Quarkonia As Tools
Aussois, 12/01/2024

Fixed-target LHCb prospects and TMD studies with quarkonia

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On behalf of the LHCb and LHCspin collaborations

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Fixed-target LHCb prospects

The LHCb experiment

General purpose forward spectrometer

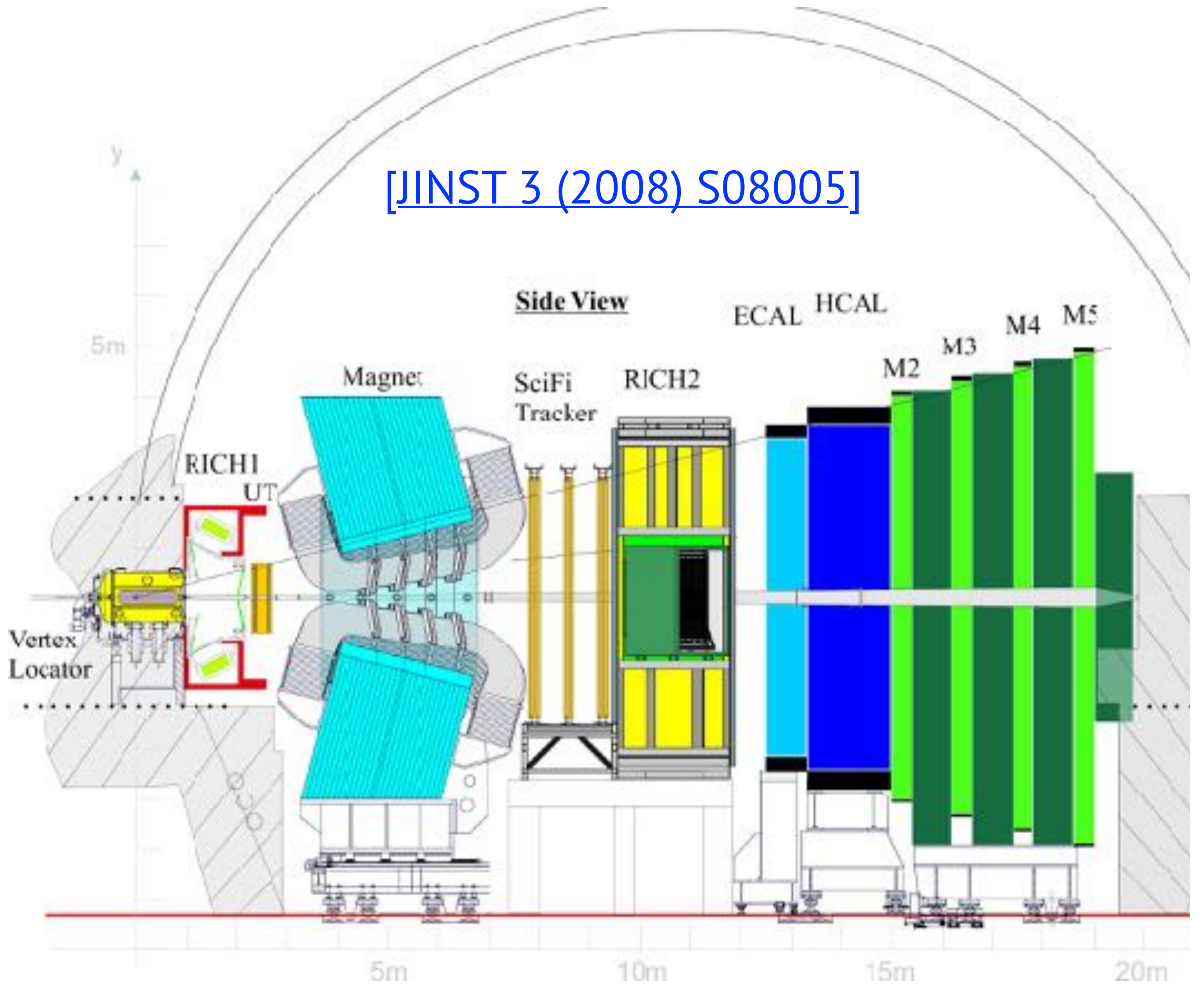
- Rapidity coverage: $2 < \eta < 5$

LHCb upgrade for Run 3 [Rita Talk]

- Factor of 5 increase in luminosity
- Major hardware upgrade
- Full-software trigger (40 MHz rate)

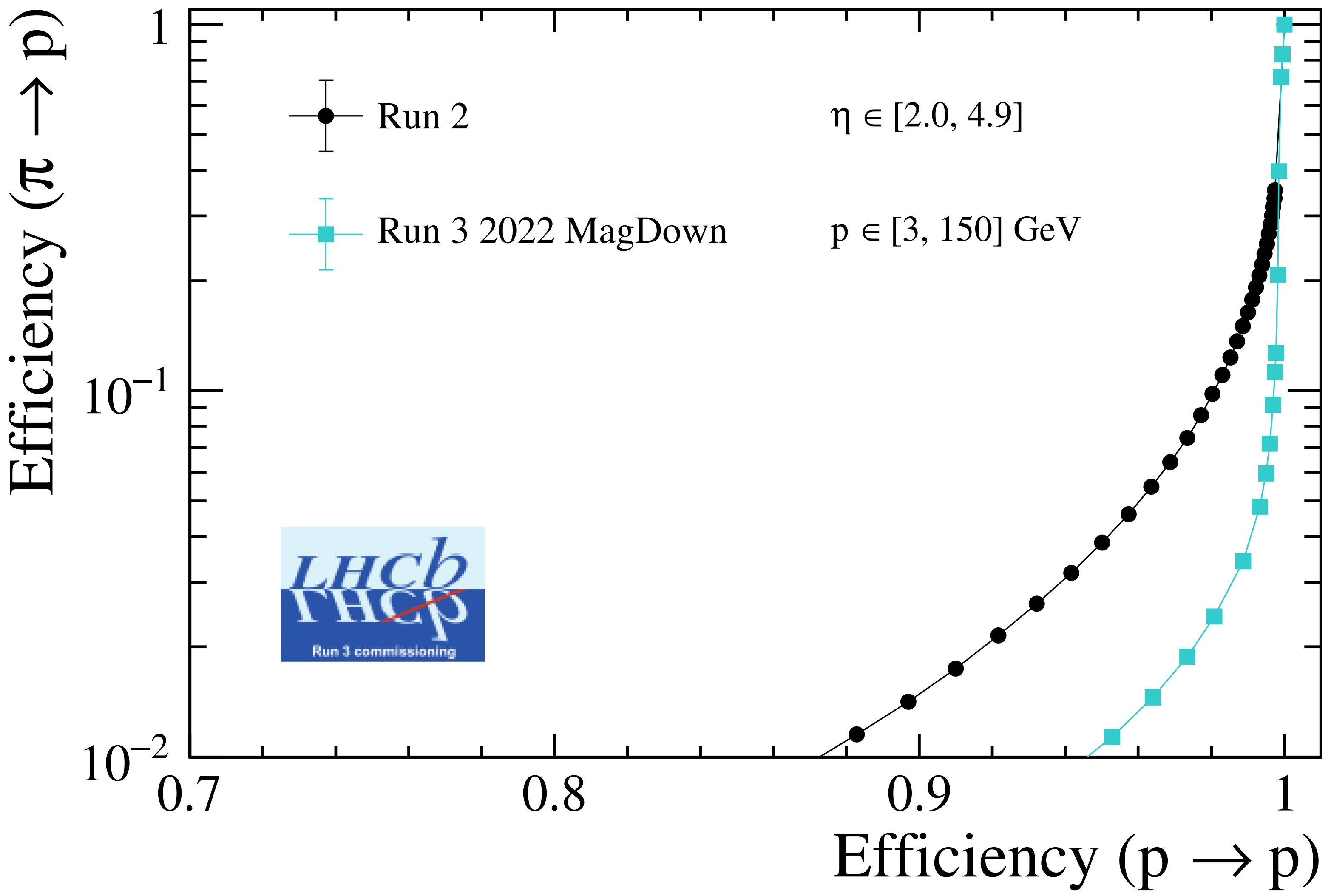
Promising preliminary performance in Run 3

- Tracking:
  $\sigma_p/p \simeq 0.5 - 1.0\,\%$
  $p \in [2{,}150]$ GeV/c
- Particle identification:
  better performance than Run 2

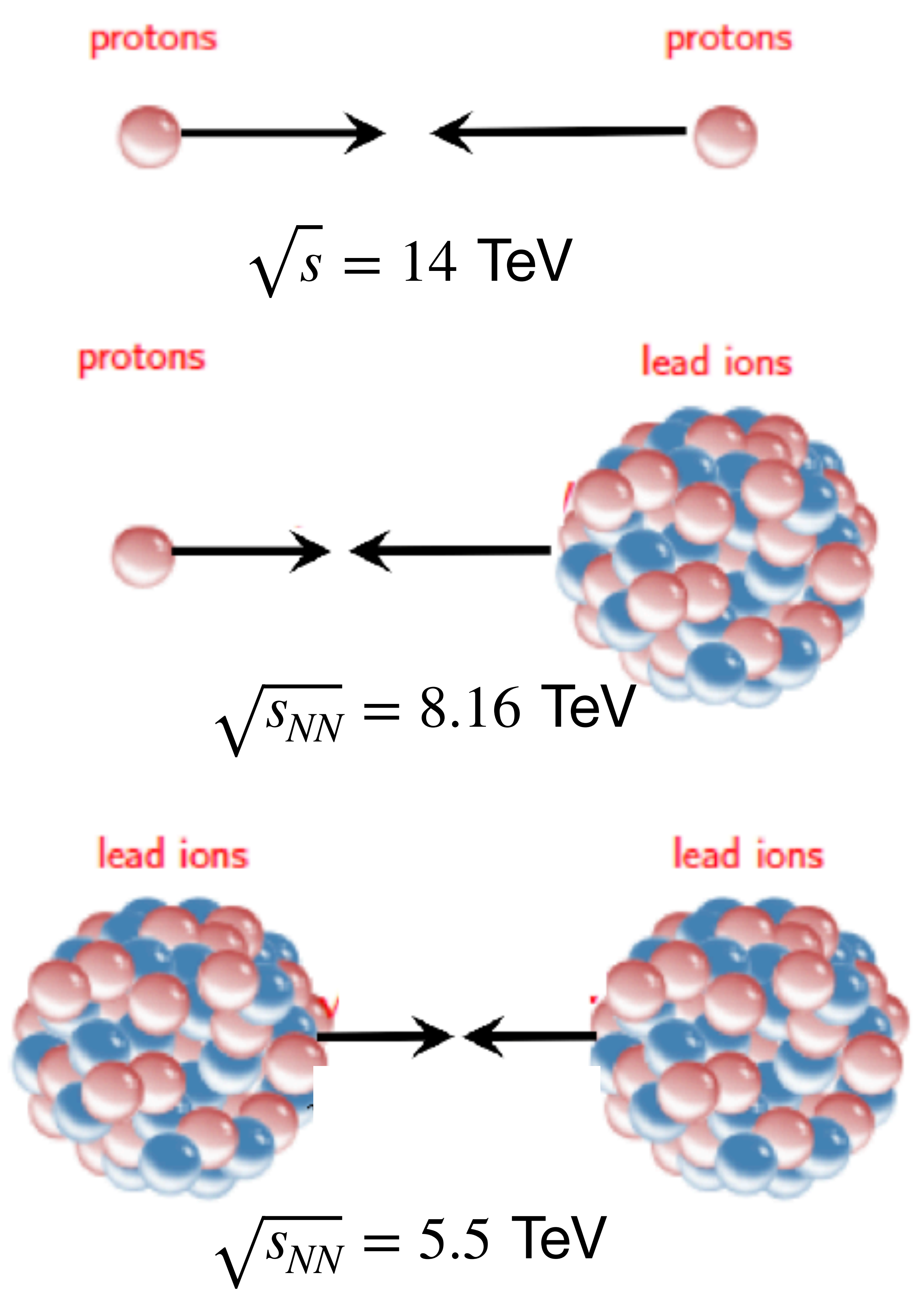


[JINST 3 (2008) S08005]

[LHCB-FIGURE-2023-019]



Collider Mode



$\sqrt{s} = 14$ TeV

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

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

Fixed-target program at LHCb

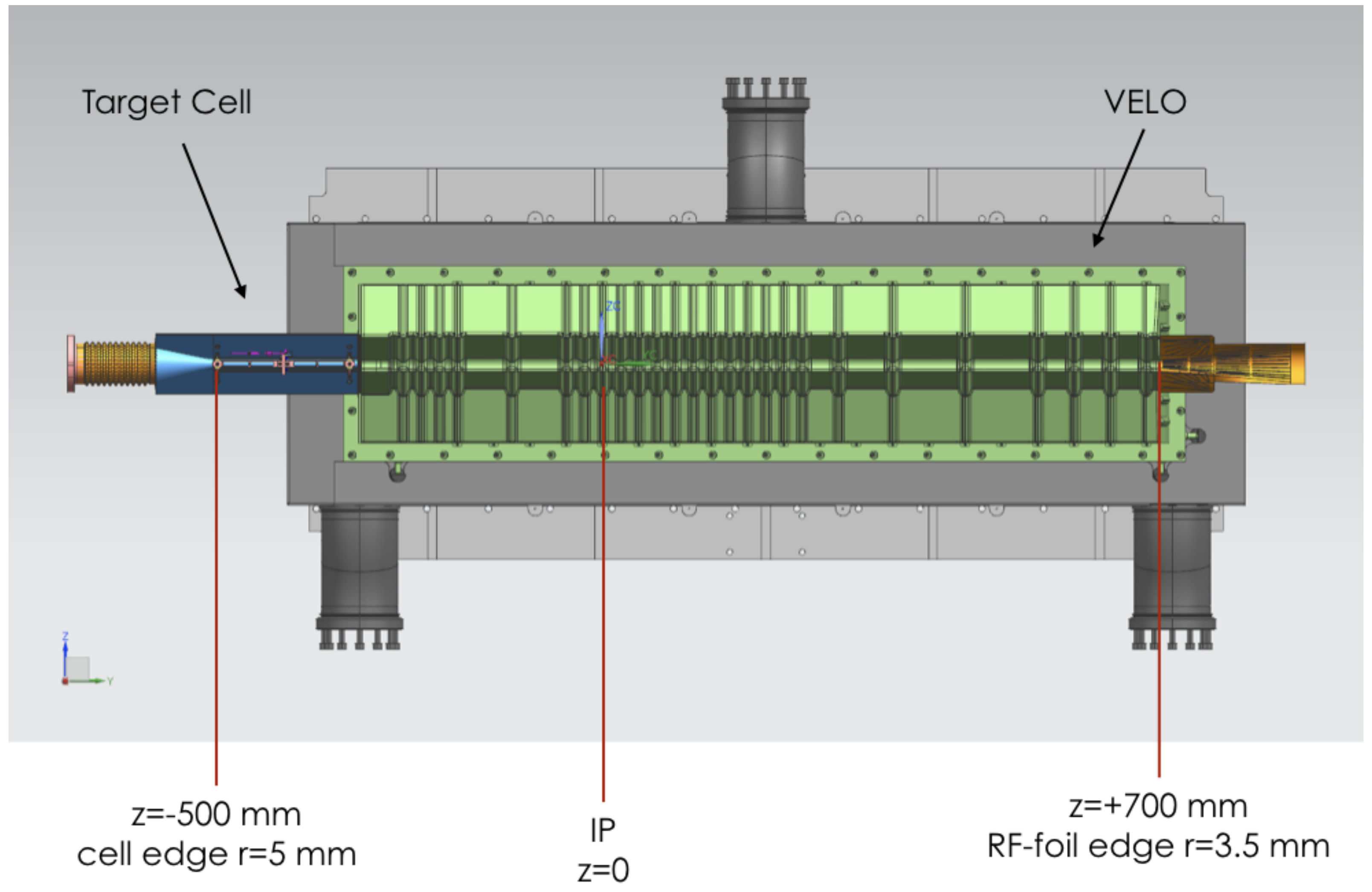
2015-2018
SMOG: first fixed-target program

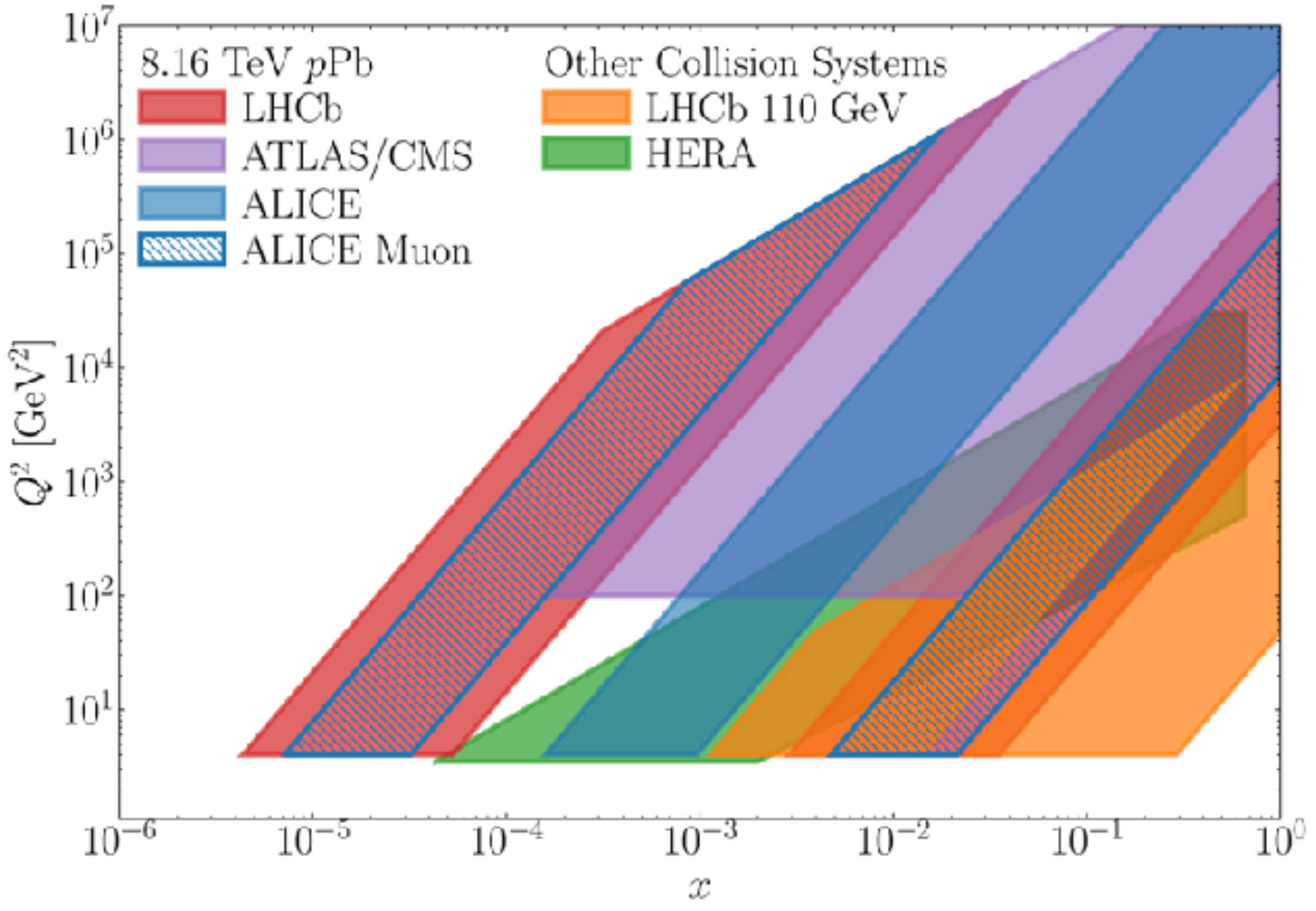
- Injection of noble gas inside the VELO

