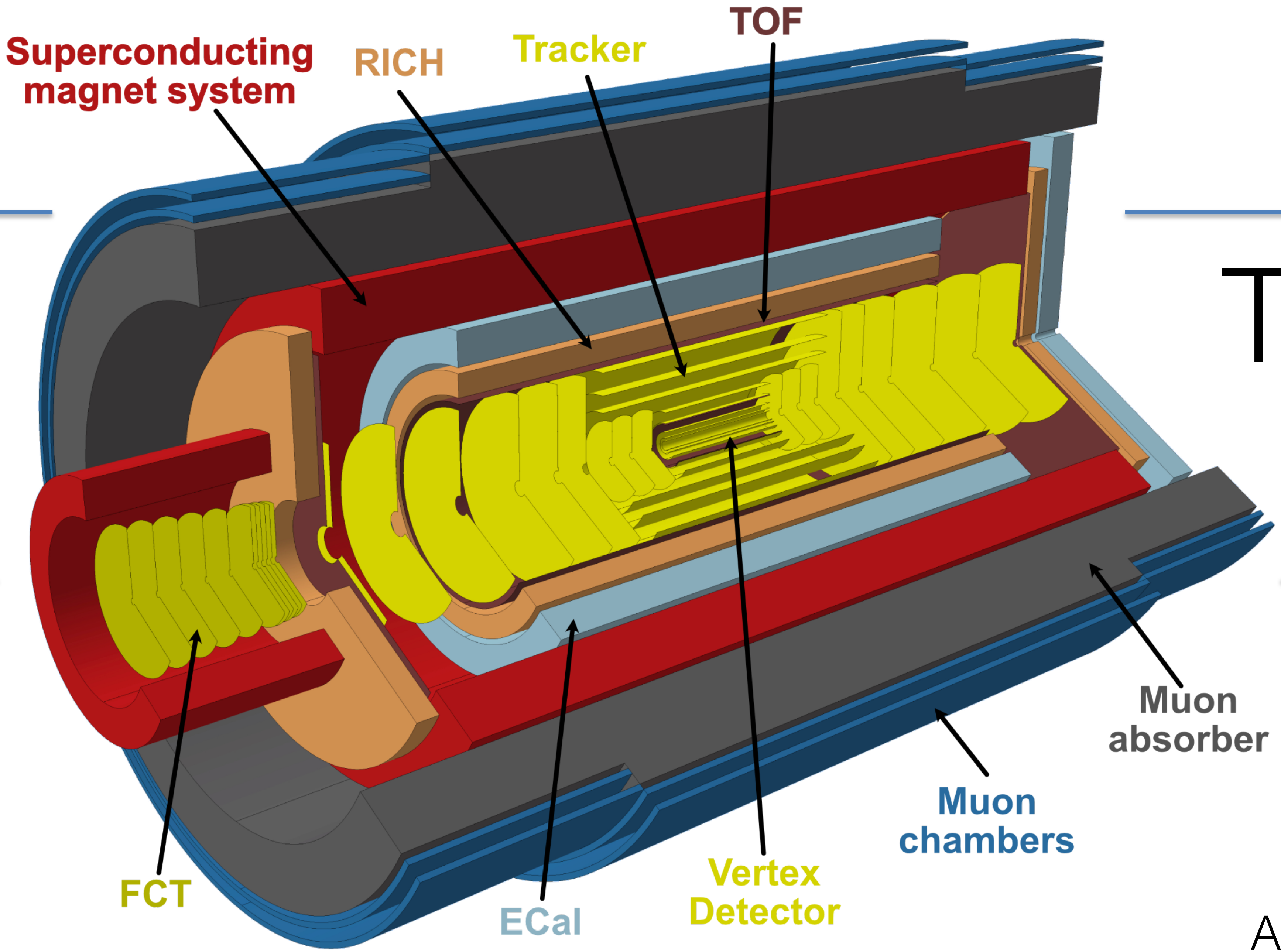


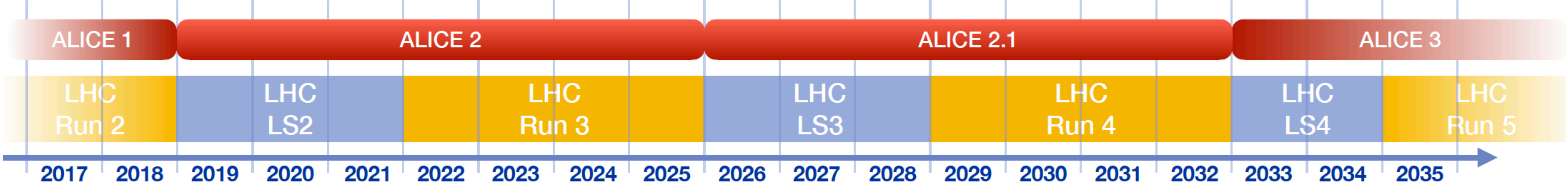
The ALICE 3 Project

Conseil Scientifique IN2P3
6 février 2023

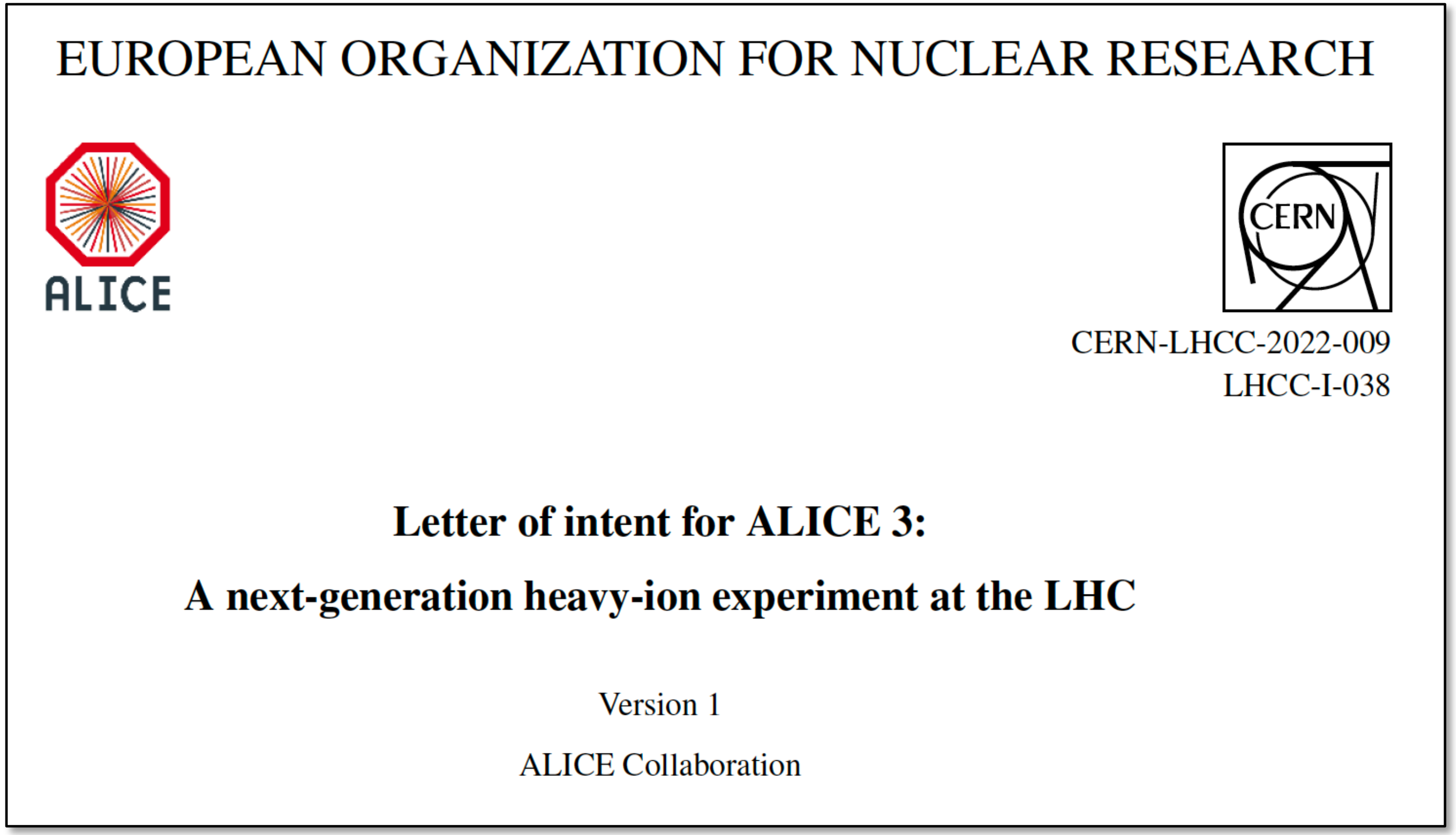
Antonio Uras for ALICE-France
IP2I Lyon – CNRS/IN2P3

Introduction: the Context

- **2018/19: first discussions of a dedicated heavy-ion program for Run 5 and 6** at the LHC within ALICE
- **European Strategy for Particle Physics Update**
  - Expression of Interest submitted to the Granada meeting (2019)
  - Recommendation: full exploitation of LHC including heavy-ion program in Runs 5 & 6
- **Further development of detector concept and physics studies within ALICE**
  - ALICE 3 workshops: October 2020, June 2021, October 2021
- **Letter of Intent**
  - Reviewed by collaboration and endorsed by Collaboration Board on 28 January 2022
  - LHCC review process started in October 2021, very positive report of the LHCC Review Panel addressed mid-March 2022


ALICE 1
ALICE 2
ALICE 2.1
ALICE 3
LHC Run 2
LHC LS2
LHC Run 3
LHC LS3
LHC Run 4
LHC LS4
LHC Run 5
2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034 2035

Introduction: the Context



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE

CERN-LHCC-2022-009
LHCC-I-038

Letter of intent for ALICE 3:
A next-generation heavy-ion experiment at the LHC

Version 1

ALICE Collaboration

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

https://cds.cern.ch/record/2803563

Selected Physics Case

- Microscopic mechanism 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

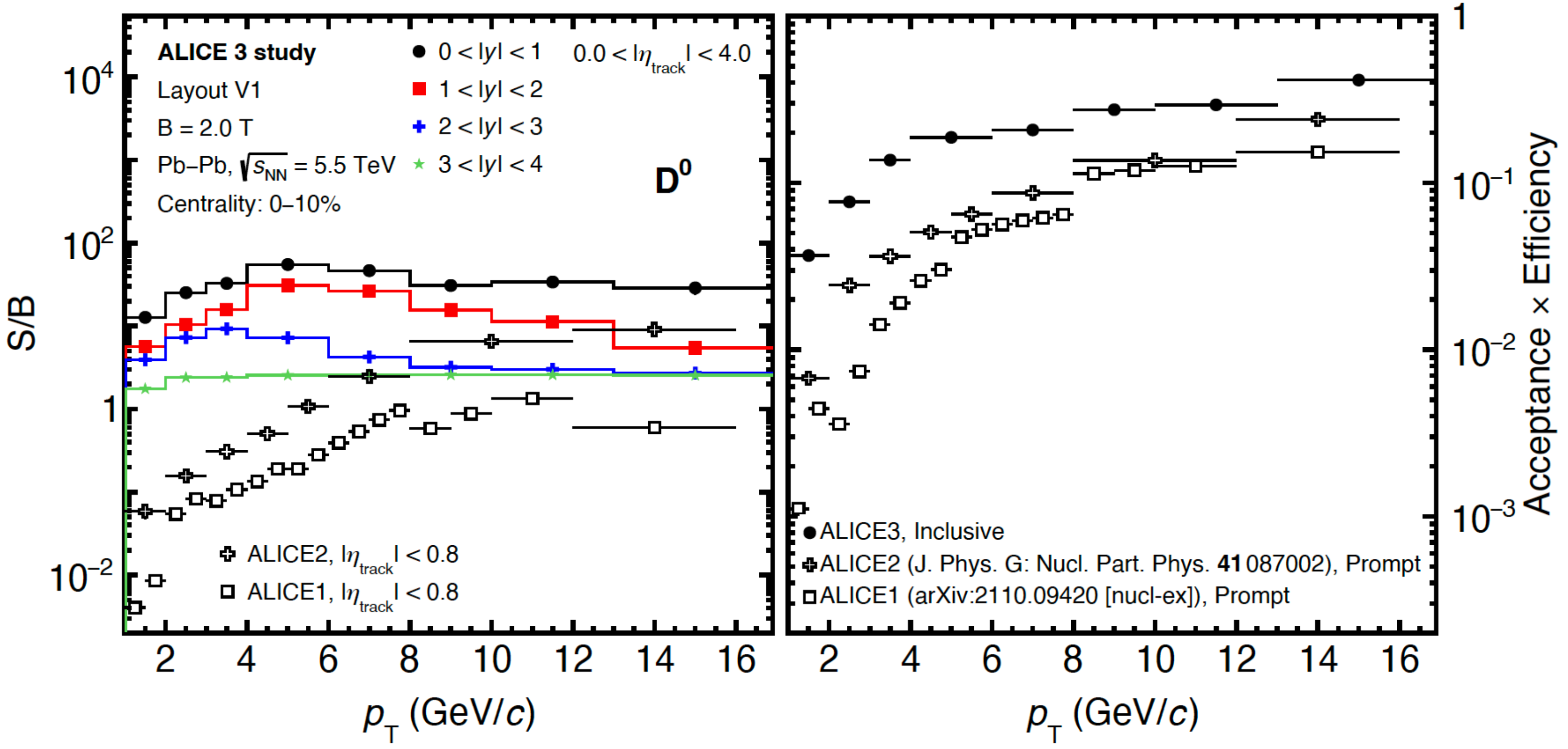
- Ultra-soft photons, BSM searches, …

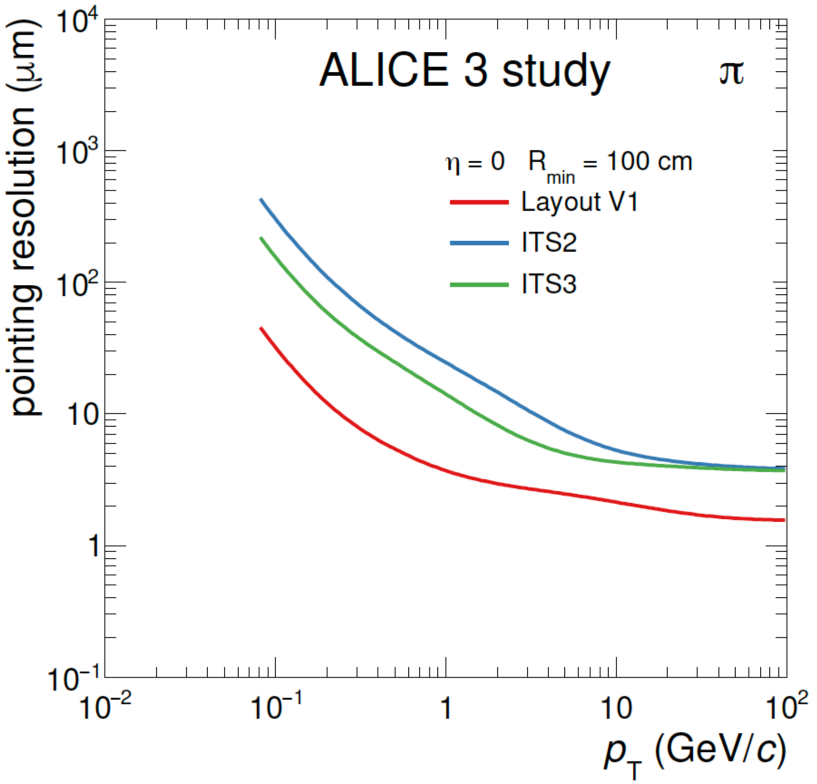
Heavy-Flavour Benchmark: D^0

Excellent pointing resolution and PID: **large S/B and efficiency** 10-20 × w.r.t. Run 3 (i.e. ITS2) for $p_T < 4$ GeV/c

Experimental benchmark giving access to the measurement of:

- Beauty meson and baryon v_2
- DD correlations
- Multi-charm baryons



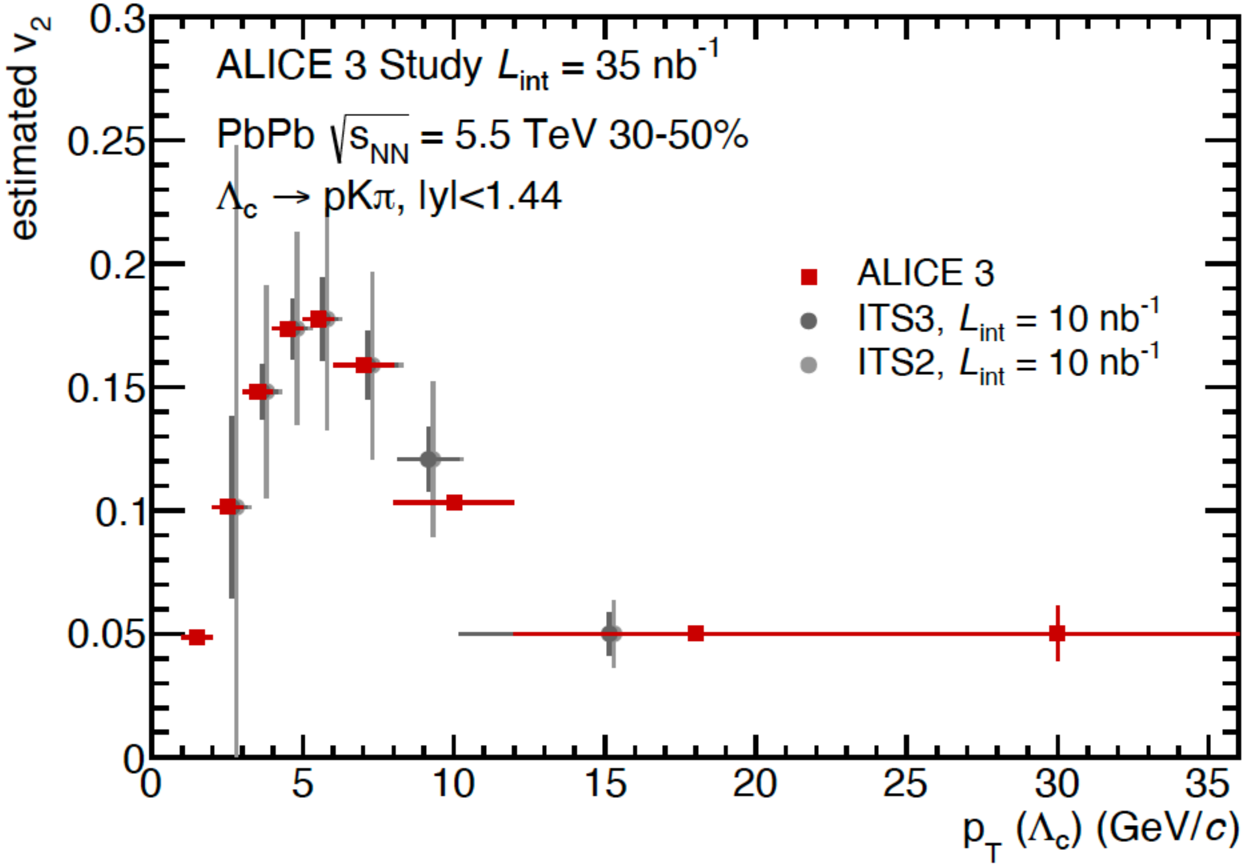


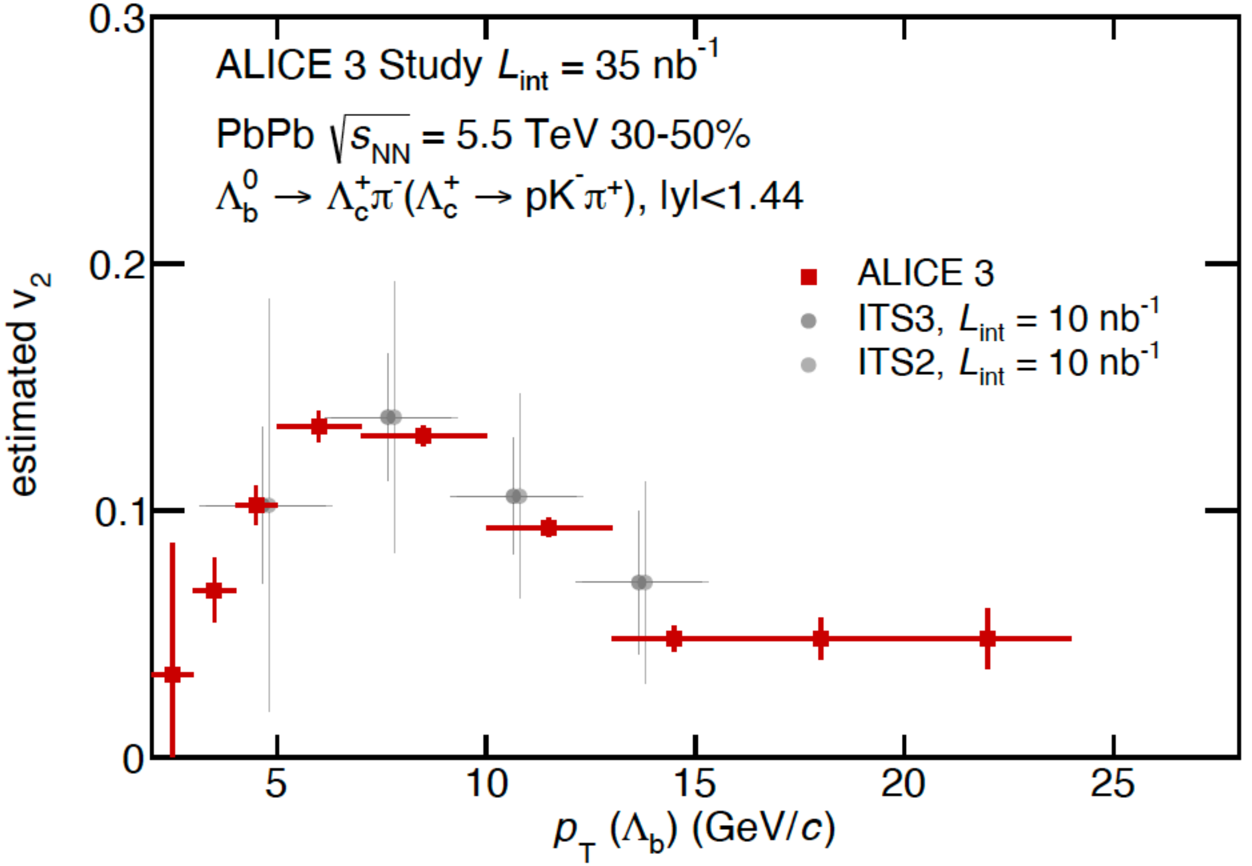
ALI-SIMUL-491785

HF Baryon v_2

Goal: disentangle effects of quark transport and hadronization

- Expect beauty thermalization slower than charm — does this affect hadronization?
- First measurements of Λ_b coupling to hydrodynamic flow (via v_2 parameter) in Run 3 and 4
- Need ALICE 3 performance for precision measurement

