in-bunch pileup separation + good vertexing to separate thermal dielectrons and HF pairs

BSM Searches in Ultra-Peripheral Collisions

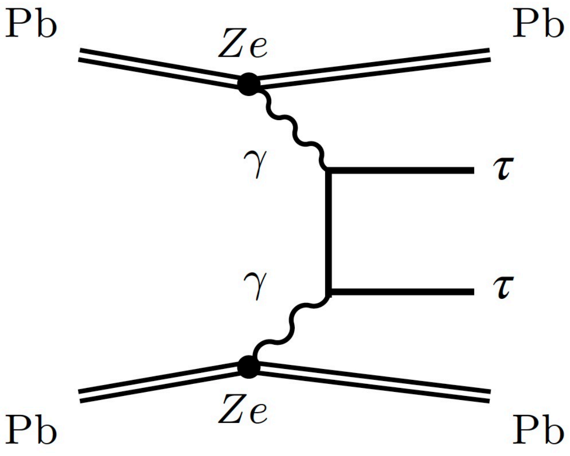
Ultra-peripheral heavy-ion collisions (UPC): clean environment + huge $Z^4 \approx 5 \cdot 10^7$ enhanced gamma+gamma rate w.r.t. pp

- **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

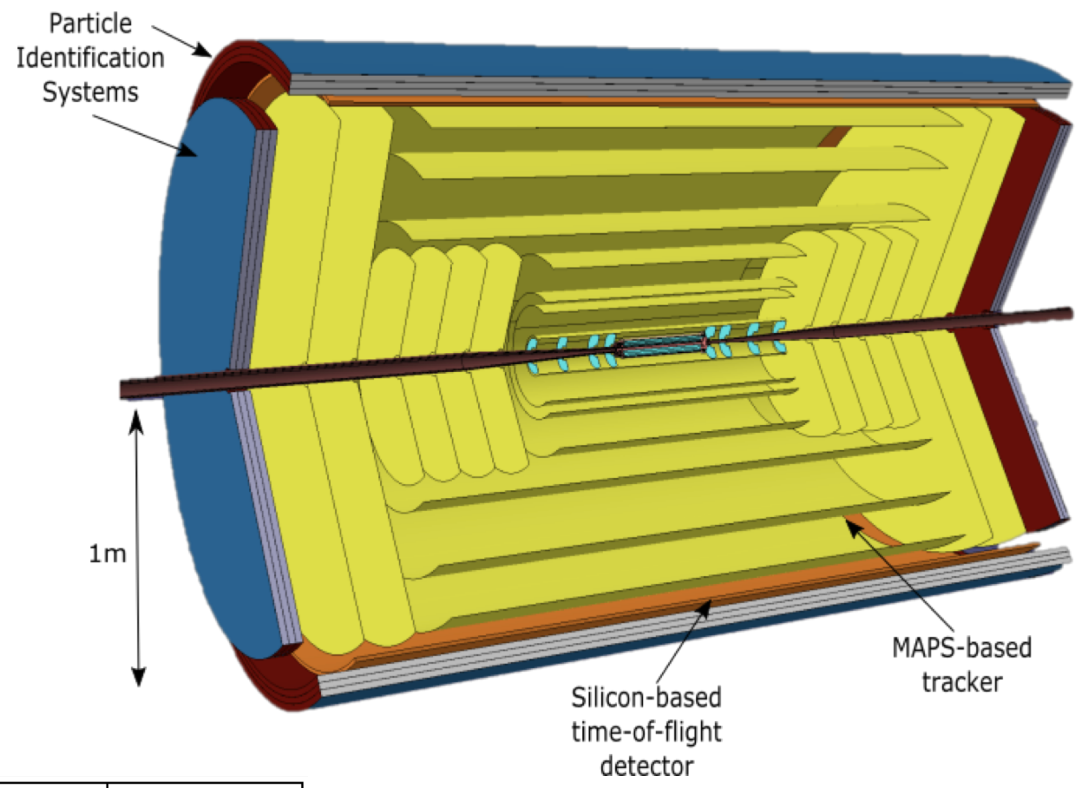


➡ **Challenge for ALICE 3:** acceptance for tau and light-by-light scattering down to low p_T?

