Polarized collisions at LHC

the LHC spin project

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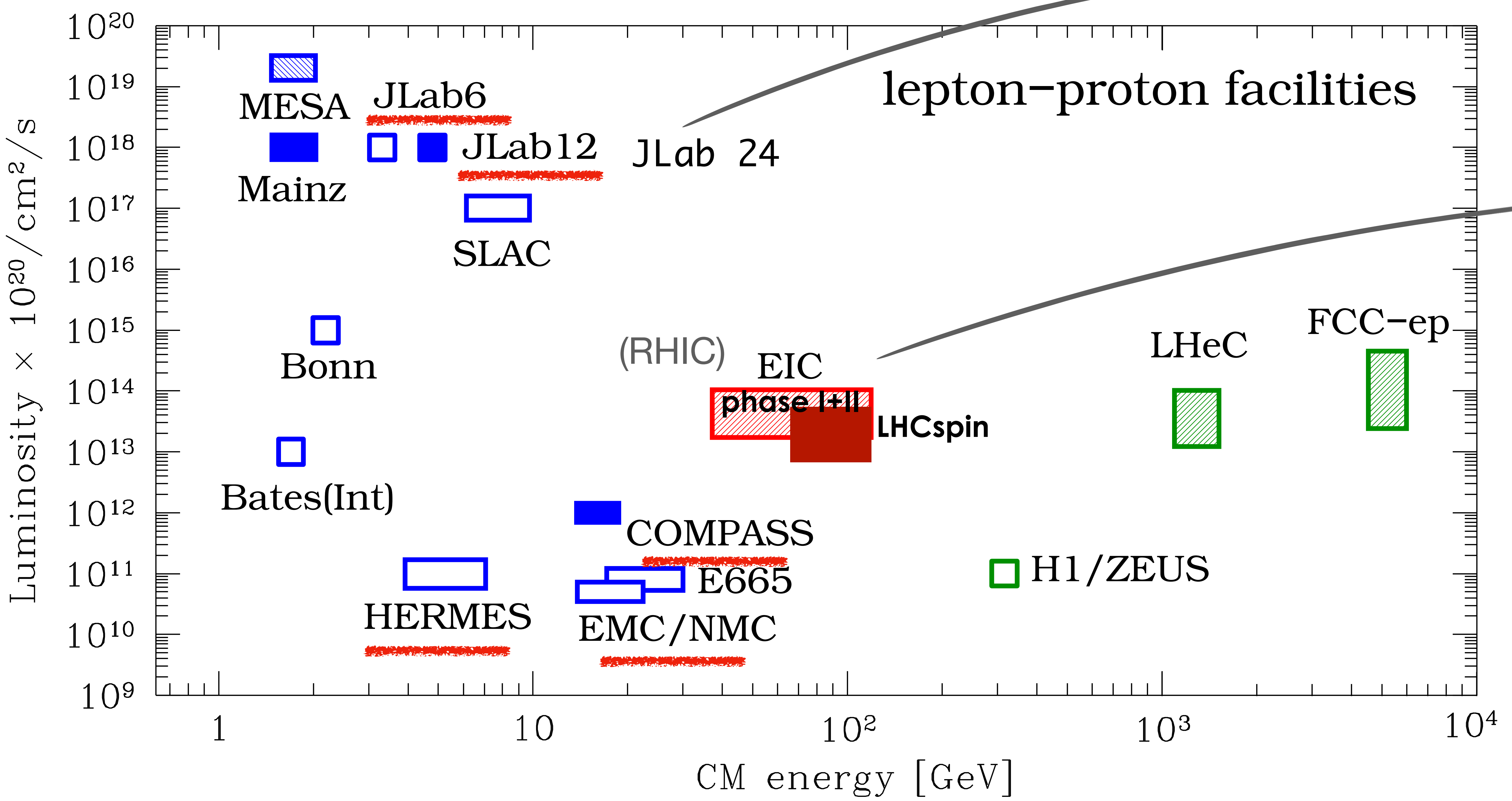
In collaboration with colleagues from:

CERN, CNRS Saclay, Duke University, FZ Julich, INFN Bari, INFN Ferrara, INFN Firenze, INFN Frascati, INFN Torino, PSI Zurich, TH Nuremberg, University of Erlangen, University of Ferrara, University of Yamagata, University of Yerevan

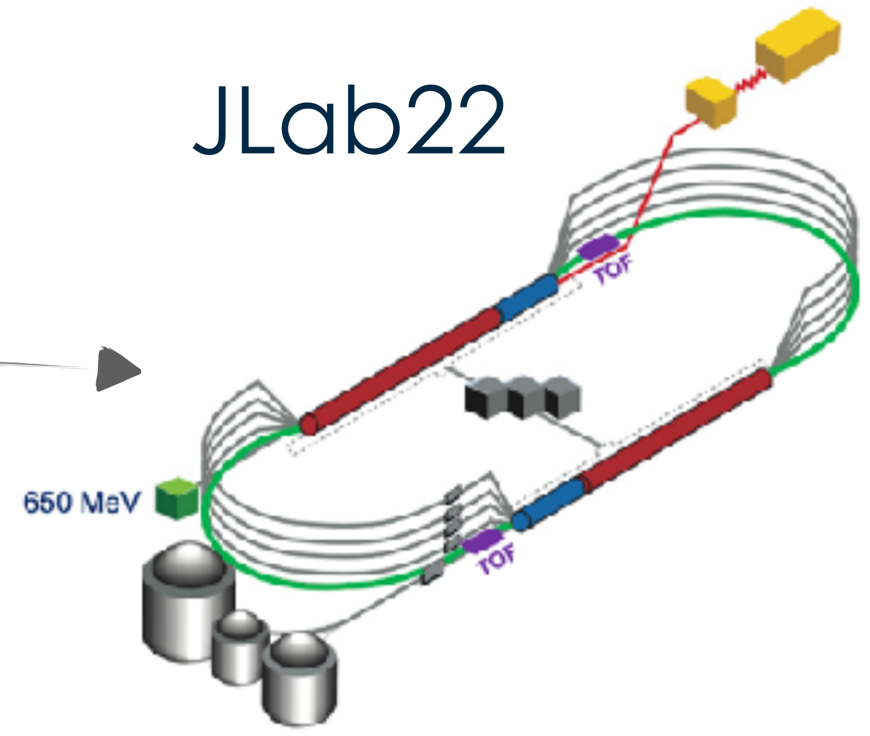
LNF 10/12/24

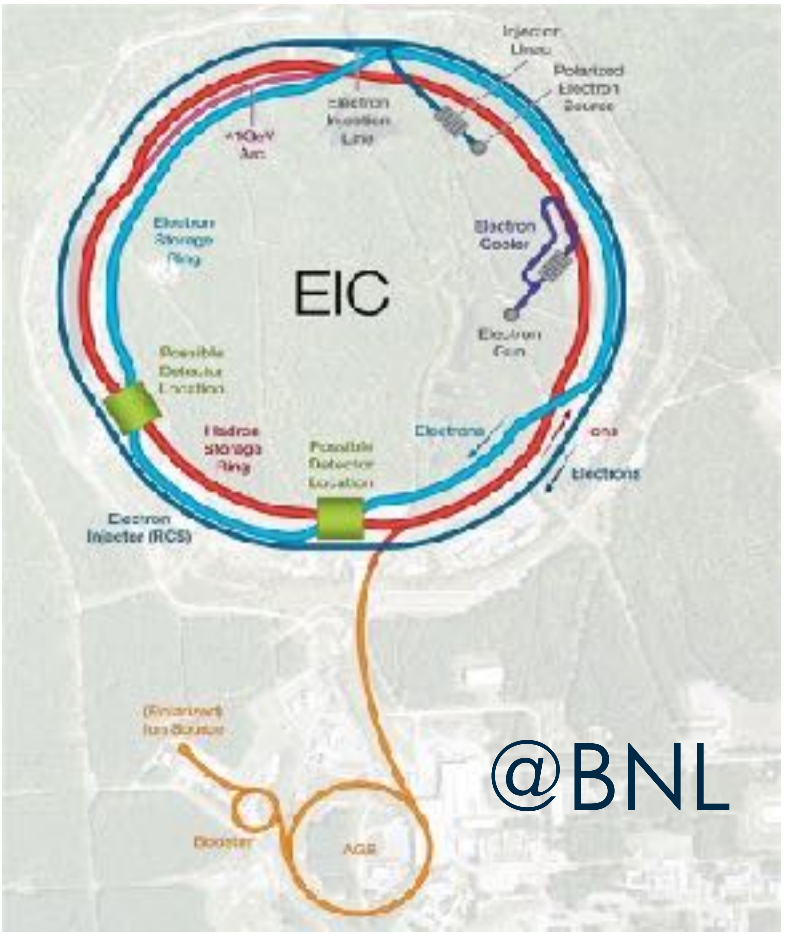
Spin is a key tool to explore a wide range of new and intriguing physics scenarios

Huge efforts in the past/present … and future



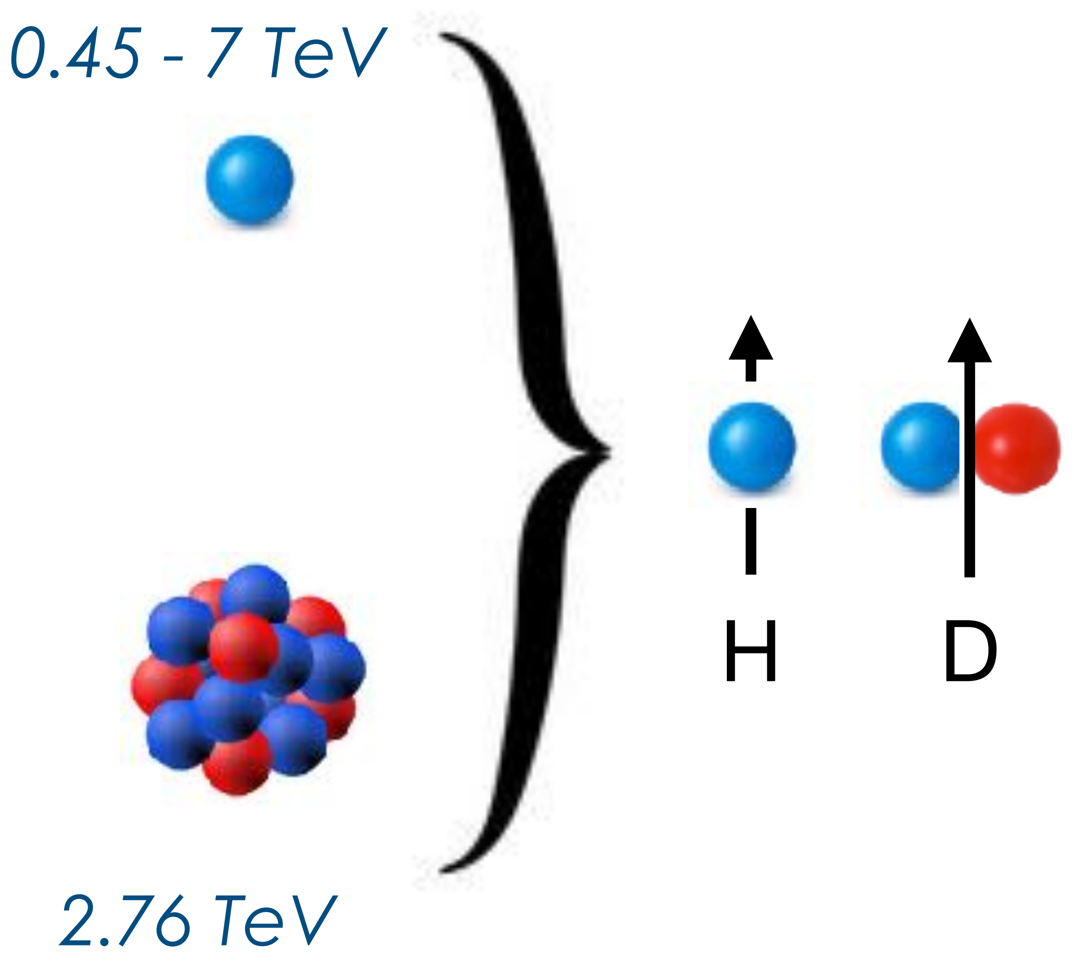
JLab22





What about LHC?

The LHC beams cannot be polarized. The only possibility to have polarized collisions is through a polarized fixed-target



pp collisions: 0.45 - 7 TeV beam on fix target

$$\sqrt{s} = \sqrt{2m_N E_p} \simeq 41 - 115\ GeV$$

$$y_{CMS} = 0 \ \rightarrow \ y_{lab} = 4.8$$

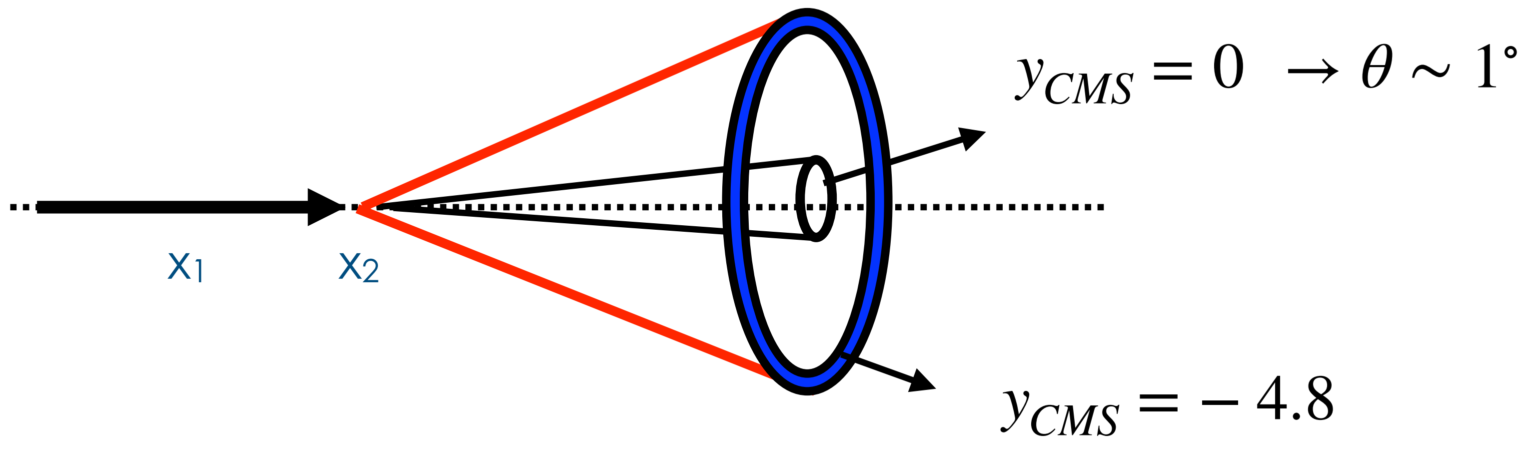
Ap collisions: 2.76 TeV beam on fix target

$$\sqrt{s_{NN}} \simeq 72\ GeV$$

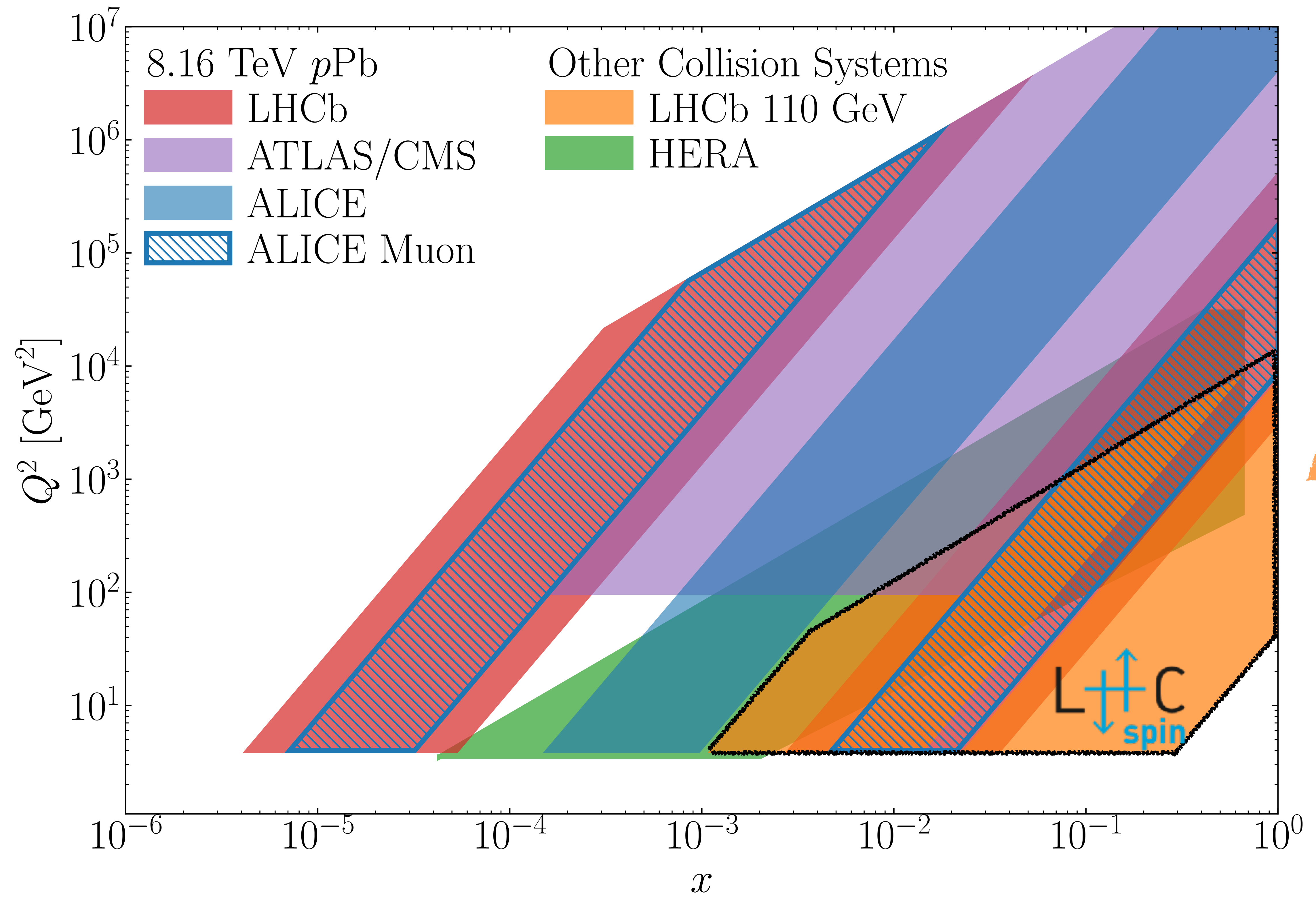
$$y_{CMS} = 0 \ \rightarrow \ y_{lab} = 4.3$$

1: beam; 2: target

Large CM boost, large x_2 values (x_F<0) and small x_1



$$\gamma = \frac{\sqrt{s_{NN}}}{2m_p} \simeq 60$$



Broad and poorly explored kinematic range

The LHCb detector

- LHCb is a general-purpose forward spectrometer, fully instrumented in $2 < \eta < 5$, and optimised for c and b hadron detection
- Excellent momentum resolution with VELO + tracking stations:

$$\sigma_p/p = 0.5 - 1.0\,\% \ (p \in [2,200]\ \text{GeV})$$

- Particle identification with RICH+CALO+MUON

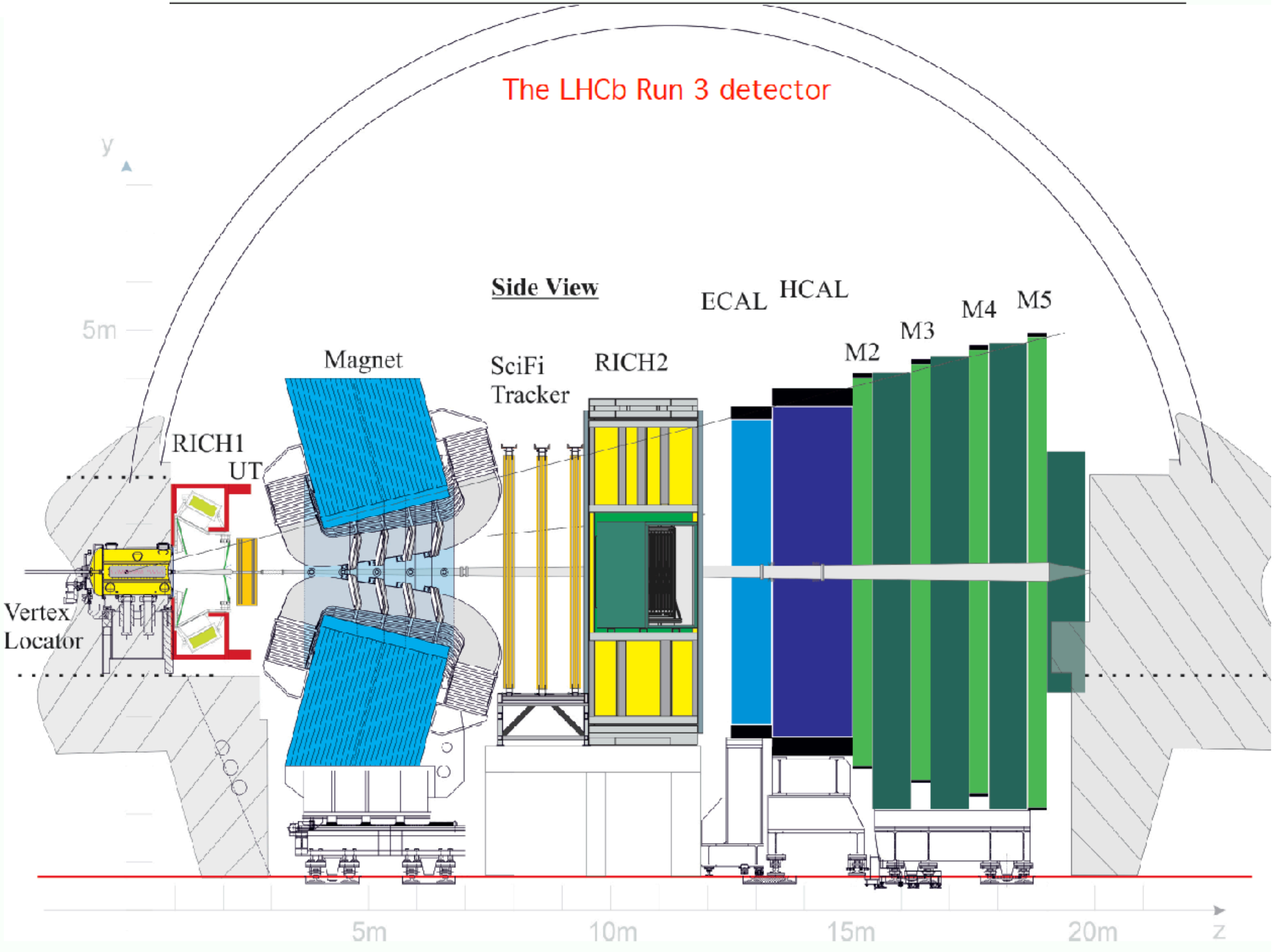
$\epsilon_\mu \sim 98\,\%$ with $\epsilon_{\pi\to\mu} \lesssim 1\,\%$

- Low momentum muon trigger:

$$p_{T_\mu} > 1.75\ \text{GeV}\ (2018)$$

will be reduced thanks to the new fully-software trigger

- Major detector upgrades performed during LS2 for the Run 3 (5x luminosity)



[JINST 3 (2008) S08005]
[IJMP A 30, 1530022 (2015)]
[Comput Softw Big Sci 6, 1 (2022)]

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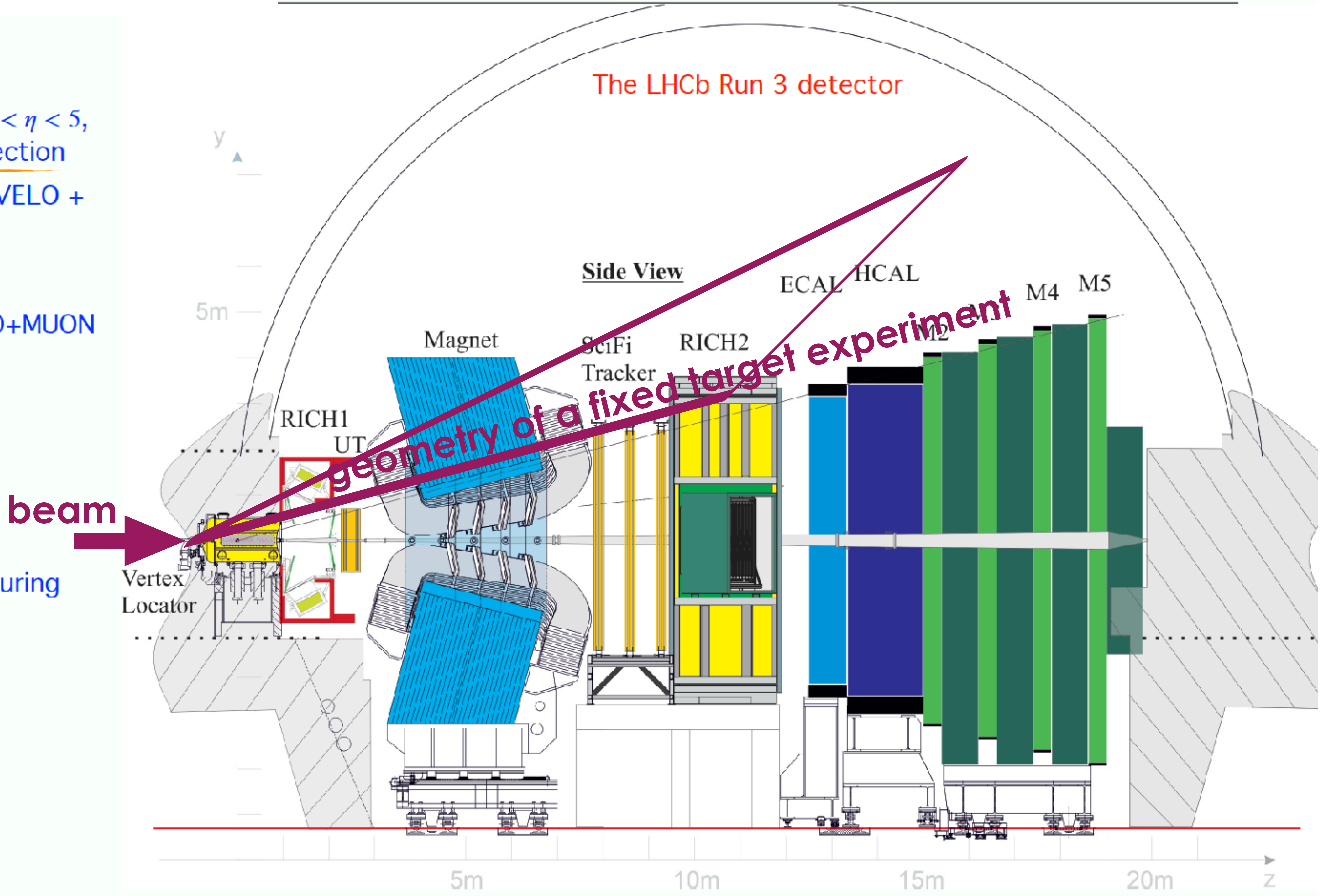


[JINST 3 (2008) S08005]

[IJMP A 30, 1530022 (2015)]

[Comput Softw Big Sci 6, 1 (2022)]