Run 3 [Gabriel Talk]
SMOG2 upgrade: openable storage cell

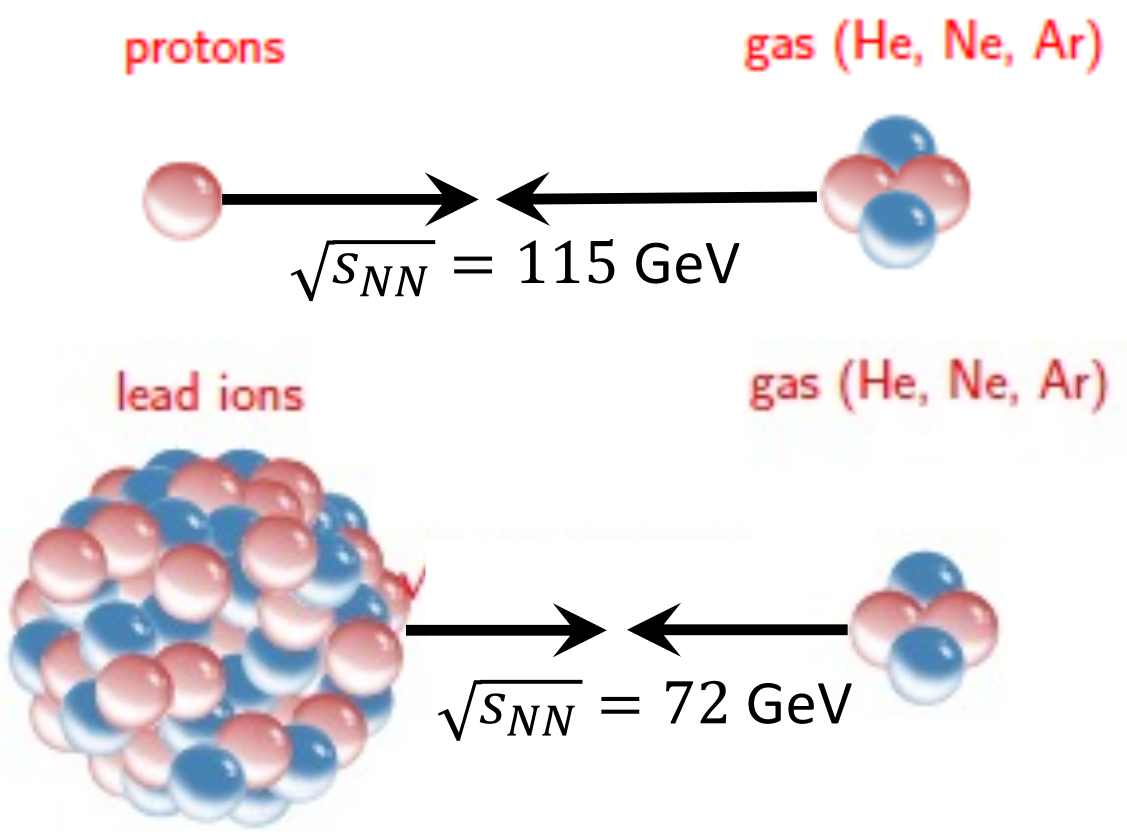
- Significantly higher areal density
- More gas species:
  H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe
- Negligible impact on LHC beam and LHCb performance

[SMOG2 TDR]





Fixed-target Mode



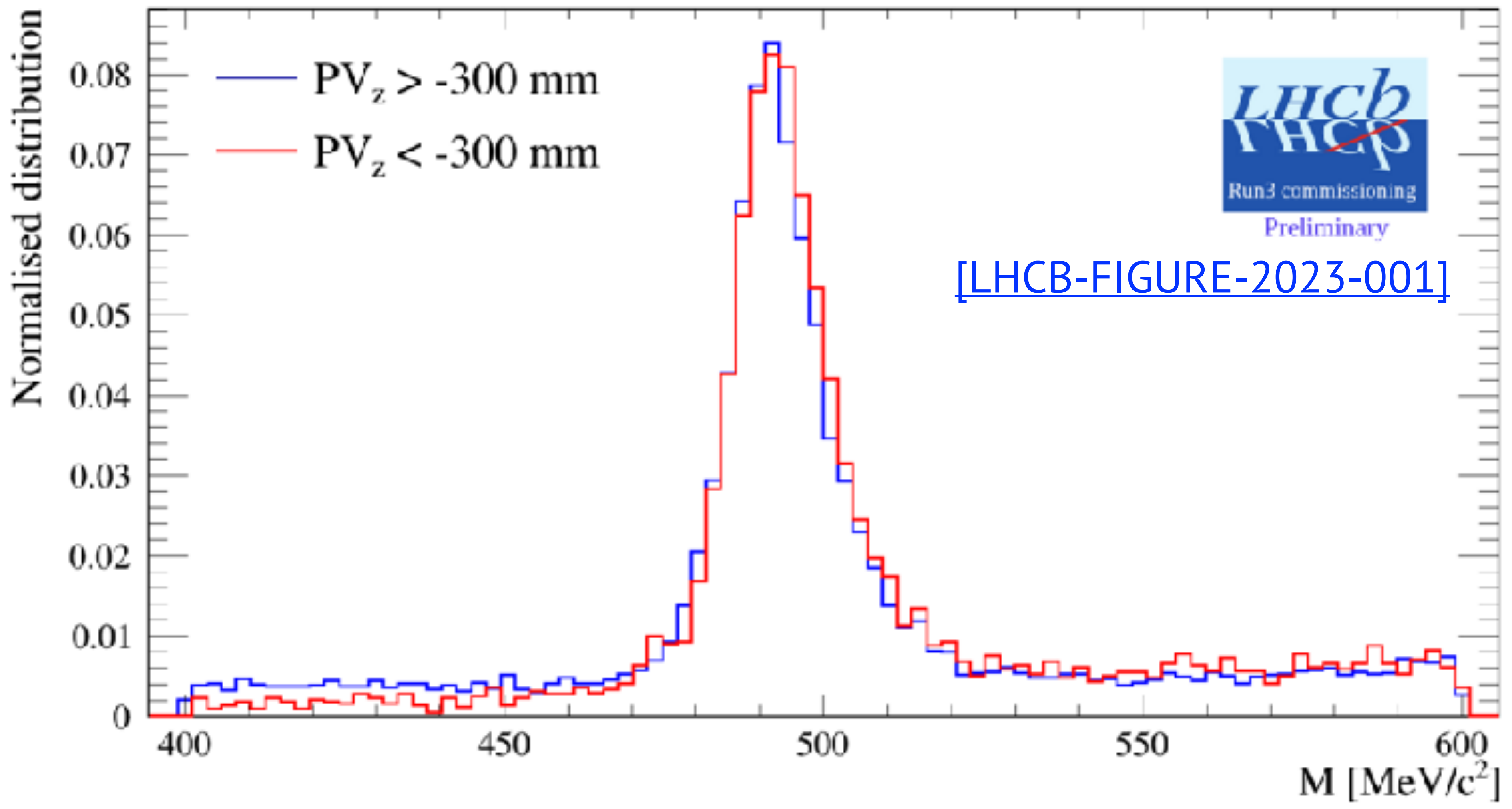
- $-2.3 \leq y_{CM} \leq 0$
- Mid-to-large x at intermediate Q^2 and negative x_F

Performance SMOG2+LHCb

Promising detector performance for fixed-target events in Run 3

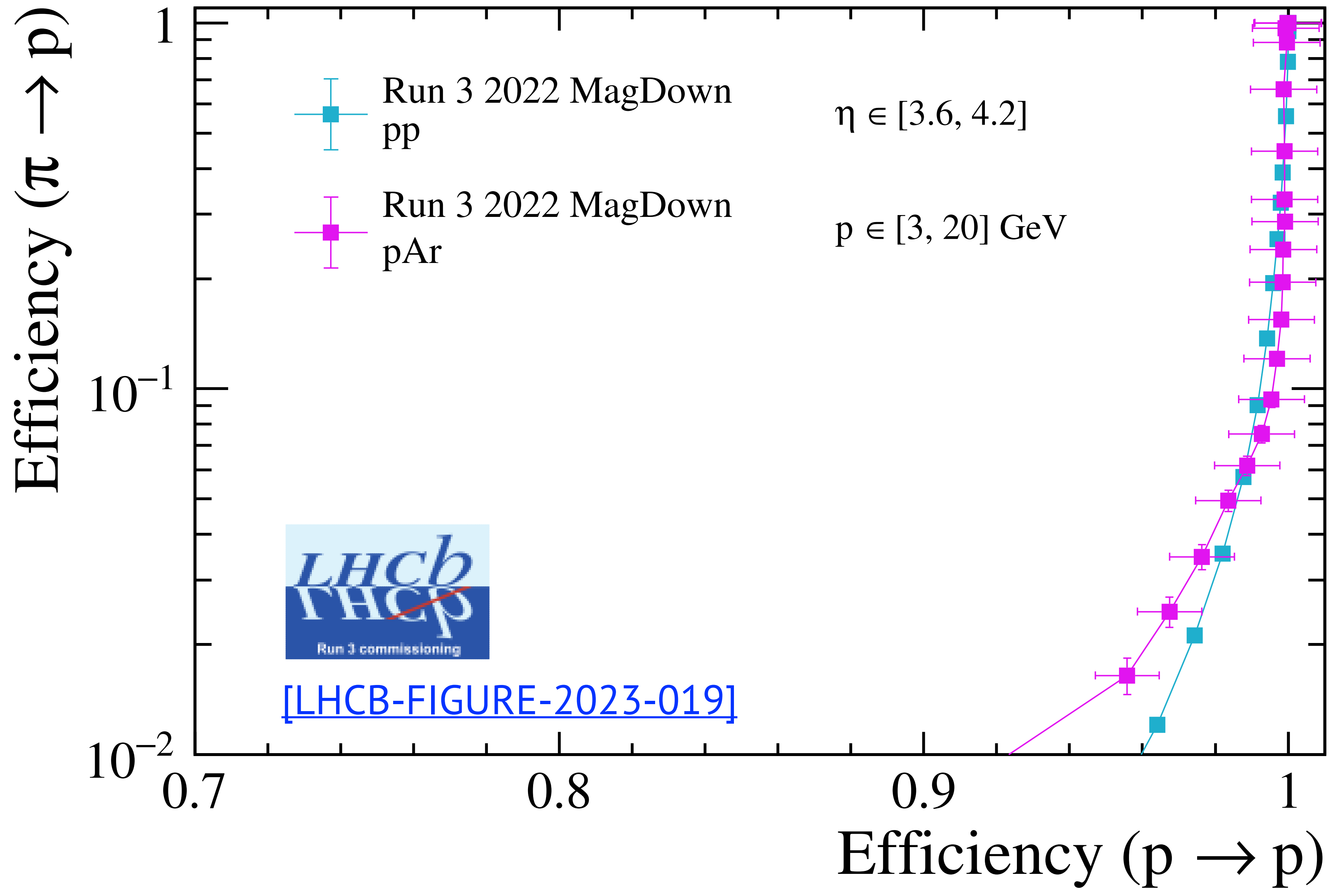
- Similar tracking and reconstruction performance
- Excellent PID performance
- LHCb can run collider and fixed-target mode simultaneously!

Mass Resolution



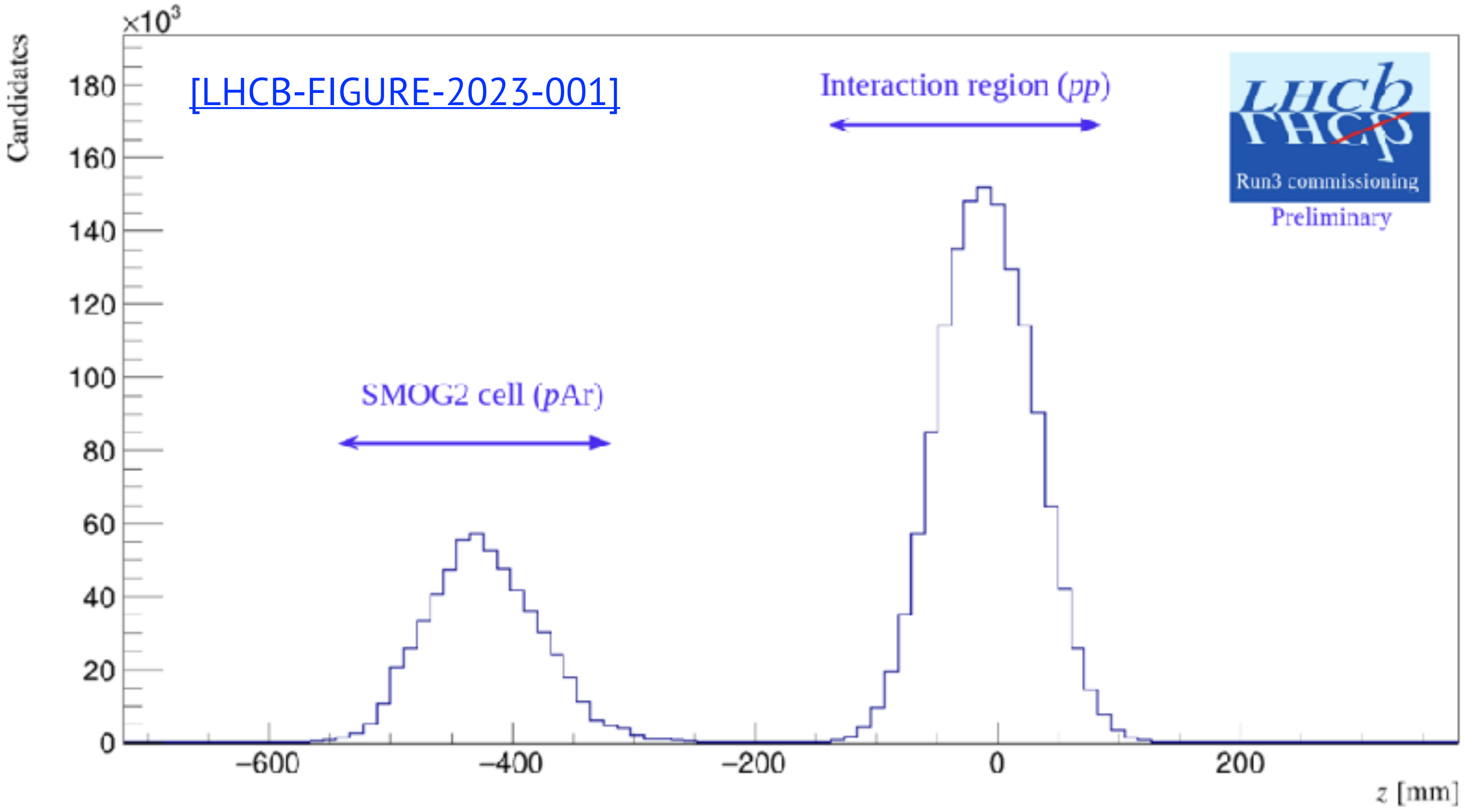
[LHCB-FIGURE-2023-001]

PID Performance



[LHCB-FIGURE-2023-019]

PV_Z Reconstruction



[LHCB-FIGURE-2023-001]

Performance SMOG2+LHCb

SMOG2 can efficiently study heavy-flavour

- ~20 min of data-taking in pAr collisions:
  $J/\psi \sim 440$ events
  $D^0 \sim 4200$ events
- Good prospectives for other quarkonia states (ex. η_c, χ_{c0})

SMOG2 enables pH collisions

- Clean K_S^0 and Λ^0 mass peaks
- Crucial ingredient for studying the nucleon structure and measuring TMDs

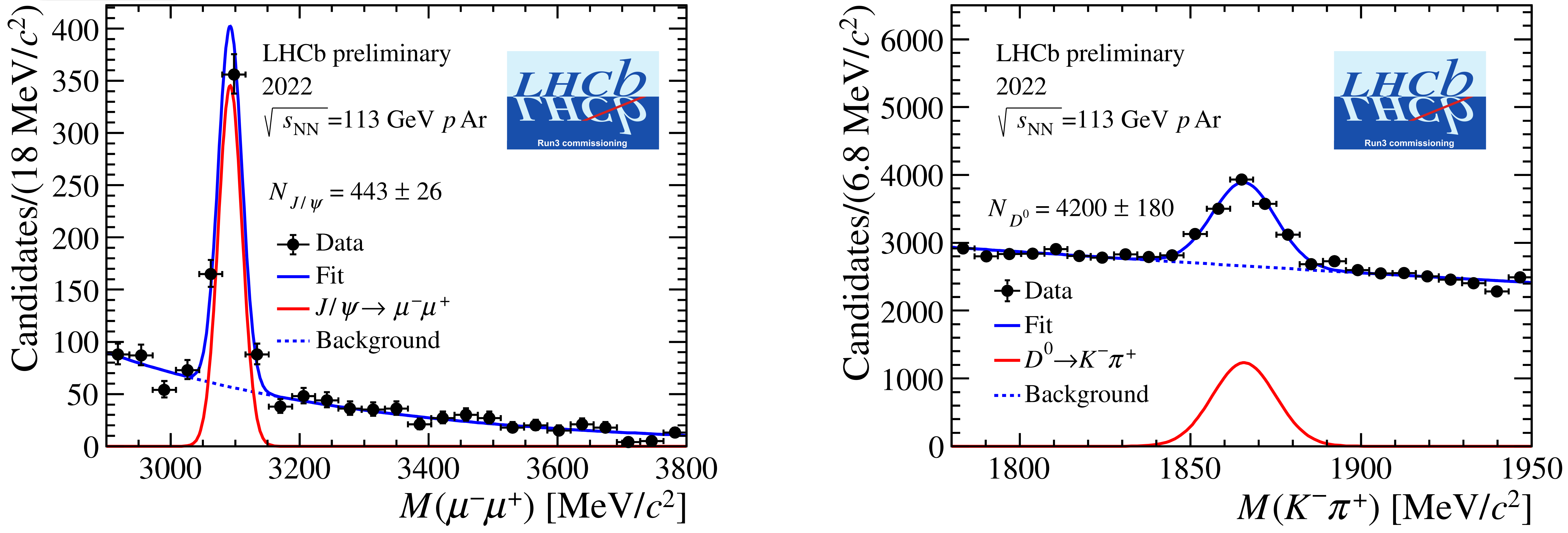
SMOG2 is performing above expectations

- LHCb subdetectors are still under commissioning
- Expecting even better performance in 2024

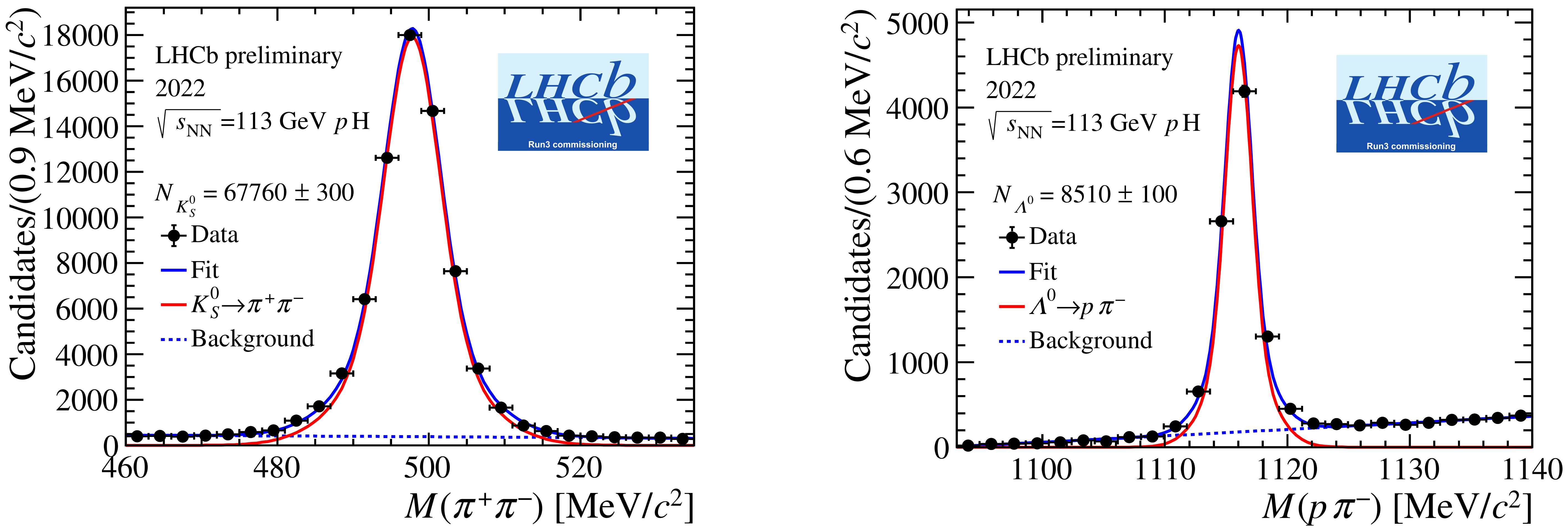
pAr

Data taking time ~ 20 min

[LHCB-FIGURE-2023-008]



pH



Physics opportunity with SMOG2

Study the nucleon structure

- Collinear PDFs:
  1-dimensional description of the nucleon structure
- Transverse Momentum Dependent (TMD) PDFs:
  - 3D generalisations of collinear PDFs in momentum space
  - Include also the dependence on the parton transverse momentum $k_\perp$

quark pol.

