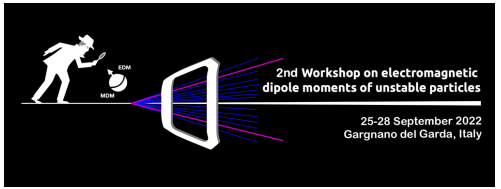
Fixed-target experimental results and perspectives at LHCb

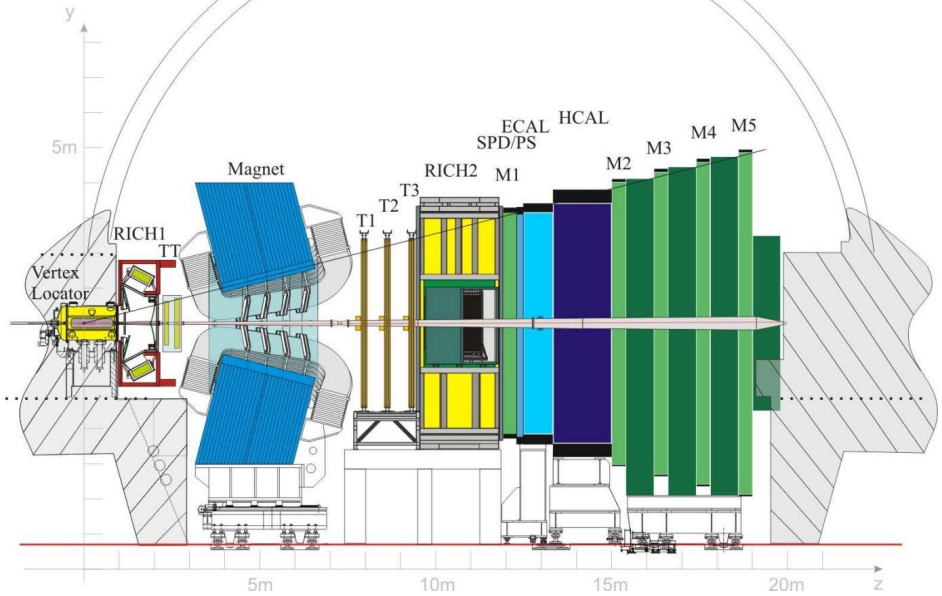


Patrick Robbe for LHCb collaborations, IJCLab Orsay, 26/09/2022

The LHCb Detector

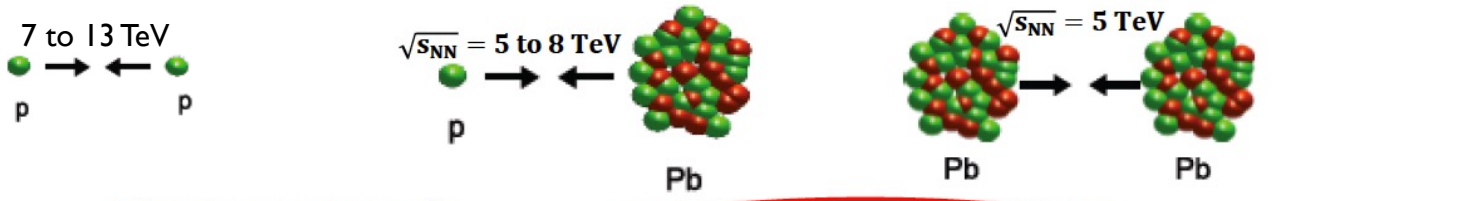
- Acceptance: $2 < \eta < 5$
- Vertex detector (VELO)
  - Impact Parameter resolution ~20 μm
- Tracking System
  - $\frac{\Delta p}{p} = 0.5 - 1\ \%$
- RICH
  - K/π/p separation
- Electromagnetic and hadronic calorimeters
- Muon system
- *Upgraded for Run 3*

Detector Run 1 – Run 2



LHCb collision modes

– Collider mode



– Fixed-target mode

Unique to LHCb
Unique energies

$\sqrt{s}_{NN}^{SPS}$ ~ 20 GeV

$\sqrt{s}_{NN}^{RHIC}$ = 200 GeV

$\sqrt{s}_{NN}^{LHC}$ = 5 TeV

$\sqrt{s_{NN}}$ = 90 to 110 GeV

p

SMOG

He, Ne, Ar

$\sqrt{s_{NN}}$ = 70 GeV

Pb

SMOG

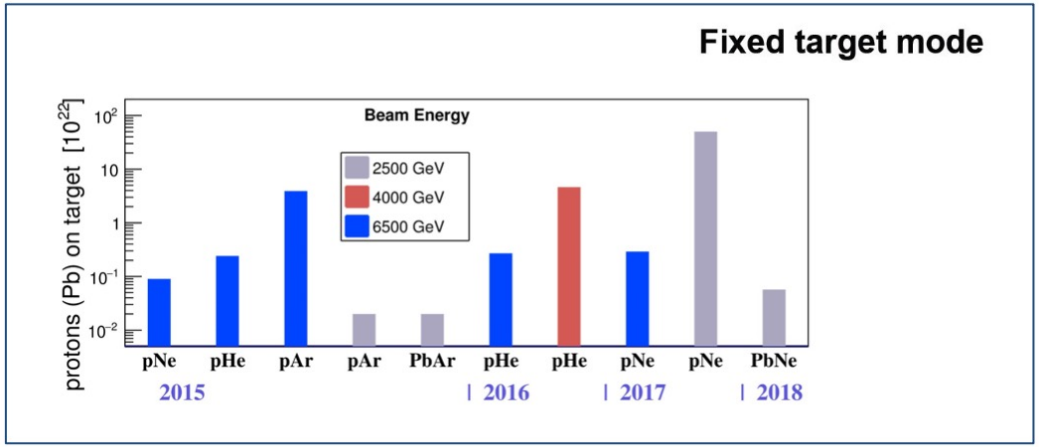
He, Ne, Ar

Nobel gases

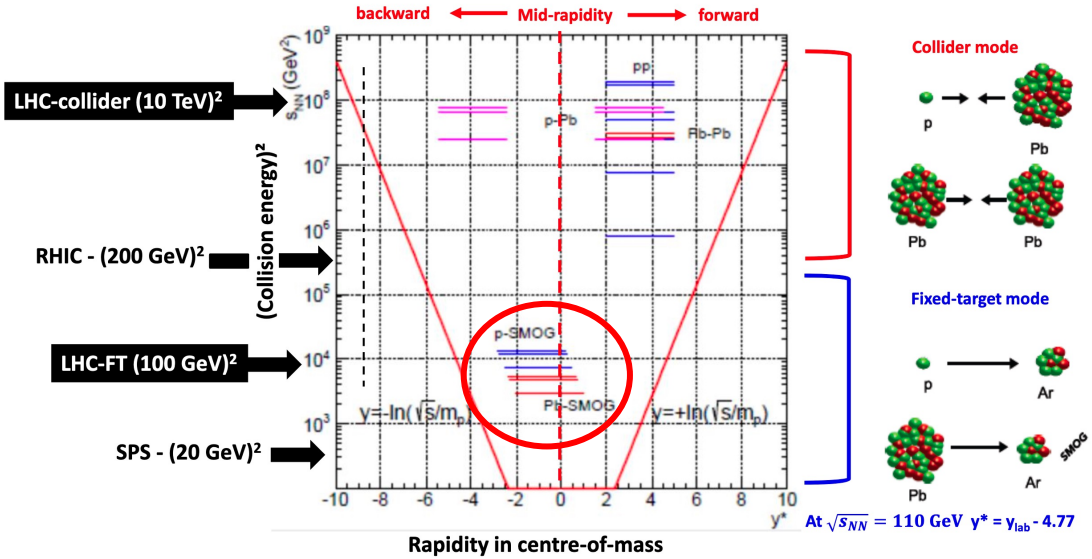
LHCb rapidity 2.5 < yLHCb < 4.5 $\Rightarrow$ $\begin{cases} \text{7 TeV beam:} & -2.3 < y^*_{LHCb} < -0.3 \\ \text{2.75 TeV beam:} & -1.8 < y^*_{LHCb} < 0.2 \end{cases}$

