The LHC spin project: status and perspectives

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STRONG-2020

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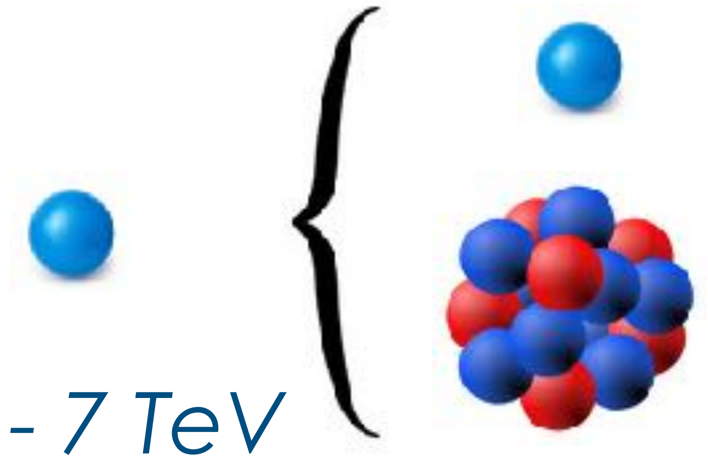
CPHI 2022
Correlations in Partonic and Hadronic Interactions (CPHI-2022)

10/3/22

The LHCspin project aims to bring spin physics at the LHC through the implementation of a new-generation compact polarized gaseous fixed target in the LHCb spectrometer

Fixed-target kinematics:

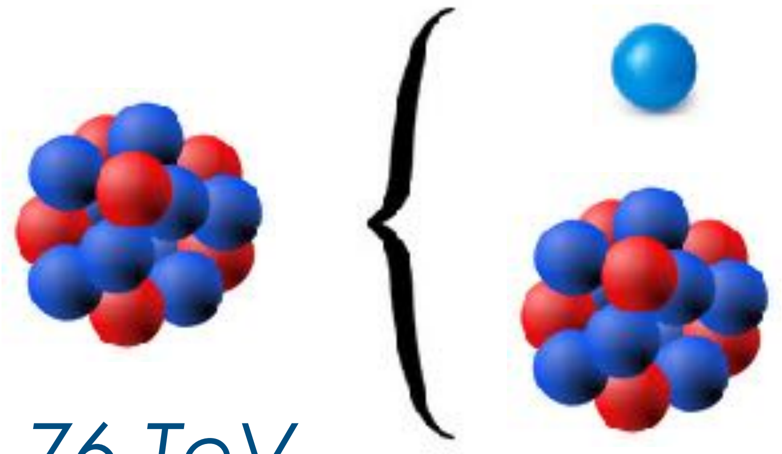


0.45 - 7 TeV

pp/pA collisions up to 7 TeV beam

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

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



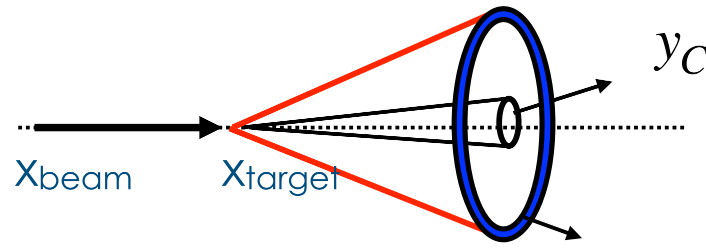
2.76 TeV

AA collisions: 2.76 TeV beam

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

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

Boost effect $\gamma = \frac{\sqrt{s}}{2m_p} \sim 60$ ⟶ access to large x^{target} physics (x_F<0)



$y_{CMS} = 0 \ \rightarrow \theta \sim 1^\circ$

$y_{CMS} = -3$

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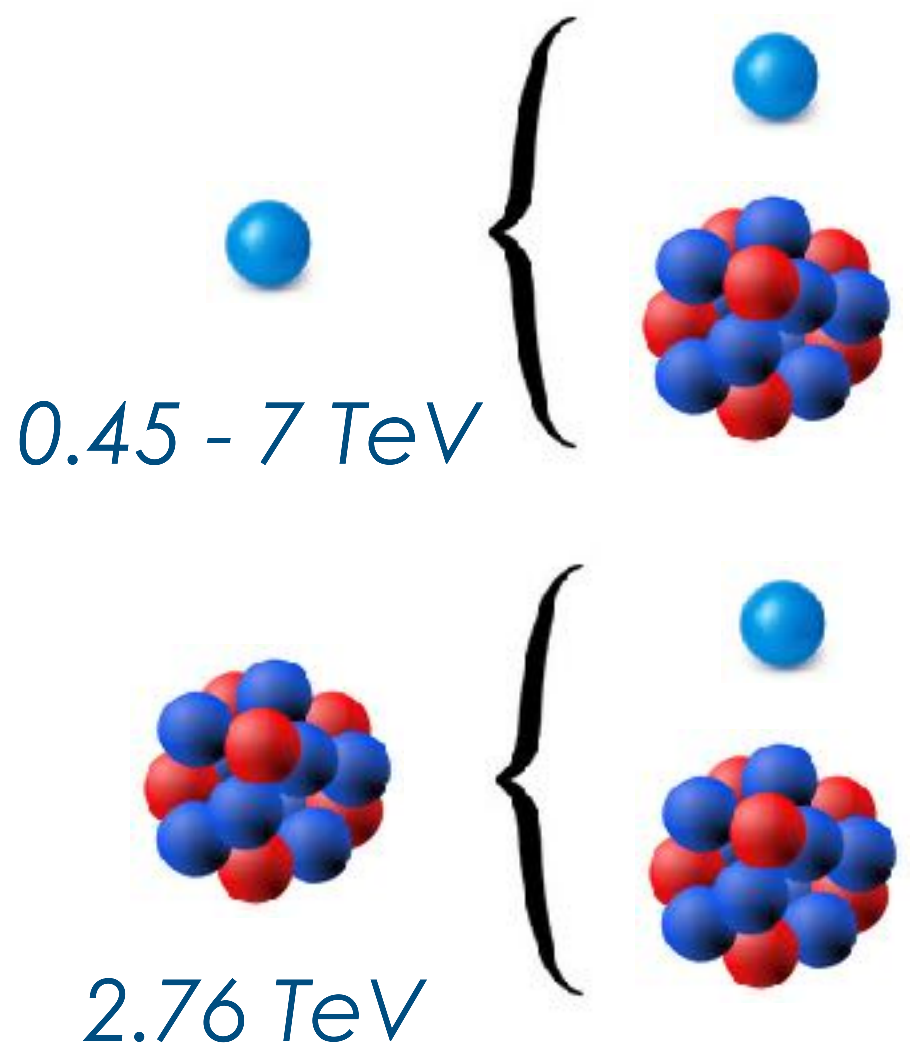

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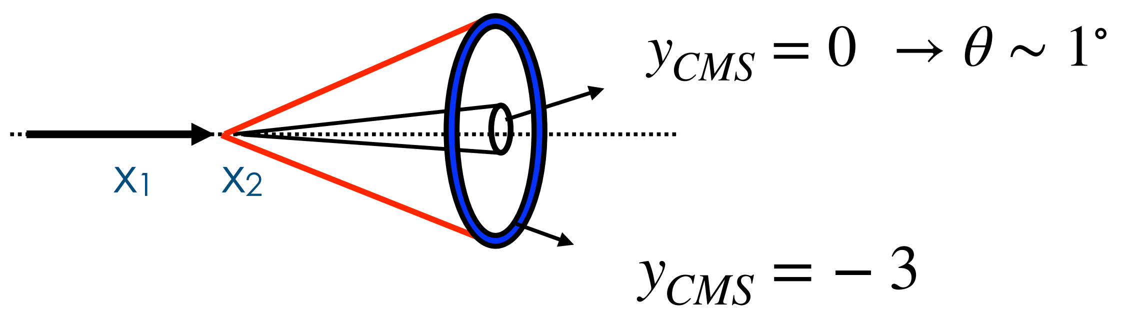
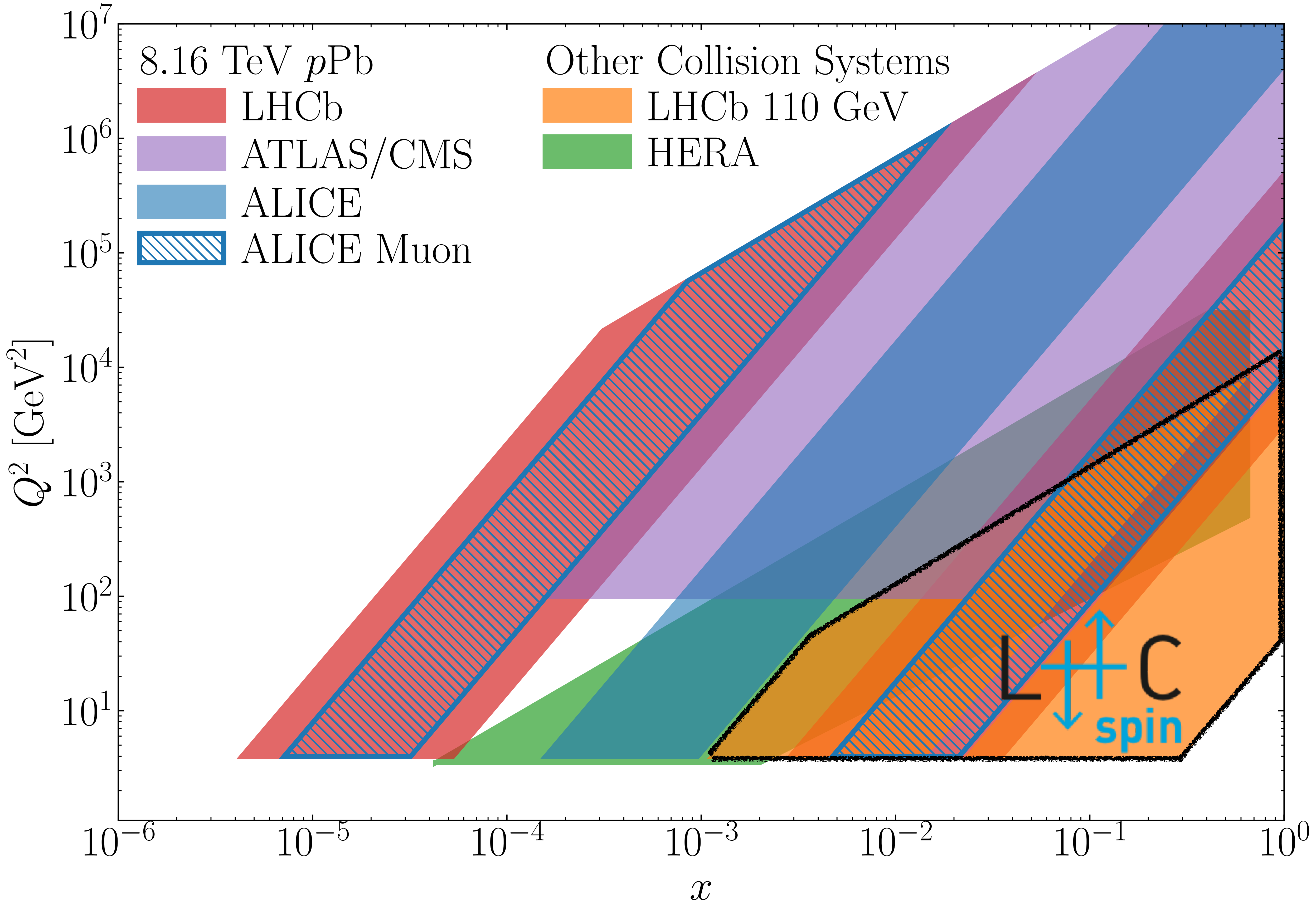


Points of strength

- development of a new generation $H^{\uparrow\downarrow}, D^{\uparrow\downarrow}$ polarized gas target from a well established technology (HERMES @ DESY, ANKE @ COSY)
- marginal impact on LHC beam lifetime and LHCb beam-beam physics program and performances
- can run in parallel with collider mode
- can benefit from both protons and heavy-ion beams
- allows also injection of non-polarized gases: H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe

