LHCb fixed-target results for Cosmic Rays physics: Results and prospects

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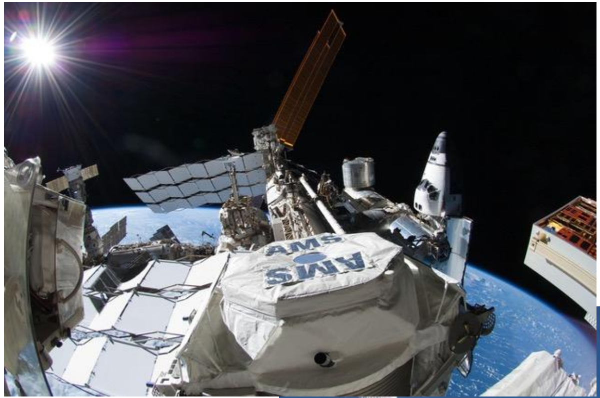
on behalf of the Ion and Fixed Target Working Group

Second Heavy Ion Workshop, 04/09/2019

Prelude

- Astroparticle physics, thanks to the latest both experimental results and theoretical progresses, has reached a **new high-precision era.**



- Interpretation of some measurements still limited by **systematic uncertainties** on hadronic cross sections.

- **Accelerator experiments** can complement the Cosmic Rays (CRs) investigations.
- **LHCb**, with its forward geometry, PID capabilities and flexibility, can provide unique inputs at the LHC energy!

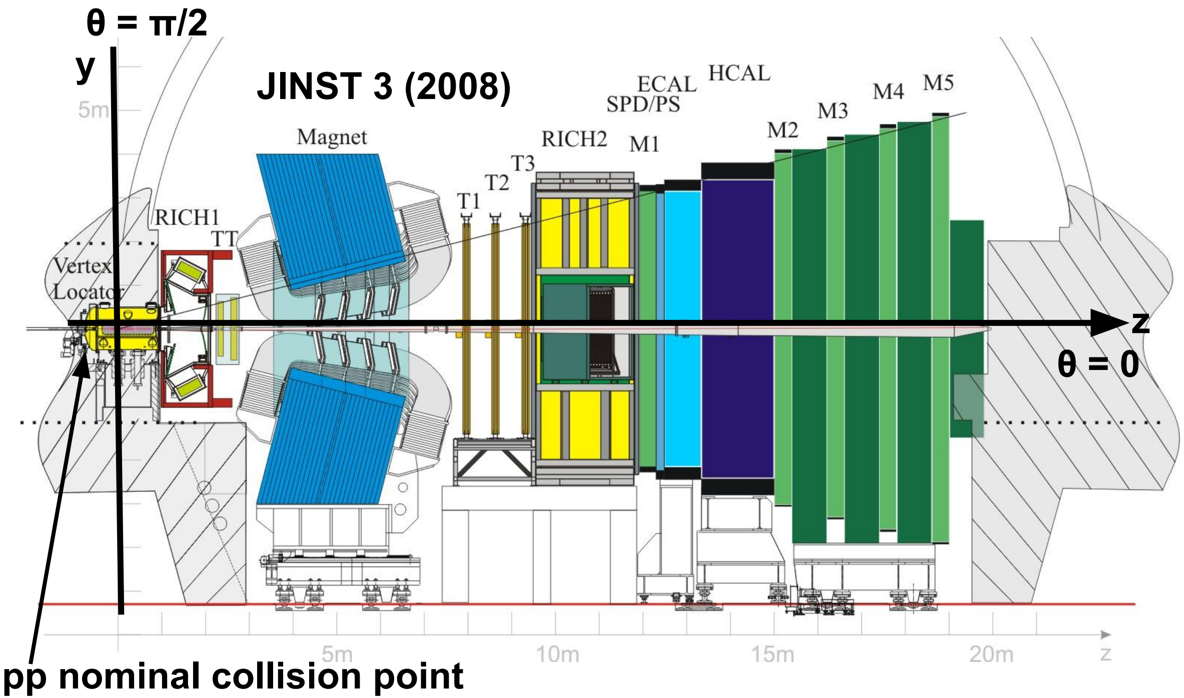
Outline

- **The LHCb experiment.**
  - Generalities and sub-detectors.
  - The Smog system and the fixed-target programme.
- **LHCb measurements of CRs physics interest**
  - Charm production and UHE neutrino.
  - Antiproton production and CRs - ISM collisions.
- **Future prospects**
  - Plans for the antiproton measurements.
  - Upgrade of the fixed-target programme: Smog2.
- **Conclusions.**

The LHCb Experiment

LHCb detector : overview

- Among the LHC detectors, dedicated to the study of **flavour physics in b sector**.

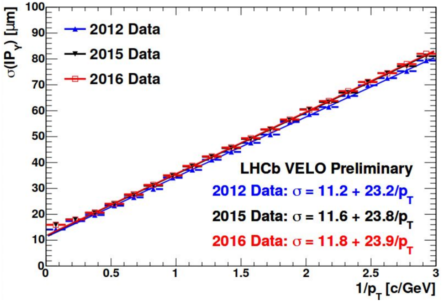


- **Single-arm spectrometer** covering the forward direction $\Theta \in [10, 250]\ mrad$ optimized for $b\bar{b}$ production.

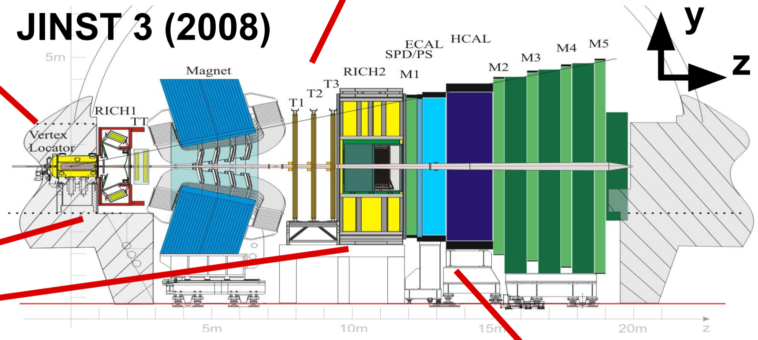
- Become a **general-purpose** experiment in the forward direction (b and c sectors, QEE and Higgs, Heavy Ion…) .

LHCb detector : subdetectors

- **VELO**: excellent **vertices and IP resolutions**.



- **Tracking system**: excellent **momentum resolution** ($\Delta p/p$ between 0.5 and 1.0%).



