From unpolarized to polarized collisions at LHCb

XXII LNF Spring School “Bruno Touschek” in Nuclear, Subnuclear and Astroparticle Physics

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13/05/2026

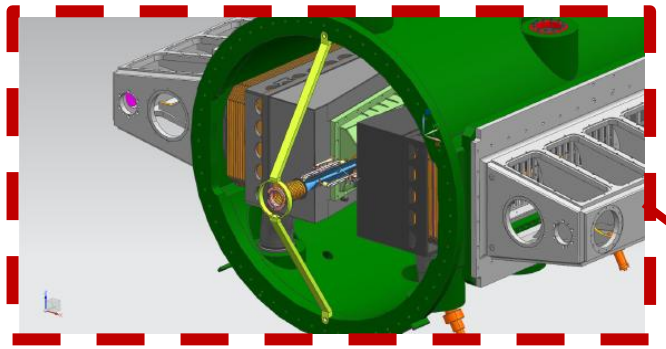
Università degli Studi di Ferrara

INFN LNF

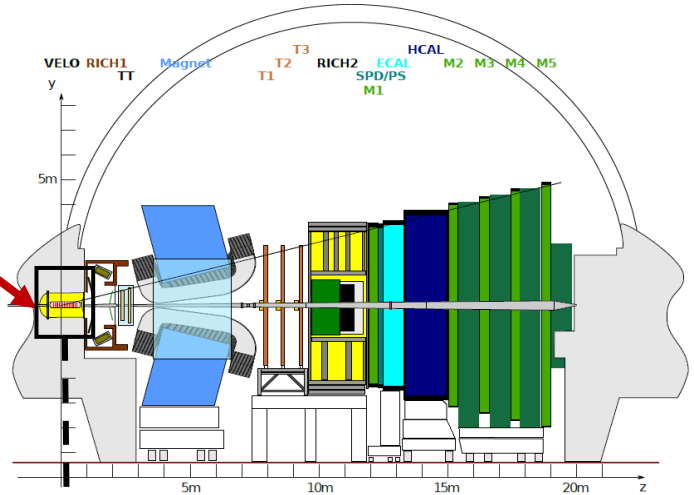
SMOG2: Fixed-target at LHCb

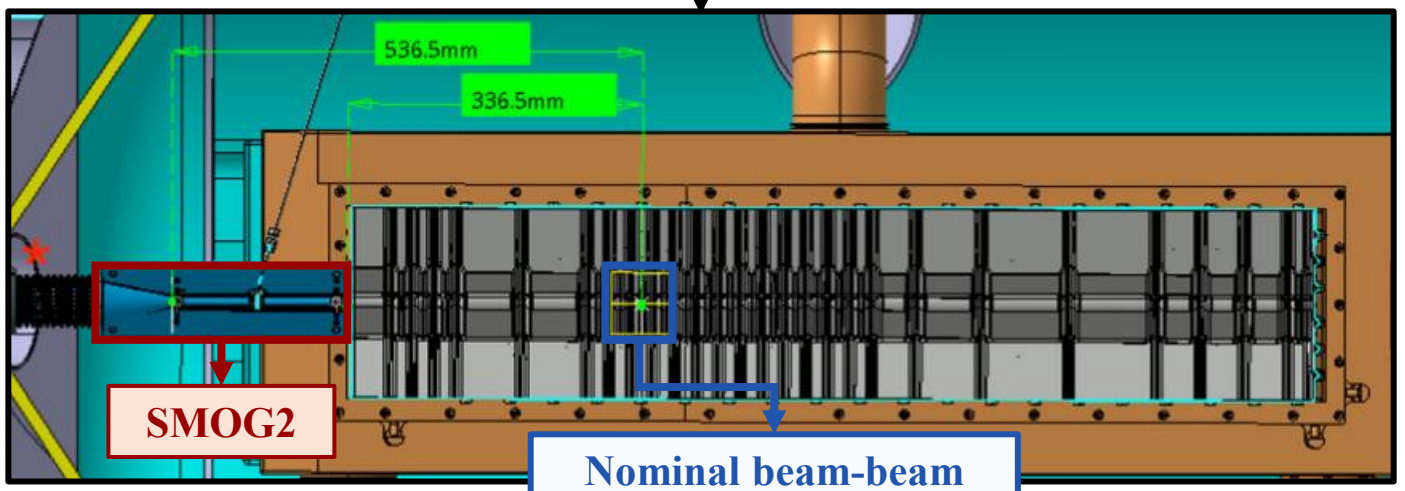
LHCb is the **only experiment in the world able to collect simultaneously** events from **proton-proton collisions** and **unpolarised proton-gas fixed-target collisions - SMOG2**

SMOG2 is a **gaseous fixed-target** system which is implemented **upstream of LHCb**