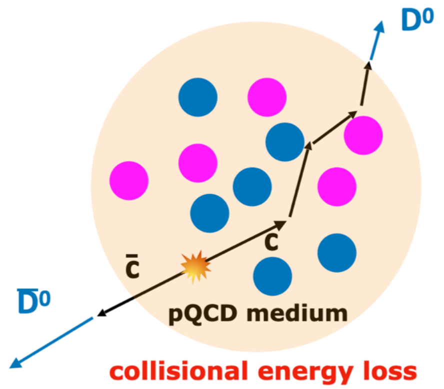




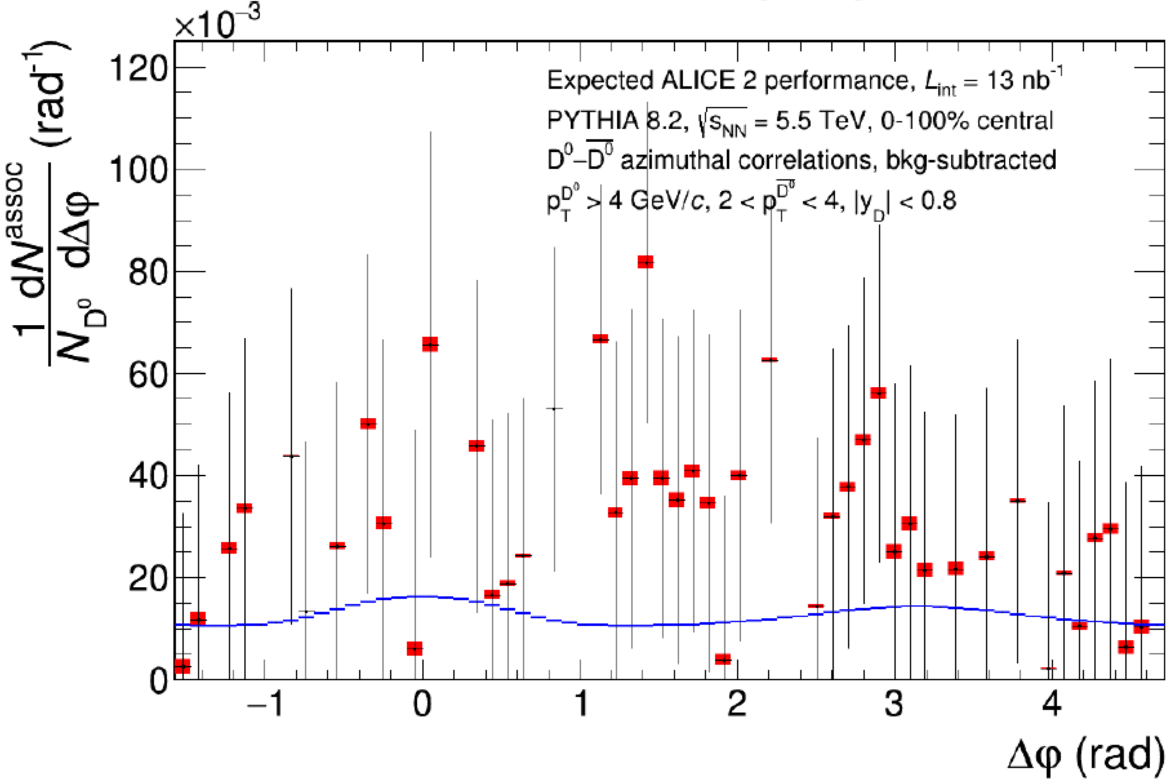
$D\bar{D}$ Azimuthal Correlations

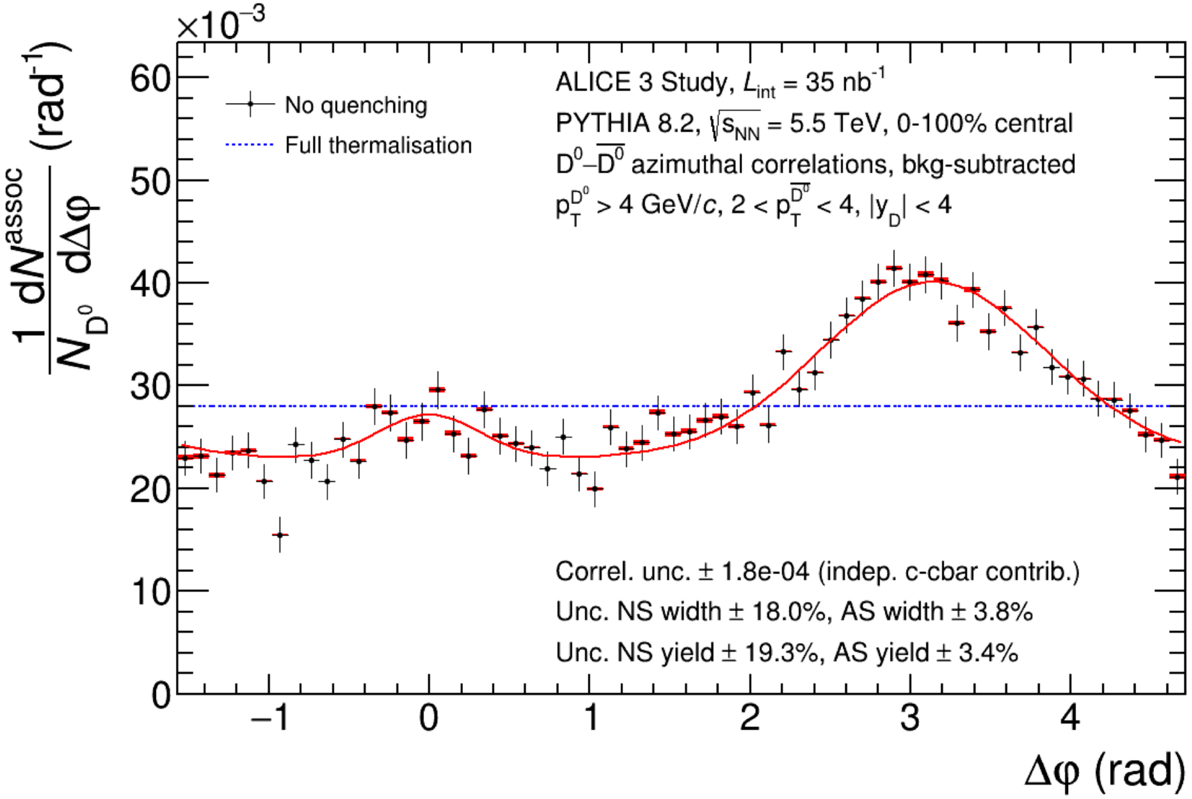
Goal: measure angular (de)correlations — direct probe of QGP scattering

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



ALICE Run 3&4 projection

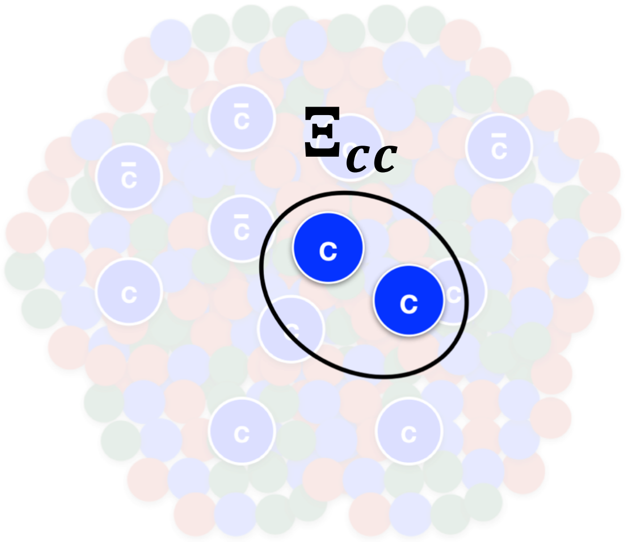




HF Hadronization Mechanisms

❖ In heavy-ion collisions, large increase of multi-HF baryons (≈ ×1000) expected via coalescence **with charm quarks from different hard scatterings (N_{ccbar} ≈ 100 in central Pb-Pb)**

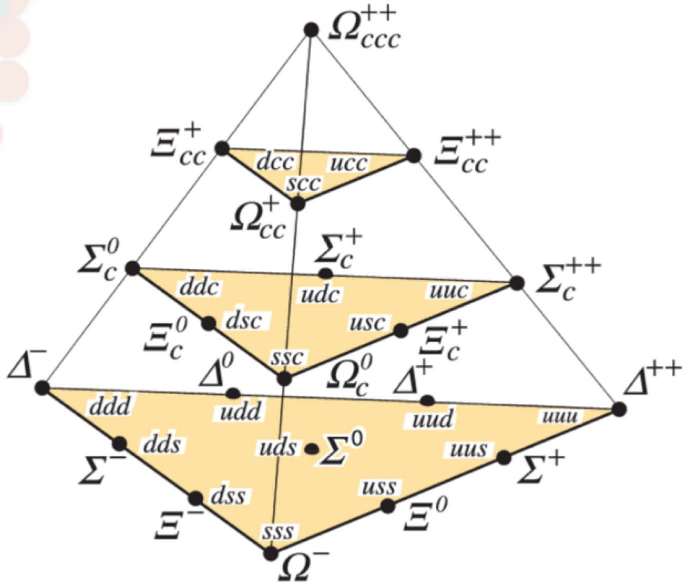
Discrimination power on the role of the various hadronization mechanisms: multi-charm baryon factory (almost purely produced out of quark coalescence)



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

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

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

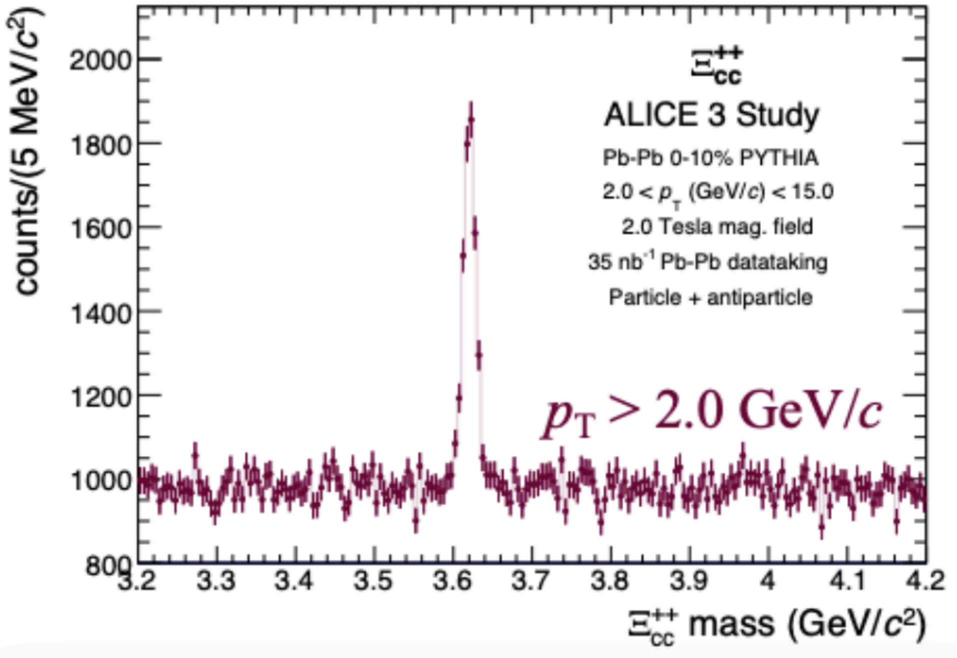


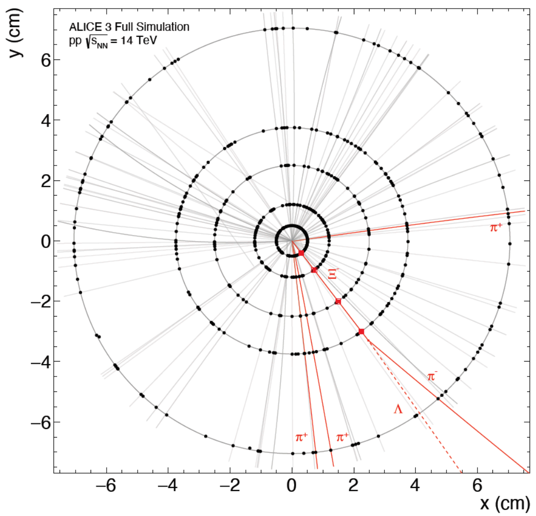
Multi-Charm Baryon Reconstruction

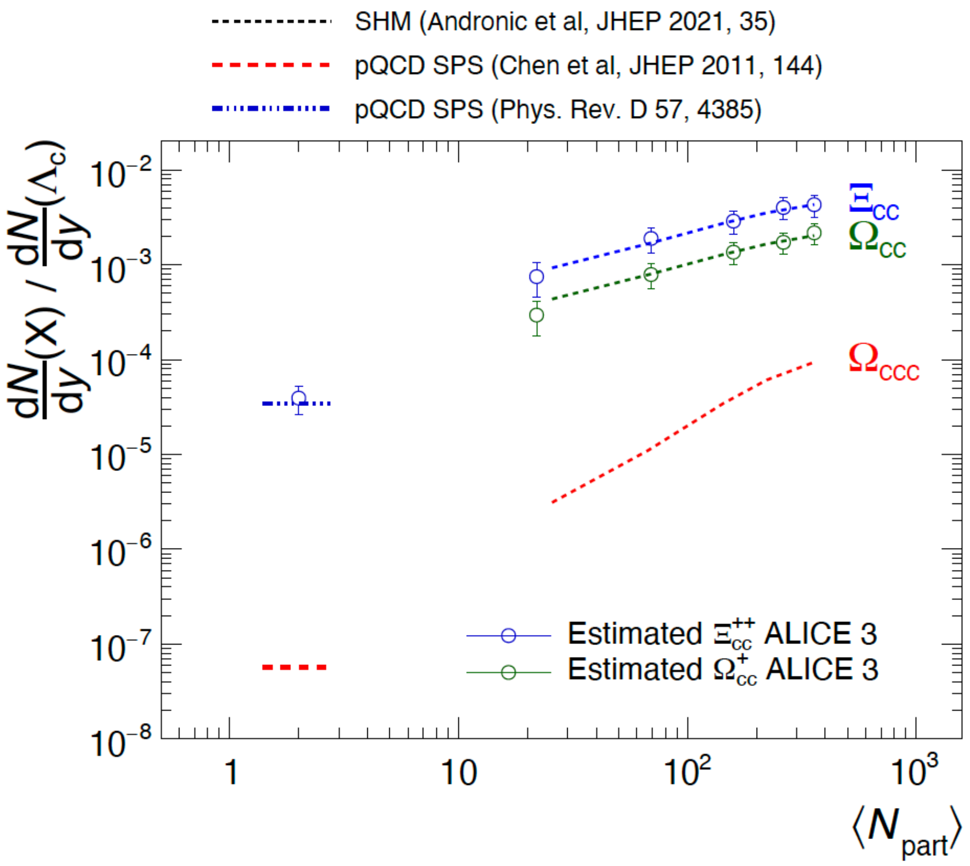
New technique: strangeness tracking with Ξ baryon provides high selectivity

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

Expected mass peak in Pb-Pb collisions

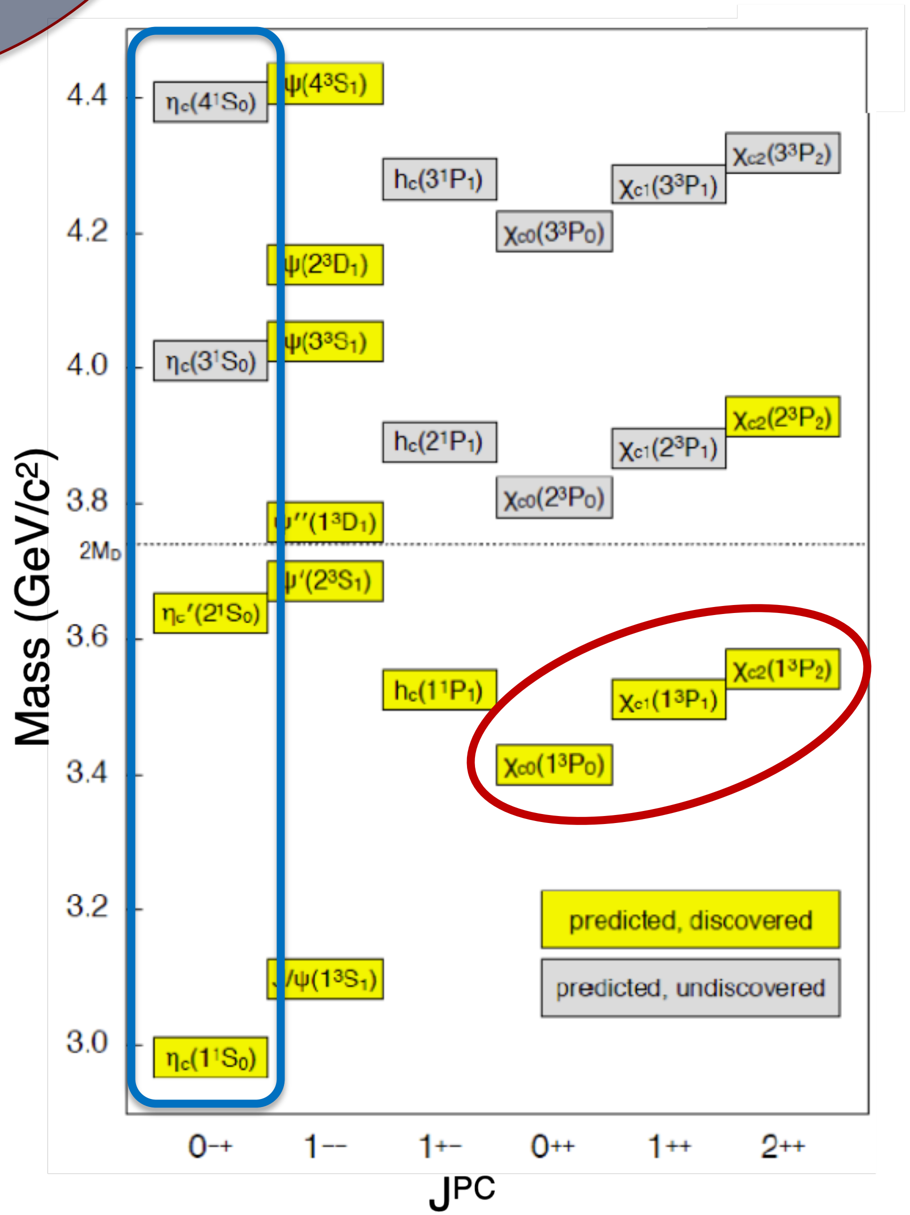






- **Multi-charm baryons vs system size: unique insight in thermalization and hadronization dynamics.**
- ALICE 3: unique experimental access in Pb-Pb collisions

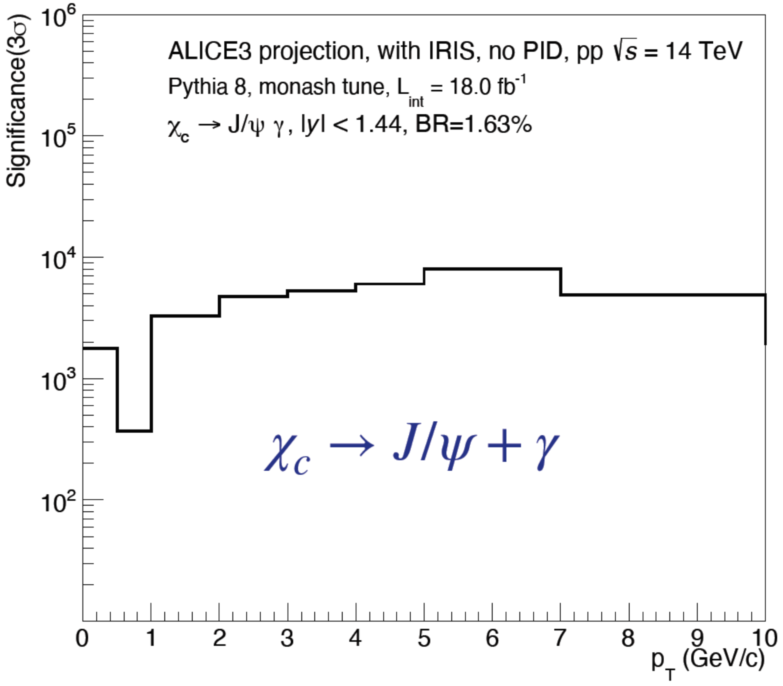
Quarkonium Measurements beyond S-wave States

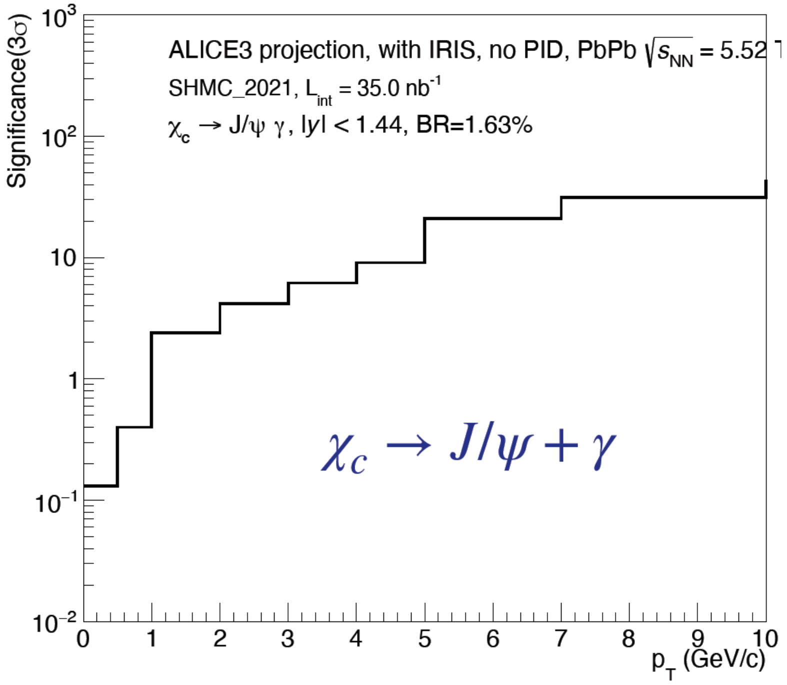


Quarkonium measurements in Heavy-Ion collisions are currently limited to S-wave states : J/ψ, ψ(2S), ϒ(nS)

χ_c states:

- ➢ Binding energy in between J/ψ and ψ(2S)
- ➢ Sizable (~ 25%) feed-down contribution to J/ψ