The physics goals of LHCspin

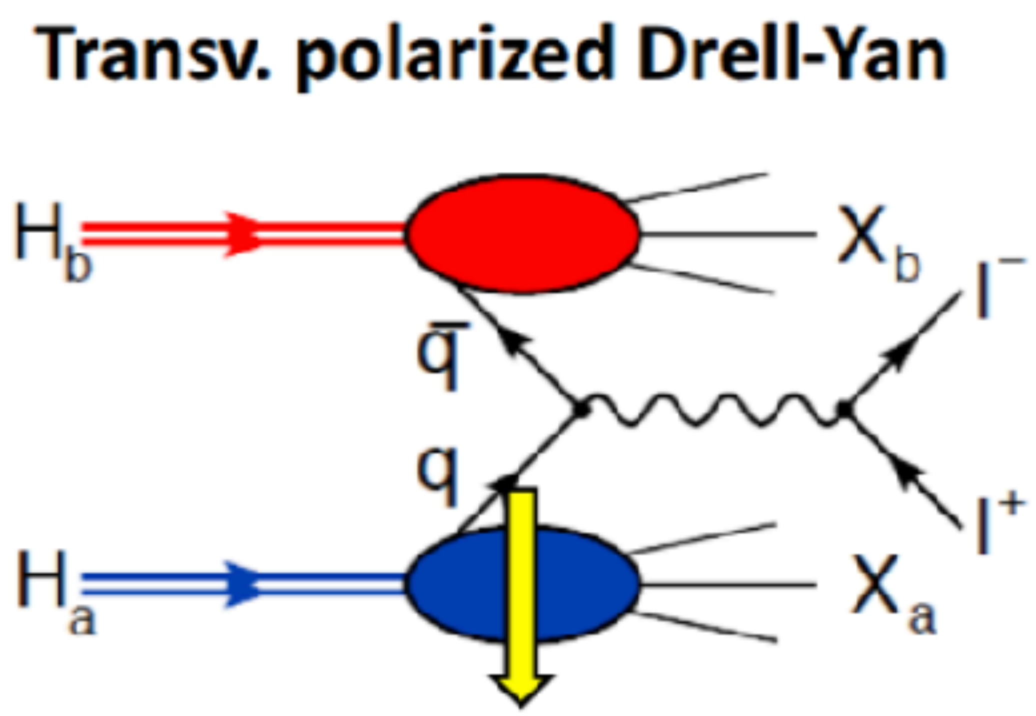
- Multi-dimensional nucleon structure in a poorly explored kinematic domain
- Measure experimental observables sensitive to both quarks and gluons TMDs, and GPDs
- Make us of new probes (charmed and beauty mesons)
- Complement present and future SIDIS results
- Test non-trivial process dependence of quarks and (especially) gluons TMDs
- Extend our understanding of the strong force in the non-perturbative regime



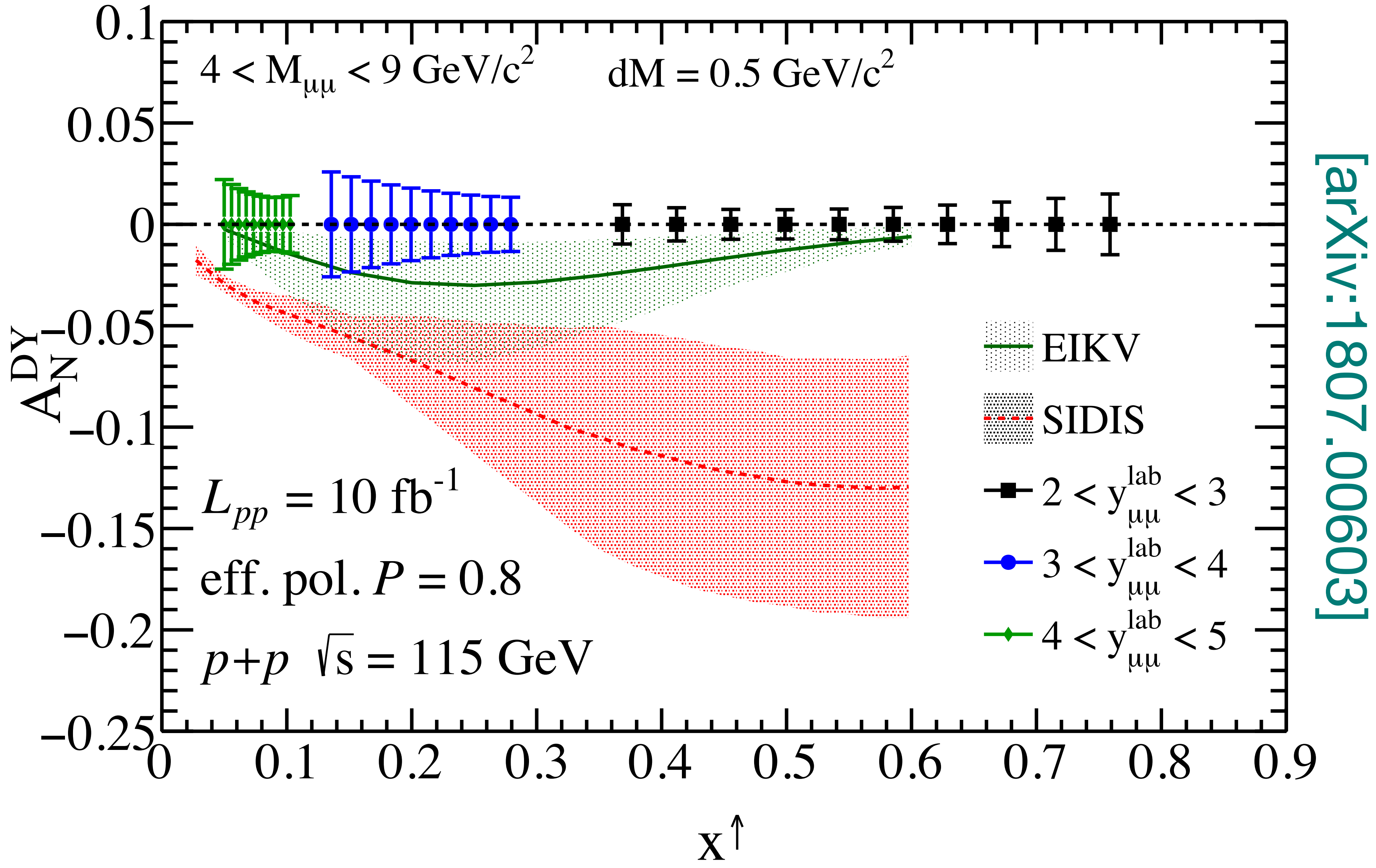
Quark TMDs

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



Golden Channel



[arXiv:1807.00603]

- **Sensitive to quark TMDs through TSSAs**

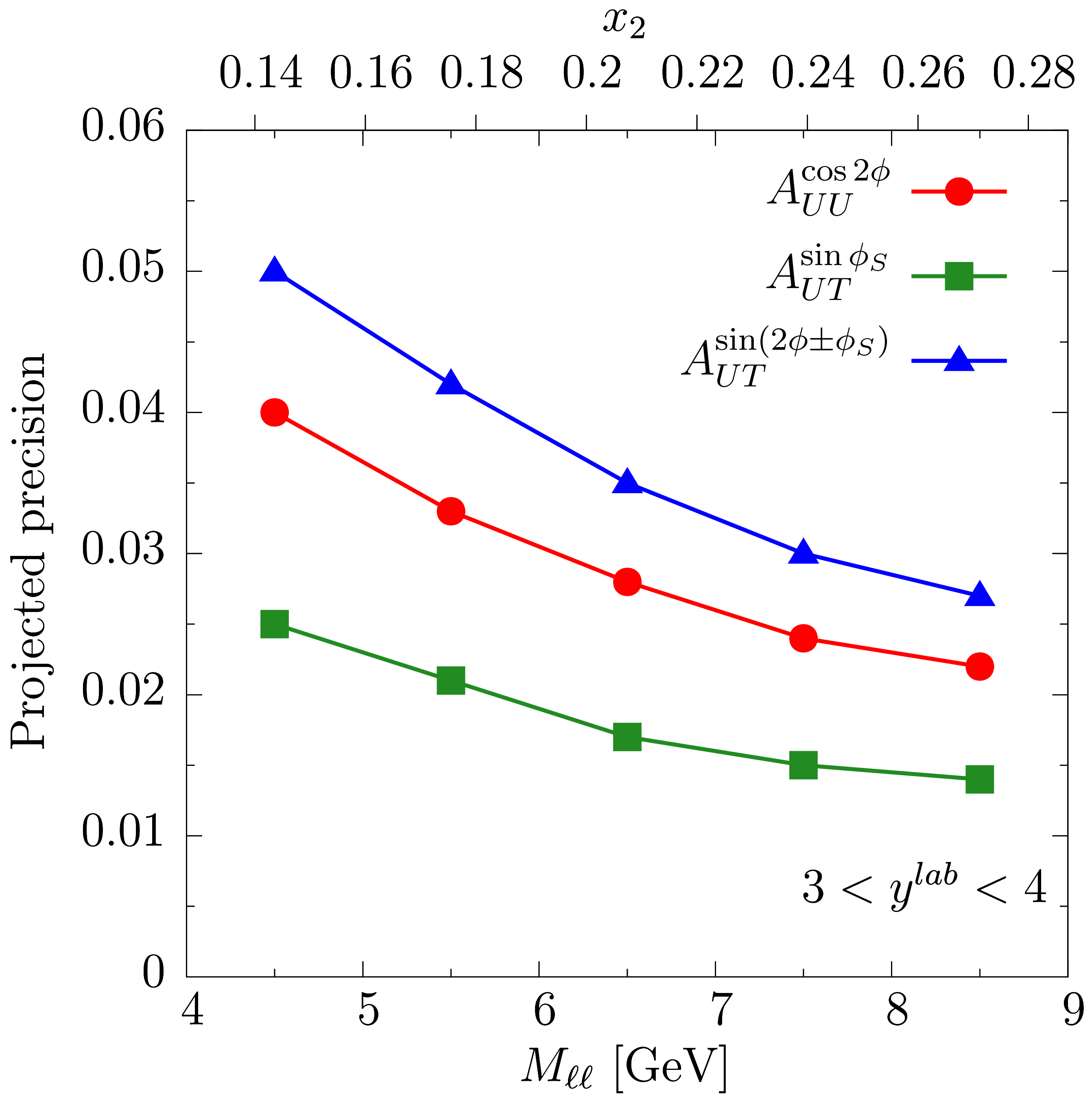
$$A_N^{DY} = \frac{1}{P}\frac{\sigma_{DY}^{\uparrow} - \sigma_{DY}^{\downarrow}}{\sigma_{DY}^{\uparrow} + \sigma_{DY}^{\downarrow}} \Longrightarrow A_{UT}^{\sin\phi_S} \sim \frac{f_1^q \otimes f_{1T}^{\perp q}}{f_1^q \otimes f_1^q},\quad A_{UT}^{\sin(2\phi-\phi_S)} \sim \frac{h_1^{\perp q} \otimes h_1^q}{f_1^q \otimes f_1^q},\ \ldots$$

(ϕ: azimuthal orientation of lepton pair in dilepton CM)

LHCb has excellent μ-ID & reconstruction for $\mu^+\mu^-$

dominant: $\bar{q}(x_{beam}) + q(x_{target}) \to \mu^+\mu^-$

suppressed: $q(x_{beam}) + \bar{q}(x_{target}) \to \mu^+\mu^-$



[arXiv:1807.00603]

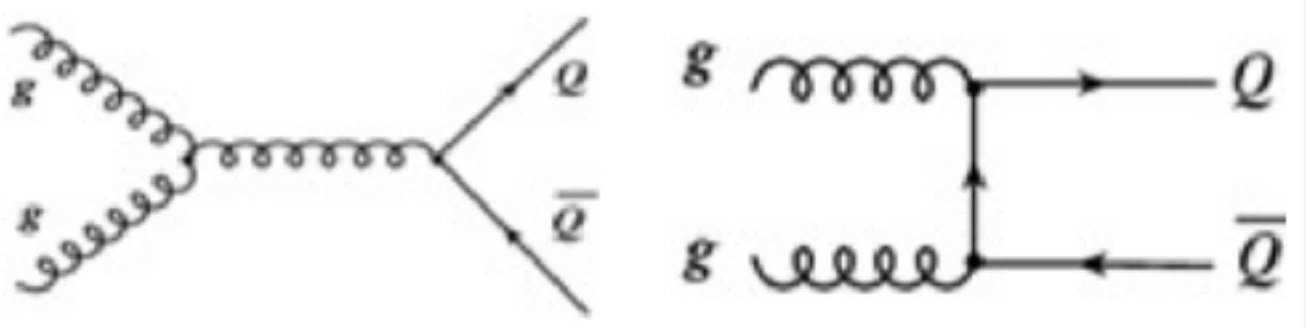
- Extraction of qTMDs does not require knowledge of FF
- Verify sign change of Sivers function wrt SIDIS $f_{1T}^{\perp}|_{DY} = -f_{1T}^{\perp}|_{SIDIS}$
- Test flavour sensitivity using both H and D targets

Gluon TMDs

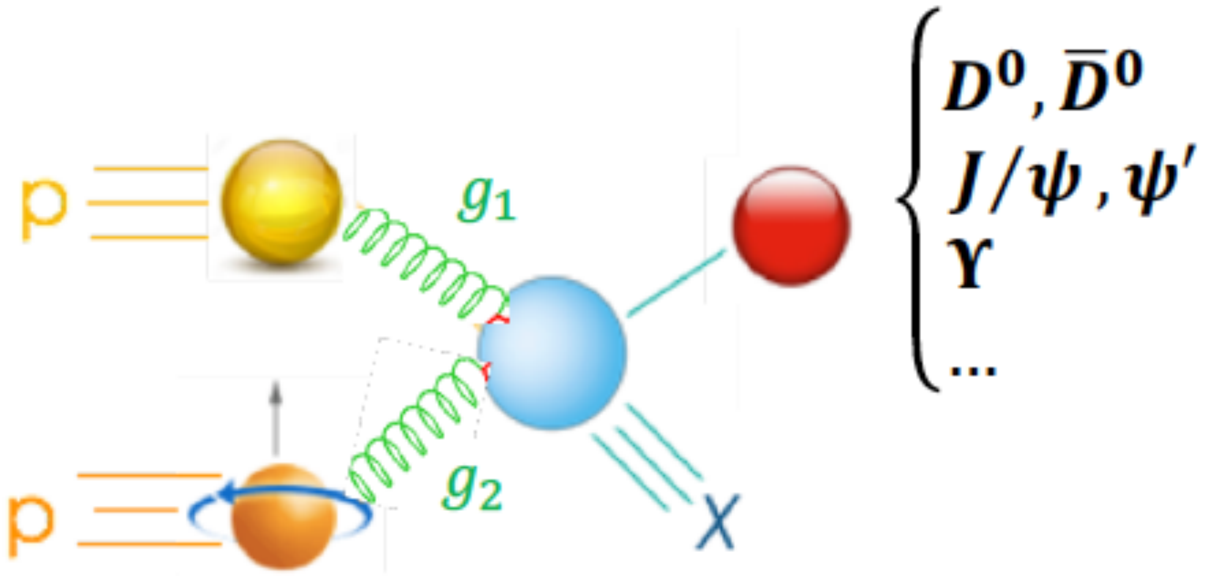
Theory framework well consolidated, but experimental access still extremely limited

nucleon pol. \ gluon pol.	U	Circularly	Linearly
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, $h_{1T}^{\perp g}$