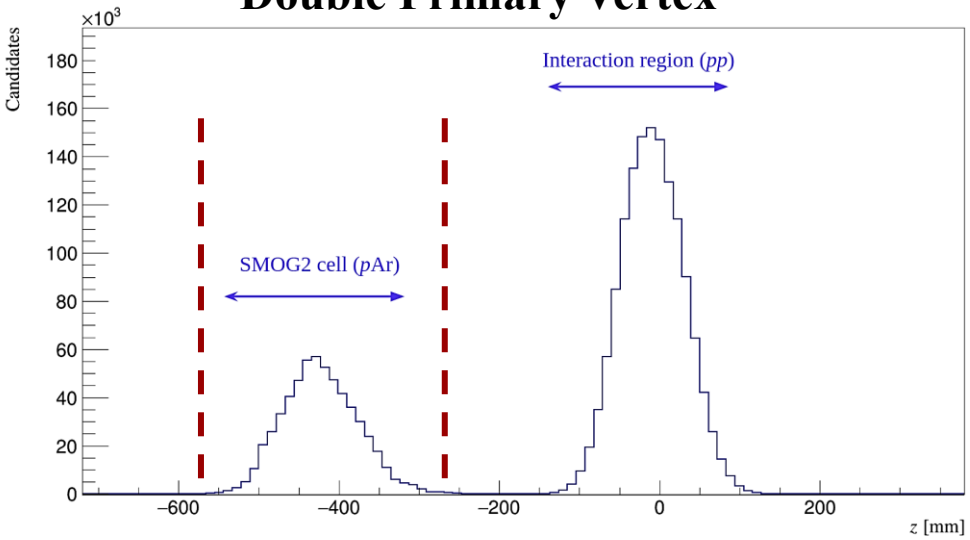


Installed in front of **VELO**





Double Primary Vertex

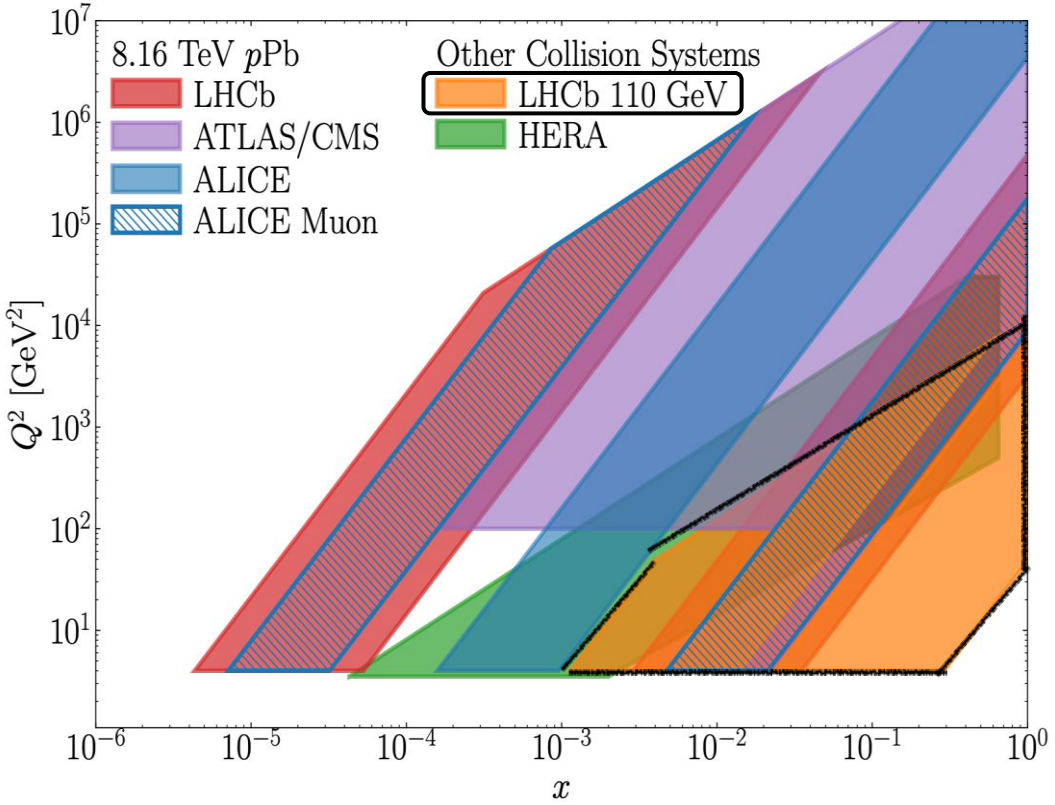


PRAB 27, 2024 111001

Feasible system with p-gas fixed target collisions and pp collisions **well separated in PV**

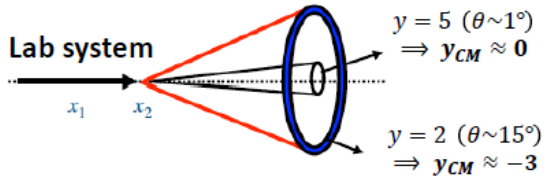
Fixed-target Kinematics at LHCb

LHCb has a single forward spectrometer has an angular coverage of $\mathbf{30\ mrad < \theta < 250\ mrad}$ which allows for **pseudorapidities in the range of** $\mathbf{2 < \eta < 5}$



Access to a **poorly explored kinematic domain** :

- ❑ with **beam-gas collisions at** $\sqrt{s_{NN}}$**~100 GeV**
- ❑ **large negative** x_F
- ❑ **large Bjorken-x** at intermediate Q^2

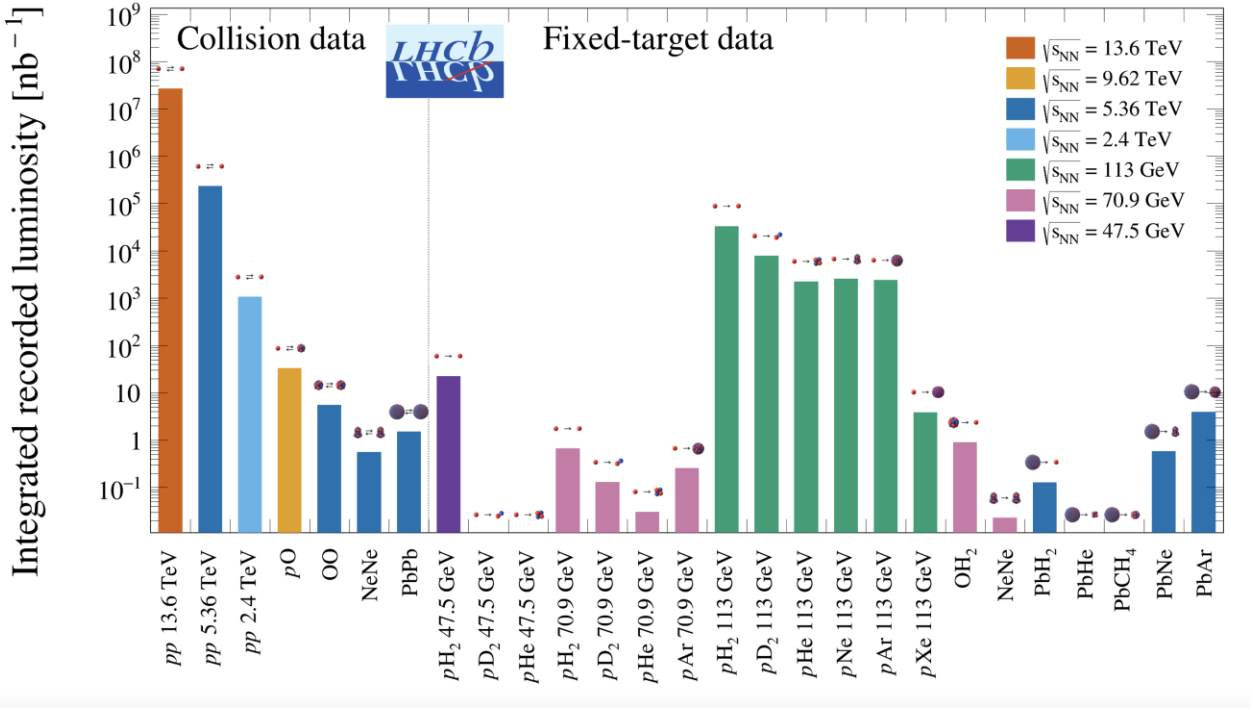


CM strongly boosted in the lab system

arXiv:2504.16034 (2025)

Fixed-target Physics Program at LHCb

Since the **beginning of Run3**, LHCb is routinely **collecting data** in collider and **fixed-target mode** simultaneously
Different gases injections allow for a **diverse and rich physics programme** which keeps on growing!



