Recent measurements and prospects from analysis of fixed-target collisions at LHCb

L. L. Pappalardo
(on behalf of the LHCb Collaboration)

HADRON 2023

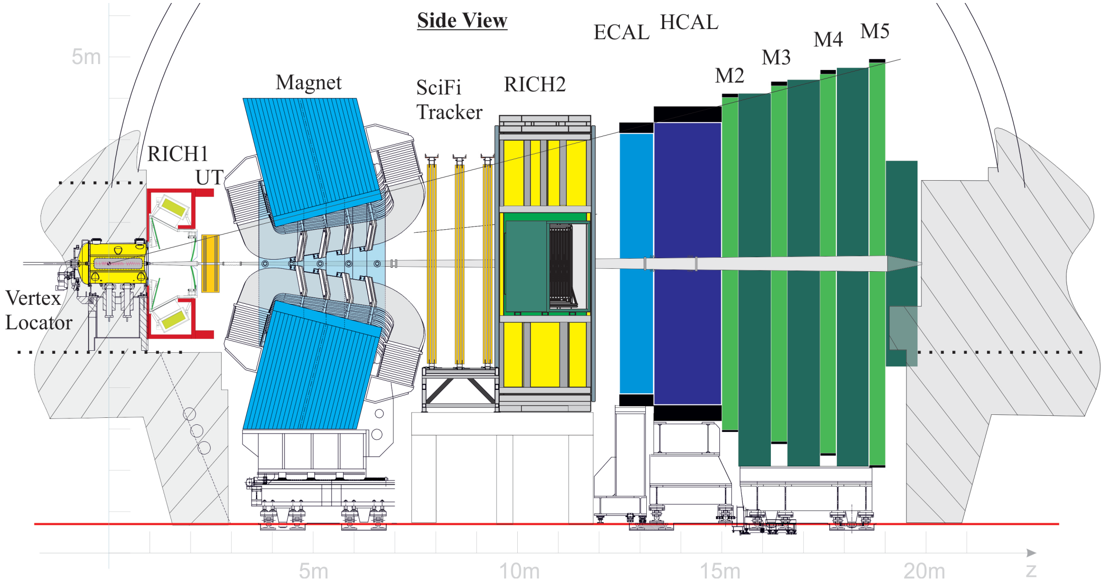
The LHCb detector

- LHCb is a **general-purpose single-arm spectrometer**, fully instrumented in $2 < \eta < 5$ and optimised for detection of charmed and beauty hadrons

  [JINST 3 (2008) S08005] [IJMPA 30 (2015)1530022]

- **Excellent particle identification and momentum resolution:** $\sigma_p/p \leq 1.0$ % ($p \in$ [2,200] GeV)

- **Precise primary and secondary vertex reconstruction**



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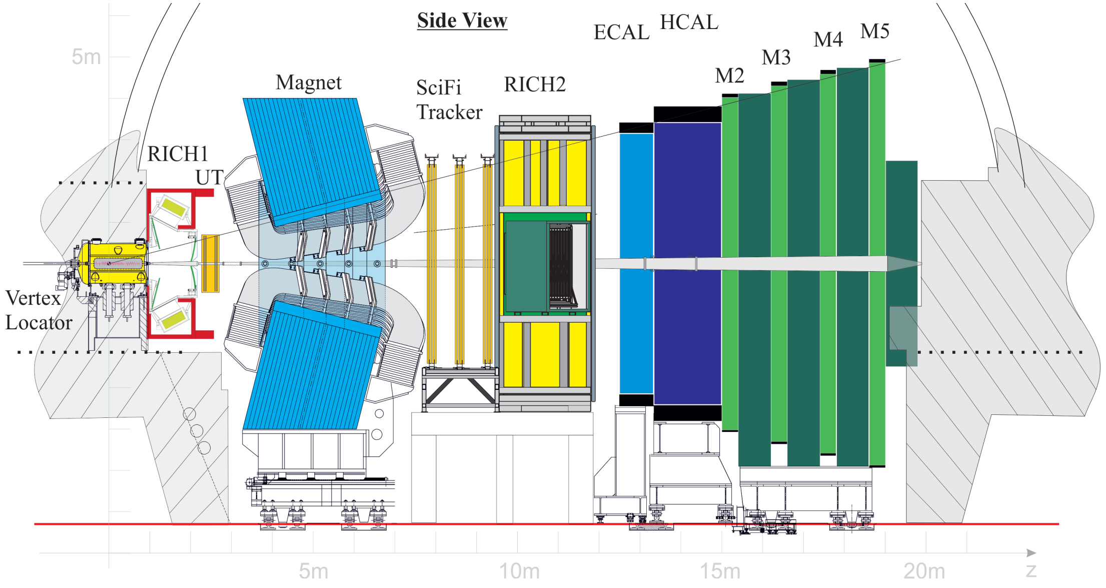
[http://arxiv.org/abs/2305.10515]



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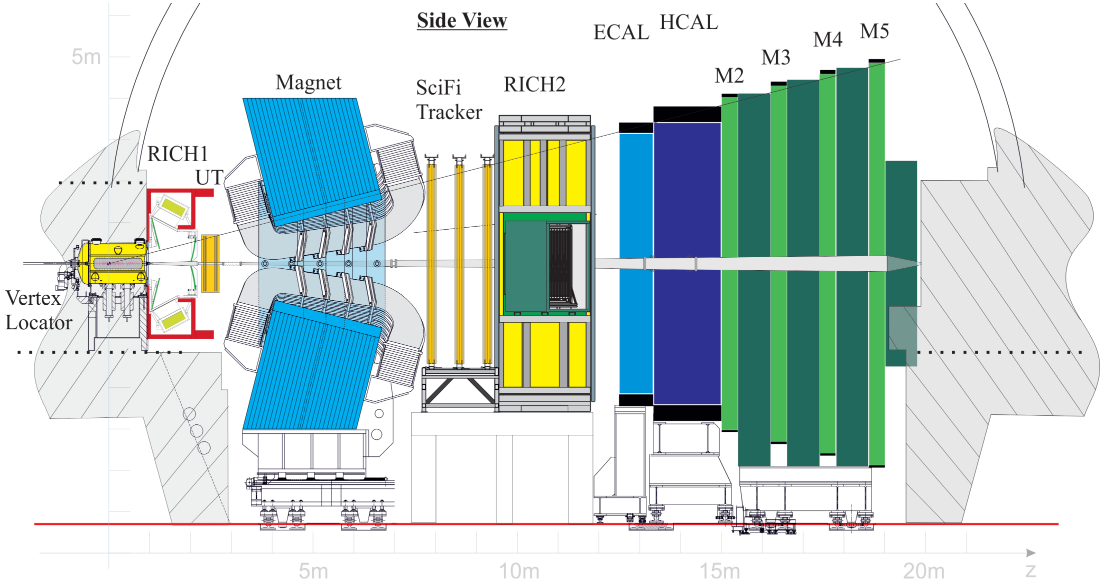
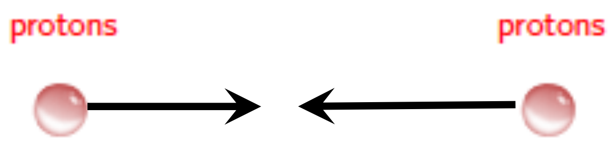
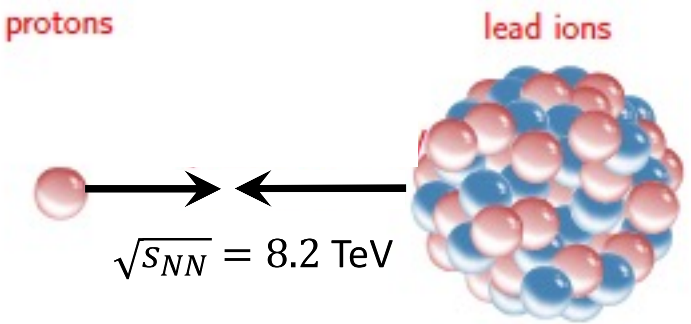


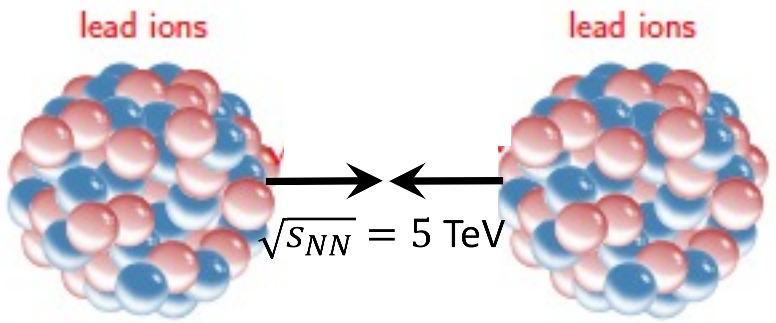
Types of collisions (Collider mode):