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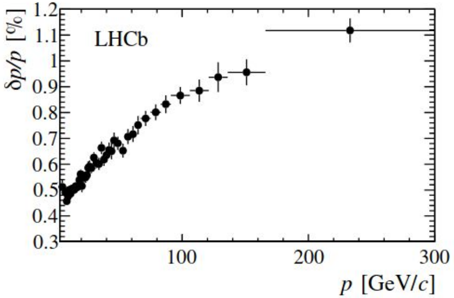
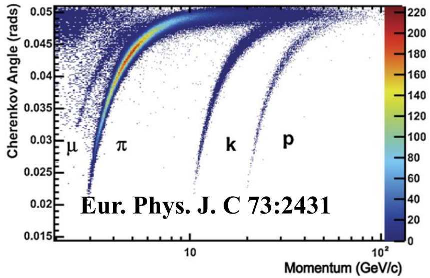


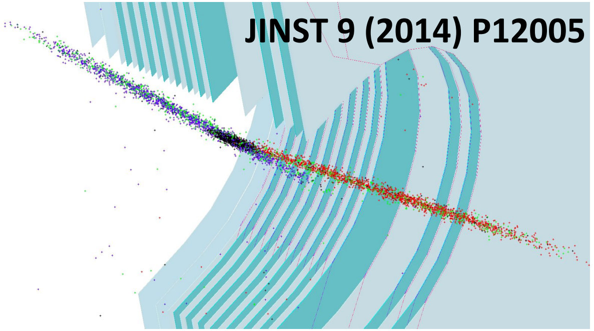
- **RICH**: excellent **separation** among kaons, pions and protons between 10 and 110 GeV/c.



- Flexible and versatile **trigger system** with a very high efficiency and bandwith (up to 15 kHz).

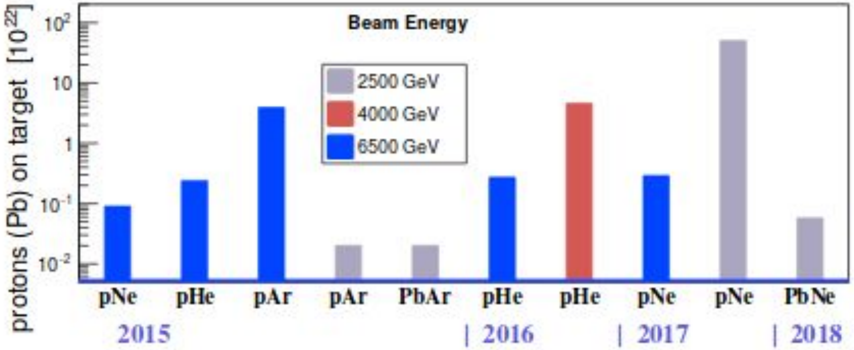
LHCb detector : Smog

- **Luminosity** uncertainties reduced complementing VdM scans with **Beam Gas Imaging.**



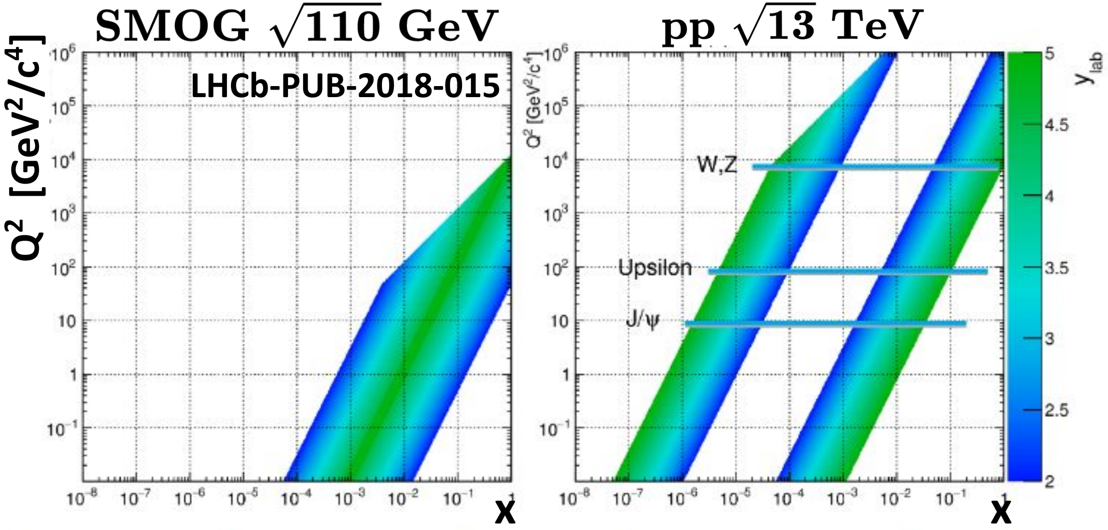
- **Smog**: system allowing the gas injection in the LHC beam pipe between ± 20 m from the nominal collision point.
- For machine safety, only some **noble gases** allowed with a maximum pressure of $2 \times 10^{-7}\ mbar$, two orders of magnitude higher than the LHC vacuum.

- Starting from 2015, LHCb can operate as a **fixed-target experiment** too.
- Wide variety of physics samples collected.



Smog opportunities

- LHCb fixed-target configuration offers unique possibilities:
  - **Wide choice** of the collision system.
  - **Luminosity**: with 10^{14} protons per beam and one meter of gas, $\mathcal{L} \sim 6 \times 10^{29} cm^{-2} s^{-1}$
  - **Energy** range $\sqrt{s_{NN}} \simeq \sqrt{2E_N M_N} \in [41, 115]\ GeV$ for beams energy in $[0.9, 7]\ TeV$, filling the gap between SpS and LHC *pp* collisions .



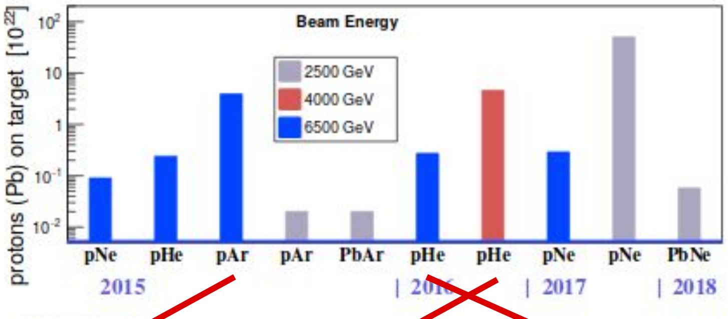
  - Access to **high values** of the Feynman-x, the fraction of the target longitudinal momentum in the cm frame:

$$x_F = \frac{p_L^*}{|max(p_L^*)|} \sim x_1 - x_2$$

being x the Bjorken-x.

