LHC fixed-target experiments

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

FONDAZIONE BRUNO KESSLER
ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS
Opportunities with JLab Energy and Luminosity Upgrade

30/09/22

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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ALICE

Solid (unpolarised) target

SMOG2

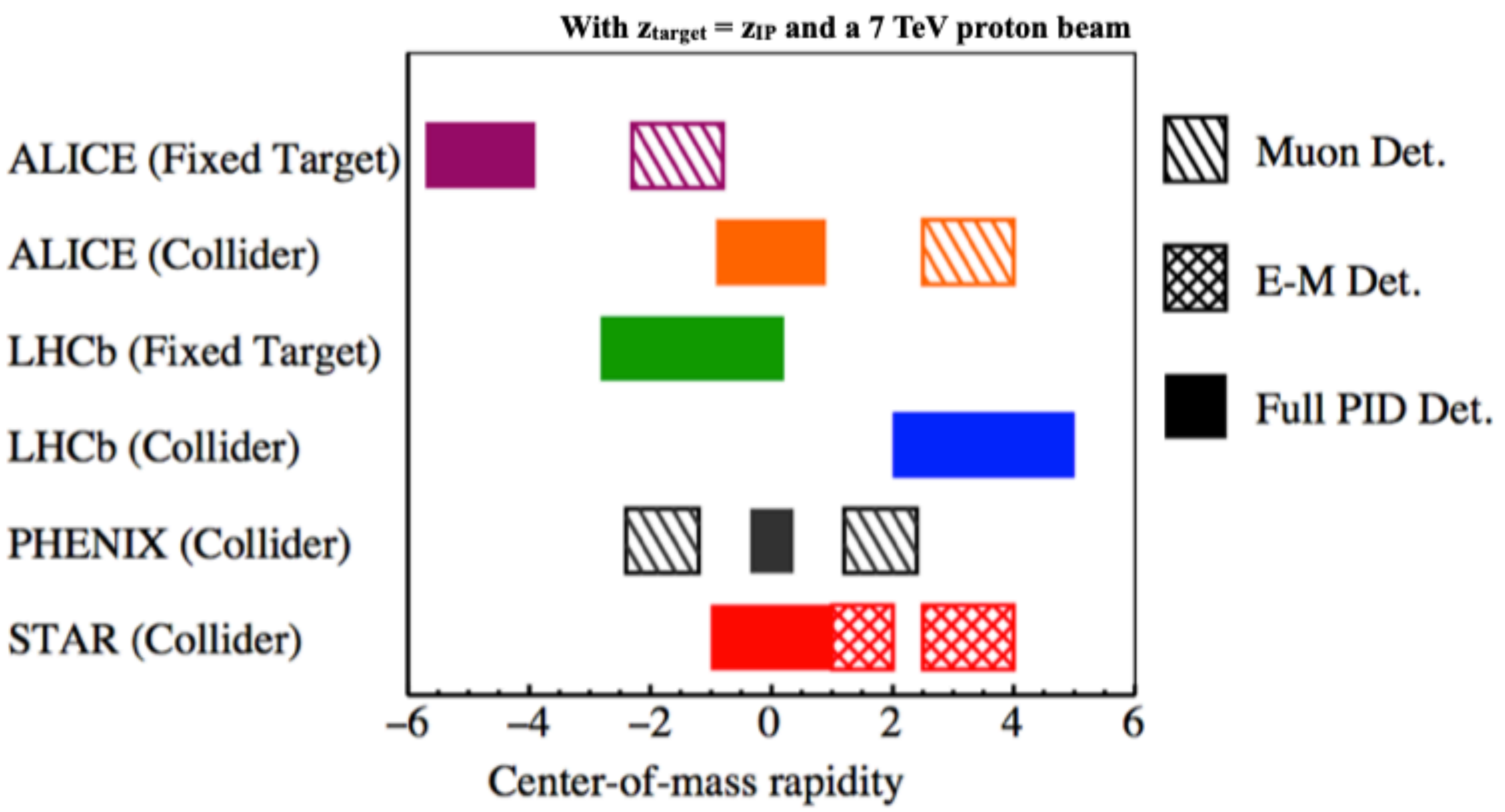
LHCb

unpolarised gas target

LHC spin

polarised (+unpolarised) gas target

Acceptance in center-of-mass rapidity



gaseous targets @ LHCb

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:

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

- Particle identification with RICH+CALO+MUON

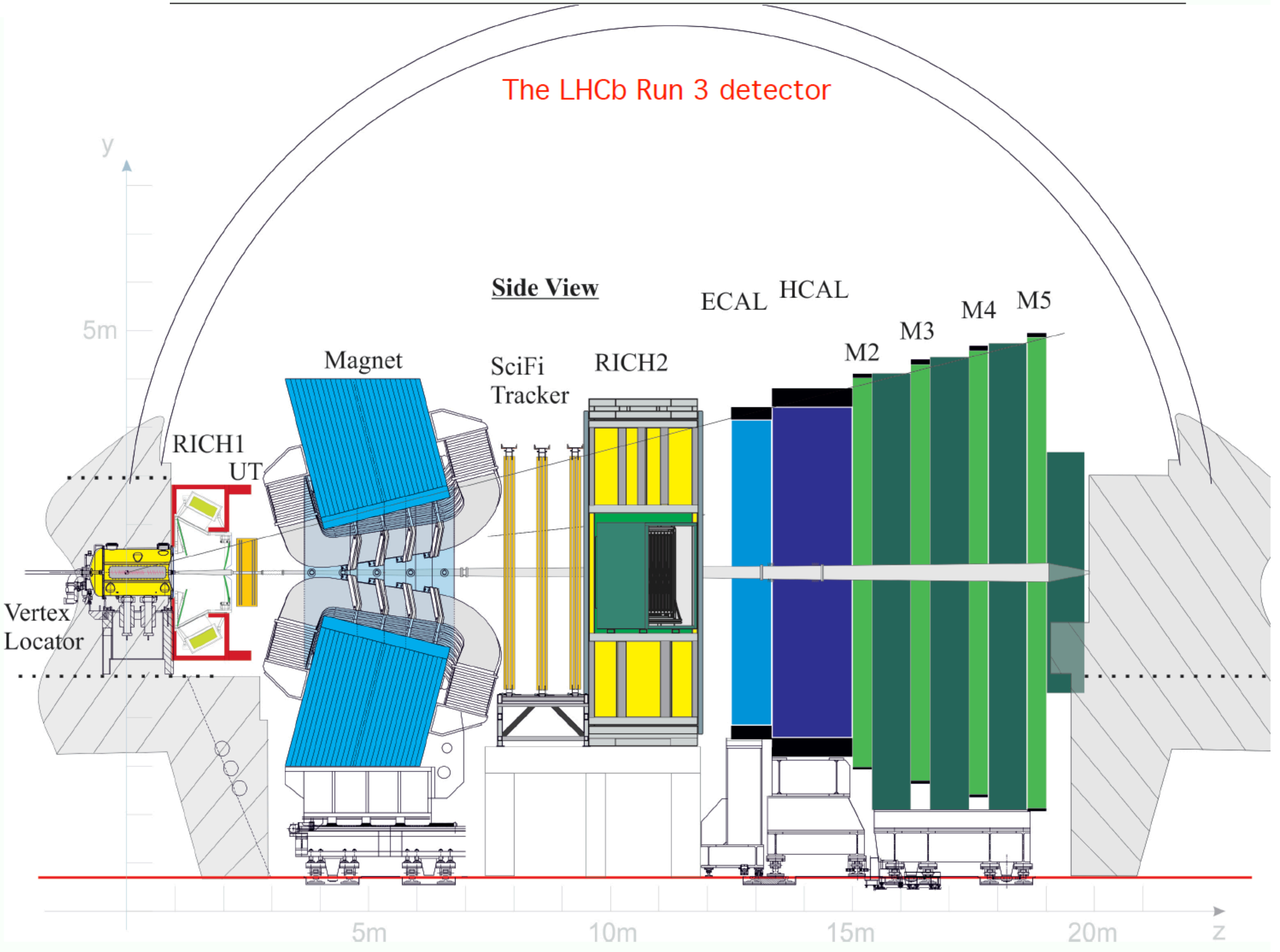
$\epsilon_\mu \sim 98\,\%$ with $\epsilon_{\pi\to\mu} \lesssim 1\,\%$

- Low momentum muon trigger:

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

will be reduced thanks to the new fully-software trigger

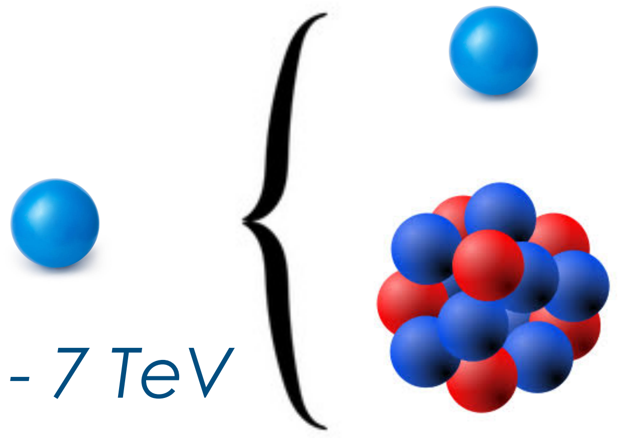
- Major detector upgrades performed during LS2 for the Run 3 (5x luminosity)



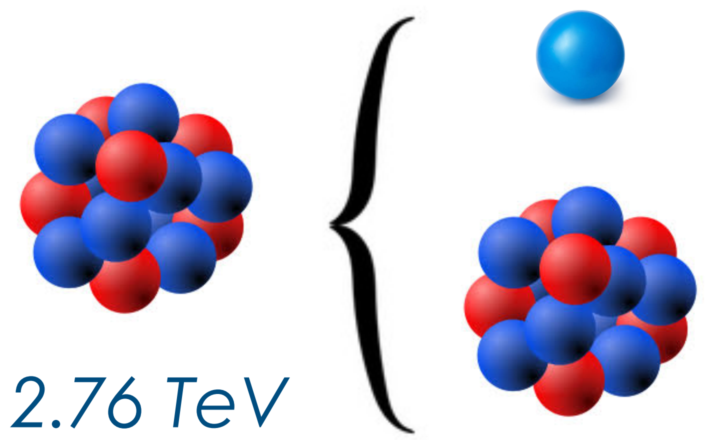
[JINST 3 (2008) S08005]

[IJMP A 30, 1530022 (2015)]

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



0.45 - 7 TeV



2.76 TeV

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

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

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

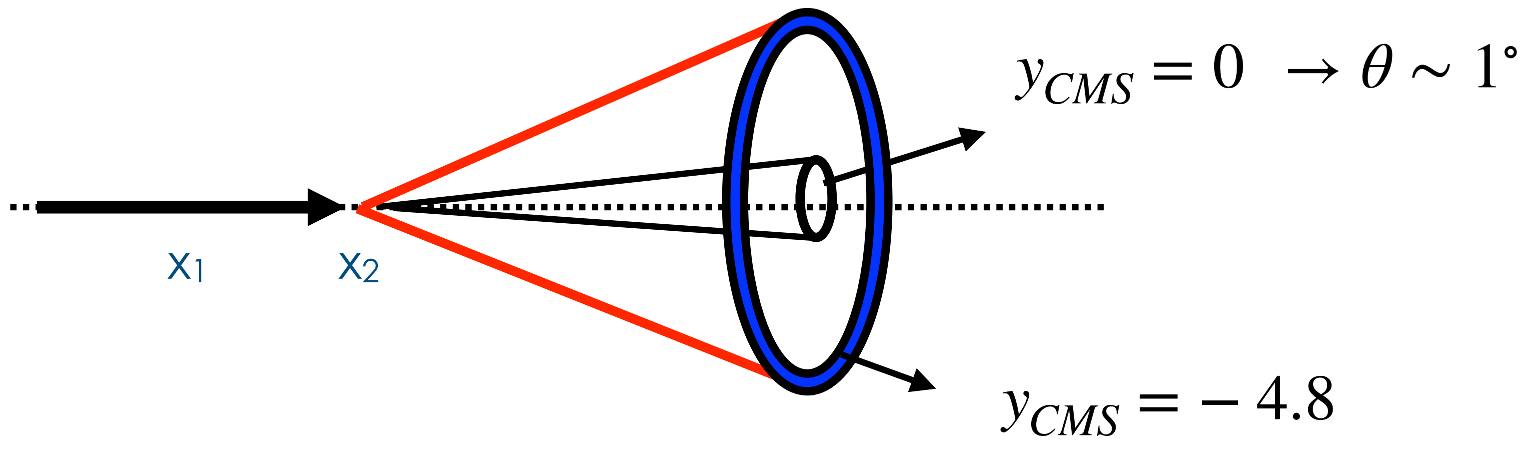
AA collisions: 2.76 TeV beam on fix target

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

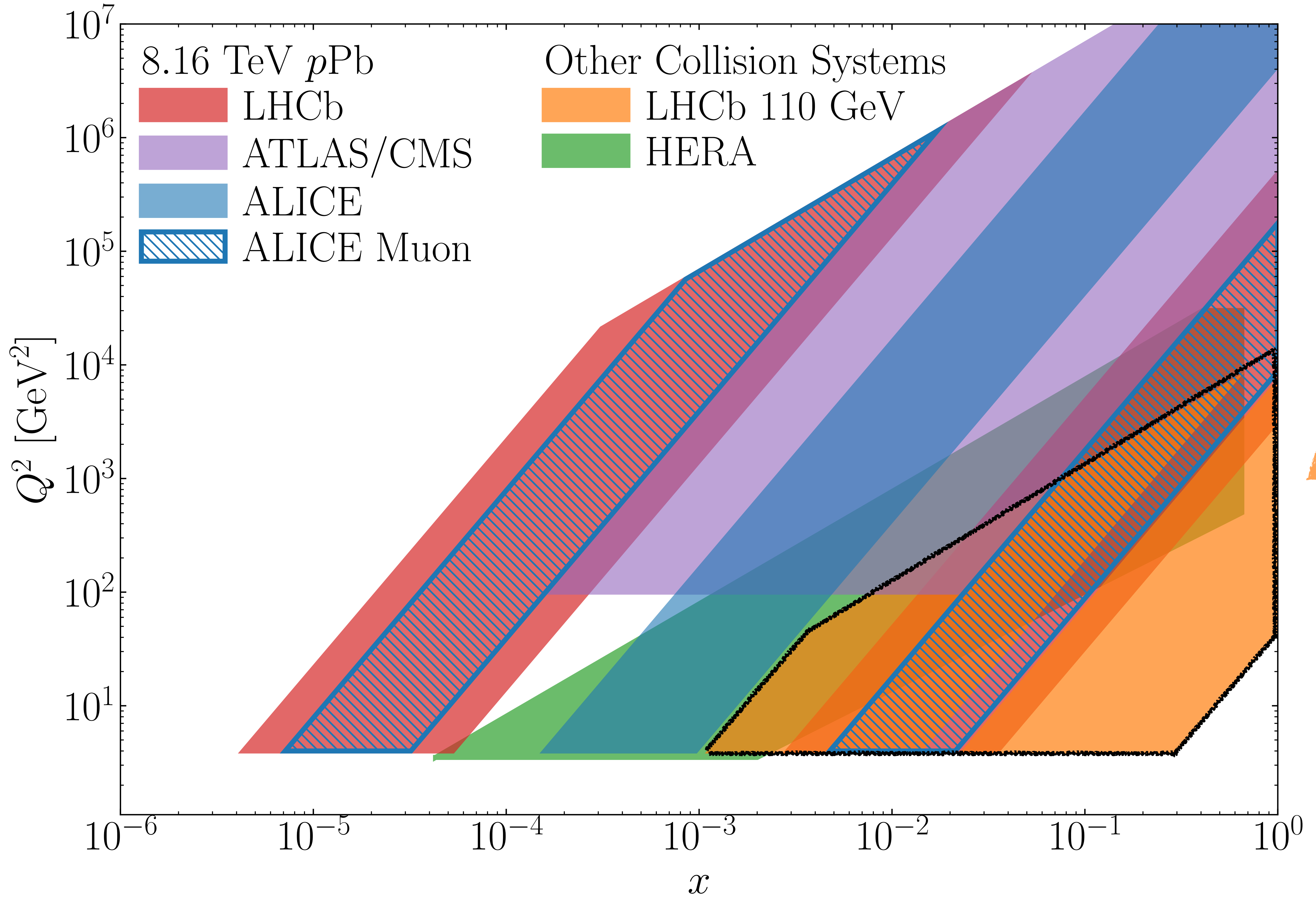
$y_{CMS} = 0 \ \rightarrow \ y_{lab} = 4.3$

1: beam; 2: target

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



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

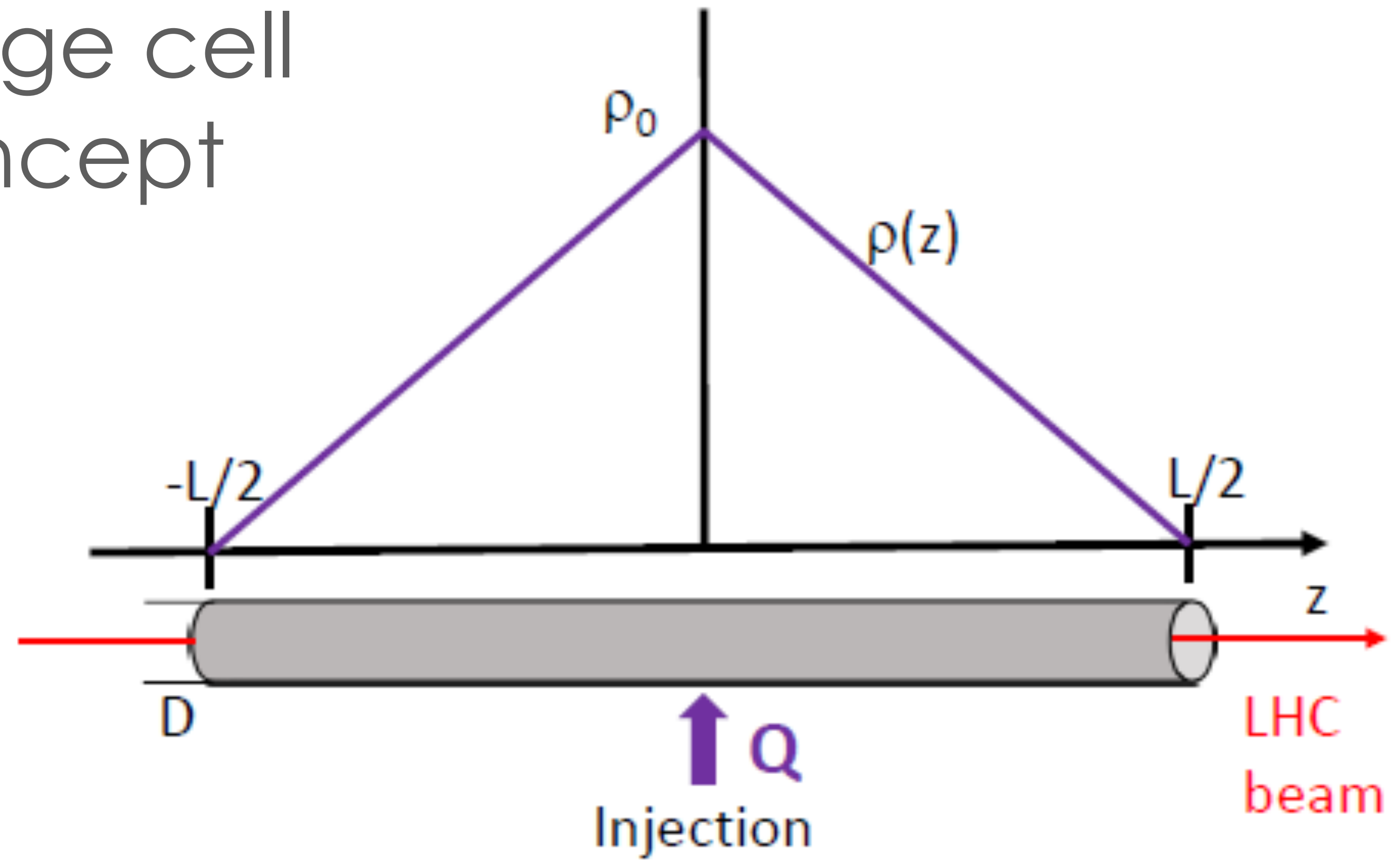


Broad and poorly explored kinematic range

SMOG2 an unpolarised target at LHCb

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

Storage cell concept



Luminosity

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

areal density

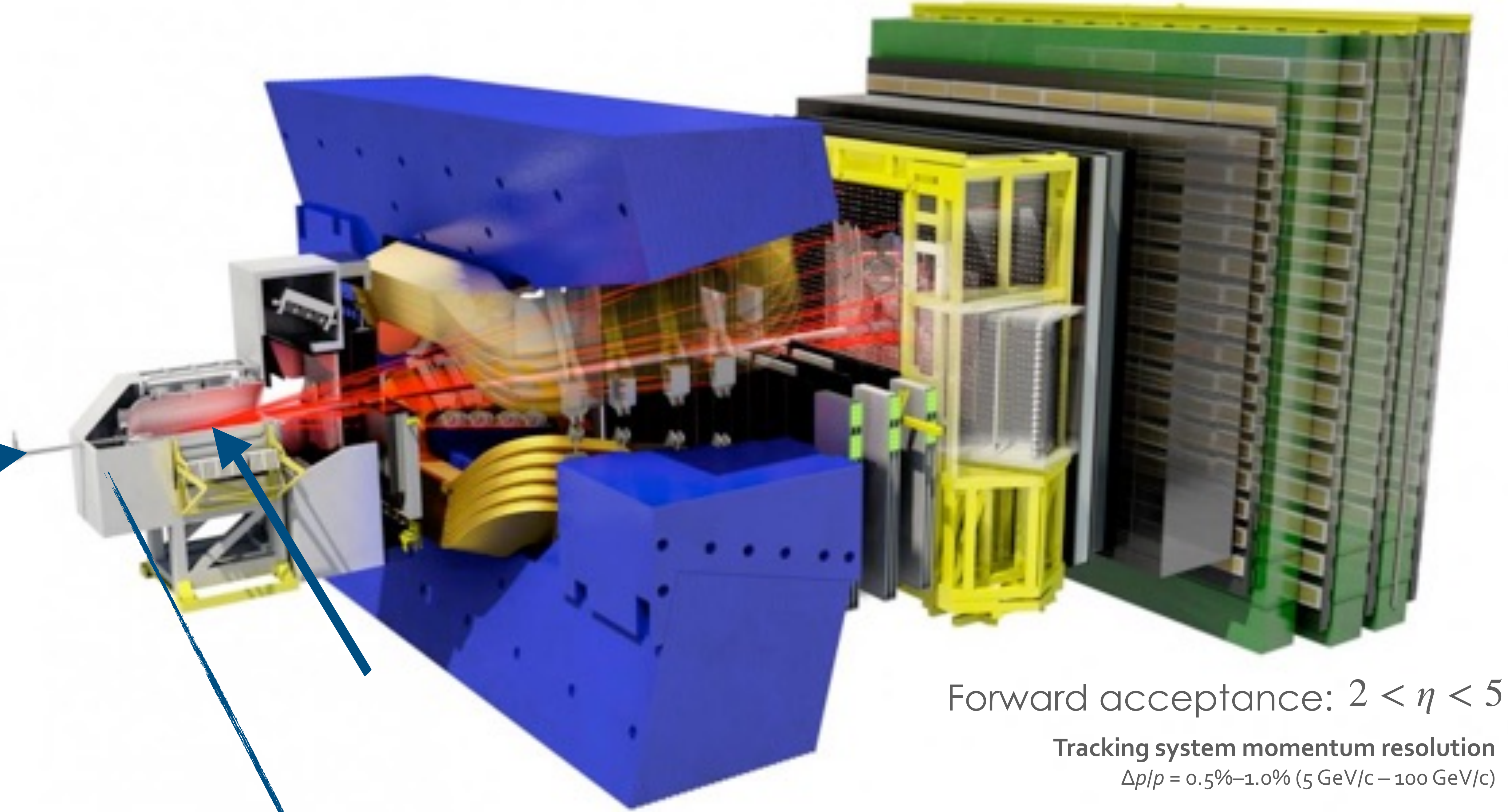
number of particles

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

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

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

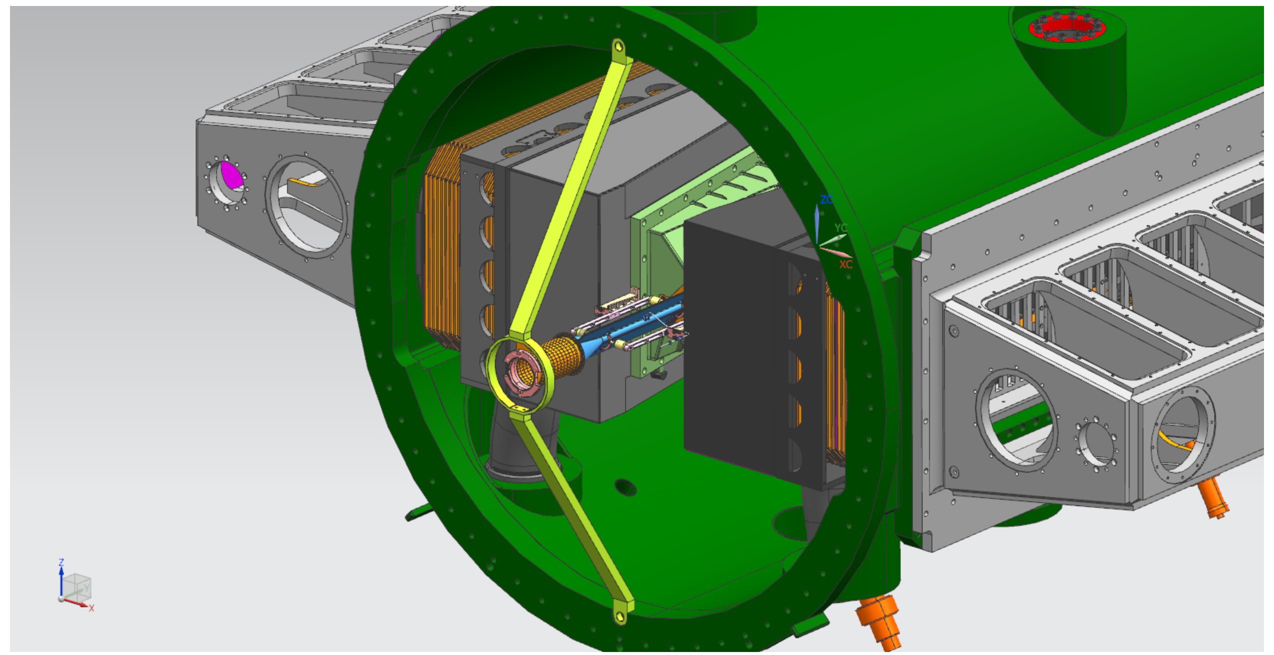
LHC beam



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



UNpolarised target (beam-gas)

SMOG2 an unpolarised target at LHCb

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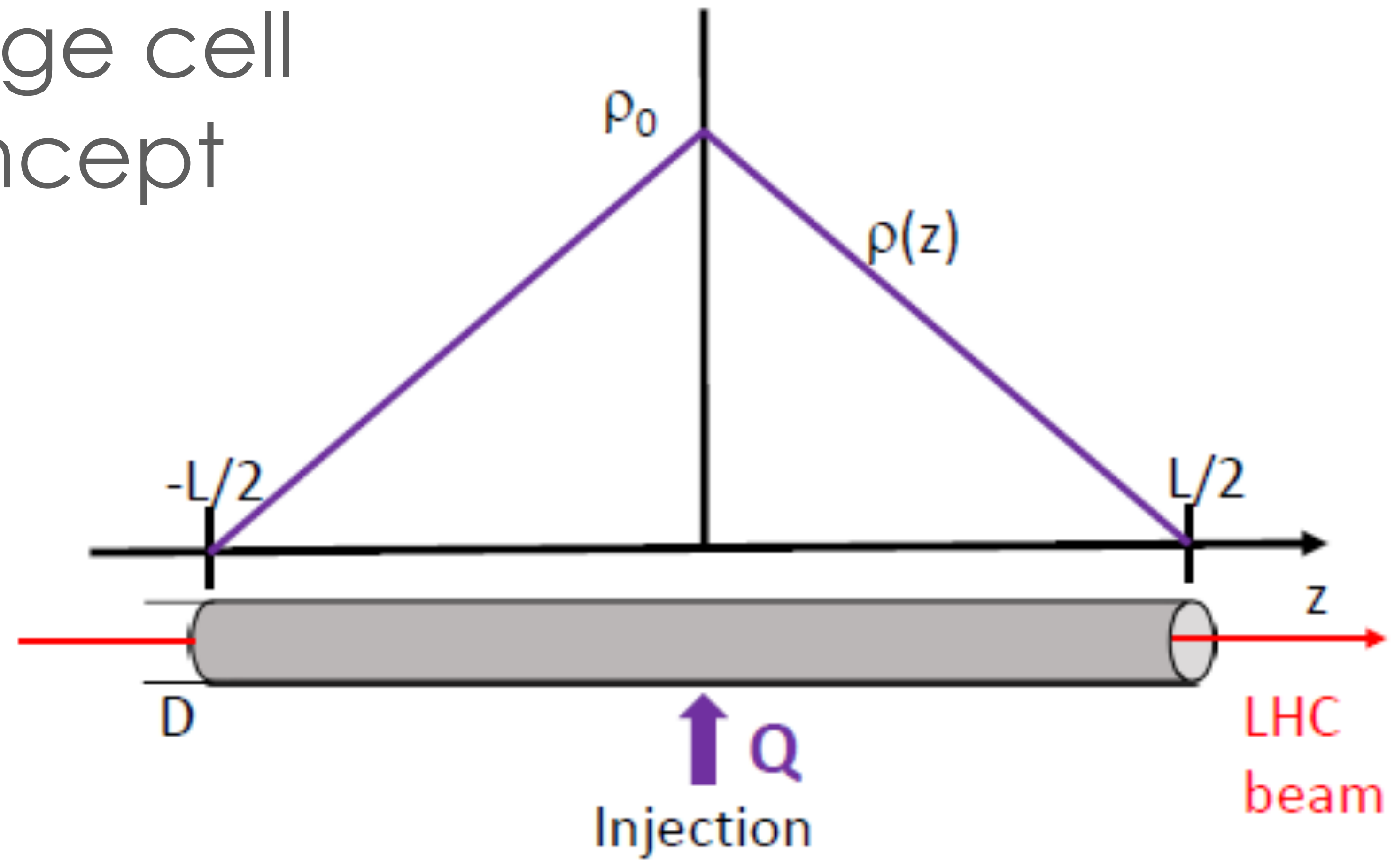

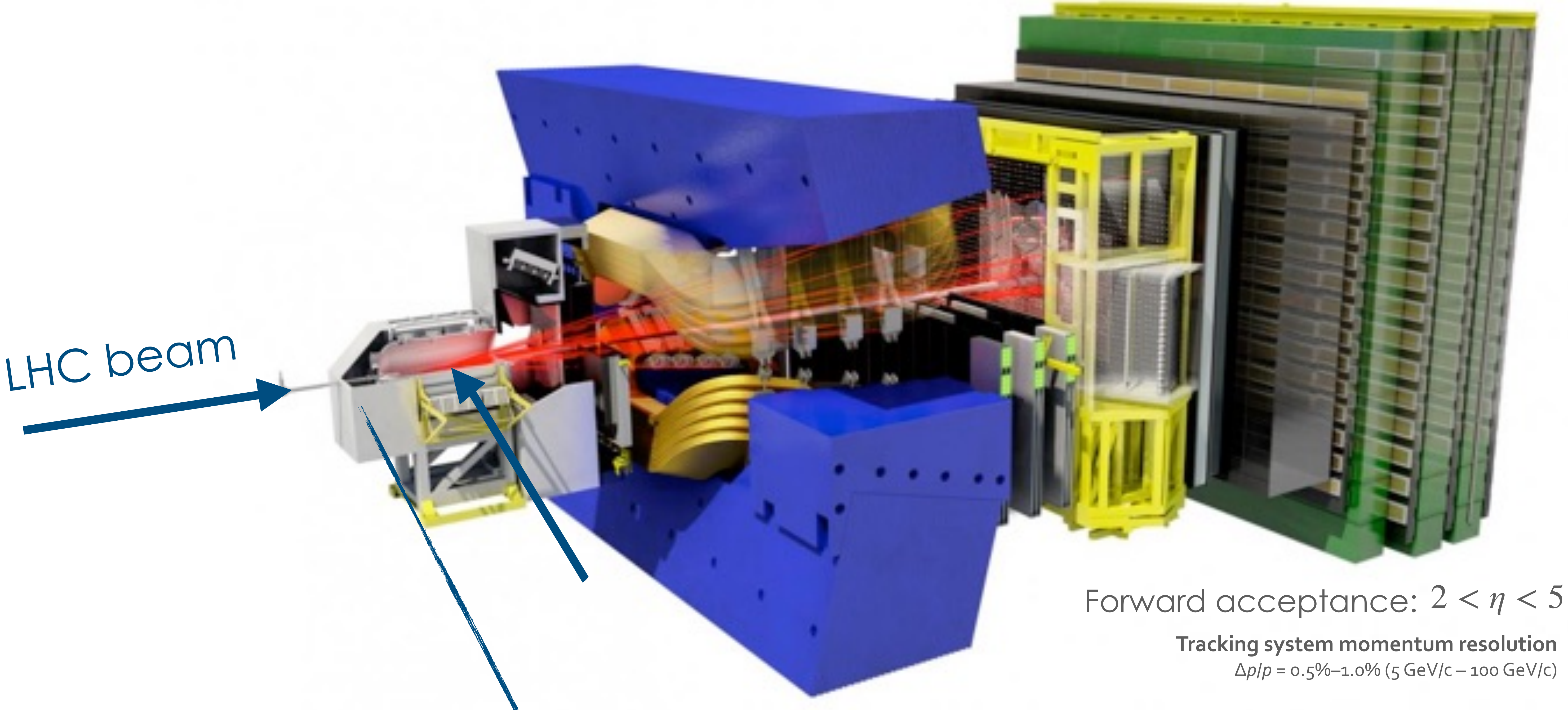

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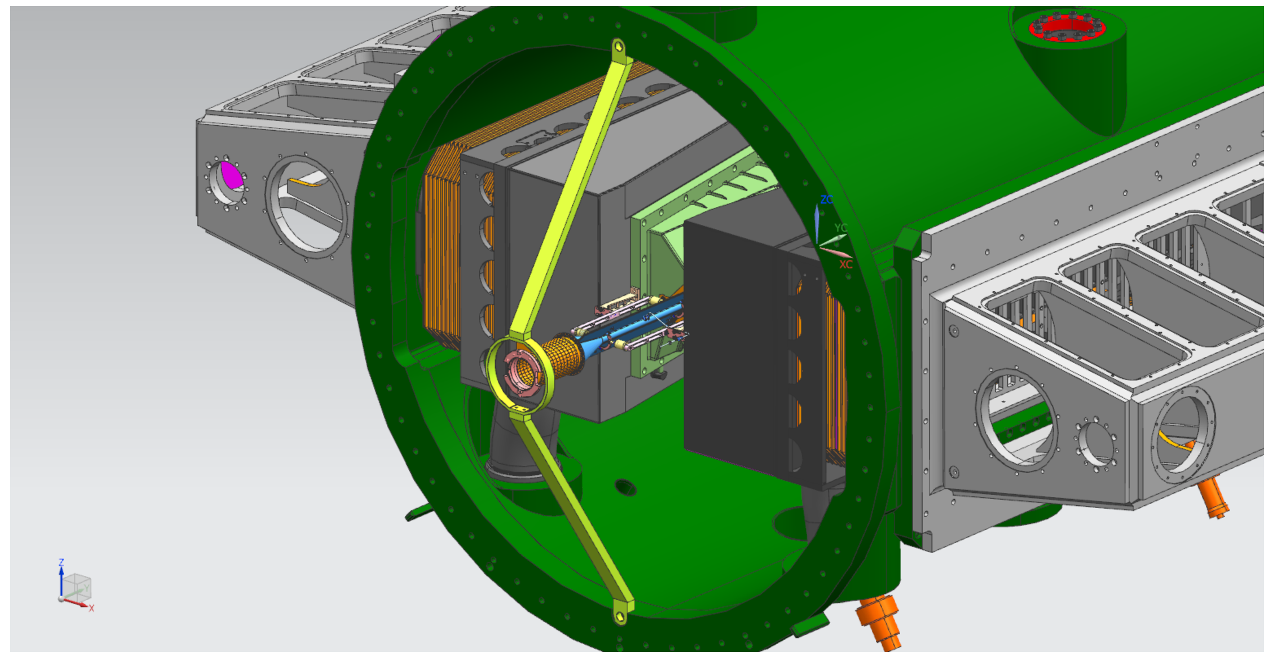

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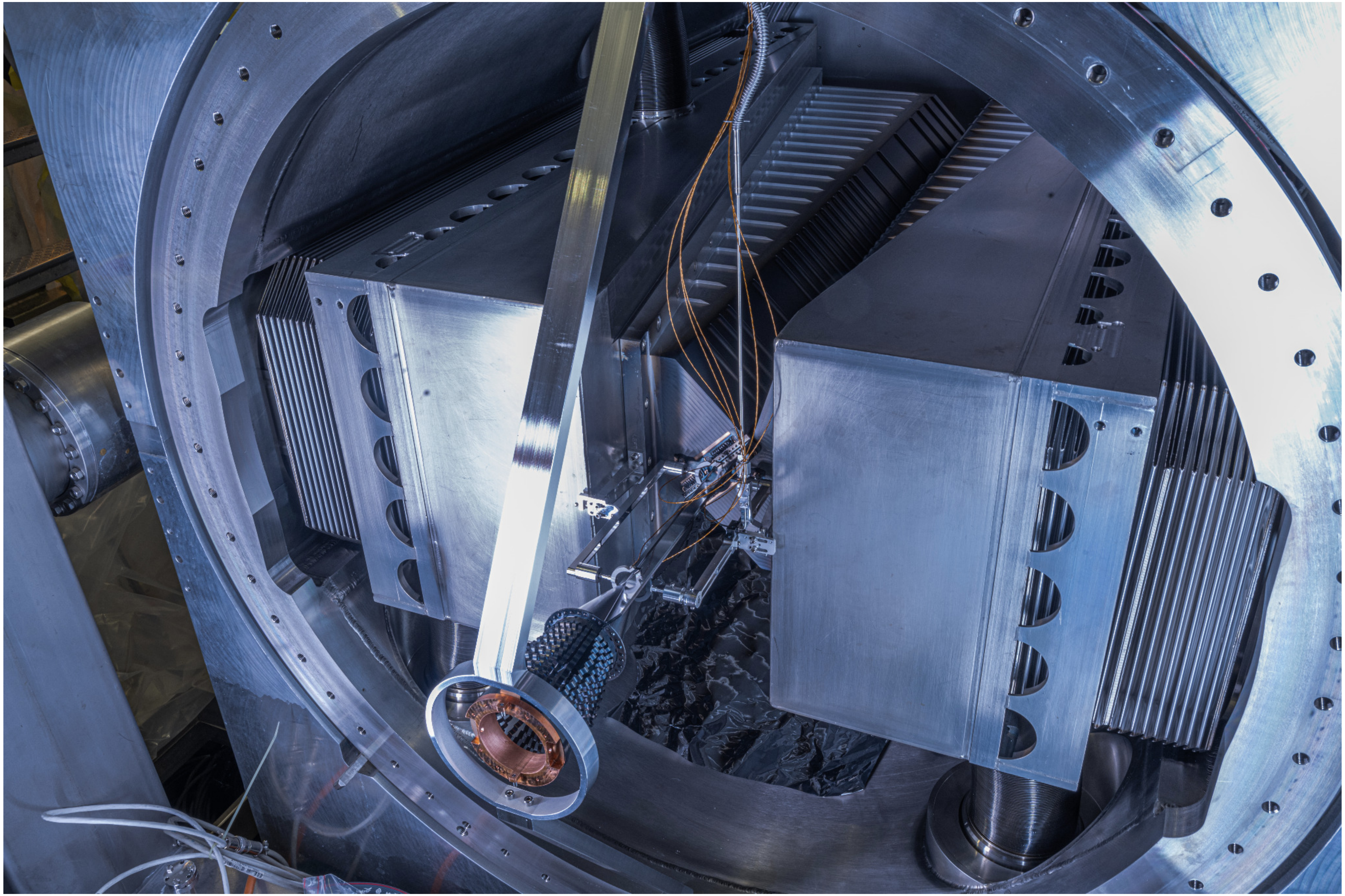
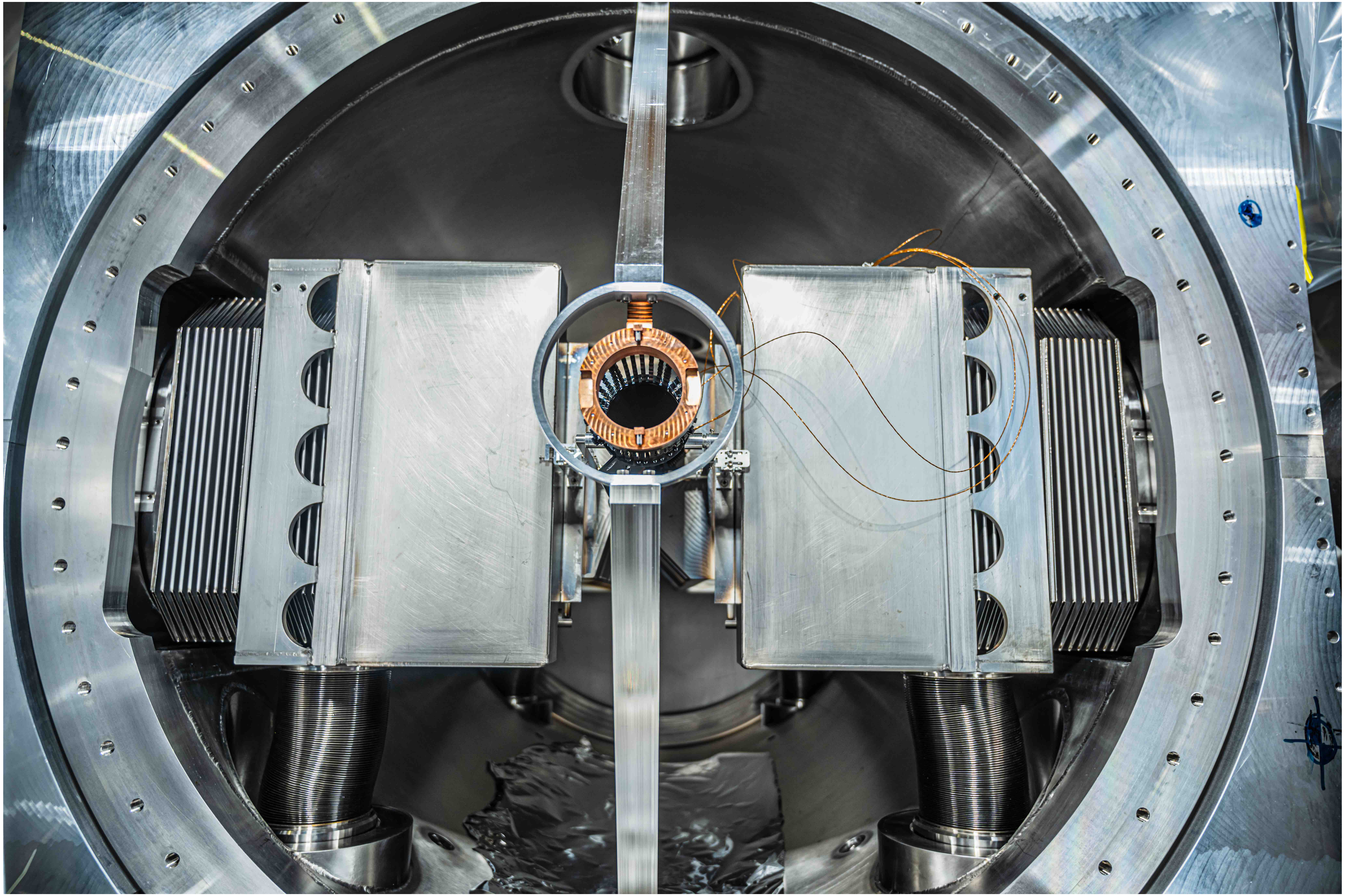
SMOG2



It is the only system present in the LHC primary vacuum

SMOG2



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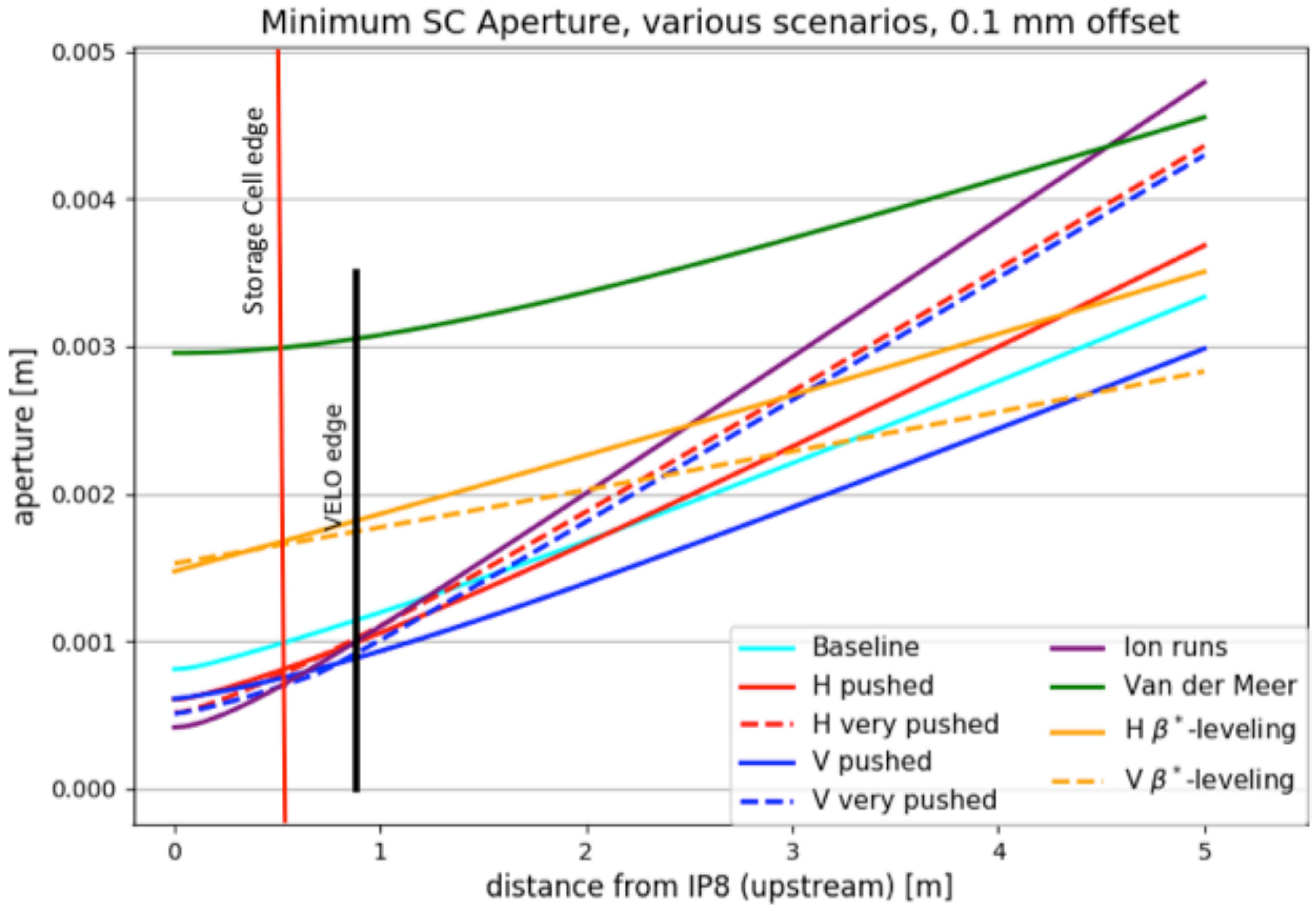
SMOG2 **Openable** Storage Cell dimensions: 200 mm (L) - 10 mm (D)