Detector Scenarios

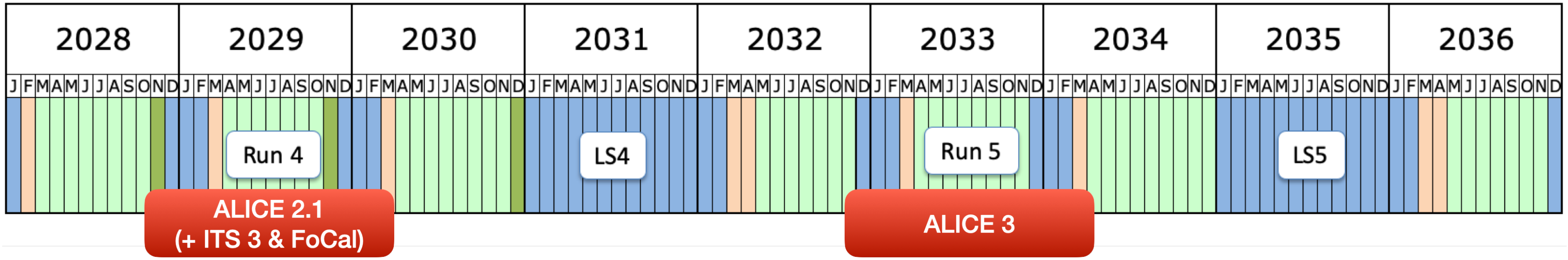
State-of-the art experiment optimized for "soft" physics from pp to Pb-Pb:

- 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:

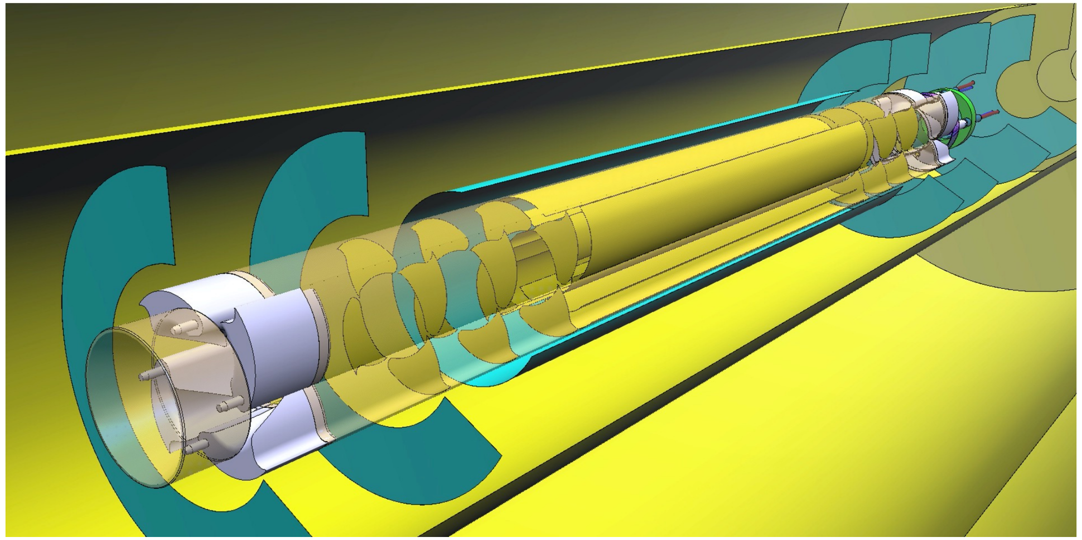
- Open ALICE 3 workshop in September/October
- End 2021: submission of the LoI to the LHCC