SMOG2 has taken data with:

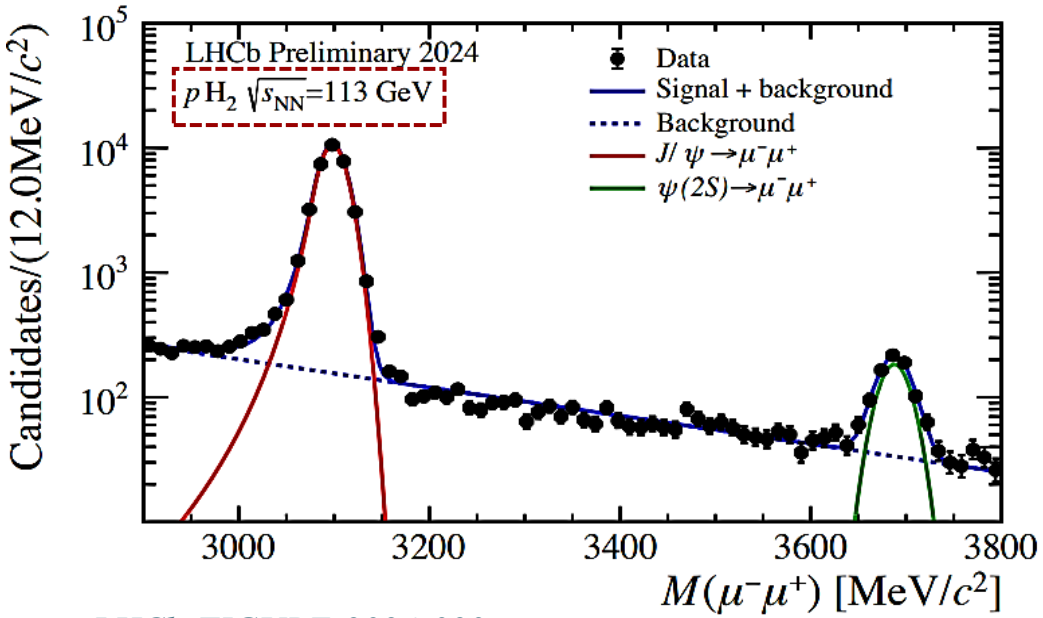
- ❑ 5 different gases injected: H_2; D_2; He; Ne; Ar and Xe
- ❑ 7 different colliding energies
- ❑ 4 different beams used: p; Ne; O and Pb

One experiment, 23 different collision systems enabled

LHCb Operation's page

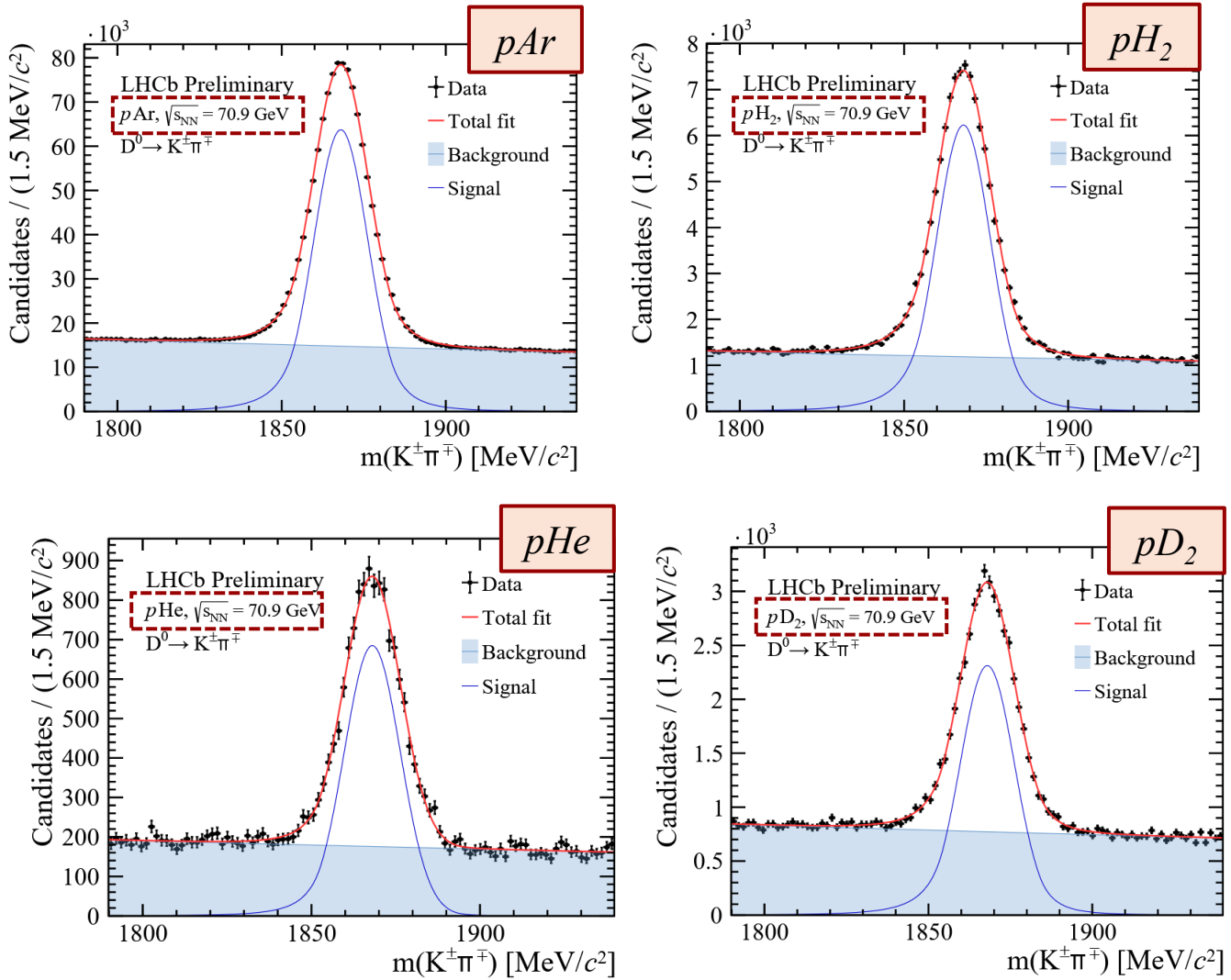
Fixed-target Physics Program at LHCb

Impressive results released on charm production from SMOG2 Run 3 data taking
D^0 peak in 4 different systems with excellent mass resolution in only 4 days of data-taking



