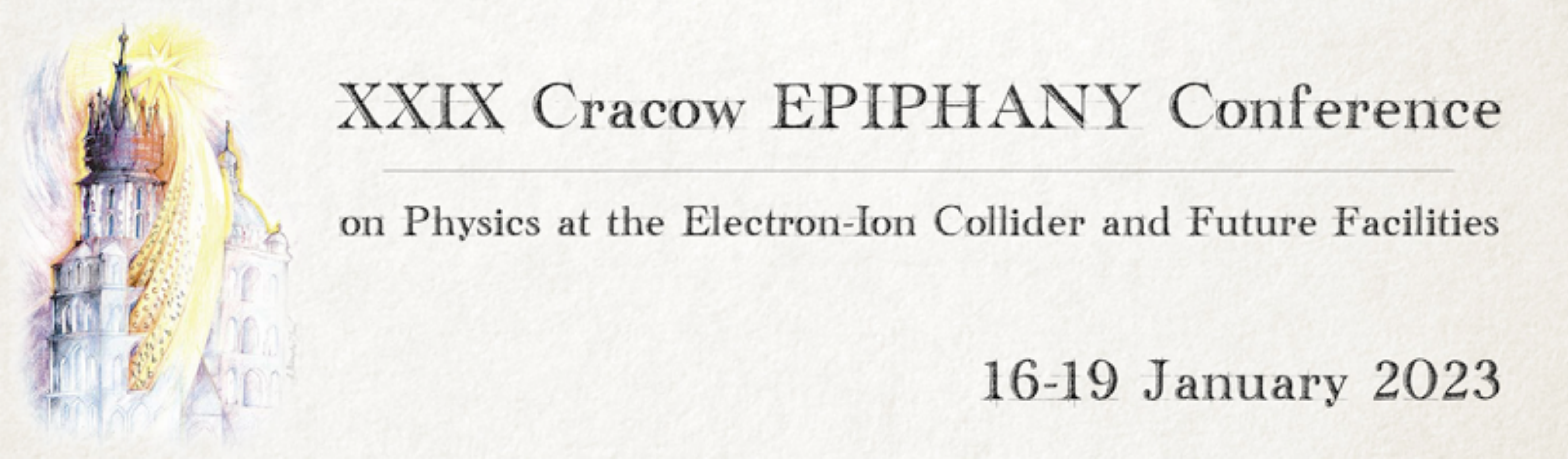
Polarised physics at the LHC

Pasquale Di Nezza



INFN LNF Istituto Nazionale di Fisica Nucleare

LHCb

STRONG 2020

The LHC beams cannot be polarised

→

The only possibility to have polarised collisions is through a polarised fixed-target

Collisions provided by a TeV-scale beam (LHC) on fixed target will exploit a unique kinematic region poorly probed. Advanced detectors make available probes never accessed before

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LHCb

SMOG2

unpolarised gas target

LHCspin

polarised (+unpolarised) gas target

The LHCb detector

- LHCb is a general-purpose forward spectrometer, fully instrumented in $2 < \eta < 5$, and optimised for c and b hadron detection
- Excellent momentum resolution with VELO + tracking stations:

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

- Particle identification with RICH+CALO+MUON

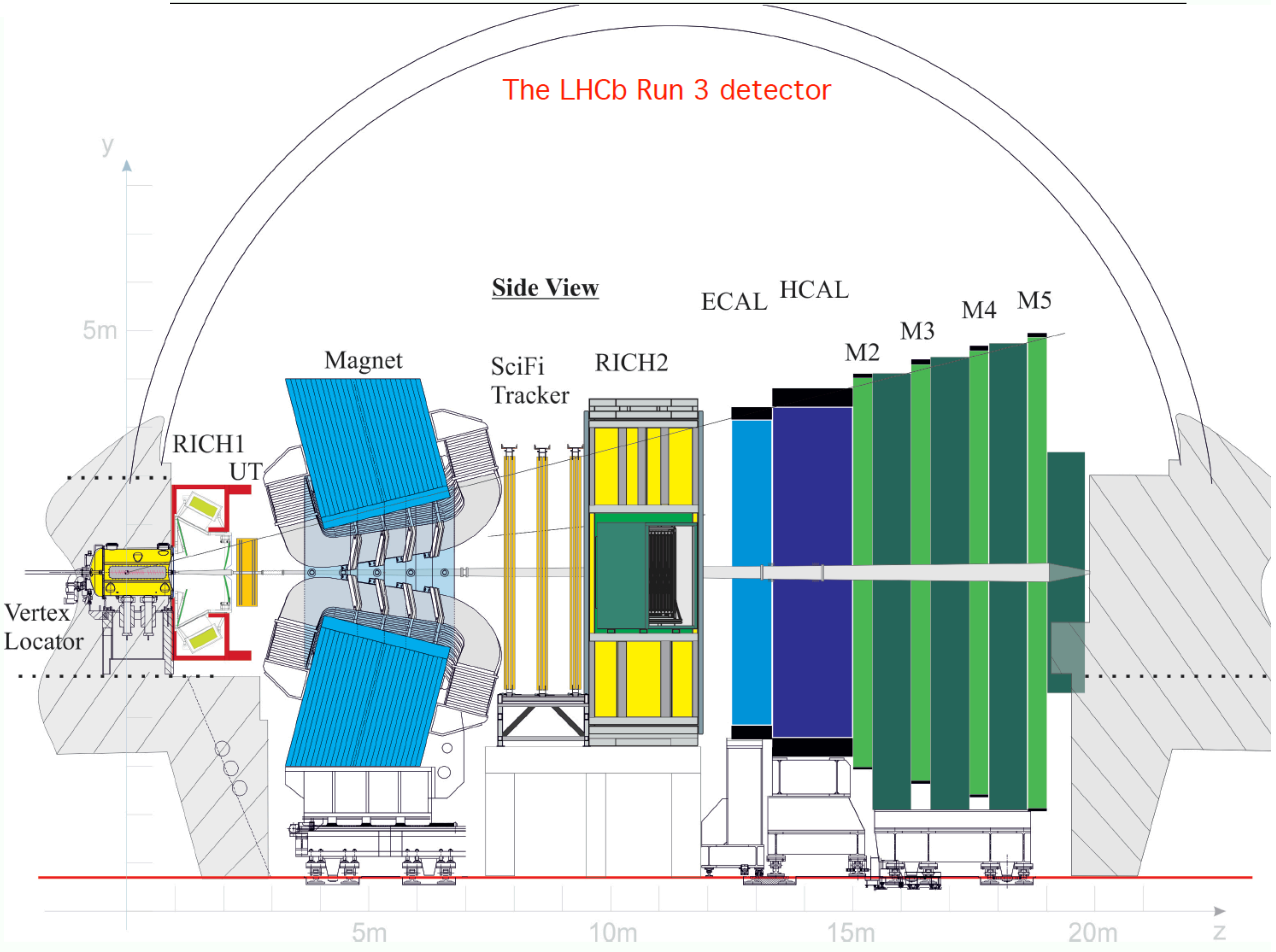
$\epsilon_\mu \sim 98\,\%$ with $\epsilon_{\pi\to\mu} \lesssim 1\,\%$

- Low momentum muon trigger:

$$p_{T_\mu} > 1.75\ \mathrm{GeV}\ (2018)$$

will be reduced thanks to the new fully-software trigger

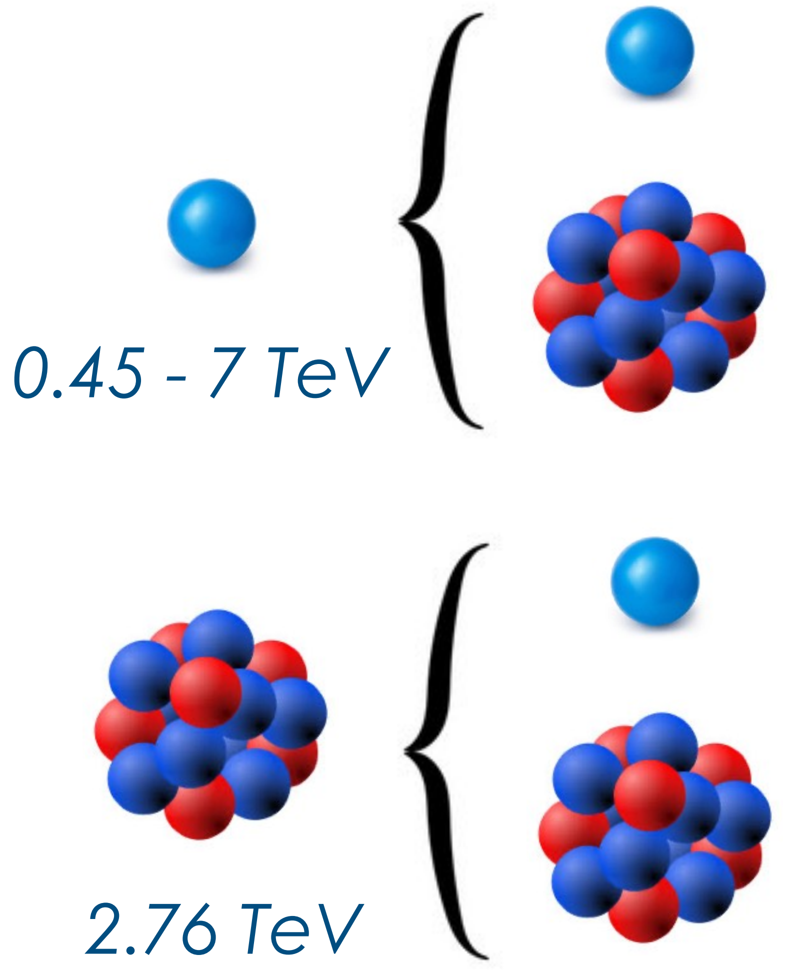
- Major detector upgrades performed during LS2 for the Run 3 (5x luminosity)



[JINST 3 (2008) S08005]

[IJMP A 30, 1530022 (2015)]

[Comput Softw Big Sci 6, 1 (2022)]



pp or pA collisions: 0.45 - 7 TeV beam on fix target

$$\sqrt{s} = \sqrt{2m_N E_p} \simeq 41 - 115\ GeV$$

$$y_{CMS} = 0 \ \rightarrow \ y_{lab} = 4.8$$

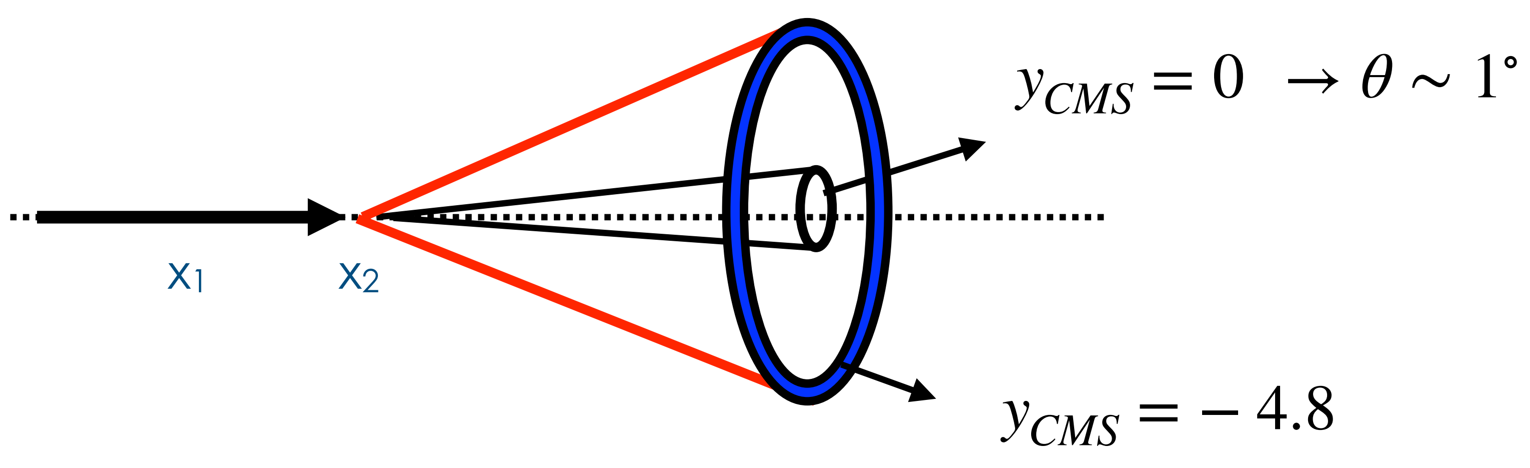
AA collisions: 2.76 TeV beam on fix target

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

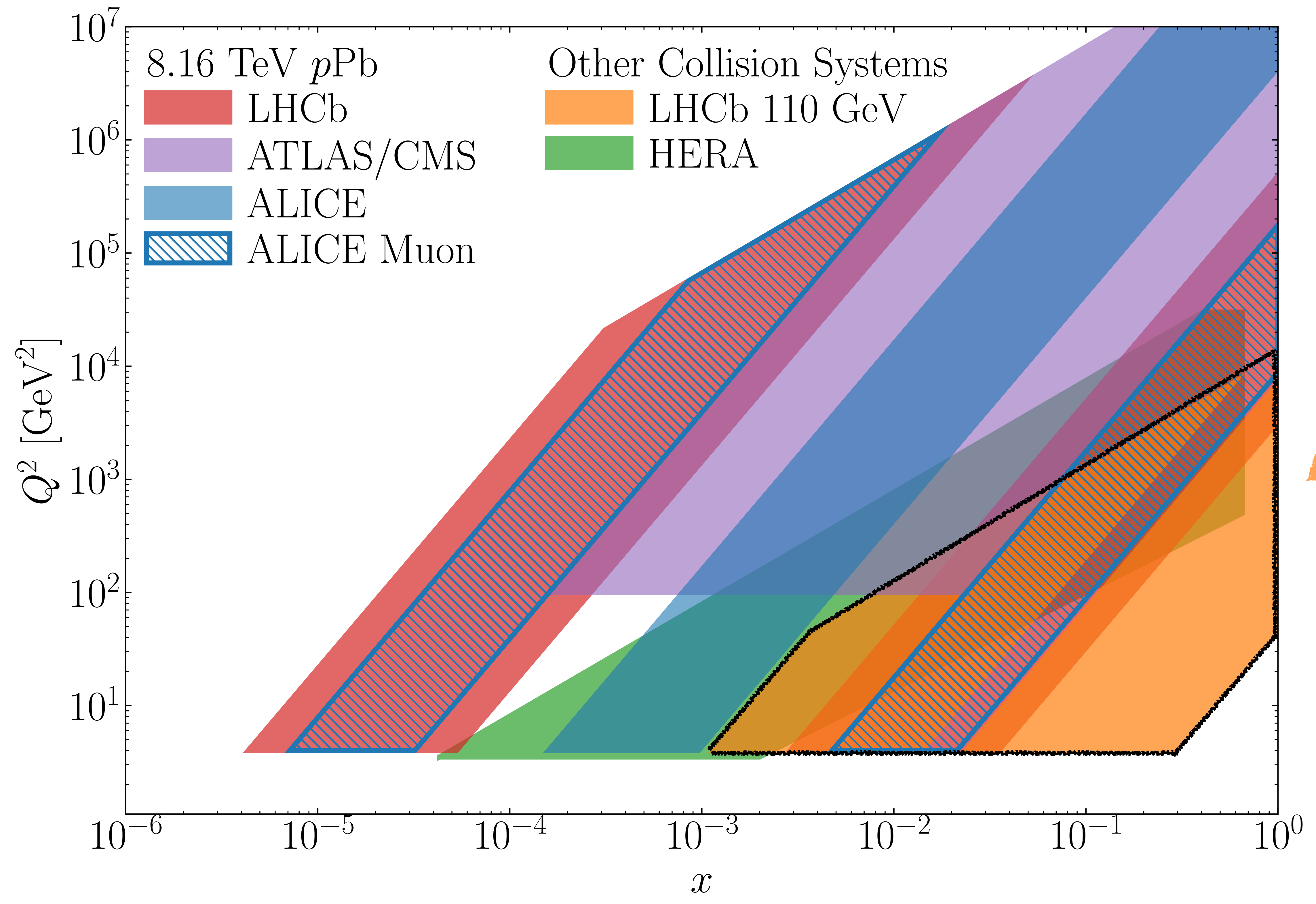
$$y_{CMS} = 0 \ \rightarrow \ y_{lab} = 4.3$$

1: beam; 2: target

Large CM boost, large x_2 values (x_F<0) and small x_1



$$\gamma = \frac{\sqrt{s_{NN}}}{2m_p} \simeq 60$$

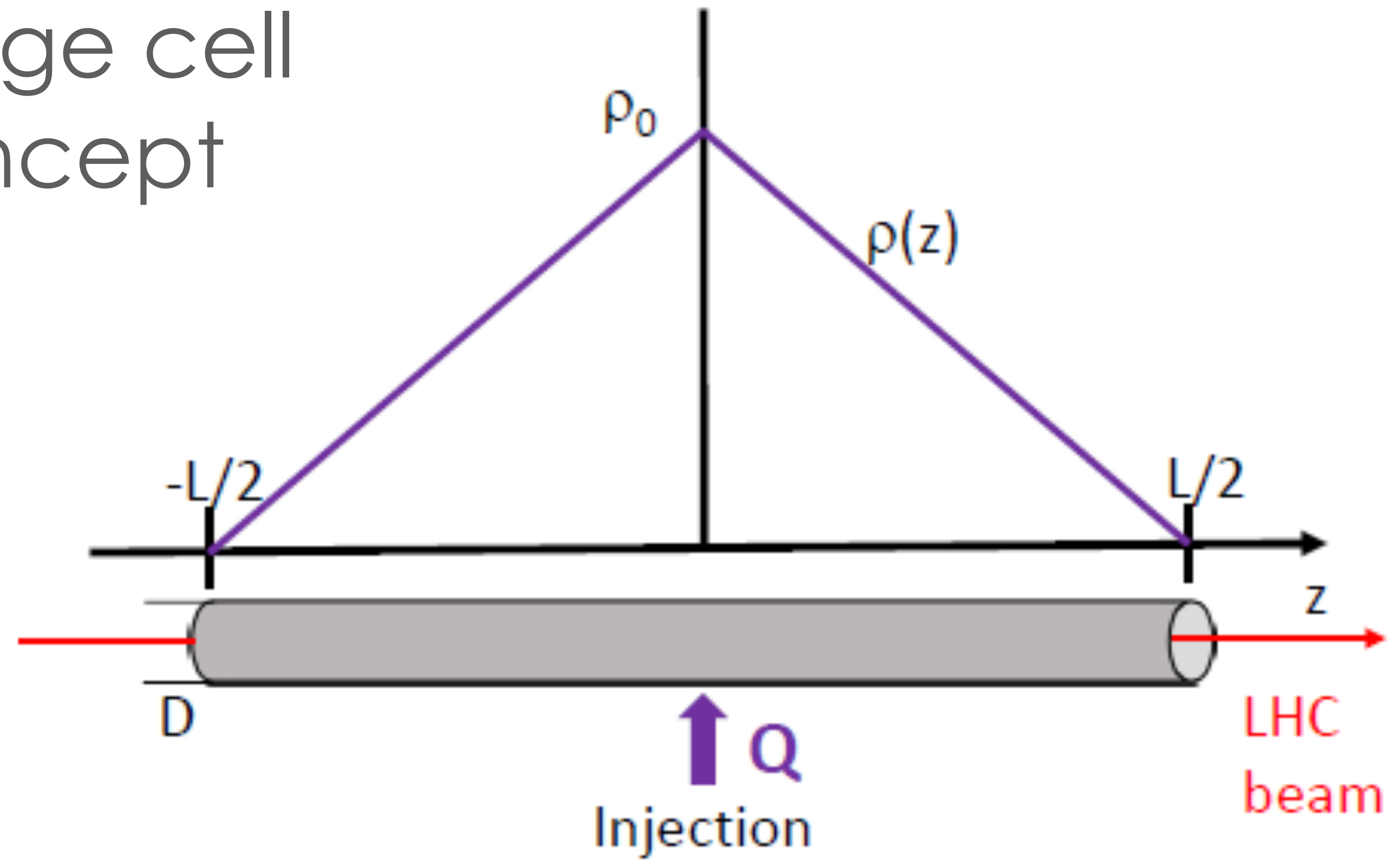


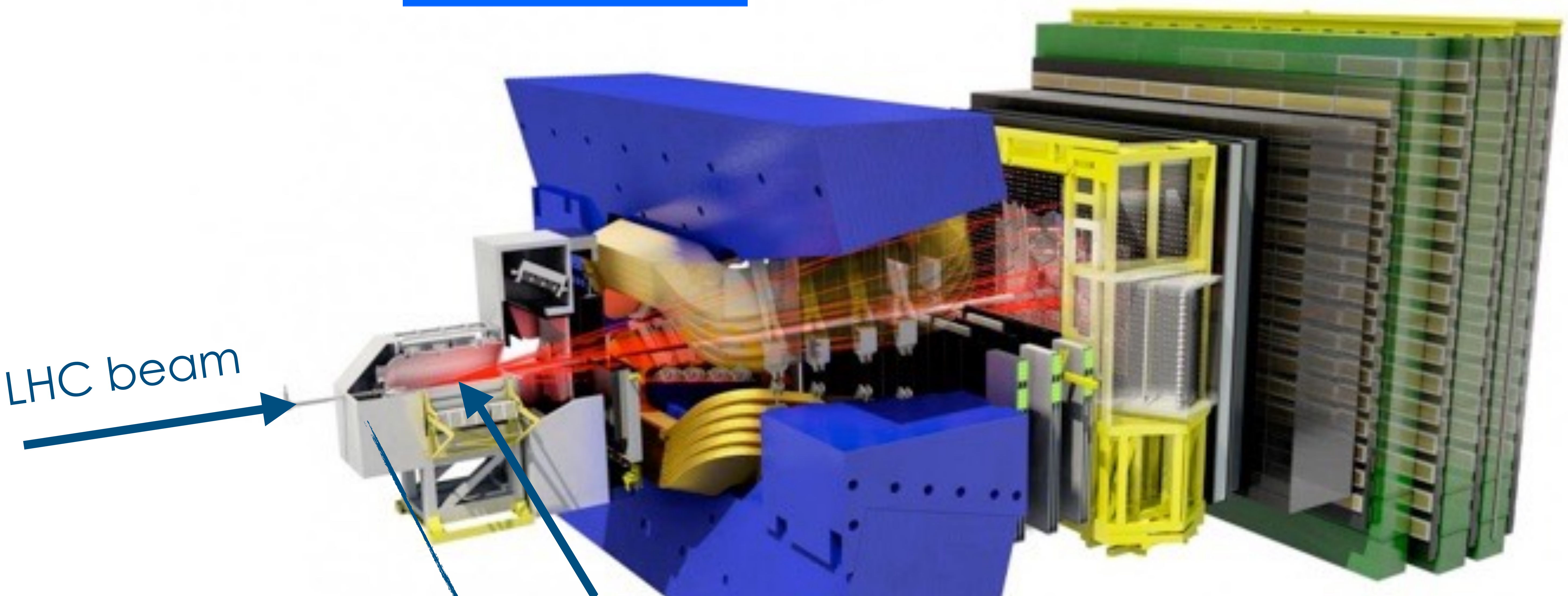
Broad and poorly explored kinematic range

SMOG2 an unpolarised target at LHCb

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

Storage cell concept



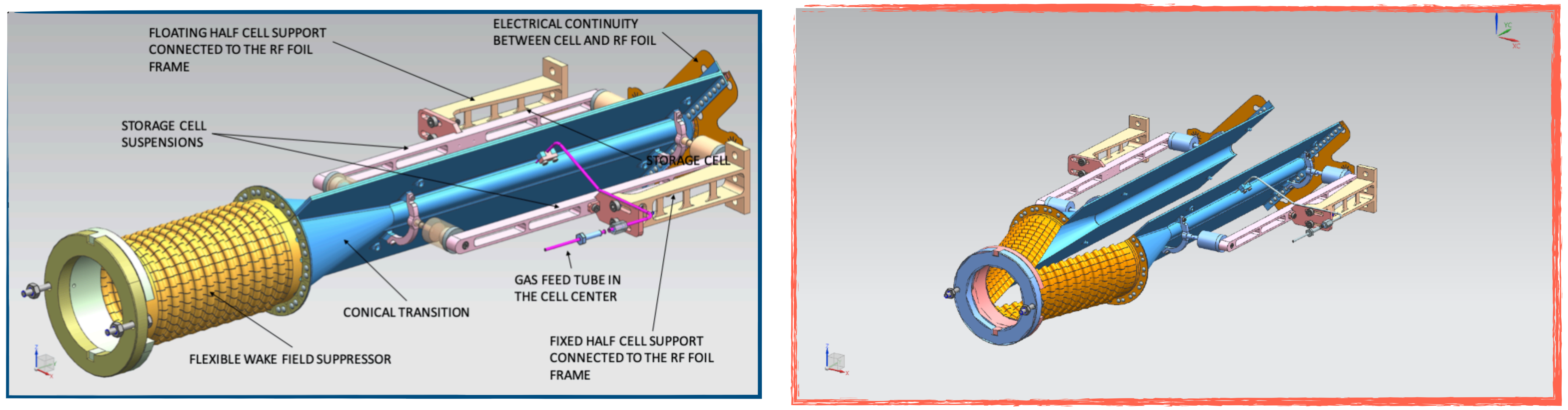


Forward acceptance: $2 < \eta < 5$

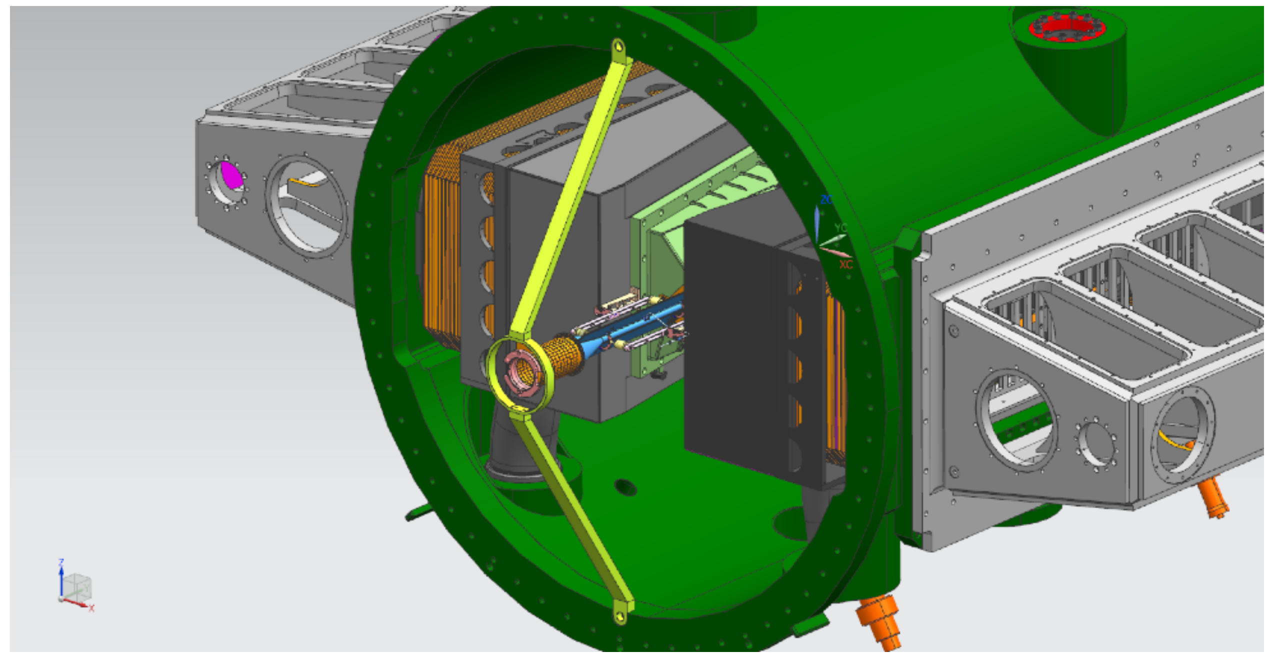
Tracking system momentum resolution
$\Delta p/p$ = 0.5%–1.0% (5 GeV/c – 100 GeV/c)

beam-beam collisions

Openable cell

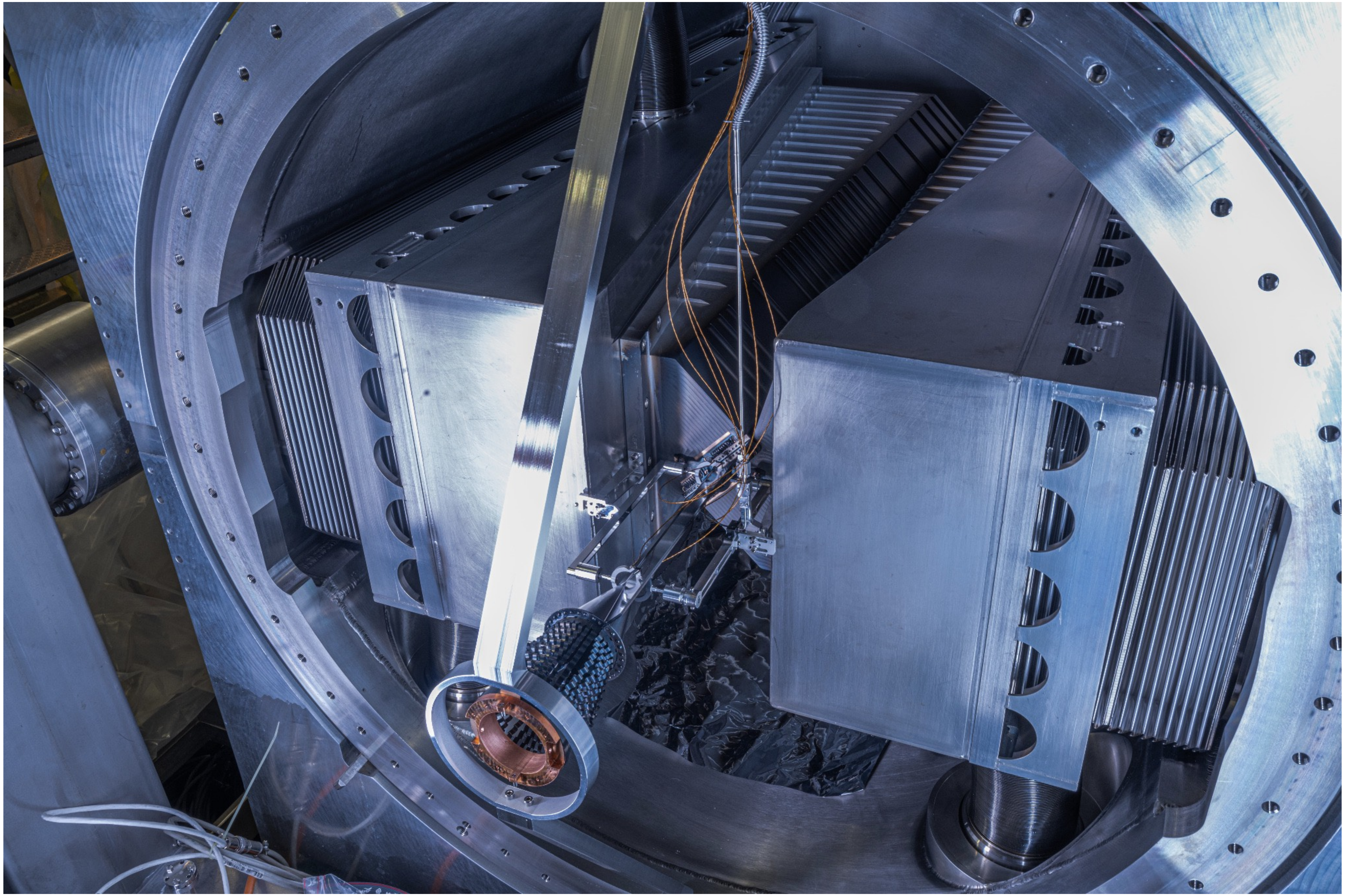


5 mm radius x 200 mm length



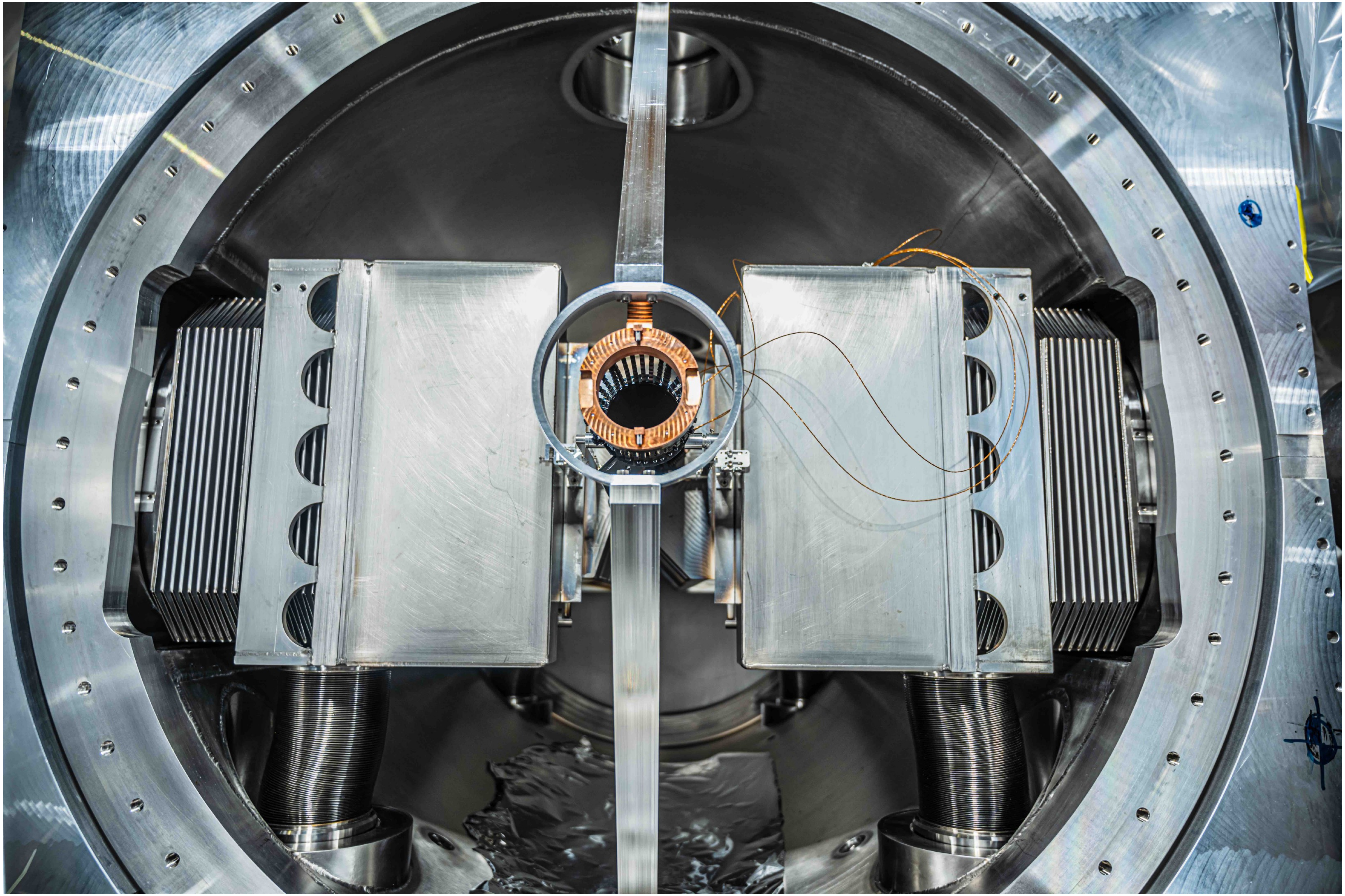
UNpolarised target (beam-gas)

