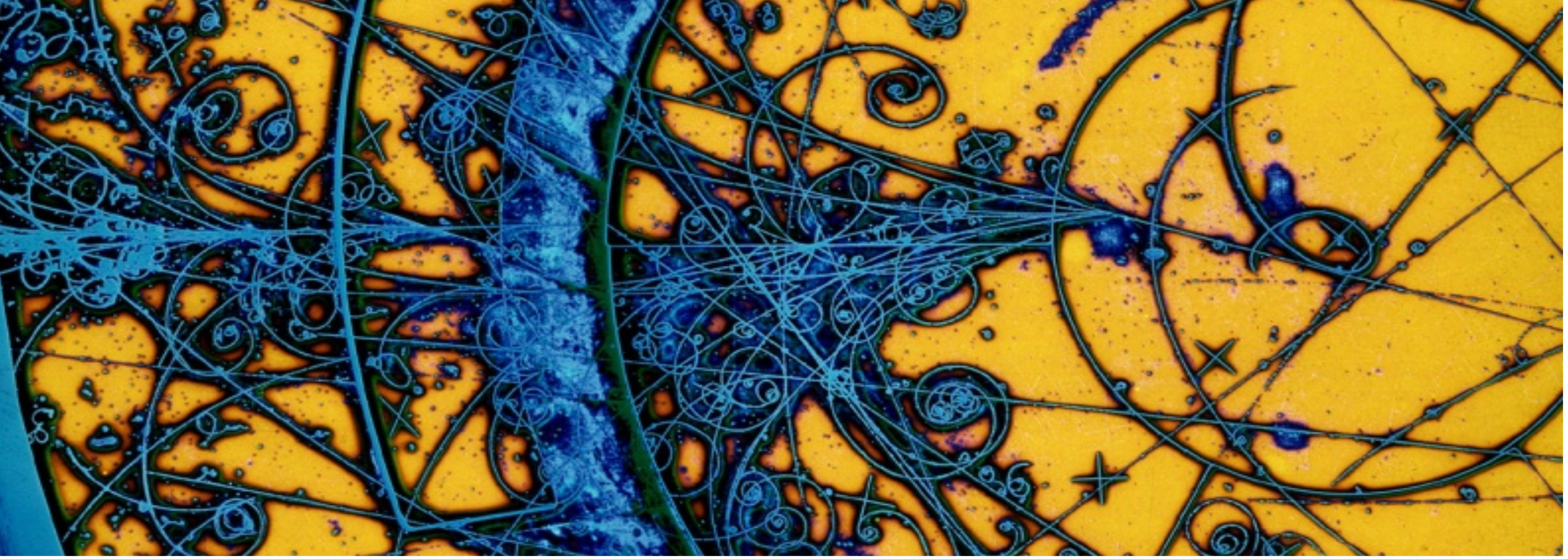

The LHCspin project

Marco Santimaria (INFN-LNF)
in collaboration with V.Carassiti, G.Ciullo, P. Di Nezza, P.Lenisa, S.Mariani, L.Pappalardo, E.Steffens

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2021 Sardinian Workshop on Spin
Cagliari, 07/09/2021

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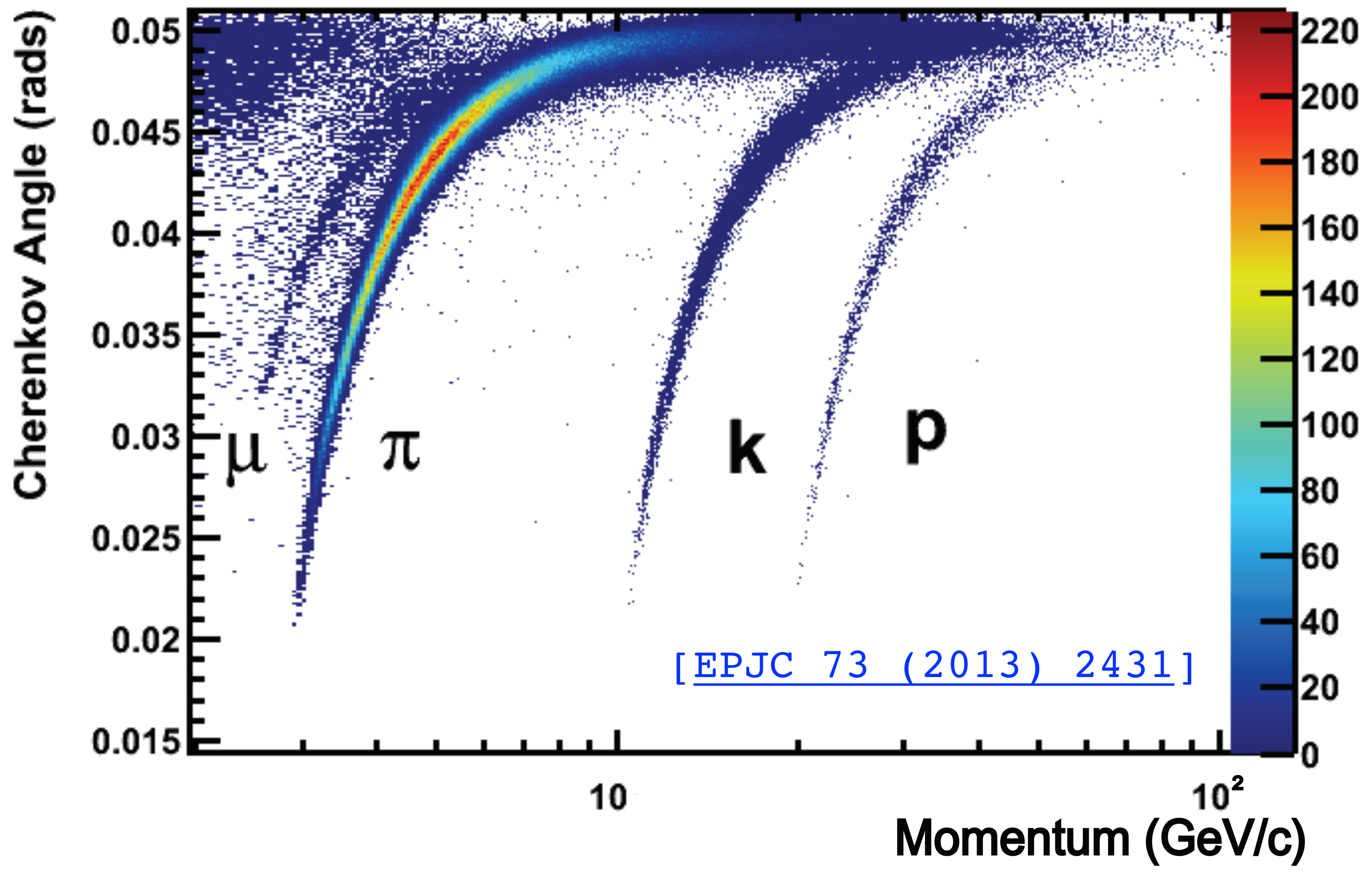
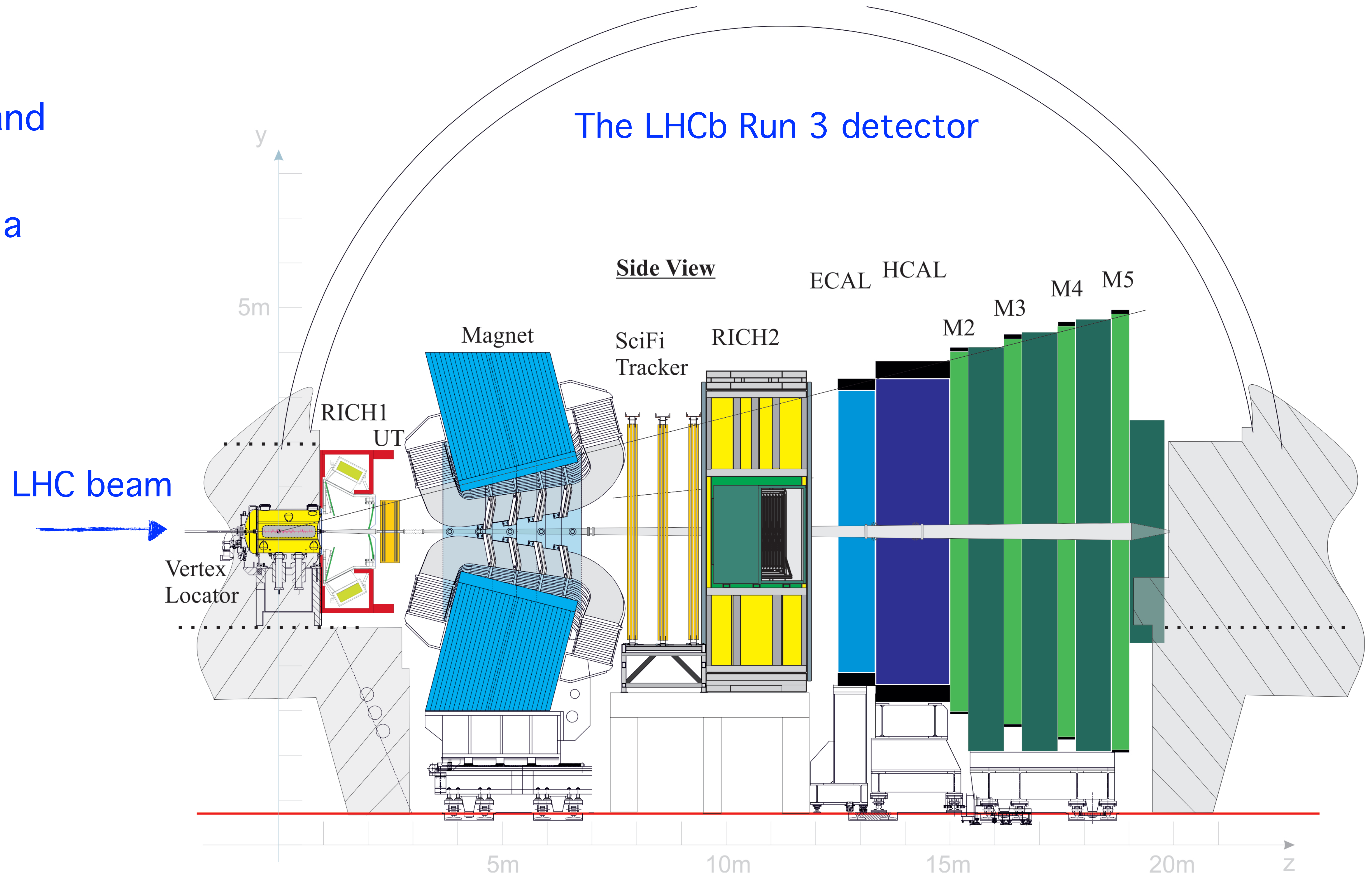
The LHCb detector

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

- LHCb is a general-purpose forward spectrometer, fully instrumented in $2 < \eta < 5$ and optimised for c and b hadron detection
- Particle identification with RICH+CALO+MUON with a unique forward coverage at LHC
- Excellent momentum resolution:

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

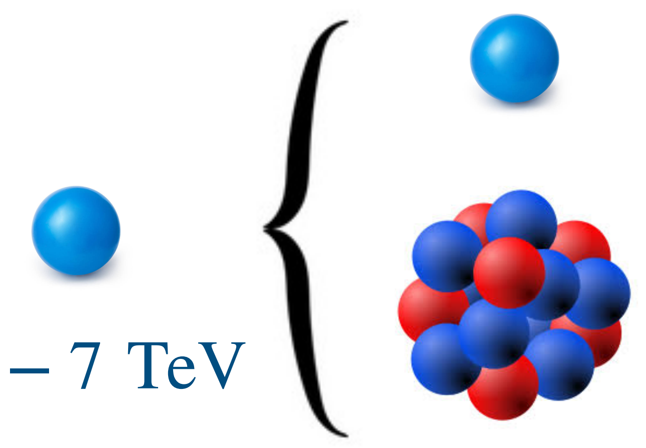




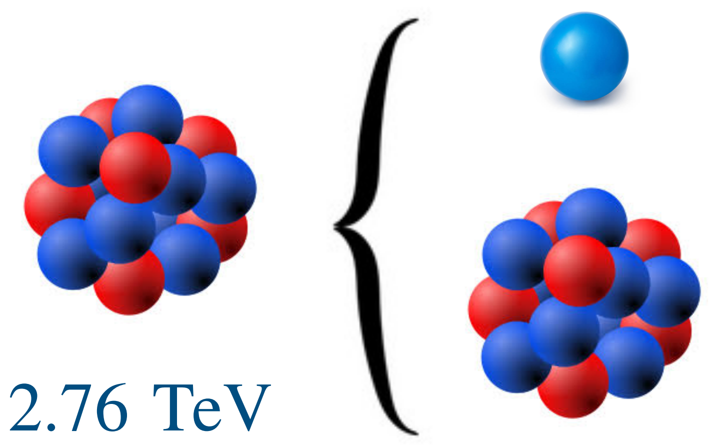
- Major hardware upgrade for the Run 3
- Fully software trigger running at 40 MHz on commercial GPUs

Fixed-target physics at LHCb: SMOG

FT kinematics at LHC:



0.9 – 7 TeV



2.76 TeV

pp/pA collisions, 7 TeV beam:

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

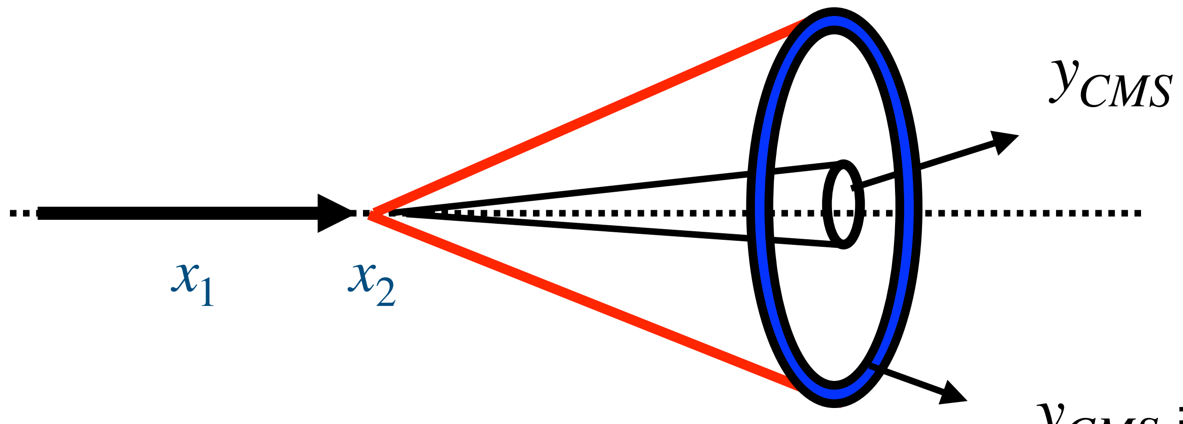
$-3.0 \leq y_{CMS} \leq 0 \;\rightarrow\; 2 \leq y_{lab} \leq 5$

AA collisions, 2.76 TeV beam:

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

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

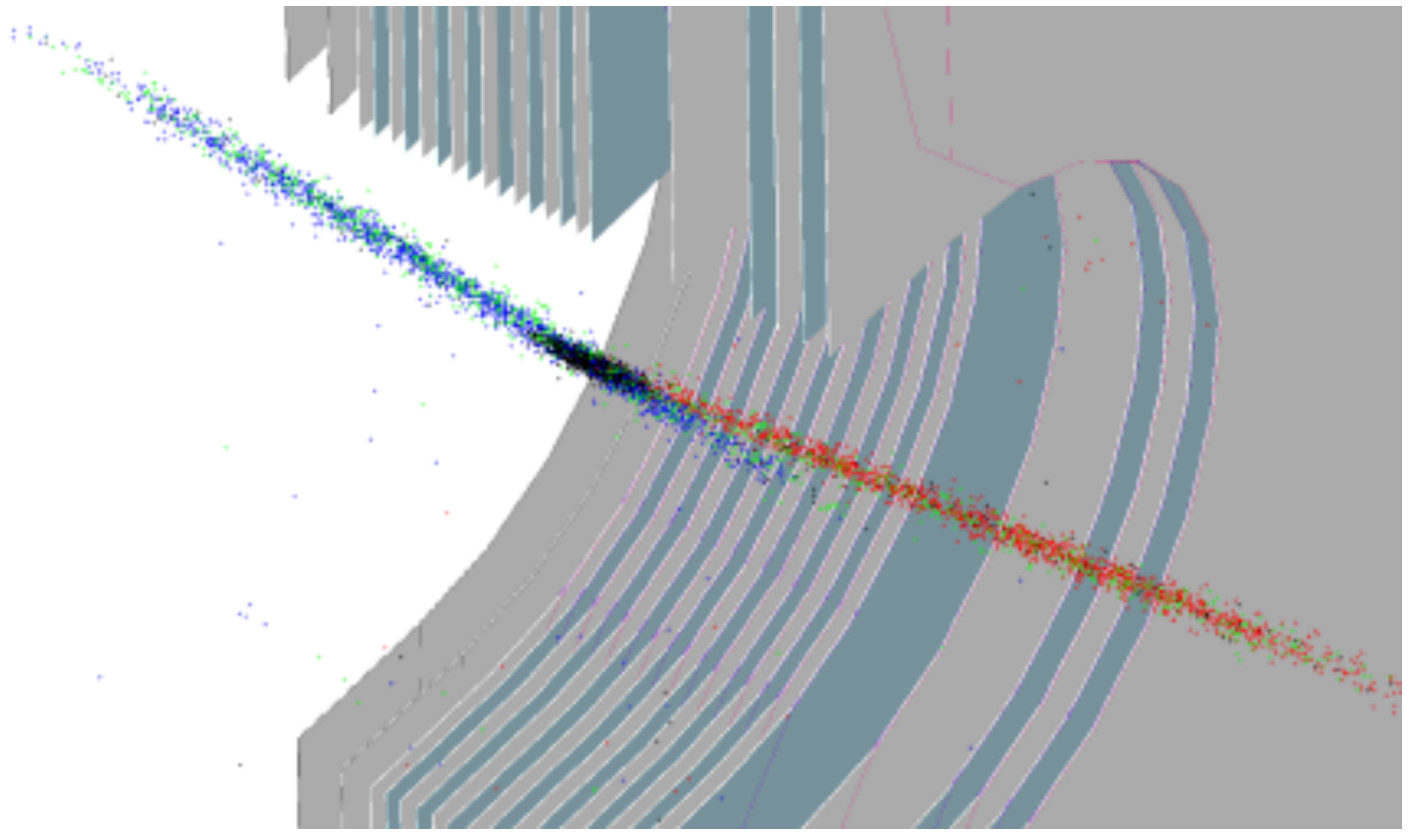
Large CM boost : access to large x_2 values ($x_F < 0$)



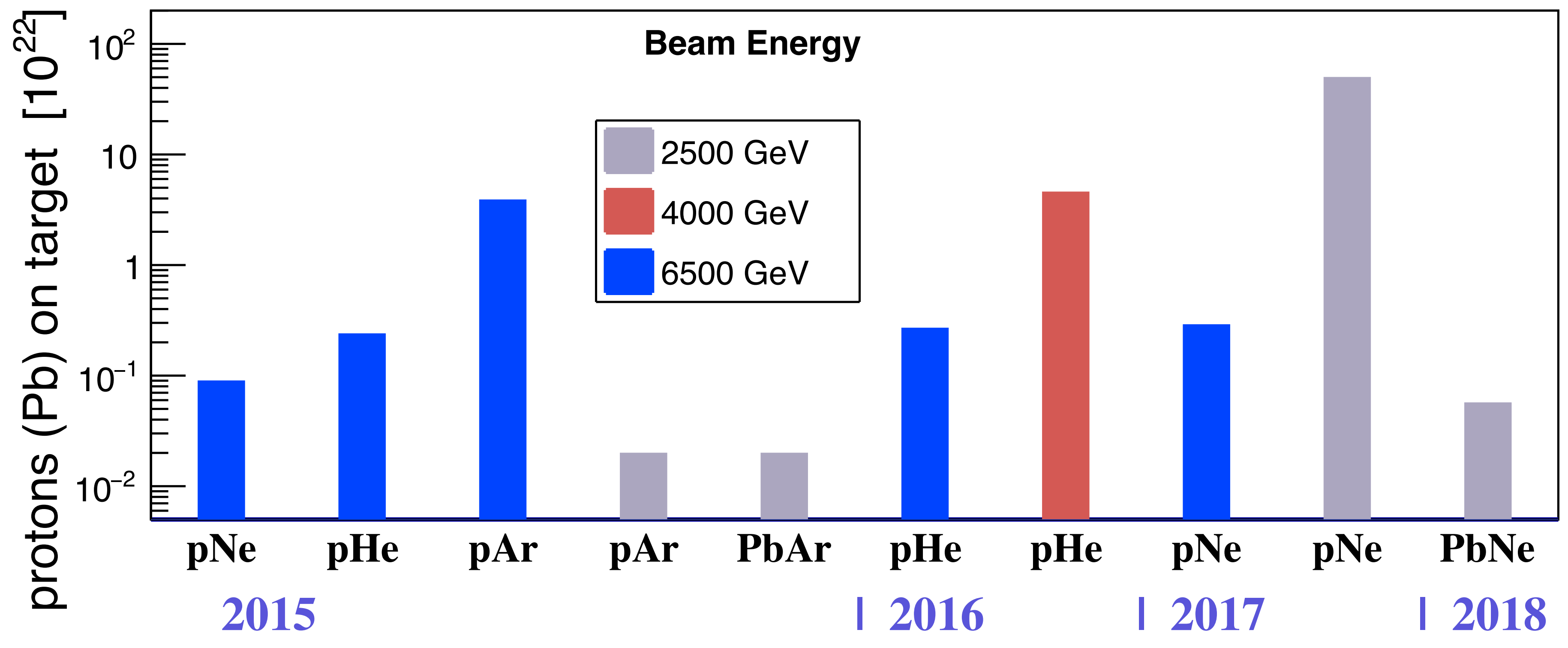
$\gamma = \frac{\sqrt{s}}{2m_p} \sim 60$

[JINST 9 (2014) P12005]

- The LHCb fixed-target physics program started with SMOG (System for Measuring the Overlap with Gas) in 2015
- Inject nobles gases into the VELO (± 20 m in the beam pipe)
- Trigger on beam-empty collisions: turns LHCb into an FT experiment!

