Istituto Nazionale di Fisica Nucleare

A fixed target for the LHC

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LHCb

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BNL, Nov 30, 2023

The LHCb detector

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

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

- Particle identification with RICH+CALO+MUON

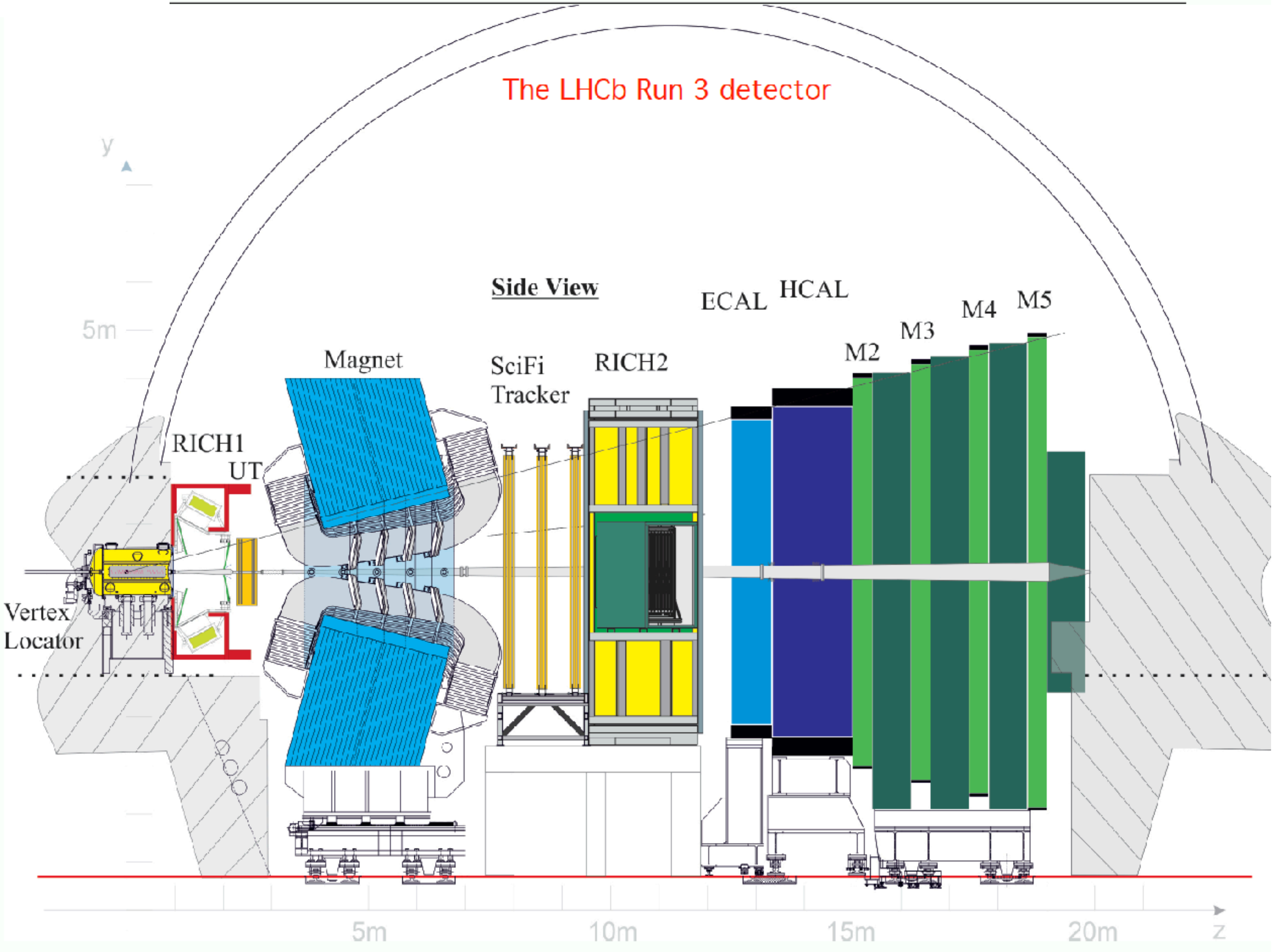
$\epsilon_\mu \sim 98\,\%$ with $\epsilon_{\pi\to\mu} \lesssim 1\,\%$

- Low momentum muon trigger:

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

will be reduced thanks to the new fully-software trigger

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

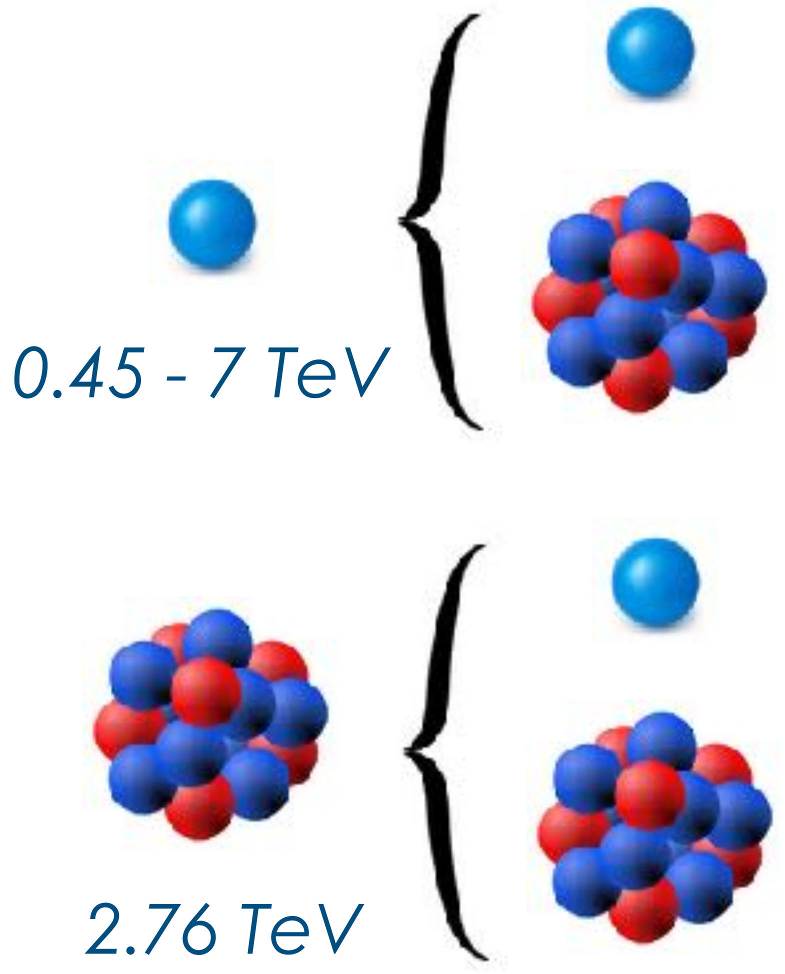


[JINST 3 (2008) S08005]

[IJMP A 30, 1530022 (2015)]

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

Collisions provided by a **TeV-scale beam** (LHC) on a fixed target explore a **unique kinematic region** that has been poorly probed before.
In addition, the advanced detector (LHCb) makes available **probes** never before accessed



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

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

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

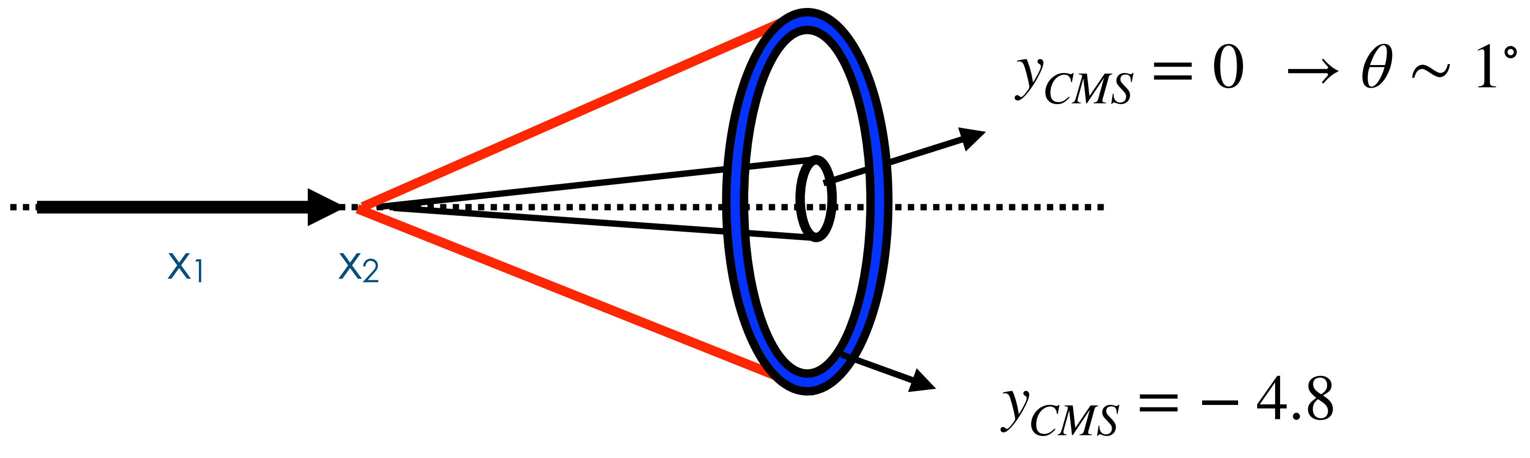
AA collisions: 2.76 TeV beam on fix target

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

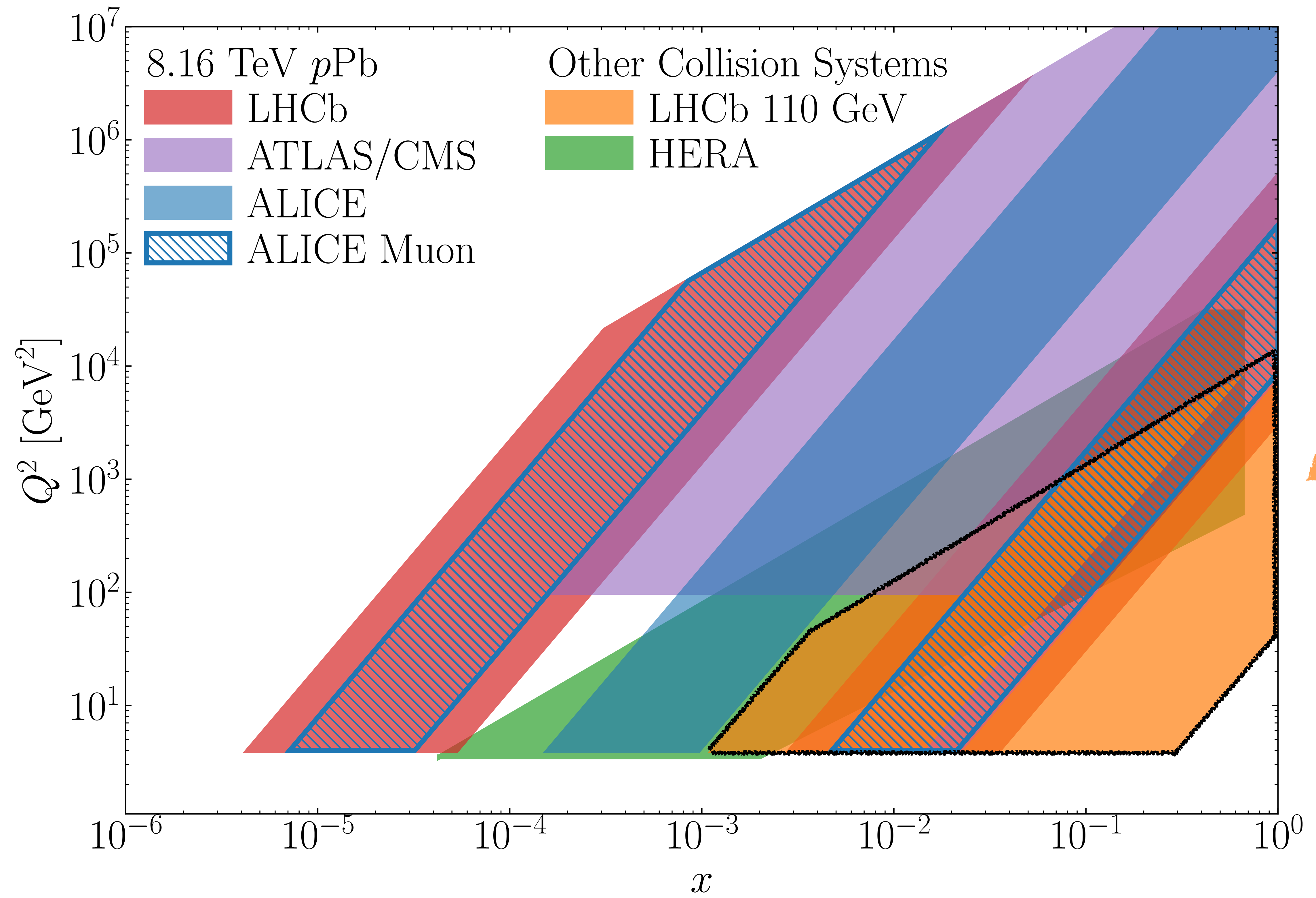
$$y_{CMS} = 0 \ \rightarrow \ y_{lab} = 4.3$$

1: beam; 2: target

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



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

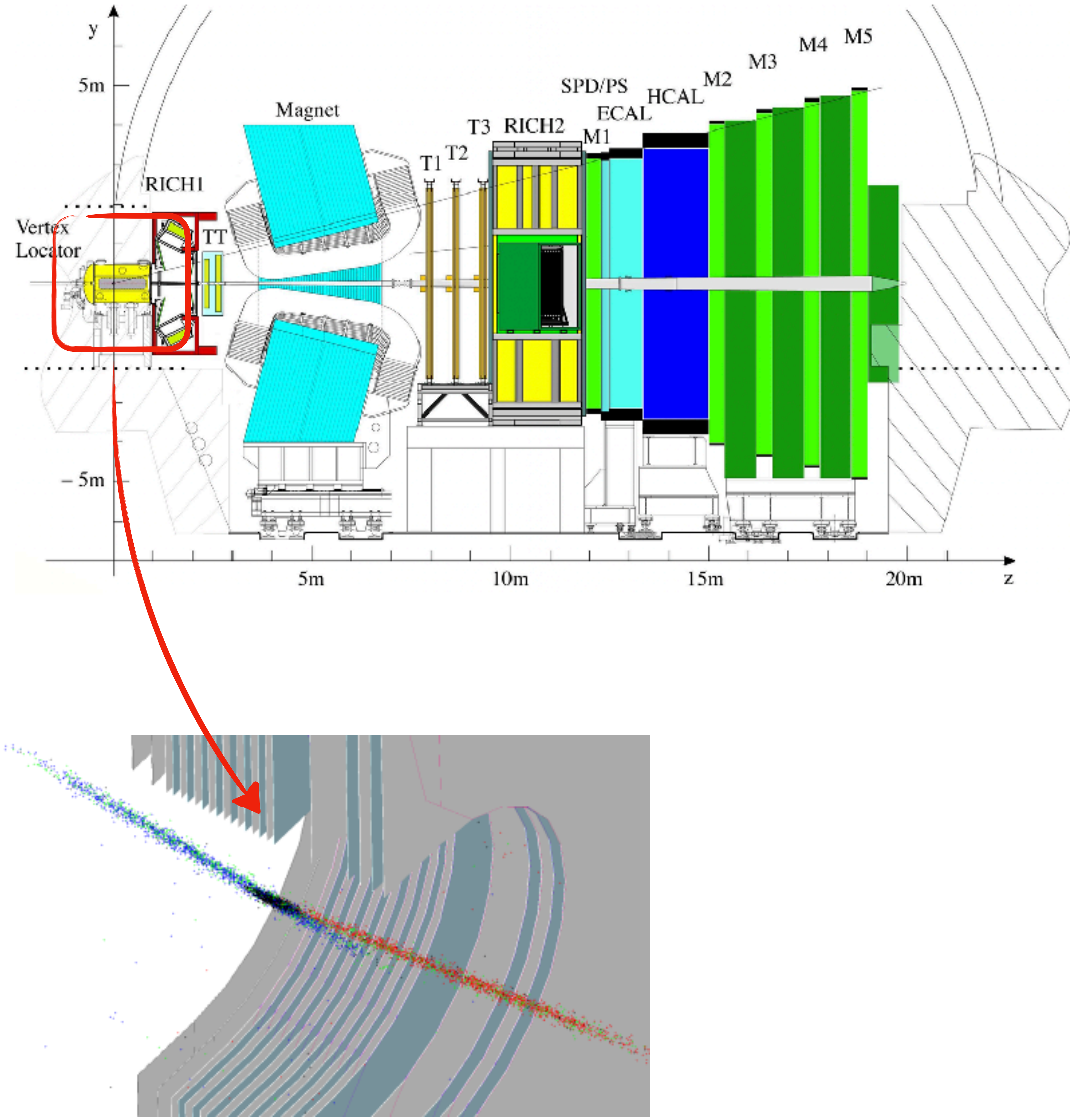


Broad and poorly explored kinematic range

mid-to-large x_{Bj} at intermediate Q^2 and negative x_F

SMOG (System for Measuring Overlap with Gas)

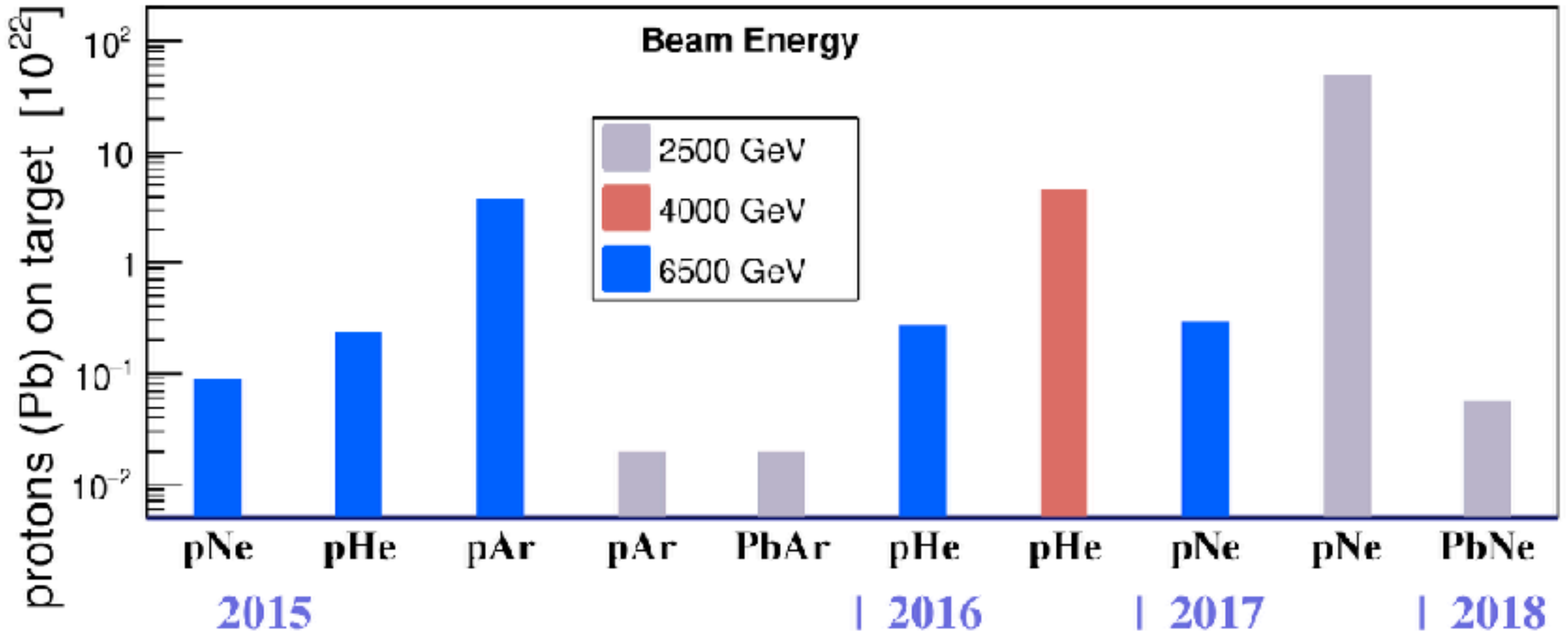
JINST 9 (2014) 12



SMOG was thought for a precise determination of the beam bunch profile, but then acted also as a prototype for a gas fixed target

Local increase of the LHC beam pipe pressure from ~10^{-9} mbar to ~10^{-7} mbar

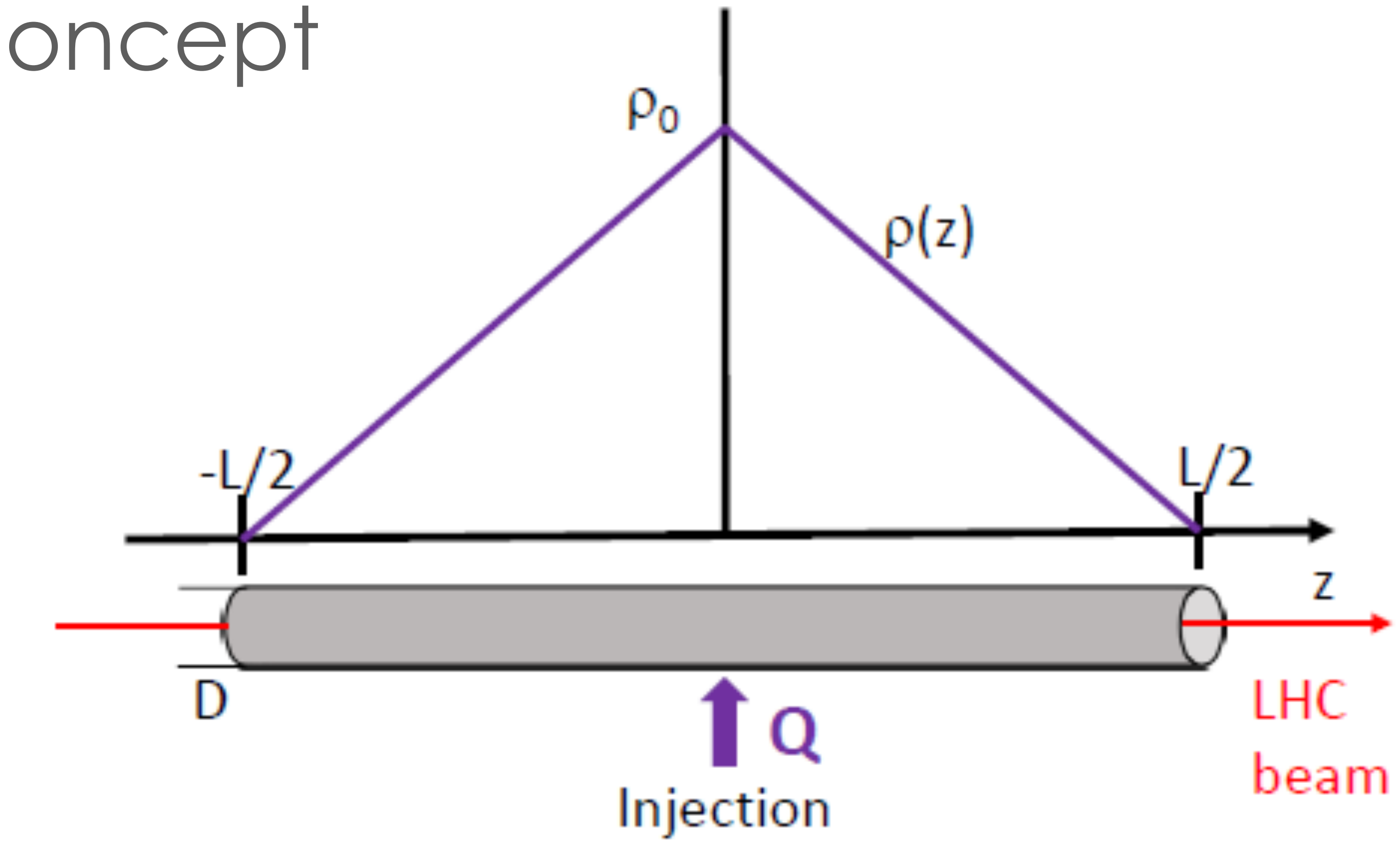
The negative aspect is the overlap of the gas volume with the beam-beam interaction region



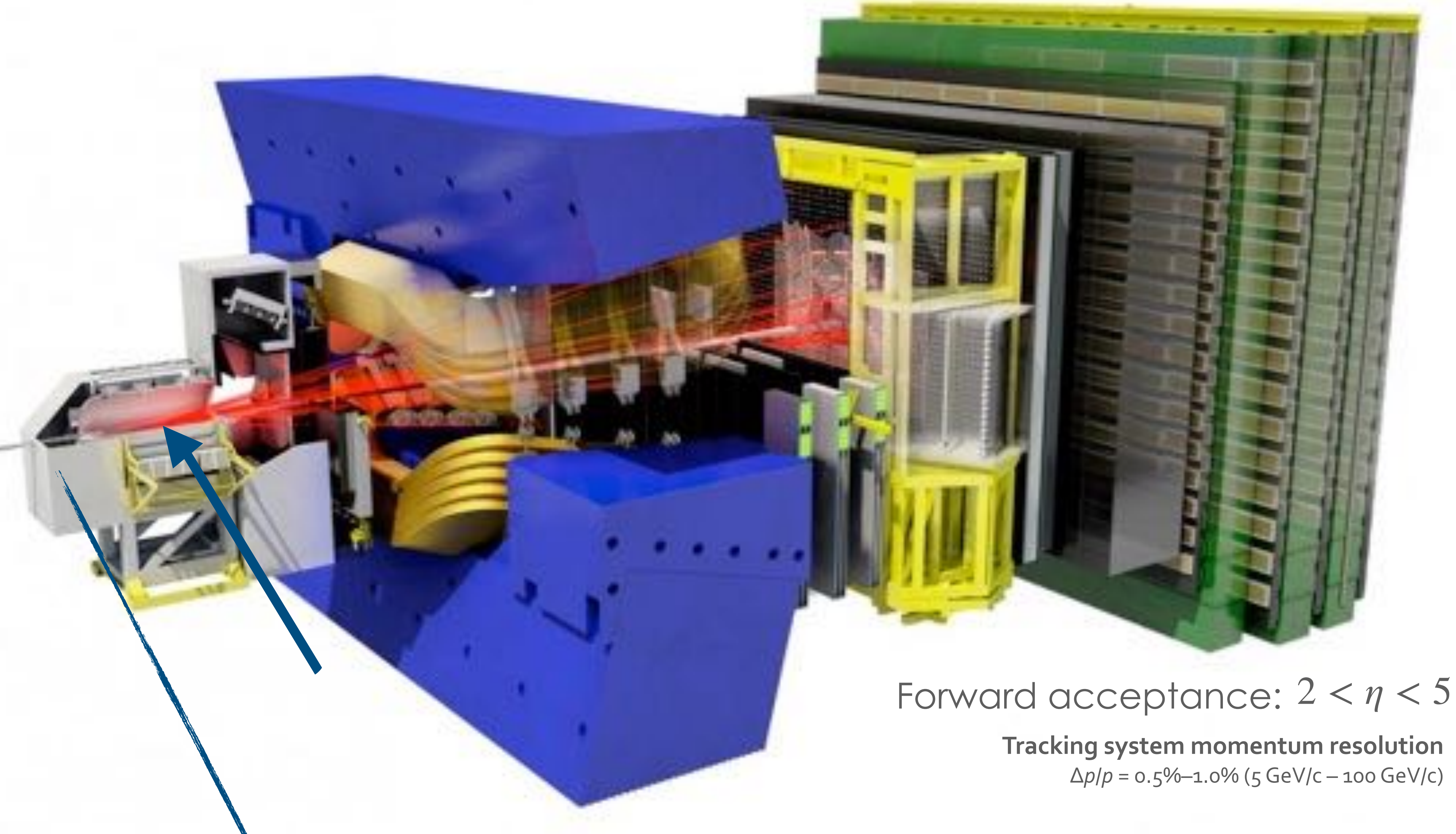
SMOG2 an unpolarised target at LHCb

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

Storage cell concept



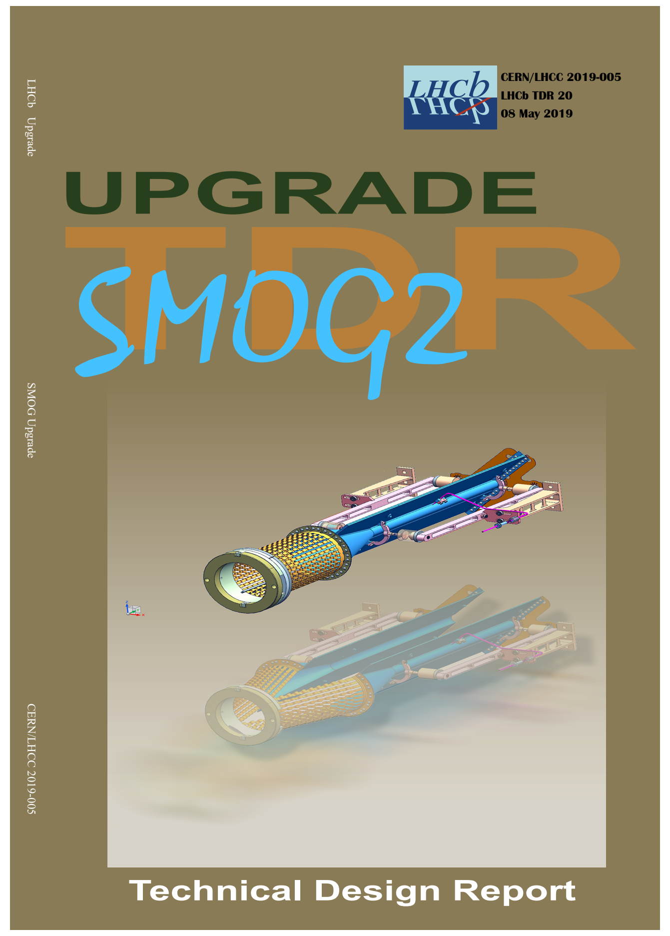
LHC beam



Forward acceptance: $2 < \eta < 5$

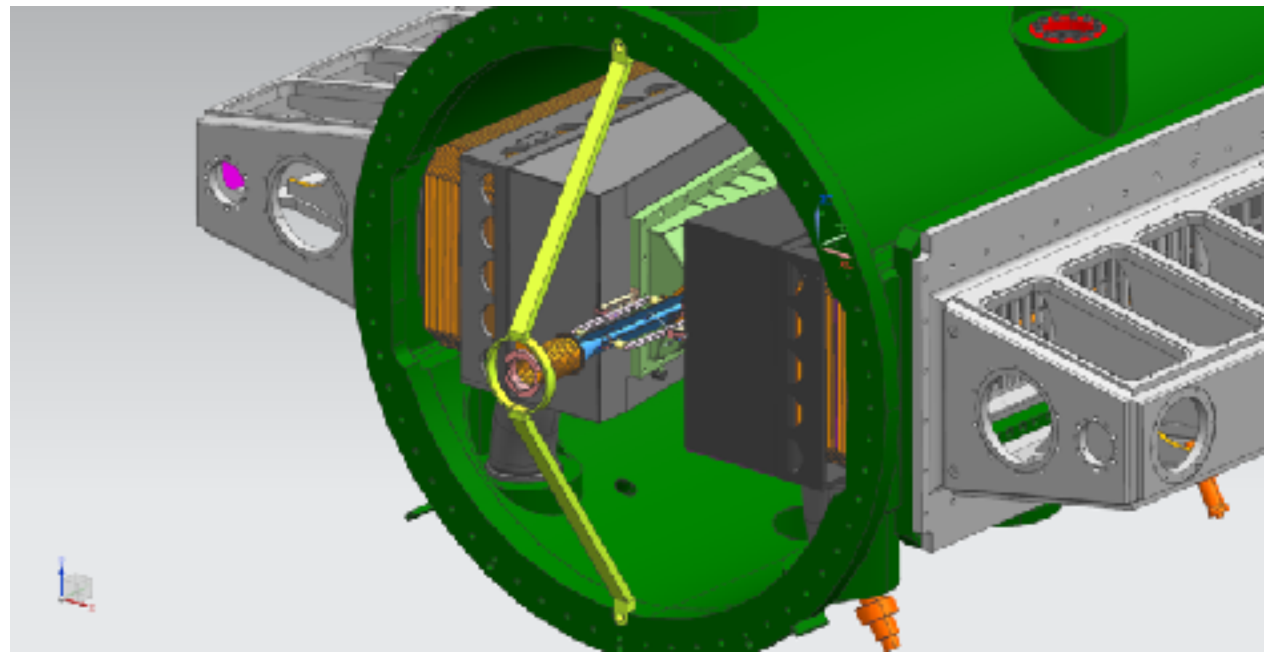
Tracking system momentum resolution
$\Delta p/p$ = 0.5%–1.0% (5 GeV/c – 100 GeV/c)