$\sqrt{s} = 13.6$ TeV



$\sqrt{s_{NN}} = 8.2$ TeV



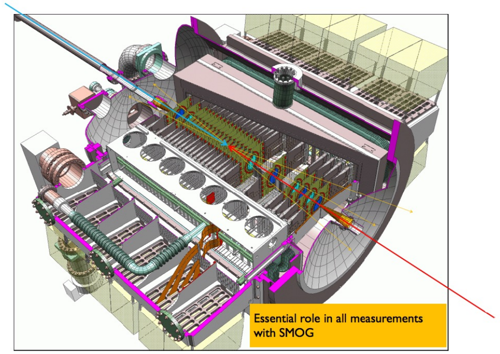
$\sqrt{s_{NN}} = 5$ TeV

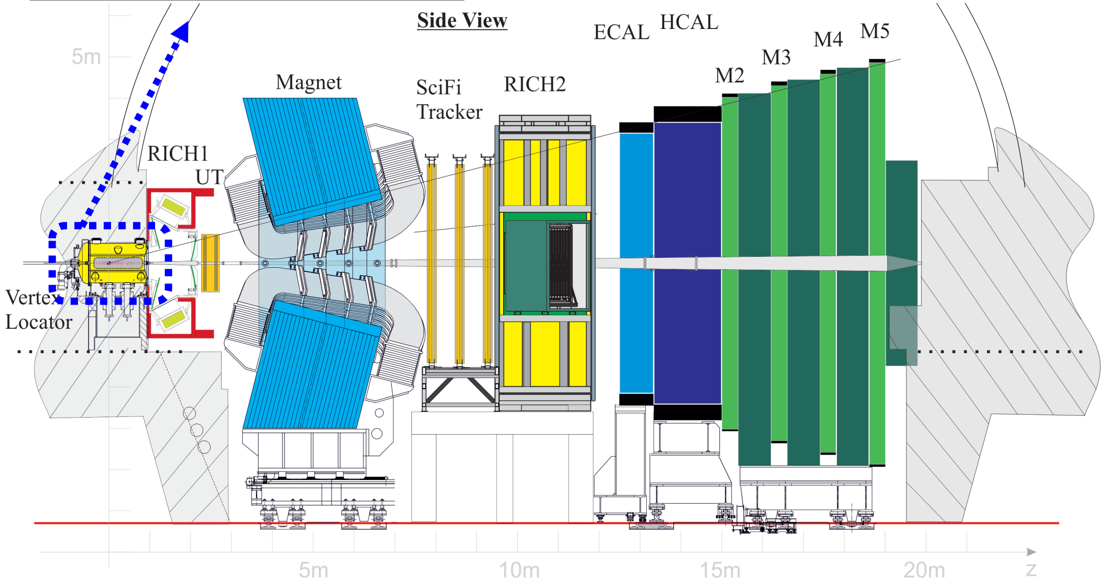
The LHCb Fixed-Target configuration

Since 2015 LHCb can also be operated as a **fixed-target experiment** with the **SMOG system**

SMOG: System for Measuring Overlap with Gas:

- Low density noble gas injected in the VELO vessel
- Gas pressure ($\sim 10^{-7}$mbar) 2 orders of magnitude higher than LHC vacuum
- Beam-gas collision rate increased by 2 orders of magnitude





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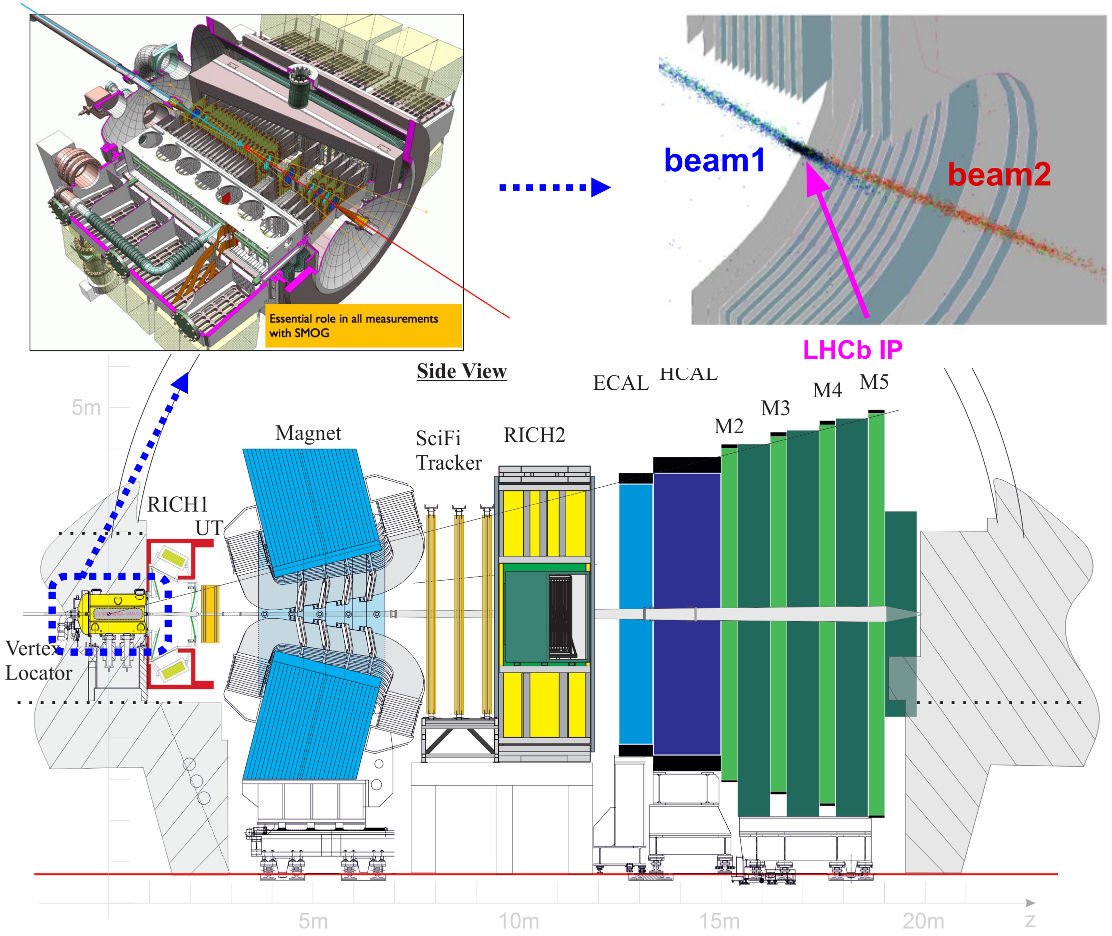
Unique opportunity to study pA/AA collisions on various targets exploiting the high-energy, high-intensity LHC beams!



