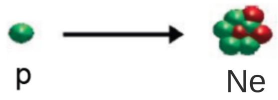
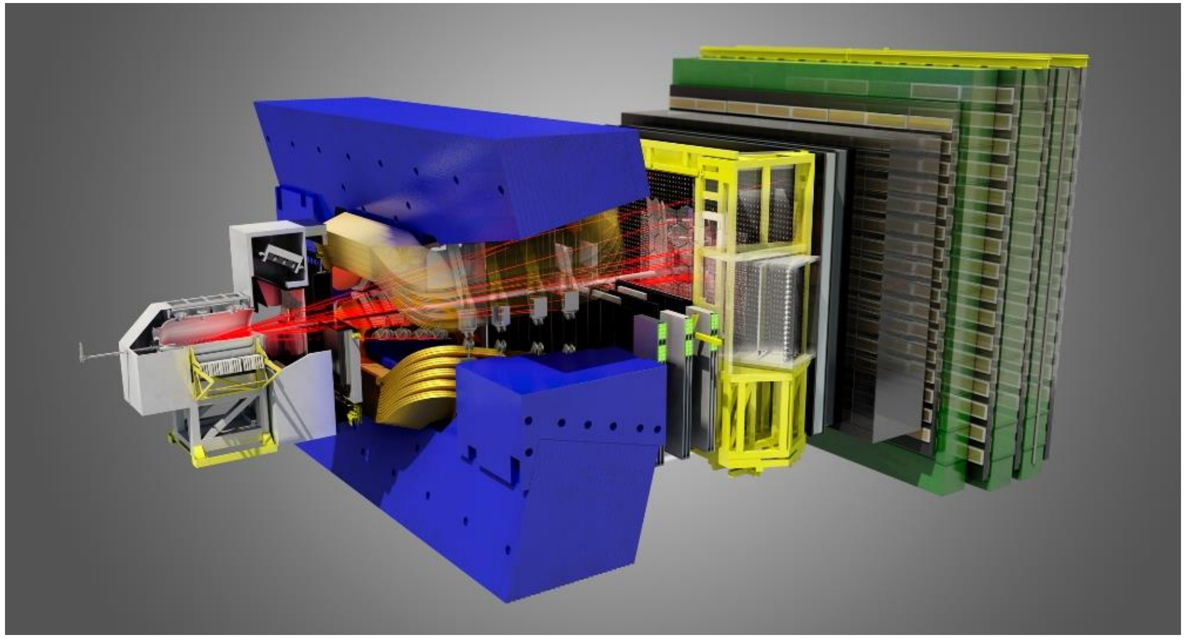




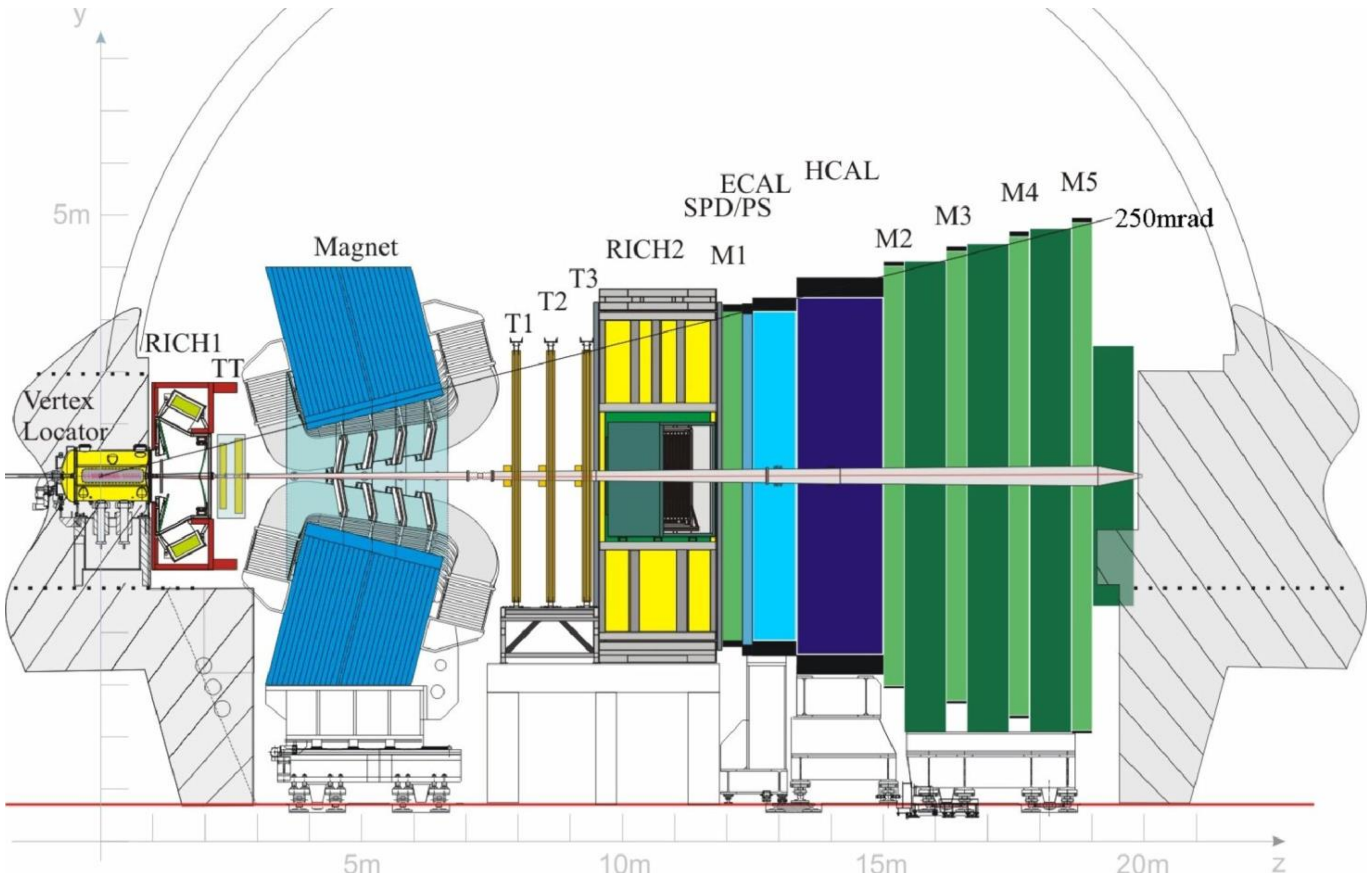
Charm production in *p*Ne collisions at LHCb

Emilie Maurice - Laboratoire Leprince Ringuet

Fixed target experiments at LHC – Strong2020 workshop
23rd June 2022

The LHCb experiment [JINST 3 (2008) S08005]

LHCb was designed for heavy flavor physics but serves now as a general purpose detector



Fully instrumented in 2 < y < 5

Excellent performance :

[Int. J. Mod Phys. A30 (2015) 1530022]

- ✓ Vertex, IP and decay time resolution
- ✓ Momentum resolution
- ✓ Particle identification

  $\epsilon_{K\to K} \approx 95\%$, $\epsilon_{\pi\to K} \approx 5\%$

  $\epsilon_{\mu\to\mu} \approx 97\%$, $\epsilon_{\pi\to\mu} \approx 1\text{-}3\%$

- ✓ **Flexible trigger down to low-p_T**

- ✓ **Unique fixed-target configuration : SMOG**

  System for Measuring Overlap with Gas

  Originally designed for luminosity measurements

  Transform LHCb in a fixed-target experiment

SMOG and kinematics

LHCb has unique capabilities to do high-precision measurements, specially in beauty and charm sector

SMOG gas injection

- Noble gases only (He, Ne, Ar)
- Injection into the LHC vaccum around the LHCb interaction point
- Pressure ~2 x 10^{-7} mbar

Colliding systems

- Proton beam (2.5 TeV, 5 TeV, 6.5 TeV)
  p-nucleus collisions : *p*He, *p*Ne, *p*Ar
- Lead beam (2.5 TeV) :
  Pb-nucleus collisions : PbNe, PbAr

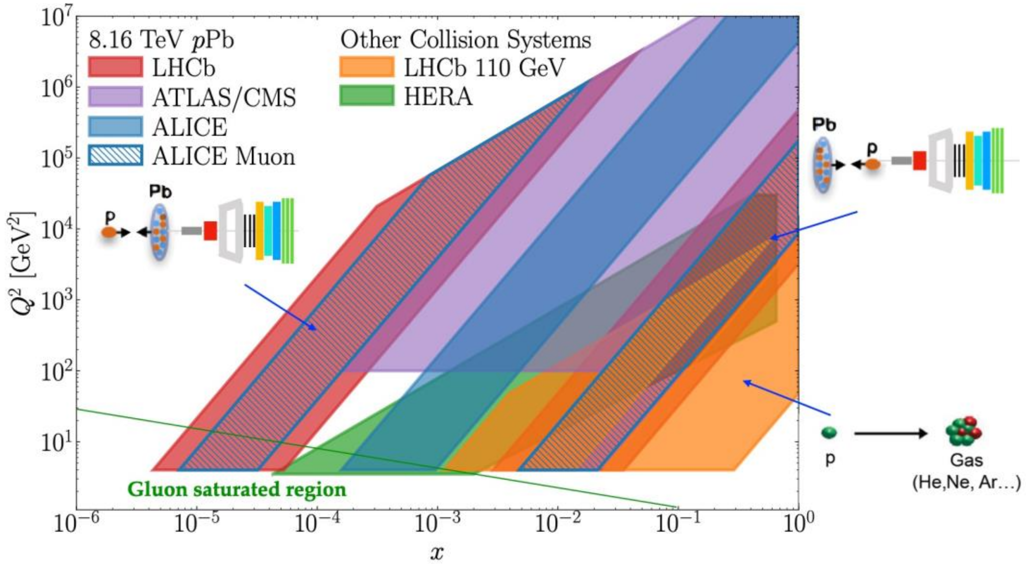
Energy at the center of mass :

$\sqrt{s_{NN}} \in [68.5, 110.4]$ GeV

→ Fill the gap between the SPS and RHIC energies

Boost from 4.29 to 4.77 leading to a rapidity in the center of mass : y* $\in [-2.5, 0.5]$

