The LHCspin project

Pasquale Di Nezza

In collaboration with: V.Carassiti, G.Ciullo, R.Engels, P.Lenisa, L.Pappalardo, M.Santimaria, E.Steffens, G.Tagliente

INFN LNF Istituto Nazionale di Fisica Nucleare

LHCb

STRONG 2020

Mainz, 26/09/22

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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SMOG2

unpolarised gas target

LHCspin

polarised (+unpolarised) gas target

More details in the following talk by E.Steffens

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

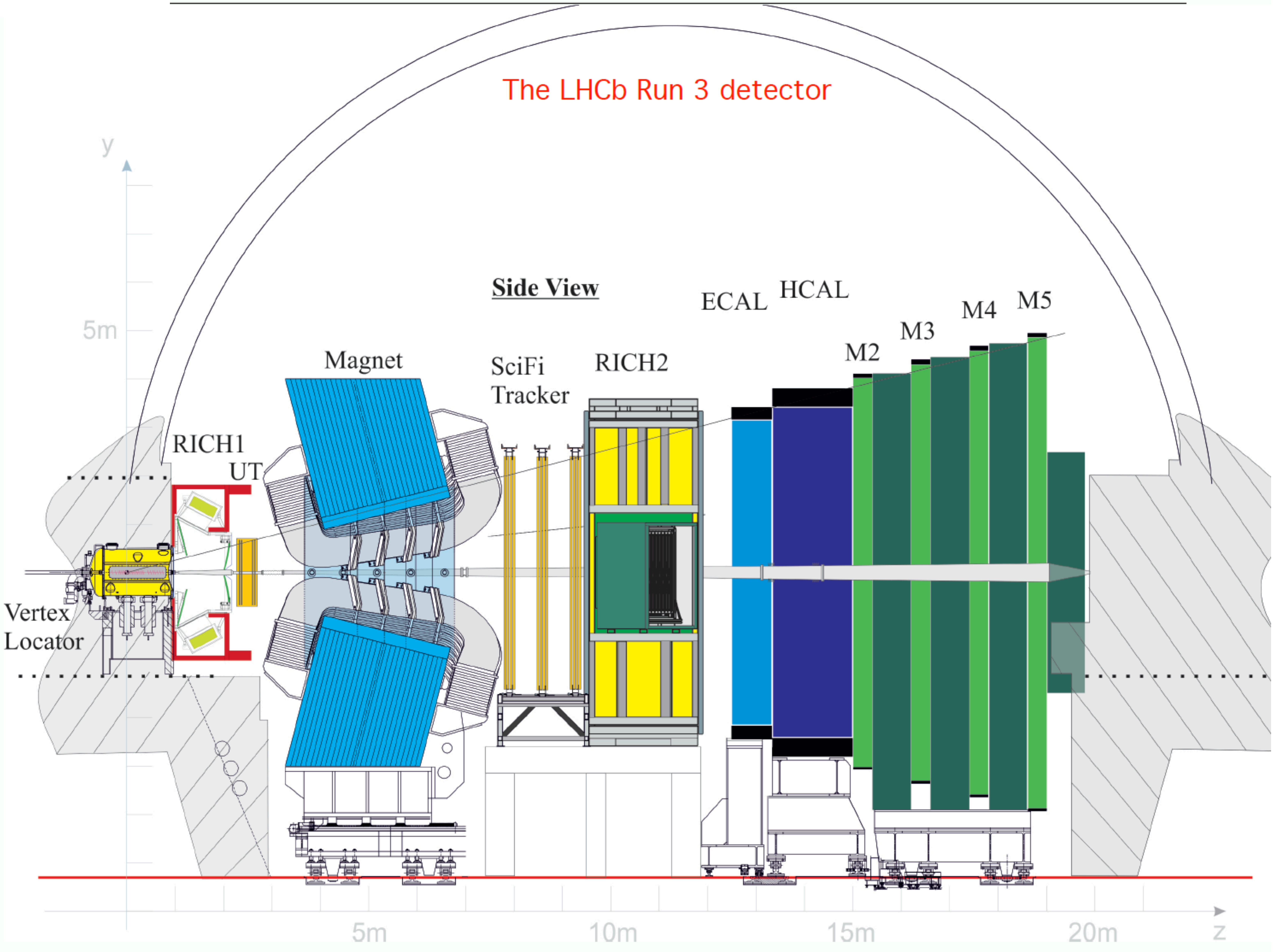
$\epsilon_\mu \sim 98\,\%$ with $\epsilon_{\pi\to\mu} \lesssim 1\,\%$

- Low momentum muon trigger:

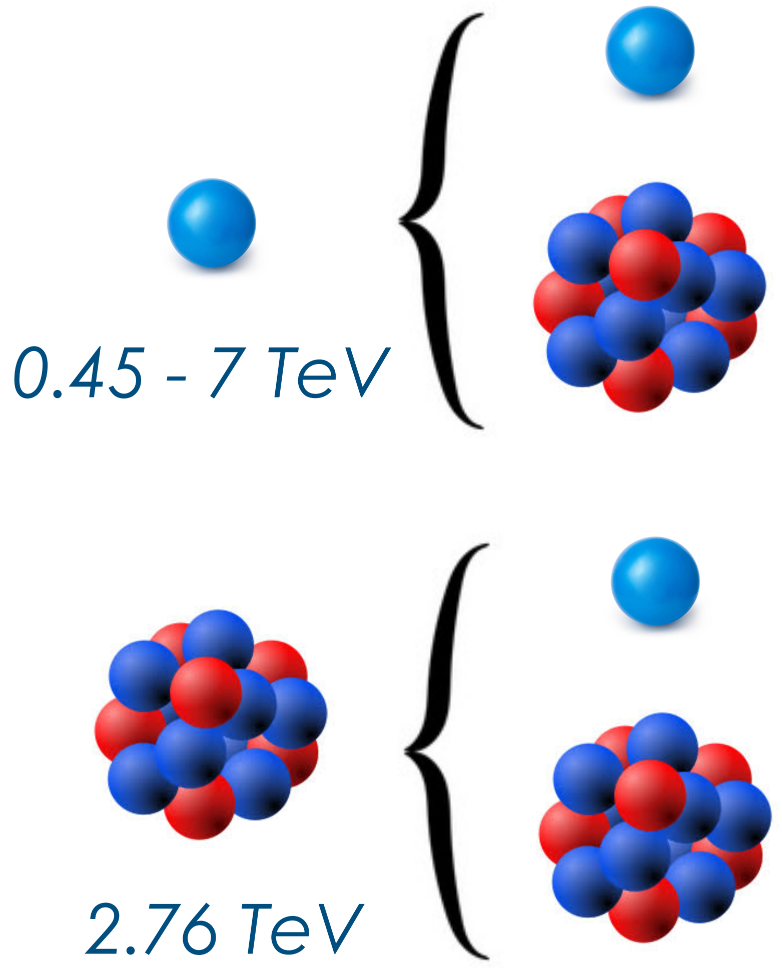
$p_{T_\mu} > 1.75$ GeV (2018)

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

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

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

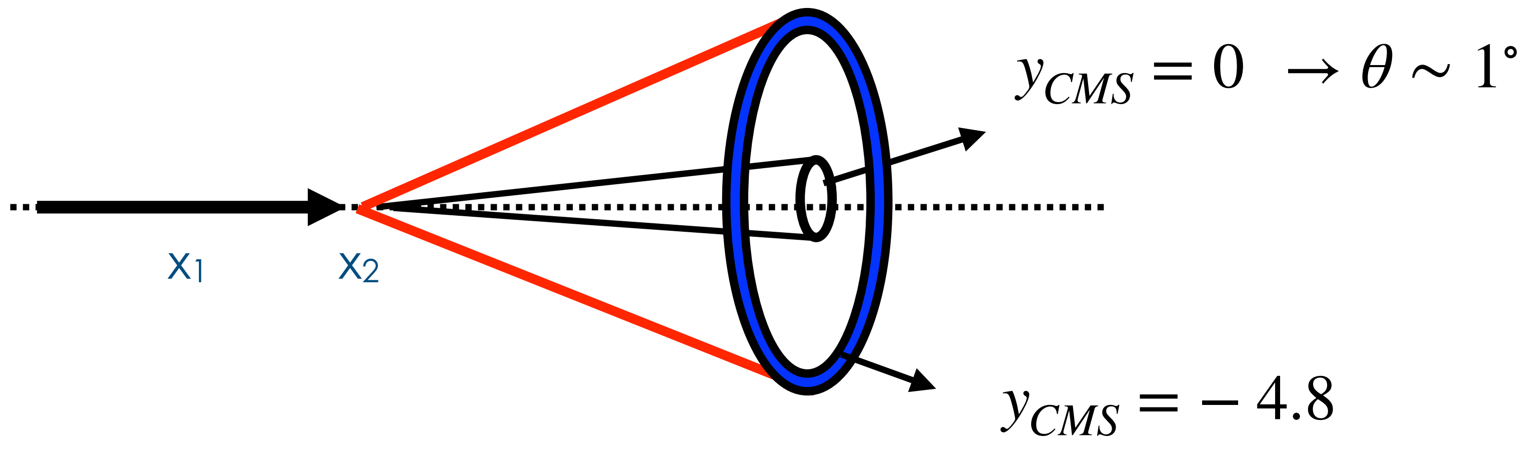
AA collisions: 2.76 TeV beam on fix target

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

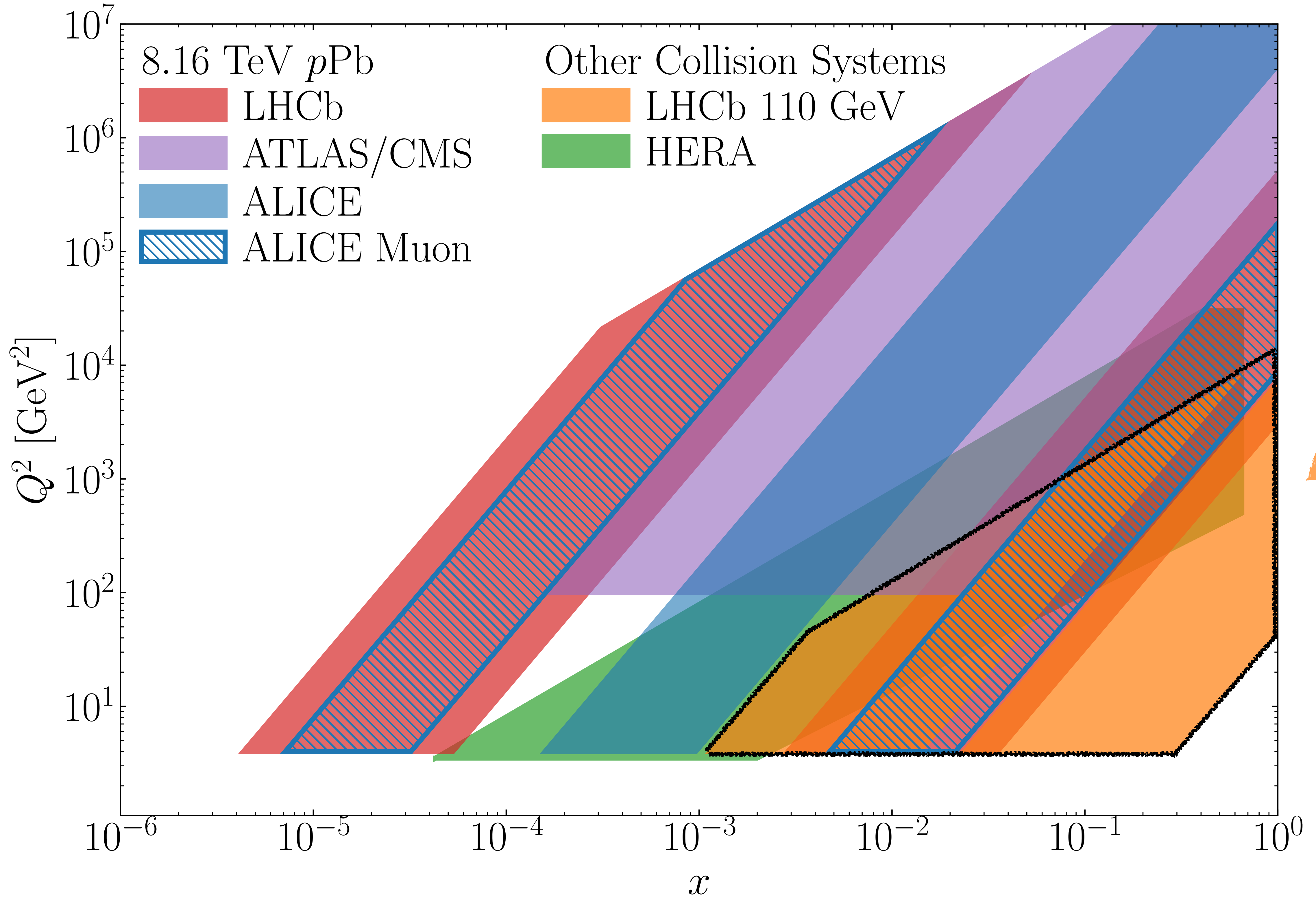
$$y_{CMS} = 0 \ \rightarrow \ y_{lab} = 4.3$$

1: beam; 2: target

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



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

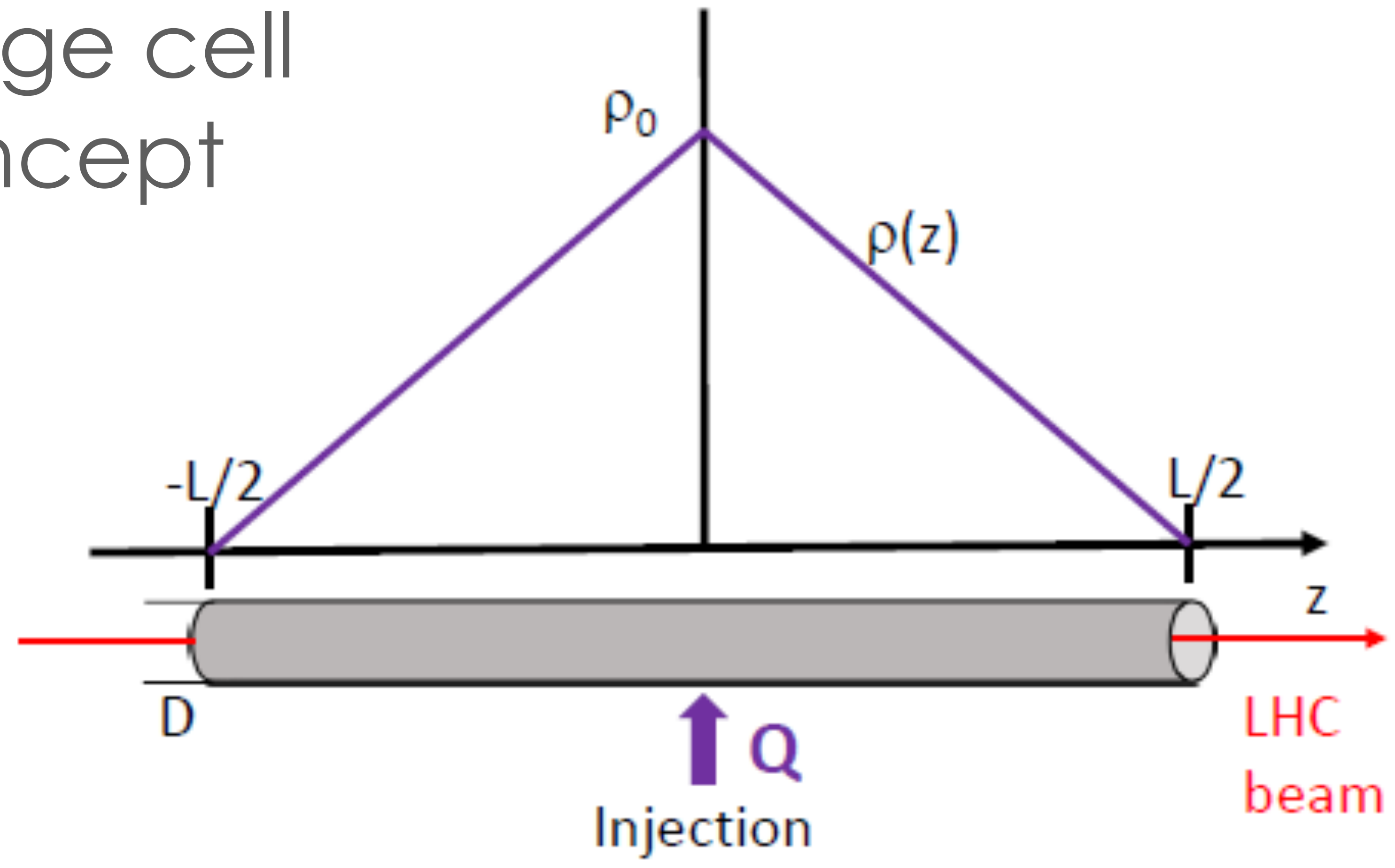


Broad and poorly explored kinematic range

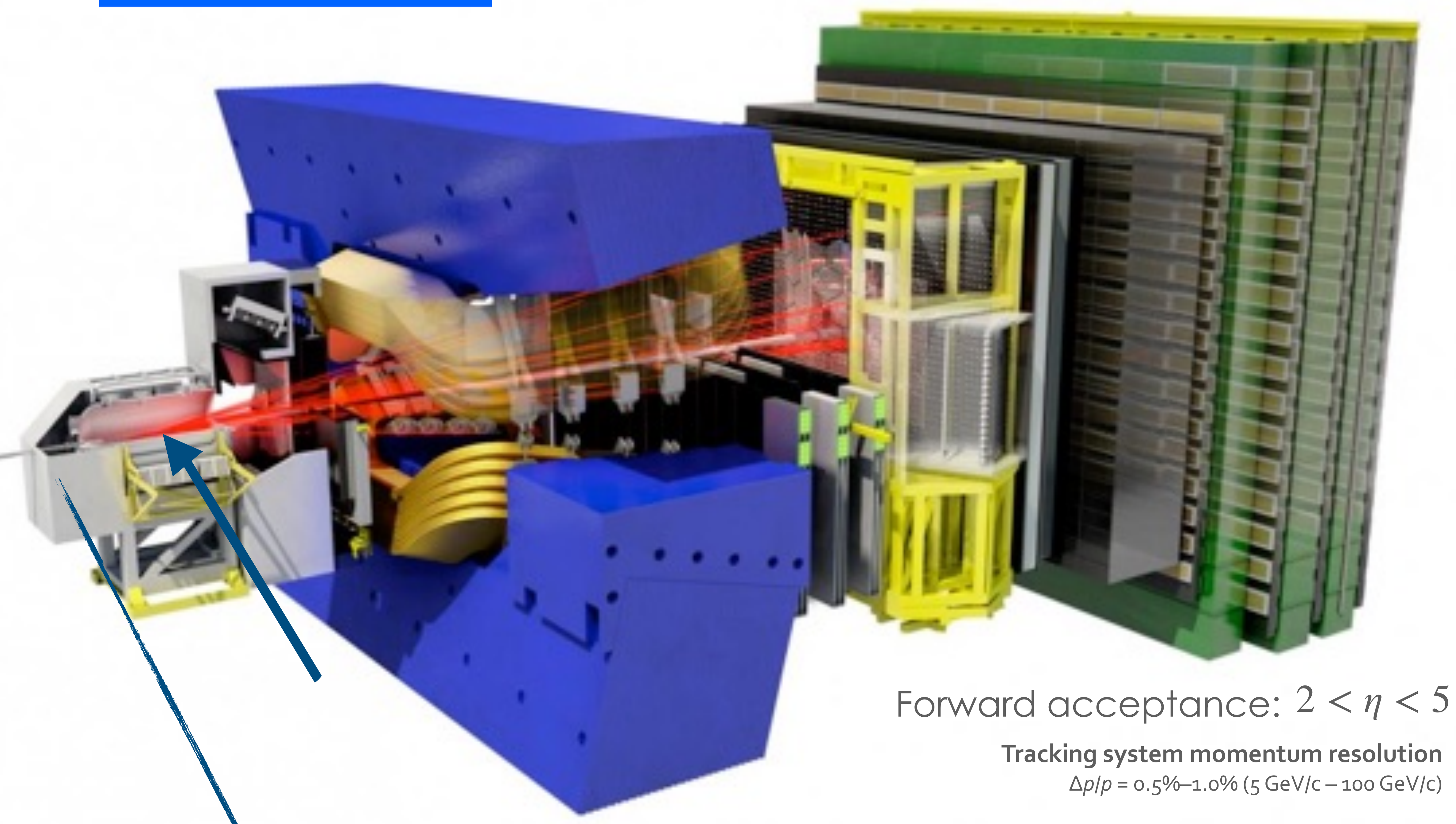
SMOG2 an unpolarised target at LHCb

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

Storage cell concept



LHC beam



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

Luminosity

$$L_{ist} = \theta\, N_p\, f_{rev}$$

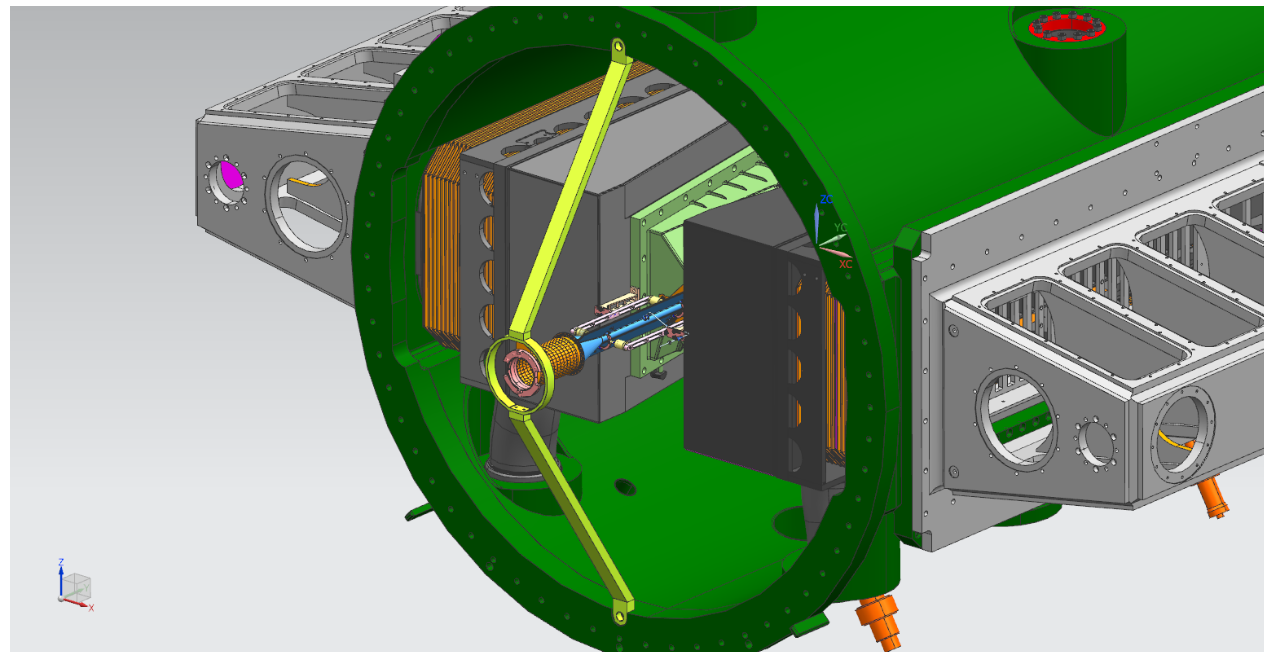
areal density

number of particles

$$N_{p/b} \cdot N_b$$

$$\rho_0 \frac{L}{2} = \frac{\Phi}{C}\frac{L}{2}$$

$$C = 3.81\sqrt{\frac{T}{M}}\frac{D^3}{L + \frac{4}{3}D}$$



UNpolarised target (beam-gas)

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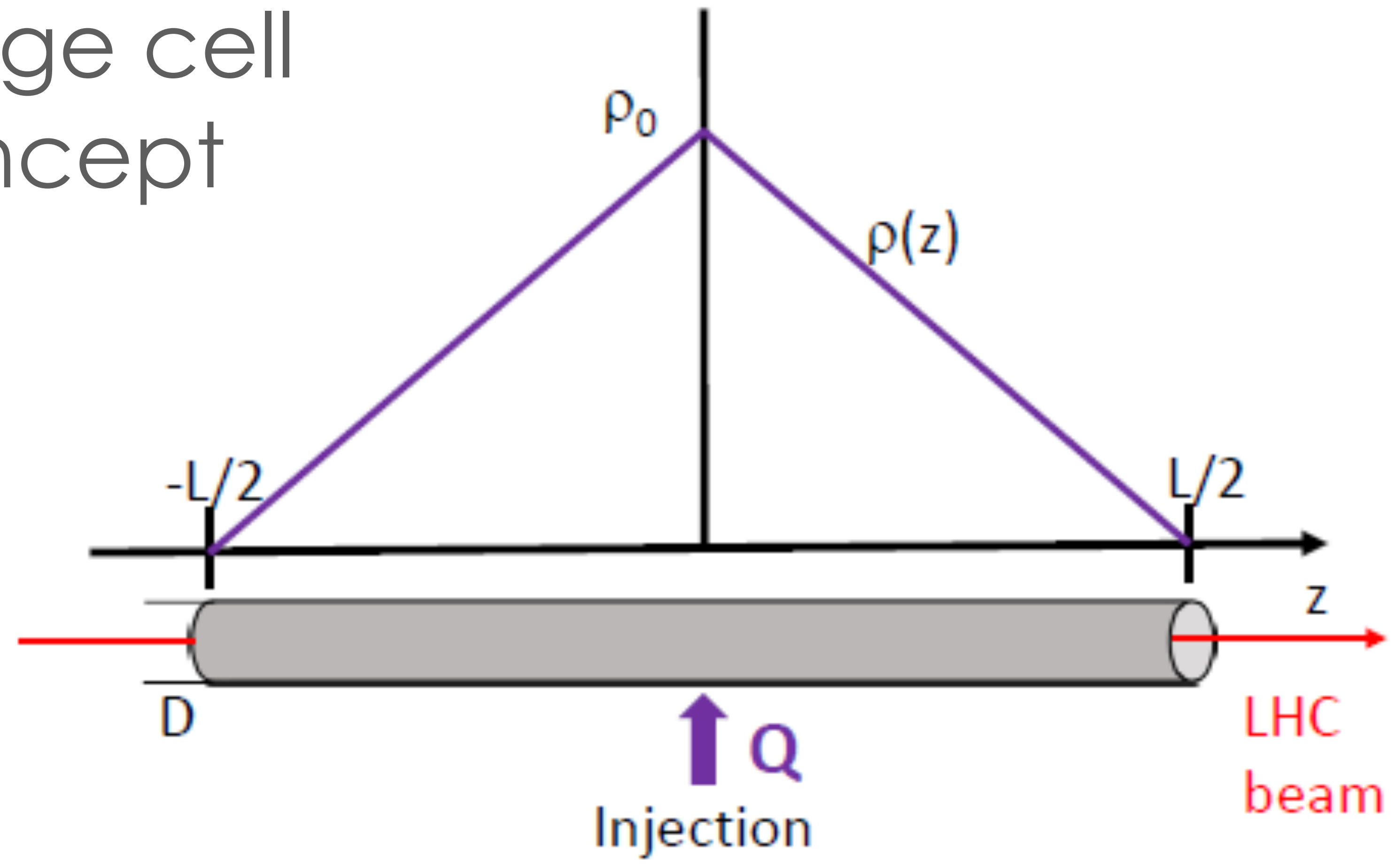

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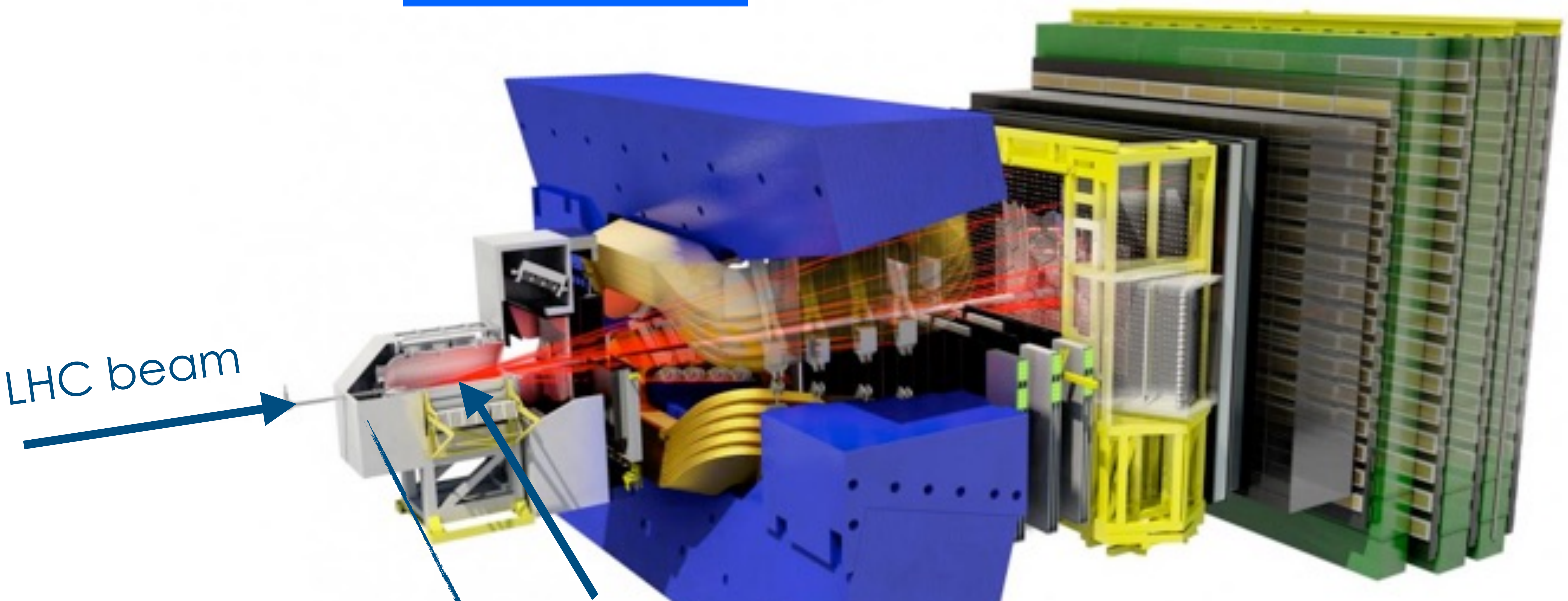

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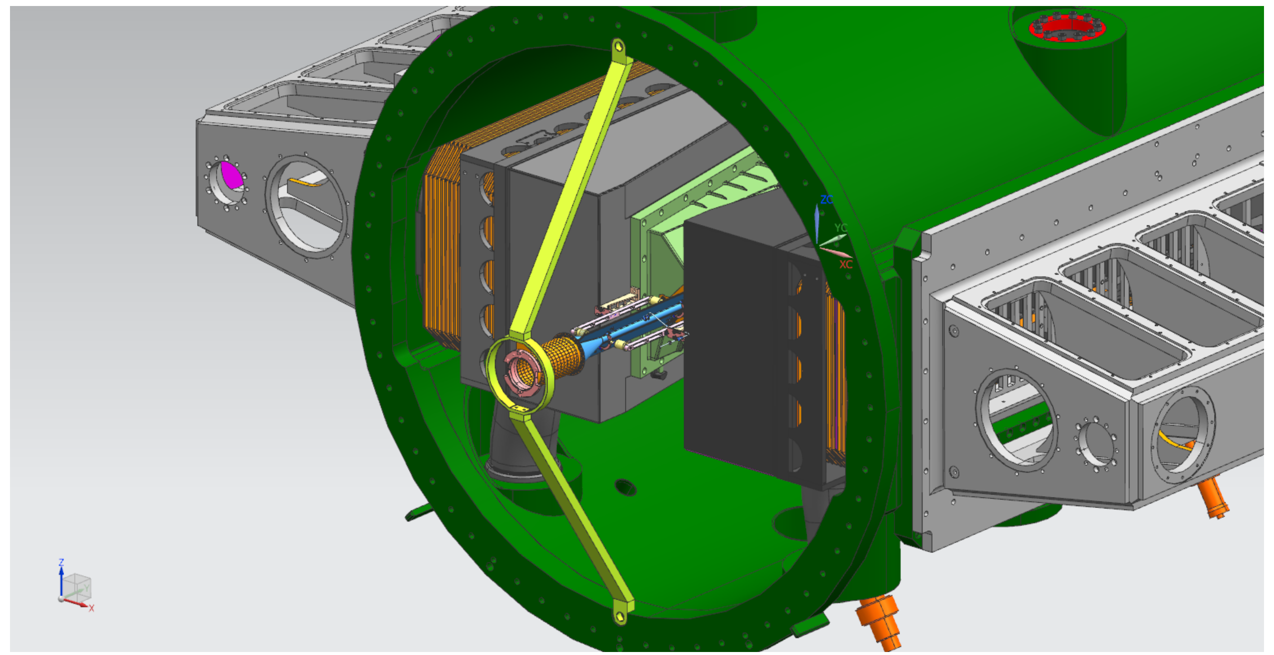

