XXIX International Workshop on Deep-Inelastic Scattering and related subjects
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The LHCspin project

Shinichi Okamura (INFN, University of Ferrara)

In collaboration with V. Carassiti, G. Ciullo, P. Di Nezza,
P. Lenisa, S. Mariani, L. Pappalardo, M. Santimaria, E. Steffens

Università
degli Studi
di Ferrara

LHC
spin

INFN
Istituto Nazionale di Fisica Nucleare

✉ shinichi.okamura@cern.ch

Outline

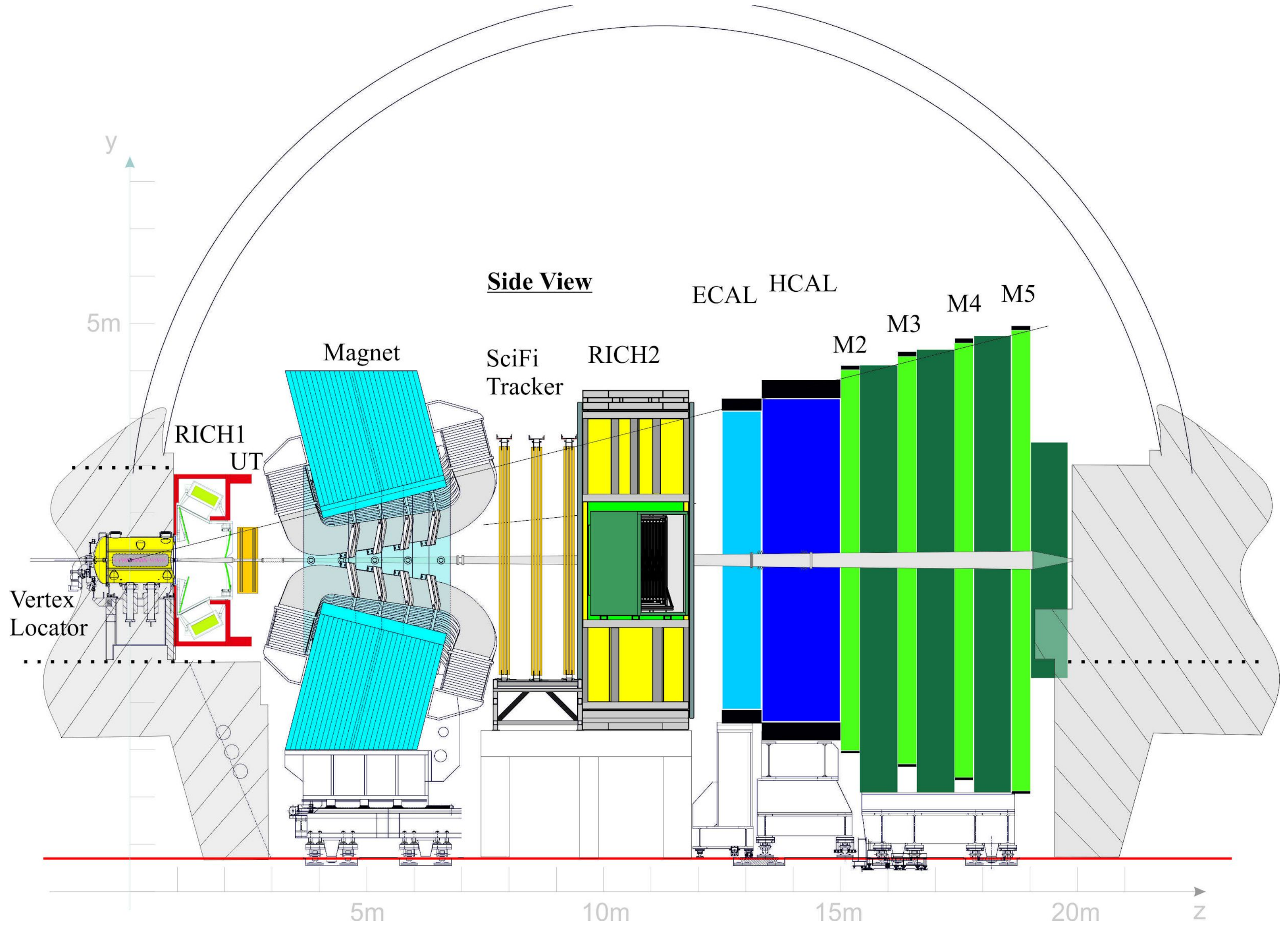
- Fixed-target program at LHCb
- The LHCspin project
- Physics opportunities
- The experimental setup
- Current status and conclusions

Fixed-target program at LHCb

The LHCb detector

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

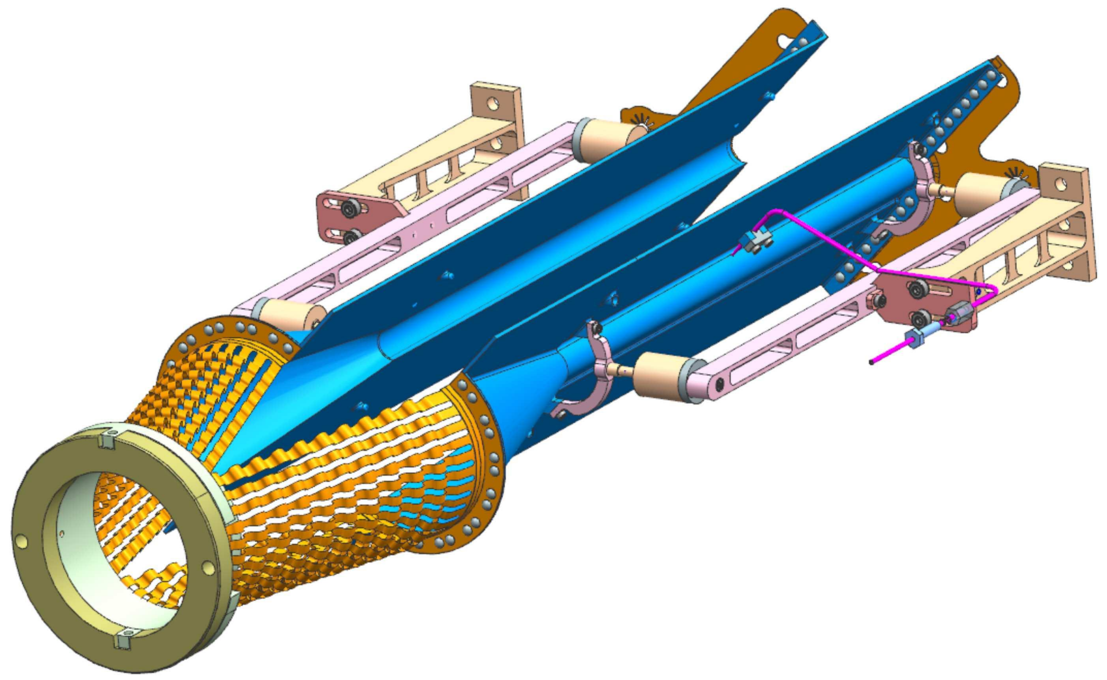
- General purpose forward spectrometer
- **$2 < \eta < 5$** rapidity coverage
- High performance in charge hadron identification
- Excellent momentum resolution over a wide momentum range
  $\sigma_p / p \sim 0.5 - 1.0$ %
  $p \in [\, 2, 200 \,]$ GeV



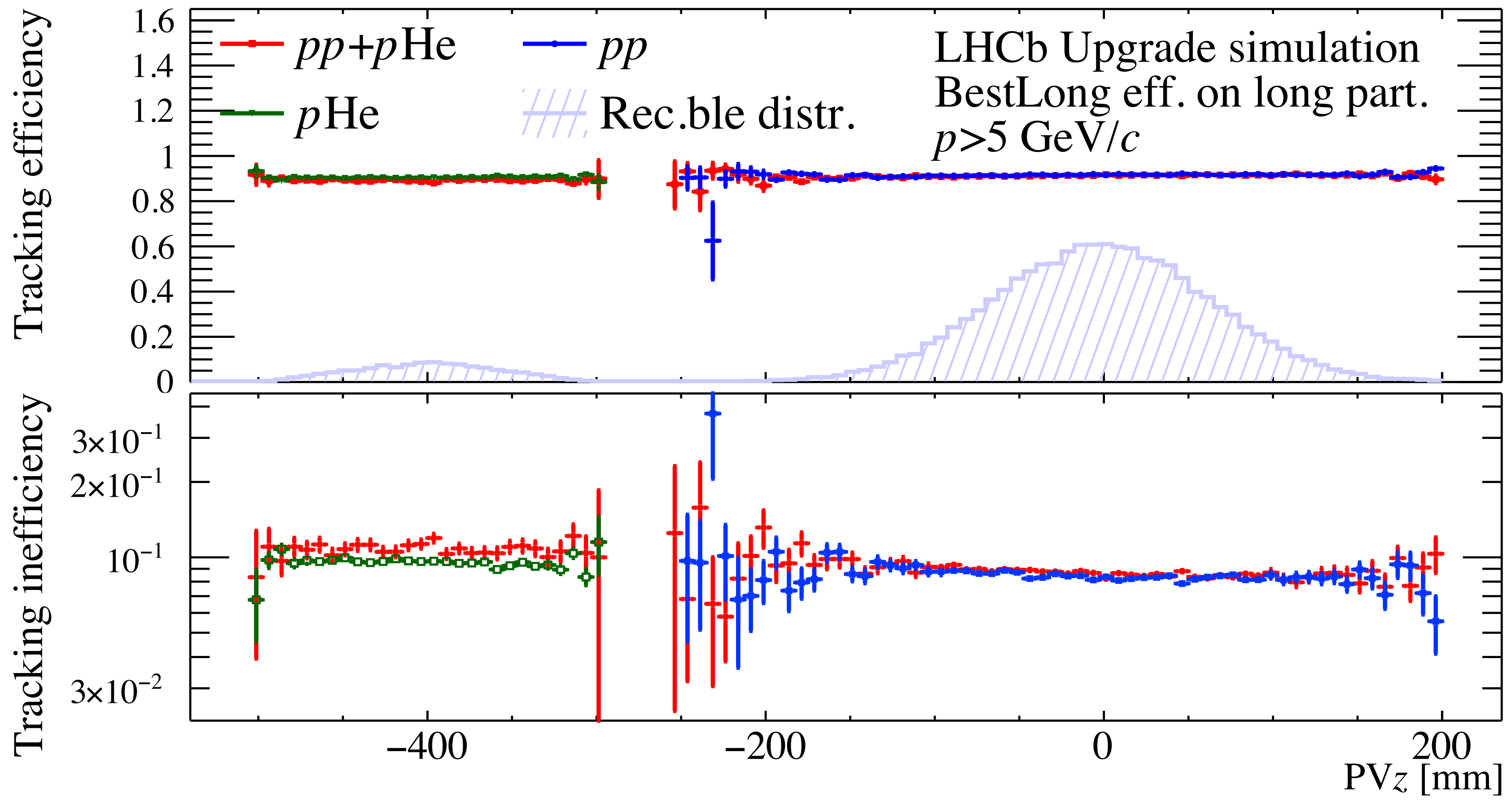
The LHCb fixed-target program: SMOG and SMOG2