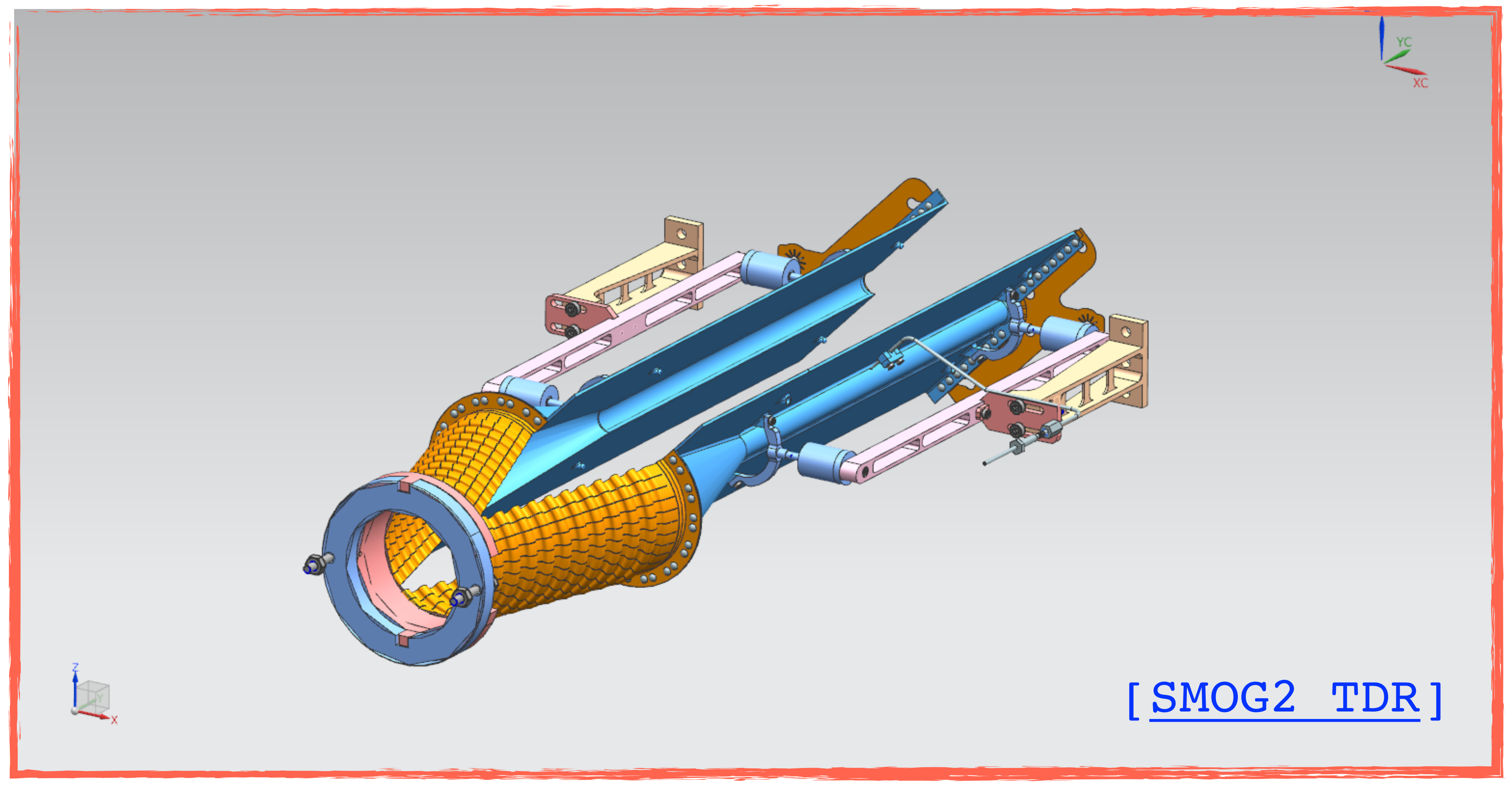


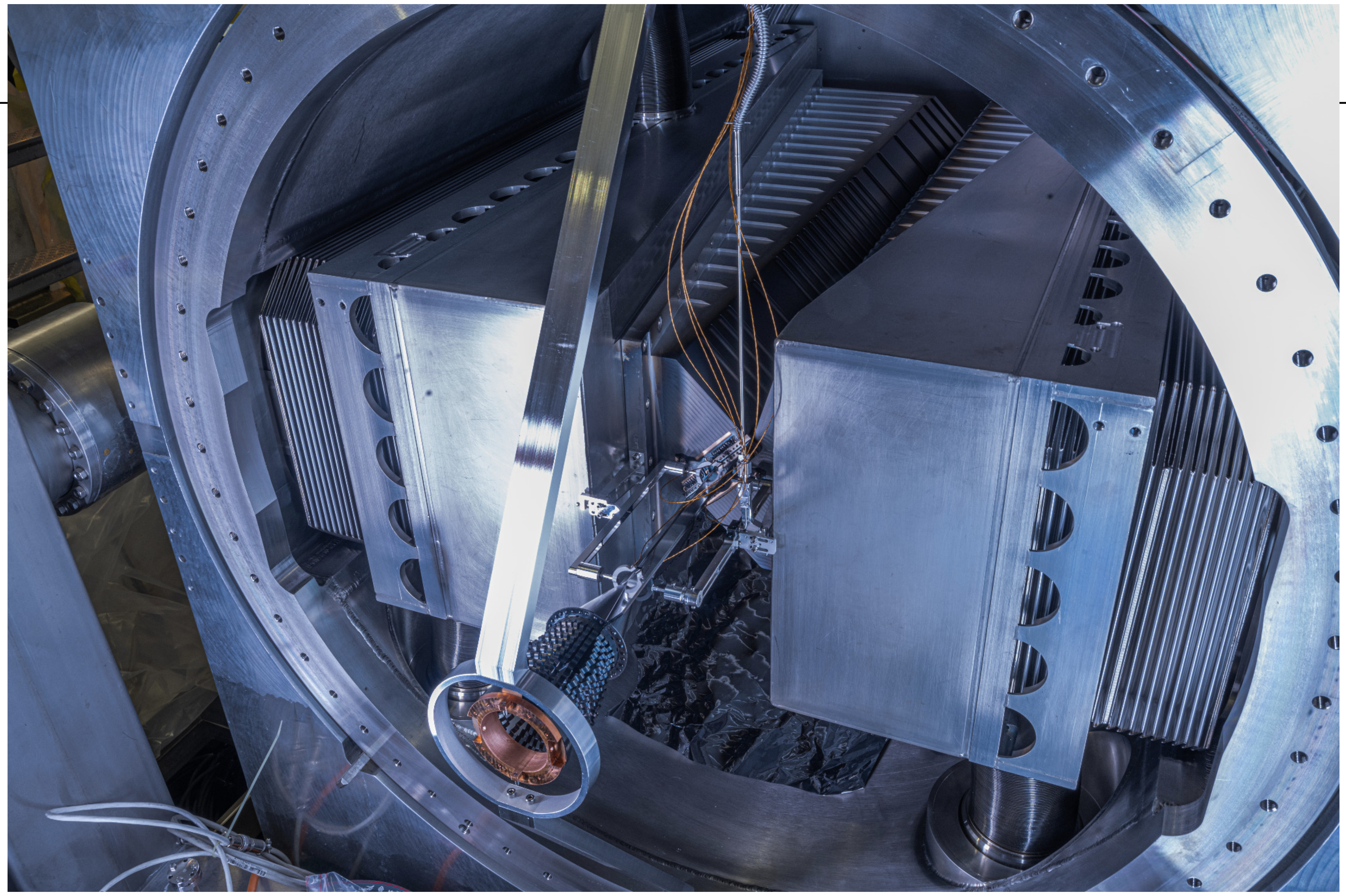
- SMOG data samples:



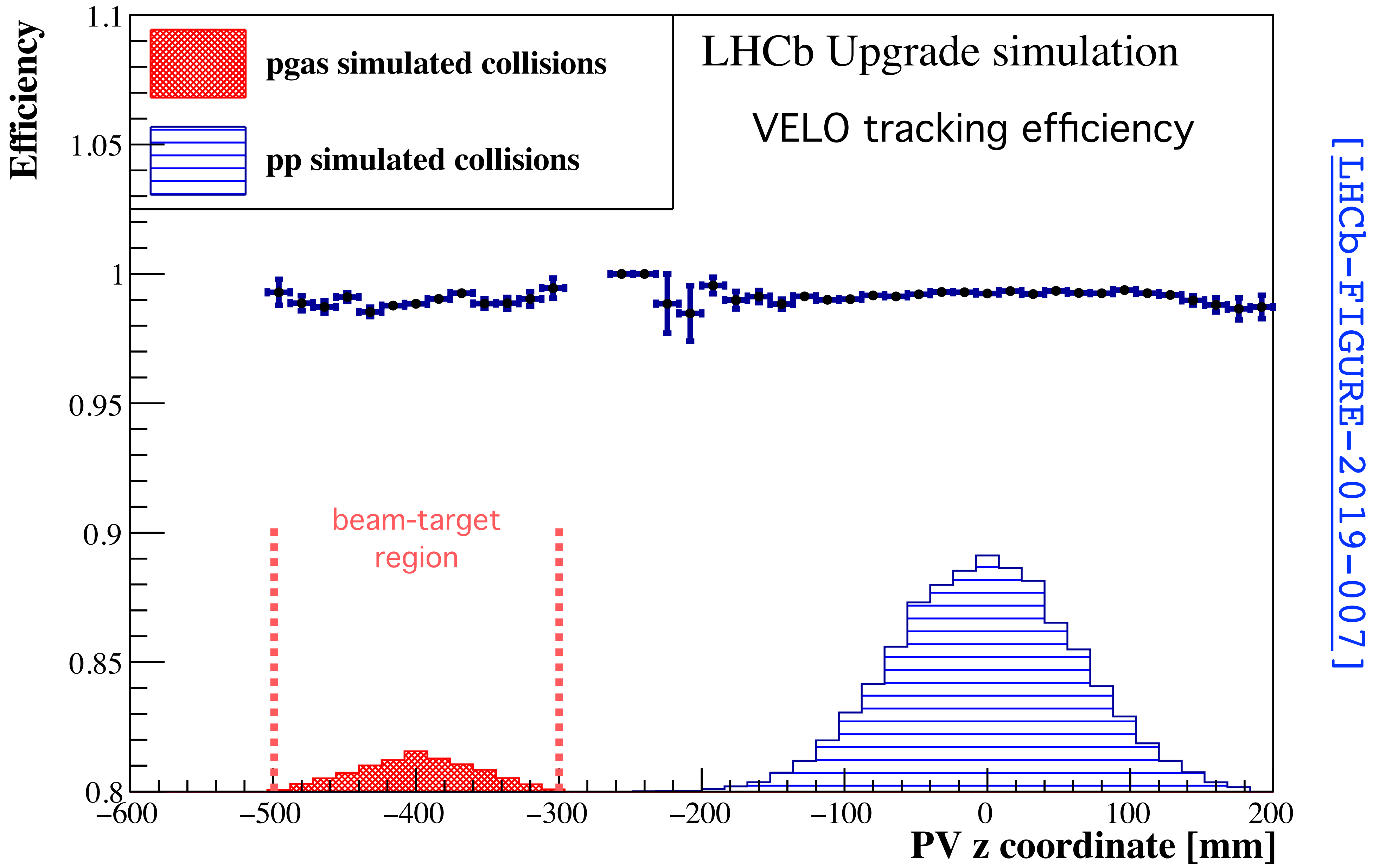
The SMOG2 gas storage cell

- A target gas cell has been installed in 2020 next to the VELO for the Run 3





- Can be filled with unpolarised $H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe$
- Boosts the density by $8 - 35$ X wrt SMOG
- Negligible impact on the beam lifetime ($\tau^{H_2}_{beam-gas} \sim 2000$ days)
- A trigger for simultaneous p-p ($\sqrt{s} = 14$ TeV) and p-gas ($\sqrt{s} = 115$ GeV) data-taking is already in place for SMOG2
- $1 - 3\,\%$ throughput decrease when adding p-gas to the LHCb event reconstruction sequence
- LHCb will be the only experiment able to run in collider- and fixed-target mode simultaneously!

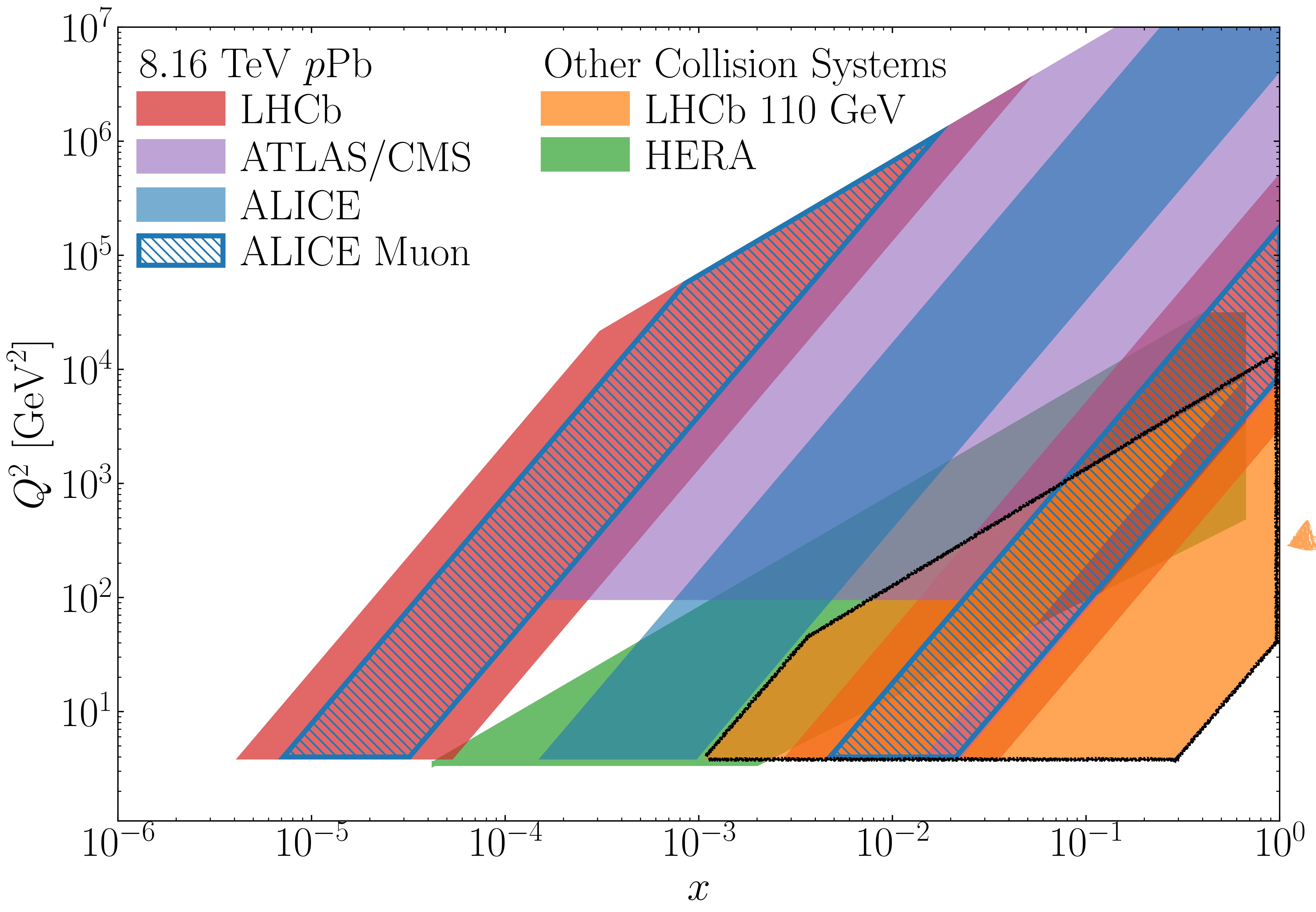


The LHCspin project

- The SMOG program sets the basis for the development of a polarised gas target (PGT), that we aim to install during LS3

Two main goals of the LHCspin project:

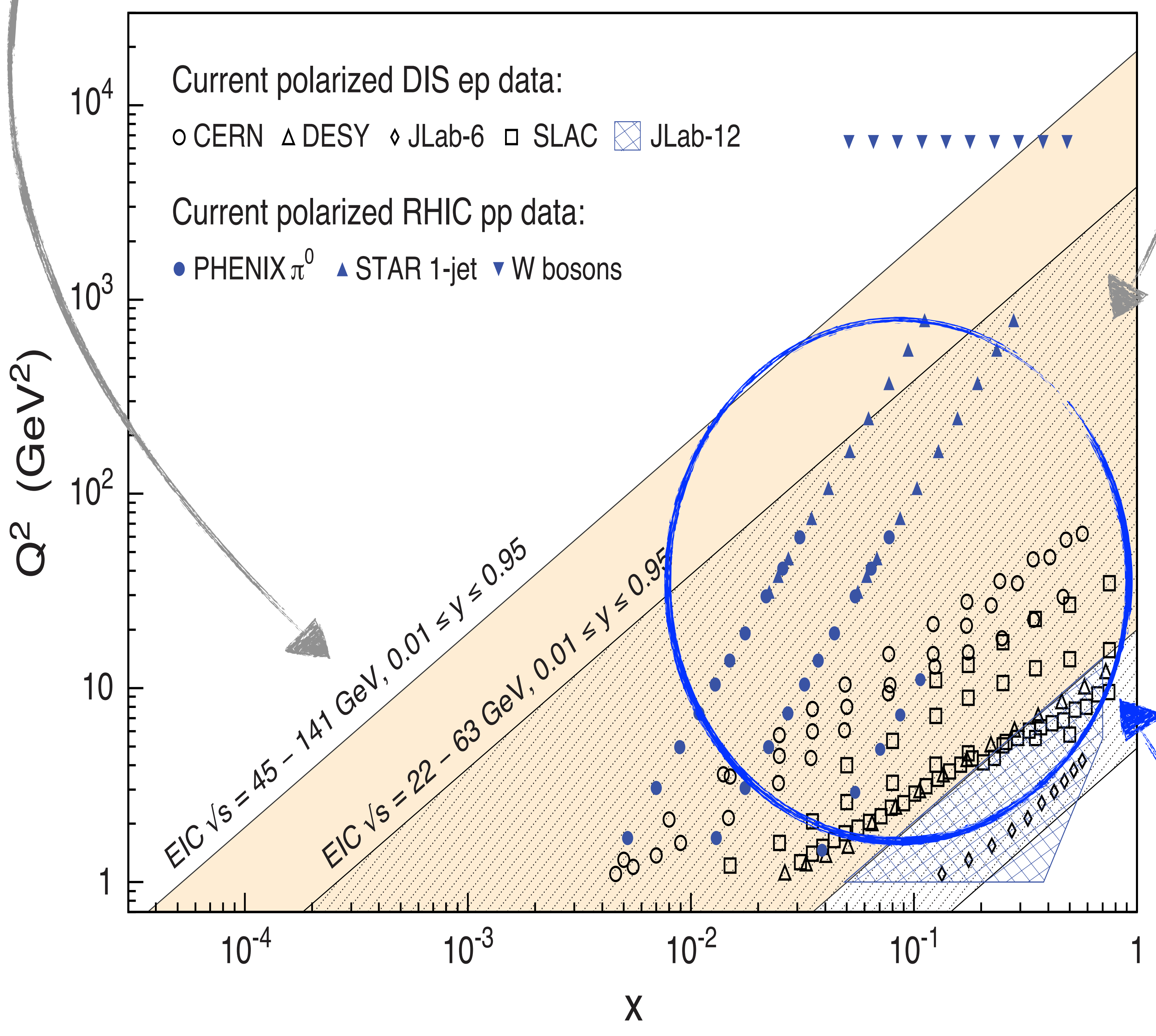
1. Extend the broad physics program with unpolarised gases to Run 4 (2028) and to the HL-LHC phase (2032)
2. Bring spin physics at the LHC for the first time



- Unique observables:
  - 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
- Unique features:
  - Broad and poorly explored kinematic range
  - High luminosity, high resolution detectors
  - Exploit both proton and heavy ions beams
  - Large variety of unpolarised gas targets
  - Polarised gas targets: $H^{\uparrow}, D^{\uparrow}$

