FIXED-CHARM: FIXED-target exploration of CHARMonium and charm mesons production

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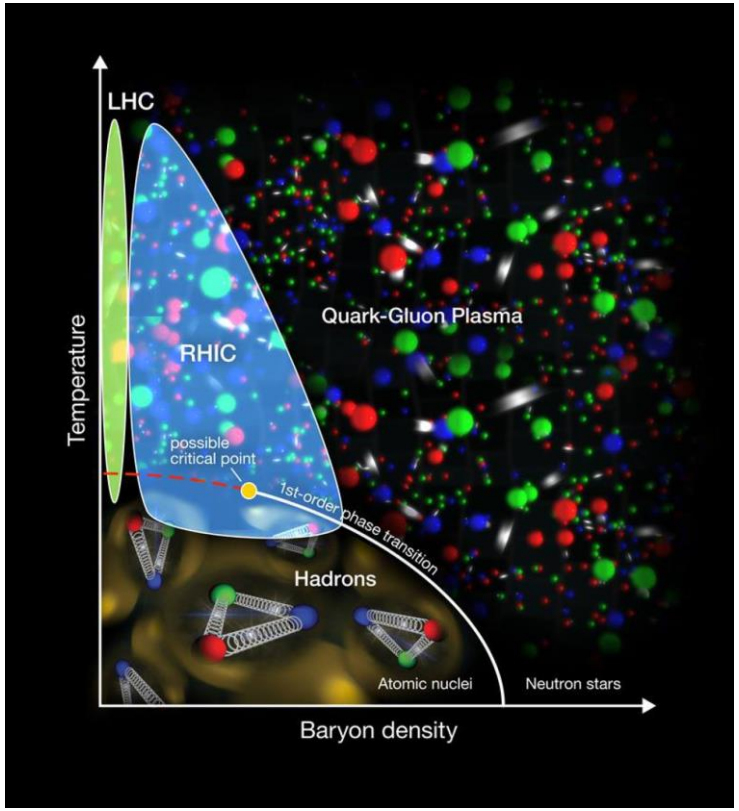
Scientific objectives: QCD medium effects on hadronization with charm quarks

Why Charm?

Charm hadron production is described by a **factorization approach**

- **Hard process**: $c\bar{c}$ pair production, calculable via perturbative QCD, thanks to the charm's large mass
- **Soft process**: hadronization, a non-perturbative phenomenon, governed by color confinement

Charmonium ($c\bar{c}$ bound states) and open-charm hadrons are privileged probes of Quantum Chromodynamics (QCD): sensitive to both perturbative and non-perturbative effects



Charm hadronization and QCD medium effects

Hadronization is strongly influenced by the surrounding medium, which varies across e^+e^-, *pp*, *p*-nucleus and heavy-ion collisions

Pb-nucleus collisions may create droplet of **Quark Gluon Plasma (QGP)**, a deconfined state of quarks and gluons with collective QCD dynamics.

The large range of parton densities accessible in Pb–nucleus collisions offers a unique opportunity to investigate the different medium effects on charmonium versus open charm hadronization.

Charmonia: priviledged probe of phase transition

- 1986 : Matsui and Satz predicted **colour screening** prevents $c\bar{c}$ binding depending on the medium energy density and the $c\bar{c}$ states dissociation temperature

  Phys. Lett. B, 178: 416-422, 1986

- Focus on 3 $c\bar{c}$ bound states: **J/ψ, χ_c and $\psi(2S)$**

  $E_{binding}$: $\psi(2S) \sim 50$ MeV, $\chi_c \sim 200$ MeV, $J/\psi \sim 500$ MeV