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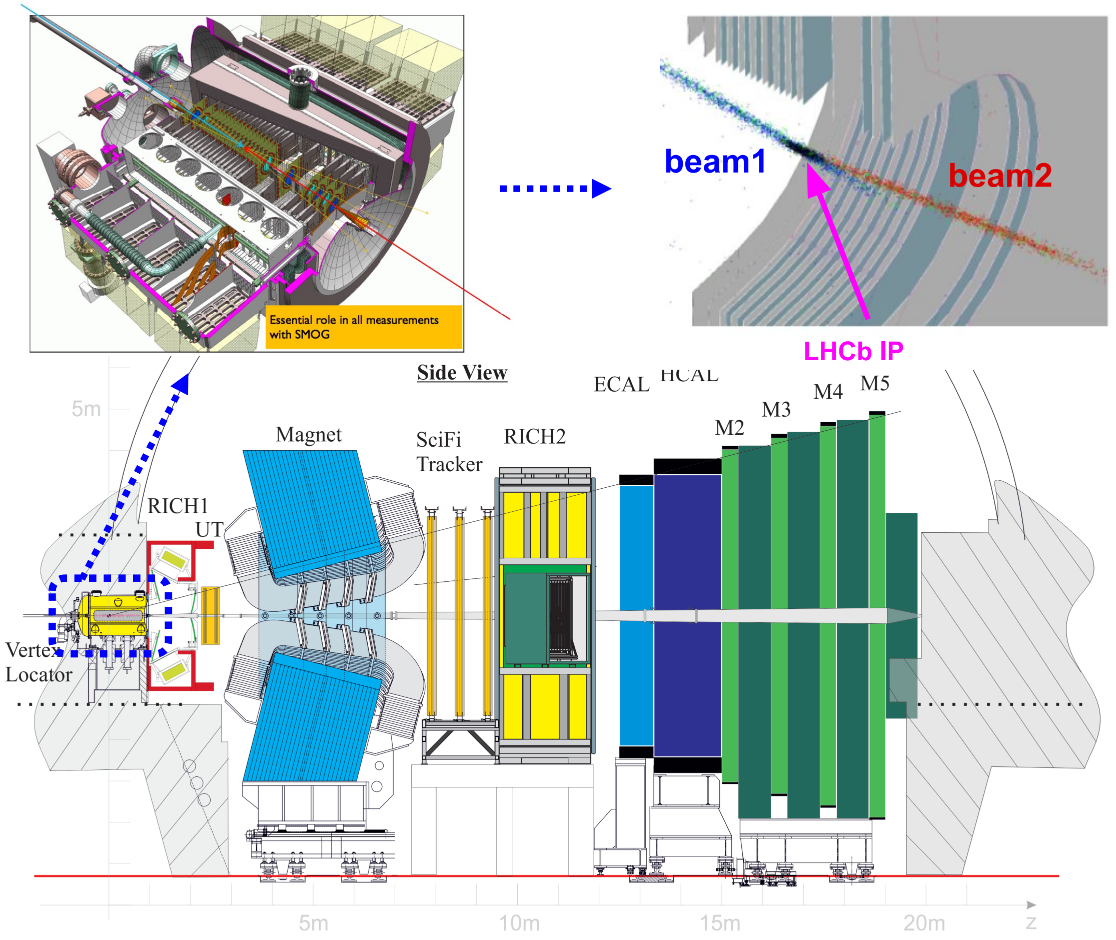

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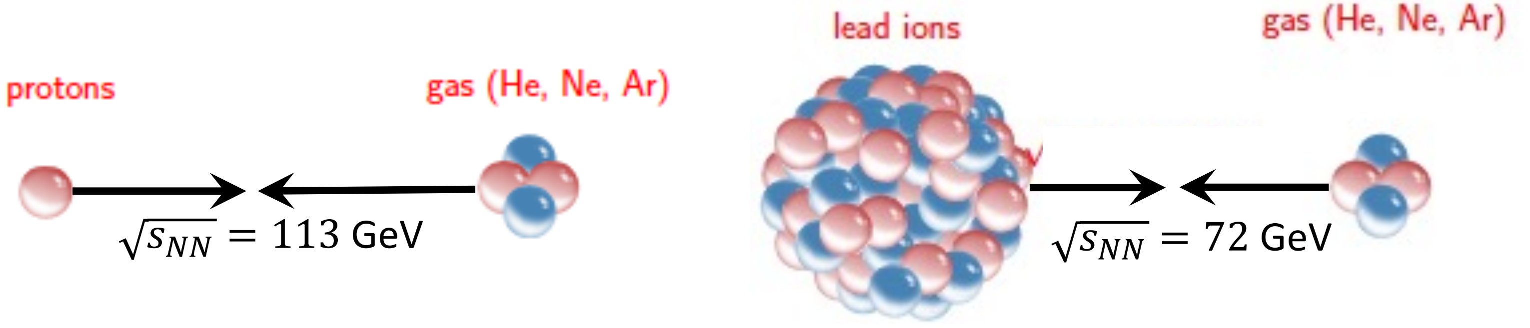

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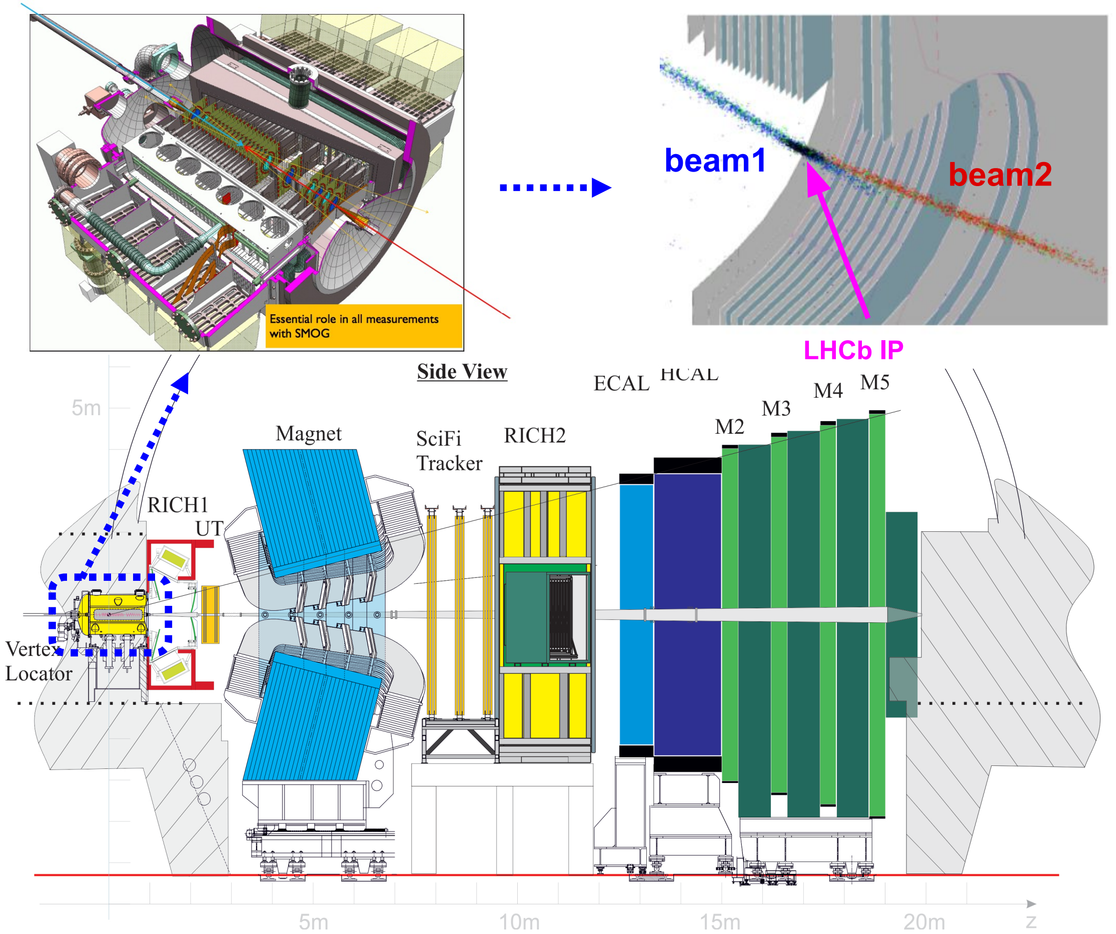

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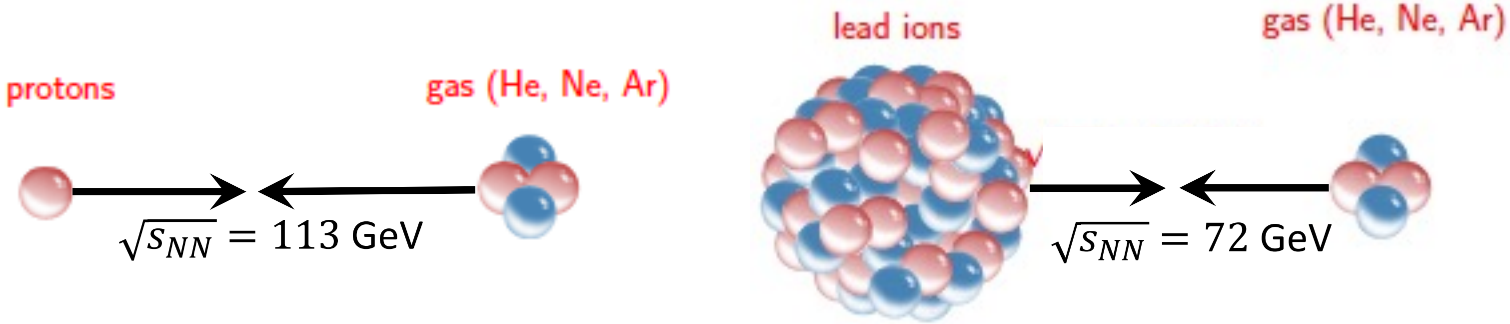