→ Covering the backward and midrapidity range



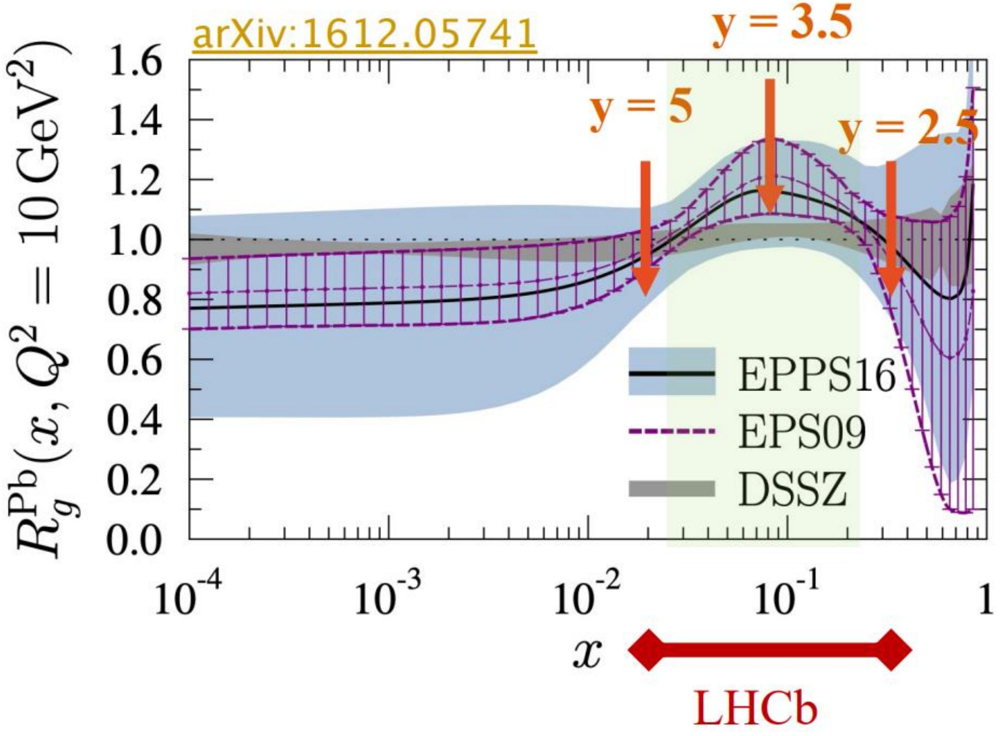
Complementary phase space coverage between fixed-target and collider modes

Charm production with the LHCb fixed-target configuration

LHCb fixed-target collisions : large rapidity coverage at large Björken-x in the target

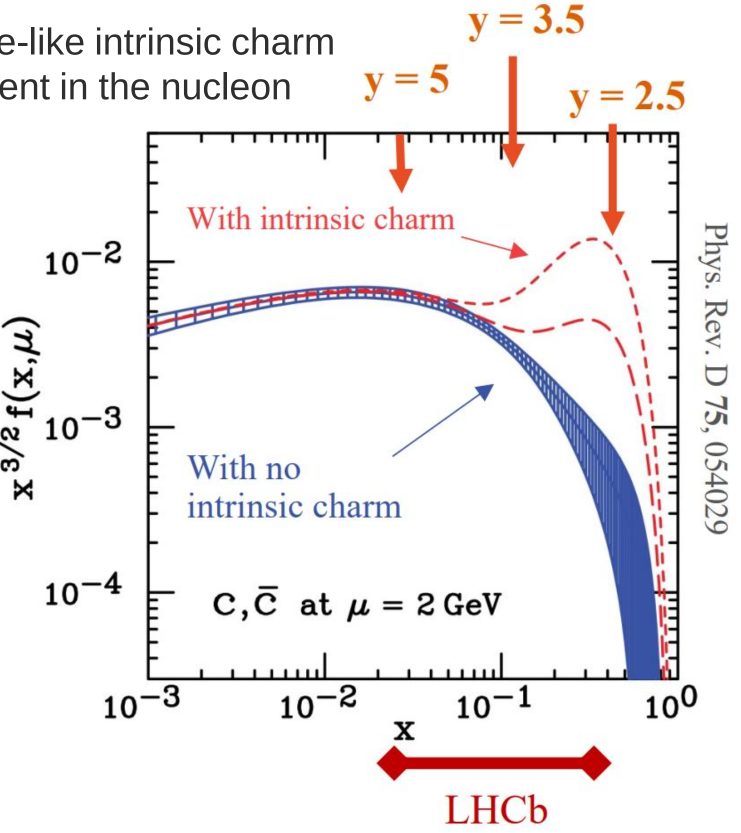
nPDF anti-shadowing region

PDF in a Pb nucleus / PDF in a single nucleon



Valence-like intrinsic charm content in the nucleon

Charm quark distributions



Björken-x : fraction of the nucleon momentum carried by a parton

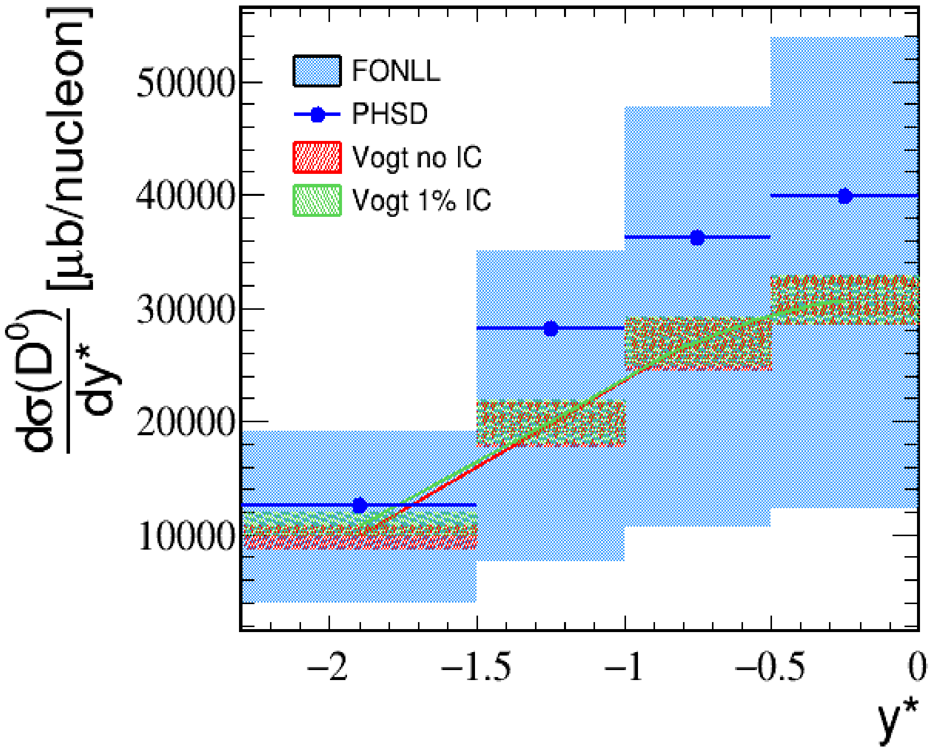
Why studying open charm production in *p*-nucleus collisions ?

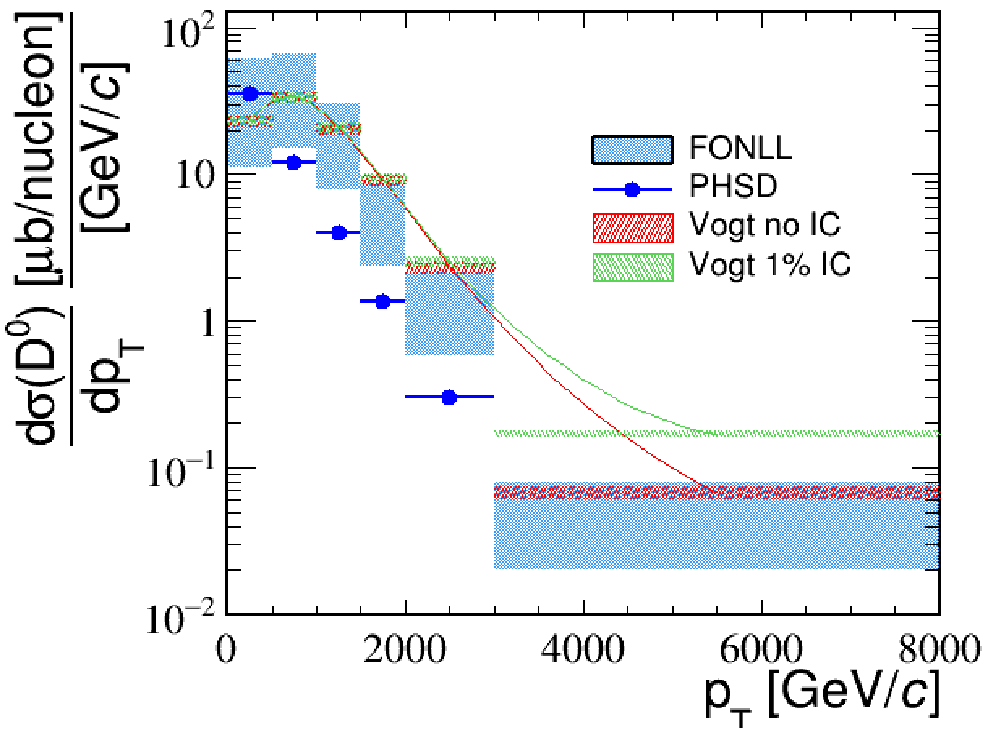
Open charm

- Should not be affected by Quark Gluon Plasma (QGP) production
- Proxy of the total amount of ccbar pairs

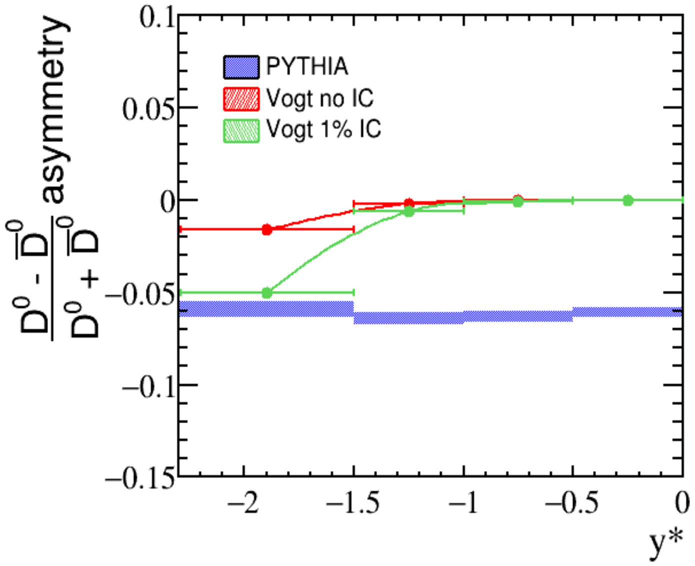
→ Reference for charmonium production ➔ J/ψ / D^0 measurement in the pipeline in *p*Ne to be compared with PbNe collisions

