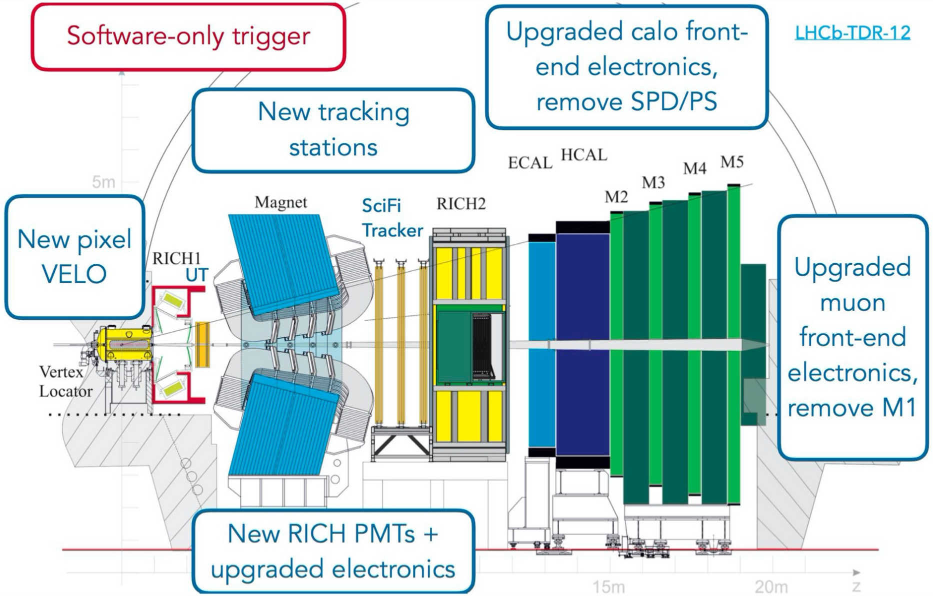
Fixed-target experimental program at LHCb

Patrick Robbe, IJCLab Orsay, 21 March 2023

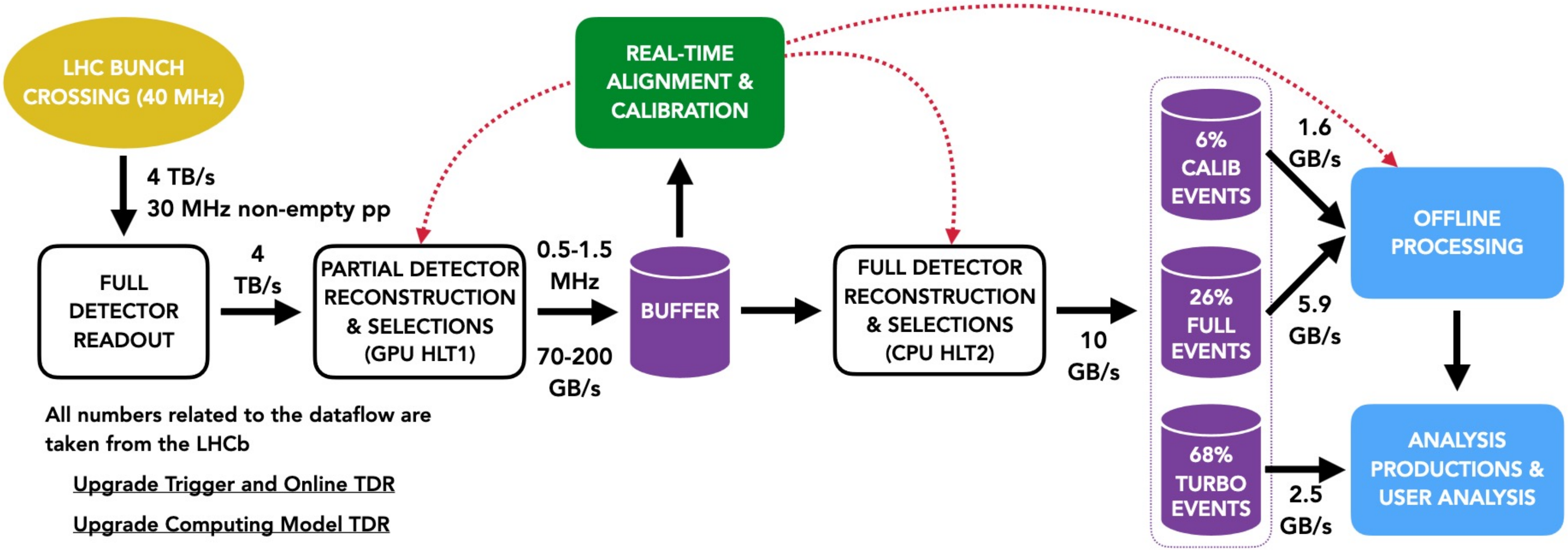
LHCb

- Physics core program: search for New Physics through ***heavy flavor decays***
  - Study *CP* violation
  - Rare *B* decays
- Optimized acceptance: $2 < \eta < 5$
- Good particle ID: e, μ, p, K, π, γ identification up to p=100 GeV
- Good vertex and proper-time resolution: Interaction point resolution better than 50 μm
- Good mass and low momentum resolution
- Efficient trigger for lepton and hadron channels: 1 MHz readout rate up to 2018 – main improvement point for first upgrade (40 MHz readout).
- LHCb became a more general detector in the forward region

LHCb Upgrade I Detector



Full Software Trigger



All numbers related to the dataflow are taken from the LHCb

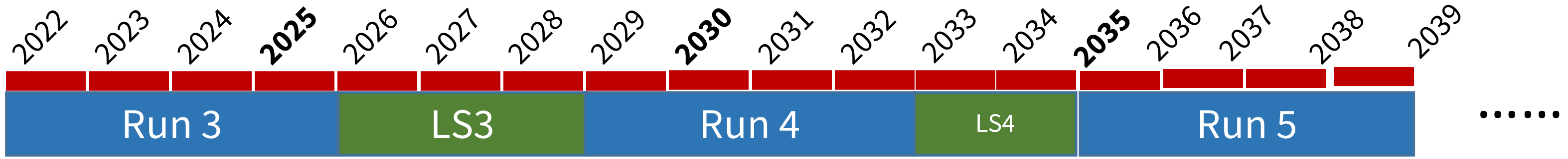
Upgrade Trigger and Online TDR

Upgrade Computing Model TDR

LHCb timeline

Initial LHCb detector (2011 – 2018):

$L = 4 \times 10^{32}$ cm^{-2} s^{-1}
~1.1 interaction per bunch crossing
~9 fb^{-1} (Run 1 + 2)



$L = 2x10^{33}$ $cm^{-2}.s^{-1}$
~5 interactions per bunch crossing
~50 fb^{-1} (Run 3 and 4)

$L = 2x10^{34}$ $cm^{-2}.s^{-1}$
~50 interactions per bunch crossing
~300 fb^{-1} (Run 5….)

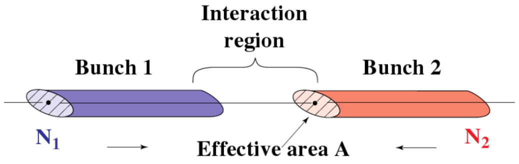
Luminosity measurement at LHCb

- Fixed-target physics started with luminosity measurements for LHCb: precise luminosity measurement is an important ingredient for many LHCb publications: cross-sections of J/ψ, Y(1S), charm, beauty, ...
- Need to calibrate the luminosity measurements:
  - Using well-know processes, like *pp* → $Z^0(\to\mu\mu)$ X but this had not good enough precision so far
  - Using dedicated LHC fills to measure directly the luminosity, L (per bunch):

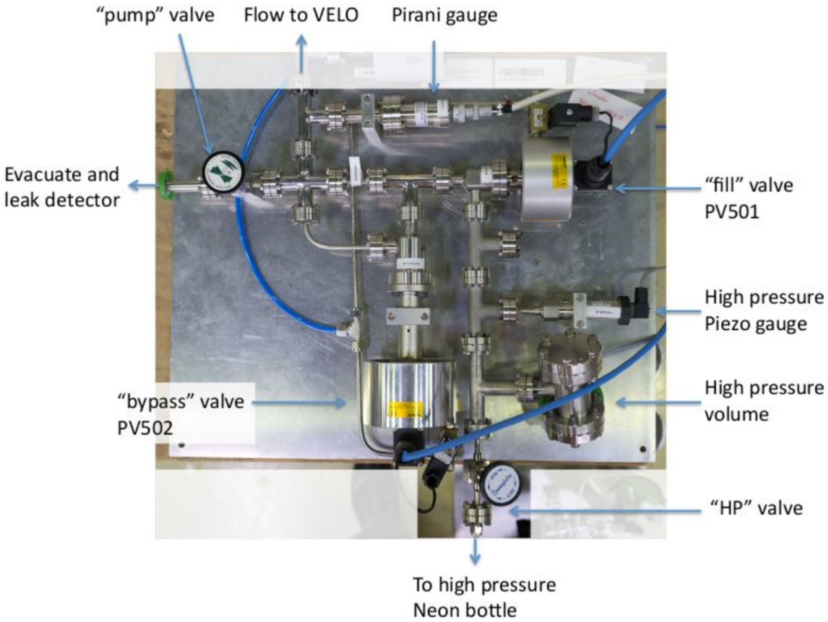
$$L=\frac{N_1 N_2 f}{A_{eff}}=N_1 N_2 f \iint \rho_1(x,y)\rho_2(x,y)\,dxdy$$