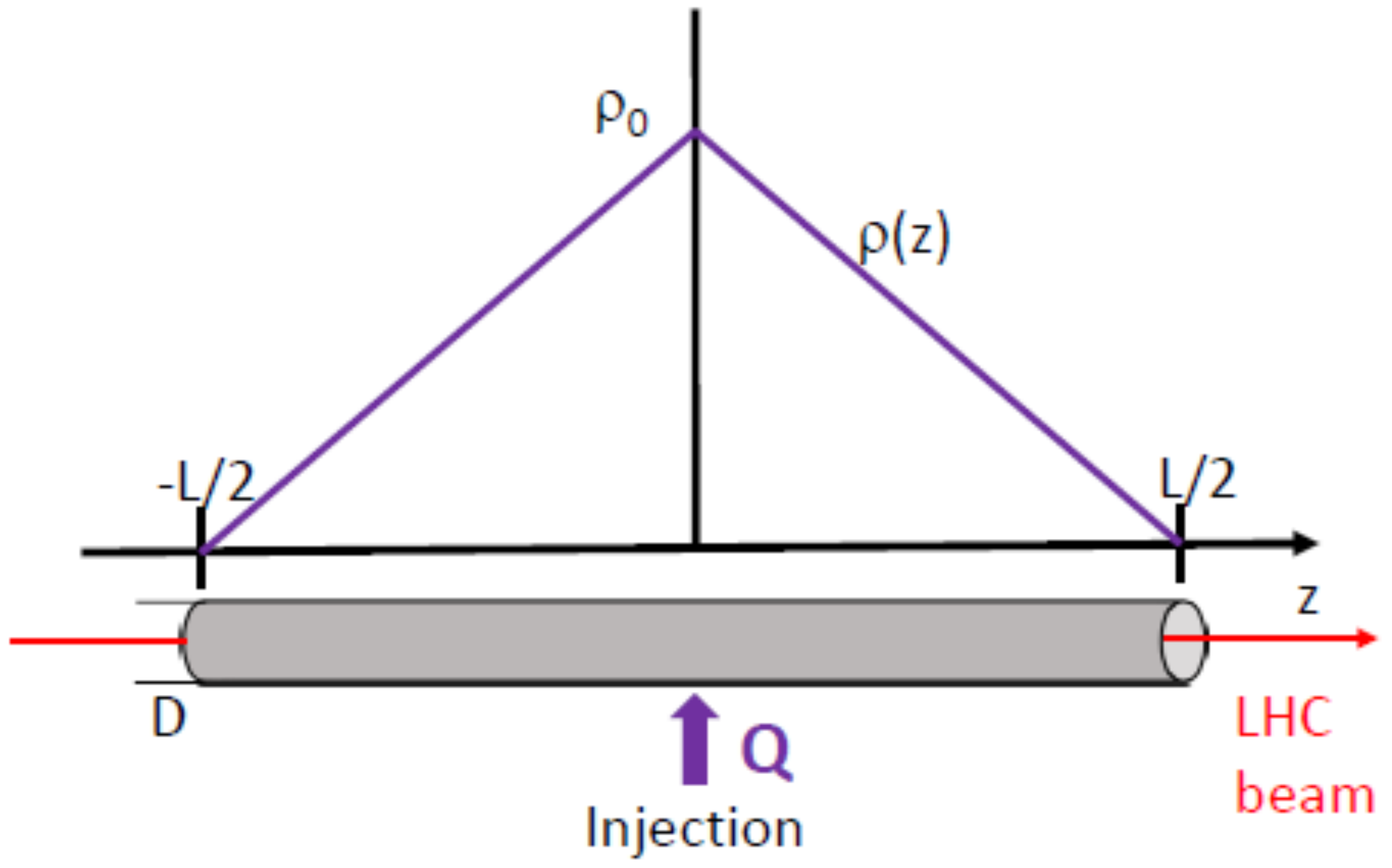
STEP 1

The installation of an unpolarised gas target proves the technical and physical feasibility of implementing this technique at the LHC

SMOG2 an unpolarized target at LHCb

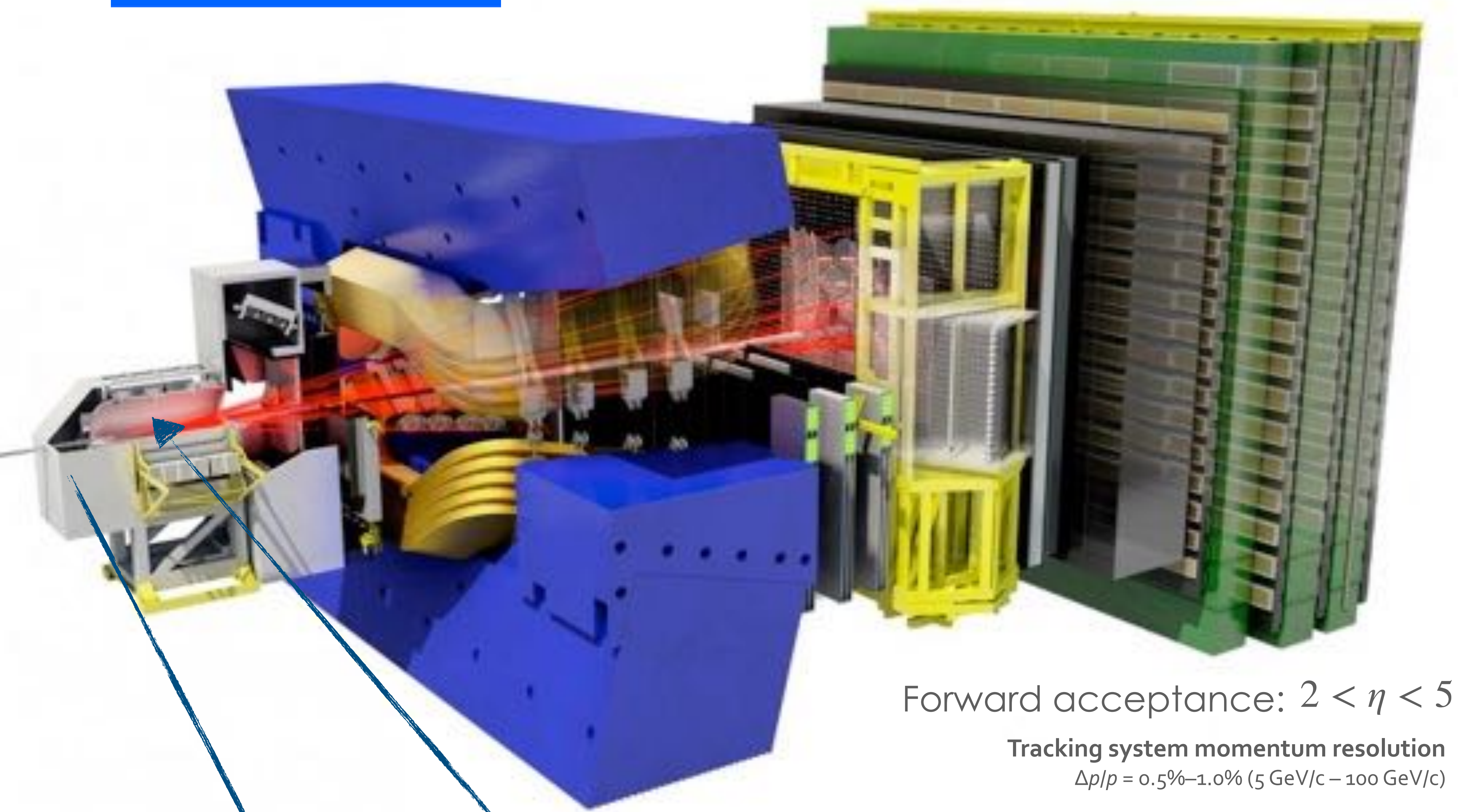
System for Measuring Overlap with Gas

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



Storage cell

LHC beam

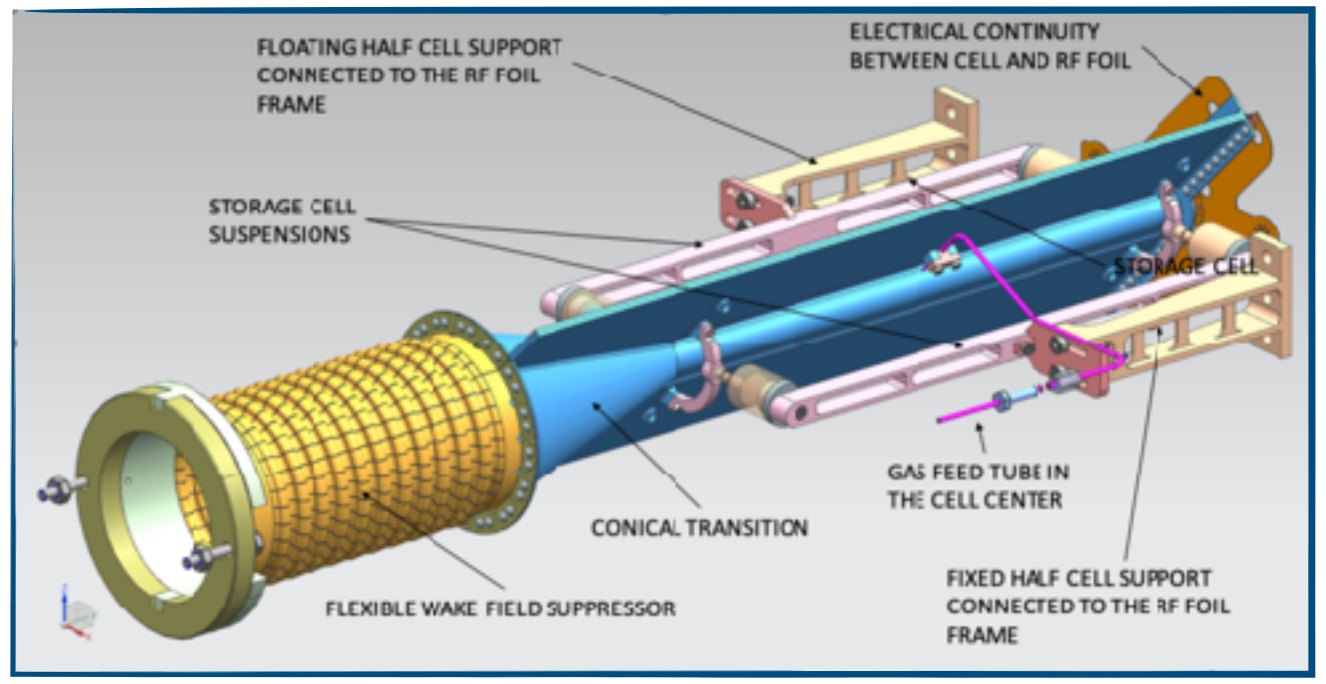


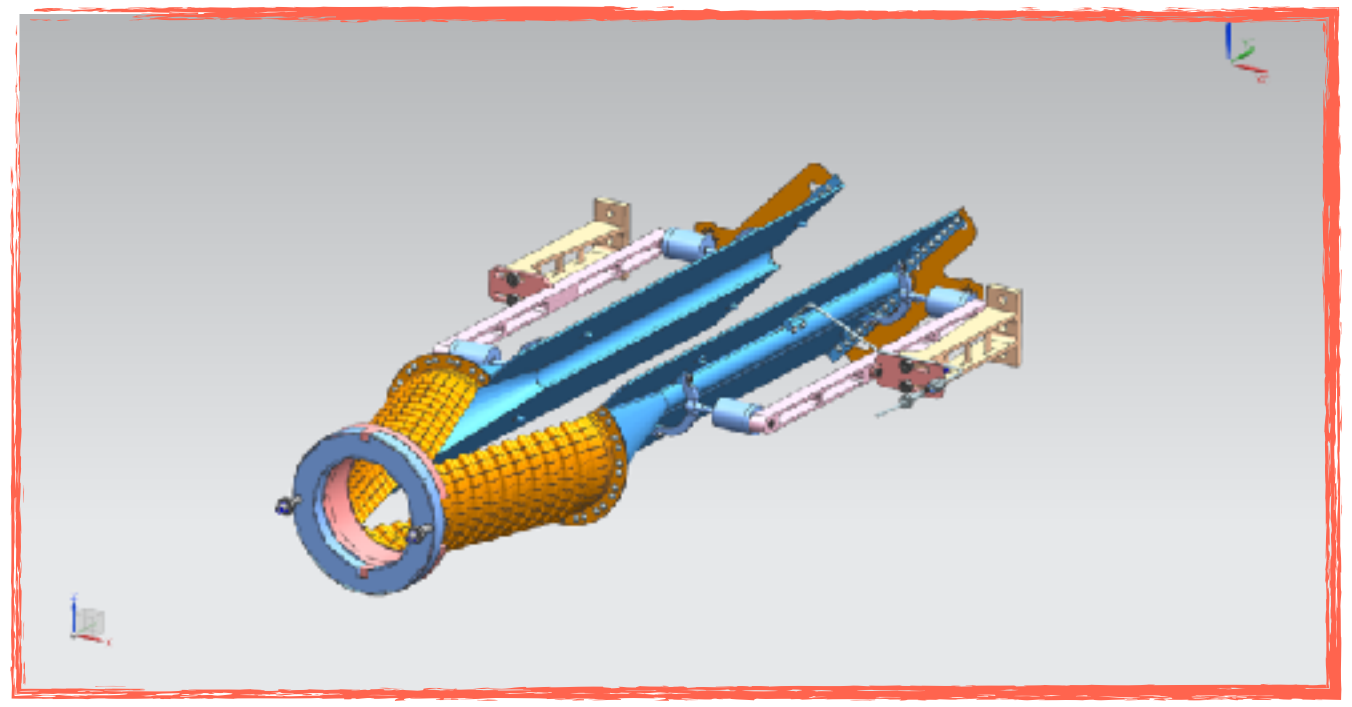
Forward acceptance: $2 < \eta < 5$

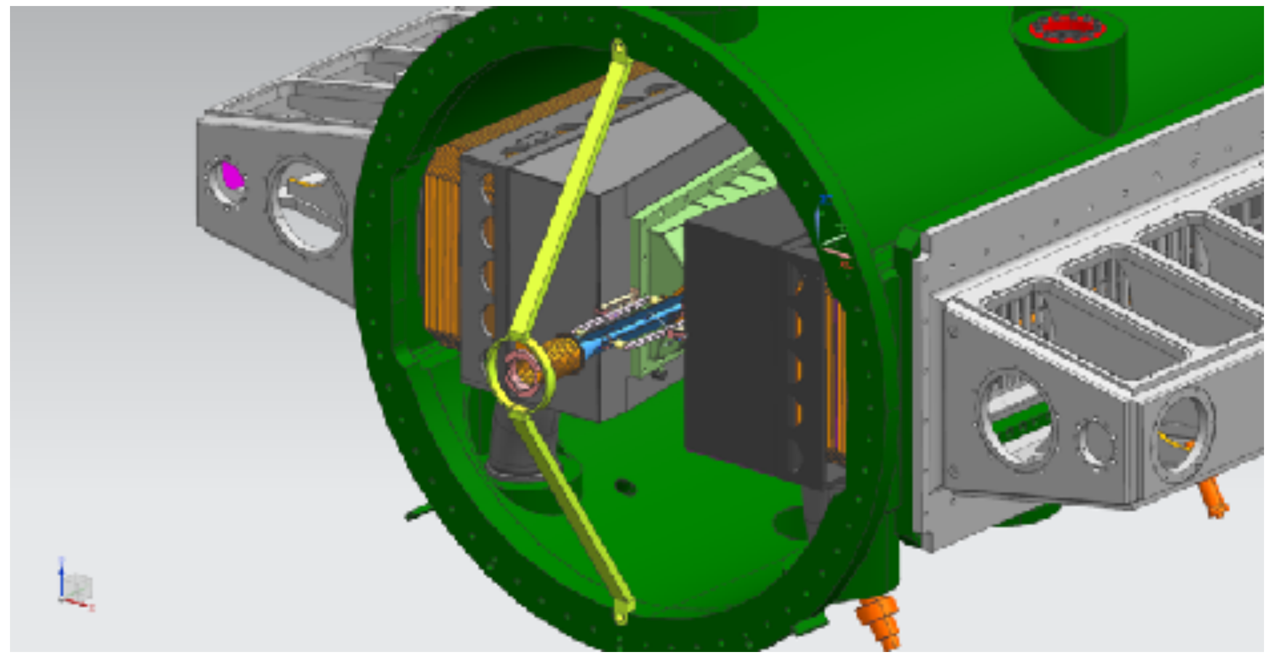
Tracking system momentum resolution
$\Delta p/p$ = 0.5%–1.0% (5 GeV/c – 100 GeV/c)

beam-beam collisions

Openable cell





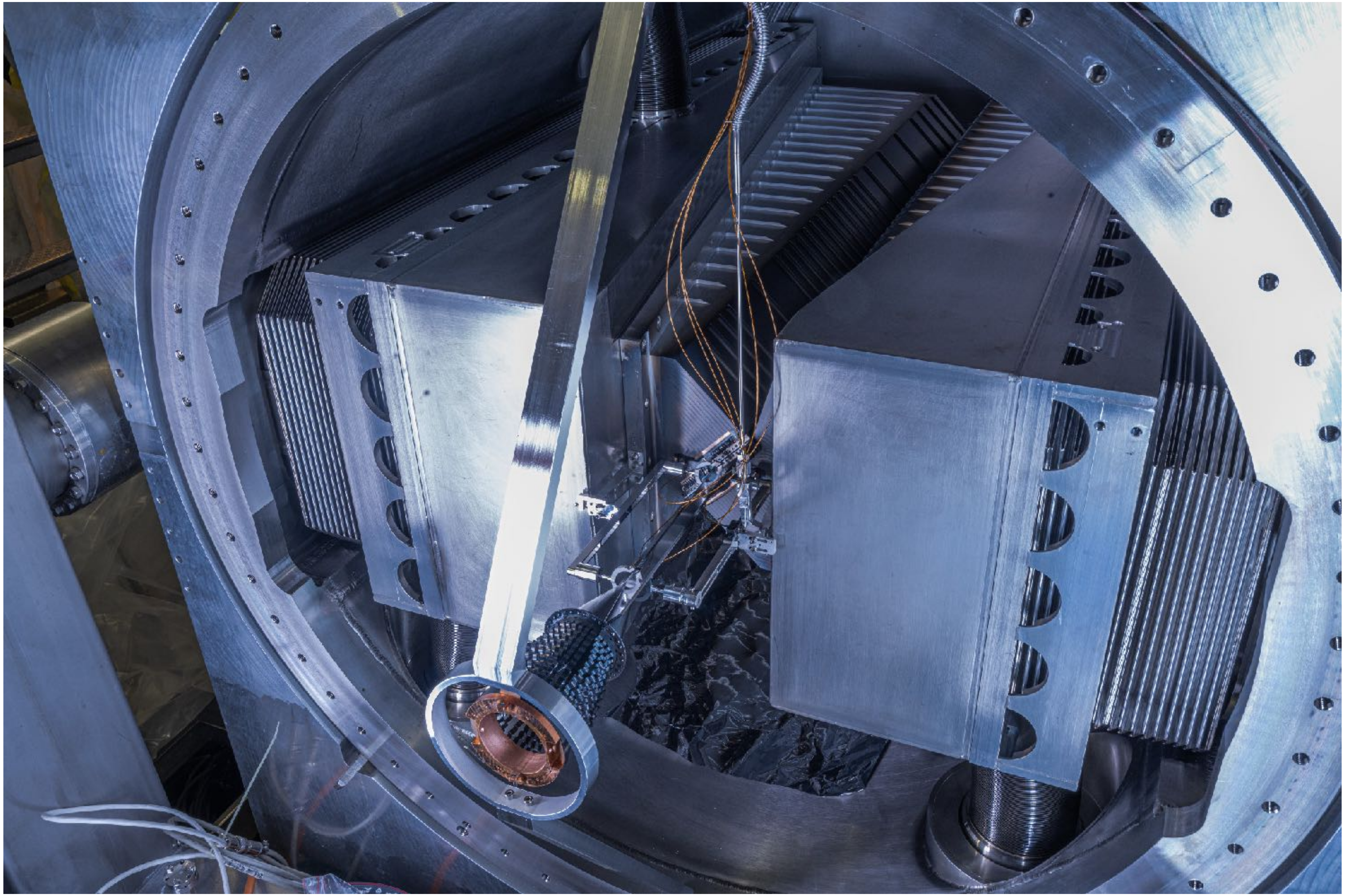


beam-gas collisions

5 mm radius x 200 mm length

SMOG2

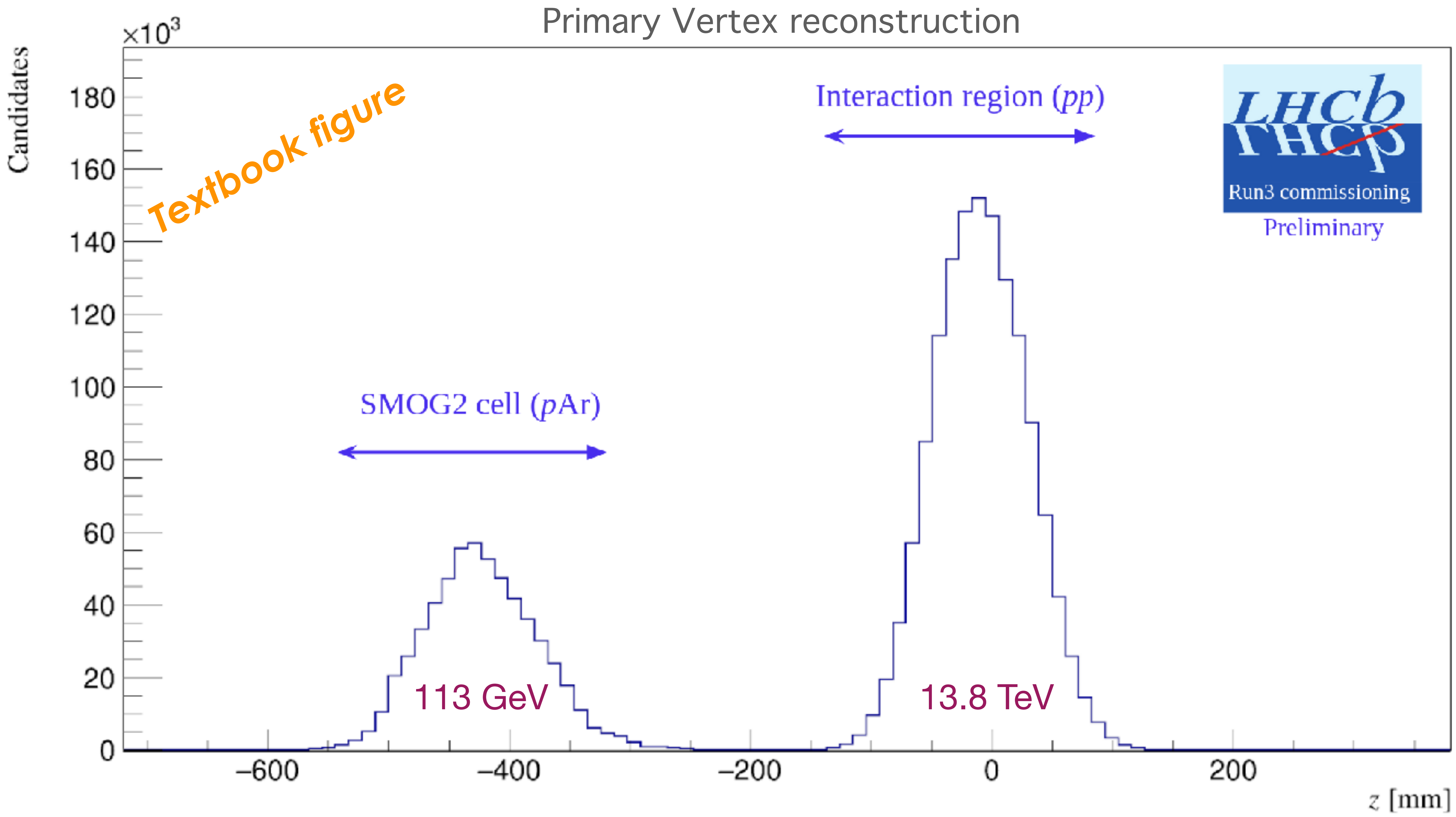
High-density gas target at the LHCb experiment
PHYSICAL REVIEW ACCELERATORS AND BEAMS **27**, *111001 (2024)*



It is the only system present in the LHC primary vacuum

PRAB 27, 111001 (2024)