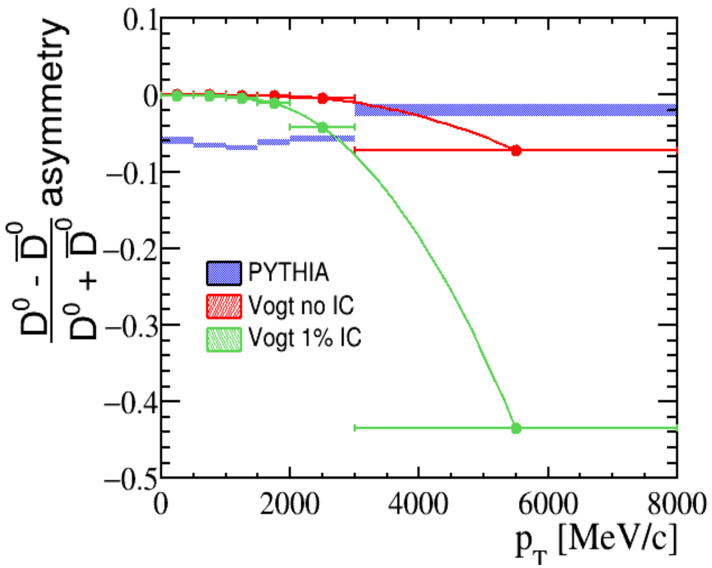
- **Cross-section relevant to investigate the nucleon content, specially regarding the intrinsic charm component**

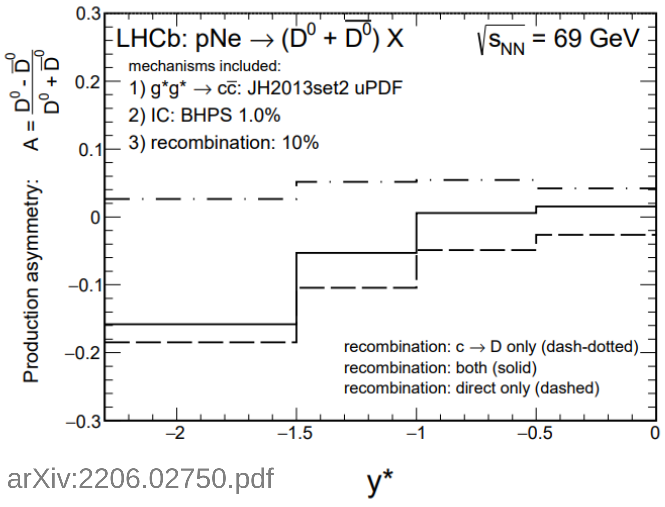


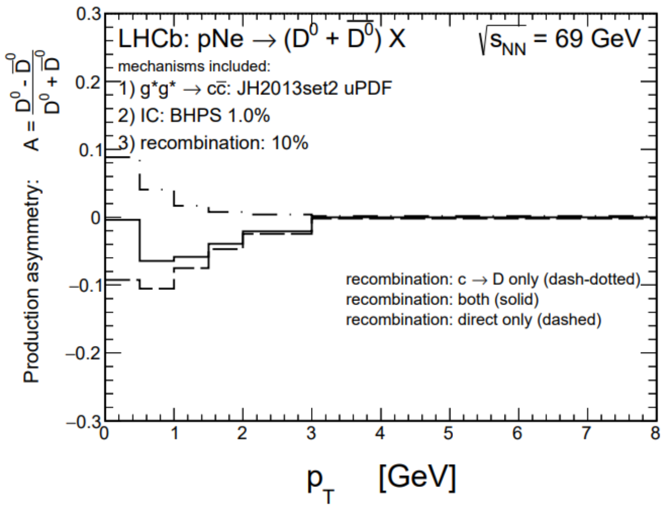


Open charm production asymmetry relevance









arXiv:2206.02750.pdf

D^0-$\overline{D}^0$ asymmetry predictions exhibit different patterns :

- Pythia : almost flat
- Higher negative asymmetry expected with 1% IC at backward rapidity and high pT
- Same tendency in rapidity expected from the recombination model but opposite p_T behavour

Open charm production asymmetry

→ Clearly relevant to improve the characterisation of the nucleus

→ **In the pipeline : D^0 asymmetry and full charm production cross-section & asymmetry measurements**

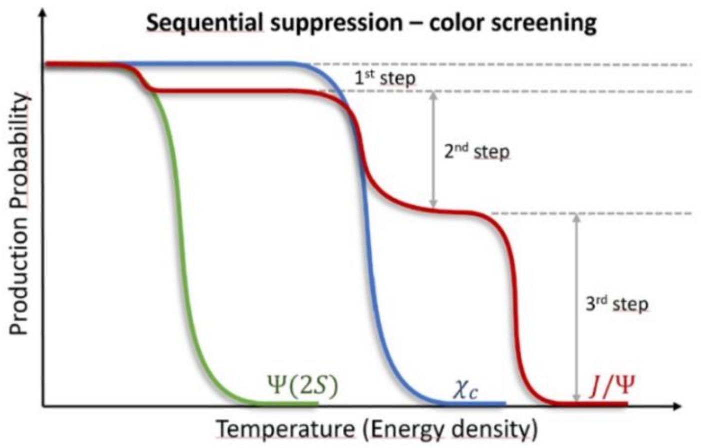
Hidden charm production measurements in *p*-nucleus collisions

Why studying the production of ccbar bound states ?

- Test the color screening mechanism in a QGP, via the sequential suppression

  At $\sqrt{s_{NN}} \sim 100$ GeV: no statistical recombination compared to higher $\sqrt{s_{NN}}$

  → See Frédéric's talk



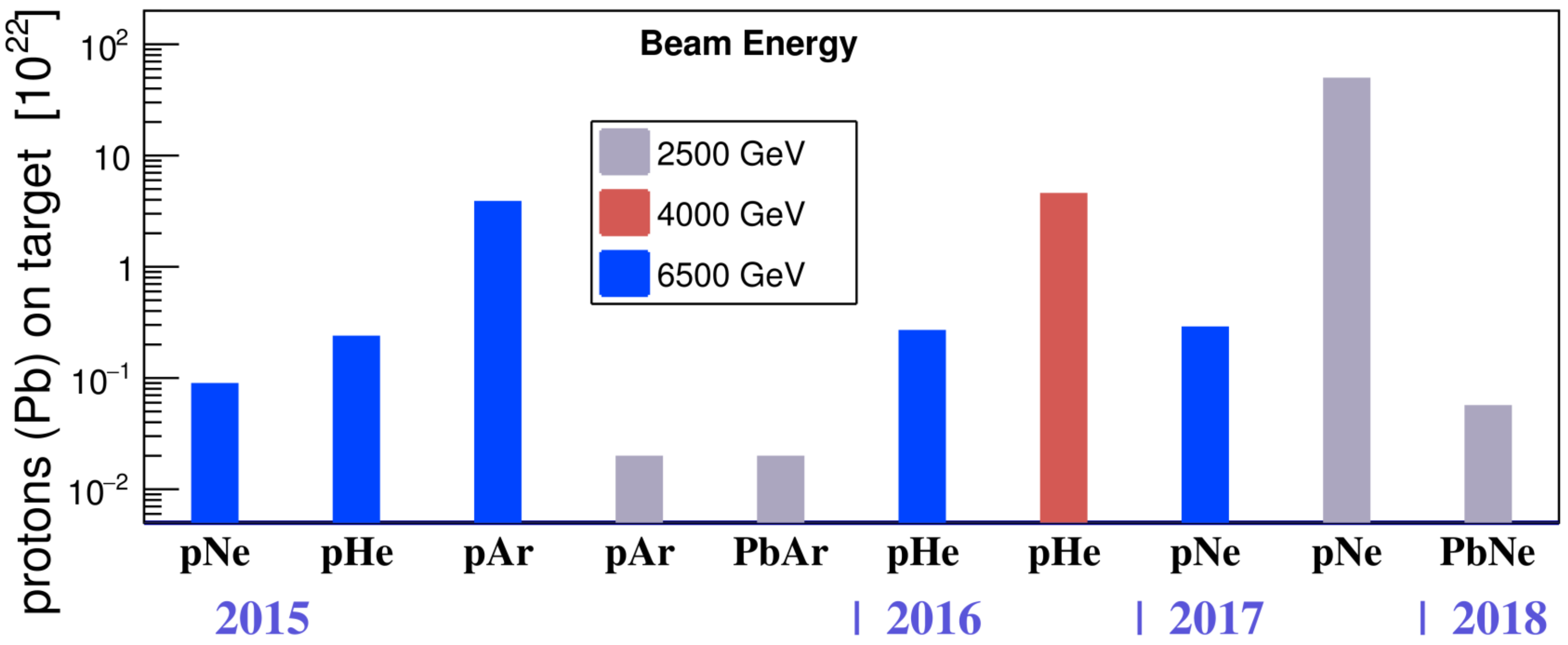
- Mandatory baseline : constraint the cold nuclear effects affecting charmonia production
  - Nuclear absorption
  - nPDF (anti-shadowing region)
  - Comovers, …

- Charmonium production mechanism is interested for itself
  - CEM / CSM / COM (NRQCD)
  - Also constraint the intrinsic charm component of the nucleon

Aim: measure J/ψ, ψ(2S) and χ_c in various proton-nucleus collisions, from *p*-H to *p*-Xe collisions

