Fixed targets at LHC

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In collaboration with:
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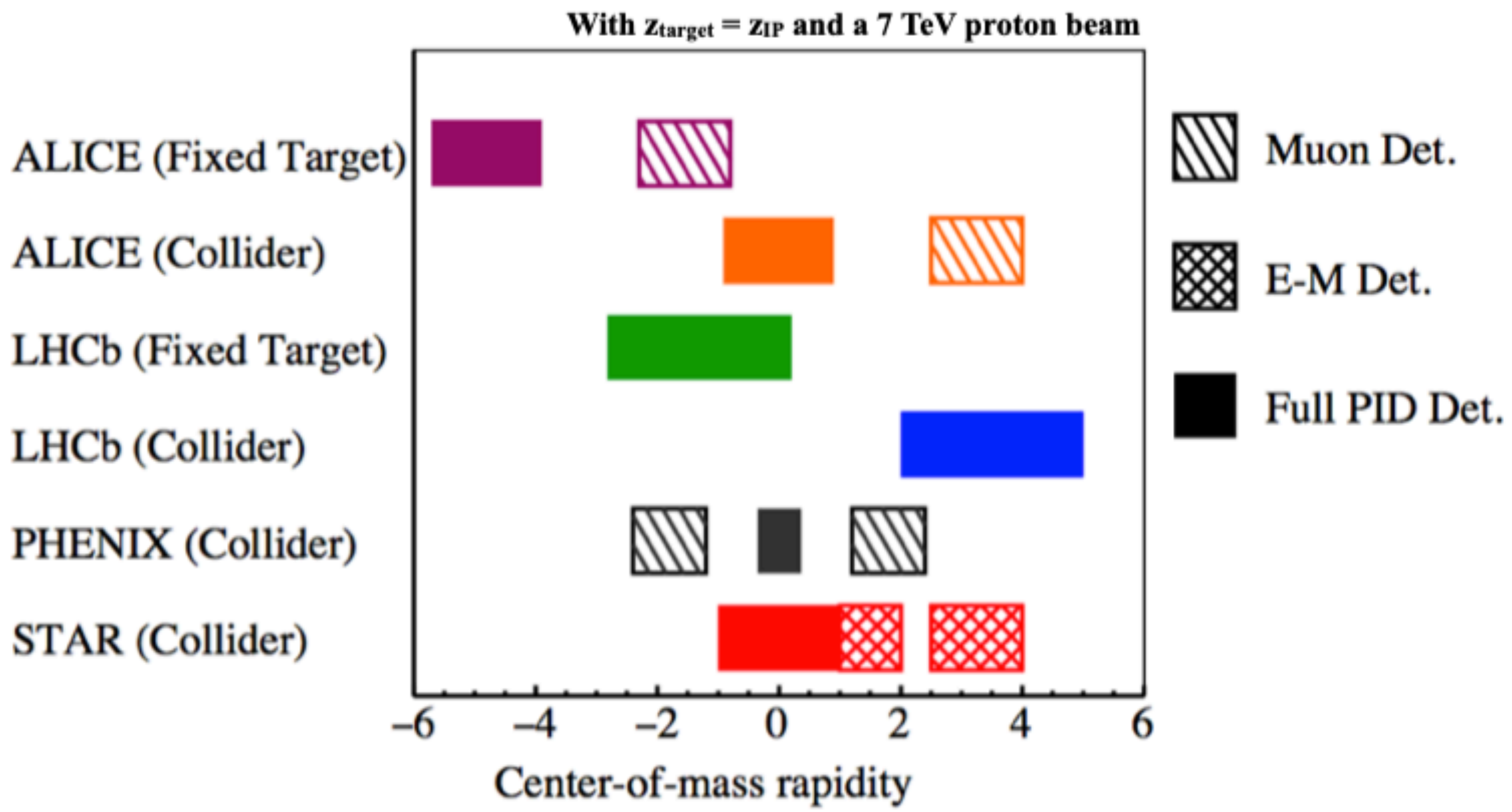
Solid (unpolarised) target

unpolarised gas target

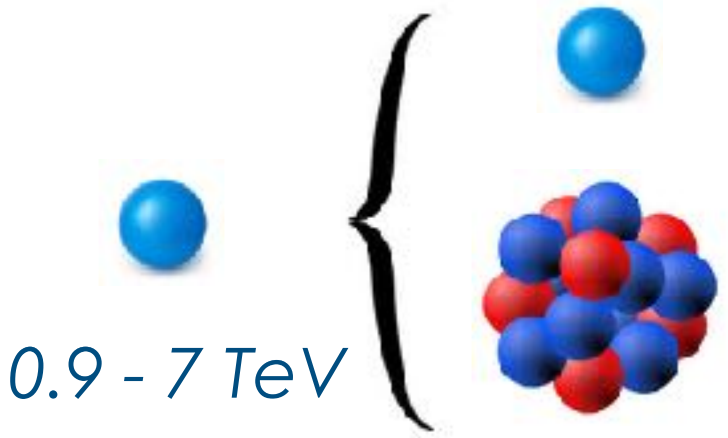
polarised (+unpolarised) gas target

Fundamental contributions to the physics potentialities

Acceptance in center-of-mass rapidity



gaseous targets @ LHCb



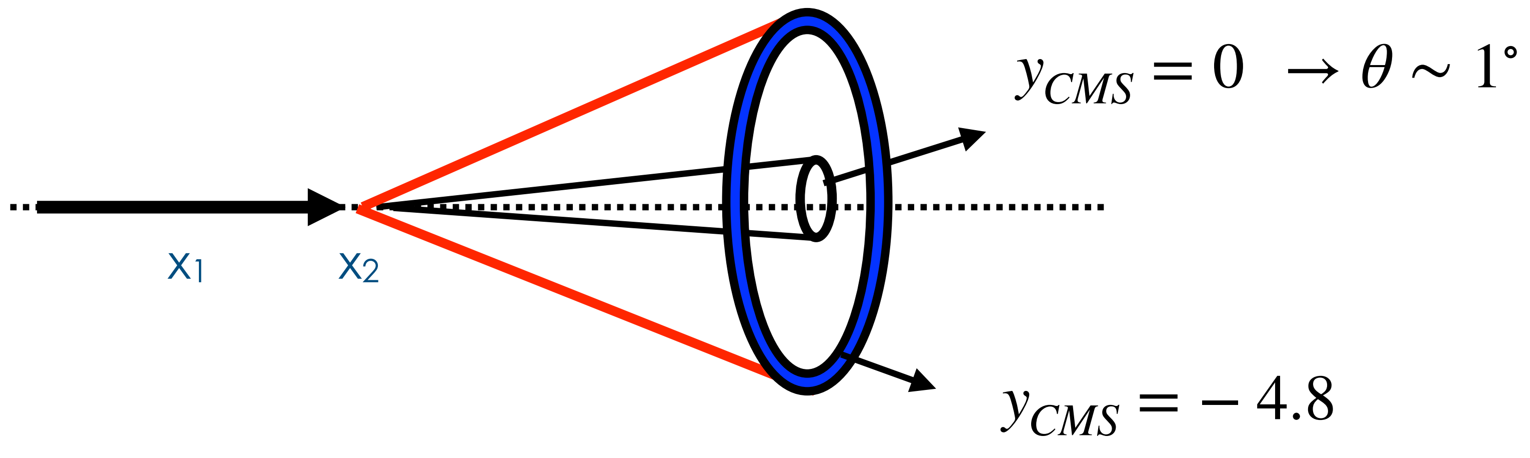
pp or pA collisions: 0.9 - 7 TeV beam on fix target

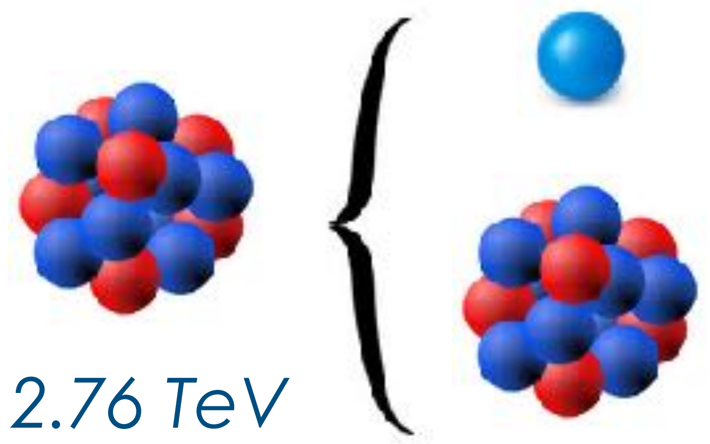
$$\sqrt{s} = \sqrt{2 m_N E_p} \simeq 41 - 115\ GeV$$

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

1: beam; 2: target

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



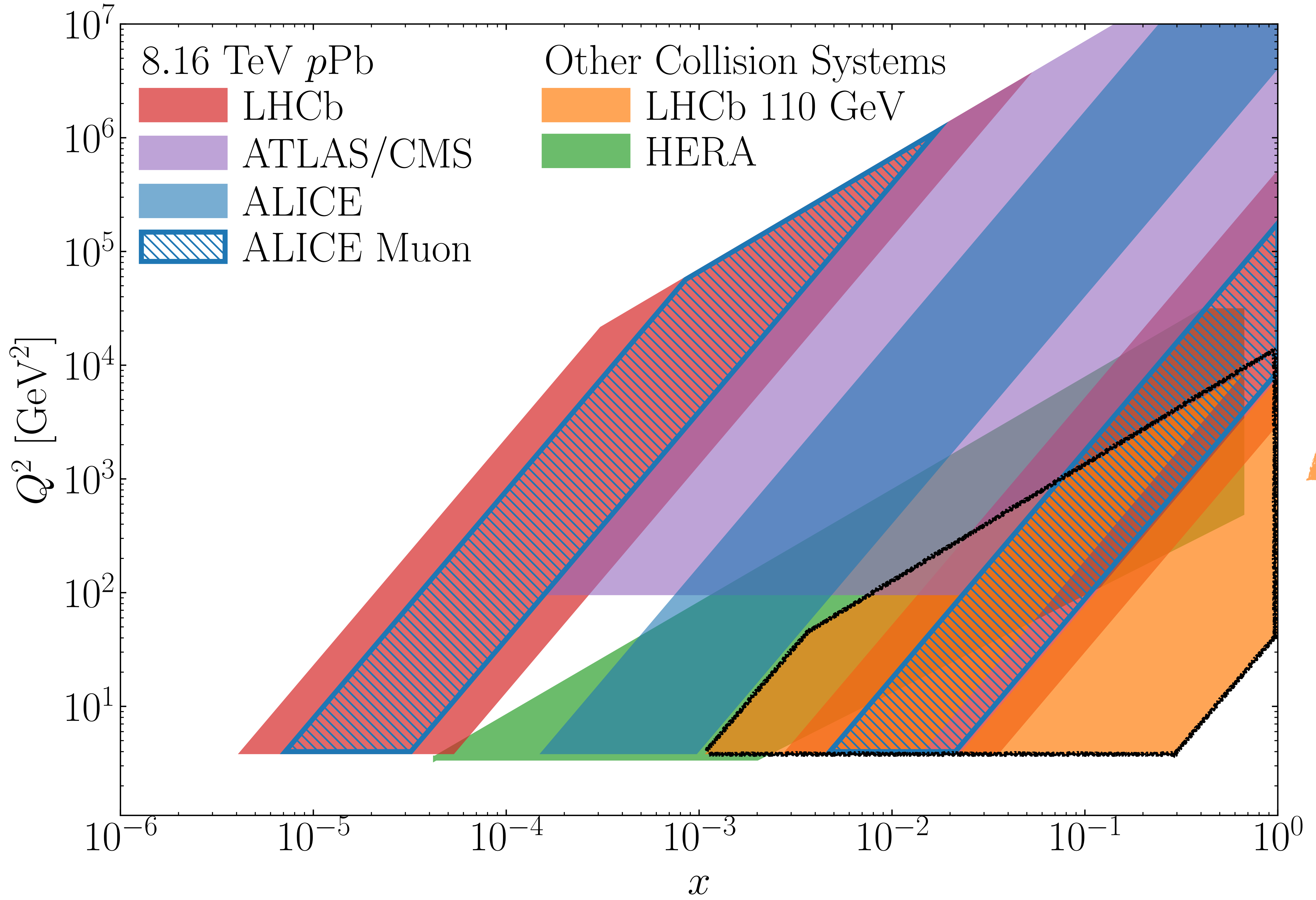


AA collisions: 2.76 TeV beam on fix target

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

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

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



Broad and poorly explored kinematic range

SMOG2 an unpolarised target at LHCb

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

Luminosity

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

areal density

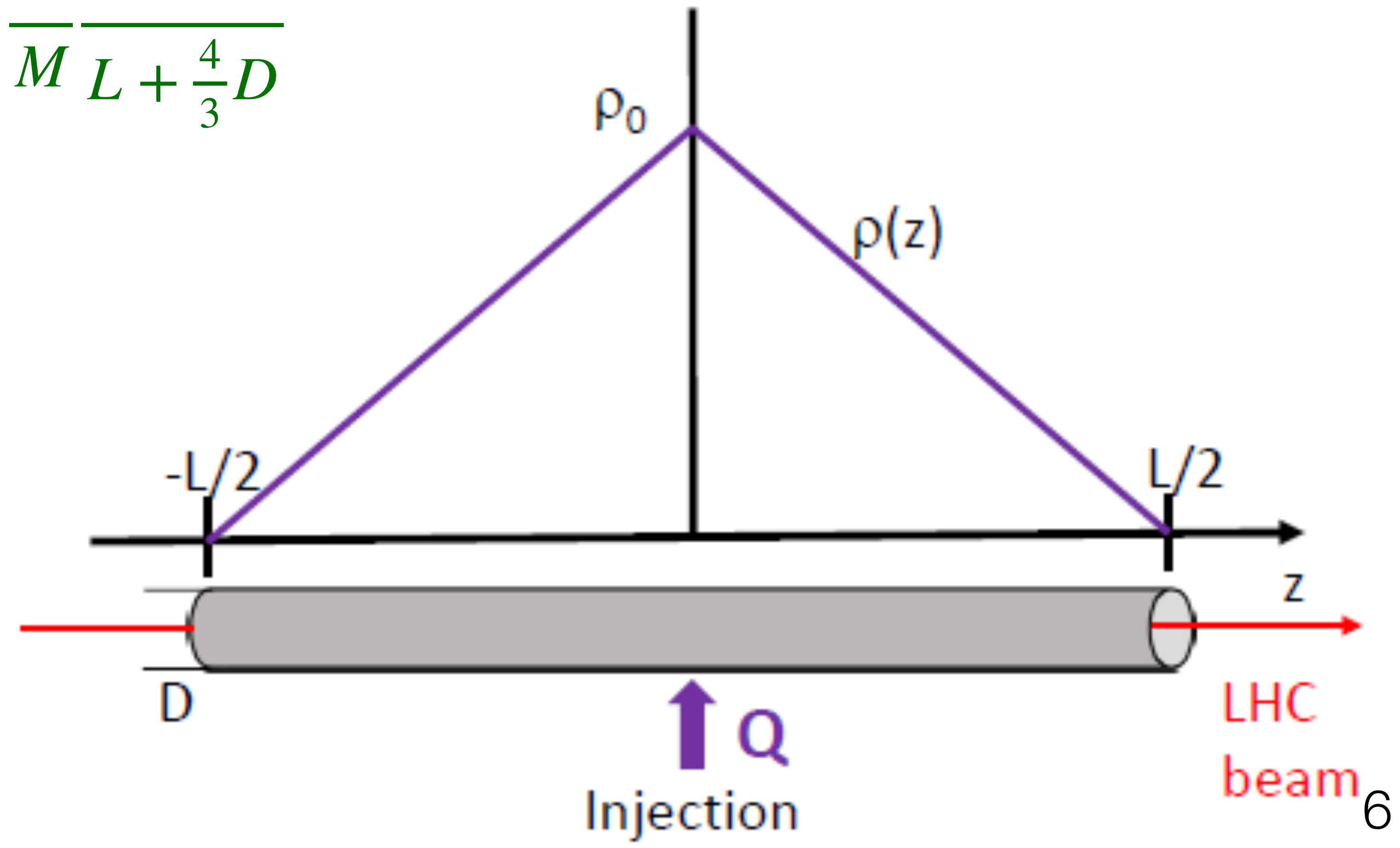
number of particles

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

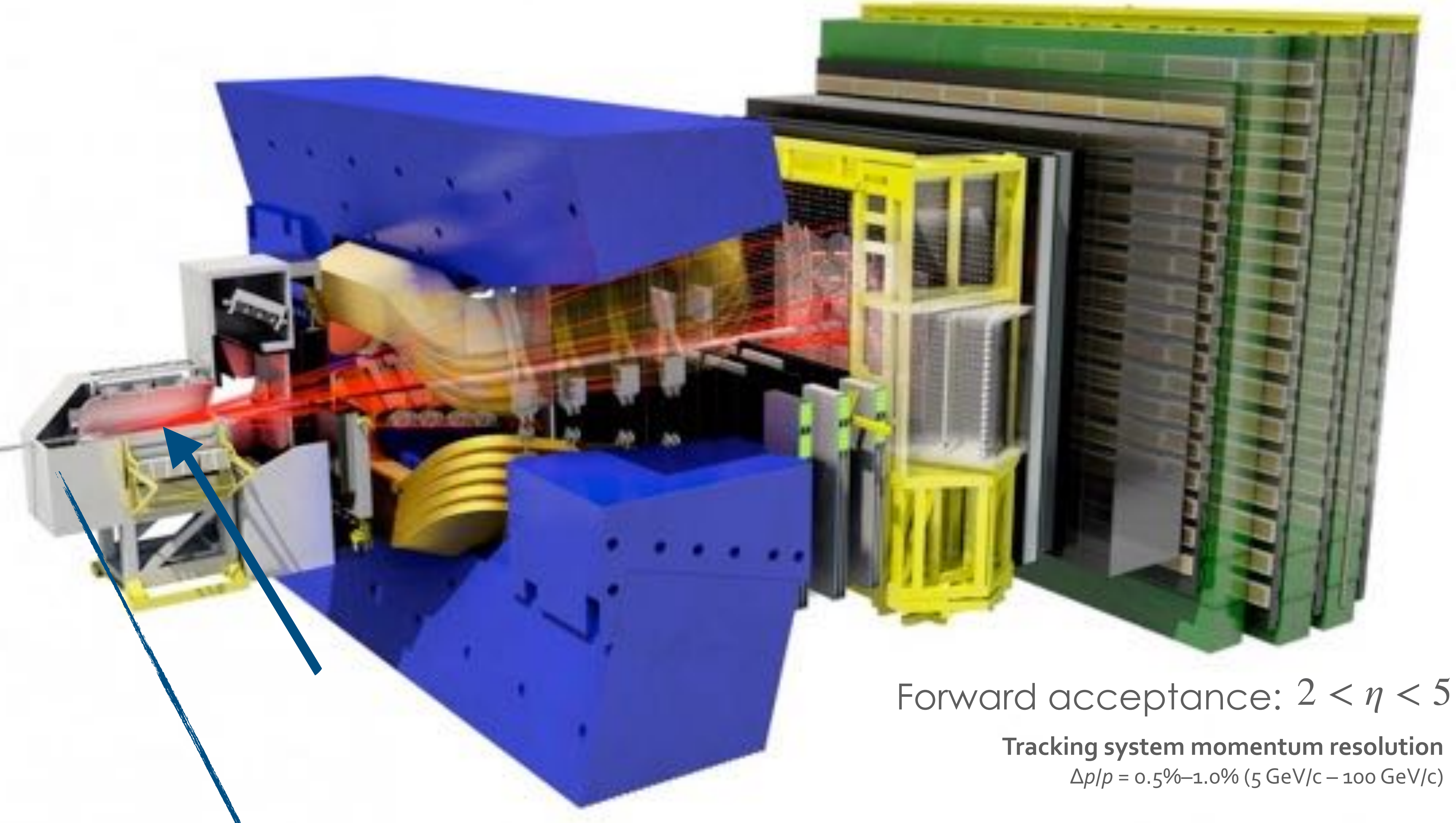
$$\rho_0 \frac{L}{2} = \frac{\Phi}{C}\frac{L}{2}$$

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

Storage cell concept



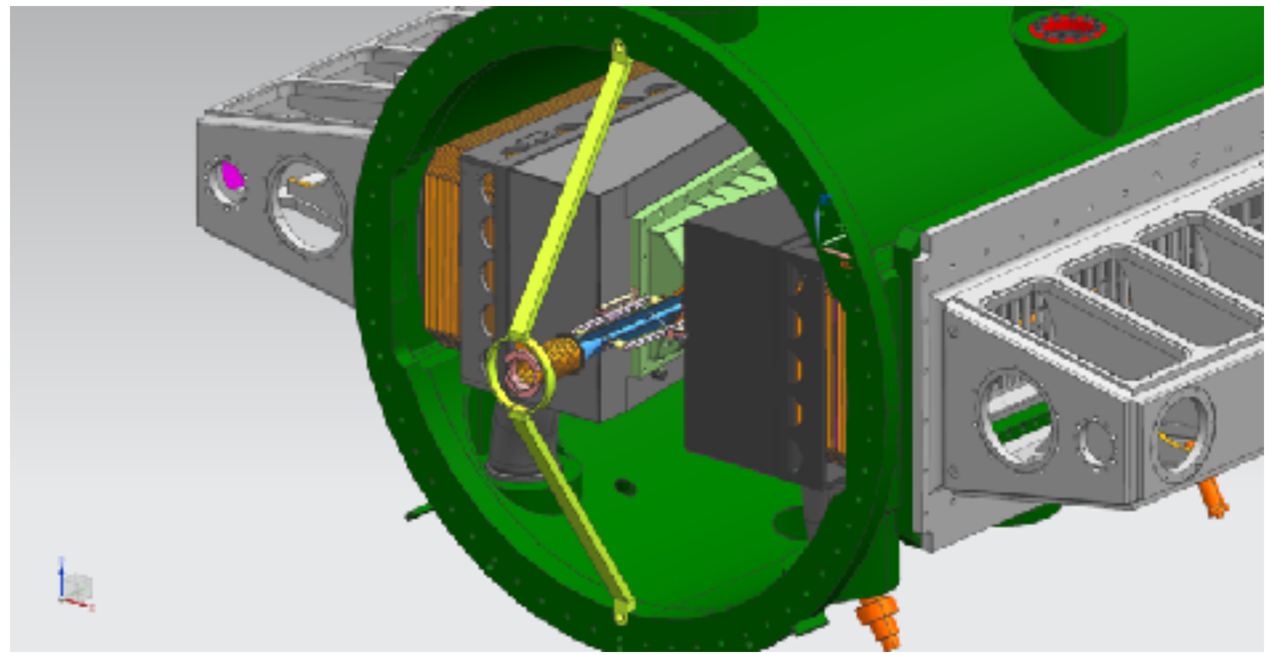
LHC beam



Forward acceptance: $2 < \eta < 5$

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

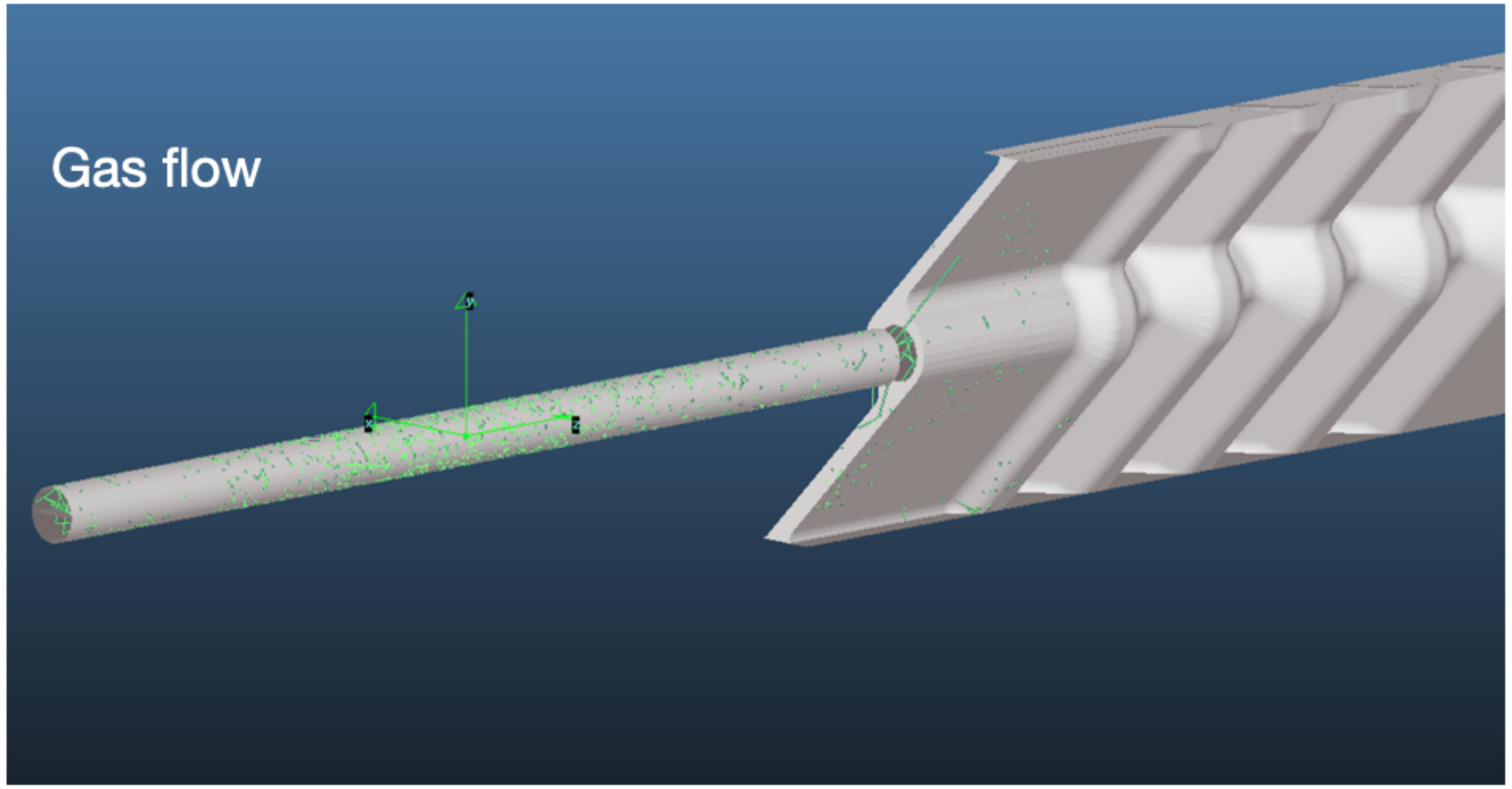
beam-beam collisions

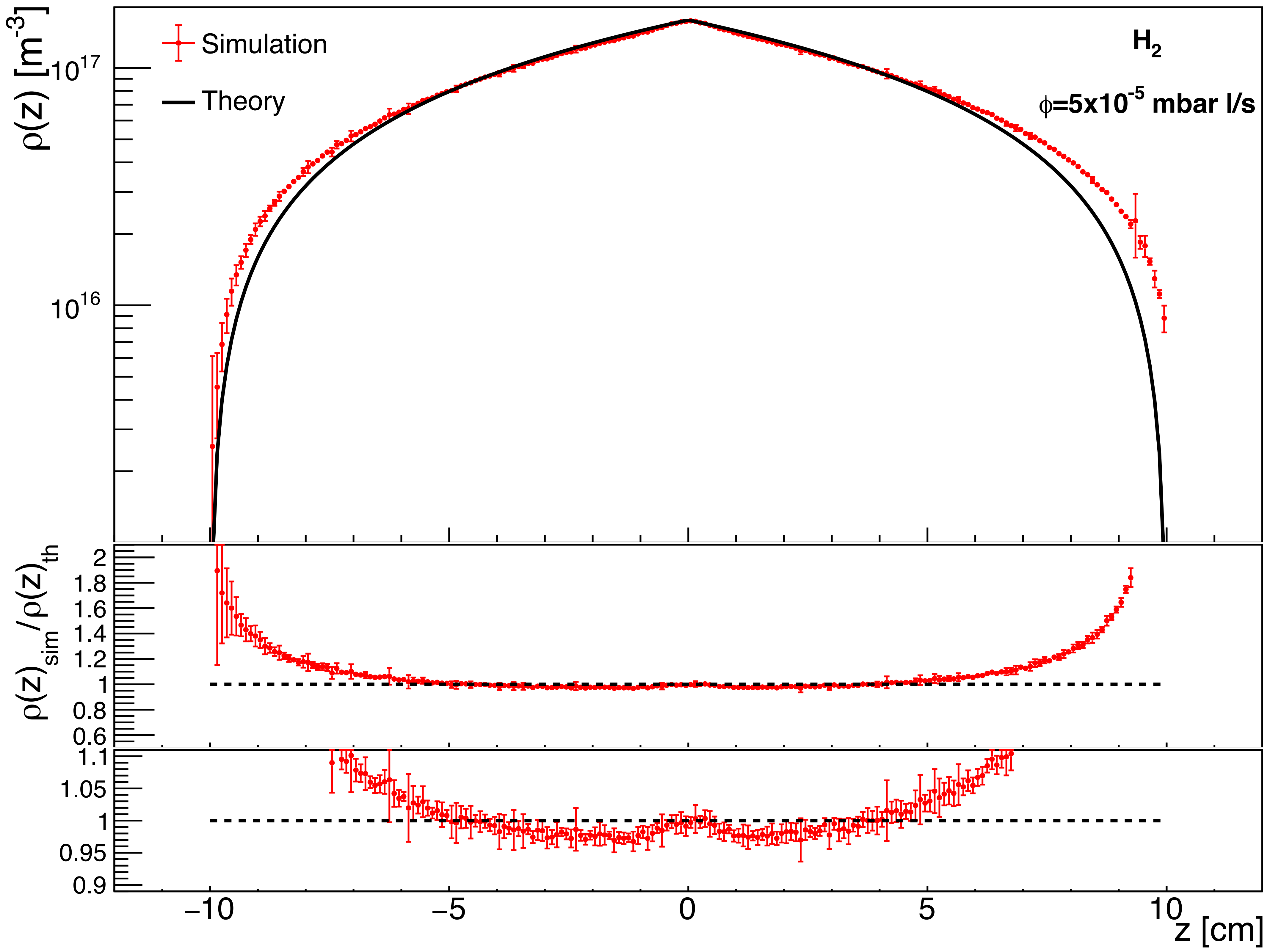


UNpolarised target (beam-gas)