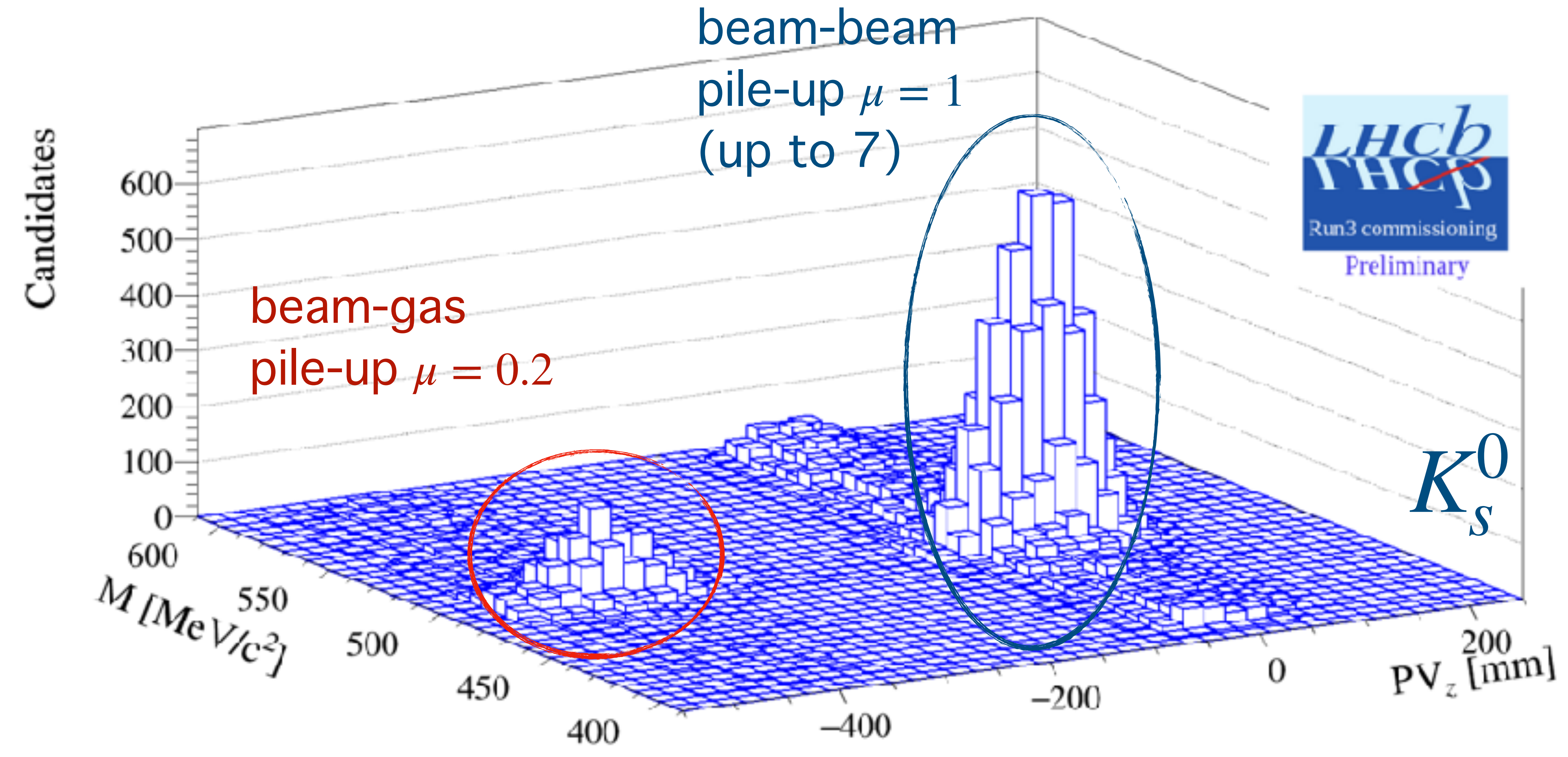
SMOG2 … *it really works*

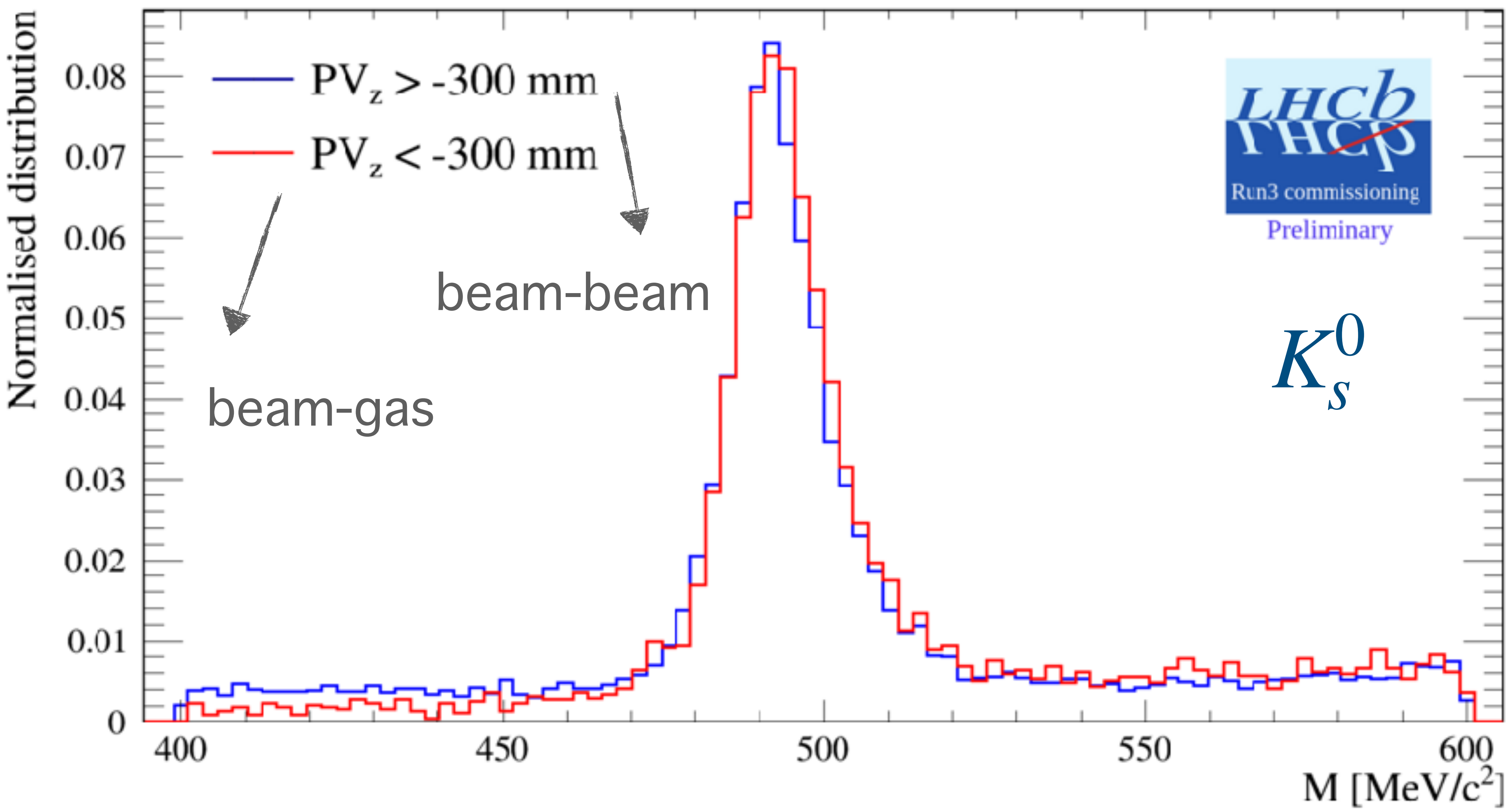


Two well separated and independent Interaction Points <u>working simultaneously</u>

SMOG2 ... it really works

LHCb-FIGURE-2023-001





$\sigma_{J/\Psi} = 16.9$ MeV for pH_2 only

$\sigma_{J/\Psi} = 17.2$ MeV for pH_2 + pp

$\sigma_{\Psi(2S)} = 21.6$ MeV for pH_2 only

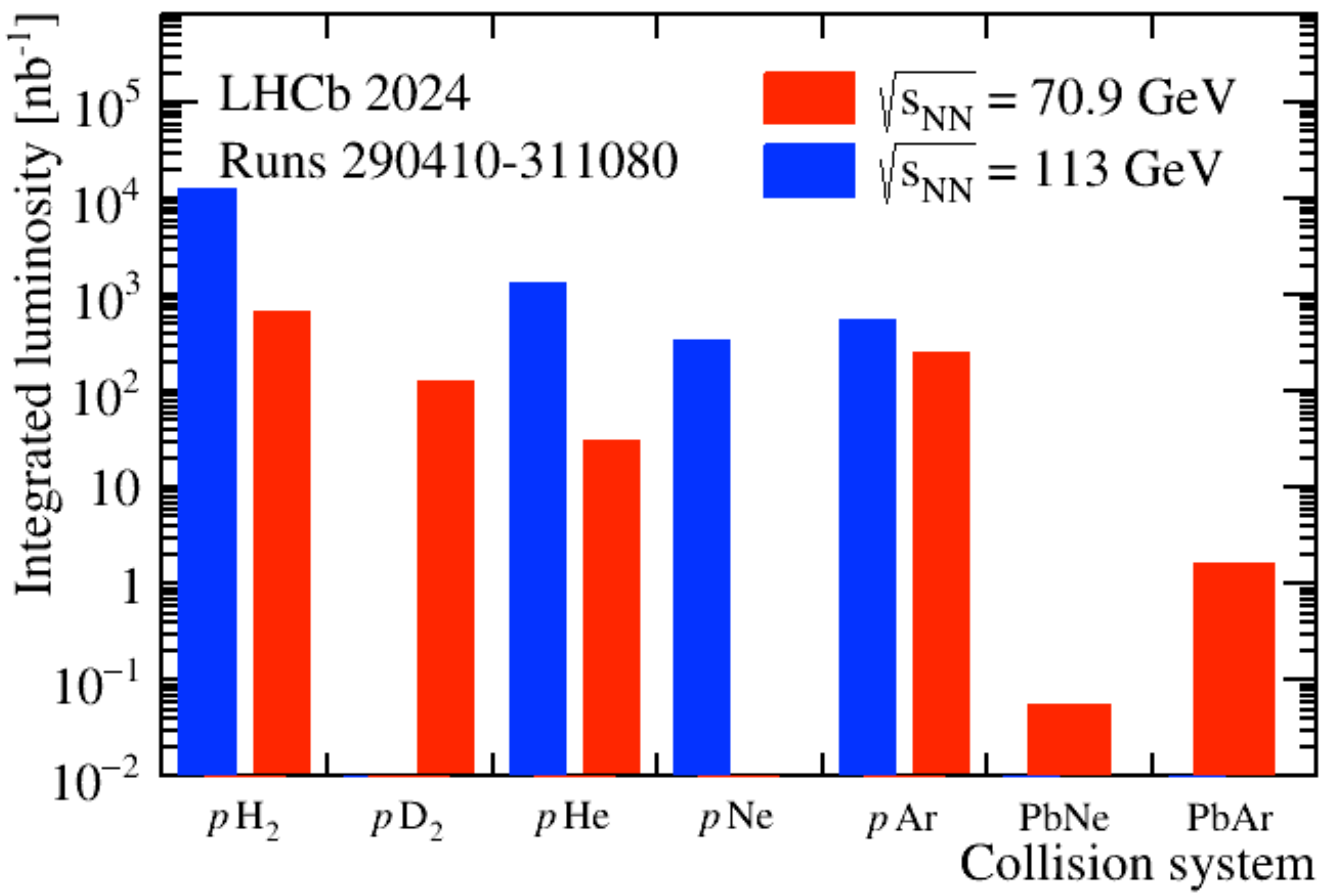
$\sigma_{\Psi(2S)} = 22.8$ MeV for pH_2 + pp

$\sigma_{D^0} = 8.8$ MeV for pH_2 only

$\sigma_{D^0} = 8.9$ MeV for pH_2 + pp

The spectrometer behaves in the same, excellent, way in case of: pp alone / pp+pgas / pgas alone

Luminosity collected on 2024



Large statistics!

Rule of thumb: 100 J/Ψ reconstructed per minute!
In 6 months of data taking >>1 M of reconstructed D^0

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

A lot of results have already been published, and much more will come

Now we know that a storage cell at the LHC is possible and performs excellently!

Therefore, we can take the next step

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Therefore, we can take the next step

The physics goals of LHCspin … just a quick overview

- Multi-dimensional nucleon structure in a poorly explored kinematic domain
- Measure experimental observables sensitive to both **quarks and gluons TMDs**
- **Make use of new probes (charmed and beauty mesons)**
- Complement present and future SIDIS results
- Test non-trivial process dependence of quarks and (especially) gluons TMDs
- Measure exclusive processes to access GPDs

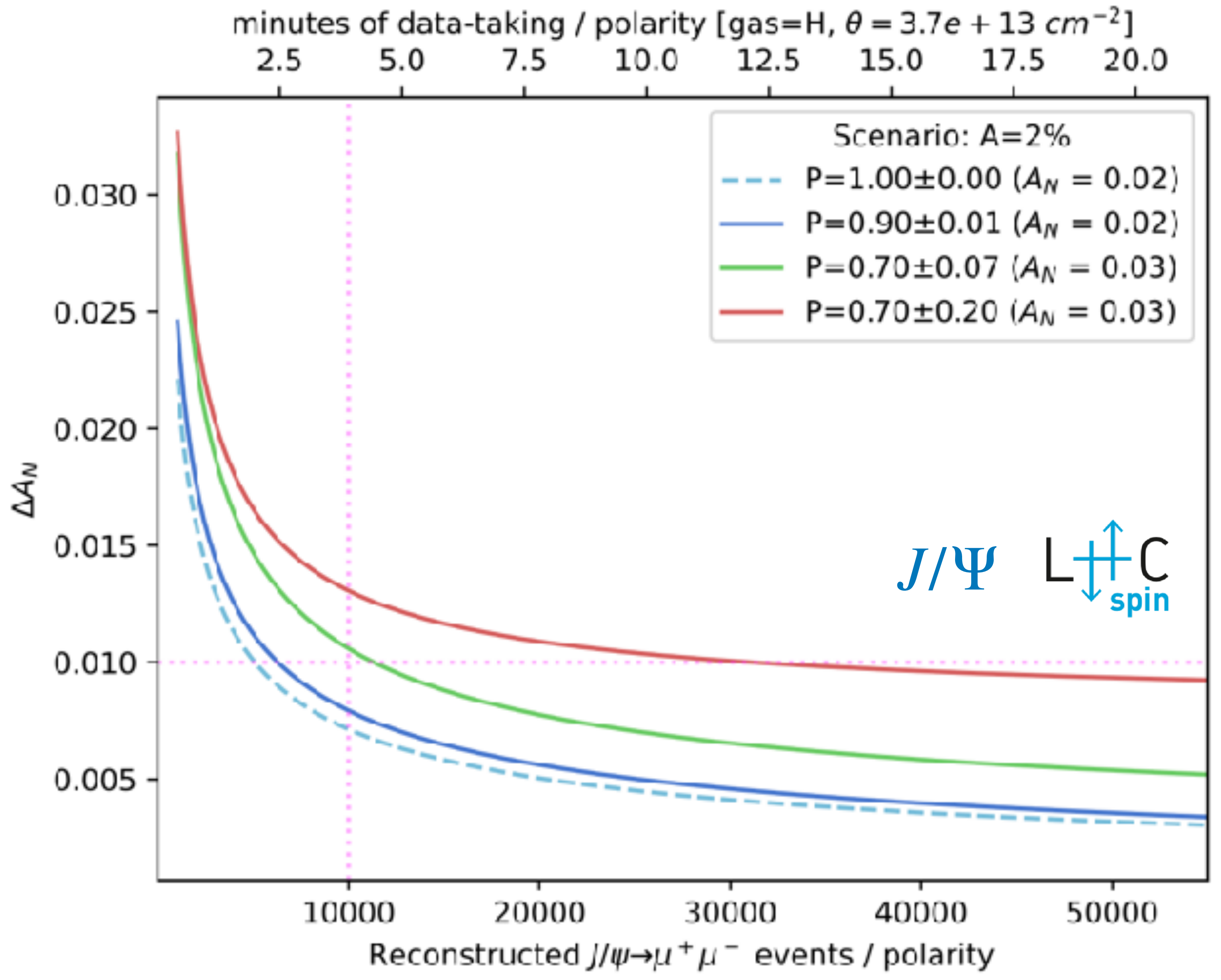
LHCspin event rates

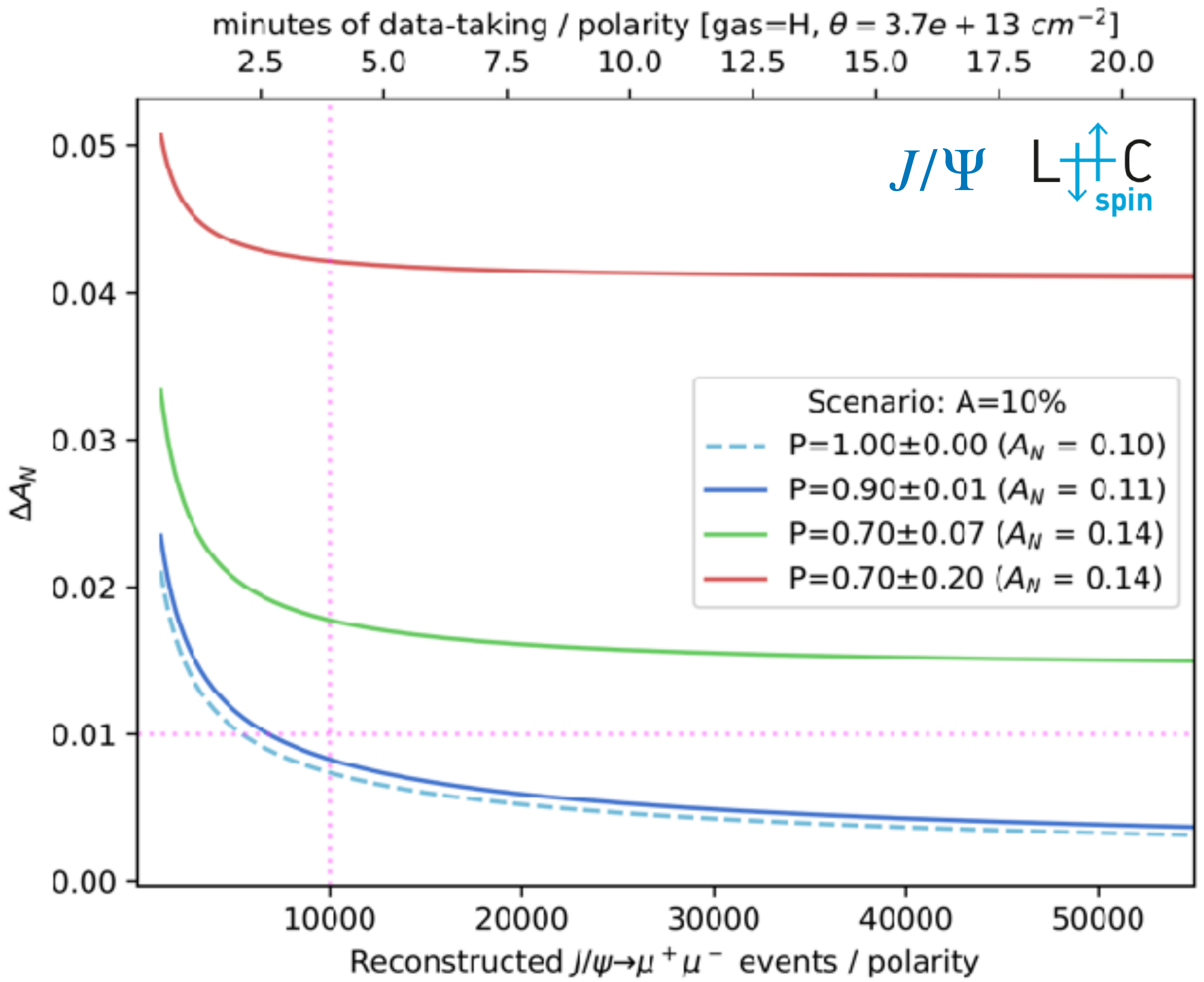
Precise *spin asymmetry* on $J/\Psi \to \mu^+\mu^-$ and $D^0 \to K^-\pi^+$ for $pH^\uparrow$ collisions in just few weeks

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

Statistics further enhanced by a factor 3-5 in LHCb upgrade II

Huge statistics





reconstructed particles

Comparing $J/\Psi \to \mu^+\mu^-$

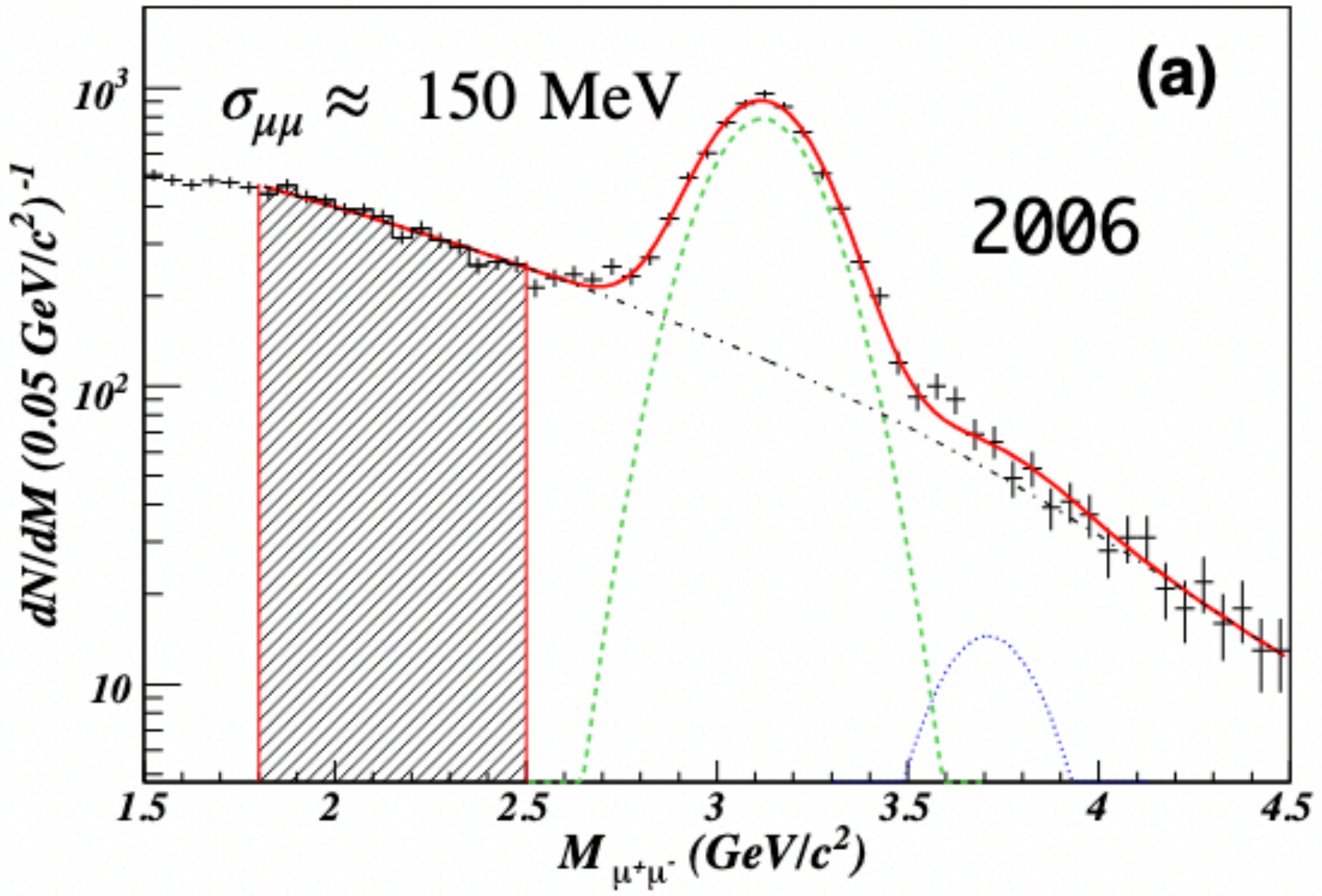
LHCspin strength point and uniqueness will be **heavy flavours**, mostly unexplored by existing
facilities with the exception of the J/Ψ, for which measurements have been performed at PHENIX and COMPASS:

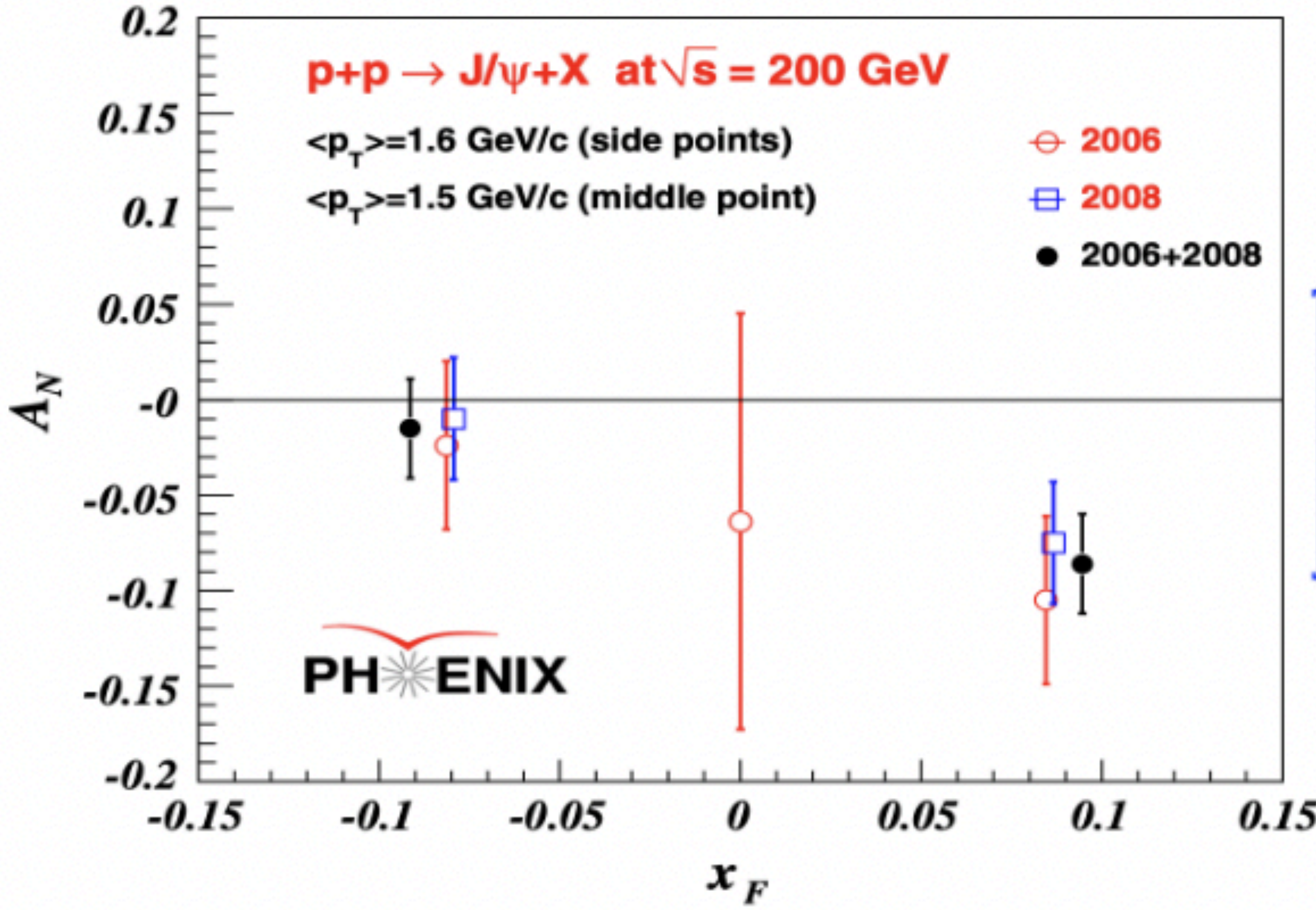
- PHENIX: ~ 21k signal candidates (2006 + 2008 data) at LHCspin they can be collected in ~10 minutes (cell) or ~7 hours (jet)

- Mass resolution: LHCb nominal
$\sigma_{\mu\mu} \simeq 13$ MeV at the mass J/Ψ and
$\sigma_{\mu\mu} \simeq 42$ MeV at the mass Υ mass

- Can also measure excited states & heavier mesons

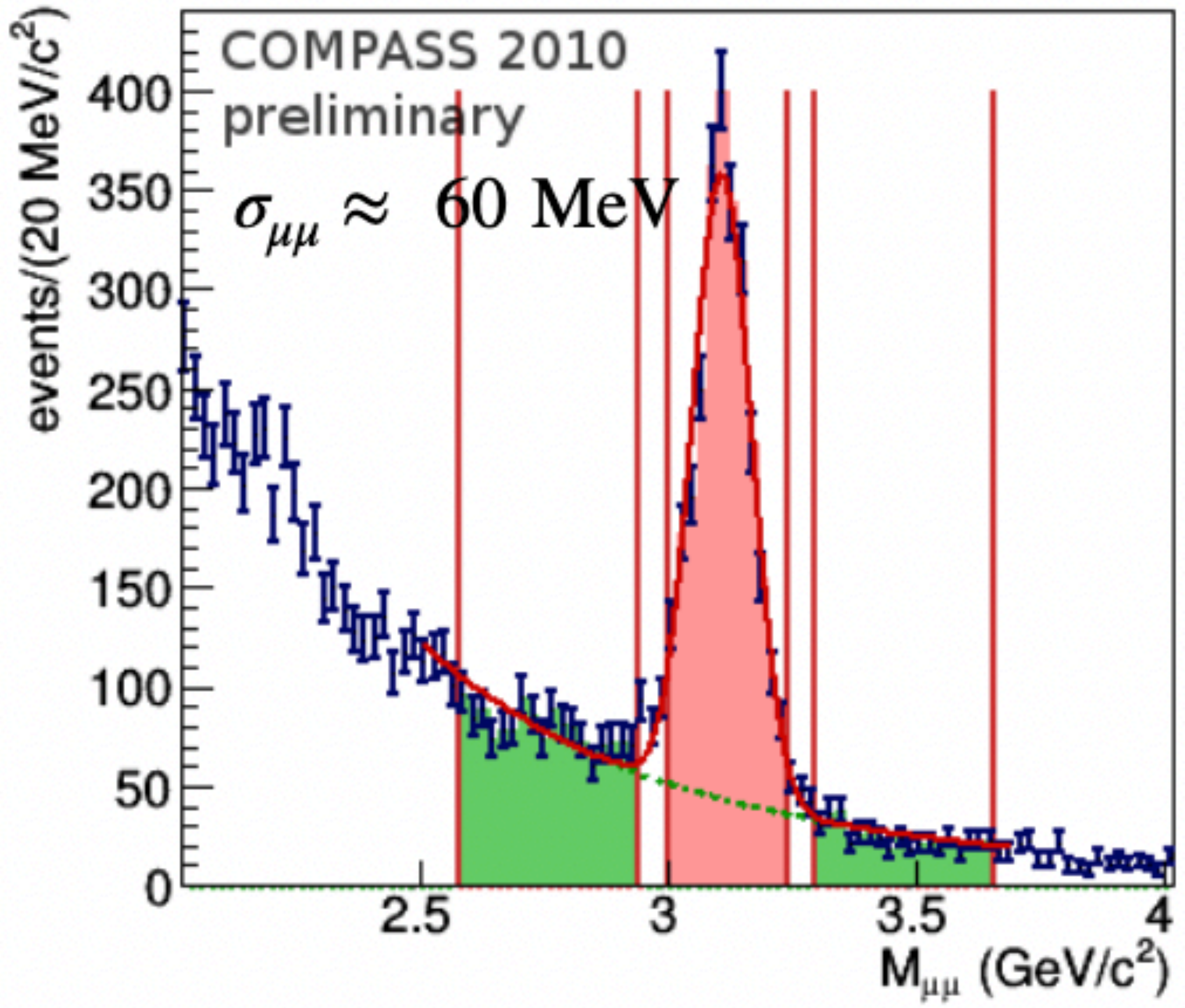
PHENIX: 2006 and 2008 data





[arXiv:1009.4864]

COMPASS: 2010 data



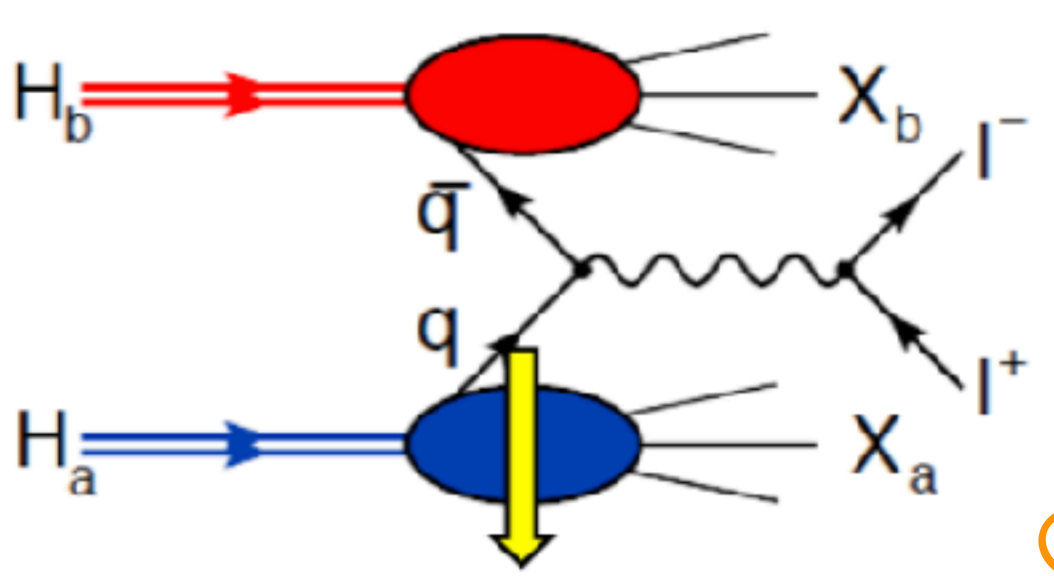
[2016 J. Phys.: Conf. Ser. 678 012050]

we can greatly complement these results with high precision measurements and much larger kinematic coverage!

