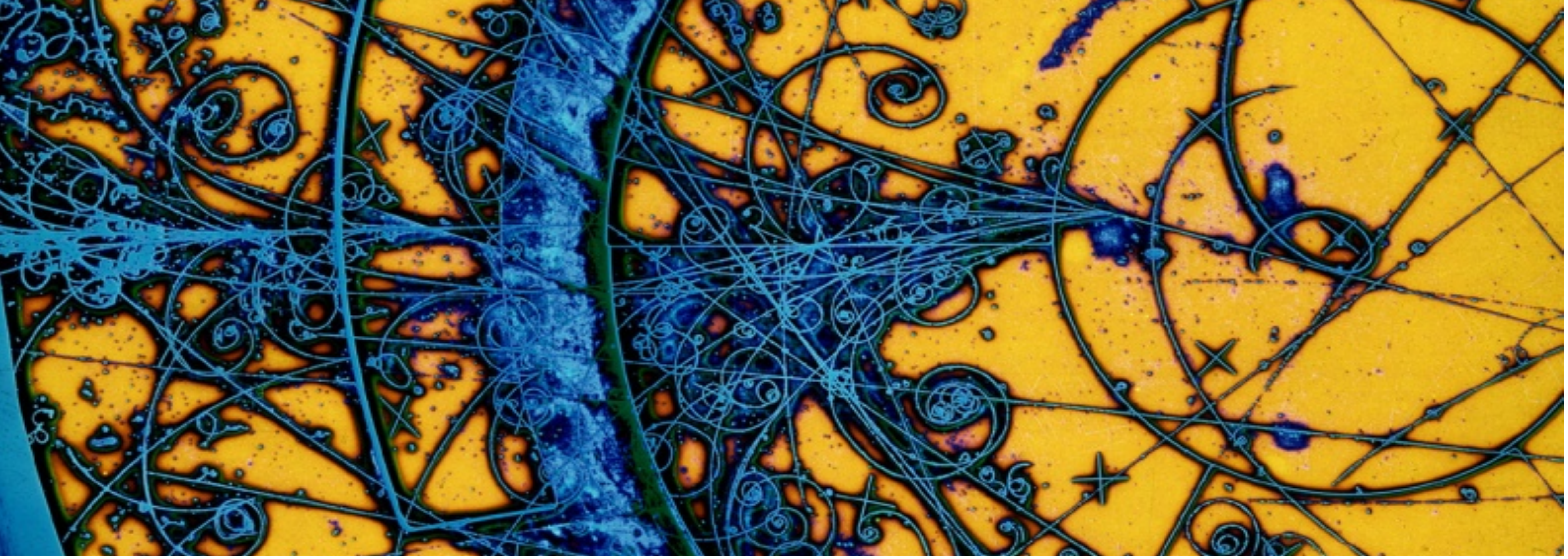

The LHCspin project

A polarised gas target at the LHC

Marco Santimaria [8]

in collaboration with

S.Bertelli[8], V.Carassiti[6], G.Ciullo[6][13], E.De Lucia[8], P. Di Nezza [8], N.Doshita[14], T.el Kordy[4], R.Engels[4], M.Ferro-Luzzi[1], C.Hadjidakis[2], T.Iwata[14], N.Koch[11], A.Kotzinian[9], P.Lenisa[6][13], C.Lucarelli[7], S.Mariani[1], M.Mirazita[8], A.Movsisyan[15], A.Nass[4], C.Oppedisano[9], L.Pappalardo[6][13], B.Parsamyan[1][9], C.Pecar[3], D.Reggiani[10], M.Rotondo[8], A.Saputi[6], E.Steffens[12], G.Tagliente[5]

(1) CERN, (2) CNRS Saclay, (3) Duke University, (4) FZ Julich, (5) INFN Bari, (6) INFN Ferrara, (7) INFN Firenze, (8) INFN Frascati, (9) INFN Torino, (10) PSI Zurich, (11) TH Nuremberg, (12) University of Erlangen, (13) University of Ferrara, (14) University of Yamagata, (15) University of Yerevan

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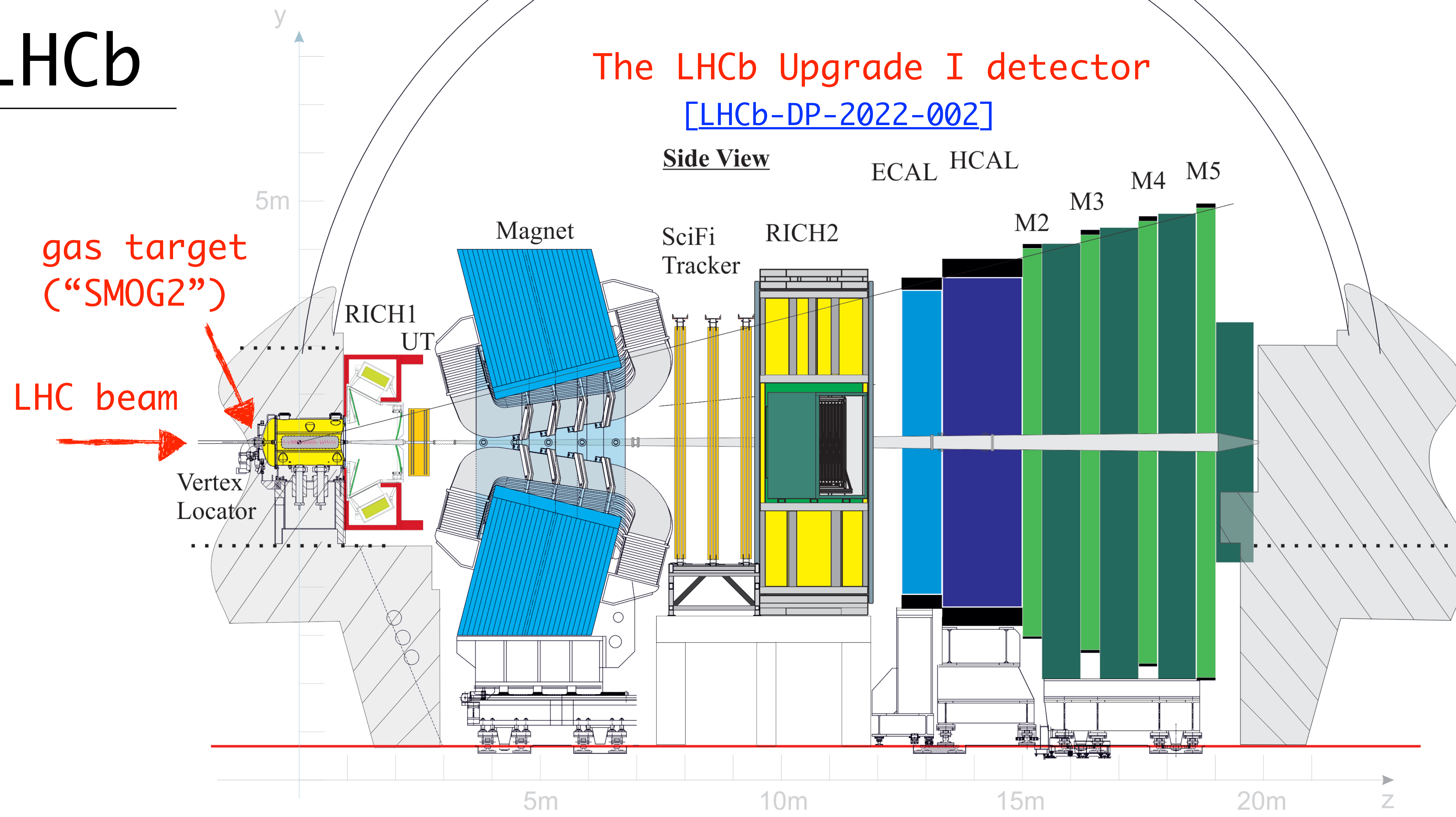
Diffraction and Low-x 2024 / Palermo 12.09.2024

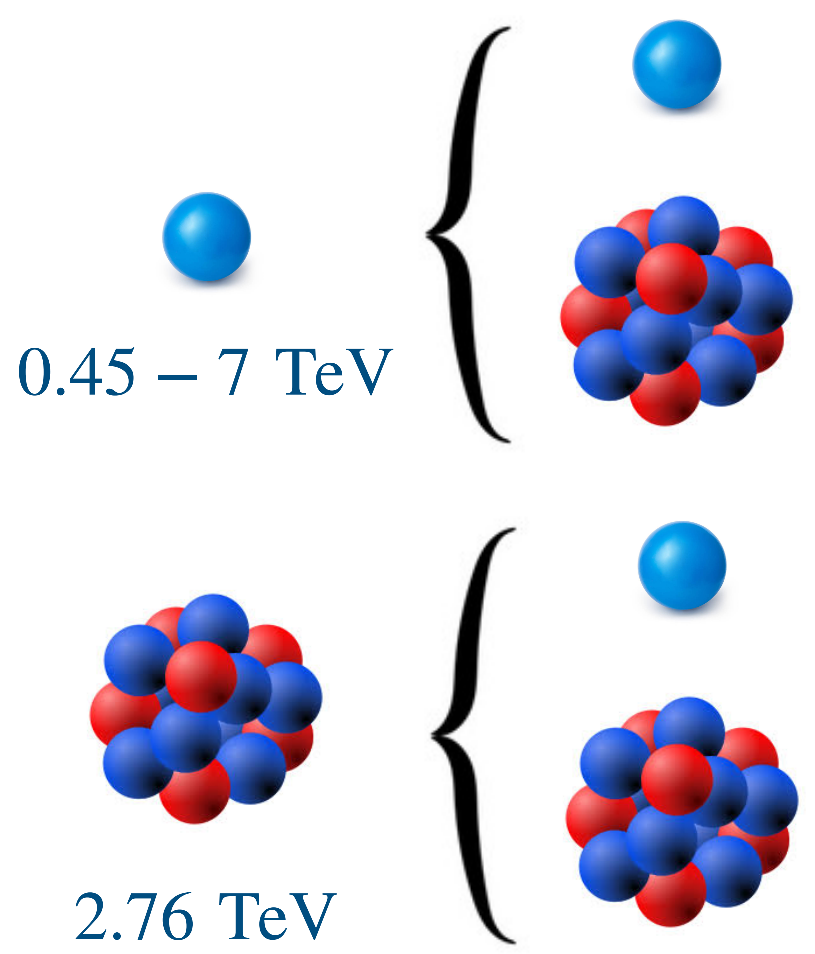
marco.santimaria@lnf.infn.it

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
- Run 3 (ongoing): new detector & fully-software trigger to face 5x luminosity increase wrt Run 2



- Fixed-target kinematics:



pp/pA collisions, 7 TeV beam:

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

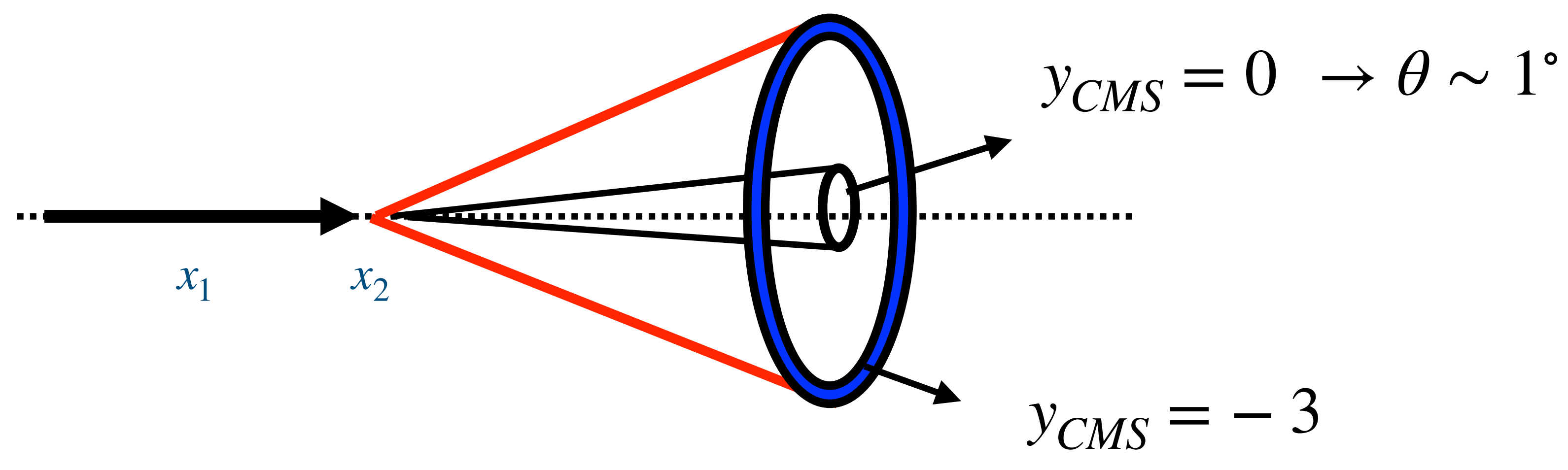
$$2 \leq y_{lab} \leq 5 \;\rightarrow\; -3.0 \leq y_{CMS} \leq 0$$

AA collisions, 2.76 TeV beam:

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

1: beam, 2: target

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

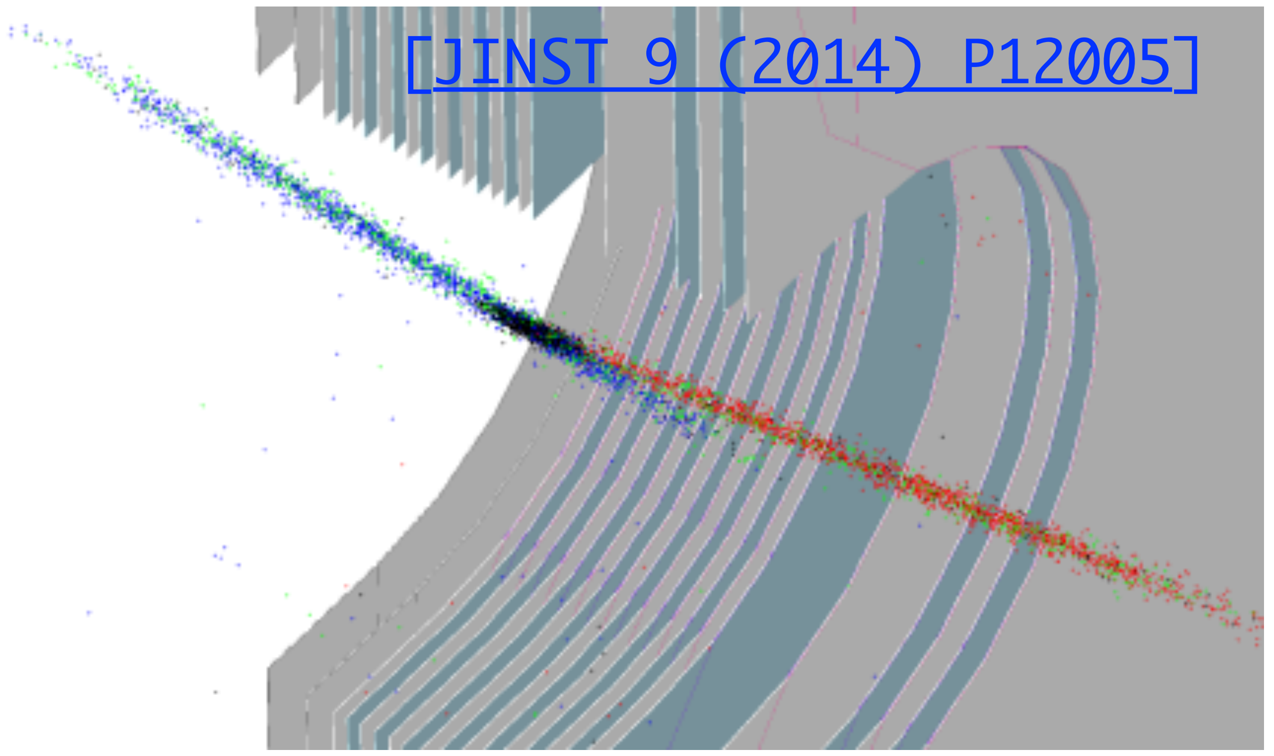


$$\gamma = \frac{\sqrt{s}}{2m_p} \sim 60$$

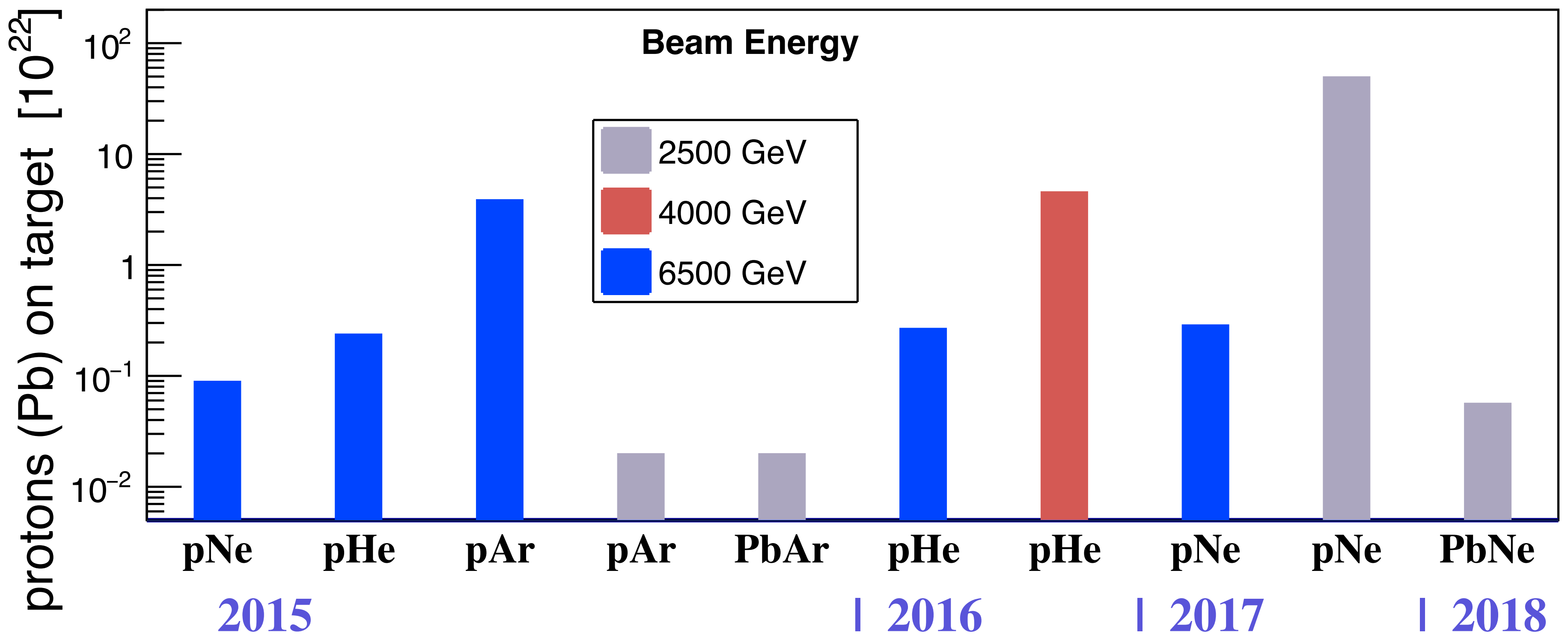
SMOG and SMOG2

[ArXiv 2407.14200 submitted to Physical Review Accelerators and Beams]

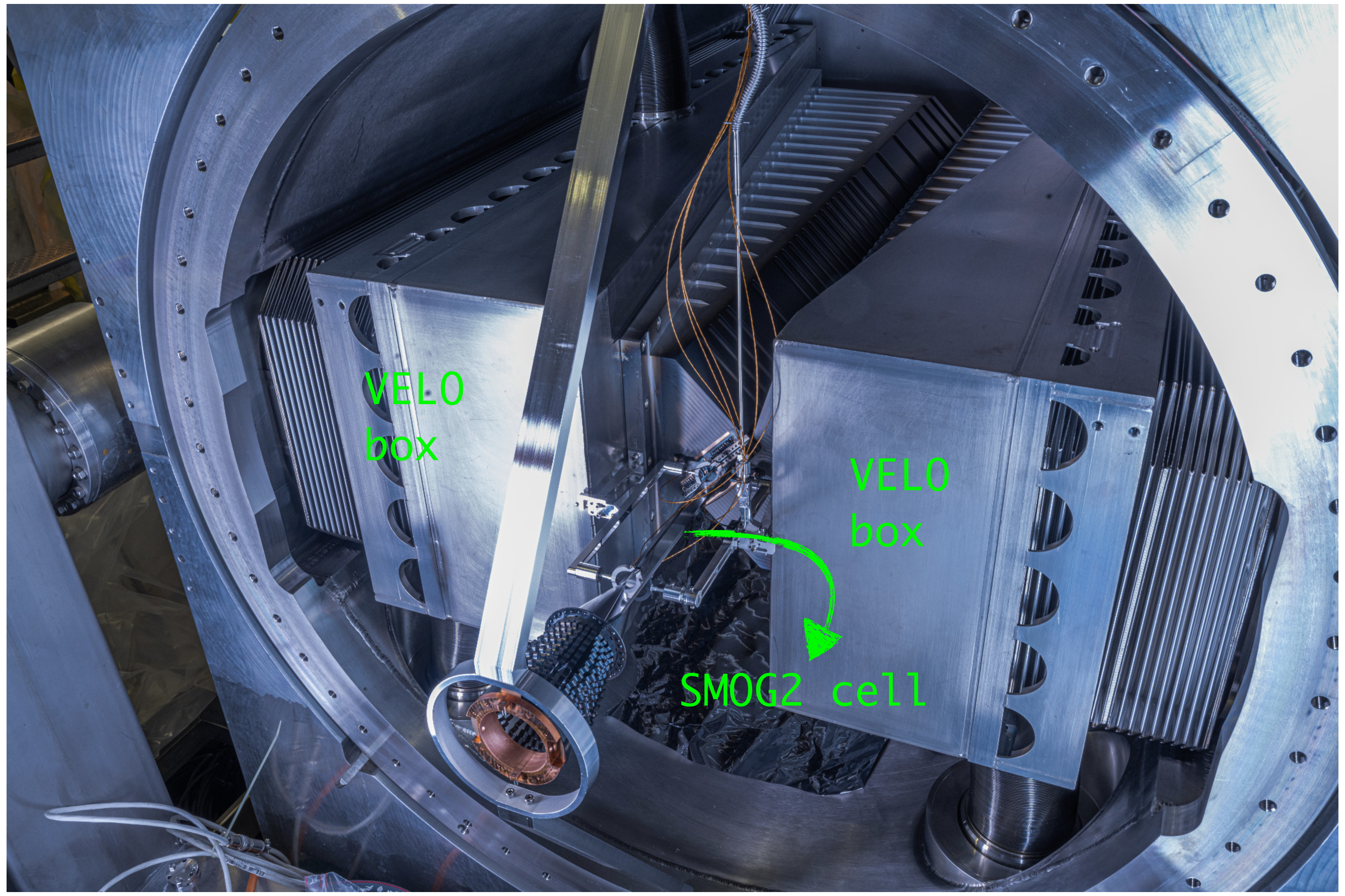
- The FT program at LHCb is active since 2015 with SMOG: inject noble gases into the VELO, populating $z = \pm 20$ m inside the beam pipe
- Trigger on beam-empty collisions: turn LHCb into a FT experiment!
- See our publications → here



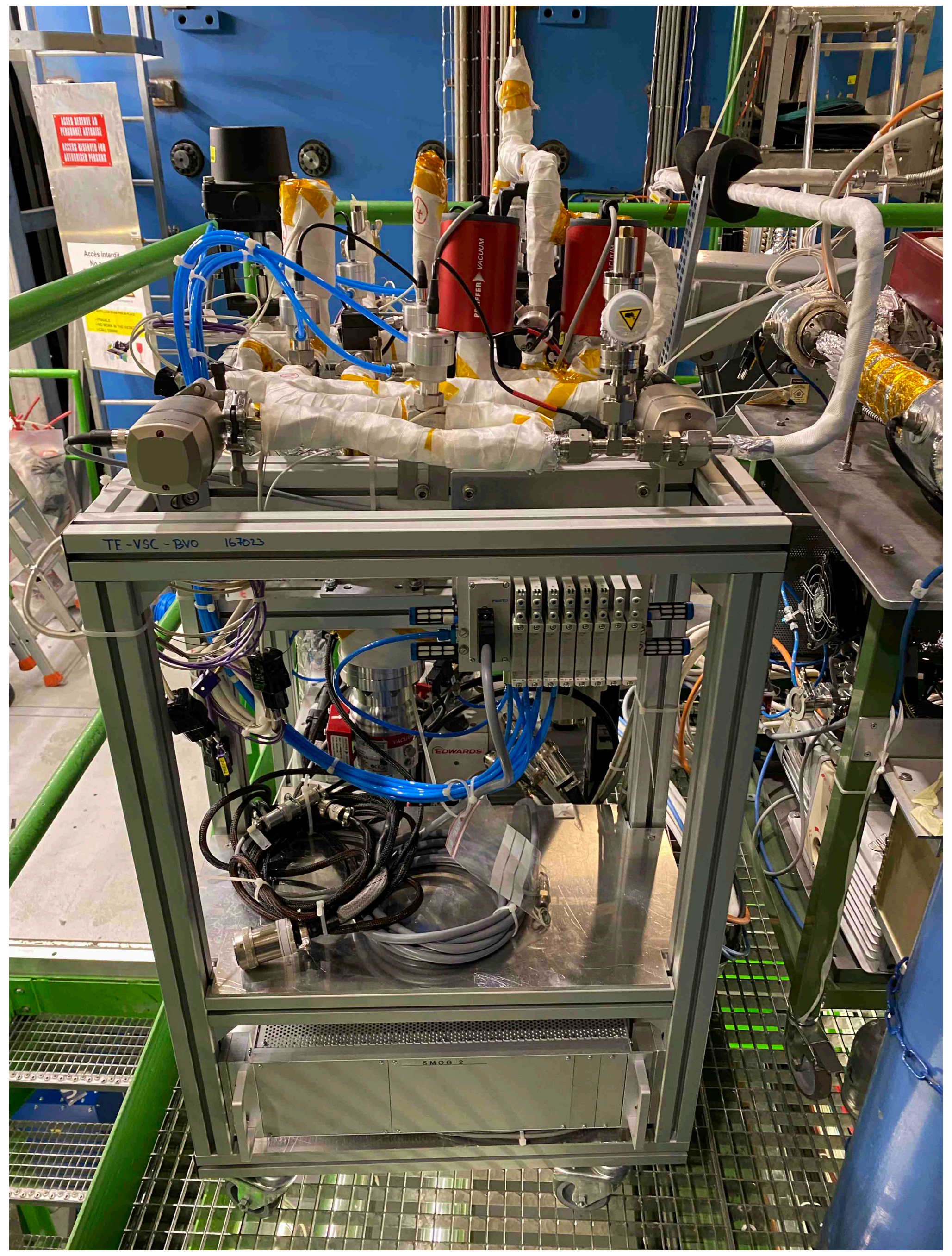
SMOG data (Run 2)