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



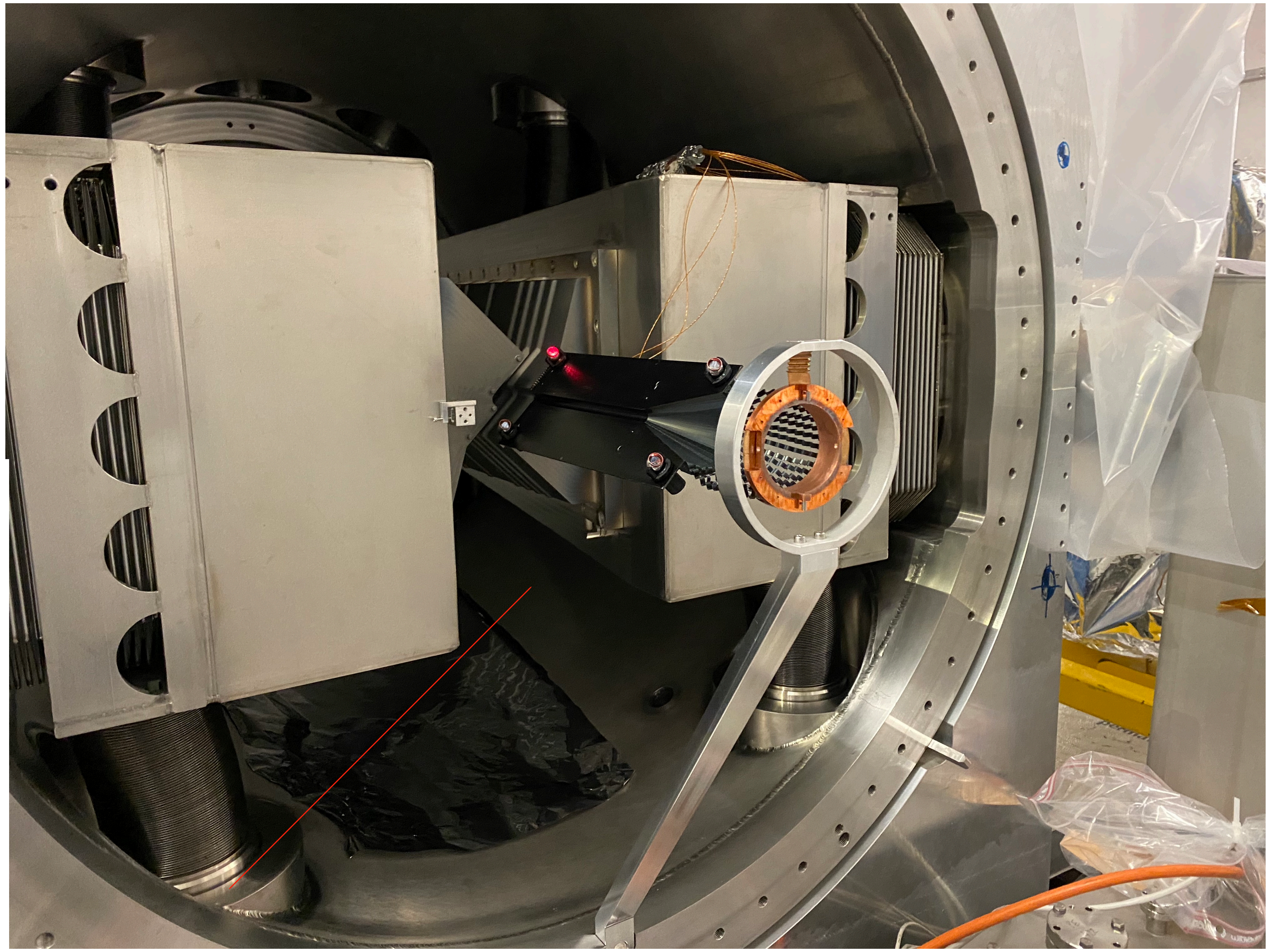


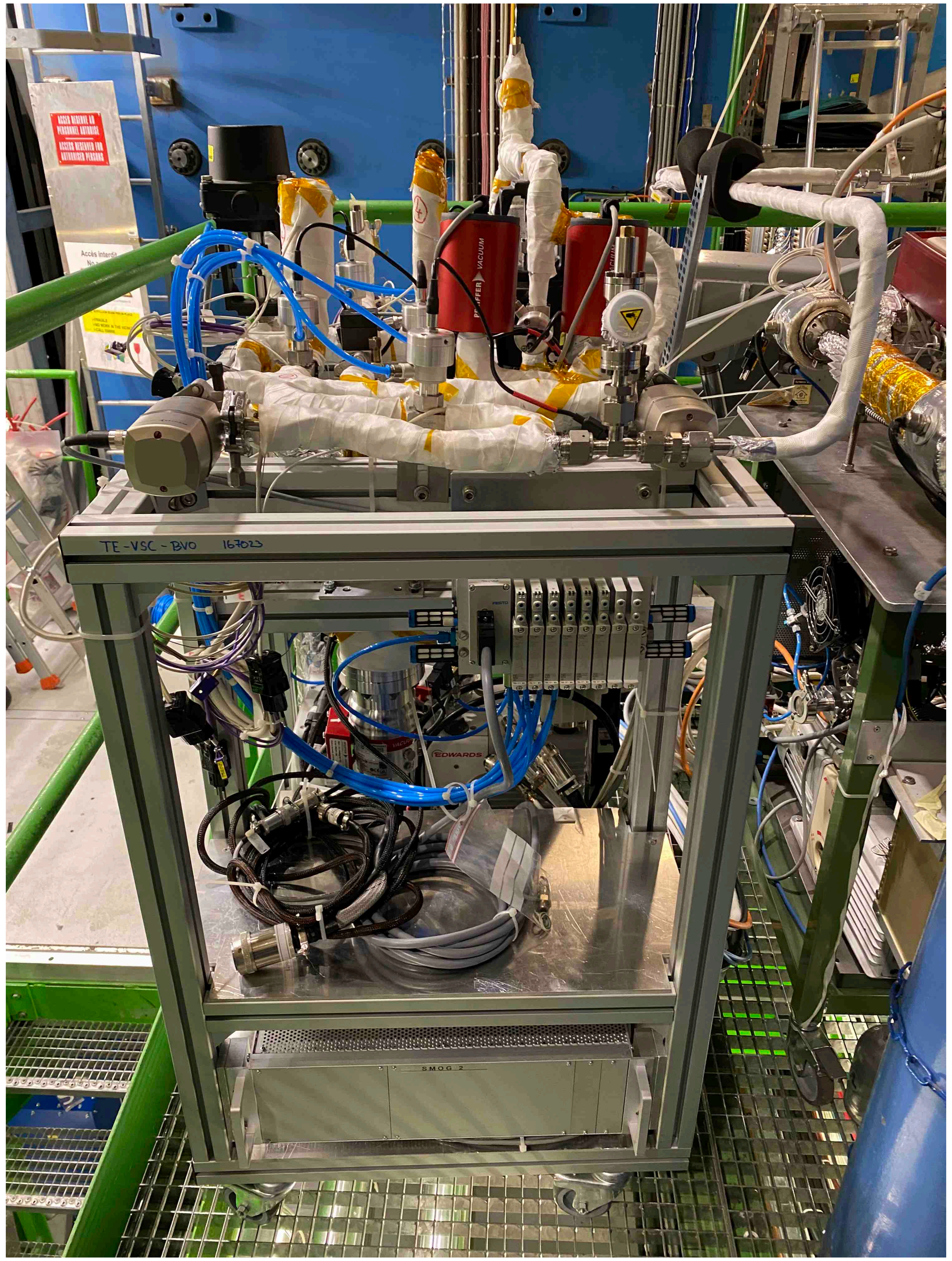
Table 9: Final position of the SMOG2 and its offset to the nominal position

	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			

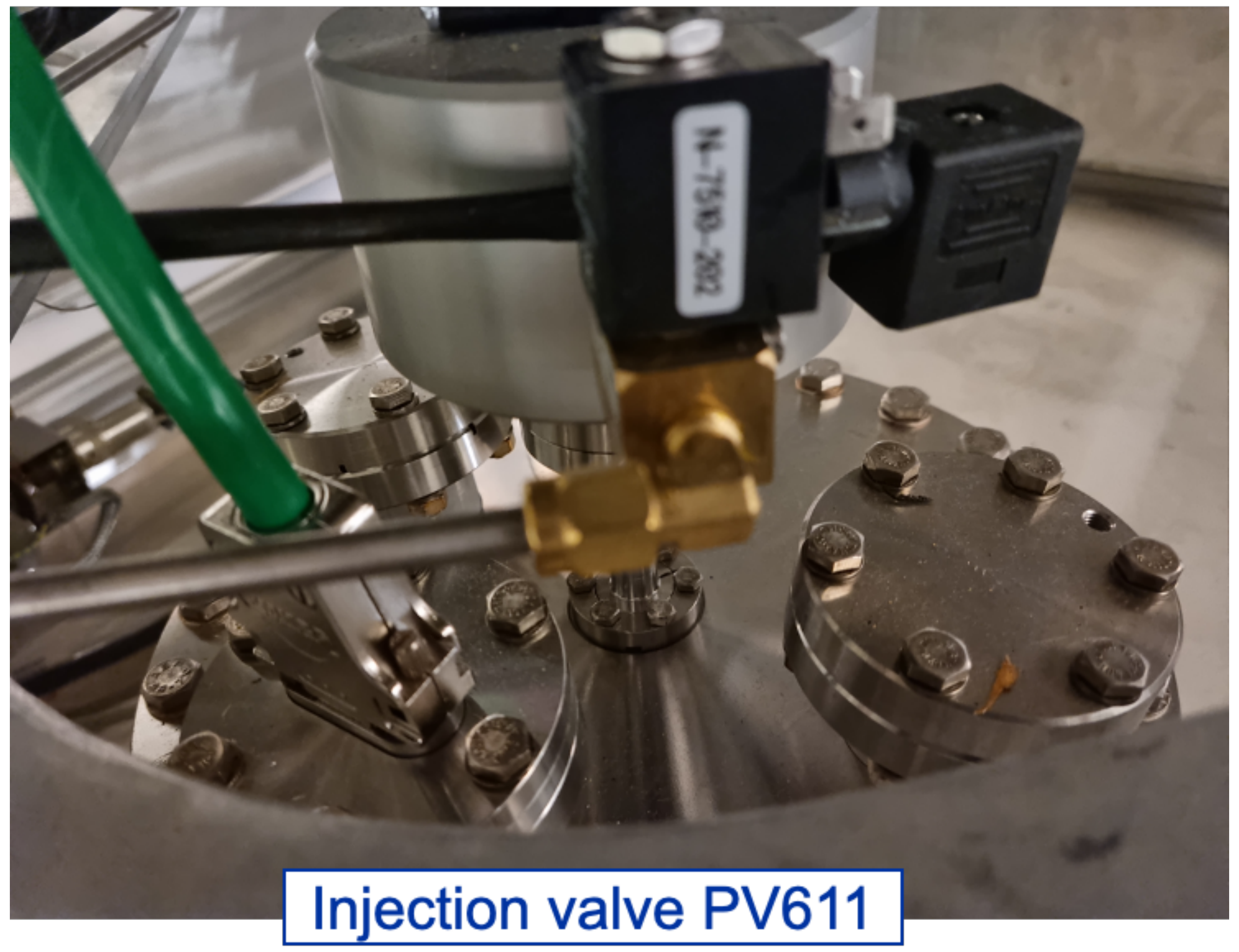
Excellent alignment reached

SMOG2

- The system is completely installed (storage cell + GFS + triggers + reconstruction)
- Negligible impact on the beam lifetime ($\tau^{\mathrm{p-H_2}}_{beam-gas} \sim 2000$ days , $\tau^{\mathrm{Pb-Ar}}_{beam-gas} \sim 500$ 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

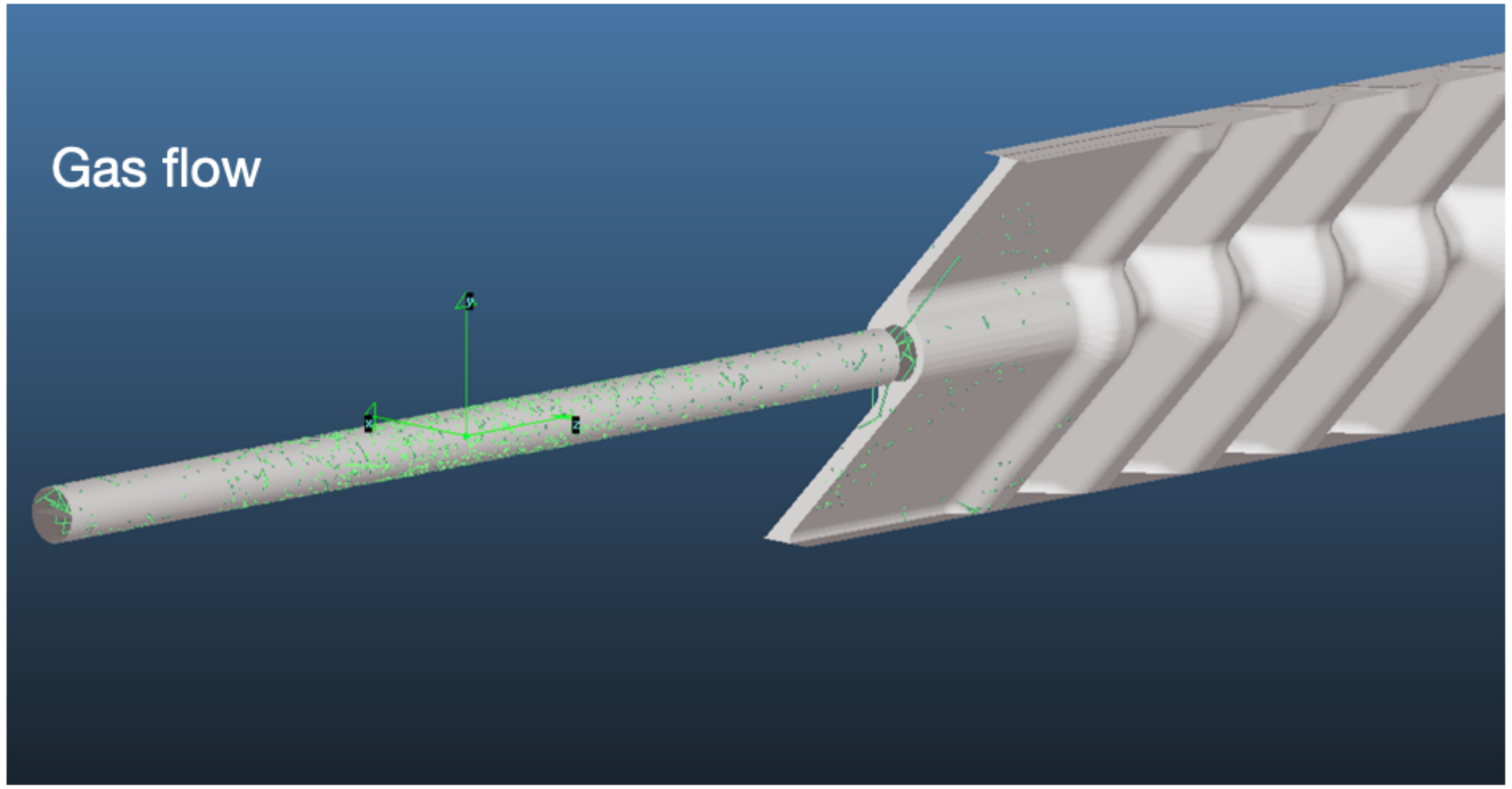


Injection valve PV611

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

The storage cell advantage: up to x50 density wrt free flow

[SMOG2 TDR]

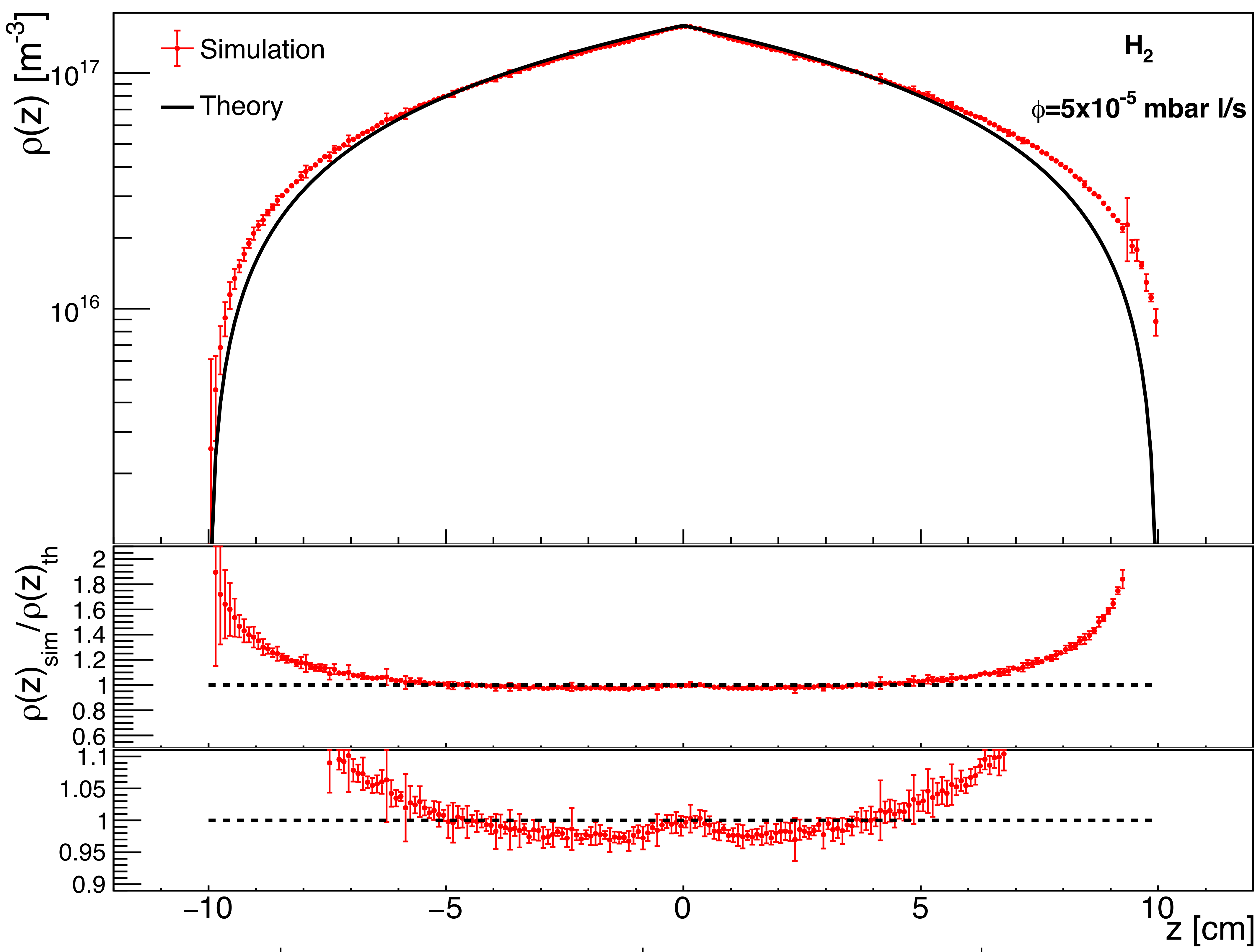


SMOG2 example pAr @115 GeV in 1yr of data taking

Int. Lumi.		80/pb
Sys.error of J/Ψ xsection		~3%
J/Ψ	yield	28 M
D^0	yield	280 M
Λ_c	yield	2.8 M
Ψ'	yield	280 k
$\Upsilon(1S)$	yield	24 k
$DY\ \mu^+\mu^-$	yield	24 k

Very high statistics with a low gas flow

Molflow simulation

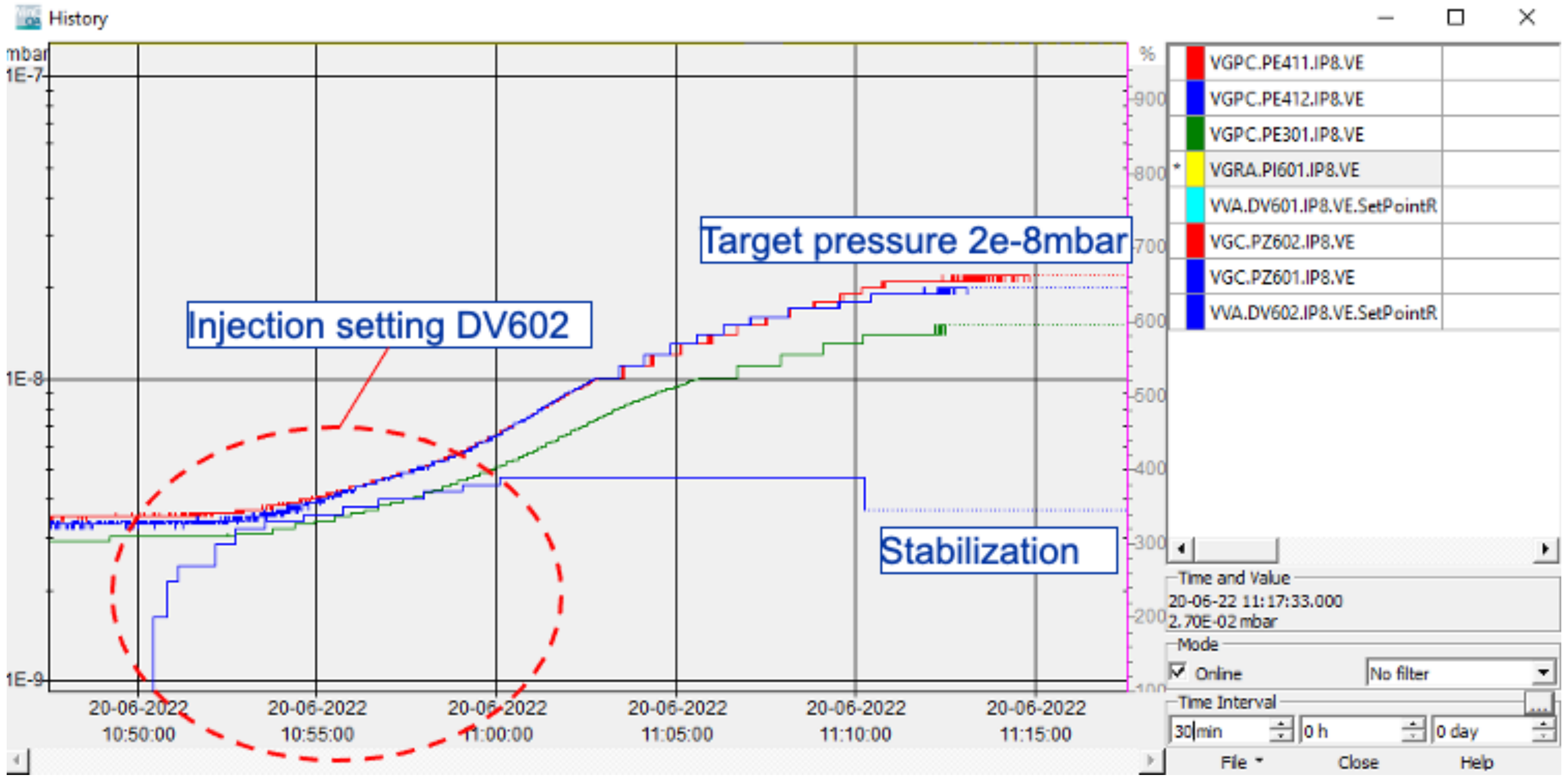


	$\theta_{sim} \times 10^{12}\ [cm^{-2}]$	$\theta_{th} \times 10^{12}\ [cm^{-2}]$	C_θ
Hydrogen	1.627	1.592	1.022
Argon	7.274	7.120	1.022

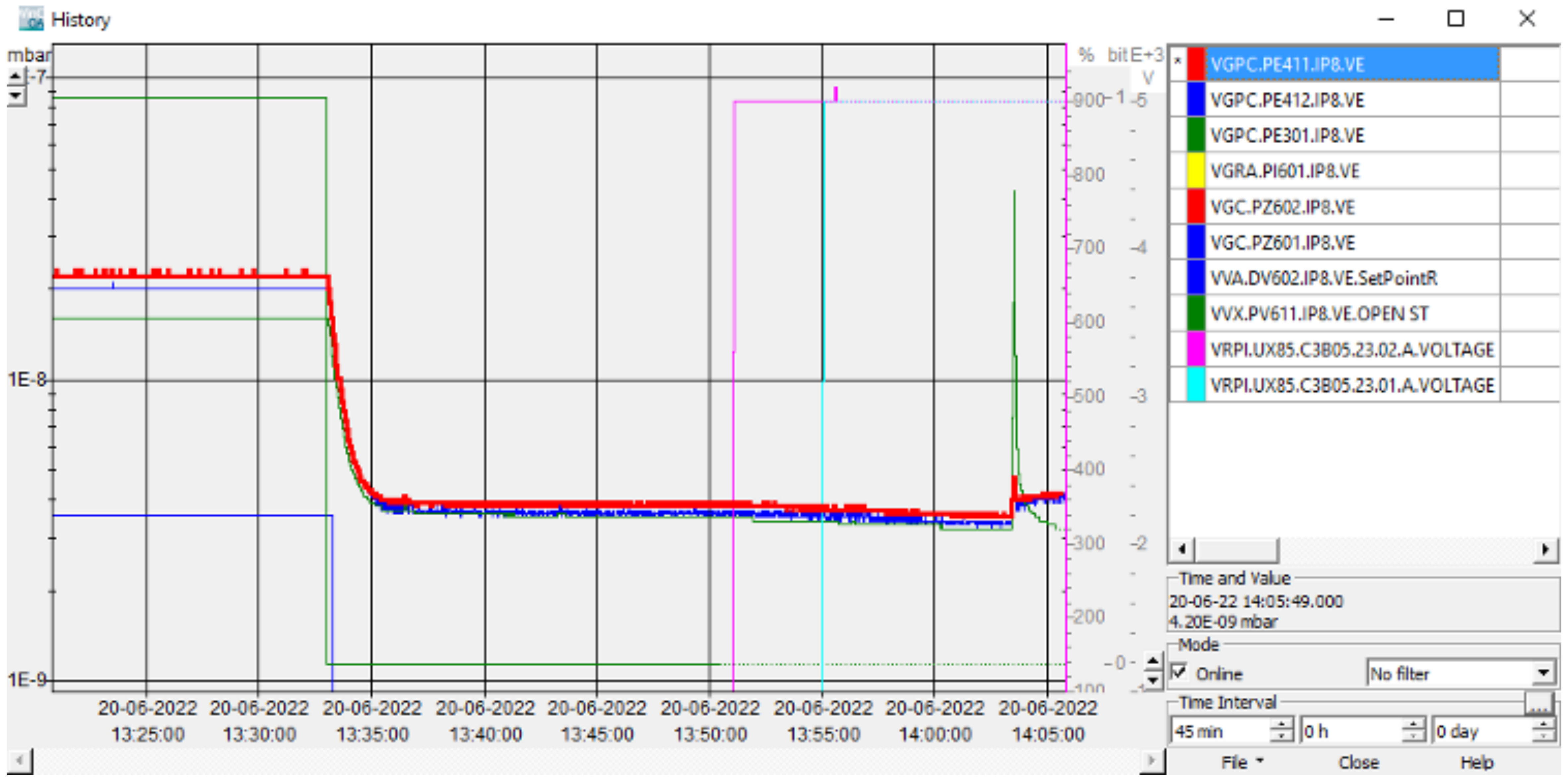
Systematic uncertainty on Luminosity: 1.5%

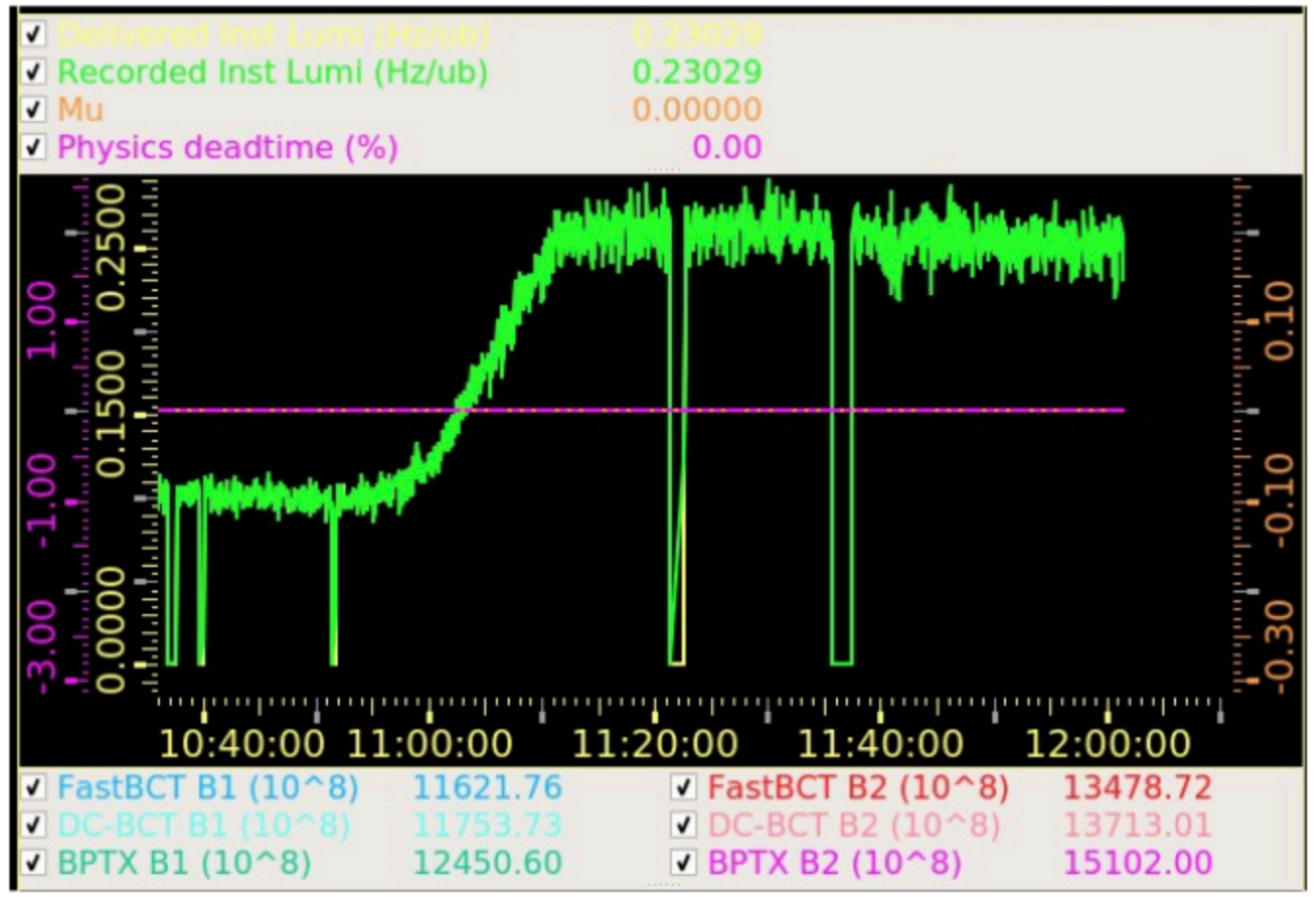
SMOG2 gas injection at LHC Run3 started in June 2022

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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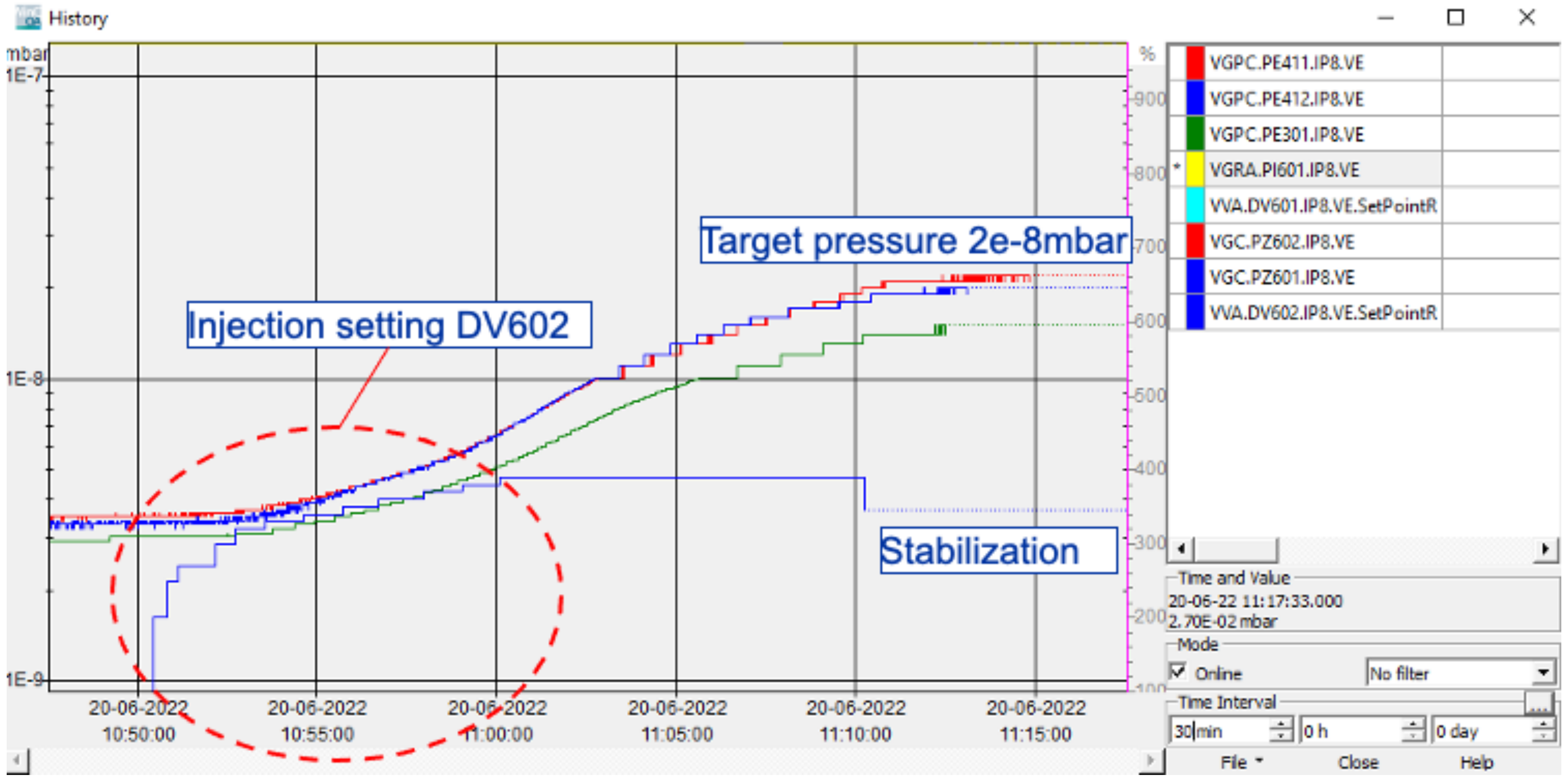

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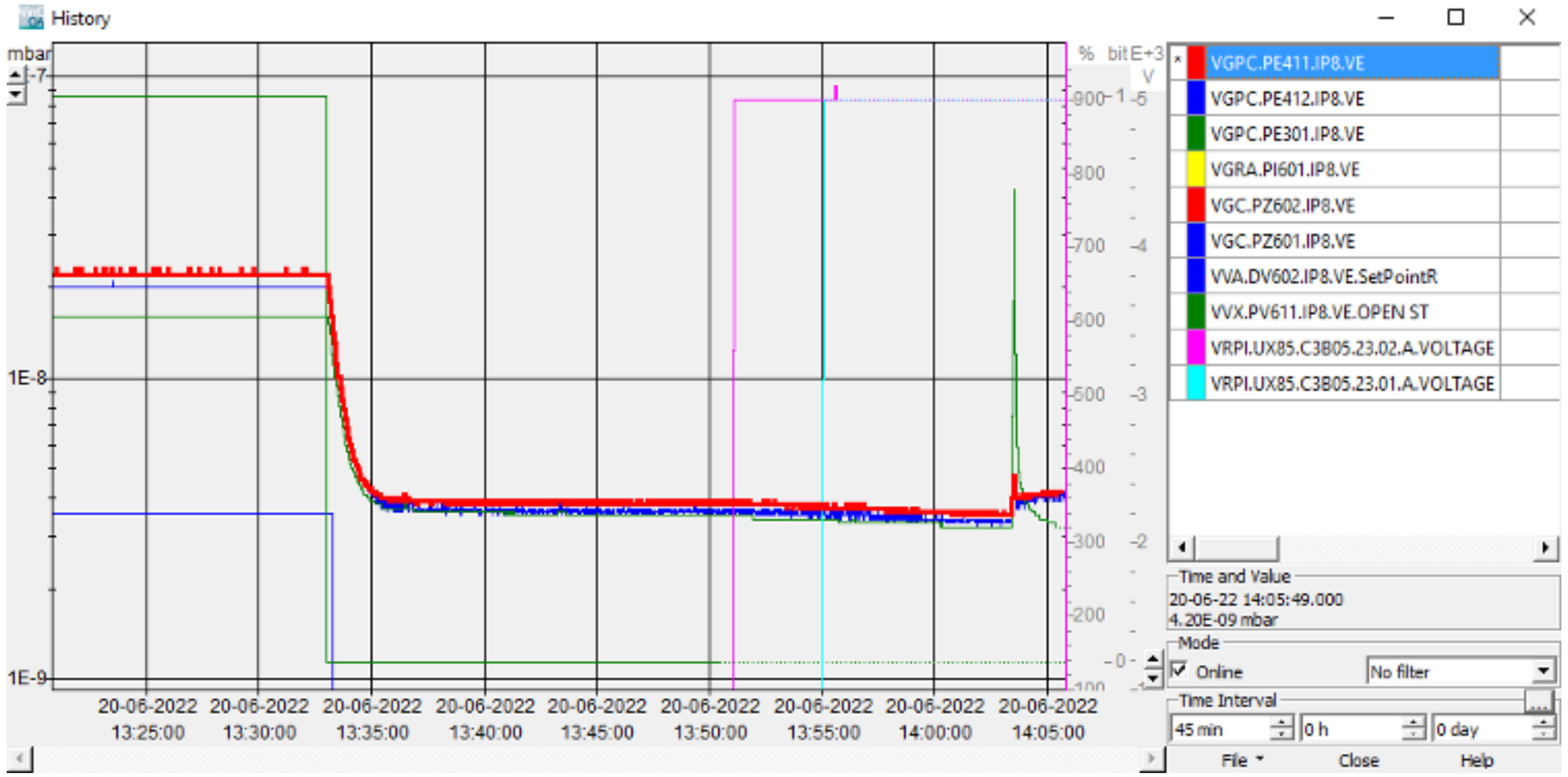
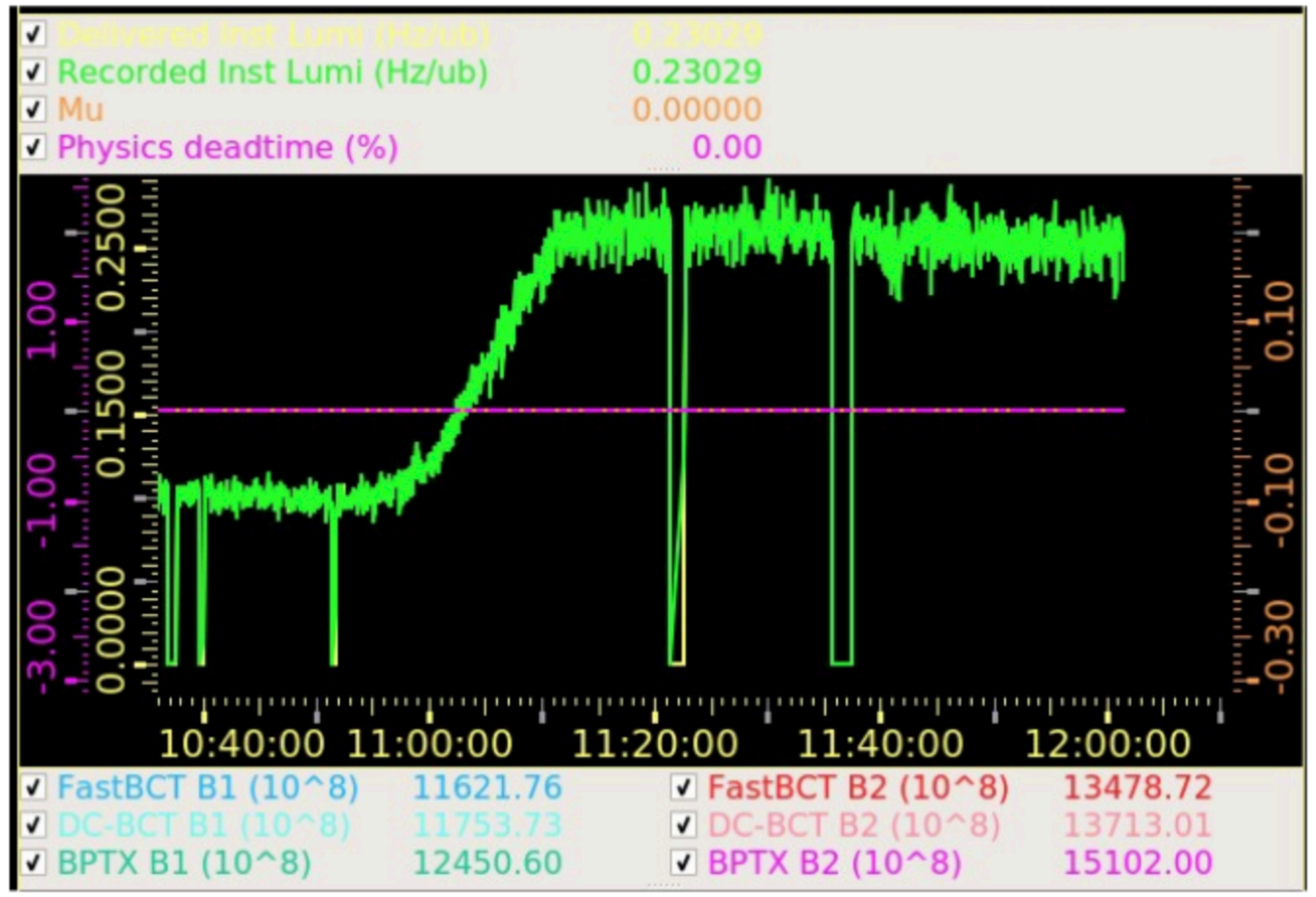




Luminosity increase seen by the LHCb luminometer (Plume)

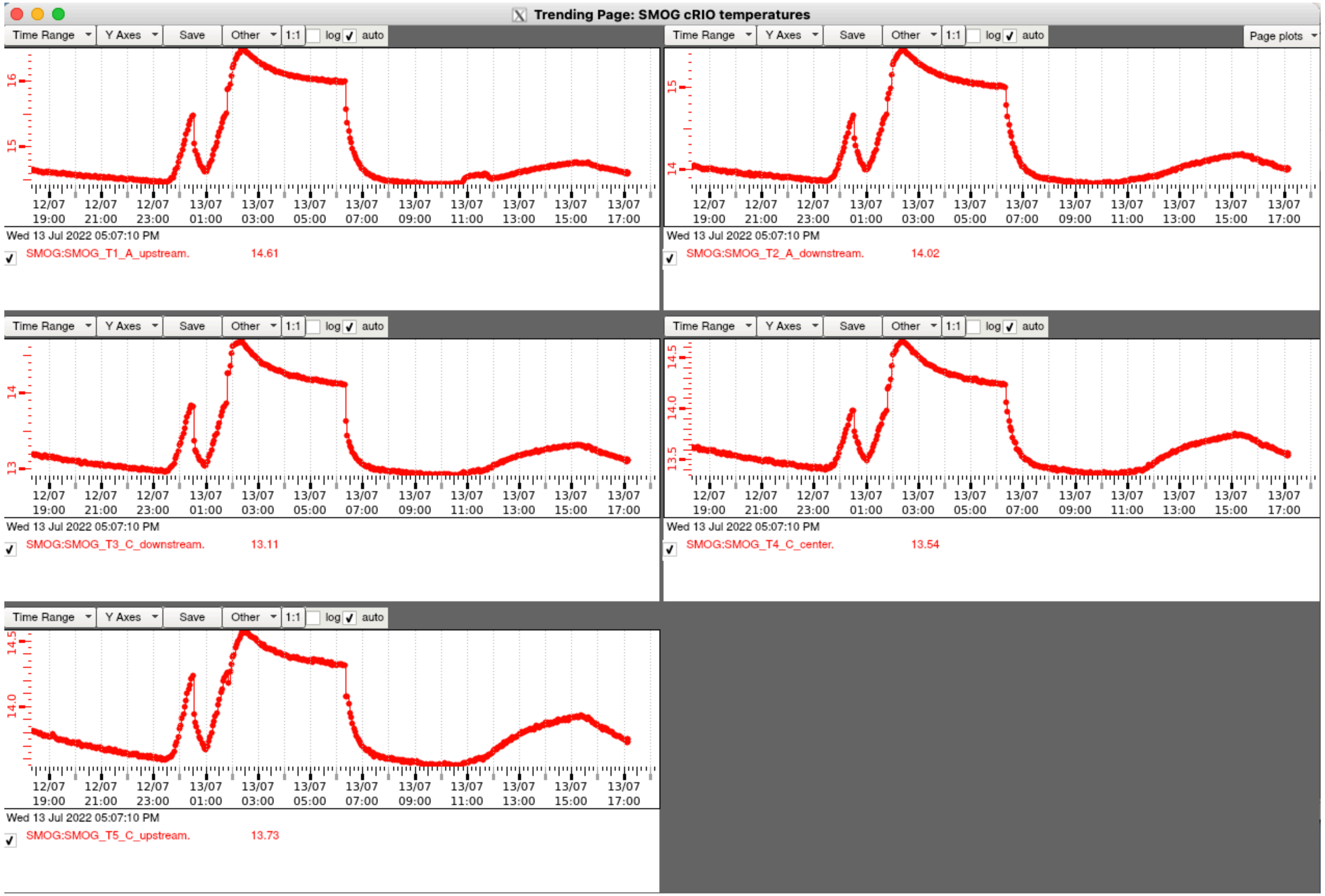
Extremely useful also for the LHCb commissioning