- J/ψ and $\psi(2S)$ suppression observed :
  - NA38/NA50 experiments, 20GeV@SPS

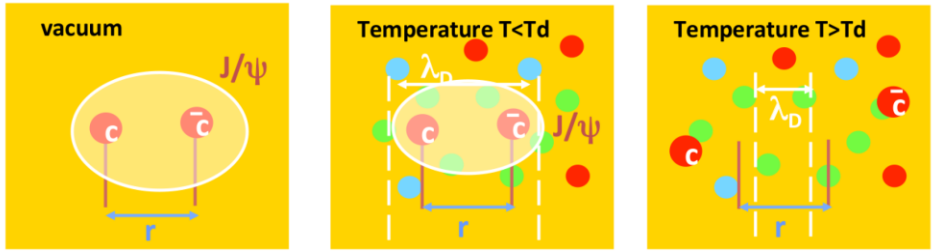
    → Limited energy density to observe a plateau for J/ψ and no capabilities to measure χ_c
  - RHIC (200GeV) and LHC (5 TeV) experiments

    → Suppression is counterbalanced by the **statistical recombination:**

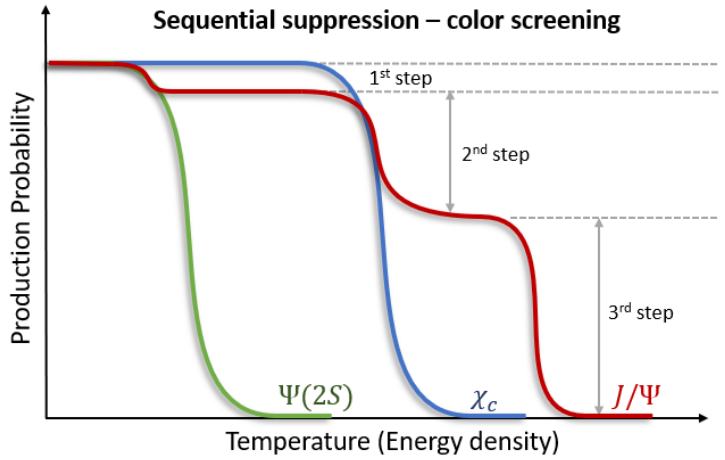
    → Nb of $c\bar{c}$ pairs increased with $\sqrt{s}$

    Difficult to properly interpret LHC measurements without disentangling the possible sequential suppression from the possible statistical recombination

    No χ_c measurement in Nucleus-Nucleus collisions



$r_{q\bar{q}} \sim 1/E_{binding} > \lambda_D \sim 1/T$



J/ψ production : 10% from $\psi(2S)$ decays, 30% from χ_c decays

A definitive observation of sequential melting would be achieved by measuring the $c\bar{c}$ bound states at $\sqrt{s_{NN}} \sim 100$ GeV where only 1 $c\bar{c}$ pair is produced and including χ_c for the first time !

Probing the QCD medium with open charm hadronisation

Open charm production is puzzling

Fragmentation functions are not universal

Coalescence : overlap of individual parton wave functions in position and velocity space

Parton density

Parton Björken-x

How does the parton density affect the open charm hadron ratio ?

Excited state D^{*+} seems to be a relevant probe

→ D^{*+}/D^0 in pp collisions $> e^+e^-$, ep collisions, but currently compatible with pPb collisions

→ **What about Nucleus-Nucleus collisions ?**

→ 68% D^{*+} decays into D^0 → Possibility to isolate prompt D^0

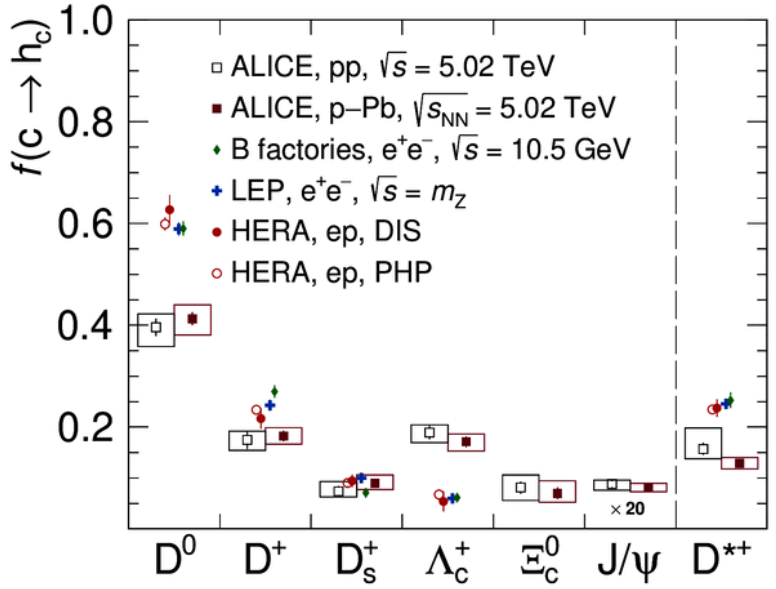
How does the parton Björken-x affect the open charm hadron production ?