SMOG2



It is the only system present in the LHC primary vacuum

SMOG2



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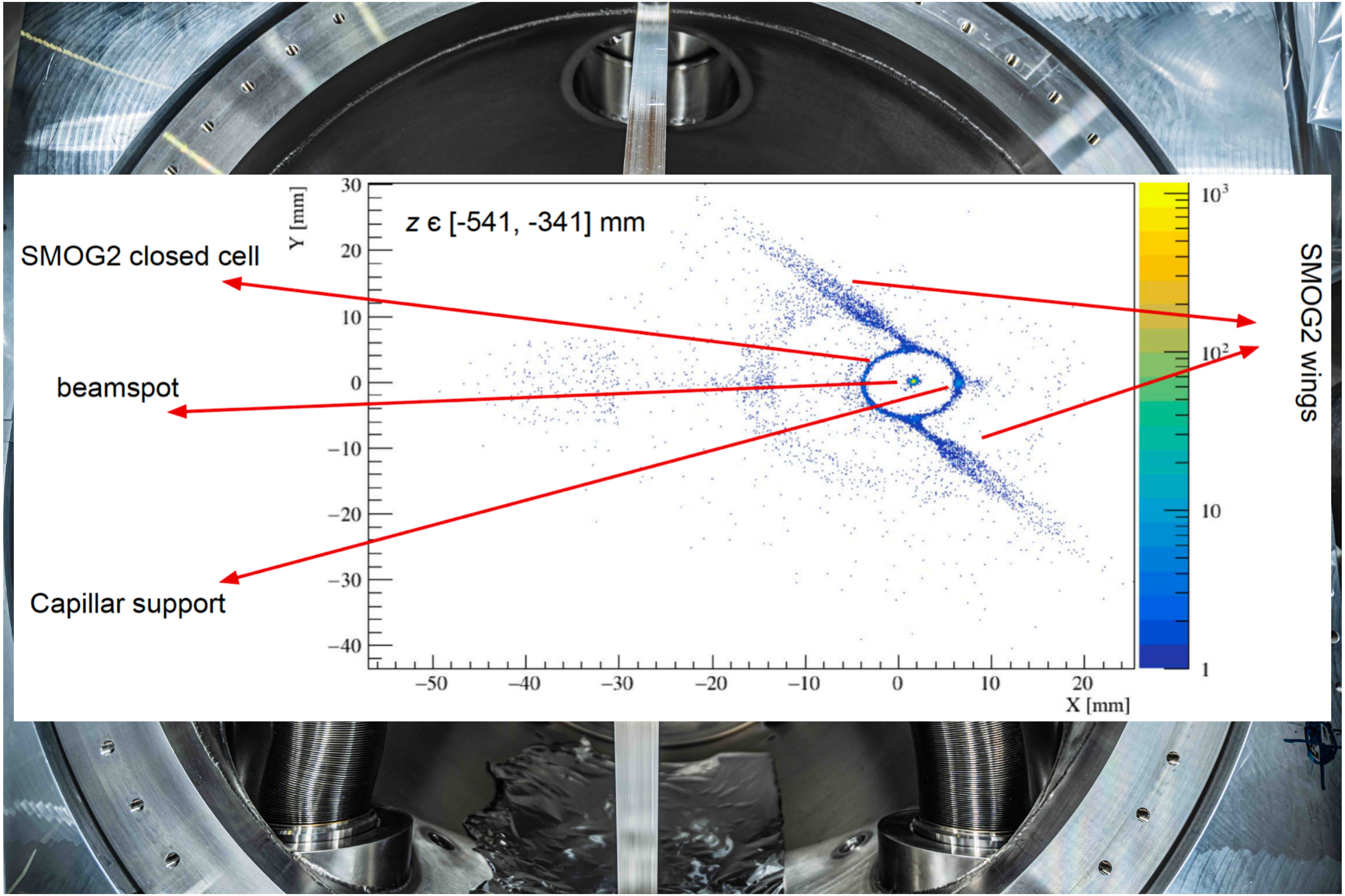
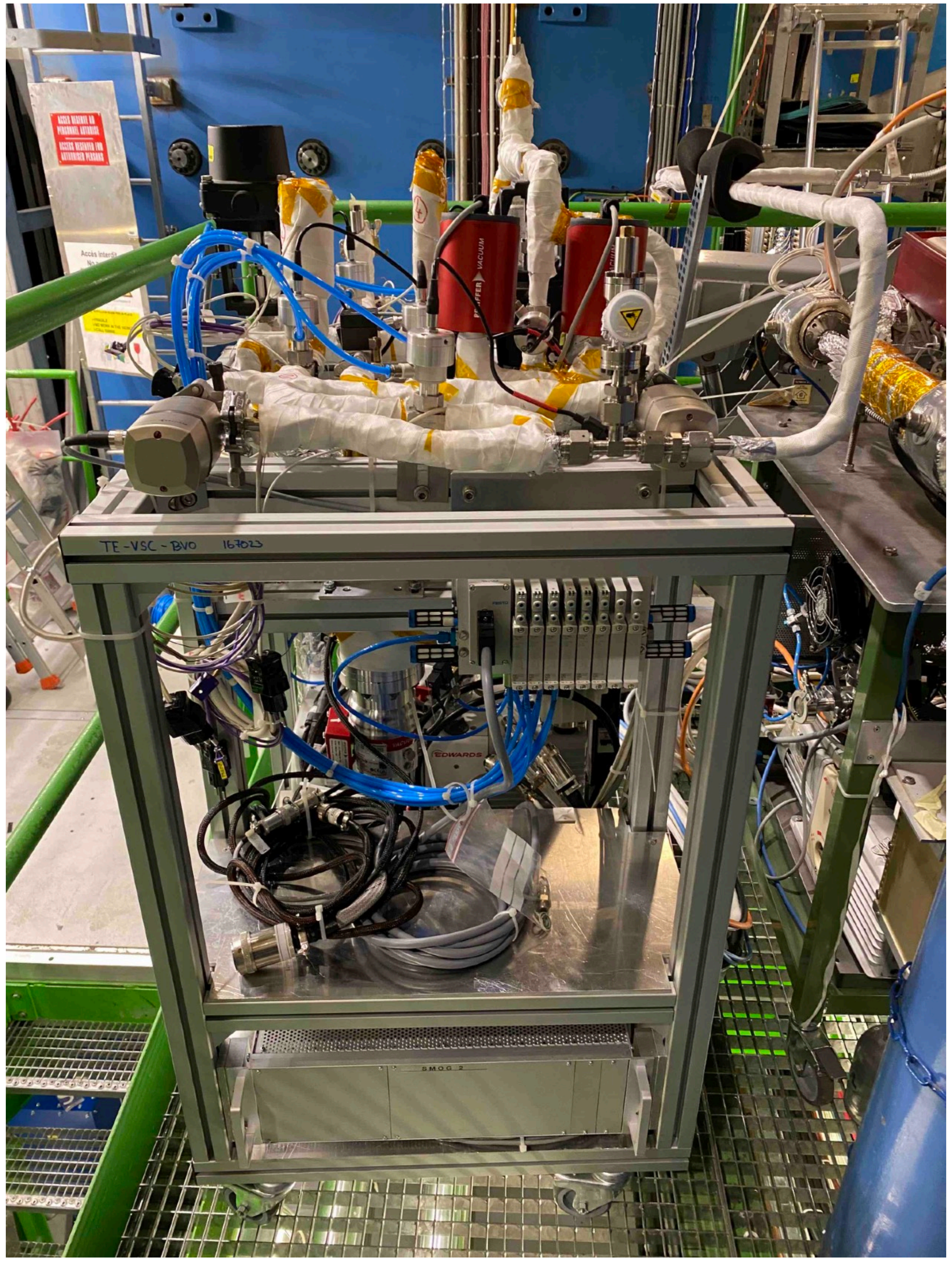


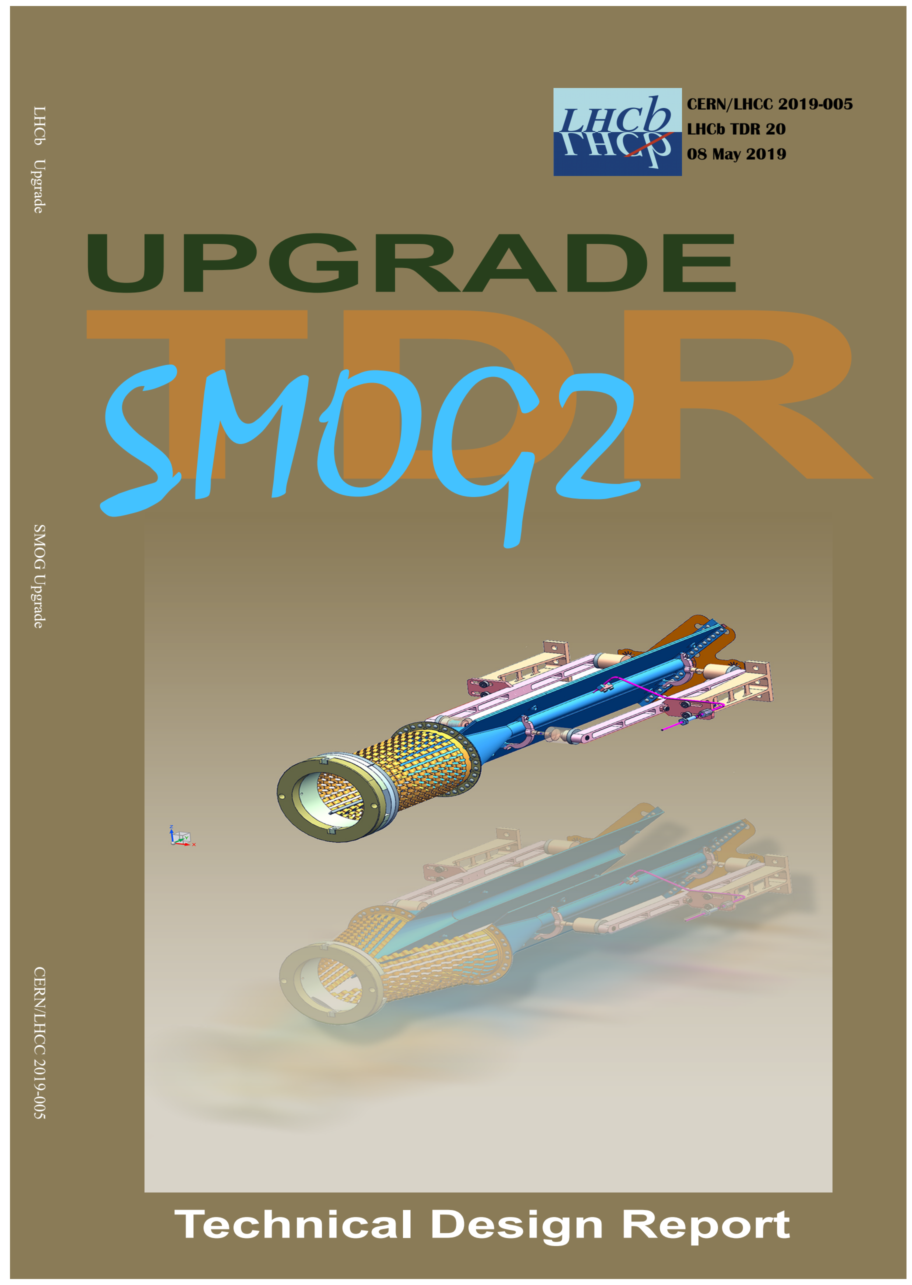
It is the only system present in the LHC primary vacuum

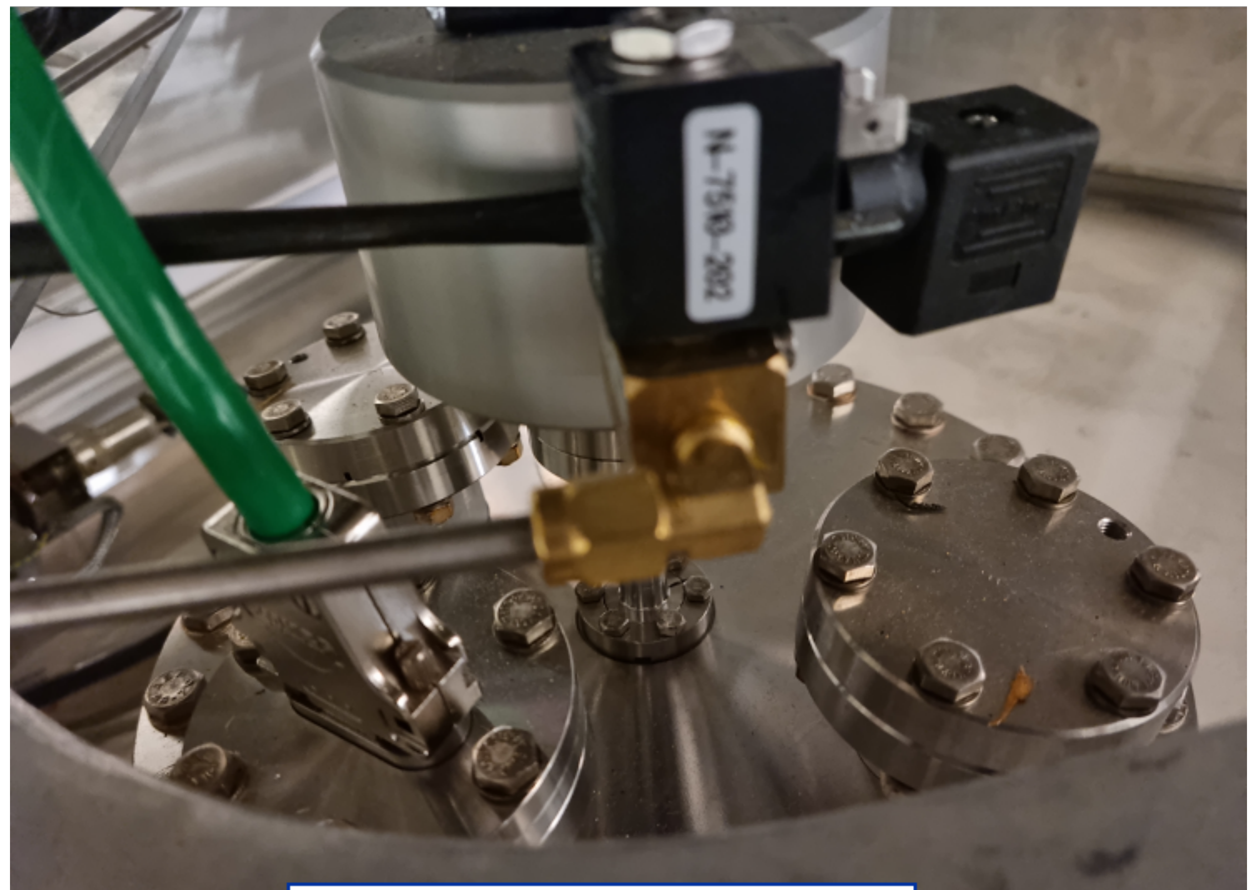
SMOG2

- The system is completely installed (storage cell + GFS + triggers + reconstruction)
- Negligible impact on the beam lifetime ($\tau^{p-H_2}_{beam-gas} \sim 2000$ days , $\tau^{Pb-Ar}_{beam-gas} \sim 500$ h)
- Injectable gases (3+1 reservoirs): H_2, D_2, N_2, O_2, He, Ne, Ar, Kr, Xe
- Flux known with $1\,\%$ precision, measured relative contamination 10^{-4}



GFS table installation



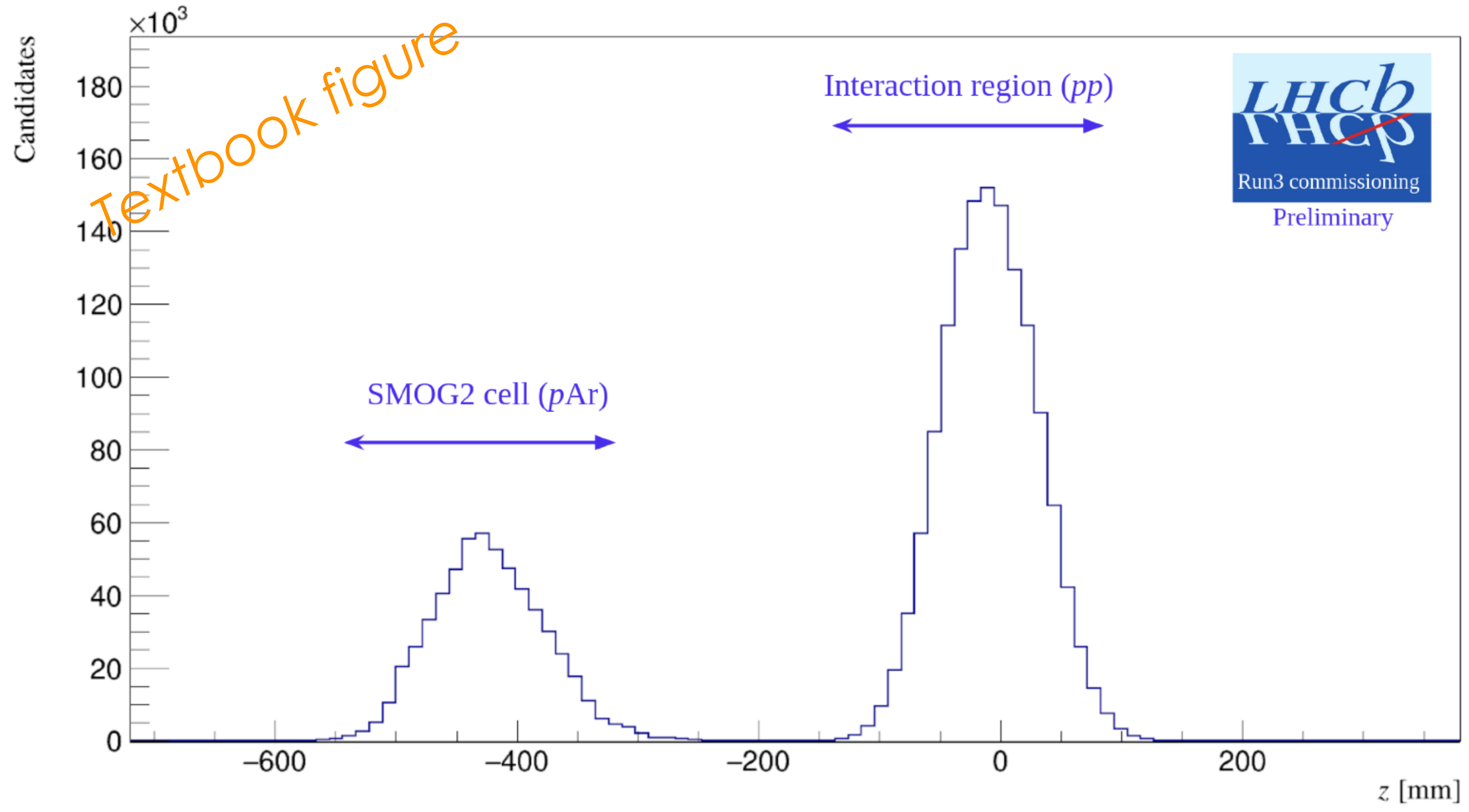


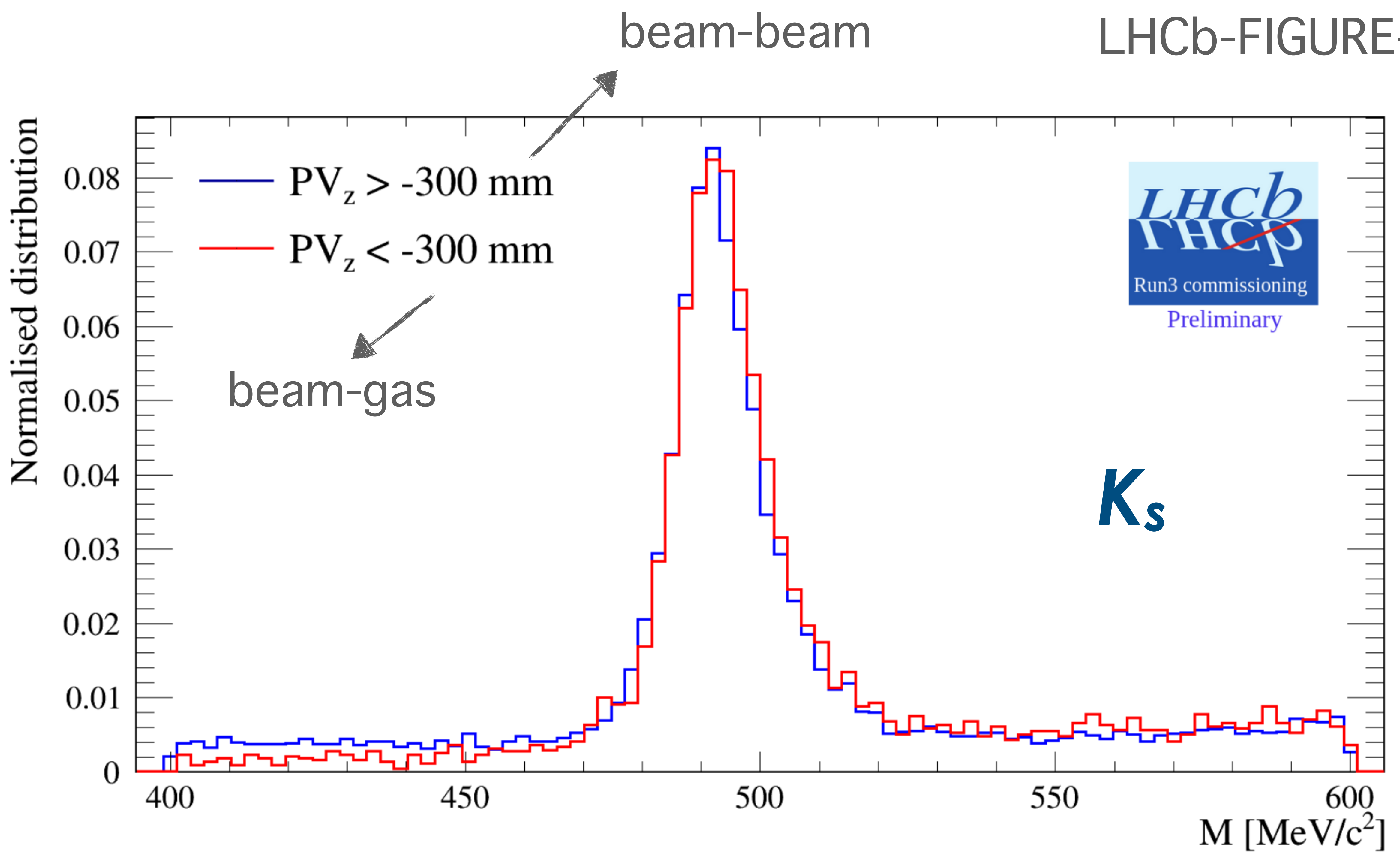
Injection valve PV611

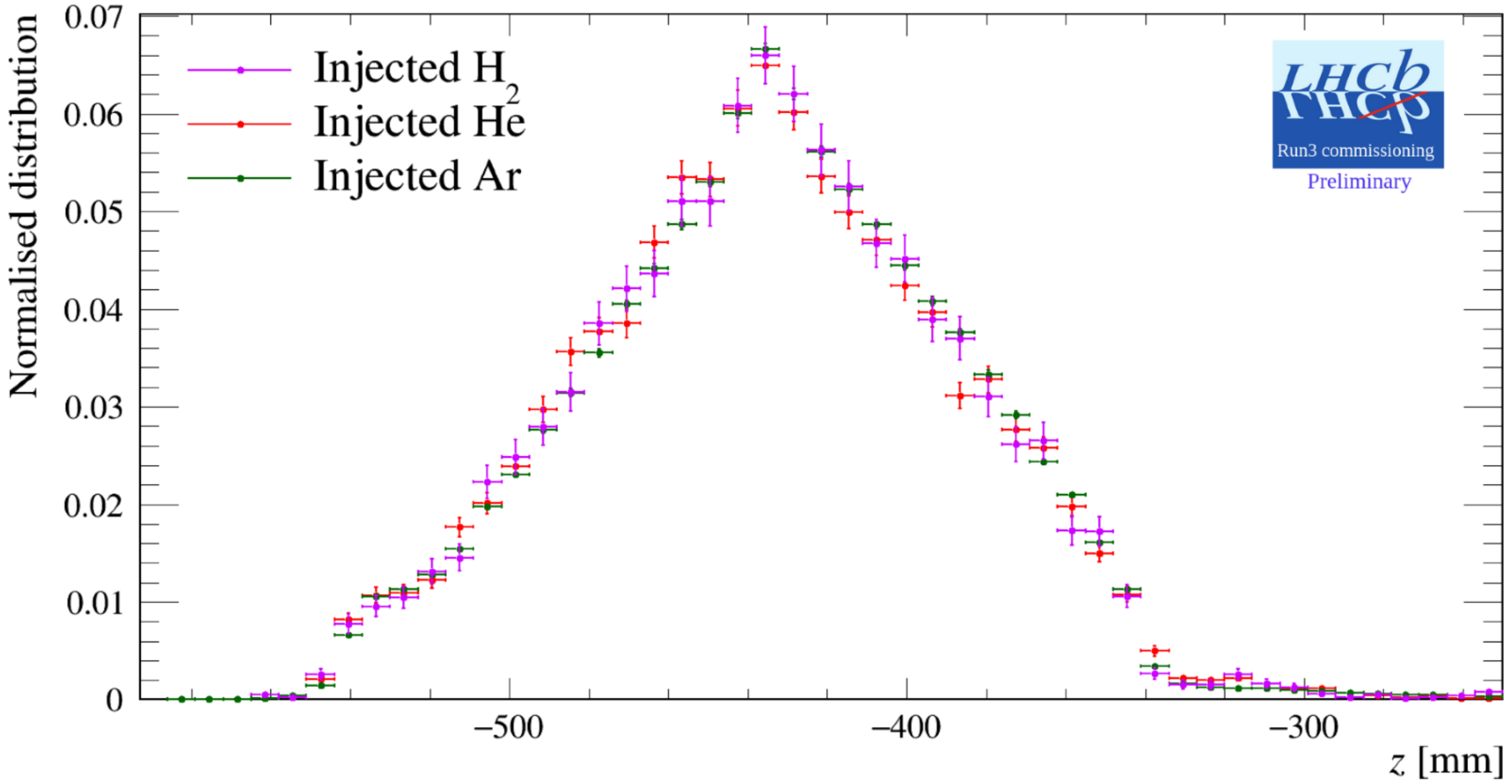
https://cds.cern.ch/record/2673690/

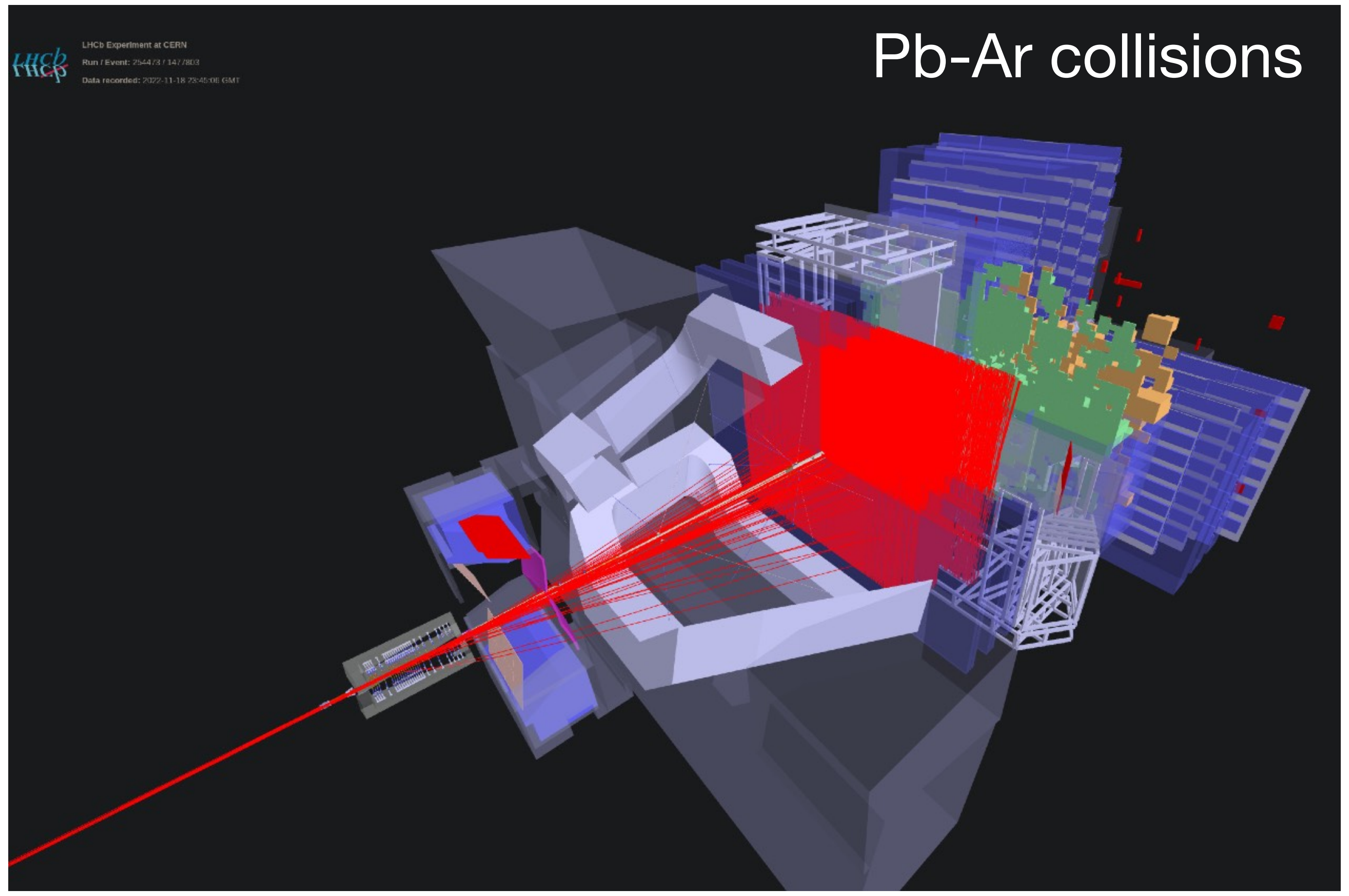
SMOG2 works!