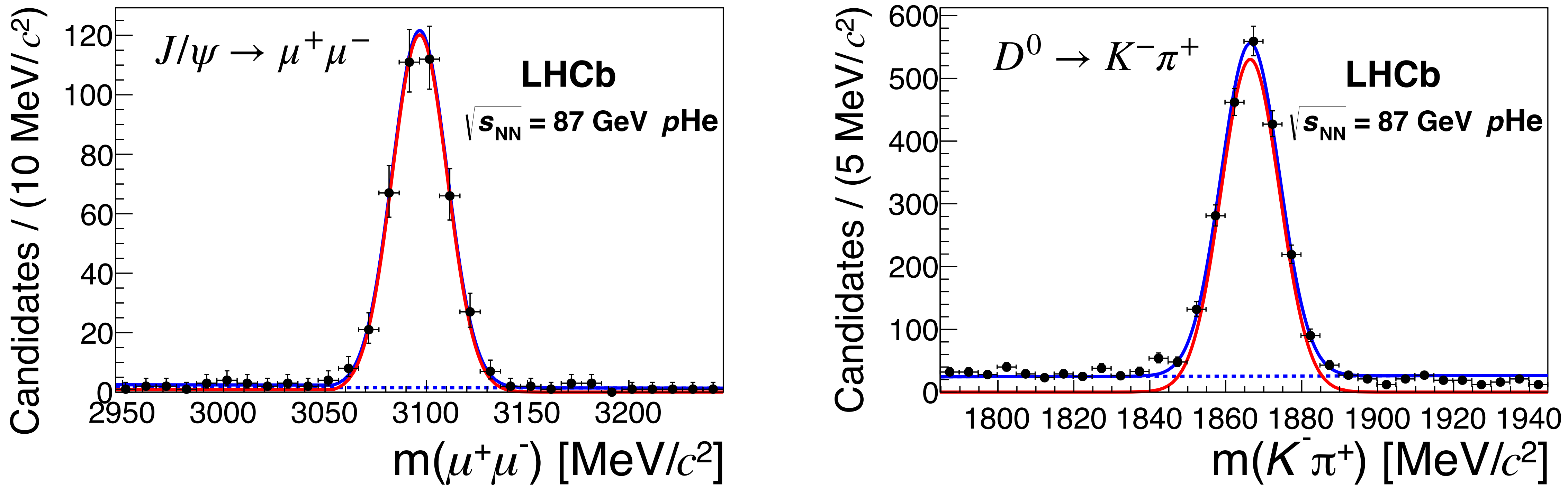
LHCspin: overview

- 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



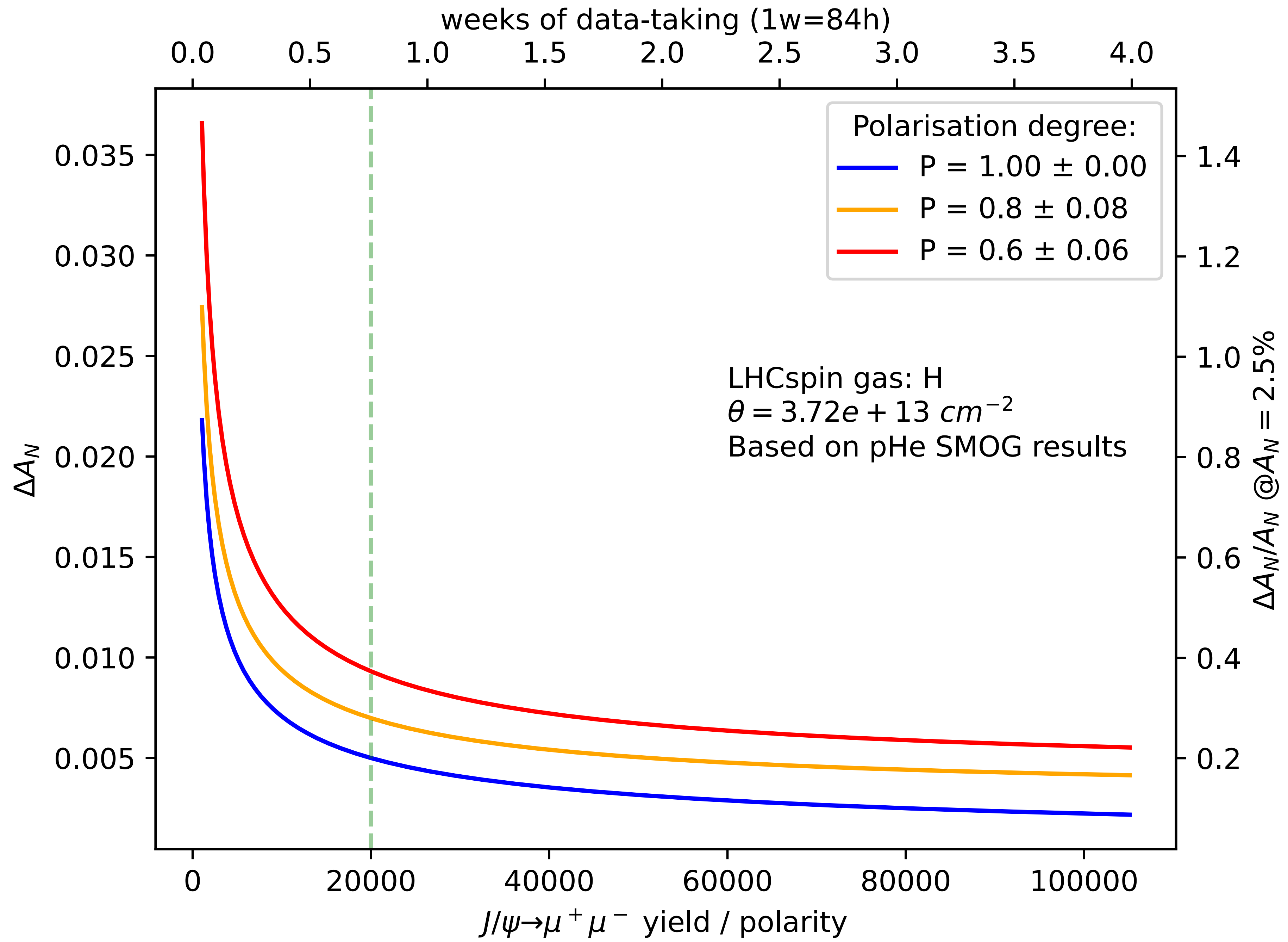
- LHCspin to best cover mid to high x at intermediate Q^2

- An example of SMOG data from 2016: $7.6\ \mathrm{nb}^{-1}$ in just $87\ \mathrm{h}$



[PRL 122 (2019) 132002]

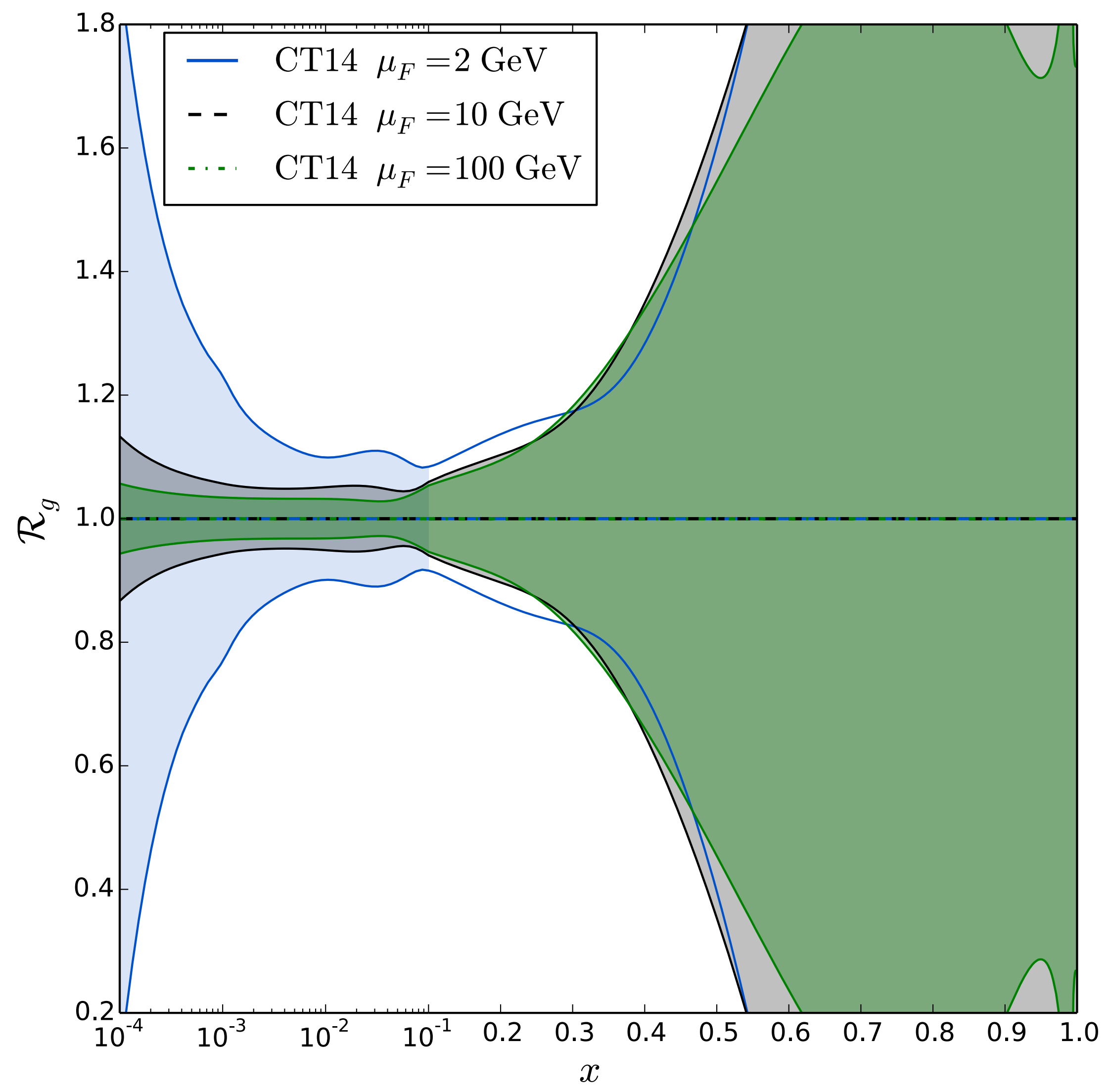
- By using the above result as reference:
- Precise spin asymmetry on $J/\psi \rightarrow \mu^+\mu^-$ for $pH^\uparrow$ collisions in few weeks!
- Statistics further enhanced by a factor $\sim 3-5$ in Upgrade II
- More in the following



PDFs

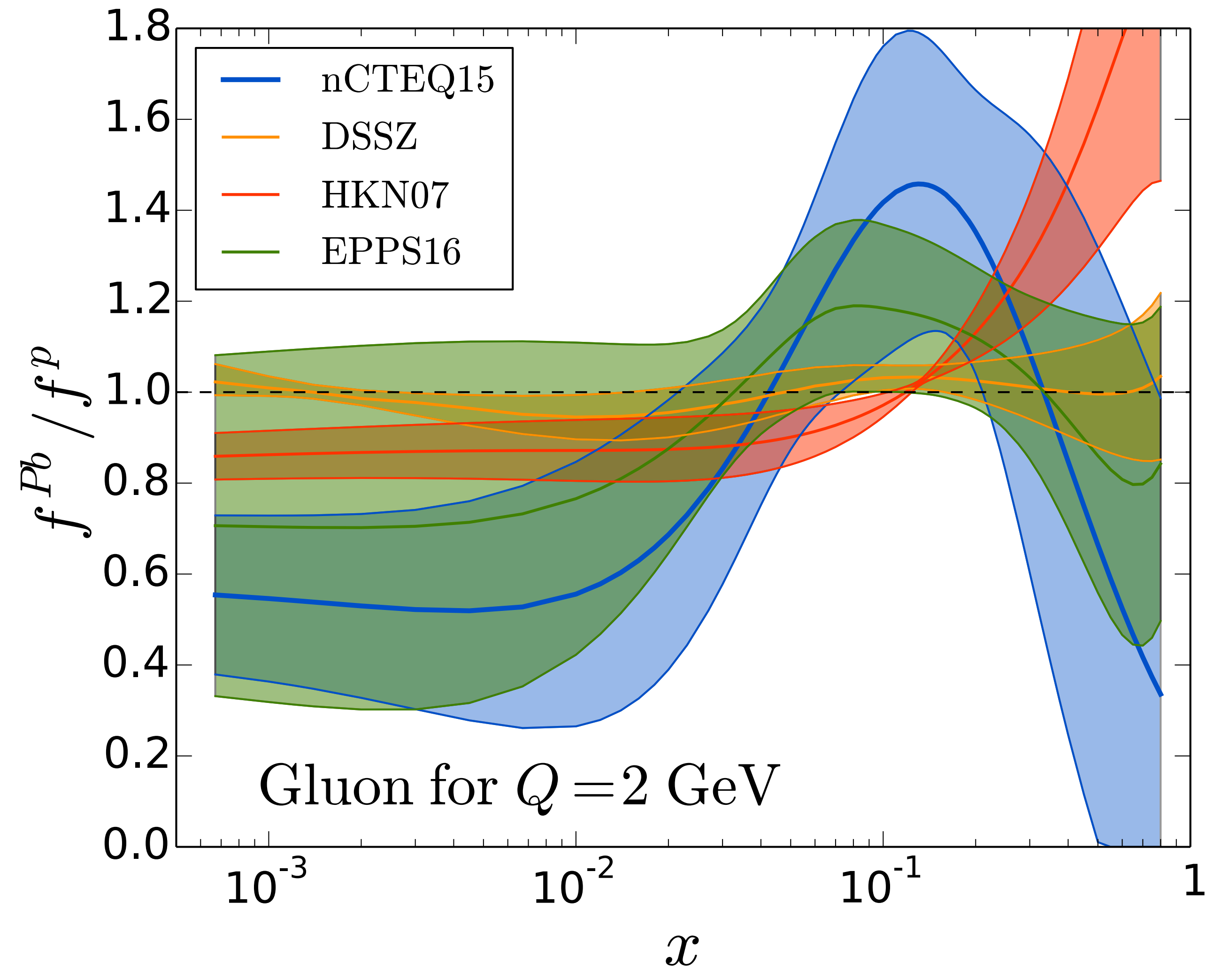
- high-x nucleon and nuclei structure is poorly known at all scales

- Probe quark PDFs via W production
- Gluon PDFs are least known, accessed with heavy flavours: a strength point of LHCb!
- PDF knowledge is a basic ingredient for HEP computations (eg for FCC)



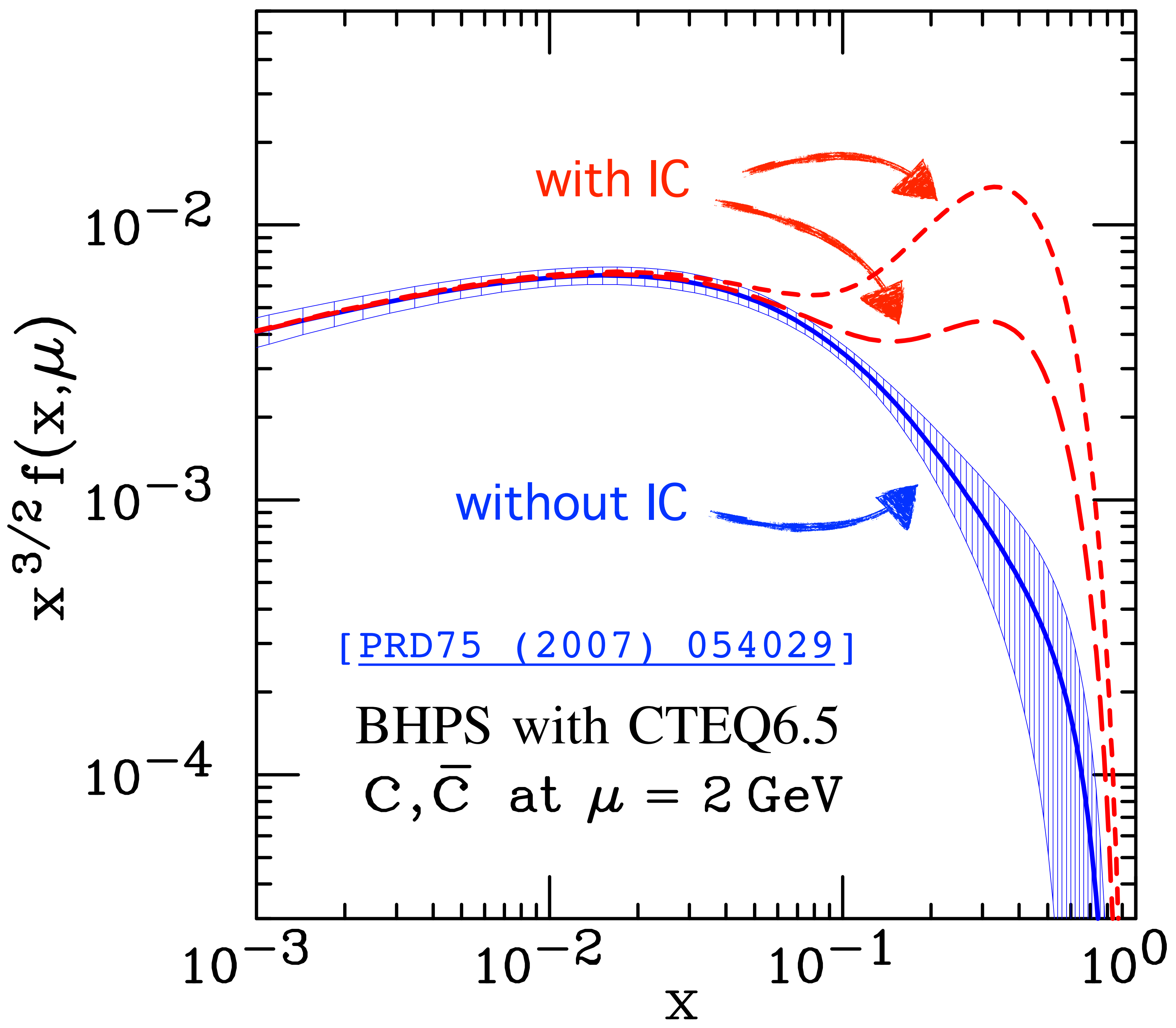
[PRD 93 (2016) 033006]

- The structure of nuclei departs from the simple sum of free p and n: EMC effect still to be understood
- → get more insight into the anti-shadowing region ($x \sim 0.1$)



[ArXiv:1807.00603]

- Intrinsic Charm (IC) component in the proton can be large at $x > 0.1$
- First search performed with SMOG: [PRL 122 (2019) 132002]

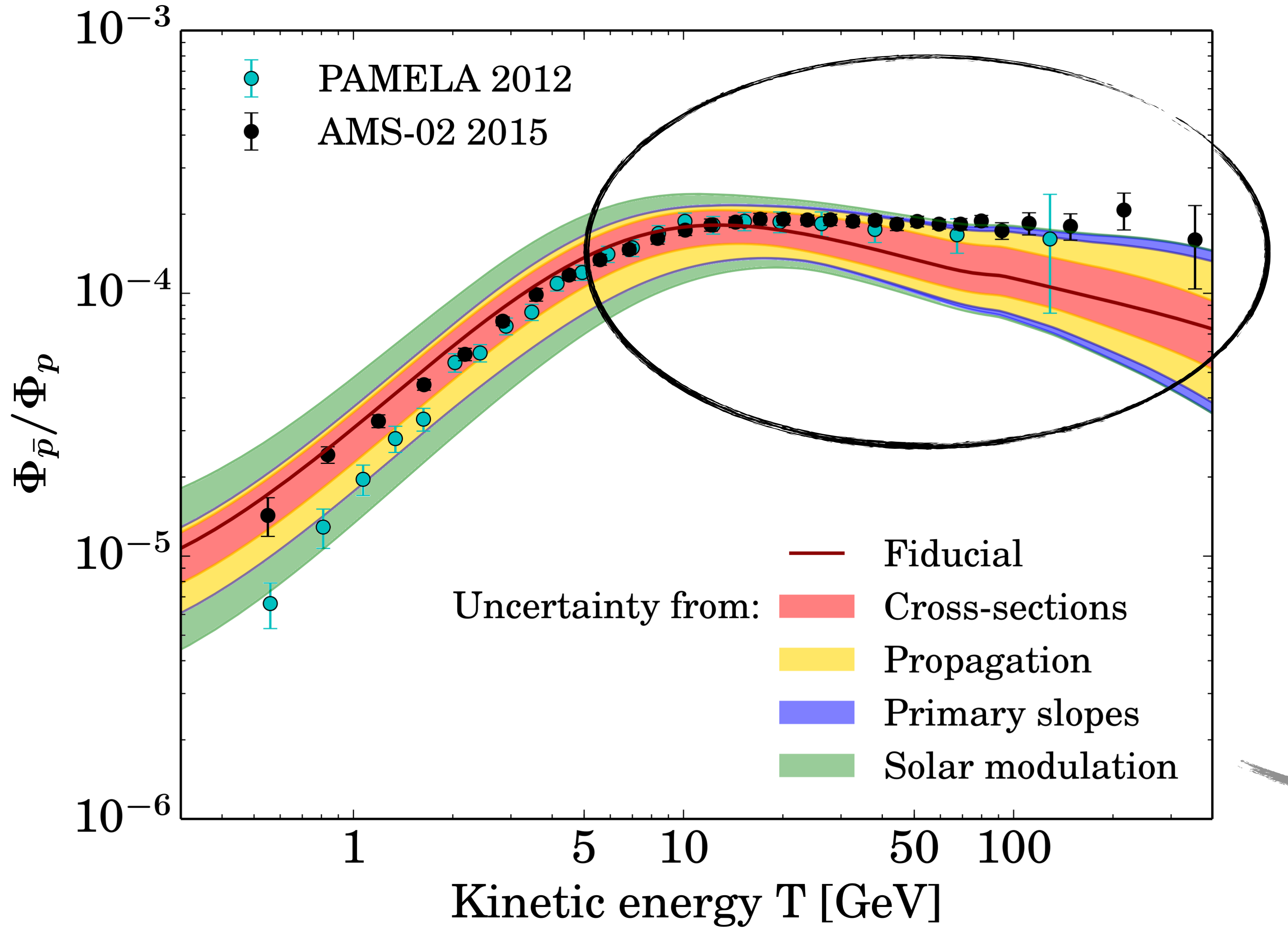


- Still to be investigated
- New intriguing LHCb result with pp collisions shown at EPS-HEP 2021! [LHCb-PAPER-2021-029 in preparation]