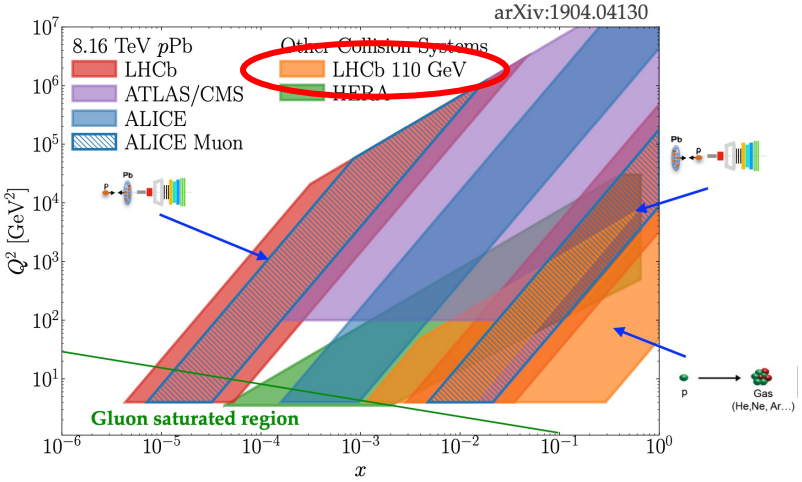
Fixed Target Physics With LHCb

- 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.



LHCb Acceptance

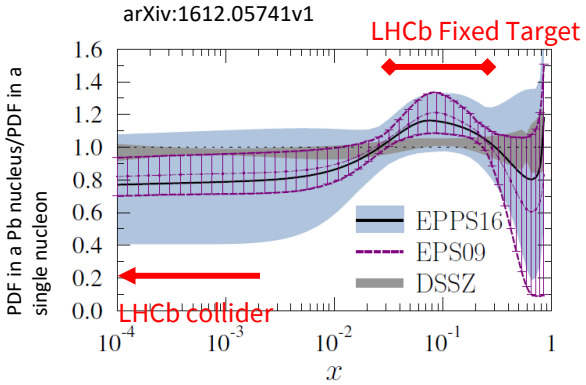




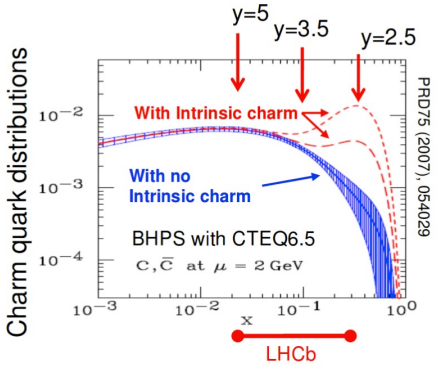
Large phase space coverage

Fixed-target physics program: SMOG

- SMOG = System for Measuring Overlap with Gas
- Noble gas at $\sim 2x10^{-7}$ mbar pressure injected in LHCb vacuum in the LHCb interaction region
- Originally used to determine luminosity: since 2015, use it to collect fixed-target collision data for physics
- $\sqrt{s_{NN}} = 69$-110 GeV, between SPS and RHIC
- $-3.0 < y^* < 0$
- Access nPDF (nuclear PDF) anti-shadowing region
- Probe intrinsic charm content in the nucleon
- Inputs to astrophysics



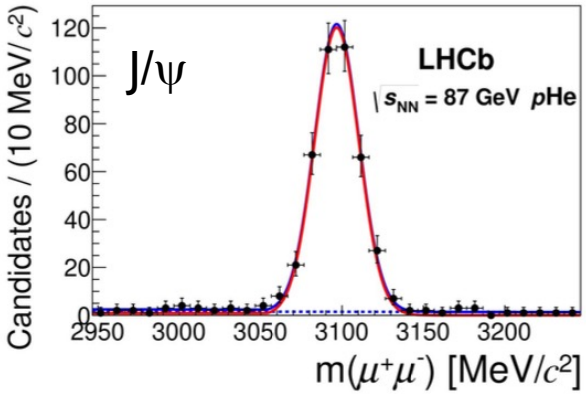
Bjorken-*x* = fraction of the nucleon momentum carried by a parton

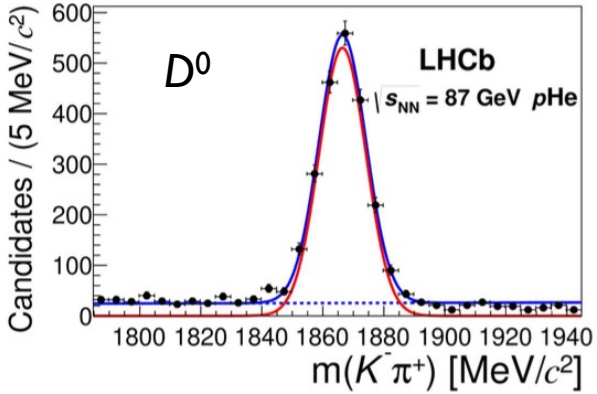


[PRL 122 (2019) 132002]

Production of charm in fixed target

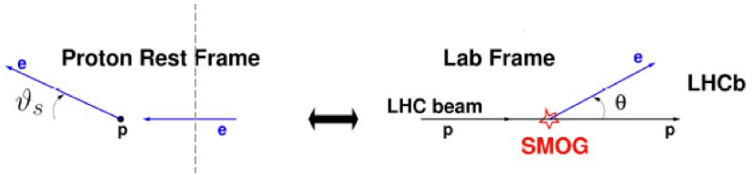
- Use two of the data samples: *p*He (4 TeV beam, 86 GeV) and *p*Ar (6.5 TeV beam, 110 GeV)
- Largest sample is *p*He, 7.6 ± 0.5 nb^{-1}
- Measurement of prompt production of J/ψ ($\rightarrow \mu^+\mu^-$) and D^0($\rightarrow K\pi$)

