JRA2: Fixed target experiments at the LHC

STRONG-2020

HORIZON 2020

Annual Meeting

Pasquale di Nezza (INFN-LNF) and Cynthia Hadjidakis (IJCLab Orsay)

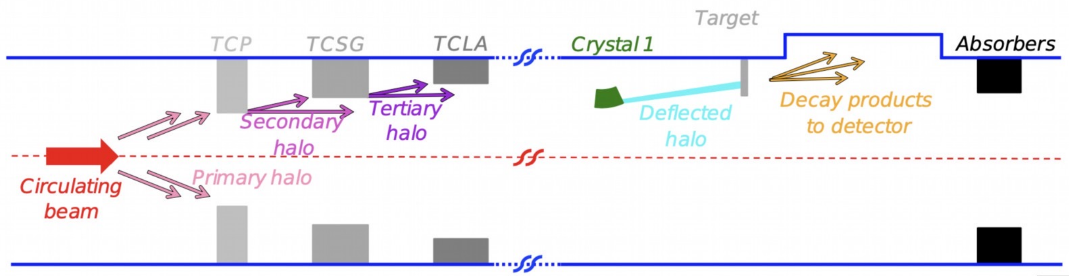
WP objectives

1. Investigation and implementation of fixed-target experiments with ALICE and LHCb detectors at high luminosity
2. Develop new theoretical ideas (rare events, large rapidities, …)
3. Quantify phenomenological opportunities with ALICE and LHCb in fixed target modes
4. Benchmark selected observables using realistic simulations

Fixed target collisions at the LHC represent a unique possibility for a laboratory for QCD and astroparticle in unexplored kinematic regions

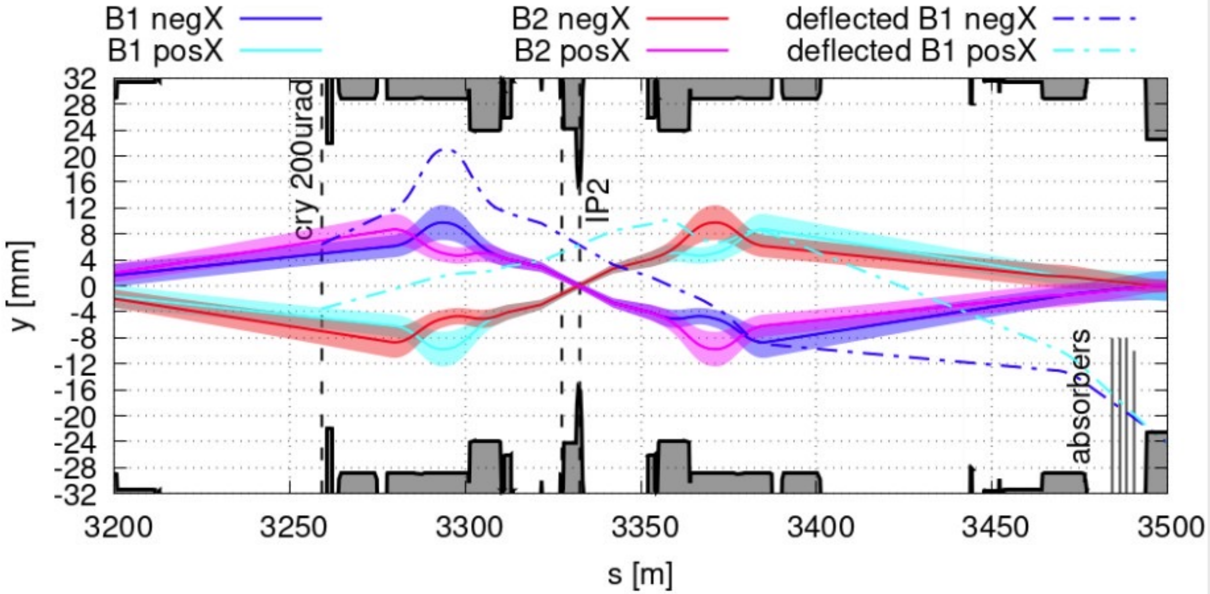
Fixed-target project in ALICE: beam splitting on solid target

- Beam splitting thanks to a bent crystal, coupled to a solid target inside ALICE
- Parasitic operation (with respect to all LHC experiments): fixed-target collisions can occur in parallel to beam-beam collisions
- Optimization of the bent crystal setup using simulations
- Expected PoT in Run 4: about 10^6 p/s in parasitic mode



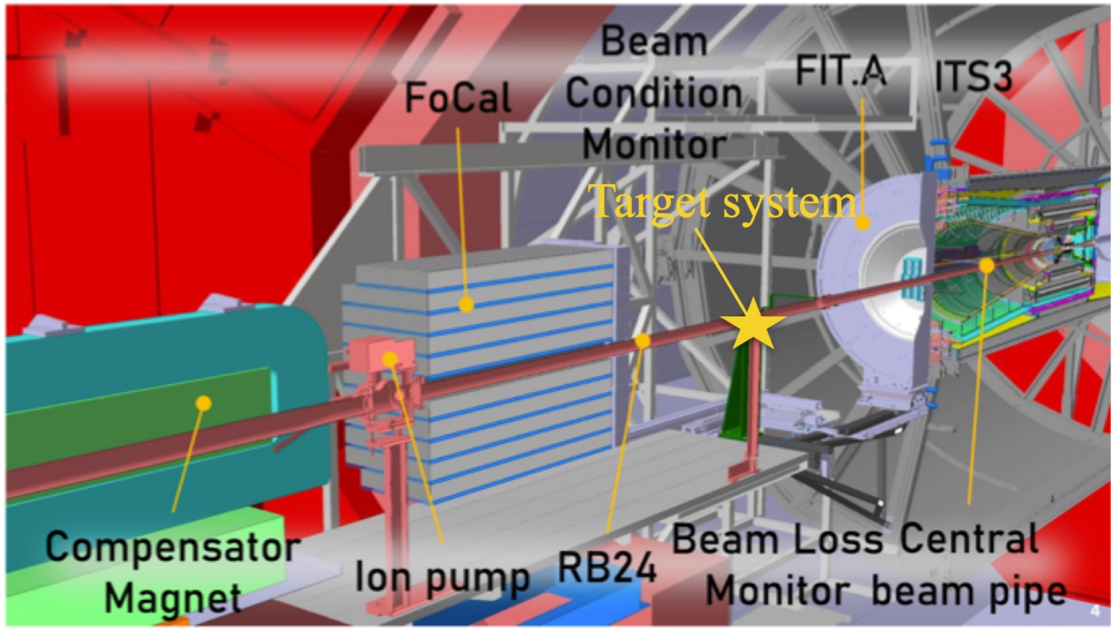
Graphics: D. Mirarchi

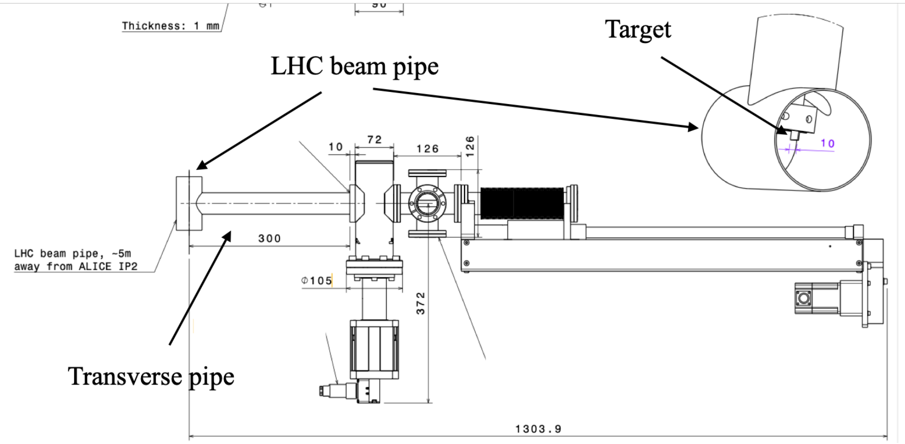
M. Patecki et al. EPJC 83(2023)1053



Target system design and integration

- Integration and vacuum constraints:
  - z~-4.8 m from IP2
  - FoCal detector behind the target system
  - Beam pipe vacuum ~10^{-10}-10^{-11} mbar
- Target design developed at IJCLab
  - Step motor for a retractable target with linear motion
  - Transverse beam pipe of ~30 cm to stay outside of FoCal acceptance
- Funding (ANR 2022/France) obtained to pursue the study (vacuum, integration)

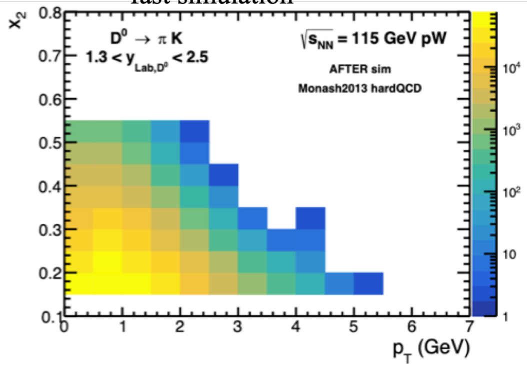




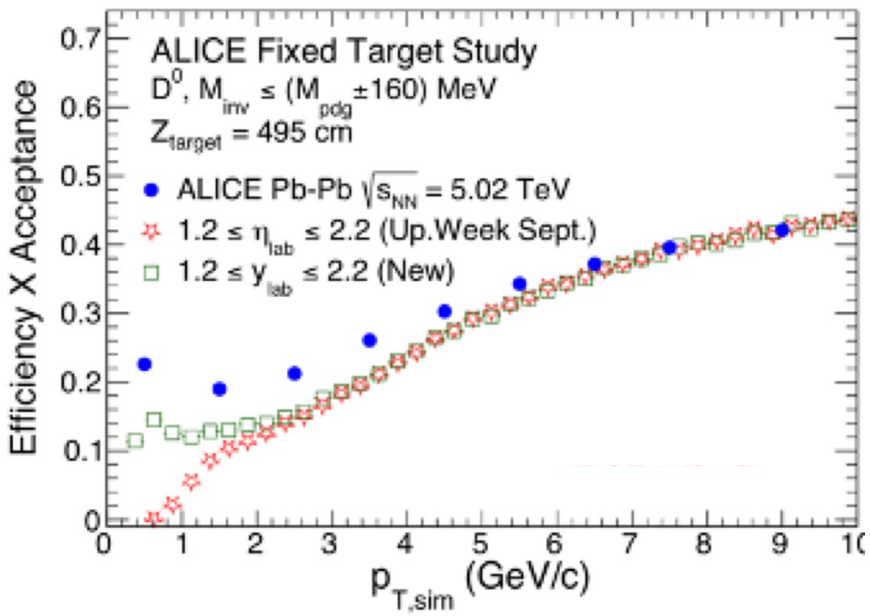
Physics performance studies

ALICE-FT physics motivations
[ESPP document]