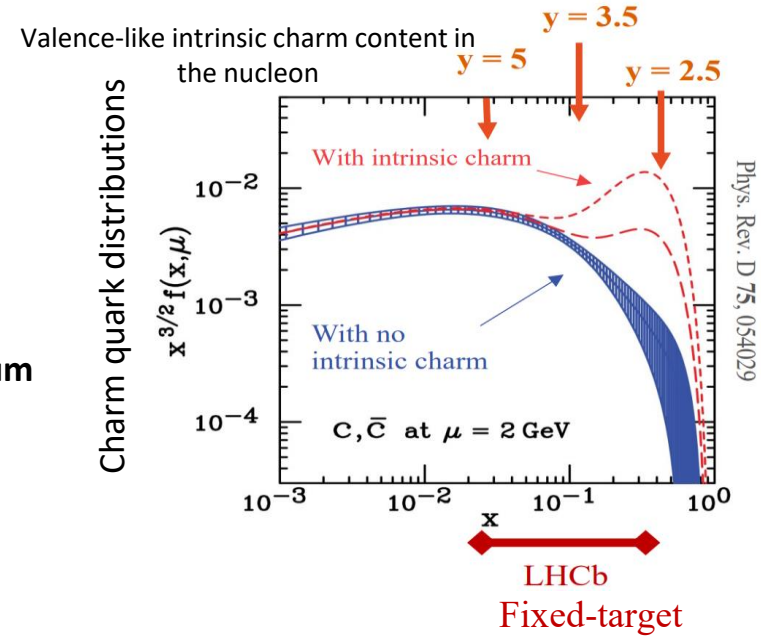
At high Björken-x, open charm hadron production is sensitive to the nucleon content

→ **Access to the intrinsic charm component**

The LHCb fixed-target configuration (high Björken-x) offers an unique opportunity to probe the QCD medium by characterizing the coaslescence phenomena over a large range of parton density

Studying $c\bar{c}$ suppression and open charm production in Nucleus-Nucleus collisions is fully complementary because they probe different aspects of the QCD medium





The LHCb experiment and its fixed-target [JINST 3 (2008) S08005, JINST 9 (2014) P12005]

