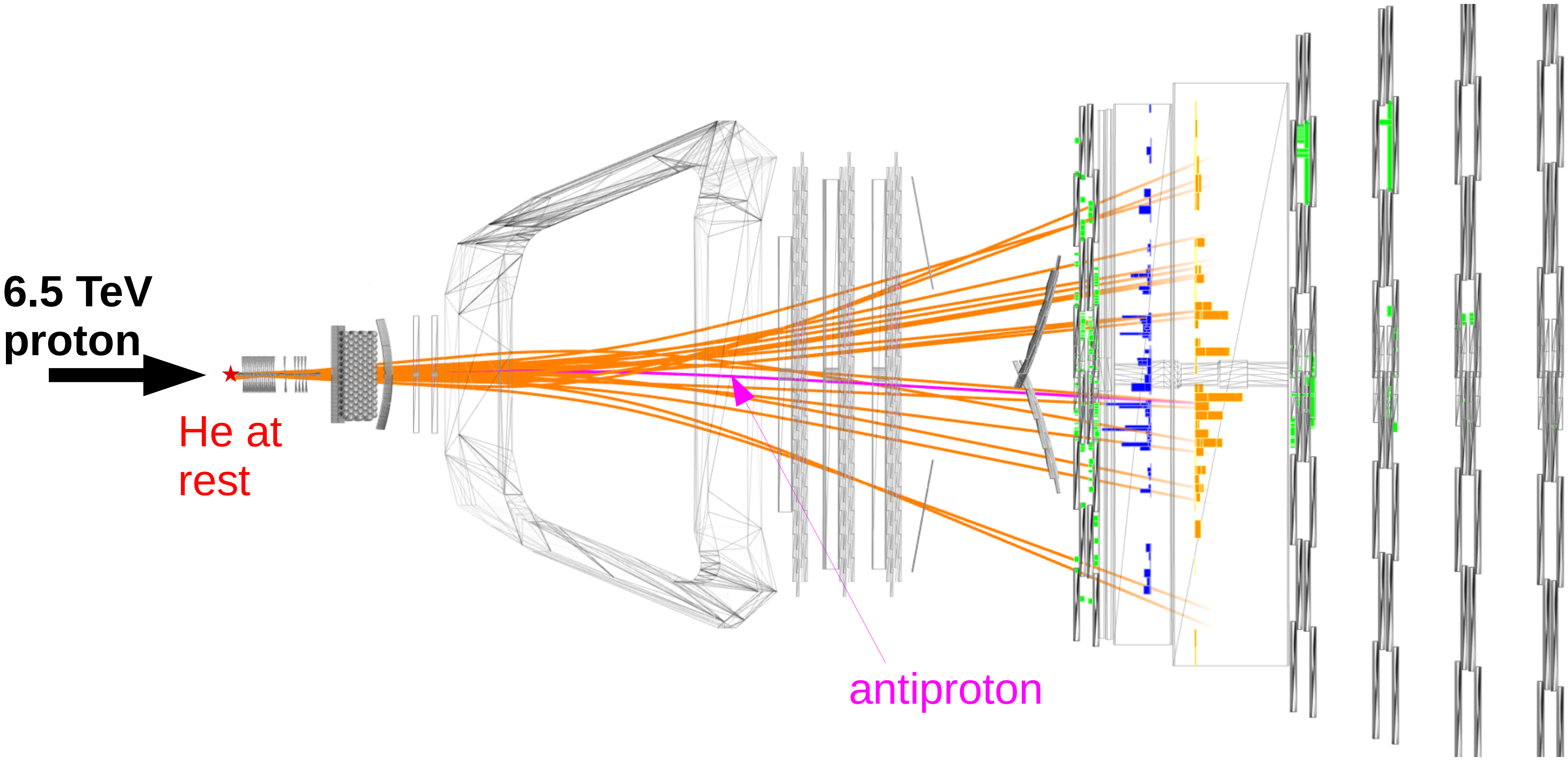
# LHCb as a fixed-target experiment

*Status and Plans toward deliverable*



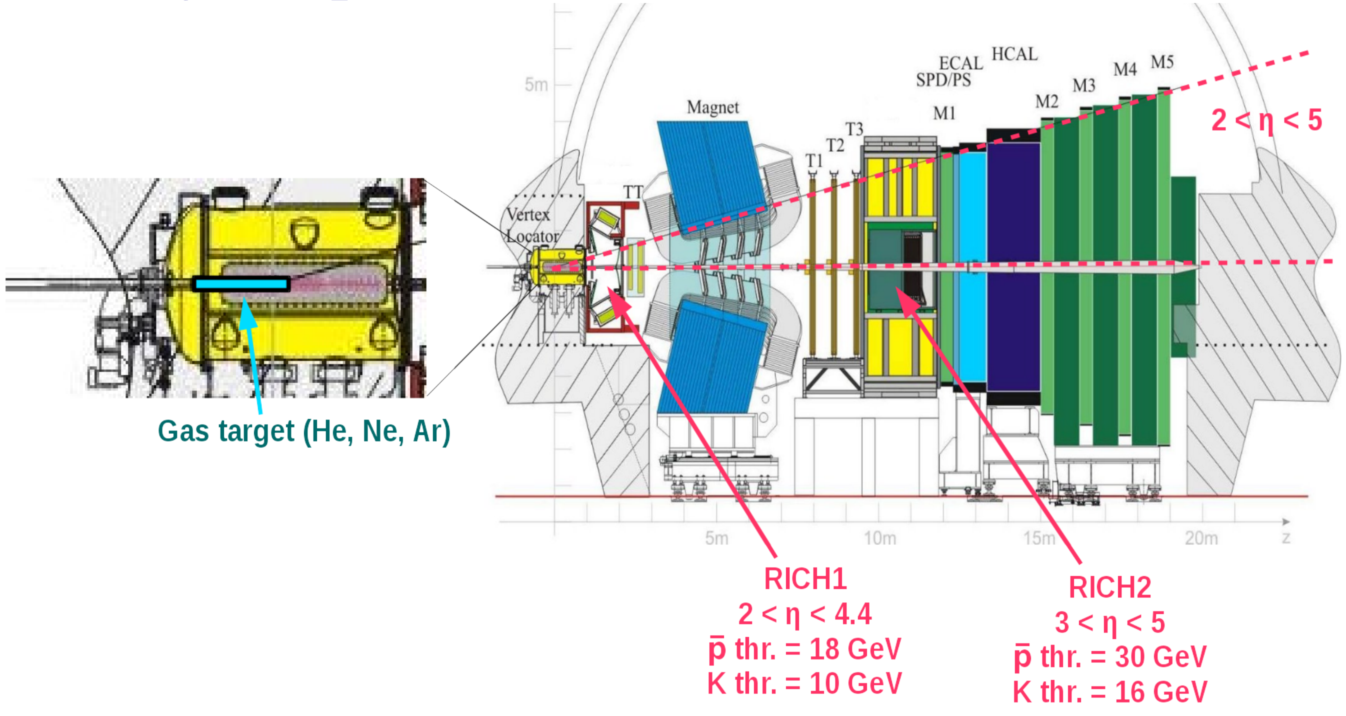


**Giacomo Graziani (INFN Firenze)**
**on behalf of the LHCb Collaboration**

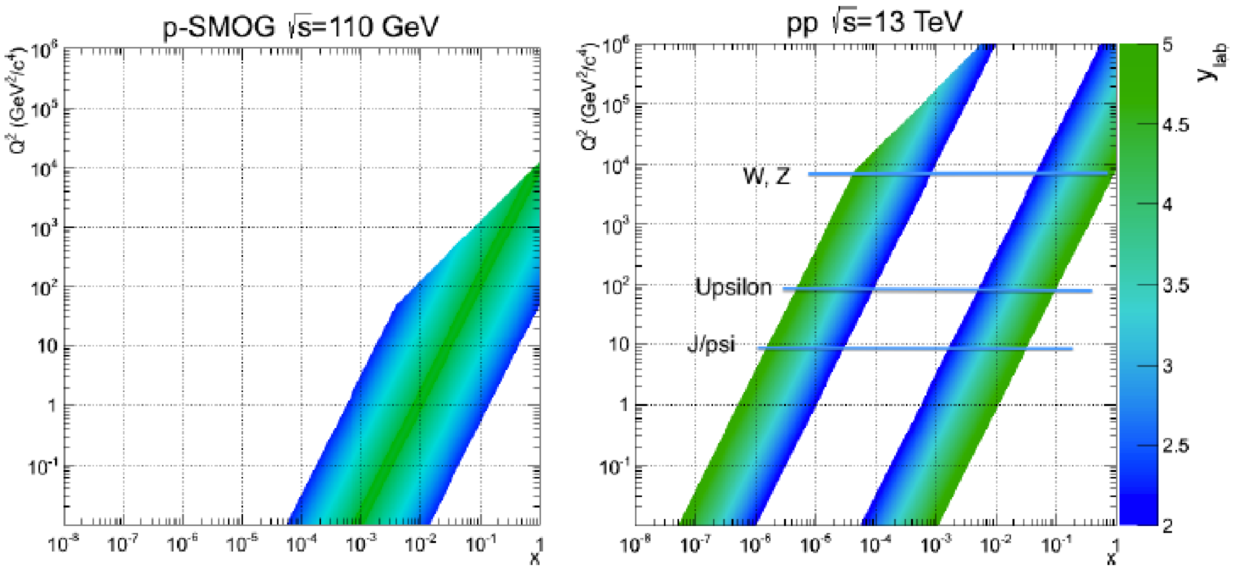

**Physics Beyond Colliders General Meeting**
**June 14, 2018**

# Reminder on LHCb Fixed Target

LHCb as a fixed target experiment, thanks to the SMOG internal gas target

