

# Project #22-153 « Fixed target at LHC and ALICE fixed target system »

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on behalf of Cynthia Hadjidakis (IJCLab) and Daniel Kikola (WUT)

IN2P3-COPIN workshop

November 21<sup>st</sup> 2023, Warsaw, France

- Physics motivations for high-luminosity fixed-target experiments at the LHC
- Implementation of a fixed-target setup in ALICE: latest studies and end of the project
- Fixed target at LHC : phenomenology studies
- Project #22-153 in IN2P3-COPIN
- Outlook

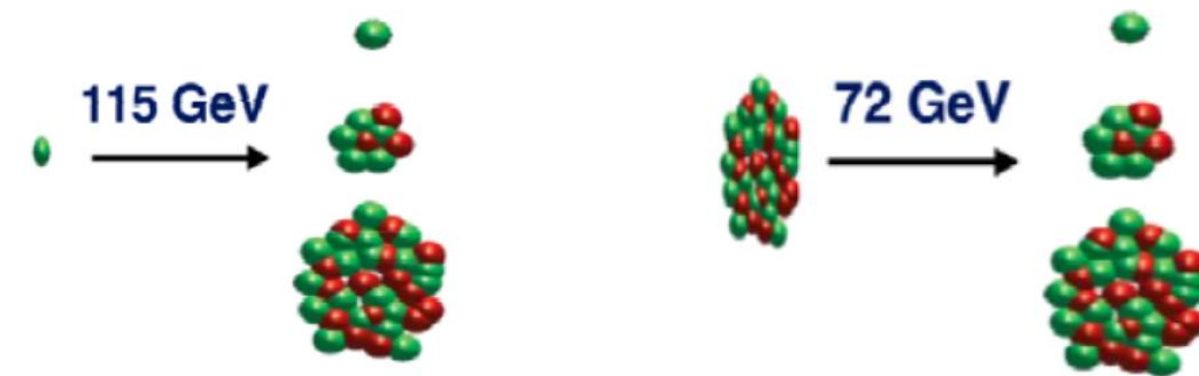
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement STRONG – 2020 - No 824093



# Fixed target mode at LHC

## Fixed target experiments @ LHC

- Energy range: 7 TeV proton / 2.76 A TeV Pb LHC beams on a fixed target

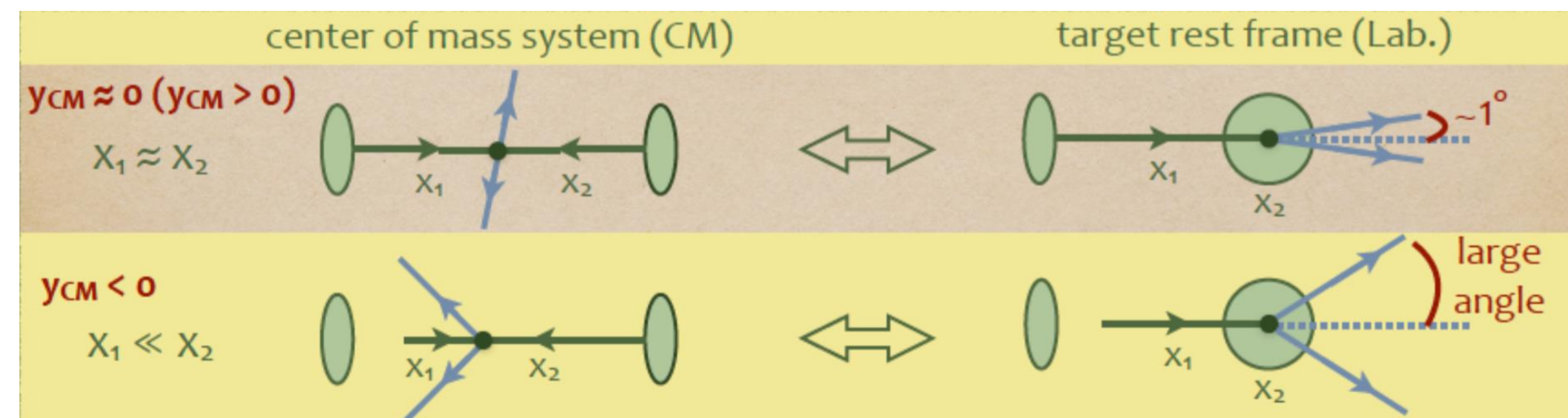


beam type	CM energy $\sqrt{s_{(NN)}}$	boost $\gamma = \sqrt{s}/2m$	y shift
proton (E = 7 TeV)	115 GeV	61	4.8
lead (E = 2.76 TeV)	72 GeV	38	4.2

→ most energetic fixed-target experiment: center-of-mass energy in-between SPS at CERN and nominal RHIC

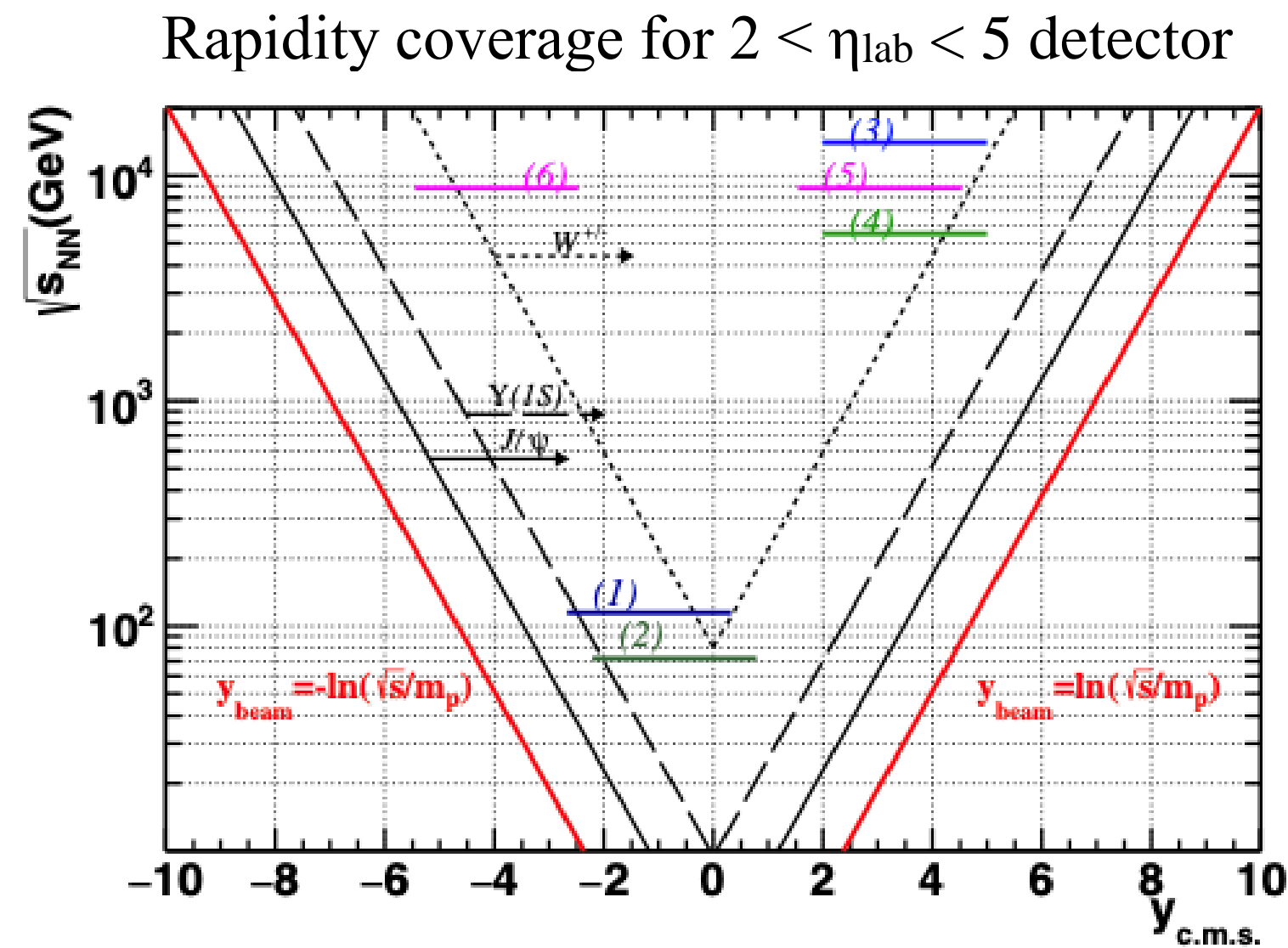
## Rapidity range

- Entire center-of-mass forward hemisphere ( $y_{CM} > 0$ ) within 1 degree
- Easy access to (very) large backward rapidity range ( $y_{CM} < 0$ ) and large parton momentum fraction in the target ( $x_2$ )



# Advantages of fixed target mode at LHC

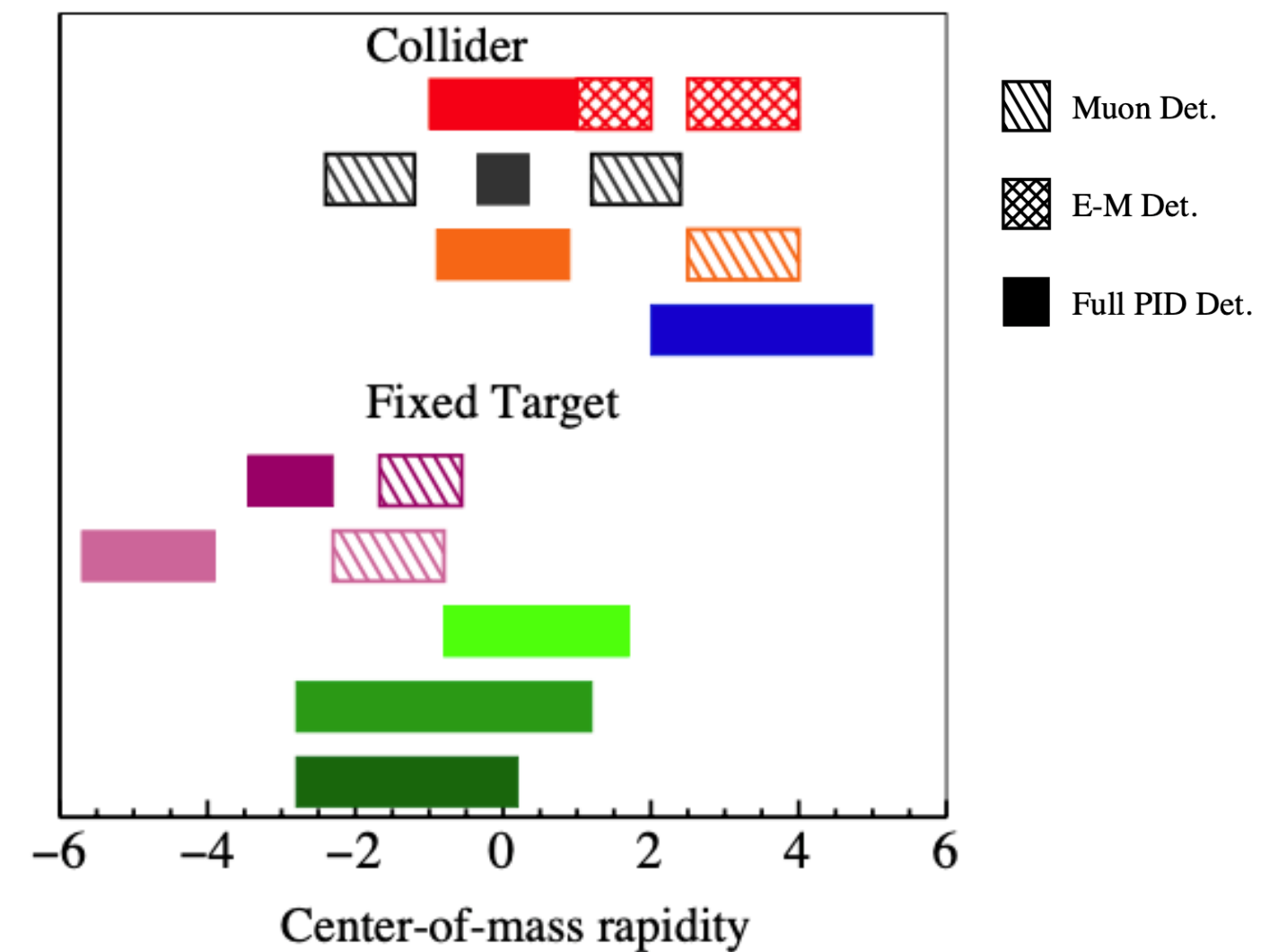
- Several advantages of fixed-target mode:
  - Accessing **high-x frontier** ( $y_{CM} < 0$  and parton momentum fraction  $x > 0.5$ )
  - Achieving **high luminosity**
  - Varying **atomic mass number** of the target
  - **Polarising** the target
- This can be realised at LHC in a parasitic mode!