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



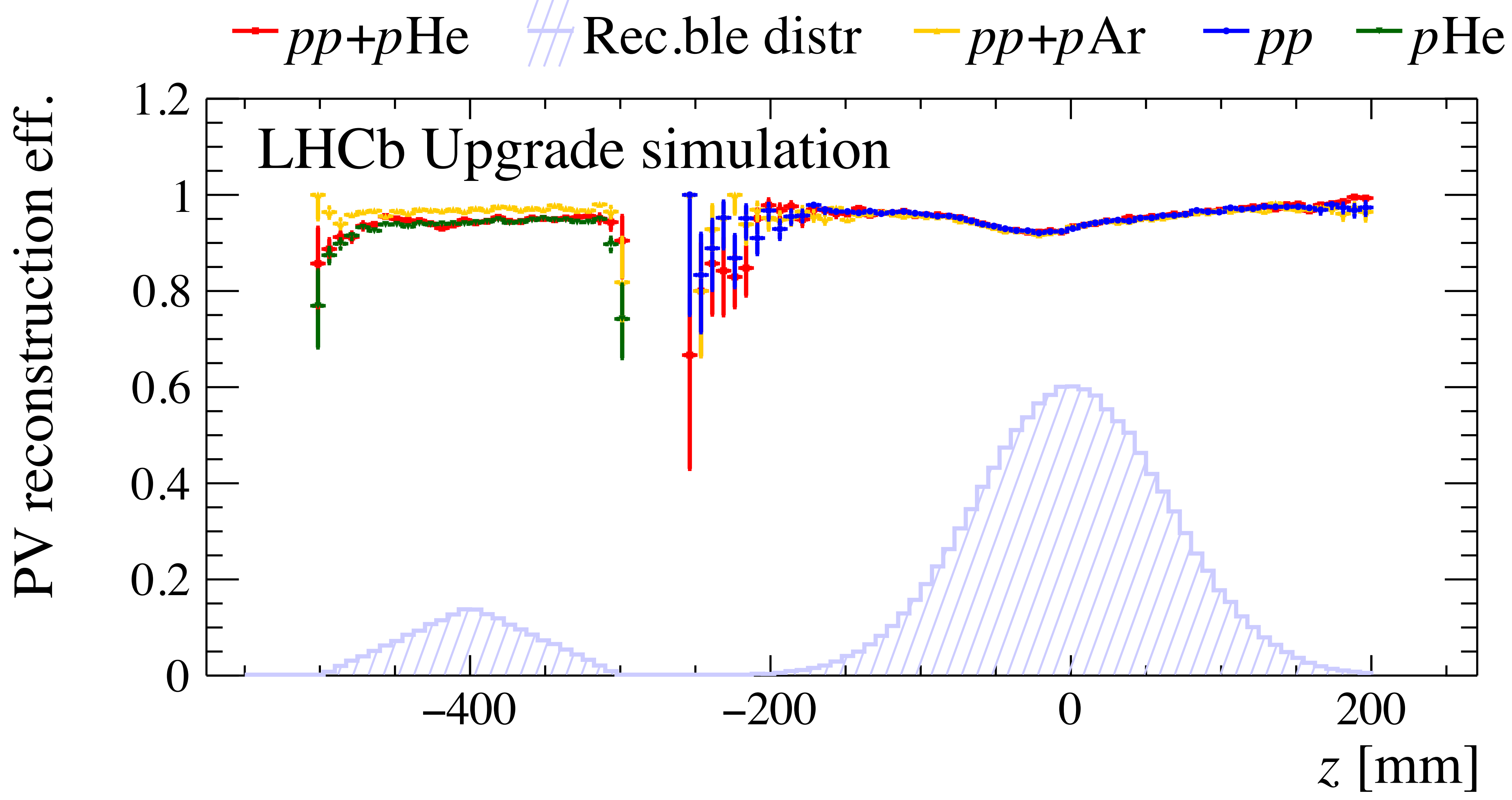
SMOG2 Gas Feed System



FT event reconstruction in Run 3

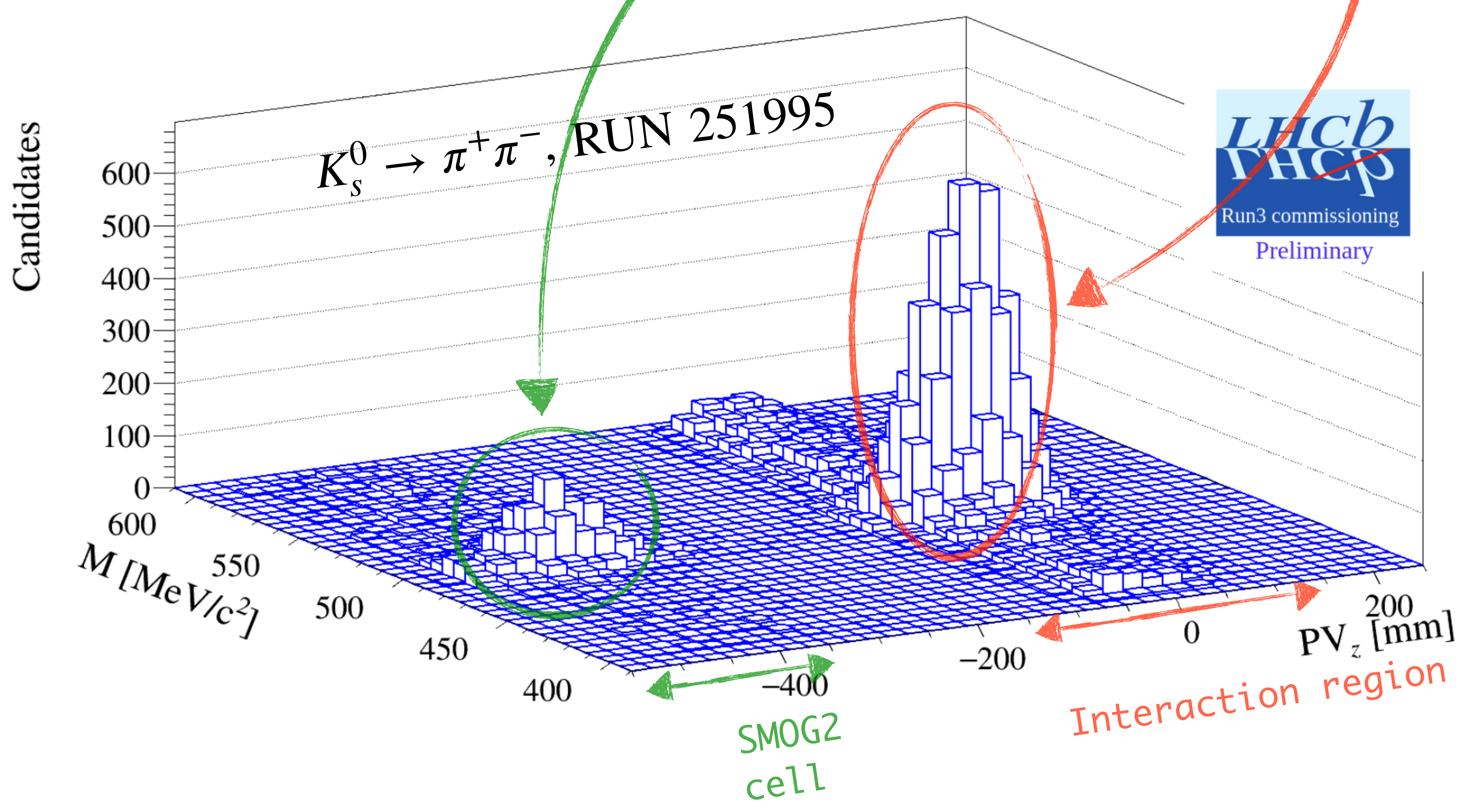
[ArXiv 2407.14200 submitted to Physical Review Accelerators and Beams]

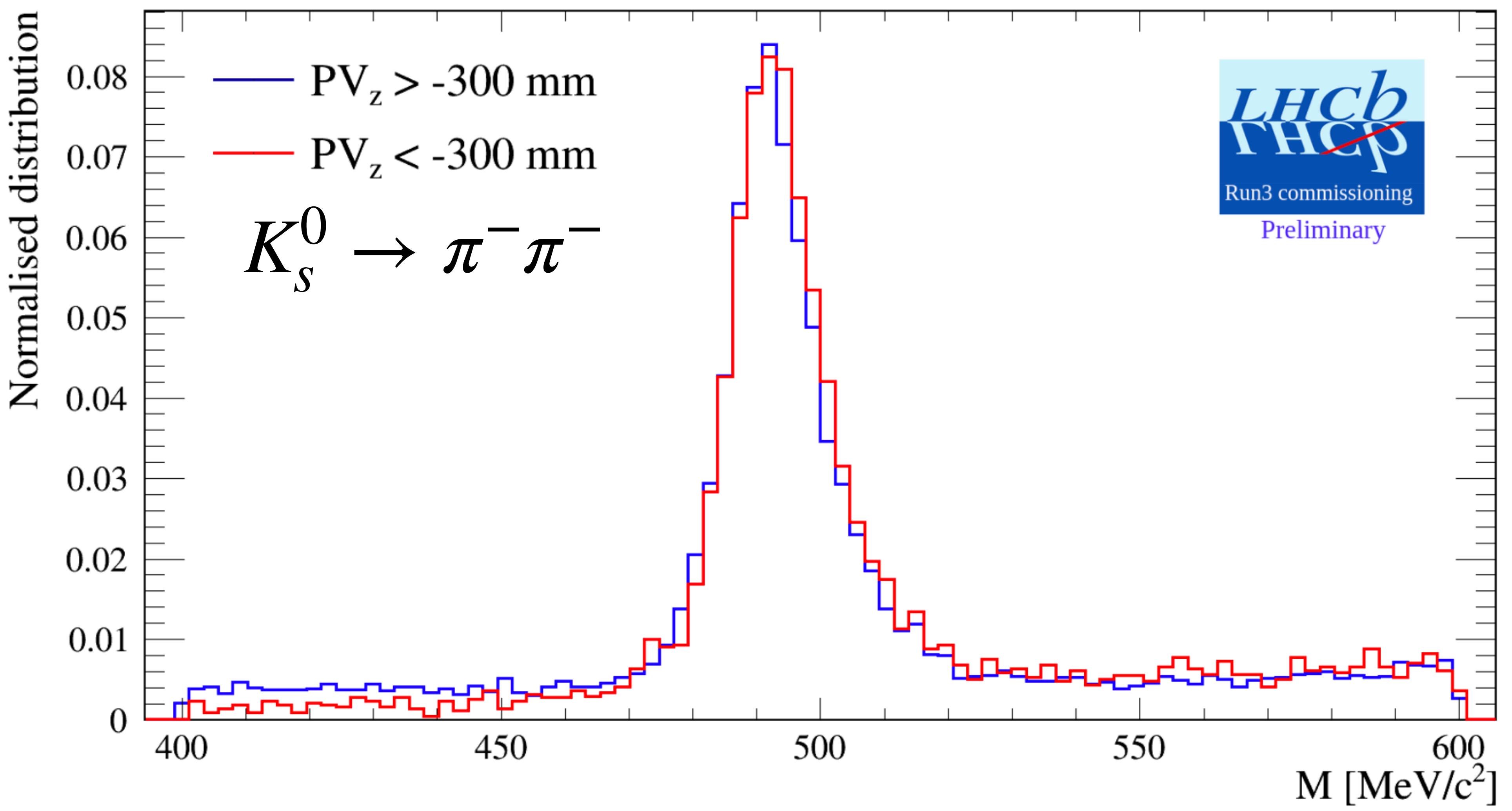
1. Beam-beam and beam-gas interactions are well detached
2. Full vertex & tracking reconstruction efficiency retained in the beam-gas region
3. Negligible increase of multiplicity → small impact in the LHCb reconstruction sequence



[LHCB-FIGURE-2022-002]

- Confirmed with 2022 data: beam-gas and beam-beam simultaneous data-taking with the same resolution!





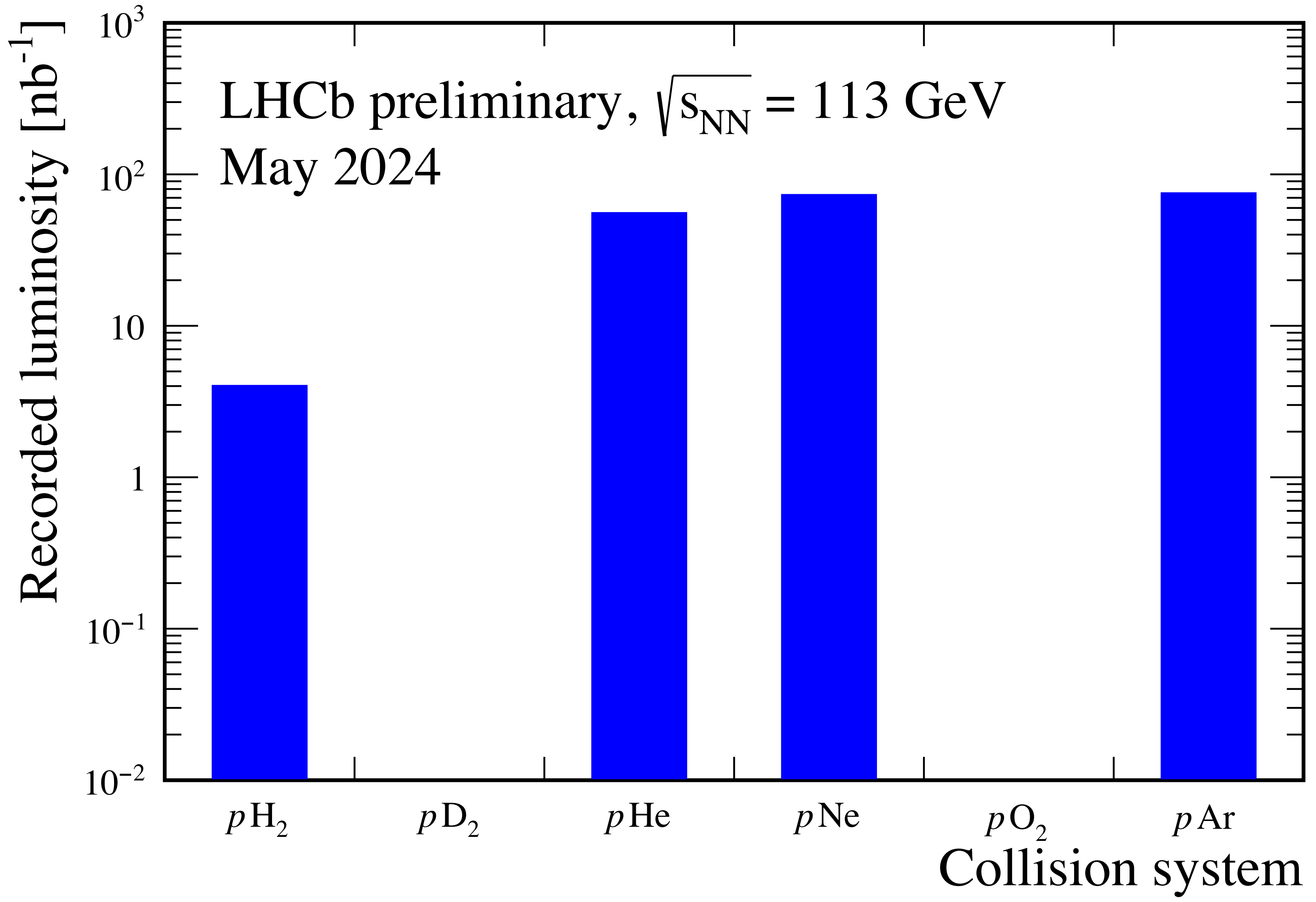
[LHCB-FIGURE-2023-001]

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

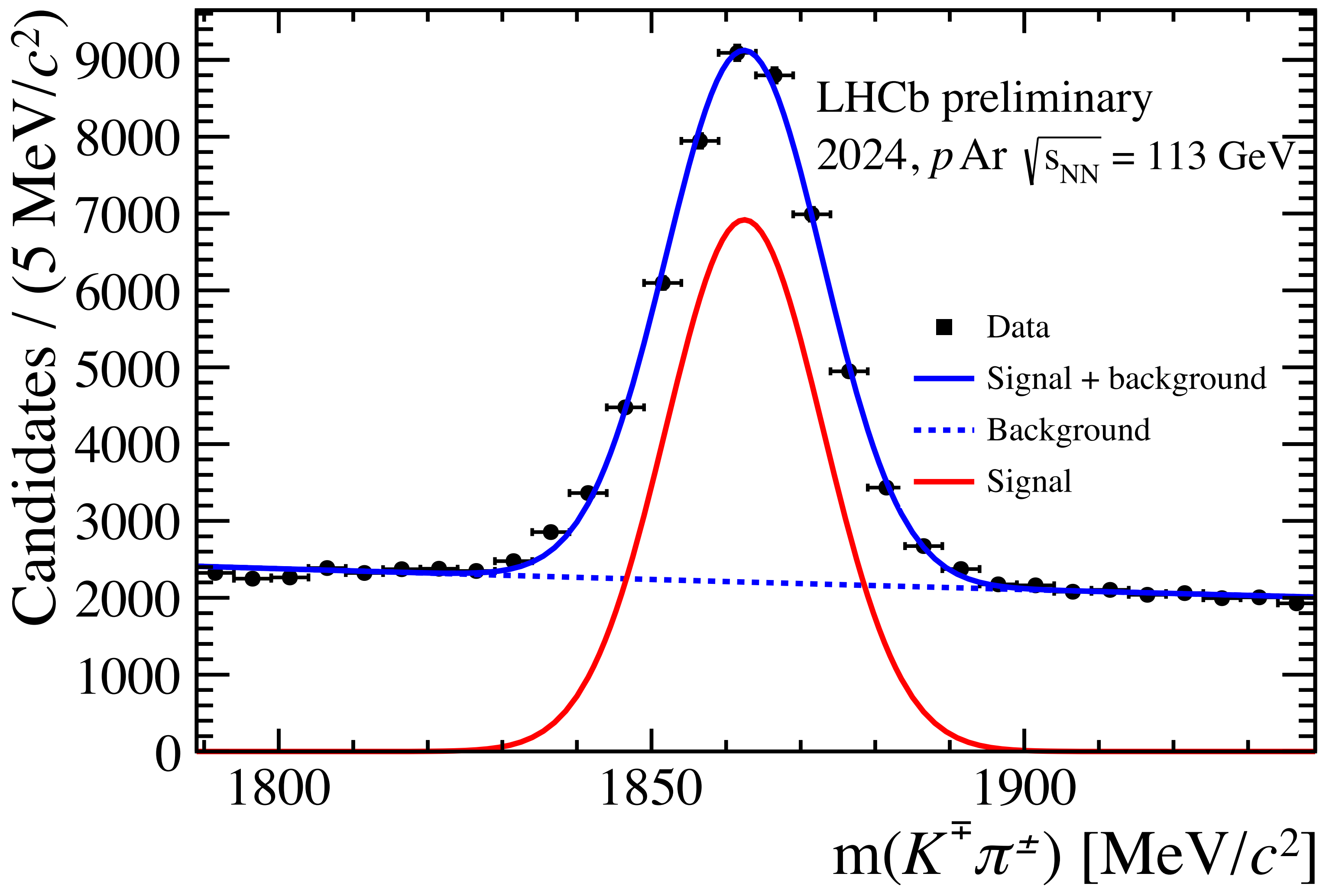
SMOG2: early 2024 data

[ArXiv 2407.14200 submitted to Physical Review Accelerators and Beams]

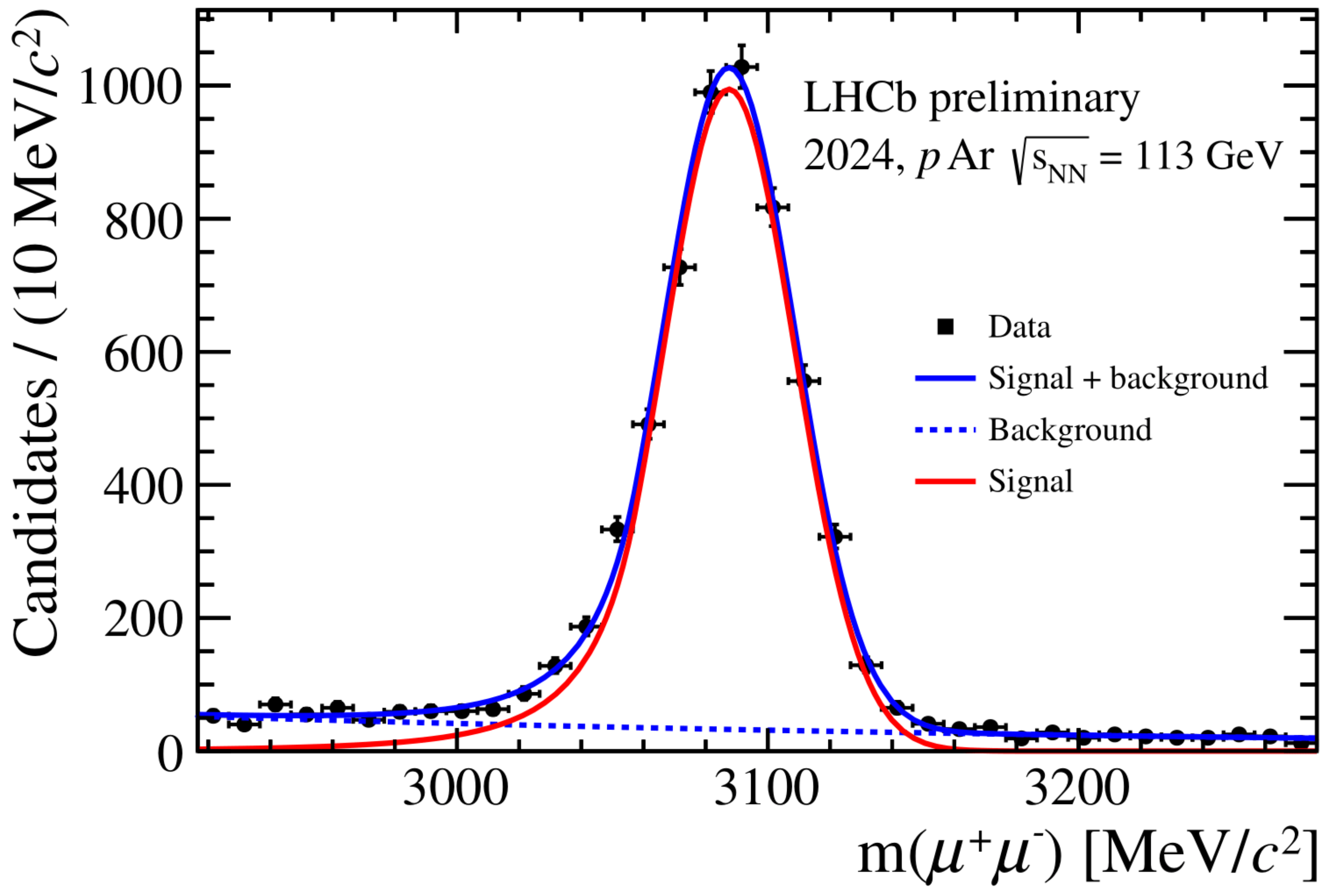
- SMOG2 is performing very well!
- Right: recorded luminosity in May 2024 (D_2, O_2 to be tested)
- Bottom plots: $52\ \mathrm{nb}^{-1}$, collected in 1h40mins
  - $J/\psi \to \mu^+\mu^-$ and $D^0 \to K^-\pi^+$ in p-Ar data-taking
  - $\Lambda \to p\pi^-$ in p-H_2 data-taking, reconstructed in the first trigger level running on GPUs [Comput Softw Big Sci 4, 7 (2020)]