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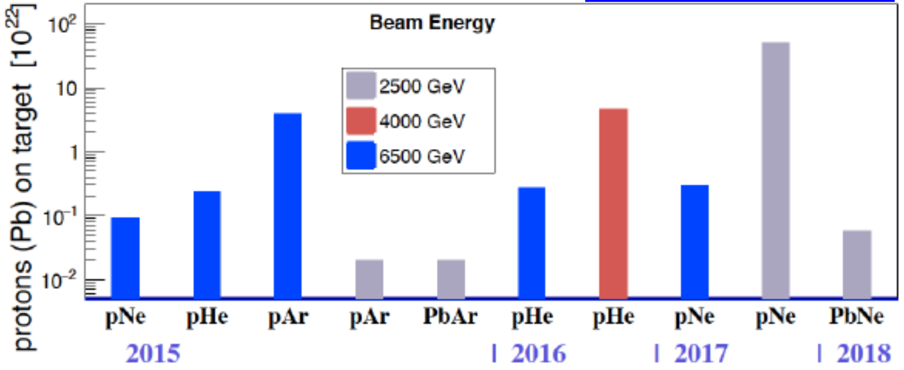
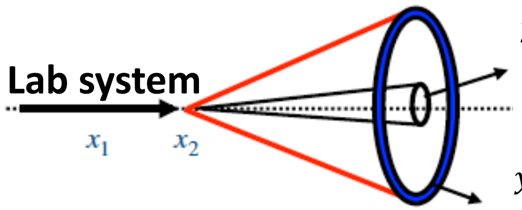


Kinematic conditions for fixed-target collisions at LHCb

Considering pA collisions with $E_p = 6.8\,TeV \implies \sqrt{s_{NN}} \approx \mathbf{113\ GeV}$

$$\boxed{\gamma = \frac{\sqrt{s_{NN}}}{2m_p} \approx 60} \implies$$



$y = 5\ (\theta \sim 1°)$
$\implies y_{CM} \approx 0$

$y = 2\ (\theta \sim 15°)$
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$$2 \leq y_{LHCb} \leq 5 \implies \boxed{-3.0 \leq y_{CM} \leq 0} \Rightarrow \begin{cases} \text{Large } x_2 \\ x_F < 0 \end{cases}$$

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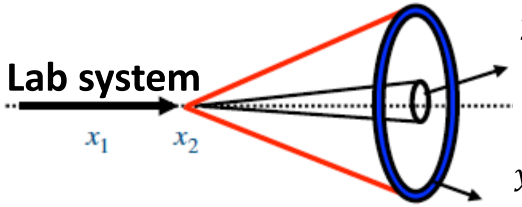

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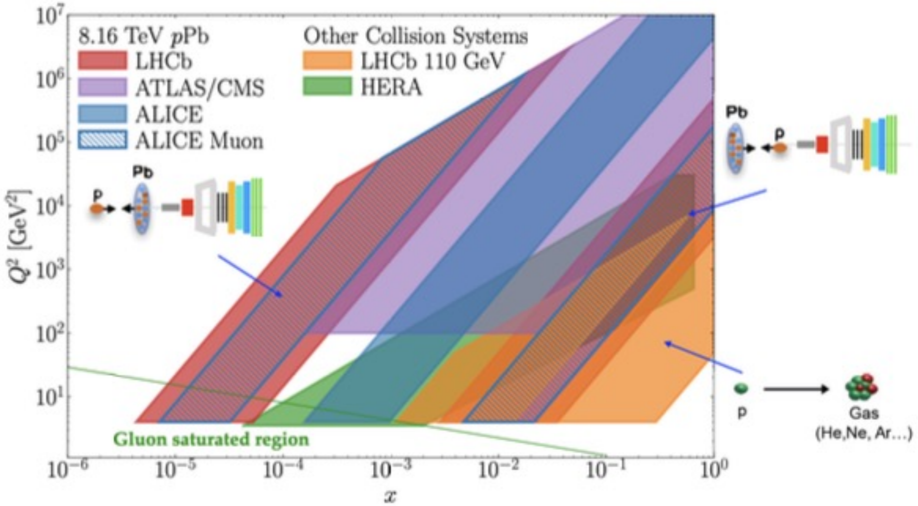

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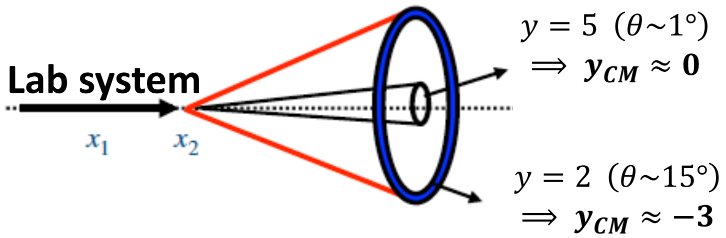

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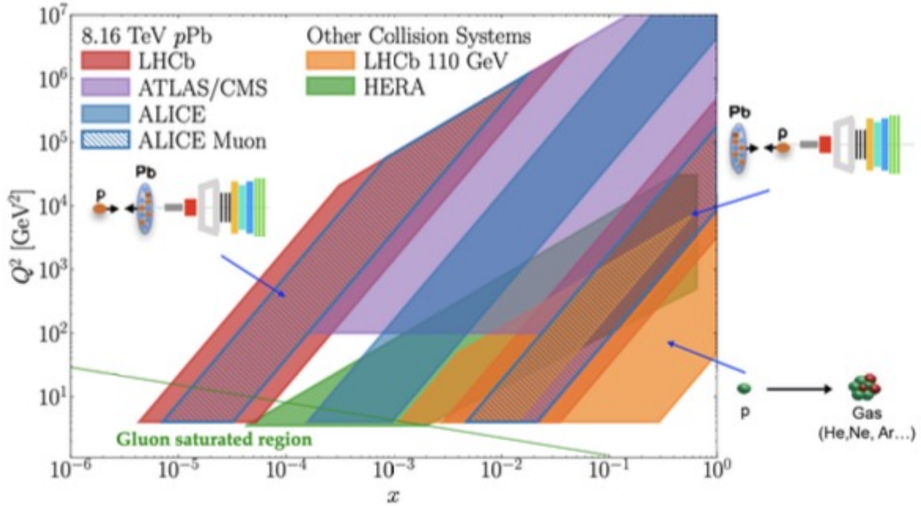
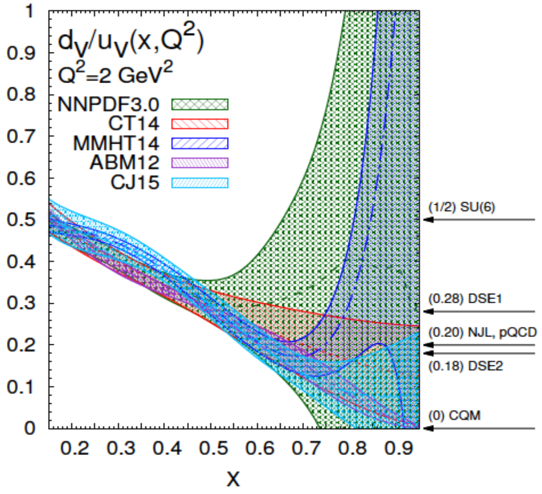


[Eur. Phys. J. C76 (2016) 383]



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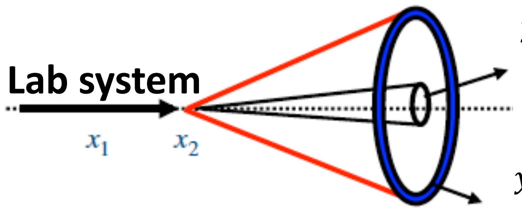

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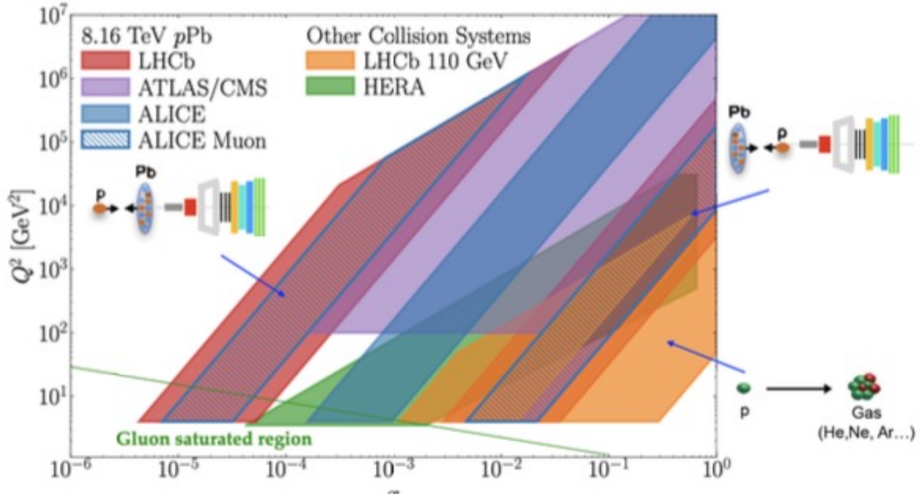