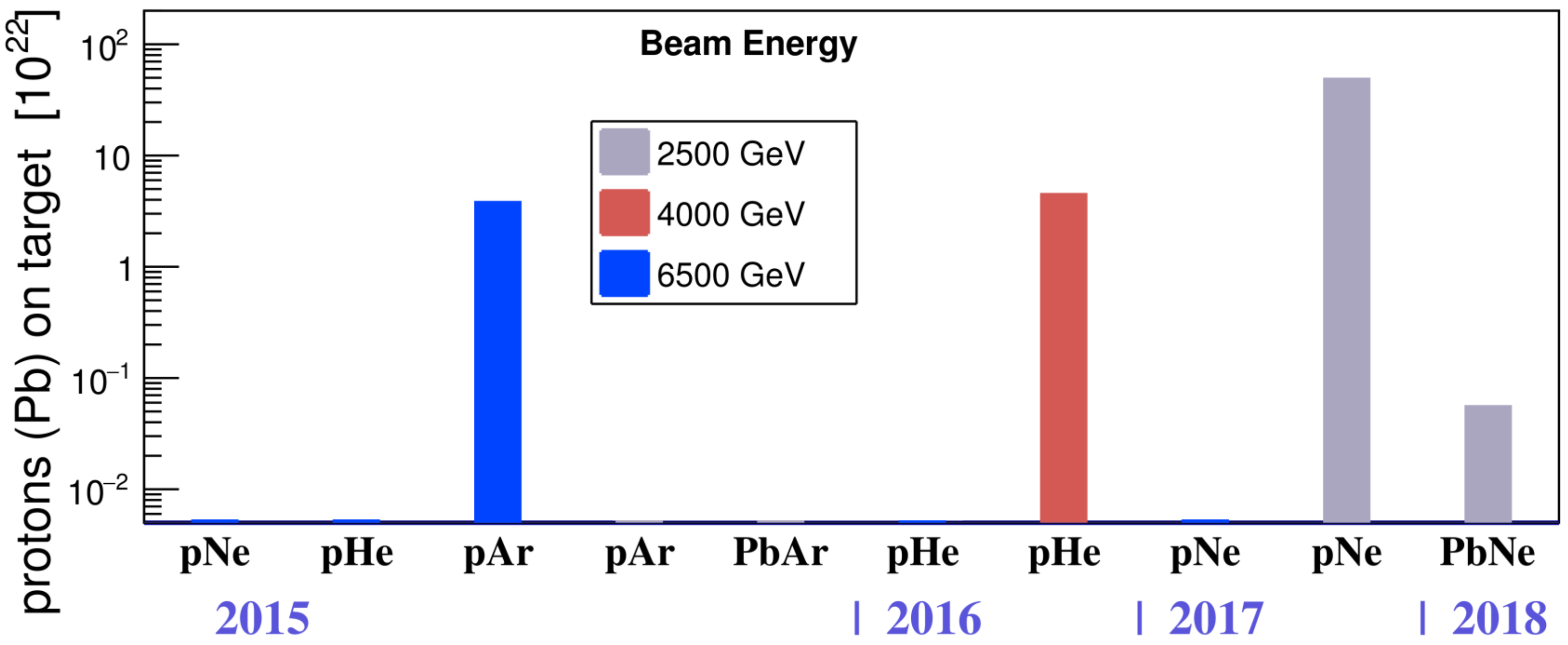
SMOG data samples

2015 – 2018 : LHC run 2 : pioneering SMOG samples



SMOG data samples

2015 – 2018 : LHC run 2 : pioneering SMOG samples



Only 3 *p*-nucleus samples and PbNe sample are relevant for charm production studies

Charm measurements in *p*Ar and *p*He samples

Phys. Rev. Lett. 122 (2019) 132002

System	$\sqrt{s_{NN}}$	Protons on target	Target A	$\mathcal{L}_{int}$
pAr	110.4 GeV	4.10^{22}	40	not available
pHe	86.6 GeV	5.10^{22}	4	7.58 ± 0.47 nb^{-1}

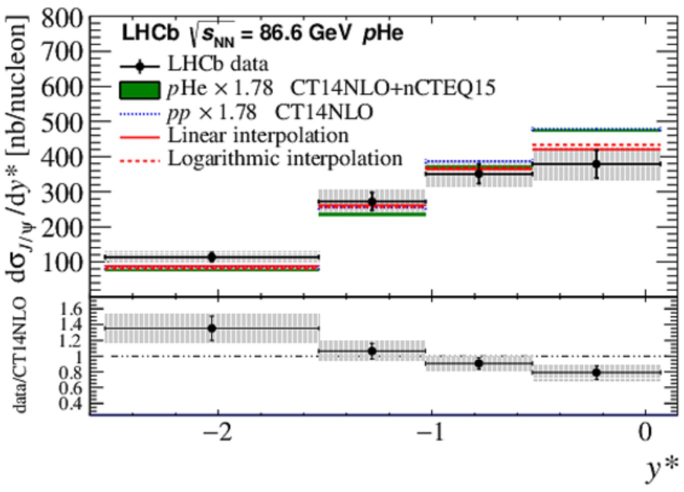
Luminosity from the yield of electrons elastically scattering on the target atoms

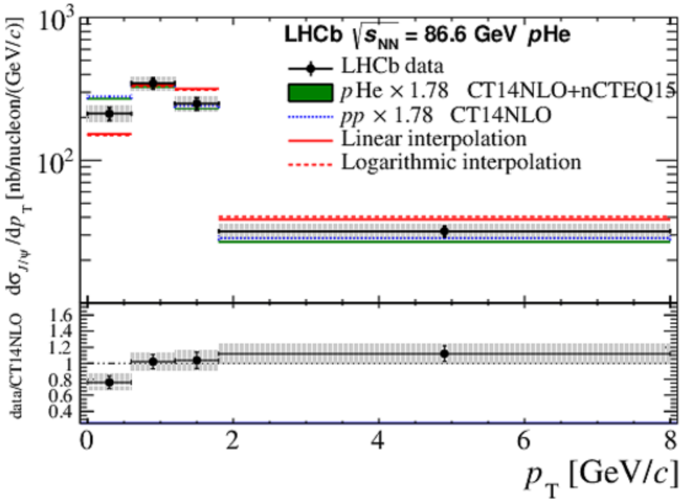
~500 J/ψ, ~2000 D^0 candidates in each sample → statistically limited

In *p*Ar sample : only differential yields
In *p*He sample : total and differential cross-sections

In full phase space :

$$\sigma_{J/\psi} = 1225.6 \pm 100.7\,\text{nb/nucleon},$$
$$\sigma_{D^0} = 156.0 \pm 13.1\,\mu\text{b/nucleon},$$





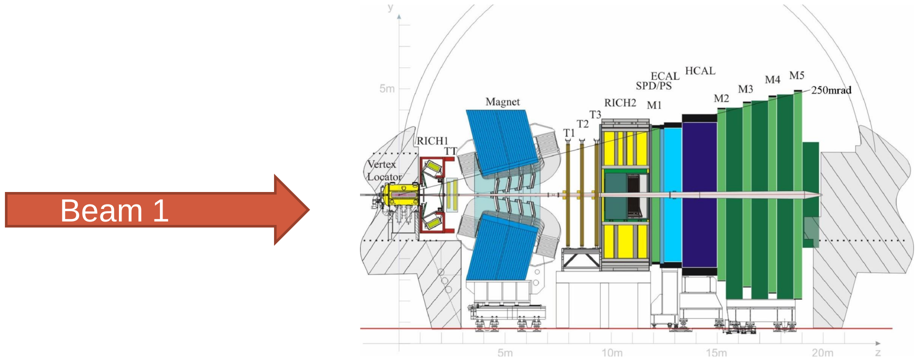
First measurement of charm production in SMOG configuration

*p*Ne sample : largest SMOG sample

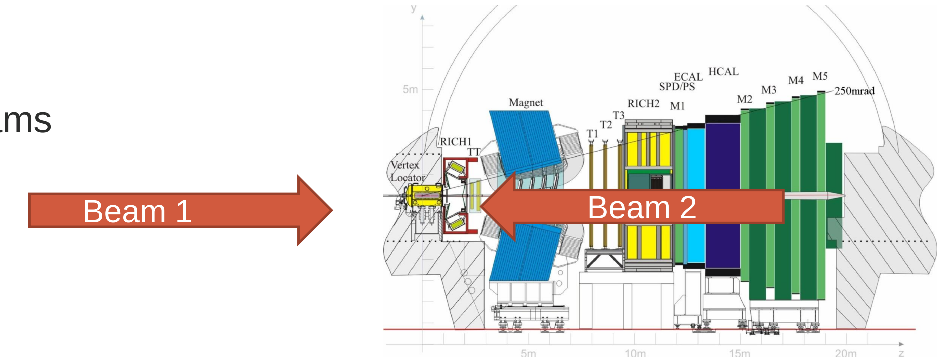
2.5 TeV high intensity proton beam, leading to $\sqrt{s_{NN}}$ = 68.5 GeV *p*Ne collisions collected during 11 days in November 2017

First SMOG data taking in parallel of standard *pp* collisions at 5 TeV

- SMOG collisions exploit beam 1 only and empty beam 2 bunches



- Standard *pp* collisions exploit both beams



Ideally, knowing the bunches in beam 1 & 2 would be sufficient to identify SMOG collisions

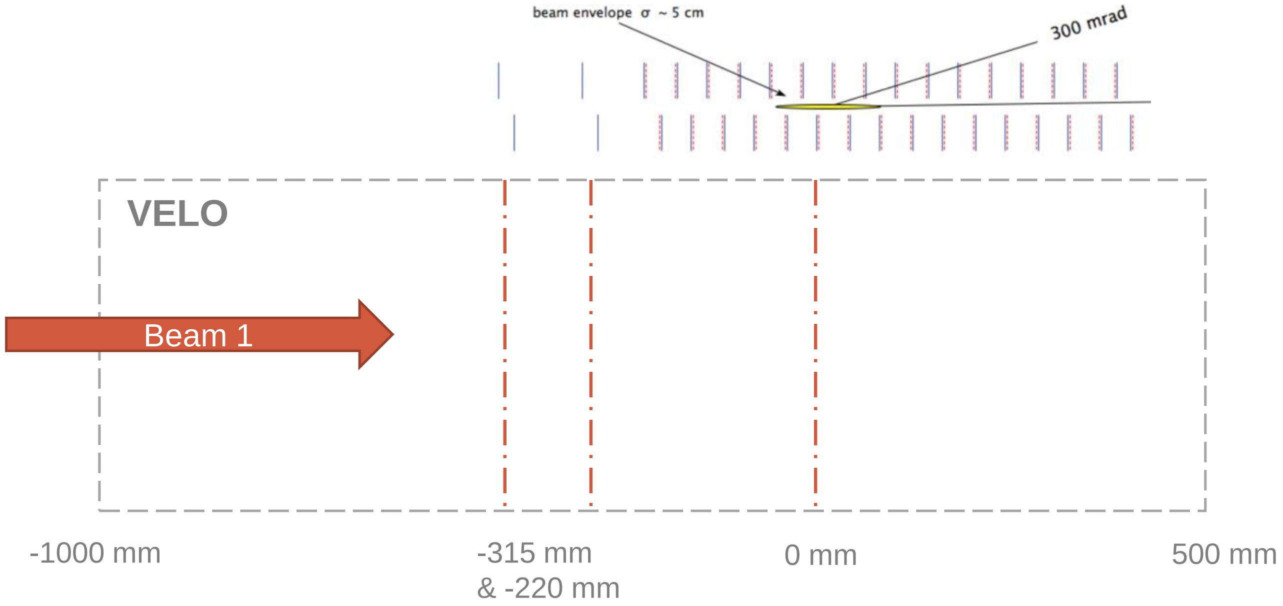
But some debunched protons from the previous bunch go to the following bunch (supposed to be empty) ➔ ghost *pp* collisions

These ghosts are a major background, specially when using high intensity proton beam

*p*Ne data quality

Choosing carefully the interaction range (primary vertex position) insures high data quality level

- ✓ LHCb detection high performance
- ✓ Remove the *pp* ghost collisions by exploiting the event topology and the pile up stations, upstream of the VErtex LOcator (VELO)



LHCb nominal interaction point region

- Inside the VELO
- *pp* interaction at PVz = 0 mm
- Pile up stations at -315 & -220 mm
- SMOG configuration : beam 1 only

*p*Ne data quality

Choosing carefully the interaction range (primary vertex position) insures high data quality level