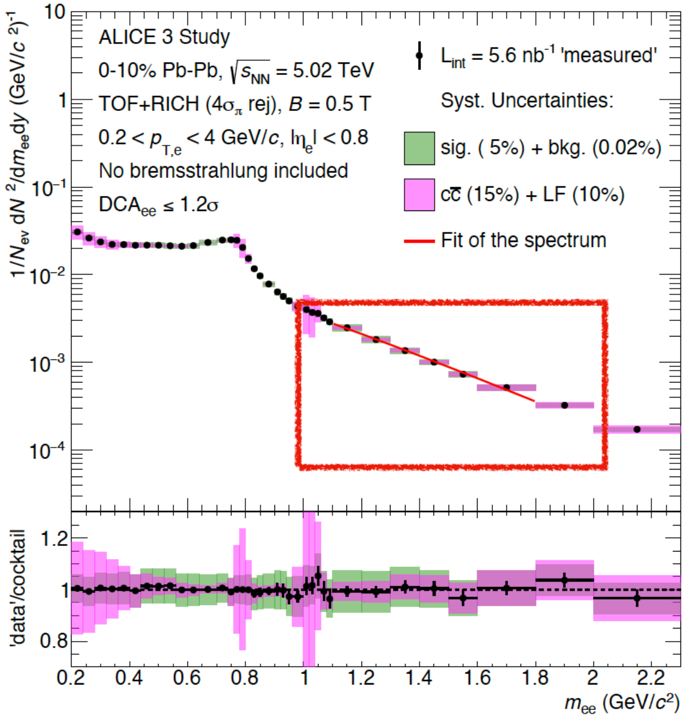




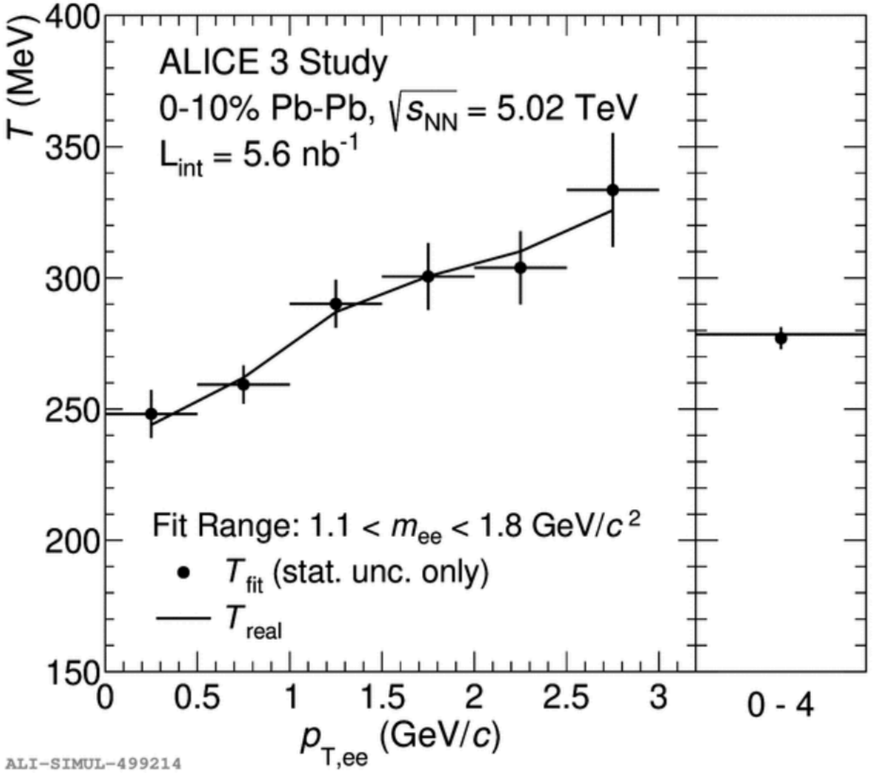
Dileptons: Accessing QGP Temperature

- **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

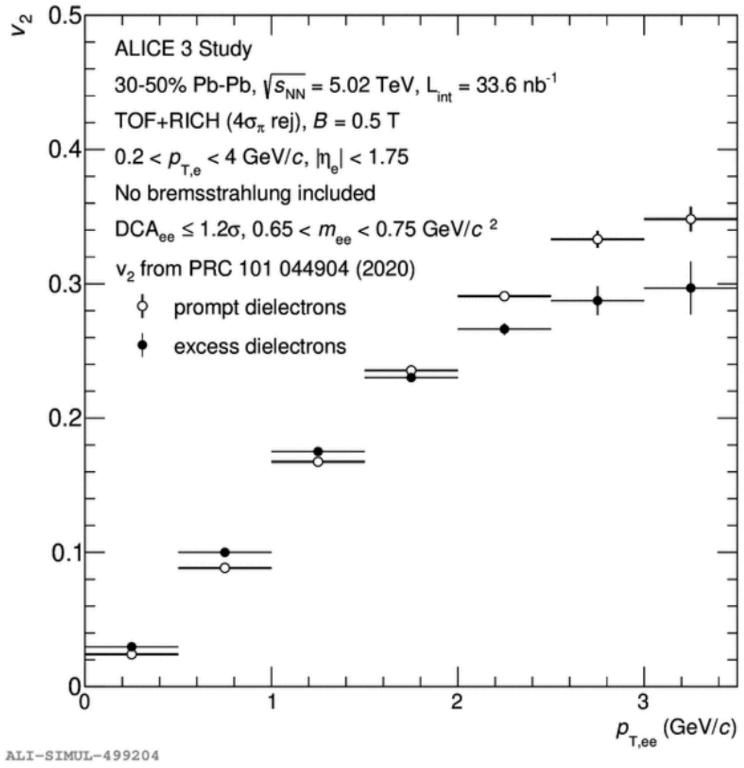
Dielectron mass distribution



Temperature from slope (M_{ee})



Dielectron v_2

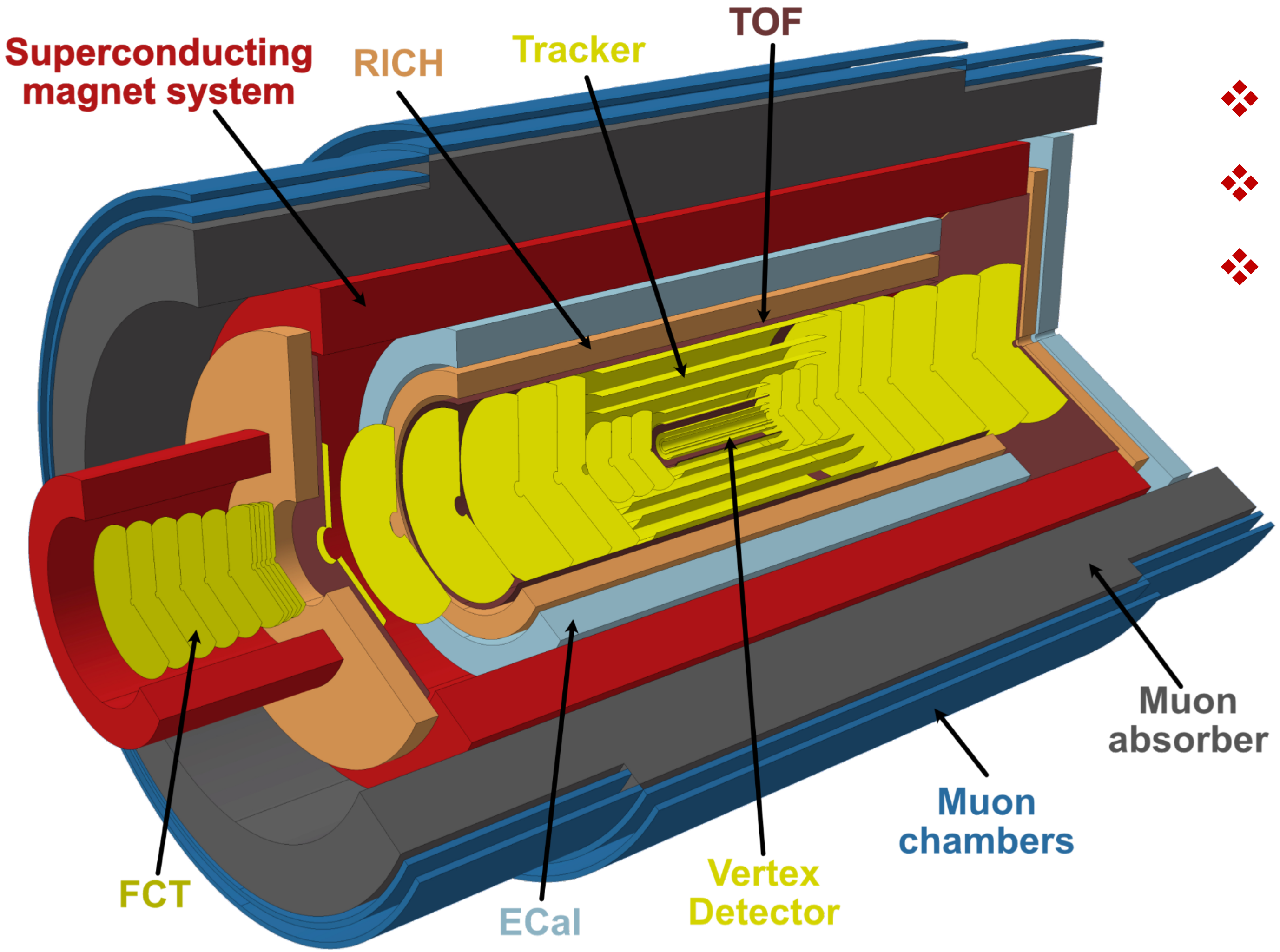


Further Topics

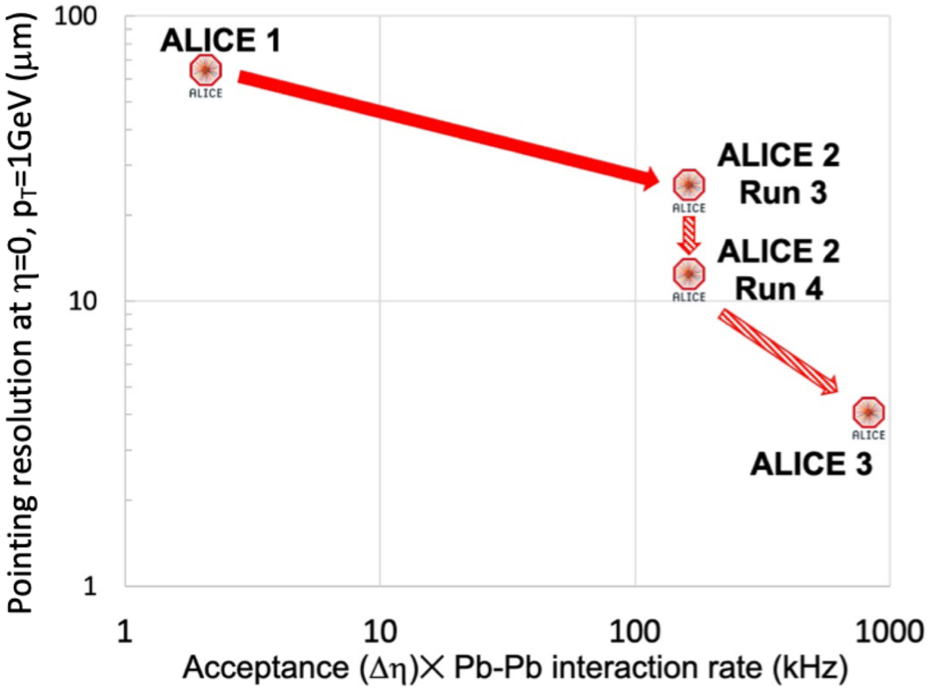
- **New nuclear states**: existence of *bound states of a charm baryon and a nucleon without Coulomb repulsion (c-deuteron n-*Λ_c *and c-triton n-n-*Λ_c*) sheds light on the charm-nucleon potential*
- **Ultra-soft photons (down to $p_T \approx 2$ MeV/c)**: Low's theorem predictions violated in previous experiments by an excess of soft-photon production. **Proposed explanations:** cold quark-gluon plasma, quark synchrotron radiation, string fragmentation. Handle to investigate fundamental non-perturbative properties of QCD
- Ultra-peripheral collisions: rare single-resonance and resonance-pair production (e.g. $\rho' \rightarrow 4\pi$, ρ-J/ψ), light-by-light scattering
- Net-baryon fluctuations: baryon number conservation, baryon number susceptibility and critical behavior
- **BSM searches**: ALPs, dark photons, long-lived particles

Detector Studies

The ALICE 3 Detector Concept



- Compact all-silicon tracker with large acceptance and high-resolution vertex detector
- Superconducting magnet system (1 T to 2 T)
- Particle identification over large acceptance
- Fast readout and online processing



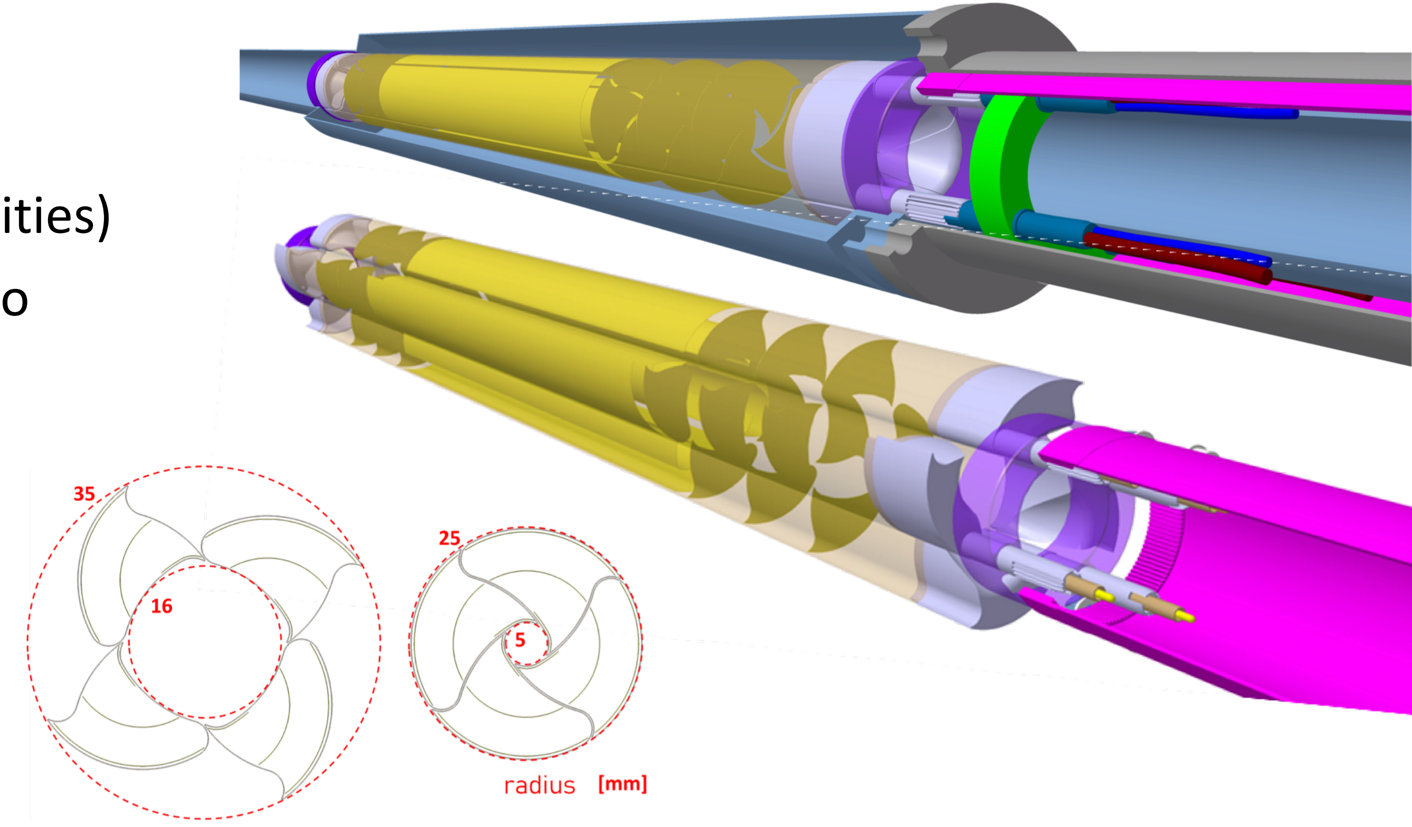
The ALICE 3 Detector Concept

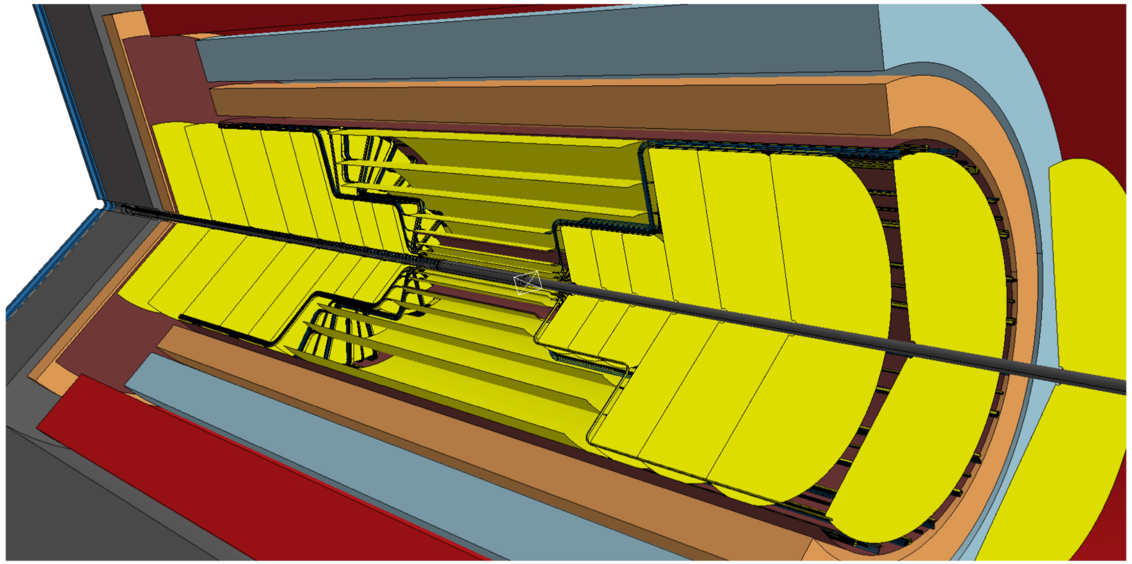
Component	Observables	$\vert\eta\vert < 1.75$ (barrel)	$1.75 < \vert\eta\vert < 4$ (forward)	Detectors
Vertexing	Multi-charm baryons, dielectrons	**Best possible DCA resolution, $\sigma_{DCA} \approx 10$ μm at 200 MeV/*c***	**Best possible DCA resolution, $\sigma_{DCA} \approx 30$ μm at 200 MeV/*c***	Retractable silicon pixel tracker: $\sigma_{pos} \approx 2.5$ μm, $R_{in} \approx 5$ mm, $X/X_0 \approx 0.1$ % for first layer
Tracking	Multi-charm baryons, dielectrons	**σ_{p_T} / p_T ~1-2 %**		Silicon pixel tracker: $\sigma_{pos} \approx 10$ μm, $R_{out} \approx 80$ cm, $X/X_0 \approx 1$ % / layer
Hadron ID	Multi-charm baryons	**π/K/p separation up to a few GeV/*c***		Time of flight: $\sigma_{tof} \approx 20$ ps RICH: aerogel, $\sigma_\theta \approx 1.5$ mrad
Electron ID	Dielectrons, quarkonia, χ_{c1}(3872)	pion rejection by 1000x up to ~2 - 3 GeV/*c*		Time of flight: $\sigma_{tof} \approx 20$ ps RICH: aerogel, $\sigma_\theta \approx 1.5$ mrad
Muon ID	Quarkonia, χ_{c1}(3872)	reconstruction of J/Ψ at rest, i.e. muons from 1.5 GeV/*c*		steel absorber: L ≈ 70 cm muon detectors
Electromagnetic calorimetry	Photons, jets	large acceptance		Pb-Sci calorimeter
	χ_c	high-resolution segment		$PbWO_4$ calorimeter
Ultrasoft photon detection	Ultra-soft photons		measurement of photons in p_T range 1 - 50 MeV/*c*	Forward Conversion Tracker based on silicon pixel sensors

Vertex Detector and Outer Tracker

Vertexing layers

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





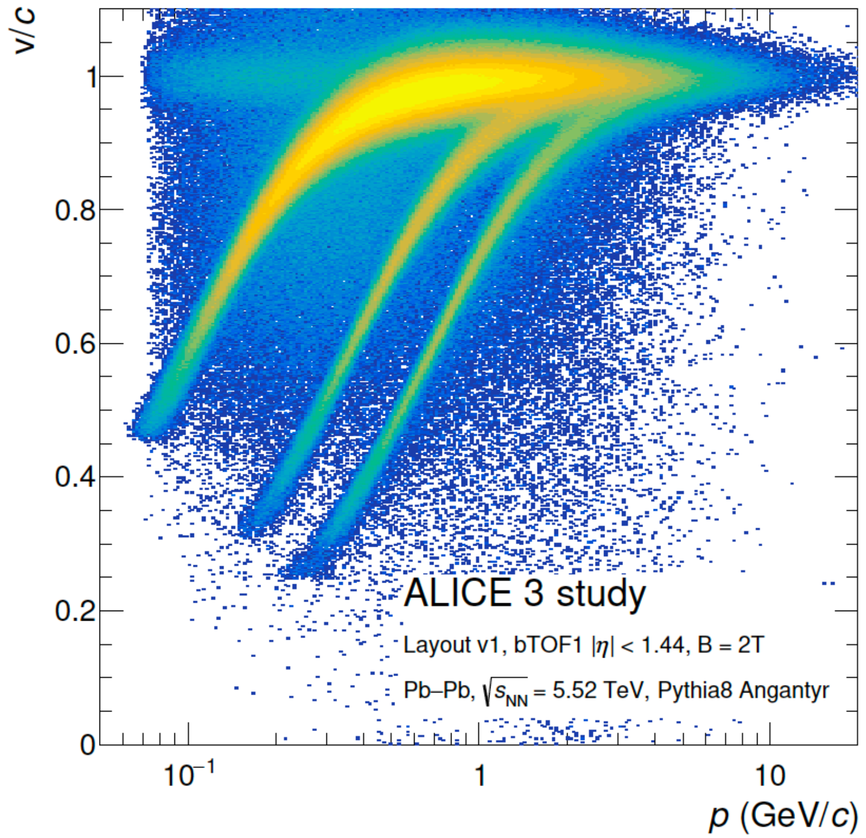
Outer Tracker (≈ 66 m²)