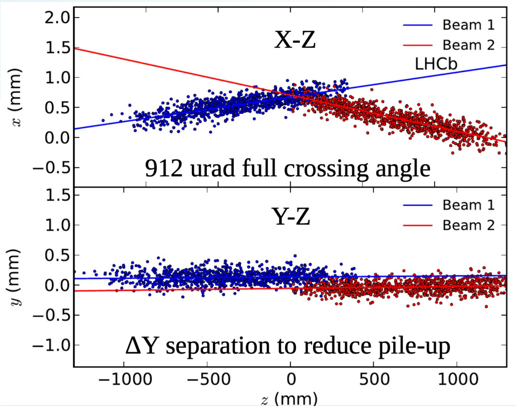
measure ρ_1 and ρ_2 from beam images reconstructed with beam-gas interactions

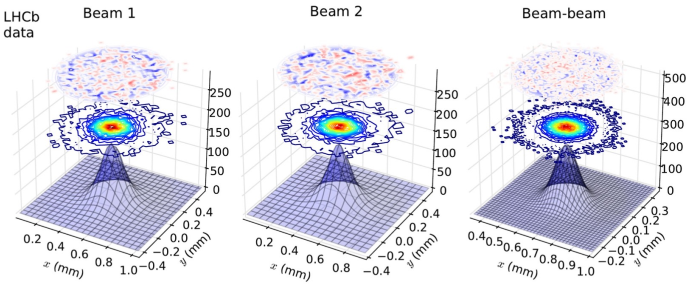
  - Where *f* is the collision frequence, N_1, N_2 are the bunch populations, ρ_1 and ρ_2 the beam profiles



SMOG





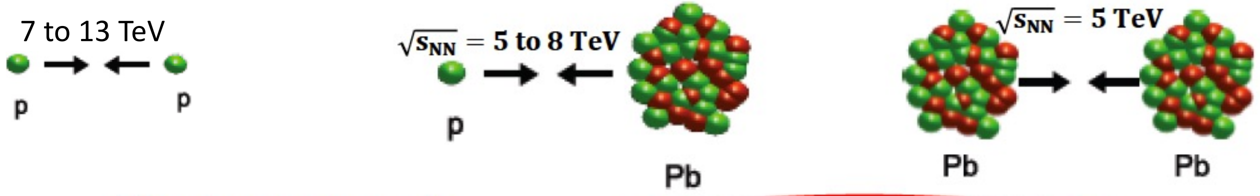


SMOG = System to Measure Overlap with Gas: inject ~10^{-7} mbar of gas in the interaction region

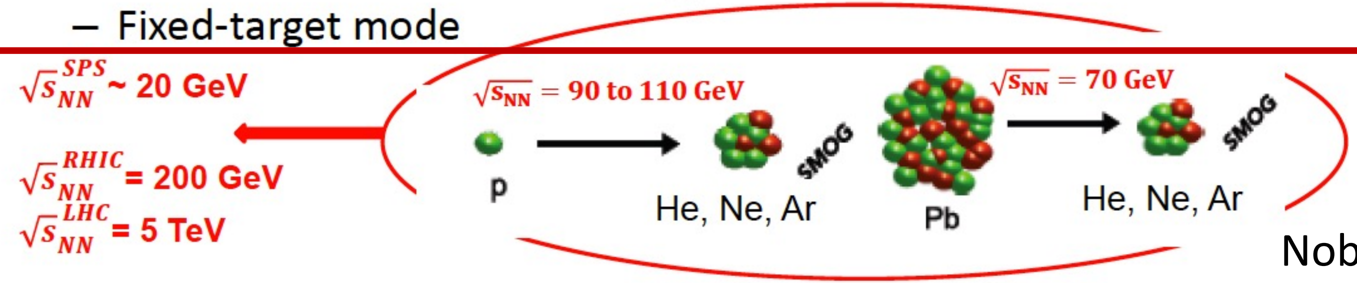
With 8 TeV *pp* collisions, reached 1.4% precision on luminosity

LHCb operation modes

– Collider mode



– Fixed-target mode



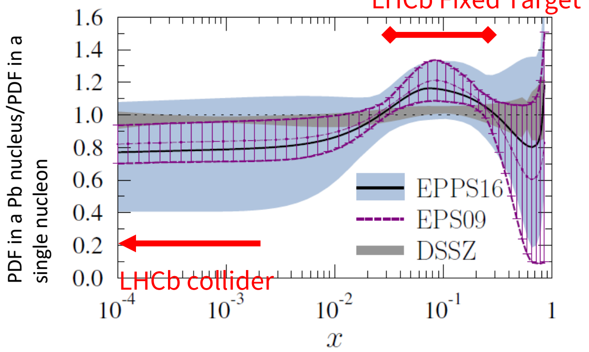
Unique to LHCb
Unique energies

Nobel gases

LHCb rapidity 2.5 < yLHCb < 4.5 $\Rightarrow \begin{cases} \text{7 TeV beam:} & -2.3 < y^*_{LHCb} < -0.3 \\ \text{2.75 TeV beam:} & -1.8 < y^*_{LHCb} < 0.2 \end{cases}$

Heavy Ion Physics with LHCb

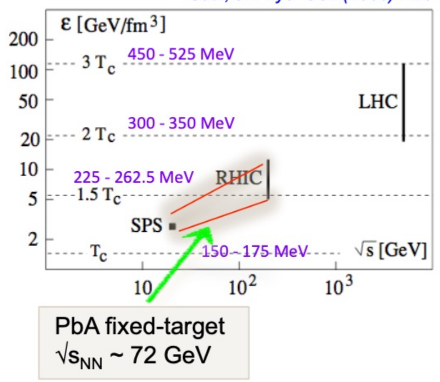
- **Proton-nucleus** collisions
  - Serve as a baseline for nucleus-nucleus collisions
  - Nuclear parton distribution function (nPDF), nuclear absorption, saturation, energy loss…
  - Unique capabilities with LHCb in the ***heavy flavor sector*** to constraint nPDF at very small (*p*Pb collisions – charm and beauty) and large (fixed target - charm) Bjorken-*x*



Bjorken-*x* = fraction of the nucleon momentum carried by a parton

- **Nucleus-nucleus** collisions in FT mode
  - 2.75 TeV Pb beam on fixed target: $\sqrt{s_{NN}}$~71 GeV (close to the 17 GeV regime reached at SPS)
    - Investigate the color screening
    - Thanks to unique capabilities, LHCb offers new opportunities in the charm sector: J/ψ, ψ’, χ_c, D^0, $D^{+/-}$, D^*, Λ_c… (in the 90’s the NA50/SPS experiment measured only J/ψ and ψ’ in PbPb @ 17 GeV)
  - Accessing similar energy density regime than SPS: operate PbAr@71 GeV, lower multiplicity than PbPb collisions, central events should be accessible

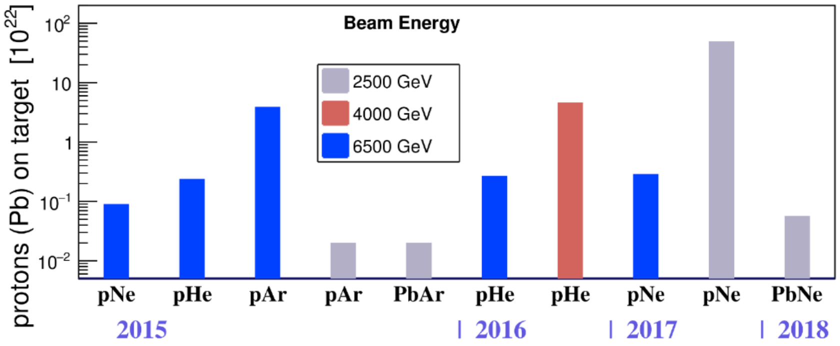
Satz, J. Phys. G32 (2006) R25

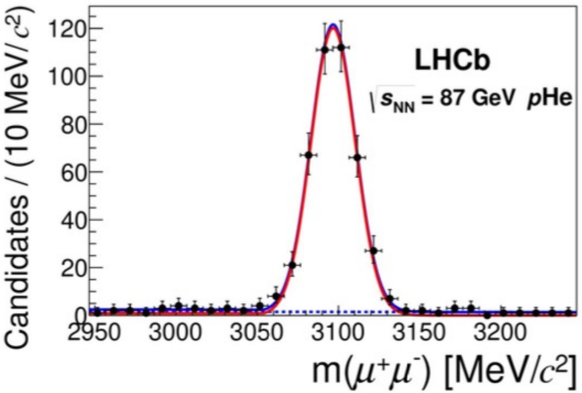


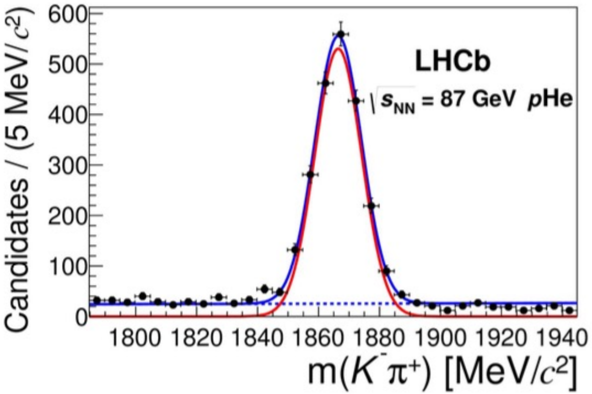
[PRL 122 (2019) 132002]