[see poster]

- Injection of **noble gases in the VELO**
- **Active program** with several analyses ongoing
- SMOG2: **openable storage cell**
  - Precise density measurements (luminosity)
  - Significantly higher areal density
  - More gas species: H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe
  - High tracking efficiency despite displaced PVZ



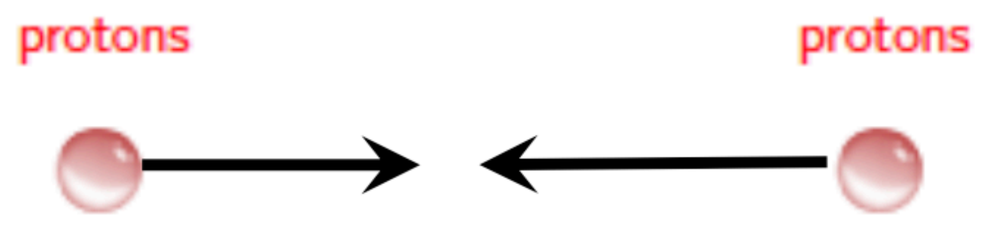
[SMOG2 TDR]



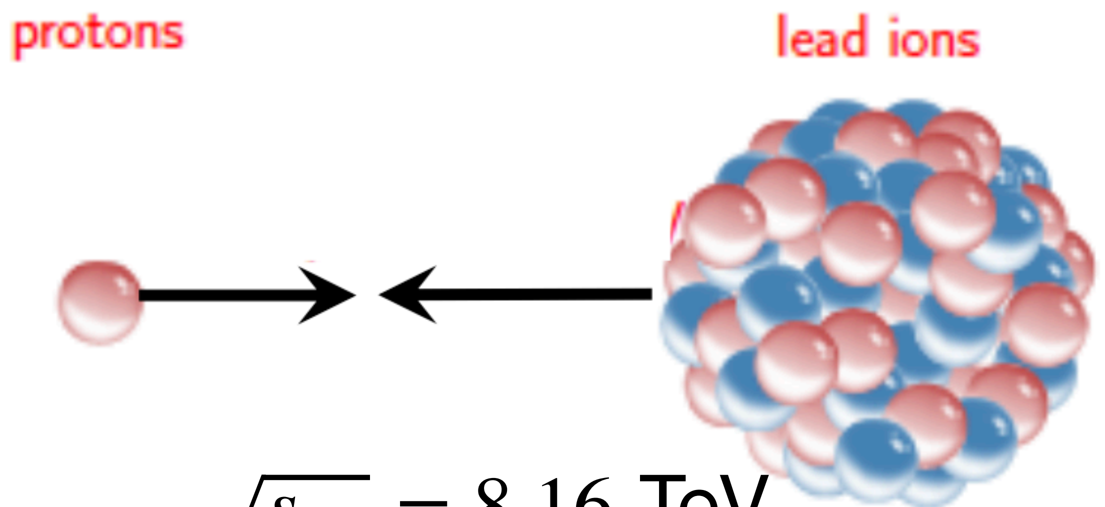
[LHCB-FIGURE-2022-002]