beam-beam collisions



areal density [cm^{-2}]

$$\theta = \frac{1}{2}\frac{\Phi}{3.81\sqrt{\frac{T}{M}}\frac{D^3}{L+1.33D}}L$$

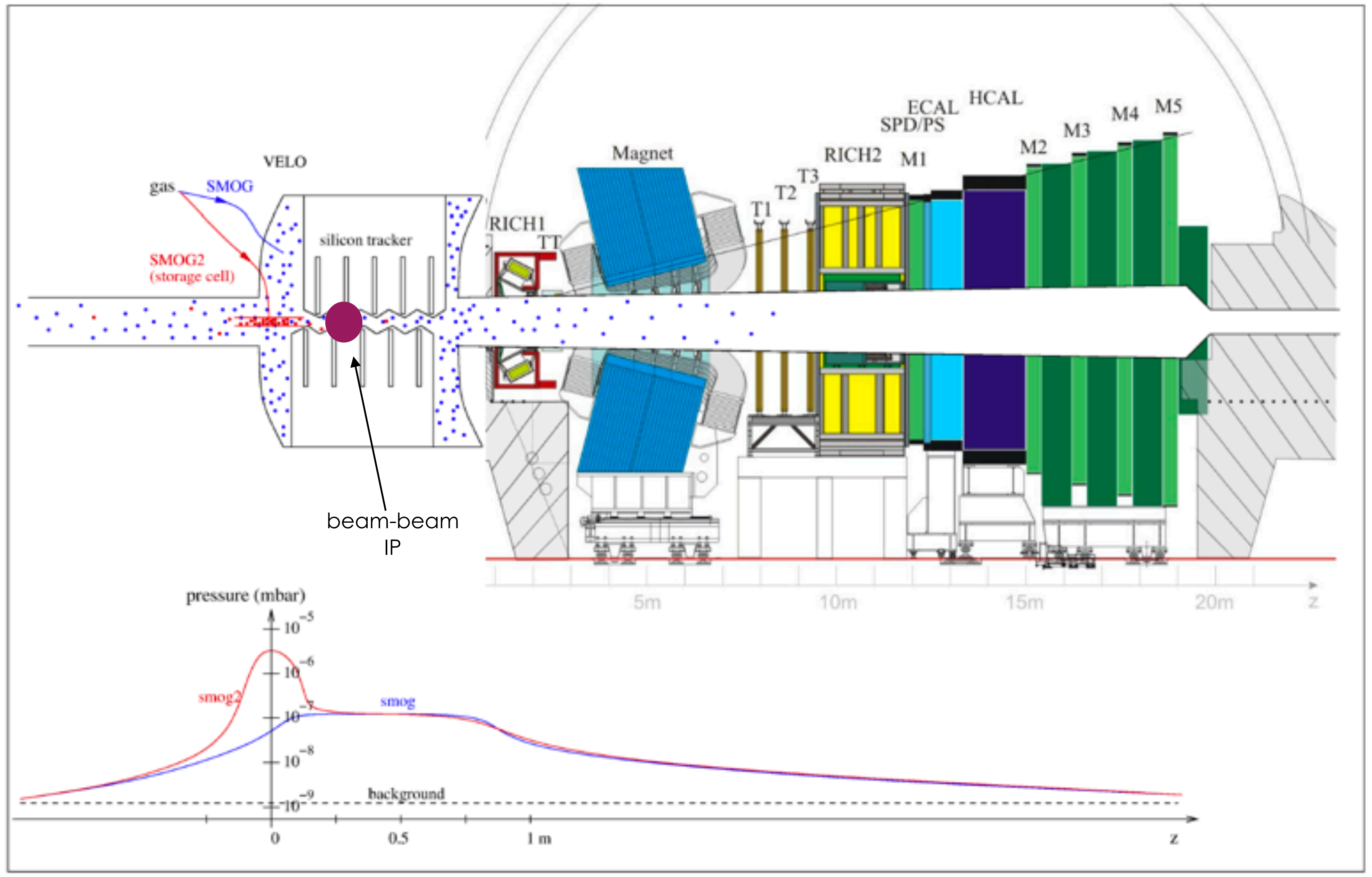


UNpolarised target (beam-gas)

SMOG2, the first LHC internal storage cell

A gas storage cell can boost the gas density by ~40 for the same flow as in Run2 with SMOG.
At the end, increasing the gas flux, we have:

SMOG2 >130 x SMOG

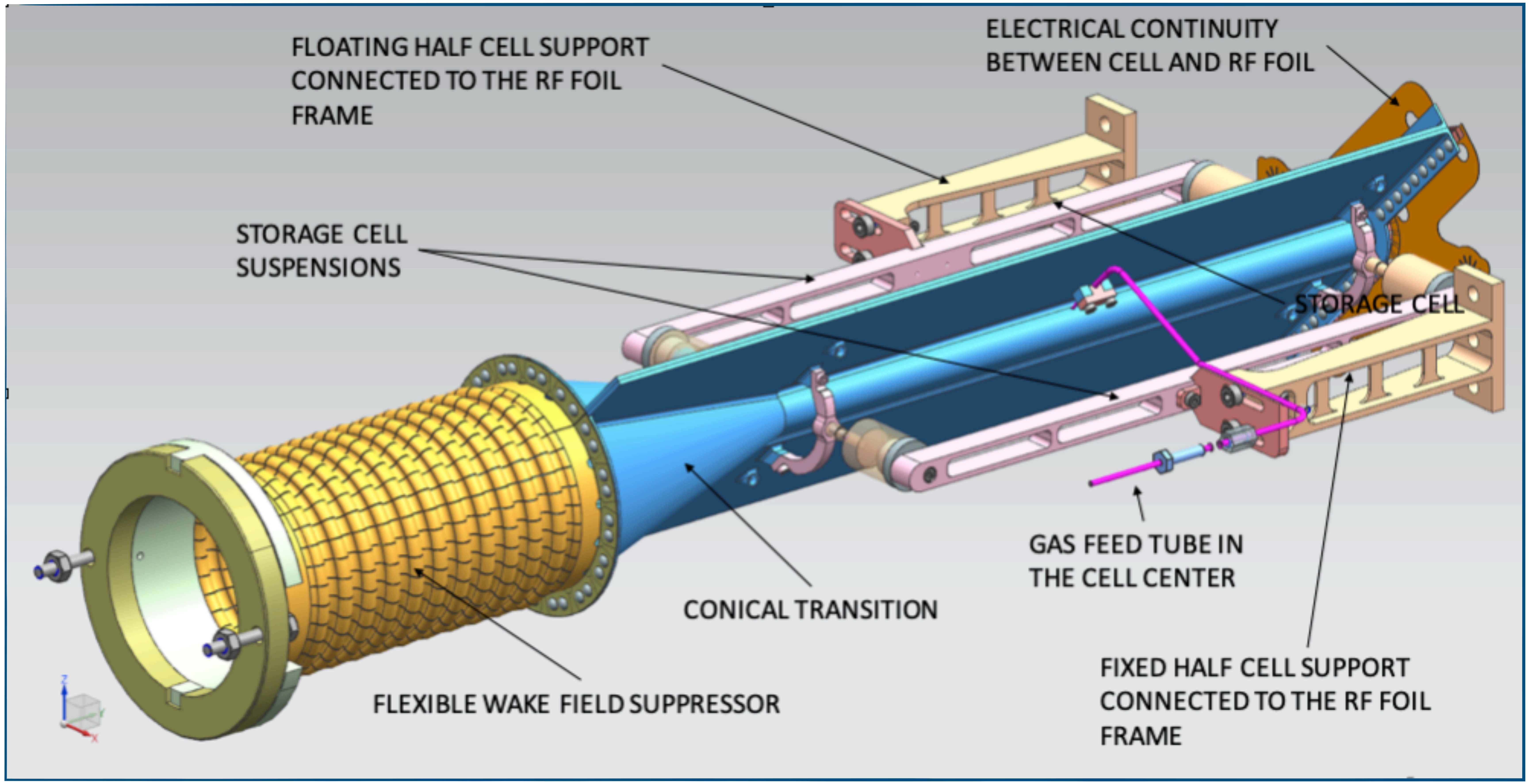


SMOG

- The interaction region is spread-out in PVz
  - only non-colliding bunches can be used
  - ghost charge pollution (debunched pp collider interactions from protons
- luminosity determination: p+e- elastic scattering as a standard candle (~6% of systematic uncertainty)

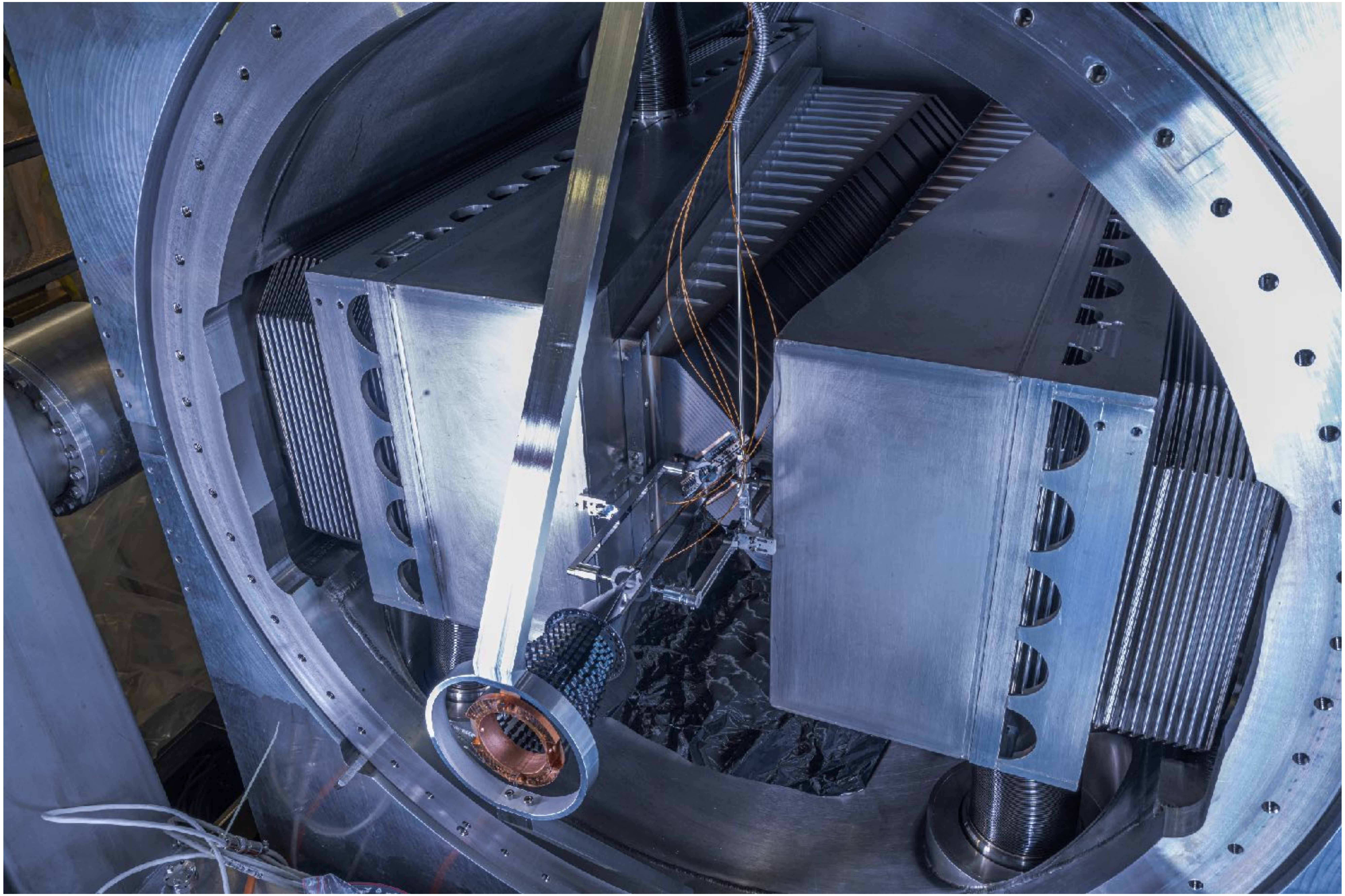
SMOG2

- Separate beam-beam and beam-gas interaction regions
  - both colliding and non-colliding bunches can be used
  - simultaneous data-taking with pp
- precise luminosity determination: direct measurement of the pressure in storage cell (~1.5% of systematic uncertainty)



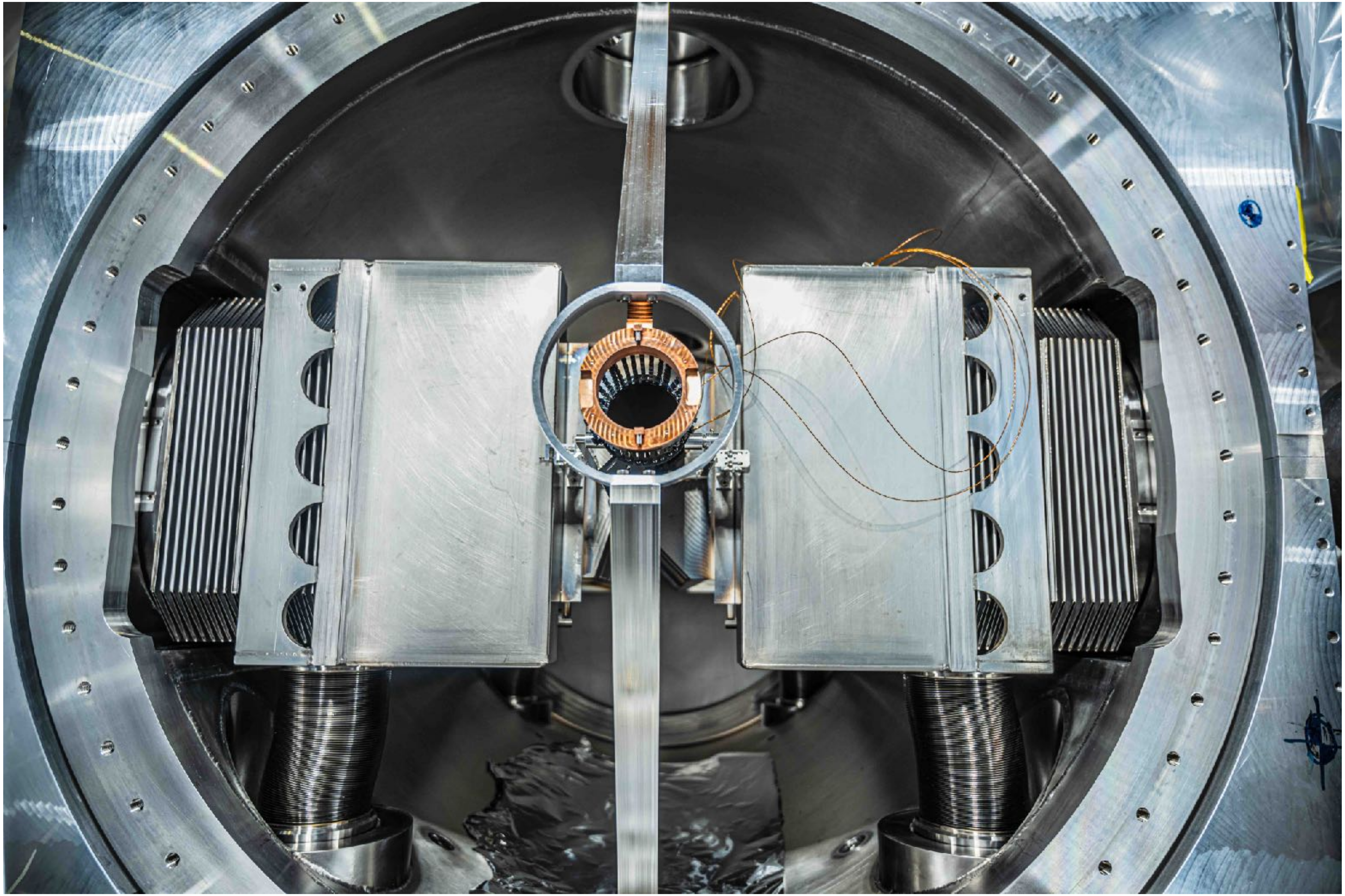
cell length = 20 cm (total length =3 8 cm)
cell diameter = 1 cm
cell wall distance from the beam = 1.5 - 5 mm
cell wall thickness = 0.2 mm

SMOG2



It is the only system present in the LHC primary vacuum

SMOG2



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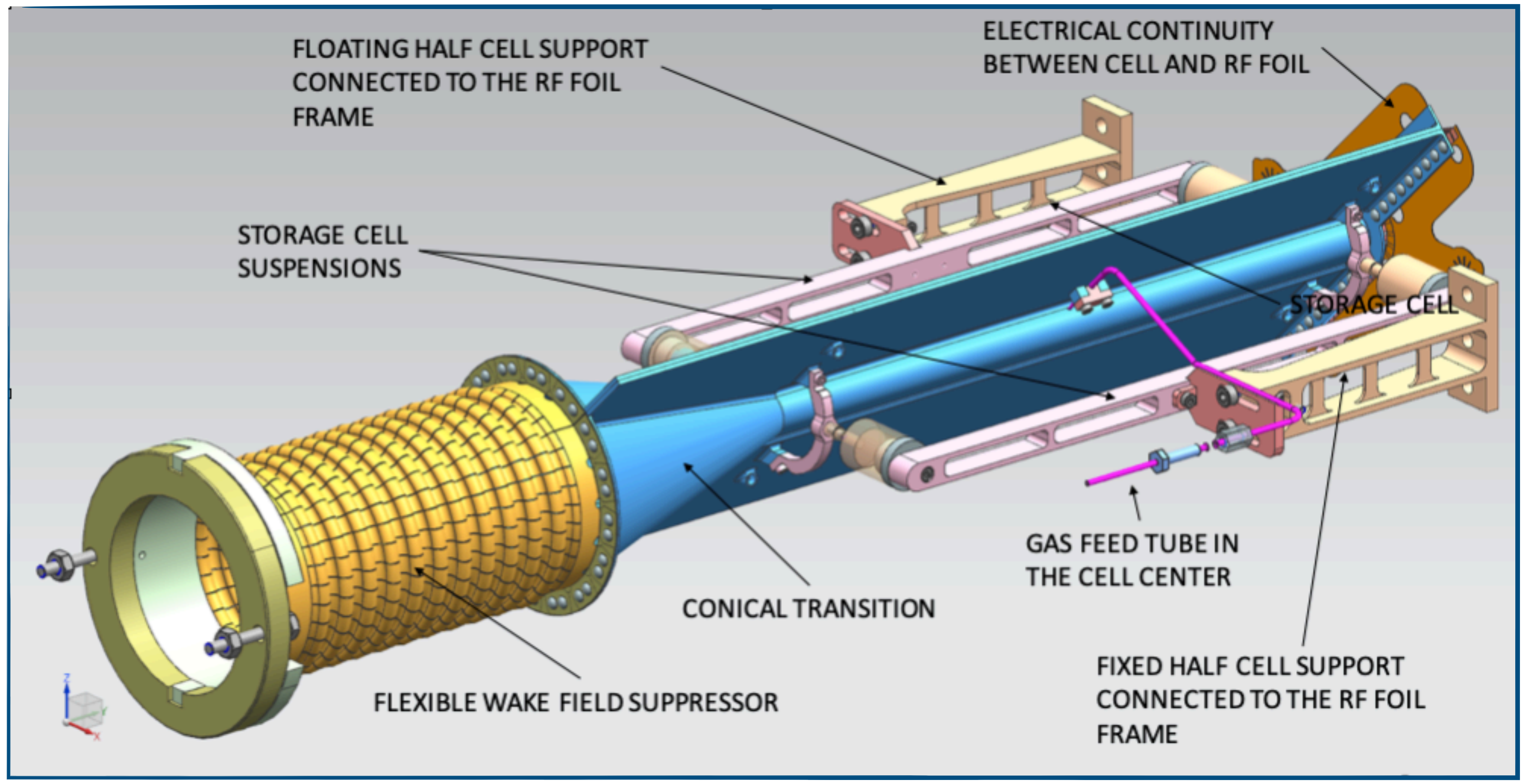
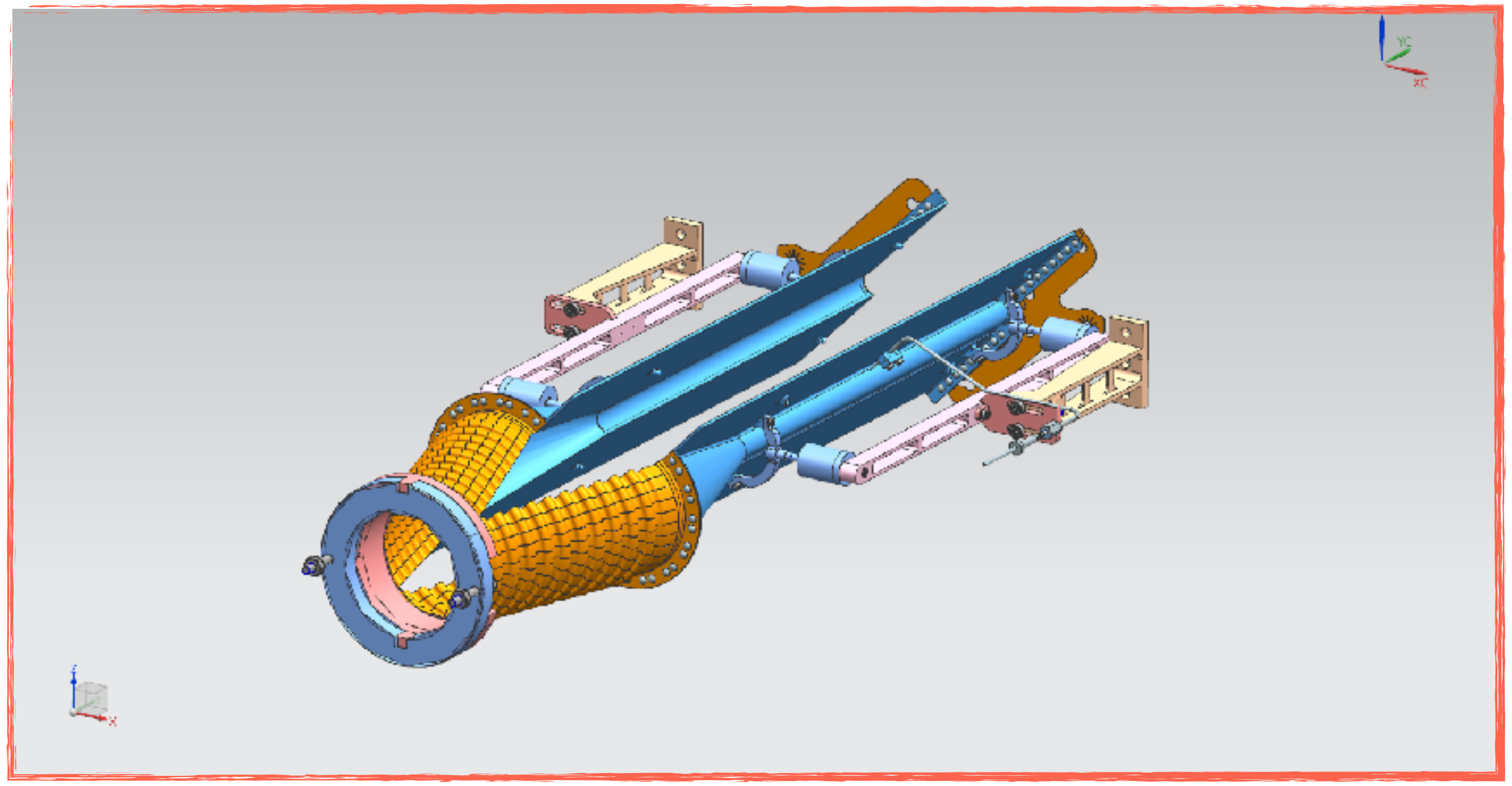
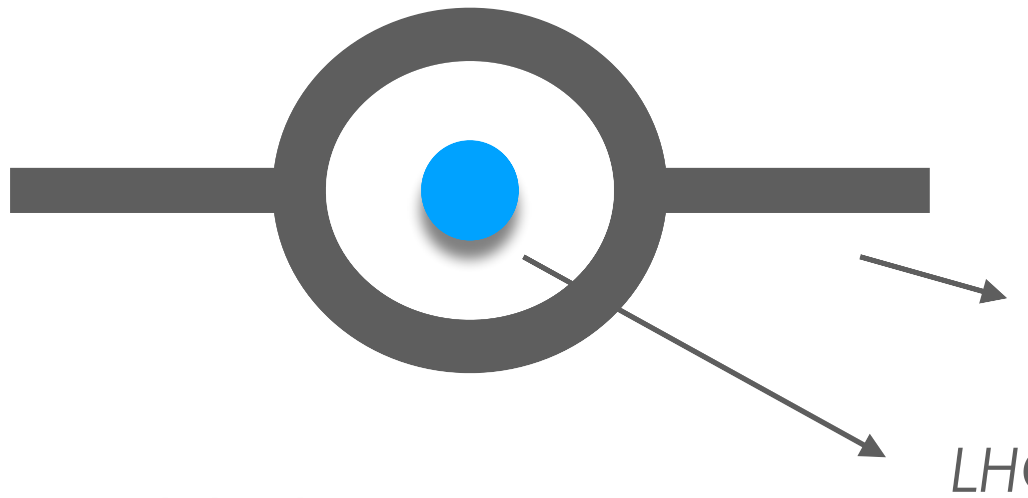
Openable cell