Production of charm in fixed target

- Use two of the data samples: *p*He (4 TeV beam, 86 GeV) and *p*Ar (6.5 TeV beam, 110 GeV)
- Largest sample is *p*He, 7.6 ± 0.5 nb
- Measurement of prompt production of J/ψ (→$\mu^+\mu^-$) and D^0(→Kπ)



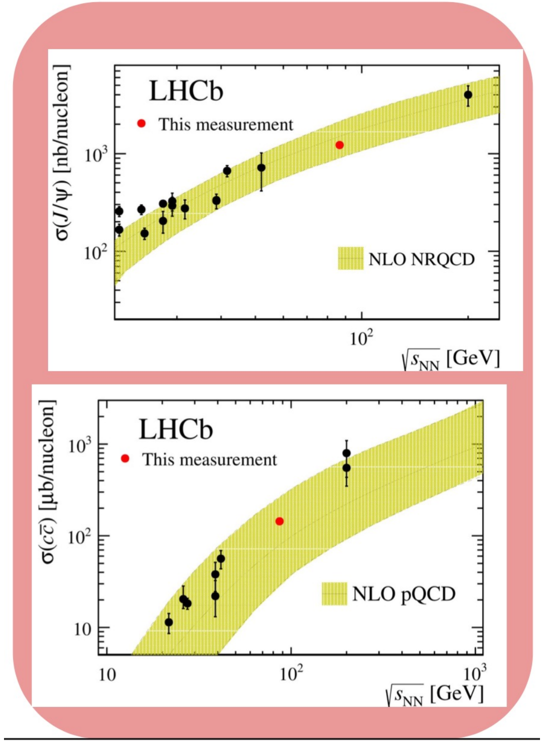




Production of charm in fixed target

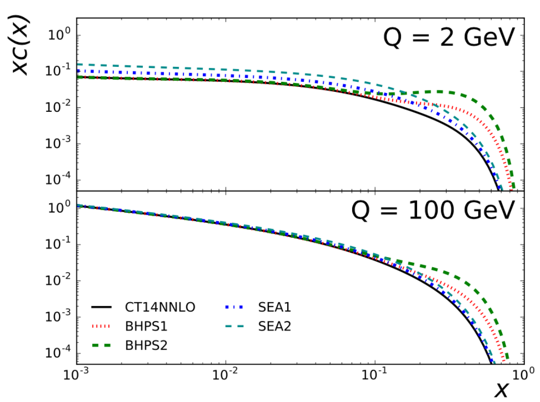
- Measured cross-sections are extrapolated to the full phase space (4π) and in the case of the D^0, to the full $c\bar{c}$ spectrum (using $f(c \to D^0)$ from external measurements)
- Compared to
  - Previous measurements at lower and higher energies
  - Predictions from NLO NRQCD for J/ψ [PLB 638 (2006) 202] and NLO pQCD for $c\bar{c}$ [NPB 373 (1992) 295]

$$\sigma_{J/\psi} = 652 \pm 33(\text{stat}) \pm 42(\text{syst})\ \text{nb/nucleon},$$
$$\sigma_{D^0} = 80.8 \pm 2.4(\text{stat}) \pm 6.3(\text{syst})\ \mu\text{b/nucleon}.$$

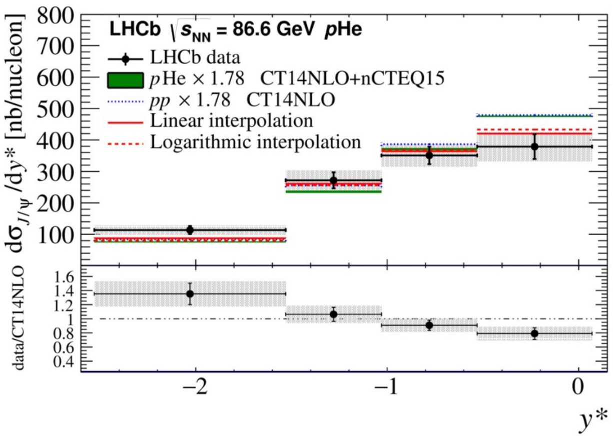


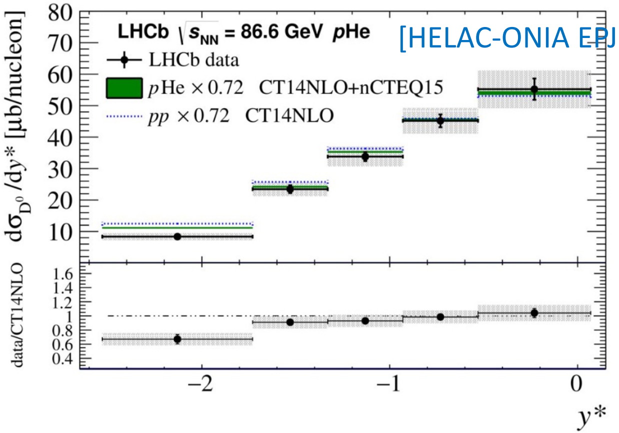
Production of charm in fixed target

- Cross-section as a function of rapidity (y^*) and p_T to test intrinsic charm content of proton (would be seen as increase of cross-section at negative rapidities compared to predictions)



Phys Rev **D93** (2016) 074008



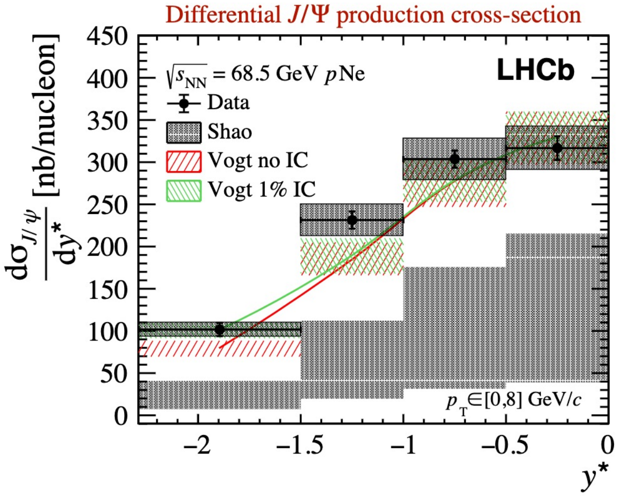


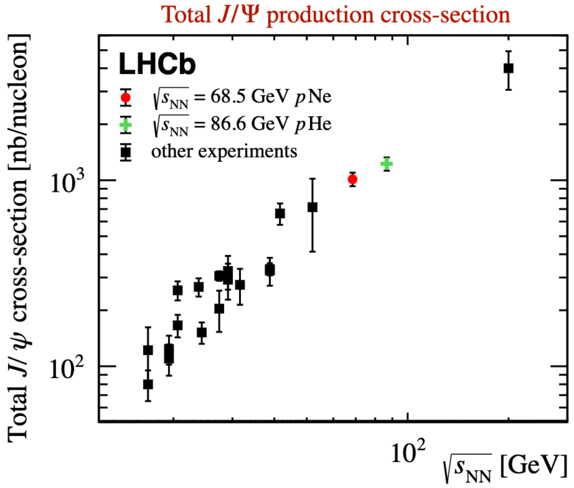
[HELAC-ONIA EPJC 77 (2017) 1]

[arXiv:2211.11645]

Production of charm in fixed target

- Added recently analysis of *p*Ne data at 68.5 GeV

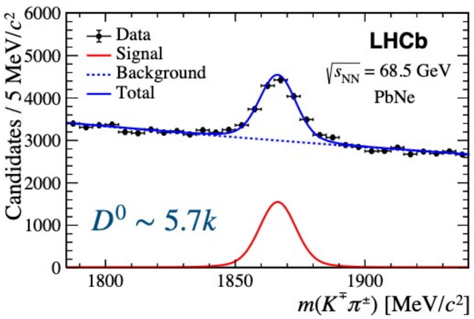


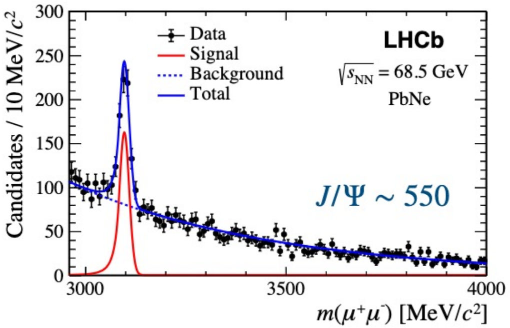


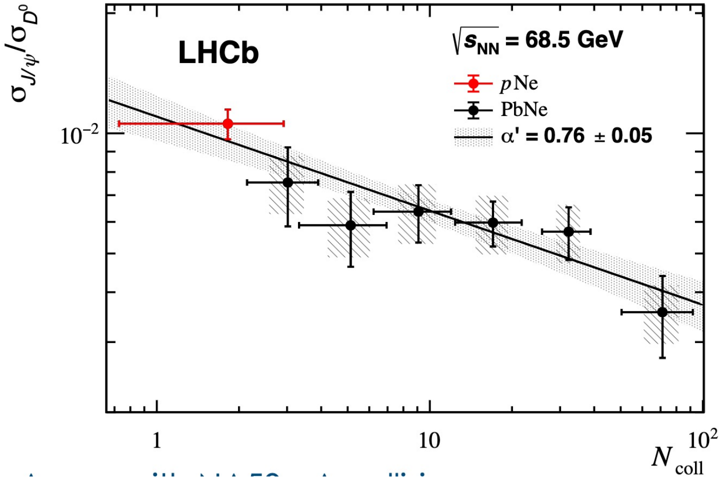
- HELAC-ONIA using CT14NLO+nCTEQ15 underpredicts the data
- Good agreement with predictions with 1% Intrinsic Charm (IC) and without [PRC 103 (2021) 035204]