Types of collisions and kinematic regions

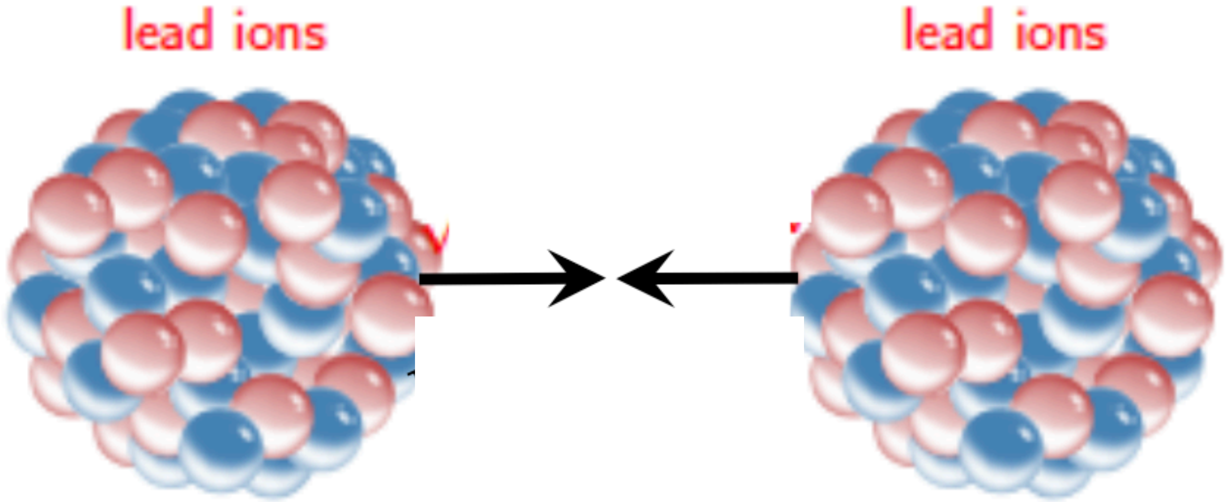
Collider mode



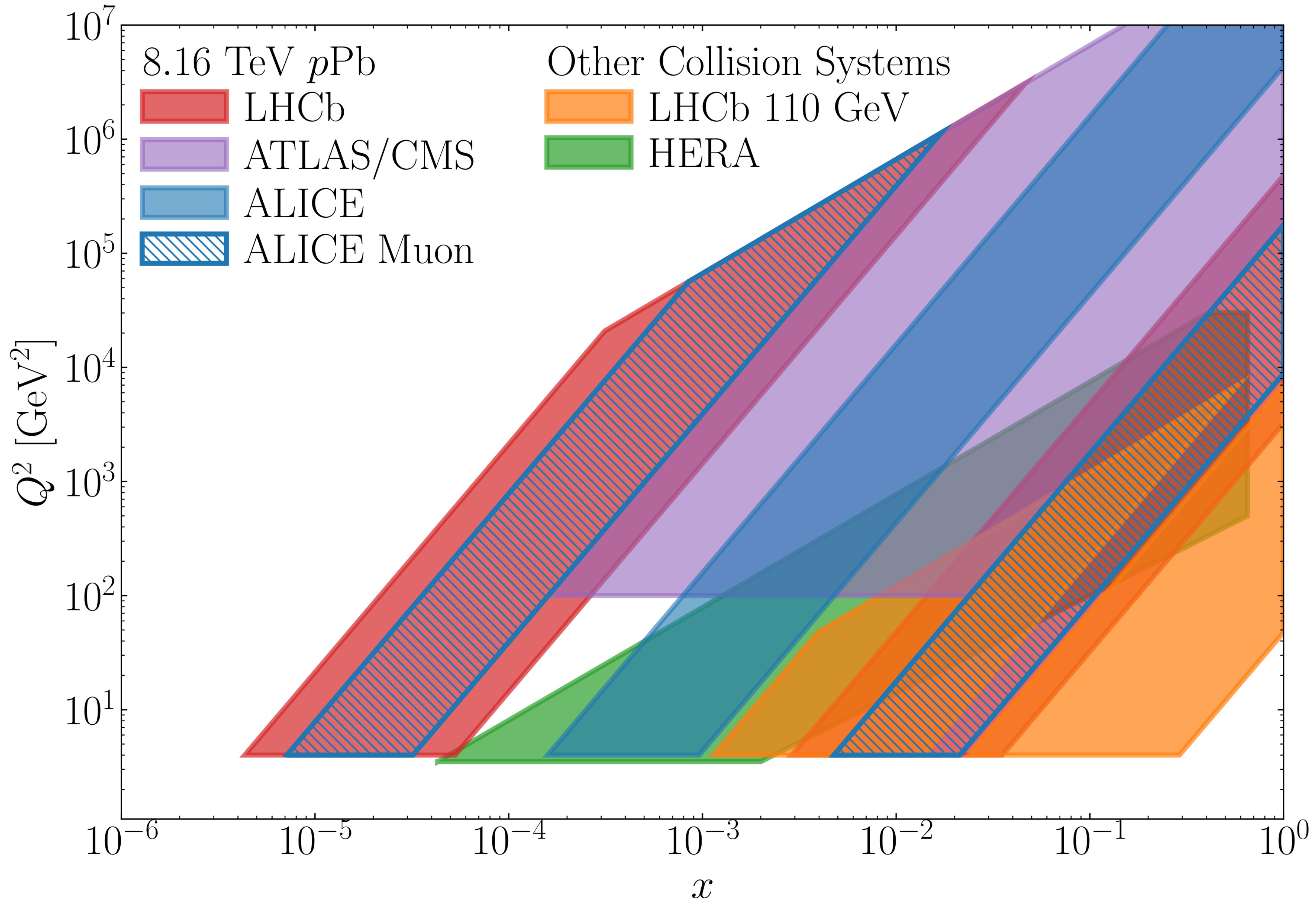
$\sqrt{s} = 14$ TeV



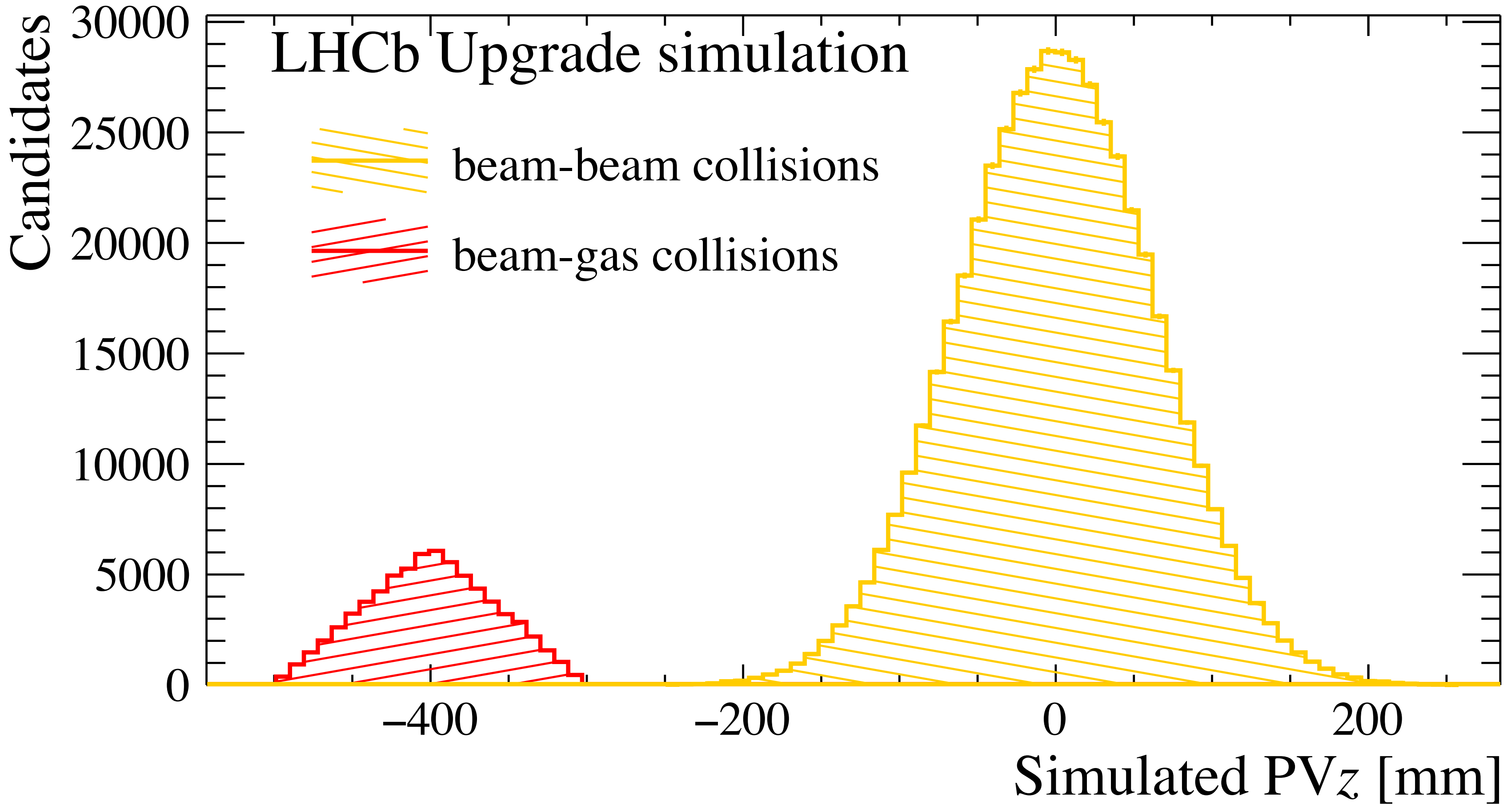
$\sqrt{s_{NN}} = 8.16$ TeV



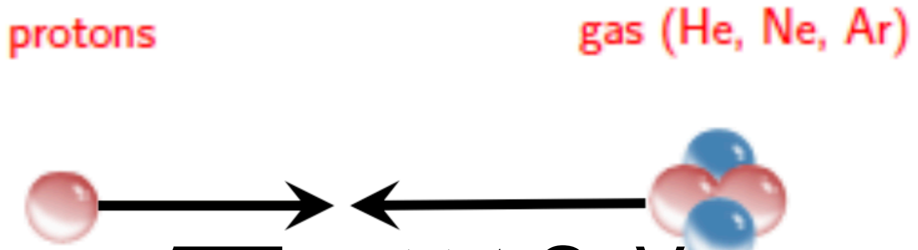
$\sqrt{s_{NN}} = 5.5$ TeV



[LHCB-FIGURE-2022-002]



Fixed-target mode



$\sqrt{s_{NN}} = 115$ GeV

- Large Lorentz boost in the laboratory system

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

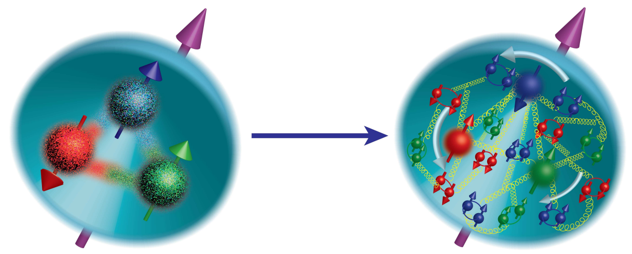
- Negative and mid rapidity in the CM

$$-3 \leq y_{CM} \leq 0$$

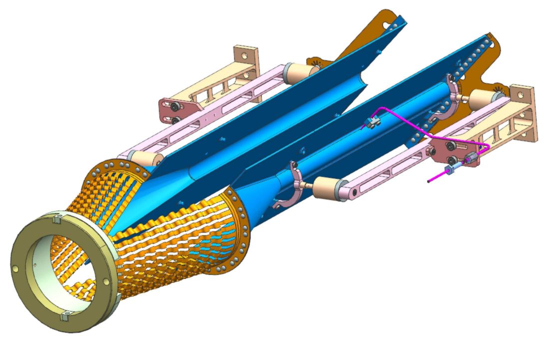
- **High x** of the target nucleon at **intermediate Q^2**
- Large and negative x_F
- Run in parallel with collider mode (SMOG2)

The LHCspin project

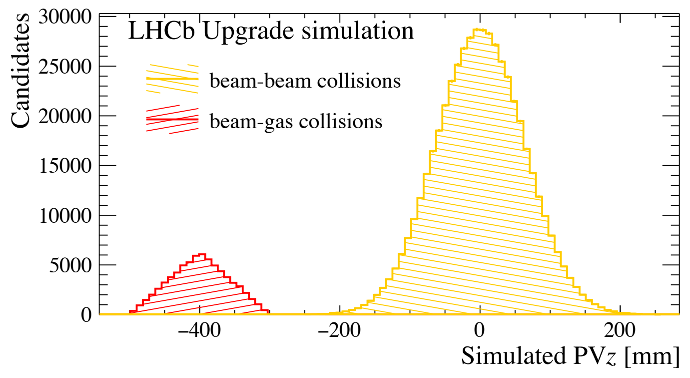
The LHCspin project



First spin-physics program at LHC



Unpolarised physics program



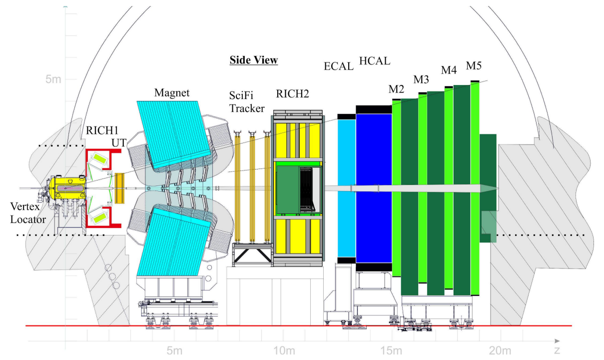
Run in parallel with collider mode

Extending the fixed-target program in Run4

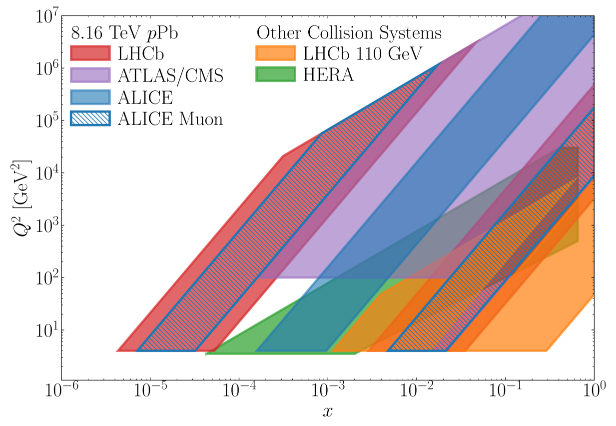
[The LHCspin project]

LHC + LHCb + transverse polarised target

$H^\uparrow, D^\uparrow$



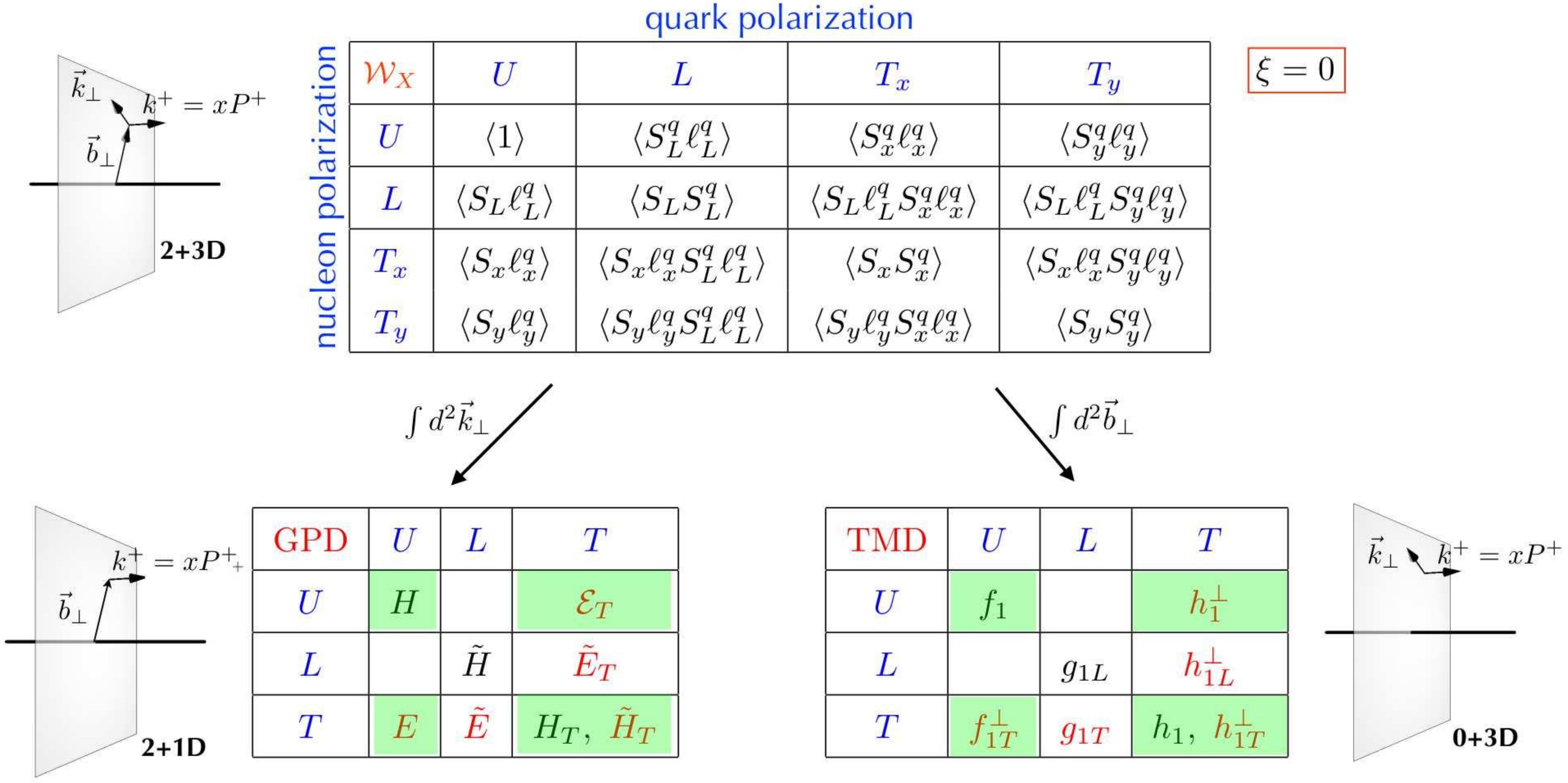
Unique kinematic conditions



Physics opportunities

Physics opportunities: TMDs and GPDs

- Spin-orbit correlations inside the nucleon



quark polarization / nucleon polarization

$\mathcal{W}_X$	U	L	T_x	T_y
U	$\langle 1 \rangle$	$\langle S_L^q \ell_L^q \rangle$	$\langle S_x^q \ell_x^q \rangle$	$\langle S_y^q \ell_y^q \rangle$
L	$\langle S_L \ell_L^q \rangle$	$\langle S_L S_L^q \rangle$	$\langle S_L \ell_L^q S_x^q \ell_x^q \rangle$	$\langle S_L \ell_L^q S_y^q \ell_y^q \rangle$
T_x	$\langle S_x \ell_x^q \rangle$	$\langle S_x \ell_x^q S_L^q \ell_L^q \rangle$	$\langle S_x S_x^q \rangle$	$\langle S_x \ell_x^q S_y^q \ell_y^q \rangle$
T_y	$\langle S_y \ell_y^q \rangle$	$\langle S_y \ell_y^q S_L^q \ell_L^q \rangle$	$\langle S_y \ell_y^q S_x^q \ell_x^q \rangle$	$\langle S_y S_y^q \rangle$