The storage cell advantage

[SMOG2 TDR]





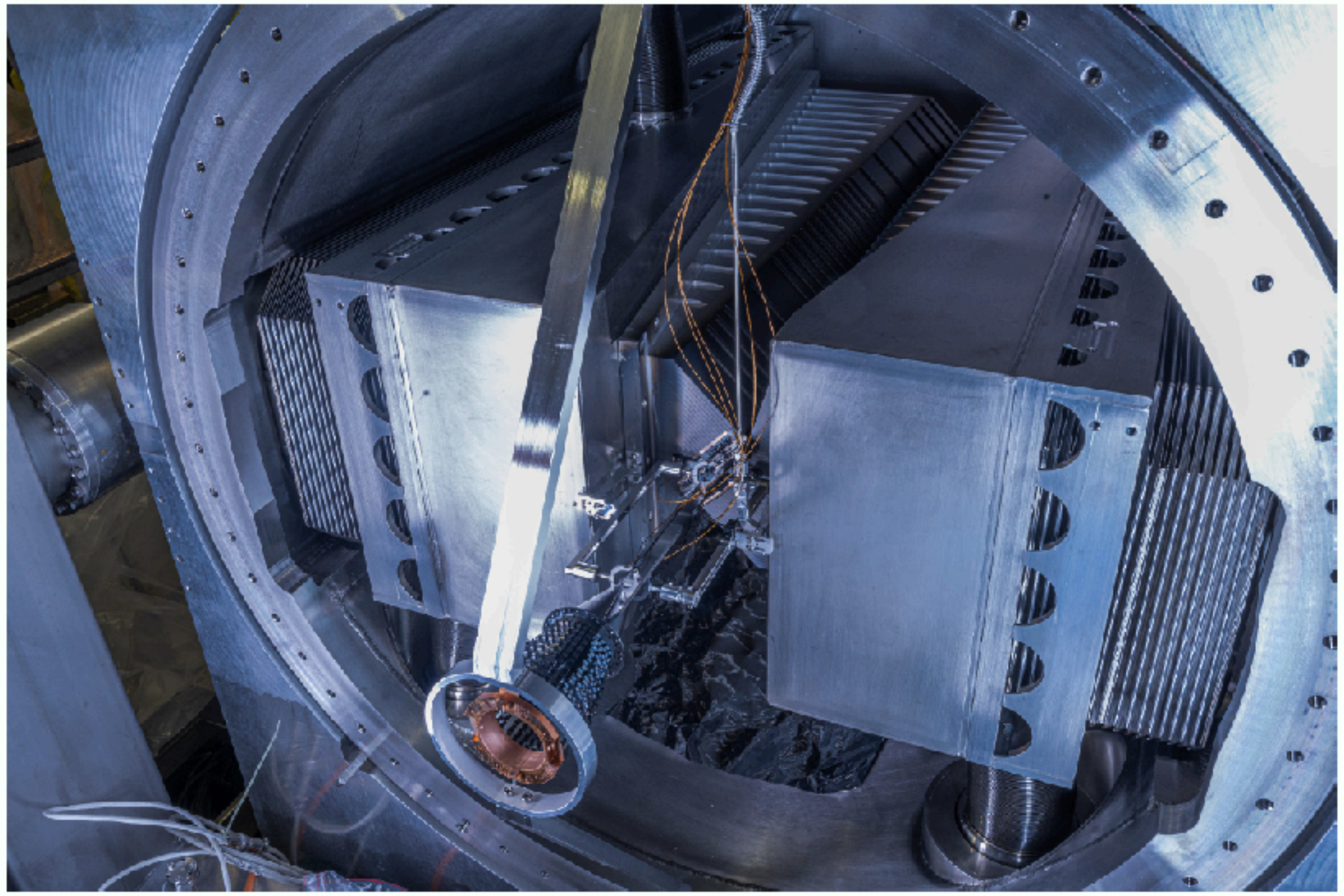
SMOG2 example pAr @115 GeV in 1yr of data taking

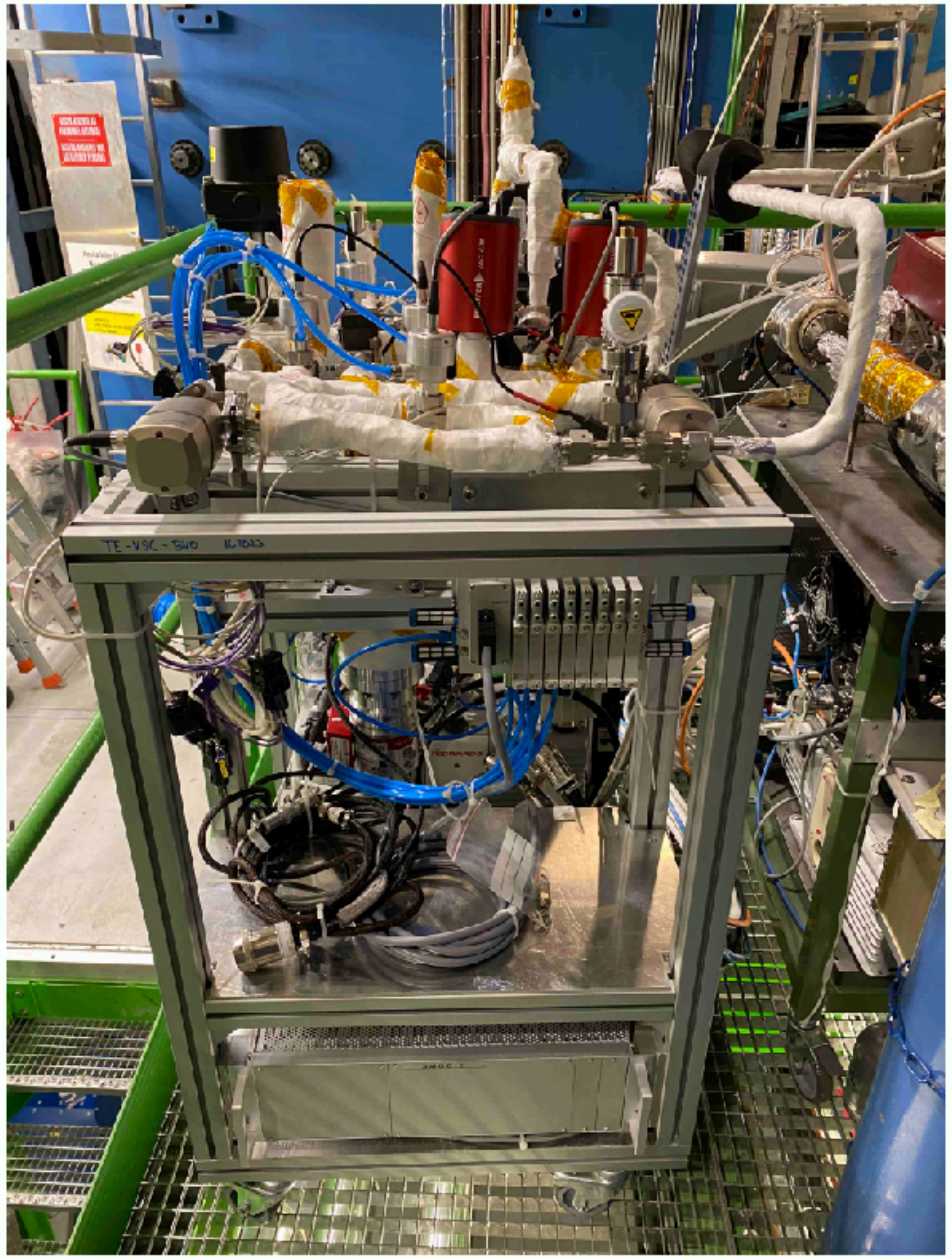
Int. Lumi.		80/pb
Sys.error of J/Ψ xsection		~3%
J/Ψ	yield	28 M
D^0	yield	280 M
Λ_c	yield	2.8 M
Ψ'	yield	280 k
$\Upsilon(1S)$	yield	24 k
$DY\ \mu^+\mu^-$	yield	24 k

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

Very high statistics with a low gas flow

A unique project itself and a great playground for LHCspin





- 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: He, Ne, Ar … H_2, D_2, N_2, O_2, Kr, Xe

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

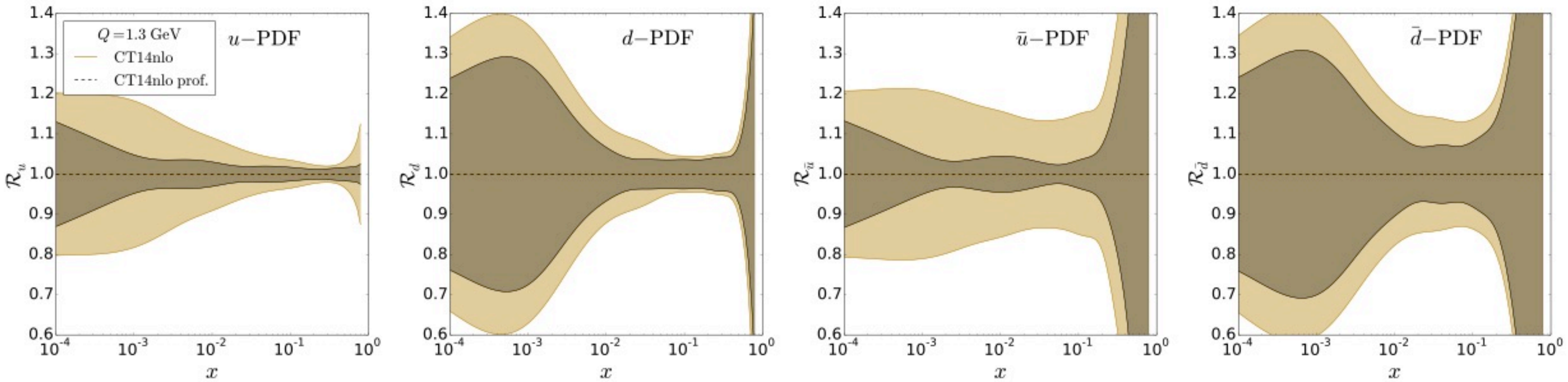
SMOG2 ... few highlights

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

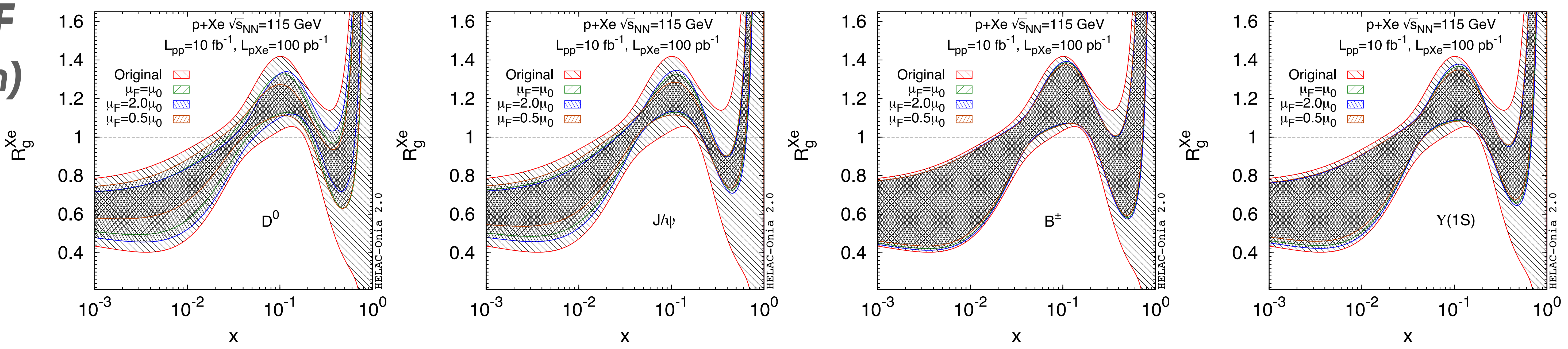
PDF

estimation with 10 fb^{-1}

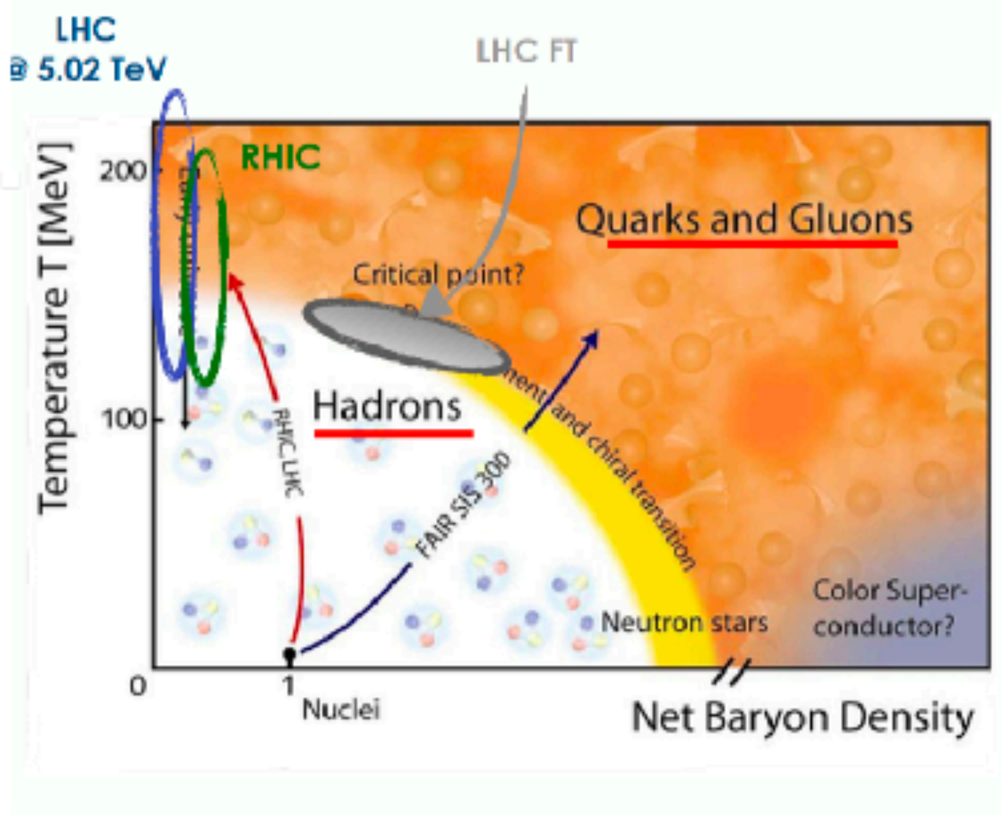
arXiv:1807.00603

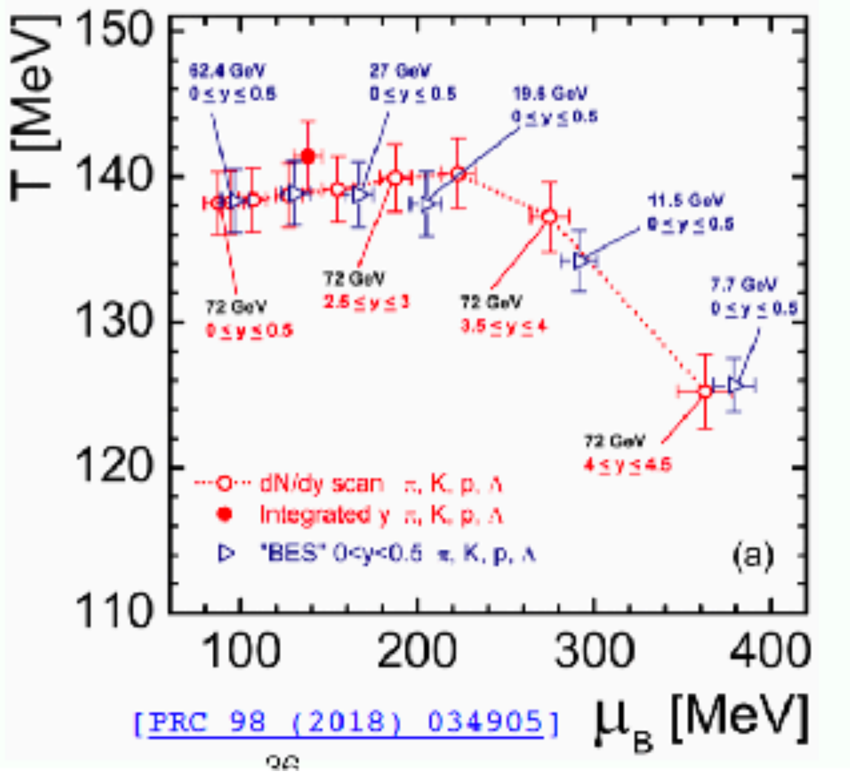


nPDF (gluon)

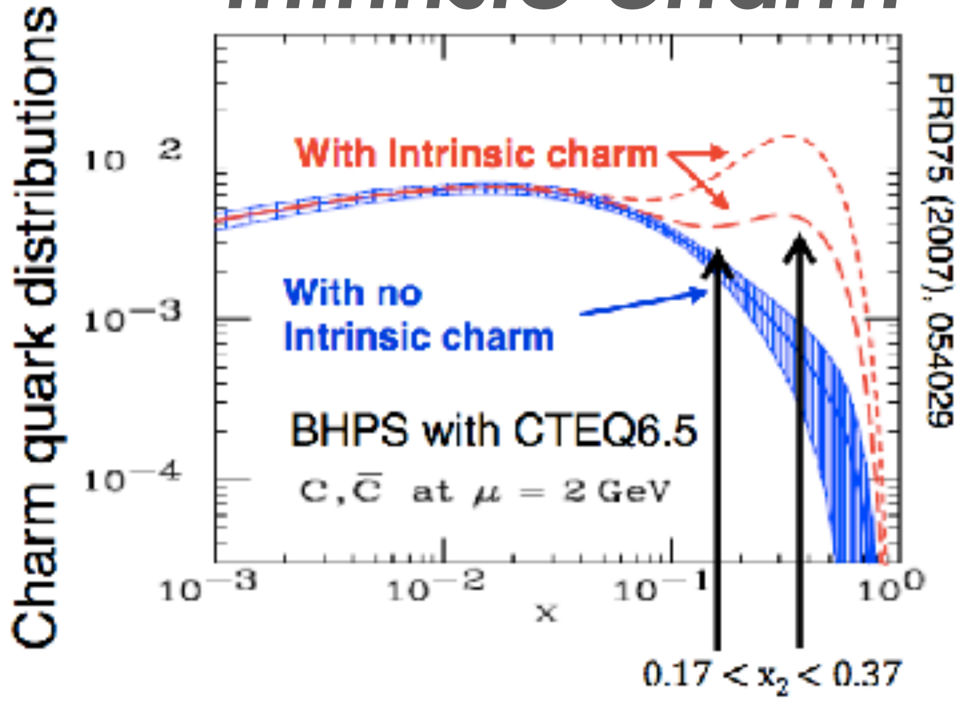


Heavy-Ion and QCD phase space



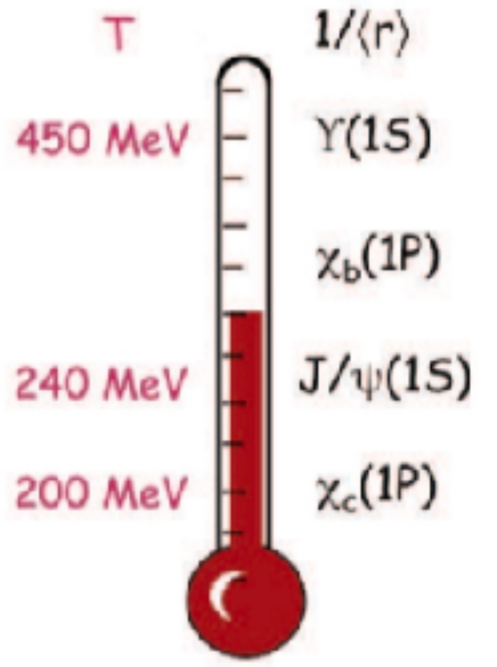


Intrinsic charm

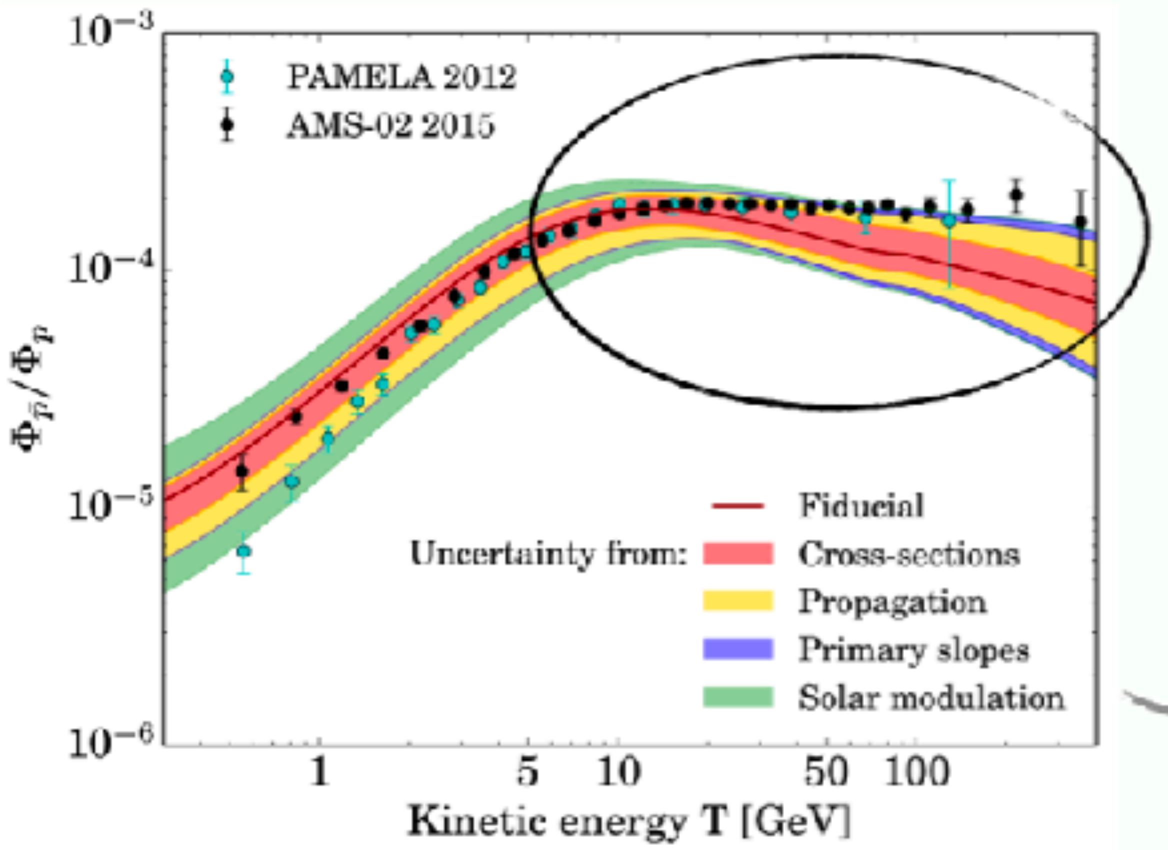


Astroparticle (DM and CR)

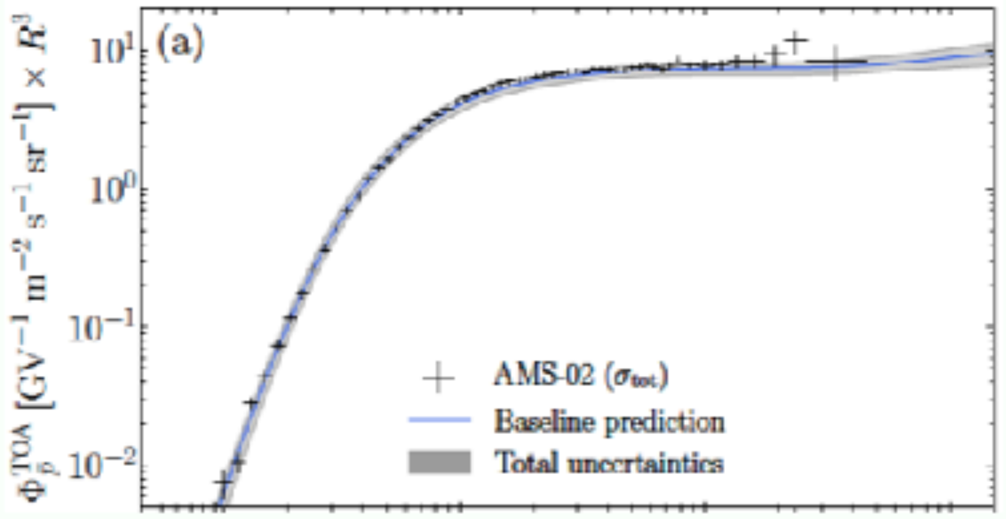
$c\bar{c}$ bound states



[JCAP09 (2015) 023]



[ArXiv:1906.07119]



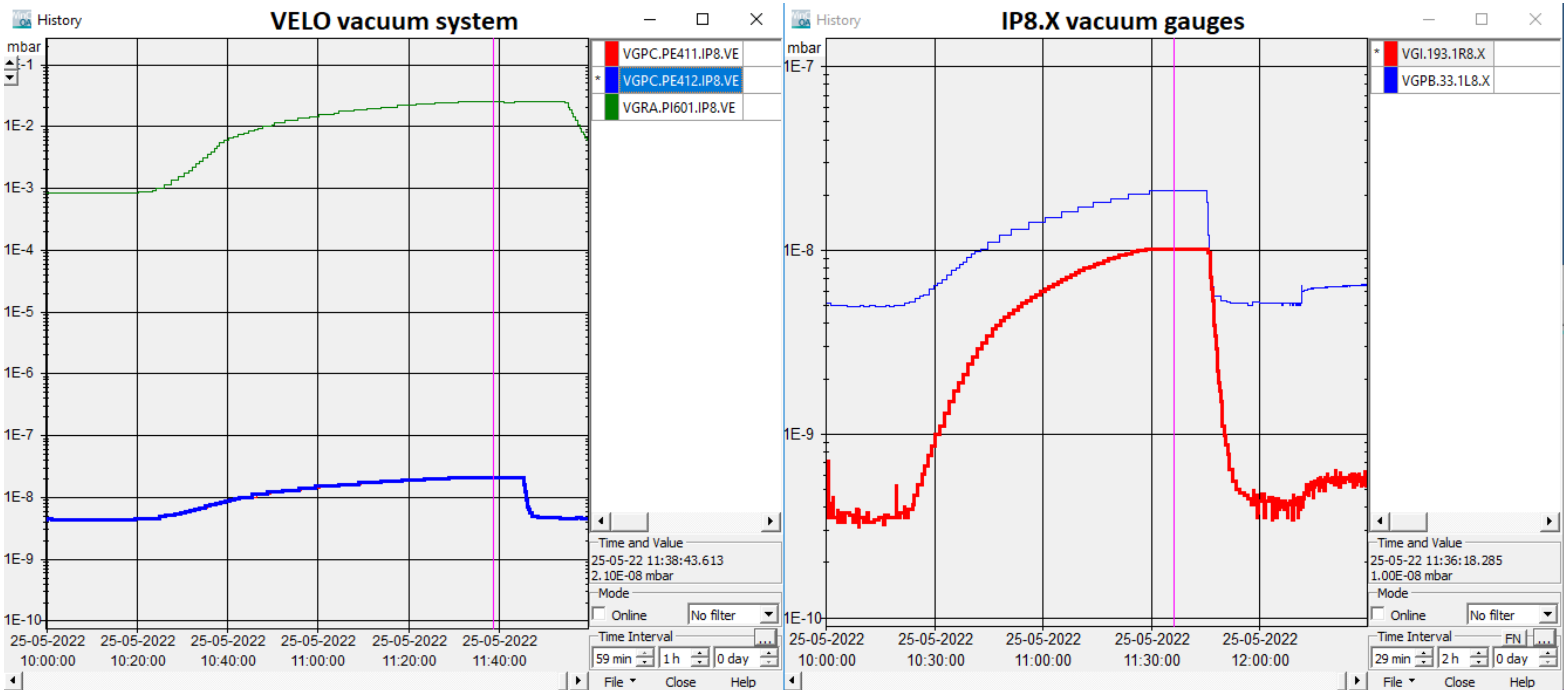
- Main uncertainty still due to cross sections!