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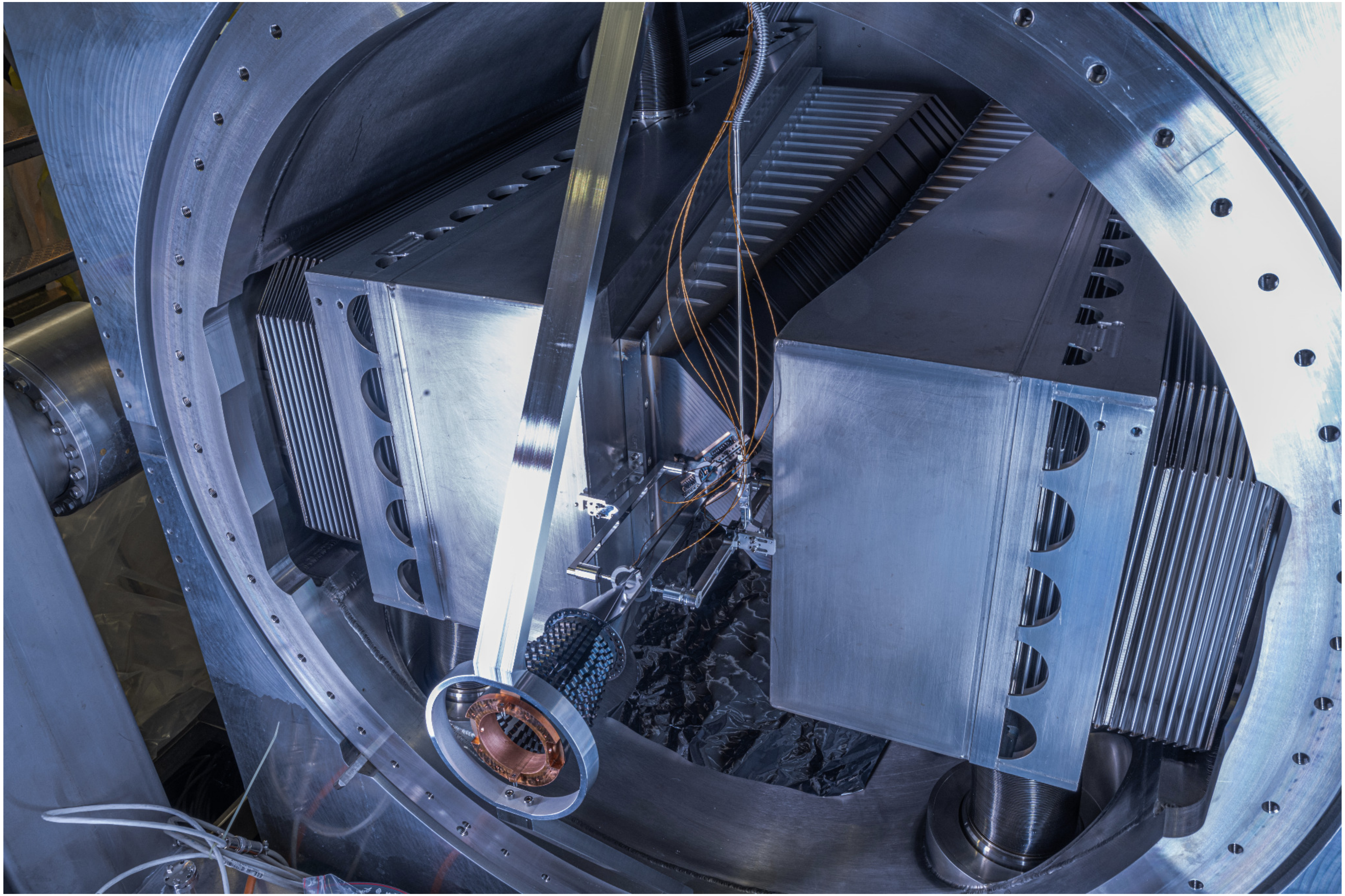
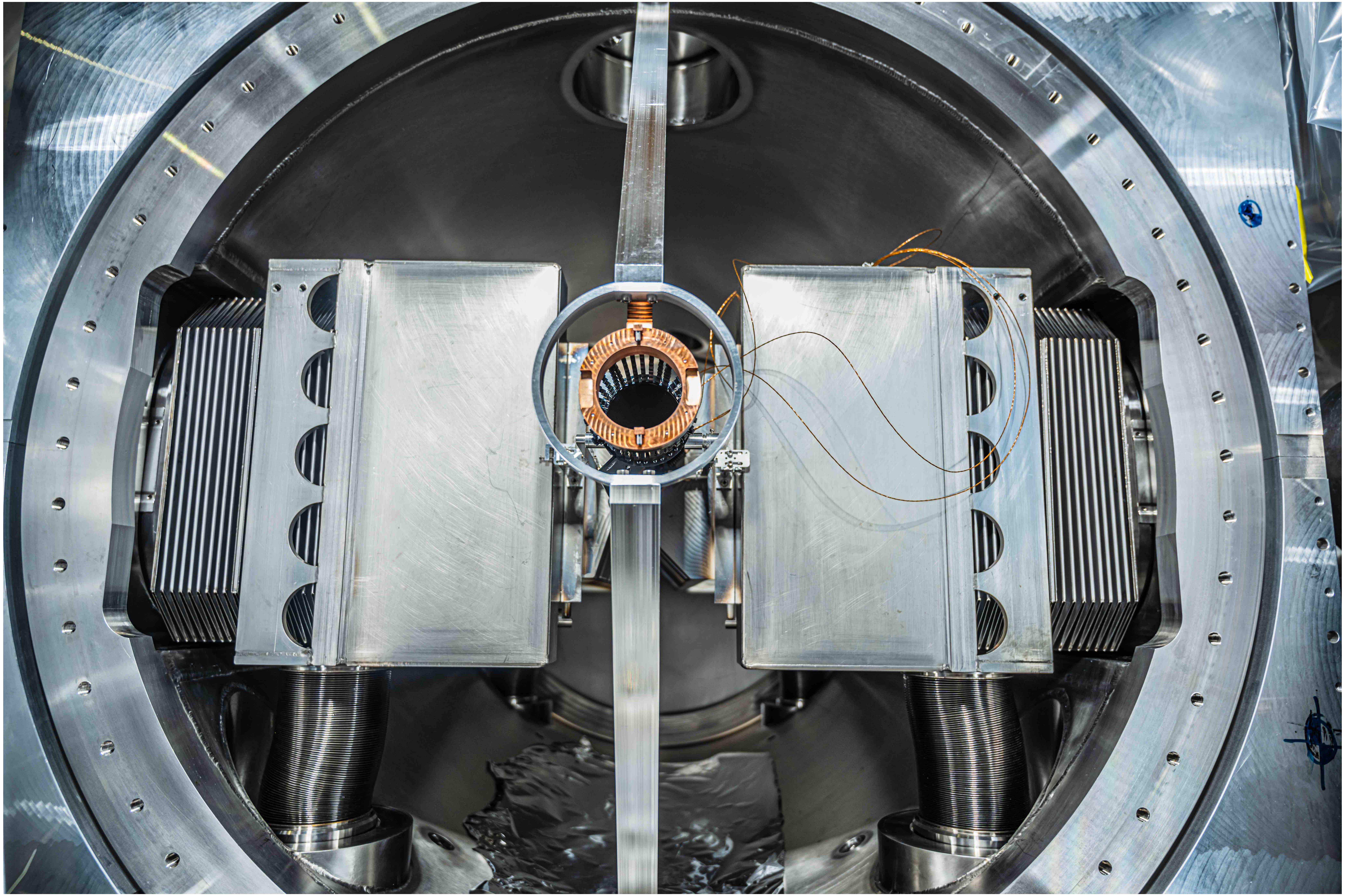


It is the only system present in the LHC primary vacuum

SMOG2



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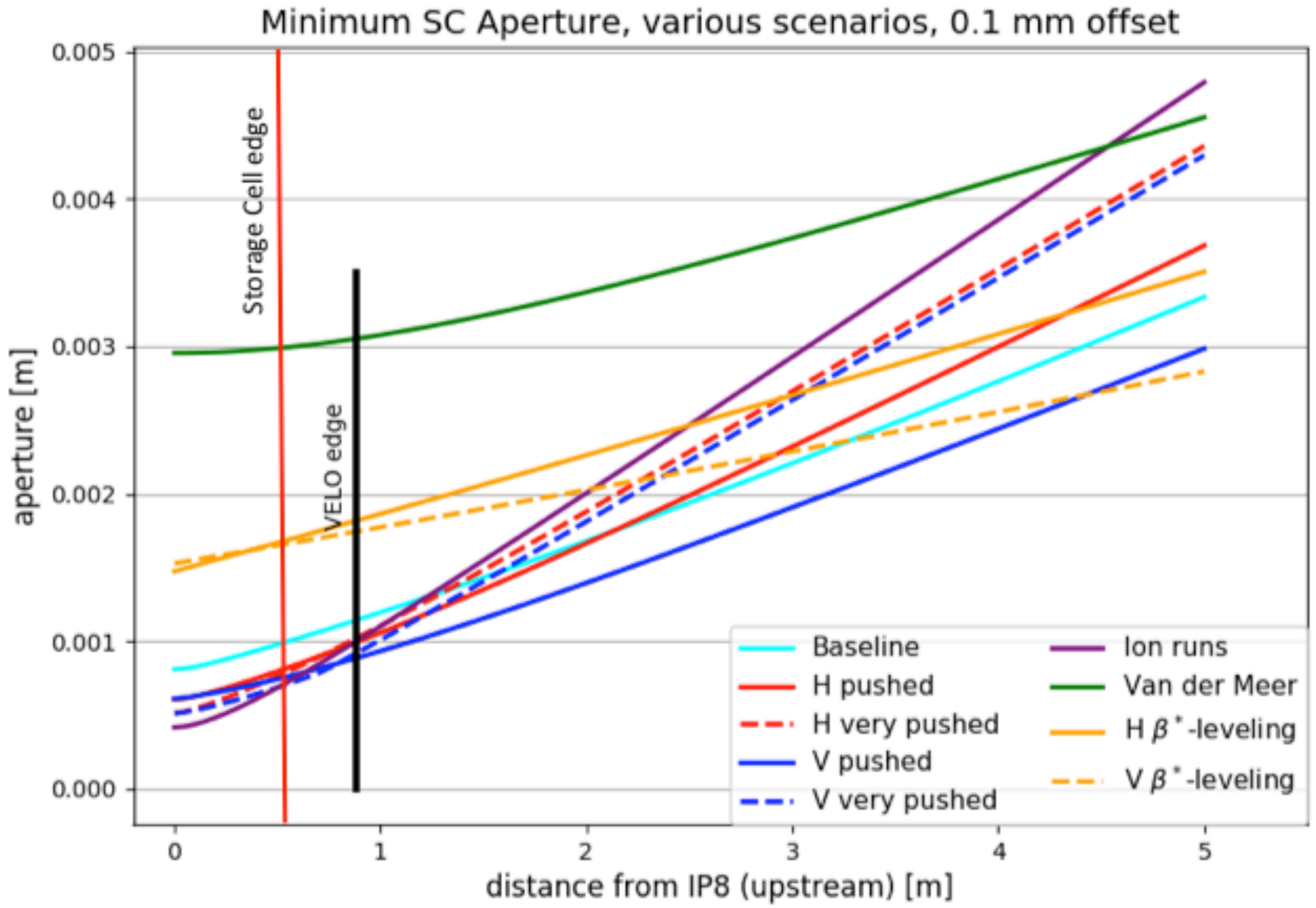
SMOG2 **Openable** Storage Cell dimensions: 200 mm (L) - 10 mm (D)

The physical aperture of 5 mm gives 2 mm margin to minimum allowed aperture (VdM scan)



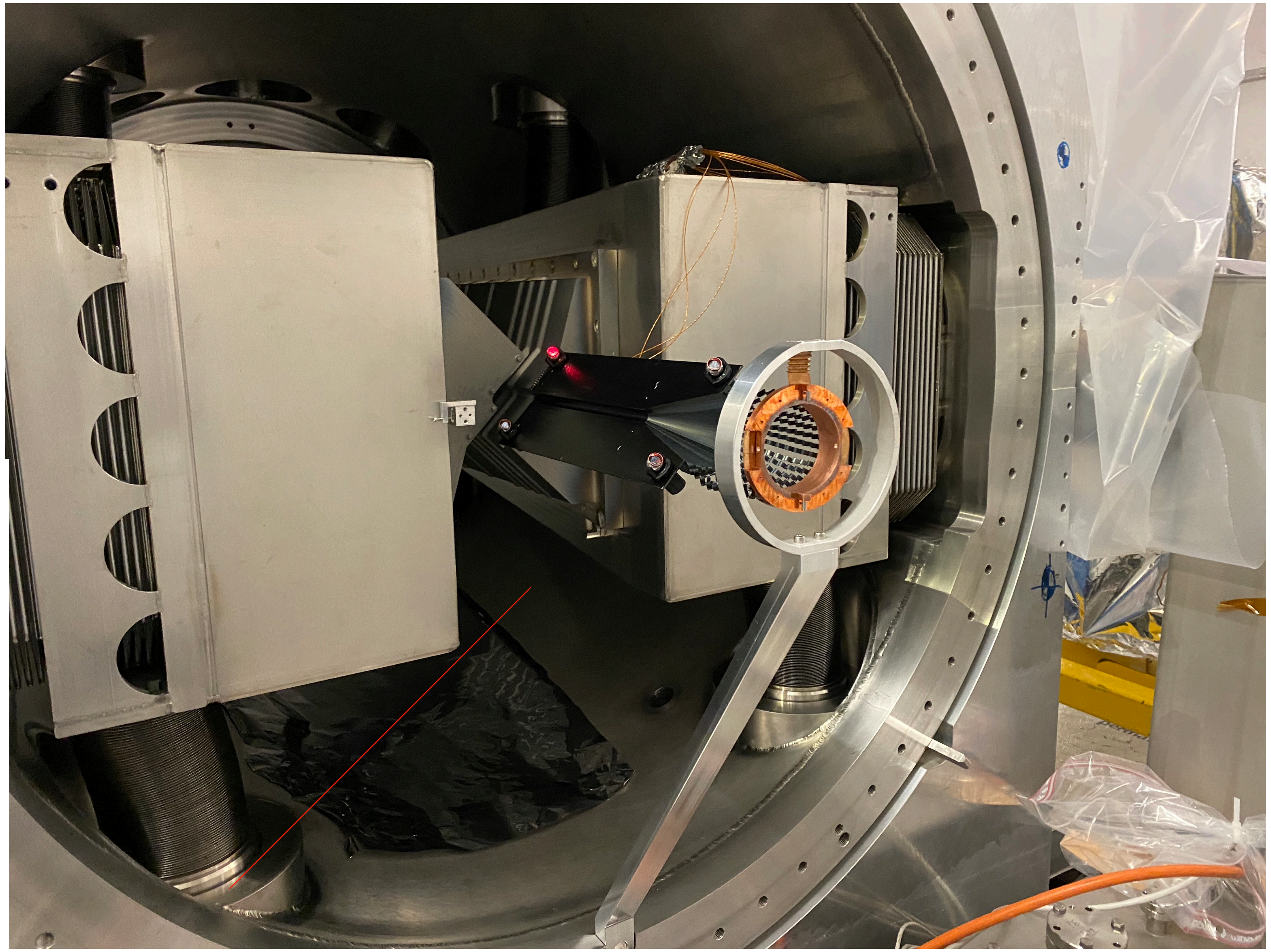


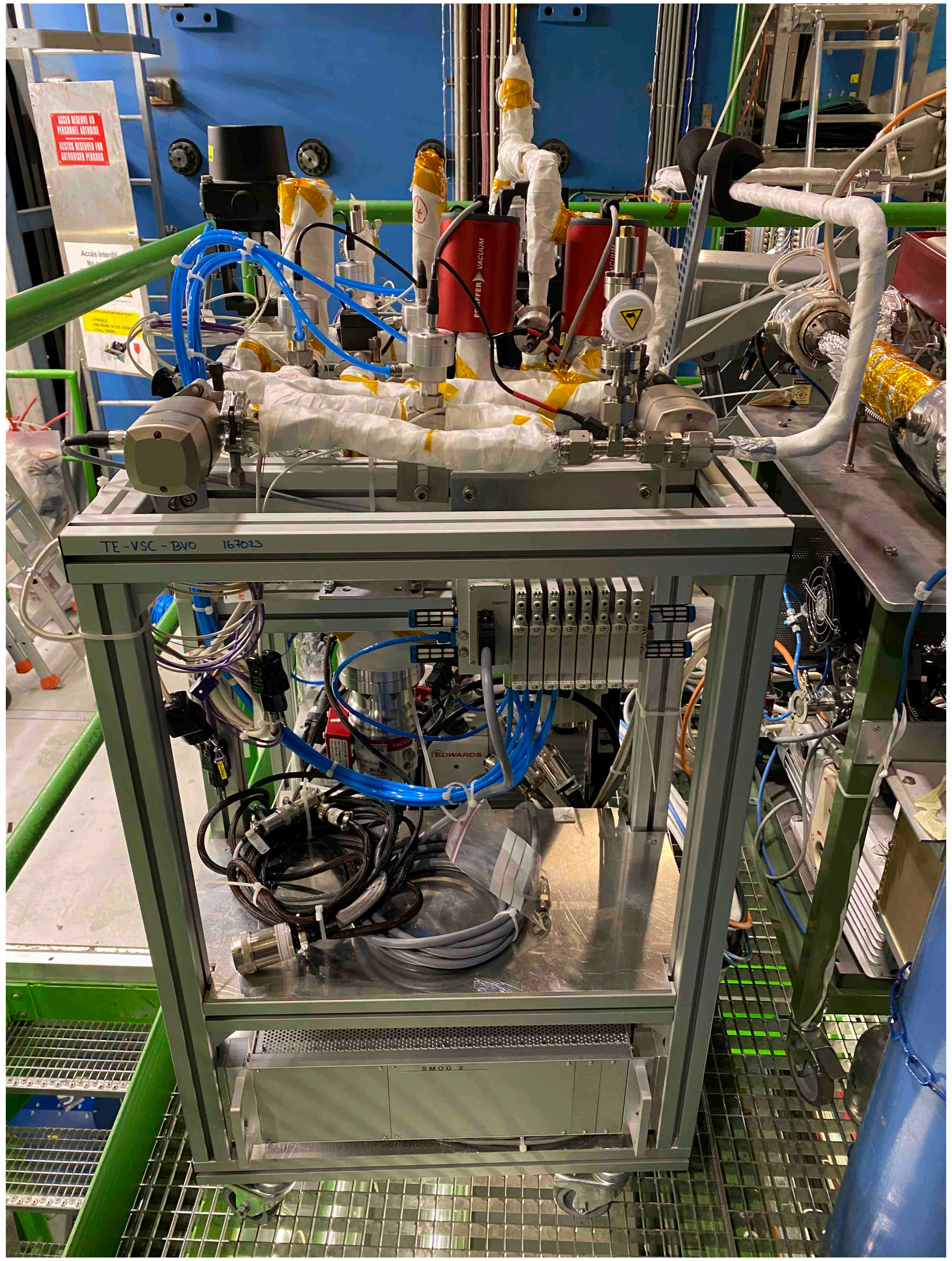
Table 9: Final position of the SMOG2 and its offset to the nominal position

	Position of SMOG2			Offset to nominal		
Name	**Xphys [m]**	**Yphys [m]**	**Zphys [m]**	**dXphys [mm]**	**dYphys [mm]**	**dZphys [mm]**
S_E	-0.00142	-0.00017	-0.61739	-0.25	0.14	0.11
S_S	-0.00136	-0.00040	-0.33739	-0.19	-0.14	0.11
S_ROLL	-0.00082	0.99983	-0.61658			

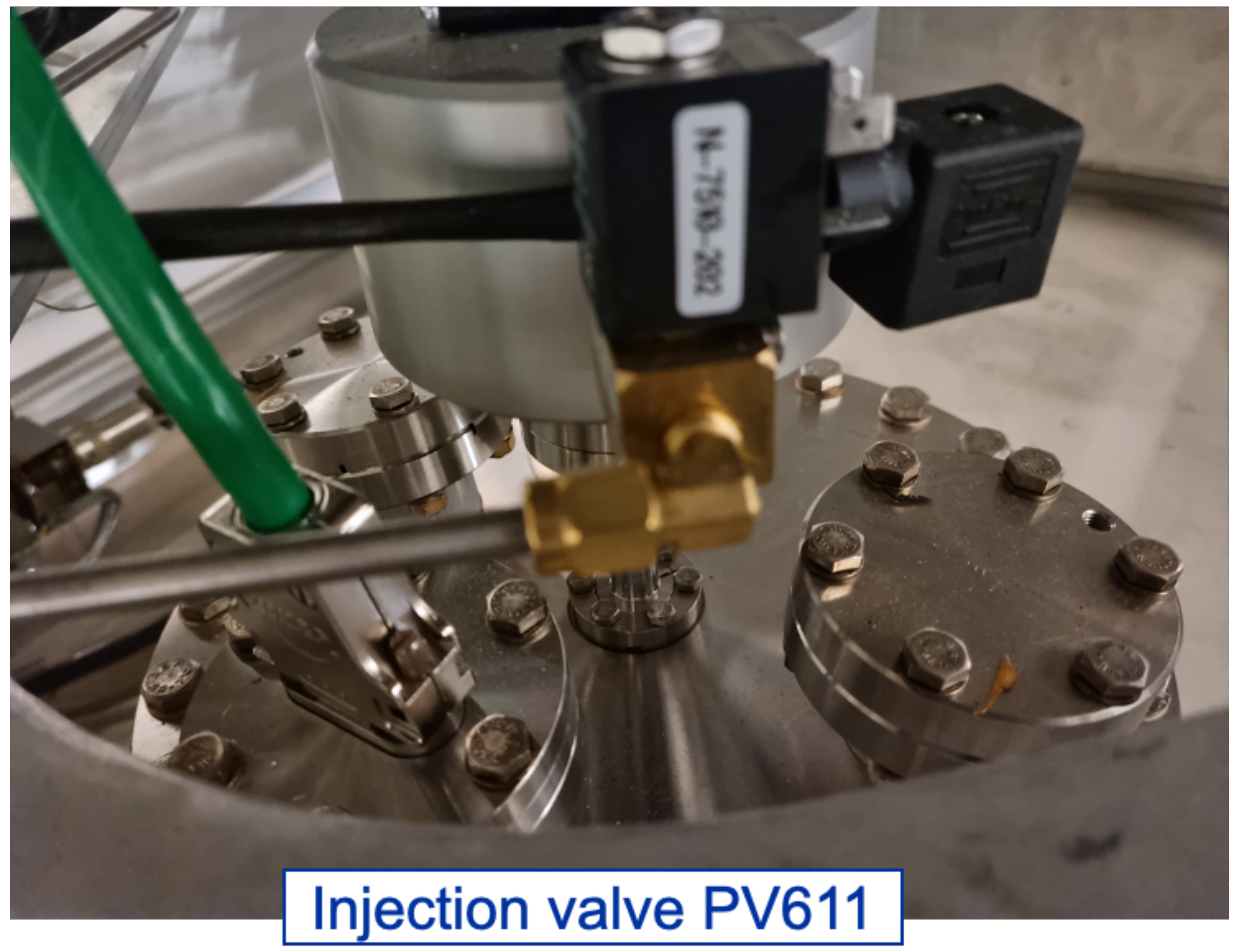
Excellent alignment reached

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): He, Ne, Ar … H_2, D_2, N_2, O_2, Kr, Xe
- Flux known with $1\,\%$ precision, measured relative contamination 10^{-4}



GFS table installation

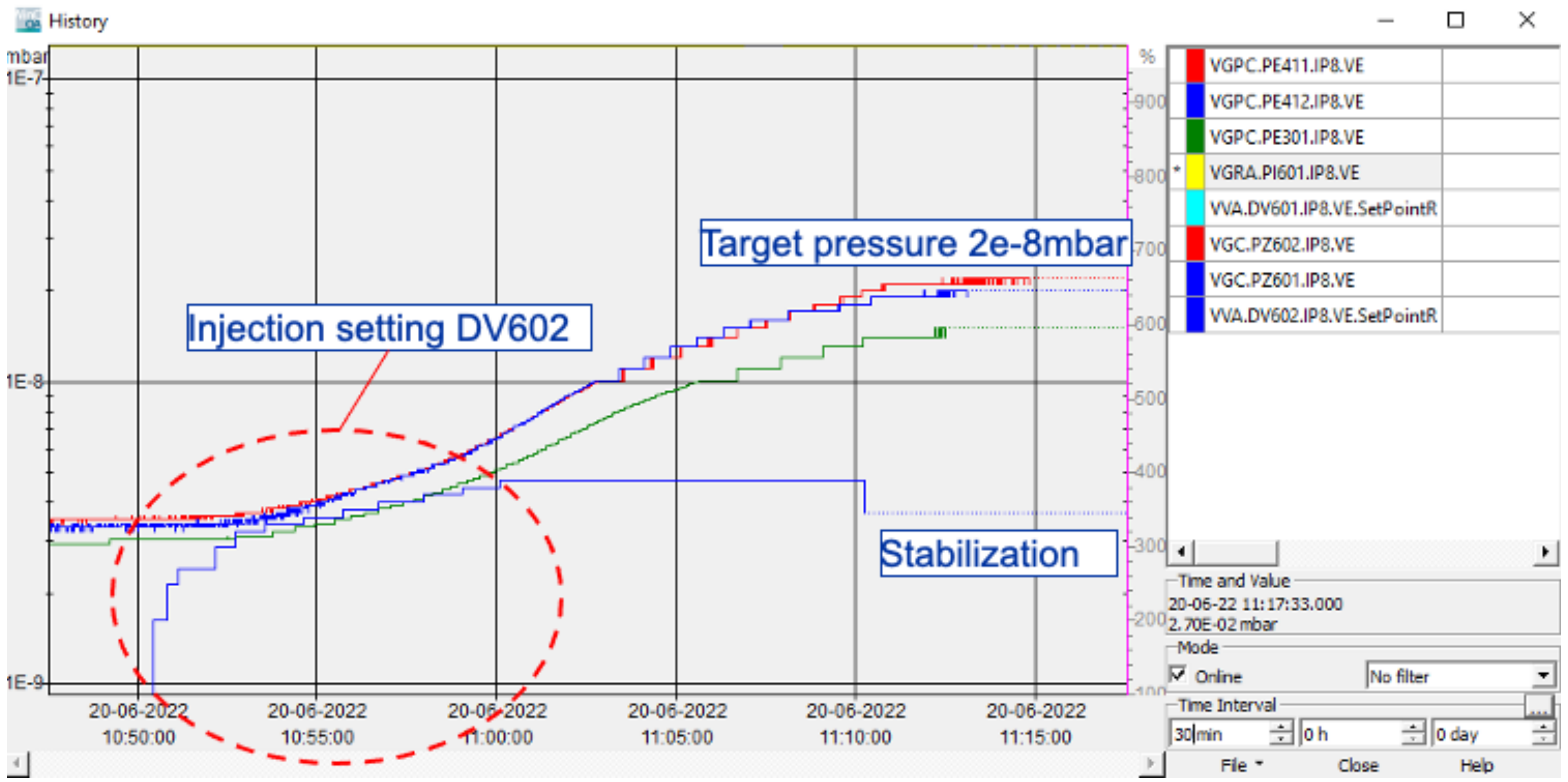


Injection valve PV611

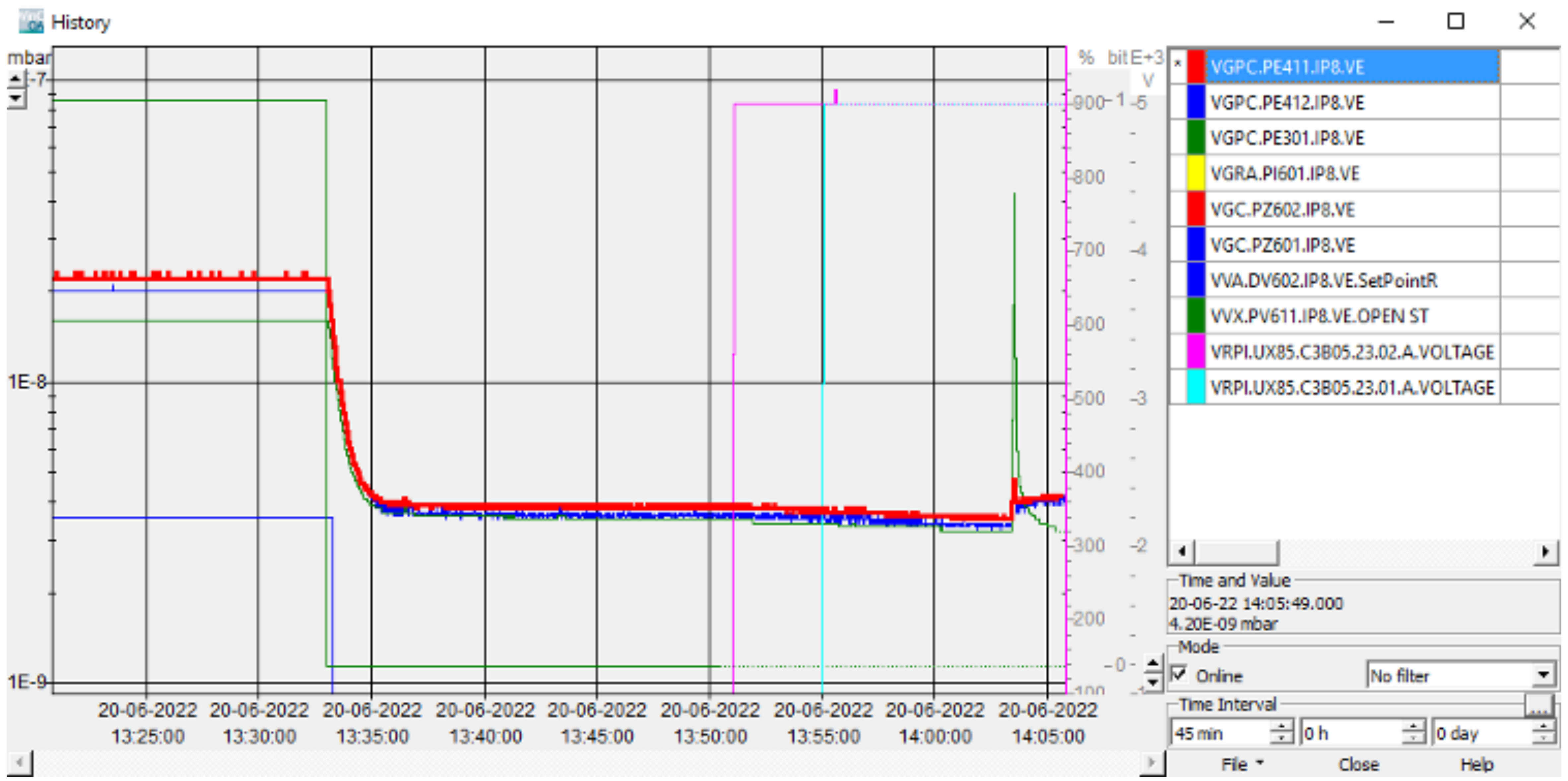
https://cds.cern.ch/record/2673690/

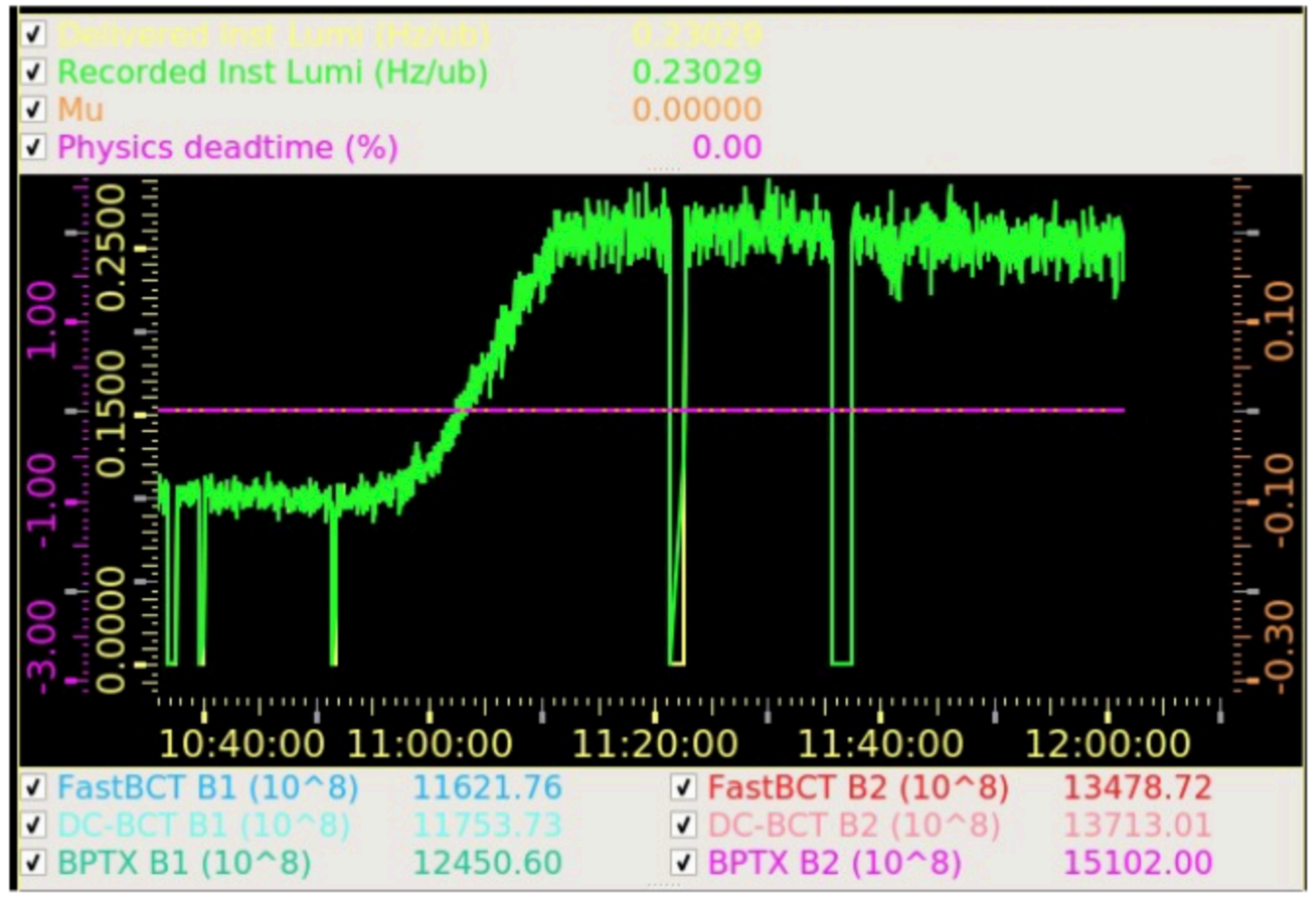
SMOG2 gas injection at LHC Run3 started in June 2022