LHCb-FIGURE-2023-001









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

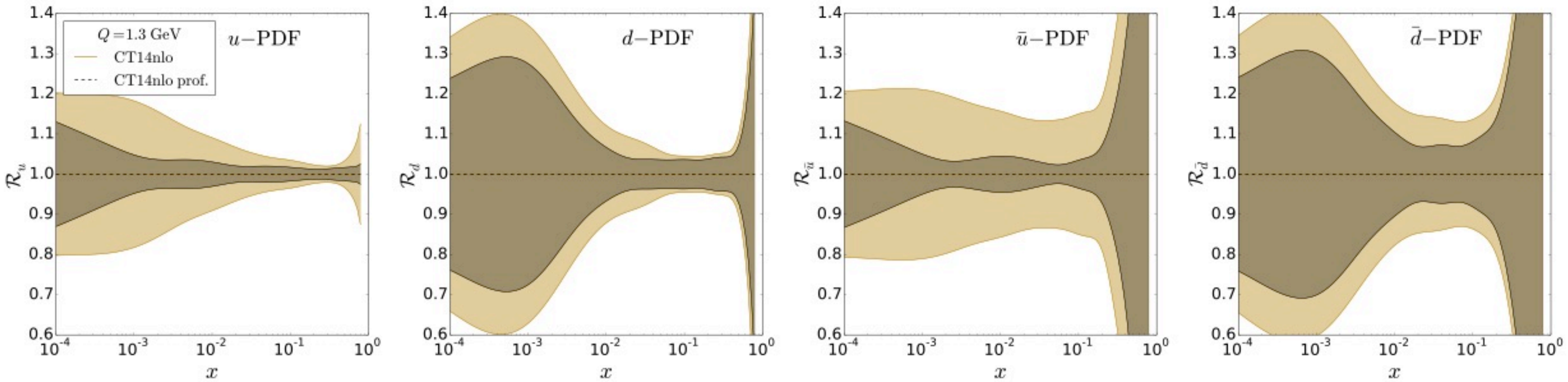
SMOG2 … few highlights

http://cds.cern.ch/record/2649878/files/

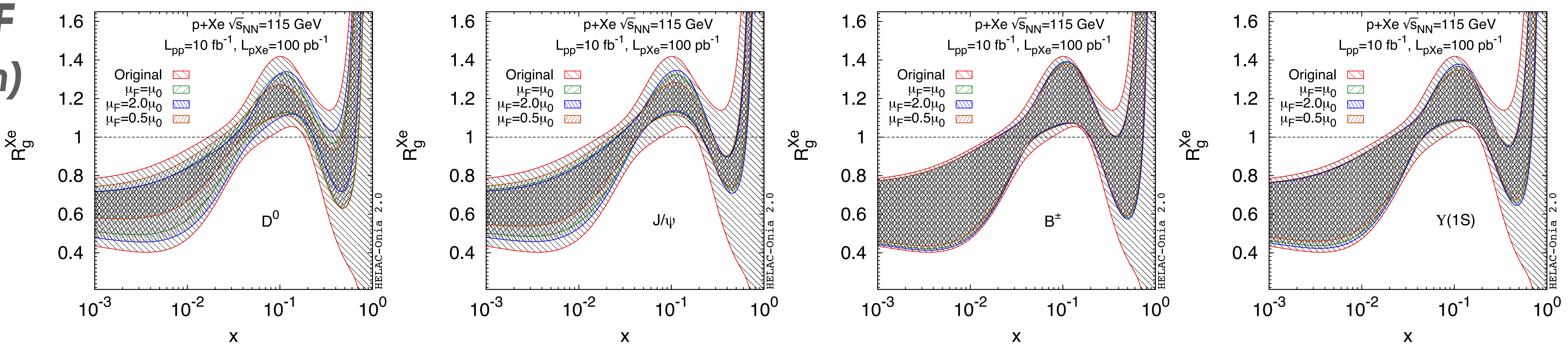
PDF

estimation with 10 fb^{-1}

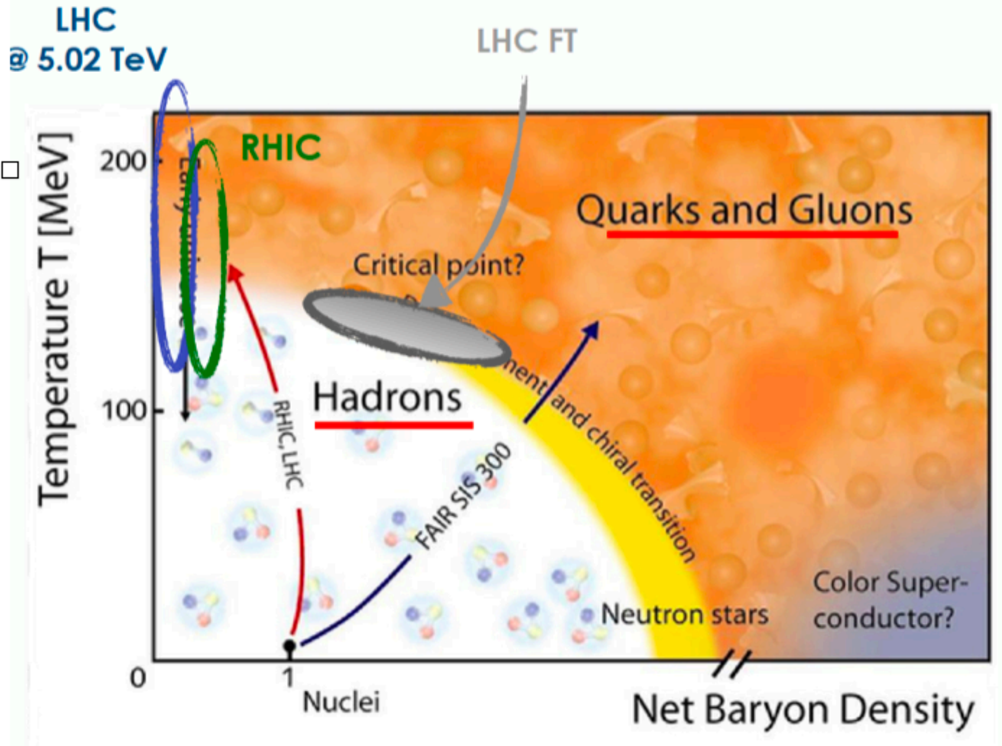
arXiv:1807.00603

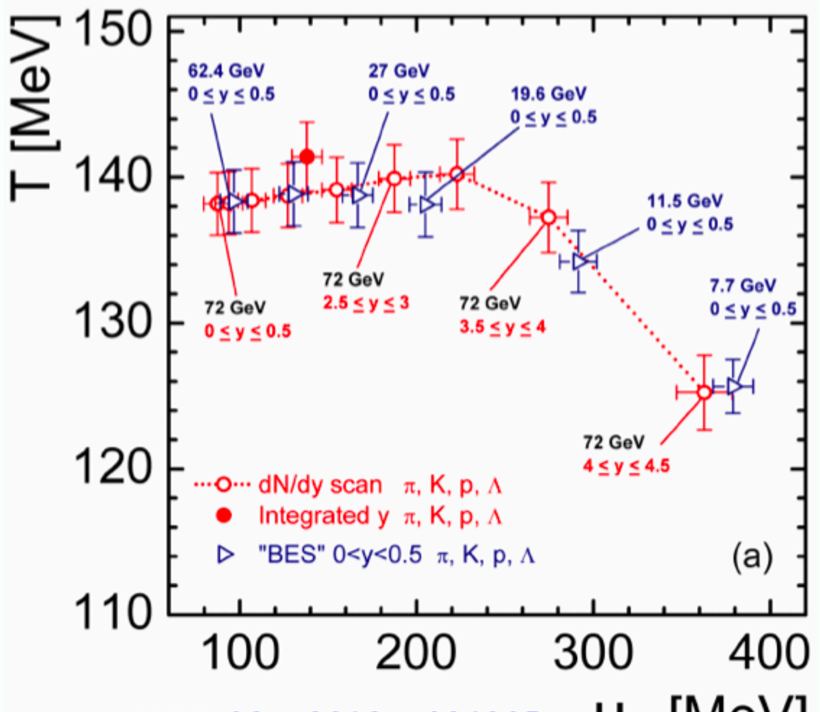


nPDF (gluon)



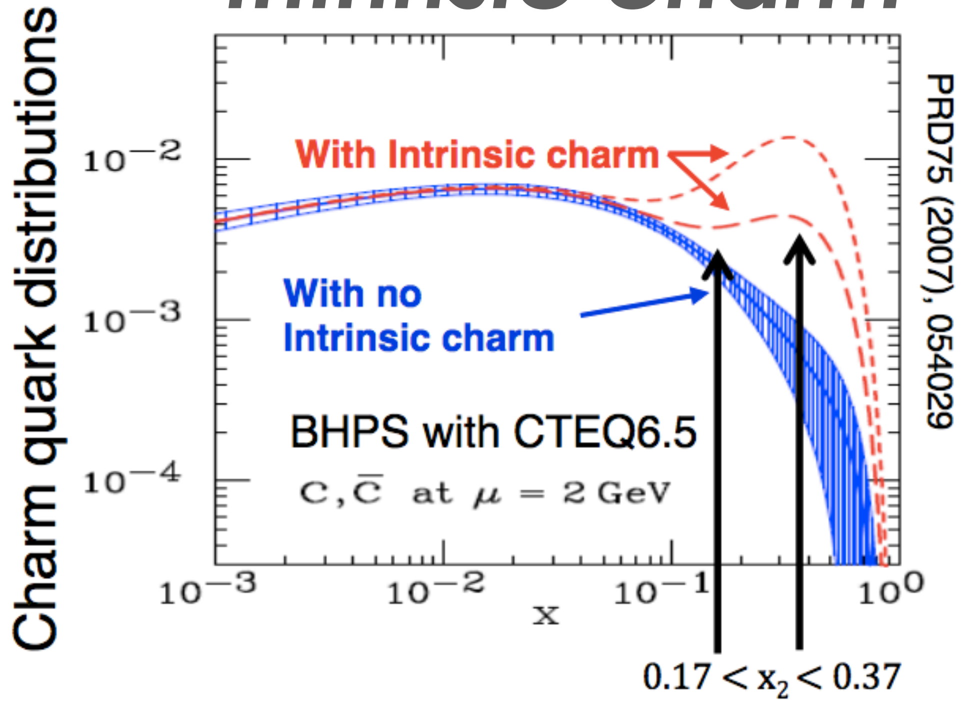
Heavy-Ion and QCD phase space



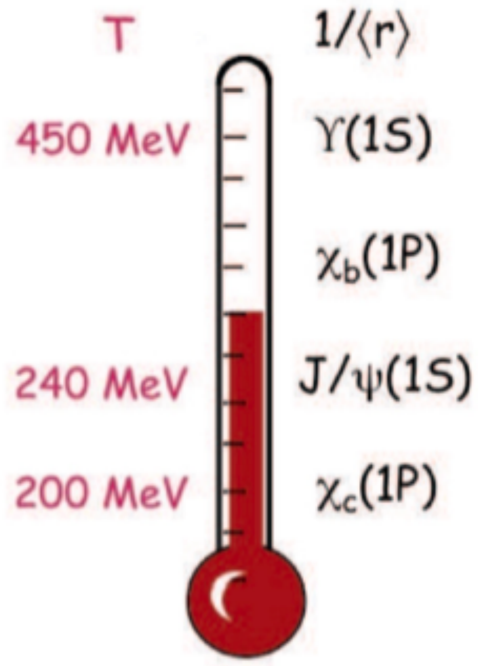


[PRC 98 (2018) 034905]

Intrinsic charm

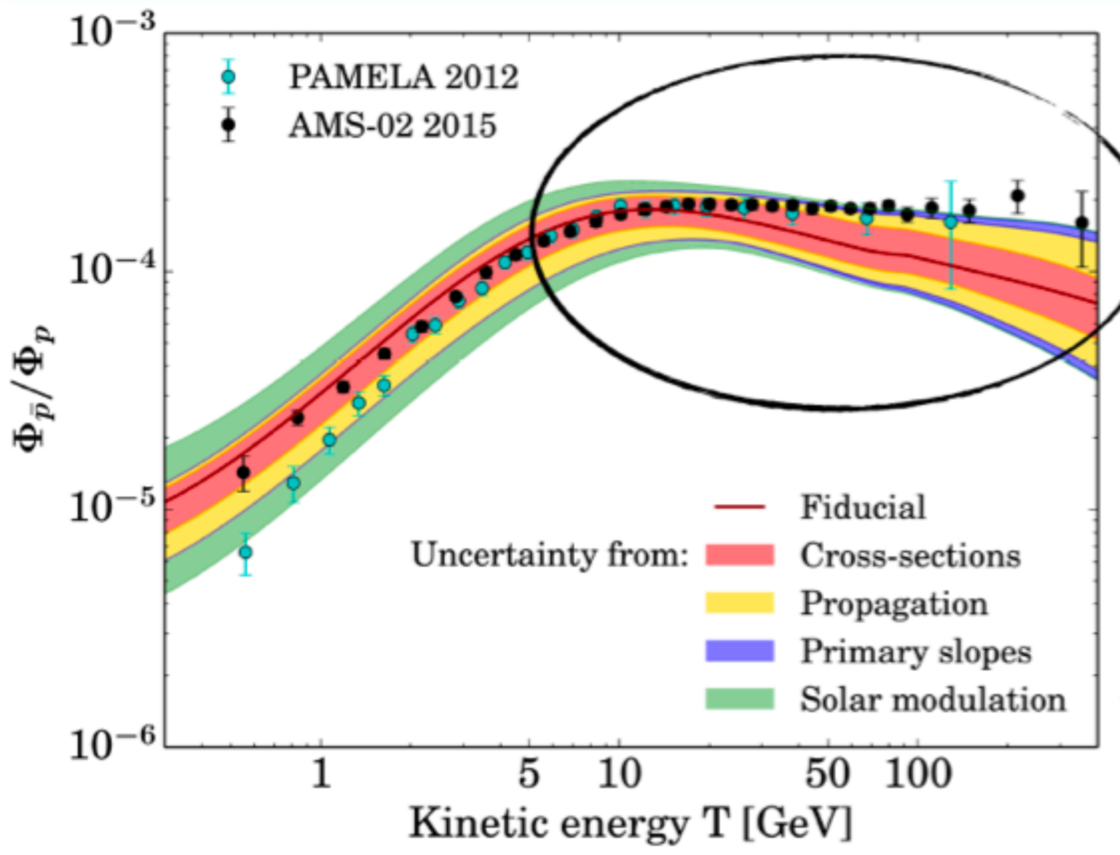


$c\bar{c}$ bound states

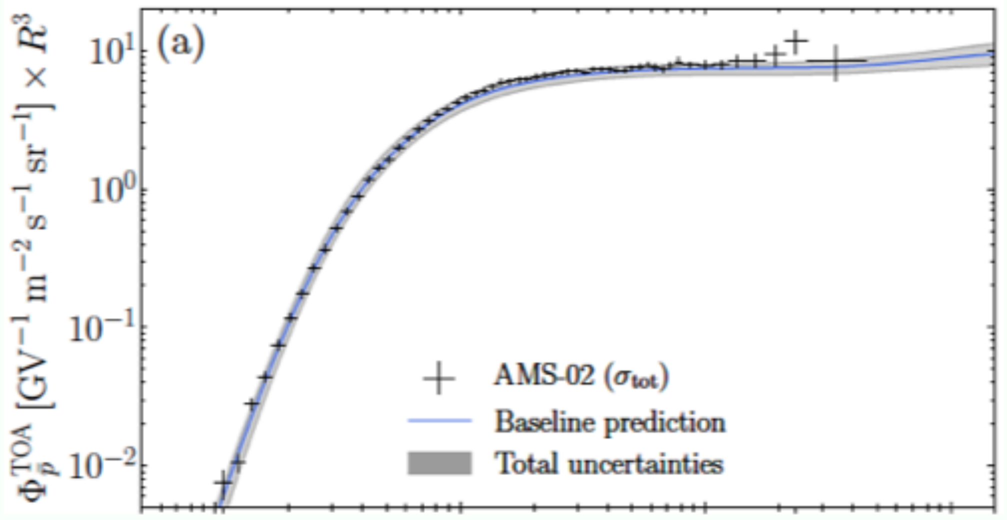


Astroparticle (DM and CR)

[JCAP09 (2015) 023]



[ArXiv:1906.07119]

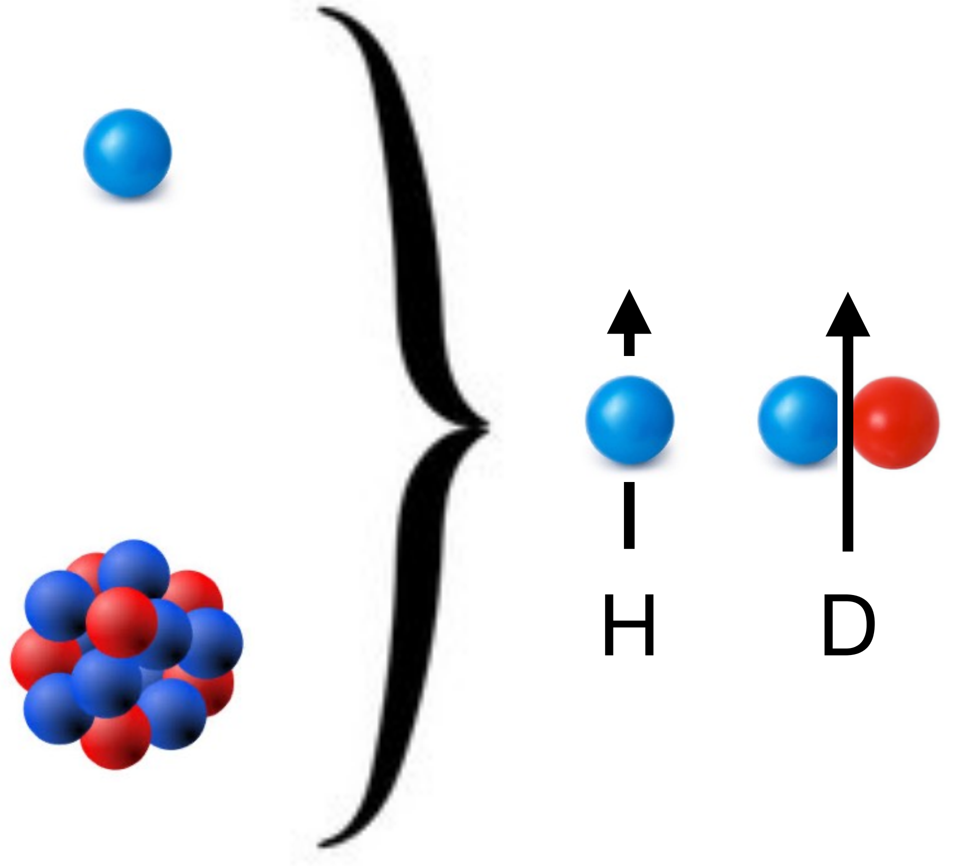


- Main uncertainty still due to cross sections!

Special Runs

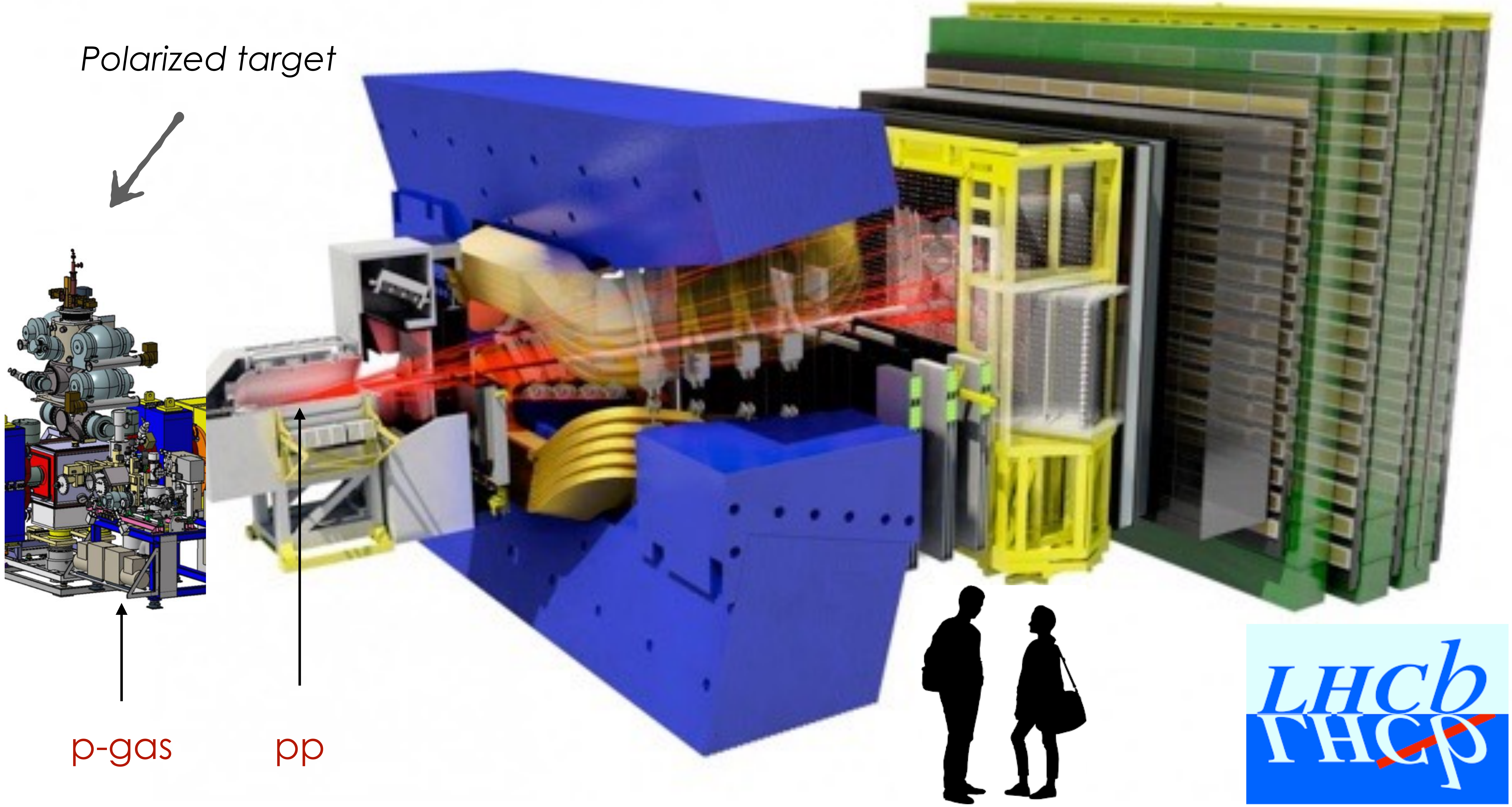
$^{16}O + p \to \bar{p} + X$ and $^{16}O + ^4He \to \bar{p} + X$ [CERN-LPCC-2018-07]

a polarised target at LHCb



Successful technology based on HERA and COSY experiments

Challenge: develop a new generation of polarized targets



SMOG2 is not only a unique project itself,

but also a great playground for LHSpin

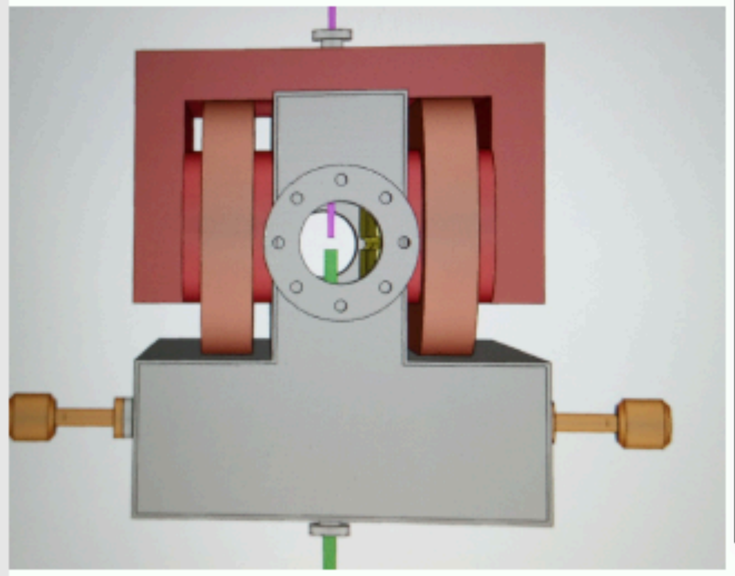
LHCspin experimental setup

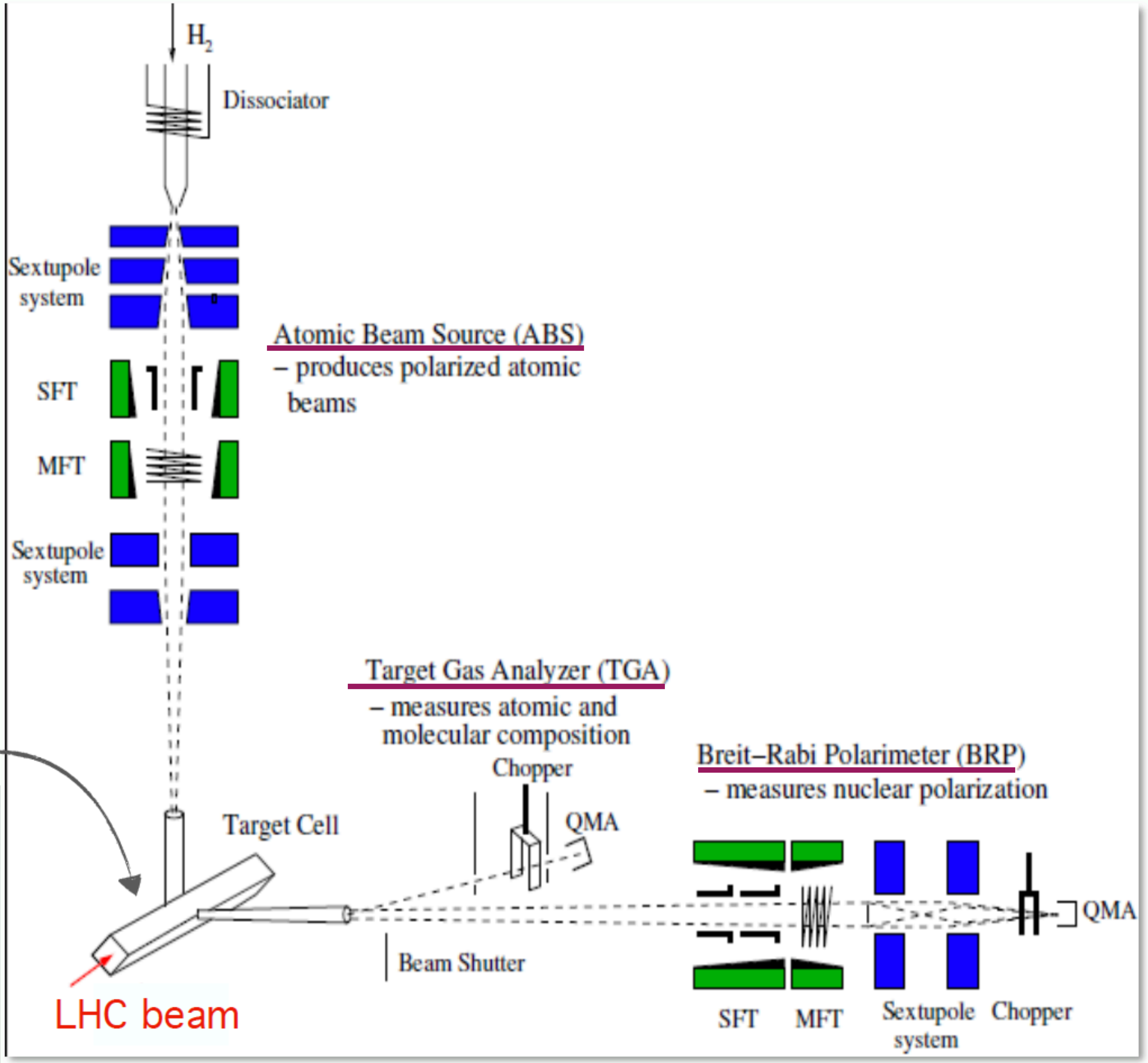
Target density (H) = 7 x 10^{13} cm^{-2}
LHC beam (Run4) = 6.8 x 10^{18} p s^{-1}

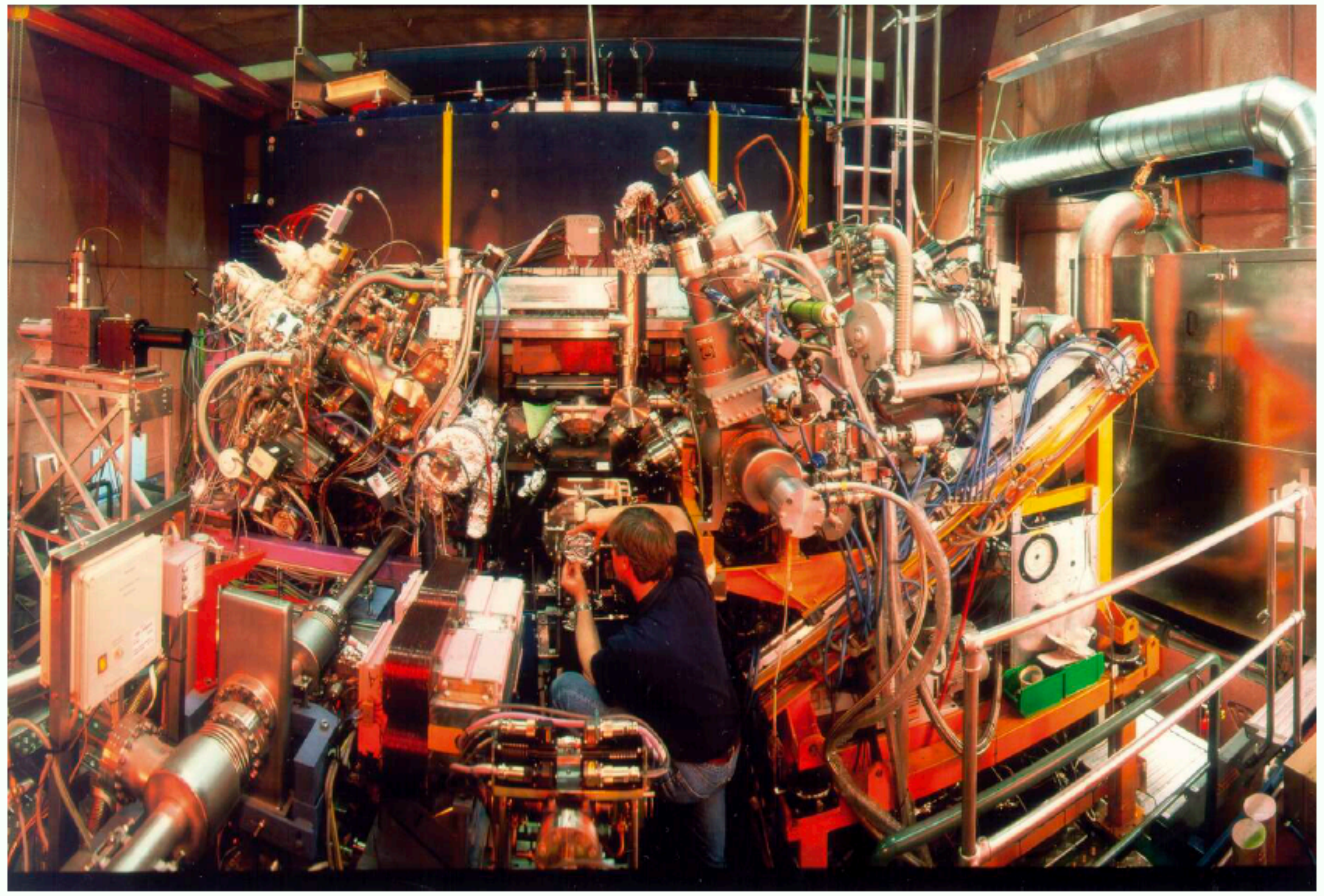
L_{pH} = 8 x 10^{32} cm^{-2} s^{-2}

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

dipole



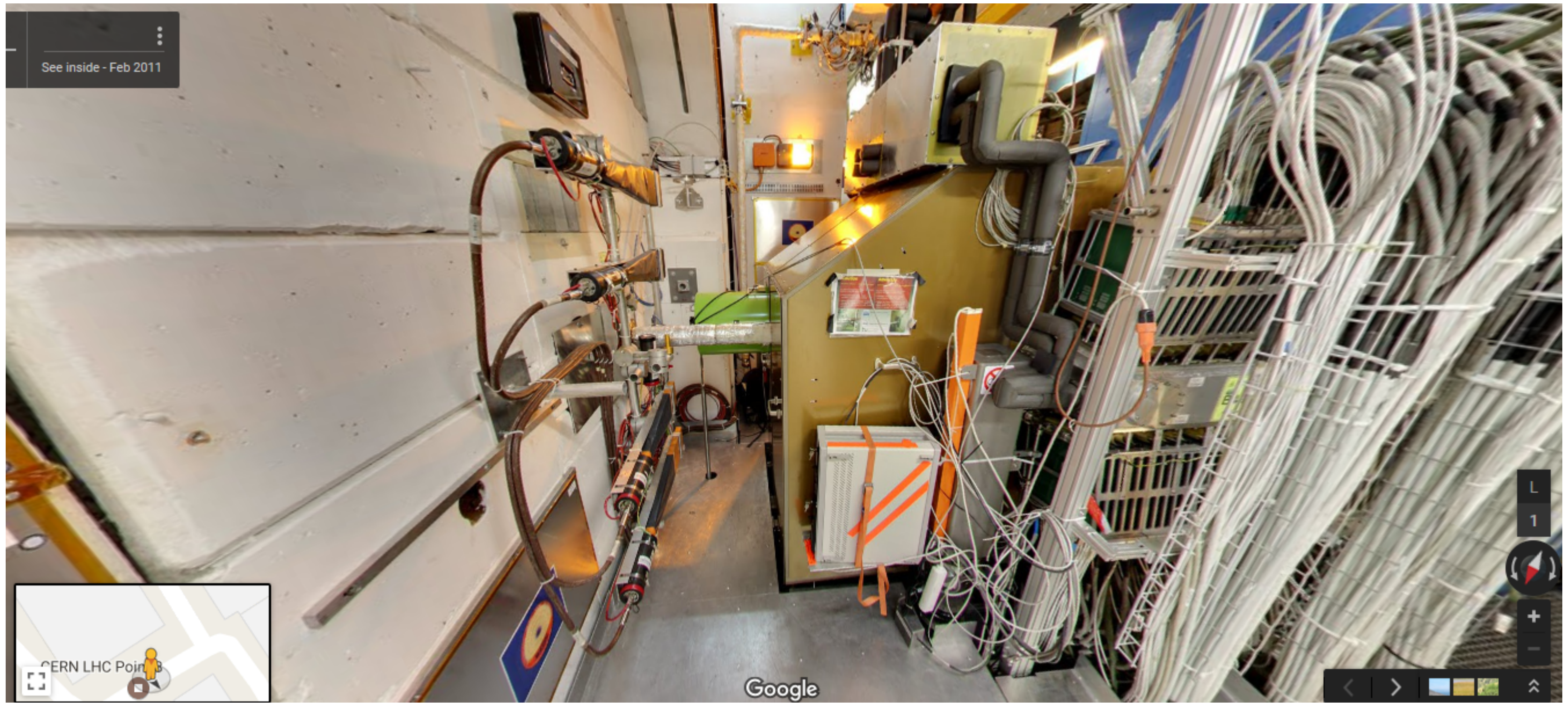




[NIMA 540 (2005) 68-101]