Run2 Smog Results

Smog results of CRs physics interest



PRL 122, (2019) 132002

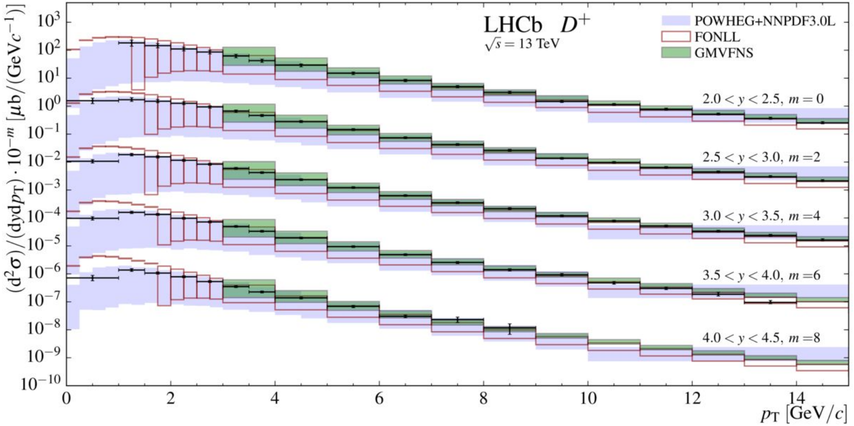
- First Measurement of **charm production** in its Fixed-Target configuration at the LHC.
- Addressing the possible **intrinsic PDF charm contribution** at large x.
- **Neutrino production** in ultra high-energy (UHE) atmospheric showers.

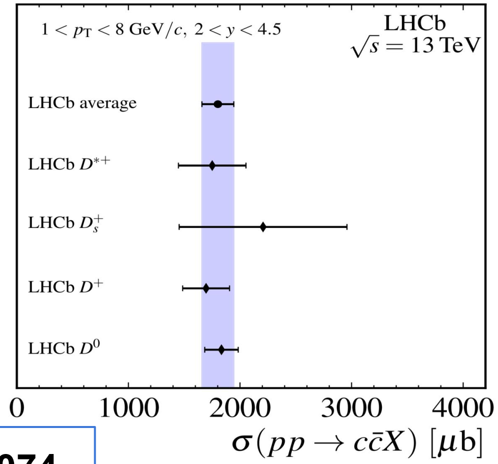
PRL 121 (2018) 222001

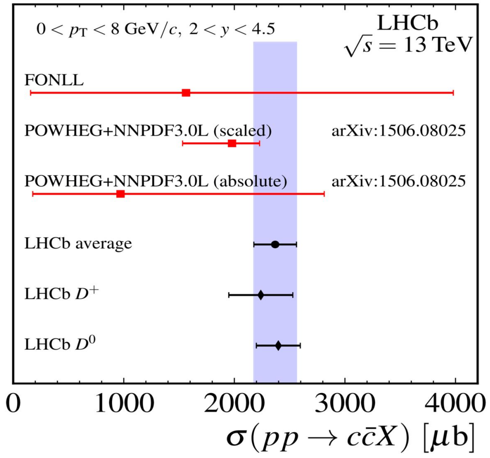
- Measurement of **antiproton production** cross section in *pHe* collisions.
- Antiproton production in CRs - ISM collisions, main background for space-borne experiments **dark matter** searches.

Charm production in *pp* at LHCb

- LHCb is leading the **charm production measurements** in the forward direction.
- Accuracy significantly smaller than theoretical uncertainty, especially at low-p_T regime.



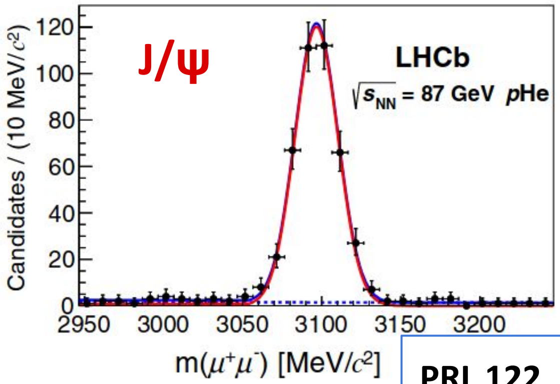


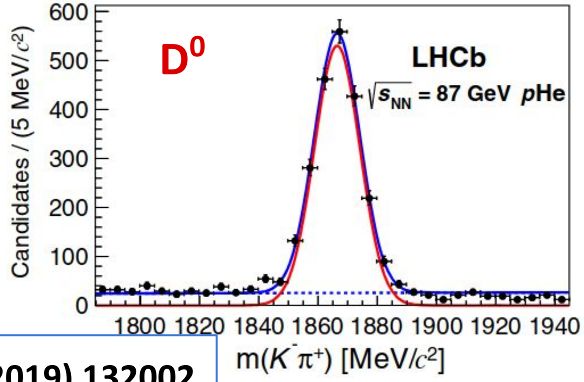


JHEP 03 (2016) 159, erratum JHEP 05 (2017) 074

Charm production in pgas at LHCb

- J/ψ and D^0 **production measurements** in *pHe* (*pAr*) at $\sqrt{s_{NN}} = 86.6\,(110.4)\ GeV$
- J/ψ di-muon and D Kπ decays considered.
- **Fiducial region** selected in $z_{PV} \in [-200, 200]\ mm$, with high reconstruction efficiency and calibration samples available and background from *pp* excluded vetoing backward activity.
- Selection with kinematic and quality criteria and extended unbinned maximum-likelihood fits to the mass distributions performed to quantify raw yields.





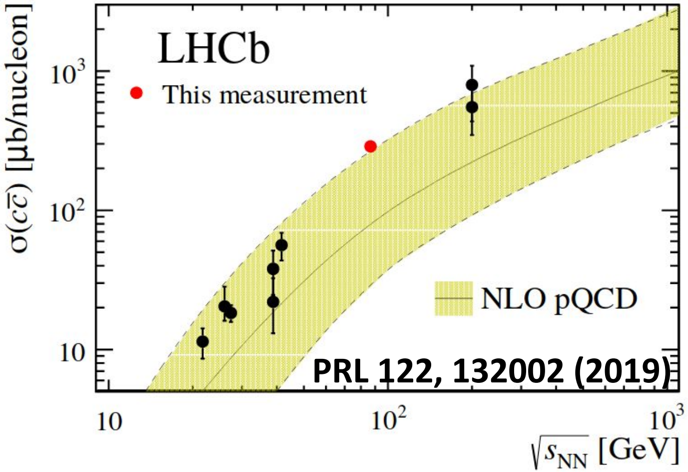
PRL 122, (2019) 132002

	pHe	pAr
J/ψ	408±22	446±21
D^0	2052±49	5241±78

Charm production in pgas at LHCb

- Luminosity measurement only available in *pHe* $\mathcal{L}_{pHe} = 7.58 \pm 0.47\ nb^{-1}$