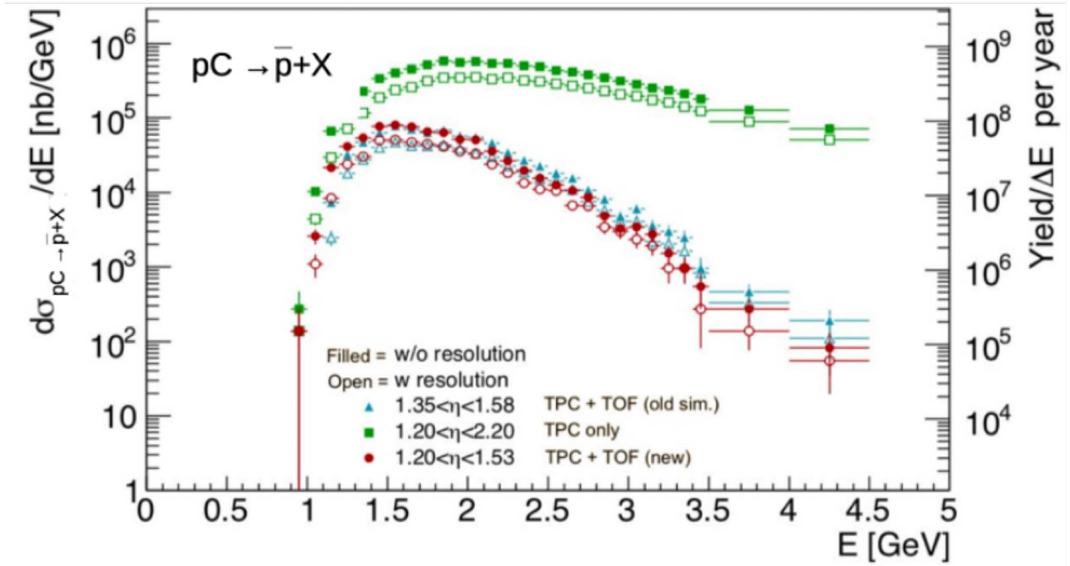
fast simulation



fast decay simulation with detector effects



fast simulation with detector effects, no PID simulated



- Open charm production: D^0 as a probe for gluon/intrinsic charm content of nucleon/nuclei at large xB
  - tracking and vertexing with ALICE TPC
  - fast decay simulations in p+W: good tracking efficiency showing that measurement of charm cross section feasible w/o additional vertex detector and down to low pT
- Antiparticle production at low E : provide inputs to cosmic rays production (inverse kinematics)
  - Large yields expected with ALICE TPC and TOF

But…

End of the ALICE-FT project early 2023 following a Management Board decision.

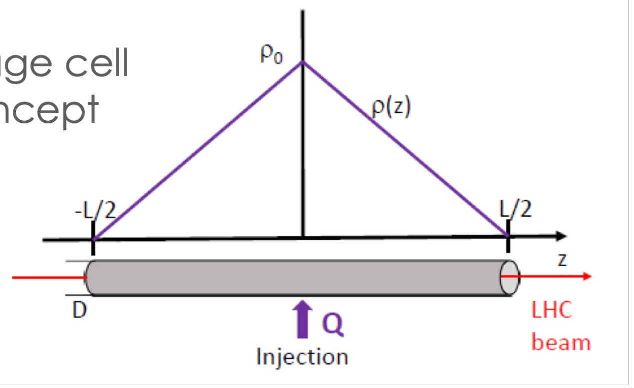
The MB appreciates the physics performance studies that have been performed and acknowledges the interest of the physics program. However, we also found that the physics performance and in particular the uniqueness of the fixed target program in ALICE are not yet fully worked out. ***The effort that would be required from Technical Coordinator*** *and the LHC vacuum groups for the further design of the target area* ***is substantial and incompatible with the work needed to successfully complete the ITS3 and FoCal upgrades for LS3.*** *The Management Board therefore concluded that the collaboration cannot afford to allocate the necessary resources to support the design and installation of a fixed target in LS3.*

Unpolarised gas target SMOG2 at LHCb

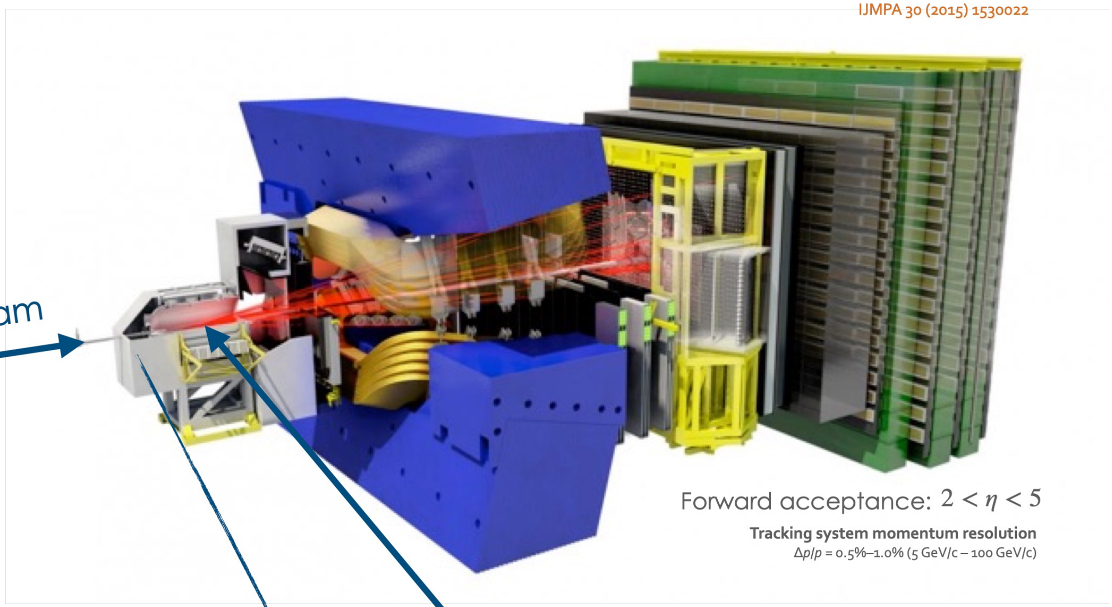
CERN-LHCC-2019-005 ; LHCB-TDR-020

JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

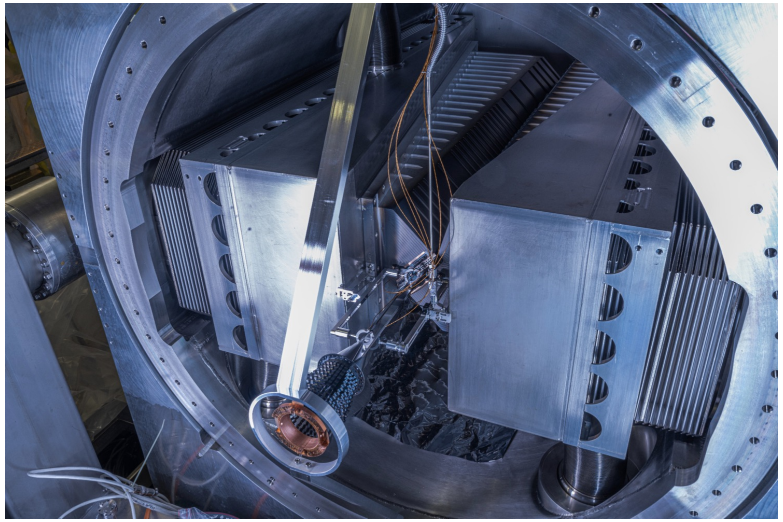
Storage cell concept

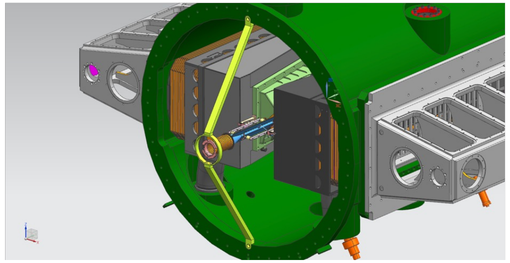


LHC beam



beam-beam collisions



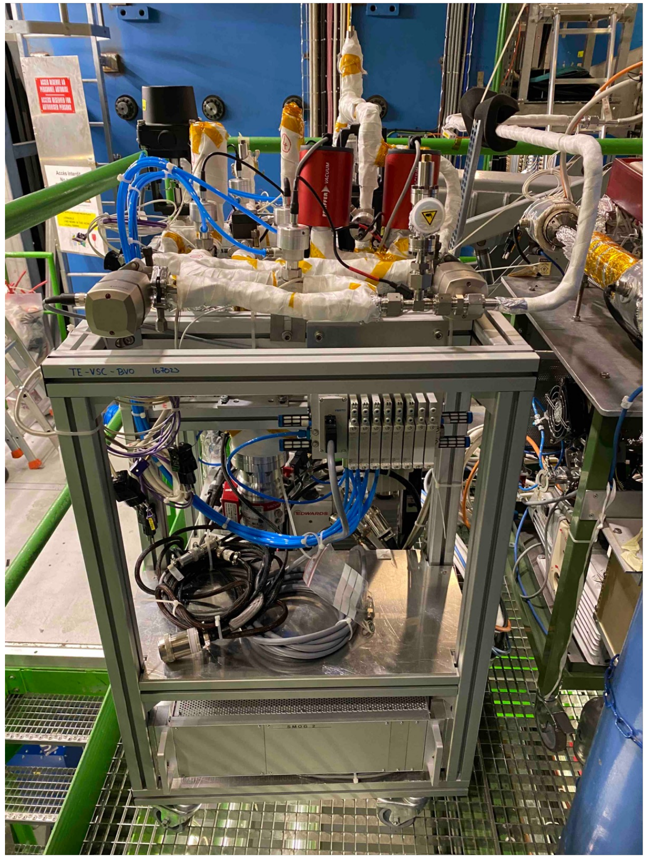


UNpolarised target (beam-gas)