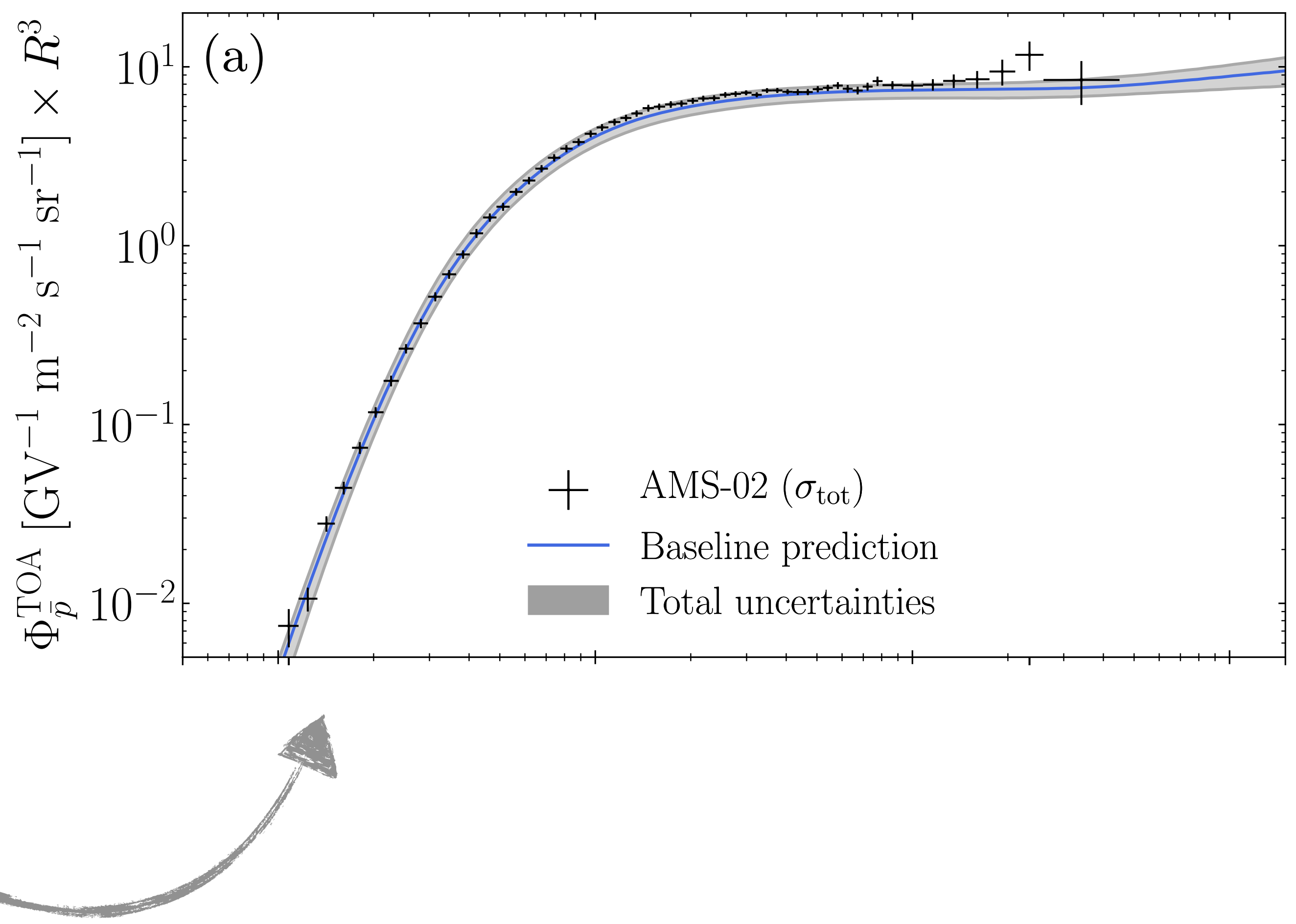
Impact on astrophysics

- $\overline{\mathrm{p}}$ production on pHe collisions, first measurement from SMOG helped the interpretation of DM annihilation
  [PRL 121 (2018) 222001]

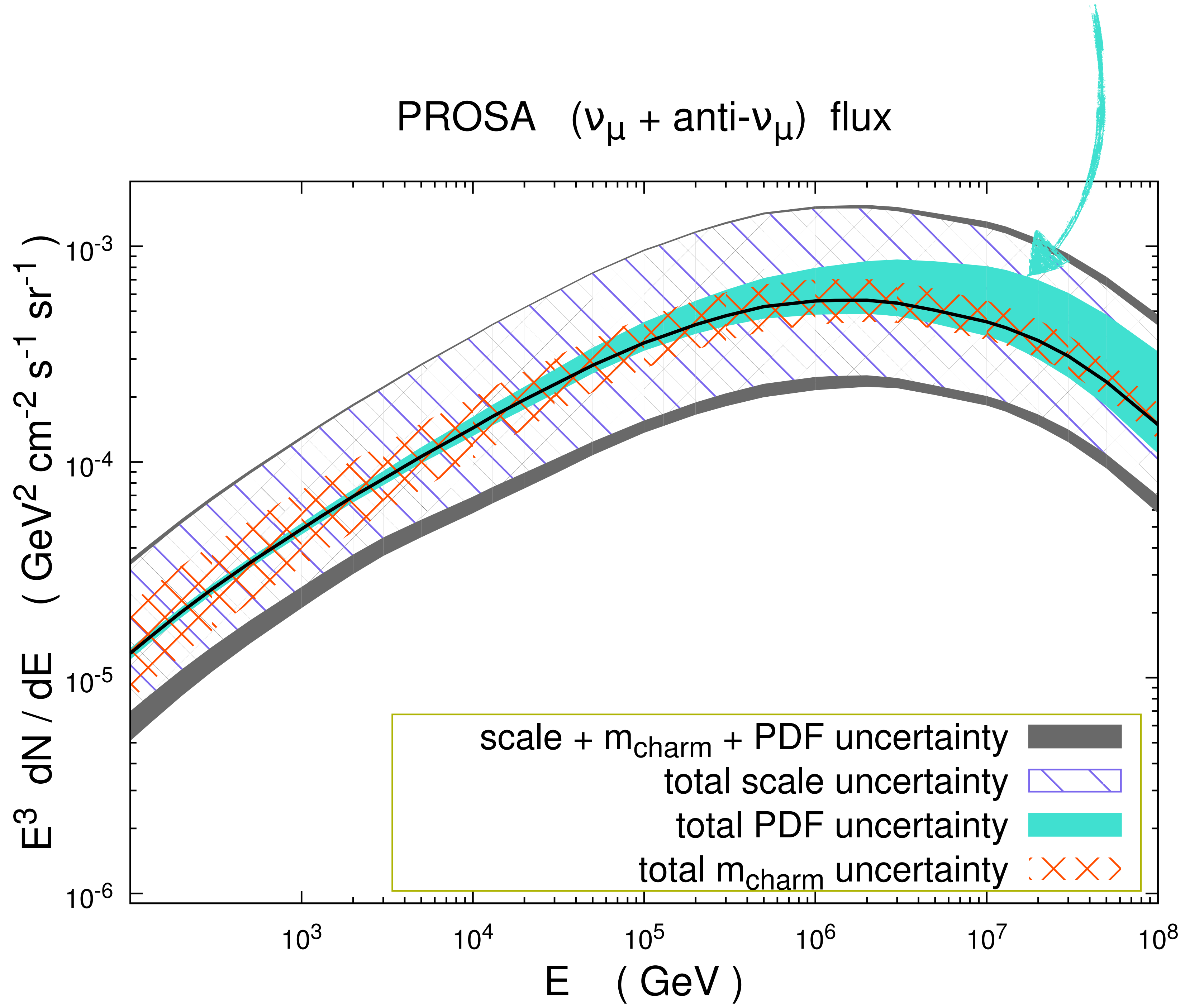
[JCAP09 (2015) 023]



[ArXiv:1906.07119]



- heavy-flavour hadroproduction measurements needed to improve the prompt ν_μ flux prediction at high energy

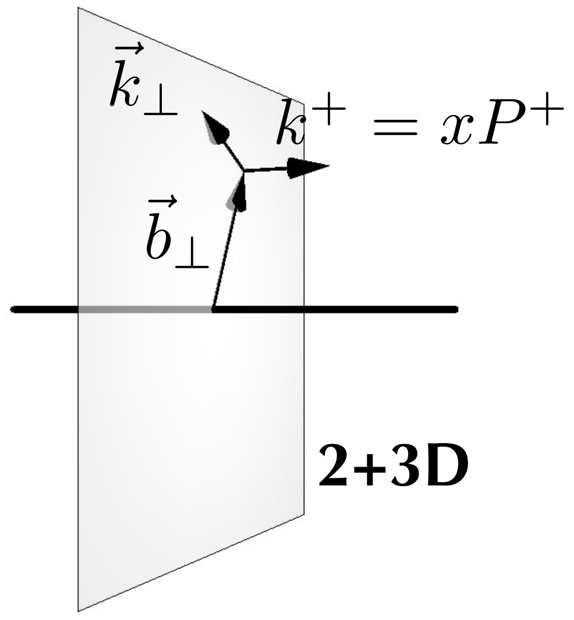


[JHEP 05 (2017) 004]

- Inputs for UHECR flux composition with pHe, pO, pN data
- $^{16}\mathrm{O}$ beam foreseen for Run 3, would reproduce the actual processes:
- $^{16}\mathrm{O} + \mathrm{p} \to \overline{\mathrm{p}} + \mathrm{X}$ and $^{16}\mathrm{O} + {}^{4}\mathrm{He} \to \overline{\mathrm{p}} + \mathrm{X}$ [CERN-LPCC-2018-07]

Multi-dimensional nucleon mapping

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

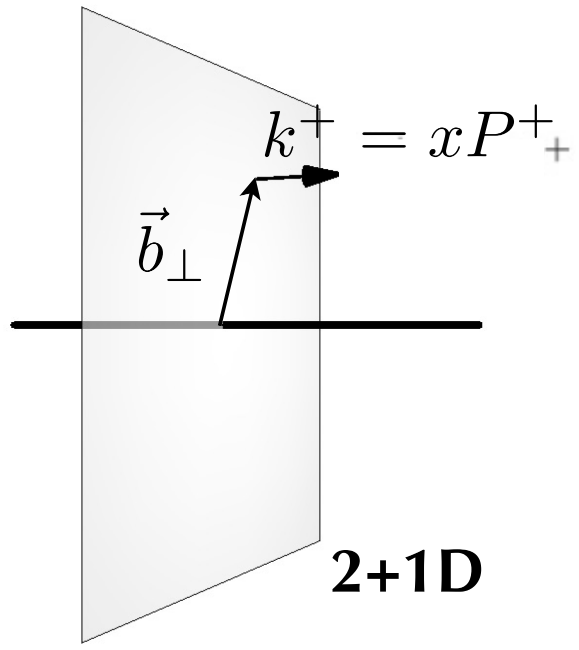


quark polarization / nucleon polarization

$\mathcal{W}_X$	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	$\langle S_y \ell_y^q \rangle$	$\langle S_y \ell_y^q S_L^q \ell_L^q \rangle$	$\langle S_y \ell_y^q S_x^q \ell_x^q \rangle$	$\langle S_y S_y^q \rangle$

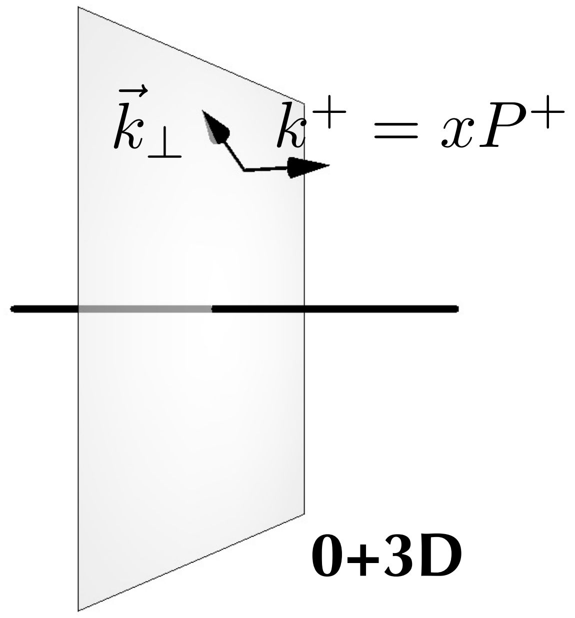
$\xi = 0$

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



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

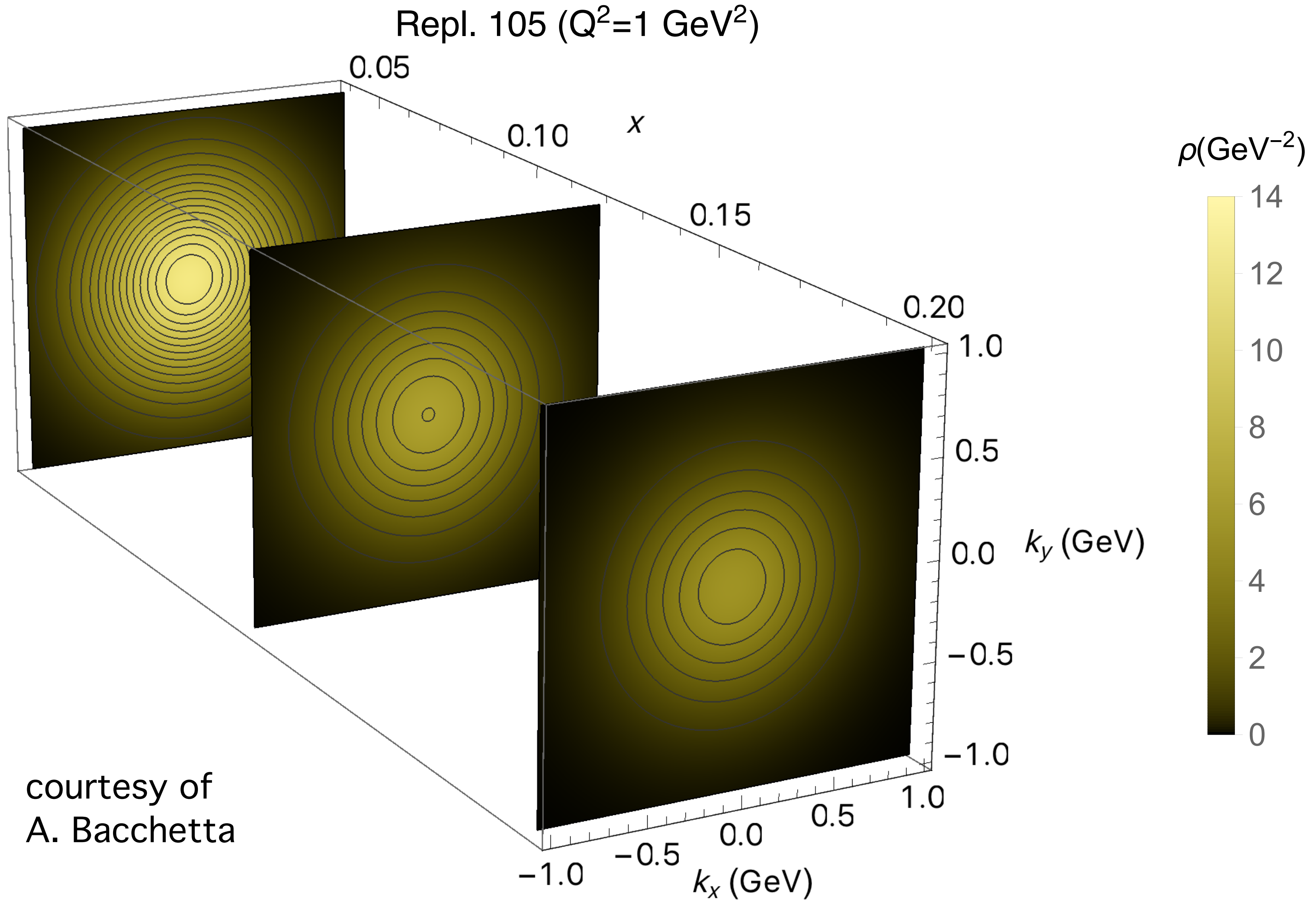


[from B. Pasquini @ DIS2021]

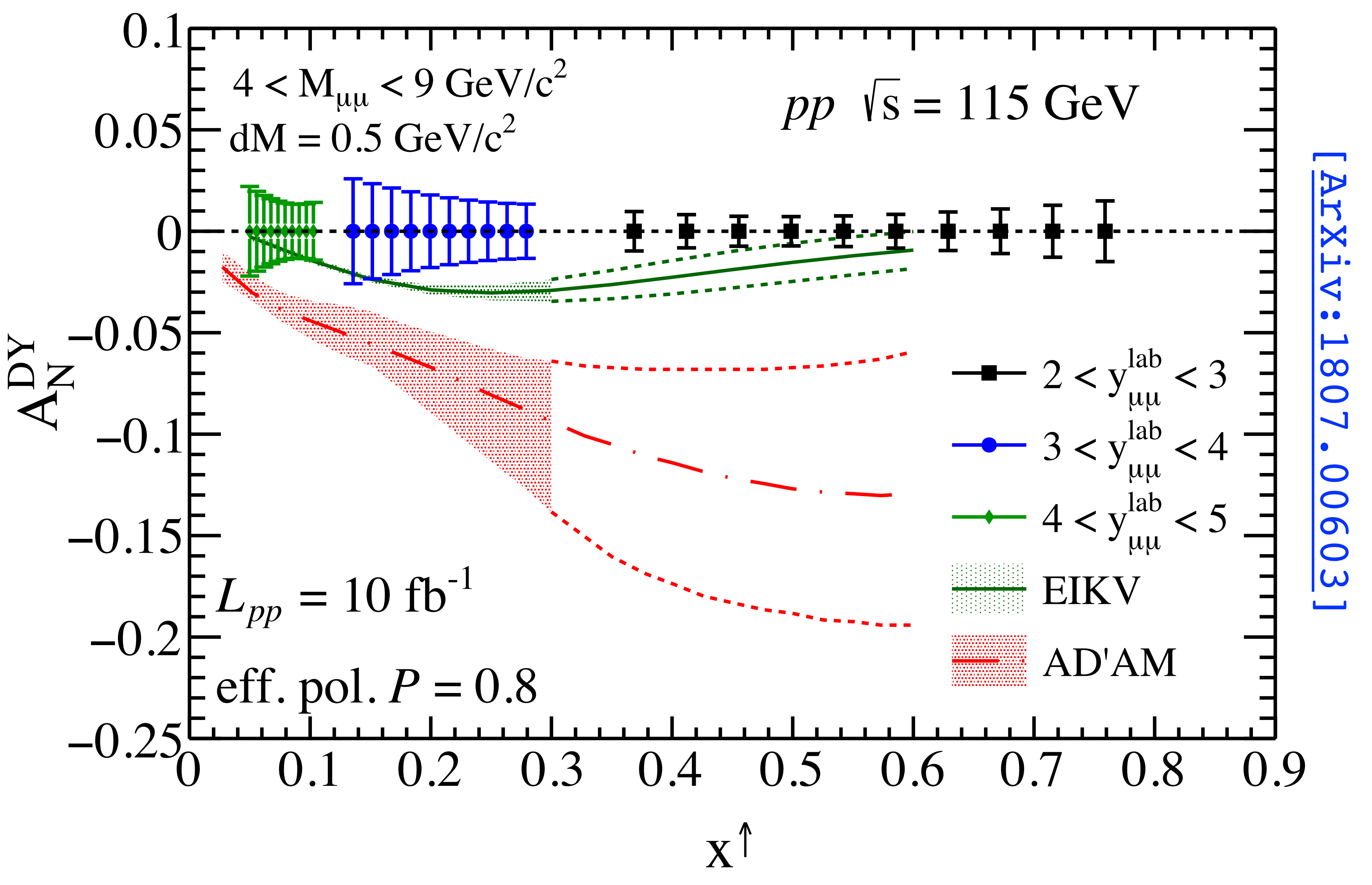
- red: vanish if no OAM $\qquad$ (green): accessible at LHCspin