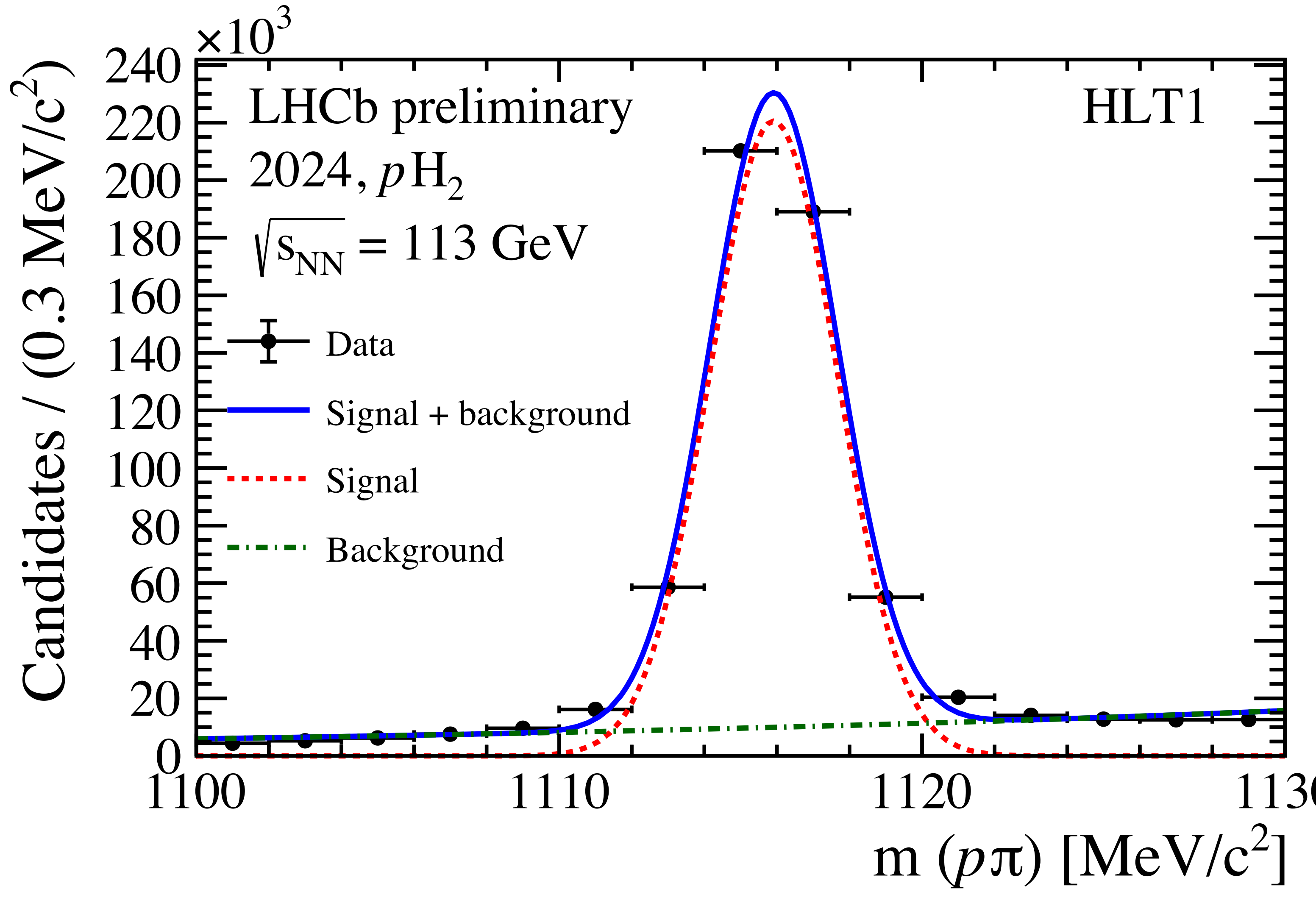
$D^0 \to K^-\pi^+$



$J/\psi \to \mu^+\mu^-$



$\Lambda \to p\pi^-$



[LHCB-FIGURE-2024-005]

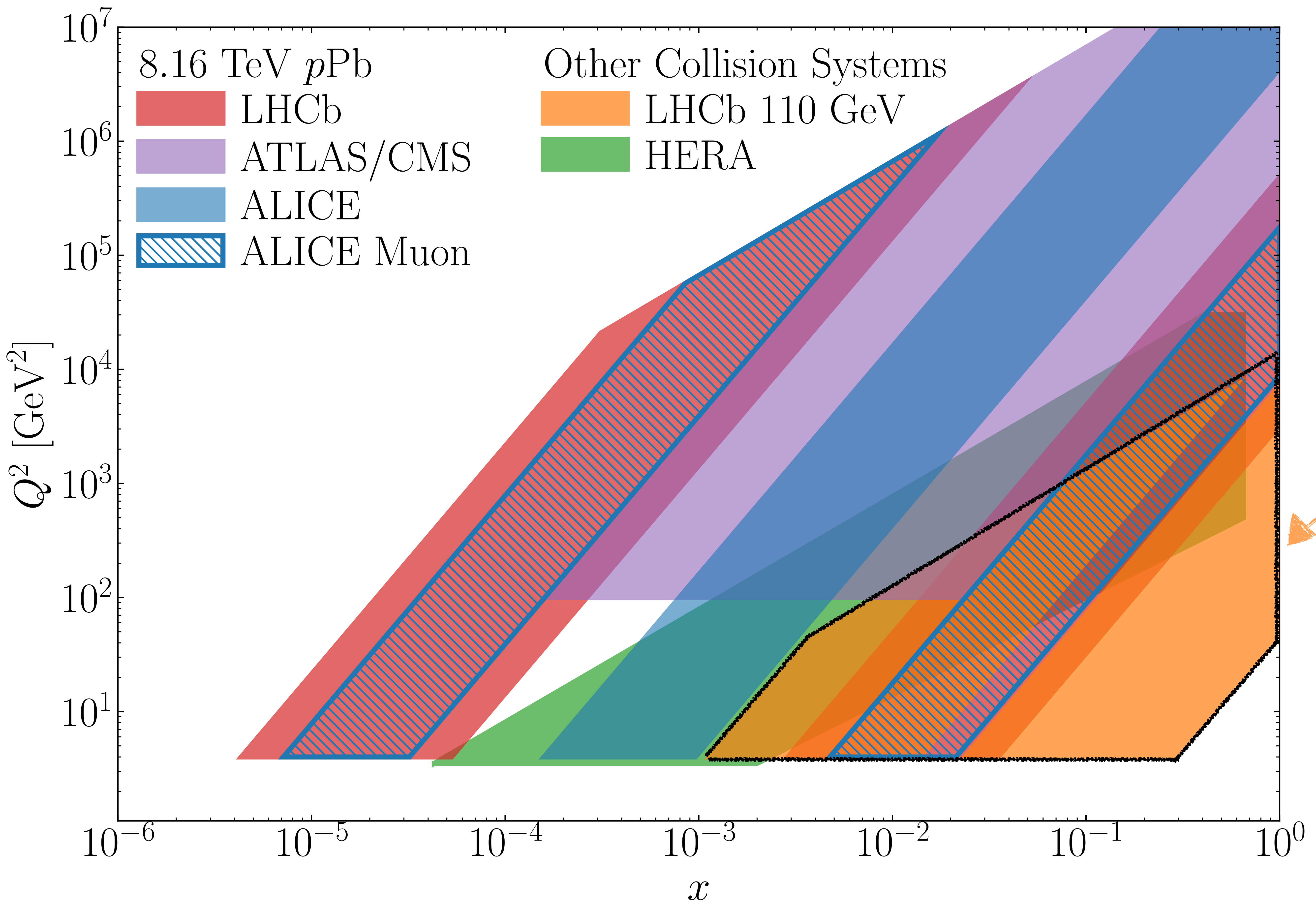
The LHCspin project

[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

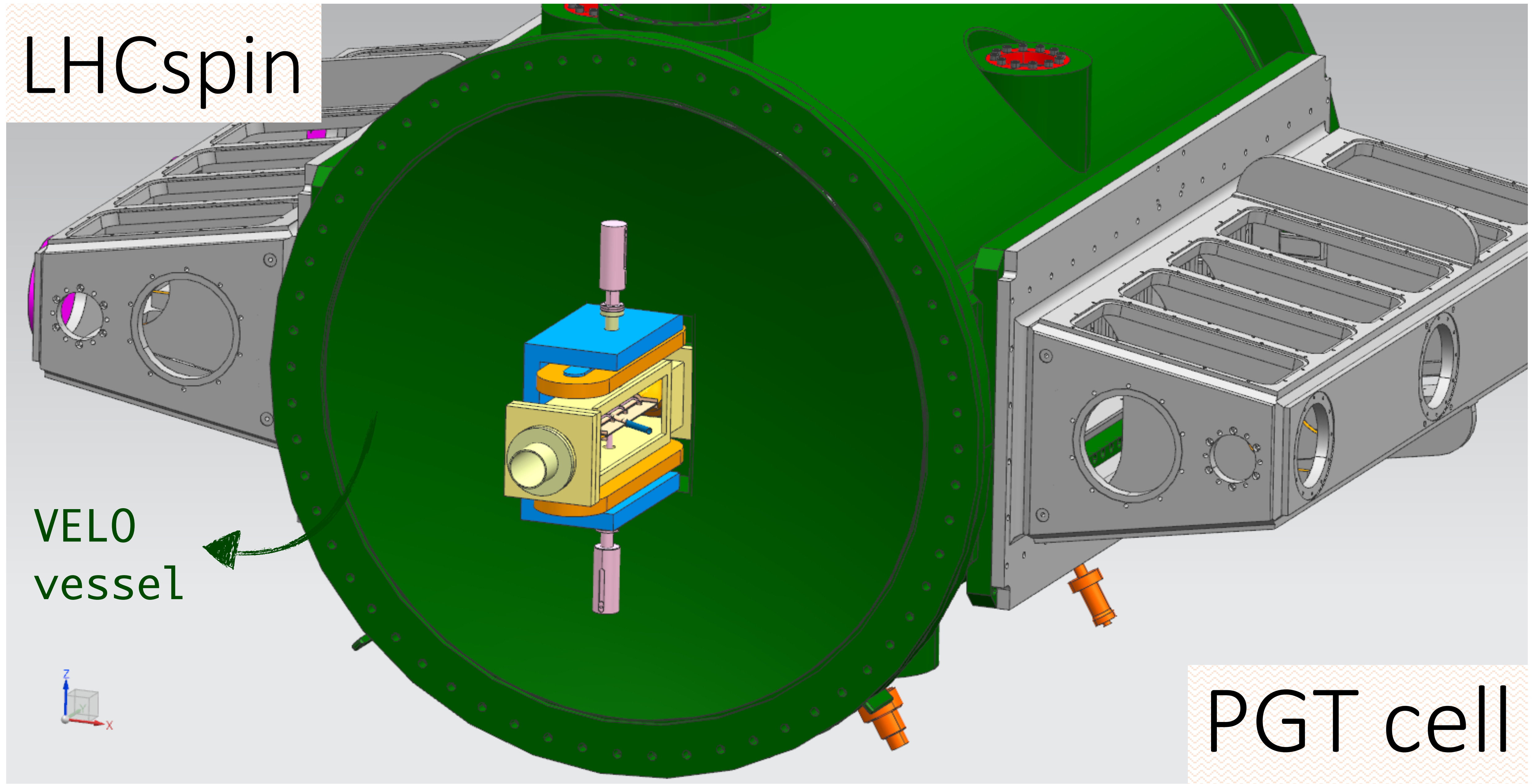


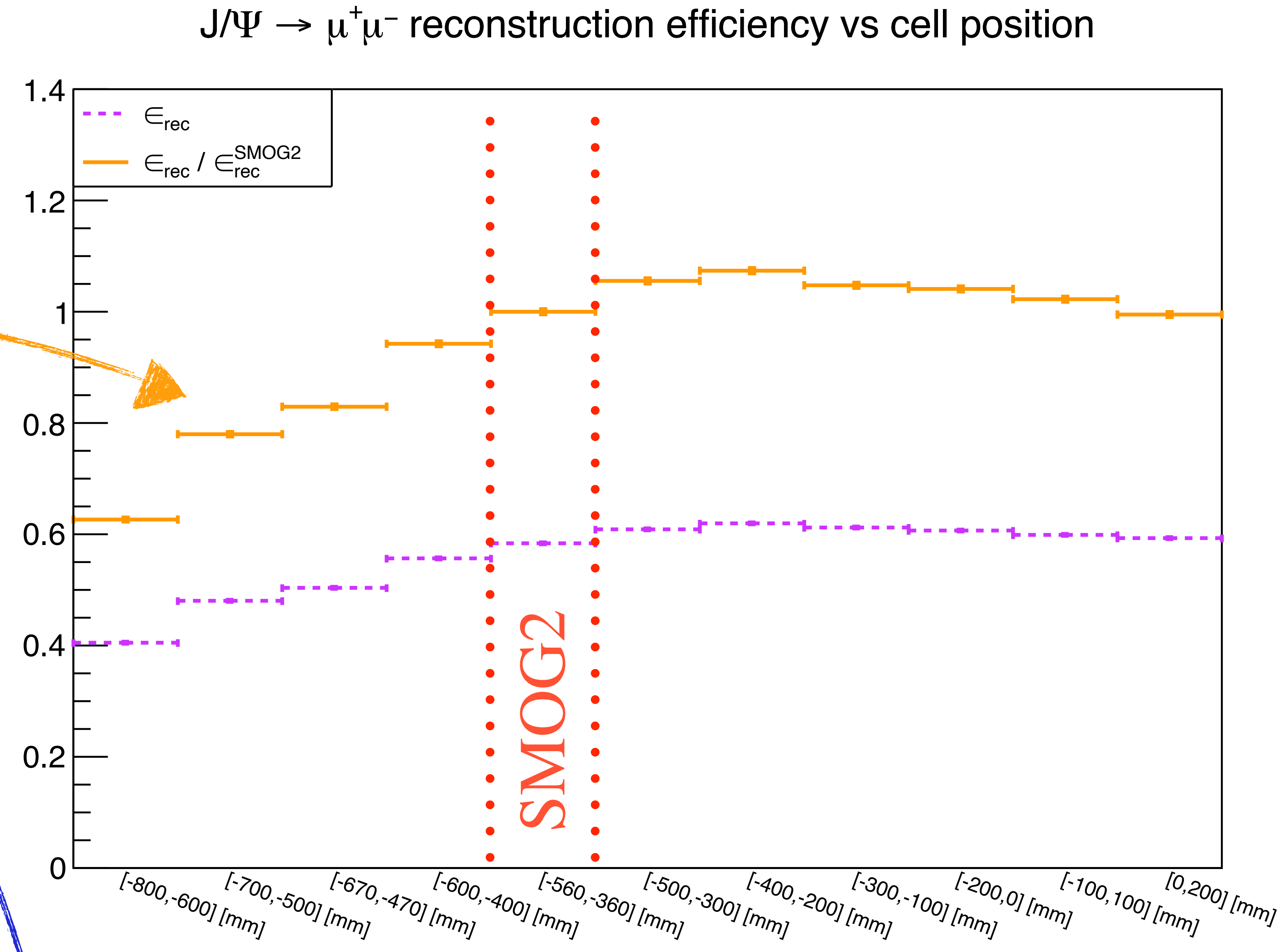
Unique QCD laboratory at LHC:

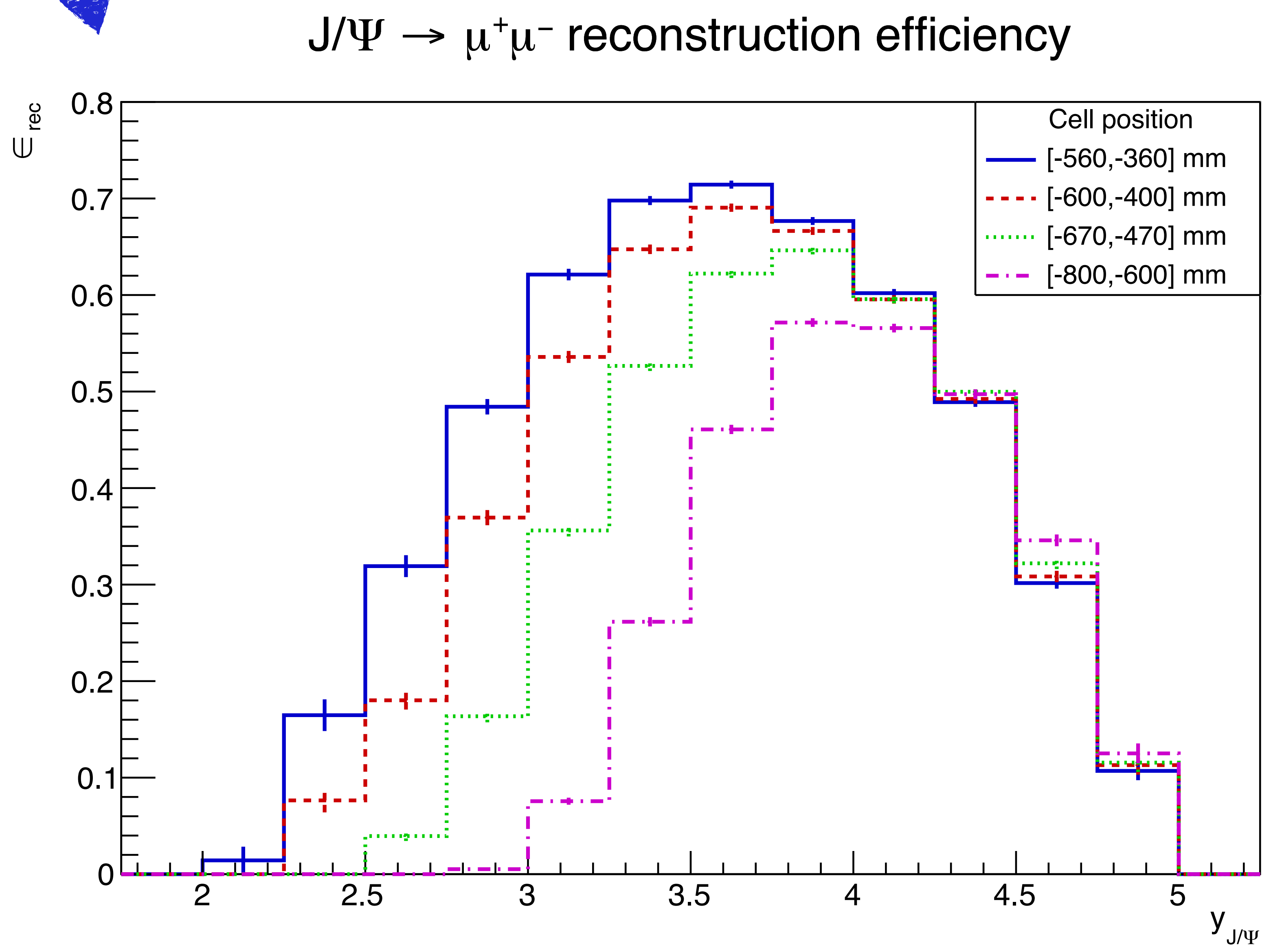
- Large-x content of g, $\bar{q}$ and heavy quarks in nucleons and nuclei
- Spin distributions of gluons inside unpolarised and polarised nucleons
- Heavy ion FT collisions at an energy in between SPS and RHIC
- Broad and poorly explored kinematic range
- High luminosity, high resolution detectors: access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

The Polarised Gas Target 1/2

- Drawing: cylindrical target cell with $L = 20$ cm and $D = 1$ cm (SMOG2 dimensions)
- LHCb simulations show broader kinematic acceptance & better reconstruction efficiency when the cell is close to the Vertex Locator (VELO) → modified flange is shown
- Our new fully-software trigger gives flexibility & room for improvement e.g. better reconstruction algorithms, dedicated trigger lines… this is already ongoing for the Run 3