Special Runs

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

Bonus slide

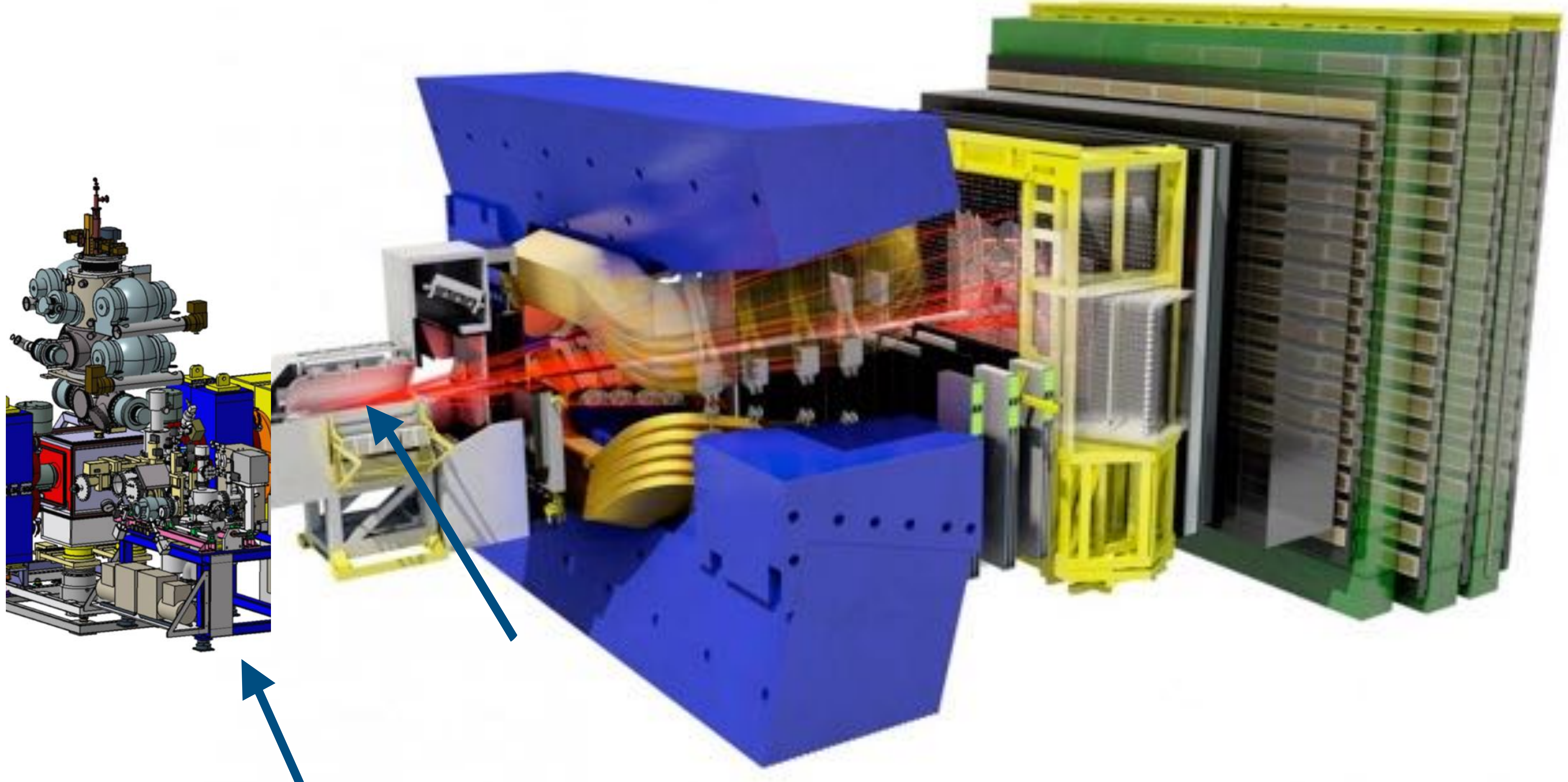
On Wednesday 26th (2 days ago), first injection of SMOG2 into LHC (Ne at ~10^{-7} mbar)



Everything worked fine: no substantial change in the LHC vacuum, vacuum recovery ~30’

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

a polarised target at LHCb



LHC beam

The LHC beams cannot be polarised

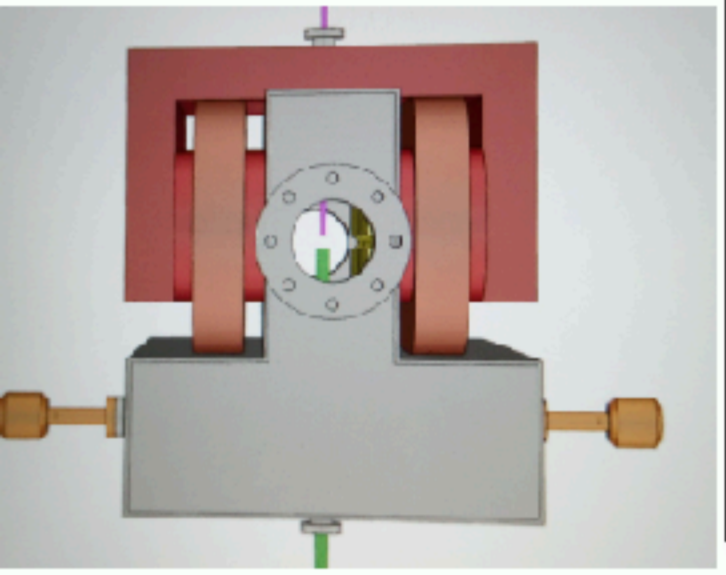
polarised target (beam-gas)

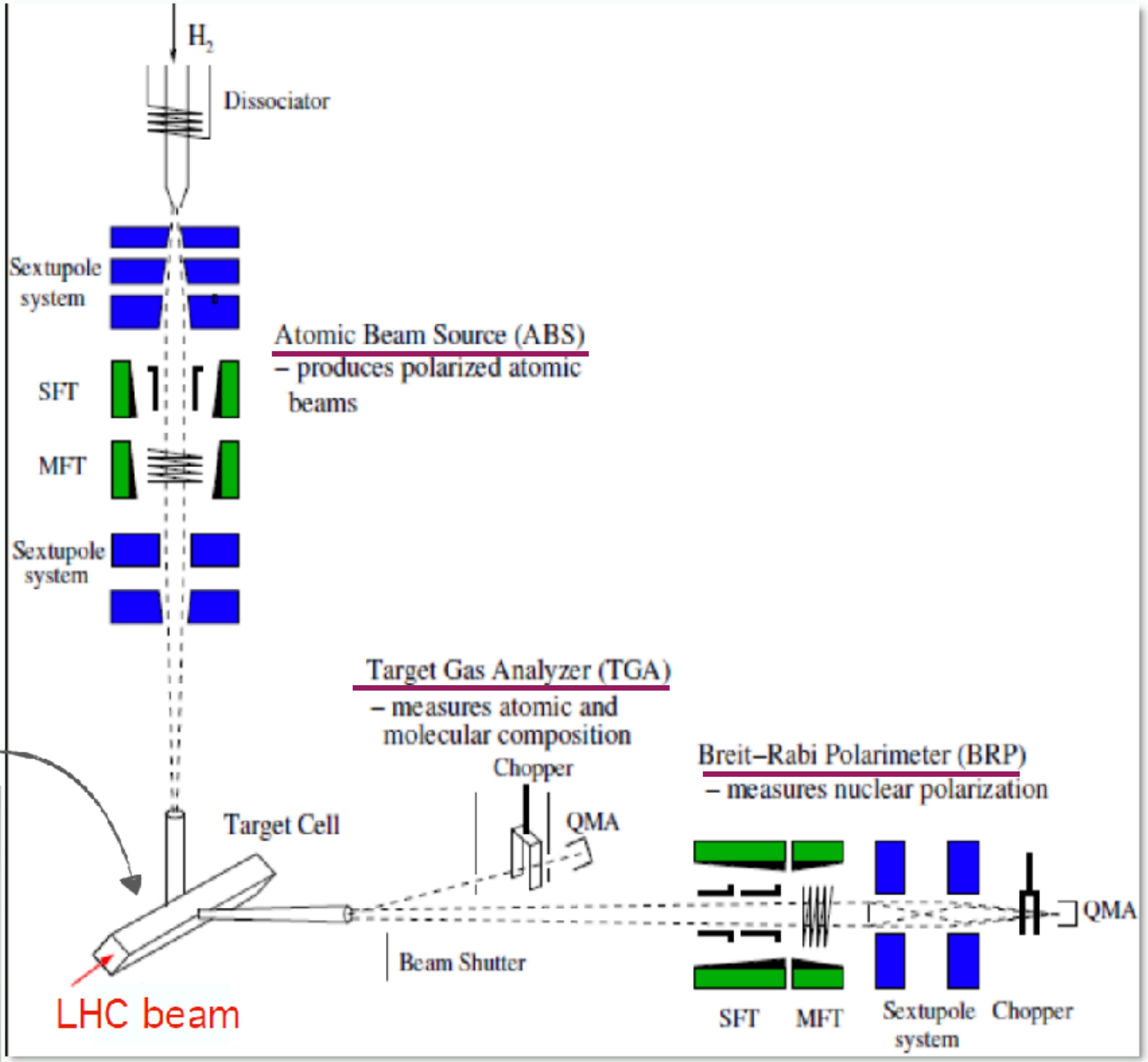
beam-beam collisions

LHCspin experimental setup

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

dipole

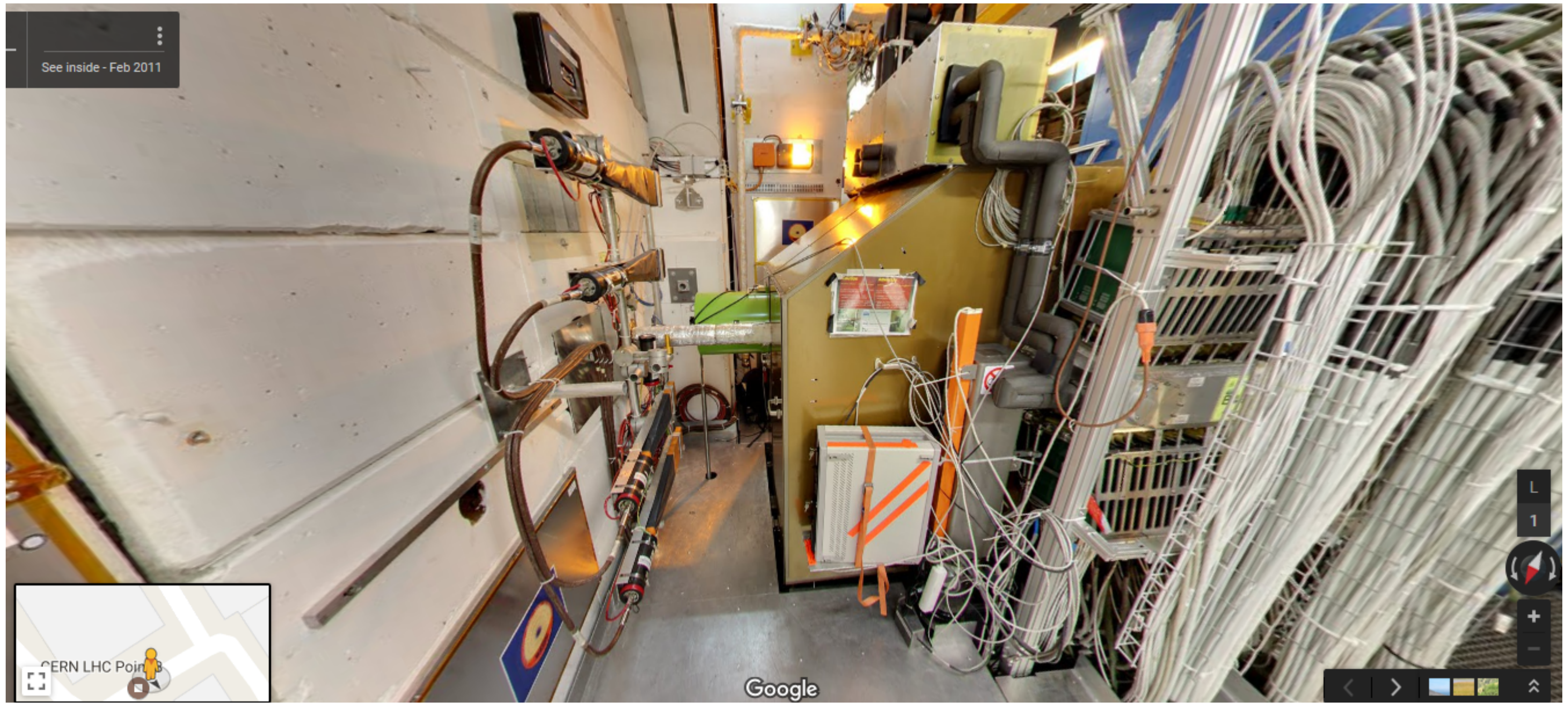




[NIMA 540 (2005) 68-101]