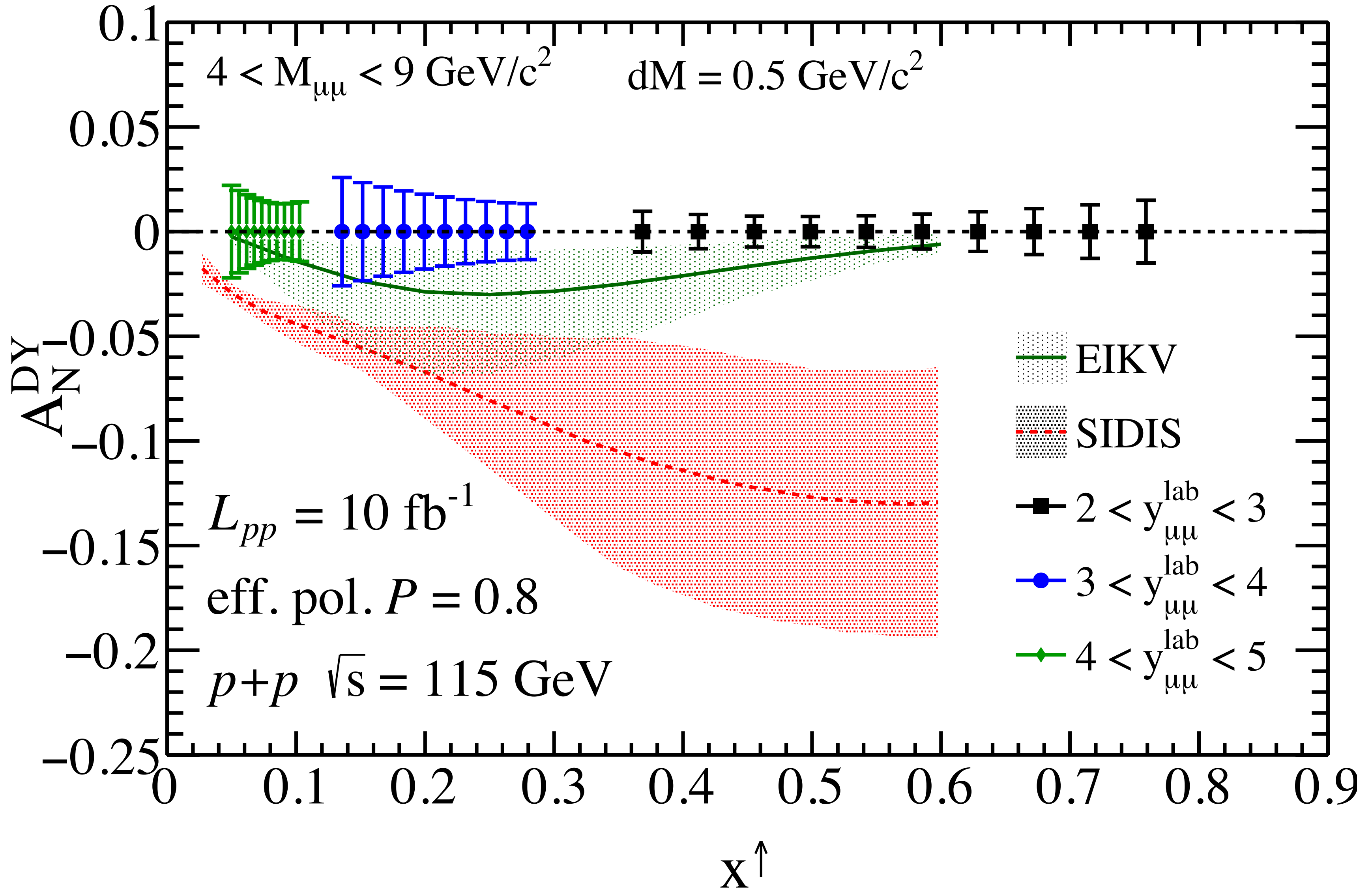
Quark TMDs

nucleon pol. \ quark pol.	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1, $h_{1T}^{\perp}$

Transv. polarized Drell-Yan



Golden Channel

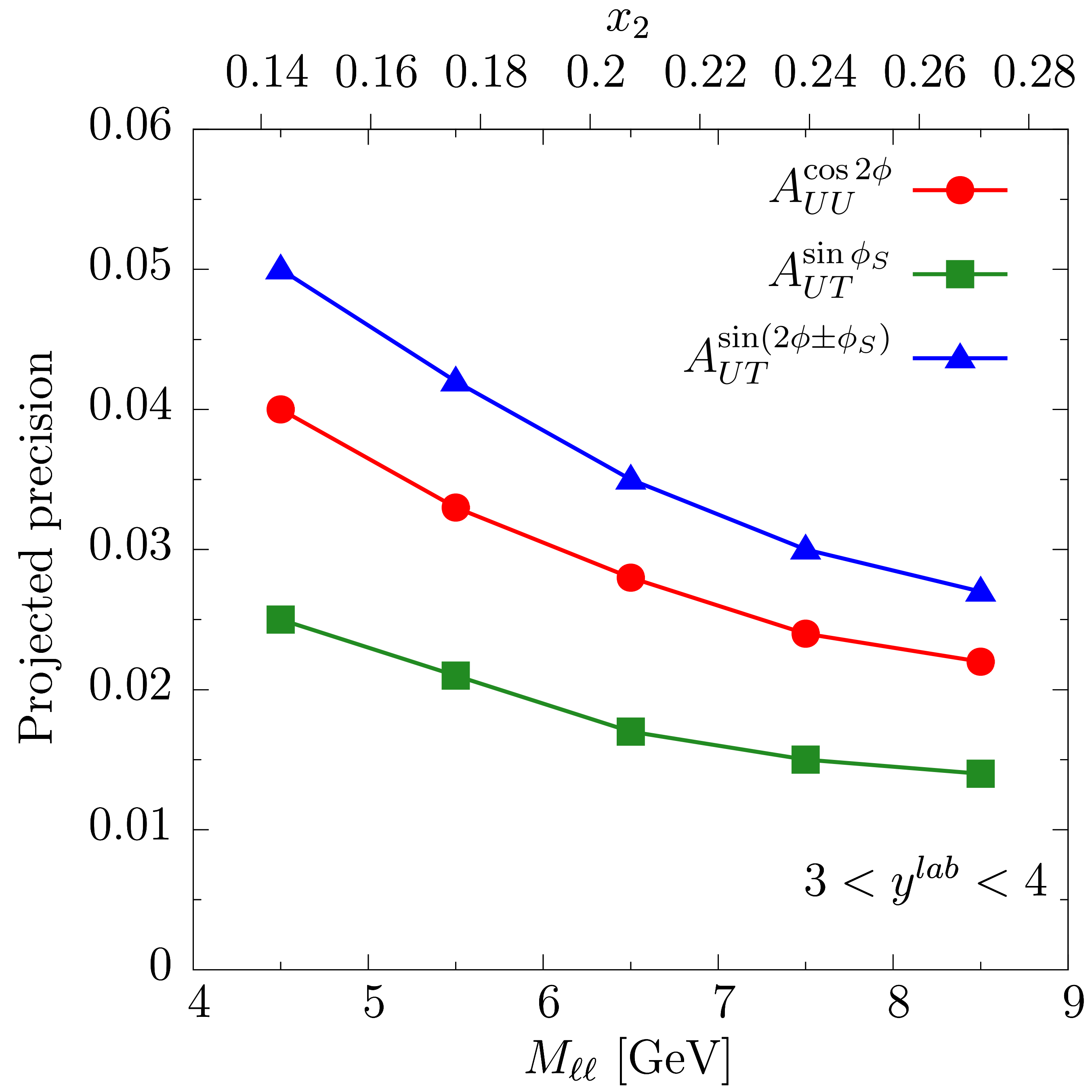


[arXiv:1807.00603]

- **Sensitive to quark TMDs through TSSAs**

$$A_N^{DY} = \frac{1}{P}\frac{\sigma_{DY}^{\uparrow} - \sigma_{DY}^{\downarrow}}{\sigma_{DY}^{\uparrow} + \sigma_{DY}^{\downarrow}} \Longrightarrow \quad A_{UT}^{\sin\phi_S} \sim \frac{f_1^q \otimes f_{1T}^{\perp q}}{f_1^q \otimes f_1^q}, \quad A_{UT}^{\sin(2\phi-\phi_S)} \sim \frac{h_1^{\perp q} \otimes h_1^q}{f_1^q \otimes f_1^q}, \ldots$$

(ϕ: azimuthal orientation of lepton pair in dilepton CM)



[arXiv:1807.00603]

LHCb has excellent μ-ID & reconstruction for $\mu^+\mu^-$ ➔ **dominant:** $\bar{q}(x_{beam}) + q(x_{target}) \rightarrow \mu^+\mu^-$
suppressed: $q(x_{beam}) + \bar{q}(x_{target}) \rightarrow \mu^+\mu^-$

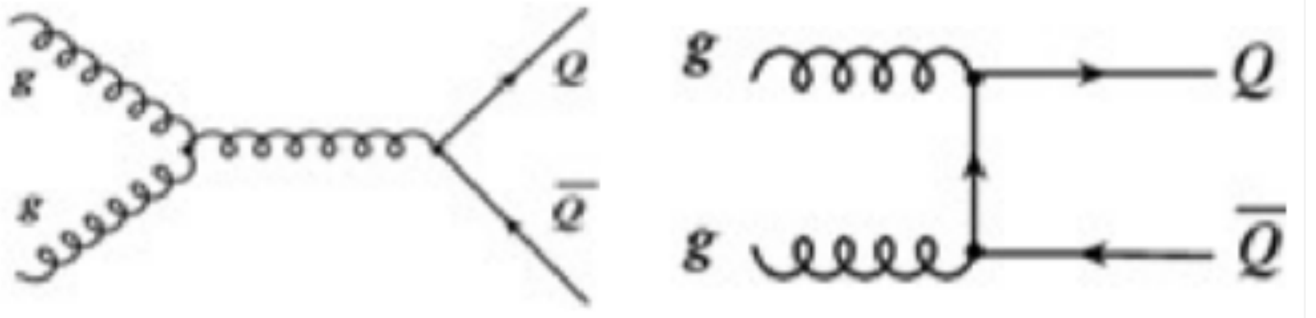
- Extraction of qTMDs does not require knowledge of FF
- Verify sign change of Sivers function wrt SIDIS $f_{1T}^{\perp}|_{DY} = -f_{1T}^{\perp}|_{SIDIS}$
- Test flavour sensitivity using both H and D targets

Gluon TMDs

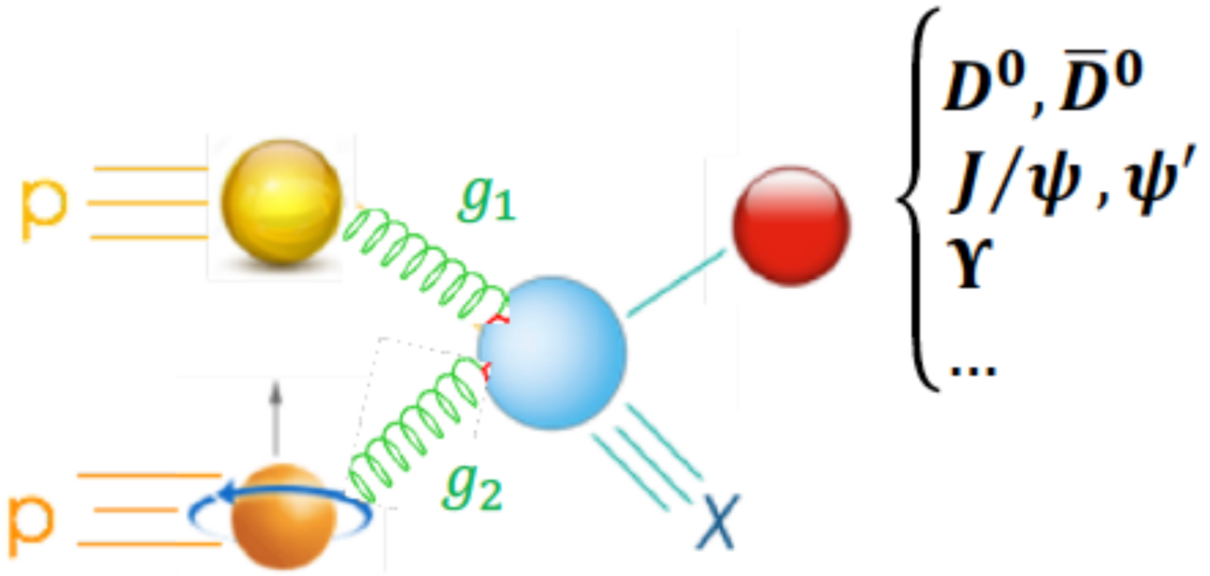
Theory framework well consolidated, but experimental access still extremely limited

nucleon pol. \ gluon pol.	U	Circularly	Linearly
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_1^g, $h_{1T}^{\perp g}$

The most efficient way to access the gluon dynamics inside the proton at LHC is to measure heavy-quark observables.
At LHC heavy quarks are produced by the dominant gg fusion process



Inclusive quarkonia production in (un)polarized pp interaction turns out to be an ideal observable to access gTMDs



TMD factorisation requires $q_T(Q) \ll M_Q$:

- Can look at associate quarkonia production, where only relative q_T needs to be small (e.g. $pp^{(\uparrow)} \to J/\Psi + J/\Psi + X$)
- Due to the large masses, easier in case of bottomonium where factorisation can hold at large q_T

Gluon TMDs

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nucleon pol. \ gluon pol.	U	Circularly	Linearly
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
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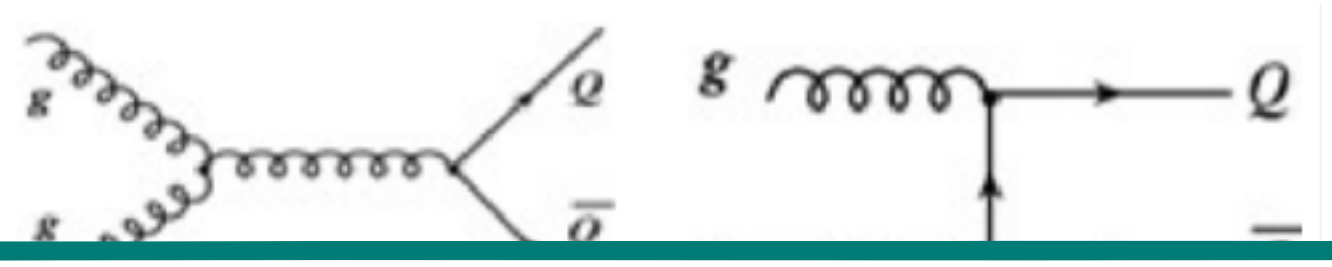
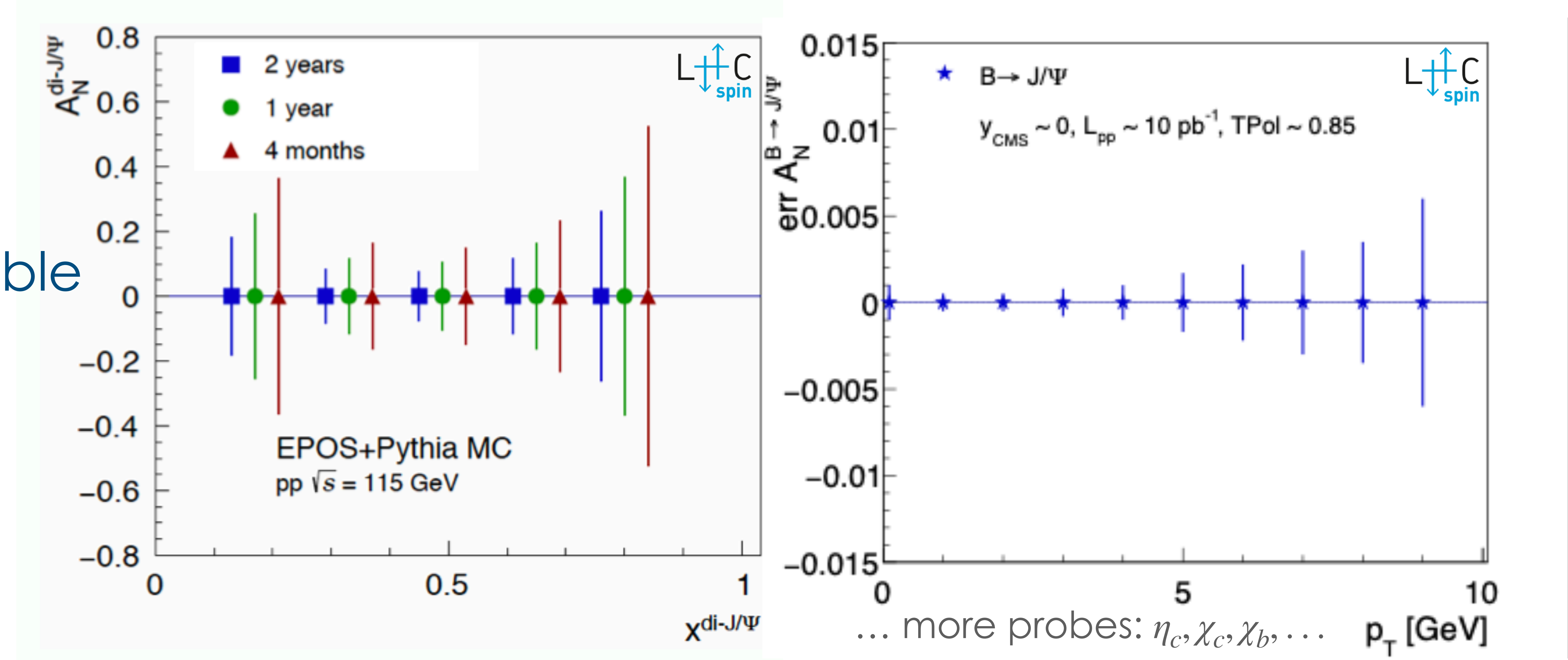


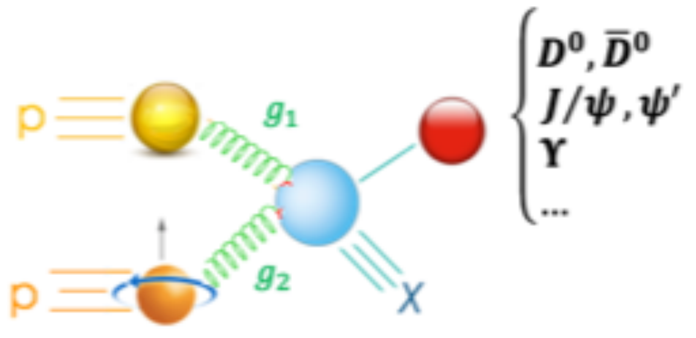
Gluon-induced asymmetries (unconstrained $h_1^{\perp g} + f_1^g$) accessible by, e.g., $di-J/\Psi$ or Υ production



… more probes: $\eta_c, \chi_c, \chi_b, \dots$

factorisation can hold at large q_T

Probing the Sivers function



gluon pol.

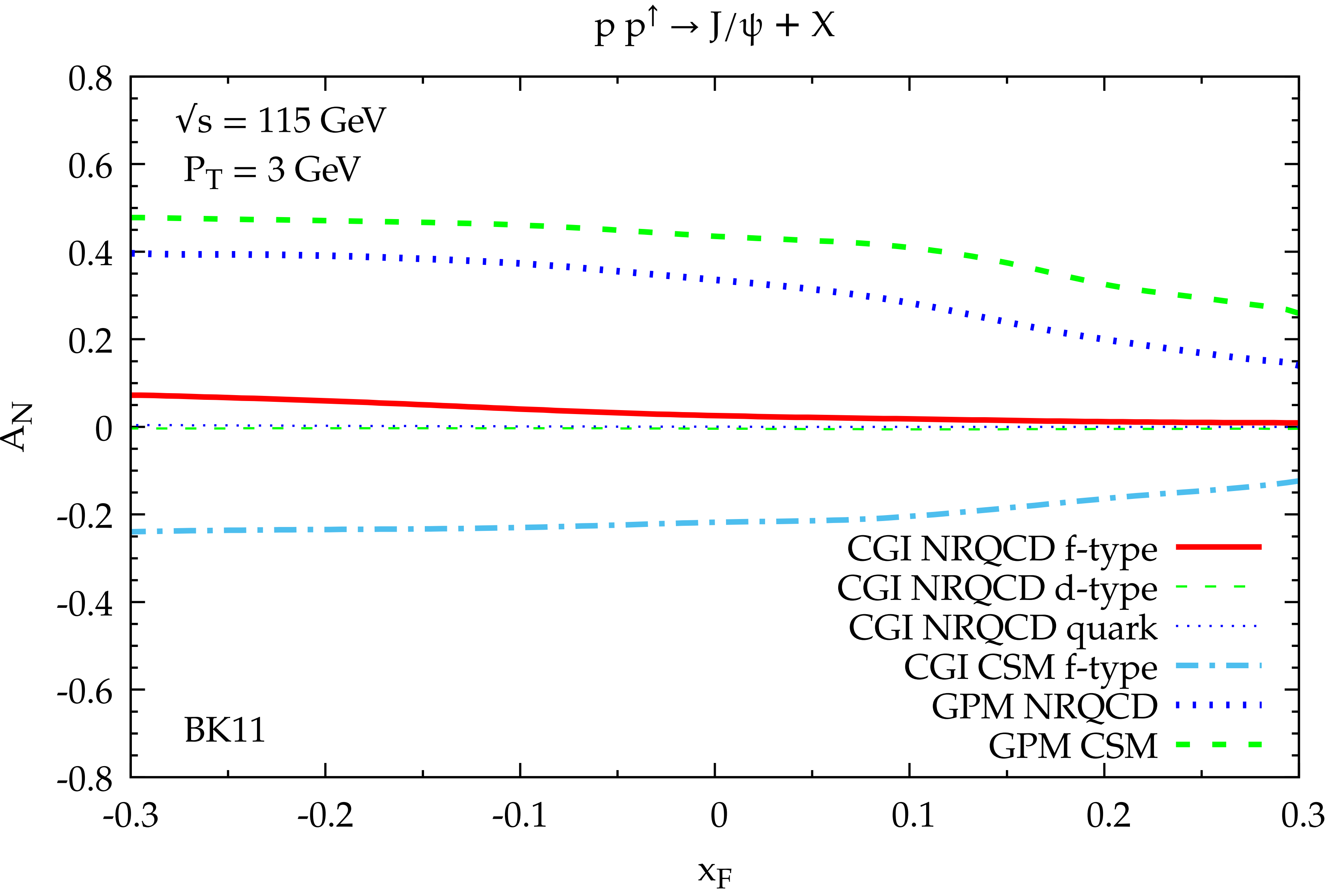
nucleon pol.	U	Circularly	Linearly
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_1^g, $h_{1T}^{\perp g}$

Can be accessed through the Fourier decomposition of the TSSAs for inclusive meson production

$$A_N = \frac{1}{P}\frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \propto [f_{1T}^{\perp g}(x_a, k_{\perp a}) \otimes f_g(x_b, k_{\perp b}) \otimes d\sigma_{gg\to QQg}] \sin\phi_S + \cdots$$

