The LHCspin project

a polarised gas target at the LHC

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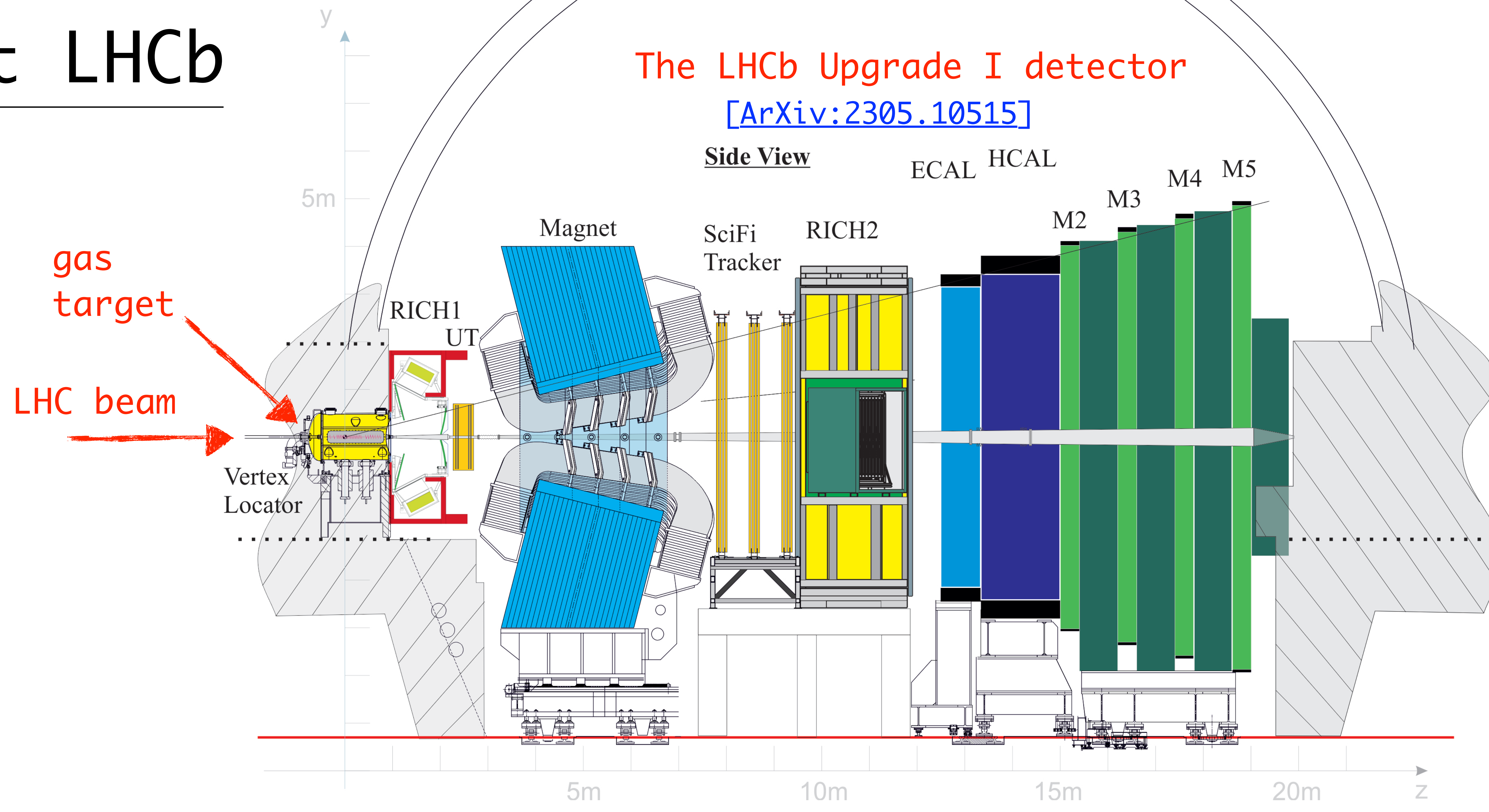
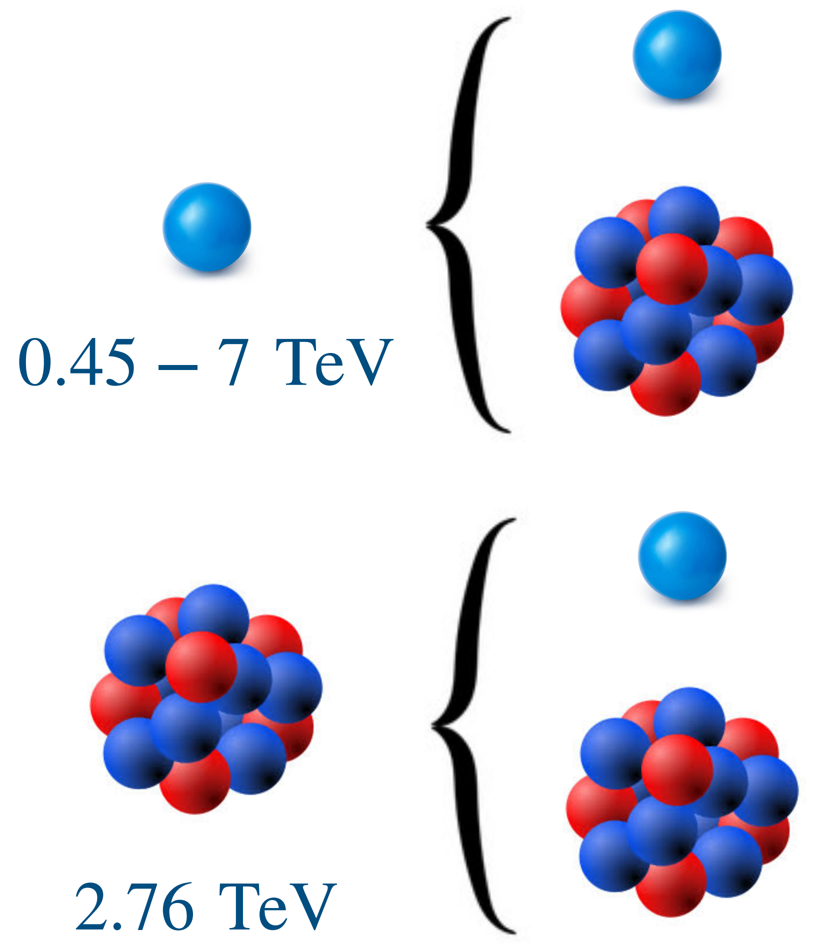
Fixed-target physics at LHCb

- LHCb is a general-purpose forward spectrometer, fully instrumented in $2 < \eta < 5$ and optimised for b- and c-hadron detection
- Excellent momentum resolution with VELO + tracking stations: $\sigma_p/p = 0.5 - 1.0\,\%$ $(p \in [2{,}200]$ GeV)
- Particle identification with RICH+CALO+MUON: $\epsilon_\mu \sim 98\,\%$ with $\epsilon_{\pi\to\mu} \lesssim 1\,\%$
- Run 3 (ongoing): new detector & software trigger to face 5x luminosity increase



- Fixed-target kinematics:



pp/pA collisions, 7 TeV beam:

$$\sqrt{s} = \sqrt{2m_N E_p} = 115 \text{ GeV}$$

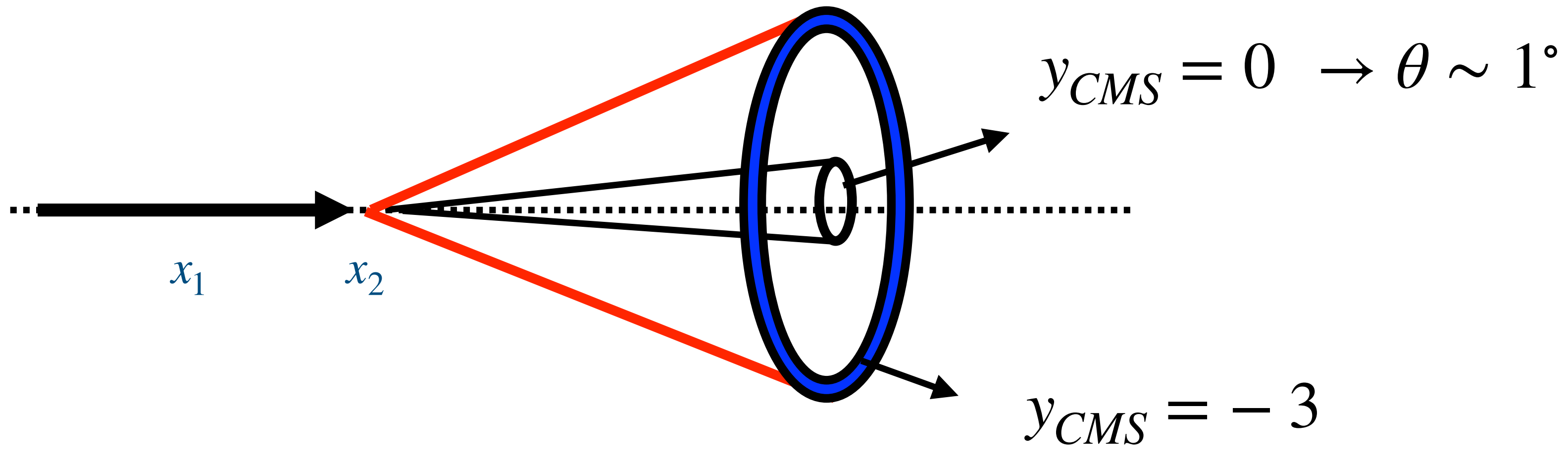
$$2 \leq y_{lab} \leq 5 \ \rightarrow -3.0 \leq y_{CMS} \leq 0$$

AA collisions, 2.76 TeV beam:

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

1: beam, 2: target

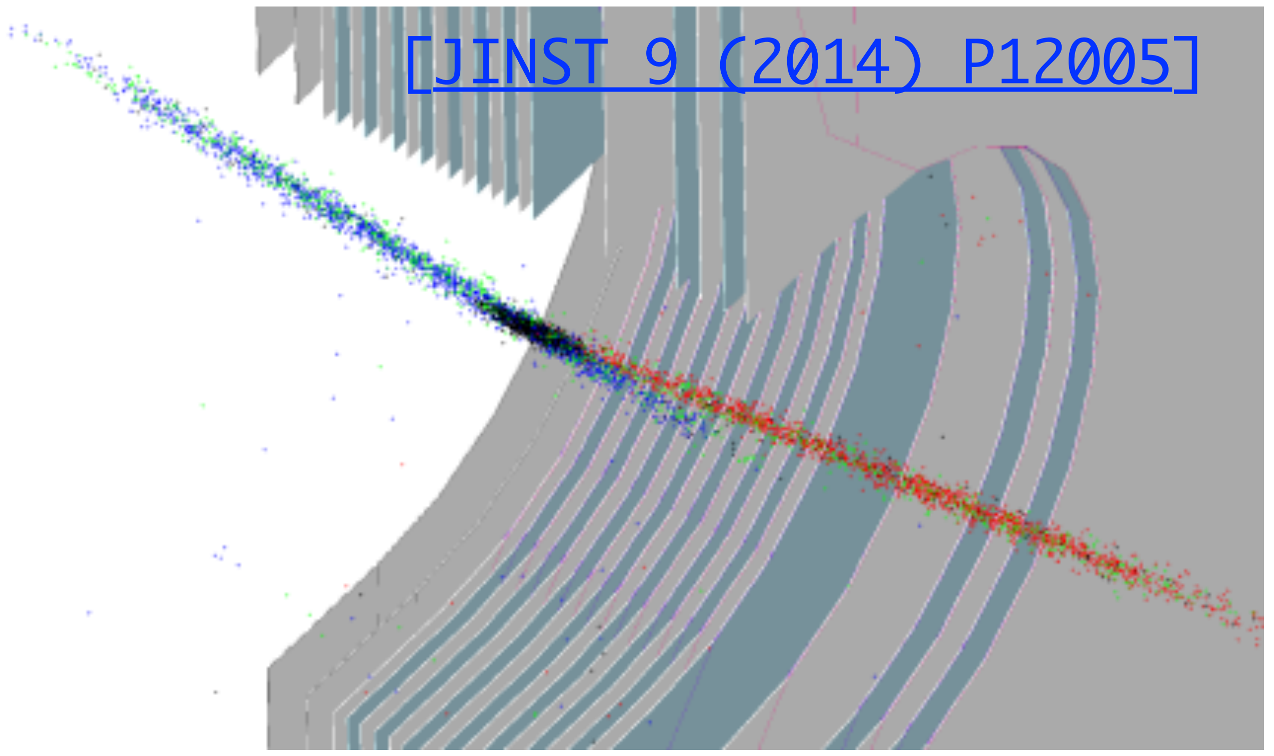
Large CM boost → large x_2 values $(x_F < 0)$



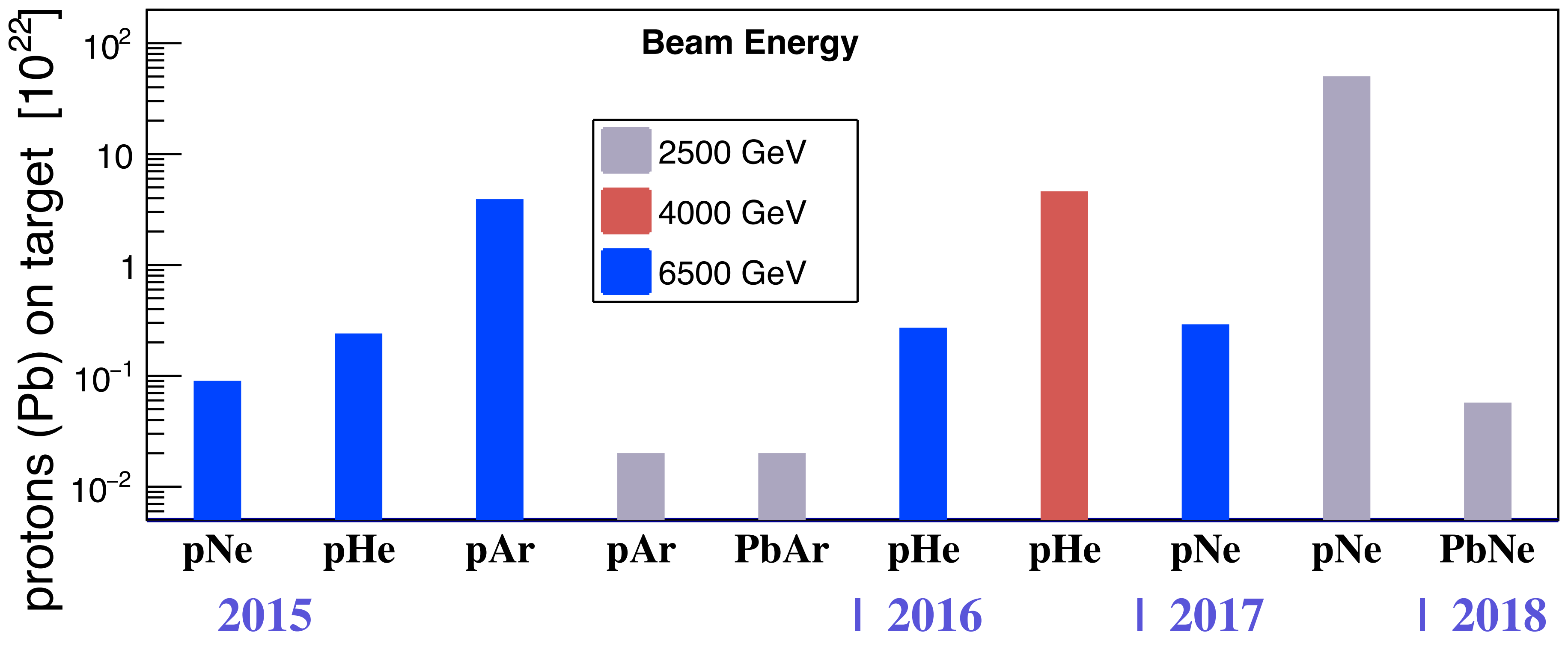
$$\gamma = \frac{\sqrt{s}}{2m_p} \sim 60$$

SMOG and SMOG2

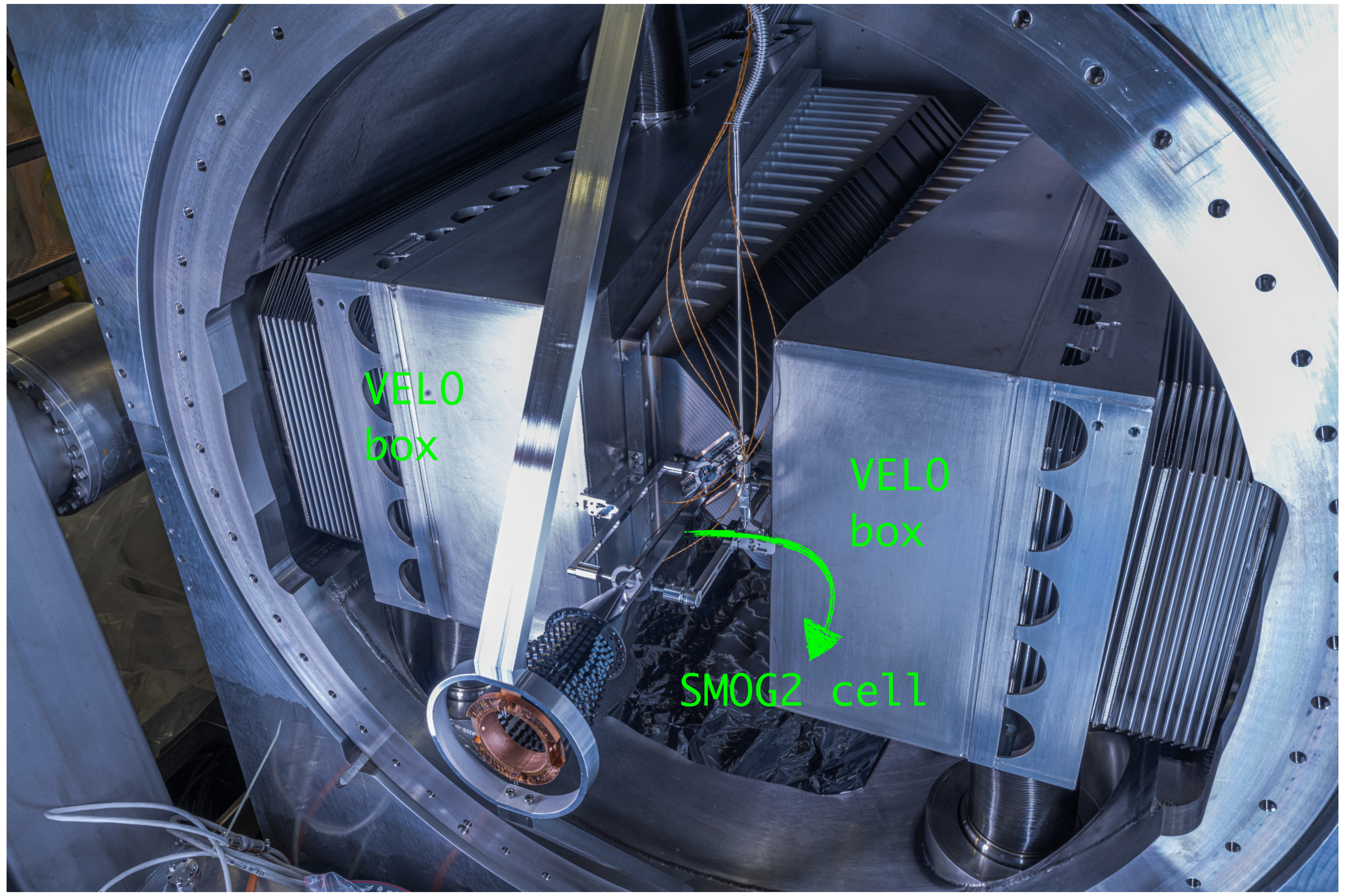
- The FT program at LHCb is active since 2015 with SMOG: inject noble gases into the VELO, populating $z = \pm 20$ m in the beam pipe
- Trigger on beam-empty collisions: turn LHCb into a FT experiment!
- See our publications → here



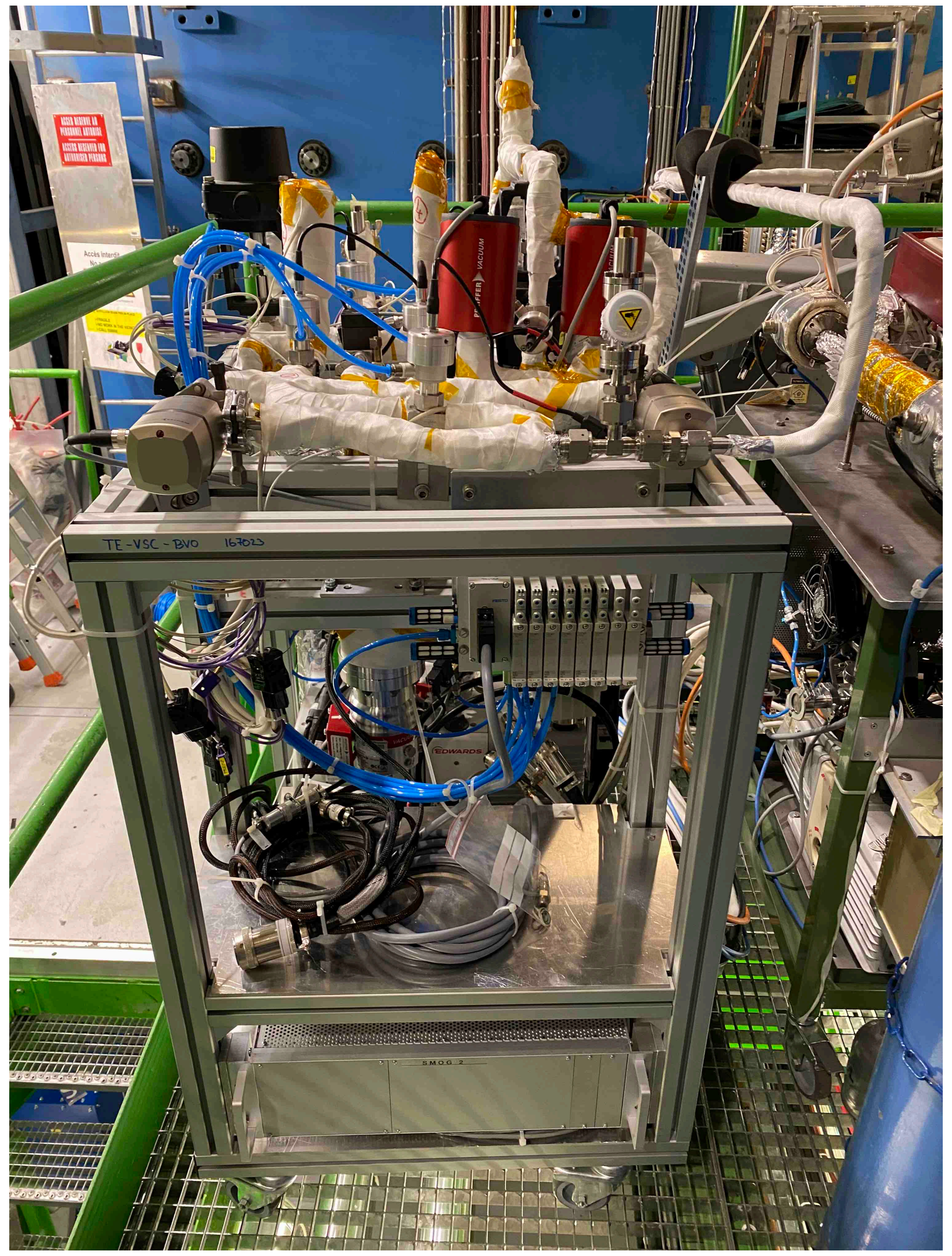
SMOG data (Run 2)



- **SMOG2 gas storage cell installed for Run 3:**
- $8-35$ X density wrt SMOG
- Negligible impact on the beam lifetime: $\tau_{beam-gas}^{p-H_2} \sim 2000$ days , $\tau_{beam-gas}^{Pb-Ar} \sim 500$ h
- Luminosity precision at the percent level thanks to new GFS and temperature probes on the cell walls
- Can be filled with: $\mathrm{He, Ne, Ar}$
- H_2 also tested successfully
- $D_2, N_2, O_2, \mathrm{Kr}, \mathrm{Xe}$ to be tested