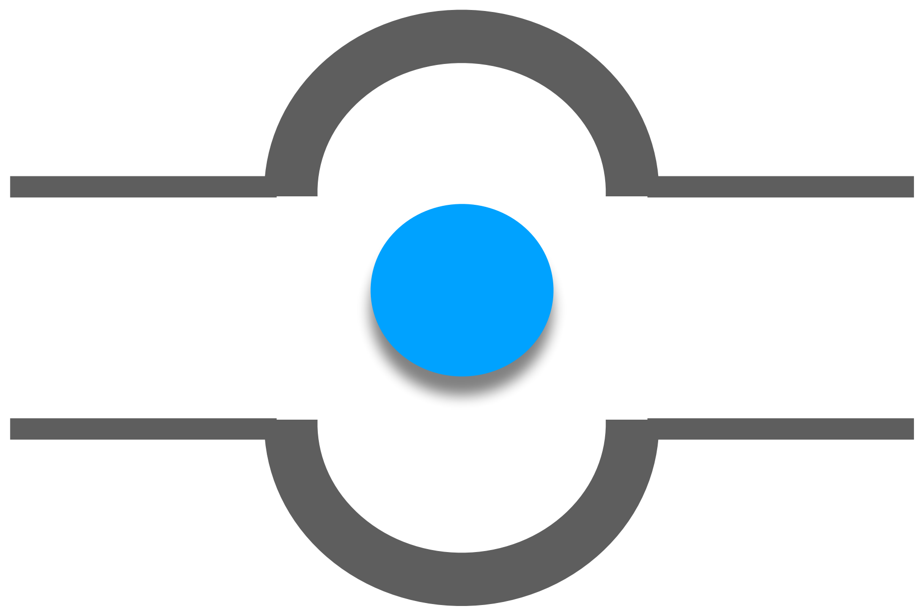
5 mm radius x 200 mm length



target cell profile

LHC transverse beam profile

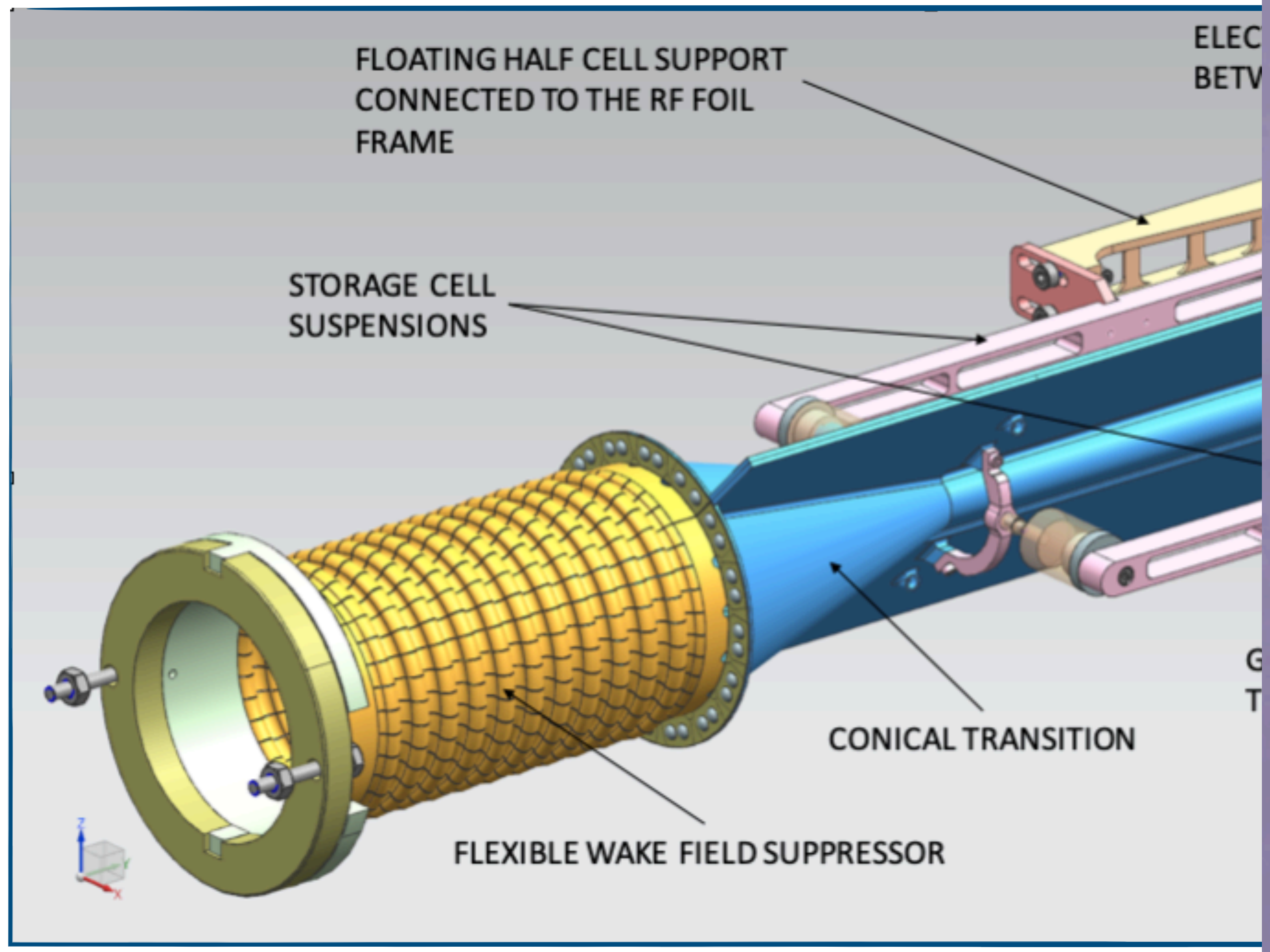
stable beam @7000 GeV

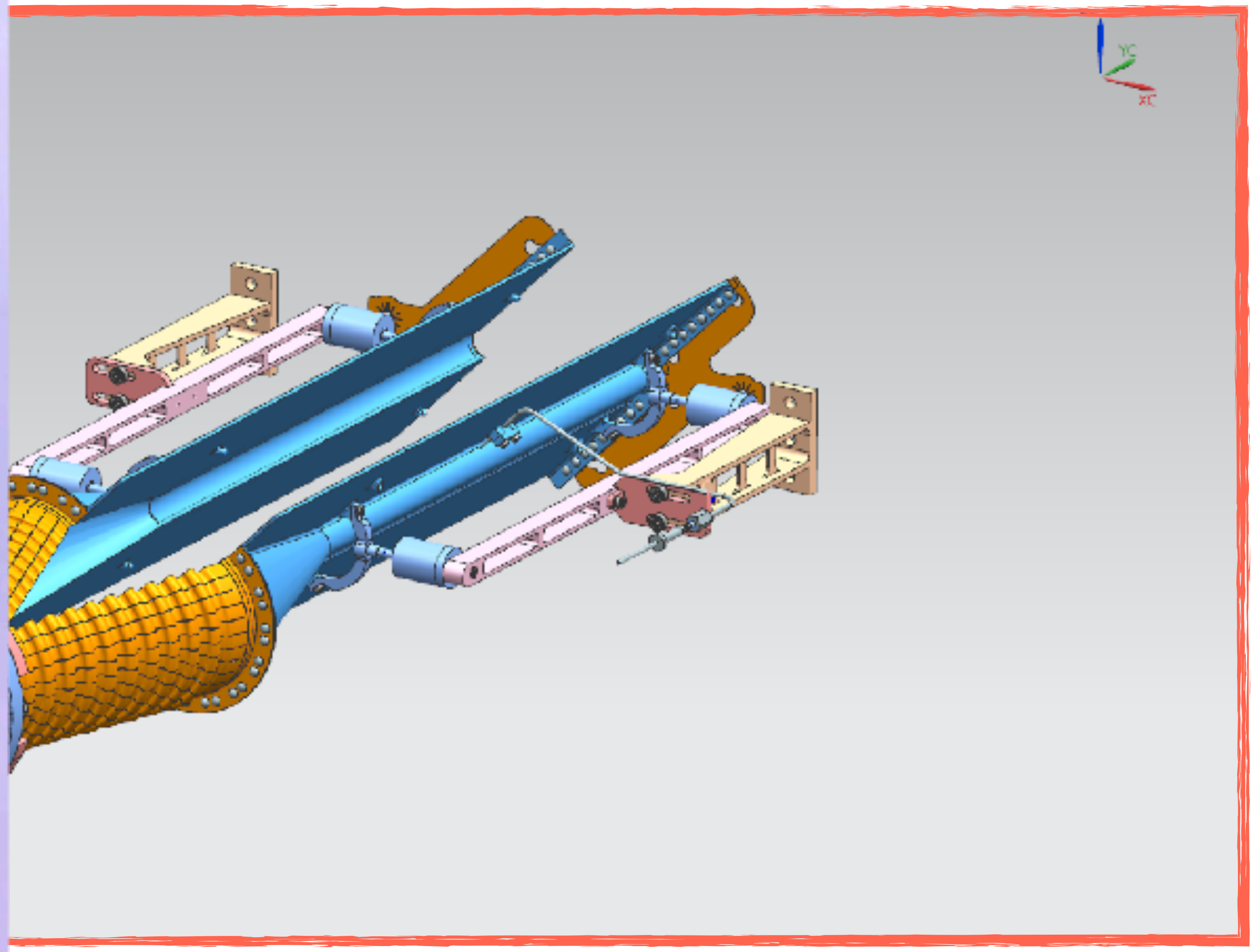


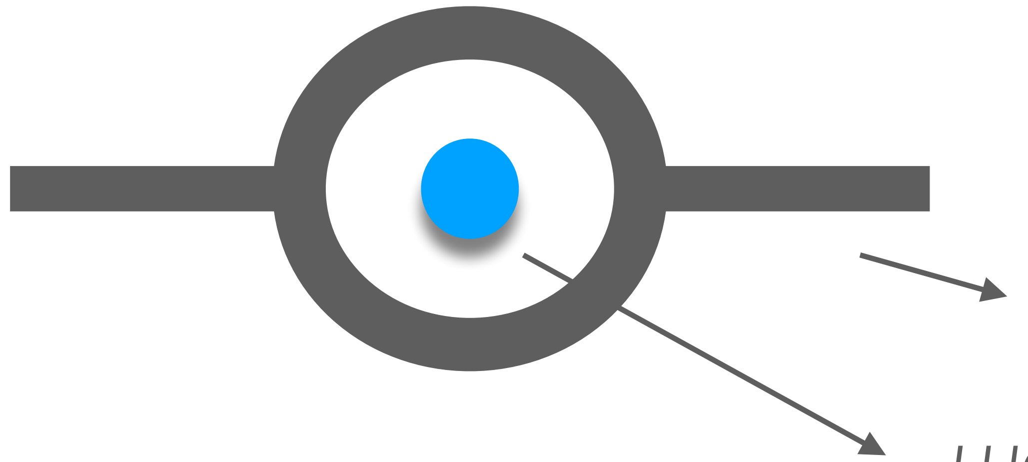
beam at the injection energy of 450 GeV

Openable cell

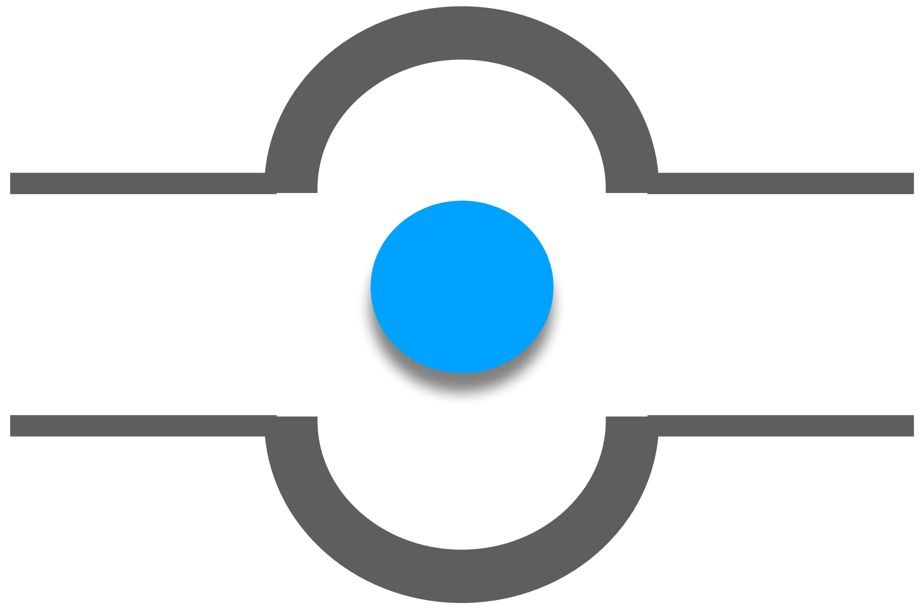
the movie is 10 times faster than reality







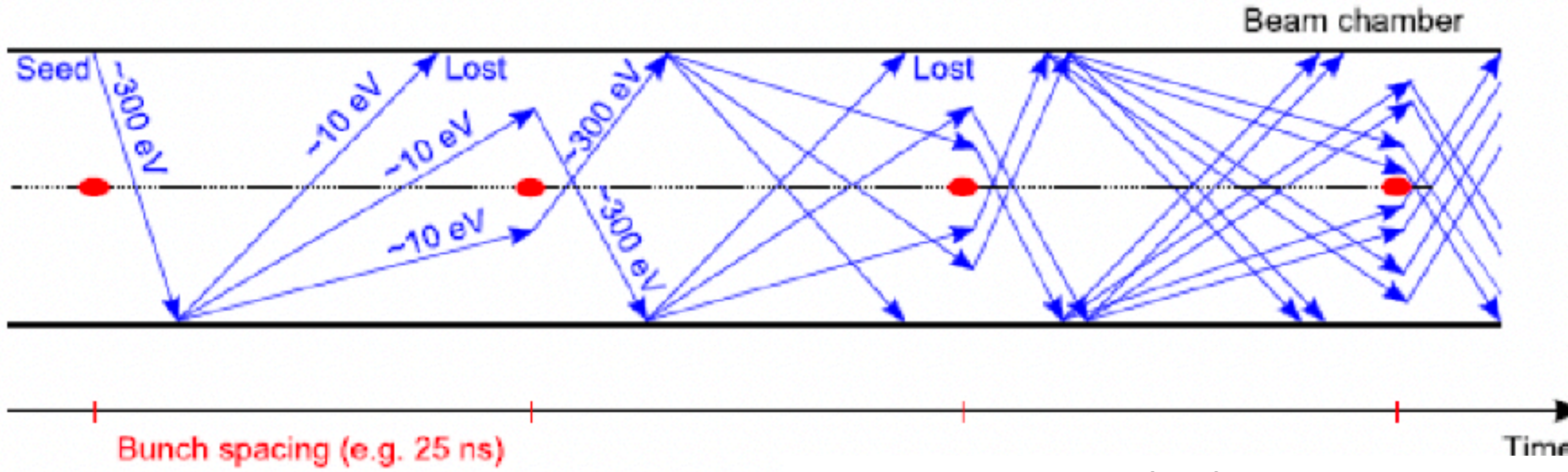
stable beam
@7000 GeV



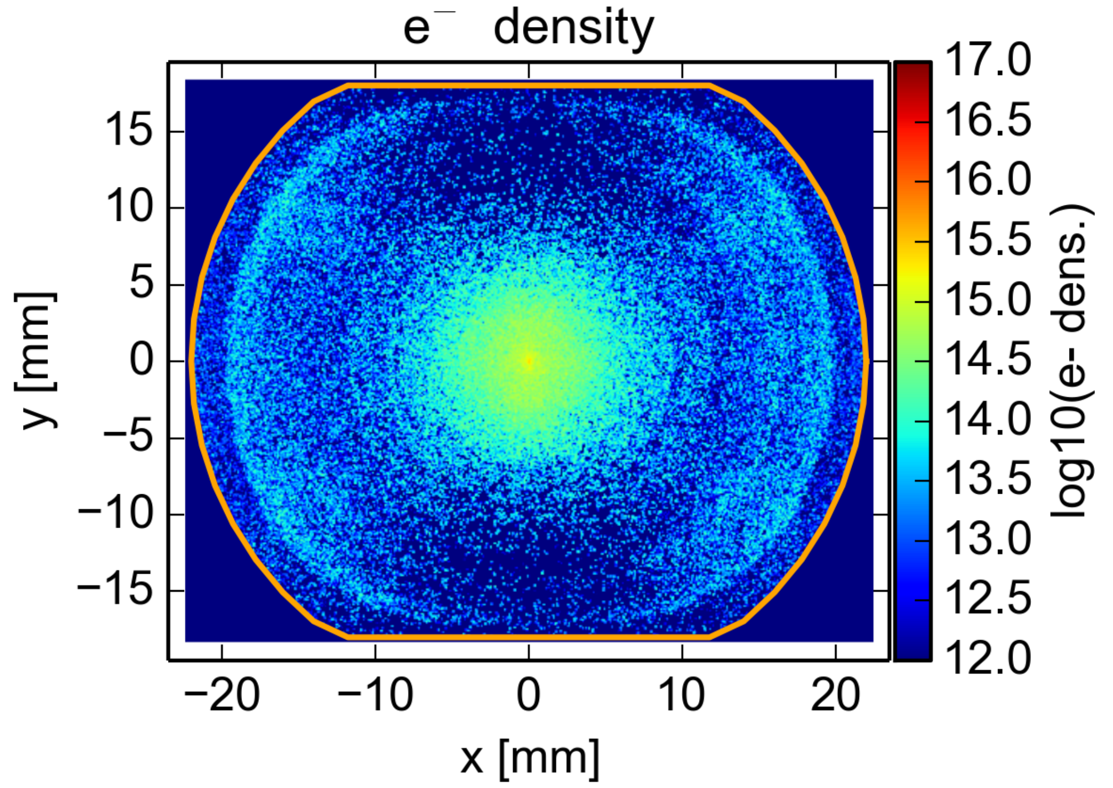
beam at the injection
energy of 450 GeV

Coating

Electron Cloud effects are observed in accelerators with positive particles. Slow electrons produced by various ionization processes are trapped near the beam. They are accelerated by the bunches towards the walls of the beam chamber, producing secondary electrons, which may lead to an avalanche multiplication effect (SEY) forming dense EC's



→ beam transverse oscillations and instabilities



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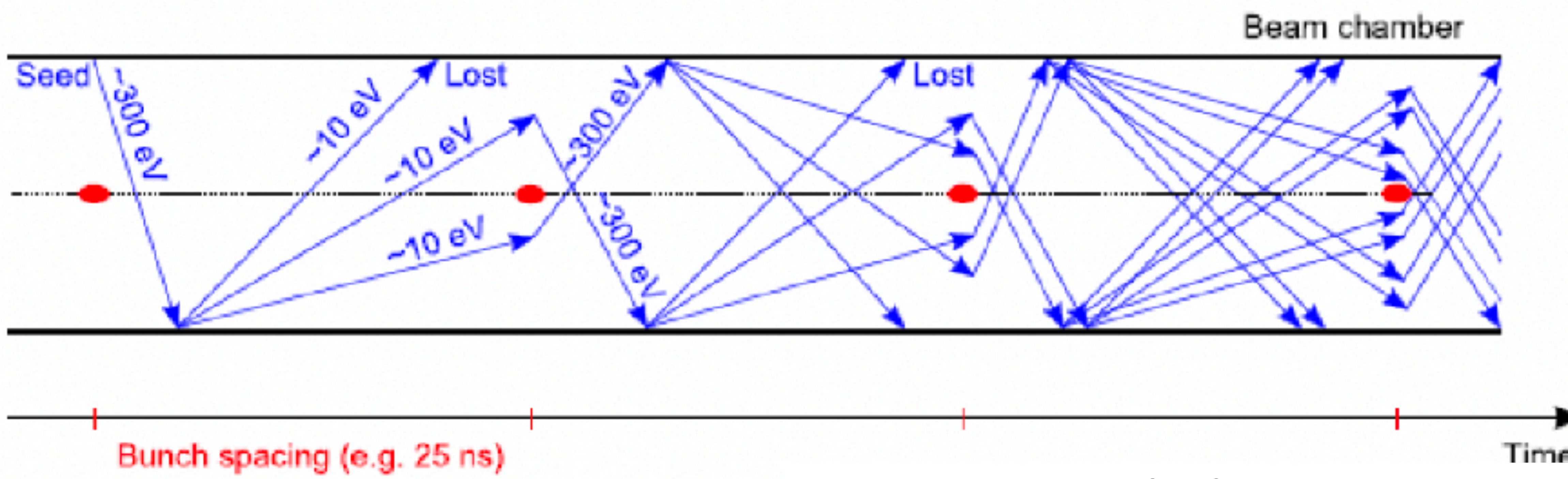

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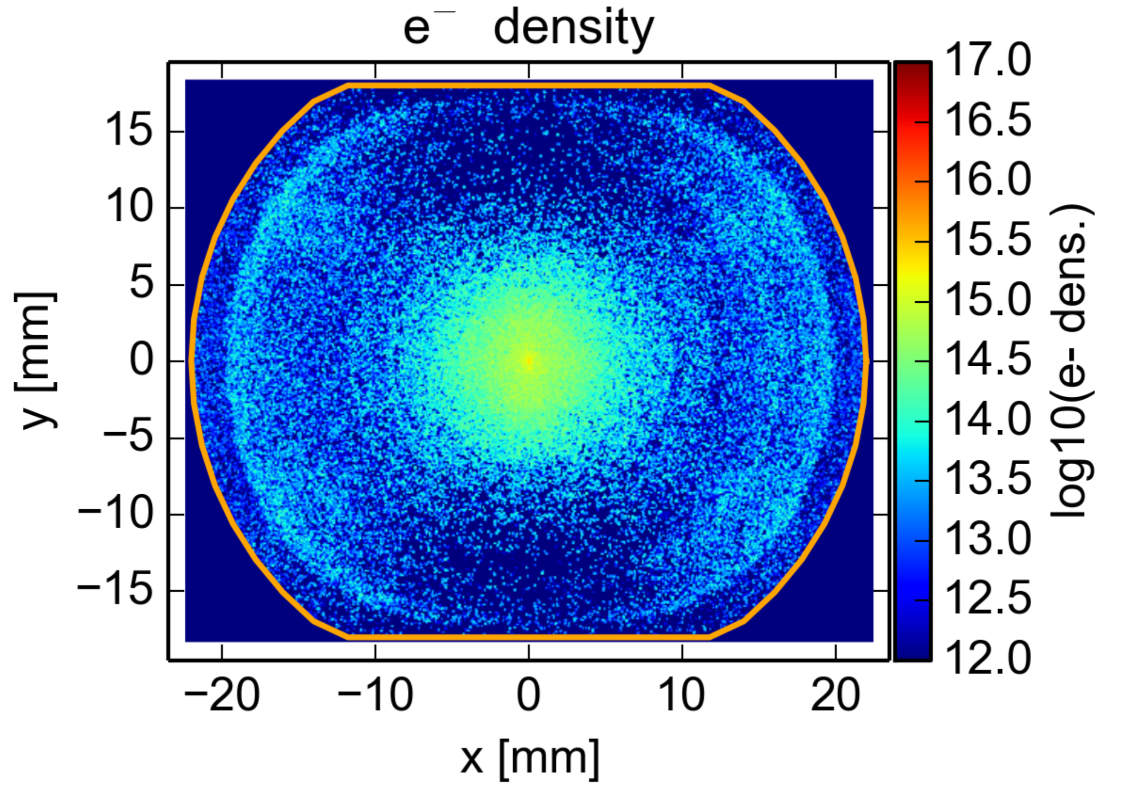
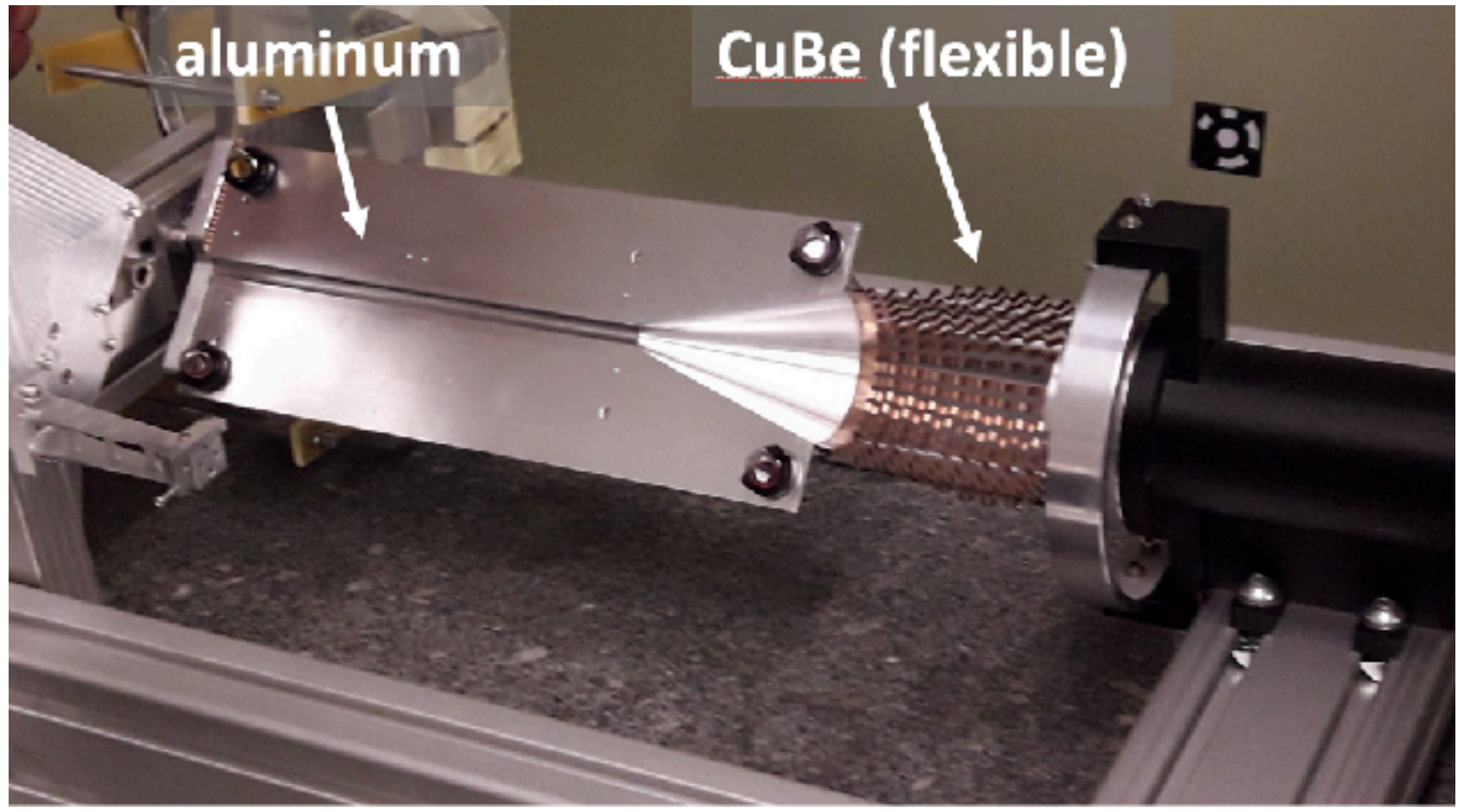
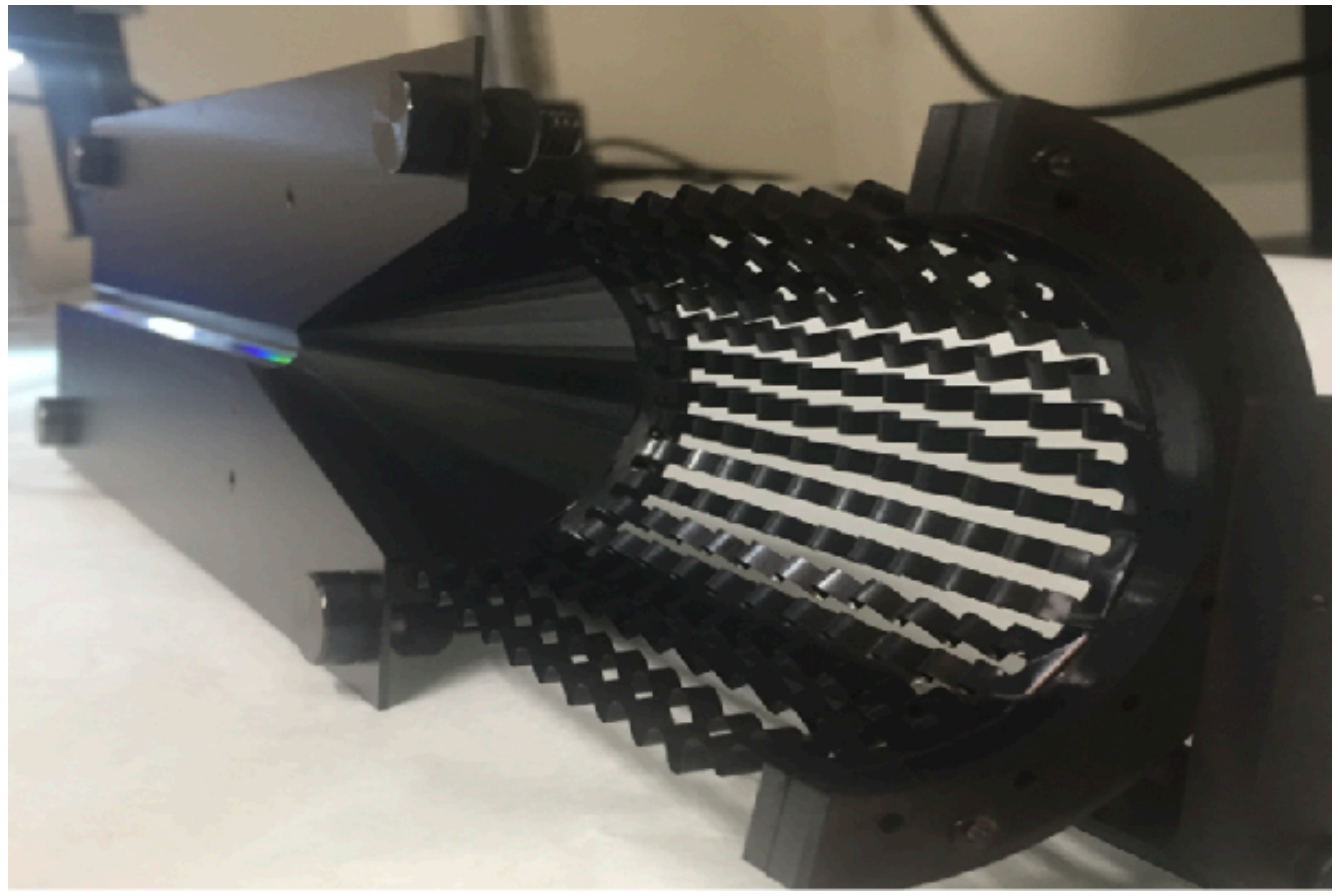


non coated



amorphous Carbon coated



final coating: 100 nm Ti + 100 nm aC

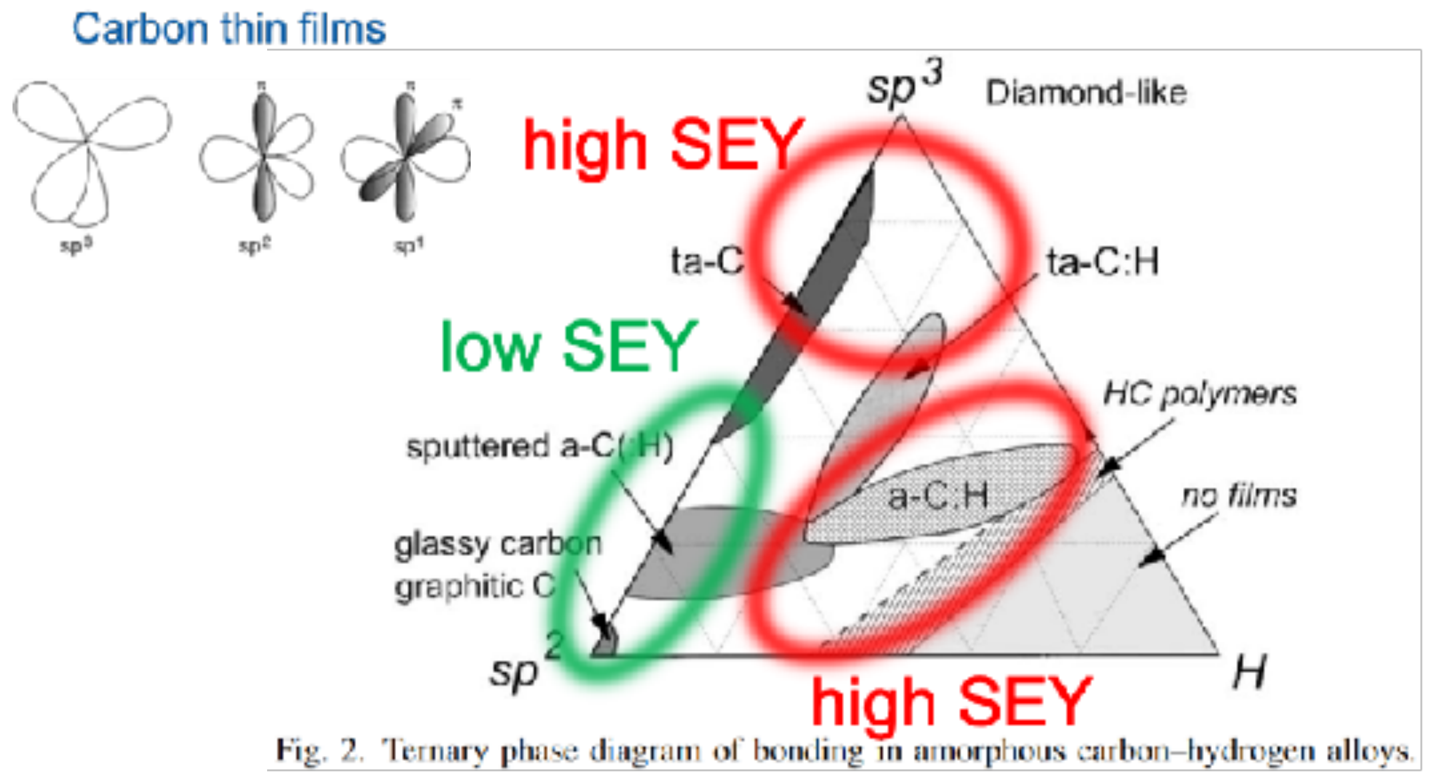


Fig. 2. Ternary phase diagram of bonding in amorphous carbon–hydrogen alloys.