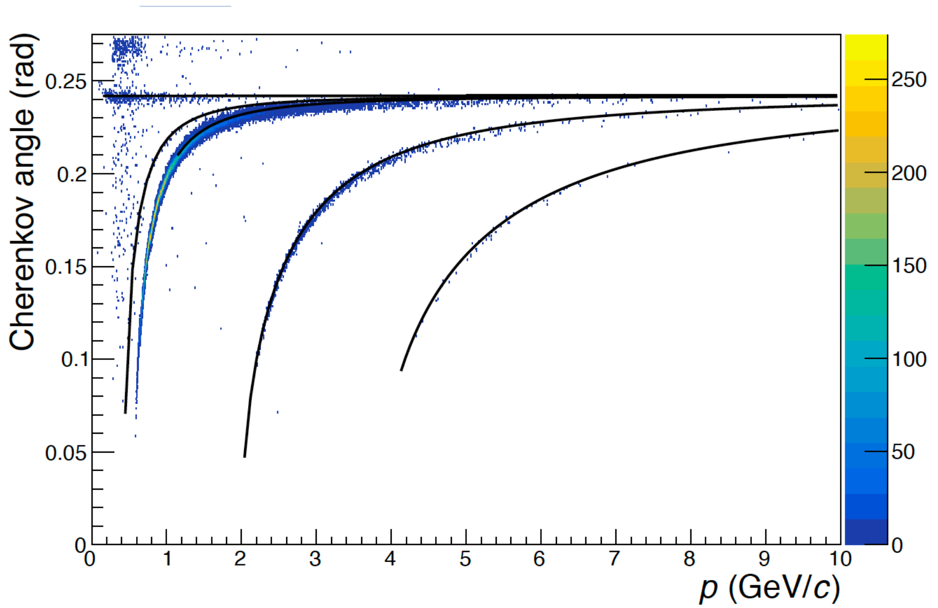
- MAPS on modules on water-cooled carbon-fiber cold plate
- Carbon-fiber space frame for mechanical support
- **R&D challenges** on powering scheme and industrialization

TOF and RICH

TOF detector: PID at low momenta

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





RICH detector (barrel + forward) :

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

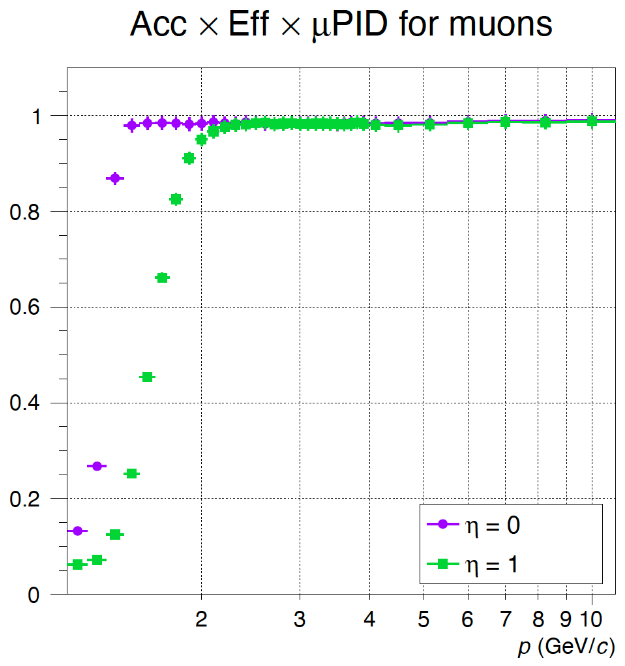
MID (HCal?) and ECal

Hadron absorber

- ≈ 70 cm non-magnetic steel → muons down to 1.5 GeV/c at $\eta = 0$
- HCal option under study (active absorber)

Muon chambers

- Search spot for muons ≈ 0.1 × 0.1 ($\eta \times \varphi$) → ≈ 5 × 5 cm^2 cell size
- Matching demonstrated with 2 layers of muon chambers
- Scintillator bars + wave-length shifting fibres + SiPM read-out



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	$R_{\text{in}} = 1.15$ m, $\lvert z\rvert < 2.7$ m	$0.16 < R < 1.8$ m, $z = 4.35$ m	$R_{\text{in}} = 1.15$ m, $\lvert z\rvert < 0.64$ m
technology	sampling Pb + scint.	sampling Pb + scint.	$PbWO_4$ crystals
cell size	$30 \times 30\ \text{mm}^2$	$40 \times 40\ \text{mm}^2$	$22 \times 22\ \text{mm}^2$
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

- **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)

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 person power

- **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 cavern and installation of ALICE 3

ALICE 3 at IN2P3

Three IN2P3 laboratories aim at participating in the ALICE 3 project (IPHC, LPSC, IP2I-Lyon)

- Common scientific program based on heavy-flavor measurements, allowing for the study of the interaction of heavy quarks with the medium (energy loss + hadronization) and the characterization of the mechanisms driving the formation and dissociation of bound states inside the medium
- Common technical project focused on the R&D and construction of the **tracking layers**, capitalizing the experience and the efforts deployed in the ITS3 project (under approval by IN2P3)

Ongoing discussions with the IN2P3 directorate and the Directors of the three labs: converging in the next months towards a technical proposal illustrating the plans for the contribution to the detector R&D and construction

Researchers FTE should by no means be inferior to the ones which allowed the successful preparation of the Upgrades of the Long Shutdown 2 in parallel with the exploitation of the Run1+Run2 data:

- 5.5 FTE at the IPHC (currently 4.5, 3.5 at the 2024 horizon if excluding new recruitments)
- 4 FTE at LPSC (currently 3, 2.5 at the 2027 horizon if excluding new recruitments)
- 4 FTE at IP2I-Lyon (currently 2, expected to rise to 3 at the end of the 2023 CNRS competition)

Summary and Conclusions

- **ALICE is preparing a next-generation, dedicated heavy-ion experiment** for LHC Run 5 and beyond, to shed light on the microscopic dynamics of the QGP
  - Temperature and properties of pre-hadronic stage, chiral symmetry restoration
  - Heavy flavor transport and thermalization
  - Hadronization and nature of hadronic states
  - Tests of infrared limits of gauge theories, new physics, …

- **Innovative detector concept** to meet the requirements of the ALICE 3 physics program
  - Fully exploiting the potential of the LHC for QGP studies
  - Building on experience with technologies pioneered in ALICE
  - Requiring R&D activities in several strategic areas

- **LoI available. Scoping Document under preparation:** establishing a plausible cost scenario in close exchange between the relevant stakeholders (Funding Agencies, CERN management, experiments, review bodies)

Backup Slides

Probing the QGP with HF Quarks

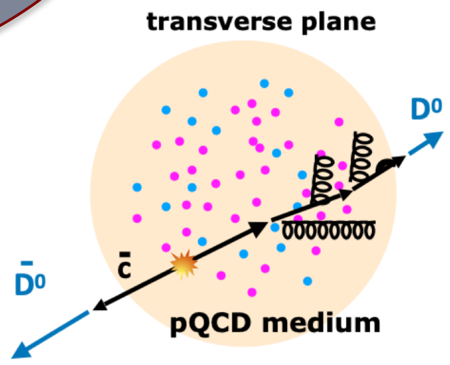
- **$m_Q \gg \Lambda_{\mathrm{QCD}}$ → early pQCD production**
- **$m_Q \gg \mathrm{T}_{\mathrm{QGP}}$ → no thermal production**
- **Charm/beauty content is conserved and traceable**

Interaction with the QGP via elastic and radiative processes: energy loss and momentum broadening. HF quarks probe the structure and the quasi-particle nature of the QGP at **different length scales**

- **Low-momentum scatterings:** Brownian motion ($m_{c,b} \gg m_{u,d,s}$) characterizing the diffusion properties of the QGP, quantified by the spatial diffusion coefficient D_s
- **High-momentum scatterings:** dominated by radiative energy loss and its $\hat{q}L^2$ dependence, probing the properties of scattering centers in the QGP

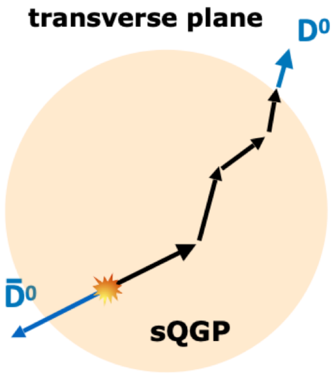
The ultimate goal of the field is to achieve a unified microscopic description of the evolving QGP that consistently relates its basic properties, such as the transport coefficients and viscosity parameters, with the experimental observables as a function of the system size

HF in Weakly- to Strongly-Coupled QGP



Short-scale, high p_T: short-distance, particulate, structure of QGP made of point-like scattering centers + radiative energy loss of HF

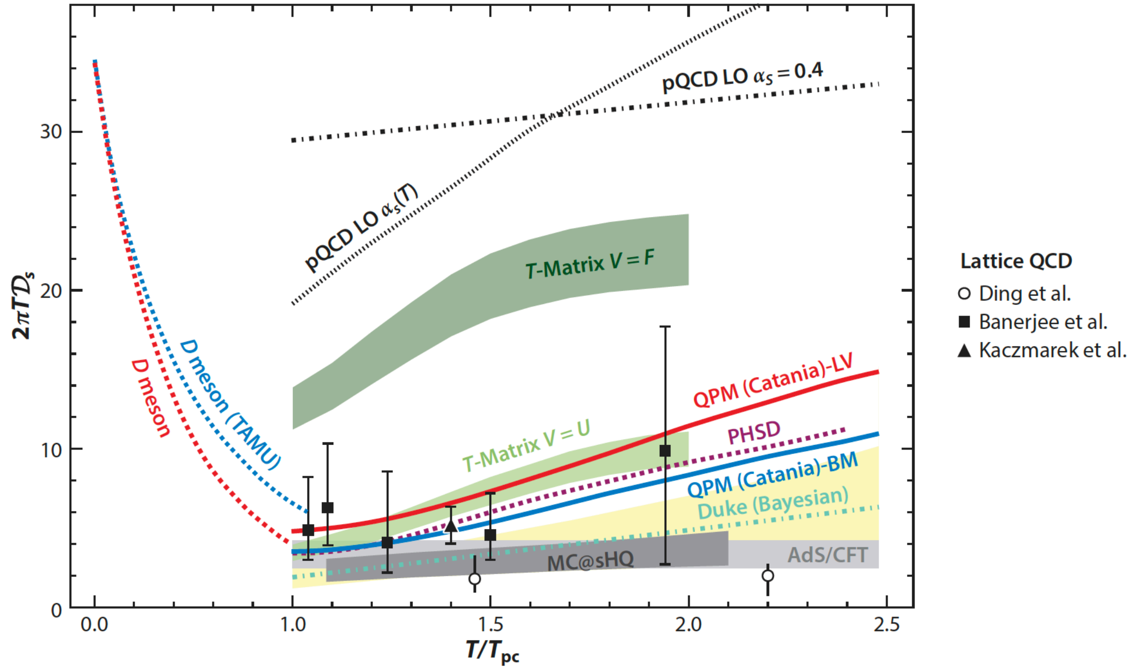
→ Di-jets asymmetry, high R_{AA}



Long-scale, low-intermediate p_T: diffusion properties of HF (D_s) in a strongly-coupled QGP. Universal information about the QGP transport properties, similar to η/s or the EM conductivity, σ_{EM}/T

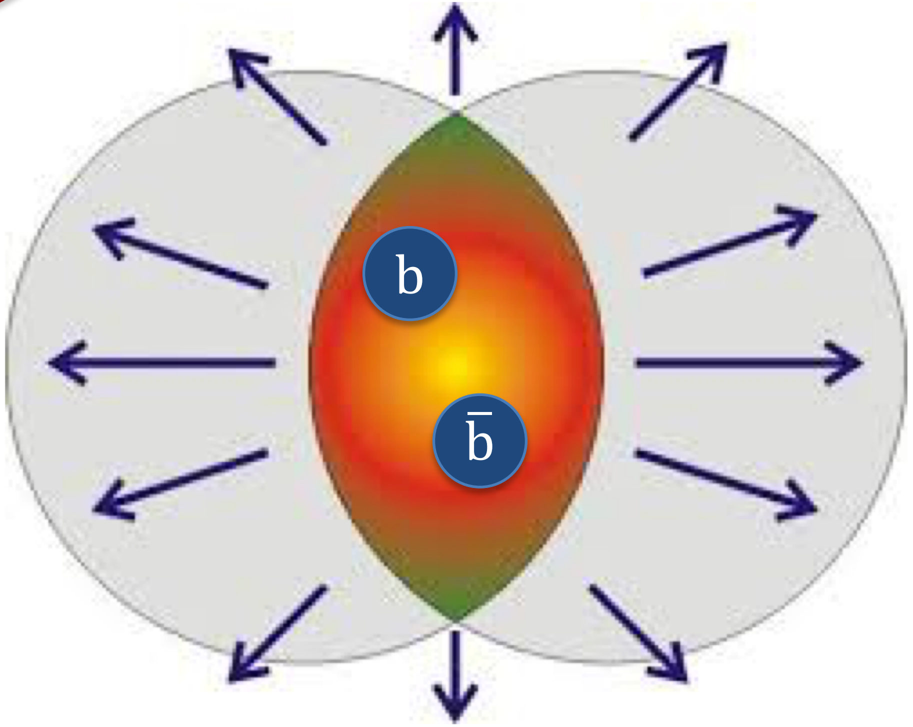
→ R_{AA}, v_2 of D/B mesons

→ Jet radial shapes



Transition from weakly, pointlike to strongly-coupled, near-ideal liquid QGP, (from perturbative to non-perturbative regime of QCD matter)

Beauty Production and Flow



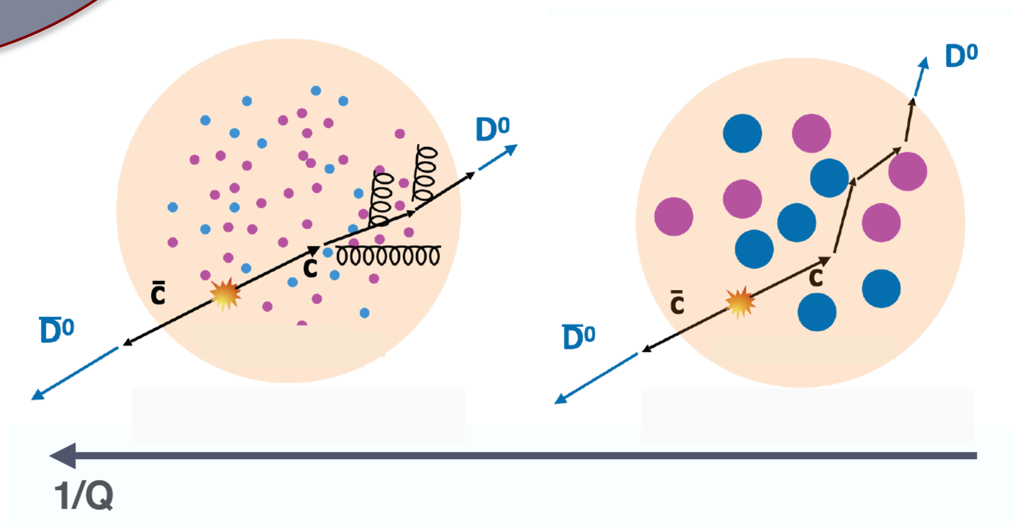
Heavy quarks "flow" with the medium, but charm and beauty quarks do it differently!

$$\tau_Q = (m_Q/T)D_s$$

- Thermalisation time of beauty quarks is about three times larger than that of charm quarks, longer than the lifetime of the QGP → beauty quarks preserve a stronger memory of the interactions with the medium

Measurements of the beauty-hadron R_{AA} and v_n coefficients + relative abundances of different beauty-hadron species (e.g. baryon-to-meson ratios) down to low p_T → crucial role to **simultaneously constrain the heavy-quark diffusion coefficient and the hadronization mechanism in the beauty sector**

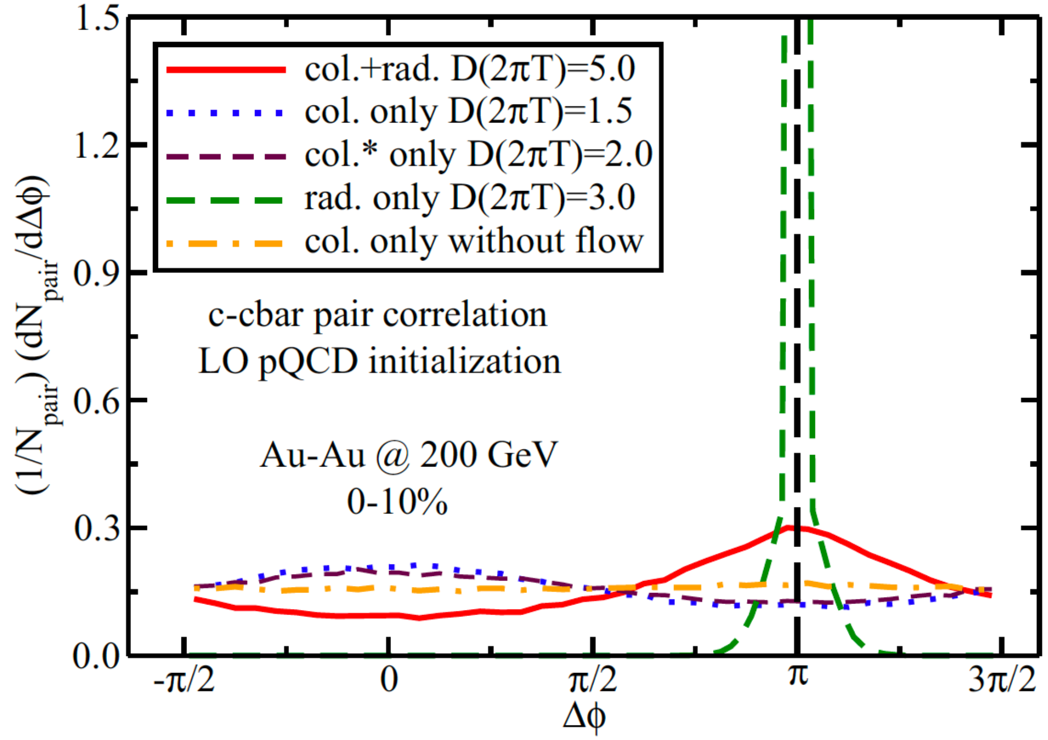
$D\bar{D}$ Azimuthal Correlations



$D\bar{D}$ pair correlations: sensitive to the motion of HF quarks in the medium and the associated momentum broadening, beyond fragmentation effects already at play in the vacuum

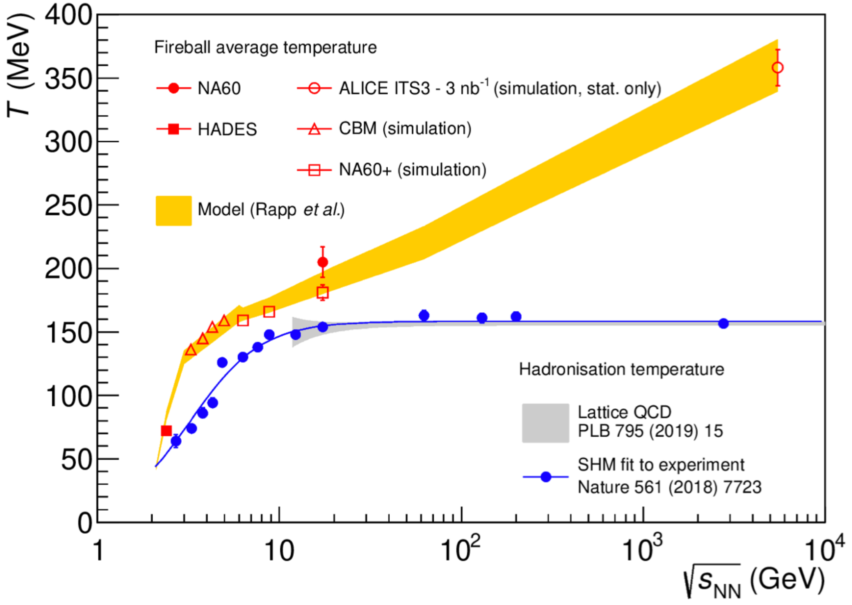
$$\hat{q} = \frac{\langle q_\perp^2 \rangle}{\lambda}$$

- 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



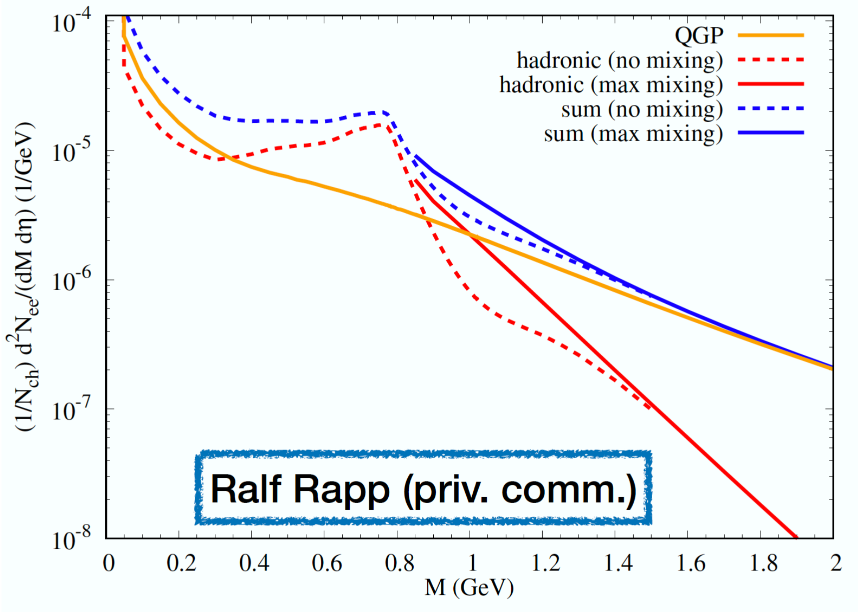
Thermal Radiation and Chiral Symmetry Restoration

Precise characterization of the initial stages of the collisions: temperature measurement with ≈ percent 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?



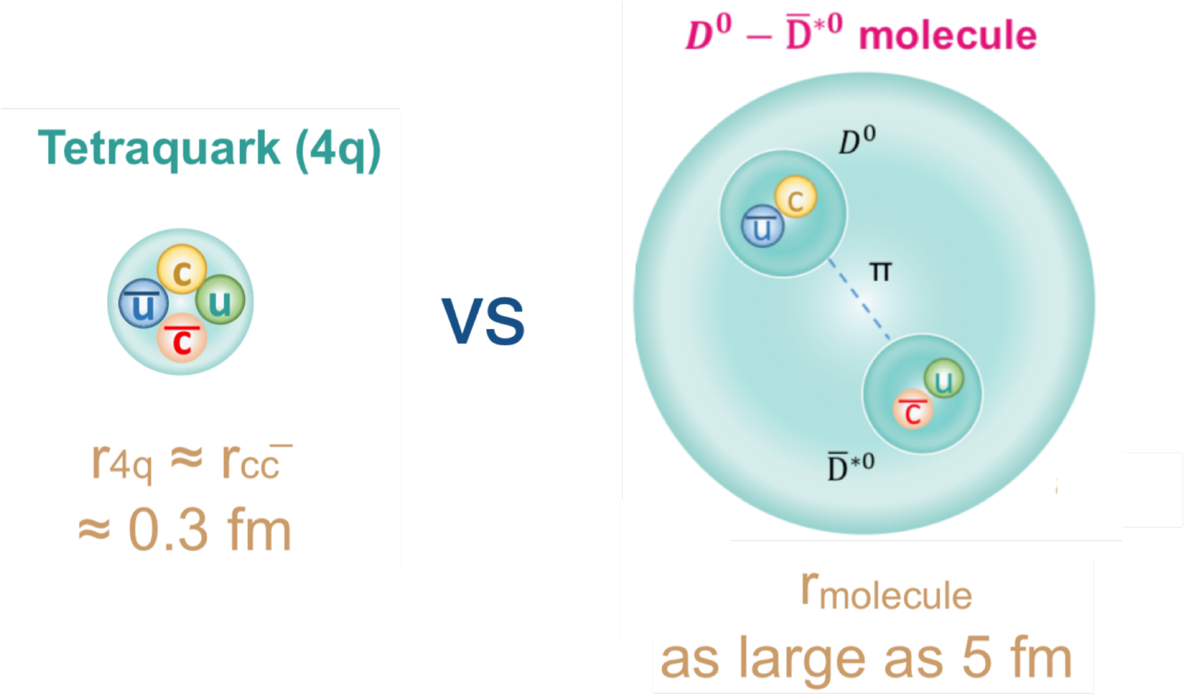
Ralf Rapp (priv. comm.)