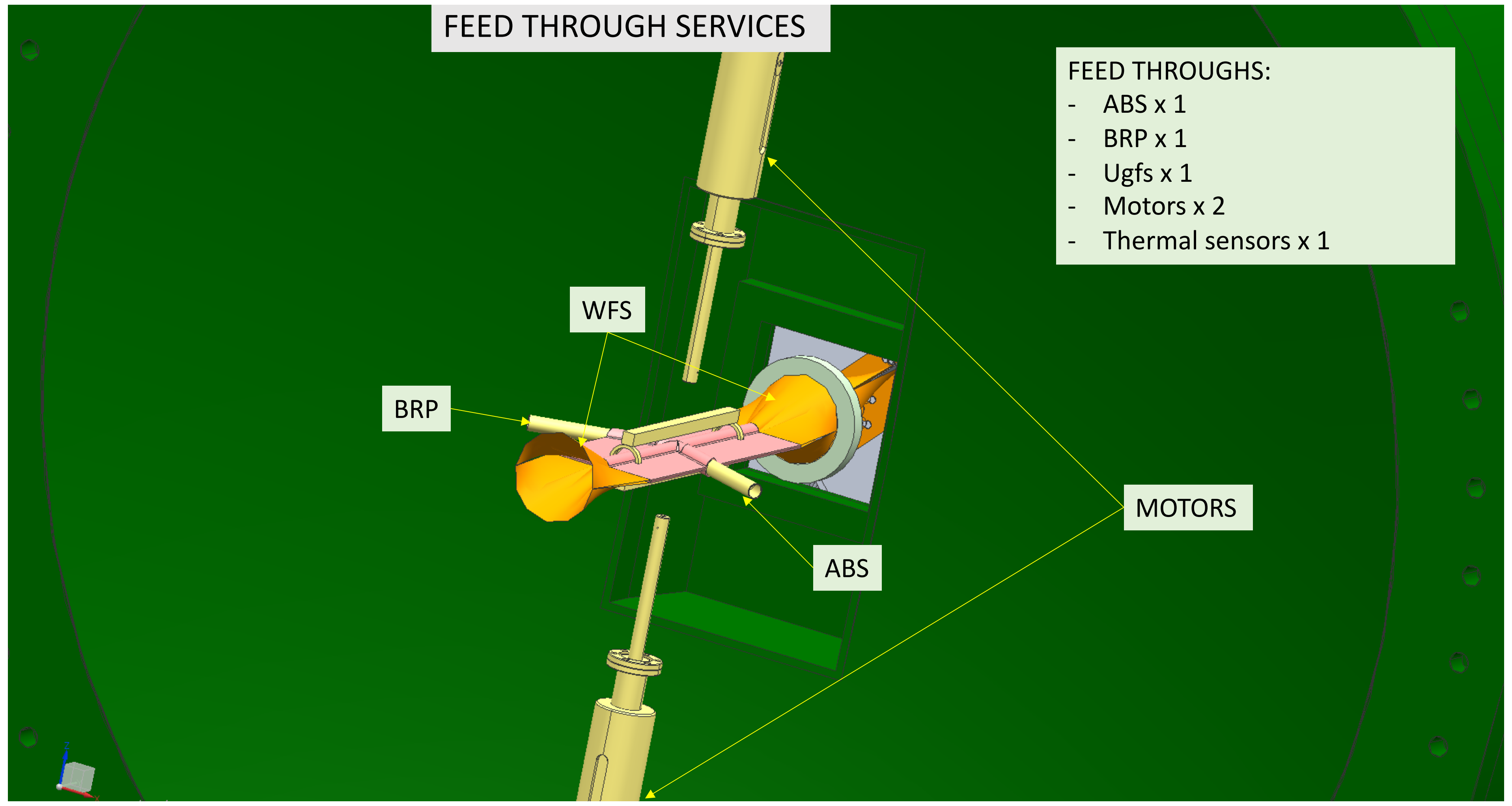


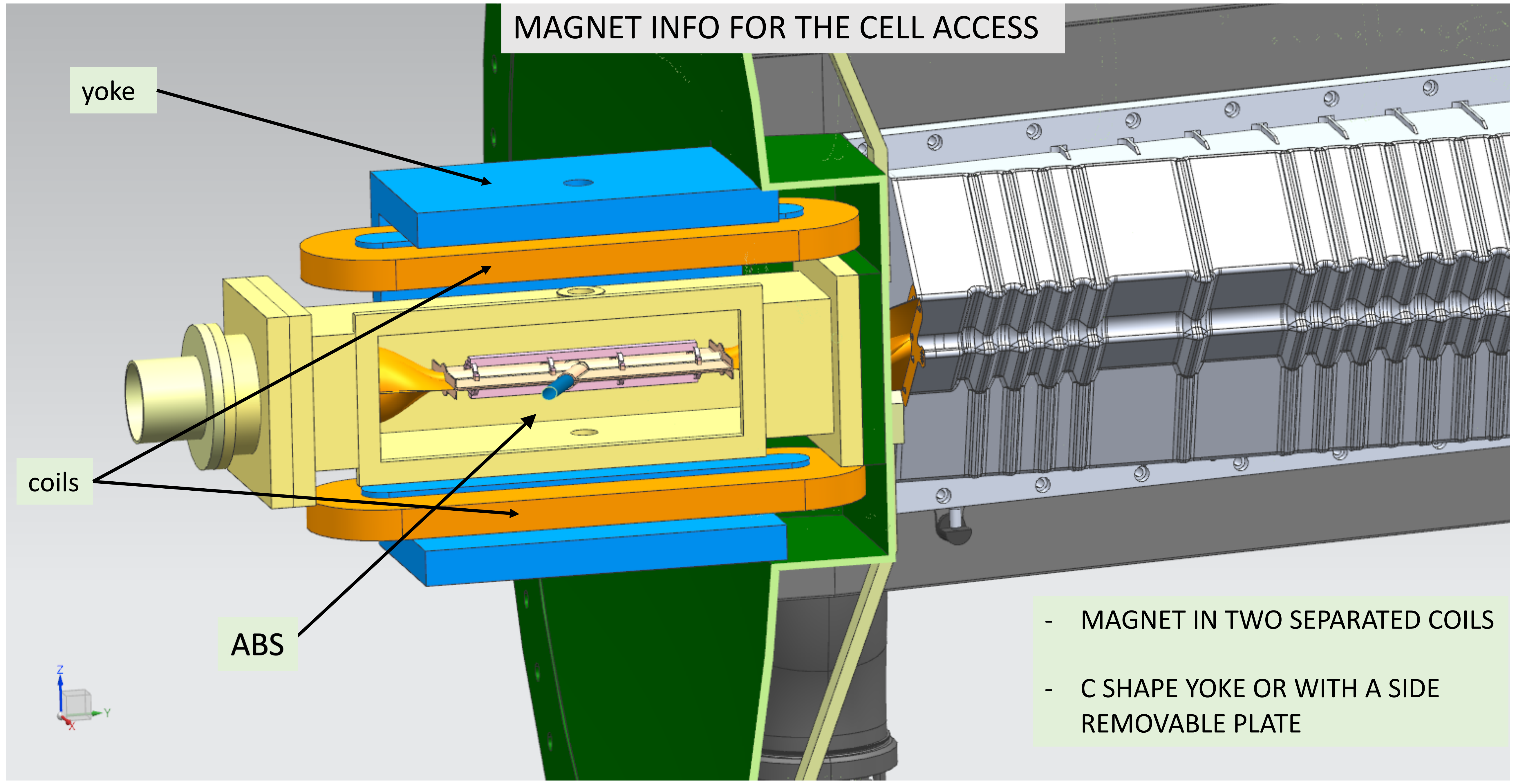




The Polarised Gas Target 2/2

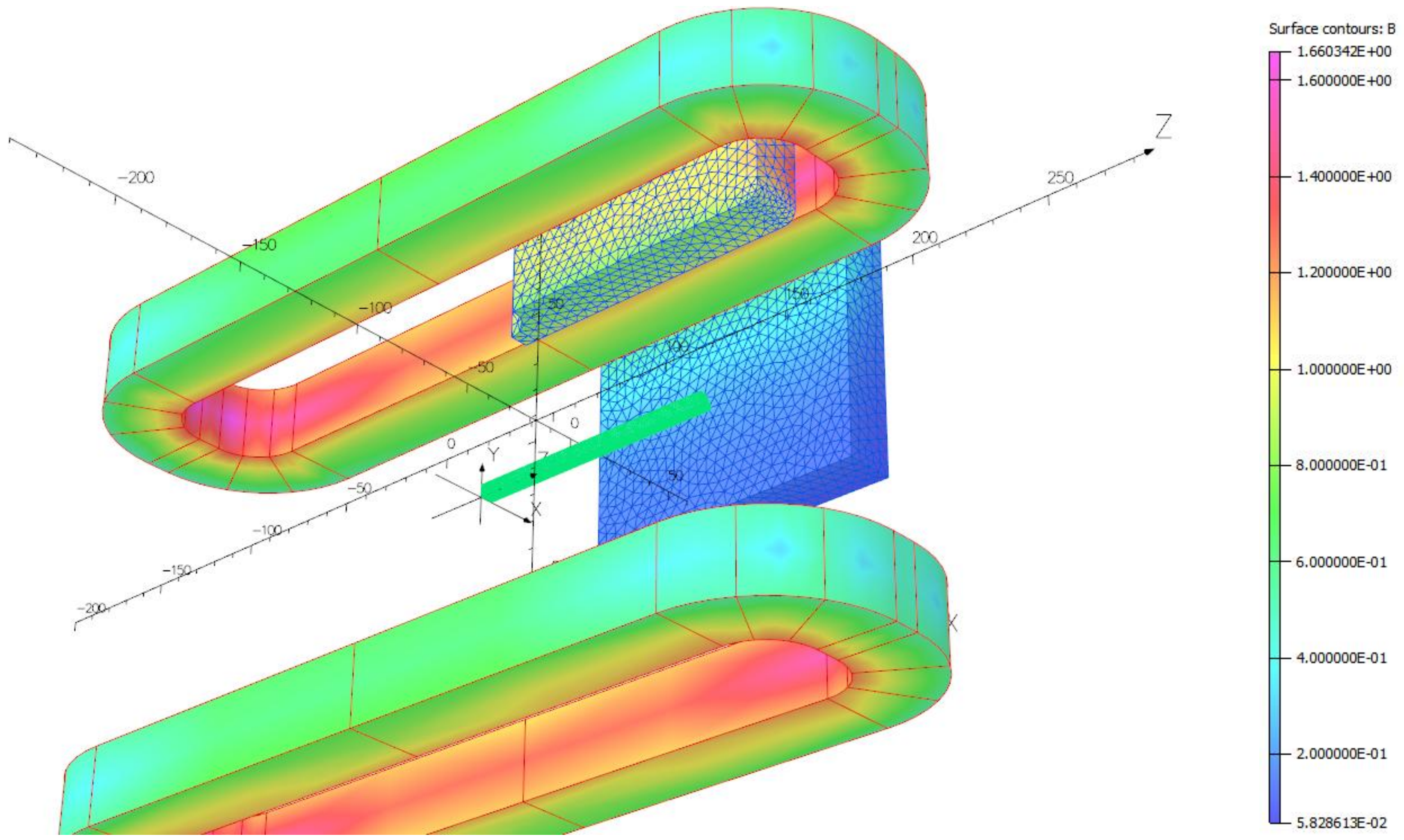
- Inject both polarised and unpolarised gases via ABS and uGFS





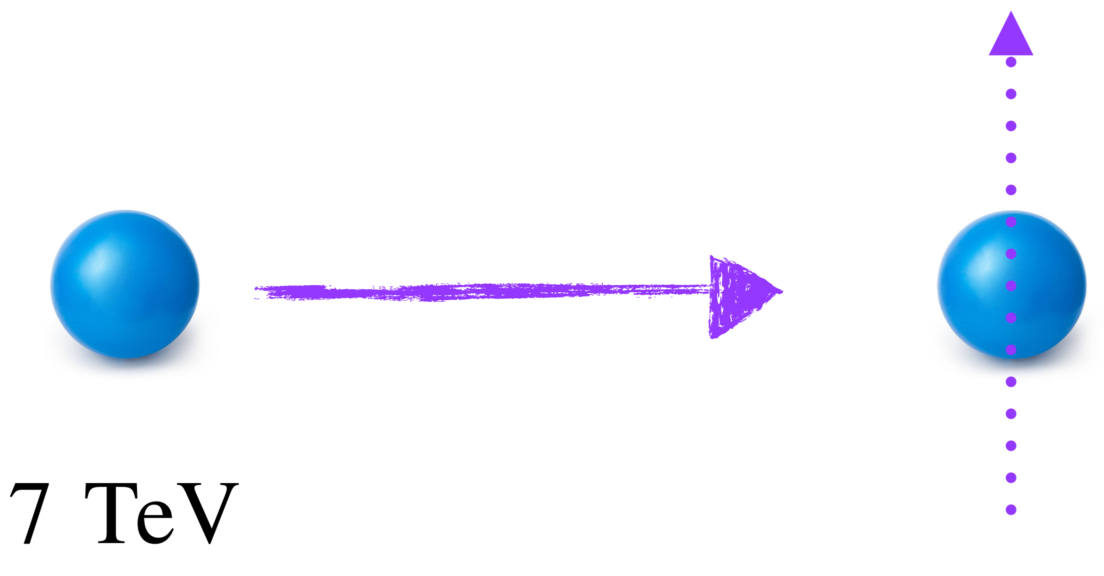
- Compact dipole magnet around the cell to provide static transverse field
- Superconductive coils + iron yoke configuration fits the space constraints
- $B = 300\ \mathrm{mT}$ with polarity inversion and $\Delta B/B \simeq 10\,\%$, suitable to avoid beam-induced depolarisation
- Possibility to switch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

[PoS (SPIN2018)]



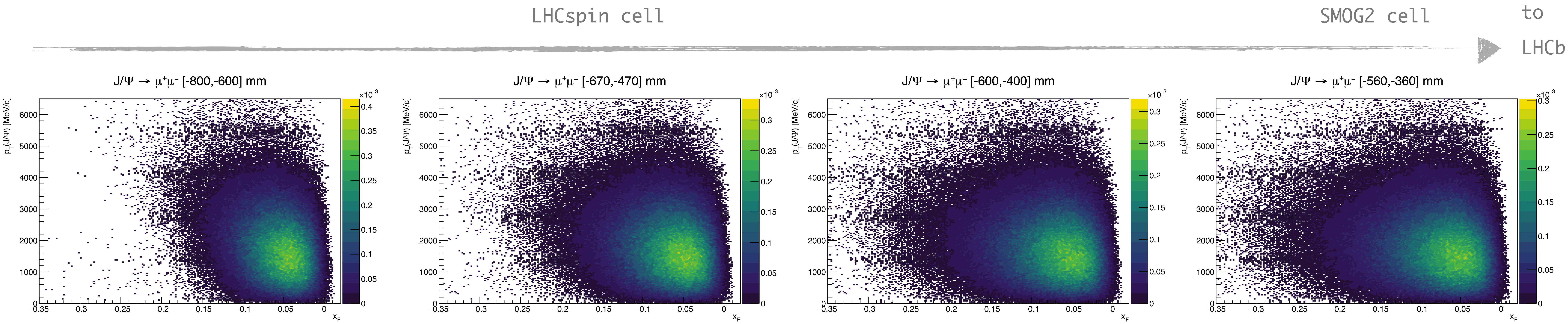
Kinematic coverage

- Full LHCb simulations of p-H fixed-target collisions at $\sqrt{s} = 115$ GeV
- Current SMOG2 region: $[-560, -360]$ mm . Possible solution to fit the PGT: $[-670, -470]$ mm
- The kinematic coverage depends on the cell position → x range shrinks when moving upstream

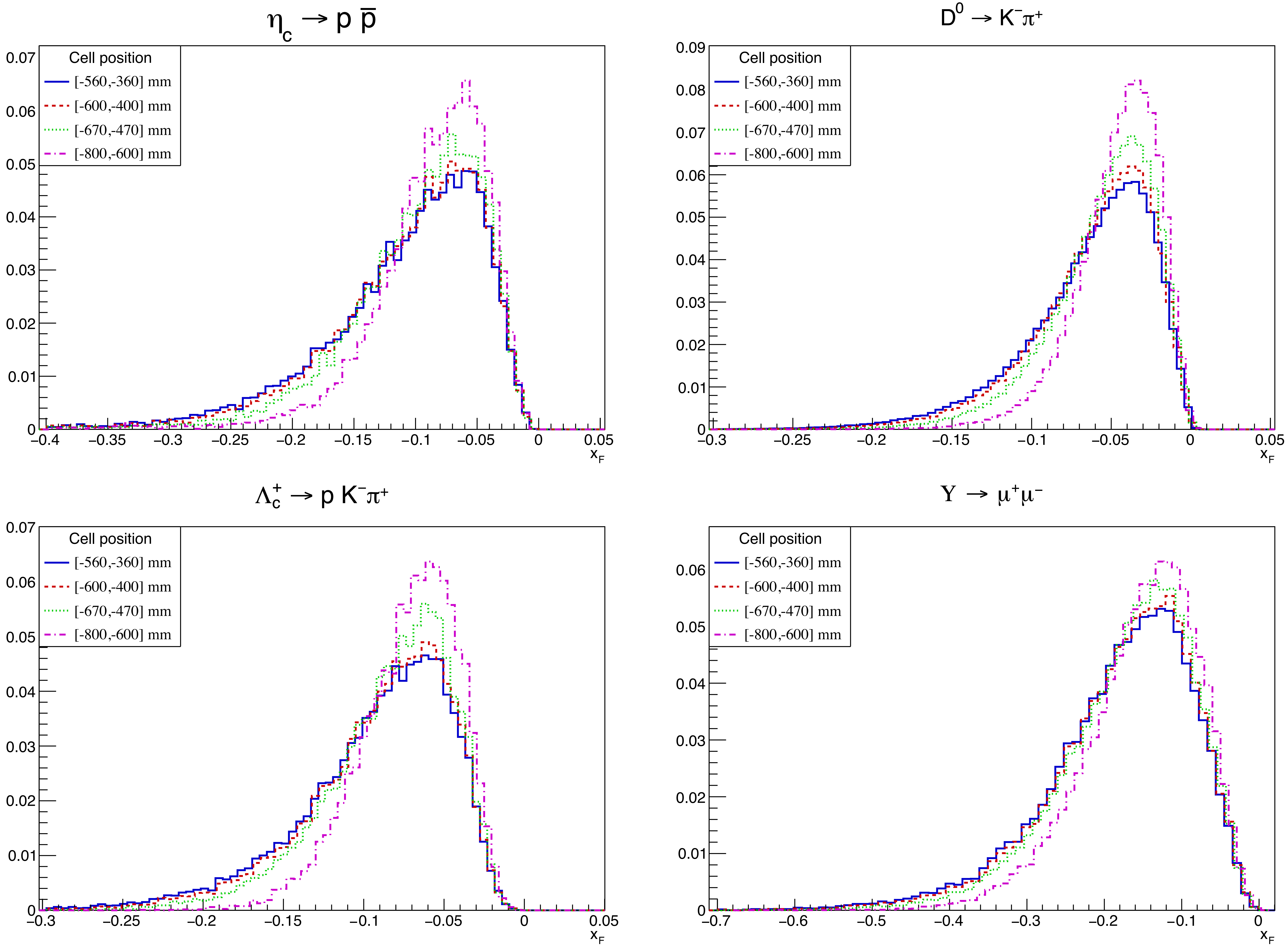


$$\sqrt{s} = \sqrt{2 m_N E_p} = 115\ \text{GeV}$$

Using $x_F = 2E_T/\sqrt{s_{NN}}\ \sinh(y^*)$
with $E_T^2 = M^2 + P_T^2$

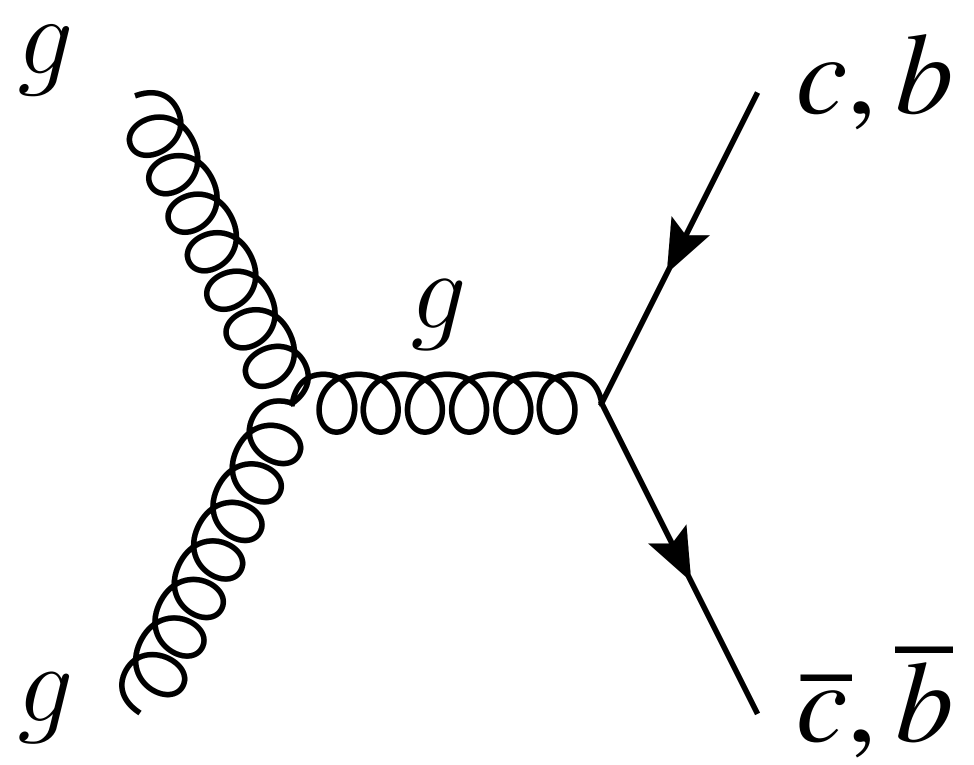


x_F acceptance

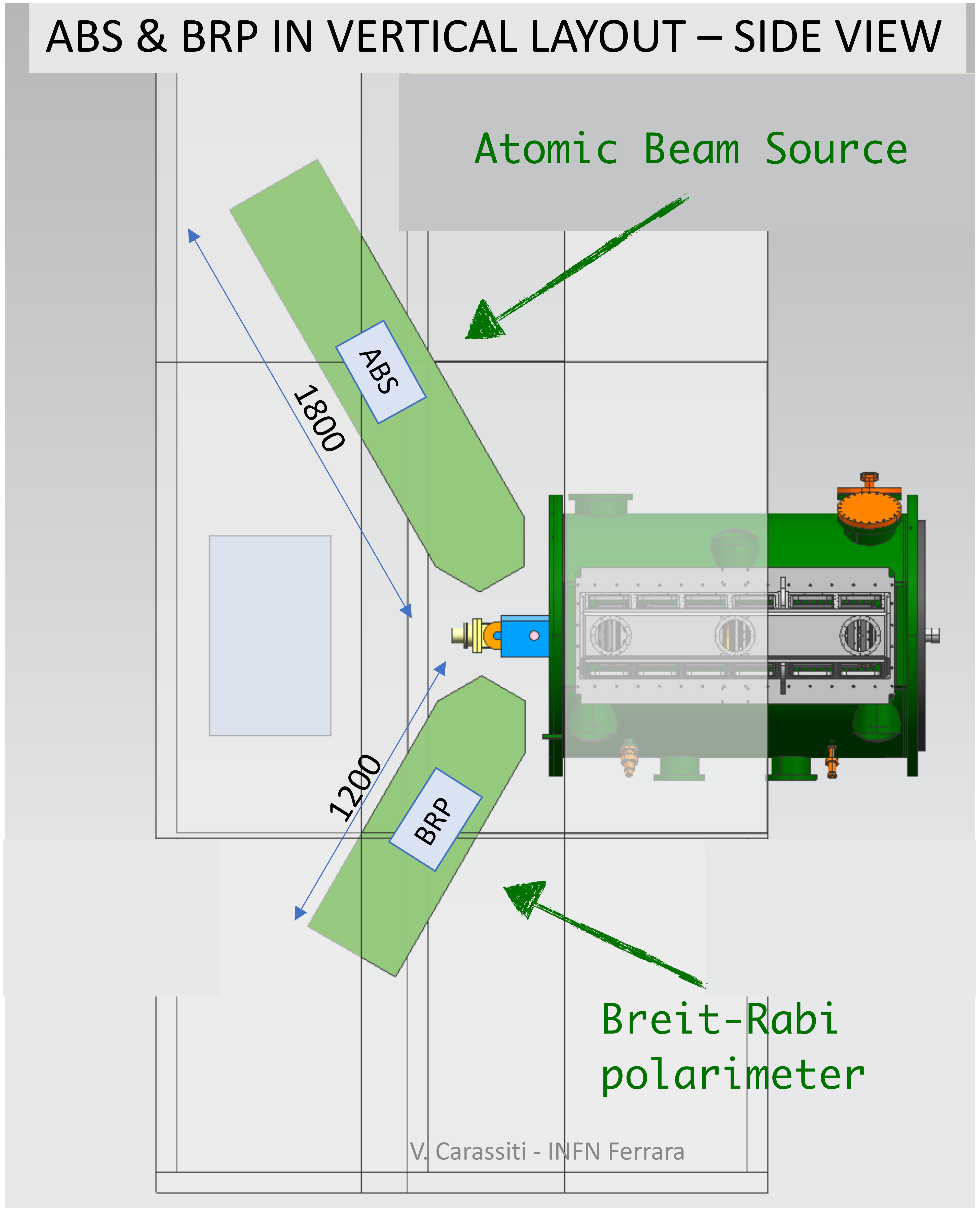


- c-hadrons will have the largest product of cross section and reconstruction efficiency
- Only a small portion of the expected statistics is shown: can cover broad x values (see next slides)

  → unique opportunity to probe gluon TMDs!



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 targets!
- No need for additional detectors in LHCb: very small cost!
- Aiming at HERMES performance:

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

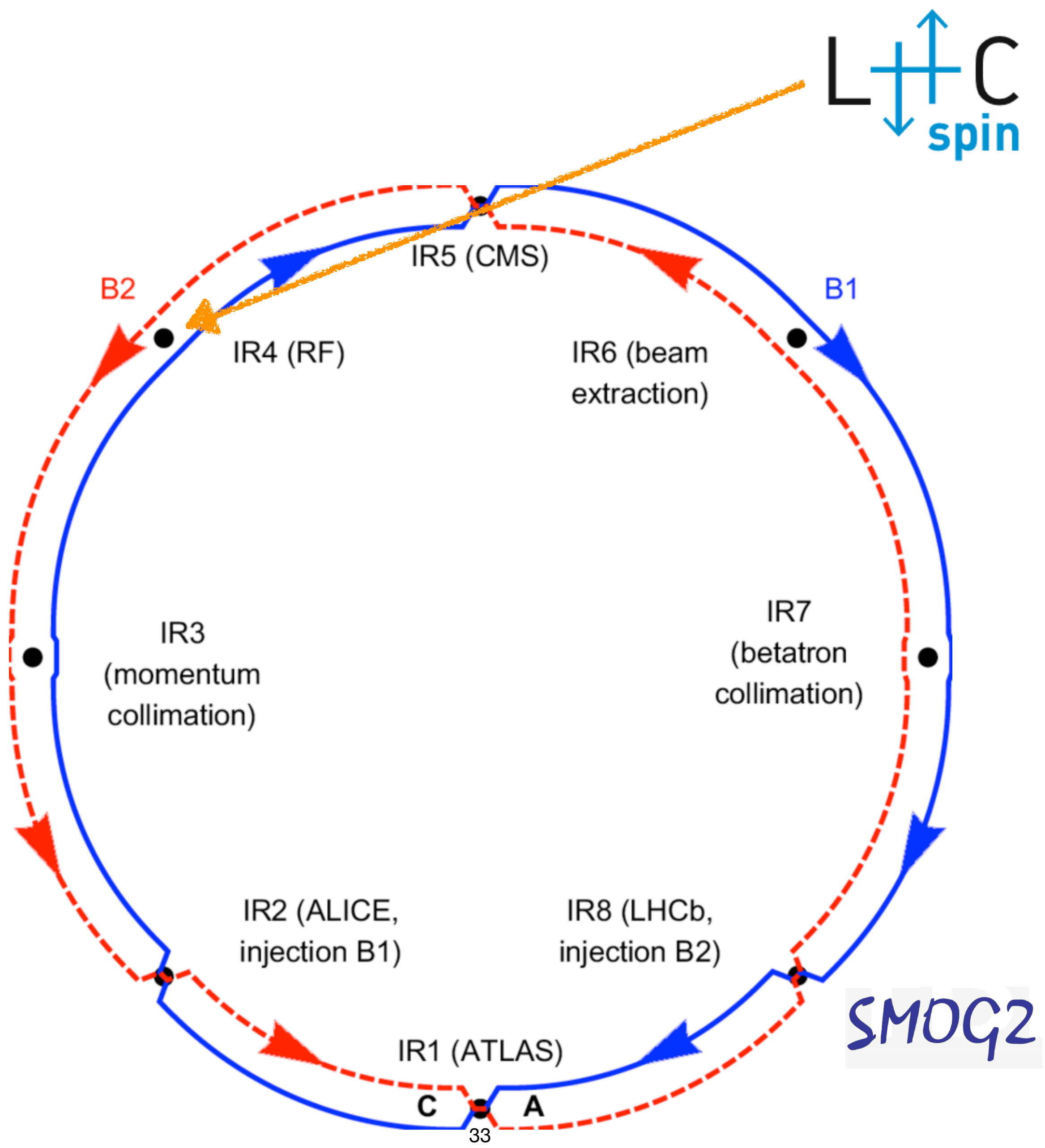
Intensity of injected H-atoms: $6.5 \times 10^{16}\ \mathrm{s}^{-1}$