LHCb-FIGURE-2024-023

- J/ψ and ψ(2S) clear invariant mass peaks in just 39h of H_2 injection



LHCb-FIGURE-2025-013

Probing Nucleon Structure

In fixed-target collisions, **Nucleon Structure can be probed** by performing **measurements** that are **sensitive to gluons and quarks PDFs and TMDs**:

- **Drell-Yan analysis**:
  - **Reduce uncertainties** on the **quark and anti-quark PDFs**.
  - **Boer-Mulders function** $h_1^{\perp}$ via the measurement of Drell-Yan (DY) cross-section
  - **Sivers function** through the studies of the Transverse Single-Spin Asymmetries **(TSSA)**

- **Heavy Meson Production**: process dominated by gluon-gluon fusion in high-energy hadronic collisions which helps to probe gluon unknown distributions

Fixed-target Physics Program at LHCb

Probing Nucleon Structure

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Possible with SMOG2 !

- ❑ **Heavy Meson Production**: process dominated by gluon-gluon interactions in high-energy hadronic collisions which helps to probe gluon unknown distributions

Measurements of charm and bottom resonances at SMOG2 which enable the study of gluon PDFs

*** For my PhD**

Currently working in the Drell-Yan cross-section analysis from *pA* collisions at SMOG2

Probing Nucleon Structure

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- ❑ **Drell-Yan analysis**:
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  - × **Sivers function** through the studies of the Transverse Single-Spin Asymmetries

    Only accessed in polarized collisions

- × **Heavy Meson Production**: process dominated by gluon-gluon interactions in high-energy hadronic collisions which helps to probe **gluon unknown distributions**

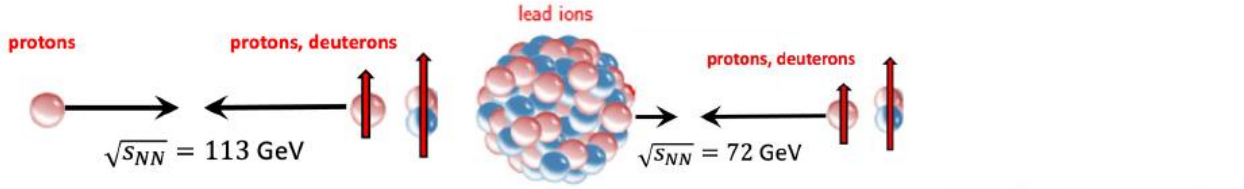
  No access to polarized gluon TMDs

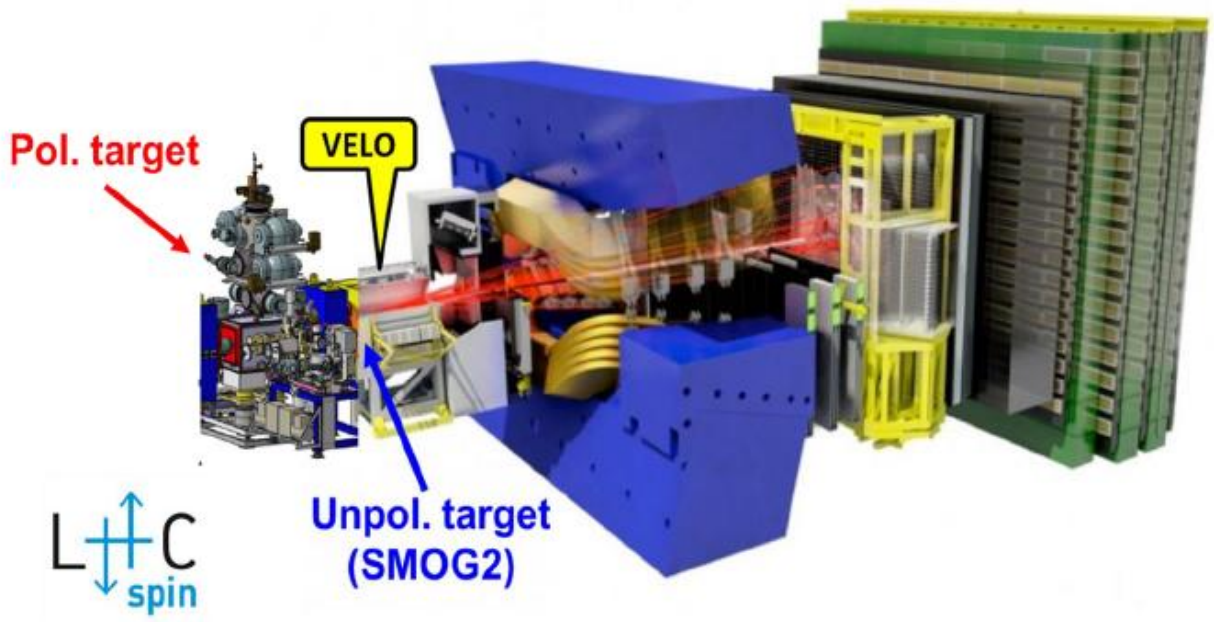
With SMOG2, we can only enable unpolarized p-gas collisions
LHC proton beam can not be polarized due to very high energies
Further extending the studies on Nucleon Structure at LHCb is only possible by implementing a polarized fixed-target