Fireball chronometer: measurement of pre-equilibrium dileptons through multi-differential (p_T, flow, polarization, DCA) measurements

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



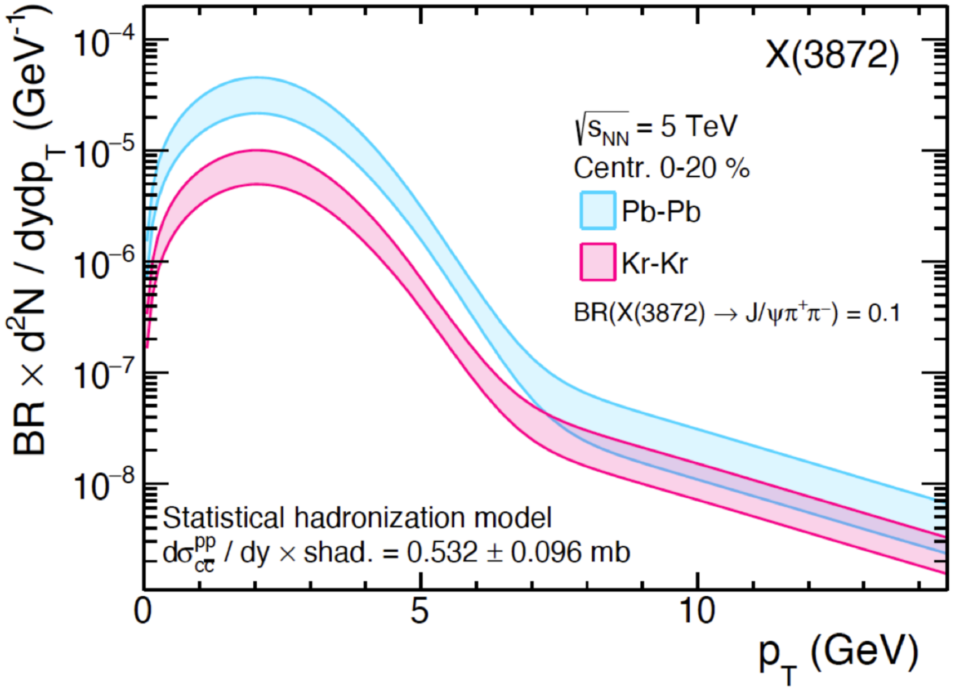
- If the case of its nature is addressed by the end of Run 4 we will have a **new, tuned tool to study HF hadronization in the QGP**

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

A. Andronic et al.: PLB 797, 2019, 134836



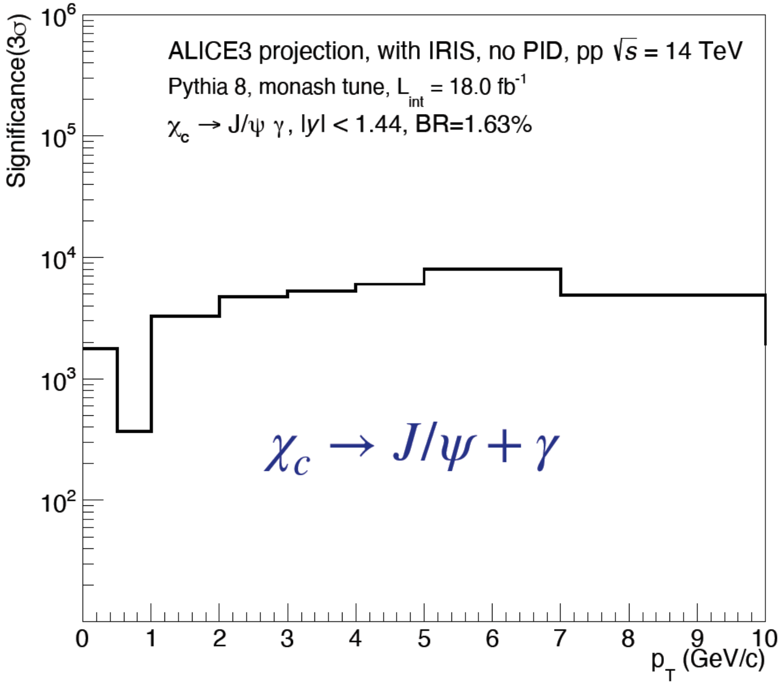
- If the case of its nature is addressed by the end of Run 4 we will have a **new, tuned tool to study HF hadronization in the QGP**

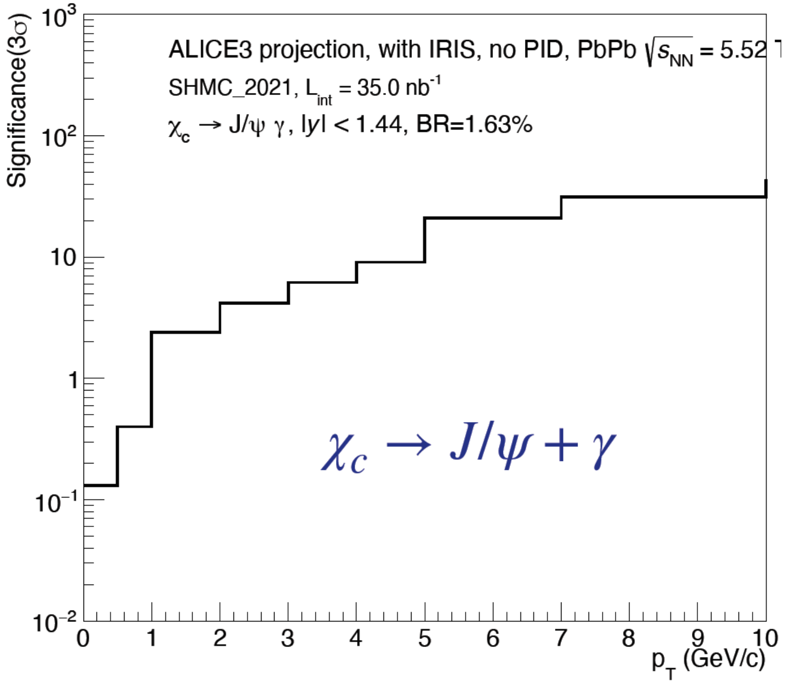
Low-p_T reach crucial for a full characterization of the hadronization mechanism

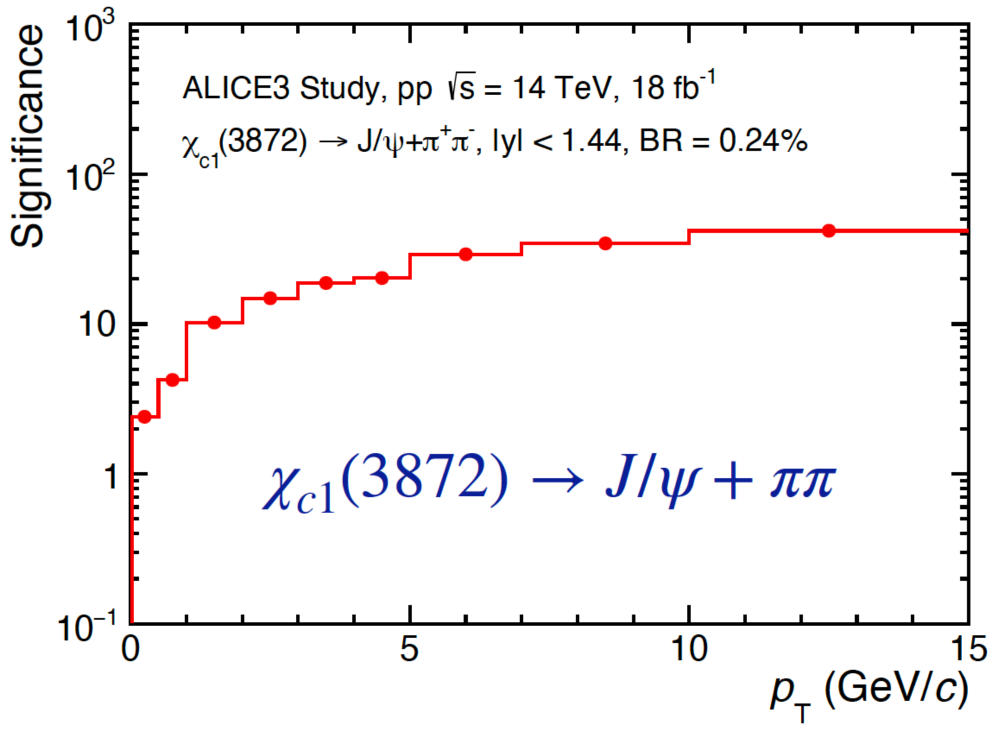
Quarkonium and Exotica Studies

Goal: understand formation and dissociation of $c\bar{c}$ states

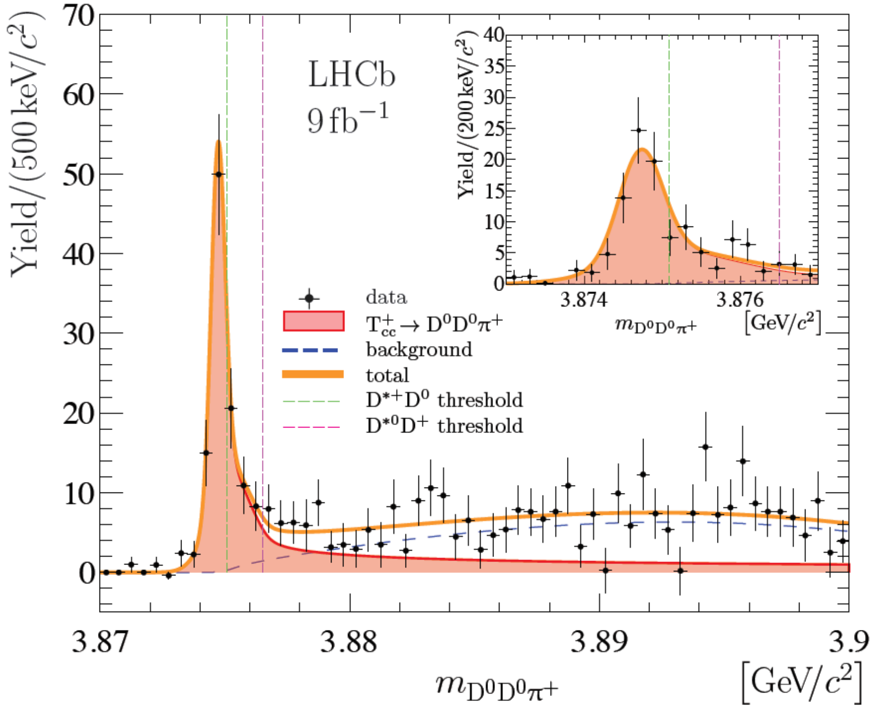
- Muon ID and ECal enable measurement of χ_c in Pb-Pb collisions down to p_T = 2 GeV/c
- χ_{c1}(3872) down to low p_T in pp, performence still to be assessed in Pb-Pb







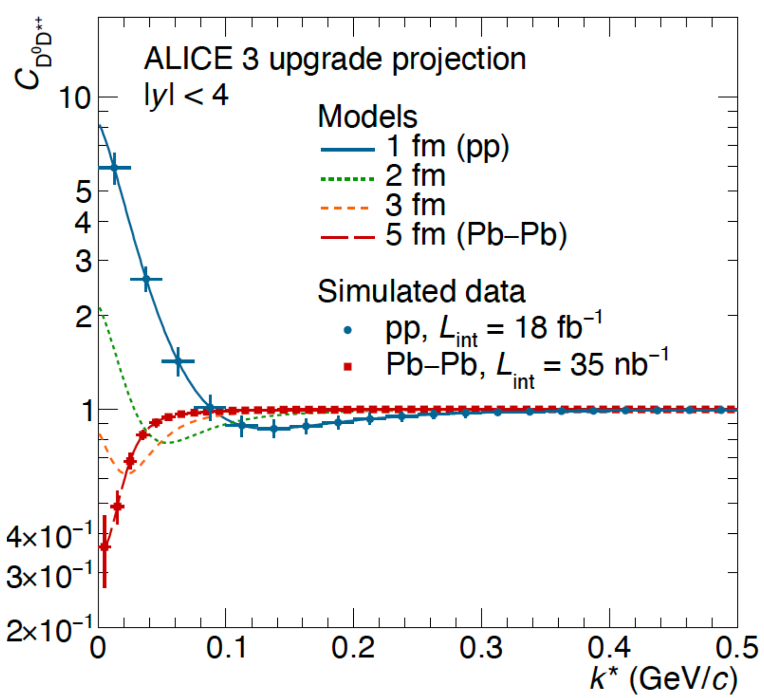
DD* Momentum Correlations



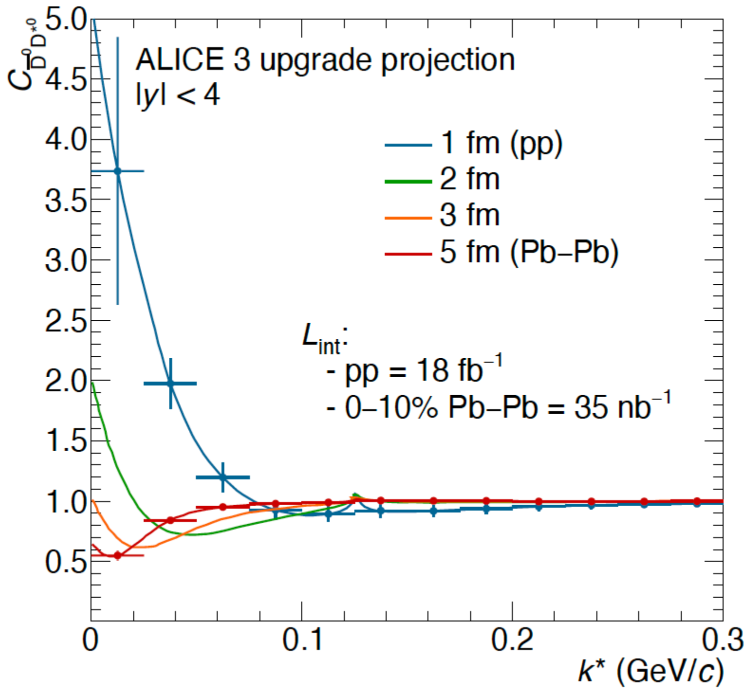
- Several exotic heavy flavour states identified: loosely bound meson molecule or tightly bound tetraquark?
- Can we pin down the nature of the states other than performing direct observations?

Studying binding potential with final state interactions through femtoscopic correlations