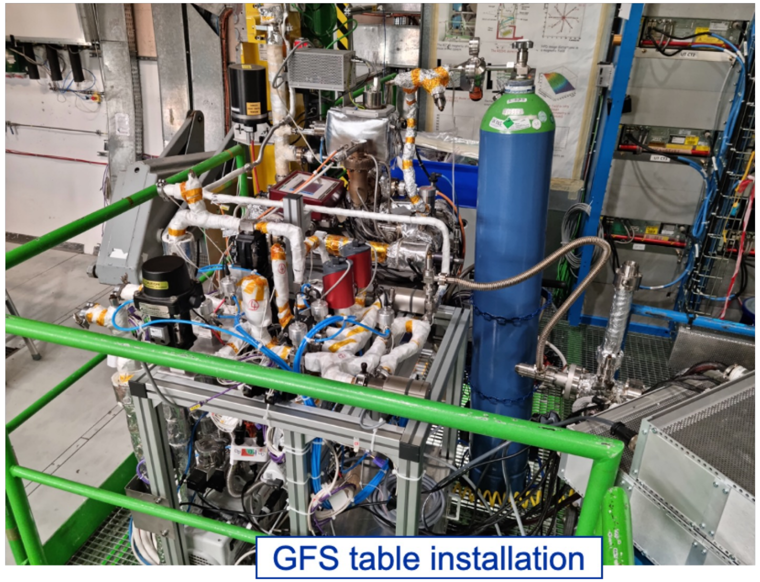
An advanced Gas Feed System for SMOG2 at LHCb

- Negligible impact on the beam lifetime ($\tau^{p-H_2}_{beam-gas} \sim 2000$ days , $\tau^{Pb-Ar}_{beam-gas} \sim 500$ h)
- Injectable gases (6 reservoirs): H_2, D_2, N_2, O_2, He, Ne, Ar, Kr, Xe
- Flux known with $1\,\%$ precision, measured relative contamination 10^{-4}