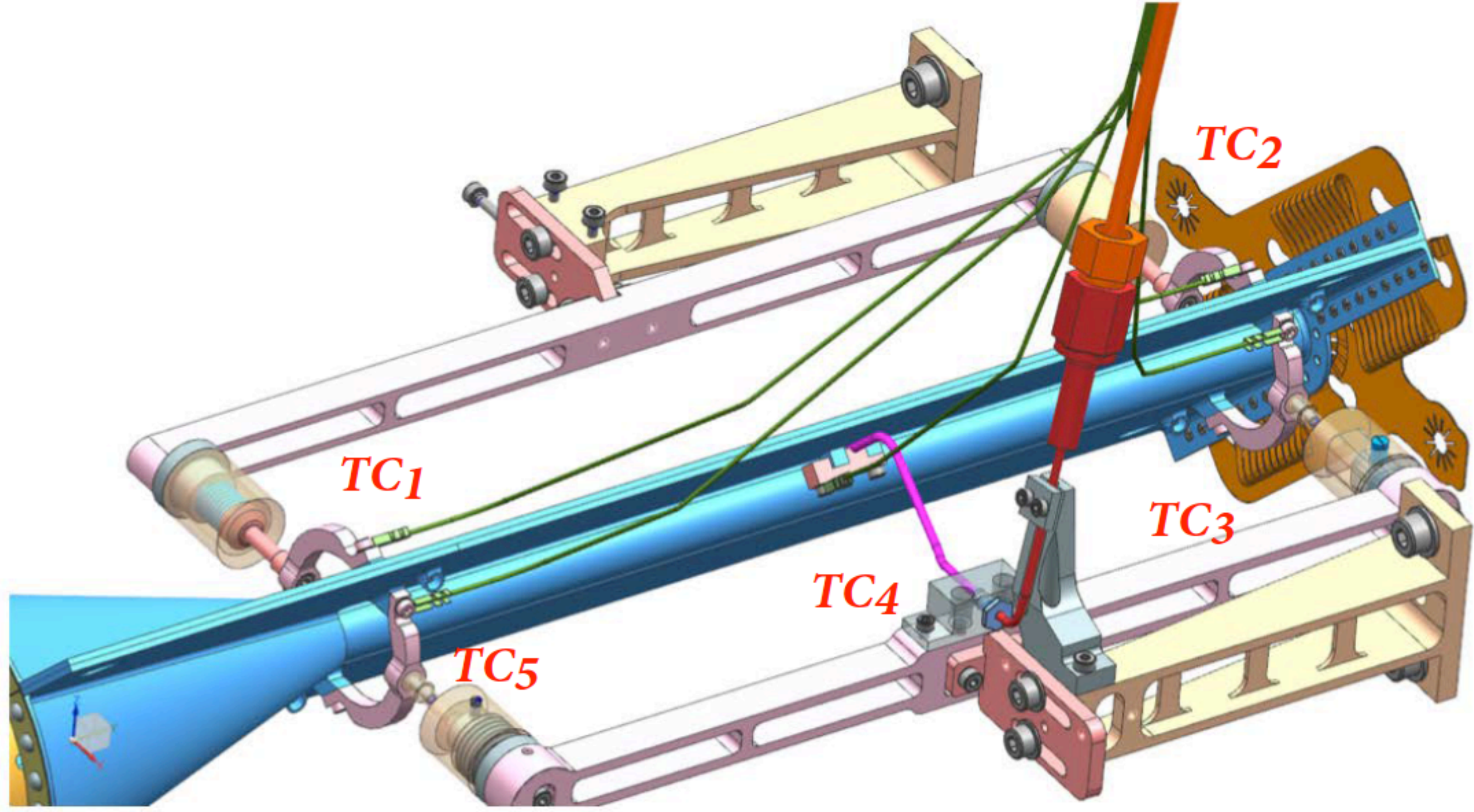
LHC official statement

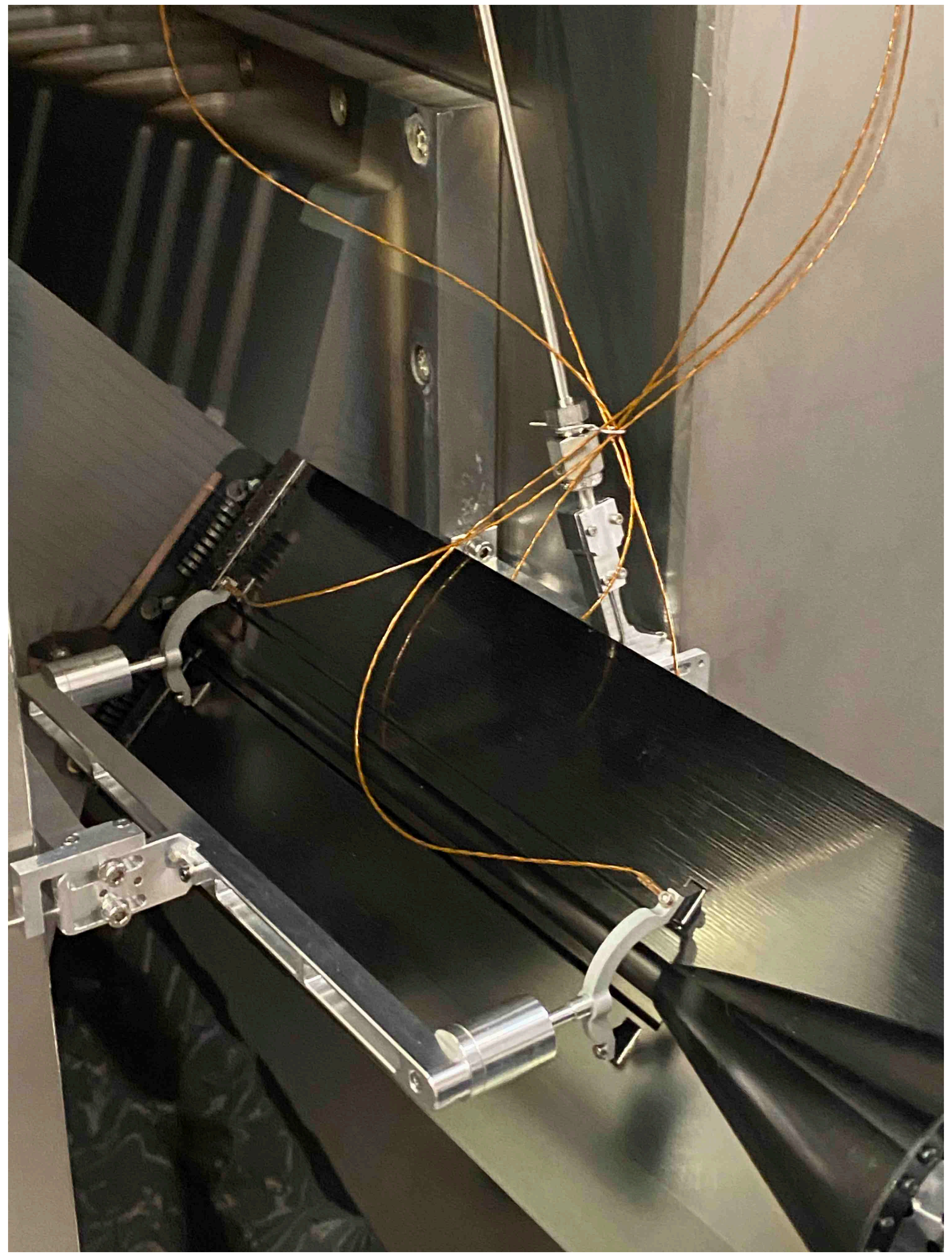
No negative feedback when there is gas injection. Green light to inject when needed

Temperature system

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





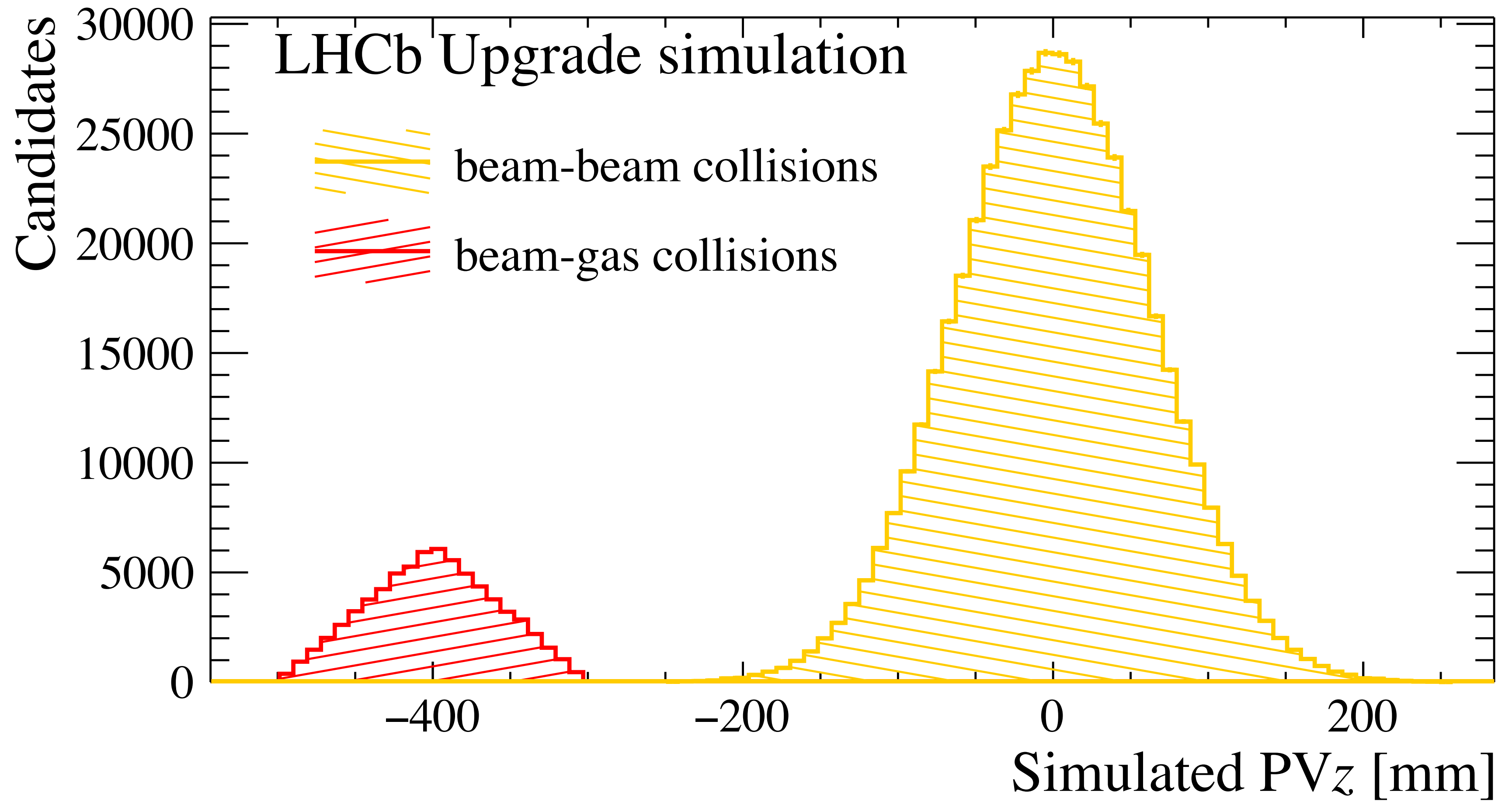


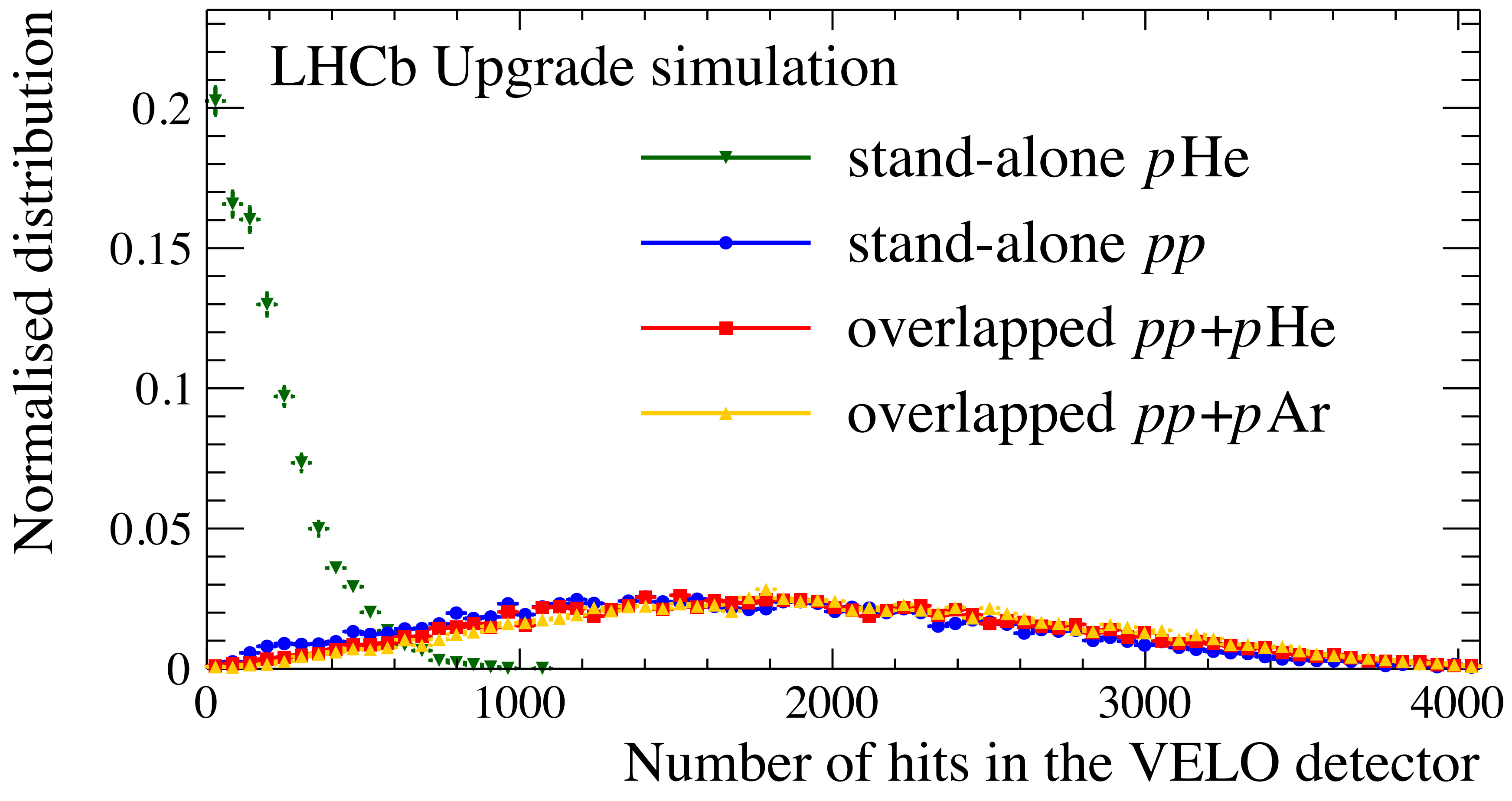
Measurements implemented in the LHC control panel, too

SMOG2/LHCspin performances

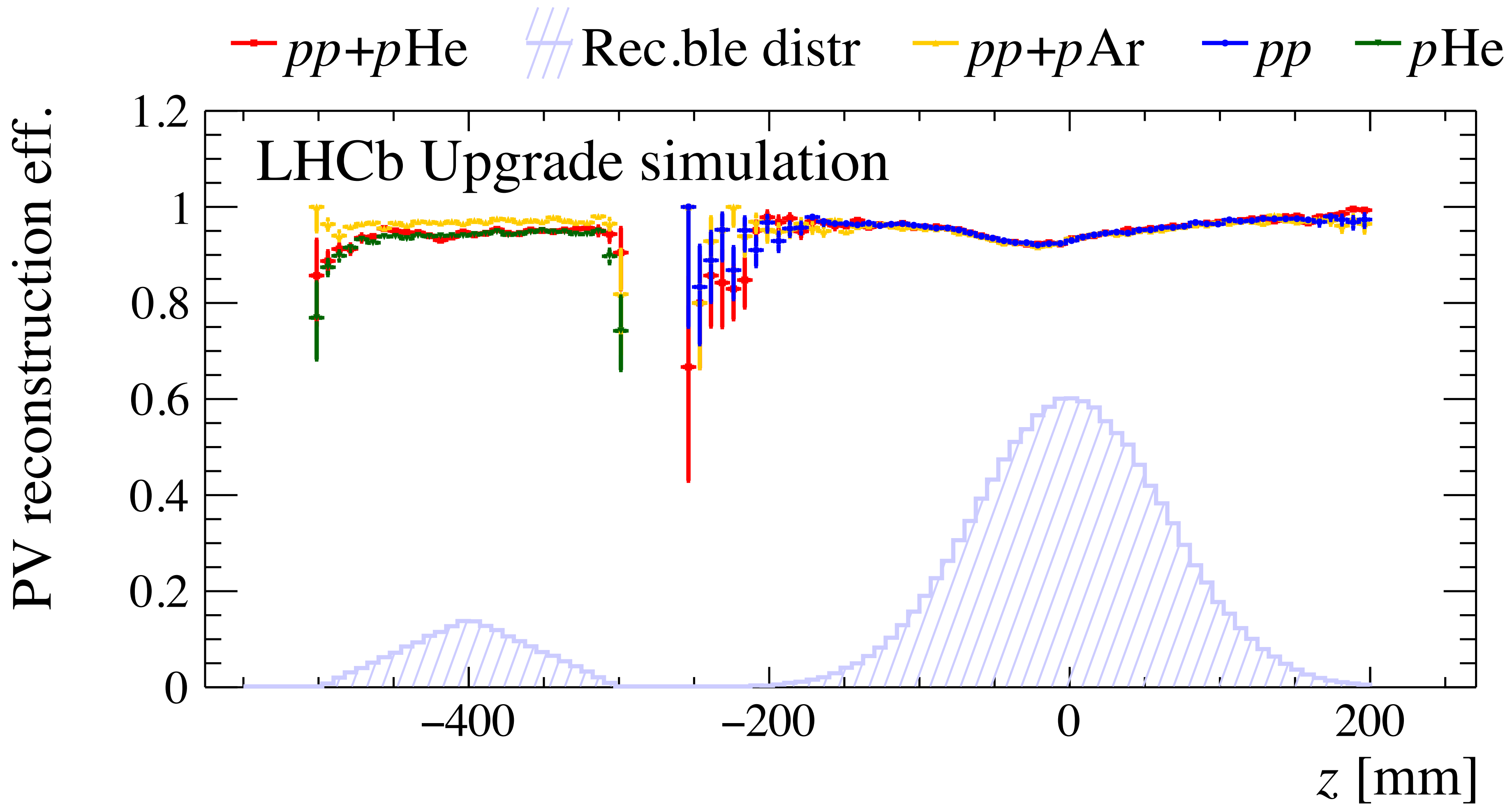
[LHCB-FIGURE-2022-002]

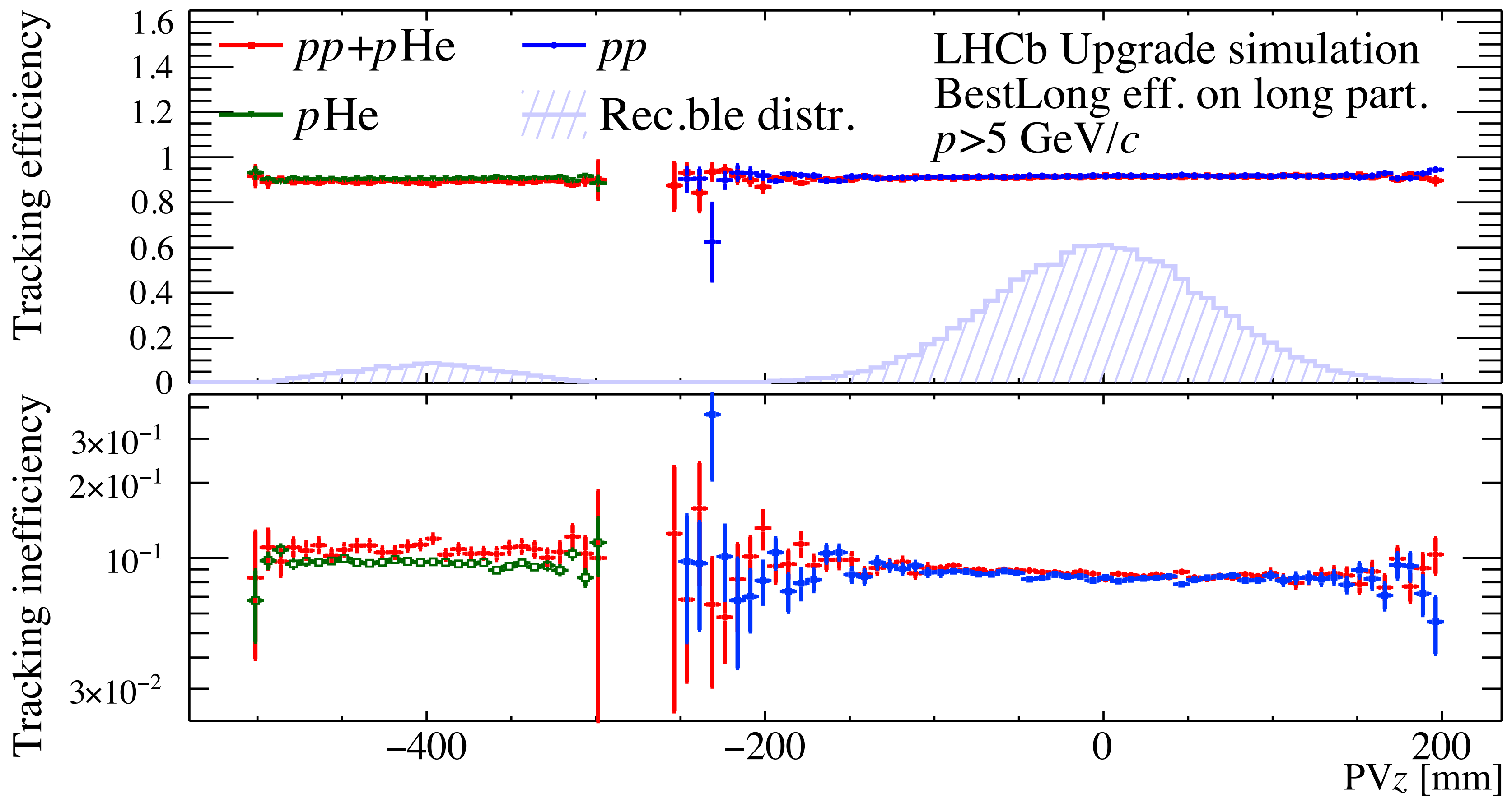
- beam-beam and beam-gas interaction regions are well detached
- Negligible increase of multiplicity: 1 – 3 % throughput decrease when adding beam-gas to the LHCb event reconstruction sequence





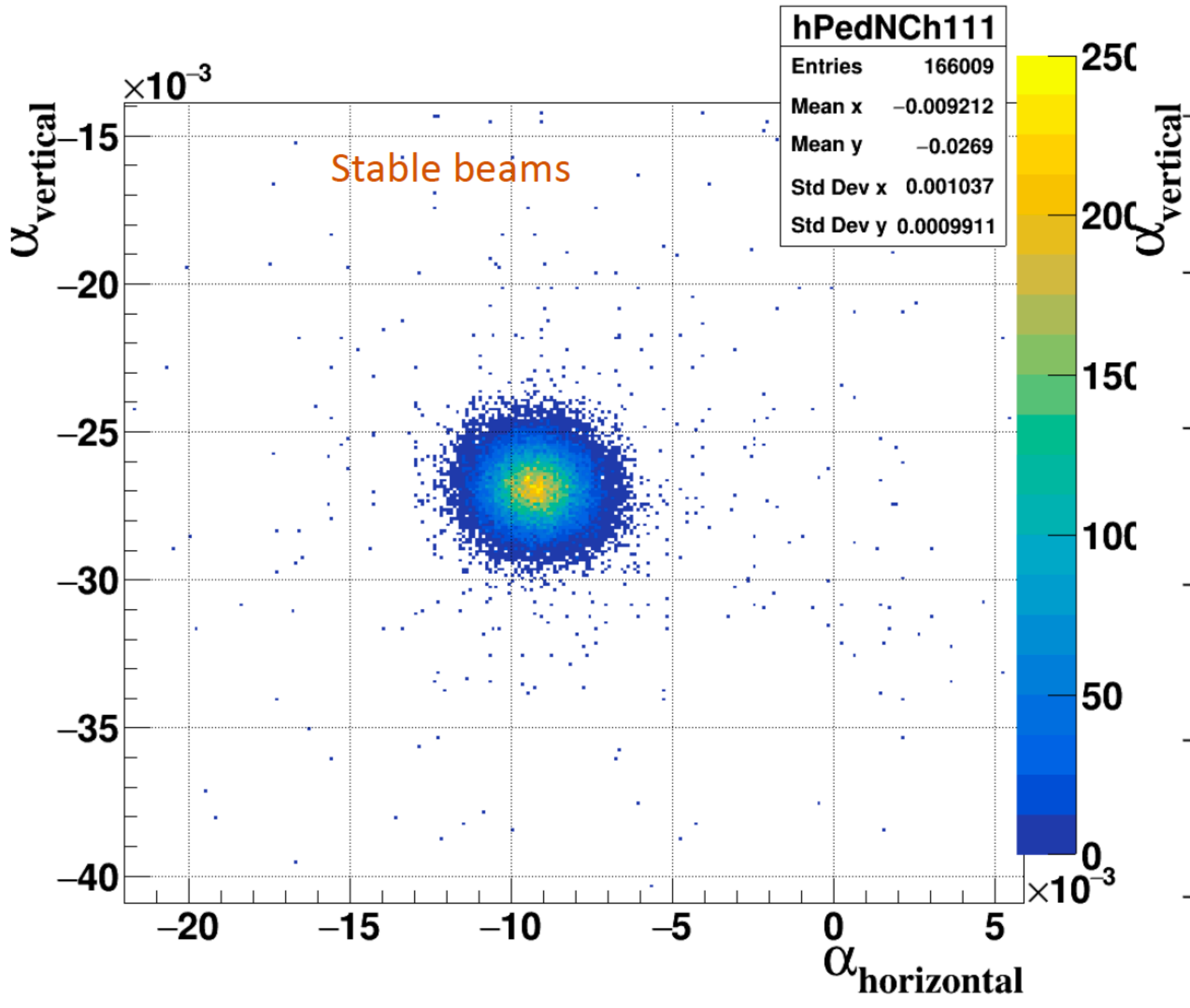
- Full reconstruction efficiency (PV & tracks) retained in the beam-gas region

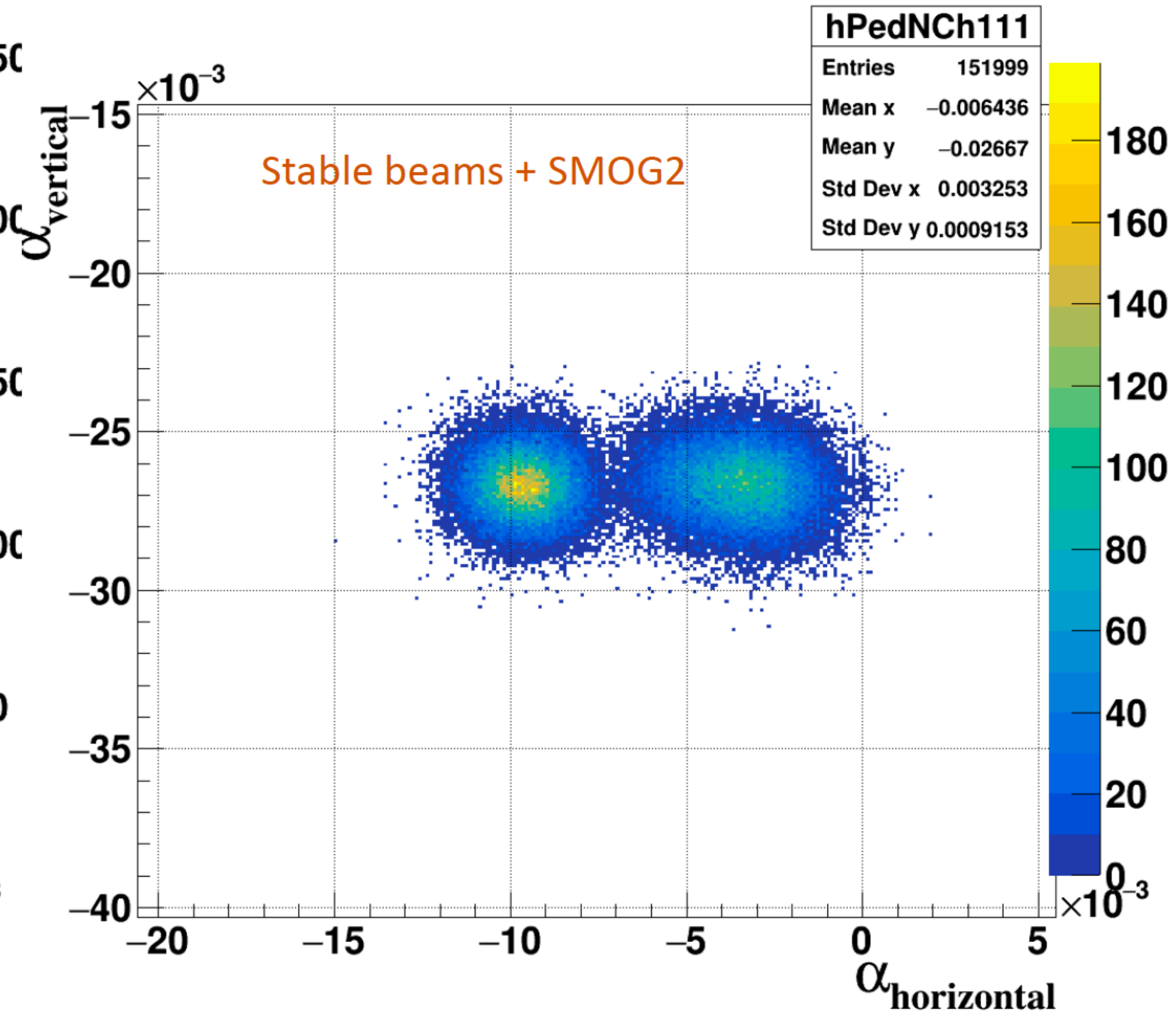


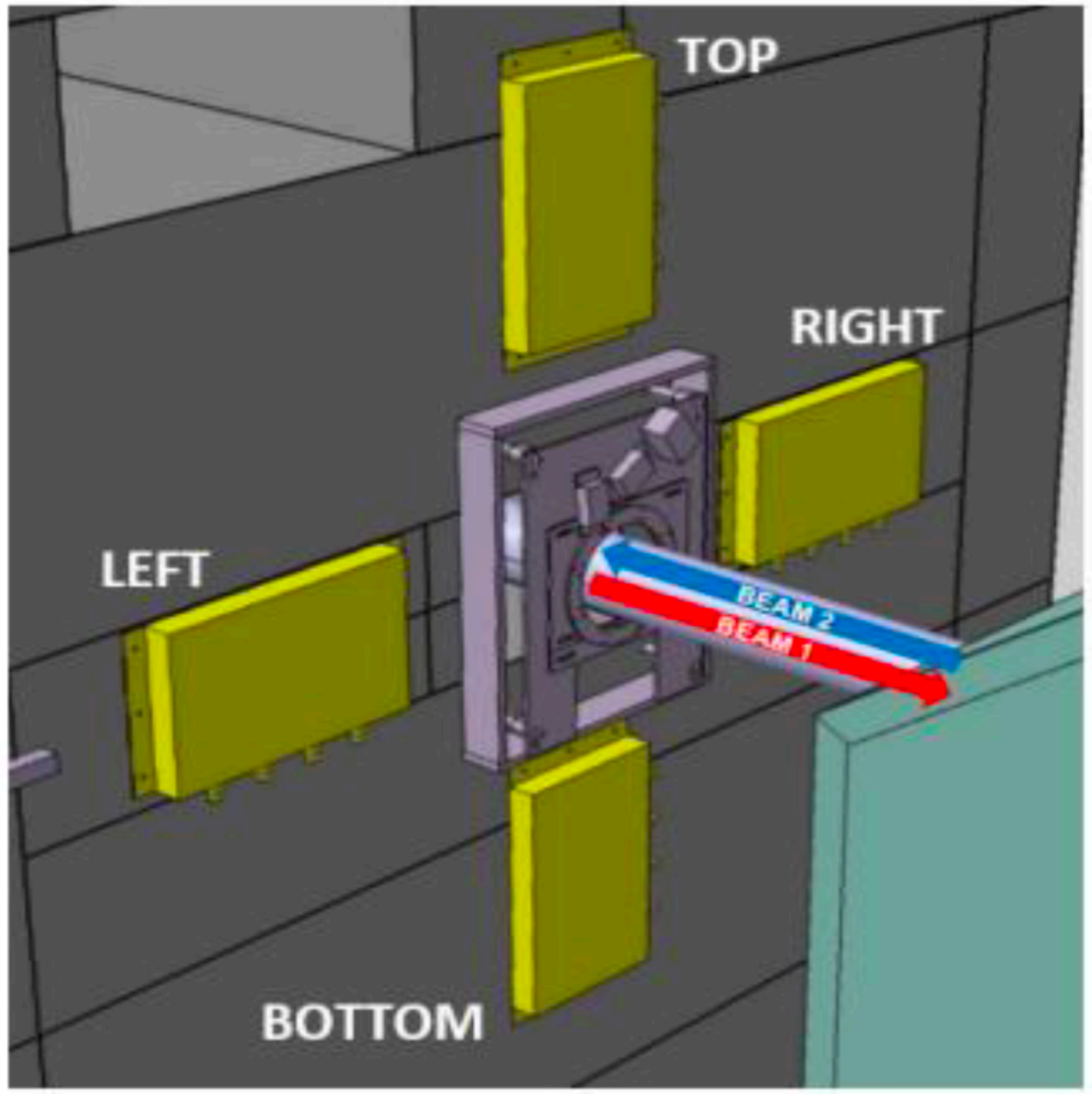


LHCb is the only experiment able to run in collider and fixed-target mode simultaneously!

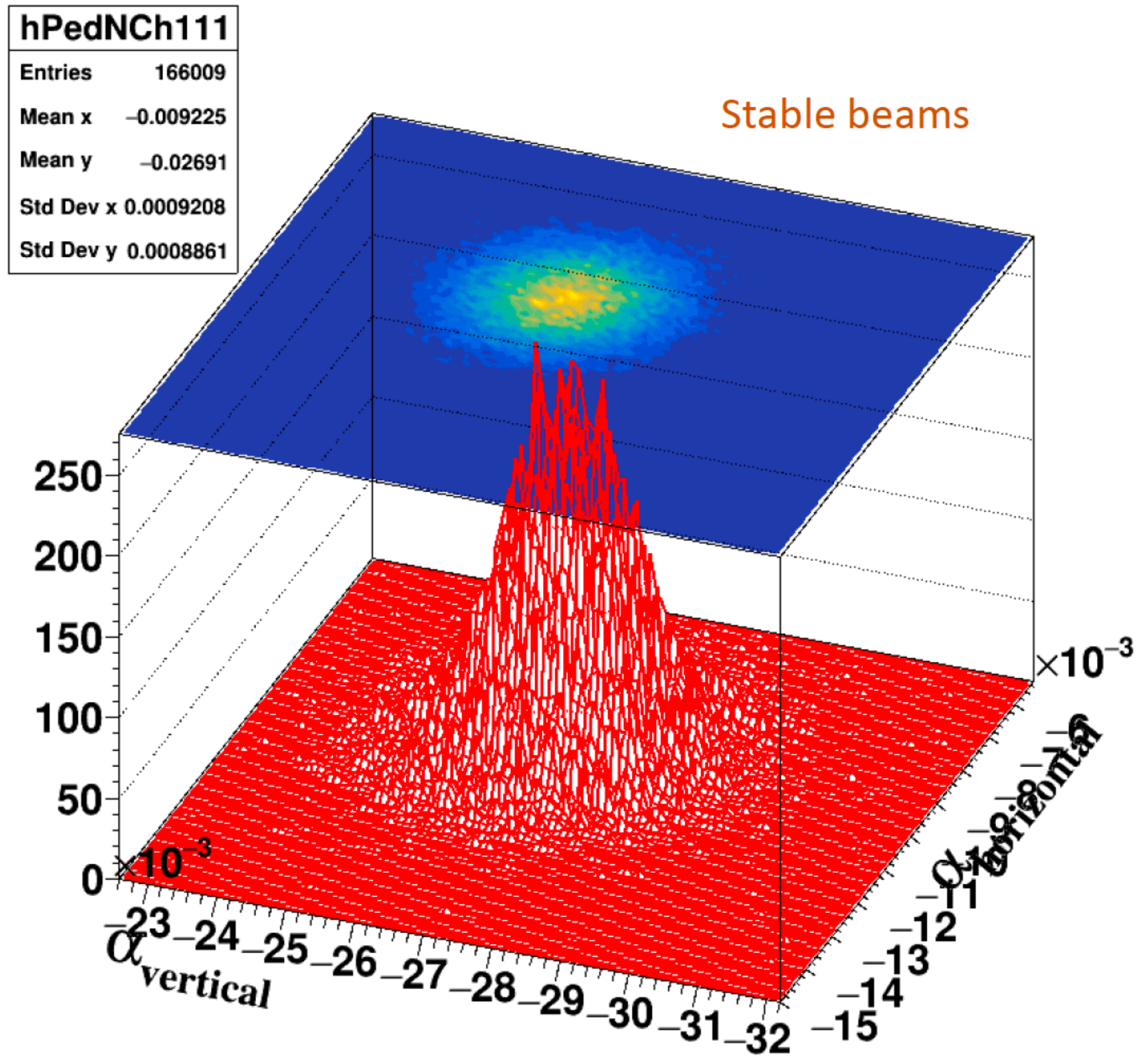
Very preliminary experimental PV distributions

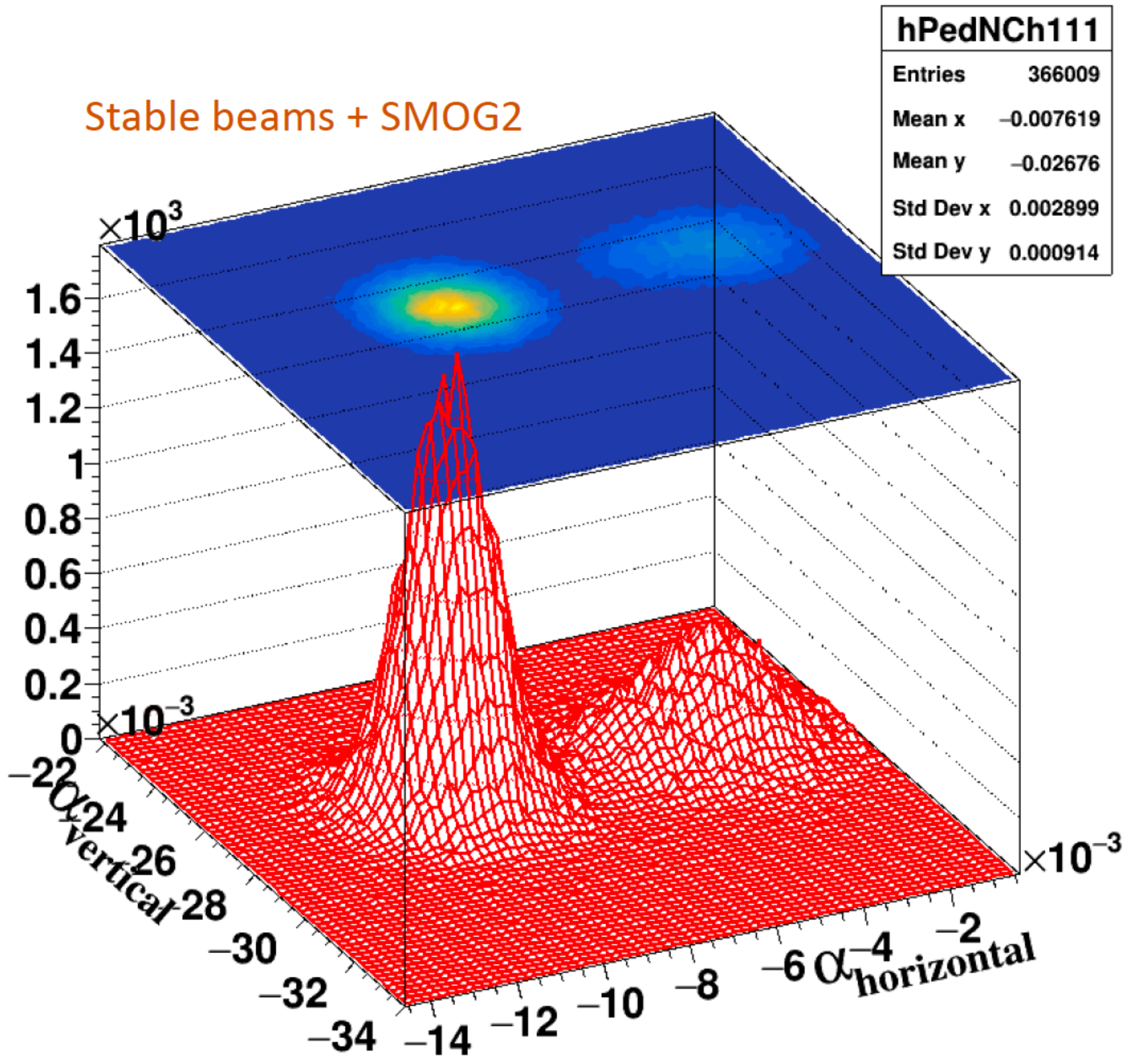






RMS-R3 modules placement around the beampipe

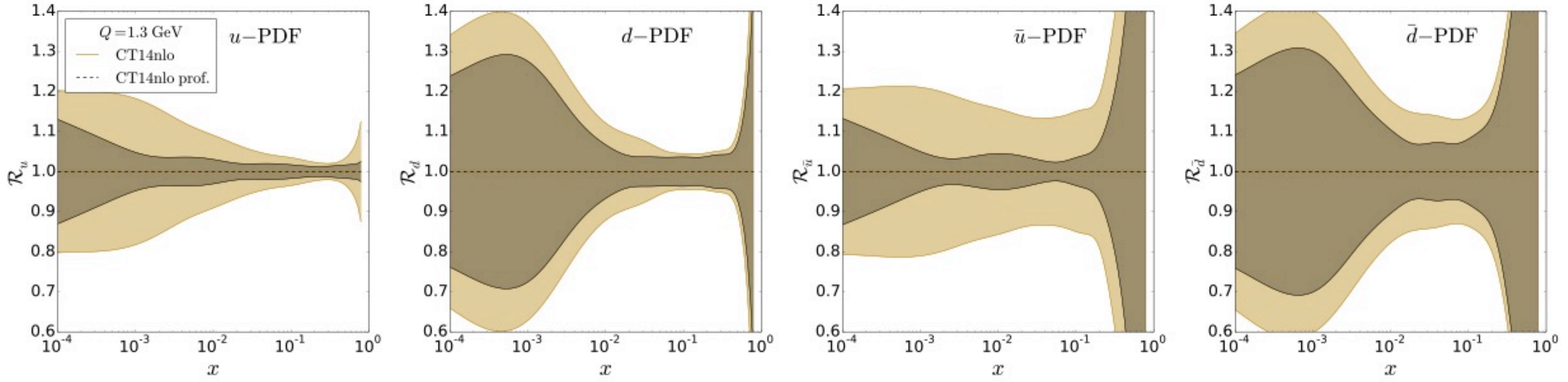




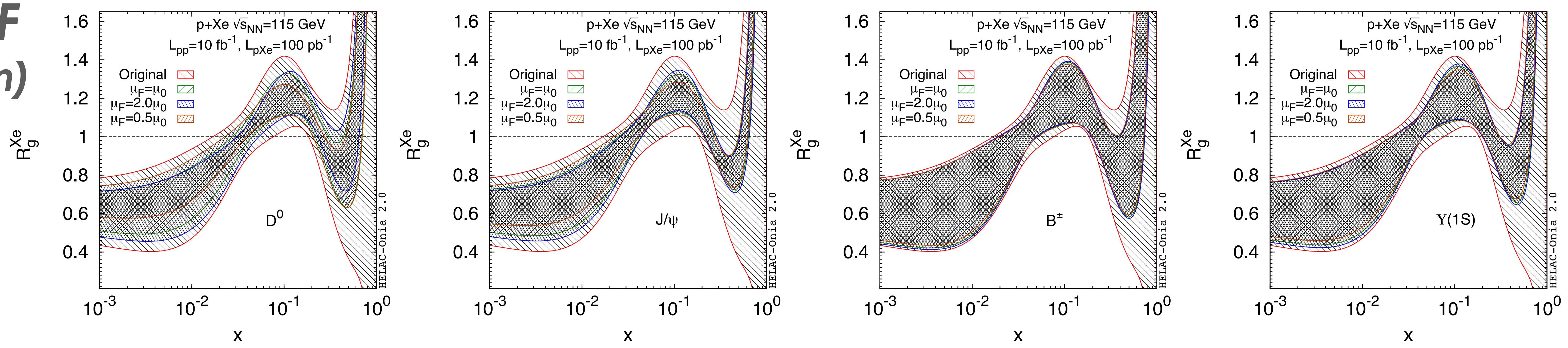
SMOG2 … few highlights

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

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



nPDF (gluon)



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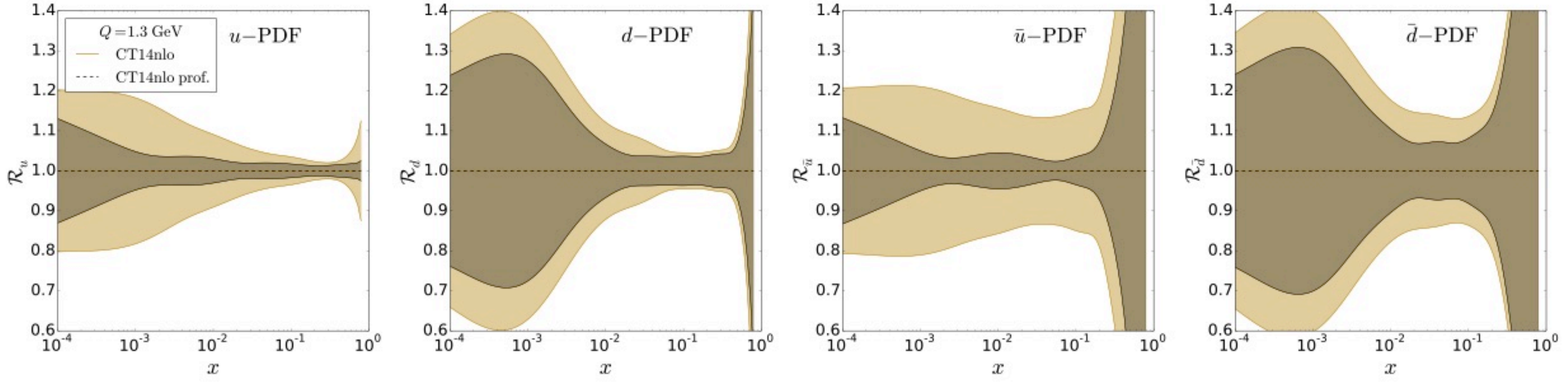

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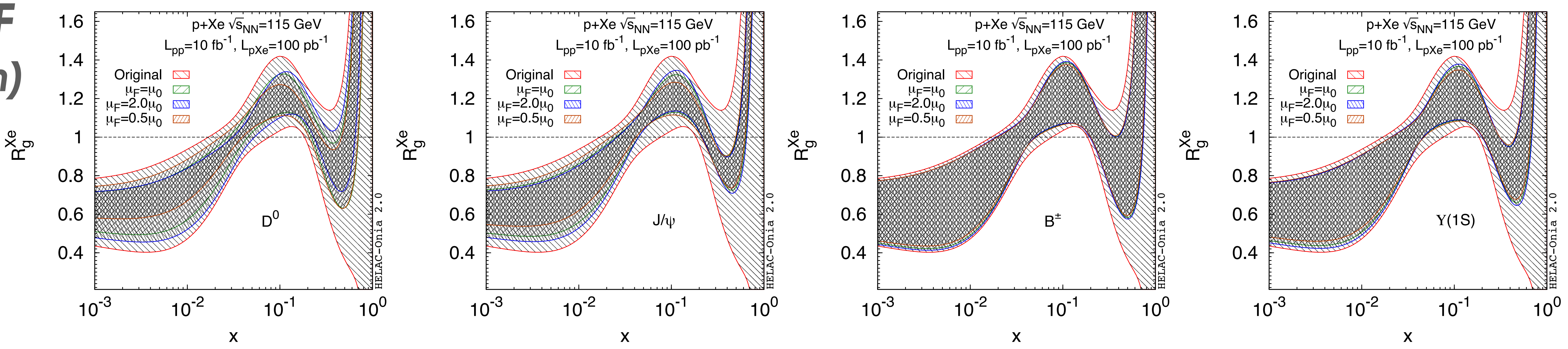
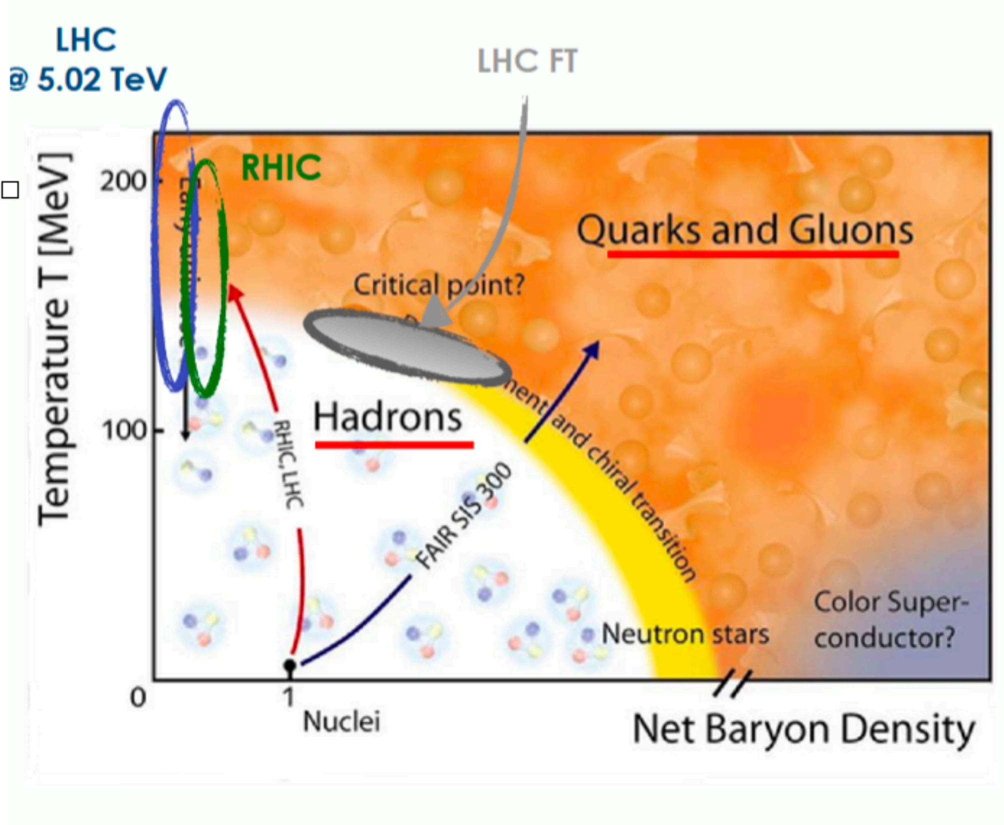
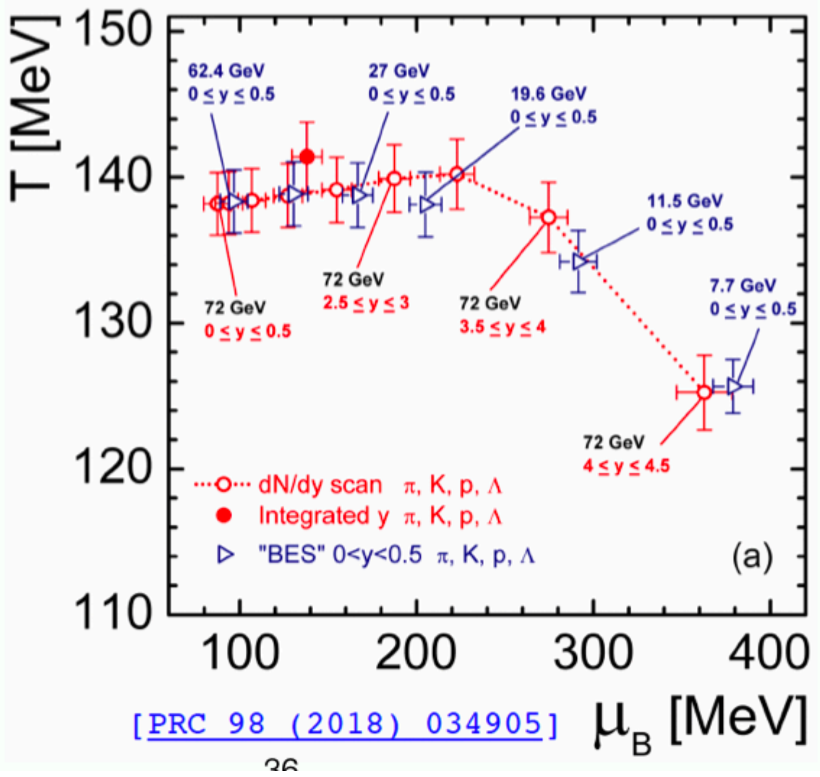
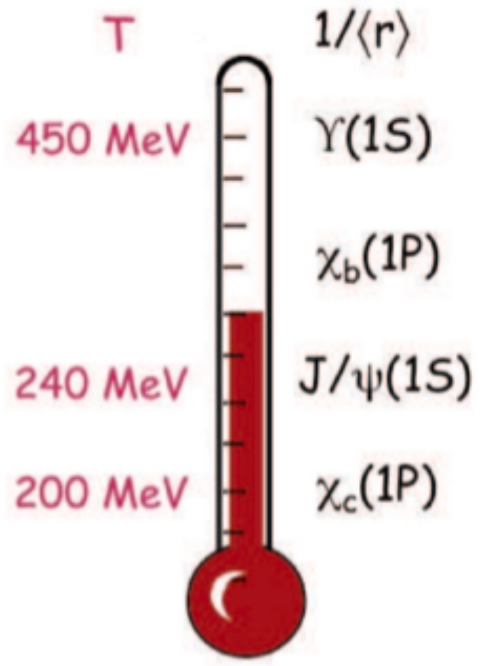