The most efficient way to access the gluon dynamics inside the proton at LHC is to measure heavy-quark observables.
At LHC heavy quarks are produced by the dominant gg fusion process



Inclusive quarkonia production in (un)polarized pp interaction turns out to be an ideal observable to access gTMDs



TMD factorisation requires $q_T(Q) \ll M_Q$:

- Can look at associate quarkonia production, where only relative q_T needs to be small (e.g. $pp^{(\uparrow)} \to J/\Psi + J/\Psi + X$)
- Due to the large masses, easier in case of bottomonium where factorisation can hold at large q_T

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		gluon pol.		
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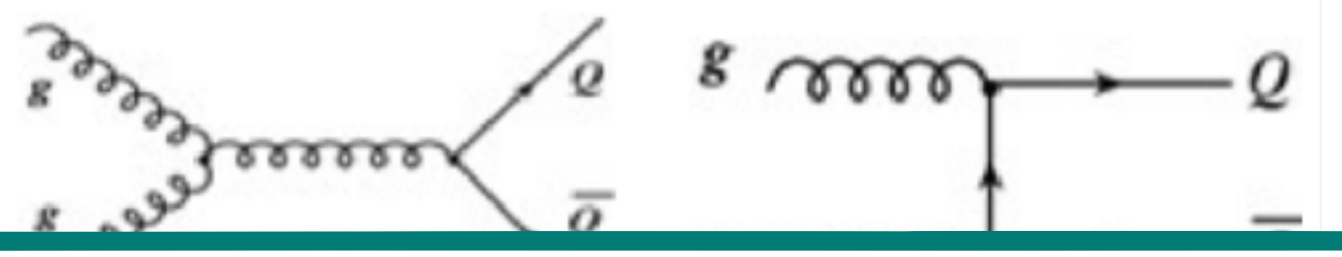
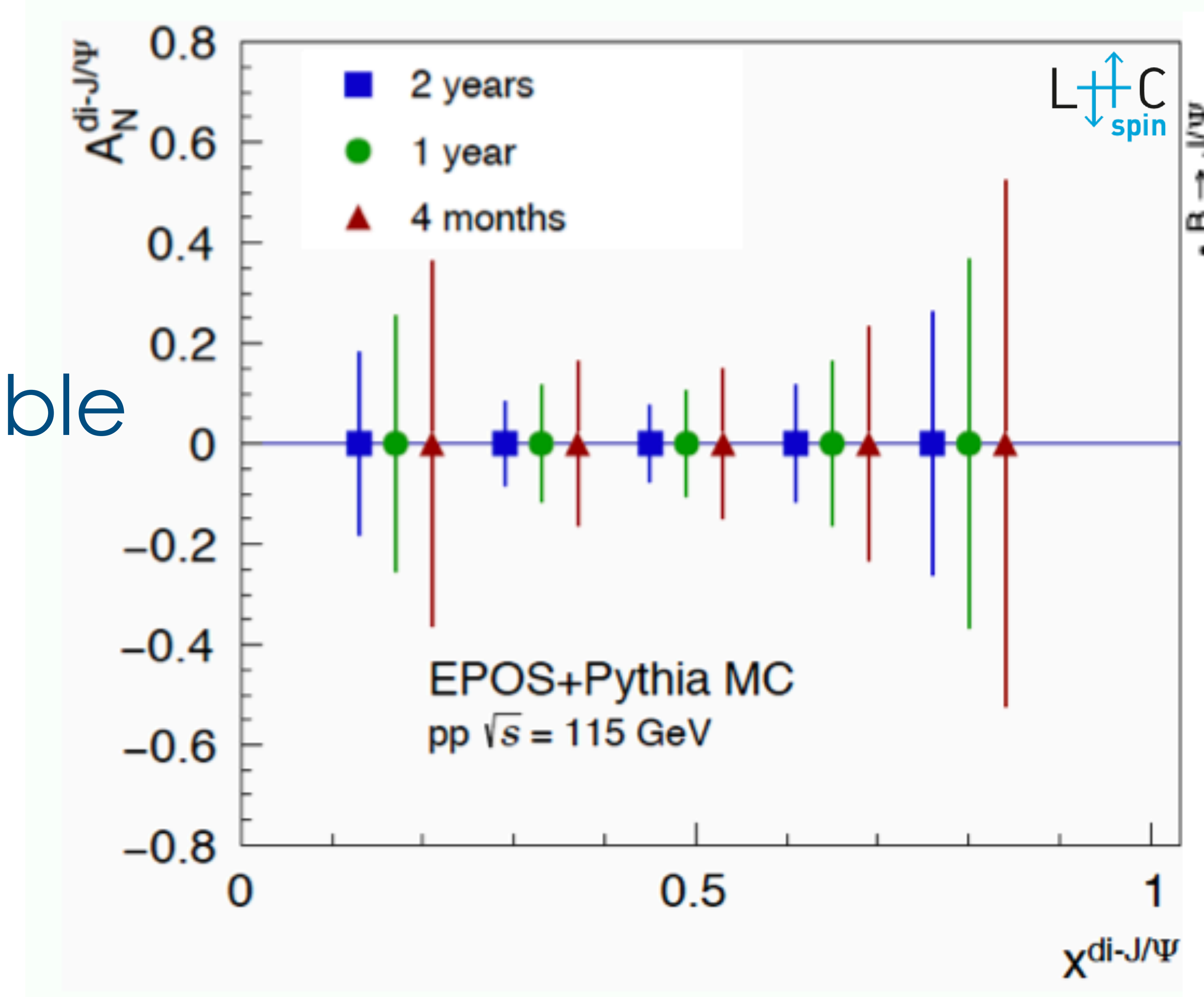
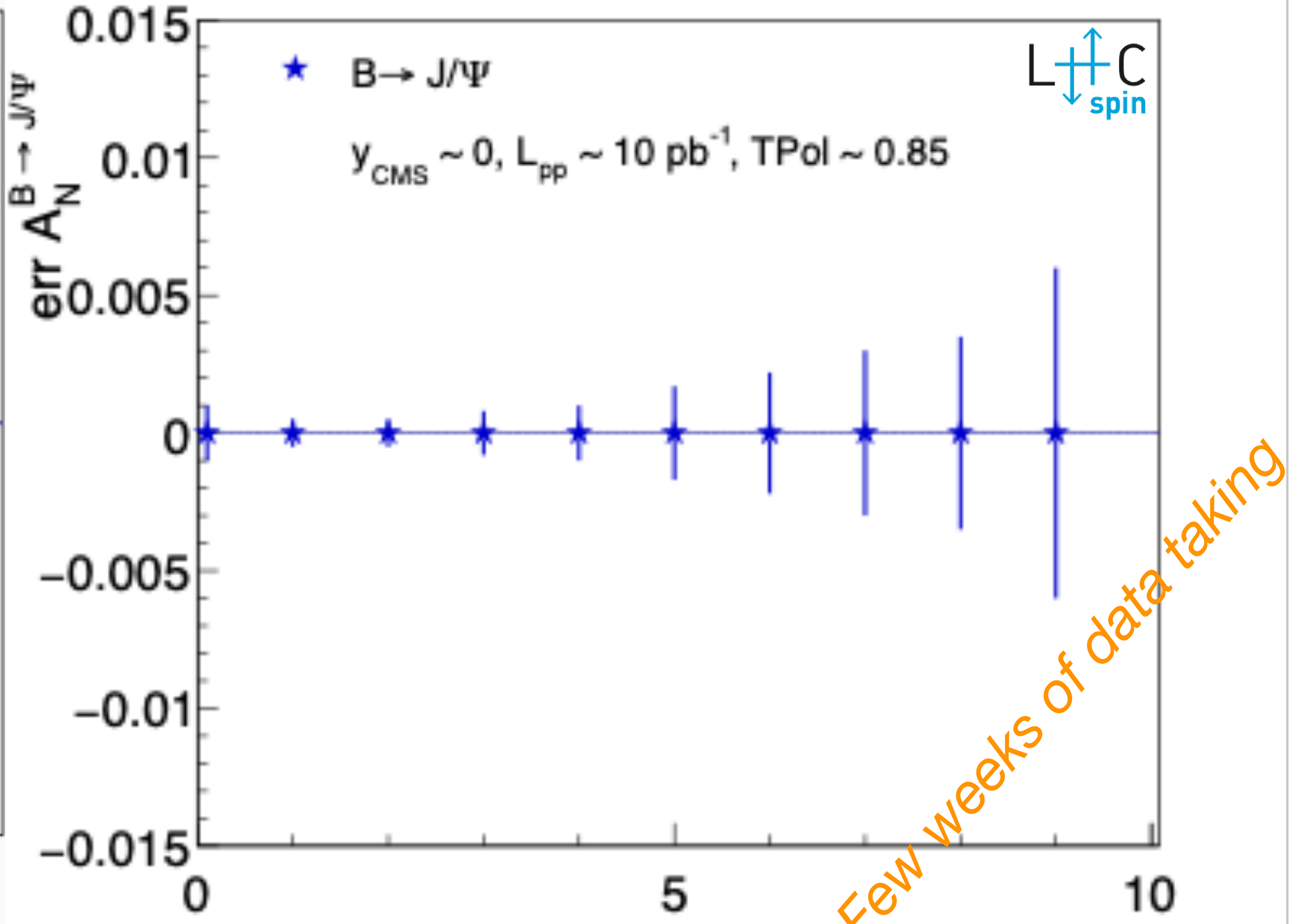


Gluon-induced asymmetries (unconstrained $h_1^{\perp g} + f_1^g$) accessible by, e.g., $di-J/\Psi$ or Υ production





… more probes: $\eta_c, \chi_c, \chi_b, \ldots$

factorisation can hold at large q_T

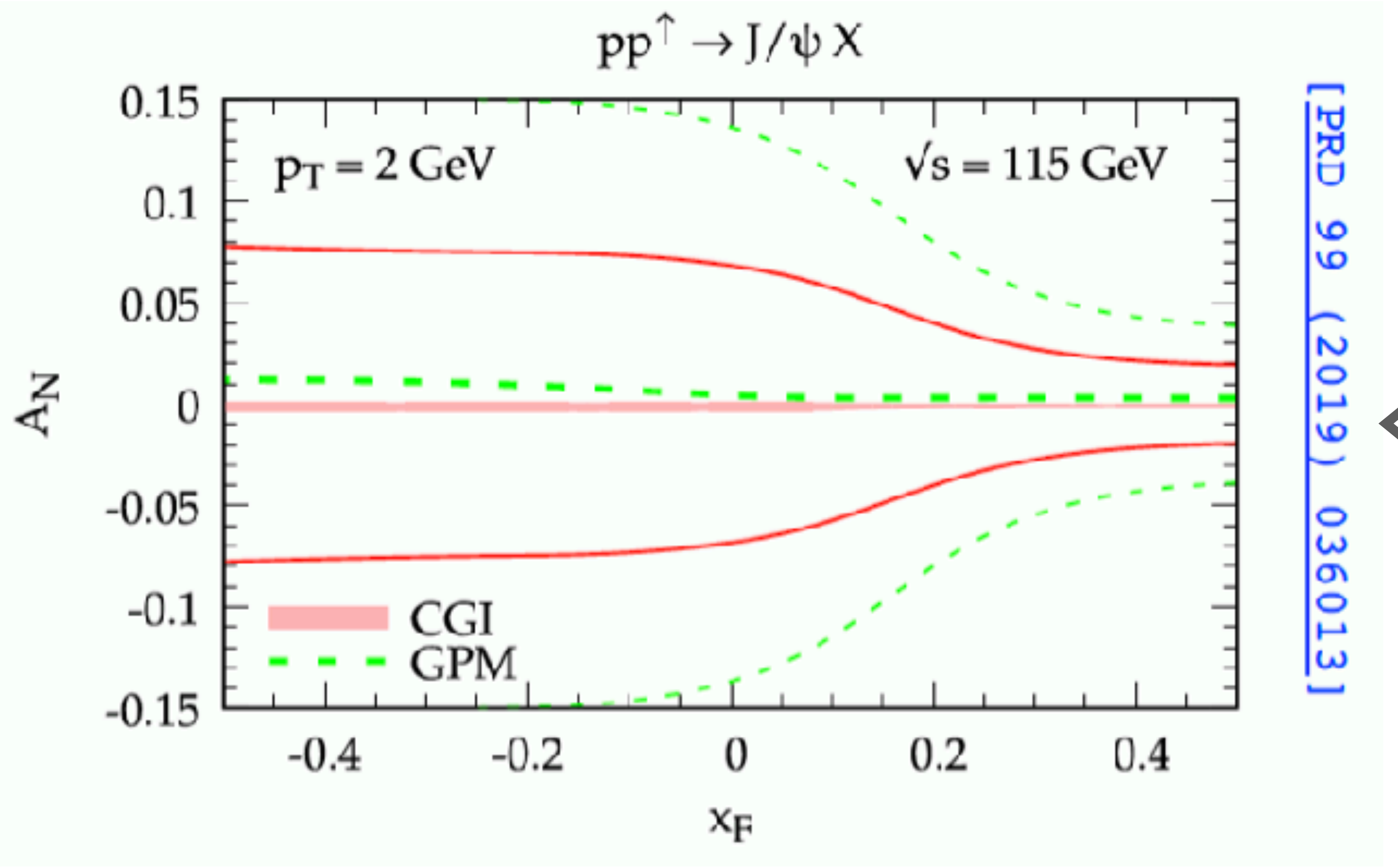
Probing the Sivers function

Can be accessed through the Fourier decomposition of the TSSAs for inclusive meson production

$$A_N = \frac{1}{P}\frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \propto \left[f_{1T}^{\perp g}(x_a, k_{\perp a}) \otimes f_g(x_b, k_{\perp b}) \otimes d\sigma_{gg\to Q\bar{Q}g}\right] \sin\phi_S + \cdots$$