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

More on the R&D

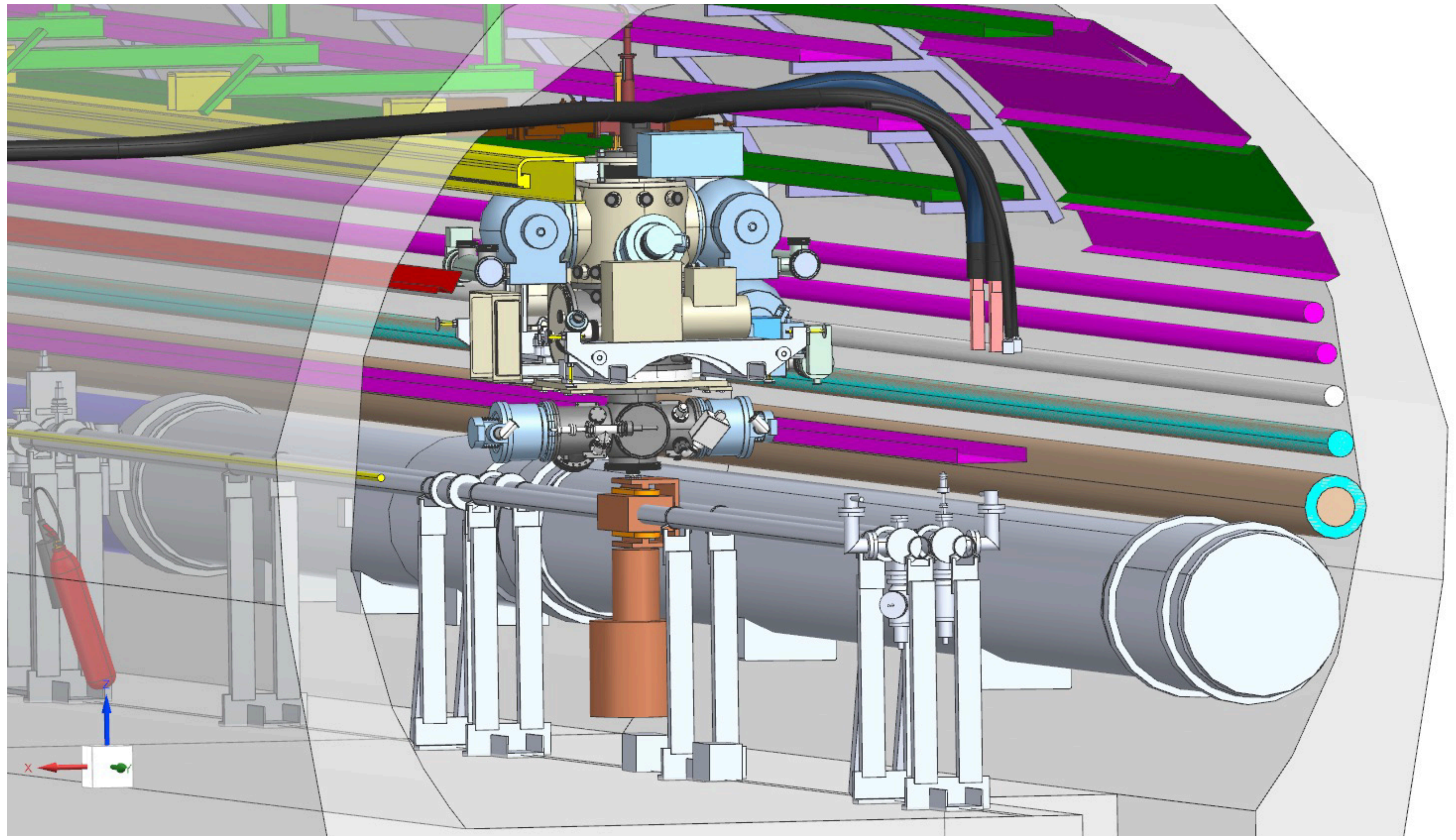
- Coating studies ongoing for the inner walls of the cell. Control secondary electron emission and hydrogen recombination [NIMA 1068 (2024) 169707]
- We want to start the R&D with a test setup at the IR4 (“Phase 1”) ahead of Run 5 installation in LHCb (“Phase 2”)
- The IR4 has a lot of space, rails and racks for the existing (and not used) “Beam Gas Vertex”

[talk] →



Existing setup at IR4

LHCspin setup at IR4



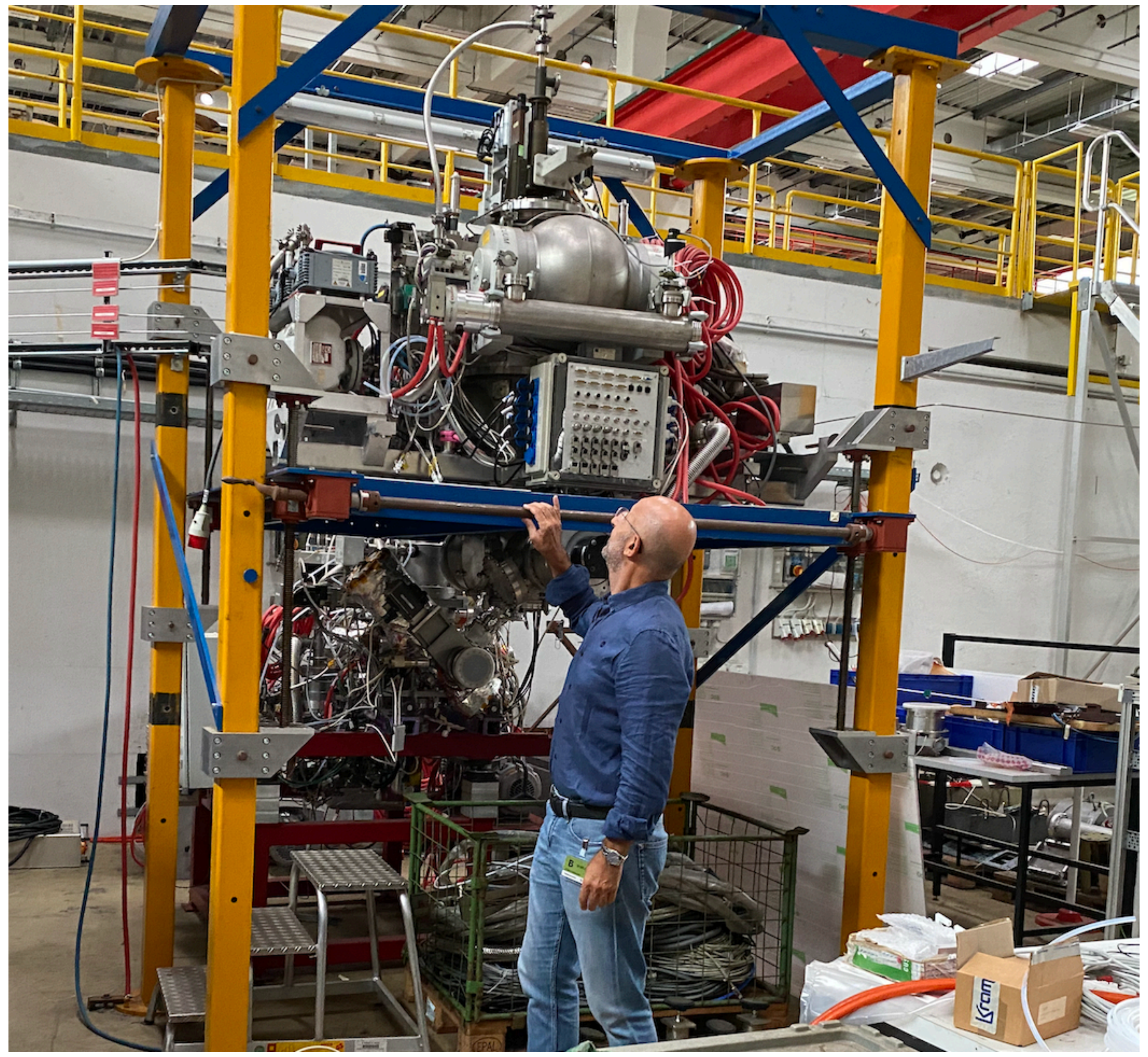
Test setup at the IR4

- The ABS is at COSY (Jülich), and will be moved to INFN-Ferrara for first tests and then installed in the IR4
- A minimal detector could also allow to make some first (unique) measurements.
  More in → this talk

ALTERNATIVE SETUP:

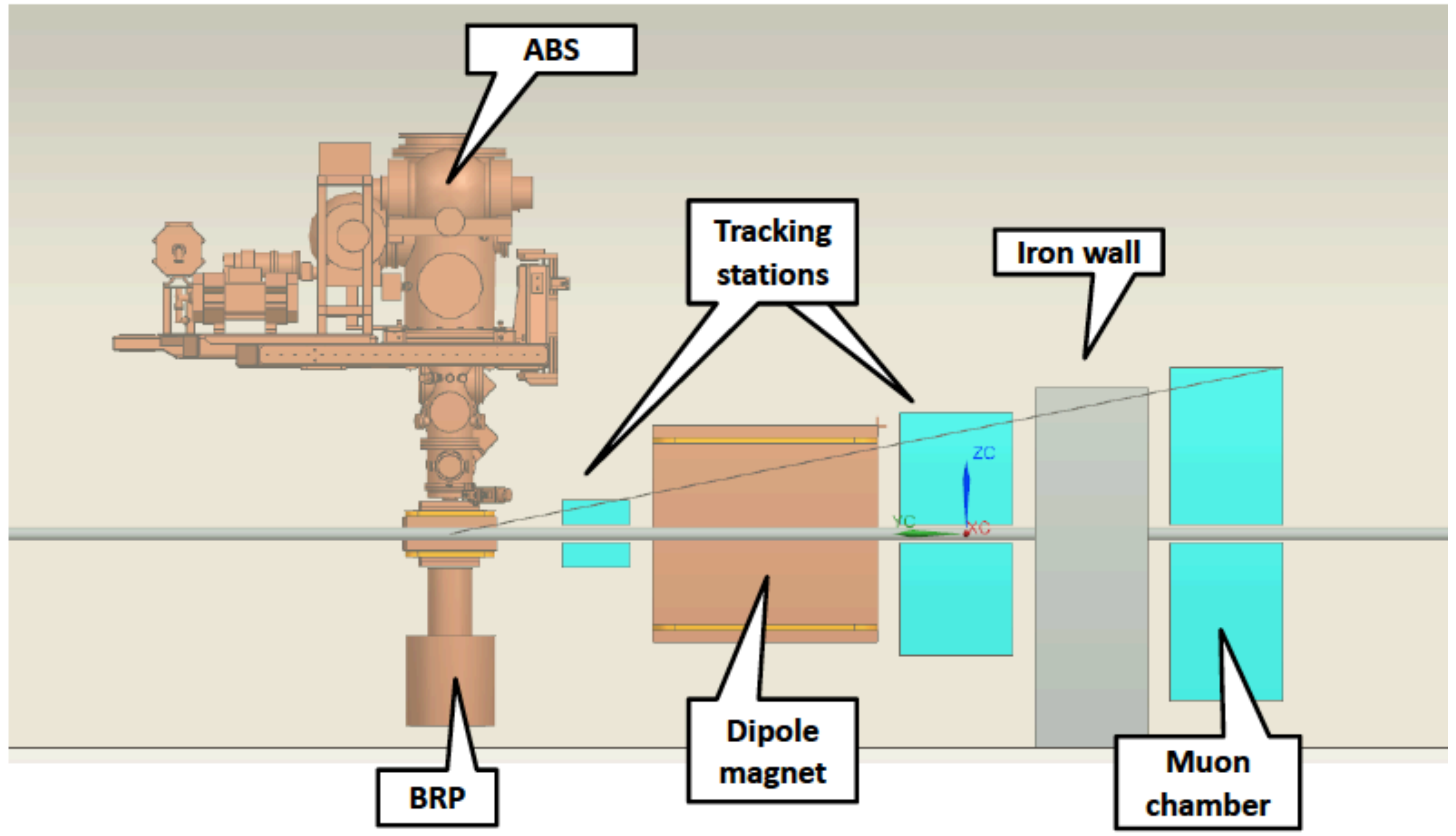
- A jet target would provide lower density ($\approx 1/40$) but higher polarisation degree
- PRO: precision measurements on high-statistics channels, easy to install
- CON: Makes kinematic binning and rare channels harder

- This R&D would be be parallel to LHCb and open to external members!



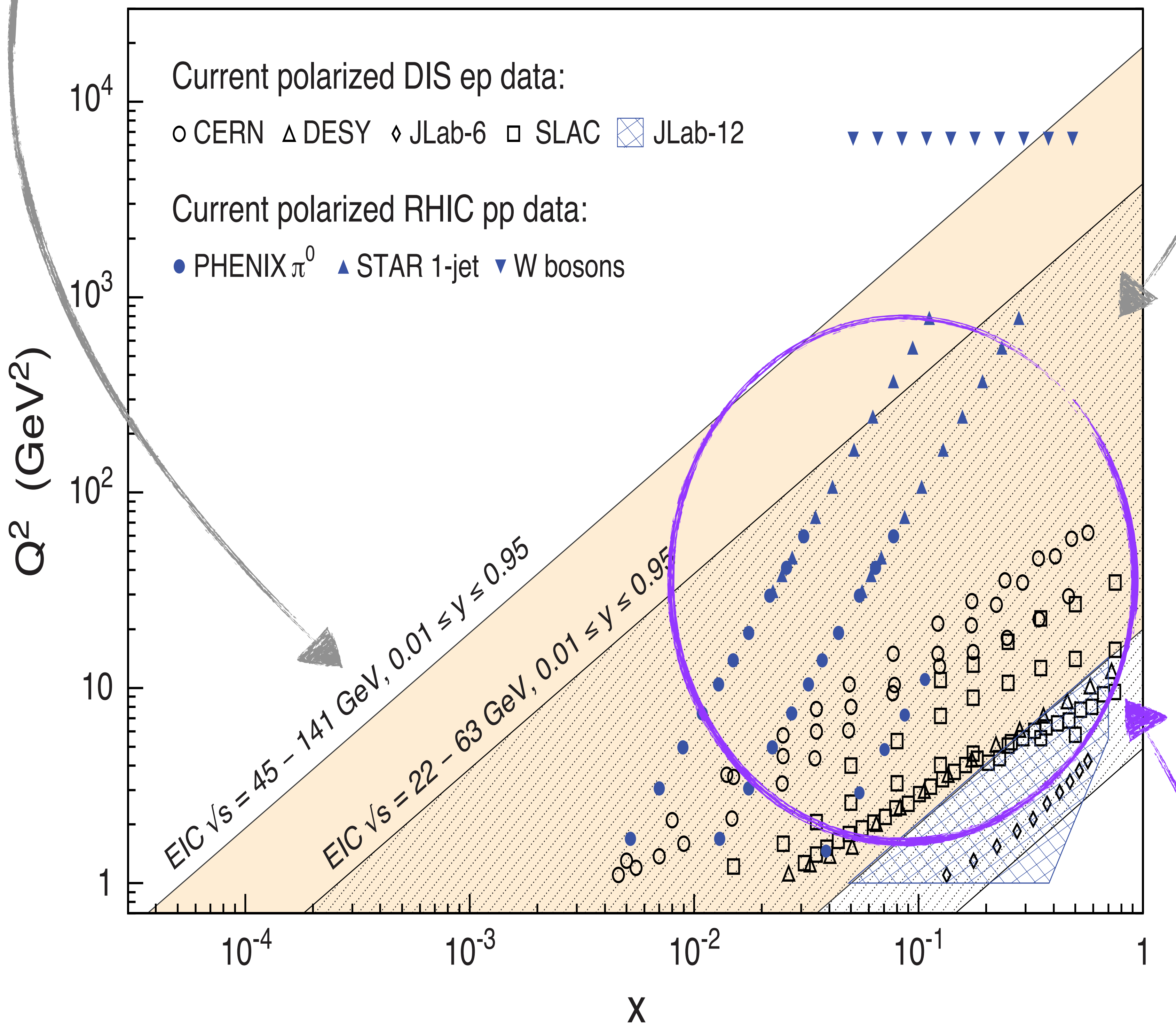
[NIMA 721 (2013) 83-98]

A minimal detector @ IR4



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. Cost: 3B$
- higher Q^2 reach with future EIC upgrade



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

- Based on the current SMOG2 performance, we can estimate for a Run of p-H collision at LHCspin:

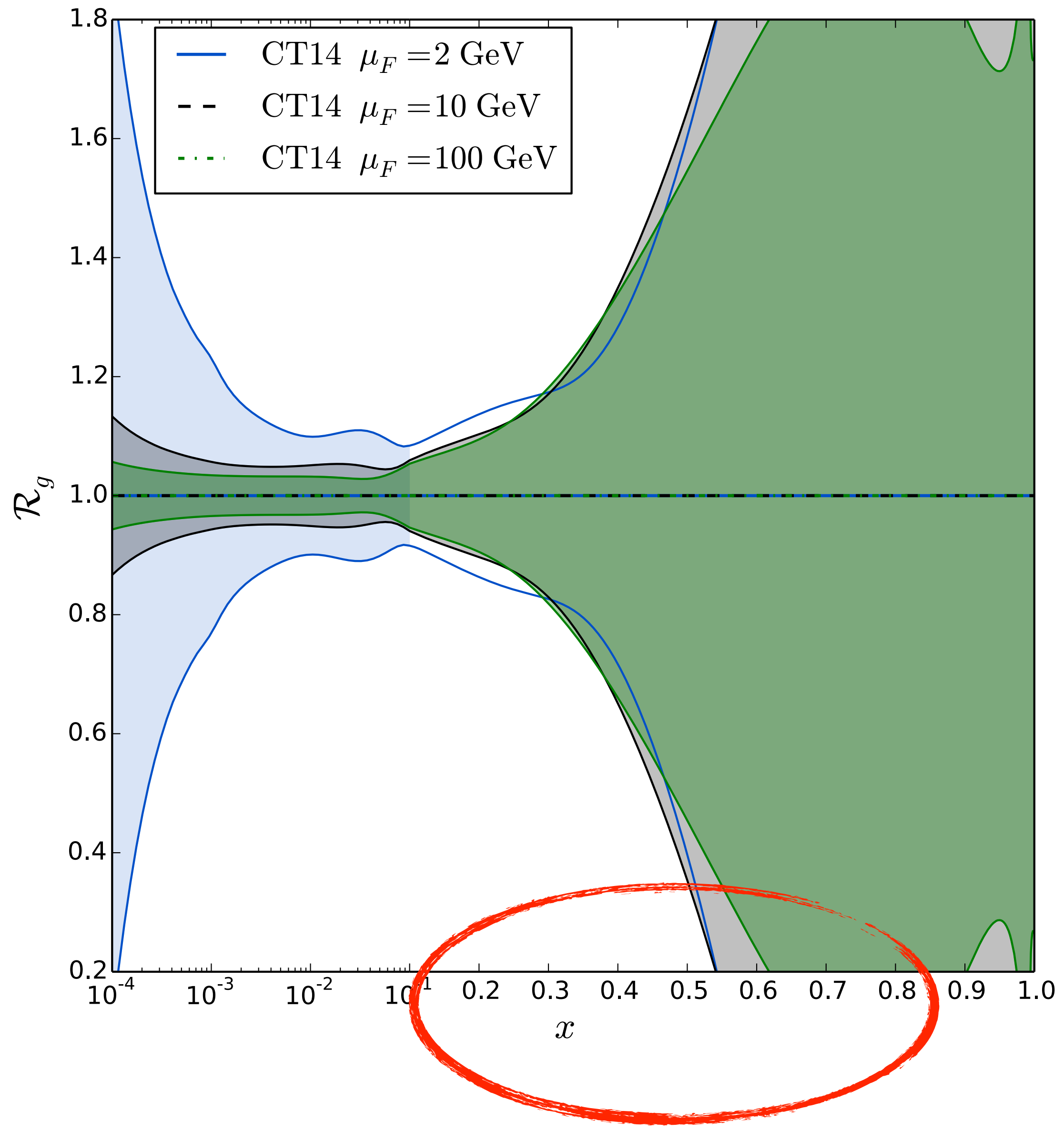
Channel	Events / week	Total yield
$J/\psi \to \mu^+\mu^-$	1.3×10^7 !!	1.5×10^9
$D^0 \to K^-\pi^+$	6.5×10^7	7.8×10^9
$\psi(2S) \to \mu^+\mu^-$	2.3×10^5	2.8×10^7
$J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (DPS)	8.5	1.0×10^3
$J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (SPS)	2.5×10^1	3.1×10^3
Drell Yan ($5 <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

- Note: fully-reconstructed & selected events!

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]

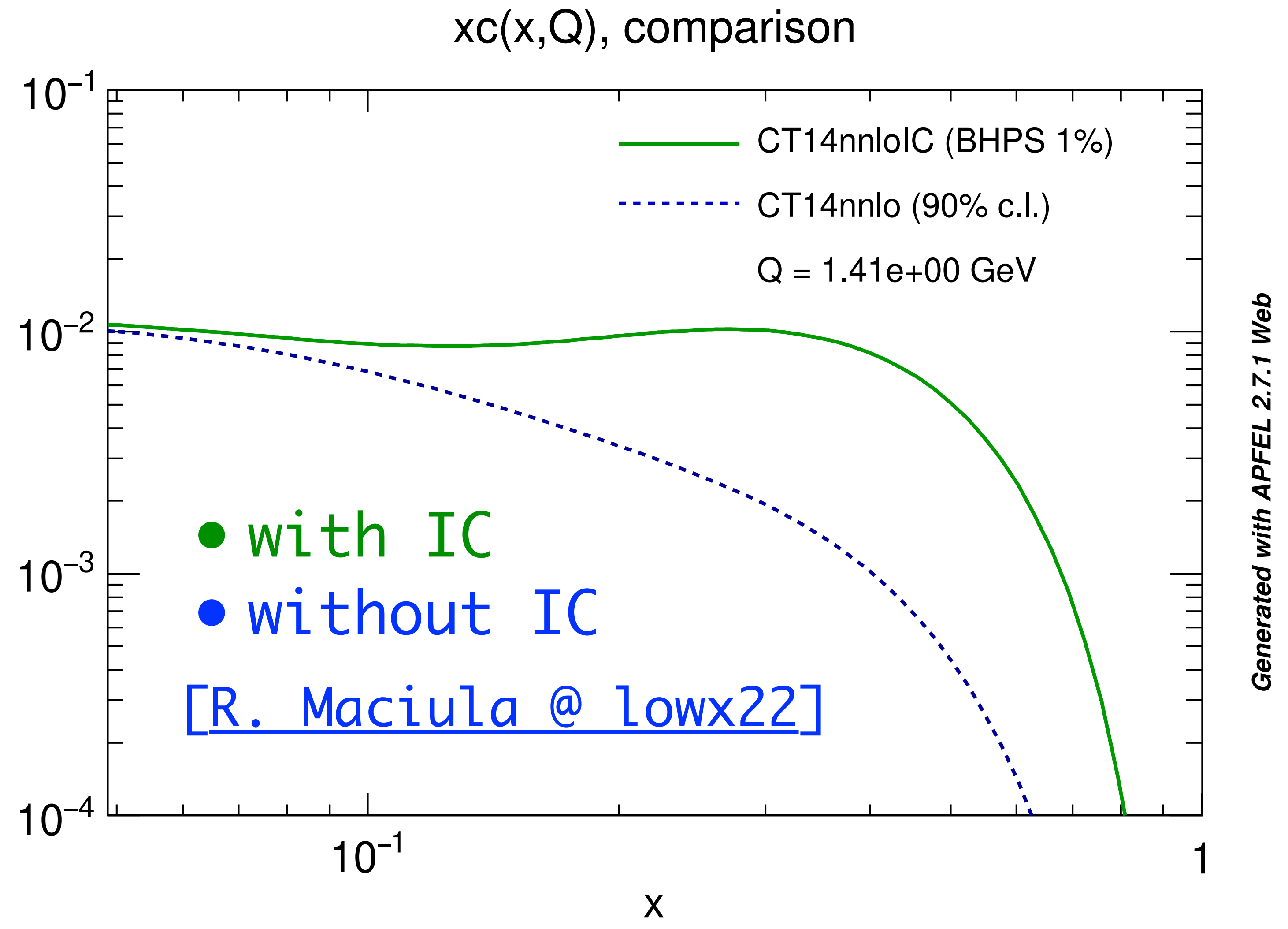


[PRD 105 (2022) 014001]

- Study the Intrinsic Charm component in the proton, first measurement done with SMOG on pHe

[PRL 122 (2019) 132002]

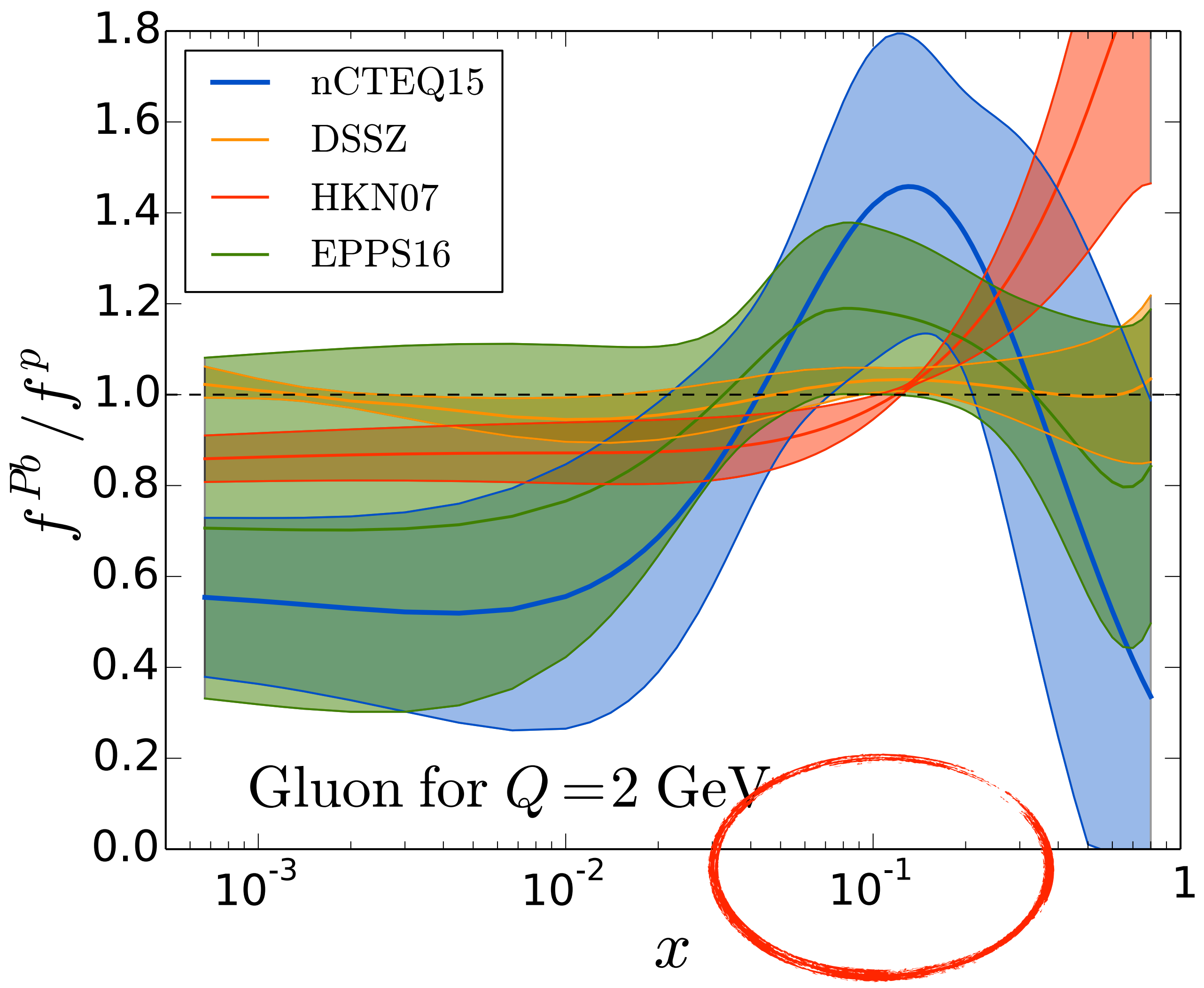
- Provide crucial inputs for neutrino fluxes, UHECR and DM annihilation