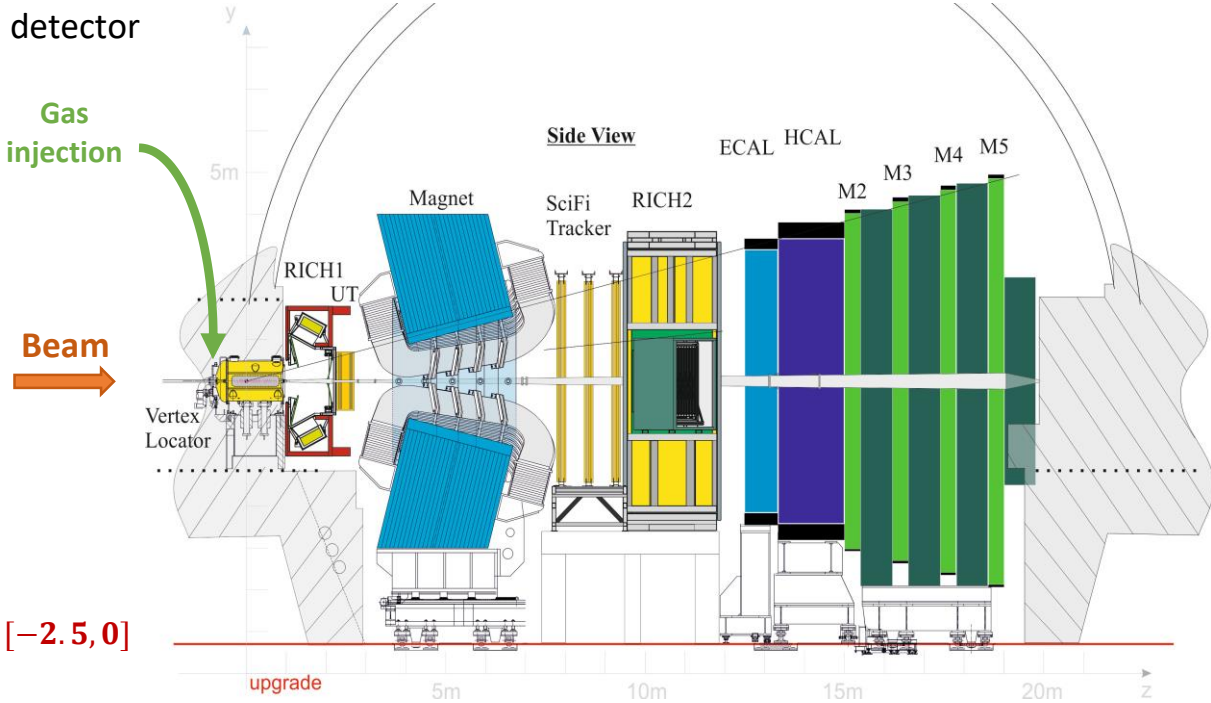
LHCb was designed for heavy flavor physics but serves now as a general purpose detector

Excellent performance [Int. J. Mod Phys. A30 (2015) 1530022]

- ✓ Vertex, IP, decay time and momentum resolution
- ✓ Particle identification: $\epsilon_{K\to K} \approx 95\%$, $\epsilon_{\pi\to K} \approx 5\%$, $\epsilon_{\mu\to\mu} \approx 97\%$, $\epsilon_{\pi\to\mu} \approx 1\text{-}3\%$

- ✓ **Unique LHC fixed-target configuration** [JINST 9 (2014) P12005]

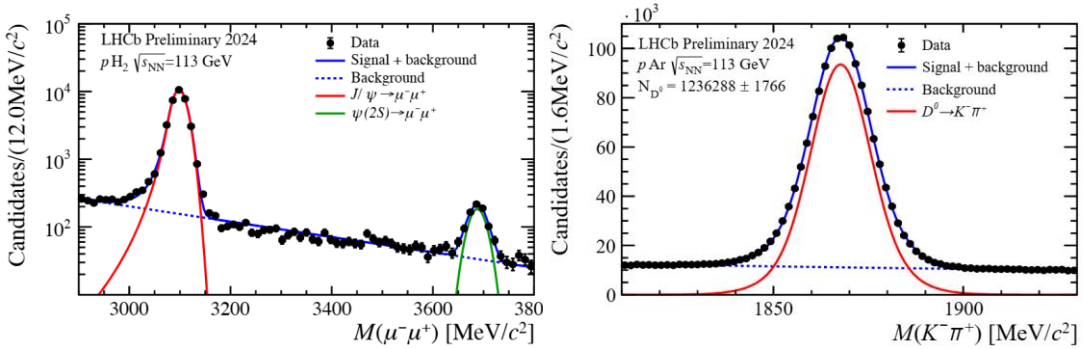
→ **Access to an unexplored energy range, $\sqrt{s} \approx 100$ GeV, and a unique rapidity range y* $\in [-2.5, 0]$**