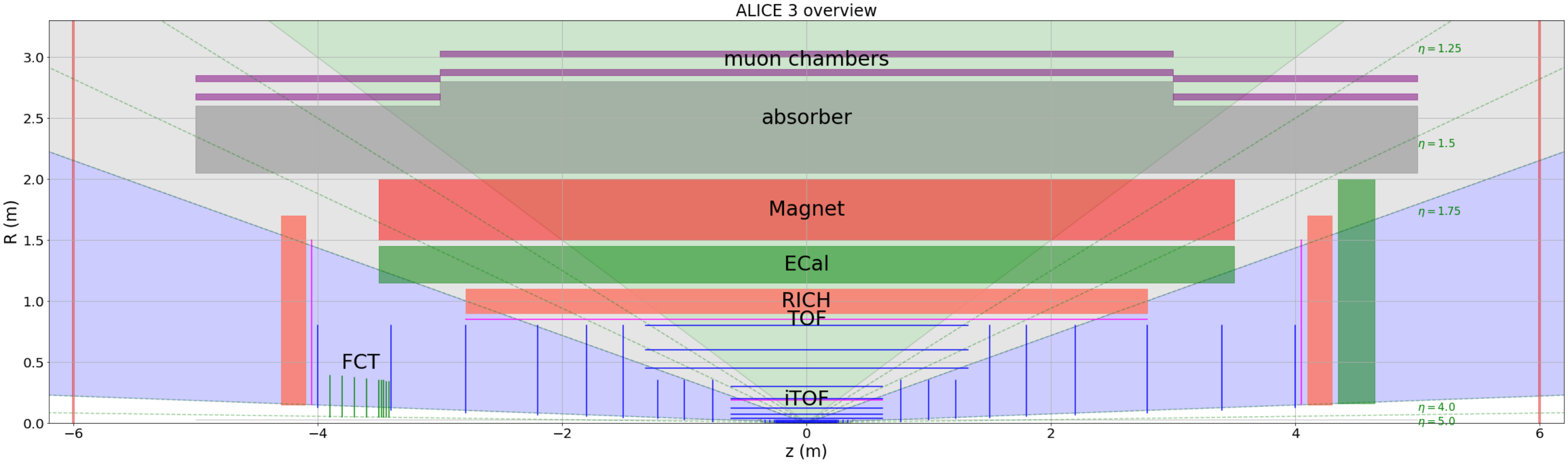
D^0D^{*+}



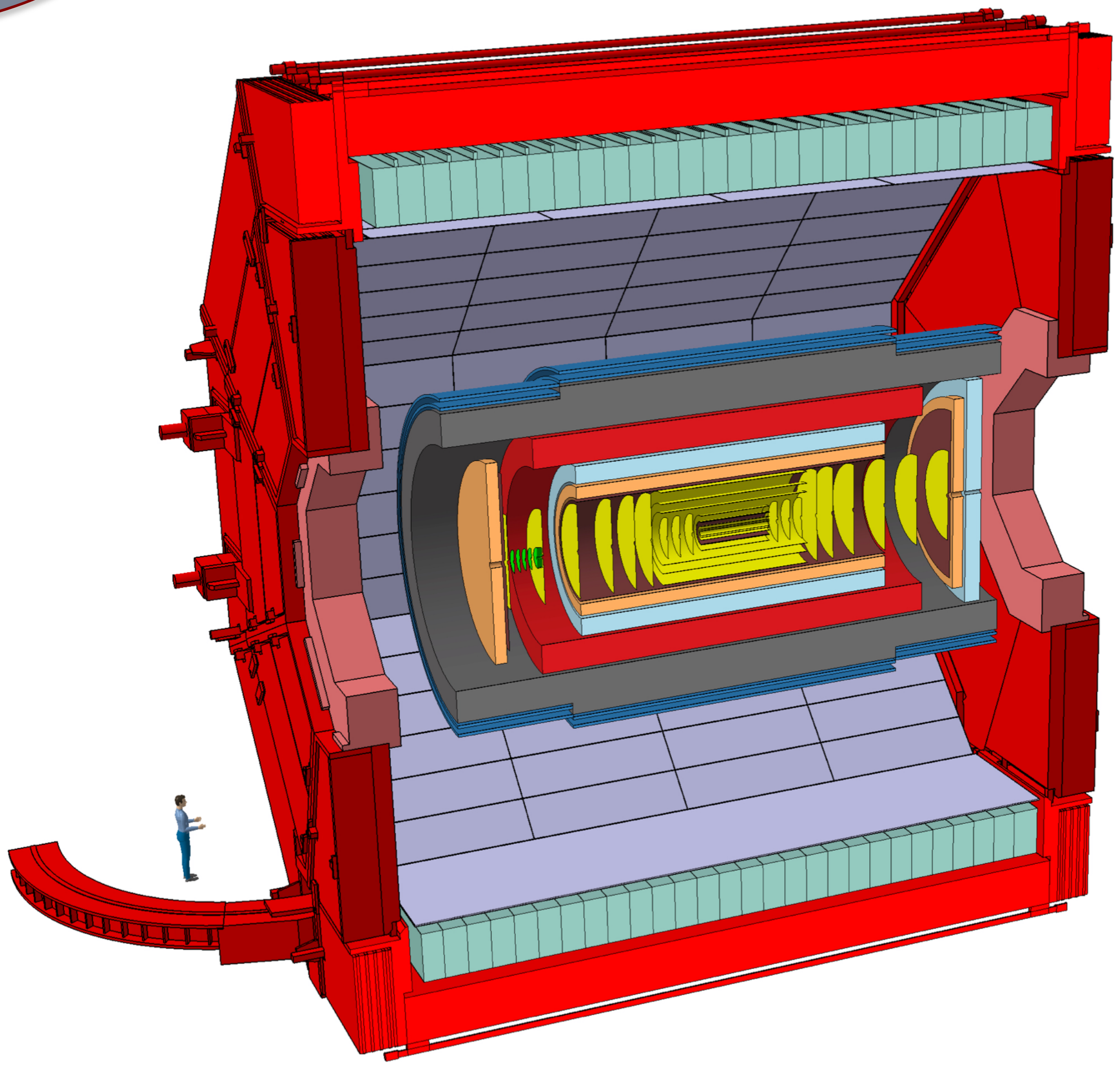
$D^0\overline{D}^{*0}$

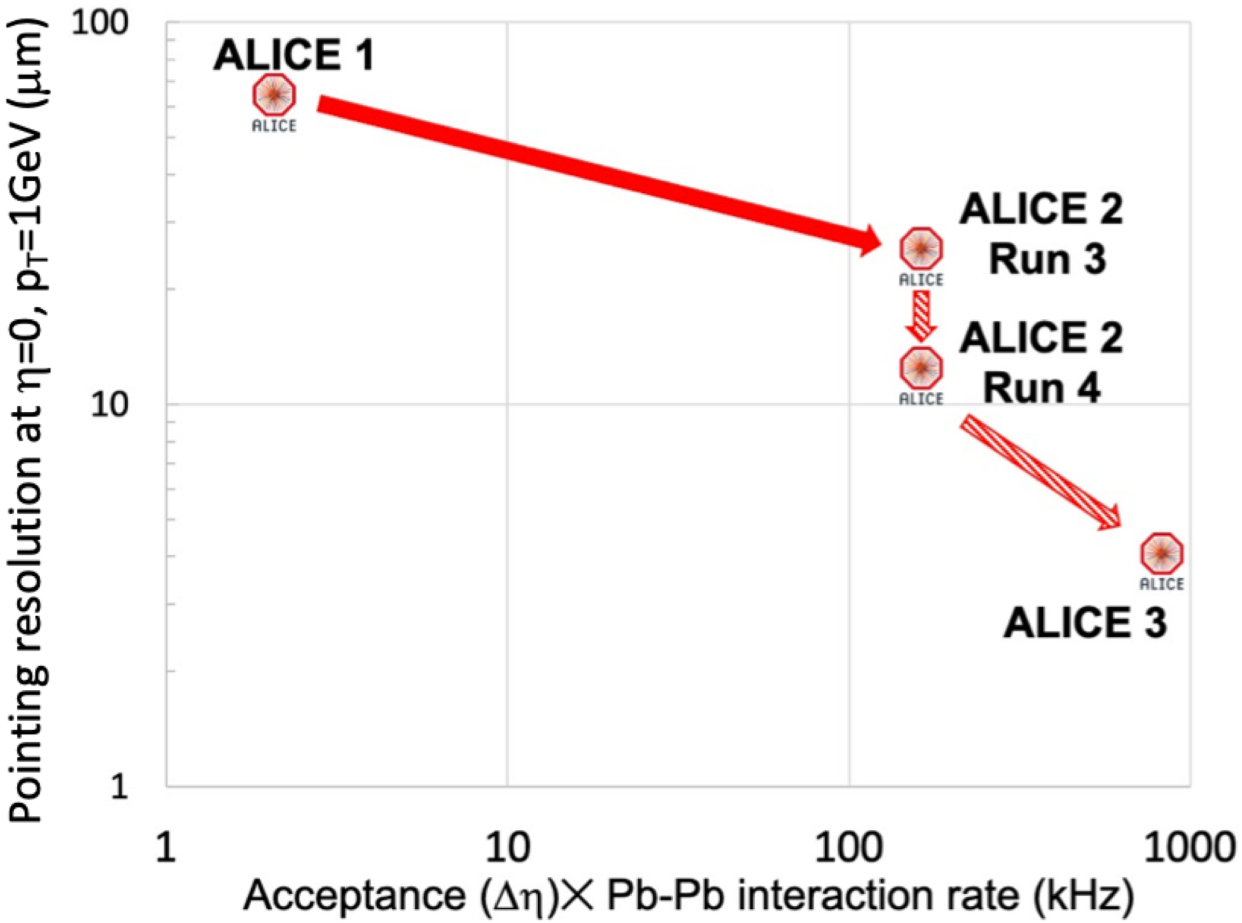


Detector Setup



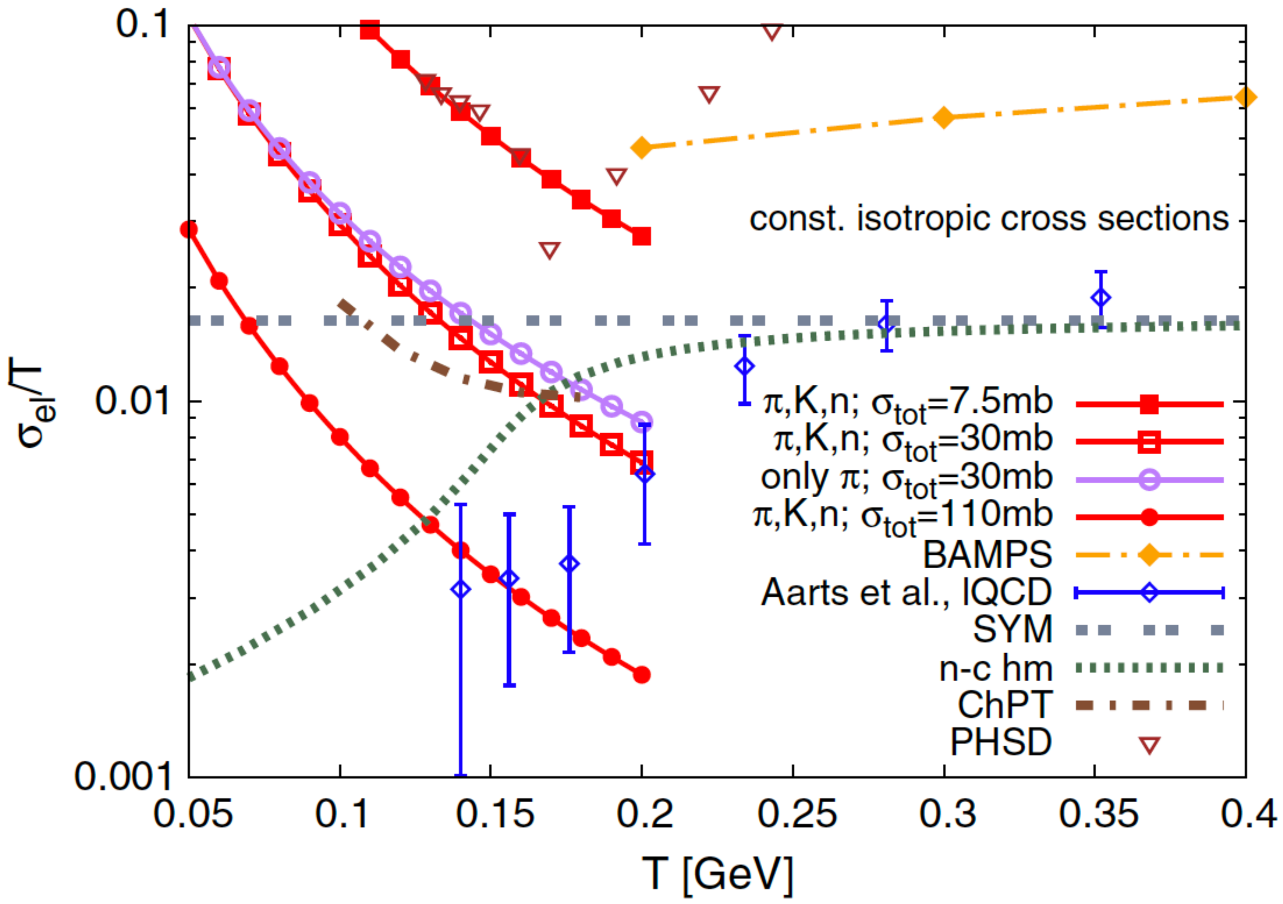
Detector Setup





Dilepton Spectra and Electric Conductivity

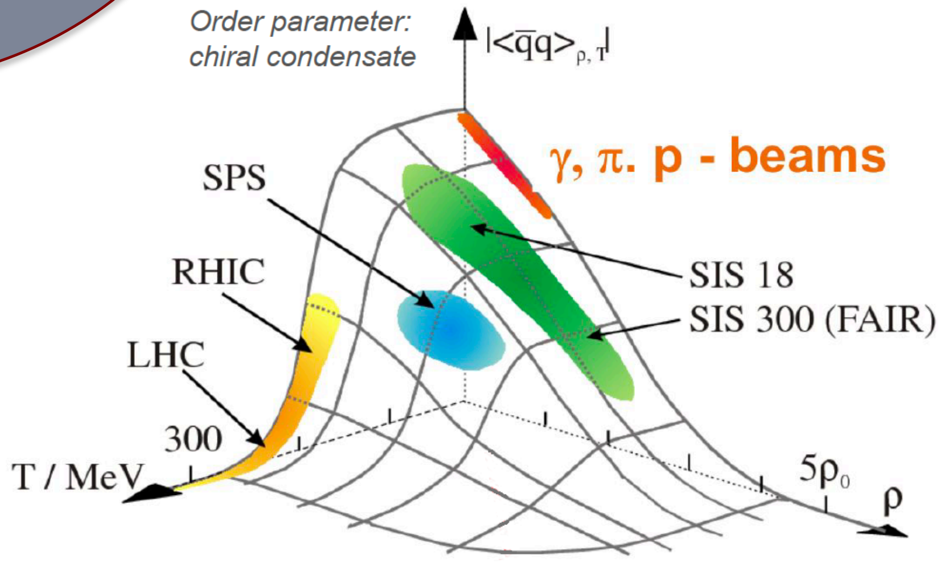
- **Electric conductivity, or electric charge diffusion coefficient:** response of an equilibrated relativistic gas of electrically charged particles, upon the influence of a small, static, electric field



- **QGP electric conductivity:** connected to lower and upper limits of thermal dilepton production spectra

Diffusion coefficients of the strongly interacting QGP: precise data needed to challenge theoretical models

Physics Motivations: Executive Summary (1)

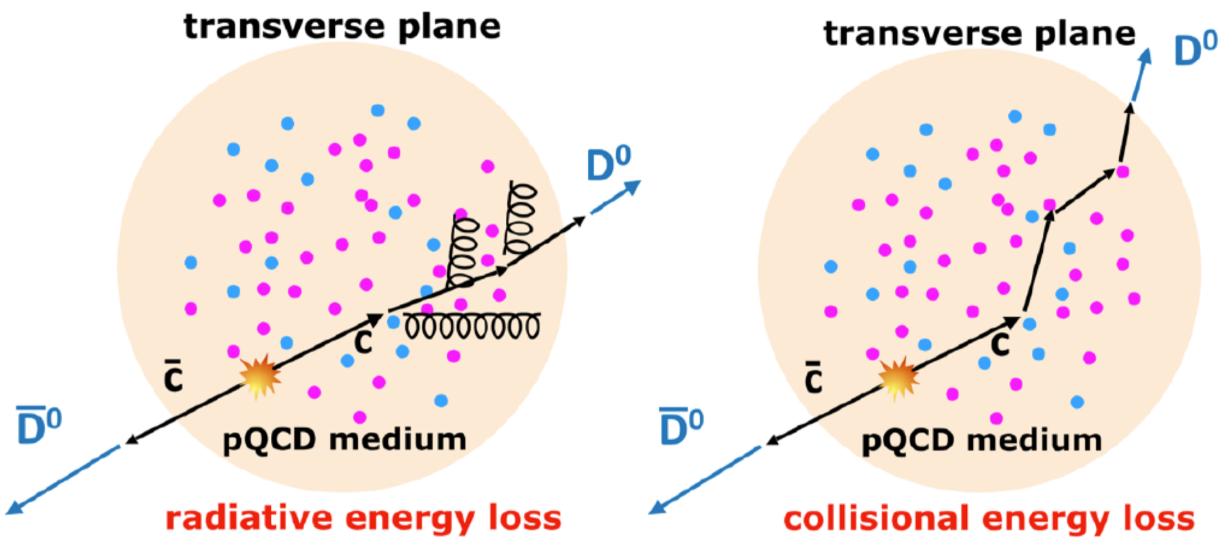


Characterization of chiral symmetry restoration at vanishing μ_B

- Dilepton mass spectra from the threshold to intermediate mass, down to zero p_T

Characterization of the microscopic mechanism of in-medium energy loss of heavy quarks

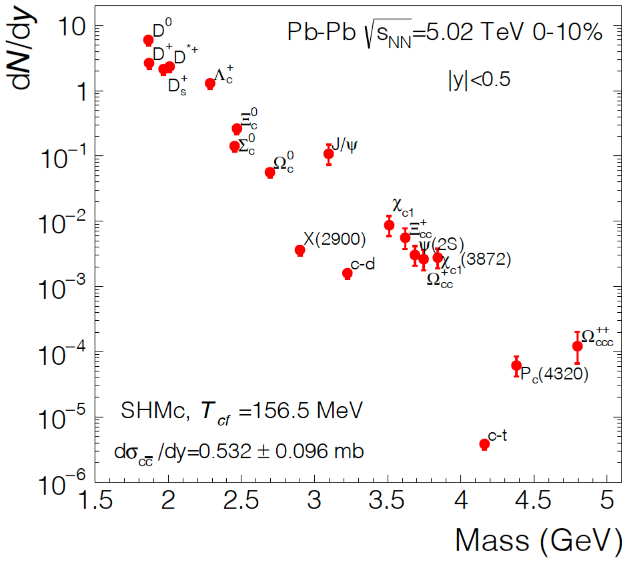
- HF correlations down to zero p_T (collisional vs radiative energy loss, flavour dependence)

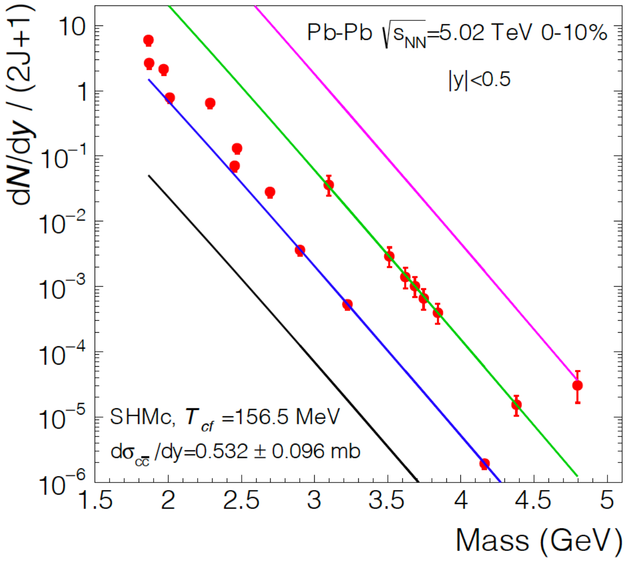


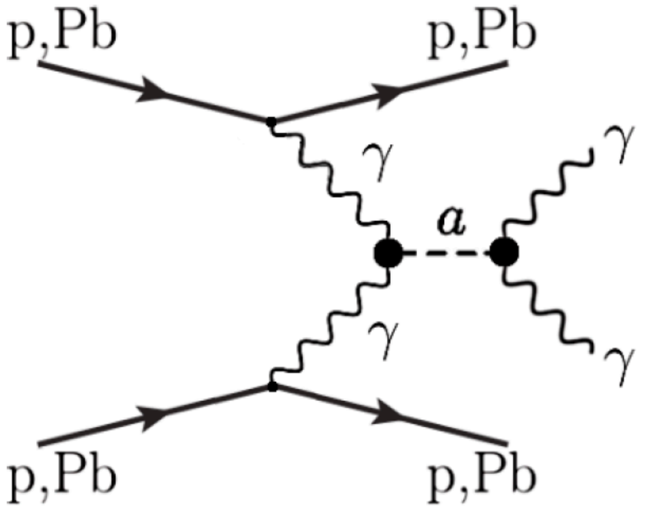
Physics Motivations: Executive Summary (2)

Hadronization mechanisms and non-conventional hadron structures:

- In-medium production rates of multi-charm states
- In-medium effects on the production of exotic states

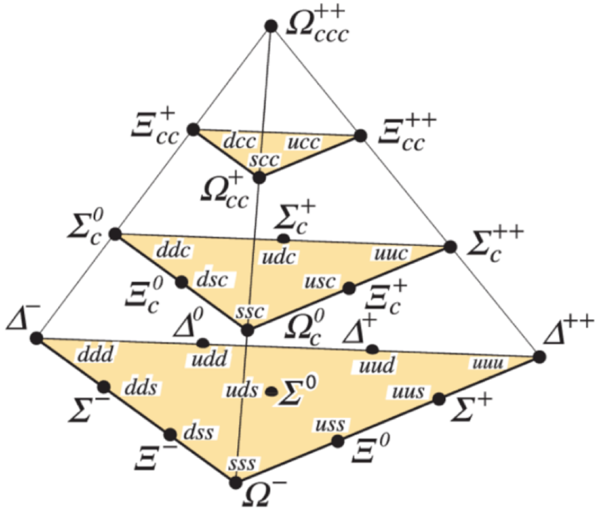






Searches for signals of new physics beyond Standard Model

- Exploiting the unique potential of (ultra-peripheral) heavy-ion collisions in a phase space

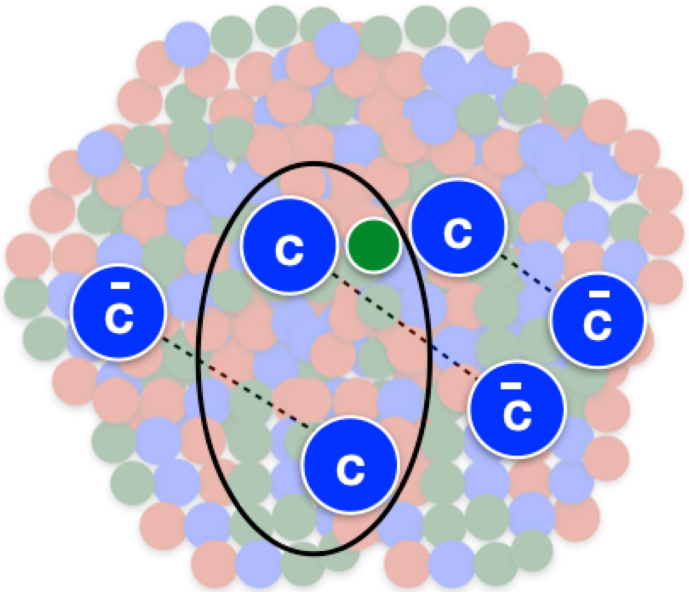


HF Hadronization Mechanisms

Hadronization mechanisms: key ingredient for a precise characterization of HF quark interactions with the medium

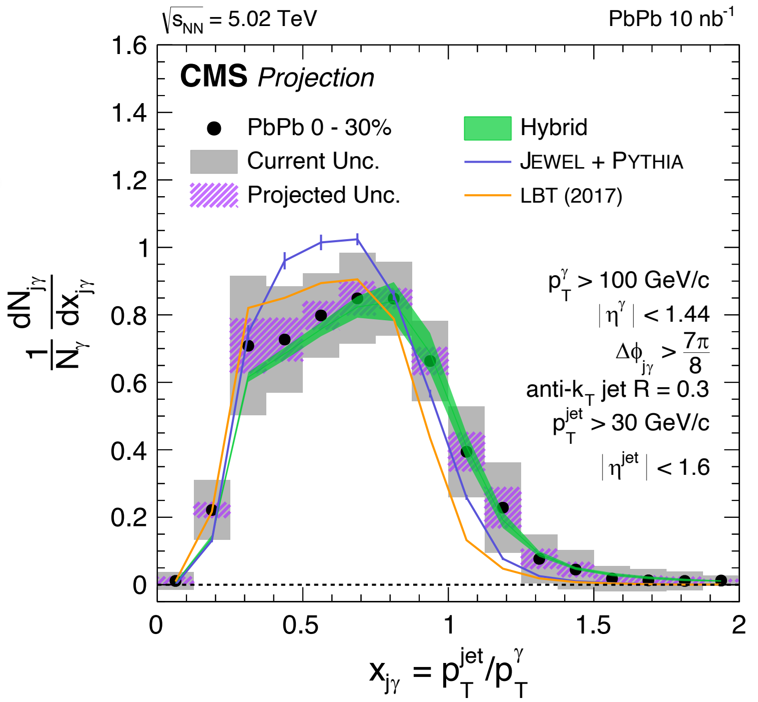
QGP has its own, specific hadronization mechanisms due to the dense environment of partons close to thermal equilibrium → quarks that are close in phase space can combine into colourless hadrons

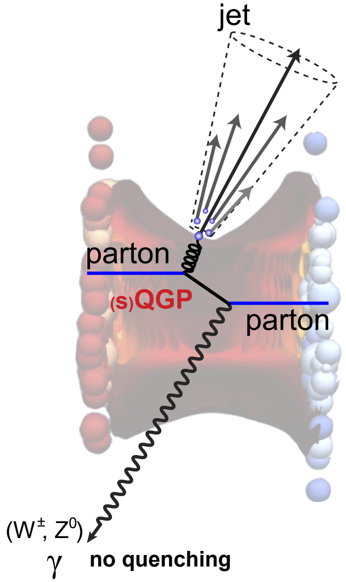
- Production of baryons and other heavy hadrons more favourable than in vacuum
- Most of the measured yields are well described by the Statistical Hadronization Model (SHM), with the abundances of light and strange hadrons following the equilibrium populations of a hadron-resonance gas at the freeze-out temperature of about 156 MeV
- **A systematic study of the relative abundances of the different heavy flavour species is needed, extending measurements to hadrons containing multiple heavy-flavour quarks, including multi-quark states**

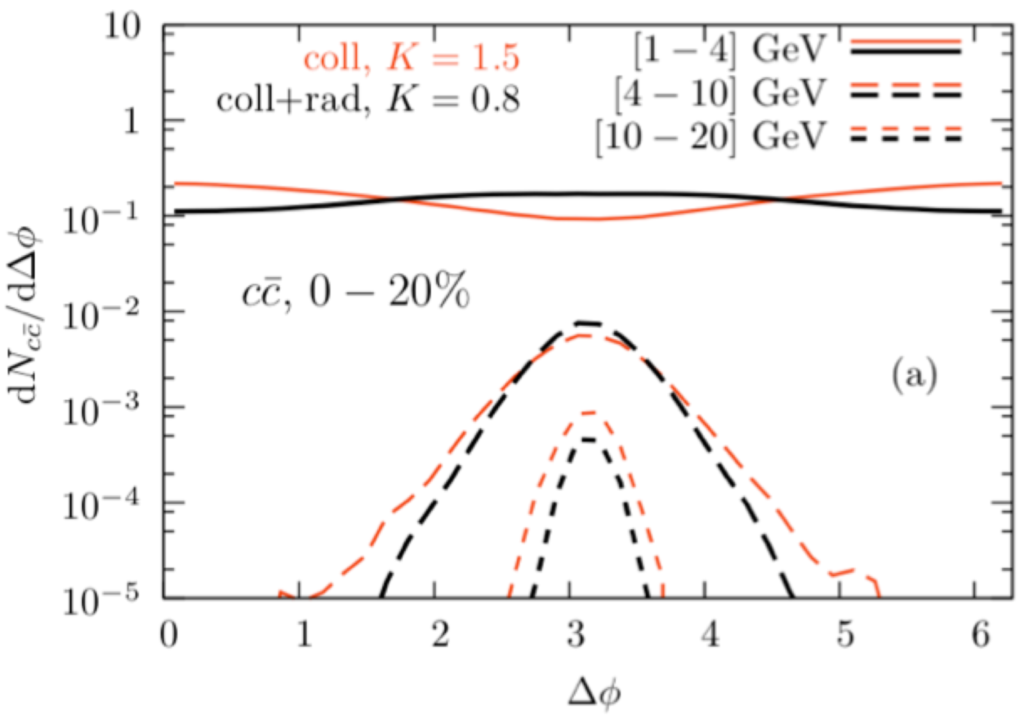


Heavy Flavor Correlations

Photon-HF correlations for an unquenched reference for energy and direction. Complementarity with CMS performance?