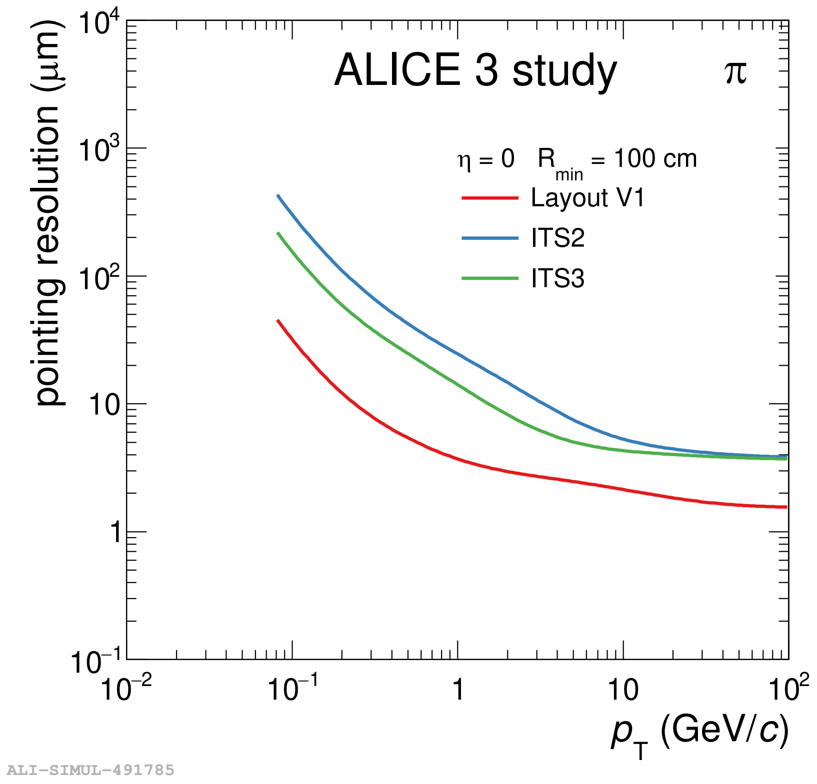


Detector Scenarios: Tracker

ALICE 3 will be equipped with a *o*(100 m^2) 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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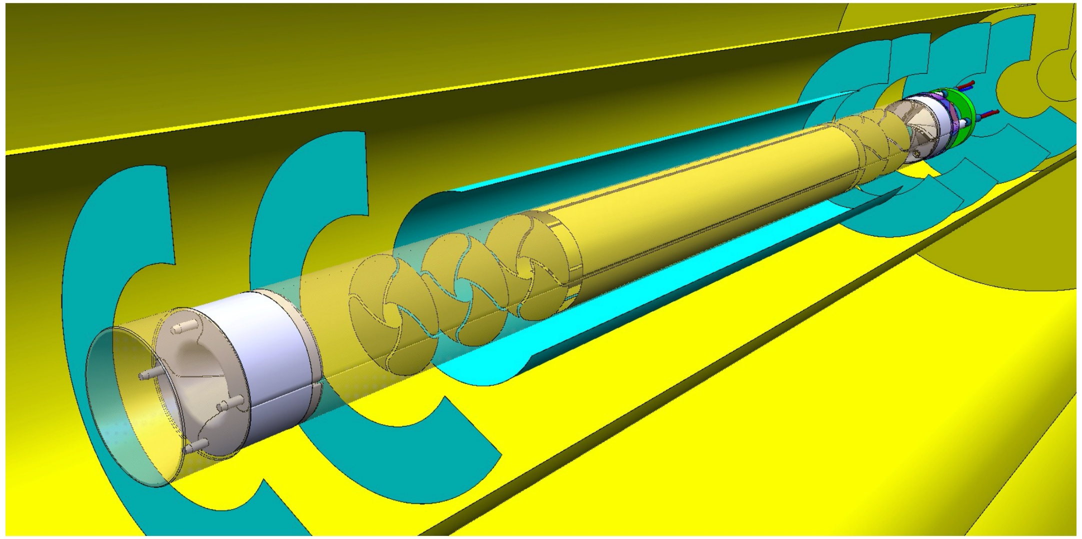