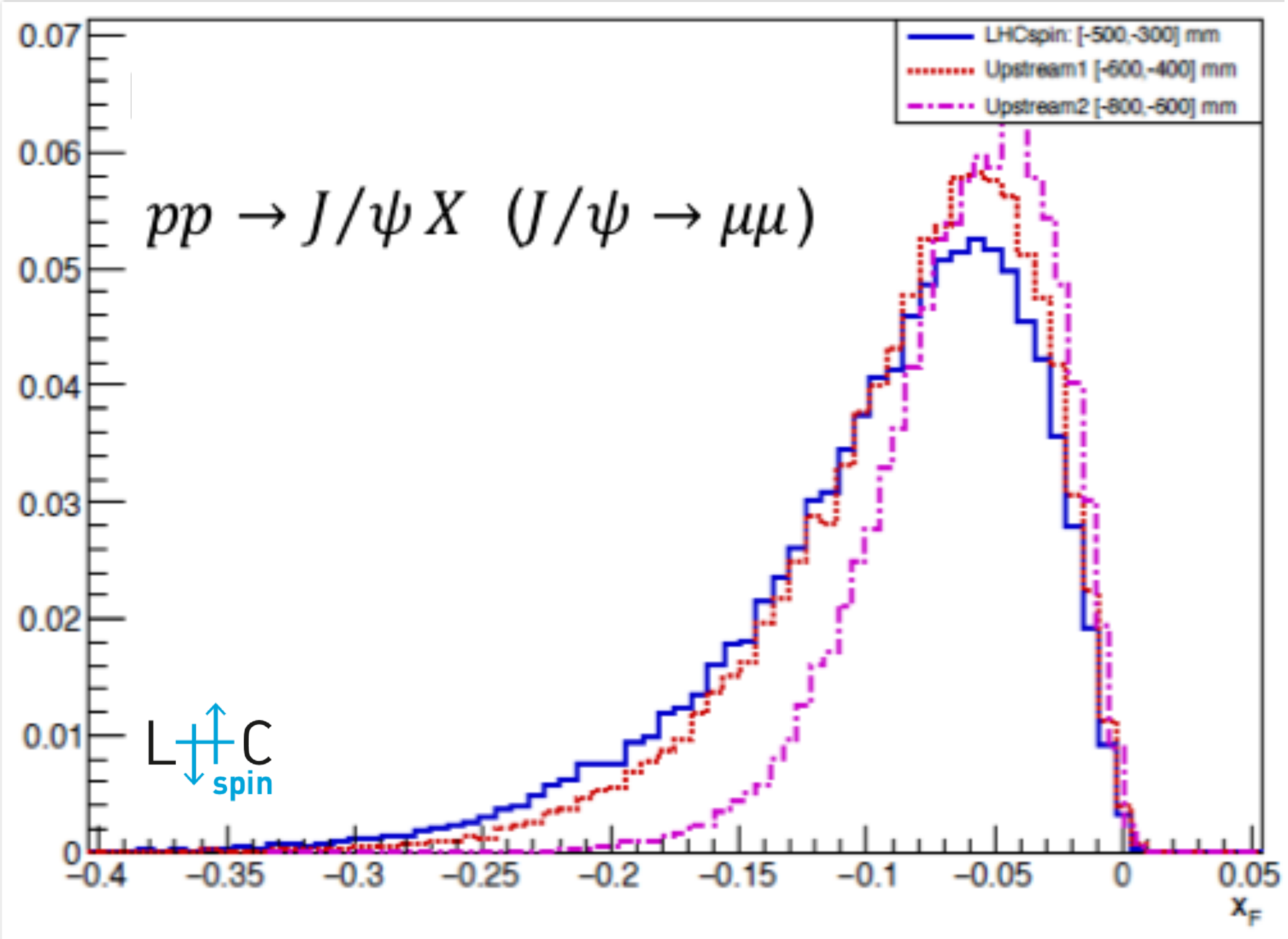
Sensitive to color exchange among IS and FS, and gluon OAM

Shed light on spin-orbit correlation of unpolarized gluons inside a transversely polarized proton