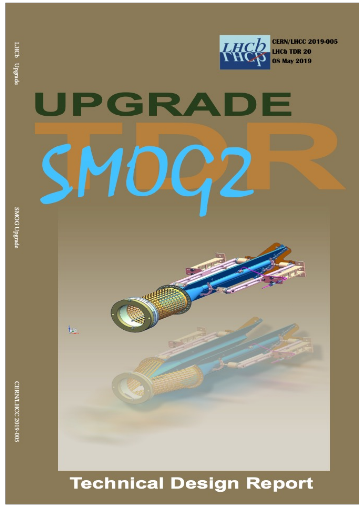
CERN-LHCC-2019-005 ; LHCB-TDR-020

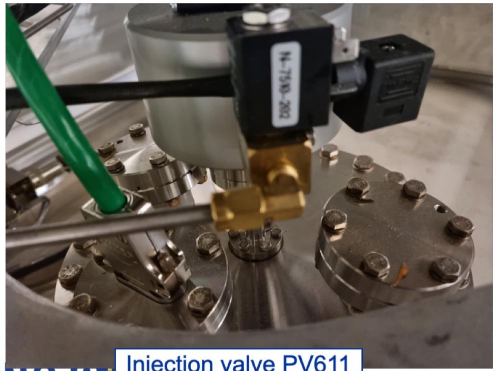


Luminosity determination with 1.5% of accuracy



GFS table installation

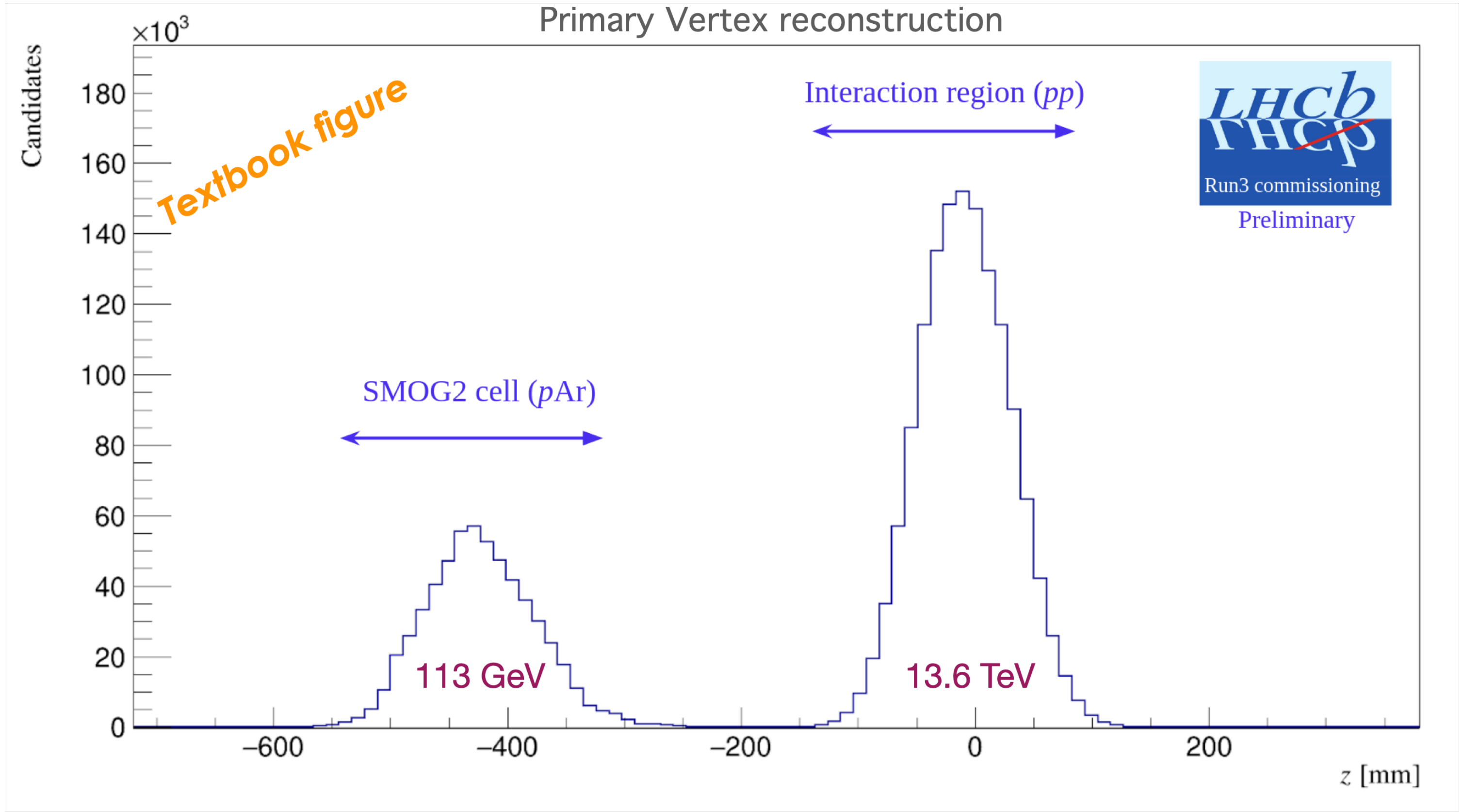




Injection valve PV611

SMOG2 first real data

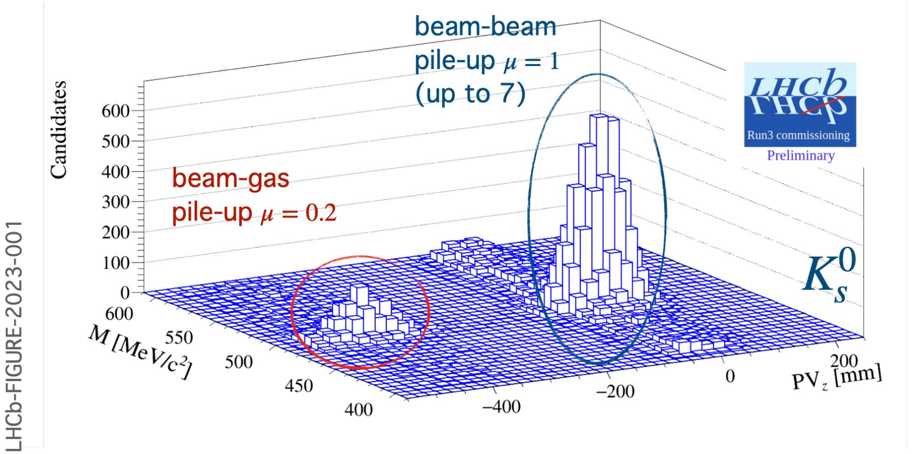
LHCb-FIGURE-2023-001

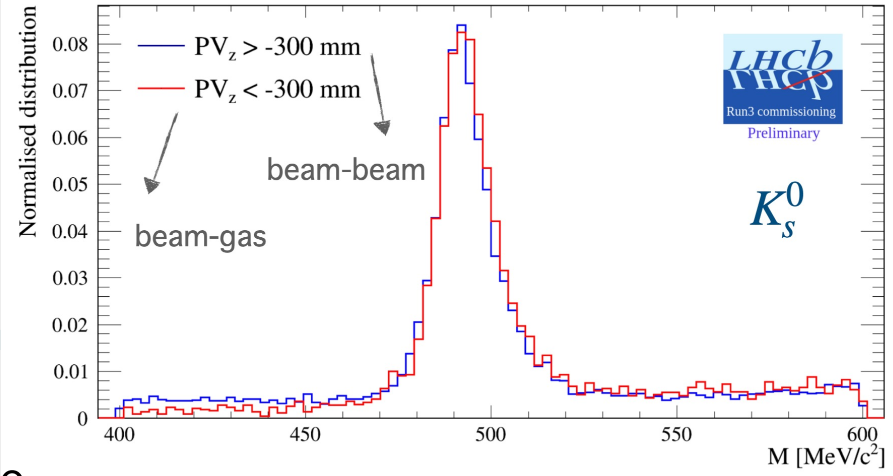


Two well separated and independent Interaction Points working simultaneously

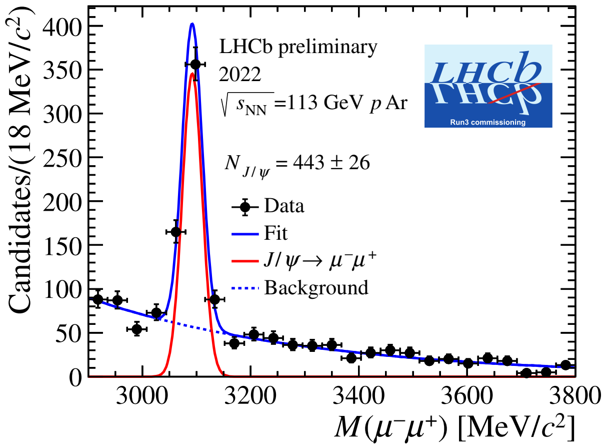
SMOG2 first real data

Excellent results in ~15 minutes of data taking, albeit low gas pressure

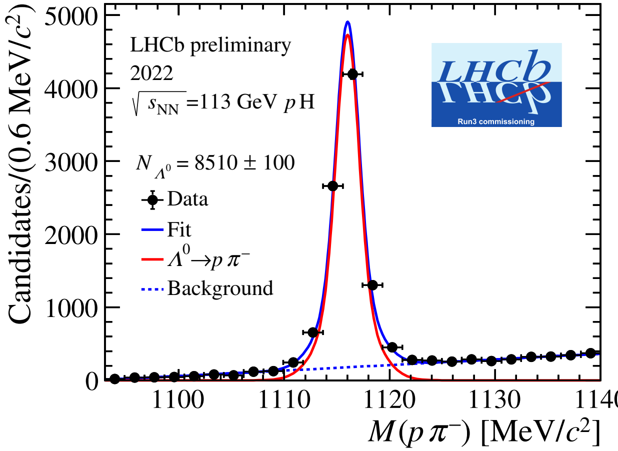




$pAr \Rrightarrow J/\psi \rightarrow \mu^-\mu^+$



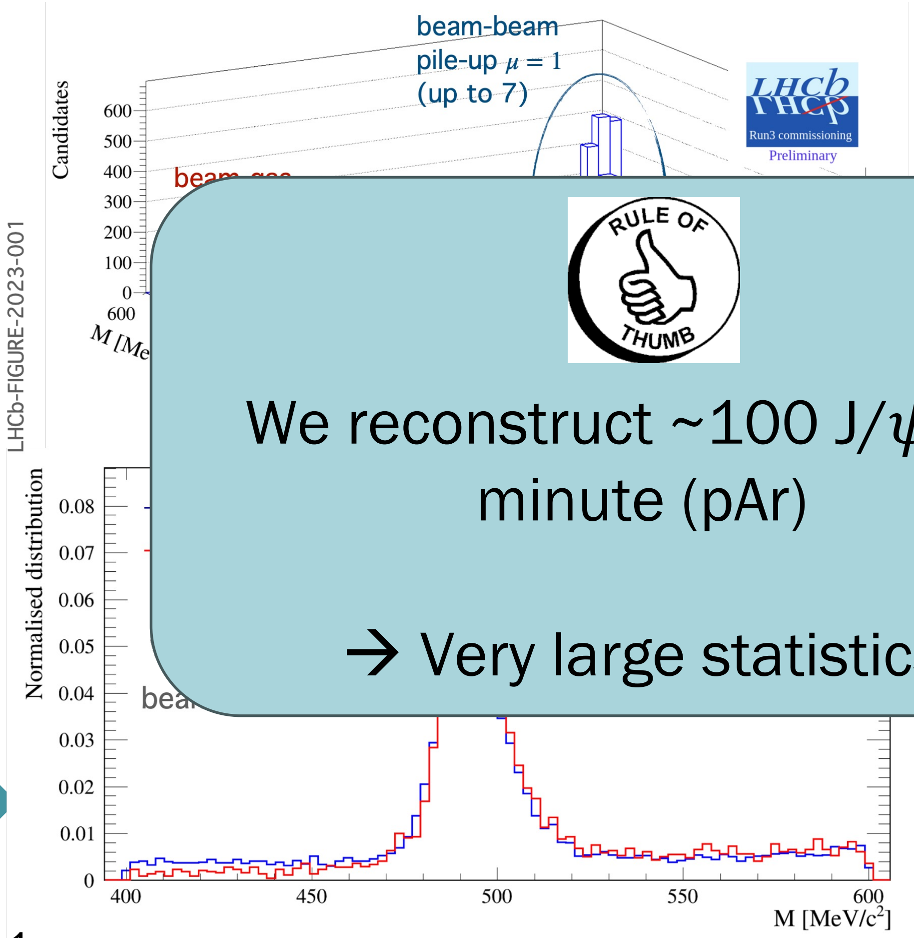
$pH \Rrightarrow \Lambda^0 \rightarrow p\pi^-$



- beam-beam and beam-gas interactions are well detached
- same resolution for beam-gas and beam-beam collisions
- negligible increase of multiplicity : small impact in the LHCb reconstruction sequence. Data flow increase of ~1%
- huge statistics

LHCb is the only experiment able to run in collider and fixed-target mode simultaneously!

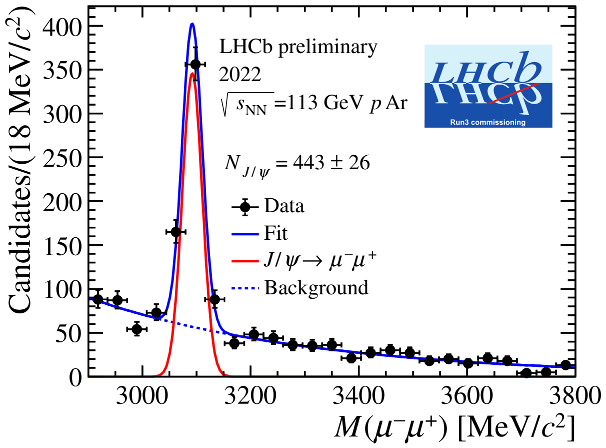
SMOG2 first real data



We reconstruct ~100 J/ψ per minute (pAr)

→ Very large statistics

$pAr \Rrightarrow J/\psi \rightarrow \mu^-\mu^+$



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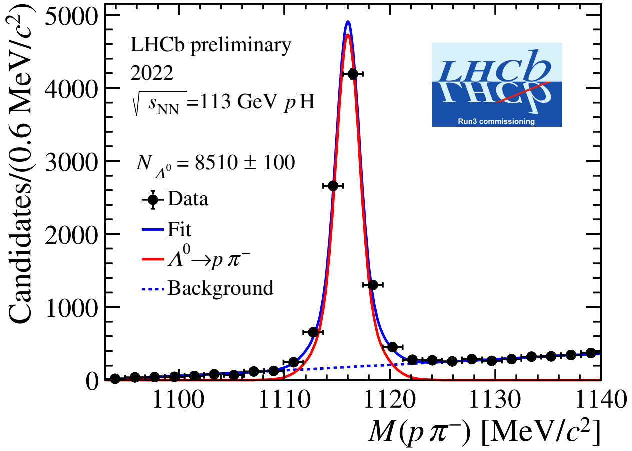

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SMOG2 first real data

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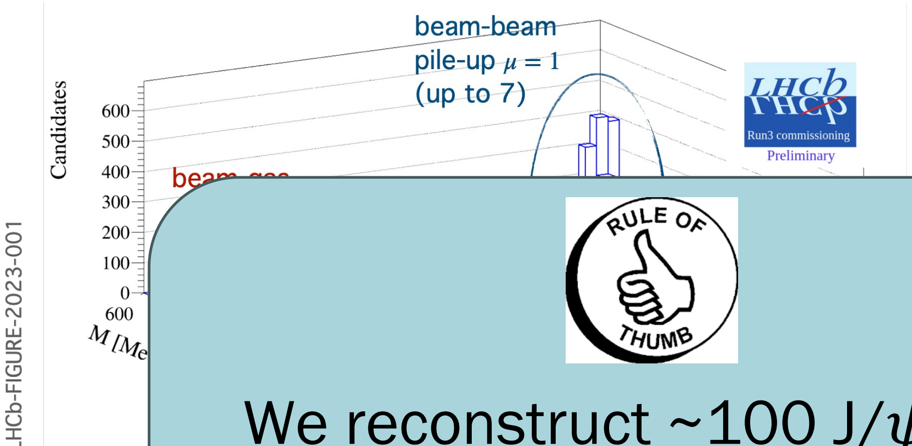

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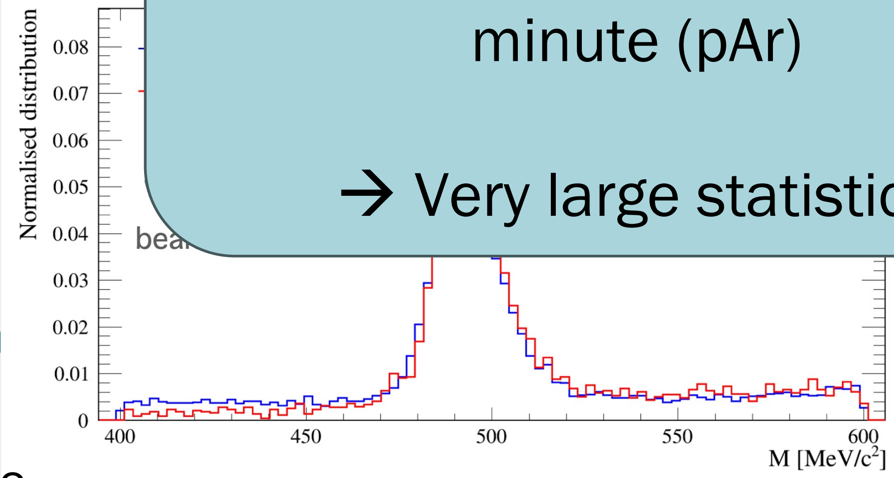