Pressure increase into the primary vacuum



Vacuum recovery after the gas injection stop in <20'





Luminosity increase seen by the LHCb luminometer (Plume)

Extremely useful also for the LHCb commissioning

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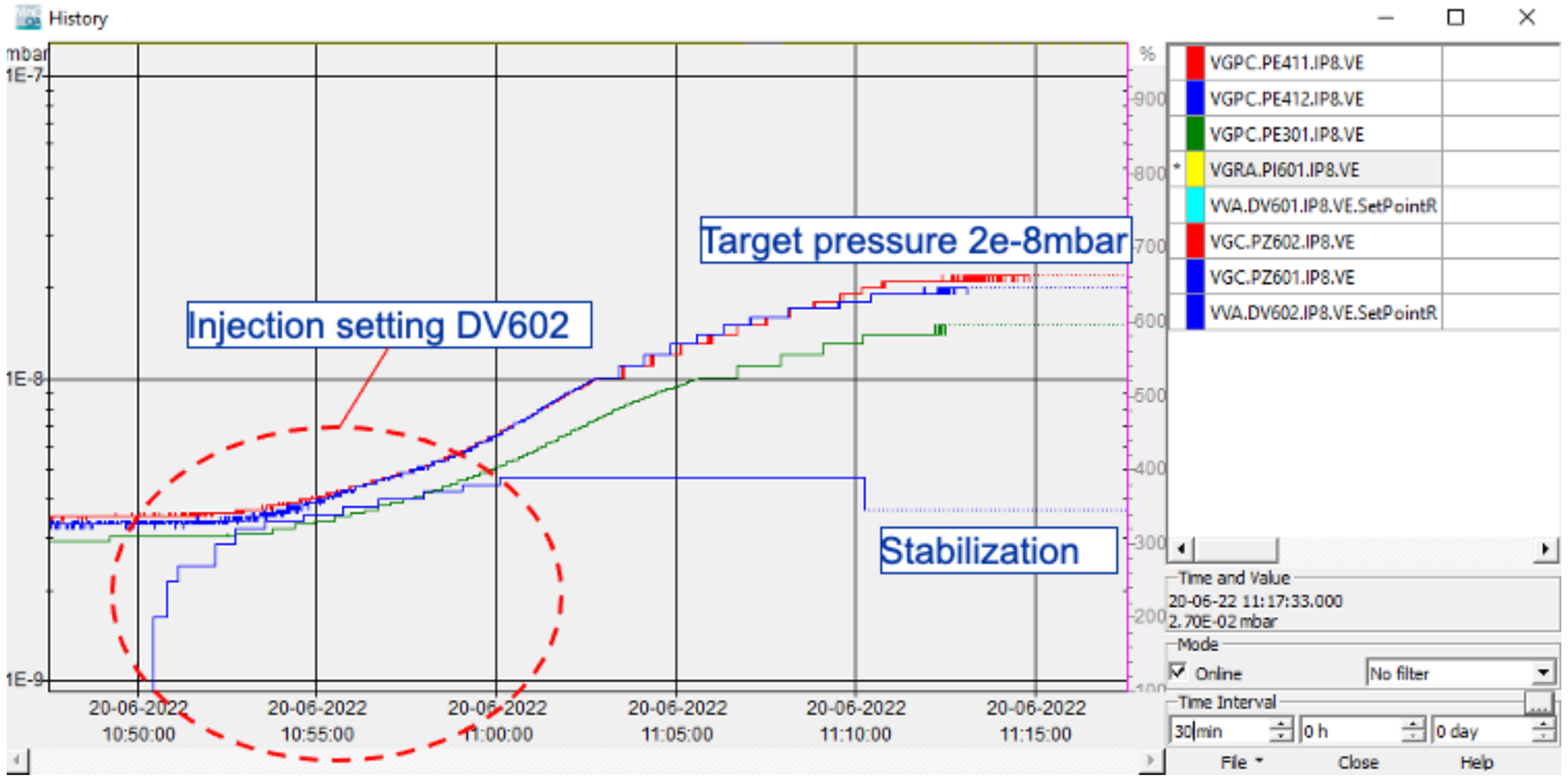

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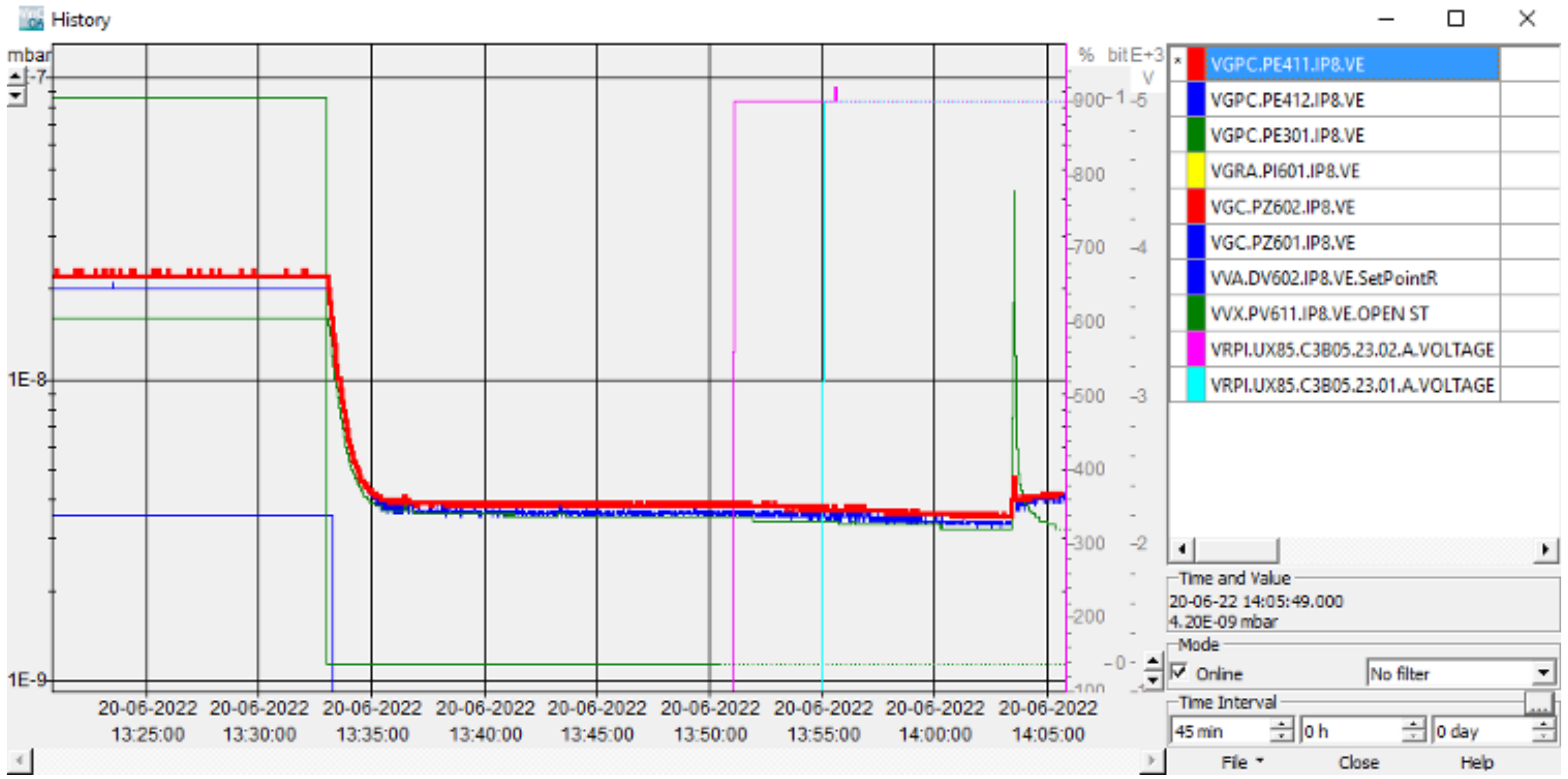

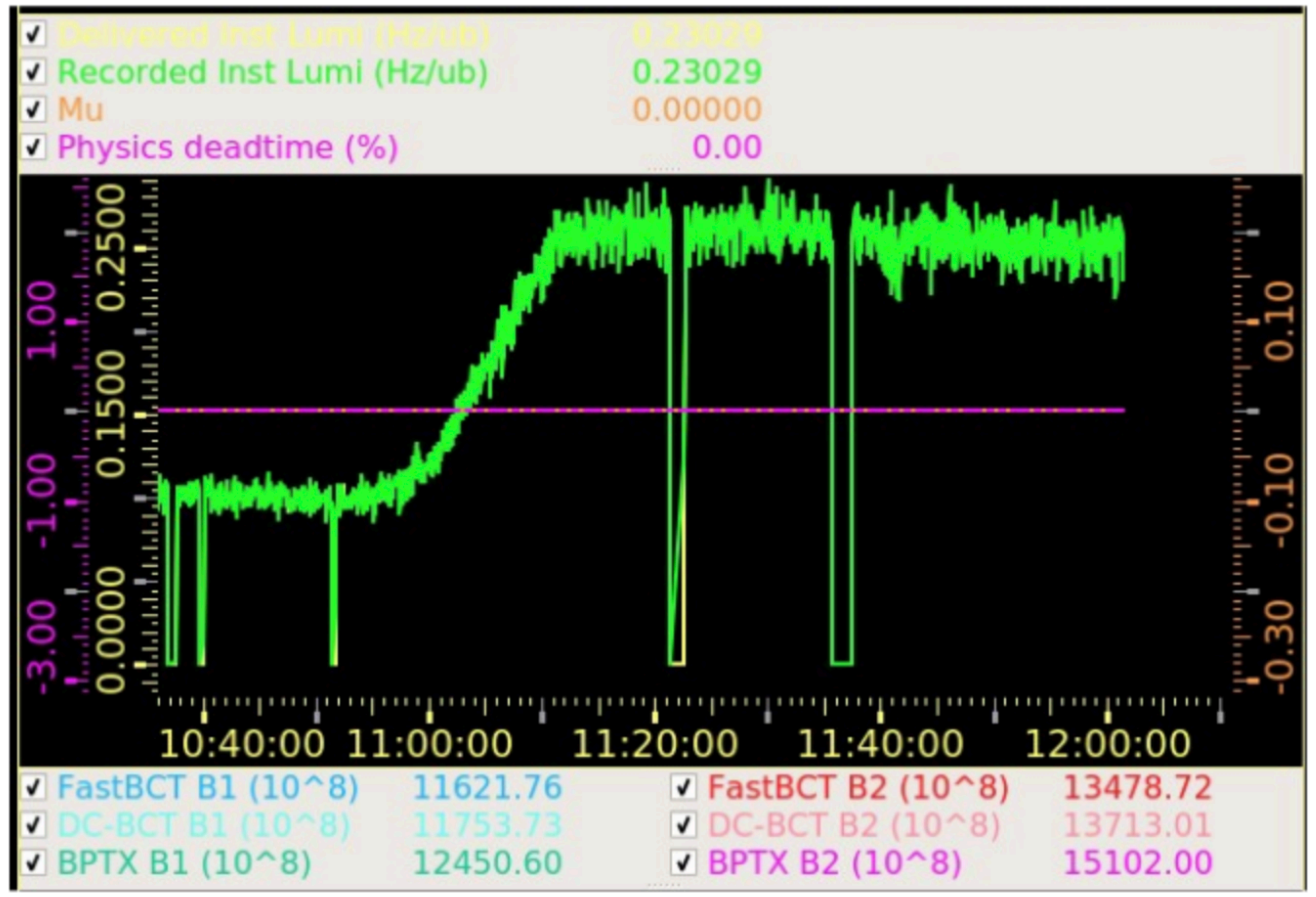

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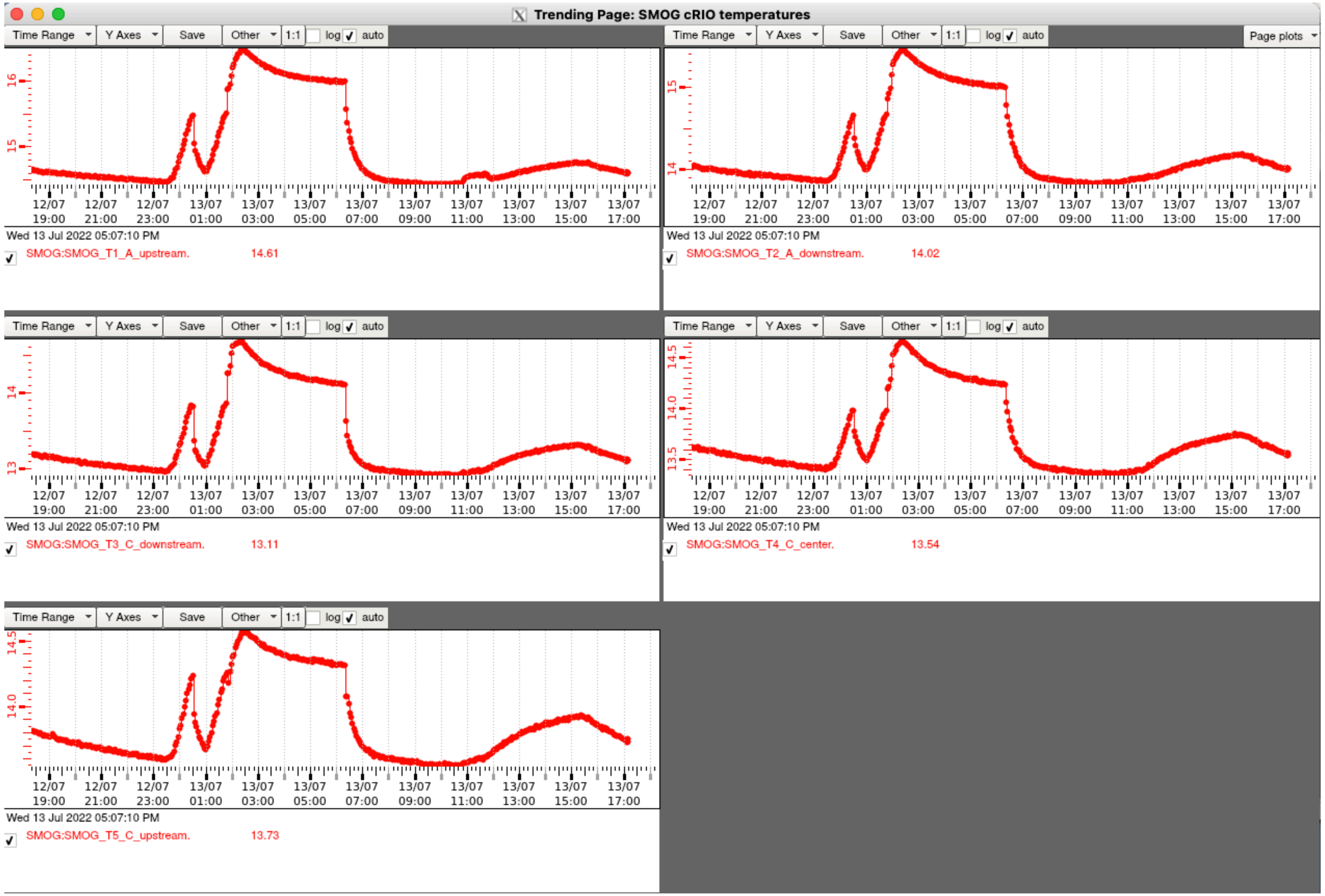
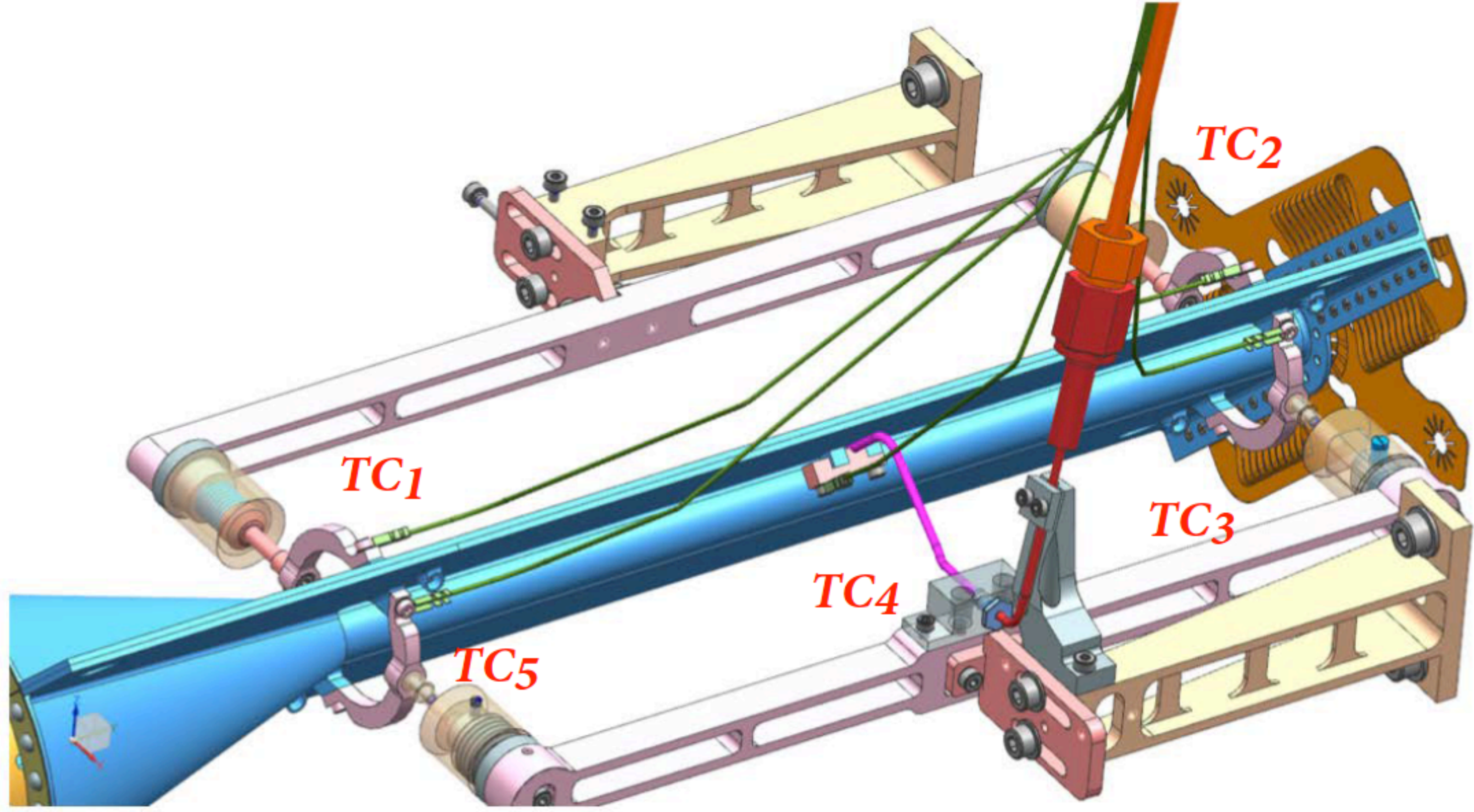
LHC official statement

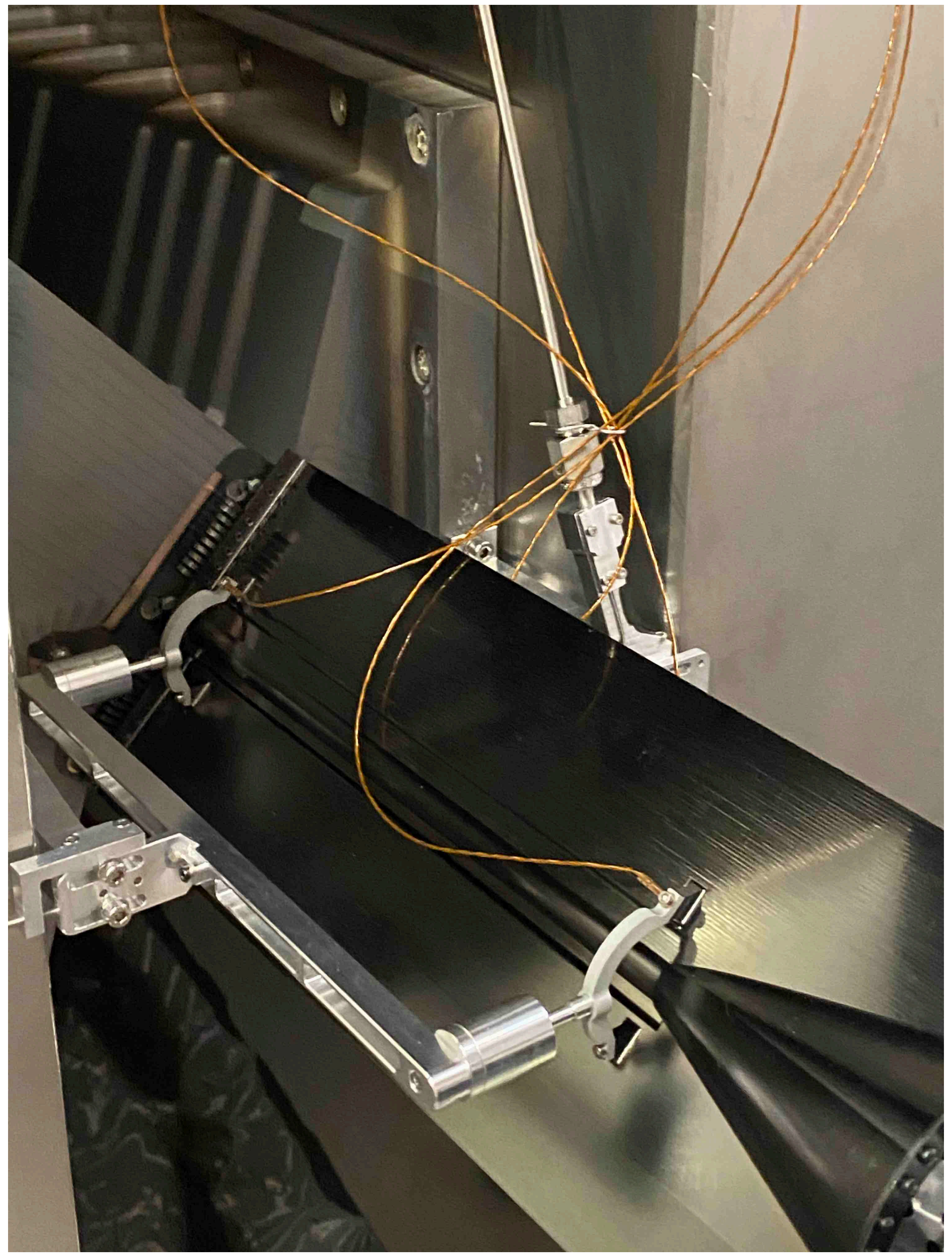
No negative feedback when there is gas injection. Green light to inject when needed

Temperature system

- 5 Temperature probes + reading system up un running
- Precision of $\Delta T = 0.2$ K







Measurements implemented in the LHC control panel, too

Temperature system

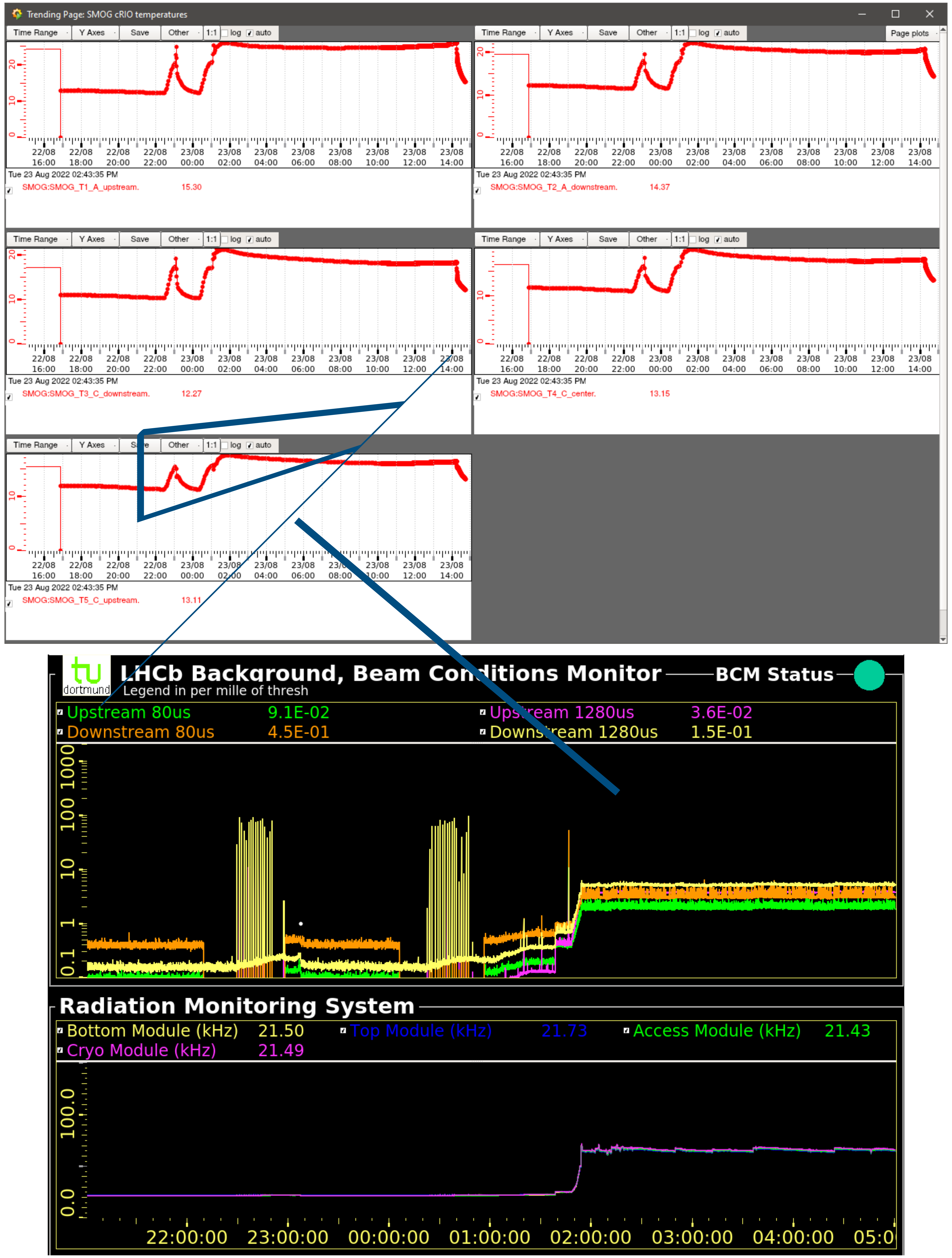
Only lately (with ~70% of the LHC bunches) we see a correlation between beam operations and cell temperature

Increase from 10 to 20˚C, as expected

Prototype tested up to 130˚C

<u>Open cell</u>: increase of the temperature, pick up of the rf modes of the beam