- (4)  $\sqrt{s} = 5.02$  TeV collider mode
- (1)  $\sqrt{s} = 115$  GeV fixed target mode
- (2)  $\sqrt{s} = 72$  GeV fixed target mode

ALICE and LHCb in fixed target mode with proton beam

- STAR
- PHENIX
- ALICE
- LHCb
- ALICE  $z_{target} = -4.7$  m
- ALICE  $z_{target} = 0$
- LHCb  $z_{target} = -1.5$  m
- LHCb  $z_{target} = -0.4$  m
- LHCb  $z_{target} = 0$

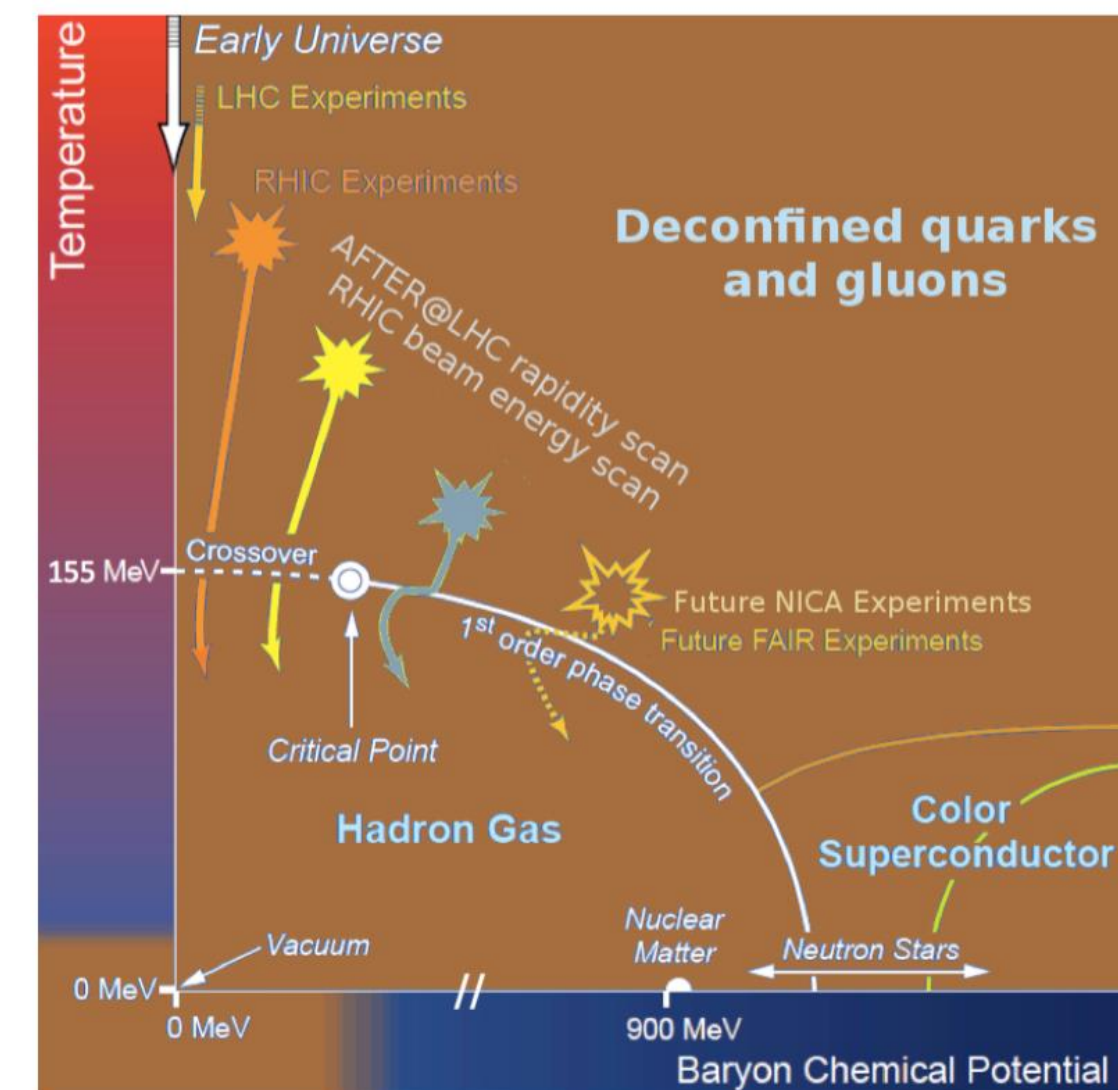
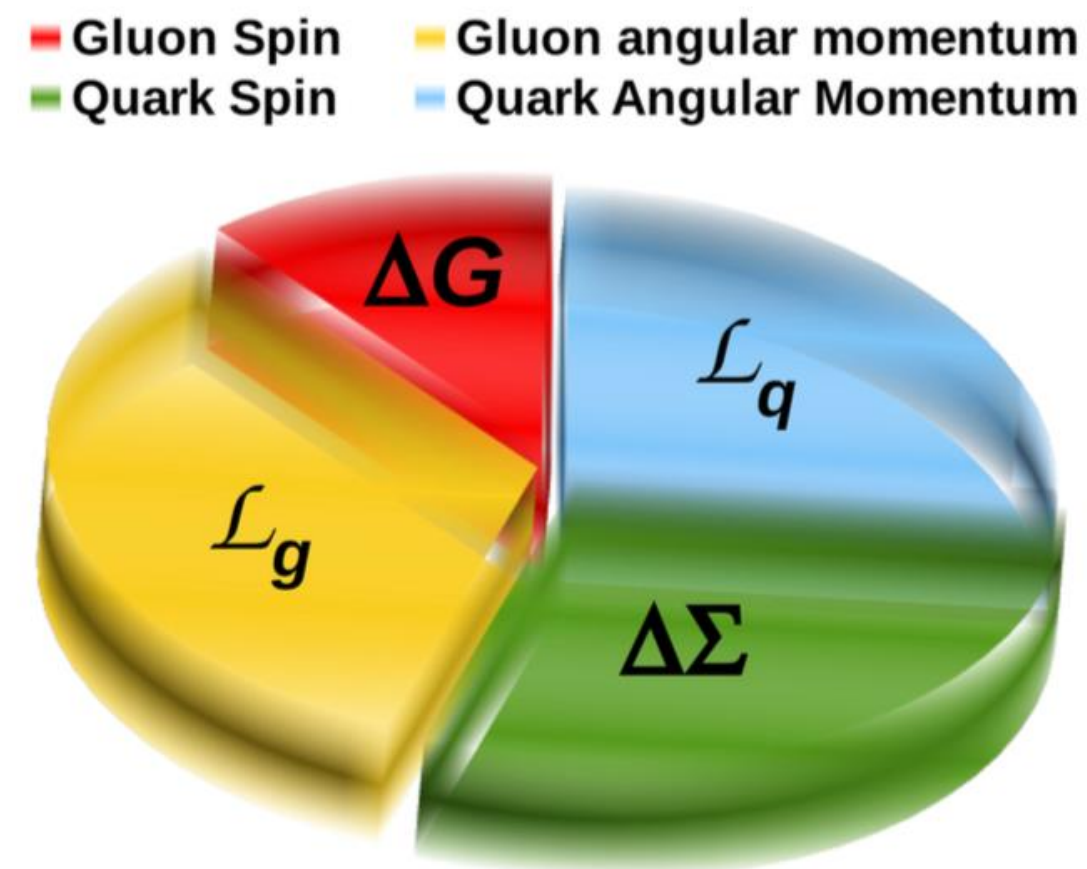
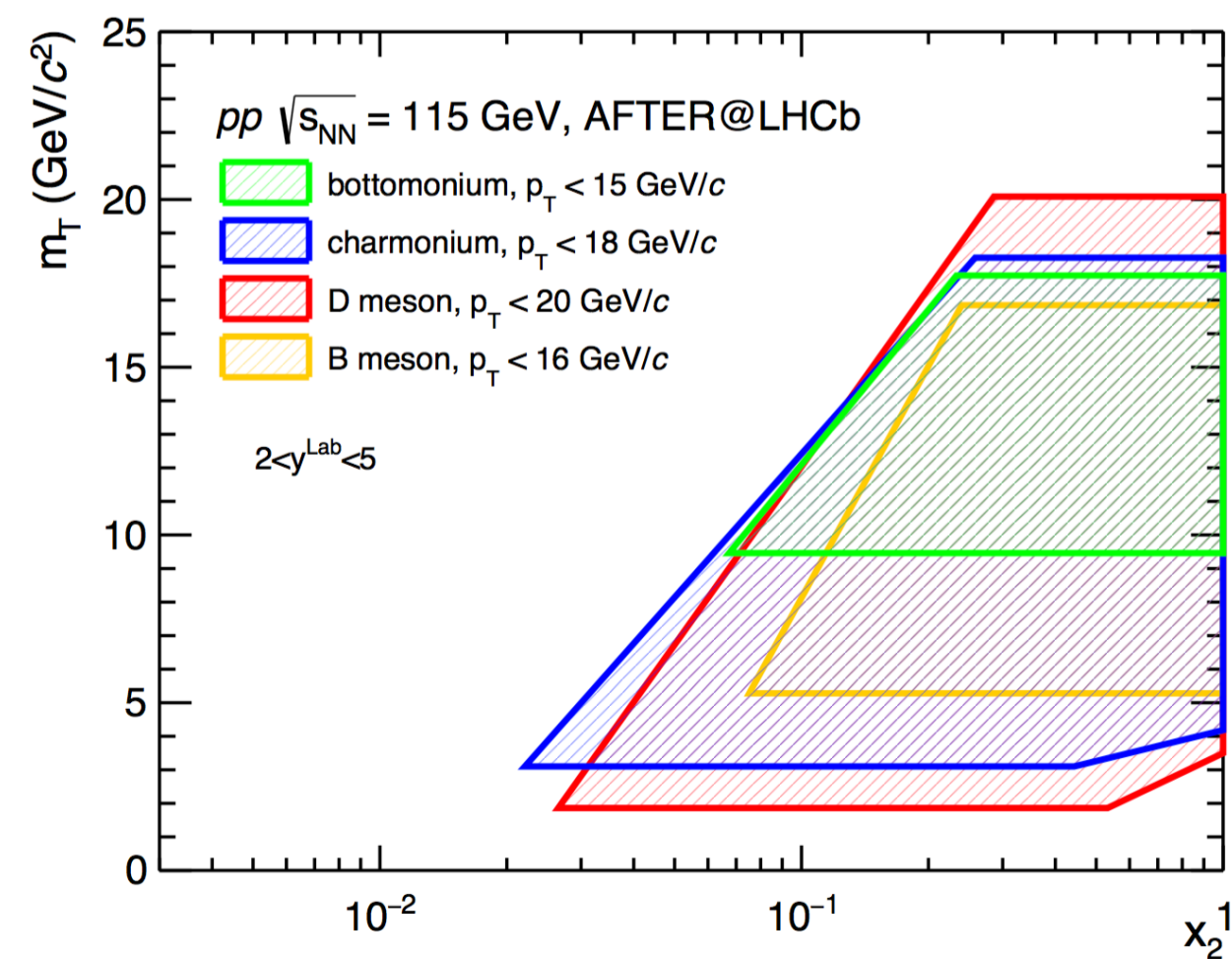


# Physics motivations

Physics programme with a fixed target mode at LHC:

- Advance our understanding of the **high- $x$  gluon, antiquark and heavy-quark content in the nucleon and nucleus and its connection to astroparticles**
- Unravel the **spin of the nucleon**: dynamics and spin distributions of quarks and gluons inside (un)polarised nucleons
- Study the **quark-gluon plasma** between SPS and RHIC energies over a broad rapidity domain

*C.H. et al. Phys.Rept.911(2021)1-83*

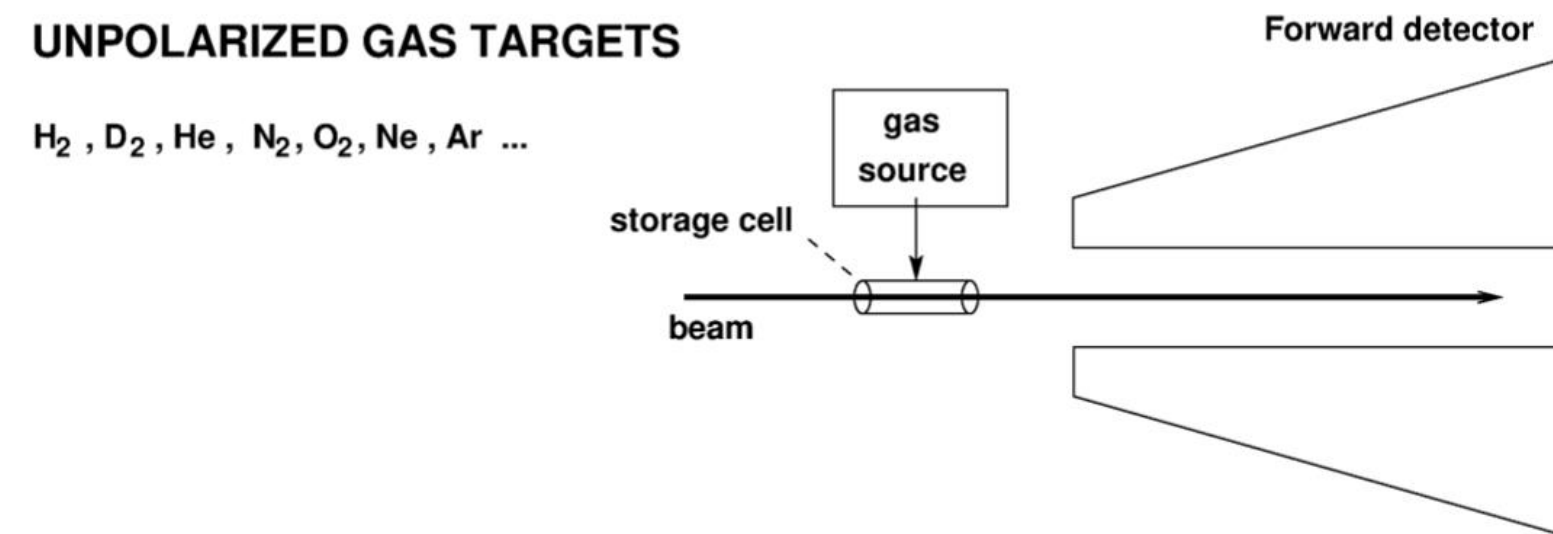


# Fixed target projects at LHC

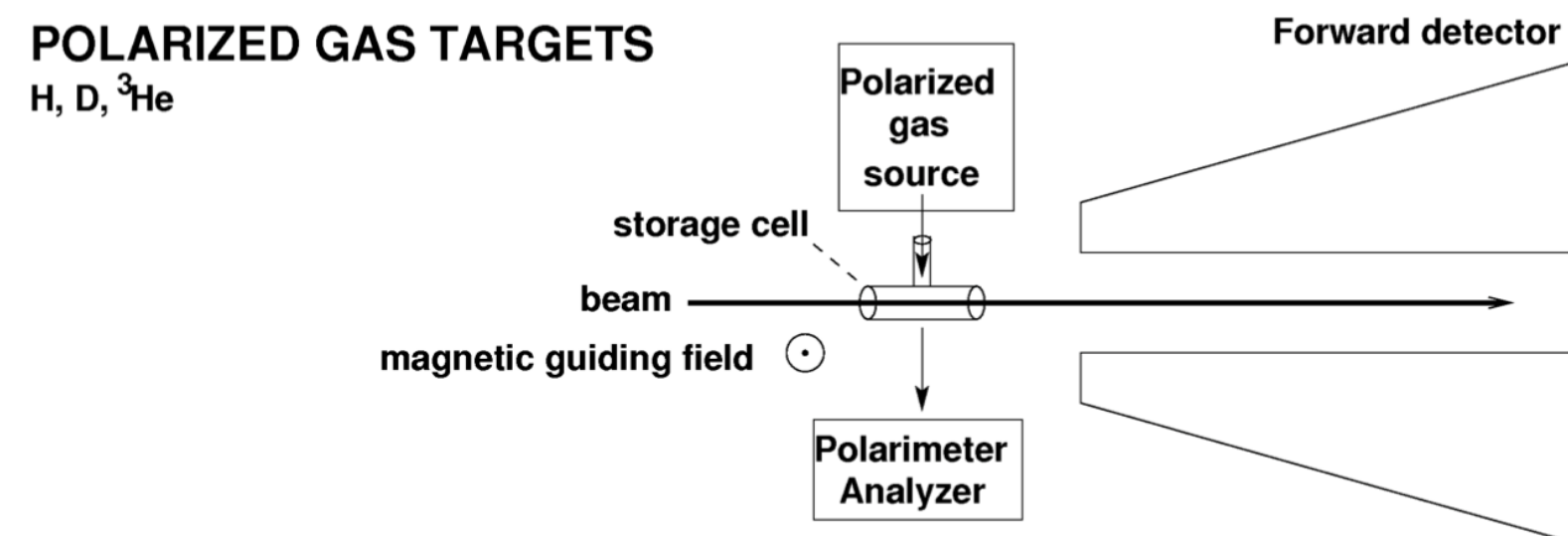
Physics Beyond Collider forum: [pbc.web.cern.ch](http://pbc.web.cern.ch)