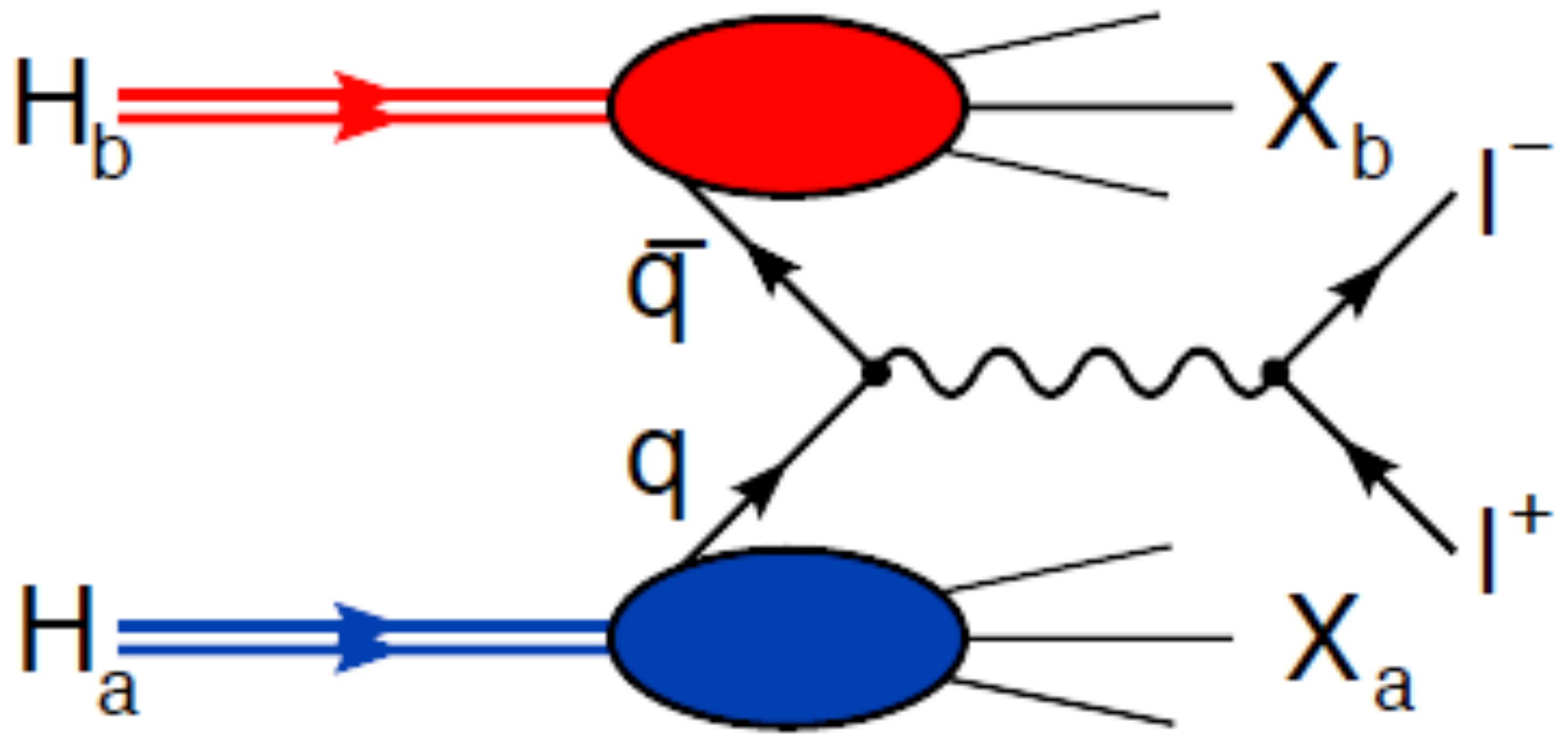
nucleon pol.

	U	L	T
SMOG2	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

Boer-Mulder TMD

Best process with SMOG2: unpolarised Drell-Yan

- Theoretically cleanest h-h hard scattering process
- Dominant process: $\bar{q}(x_{beam}) + q(x_{target}) \rightarrow \mu^+\mu^-$
- Probe valence quarks of the target at large x



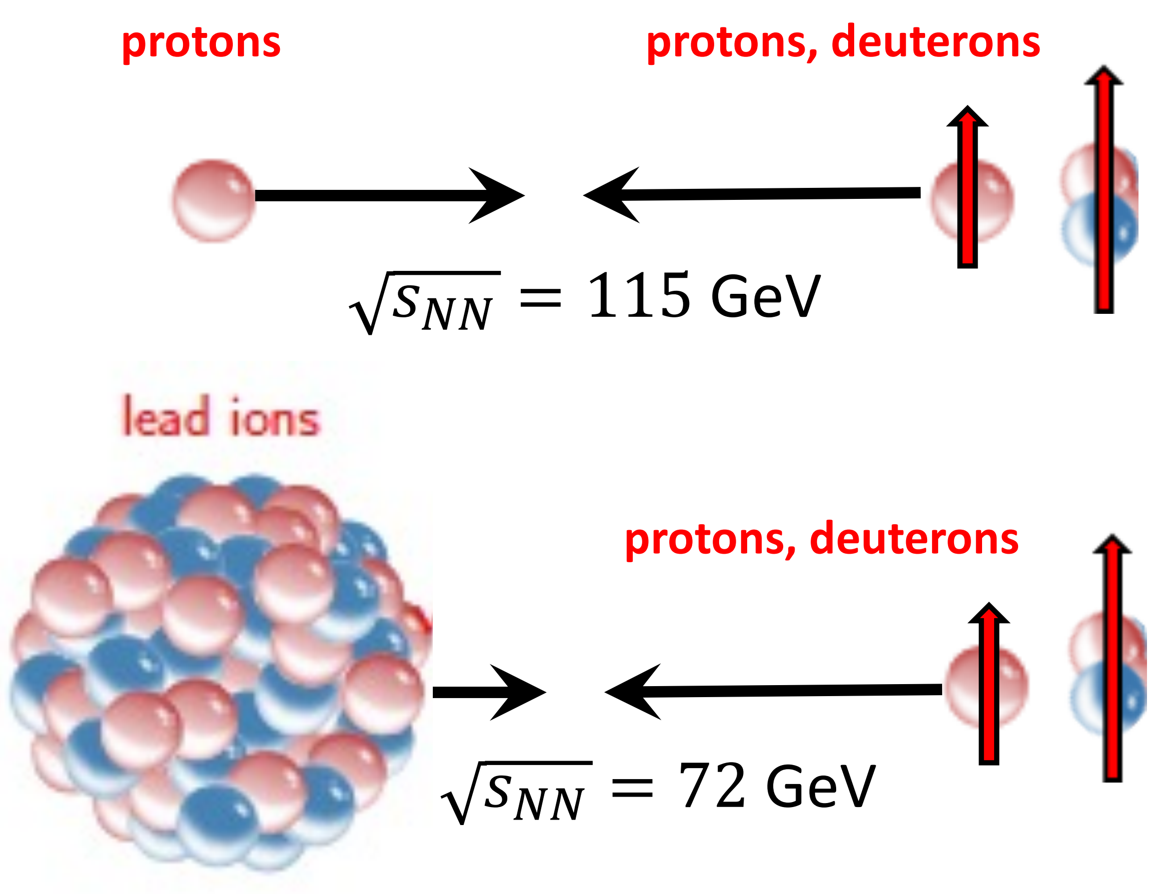
Sensitive to Boer-Mulder TMD $h_1^\perp$

- Describe the transverse momentum distribution of a transversely polarised quark in an unpolarised nucleon

The LHCspin project

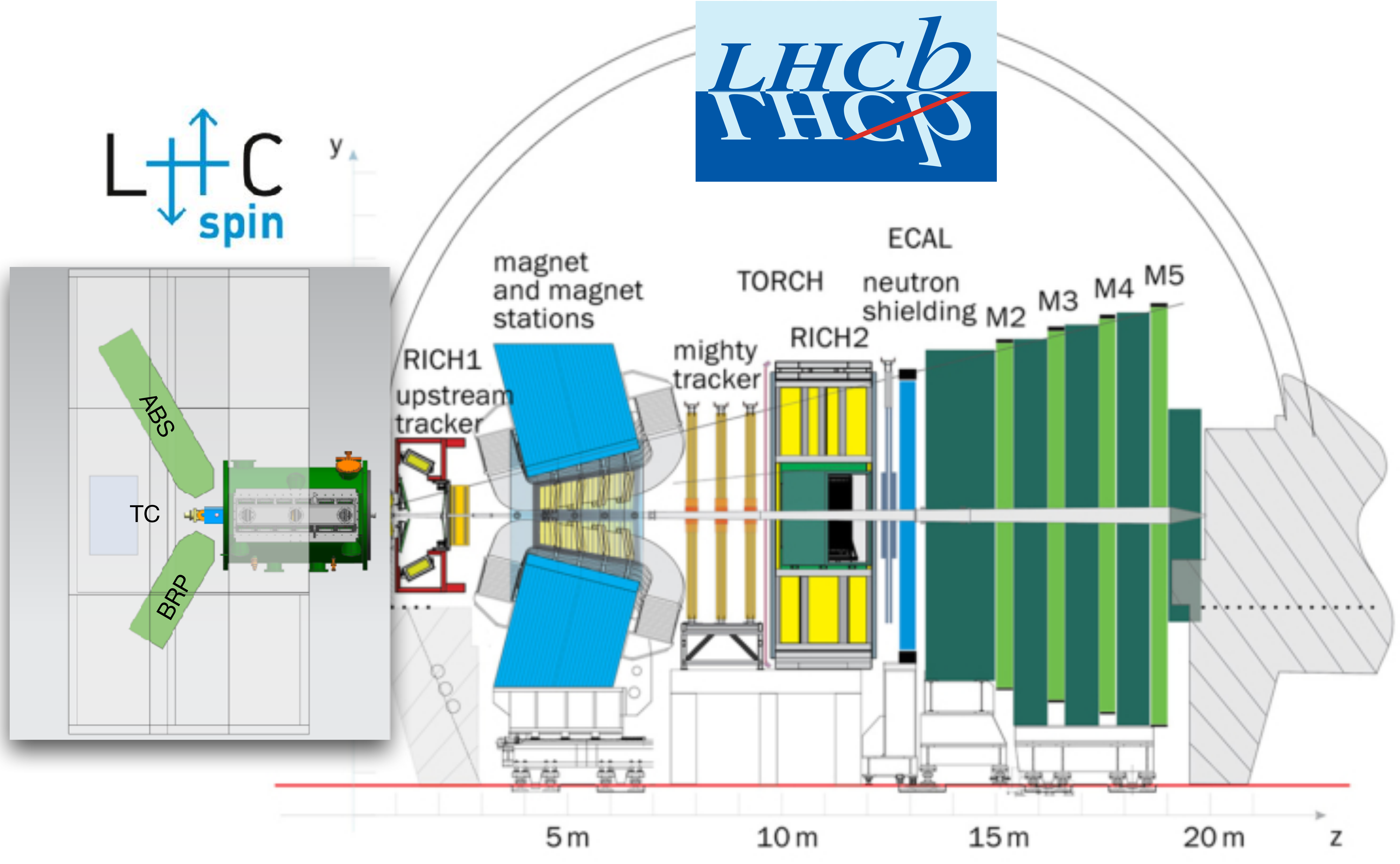
The LHCspin project

Polarised Mode



- **LHCspin**: development of a new generation of polarised targets (baseline HERMES)
- **LHCb**: excellent capabilities to reconstruct quarkonia
- First spin-physics program @ LHC

Run 5



Overview of the setup

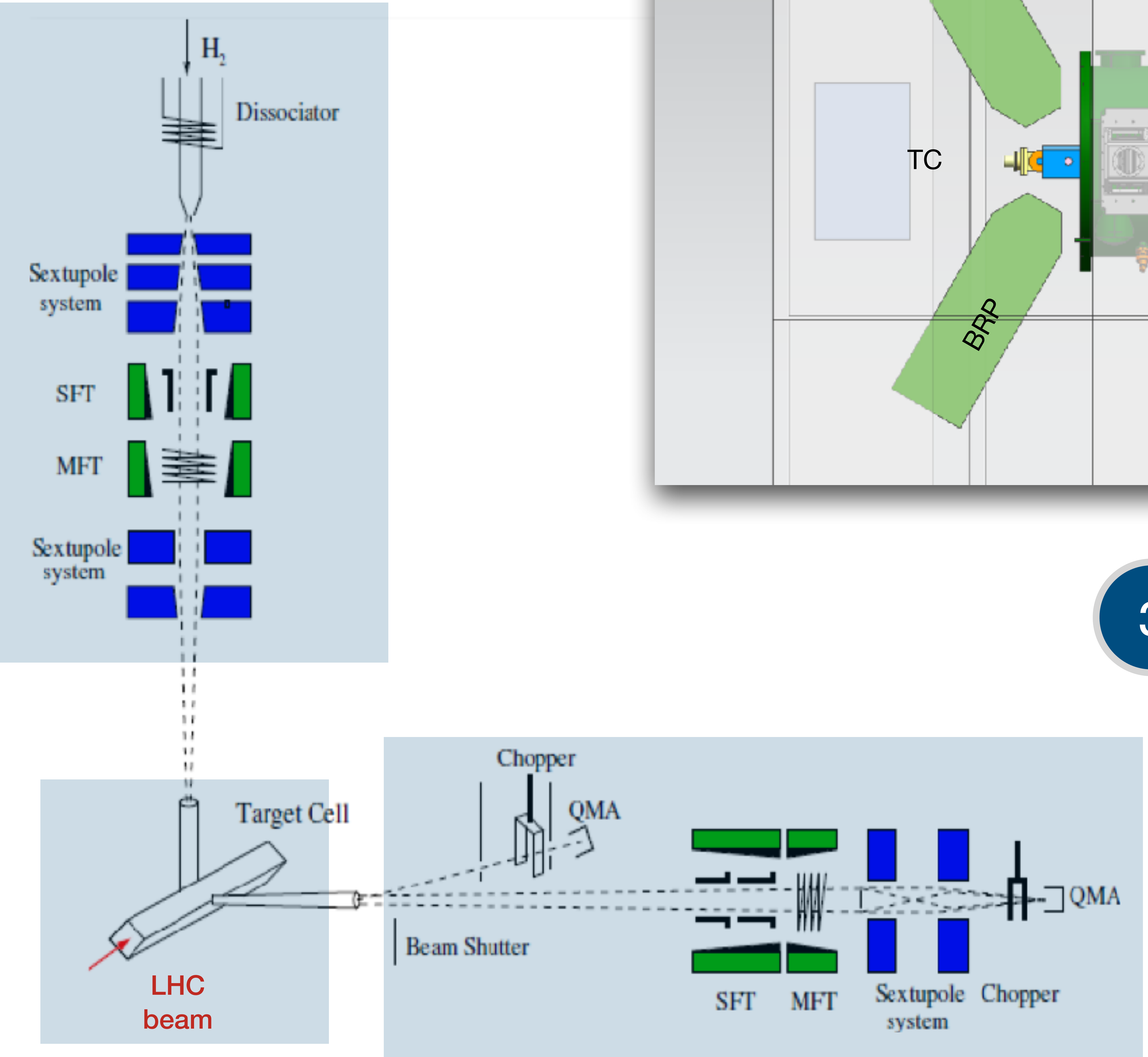
1 Atomic Beam Source (ABS)

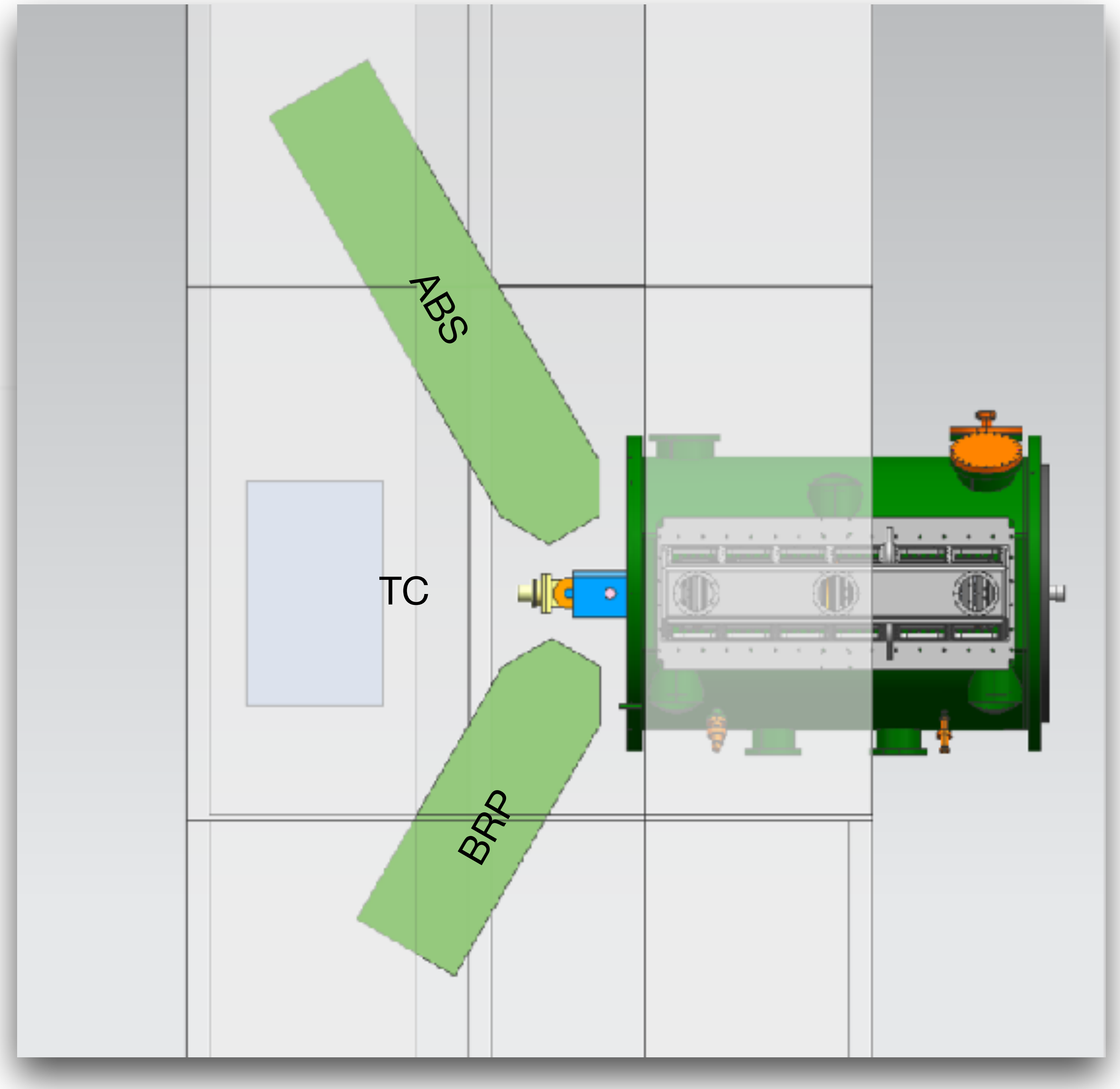
- Input: unpolarised molecules
- Output: high intensity, collimated, polarised atomic beam

2 Target Cell (TC)

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

[NIMA 540 (2005) 68-101]





3 Diagnostic System

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

Target cell and magnet

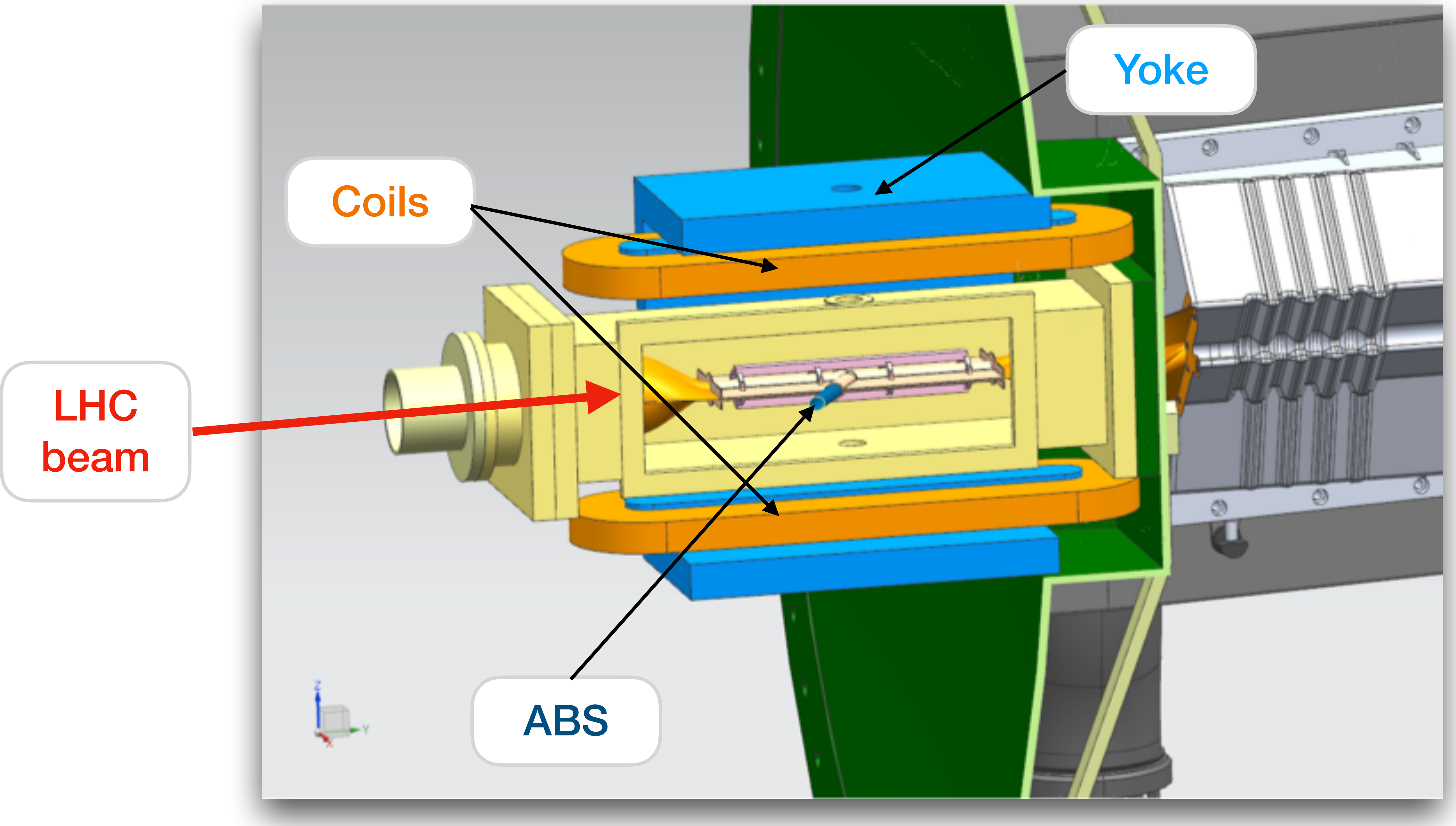
[PoS (SPIN2018)]