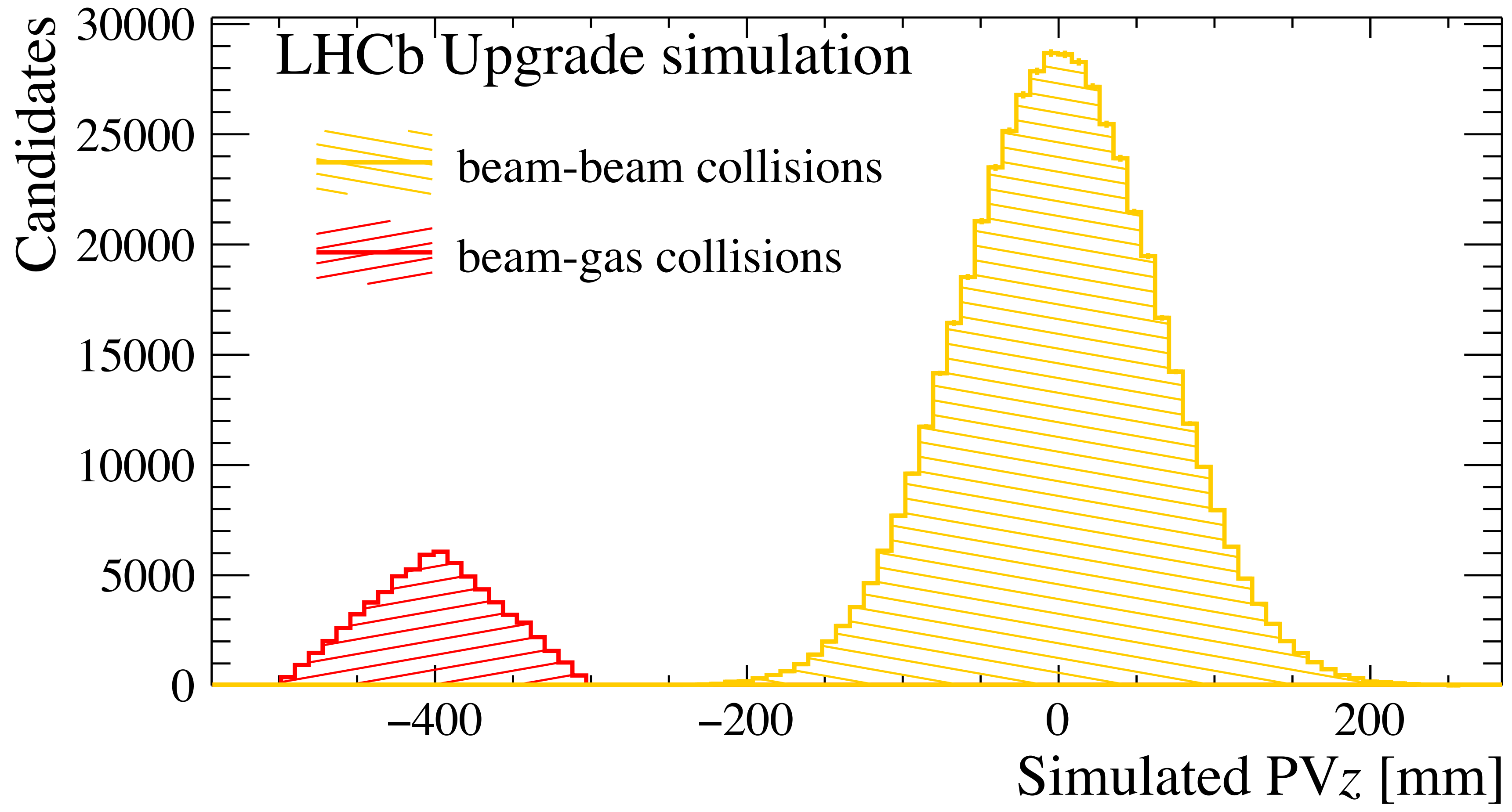
<u>Closed cell</u>: decrease

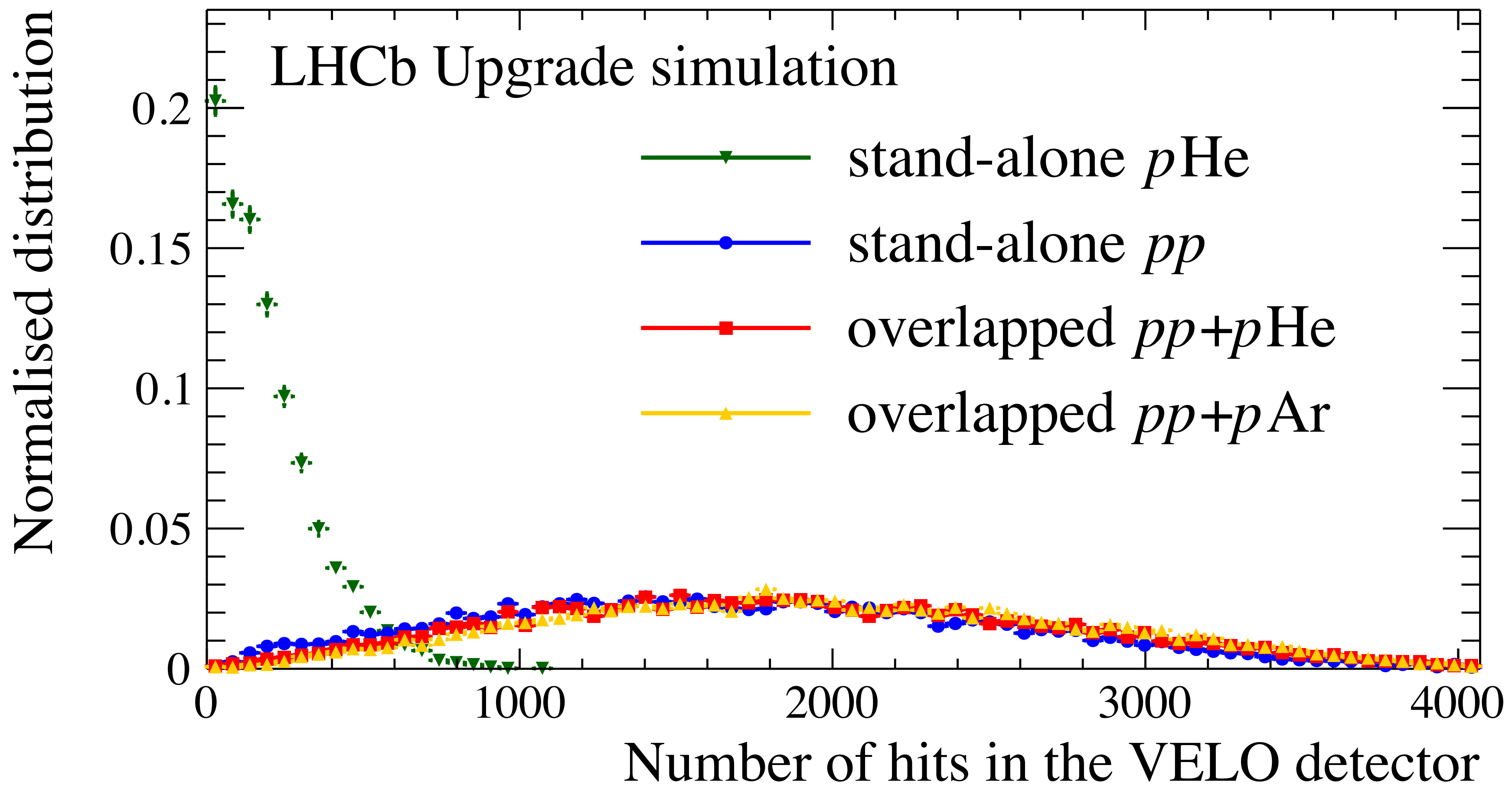


SMOG2/LHCspin performances

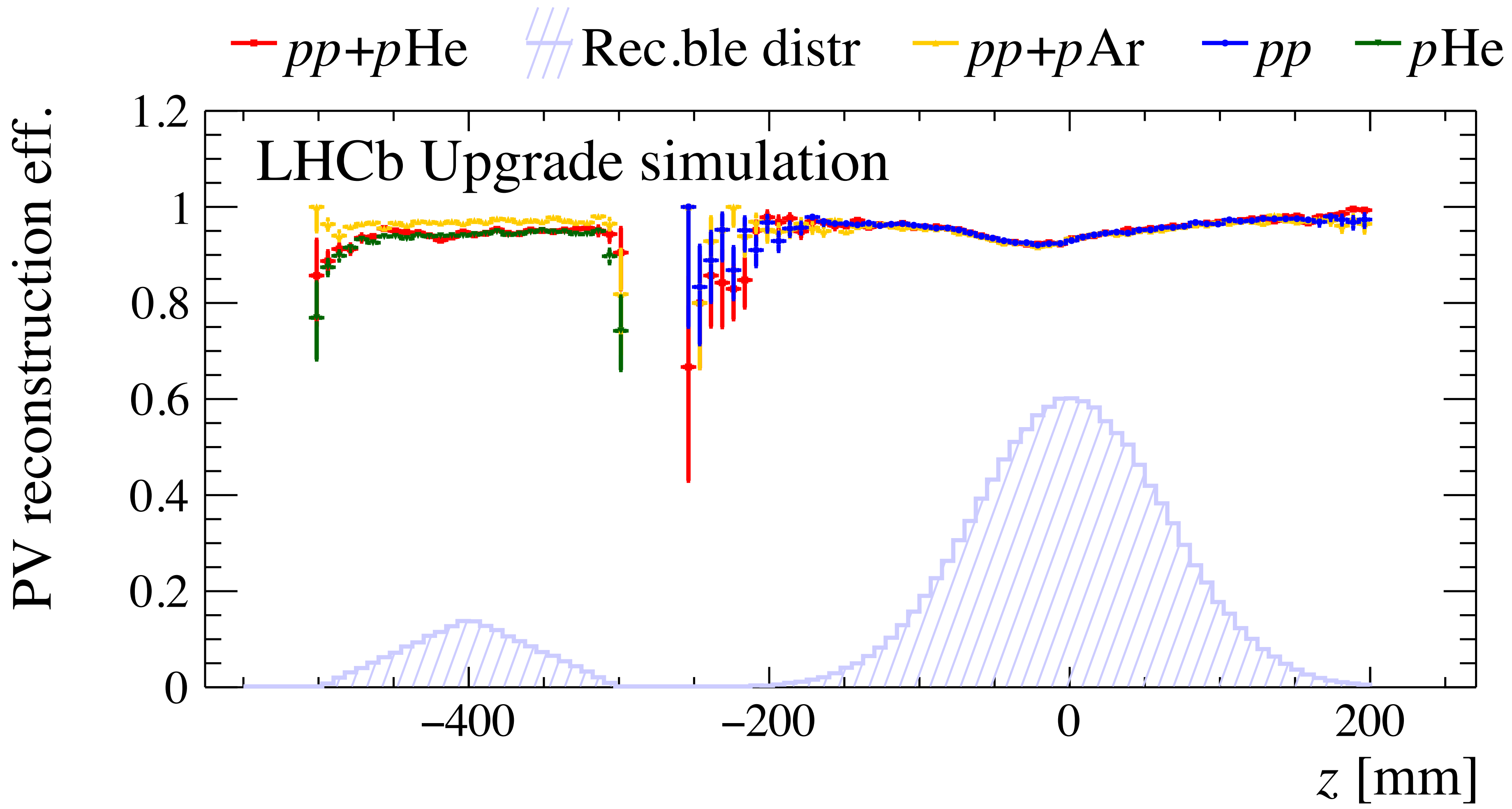
[LHCB-FIGURE-2022-002]

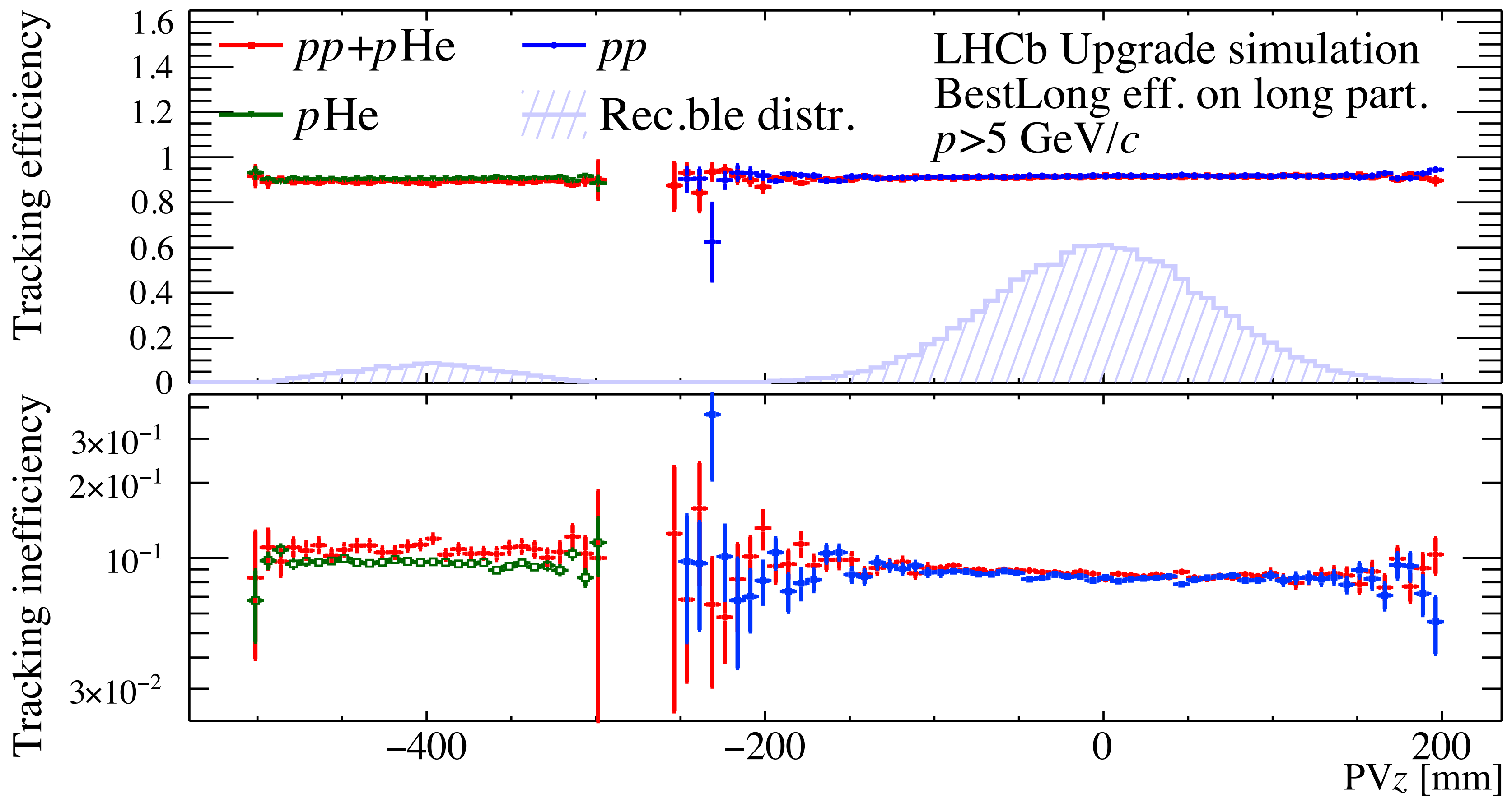
- beam-beam and beam-gas interaction regions are well detached
- Negligible increase of multiplicity: $1-3\,\%$ throughput decrease when adding beam-gas to the LHCb event reconstruction sequence





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



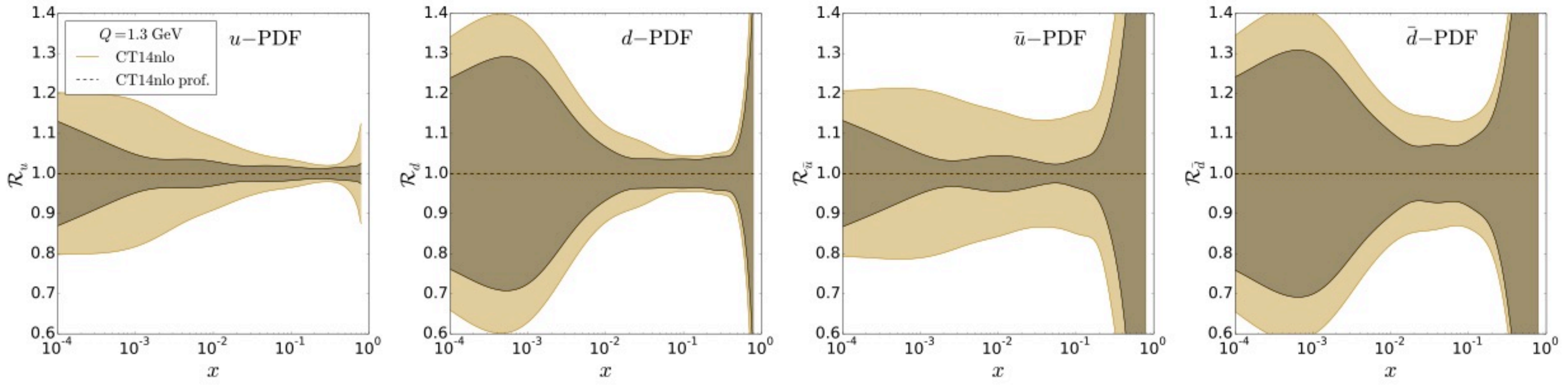


LHCb is the only experiment able to run in collider and fixed-target mode simultaneously!

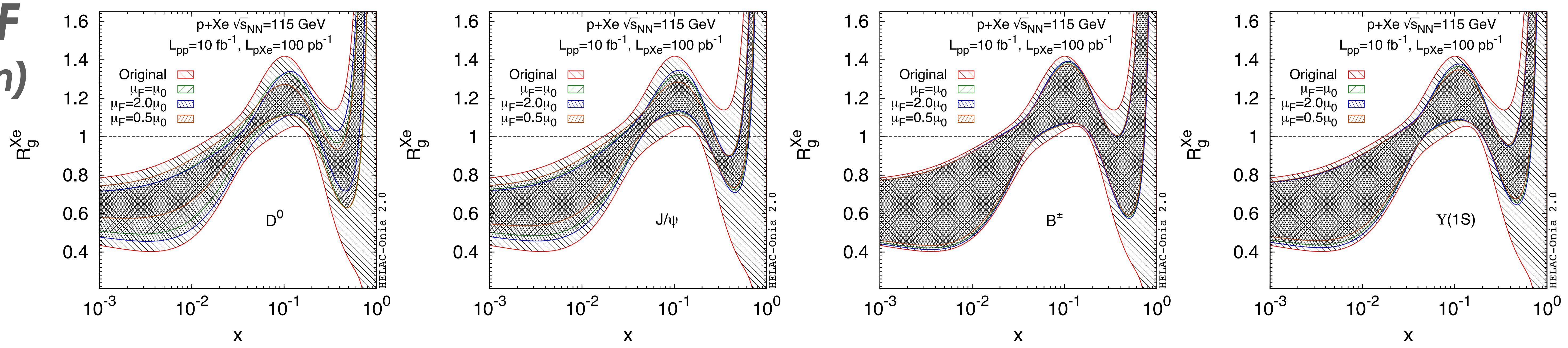
SMOG2 … few highlights

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

PDF estimation with 10 fb^{-1} arXiv:1807.00603



nPDF (gluon)



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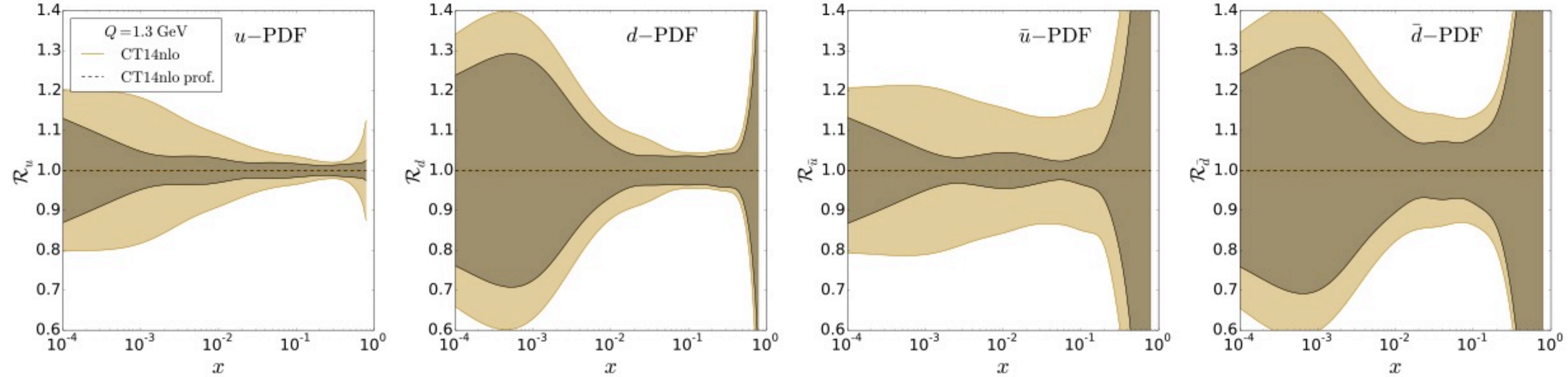

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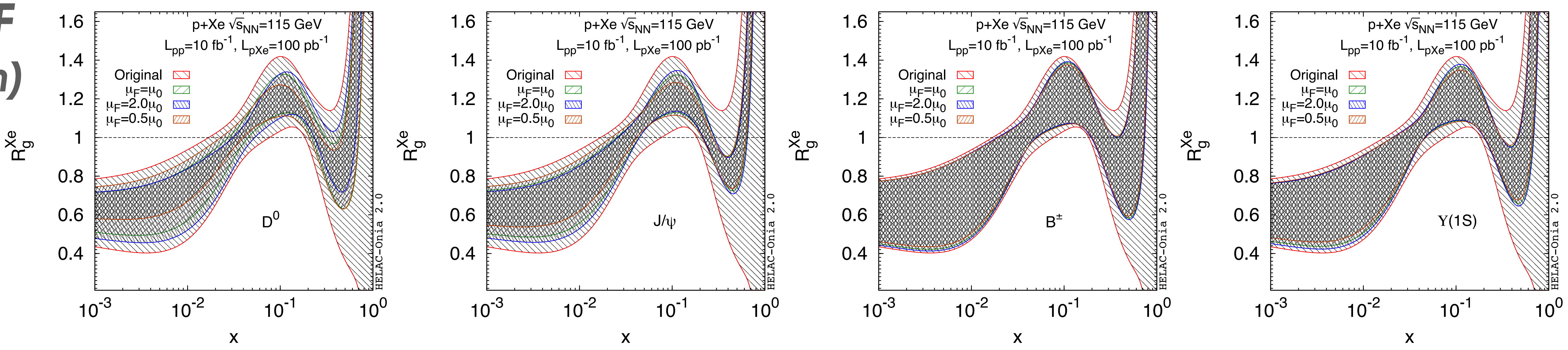
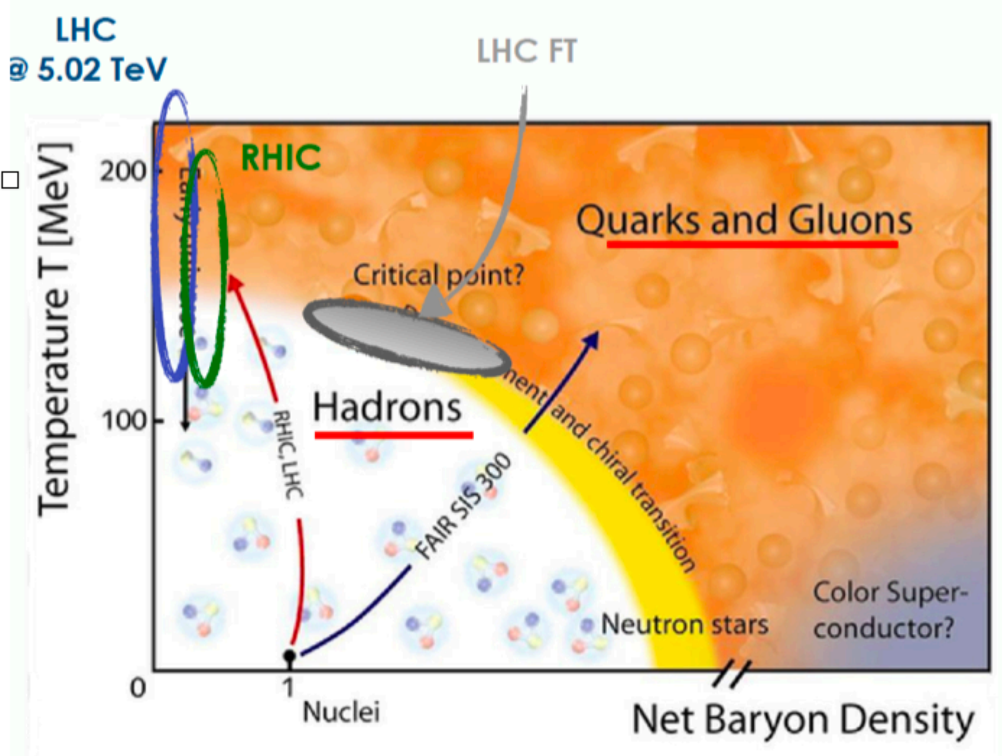
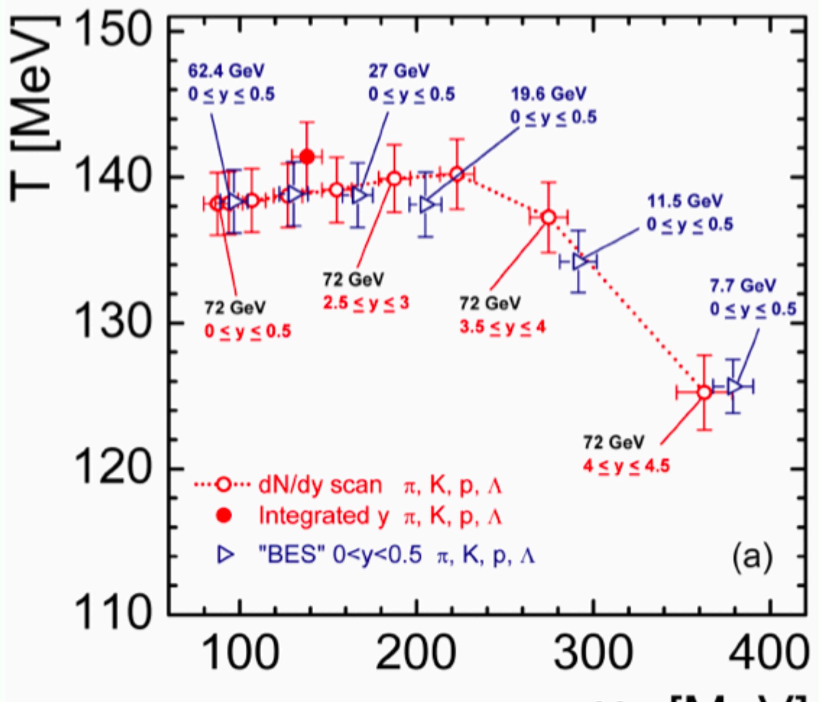


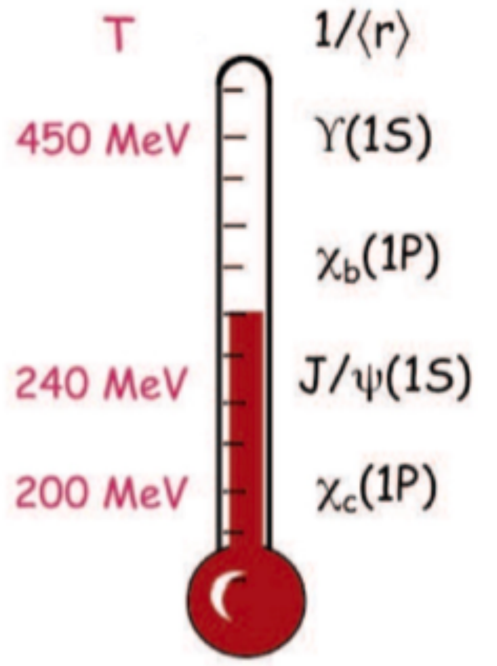
Heavy-Ion and QCD phase space





[PRC 98 (2018) 034905]

$c\bar{c}$ bound states



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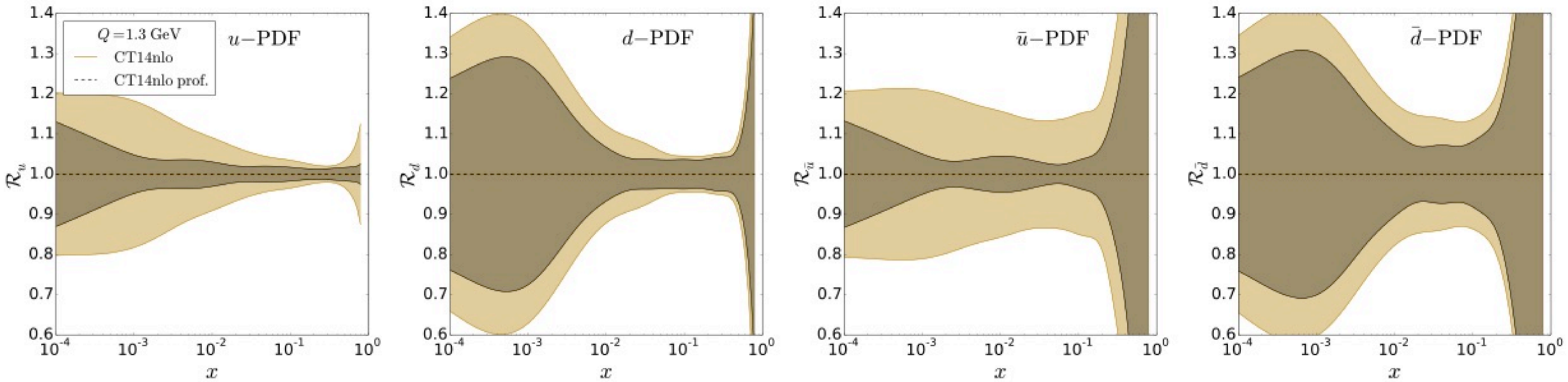

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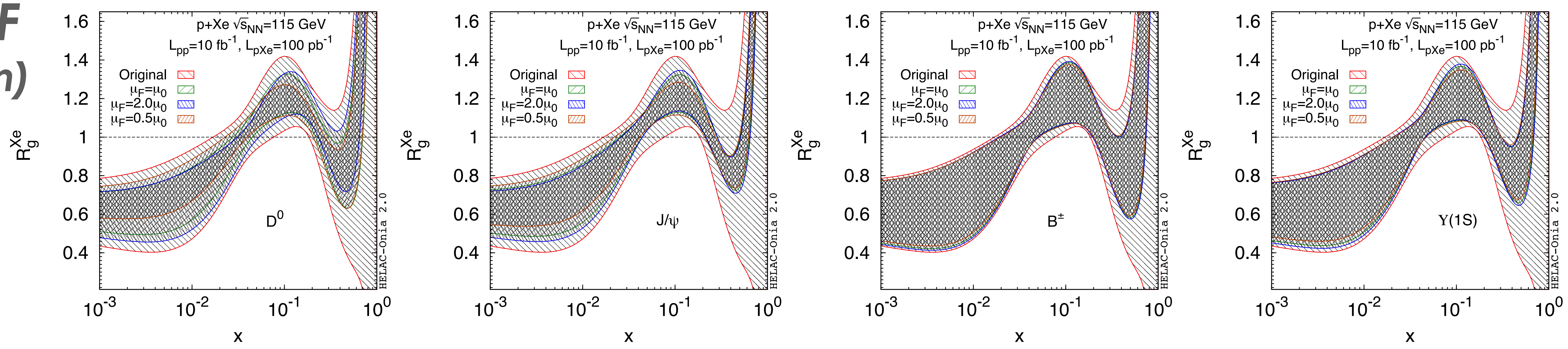

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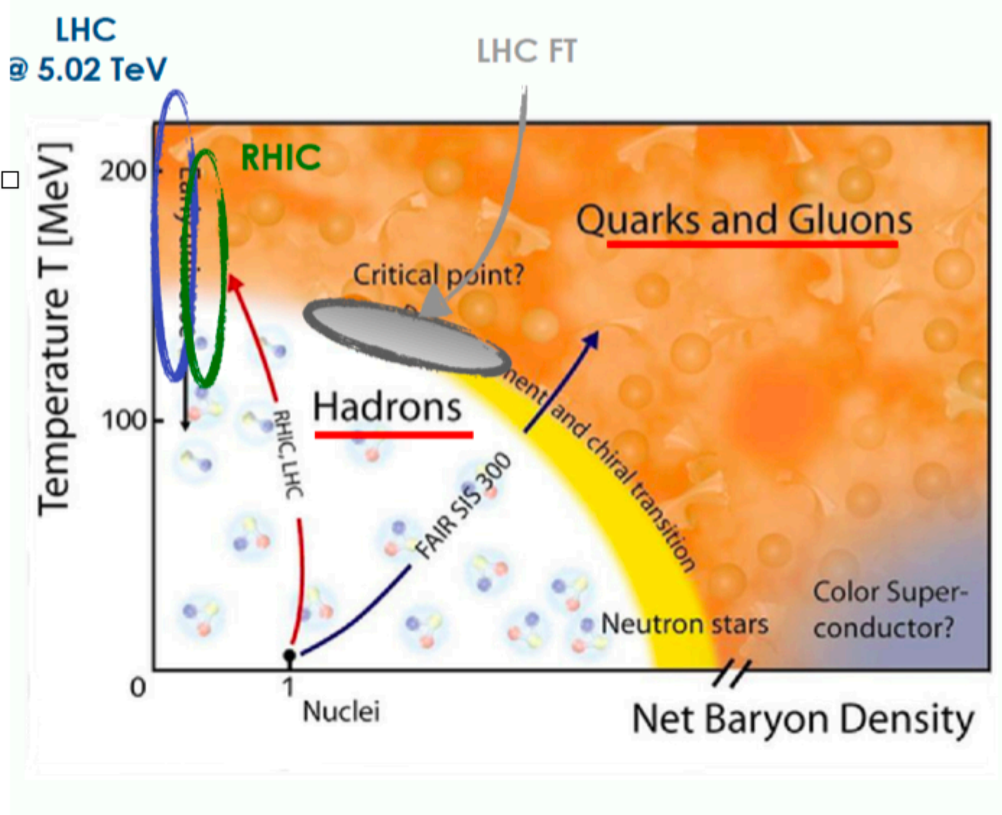