*Cern Yellow Report, Vol. 4 (2020), DOI:10.23731/CYRM-2020-004*

## Gas targets

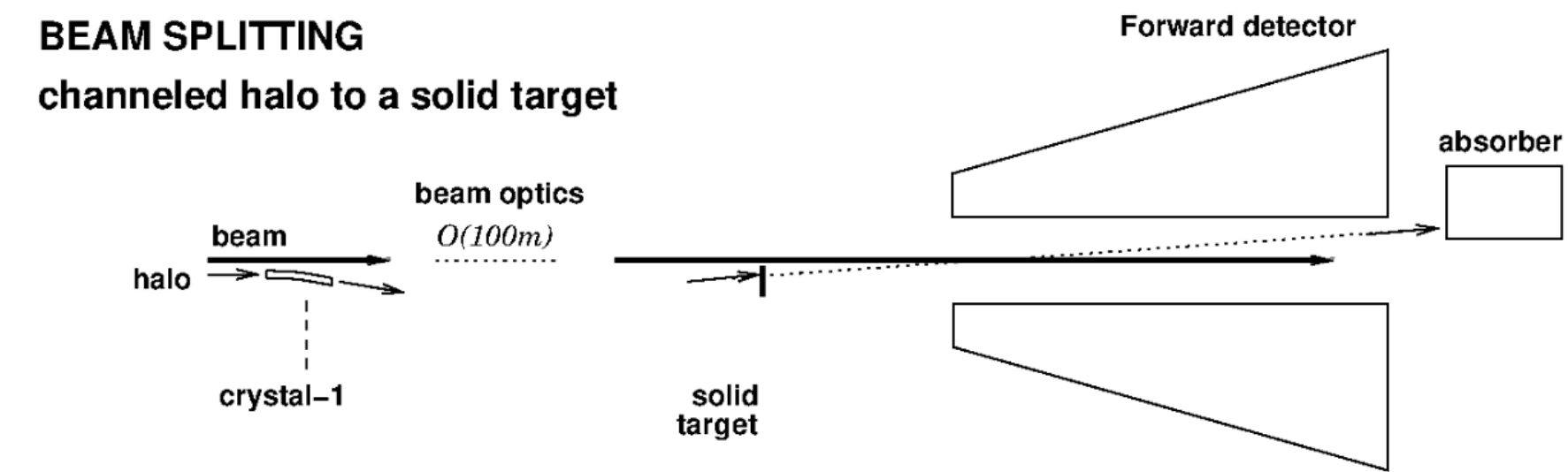


**SMOG2 - LHCb (Run 3)** *LHCb-TDR-020*

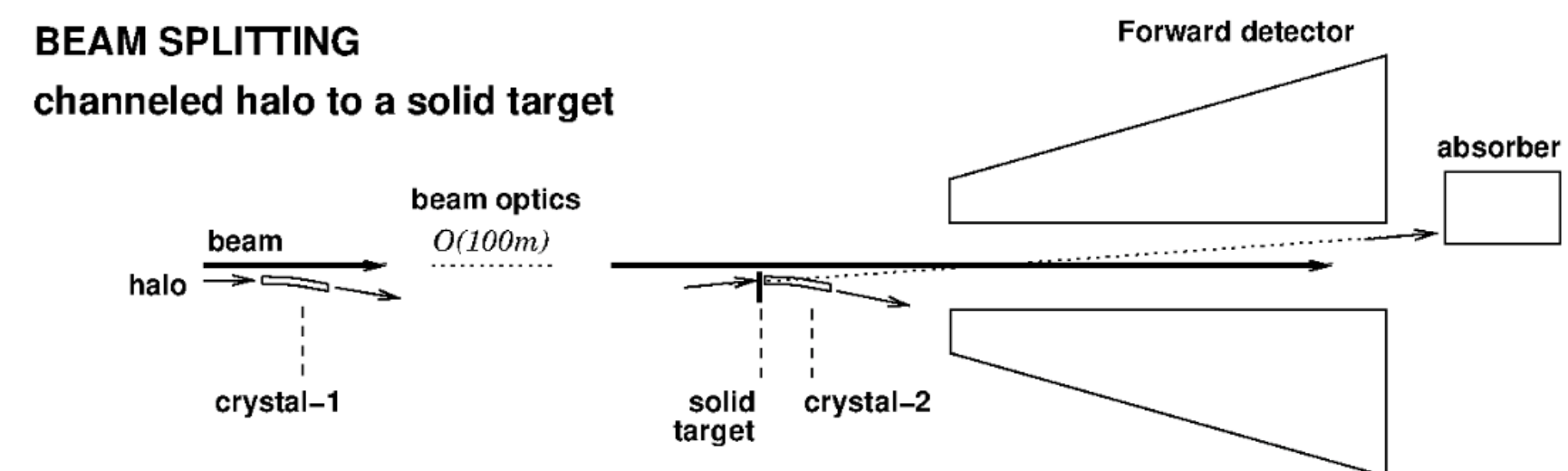


**LHCSpin - LHCb** *arXiv:1901.08002*  
**IR3 test setup**

## Solid targets



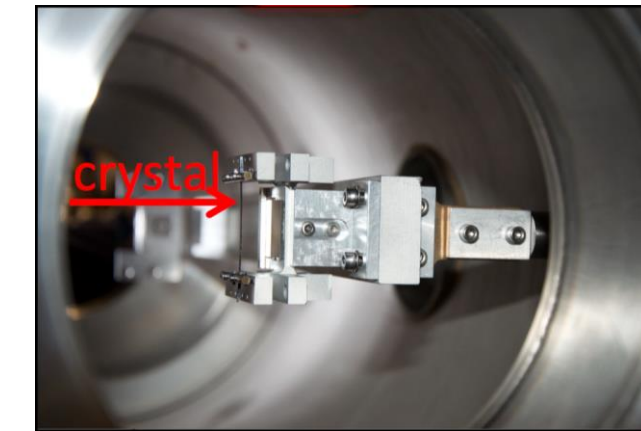
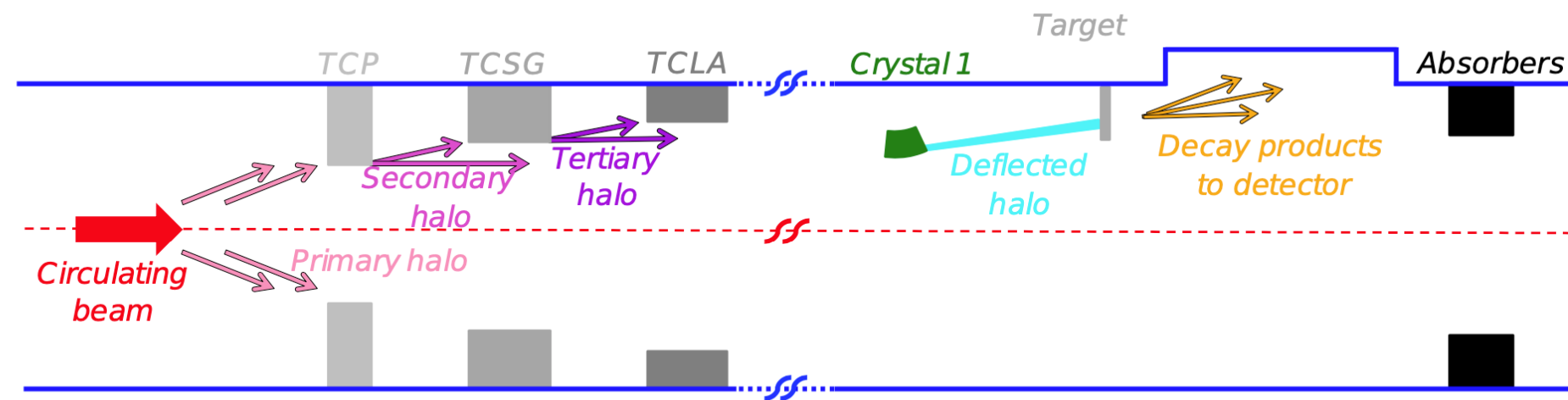
**ALICE-FT** *ESPP document*



**Double crystal channeling - LHCb and IR3 test setup**

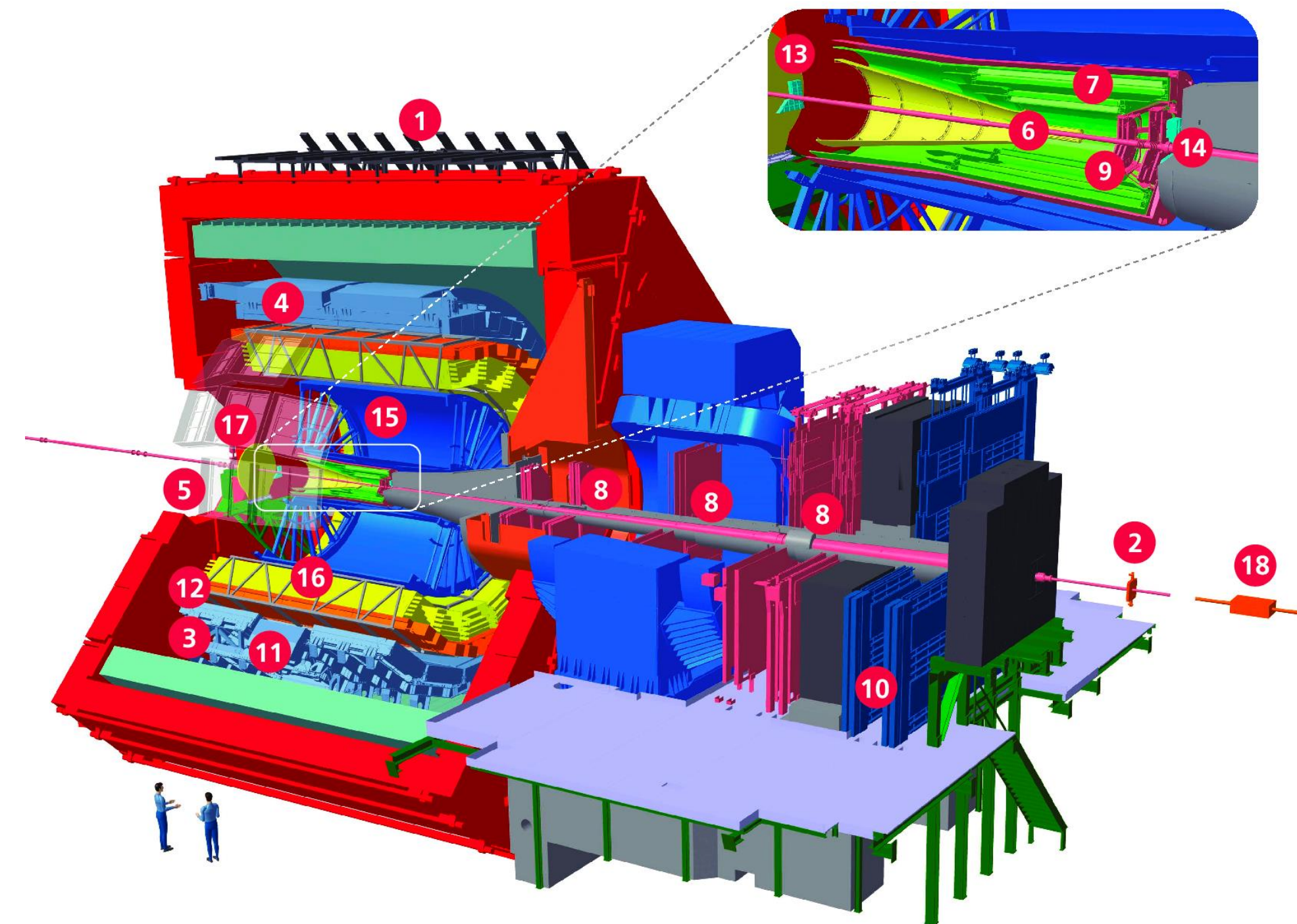
- *baryons channeled in a second crystal behind the target*
- *measure baryon magnetic/electric dipole moment*

# Fixed target project in ALICE



Graphics: D. Mirarchi

- Beam splitting thanks to a bent crystal, coupled to a solid target inside ALICE, followed by a system of absorbers
- Part of the secondary halo is intercepted by the crystal
- 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: provide a maximum flux of protons on target (PoT) to the experiment that can be handled by the DAQ system and keep new LHC loss spikes within acceptable limites (e.g. not larger than usual ones)