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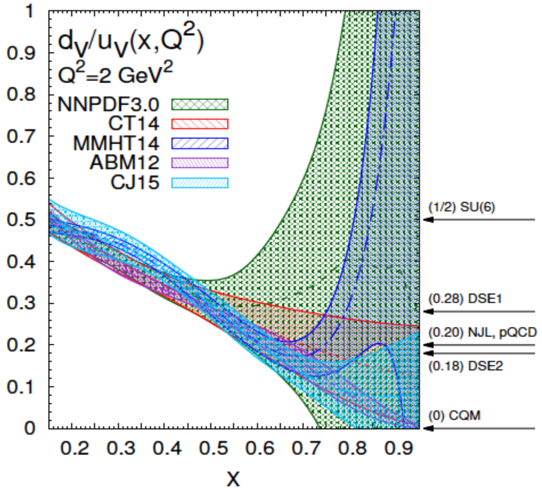
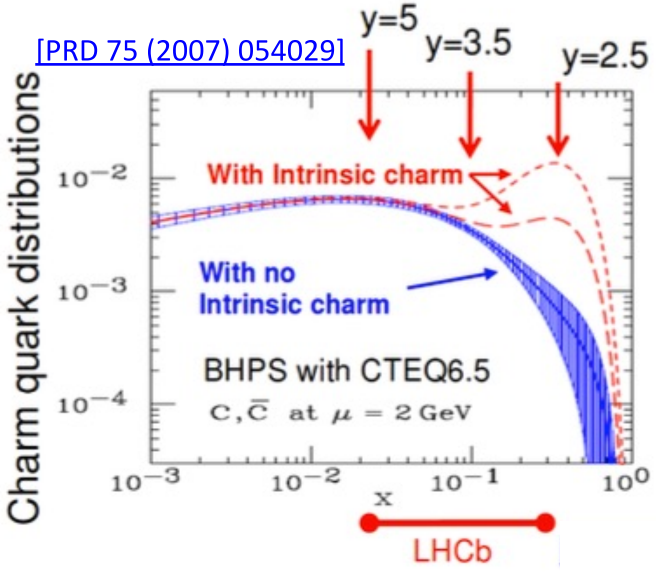


[PRD 75 (2007) 054029]



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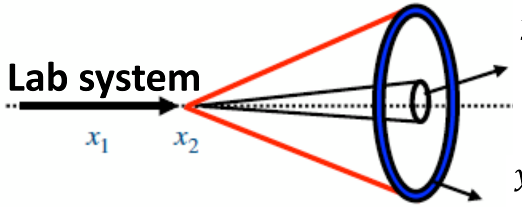

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- probe nuclear anti-shadowing and EMC region

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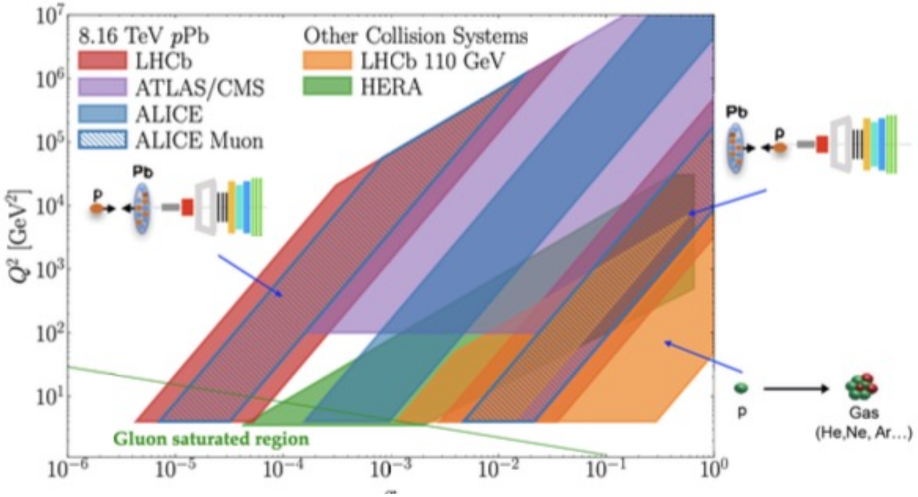
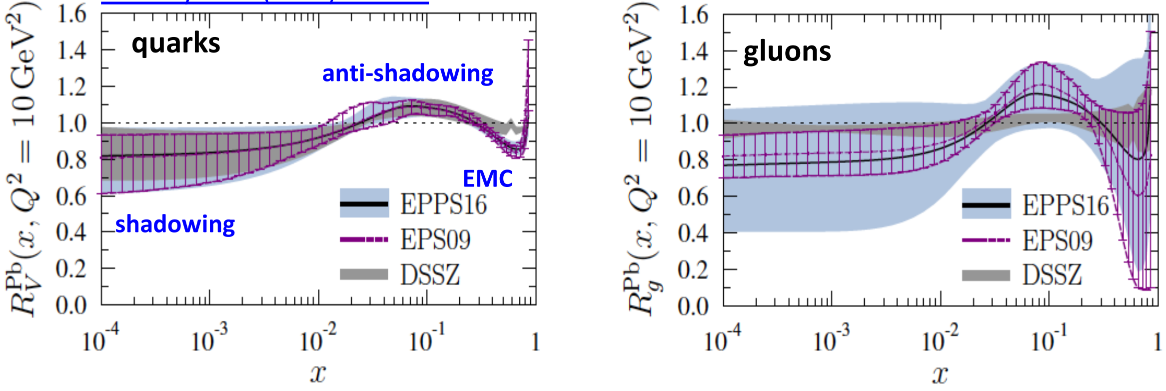


Eur. Phys. J. C (2017) 77: 163



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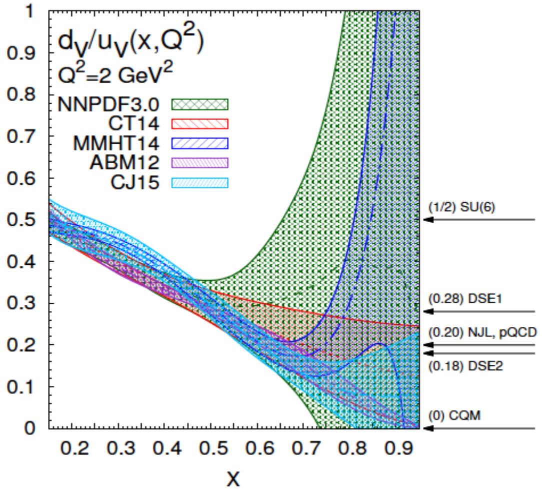

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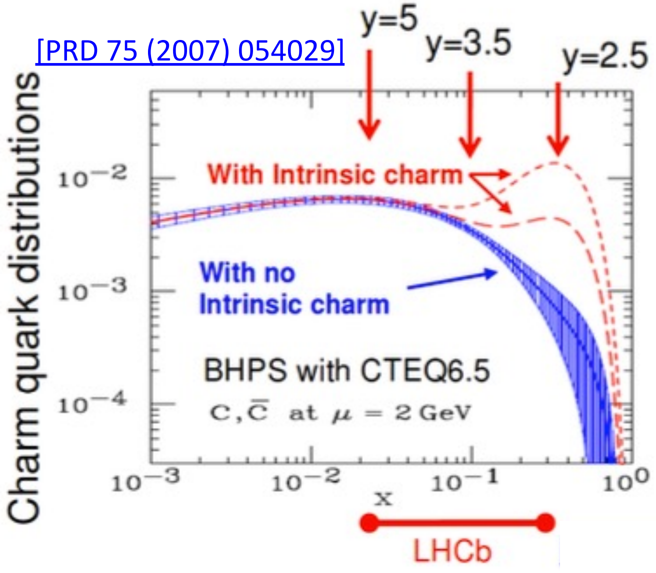
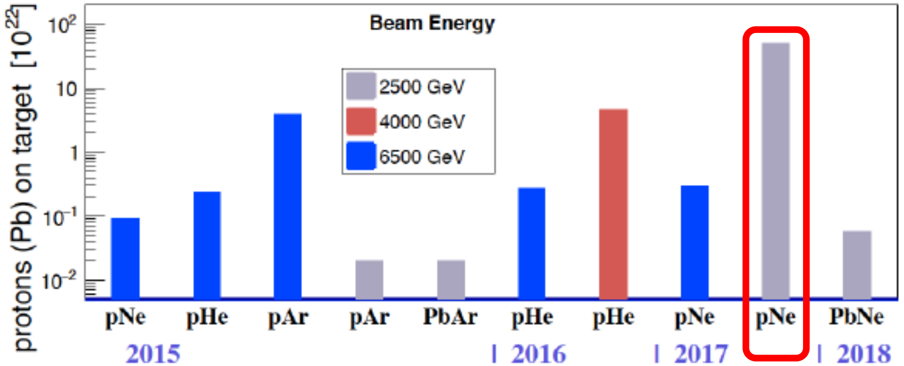