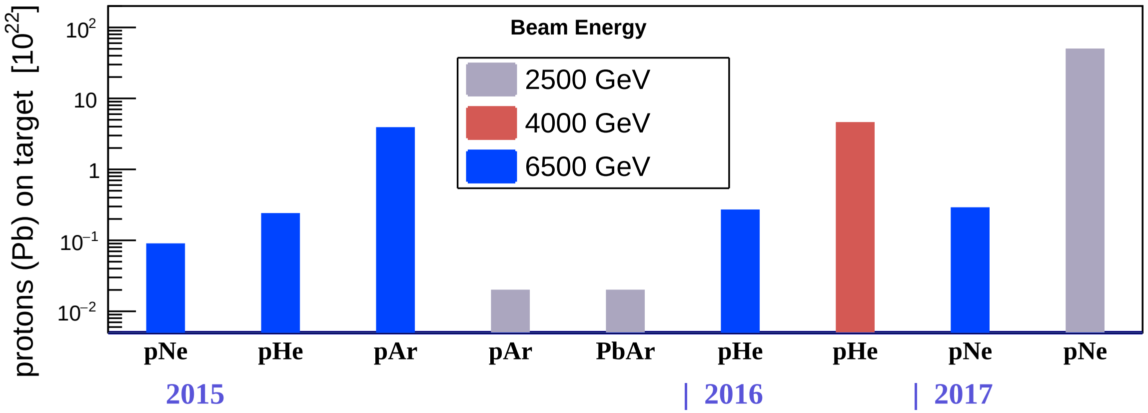



- pA collisions at unique energy scale $\sqrt{s_{\mathrm{NN}}} \sim 100$ GeV
- Unique coverage for (n)PDF at large $x$



# Run2 SMOG data samples

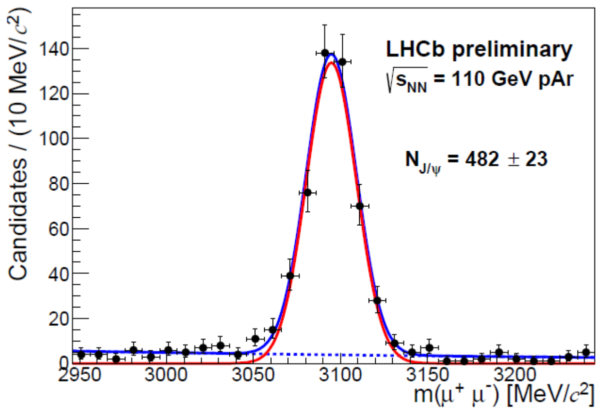
Samples acquired so far

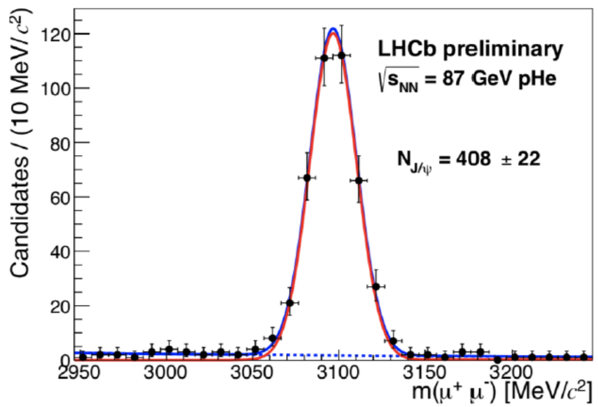



$$\int \mathcal{L}dt \sim 5\ \text{nb}^{-1} \times \frac{pot}{10^{22}} \times \frac{p_{gas}}{2 \times 10^{-7}\text{mbar}} \times \text{Exp\_Efficiency}$$