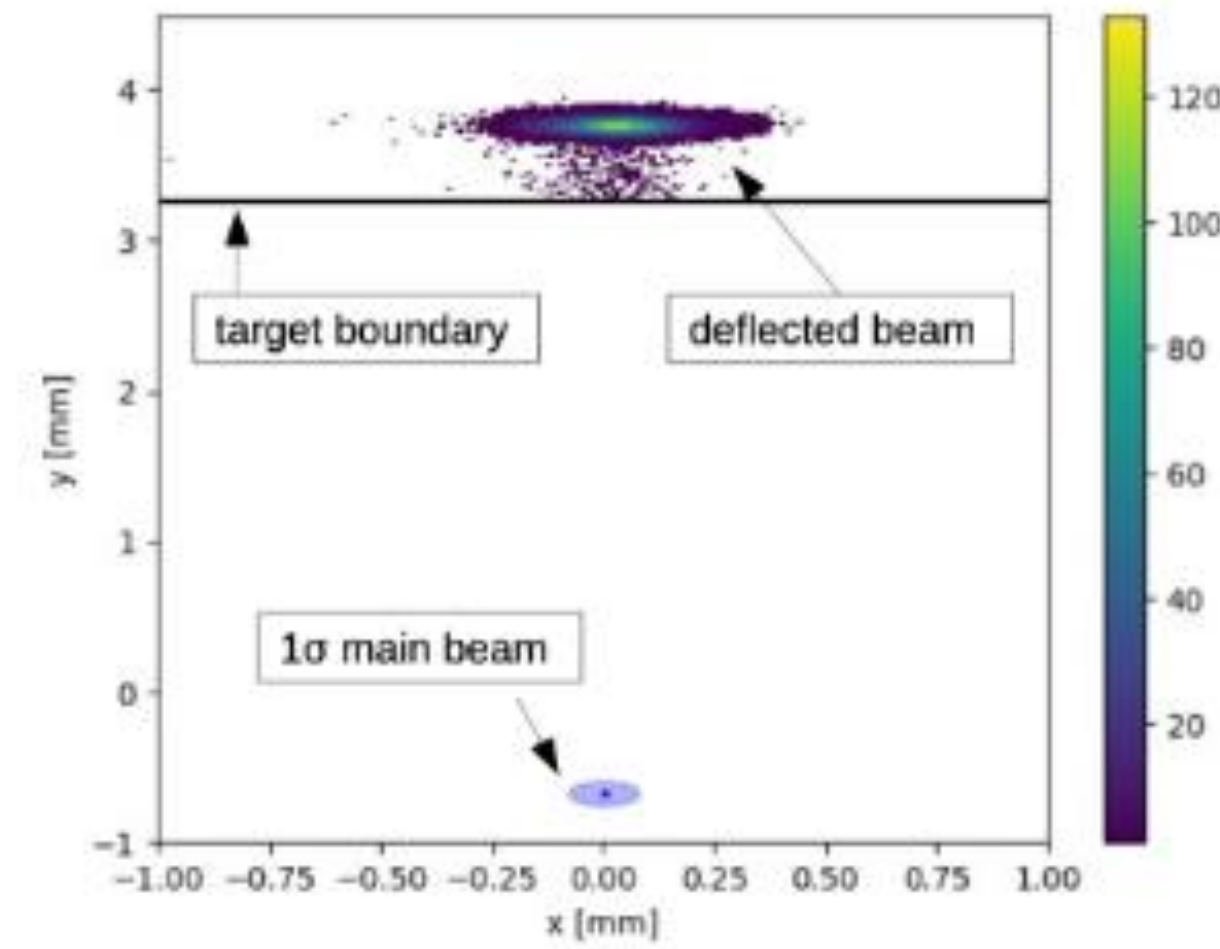


# Crystal layout for ALICE

## Crystal channeling:

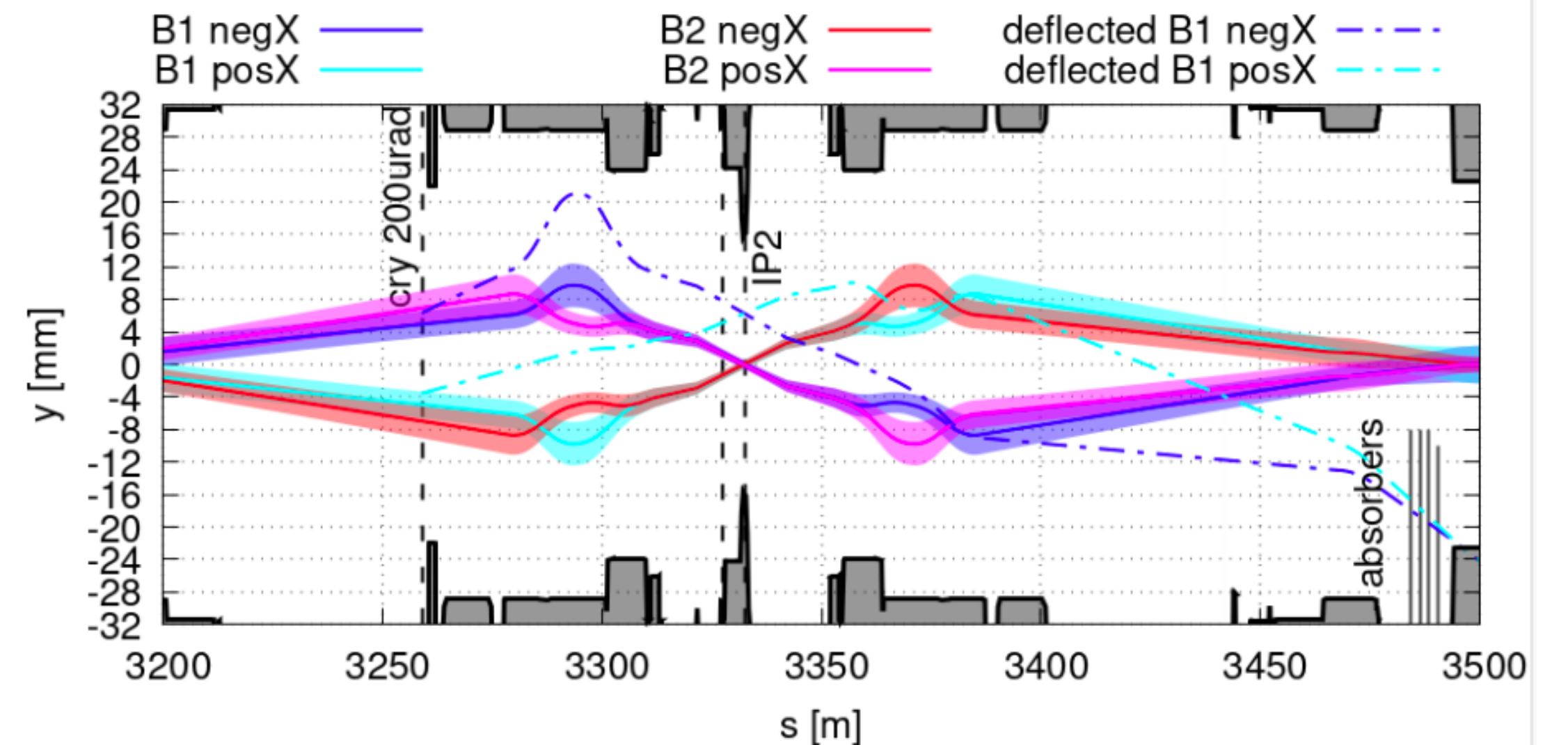
- Proton beam collimation and integration studies performed in collaboration with LHC collimation team
- Deflected halo in the vertical plane and nicely collimated
- Parasitic operation (with respect to all LHC experiments): fixed-target collisions can occur with stable beams in parallel to beam-beam collisions
- Optimization of the bent crystal setup: provide a maximum flux of protons on target (PoT) to the experiment and keep new LHC loss spikes within acceptable limits
- Expected PoT in Run 4:  $10^6$  p/s as a minimal limit in parasitic mode, equivalent to, for 1cm target length:
  - $L = 1.1/\text{pb}/\text{year}$  in pC
  - $L = 0.6/\text{pb}/\text{year}$  in pTi and pW
- Lead beam studies started
- Proof-of-principle setup in IR3 during Run 3 for double crystal with W target proposed by LHC collimation team ([EDMS link](#)): essential to validate the simulations

*M. Patecki, ICFA HB2021 proceedings*



*M. Patecki et al.*

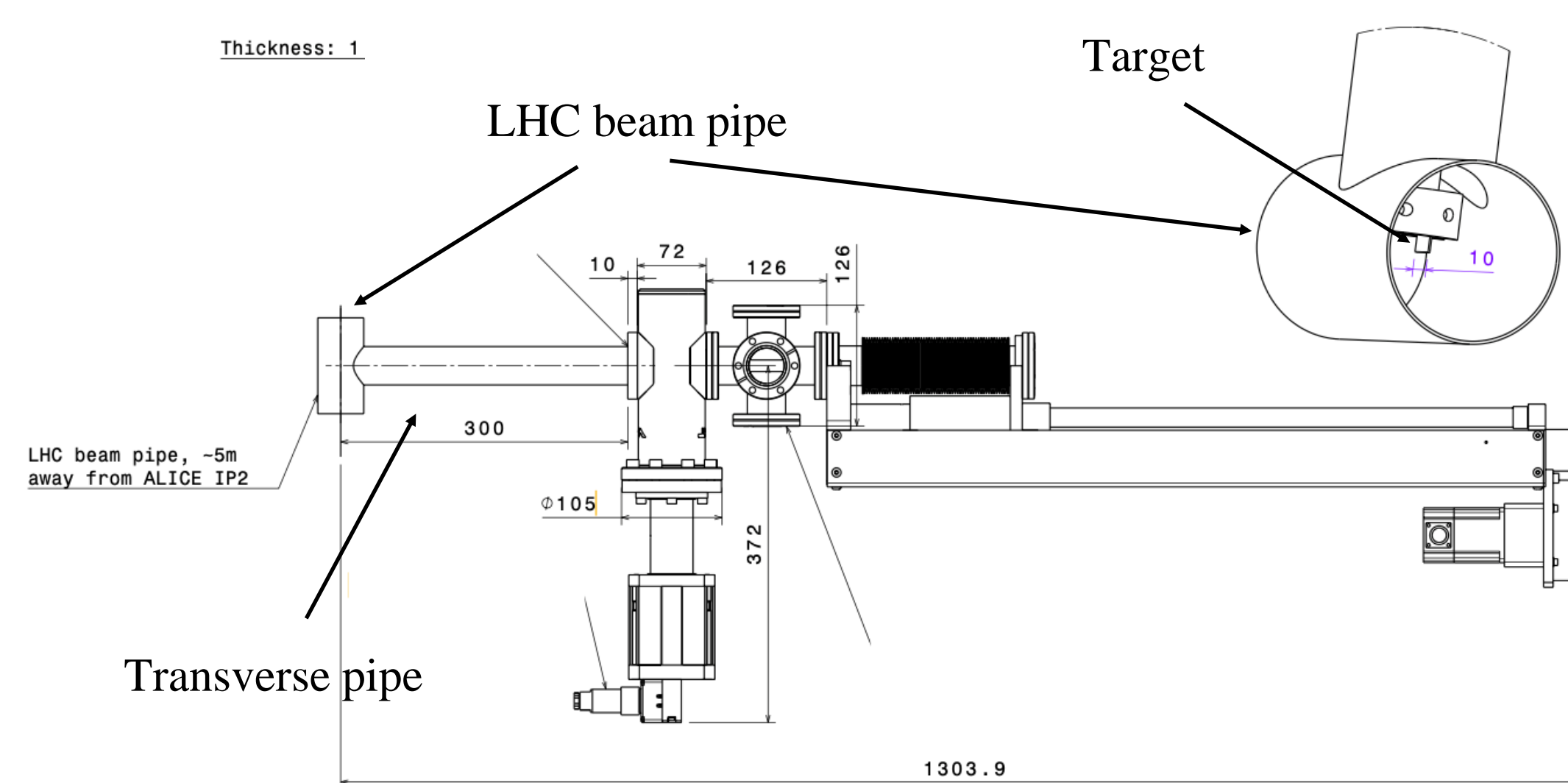
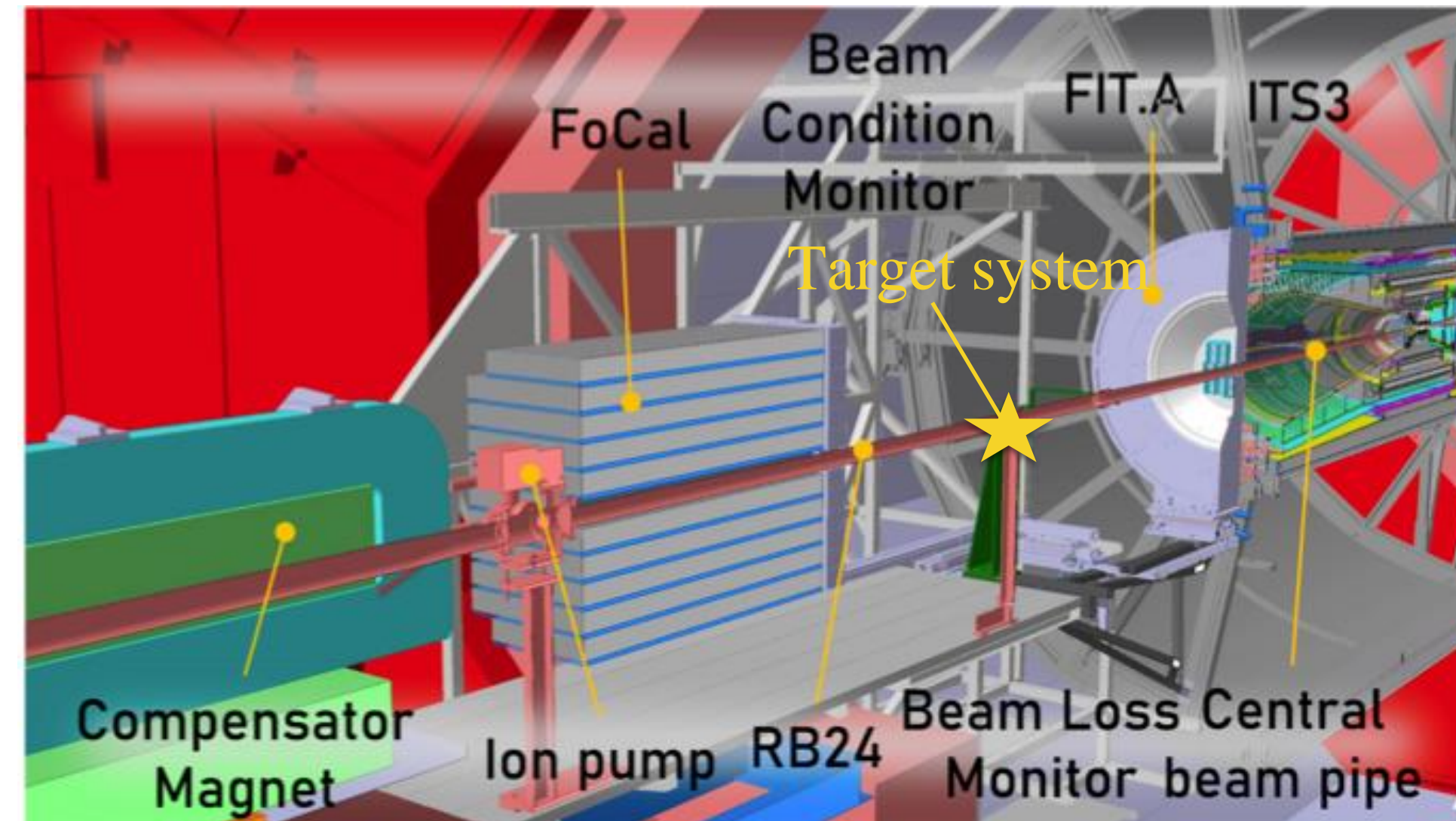
*Eur. Phys. J. C (2023) 83:1053*