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 **up to** $70\,\%$ **,** $\Delta P/P \sim 10 - 15\,\%$

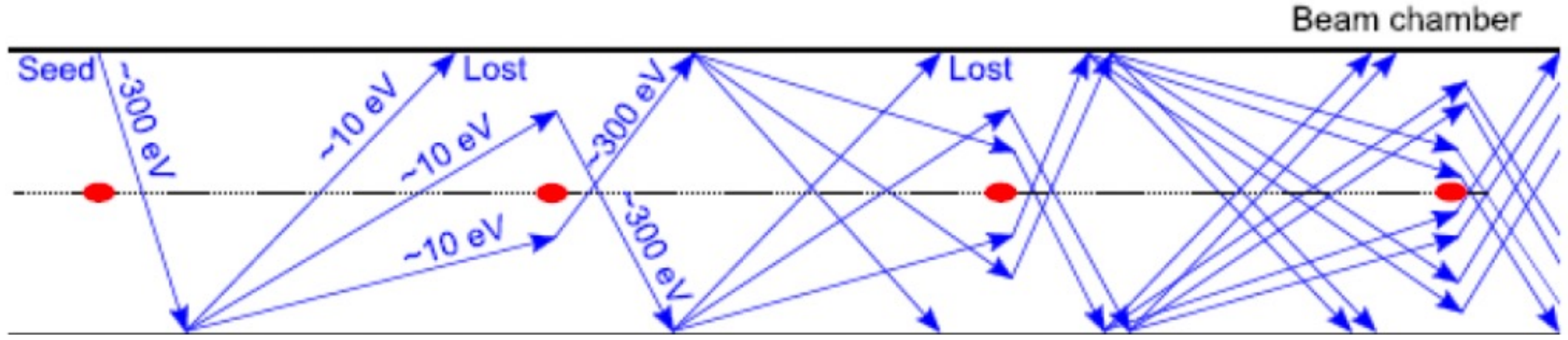
Dipole Magnet

- $B \simeq 300$ **mT**, to maintain transverse polarisation
- Uniformity $\Delta B/B \sim 10\,\%$, to suppress beam-induced depolarisation
- Superconductive coils + iron yoke
- Possibility to **rapidly invert the polarity**



Cell Coating

- **Minimise $H^{\uparrow}$ depolarisation** due to wall collisions
- Ensure low **Secondary Electron Yield** (SEY)
- Current coating: Amorphous Carbon
- Challenging R&D ongoing



Physics opportunities

The physics goal of LHCspin

Study strong interaction in the non-perturbative regime of QCD

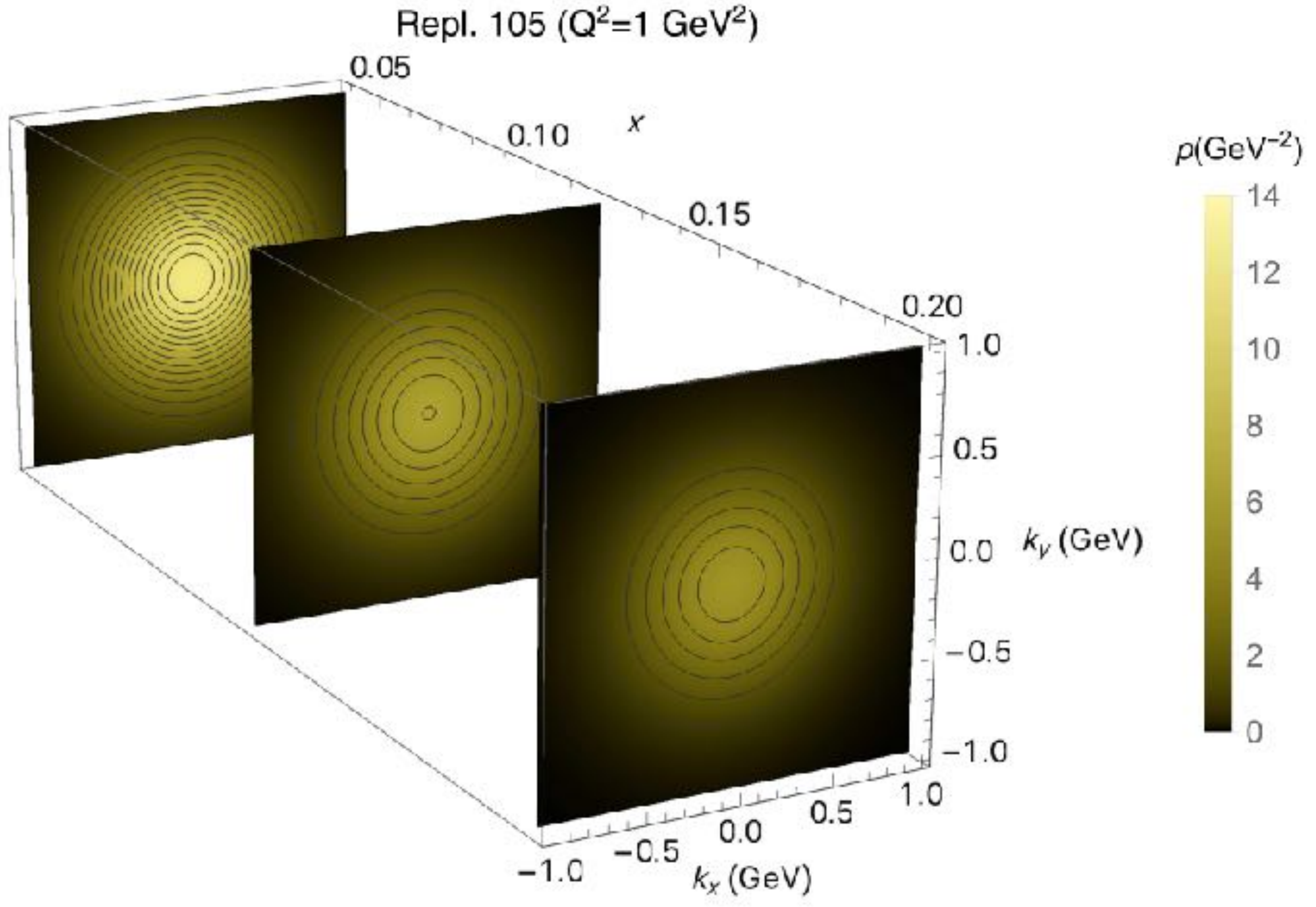
- Provide detailed map of the nucleon partonic structure
- Interpretation of any high-energy process involving hadrons

Polarised target: access to several TMDs

- Access to quark and gluon TMDs
- Complement present and future SIDIS results (HERMES, COMPASS, JLAB, …EIC):
- Study process dependence (non-universality)

Quarkonia as Tools to study Gluon TMDs

- Experimental access very limited (PHENIX, COMPASS)
- LHCspin + LHCb: a unique facility to study gTMDs
- Gluon Sivers function: $f_{1T}^{\perp,g}$



[JHEP 06 (2017) 081]

quark pol.

nucleon pol.

	U	L	T
SMOG2	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
LHCspin	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

gluon pol.

nucleon pol.

	U	Circ.	Lin.
SMOG2	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
LHCspin	$f_{1T}^{\perp g}$	g_{1T}^g	$h_1^{\perp g}, h_{1T}^{\perp g}$

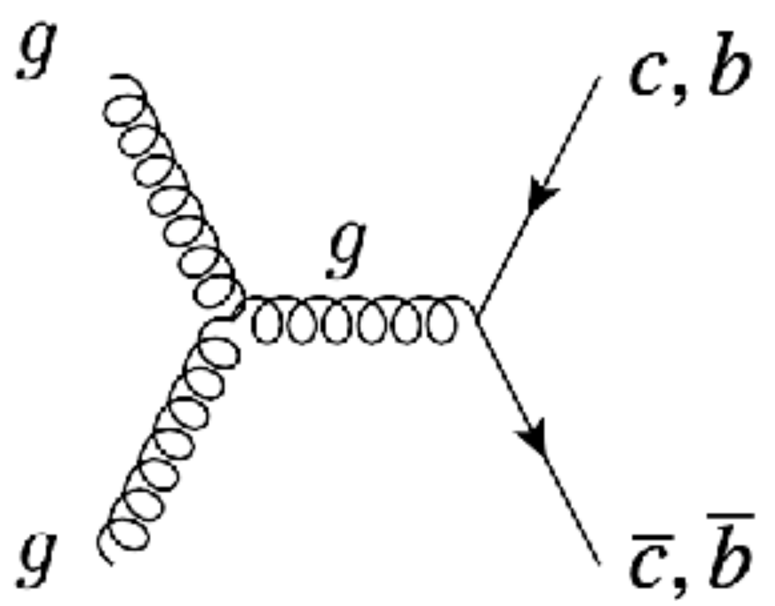
Gluon Sivers function

Gluon TMDs

Process

Heavy-quark production

- Most efficient way to access gluon dynamics
- Gluon fusion: main channel @LHC

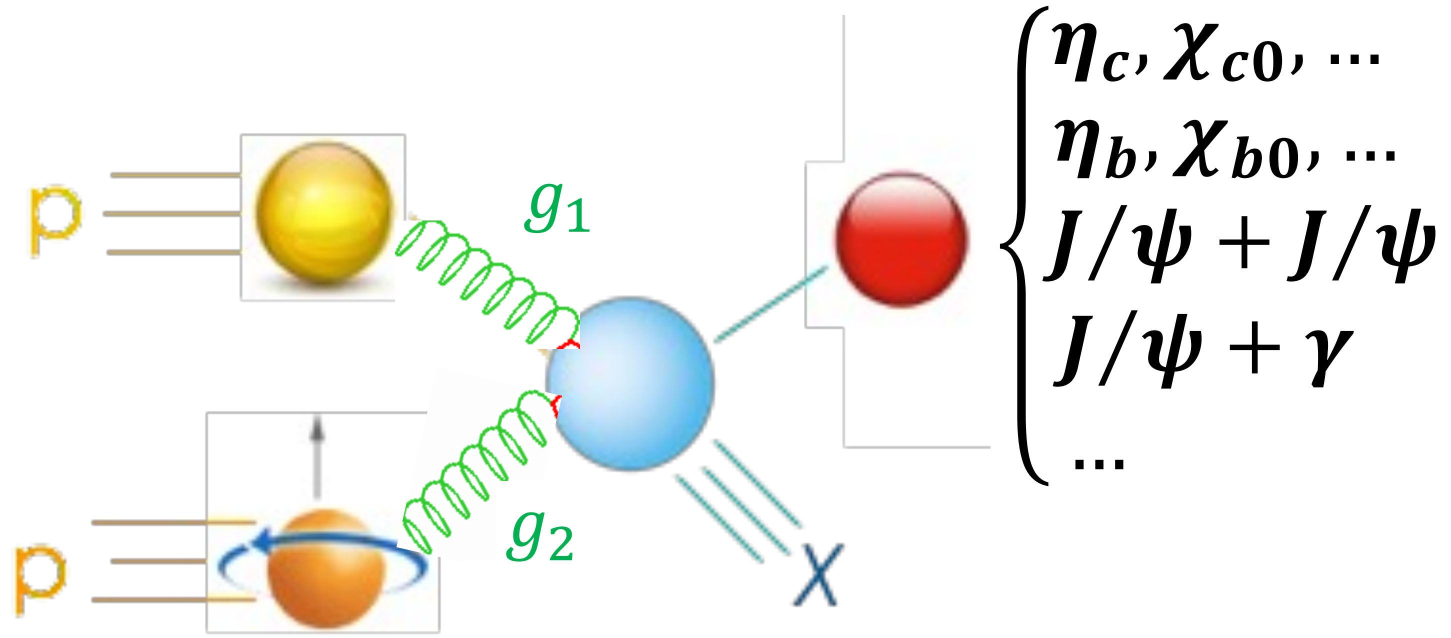


Inclusive C-even quarkonia production

e.g. η_c, χ_{c0} ideal process to study gluon TMDs

Associate quarkonia production

allows broader kinematic range for TMD factorisation but statistically limited in fixed-target collisions



$$\begin{cases} \eta_c, \chi_{c0}, \dots \\ \eta_b, \chi_{b0}, \dots \\ J/\psi + J/\psi \\ J/\psi + \gamma \\ \dots \end{cases}$$

Observable

Transverse Single Spin Asymmetry (TSSA)

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

Fourier decomposition

$$A_N \propto \boxed{A^{sin(\phi_s)} \; \sin(\phi_S)} \; + \; \dots$$

Dominant term

$$A^{sin(\phi_S)} \propto f_1^g \otimes \boxed{f_{1T}^{\perp g}}$$

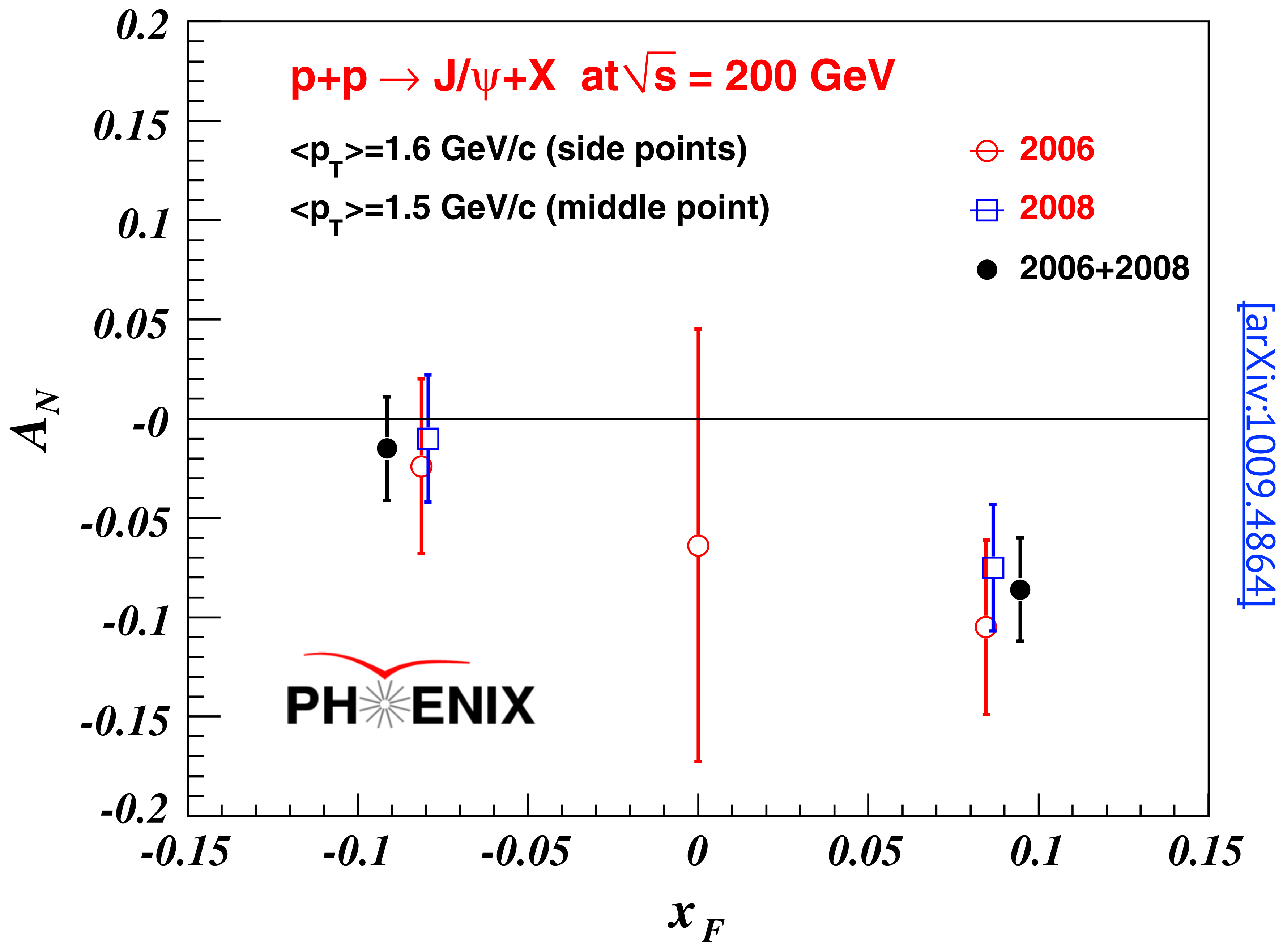
Gluon Sivers function

- $\sin(\phi_S)$: dominant term in the expansion
- $A^{sin(\phi_S)}$: azimuthal amplitude sensitive to Gluon Sivers function

Current experimental access to gTMDs

PHENIX

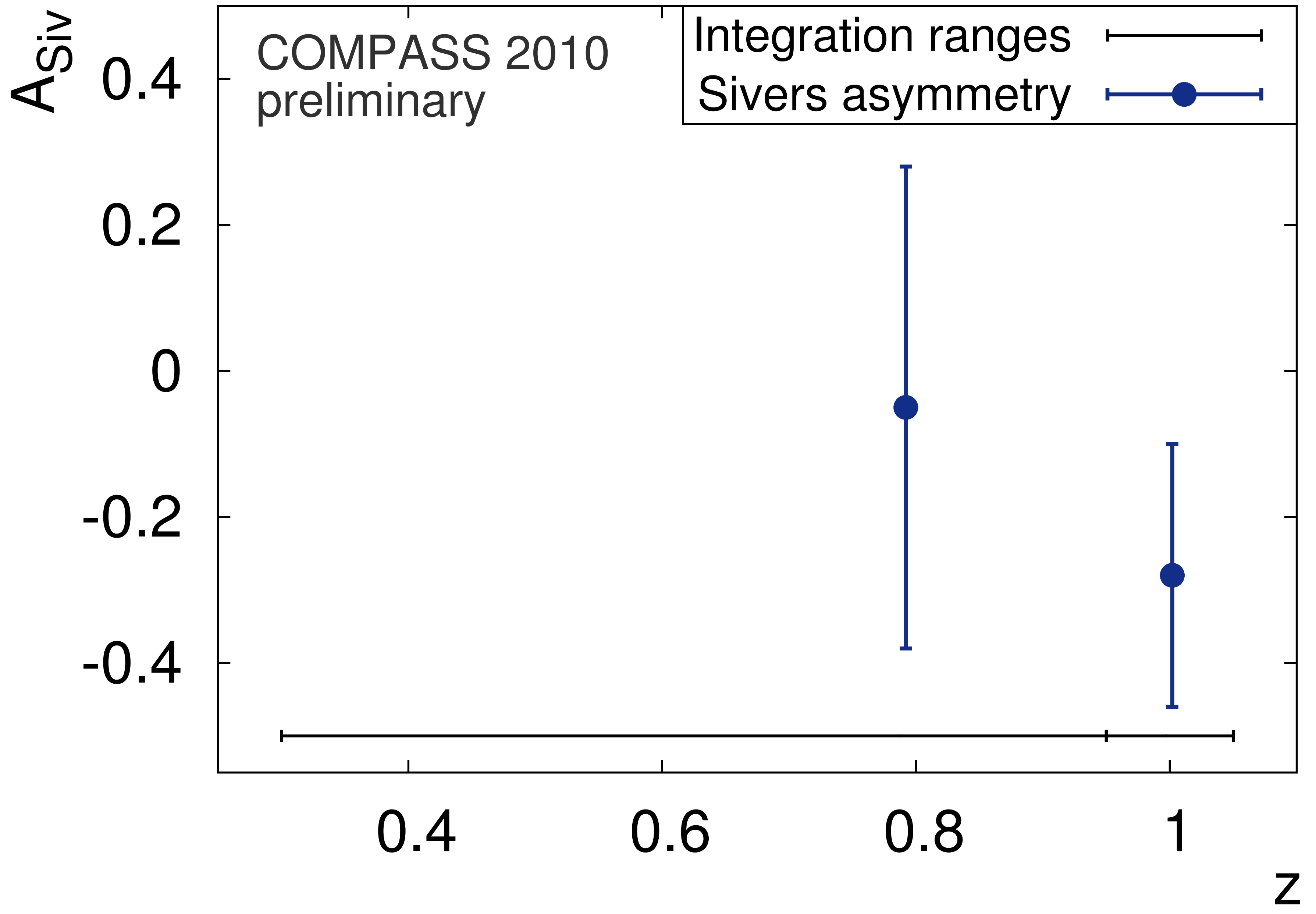
- Inclusive J/ψ measurements in **polarised** pp
- J/ψ: **~ 21'000 signal** candidates in 2006+2008 data