First two papers being submitted very soon:

- charm cross section, based on $\sim 400$ J/ψ $\rightarrow \mu^+\mu^-$ and $\sim 2000$ $D^0 \rightarrow K\pi$ decays from pHe@86 GeV, (and differential shapes from similar sample in pAr@110 GeV)

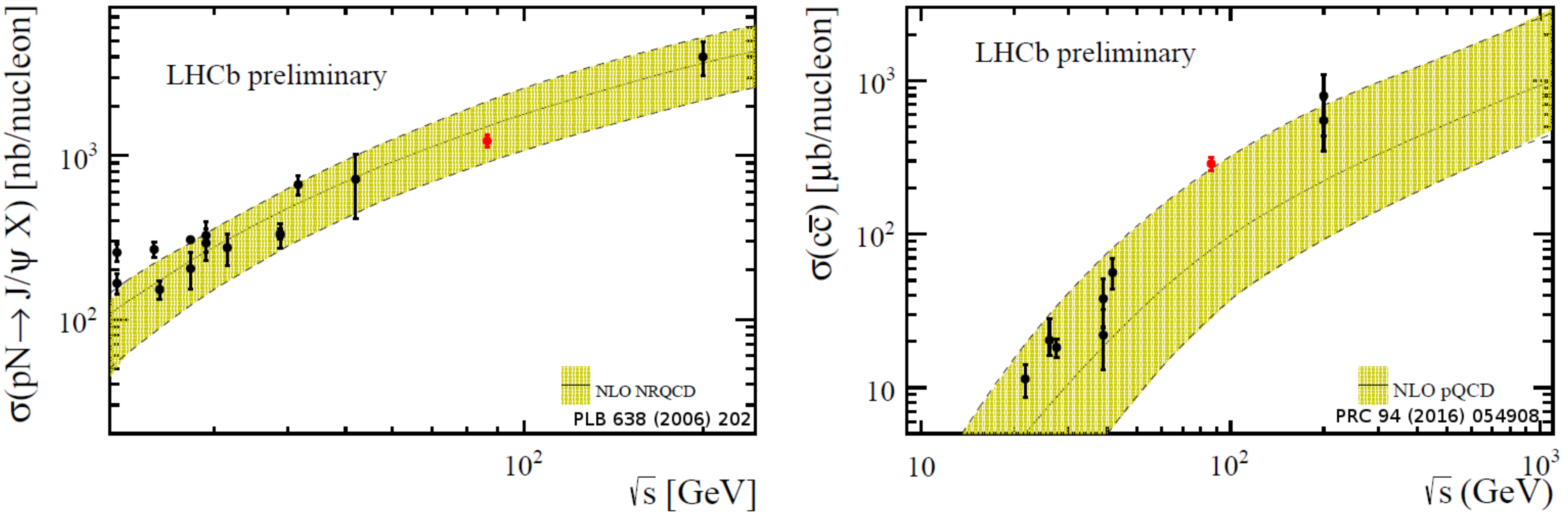



- antiproton production from pHe@110 GeV (important for cosmic ray physics)

# Charm results

presented at Quark Matter last month

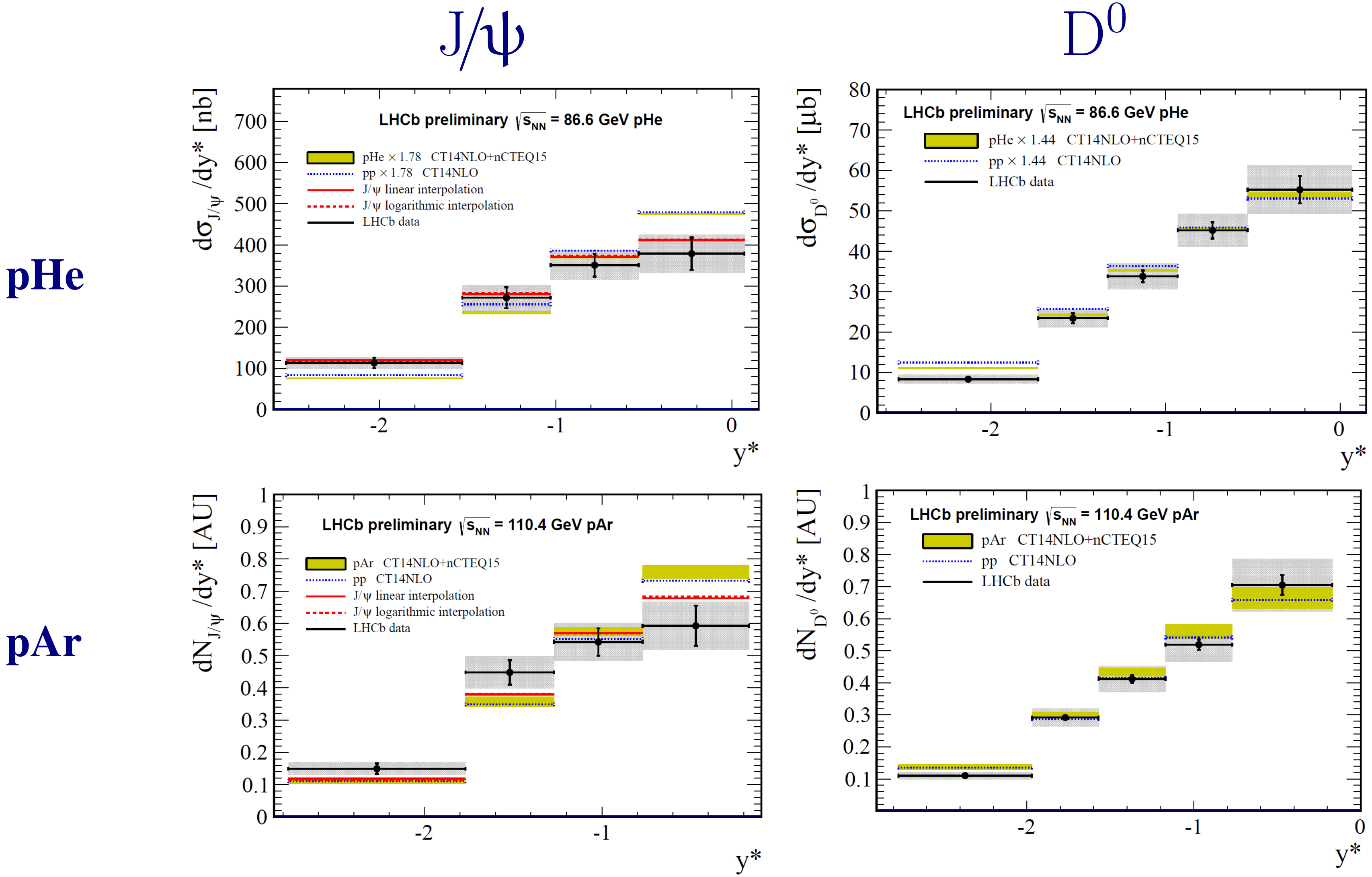



$$\sigma_{J/\psi}^{86.6\ \text{GeV}} = 1225.6 \pm 62.0(stat.) \pm 81.6(syst.)\ \text{nb/nucleon}$$