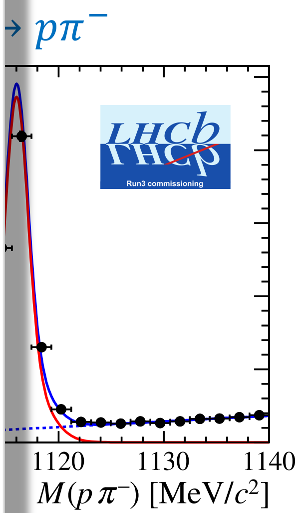

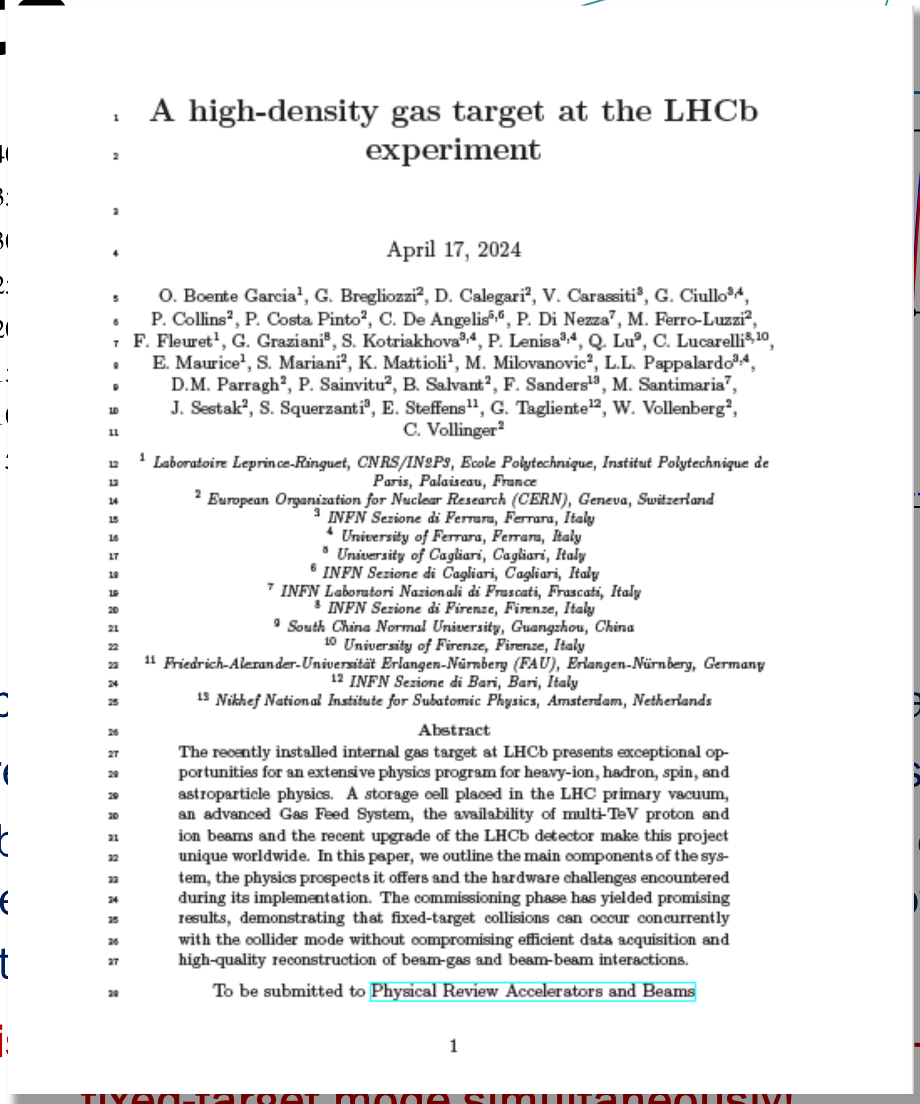

A high-density gas target at the LHCb experiment

April 17, 2024

O. Boente Garcia[1], G. Bregliozzi[2], D. Calegari[2], V. Carassiti[3], G. Ciullo[3,4], P. Collins[2], P. Costa Pinto[2], C. De Angelis[5,6], P. Di Nezza[7], M. Ferro-Luzzi[2], F. Fleuret[1], G. Graziani[8], S. Kotriakhova[3,4], P. Lenisa[3,4], Q. Lu[9], C. Lucarelli[8,10], E. Maurice[1], S. Mariani[2], K. Mattioli[1], M. Milovanovic[2], L.L. Pappalardo[3,4], D.M. Parragh[2], P. Sainvitu[2], B. Salvant[2], F. Sanders[13], M. Santimaria[7], J. Sestak[2], S. Squerzanti[3], E. Steffens[11], G. Tagliente[12], W. Vollenberg[2], C. Vollinger[2]

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[4] University of Ferrara, Ferrara, Italy
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[6] INFN Sezione di Cagliari, Cagliari, Italy
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[9] South China Normal University, Guangzhou, China
[10] University of Firenze, Firenze, Italy
[11] Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen-Nürnberg, Germany
[12] INFN Sezione di Bari, Bari, Italy
[13] Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands

Abstract

The recently installed internal gas target at LHCb presents exceptional opportunities for an extensive physics program for heavy-ion, hadron, spin, and astroparticle physics. A storage cell placed in the LHC primary vacuum, an advanced Gas Feed System, the availability of multi-TeV proton and ion beams and the recent upgrade of the LHCb detector make this project unique worldwide. In this paper, we outline the main components of the system, the physics prospects it offers and the hardware challenges encountered during its implementation. The commissioning phase has yielded promising results, demonstrating that fixed-target collisions can occur concurrently with the collider mode without compromising efficient data acquisition and high-quality reconstruction of beam-gas and beam-beam interactions.

To be submitted to Physical Review Accelerators and Beams

1

m-b … ached
he re … sions
gligib … e
Cb re … f ~1%
- huge st…

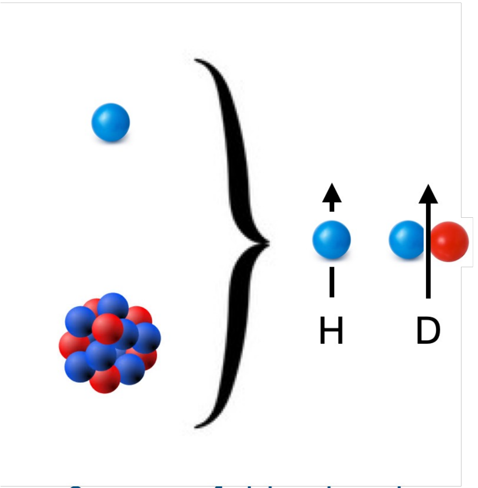
LHCb i… -and fixed-target mode simultaneously!

Upgrade to a polarized gas target

arXiv:1901.08002
Acta Phys.Polon.Supp. 16 (2023) 7
PoS PSTP2022 (2023) 001

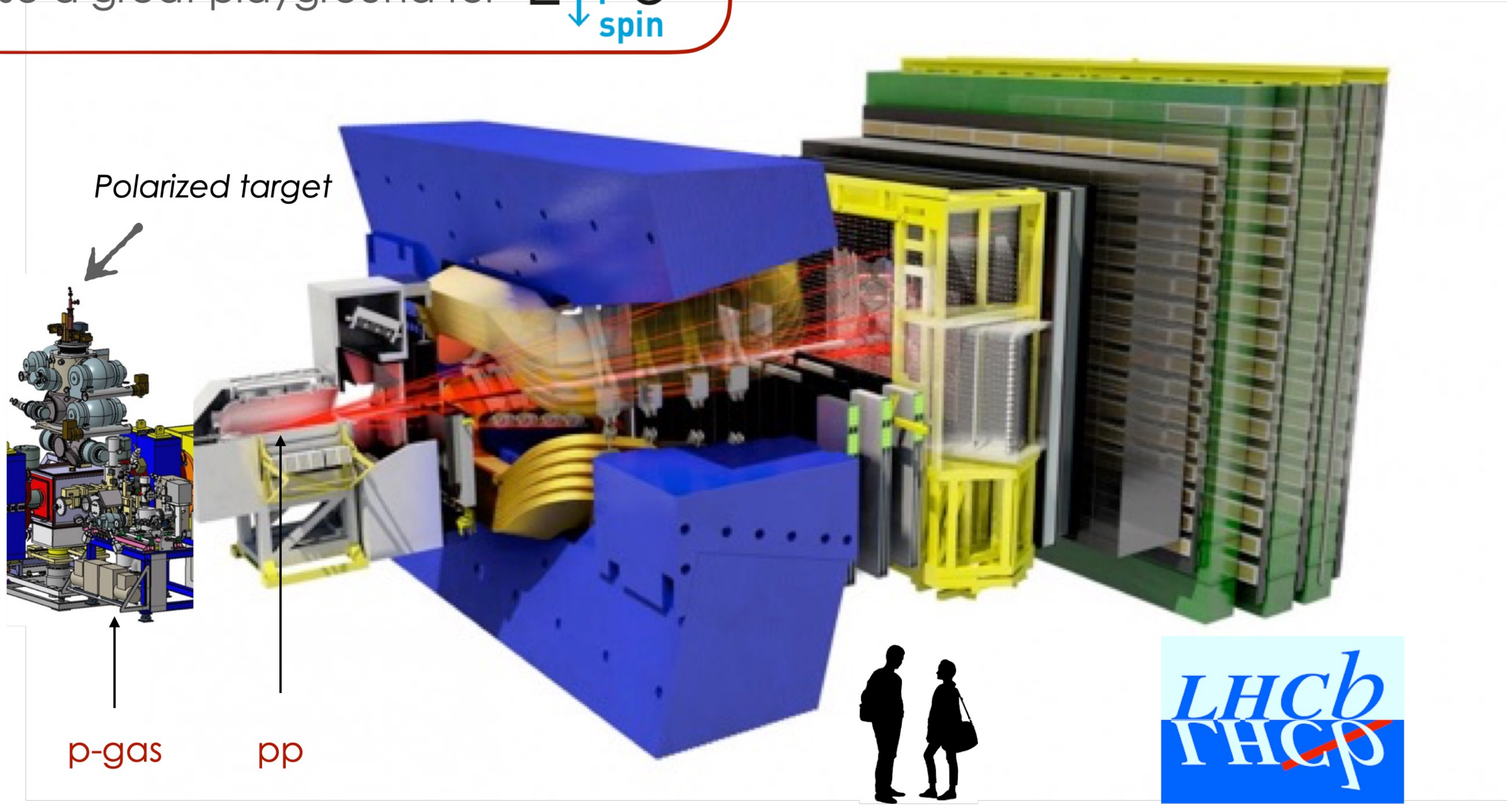
SMOG2 is not only a unique project itself,

but also a great playground for LHCspin



Successful technology based on HERA and COSY experiments

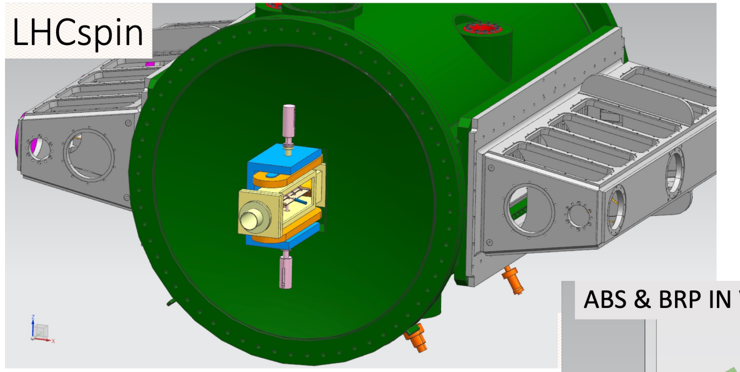
Challenge: develop a new generation of polarized targets