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

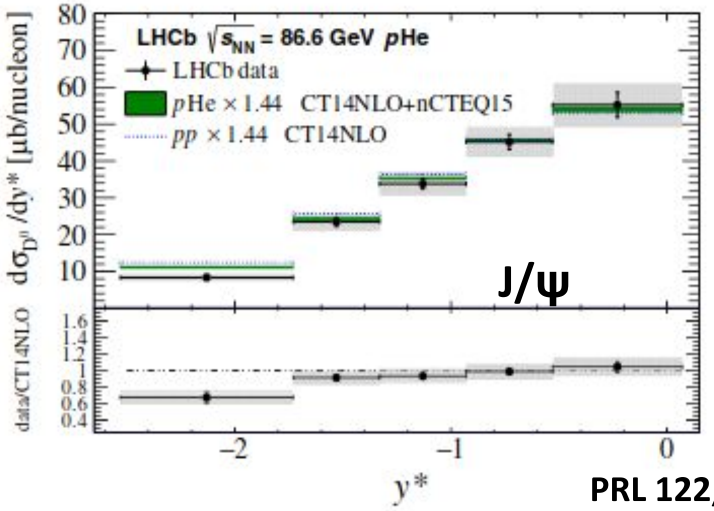


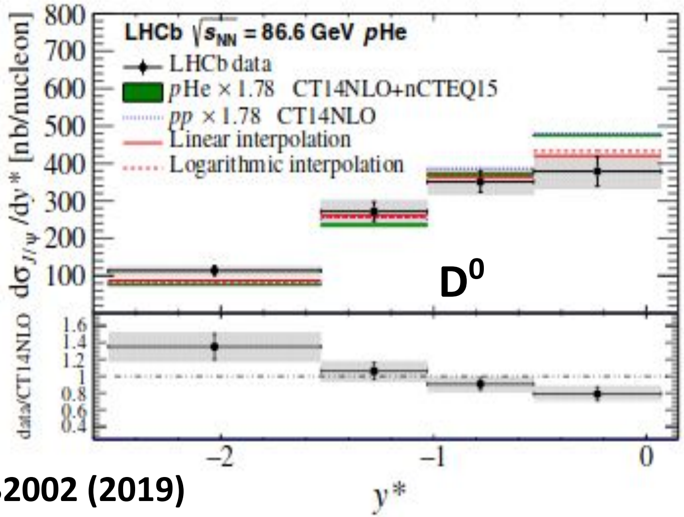
PRL 122, 132002 (2019)

- Measured results extrapolated to full phase space and D^0 fragmentation factor considered to obtain $c\bar{c}$ production cross section.
- High precision result at an **unexplored energy scale**.
- Some **tension** wrt theoretical expectation.

Charm production in pgas at LHCb

- σ studied wrt y* and p_T to compare data with HELAC-ONIA theoretical expectations.
- Globally, predictions **underestimation** of data by a scale factor 1.78 (1.44) for J/ψ (D^0).
- No evidence for a strong intrinsic charm contribution, which should manifest as an excess in the first y* bin (high target x).





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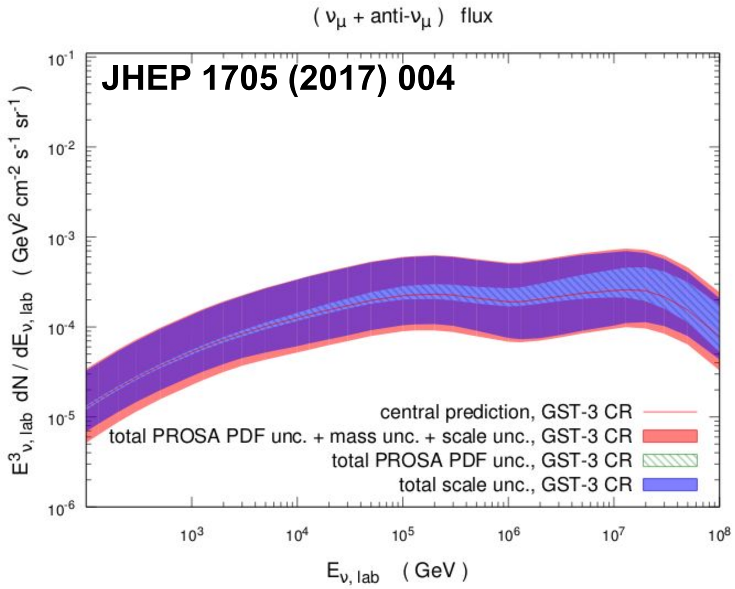
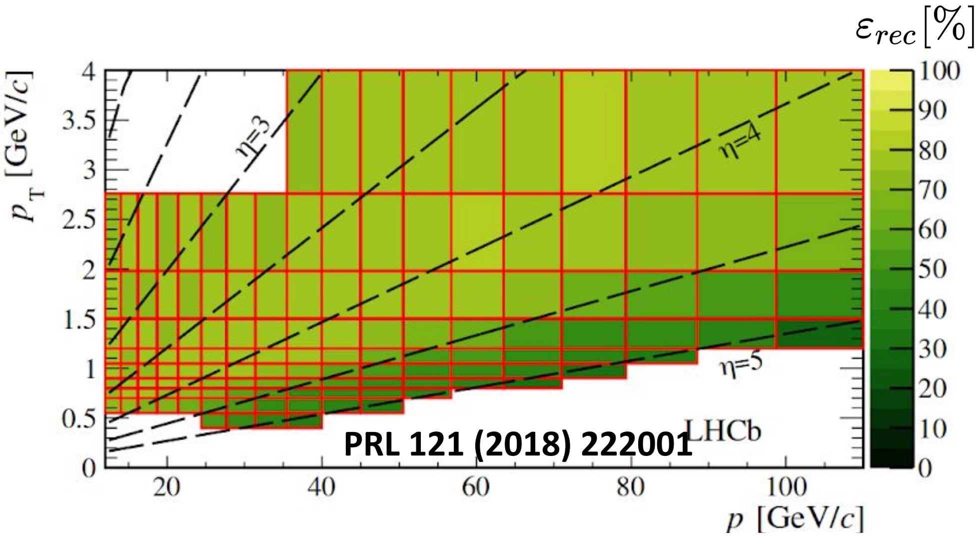
Impact on CRs physics



- Large volume **neutrino** telescopes (IceCube, KM3NET) are observing high-energy neutrinos (up to the PeV scale).
- Main background to astrophysical neutrinos is the forward decay of **charm compounds** originated from CRs scatterings with the atmosphere.
- LHCb data widely used in the PDF fits allowing to reduce QCD uncertainties.

Antiproton production measurement

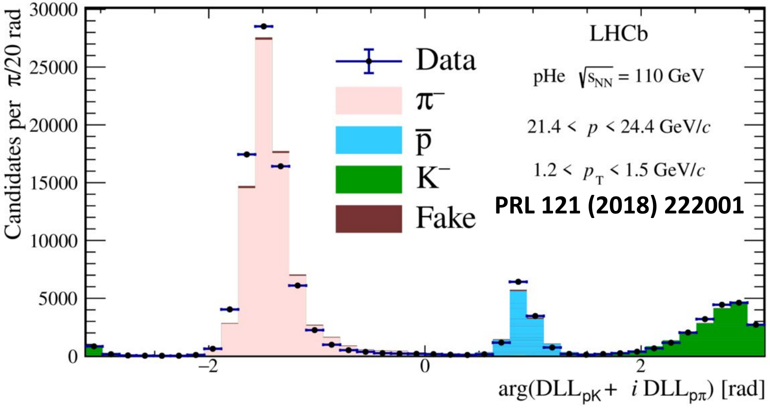
- **First measurement** of the $\bar{p}$ production cross section in *pHe* data at $\sqrt{s_{NN}} = 110\ GeV$
- **Kinematic** $p \in [12, 110]\ GeV/c,\ \ p_T \in [0.4, 4]\ GeV/c$ and **geometrical** $PV_z \in [-700, 100]\ mm$ fiducial regions chosen to optimize reconstruction and particle identification efficiencies.