HERMES PGT

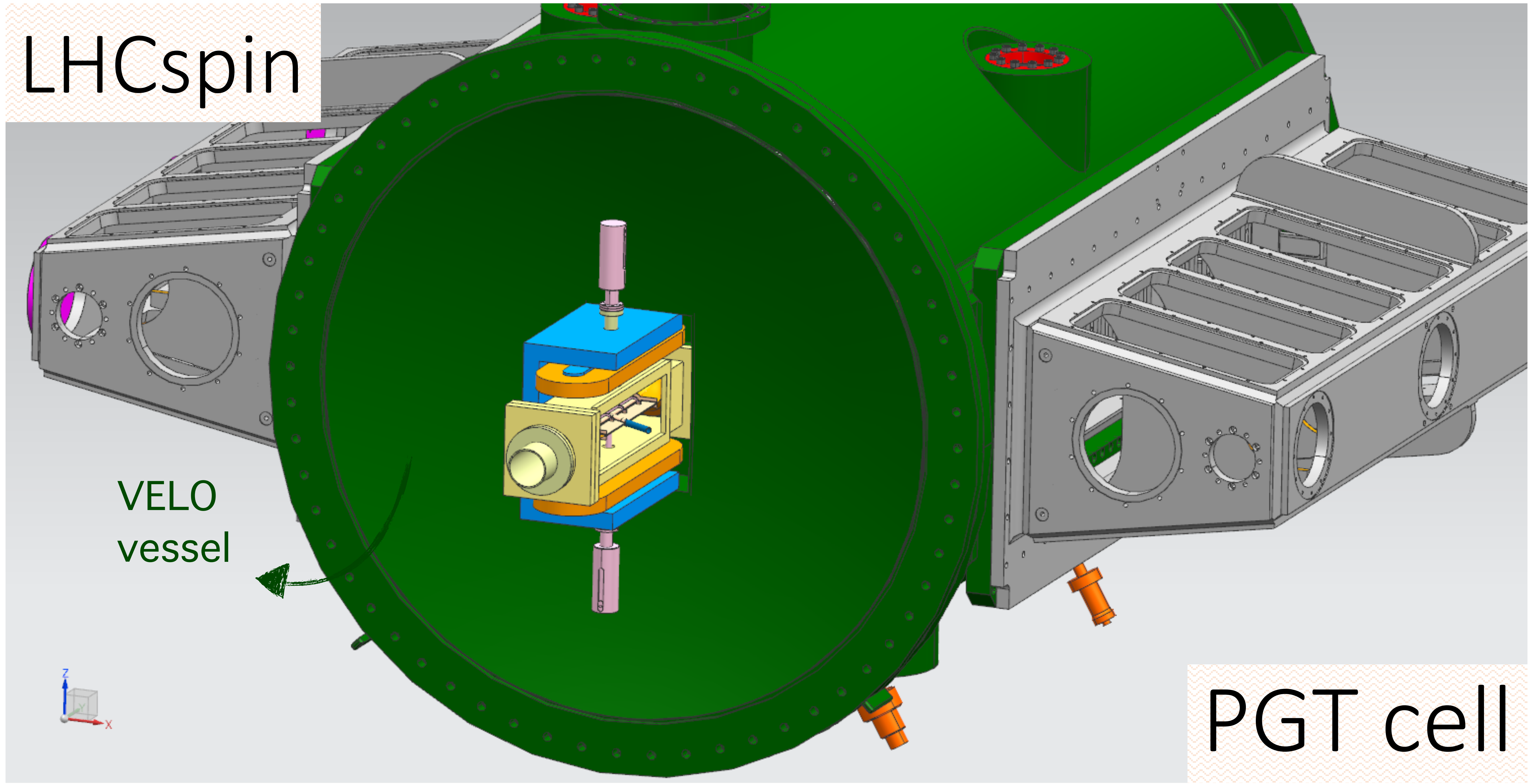
From there to here

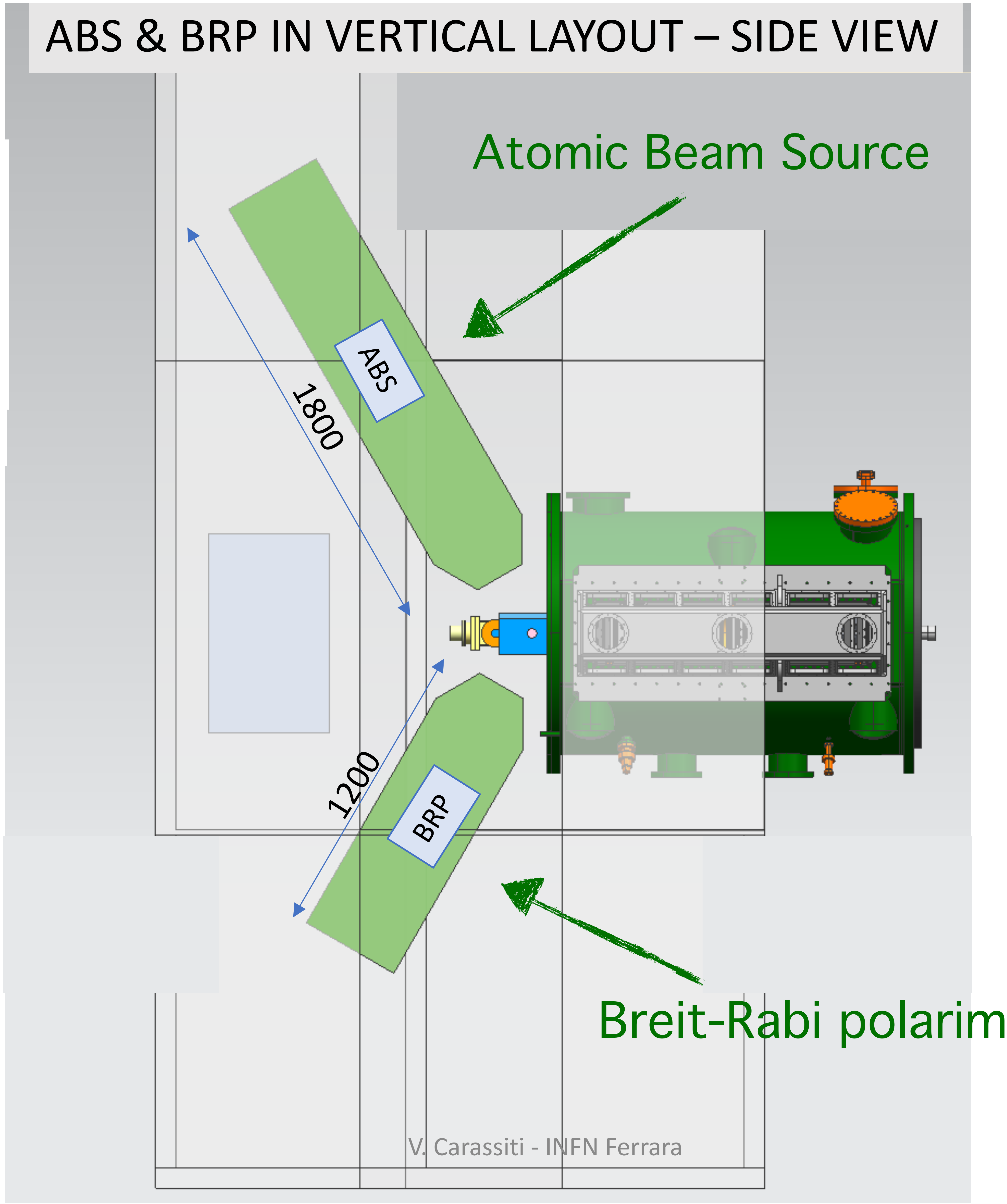


Space available in front of LHCb

PGT implementation into LHCb

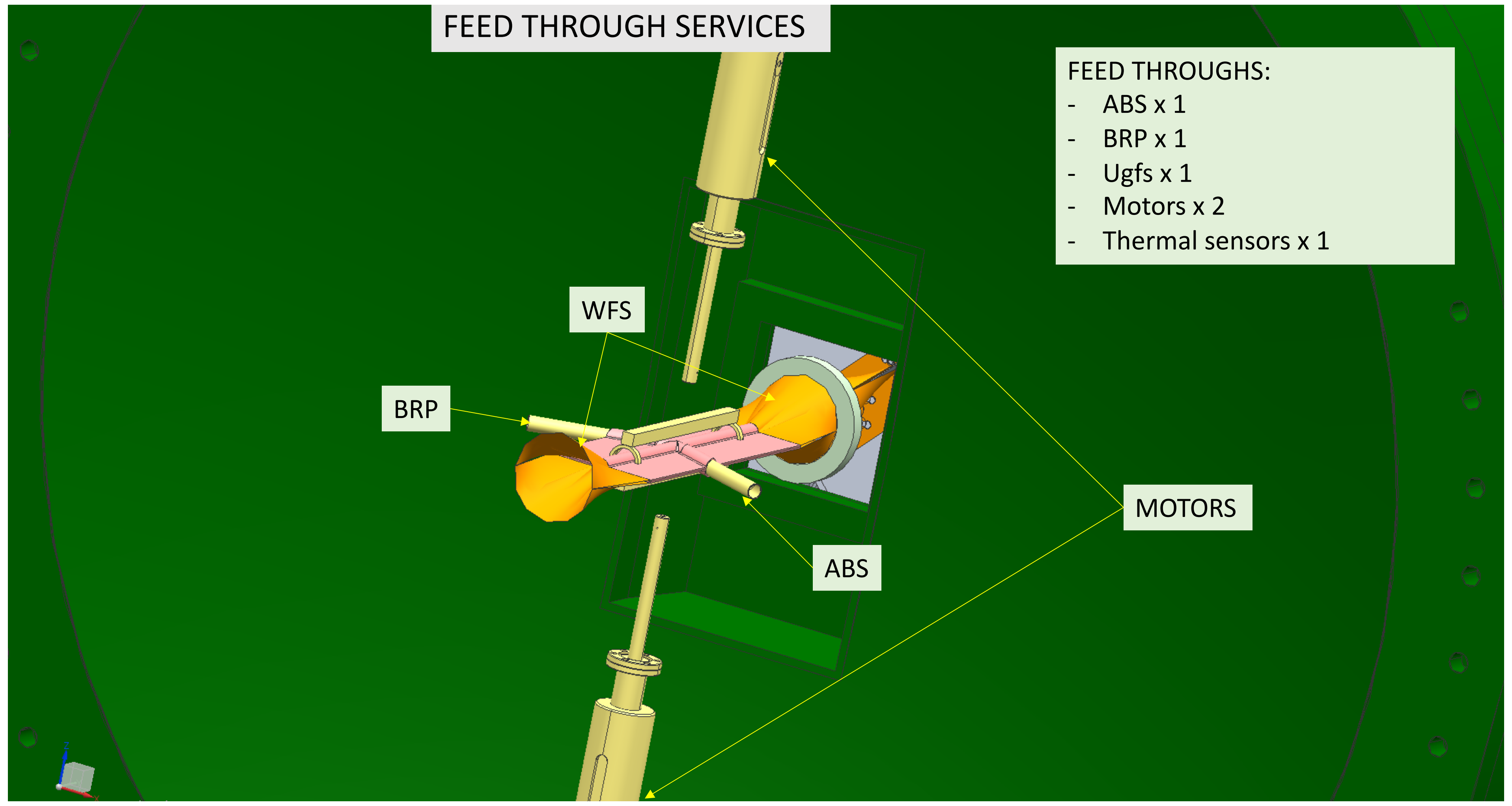
- Cylindrical target cell with SMOG2 dimensions: $L = 20$ cm and $D = 1$ cm
- Full LHCb simulations show broader kinematic acceptance & higher efficiency in the same position of the SMOG2 cell



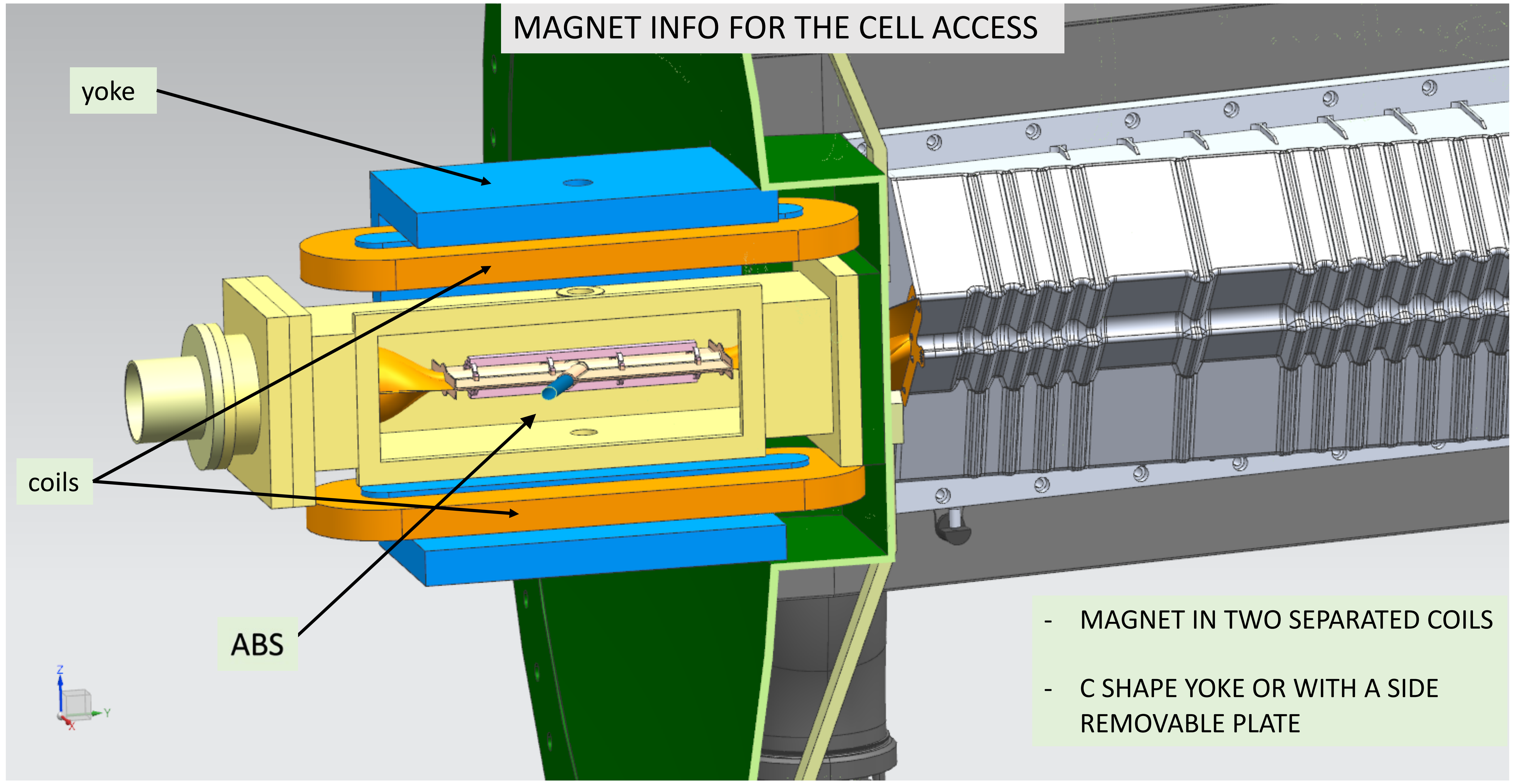


PGT implementation into LHCb

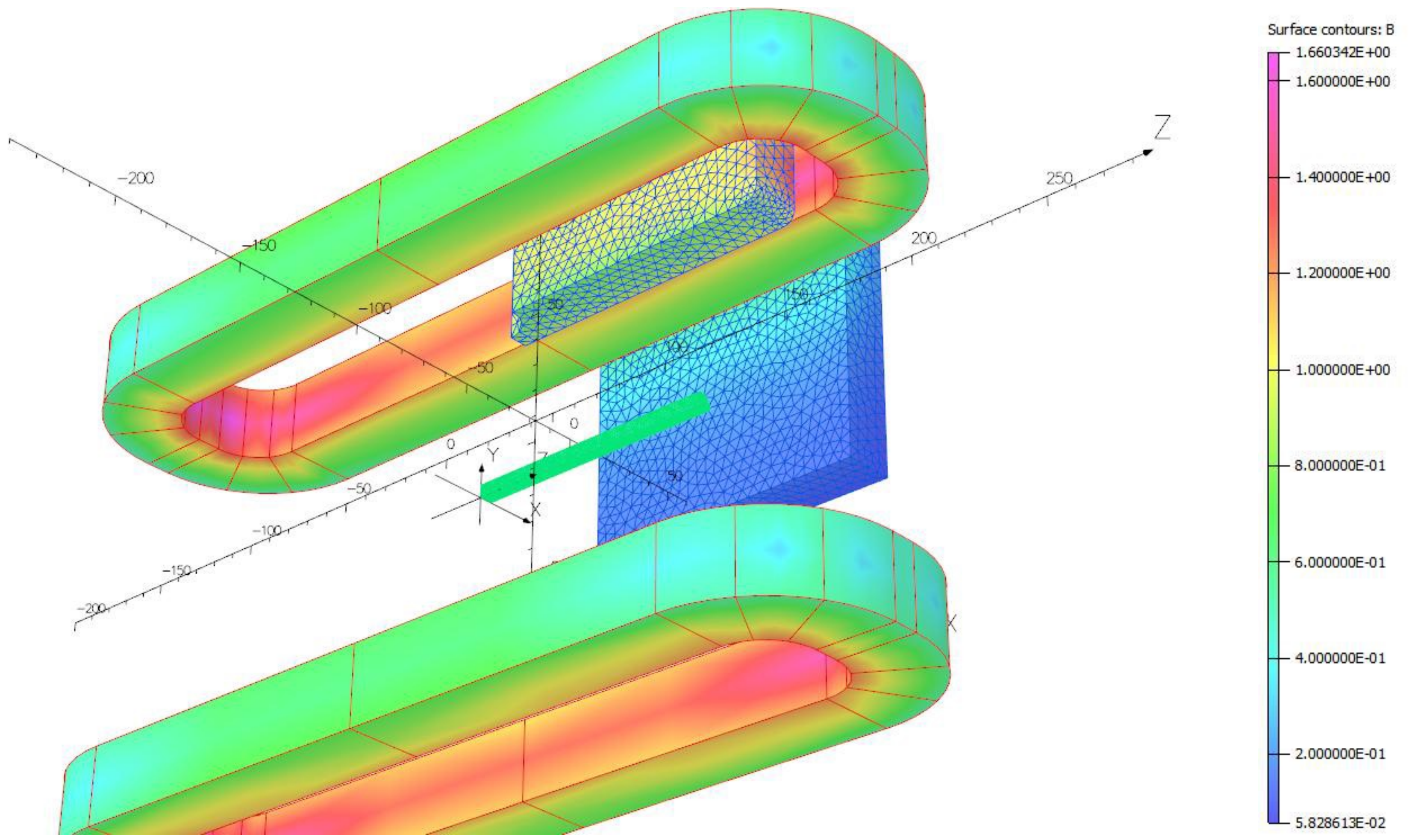
- Inject polarised gas via ABS and unpolarised gas via UGFS



Transverse polarisation



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



Possibility to switch to a solenoid and provide longitudinal polarisation (e.g. in LHC Run 5)

Role of the storage cell coating

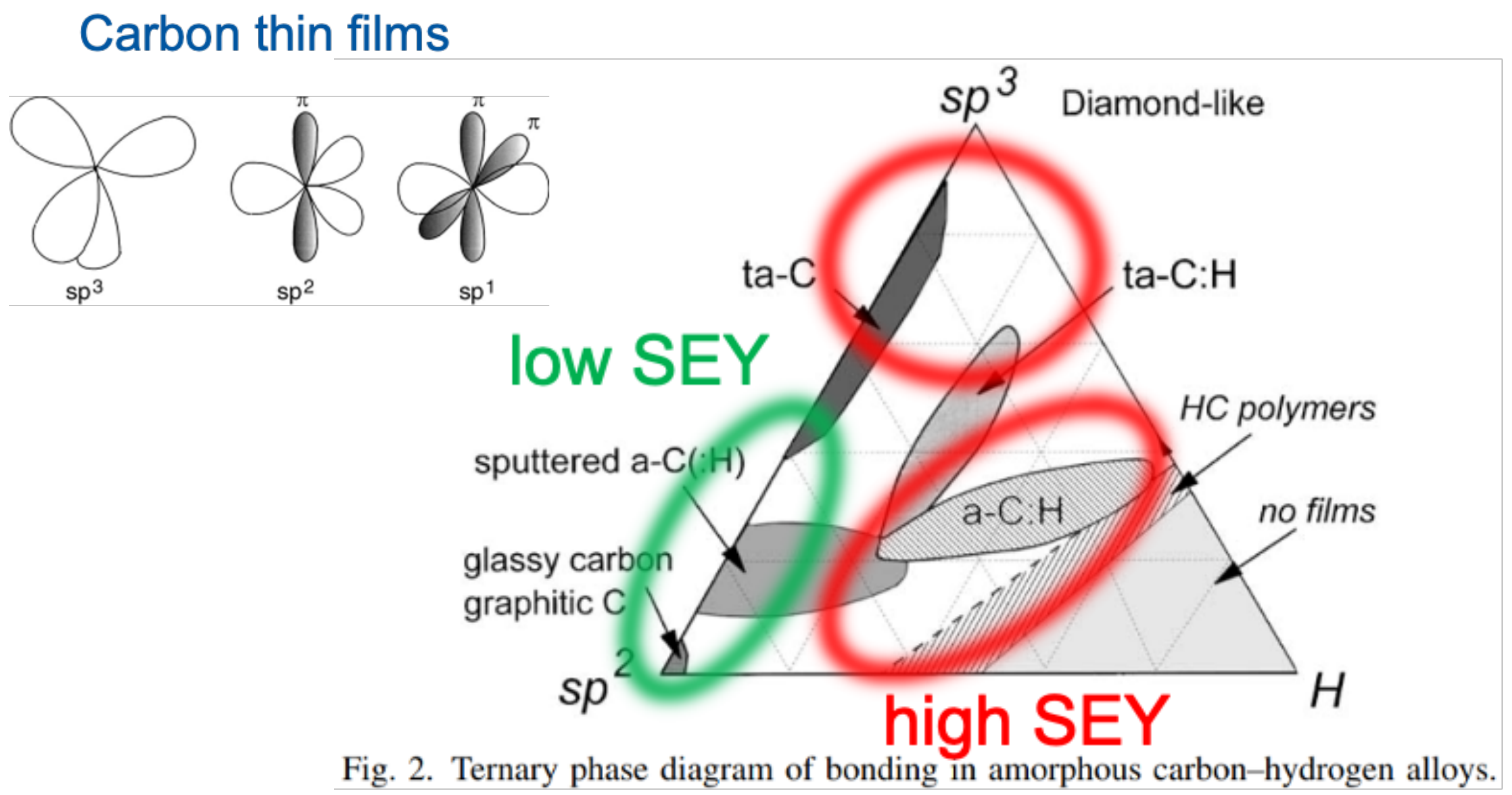
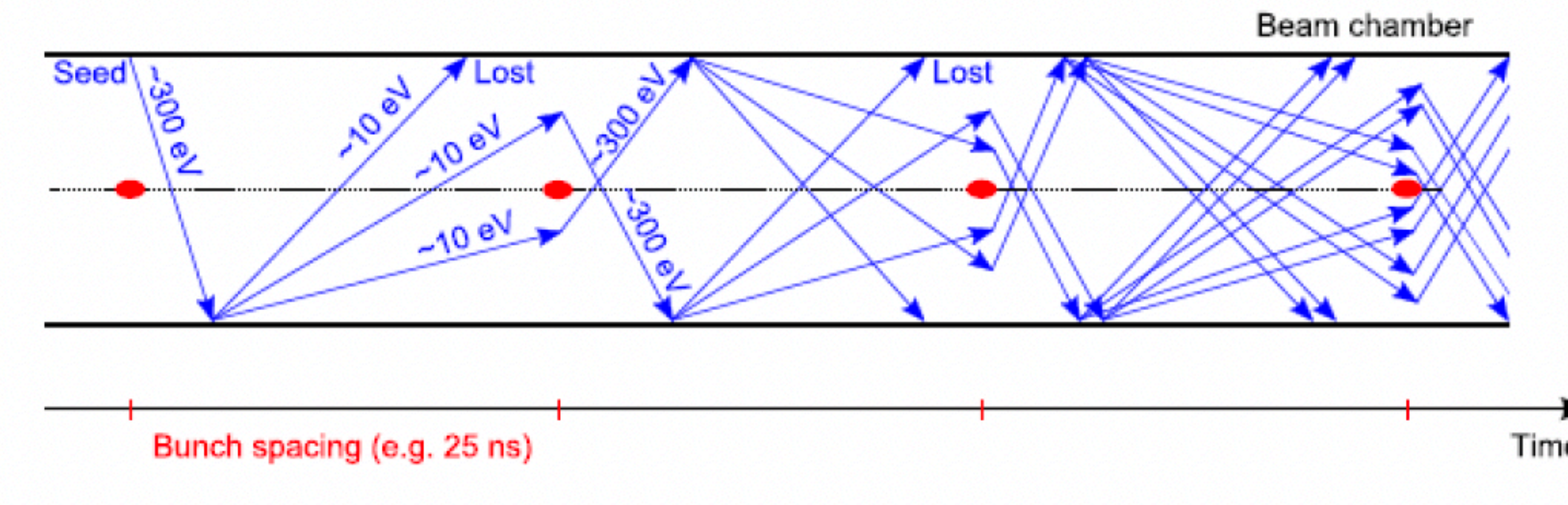


Fig. 2. Ternary phase diagram of bonding in amorphous carbon–hydrogen alloys.

J. Robertson / Materials Science and Engineering R 37 (2002) 129–281



The material of the cell walls must have a low Secondary Electron Yield (e-cloud)

As for SMOG2, Amorphous Carbon is ok. Has it a low H recombination as well?

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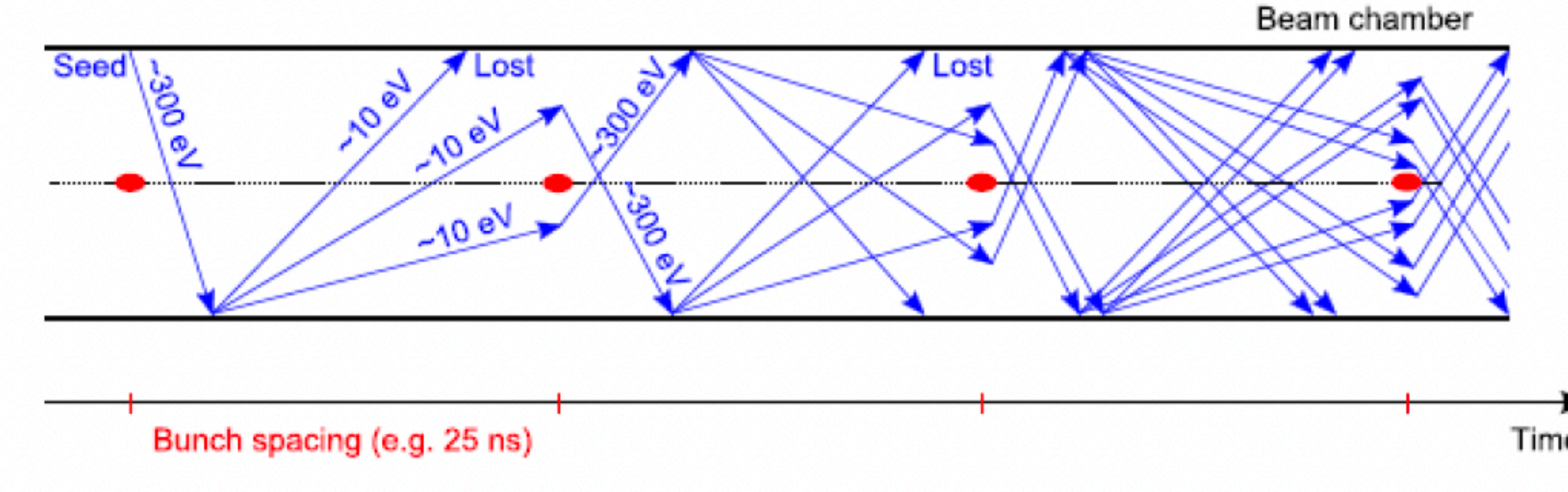
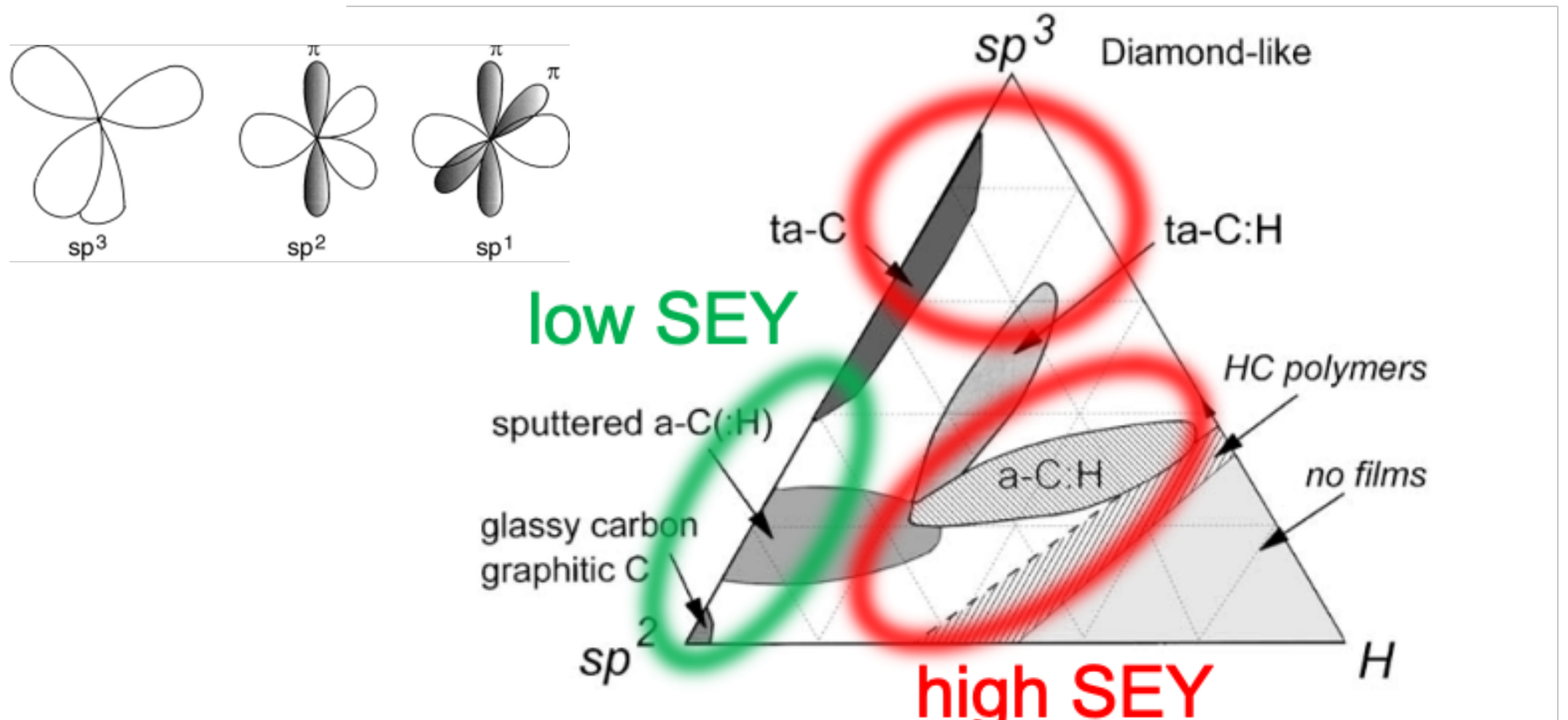


Carbon thin films



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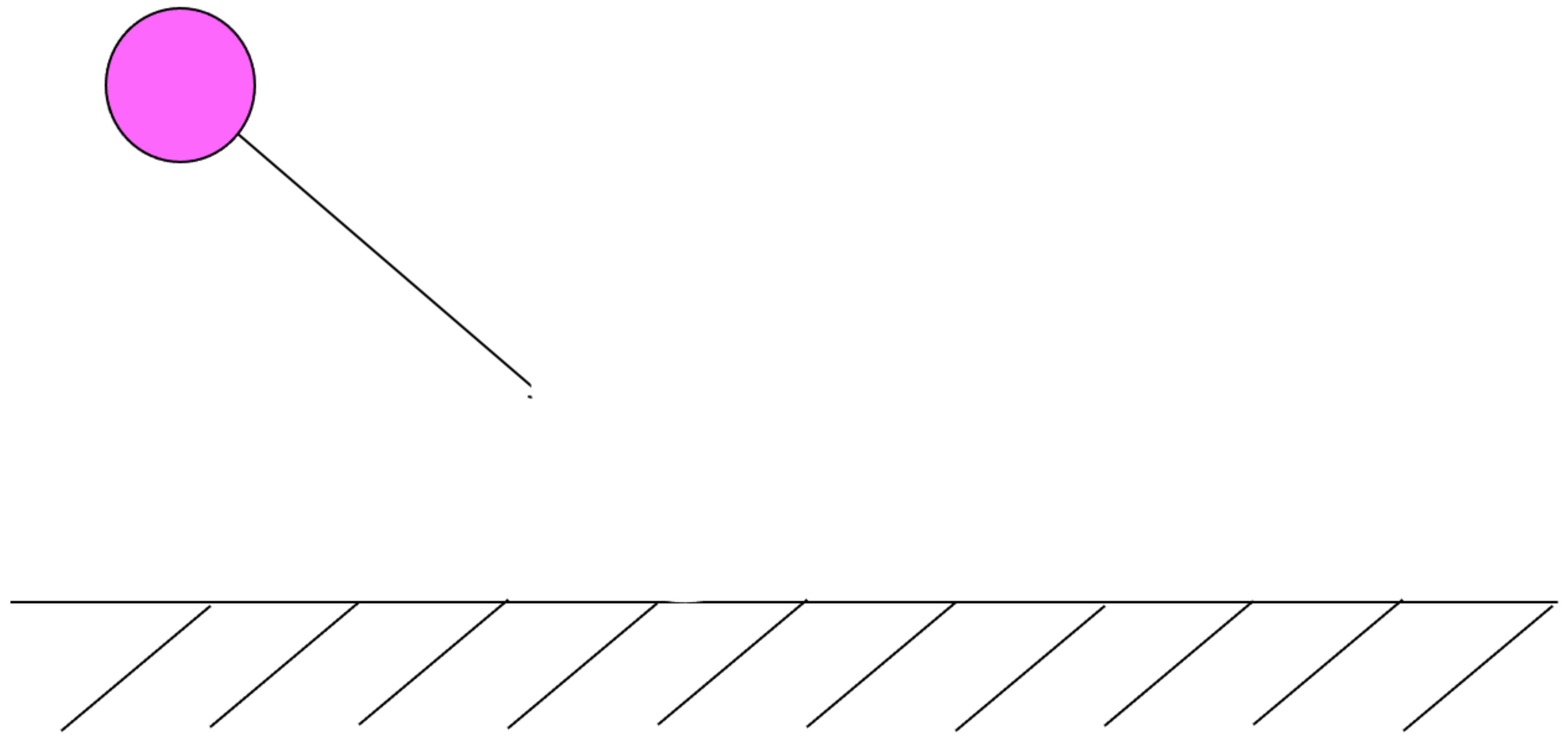
Eley-Rideal Mechanism