[arXiv:1009.4864]

COMPASS

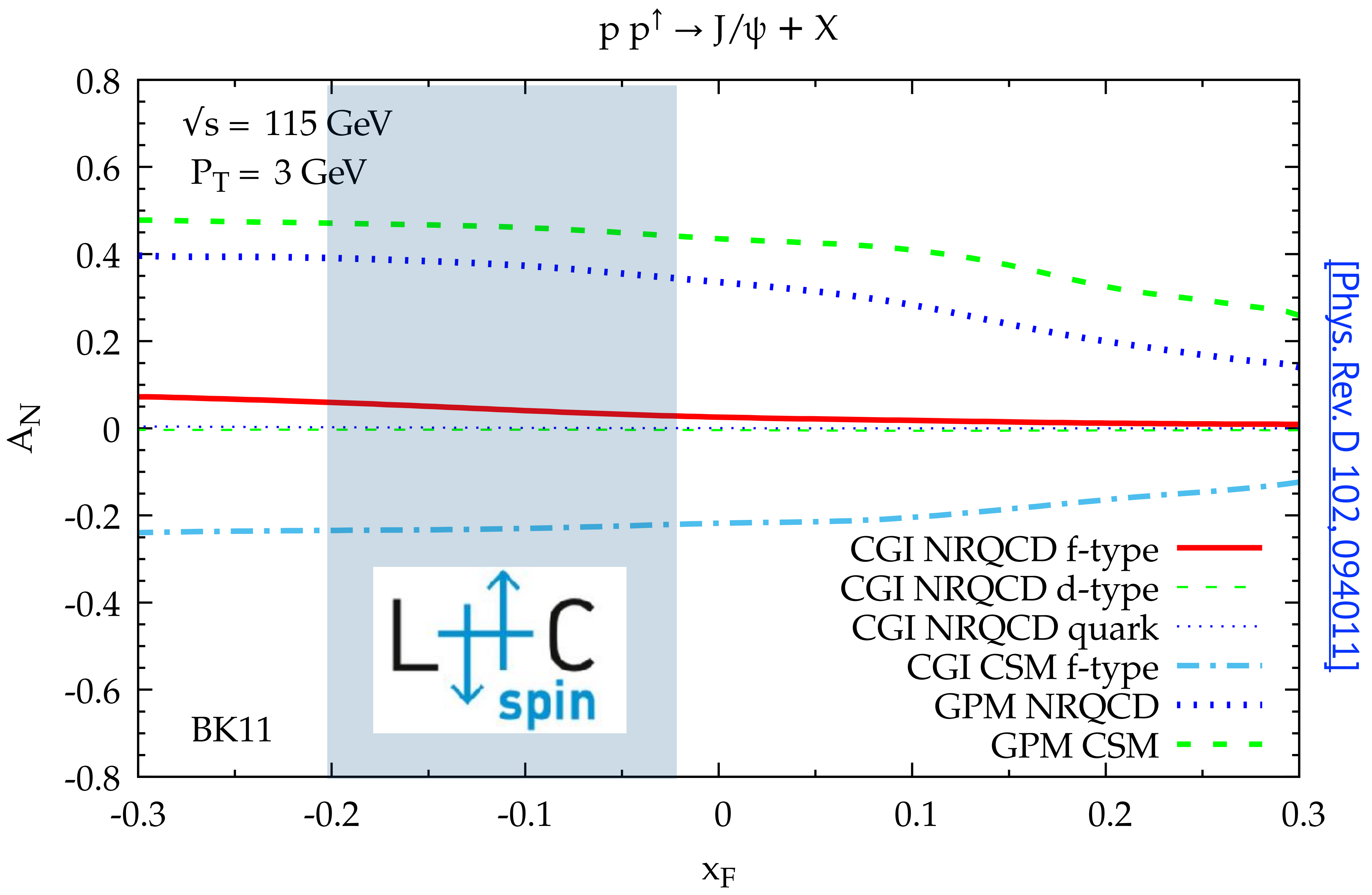
- **SIDIS measurements**: 160 GeV/c muon beam and transversely polarised proton target in 2010
- J/ψ: **~6600 signals** candidates in 2010 data



[arXiv:1701.02453v]

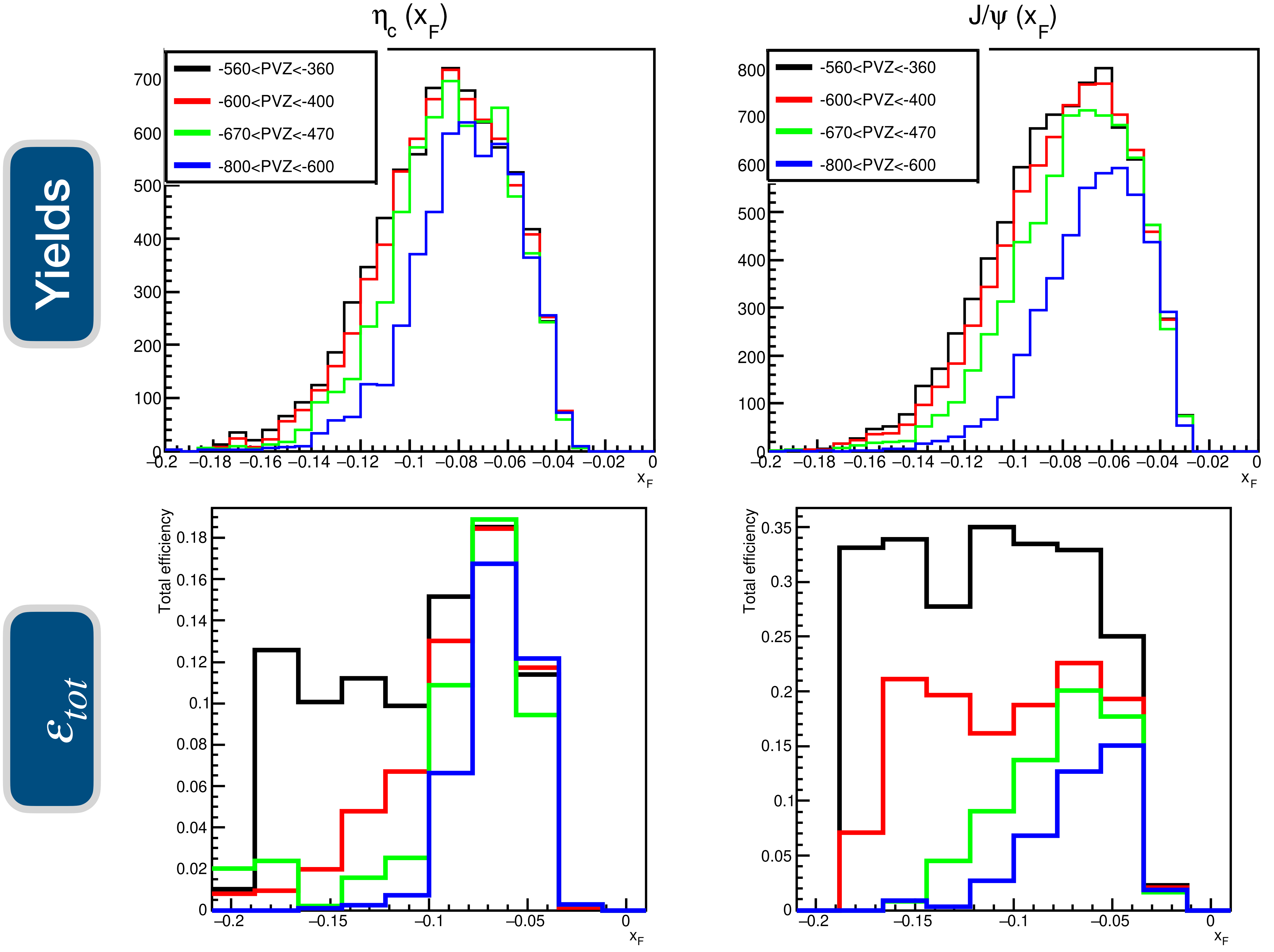
Projections for gTMDs

Theoretical Predictions ⇄ **Simulated Projections**



- Predictions for polarised FT measurements at LHCb
- Expected up to **40 asymmetry for $x_F < 0$**
- **LHCspin potential:** distinguish among theoretical predictions of Gluon Sivers function

- **High statistics and good tracking** efficiency for $x_F \in [-0.2,\, 0]$
- Keep the **cell close the VELO** to maximise kinematic coverage



Preliminary analysis tool with pseudo-data

Simulation

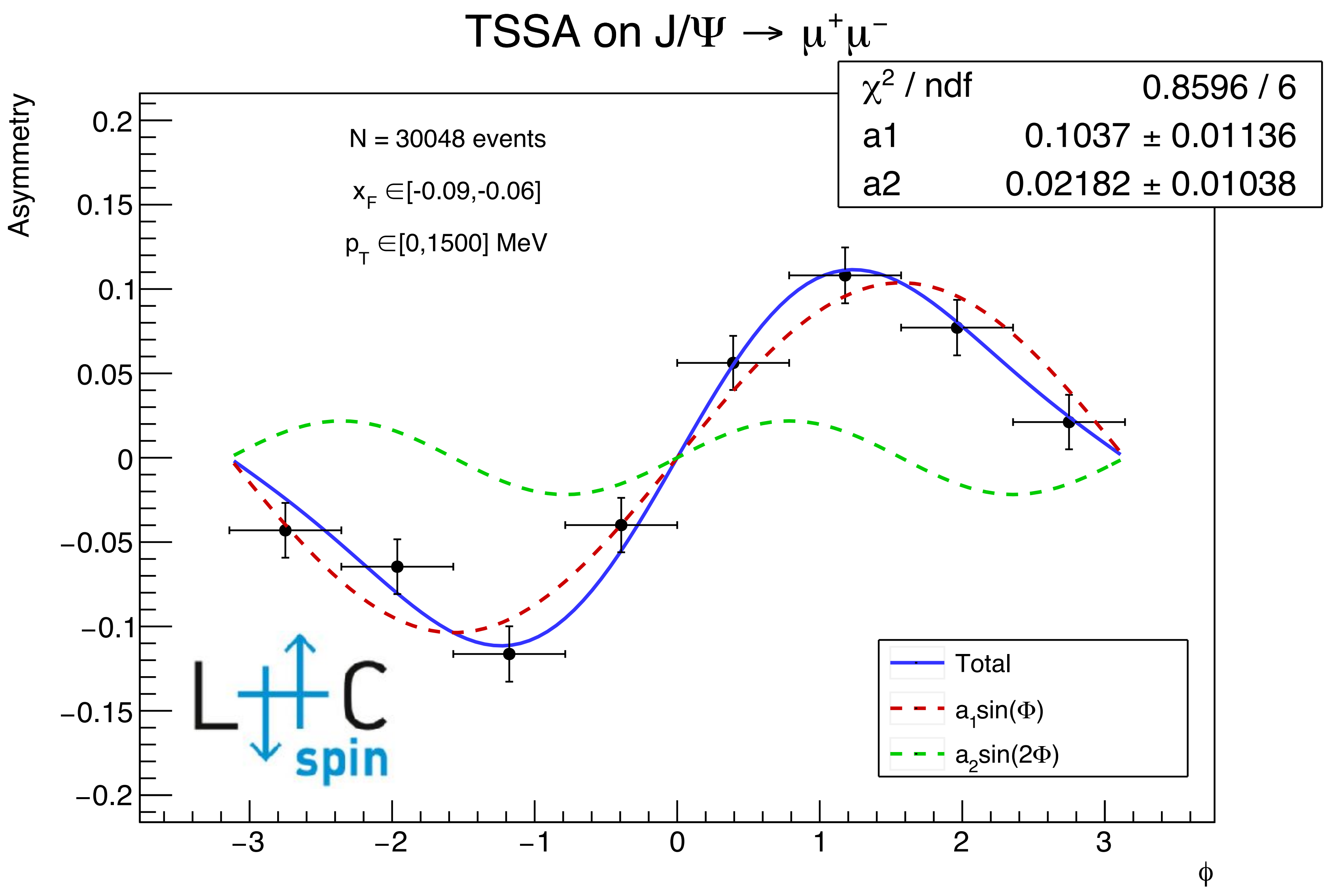
- Simulated ~ 30 k unpolarised MC events (PYTHIA8 + EPOS)
- **Spin dependence** introduced in the simulation using a simple model for the polarised cross section, corresponding to $A_N \sim 10\,\%$

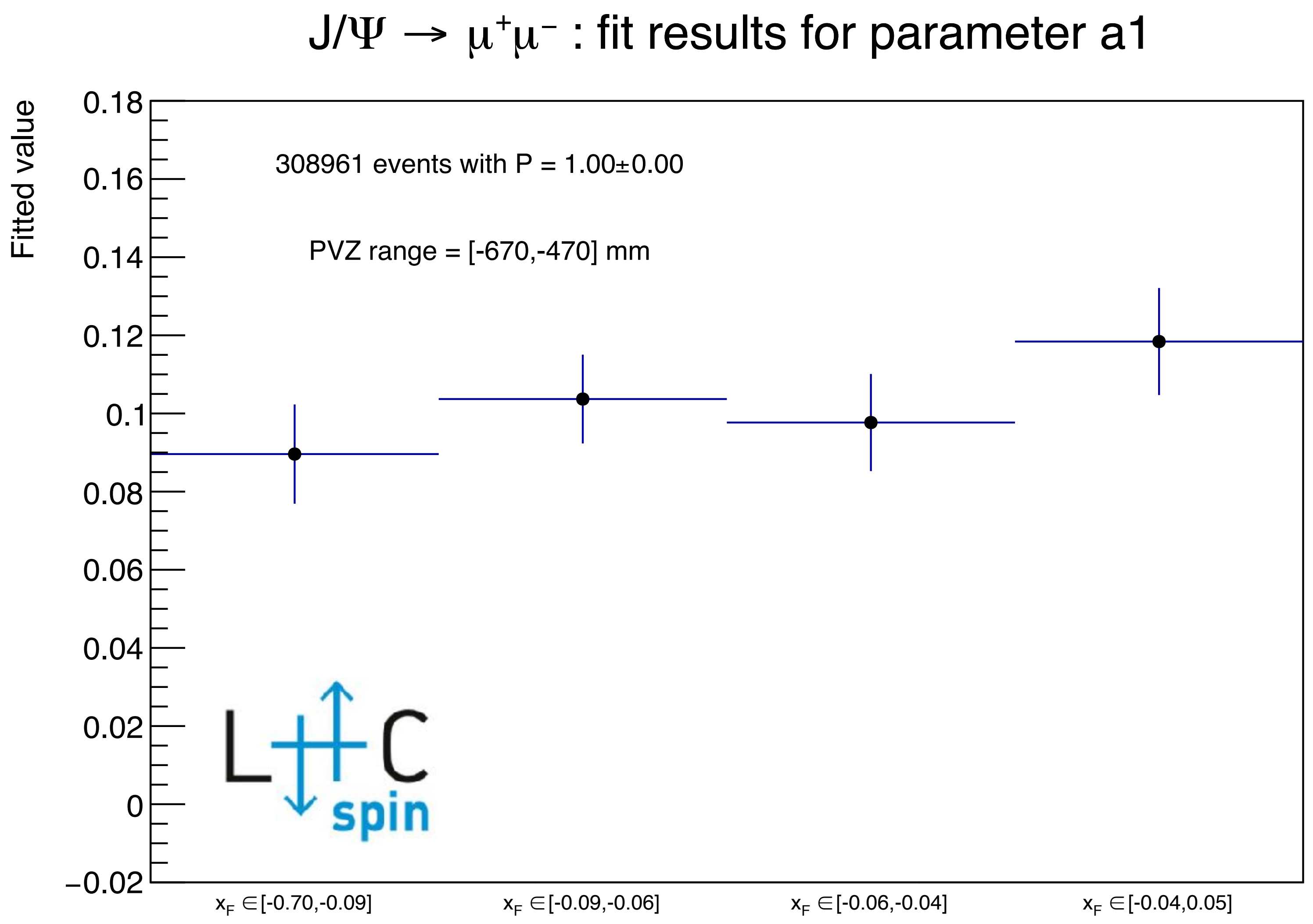
Reco & Fit

- **Sinusoidal azimuthal dependence** observed in bins of ϕ consistent with the model (no bias)
- **Fit pseudo-data with harmonic functions** $f = a_1 \sin(\phi) + a_2 \sin(2\phi)$ and extract amplitudes a_1, a_2

Projections

- **Few days of data-taking** can provide sufficient precision
- **Just a starting point** to be refined and tested with different models





Expected performance for different scenarios

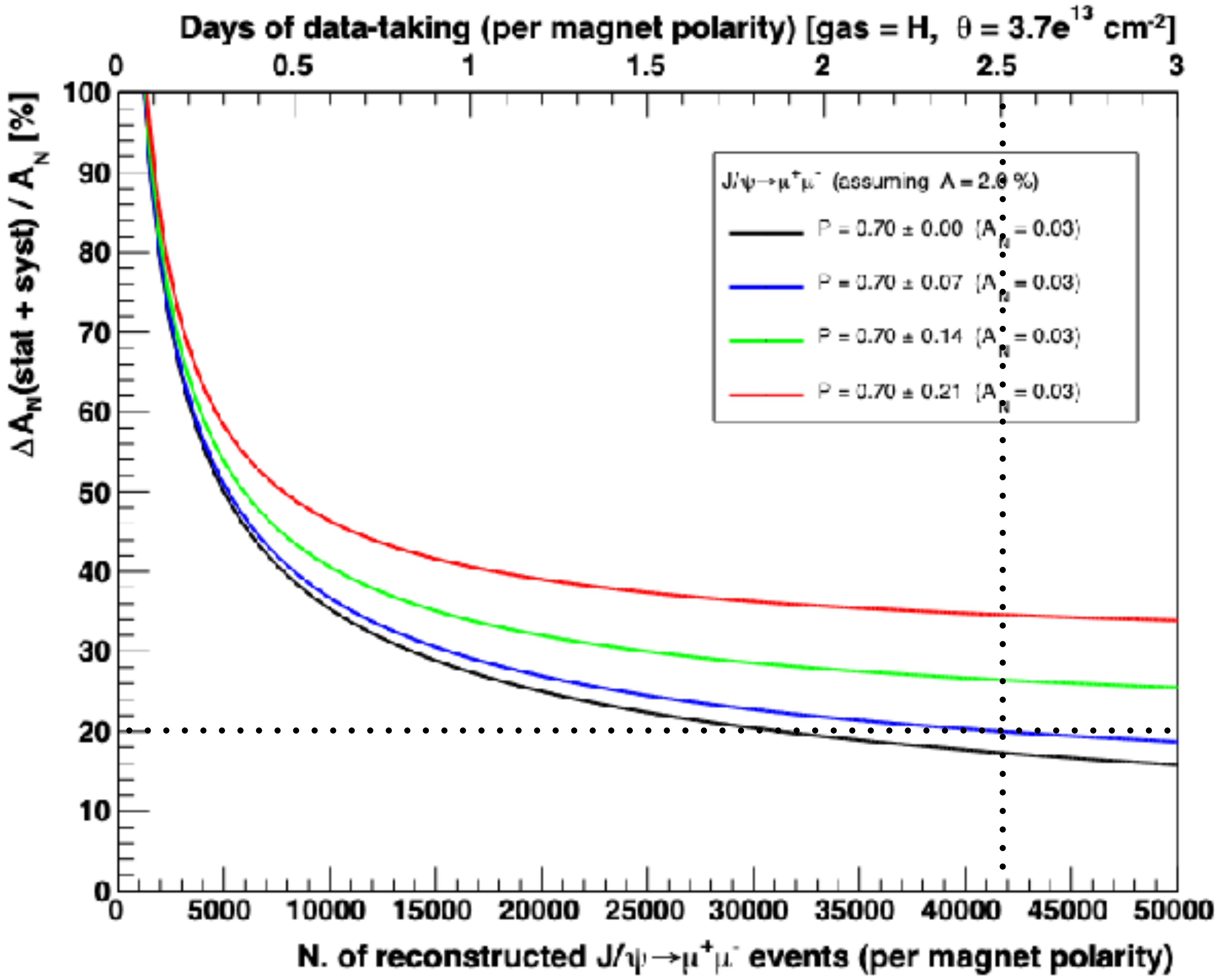
$$A_N = \frac{1}{P} A = \frac{1}{P} \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

How much data-taking time to get precise measurement on A_N?