D^0 and J/ψ in PbNe collisions at 68 GeV

- Centrality of collisions determined from total energy deposited in ECAL



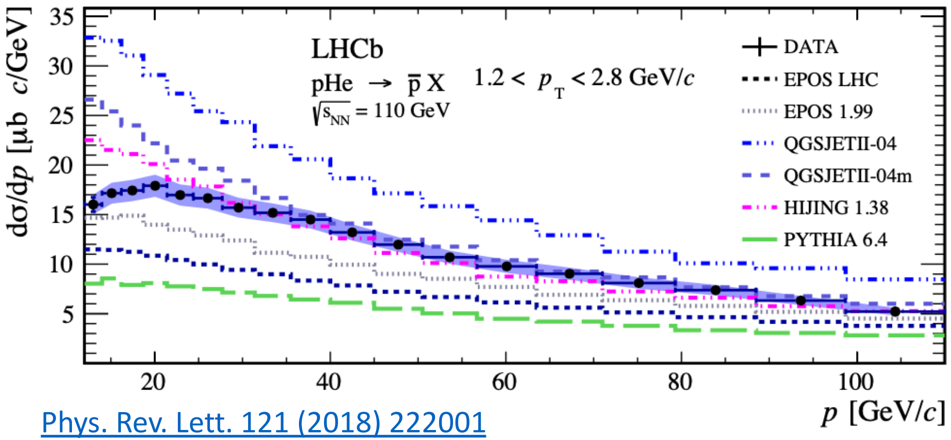




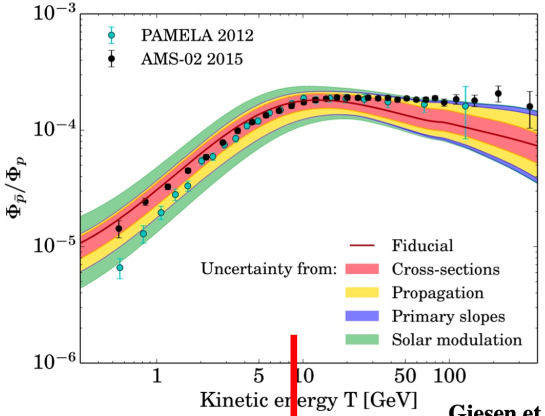
- J/ψ production affected by additional nuclear effects than D^0 but no anomalous J/ψ suppression i.e. no sign of QGP formation

SMOG: *prompt* anti-protons in *p*He collisions at 110 GeV

- Interesting to reduce uncertainties on anti-proton production in inter-stellar medium: pHe → $\bar{p}$X is ~40% of secondary cosmic anti-proton

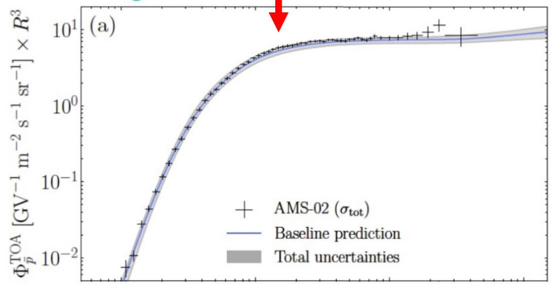


[Phys. Rev. Lett. 121 (2018) 222001](https://doi.org/10.1103/PhysRevLett.121.222001)



Giesen et al., JCAP 1509, 023

After LHCb results

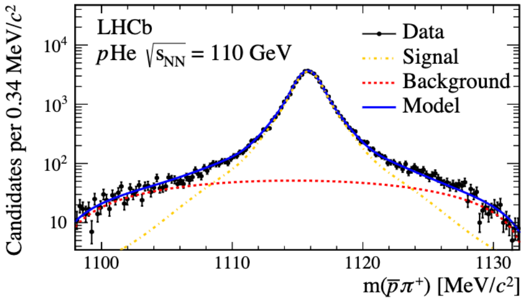


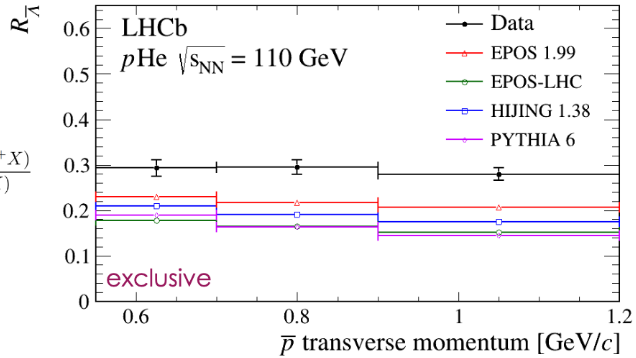
Phys. Rev. Research 2, 023022 (2020)

SMOG: *detached* anti-protons in *p*He collisions at 110 GeV

- Exclusive selection of $\bar{\Lambda} \to \bar{p}\pi^+$

exclusive

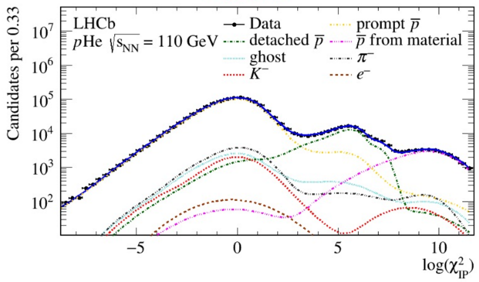


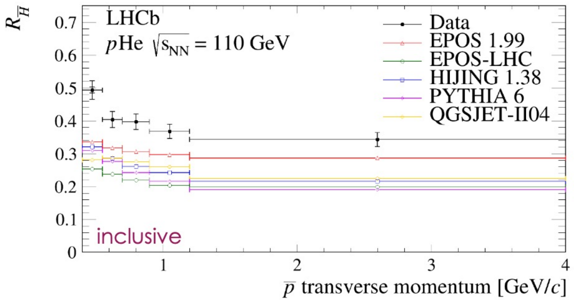


$$R_{\bar{\Lambda}} \equiv \frac{\sigma(p\mathrm{He} \to \bar{\Lambda}X \to \bar{p}\pi^+X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}}X)}$$

- Inclusive selection of $\bar{p}$ with large impact parameter (IP)

inclusive





$$R_{\bar{H}} \equiv \frac{\sigma(p\mathrm{He} \to \bar{H}X \to \bar{p}X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}}X)}$$

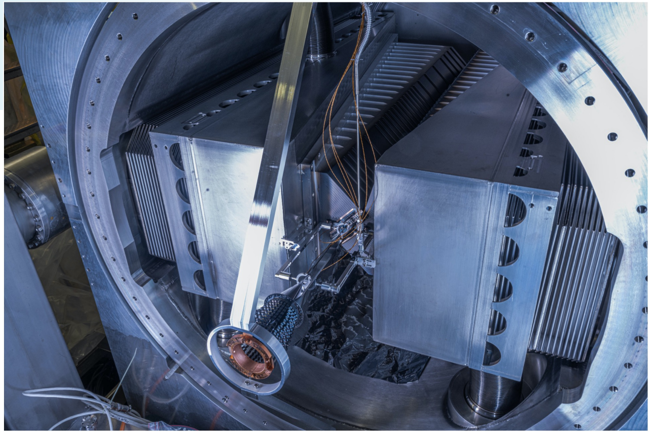
Fraction of $\bar{p}$ from hyperon decay

SMOG2

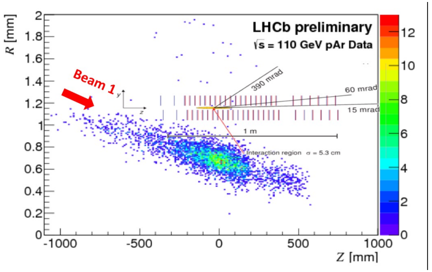
- SMOG proved that a fixed target physics program at LHCb works, but has limitations:
  - Fixed target data taking was mostly done during dedicated short runs, at maximum during 1 continous week: low statistics
  - The pressure of the injected gas is limited because the gas flow is not contained and goes into the LHC beam pipe
  - Changing types of gases is a long operation: requires access close to the VELO, i.e. stopping the LHC operation
  - The position of the interactions is distributed along a large area: strong variations of the detector efficiency as a function of that position
- To address all these difficulties: upgrade of SMOG system = SMOG2