$\xi = 0$

GPD	U	L	T
U	🟩 H		🟩 $\mathcal{E}_T$
L		$\tilde{H}$	$\tilde{E}_T$
T	🟩 E	$\tilde{E}$	🟩 $H_T,\ \tilde{H}_T$

TMD	U	L	T
U	🟩 f_1		🟩 $h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	🟩 $f_{1T}^\perp$	g_{1T}	🟩 $h_1,\ h_{1T}^\perp$

🟩 : accessible at LHCspin

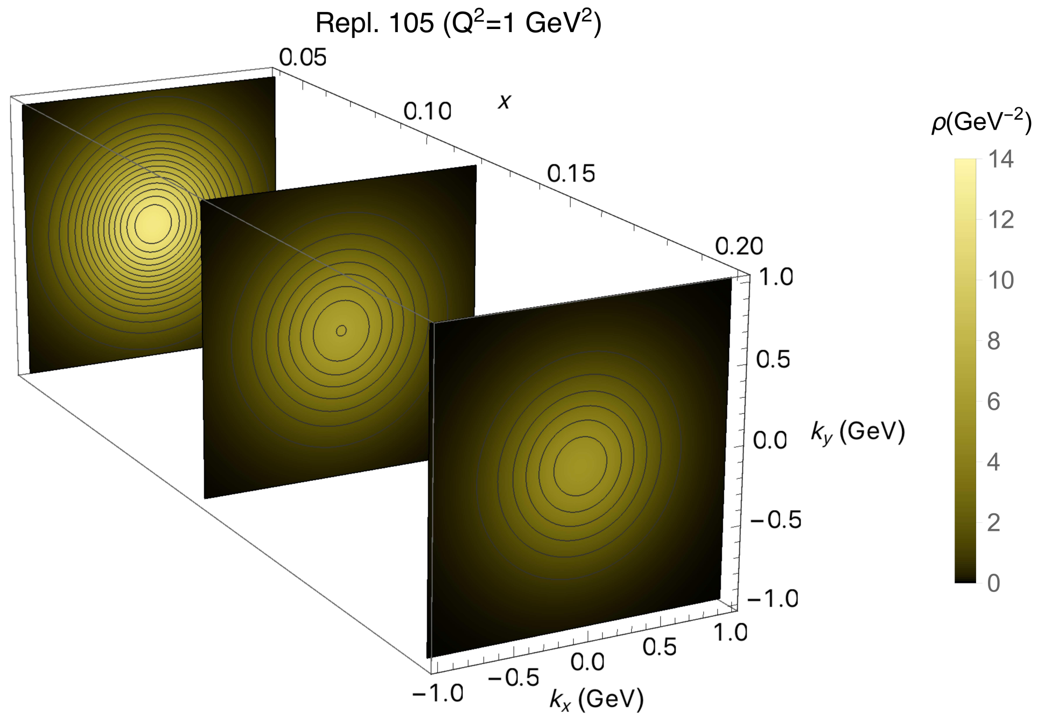
[from B. Pasquini DIS2021]

Quark TMDs

[from L. Pappalardo SPIN2021]

Goal

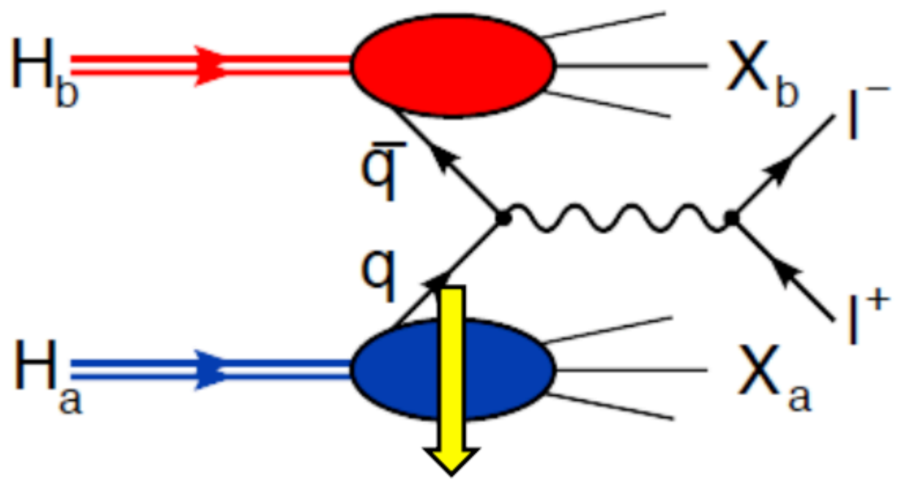
- Boer-Mulders function $h_1^{\perp,q}(x,p_T^2)$
- Quark Sivers function $f_{1T}^{\perp,q}(x,p_T^2)$
- Nucleon tomography



[JHEP 06 (2017) 081]

Process

Transv. (un)polarised Drell-Yan



- Clean process
- LHCb well suited to reconstruct **di-μ final state**

Observable

Transverse single spin asymmetry (**TSSA**)

$$A_N^{DY} = \frac{1}{P}\frac{\sigma_{DY}^{\uparrow}-\sigma_{DY}^{\downarrow}}{\sigma_{DY}^{\uparrow}+\sigma_{DY}^{\downarrow}}$$

$$\downarrow$$

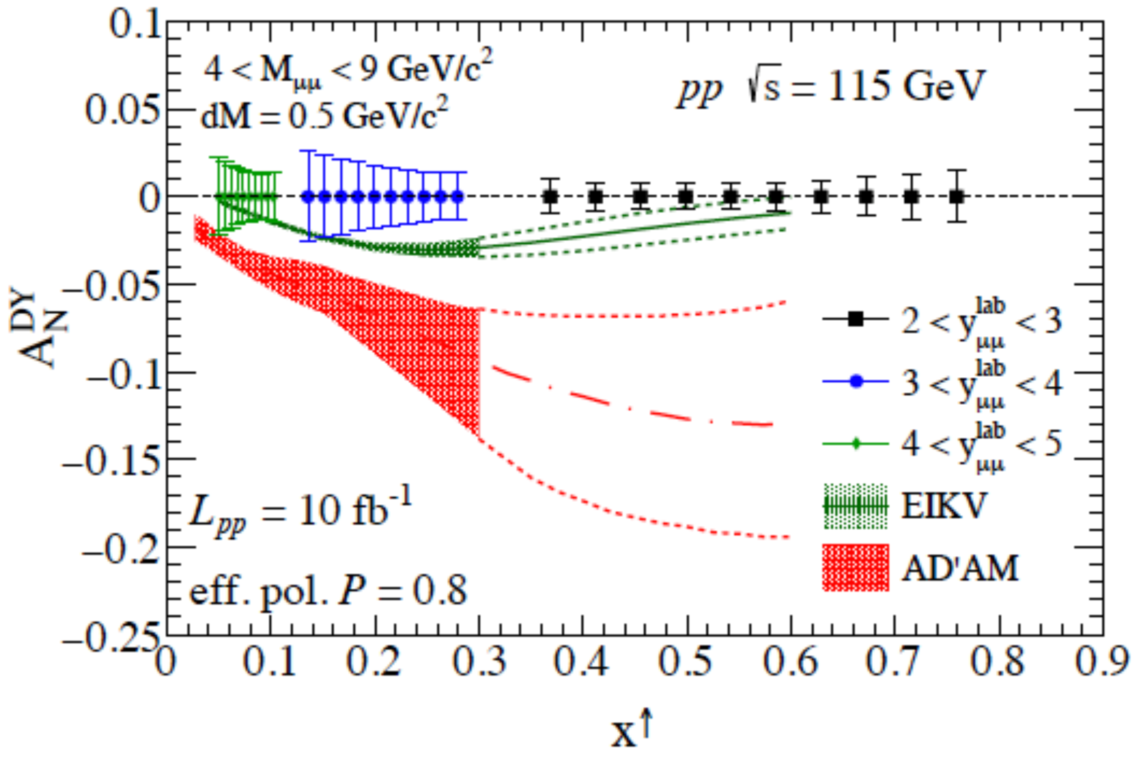
$$A_{UU}^{cos2\phi} \sim \frac{h_1^{\perp,q}\otimes h_1^{\perp,\bar{q}}}{f_1^q\otimes f_1^{\bar{q}}}$$ ●

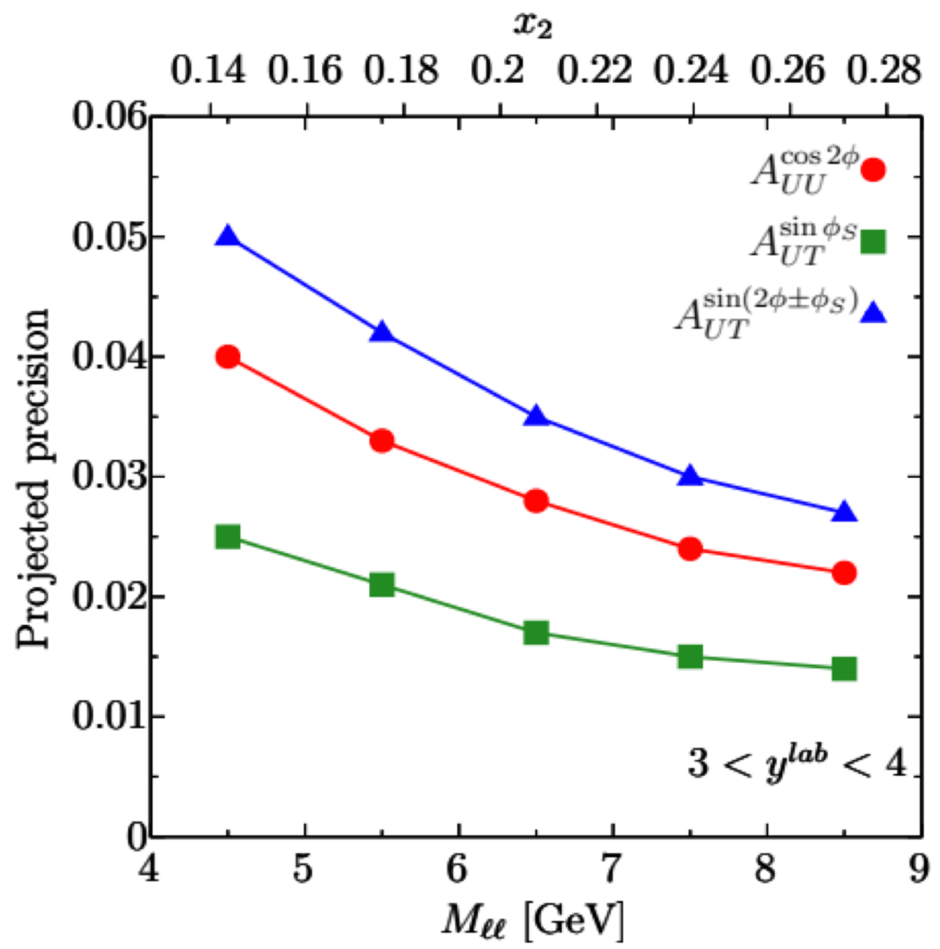
$$A_{UT}^{sin\phi_S} \sim \frac{f_1^q\otimes f_{1T}^{\perp,\bar{q}}}{f_1^q\otimes f_1^{\bar{q}}}$$ ■

$$A_{UT}^{\sin(2\phi+\phi_S)} \sim \frac{h_1^{\perp,q}\otimes h_{1,T}^{\perp,\bar{q}}}{f_1^q\otimes f_1^{\bar{q}}}$$ ▲