Heavy-Ion and QCD phase space





$c\bar{c}$ bound states



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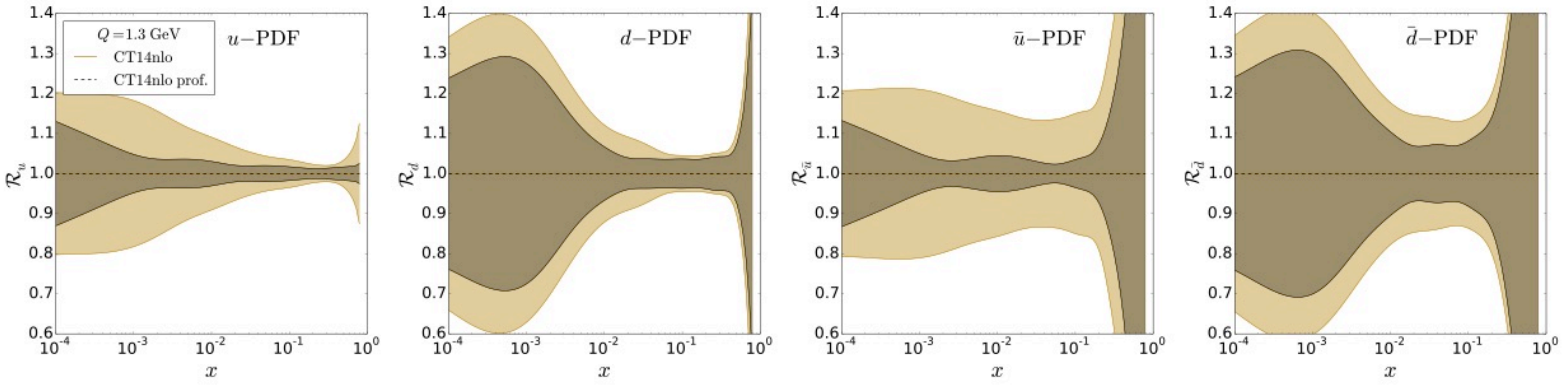

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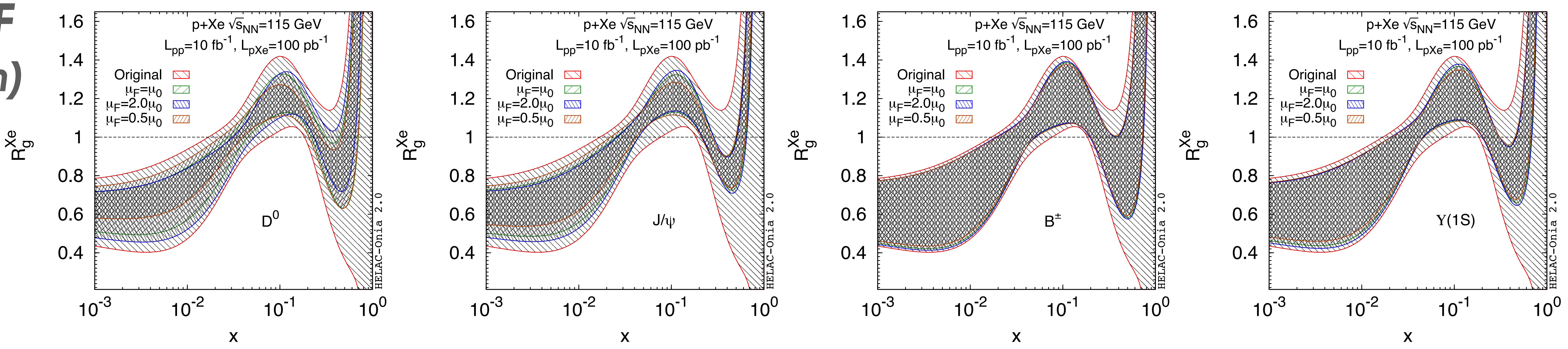

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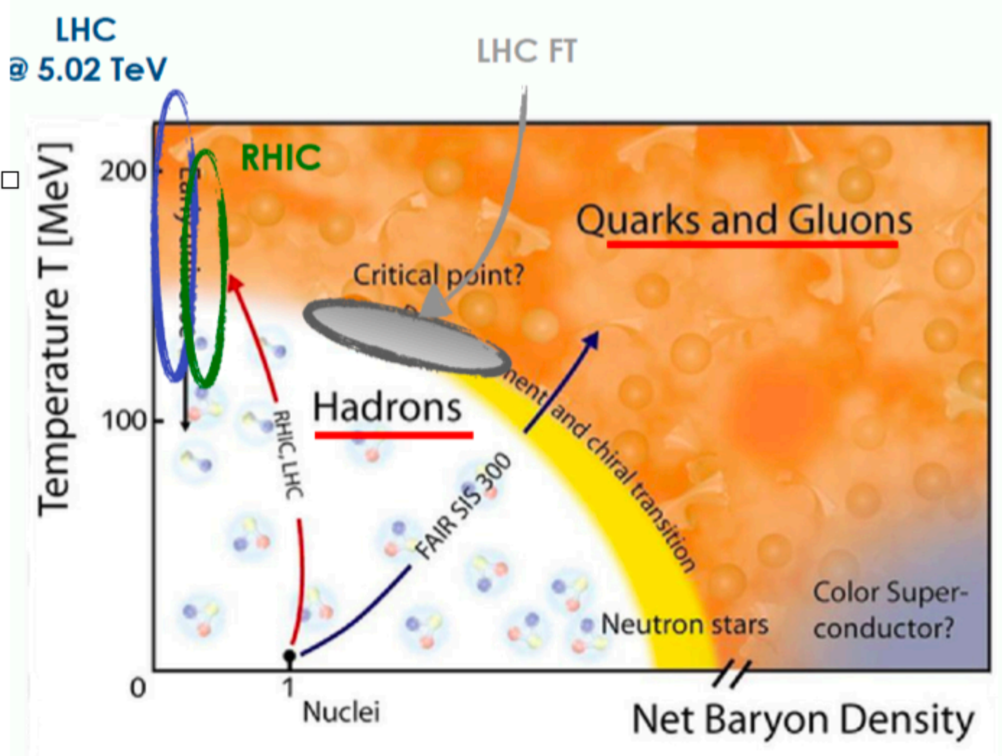

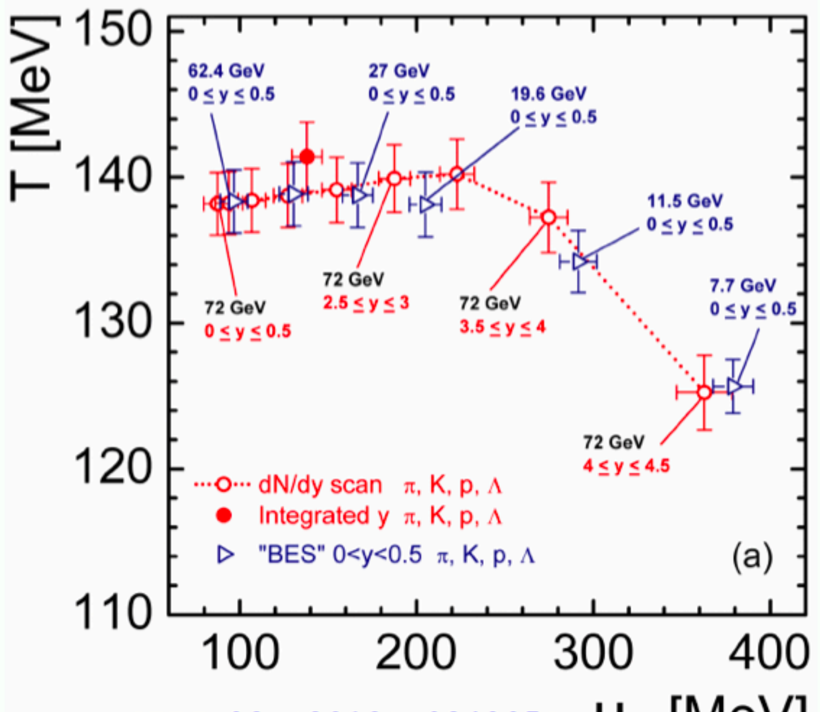

[PRC 98 (2018) 034905]

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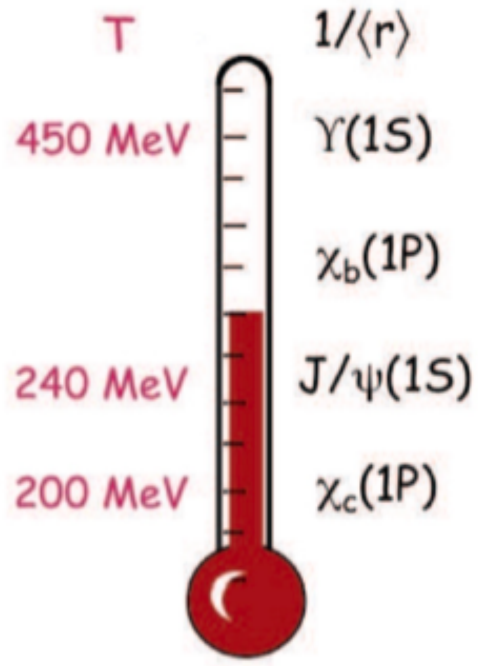
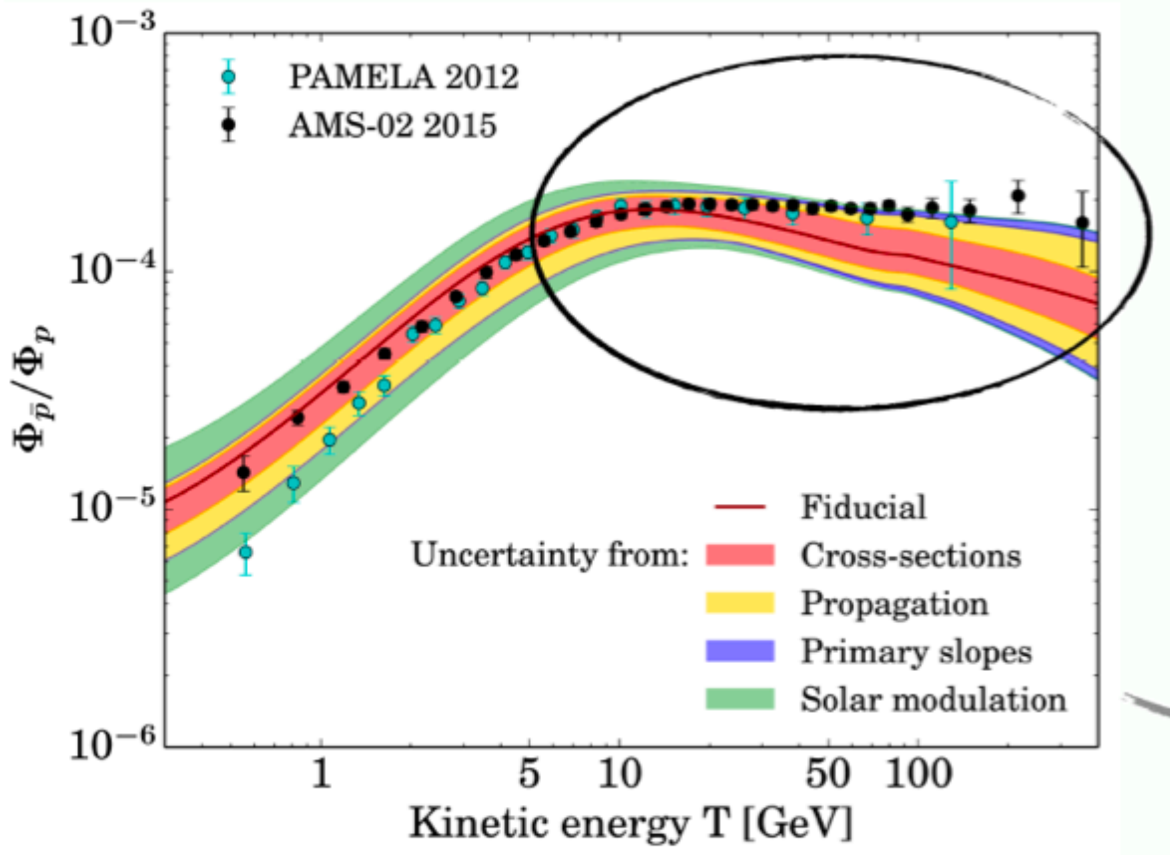
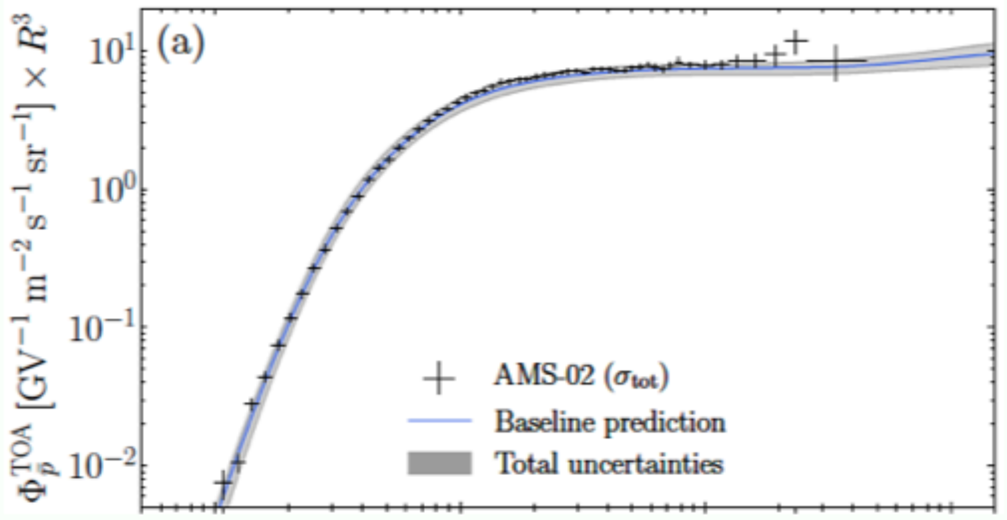


Astroparticle (DM and CR)

[JCAP09 (2015) 023]



[ArXiv:1906.07119]



- Main uncertainty still due to cross sections!

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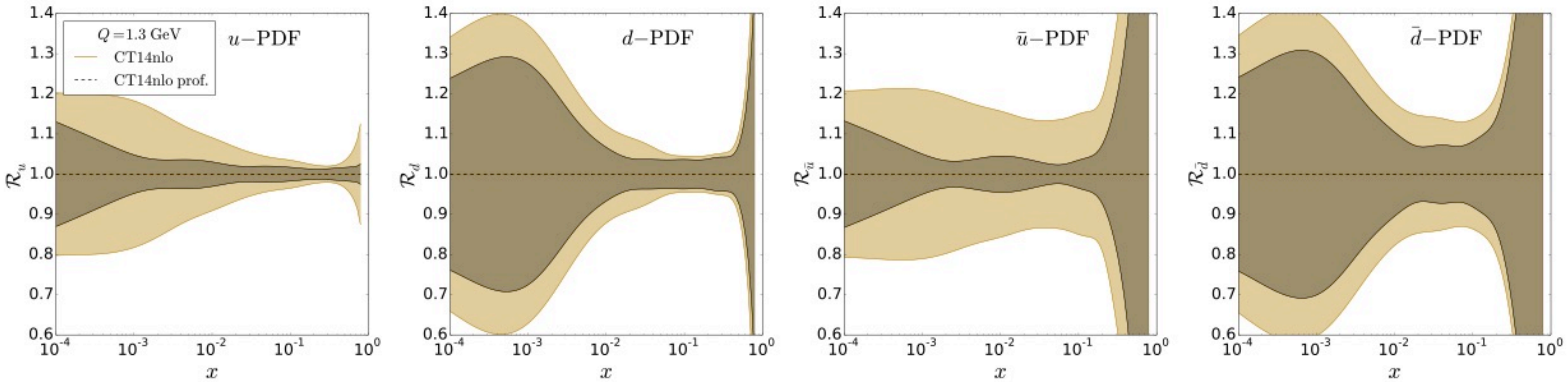

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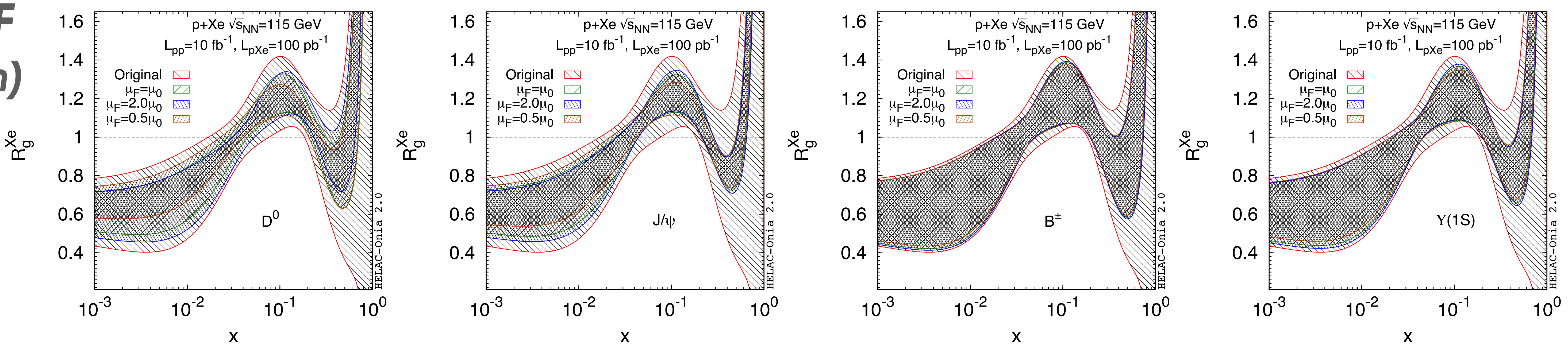
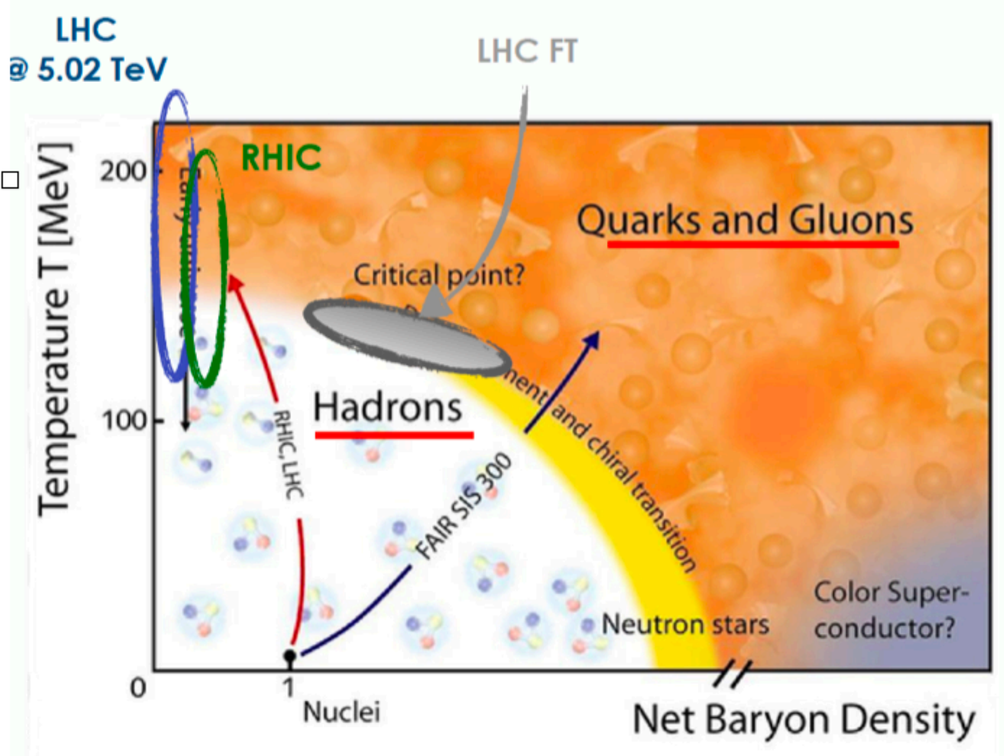
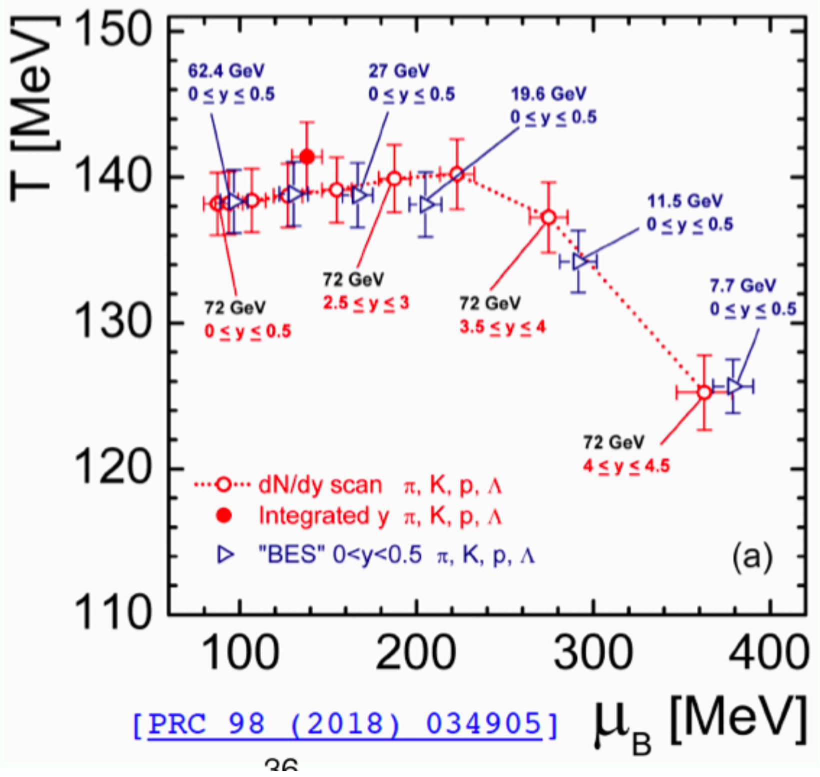
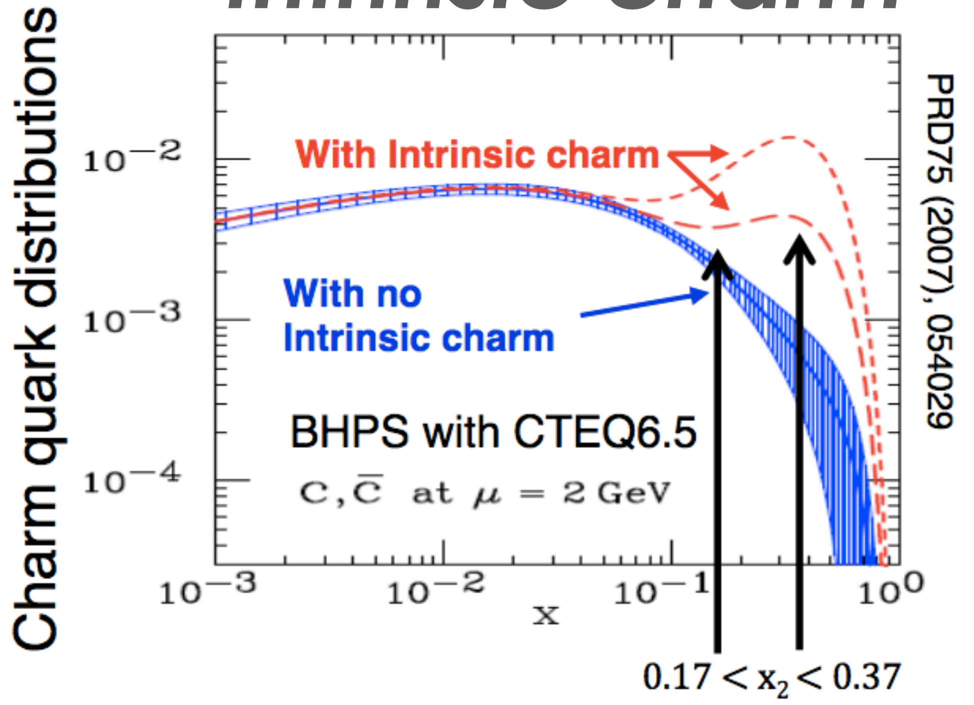


Heavy-Ion and QCD phase space

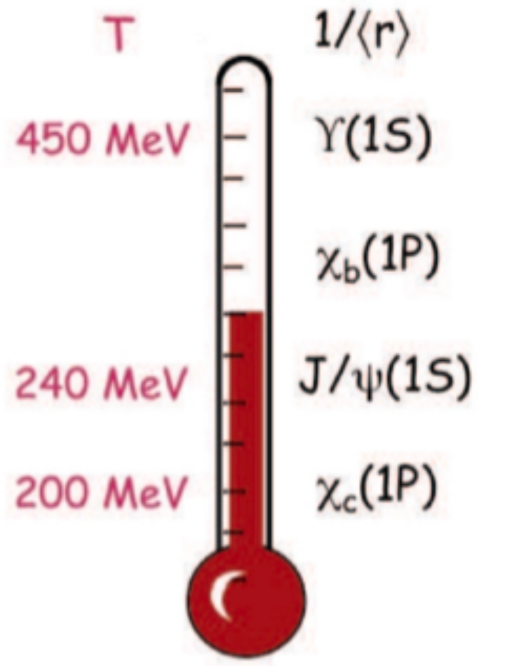




Intrinsic charm

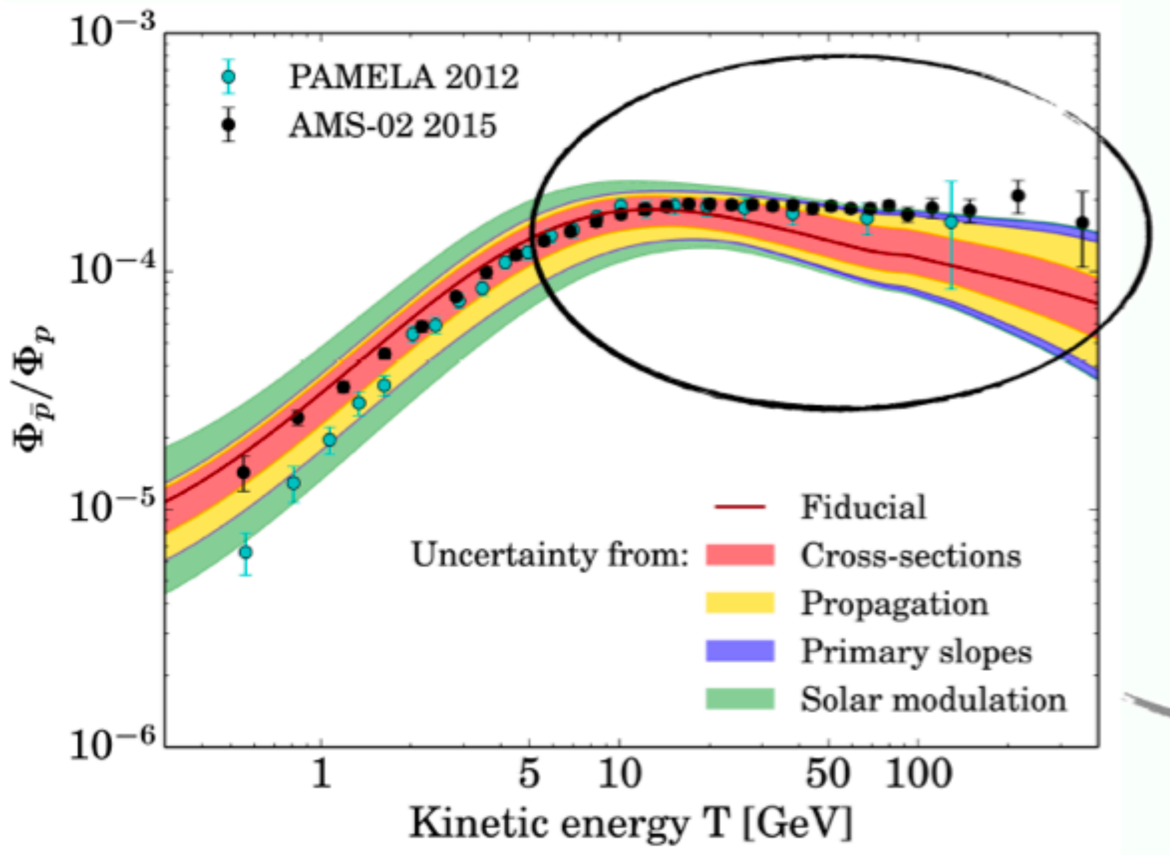


$c\bar{c}$ bound states

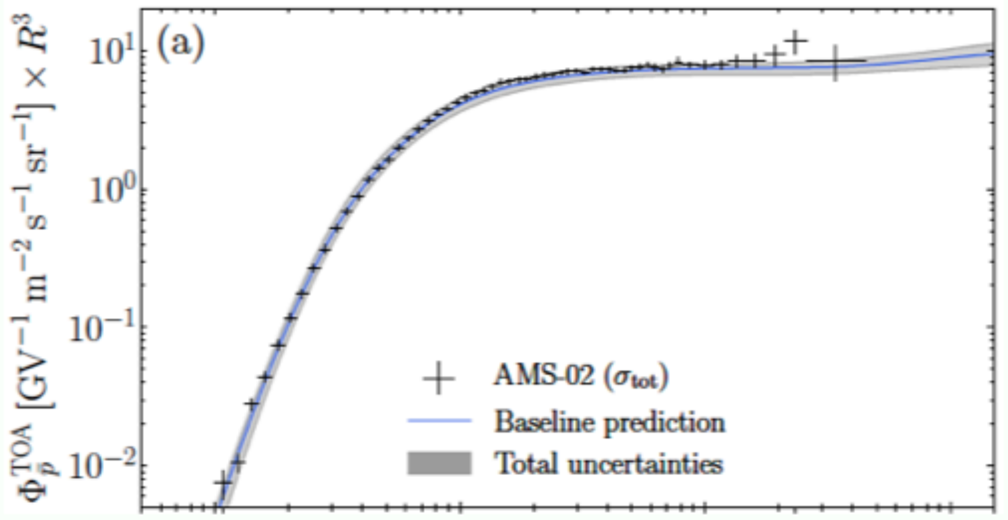


Astroparticle (DM and CR)

[JCAP09 (2015) 023]



[ArXiv:1906.07119]



- Main uncertainty still due to cross sections!

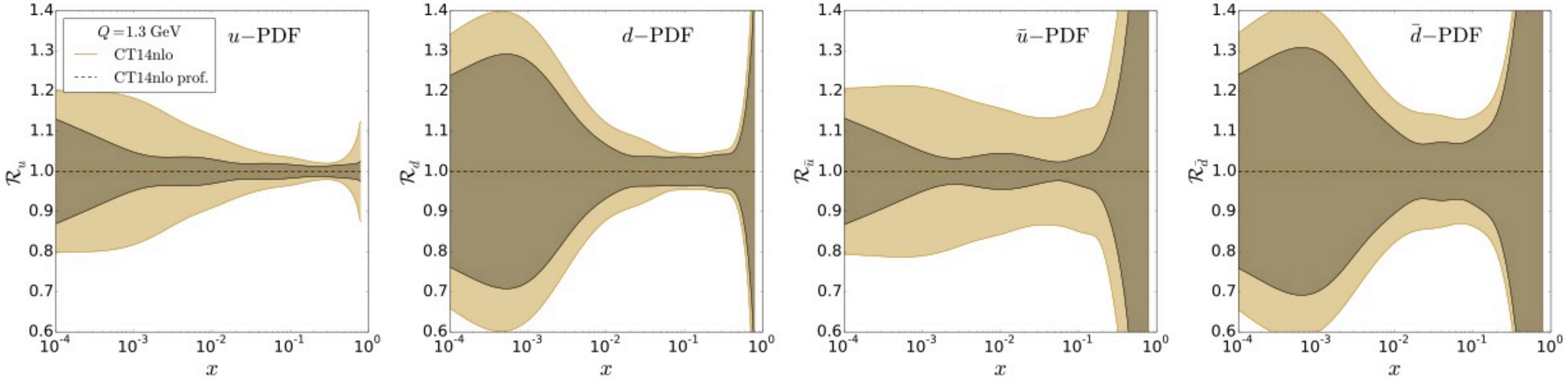
SMOG2 … few highlights

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

PDF

estimation with 10 fb^{-1}

arXiv:1807.00603



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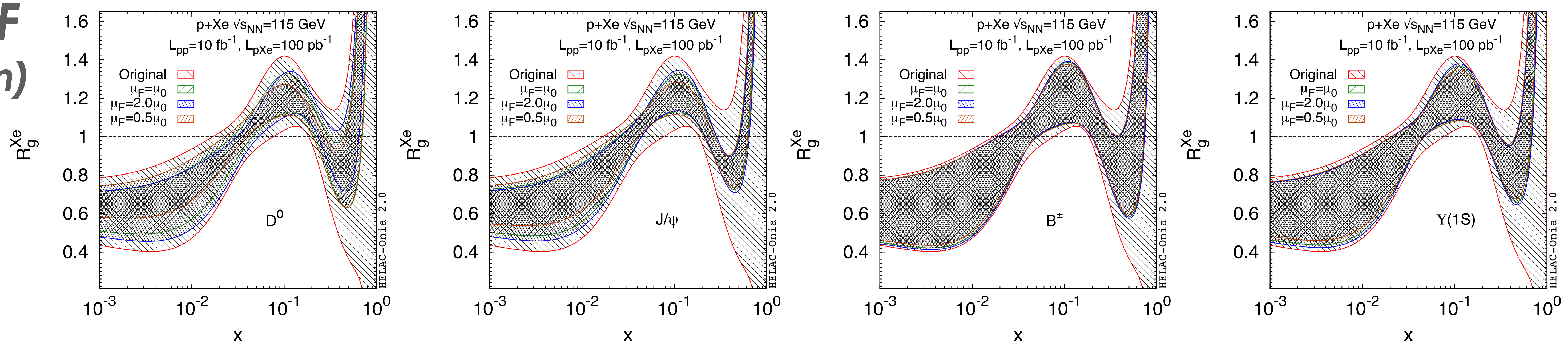
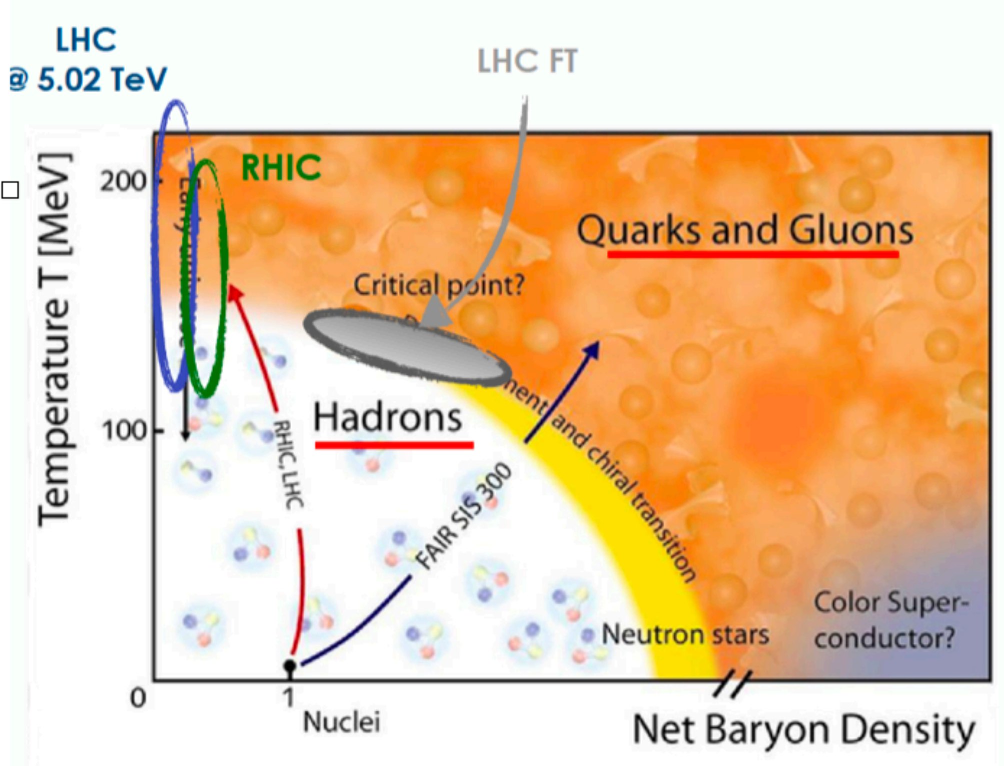
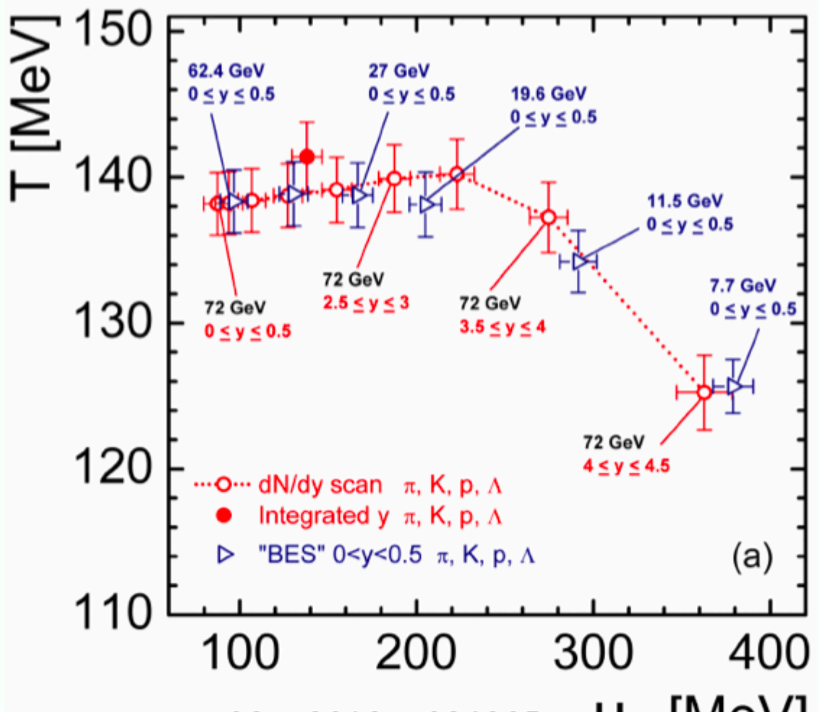


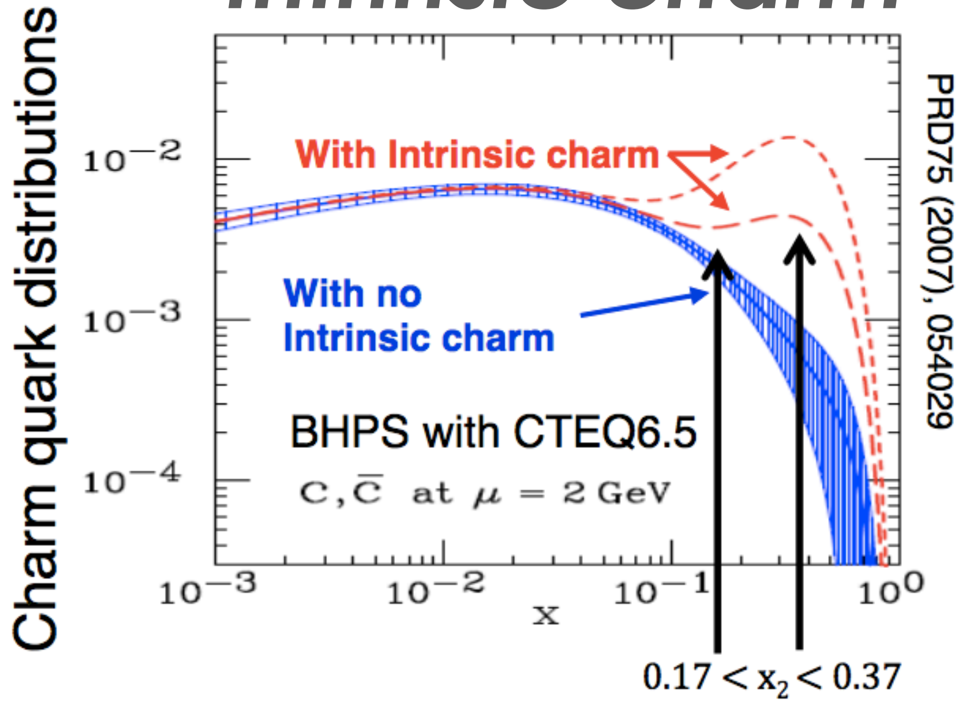
Heavy-Ion and QCD phase space



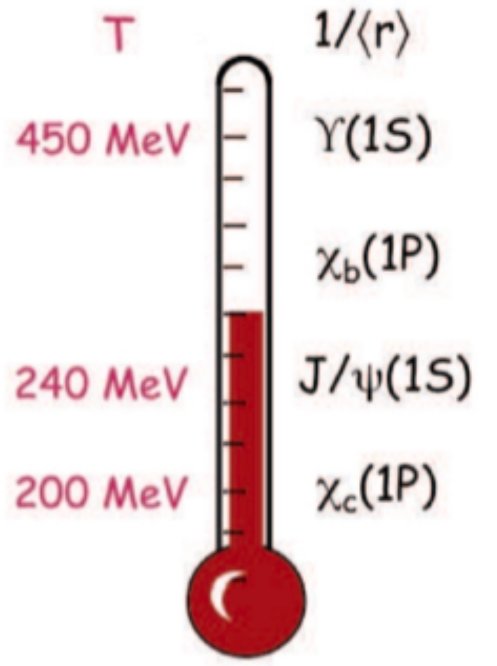


[PRC 98 (2018) 034905]

Intrinsic charm

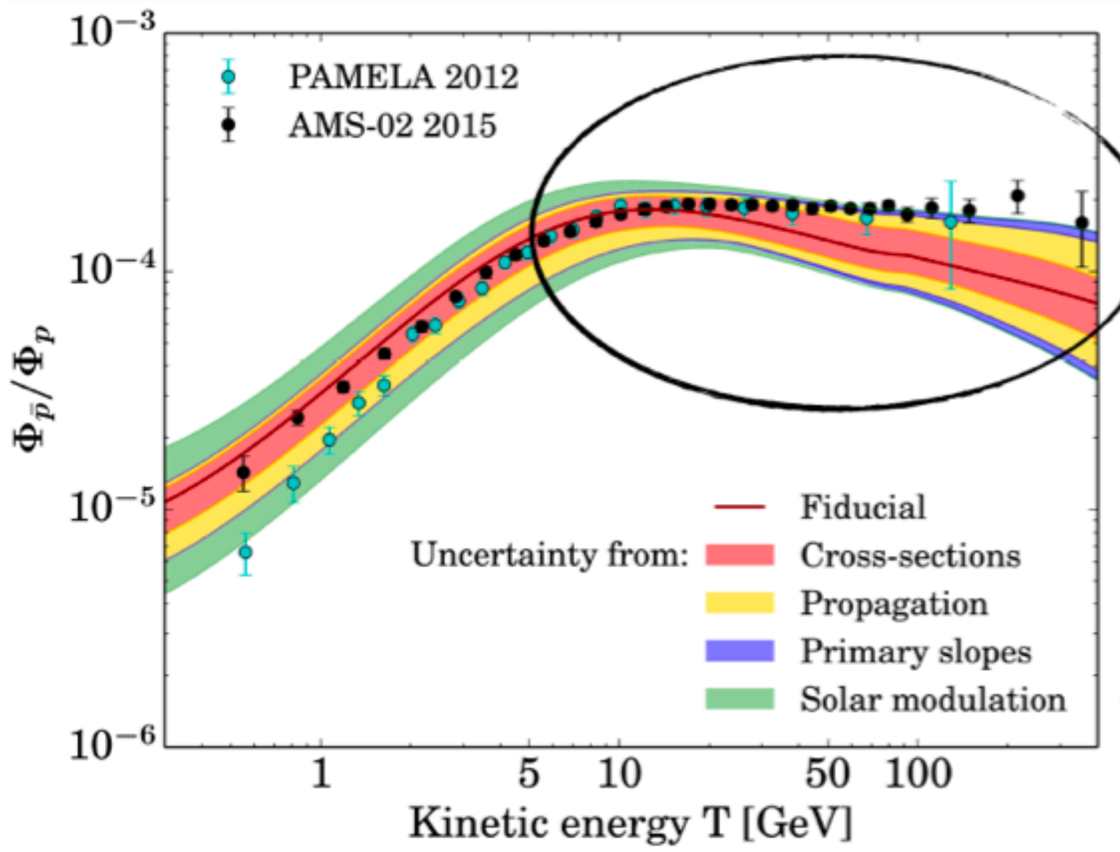


$c\bar{c}$ bound states

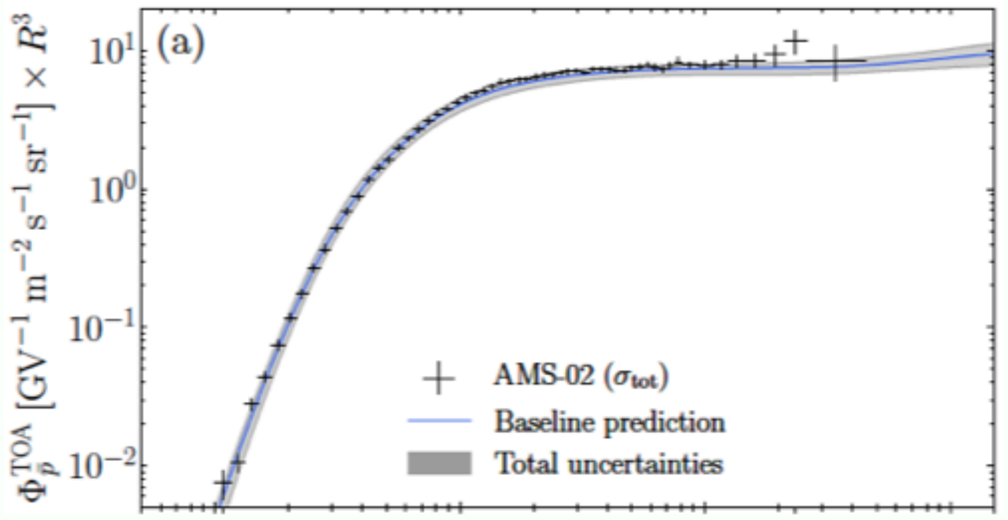


Astroparticle (DM and CR)

[JCAP09 (2015) 023]



[ArXiv:1906.07119]

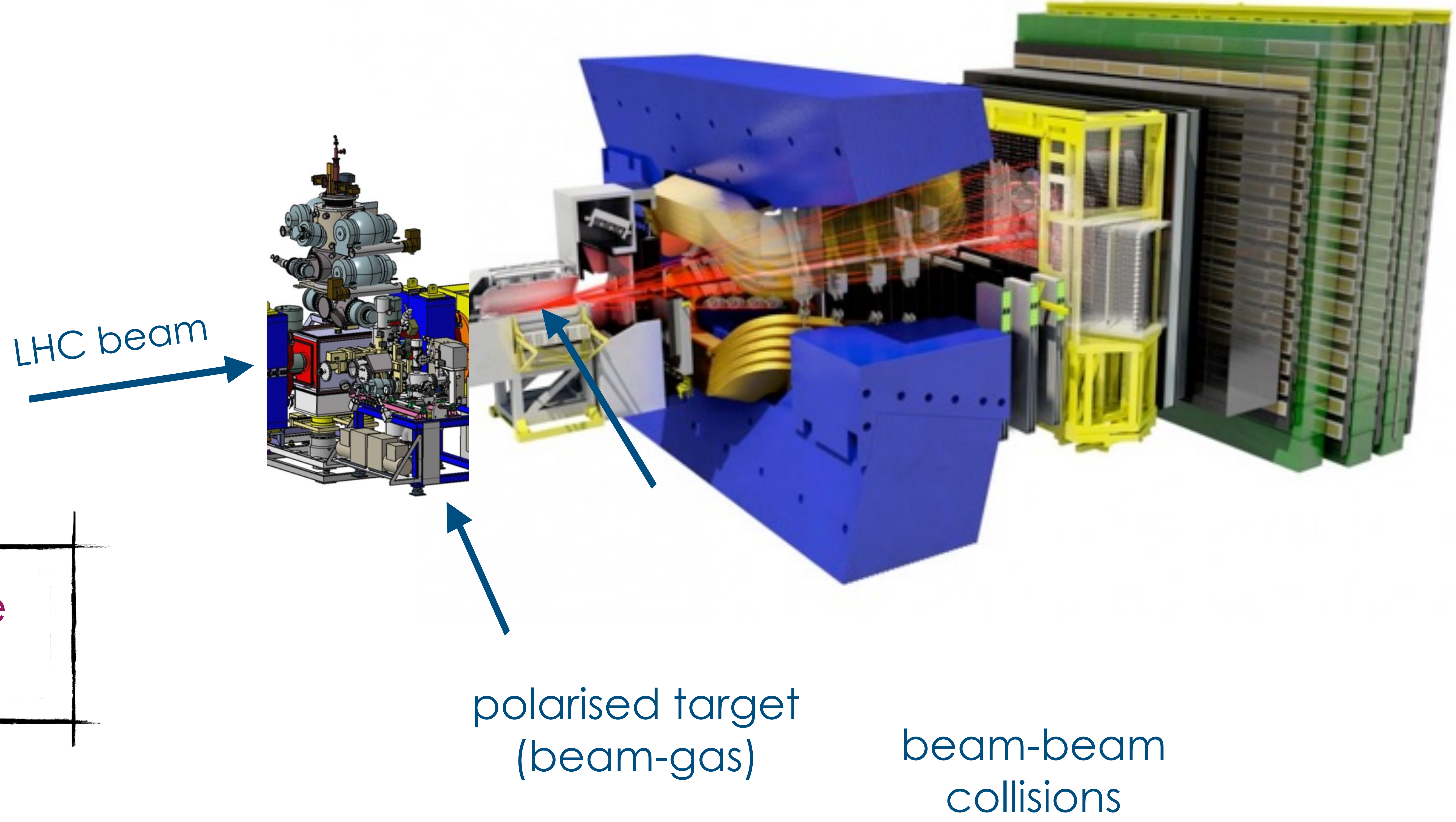


- Main uncertainty still due to cross sections!