- ONLY **promptly-produced** antiprotons considered in this analysis: detached component from **anti-hyperion** decays reduced cutting on the χ^2_{IP} (the goodness of the hypothesis that a particle comes from the primary vertex)

Antiproton production measurement (II)

- Number of antiprotons determined through a simultaneous fit to the PID variables in each geometric-kinematic bin.
- Templates from *pp* and *pHe* calibration samples and from simulation.



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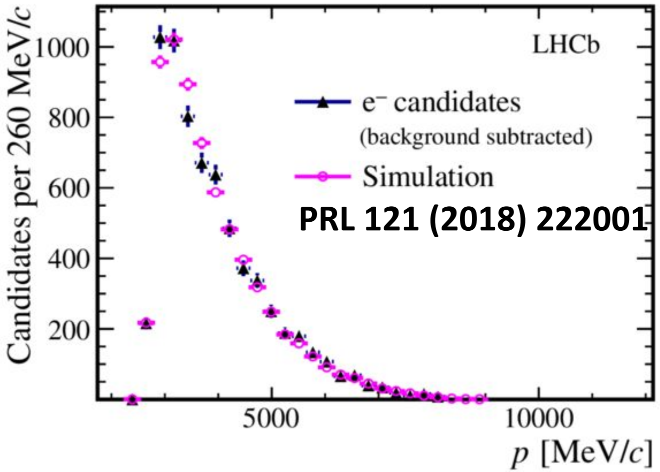


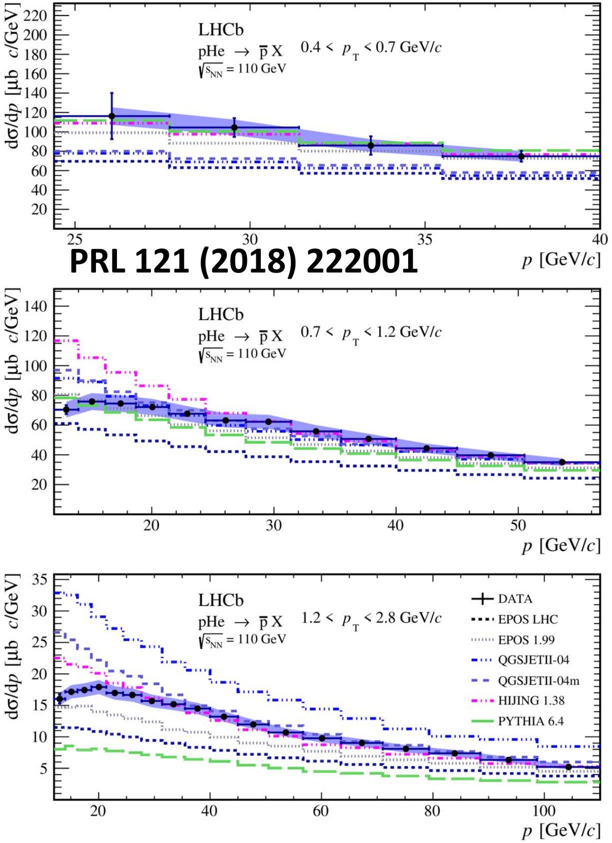
PRL 121 (2018) 222001

- Smog luminosity not directly measurable.
- Luminosity measured with **p-e elastic scatterings,** reconstructed as an isolated negative-charged particle.
- Charged-symmetric background studied with e^+

$$\Longrightarrow \mathcal{L} = 484 \pm 7 \pm 29\ \mu b^{-}$$

- The 6% systematic uncertainty, due to the low electron reconstruction efficiency, is the dominant term on σ.

Antiproton production measurement (III)



PRL 121 (2018) 222001

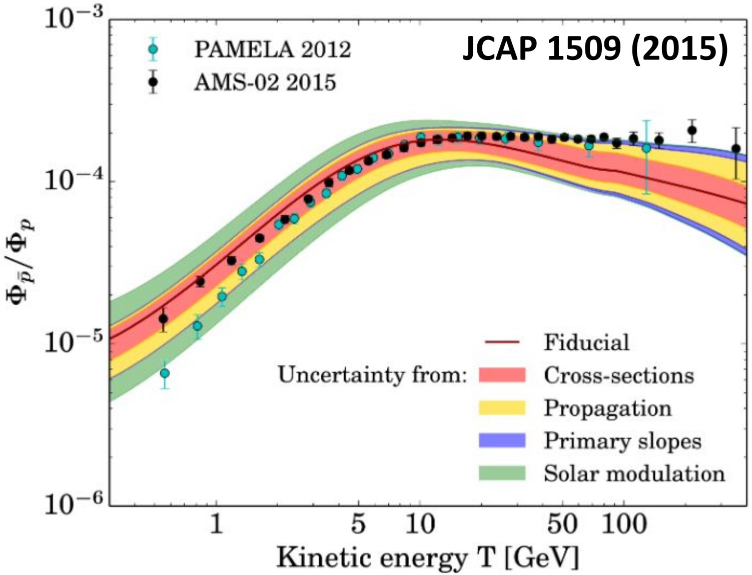
- Measured cross section compared to **EPOSLHC, EPOS 1.99**, **QGSJETII**, **HIJING 1.38**, **PYTHIA6.**
- Experimental uncertainties lower than the spread among theoretical models.
- Total visible cross section consistent with expectations:

$$\sigma_{vis}^{LHCb} / \sigma_{vis}^{EPOS-LHC} = 1.08 \pm 0.07 \pm 0.03$$

- Measured excess due to **antiproton multiplicity.**

CRs antiprotons in 2015

- **CRs antimatter** studied by the space-borne experiments with increasing precision.
- Excesses wrt the antiparticles produced by collisions of the primary CRs with the interstellar medium (ISM), mainly *H* and *He*, could be due to **DM decays or annihilations**.