$$\sigma_{D^0}^{86.6\ \text{GeV}} = 156.0 \pm 4.6(stat.) \pm 12.3(syst.)\ \mu\text{b/nucleon}$$

Scaling the $D^0$ cross-section with the global fragmentation ratio $f(c \to D^0) = 0.542 \pm 0.024$, $c\bar{c}$ production cross section can be obtained:

$$\sigma_{c\bar{c}}^{86.6\ \text{GeV}} = 287.8 \pm 8.5(stat.) \pm 25.7(syst.)\ \mu\text{b/nucleon}$$




rapidity distributions in backward region compatible with predictions without Intrinsic Charm from the HELAC-ONIA NRQCD model [ Lansberg and Shao, EPJC 77:1 (2017) ] in both pHe and pAr samples.

➡ strong constraints on IC (unless tricky cancellations with nuclear effects)

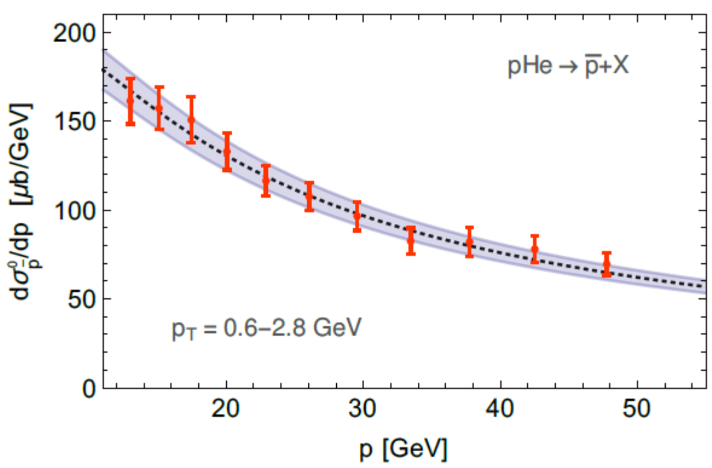
Desiderata: increase data size for better accuracy, access other heavy states, extend to other targets ($H_2$ for pp reference, heavier targets)

# Soft QCD for Cosmic Ray physics

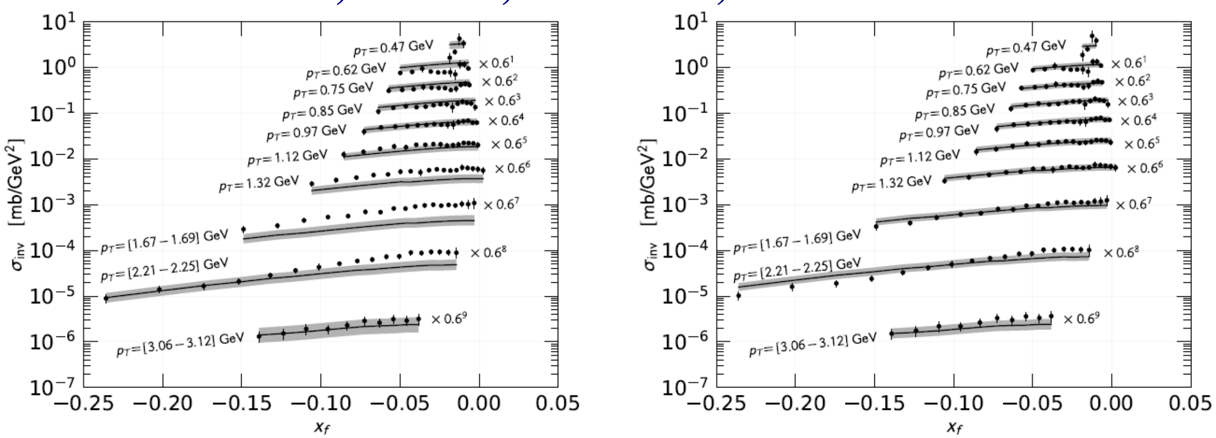
- First physics result is prompt $\overline{\mathrm{p}}$ production in pHe@110 GeV **LHCb-CONF-2017-002**
- Very important for understanding $\overline{\mathrm{p}}$ production from cosmic rays on interstellar medium (background to DM searches)

  Preliminary result already exploited to improve understanding of scaling violation:

**Reinert and Winkler, arXiv:1712.00002**




**Korsmeier, Donato, Di Mauro, arXiv:1802.03030**



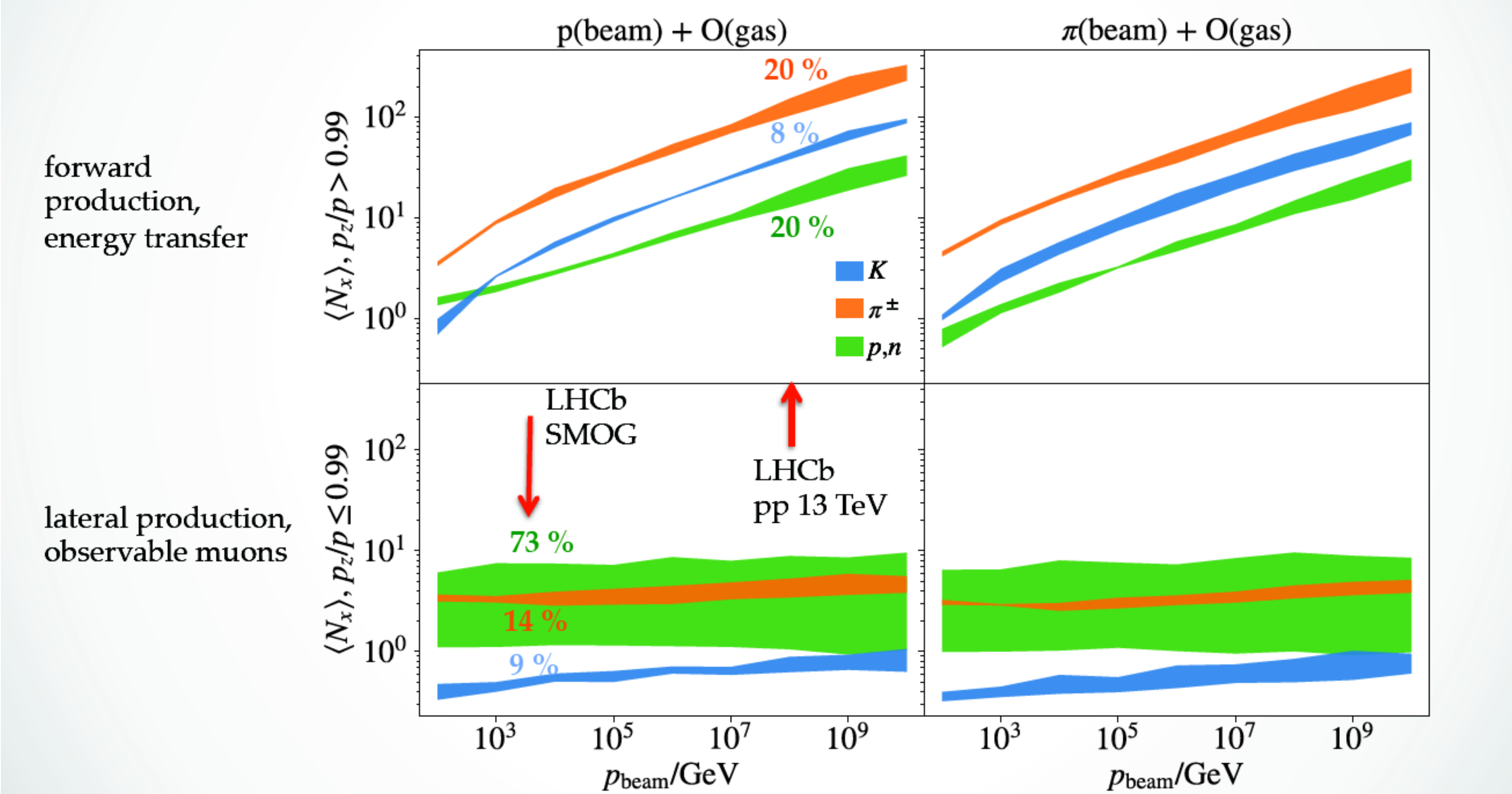

comparing data with different parameterizations for scaling

More in the pipeline:

- inclusion of data @ 87 GeV and hopefully new data to be taken at lower energy
  ➨ study scaling violations, bridge to measurements at SPS
- inclusion of $\overline{\mathrm{p}}$ from anti-hyperons (predicted to be 20-30 %)

Desiderata: also measure in $pp$ with $H_2$ target, and use $D_2$ target to constrain isospin violation for $\overline{\mathrm{p}}/\overline{n}$ production

- Understanding of lateral development of UHE cosmic rays (muon puzzle).
  Large spread for muon flux predictions among different models, mostly from uncertainty on baryon production ($\sim 70\%$). Measurements at 10% accuracy would greatly help constraining the models.




(plot by H.Dembinsky) the curves indicate the contributions from the different "grand-mothers" to muon multiplicity in the showers

Production in pN and pO can be extrapolated from available pHe, pNe, pAr data

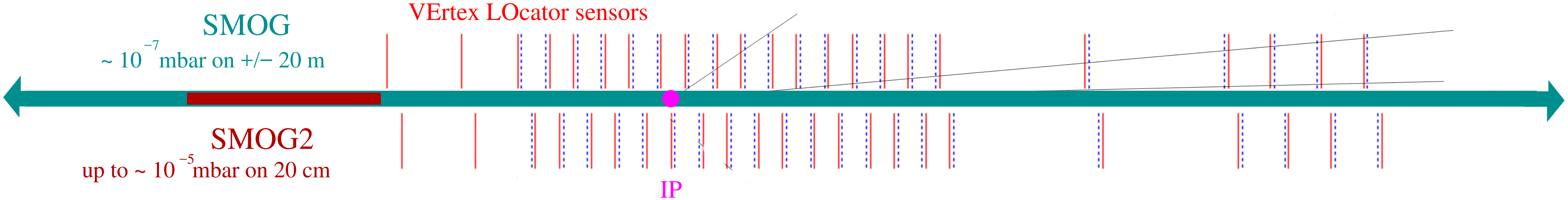
Desiderata: $N_2$ target for more direct measurement

# Goals for LHC Run3

- increase data size: better accuracy, access rarer states
- extend target choice:
  - **Hidrogen** and **Deuterium** would allow to have *pp* reference measurements, studies of GPDs/TMDs (through unpolarized observables), more $\overline{\mathrm{p}}$ production for CR in space (production in pp and isospin violation)
  - **Nitrogen** for atmospheric CR
  - **Heavier** gas (Kr, Xe?). Upgraded LHCb detector (from Run3) will allow better reconstruction of central event