Special Runs

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

LHCspin a polarised target at LHCb

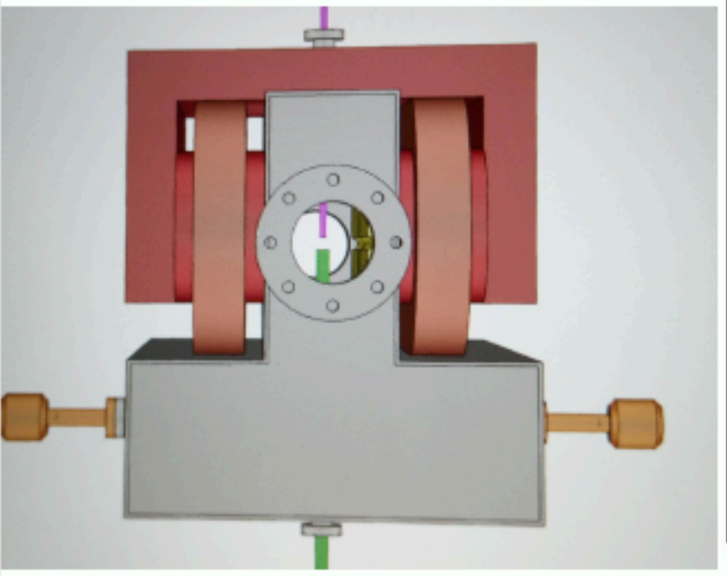


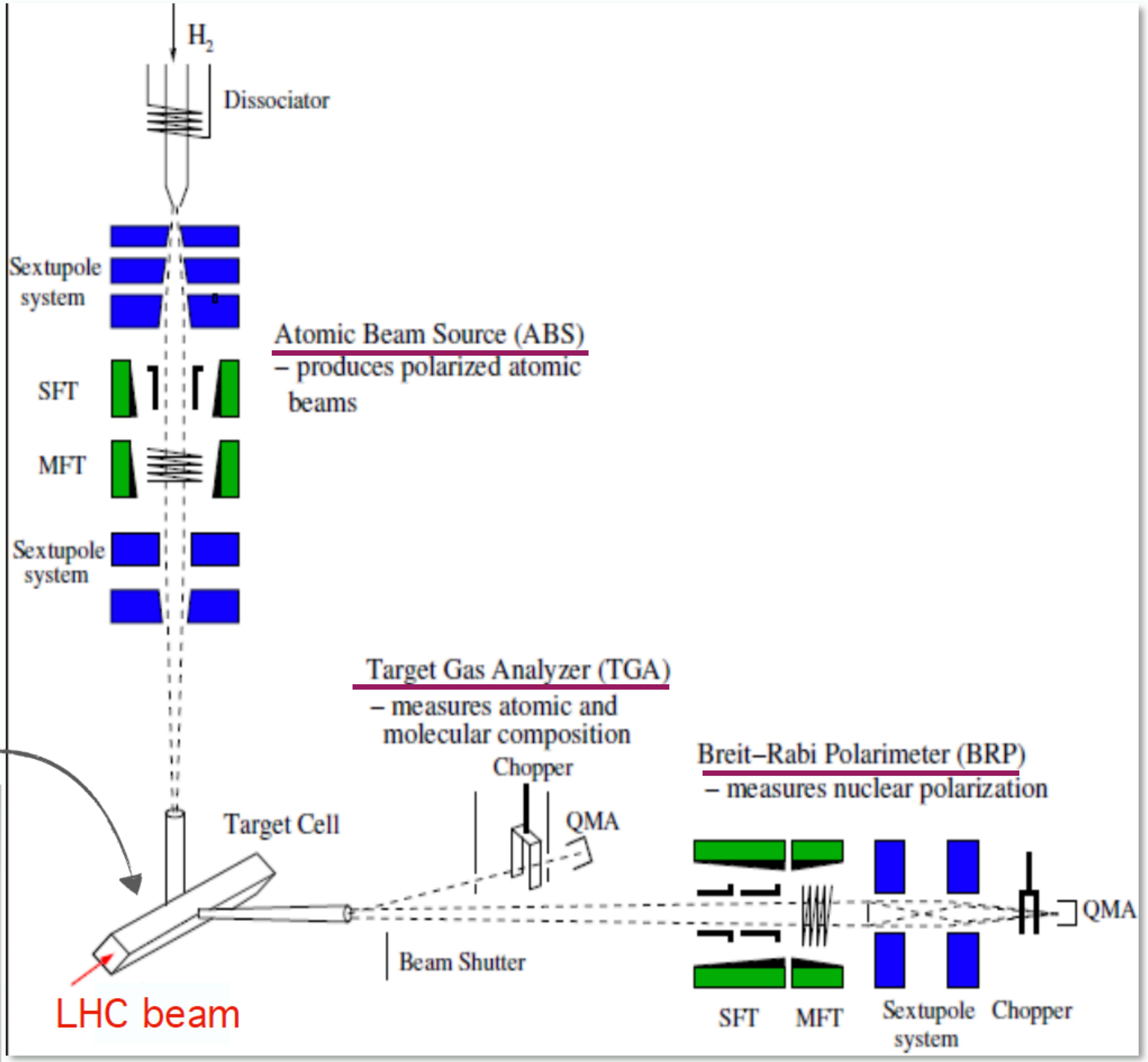
The LHC beams cannot be polarised

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

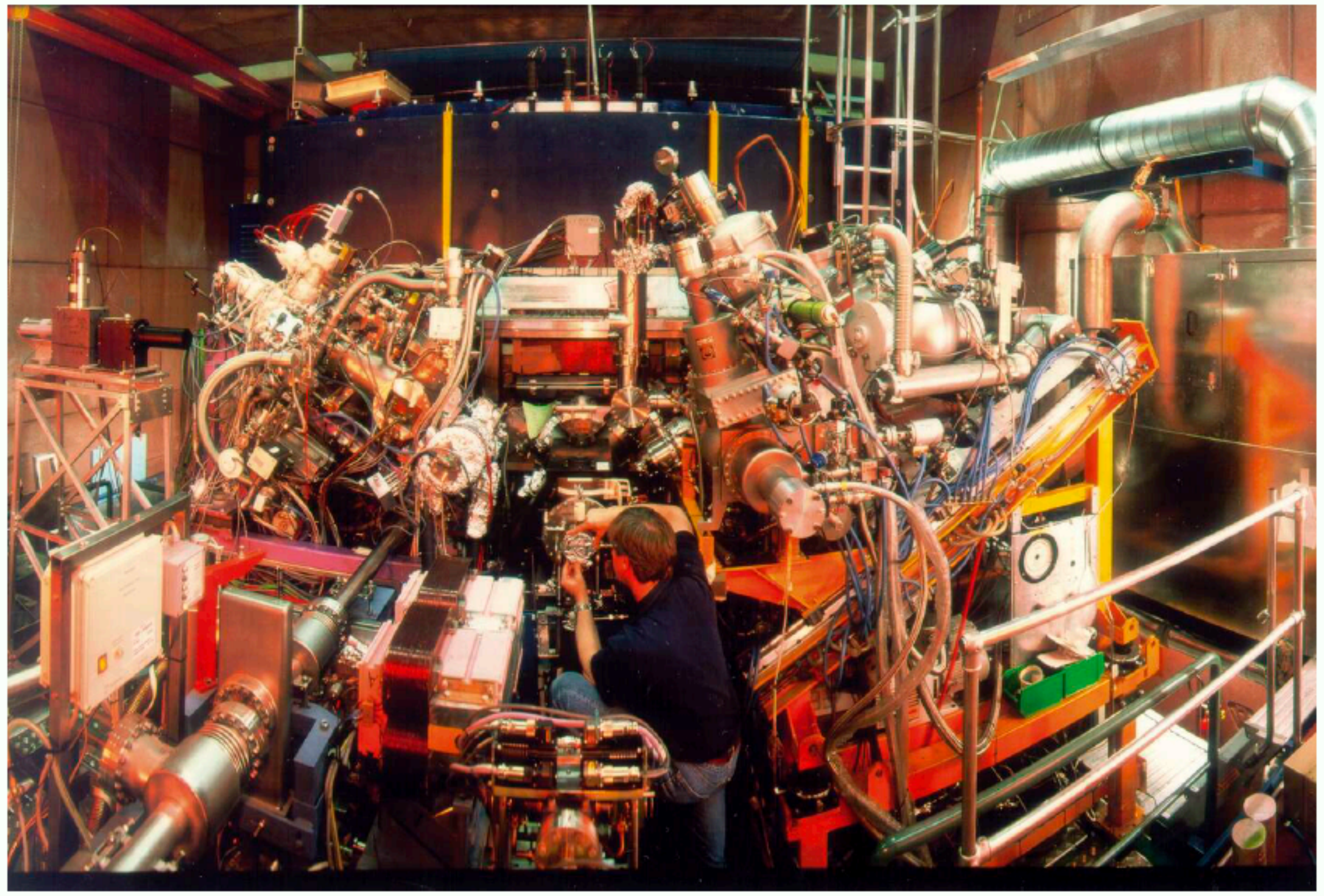
LHCspin experimental setup

dipole





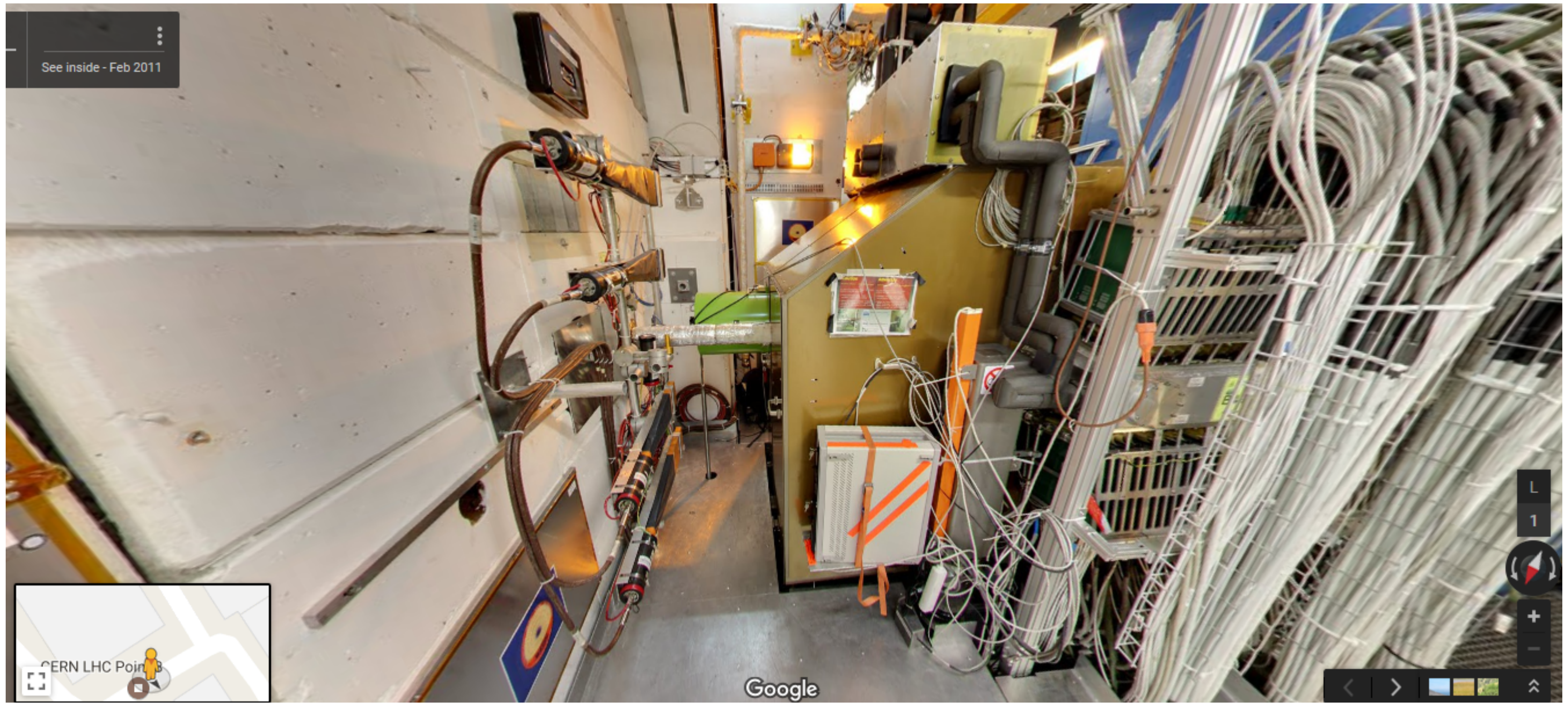
- Start from the well established HERMES setup @ DESY…
- … to create the next generation of fixed target polarisation techniques!



[NIMA 540 (2005) 68–101]

HERMES PGT

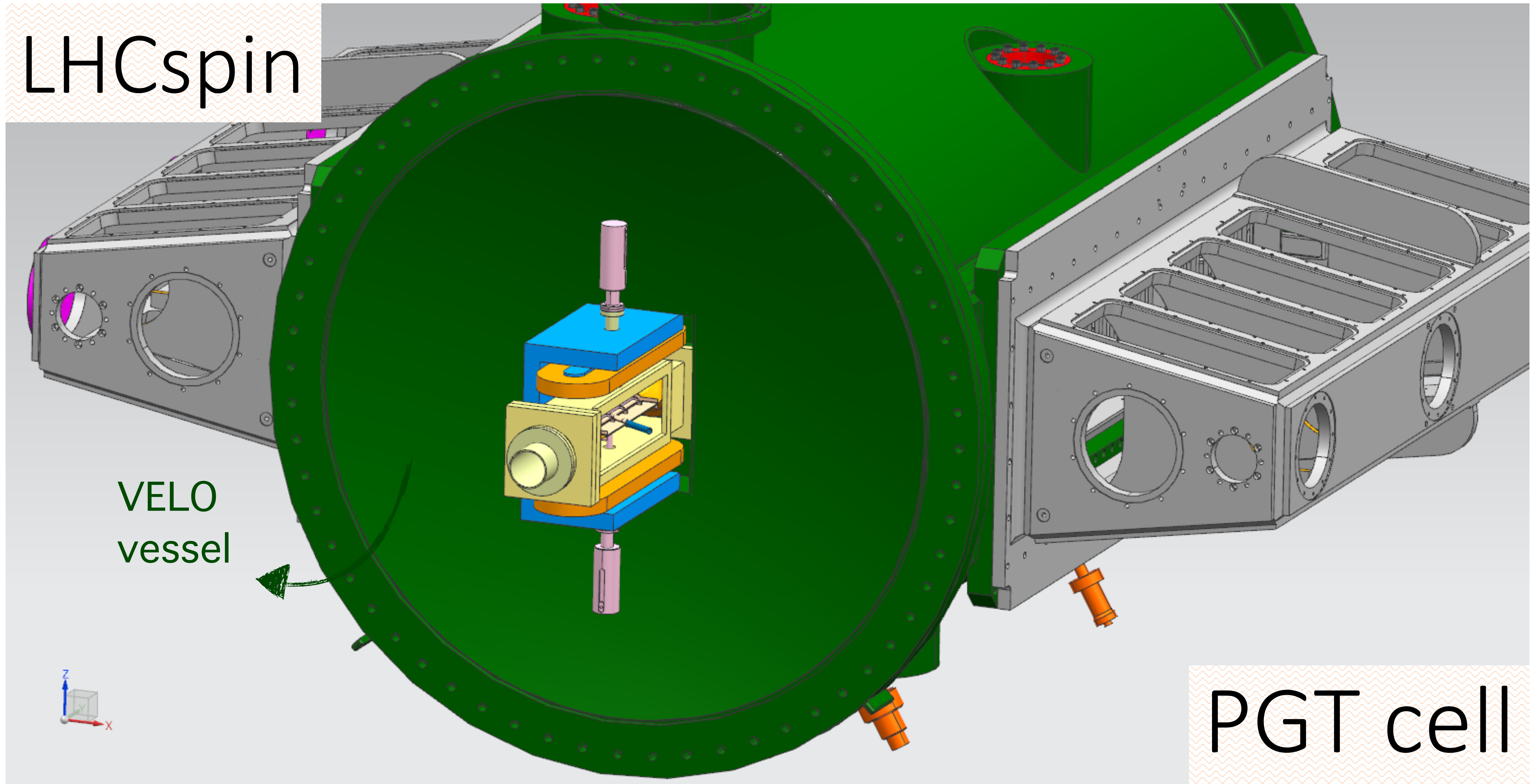
From there to here

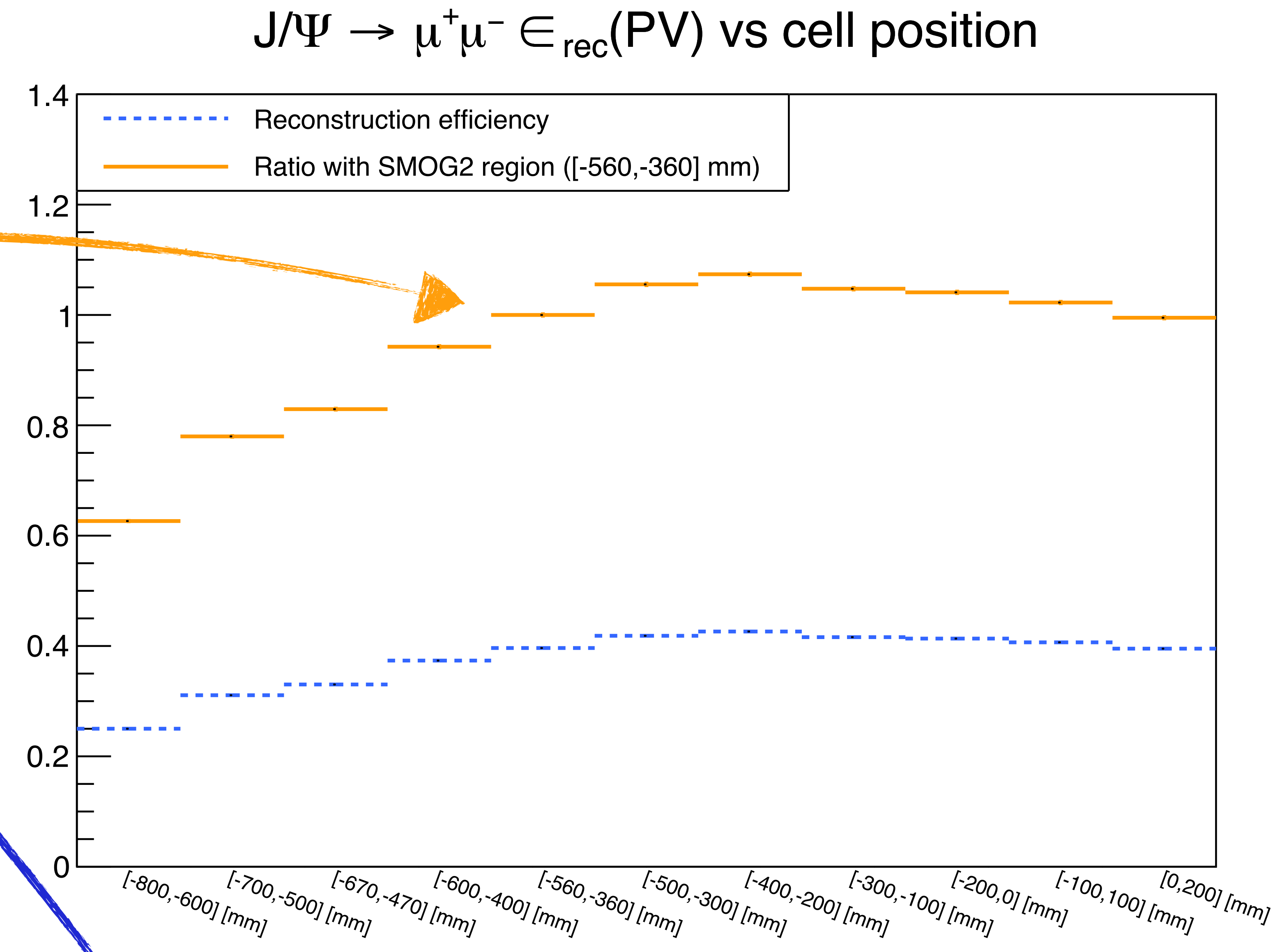


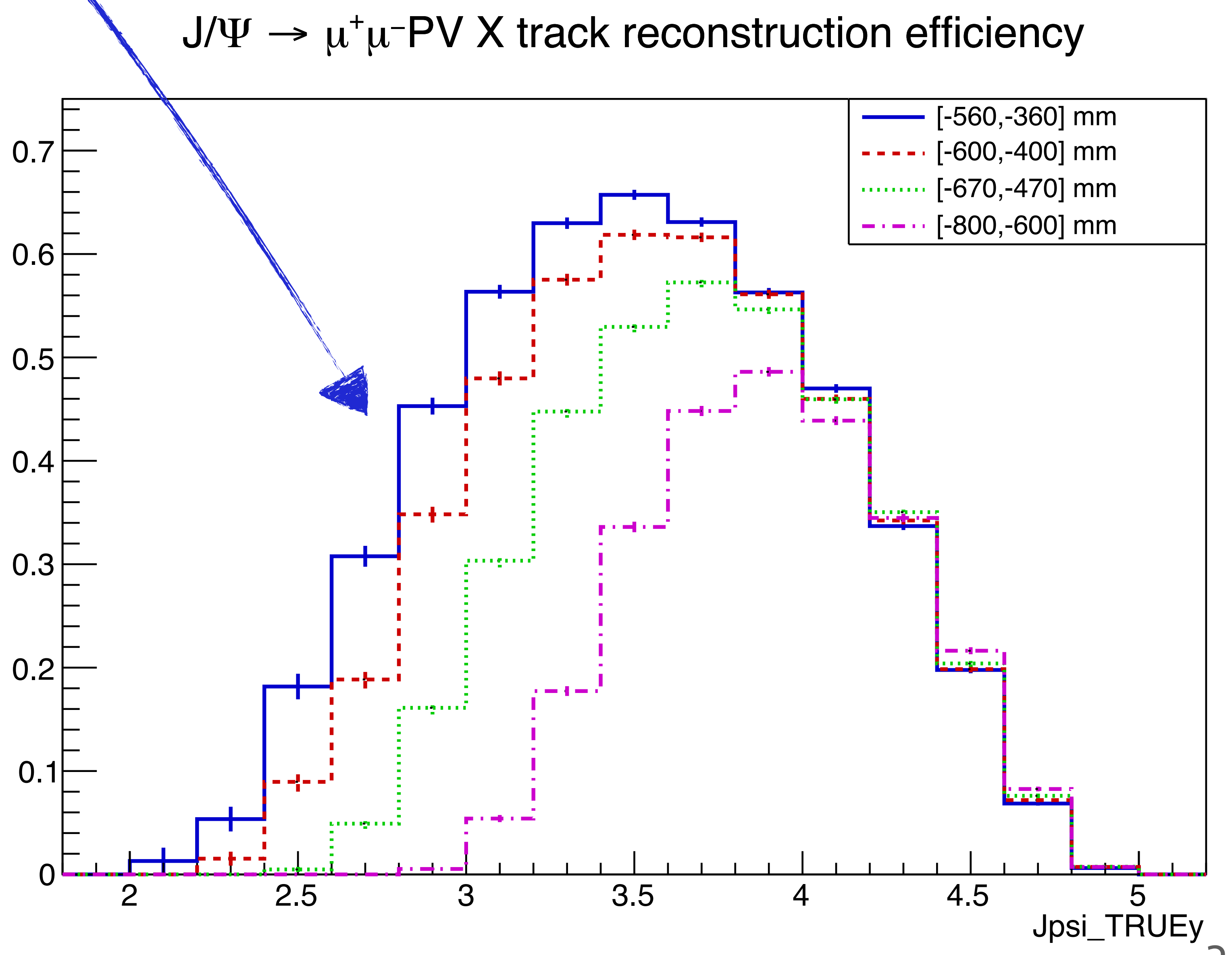
Space available in front of LHCb

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

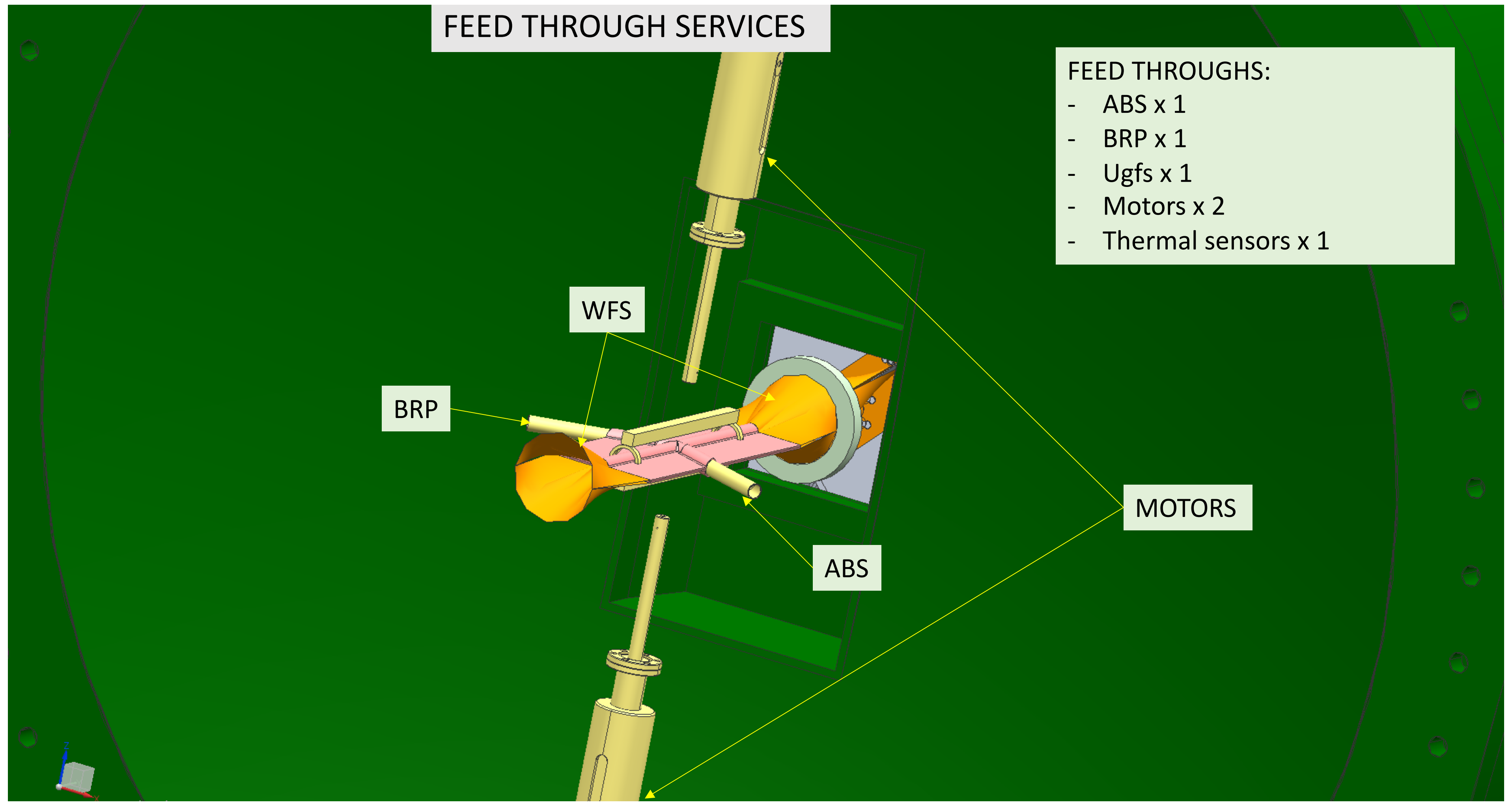


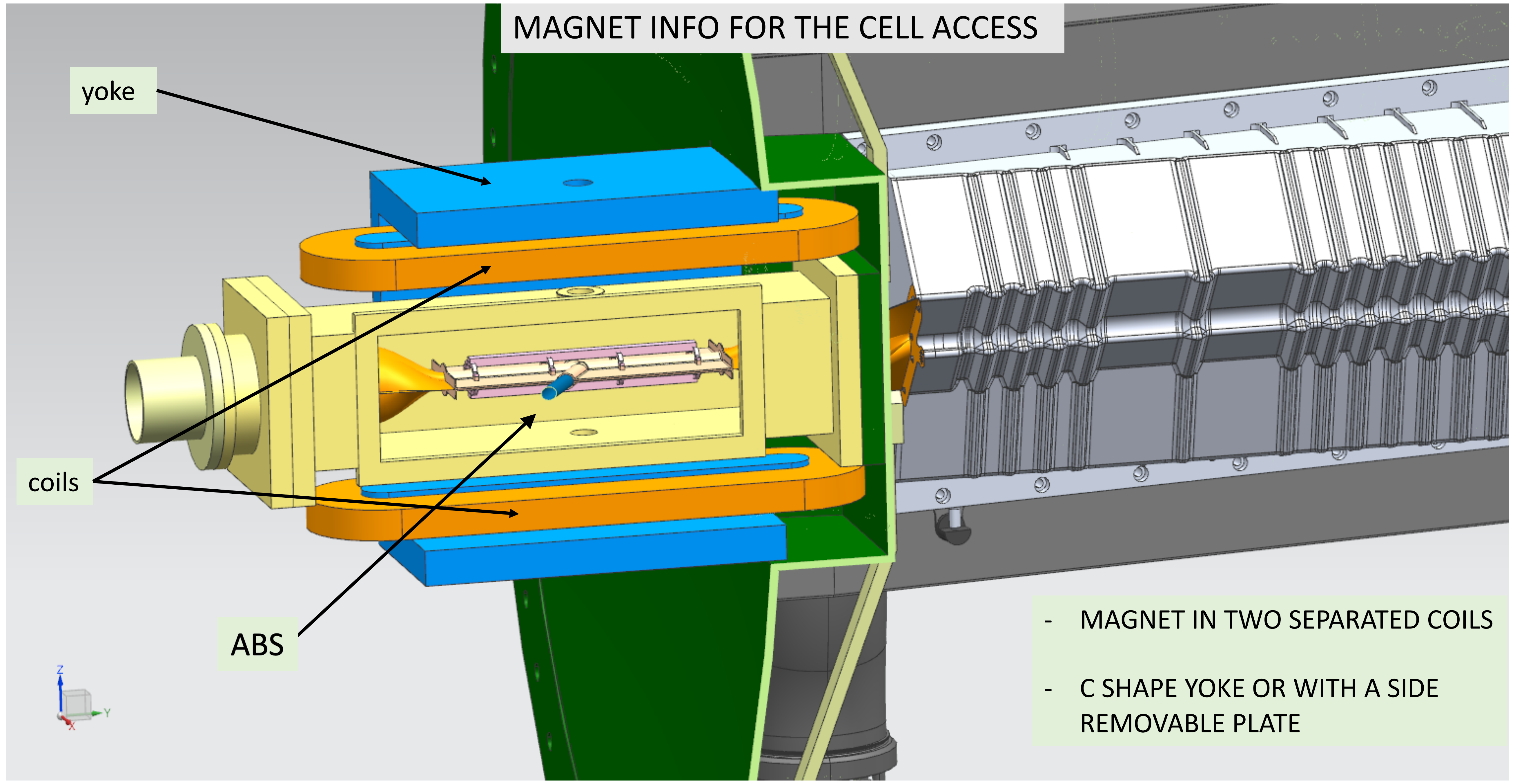




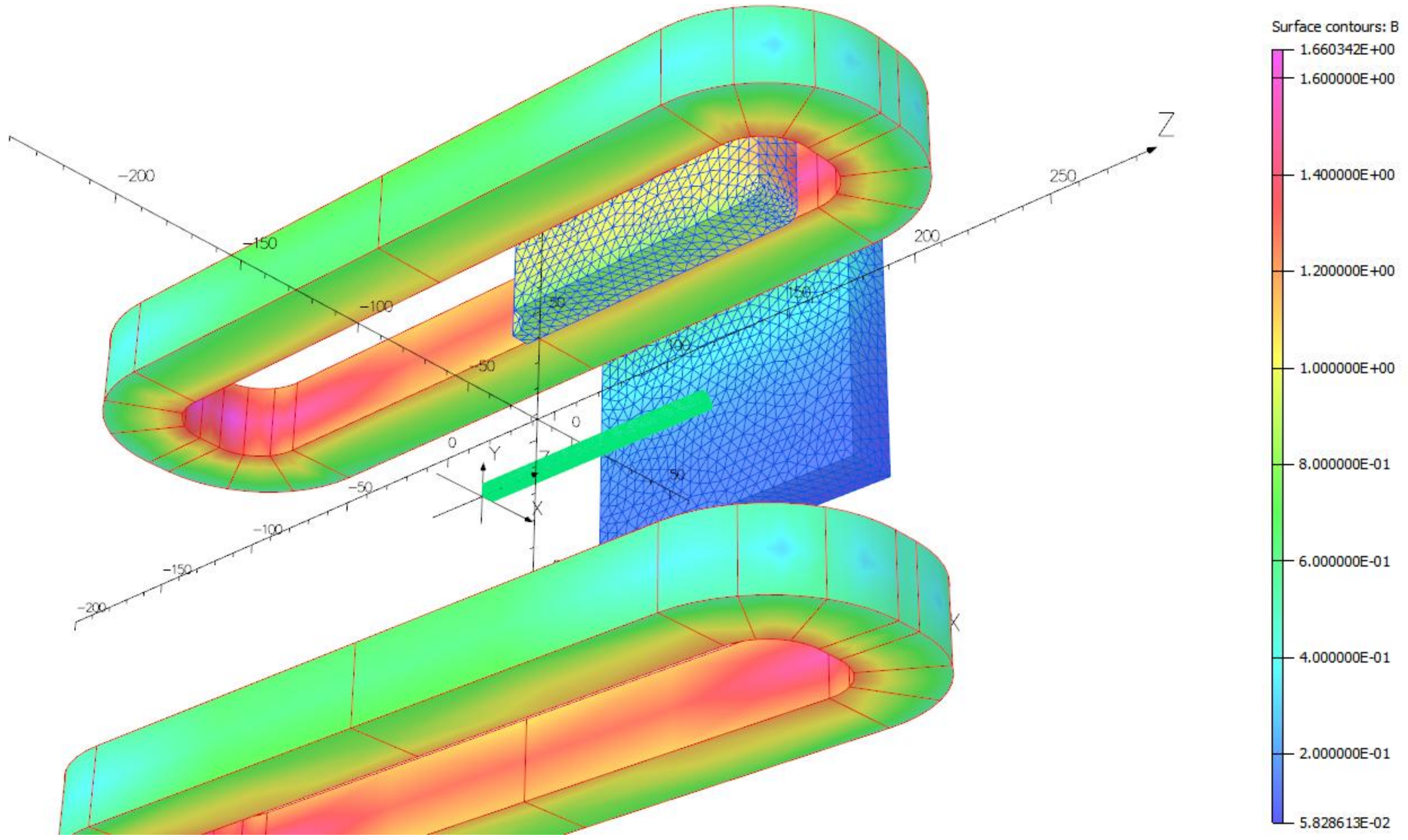
PGT implementation into LHCb

- Inject both polarised and unpolarised gases via ABS and UGFS



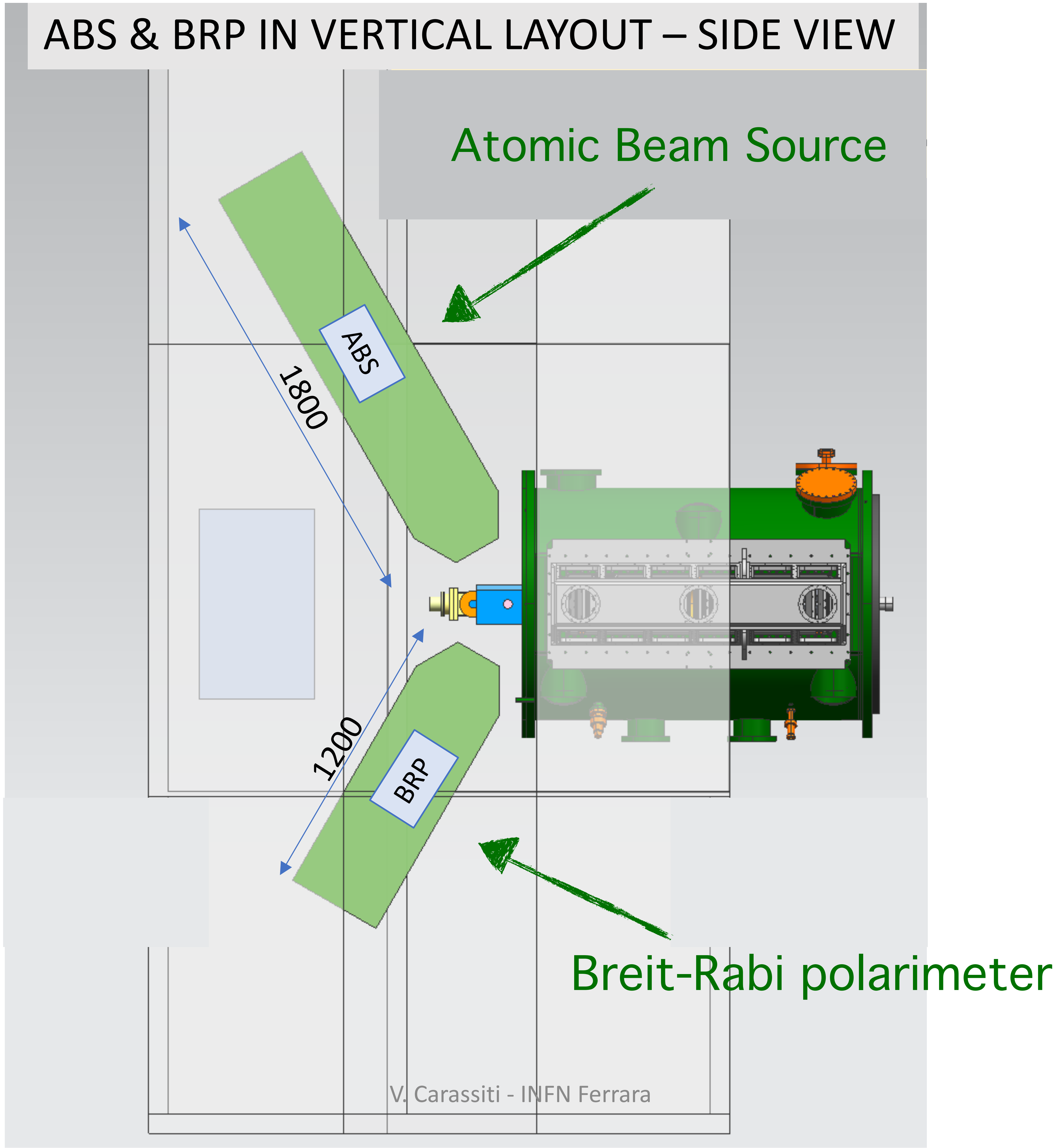


- Compact dipole magnet → static transverse field
- Superconductive coils + iron yoke configuration fits the space constraints
- $B = 300$ mT with polarity inversion, $\Delta B/B \simeq 10\,\%$, suitable to avoid beam-induced depolarisation [PoS (SPIN2018)]



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):
$\sim 8 \times 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Role of the storage cell coating

Carbon thin films

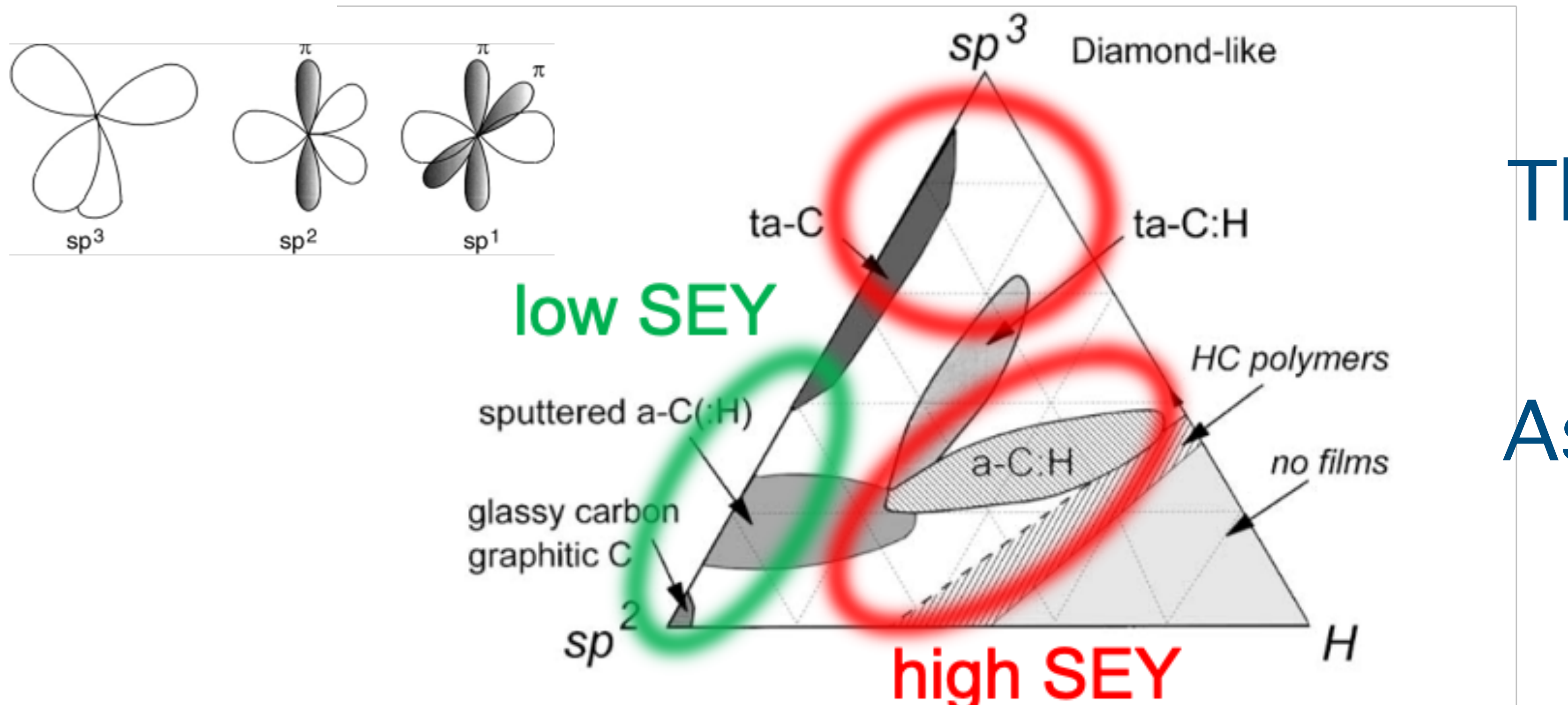


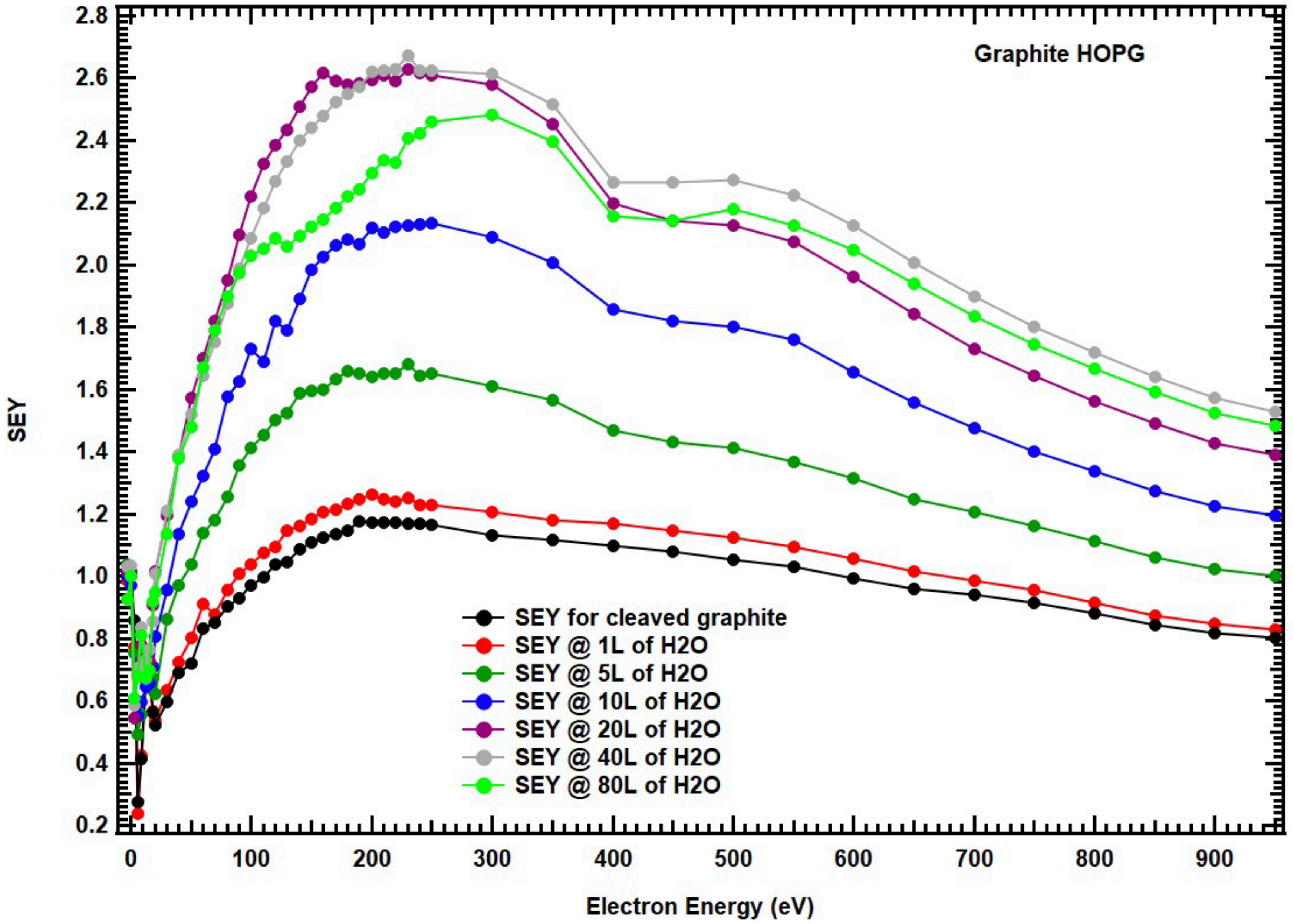
Fig. 2. Ternary phase diagram of bonding in amorphous carbon–hydrogen alloys.