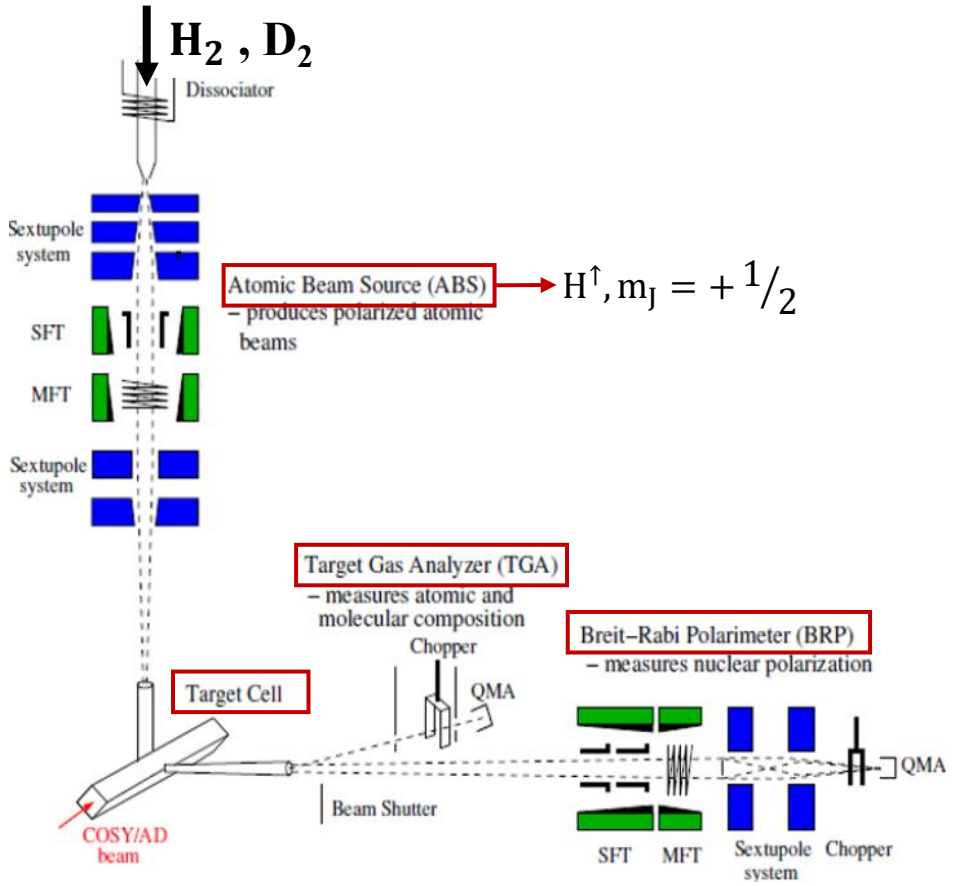
LHCspin: Polarized Fixed-target for LHCb

LHCspin is an **LHCb R&D** that aims to install a **polarized gaseous target in the LHCb spectrometer for Run 5** (upgrade of SMOG2)

The goal is to **develop a new generation of molecular polarized gas target** starting from the **technology used at HERMES and COSY** to **study multi-dimensional nucleon structure**







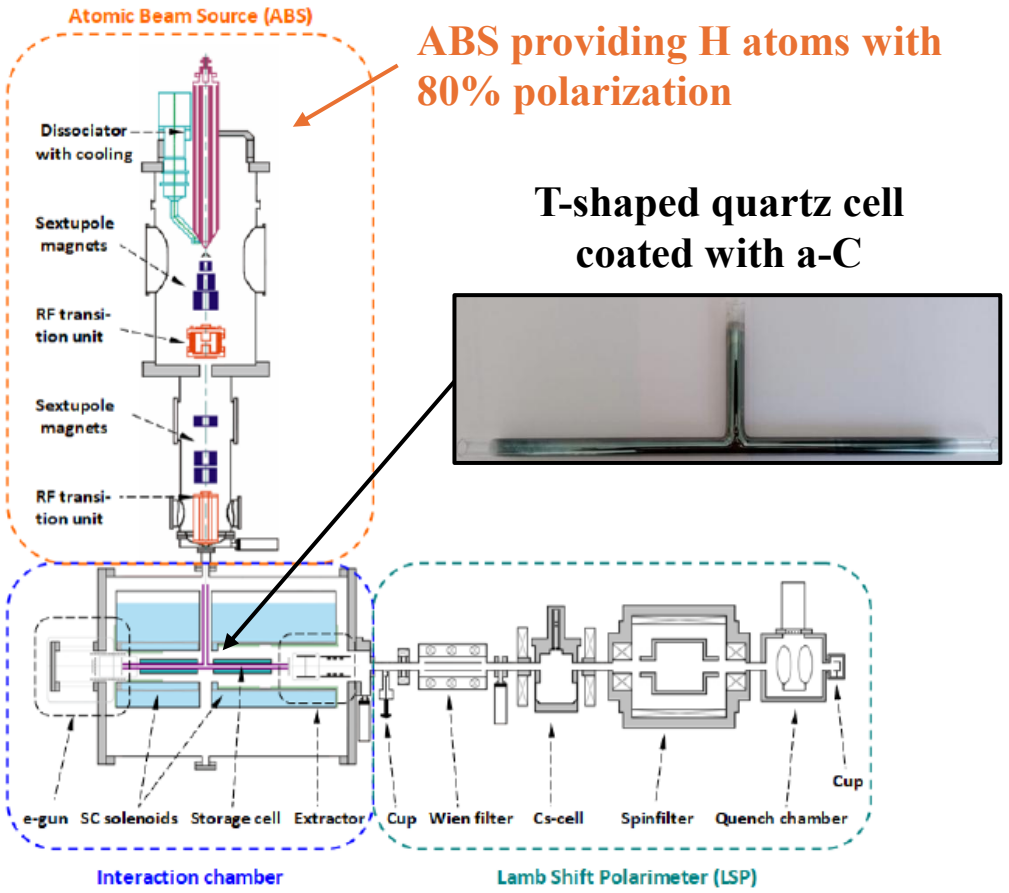
LHCspin: Coating Issue

A suitable coating must be applied to target cell to **suppress the recombination** and **depolarization** of the atoms injected into the cell

Surface coatings previously used for polarized targets (Drifilm, Teflon, water ice, etc) are not allowed at LHC

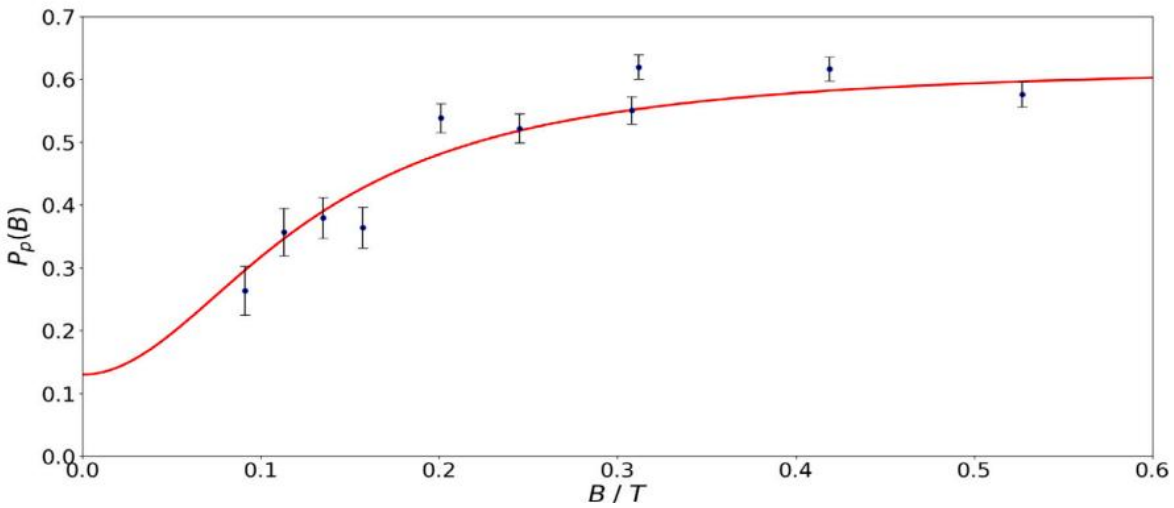
Amorphous carbon (SEI) is proposed (already used in SMOG2 cell)