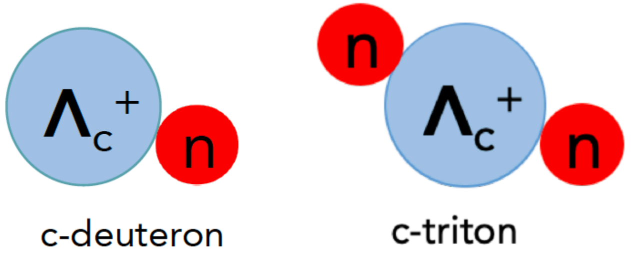




Away-side HF-HF correlations: sensitive to radiative vs elastic energy loss. Exploiting the larger "collinearity" found in radiative collisions, which could be seen in long-range azimuthal correlations

Nuclear States: Charm-Deuteron

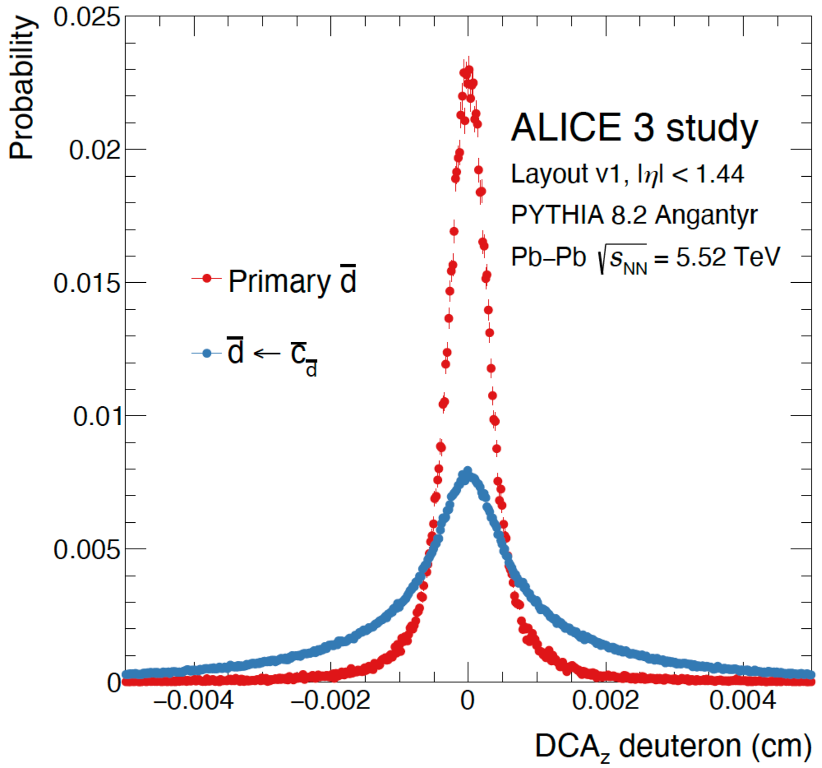
- *The lightest possible bound states of a charm baryon and a nucleon without Coulomb repulsion are bound states of Λc and a neutron: c-deuteron and c-triton.*

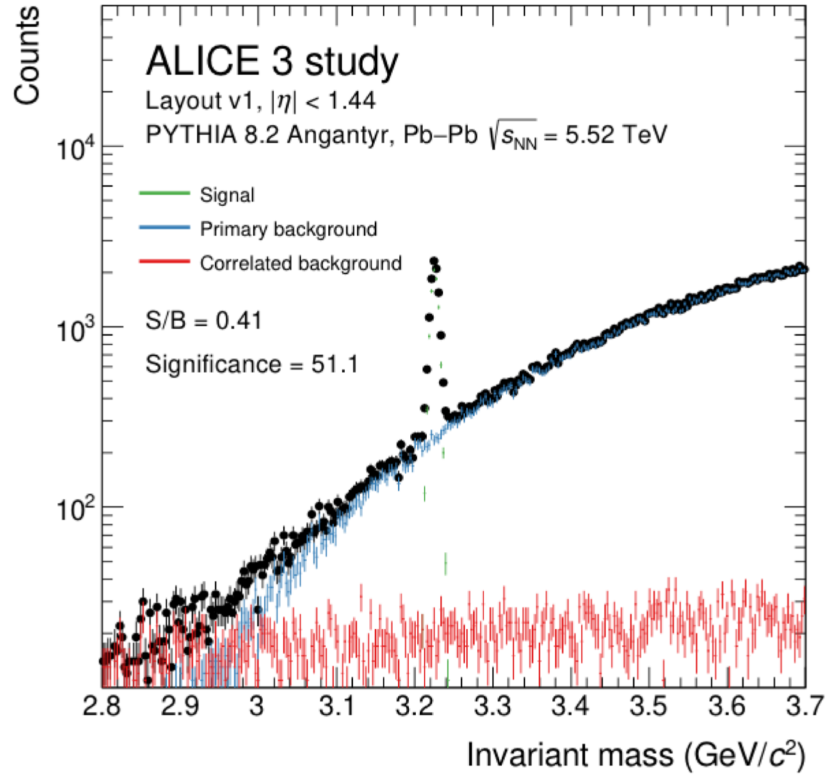


- *Their possible (non) existence sheds light on the charm-nucleon potential.*

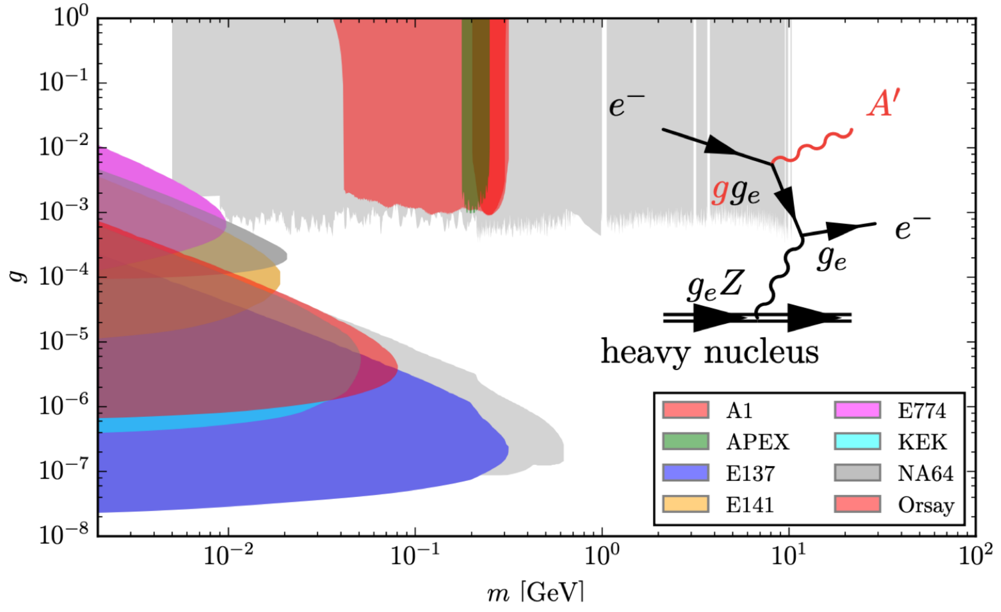
- *Most promising decay channels:*

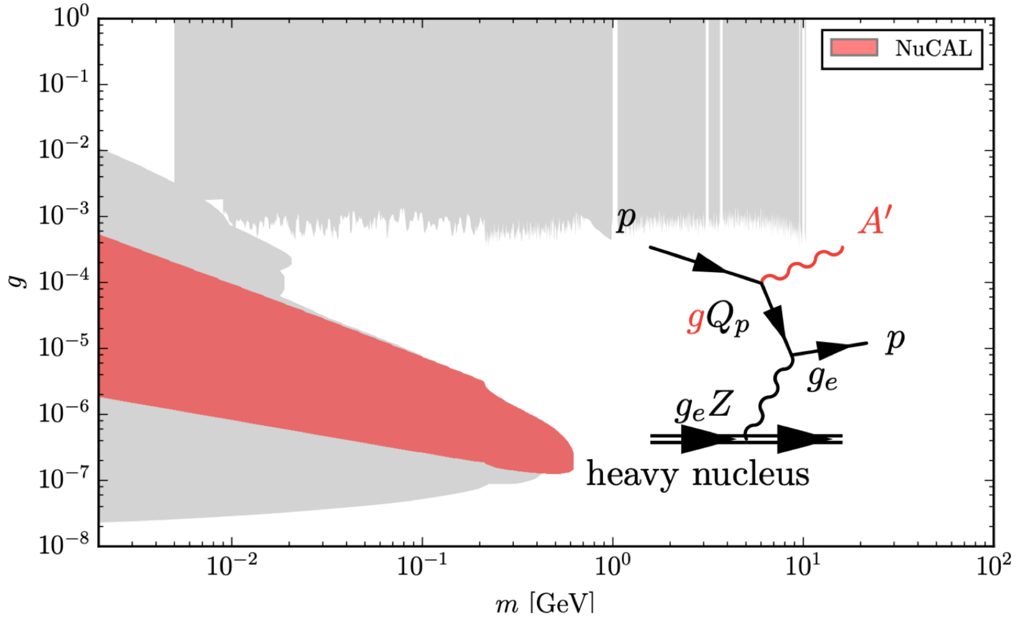
– cd   d + K- + π+
– ct   t + K- + π+

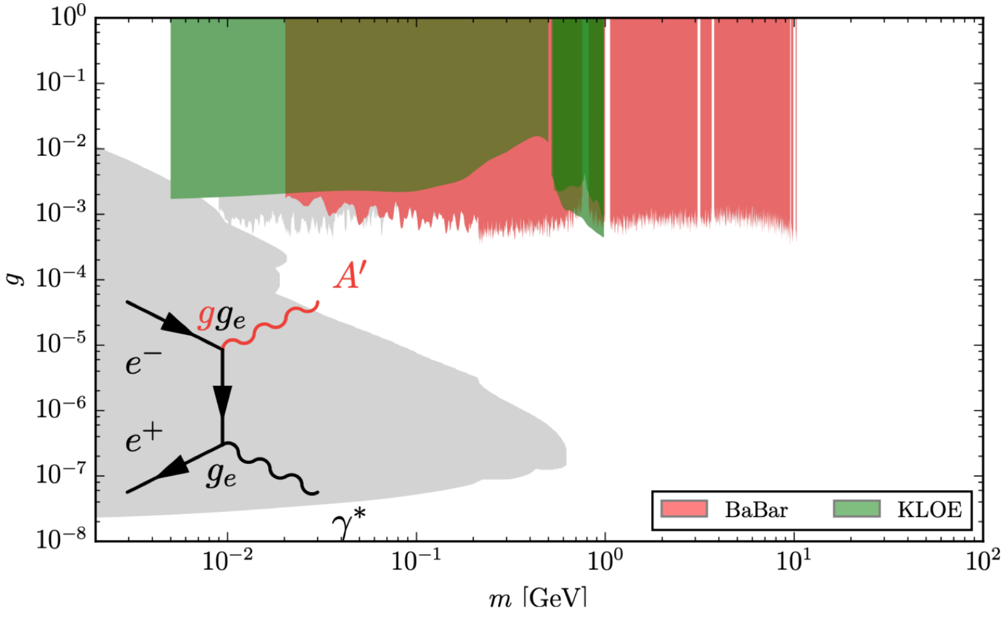


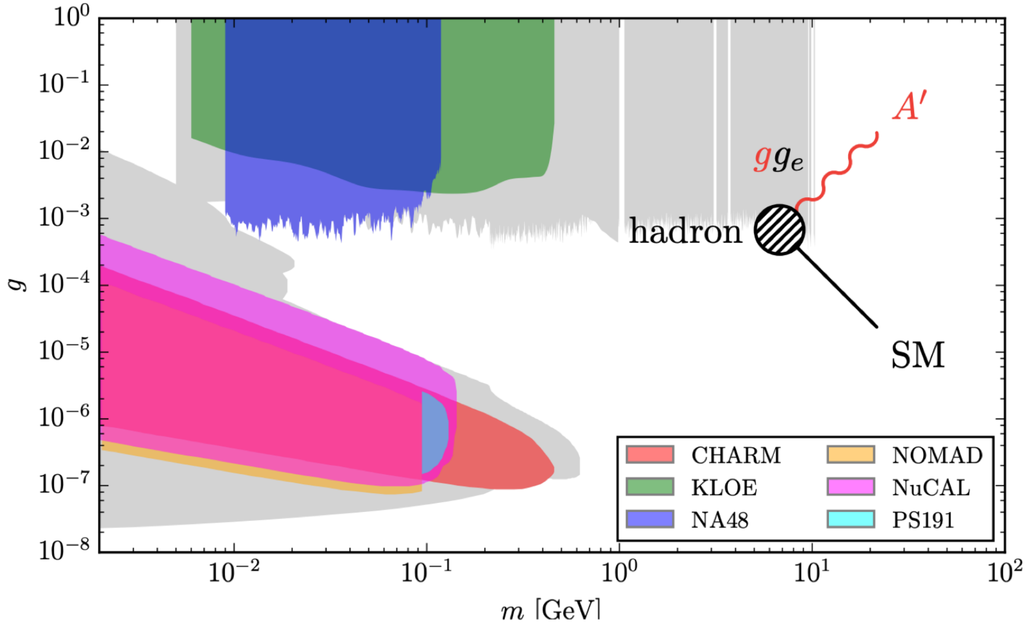


Physics Motivations







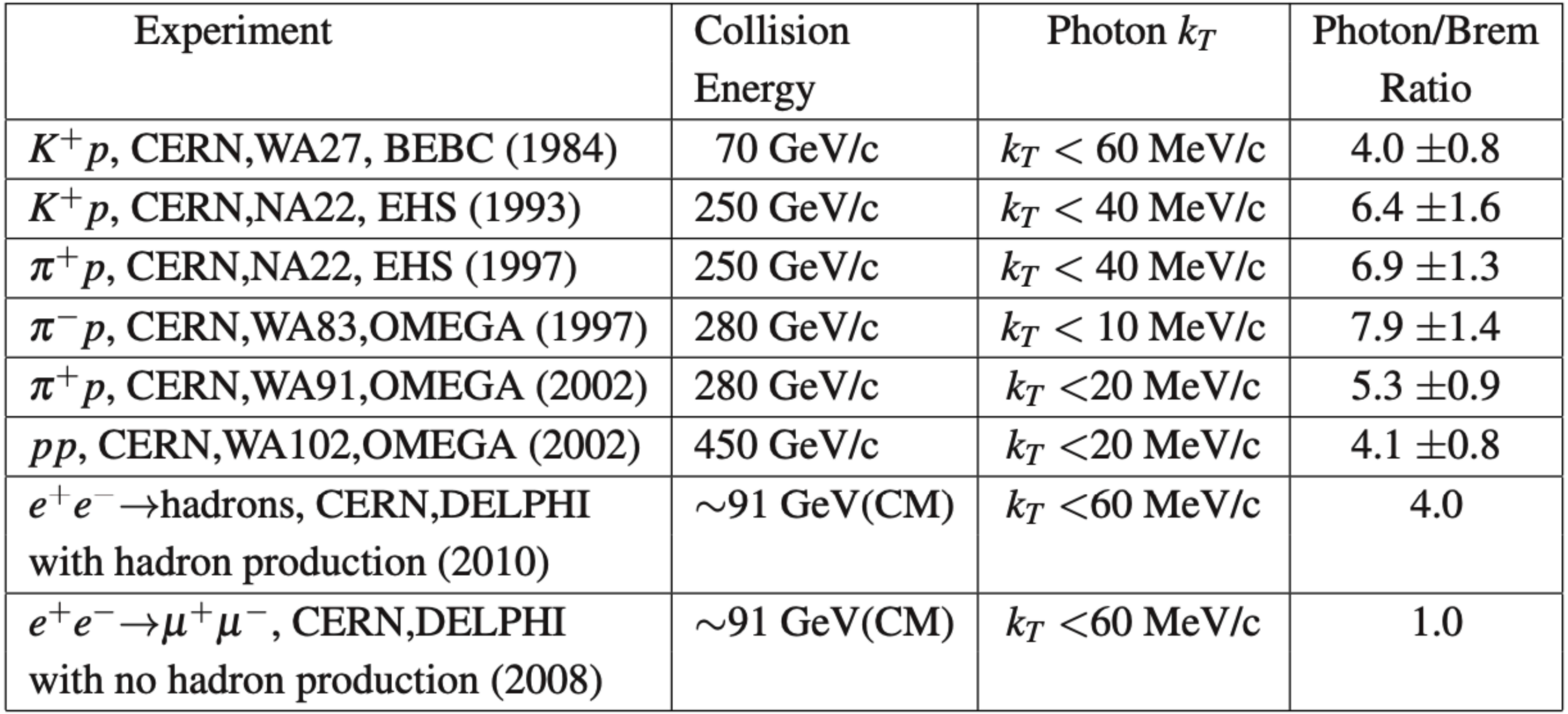


https://indico.cern.ch/event/937309/contributions/3998000/attachments/2109935/3549091/gunji_APW_2020_0925.pdf

Soft Photons: Testing Low's Theorem

Experiments

[Cheuk-Yin Wong, arXiv:1404.0040v1]



Experiment	Collision Energy	Photon k_T	Photon/Brem Ratio
K^+p, CERN,WA27, BEBC (1984)	70 GeV/c	$k_T < 60$ MeV/c	4.0 ±0.8
K^+p, CERN,NA22, EHS (1993)	250 GeV/c	$k_T < 40$ MeV/c	6.4 ±1.6
π^+p, CERN,NA22, EHS (1997)	250 GeV/c	$k_T < 40$ MeV/c	6.9 ±1.3
π^-p, CERN,WA83,OMEGA (1997)	280 GeV/c	$k_T < 10$ MeV/c	7.9 ±1.4
π^+p, CERN,WA91,OMEGA (2002)	280 GeV/c	$k_T <$20 MeV/c	5.3 ±0.9
pp, CERN,WA102,OMEGA (2002)	450 GeV/c	$k_T <$20 MeV/c	4.1 ±0.8
$e^+e^-\rightarrow$hadrons, CERN,DELPHI with hadron production (2010)	∼91 GeV(CM)	$k_T <$60 MeV/c	4.0
$e^+e^-\rightarrow\mu^+\mu^-$, CERN,DELPHI with no hadron production (2008)	∼91 GeV(CM)	$k_T <$60 MeV/c	1.0

Soft photon puzzle: excess above hadronic bremsstrahlung

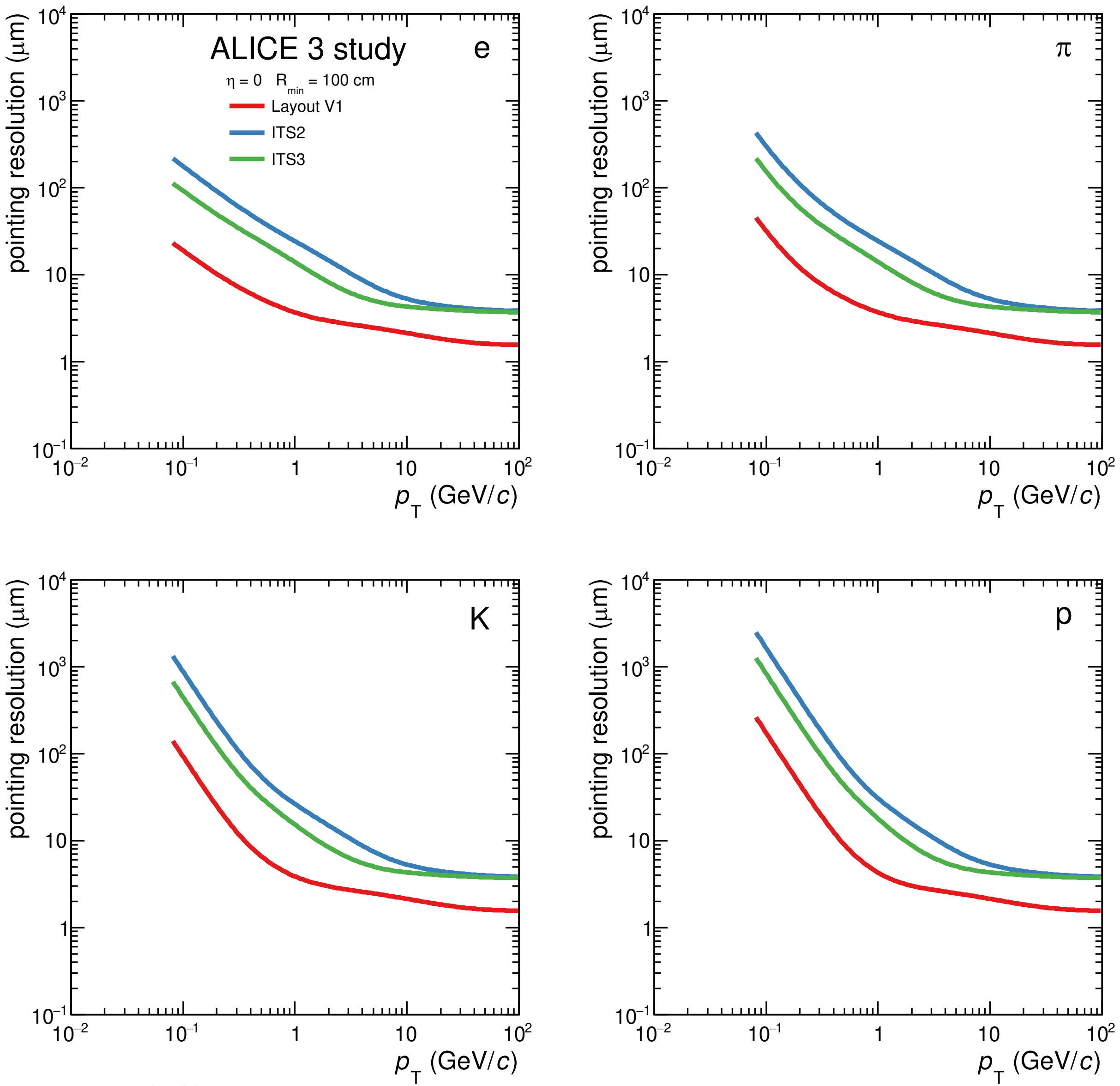
Detector Scenarios: Tracker

Ultra-light tracker:

≈ 0.05 % X_0 vertexing layers

≈ 0.5 % X_0 tracking layers

Large acceptance: $|\eta| < 4.0$, full azimuth down to very low p_T

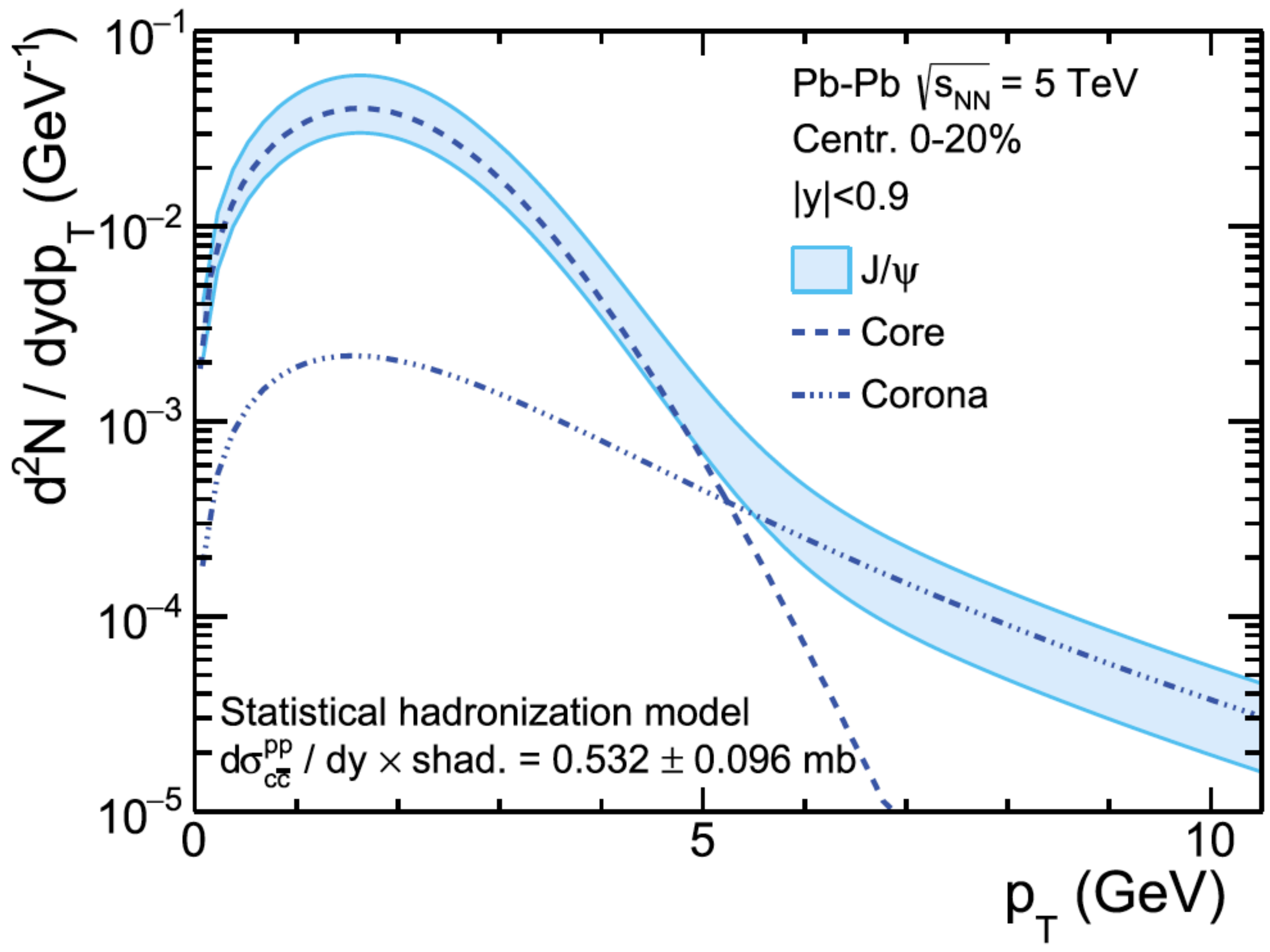


ALI-SIMUL-491681

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

Great potential for charm measurements

Charmonium States in the SHM



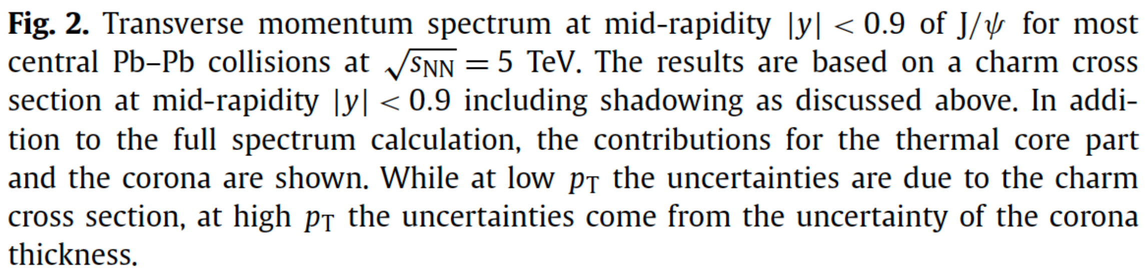
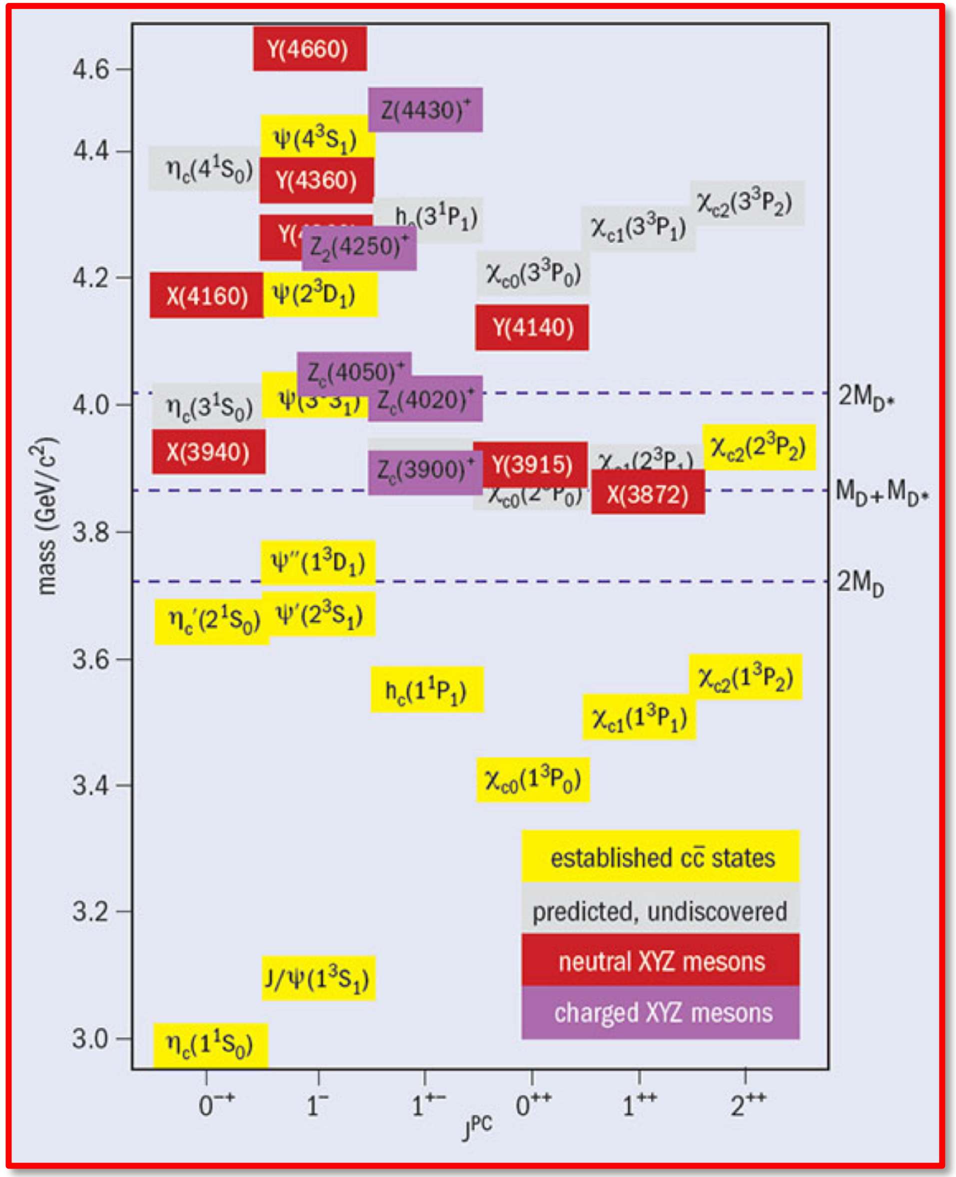


Fig. 2. Transverse momentum spectrum at mid-rapidity $|y| < 0.9$ of J/ψ for most central Pb–Pb collisions at $\sqrt{s_{NN}} = 5$ TeV. The results are based on a charm cross section at mid-rapidity $|y| < 0.9$ including shadowing as discussed above. In addition to the full spectrum calculation, the contributions for the thermal core part and the corona are shown. While at low p_T the uncertainties are due to the charm cross section, at high p_T the uncertainties come from the uncertainty of the corona thickness.

A. Andronic et al.: PLB 797, 2019, 134836

More to Come on Heavy-Flavor Exotica?

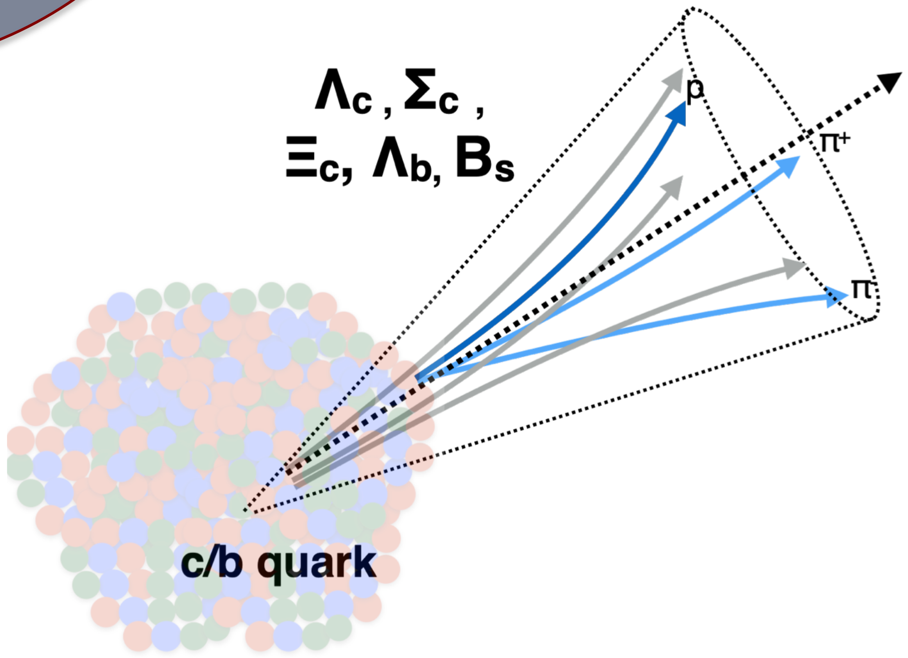
- So far only the X(3872) has been observed as a prompt state: what about the others?
- Can we establish a direct comparison between the yields of deuteron, He nuclei, and X states?
- What about X states decaying into pairs of J/ψ, D mesons, or ϒ ?
- **What about multi-charm exotic states like T_{cc}^+ ?**



Theory needs inputs on the p_T, rapidity, and multiplicity dependence of yields

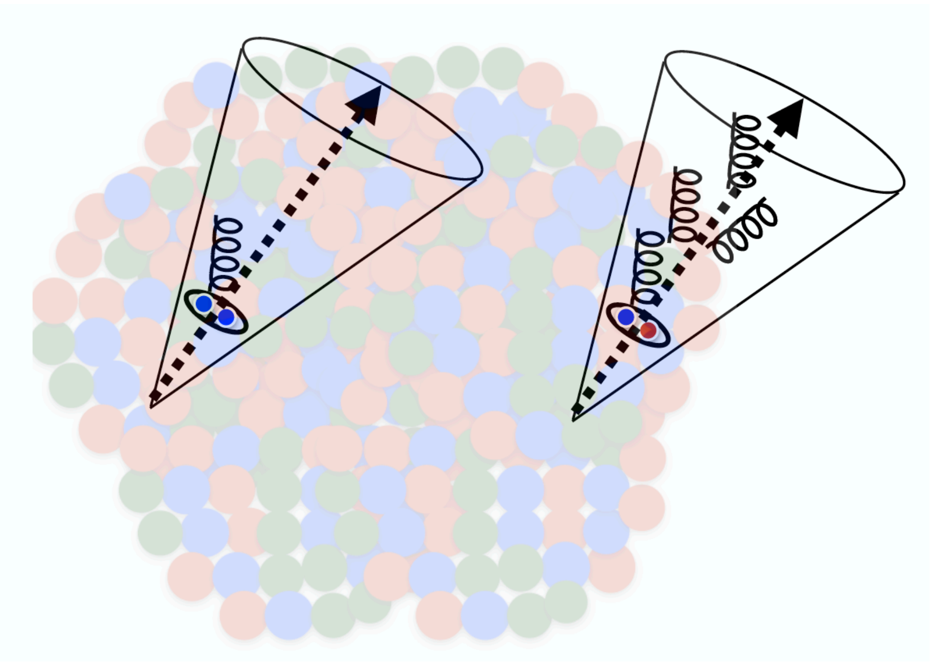
For a recent review of the available theoretical approaches >> https://indico.in2p3.fr/e/tcc_2021

In-jet HF Hadrochemistry and Fragmentation



- **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



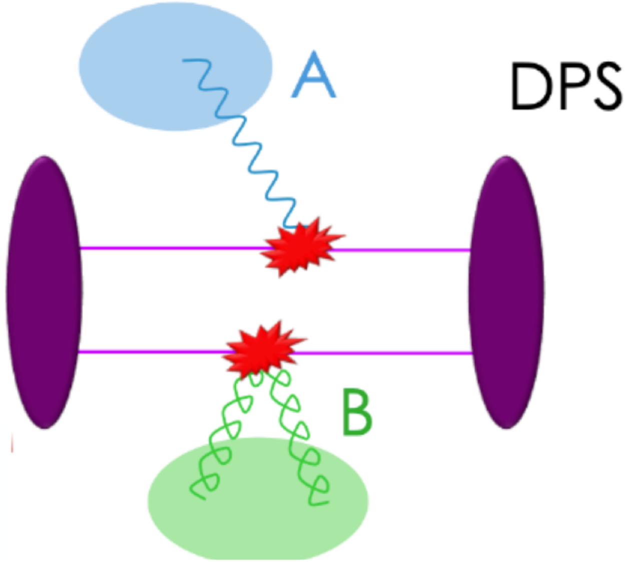
- **Insights into the properties of in-medium propagation of quarkonium states inside the QGP:** fragmentation shower of quarkonium and open HF inside jets in AA collisions

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

3. Last, but not least

- Double Parton Scattering
- Ultra-soft photons
- Beyond Standard Model Searches
- (Small systems, …)

Double Parton Scattering: Quarkonia and Open HF

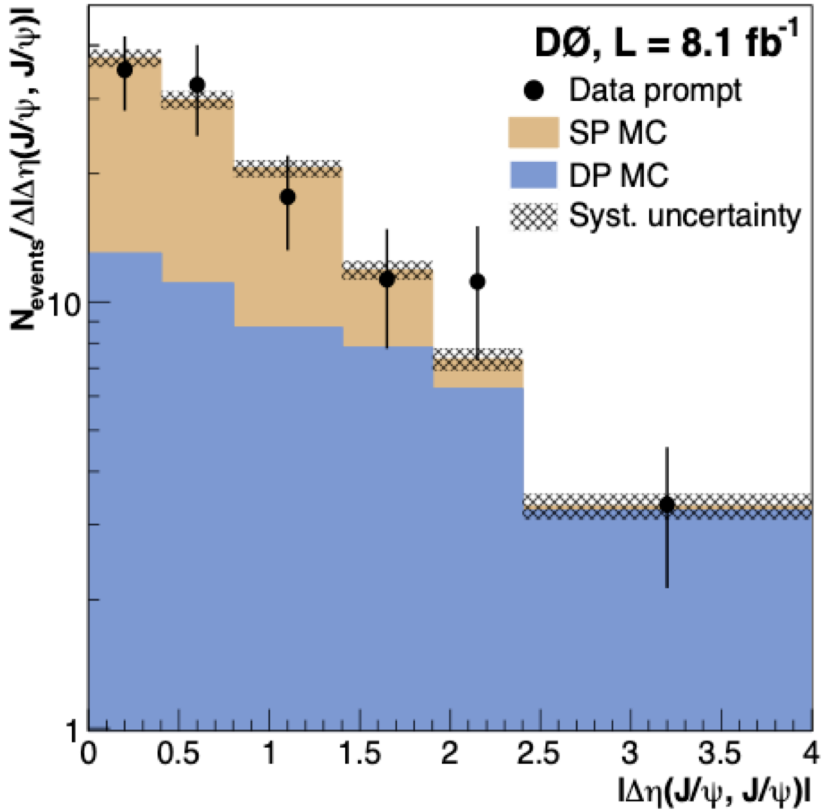


Measurements of the production of quarkonia “in association” with another final state particle

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

- **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”**



Ultra-Soft Photons: Testing Low’s Theorem

- **Soft photons ($p_{\mathrm{T}}^{\gamma} \ll p_{\mathrm{T}}^{hadrons} \approx$ 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

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

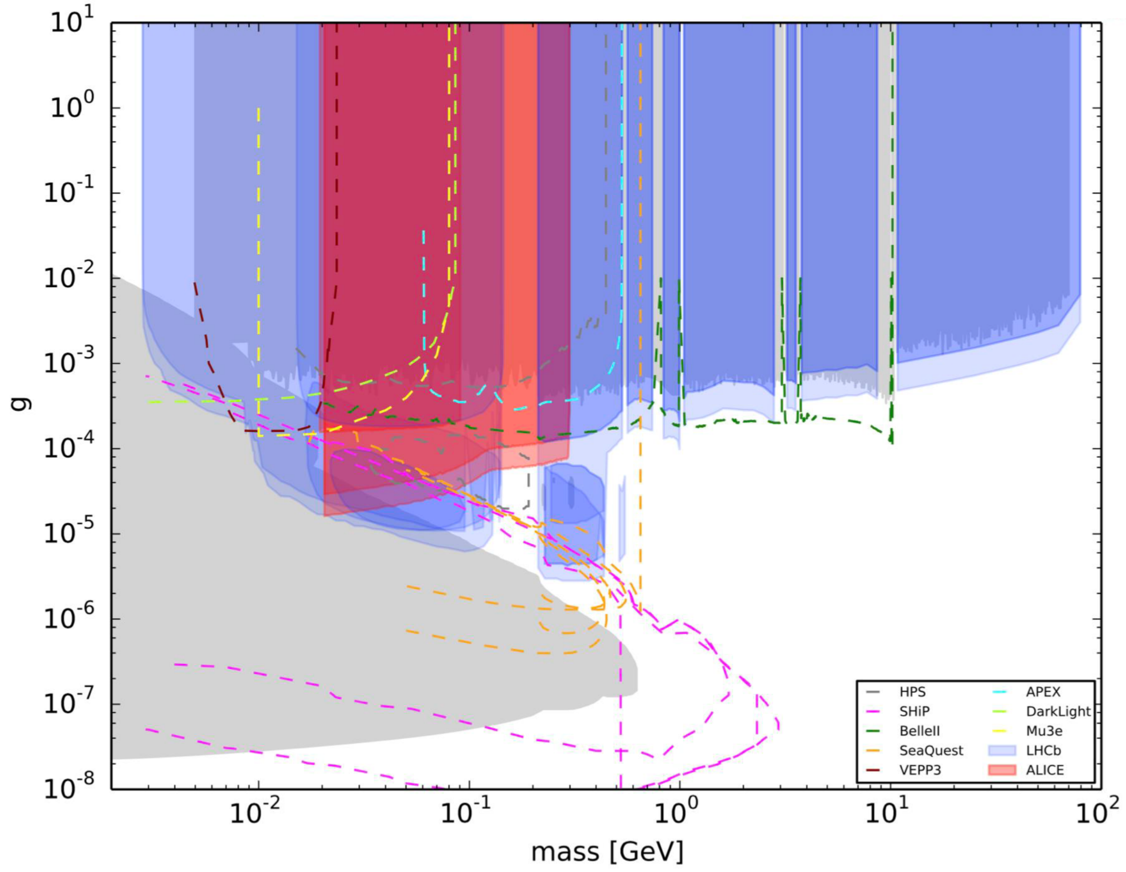
- **Soft photon puzzle:** nearly every measurement shows factor 2–5 enhancement w.r.t. Low’s theorem predictions. **Proposed explanations:** cold quark-gluon plasma, quark synchrotron radiation, string fragmentation. Handle to investigate fundamental non-perturbative properties of QCD

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

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)

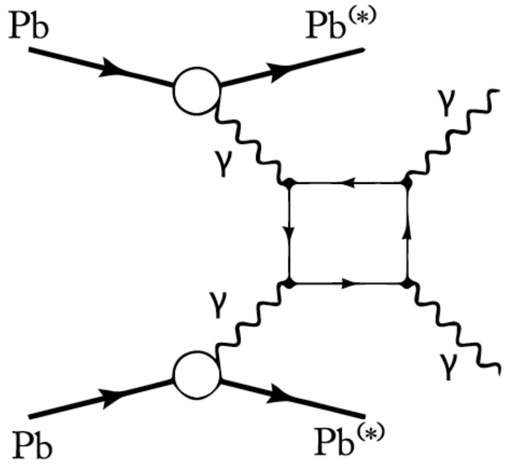
Requirements for ALICE 3

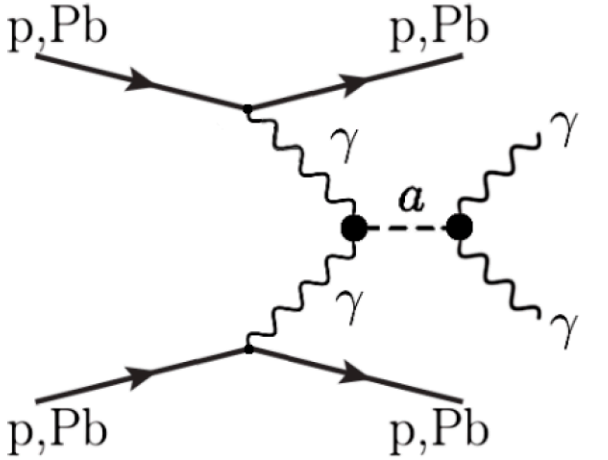
- Good electron ID capability for wide momentum range (low momenta from π^0 Dalitz decays to high momenta from DY and thermal dielectrons)
- High-rate capability and in-bunch pileup separation + good vertexing to separate thermal dielectrons and HF pairs

BSM Searches in Ultra-Peripheral Collisions

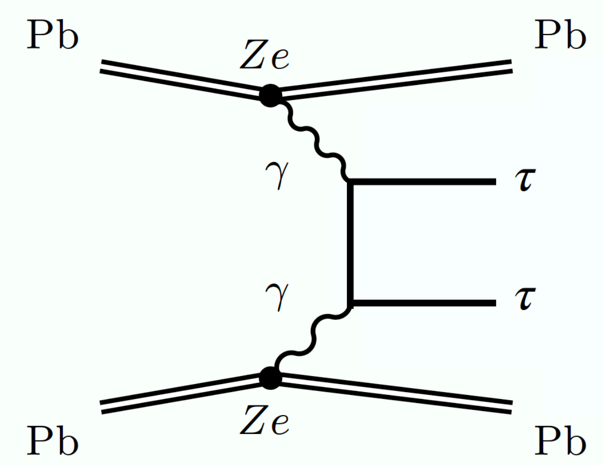
Ultra-peripheral heavy-ion collisions (UPC): clean environment + huge $Z^4 \approx 5 \cdot 10^7$ enhanced gamma+gamma rate w.r.t. pp

- **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?