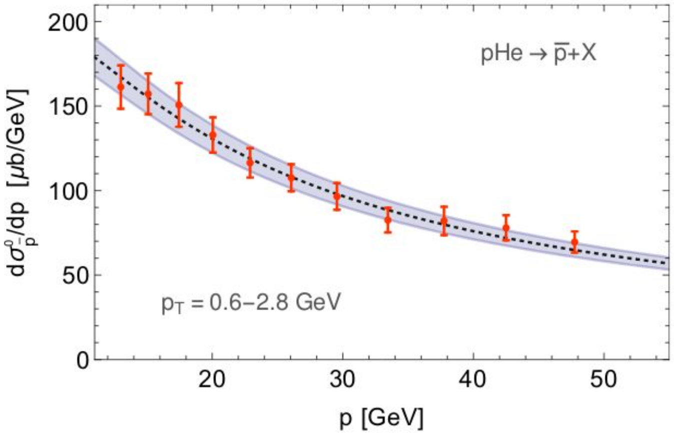


- In 2015, AMS-02 $\bar{p}/p$ data showed a **tension at high energy** wrt theoretical expectations.
- Results interpretation limited by the **poor knowledge** of the antiprotons production and transport models:
  - Poor data for $\sigma(pp \to \bar{p}X)$
  - No data at all for $\sigma(pHe \to \bar{p}X)$

CRs antiprotons now

- LHCb $\sigma(pHe \to \bar{p}X)$ measurement well received by the theoretical community:
  - Constraint of the **extrapolation** of the cross section from a proton to a helium target.
  - Choice of the cross-sections evolution with energy parametrization **(scaling violation)**.

JCAP 1801 (2018) 055



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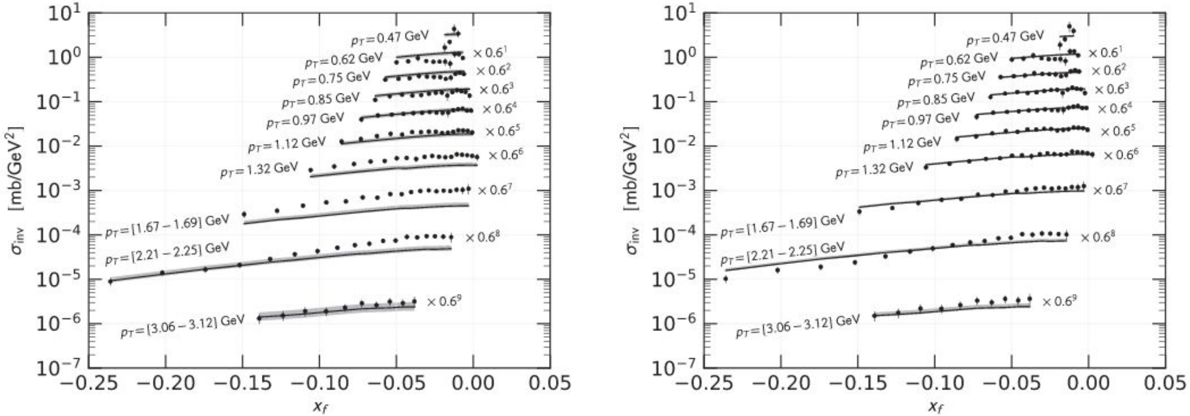
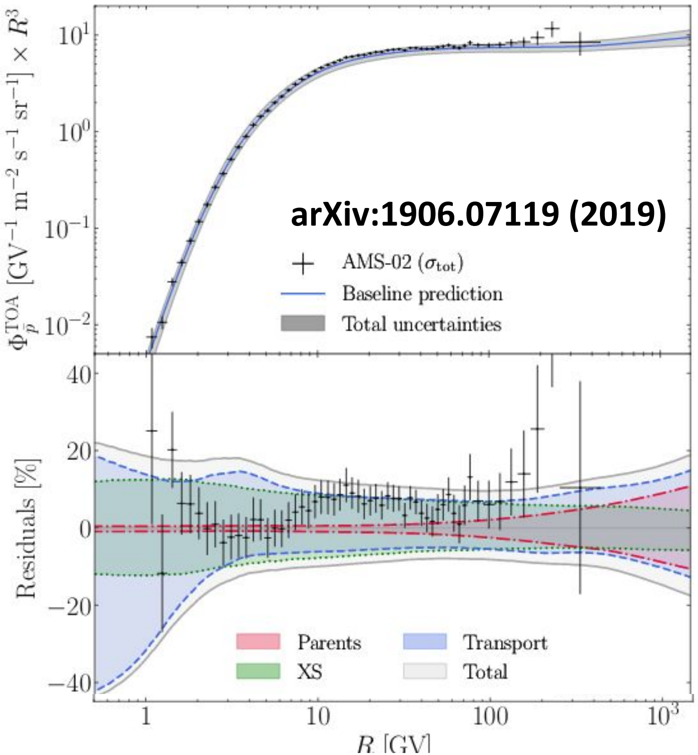


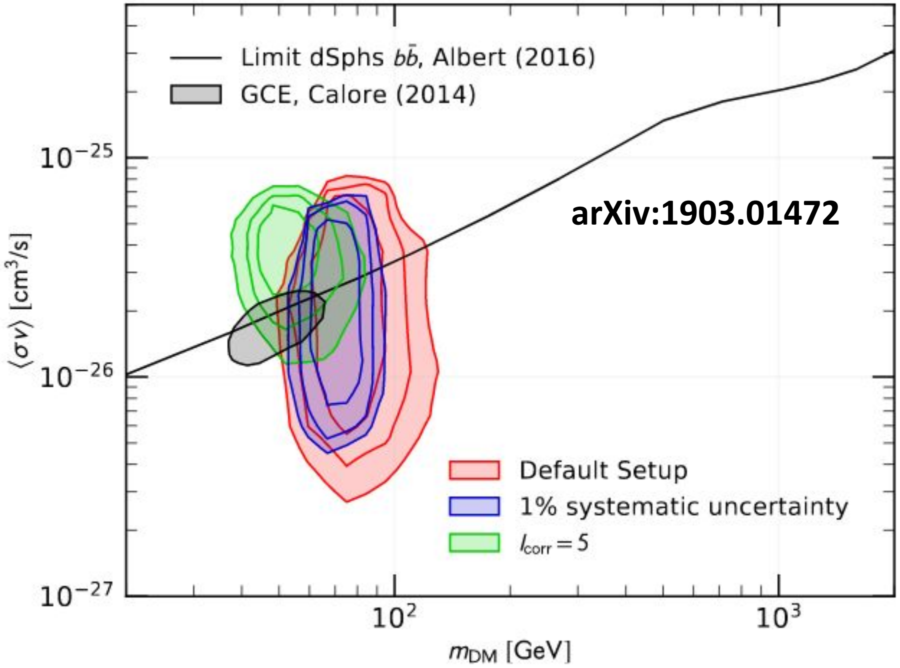
CRs antiprotons now (II)



- Update of the prediction of the **antiproton flux** in CRs.
- Better agreement with the AMS-02 measurement.

- <u>Paper conclusions</u>: AMS data are **consistent** with the only secondary production hypothesis.