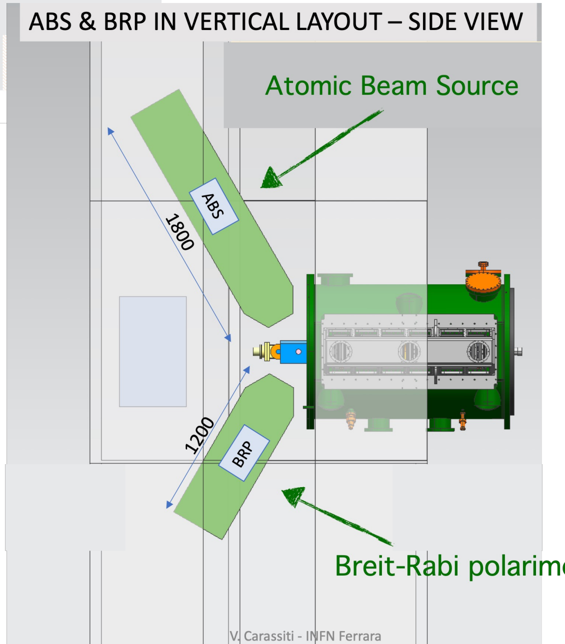


Possible configurations being investigated

L_{pH} = 2.5x10^{32} cm^{-2}s^{-1}

With a storage cell a la SMOG2

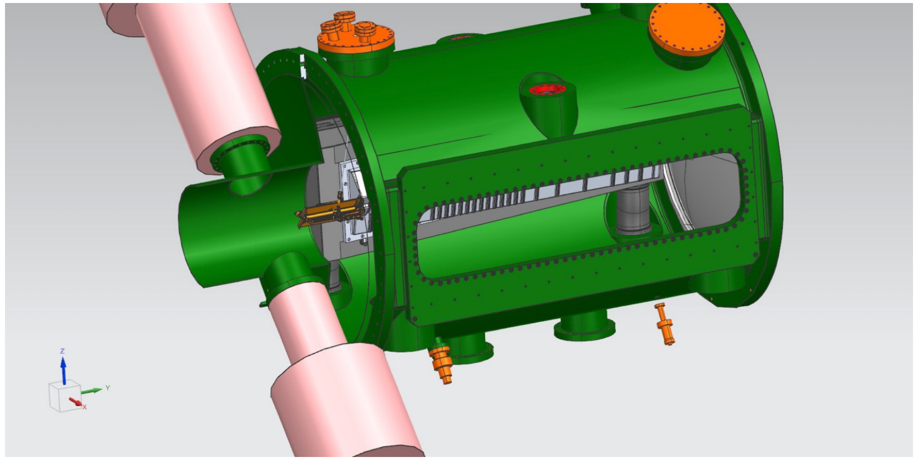




Lower polarization
High luminosity

L_{pH} = storage cell/40

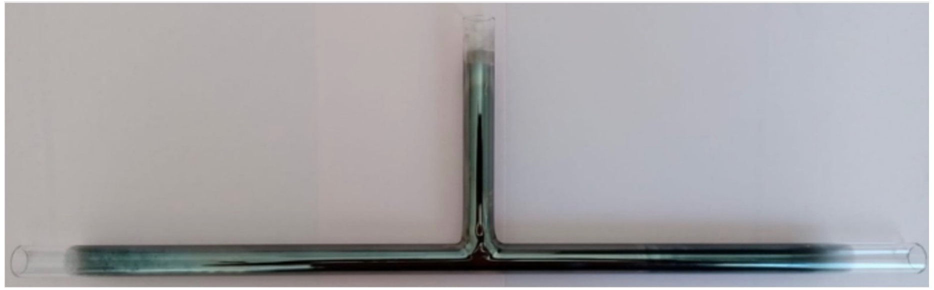
Using a jet target to avoid recombination effects

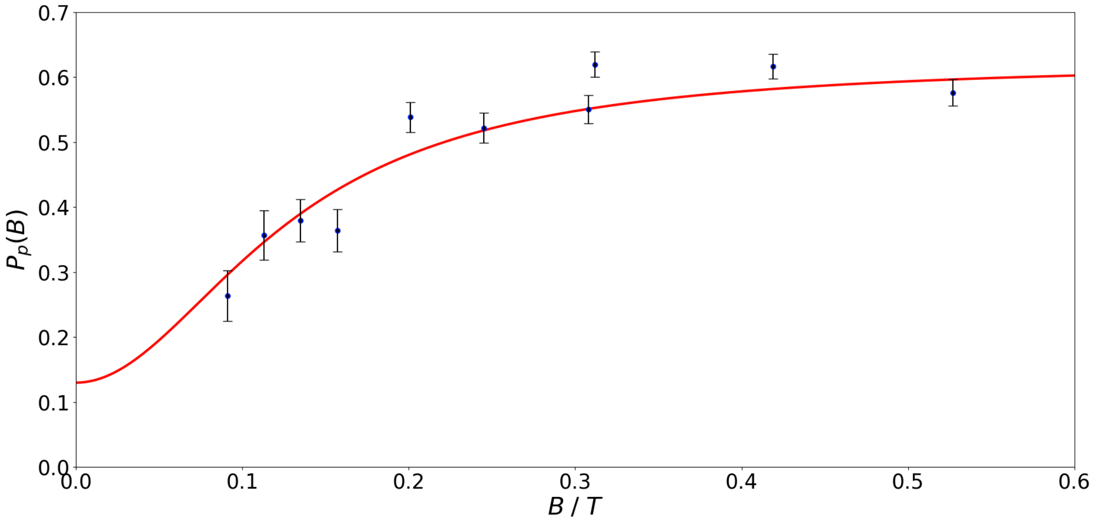


Higher polarization
Lower luminosity

3rd option
Molecular beam + storage cell

A test was performed at FZ-Julich on a quartz storage cell coated at CERN with amorphous carbon, just like the SMOG2 storage cell





Proton polarization in a polarized molecule (P_{m0}=0.59)
The recombination is >98%

Amorphous Carbon-coated Storage Cell Tests for the Polarized Gas Target at LHCb

T. El-Kordy[a,b,*], P. Costa Pinto[c], P. Di Nezza[d], R. Engels[b,e], M. Ferro-Luzzi[c], N. Faatz[b,e,f], K. Grigoryev[b], C. Kannis[g], S. Pütz[b,h], H. Sharma[a,b], V. Verhoeven[b,h]

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Abstract

The LHC beams cannot be polarized. Hence, the implementation of a dense polarized gas target at the LHCb experiment at CERN, to be operated simultaneously with beam-beam collisions, will enable high-energy fixed target interactions to explore a range of spin physics measurements. Using an atomic beam source at the Forschungszentrum Jülich to provide a polarized atomic hydrogen beam, we investigated the properties of a storage cell coated with amorphous carbon. A notable recombination rate, lying between 93 and 100%, and a preservation of polarization during recombination exceeding 74% was observed. We were able to generate H_2 molecules with a nuclear polarization of −0.59. Remarkably, no water layer accumulated on

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Email address: tarek.el-kordy@alumni.fh-aachen.de (T. El-Kordy)

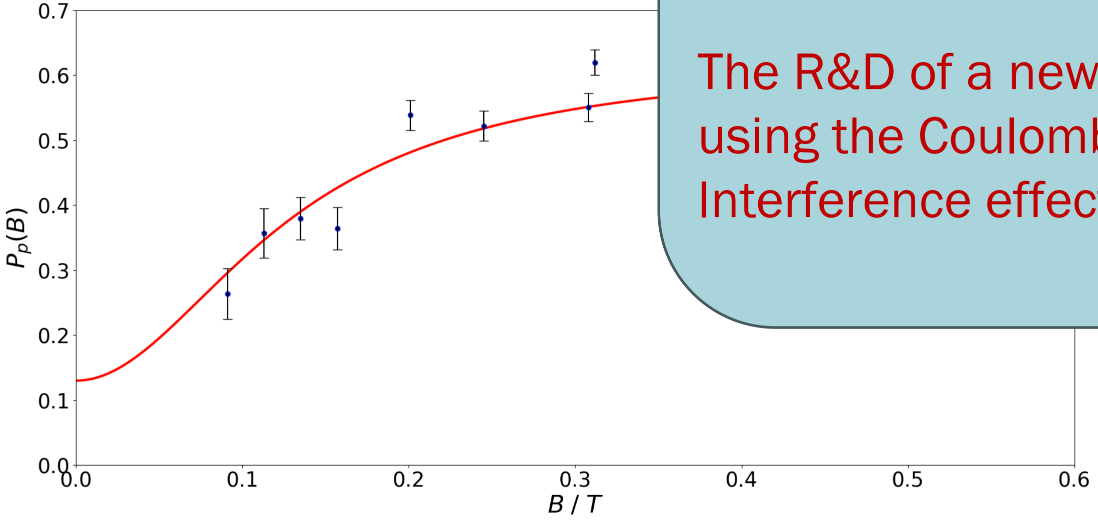
Preprint subm Screenshot *m. Methods Phys. Res. A* *June 5, 2024*