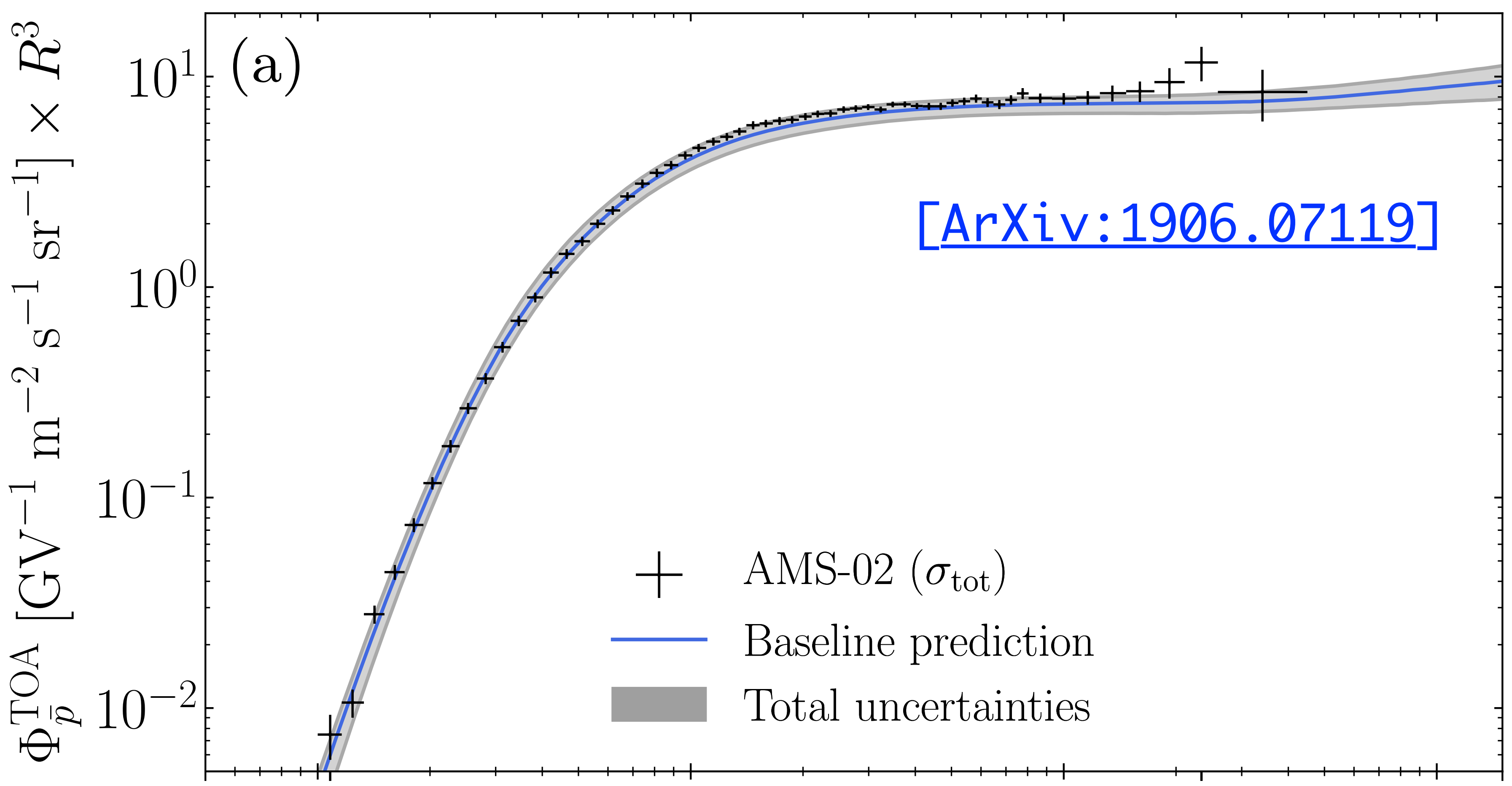


[JHEP 05 (2017) 004] [ARNPS 61 (2011) 467-489]

- Investigate the structure of nuclei: especially in the anti-shadowing region ($x \sim 0.1$)

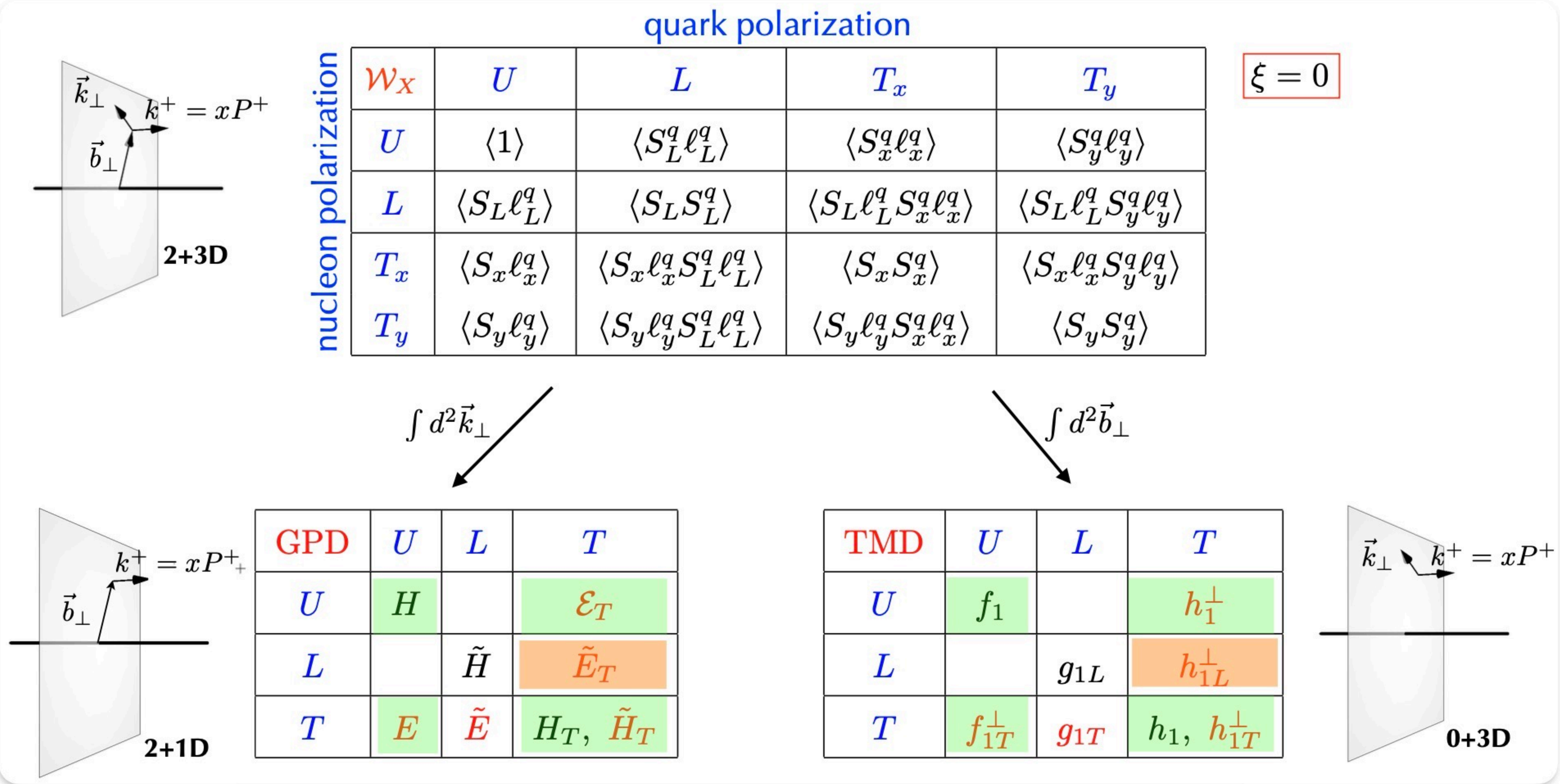
[ArXiv:1807.00603]





Polarised target: multi-dimensional nucleon mapping

- Investigate the 3D structure of the nucleon: GPDs and TMDs



$\mathcal{W}_X$	U	L	T_x	T_y
U	$\langle 1 \rangle$	$\langle S^q_L \ell^q_L \rangle$	$\langle S^q_x \ell^q_x \rangle$	$\langle S^q_y \ell^q_y \rangle$
L	$\langle S_L \ell^q_L \rangle$	$\langle S_L S^q_L \rangle$	$\langle S_L \ell^q_L S^q_x \ell^q_x \rangle$	$\langle S_L \ell^q_L S^q_y \ell^q_y \rangle$
T_x	$\langle S_x \ell^q_x \rangle$	$\langle S_x \ell^q_x S^q_L \ell^q_L \rangle$	$\langle S_x S^q_x \rangle$	$\langle S_x \ell^q_x S^q_y \ell^q_y \rangle$
T_y	$\langle S_y \ell^q_y \rangle$	$\langle S_y \ell^q_y S^q_L \ell^q_L \rangle$	$\langle S_y \ell^q_y S^q_x \ell^q_x \rangle$	$\langle S_y S^q_y \rangle$

GPD	U	L	T
U	H		$\mathcal{E}_T$
L		$\tilde{H}$	$\tilde{\mathcal{E}}_T$
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)

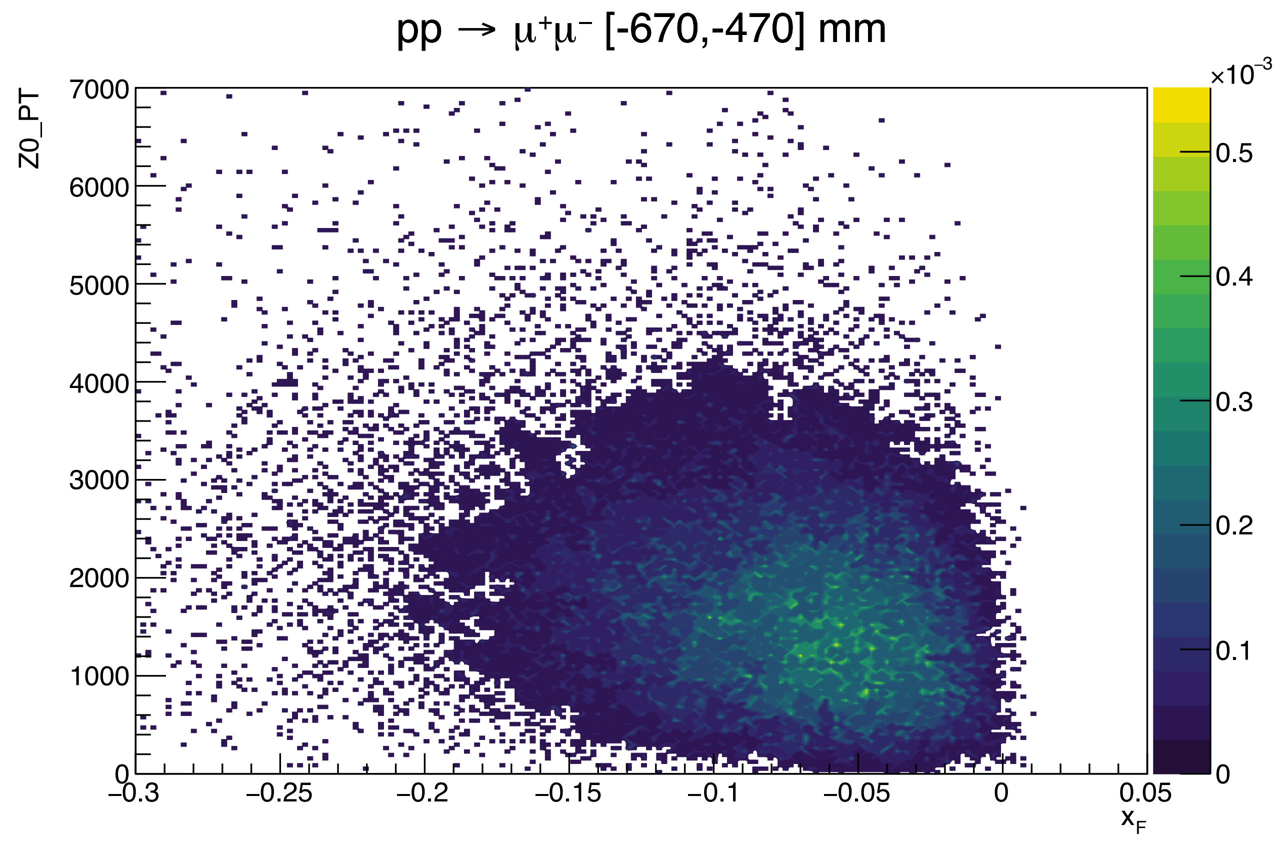
: accessible at LHCspin (solenoid)

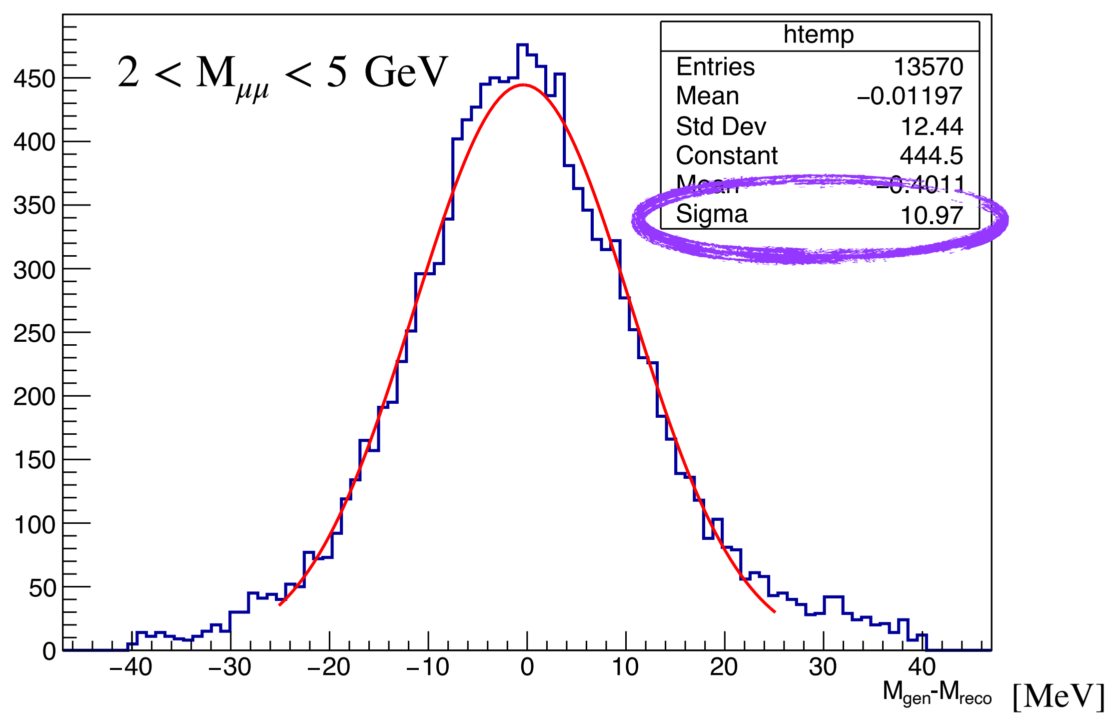
TMDs

- 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)

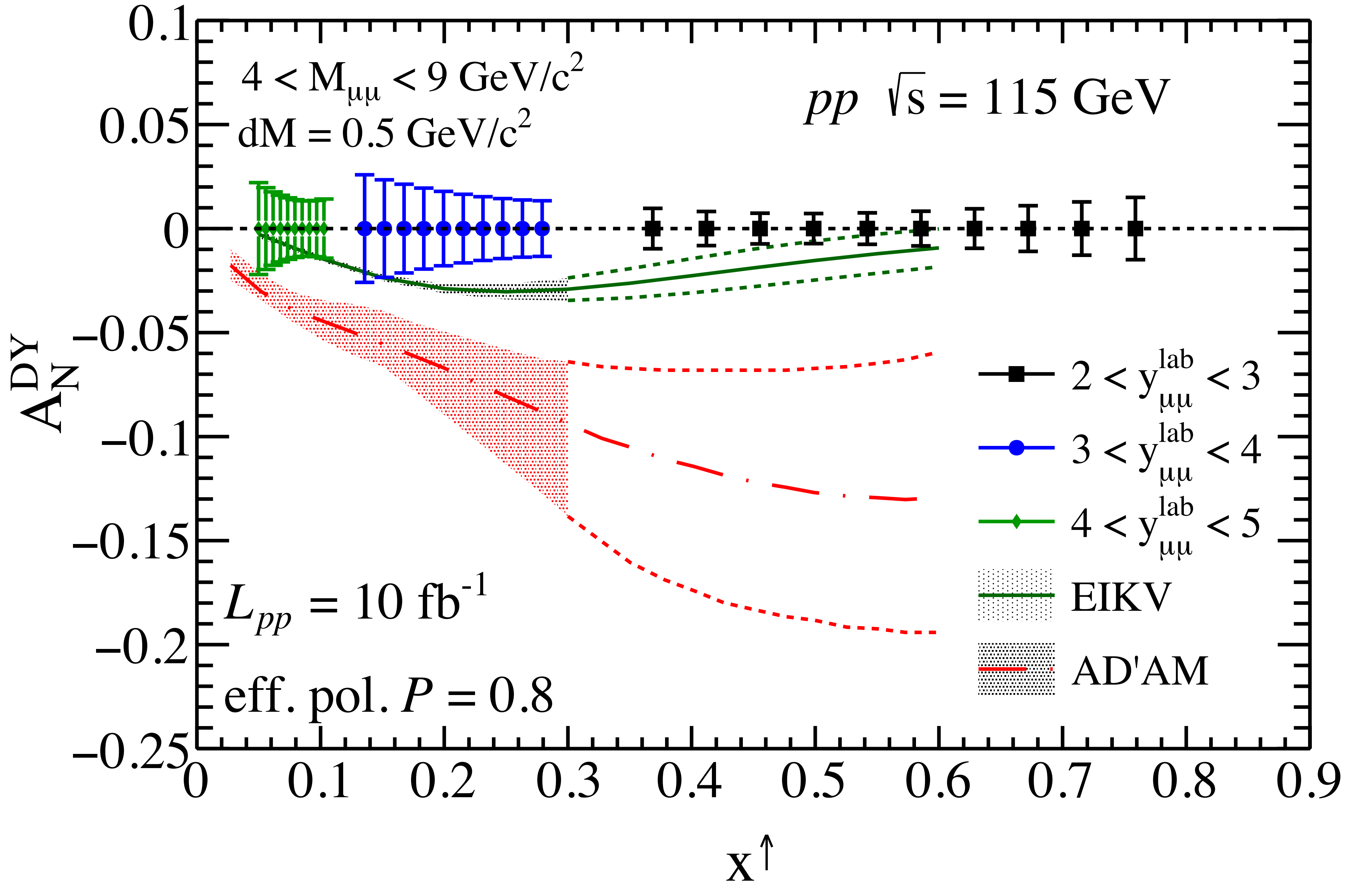
$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \longrightarrow A_N \sim \frac{f_1^q(x_1, k_{T1}^2) \otimes f_{1T}^{\perp\bar{q}}(x_2, k_{T2}^2)}{f_1^q(x_1, k_{T1}^2) \otimes f_1^q(x_2, k_{T2}^2)}$$

- Drell-Yan kinematics @ LHCspin (~30k events) and ~11 MeV mass resolution





- Projections of polarised DY with $10\ \mathrm{fb}^{-1}$ of data from [ArXiv:1807.00603] :



- Precise measurements but also unique features:
  - Verify the sign change of the Sivers TMD in DY wrt SIDIS:

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

  - + isospin effect with polarised deuterium

More TMDs

- 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

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

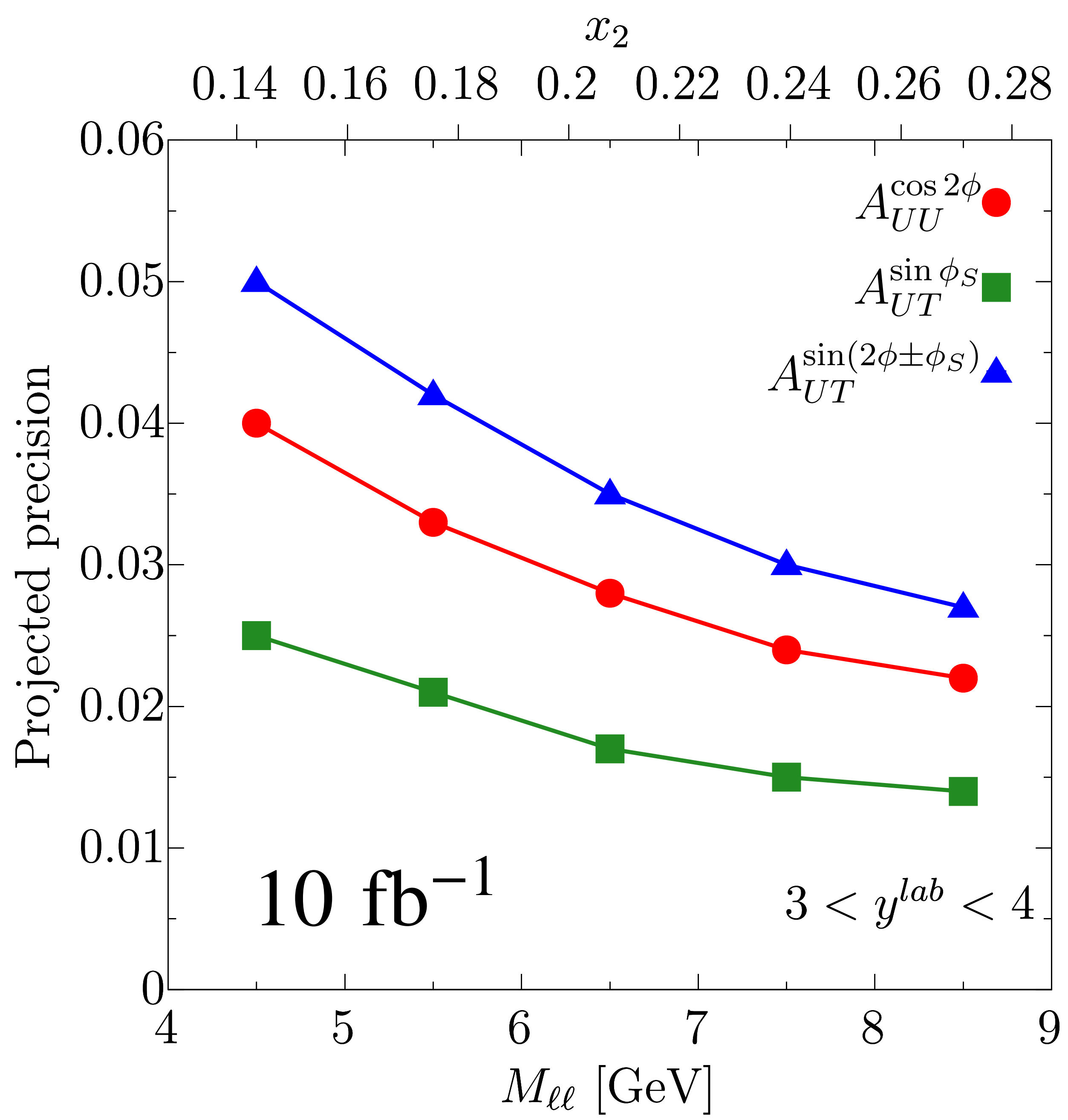
$$A_{UT}^{sin\phi_S} \sim \frac{f_1^q(x_1,k_{1T}^2)\otimes f_{1T}^{\perp\bar{q}}(x_2,k_{2T}^2)}{f_1^q(x_1,k_{1T}^2)\otimes f_1^{\bar{q}}(x_2,k_{2T}^2)}$$