TMDs

- 3D momentum "tomography" of hadrons:



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



- To access the transverse motion of partons inside a polarised nucleon: measure TMDs via TSSAs at high $x^{\uparrow}$

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

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

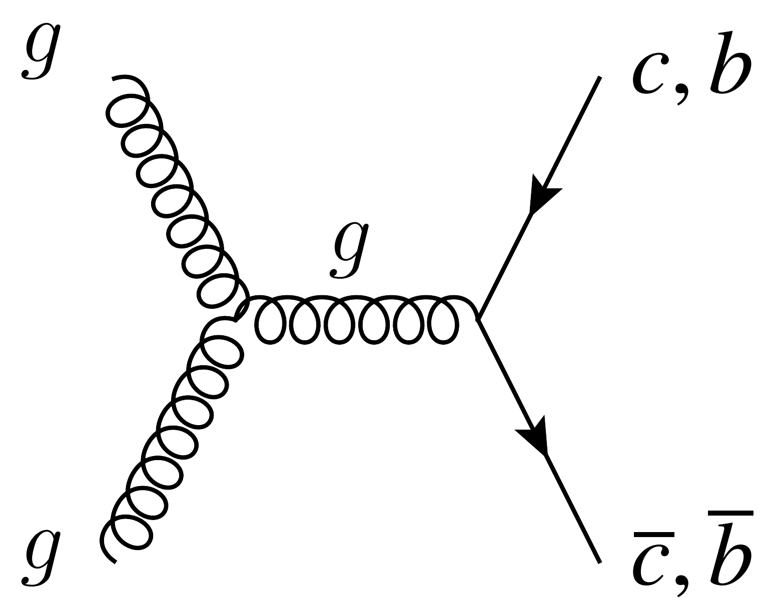
$$f_{1T}^{\perp q}(x, k_T^2)_{\text{DY}} = -f_{1T}^{\perp q}(x, k_T^2)_{\text{SIDIS}}$$

- + isospin effect with polarised deuterium

  - Sea-quark component accessed via $W^{\pm}$ boson production, with $\Delta A_N \sim 0.1 - 0.2$

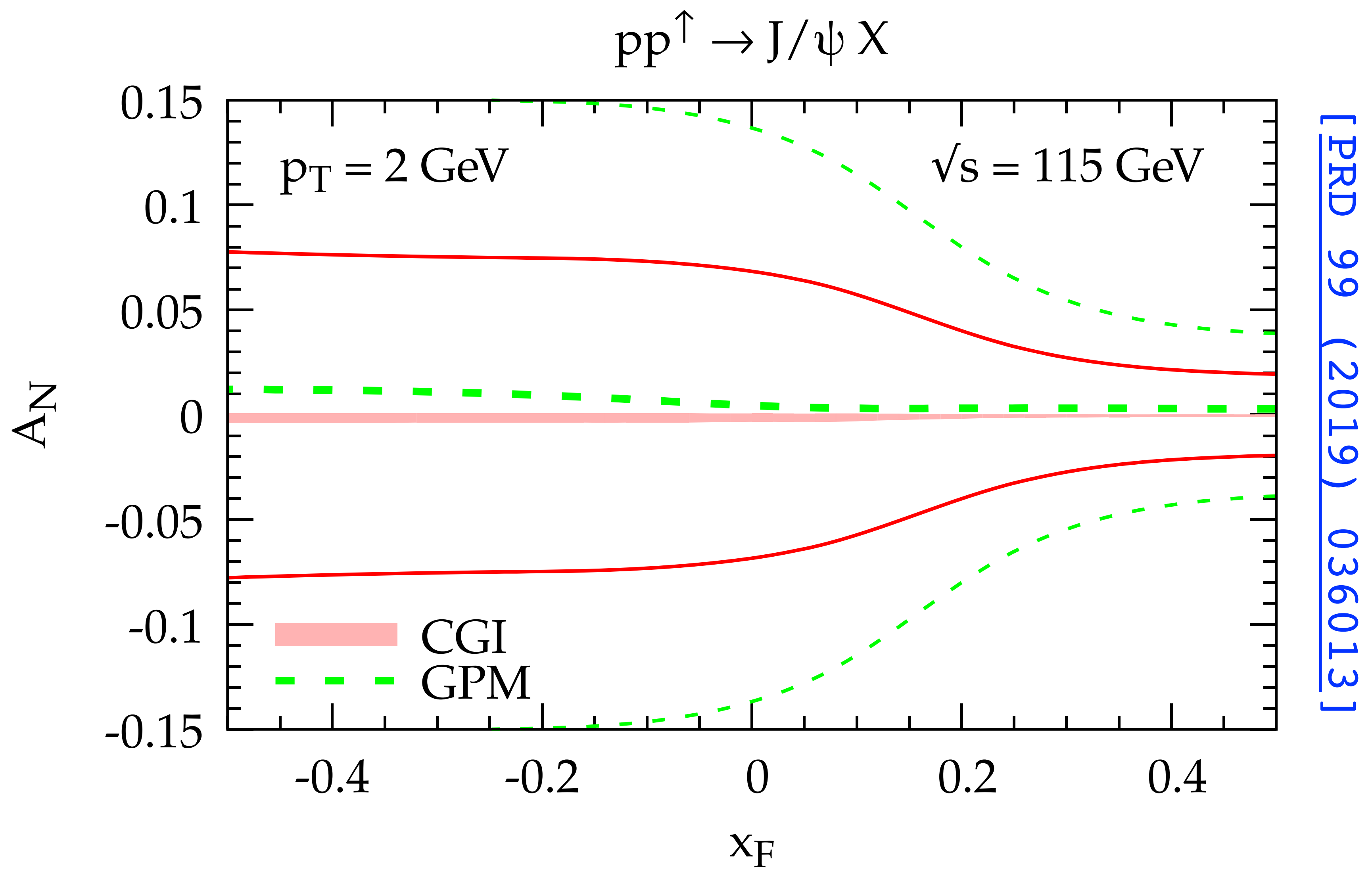
The Sivers function

- Heavy-flavour mainly produced via gg at the LHC: a strength point of LHCb!
- Gluon Sivers function can be probed with quarkonia and open heavy-flavour production

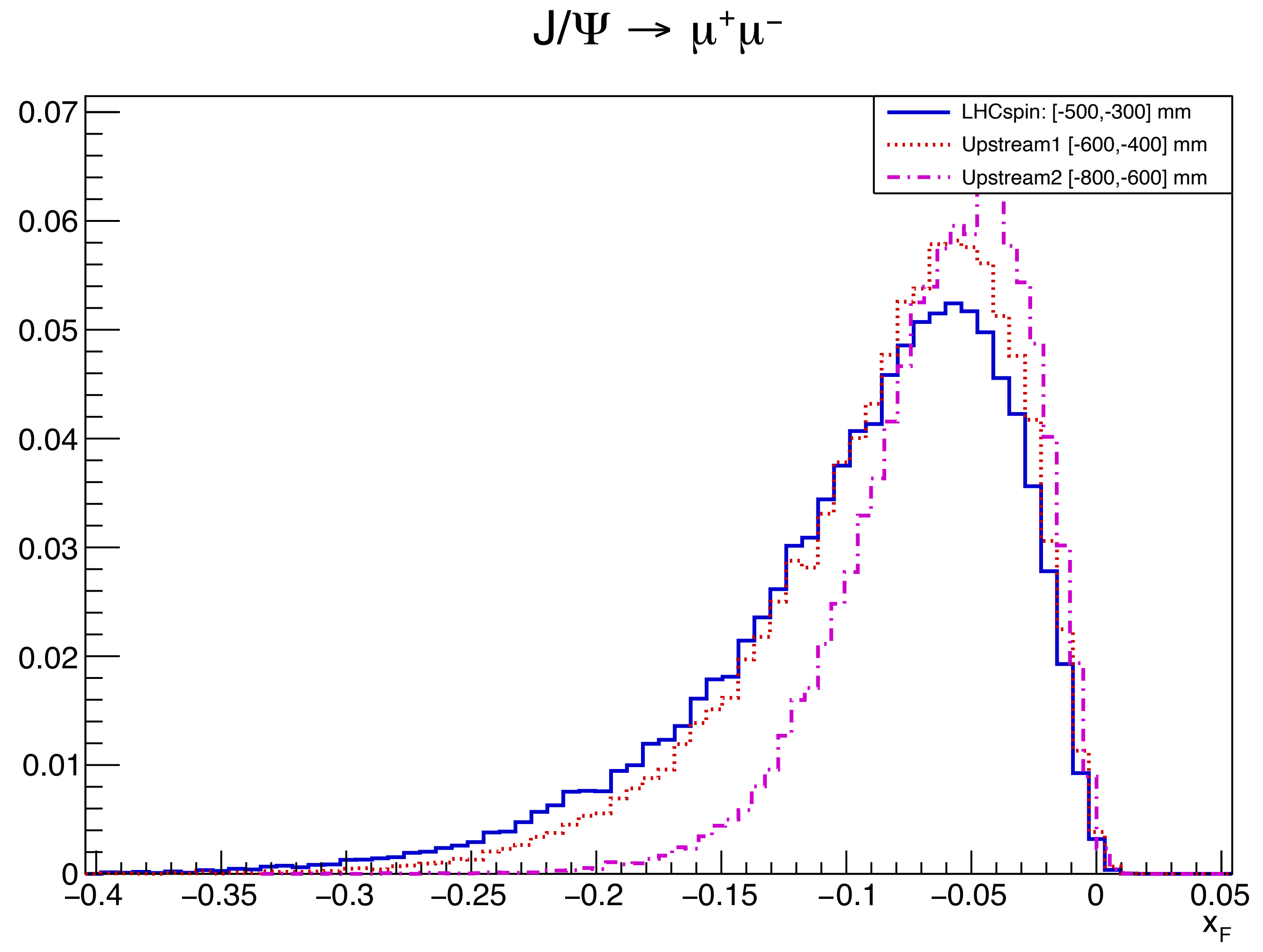


- broad x range at a scale $M_T = \sqrt{M^2 + P_T^2}$
- lot of probes: η_c, χ_c, χ_b, $J/\psi J/\psi$ ...

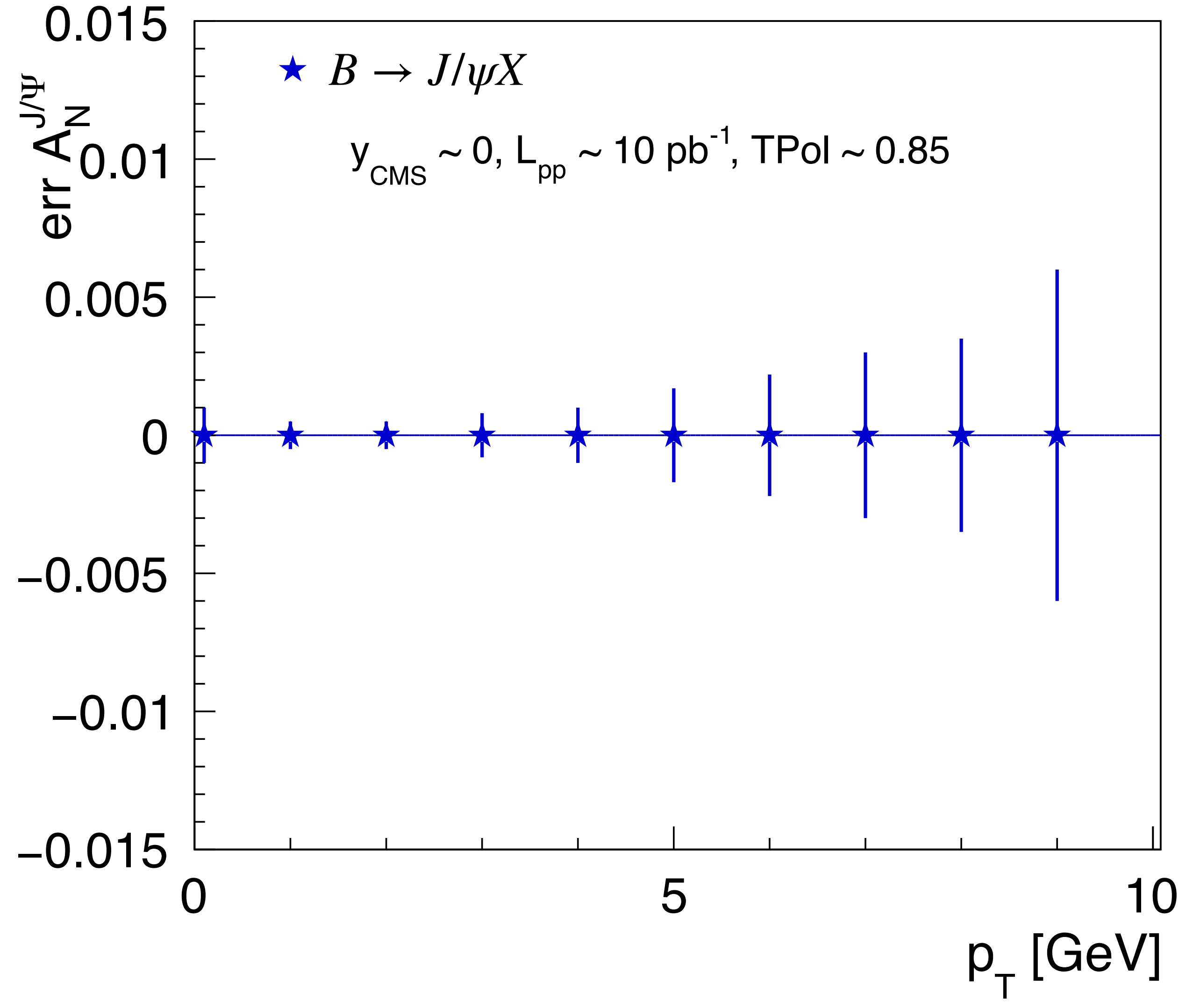
- A_N predictions for FT at LHC



- Full upgrade LHCb simulation for fixed-target $J/\Psi \to \mu^+\mu^-$



- Few days of data: $B \to J/\Psi$ decays



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

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

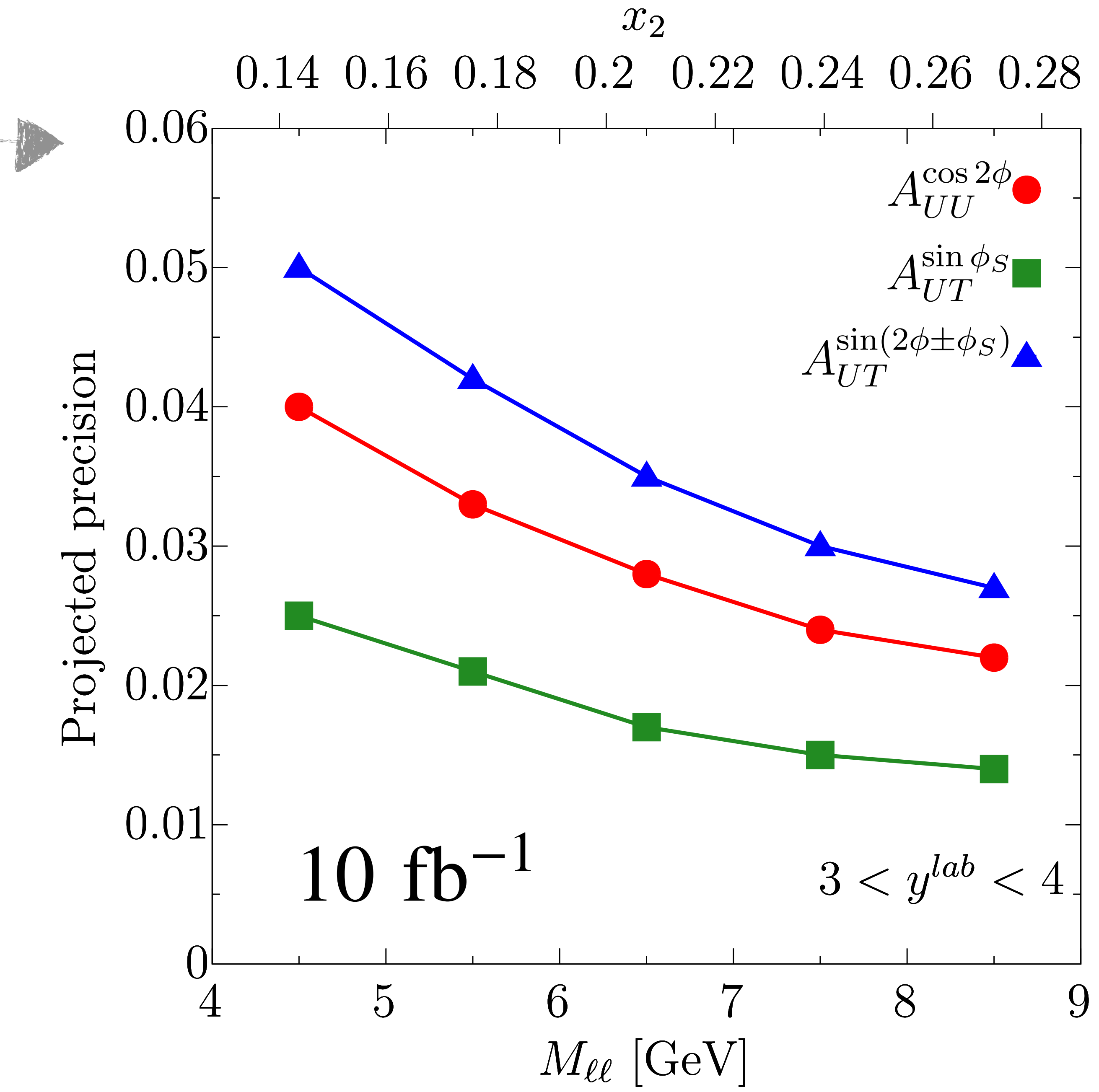
$$A_{UT}^{sin\phi_S} \sim \frac{f_1^q(x_1,k_{1T}^2)\otimes f_{1T}^{\perp \bar{q}}(x_2,k_{2T}^2)}{f_1^q(x_1,k_{1T}^2)\otimes f_1^{\bar{q}}(x_2,k_{2T}^2)}$$

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

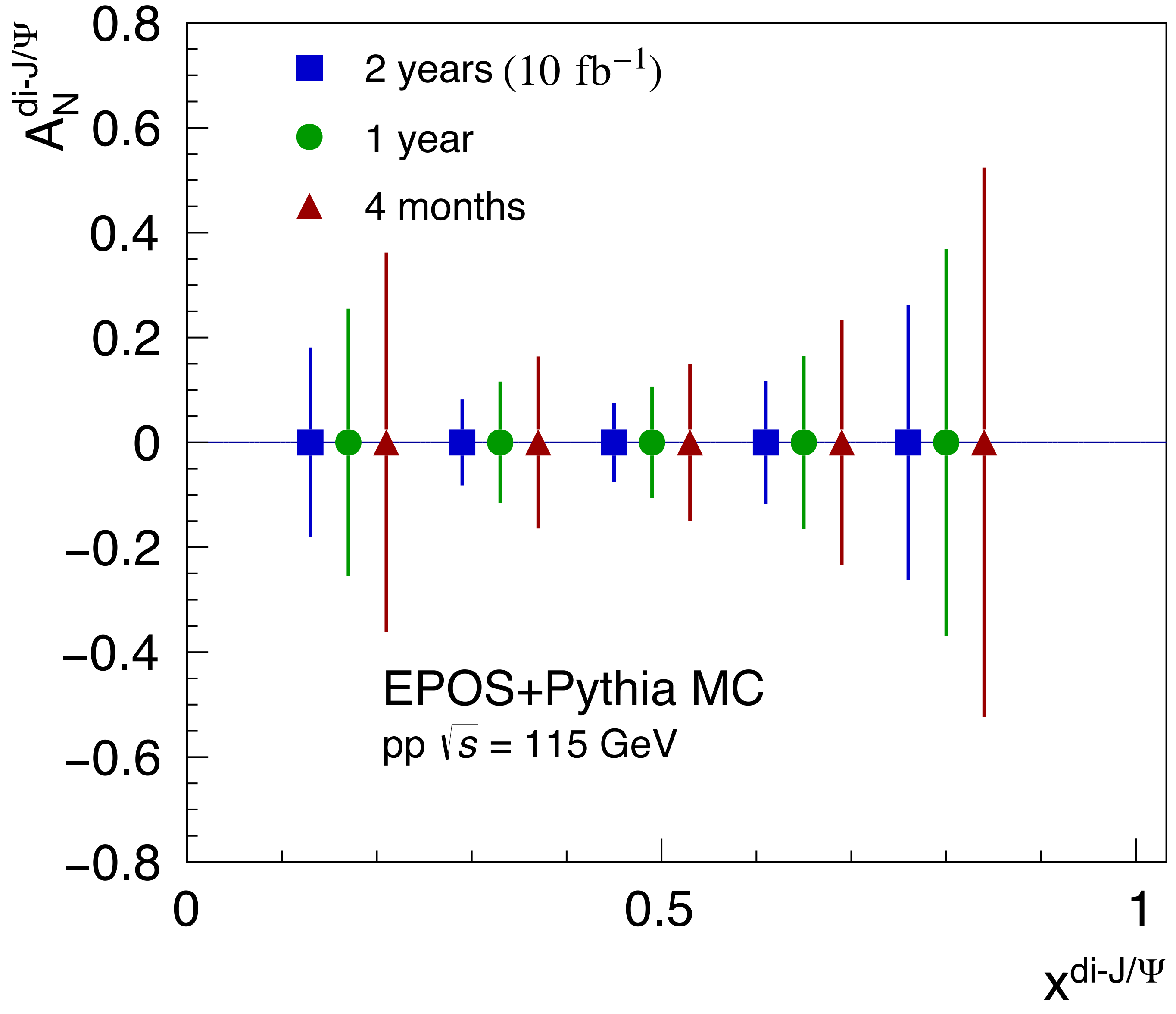
$$A_{UT}^{sin(2\phi-\phi_S)} \sim \frac{h_1^{\perp q}(x_1,k_{1T}^2)\otimes h_1^{\bar{q}}(x_2,k_{2T}^2)}{f_1^q(x_1,k_{1T}^2)\otimes f_1^{\bar{q}}(x_2,k_{2T}^2)}$$