- $\theta_H \sim 3.7 \times 10^{13}\ \mathrm{cm}^{-2}$
- $\mathscr{L} \sim 1.6 \times 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (Run 4)
- 2 different asymmetry hypothesis
  $A = 2\,\%$
  $A = 10\,\%$
- $P \sim 70\,\%$, 4 different scenarios:
  $\Delta P/P$ ~ 0%
  $\Delta P/P$ ~ 10%
  $\Delta P/P$ ~ 20%
  $\Delta P/P$ ~ 30%

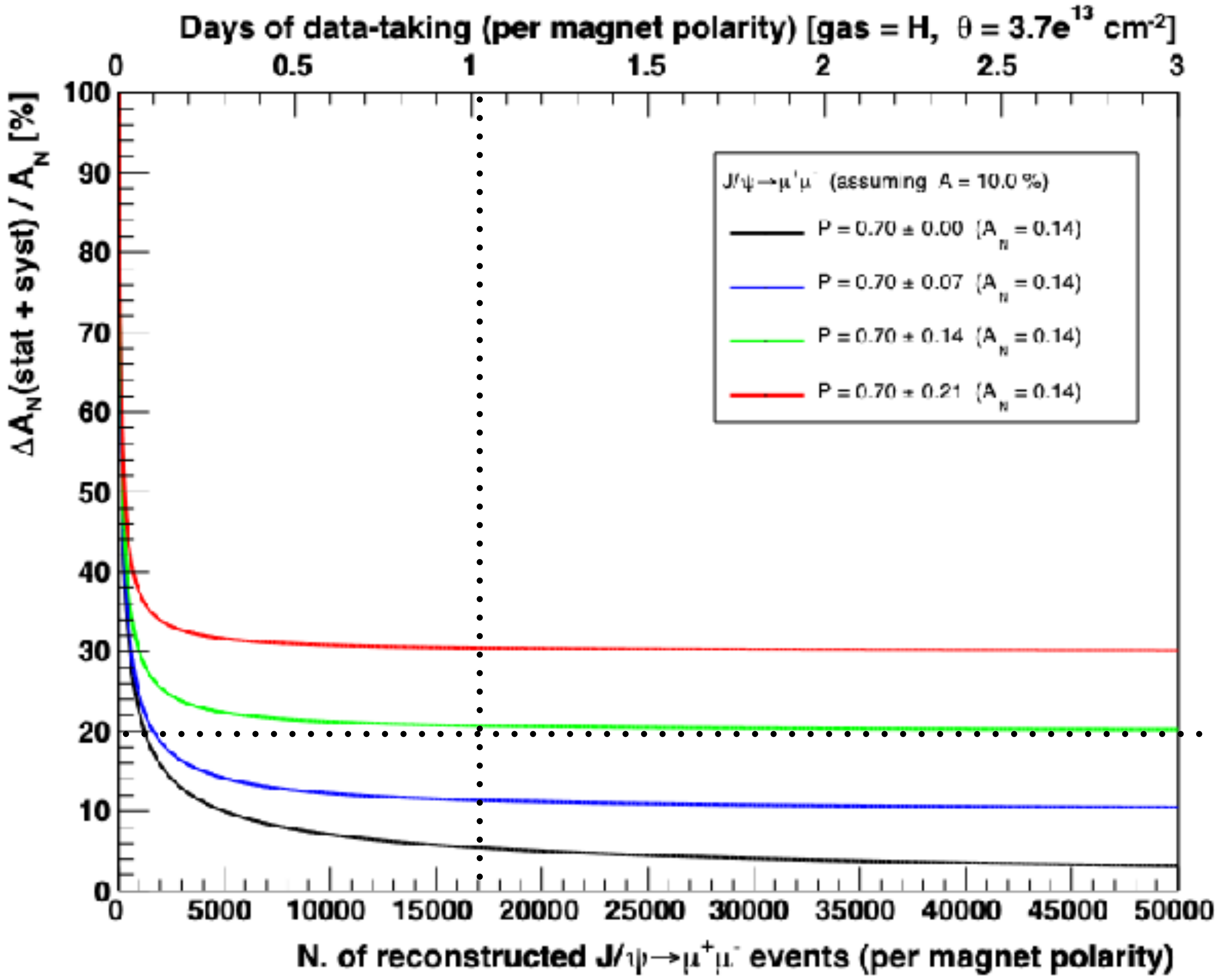
} Cell target realistic scenario

$A = 2\,\%$



- $\Delta P/P$ ~ 10%
- Data-taking time: 2.5 days

$A = 10\,\%$



- $\Delta P/P$ ~ 20%
- Data-taking time: 1 day

Outlook and summary

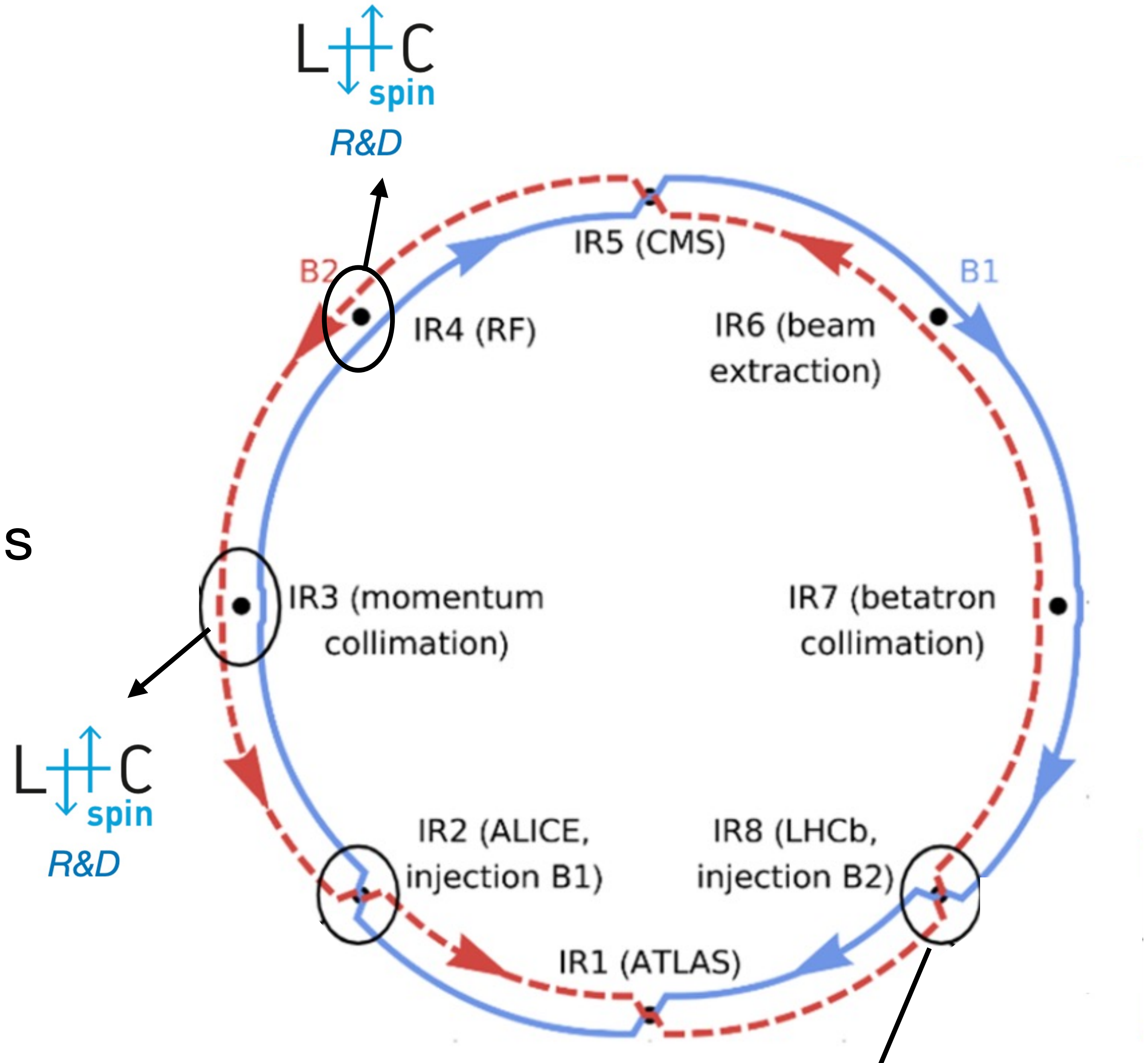
The plan for the upcoming years

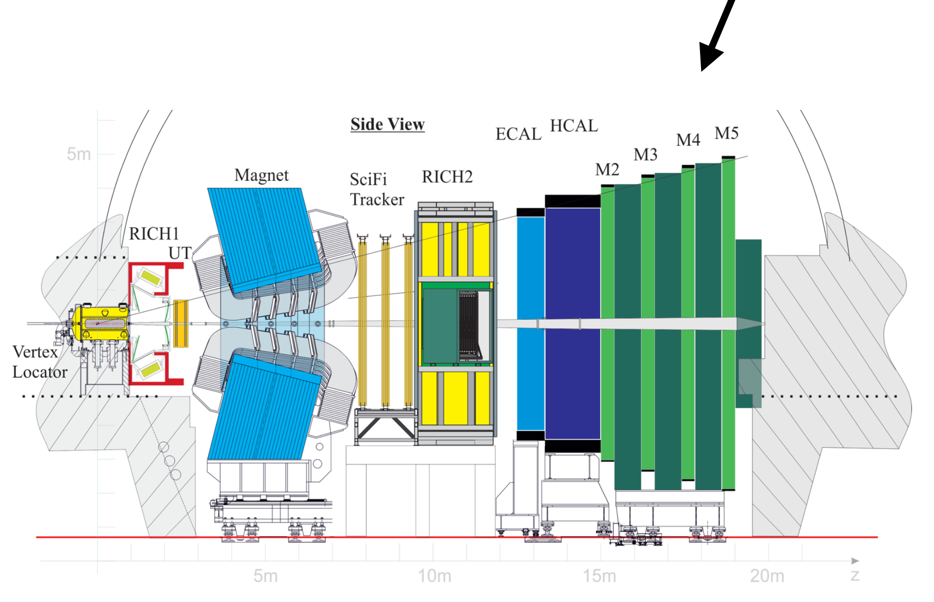
Pre-requisites for the approval of the LHCspin project at LHCb (Run5)

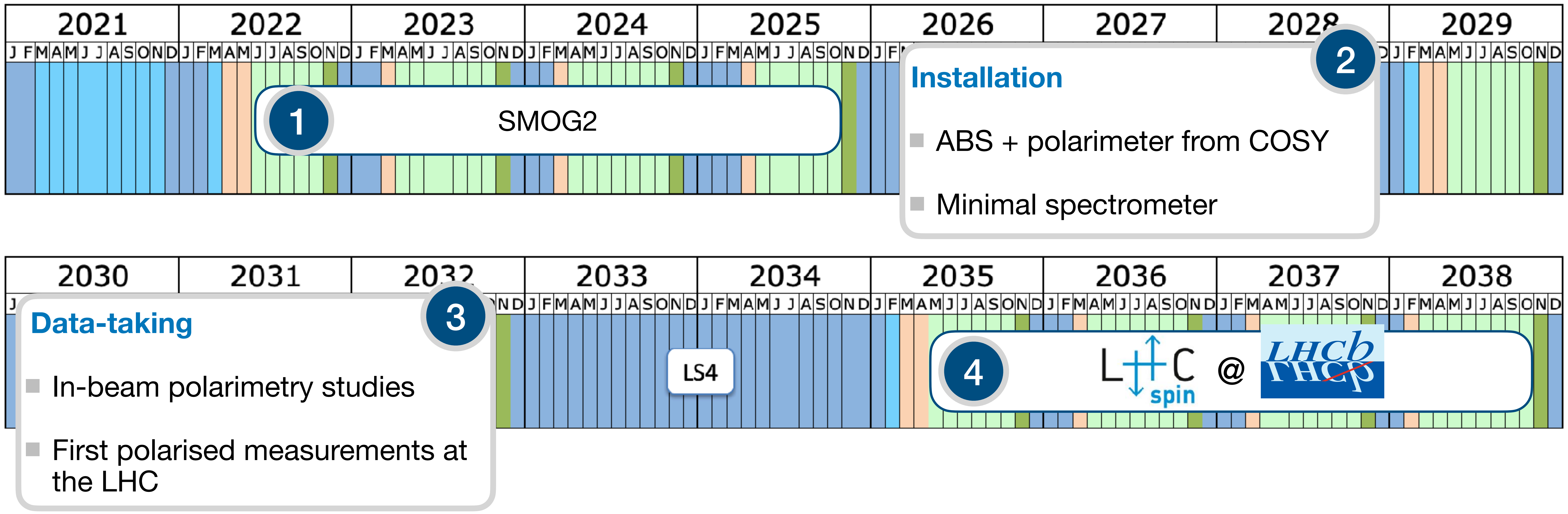
- R&D campaign for the apparatus towards the final setup for LHCb
- Feasibility studies in a dedicated experimental area (IR3, IR4) served by LHC beams

Proto-collaboration is being formed with all the necessary expertise

- Polarimetry
- Spectrometer







① SMOG2

② **Installation**

- ABS + polarimeter from COSY
- Minimal spectrometer

③ **Data-taking**

- In-beam polarimetry studies
- First polarised measurements at the LHC

④ LHCspin @ LHCb

🟦 Shutdown/Technical stop
🟩 Protons physics
🟩 Ions
🟧 Commissioning with beam
🟦 Hardware commissioning/magnet training

Summary

SMOG2: unpolarised LHCb fixed-target program

- Preliminary performance above the expectations
- Good prospectives for quarkonia reconstruction: $J/\psi, \eta_c, \chi_{c0}, \ldots$
- First study of TMDs: access to Boer-Mulders function $h_1^\perp$

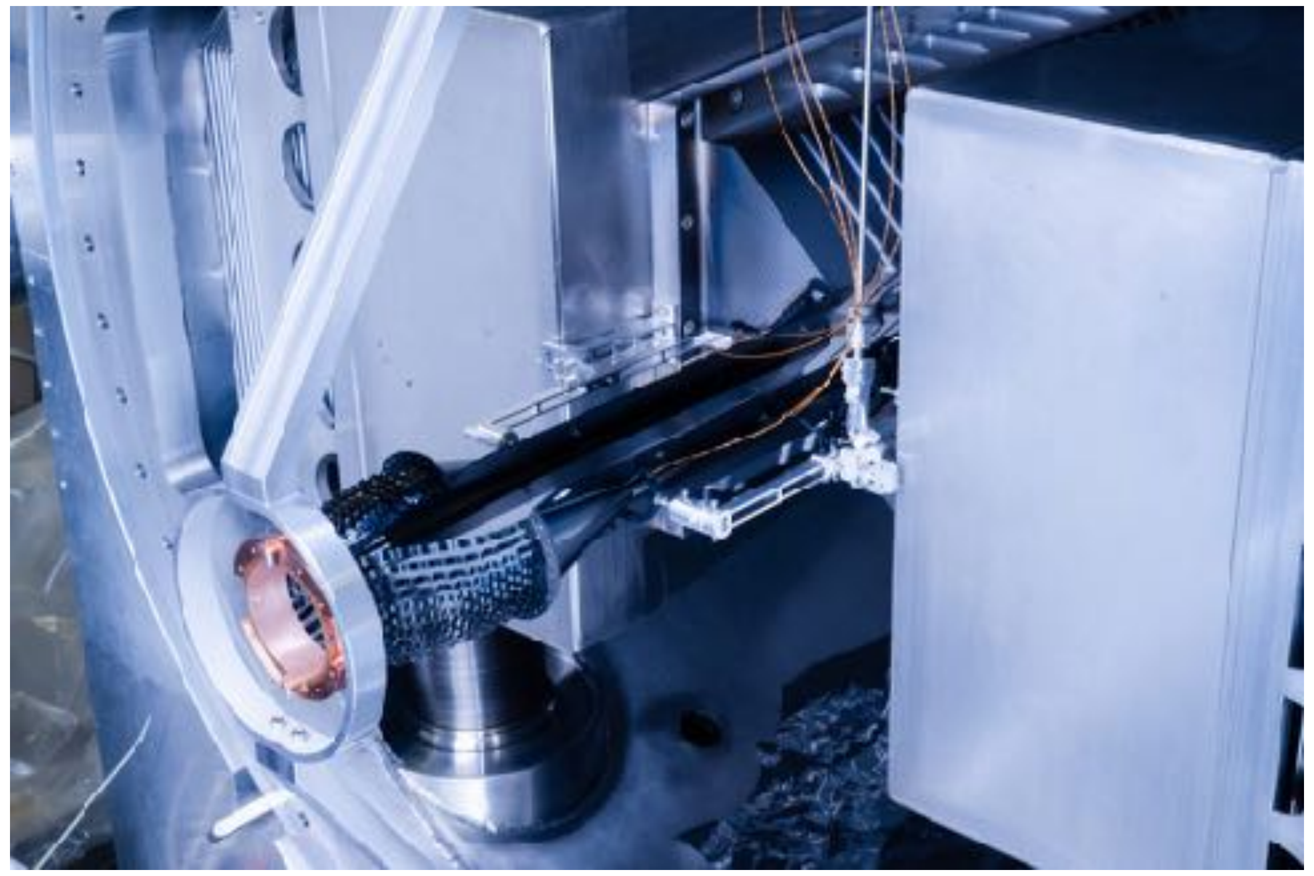
LHCspin: first-spin physics program @ LHC

- HERMES-like polarised target setup
- Challenging R&D but worth the effort!