HERMES PGT

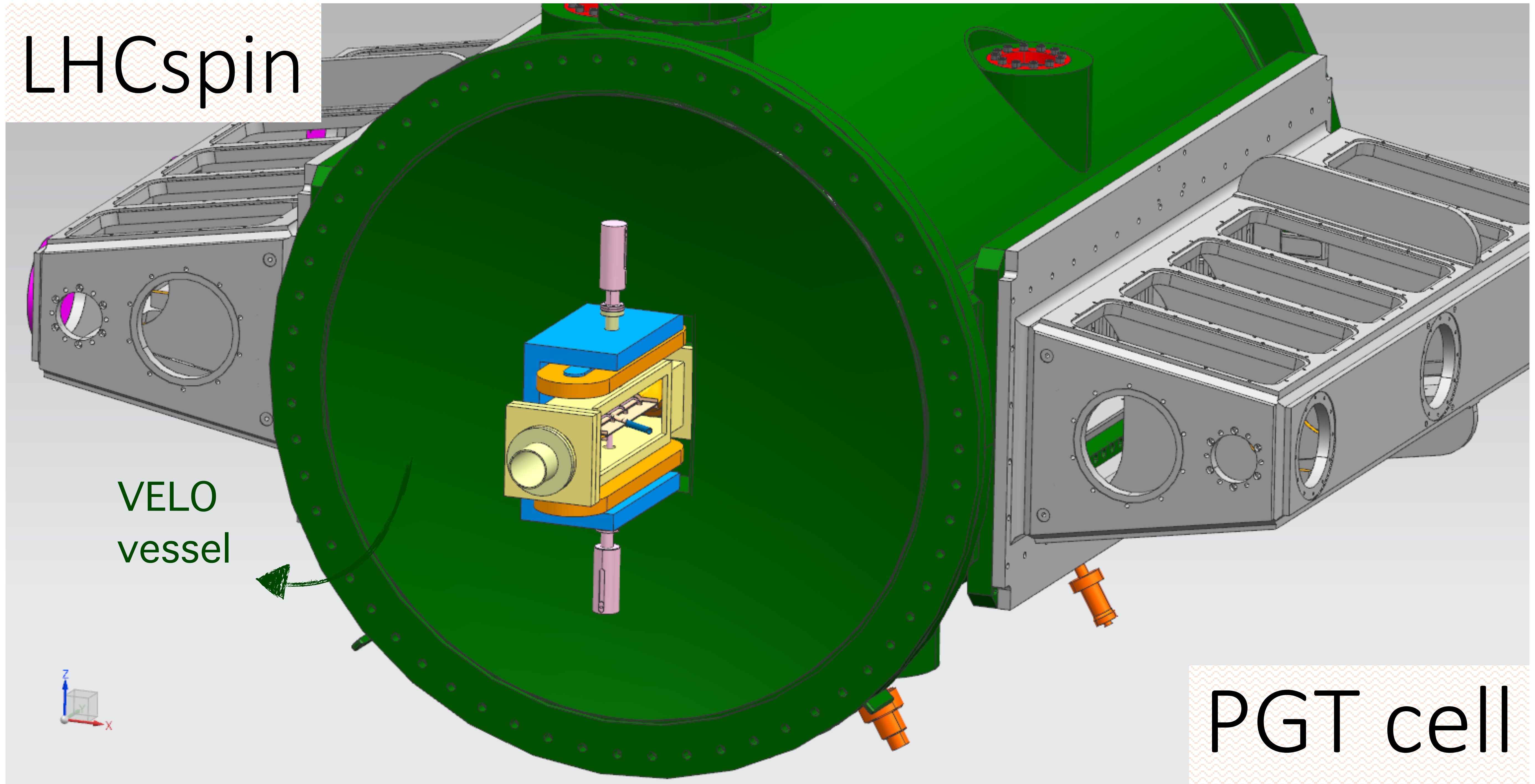
From here to here

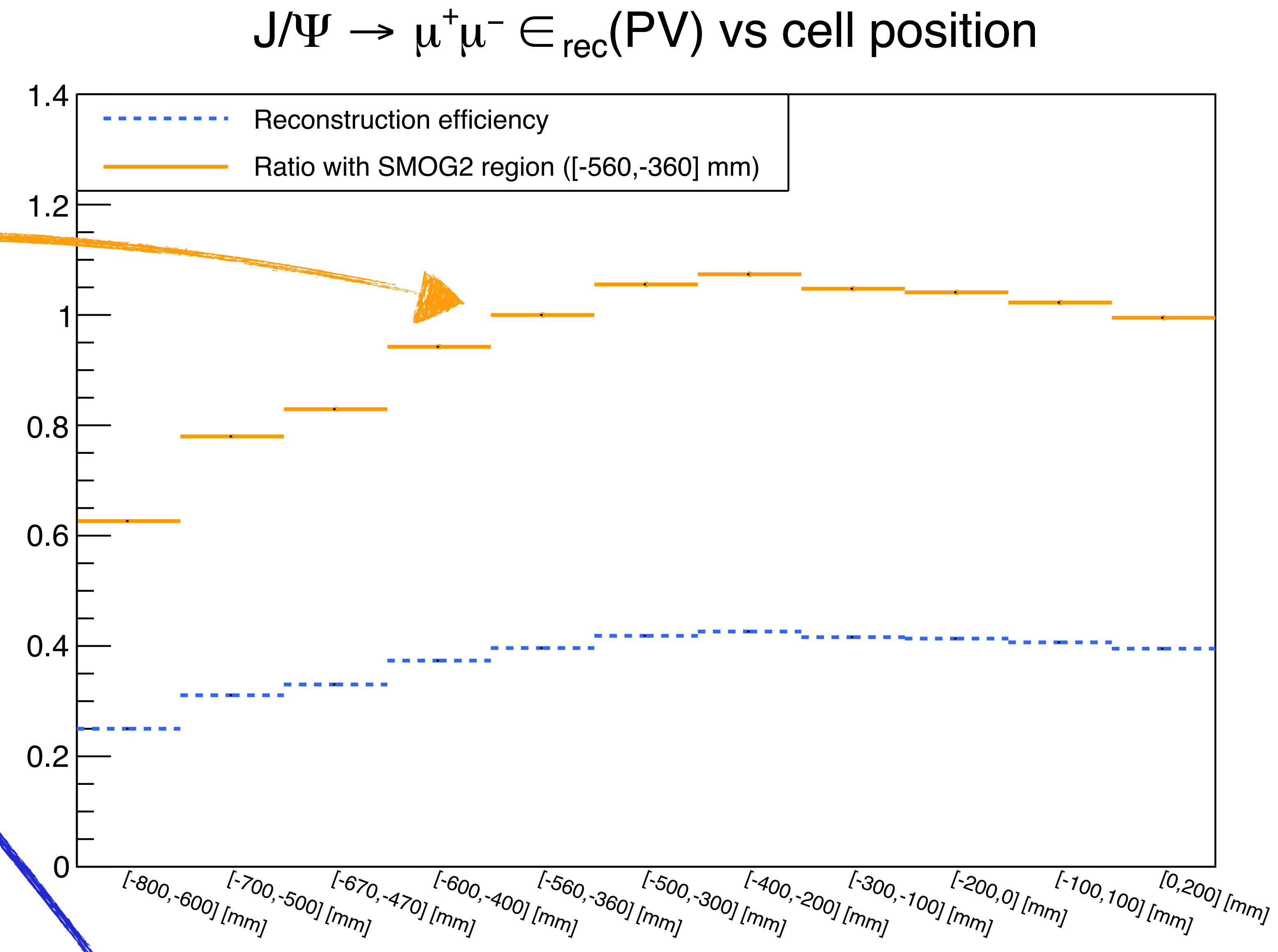


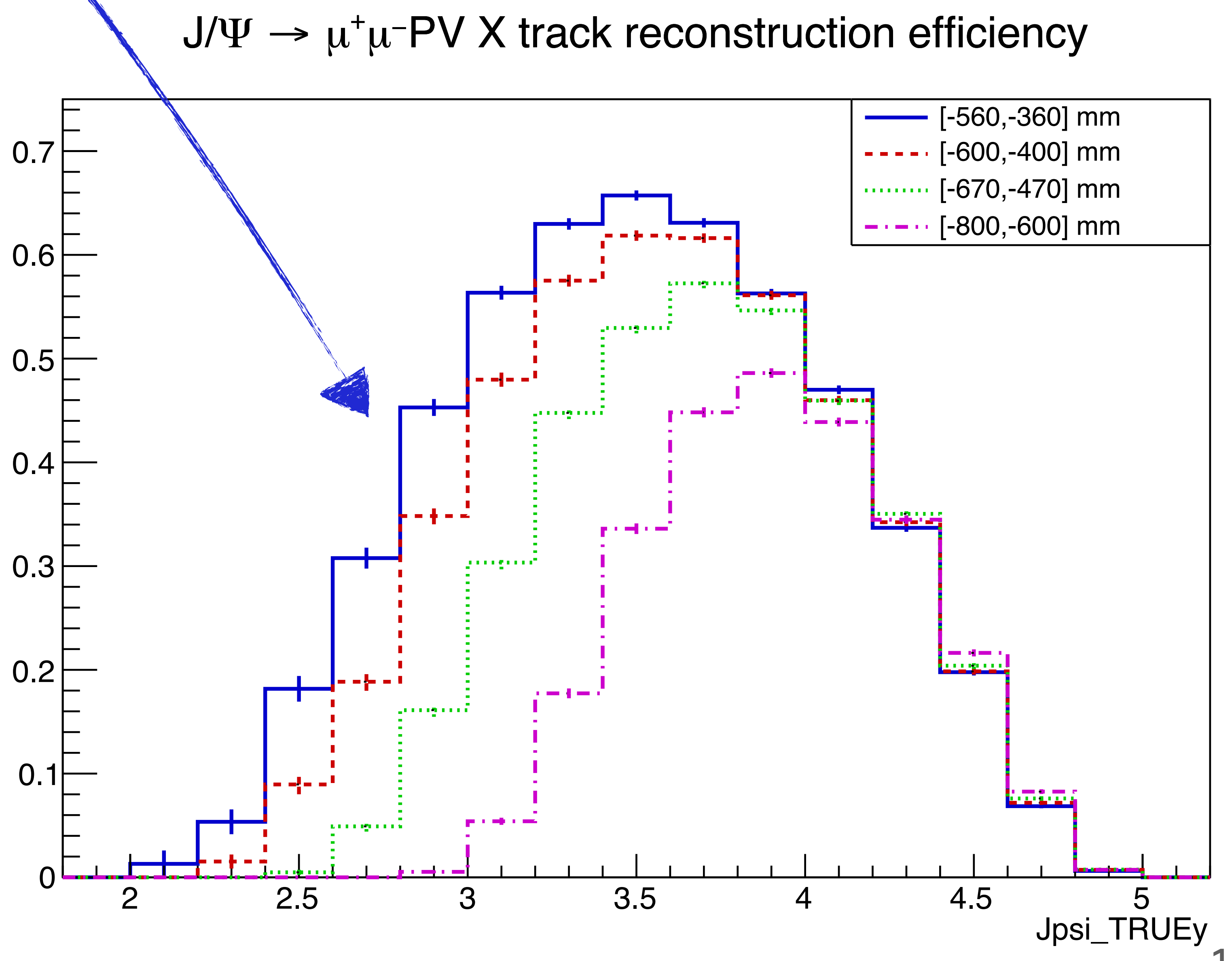
Space available in front of LHCb

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

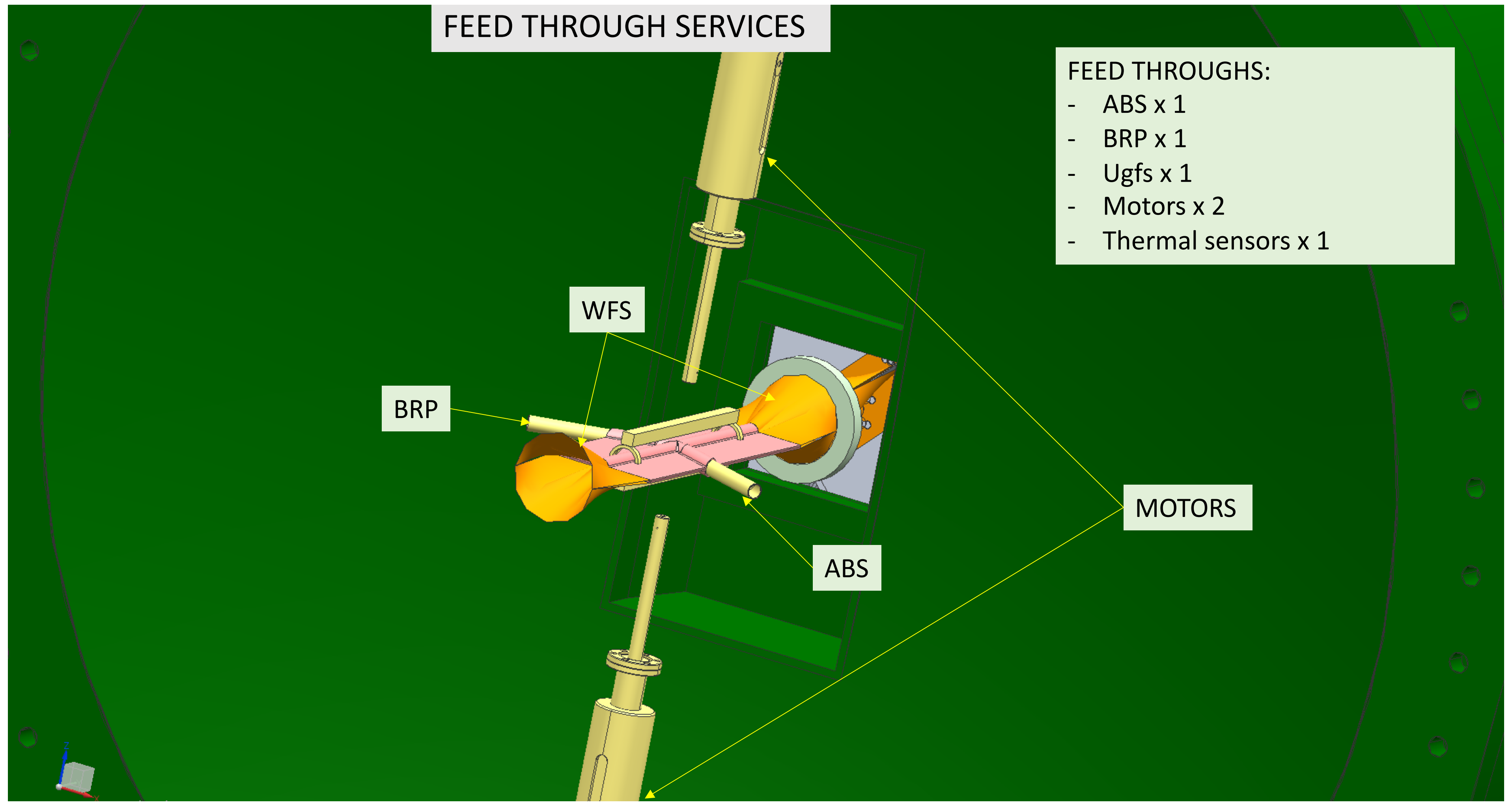


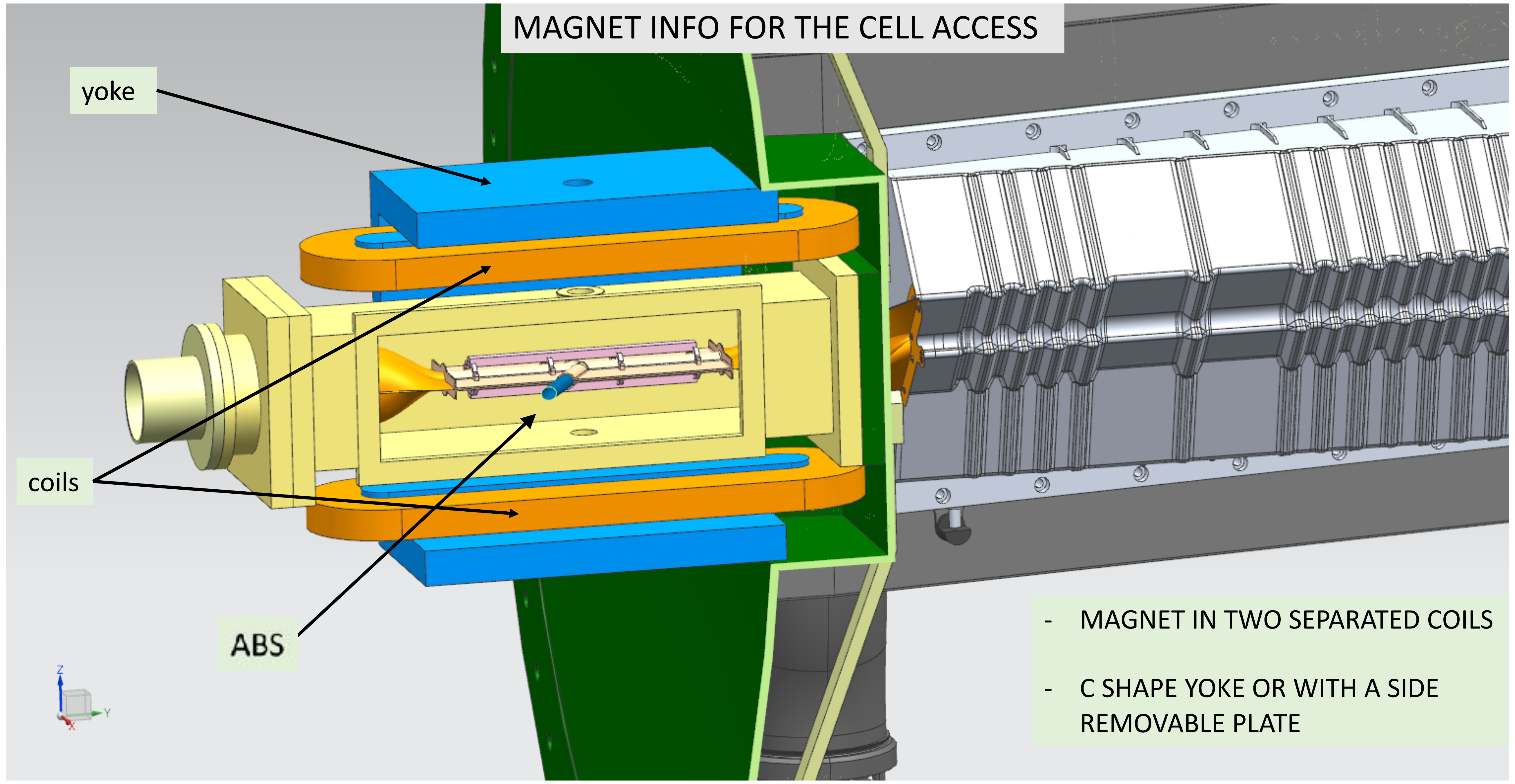




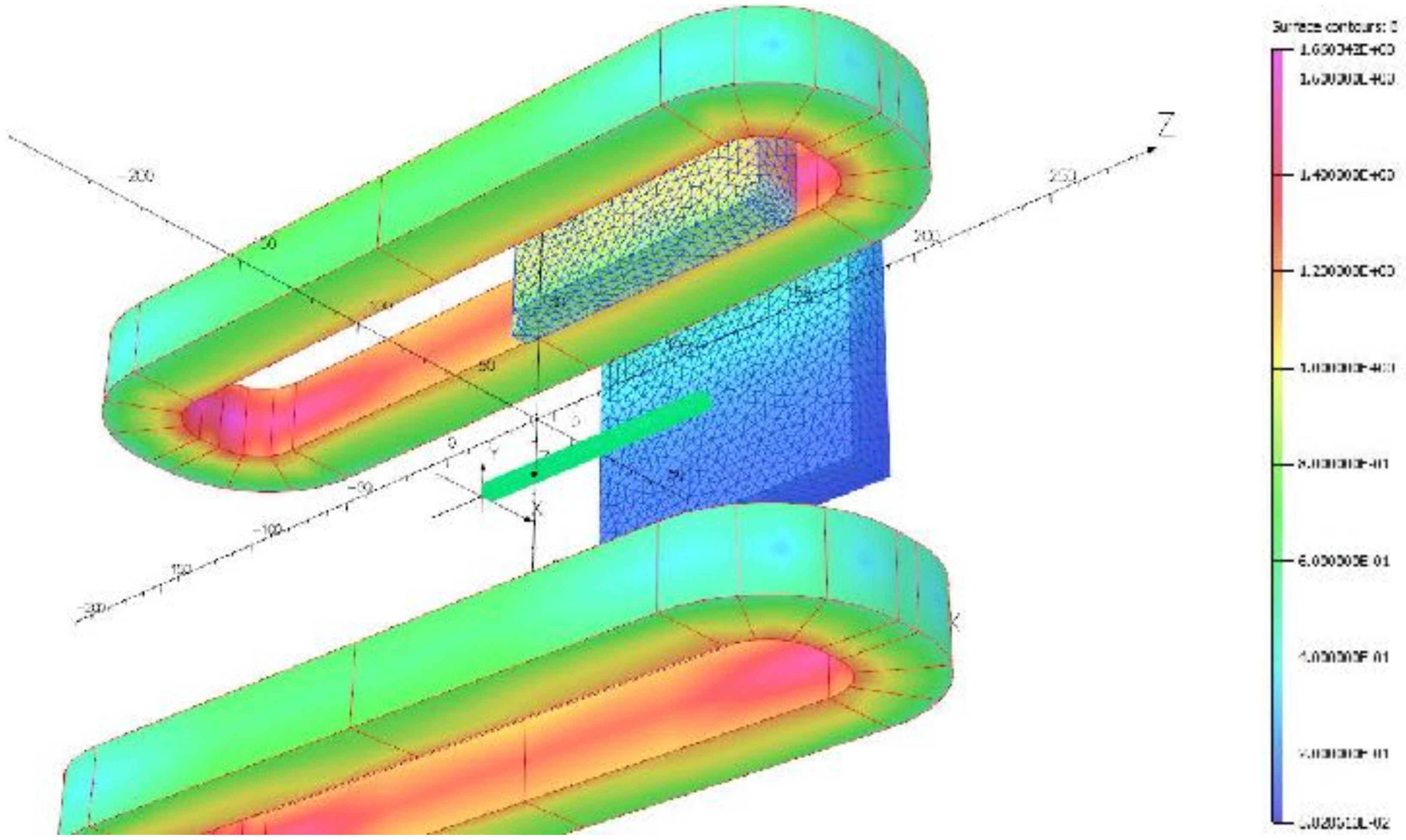
PGT implementation into LHCb

- Inject both polarised and unpolarised gases via ABS and UGFS



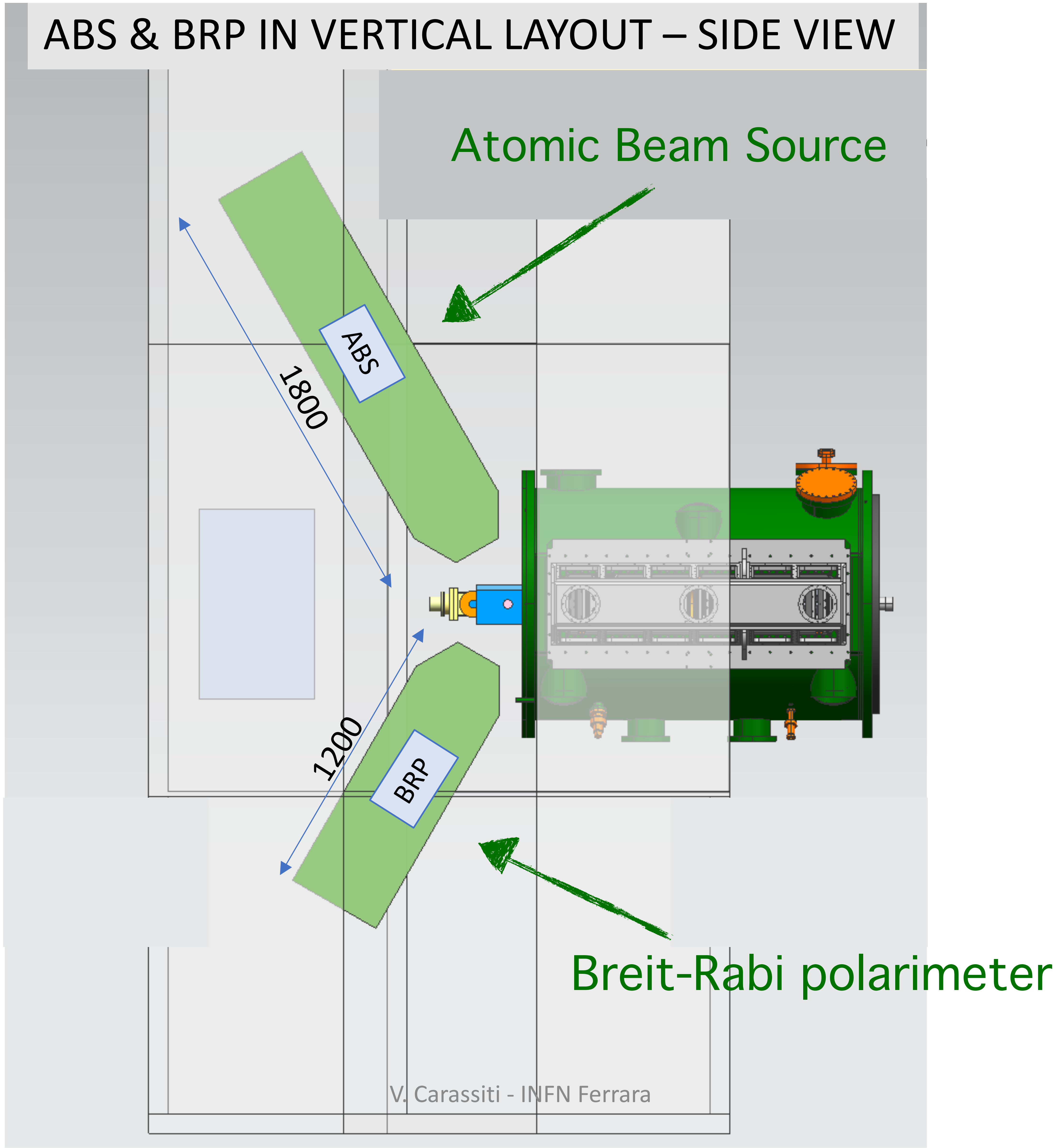


- Compact dipole magnet → static transverse field
- Superconductive coils + iron yoke configuration fits the space constraints
- $B = 300$ mT with polarity inversion, $\Delta B/B \simeq 10\,\%$, suitable to avoid beam-induced depolarisation [PoS (SPIN2018)]



Possibility to switch to a solenoid and provide longitudinal polarisation (e.g. in 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:
$\phi = 6.5 \times 10^{16}\ \mathrm{s}^{-1}$

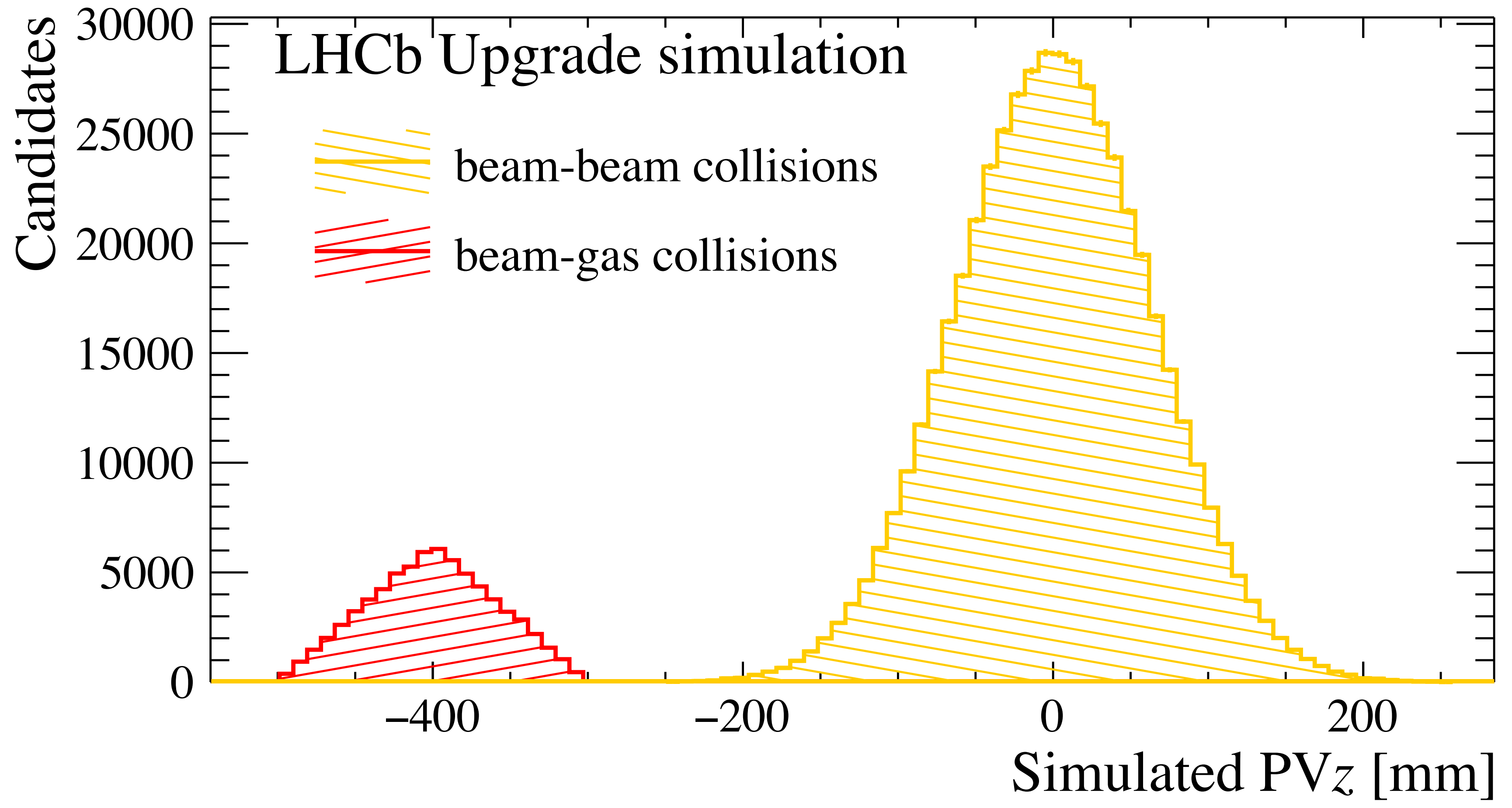
Achievable Luminosity (HL-LHC):
$\sim 8 \times 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

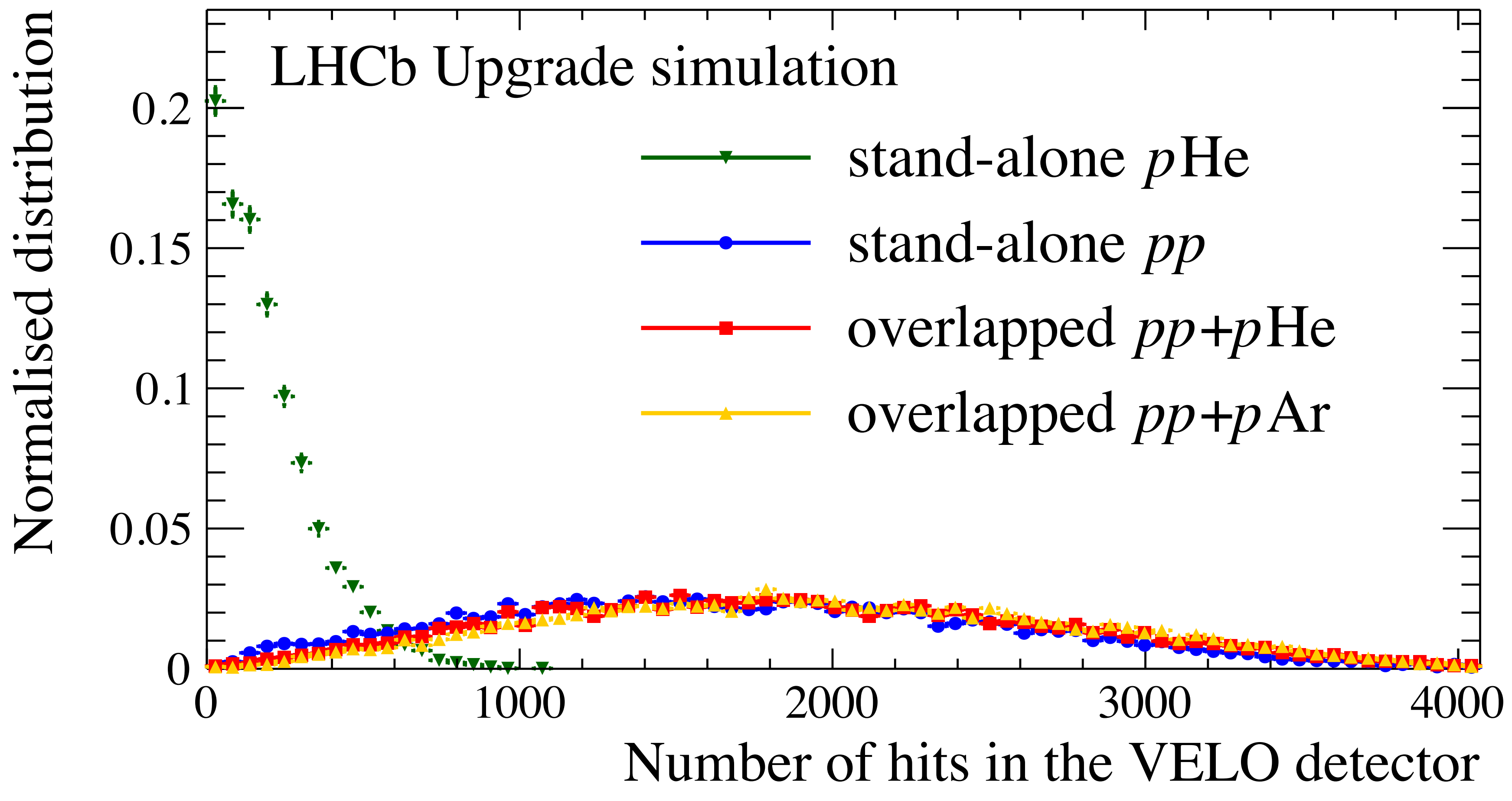
- Backup solution is being investigated: a jet target provides lower density but higher polarisation degree

SMOG2/LHCspin performances

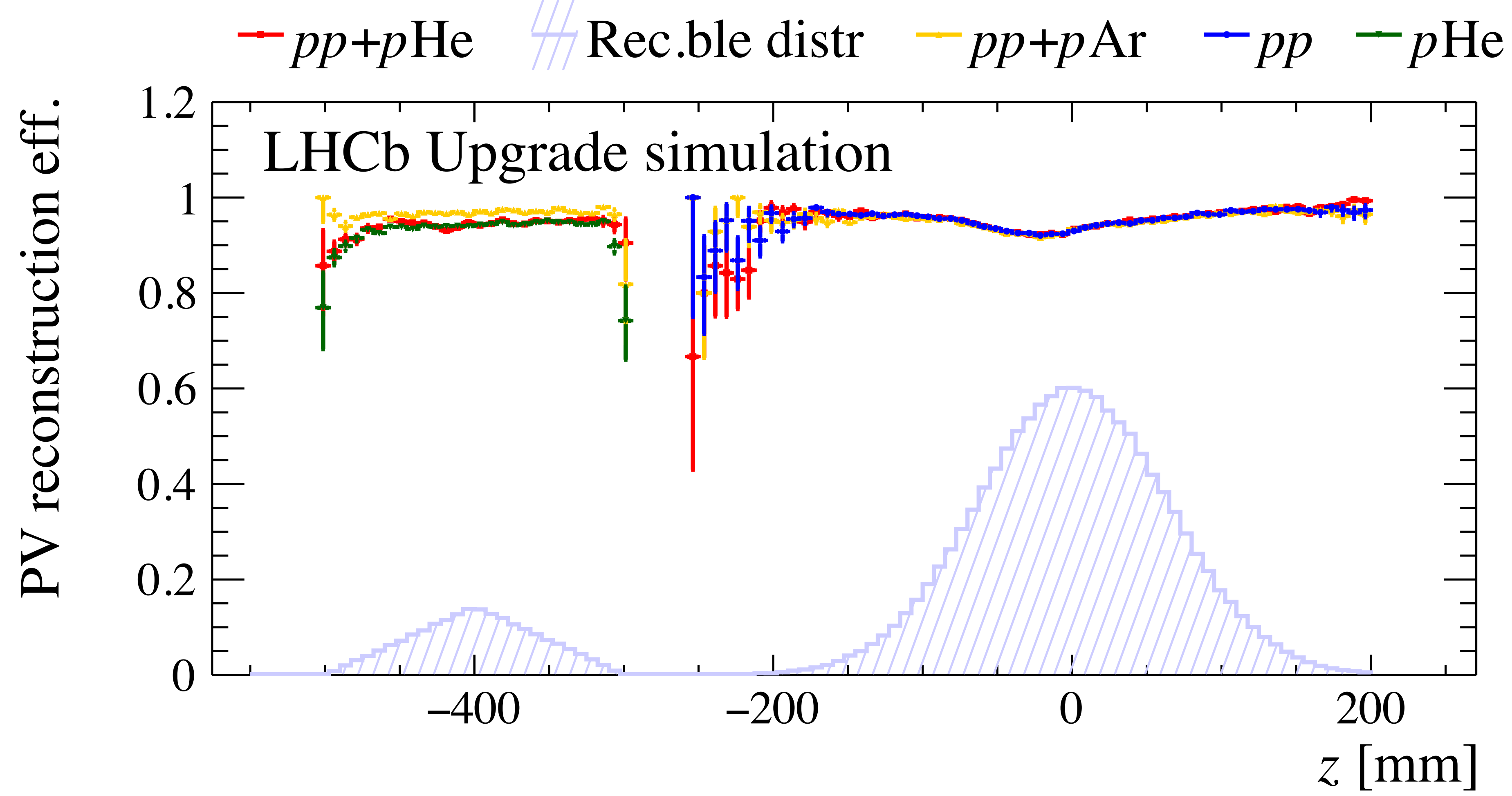
[LHCB-FIGURE-2022-002]

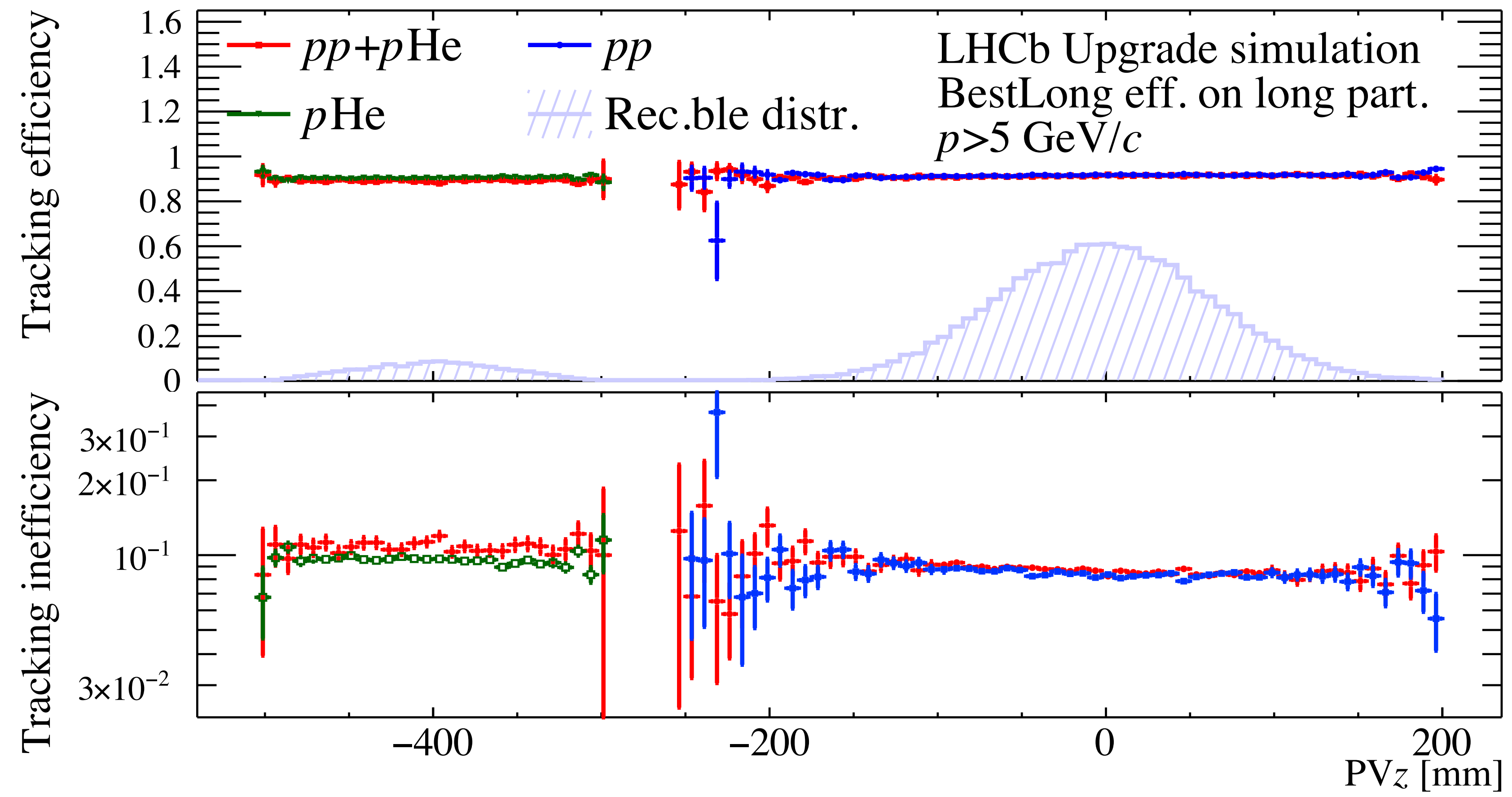
- beam-beam and beam-gas interaction regions are well detached
- Negligible increase of multiplicity: $1-3\,\%$ throughput decrease when adding beam-gas to the LHCb event reconstruction sequence