- ✓ **Feasibility studies of charm production during Run 2** with statistically limited data samples, from *p*He to PbNe [PRL 122 (2019) 132002, EPJC83 (2023) 541, EPJC83 (2023) 625, EPJC83 (2023) 658]

New fixed-target for LHC Run 3: SMOG2 enabling high-luminosity fixed-target physics

- ✓ Storage cell upstream of *pp* interaction point → Continuous fixed-target data-taking
- ✓ Supports hydrogen and deuterium injection
- ✓ Thanks to the LHCb upgraded tracker, **access to the most central PbAr collisions where QGP is expected to be produced !**



Exploit the full charm potential of fixed-target Pb–Nucleus collisions

A unique opportunity to probe the modification of hadronization mechanisms in Pb-Nucleus collisions, including deconfined matter

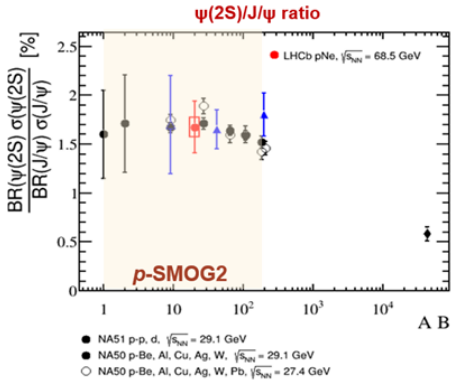
Charmonium studies
Fundamental test of color screening

1. $\psi(2S)$ / J/ψ production measurements in PbAr collisions

Focus on $J/\psi \to \mu^+ \mu^-$, $\psi(2S) \to \mu^+ \mu^-$

Complete the $\psi(2S)$ / J/ψ suppression picture

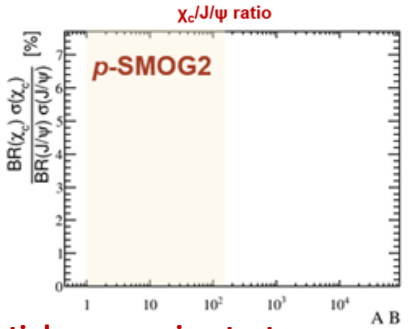
Already done at LHC Run2 (statistically limited)



2. First measurement of χ_c production in PbAr collisions

Focus on $\chi_c \to J/\psi\,(\to \mu^+ \mu^-)\,\gamma$

New in nucleus-nucleus collisions !
χ_c production studies ongoing with *p*H



Cornerstone of the $c\bar{c}$ sequential suppression test

Open charm hadronization studies
Characterization of hadronization at high-x

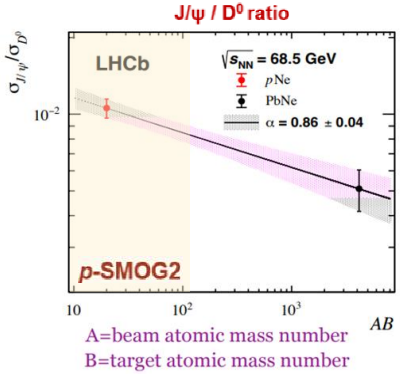
1. D^0 production measurement

Most of the c or $\bar{c}$ hadronize into D^0 or $\overline{D^0}$

Relevant **proxy** of the total amount of the number of $c\bar{c}$ pairs produced

→ Reference for the $c\bar{c}$ sequential suppreesion

Already done at LHC Run2 (statistically limited)



Also relevant to test the hadronization mechanisms (fragmentation, coalescence)

2. D^{*+} / D^0 production measurement

Focus on $D^{*+} \to D^0\,(\to K^-\pi^+)\,\pi^+$

Is the ratio Vector / Pseudo Scalar meson affected by the local environment ?