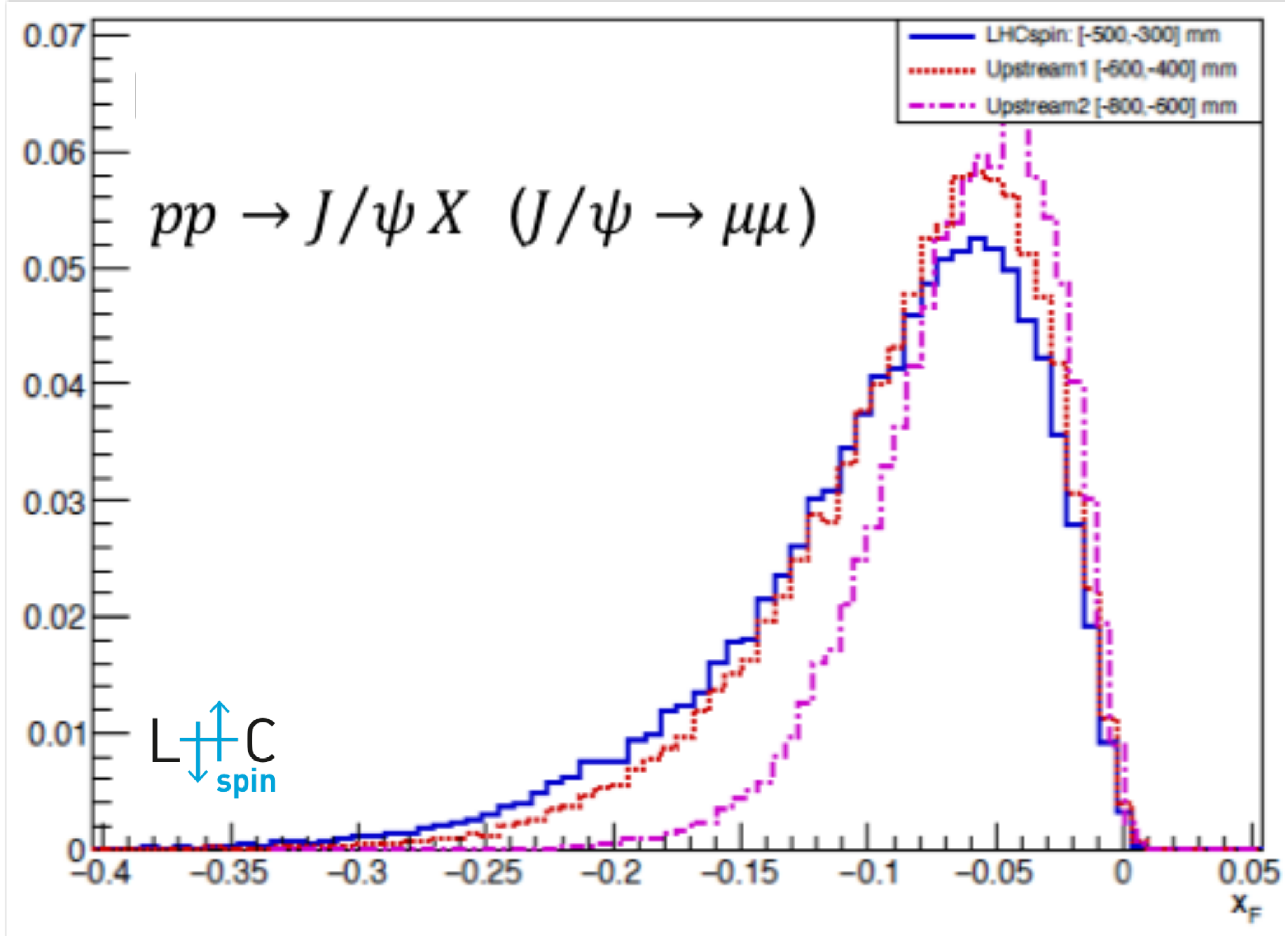
Sensitive to color exchange among IS and FS, and gluon OAM

Shed light on spin-orbit correlation of unpolarized gluons inside a transversely polarized proton

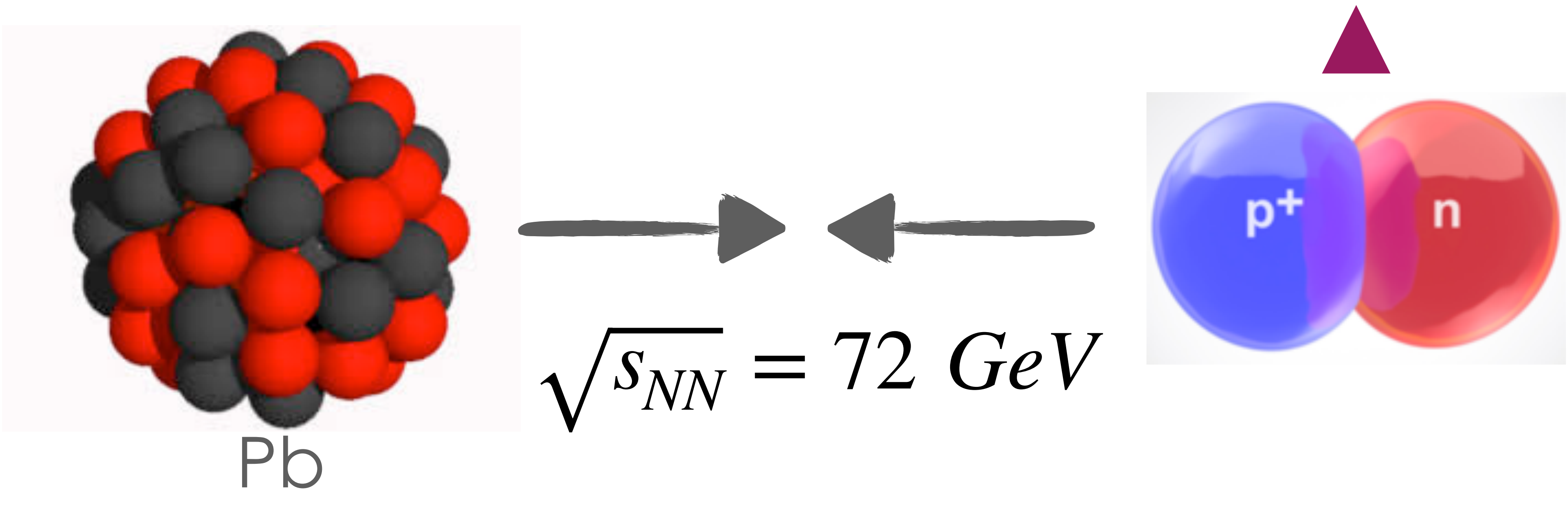


Phys. Rev. D 102, 094011 (2020)

Predictions for J/Ψ production based on GPM & CGI-GPM
Expected amplitudes could be very large in the $x_F < 0$ region

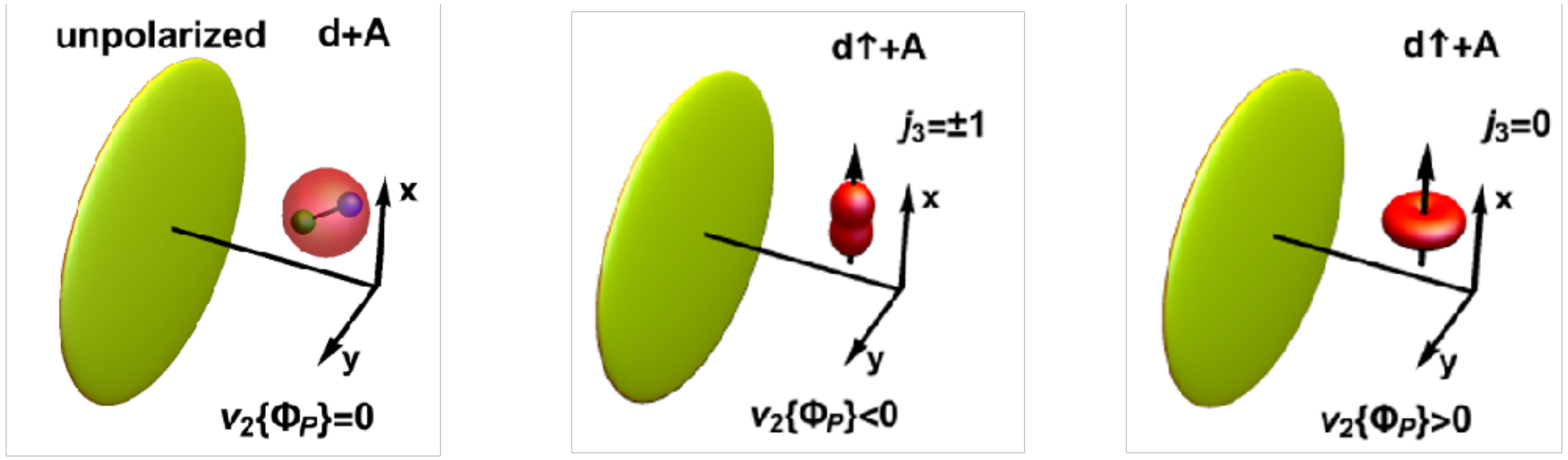


Spin physics in heavy-ion collisions



- probe collective phenomena in heavy-light systems through **ultra-relativistic collisions of heavy nuclei with trasv. pol. deuterons**

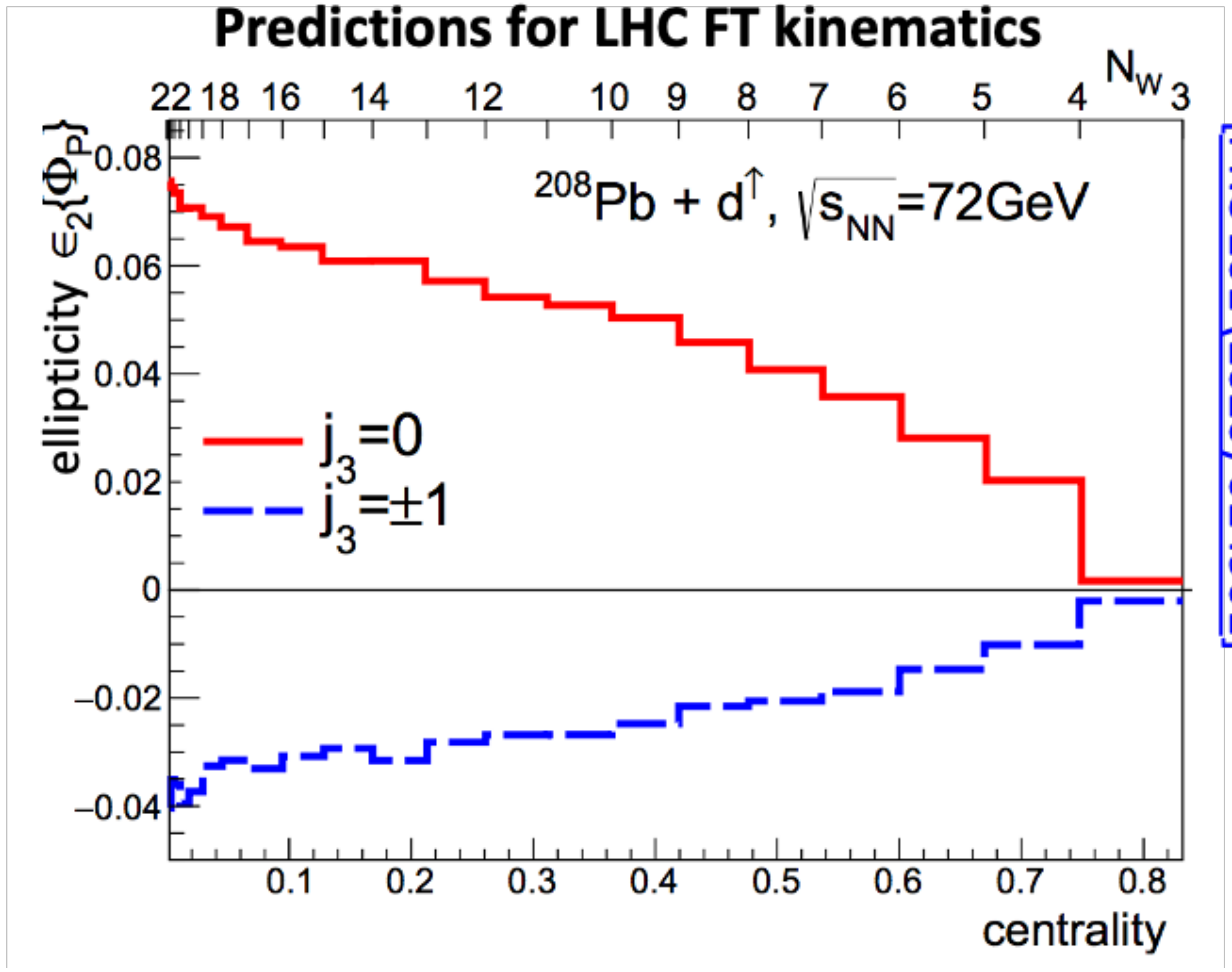
- polarized light target nuclei offer a unique opportunity to control the orientation of the formed fireball by measuring the **elliptic flow** relative to the polarization axis (**ellipticity**).



Unpol. deuterons: the **fireball is azimuthally symmetric** and $v_2 \approx 0$.

$j_3 = \pm 1 \rightarrow$ **prolate fireball** stretched along the pol. axis, corresponds to $v_2 < 0$

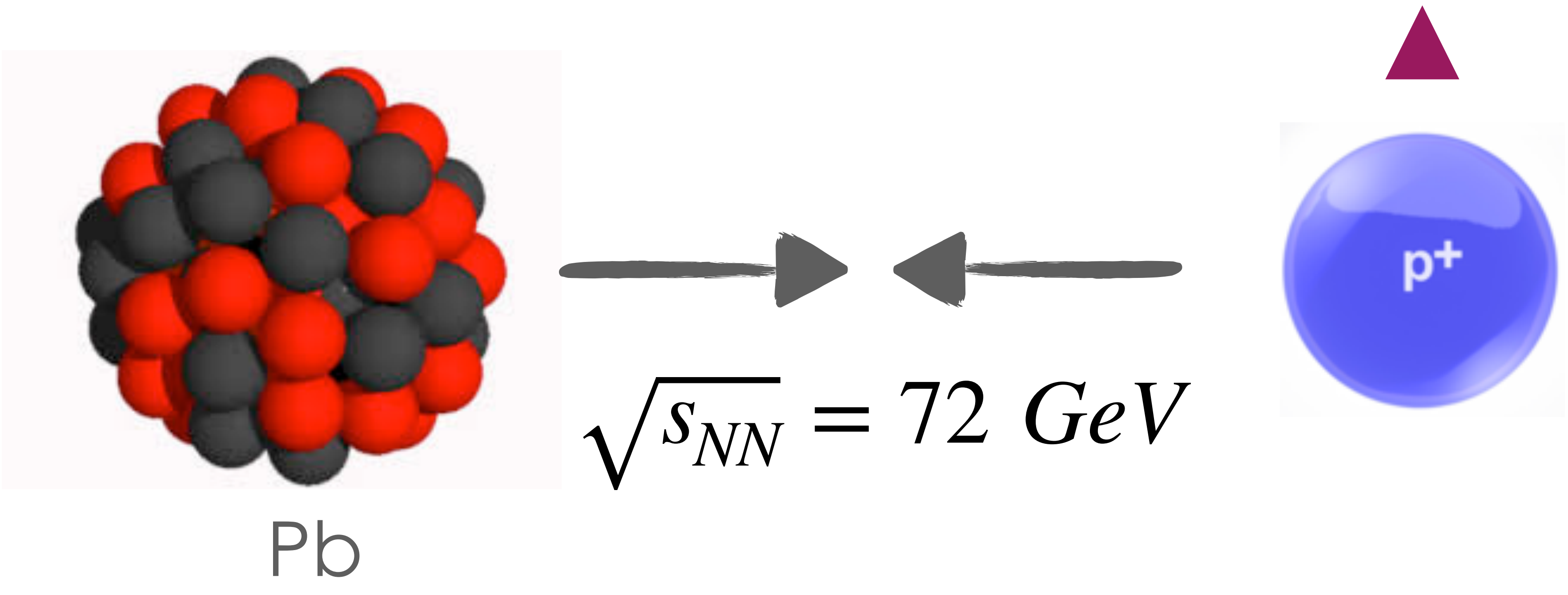
$j_3 = 0 \rightarrow$ **oblate fireball** corresponds to $v_2 > 0$



[PRC 101 (2020) 024901]

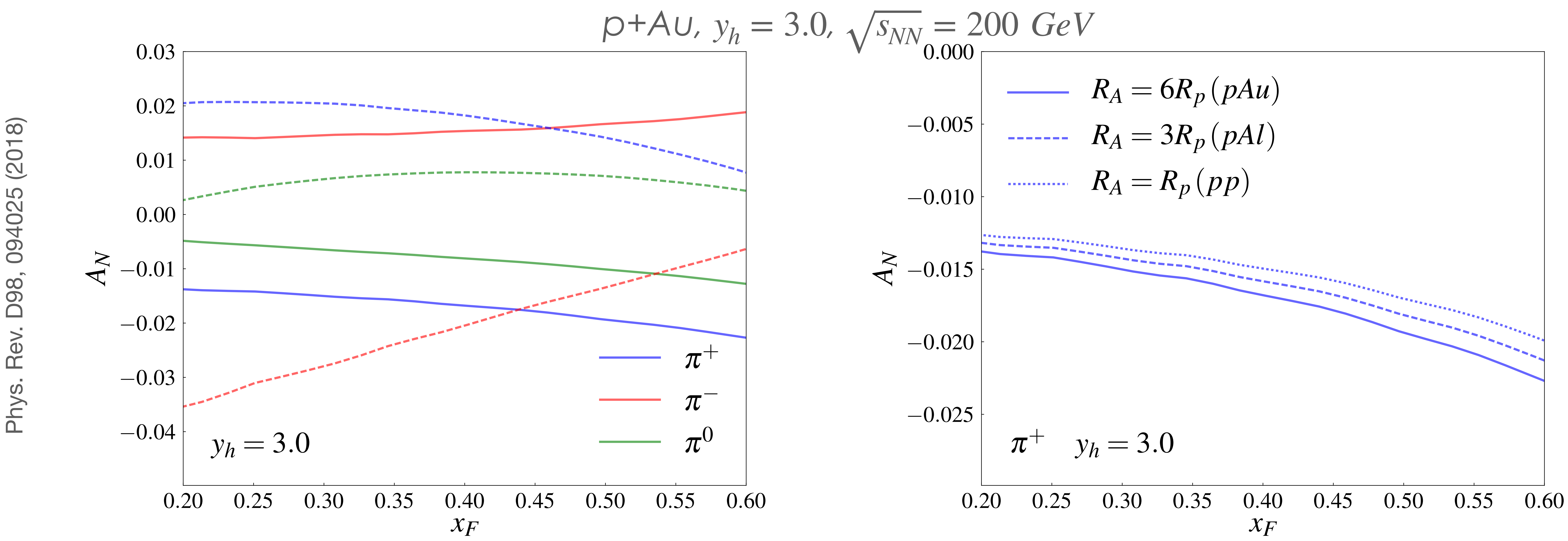
Wojciech Broniowski, Piotr Bozek

Spin physics in heavy-ion collisions



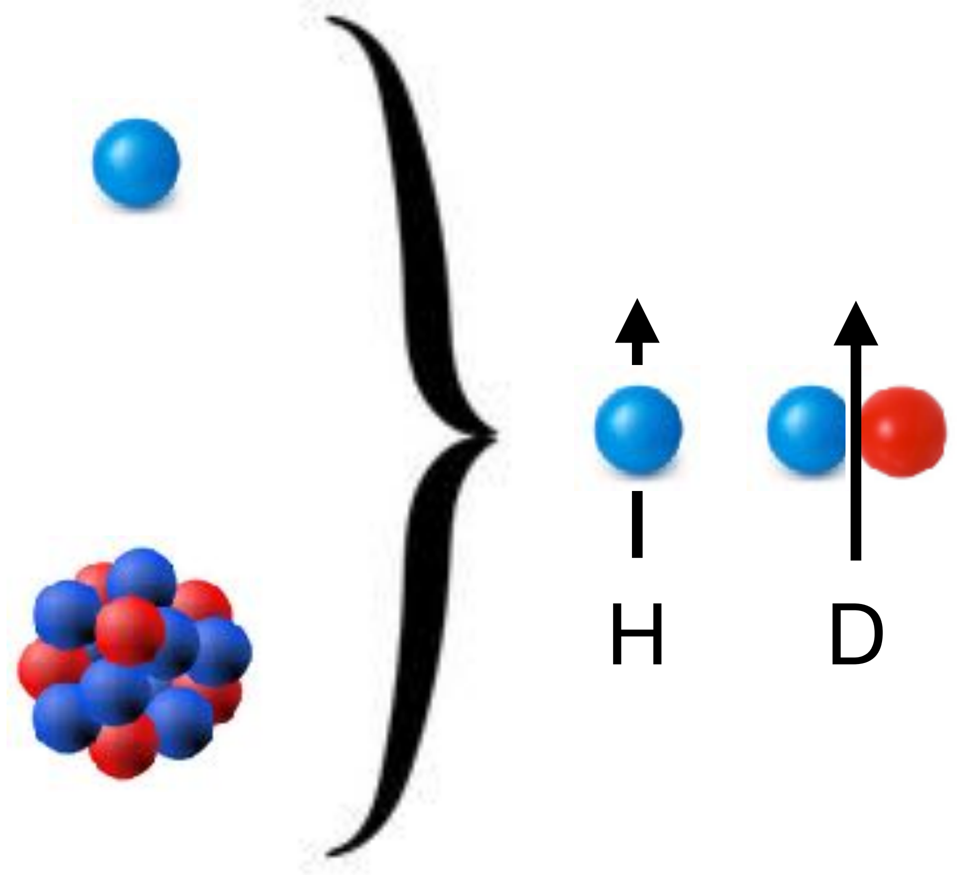
Single spin asymmetries in ultra-peripheral $p^{\uparrow}A \to hAX$ collisions

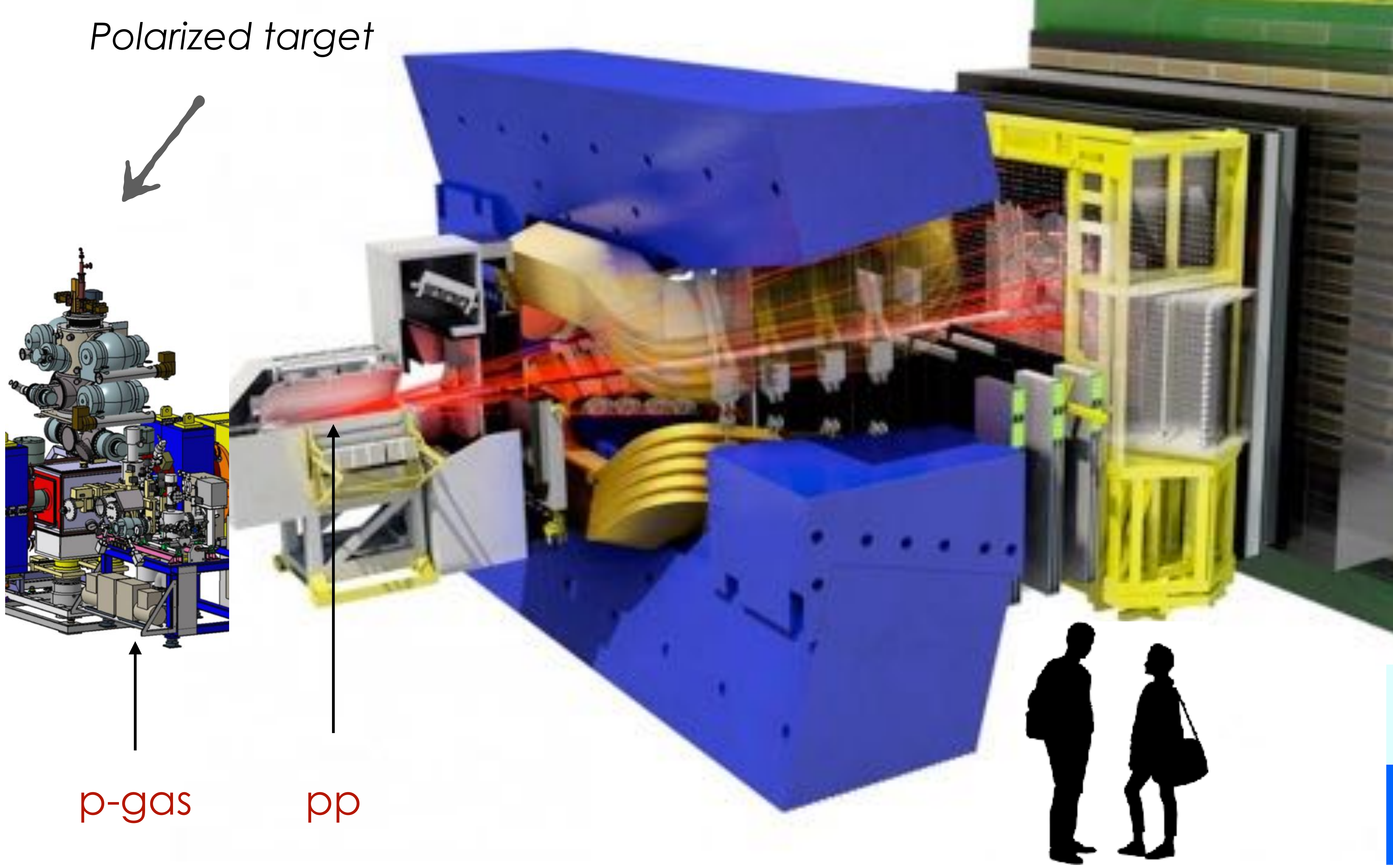
to test the assumed dominance of the contribution from twist-three fragmentation functions



kinematic region and required precision well fit the LHCspin potentialities

LHCspin a polarized target at LHCb





Successful technology based on HERA and COSY experiments

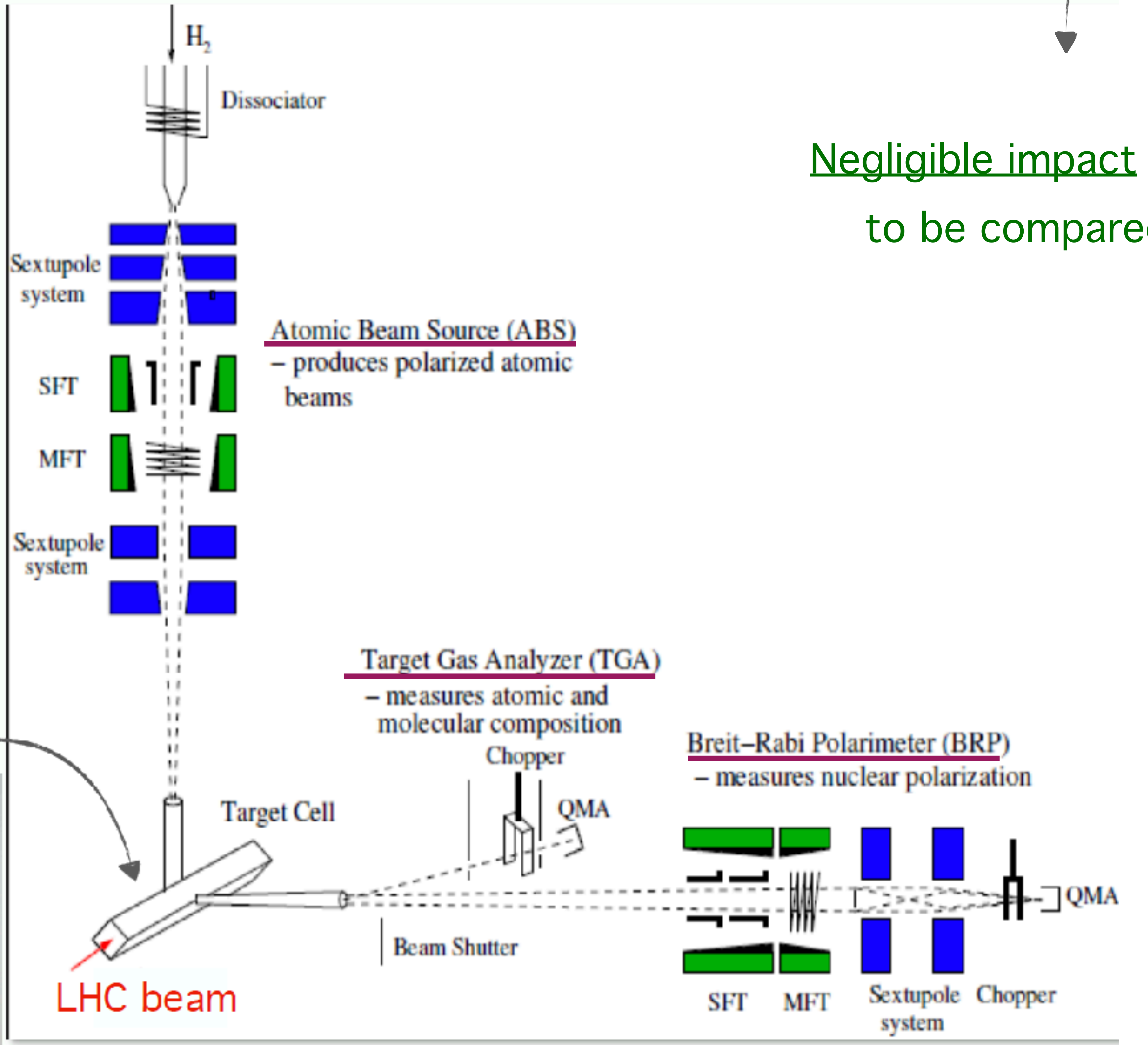
… but an extensive R&D is also required

LHCspin experimental setup

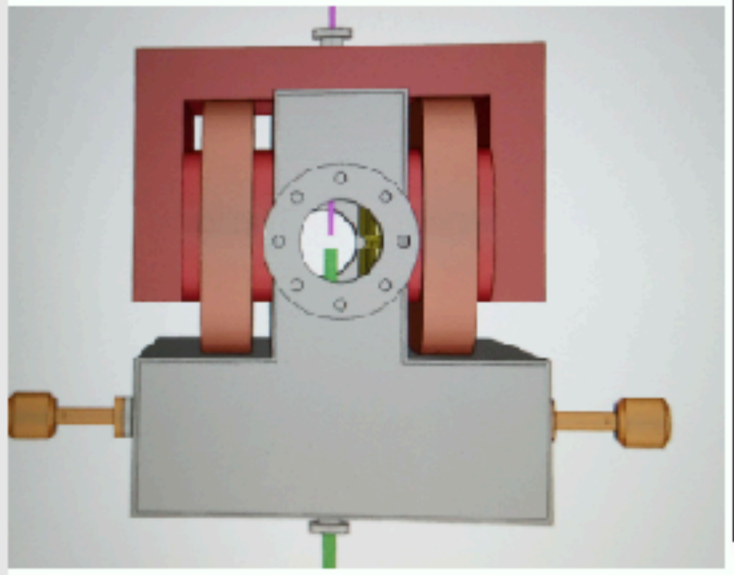
Target density (H) = 3.7×10^{13} cm^{-2}
LHC beam (Run5) = 6.8×10^{18} p s^{-1}