FZ-Jülich apparatus for coating studies



- Results showing **nearly complete recombination** with a **surviving nuclear polarization up to ~60%**
- ~75% of original atomic polarization is preserved during recombination
- Density of the molecular target is increased by a factor of $\sqrt{2}$, compensating loss in polarization

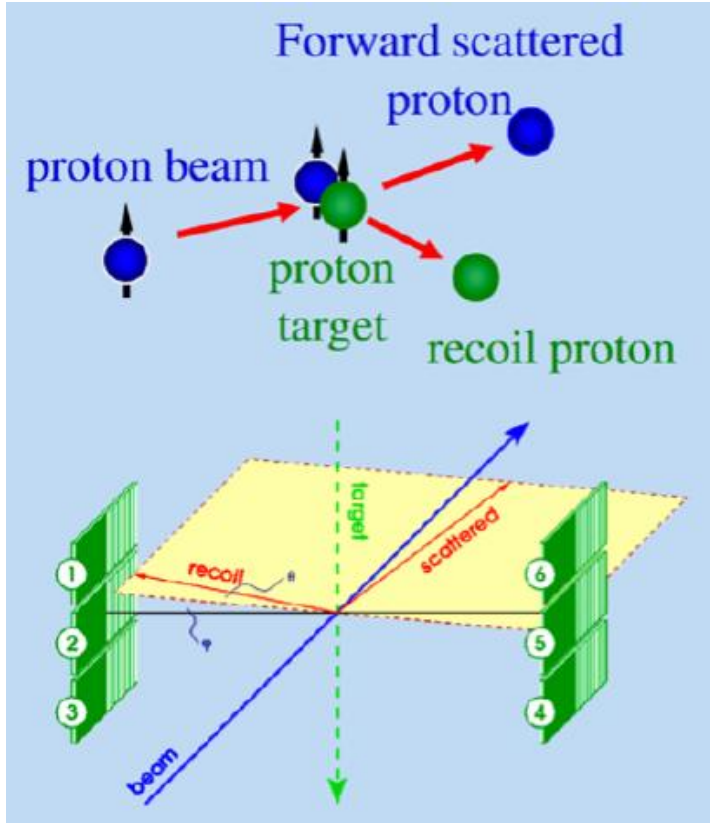
Possibility to develop a new type of molecular Polarized Gas Target



Nuclear Instruments and Methods in Physics Research A 1068 (2024) 169707

LHCspin: Absolute Polarimeter

Standard method to measure polarization (Breit-Rabi Polarimeter) is not suited to measure the nuclear polarization of molecules – **an Absolute Polarimeter system is needed!**

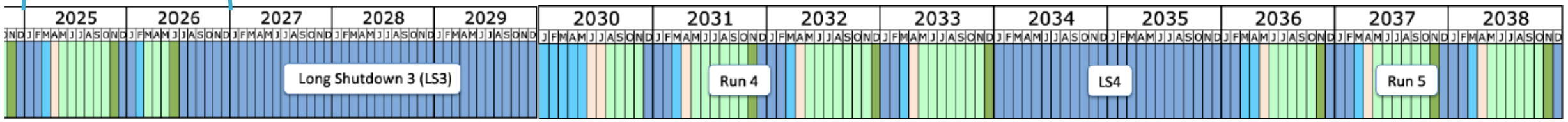


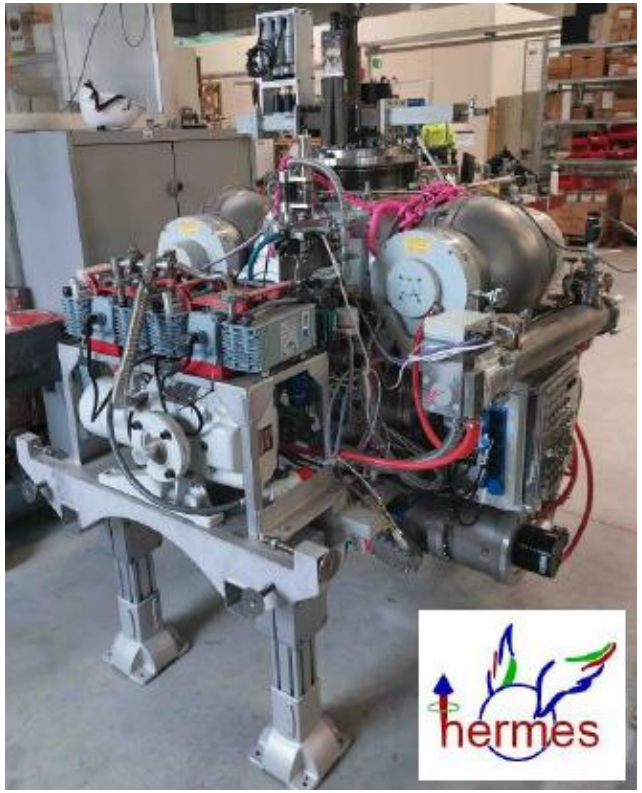
- We use **as a polarimeter pair of silicon strip detectors** that **identify recoiling protons** and **measure left-right asymmetries** in **elastic $p - H^{\uparrow}$ scattering**
- Technique previously applied to RHIC, but at smaller energies
- **There are theorical predictions based in the Coulomb-Nuclear Interference (CNI) model** for the **analysing power A_N at 7 TeV**
- These predictions need to be **validated and tunned by measurement!**

Phase 1 of R&D

LHCspin: Timeline

Current Stage





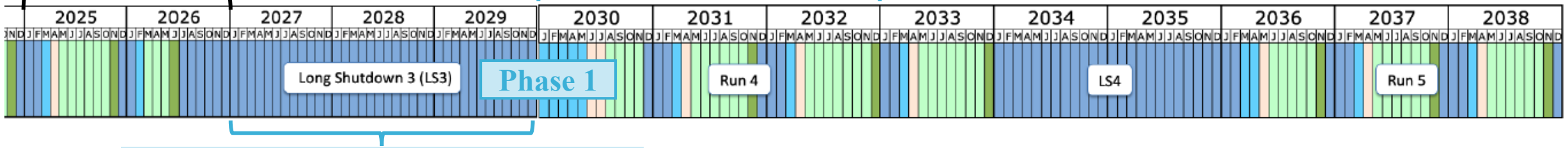
INFN Sezione Ferrara

- ABS has been already moved from FZ-Jülich to INFN-Ferrara
- Refurbishment, first tests and characterization of the set-up ongoing in INFN-Ferrara