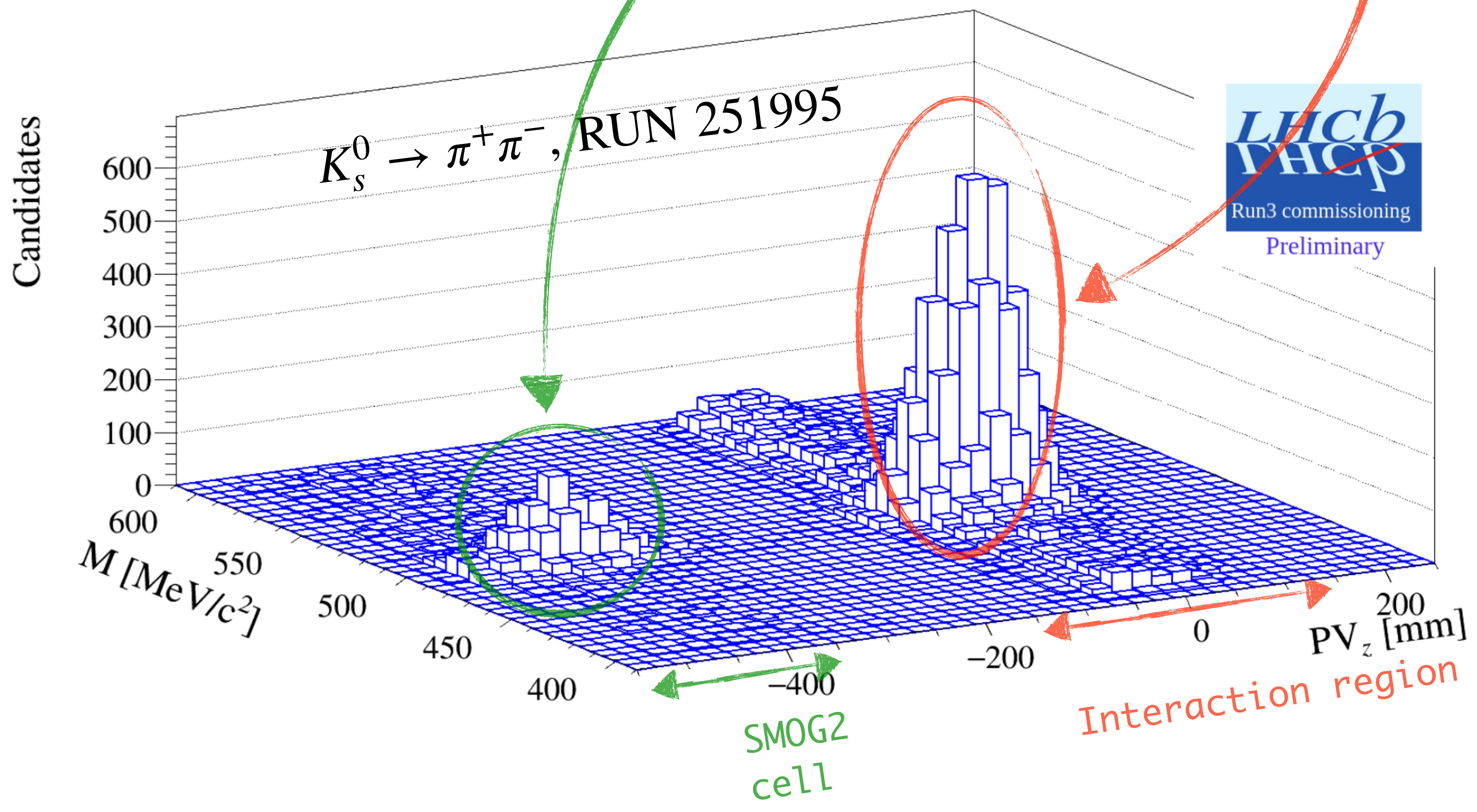
SMOG2 Gas Feed System

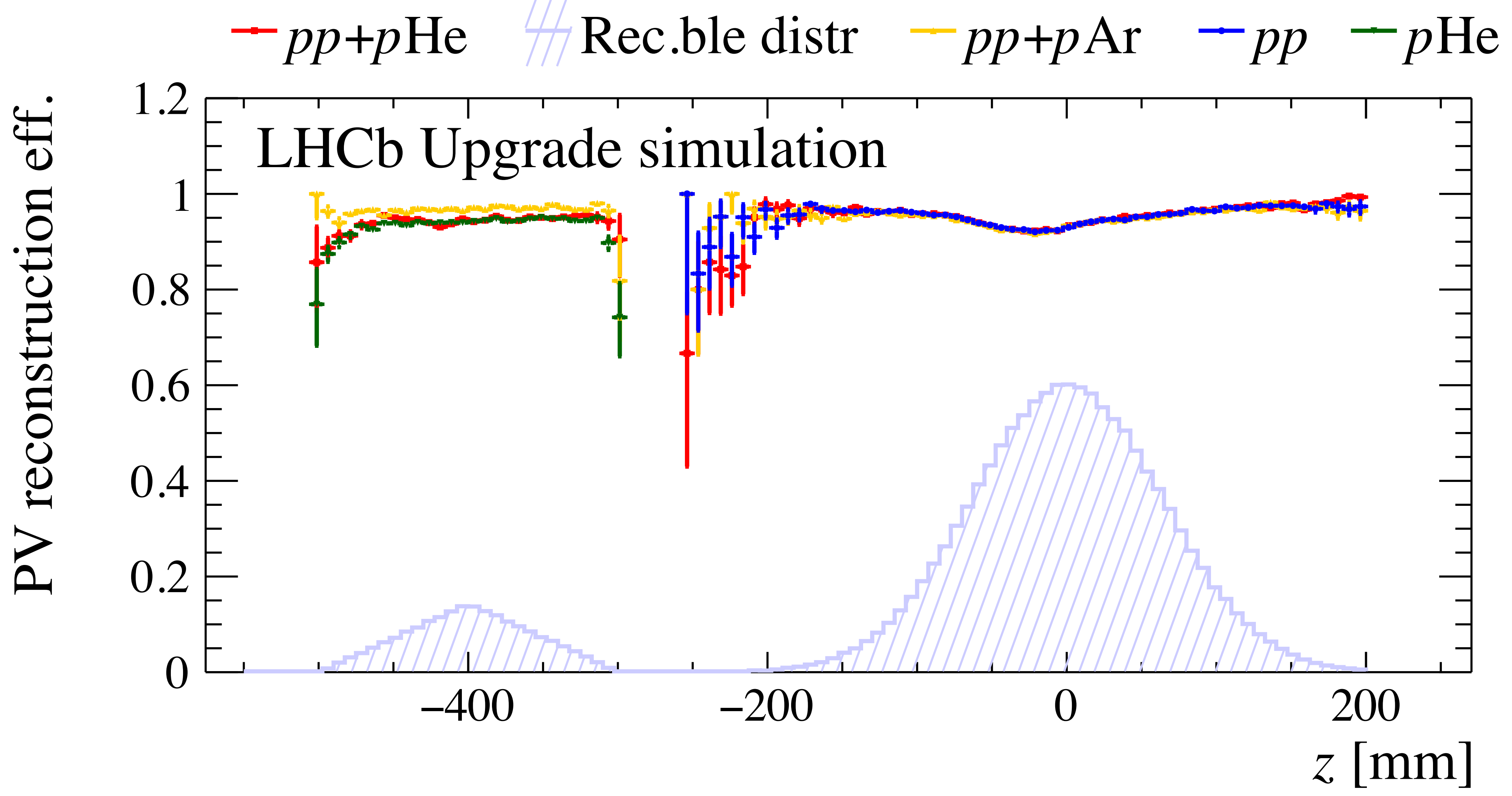


Fixed-target event reconstruction in Run 3

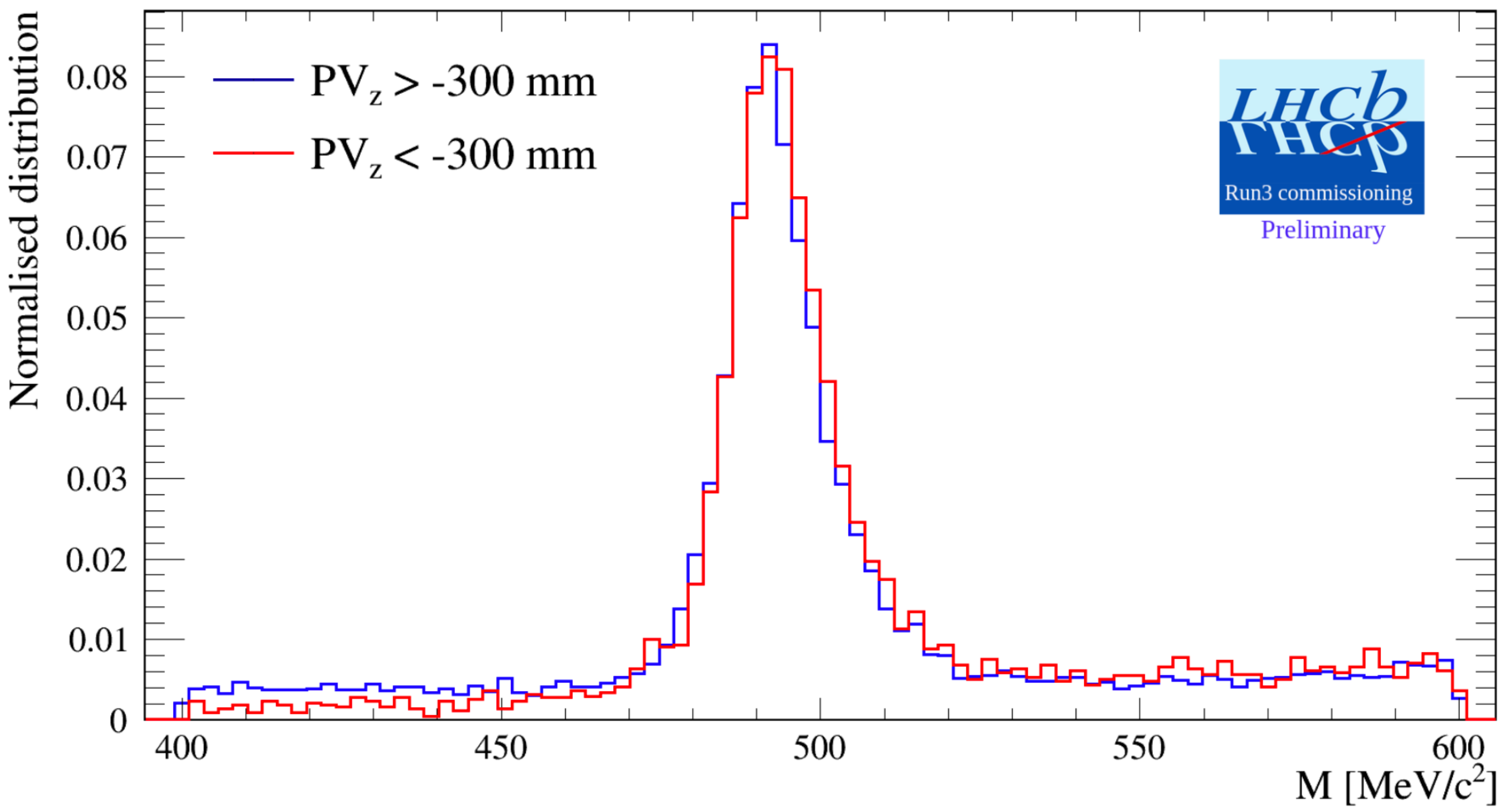
1. beam-beam and beam-gas interactions are well detached
2. Full vertex & tracking reconstruction efficiency retained in the beam-gas region
3. Negligible increase of multiplicity → small impact in the LHCb reconstruction sequence

- Confirmed with early data: beam-gas and beam-beam simultaneous data-taking with the same resolution!





[LHCB-FIGURE-2022-002]

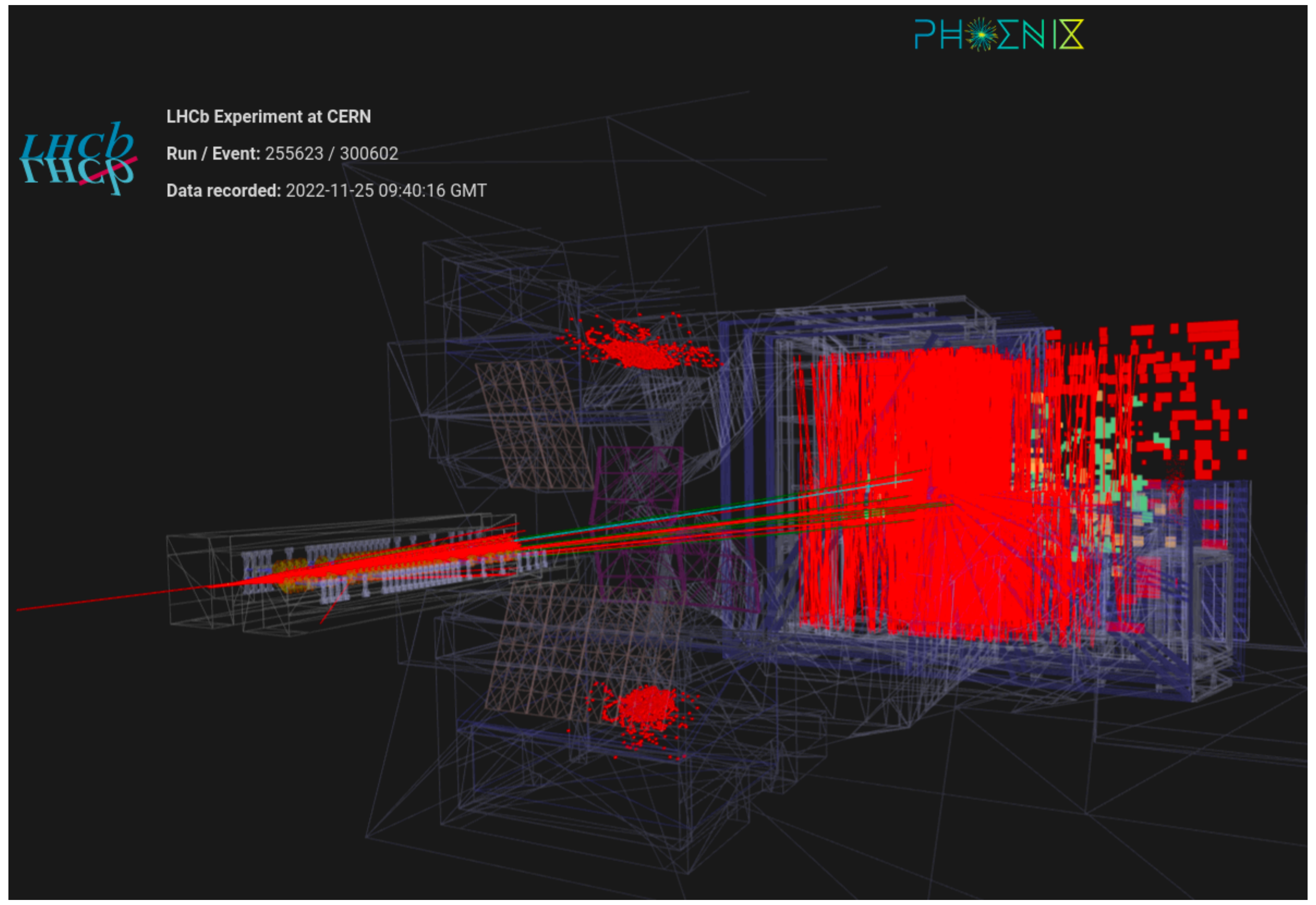


[LHCB-FIGURE-2023-001]

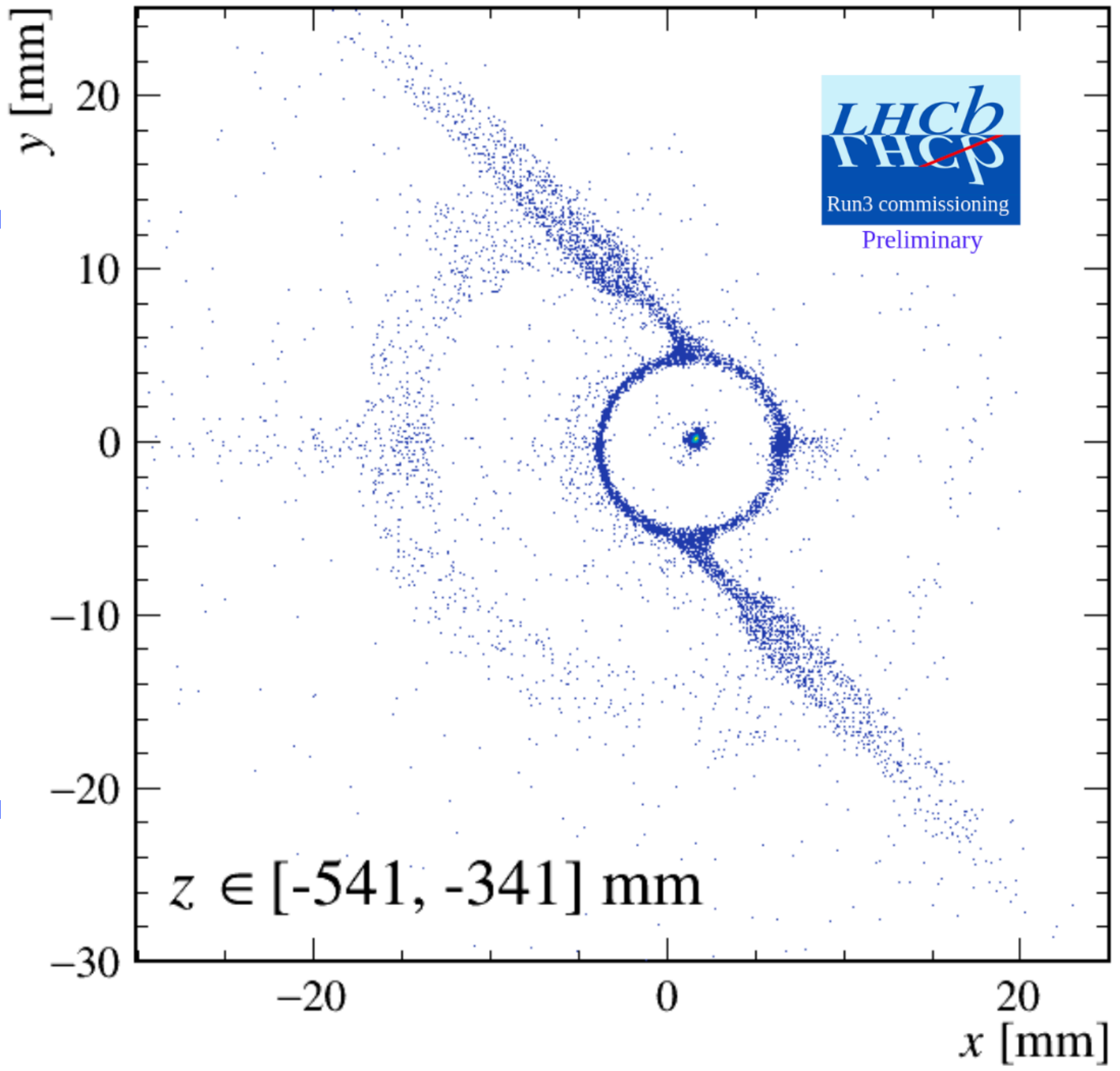
- LHCb is the only experiment able to run in collider- and fixed-target mode simultaneously!

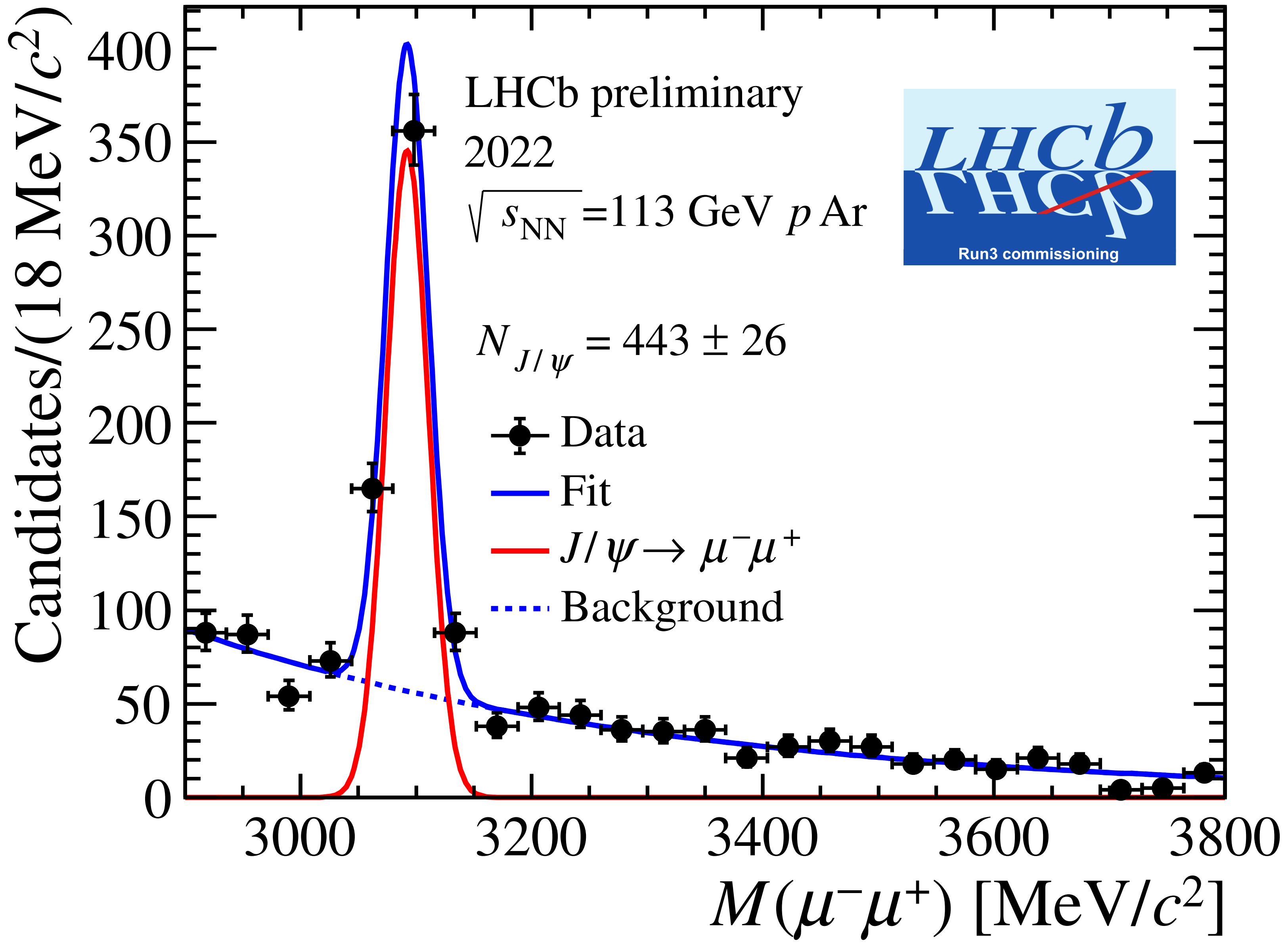
Early SMOG2 results

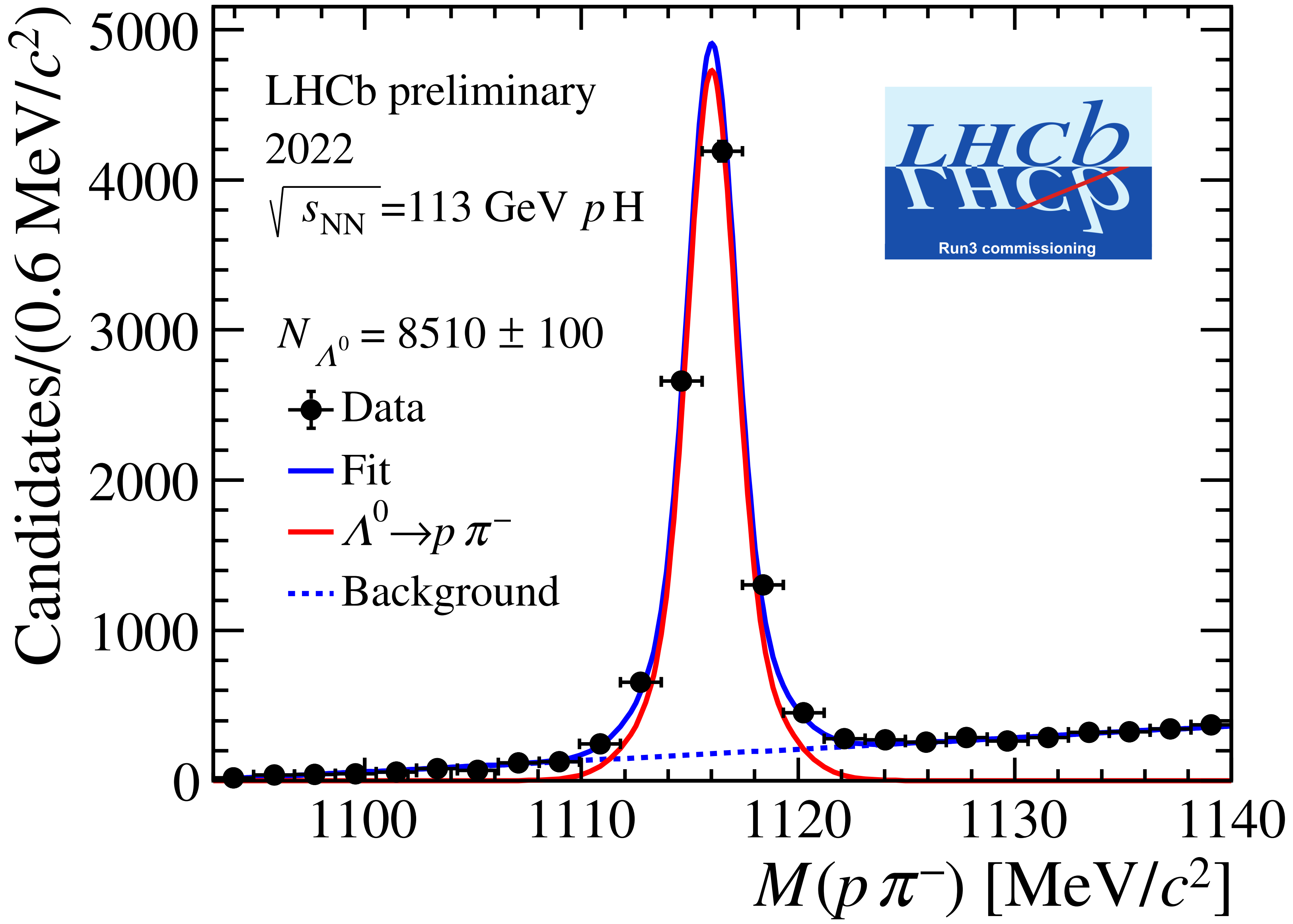
- Right: event display from a Run 3 p-Ar collision
- Bottom: tomography of the closed SMOG2 cell from residual gas & secondary interactions
- $J/\psi \to \mu^+\mu^-$ from 18 minutes of p-Ar data-taking
- $\Lambda \to p\pi^-$ from 20 minutes of p-H_2 data-taking
- Excellent results albeit low gas pressure & preliminary sub-detector performance as we're commissioning them!