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

Negligible impact on the LHC beam lifetime, $\tau^{p-H}_{beam-gas} \sim 2000$ days
to be compared with the typical 10h of the beam lifetime



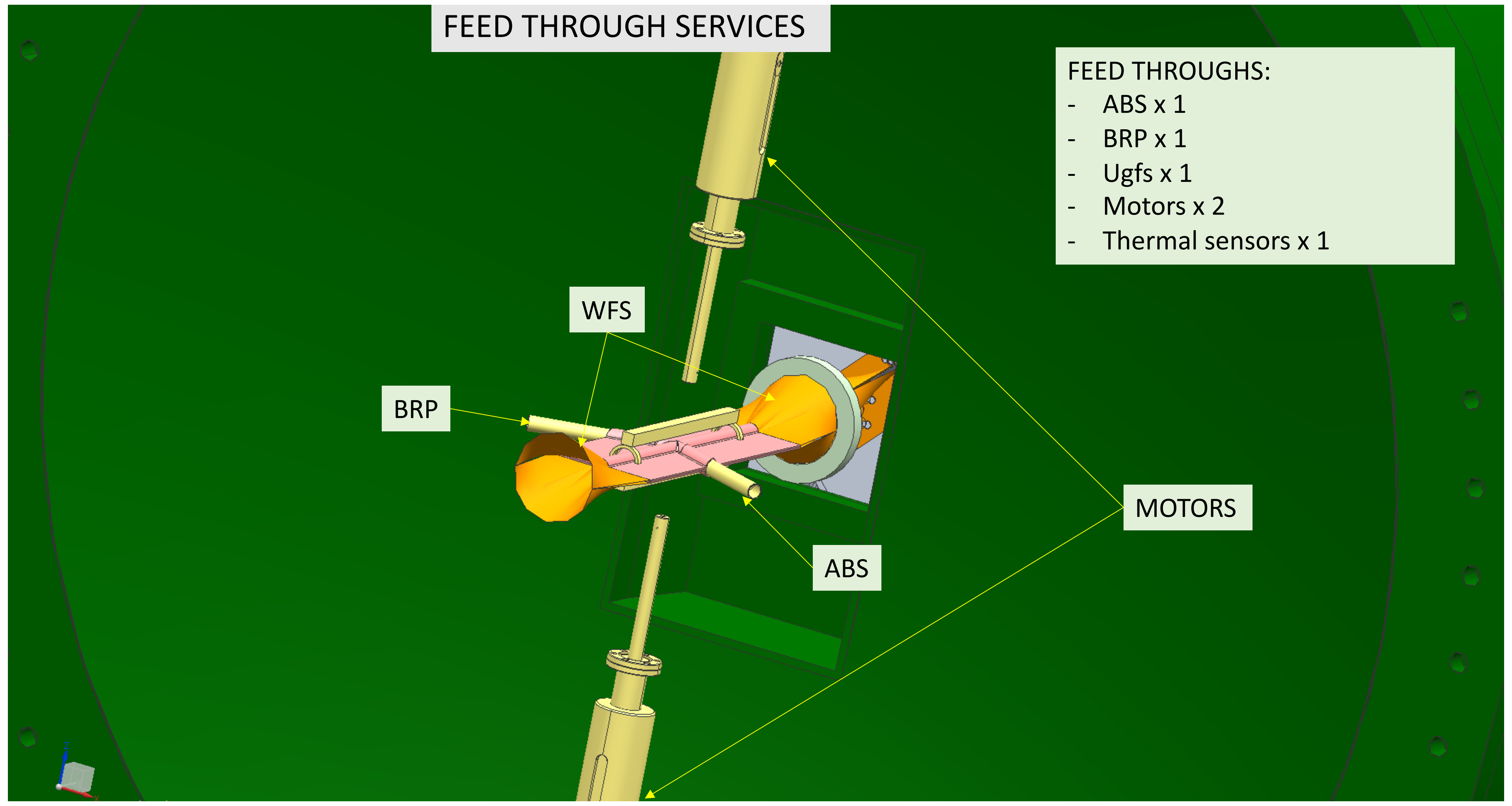
dipole



[NIMA 540 (2005) 68-101]

PGT implementation into LHCb

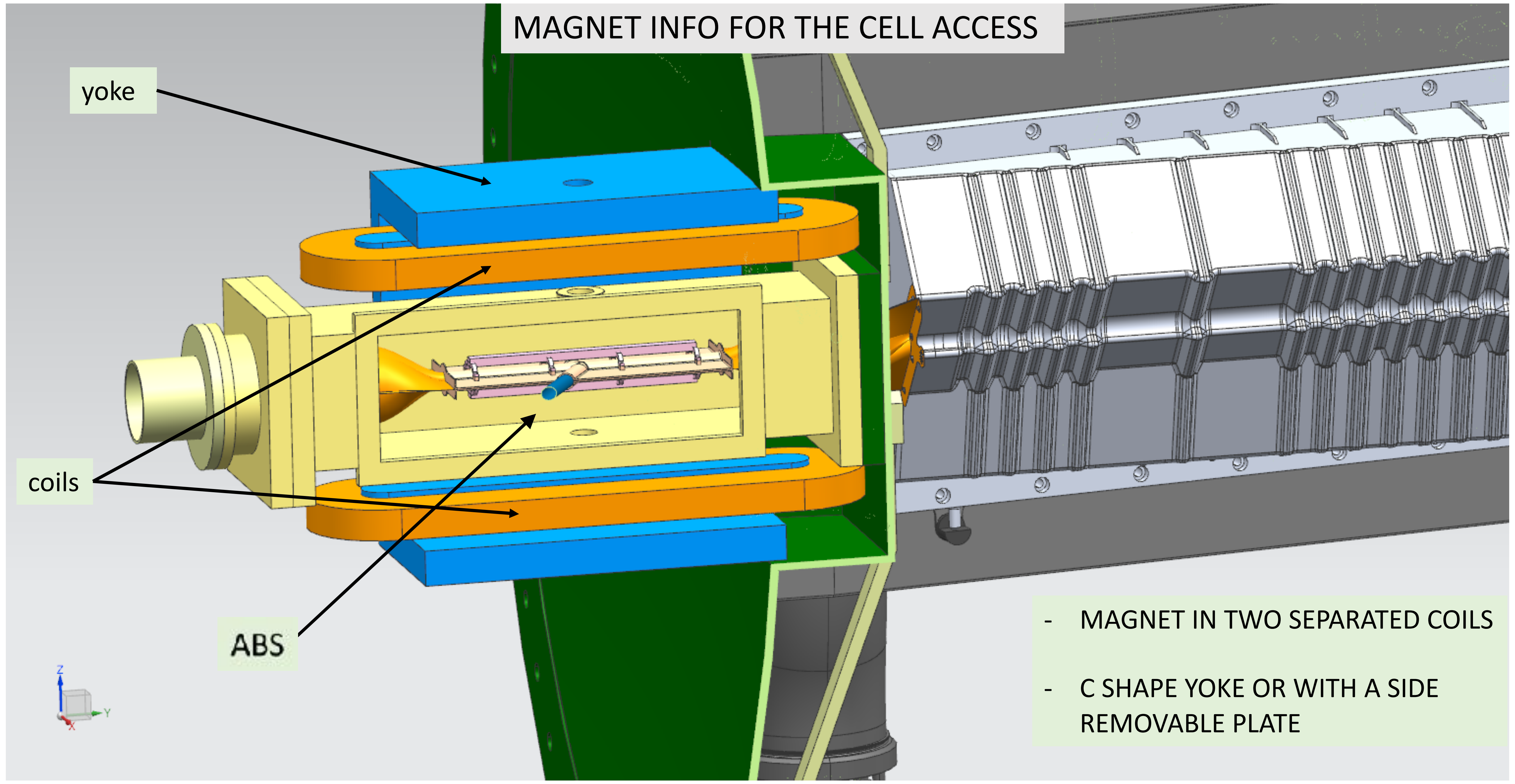
- Inject polarized gas via ABS and unpolarized gas via UGFS

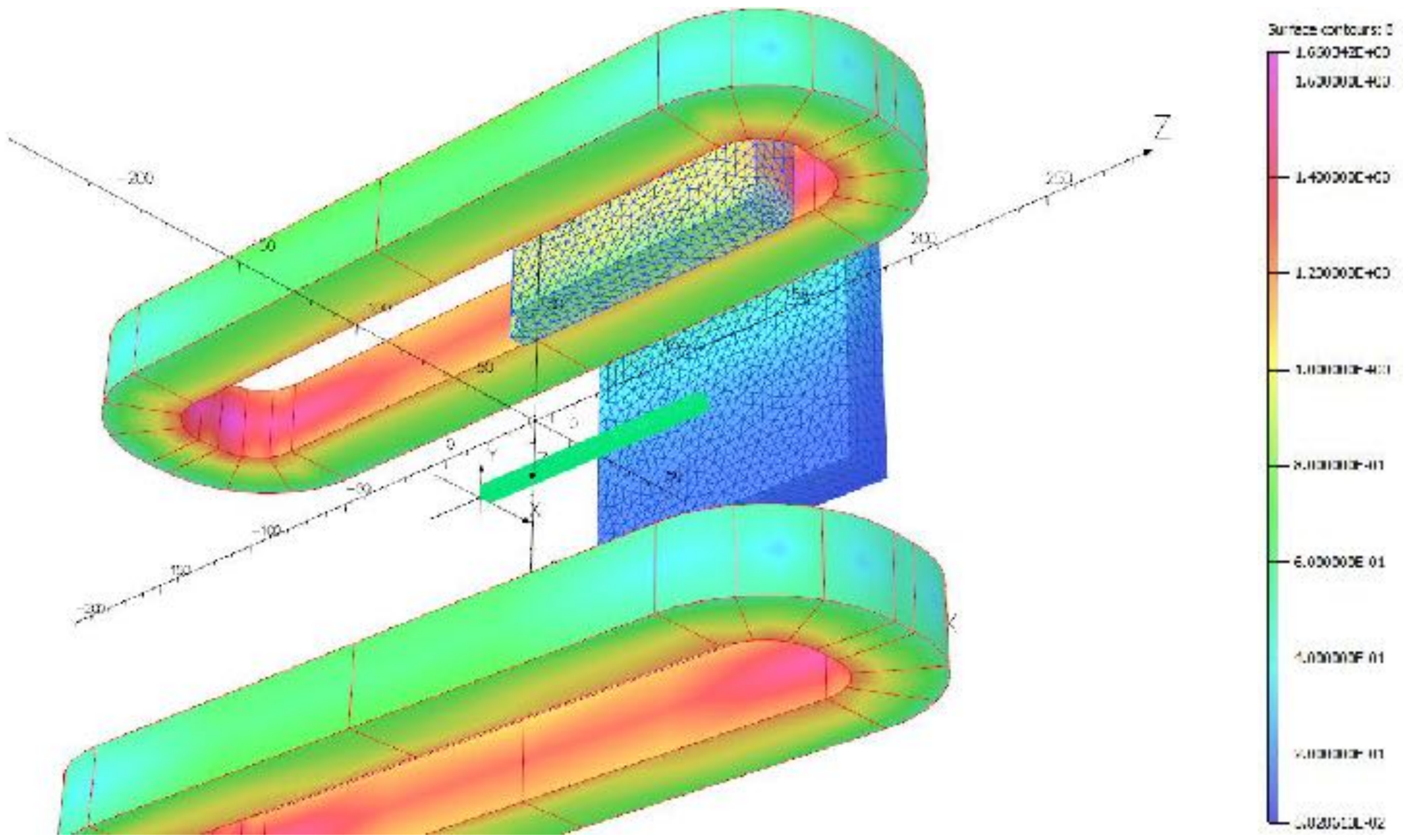


- Compact dipole magnet → static transverse field
- Superconductive coils + iron yoke configuration fits the space constraints
- $B = 300$ mT with polarity inversion, $\Delta B/B \simeq 10\,\%$, suitable to avoid beam-induced depolarization [PoS (SPIN2018)]

Possibility to switch to a solenoid and provide longitudinal polarization

Transverse polarization



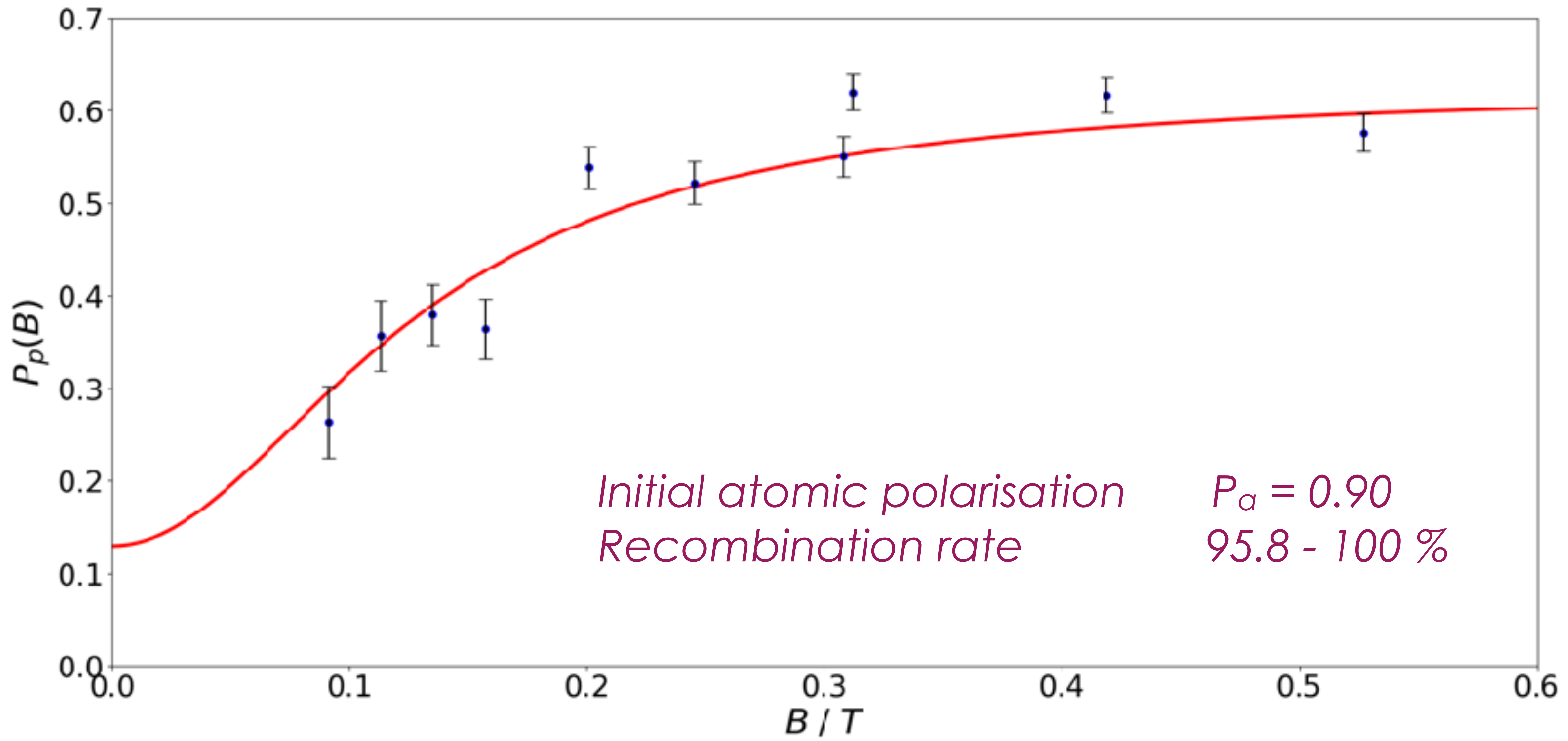


Role of the storage cell coating

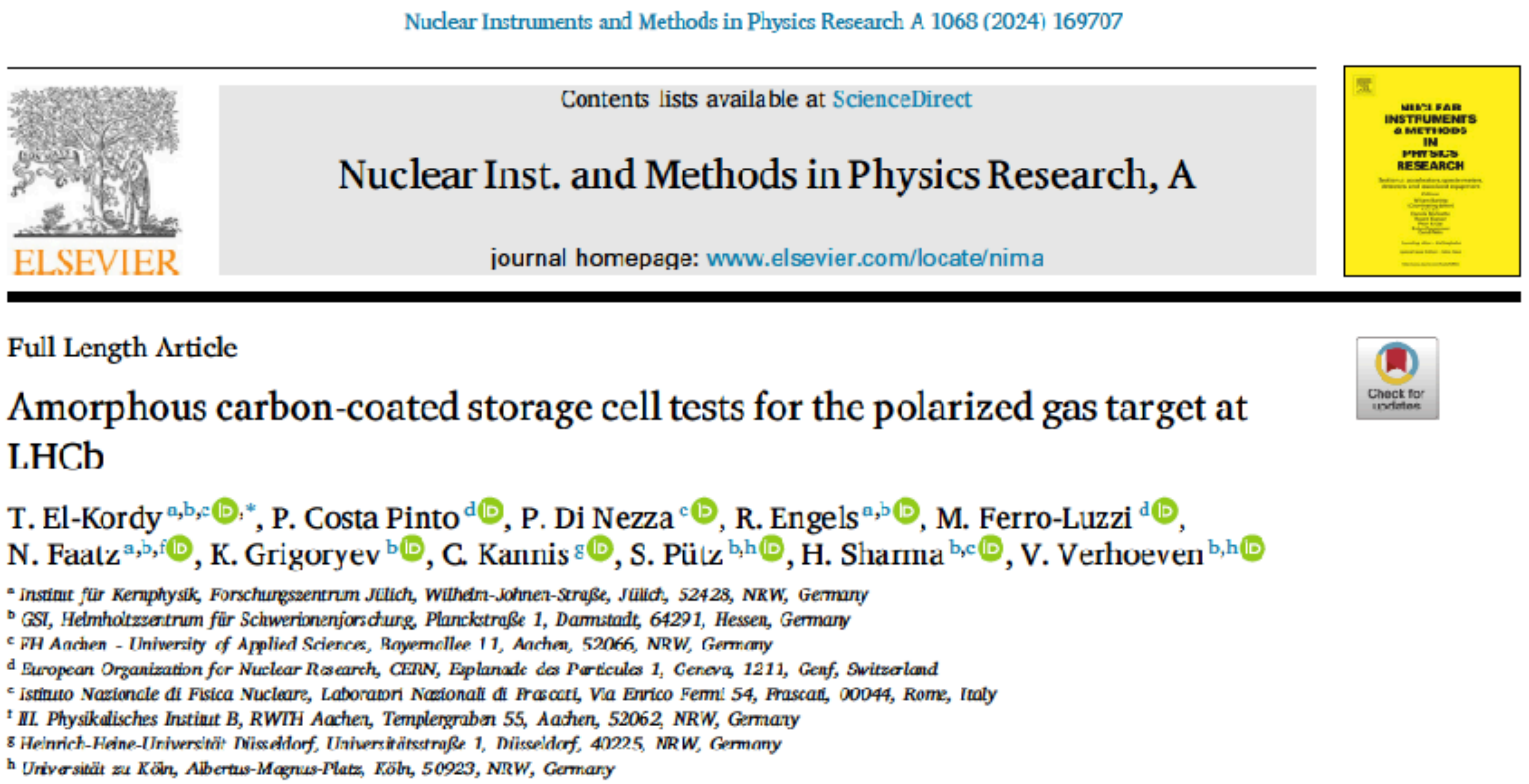
In previous experiments at HERA and COSY, Dryfilm (silicon) or Teflon (fluoride) coating, combined with ice layers, kept the SEY low and prevented recombination → This is not possible at LHC: no fluoride, no silicon materials allowed

The amorphous Carbon coating (the one used for SMOG2) provides almost full recombination and keeps a reasonable polarization

PoS PSTP2022 (2023) 036
PRL 124, 113003 (2020)
PRL 115, 113007 (2015)



Proton vector polarization for different magnetic fields



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Full Length Article

Amorphous carbon-coated storage cell tests for the polarized gas target at LHCb

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We can develop a new storage cell using polarized molecules →

- high density target
- but an <u>absolute polarimeter</u> is needed

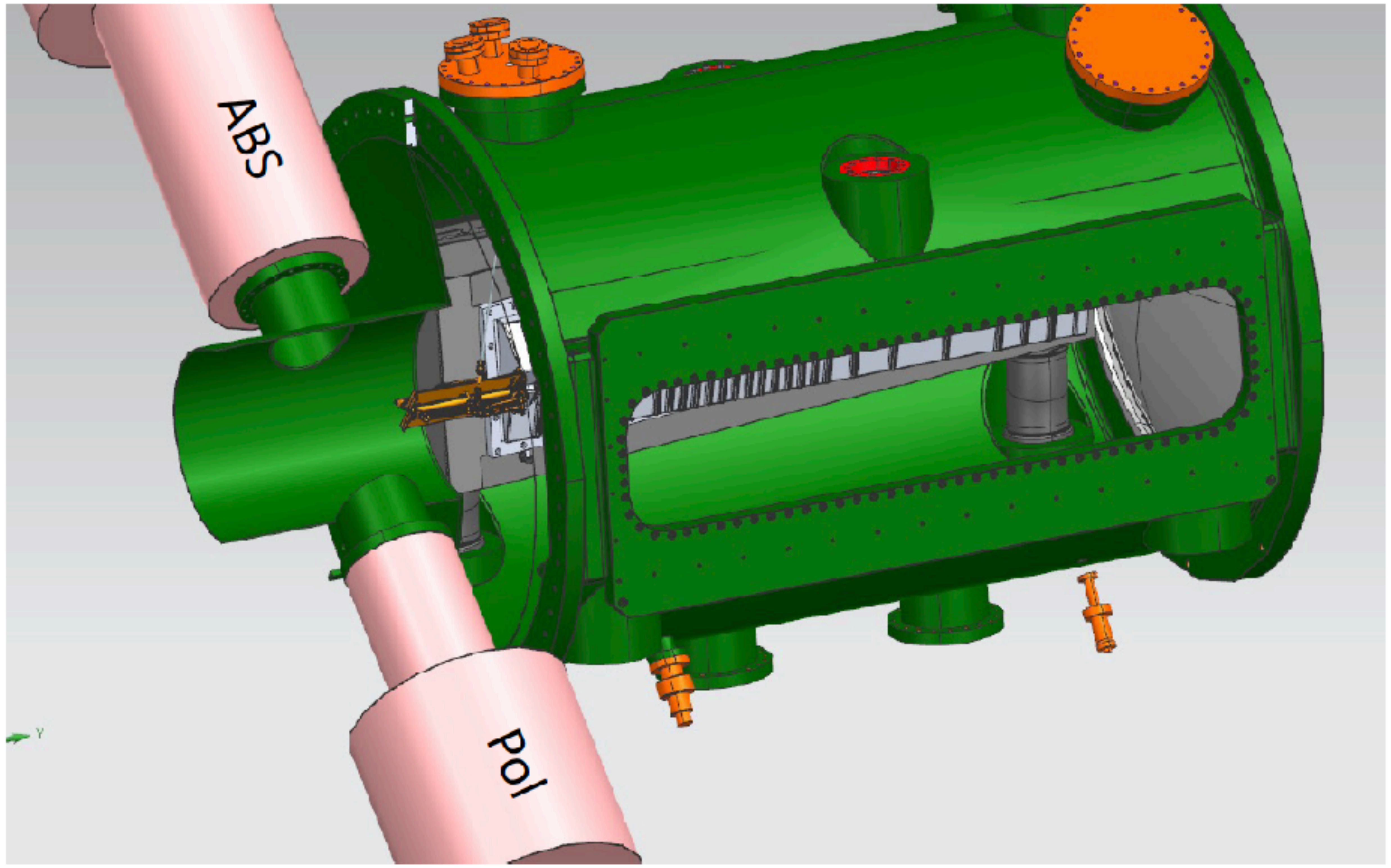
The backup: the jet target

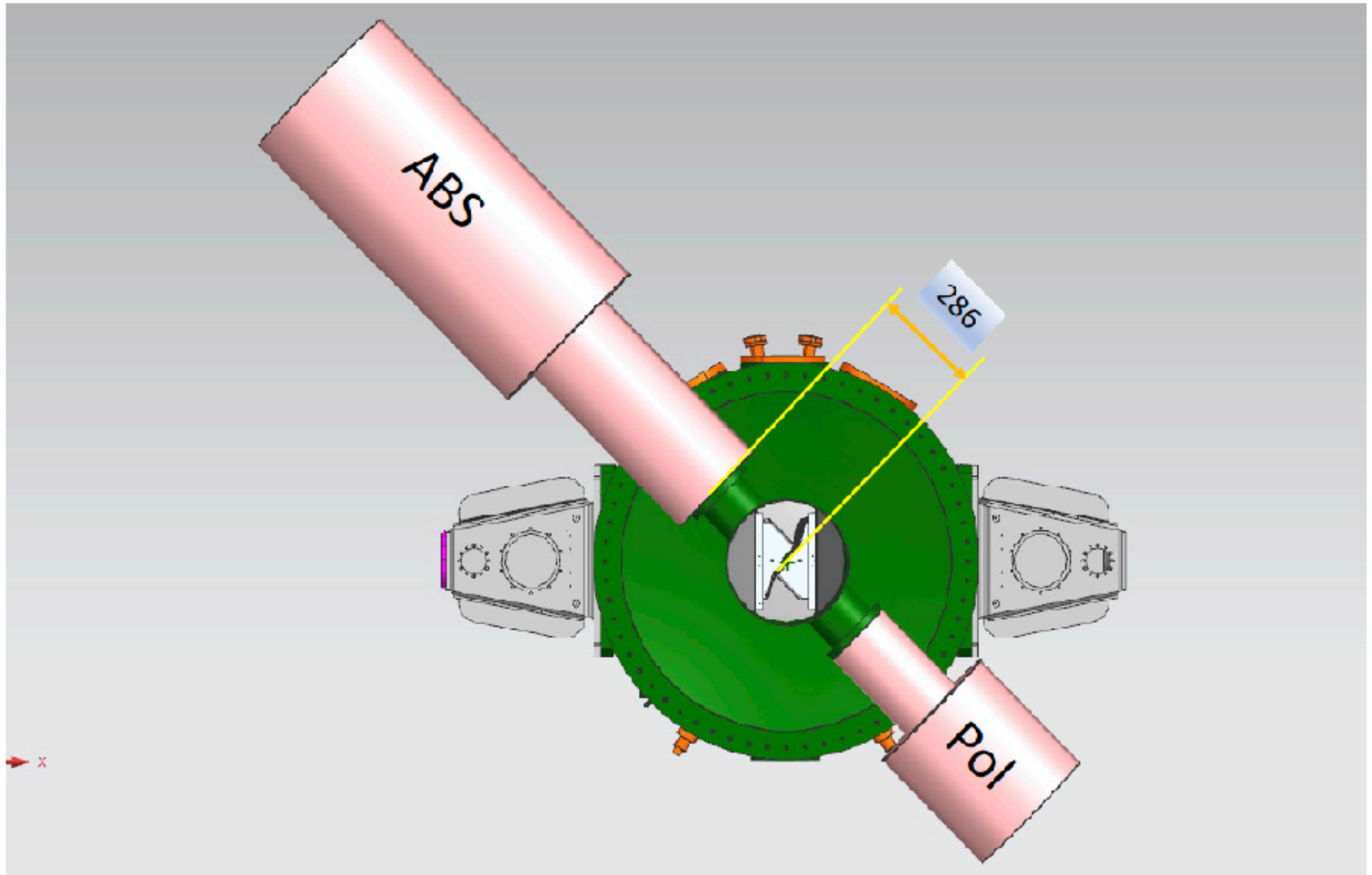
Alternative solution with **jet target** also under evaluation:

- lower density ($\sim 10^{12}$ atoms$/cm^2$)
- higher polarization (up to 90%)
- lower systematics in P measurement (virtually close to 0)

Pro
-no recombination
-high polarisation
-very small systematics on the polarisation measurements

Contra
-x40 less luminosity than the cell solution
(tolerable for the standard channels, relevant for the rare probes)





In this case the small dipole becomes a simple small Helmholtz coil that has basically no impact on the LHCb current or future setup

The plan is to develop the project in 2 phases:

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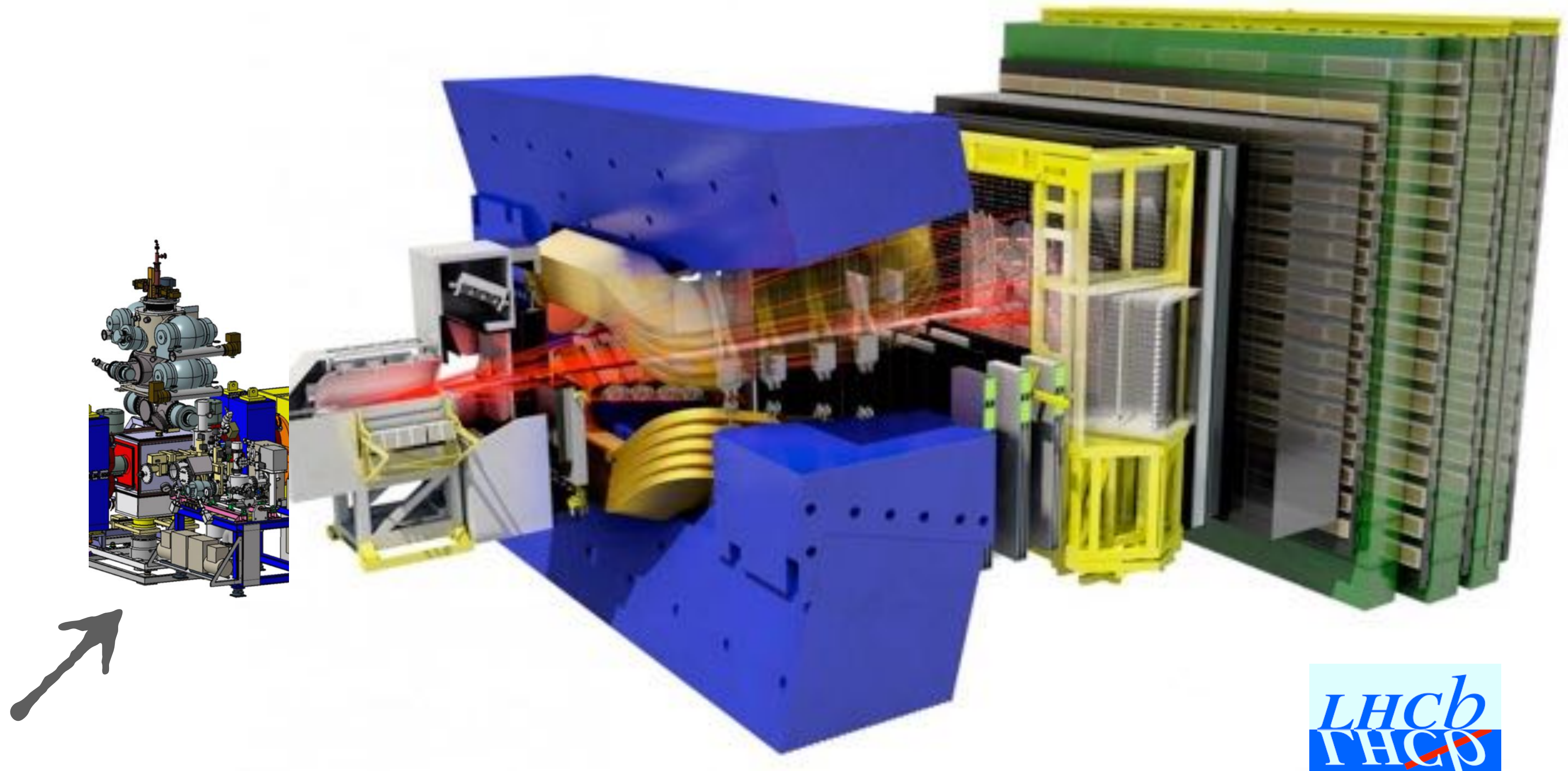
2

Install the PGT in LHCb for the Run5 and exploit all the enormous potentialities due to the LHCb (upgrade II) spectrometer: c-, b-quark reconstruction, rare probes, RTA, …



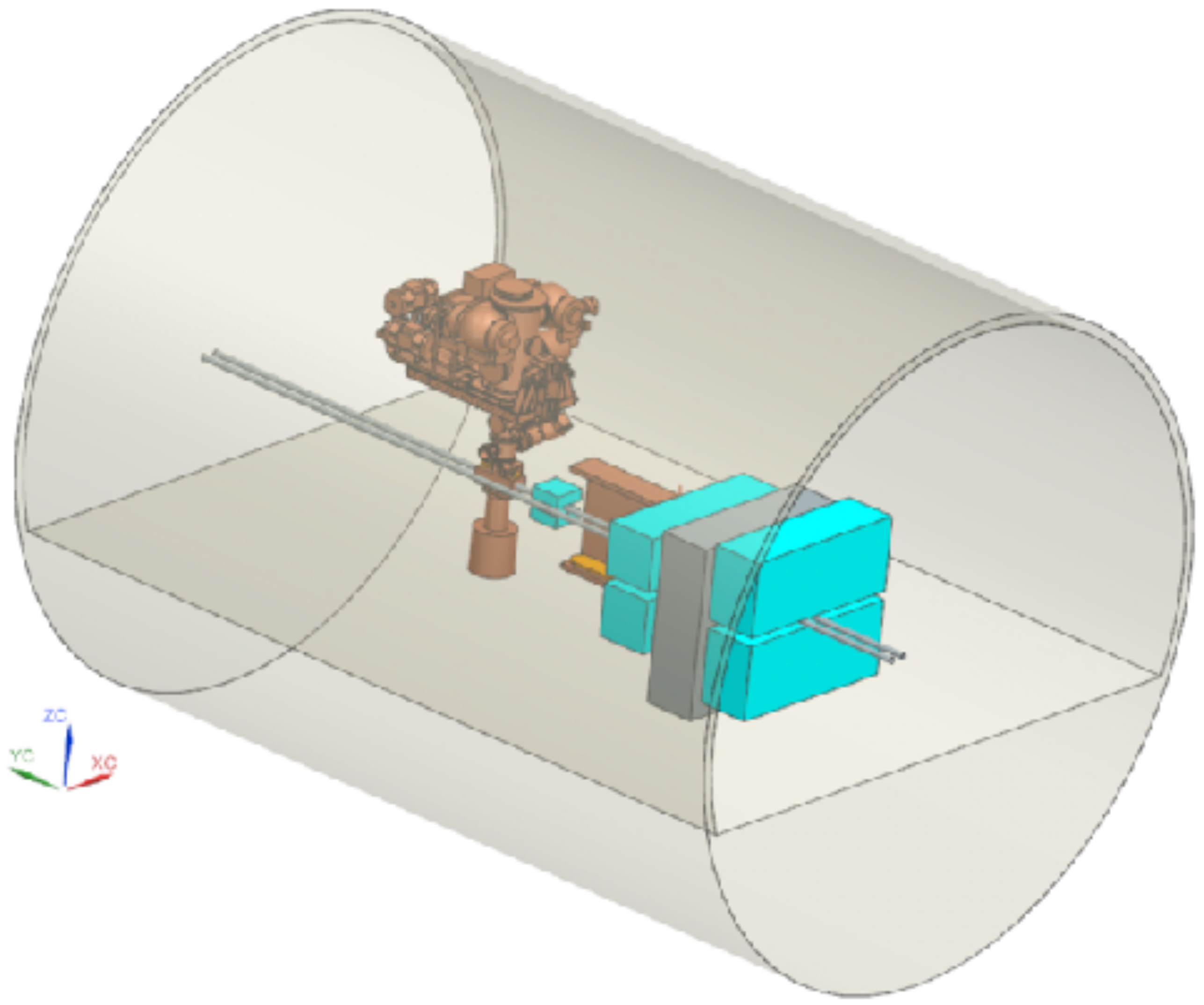
Polarized target

The plan is to develop the project in 2 phases:

1

Develop a compact - LHCb independent - apparatus capable of:

- conducting R&D to have a “plug & play” PGT for Run5
- perform physics measurements never accessed before
- perform measurements connected to LHC
- etc…



2

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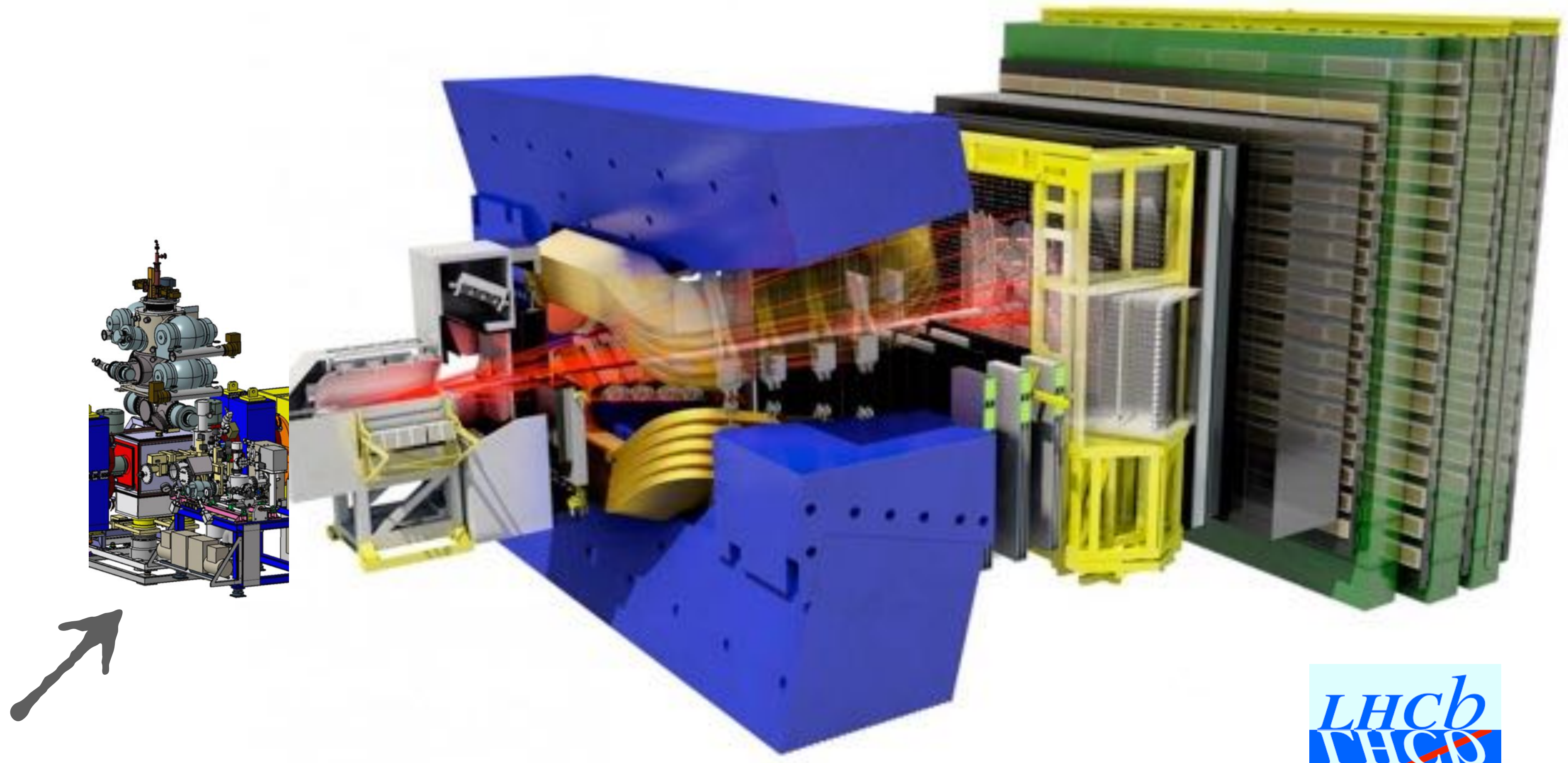
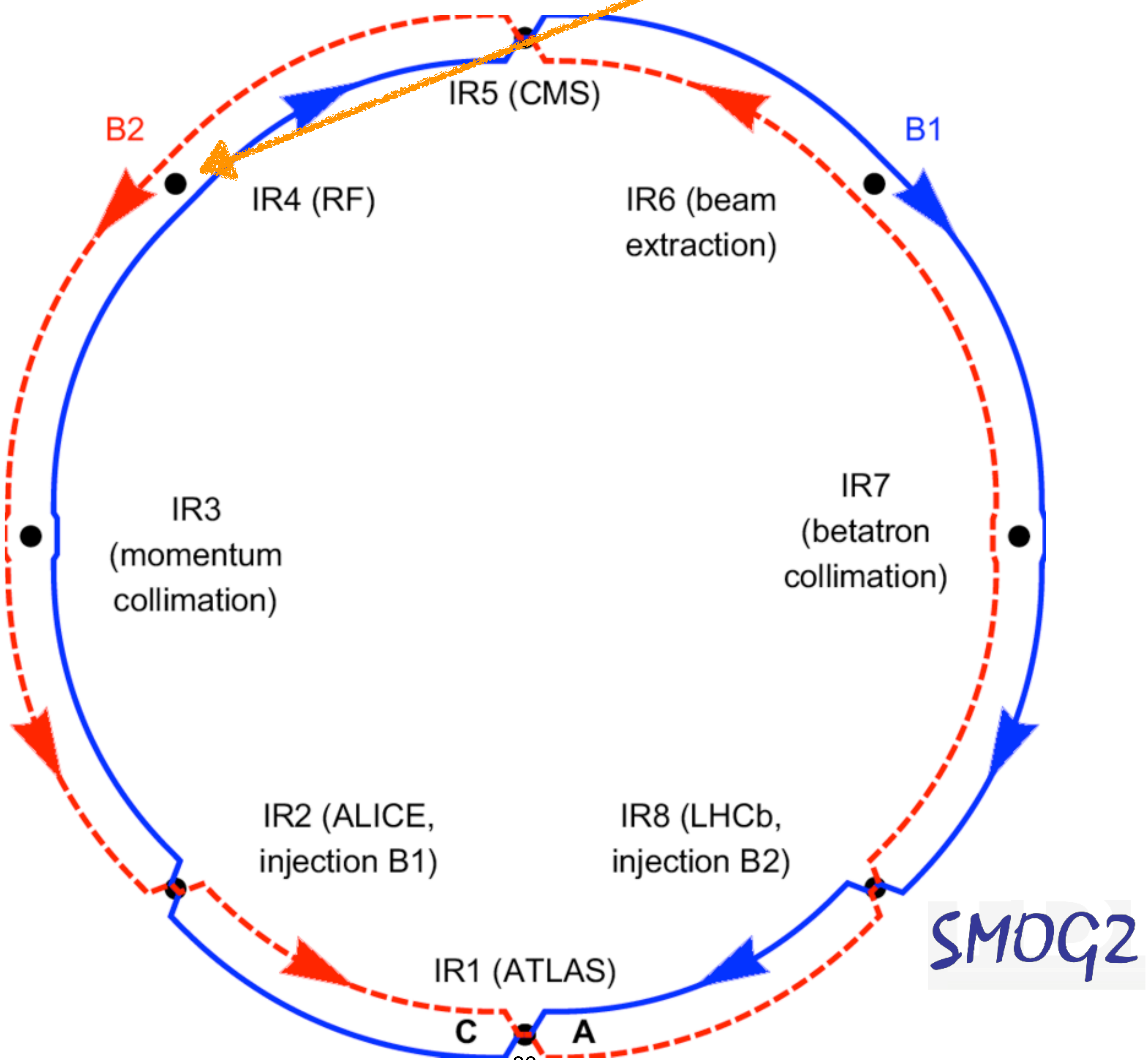


Polarized target

The LHC Interaction Regions



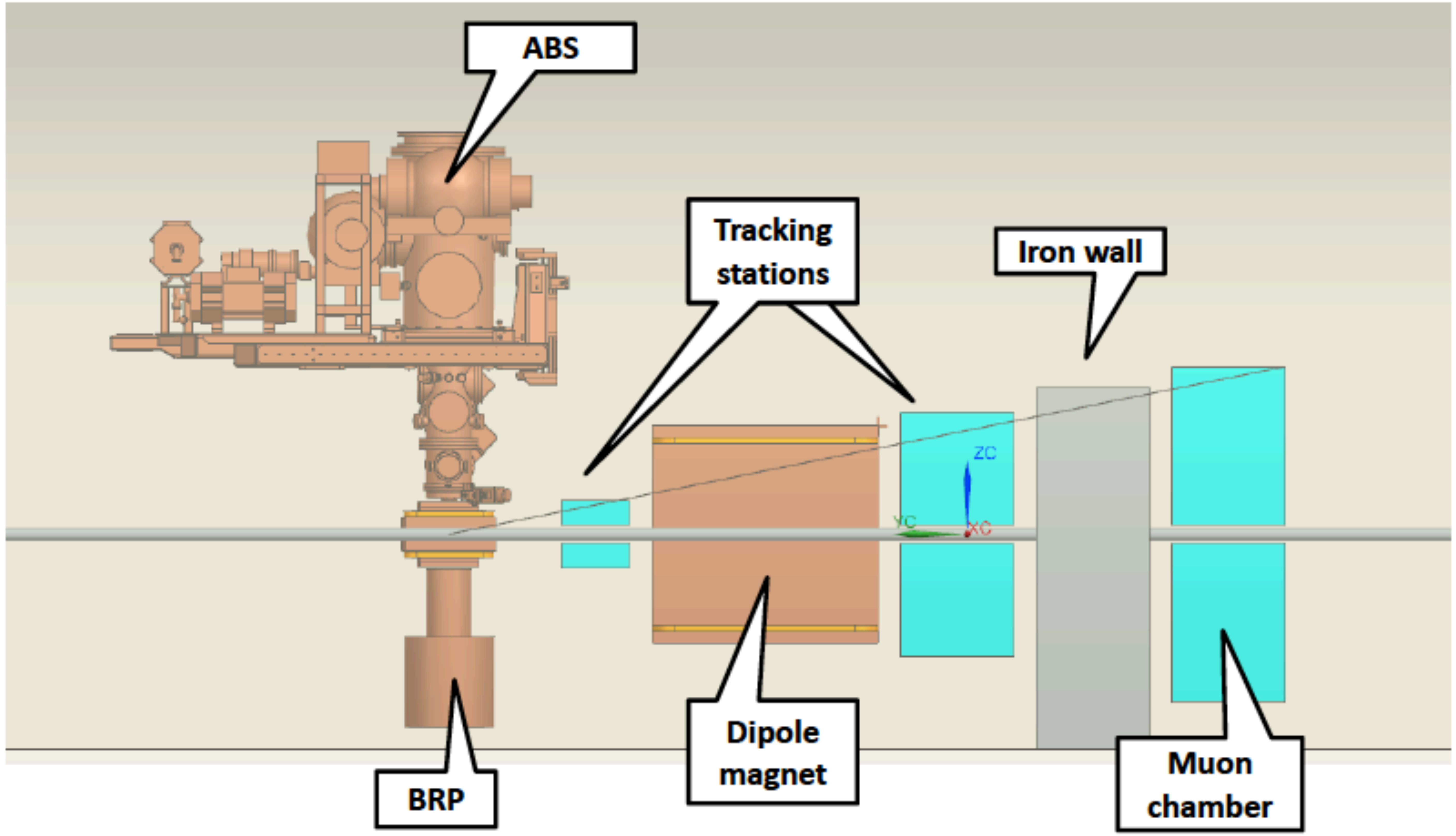
The LHC Interaction Region 4

Detector concept at the IR4

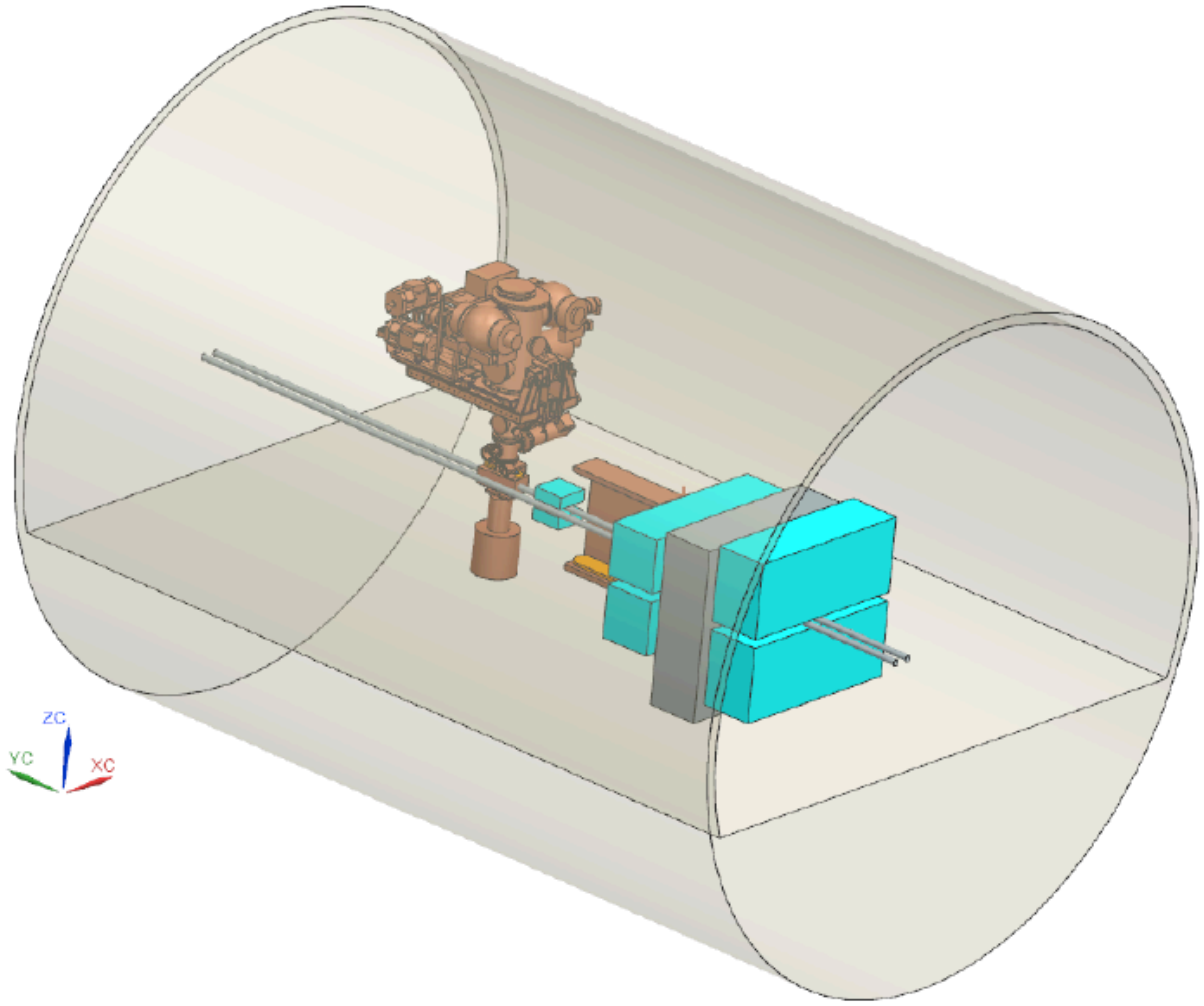
Goals:
- proof of principle of the future (large-scale) experiment with LHCb.
- measurement of single-spin asymmetries in inclusive hadron production in $pH^{\uparrow}$ and $PbH^{\uparrow}$ (see next slides)

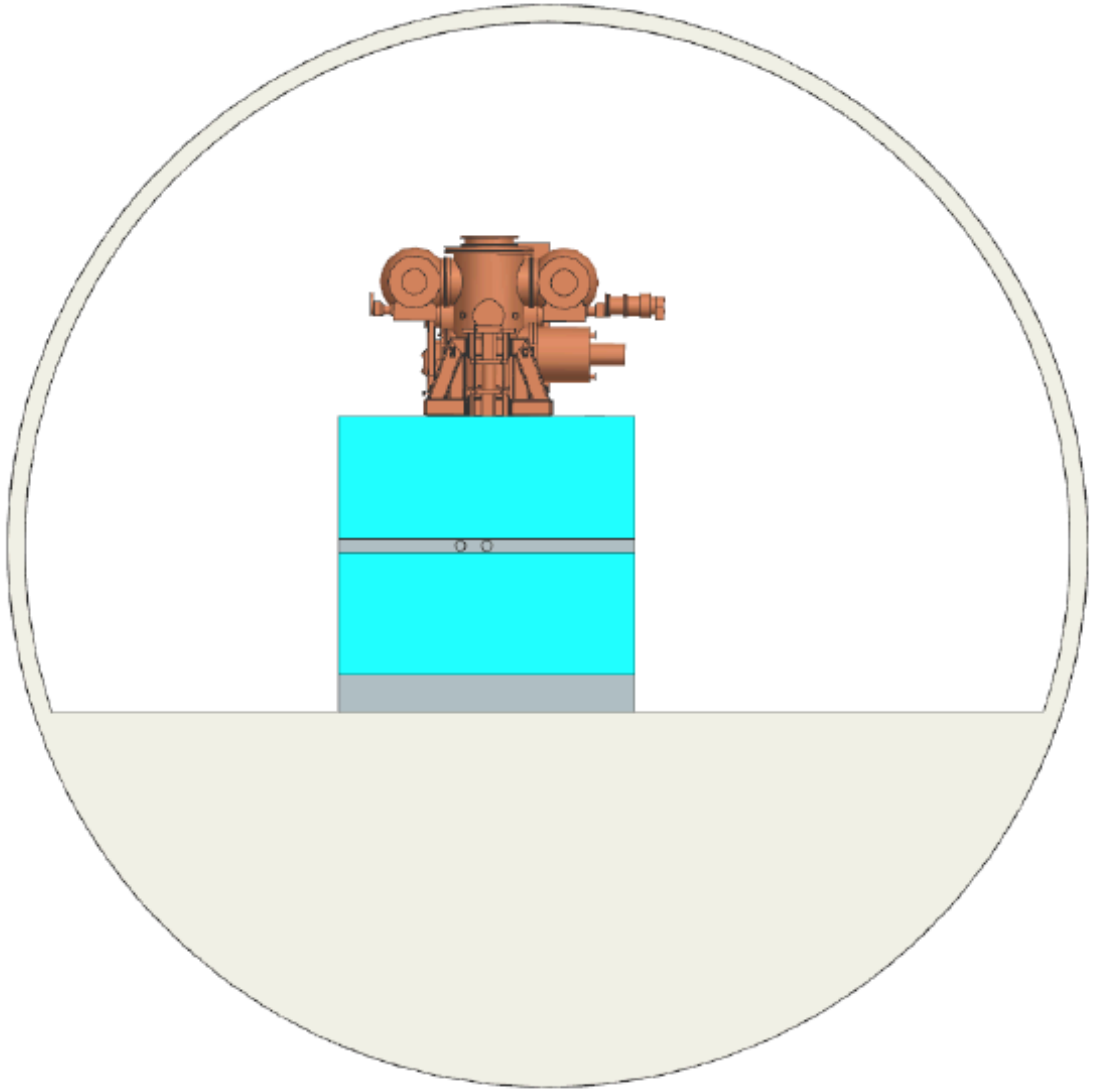
Apparatus:
- jet-target (but could be done also with storage cell)
- full (minimal) spectrometer: dipole magnet, tracking stations, muon system
- simple PID detectors (Calo, RICH)?