Recent charm production analyses

Charm production in pNe @ $\sqrt{s_{NN}} = 68.5$ GeV

LHCb-PUB-2018-015



Data: pNe at $\sqrt{s_{NN}} = 68.5$ GeV ($\mathcal{L}_{pNe} = 21.7 \pm 1.4\, nb^{-1}$)

LHCb-PUB-2018-015

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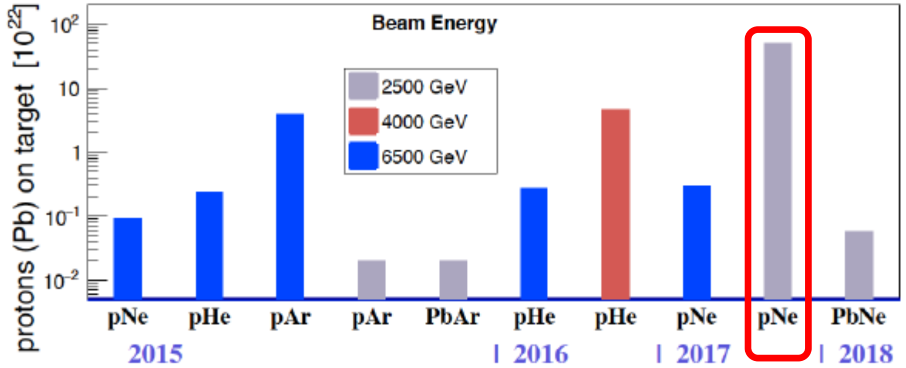

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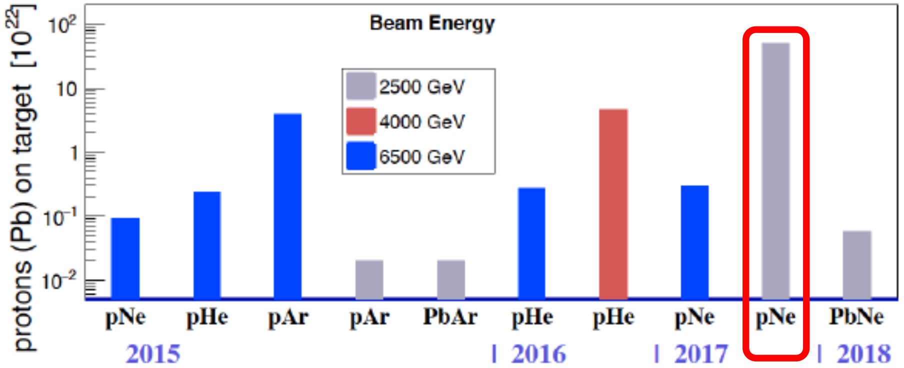

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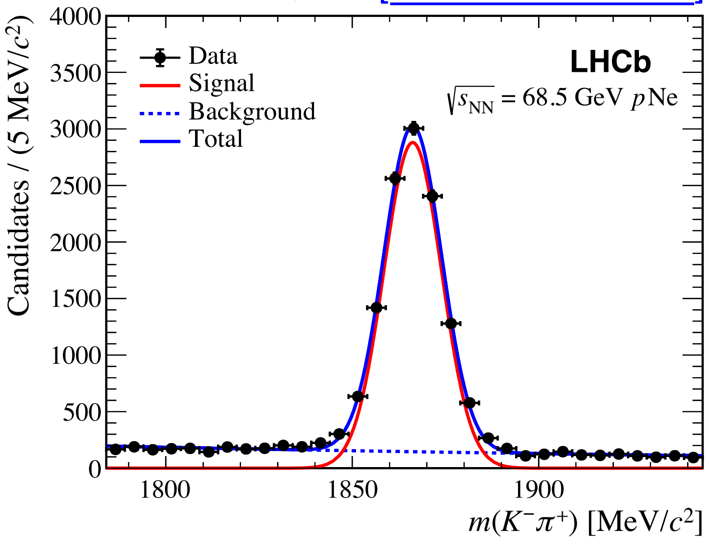
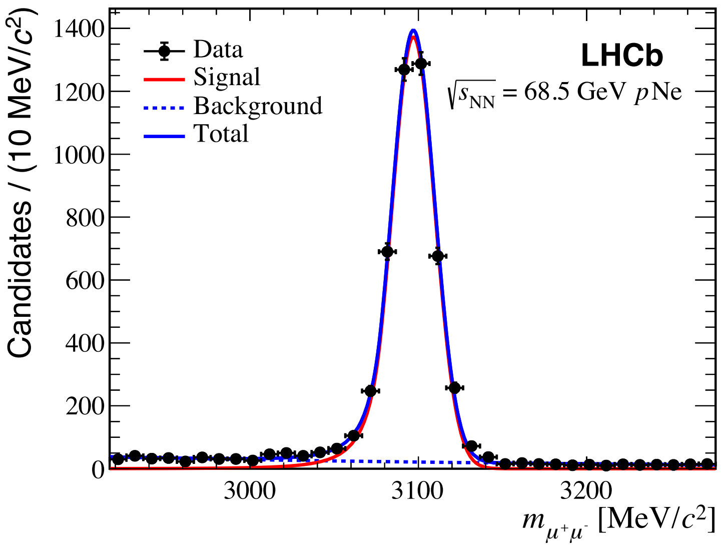
Decays reconstruction:
- $D^0 \to K^-\pi^+$, $\overline{D^0} \to K^+\pi^-$
- $J/\psi \to \mu^+\mu^-$
- $\psi(2S) \to \mu^+\mu^-$

$D^0 \to K^-\pi^+$ [arXiv:2211.11633]



$J/\psi \to \mu^+\mu^-$ [arXiv:2211.11645]



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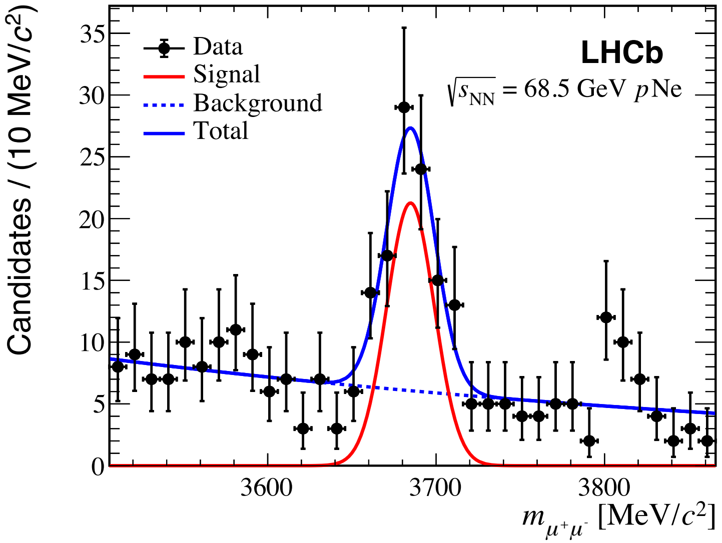
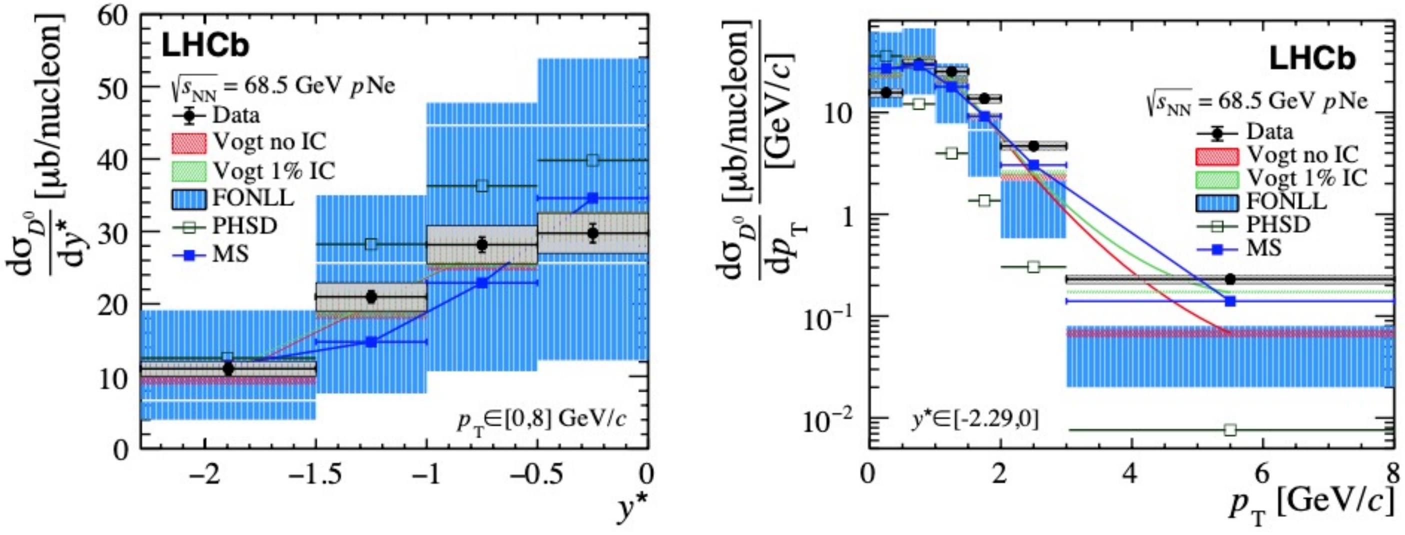