Test the hadronization universality

Complementary studies on LHC run 3 data
Including preparation of LHC run 4 trigger

Budget and ressources

To successfully carry out these two complementary studies, two postdocs of 3-years are required:

Postdoc Jpsi

Charmonium studies
Fundamental test of color screening

1. $\psi(2S)$ / J/ψ production measurements in PbAr collisions
2. First measurement of χ_c production in PbAr collisions

Postdoc D0

Open charm hadronization studies
Characterization of hadronization at high-x

1. D^0 production measurement
2. D^{*+} / D^0 production measurement

Both postdocs will

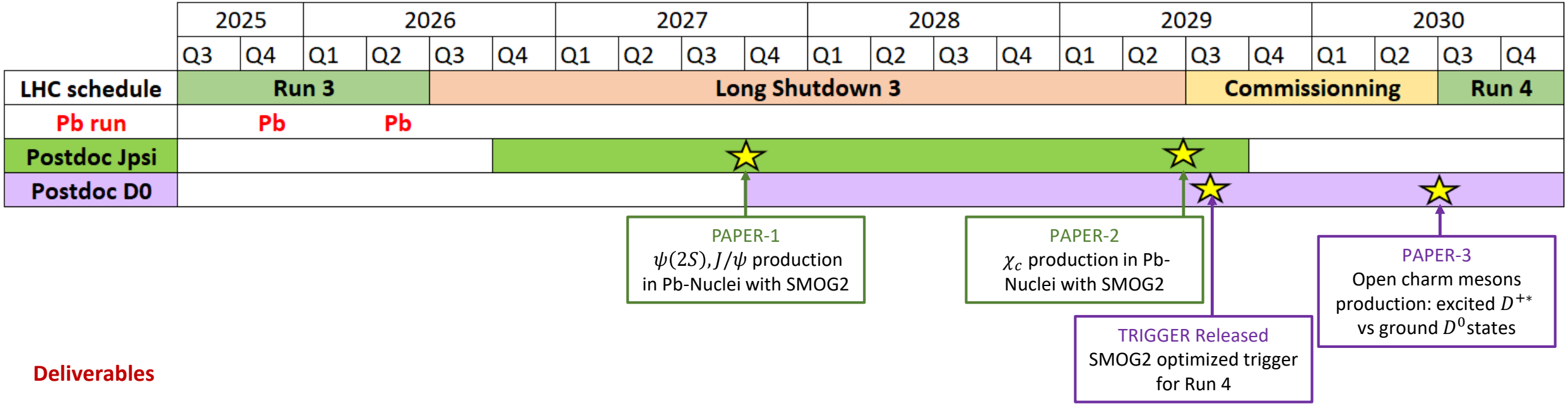
- **fully exploit the Run 3 SMOG2 data taking**, and will also **prepare the trigger** configuration to optimize the data acquisition during Run 4
- regularly visit CERN for **collaboration meetings** (physics, software) and present their results at prestigious **conferences** as well as specialized **workshops**
- **foster collaboration** with experimentalists and theorists through **short- and medium-term research stays abroad**, such as at Universidad de Santiago.

Requested budget: 458k €

- 195k € for a young 3-years postdoc + 240k € for an experienced 3-years postdoc
- 15k € for travel (collaboration meetings, to conference) corresponding to 2.5k€/year/person
- 8k € for short and medium-term research stays abroad, notably at CERN and Universidad de Santiago, to foster collaboration

All analysis tools will follow FAIR data principles and be openly shared to ensure full reproducibility and reuse by the broader community

Deliverables of FIXED-CHARM



Deliverables

- 3 papers in total
- Optimized SMOG2 trigger for LHC Run 4

Dissemination

- Talks in high-level conferences (such as Quark Matter, Hard Probes conferences) and in specialized workshops
- Organization of regular virtual workshops with theorists and phenomenologists to discuss results, model predictions and explore possible joint publications

Conclusions of FIXED-CHARM

FIXED-CHARM is connected to the CERN/LHC infrastructure (Virtual Access project)

FIXED-CHARM aims to exploit the unique Pb–nucleus dataset collected with the LHCb fixed-target configuration to unambiguously test sequential suppression through charmonium studies, and to complementarily characterize open charm hadronization in a regime of high parton density and large Björken-x

Total request: €458k