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

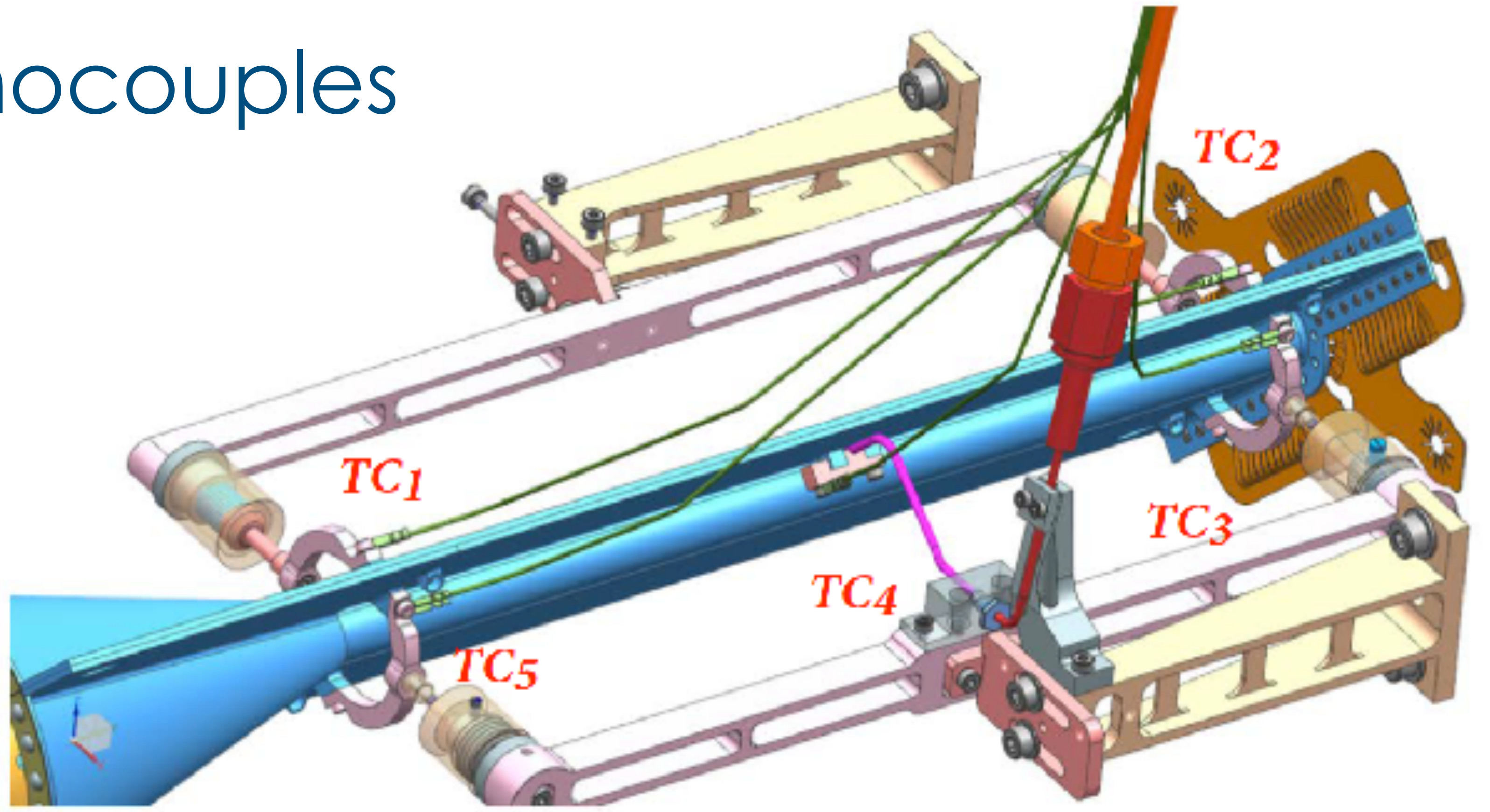
At the LHC the threshold of electron density is around 10^{18} m^{-3}

Our amorphous carbon coating is well below this limit with SEY<2.3 (ratio of emitted secondary electrons to incident primary electrons)

Temperature monitoring

Excited modes of the beam can dissipate substantial heat into the storage cell.
It is mandatory to have a resistant system and to monitor the temperatures

5 thermocouples



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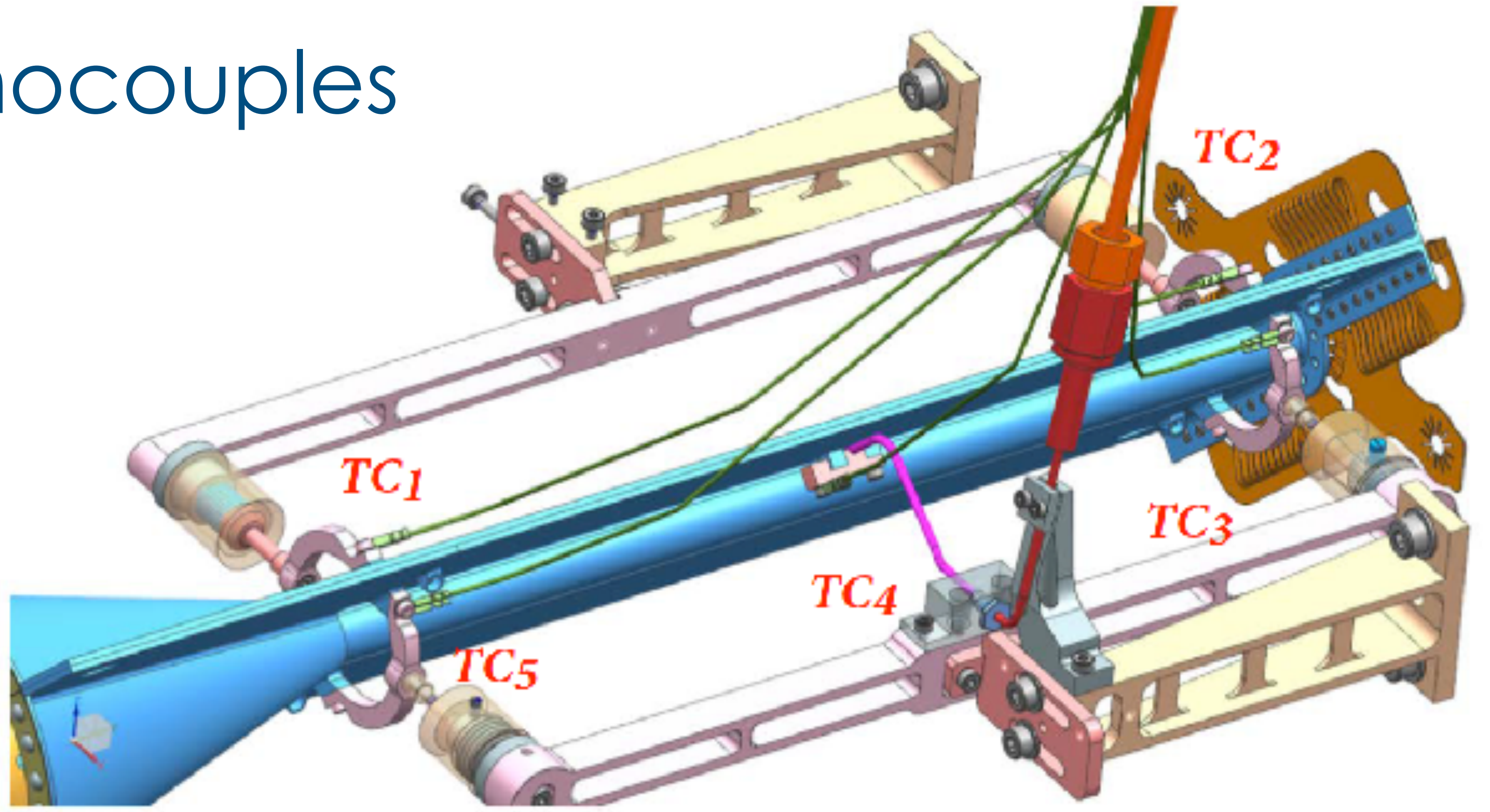
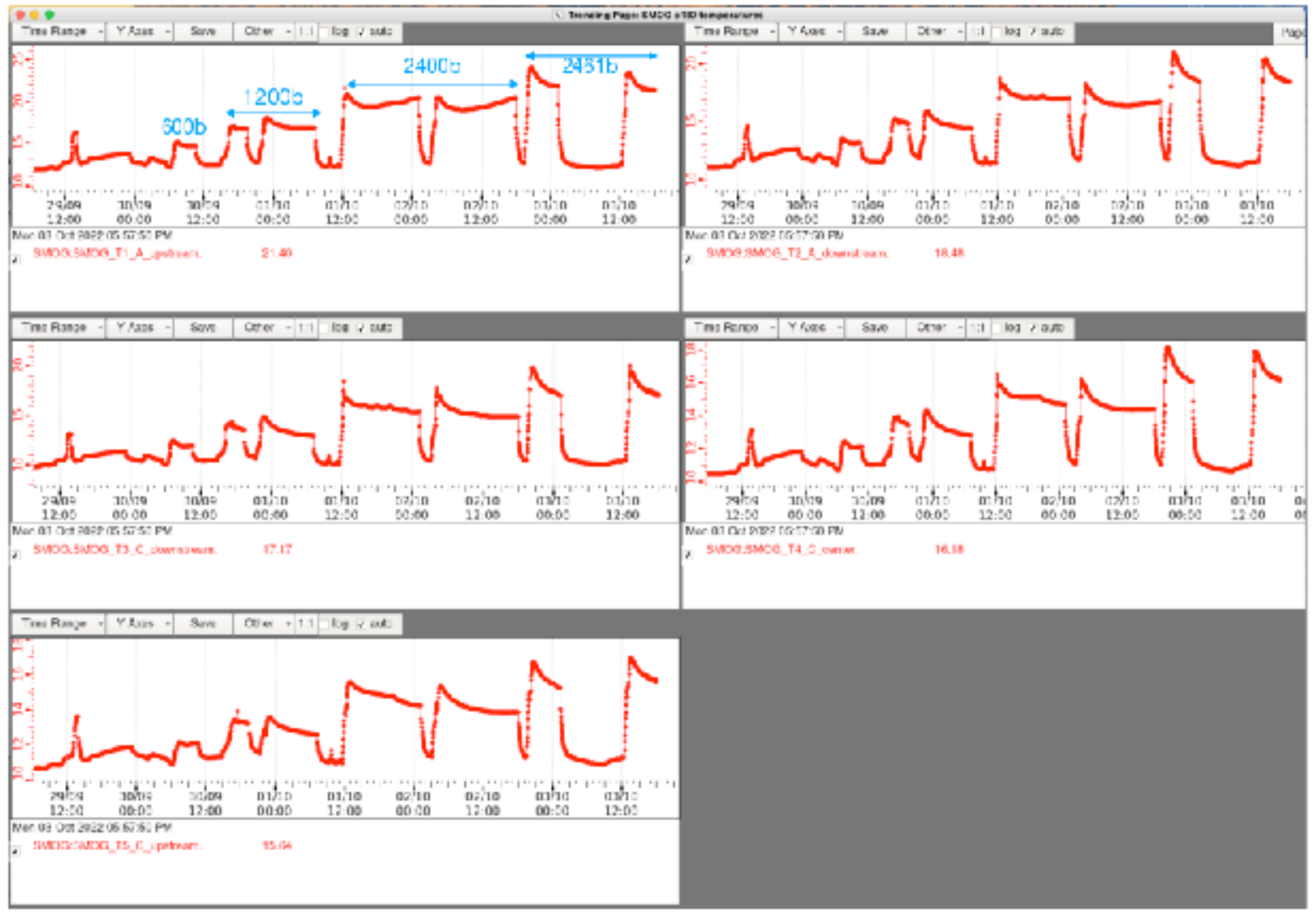
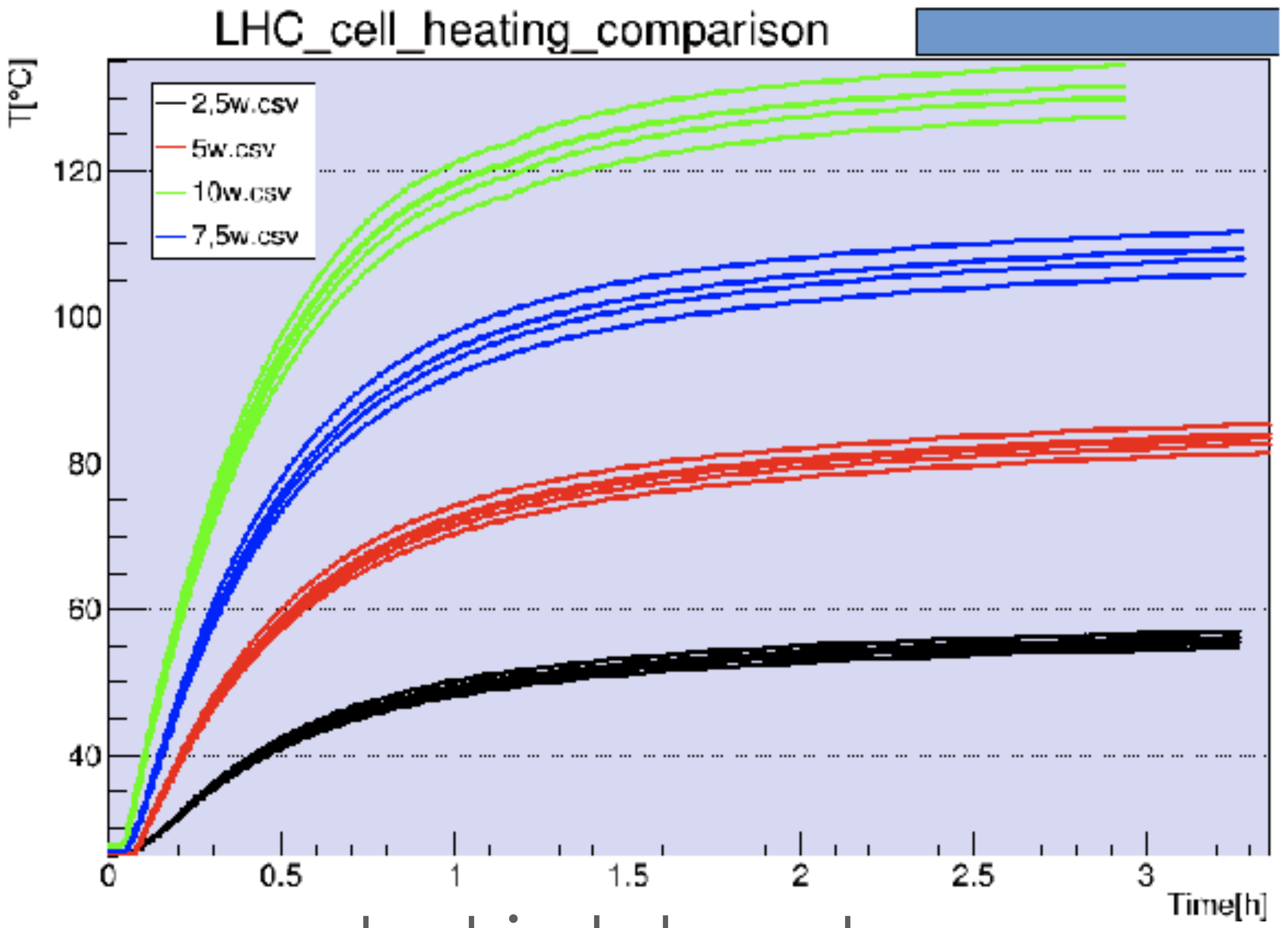




- typical example of the temperature behaviour during fills with different number of bunches
- the temperature increases during the beam injection and tuning, and decreases during the stable beam run
- the effect is enhanced when the cell is open because it picks up RF modes of the beam



test in laboratory

-prototype cell tested up to 130 C
-in reality, on beam, we never exceeded 42 C

Other important aspects for beam stability include Impedance calculation and the shape of the Wake Field Suppressors … too detailed to be discussed here

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Beam lifetime reduction

When the gas is injected a beam-loss mechanism occurs due to the beam-gas collisions.
The impact on the beam lifetime can be described in terms of the total beam-gas hadronic cross section and the expected luminosity:

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The impact on the beam lifetime can be described in terms of the total beam-gas hadronic cross section and the expected luminosity:

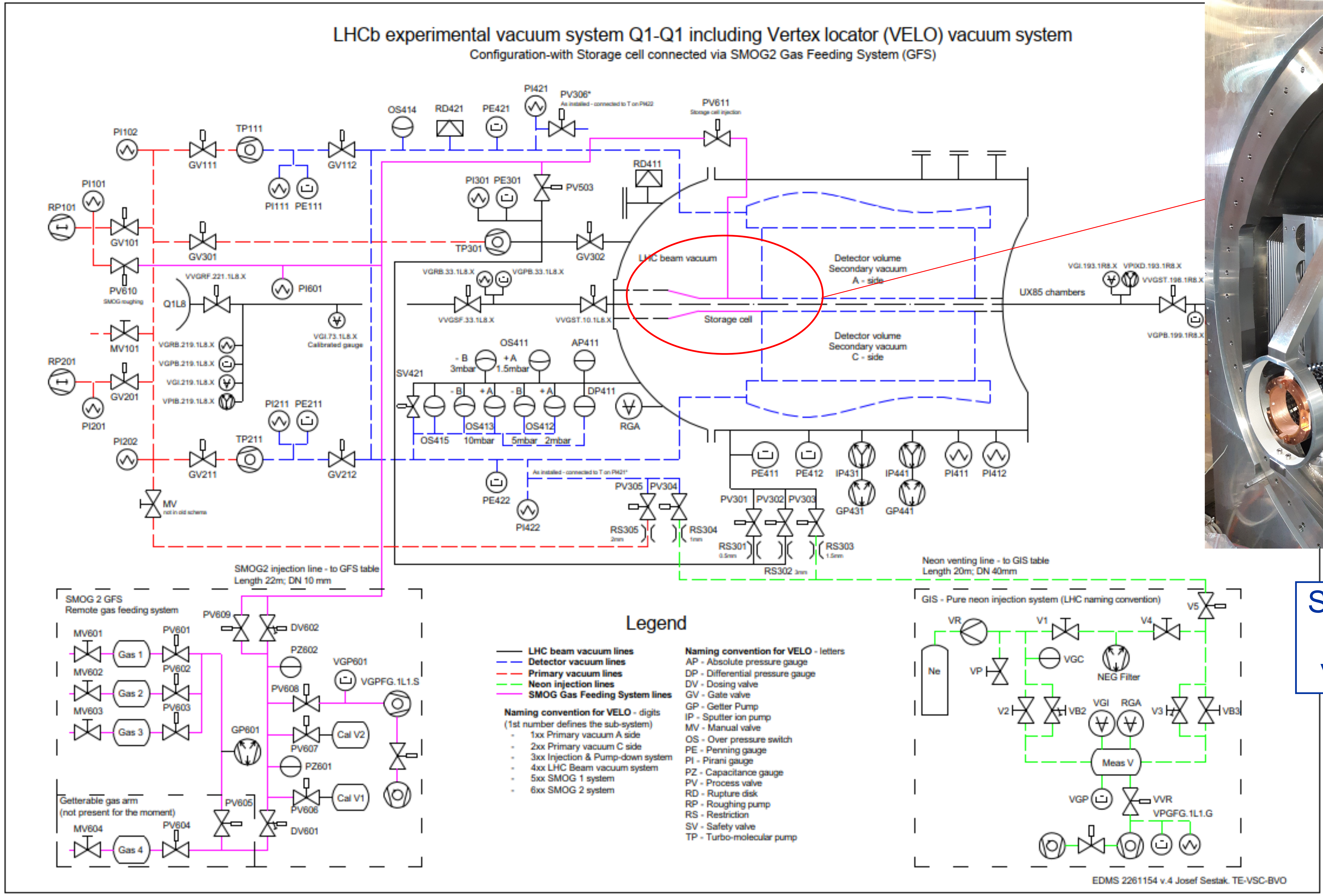
$$\tau_{loss}^{-1} = \frac{dN_{beam}}{dt} \cdot \frac{1}{N_{beam}} = \frac{1}{N_{beam}} \cdot L \cdot \sigma_{loss}$$

Beam	Target Gas	σ_{loss} (barn)	τ_{loss} (days)	Relative loss in 10 h
p	H	0.05	2060	0.02 %
p	Ar	1.04	97	0.4 %
Pb	Ar	4.63	22	1.9 %

Considering that the typical LHC beam life time is of 10-15 h, the beam lifetime reduction is **completely negligible**

SMOG2
Gas Feed System

- 6 gas reservoirs
- Injectable gases: H_2, D_2, N_2, O_2, He, Ne, Ar, Kr, Xe



SMOG 2 Storage cell integration in the VELO vacuum tank

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

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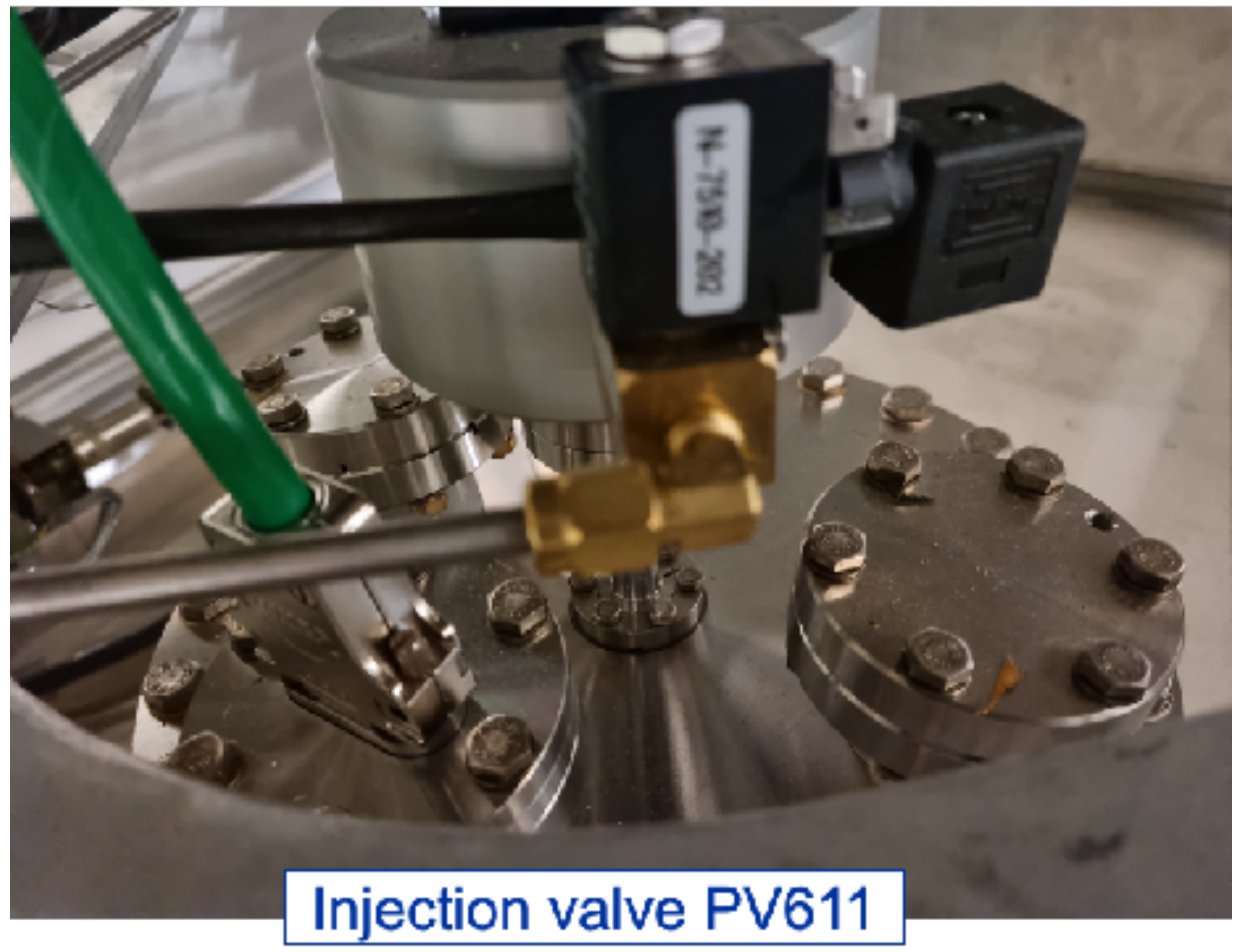
GFS table installation


Injection valve PV611

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

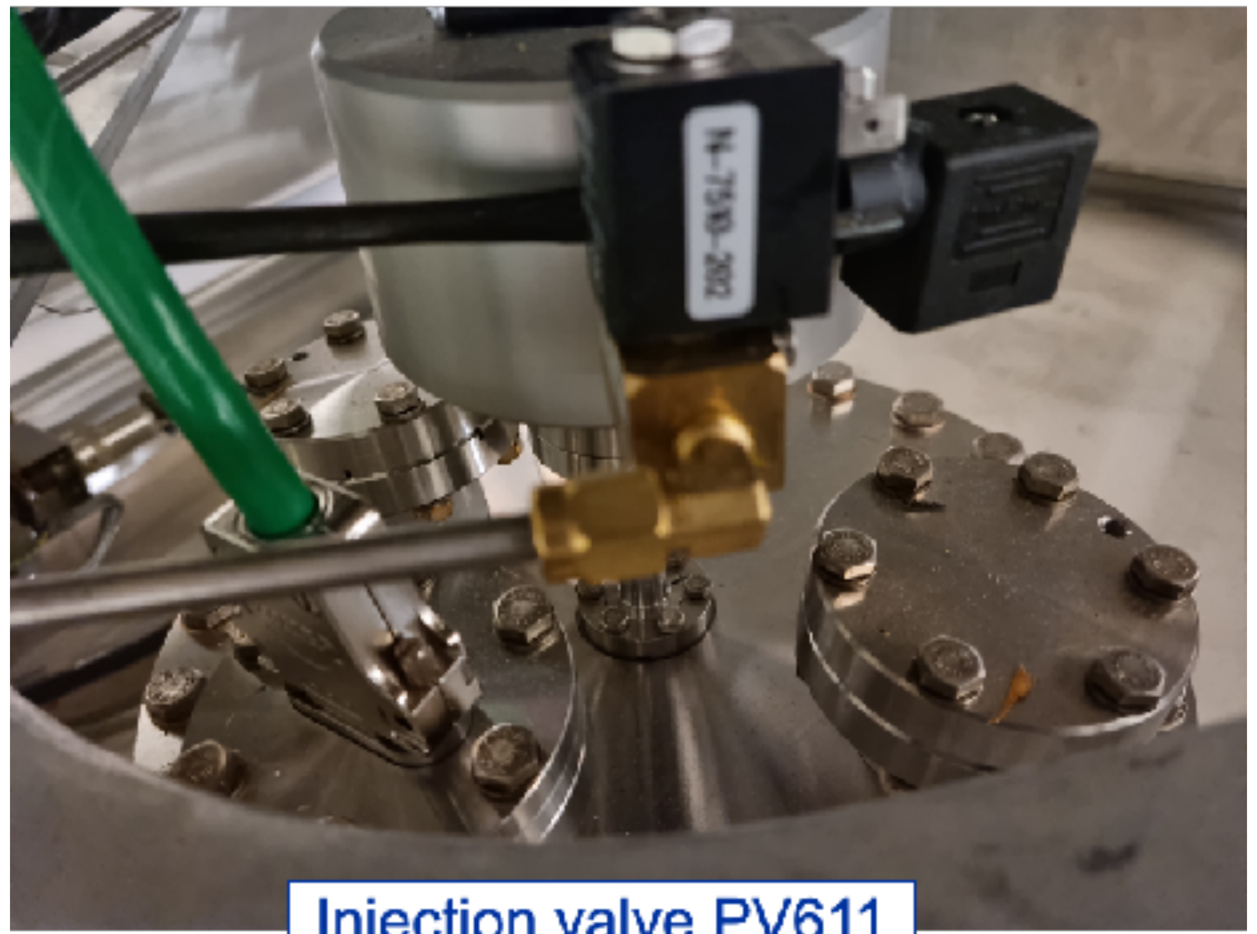
SMOG2
Gas Feed System

- 6 gas reservoirs
- Injectable gases: H_2, D_2, N_2, O_2, He, Ne, Ar, Kr, Xe

Luminosity determination:
- geometry known at O(10 μm)
- 5 temperature probes O(0.1 K)
- gas flux known O(1%)
- gas purity O(10^{-4})