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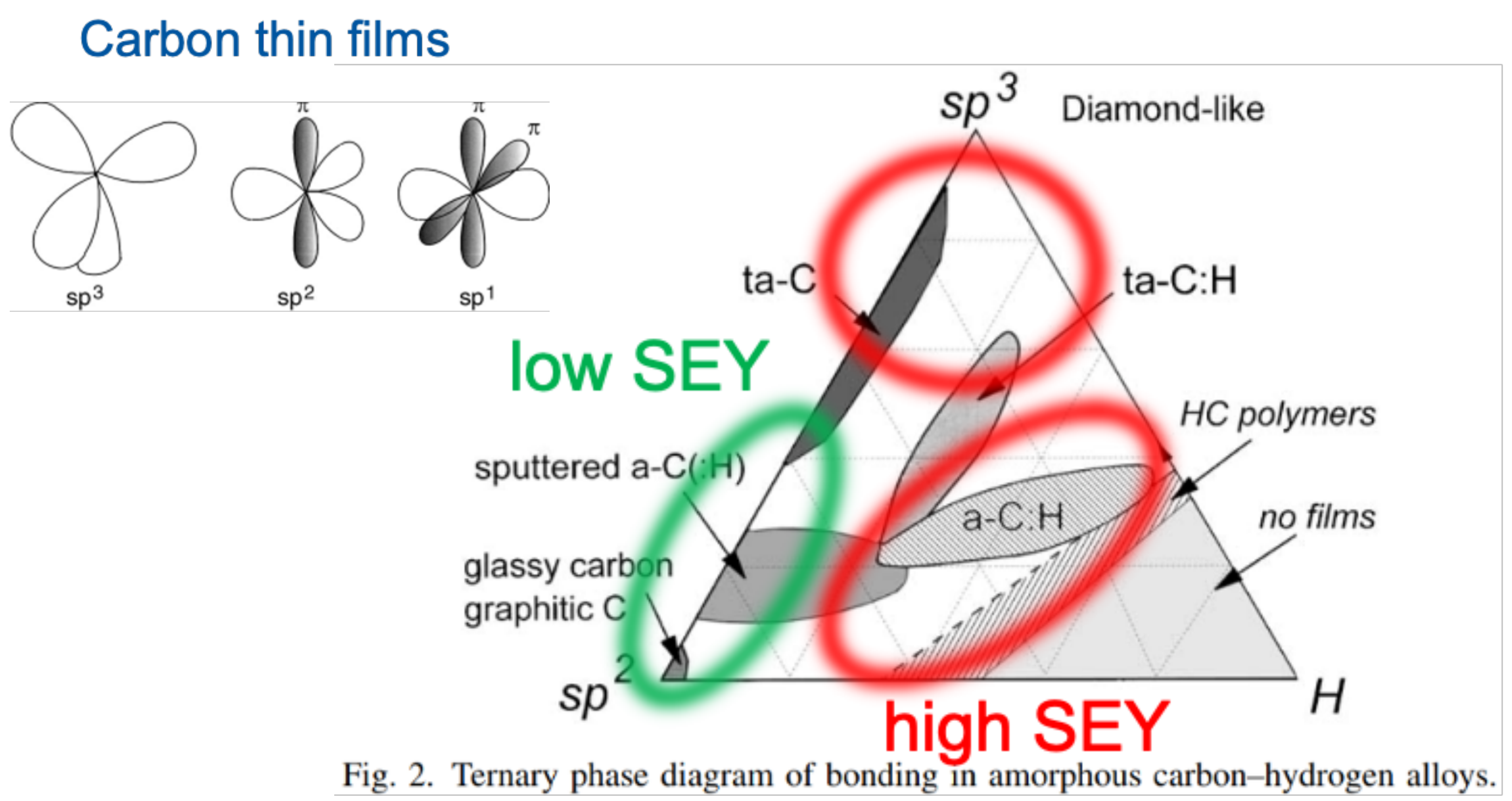

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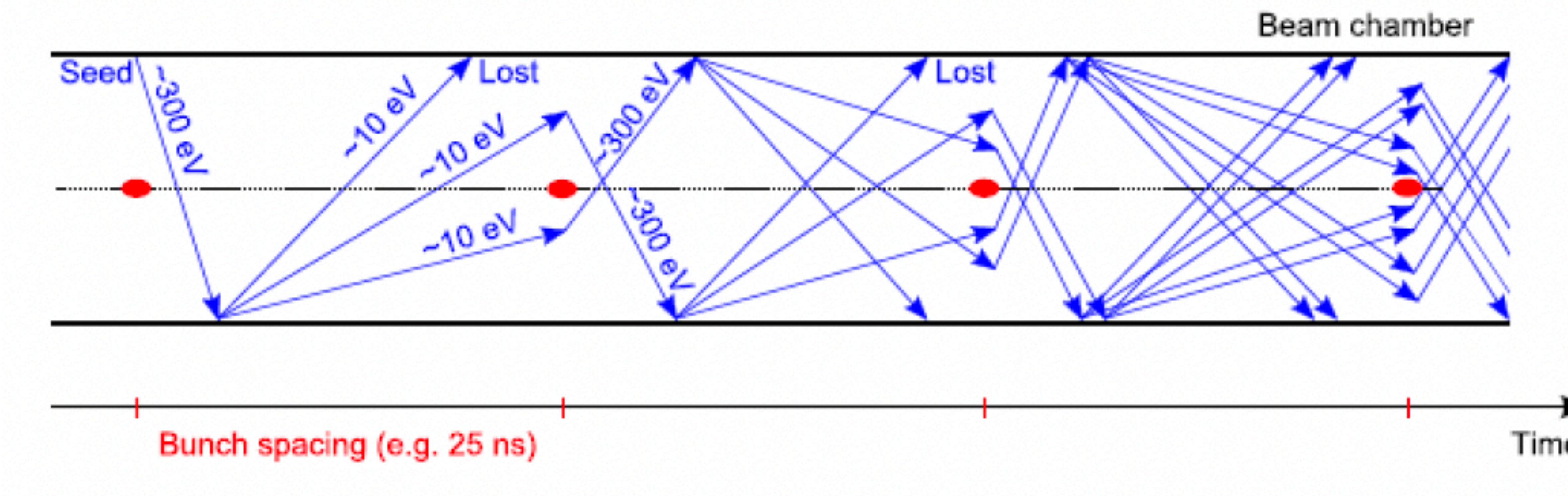

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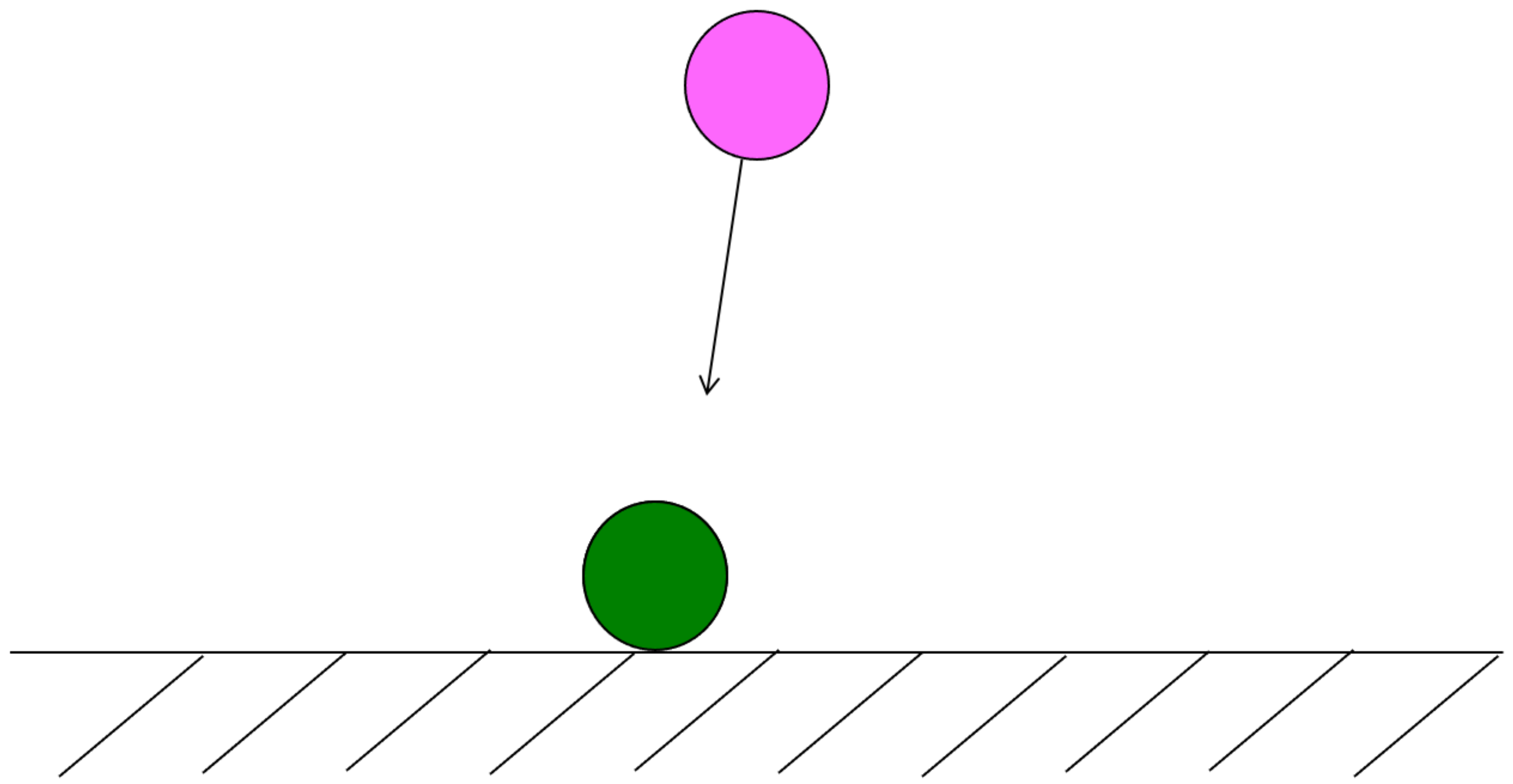

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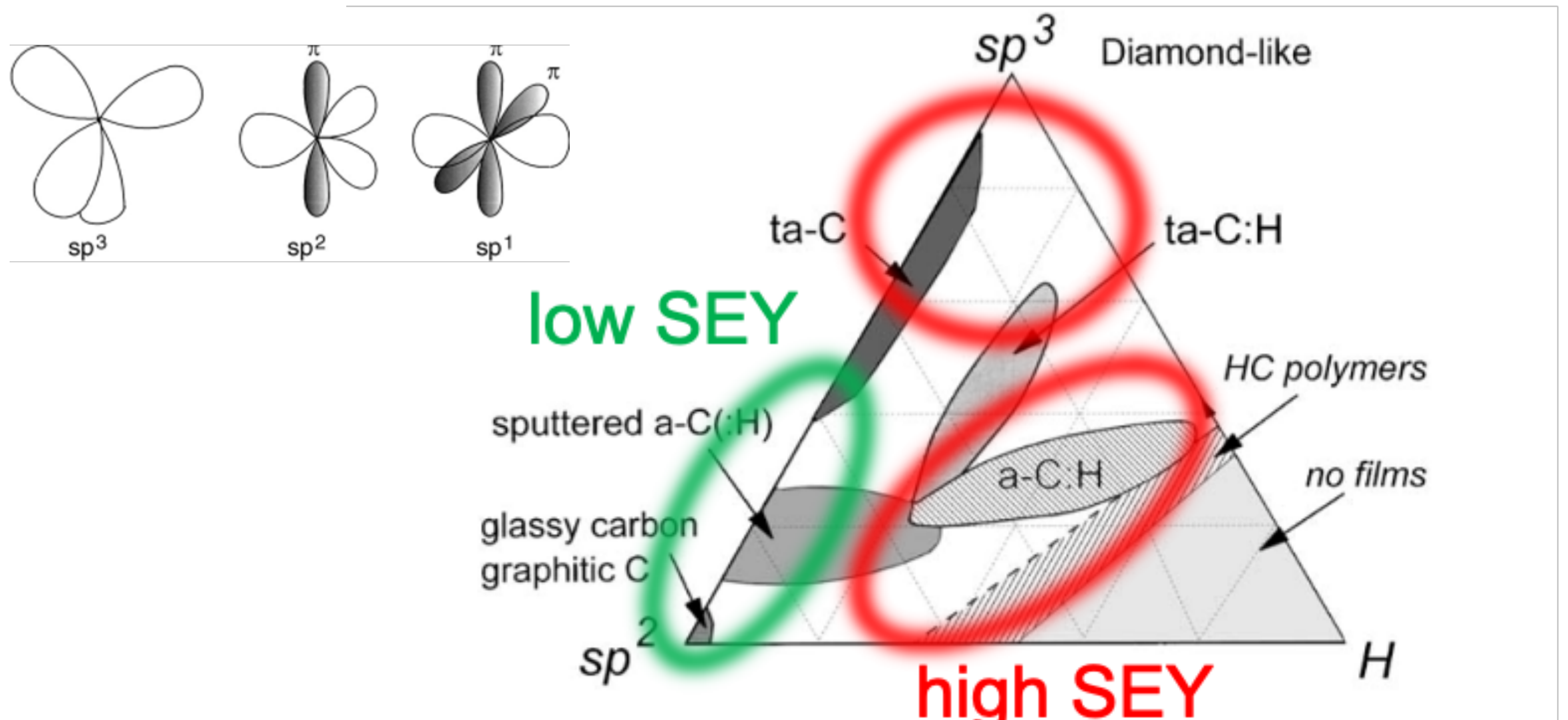

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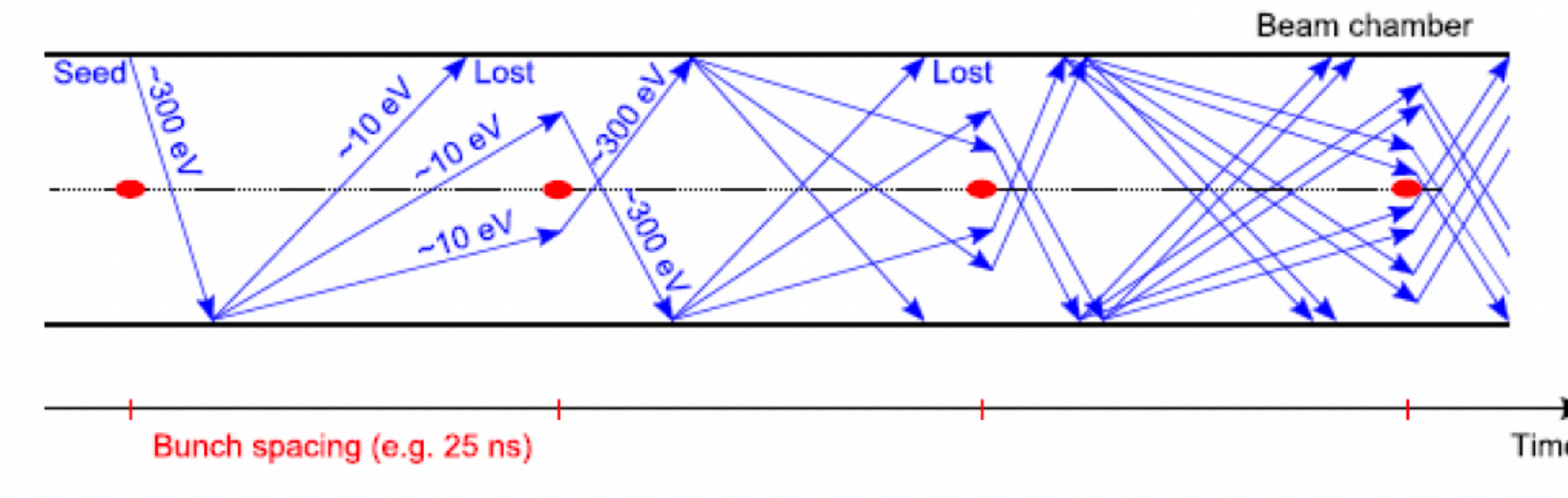

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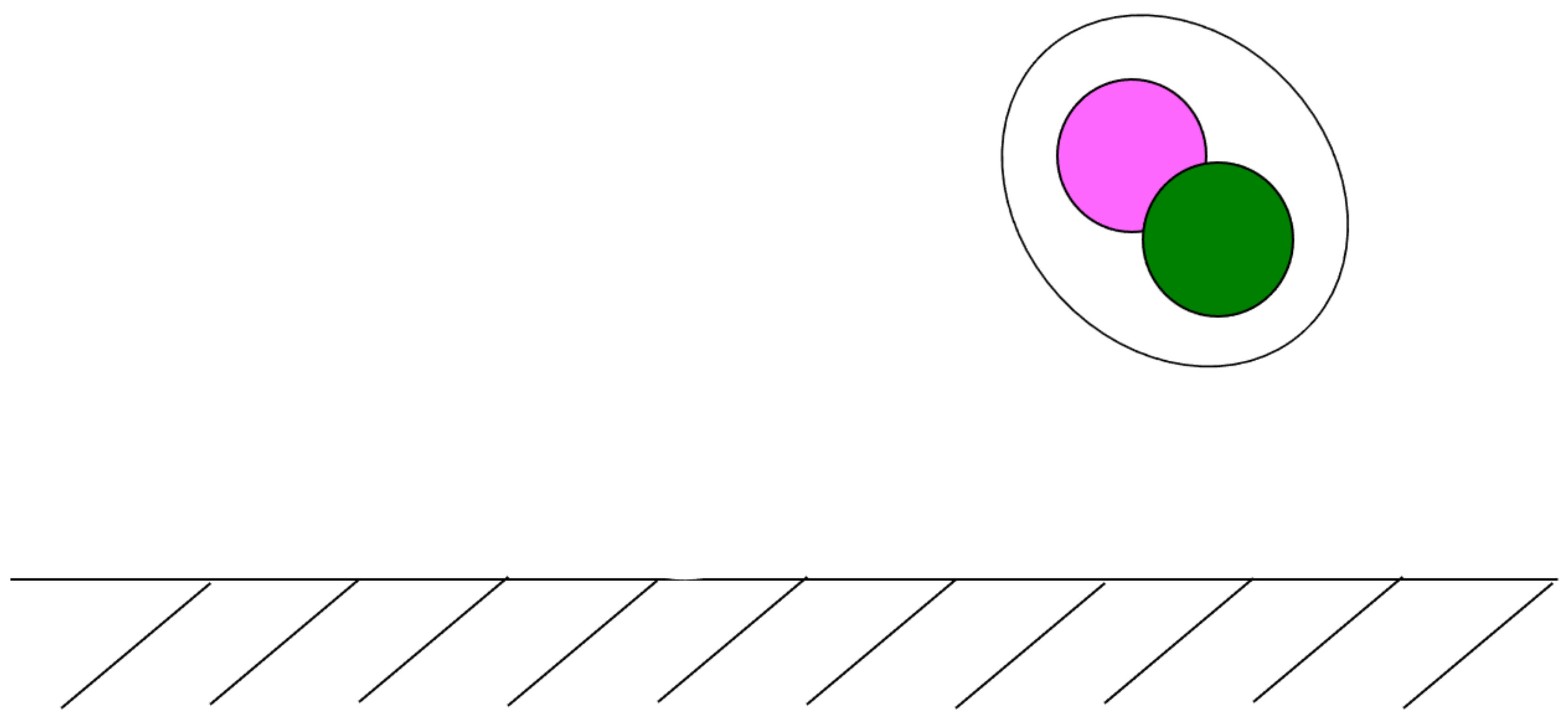
Eley-Rideal Mechanism

$P_m = 0.5\ P_a$



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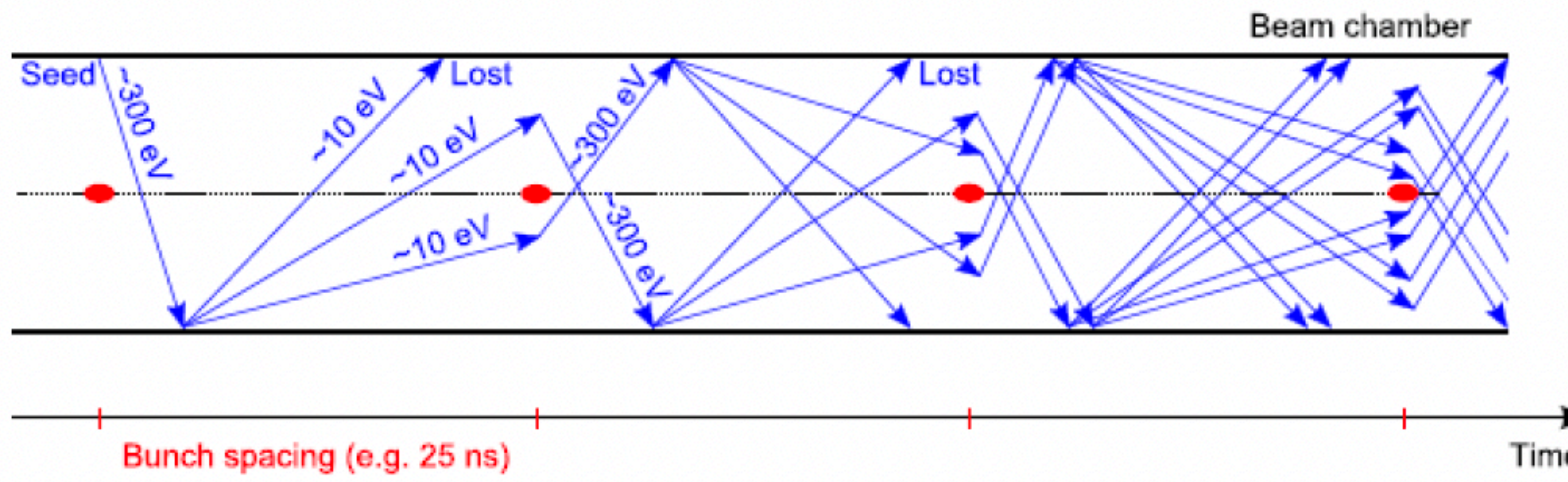

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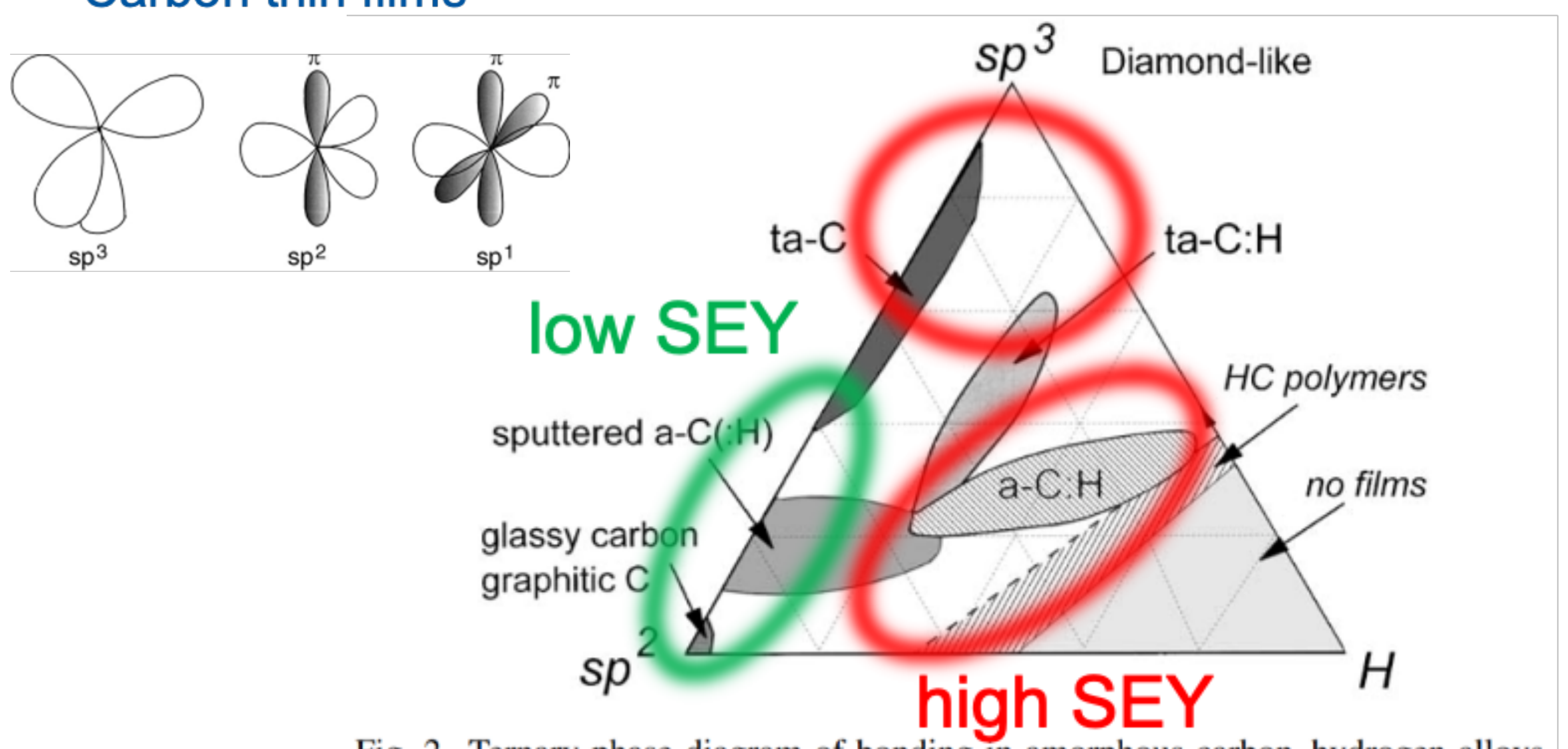

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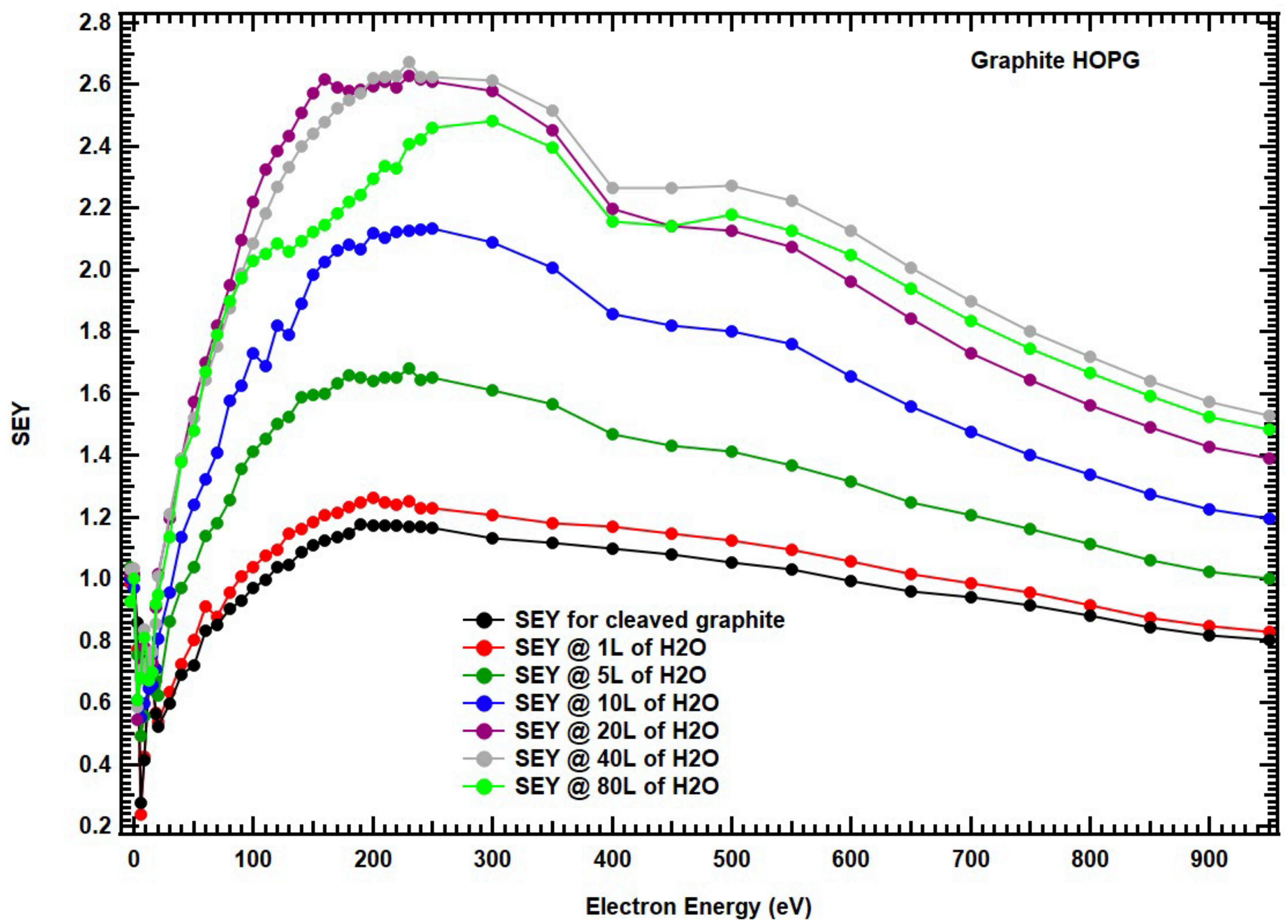
Studies ongoing in order to understand if **carbon films with low secondary Electron Yield** cope with the required **"recombination" rate** of polarized H atoms injected in the storage cell



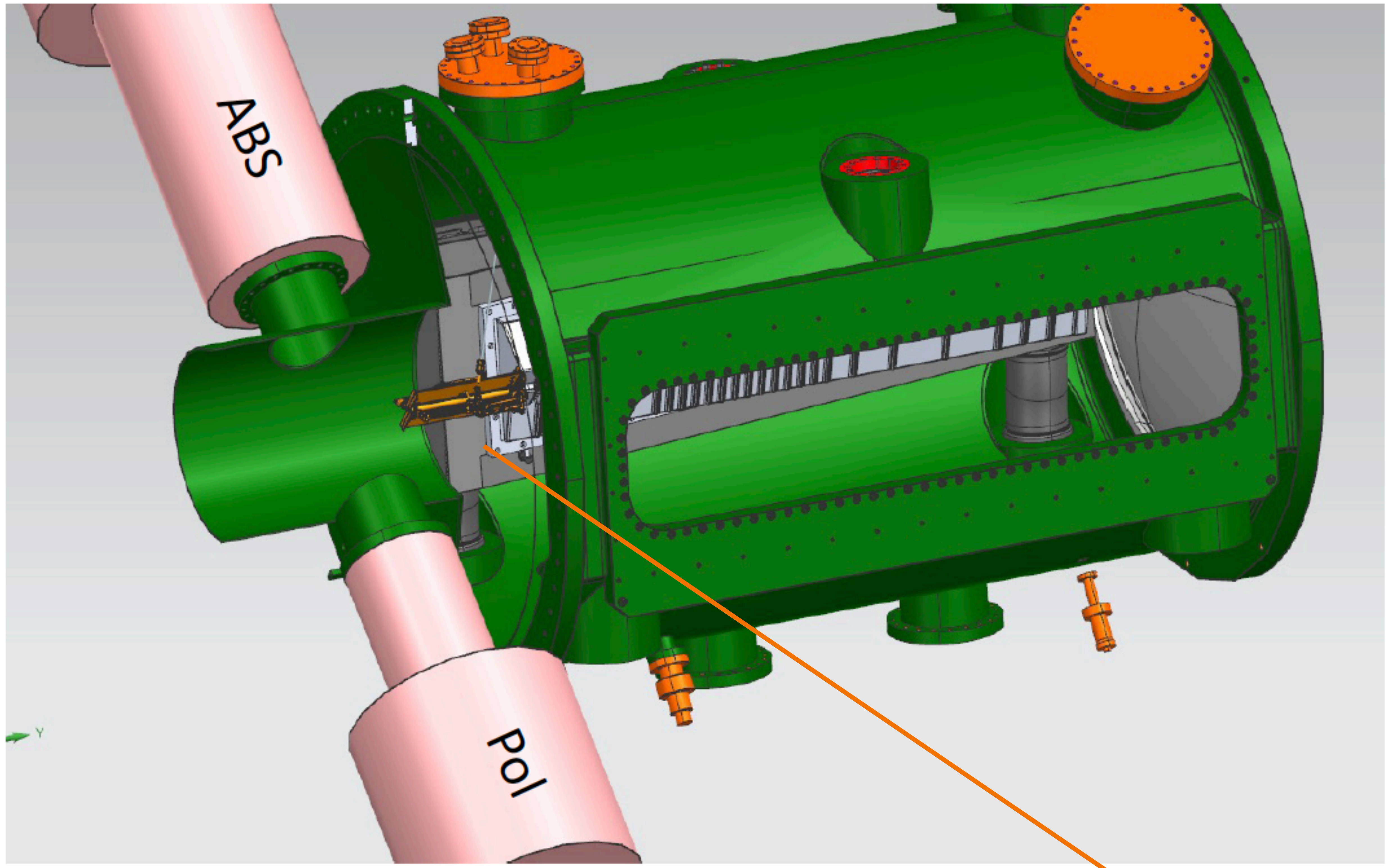
… or follow the HERMES experience to have an ice coating (low SEY, low H recombination)