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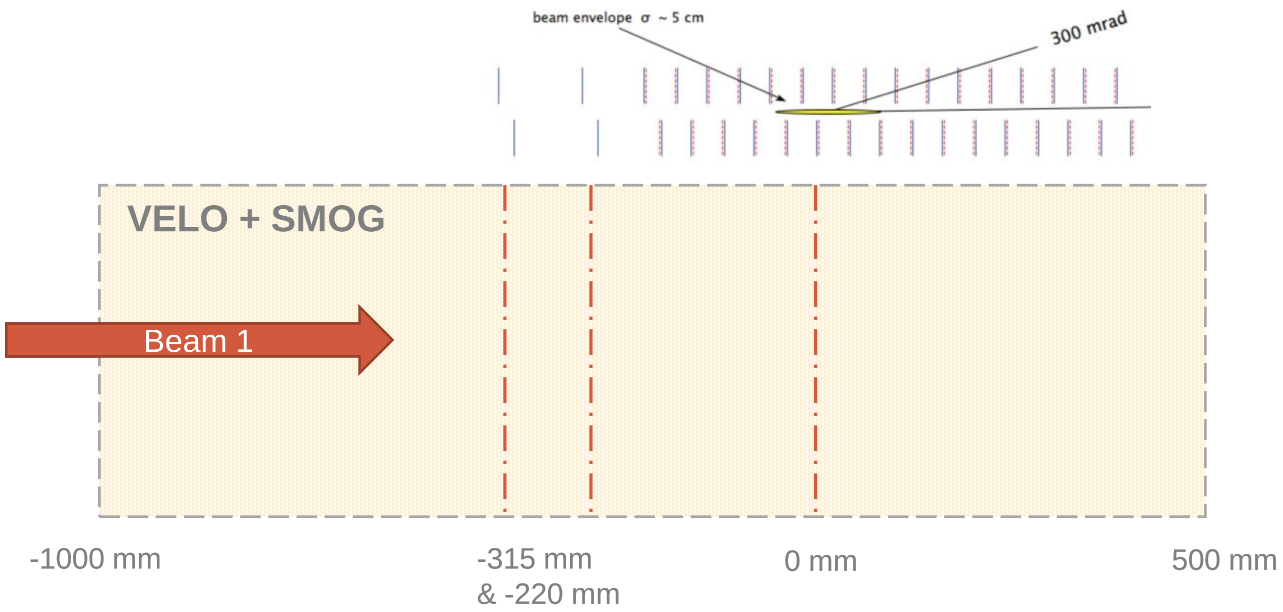


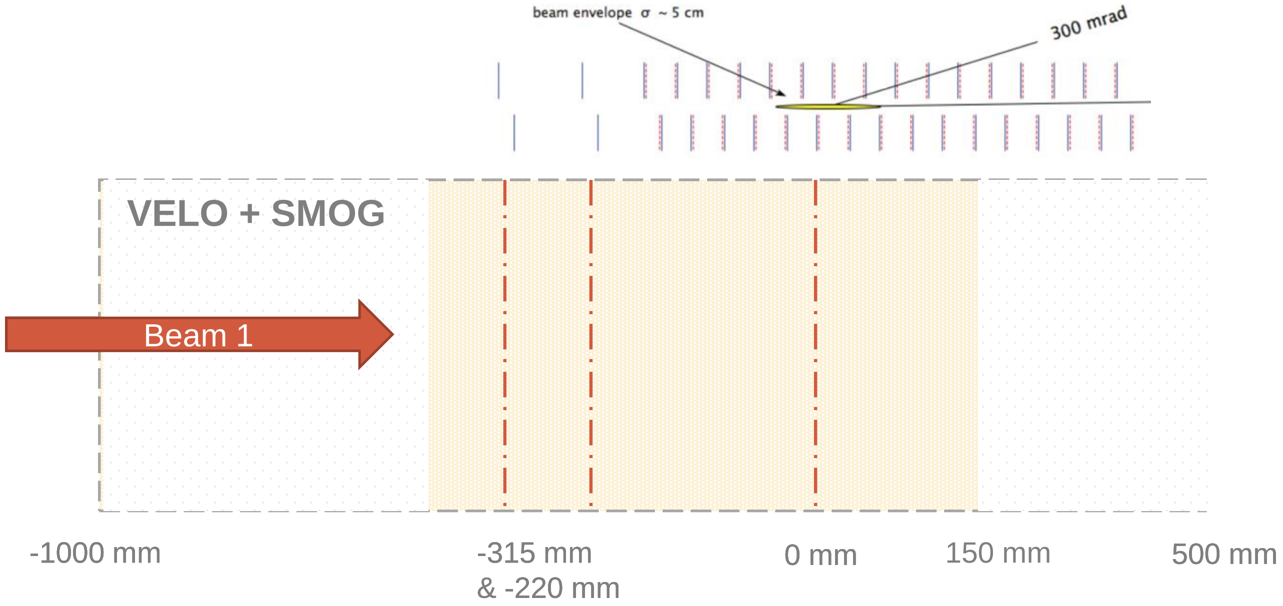
SMOG injection

- Spread out within ± 20m
- Interactions between beam 1 and the gas occur everywhere in this range

*p*Ne data quality

Choosing carefully the interaction range (primary vertex position) insures high data quality level

- ✓ LHCb detection high performance
- ✓ Remove the *pp* ghost collisions by exploiting the event topology and the pile up stations, upstream of the VErtex LOcator (VELO)



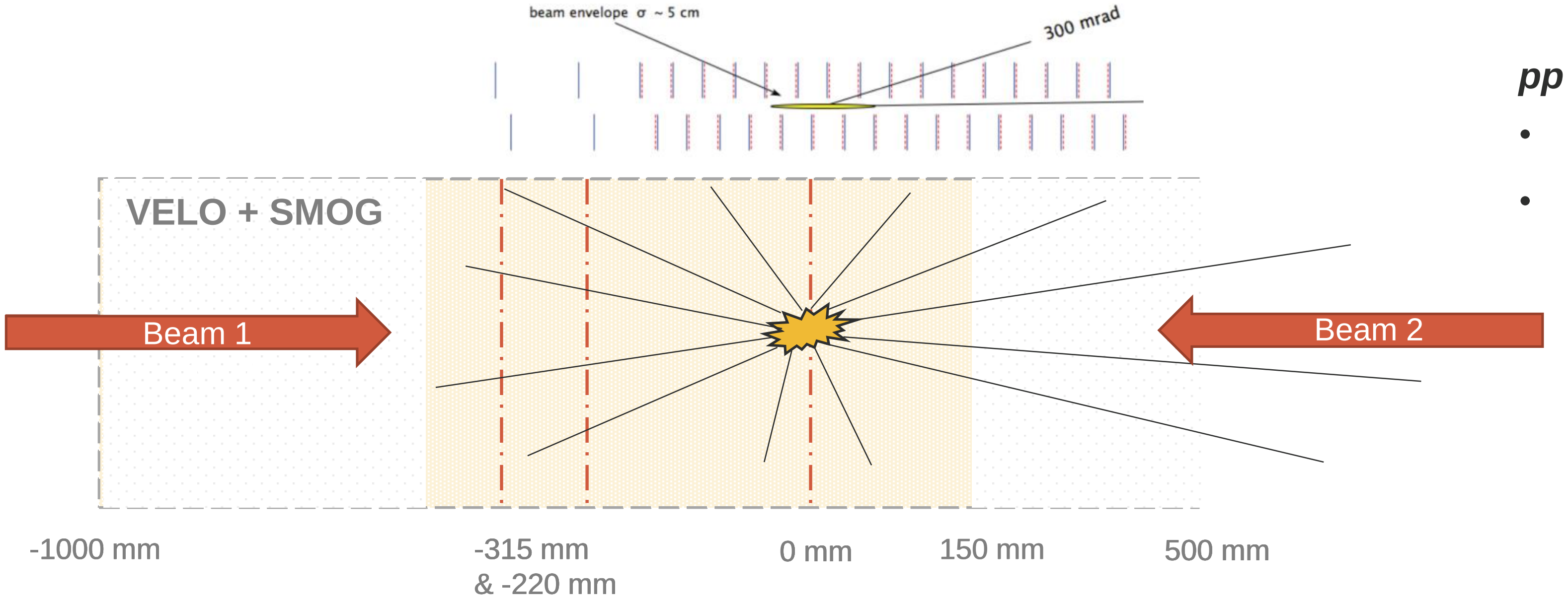
LHCb performance drops for

- Interactions at z > 150 mm
- Interactions at z < -500 mm

*p*Ne data quality

Choosing carefully the interaction range (primary vertex position) insures high data quality level

- ✓ LHCb detection high performance
- ✓ Remove the *pp* ghost collisions by exploiting the event topology and the pile up stations, upstream of the VErtex LOcator (VELO)



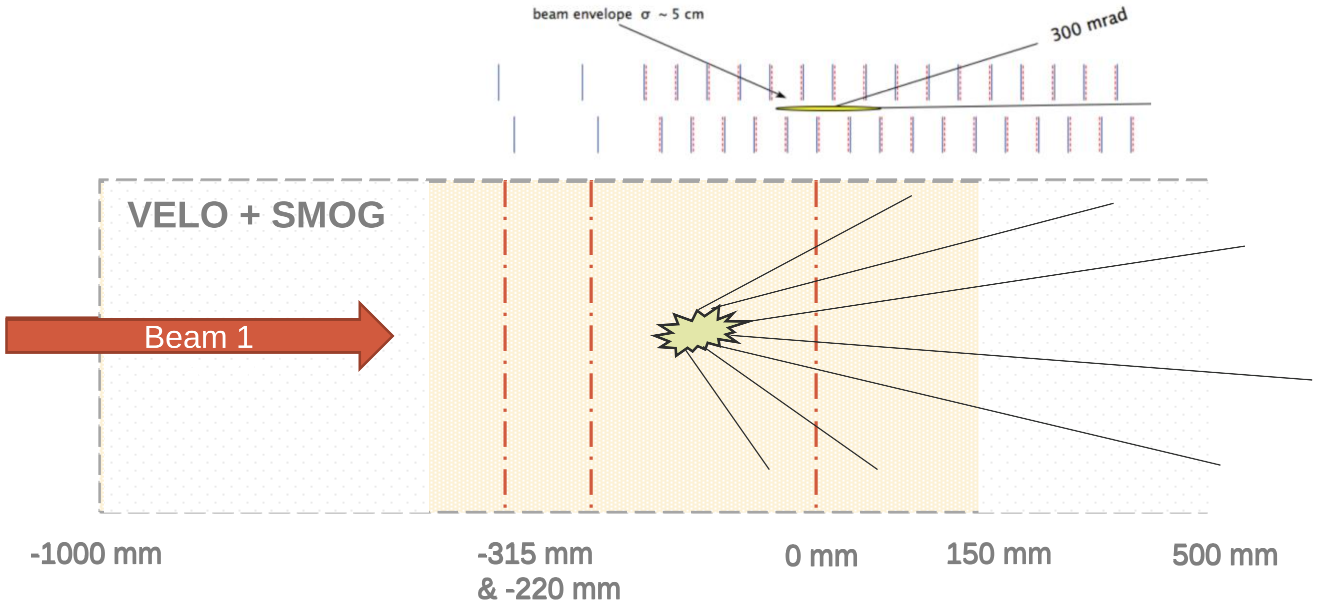
***pp* (ghost) collisions**

- Particles emission in 4π
- Hits in Pile up stations

*p*Ne data quality

Choosing carefully the interaction range (primary vertex position) insures high data quality level