LHCspin: Timeline

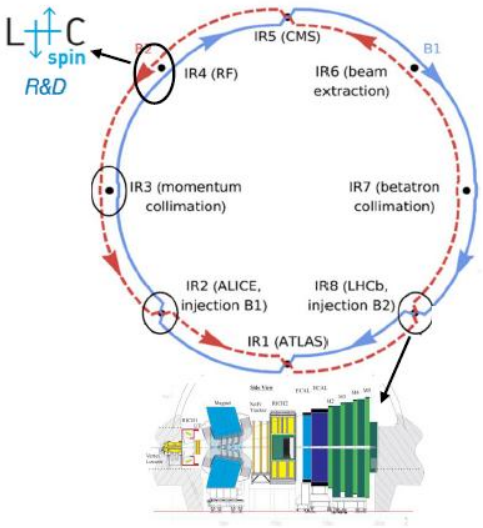
Current Stage

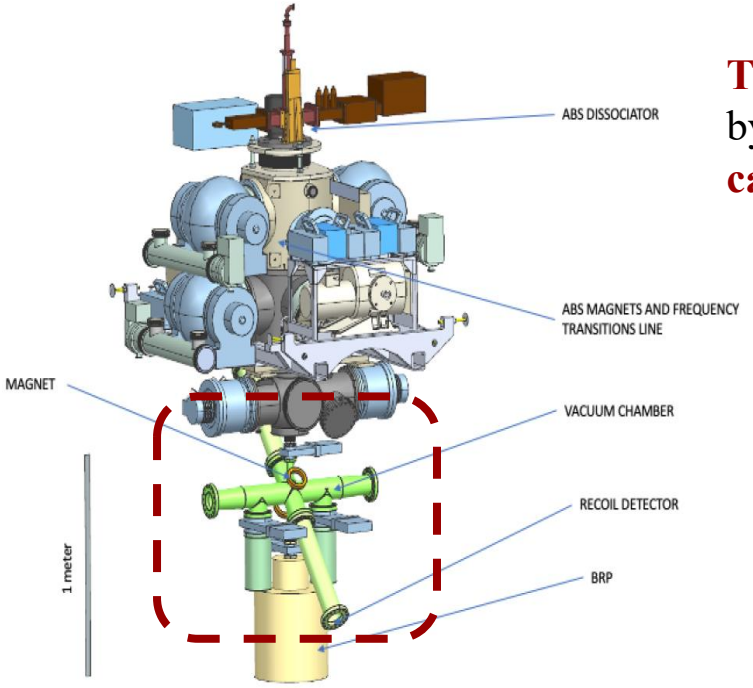
Polarimetry Measurements in IR4



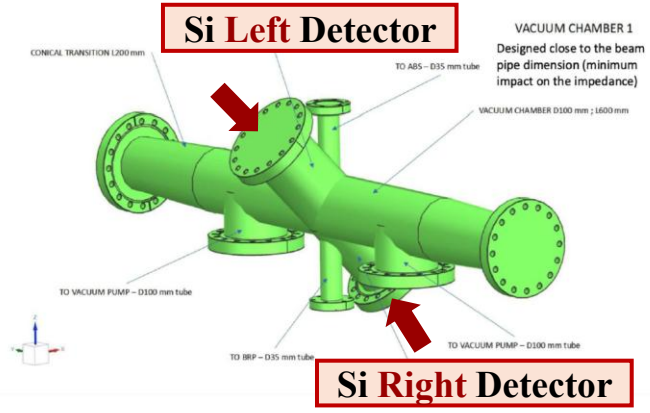
Absolute Polarimeter Installation in IR4

IR4 is the ideal place testing the AP system with a lot of space, rails and racks for the existing "Beam Gas Vertex"



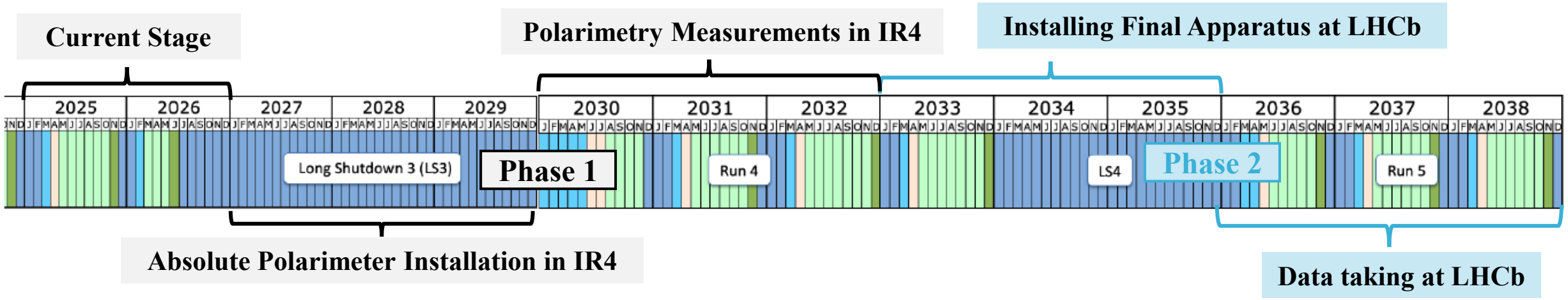


The left-right asymmetries measured by the **Si detector system** must be **calibrated with the BRP measurement**