# Target system integration and design

## ALICE-FT

- Integration and vacuum constraints:
  - $z \sim -4.8$  m from IP2
  - Target system in the horizontal plane
  - FoCal detector behind the target system
  - Beam pipe vacuum  $\sim 10^{-10}$ - $10^{-11}$  mbar
- Target design developed at IJCLab
  - Step motor for a retractable target with linear motion
  - Transverse beam pipe of  $\sim 30$  cm to stay outside of FoCal acceptance



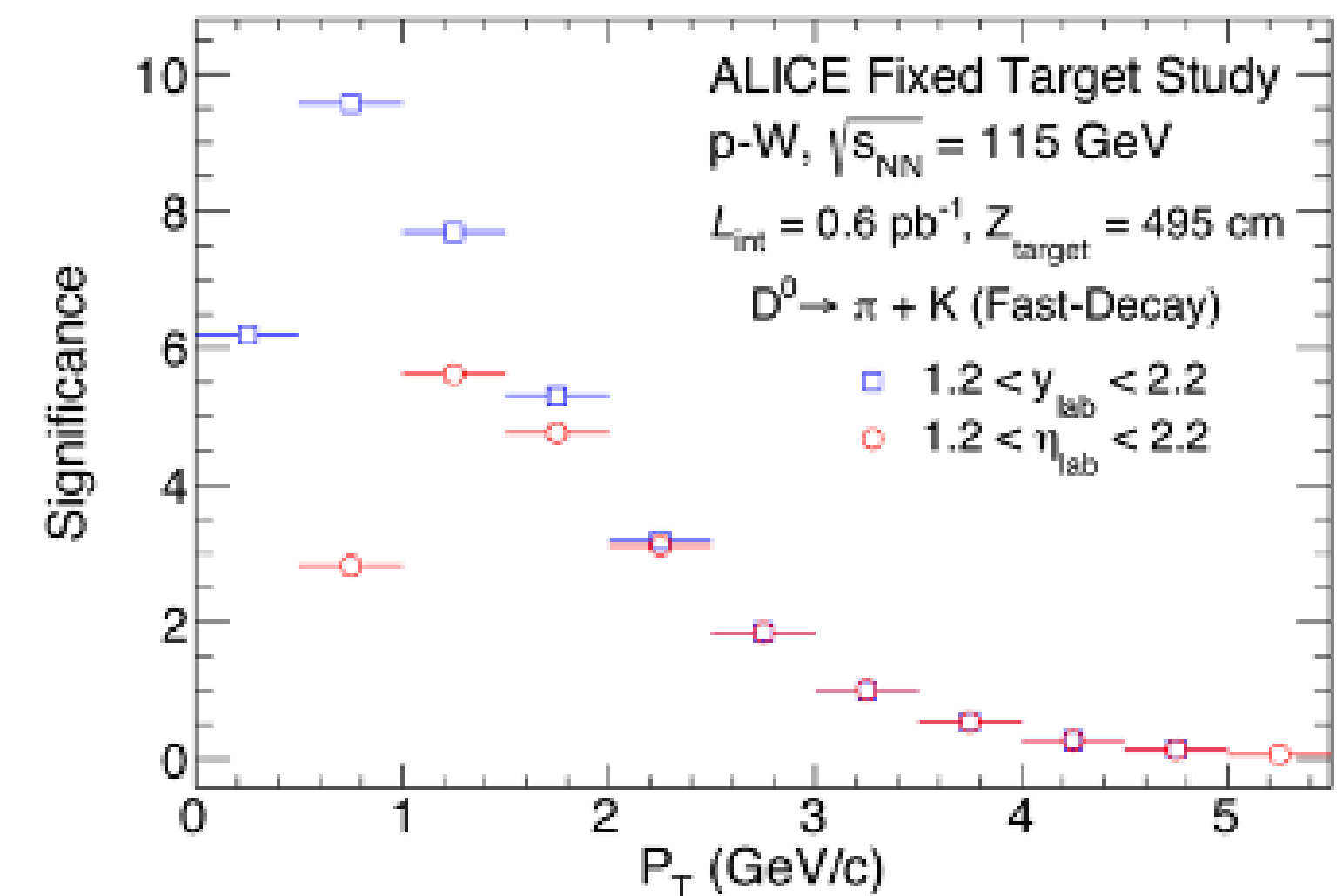
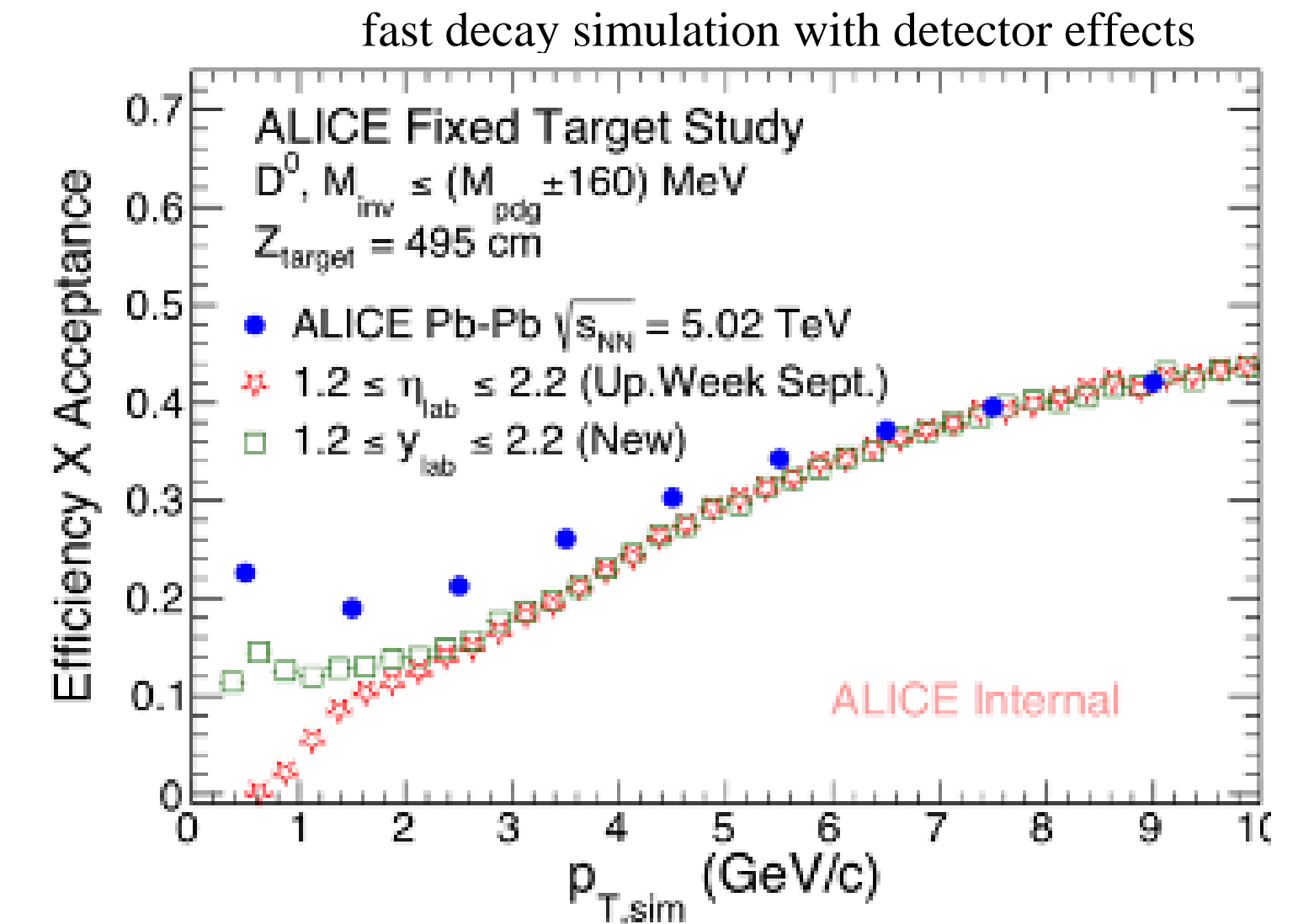
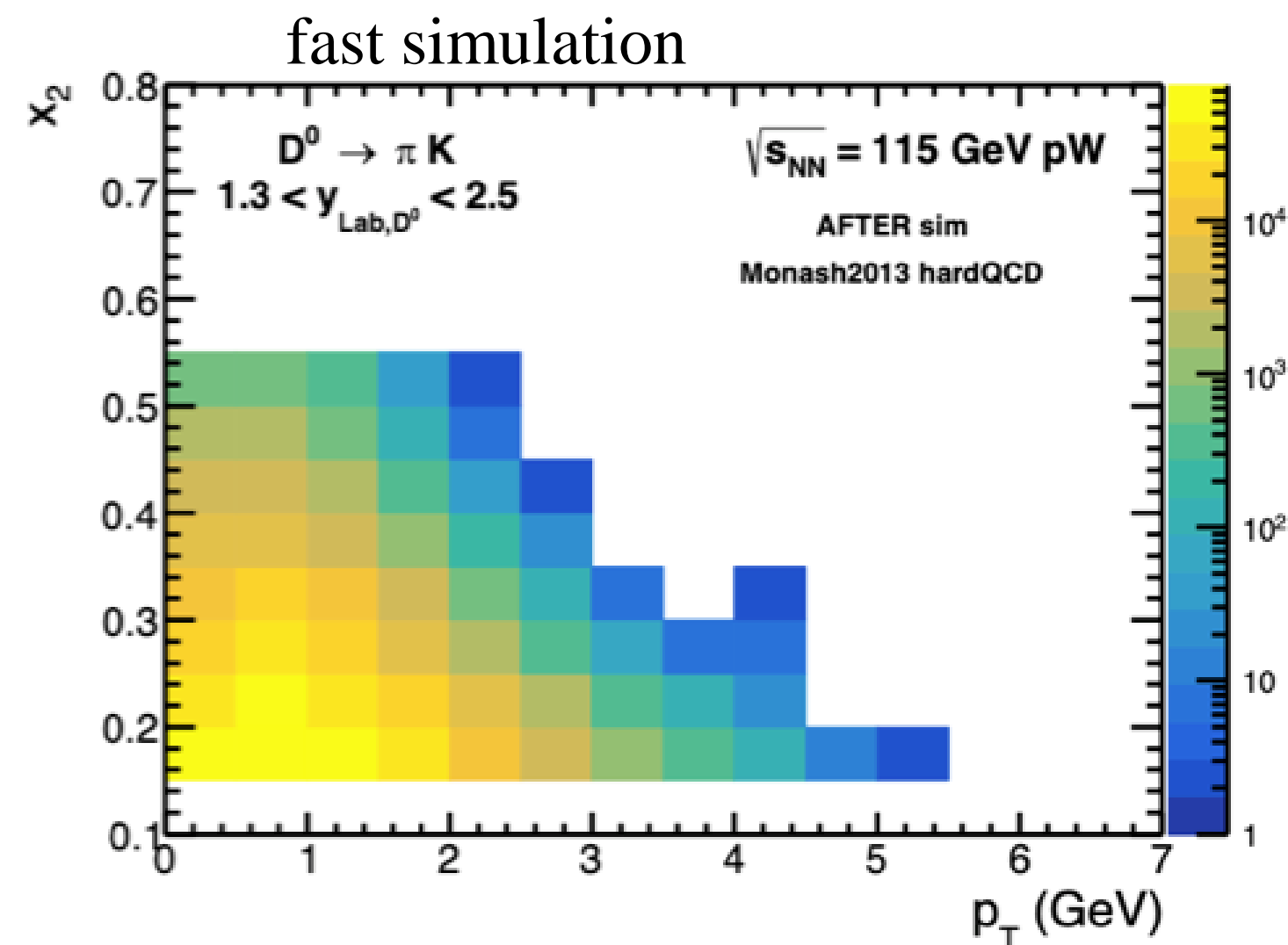


# ALICE-FT performance studies

ALICE-FT physics motivations [ESPP document](#)

## Open charm production

- Tracking and vertexing with ALICE TPC
- Fast decay simulations in p+W at  $\sqrt{s_{NN}} = 115$  GeV
- $D^0$  as a probe for gluon/intrinsic charm content of nucleon/nuclei at large  $x_B$  (selection on  $K+\pi$  invariant mass)
- Good acceptance x efficiency and significance of 10 at low  $p_T$  that can be improved with event mixing
- Measurement of charm cross section feasible w/o additional vertex detector