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

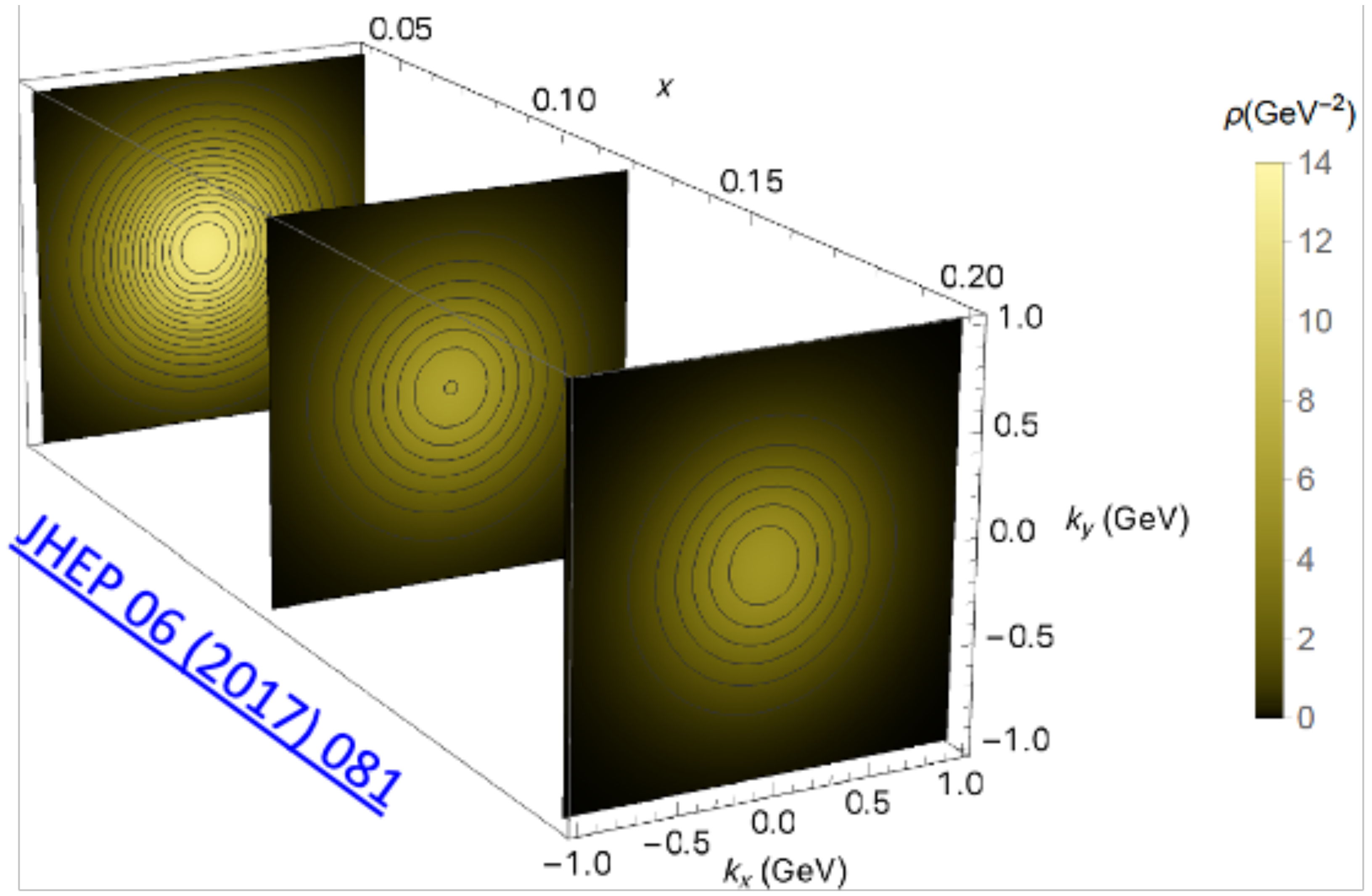




LHCb is the only experiment able to run in collider and fixed-target mode simultaneously!

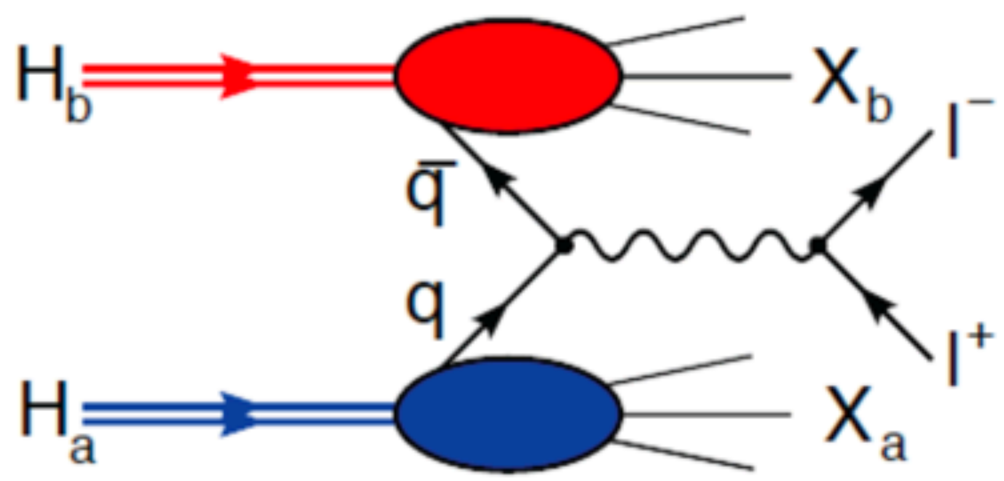
The physics goals of LHCspin

- 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



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

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?

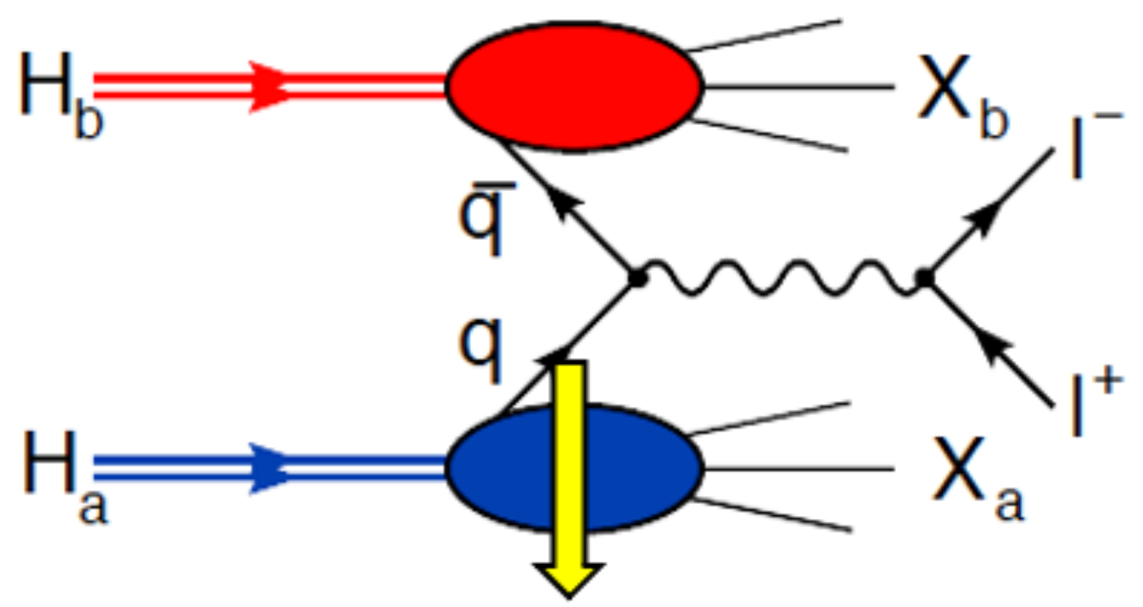
… still a lot to be understood and investigated

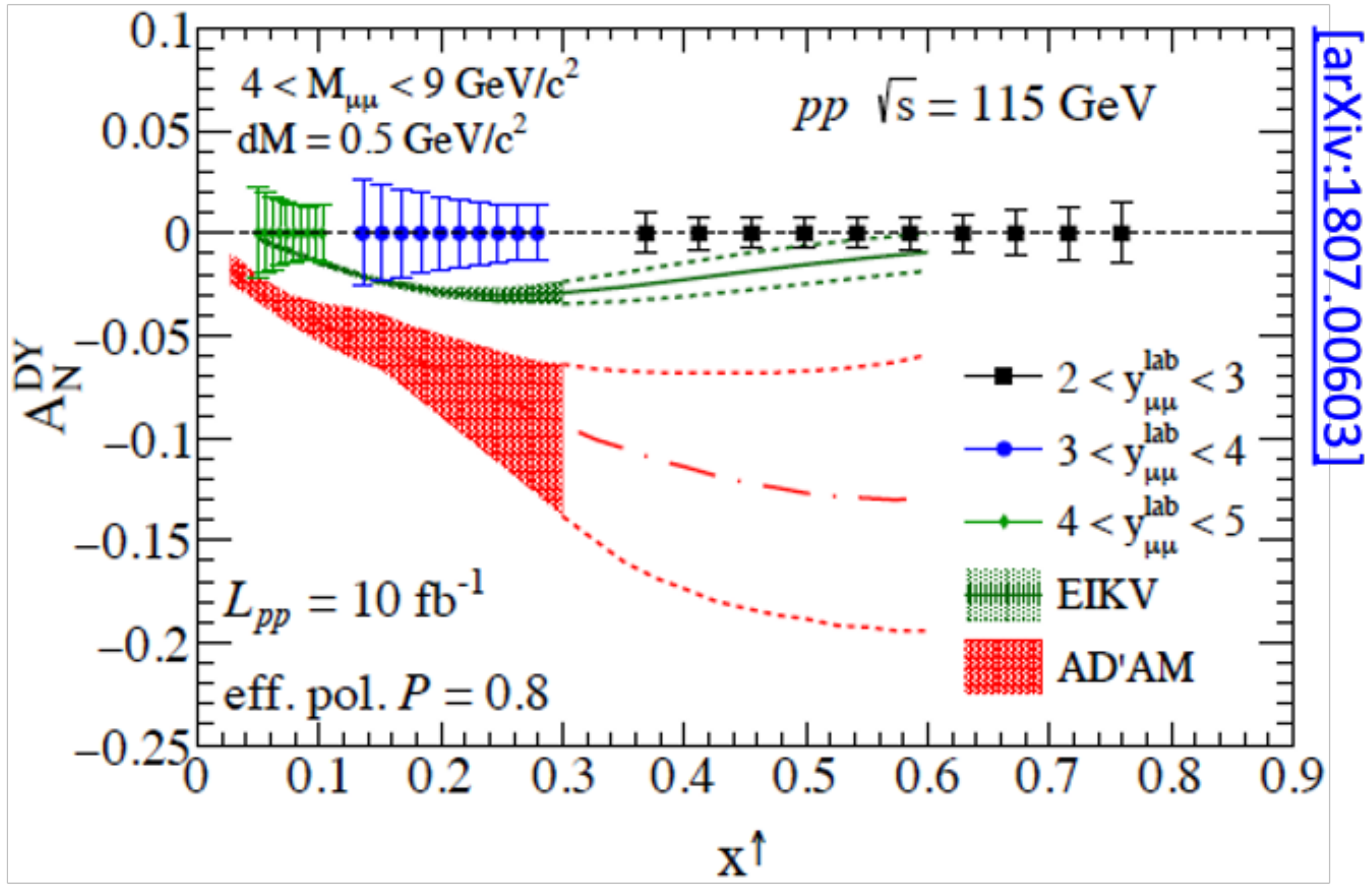
Quark TMDs

quark pol. / nucleon pol.

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

Transv. polarized Drell-Yan





- **Sensitive to quark TMDs through TSSAs**

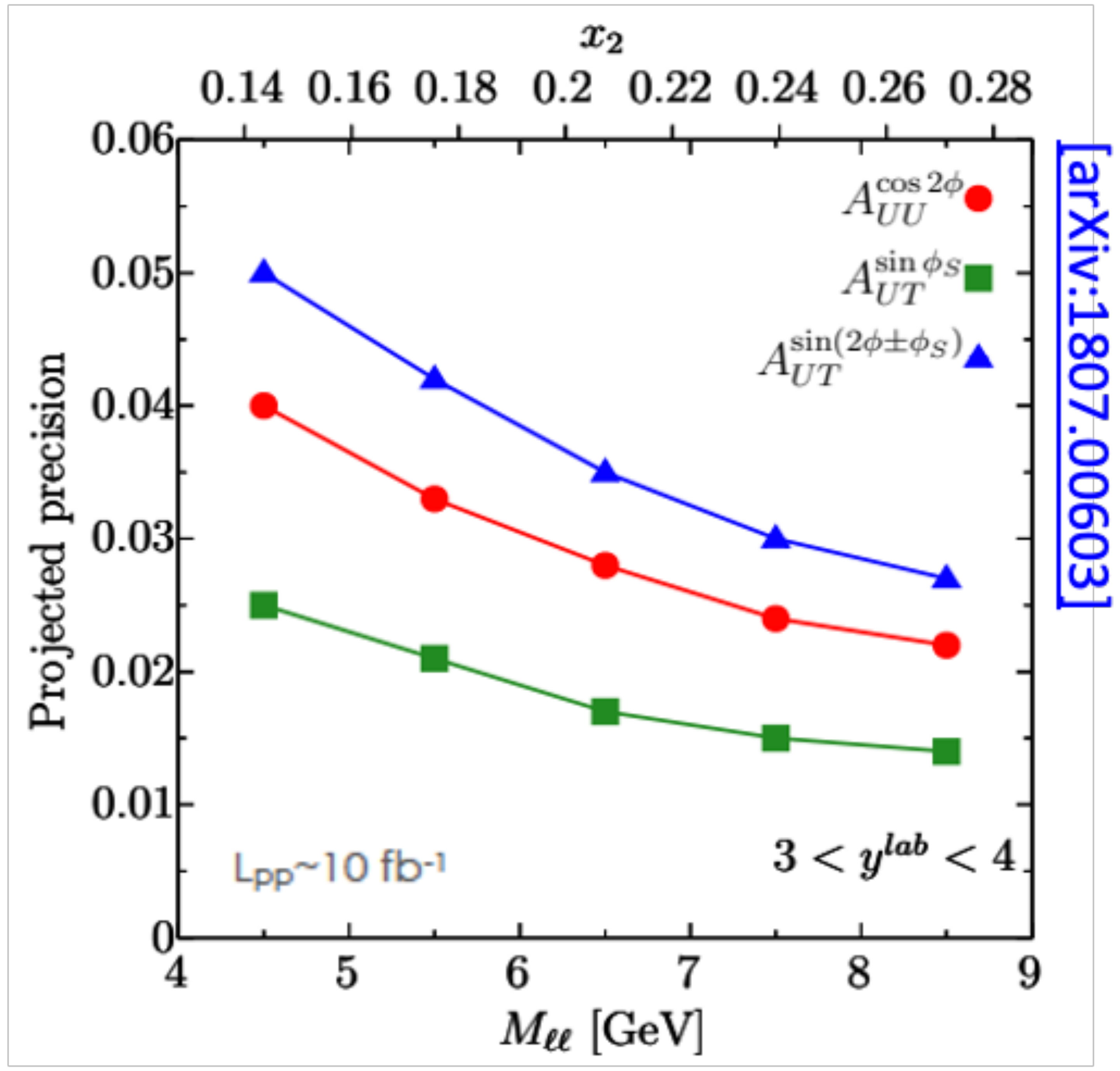
$$A_N^{DY} = \frac{1}{P}\frac{\sigma_{DY}^{\uparrow} - \sigma_{DY}^{\downarrow}}{\sigma_{DY}^{\uparrow} + \sigma_{DY}^{\downarrow}} \Longrightarrow \quad A_{UT}^{\sin\phi_S} \sim \frac{f_1^q \otimes f_{1T}^{\perp q}}{f_1^q \otimes f_1^q}, \quad A_{UT}^{\sin(2\phi-\phi_S)} \sim \frac{h_1^{\perp q} \otimes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

(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



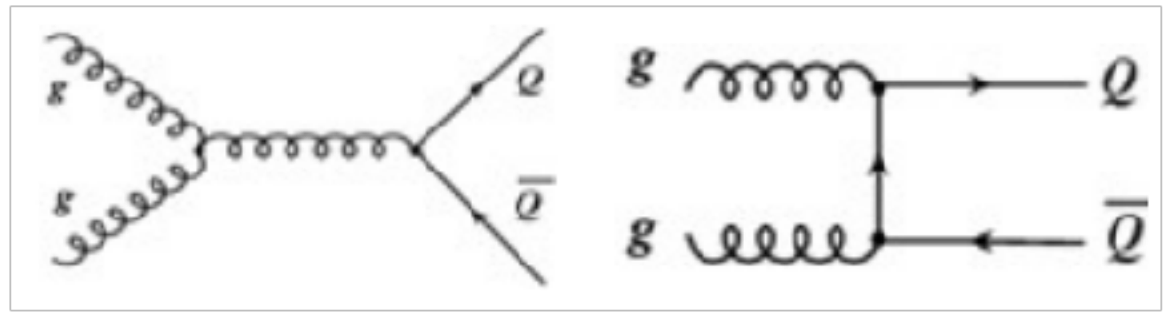
Probing the gTMDs

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

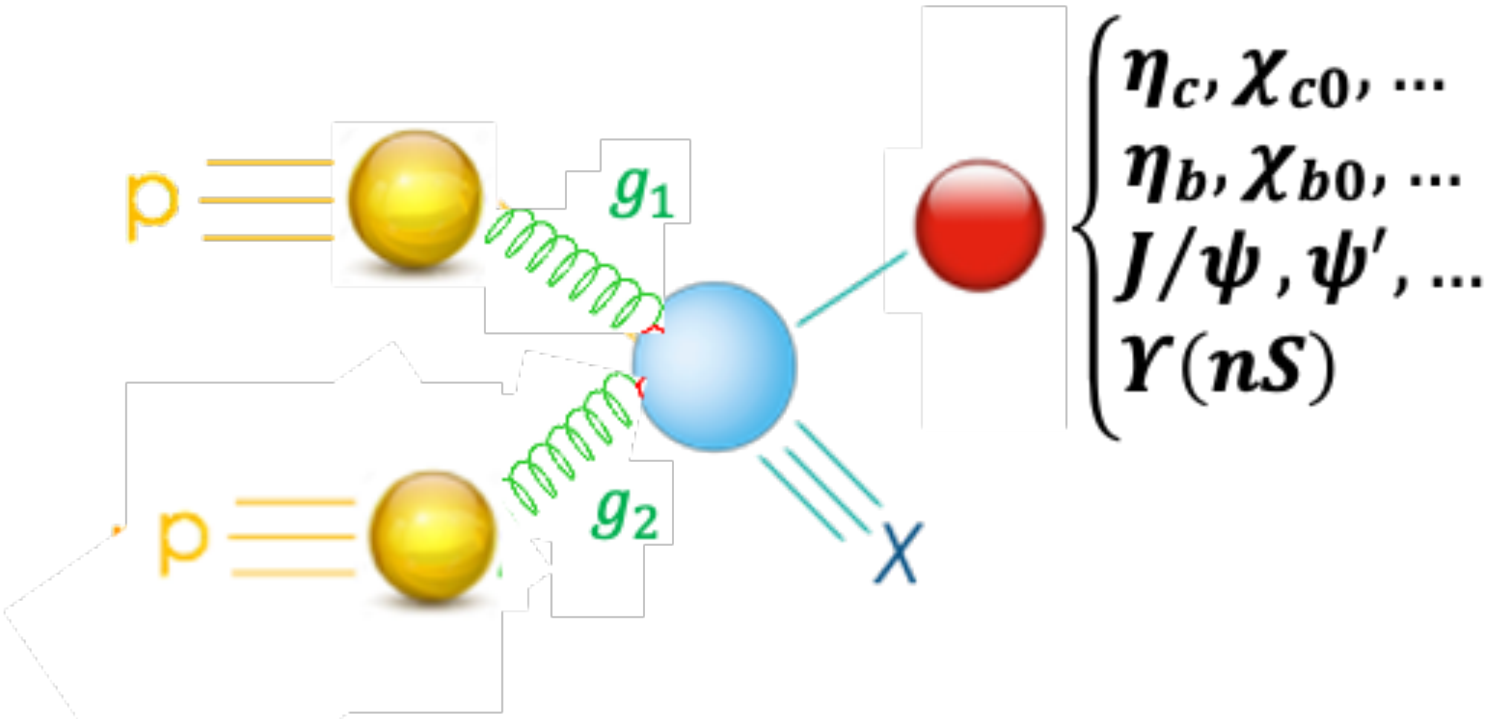
Theory framework well consolidated **…but experimental access still extremely limited!**

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!)

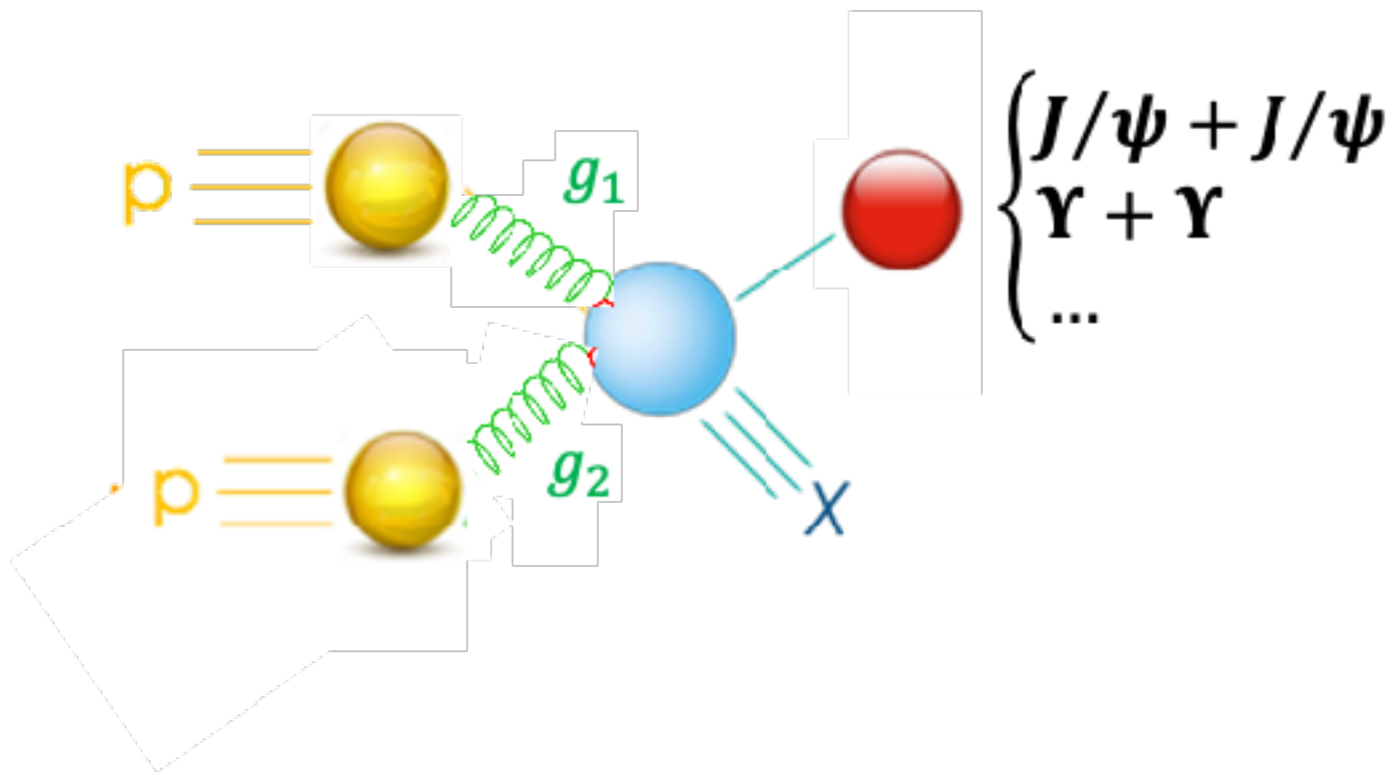
Probing the gTMDs

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M_{QQ}\mathrm{d}Y_{QQ}\mathrm{d}^2\boldsymbol{P}_{QQ_T}\mathrm{d}\Omega} = \frac{\sqrt{M_{QQ}^2 - 4M_Q^2}}{(2\pi)^2 8s\, M_{QQ}^2}$$

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

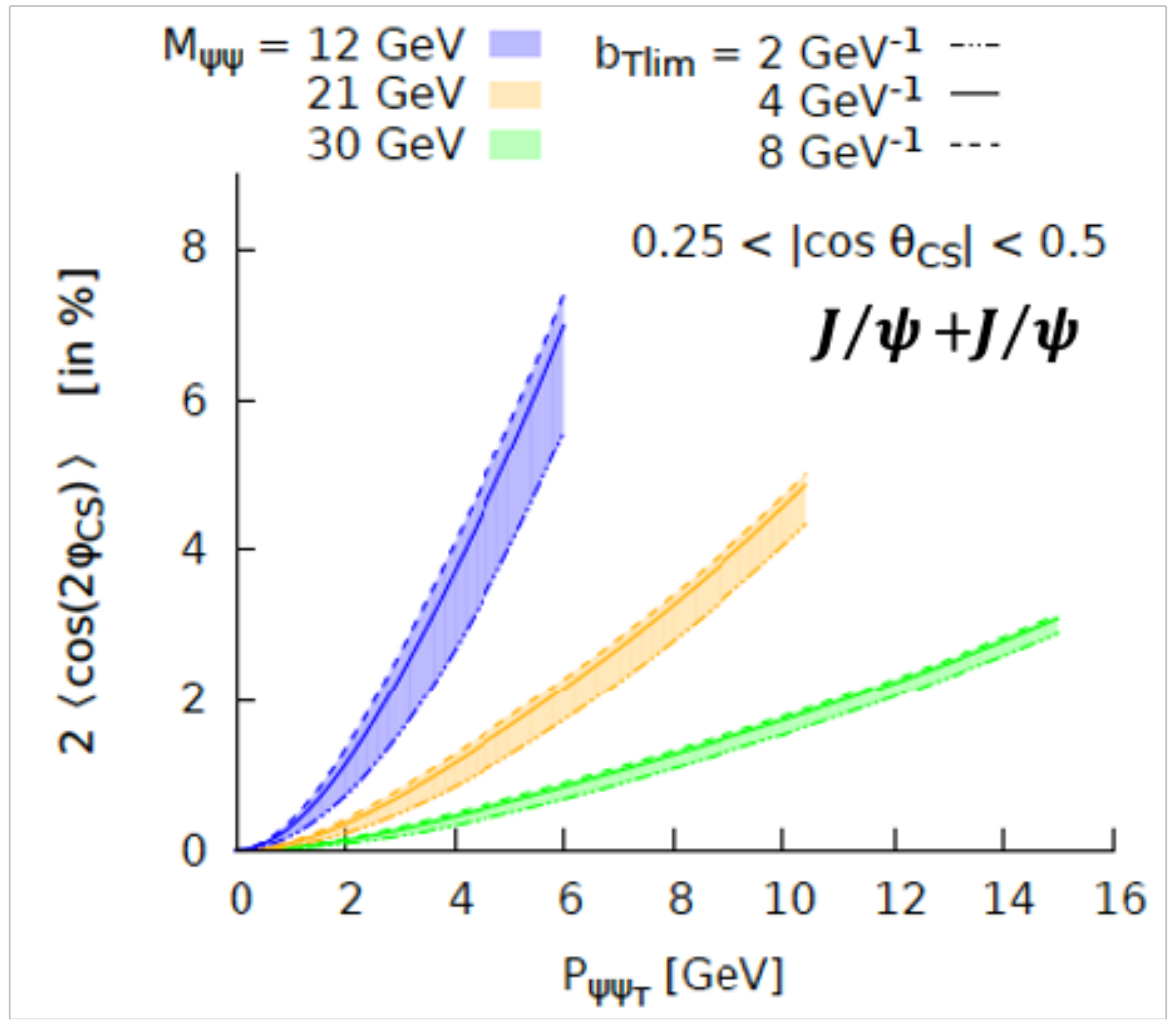
$$+F_2(M_{QQ},\theta_{\mathrm{CS}})\,\mathcal{C}\Big[w_2 h_1^{\perp g} h_1^{\perp g}\Big](x_{1,2},\boldsymbol{P}_{QQ_T})$$