[LHCB-FIGURE-2023-001]







[LHCB-FIGURE-2023-008]

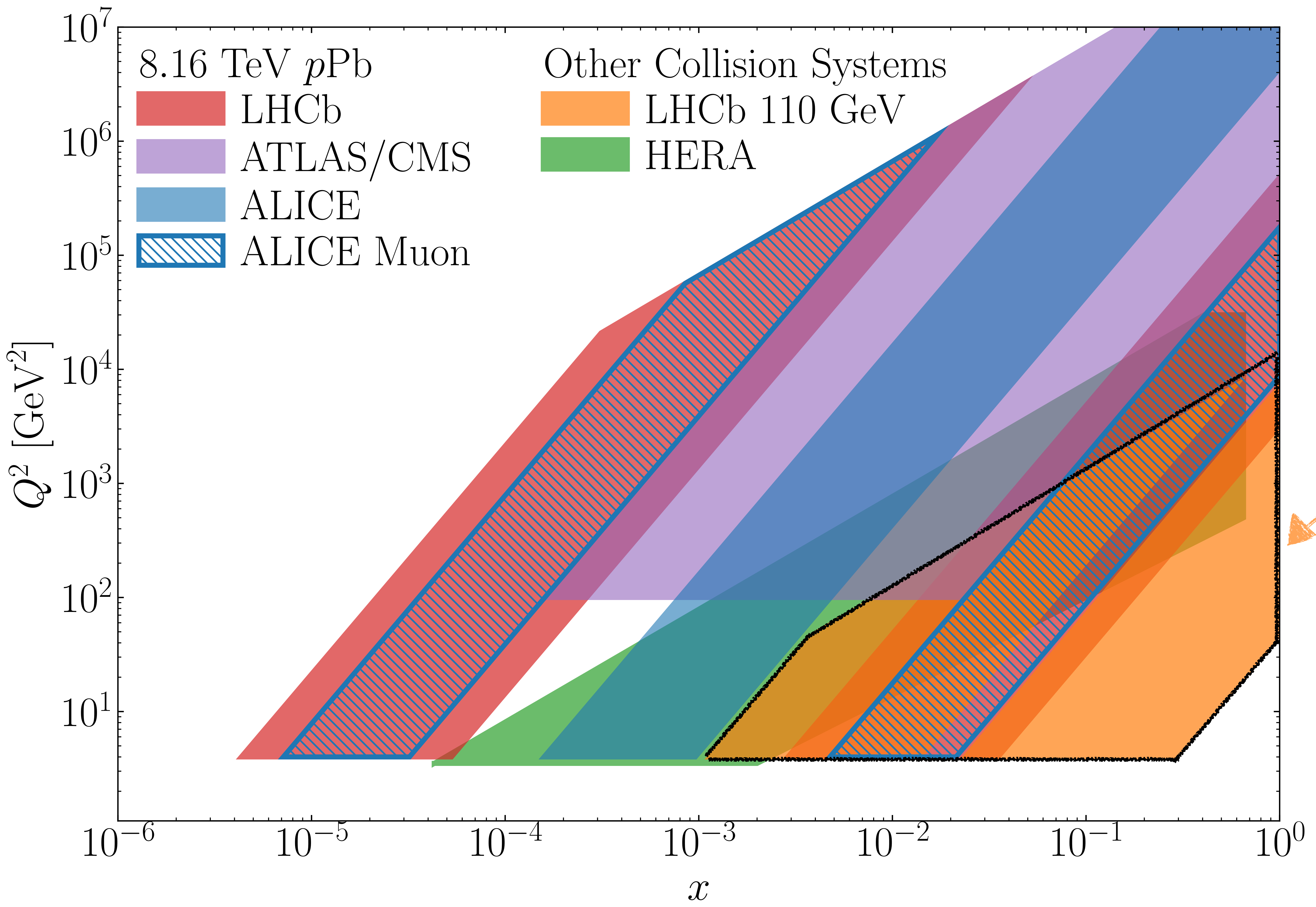
The LHCspin project

[EPJ WoC 276, 05007 (2023)]

- SMOG2 sets the basis for the development of a polarised gas target (PGT)

Two main goals of the "LHCspin" project:

1. Extend the broad physics program with unpolarised gases to Run 4 (2029) and Run 5 (2035, HL-LHC)
2. Bring spin physics at the LHC for the first time

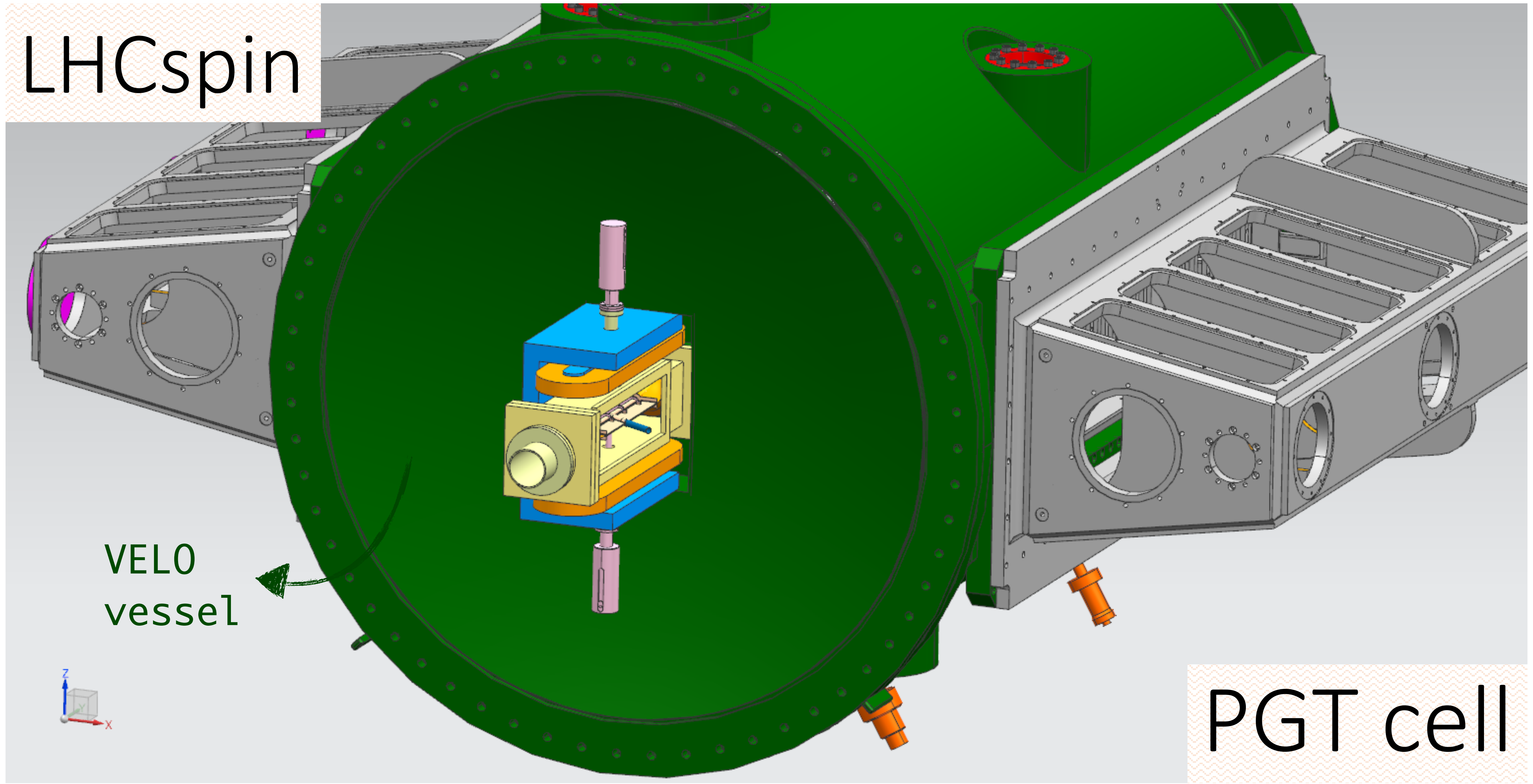


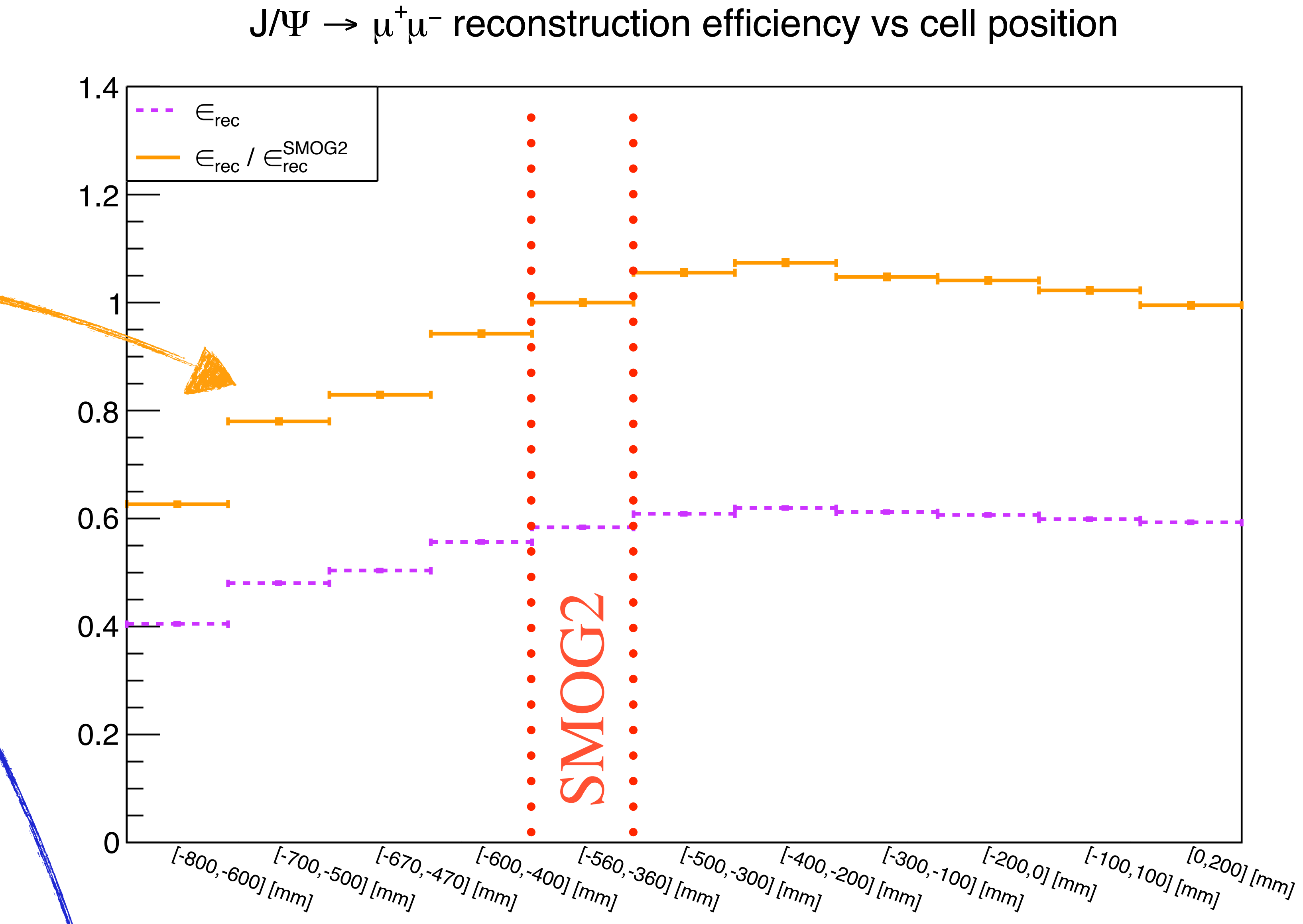
Unique QCD laboratory at LHC:

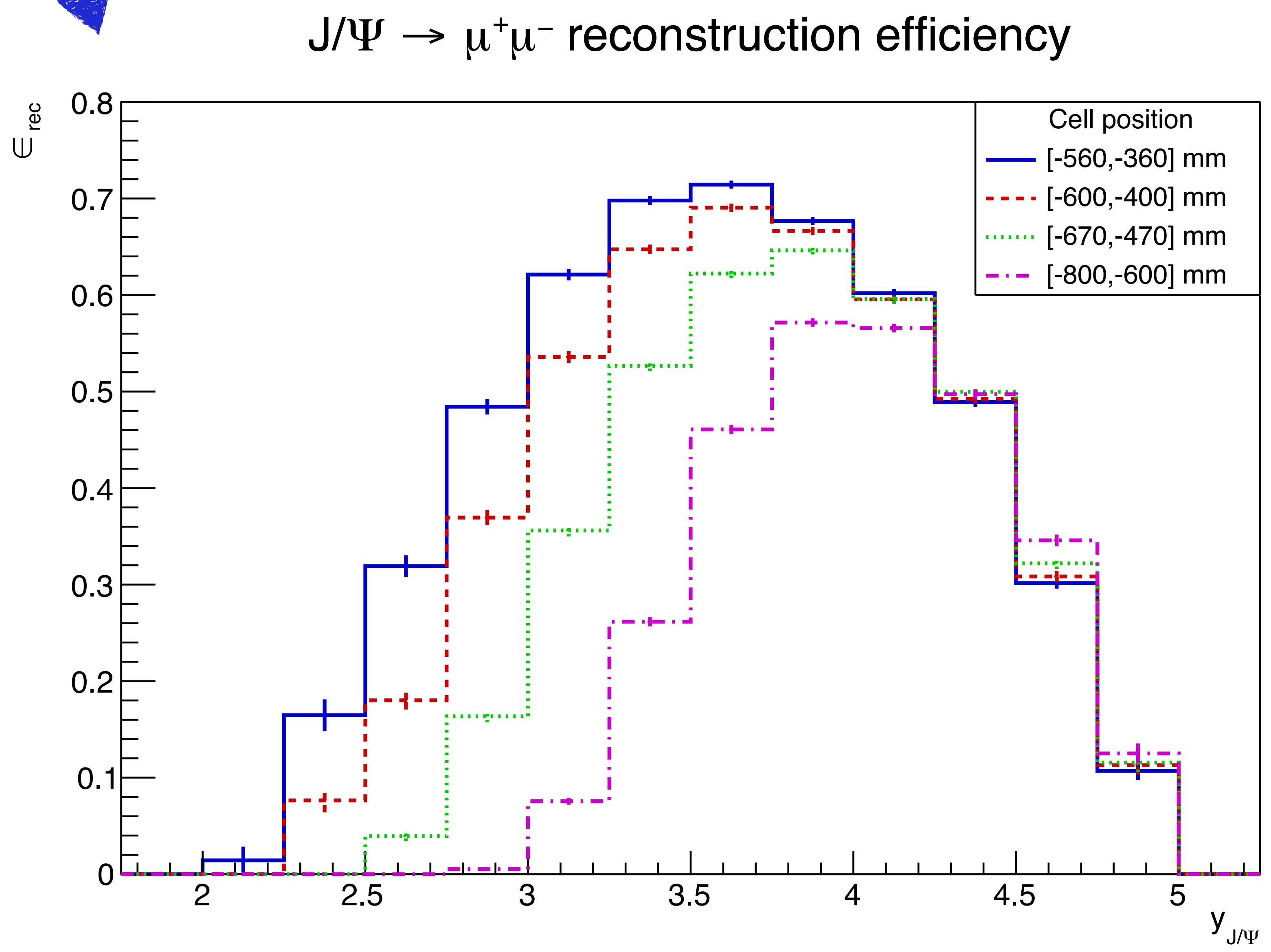
- Large-x content of g, $\bar{q}$ and heavy quarks in nucleons and nuclei
- Spin distributions of gluons inside unpolarised and polarised nucleons
- Heavy ion FT collisions at an energy in between SPS and RHIC
- Broad and poorly explored kinematic range
- High luminosity, high resolution detectors: access to a large variety of probes incl. exotic
- Several unpolarised gas targets
- Polarised gas targets: $H^{\uparrow}, D^{\uparrow}$

The Polarised Gas Target

- Drawing: cylindrical target cell with $L = 20$ cm and $D = 1$ cm (same dimensions of SMOG2) and modified VELO flange
- LHCb simulations show broader kinematic acceptance & higher efficiency when the cell is close to the VELO
- Our new fully-software trigger gives flexibility & room for improvement e.g. better reconstruction algorithms, dedicated trigger lines…

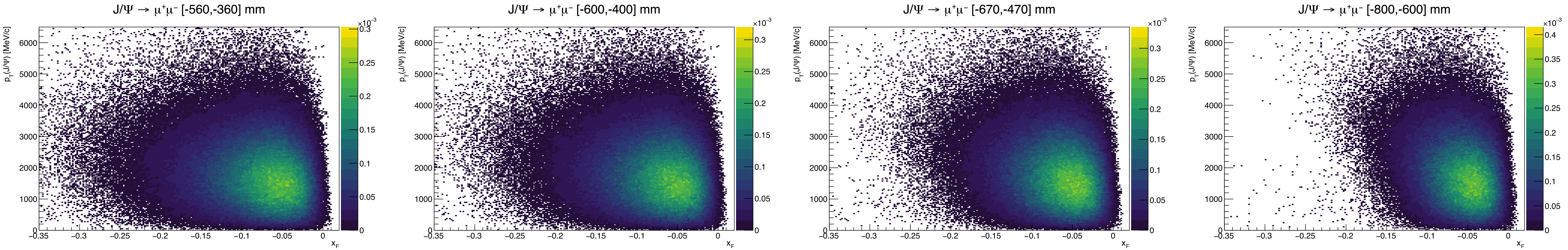




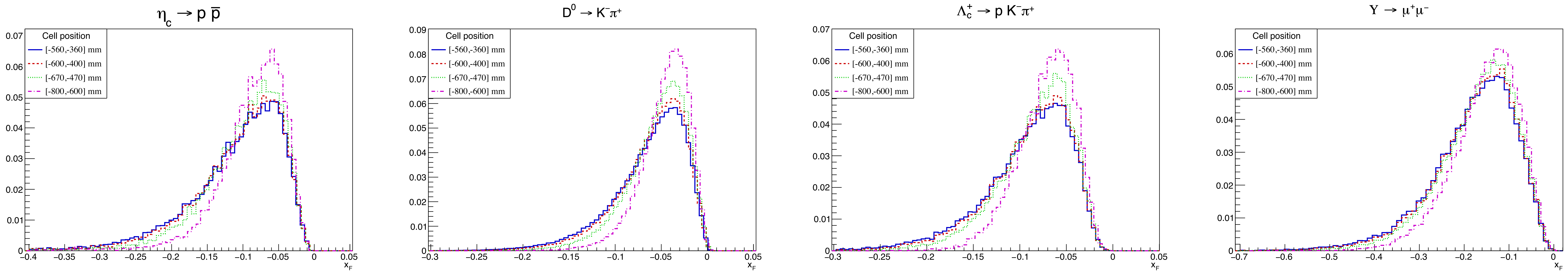


Kinematic coverage

- LHCb p-H FT simulations at $\sqrt{s} = 115$ GeV. Using $x_F = 2E_T/\sqrt{s_{NN}}\ \sinh(y^*)$ with $E_T^2 = M^2 + P_T^2$
- Actual SMOG2 region $[-560, -360]$ mm as a reference, $[-670, -470]$ mm a possible solution to fit the LHCspin setup
- The kinematic coverage depends on the cell position → p_T slightly affected, x range shrinks when moving upstream:

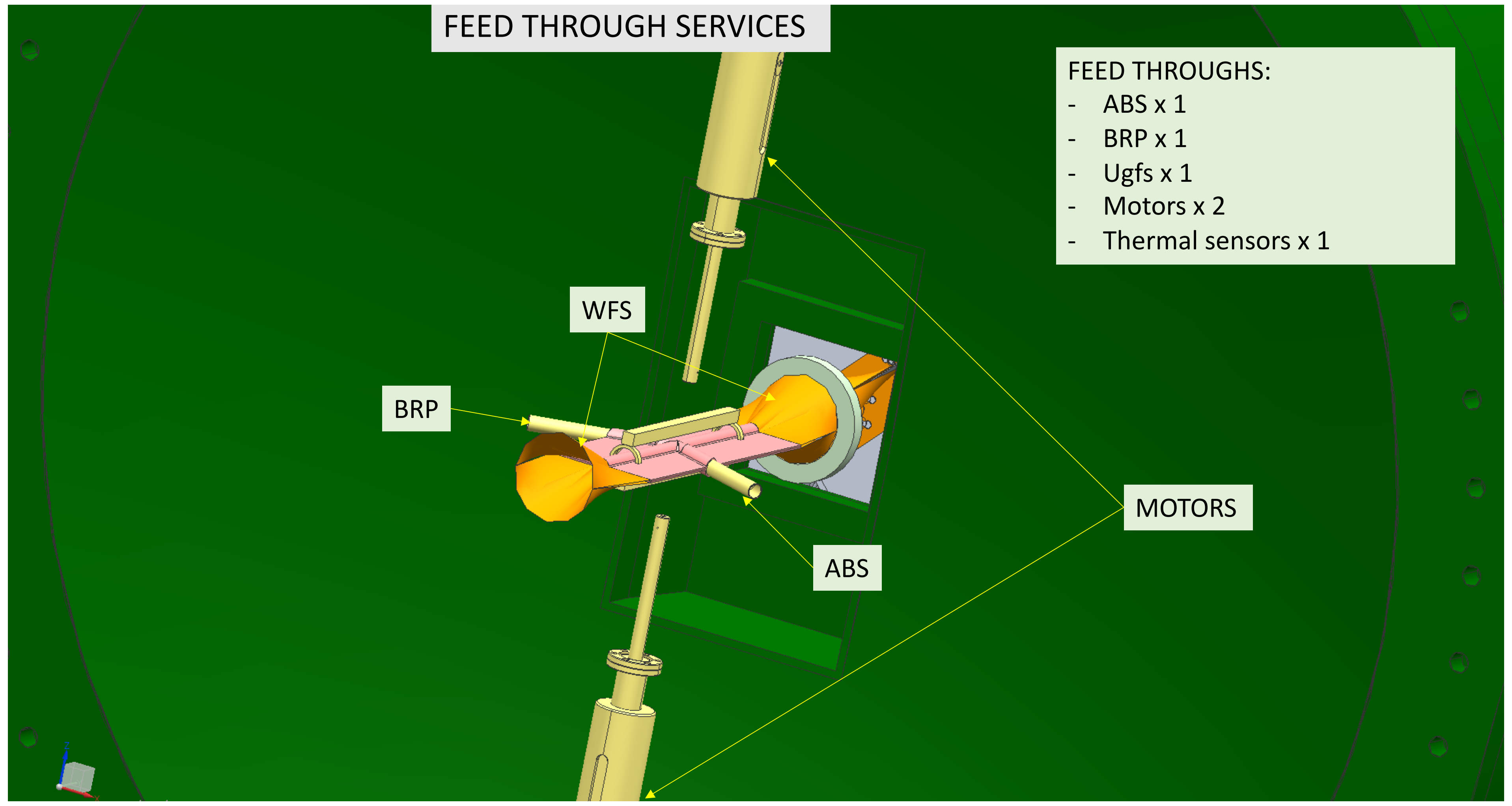


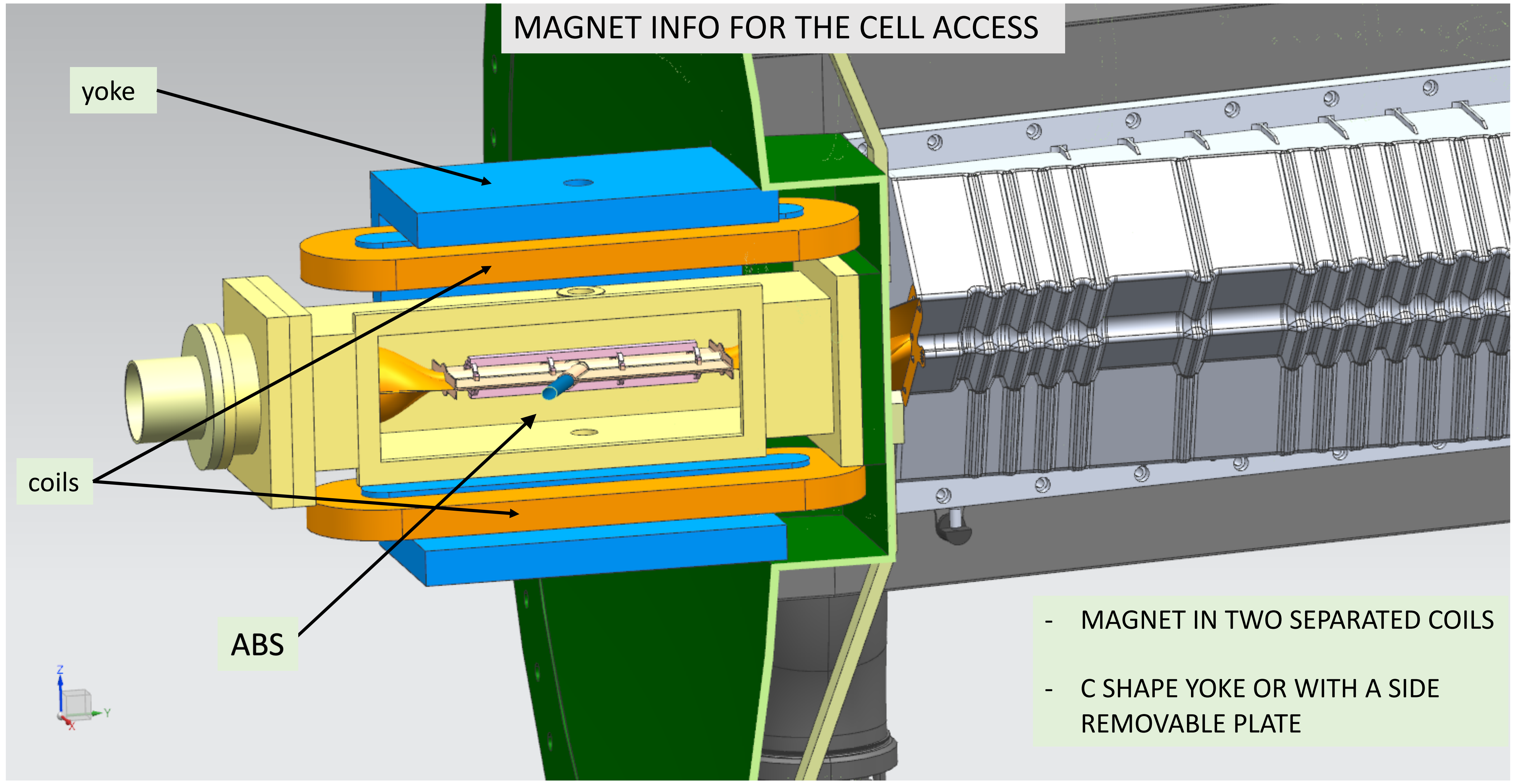
- x_F spectra for some channels:



The Polarised Gas Target

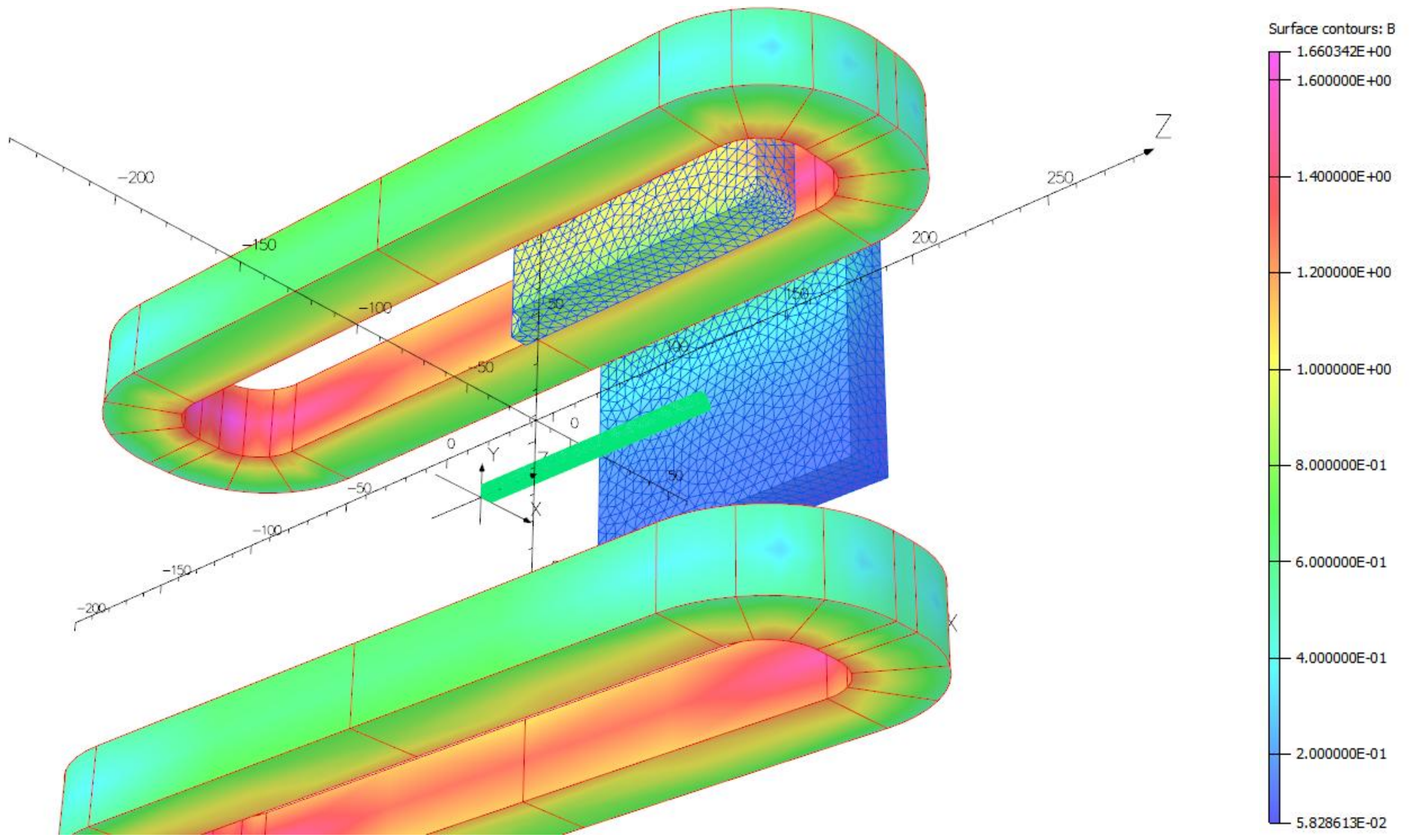
- Inject both polarised and unpolarised gases via ABS and uGFS



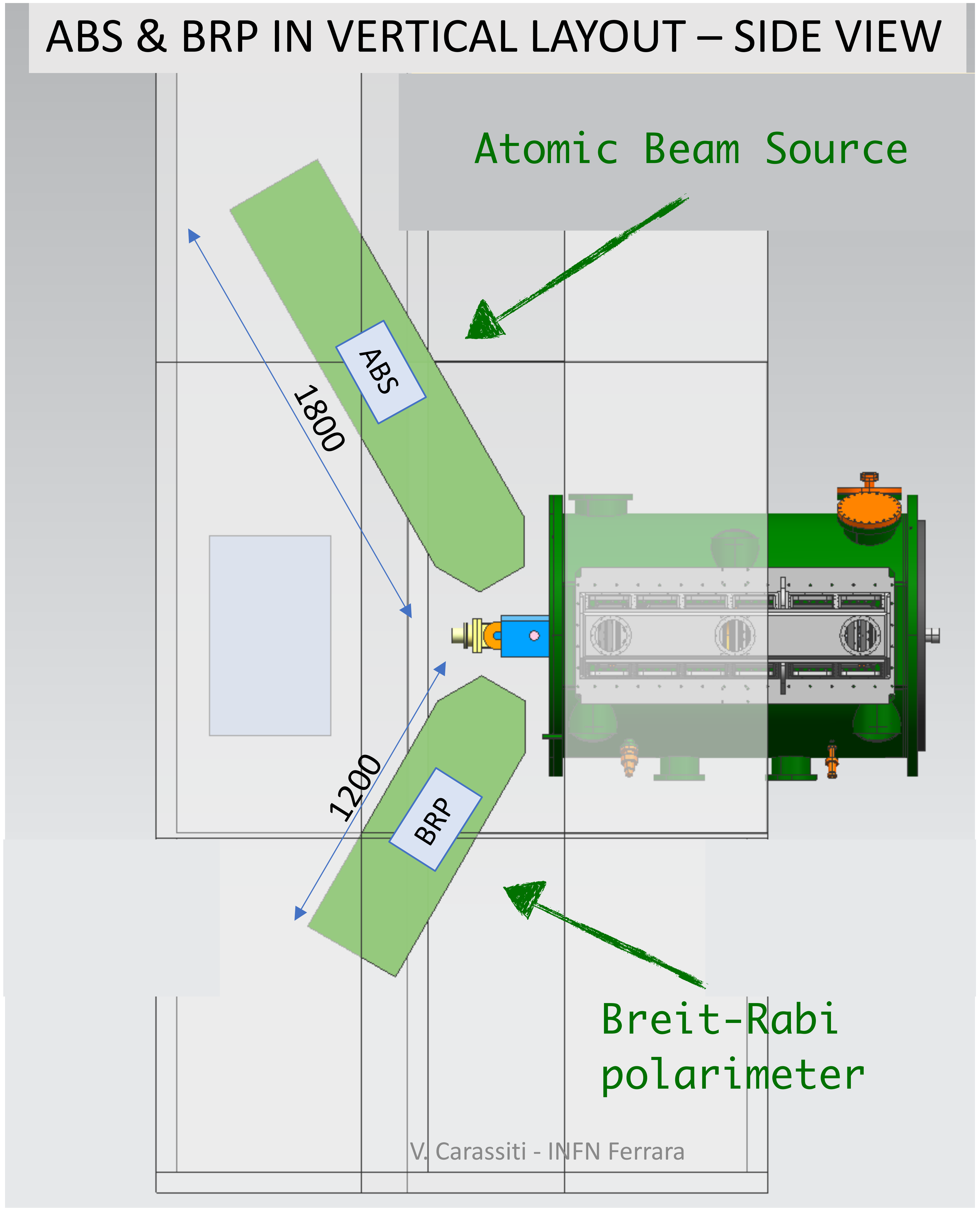


- Compact dipole magnet around the cell to provide static transverse field
- Superconductive coils + iron yoke configuration fits the space constraints
- $B = 300$ mT with polarity inversion and $\Delta B/B \simeq 10\,\%$, suitable to avoid beam-induced depolarisation
- Possibility to switch to a solenoid and provide longitudinal polarisation

[PoS (SPIN2018)]



ABS and BRP R&D



[NIMA 540 (2005) 68-101]

- Starting from the well established HERMES setup @ DESY ... to create the next generation of polarised fixed-targets!
- Reduce the size of both ABS and BRP to fit into the available space in the LHCb cavern: a challenging R&D!
- No need for additional detectors in LHCb!
- Aiming at HERMES performance:

  Polarisation degree: $\approx 85\,\%$

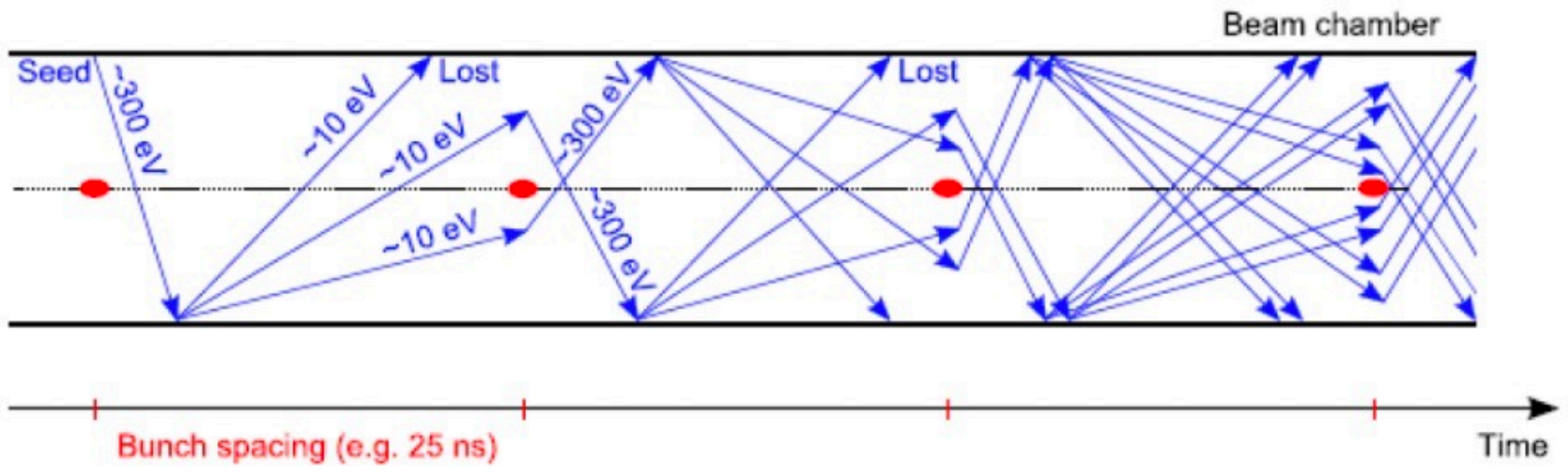
  Intensity of injected H-atoms: $6.5 \times 10^{16}\ \mathrm{s}^{-1}$

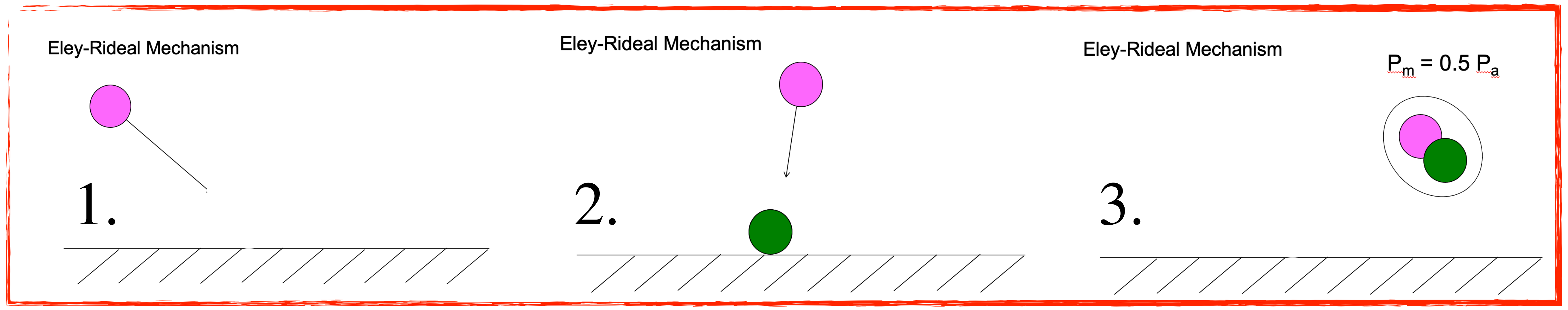
  FT luminosity (HL-LHC): $\sim\ 8 \times 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

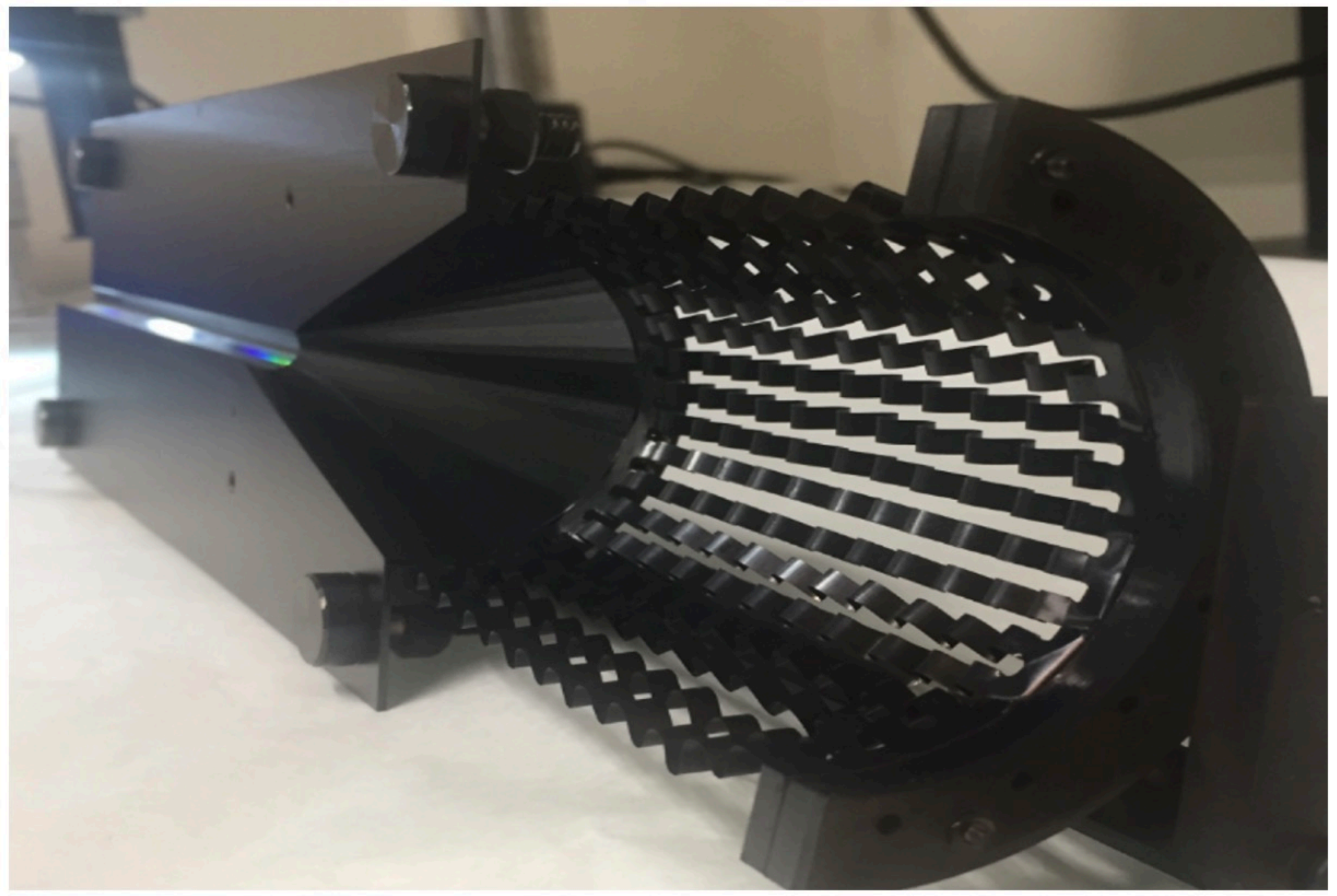
Cell coating for the LHC

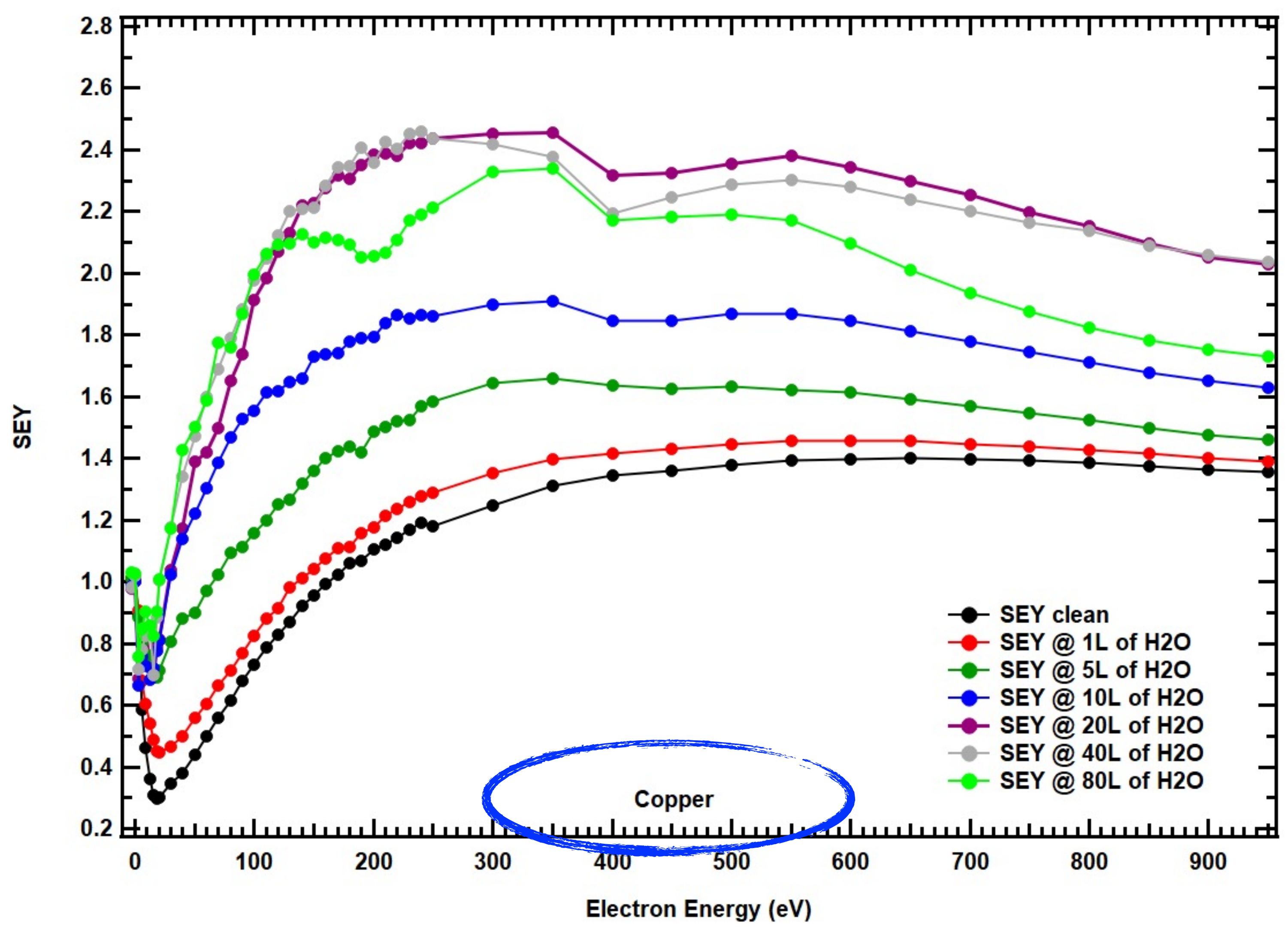
- The storage cell must have a low secondary electron yield (SEY)
- This is already achieved in SMOG2 via carbon-coating (bottom picture)