ΔL 1.5% of accuracy

GFS table installation



Injection valve PV611

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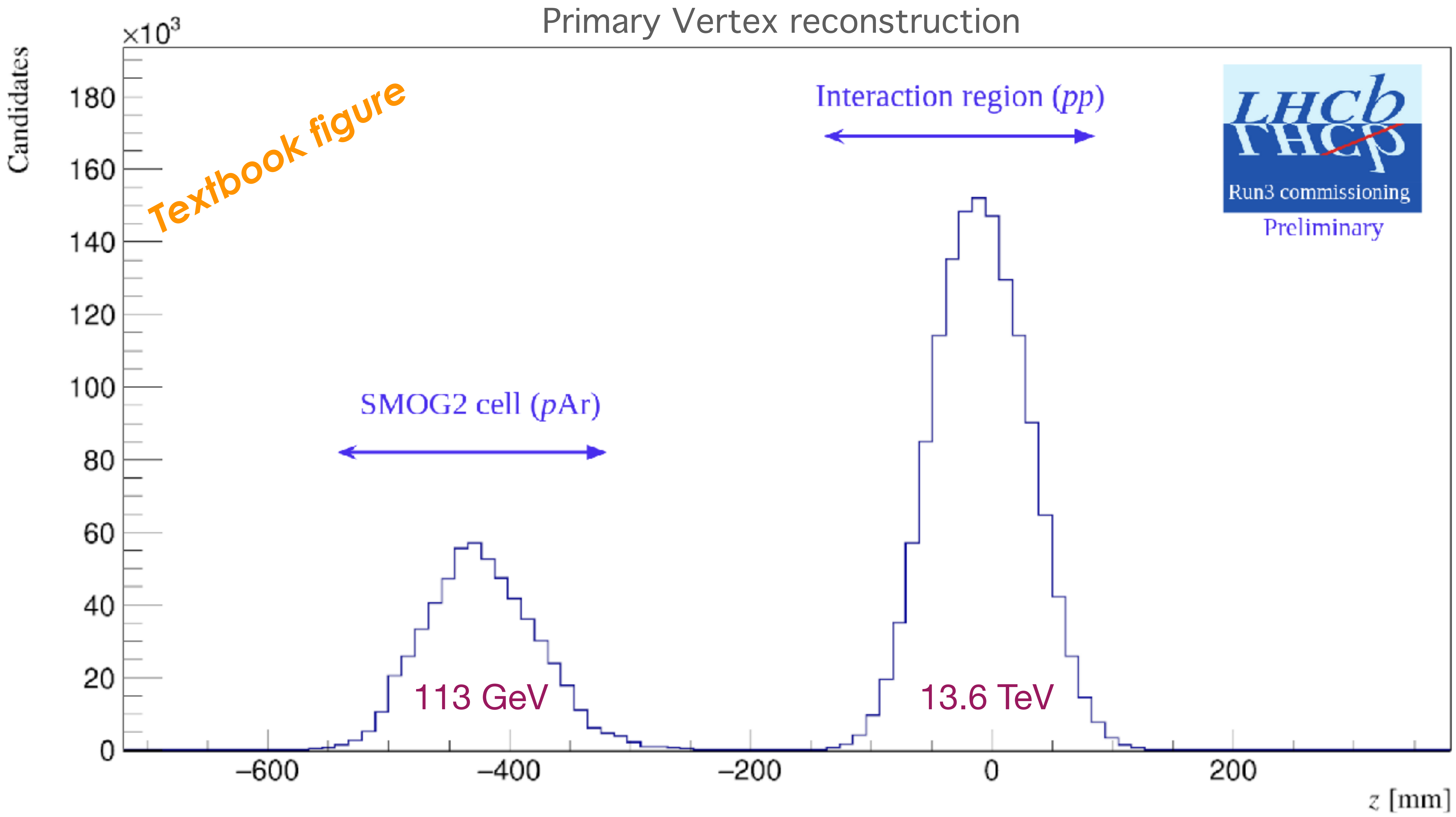
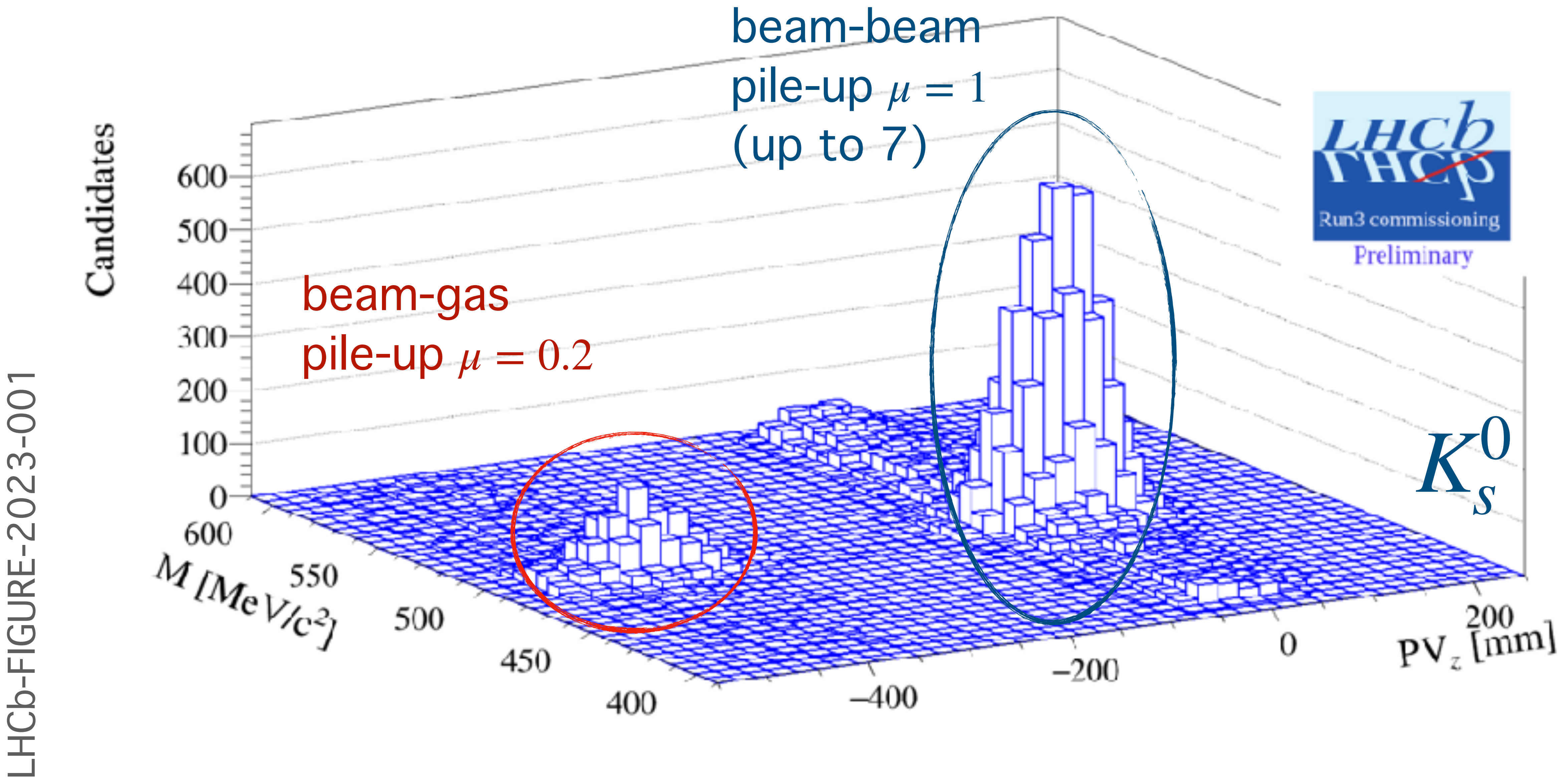
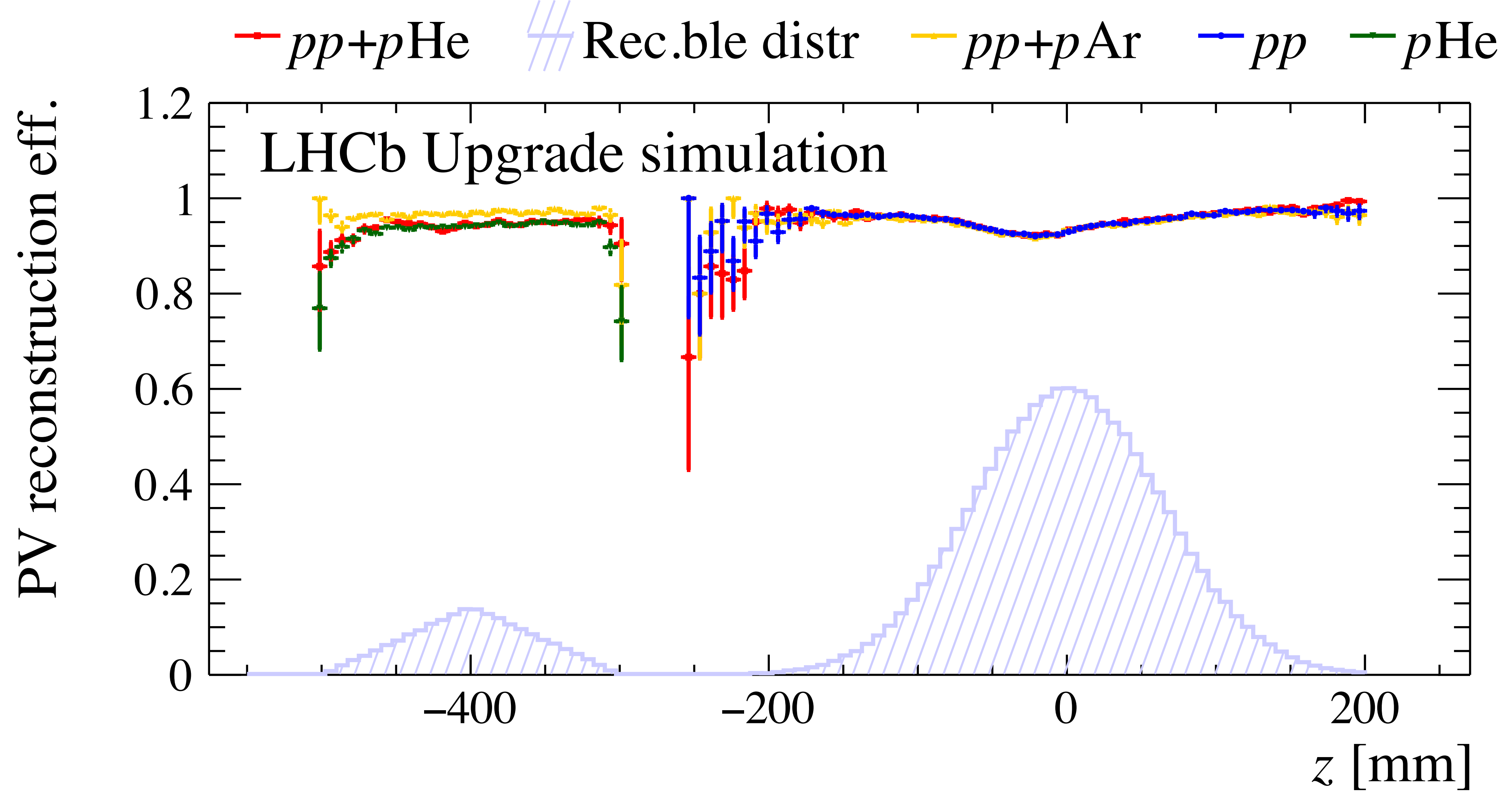
SMOG2 … wow-factor!

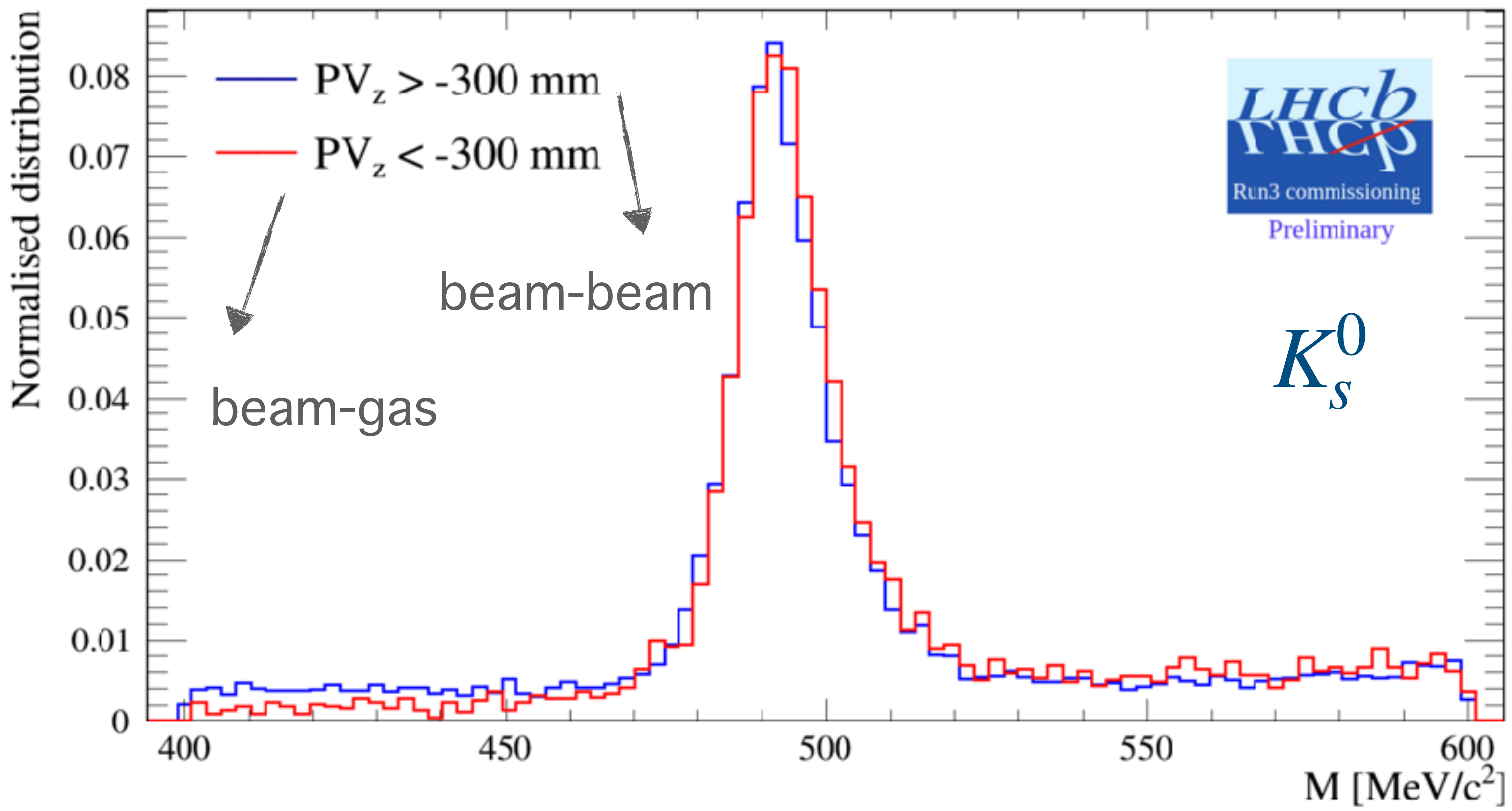


Two well separated and independent Interaction Points working simultaneously

SMOG2 ... wow-factor!



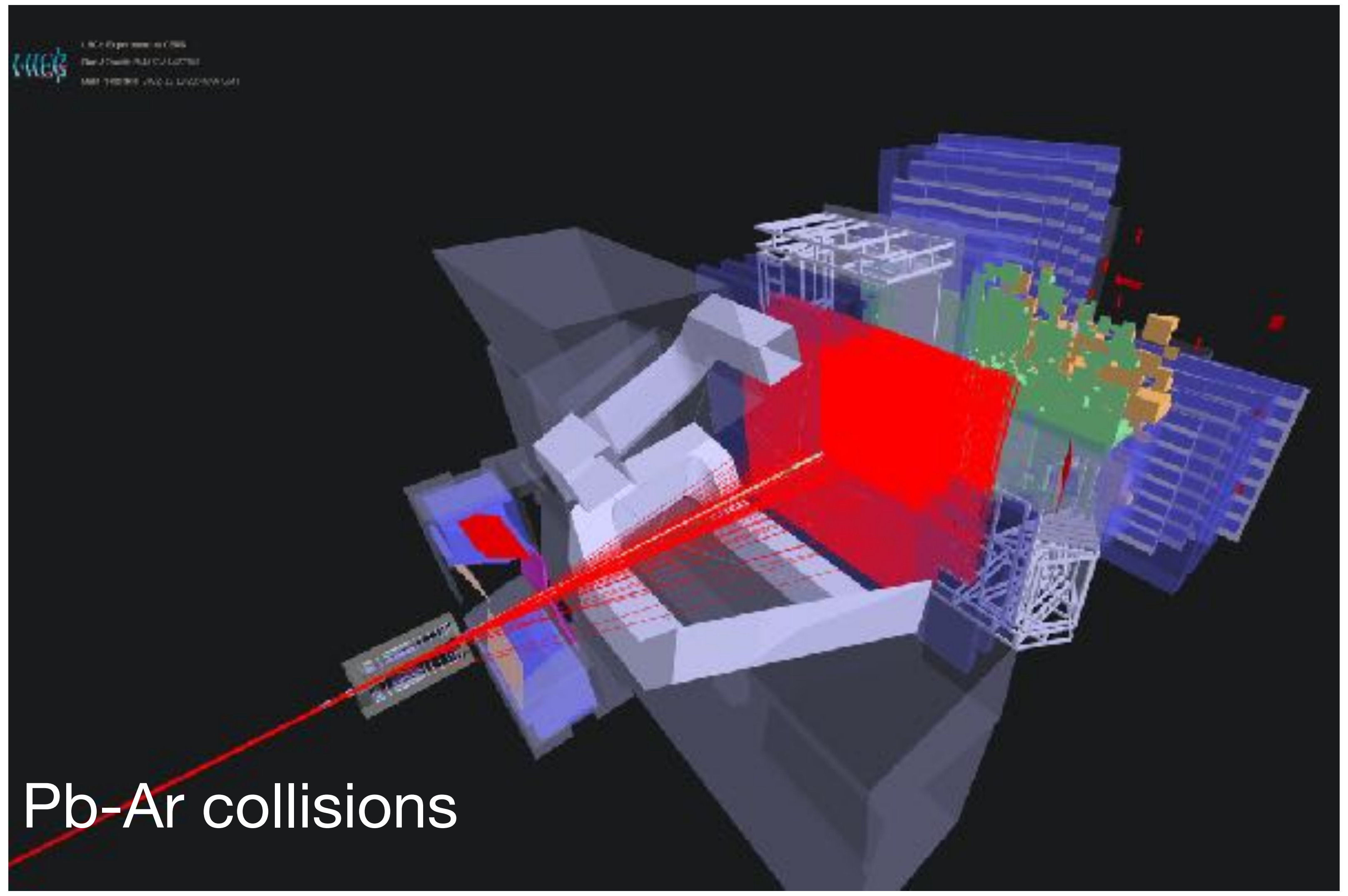




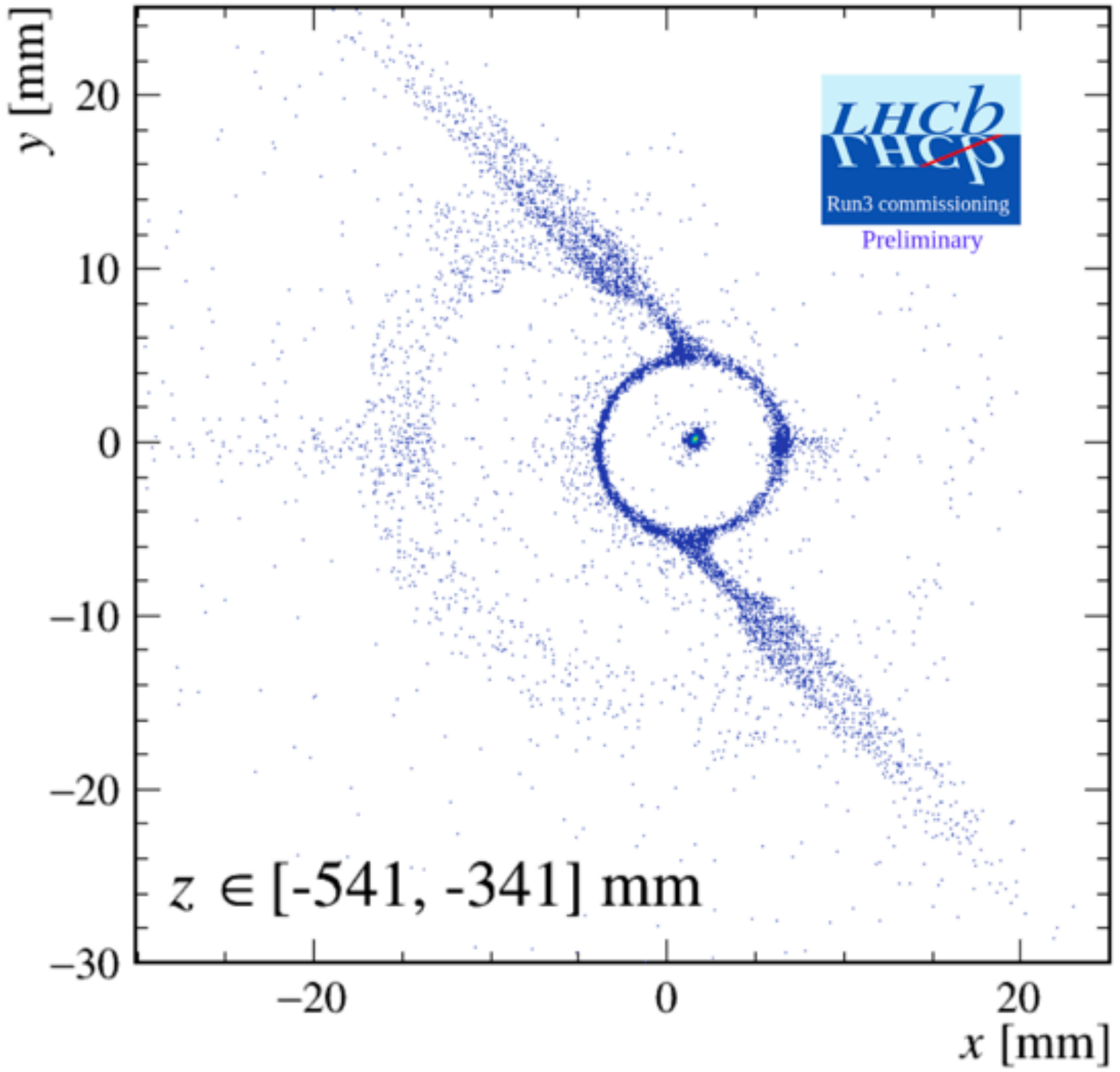
- beam-beam and beam-gas interactions are well detached
- same resolution for beam-gas and beam-beam collisions
- negligible increase of multiplicity small impact in the LHCb reconstruction sequence. Data flow increases of ~1%

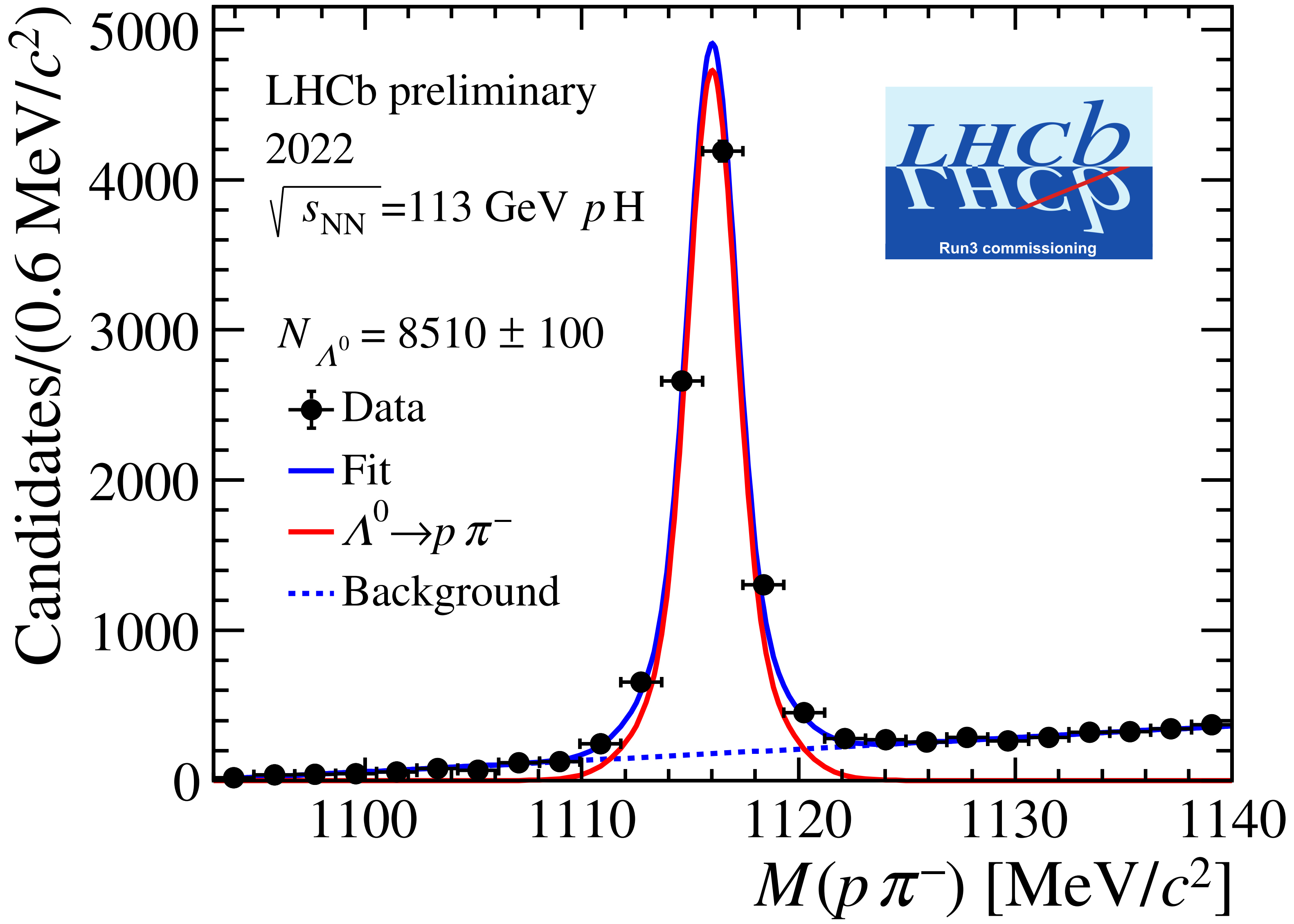
LHCb is the only experiment able to run in collider and fixed-target mode simultaneously!