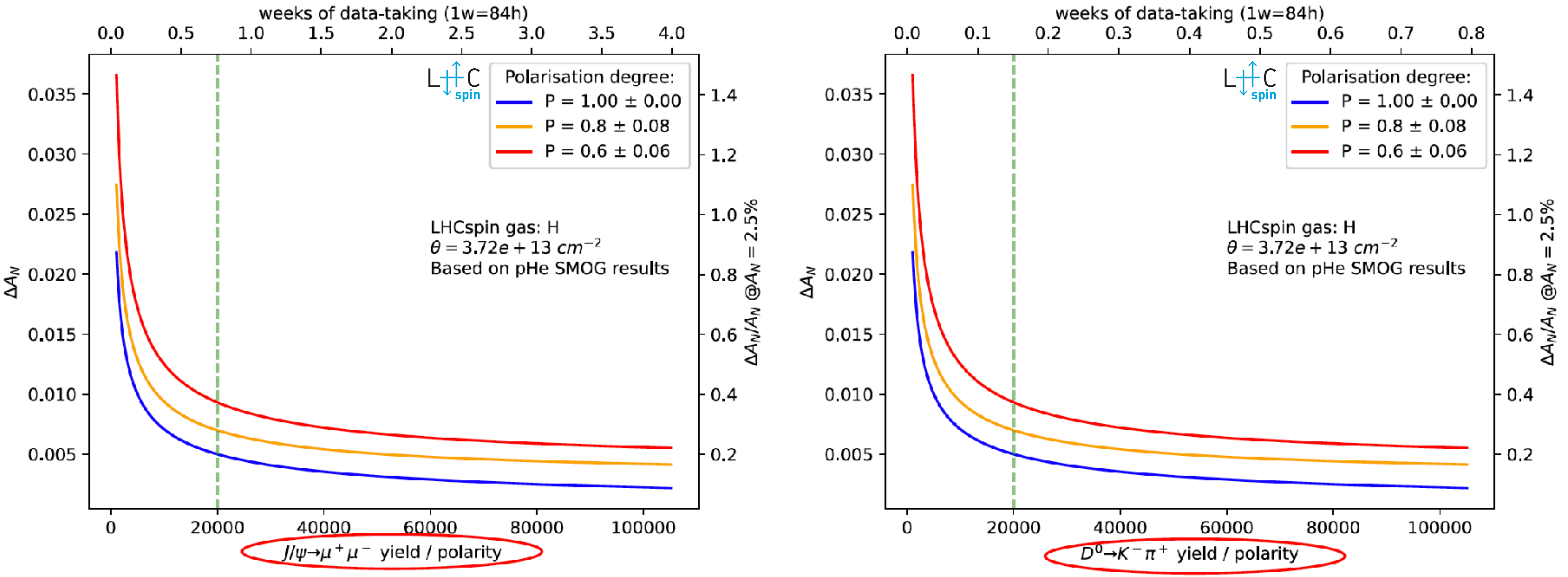


Predictions for J/Ψ production based on GPM & CGI-GPM

Expected amplitudes could reach 5-10% in the $x_F < 0$ region

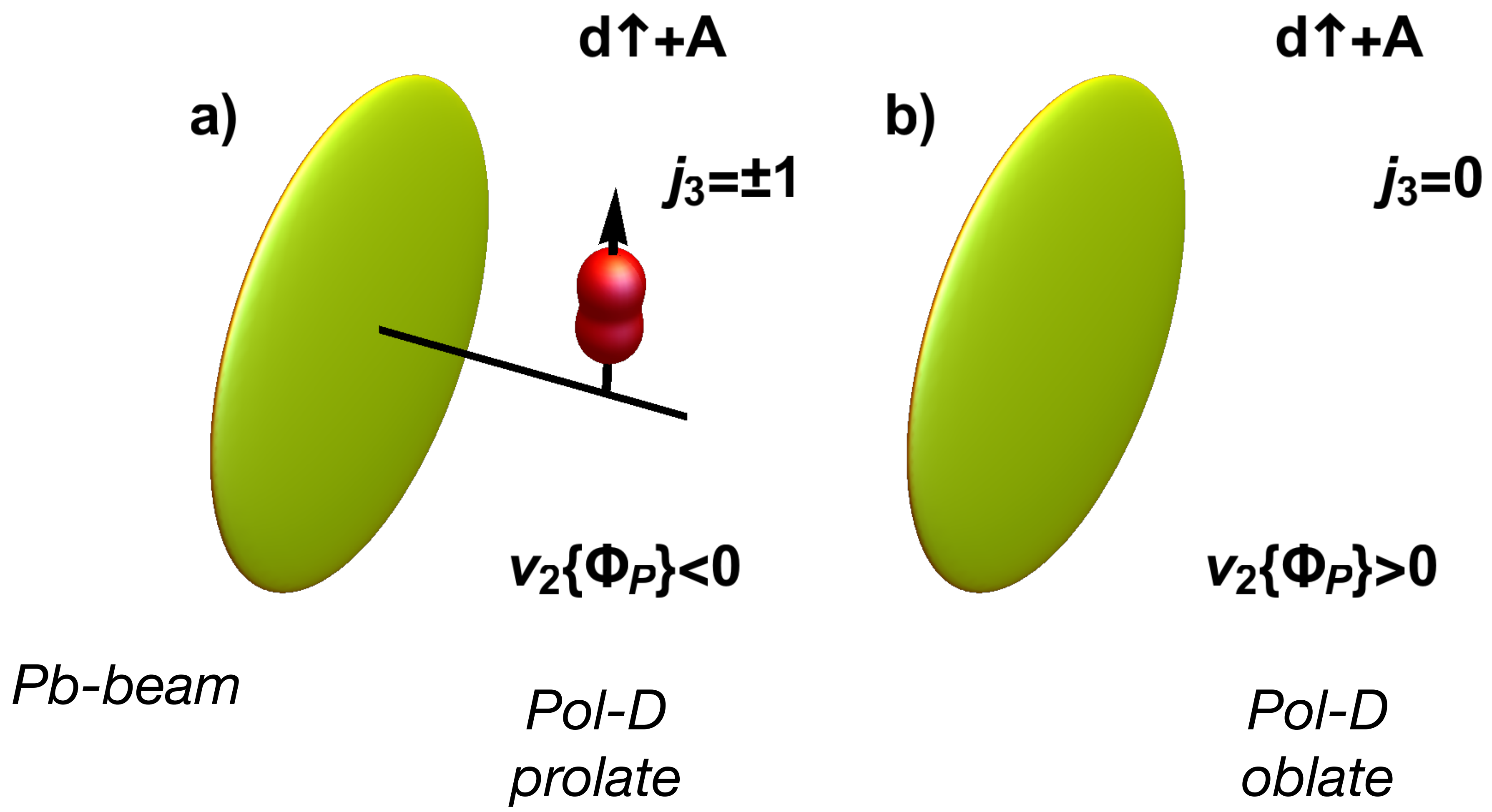


Examples of expected performances

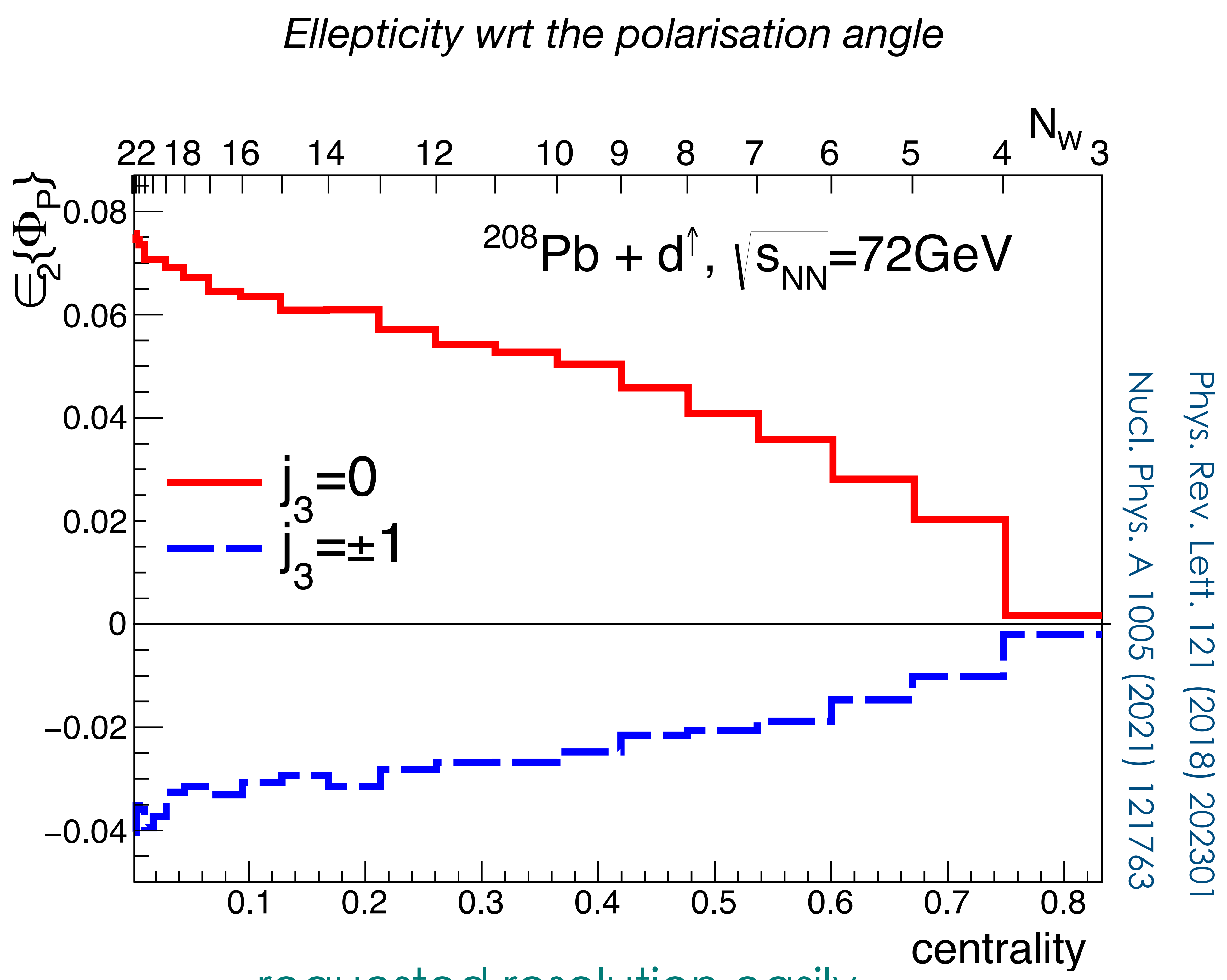


reconstructed particles

A new opportunity: spin physics in heavy-ion collisions



Φ_p polarisation angle



requested resolution easily achievable with LHCspin

Deep insight into the dynamics of small systems.

Spin adds a privileged direction to the collectivity phenomena studies

The collective evolution produces elliptic flow which can be quantified with respect to the (fixed) polarization axis

International framework and feedback

Several experiments dedicated to spin physics, but with many limitations:
very low energy, no rare probes, no ion beam, … → LHCspin is unique in this respect

LHCspin is complementary to EIC

[D. Boer: arXiv:1611.06089]

unpolarized gluon TMD

	DIS	DY	SIDIS	$pA \to \gamma\, \text{jet}\, X$	$e\,p \to e'\, Q\,\overline{Q}\, X$ $e\,p \to e'\, j_1\, j_2\, X$	$pp \to \eta_{c,b}\, X$ $pp \to H\, X$	$pp \to J/\psi\, \gamma\, X$ $pp \to \Upsilon\, \gamma\, X$
$f_1^{g\,[+,+]}$ (WW)	×	×	×	×	√	√	√
$f_1^{g\,[+,-]}$ (DP)	√	√	√	√	×	×	×

linearly polarized gluon TMD

	$pp \to \gamma\, \gamma\, X$	$pA \to \gamma^*\, \text{jet}\, X$	$e\,p \to e'\, Q\,\overline{Q}\, X$ $e\,p \to e'\, j_1\, j_2\, X$	$pp \to \eta_{c,b}\, X$ $pp \to H\, X$	$pp \to J/\psi\, \gamma\, X$ $pp \to \Upsilon\, \gamma\, X$
$h_1^{\perp\, g\,[+,+]}$ (WW)	√	×	√	√	√
$h_1^{\perp\, g\,[+,-]}$ (DP)	×	√	×	×	×

TMDs (Sivers) [D. Boer: arXiv:1611.06089, D. Boer et al. HEPJ 08 2016 001]

	DY	SIDIS	$p^\uparrow A \to h\, X$	$p^\uparrow A \to \gamma^{(*)}\, \text{jet}\, X$	$p^\uparrow p \to \gamma\, \gamma\, X$ $p^\uparrow p \to J/\psi\, \gamma\, X$ $p^\uparrow p \to J/\psi\, J/\psi\, X$	$e\,p^\uparrow \to e'\, Q\,\overline{Q}\, X$ $e\,p^\uparrow \to e'\, j_1\, j_2\, X$
$f_{1T}^{\perp\, g\,[+,+]}$ (WW)	×	×	×	×	√	√
$f_{1T}^{\perp\, g\,[+,-]}$ (DP)	√	√	√	√	×	×

$f_{1T}^{\perp g[+,+]}$ (Weizsacker-Williams type or "**f-type**") → antisymmetric colour structures

$f_{1T}^{\perp g[+,-]}$ (Dipole s type or "**d-type**") → symmetric colour structures

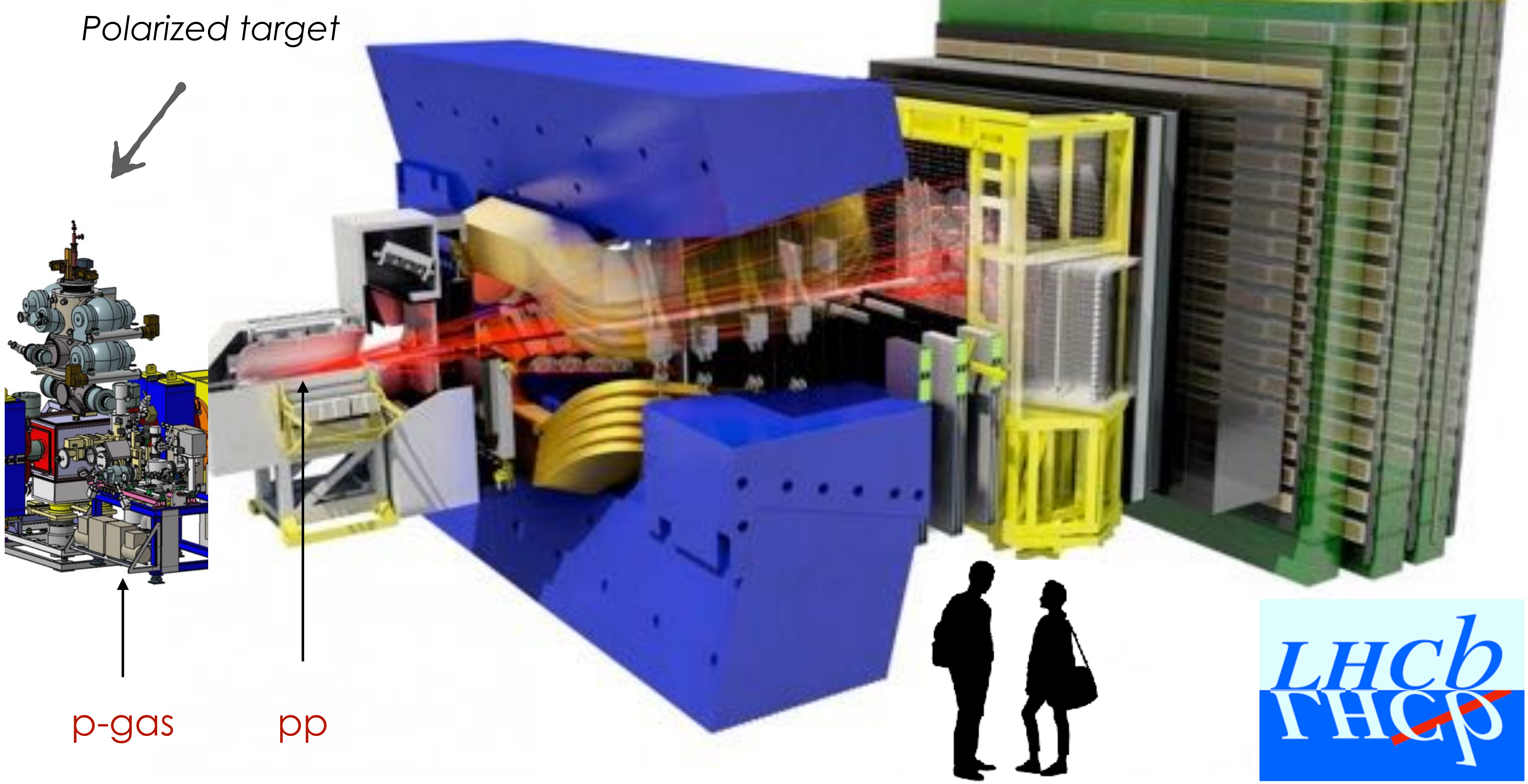
Can be measured at the Electron Ion-Collider (EIC)

Can be measured at LHCspin

"Ambitious and long term LHC-Fixed Target research program. The efforts of the existing LHC experiments to implement such a programme, including specific R&D actions on the collider, deserve support" (European Strategy for Particle Physics)

"This would be unique and highly complementary to existing and future measurements in lepton-proton collisions, because the asymmetries in question have a process dependence between pp and lp that is predicted by theory" (CERN Physics Beyond Collider)

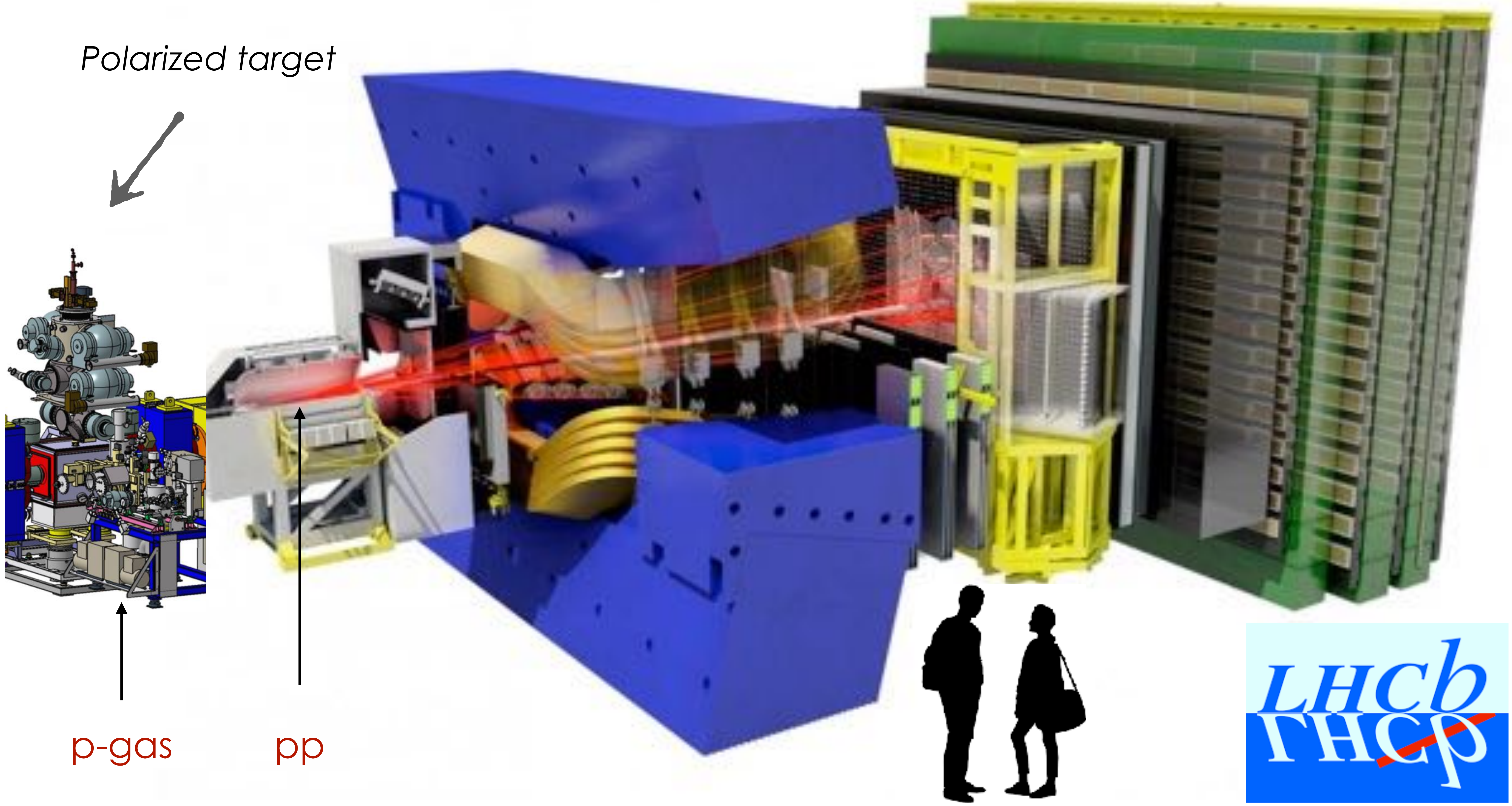
The hardware system



Successful technology based on HERA and COSY experiments

Challenge: develop a new generation of polarized targets

The hardware system



Successful technology based on HERA and COSY experiments

Challenge: develop a new generation of polarized targets

- *High density, high polarization, no dilution, high frequency spin inversion, polarized H and D*
- New coating materials: low Secondary Electron Yield (SEY) and suppress atomic recombination
- Compact Atomic Beam Source and Breit-Rabi Polarimeter
- Openable storage cell