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?

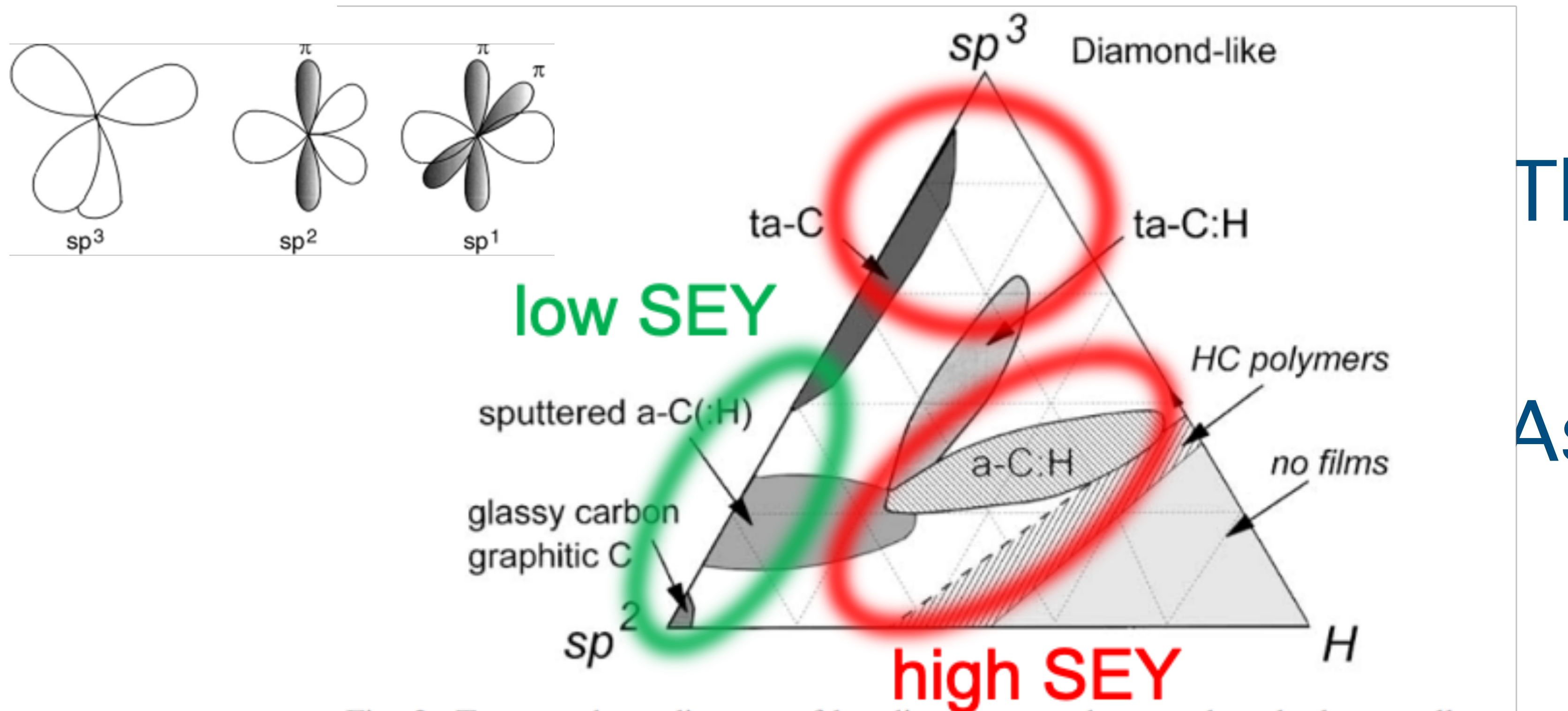
Studies ongoing in order to understand if **carbon films with low secondary Electron Yield** cope with the required **"recombination" rate** of polarized H atoms injected in the storage cell



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

Role of the storage cell coating

Carbon thin films



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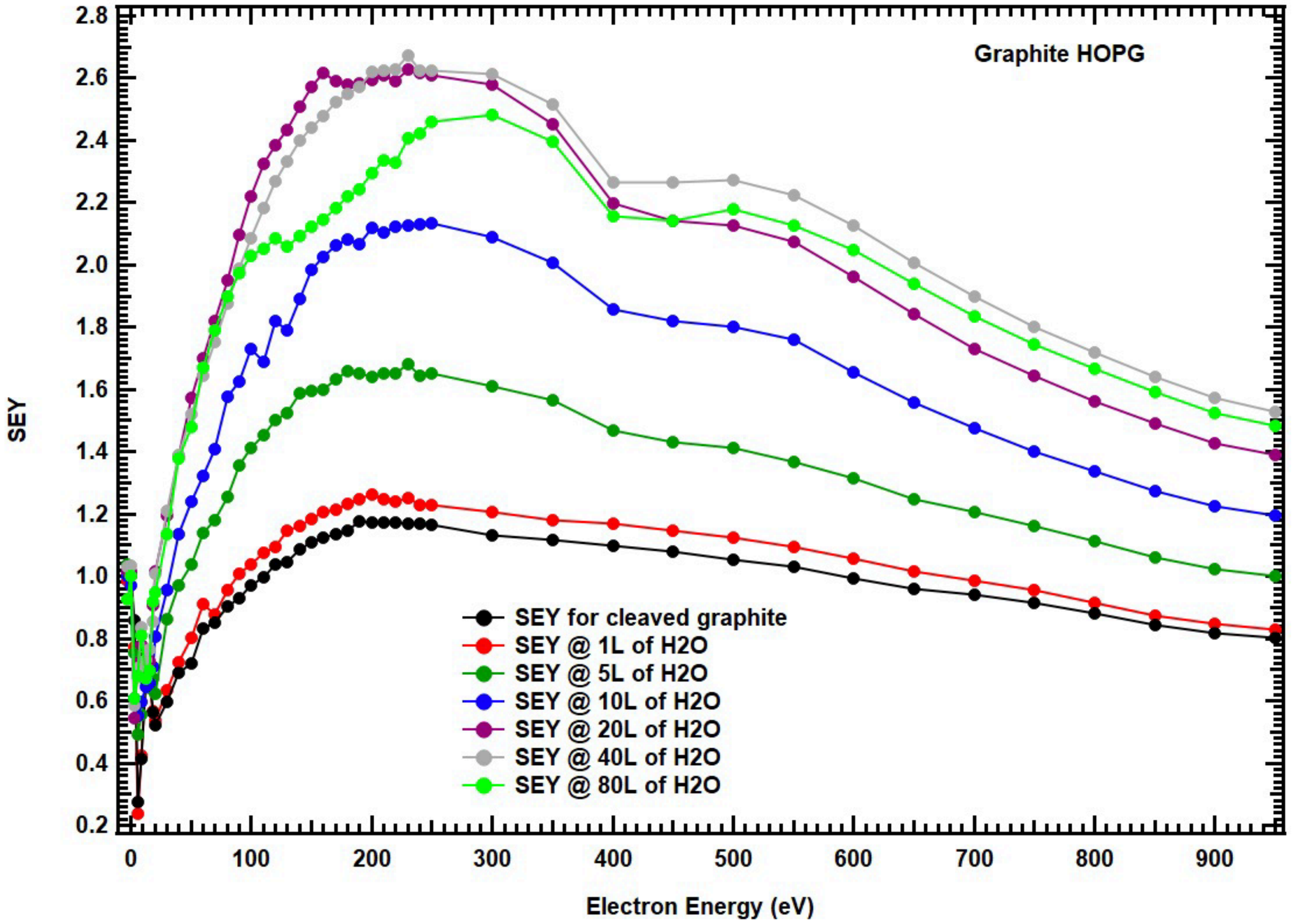
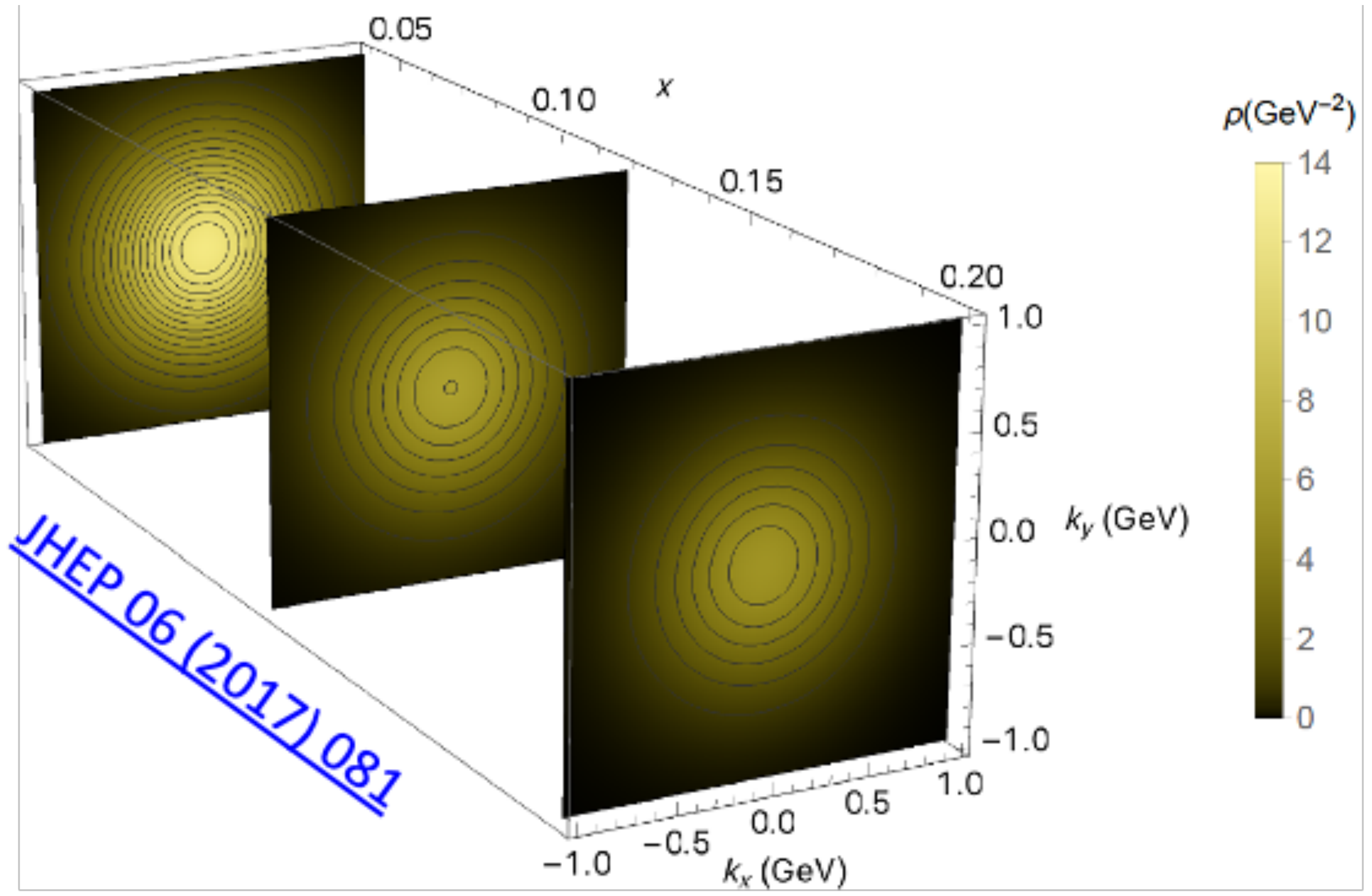


... or follow the HERMES experience to have an ice coating (low SEY, low H recombination)

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 physics goals of LHCspin

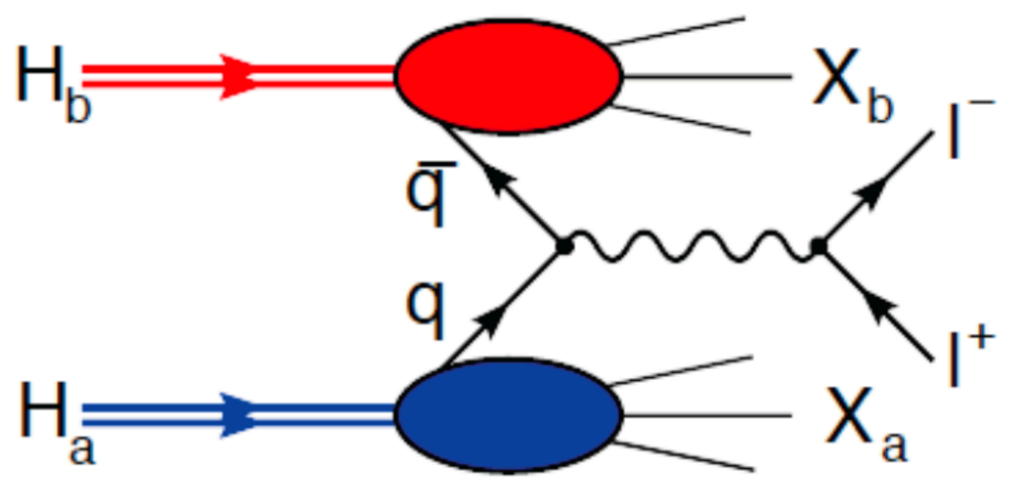
- Multi-dimensional nucleon structure in a poorly explored kinematic domain
- Measure experimental observables sensitive to both **quarks and gluons TMDs**
- **Make use of new probes (charmed and beauty mesons)**
- Complement present and future SIDIS results
- Test non-trivial process dependence of quarks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



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

Unpolarized Drell-Yan



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

- Sensitive to unpol. and BM TMDs for $q_T \ll M_T$

$$d\sigma_{UU}^{DY} \propto f_1^{\bar{q}} \otimes f_1^{q} + \cos 2\phi \; h_1^{\perp,\bar{q}} \otimes h_1^{\perp,q}$$

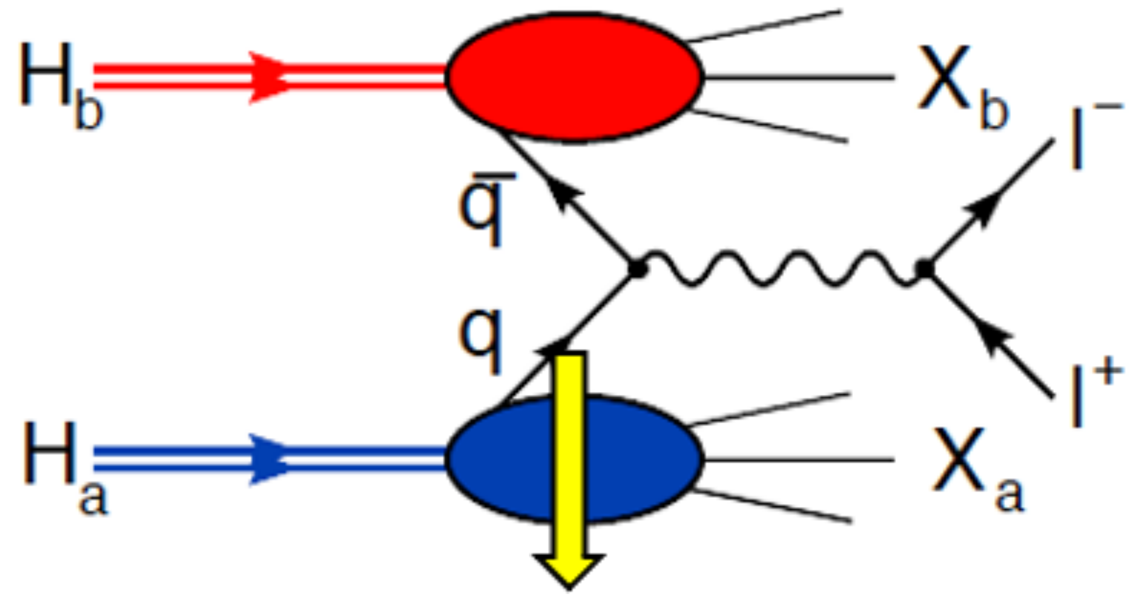
- H & D targets allow to study the antiquark content of the nucleon
- SeaQuest (E906): $\bar{d}(x) > \bar{u}(x)$ $\rightarrow$ proton sea is not flavour symmetric
- intrinsic heavy quarks?

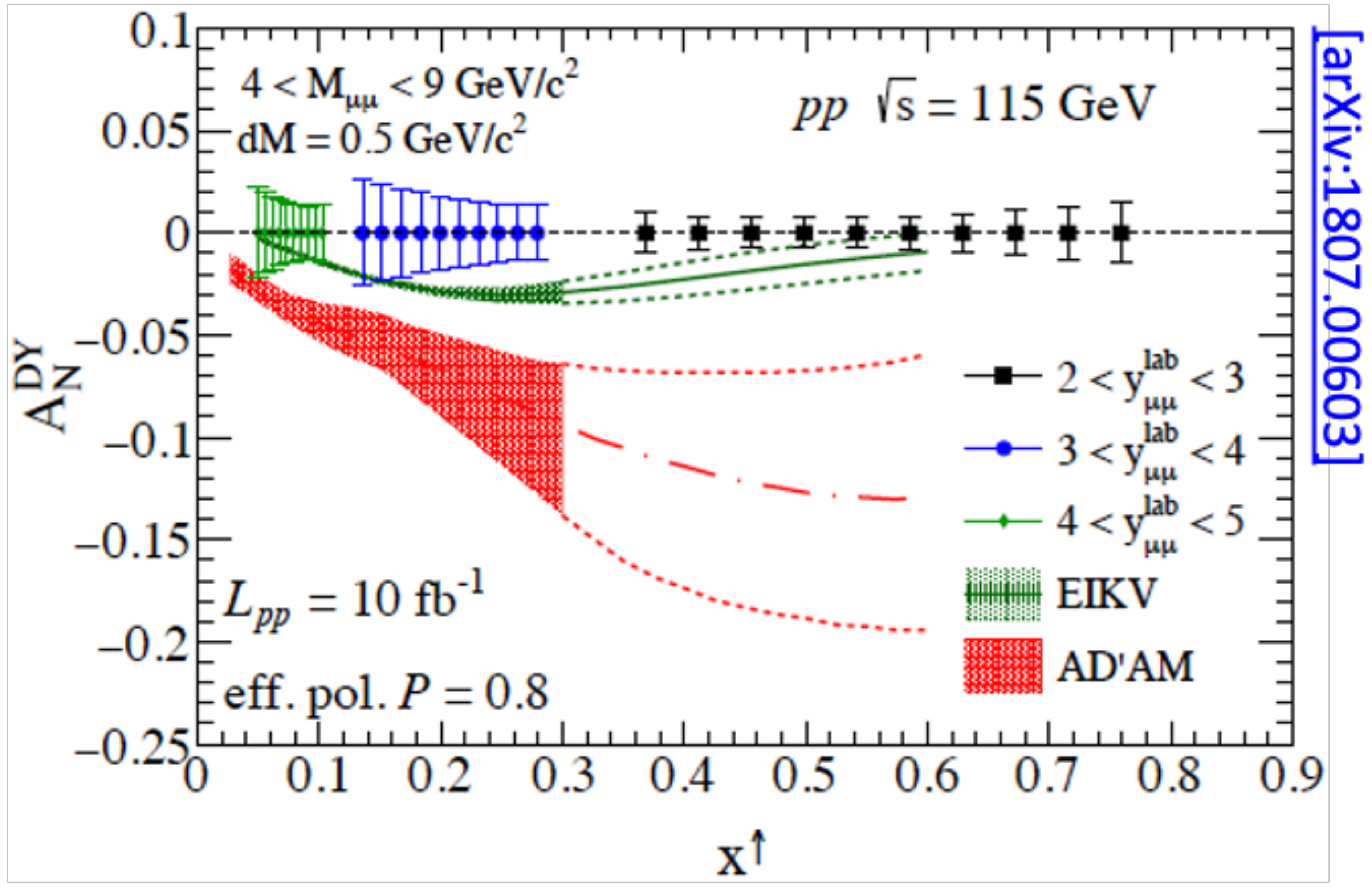
… still a lot to be understood and investigated

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





- **Sensitive to quark TMDs through TSSAs**

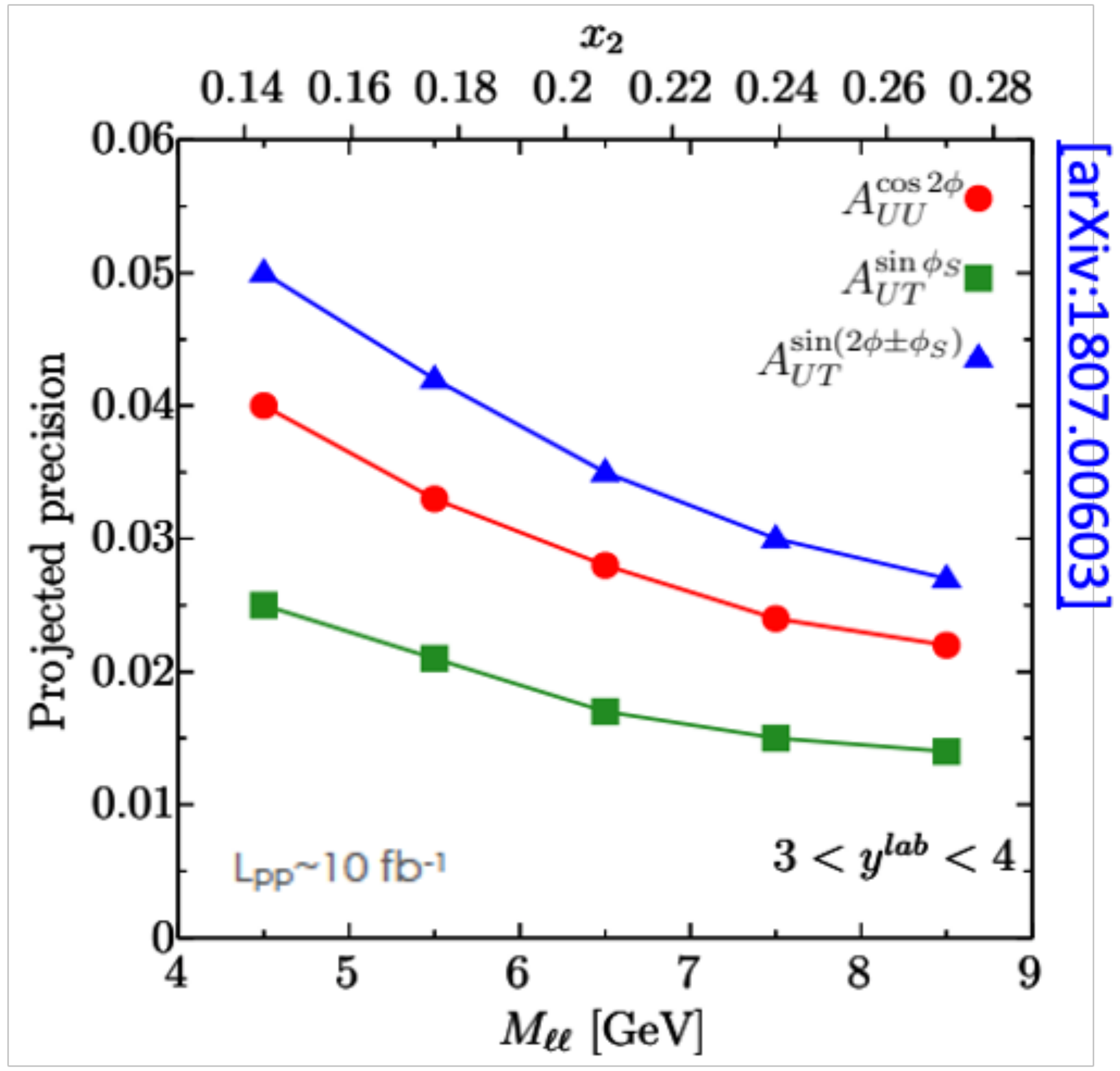
$$A_N^{DY} = \frac{1}{P}\frac{\sigma_{DY}^{\uparrow} - \sigma_{DY}^{\downarrow}}{\sigma_{DY}^{\uparrow} + \sigma_{DY}^{\downarrow}} \Longrightarrow \quad A_{UT}^{sin\phi_S} \sim \frac{f_1^q \otimes f_{1T}^{\perp q}}{f_1^q \otimes f_1^q}, \quad A_{UT}^{sin(2\phi-\phi_S)} \sim \frac{h_1^{\perp q} \otimes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

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

- Extraction of qTMDs from DY does not require knowledge of FF
- Verify sign change of Sivers function wrt SIDIS

$$f_{1T}^{\perp}\big|_{DY} = -f_{1T}^{\perp}\big|_{SIDIS}$$

- Test flavour sensitivity using both H and D targets

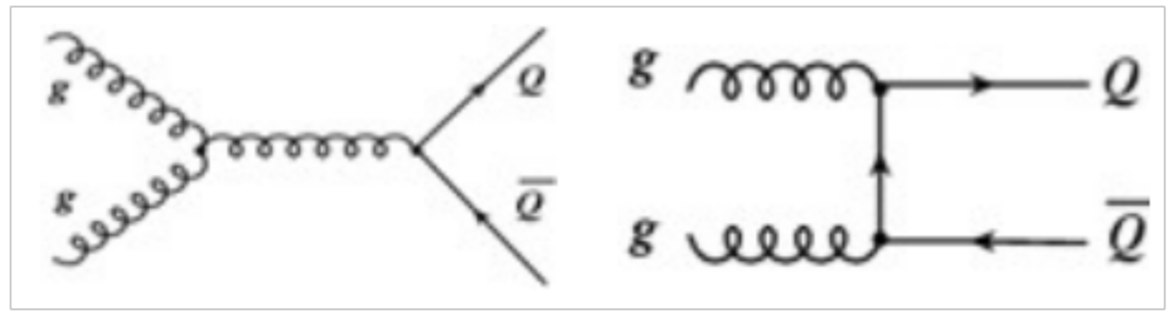


Probing the gTMDs

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

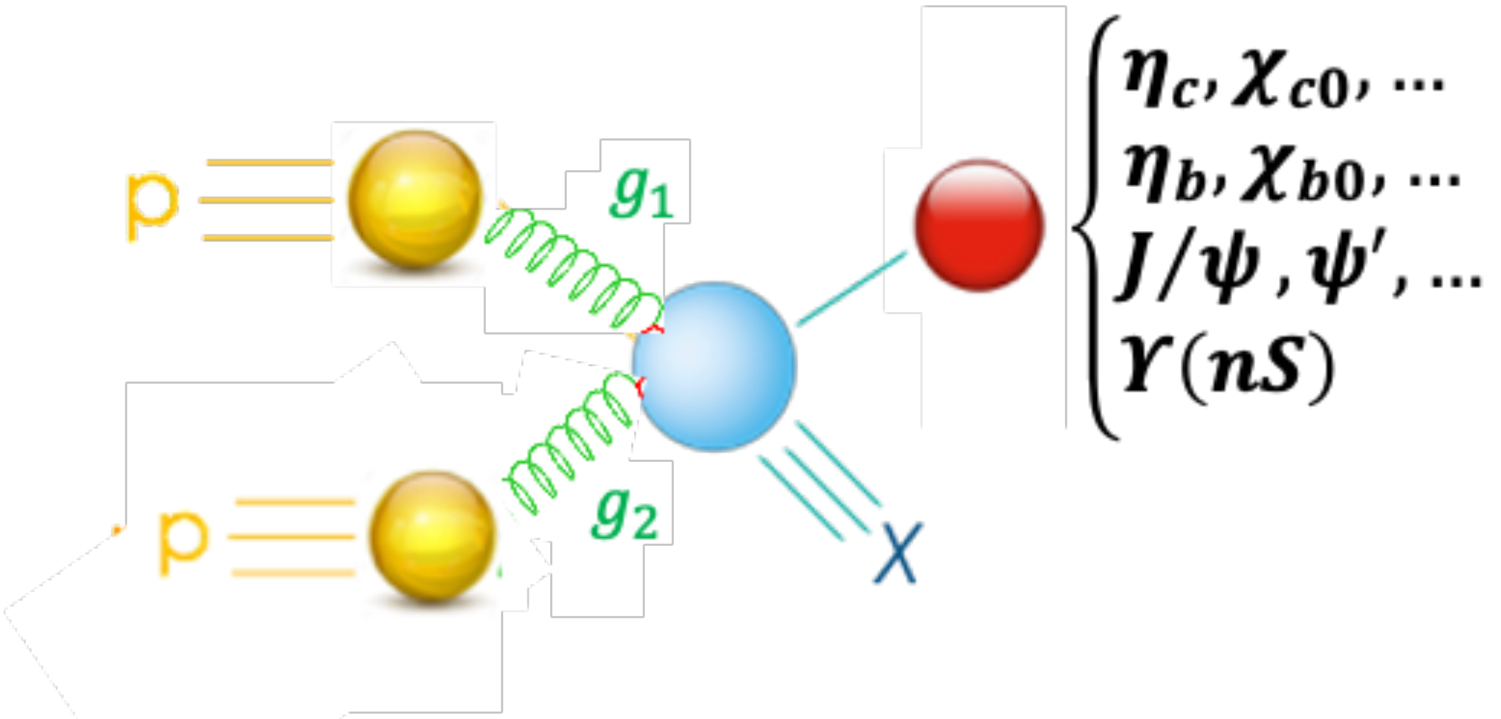
Theory framework well consolidated **…but experimental access still extremely limited!**

In high-energy hadron collisions, heavy quarks are dominantly produced by gg fusion:



The most efficient way to access the gluon dynamics inside the proton at LHC is to **measure heavy-quark observables**

- **Inclusive quarkonia production in (un)polarized pp interaction** ($pp^{(\uparrow)} \to [Q\bar{Q}]X$) turns out to be an ideal observable to access gTMDs (assuming TMD factorization)



- TMD factorization requires $q_T(Q) \ll M_Q$. Can look at **associate quarkonia production**, where only the relative q_T needs to be small:

E.g.: $pp^{(\uparrow)} \to J/\psi + J/\psi + X$

•Due the larger masses this condition is more easily matched in the case of **bottomonium**, where TMD factorization can hold at larger q_T (although very challenging for experiments!)

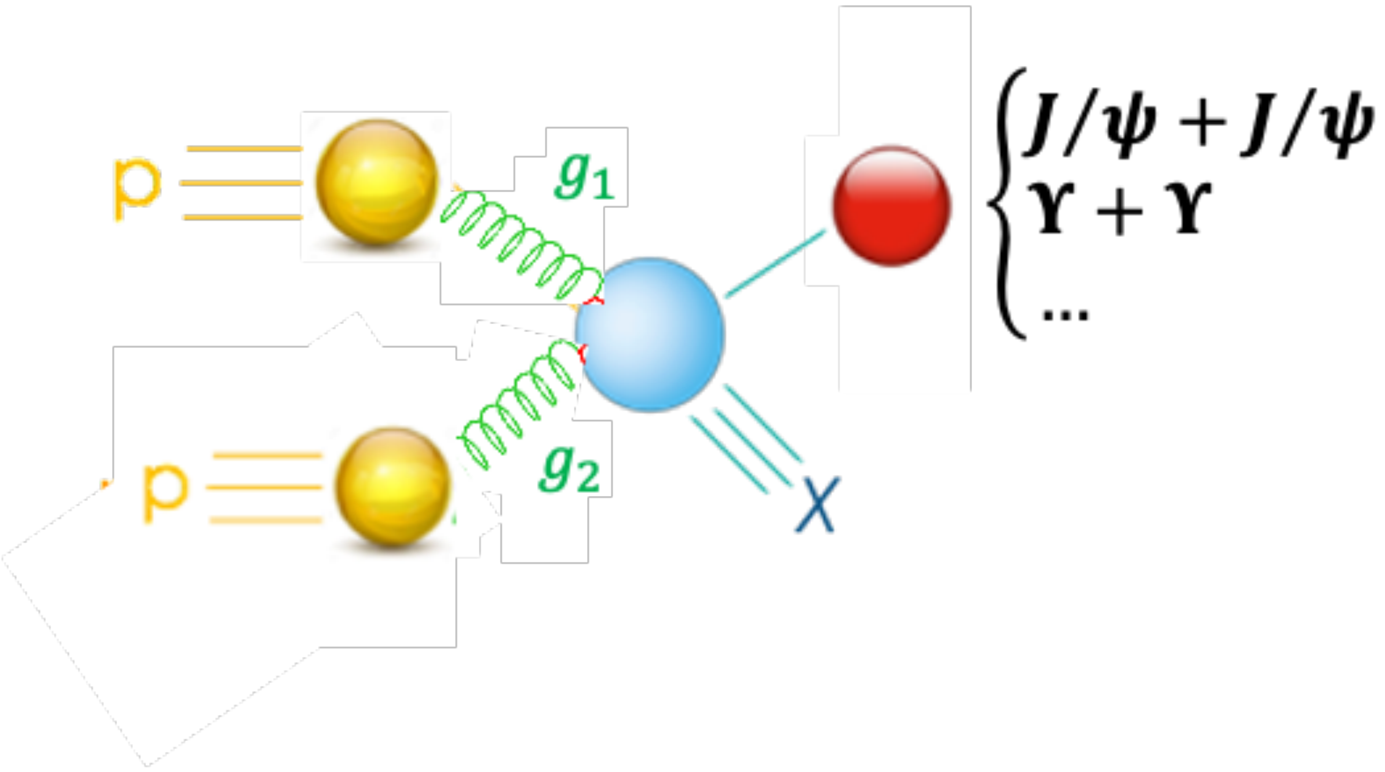
Probing the gTMDs

$$\frac{d\sigma}{dM_{QQ}dY_{QQ}d^2P_{QQ_T}d\Omega} = \frac{\sqrt{M_{QQ}^2-4M_Q^2}}{(2\pi)^2 8s\, M_{QQ}^2}$$

$$\Big\{F_1(M_{QQ},\theta_{CS})\,\mathcal{C}\big[f_1^g f_1^g\big](x_{1,2},P_{QQ_T})$$

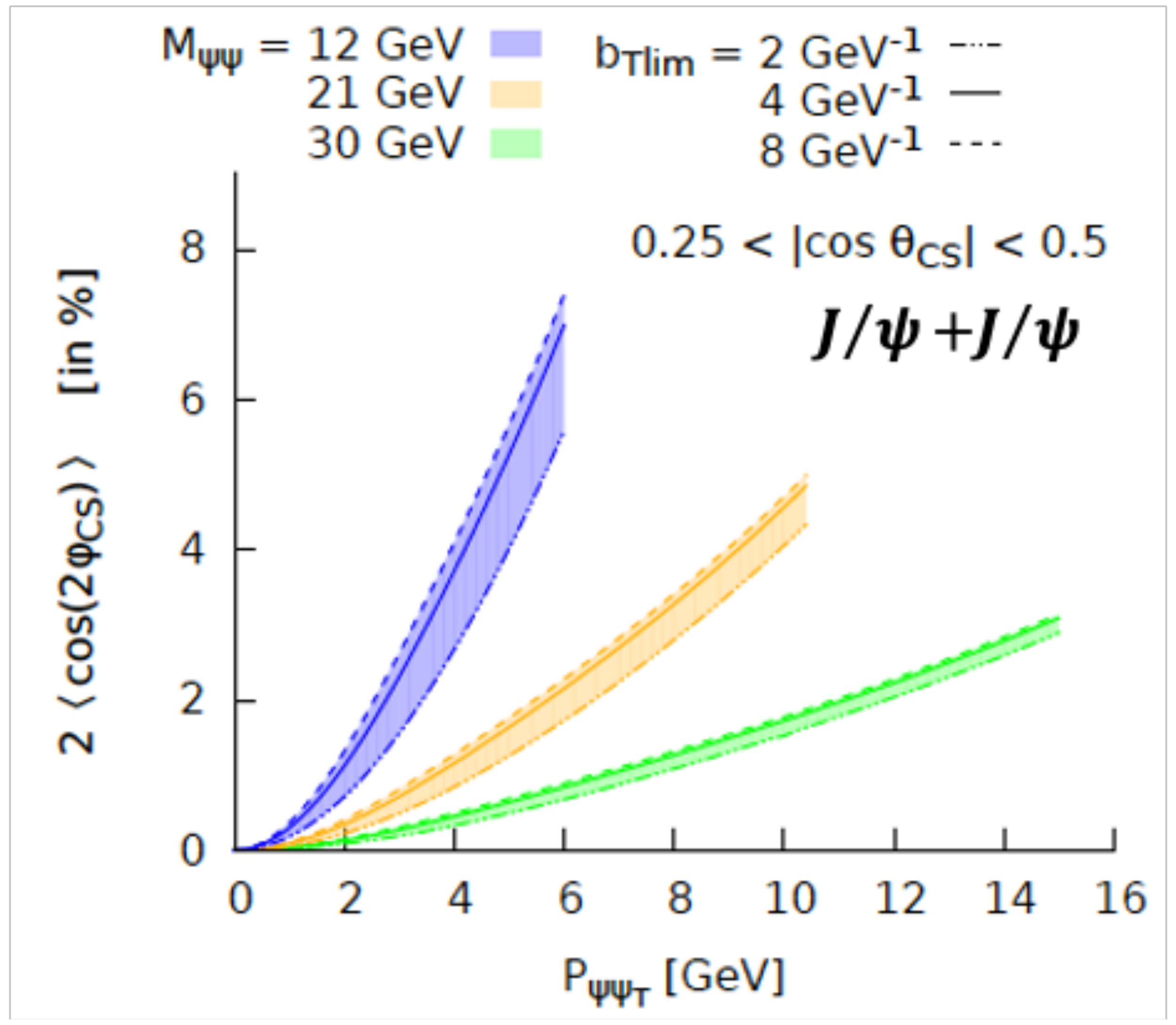
$$+F_2(M_{QQ},\theta_{CS})\,\mathcal{C}\big[w_2 h_1^{\perp g} h_1^{\perp g}\big](x_{1,2},P_{QQ_T})$$

$$+\Big(F_3(M_{QQ},\theta_{CS})\,\mathcal{C}\big[w_3 f_1^g h_1^{\perp g}\big](x_{1,2},P_{QQ_T})+F_3'(M_{QQ},\theta_{CS})\,\mathcal{C}\big[w_3' h_1^{\perp g} f_1^g\big](x_{1,2},P_{QQ_T})\Big)\cos 2\phi_{CS} +F_4(M_{QQ},\theta_{CS})\,\mathcal{C}\big[w_4 h_1^{\perp g} h_1^{\perp g}\big](x_{1,2},P_{QQ_T})\cos 4\phi_{CS}\Big\}$$

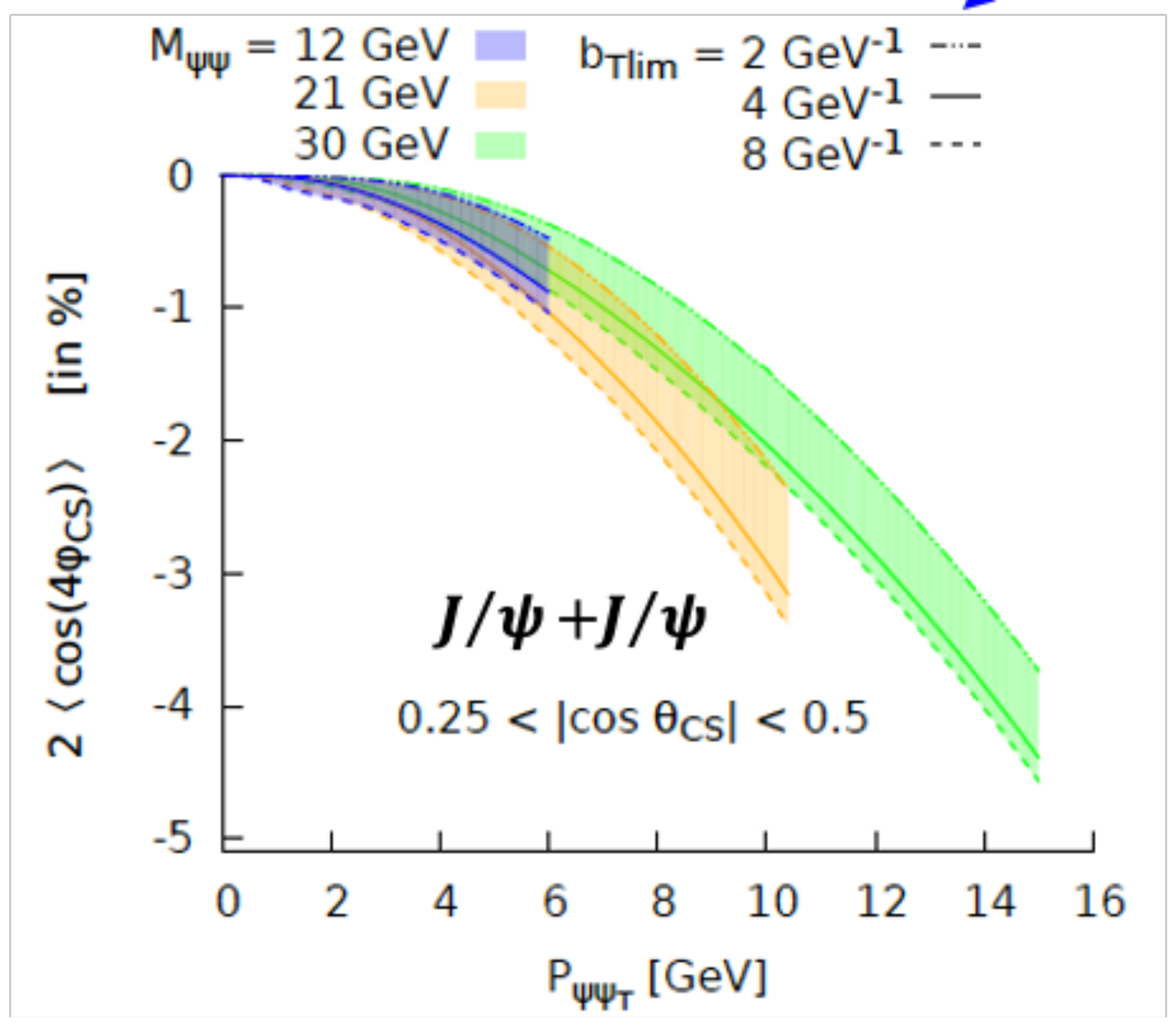


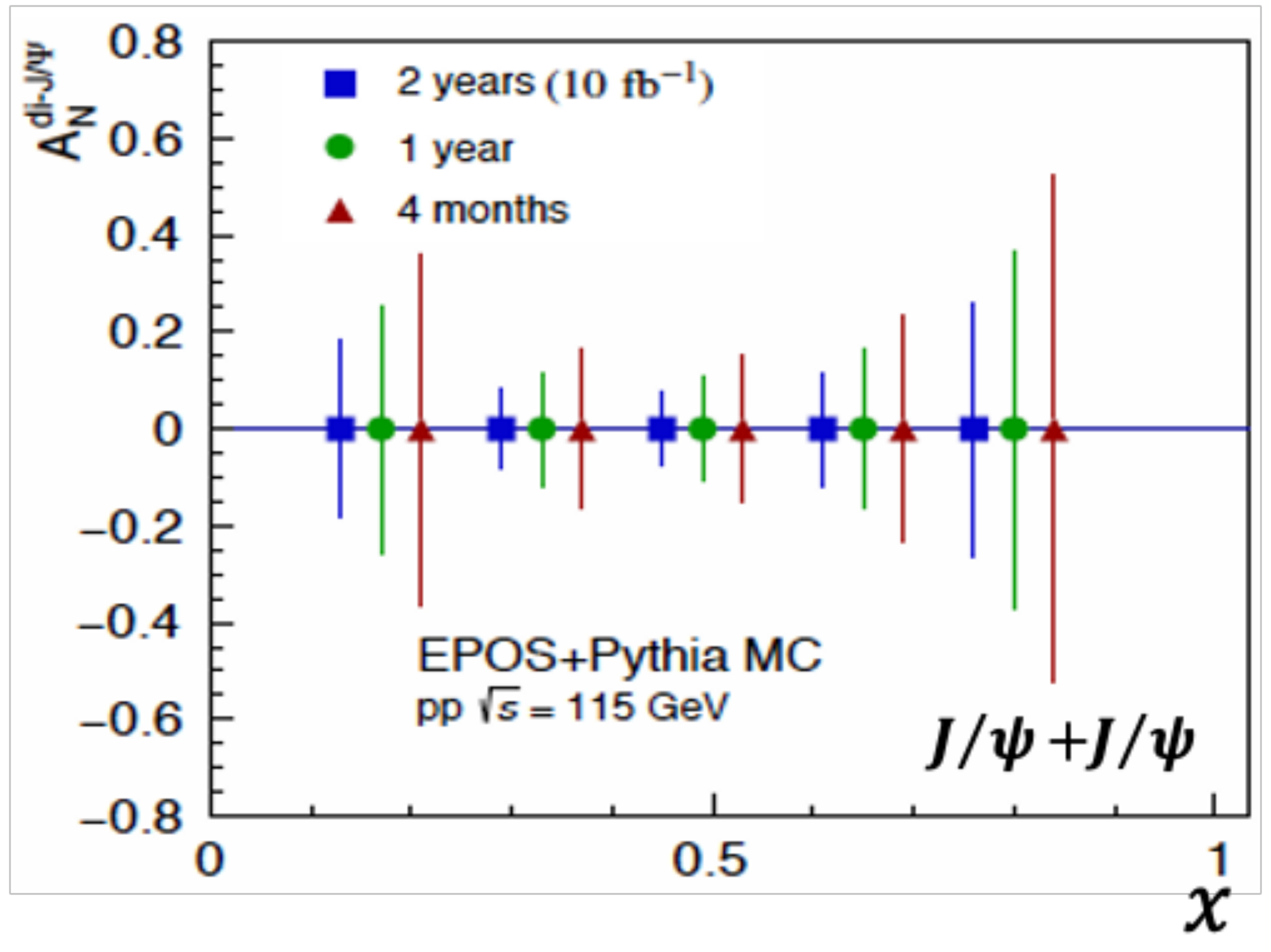
nucleon pol. \ gluon pol.	U	Circularly	Linearly
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_1^g,\ h_{1T}^{\perp g}$

Predictions based on CSM + TMD evolution for $x_1 \sim x_2 \sim 10^{-3}$ at forward rapidity [EPJ C 80, 87 (2020)]



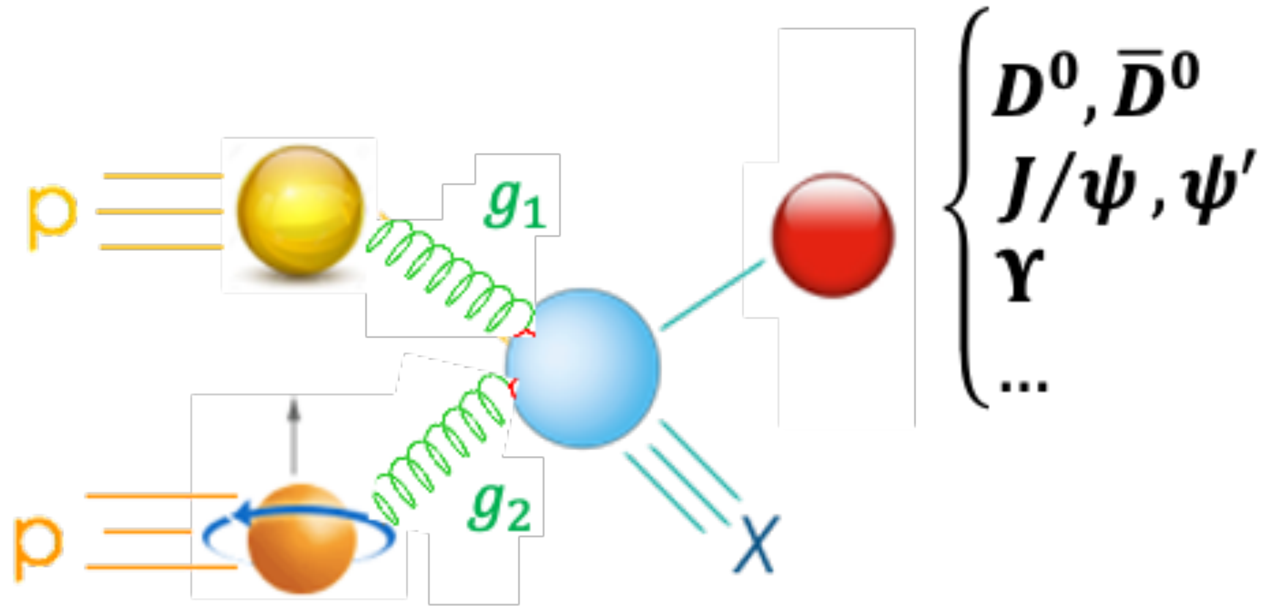
Azimuthal amplitudes ~5%!