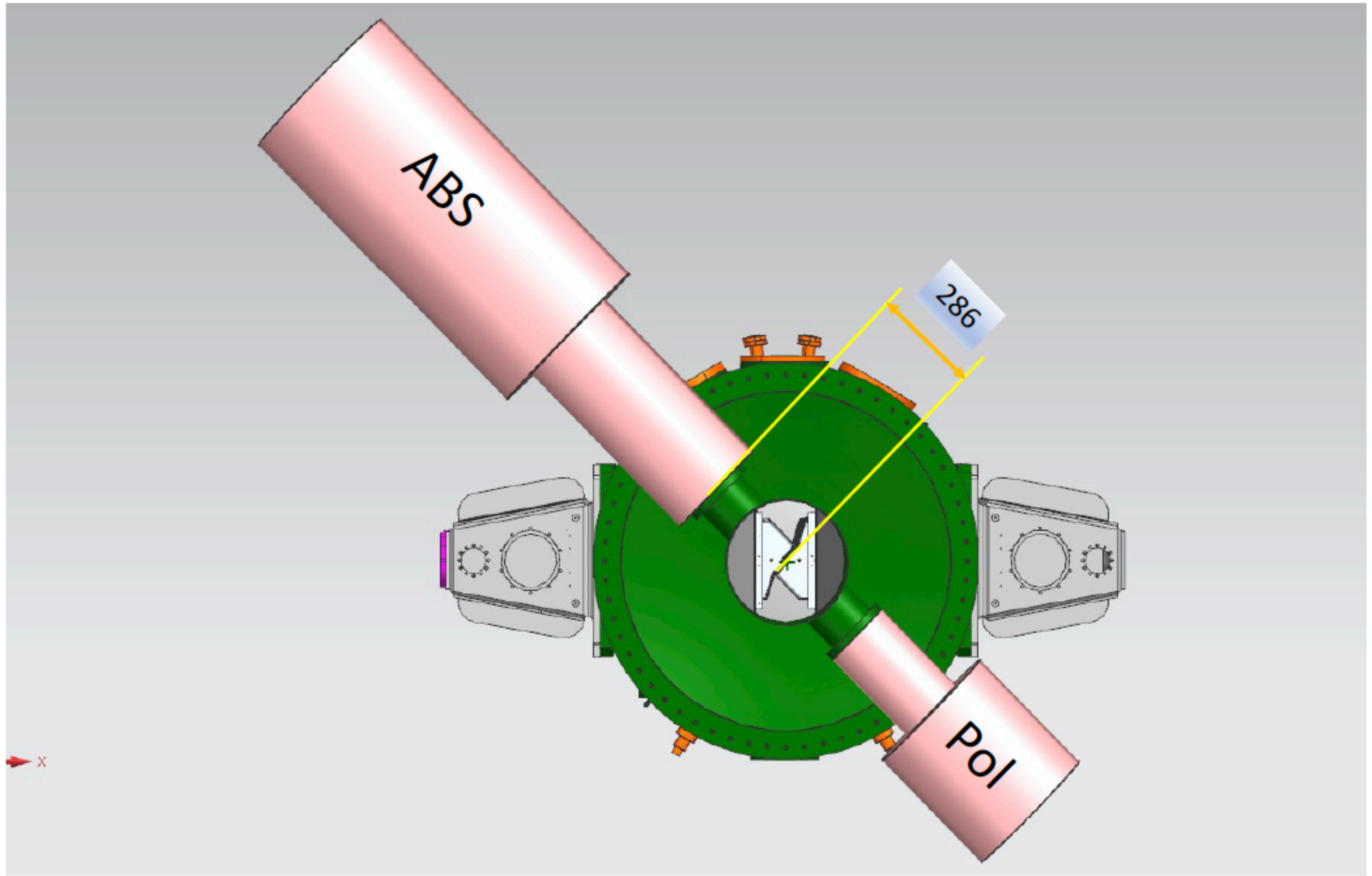
Backup solution is also being investigated: a jet target that provides lower density (~10^{12} atoms/cm^2) but higher polarisation degree (up to 90%) and lower systematics

The jet target option

Alternative solution with **jet target** also under evaluation:

- lower density ($\sim 10^{12}$ atoms$/cm^2$)
- higher polarization (up to 90%)
- lower systematics in P measurement (virtually close to 0)



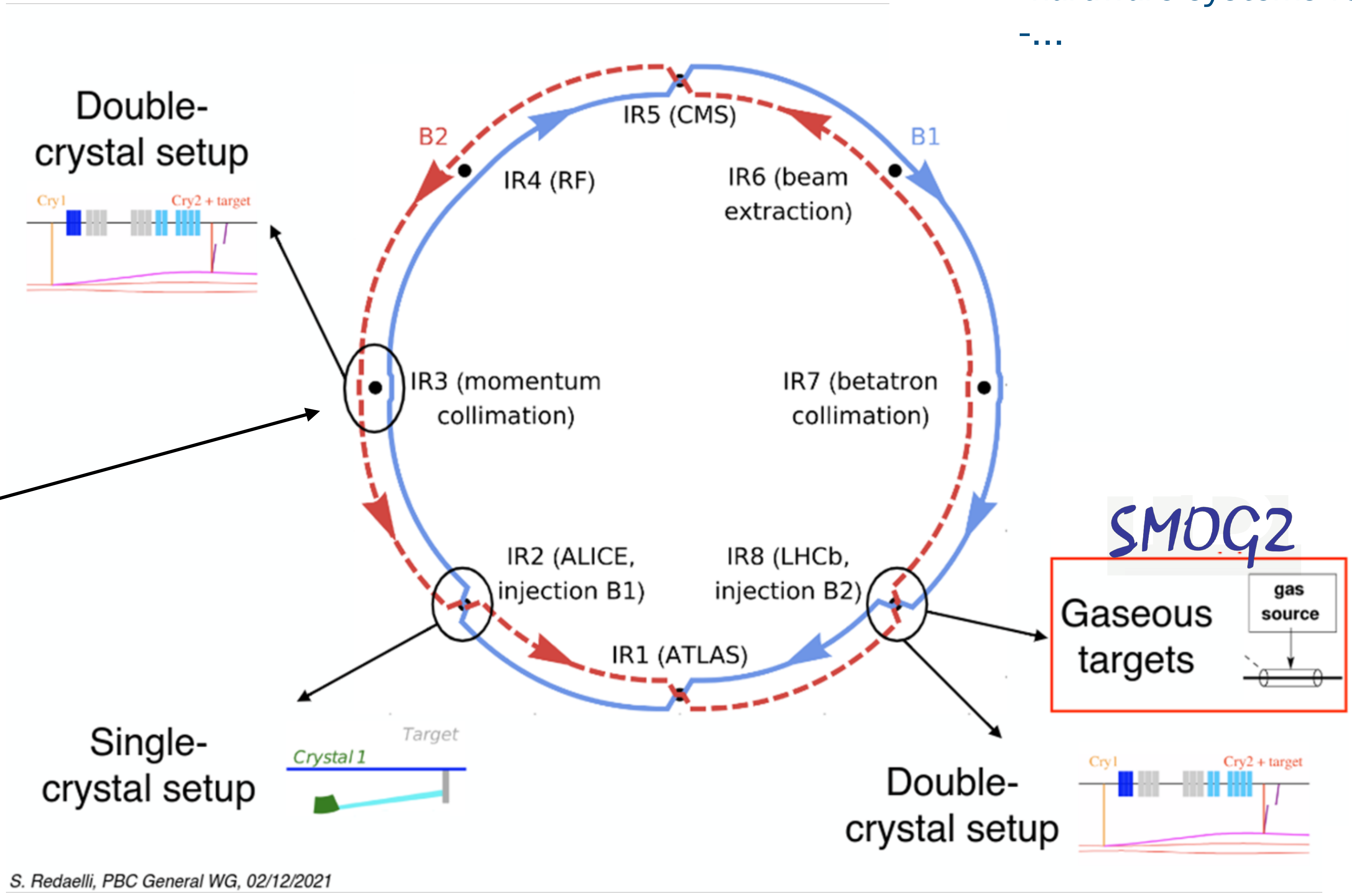


SMOG2

The LHC Interaction Region 3

IR3 is a great opportunity to perform R&D on beam:
-mutual polarised target - beam interaction (BID, impedance, aperture, ...)
-hardware systems for LHCspin
-...

R&D



The physics goals of LHCspin … just a quick overview

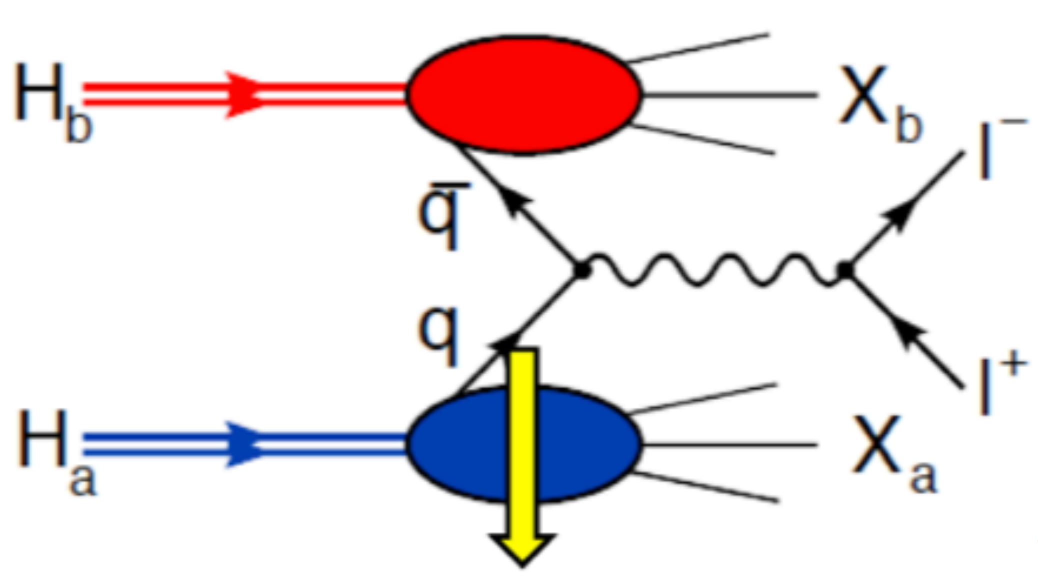
- Multi-dimensional nucleon structure in a poorly explored kinematic domain
- Measure experimental observables sensitive to both **quarks and gluons TMDs**
- **Make use of new probes (charmed and beauty mesons)**
- Complement present and future SIDIS results
- Test non-trivial process dependence of quarks and (especially) gluons TMDs
- Measure exclusive processes to access GPDs

Quark TMDs

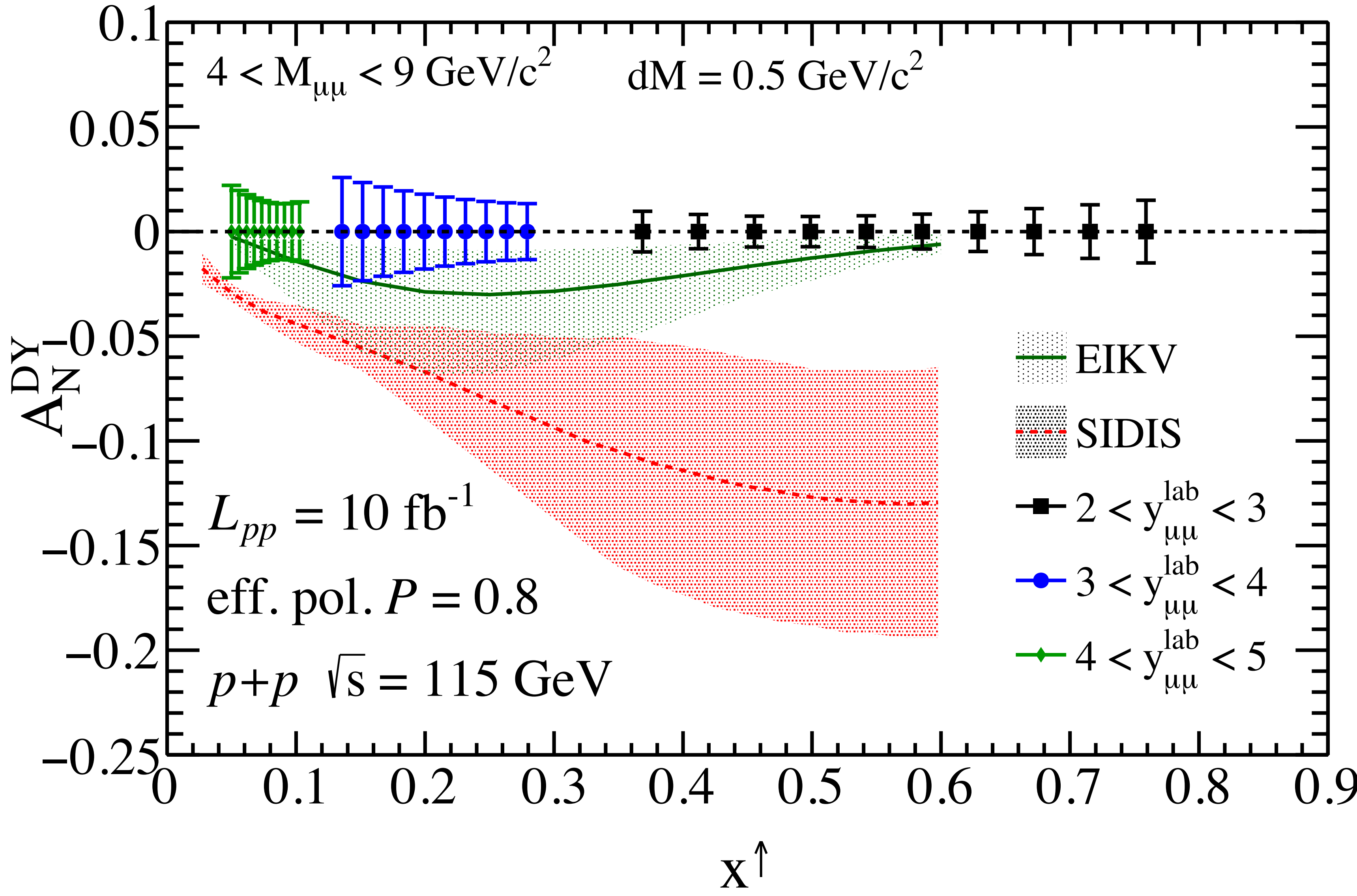
quark pol. / nucleon pol.

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

Transv. polarized Drell-Yan



Golden Channel

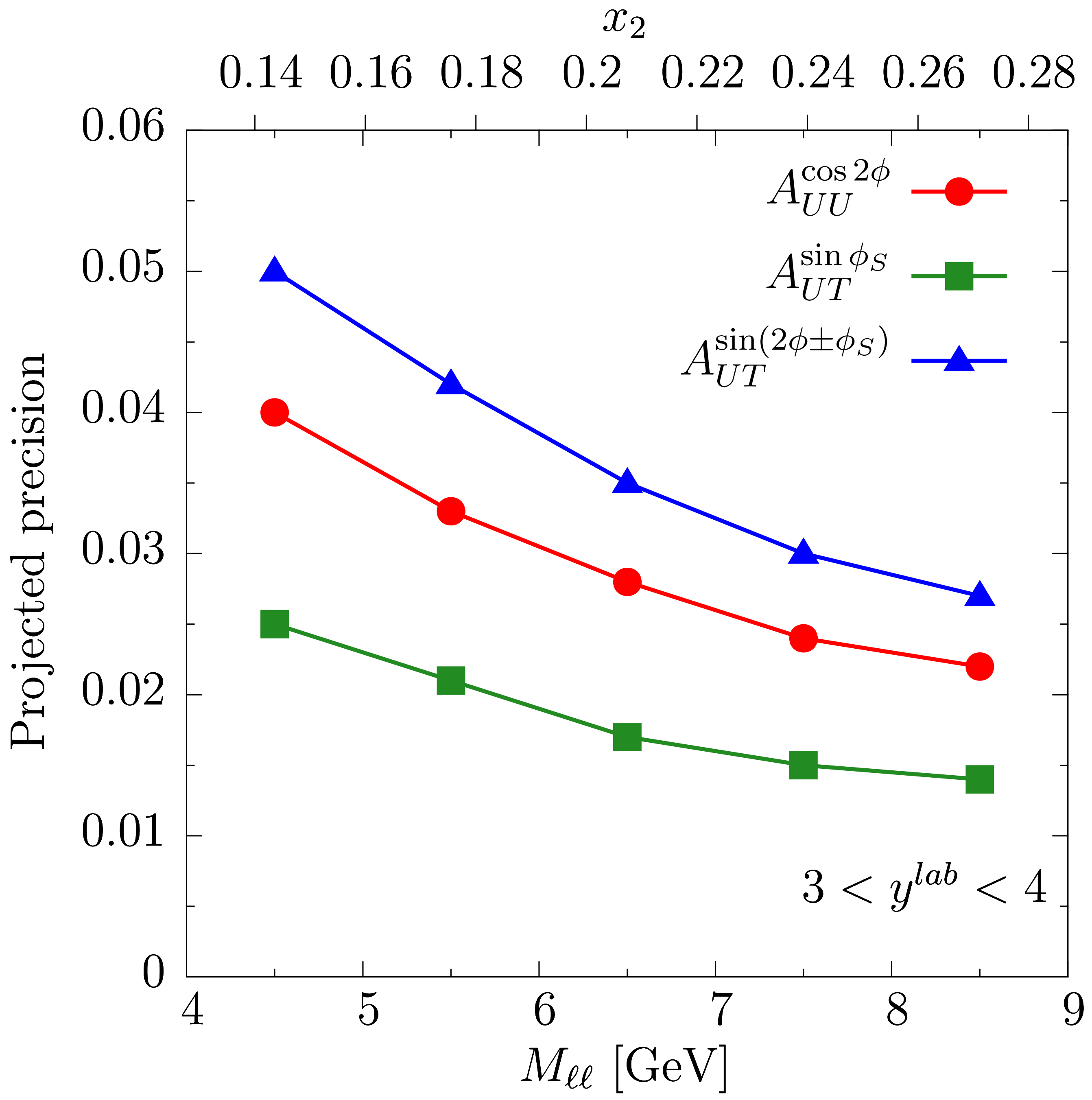


[arXiv:1807.00603]

- **Sensitive to quark TMDs through TSSAs**

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

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



[arXiv:1807.00603]

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

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

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

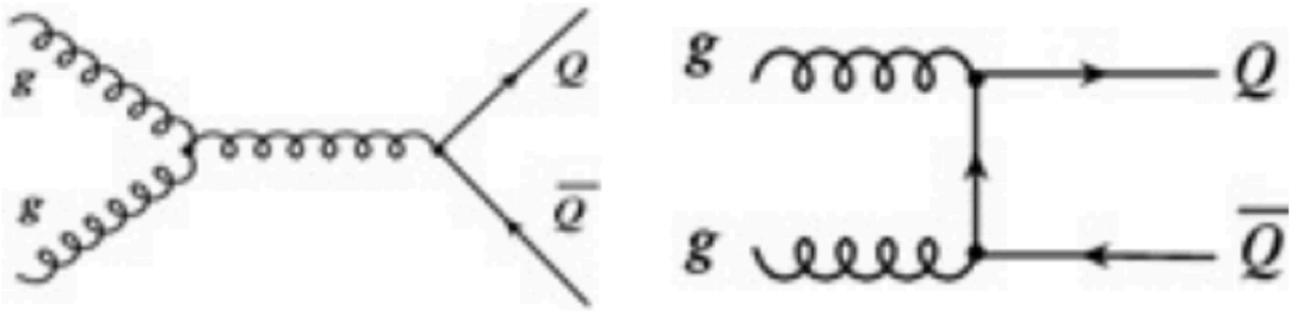
- Extraction of qTMDs does not require knowledge of FF
- Verify sign change of Sivers function wrt SIDIS $f_{1T}^{\perp}|_{DY} = -f_{1T}^{\perp}|_{SIDIS}$
- Test flavour sensitivity using both H and D targets

Gluon TMDs

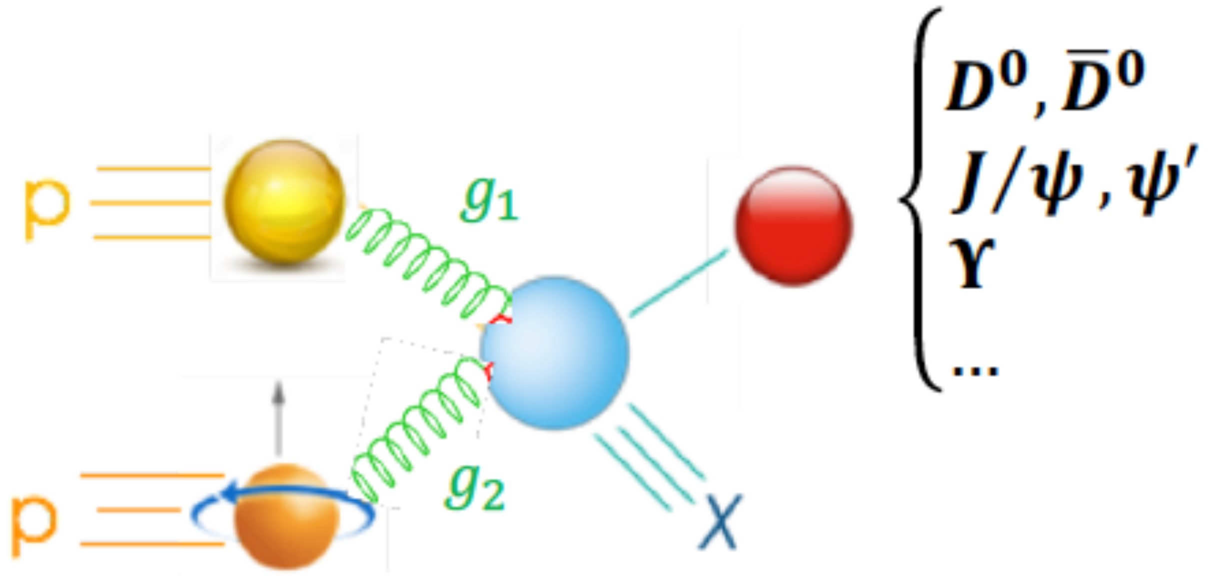
Theory framework well consolidated, but experimental access still extremely limited

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

Gluon TMDs

Theory framework well consolidated, but experimental access still extremely limited

		gluon pol.		
nucleon 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	$h_1^g,\ h_{1T}^{\perp g}$

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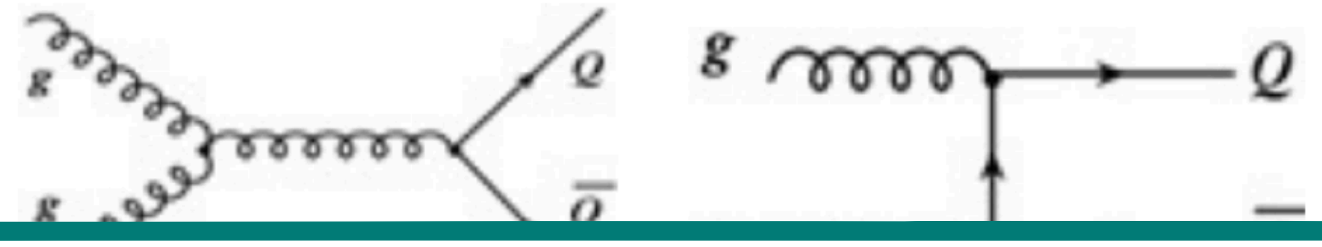
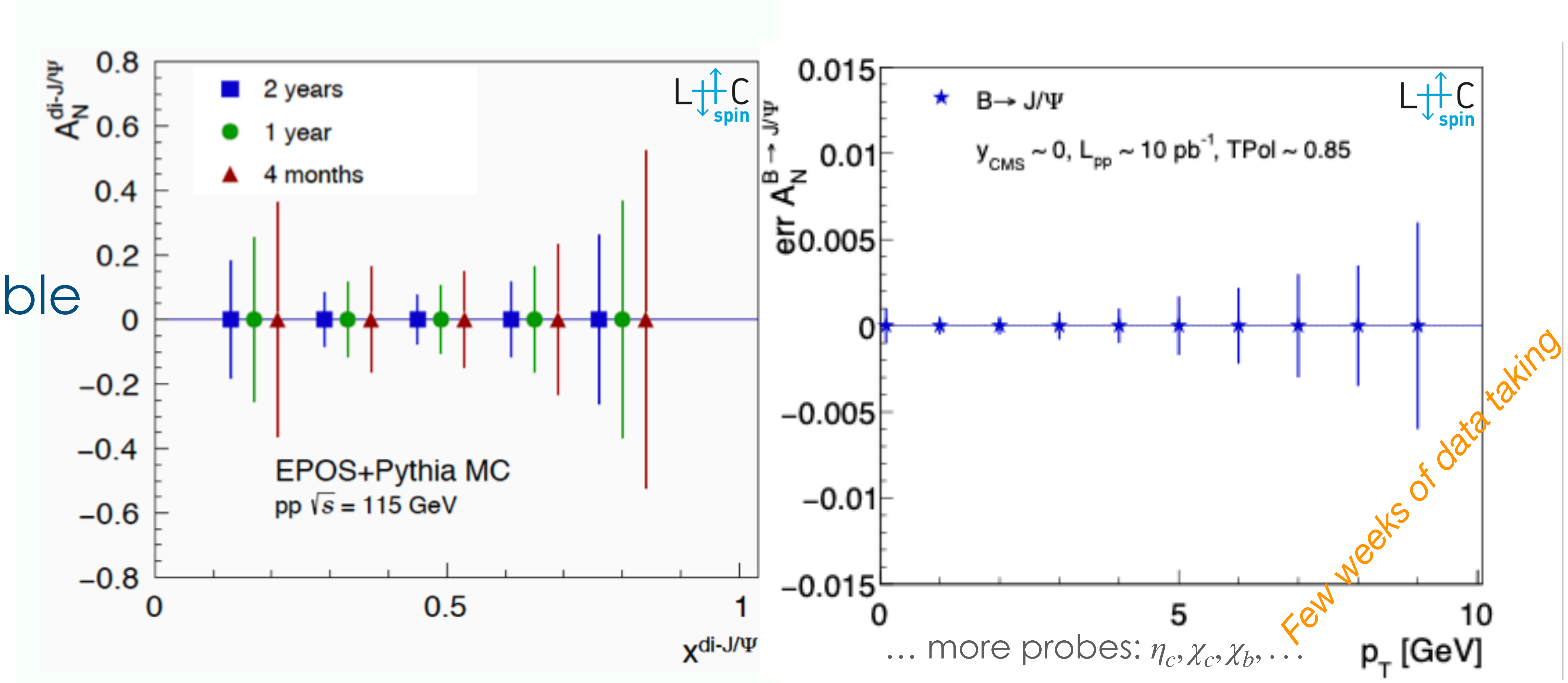


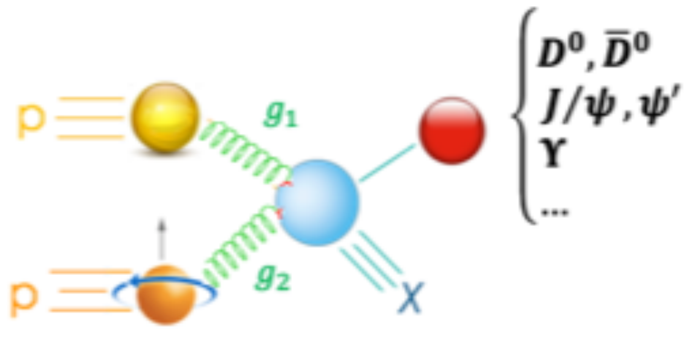
Gluon-induced asymmetries (unconstrained $h_1^{\perp g}\ +\ f_1^g$) accessible by, e.g., $di-J/\Psi$ or Υ production



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

factorisation can hold at large q_T

Probing the Sivers function



gluon pol. (columns) / nucleon pol. (rows)

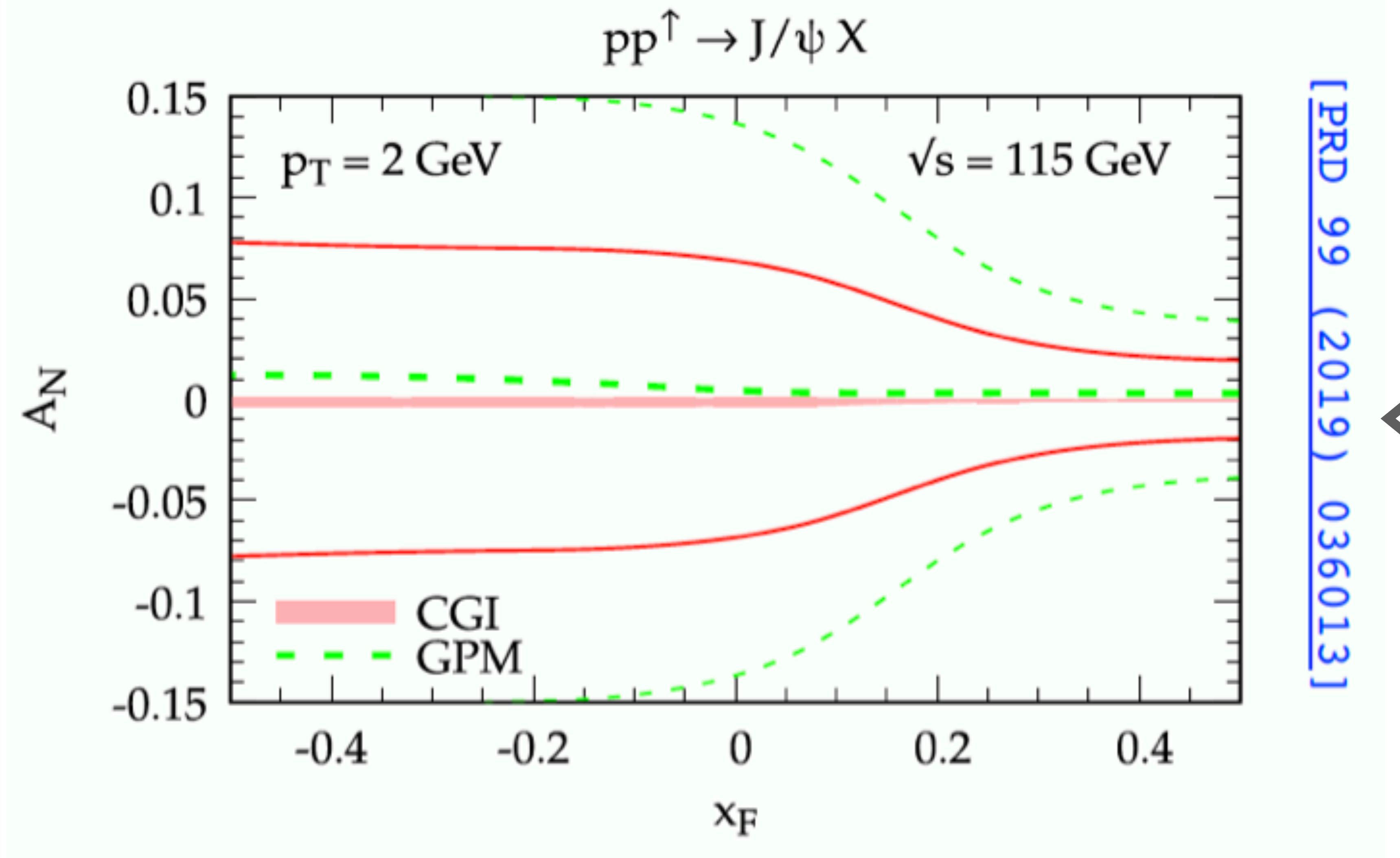
	U	Circularly	Linearly
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_1^g, $h_{1T}^{\perp g}$

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

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

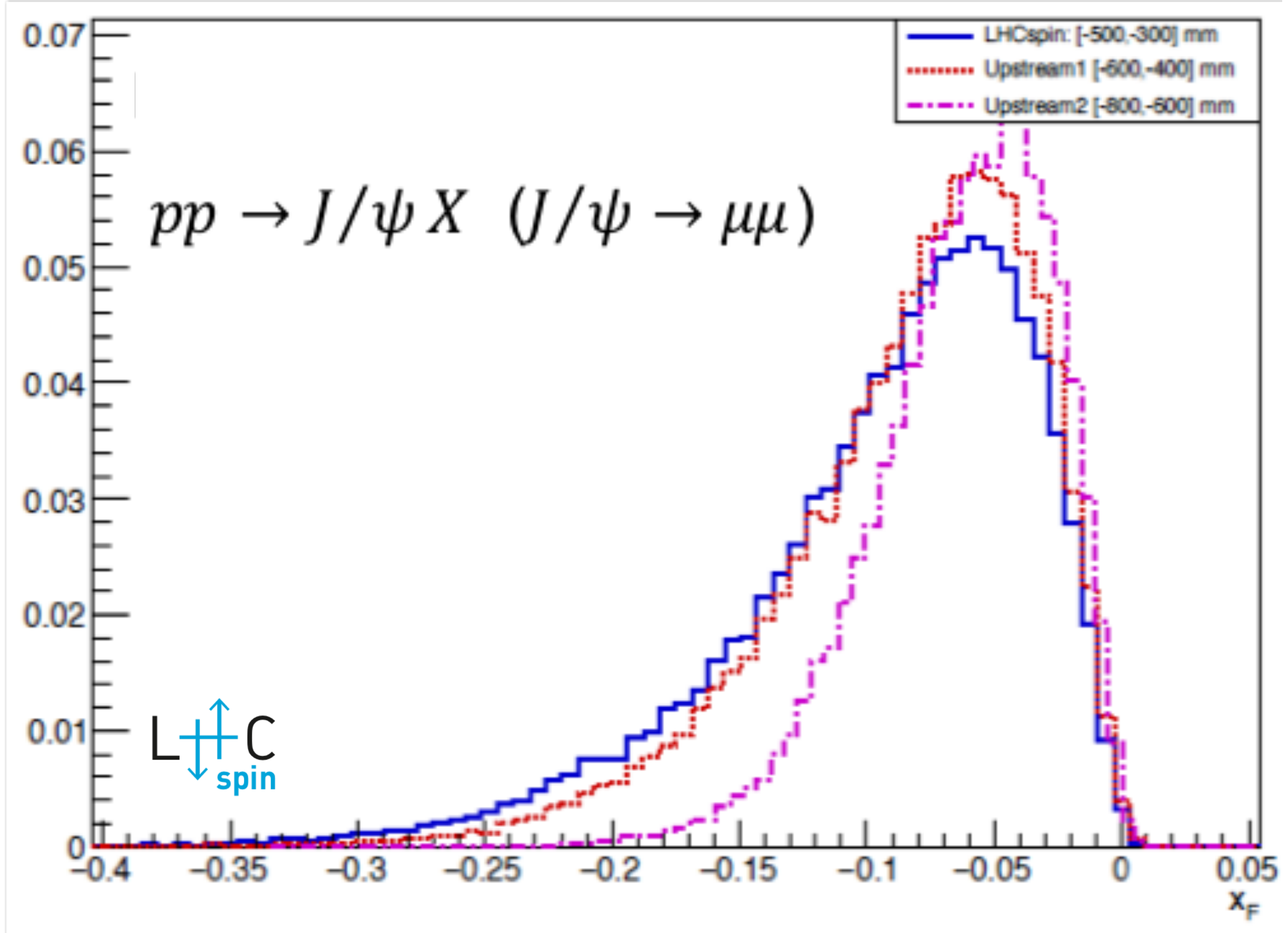
Sensitive to color exchange among IS and FS, and gluon OAM