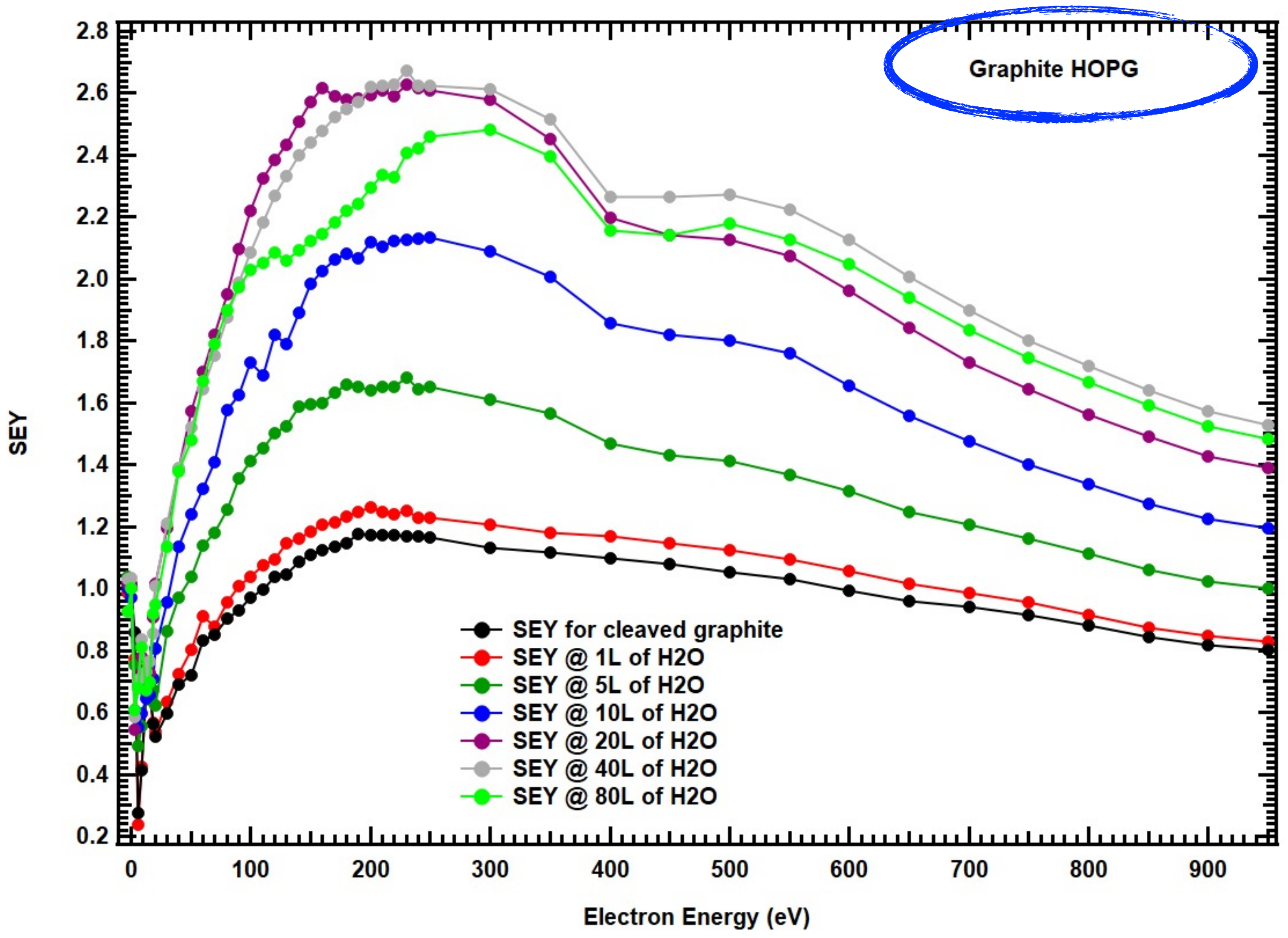
- In a polarised target, hydrogen recombination must be kept low too
- A thin layer of ice is a possible solution: renewable surface but needs cooling
- SEY vs ice layers measured, recombination measurements ongoing





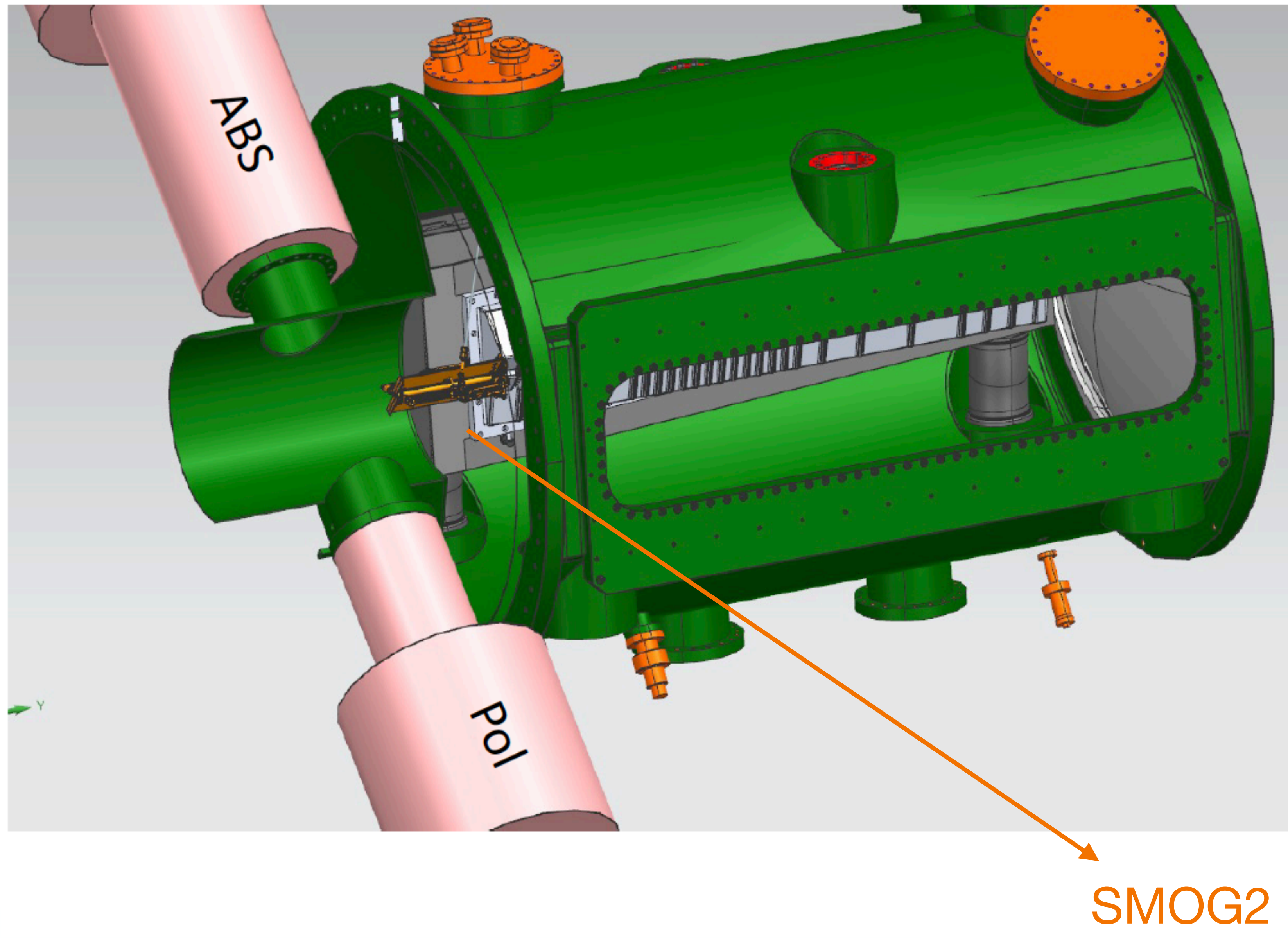






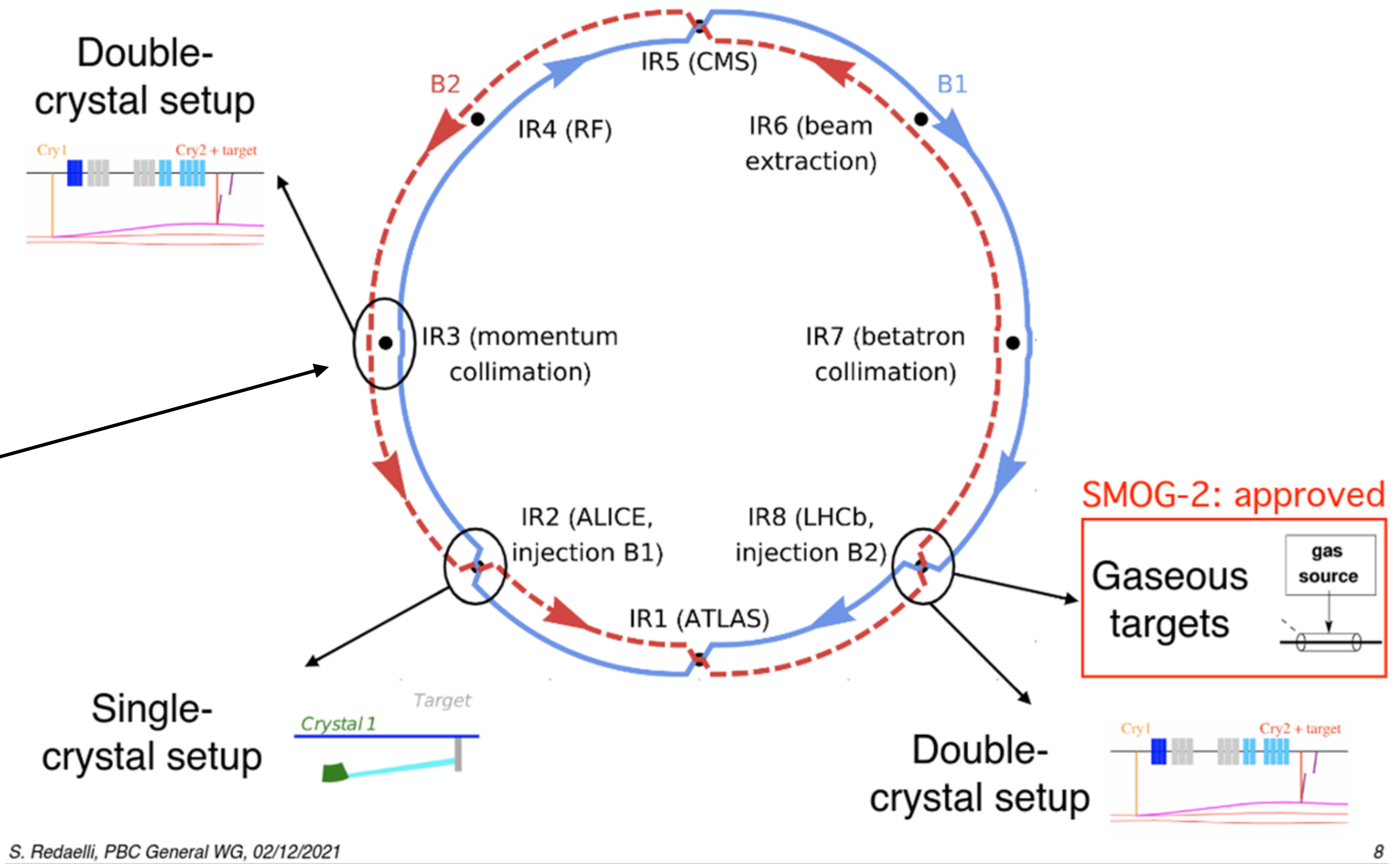
More on the R&D

- Drifilm + ice was very successful at HERMES but challenging at LHC
- Alternative solution is being investigated in parallel: a jet target would provide lower density ($\approx 1/40$) but higher polarisation degree
- $\theta_{jet} \approx 10^{12}\ \mathrm{cm}^{-2}$ but $P \approx 90\,\%$ with very small systematic error
- PRO: precision measurements on high-statistics channels
- CON: Makes kinematic binning and rare channels harder



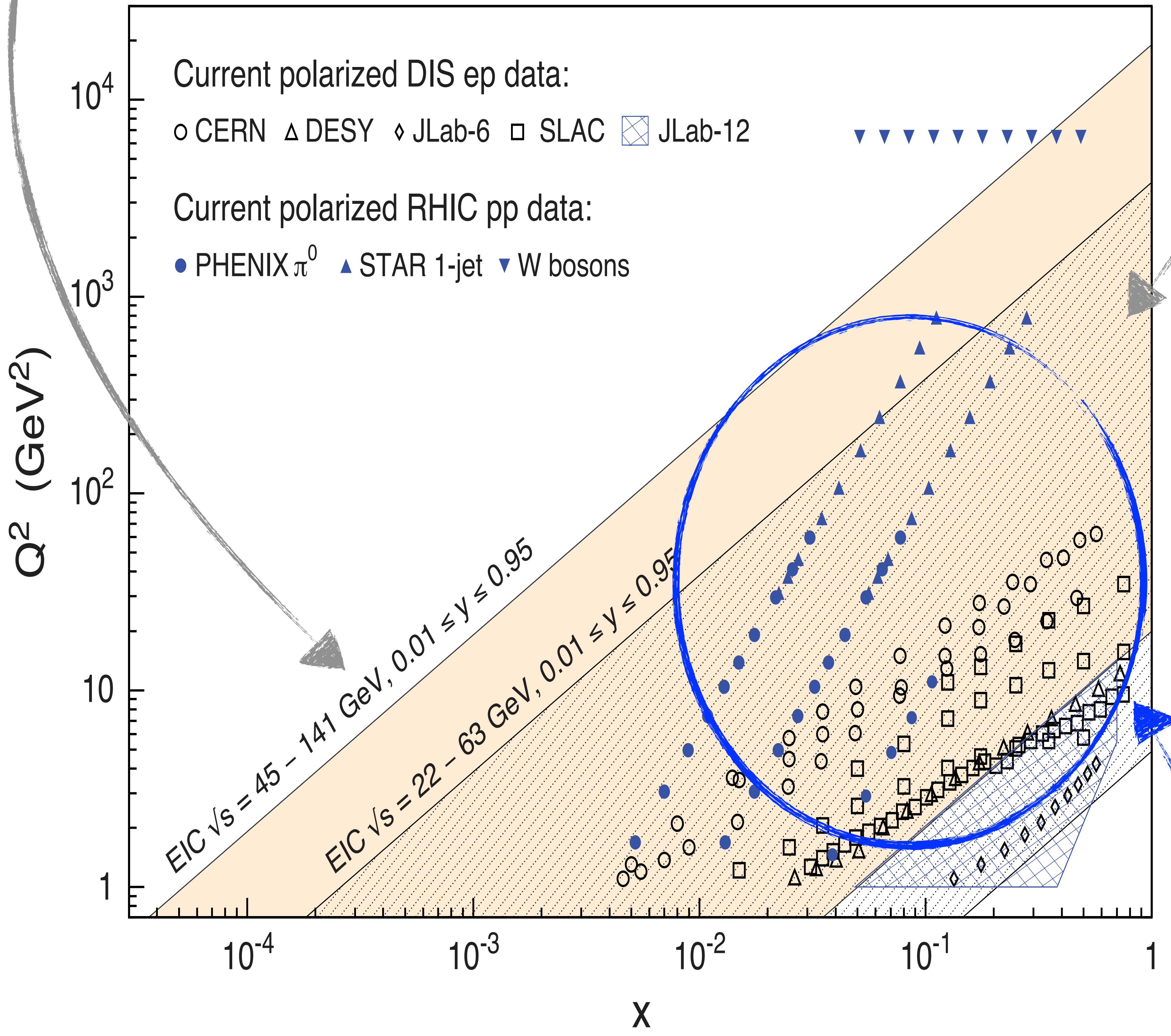
- We are also exploring the possibility of a test setup at the IR3 of the LHC
- Useful to study a new compact polarimeter system, understanding the beam interactions etc.
- This activity would be parallel to LHCb and open to external members

LHC spin
R&D



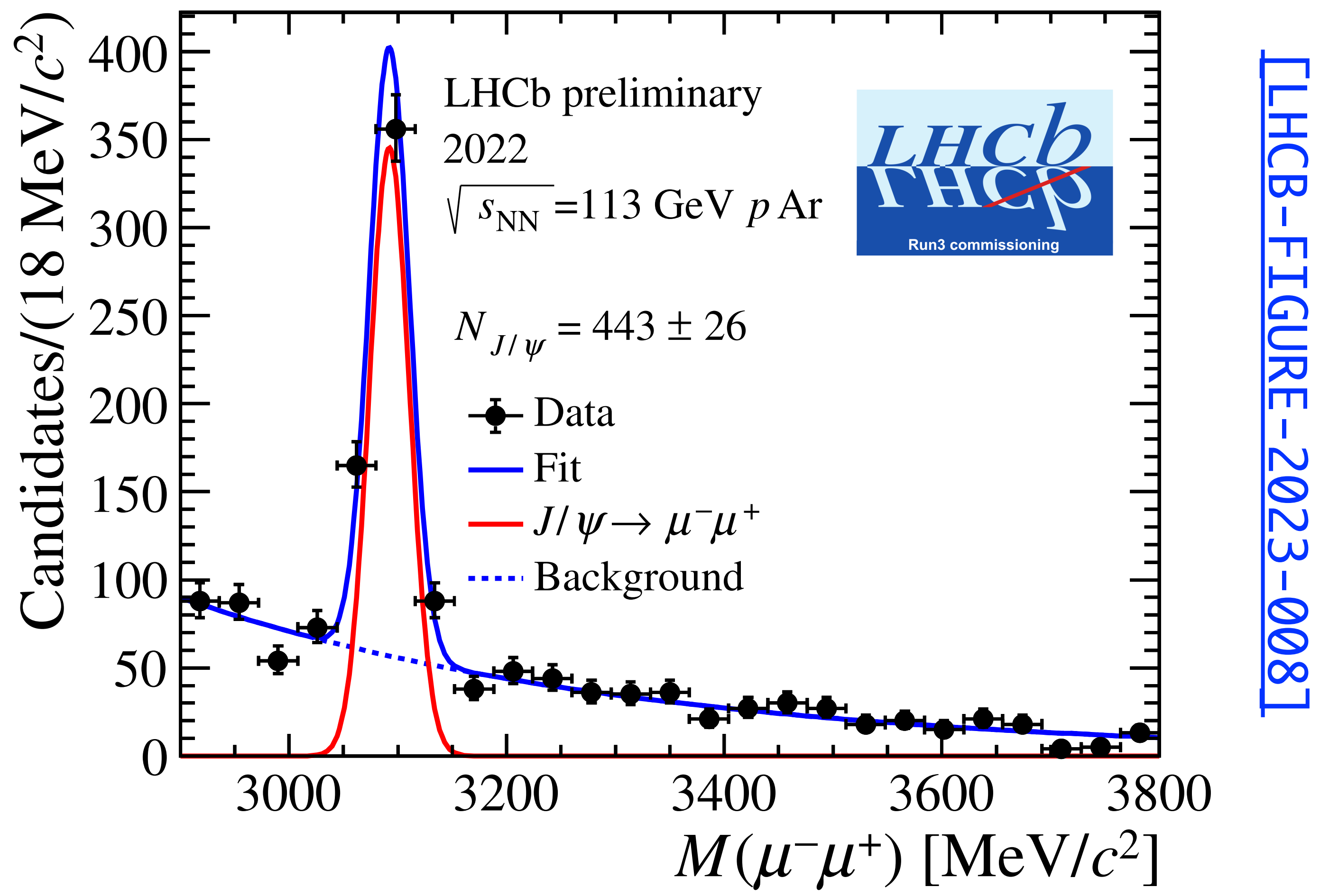
LHCspin physics: overview

- Complementarity is the key:
- 12 GeV JLab probing high-x, low Q^2
- EIC measurements to focus on low-x, starting ~2035
- higher Q^2 reach with future EIC upgrade



- LHCspin to best cover mid- to high-x at intermediate Q^2

- SMOG2 is performing above the expectation: early data-taking with low pressure: 443 $J/\psi \to \mu^+\mu^-$ in just 18 minutes while all sub-detectors are undergoing commissioning!



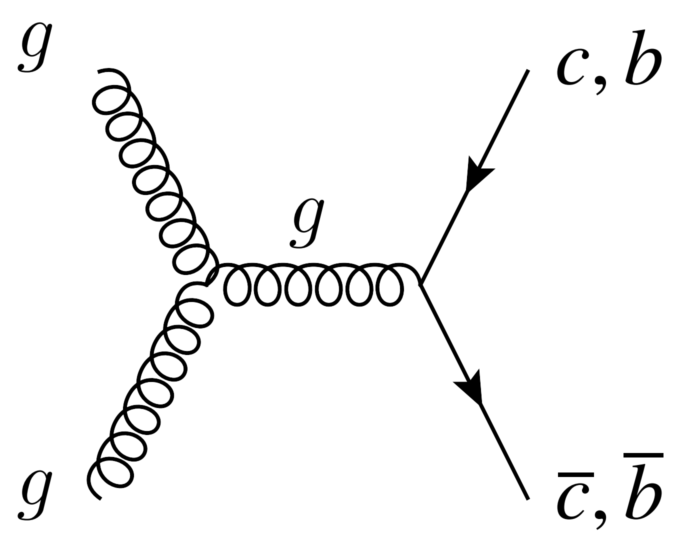
[LHCB-FIGURE-2023-008]

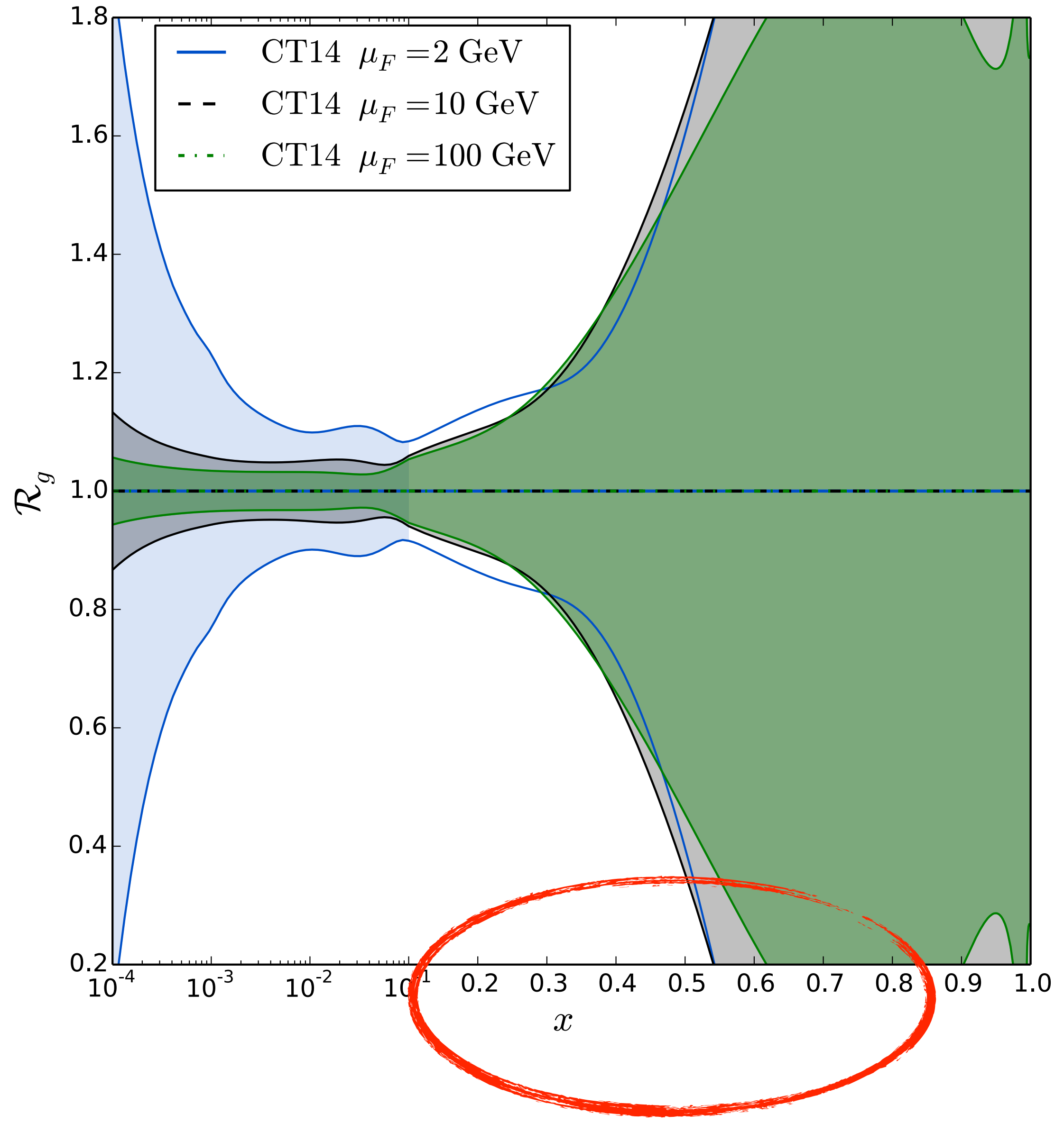
- Based on this important milestone, we can estimate for a Run of p-H collision at LHCspin:

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

Unpolarised targets: PDFs

- high-x nucleon and nuclei structure is poorly known at all scales

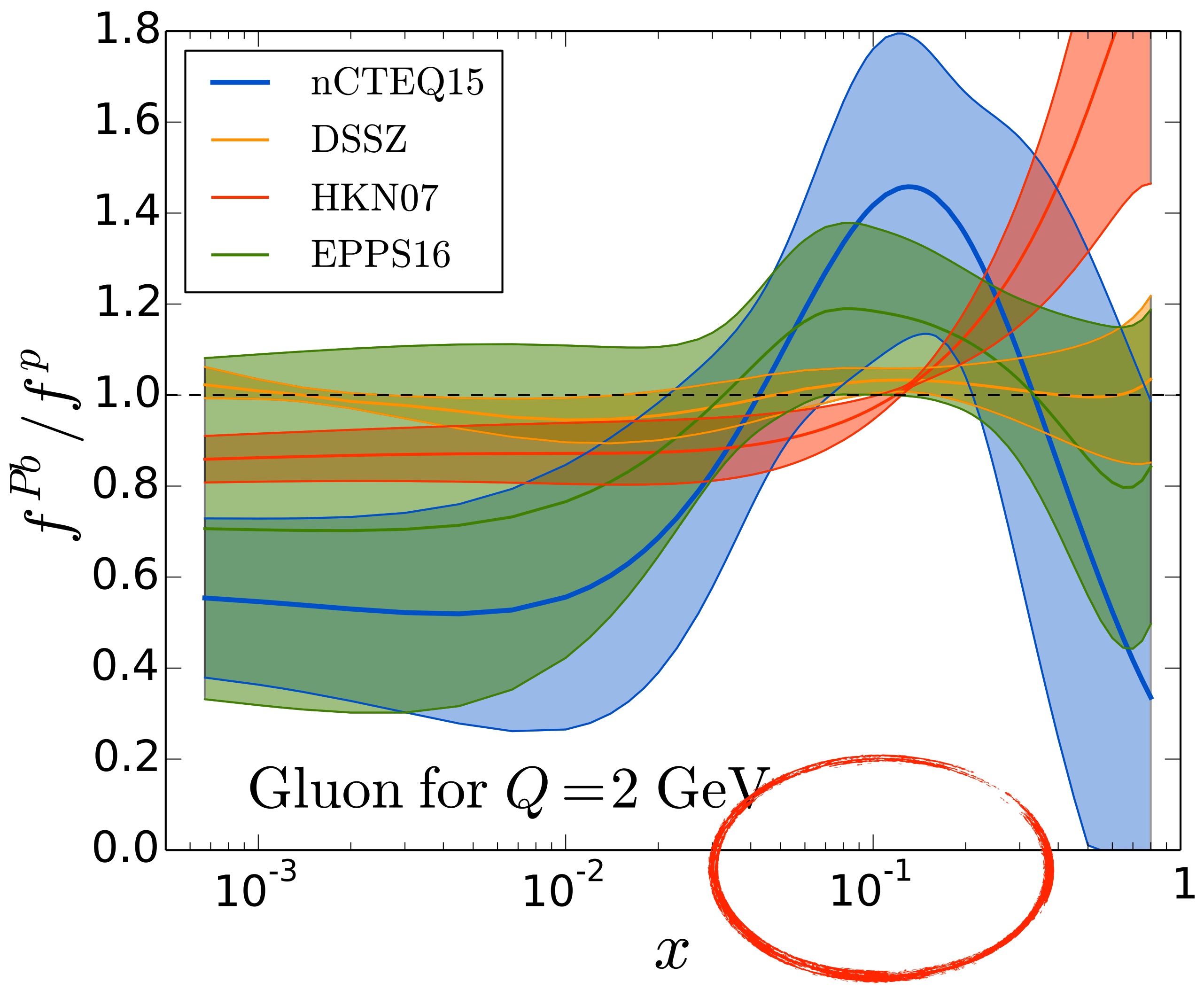




- Gluon PDFs are least known, accessed with heavy flavours: a strength point of LHCb!
  [PRD 93 (2016) 033006]

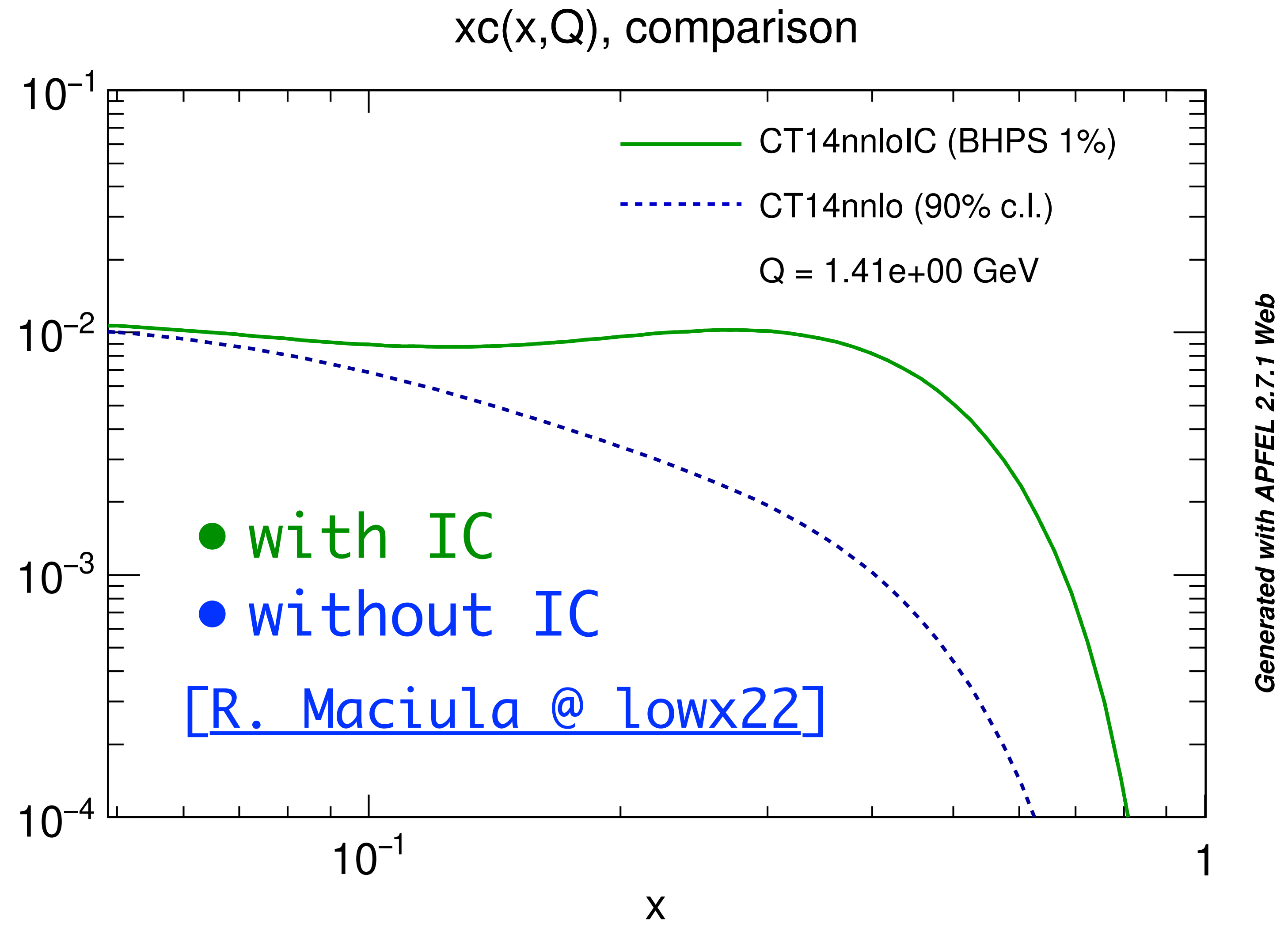
- Investigate the structure of nuclei: EMC effect still to be understood
- → get more insight into the anti-shadowing region ($x \sim 0.1$)

  [ArXiv:1807.00603]



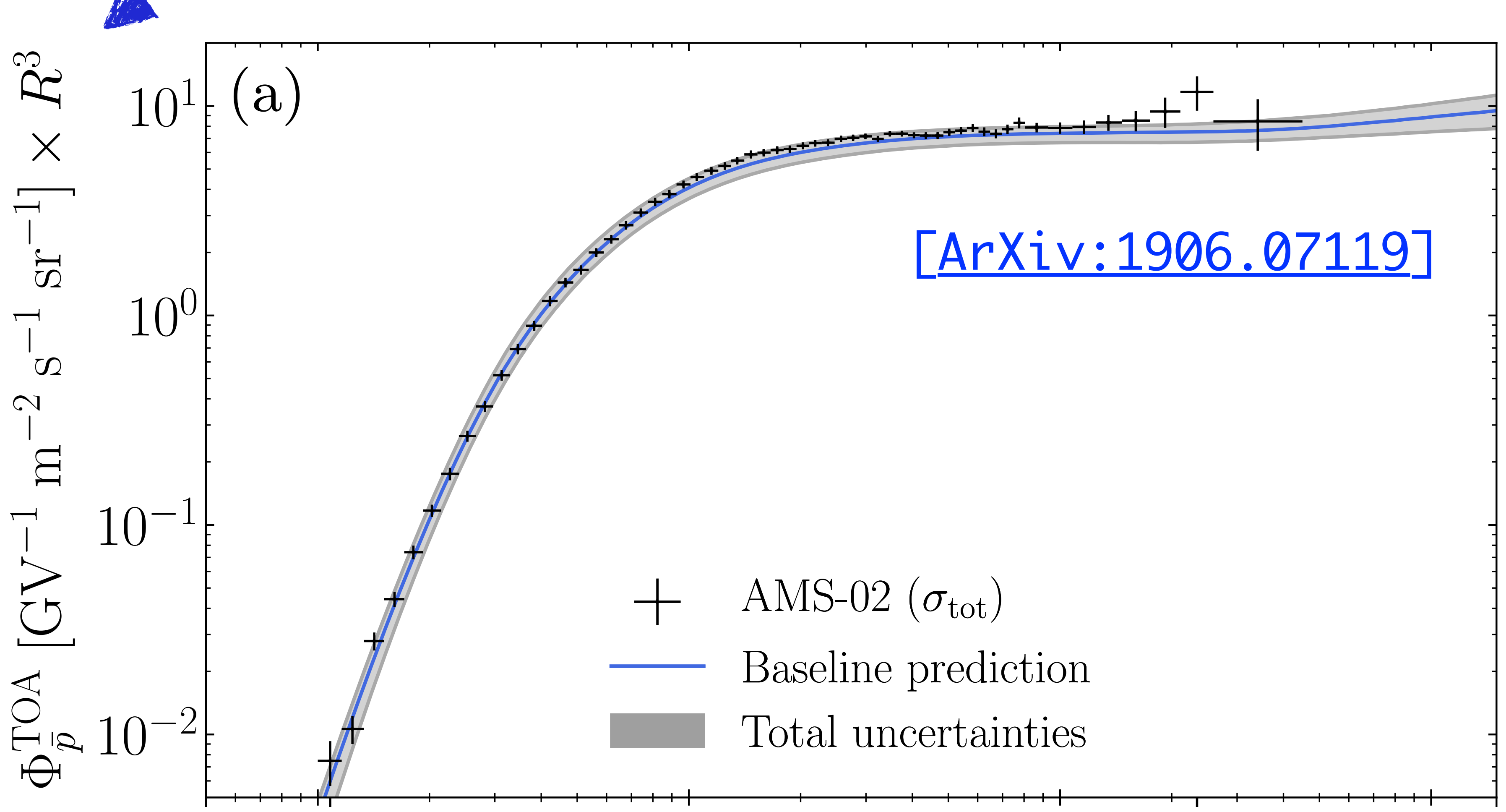
[PRD 105 (2022) 014001]

- Study the Intrinsic Charm component in the proton, first measurement done with SMOG on pHe
  [PRL 122 (2019) 132002]



- Provide crucial inputs for neutrino fluxes, UHECR and DM annihilation

[JHEP 05 (2017) 004] [ARNPS 61 (2011) 467-489]

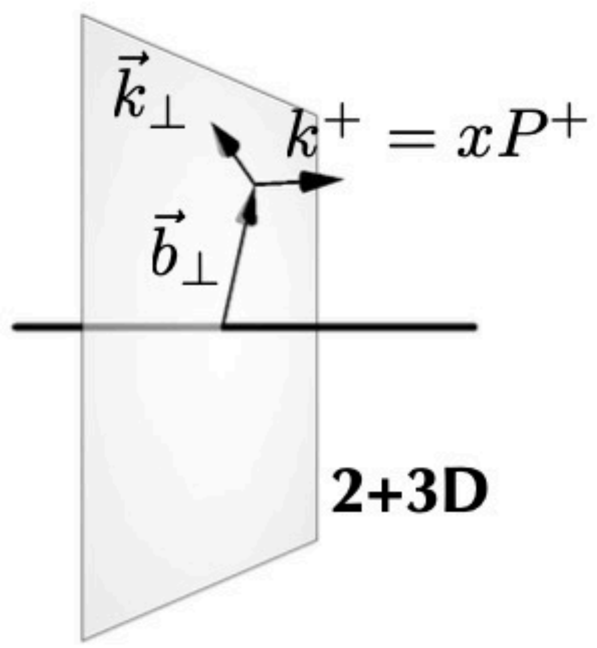


Polarised target: multi-dimensional nucleon mapping

- Overcome the 1D view of the nucleon and investigate its spin structure: GPDs and TMDs

quark polarization

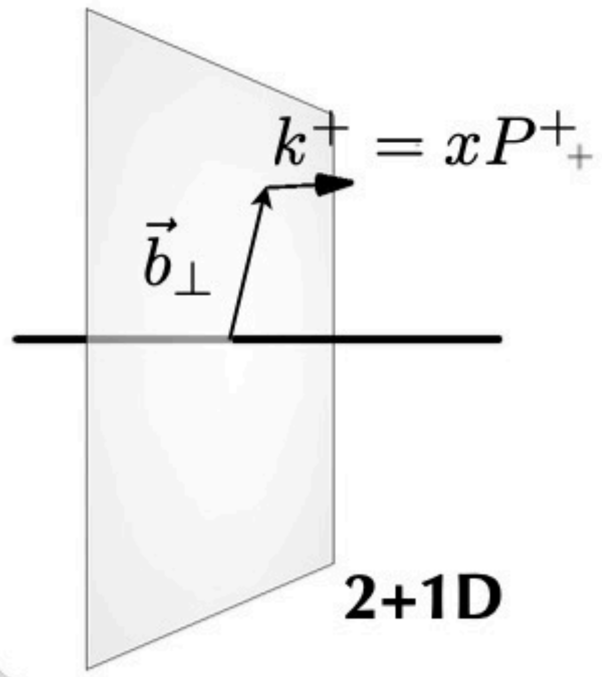
$\xi = 0$



nucleon polarization

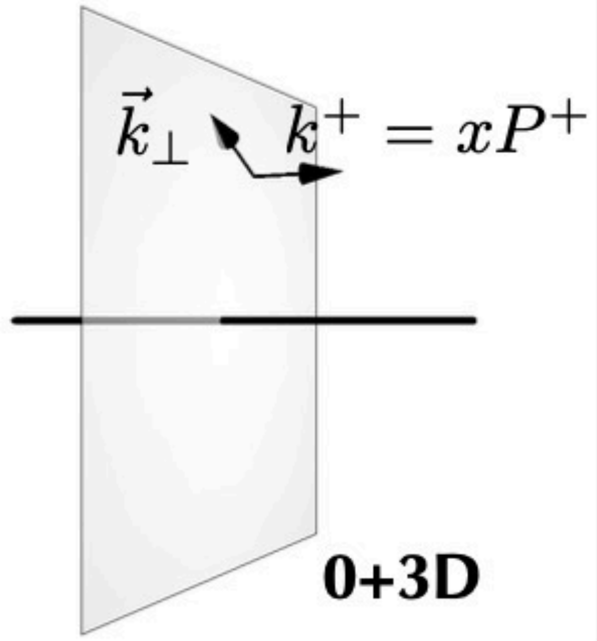
$\mathcal{W}_X$	U	L	T_x	T_y
U	$\langle 1 \rangle$	$\langle S_L^q \ell_L^q \rangle$	$\langle S_x^q \ell_x^q \rangle$	$\langle S_y^q \ell_y^q \rangle$
L	$\langle S_L \ell_L^q \rangle$	$\langle S_L S_L^q \rangle$	$\langle S_L \ell_L^q S_x^q \ell_x^q \rangle$	$\langle S_L \ell_L^q S_y^q \ell_y^q \rangle$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

$\int d^2\vec{k}_\perp$ $\qquad$ $\int d^2\vec{b}_\perp$



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}	$h_1,\ h_{1T}^\perp$



[from B. Pasquini @ DIS2021]

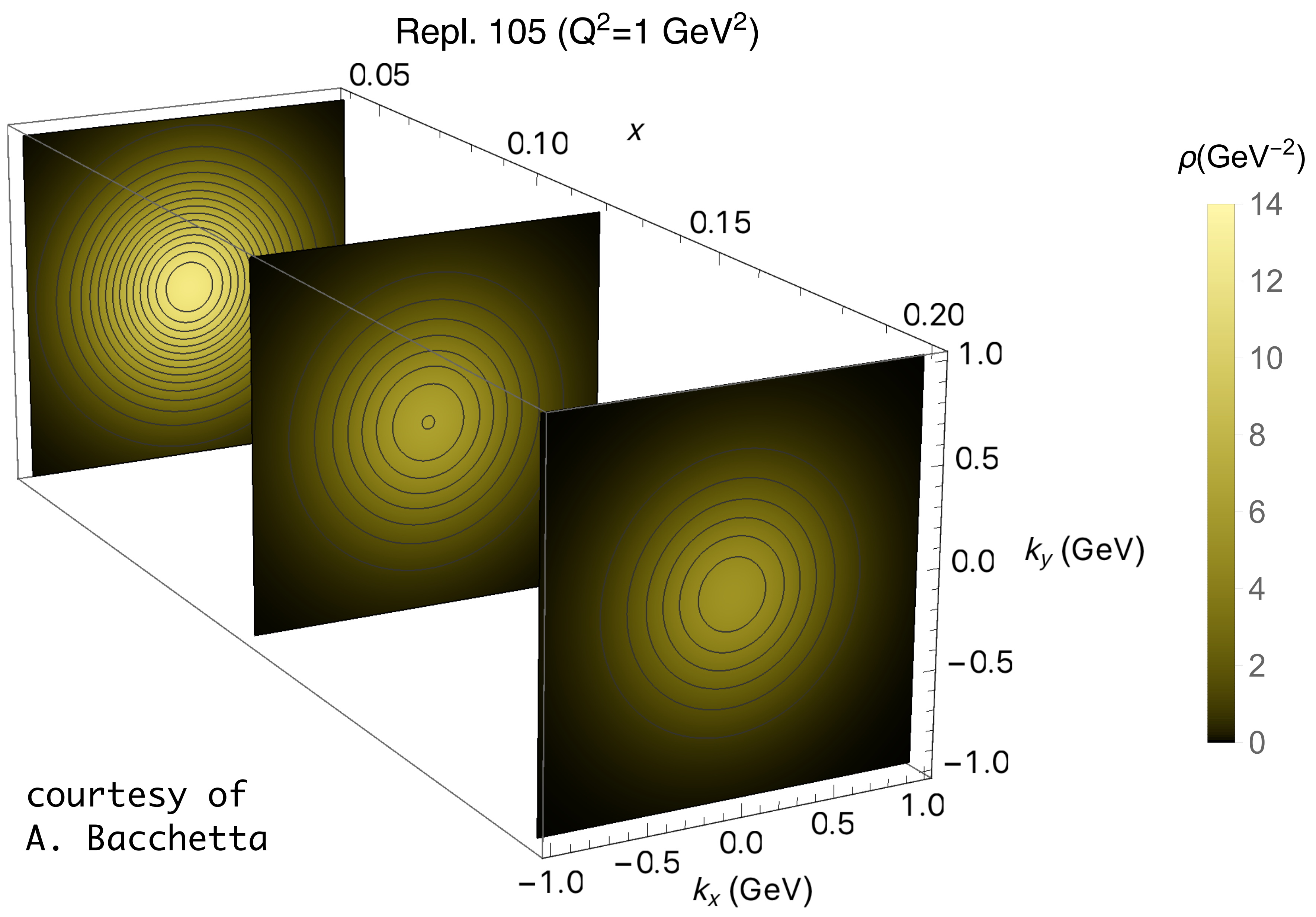
- red: vanish if no OAM

: accessible at LHCspin (dipole)

: accessible at LHCspin (solenoid)

TMDs

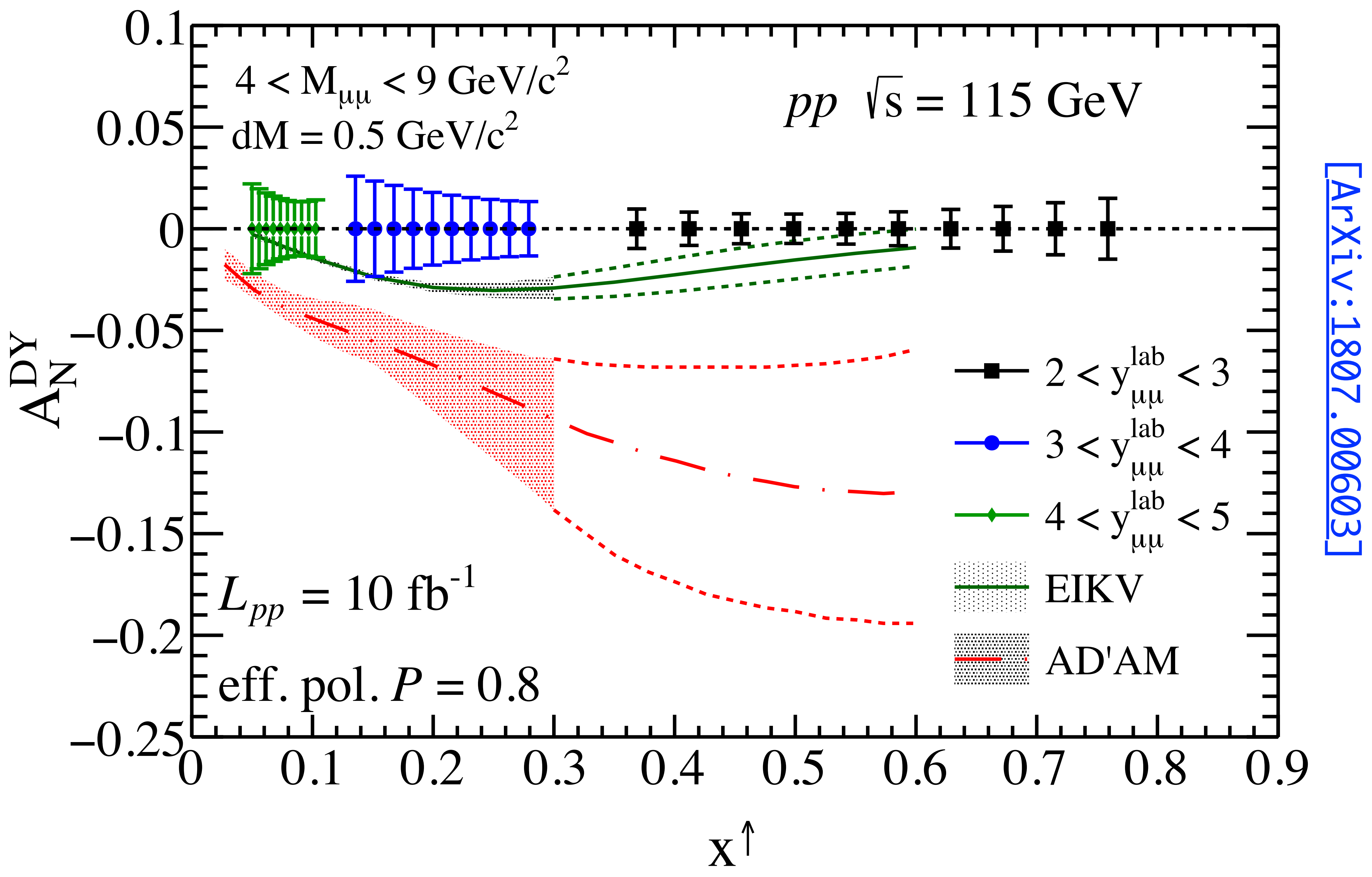
- 3D momentum "tomography" of hadrons:



- To access the transverse motion of partons inside a polarised nucleon: measure TMDs via TSSAs at high $x_2^\uparrow$ (and low x_1)

$$A_N = \frac{1}{P}\frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \longrightarrow A_N \sim \frac{f_1^q(x_1, k_{T1}^2) \otimes f_{1T}^{\perp\bar{q}}(x_2, k_{T2}^2)}{f_1^q(x_1, k_{T1}^2) \otimes f_1^q(x_2, k_{T2}^2)}$$

- Projections of polarised Drell-Yan data with 10 fb^{-1}



- Verify the sign change of the Sivers TMD in DY wrt SIDIS:

$$f_{1T}^{\perp q}(x, k_T^2)_{\rm DY} = -f_{1T}^{\perp q}(x, k_T^2)_{\rm SIDIS}$$

- \+ isospin effect with polarised deuterium

More TMDs

- Plenty of observables with polarised DY: azimuthal asymmetries of the dilepton pair to probe TMDs
- h_q^1 : transversity → difference in densities of quarks having T pol. ↑↑ or ↑↓ in T pol. nucleon
- $f_{1T}^{\perp q}$: Sivers → dependence on p_T orientation wrt T pol. nucleon
- $h_1^{\perp q}$: Boer-Mulders → dependence on p_T orientation wrt T pol. quark in unp. nucleon
- $h_{1T}^{\perp q}$: pretzelosity → dependence on p_T and T. pol of both T pol. quark and nucleon
- f_1^q : unpolarised TMD, always present at the denominator

$$A_{UU}^{cos2\phi} \sim \frac{h_1^{\perp q}(x_1,k_{1T}^2)\otimes h_1^{\perp\bar{q}}(x_2,k_{2T}^2)}{f_1^q(x_1,k_{1T}^2)\otimes f_1^{\bar{q}}(x_2,k_{2T}^2)}$$

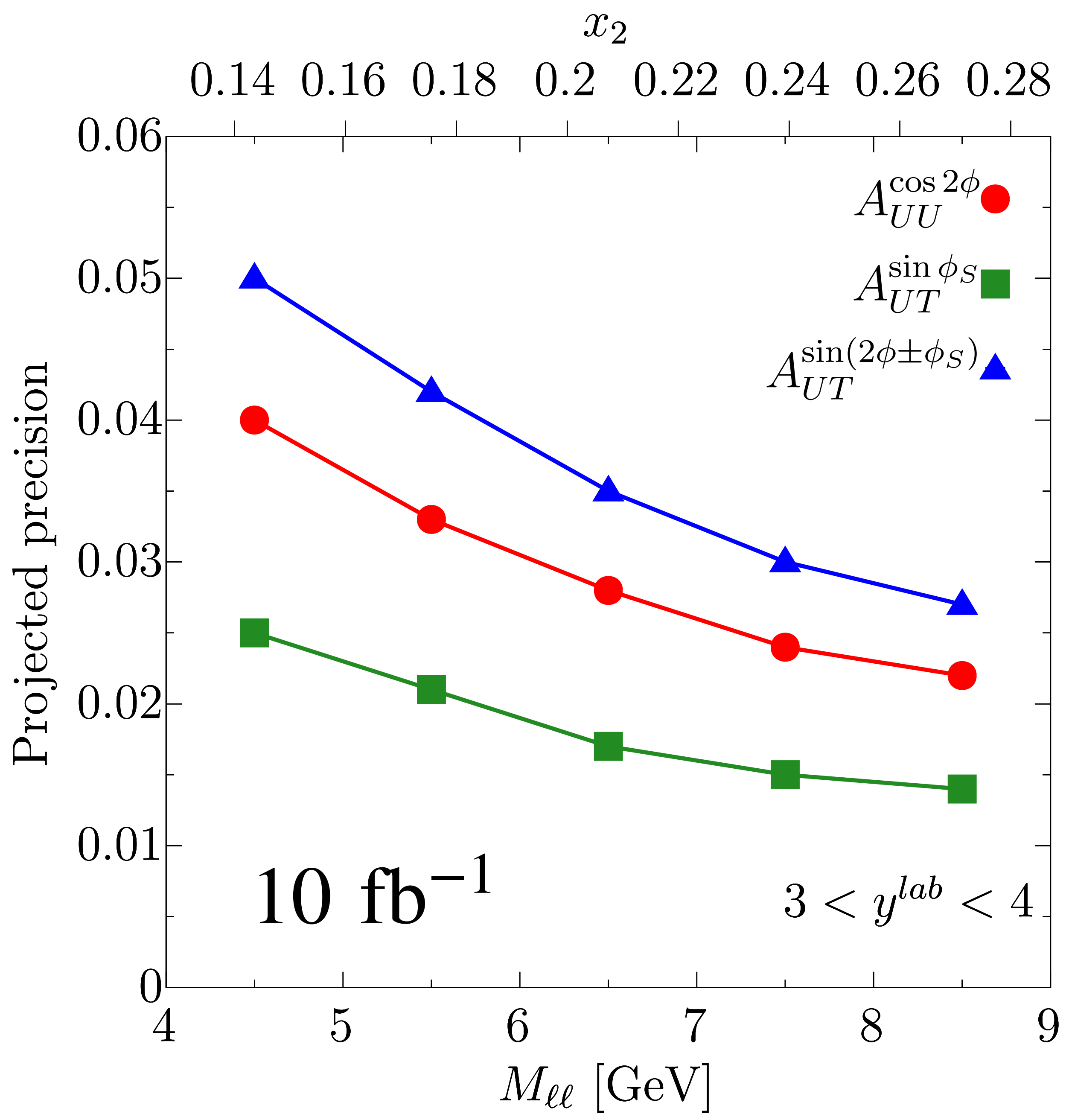
$$A_{UT}^{sin\phi_S} \sim \frac{f_1^q(x_1,k_{1T}^2)\otimes f_{1T}^{\perp\bar{q}}(x_2,k_{2T}^2)}{f_1^q(x_1,k_{1T}^2)\otimes f_1^{\bar{q}}(x_2,k_{2T}^2)}$$

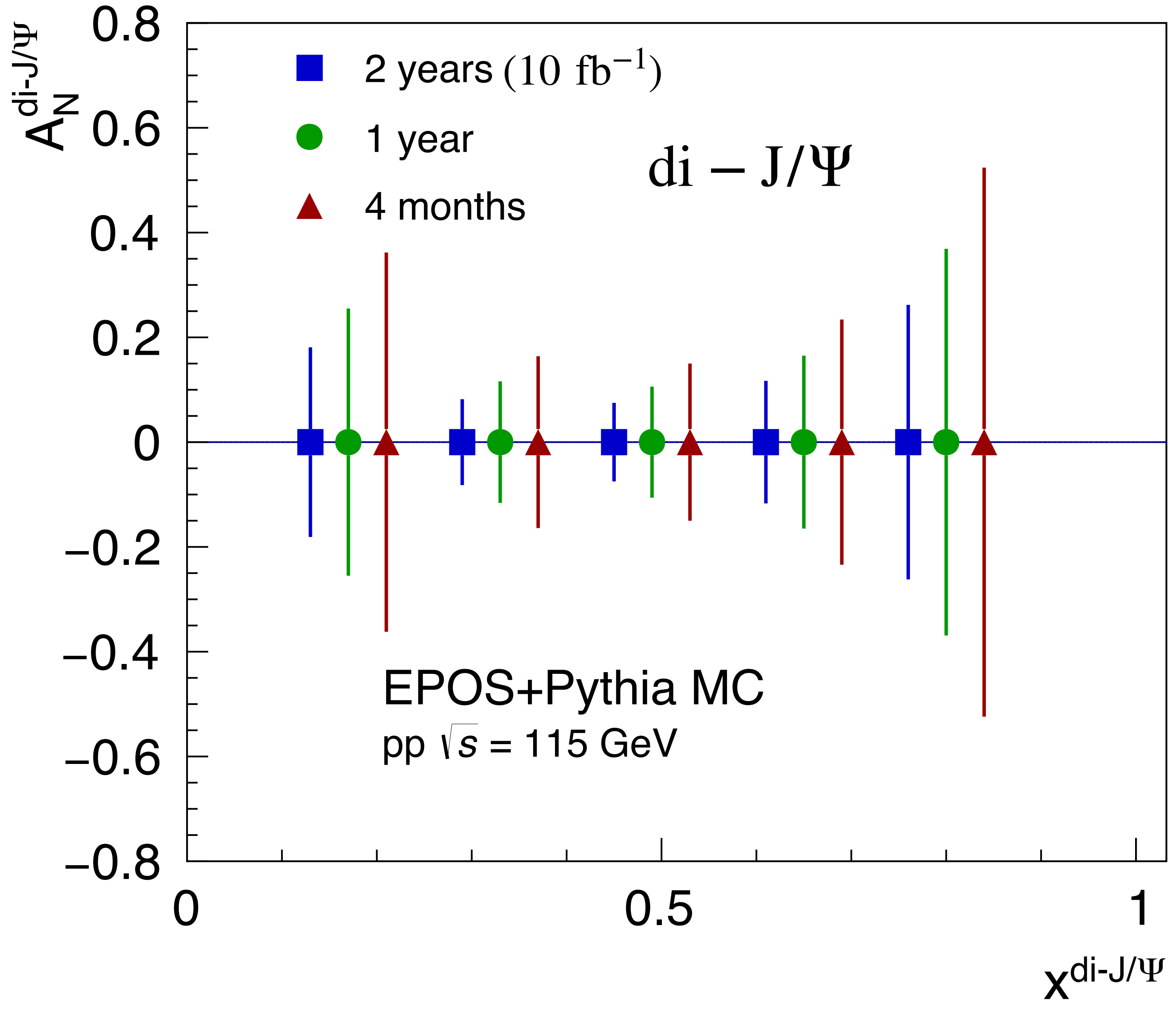
$$A_{UT}^{sin(2\phi+\phi_S)} \sim \frac{h_1^{\perp q}(x_1,k_{1T}^2)\otimes h_{1T}^{\perp\bar{q}}(x_2,k_{2T}^2)}{f_1^q(x_1,k_{1T}^2)\otimes f_1^{\bar{q}}(x_2,k_{2T}^2)}$$

$$A_{UT}^{sin(2\phi-\phi_S)} \sim \frac{h_1^{\perp q}(x_1,k_{1T}^2)\otimes h_1^{\bar{q}}(x_2,k_{2T}^2)}{f_1^q(x_1,k_{1T}^2)\otimes f_1^{\bar{q}}(x_2,k_{2T}^2)}$$

- Polarised Drell-Yan to access unpolarised TMDs of sea quarks and polarised TMDs in the valence region
- gluon-induced asymmetries: $h_1^{\perp g}$ never measured, can be accessed together with the f_1^g TMD (also unconstrained) in di-J/ψ and Υ production

[ArXiv:1807.00603] [PLB 784 (2018) 217-222]





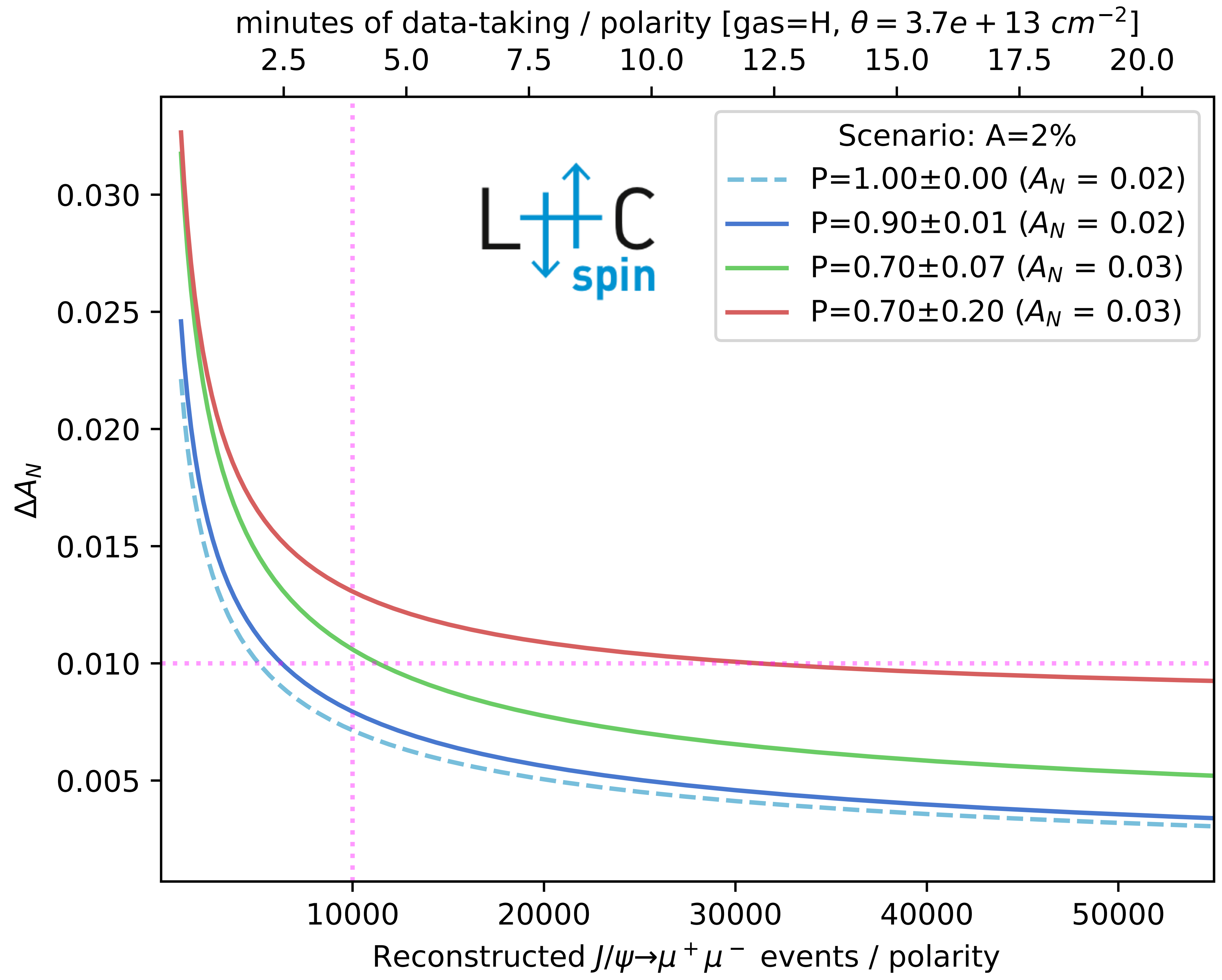
Expected precision on A_N

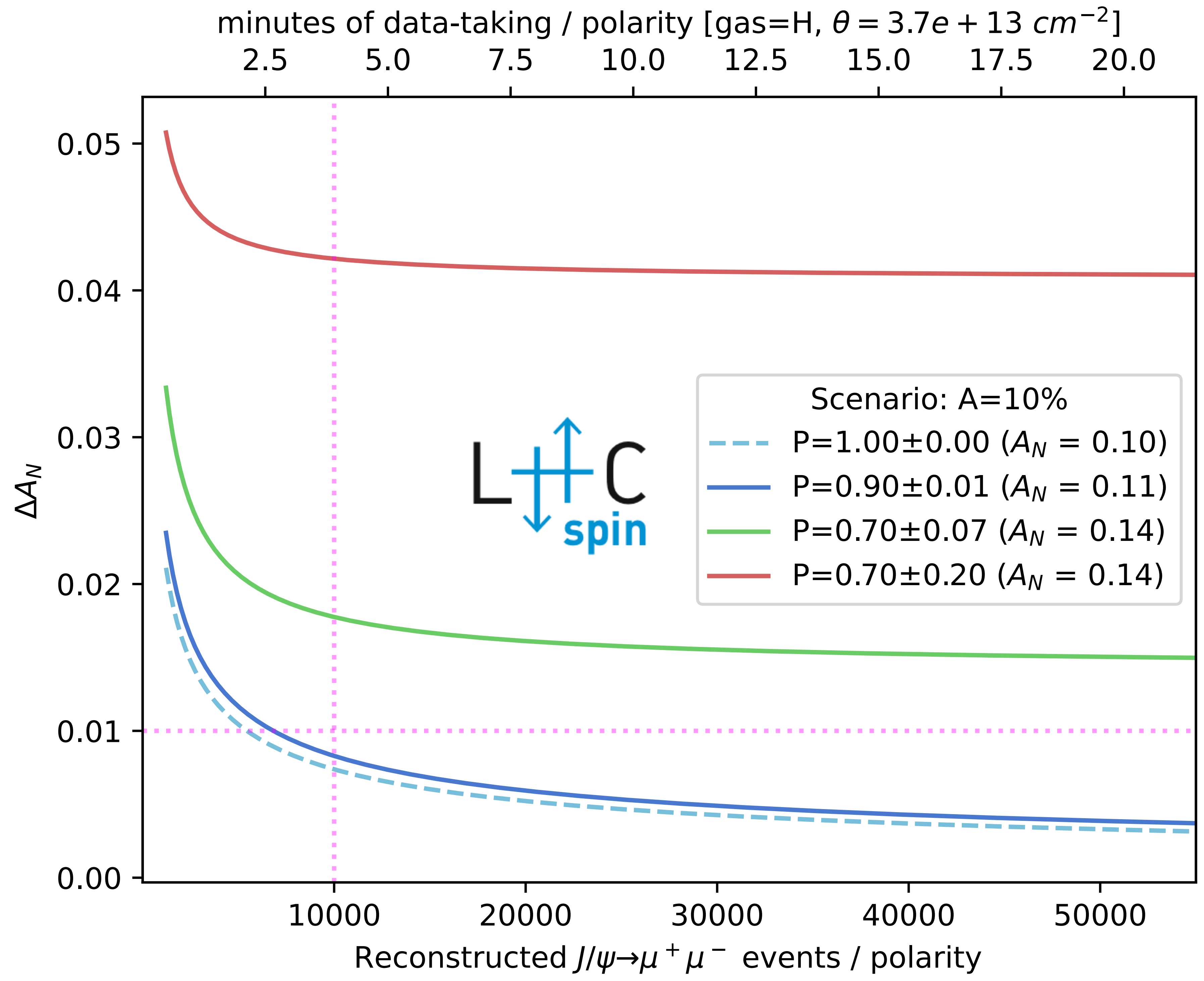
- Expected uncertainty on a TSSA at LHCspin:

$$A_N = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} \quad \rightarrow \quad \Delta A \approx \frac{1}{\sqrt{2N^{\uparrow}}}$$

- ΔA_N showed for different polarisation degrees on two scenarios: small asymmetry $A = 2\,\%$ (left) and large asymmetry $A = 10\,\%$ (right)

- Systematic limit from P reached after few minutes for $J/\psi \rightarrow \mu^+\mu^-$: precision TSSA measurements possible with very short $pH^{\uparrow}$ runs during Run 4!
- Event rate further enhanced during HL-LHC (Upgrade II)
- Cell target example: $P = 0.70 \pm 0.07$, $\theta = 3.7 \times 10^{13}/\text{cm}^2$ (used in the plots)
- Jet target example: $P = 0.90 \pm 0.01$, $\theta \approx 10^{12}/\text{cm}^2$

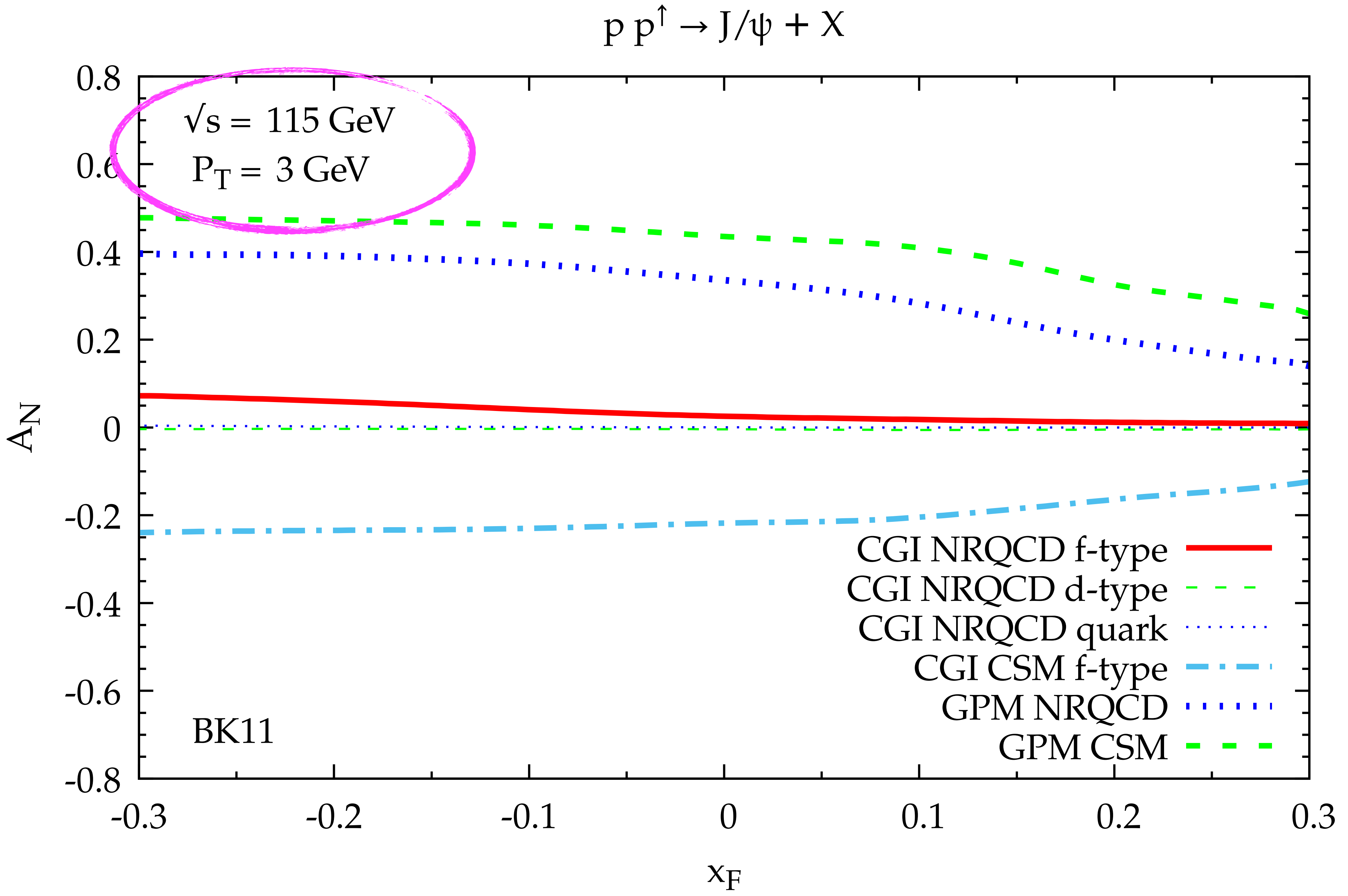




An example measurement: GSF

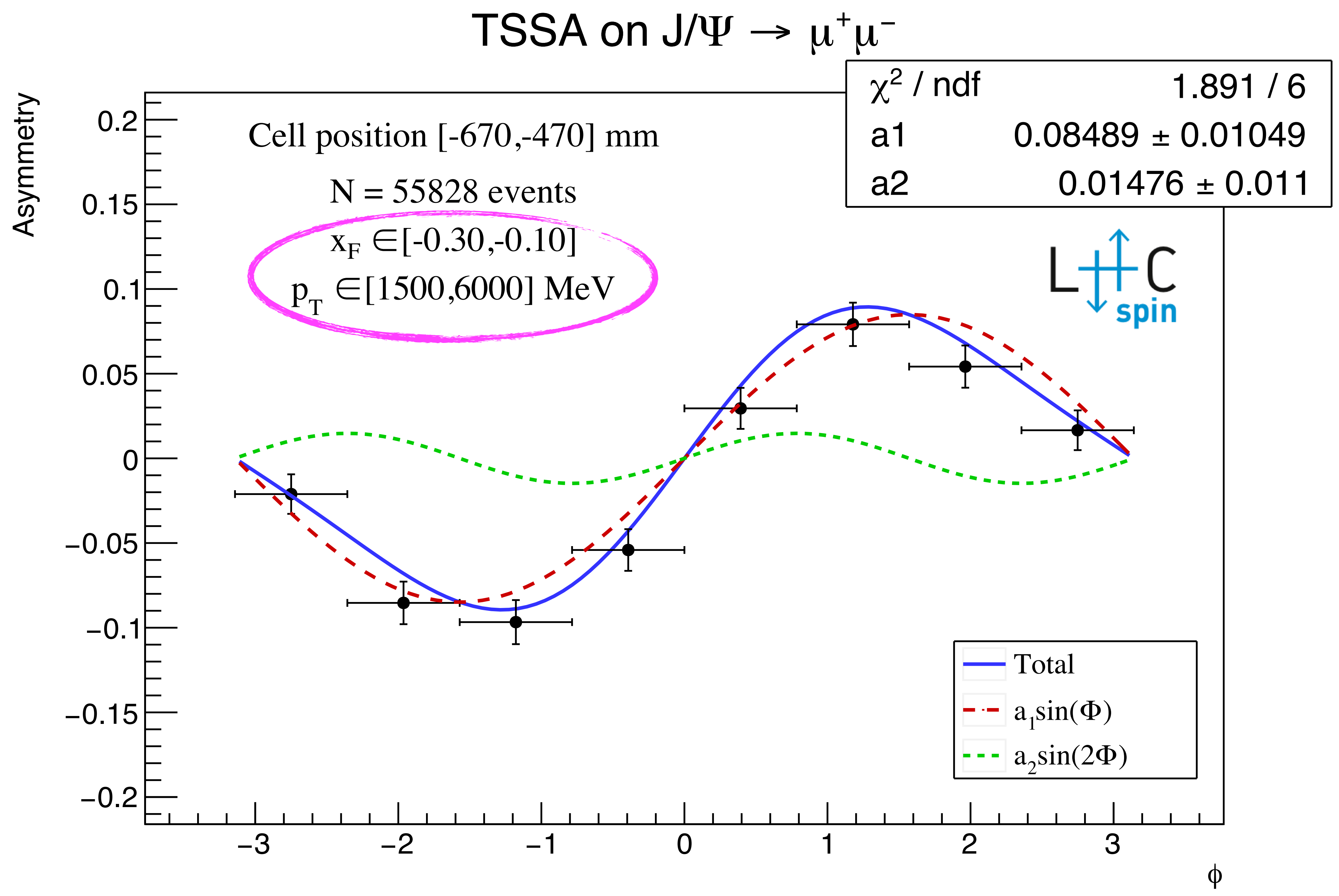
[JHEP 12 (2020) 010]