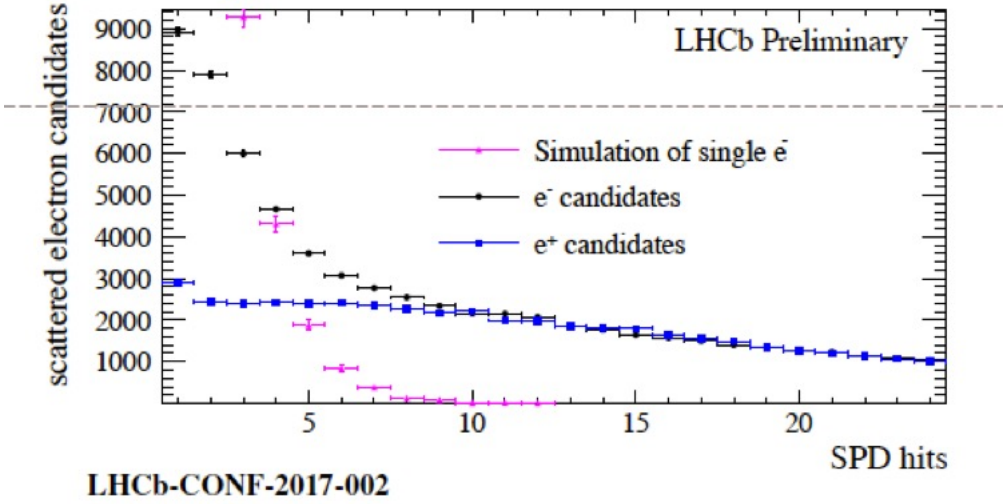




Fixed-target luminosity

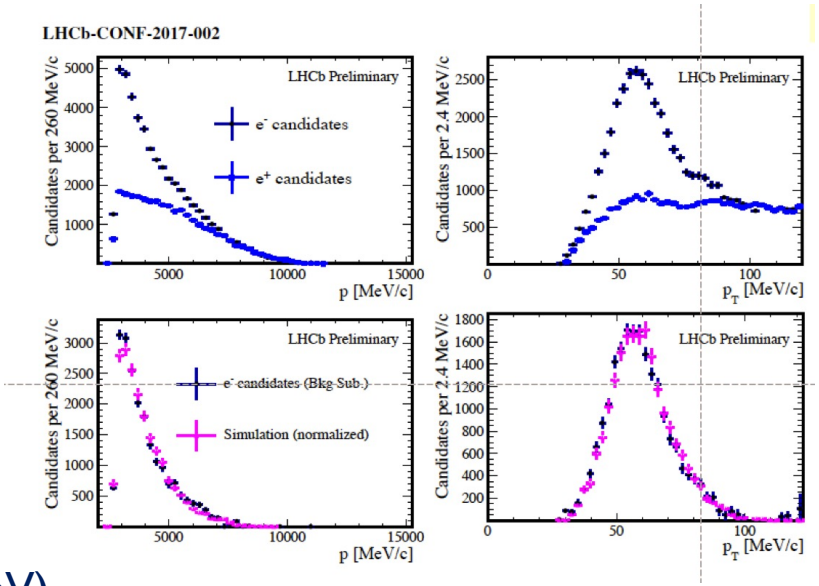
- Use p-e^- elastic scattering (Mott)
- Pro:
  - Only elastic regime in LHCb acceptance:
    - θ>10 mrad → θ_s< 29 mrad, Q^2<0.01 GeV^2
    - Cross-section very well-known
  - Clear event signature: single low p_T electron track and nothing else
  - Background comes mainly from conversions: it is charge-symmetric 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





Fixed-target luminosity

- Electron spectra in very good agreement with simulation
- Data confirm charge symmetry of background
- Systematic from variations of selection cuts: largest dependency is on azimuthal angle



$$\mathcal{L} = 0.443 \pm 0.011 \pm 0.027\,\mathrm{nb}^{-1}$$

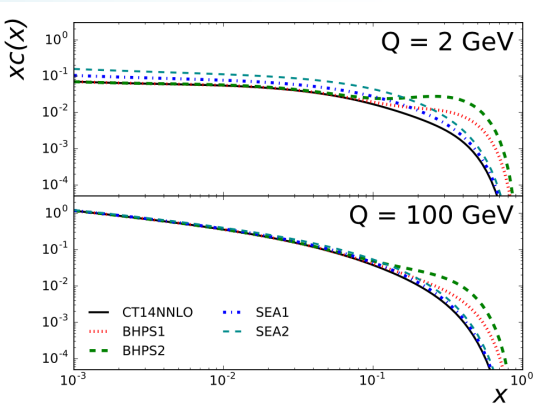
(*p*He at 110 GeV)

- Equivalent to gas pressure of 2.4×10^{-7} mbar, as expected

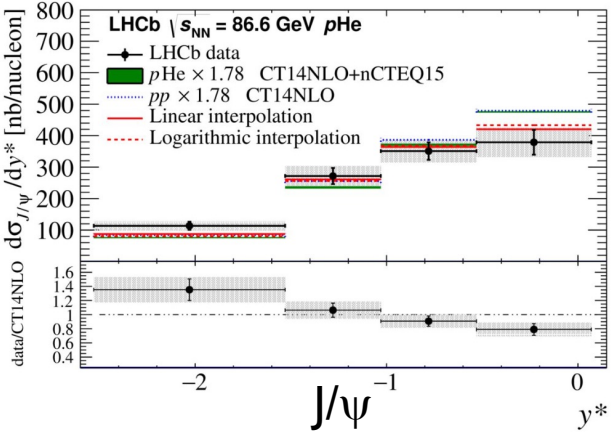
Production of charm in fixed target

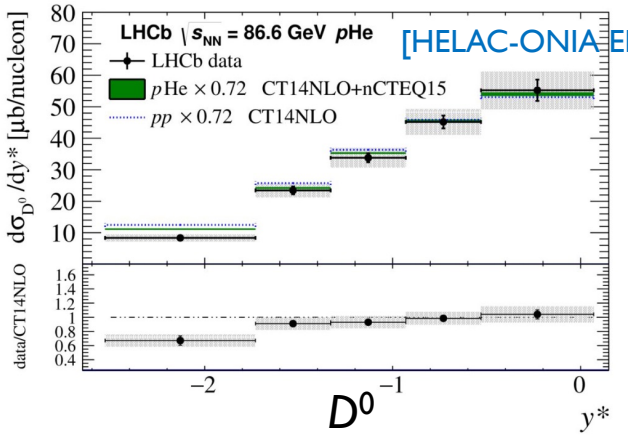
[PRL 122 (2019) 132002]

- 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

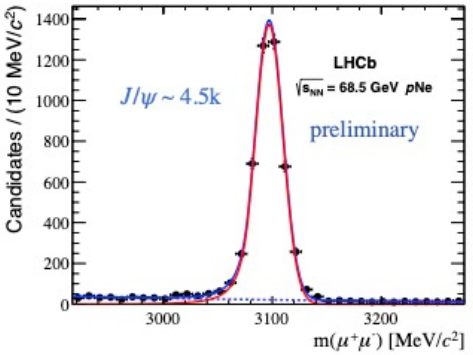


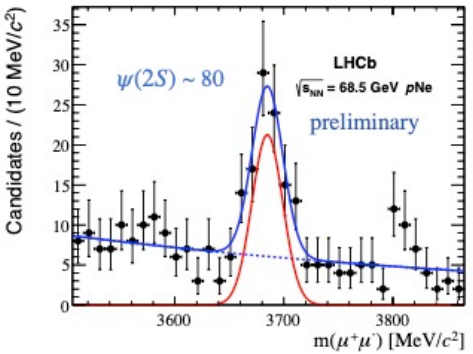


[HELAC-ONIA EPJC 77 (2017) 1]