- ✓ LHCb detection high performance
- ✓ Remove the *pp* ghost collisions by exploiting the event topology and the pile up stations, upstream of the VErtex LOcator (VELO)



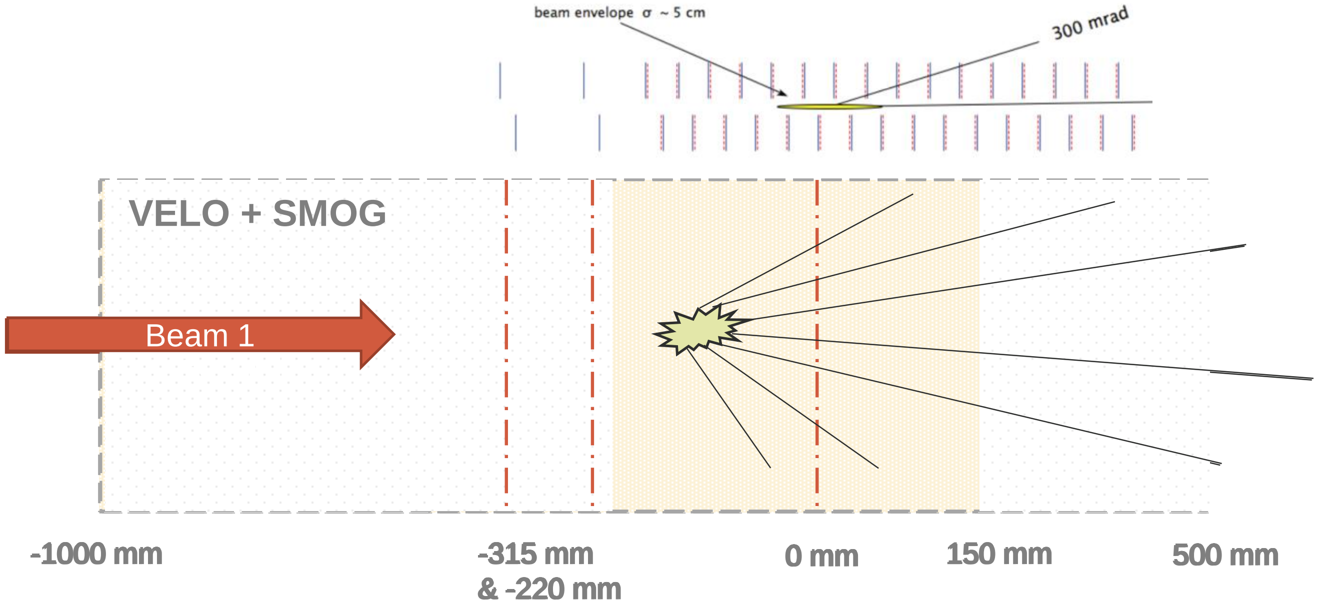
SMOG collisions

- Hits only forward
- No hits in Pile up stations for interactions at z > -200 mm
- Dedicated study optimized number of hits in Pile up stations

*p*Ne data quality

Choosing carefully the interaction range (primary vertex position) insures high data quality level

- ✓ LHCb detection high performance
- ✓ Remove the *pp* ghost collisions by exploiting the event topology and the pile up stations, upstream of the VErtex LOcator (VELO)



SMOG interaction range

- Reduced to [-200, 150] mm
- Only contamination from *pp* ghost events with very low number of emitted particles

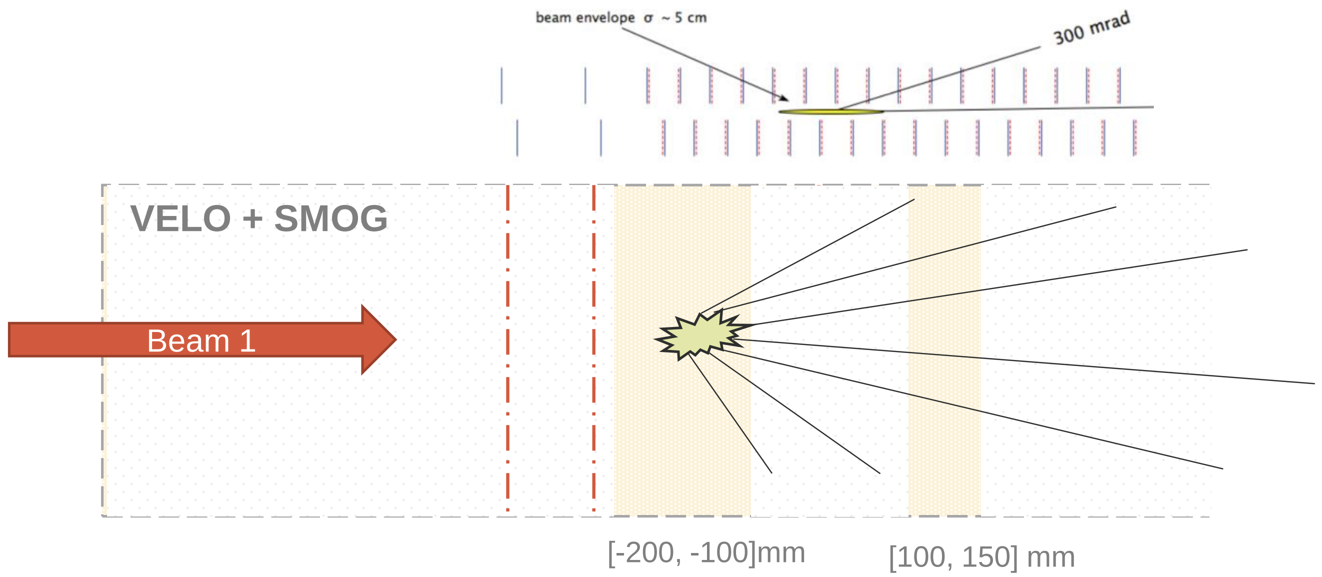
With high intensity beam, the remaining ghost contamination is too high and affects the cross-section measurement

➔ By removing the central range [-100, 100] mm, the contamination is reduced to a 2% systematic uncertainty on charm cross section

*p*Ne data quality

Choosing carefully the interaction range (primary vertex position) insures high data quality level

- ✓ LHCb detection high performance
- ✓ Remove the *pp* ghost collisions by exploiting the event topology and the pile up stations, upstream of the VErtex LOcator (VELO)



SMOG final interaction range : [-200, -100] mm and [100, 150] mm

J/ψ candidates in *p*Ne collisions

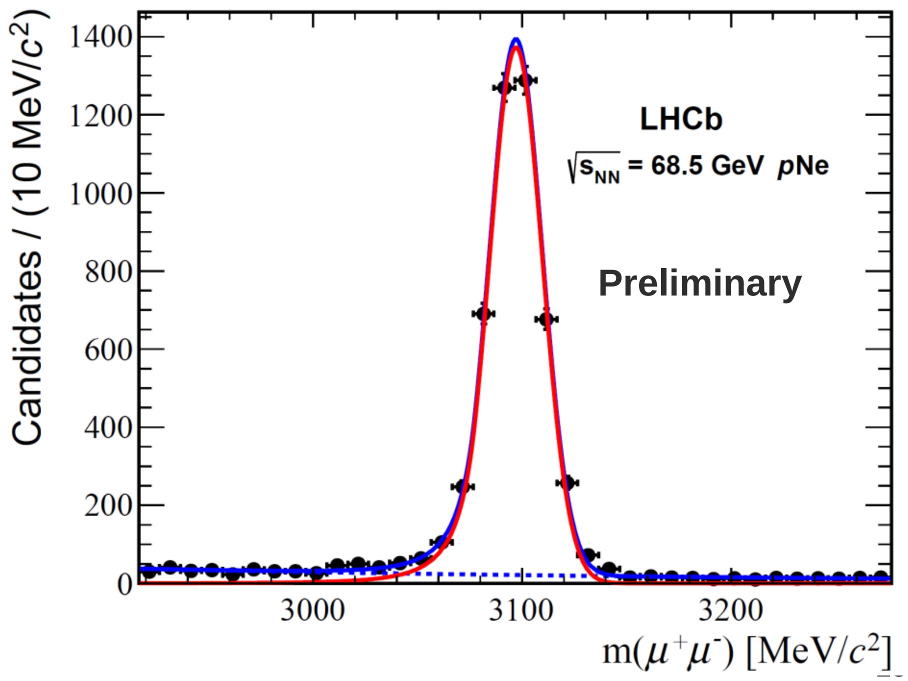
LHCb-PAPER-2022-014
in preparation

J/ψ reconstructed via its dimuon decay

Trigger requirements : 2 well-reconstructed muons, forming an invariant mass > 2700 MeV/c²

Offline selection :

- Primary vertex, with at least 4 tracks in the VELO, within [-200, -100] or [100, 150] mm
- Good-quality vertex formed from 2 oppositely signed muons
- Muons : well-identified, p_T > 500 MeV/c, consistent with the primary vertex



4 542 J/ψ → μ^+ + μ^- candidates

- Enough candidates to study J/ψ in y* x p_T bins (2 dimensions binning scheme)

J/ψ differential cross section in *p*Ne collisions

LHCb-PAPER-2022-014
in preparation

Cross section defined as:

$$\sigma = \frac{N_{\mathrm{Signal}}^{\mathrm{After\ correction}}}{\mathcal{L} \times A_{\mathrm{nucleus}} \times BR}$$