3rd option
Molecular beam + storage cell

A test was performed at FZ-Julich on a quartz storage cell coated at CERN with amorphous carbon, just like the SMOG2 storage cell

This could be the first polarized molecular beam source ever used in spin physics

The R&D of a new polarimeter using the Coulomb Nuclear Interference effect (CNI) is needed



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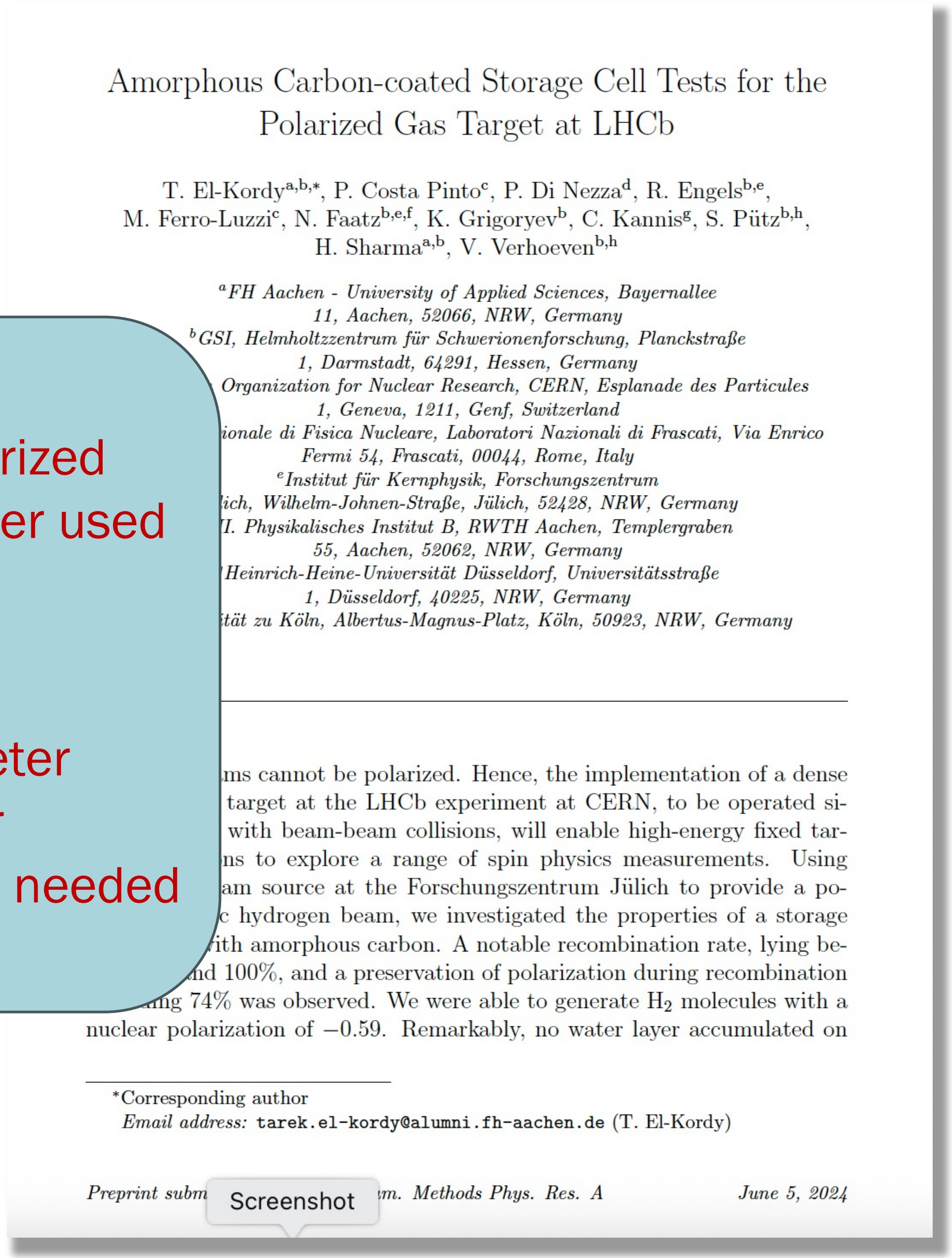
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Heinrich-Heine-Universität Düsseldorf, Universitätsstraße 1, Düsseldorf, 40225, NRW, Germany
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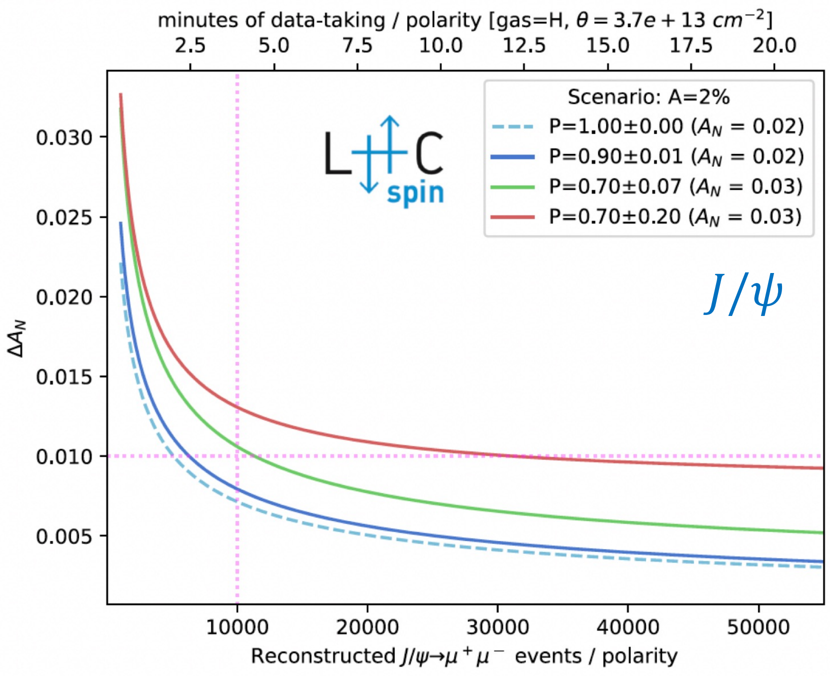
Preprint subm Screenshot m. Methods Phys. Res. A June 5, 2024

LHC spin event rates (with the Storage Cell configuration)

Precise spin asymmetry on $J/\psi \longrightarrow \mu^+\mu^-$ for $pH^{\uparrow\downarrow}$ collisions in just few weeks with Run3 luminosity!
Statistics further enhanced by a factor 3-5 in LHCb upgrade II

$L_{pH} = 2.5 \times 10^{32}\ cm^{-2}s^{-1}$



reconstructed particles

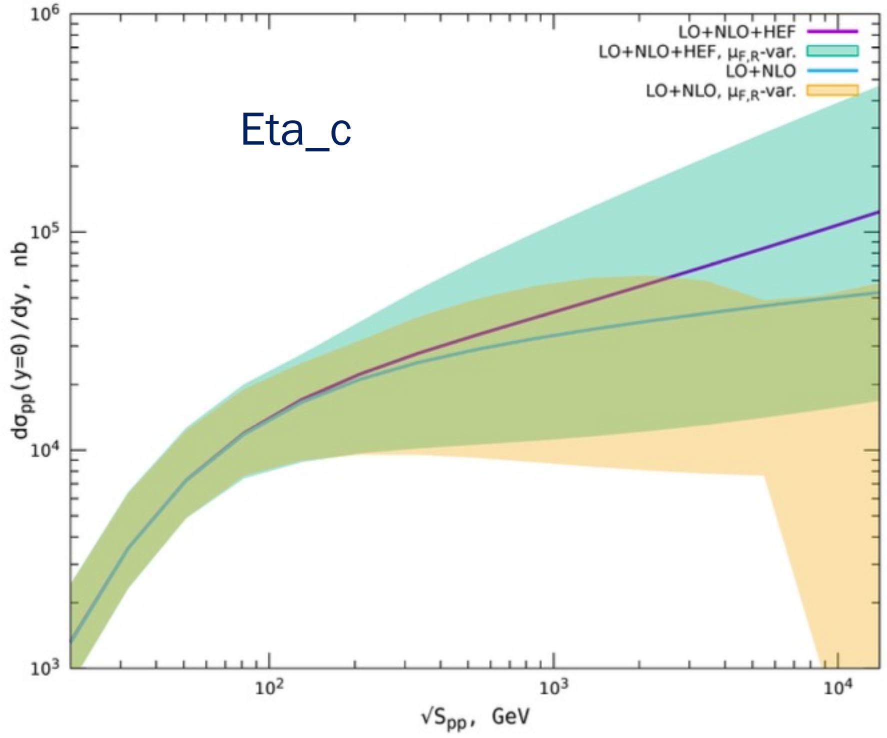
Channel	Events / week	Total yield
$J/\psi \to \mu^+\mu^-$	1.3×10^7 !!	1.5×10^9
$D^0 \to K^-\pi^+$	6.5×10^7	7.8×10^9
$\psi(2S) \to \mu^+\mu^-$	2.3×10^5	2.8×10^7
$J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (DPS)	8.5	1.0×10^3
$J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (SPS)	2.5×10^1	3.1×10^3
Drell Yan ($5 < M_{\mu\mu} < 9$ GeV)	7.4×10^3	8.8×10^5
$\Upsilon \to \mu^+\mu^-$	5.6×10^3	6.7×10^5
$\Lambda_c^+ \to pK^-\pi^+$	1.3×10^6	1.5×10^8

Phenomenology studies

- Rapidity-differential cross section of eta_c production vs energy
- HEF resummation cures negative cross section issue at high energy
- Large scale uncertainty: NLL computation needed and ongoing