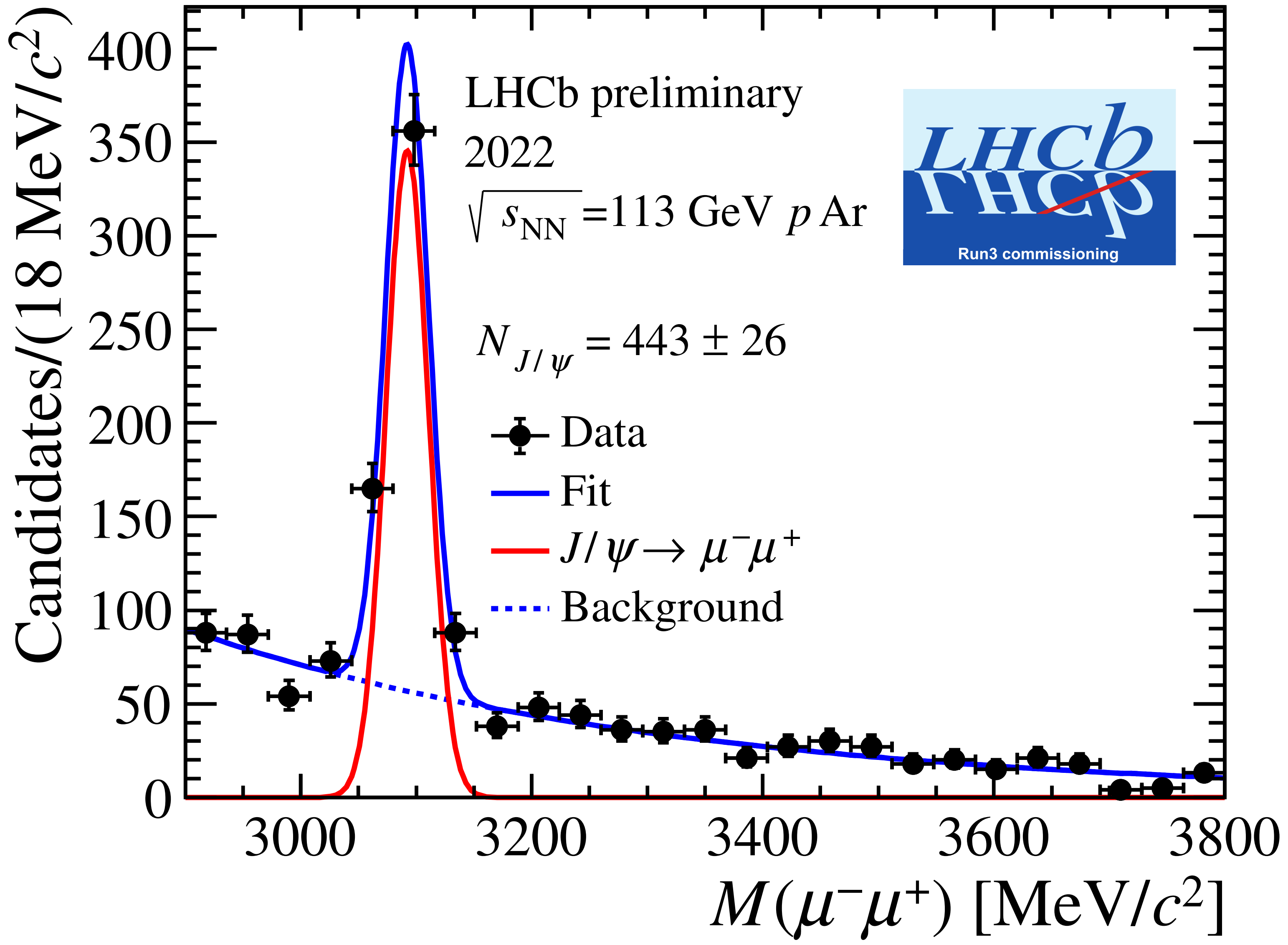
SMOG2 *early data*



tomography of the cell from residual gas & secondary interactions







LHCb-FIGURE-2023-008

excellent results in ~10 minutes of data taking, albeit low gas pressure & preliminary sub-detector performance as we were commissioning them

SMOG~~2~~ … few of the several results

demonstrator, no storage cell

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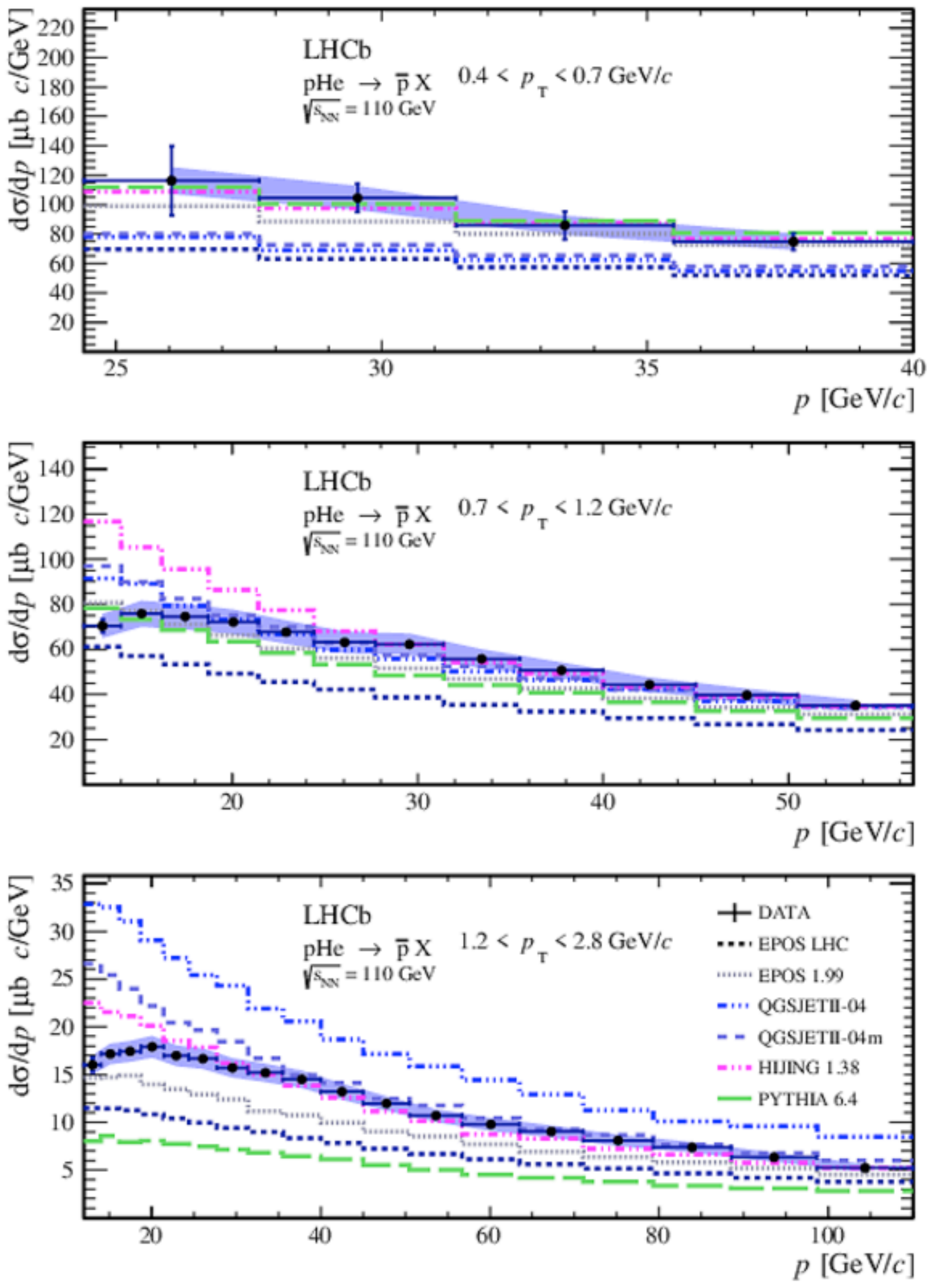
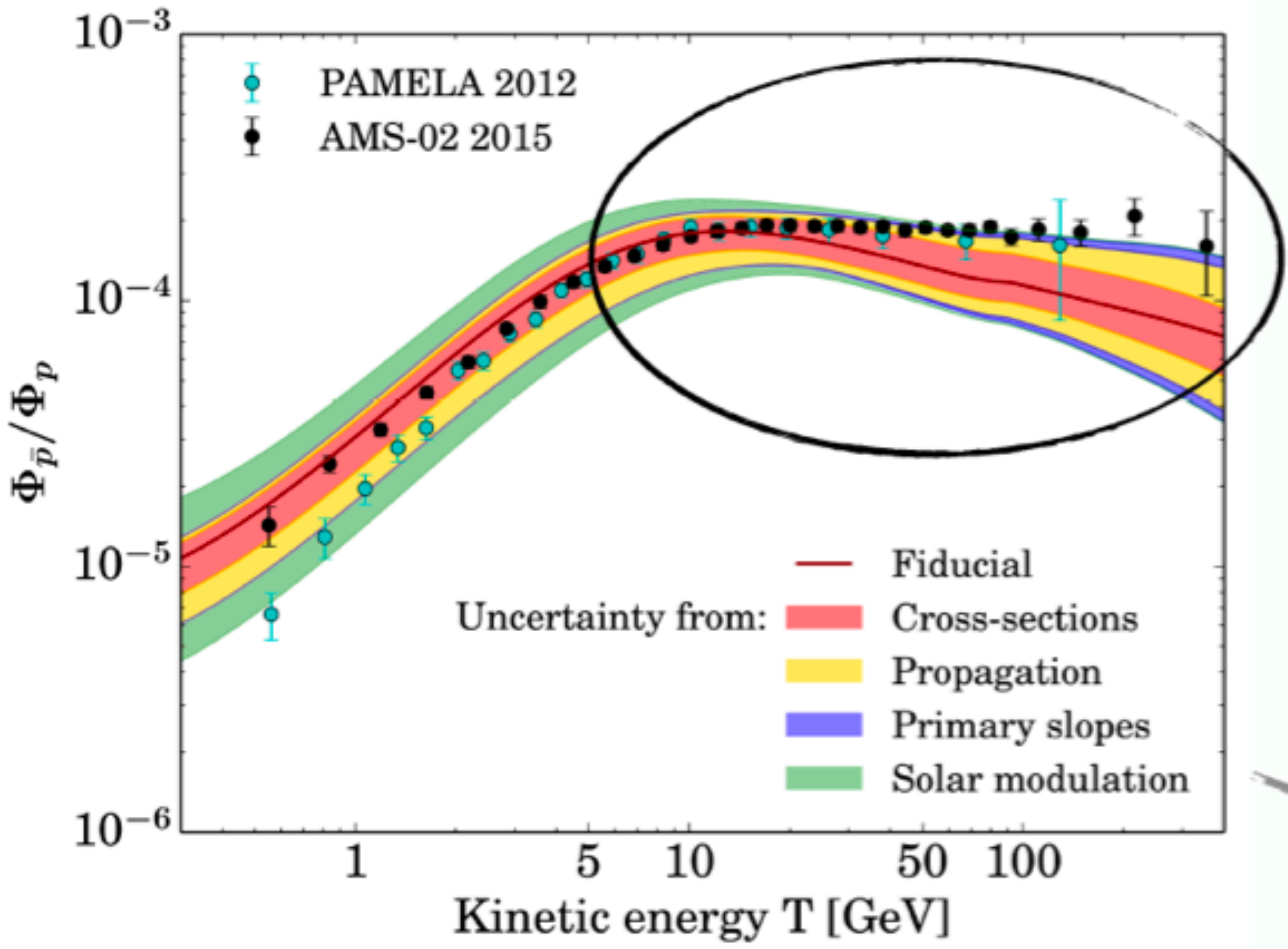
Phys. Rev. Lett. 121 (2018) 222001



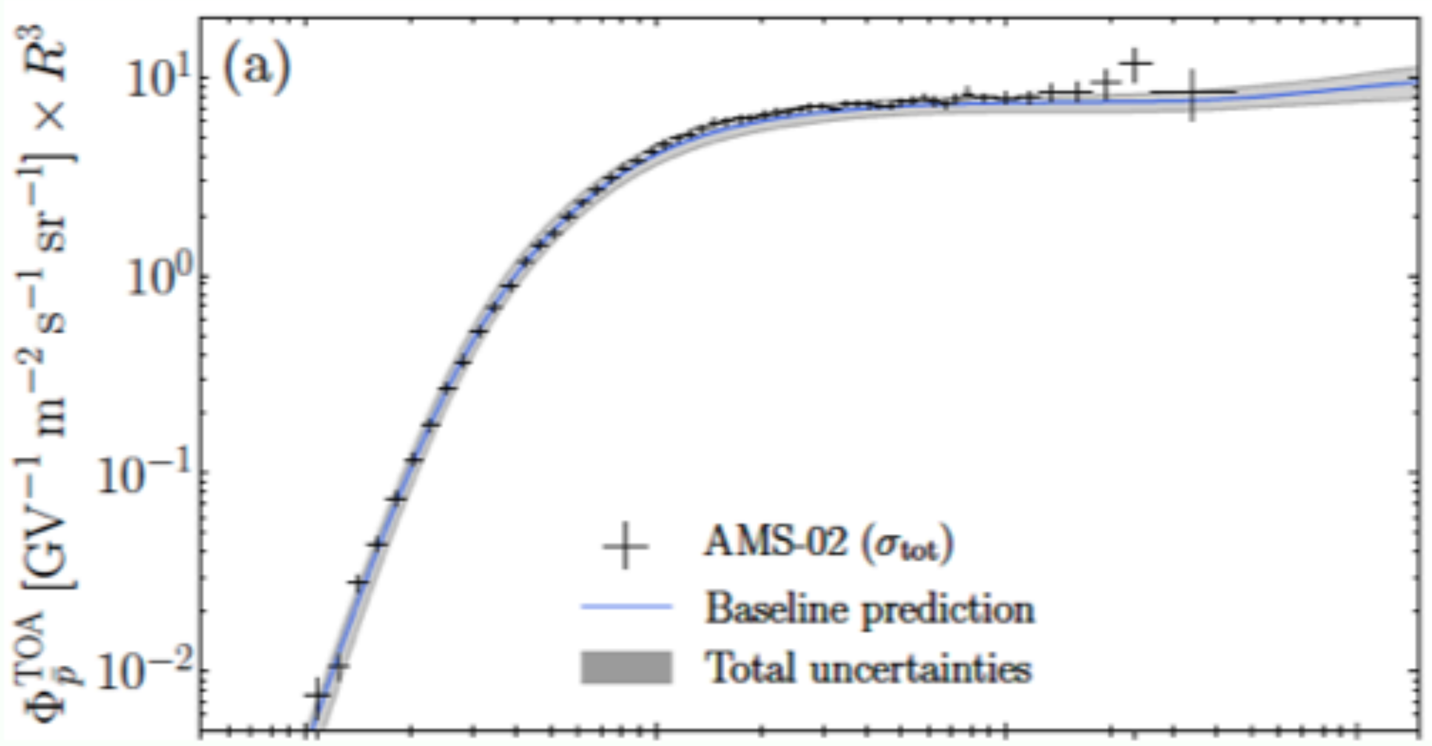
AMS2 results after having considered the LHCb results of

$$pHe \to \bar{p}X$$

[JCAP09 (2015) 023]



Phys. Rev. Research 2, 023022 (2020)



main uncertainties due to unknown cross sections

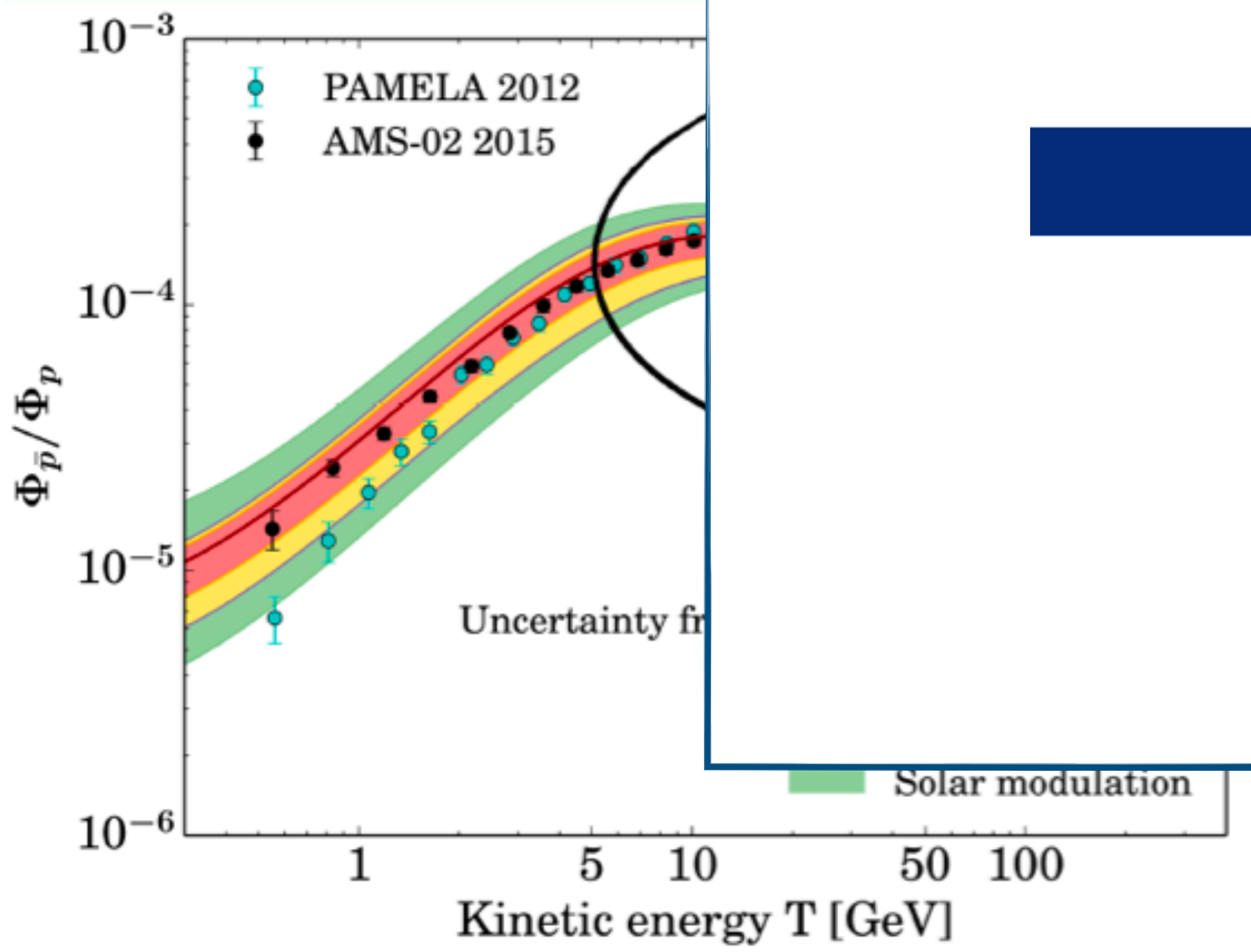
SMOG ... few of the several results

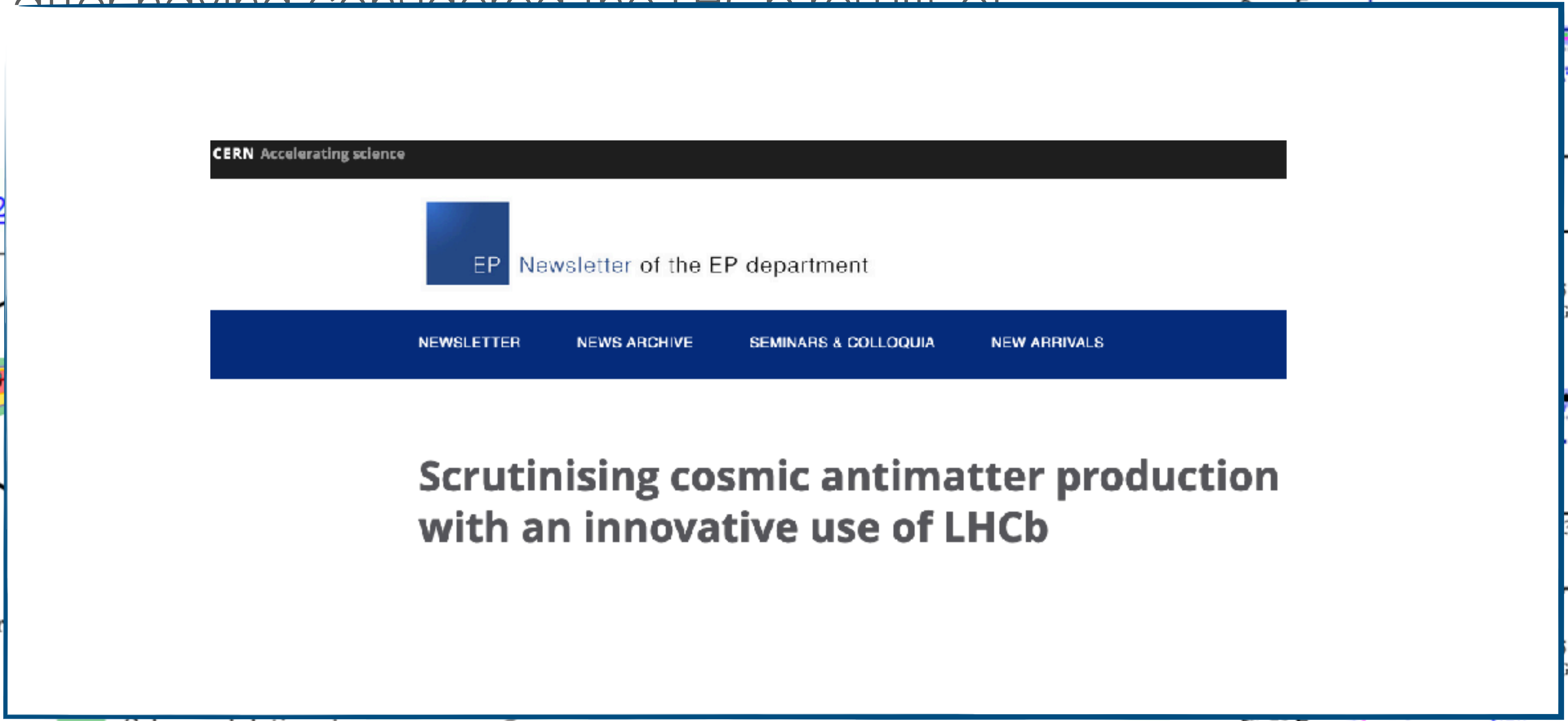
demonstrator, no storage cell

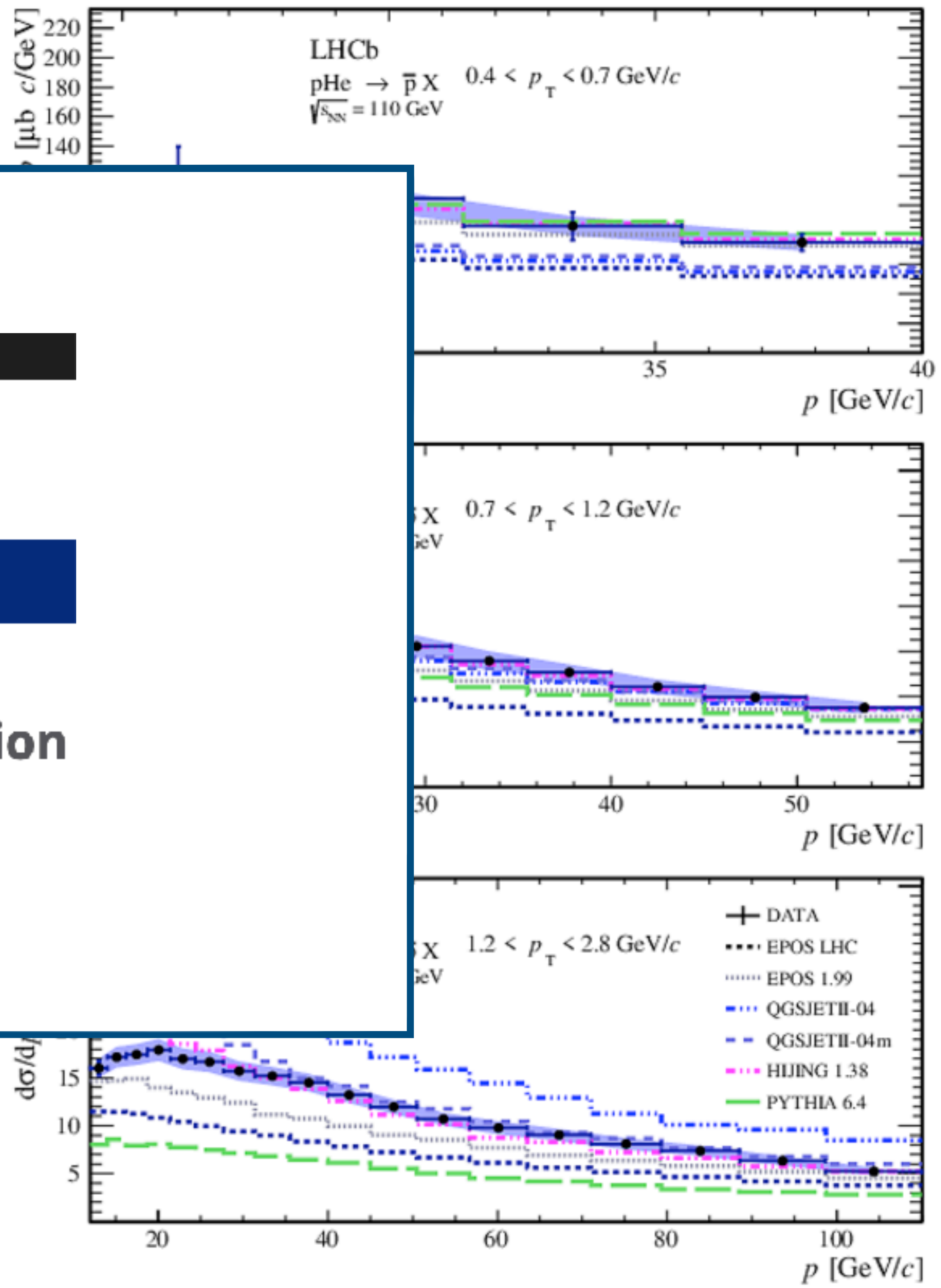
Phys. Rev. Lett. 121 (2018) 222001

AMS2 results after having considered the LHCb results of

[JCAP09 (2







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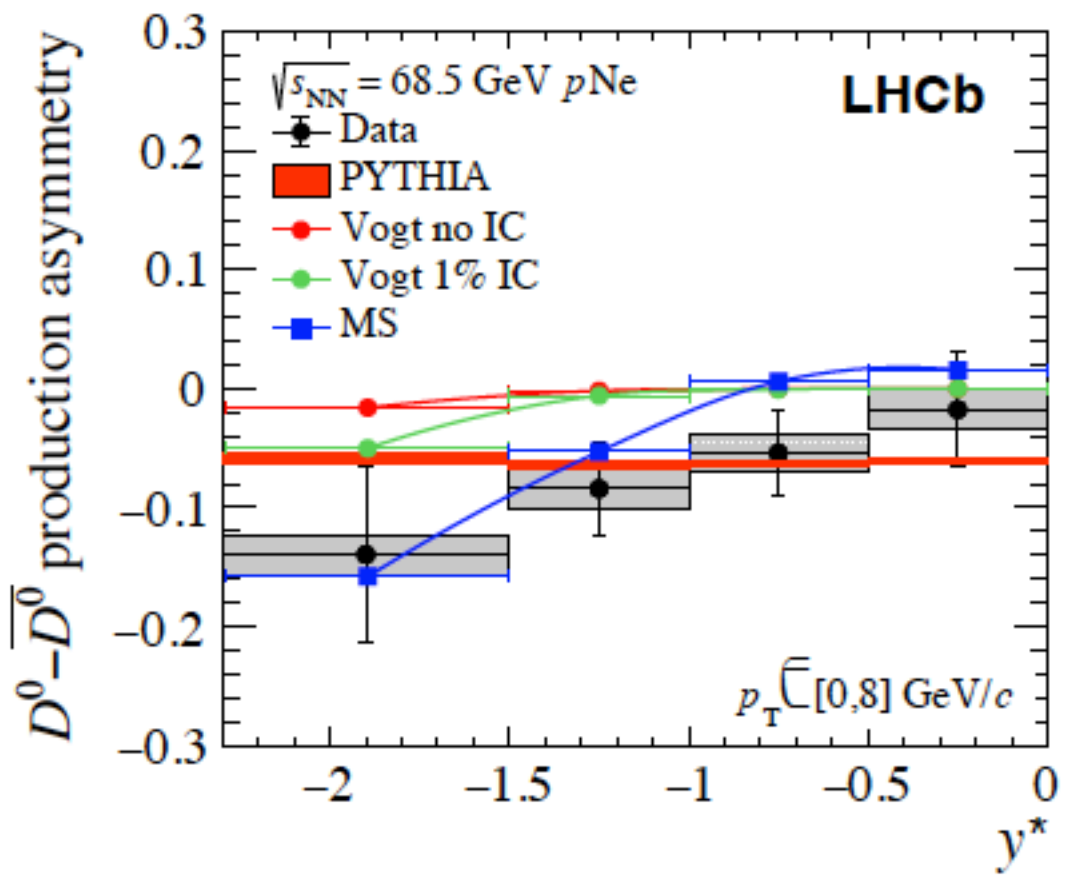
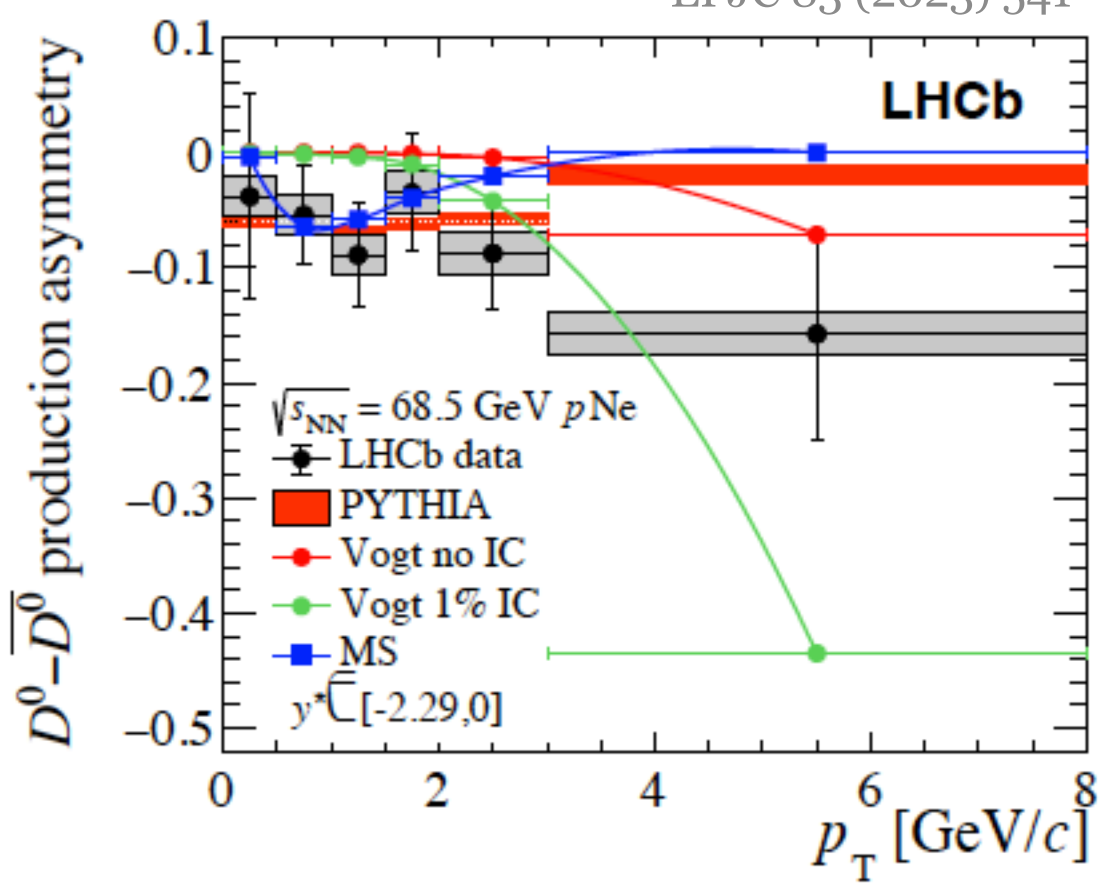
D^0 Production Asymmetry