Charm production in pNe @ $\sqrt{s_{NN}} = 68.5$ GeV

D^0 differential cross section [arXiv:2211.11633]



- FONLL and PHSD predictions describe well the y^* dependence but fail to reproduce the p_T dependence of data.
- A reasonably good agreement is found for Vogt and MS predictions:
- Vogt (w/wo 1% IC) include shadowing effects.
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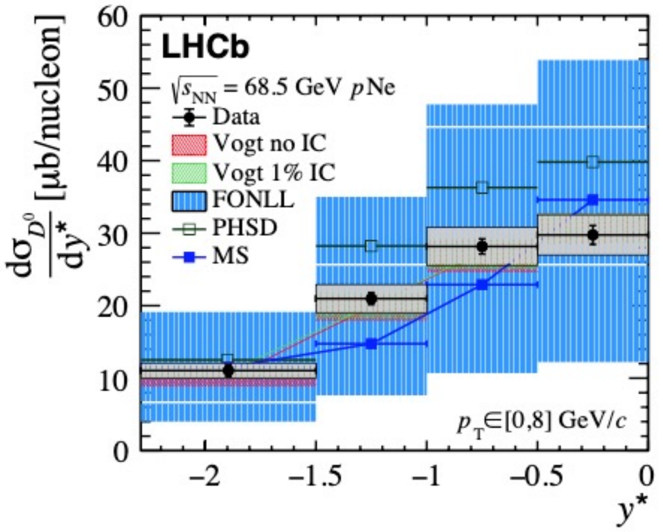

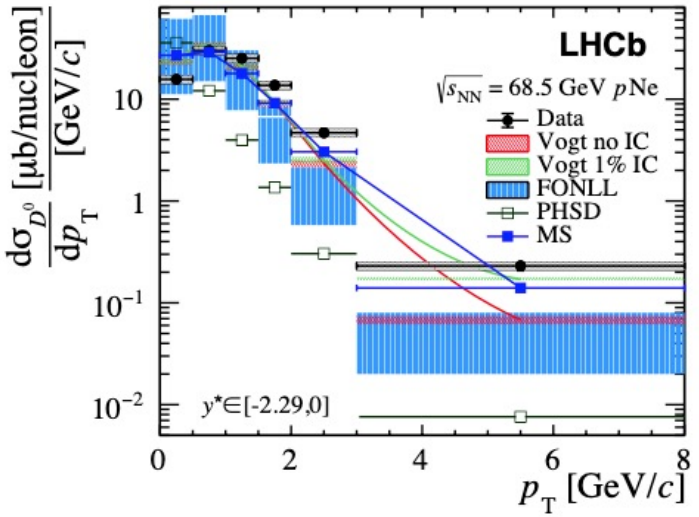

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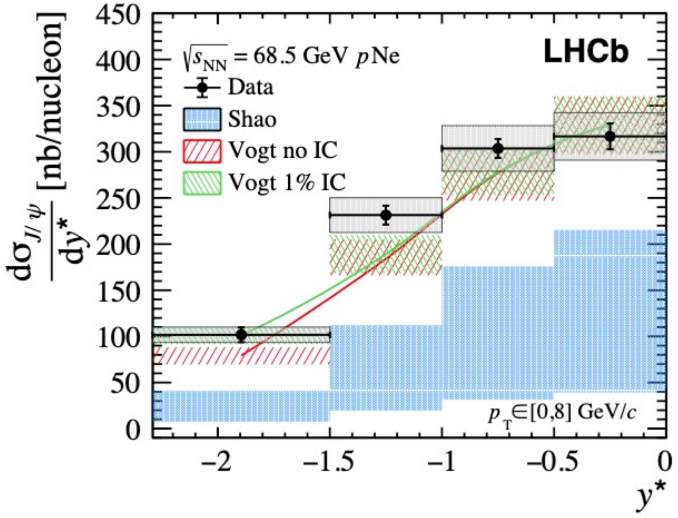

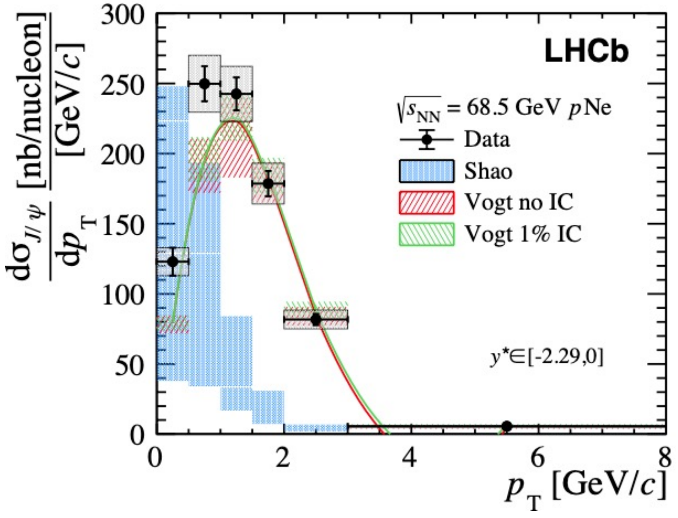

- Shao: based on **HELAC-ONIA** with CT14NLO and nCTEQ15 PDF sets. Fails to reproduce data.
- Vogt (w/wo 1% IC) predictions based on EPPS16 nPDFs and include nuclear absorption and multiple scattering effects. Provide a reasonably good agreement with data.

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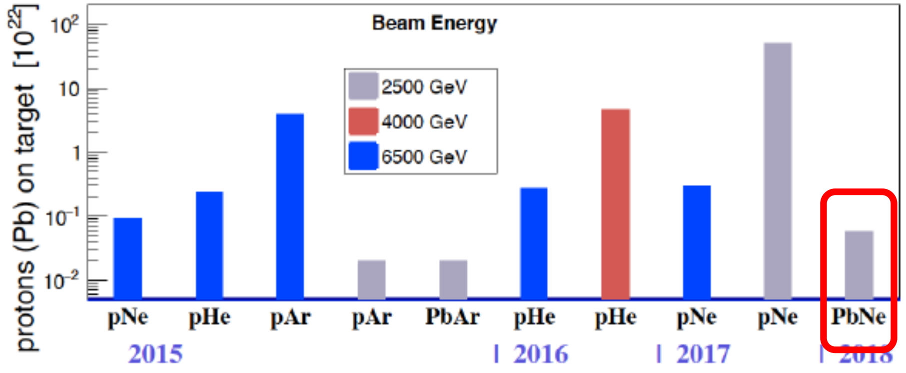
Charm production in PbNe @ $\sqrt{s_{NN}} = 68.5$ GeV



Motivation: search for QGP formation signals

Data: PbNe at $\sqrt{s_{NN}} = 68.5$ GeV $(\mathcal{L}_{pNe} \sim 0.3\, nb^{-1})$