Charmonium in pNe collisions at 68.5 GeV

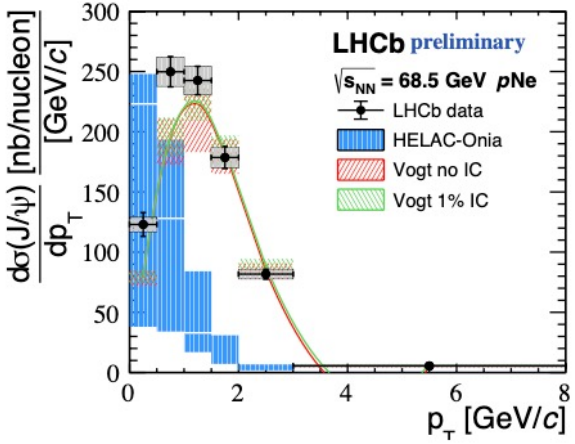
- Charmonium production modified by initial and final state effects in proton-nucleus collisions
  - Modification of PDFs inside nuclei, CGC: common to J/ψ and ψ(2S)
  - Nuclear absorption, multiple scattering, energy loss
  - Comovers: different between J/ψ and ψ(2S)
- Dataset: collisions of 2.5 TeV protons and Ne nuclei at rest: $\sqrt{s_{NN}}$ =68.5 GeV
- Luminosity $21.7 \pm 1.4\ nb^{-1}$
- Center-of mass rapidity coverage $-2.3 < y^* < 0$

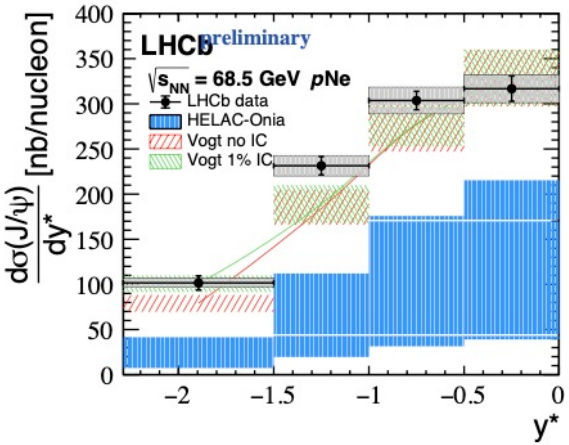




Charmonium in pNe collisions at 68.5 GeV

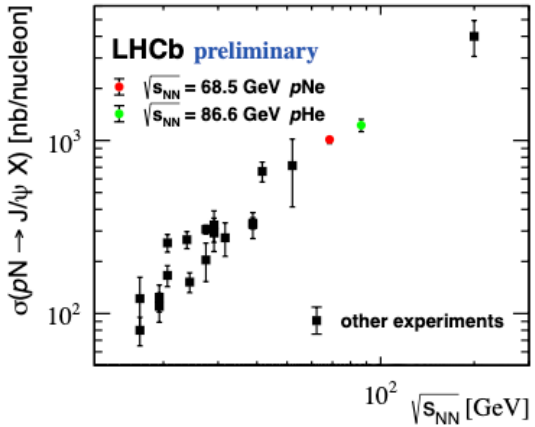
Differential J/ψ production cross-section

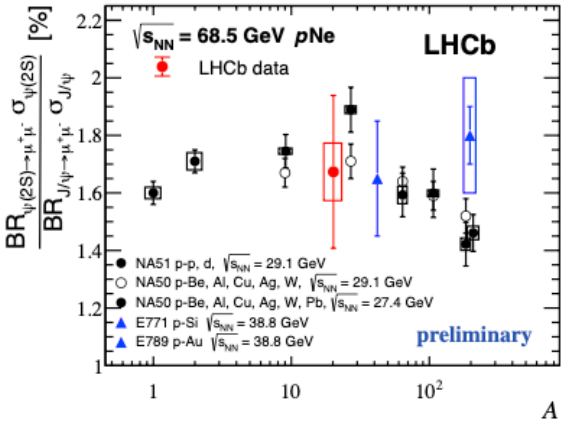




- HELAC-ONIA using CT14NLO and nCTEQ15 under-predicts the data
- Good agreement with predictions with and without intrinsic charm contribution [PRC103 (2021) 035204]

Charmonium in pNe collisions at 68.5 GeV

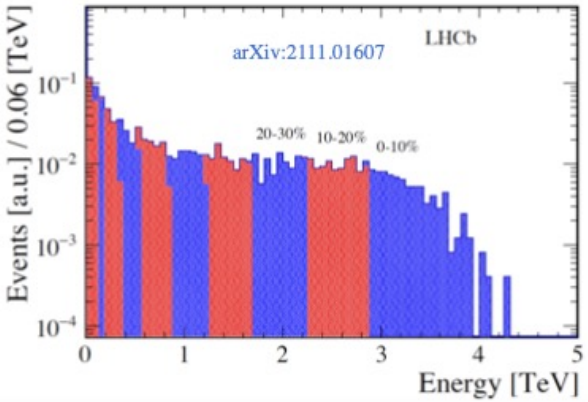


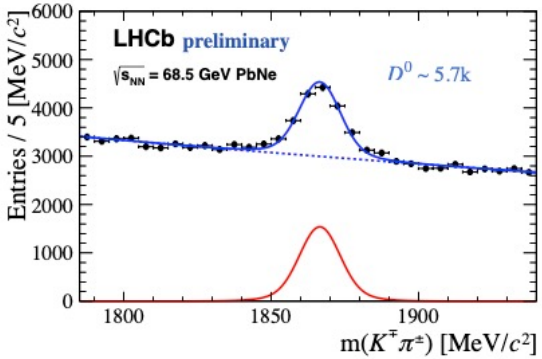


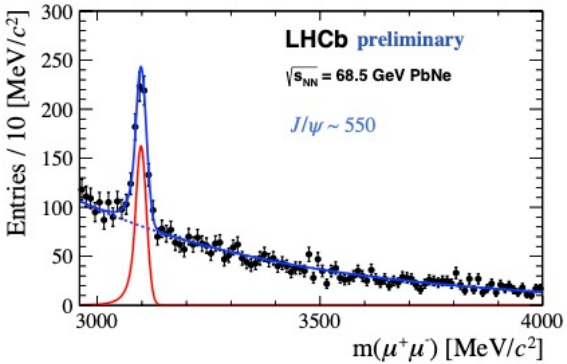
- Total J/ψ cross-section: extrapolation to full phase space using Pythia8+CT09MCS PDF, assuming forward-backward symmetry
  - Shows a power-low dependency with center-of-mass energy $\sqrt{s_{NN}}$
- ψ(2S) to J/ψ production ratio in good agreement with other proton-nucleus measurements at small values of target atomic mass number, A
- First measurement of ψ(2S) to J/ψ production ratio with SMOG

D^0 and J/ψ in PbNe collisions at 68.5 GeV

- First measurement in fixed-target nucleus-nucleus collisions at the LHC
- Search for the potential formation of quark-gluon plasma.
- Look for suppression of charmonium states
- Dataset: 2.5 TeV lead ions on Ne nuclei: $\sqrt{s_{NN}}$ =68.5 GeV
- Centrality of the collision determined from the total energy deposited in ECAL