Proposed solution: **SMOG2**

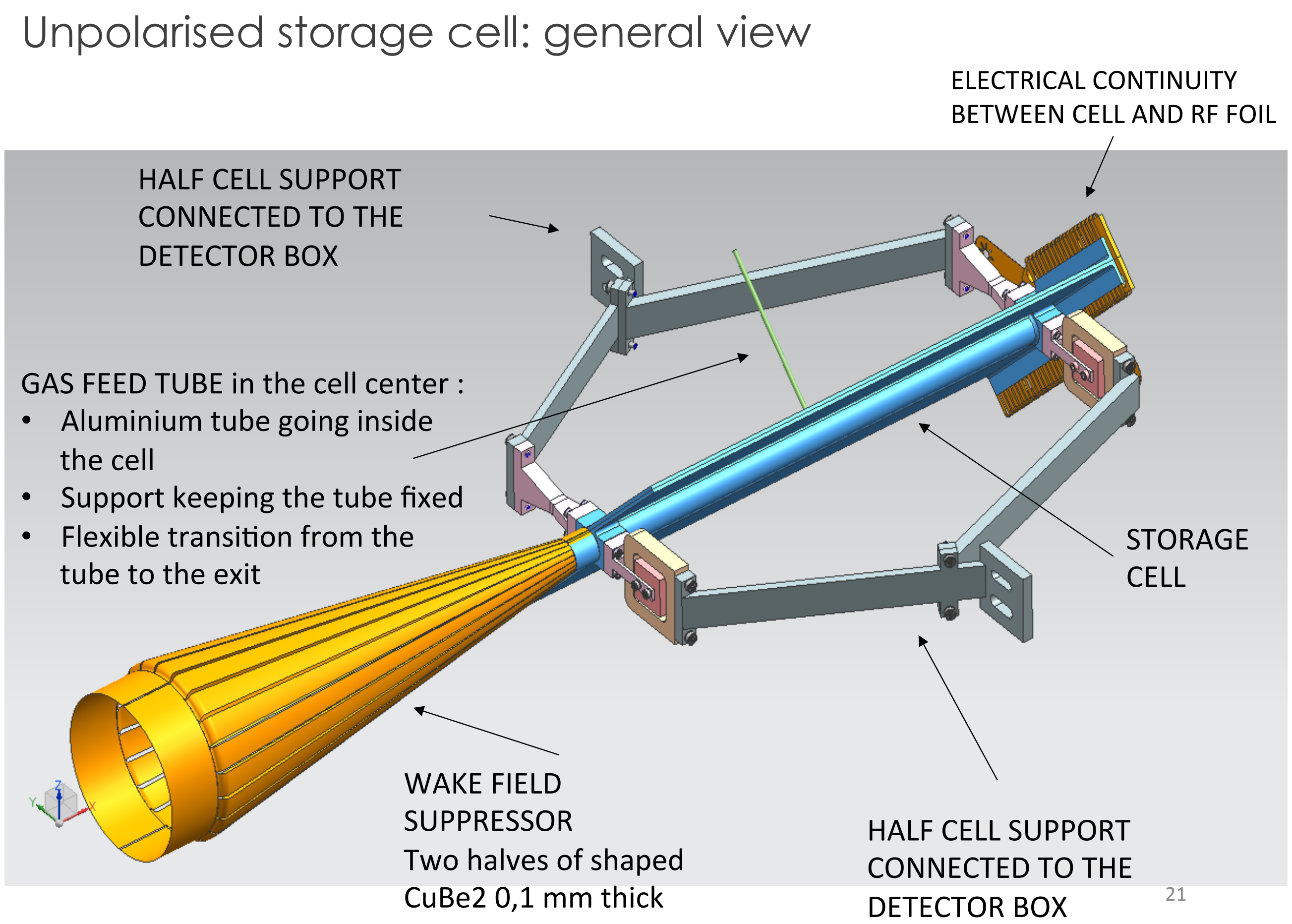
- contain gas in 20 cm long storage cell
  ➡ allow up to x100 increase of gas density wrt current SMOG




- lower contamination of beam line ➡ more gas species possible
- better control over injected gas density (better accuracy on absolute cross sections)

# SMOG2 status

- Design is well advanced




- Physics case supported by LHCb, engineering review ongoing
- see yesterday's talk by S.Radaelli

# Baseline scenario for Run3

Beware: SMOG2 approval still pending.
Assumed numbers below are guesstimates,
not approved by LHCb

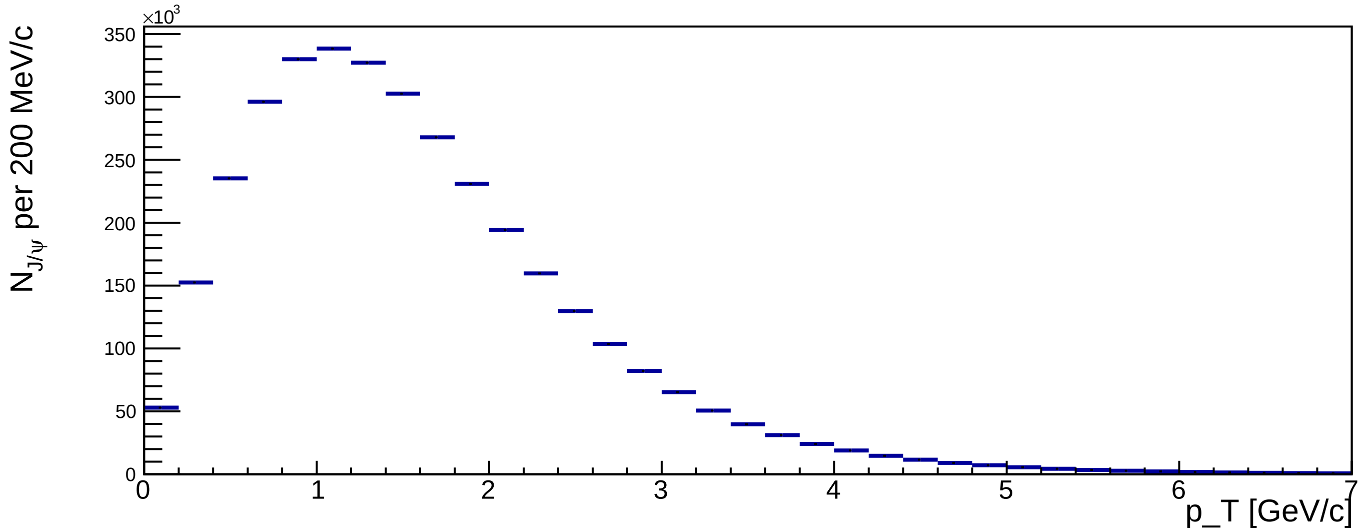
| | |
|---|---|
| pH @ 115 GeV | $\sim$ 10/pb |
| pD @ 115 GeV | $\sim$ 10/pb |
| pAr@ 115 GeV | $\sim$ 10/pb |
| PbAr@ 72 GeV | $\sim$ 5/nb |
| pAr @ 72 GeV | $\sim$ 1/pb |