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

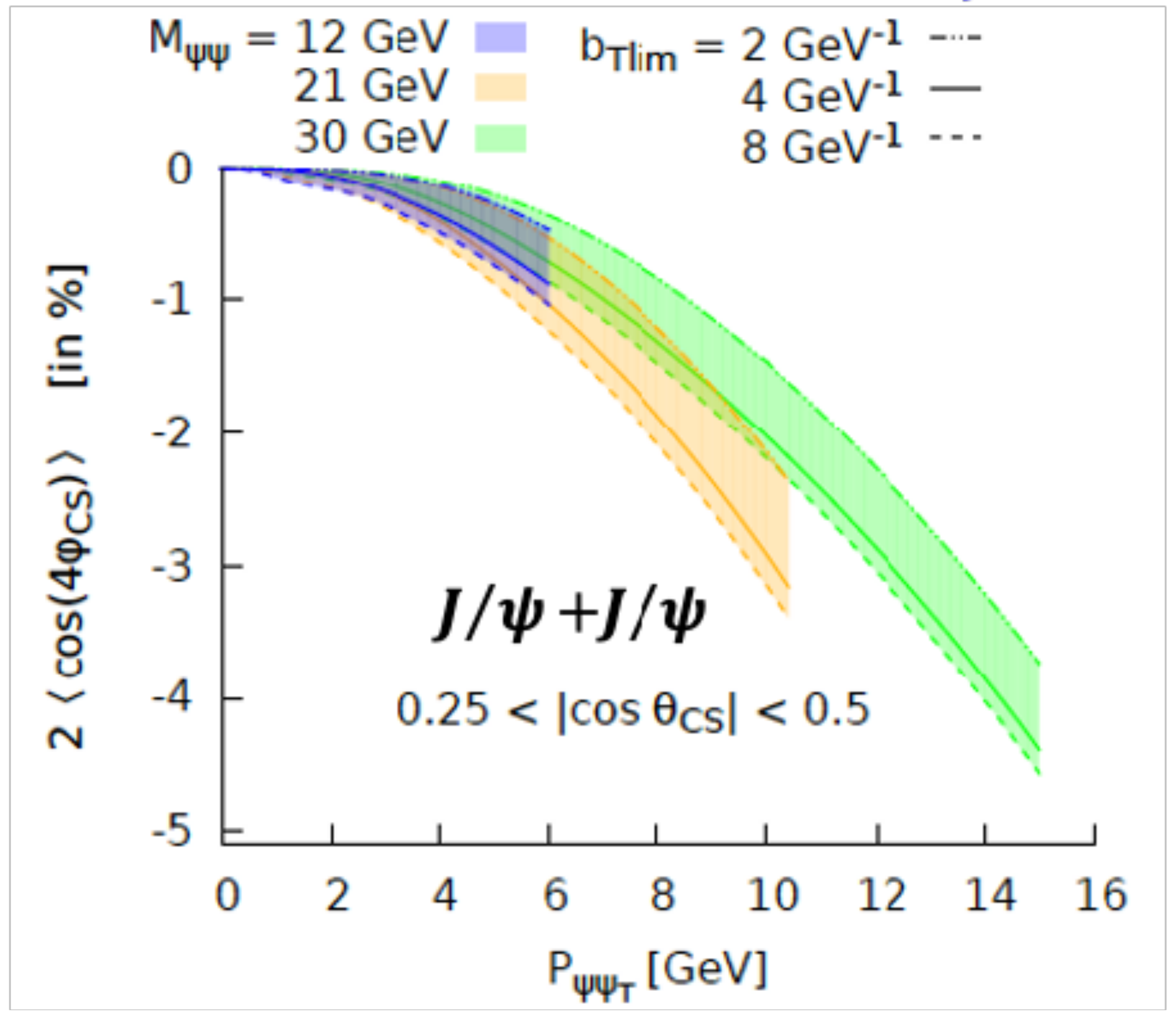


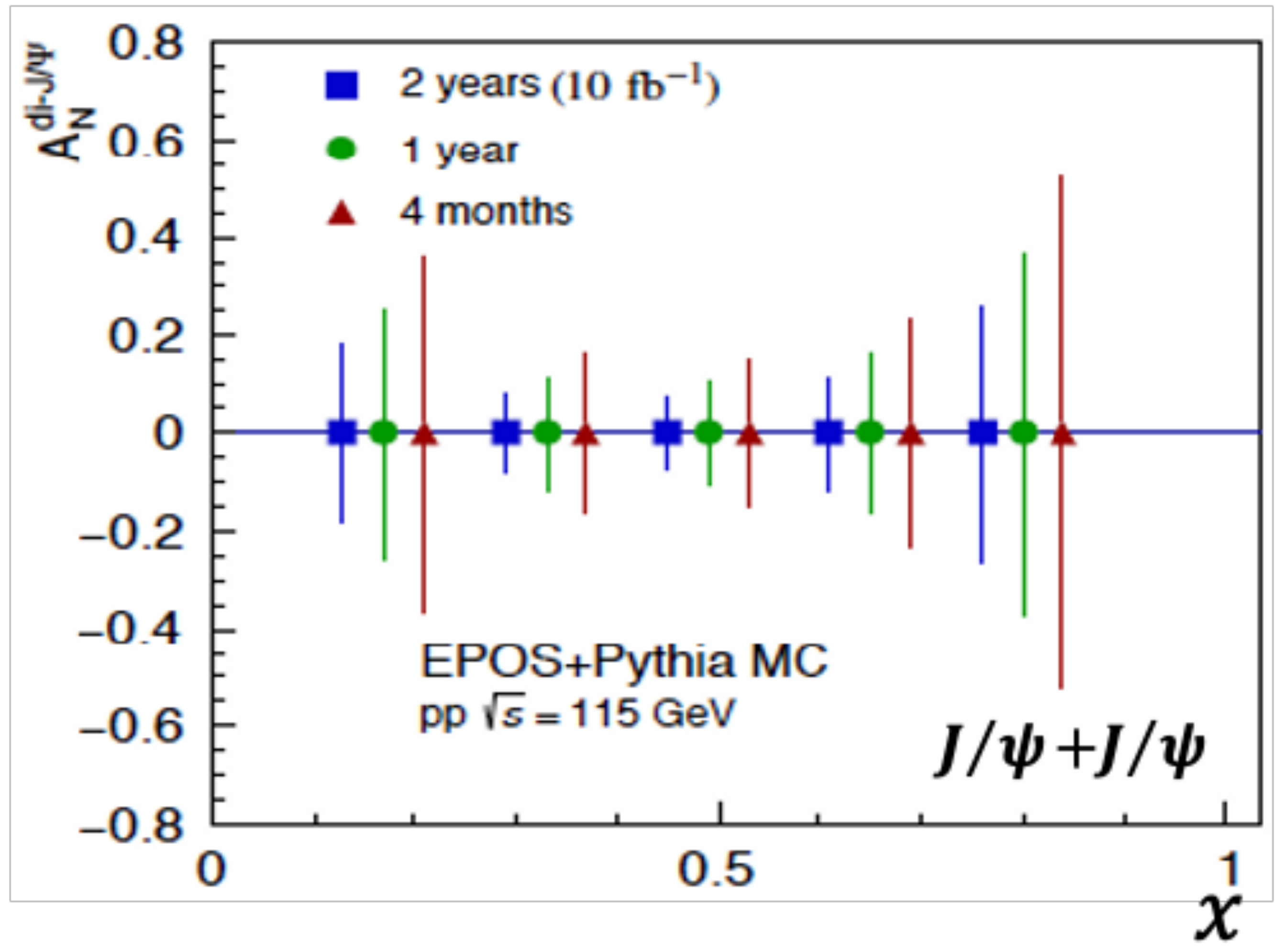
nucleon pol. \ gluon pol.	U	Circularly	Linearly
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_1^g,\ h_{1T}^{\perp g}$

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



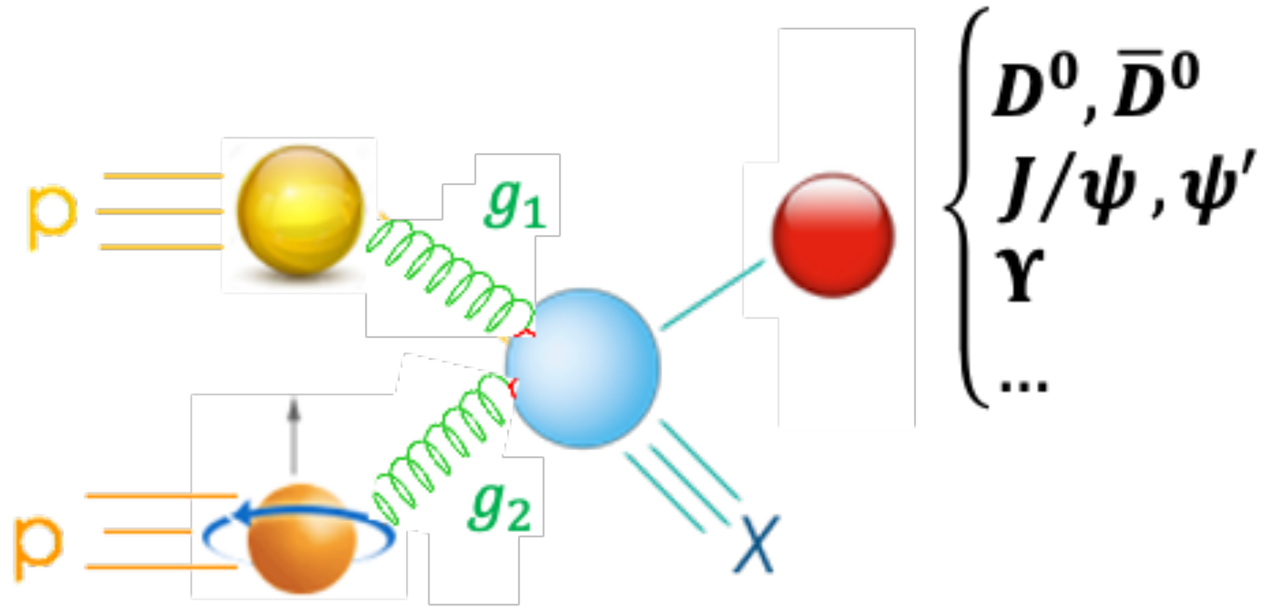
Azimuthal amplitudes ~5%!





Probing the gluon Sivers function

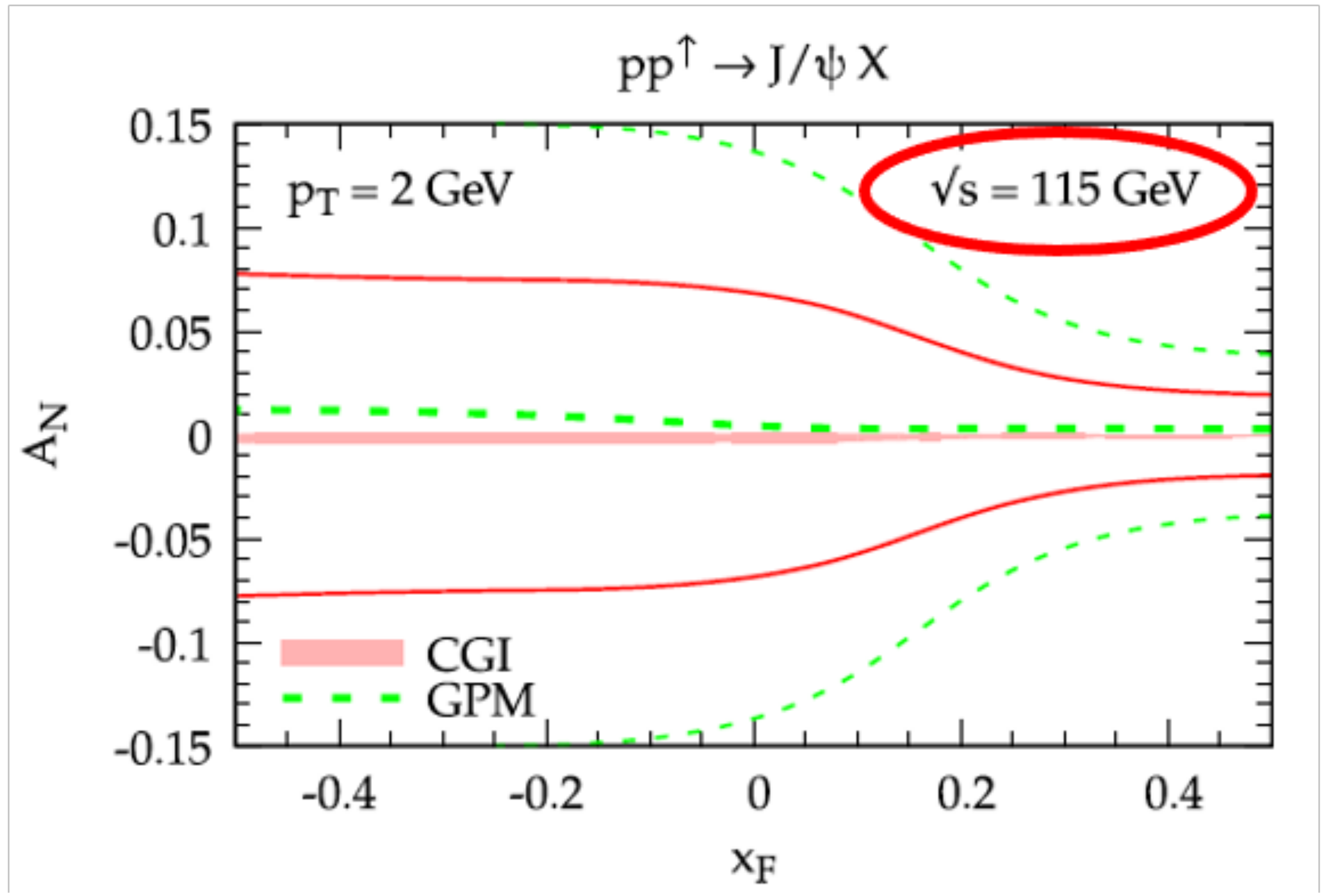
$$\Gamma_T^{\mu\nu}(x, \boldsymbol{p}_T) = \frac{x}{2}\left\{ g_T^{\mu\nu} \frac{\epsilon_T^{\rho\sigma} p_{T\rho} S_{T\sigma}}{M_p} f_{1T}^{\perp g}(x, \boldsymbol{p}_T^2) + \ldots \right\}$$



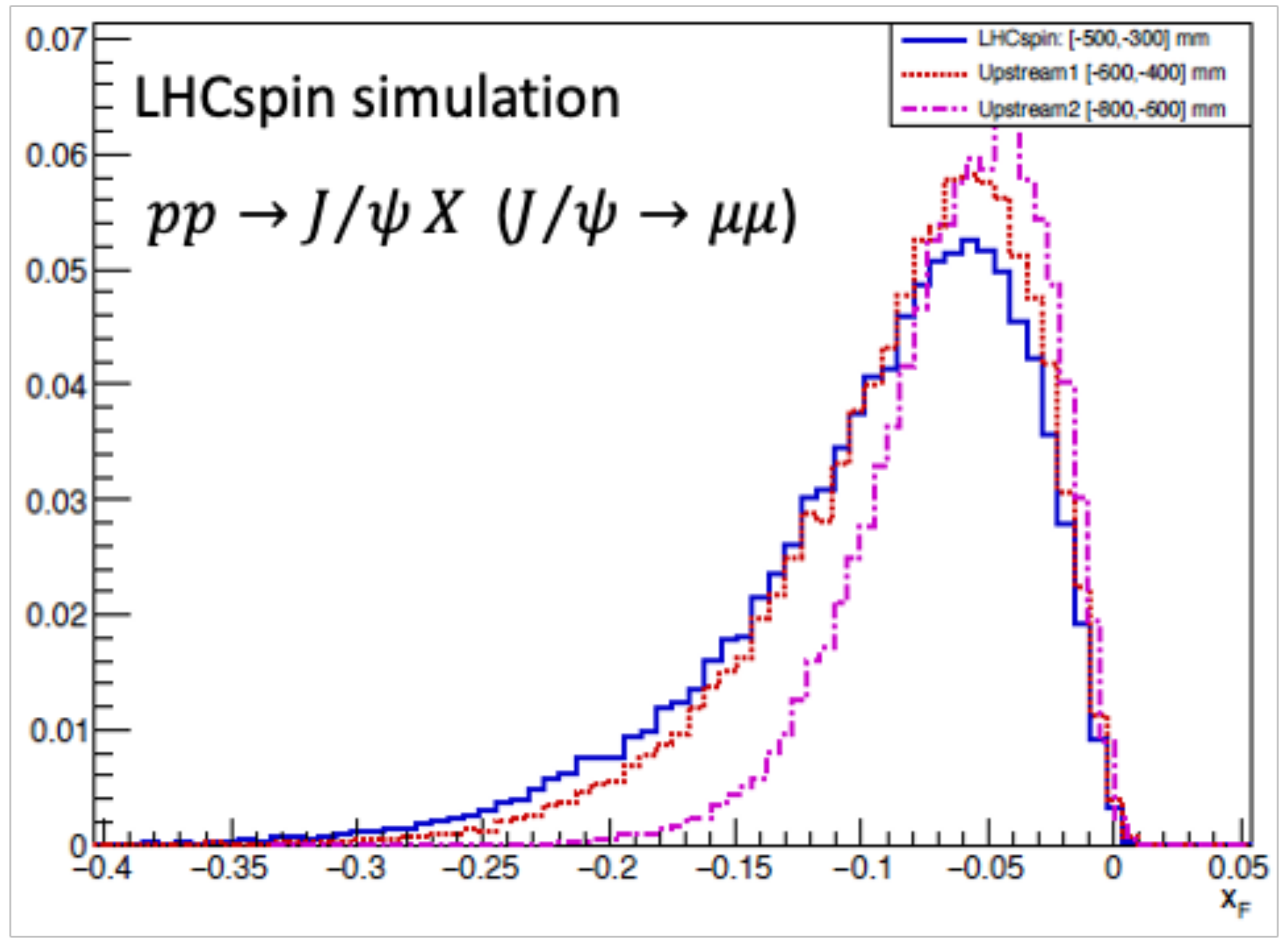
nucleon pol. \ gluon pol.	U	Circularly	Linearly
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_1^g,\ h_{1T}^{\perp g}$

- 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**

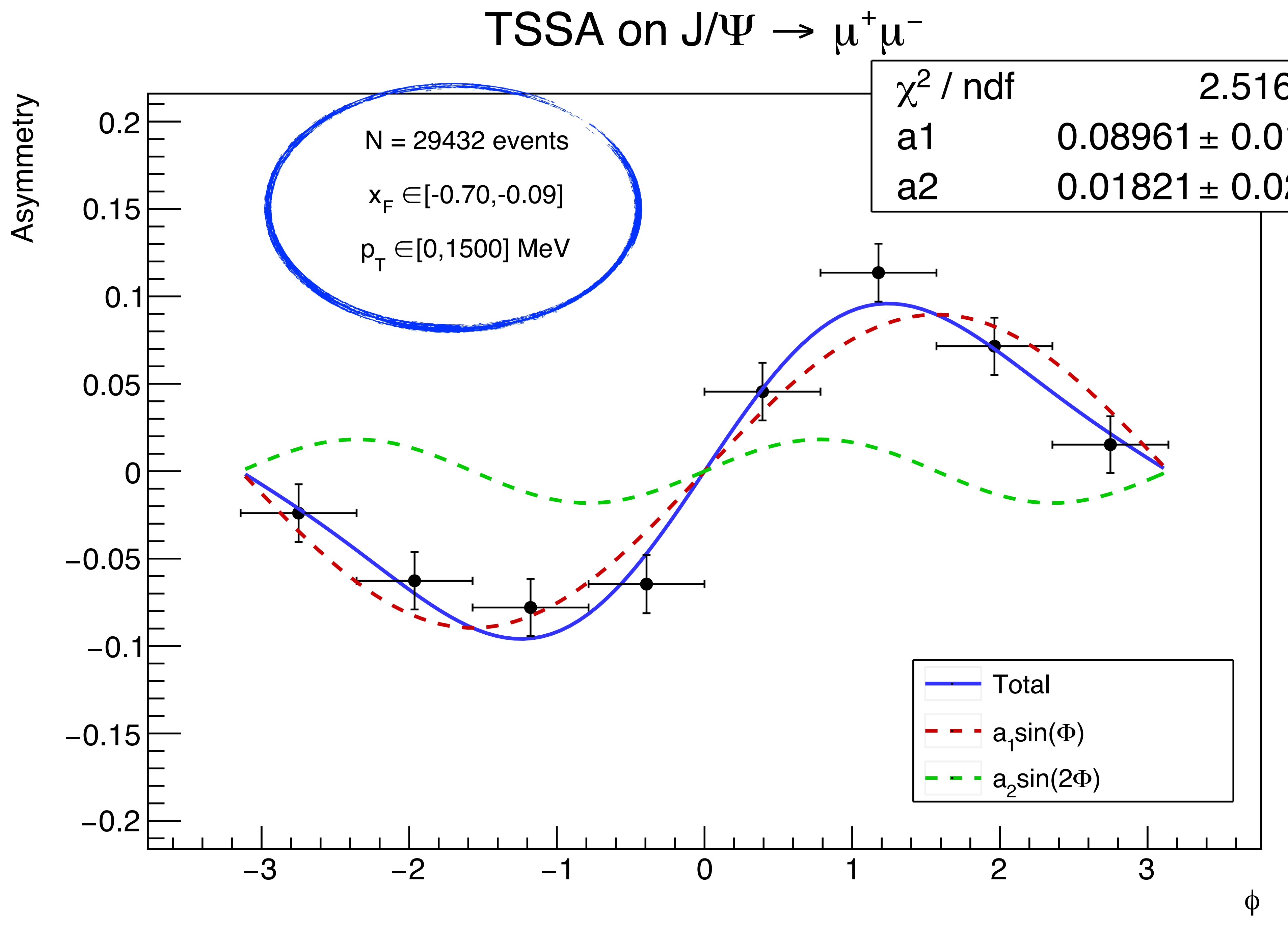
$$A_N = \frac{1}{P}\frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \propto \left[f_{1T}^{\perp g}(x_a, k_{\perp a}) \otimes f_g(x_b, k_{\perp b}) \otimes d\sigma_{gg \to Q\bar{Q}g} \right] \sin\phi_S + \cdots$$

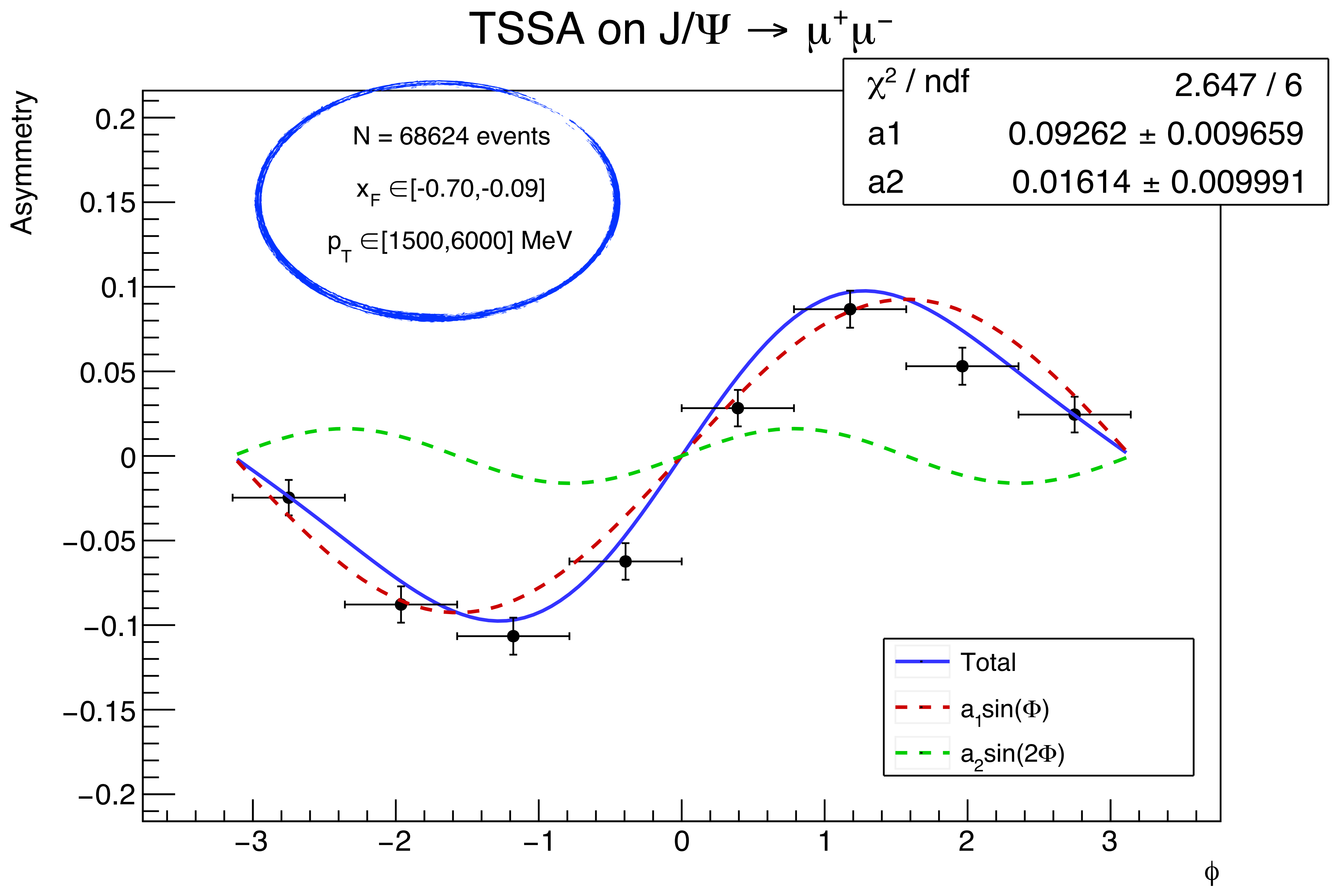


- **Predictions for pol. FT meas. at LHC (LHCspin-like)**
- [PRD 99, 036013 (2019)]
- $pp^\uparrow \to J/\psi + X$
- **based on GPM & CGI-GPM**
- **Expected amplitudes could reach 5-10% in the $x_F < 0$ region**