Probing the gluon Sivers function

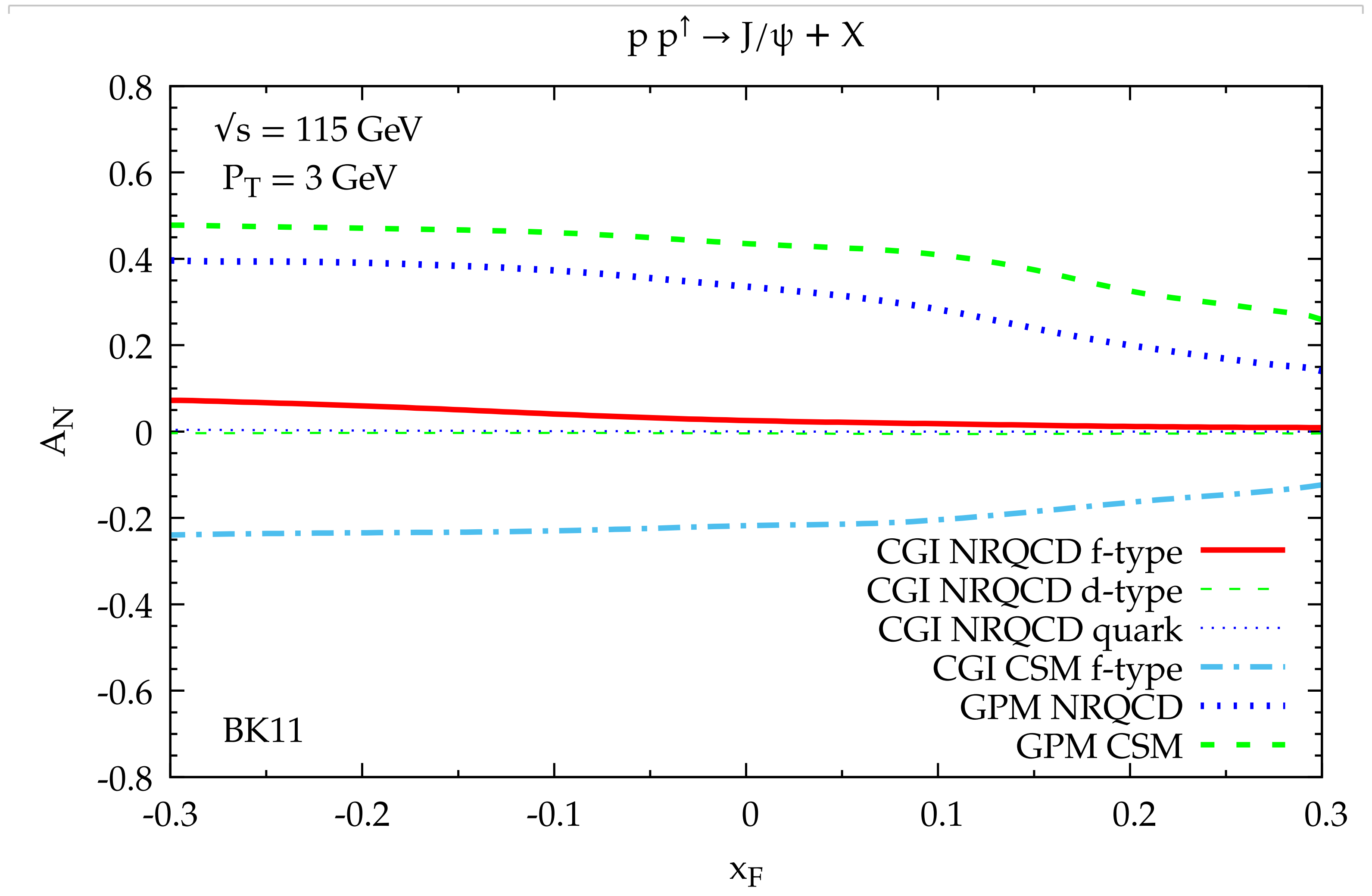
$$\Gamma_T^{\mu\nu}(x,\boldsymbol{p}_T) = \frac{x}{2}\left\{ g_T^{\mu\nu}\frac{\epsilon_T^{\rho\sigma} p_{T\rho} S_{T\sigma}}{M_p} f_{1T}^{\perp g}(x,\boldsymbol{p}_T^2) + \ldots \right\}$$



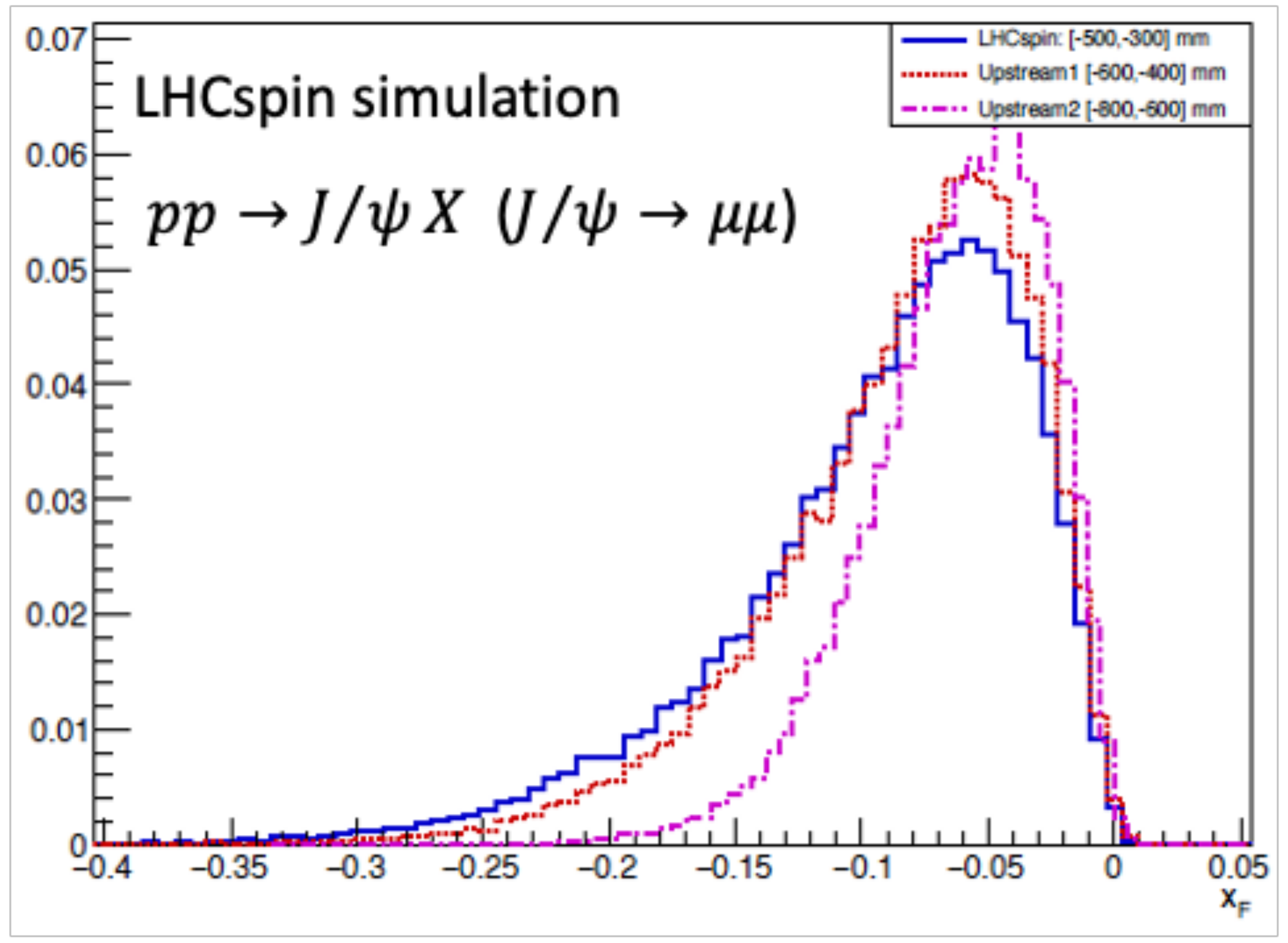
	gluon pol.		
nucleon pol.	U	Circularly	Linearly
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_1^g, $h_{1T}^{\perp g}$

- Sheds light on spin-orbit correlations of unpol. gluons inside a transv. pol. proton
- sensitive to color exchange among IS and FS and gluon OAM
- expected to be small (quasi-saturation of Burkardt sum rule by $f_{1T}^{\perp q}$ and QCD predictions in large-N_c limit)
- can be accessed through the Fourier decomposition of the TSSAs for **inclusive heavy meson production**

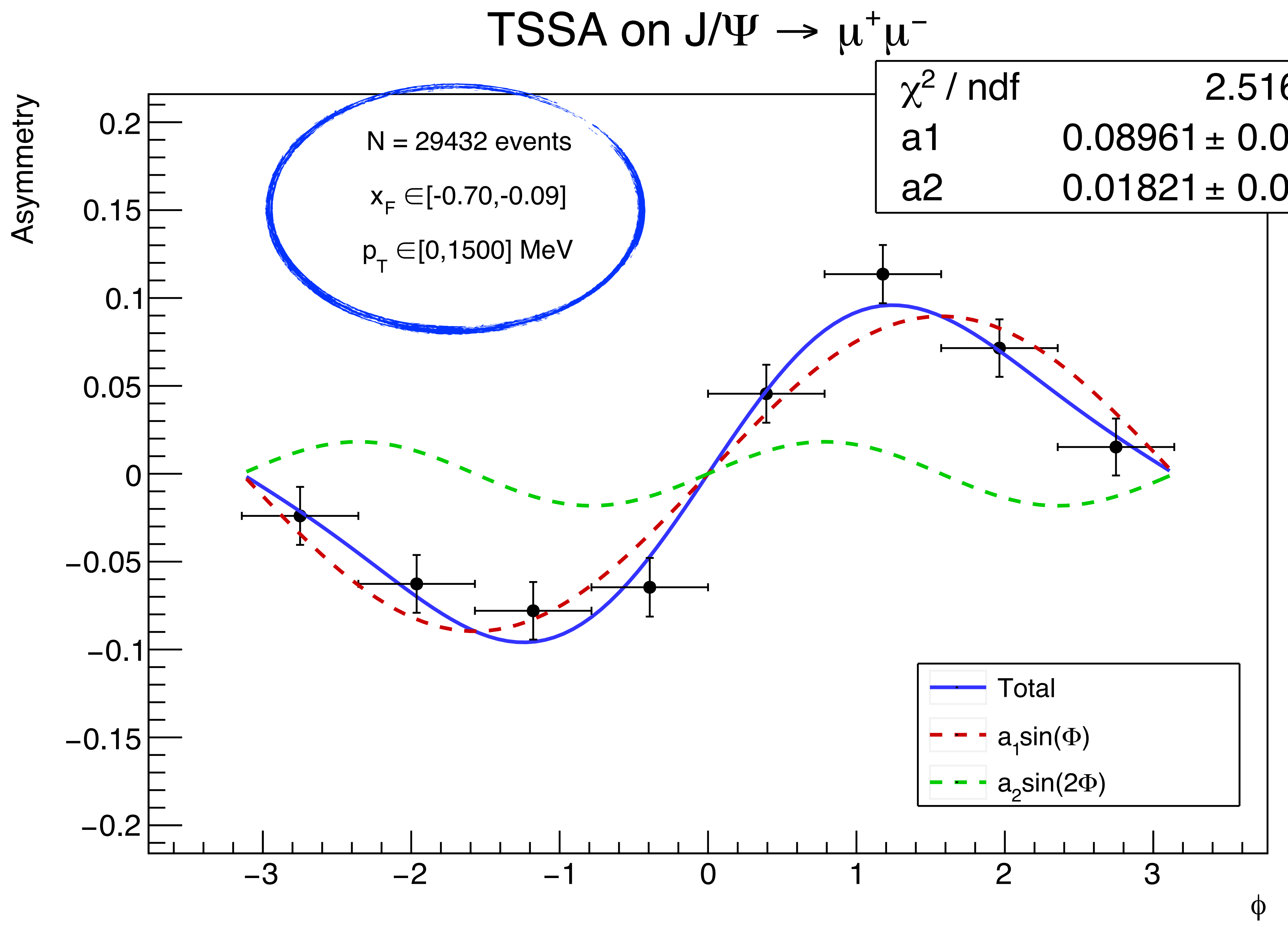
$$A_N = \frac{1}{P}\frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \propto \left[f_{1T}^{\perp g}(x_a, k_{\perp a}) \otimes f_g(x_b, k_{\perp b}) \otimes d\sigma_{gg\to Q\bar{Q}g}\right] \sin\phi_S + \cdots$$

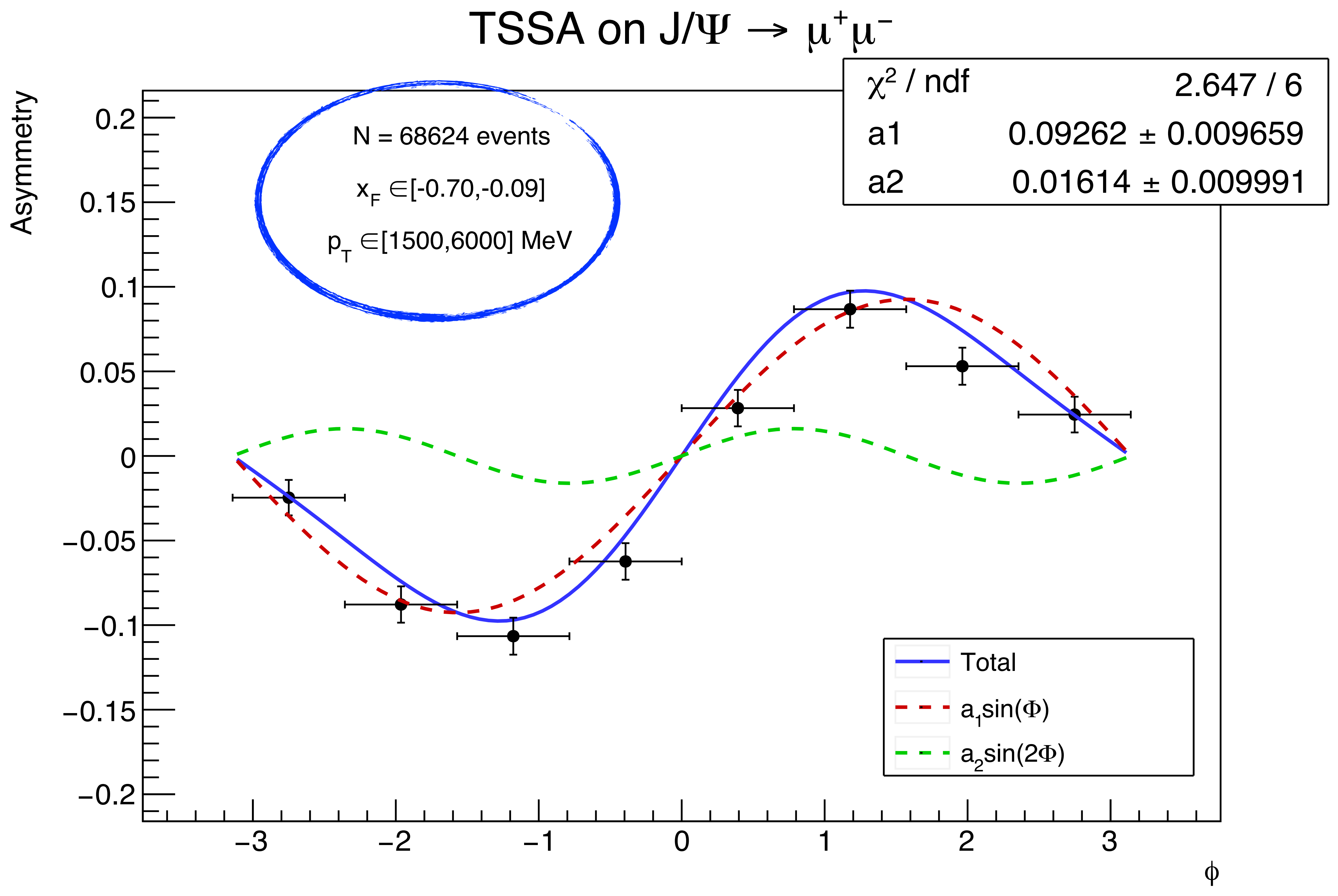


- **Predictions for pol. FT meas. at LHC (LHCspin-like)**
- Phys. Rev. D 102, 094011 (2020)
- $pp^\uparrow \to J/\psi + X$
- **based on GPM & CGI-GPM**
- **Expected amplitudes could reach 5-10% in the** $x_F < 0$ **region**

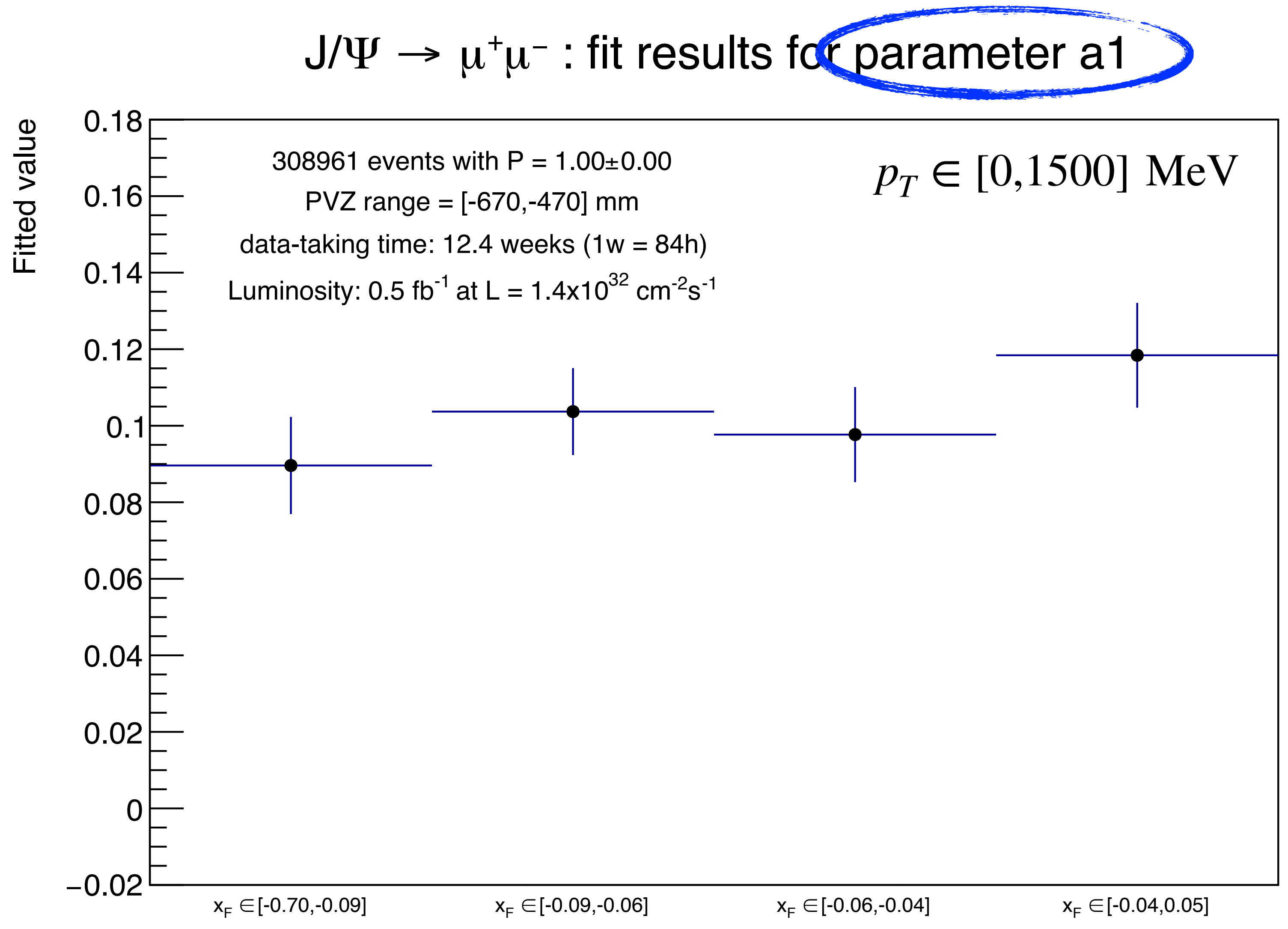


A TSSA analysis at LHCspin with $J/\Psi \rightarrow \mu^+\mu^-$ events





[JHEP 12 (2020) 010]



- Full LHCb simulations of $J/\Psi \rightarrow \mu^+\mu^-$ 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

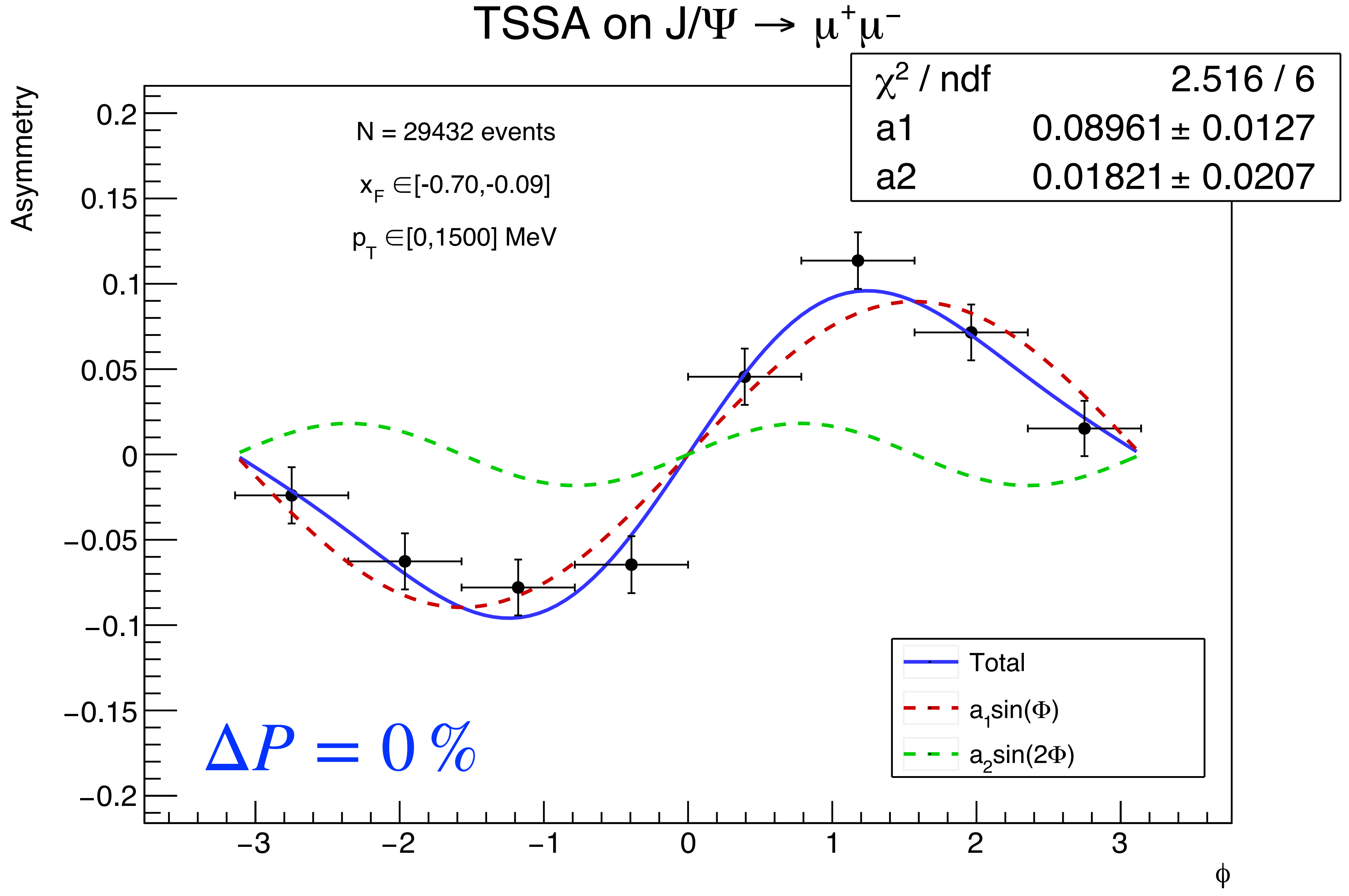
- To estimate the systematic error due to the measurement of the polarisation degree, the analysis is repeated with different ΔP
- Very relevant for the R&D (e.g. cell vs jet target). With the shown analysis* :
- 5% error (realistic value) → negligible effect
- 20% error → 30-40% of the stat. error
-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

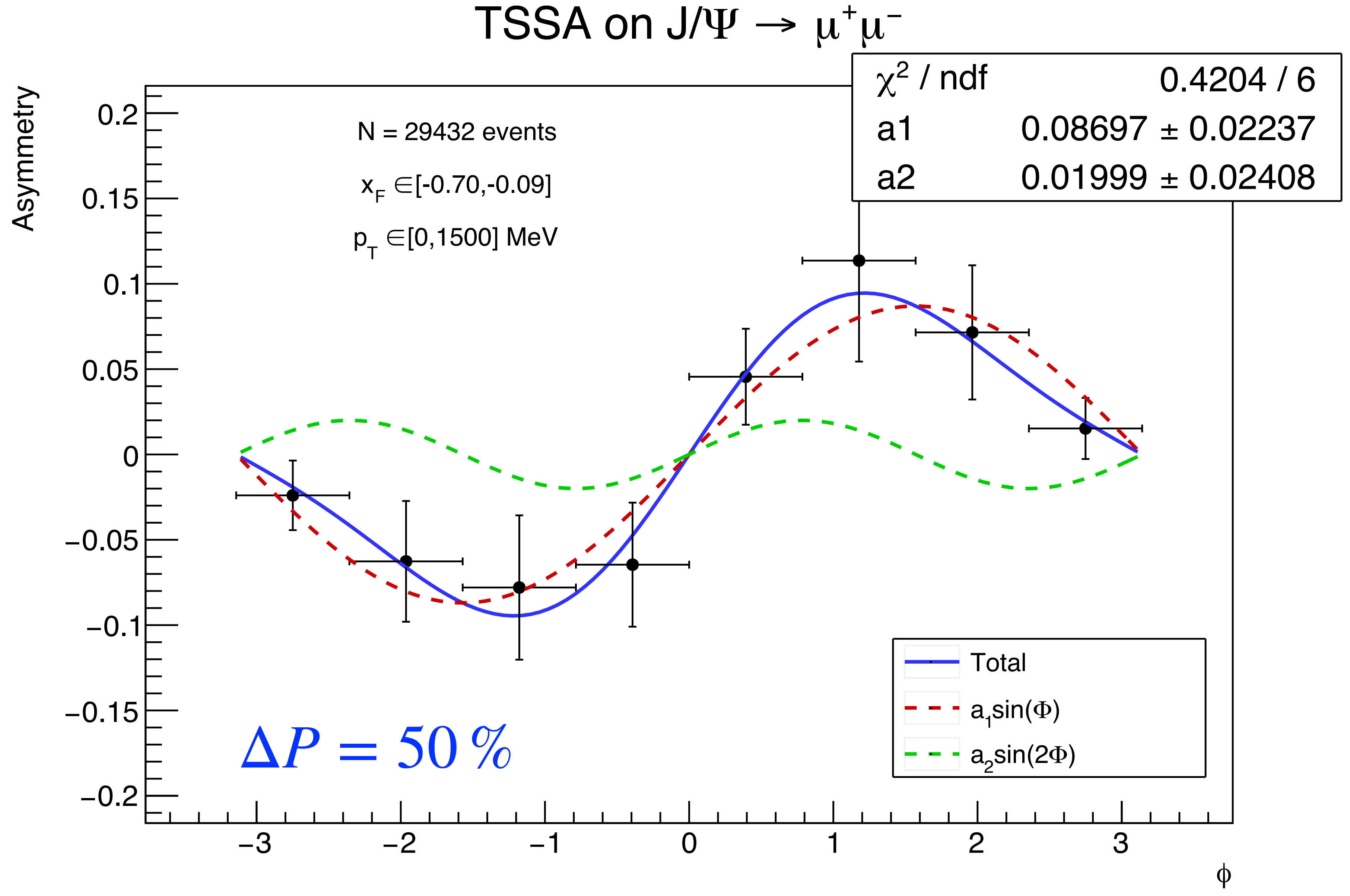
$\Delta P = 5\,\%$

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

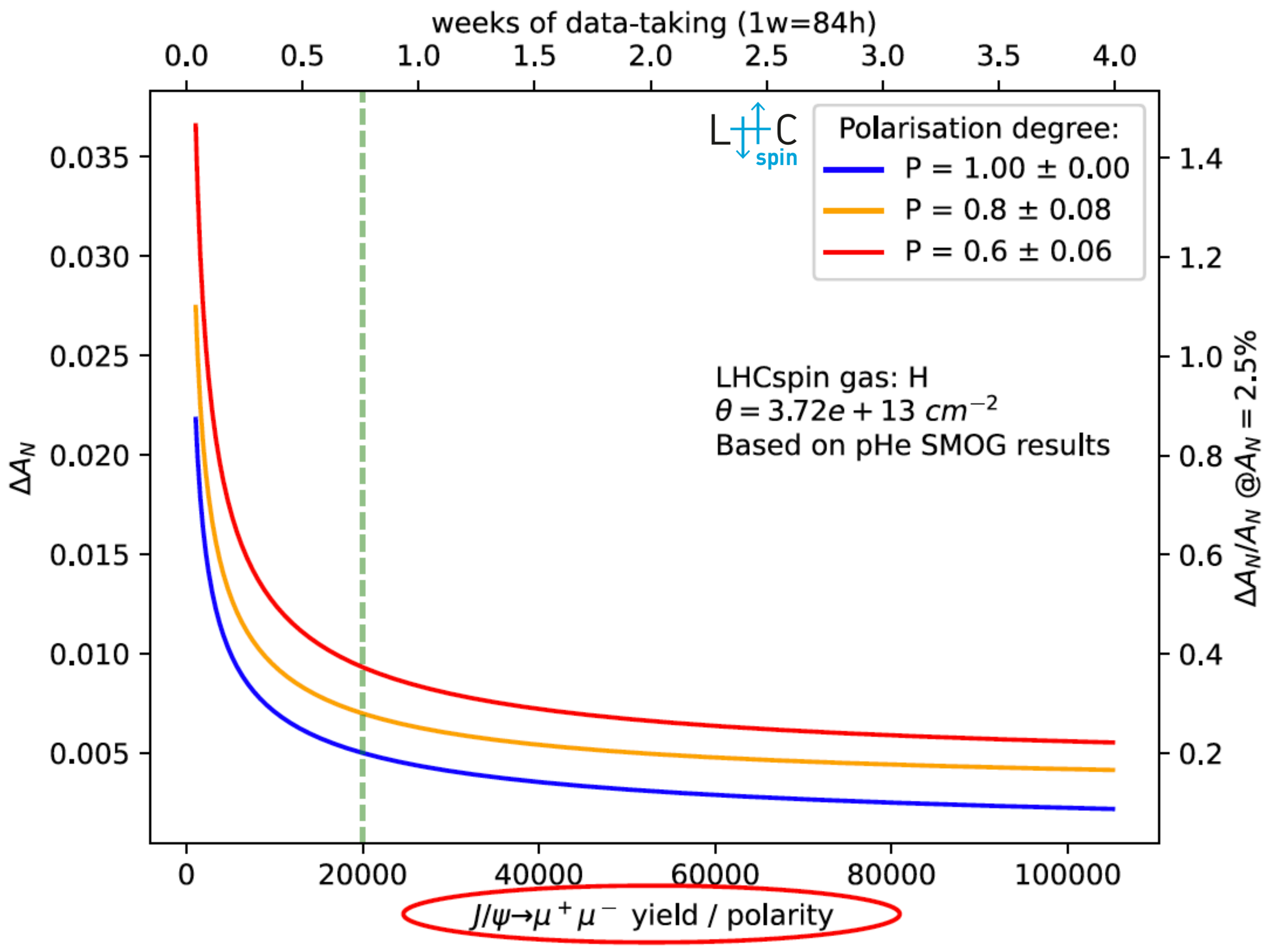


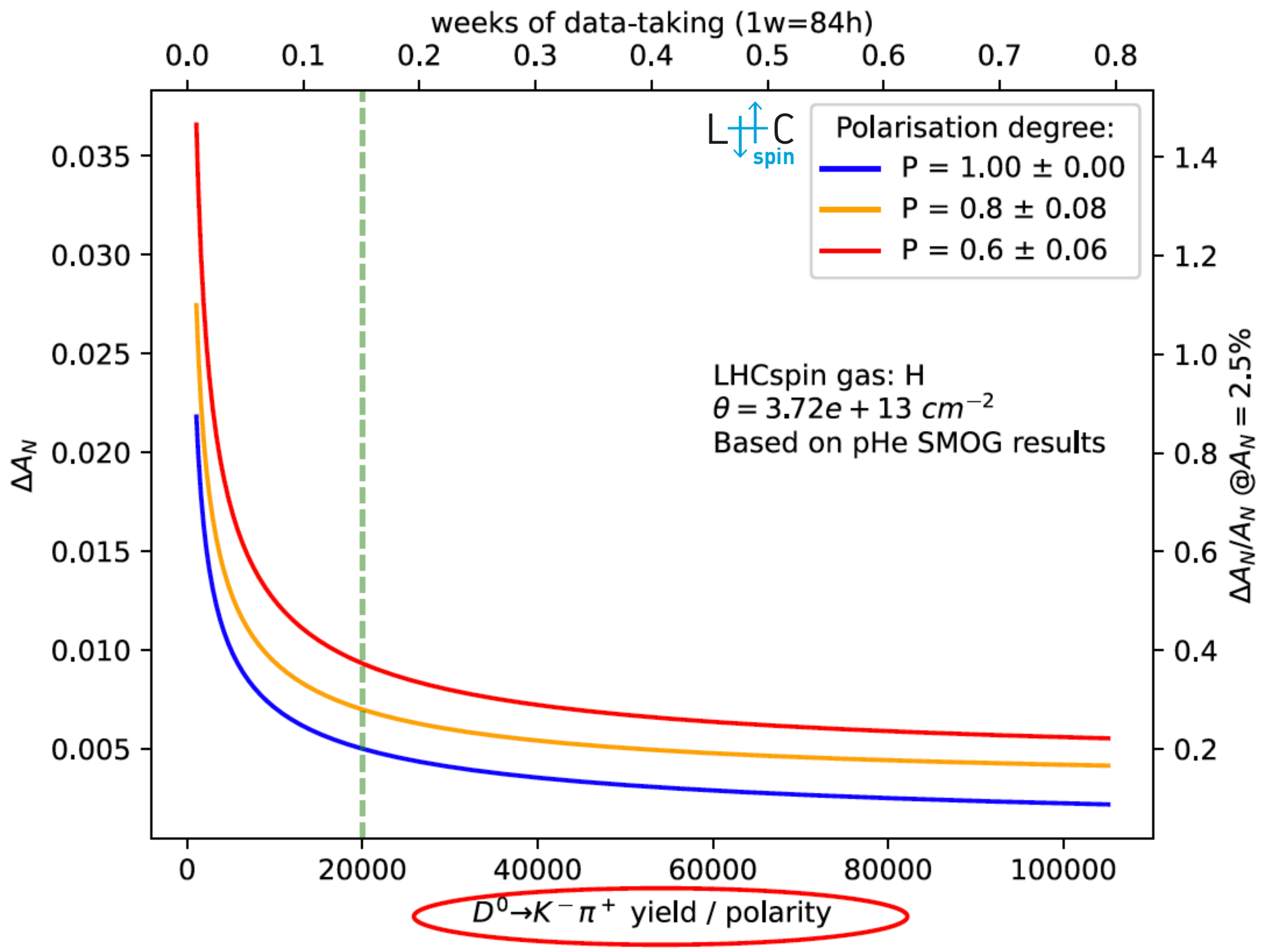


* i.e. ~ 3 months of data-taking with this example model, channel and kinematic binning

LHCspin event rates

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





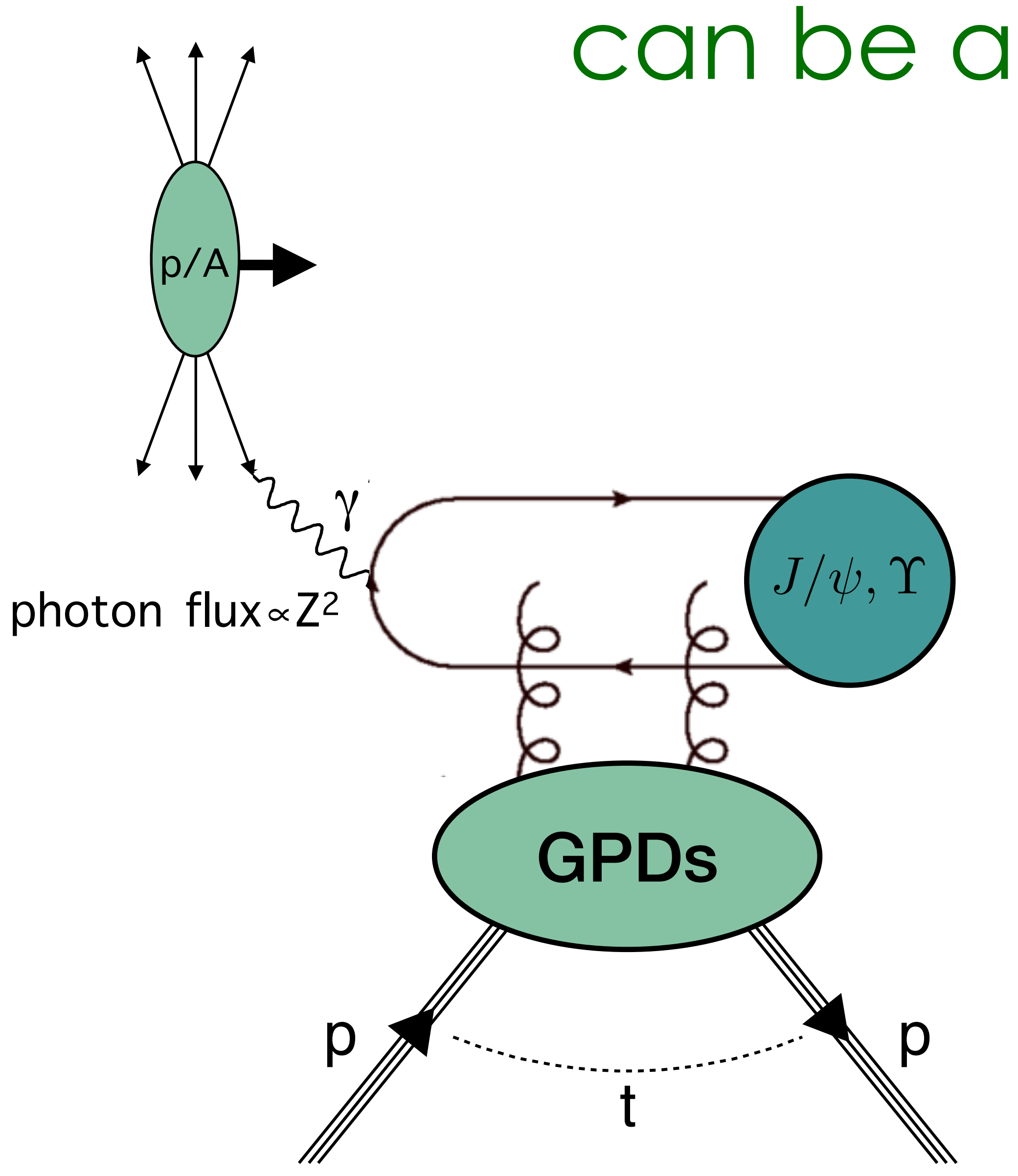
reconstructed particles

UPC and gGPDs

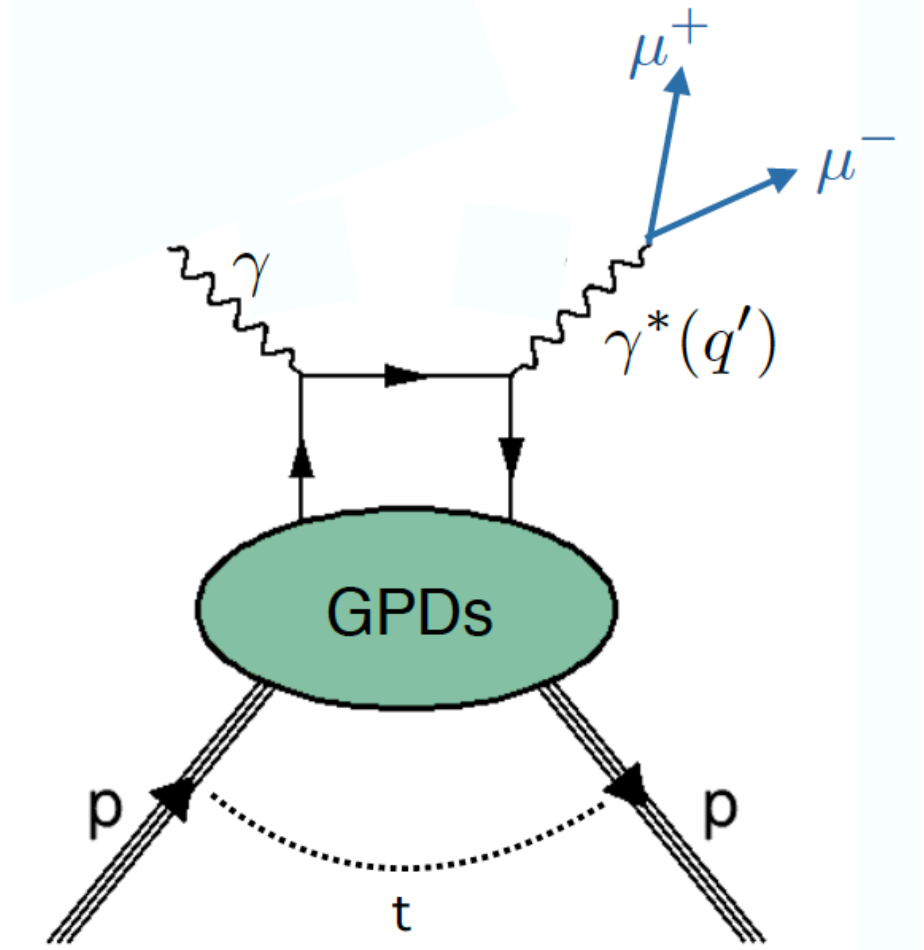
Accessible already with SMOG2 for the unpol part

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



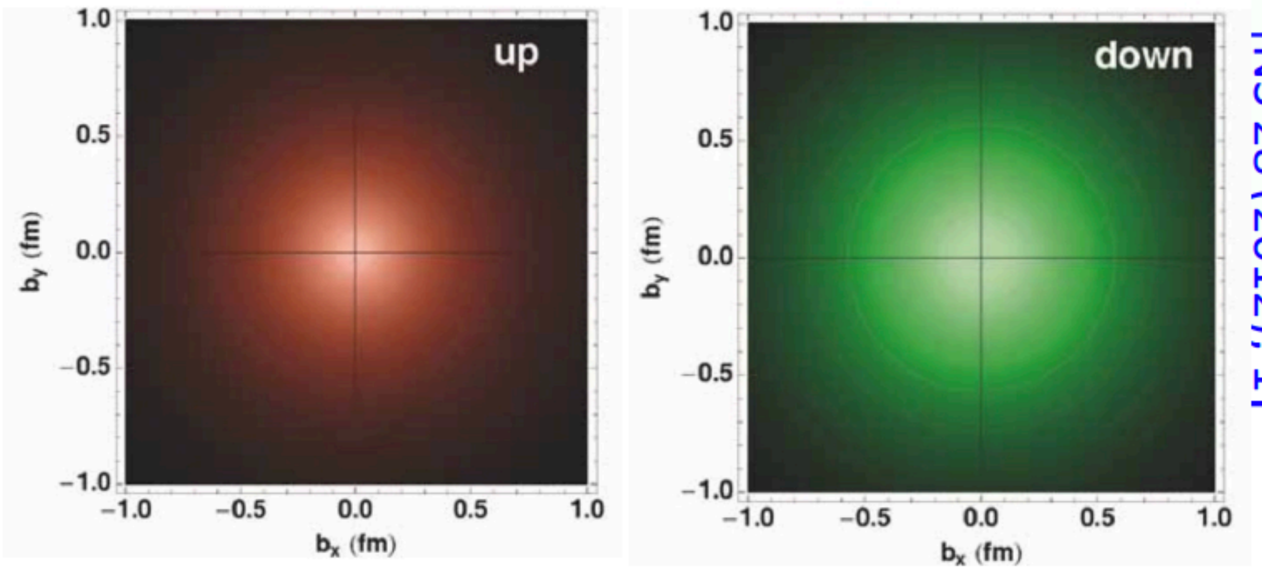
Timelike Compton scattering (TCS)
(access via angular modulation)
hard scale = large q^2 (in practice few GeV^2)

- 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]

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



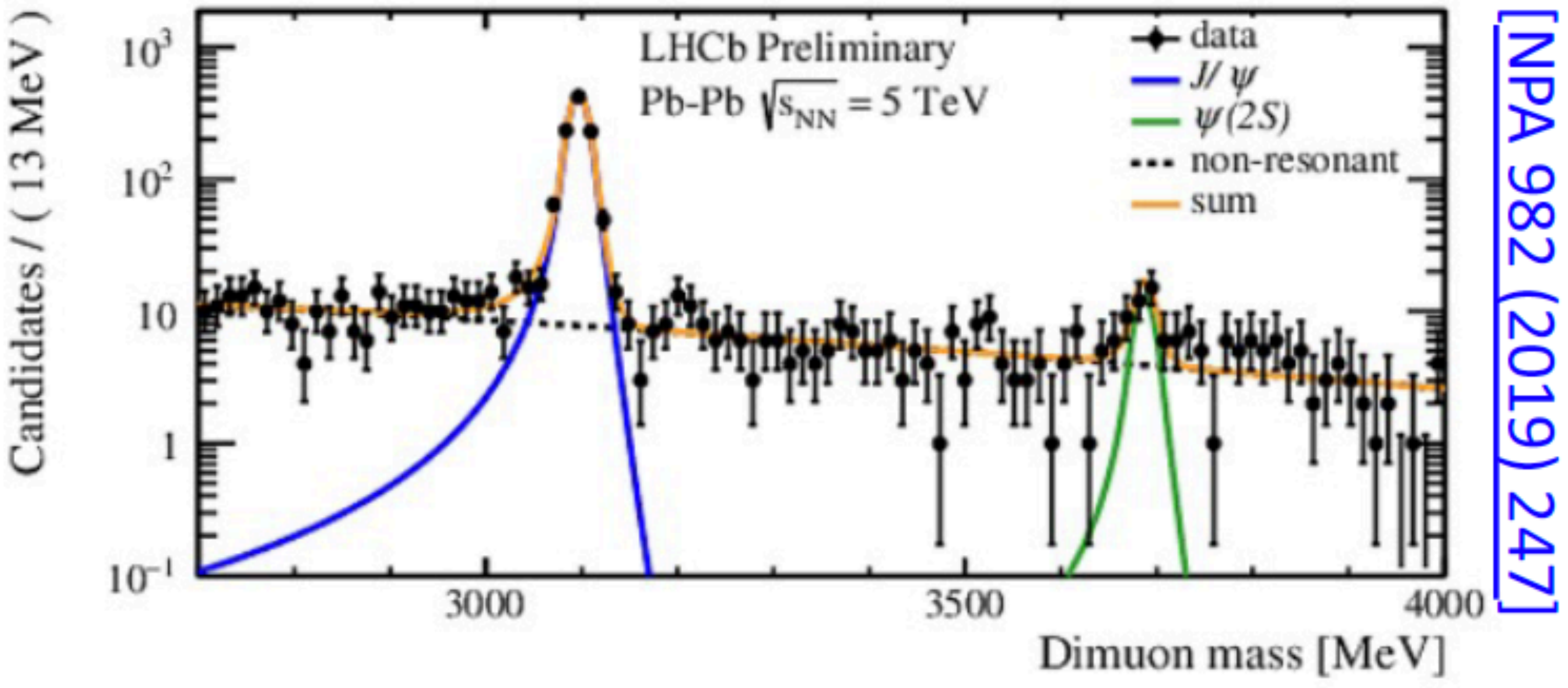
[NS 28 (2012), 1]

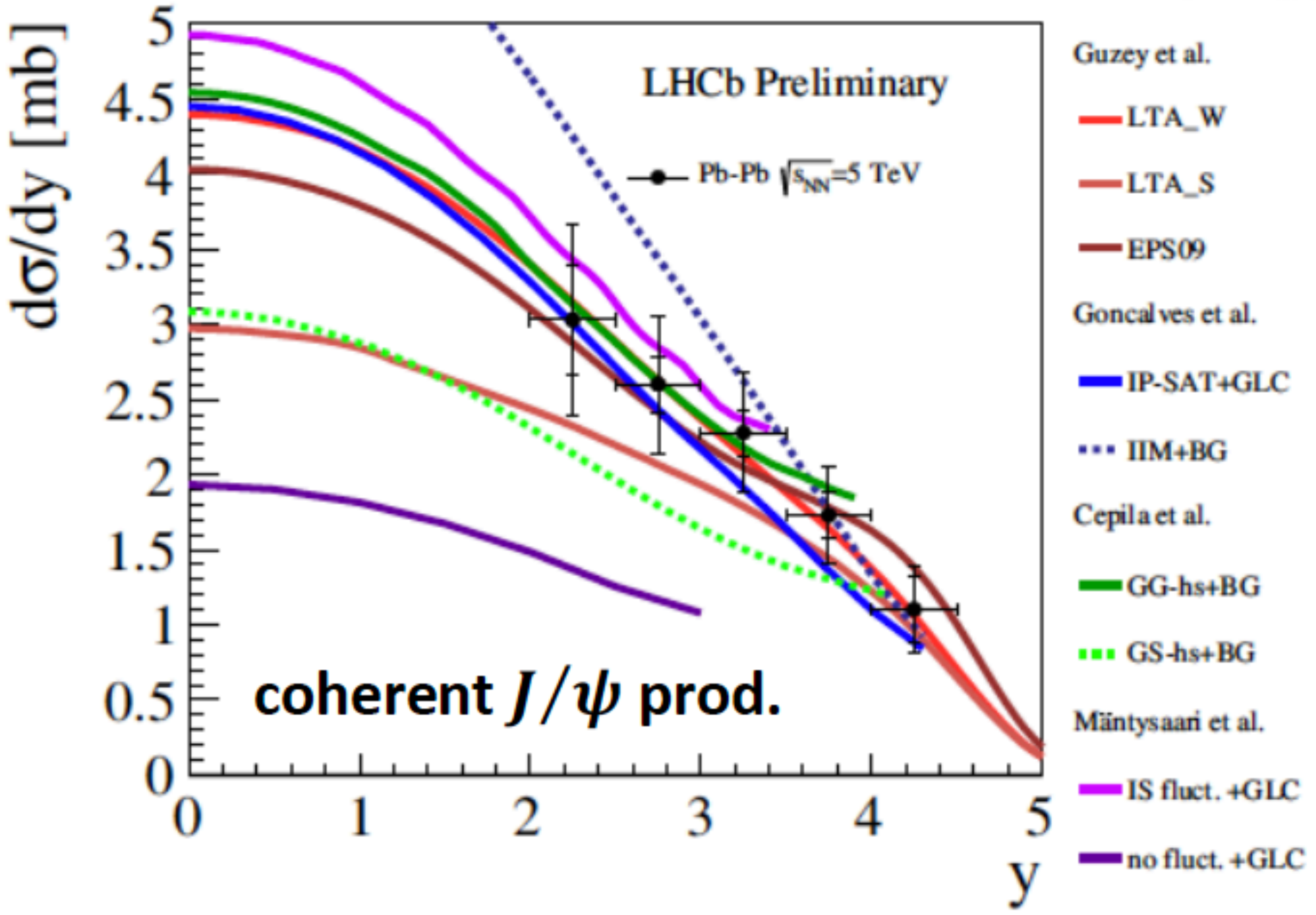
LHCspin could allow to access the GPD E^g (a key ingredient of the Ji sum rule)

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

UPC and gGPDs

First results from LHCb in PbPb UPC





SMOG2

Continuum 2 muons, statistical uncertainty on cos(ϕ) modulation, p_T cut included

pp	pD	pAr	pKr	pXe
30 %	–	10 %	20 %	15 %

Continuum 2 muons, statistical uncertainty on cos(ϕ) modulation, p_T cut not included

Pbp	PbAr
–	30 %

Note: luminosity uncertainty does not enter and rest of systematic uncertainties expected small, since modulation.