Needed expertise (apart from pol. target):
- dipole magnet
- tracking detectors (Si strip, SciFi, drift chambers?)
- muon chambers (MWPC?)
- electronics
- DAQ
- slow control
- tracking/reconstruction algorithms
- ...



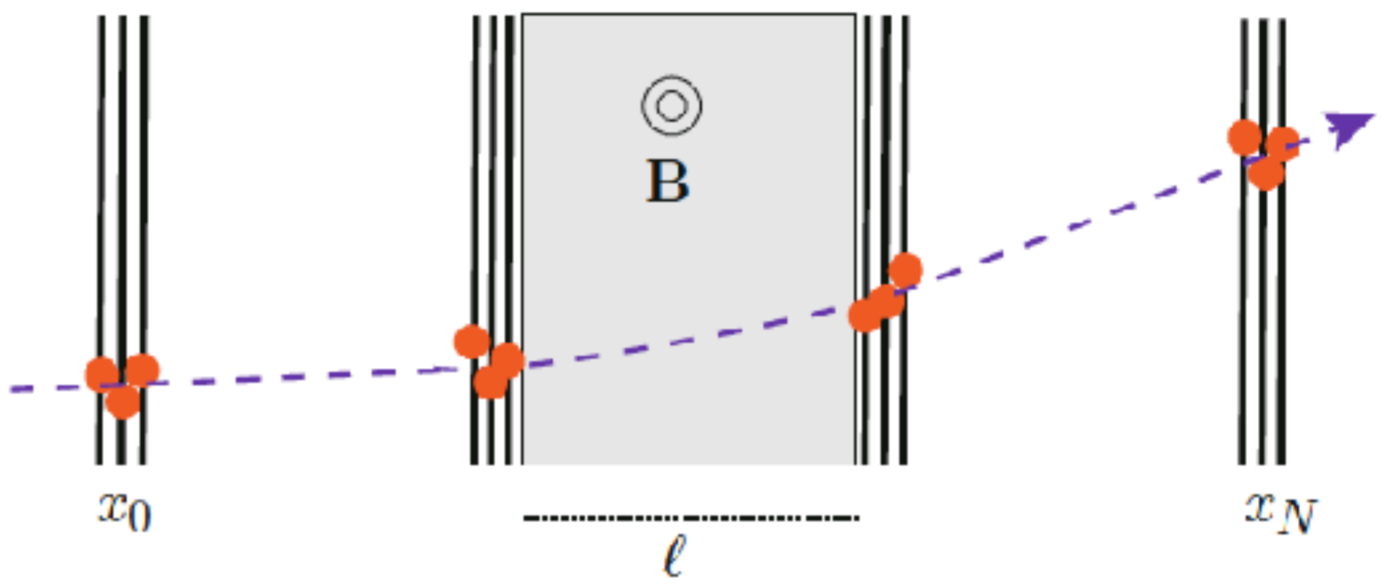
Detector concept at the IR4



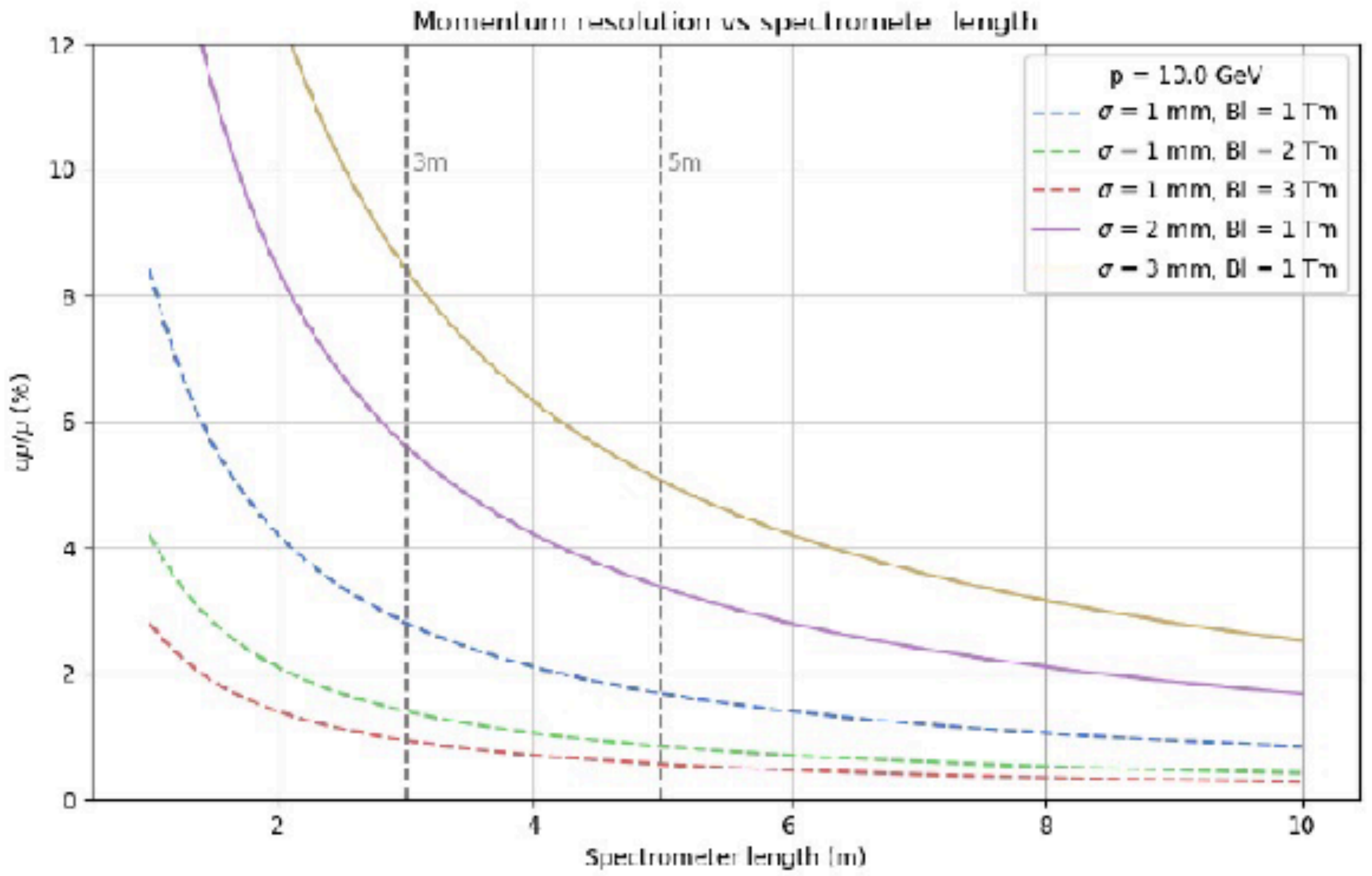


CAD LHC tunnel: JP Corso, CERN

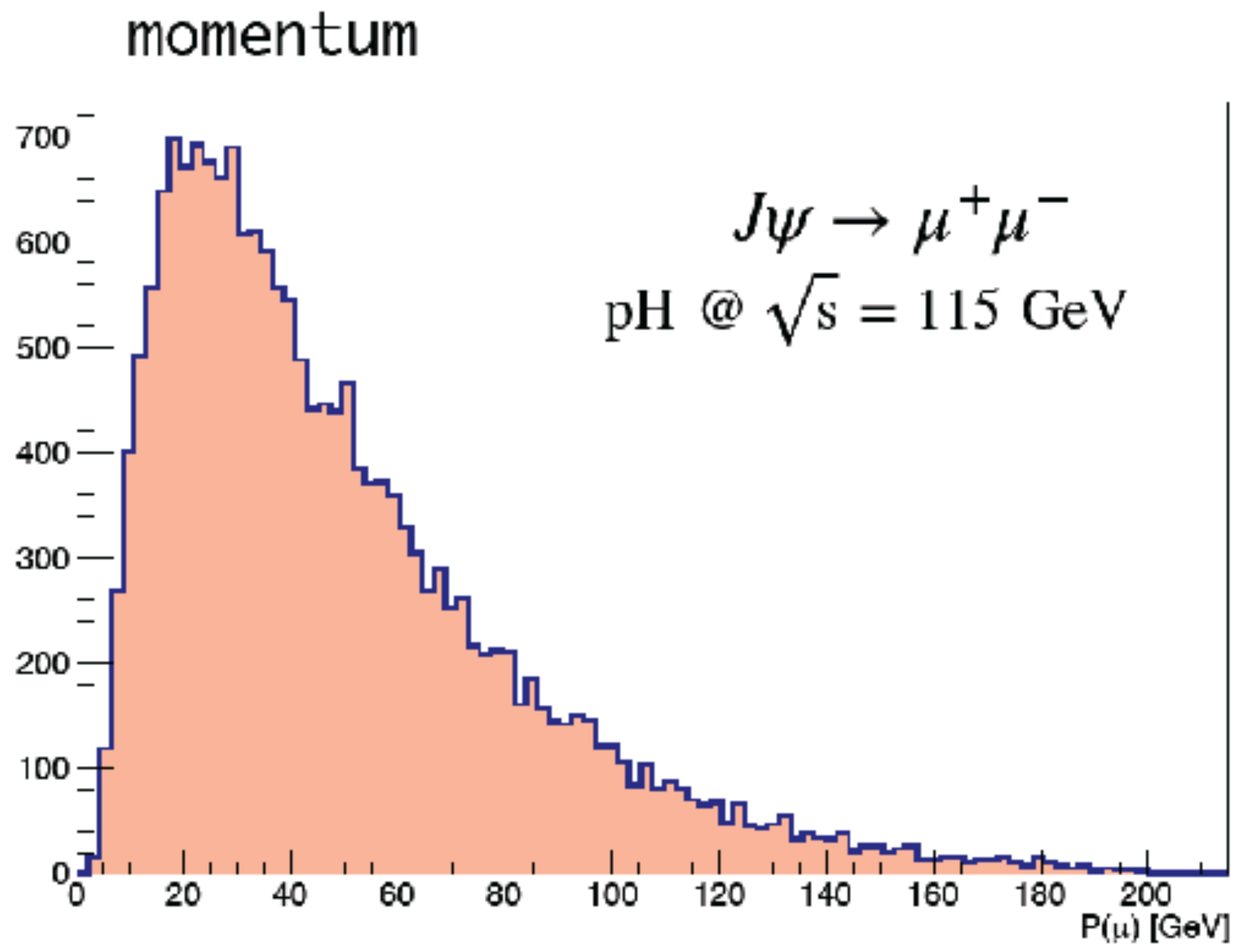
Even though the focus will be on polarimetry and beam interactions, we performed preliminary calculations to determine if a simple detector could meet our needs

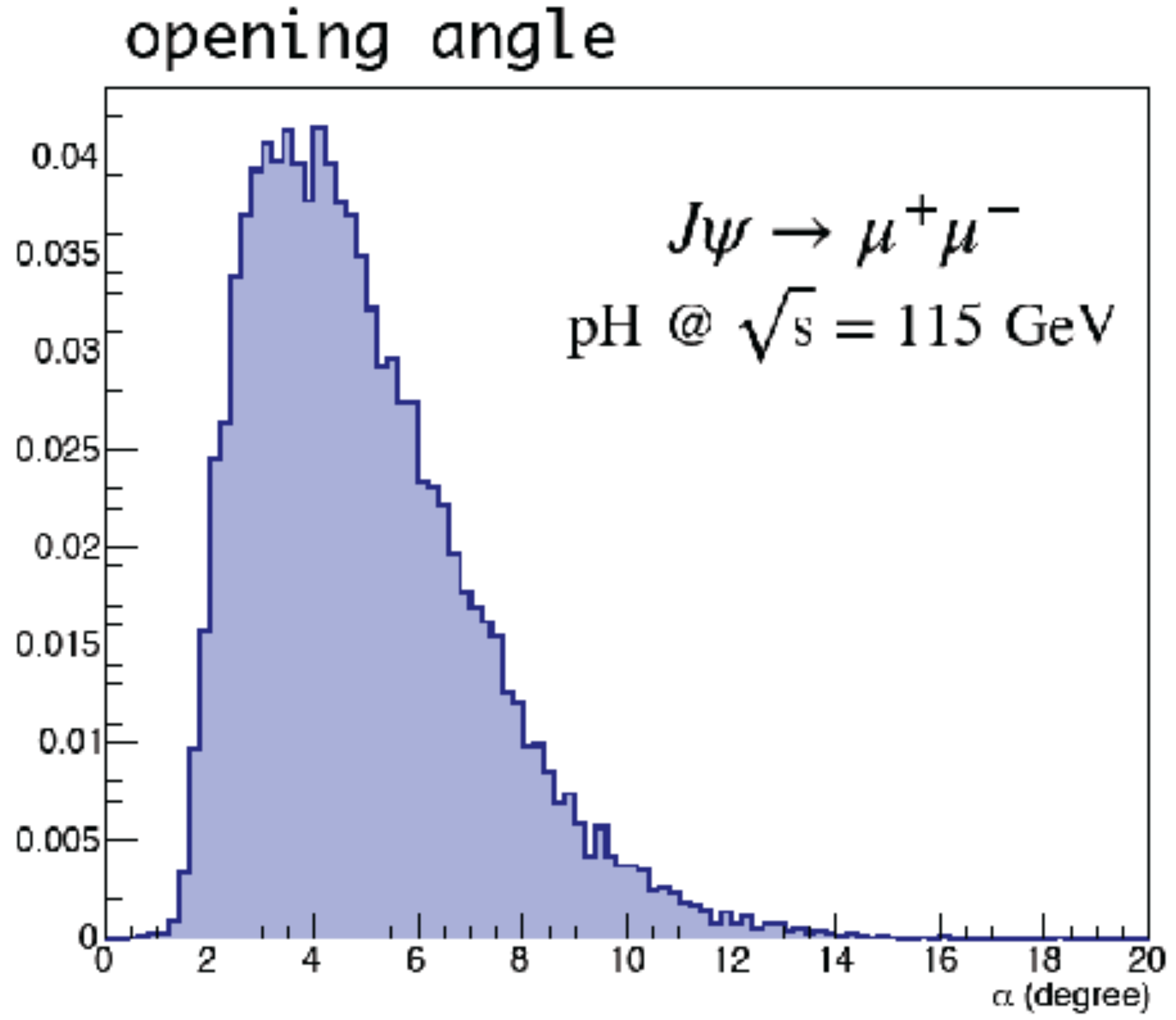


$$\frac{\delta p}{p} = \frac{8\sigma}{\sqrt{N+1}} \frac{1}{0.3z \cdot Bl \cdot L} p$$



we can achieve a resolution $\delta p/p < 1\,\%$ within a few meters of lever arm (depending on space constraints) for momenta up to a few GeV and with N = 10 hit measurements

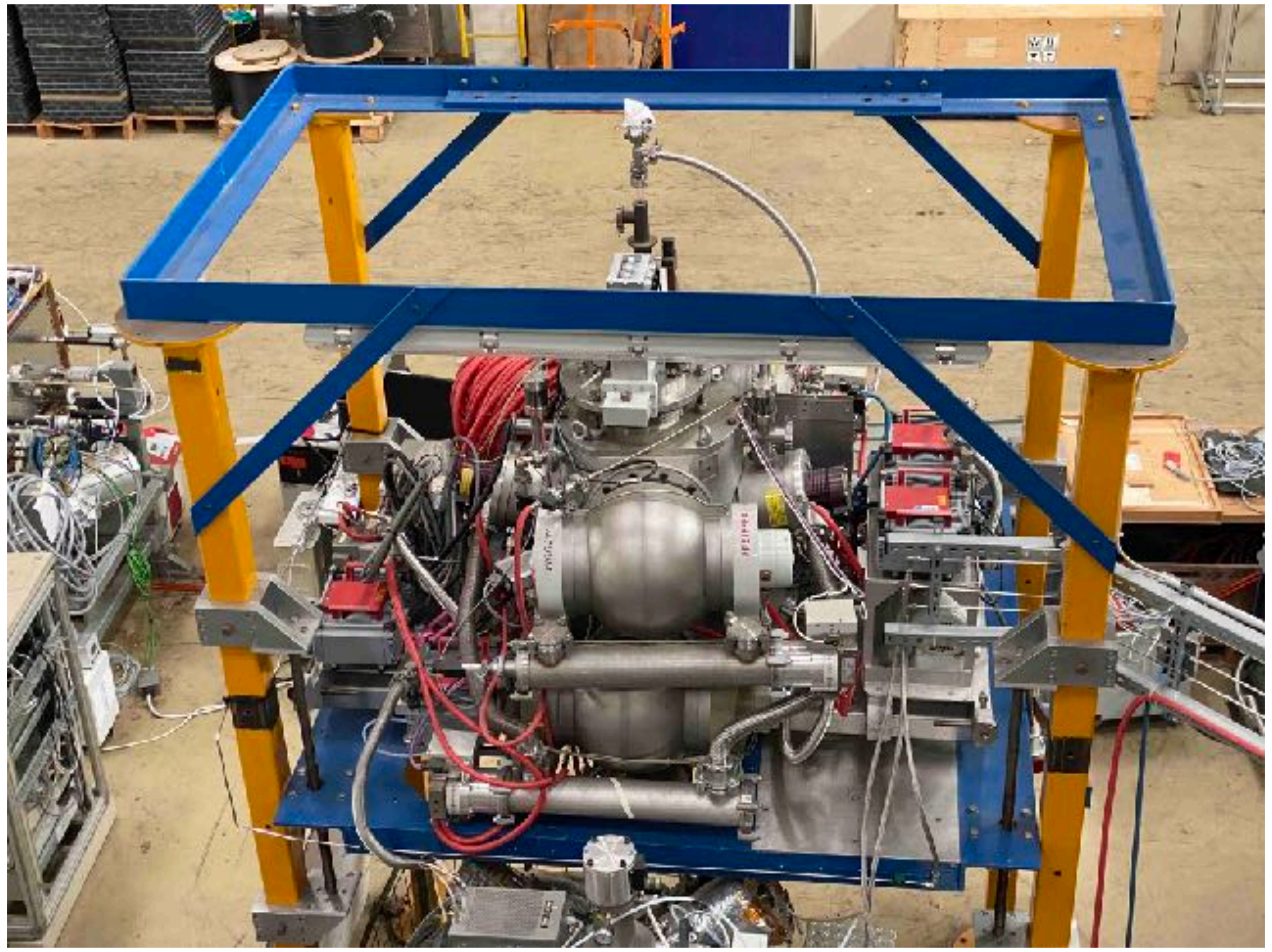




with $\delta p/p \sim 1\,\%$ we have $\delta m \sim 40$ MeV, excellent for any other measurement

it is even possible to have a ToF PID $@3\sigma$ level for $\pi - K$
$p \sim 1\ GeV \rightarrow \sigma_T \mathcal{O}(100)\ ps$

The target system has been moved from Julich to Ferrara. We have identified the tasks required for the initial phase of refurbishment and modifications to ensure compliance with LHC requirements



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-LHCC-2024-010
LHCb-TDR-026
September 2, 2024

LHCb Upgrade II Scoping Document

LHCb collaboration

Abstract

A second major upgrade of the LHCb detector is necessary to allow full exploitation of the LHC for flavour physics. The new detector will be installed during long shutdown 4 (LS4), and will operate at a maximum luminosity of $1.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. By upgrading all subdetectors and adding new detection capability it will be possible to accumulate a sample of $300\,\mathrm{fb}^{-1}$ of high energy pp collision data, giving unprecedented and unique discovery potential in heavy flavour physics and other areas. The baseline LHCb Upgrade II detector has been presented in a Framework Technical Design Report that was approved in 2022. Here, updates are presented alongside scoping options with reduced detection capability and operational luminosity. The costs and physics performance of each scenario are discussed, and an overview of the project management plans is presented.

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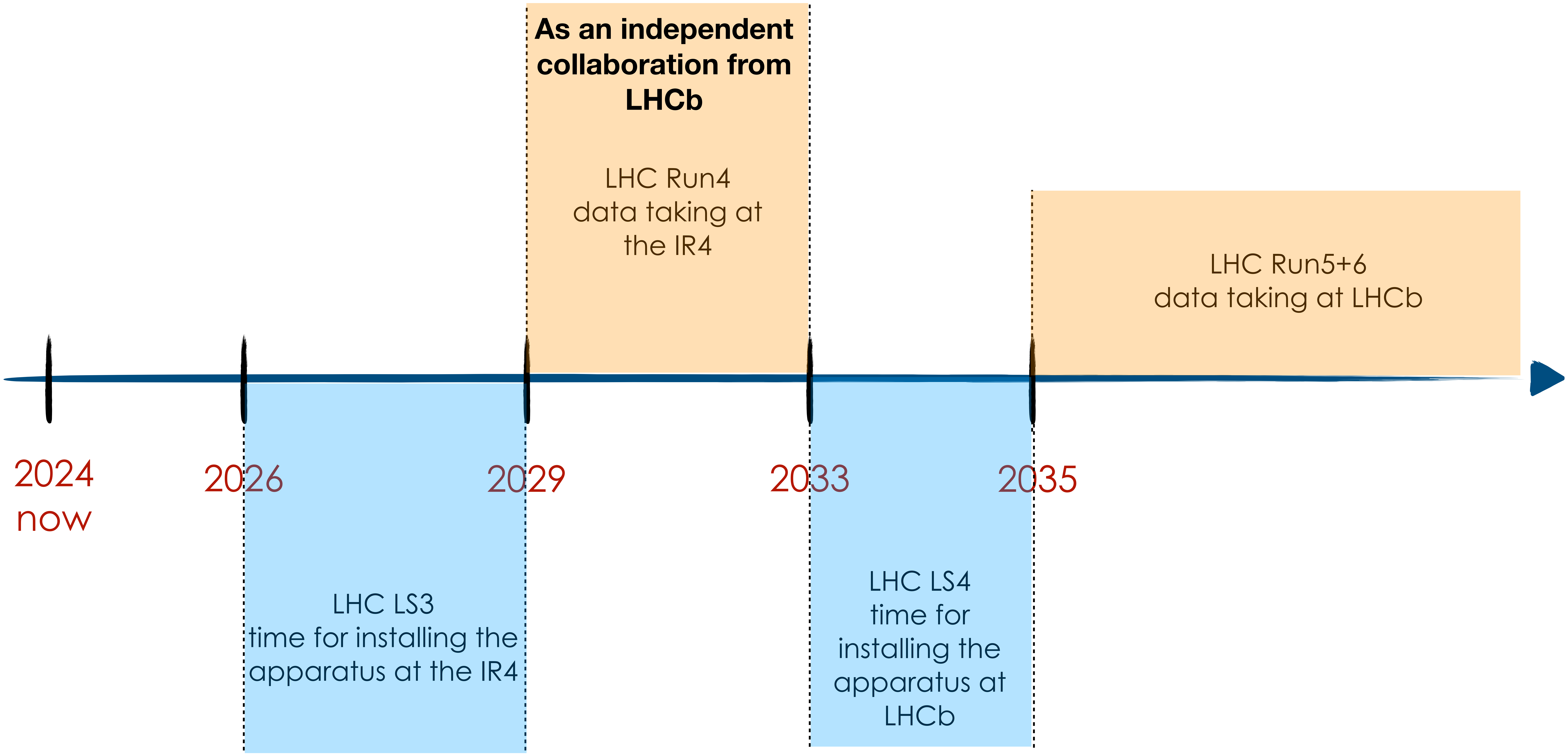
The polarized target is part of the LHCb Scoping Document for the Upgrade II

The interaction with the LHC experts is ongoing. The idea is to submit to LHC a CDR-like document for the end of March 2025

Timetable


As an independent collaboration from LHCb
LHC Run4
data taking at the IR4
LHC Run5+6
data taking at LHCb
2024
now
2026
2029
2033
2035
LHC LS3
time for installing the apparatus at the IR4
LHC LS4
time for installing the apparatus at LHCb

Conclusions

LHCspin is an innovative and unique project conceived to bring polarized physics at the LHC. It is exceptionally ambitious, demonstrating remarkable potential for advancing physics

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It will pave the way for another new frontier in spin physics