- Compatibility with LHC (aperture, impedance, cooling, induced depolarization, vacuum, …)

The hardware system

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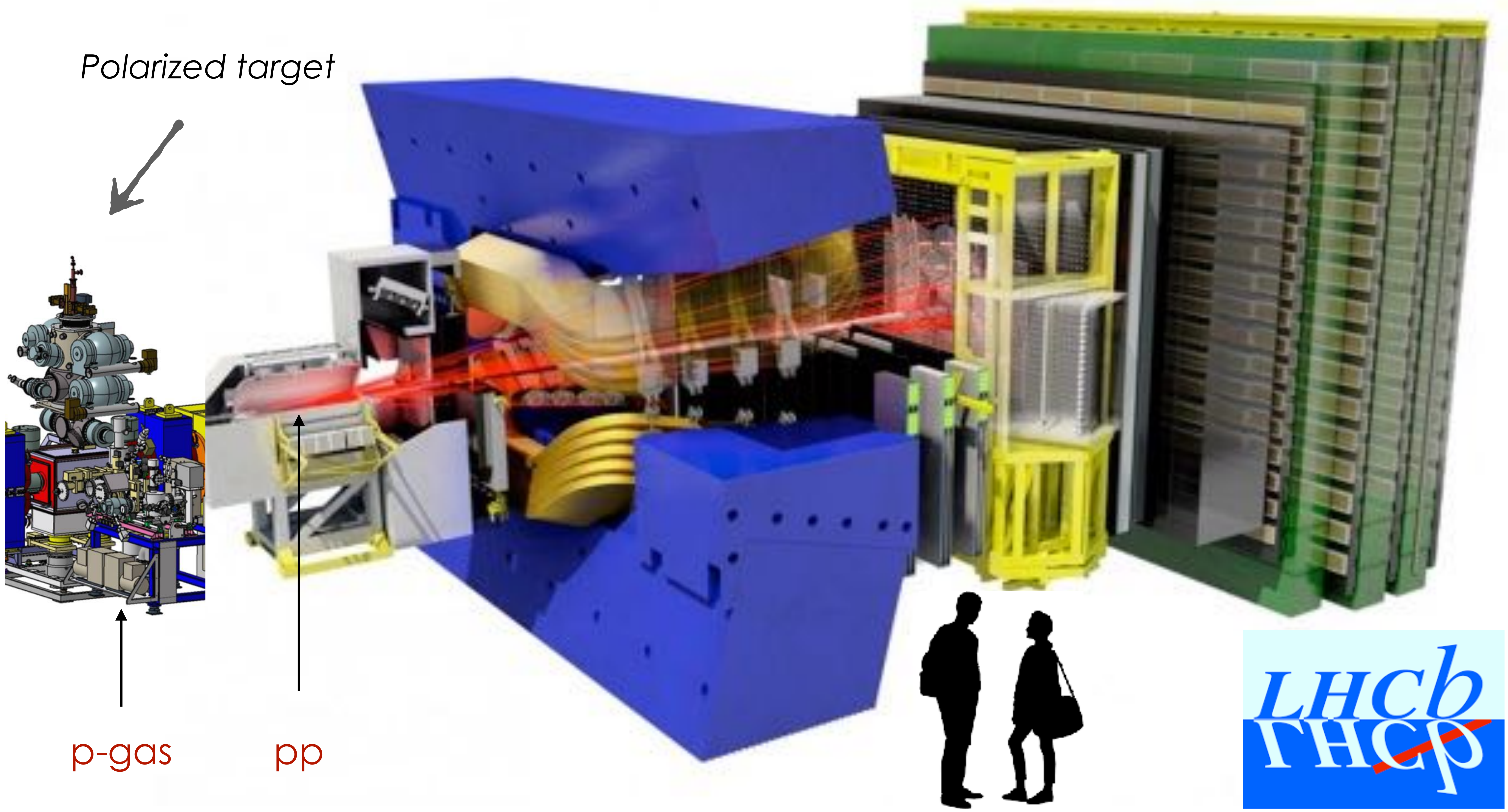


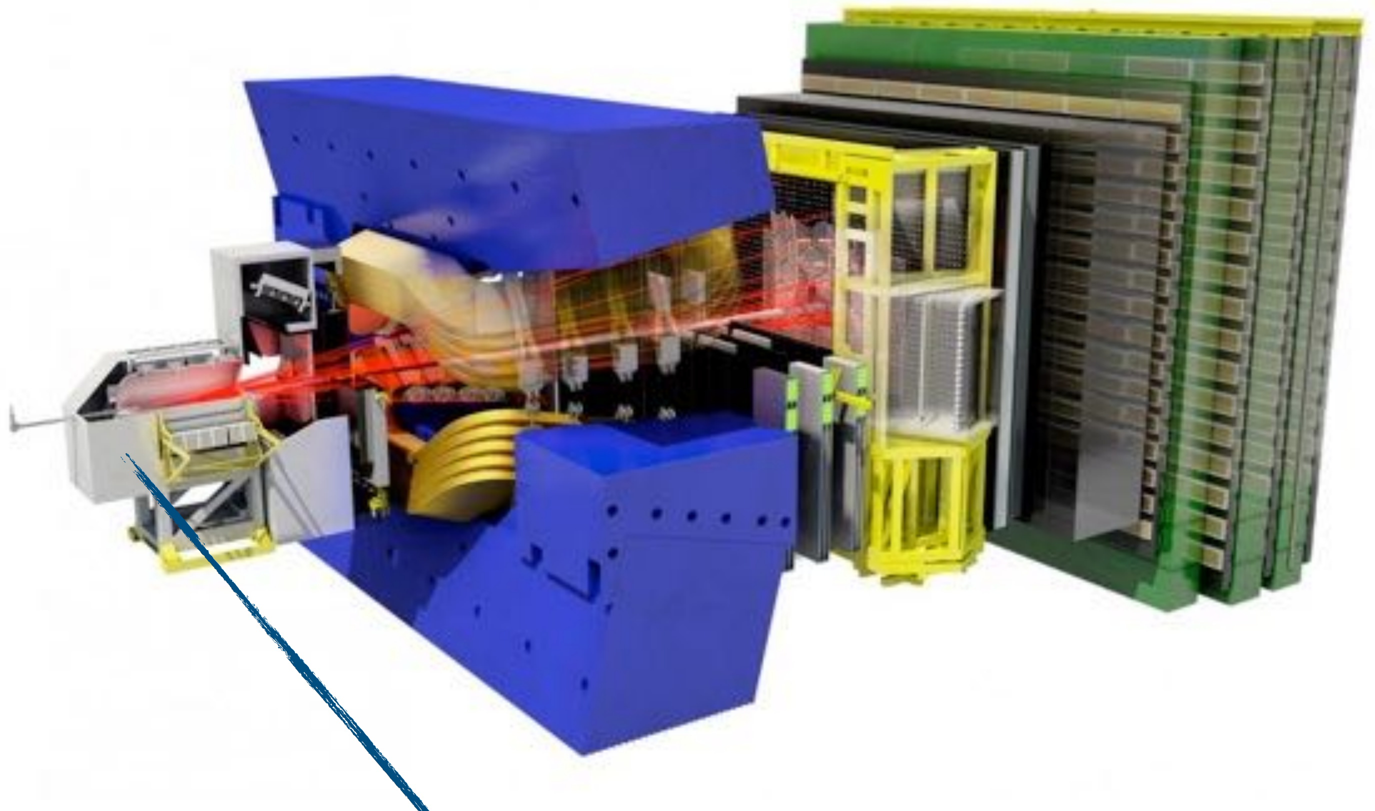
Target density (H) = 7 x 10^{13} cm^{-2}
LHC beam (Run4) = 6.8 x 10^{18} p s^{-1}

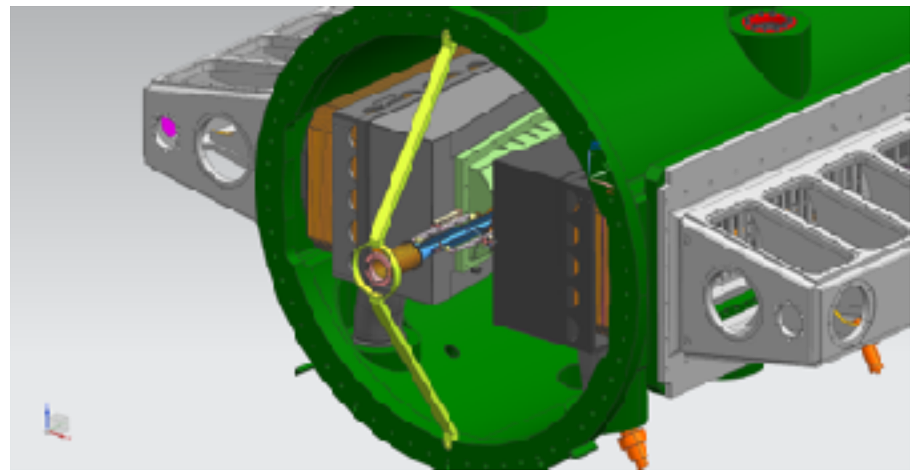
L_{pH} = 5 x 10^{32} cm^{-2} s^{-2}

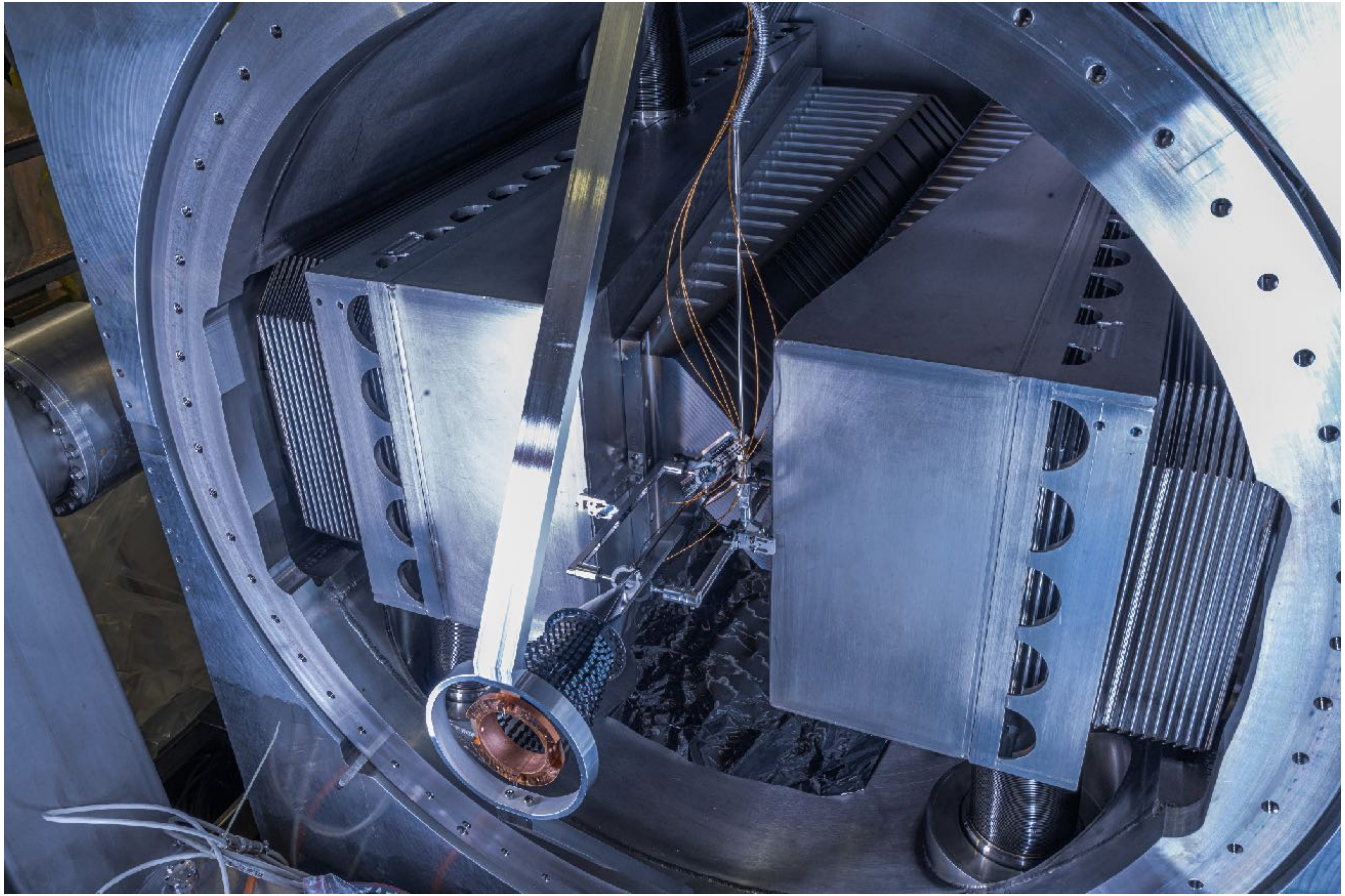
LHC beam life time 1/e reduction in **3300 h** (wrt **10 h** typical LHC beam)