Polarised physics opportunities

- Nucleon tomography in momentum space
- First insights on gTMDs
- Comparison with SIDIS experiments

SMOG2



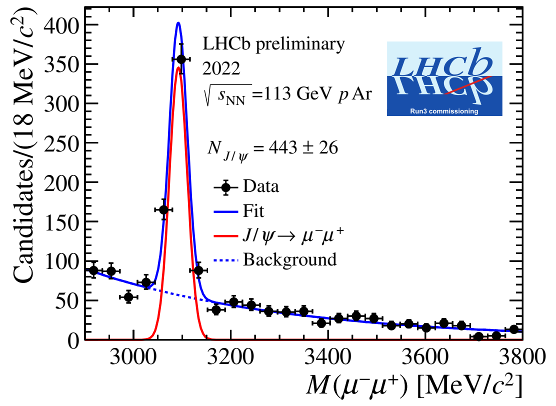
LHC spin + LHCb

Backup

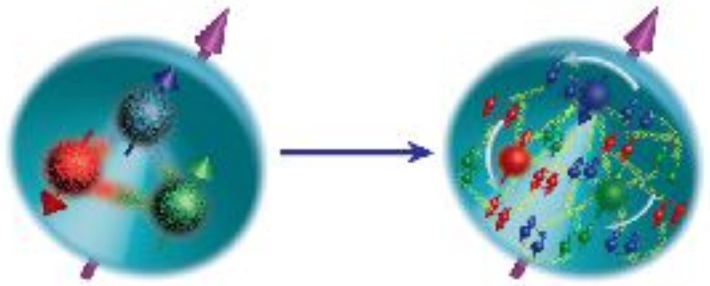
The LHCspin project

[The LHCspin project]

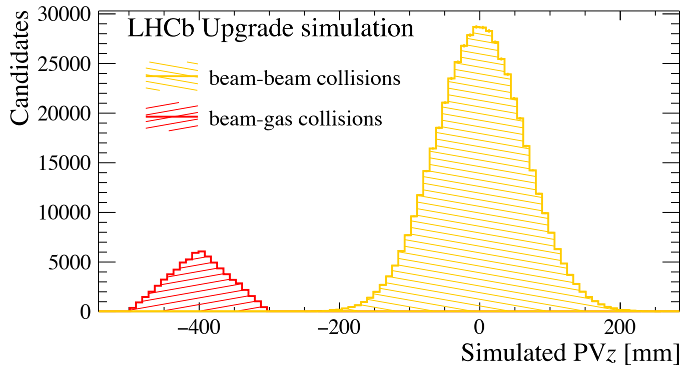
Use of unique probes: quarkonia, heavy-mesons



First spin-physics program at LHC

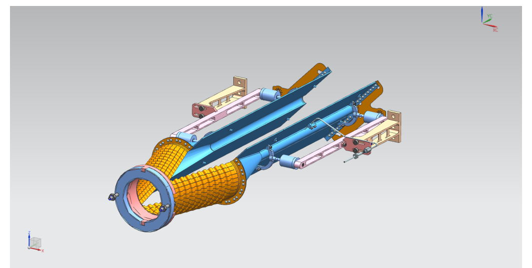


Run in parallel with collider mode



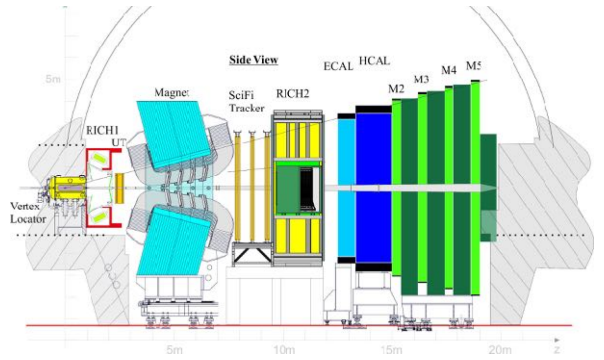
LH↑↓C spin

Extending the unpolarised LHCb fixed-target program in Run 5

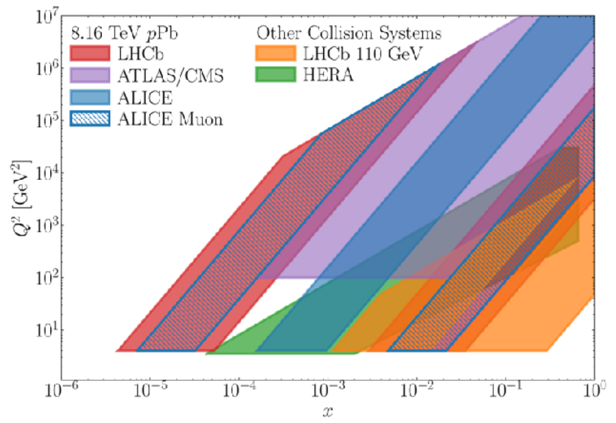


LHC + LHCb + trasvers polarised target

$H^{\uparrow}, D^{\uparrow}$



Unique kinematic conditions



Quark & Gluon TMDs

Quark TMDs

Leading twist:
8 quark TMDs

quark pol.

nucleon pol.

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

- **Significant experimental progress** in the last 15 years!
  - Main results from SIDIS
    (HERMES, COMPASS, JLAB, → EIC)
- **Drell-Yan in h-h collisions (LHC)**: offers a complementary approach to SIDIS (COMPASS, RHIC)
- Several extractions already available from global analyses
- Now entering the **precision era**

Gluon TMDs

Leading twist:
8 gluon TMDs

gluon pol.

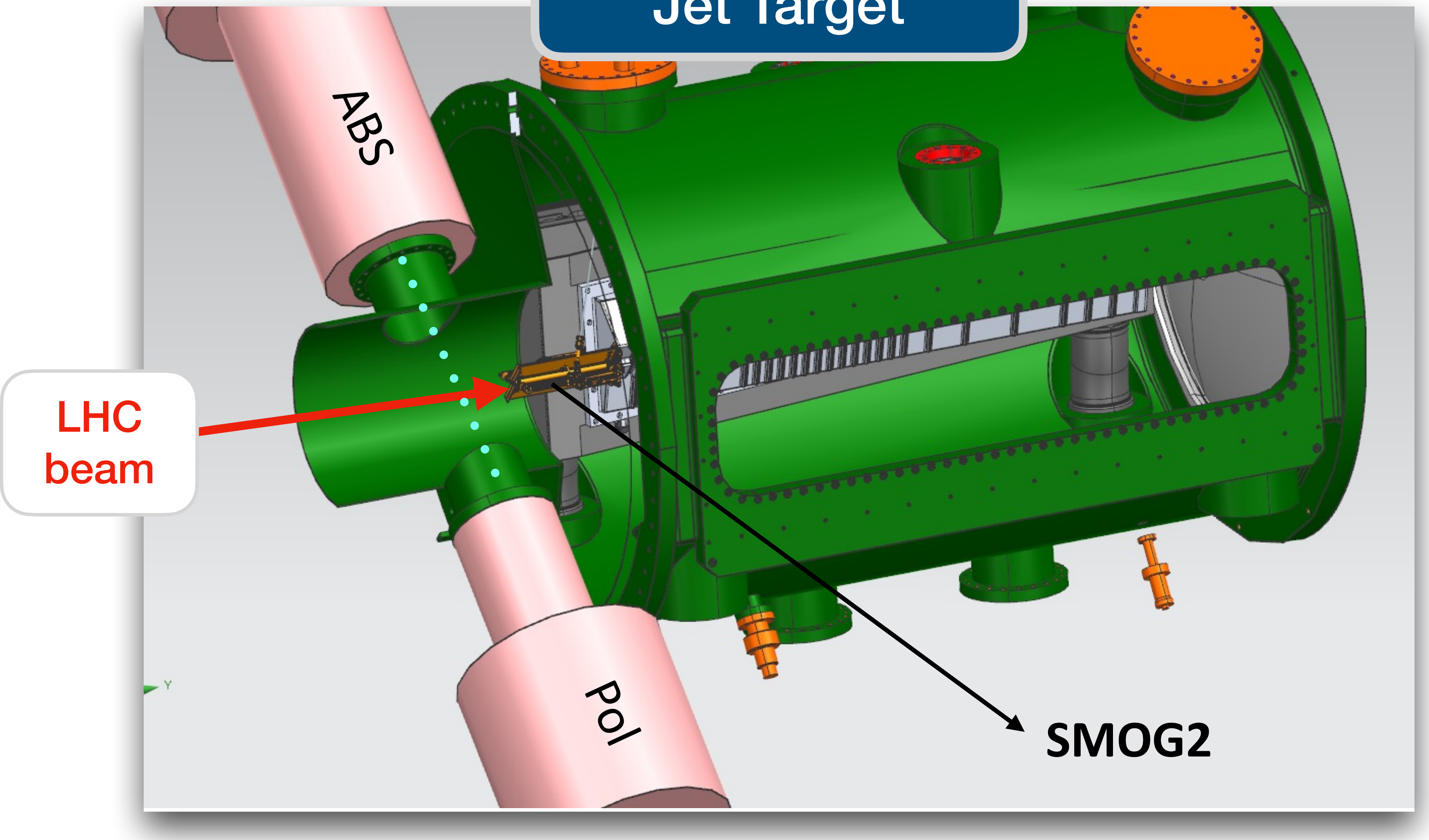
nucleon pol.

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

- Theory framework well consolidated ...but **experimental access still extremely limited**!
- Main differences with Quark TMDs:
  - Different naïve-time-reversal properties
  - **Process dependence** originating by ISI/FSI encoded in the gluon correlator gauge links
- **Quarkonia as Tools to study Gluon TMDs**

Jet Target vs Storage Cell

Jet Target



✅ Higher polarisation (P up to 90%)

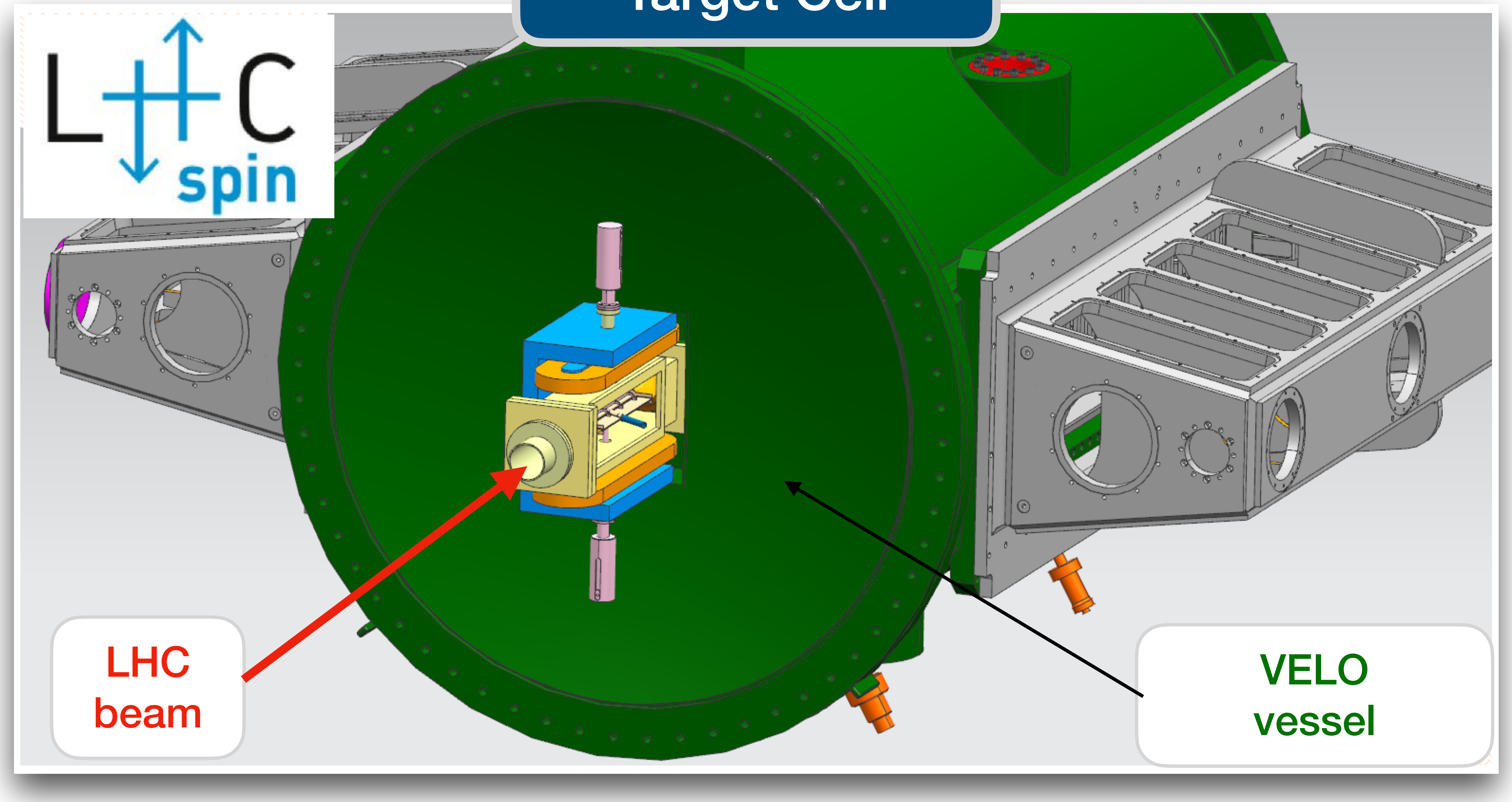
✅ Lower systematics in polarisation ($\Delta P/P$~ 1-2 %)

✅ Compatible with SMOG2

❌ Small target density: ($\sim 10^{12}$ atoms/cm^2)

❌ Luminosity ~ 40 factor smaller

Target Cell



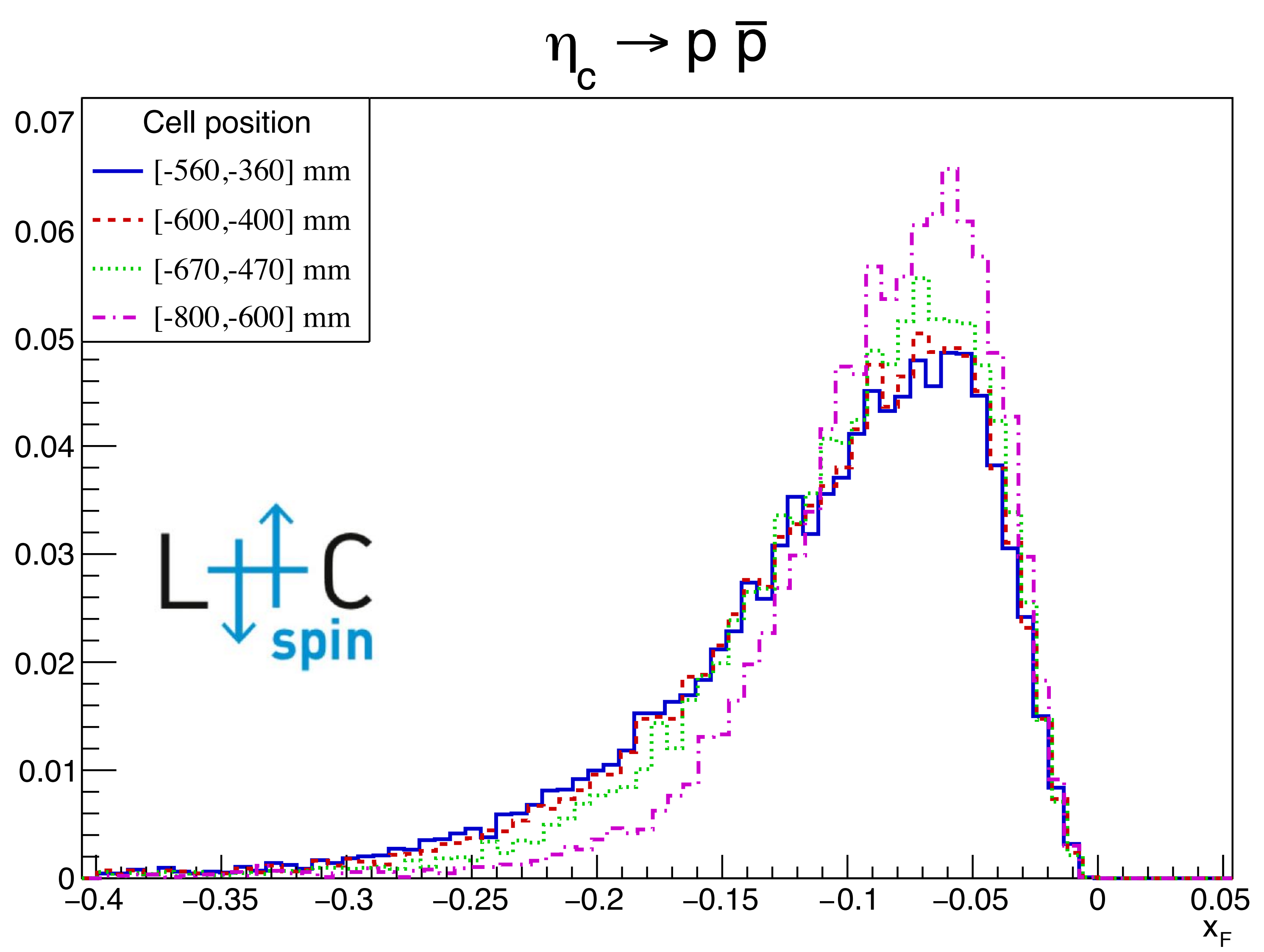
✅ High target density $\theta \sim 3.7 \times 10^{13}$ atoms/cm^2

✅ Luminosity in Run 5 $\mathscr{L} \sim (2-4) \times 10^{32}$cm^{-2}s^{-1}

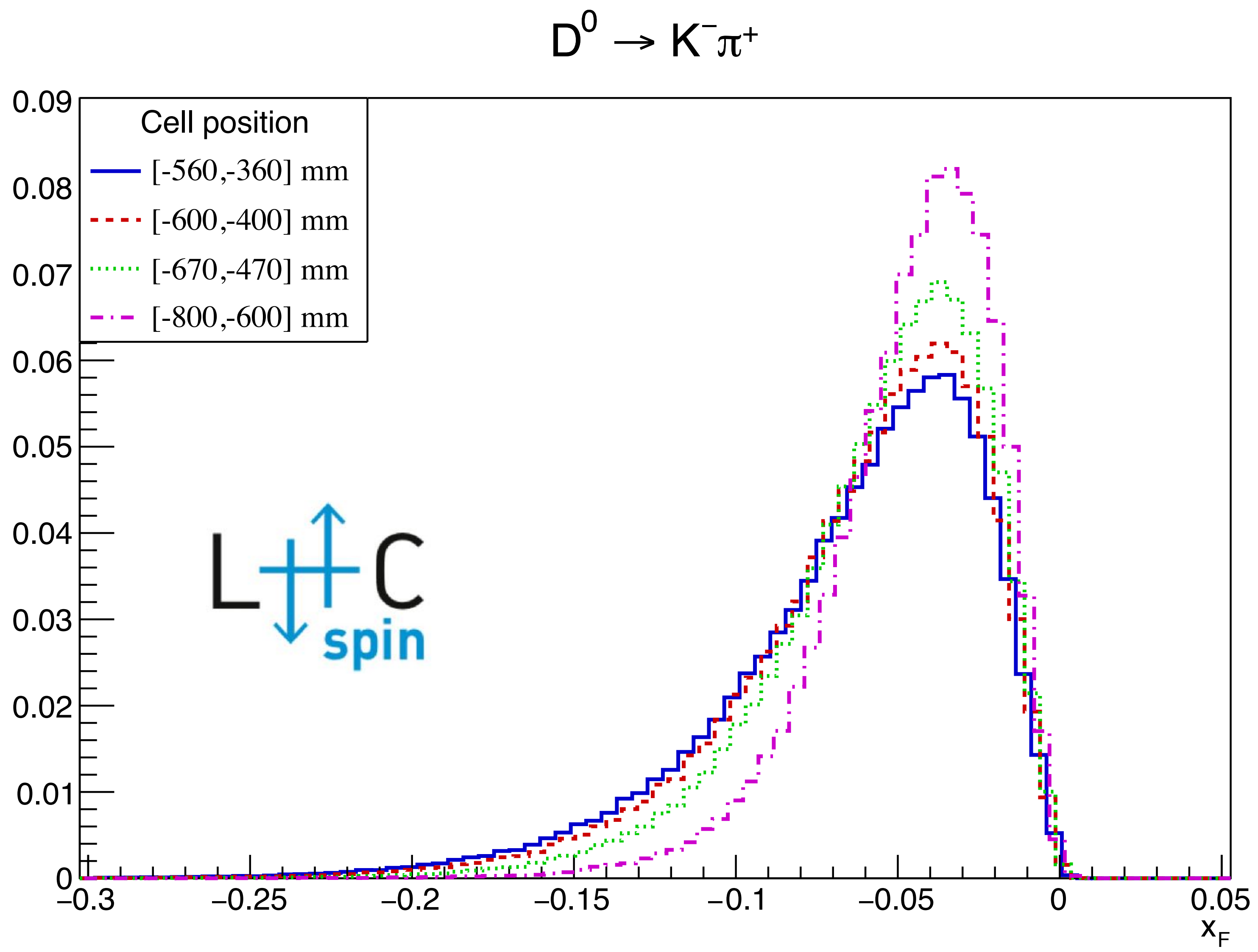
❌ Depolarisation due to wall collisions (P up to 70%)

❌ Significant systematics uncertainty on polarisation ($\Delta P/P$~ 10-15%)