Projections

[arXiv:1807.00603]





gluon TMDs

Predictions for polarised FT measurements at LHCb
[PRD 99, 036013 (2019)]

Goal

- Experimental access extremely limited
- LHCspin: a unique facility to study gTMDs
- gluon Sivers function

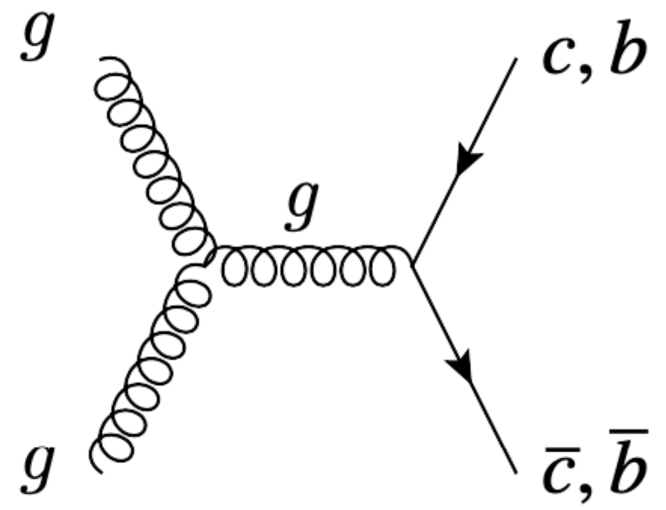
$f_{1T}^{\perp,g}$

gluon pol.

nucleon pol.

	U	Circ.	Lin.
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	f_{1T}^g	g_{1T}^g	$h_1^{\perp g}, h_{1T}^{\perp g}$

Process



- Heavy quarks are mainly produced via **gluon fusion**
- Factorisation theorem (**$p_T << M_q$**)

$pp^{\uparrow} \rightarrow J/\psi + \gamma + X$ $\quad$ $pp^{\uparrow} \rightarrow J/\psi + J/\psi + X$

$pp^{\uparrow} \rightarrow \psi' + \gamma + X$ $\quad$ $pp^{\uparrow} \rightarrow J/\psi + \psi' + X$

$pp^{\uparrow} \rightarrow \Upsilon + \gamma + X$ $\quad$ $pp^{\uparrow} \rightarrow \Upsilon + \Upsilon + X$

Observable

Transverse single spin asymmetry (**TSSA**)

$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

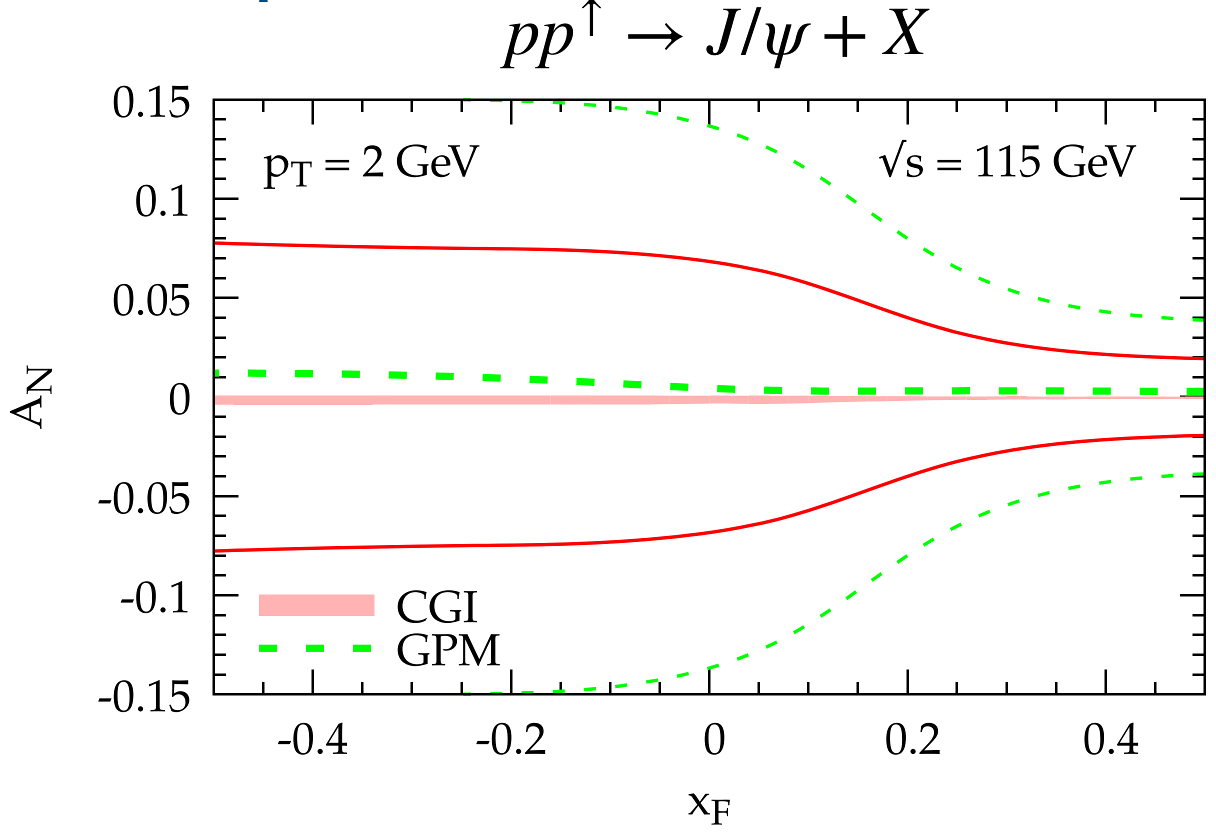
$$A^{sin(\phi_S)} \propto f_1^g \otimes f_{1T}^{\perp g} \otimes d\sigma_{gg \rightarrow Q\bar{Q}g}$$

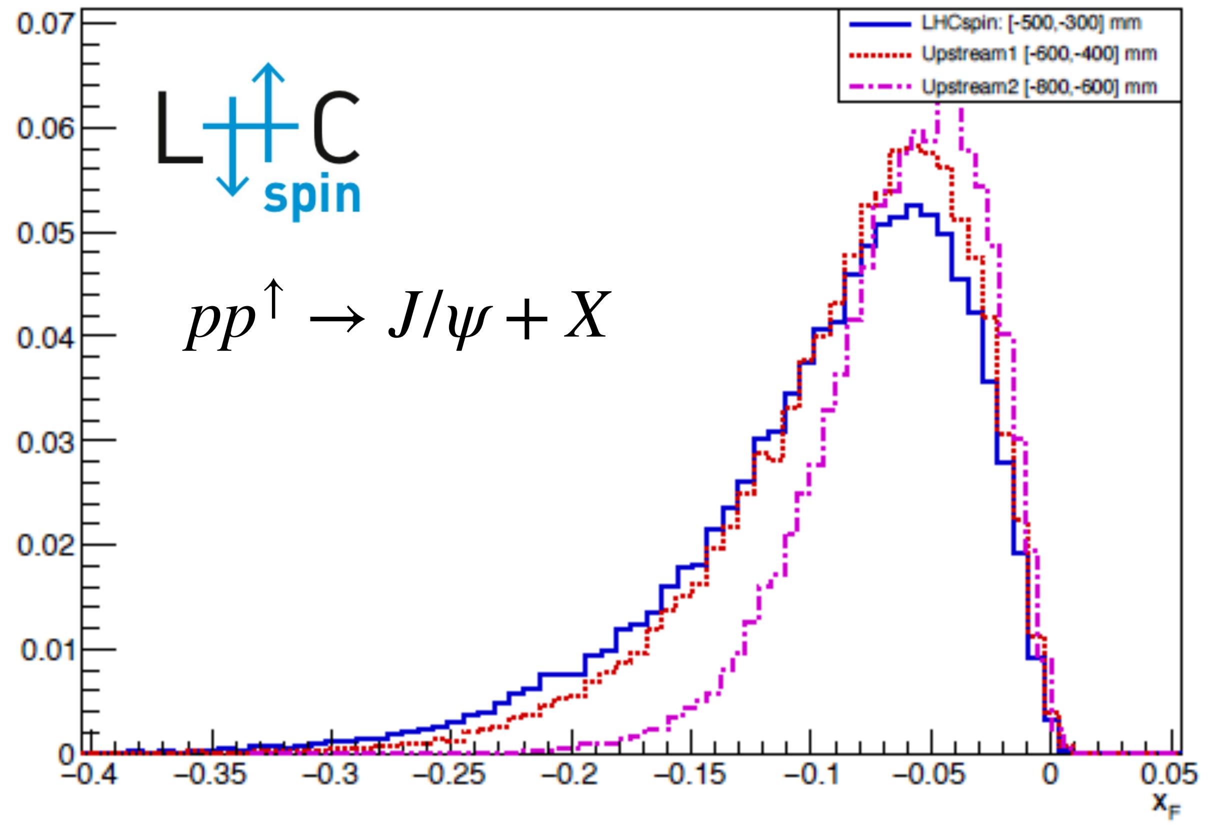
…

g Sivers function

Projections

Expected **0-10% asymmetry in $x_F < 0$**





The experimental setup

Overview of the setup

Development of a **new generation of polarised targets** based on HERMES experiment (DESY)