- Gluon Sivers Function (GSF) can be probed with quarkonia and open heavy-flavour production
- broad x range at a scale $M_T = \sqrt{M^2 + P_T^2}$ with several unique probes: $\eta_c, \chi_c, \chi_b, J/\psi J/\psi$ …
- A_N predictions on $J/\Psi \to \mu^+\mu^-$ with LHCspin kinematics:



[PRD 102 (2020) 094011]

- This can easily be measured with LHCspin!
- Full LHCb simulation for fixed-taget p-H collisions
- Emulate the polarisation according to a given model → fit the resulting pseudo-data
- $A_N \sim 0.1 \pm 0.01$ with $4\ x_F \times 2\ p_T \times 8\ \phi$ bins on $J/\Psi \to \mu^+\mu^-$
- $\Delta P = 5\,\%$, negligible in this example



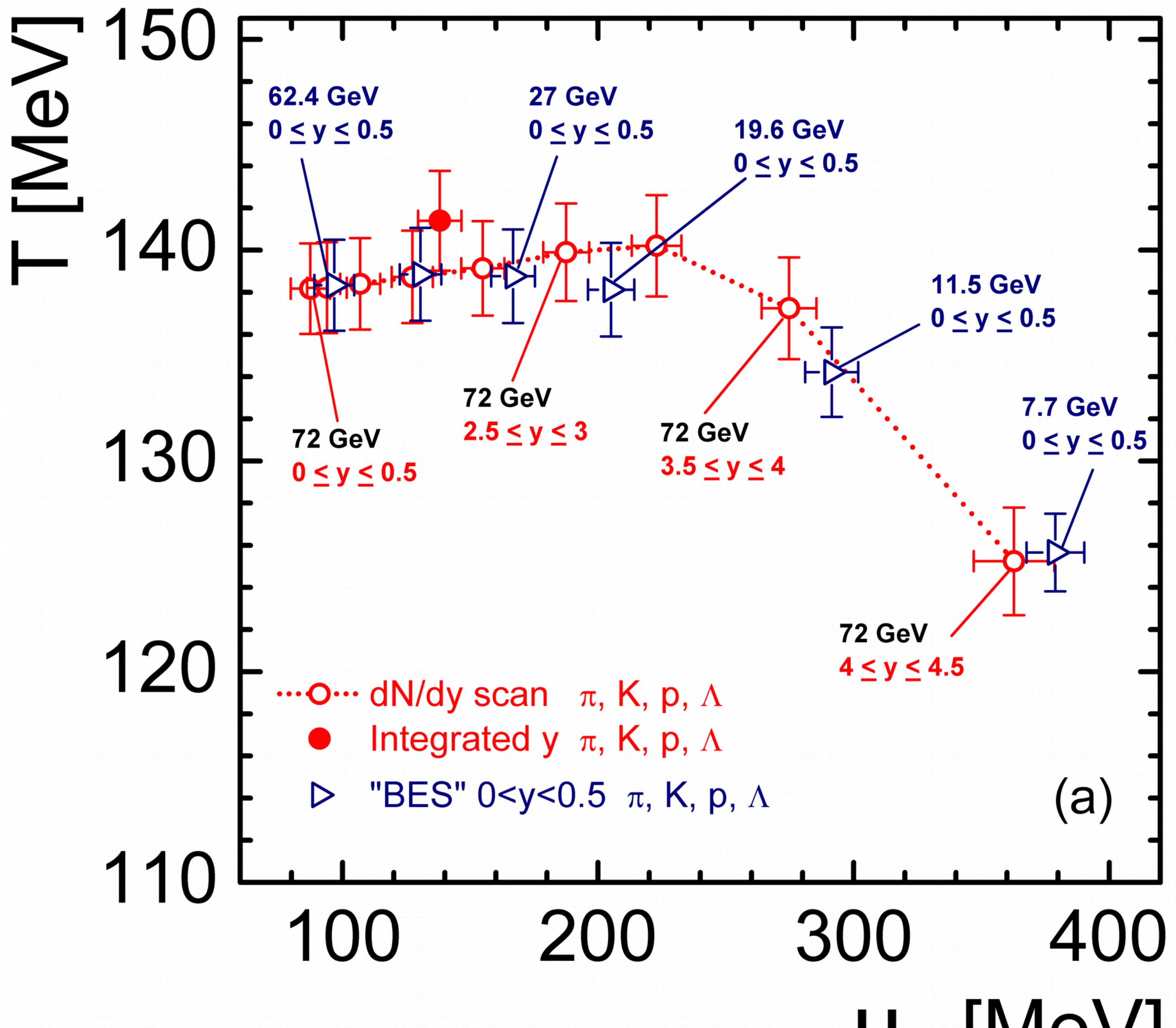
Conclusions

- The FT program at LHCb is active since Run 2, now greatly enriched with the SMOG2 cell for Run 3
- SMOG2 early results demonstrate simultaneous beam-gas and beam-beam data-taking with excellent performance
- LHCspin is the natural evolution to extend SMOG2 and to bring spin physics for the first time at the LHC
- Vast physics program with both unpolarised and polarised gases, with plenty of observables & unique final states (some examples shown, find some more in the backup slides)
- High degree of complementarity with existing facilities & EIC
- The R&D calls for a new generation of polarised gas targets: challenging task but worth the effort!

backup slides

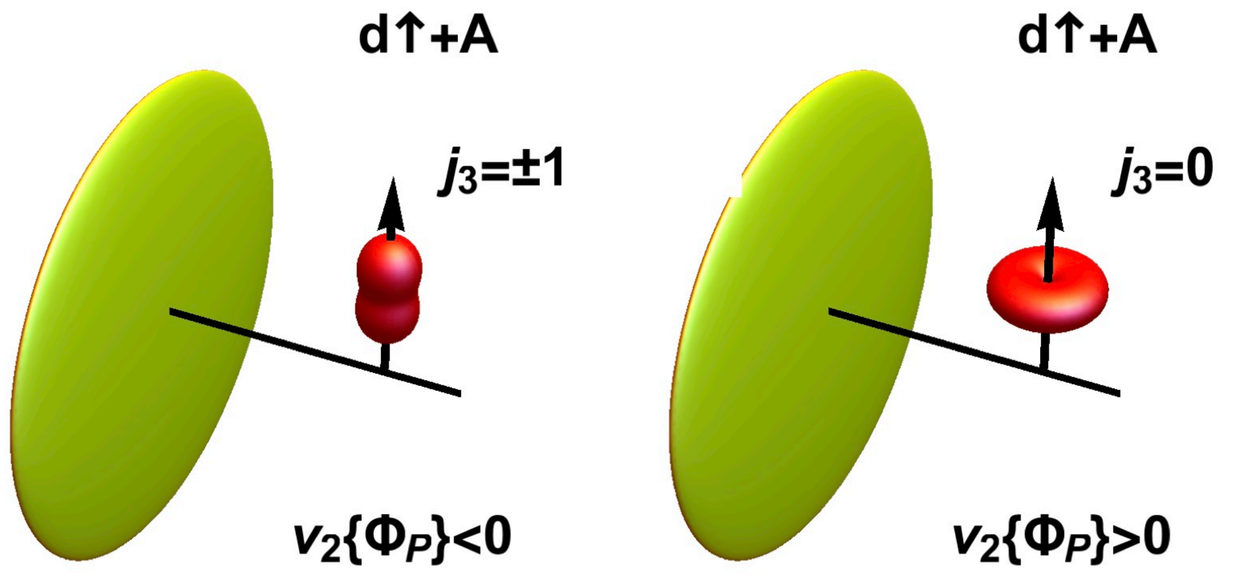
Heavy ion fixed-target collisions

- The LHC delivers proton beam at $7\ \mathrm{TeV}$ and lead beam at $2.76\ \mathrm{TeV}$, while the storage cells technology allows for an easy target change
- Great opportunities to probe nuclear matter over a new rapidity domain at $\sqrt{s} = 72\ \mathrm{GeV}$
- Suppression of $c\bar{c}$ bound states as QGP thermometer
- Complement the RHIC Beam Energy Scan (BES) with a y scan

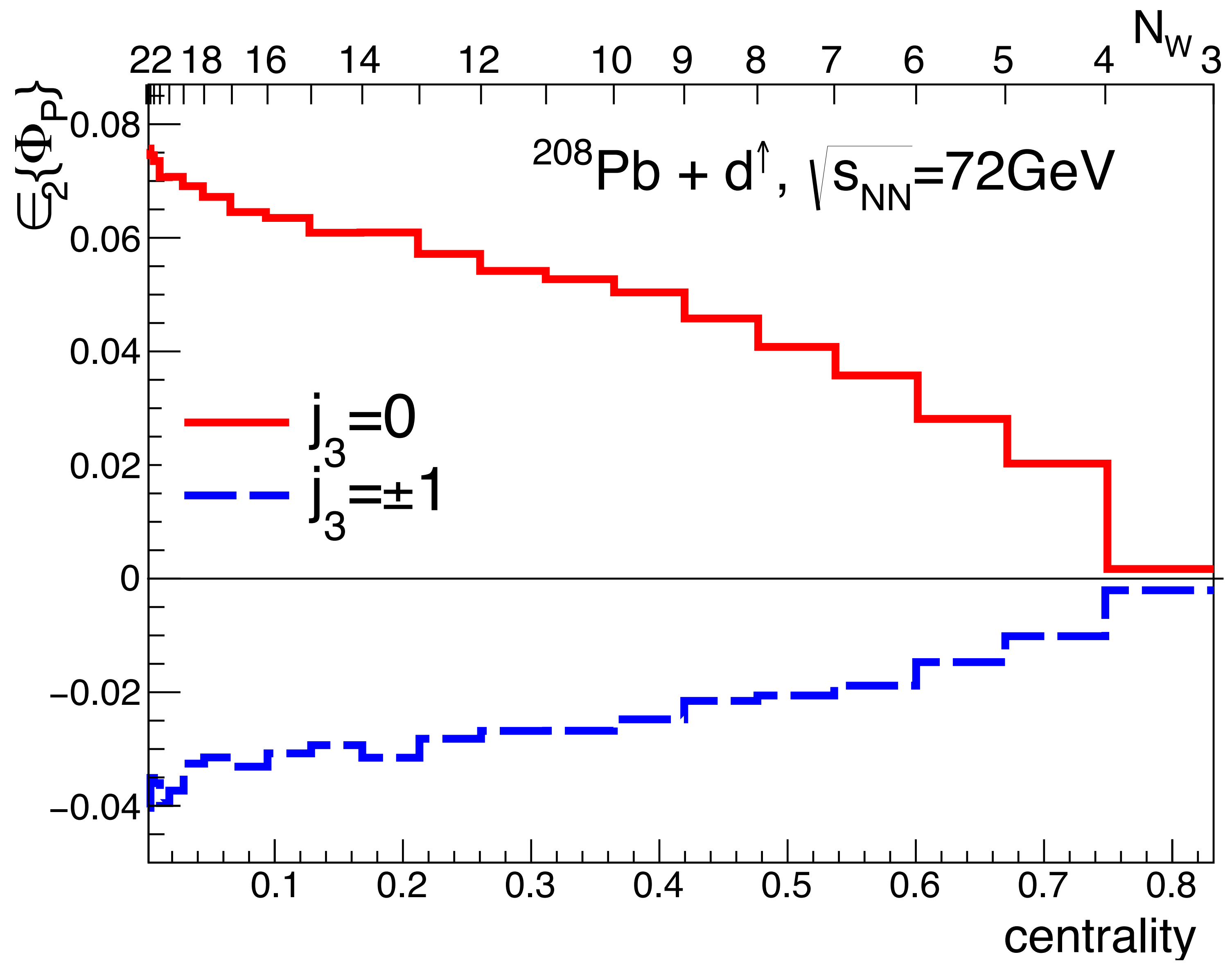


[PRC 98 (2018) 034905]

- Probing the dynamics of small systems via Ultra-relativistic collisions of heavy nuclei (Pb) on transversely polarised deuterons ($D^{\uparrow}$)
- Deformation of $D^{\uparrow}$ is reflected in the orientation of the generated fireball in the transverse plane



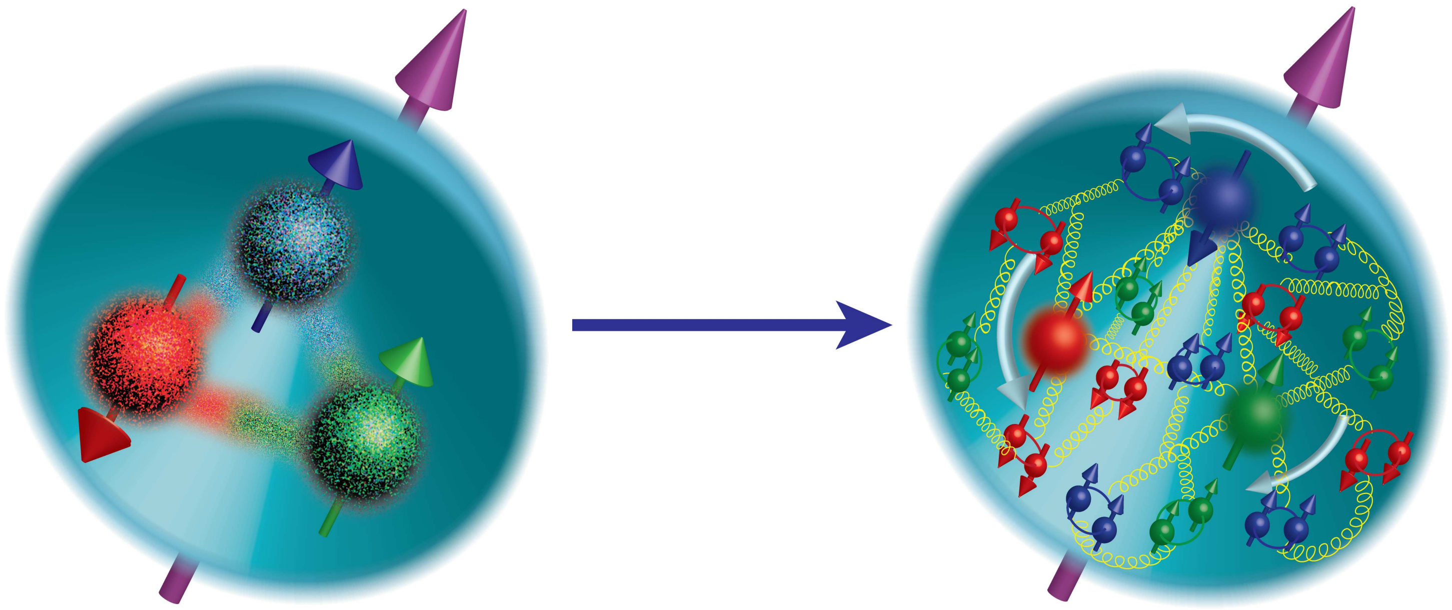
D polarised along Φ_p , perpendicular to the beam



[PRC 101 (2020) 024901]

The spin puzzle & GPDs

- TMDs → nucleon spin



- Orbital Angular Momentum (OAM) information via TMDs is only indirect: position and momentum correlations are needed
- Quark OAM from GPD moments via Ji Sum Rule:

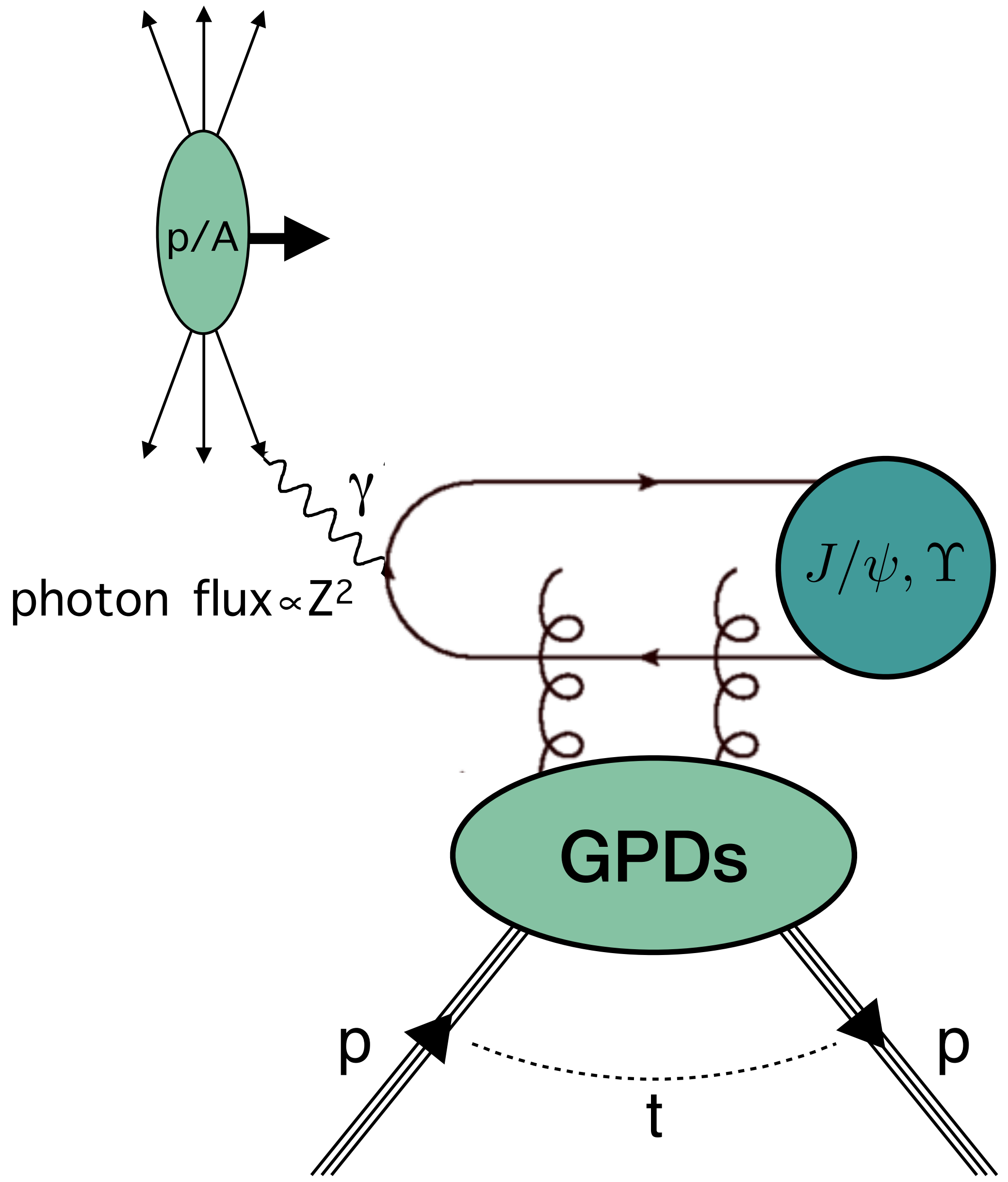
$$\frac{1}{2} = J^q(\mu) + J^g(\mu) = \frac{1}{2}\Delta\Sigma(\mu) + L_z^q(\mu) + J^g(\mu)$$

[PRL 78 (1997) 610-613]

- Experimental hints of large OAM contribution
- GPDs can be probed via UltraPeripheral Collisions (UPCs), dominated by EM interaction

- Exclusive dilepton / exclusive quarkonia production, the latter being sensitive to gluon GPDs

[PRD 85 (2012) 051502]

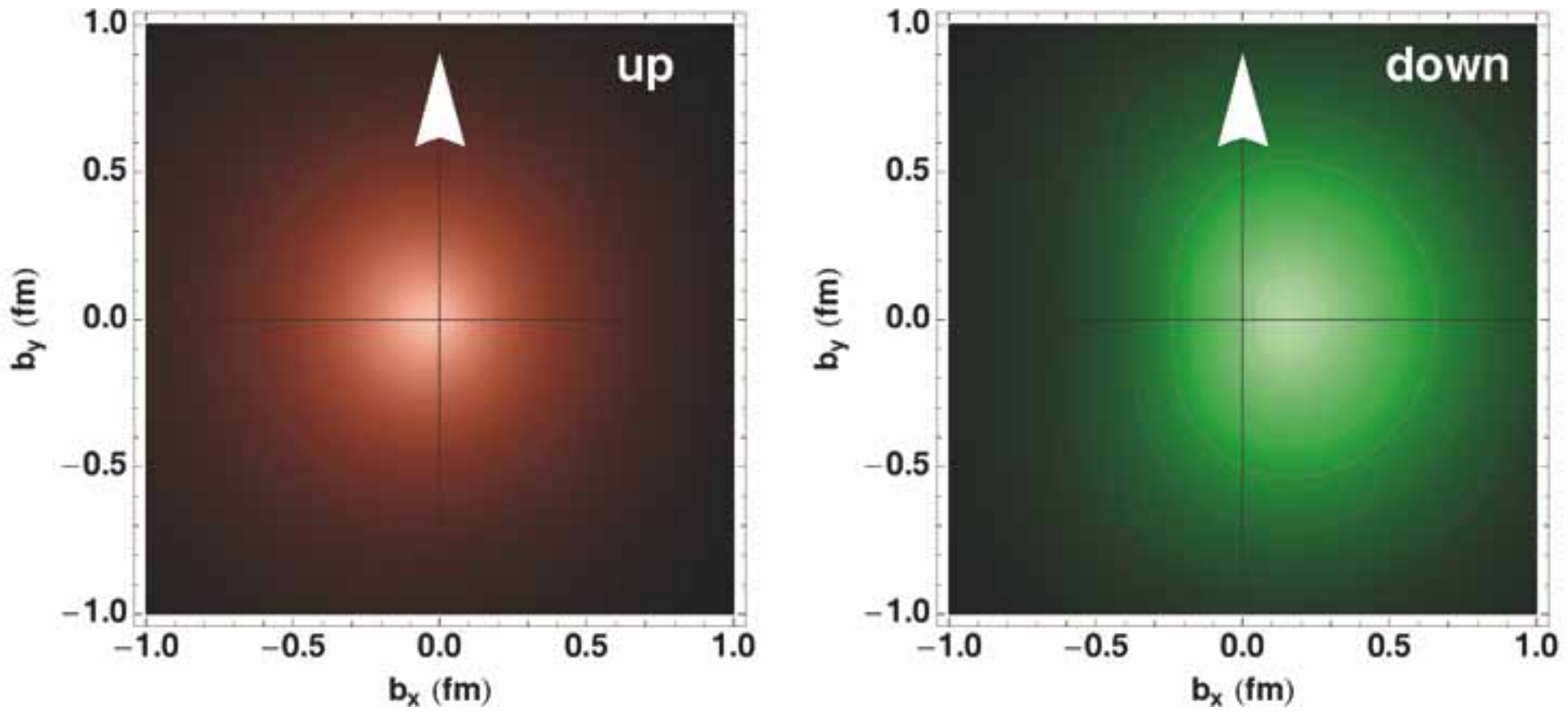


- UPCs already studied at LHC in collider mode
- LHCspin to access the unknown E_g via TSSAs: a key element of the sum rule

[ArXiv:1709.09044]

- GPDs to make a 3D "picture" of the proton

[PRL 99 (2017) 112001]



[NS 28 (2012) 1-2]