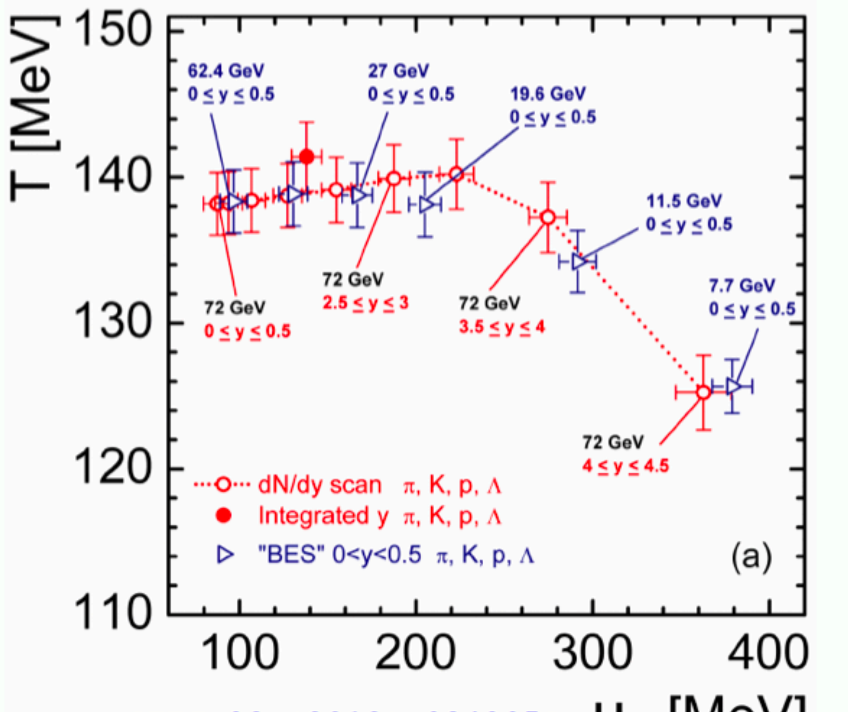

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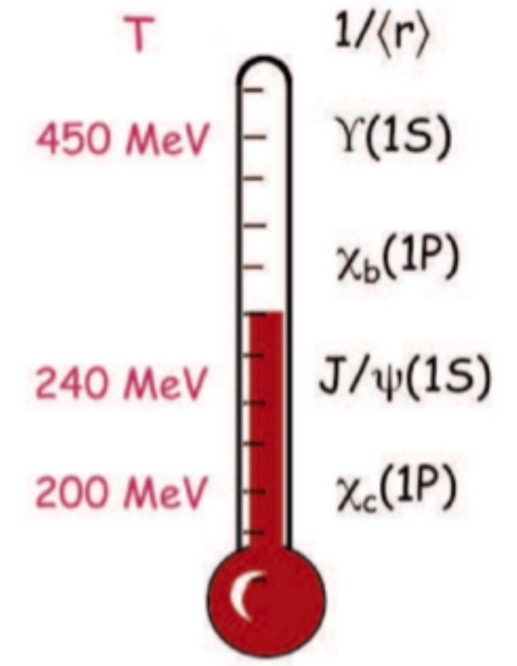
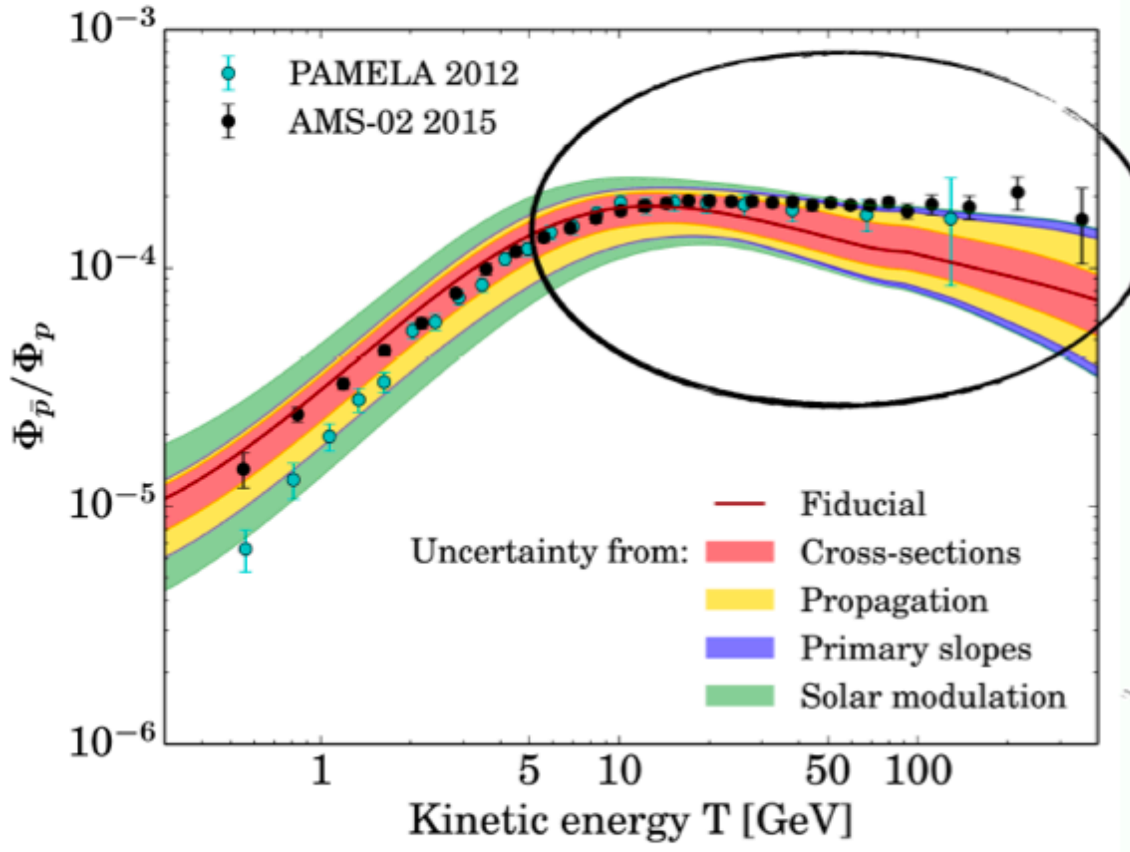
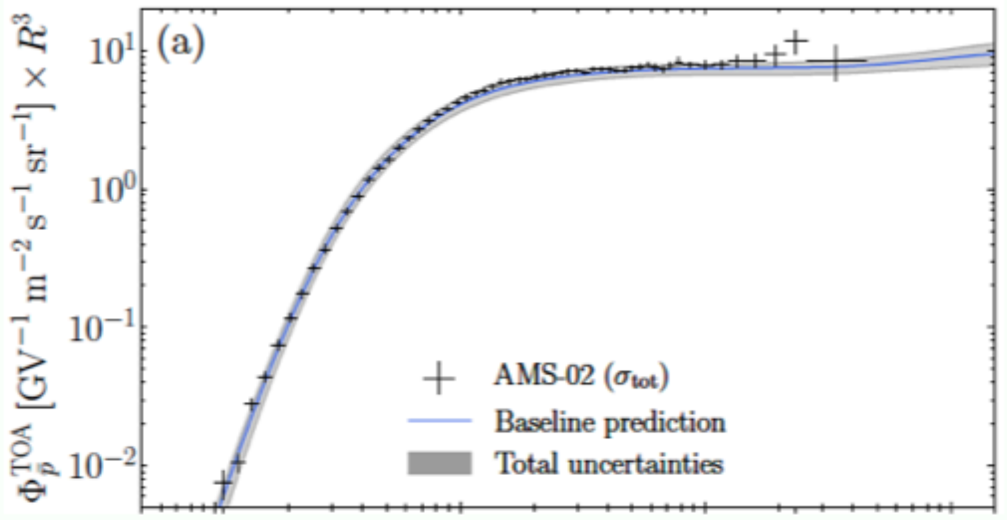


Astroparticle (DM and CR)

[JCAP09 (2015) 023]



[ArXiv:1906.07119]



- Main uncertainty still due to cross sections!

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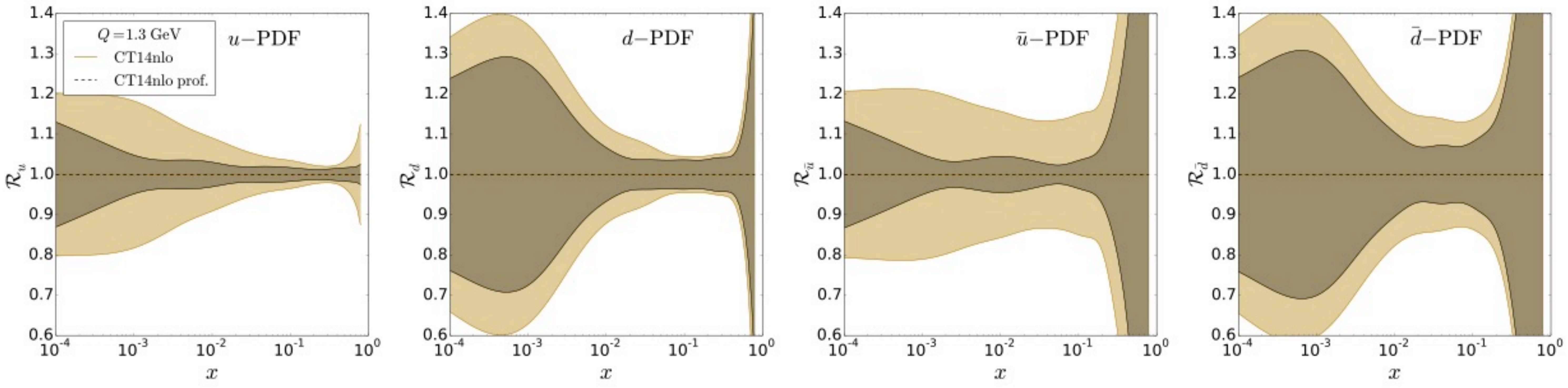

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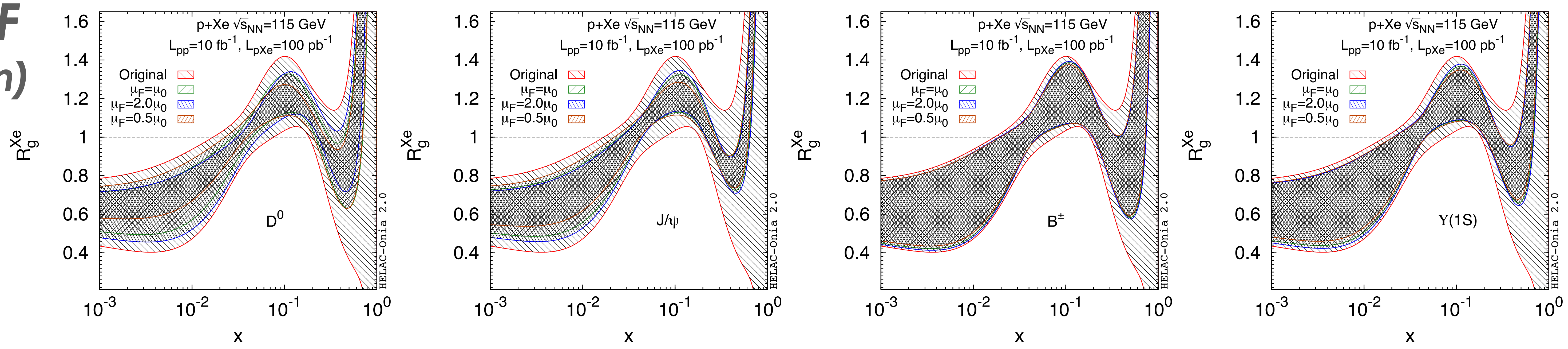

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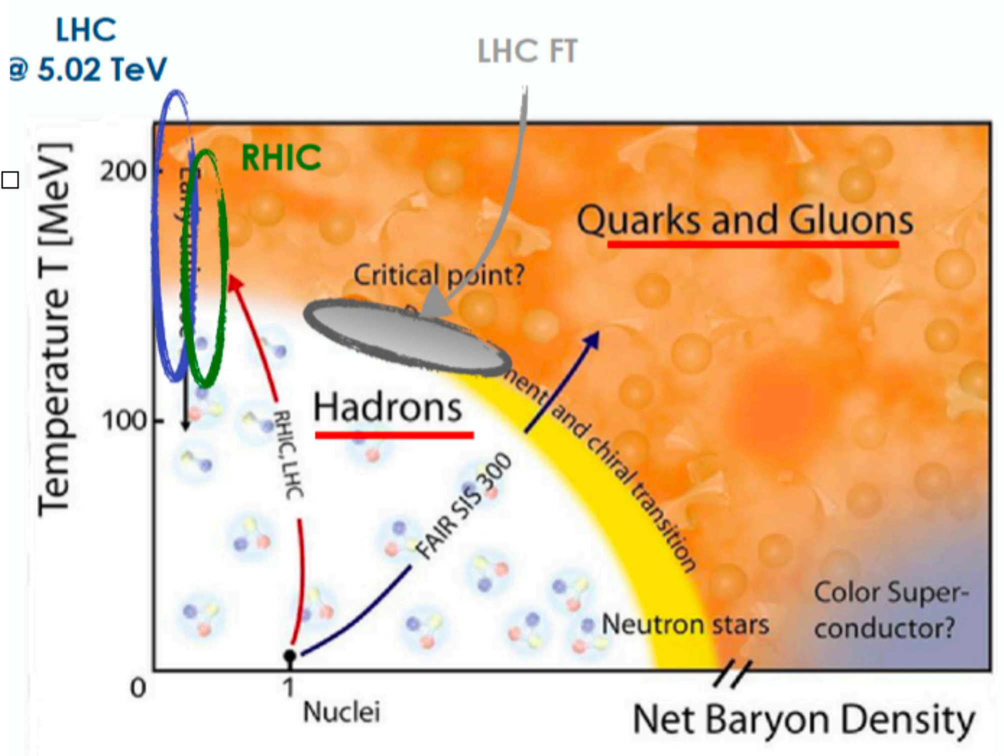
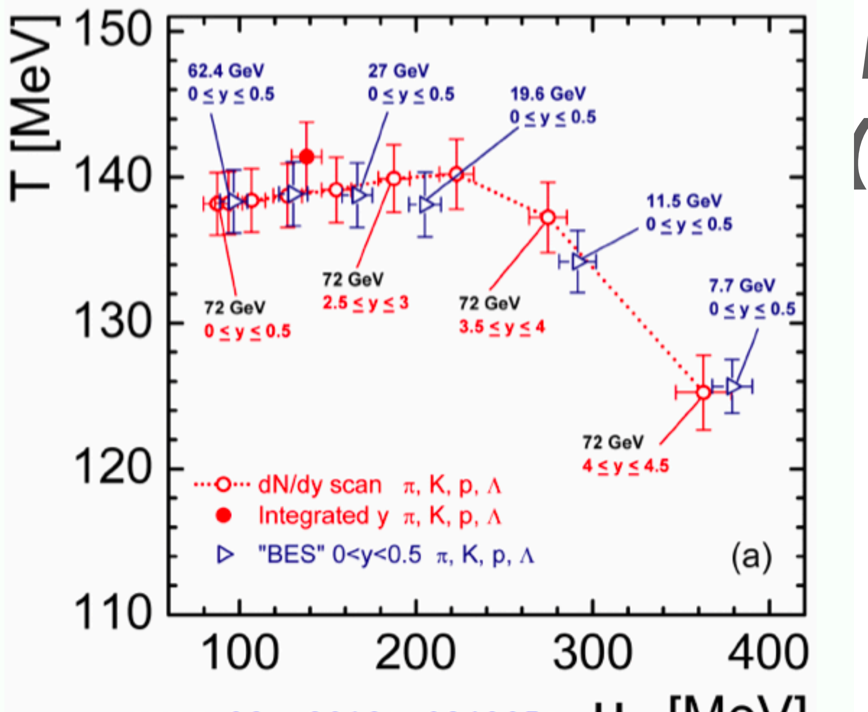
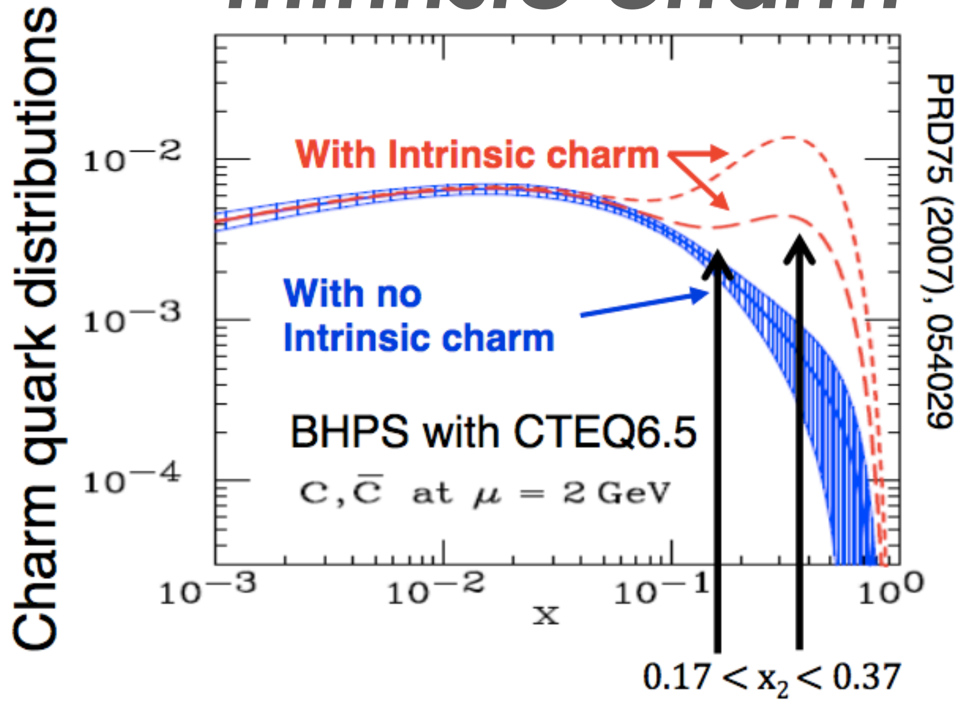




[PRC 98 (2018) 034905]

Intrinsic charm



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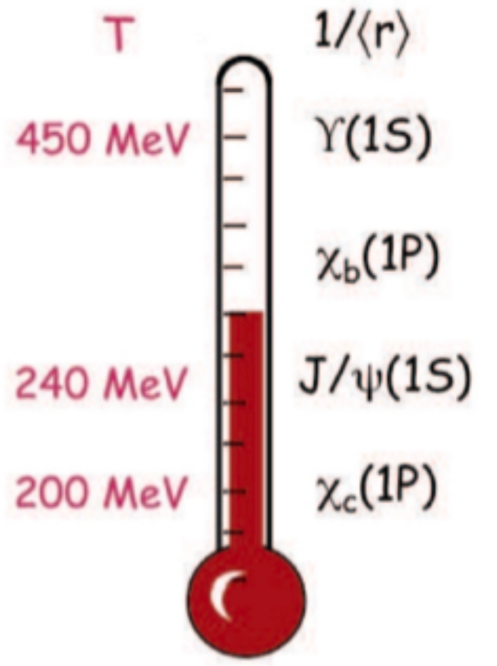

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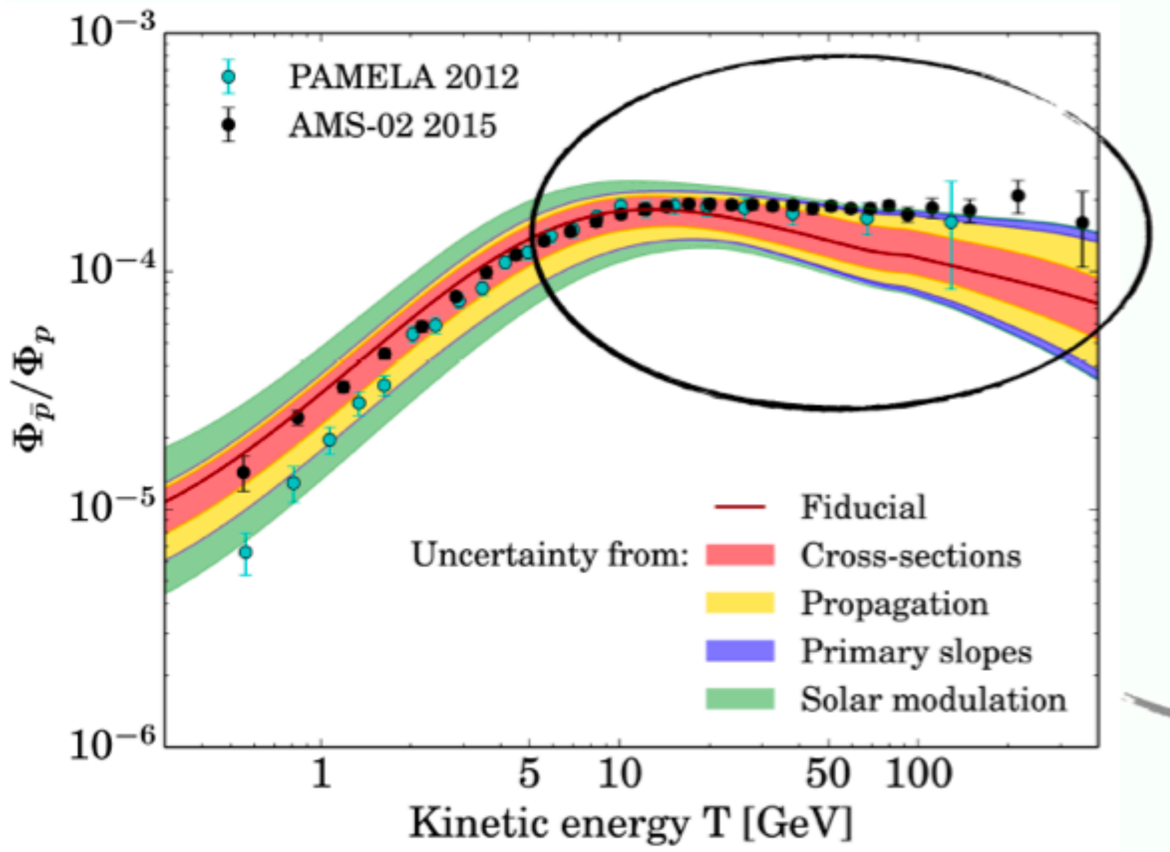
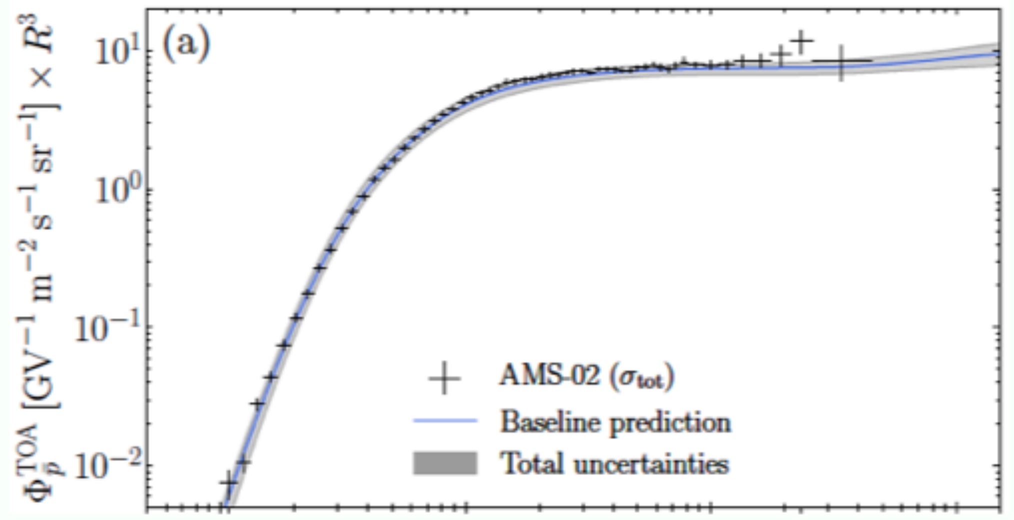


[ArXiv:1906.07119]



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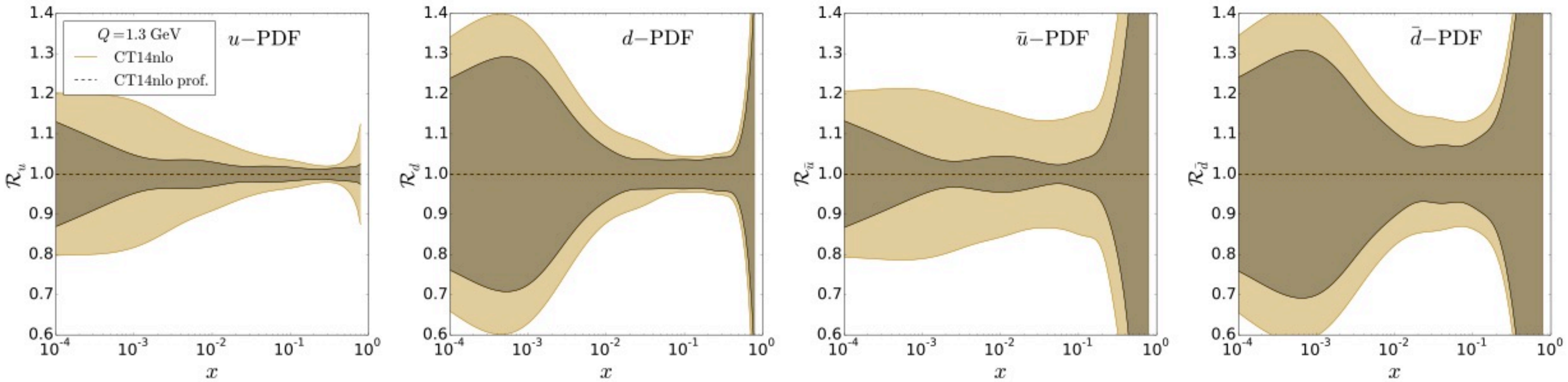

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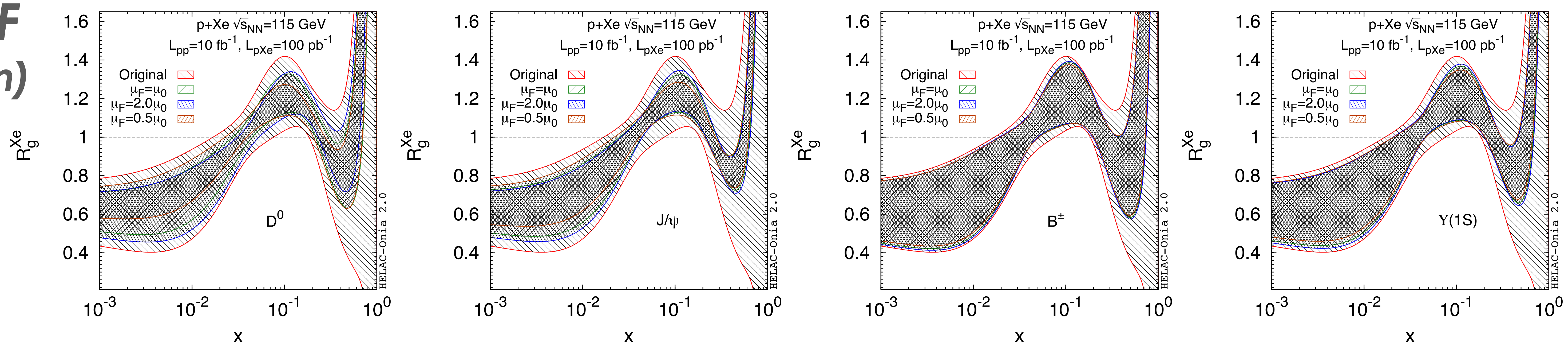
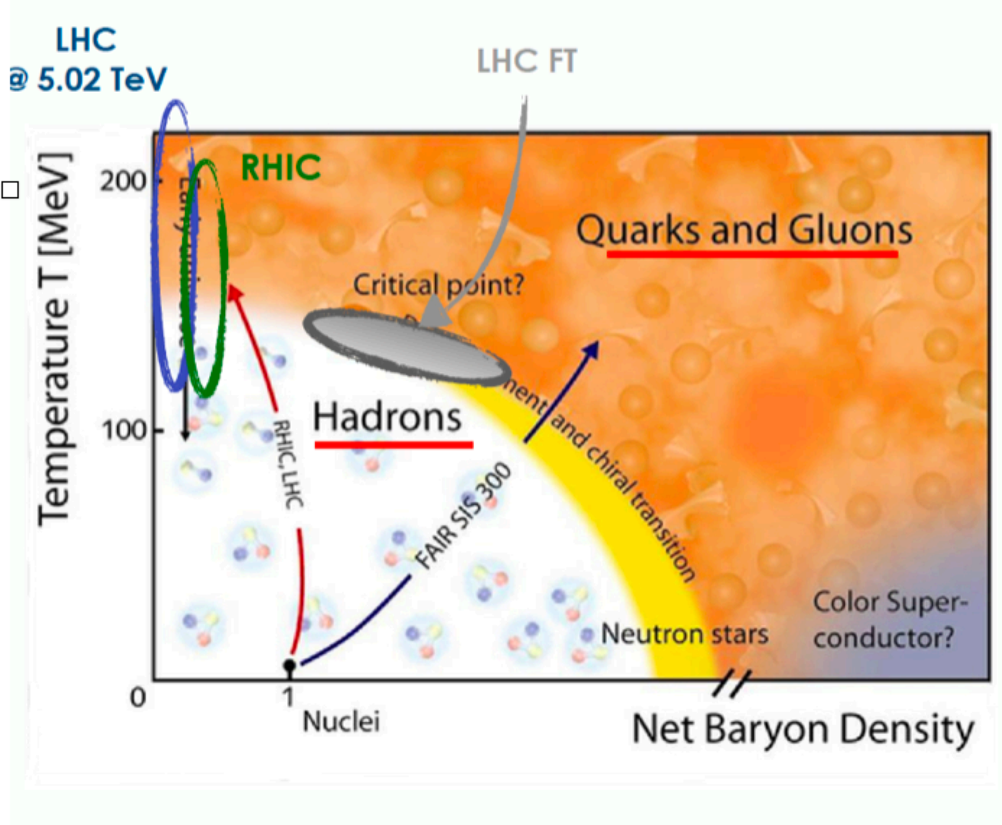
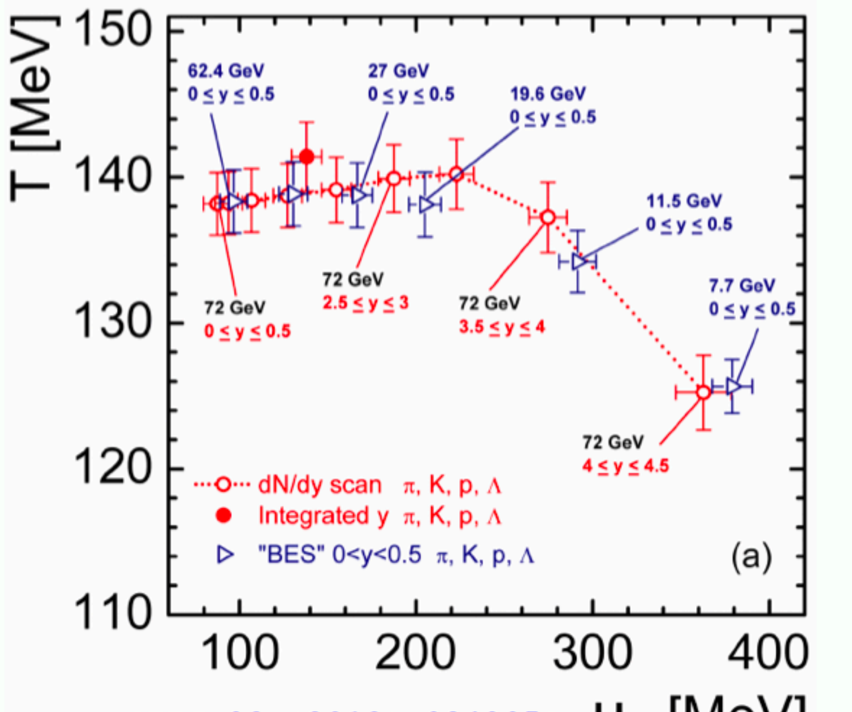