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

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

- 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 Υ and di-J/ψ production

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



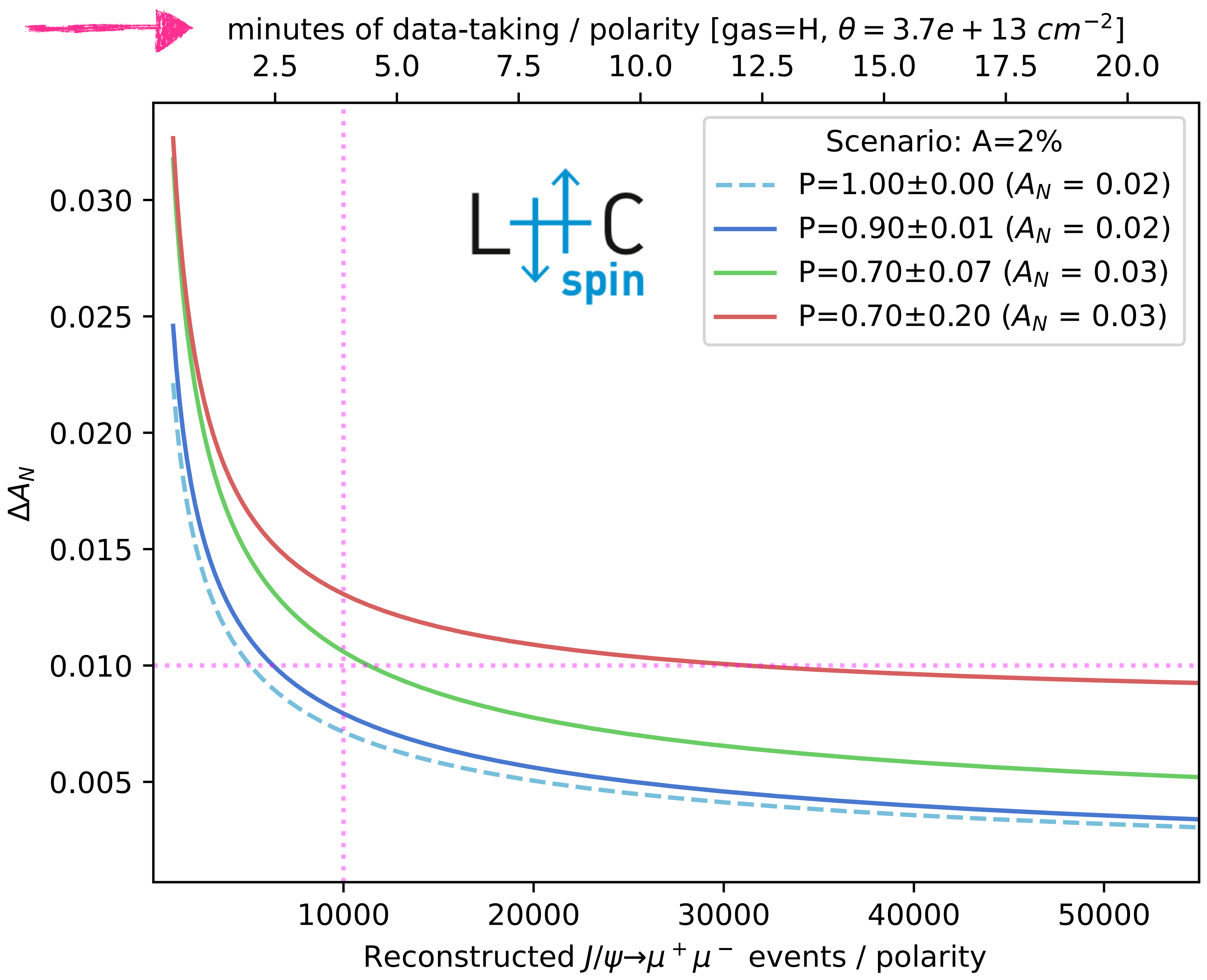
Expected precision on A_N

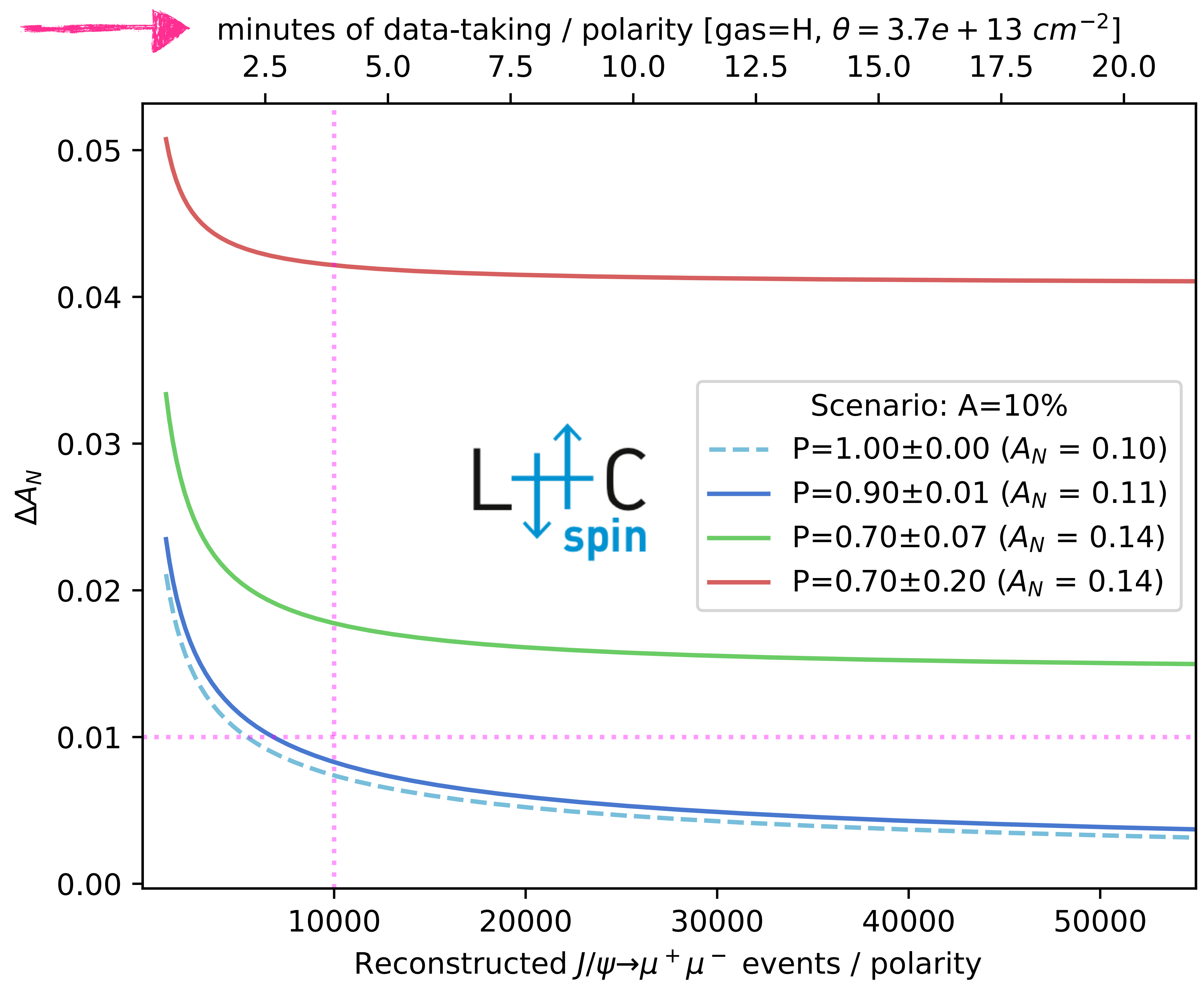
- Convert the expected rate into the uncertainty on a TSSA at LHCspin:

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

- 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!
  - Cell target example: $P = 0.70 \pm 0.07$, $\theta = 3.7 \times 10^{13}/\mathrm{cm}^2$ (used in the plots)
  - Jet target example: $P = 0.90 \pm 0.01$, $\theta \approx 10^{12}/\mathrm{cm}^2$

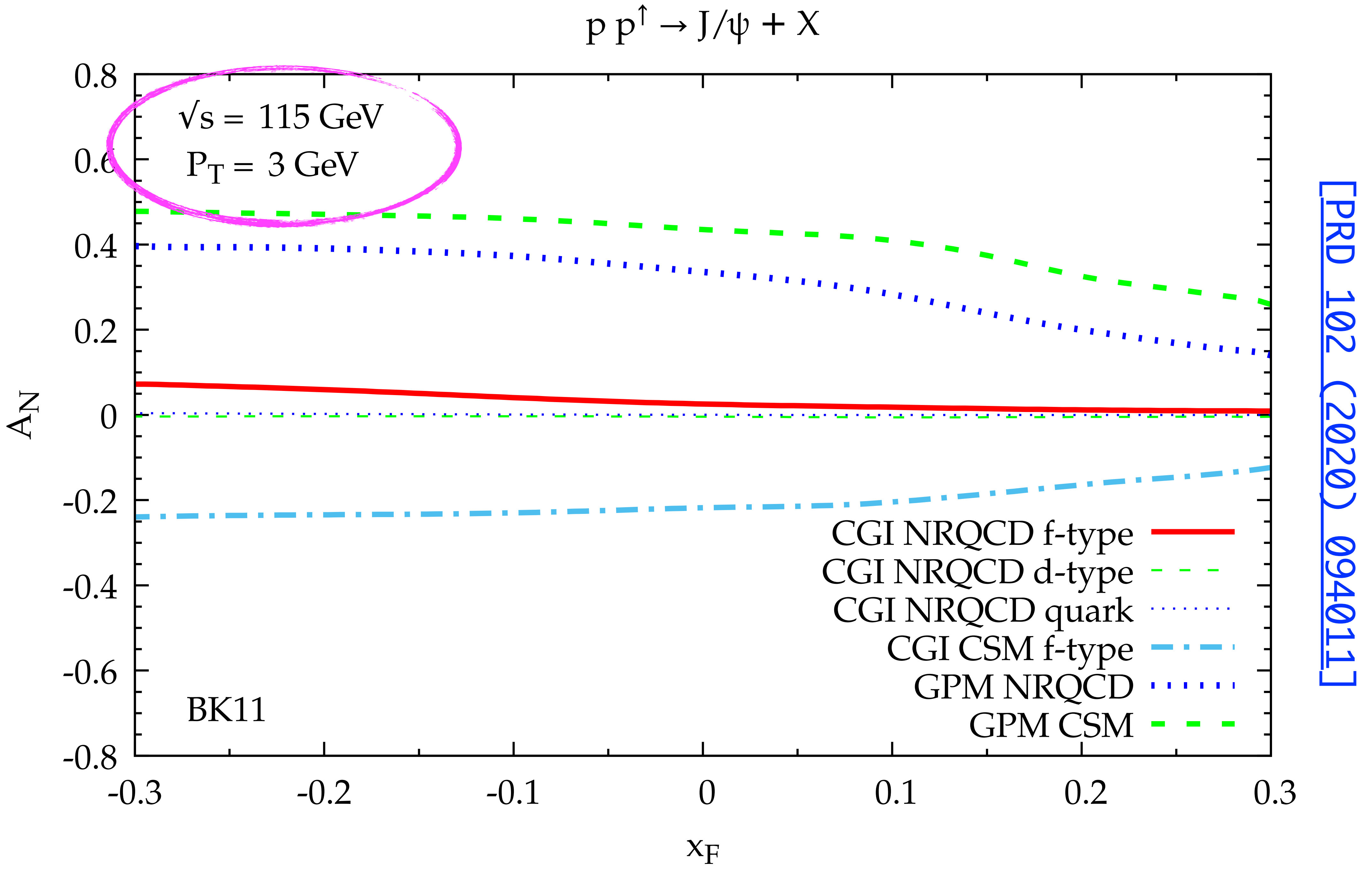




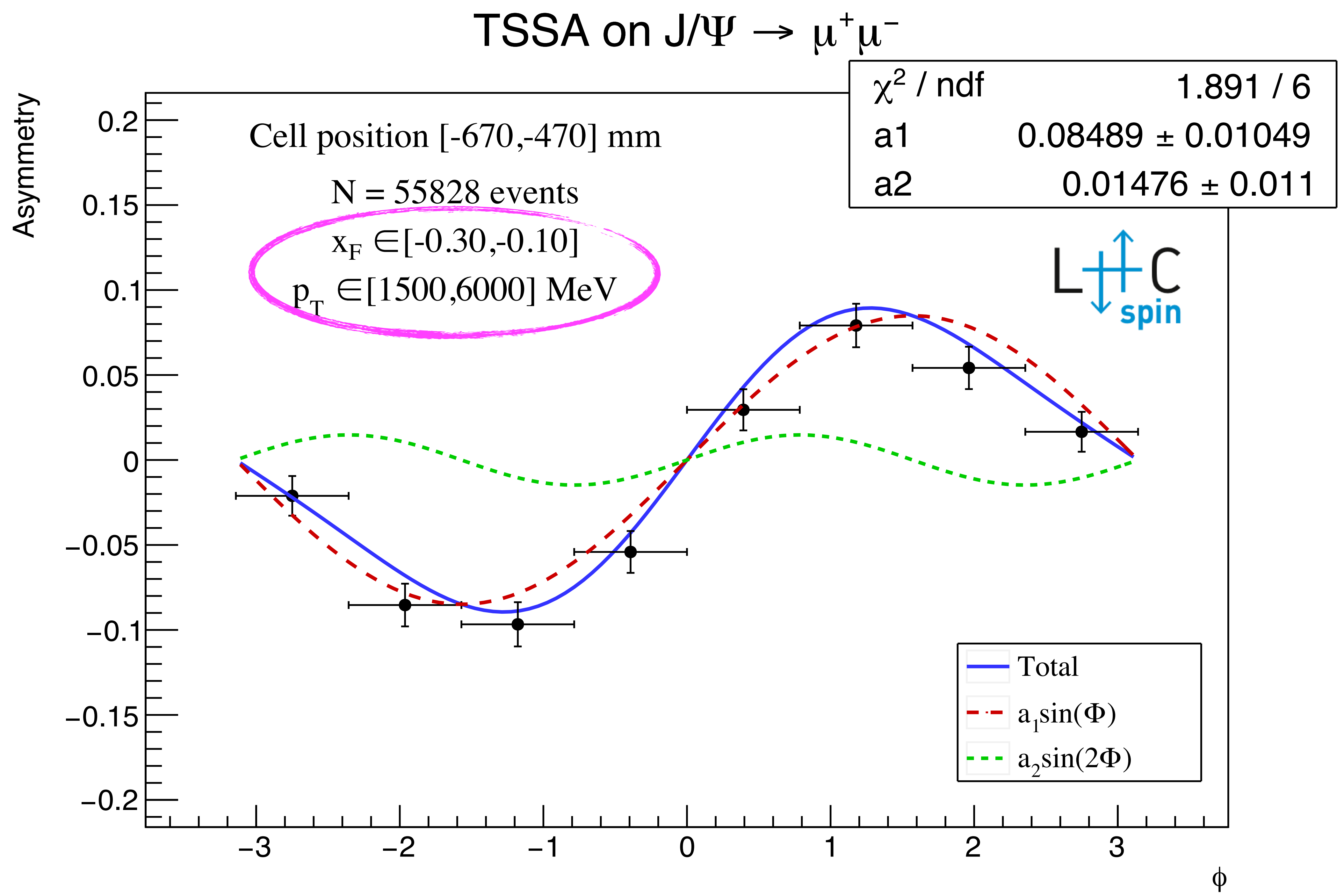
An example measurement: GSF

[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: $\eta_c, \chi_c, \chi_b, J/\psi J/\psi$ with excellent mass resolution (see → backup)
- A_N predictions on $J/\Psi \to \mu^+\mu^-$ with LHCspin kinematics:



- This can easily be measured with LHCspin!
- Use LHCb simulations & 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

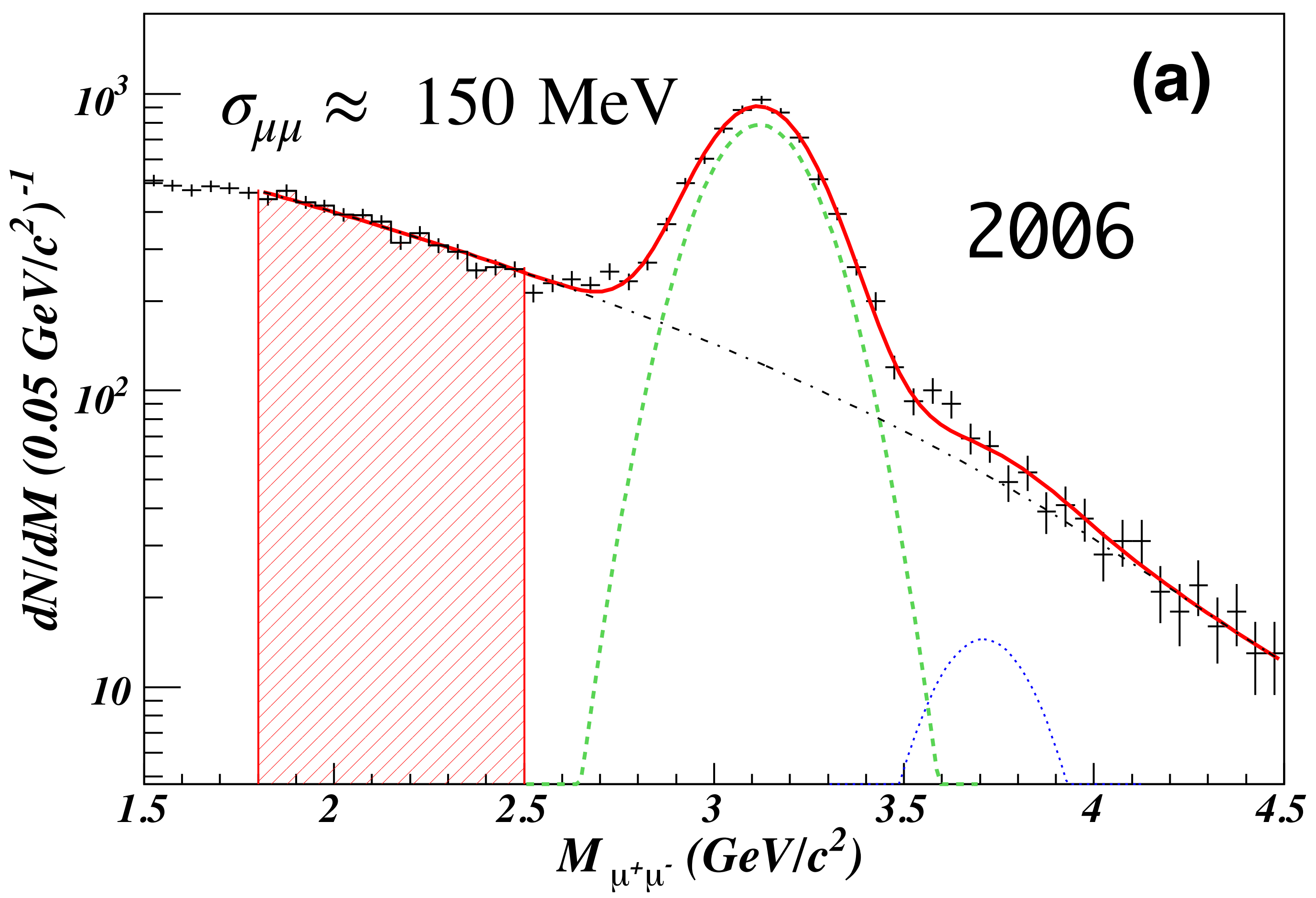
- The FT program at LHCb is active since Run 2, now greatly enriched with the SMOG2 cell for Run 3
- SMOG2 early results demonstrate simultaneous beam-gas and beam-beam data-taking with excellent performance
- LHCspin is part of the LHCb “Upgrade 2” and represents the natural evolution of SMOG2 to bring 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 (only a few examples shown, see more in the backup and in → this talk)
- High degree of complementarity with existing facilities & EIC
- A simple setup at IR4 will serve as a starting point for the R&D and possibly to make interesting measurements. Get in touch if you’re interested!

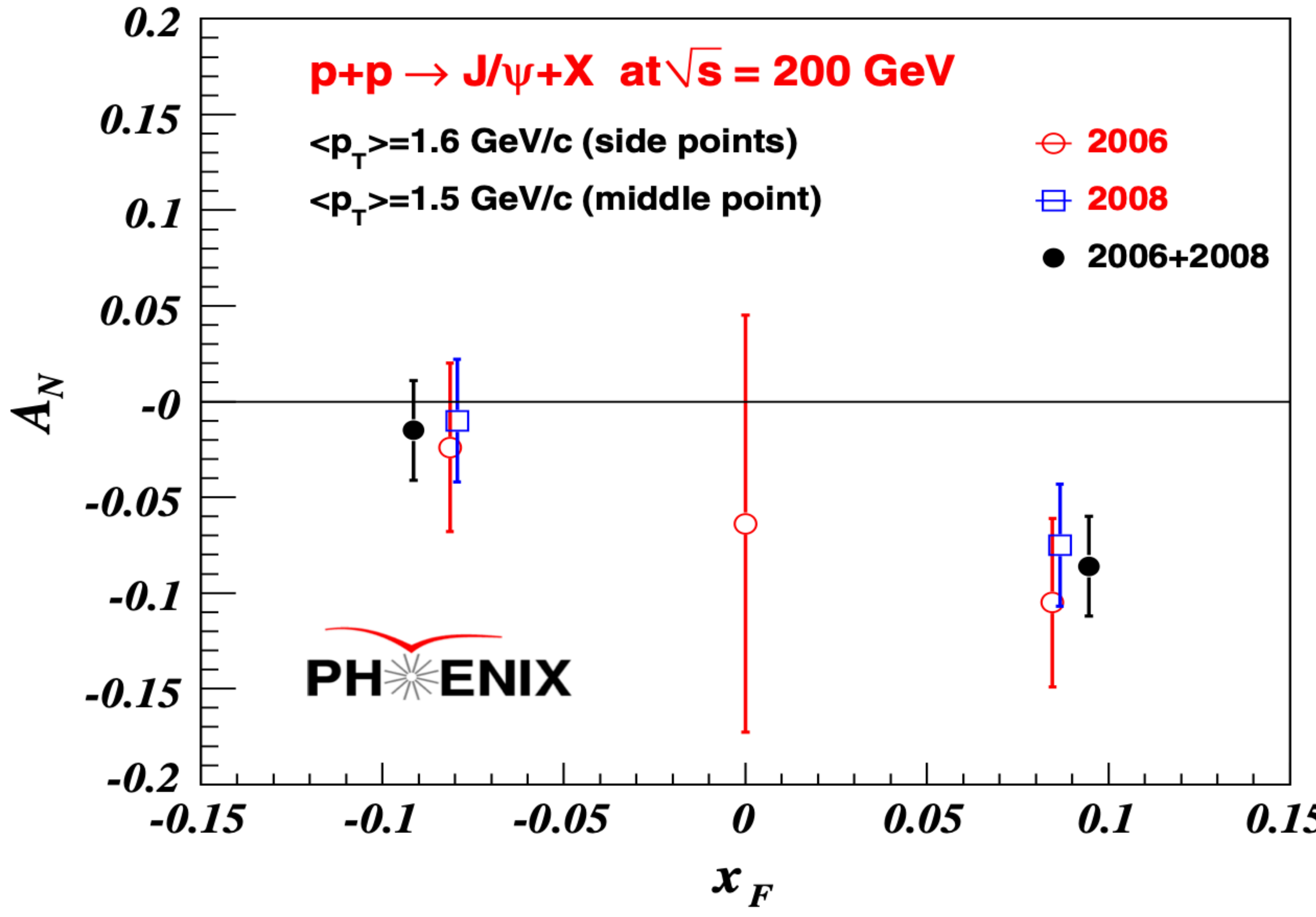
Comparing $J/\psi \to \mu^+\mu^-$ with PHENIX and COMPASS

- 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 $\sigma_{\mu\mu} \approx$ 13 MeV at the J/ψ mass and $\sigma_{\mu\mu} \approx$ 42 MeV at the Υ mass
  - Can also measure excited states & heavier mesons