SMOG2

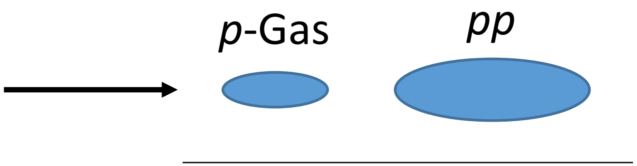
Installed in August 2020



- New storage cell installed at LHCb to boost significantly the fixed target program
- Increase of the luminosity by up to 2 orders of magnitude using the same gas flow as SMOG, but with higher density
- *Possibility to inject H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe* with multiple gas lines and a dedicated gas feed system
- New Gas Feed System. Gas density (luminosity) measured with greatly improved precision (few %)
- Well defined interaction region upstream the nominal IP: strong background reduction, no mirror charges effect, possibility to use all the bunches. *pp* and *p*-Gas simultaneous data taking may be possible thanks to software trigger.
- In beam-beam slots:

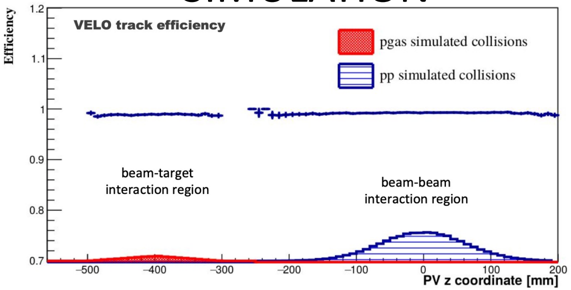


SMOG



SMOG2

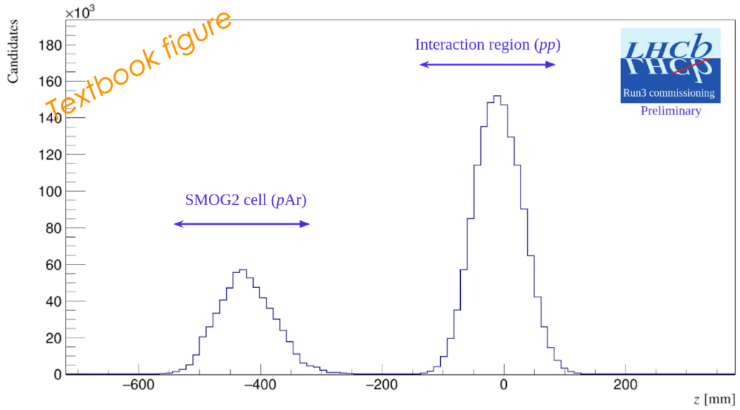
SIMULATION

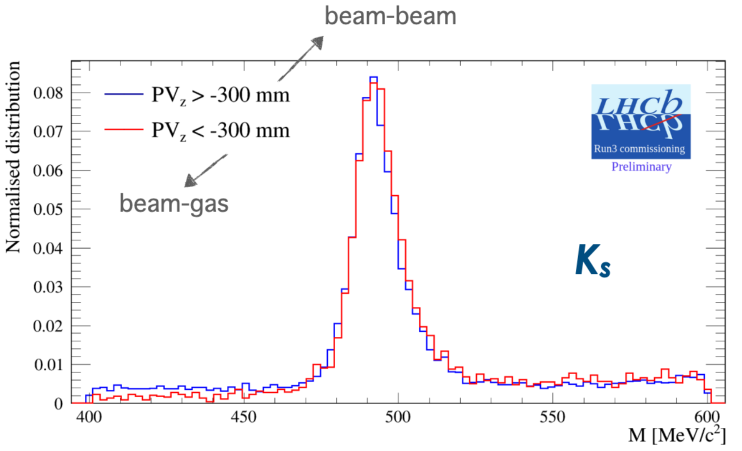


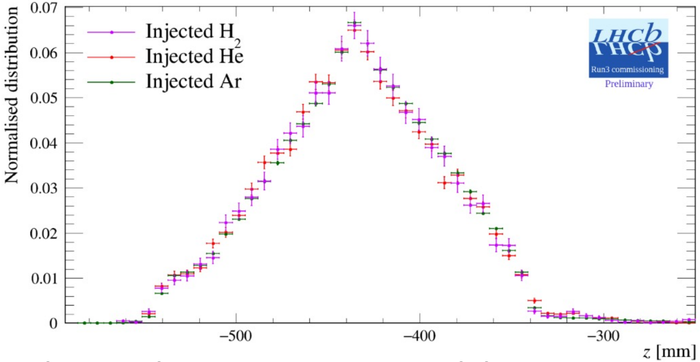
Yields per year

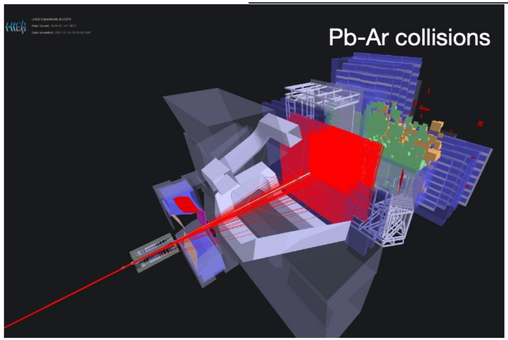
	pAr
J/Ψ	28 M
D^0	280 M
Λ_c^+	3 M
$\Psi(2S)$	5 M
$\Upsilon(1S)$	24 k
$DY_{low\ mass}$	24 k

SMOG2 Commissioning (2022): H_2, He, Ar









LHCb is the only experiment able to run simultaneously in fixed target and collider modes

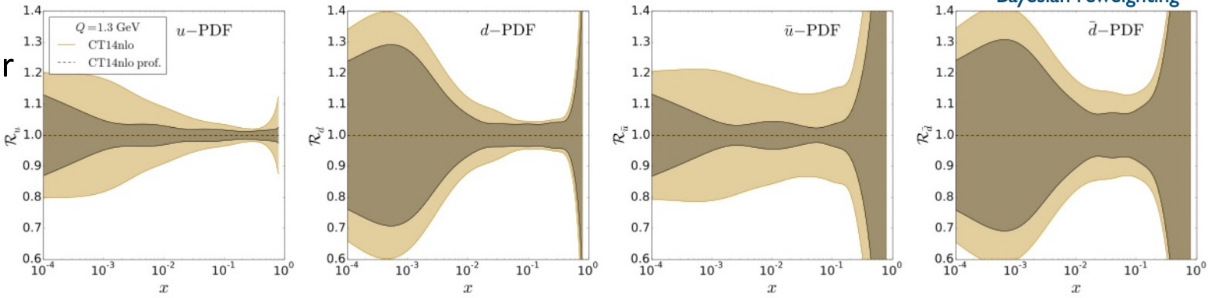
SMOG2: High x physics

Reduction of PDF uncertainties is crucial for Beyond Standard Model searches

arXiv:1807.00603

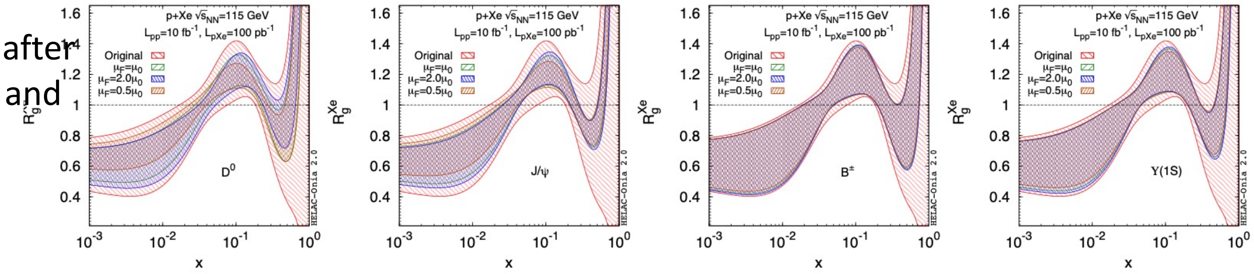
Bayesian reweighting

PDF uncertainties before and after including estimated Drell-Yan production SMOG2 data (Q= 1.3 GeV)



PDF

nPDF uncertainties before and after including estimated D^0, J/ψ, B^+ and Y(1S) production SMOG2 data

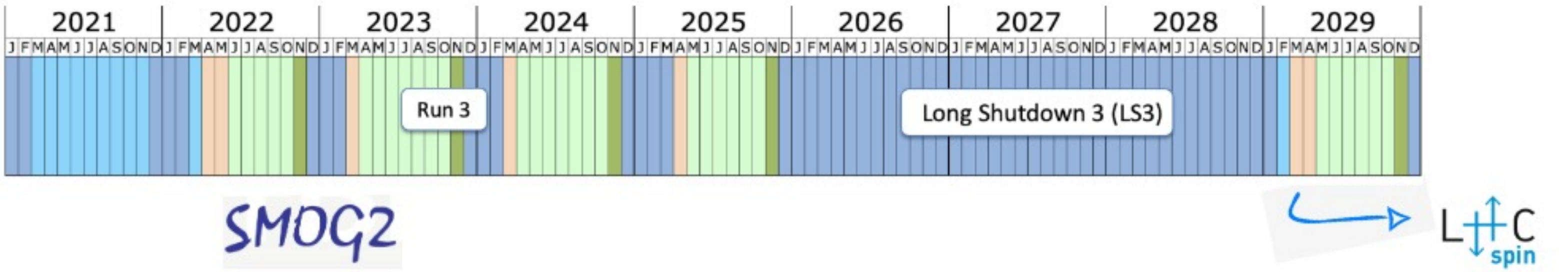


nPDF (gluon)