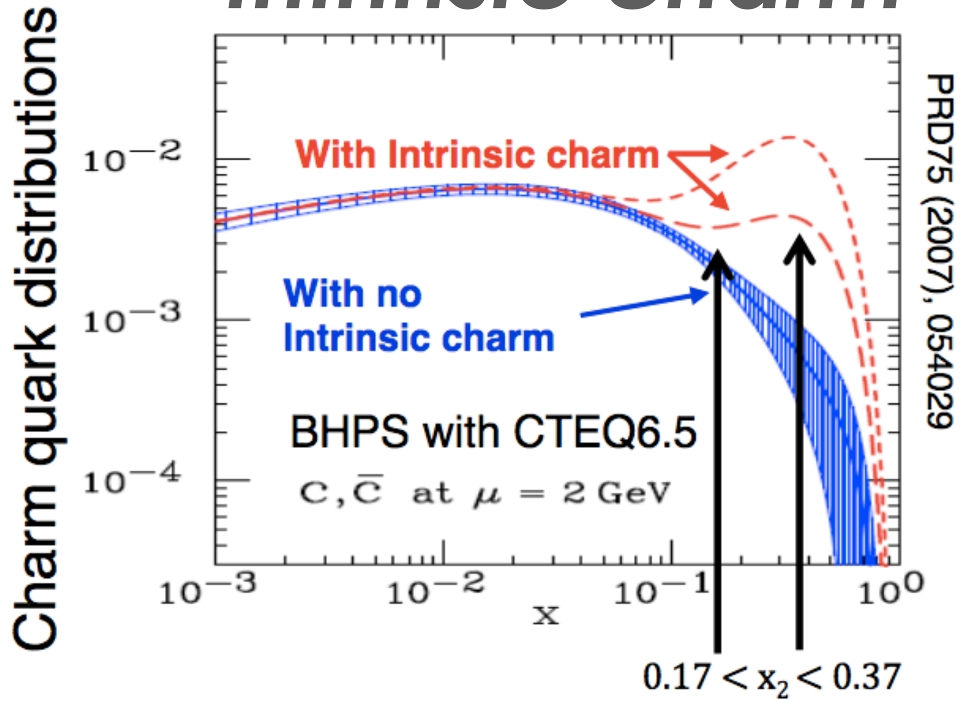
Heavy-Ion and QCD phase space





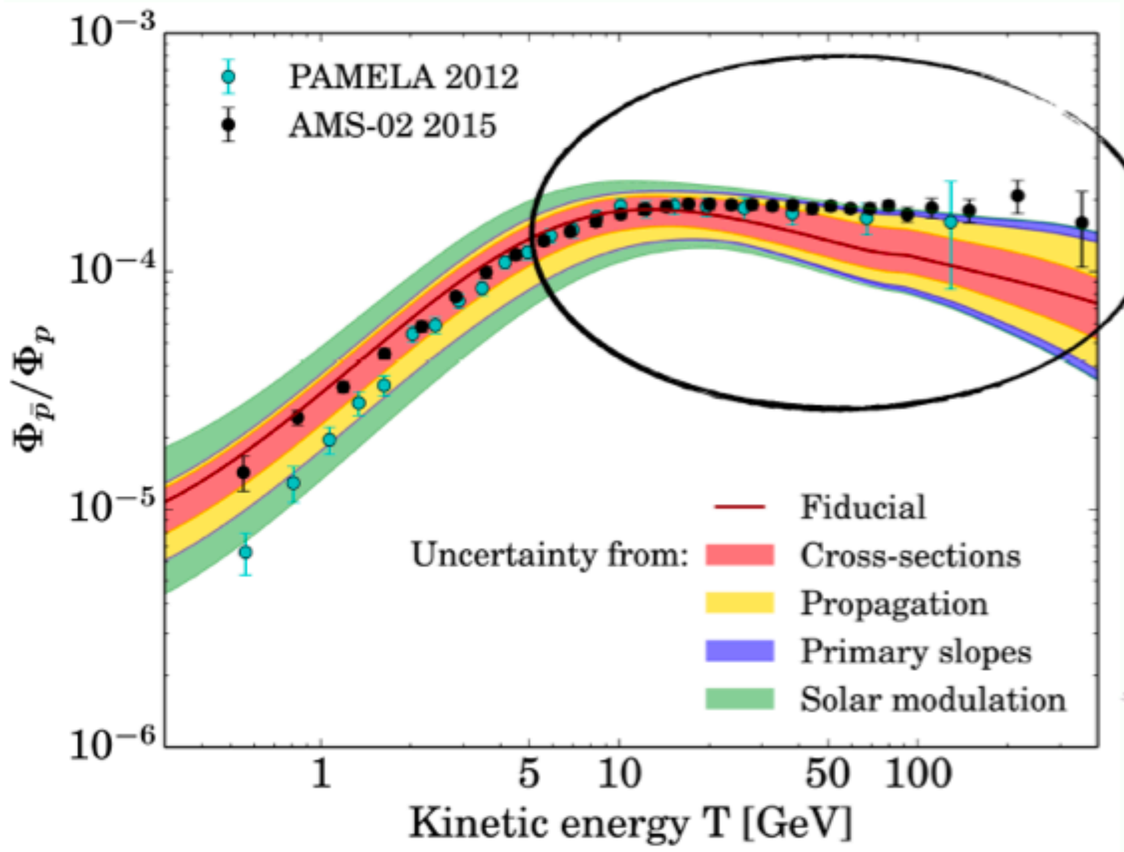
[PRC 98 (2018) 034905]

Intrinsic charm

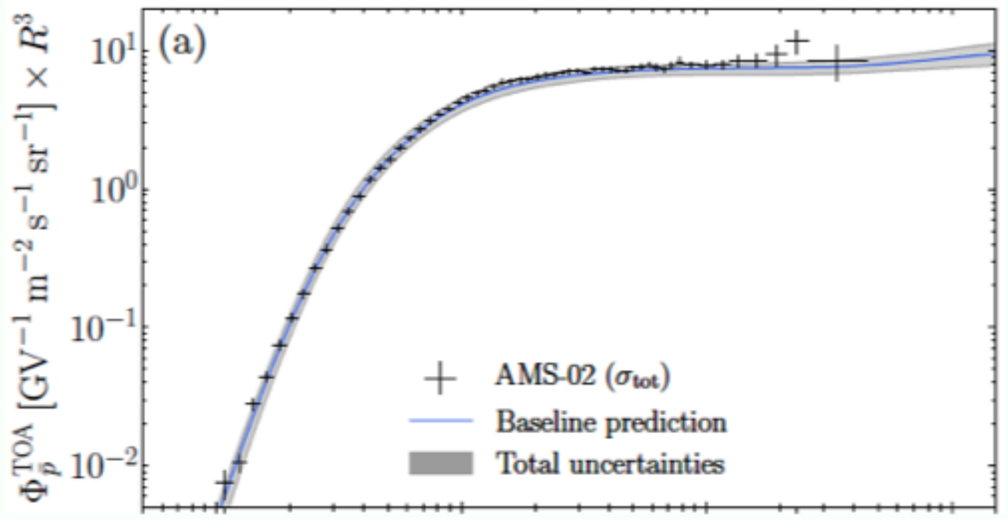


Astroparticle (DM and CR)

[JCAP09 (2015) 023]

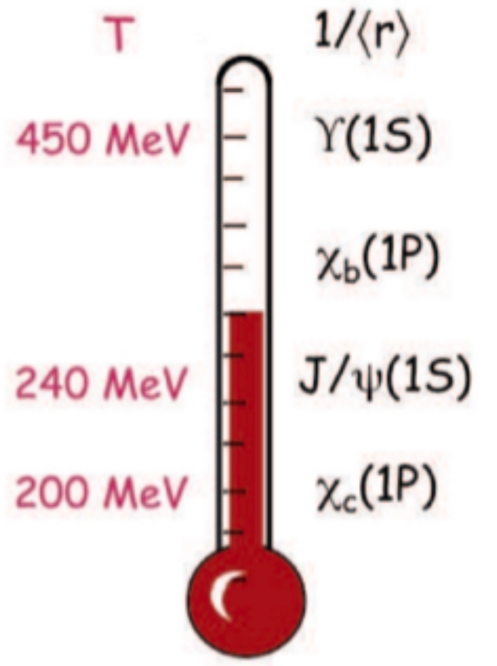


[ArXiv:1906.07119]



- Main uncertainty still due to cross sections!

$c\bar{c}$ bound states



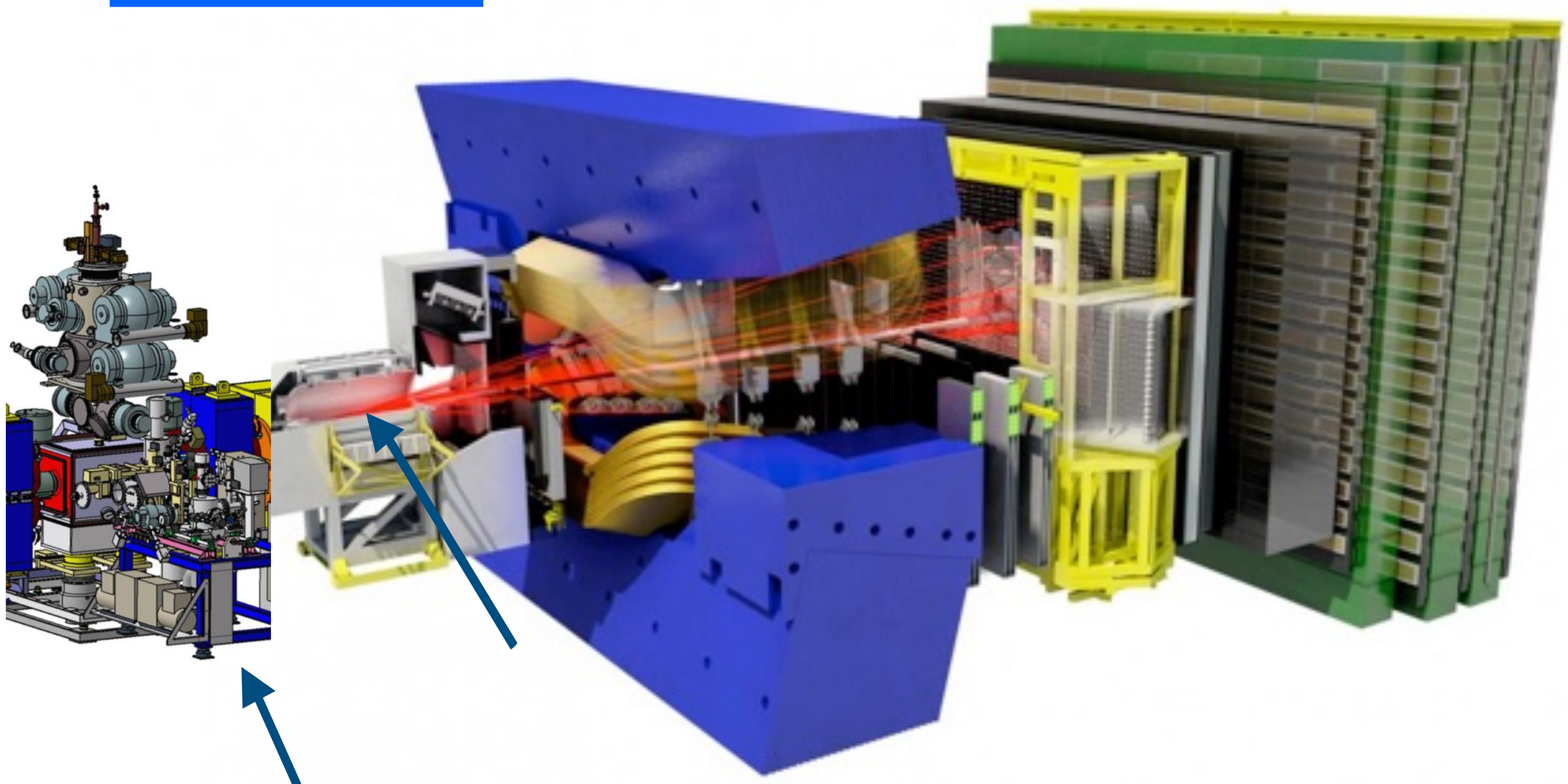
Special Runs

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

a polarised target at LHCb

https://arxiv.org/abs/1901.08002
https://arxiv.org/abs/2111.04515

LHC beam



polarised target
(beam-gas)

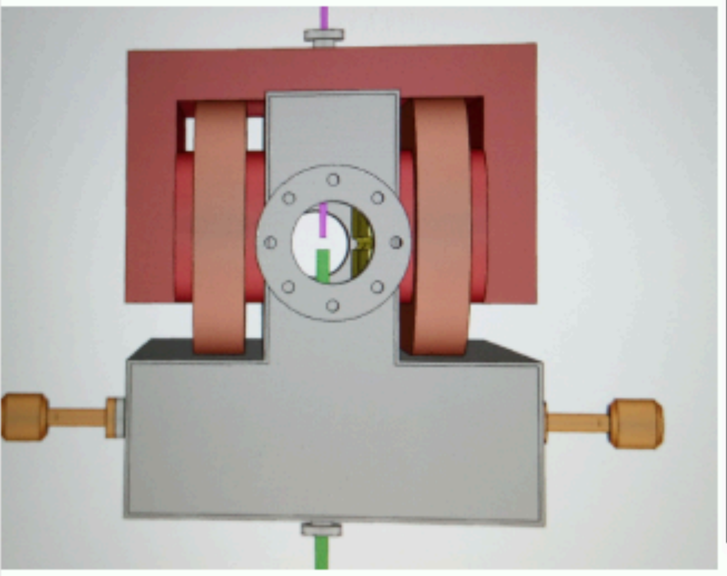
beam-beam
collisions

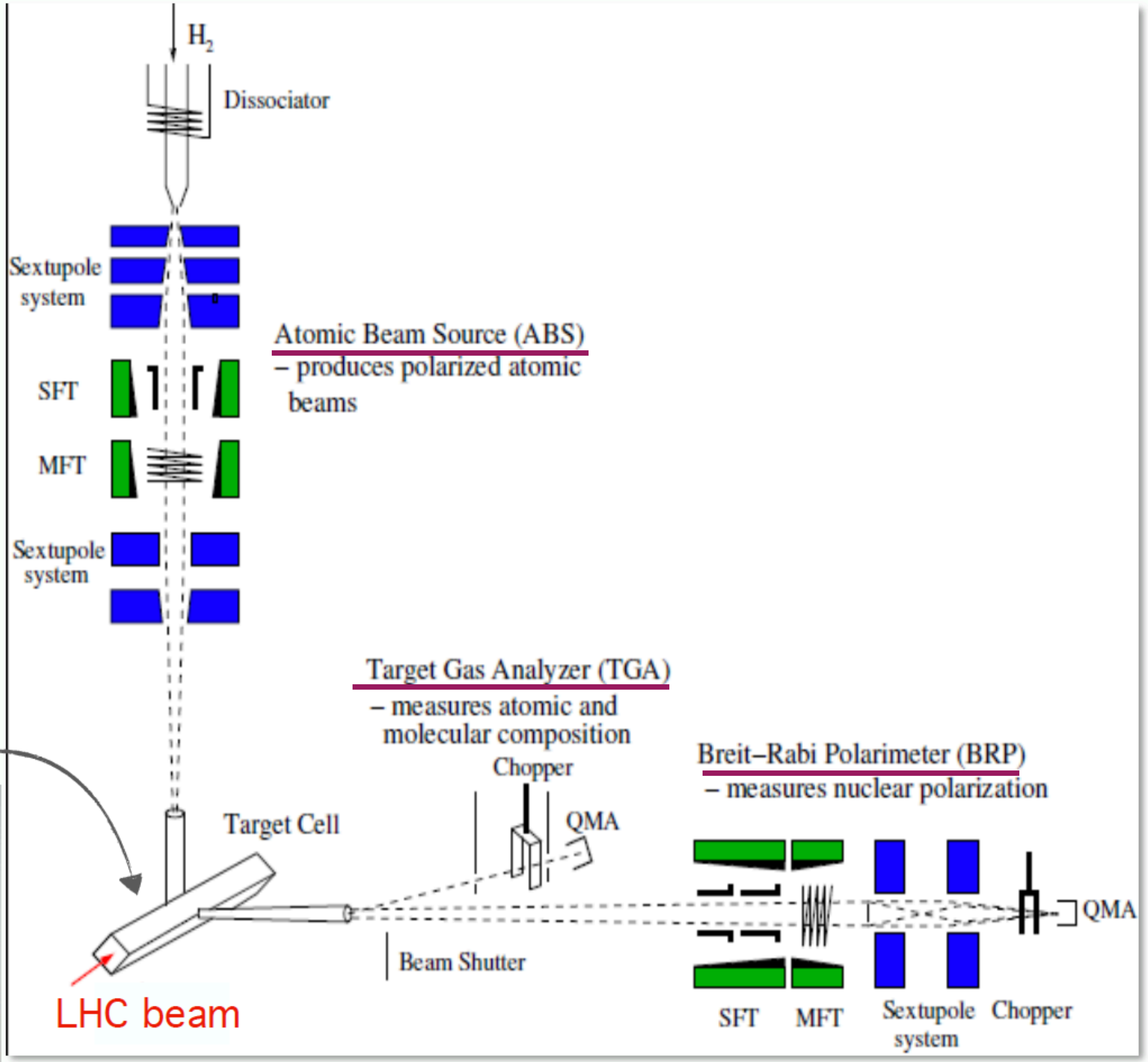
The LHC beams cannot be polarised

SMOG2 is not only a unique project itself, but also a great playground for LHCspin

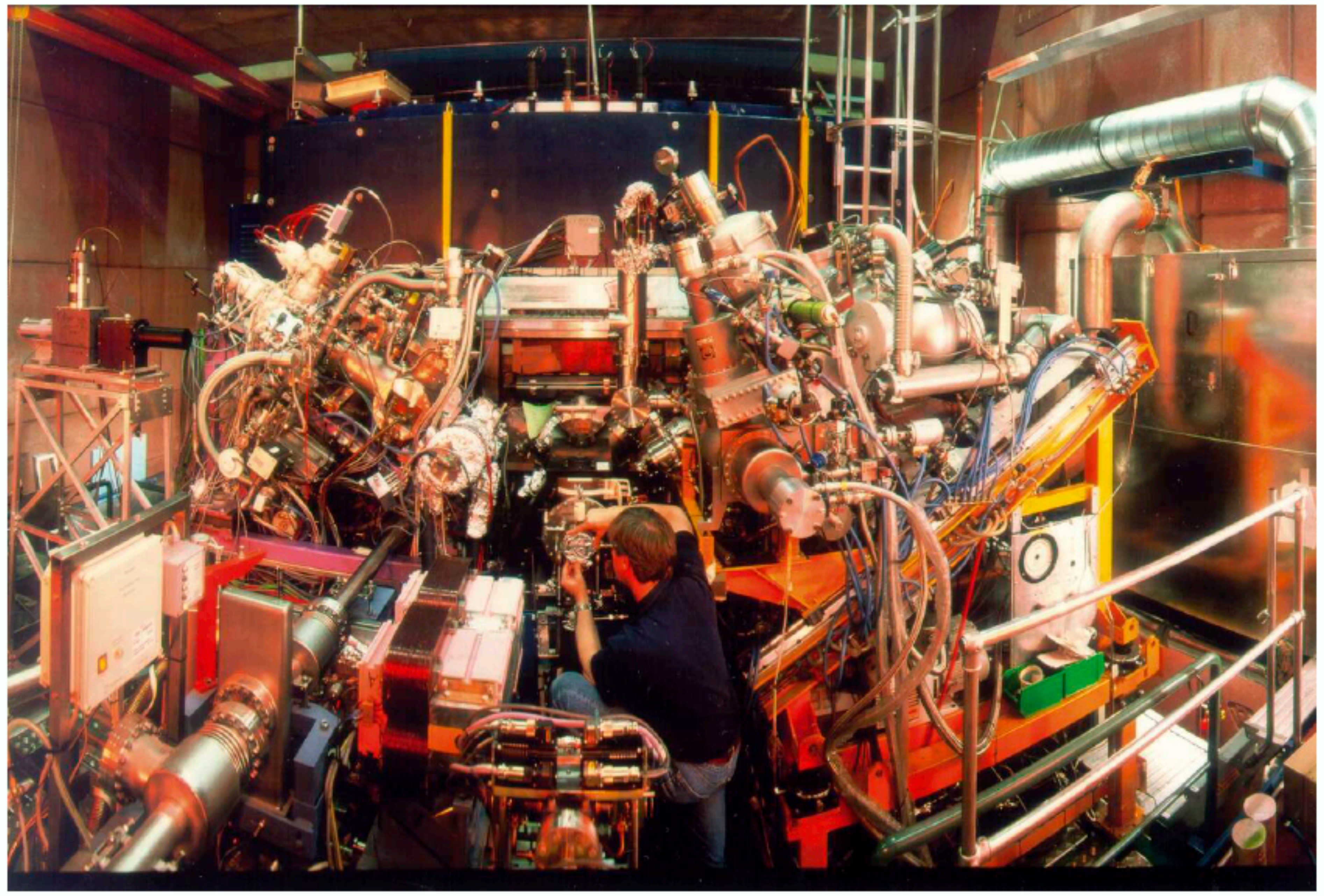
LHCspin experimental setup

dipole





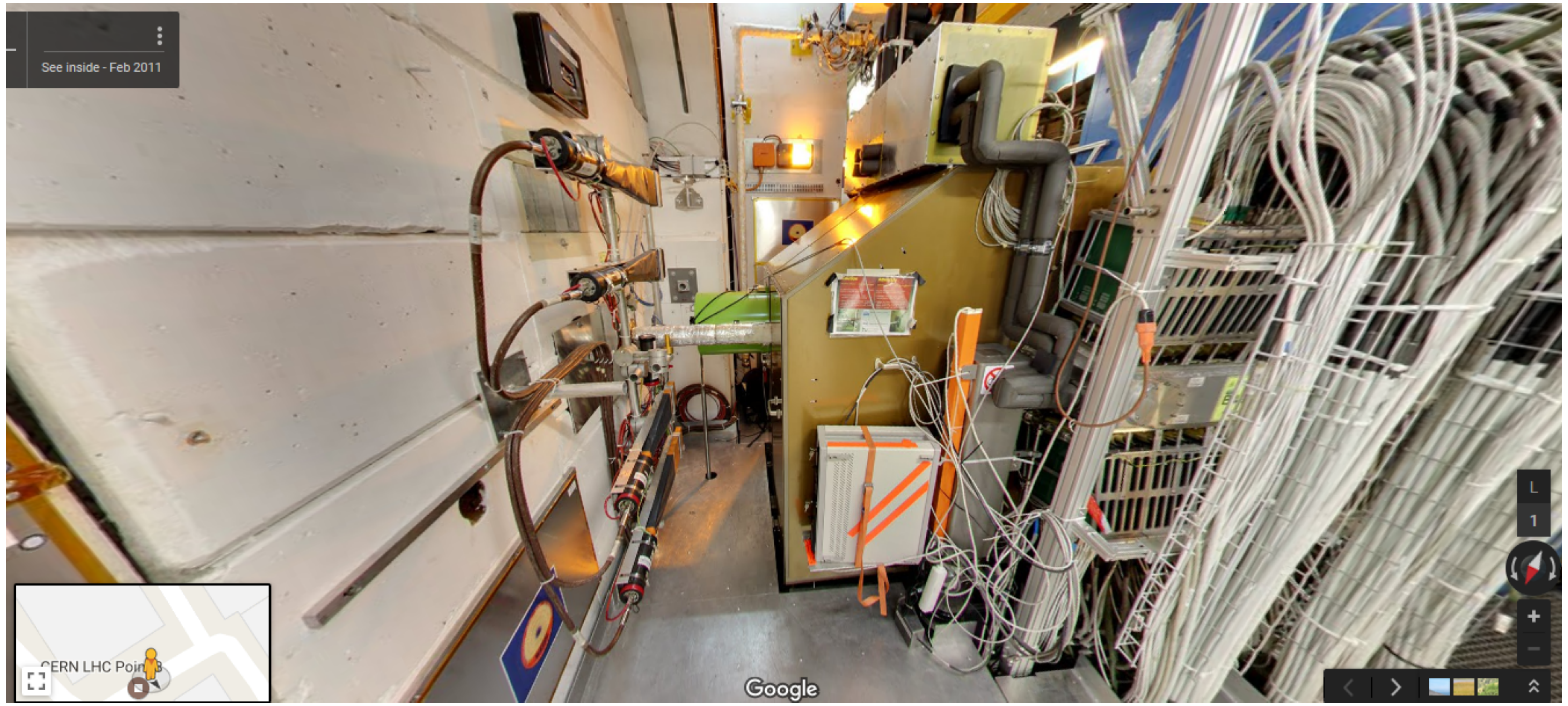
- Start from the well established HERMES setup @ DESY...
- ... to create the next generation of fixed target polarisation techniques!



[NIMA 540 (2005) 68-101]

HERMES PGT

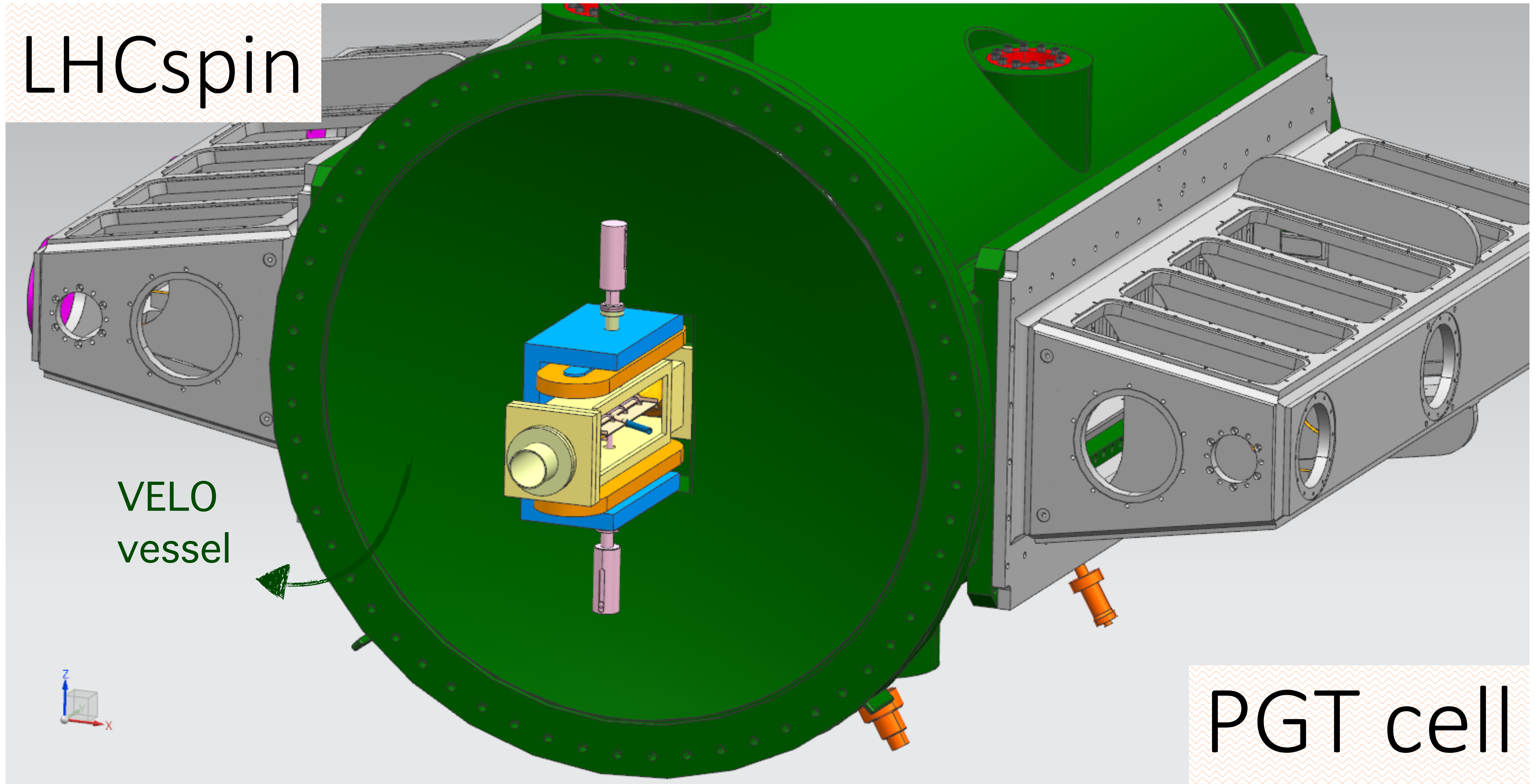
From there to here

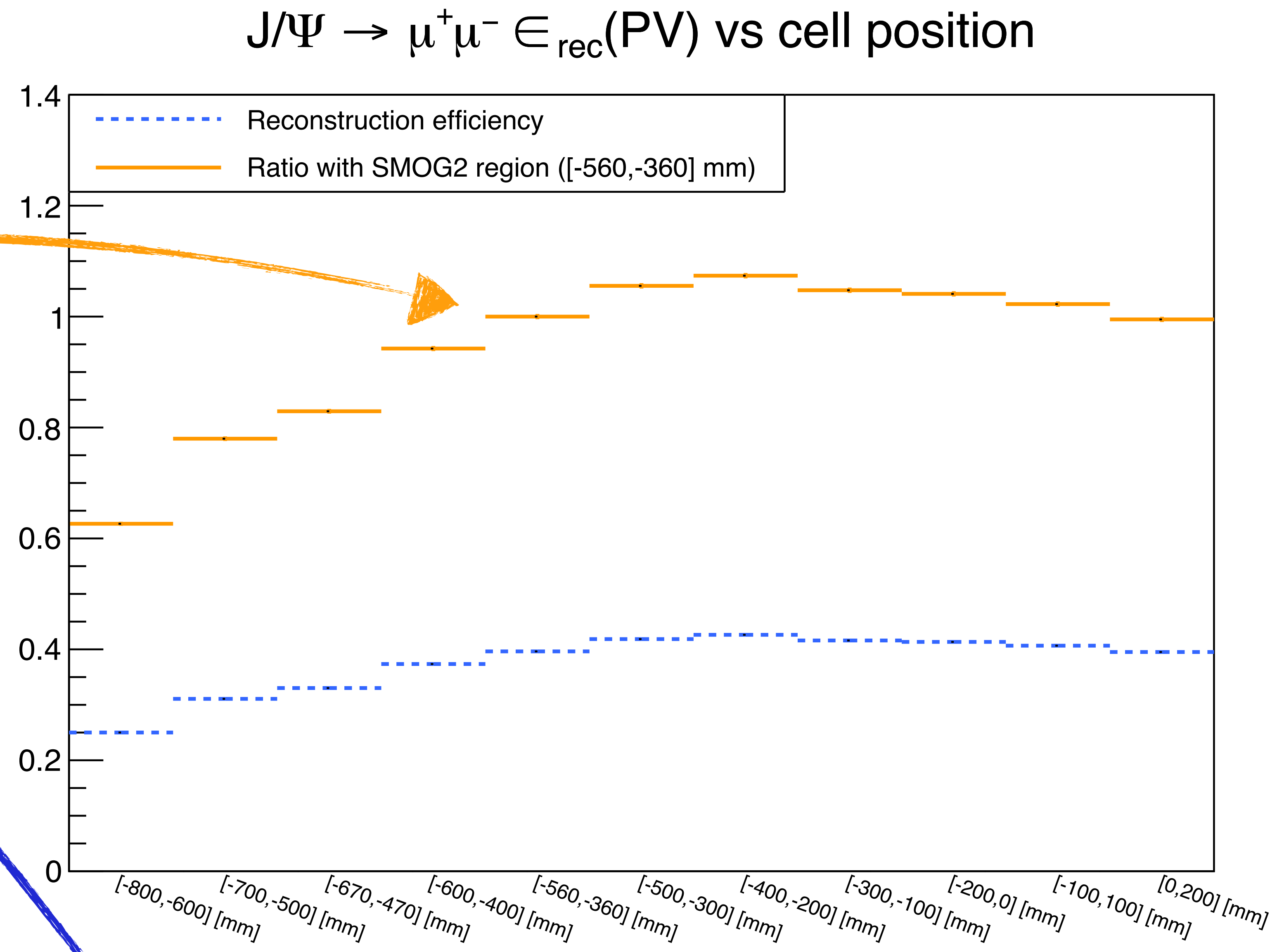


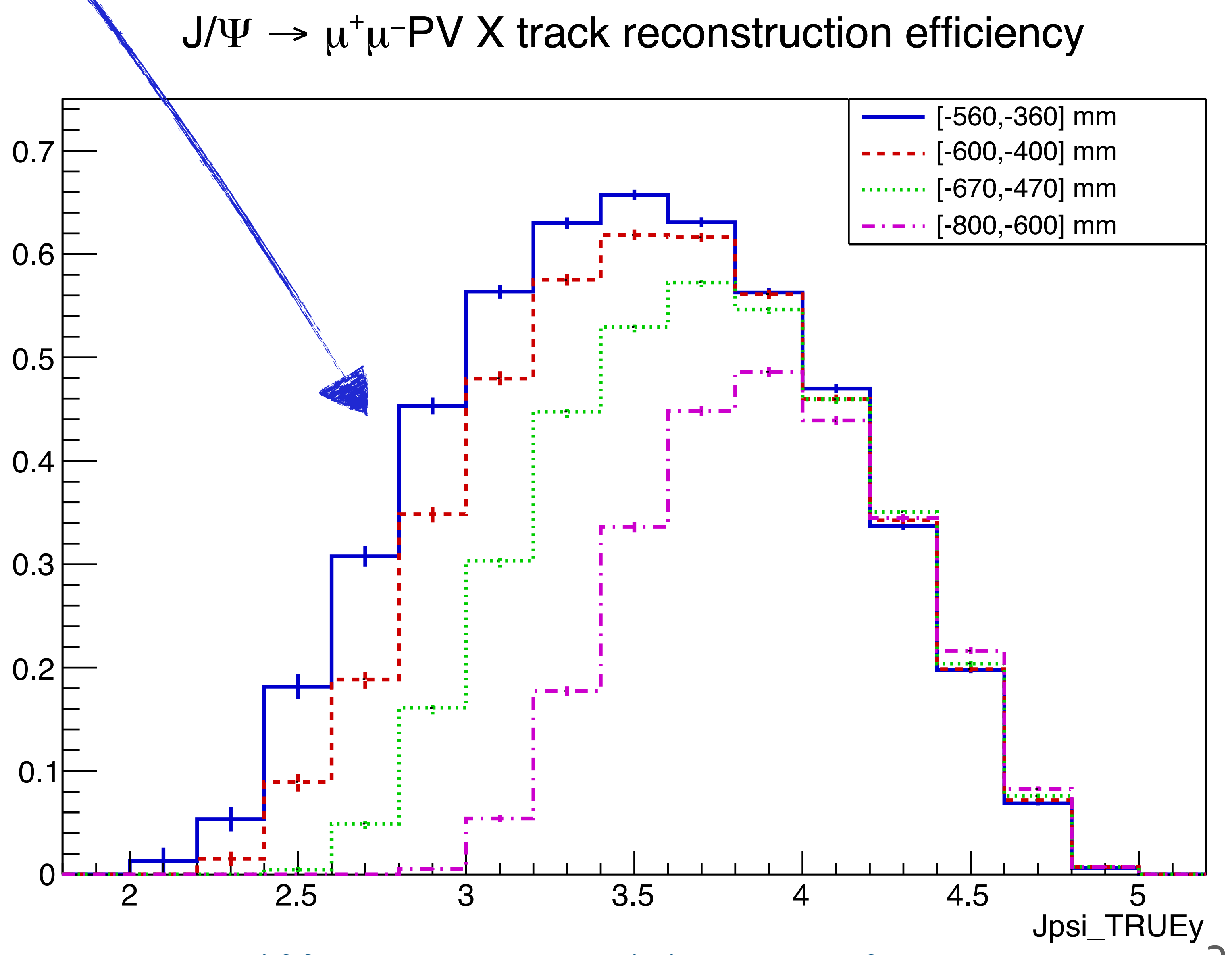
Space available in front of LHCb

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
- Work ongoing to develop dedicated trigger lines and to improve reconstruction algorithms for Run 3