The gas target has no impact to the other LHC experiments

SMOG2 the first gas target with storage cell at LHC/LHCb

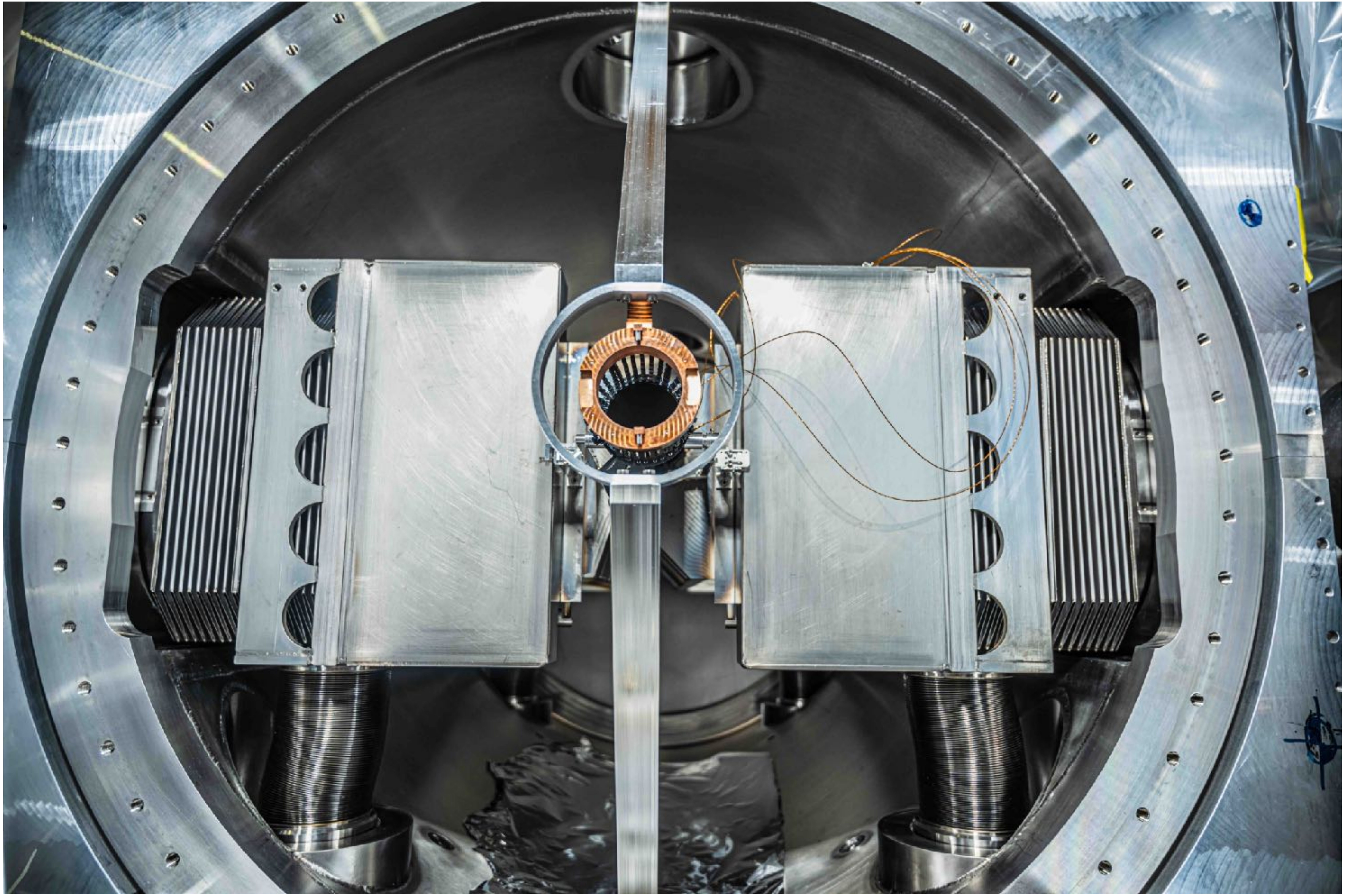






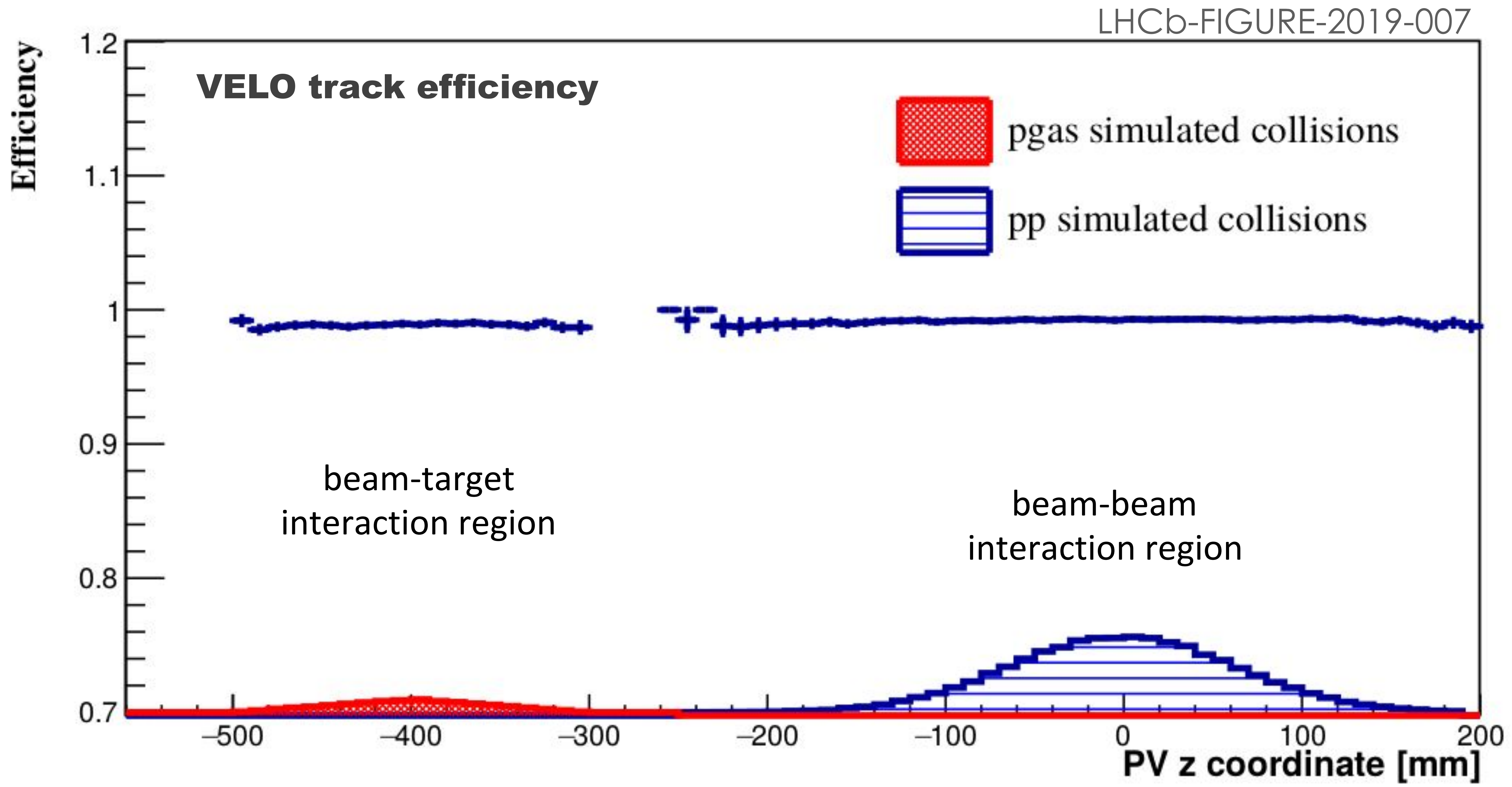
Besides the unique scientific production, the SMOG2 system, during the LHC Run 3 (from 2022), will deliver the first data usable for studying the mutual target-beam interactions providing a fundamental playground for the R&D of LHCspin

SMOG2



It is the only object in the LHC primary vacuum

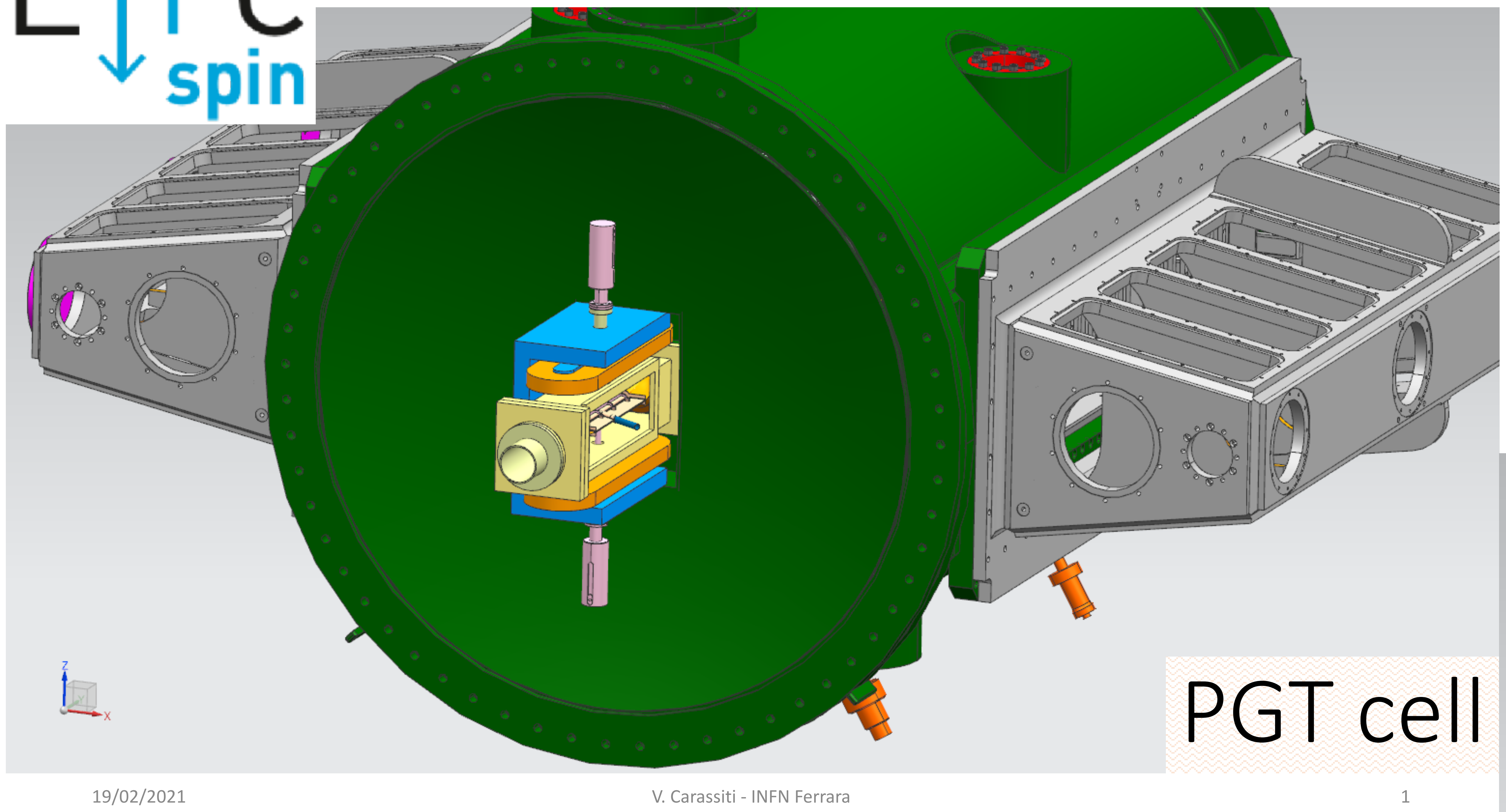
Simultaneous run for p-gas @ 115 GeV and pp @ 14 TeV