68.5 GeV

EPJC 83 (2023) 541

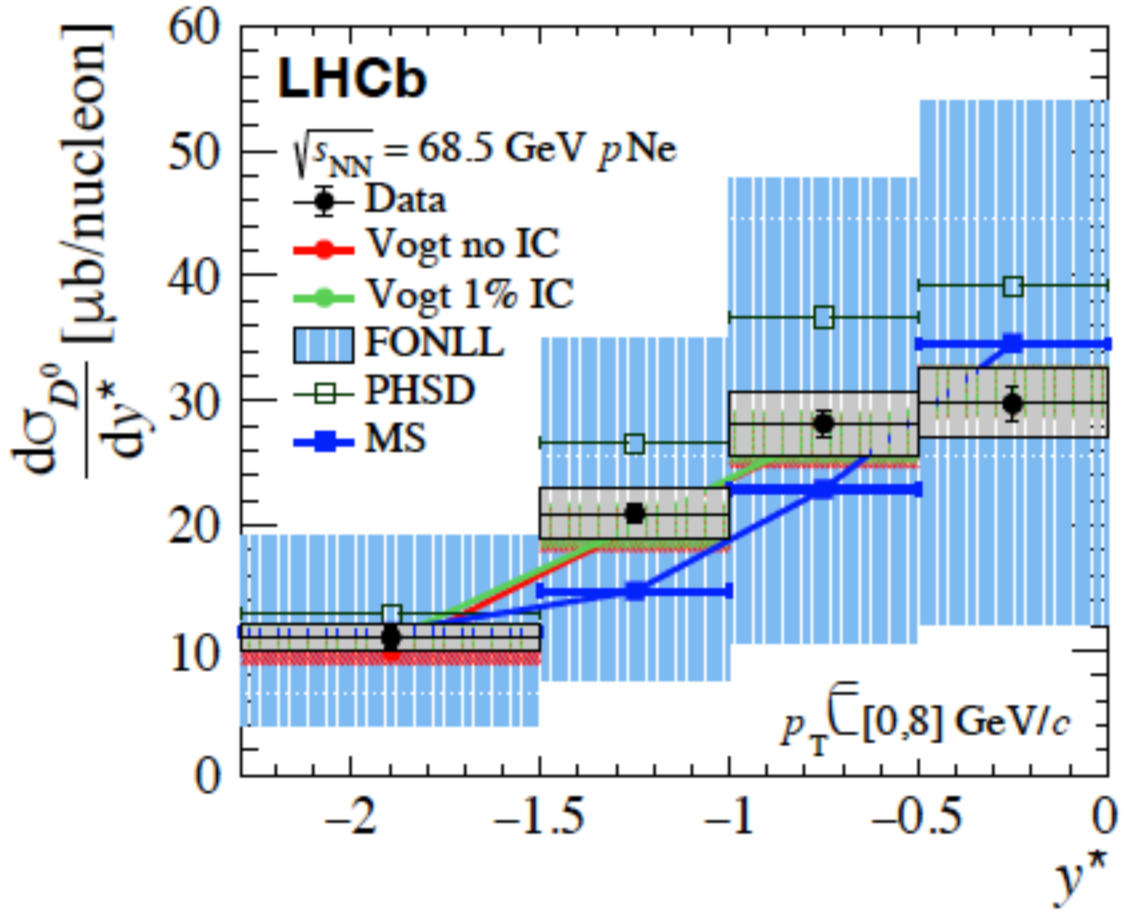


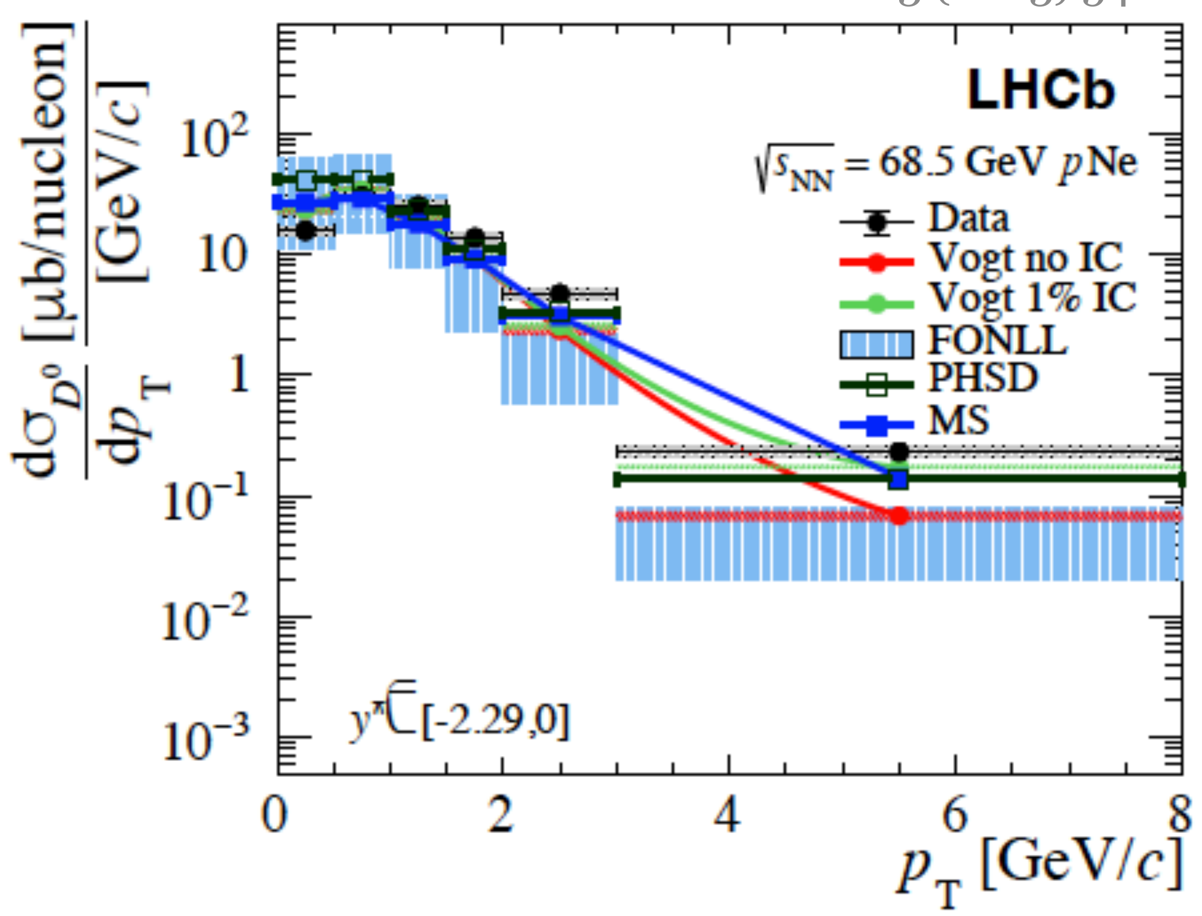


68.5 GeV

D^0 differential cross sections

EPJC 83 (2023) 541

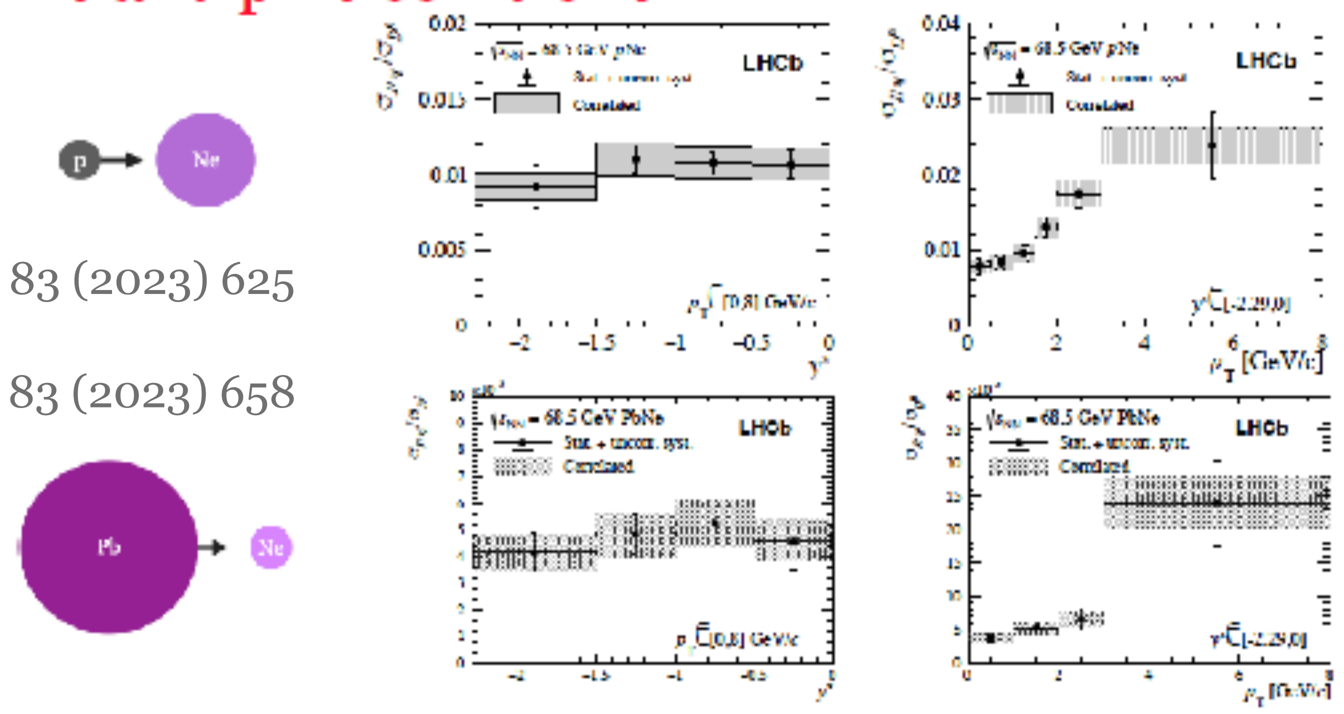


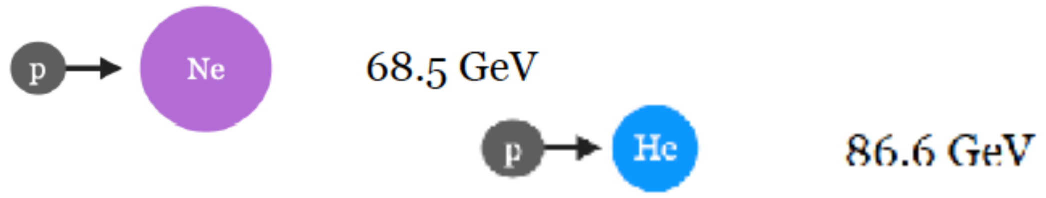


Cross section ratios of J/ψ and D^0 production in PbNe and pNe collisions

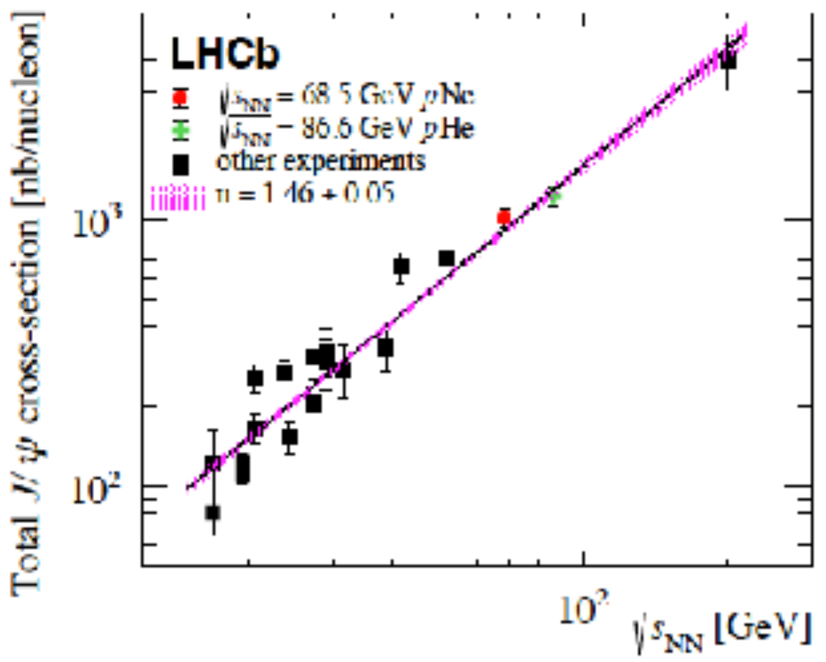
EPJC 83 (2023) 625

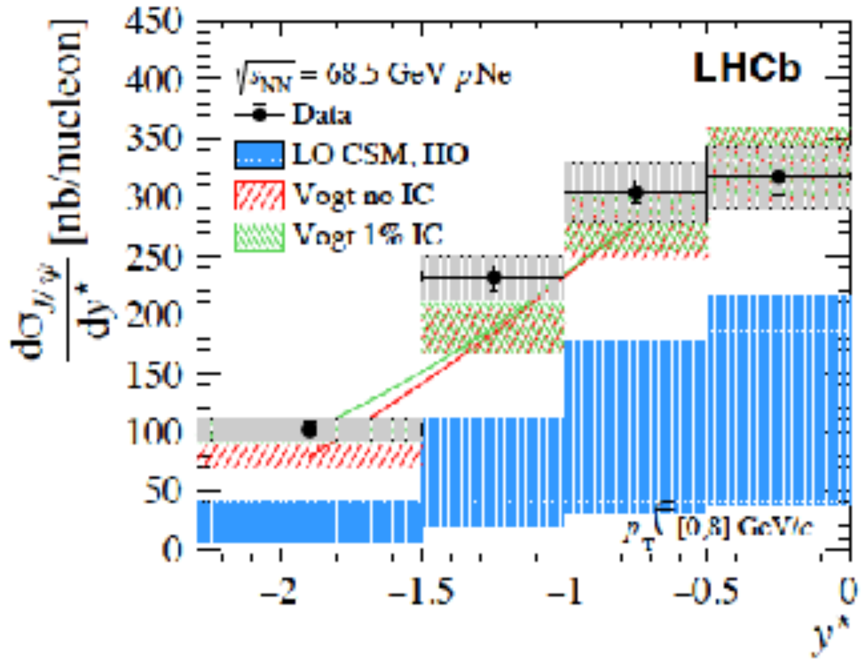
EPJC 83 (2023) 658

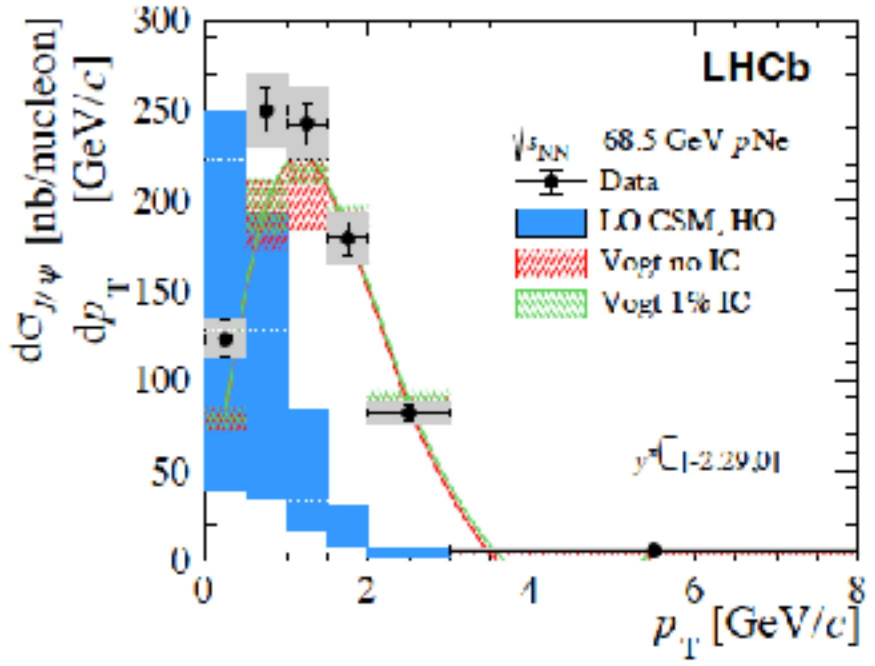




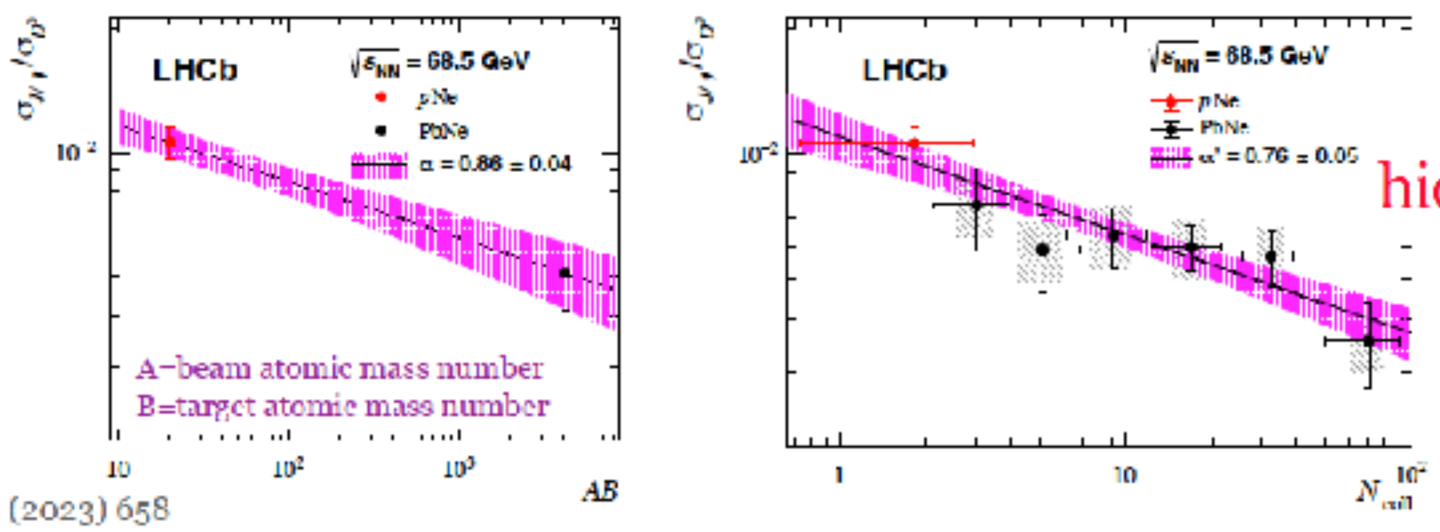
EPJC 83 (2023) 625







J/ψ cross section



Nuclear effects on hidden vs open charm

PbNe: EPJC 83 (2023) 658
pNe: EPJC 83 (2023) 625

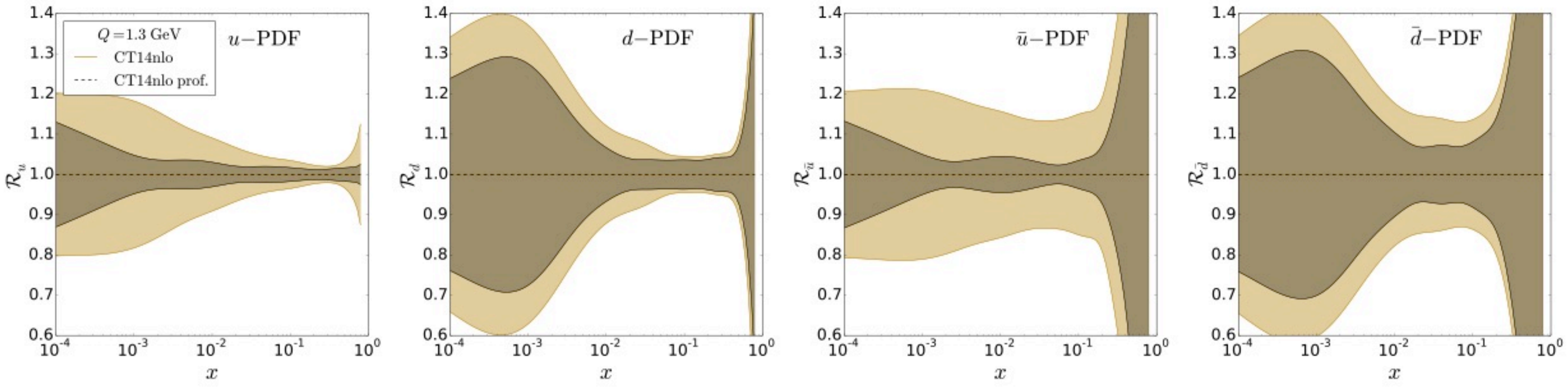
SMOG2 some of the highlights

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

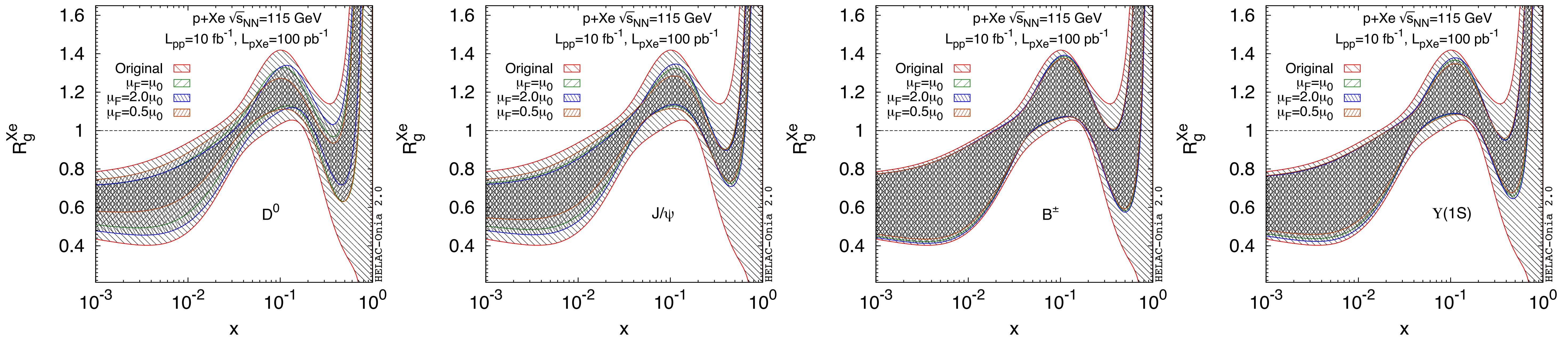
PDF

estimation with 10 fb^{-1}

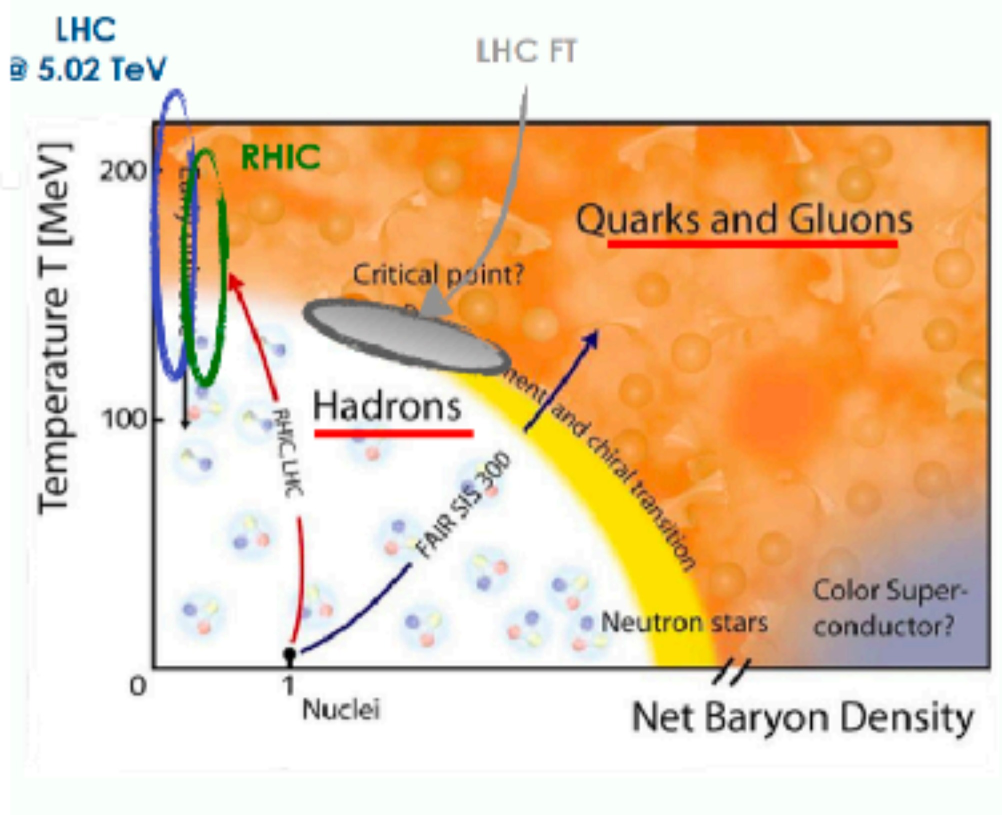
arXiv:1807.00603

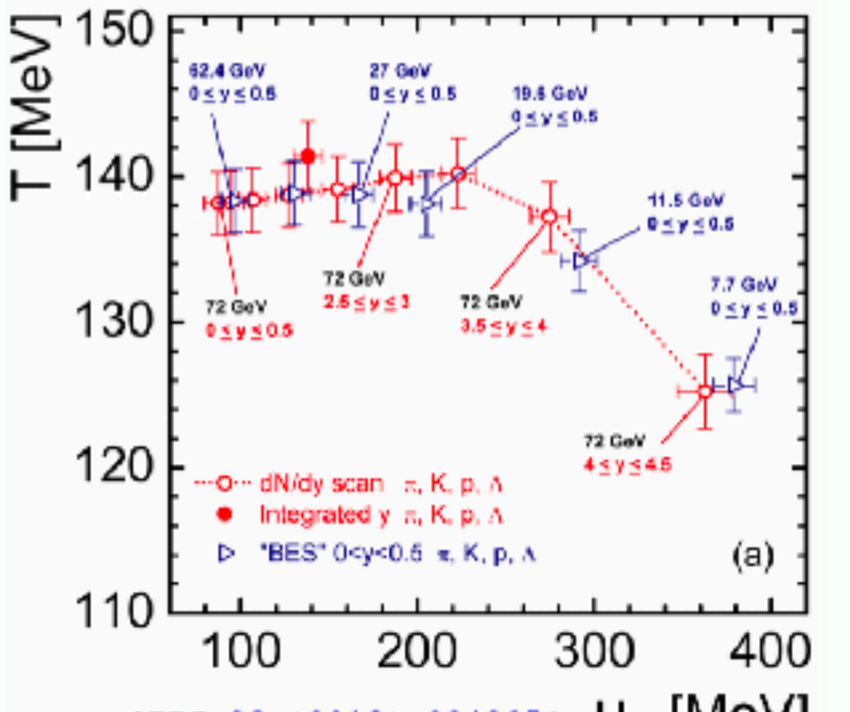


nPDF (gluon)