CRs antiprotons now (III)

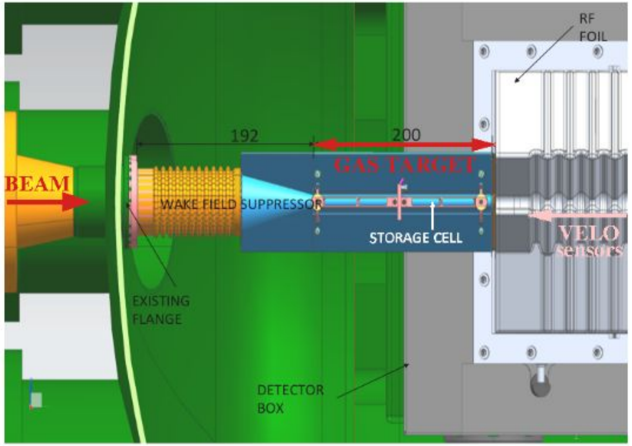


- Other studies still suggest a **contribution from DM** decay or annihilation processes.
- The significance (3σ) is **decreased** wrt previous versions thanks to the new scaling variation parametrization.

Future Prospects: Smog2

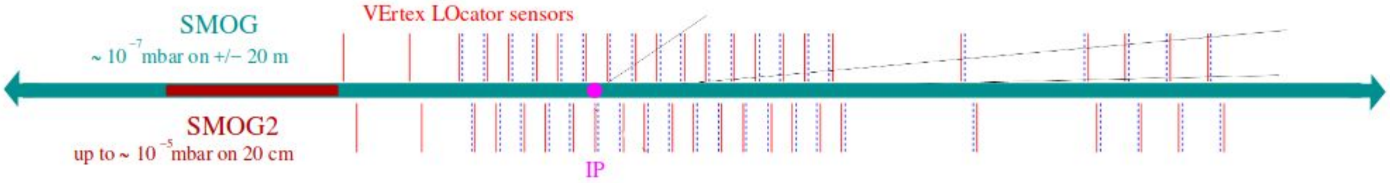
Smog programme upgrade

- **Smog2** : **upgrade** of the fixed-target LHCb programme for 2021 data-taking of a gas confinement cell covering the [-500, -300] *mm* region.



LHCB-TDR-020

- Possible to increase the **gas density** up of **two orders of magnitude** for the same gas flow of Smog.
- Gas pressure **precisely measured**, decreasing the measurement dominant systematic uncertainty.
- **More gases** can in principle (with machine approval) be injected like H, O, N….
- Possible to have a **simultaneous data-taking** with *pp* being the interaction region displaced wrt nominal IP.



Smog2 physics opportunities

- **Data-taking** strategy not defined yet. Work is ongoing to quantify the gas flow compatible with machine safety for every species and the background to pp core physics caused by pgas collisions for simultaneous acquisition (and vice versa).
- Expected average number of collisions is $\mu \sim 0.2 - 0.3$.
- If compatible with online selection requirements, **all bunch crossings** can be exploited.

LHCb-PUB-2018-015

System	$\sqrt{s_{NN}}$ (GeV)	< pressure> (10^{-5} mbar)	ρ_S (cm^{-2})	$\mathcal{L}$ ($cm^{-2}s^{-1}$)	Rate (MHz)	Time (s)	$\int \mathcal{L}$ (pb^{-1})
pH_2	115	4.0	2.0×10^{13}	6×10^{31}	4.6	2.5×10^6	150
pD_2	115	2.0	1.0×10^{13}	3×10^{31}	4.3	0.3×10^6	9
pAr	115	1.2	0.6×10^{13}	1.8×10^{31}	11	2.5×10^6	45
pKr	115	0.8	0.4×10^{13}	1.2×10^{31}	12	2.5×10^6	30
pXe	115	0.6	0.3×10^{13}	0.9×10^{31}	12	2.5×10^6	22
pHe	115	2.0	1.0×10^{13}	3×10^{31}	3.5	3.3×10^3	0.1
pNe	115	2.0	1.0×10^{13}	3×10^{31}	12	3.3×10^3	0.1
pN_2	115	1.0	0.5×10^{13}	1.5×10^{31}	9.0	3.3×10^3	0.1
pO_2	115	1.0	0.5×10^{13}	1.5×10^{31}	10	3.3×10^3	0.1
PbAr	72	8.0	4.0×10^{13}	1×10^{29}	0.3	6×10^5	0.060
PbH_2	72	8.0	4.0×10^{13}	1×10^{29}	0.2	1×10^5	0.010
pAr	72	1.2	0.6×10^{13}	1.8×10^{31}	11	3×10^5	5

- **Rich** physics programme achievable with a wide choice of targets!

Possible scenario, pending LHC approval for gas flows

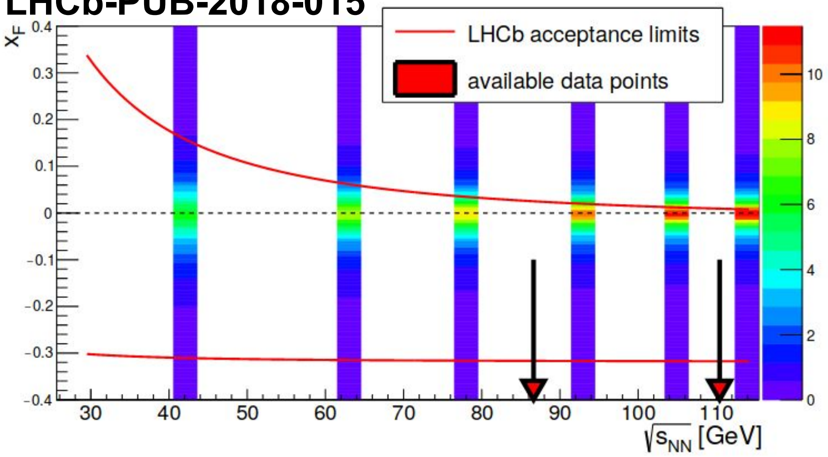
Smog2 opportunities for HI

LHCb-PUB-2018-015

- Many measurements of Heavy Ion physics interest can be addressed:
  - **Quarkonium** ($q\bar{q}$ compounds) **production measurements** in many collision systems and acceptances are needed to better understand the **sequential suppression**. Smog2 increase in luminosity will allow to study χ_c and ψ(2S).
  - **Drell-Yan** di-muon pairs above the J/ψ mass are widely produced in Smog2 and the extension of the kinematic coverage gives access to the sea quark PDFs.
  - Many flow observables and correlations addressable at central rapidities.
  - Charmonia and bottomonia **photoproduction** measurements (and also ρ^0, ω, η_c...).
  - Λ_c^+ polarization measurement as an interesting QCD benchtest.