- polarised Drell-Yan to access quark TMDs
- 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]

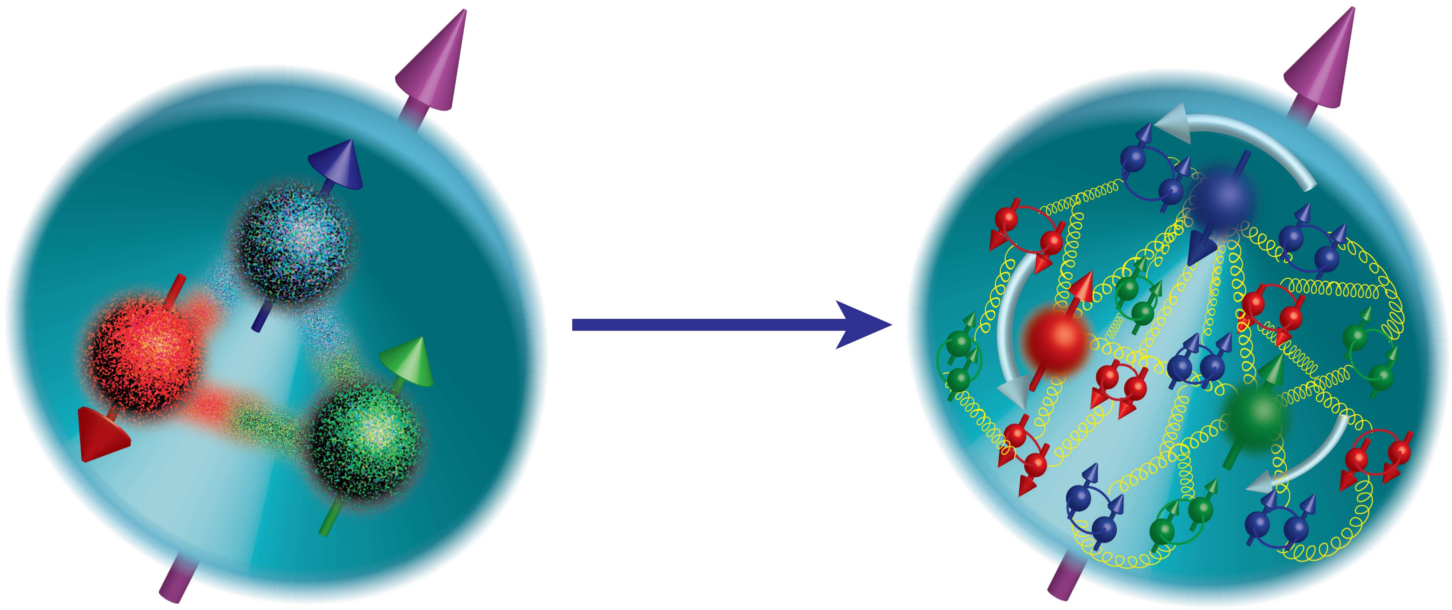


- J/Ψ J/Ψ channel



The spin puzzle & GPDs

- TMDs → nucleon spin



- OAM information via TMDs is only indirect: position and momentum correlations are needed
- Instead, quark OAM from GPD moments via Ji Sum Rule:

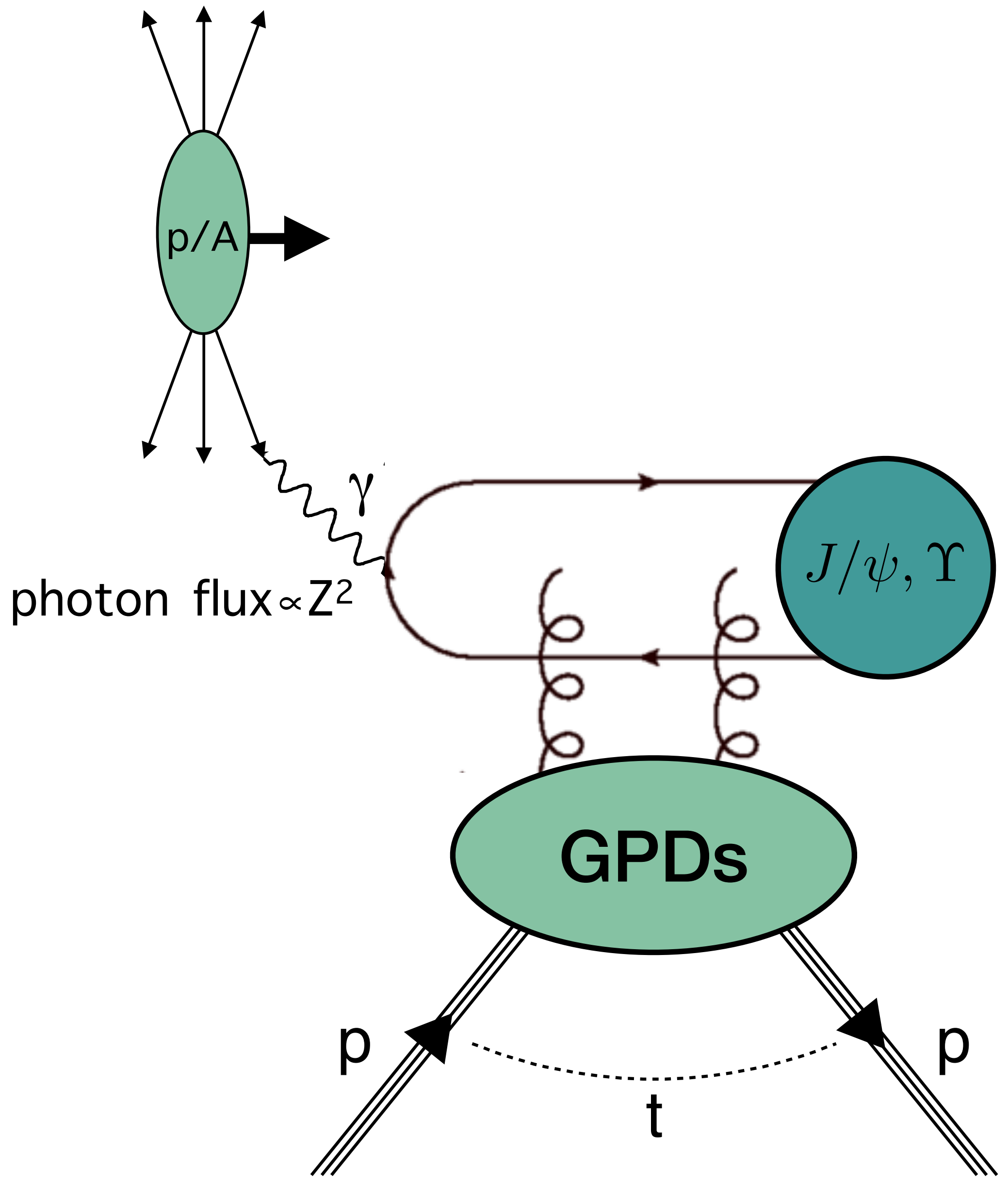
$$\frac{1}{2} = J^q(\mu) + J^g(\mu) = \frac{1}{2}\Delta\Sigma(\mu) + L_z^q(\mu) + J^g(\mu)$$

[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

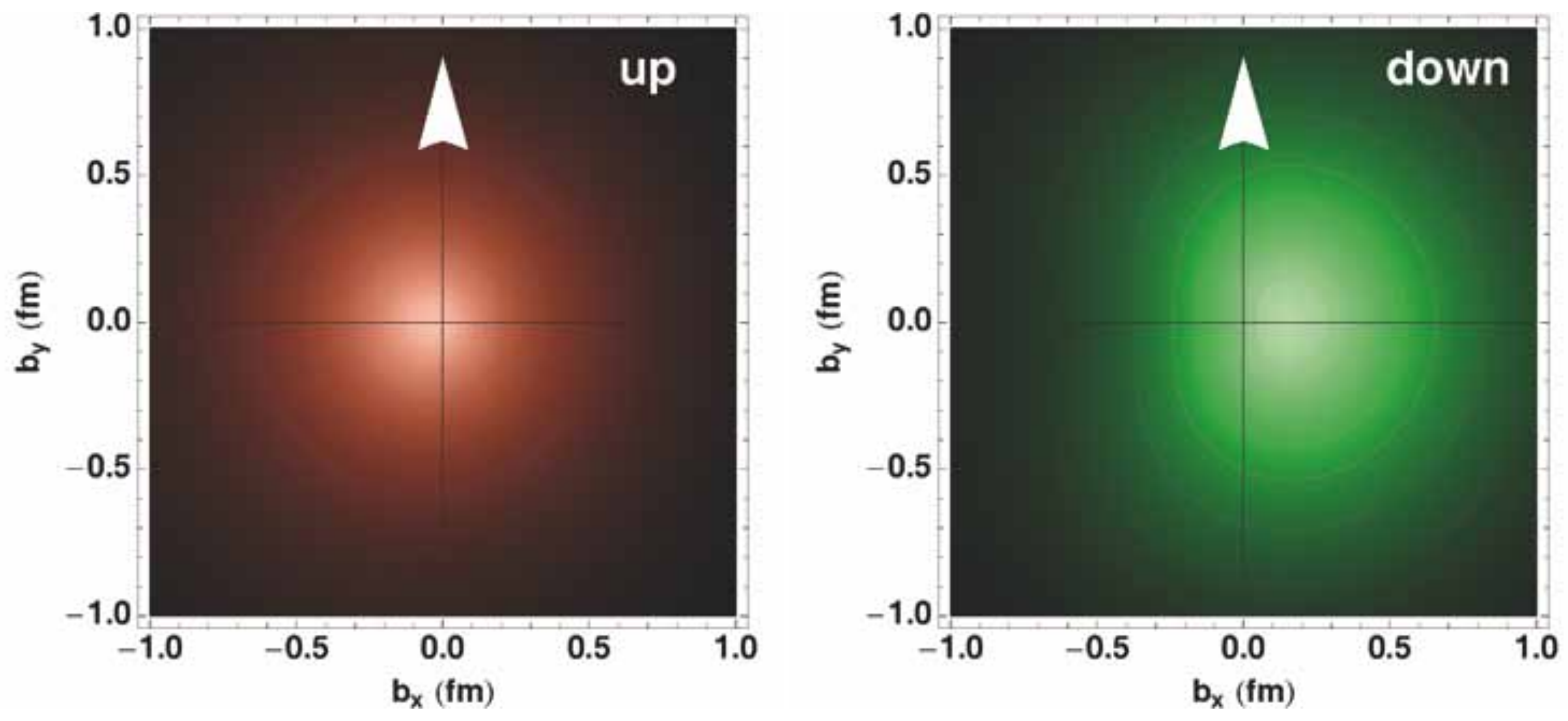
[PRD 85 (2012) 051502]



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

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

[PRL 99 (2017) 112001]

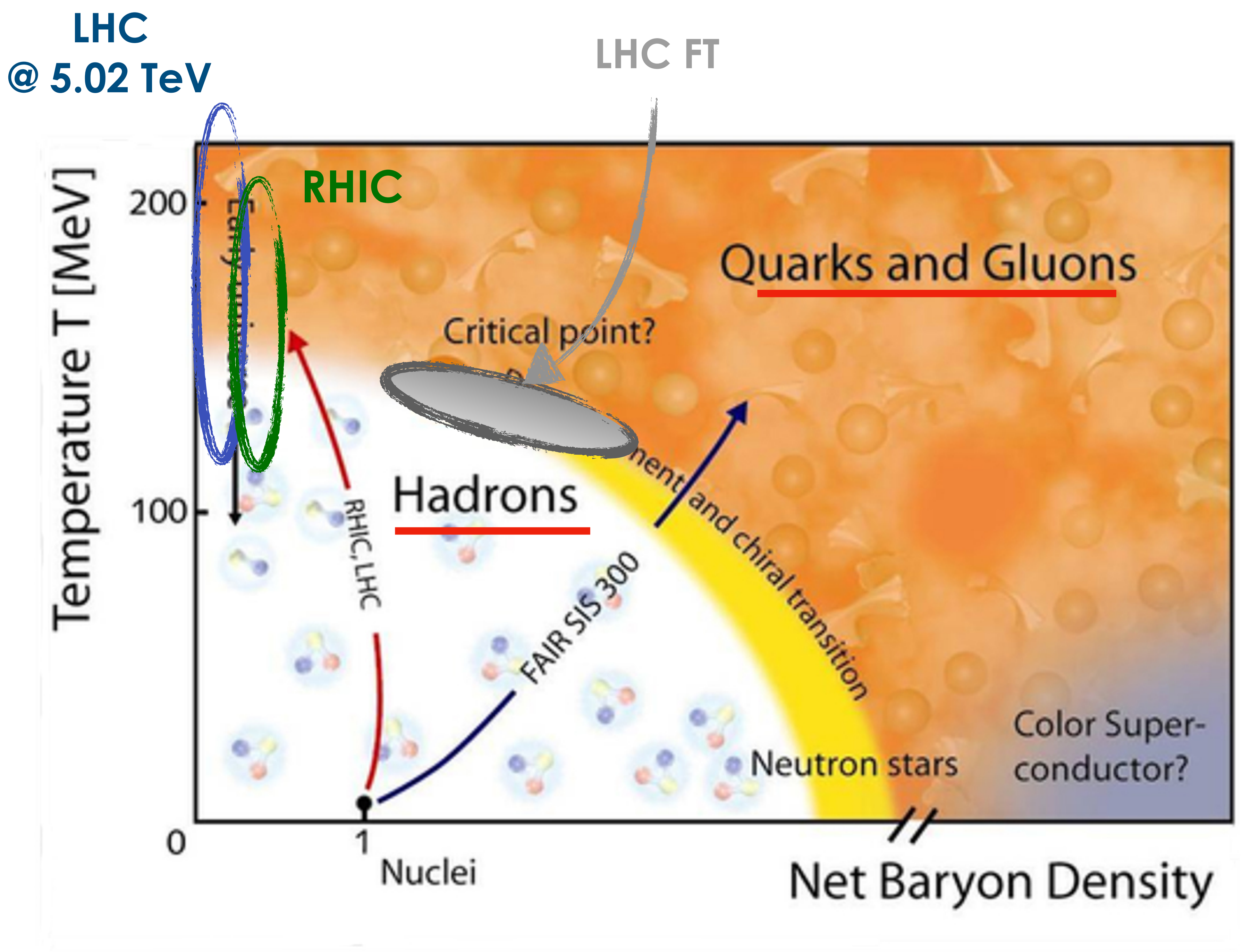


[NS 28 (2012) 1-2]

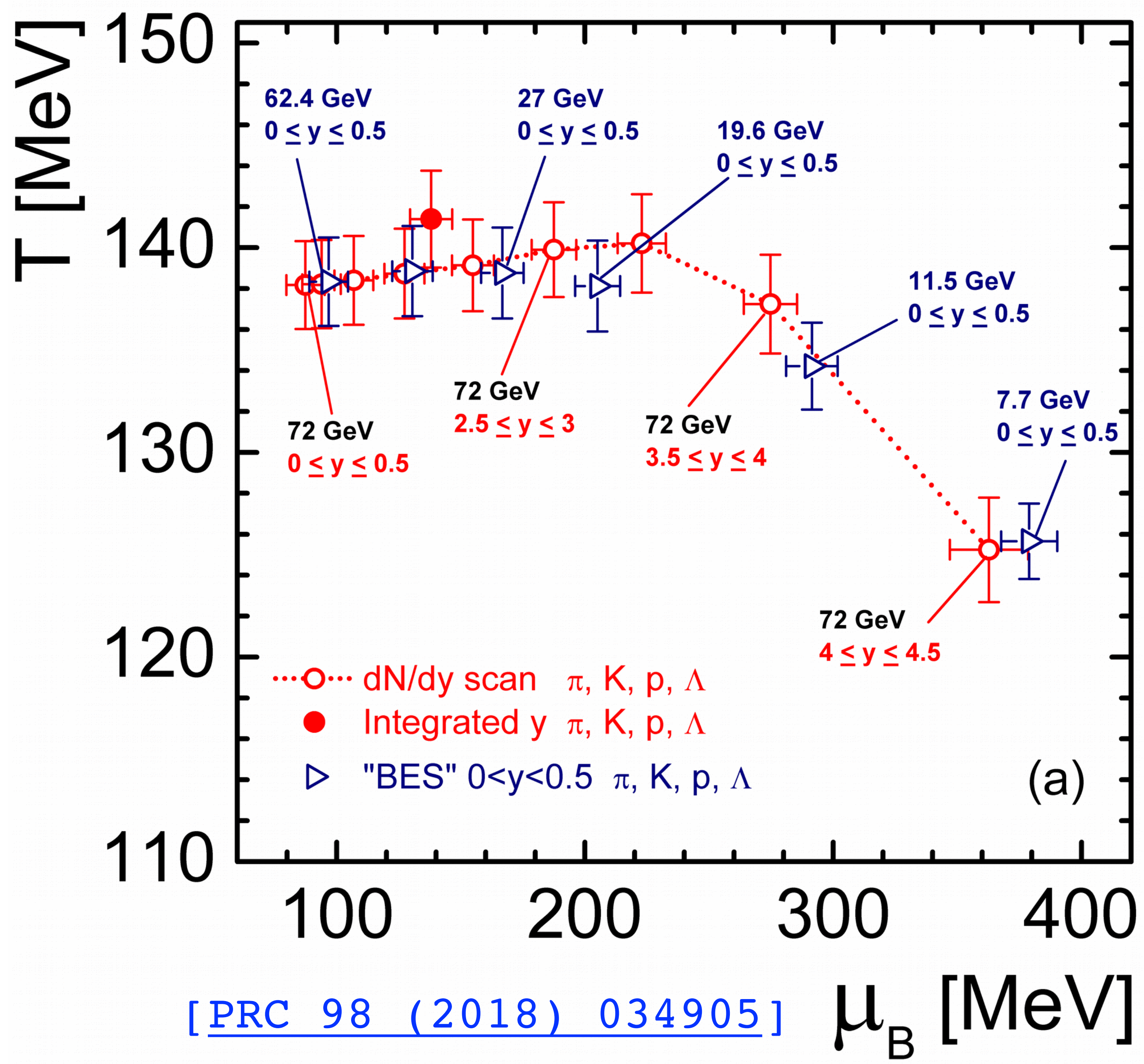
Heavy ion fixed-target collisions

- 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 $\sqrt{s} = 72\ \mathrm{GeV}$

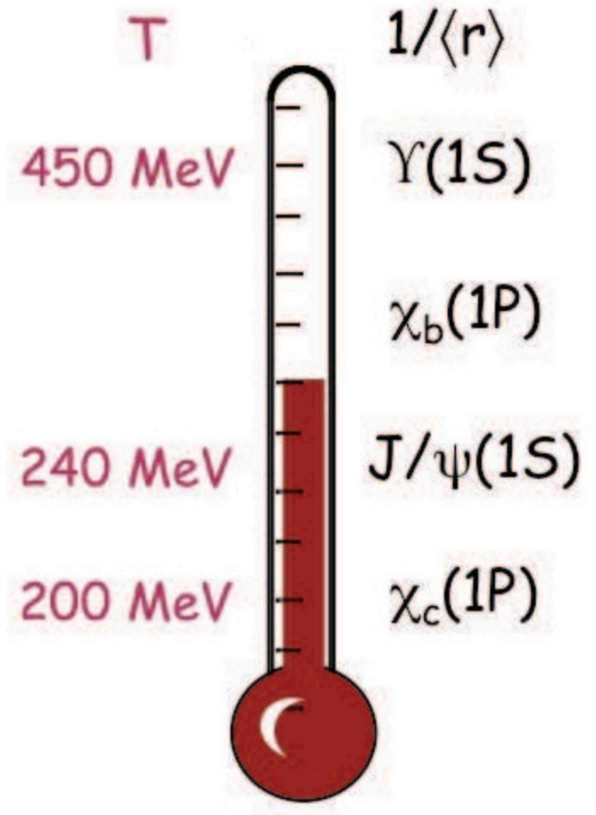
- Hints for deconfinement at this energy: FT collisions to explore the transition region



- Complement the RHIC Beam Energy Scan (BES) with a y scan



[PRC 98 (2018) 034905]