M. Nefedov et al. arXiv:2306.02425

μ_F and μ_R **5pt. variation, NLO vs. matching**

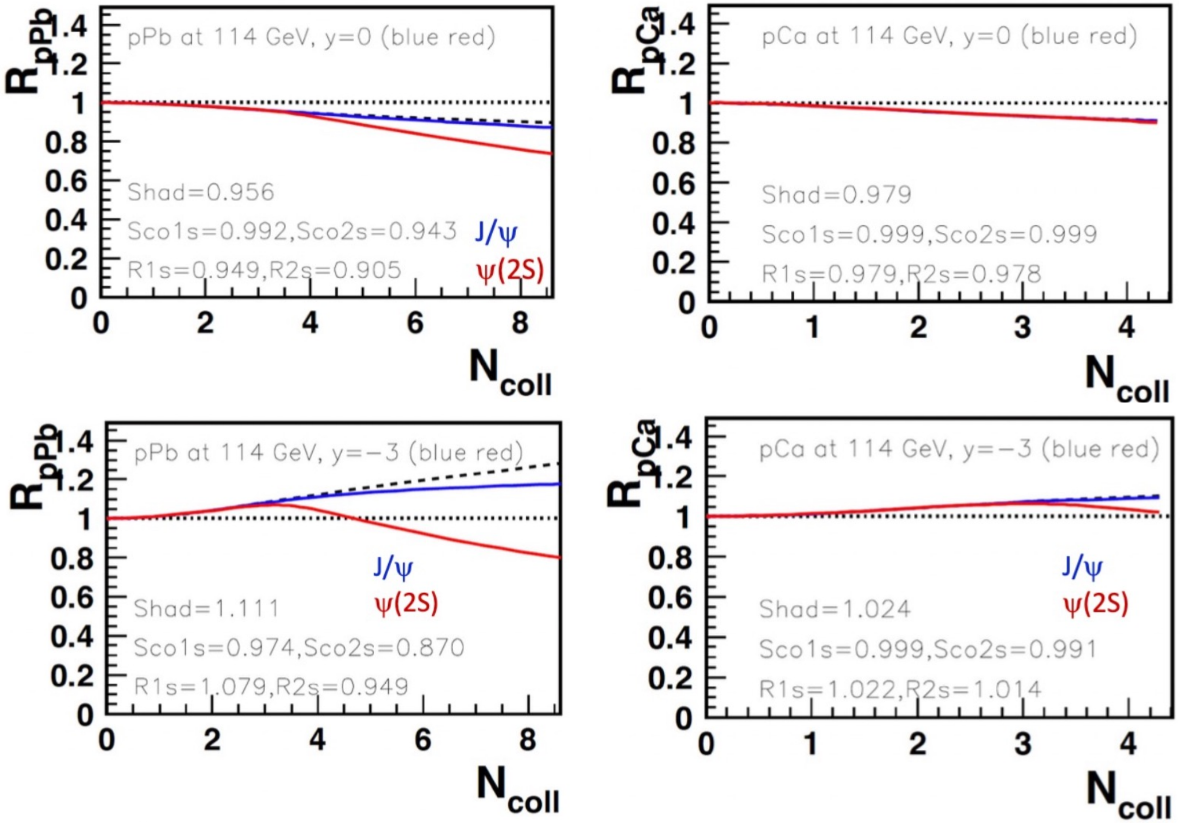


nPDF modification included
Nuclear absorption not included

Phenomenology studies

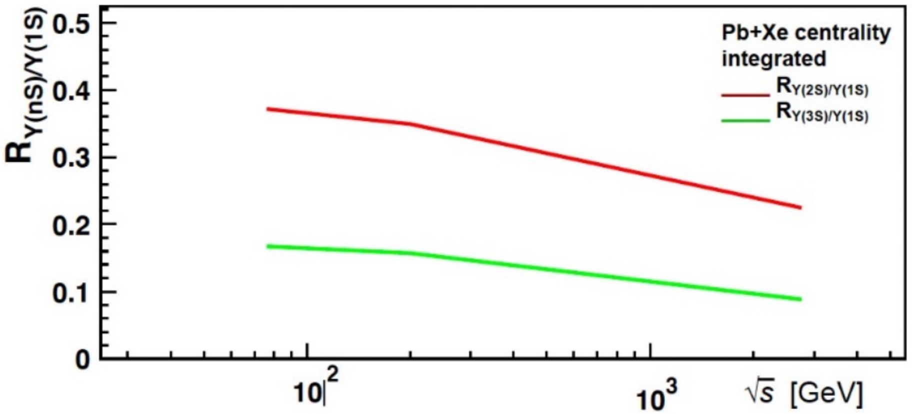
Midrapidity

Backward rapidity



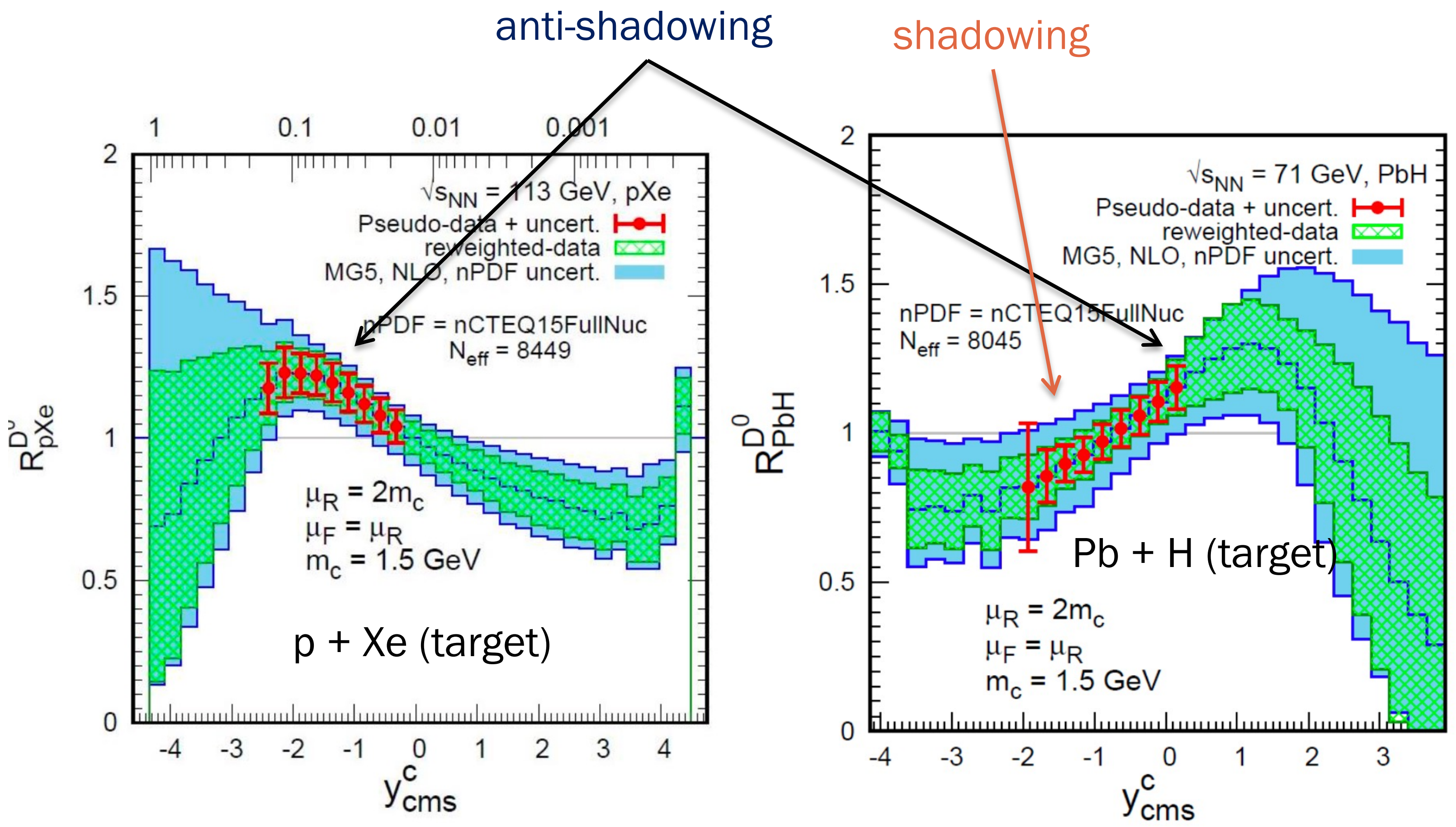
- Comover interaction models at fixed target LHC energies
  - Heavy vs light nuclear targets
  - Charmonia vs bottomia

Paper in preparation: predictions for FTE@LHC by Miguel Escobedo and Elena G. Ferreiro



Impact of D meson SMOG2 pseudo-data on nPDF

- D^0 meson from Madgraph (NLO charm production) and nCTEQ15 nPDF
- SMOG2 possible collision systems:
    - pA: pH, pHe, pAr, pKr, **pXe**
    - Ap: ArH, OH, KrH, XeH, **PbH**
- D meson pseudo-data dominated by systematic uncertainties except in some y-range of Pb(beam)+H(target)
- Reweighting technique : gluon nPDF constrained by D meson production
- Next: similar studies with B^+ and B^0 production



$x_2 \in [0.33, 0.032]$

$$x2 = \frac{2m_c}{113} e^{-y}$$

$x_1 \in [0.0053, 0.056]$

$$x1 = \frac{2m_c}{71} e^{y}$$

Anton Safronov - work in progress

FTE@LHC dedicated workshops

***Jan. 2023* STRONG-2020 workshop « Fixed target experiments at LHC »**
Aussois/France https://indico.cern.ch/event/1222068/

***Jun. 2022* Fixed target experiments at LHC - STRONG2020 workshop**
CERN https://indico.cern.ch/event/1143479/

***Jun. 2021* Joint workshop « GDR-QCD/QCD@short distances and STRONG2020/PARTONS/FTE@LHC/NLOAccess »**
https://indico.ijclab.in2p3.fr/event/7201/

***Nov. 2019* kick-off meeting FTE@LHC - STRONG2020**
CERN https://indico.cern.ch/event/853688/overview

Conclusions

The activity was extremely productive in terms of both R&D and physics results:

1. Completion of the R&D for a solid target at ALICE
2. Gas-target development in LHCb:
    - SMOG2 running since Run3 allowing LHCb to run in fixed target and collider mode simultaneously
    - LHCspin project made relevant steps in R&D and is now an official project of the LHCb upgrade-II
3. Phenomenological and theoretical studies produced interesting results using meta-data