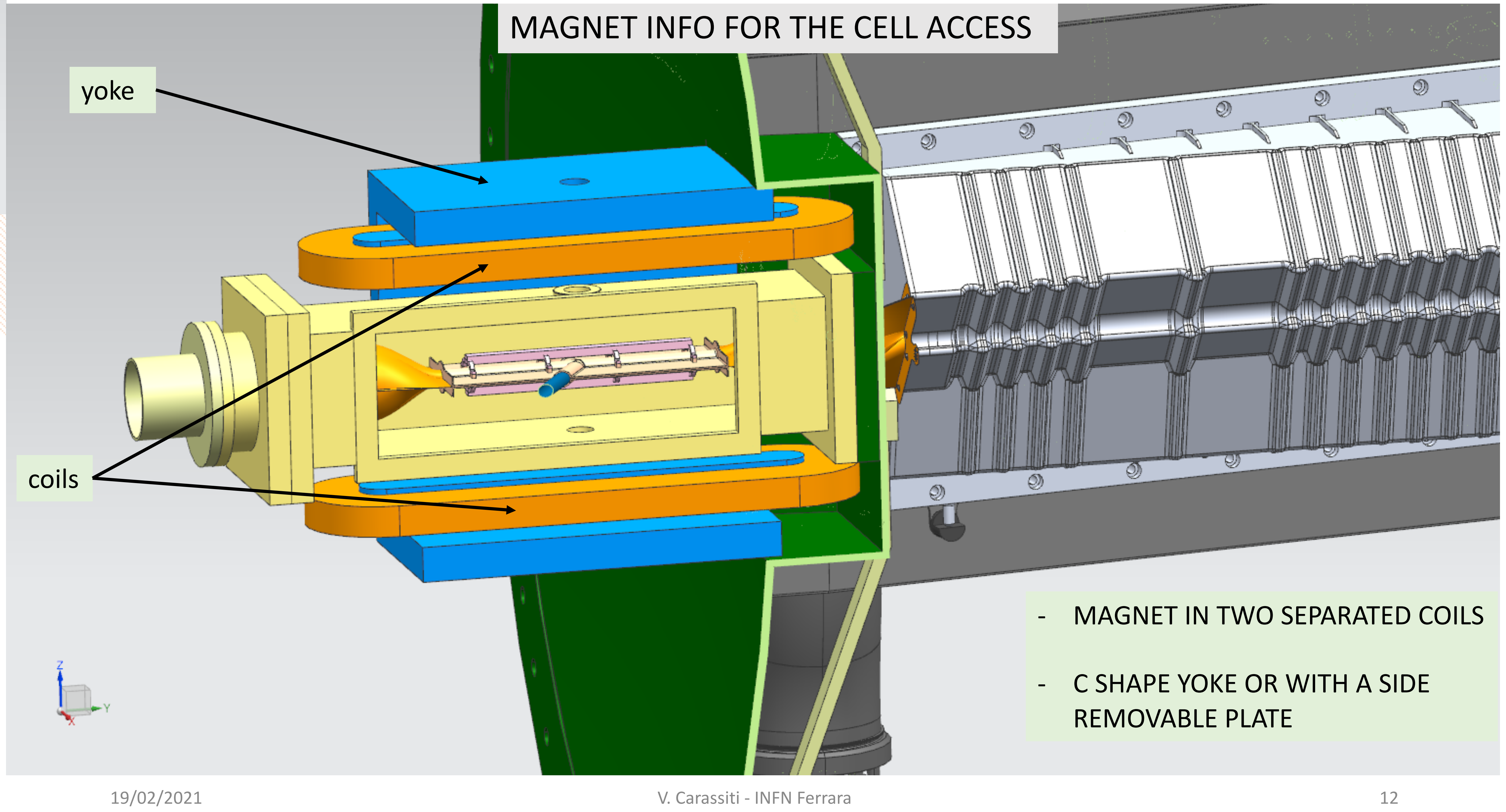
The two systems don't interfere each other and the reconstruction efficiencies stay unchanged

The DAQ data flow increases of 1-3% only

No need for additional detectors



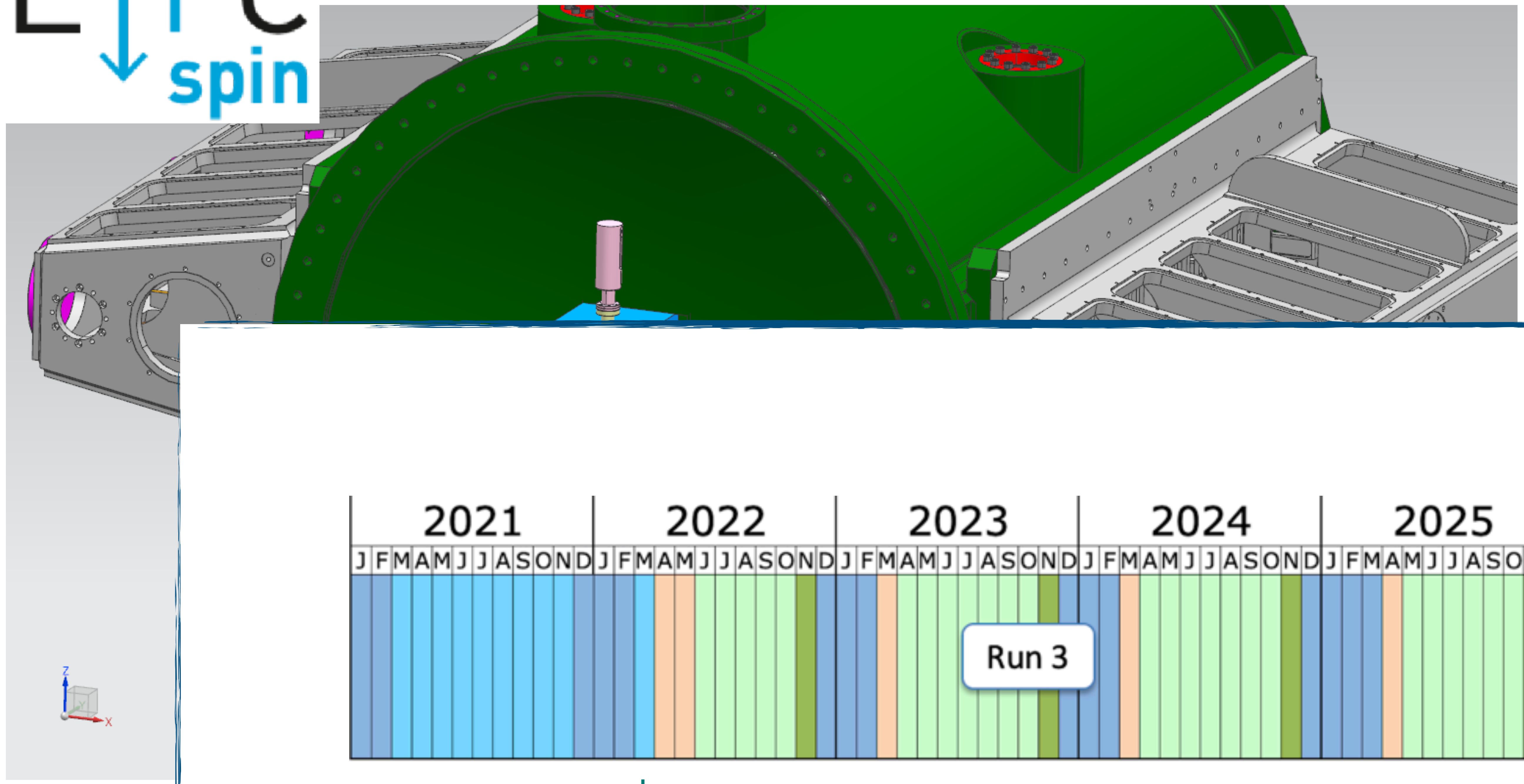
Compact (superconductive) dipole
for transverse field of 300 mT
(uniformity $\Delta B/B \sim 10\,\%$)



The Atomic Beam Source, the Polarimeter and the Gas Analyzer are not drawn (still in a very early stage of the R&D)

LHCspin represents the only way to have polarised collisions at the LHC

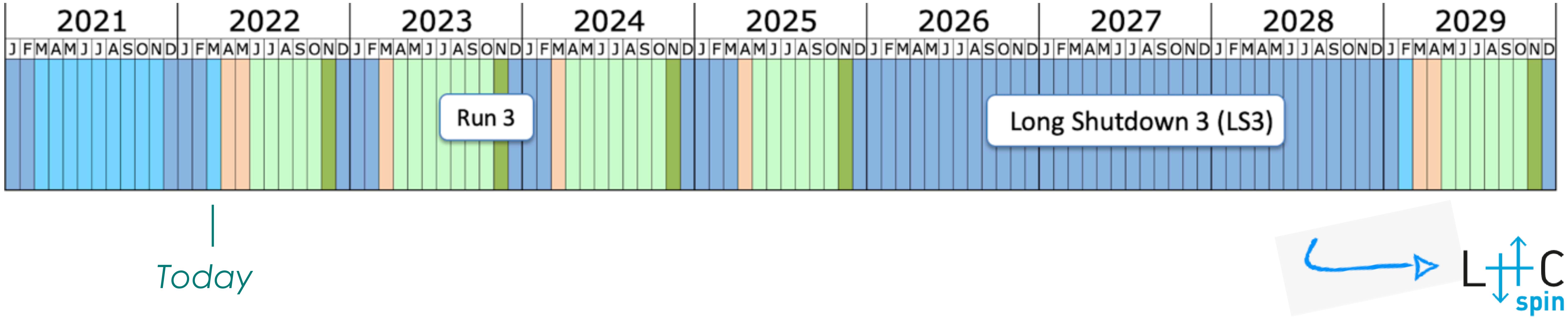
No need for additional detectors

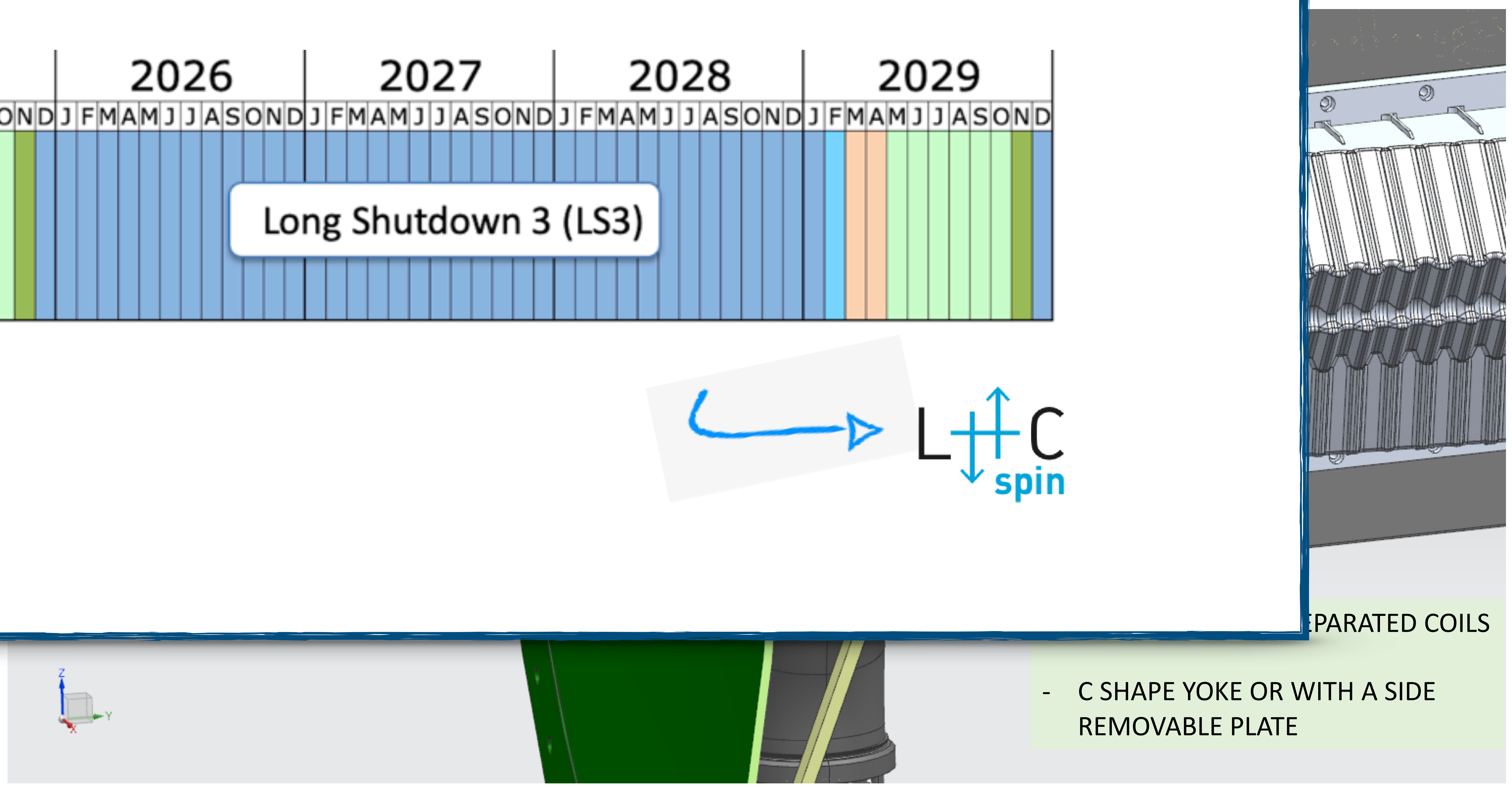


Compact (superconductive) dipole

300 mT

~ 10 %)





The A…
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Conclusions

- LHCspin is an innovative project conceived to bring polarized physics at the most powerful collider (LHC) exploiting the unique kinematic conditions provided by a TeV-scale beam, with one of the most advanced fully instrumented forward spectrometer (LHCb)
- The installation of the first storage cell target for unpolarized gases (SMOG2) already happened in August 2020. It will start taking data from LHC Run3 (2022) and is a fantastic playground for the LHCspin R&D
- LHCspin is extremely ambitious in terms of both physics reach and technical complexity

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- LHCspin is extremely ambitious in terms of both physics reach and technical complexity

LHCspin represents a unique possibility … in a realistic time schedule and costs