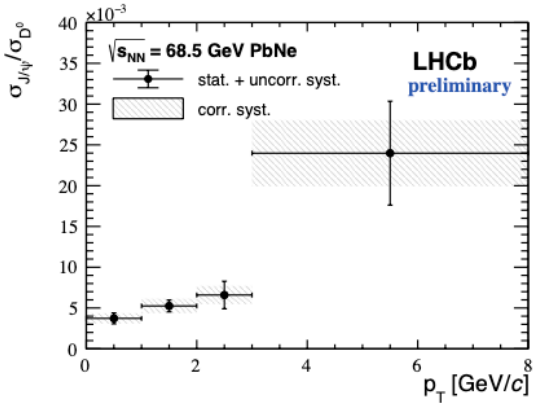




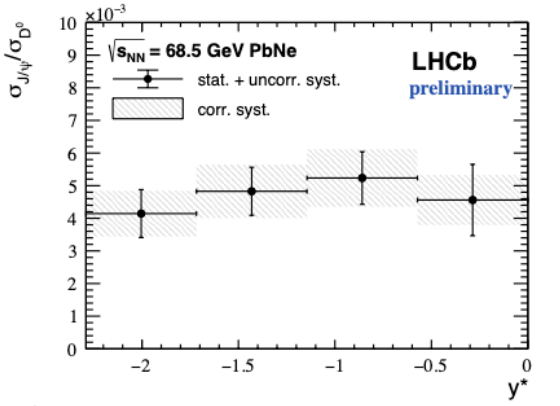


D^0 and J/ψ in PbNe collisions at 68.5 GeV

Production ratio J/ψ / D^0 vs. p_T and y*



- Depends strongly on p_T

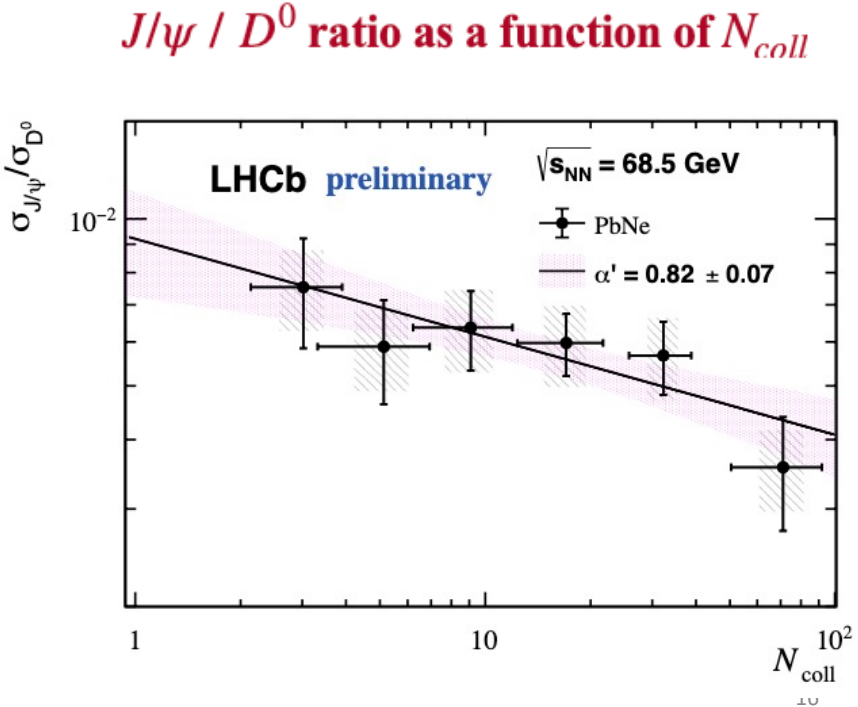


- Compatible with no dependence on rapidity

- Suppression of $c\bar{c}$ bound states: measure charmonium together with the total charm quark production
- Production of D^0 mesons is a large fraction of the total charm quark production and is a reference for studying suppression of charmonium in the collision

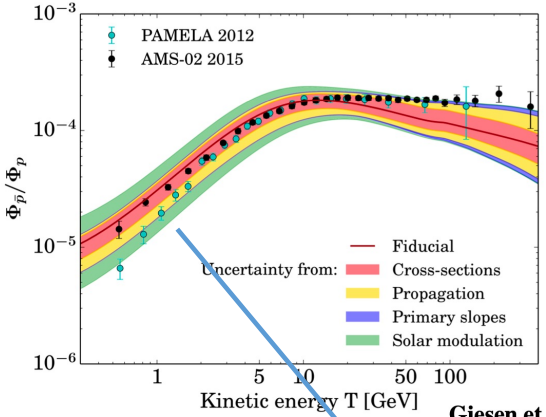
D^0 and J/ψ in PbNe collisions at 68.5 GeV

- Assuming
  - $\sigma_{J/\psi} \propto \langle N_{coll} \rangle^{\alpha'}$ and
  - $\sigma_{D^0} \propto \langle N_{coll} \rangle$:
  - -> $\frac{\sigma_{J/\psi}}{\sigma_{(D^0)}} \propto \langle N_{coll} \rangle^{\alpha'-1}$
- $\alpha' = 0.82 \pm 0.07$
- Agree with measurements from proton-nucleus collisions by NA50 [PLB410 (1997) 337]
- J/ψ production affected by additional nuclear effects compared to D^0 but no anomalous J/ψ suppression is observed that could indicate formation of QGP

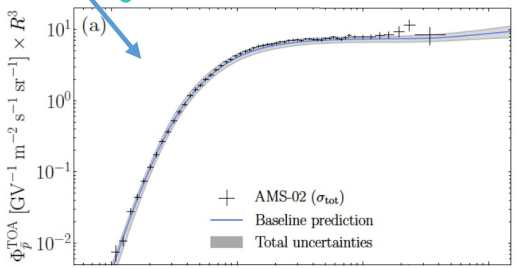


SMOG: anti-protons in *p*He collisions at 110 GeV

- Interesting to reduce uncertainties on anti-proton production in inter-stellar medium (H and He): *p*He $\rightarrow \overline{p}$X is ~40% of secondary cosmic anti-proton

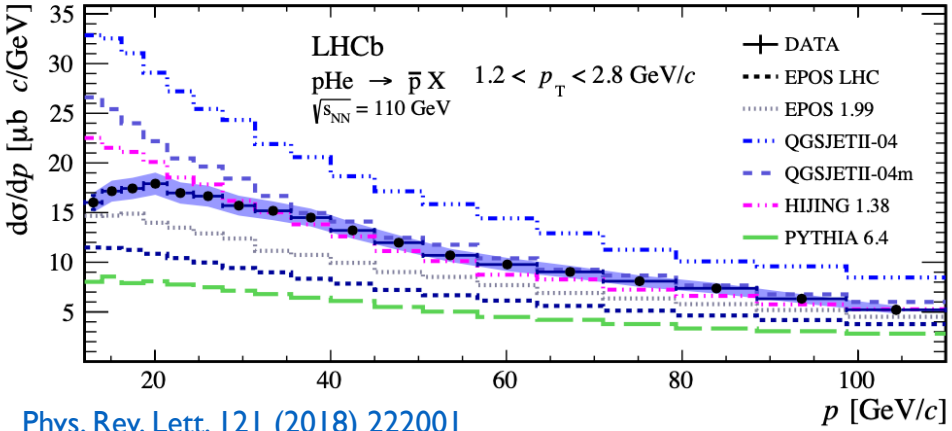


Giesen et al., JCAP 1509, 023



Phys. Rev. Research 2, 023022 (2020)