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



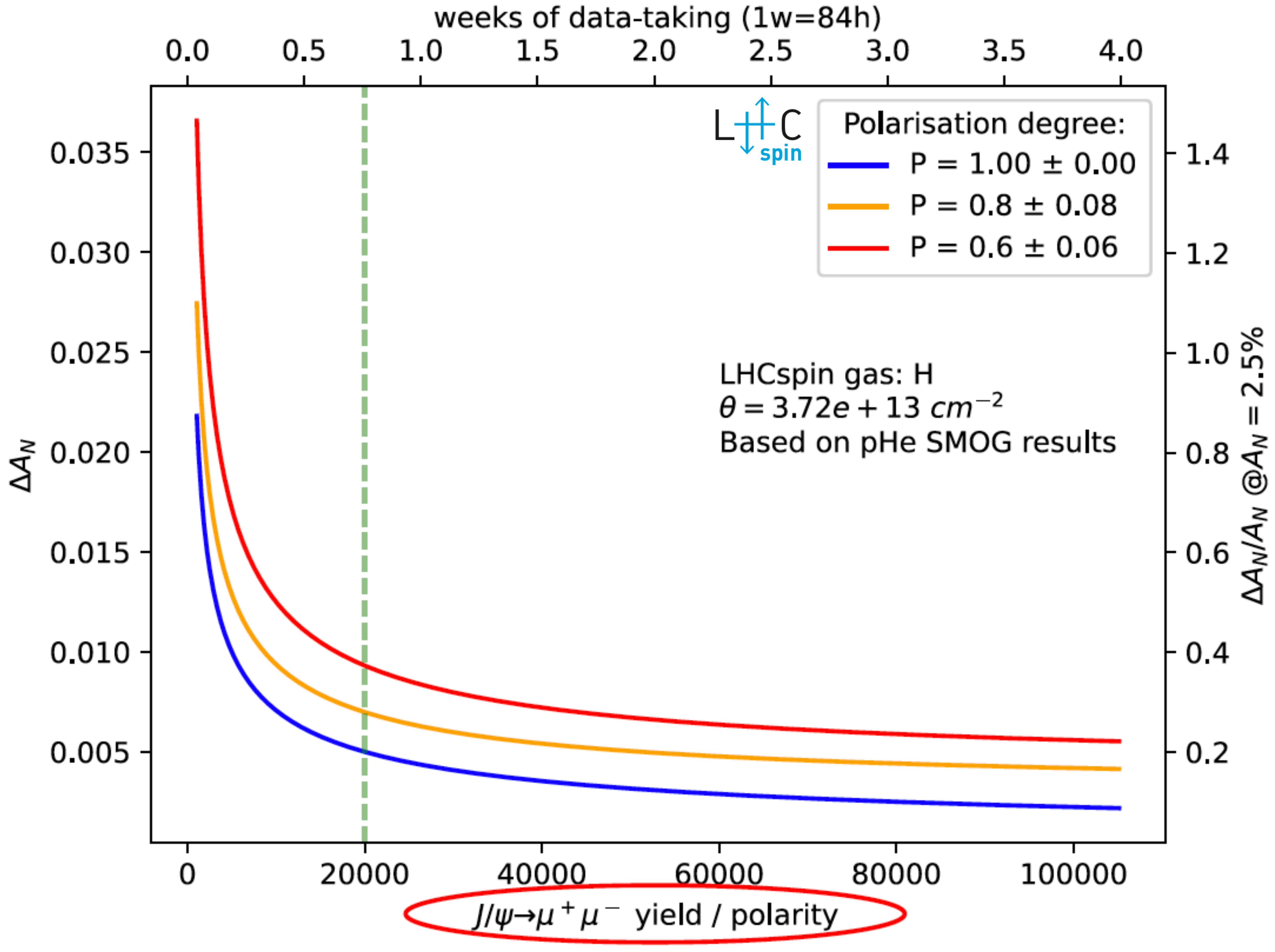
Predictions for J/Ψ production based on GPM & CGI-GPM

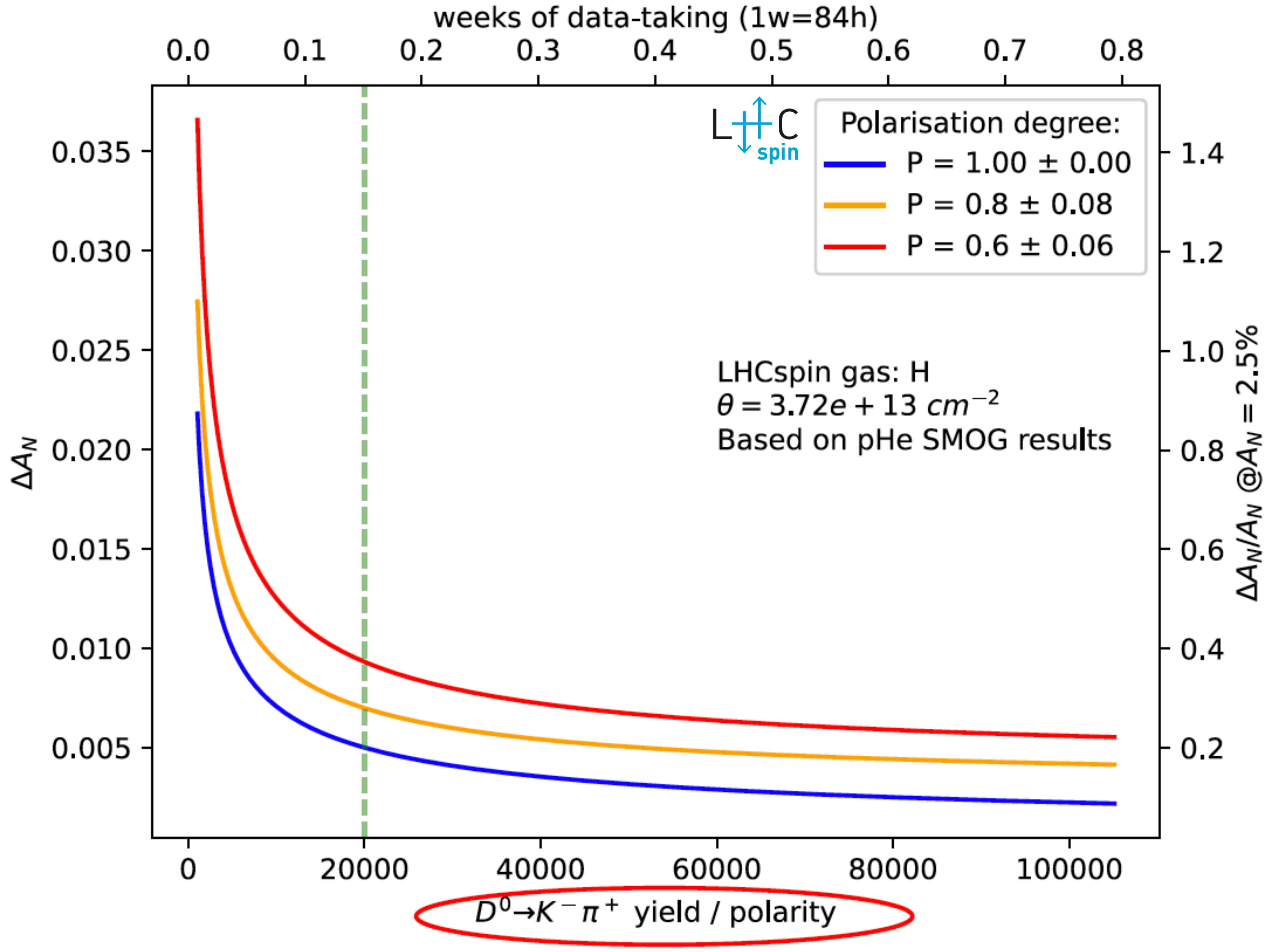
Expected amplitudes could reach 5-10% in the $x_F < 0$ region



LHCspin event rates

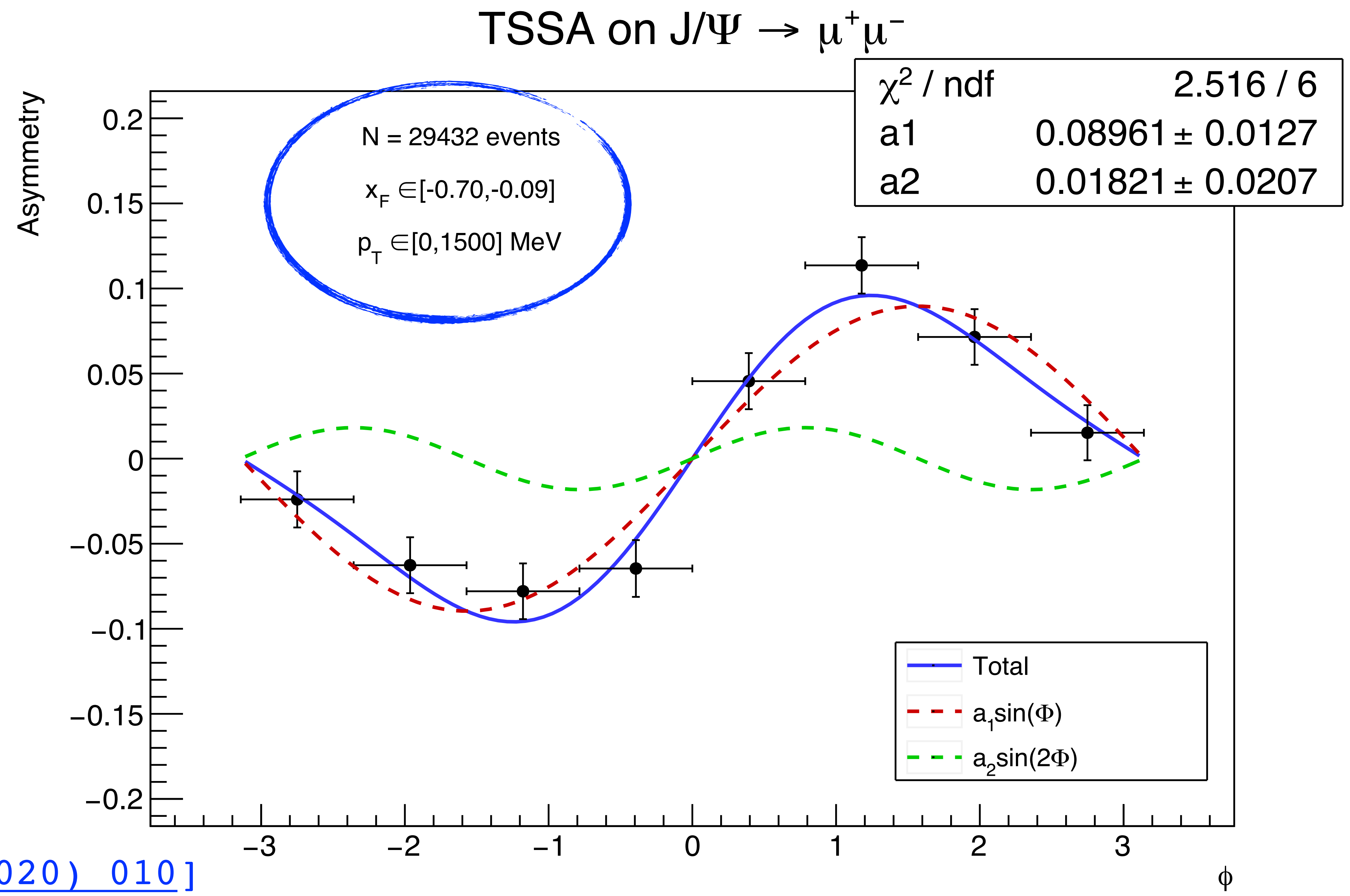
Precise spin asymmetry on $J/\Psi \to \mu^+\mu^-$ and $D^0 \to K^-\pi^+$ for $pH^\uparrow$ collisions in just few weeks with Run3 luminosity!
Statistics further enhanced by a factor 3-5 in LHCb upgrade II

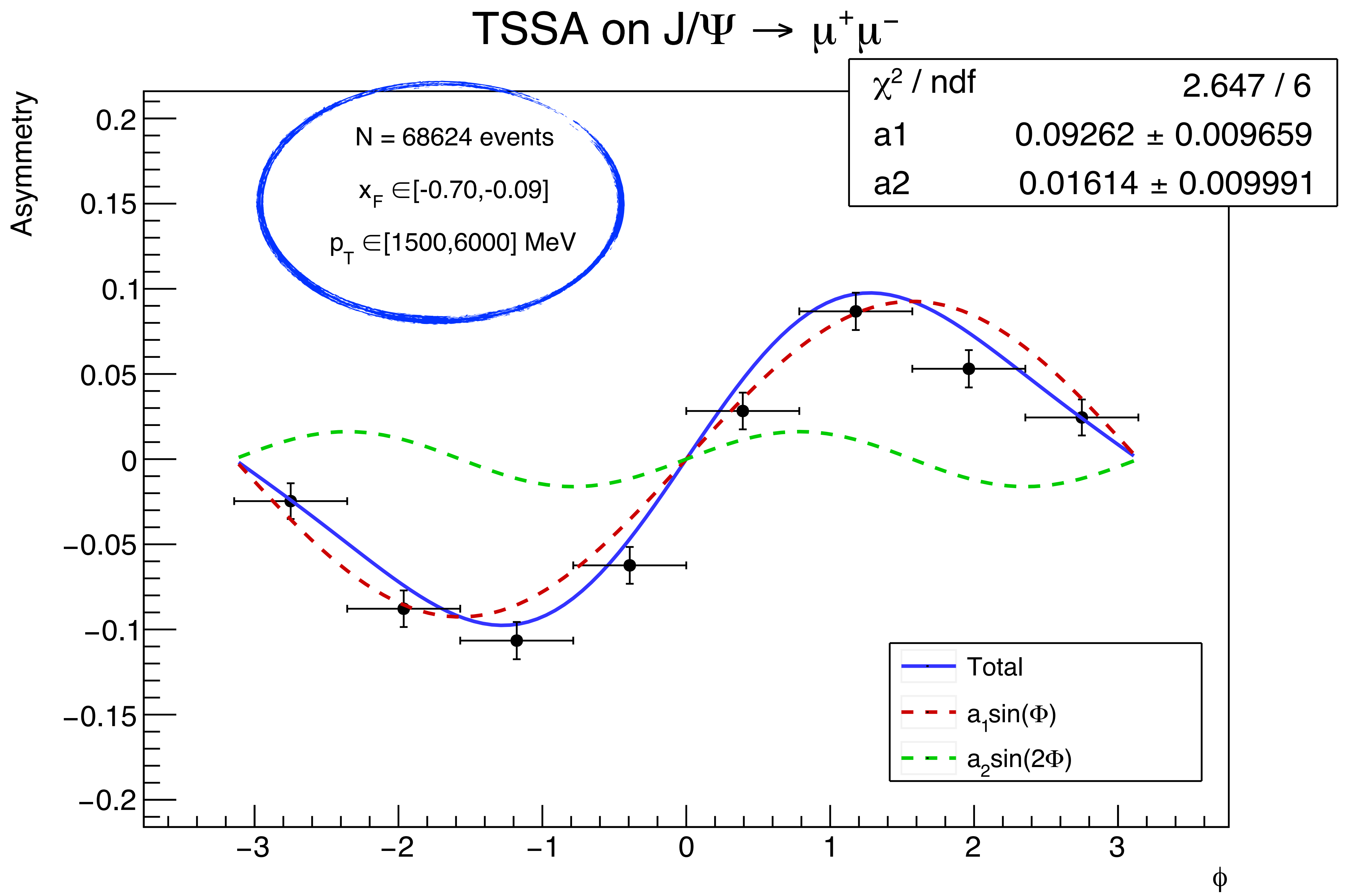




reconstructed particles

A TSSA analysis at LHCspin with $J/\Psi \to \mu^+\mu^-$ events (toy model)

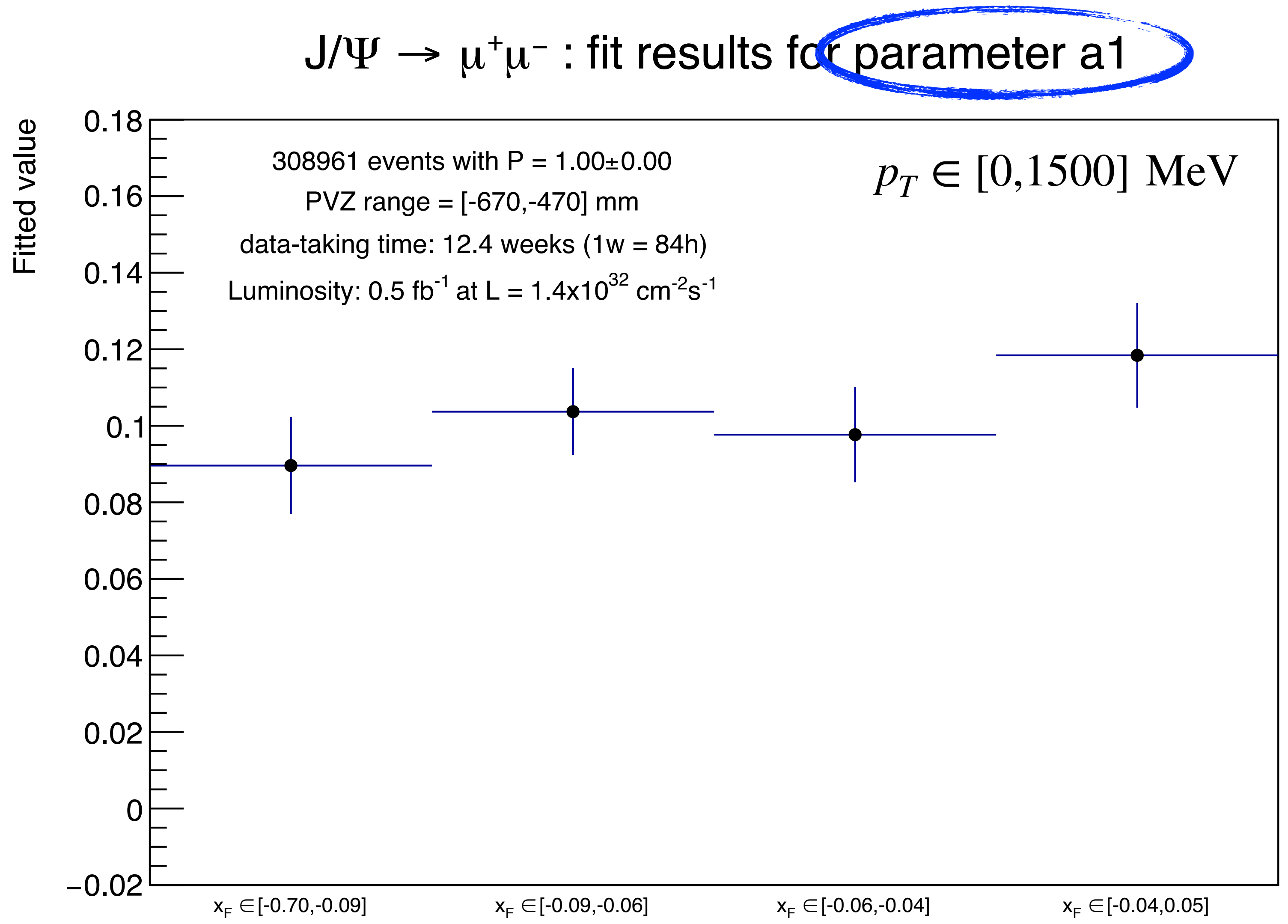




[JHEP 12 (2020) 010]

$$\rho = \frac{1}{2}\left[1 + \left(a_1 + a_2\frac{x-\overline{x}}{x_{max}} + a_3\frac{p_T - \overline{p_T}}{p_{T\ max}}\right)\sin\phi + \left(b_1 + b_2\frac{x-\overline{x}}{x_{max}} + b_3\frac{p_T-\overline{p_T}}{p_{T\ max}}\right)\sin 2\phi\right]$$

- Full LHCb simulations of $J/\Psi \to \mu^+\mu^-$ in pH collisions → emulate the target polarisation by assigning a ↑↓ tag according to a given model. In this example: 10% asymmetry on $\sin\phi$, 2% on $\sin 2\phi$ + mild x_F, p_T dependence
- Fit the polarised data with the sum of two Fourier amplitudes $(a_1,\ a_2)$ in $4\ x_F \times 2\ p_T \times 8\ \phi$ bins
- Within this statistics, corresponding to ~ 3 months of data-taking, $A_N \sim 0.1 \pm 0.01$



Knowledge of the polarisation degree

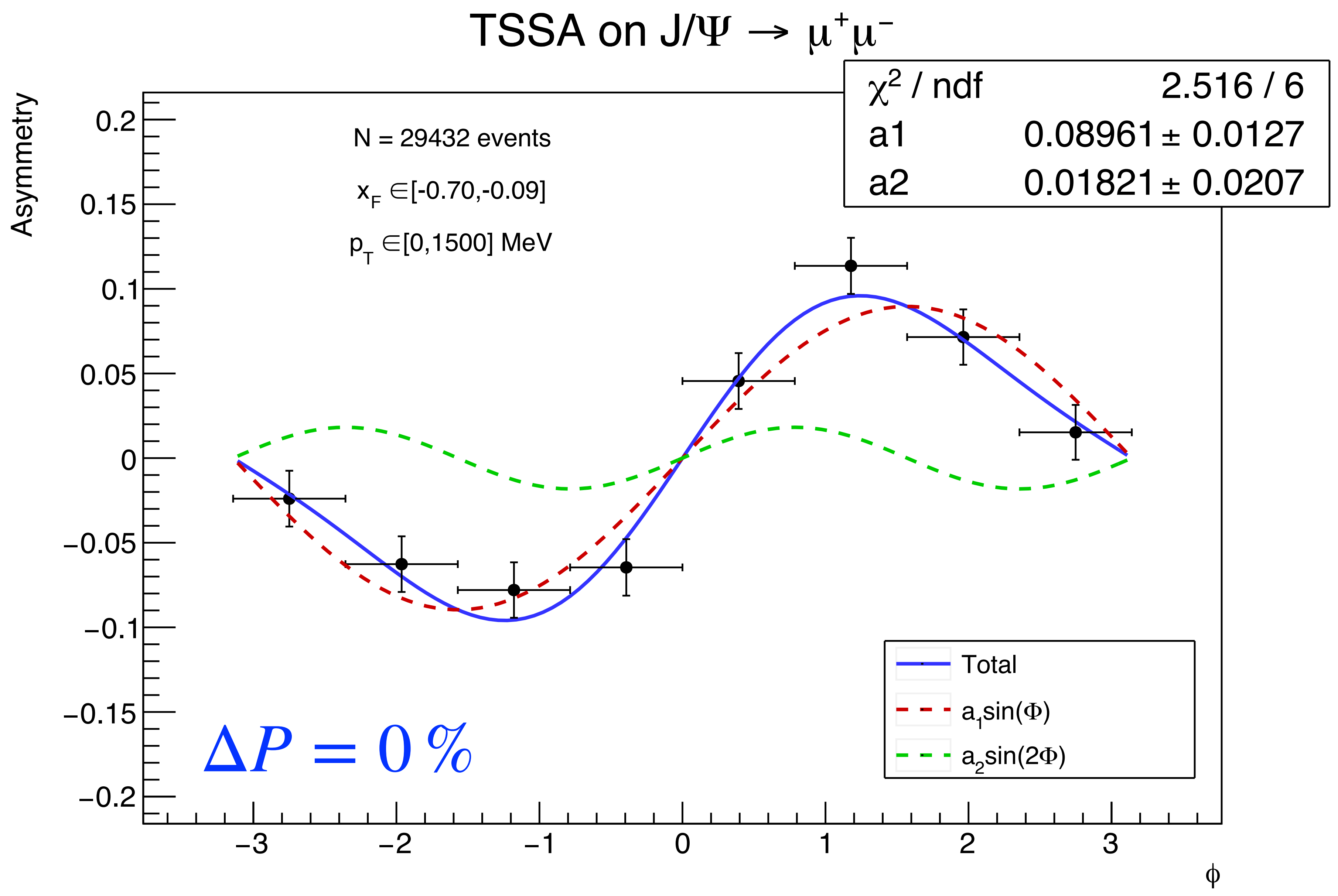
- To estimate the systematic error due to the measurement of the polarisation degree, the analysis is repeated with different ΔP
- Very relevant for the R&D (e.g. cell vs jet target). With the shown analysis* :
- 5% error (realistic value) → negligible effect
- 20% error → 30-40% of the stat. error
- 50% error → syst. dominated

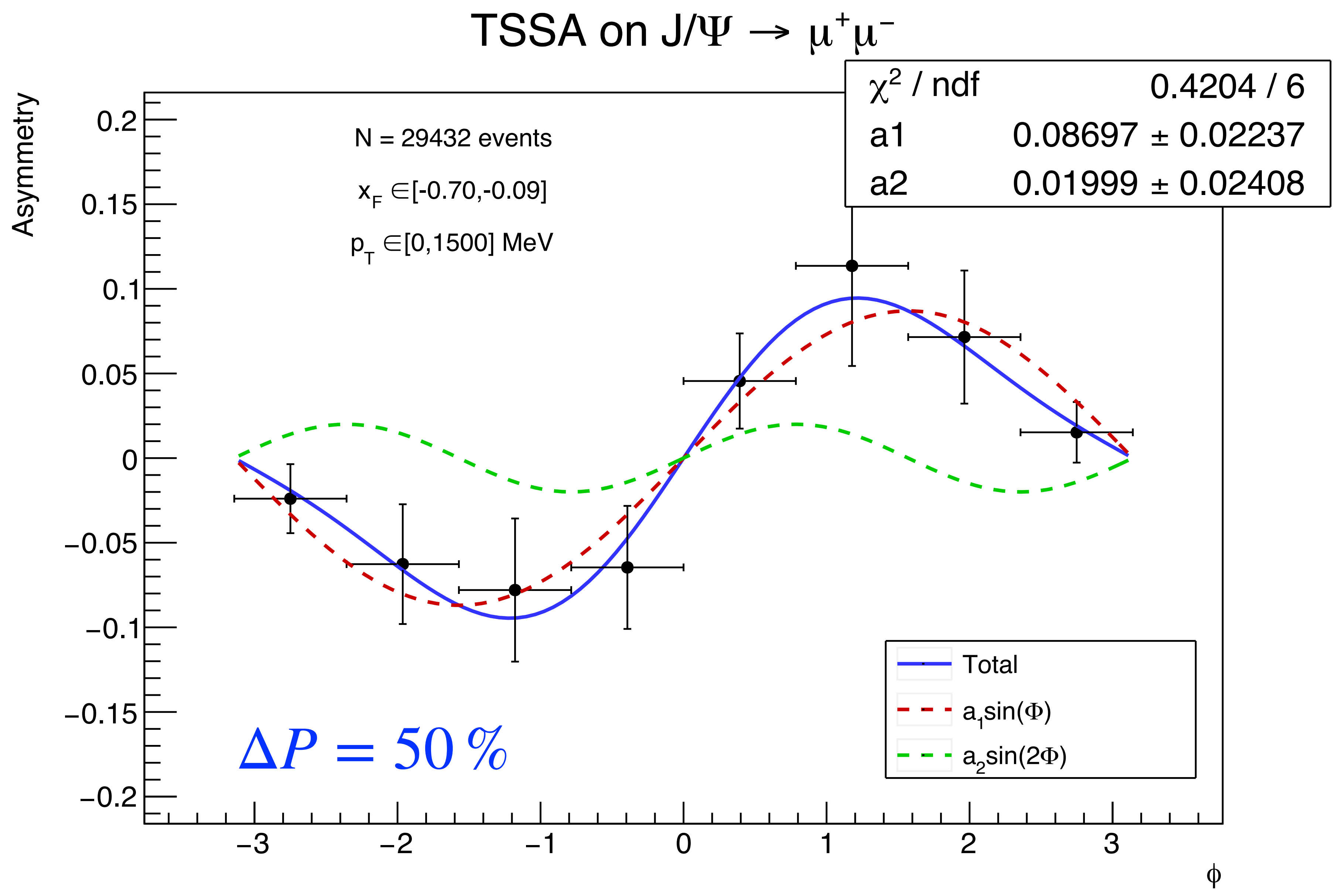
$\Delta P = 5\,\%$

p_T (MeV)	x_F	a_1
[0,1500]	[-0.70,-0.09]	0.089 ± 0.013
[0,1500]	[-0.09,-0.06]	0.104 ± 0.012
[0,1500]	[-0.06,-0.04]	0.098 ± 0.013
[0,1500]	[-0.04,0.05]	0.117 ± 0.014
[1500,6000]	[-0.70,-0.09]	0.092 ± 0.010
[1500,6000]	[-0.09,-0.06]	0.108 ± 0.011
[1500,6000]	[-0.06,-0.04]	0.105 ± 0.012
[1500,6000]	[-0.04,0.05]	0.105 ± 0.012

$\Delta P = 20\,\%$

p_T (MeV)	x_F	a_1
[0,1500]	[-0.70,-0.09]	0.087 ± 0.014
[0,1500]	[-0.09,-0.06]	0.103 ± 0.016
[0,1500]	[-0.06,-0.04]	0.097 ± 0.016
[0,1500]	[-0.04,0.05]	0.114 ± 0.017
[1500,6000]	[-0.70,-0.09]	0.090 ± 0.013
[1500,6000]	[-0.09,-0.06]	0.108 ± 0.015
[1500,6000]	[-0.06,-0.04]	0.104 ± 0.015
[1500,6000]	[-0.04,0.05]	0.102 ± 0.015





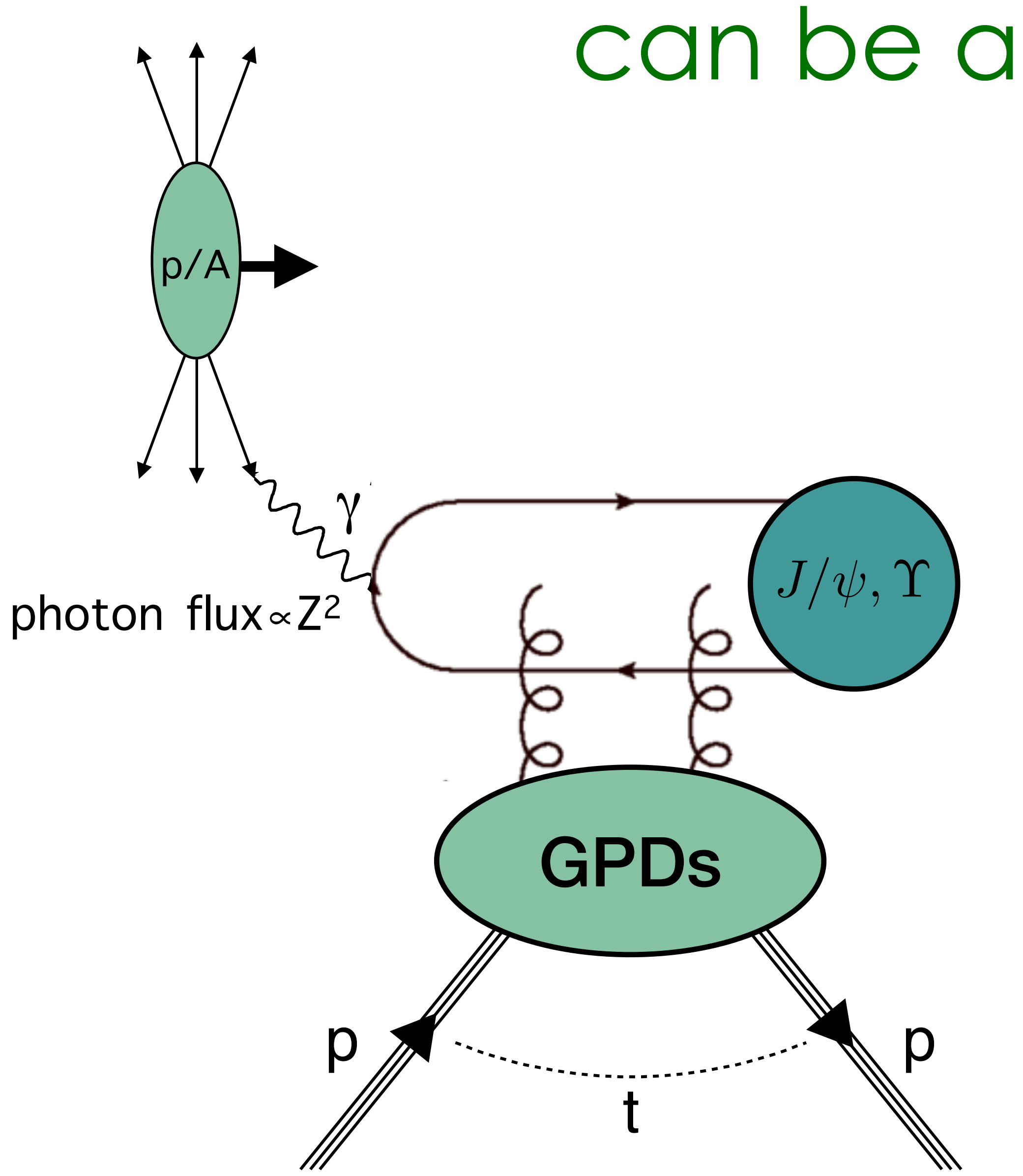
* i.e. ~ 3 months of data-taking with this example model, channel and kinematic binning