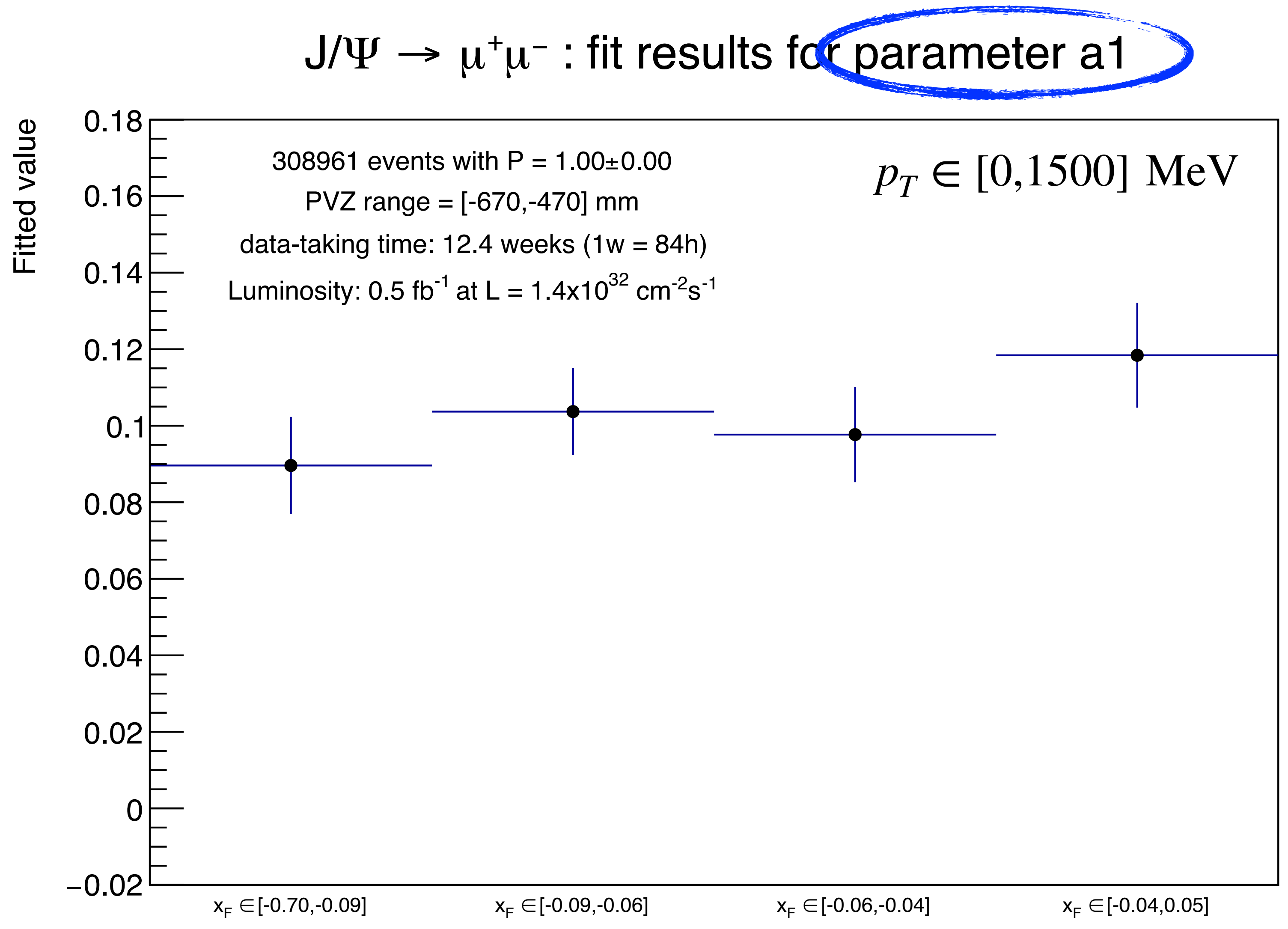
A TSSA analysis at LHCspin with $J/\Psi \to \mu^+\mu^-$ events





[JHEP 12 (2020) 010]

- Full LHCb simulations of $J/\Psi \to \mu^+\mu^-$ in pH collisions → emulate the target polarisation by assigning a $\uparrow\downarrow$ 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

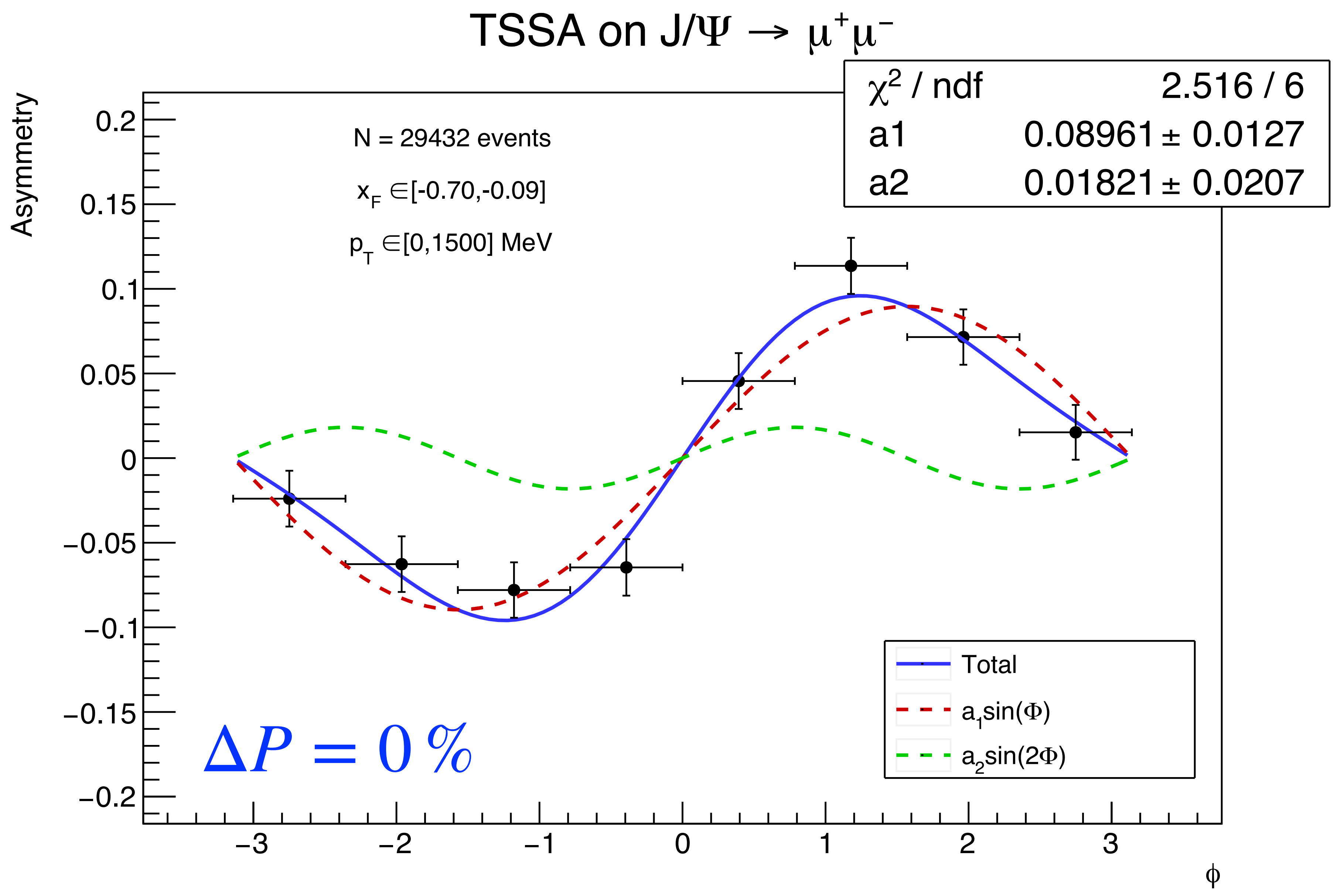
- To estimate the systematic error due to the measurement of the polarisation degree, the analysis is repeated with different ΔP
- Very relevant for the R&D (e.g. cell vs jet target). With the shown analysis* :
- 5% error (realistic value) → negligible effect
- 20% error → 30-40% of the stat. error
-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

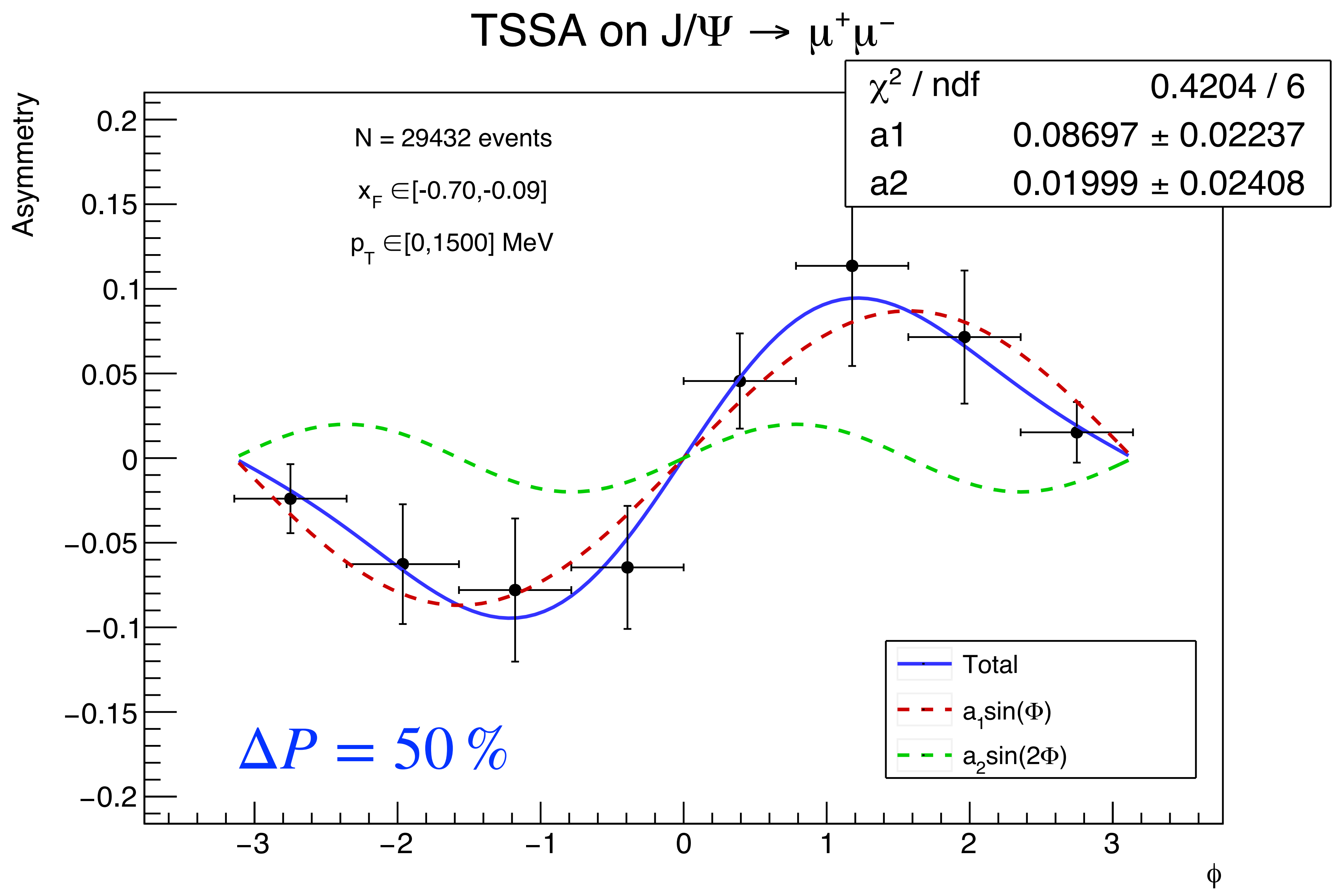
$\Delta P = 5\,\%$

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

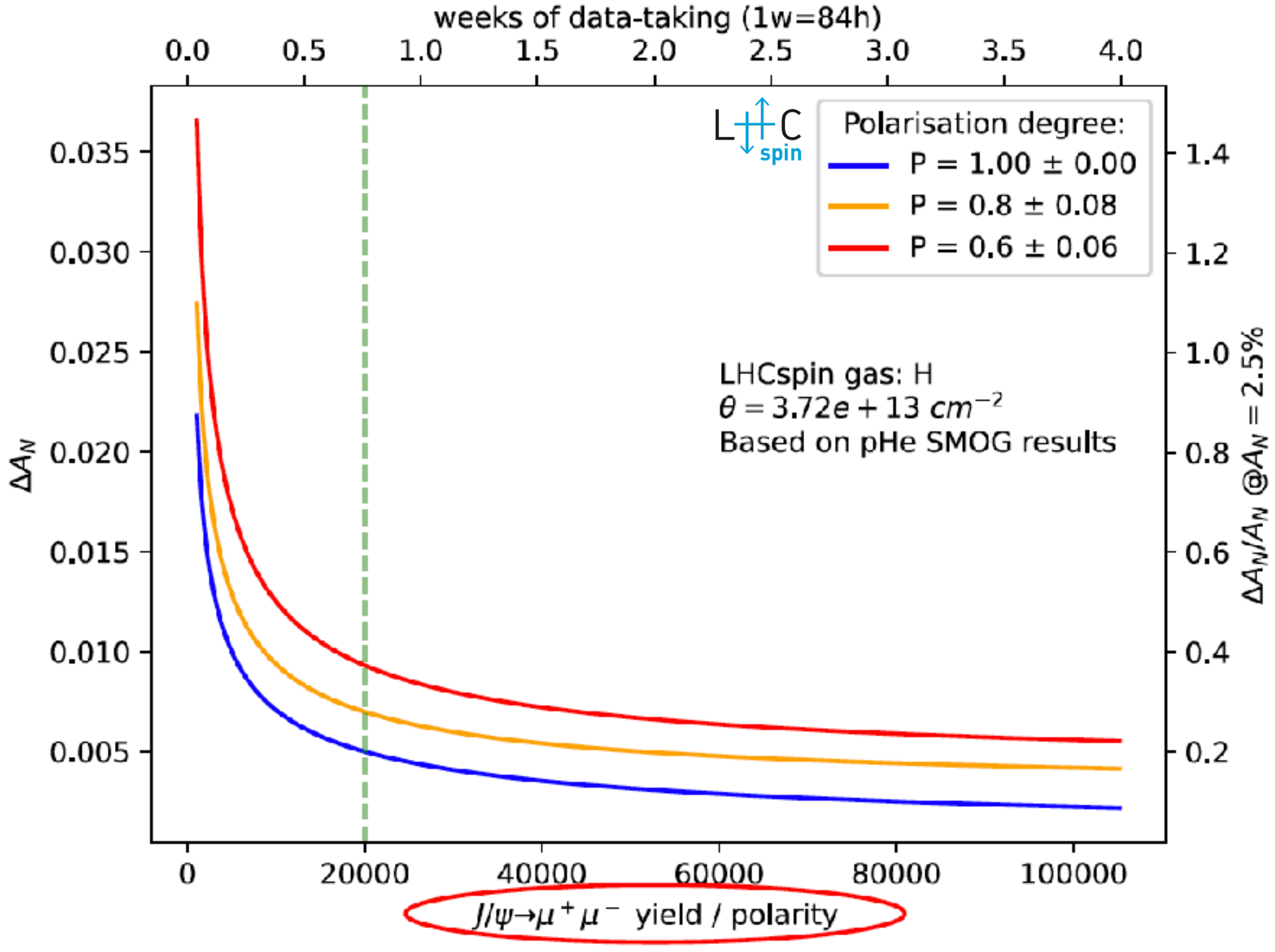


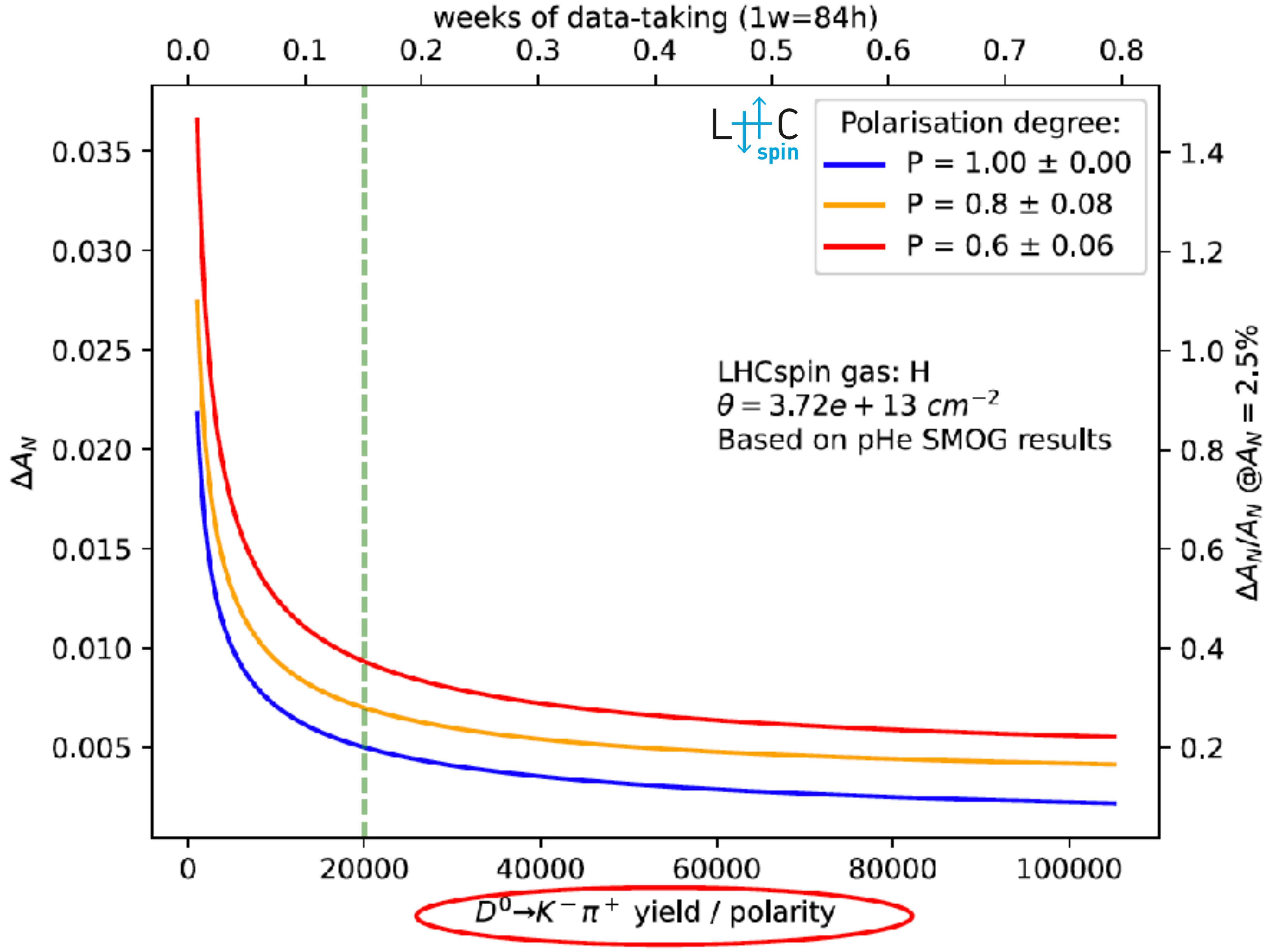


* i.e. ~ 3 months of data-taking with this example model, channel and kinematic binning

LHCspin event rates

Precise spin asymmetry on $J/\Psi \to \mu^+\mu^-$ 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



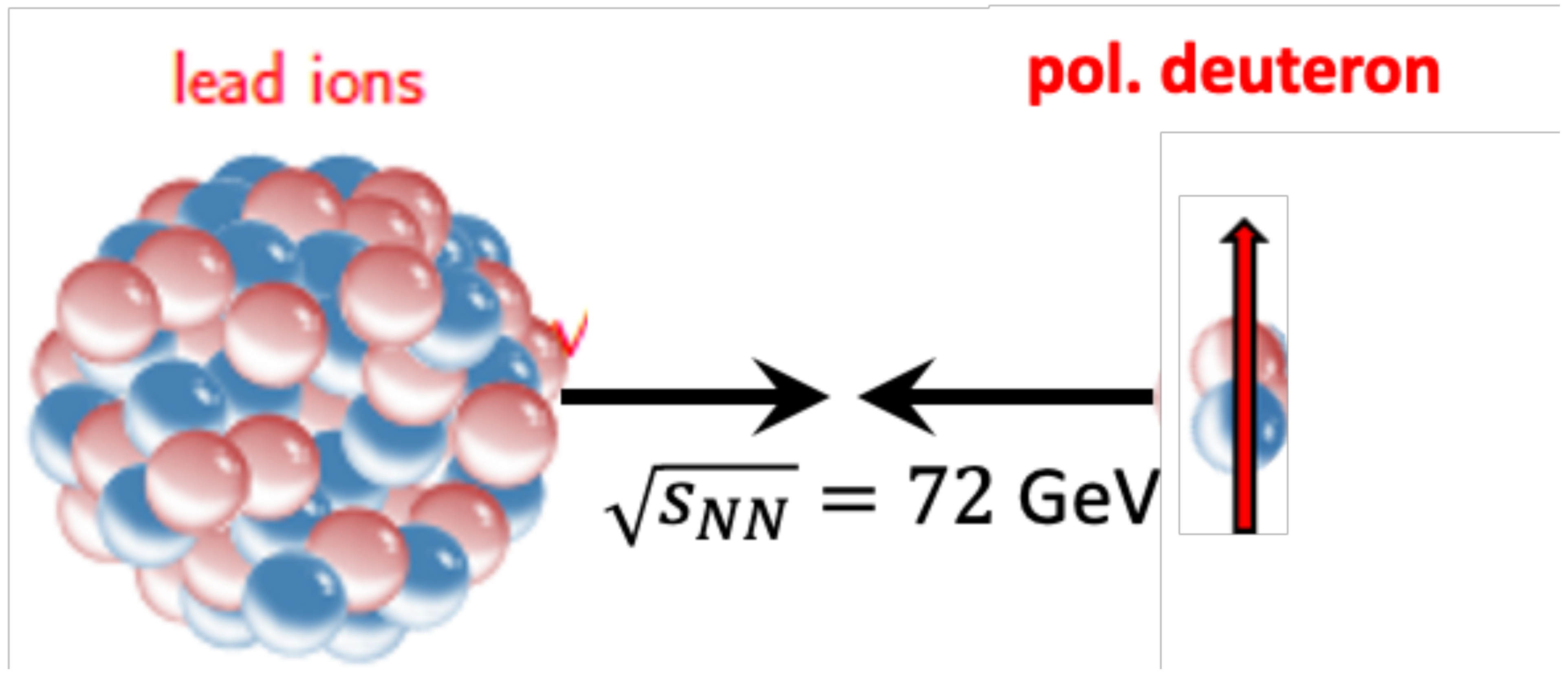


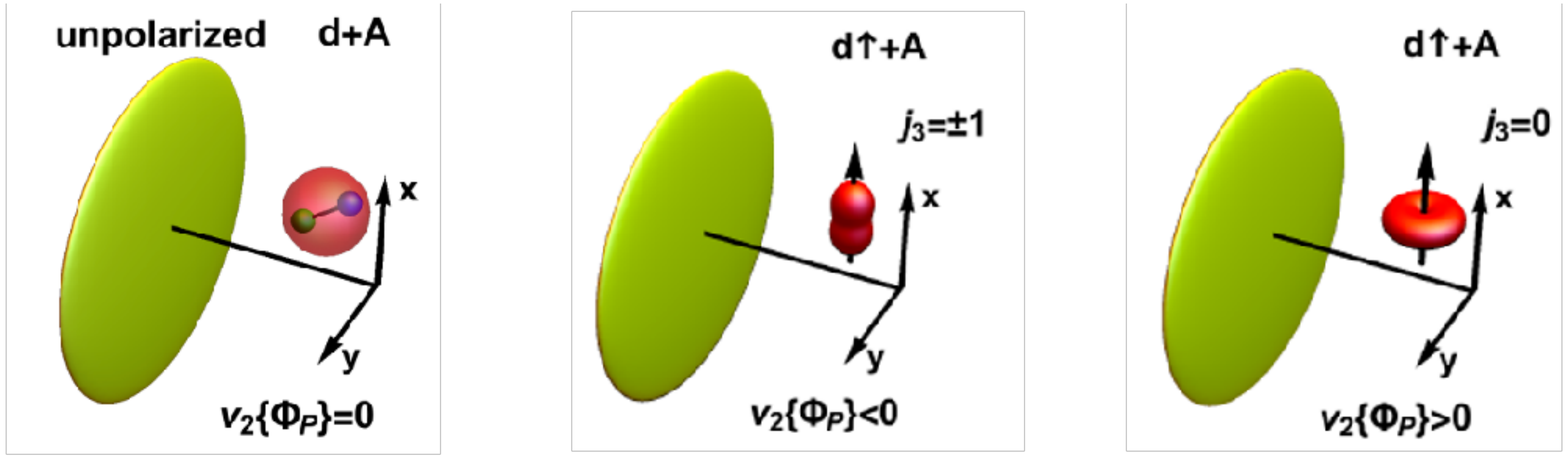
reconstructed particles

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**).

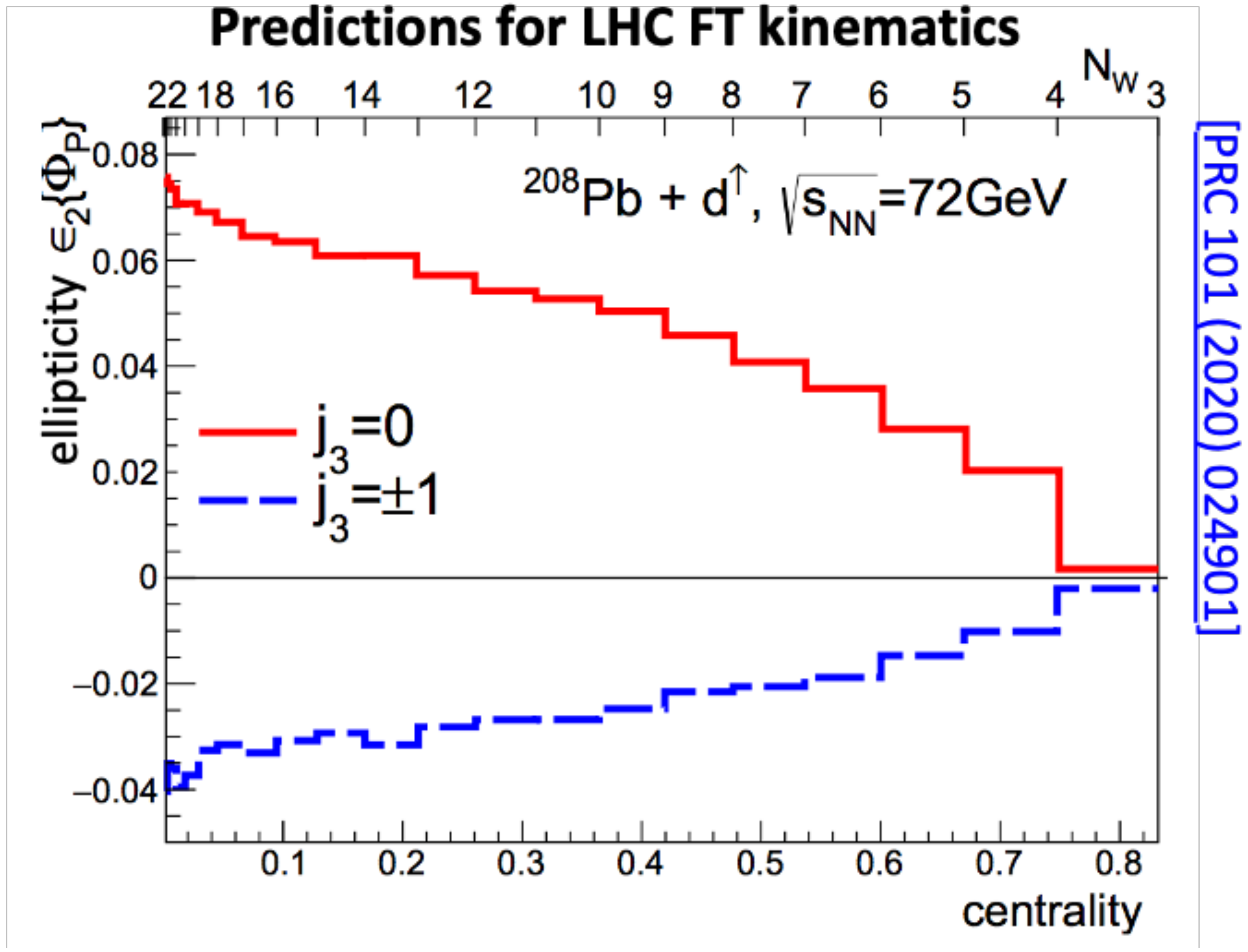




Unpol. deuterons: the **fireball is azimuthally symmetric** and $v_2 \approx 0$.