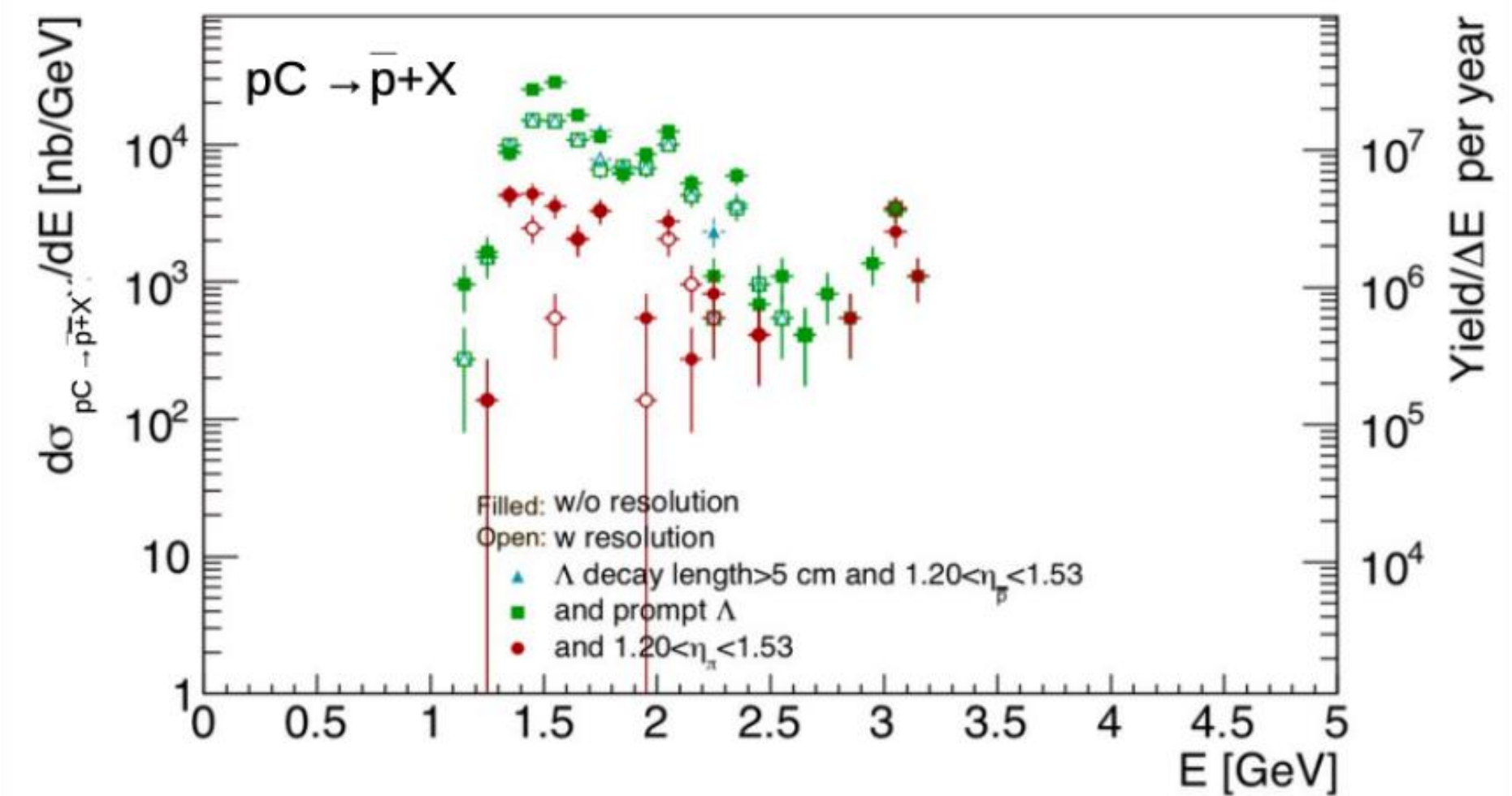
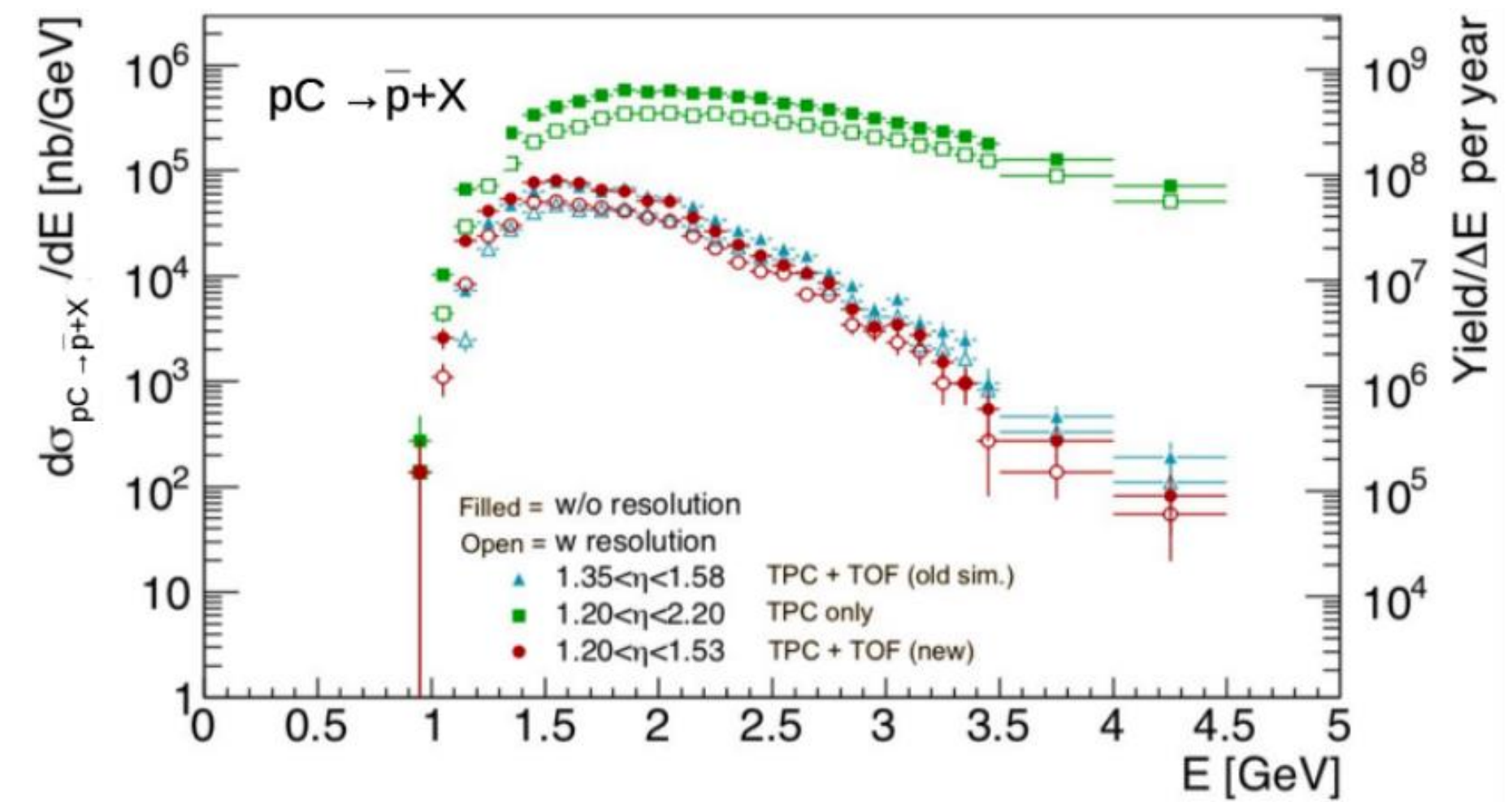


# ALICE-FT performance studies

## Antiparticules

- Antiproton important input for theoretical calculations of secondary cosmic antiproton spectrum:
  - p+C (target)  $\rightarrow$  antiproton of low E: inverse kinematic process of high energetic C+H (target)  $\rightarrow$  antiproton of large E
- Large yield expected in the TPC and TOF
- Antiproton feed-down could be as well measured by measuring anti- $\Lambda$  (Anti- $\Lambda \rightarrow$  antiproton +  $\pi$ )

fast simulation with detector effects, no PID simulated



# but...

## ALICE Management Board decision (early 2023)

*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.***

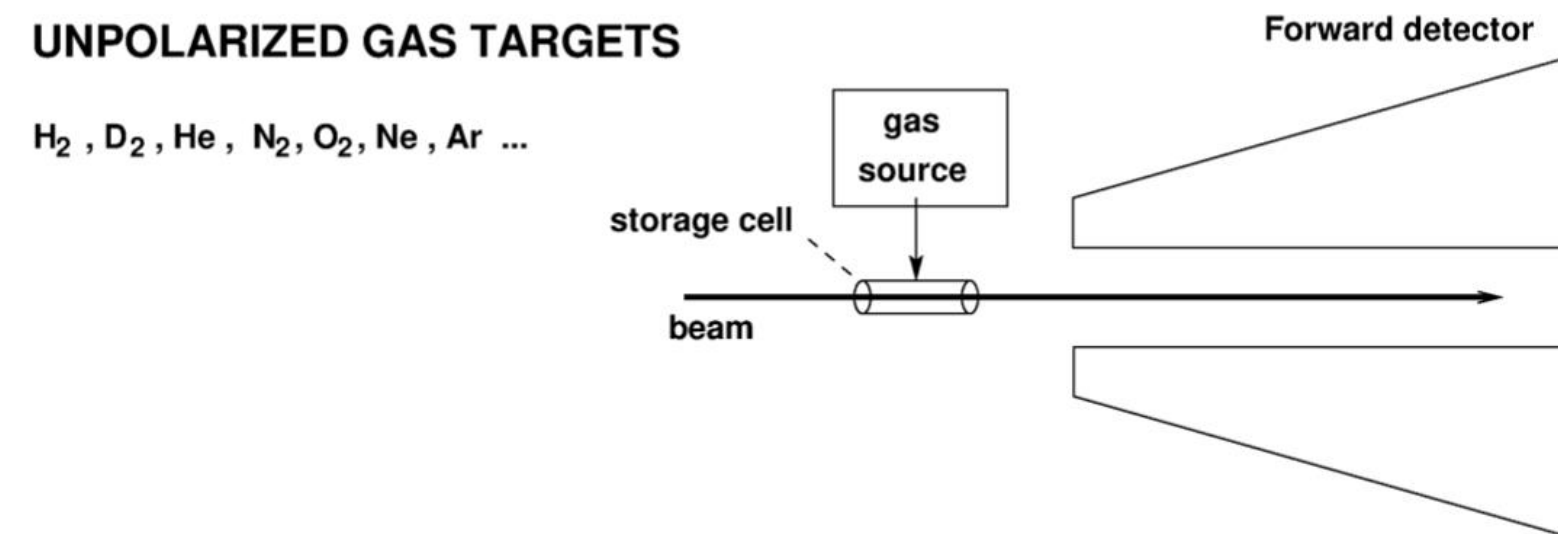
**End of the ALICE-FT project**

# Reminder: fixed target projects at LHC

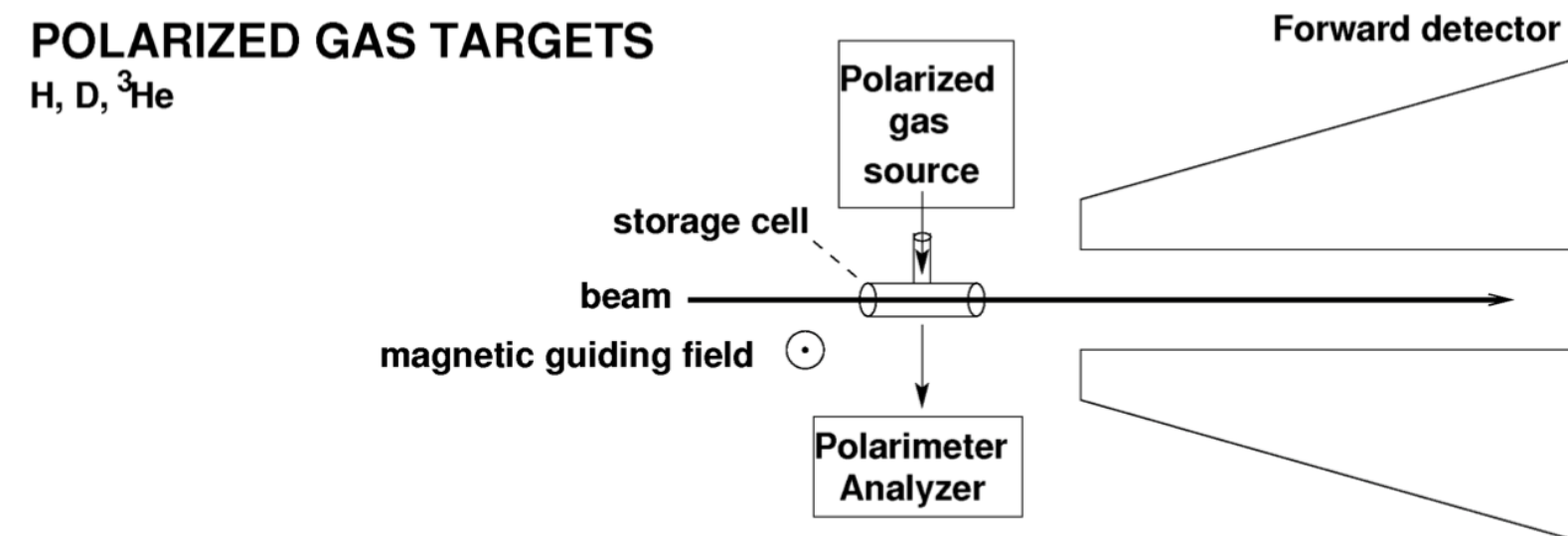
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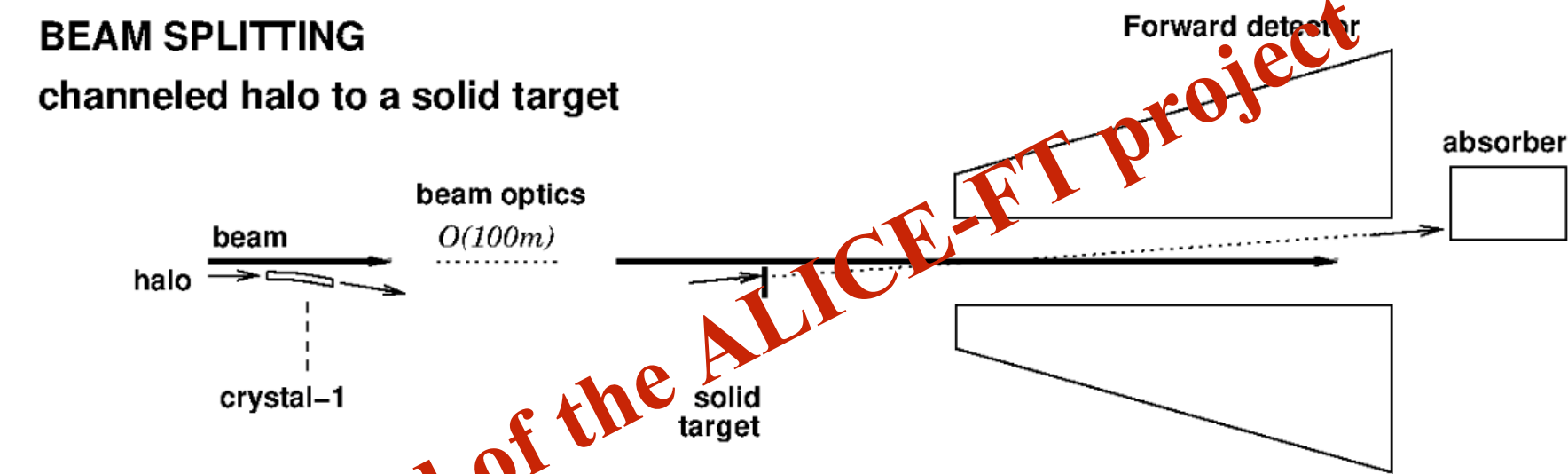