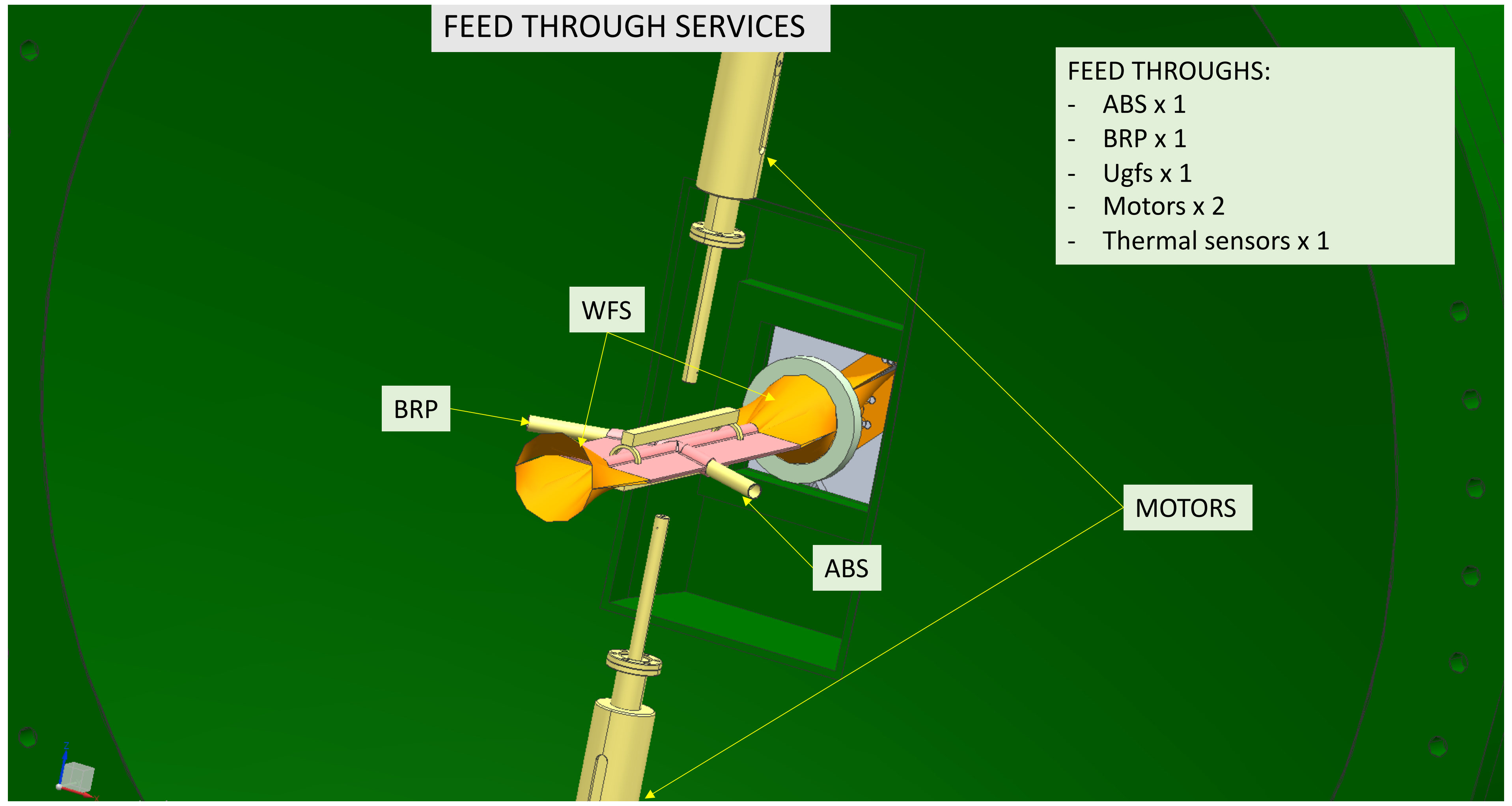


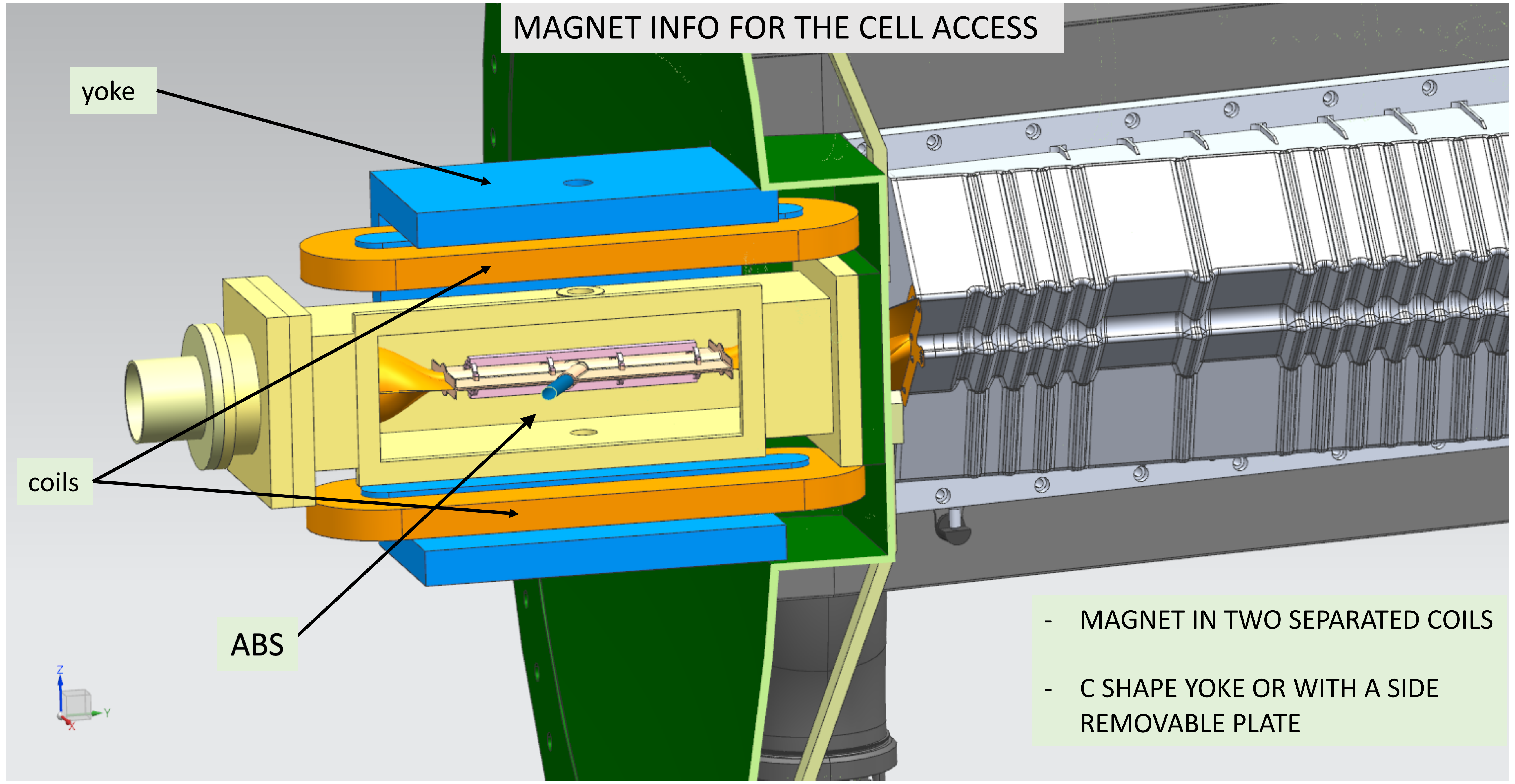


different positions of the cell

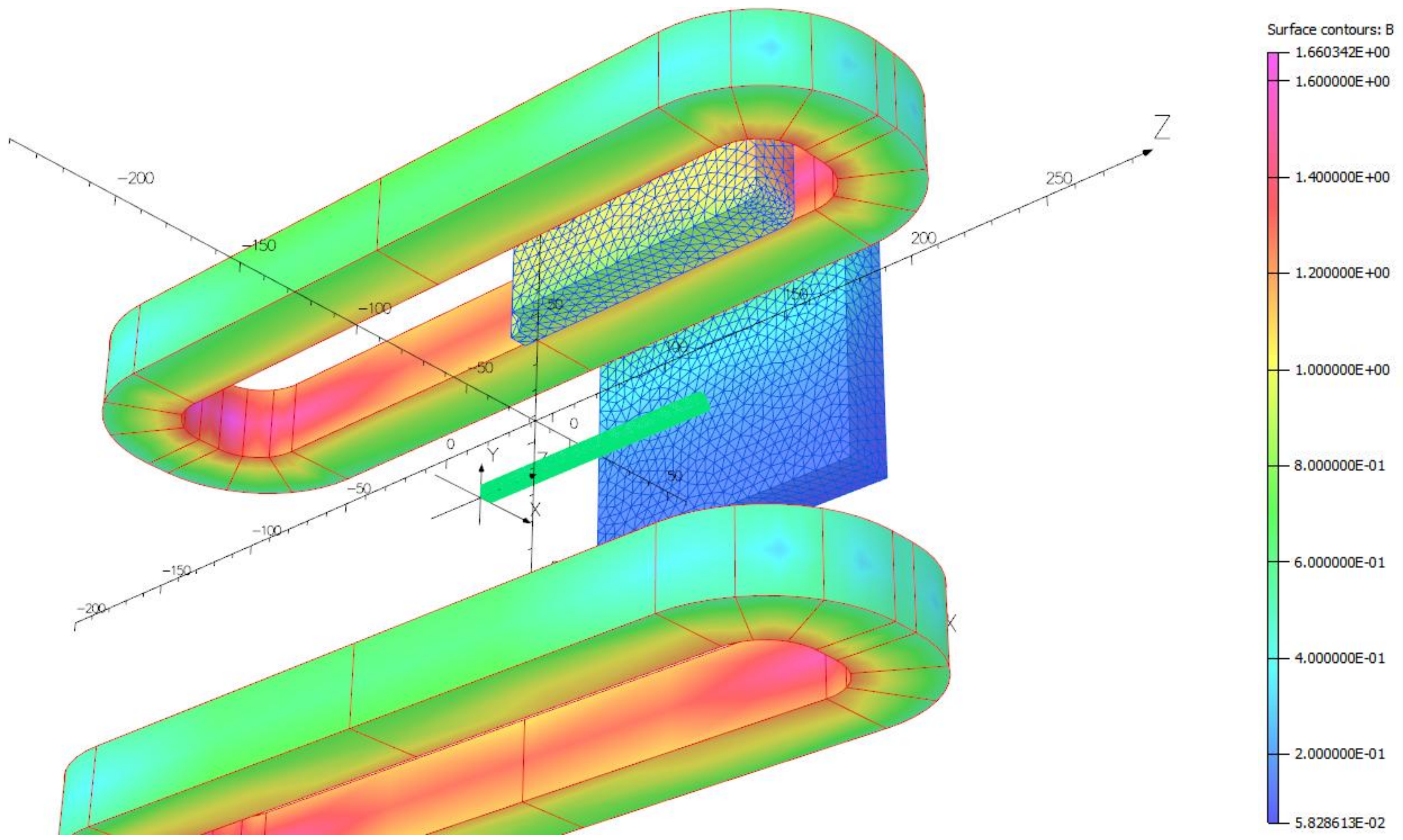
PGT implementation into LHCb

- Inject polarised gas via ABS and unpolarised gas via UGFS



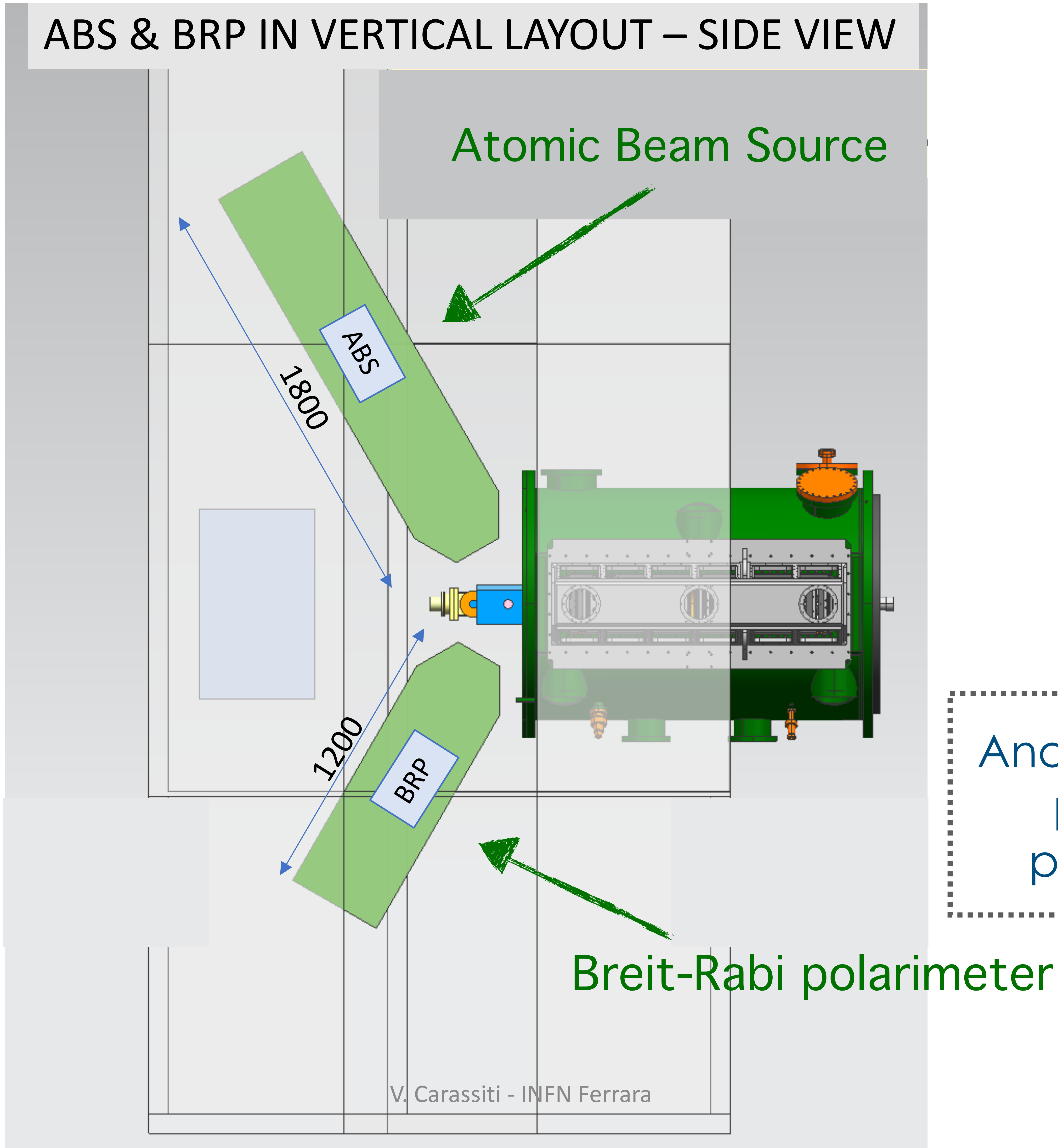


- Compact dipole magnet → static transverse field
- Superconductive coils + iron yoke configuration fits the space constraints
- $B = 300$ mT with polarity inversion, $\Delta B/B \simeq 10\,\%$, suitable to avoid beam-induced depolarisation [PoS (SPIN2018)]



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

ABS & BRP implementation into LHCb



- 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 in LHCb: only a modification of the VELO flange is needed
- $P \simeq 85\,\%$ achieved at HERMES

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

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

Another 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

(see E.Steffens' talk)

The physics goals of LHC spin

- 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

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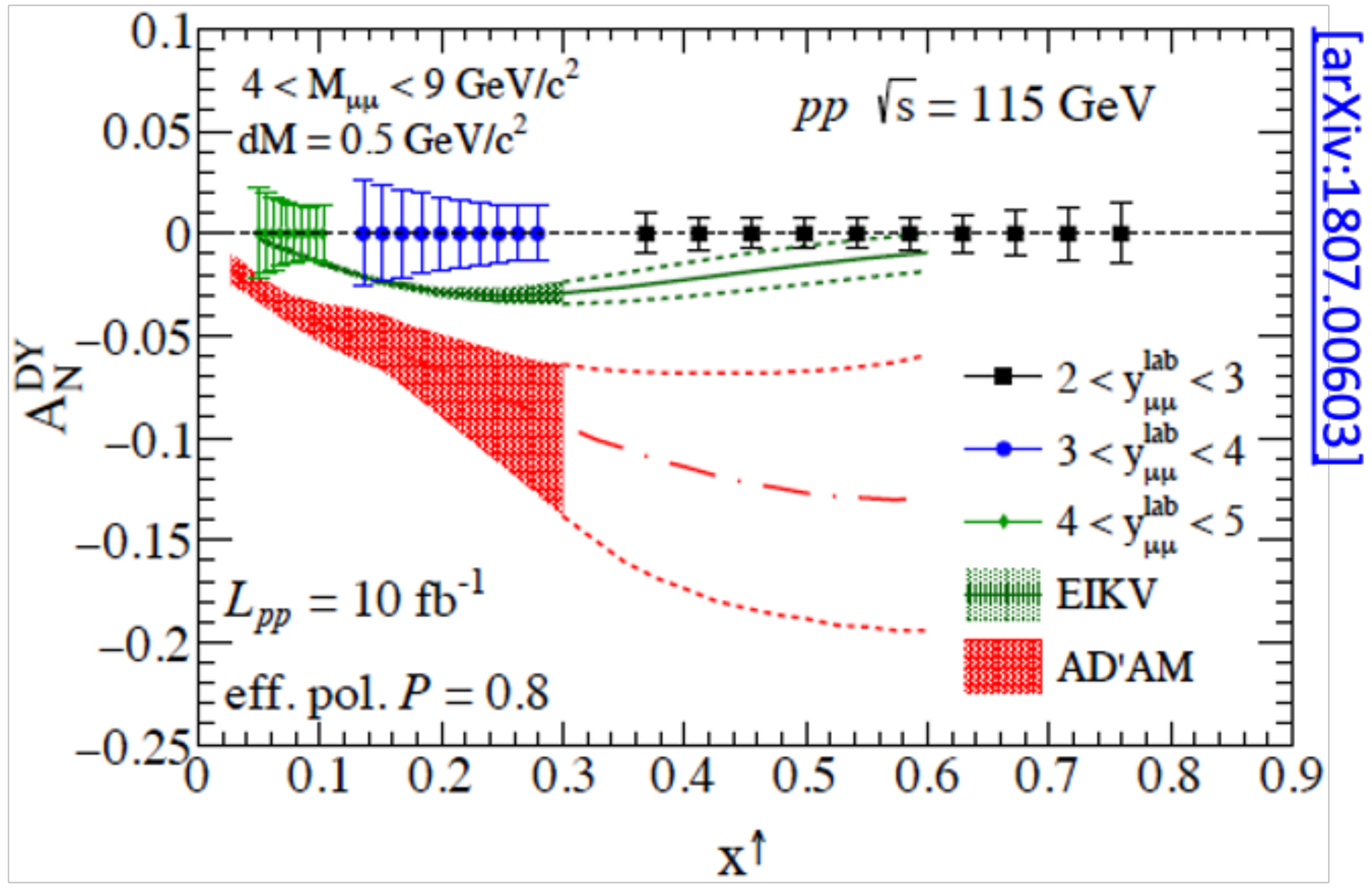
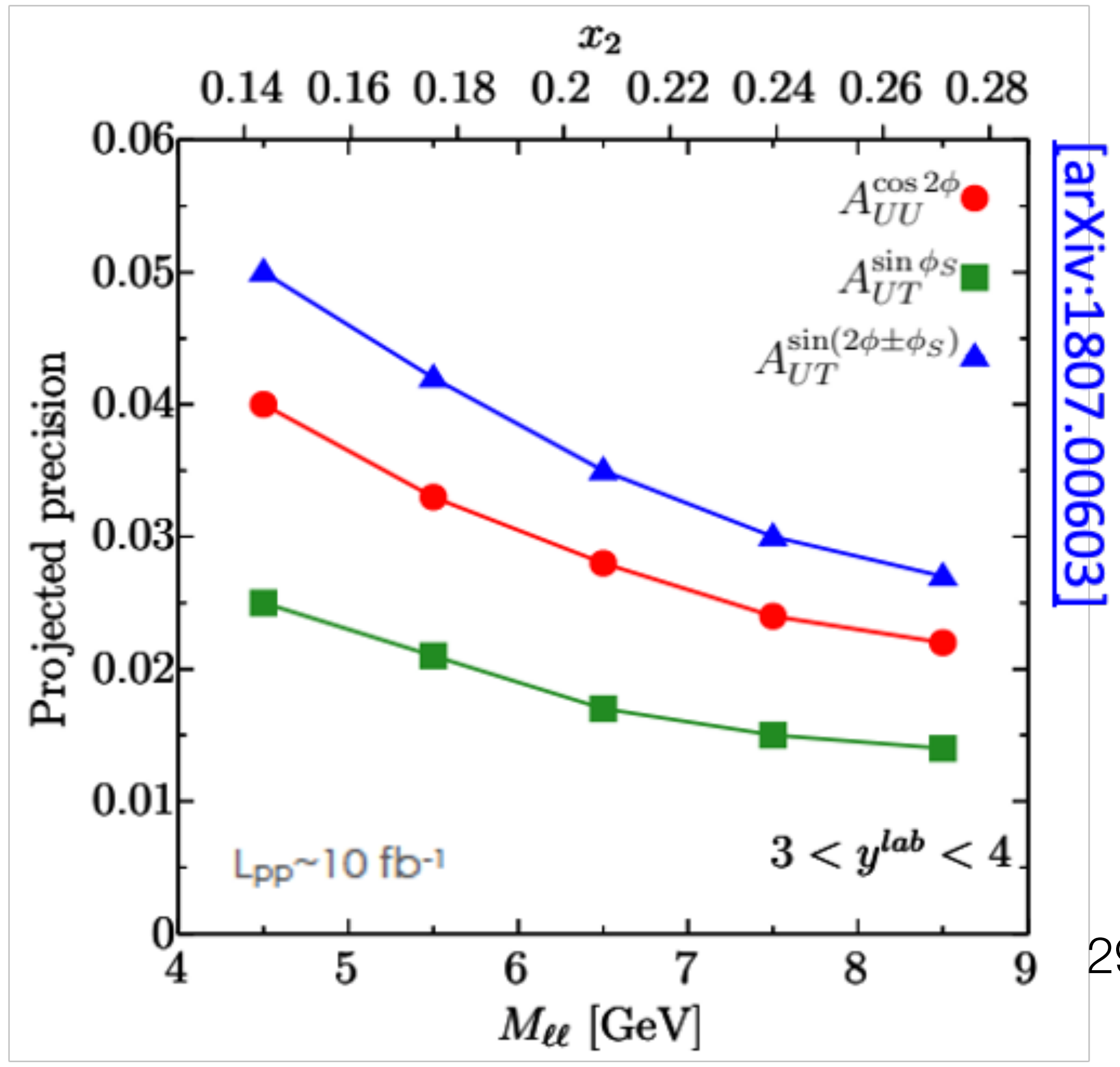


Drell-Yan as a golden channel: theoretically cleanest hard h-h scattering process

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

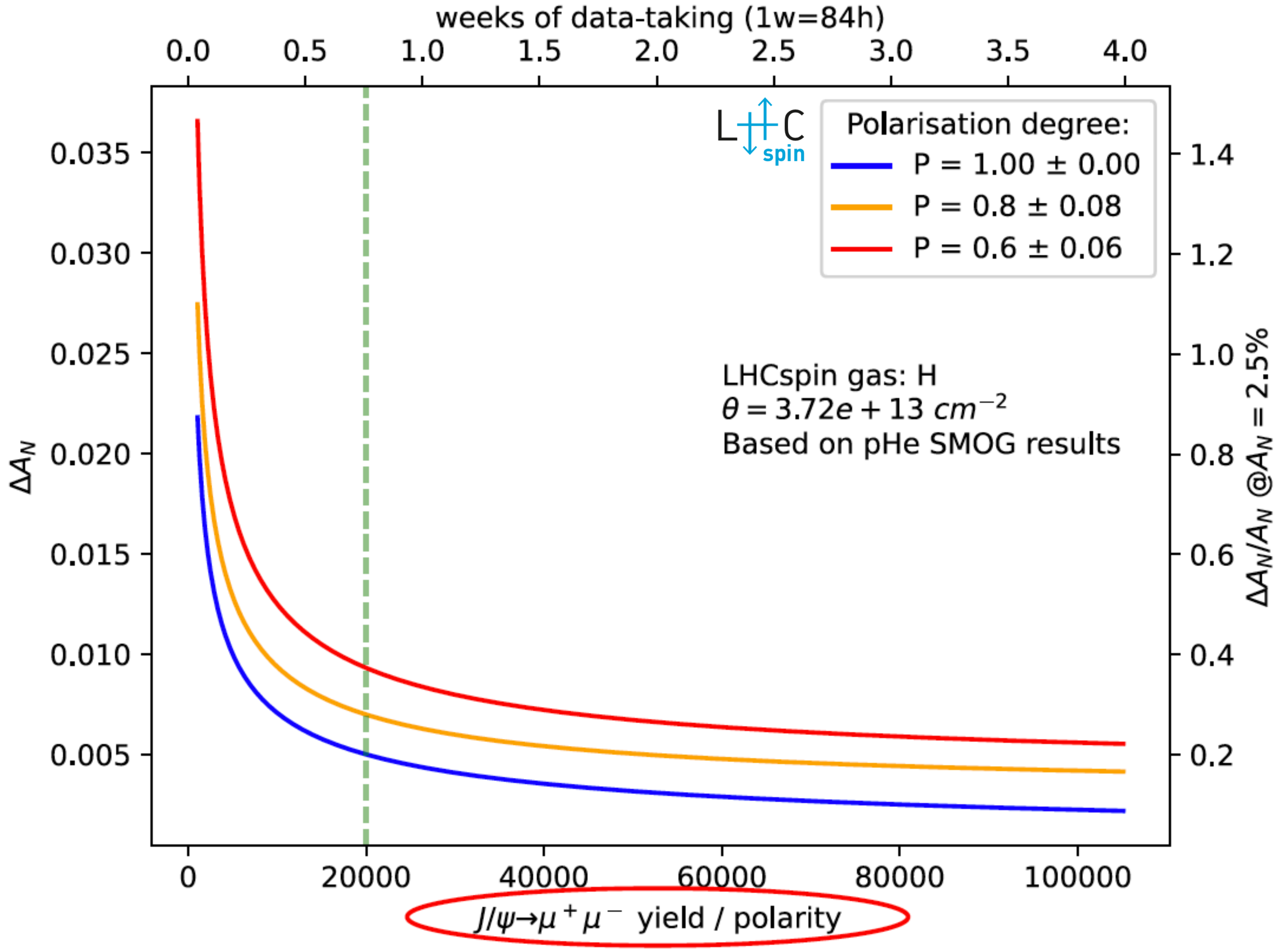
dominant: $\bar{q}(x_{beam}) + q(x_{target}) \rightarrow \mu^+\mu^-$