Prompt



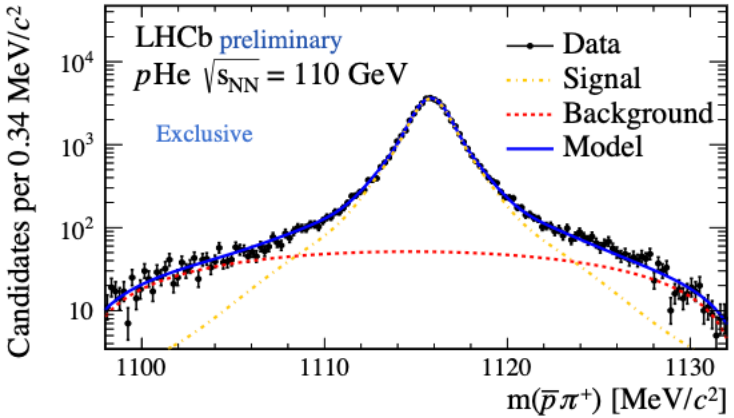
Phys. Rev. Lett. 121 (2018) 222001

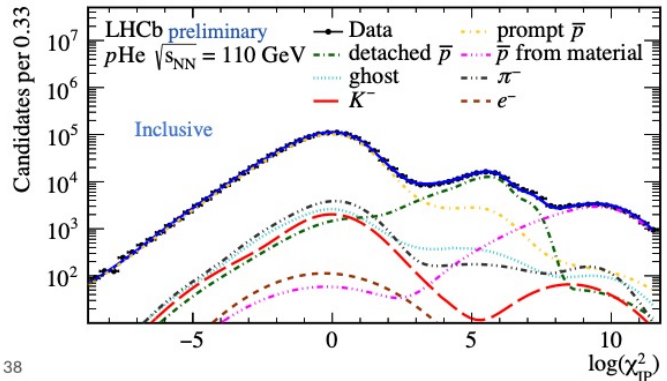
EPOS LHC PRC92 (2015) 034906
EPOS 1.99 Nucl.Phys.Proc.Suppl. 196 (2009) 102
QGSJETII-04 PRD83 (2011) 014018
QGSJETII-04m Astr. J. 803 (2015) 54
HIJING 1.38 Comp. Phys. Comm. 83 307
PYTHIA 6.4 (2pp + 2pn) JHEP 05 (2005) 026

LHCb-PAPER-2022-006
arXiv:2205.09009

Detached anti-protons in pHe collisions at 110 GeV

- Exclusive measurement: dominant contribution from $\overline{\Lambda}$ reconstructed, $\overline{\Lambda} \to \bar{p}\pi^+$: $(50.7 \pm 0.3)\times10^{-3}$ candidates
- Inclusive measurement:
  - Track from anti-hyperon decay: $\overline{H} = \overline{\Lambda}, \overline{\Sigma}, \overline{\Xi}, \overline{\Omega}$
  - Fit of $\bar{p}$ impact parameter:
    - Prompt, detached, secondary interaction in material

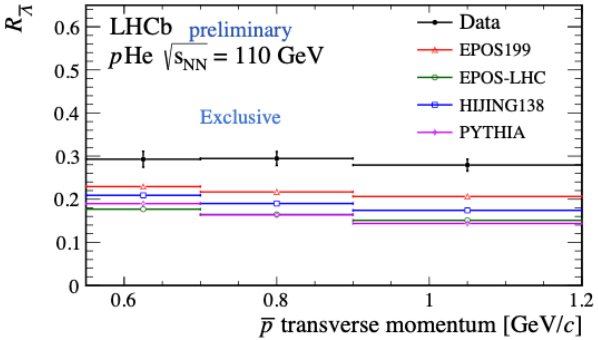




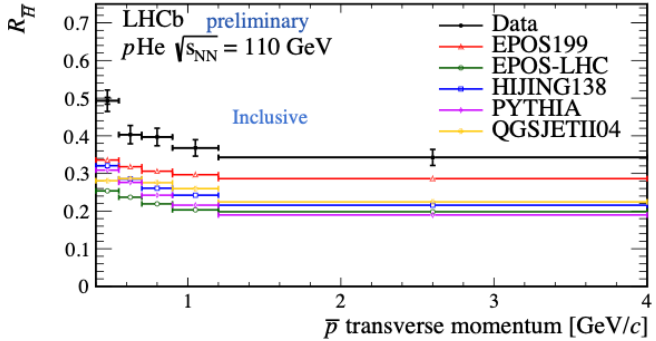
LHCb-PAPER-2022-006
arXiv:2205.09009

Detached anti-protons in pHe collisions at 110 GeV

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



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



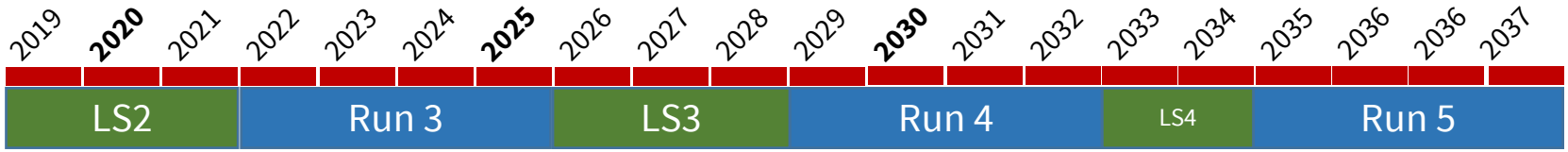
- Sizeable underestimation of detached $\bar{p}$ constribution in most models used in cosmic ray physics.

Prospects

ATLAS
CMS

LHC: L = 2-3x10^{34} $cm^{-2}.s^{-1}$
~80 interactions per bunch crossing

HL-LHC, Phase II Upgrade : L = 7.5x10^{34} $cm^{-2}.s^{-1}$
~200 interactions per bunch crossing



LHC

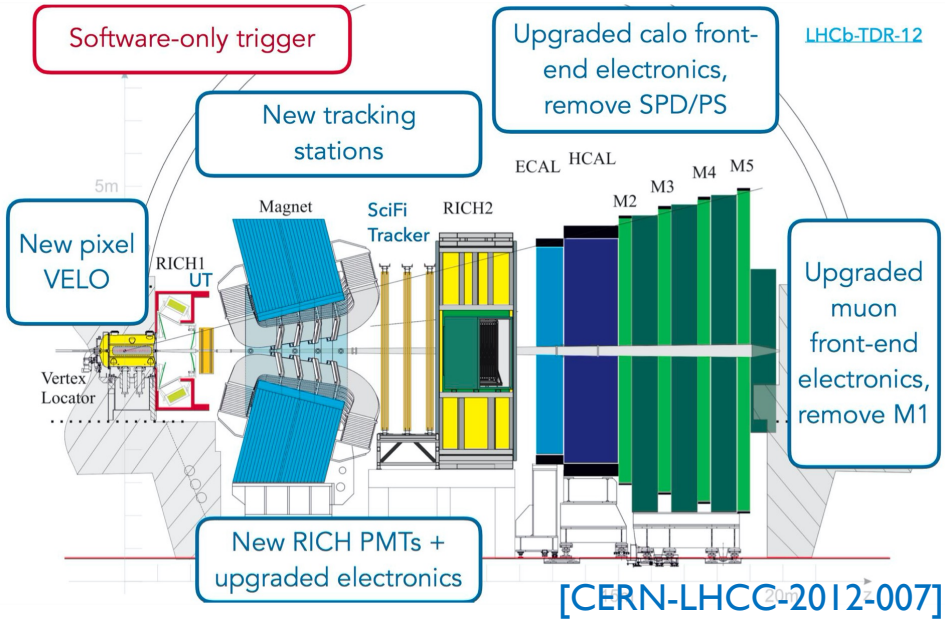
LHCb

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

Upgrade II : L = 1.5x10^{34} $cm^{-2}.s^{-1}$
~50 interactions per bunch crossing
~300 fb^{-1} (Run 5….)