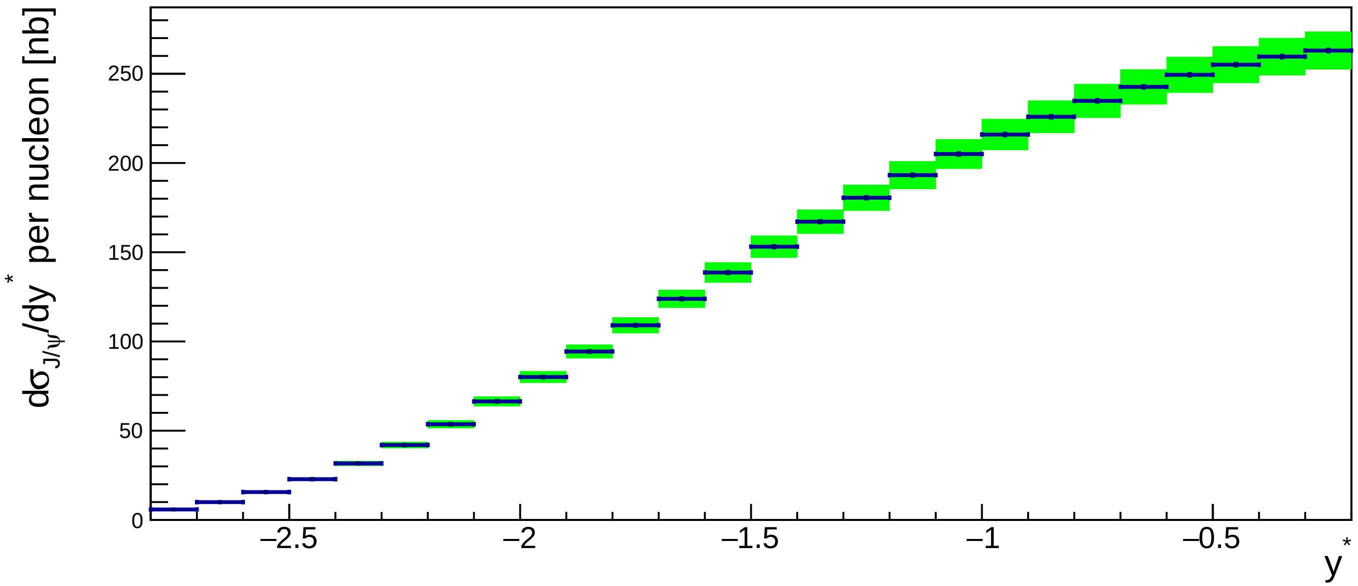
# Physics Reach

| | Current SMOG result pHe@86 GeV | SMOG largest sample pNe@68 GeV | SMOG2 example pAr@115 GeV |
|---|---|---|---|
| Int. Lumi. | 7.6/nb | $\sim$ 100/nb | $\sim$ 10/pb |
| syst. error on $J/\psi$ x-sec. | 7% | 6 - 7% | 3 - 4 % |
| $J/\psi$ yield | 400 | 15k | 3.5M |
| $D^0$ yield | 2000 | 100k | 35M |
| $\Lambda_c$ yield | 20 | 1k | 350k |
| $\psi'$ yield | negl. | 150 | 35k |
| $\Upsilon(1S)$ yield | negl. | 10 | 3k |
| DY $\mu^+\mu^-$ yield ($5 < M < 9$ GeV) | negl. | 10 | 3k |

Notes:

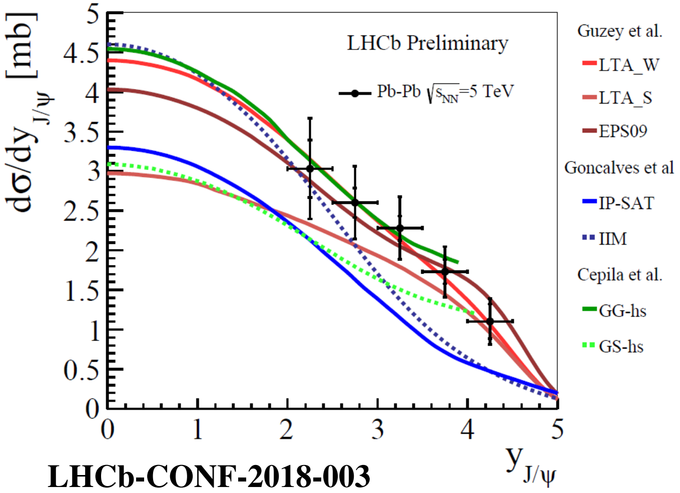
- list is far from being exhaustive;
- extrapolations are crude estimates, just to provide figures of merit;
- assuming quarkonium absorption by the nuclear target leading to a decrease of its cross section by a factor 0.75 (0.6) in pNe and 0.5 (0.4) in pAr for $J/\psi$ ($\psi'$) with respect to pHe.
- the smaller systematic uncertainty with SMOG2 is expected from the reduction of the dominant uncertainty on the luminosity (6%) for SMOG data .




Extrapolations of $J/\psi$ spectrum and X-section measurement to 10 $pb^{-1}$ of pAr@115 GeV

# More possibilities



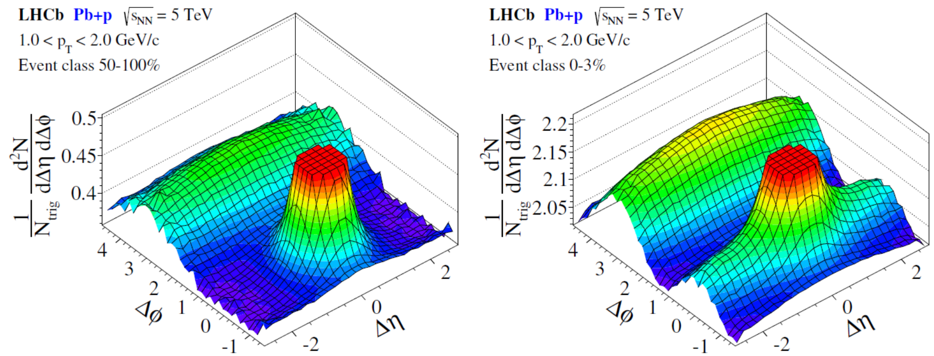

LHCb-CONF-2018-003

- UPC physics : interesting cross-section for photoproduced J/ψ in LHCb-FT (∼ 300 pb in $pAr$), can complement studies made/ongoing by LHCb in collisions ($pp$, $pPb$, $PbPb$)

**Lansberg et al., JHEP 1509 (2015) 087, Massacrier et al, arXiv:1709.09044,**

**Goncalves and Jaime, arXiv:1802.04713**

- Potential to study elliptic flow over 3 units of pseudorapidity with full instrumentation at unique energy scale;
  - dihadron correlation studies already demonstrated by LHCb in pPb
  - yields with SMOG2 could allow flow studies with charmed particles
  - no studies in FT performed yet