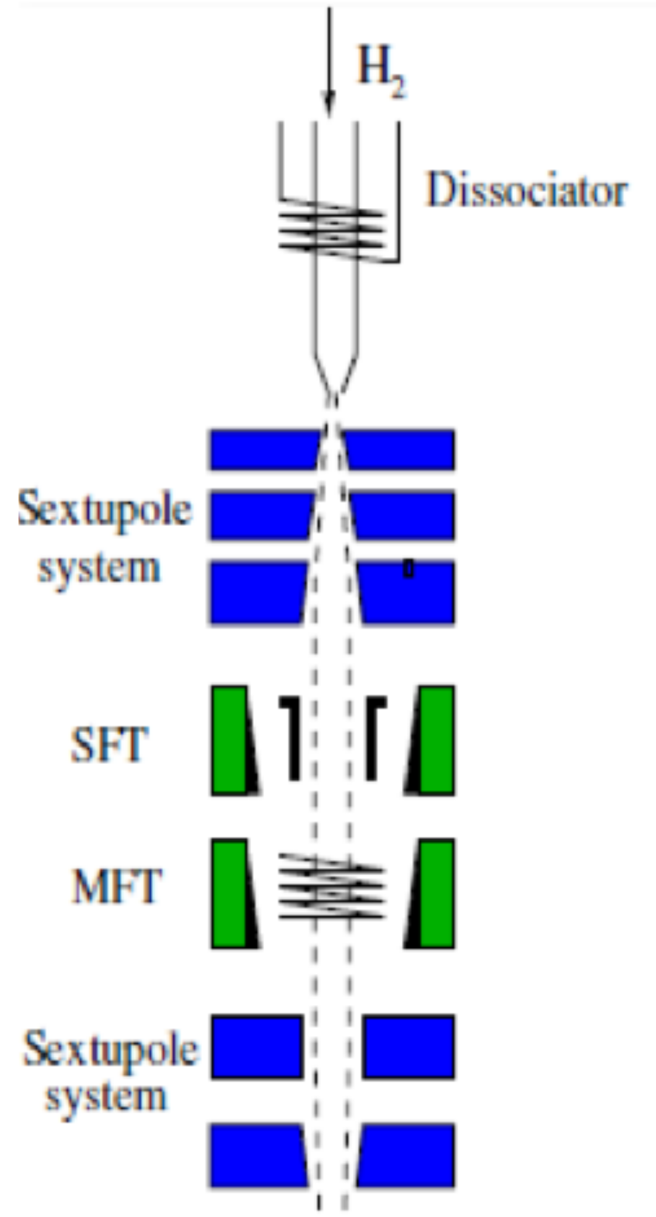
1 Atomic Beam Source (ABS)

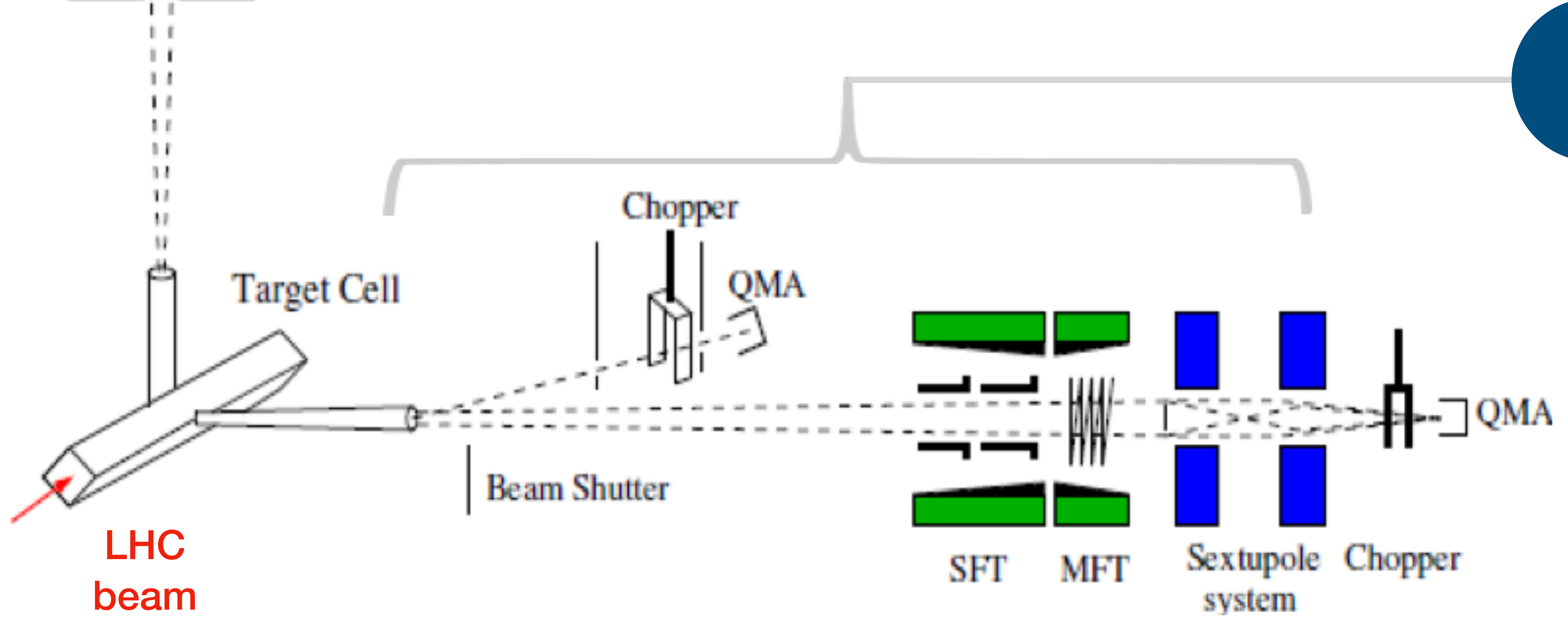
- Input: unpolarised molecules
- Output: high intensity, collimated, polarised atomic beam

2 Target Cell (TC)

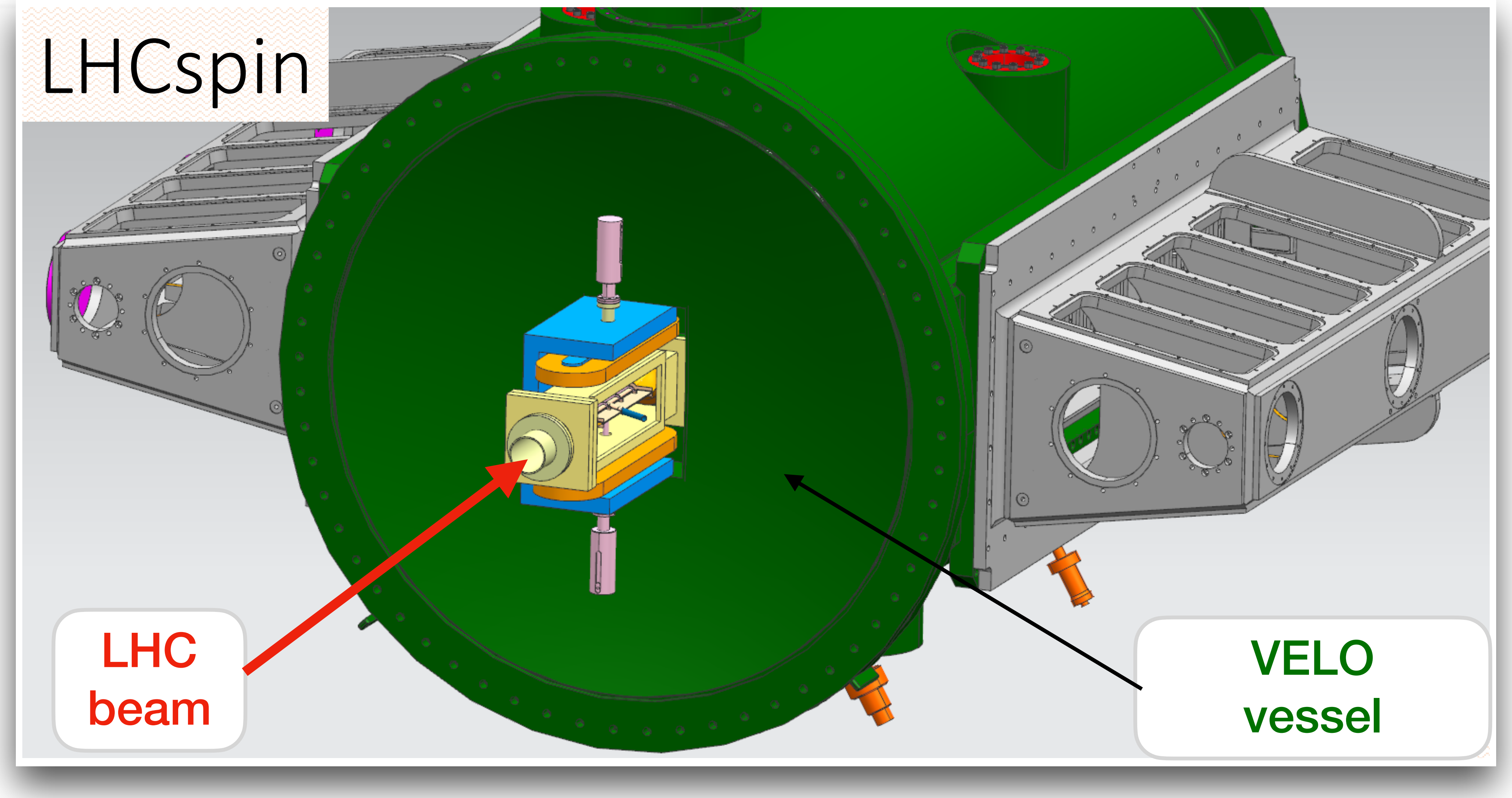
- T-shaped openable storage cell
- Dipole holding magnet (transverse polarisation)

[NIMA 540 (2005) 68-101]