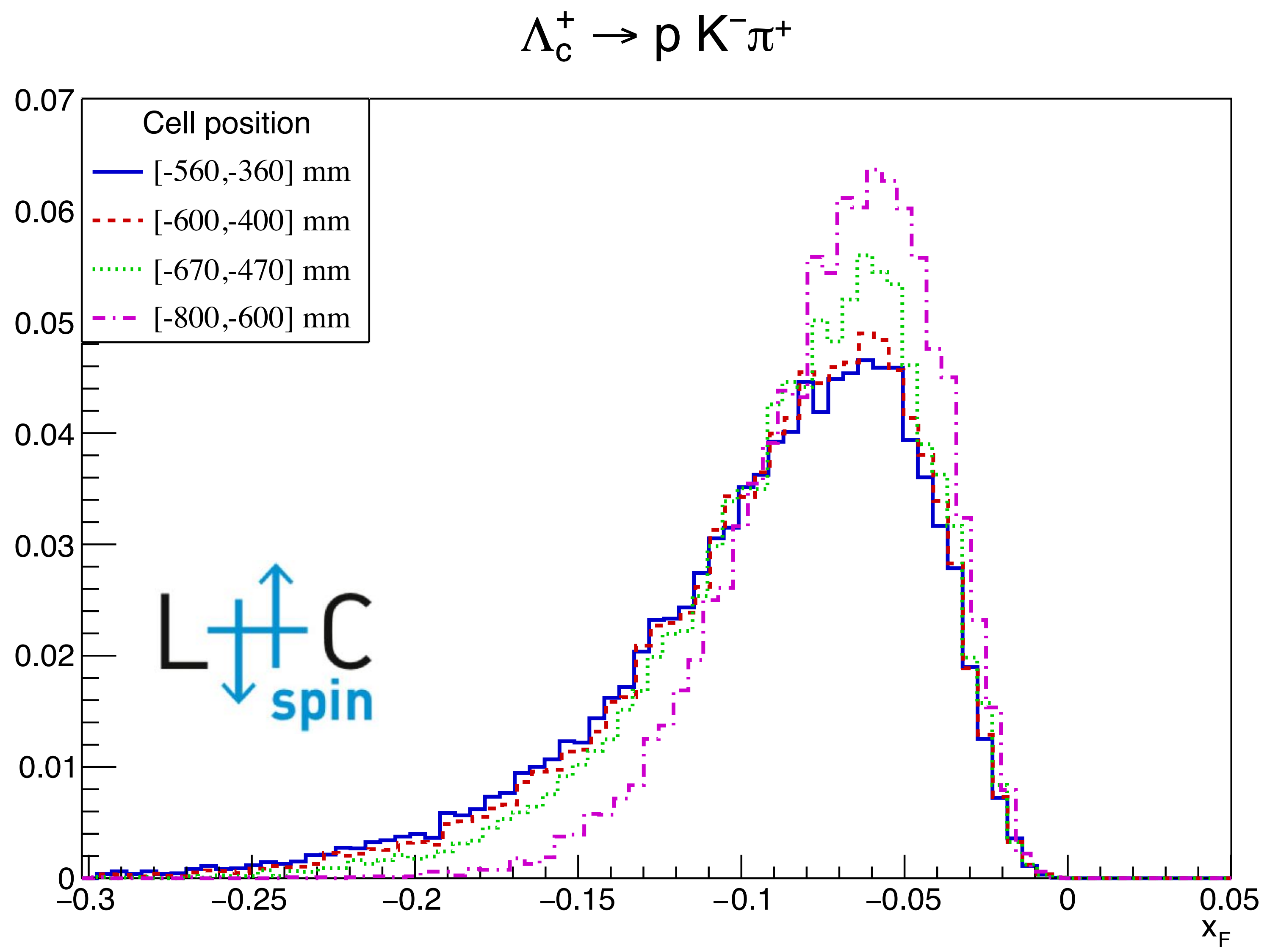
Heavy flavour channels: examples



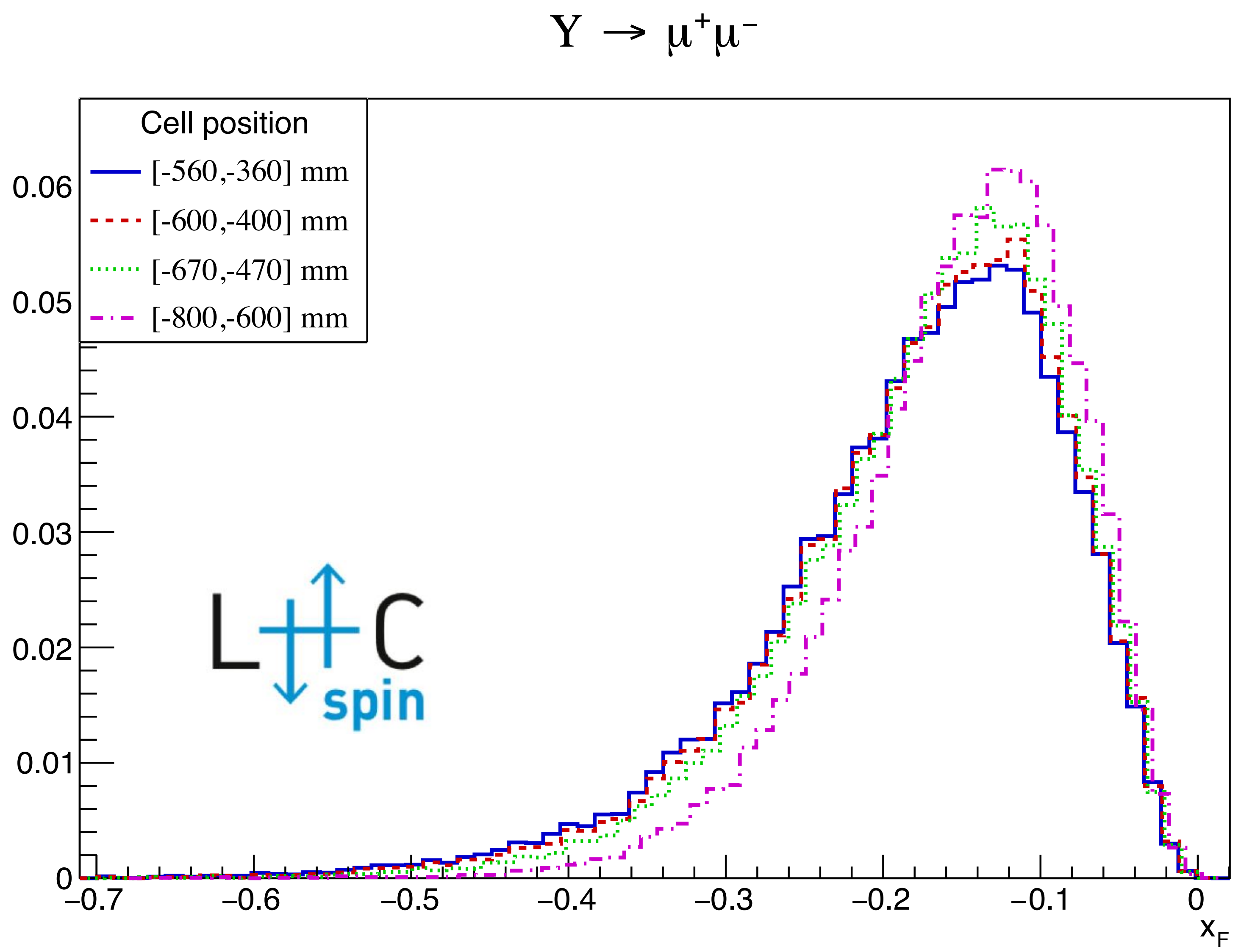
$\eta_c \rightarrow p\,\bar{p}$



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



$\Lambda_c^+ \rightarrow p\,K^-\pi^+$



$\Upsilon \rightarrow \mu^+\mu^-$

- Kinematic coverage for $\eta_c, D^0, \Lambda_c^+, \Upsilon$ for different cell positions

- **c-hadrons** will have the largest product of cross section and reconstruction efficiency

- Exotic probes and **b-hadrons** are also possible

- Unique opportunity to **probe gluon TMDs** over a broad x range!

Quark TMDs

[from L. Pappalardo SPIN2021]

Goal

- Nucleon tomography
- Test one of the most important predictions of the TMD factorisation formalism:

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

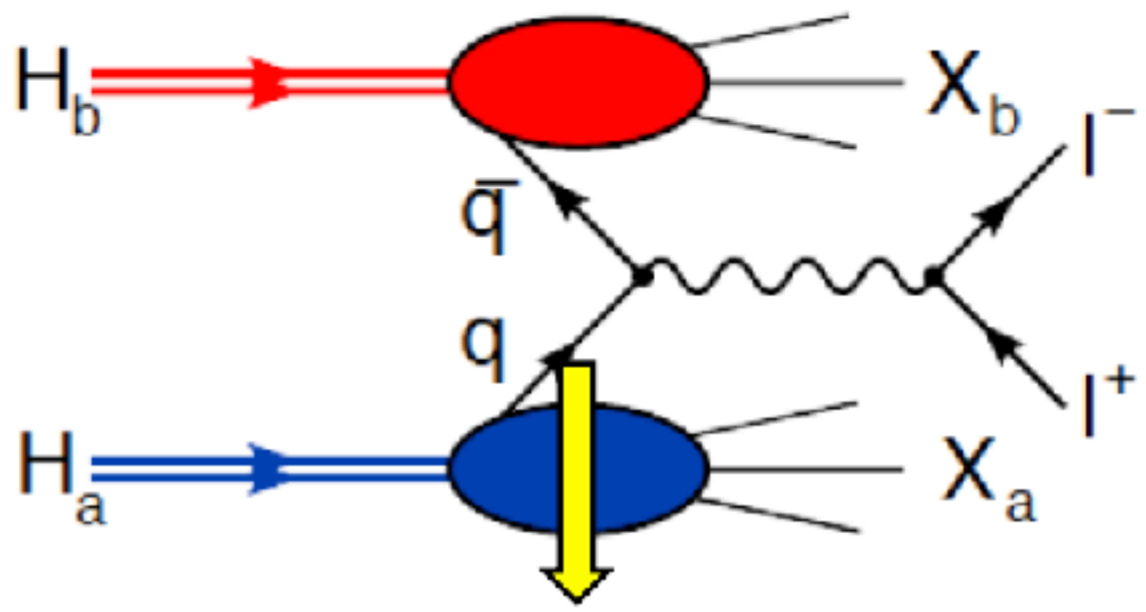
quark pol.

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

nucleon pol.

Process

Transversely polarised Drell-Yan



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

Observable

Transverse Single Spin Asymmetry (**TSSA**)

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

Fourier analysis ↓

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

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

Quark Sivers function

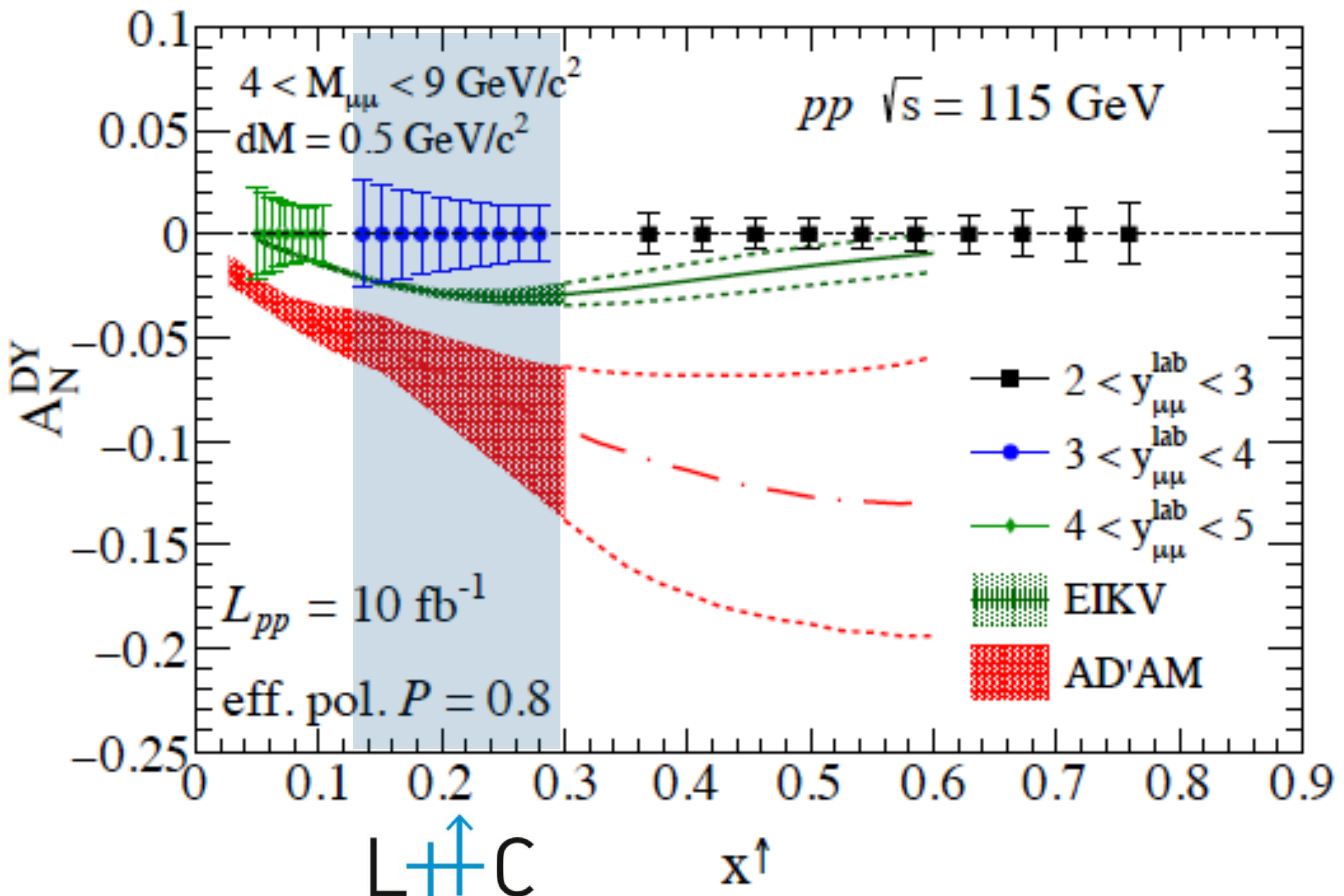
$$A_{UT}^{sin(2\phi+\phi_S)} \sim \frac{h_1^q \otimes h_{1,T}^{\perp,\bar{q}}}{f_1^q \otimes f_1^{\bar{q}}}$$

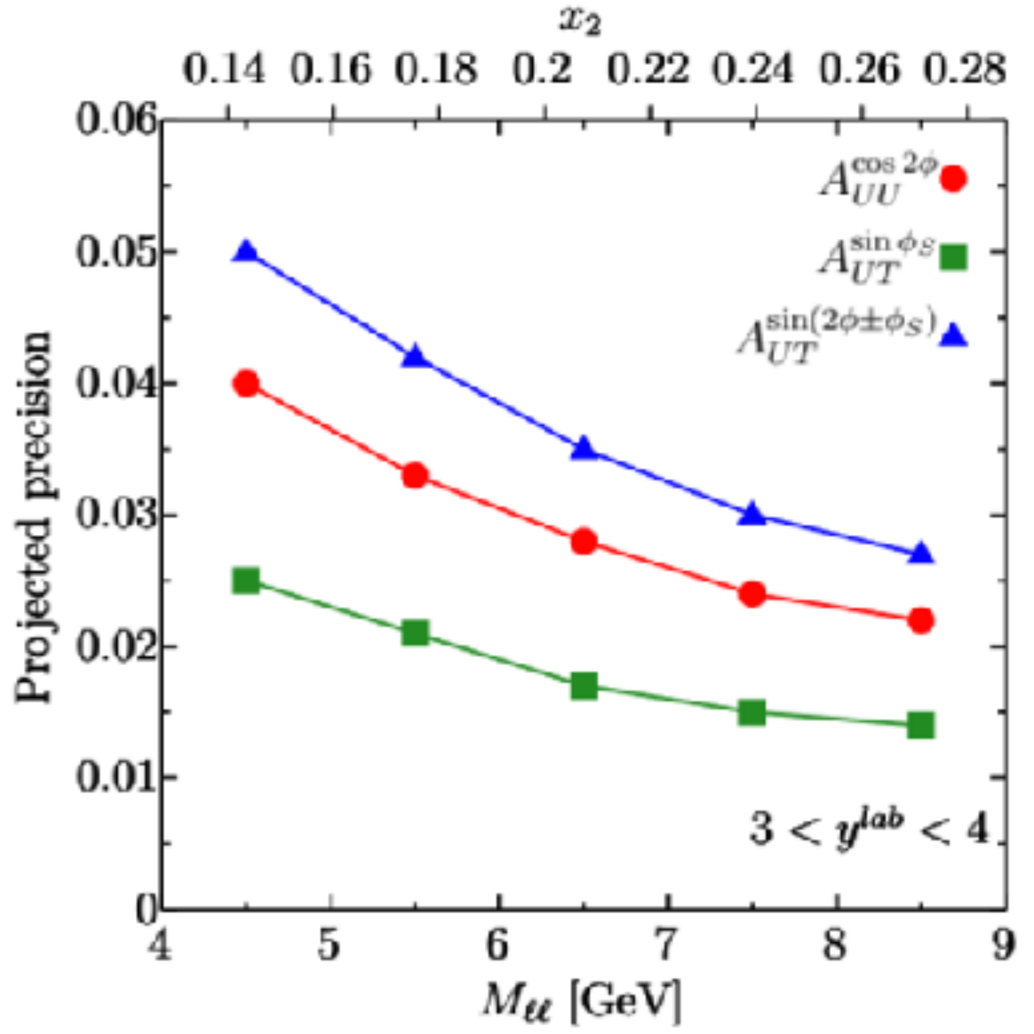
Projections for qTMDs

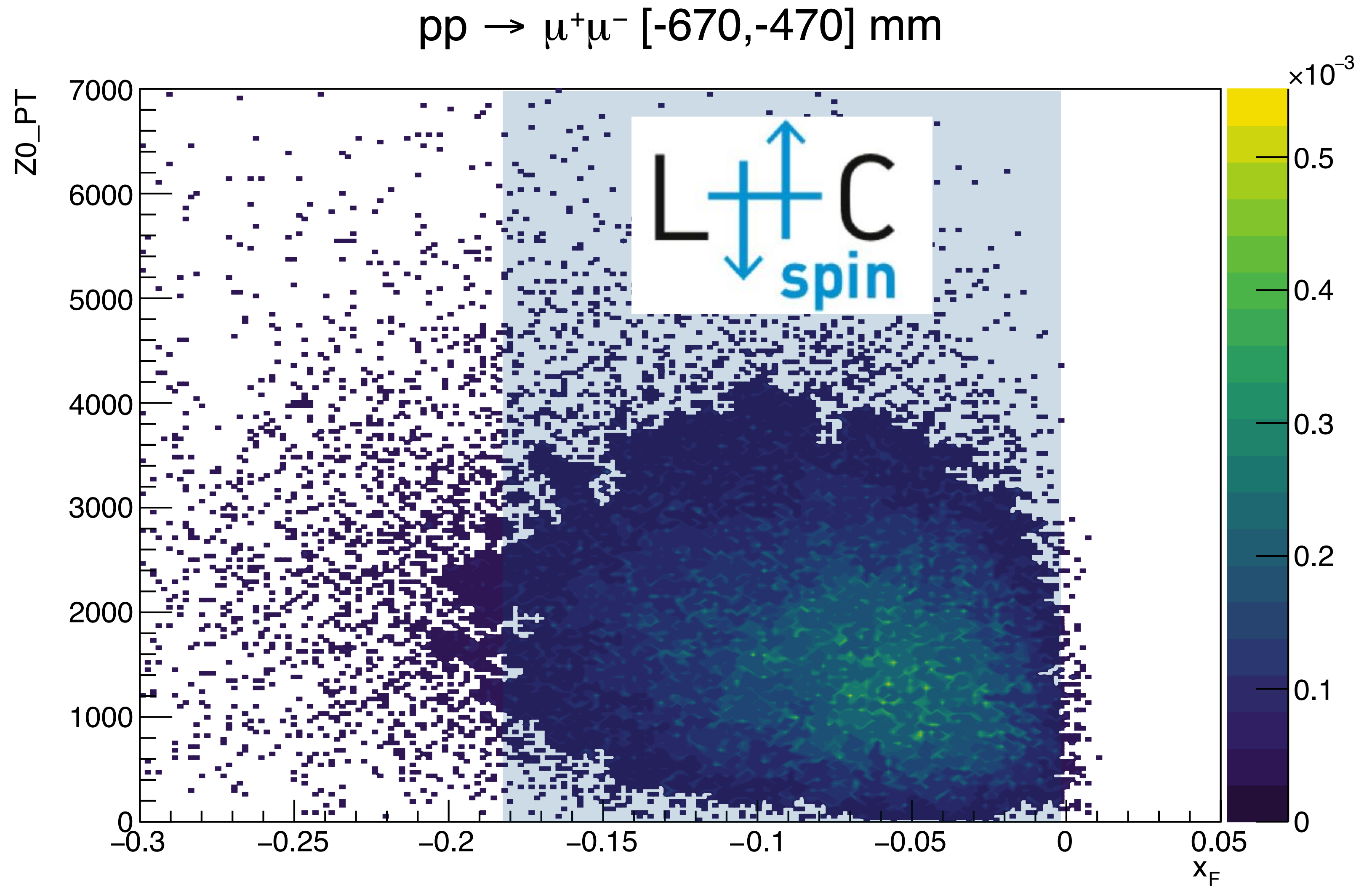
[from L. Pappalardo SPIN2021]

Theoretical Predictions ⇄ **Simulated Projections**

[arXiv:1807.00603]







- Theoretical **prediction of the A_N^{DY}**
  → Strict constraints on the Sivers effect for quarks

- Expected precision for different **angular modulations of the DY production** as a function of $M_{\ell\ell}$
  → verify the change of sign $(f_{1T}^{\perp,q})_{DY} = -(f_{1T}^{\perp,q})_{SIDIS}$

- Kinematic coverage with ~30k events ($pp \to \mu^+\mu^-$)

- A good precision can be attained with ~1M events and 20-40 MeV mass resolution

- Dedicated trigger lines can be implemented