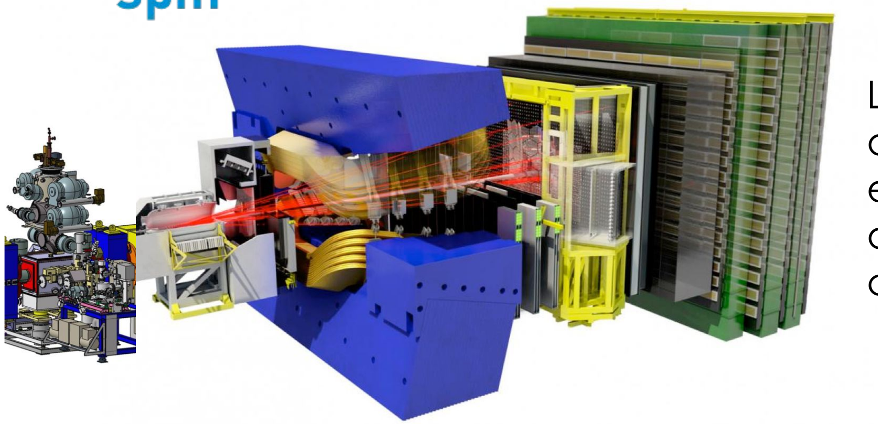

**Phys. Lett. B762 (2016) 473-483**

- Λ polarization induced by vorticity in HI collisions
  (see Becattini et al., PRC 88, 034905 (2013), STAR results on Nature 548, 62-65 )
  Fixed target collisions have the correct energy scale
  (effect fading away at LHC collision energy)

# Longer term: Polarized Target

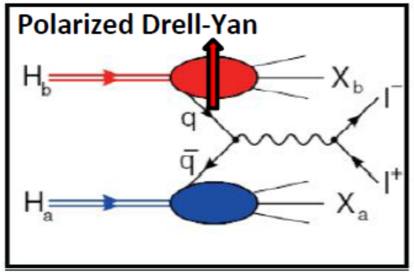
**P. Di Nezza et al**

## LHC spin : a polarized fixed target @LHCb



LHCSpin aims to bring un/polarized physics at the LHC as a new tool, using the existing, advanced and upgraded LHCb detector in parallel fixed-target and collider data taking

- Unique kinematic conditions (identical to those of SMOG2): $\sqrt{s}\approx 115$ GeV, $-4.8<y^*<0$, $x\to 1$
- Wide range of possible reactions:
  polarized: $pp\uparrow$, $pd$, unpolarized: $pA$ , $PbA$ (A=H, He, O, Ne, Ar, Kr, Xe)
- Broad and ambitious physics program:
  -3D nucleon structure: quark and gluon Transverse-Momentum-Dependent PDFs (TMDs),
  -fundamental tests of QCD (universality, factorization)
  -effects of cold nuclear matter (EMC, jet-quenching, etc)
  -QGP formation, Intrinsic heavy quarks … and much more!
- Possibility to run in parallel with normal collider mode
- Marginal impact on LHC beam and LHCb mainstream physics
- Polarized gas target technology well established (10 years @ HERMES) and very high performances (P>80%)




## Main reactions accessible at LHCb

- $pp^{(\uparrow)} \to \eta_c + X \quad (pp^{(\uparrow)} \to \chi_{c,b} + X)$
- $pp^{(\uparrow)} \to J/\psi + X$
- $pp^{(\uparrow)} \to \Upsilon + X$
- $pp^{(\uparrow)} \to J/\psi + J/\psi + X$
- $pp^{(\uparrow)} \to J/\psi + \gamma + X$
- $pp^{(\uparrow)} \to \Upsilon + \gamma + X$

☛ **Pol and unpol gluon PDFs**

- $pp \to \mu^+\mu^- + X \quad (pp \to e^+e^- + X)$
- $pd \to \mu^+\mu^- + X \quad (pd \to e^+e^- + X)$

☛ **momentum distrib. of sea quarks & unpolarized TMDs of valence and sea quarks**

- $pp^{\uparrow} \to \mu^+\mu^- + X \quad (pp^{\uparrow} \to e^+e^- + X)$
- $pd^{\uparrow} \to \mu^+\mu^- + X \quad (pd^{\uparrow} \to e^+e^- + X)$

☛ **TMDs of valence and sea quarks**

- pA, PbA $(A = He, Ne, Ar, Kr, \ldots)$

☛ **Nuclear matter effects, QGP, etc**

Gluon Sivers function (unknown) accessible through Single Transverse Spin Asymmetries:

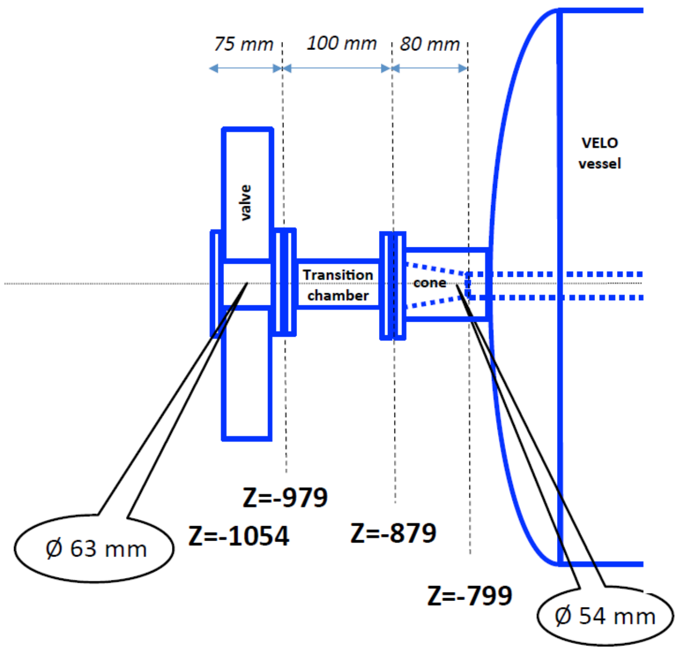
$$A_N = \frac{1}{P}\frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \sim \frac{1}{P}\frac{N_h^{\uparrow} - N_h^{\downarrow}}{N_h^{\uparrow} + N_h^{\downarrow}} \propto \left[f_{1T}^{\perp g}(x_a, k_{\perp a}) \otimes f_g(x_b, k_{\perp b}) \otimes d\sigma_{gg \to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

-sensitive to gluon orbital angular momentum
-spin-orbit correlation of gluons inside proton
-process dependent (→ test of QCD Universality)

Studies of single spin asymmetries provide unique insight in understanding dynamics and spin of partons inside the nucleon. Physics reach under extensive study, in particular by AFTER

# Conclusions

- LHCb fixed target group mostly busy with exploiting current SMOG data. The two first physics papers to be submitted soon to PRL
- Progress with the SMOG2 proposal opens great possibilities for a substantial increase of data size and choice of target gas species wrt the current SMOG program already for Run3;
- LHCspin group also working on polarized target proposal for Run4/Run5.
  LHCb is evaluating this proposal (as well as the crystal target and solid target ones) in a dedicated panel (FITPAN). First concrete step: install valve to isolate VELO vacuum from the upstream region where these targets could be installed




- draft of the PBC document being prepared