**SMOG2 - LHCb (Run 3)** *LHCb-TDR-020*

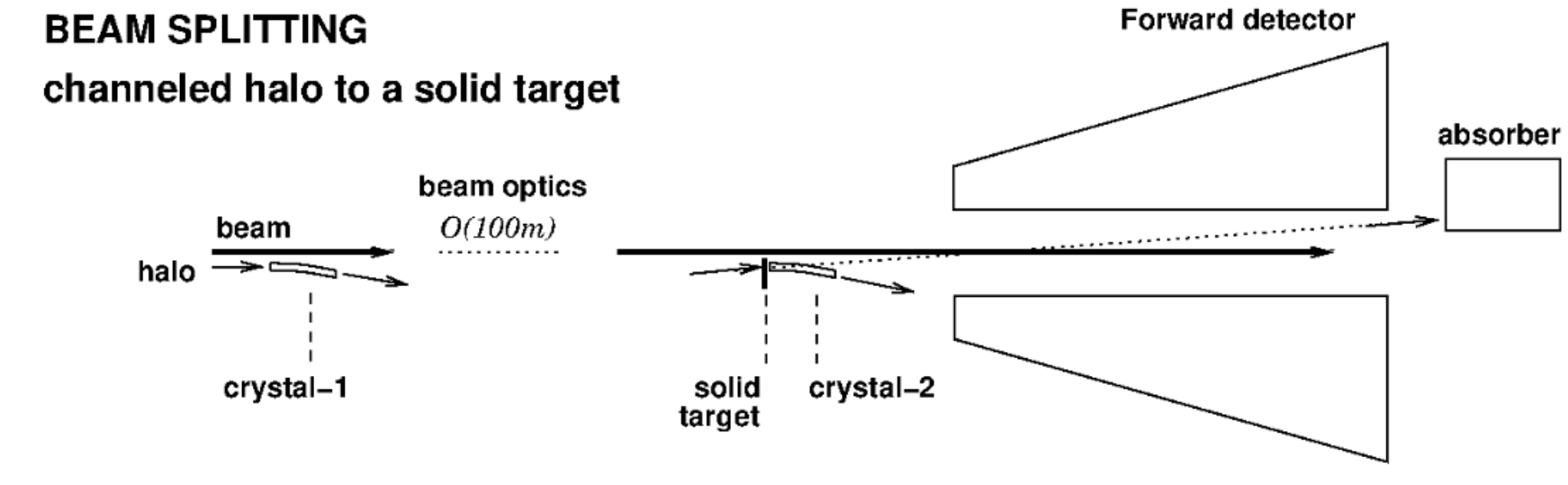


**LHCSpin - LHCb** *arXiv:1901.08002*

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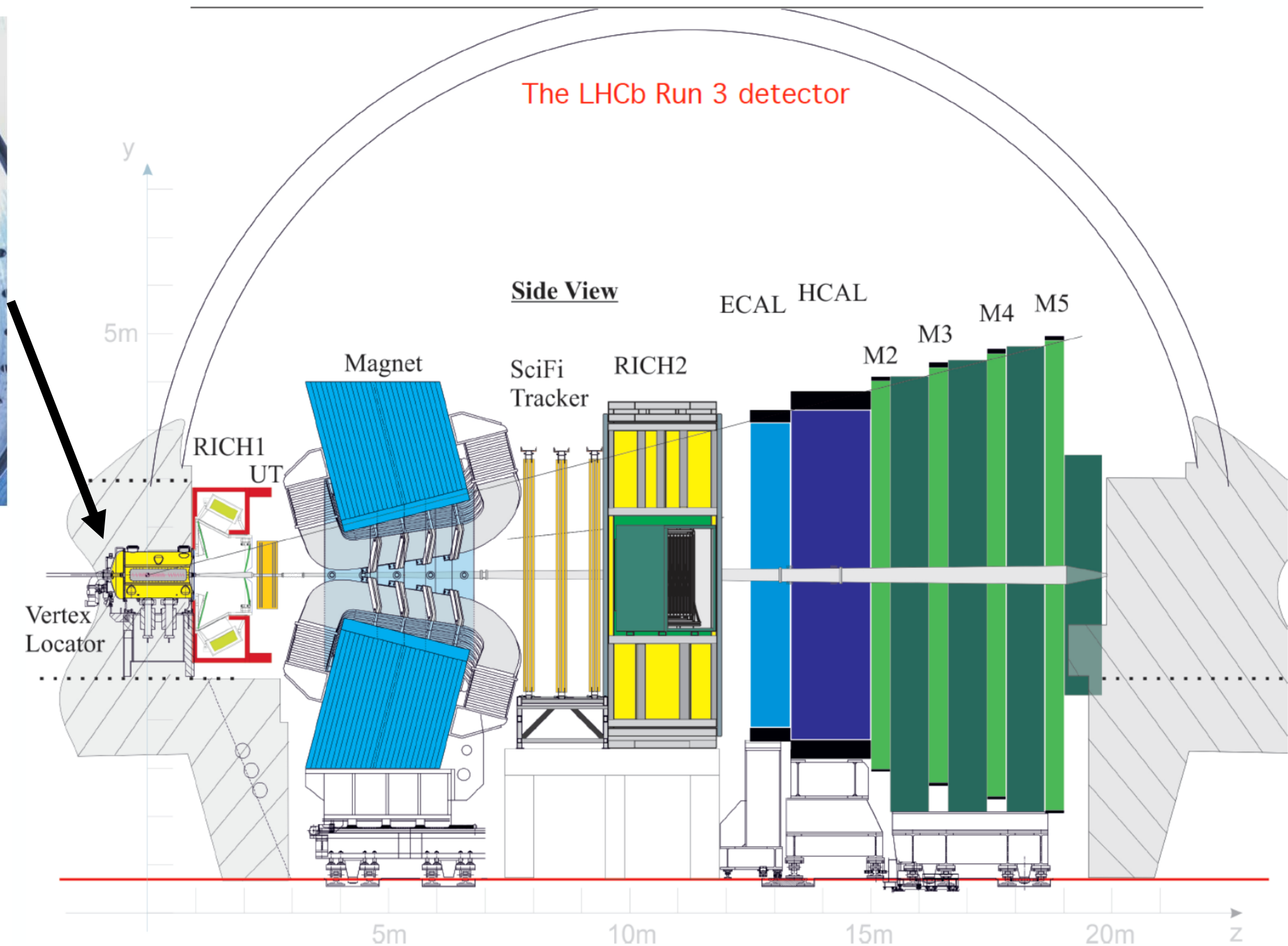
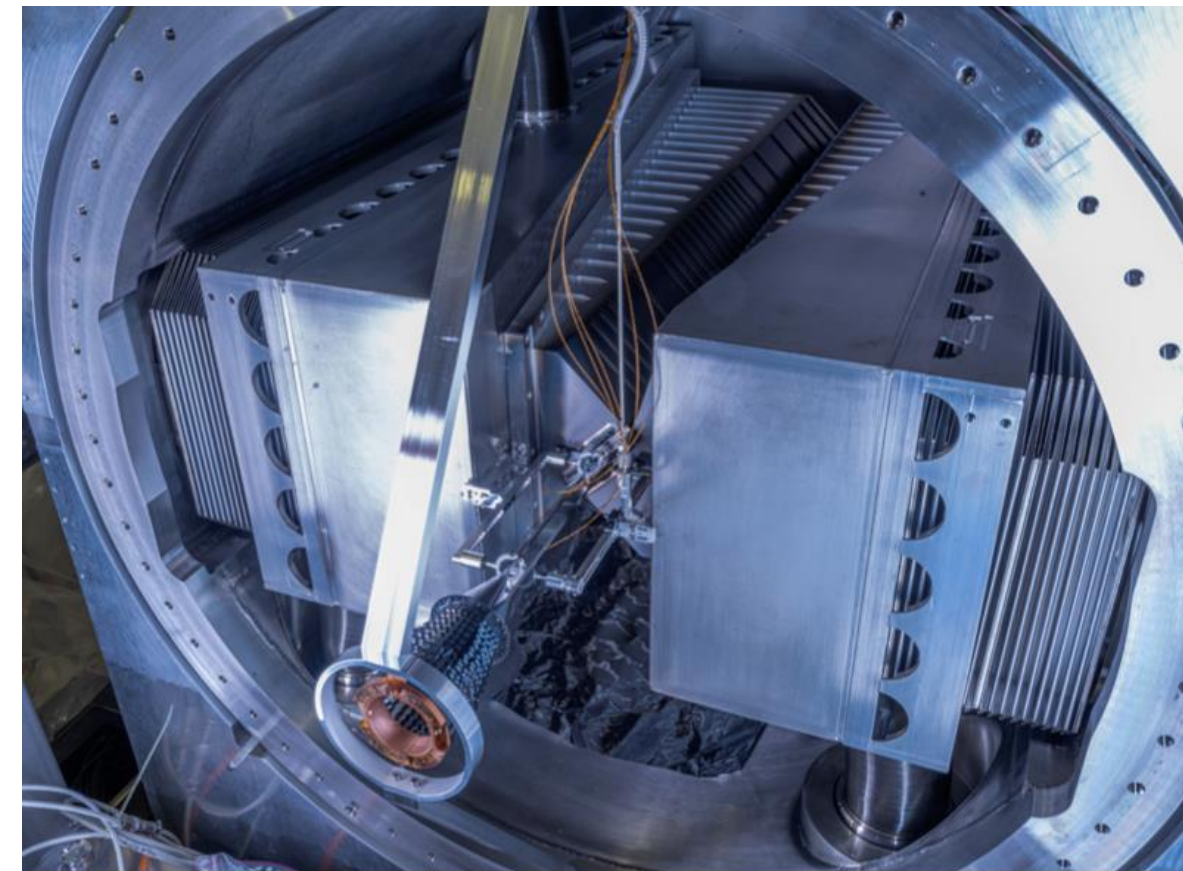
**End of the ALICE-FT project**  
[ALICE-FT ESPP document](#)



**Double crystal channeling - LHCb and IR3 test setup**

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# SMOG2 at LHCb



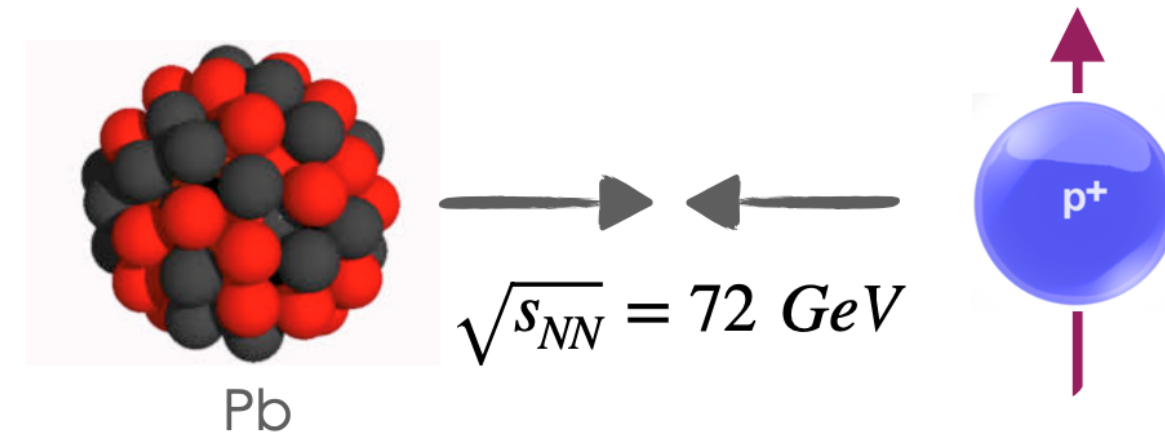
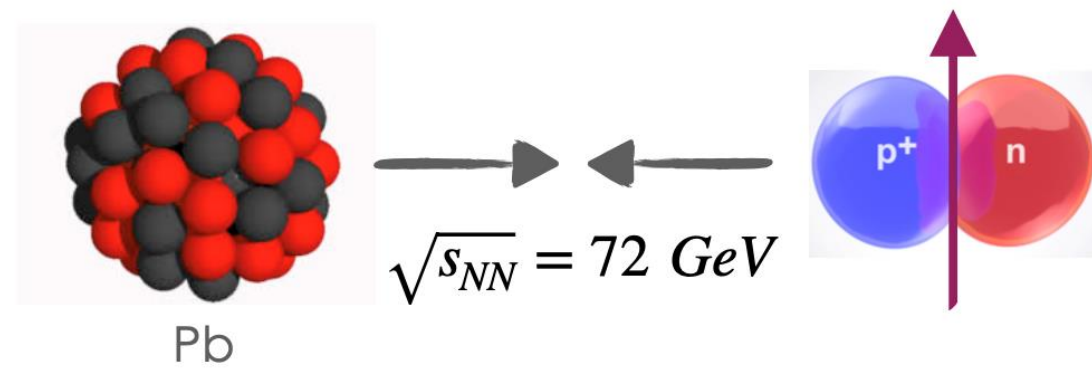
## SMOG2:

- Openable storage cell of 20 cm long attached to the LHCb VELO (vertex detector)
- SMOG2 installed in LHC Long Shutdown 2 for Run 3
- Gas wishlist:
  - $H_2$ ,  $D_2$ , He,  $N_2$ ,  $O_2$ , Ne, Ar, Kr, Xe (studies for non noble gas and heavy gas,  $H_2$  already injected in 2022)

## Phenomenology studies within the project #22-153:

- open charm production and  $DD\bar{b}$  asymmetry with proton beam and various gas targets. Use of reweighting method (A. Safranov) to estimate the impact of the proposed measurements on nuclear Parton Distribution Functions (nPDFs)