UPC and gGPDs

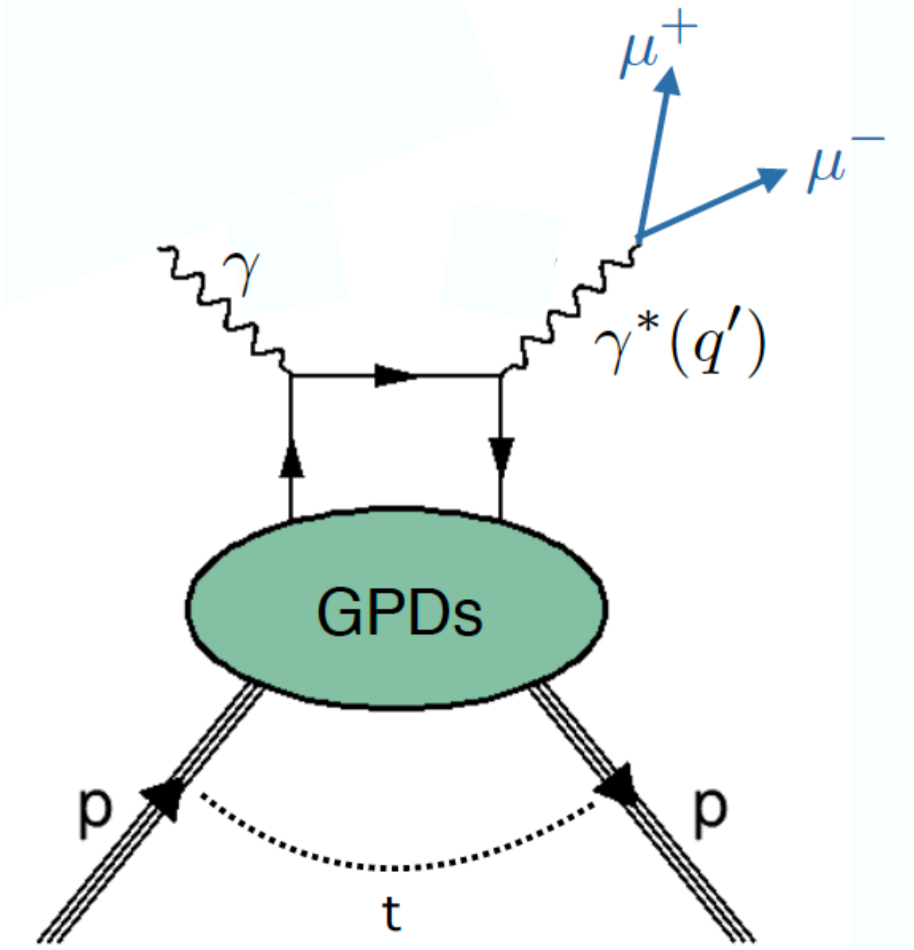
Accessible already with SMOG2 for the unpol part

can be accessed at LHC in Ultra-Peripheral collisions (UPC)

Recall:
-barely explored high-x_B region
-moderate Q^2



Exclusive meson production
hard scale = quark mass



Timelike Compton scattering (TCS)
(access via angular modulation)
hard scale = large q^2 (in practice few GeV^2)

- Impact parameter larger than sum of radii
- Process dominated by EM interactions
- Gluon distributions probed by pomeron exchange
- Exclusive quarkonia prod. sensitive to gluon GPDs

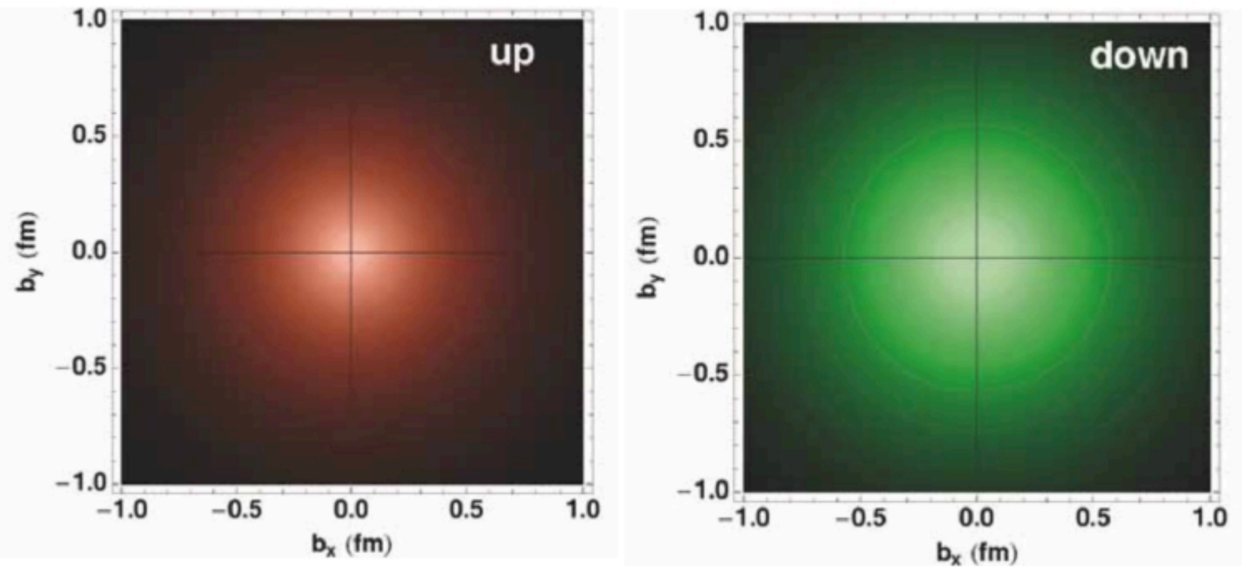
[PRD 85 (2012), 051502]

LHCspin could allow to access the GPD E^g (a key ingredient of the Ji sum rule)

$$J^g = \frac{1}{2}\int_0^1 dx \Big(H^g(x,\xi,0) + E^g(x,\xi,0) \Big)$$

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

3D maps of parton densities in coordinate space



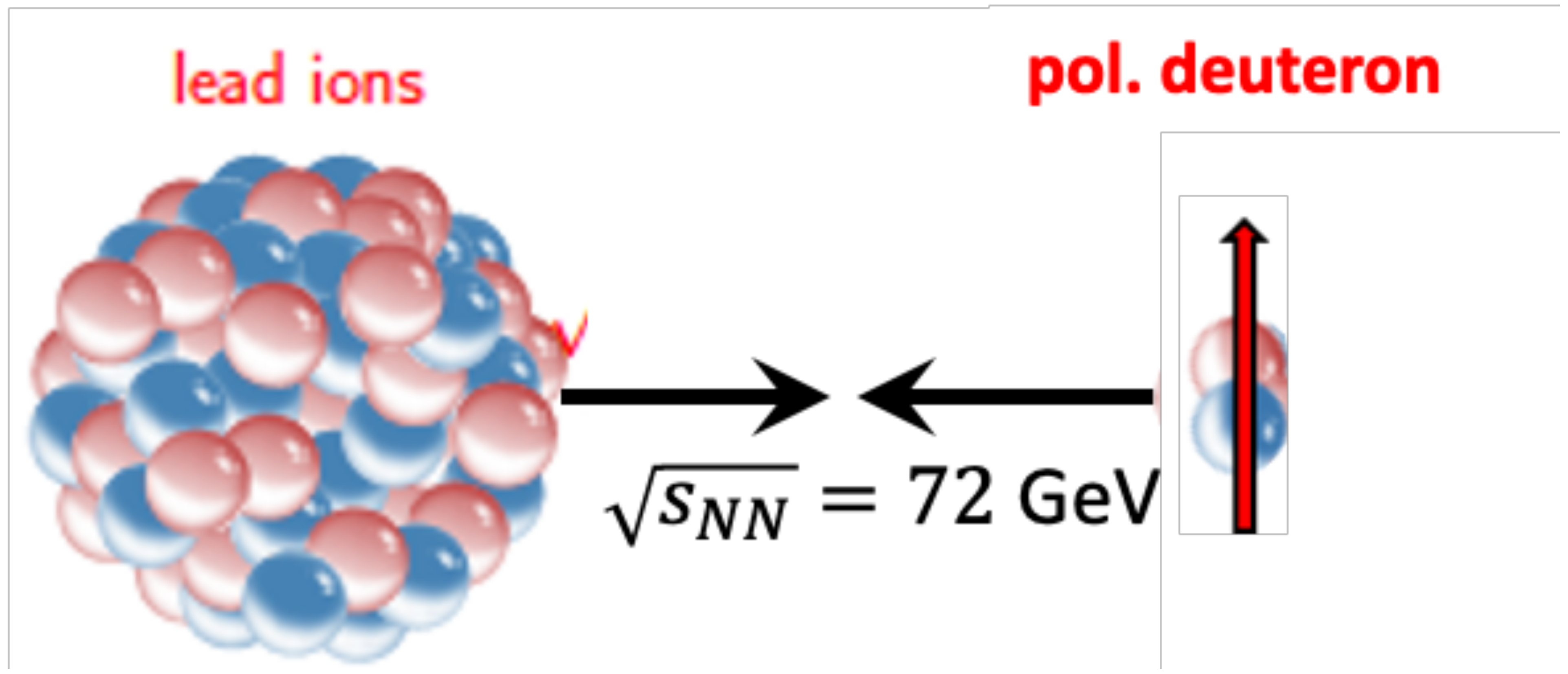
[NS 28 (2012), 1]

J/ψ, total uncertainty on cross section, assuming 4% uncertainty on luminosity

pp	pD	pAr	pKr	pXe
10 %	–	5 %	5 %	5 %

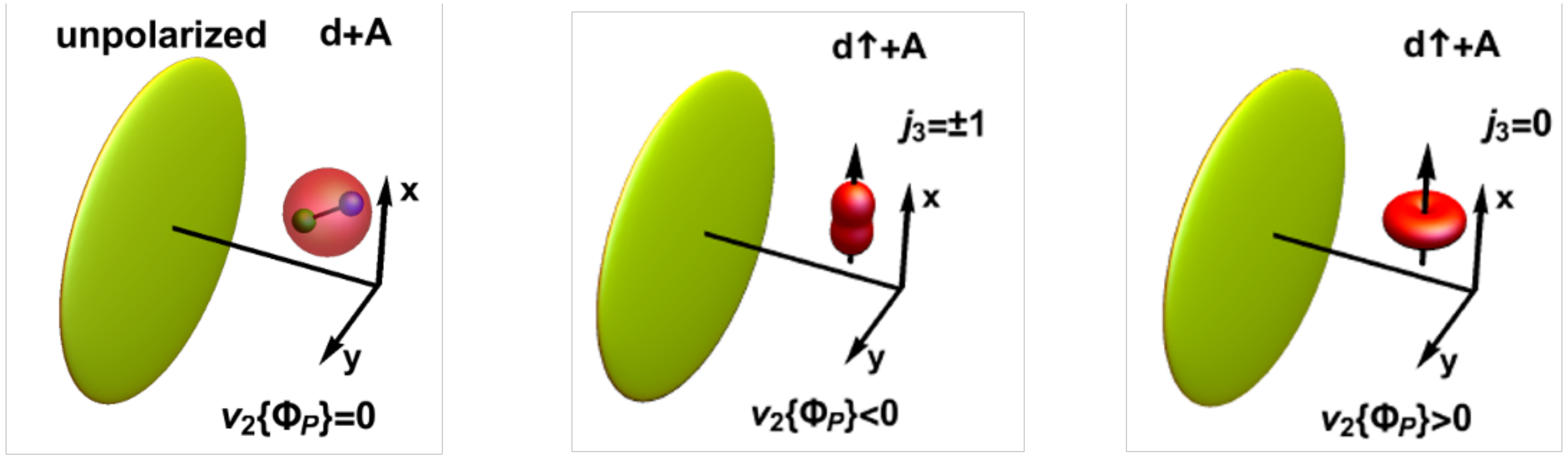
Pbp	PbAr
–	5 %

Spin physics in heavy-ion collisions



- probe collective phenomena in heavy-light systems through **ultra-relativistic collisions of heavy nuclei with trasv. pol. deuterons**

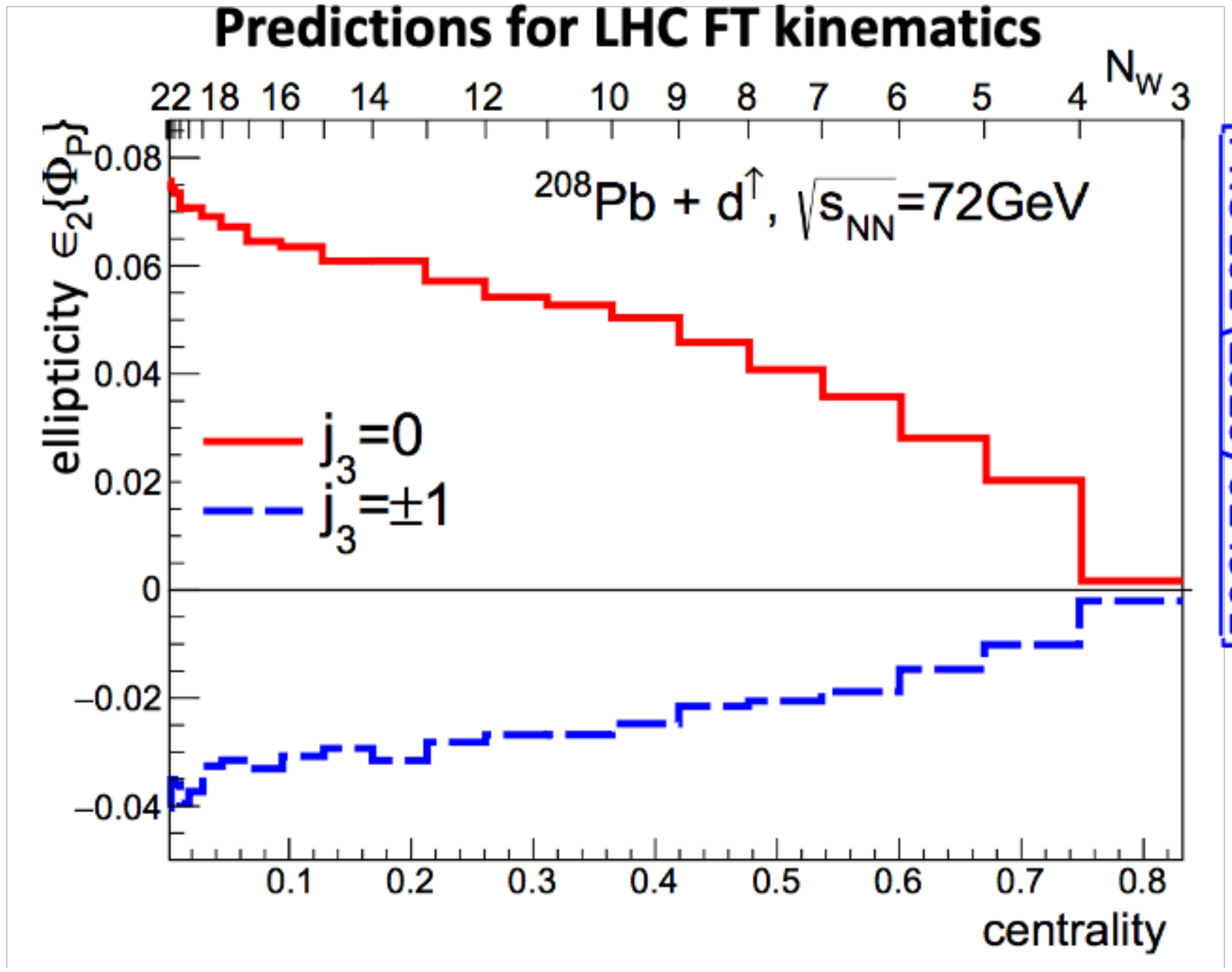
- polarized light target nuclei offer a unique opportunity to control the orientation of the formed fireball by measuring the **elliptic flow** relative to the polarization axis (**ellipticity**).



Unpol. deuterons: the **fireball is azimuthally symmetric** and $v_2 \approx 0.$

$j_3 = \pm 1$ → **prolate fireball** stretched along the pol. axis, corresponds to $v_2 < 0$

$j_3 = 0$ → **oblate fireball** corresponds to $v_2 > 0$



[PRC 101 (2020) 024901] *Wojciech Broniowski, Piotr Bozek*

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

linearly polarized gluon TMD

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

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

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

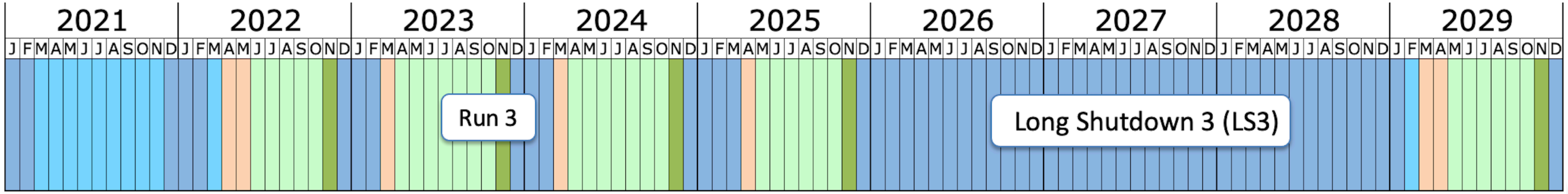
Recognised relevance

The polarised physics is very alive and will benefit of complementary probes, from LHC to EIC

Fixed target physics at LHC is an exiting reality

SMOG2 already operative and taking unpolarised data

LHCspin is an innovative and unique project conceived to bring polarized physics at the LHC. It is extremely ambitious in terms of both physics reach and technical complexity. It could be installed in a realistic time schedule and costs



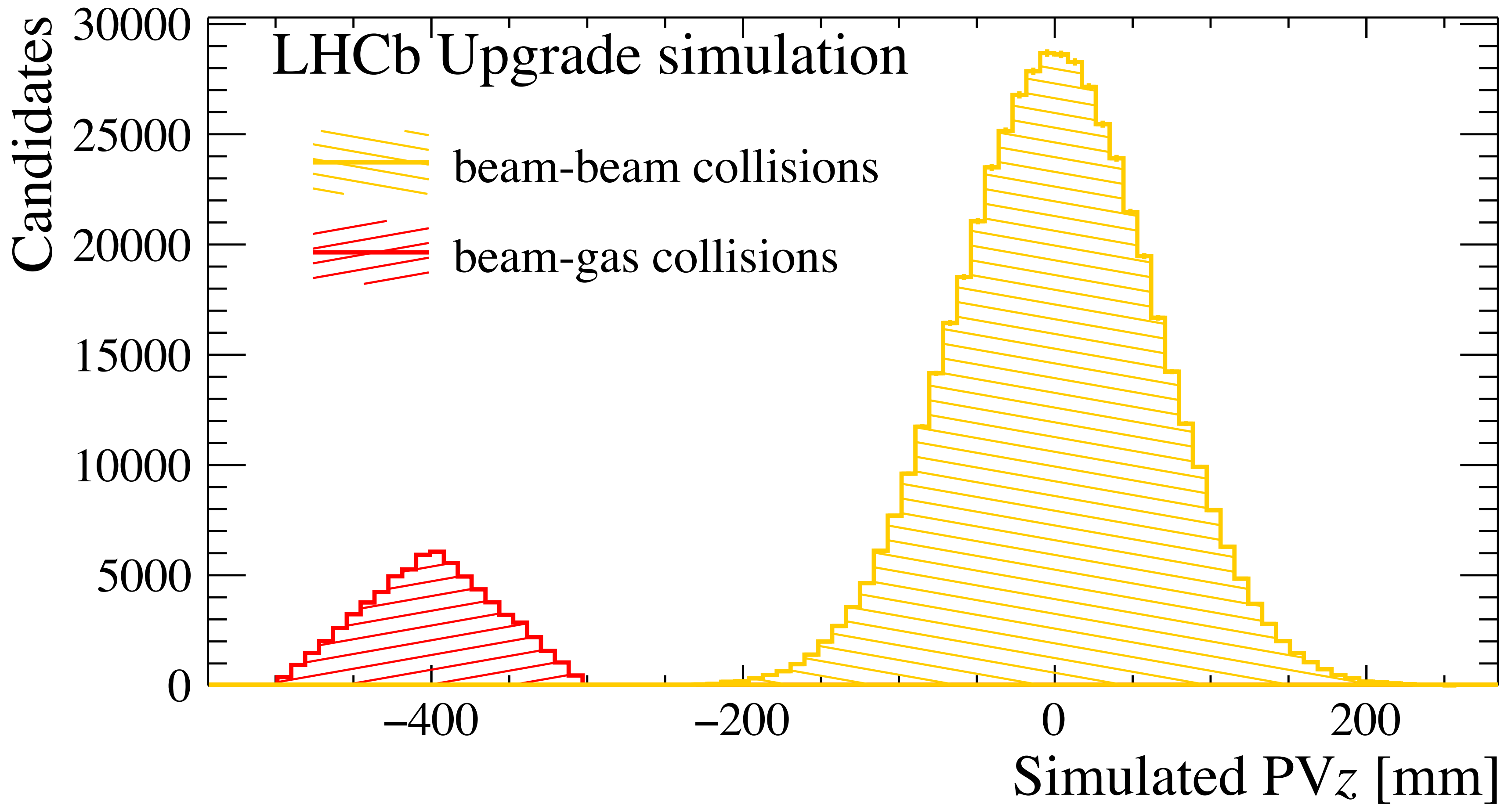
SMOG2

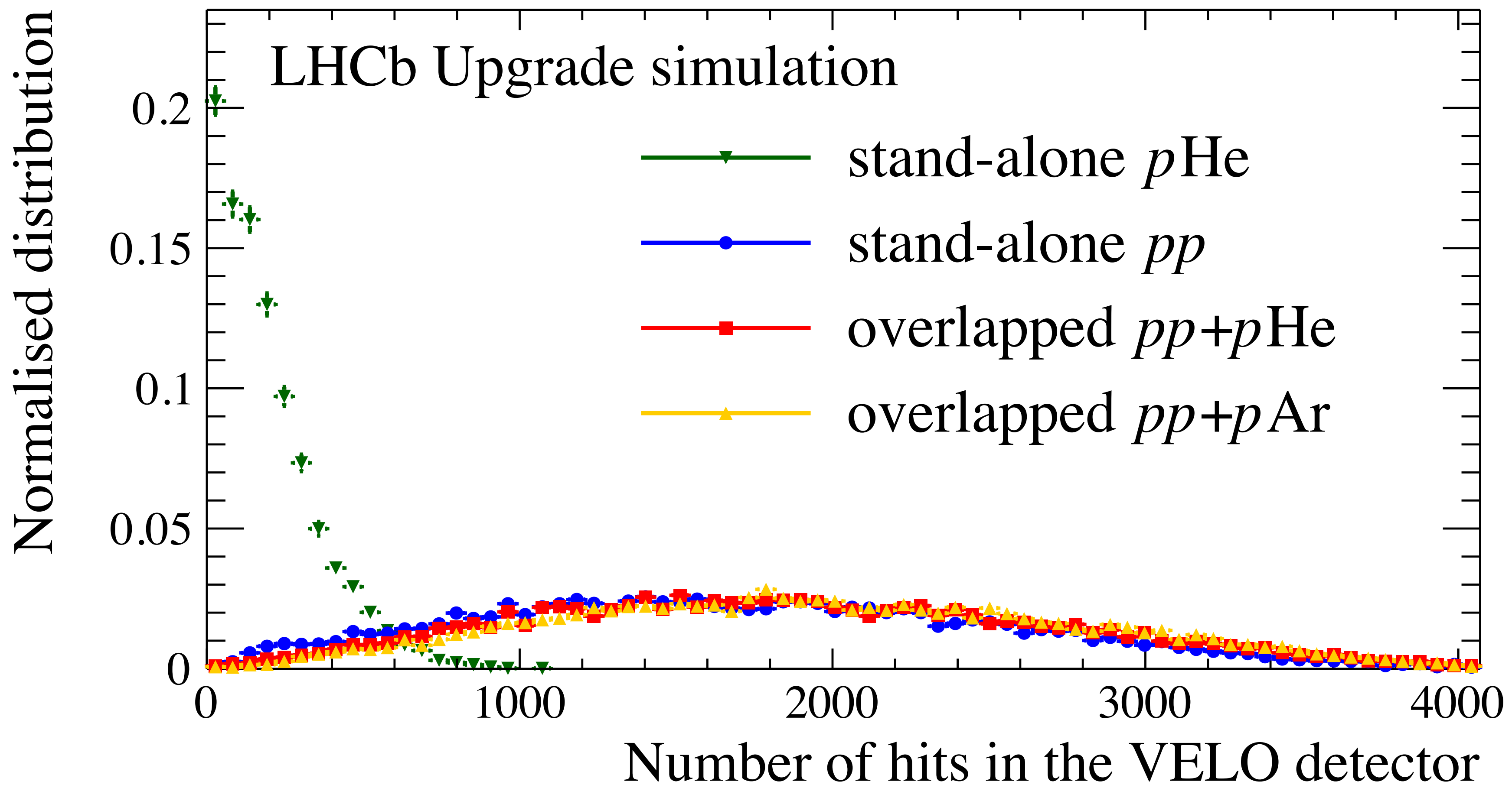
LHCspin

SMOG2/LHCspin performances

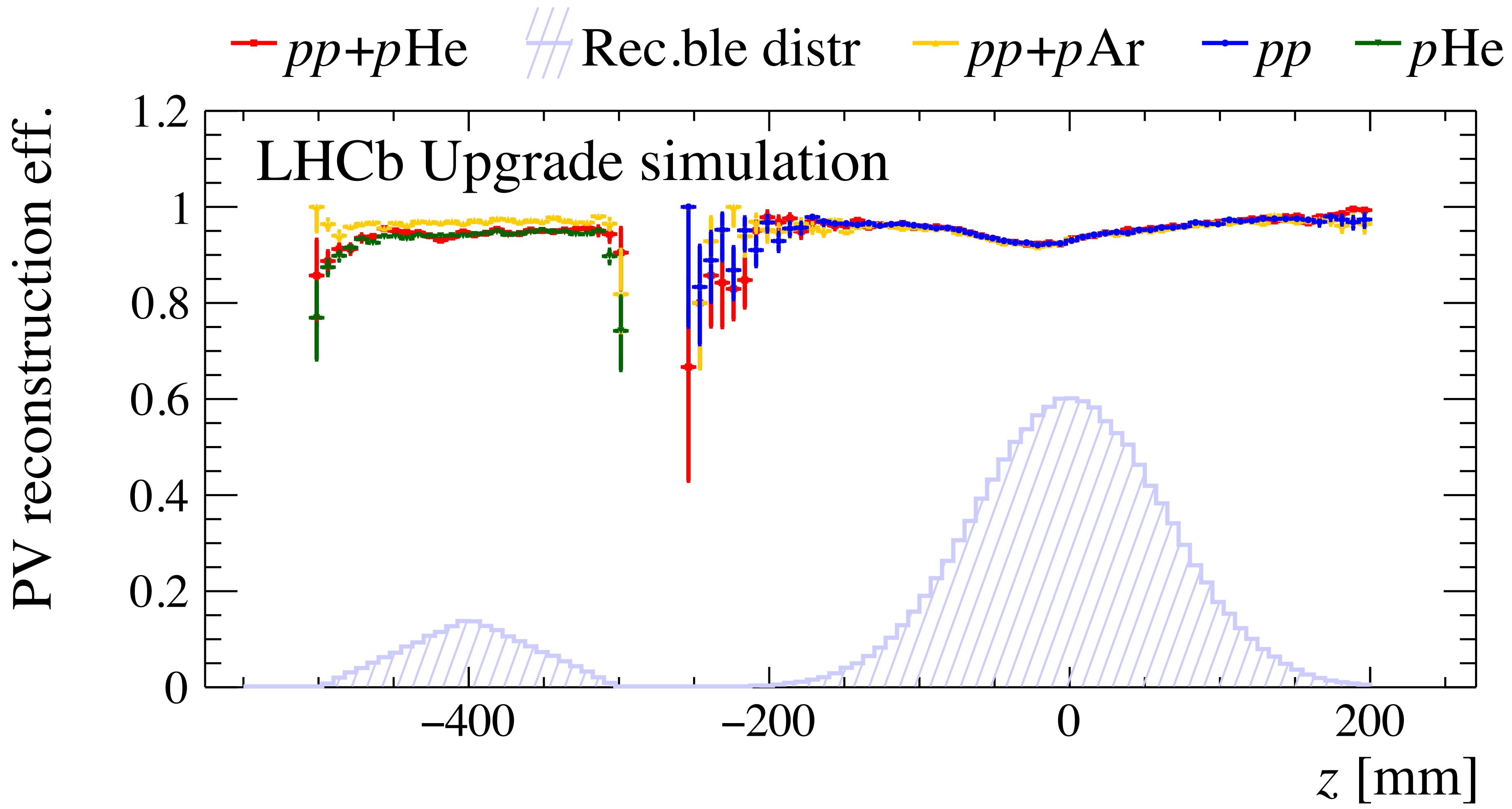
[LHCB-FIGURE-2022-002]

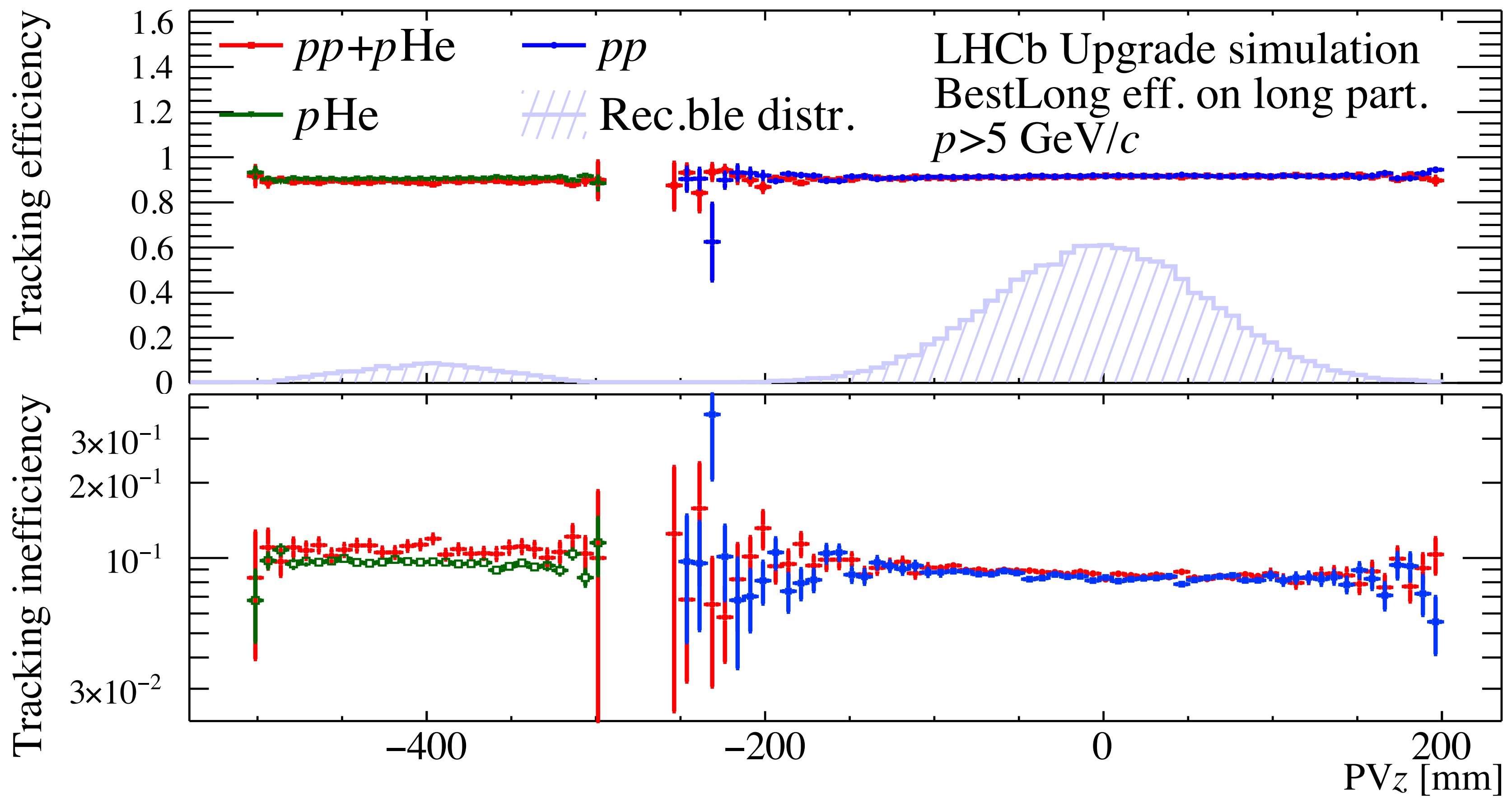
- beam-beam and beam-gas interaction regions are well detached
- Negligible increase of multiplicity: $1 - 3\,\%$ throughput decrease when adding beam-gas to the LHCb event reconstruction sequence





- Full reconstruction efficiency (PV & tracks) retained in the beam-gas region





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