Number of efficiency corrected events after selections

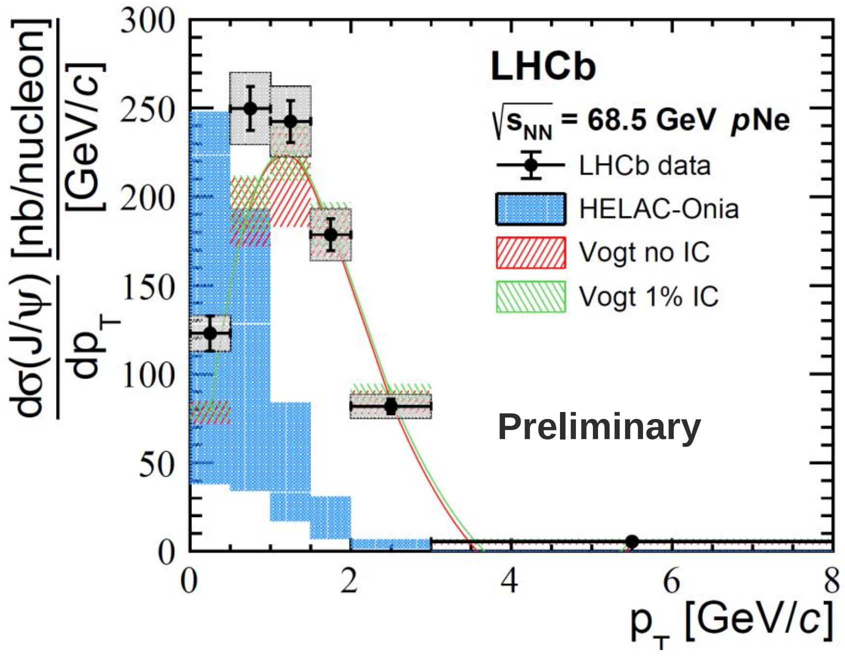
luminosity

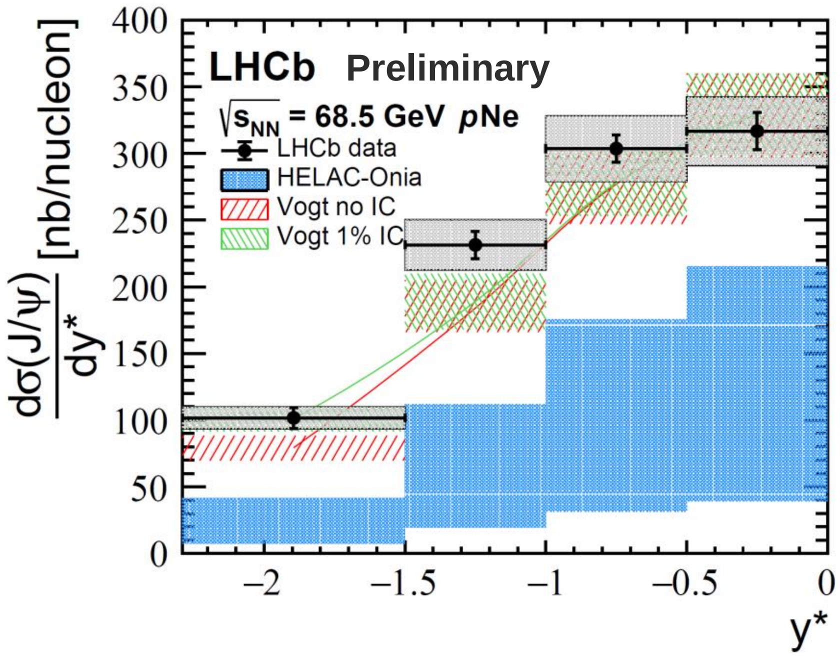
Atomic number Ne

Branching ratio

Cross-section computed within the different bins

Final results are integrated over y* or p_T





- ✓ HELAC-ONIA using CT14NLO and nCTEQ15 under shoot the data
- ✓ Good agreement with predictions with (1%) Intrinsic Charm (IC) and without it [PRC103 (2021) 035204]

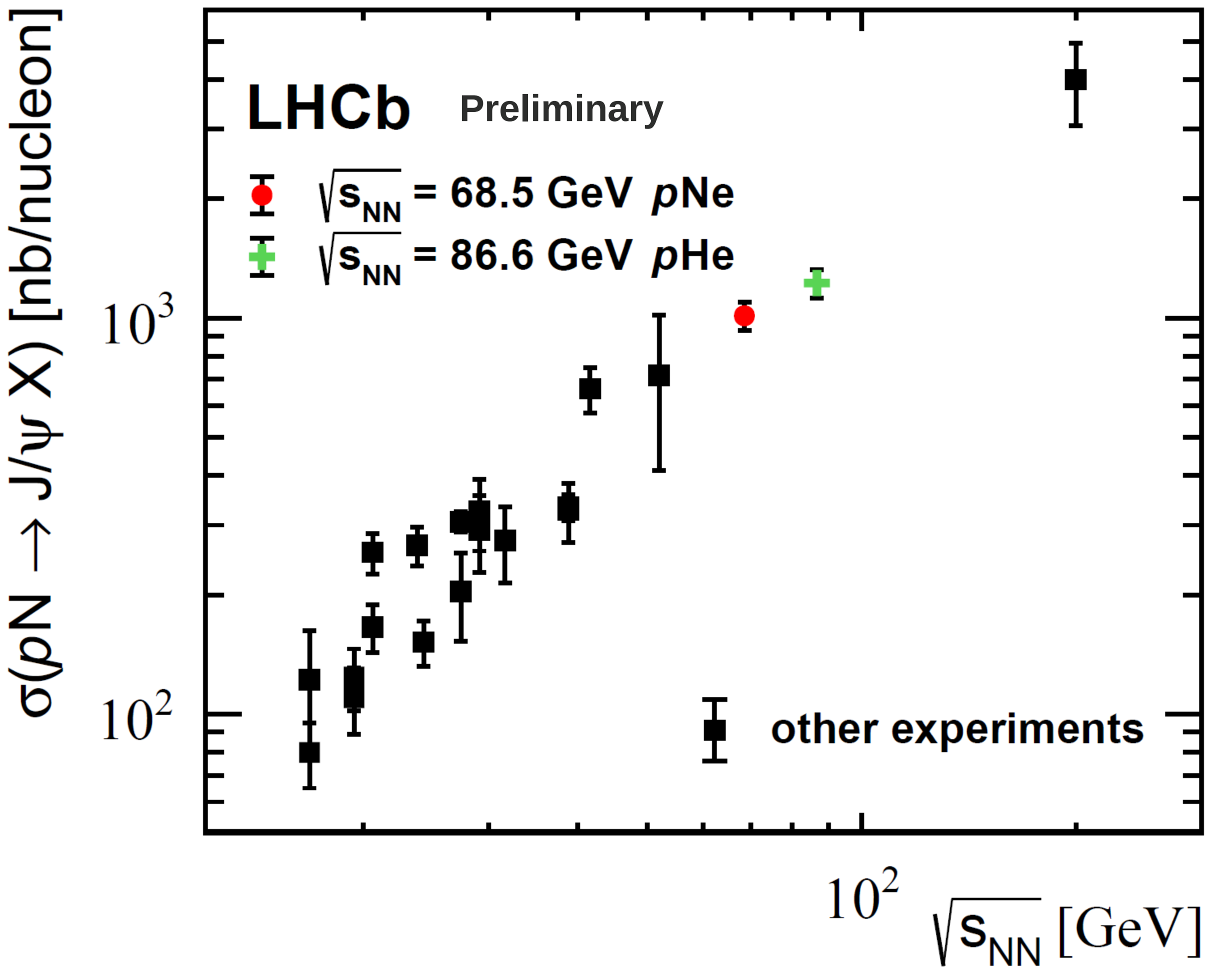
J/ψ total cross section in *p*Ne collisions

LHCb-PAPER-2022-014
in preparation

$$\sigma^{J/\psi}_{y*\in[-2.29,0]} = 506.2 \pm 7.9\ (\mathrm{stat})\ \pm 24.8\ (\mathrm{syst})\mathrm{nb/A}$$

Extrapolation to full phase space using Pythia8+CT09MCS PDF, assuming forward-backward symmetry