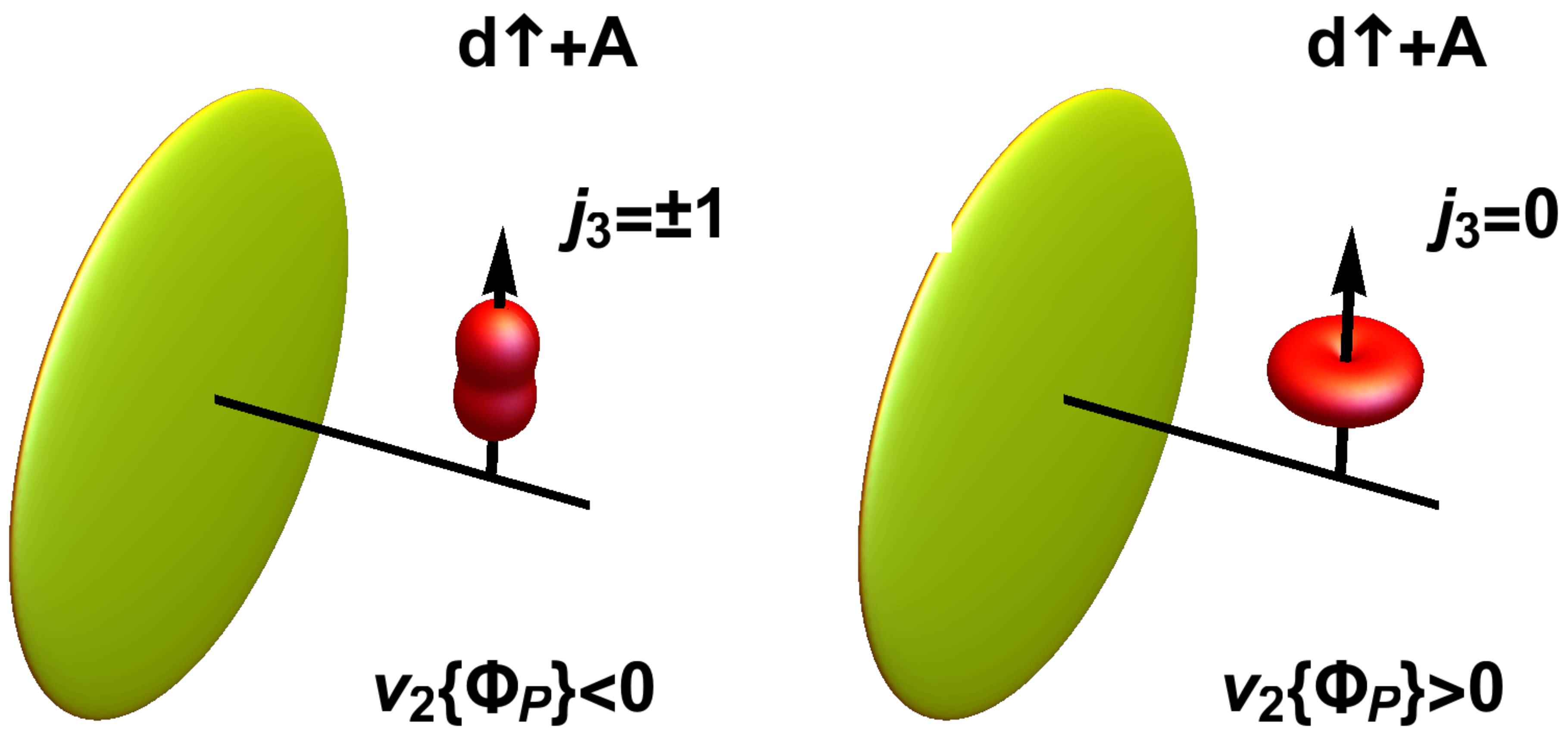


- Suppression of $c\bar{c}$ bound states as QGP thermometer
- States with different binding energy → different dissociation temperature
- LHCspin to access unique probes

[IJMPA 28 (2013) 1340012]

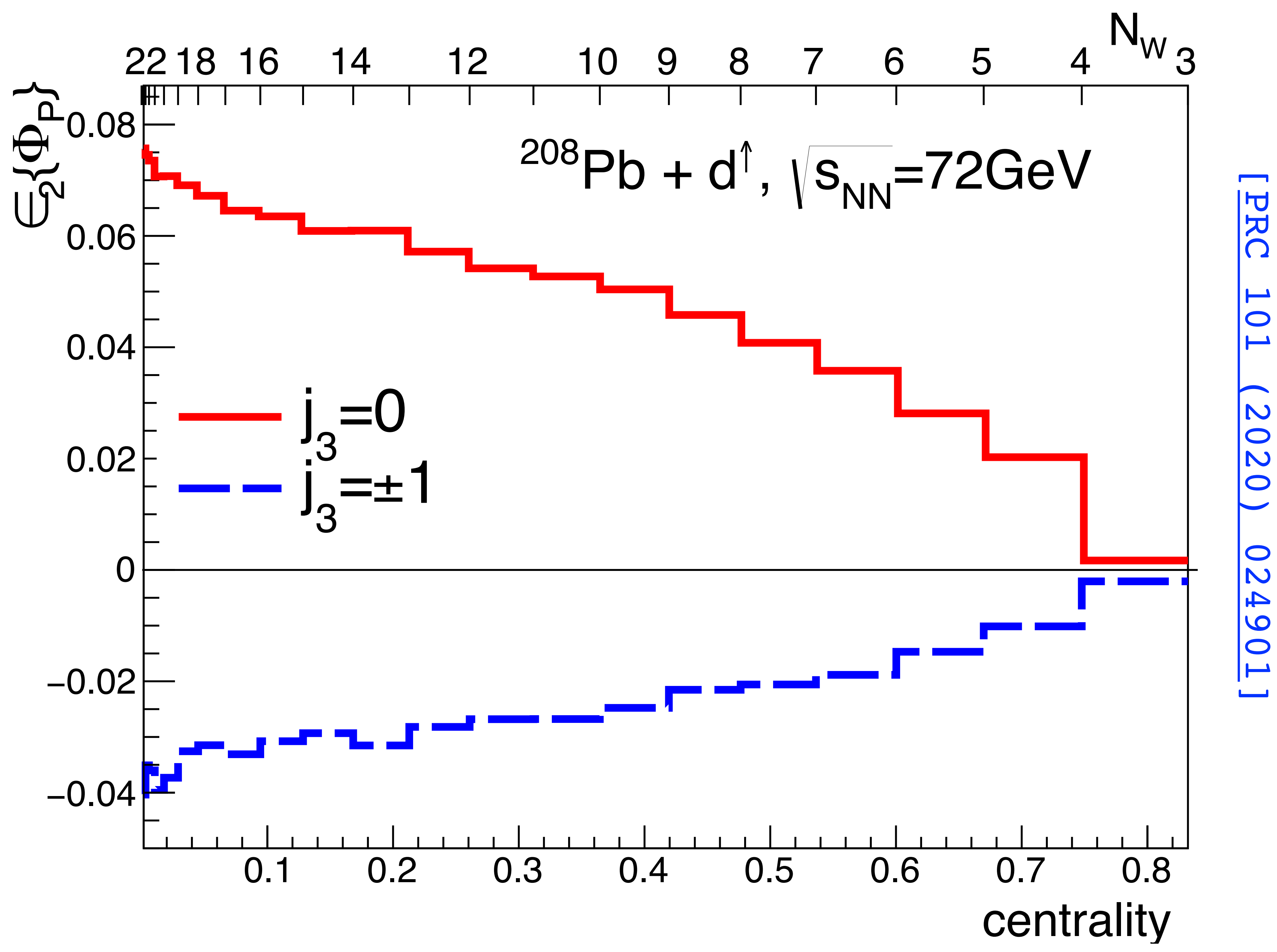
Heavy ion fixed-target collisions

- Interesting topic joining heavy ions and polarisation: probing the dynamics of small systems
- 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



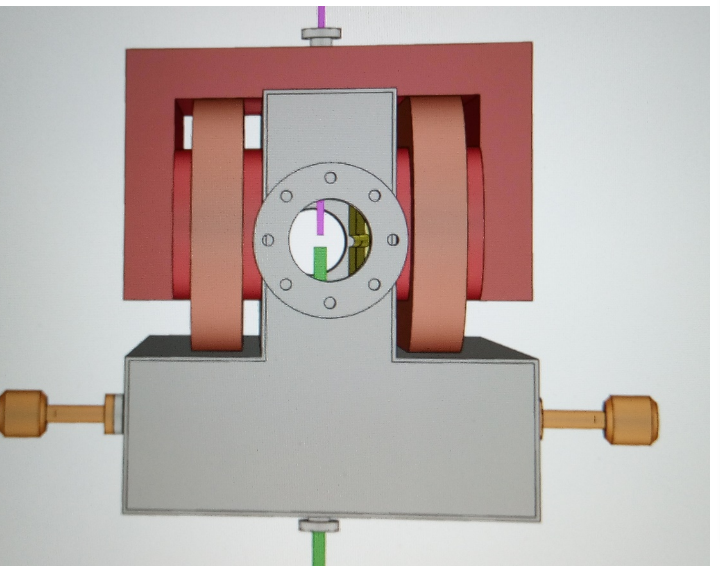
D polarised along Φ_p ,
perpendicular to the beam

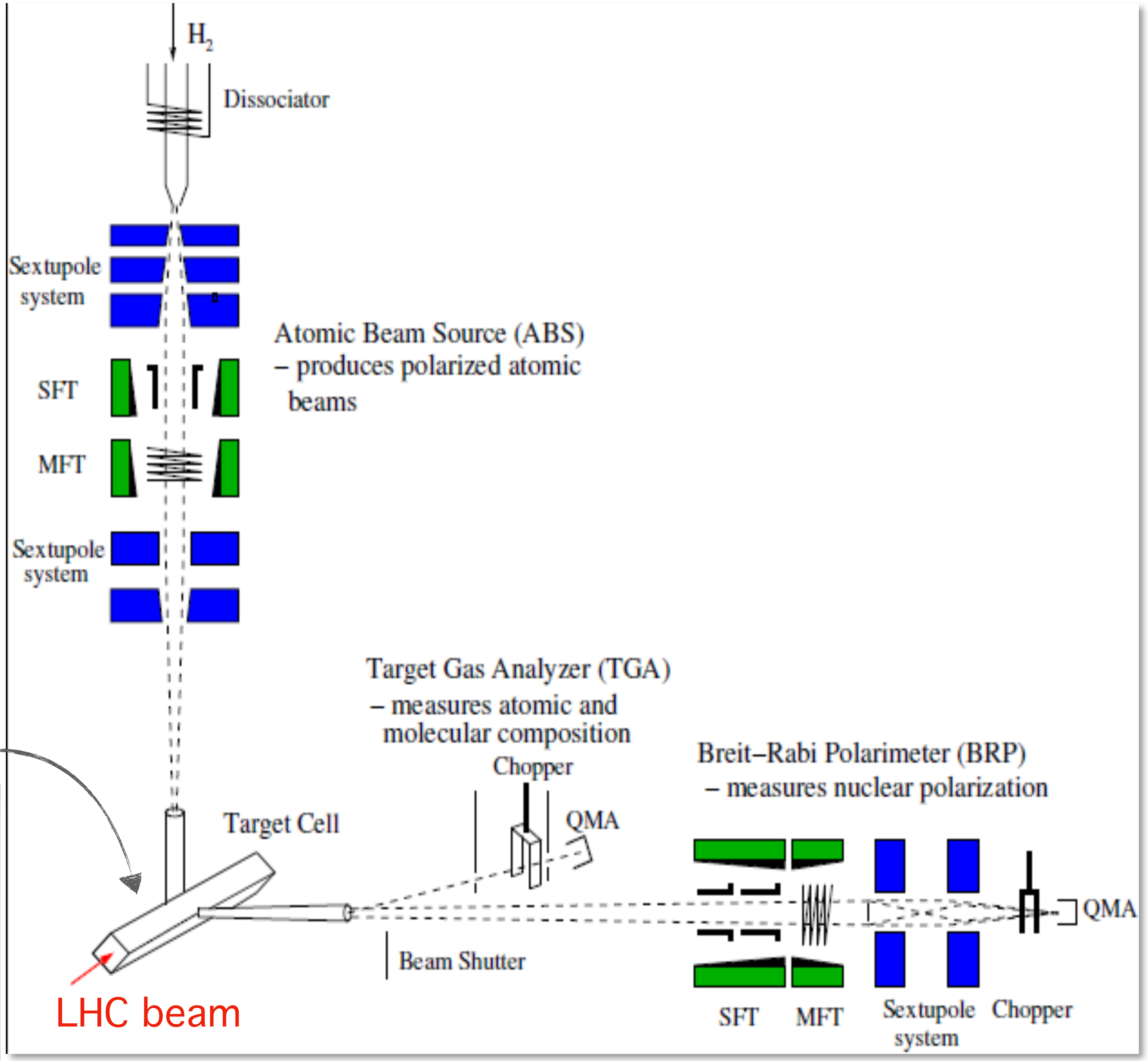
- Quantified by the ellipticity, ϵ_2 wrt Φ_p



LHCspin setup

dipole



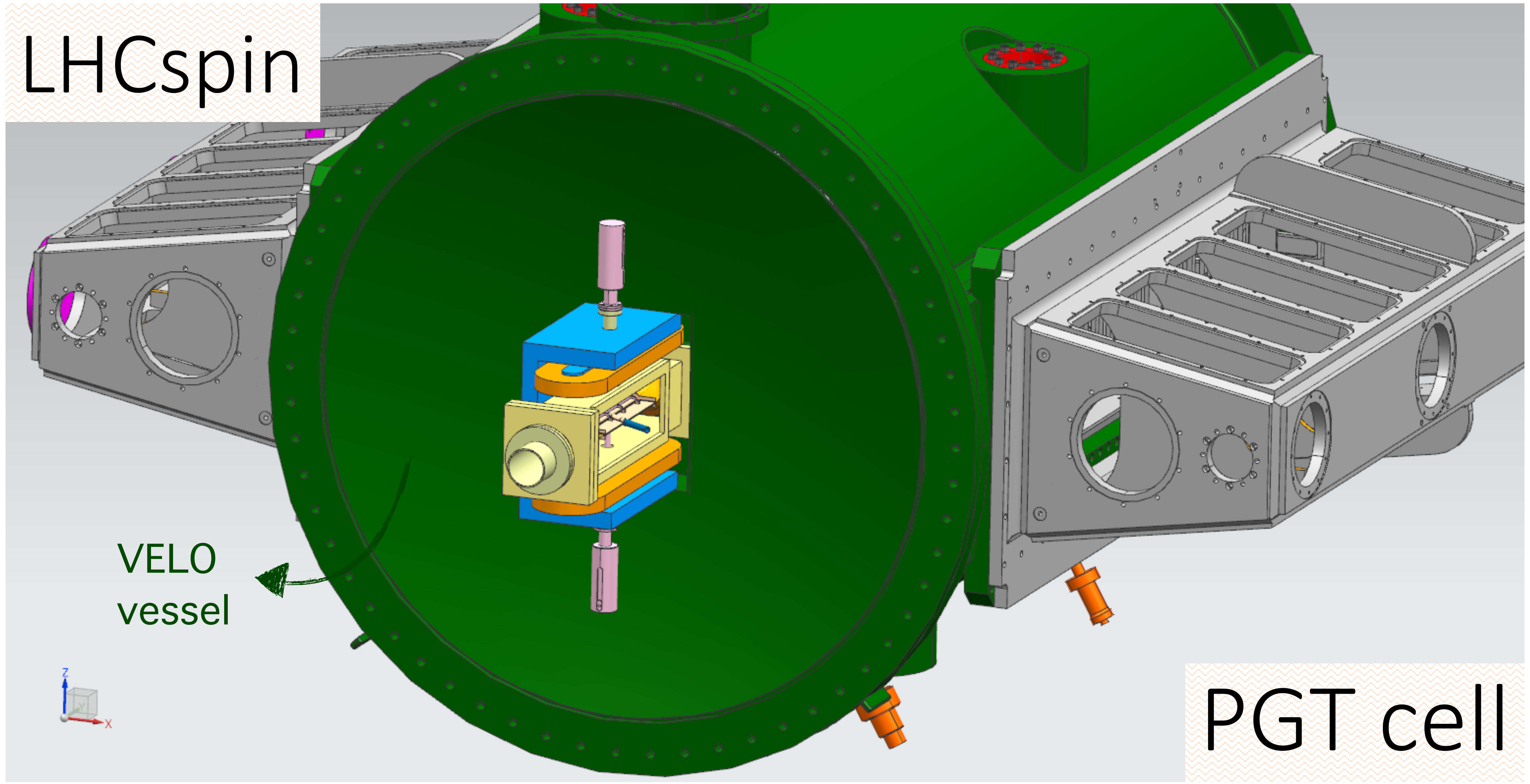


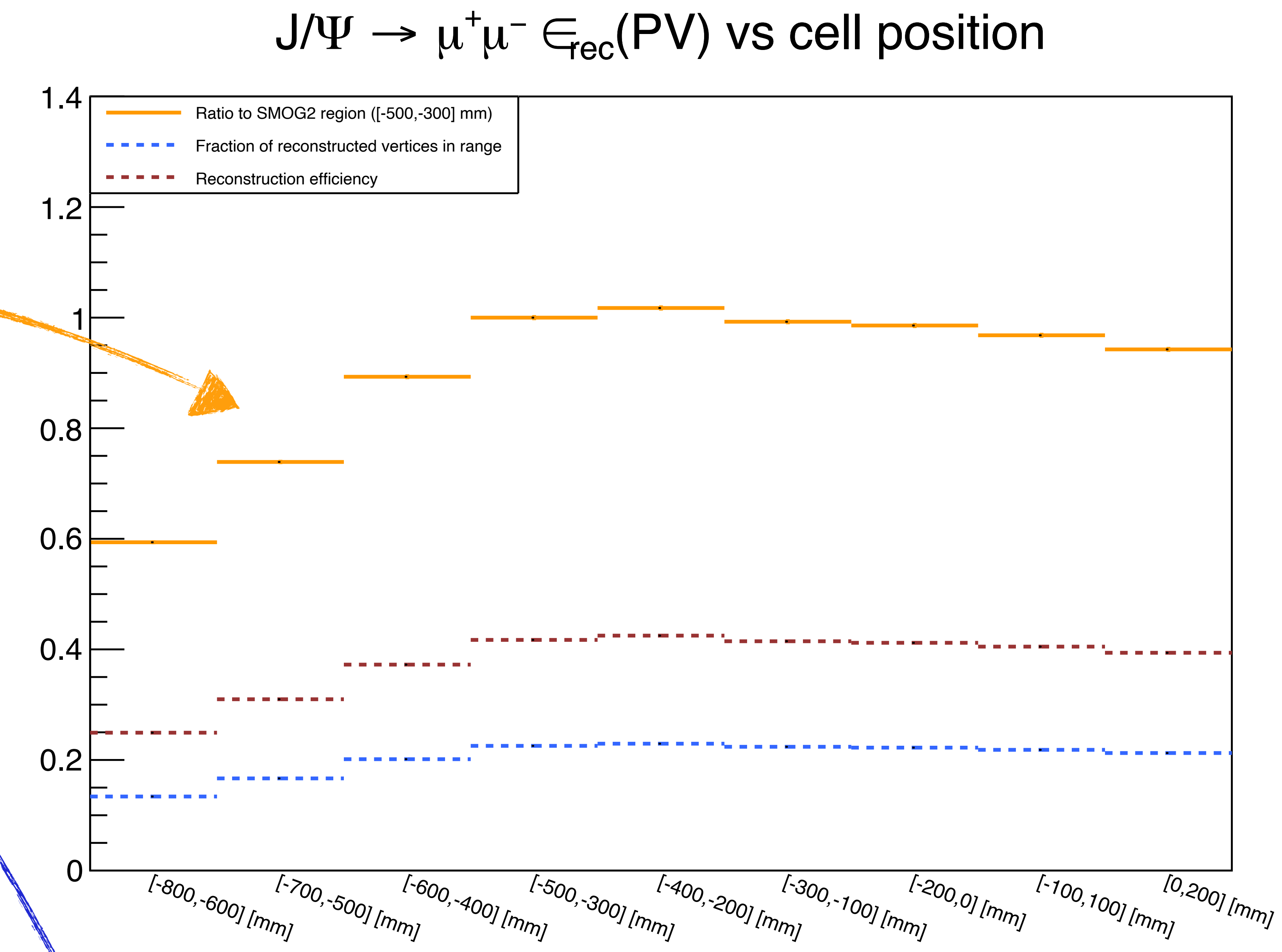
- Start from the well established HERMES setup @ DESY…
- … to create the next generation of fixed target polarisation techniques!