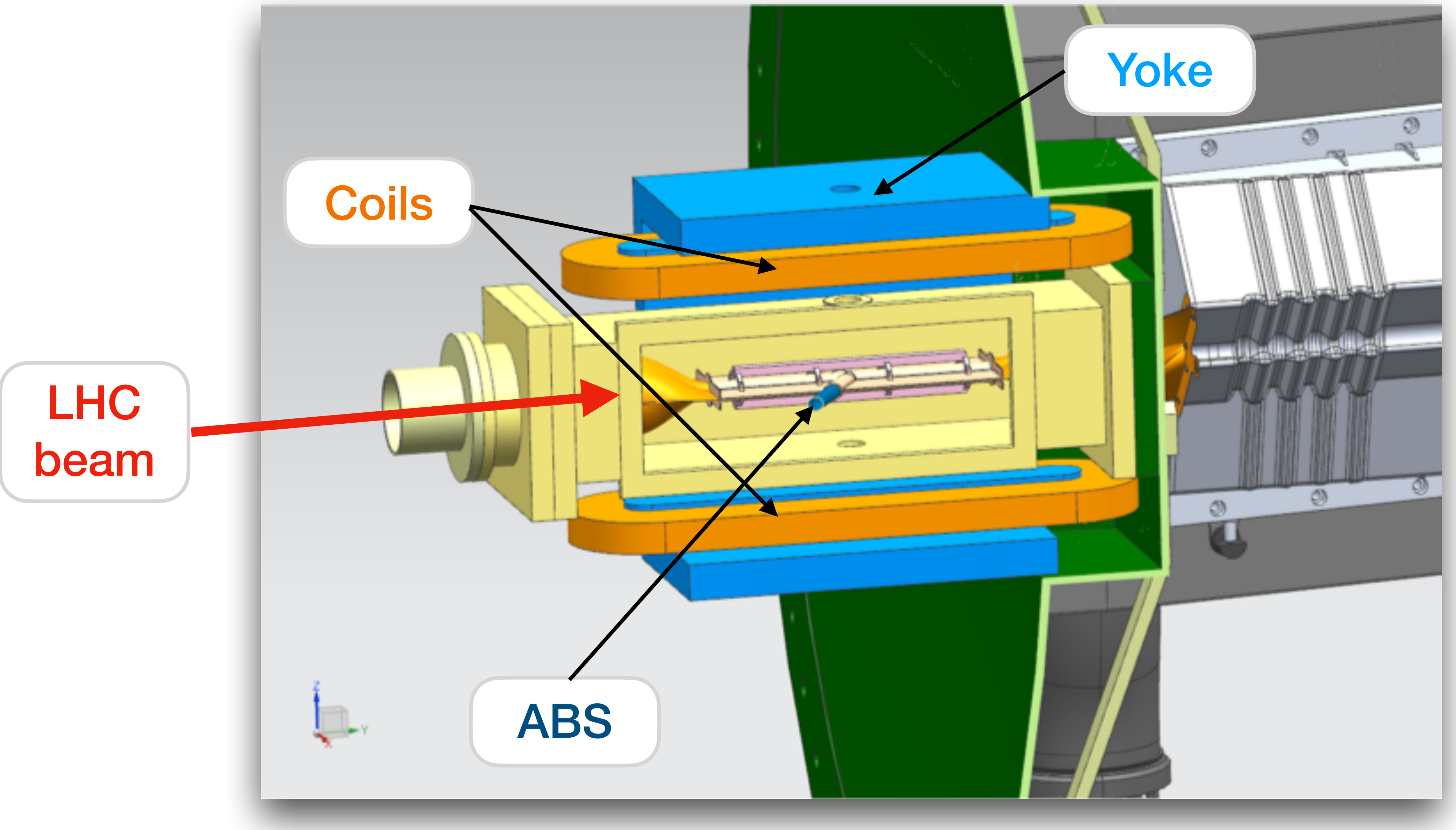
Courtesy of V. Carassiti

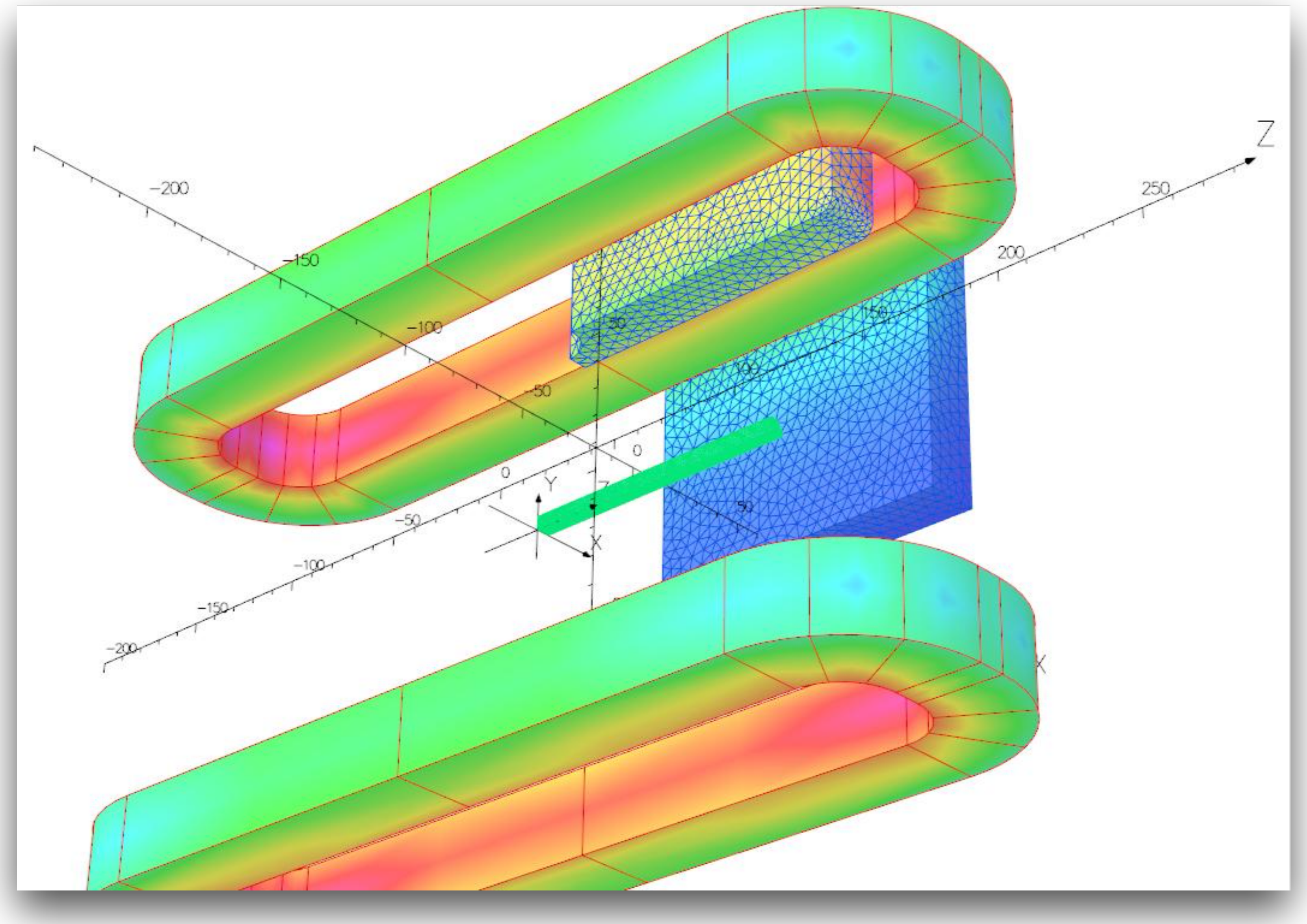


3 Diagnostic system

- **T**arget **G**as **A**nalyser: atomic fraction
- **B**reit-**R**abi **P**olarimeter: polarisation degree

Target cell and magnet





Target Cell

- Almost same position of the SMOG2 cell (L = 20 cm, D = 1 cm)
- Inject both unpolarised and **polarised gas** (only way to bring polarised physics at LHC)
- $P \simeq 85\ \%$ achieved at HERMES

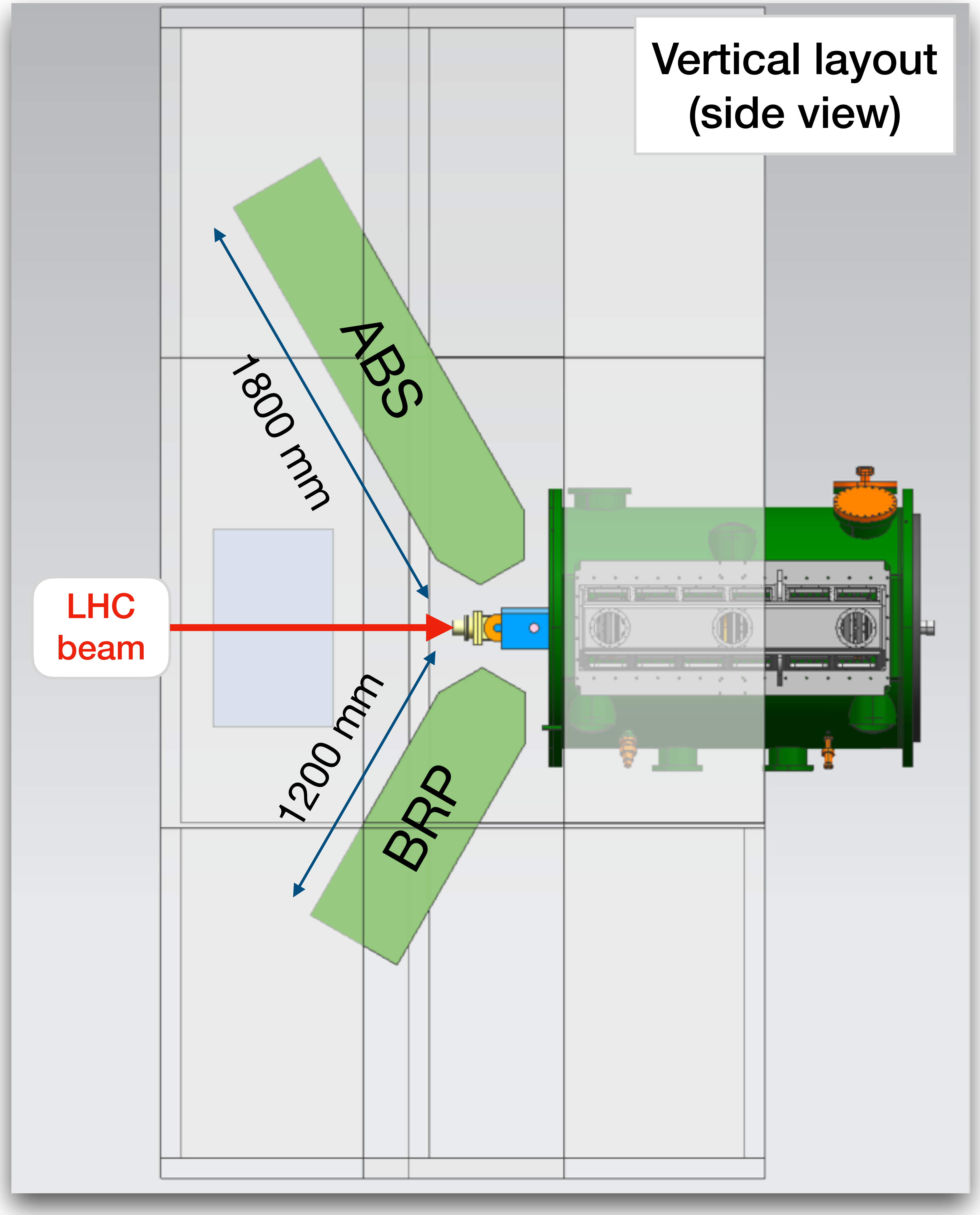
Dipole magnet

- Superconductive coils + iron yoke
- Possibility to rapidly invert the polarity
- B ≃ **300 mT**, to maintain transverse polarisation
- Uniformity **ΔB/B ~ 10%**, to suppress beam-induced depolarisation

[PoS (SPIN2018)]