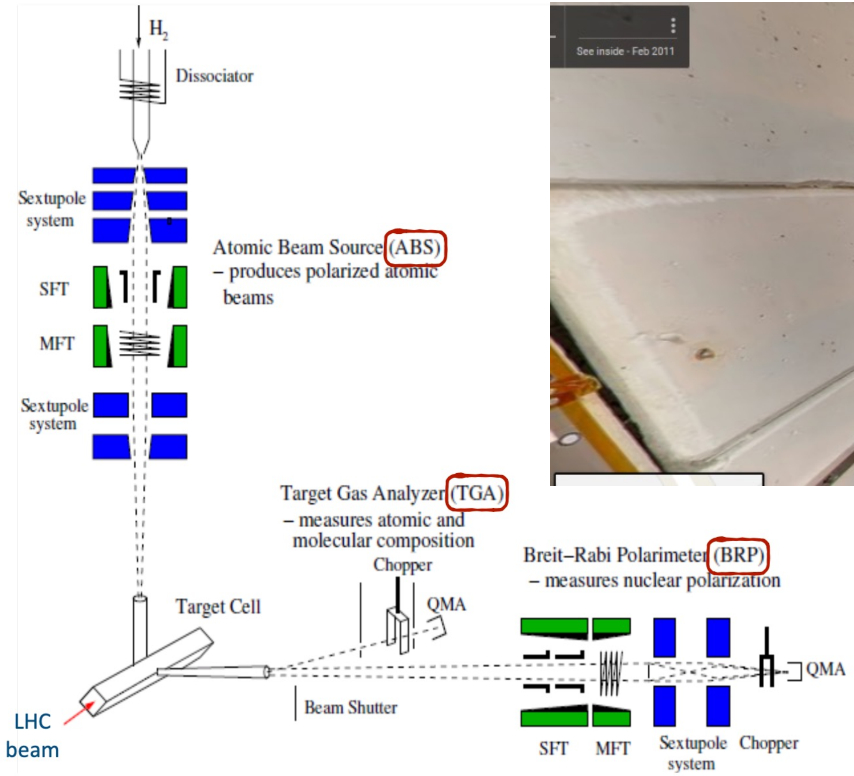
Unique constraints on gluon nPDFs at high-x and low scales

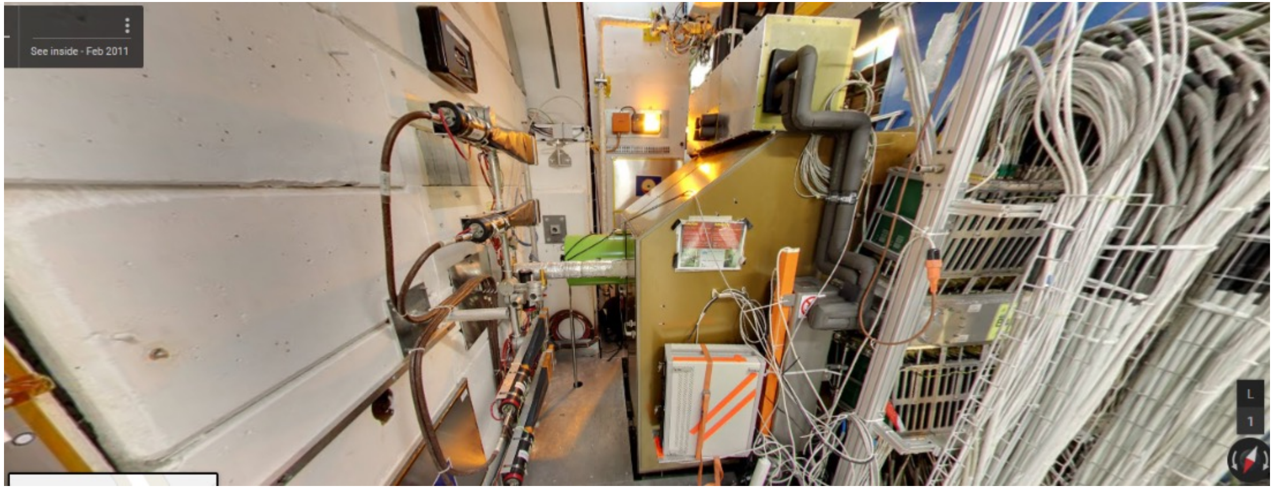
Beyond SMOG2: Polarized Gas Target

- LHC beams cannot be polarized but one possibility is to have polarised collisions through a polarized fixed-target, at LHCb
- R&D starting from the HERMES setup @ DESY
- Target density (H) = 7x10^{13} cm^{-2} with LHC beam : L_{pH} = 8x10^{32} cm^{-2}.s^{-2}
- Negligible impact on the beam lifetime



Polarized Gas Target

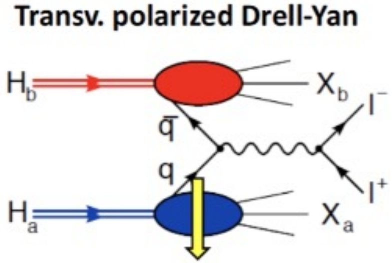


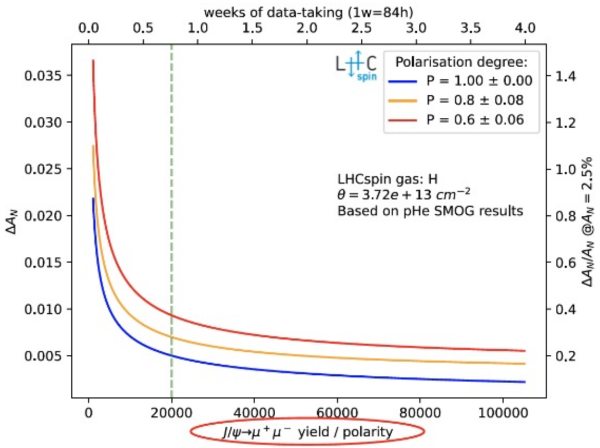


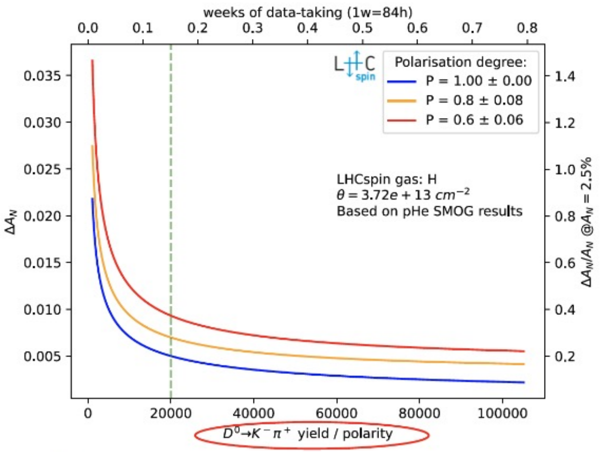
Space in front of LHCb ~1.5 m

Physics with polarized gas target

- Study multi-dimensional nucleon structure in a region (same than SMOG/SMOG2) not well known
- Measure experimental observables sensitive to quark and gluon TMDs
- Use new probes (charm and beauty)
- Measure exclusive processes to access GPDs







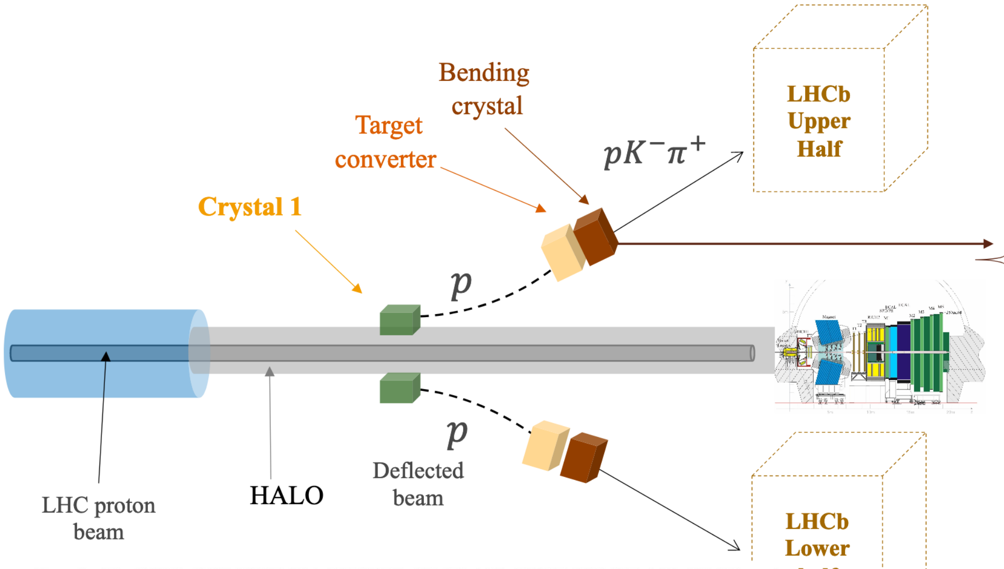
reconstructed particles

Precise spin asymmetry on $J/\psi \to \mu^+\mu^-$ and $D^0 \to K^-\pi^+$ for $pH^\uparrow$ collisions in just few weeks

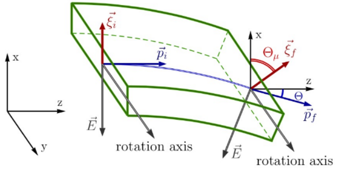
[EPJC 77 (2017) 181]
[JHEP 8 (2017) 120]
[EPJC 77 (2017) 828]

Target with crystals

- Measurement of charm quark MDM and EDM via spin precession of Λ_c baryons produced in a fixed target, using crystals in LHCb or a dedicated experiment @ LHC IR3



$$\Theta_\mu \approx \gamma\left(\frac{g}{2}-1\right)\Theta$$



Need initial ($\vec{\xi_i}$) and final ($\vec{\xi_f}$) Λ_c^+ polarization

$\vec{\xi_i}$: Produce polarized baryons using a target-crystal before the bending crystal

$\vec{\xi_f}$: Measured using dedicated experiment or LHCb

Detailed in LHCb-INT-2017-011, EPJC 77 (2017) 181, JHEP 2017(8):120 (2017) and EPJC 77 (2017) 828.