LHCb Phase I Upgrade (Run 3 and 4)

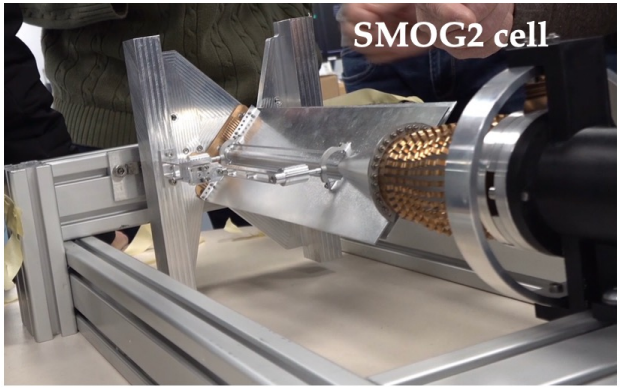
- New detector installed during LS2, starting taking data now and will continue through Run 4



- Increase reach for higher multiplicity collisions with new detectors
- Full software trigger:
  - Remove hardware L0 trigger
  - Readout full detector at 40 MHz

LHCb Run 3: SMOG 2

[LHCb-TDR-020]

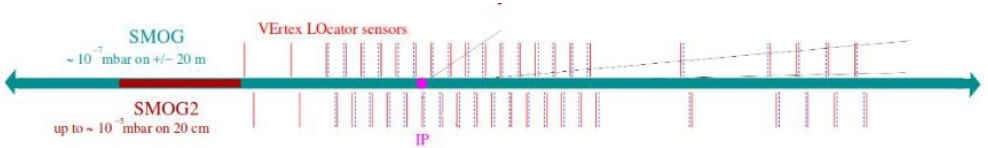


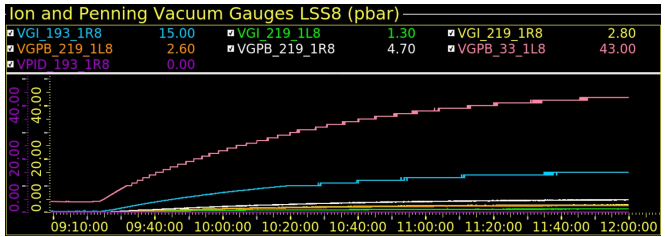
- Fixed target setup upgraded, with a storage cell between -50 cm and -30 cm, upstream of IP
  - Well defined interaction region
  - Increase of gas pressure and luminosity by 2 orders of magnitude
  - Gas feed system to switch quickly between different types of gases (H, D, He, N, O, Ne, Ar) and to measure precisely the gas density (for absolute cross-section measurements)

[LHCB-PUB-2018-015]

	SMOG largest sample p–Ne@68 GeV	SMOG2 example p–Ar@115 GeV
Integrated luminosity	$\sim 100\ \text{nb}^{-1}$	$100\ \text{pb}^{-1}$
syst. error on J/ψ x-sec.	6–7%	2–3 %
J/ψ yield	15k	35M
D^0 yield	100k	350M
Λ_c yield	1k	3.5M
$\psi(2S)$ yield	150	400k
$\Upsilon(1S)$ yield	4	15k
Low-mass ($5 < M_{\mu\mu} < 9\ \text{GeV}/c^2$) Drell-Yan yield	5	20k

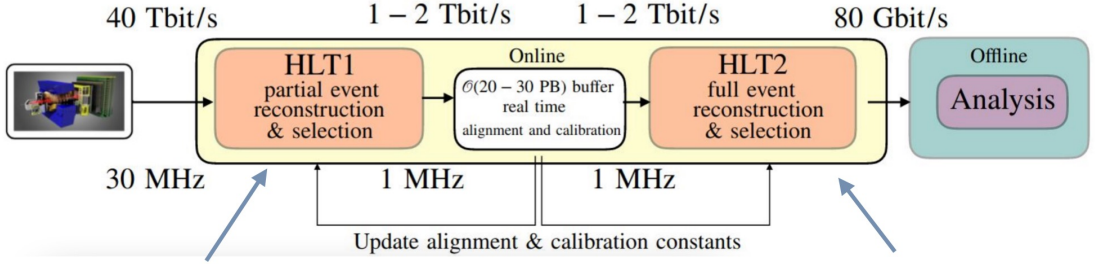
~1 year of data taking in parallel with *pp* collisions





Gas injection during stable beams on July 6

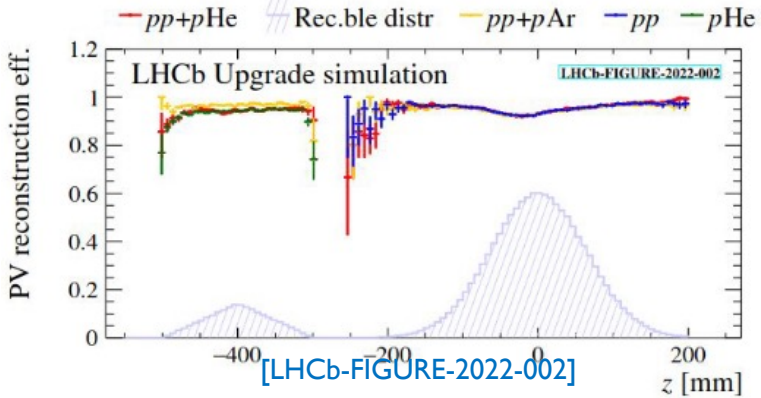
LHCb Run 3: Trigger Scheme



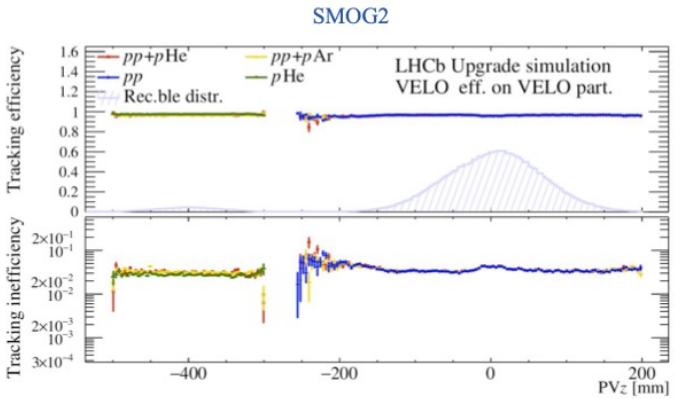
- Tracking only on GPUs.
- First trigger selections based on tracking only.