Smog2 opportunities for CRs

LHCb-PUB-2018-015

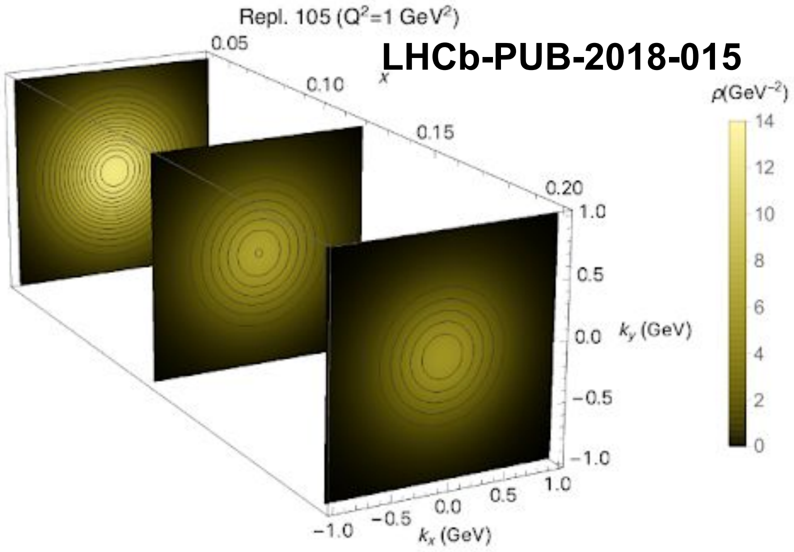


- **Antiproton measurements**:
  - Runs at low beam energy (up to 0.9 TeV) are sensible to positive Feynman-x values.
  - Constraint of the **evolution with energy** (scaling violation).

- Injecting hydrogen and deuterium the $\sigma(pD \to \bar{p}X)/\sigma(pp \to \bar{p}X)$ measurement can constrain the anti-neutron production (**isospin violation**).
- Secondary particles (light mesons, γ, and anti-nuclei) **production and spectra** measurable.
- Nitrogen and oxygen runs will allow to study atmospheric showers, notably for muons.
- Proposal to perform runs with **oxygen beams**. With a H target, access to the extremely forward region of the *pO* system. **CERN-LPCC-2018-07**

Smog2 opportunities for Nucleon structure

- The Smog2 kinematic (high-x at moderately high-Q^2) offers a unique opportunity to probe **quark and gluon PDFs**.



- PDFs dependence from the transverse momentum (**TDMs**) to address the parton orbital angular momentum.
- **Nucleon tomography.**

Conclusions

- Thanks to its forward geometry, its performances and the faculty to inject gases into the beam pipe, LHCb started a successful **fixed-target** programme!
- Two main results for Cosmic Rays physics interest:
  - **Charm production** in *pHe* and *pAr* collisions, other than in beam-beam collisions, is helpful to the modelling of **atmospheric neutrino production at ultra high energy**.
  - **Antiproton production** in *pHe* collision measurement is a key input to model background for Dark Matter indirect search from Cosmic Rays - Interstellar Medium scatterings.
- Fruitful **collaboration** with the theoretical astroparticle community.
- **Upgrade** of the fixed target programme consisting in the installation of a gas confinement cell approved. Further **widening** of the physics opportunities!

Thanks for your attention!

BACKUP

D^0 and J/ψ production: systematics

PRL 122, 132002 (2019)

Source		J/ψ	D^0
Correlated between bins			
Signal selection efficiency	pAr	1.4%	1.4%
	pHe	1.1%	1.1%
Tracking efficiency	pAr	1.9%	3.5%
	pHe	1.1%	3.2%
Particle identification efficiency	pAr	(1.8 – 1.9)%	(4.3 – 5.4)%
	pHe	(0.9 – 1.0)%	(1.1 – 2.6) %
Uncorrelated between bins			
Signal determination	pAr	(0 – 0.9)%	(1.6 – 2.6)%
	pHe	(0 – 0.9)%	(1.6 – 2.5)%
Tracking efficiency	pAr	(0.1 – 1.9)%	(0.2 – 2.6)%
	pHe	(0.2 – 1.8)%	(0.3 – 2.7)%
Simulation sample	pAr	(1.8 – 2.0)%	(2.4 – 2.5)%
	pHe	(1.7 – 3.4)%	(2.5 – 2.8)%
Particle identification efficiency	pAr	(0 – 1.9)%	(0 – 5.6)%
	pHe	(0 – 0.8)%	(0 – 3.7)%
Statistical uncertainties	pAr	(7.8 – 12.7)%	(2.8 – 5.8)%
	pHe	(7.9 – 11.3)%	(4.2 – 10.1)%

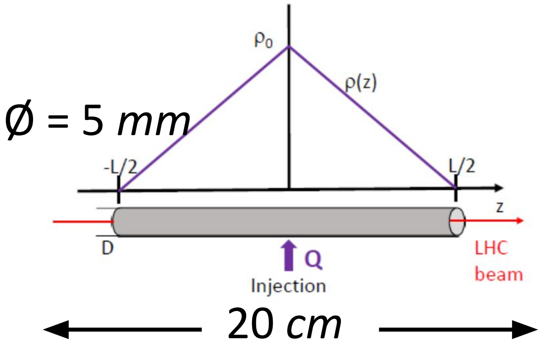
Antiproton measurement: systematics

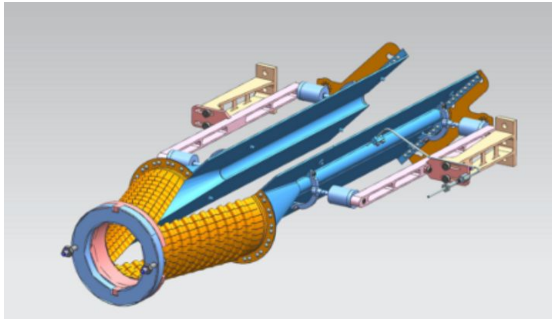
PRL 121 (2018) 222001

Statistical	
$\overline{p}$ yields	$0.5-11\%$ ($<2\%$ for most bins)
Luminosity	$1.5-2.3\%$
Correlated systematic	
Luminosity	6.0%
Event and PV selection	0.3%
PV reconstruction	$0.4-2.9\%$
Tracking	$1.3-4.1\%$
Non-prompt background	$0.3-0.5\%$
Target purity	0.1%
PID	$3.0-6.0\%$
Uncorrelated systematic	
Tracking	1.0%
IP cut efficiency	1.0%
PV reconstruction	1.6%
PID	$0-36\%$ ($<5\%$ for most bins)
Simulated sample size	$0.4-11\%$ ($<2\%$ for most bins)

- Dominant contribution from **luminosity** measurement: motivation for Smog2 upgrade
- PID contribution sub-dominant: campaign started to produce higher-statistics **calibration samples**.

Smog2 cell





- **Gas injection** in the cell from its half, thus the gas pressure follows a triangular profile.
- System composed of **two retractable halves** to follow the Velo closing procedure.
- Light and thin material, to keep low the **material budget** and appropriately **coated** to prevent electron clouds to form.
- **Electrical connectivity** ensured by the wake field suppressor.
- Approved by the LHCC, installation foreseen in **November**.