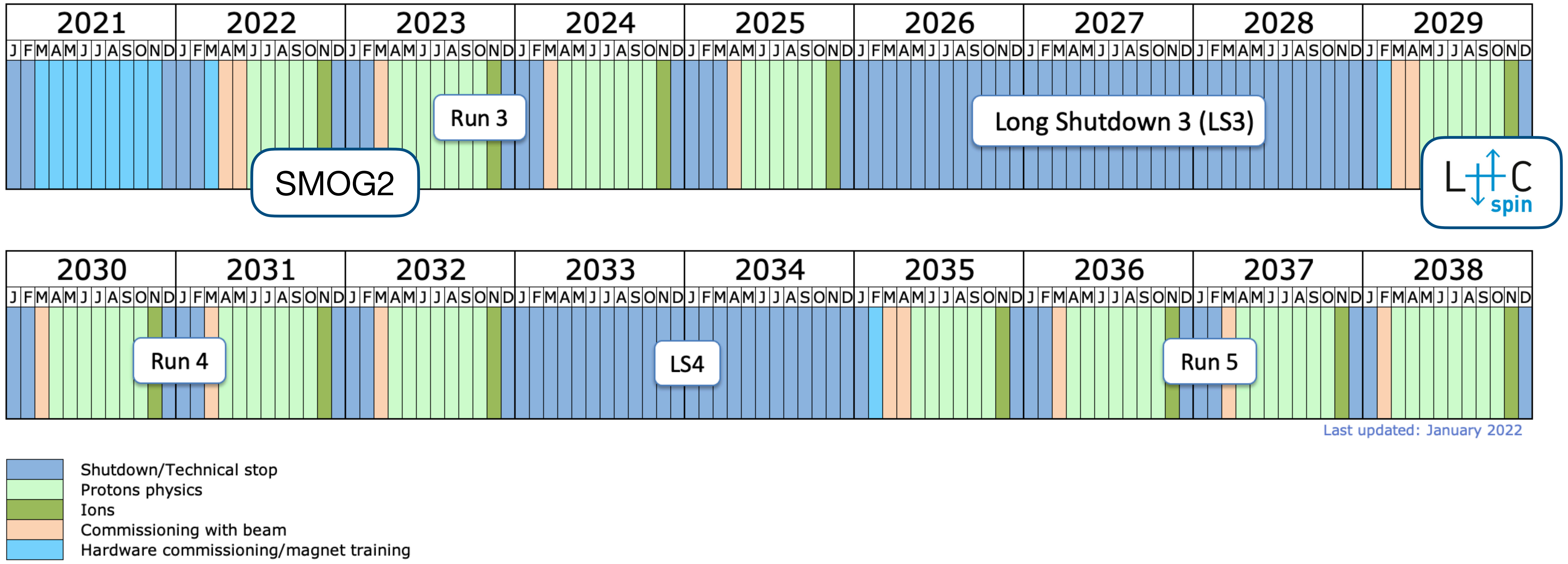
ABS and BRP

- R&D phase
- No need for additional detectors
- Design **compact ABS and diagnostic system** to fit inside the limited available space in the VELO alcove
  - Injected intensity of H-atoms: $\sim 6.5 \times 10^{16} s^{-1}$
  - Achievable luminosity (HL-LHC): $\sim 8 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$
- **Interface** with the **LHC**
  - Coating of the internal walls of the cell
    - Low molecular recombination rate
    - Low Secondary Electron Yield (SEY)



Conclusions

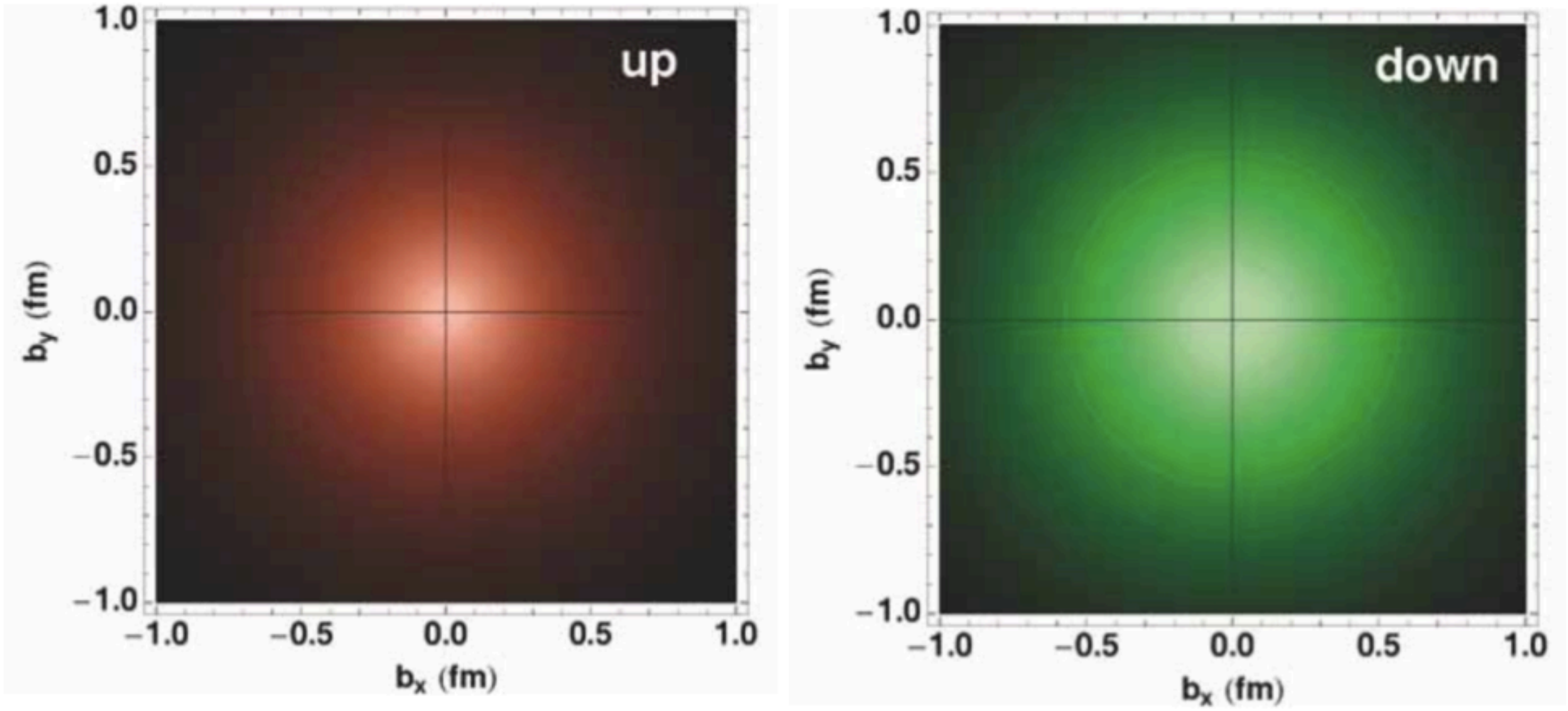
- **Extend the LHCb fixed-target program**
  - LHCb spectrometer well suited for fixed-target collisions
  - Unpolarised and polarised target
  - Poorly explored kinematic region
- **Physics opportunities**
  - Nucleon tomography in momentum space
  - First insights on gTMDs
  - Access to spin-dependent GPDs
  - Comparison with SIDIS experiments
- **Setup and current status**
  - HERMES-like polarised target setup
  - A challenging R&D but worth the effort!



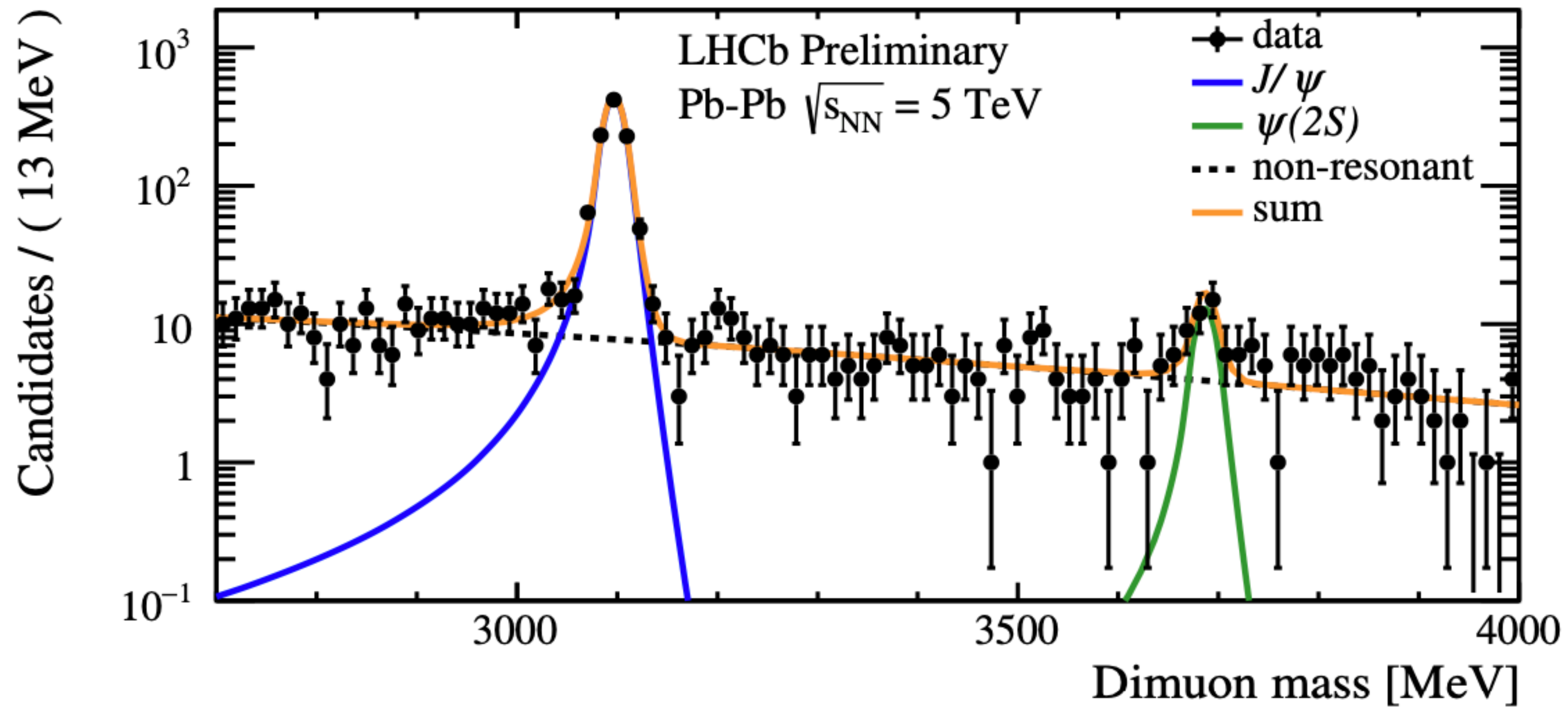
Backup

Generalised Parton Distribution (GPD)

[NS28 (2012), 1]



[NPA982 (2019) 247]



- Build a **3D maps in coordinate space**
- Exclusive quarkonia production in **ultra peripheral collisions** (UPC)
- Process dominated by the **EM interaction**
- Access to the **Parton Orbital Angular Momentum** (OAM) via the Ji sum rule [PRL 78 (1997) 610-613]

$$\frac{1}{2} = J^q(\mu) + J^g(\mu) = \frac{1}{2}\Delta\Sigma(\mu) + L_z^q(\mu) + J^g(\mu)$$

- **First measurements of J/ψ production** in UPC in PbPb collisions at LHCb