$j_3 = \pm1 \rightarrow$ **prolate fireball** stretched along the pol. axis, corresponds to $v_2 < 0$

$j_3 = 0 \rightarrow$ **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

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

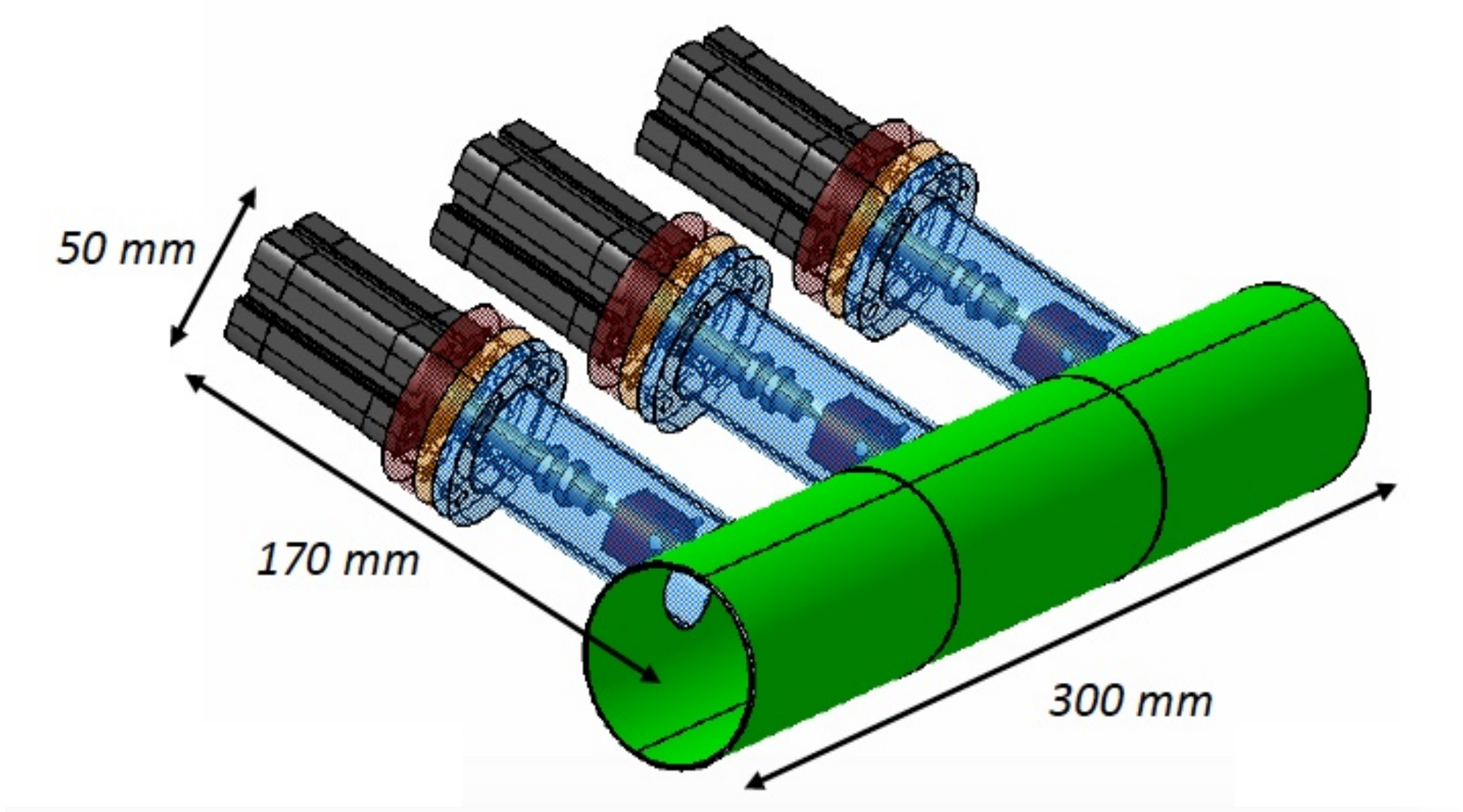
solid target @ ALICE

The ALICE unpolarised solid target

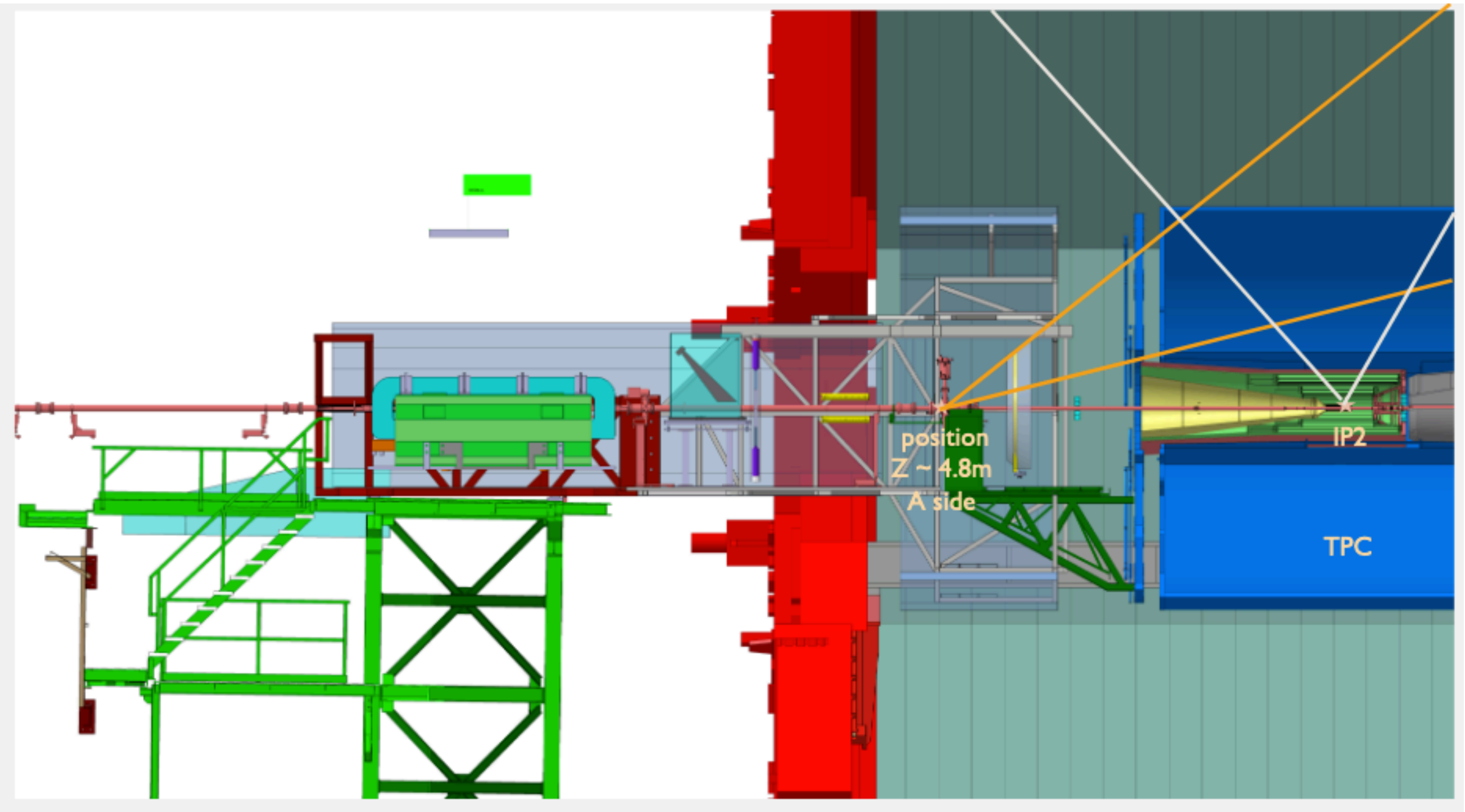
Two main physics goals:

- Advance our 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

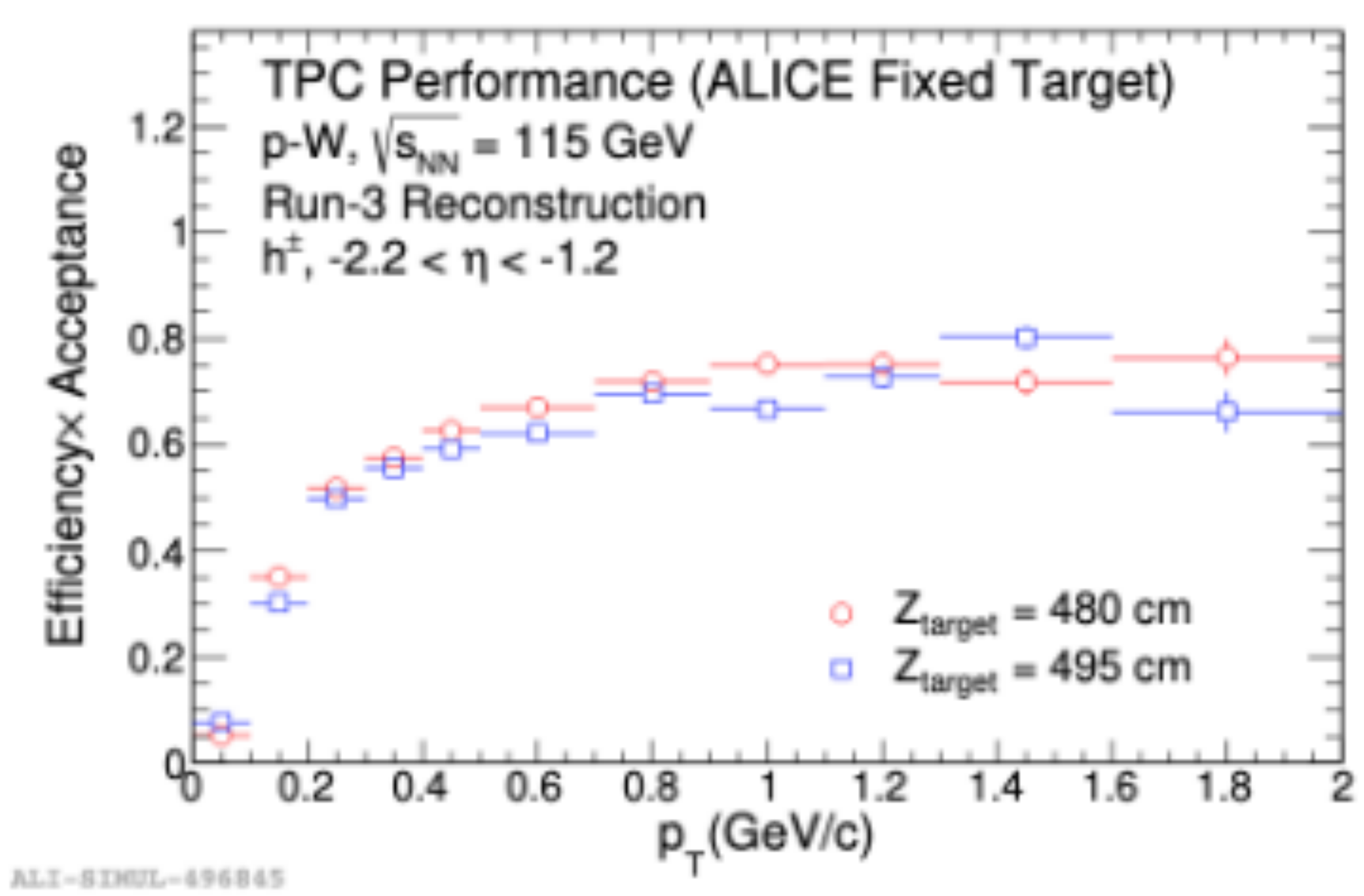


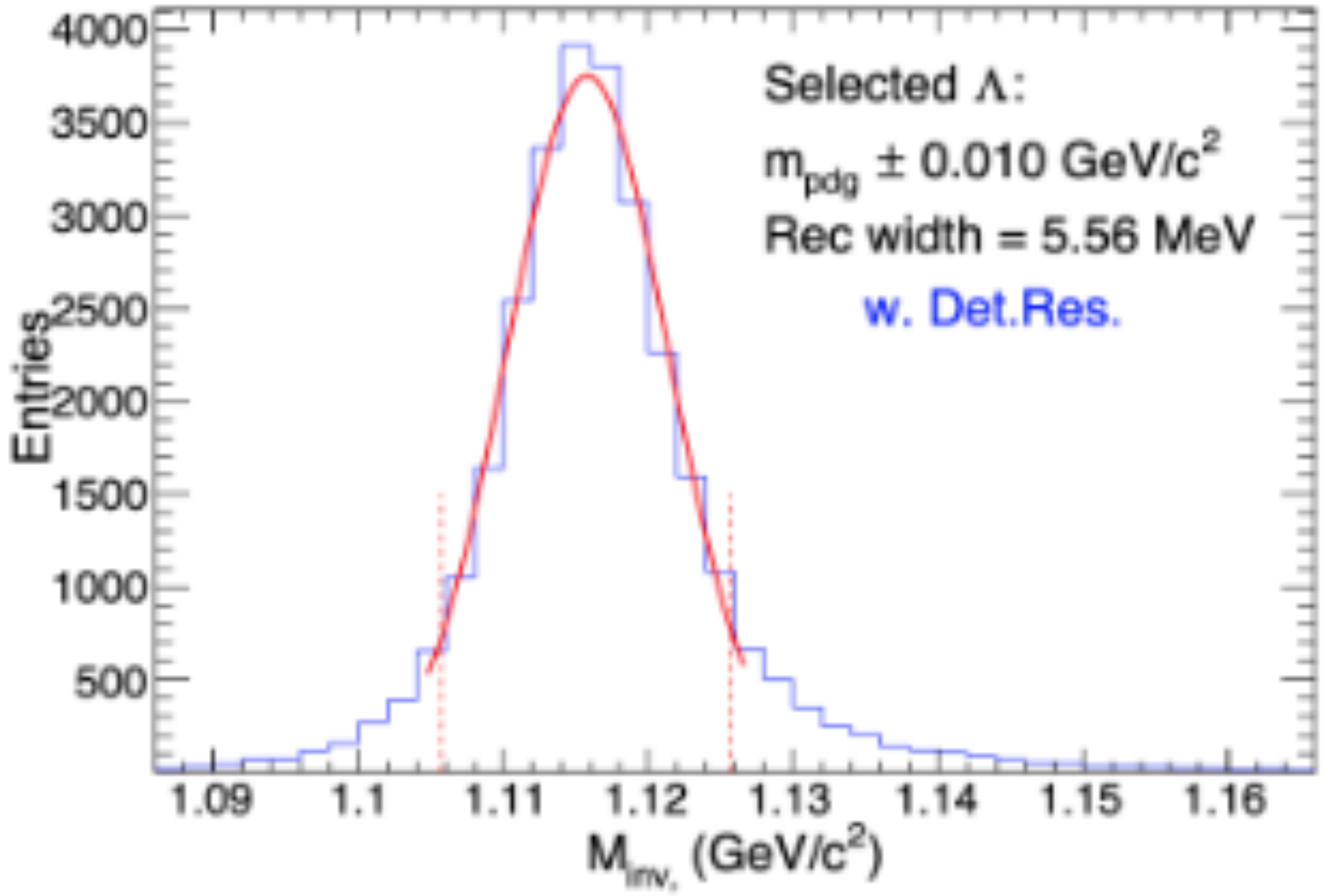
retractable solid target

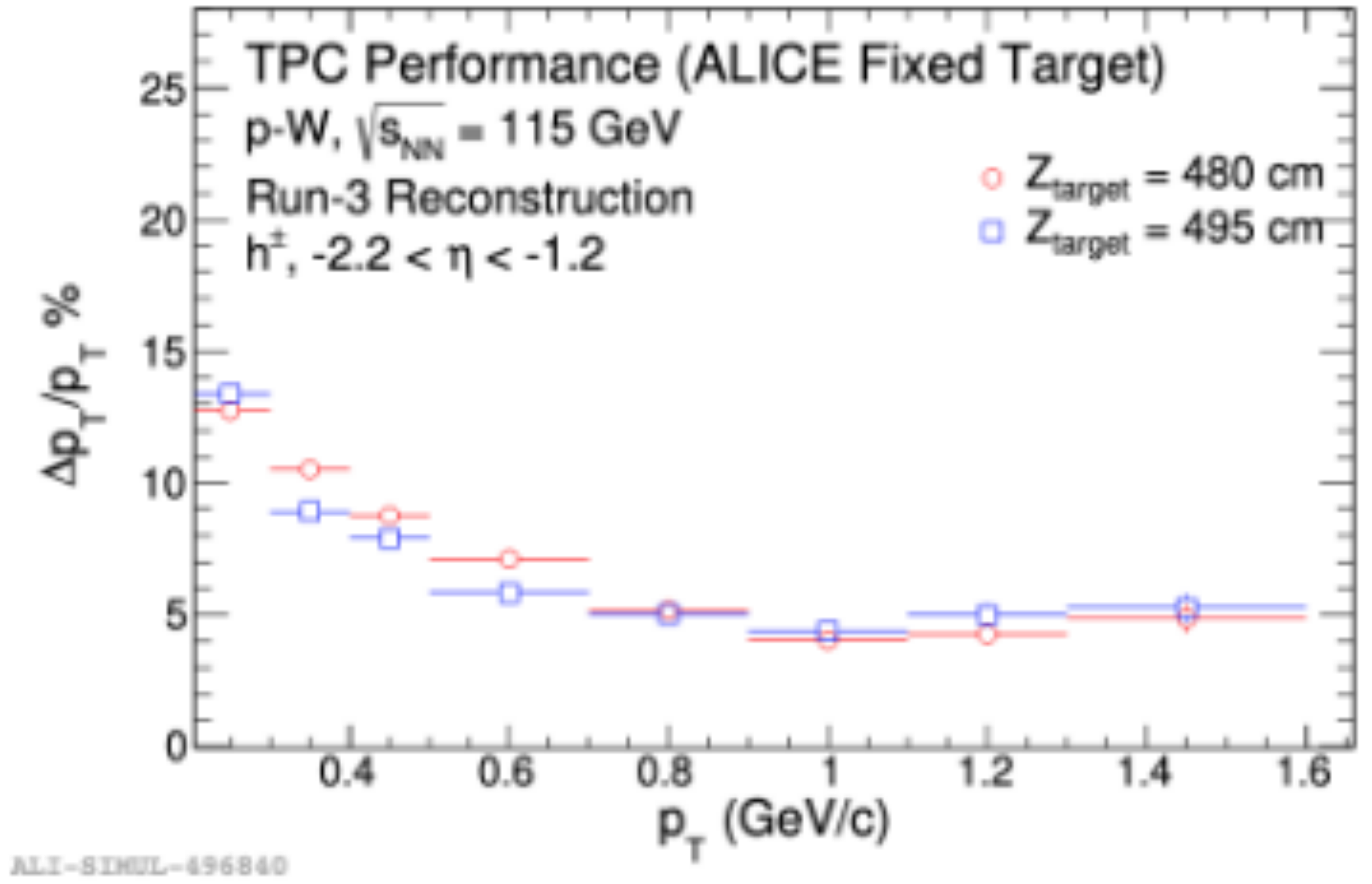


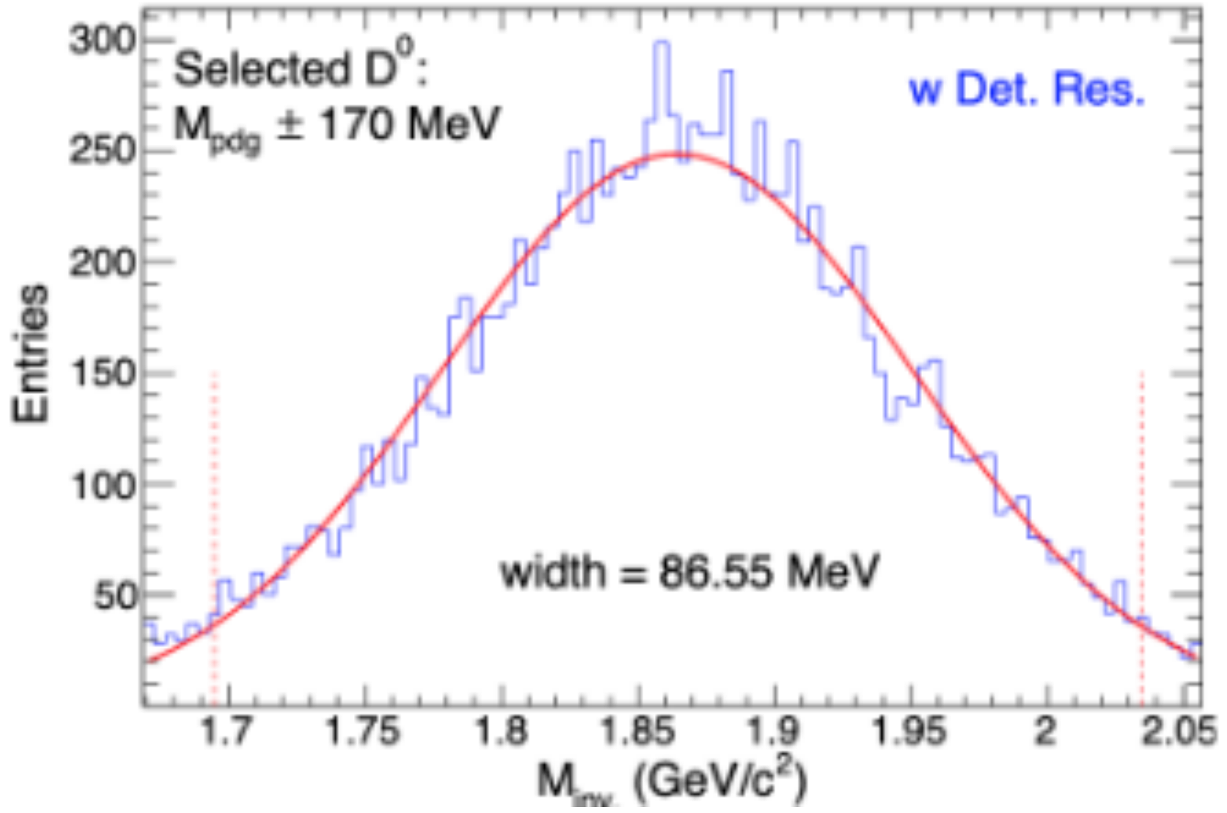
Some of the performances

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

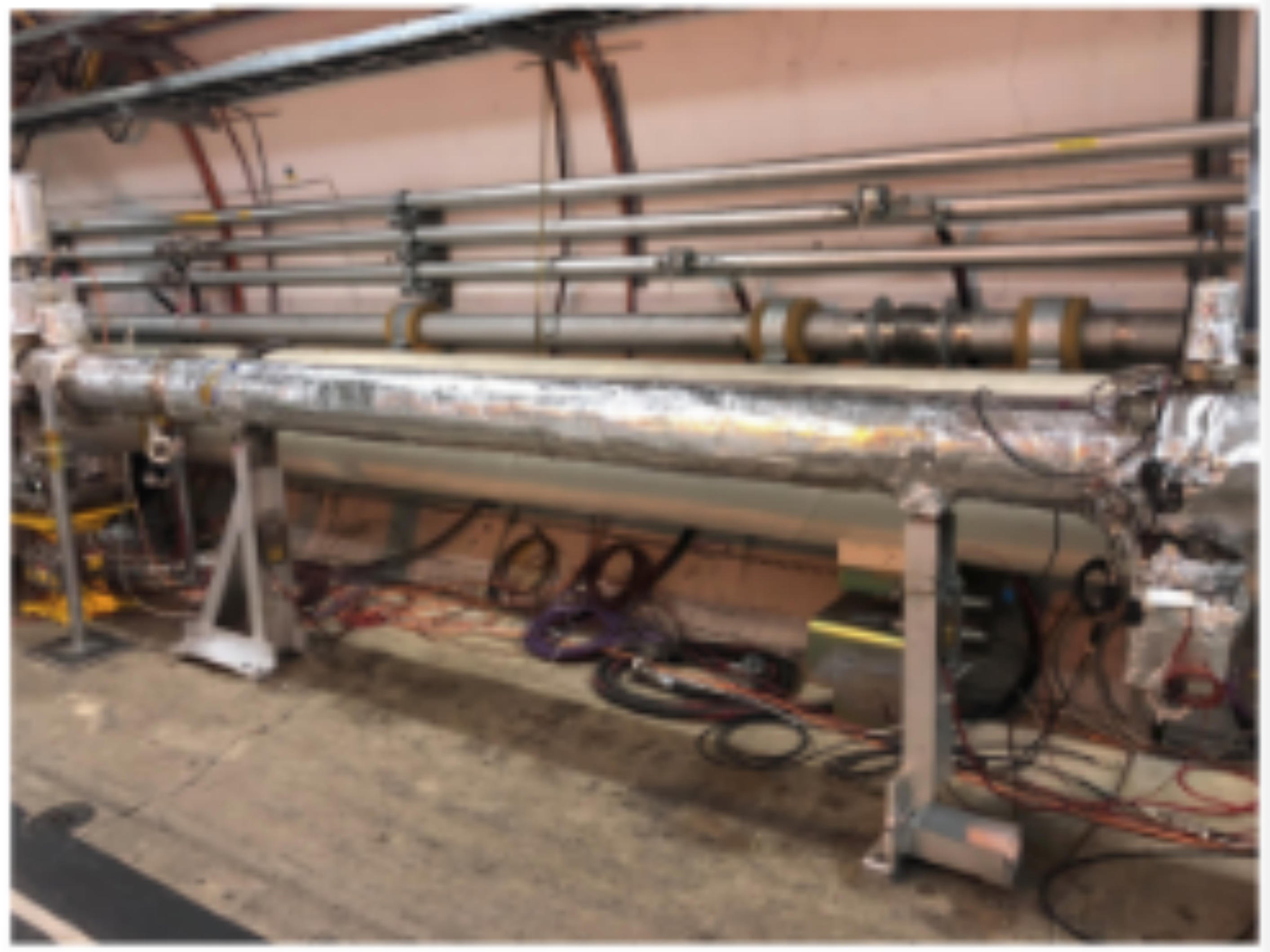








space availability at z = 3259 m



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

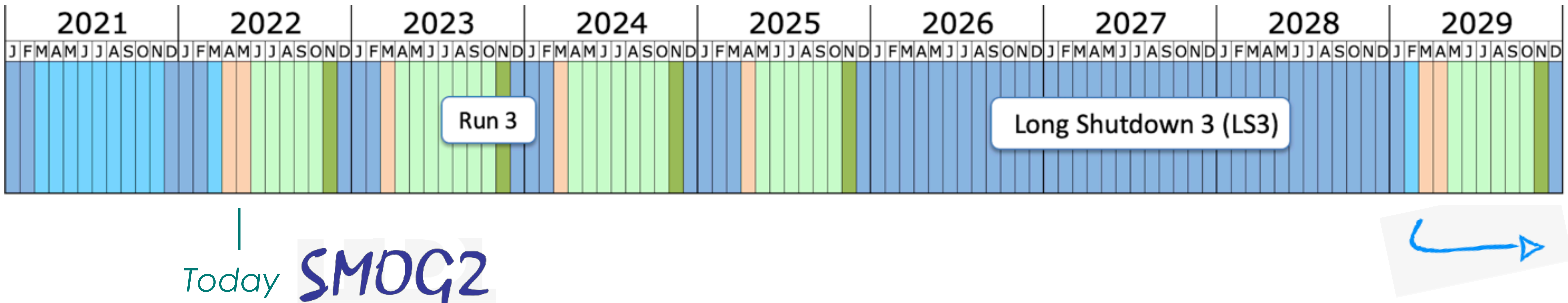
Λ: efficiency and p_T resolution sufficient for analysis (without extra vertex detector)

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

Conclusions



SMOG2

LHCspin

ALICE FT

Fixed target physics at LHC is an exiting reality

ALICE has potentialities in the unpolarised case showing complementarity to LHCb

LHCb {
SMOG2 already operative and ready to take 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