# LHCSpin in IR3 and LHCb

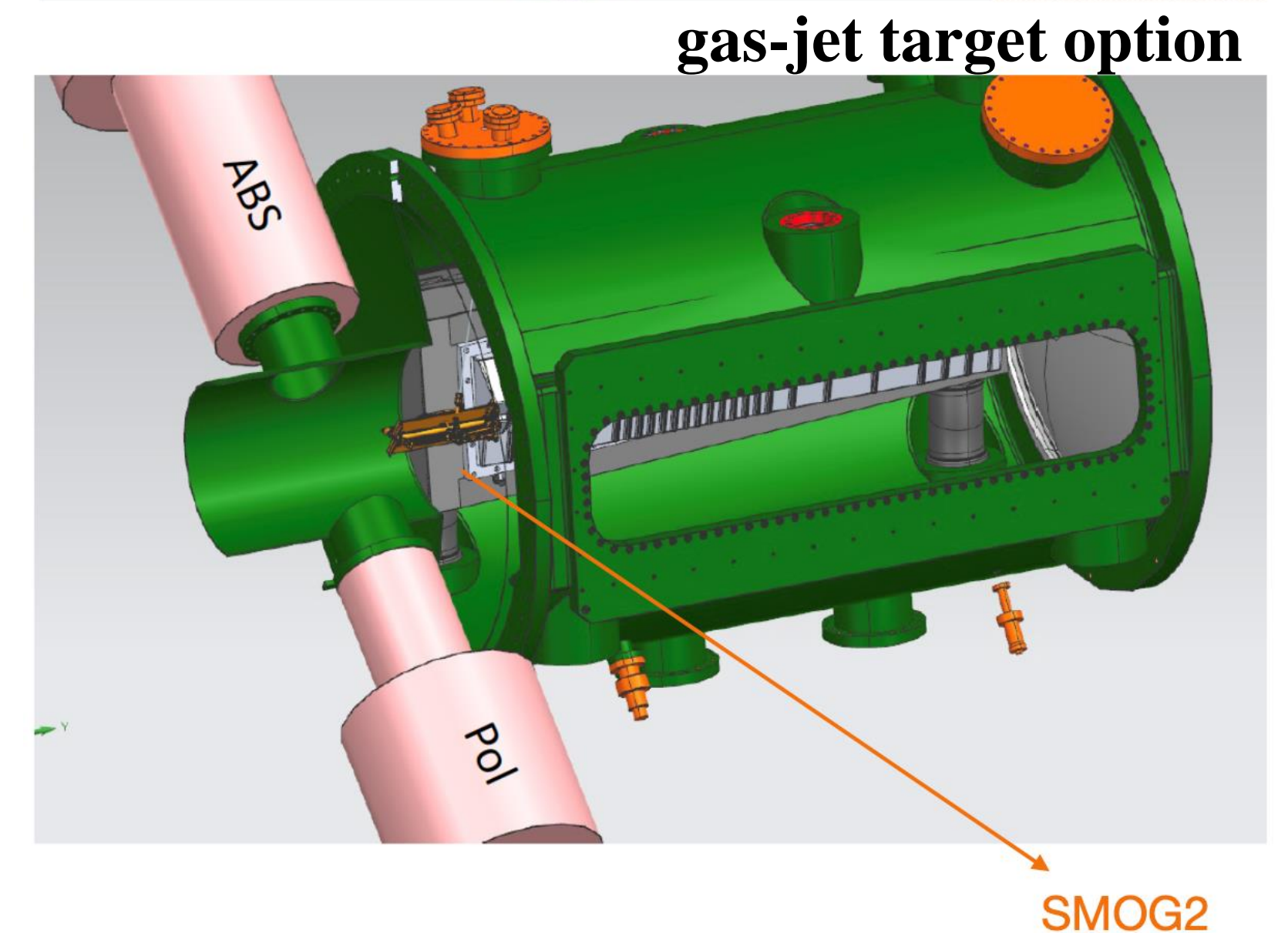
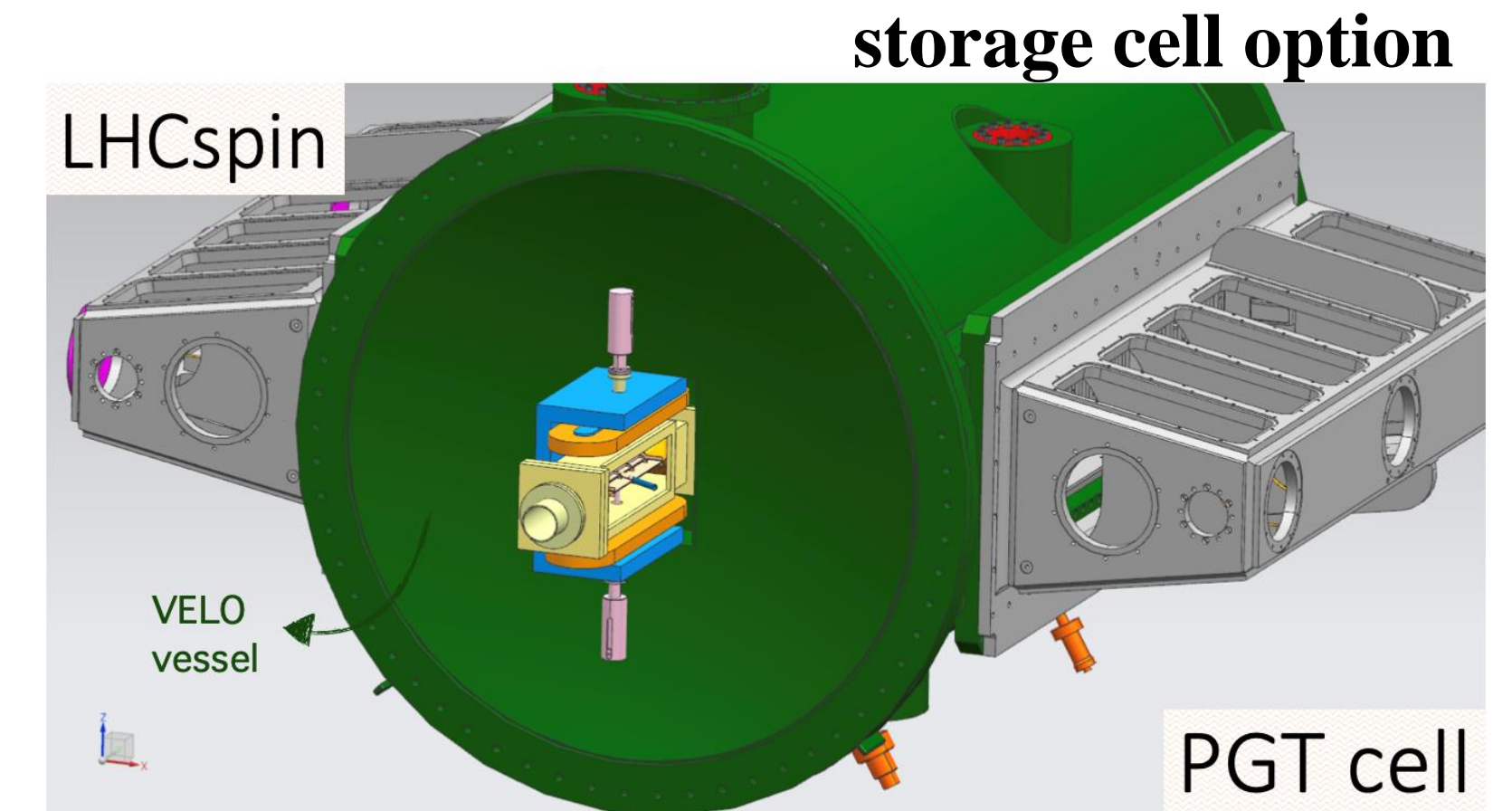


## LHCSpin:

- Storage cell with (un)polarised gas
- Target cell: transversally or longitudinally polarised targets:  $H^\uparrow$ ,  $D^\uparrow$
- R&D on target cell coating ongoing (recombination mechanism high for SMOG2 amorphous carbon coating)
- Gas-jet target option considered: lower density but higher gas polarisation (up to 90%) and low systematics on polarisation measurement
- Tests foreseen at IR3 during Run 3
- Aim at LHC Run 4 and beyond

## Phenomenology studies within the project #22-153:

- ultra-peripheral collisions with polarised deuteron target to probe the spin structure of the nucleon



# Project #22-153 « Fixed target at LHC and ALICE fixed target system » in IN2P3-COPIN

## 2023

- Visit of A. Kusina and A. Colpani Serri
- [FTE@LHC STRONG-2020 workshop](#) at Aussois in 2023 (D. Kikola, C. Van Hulse, K. Pressard, C. Hadjidakis, J.P. Lansberg, L. Massacrier, K. Lynch, M.R. Haque, M. Patecki, A. Safranov, A. Colpani Serri)
- Participation to workshop and conferences:
  - [Quarkonium as Tools 2023](#) (C. Van Hulse, A. Shatat, C. Flore, M. Nefedov, J.P. Lansberg, C. Hadjidakis, L. Massacrier, D. Kikola, A. Colpani Serri, ...)
- Publications:
  - M. Patecki et al., "HL-LHC layout for fixed-target experiments in ALICE based on crystal-assisted beam halo splitting", Eur. Phys. J. C (2023) 83:1053
- Internal document:
  - ALICE internal document, "Summary of key points for the ALICE fixed target project", FT-ALICE group, December 2022
  - ALICE internal note, "Performance of the Time Projection Chamber of ALICE for fixed target collisions", M.R. Haque et al., March 2023

## 2024

- Quarkonia as Tools workshop in Aussois January 2024: D. Kikola, J.P. Lansberg, A. Safranov, L. Manna, D. Mallick
- Contributions to the physics programme also involve J. Wagner, A. Kusina and L. Szymanowski in Poland, and I. Schienbien, J.P. Lansberg, M. Nefedov, K. Lynch and S. Wallon in France.
- Estimated duration for IN2P3 scientists in COPIN: 18 days (C. Hadjidakis, L. Massacrier, 2024 IJCLab postdoc / for COPIN scientists in France: 18 days (D. Kikola, A. Safranov, L. Manna)

# Outlook

- Three main physics motivations for high-luminosity fixed-target experiments at LHC:
  - High- $x$  frontier**: nucleon and nuclear structure and connections with astroparticles
  - Nucleon spin** and the transverse dynamics of partons
  - Quark Gluon Plasma** over a broad rapidity domain
- Compelling physics case for a fixed-target programme in ALICE (ALICE-FT project) and promising developments but.... ALICE management could not afford to allocate the necessary resources to support the project. This ended the ALICE-FT project.
- The **project #22-153** « Fixed target at LHC and ALICE fixed target system » becomes « **Fixed target at LHC** » : there are many things to do on fixed target at LHC !
- Phenomenology studies on open charm and quarkonium production ongoing and future studies (2024) planned.



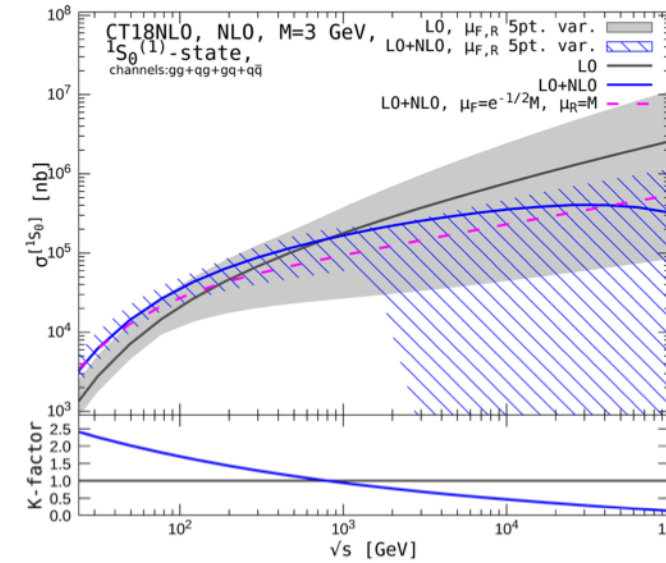
# Phenomenology studies

## $p_T$ -integrated quarkonium cross sections via matching of NLO and High-Energy Factorisation (M.Nefedov, NCBJ Warsaw)

The matching with HEF resummation of logarithms of **partonic** center of mass energy resolves the instability problem of NLO calculation at high  $\sqrt{s_{pp}}$  and  $\sqrt{s_{\gamma p}}$ , and provides *uniformly accurate predictions over wide range of energies, including the LHC fixed-target energy range (69-115 GeV)*.

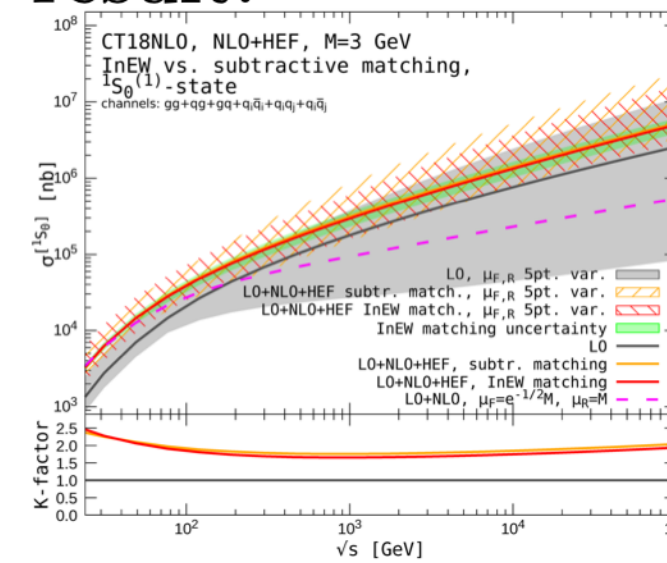
$\eta_c$ -hadroproduction [JHEP 05 (2022) 083]:

NLO result:



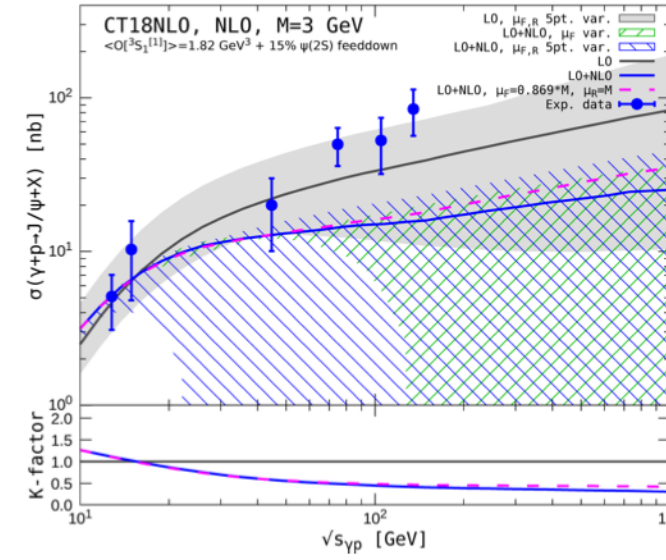
Matched NLO+HEF

result:



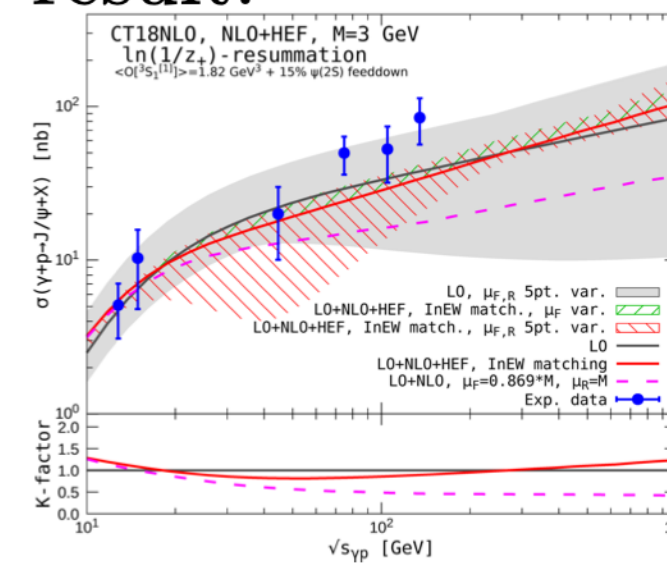
$J/\psi$ -photoproduction [paper in prep.]:

NLO result:



Matched NLO+HEF

result:



- ▶ The NLO calculation for  $J/\psi$  photoproduction is reproduced using dipole-subtraction method
- ▶ Calculation of rapidity-differential production cross section is in progress
- ▶ Calculations of  $\chi_{c0,2}$  production cross sections are in progress