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

PHENIX: 2006 and 2008 data

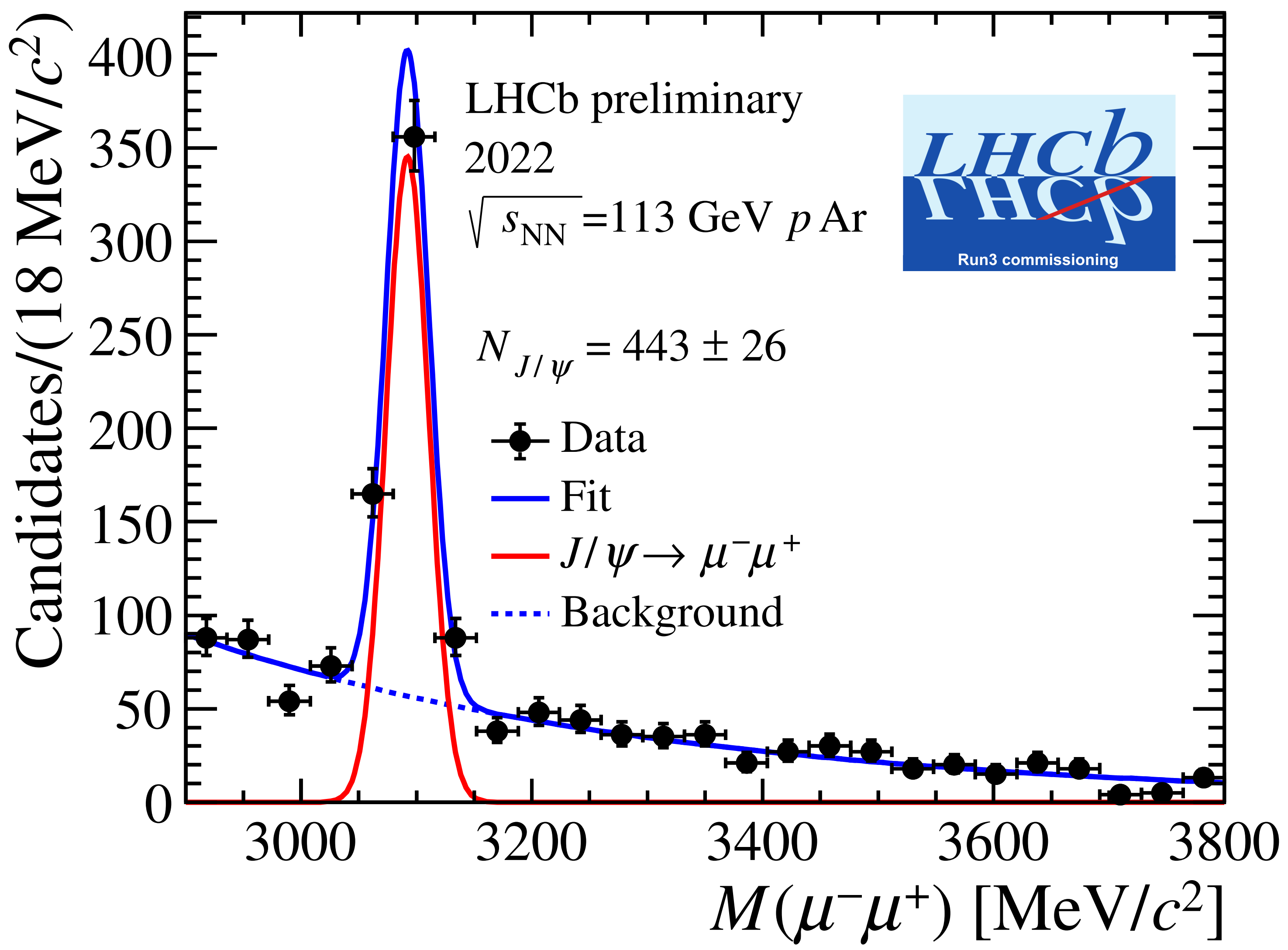




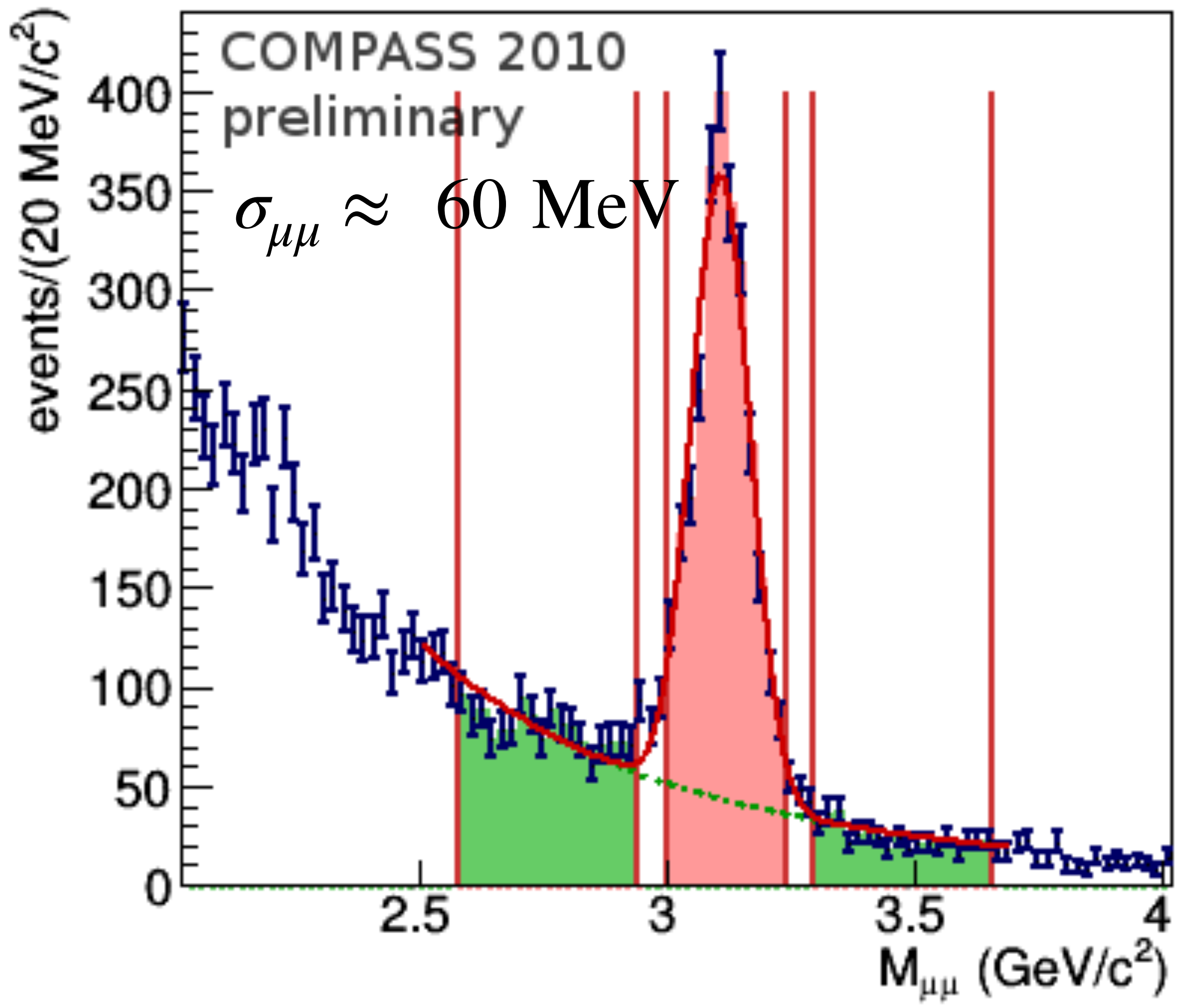
[arXiv:1009.4864]

SMOG2: 18 minutes test

[LHCB-FIGURE-2023-008]



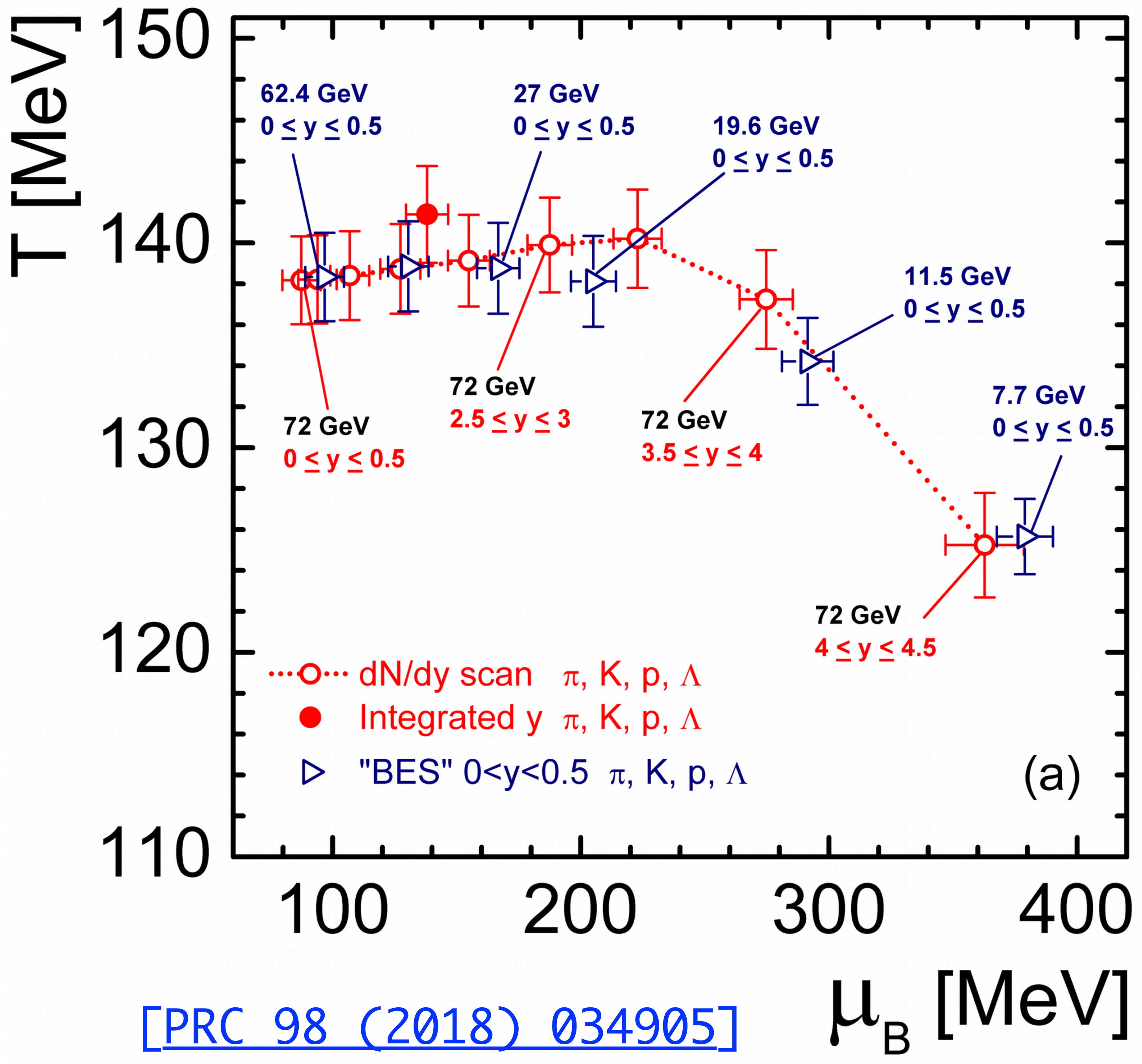
COMPASS: 2010 data



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

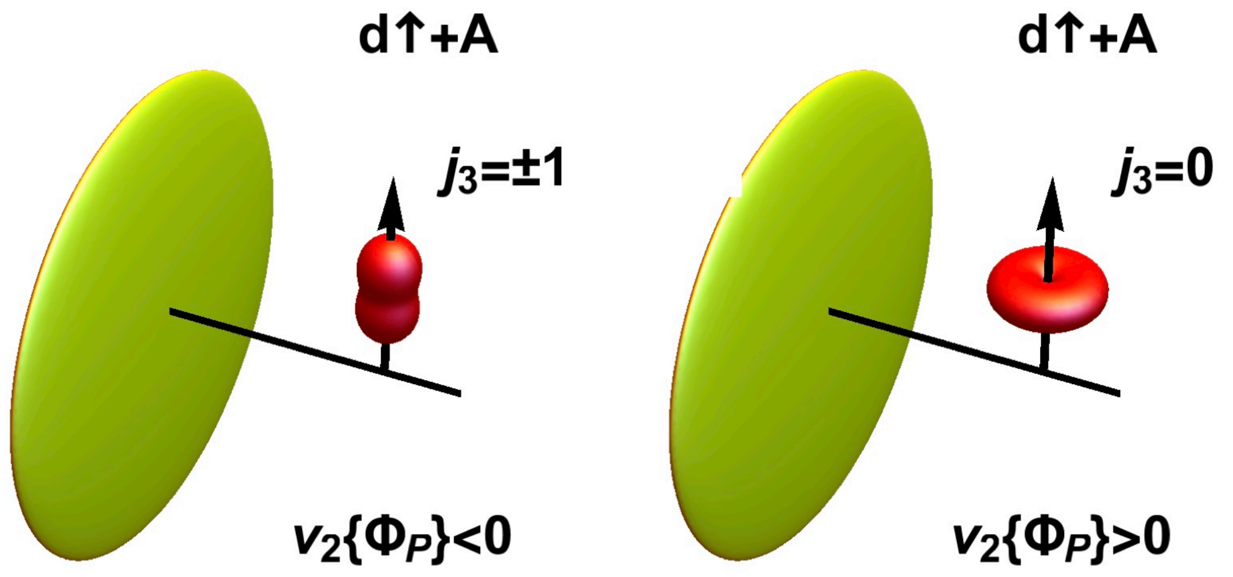
Heavy ion fixed-target collisions

- 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

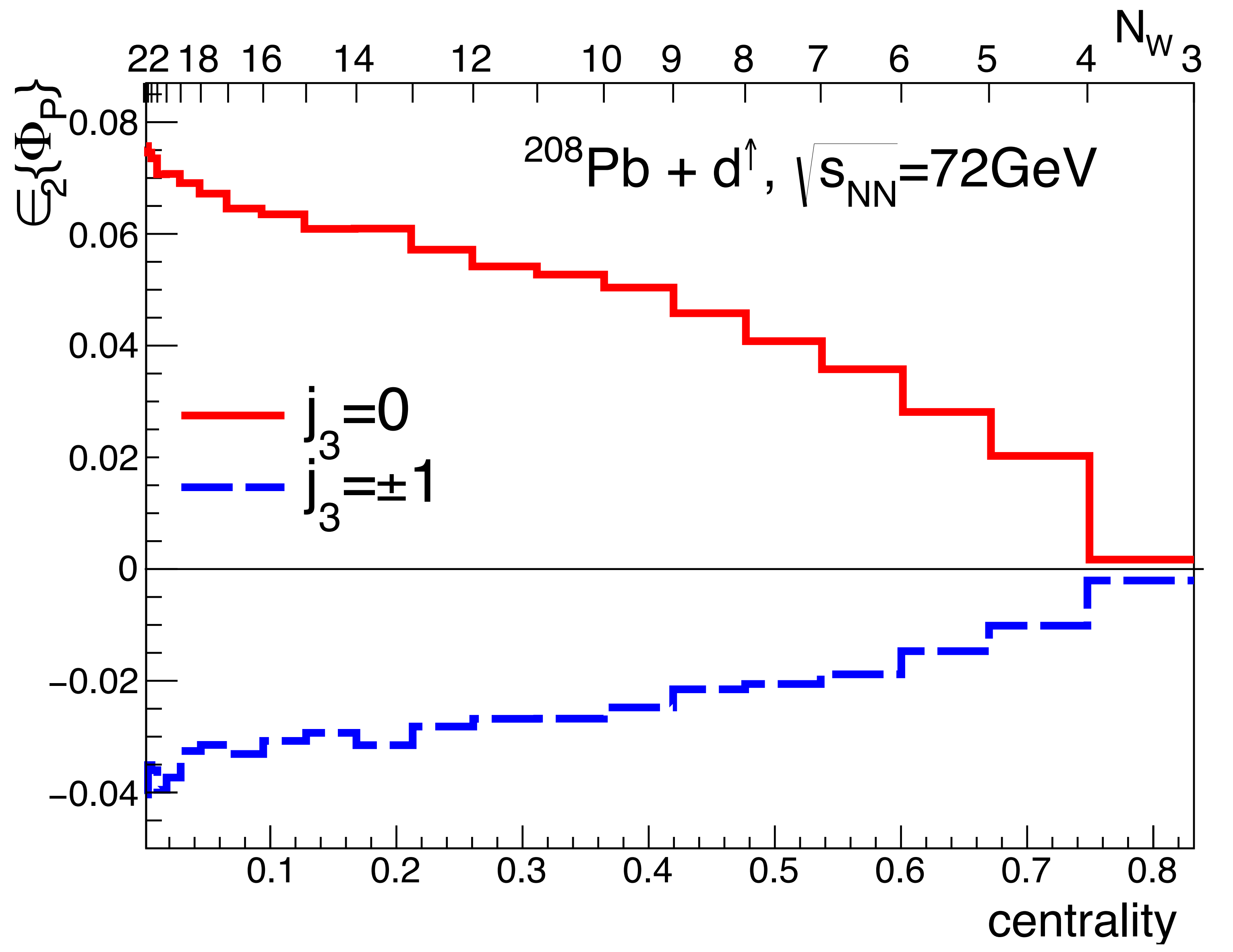


[PRC 98 (2018) 034905]

- 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



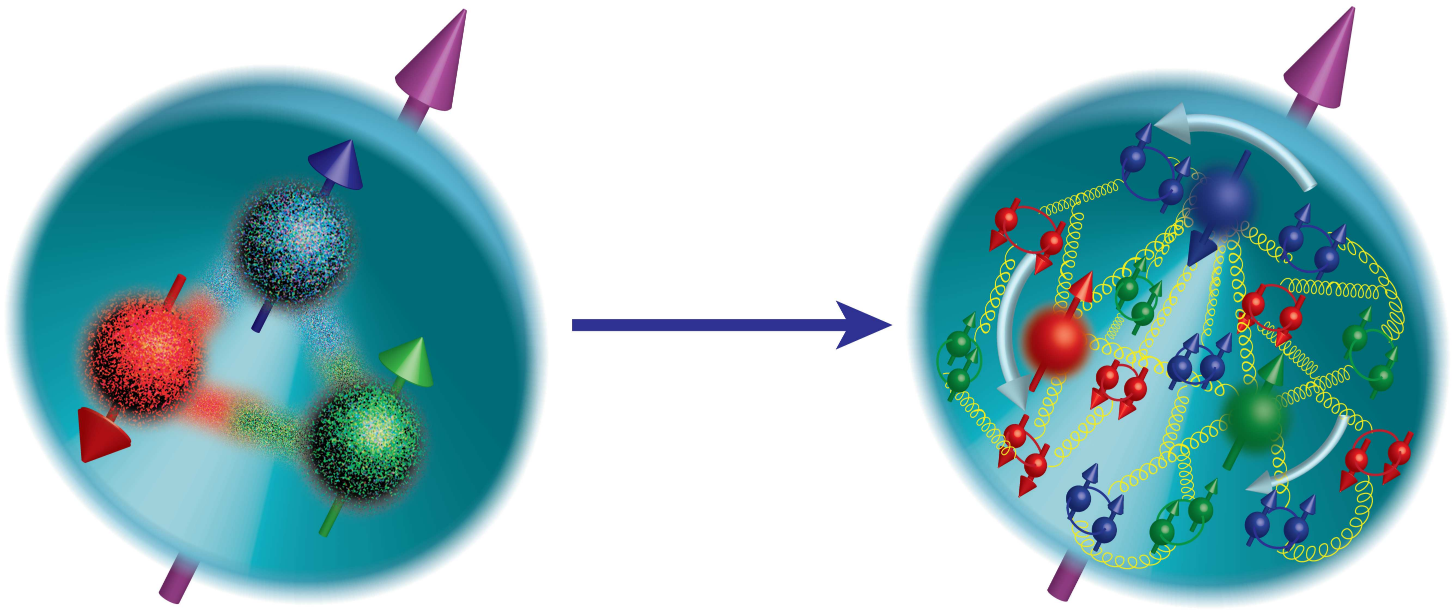
D polarised along Φ_p , perpendicular to the beam



[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:

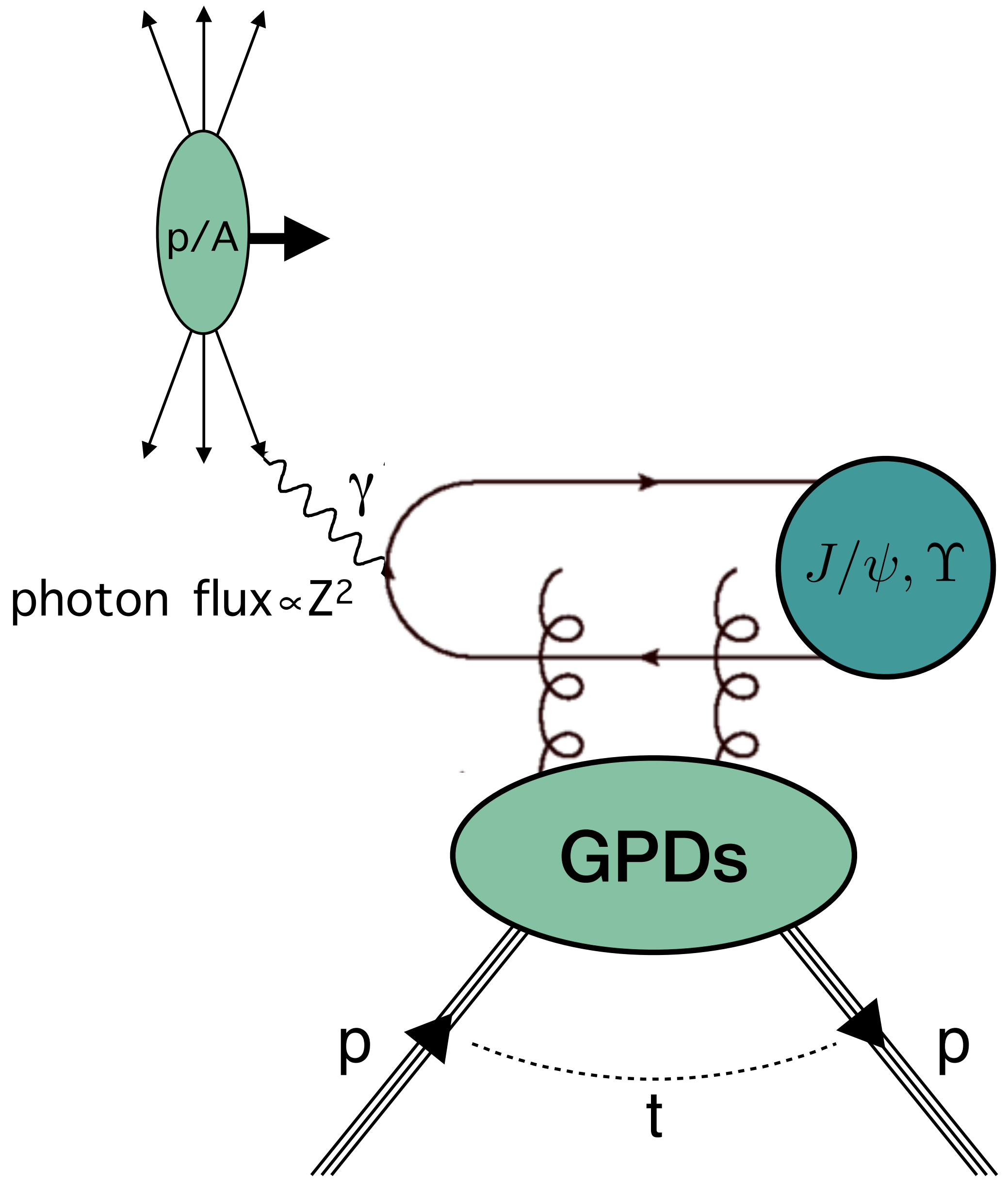
$$\frac{1}{2} = J^q(\mu) + J^g(\mu) = \frac{1}{2}\Delta\Sigma(\mu) + L_z^q(\mu) + J^g(\mu)$$

[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]

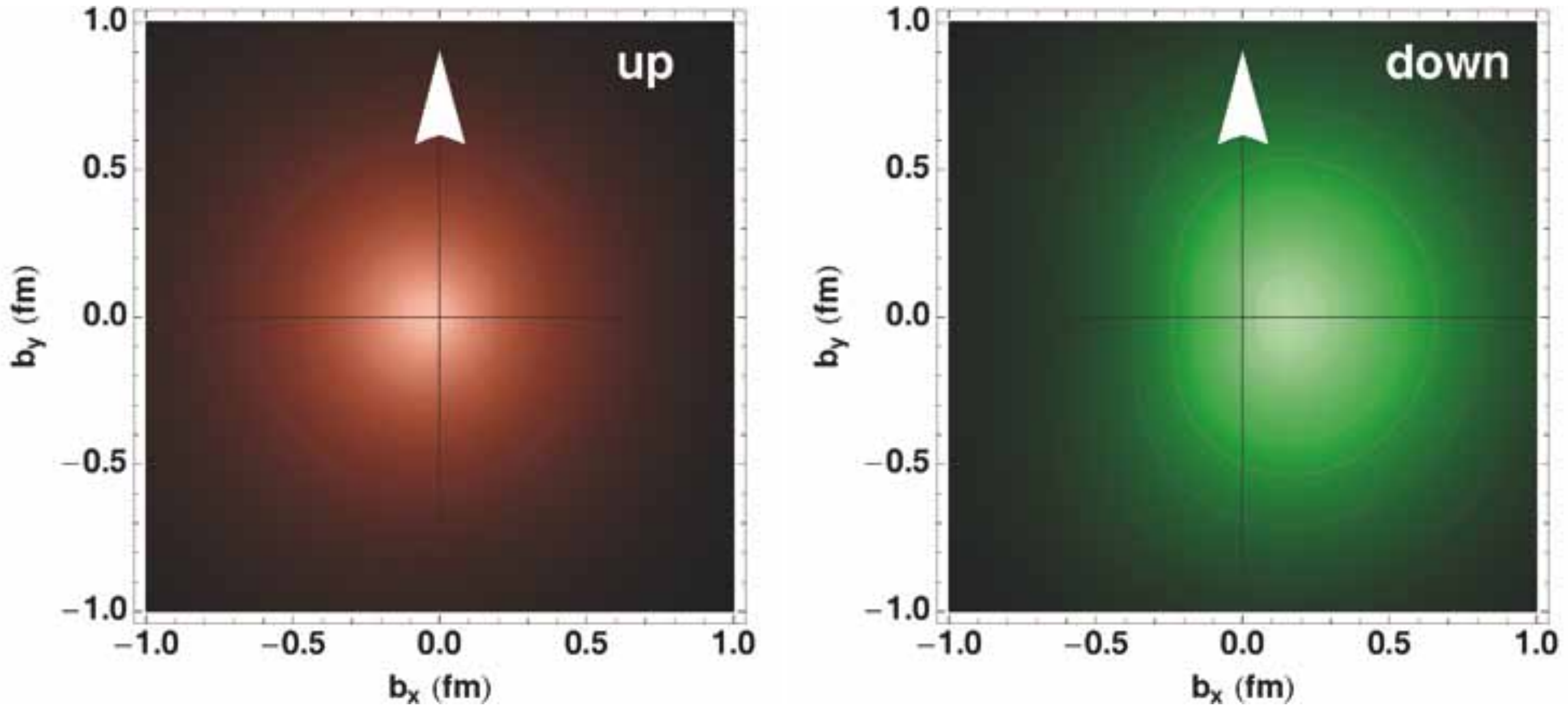


- UPCs already studied at LHC in collider mode
- LHCspin to access the unknown E_g via TSSAs: a key element of the sum rule

[ArXiv:1709.09044]

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

[PRL 99 (2017) 112001]



[NS 28 (2012) 1-2]