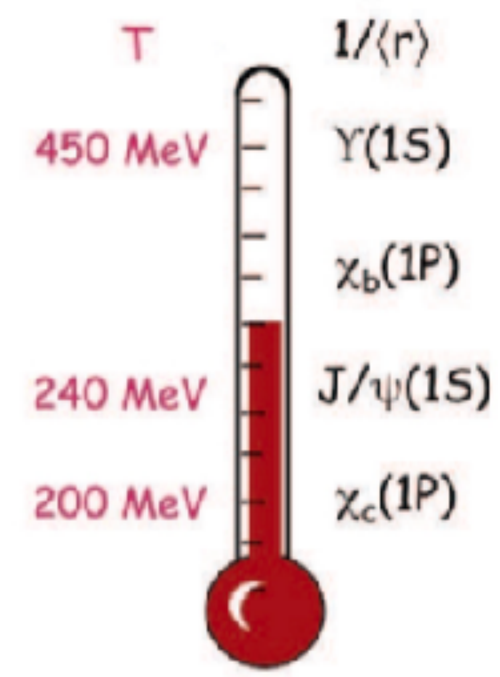


Heavy-Ion and QGP phase space

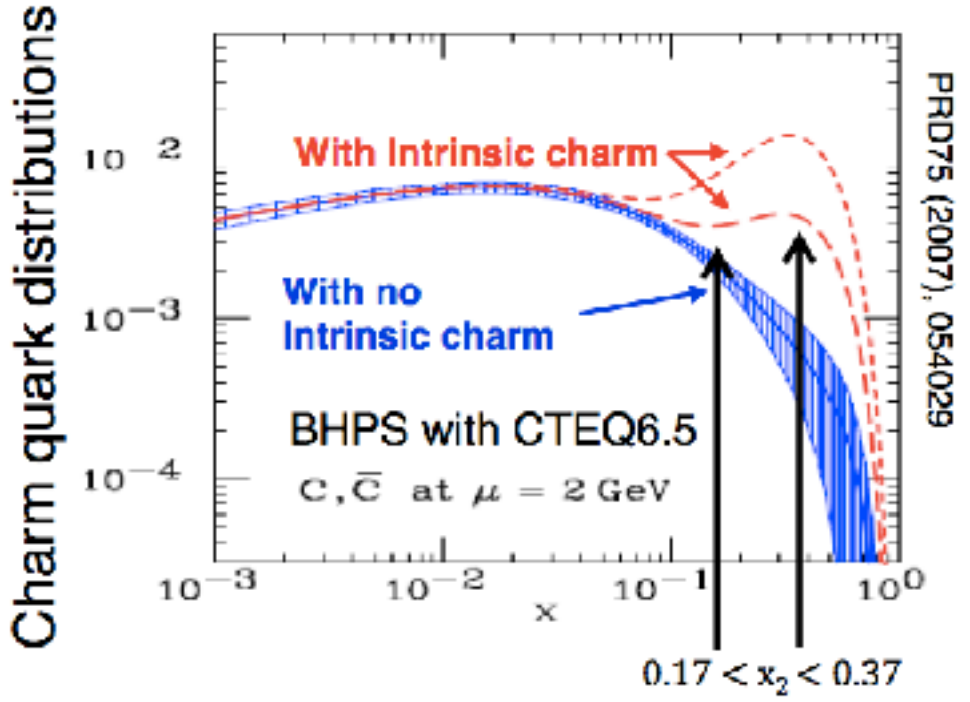




$c\bar{c}$ bound states



Intrinsic charm



LHC Special Runs

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

We can already enter in the field of the polarized physics

f_1^q	$h_1^{\perp,q}$	Boer-Mulders
f_1^g	$h_1^{\perp,g}$	linearly-polarized gluon TMD

some of the highlights

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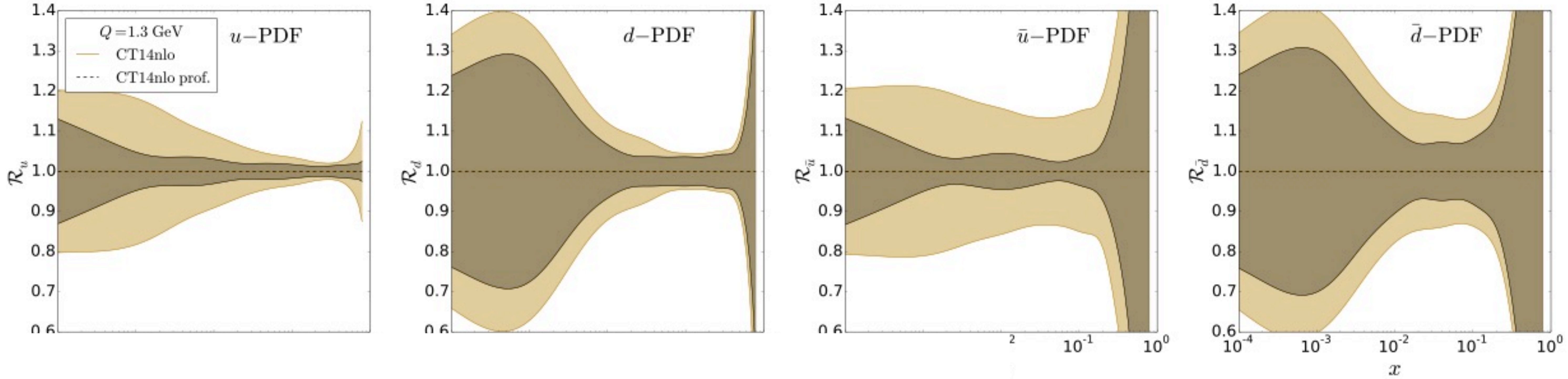
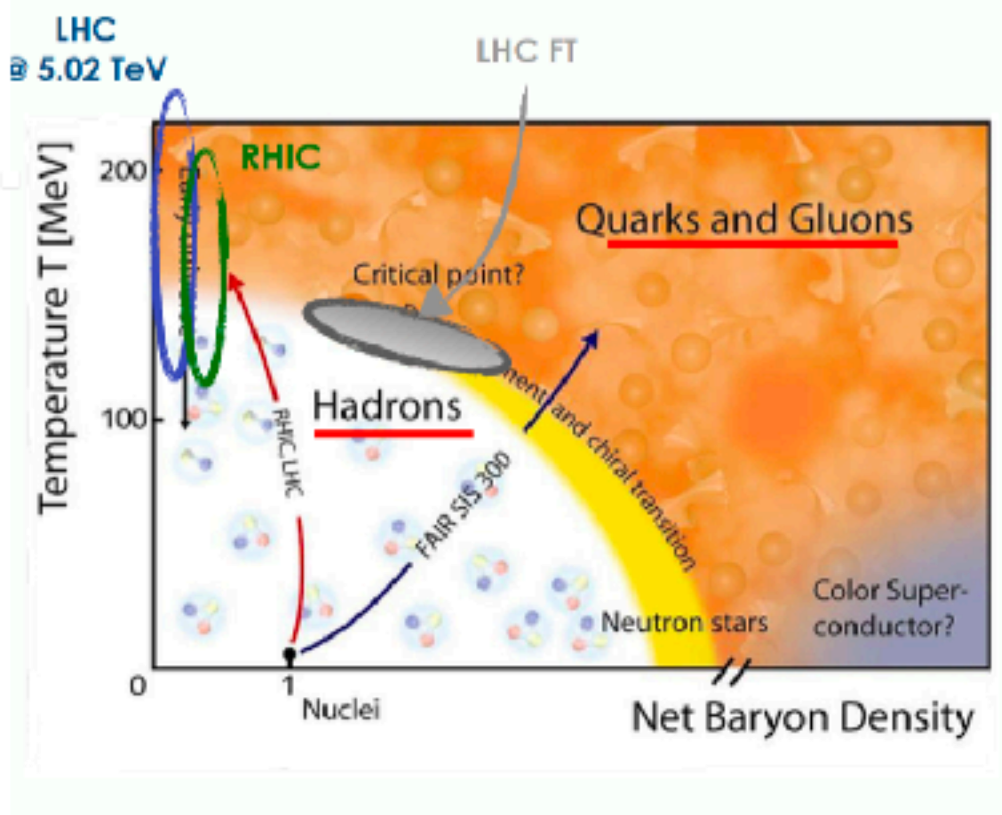
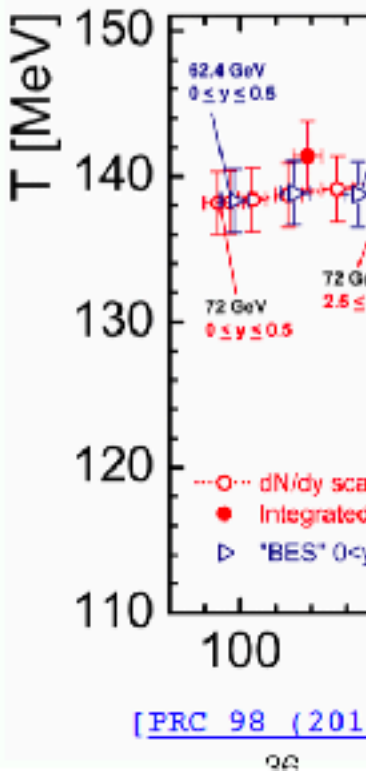


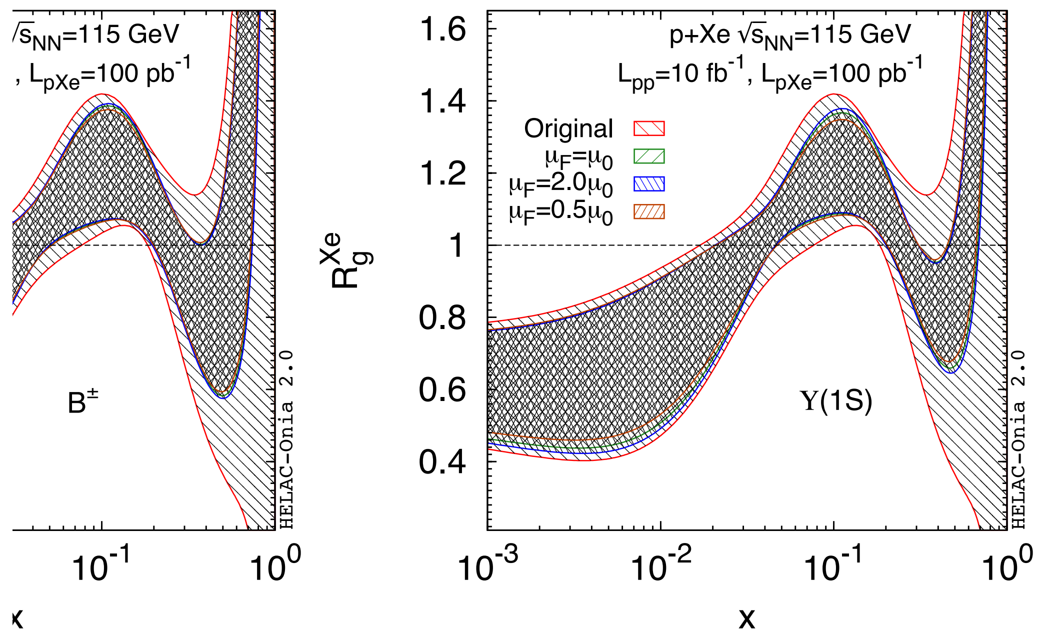
Heavy-Ion and QCD phase space



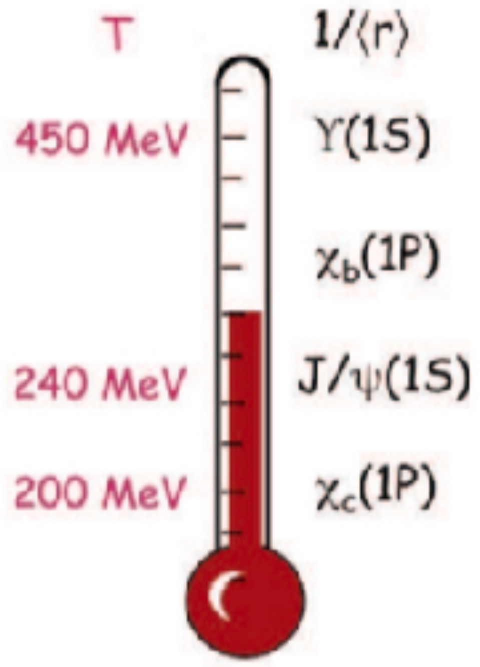


SMOG2 example pAr @115 GeV in 1yr of data taking

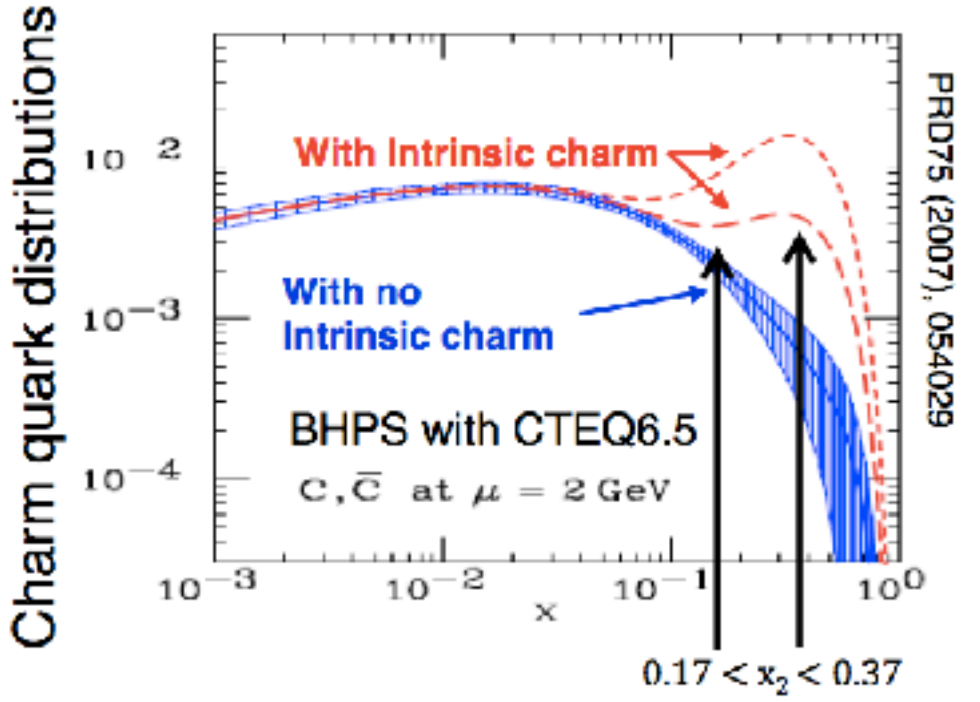
J/Ψ	yield	70 M
D^0	yield	700 M
Λ_c	yield	7 M
Ψ'	yield	700 k
$\Upsilon(1S)$	yield	60 k
$DY\ \mu^+\mu^-$	yield	60 k



$c\bar{c}$ bound states



Intrins



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

…already enter in the field of the polarized physics

f_1^q	$h_1^{\perp,q}$	Boer-Mulders
f_1^g	$h_1^{\perp,g}$	linearly-polarized gluon TMD

The LHC beams cannot be polarised

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

SMOG2 LHCb

unpolarised gas target

LHCspin

polarised (+unpolarised) gas target

LHCspin the polarised target project

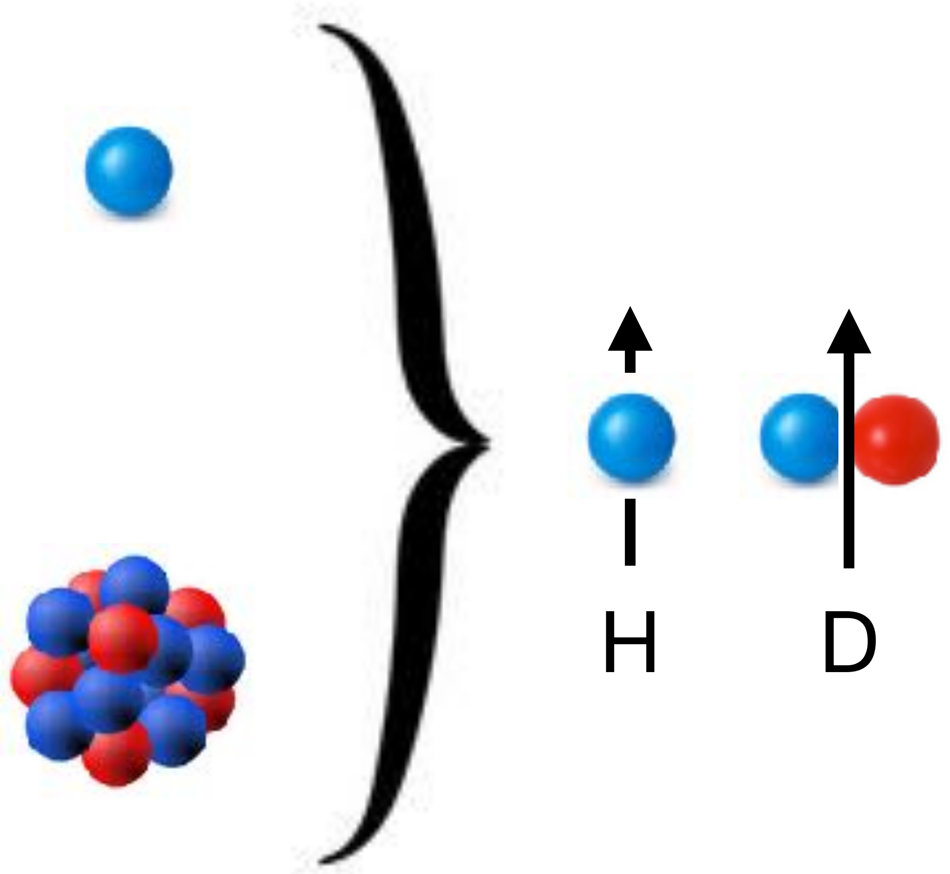
SMOG2 is not only a unique project itself,

but also a great playground for LHCspin

L↕C spin the polarised target project

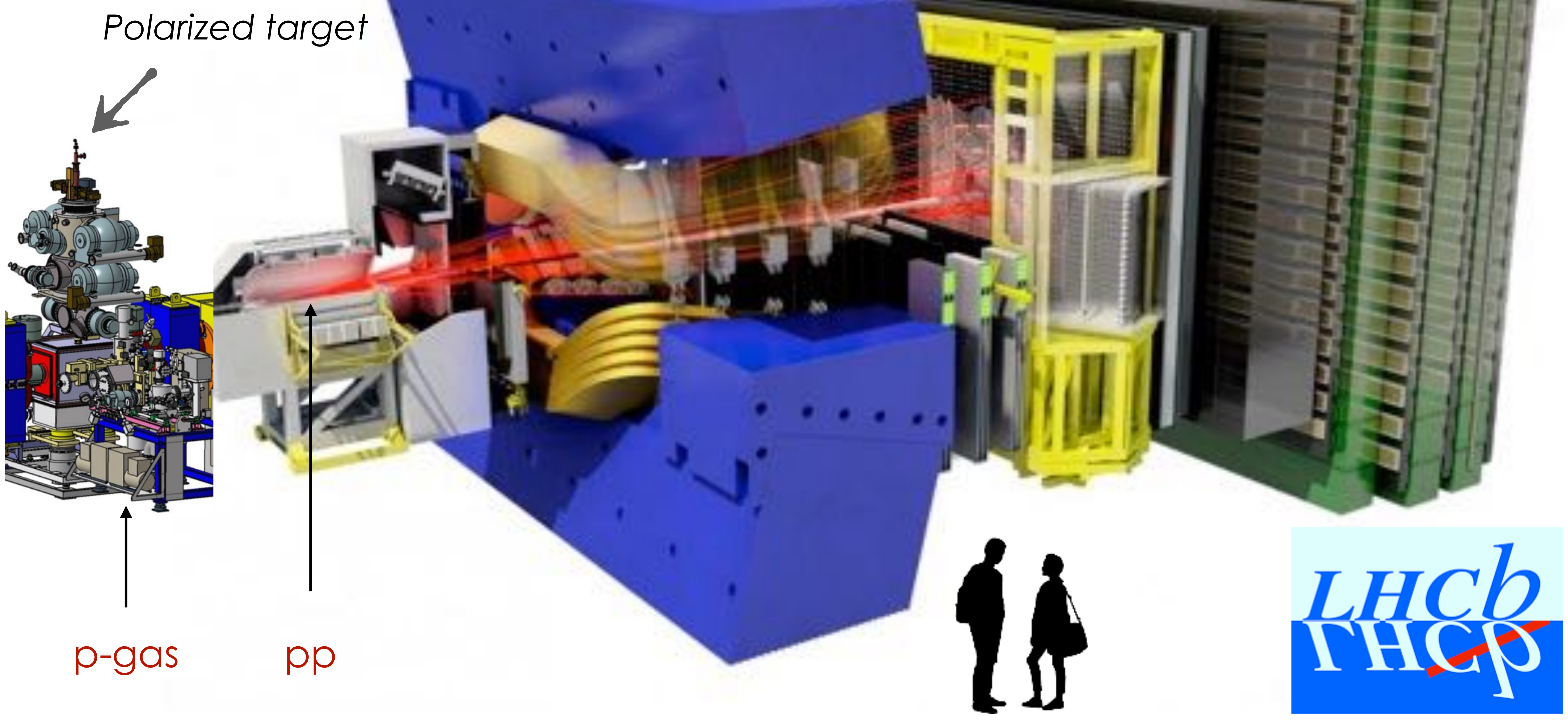
arXiv:1901.08002
Acta Phys.Polon.Supp. 16 (2023) 7
PoS PSTP2022 (2023) 001

SMOG2 is not only a unique project itself,
but also a great playground for L↕C spin

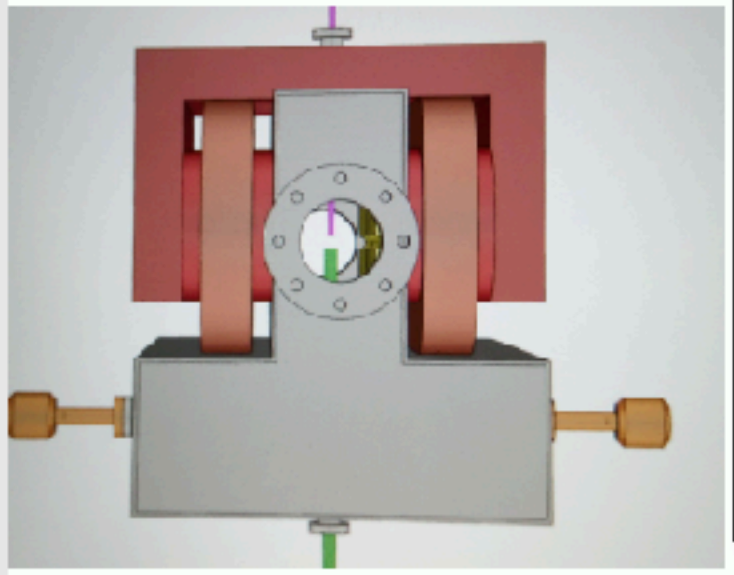


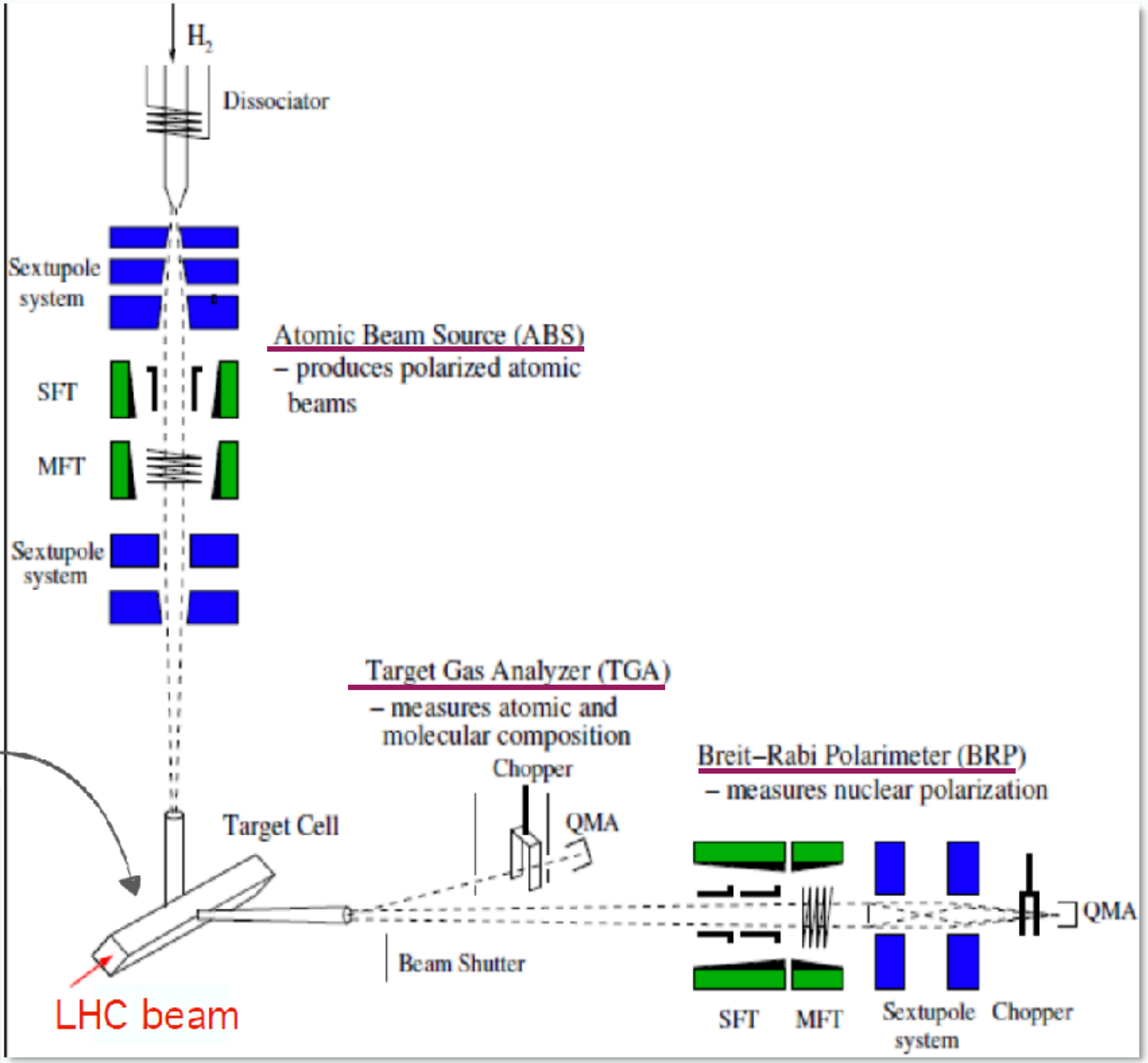
Successful technology based on HERA and COSY experiments

Challenge: develop a <u>new generation</u> of polarized targets



experimental setup





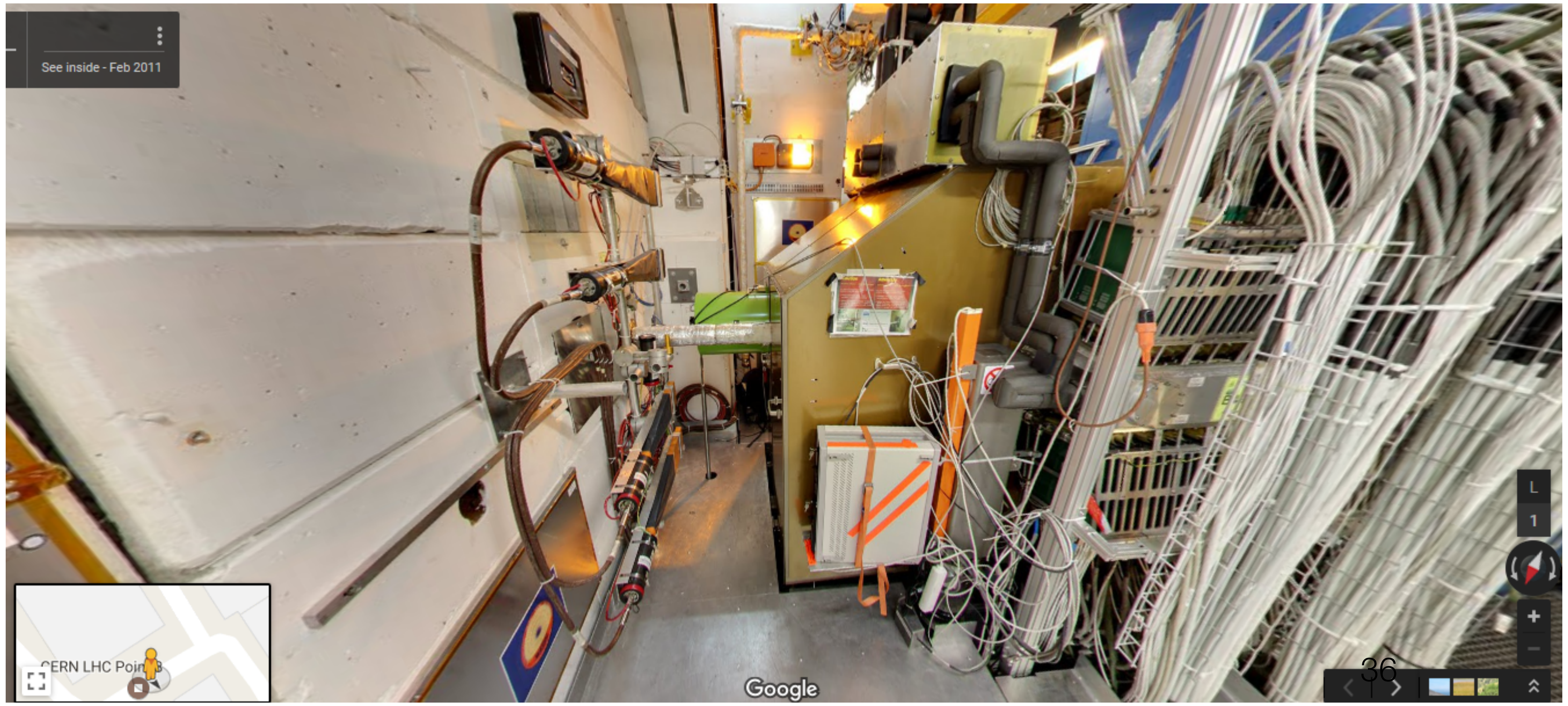
Target density (H) = 7 x 10^{13} cm^{-2}
LHC beam (Run4) = 6.8 x 10^{18} p s^{-1}

$\mathbf{L_{pH} = 8 \times 10^{32}\ cm^{-2}\ s^{-1}}$

[NIMA 540 (2005) 68-101]

HERMES PGT

From there to here



Space available in front of LHCb

Fixed target physics at the LHC is an exciting reality

Fixed target physics at the LHC is an exciting reality

SMOG2 is the first fixed target at a multi-TeV beam

It gives access to a new kinematic domain, rare probes, collisions from proton to heavy nuclei, high statistics

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LHCb is the first experiment (just upgraded) able to run in collider and fixed target mode simultaneously

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LHCspin is conceived to bring polarized physics at the LHC. It is exceptionally ambitious in terms of both its potential for advancing physics and its technical complexity … we are working on it!