Conclusions

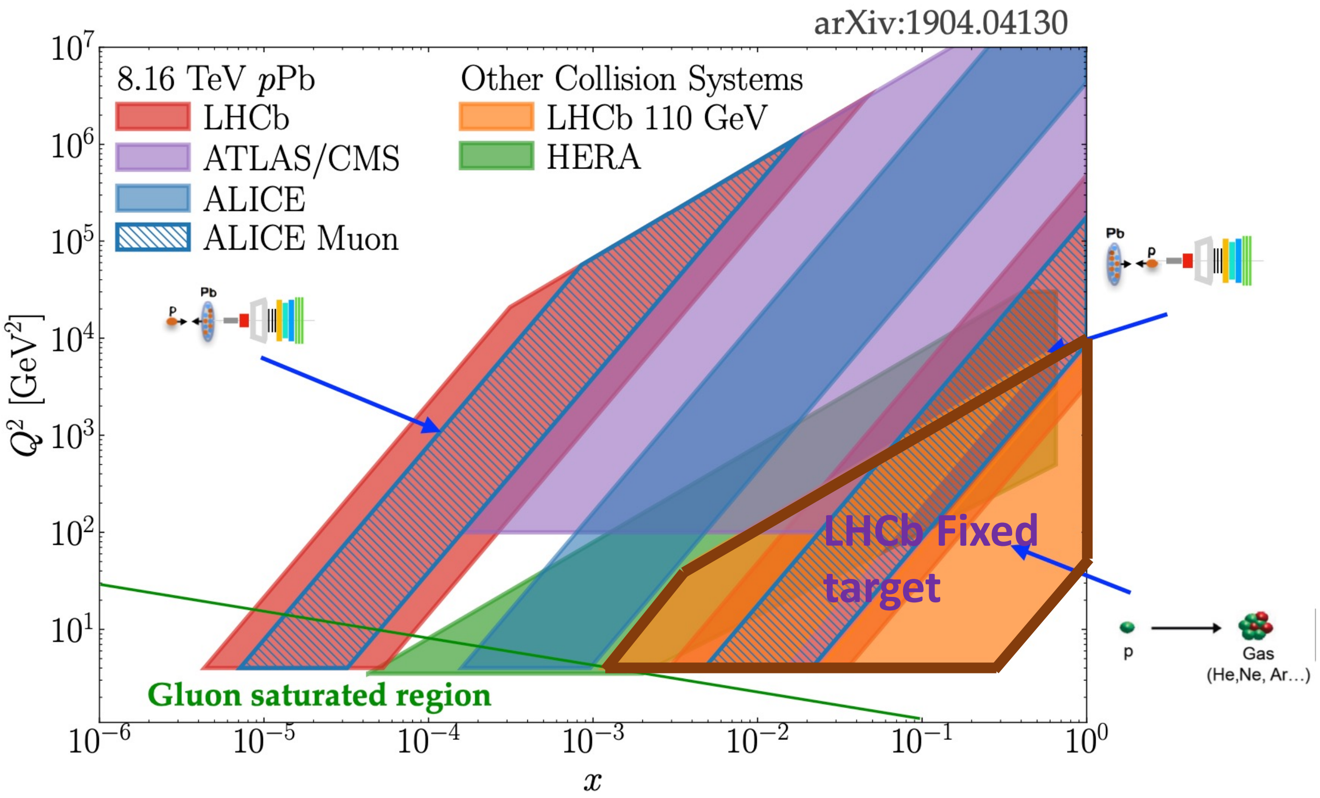
- Fixed-target physics at LHCb/LHC feasibility established with SMOG during Run 2 of LHCb: limited by statistics

- Success of this first phase encouraged many new projects

- Installation of SMOG2 will boost significantly physics output

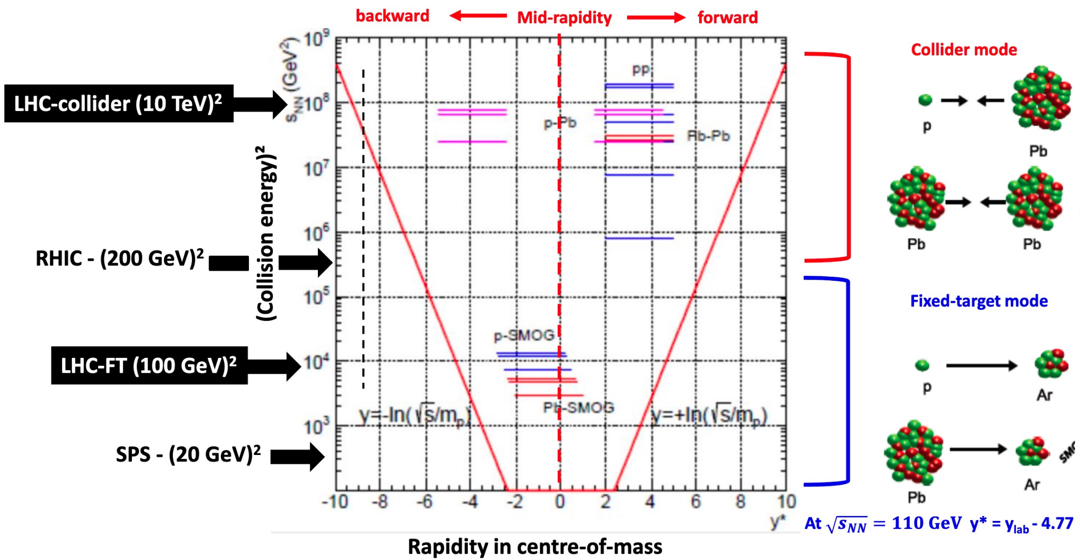
- New projects at LHCb and IR3 under design to explore new directions (polarized target, MDM-EDM, ...)

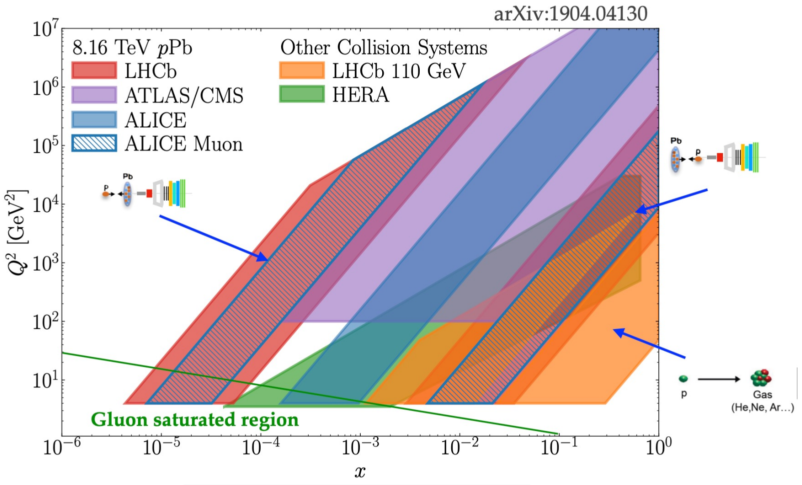
Fixed-target coverage



LHCb Heavy Ion Physics Program

The fixed-target is mainly connected to the LHCb QCD/Heavy Ion Physics Program: so far mostly concentrated on study of heavy-flavor production in *p*Pb collisions, with well established performances and large statistics