- Tracking + PID on CPUs.
- More complexe trigger selection possible.

Possibility to run in parallel *pp* and fixed target collisions thanks to new trigger scheme and performances of reconstruction

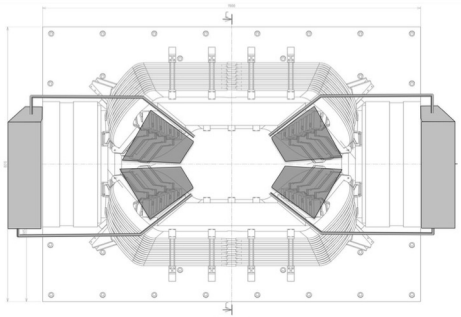


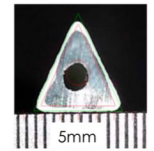
[LHCb-FIGURE-2022-002]

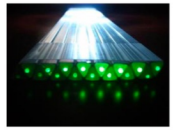


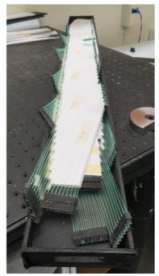
LHCb Run 4: Magnet Tracking Stations (MS)

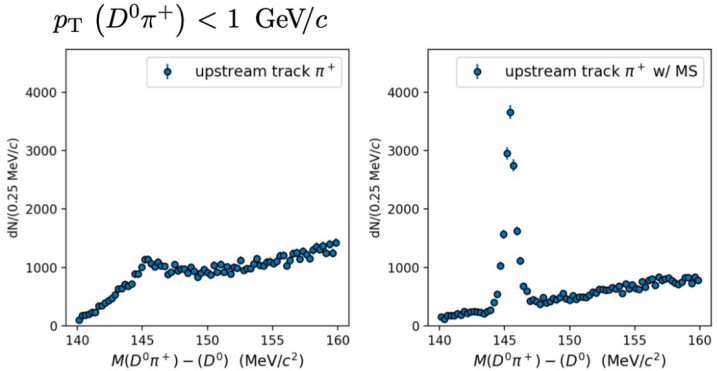
- Proposal to add tracking stations inside the magnet to increase coverage at low η and p_T
  - Soft pion (eg. $D^{*+} \rightarrow D^0\pi^+$) and converted photons ($\chi_c \rightarrow J/\psi\ \gamma$)
- Technology: Triangular Extruded Scintillating Bars (same as D0), ongoing R&D
- Plan to install a small prototype inside the magnet during 2022 Year-End Technical Stop and full detector during LS3

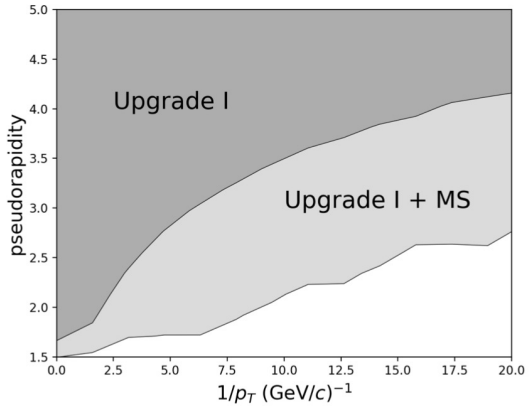






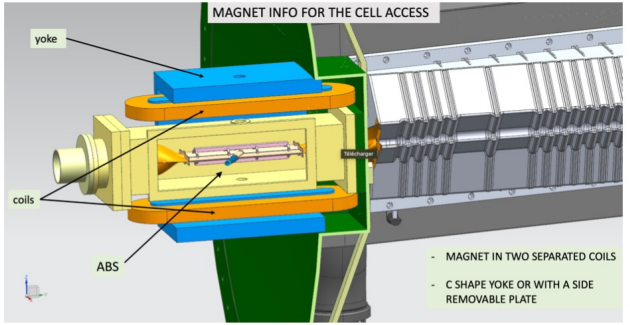


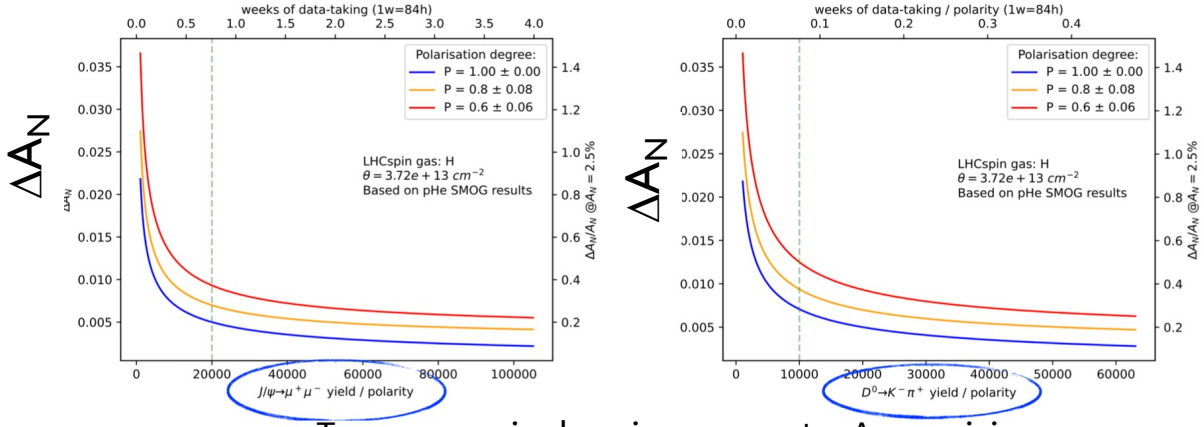




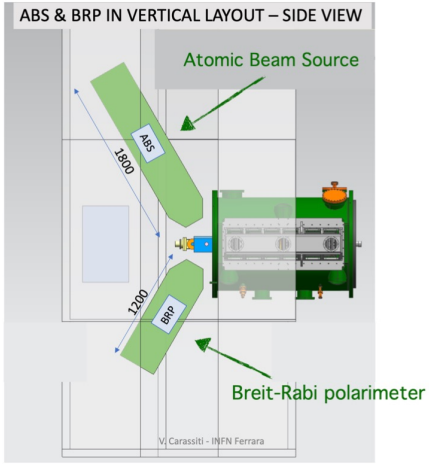
LHCb Run 5: polarized gas target

- R&D has started for a polarized gas target to complement SMOG2 (LHCspin)
  - Compact dipole magnet static : transverse field
  - Superconductive coils and iron yoke configuration fits the space constraints (small space upstream of VELO)
  - B = 300 mT, $\Delta B/B$ = 10%. Possibility to invert polarity.
- Achievable luminosity: 8 x 10^{32} $cm^{-2}.s^{-1}$





Transverse single spin asymmetry A_N precision



Conclusions

- Feasibility of a fixed-target physics program at LHCb established with SMOG, still with low statistics for heavy flavour physics
- SMOG2 installed and ready for data taking in Run 3: will increase a lot the possibilities
- Ideas for future upgrades starting