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

pp	pD	pAr	pKr	pXe
10 %	–	5 %	5 %	5 %

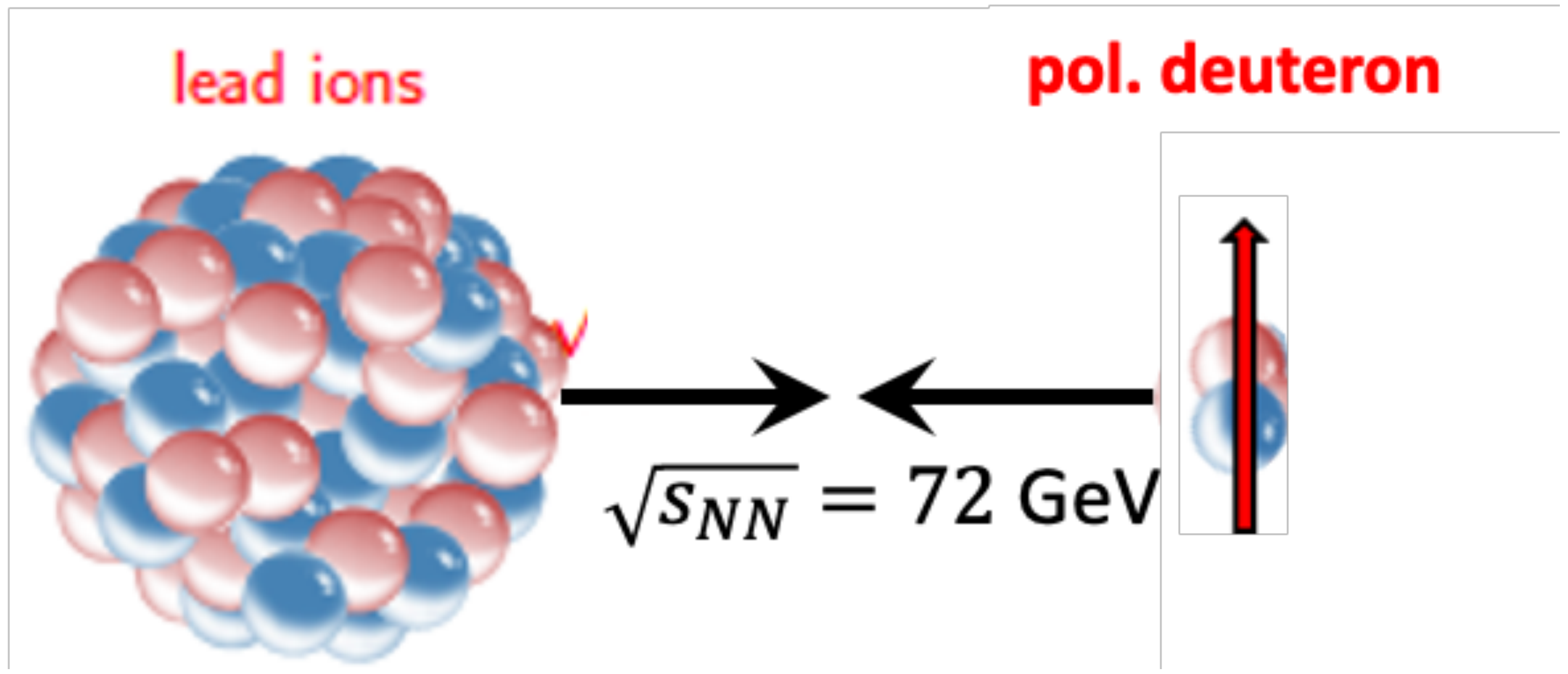
Pbp	PbAr
–	5 %

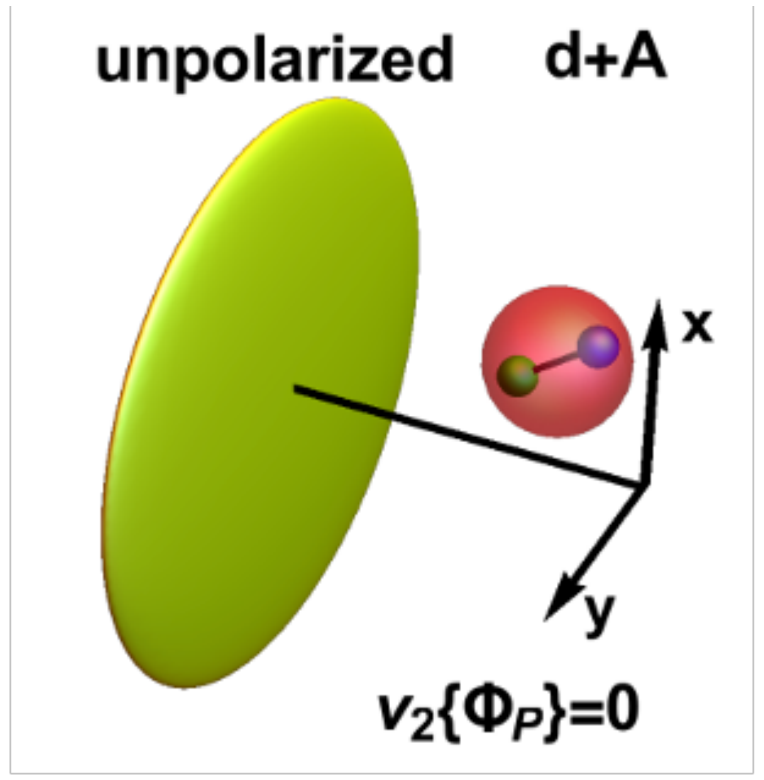
C. van Hulse's slide

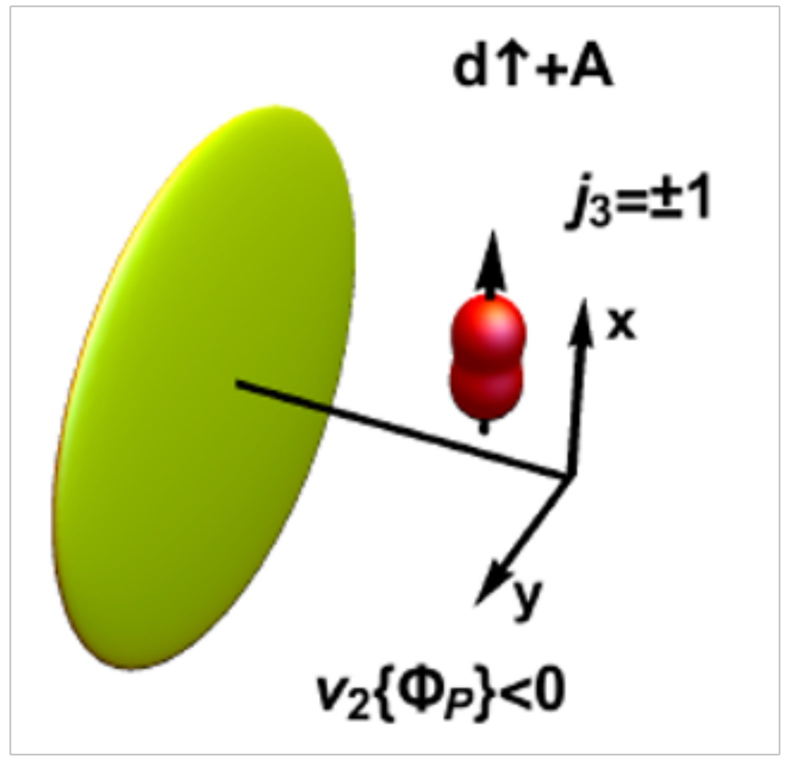
Spin physics in heavy-ion collisions

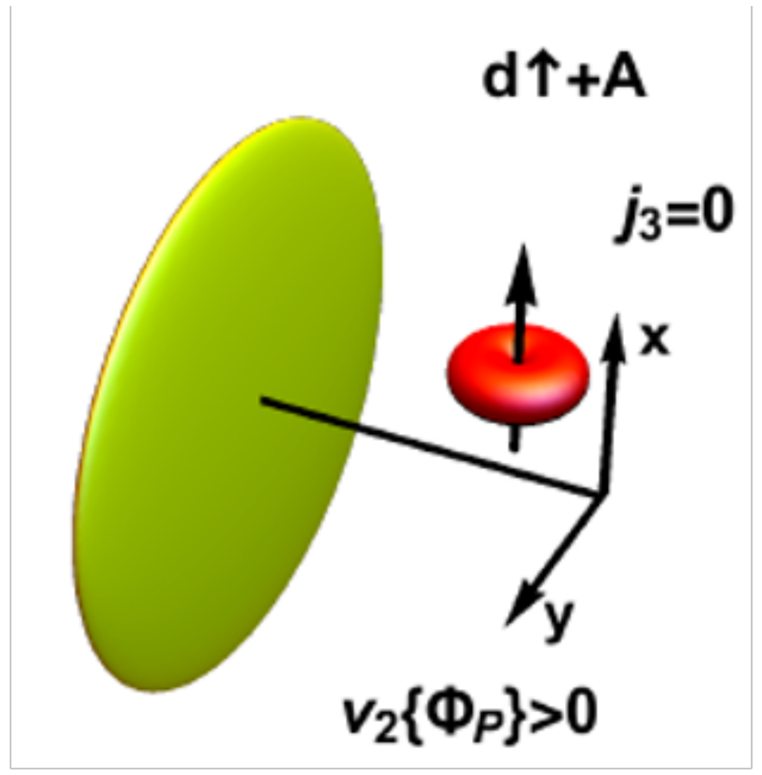
- probe collective phenomena in heavy-light systems through **ultra-relativistic collisions of heavy nuclei with trasv. pol. deuterons**

- 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**).





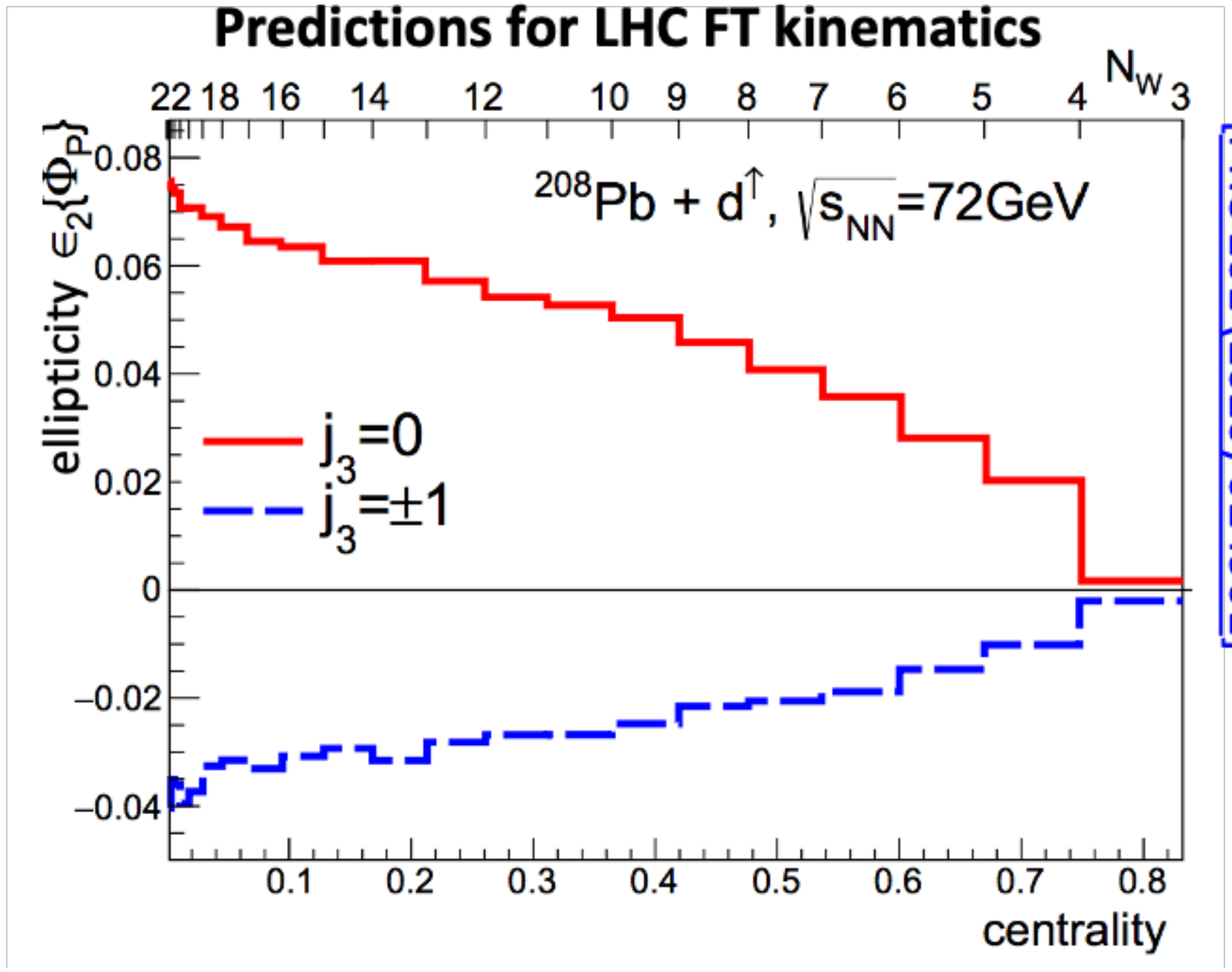




Unpol. deuterons: the **fireball is azimuthally symmetric** and $\boldsymbol{v_2 \approx 0}$.

$j_3 = \pm1$ → **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]

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)

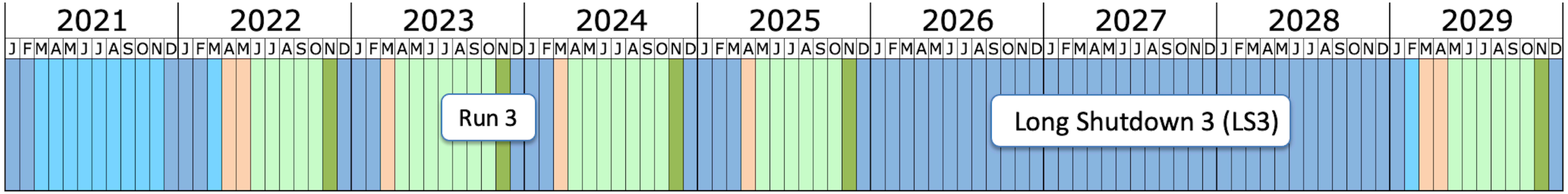
Can be measured at LHCspin

"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)

Recognised relevance

Conclusions



Today SMOG2

LHCspin

ALICE FT

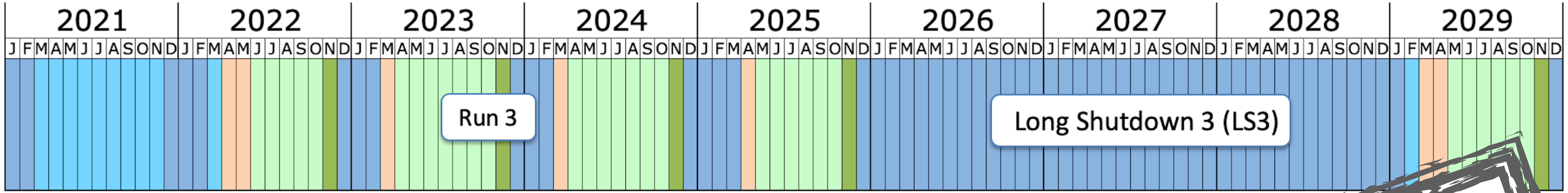
<u>Fixed target physics at LHC is an exiting reality</u>

ALICE has potentialities in the unpolarised case showing complementarity to LHCb

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 <u>realistic time schedule and costs</u>

Conclusions



Today SMOG2

LICE
FT

Complementarity is the key

This physics is very alive and has still a lot to say from JLab20+ to LHC

Fixed target physics at LH

ALICE has potentialities in ... ntarity to LHCb

... ive and taking unpolarised data

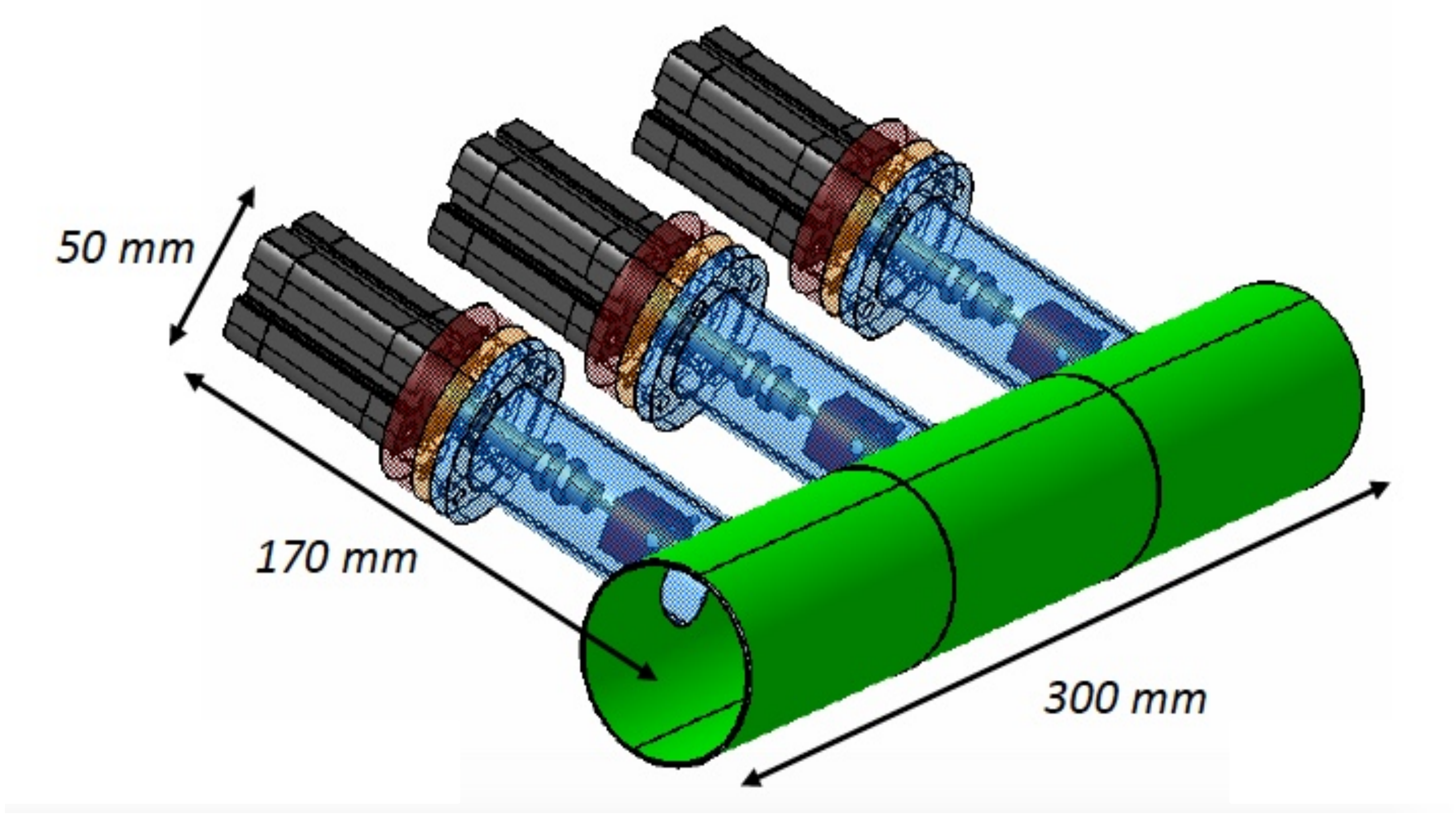
spin is an innovative and unique project conceived to bring polarized physics at the LHC. It is extremely ambitious in terms of both physics reach and technical complexity. It could be installed in a realistic time schedule and costs solid target @ ALICE

The ALICE unpolarised solid target

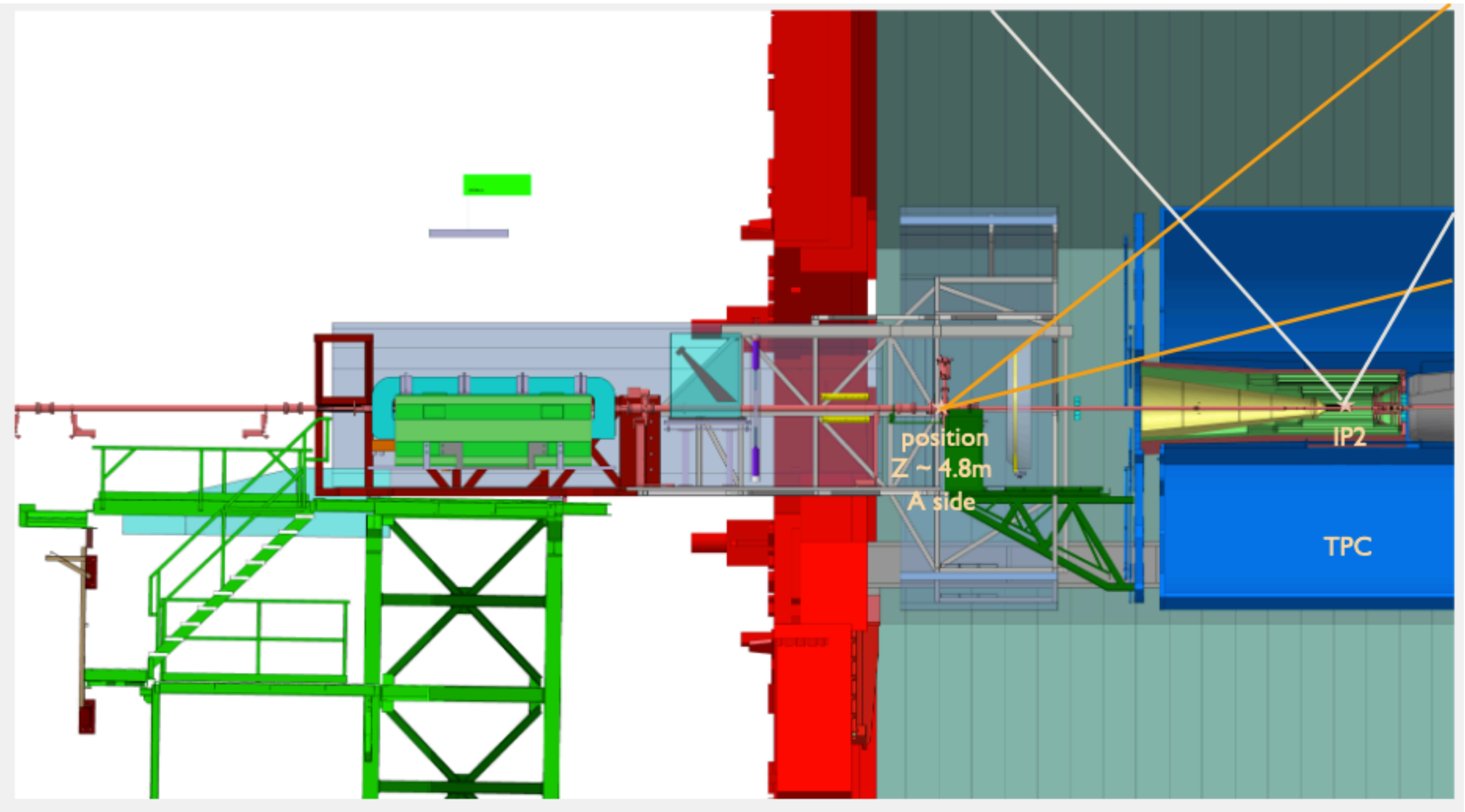
Two main physics goals:

- Advance the understanding of the large-x gluon, antiquark and heavy-quark content in the nucleon and nucleus (structure of nucleon and nuclei at large-x, gluon EMC effect in nuclei, intrinsic charm in nucleon)
- Study heavy-ion collisions between SPS and RHIC energies towards large rapidities (longitudinal expansion of QGP formation, collectivity in small systems with heavy quarks, factorisation of CNM effects)

- Proton beam halo channelled with a bent crystal on a retractable solid target (C,W, Ti, …)
- Backward cms rapidity coverage with forward detectors in the lab thanks to the boost

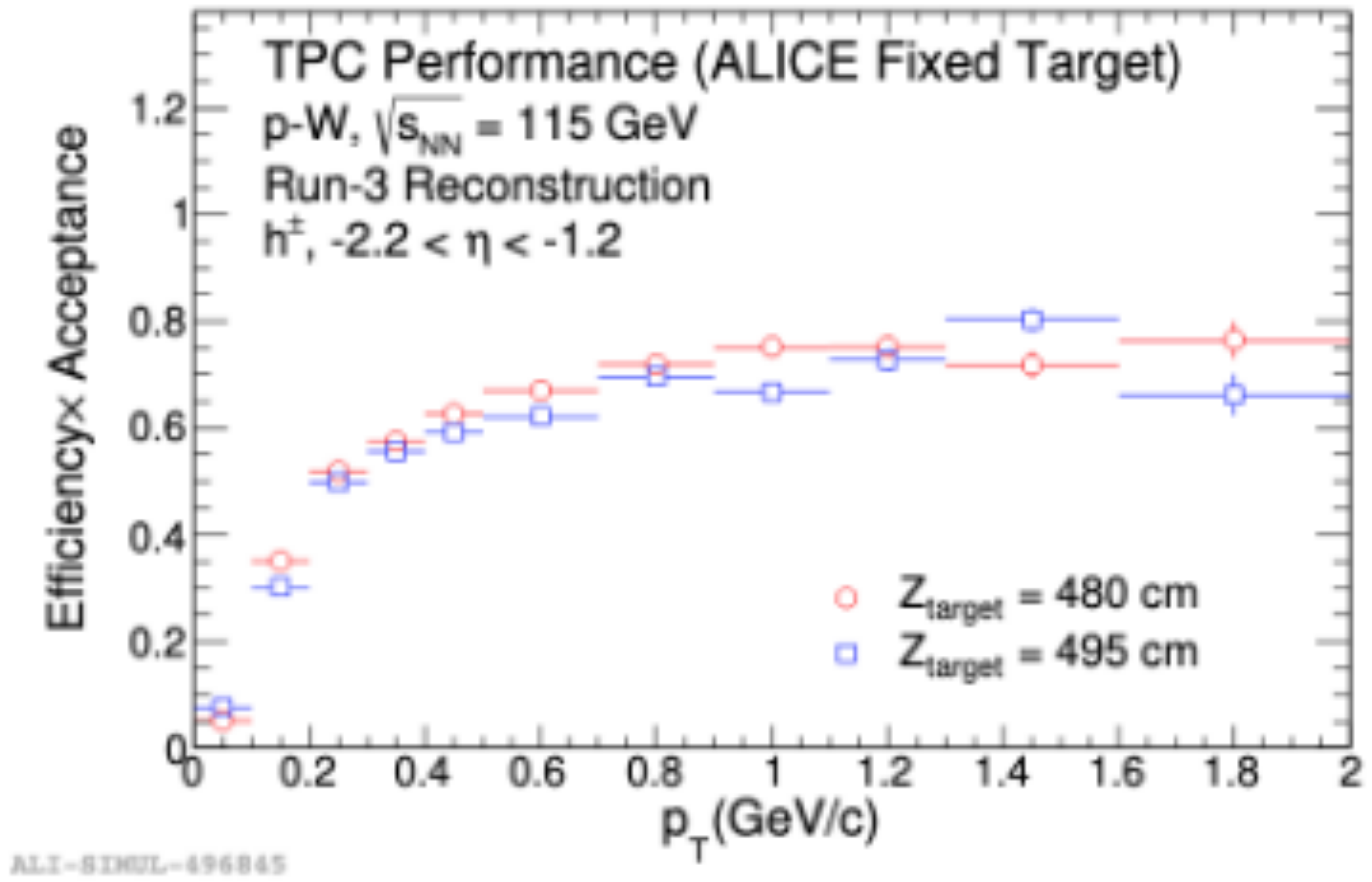


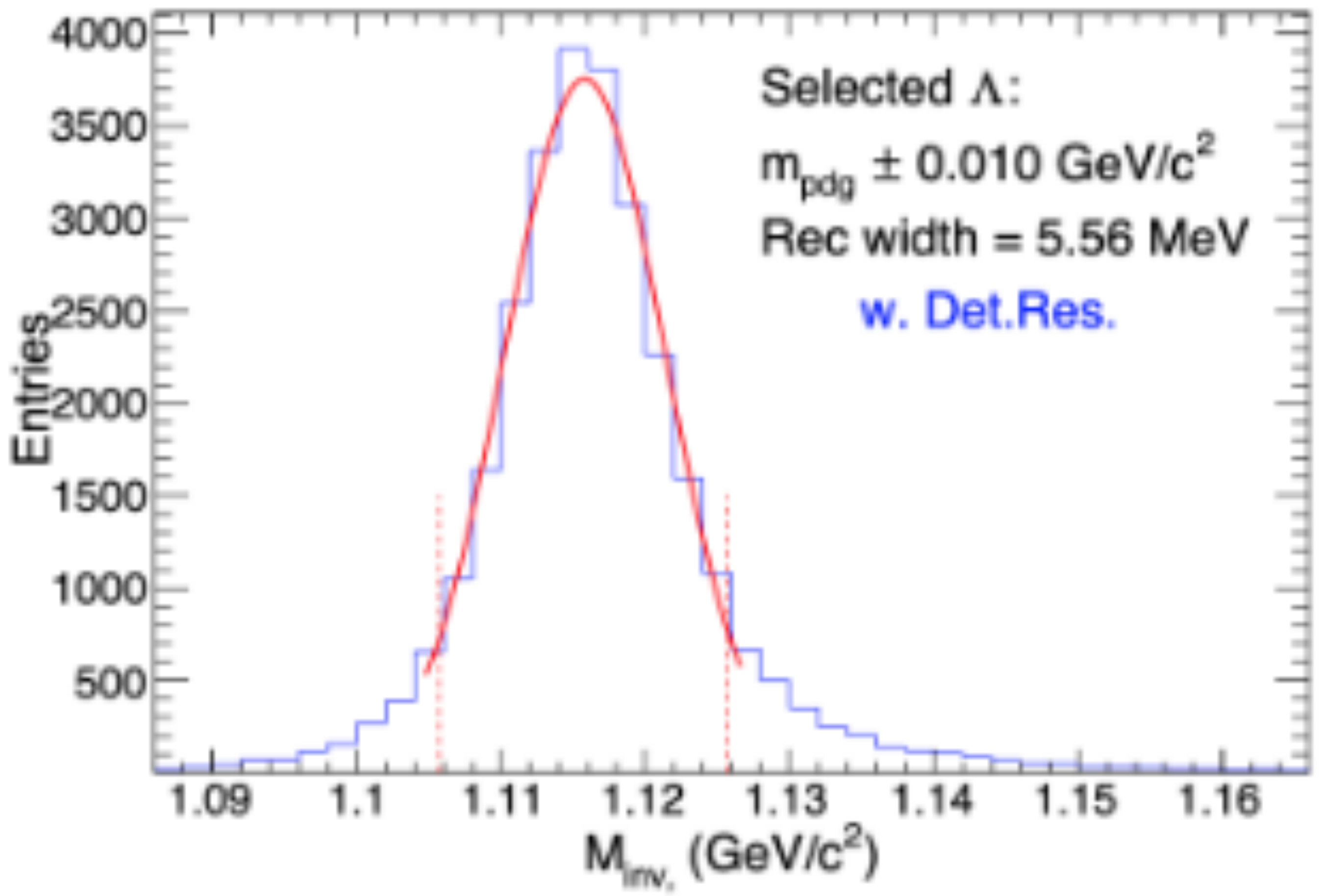
retractable solid target

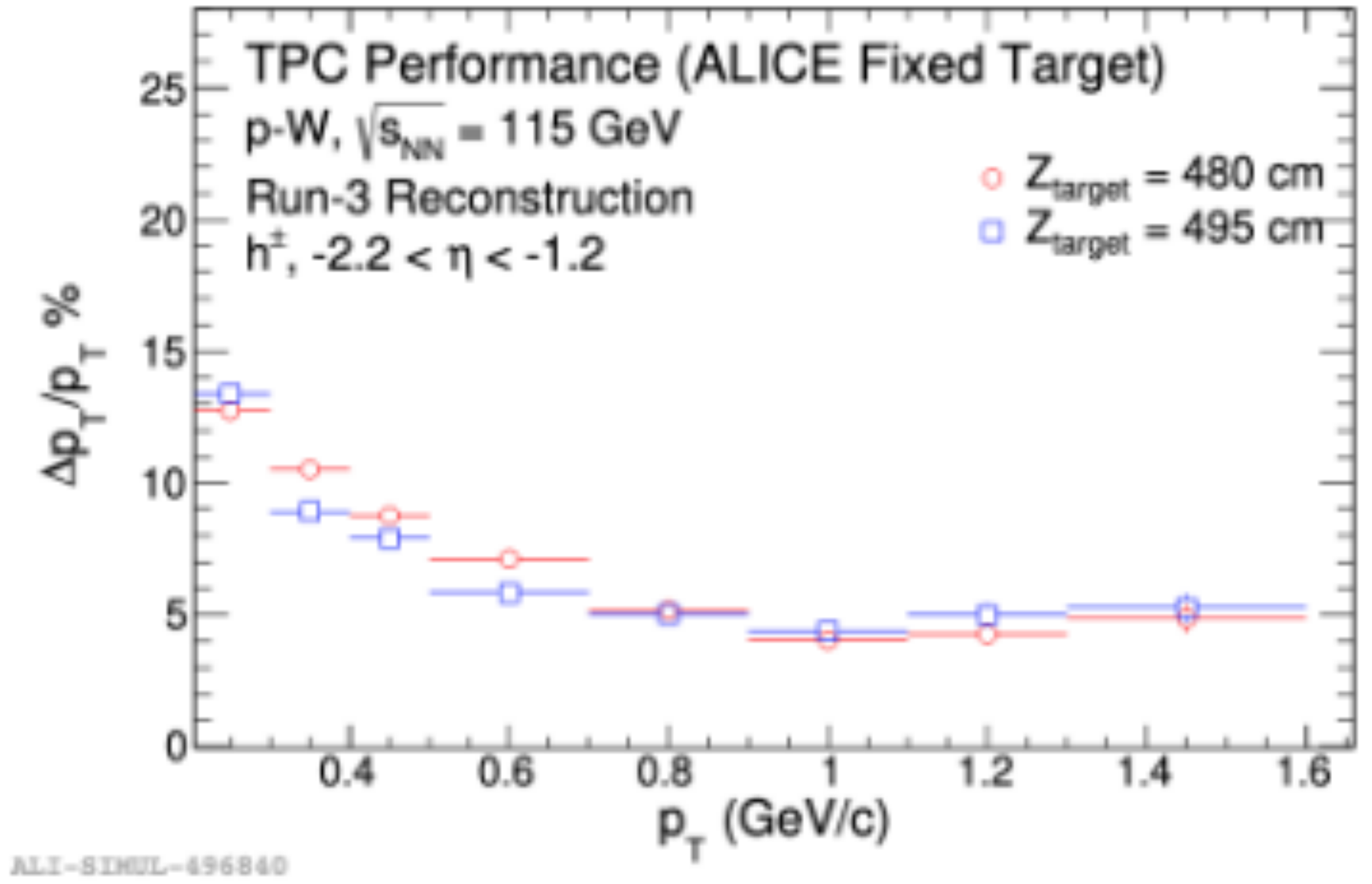


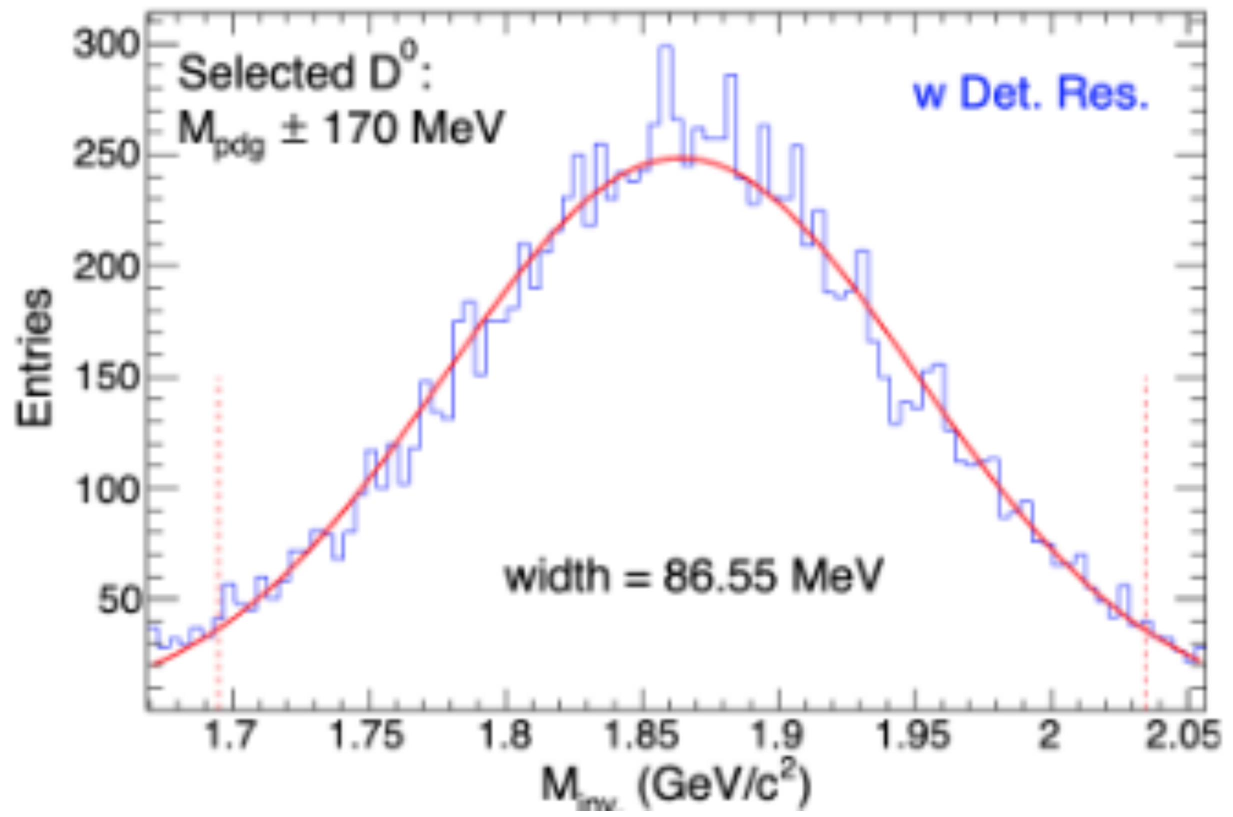
Some of the performances

R.Haque https://indico.cern.ch/event/1142976

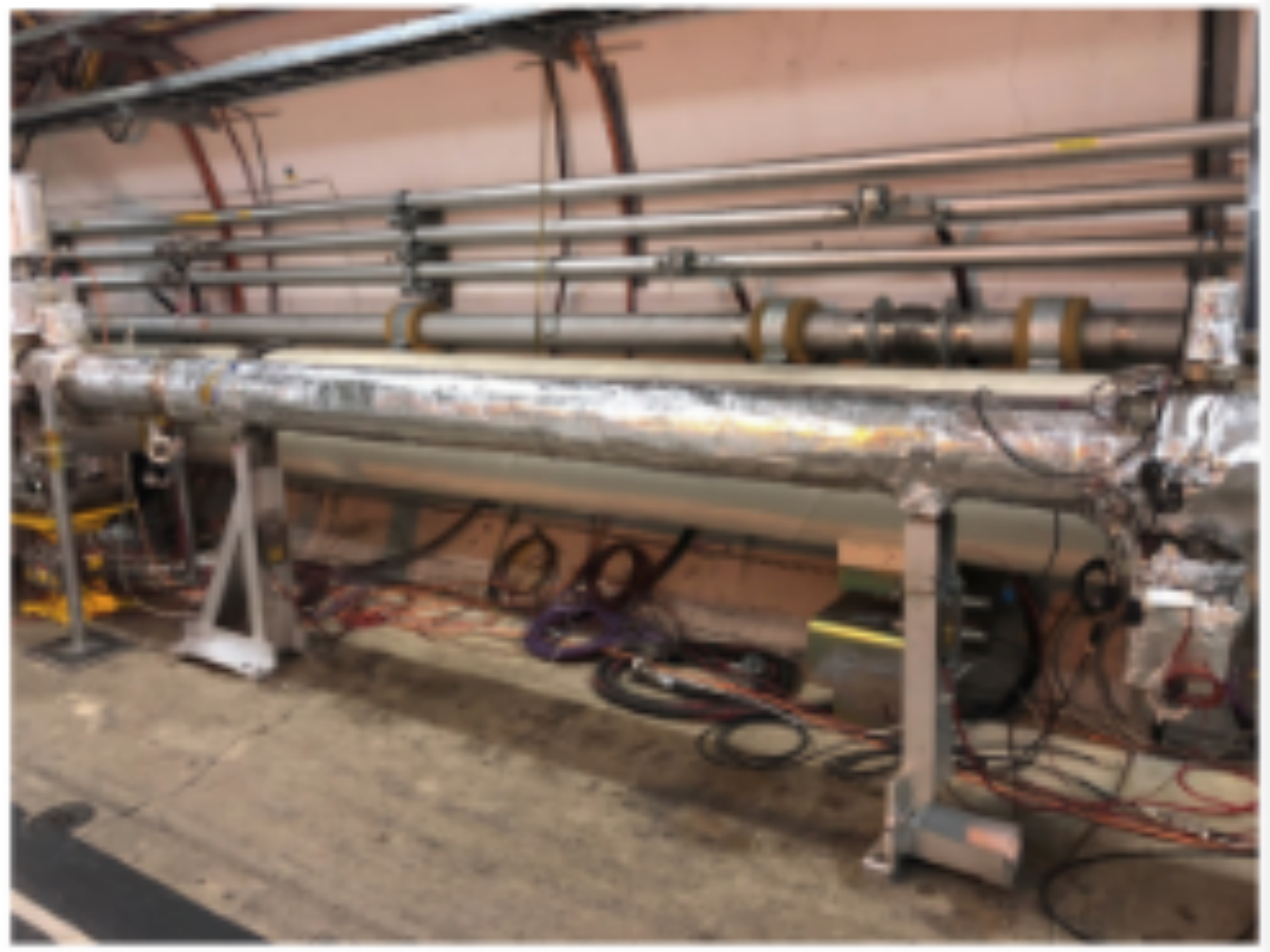








space availability at z = 3259 m



Proton beam collimation studies performed: loss maps, positioning of the crystal system and of the absorbers

C. Hadjidakis: https://indico.cern.ch/event/1142976

LOI in ALICE (2022) —> aim for installation during LS3 (2026-2028)

Some of the results achieved

- Λ: efficiency and p_T resolution sufficient for analysis (without extra vertex detector)
- D^0: TPC vertex resolution not sufficient to use secondary vertex method for analysis. Investigating combinatorial background method, reduced target size and constraints on beam spot position for tracking
- Integration solutions to comply with FOCAL and ITS motion constraints during EYETS
- Physics performance with realistic detector conditions