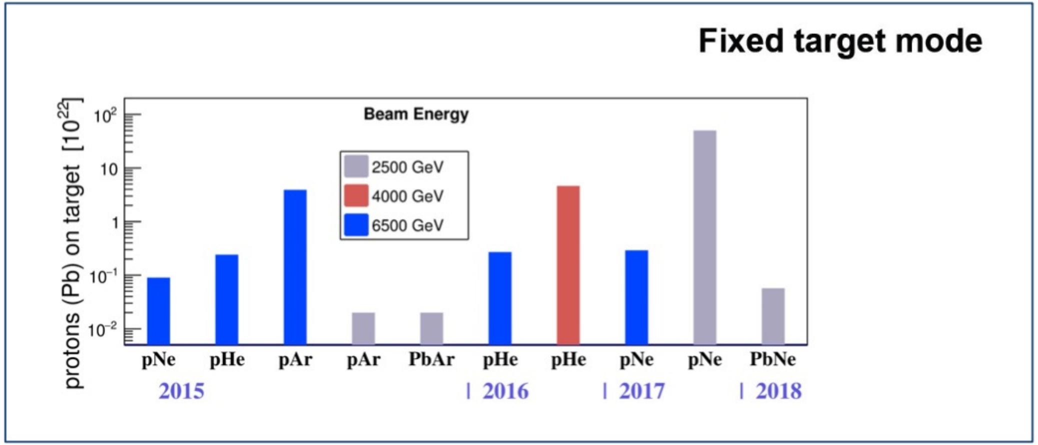




Large phase space coverage

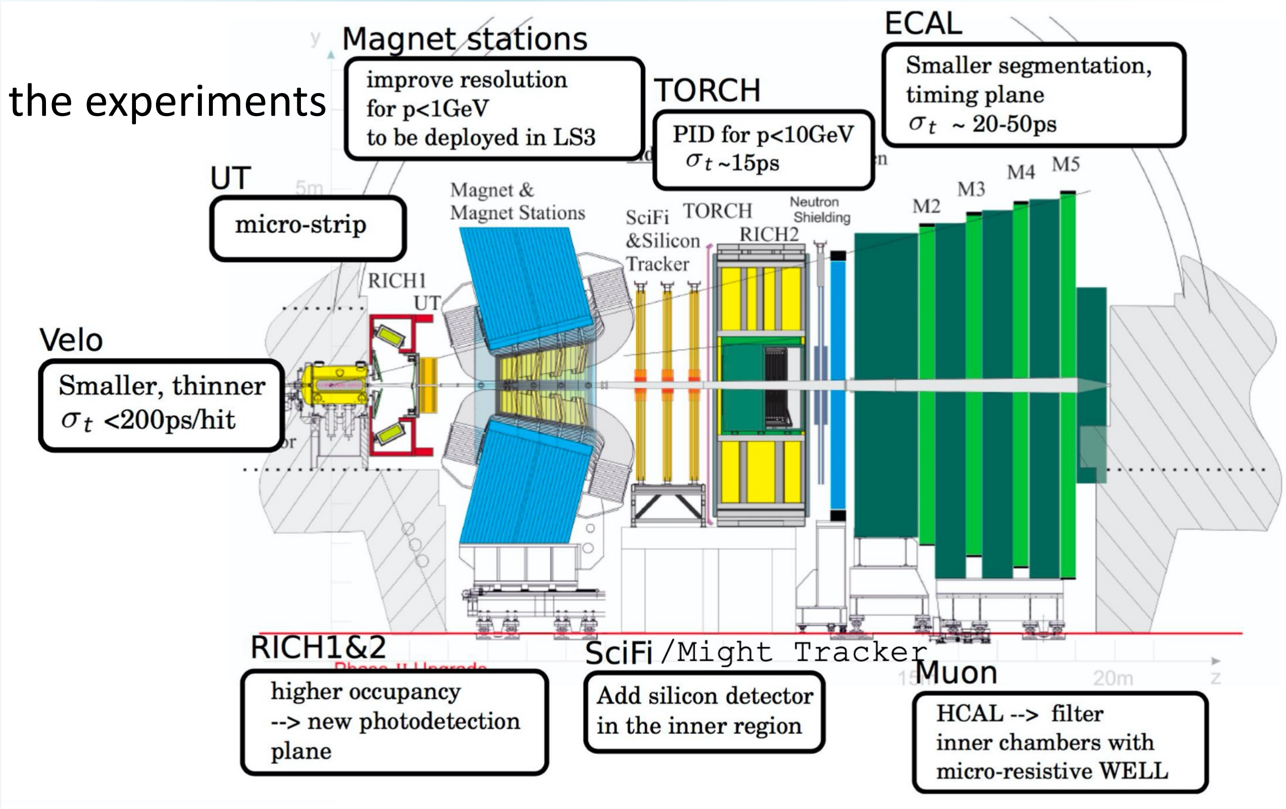
Fixed Target Physics With LHCb

- Inject gas between 1 day and 2 weeks.
- The pressure is so low that it does not interfere with the running of the LHC and data can be collected also in parallel with *pp* collisions by LHCb.
- Operation in 2015 demonstrated that running with SMOG in completely transparent for the LHC: it is considered now as routine operation.
- During Heavy Ion runs, we also took data in parallel collisions/beam-gas.



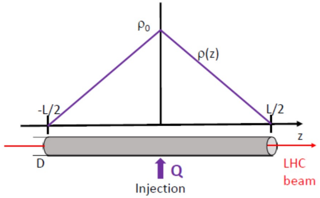
Upgrade Ib and II

Changes to all parts of the experiments

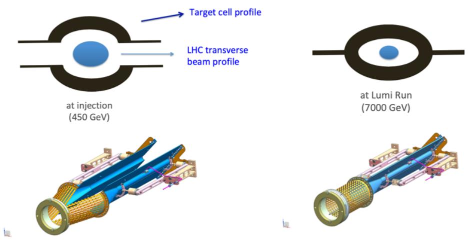


SMOG2 storage cell

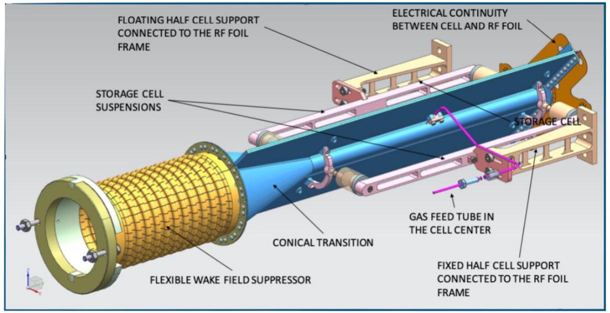
- The storage cell is a tube (20 cm length, 1 cm diameter) where the gas is injected at the center from a gas-feed system



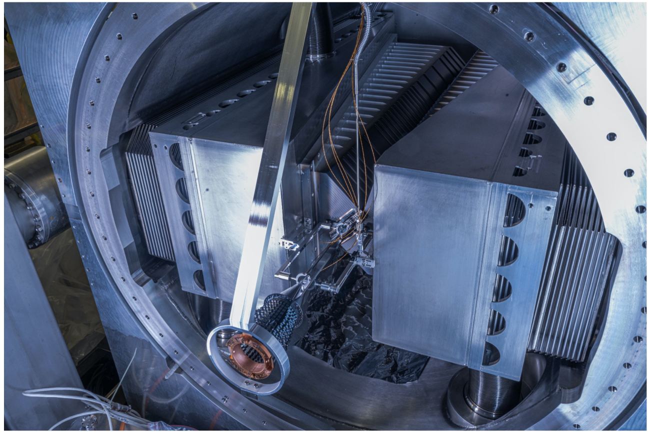
- Similarly to the VELO, the cell must be opened when the beam is not stable (at 3 cm)



Solution adopted for SMOG2: L = 20 cm, R = 0.5 cm
for LHCspin: L = 30 cm, R = 0.5 cm

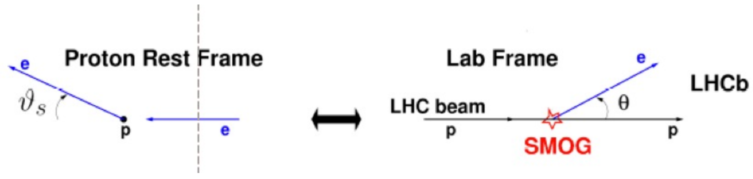


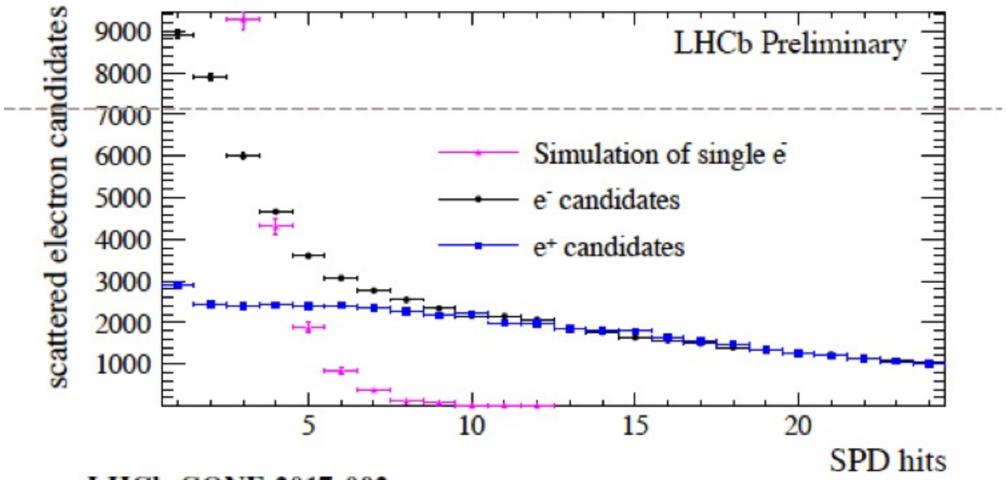
Installed in August 2020



Fixed-target luminosity

- Use p-e^- elastic scattering (Mott)
- Pro:
  - Only elastic regime in LHCb acceptance:
    - θ>10 mrad → θ_s< 29 mrad, Q^2<0.01 GeV^2
    - Cross-section very well-known
  - Clear event signature: single low p_T electron track and nothing else
  - Background comes mainly from conversions: it is charge-symmetric and can be estimated precisely from single positron events
- Cons:
  - Small cross-section (1000 less than hadronic cross-section)
  - Low momentum electrons = low acceptance and reconstruction efficiency





LHCb-CONF-2017-002