Exhibits a power-law dependency with the center-of-mass energy



Ψ(2S) candidates in *p*Ne collisions

LHCb-PAPER-2022-014
in preparation

Ψ(2S) reconstructed via its dimuon decay

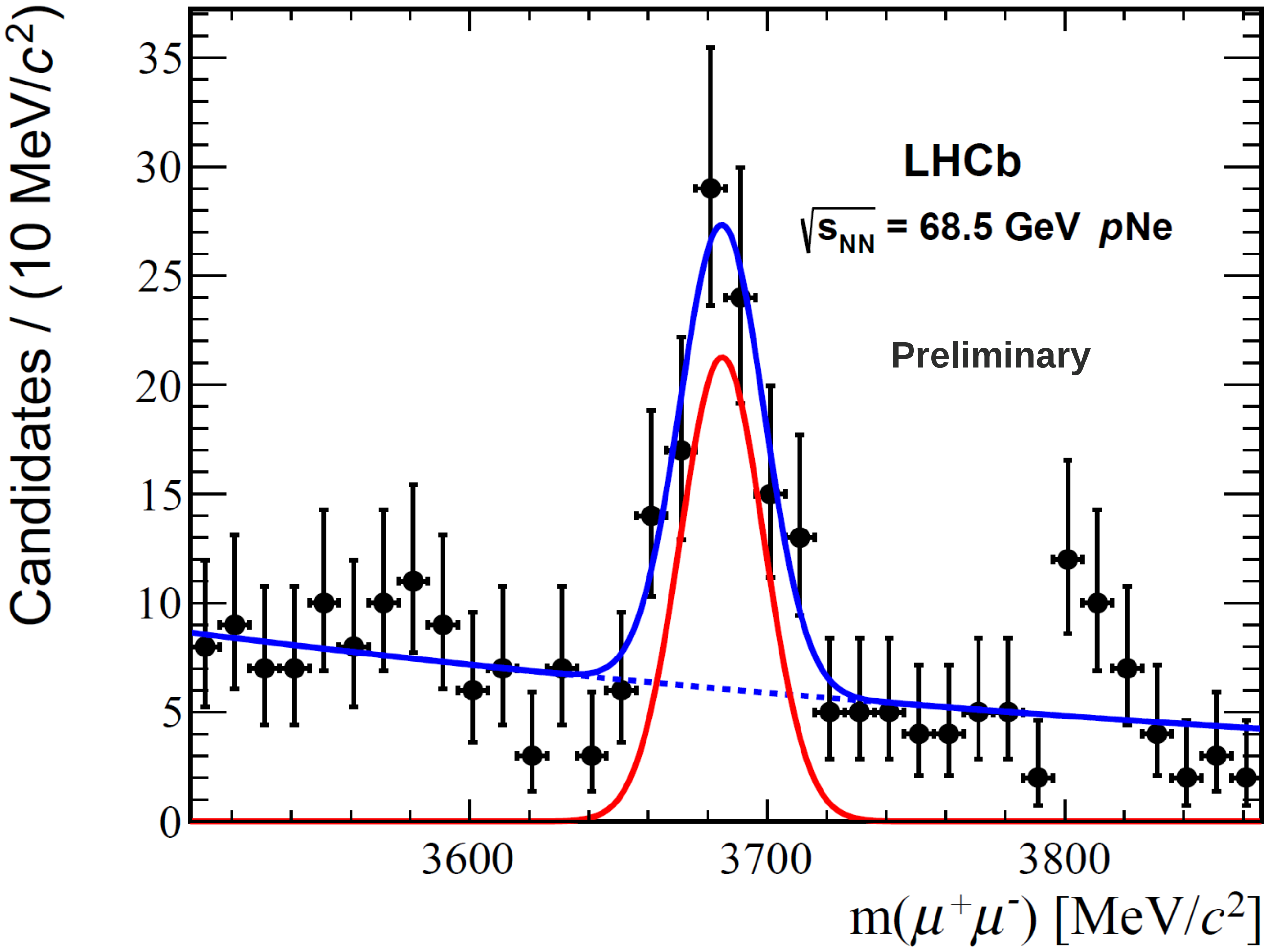
Selection and trigger identical to J/ψ

76 ψ(2S) → $\mu^+ + \mu^-$ candidates

Not enough candidates to do differential measurements

But can benefit from similarities (efficiencies) with J/ψ → $\mu^+ + \mu^-$

➔ ψ(2S) / J/ψ measurement



ψ(2S)/J/ψ in *p*Ne collisions

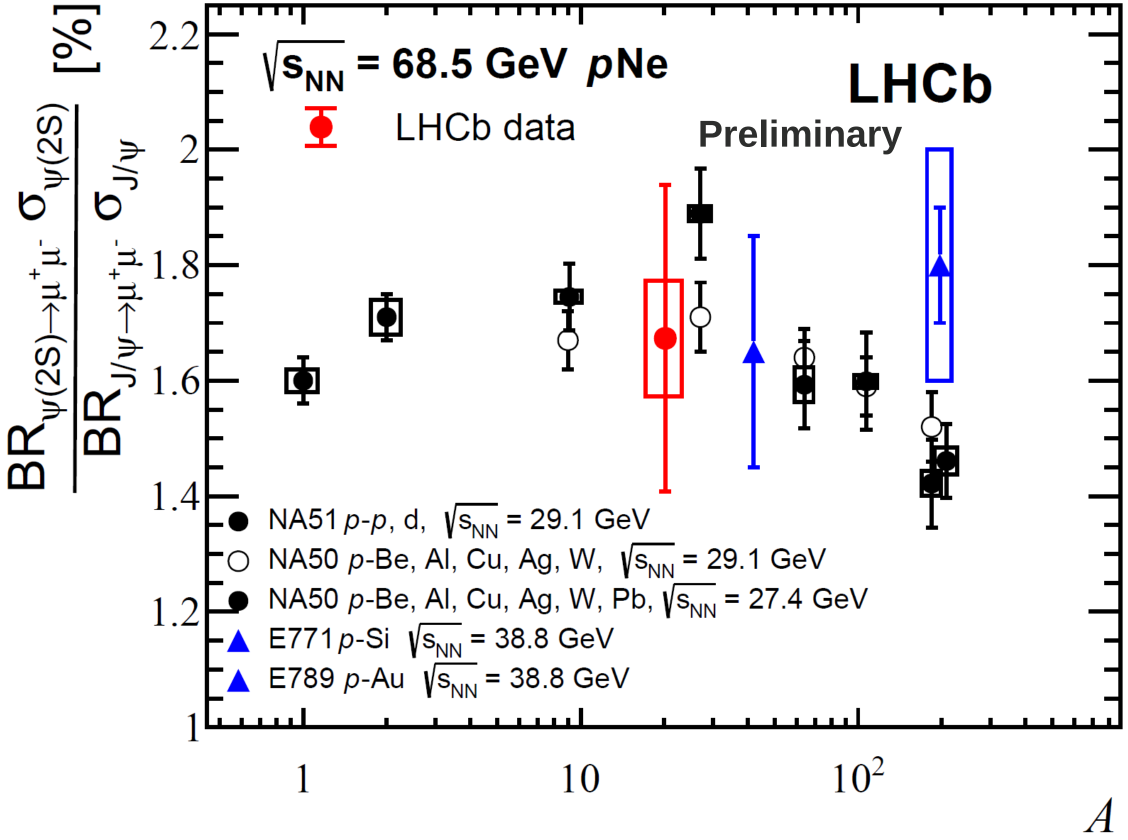
LHCb-PAPER-2022-014
in preparation

$$\frac{Br_{\psi(2S)\to\mu^+\mu^-}\sigma_{\psi(2S)}}{Br_{J/\psi\to\mu^+\mu^-}\sigma_{J/\psi}} = 1.67 \pm 0.27\ (\text{stat.}) \pm 0.10\ (\text{syst.})\ \%$$

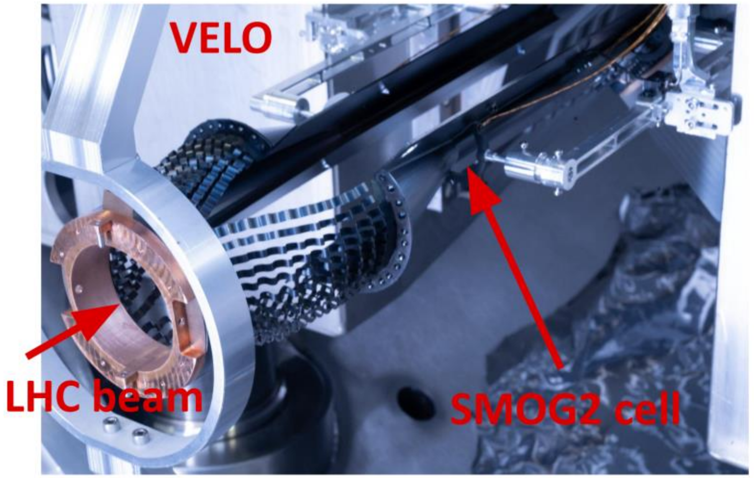
Compatible with other measurements in *p*-A collisions

Statistically limited in SMOG samples

Teaser for SMOG2 !

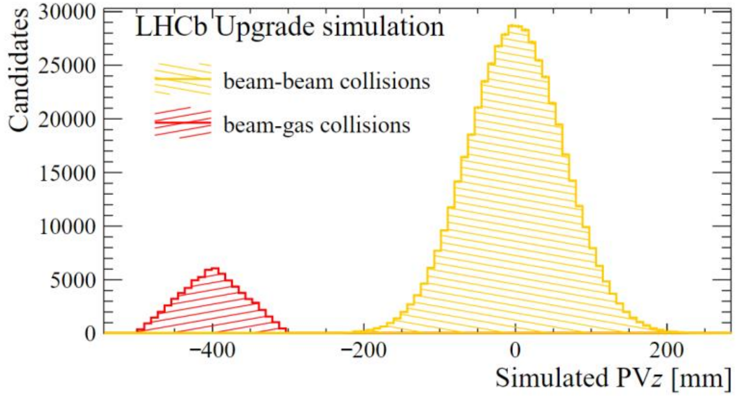


The LHCb fixed target upgrade : SMOG2



From 2022, 20-cm-long gas storage cell (SMOG2) upstream of the LHCb nominal IP

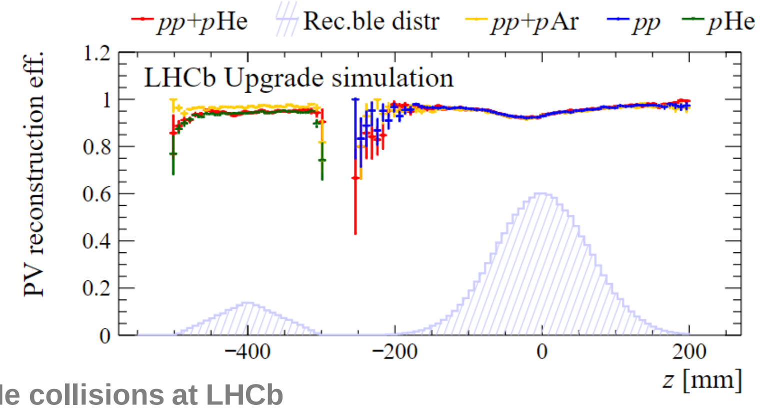
- Gas pressure up to x100 with the same flow as Run2
- Opportunity to operate simultaneously in collider and fixed-target modes



Separation of the interaction region wrt beam-beam

- Dedicated reconstruction and trigger studies
- First injections on May 25th (no beam), June 13th and 20th (with beam)

No showstopper found



With SMOG2, unique opportunity to extend LHCb heavy-ion program

Charm production with SMOG2

LHCb-PUB-2018-015.pdf

	SMOG published result pHe@87 GeV	SMOG2 example pAr@115 GeV
Integrated luminosity	7.6 nb^{-1}	$\sim$ 45 pb^{-1}
syst. error on J/ψ x-sec.	7%	2 - 3 %
J/ψ yield	400	15M
D^0 yield	2000	150M
Λ_c^+ yield	20	1.5M
$\psi(2S)$ yield	negl.	150k
$\Upsilon(1S)$ yield	negl.	7k
Low-mass Drell-Yan yield	negl.	9k

Open and hidden charm measurements will greatly benefit from SMOG2 :

- **Statistics** : from simultaneous runs & increase of local gas pressure
    - Expect at least 100k J/ψ, 2k ψ(2S), 6k χ_c per *p*-A samples
- **Colliding systems** : possibility to inject heavy noble (Kr, Xe) and non-noble (H_2, D_2, O_2) gases
    - Access to a large energy density range, from *p*H to *p*Xe
- **Performances**
    - Similar charm efficiencies (acceptance, tracking, selection, particle identification, trigger)

LHCB-TDR-020.pdf

Global efficiencies					
	ε_{SMOG2}	ε_{SMOG_A}	ε_{SMOG_B}	$\Delta\varepsilon_1$	$\Delta\varepsilon_2$
$J/\psi \to \mu^+\mu^-$	58%	63%	60%	−5%	−2%
$D^0 \to K^-\pi^+$	35%	46%	41%	−11%	−6%

- Enough data to develop fixed-target dedicated data-driven methods
  First data-driven method for particle identification performance **[LHCb-DP-2021-007]**

Conclusions

LHCb has an unique fixed-target configuration, covering high Bjorken-x range

From SMOG : demonstration of charm production measurements feasibility

- First charm production measurement in *p*Ar and *p*He collisions [Phys. Rev. Lett. 122 (2019) 132002]
- Hidden charm production measurement in *p*Ne collisions [LHCb-PAPER-2022-2014]
- Various open charm measurements (D^0, Λ_c, …) in *p*Ne collisions to come

➔ First constraints on J/ψ and D^0 production models at $\sqrt{s_{NN}} \sim 100$ GeV

To SMOG2 : Toward QGP characterization and stringent QCD constraints !

- New detector from 2022, improvement of the tracking performances
- Ambitious fixed-target program : higher local pressure, not only noble gases

Unique results with the LHCb fixed-target program

Many new exciting opportunities ahead !