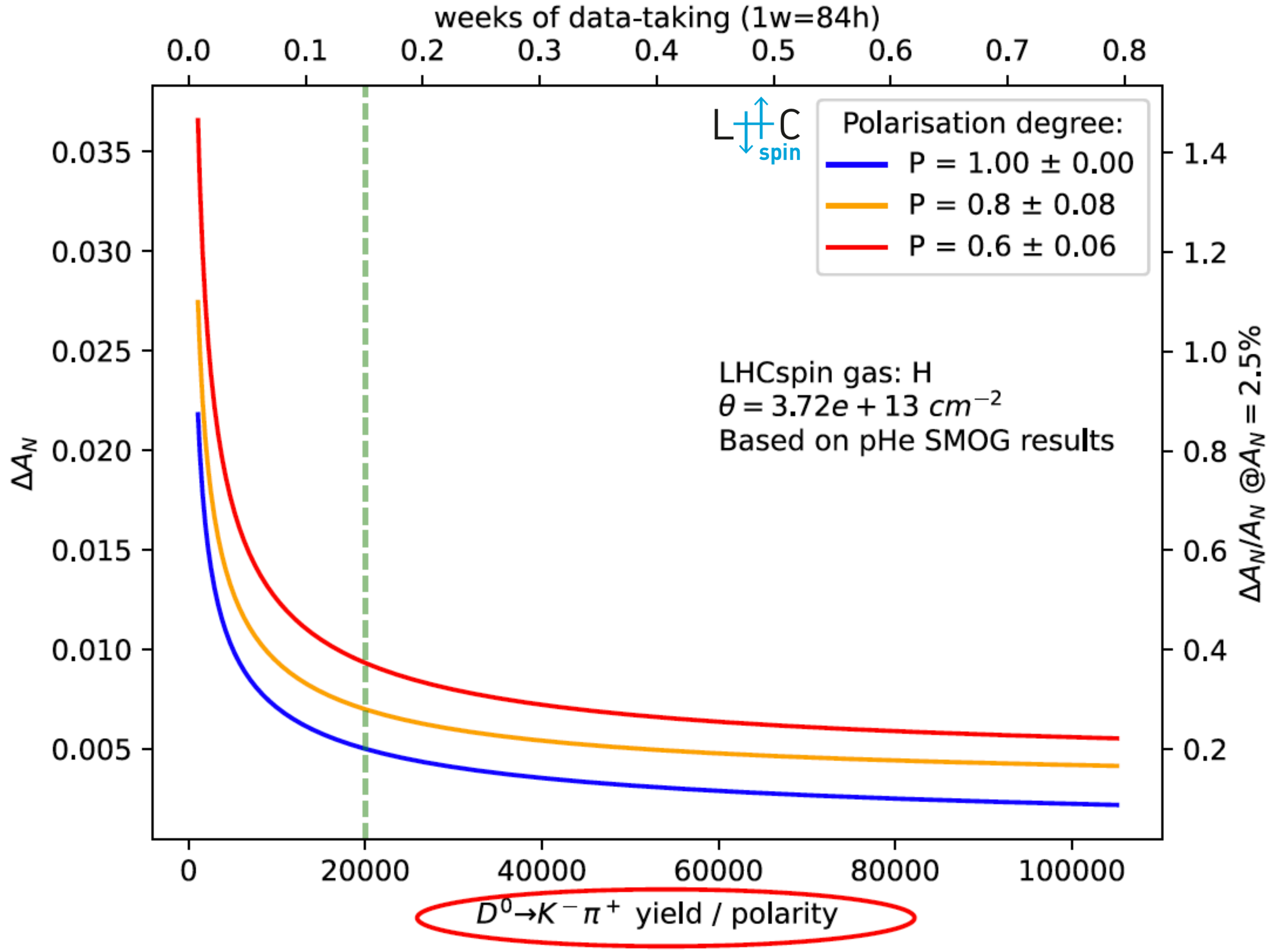
suppressed: $q(x_{beam}) + \bar{q}(x_{target}) \rightarrow \mu^+\mu^-$



LHCspin event rates

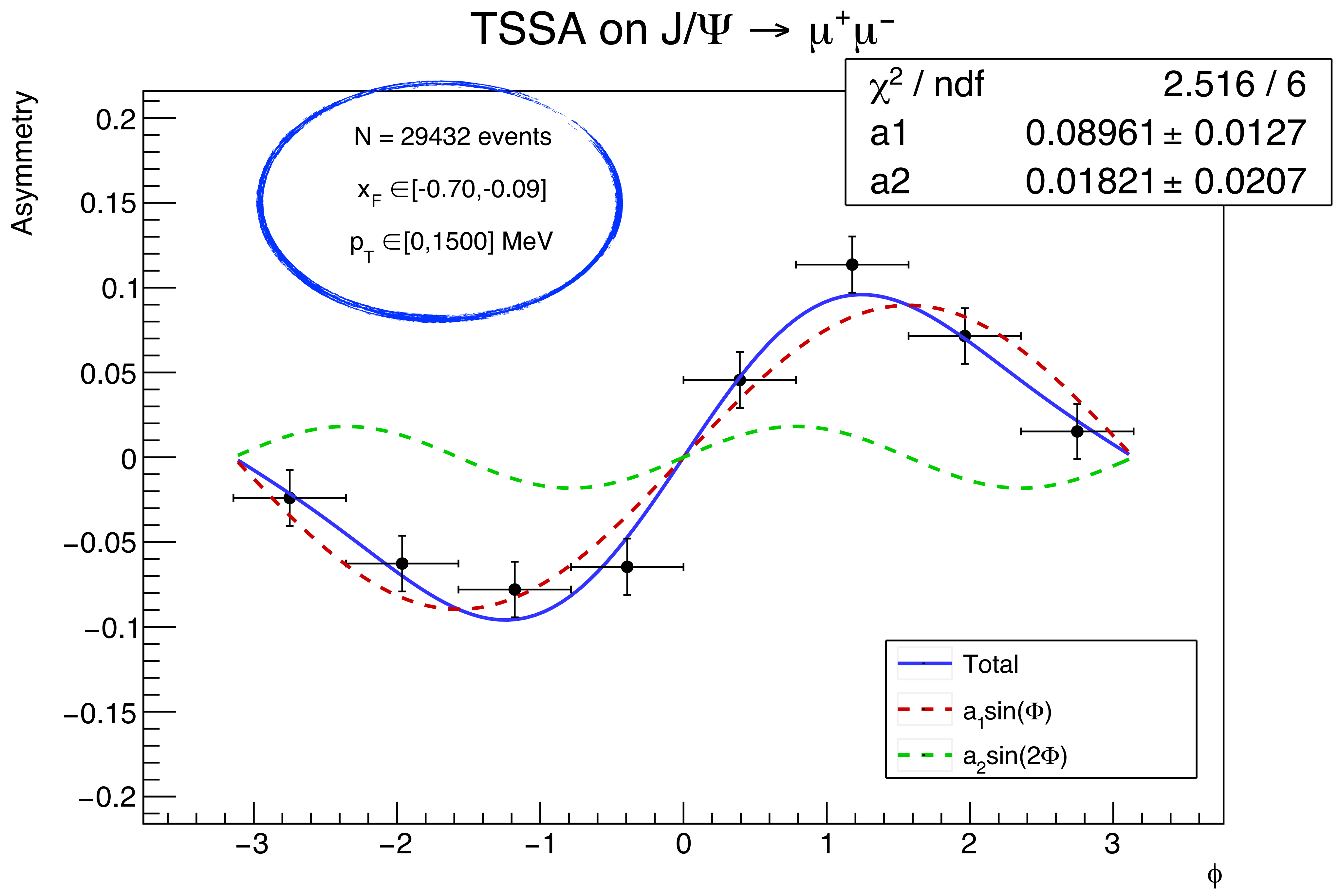
Precise spin asymmetry on $J/\Psi \to \mu^+\mu^-$ and $D^0 \to K^-\pi^+$ for $pH^\uparrow$ collisions in just few weeks with Run3 luminosity!
Statistics further enhanced by a factor 3-5 in LHCb upgrade II

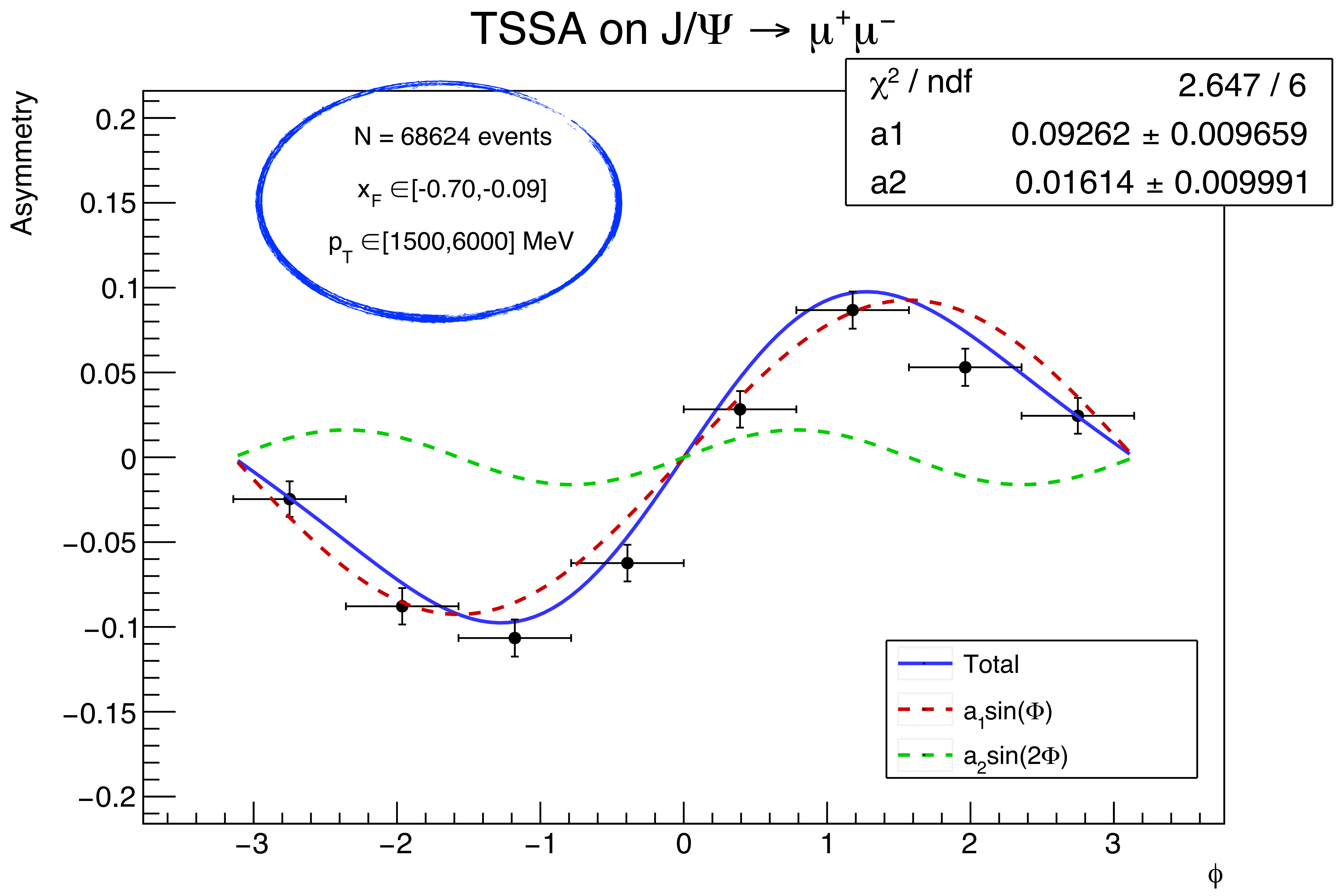




reconstructed particles

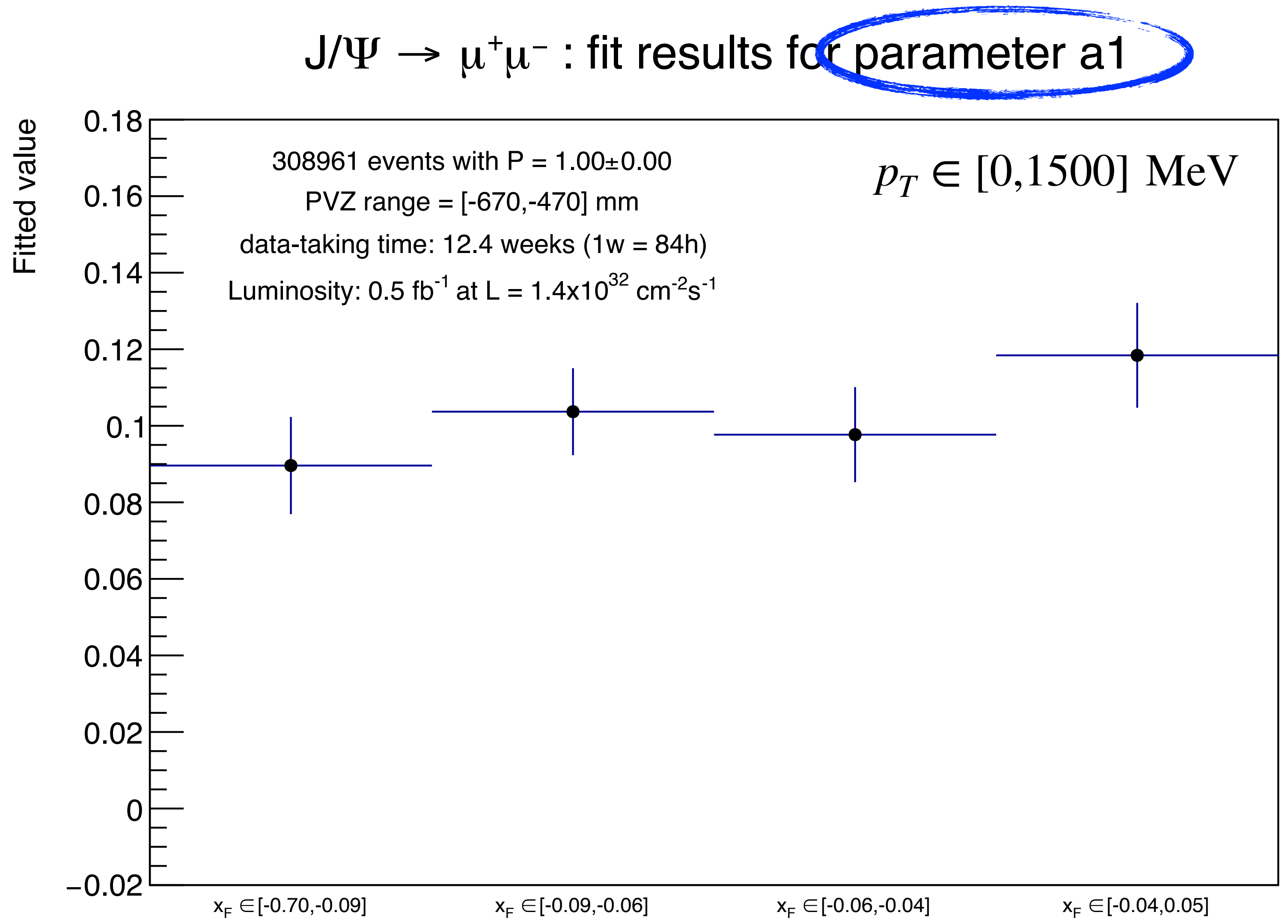
A TSSA analysis at LHCspin with $J/\Psi \to \mu^+\mu^-$ events





[JHEP 12 (2020) 010]

- 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

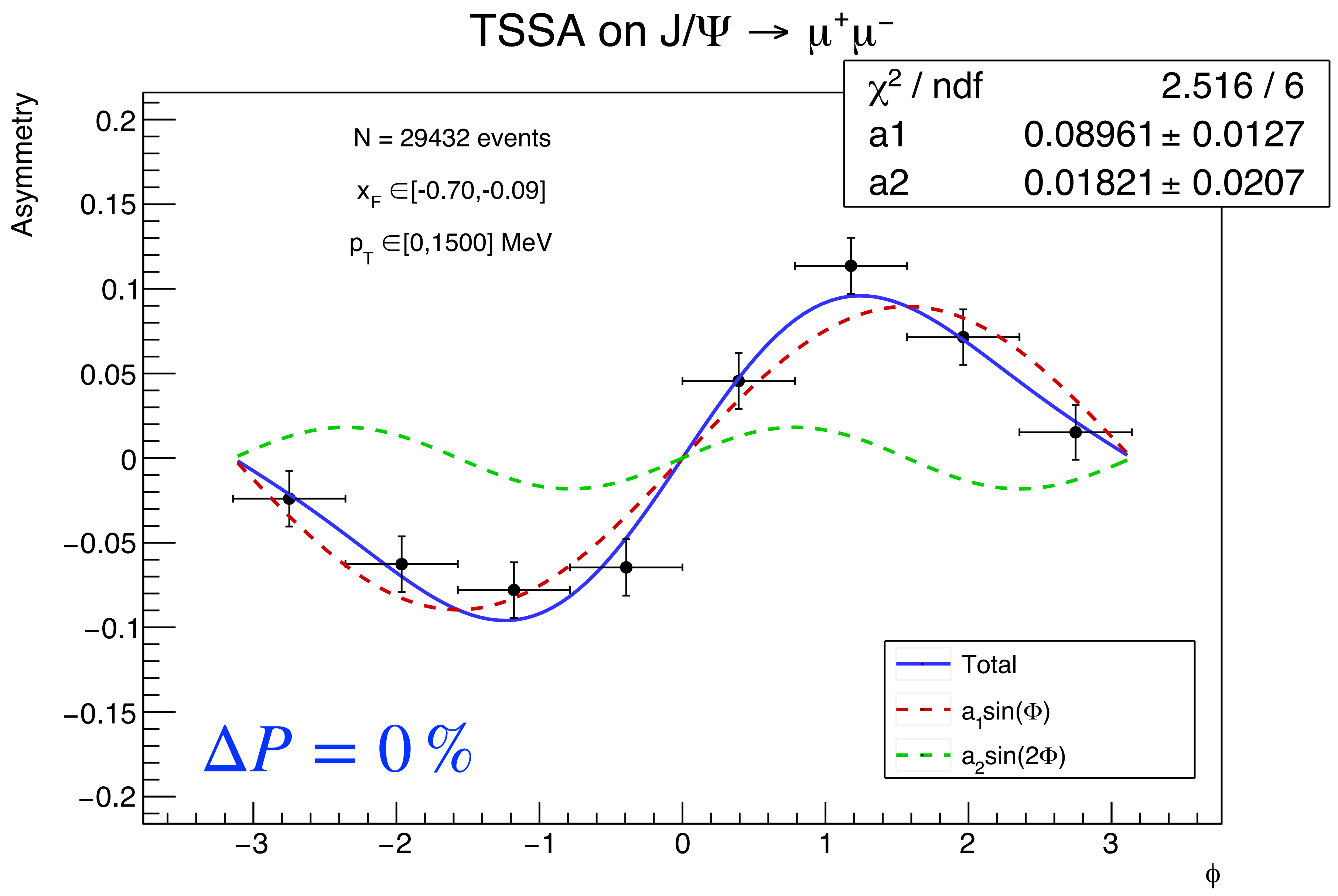
- To estimate the systematic error due to the measurement of the polarisation degree, the analysis is repeated with different ΔP
- Very relevant for the R&D (e.g. cell vs jet target). With the shown analysis* :
- 5% error (realistic value) → negligible effect
- 20% error → 30-40% of the stat. error
-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

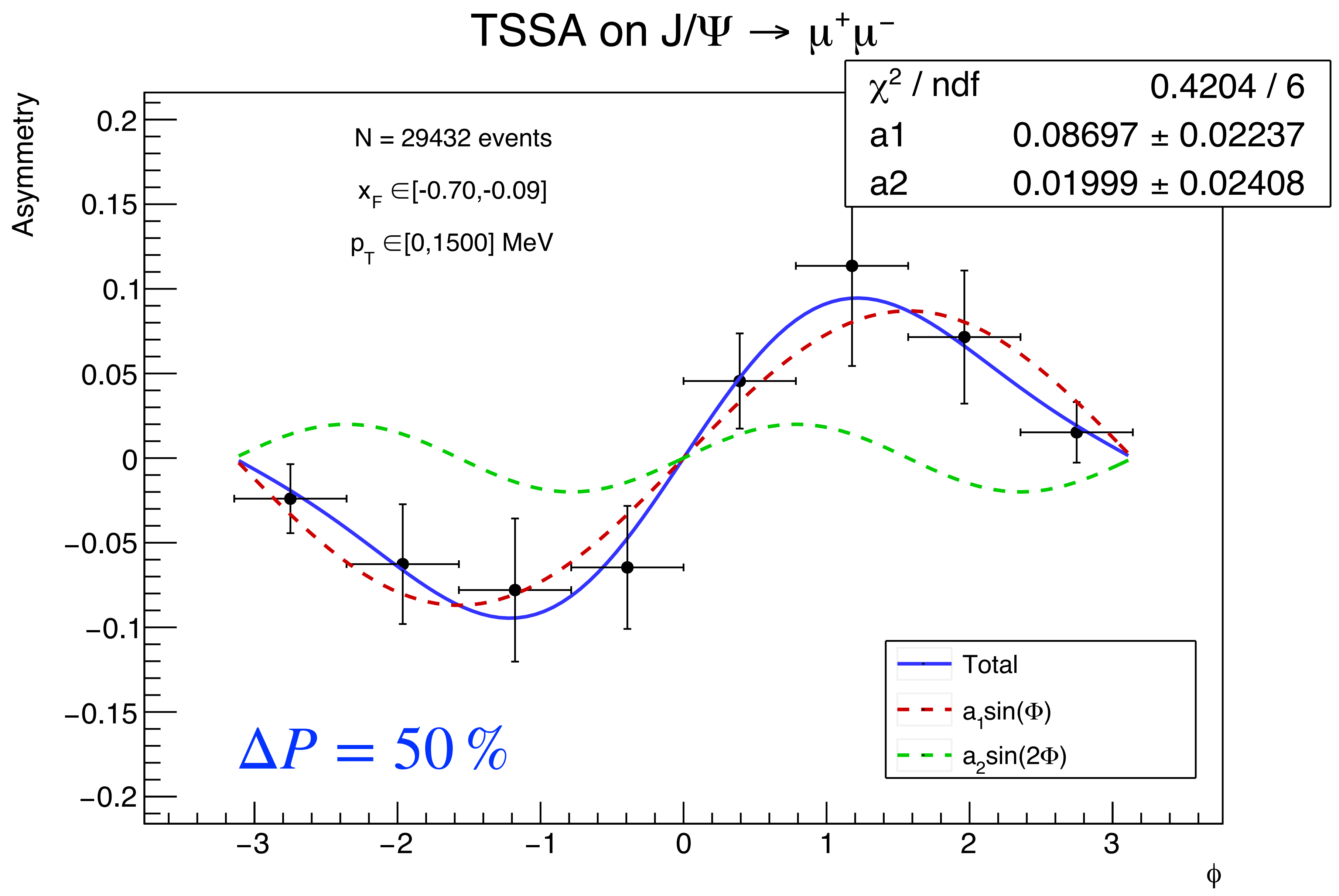
$\Delta P = 5\,\%$

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



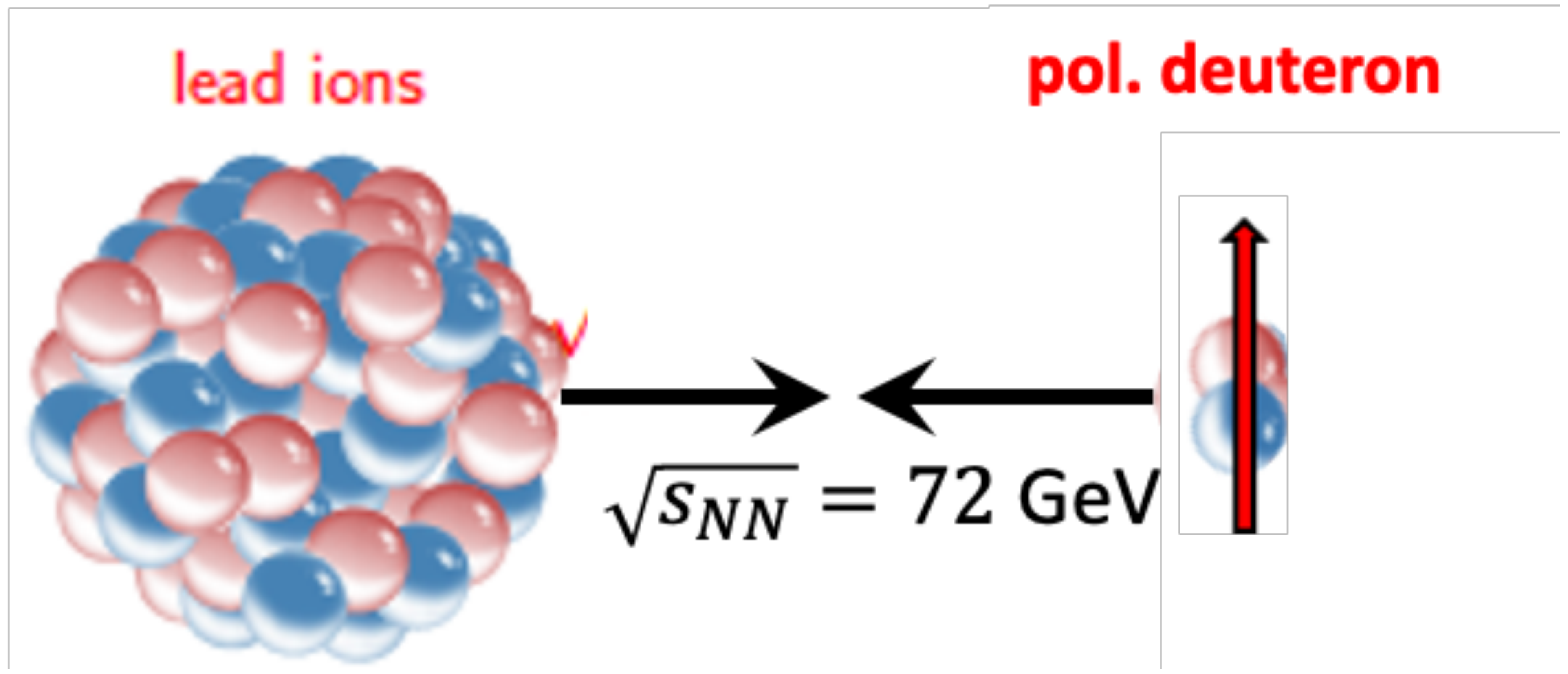


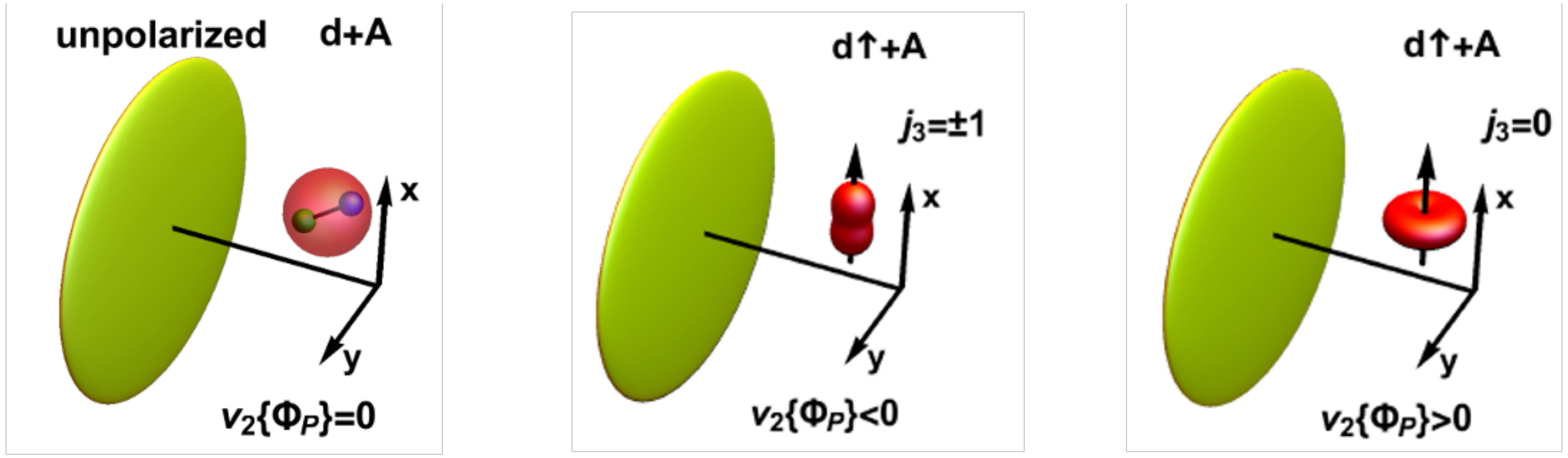
* i.e. ~ 3 months of data-taking with this example model, channel and kinematic binning

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**).

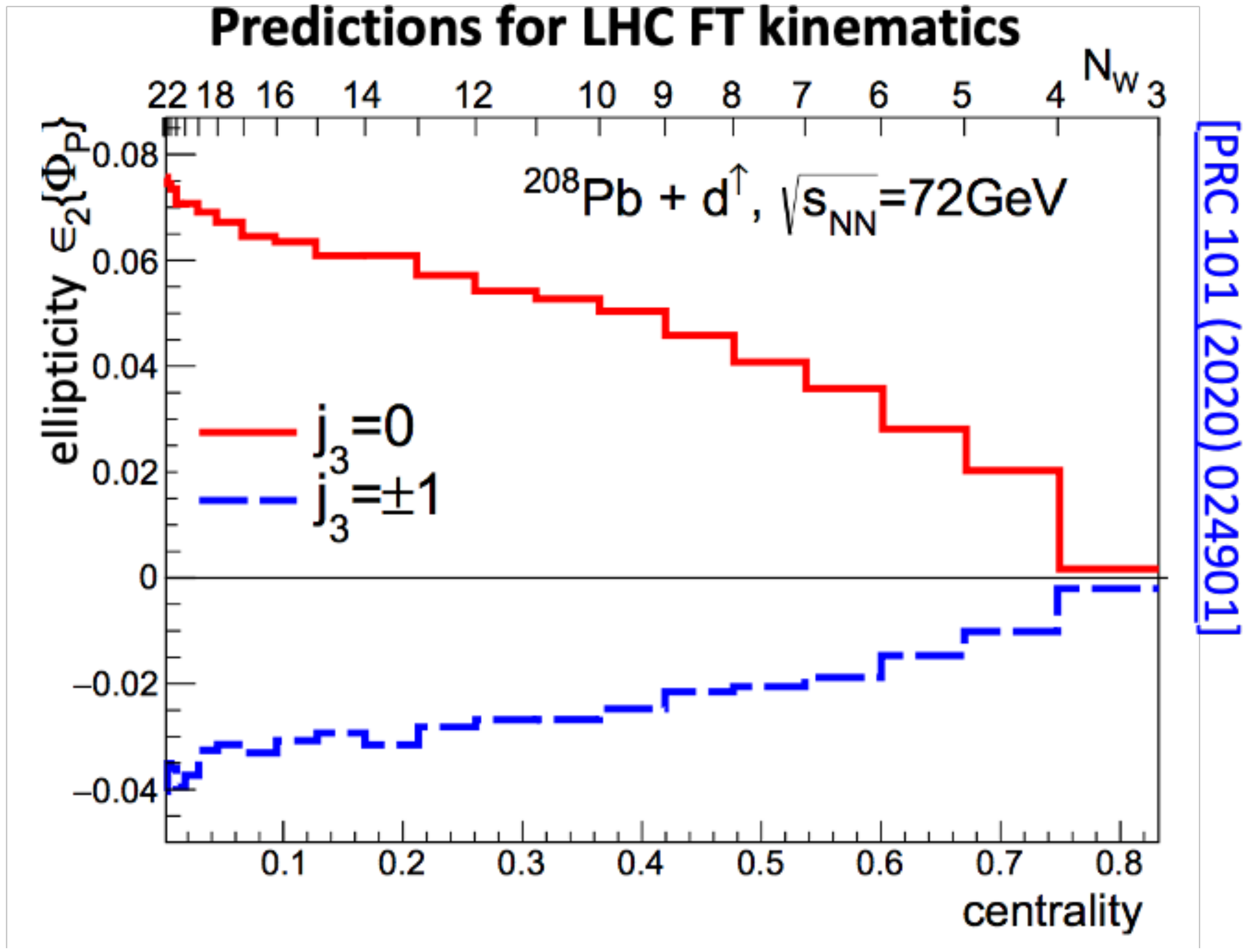




Unpol. deuterons: the **fireball is azimuthally symmetric** and $v_2 \approx 0$.

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

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



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

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

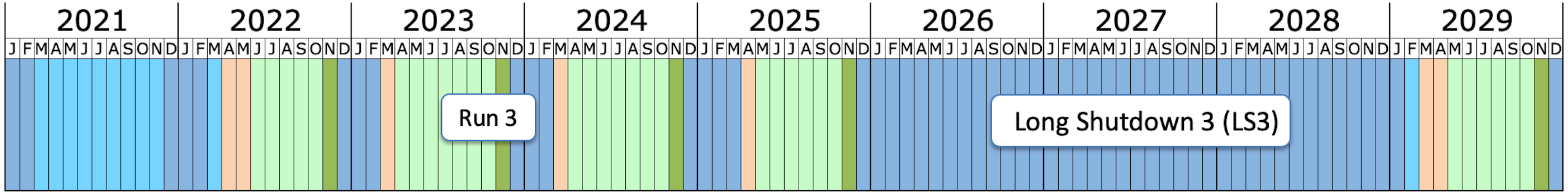
☐ (blue) Can be measured at LHCspin

"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

Conclusions



SMOG2

LHCspin

Fixed target physics at LHC is an exiting reality

LHCb { 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