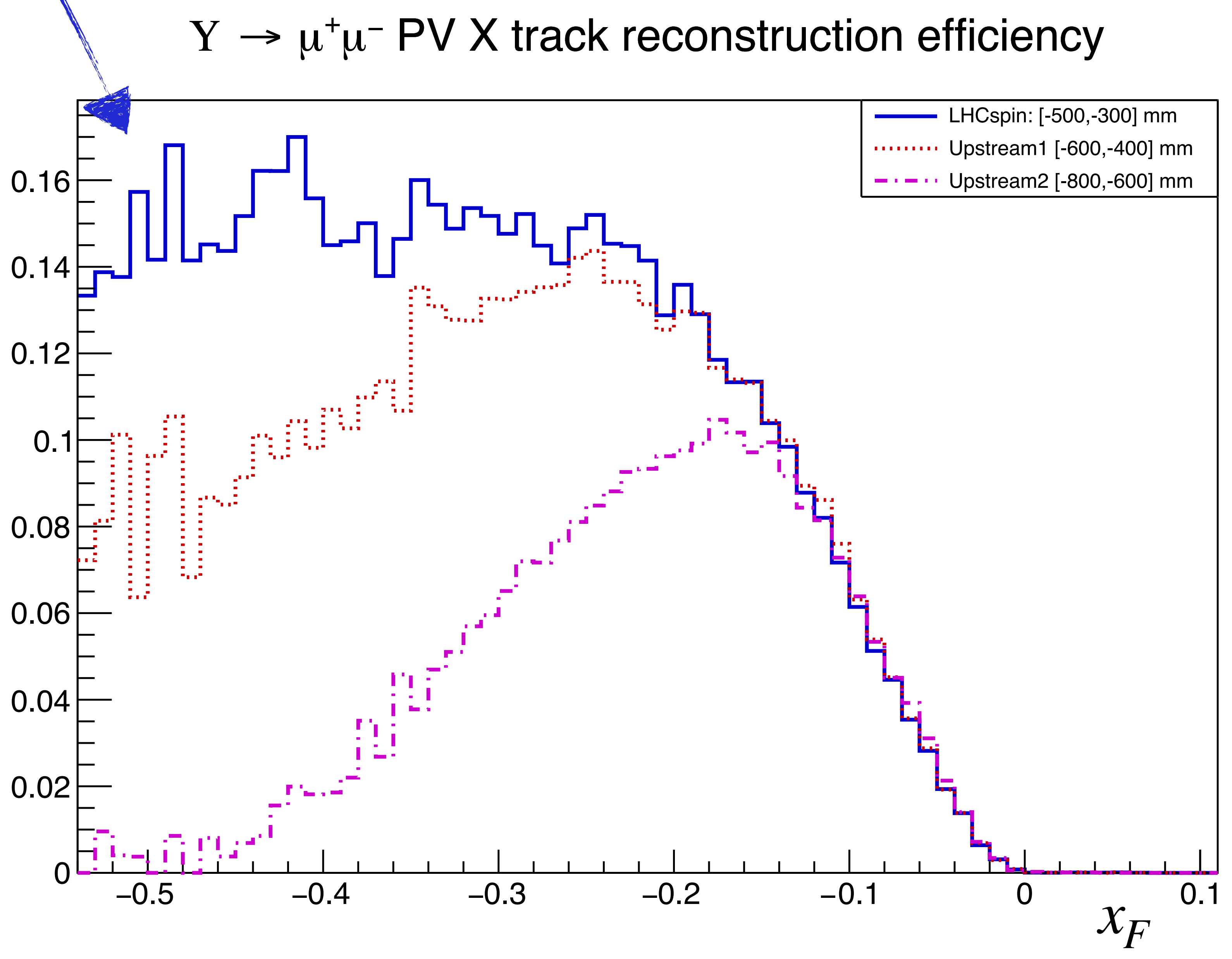
[NIMA 540 (2005) 68-101]

The Polarised Gas Target

- Cylindrical target cell with $L = 20$ cm and $D = 1$ cm
- LHCb simulations with upgrade geometry show broader kinematic acceptance & higher efficiency at the same position of the SMOG2 cell
- Work ongoing to develop ad-hoc trigger lines and to improve reconstruction algorithms for Run 3

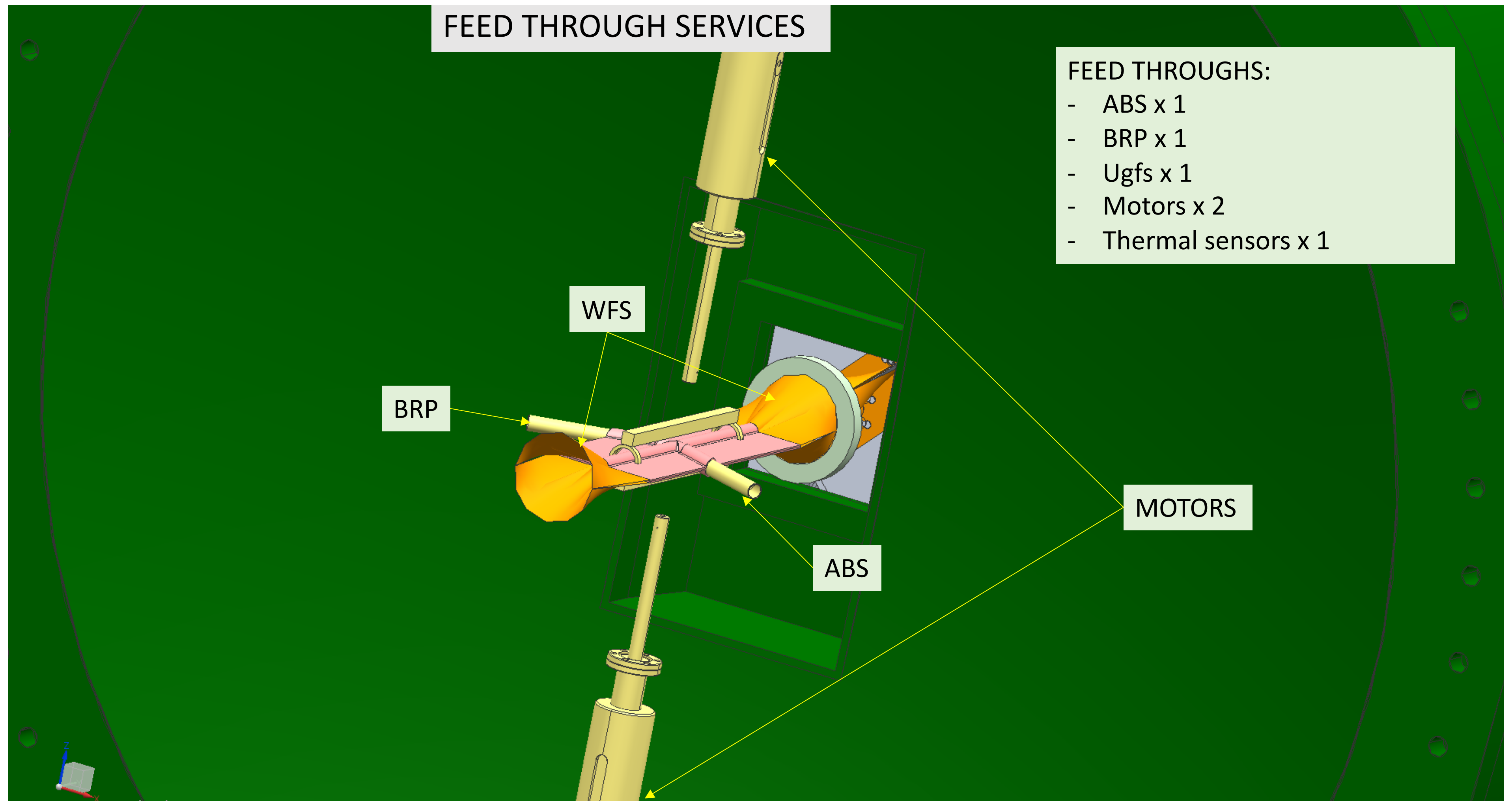


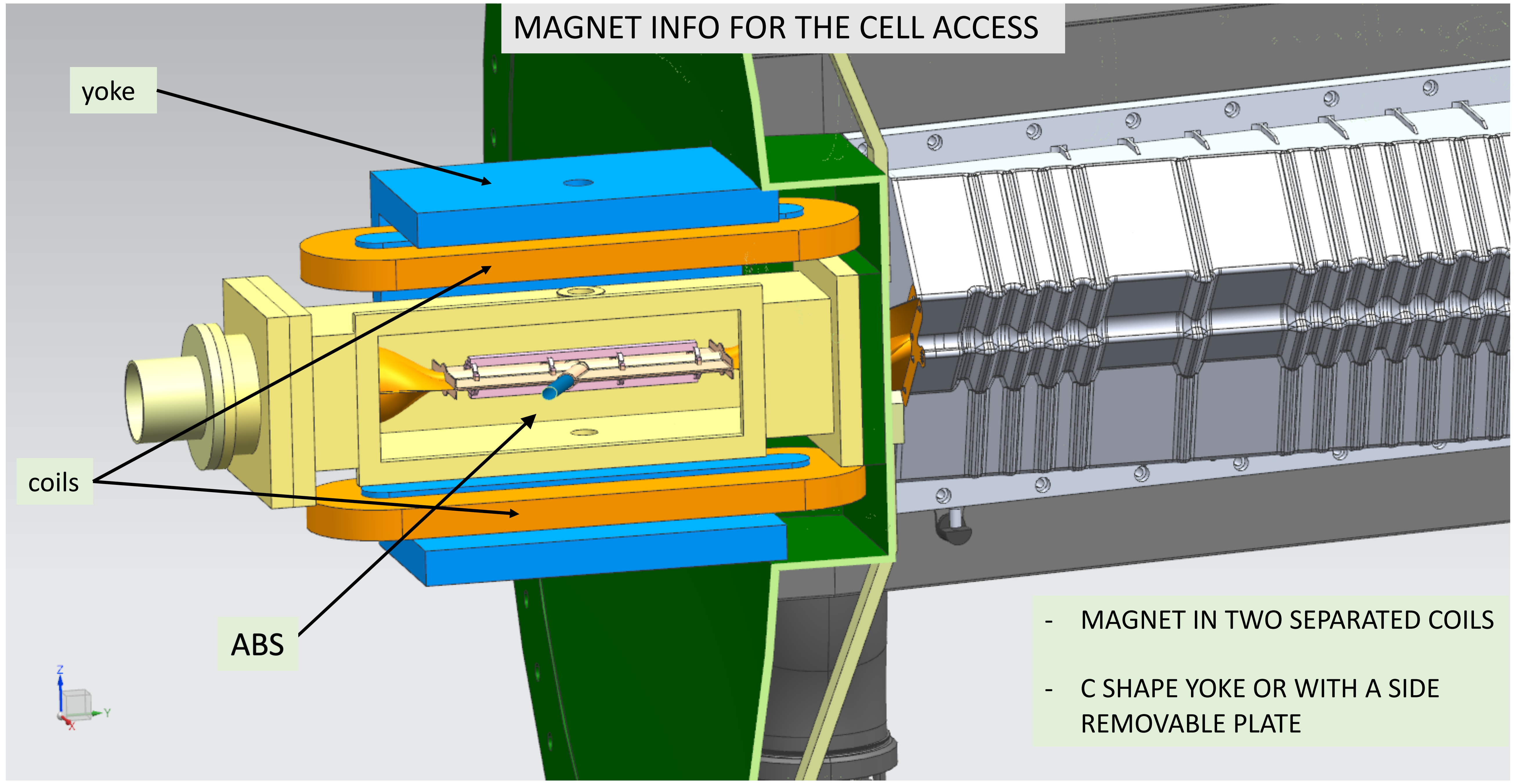




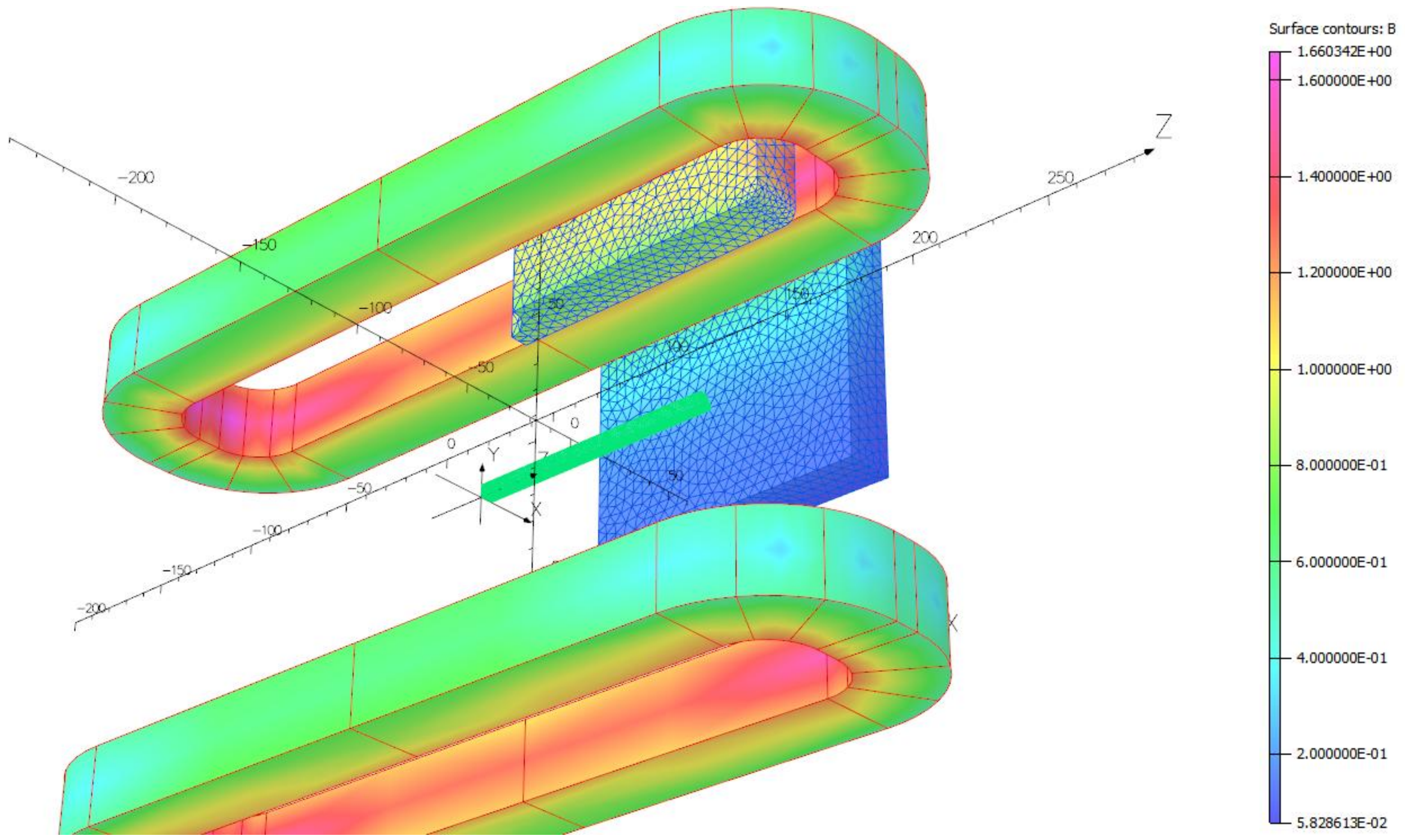
The Polarised Gas Target

- Inject both polarised and unpolarised gases via ABS and UGFS

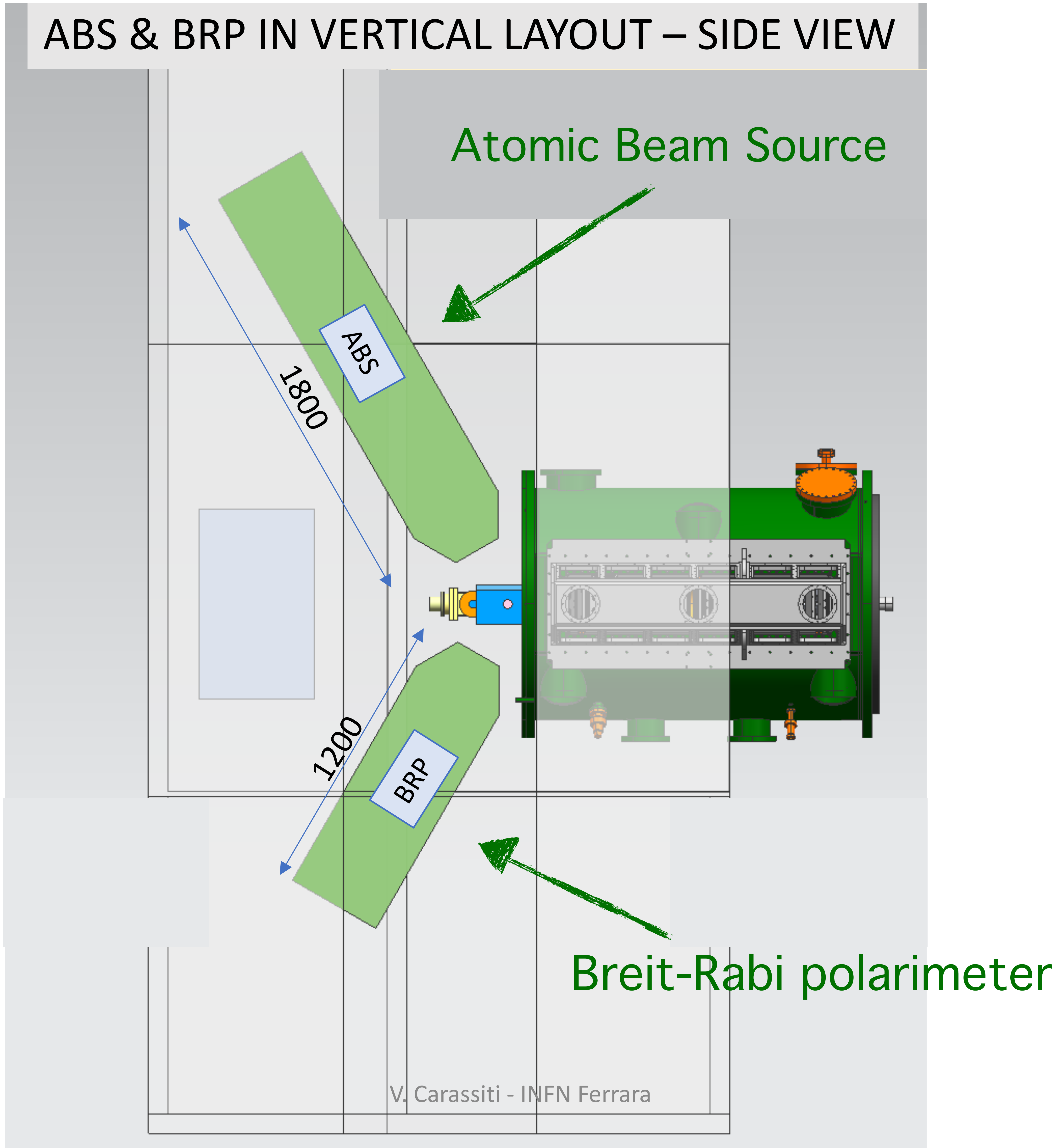




- Compact dipole magnet → static transverse field
- Superconductive coils + iron yoke fits the constraints
- $B = 300$ mT with polarity inversion
- $\Delta B/B \simeq 10\,\%$, suitable to avoid beam-induced depolarisation [PoS (SPIN2018)]



ABS and BRP R&D



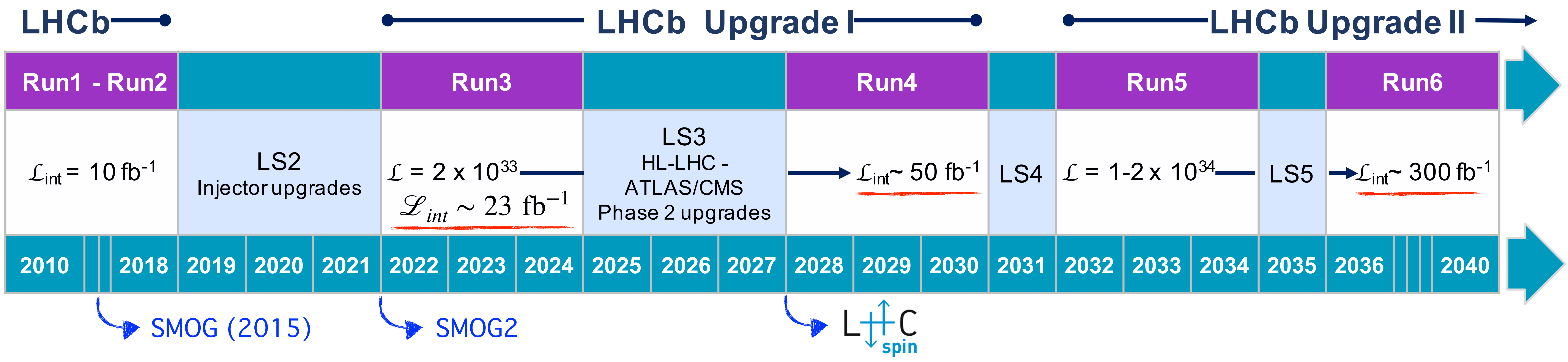
- Reduce the size of both ABS and BRP to fit into the available space in the LHCb cavern
- A challenging R&D!
- No need for additional detectors to LHCb
- $P \simeq 85\,\%$ achieved at HERMES

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

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

- R&D ongoing for the cell inner coating to achieve low SEY
- Alternative solution with jet target also under evaluation: lower density but higher polarisation degree

Conclusions



- The FT program at LHCb is active since Run 2, now enriched with the SMOG2 cell for Run 3
- LHCspin: natural evolution to bring spin-physics for the first time at LHC, exploiting the well-suited LHCb detector
- Nucleon spin and 3D structure investigation is worldwide pursued, yet very little is known, especially on the gluon sector
- The R&D calls for a new generation of polarised gas targets: challenging task but worth the effort!
- Very rich physics program, featuring new opportunities and unique probes
- Complementary to existing facilities and the future EIC