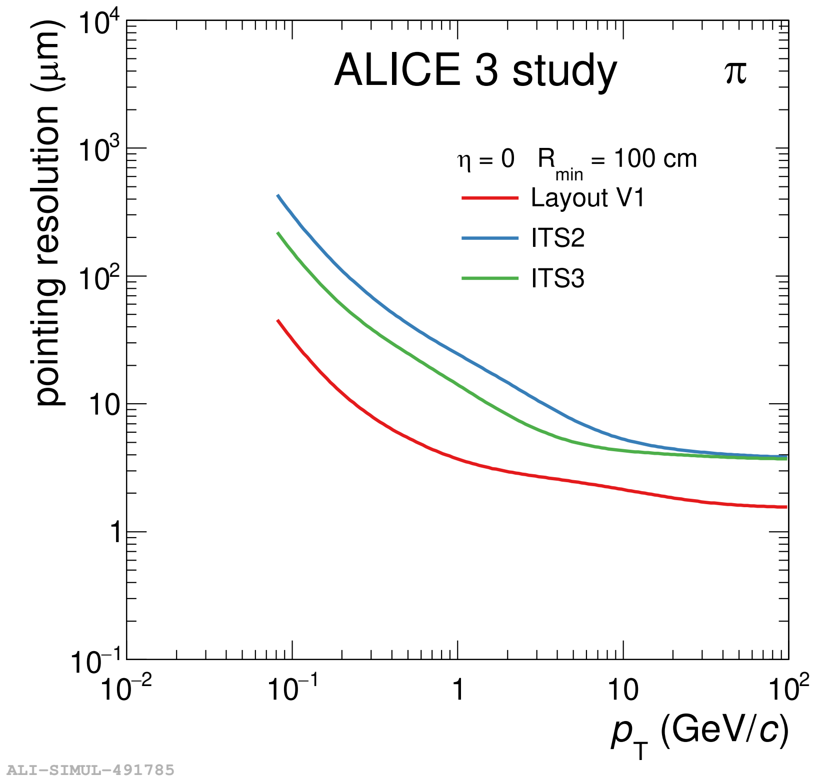

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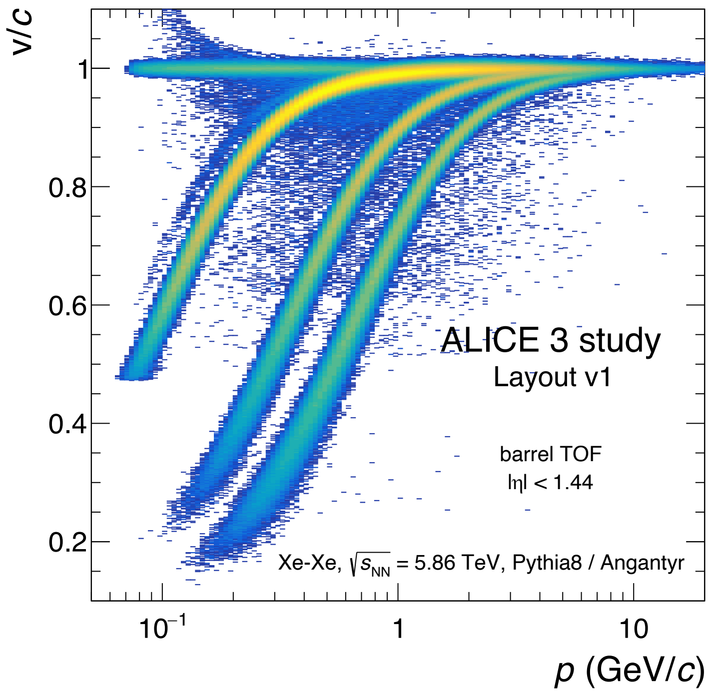
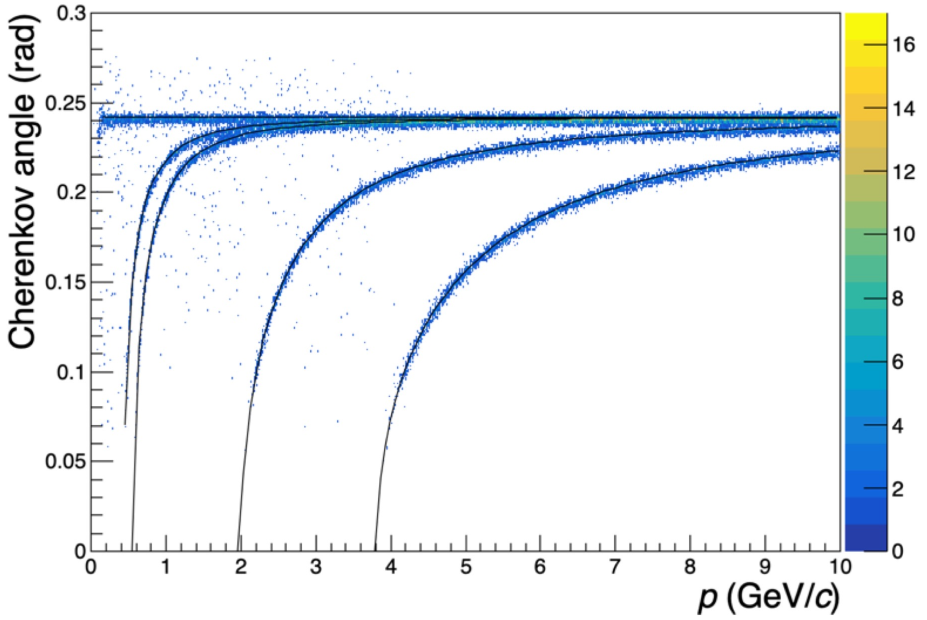
Detector Scenarios: PID

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

Backup Slides