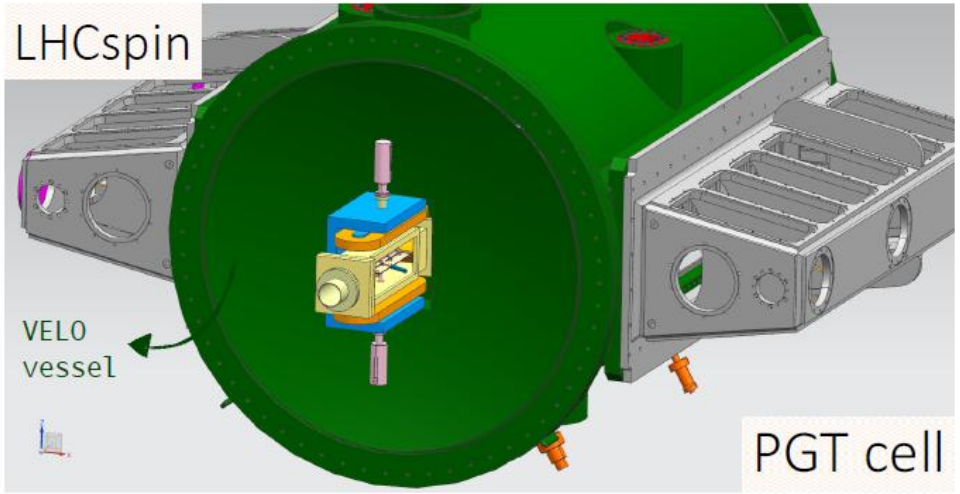


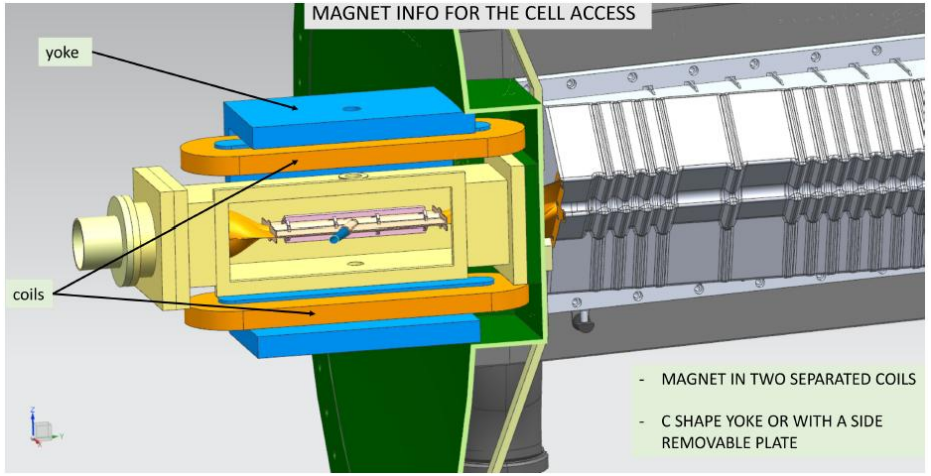
In my PhD, I am working on GEANT4 simulations of AP system in light of the future measurements at IR4

LHCspin: Timeline



Phase 2 Apparatus





arXiv:2504.16034 (2025)

LHCspin: Expected Performance

Considering SMOG2 previous performance, MC simulations have been conducted on LHCspin to evaluate its potential in probing several physics channel.

Number of fully-reconstructed and **selected events for LHCspin.**

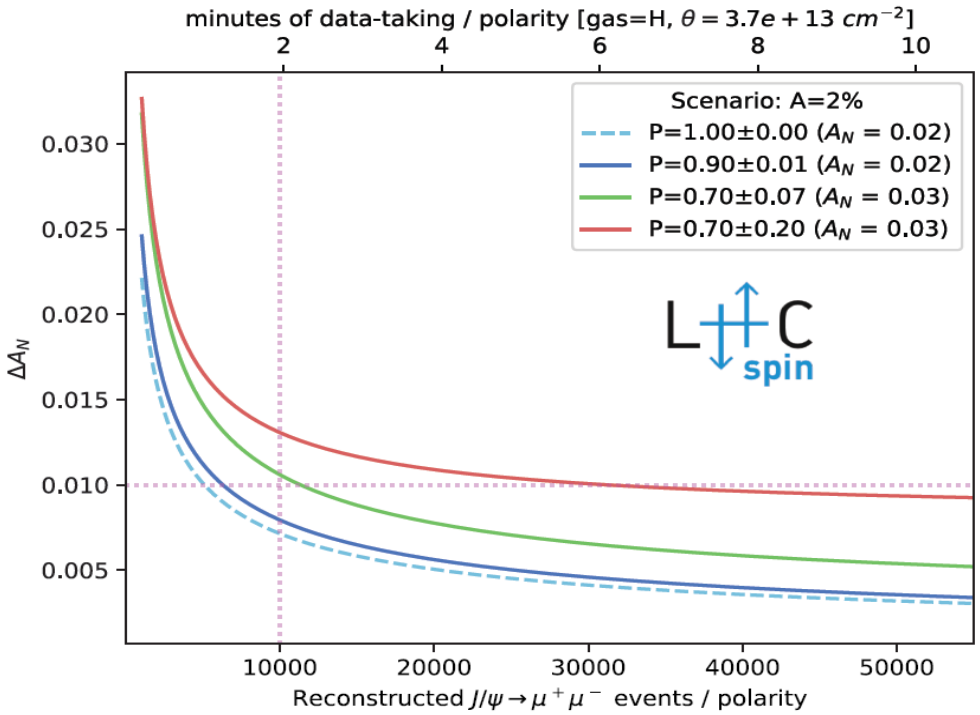
Channel	Event/week	Total yield
$J/\psi \to \mu^+\mu^-$	2.6×10^7	3.1×10^9
$D^0 \to K^-\pi^+$	1.3×10^8	1.6×10^{10}
$\psi(2S) \to \mu^+\mu^-$	4.6×10^5	5.5×10^7
$J/\psi\, J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (DPS)	1.7×10^1	2.1×10^3
$J/\psi\, J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (SPS)	5.1×10^1	6.1×10^3
Drell-Yan $(5 < M_{\mu^+\mu^-} < 9$ GeV$)$	1.5×10^4	1.8×10^6
$\Upsilon \to \mu^+\mu^-$	1.1×10^4	1.3×10^6
$\Lambda c^+ \to pK^-\pi^+$	2.6×10^6	3.1×10^8

arXiv:2504.16034 (2025)

Huge statistics predicted!

Reconstructed J/ψ

Expected precision for A_N



Within **2 minutes of data-taking:**

- **10000 J/ψ events** are **reconstructed**
- $\Delta A_N \approx 1\%$ **with Target Polarizations of at least 70%**

Summary

- LHCb is currently the only experiment in the world to operate in both collider and fixed-target mode (SMOG2)
- LHCb has been taking data in fixed-target mode since the beginning of Run 3, taking data with 23 different collision systems
- From SMOG2 data-taking in Run 3, there are already many published results, from cosmic rays, to dark matter, and heavy flavour production
- Based in SMOG2 success, we propose to further advance LHCb physics program by enabling polarized fixed-target collisions - LHCspin
- LHCspin will install a polarized fixed-target system in LHC during Run 4 (Phase 1) and Run 5 (Phase 2)
- MC simulation show excellent prospect for LHCspin data taking during Run 5 with a lot of statistics

With LHCspin, LHCb will become the **first experiment** to **deliver simultaneously unpolarized beam–beam collisions** and **both polarized and unpolarized beam–target collisions**

Thank you for your attention!

Looking forward any questions!