Selection: same kinematic as in pNe $(0 < p_T < 8$ GeV/c; $-2.29 < y^* < 0)$

Challenges: larger detector occupancy, larger background than in pNe, but clean J/ψ and D^0 signals

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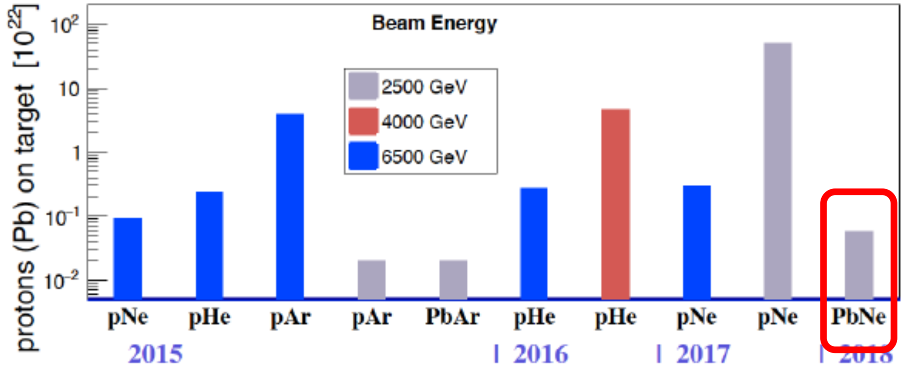

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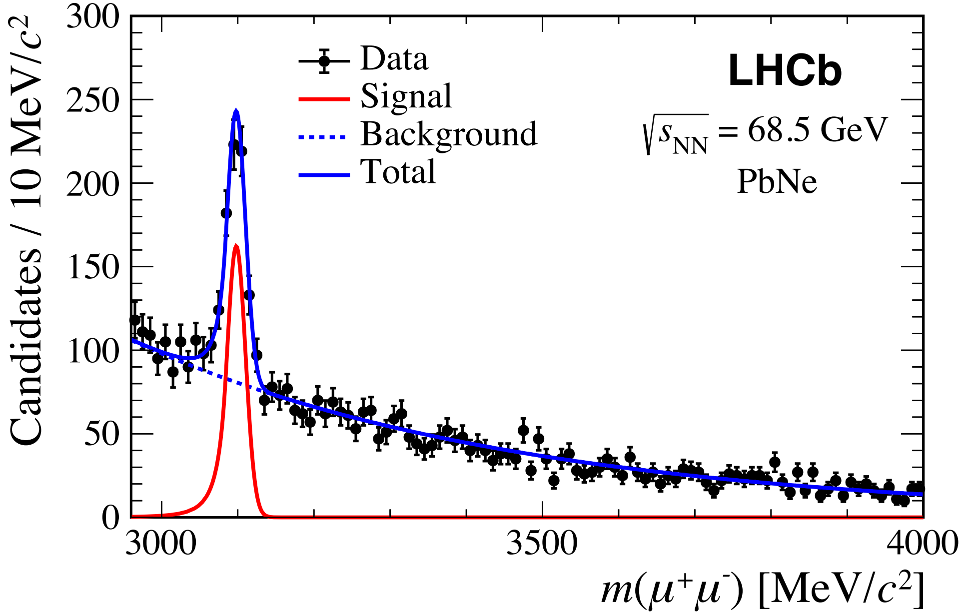
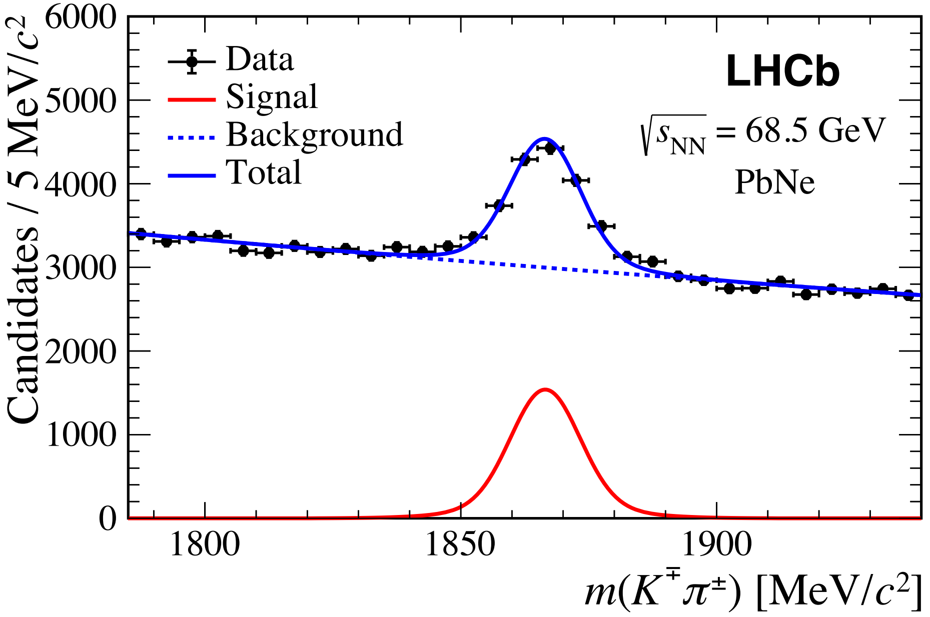
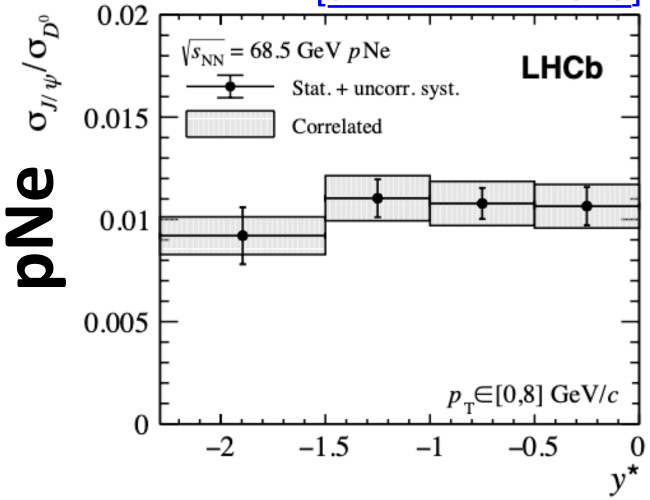


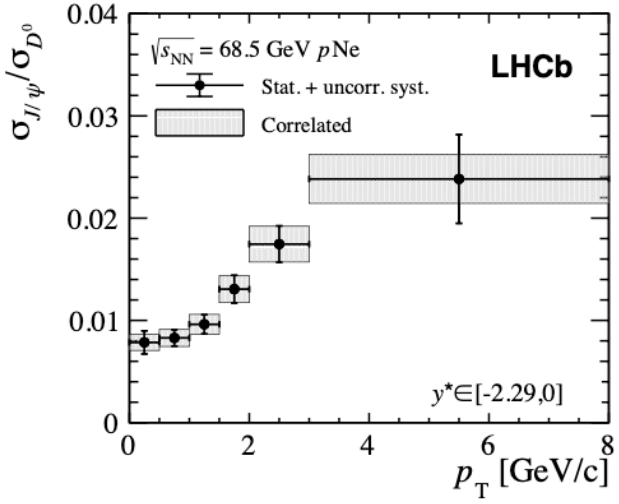


Comparing charm production in pNe and PbNe @ $\sqrt{s_{NN}} = 68.5$ GeV

[arXiv:2211.11645]

pNe



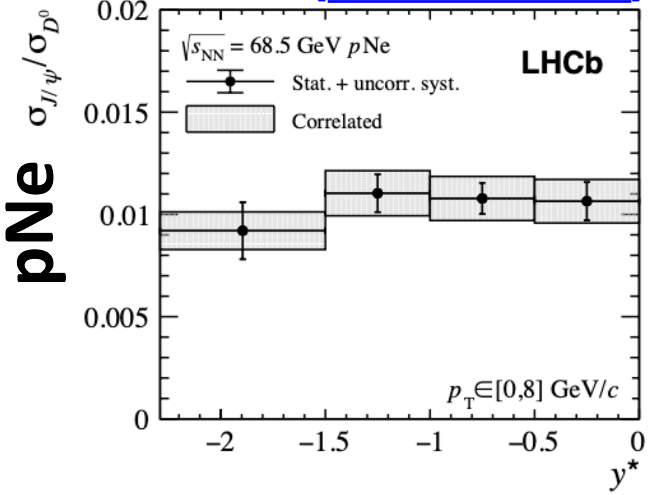


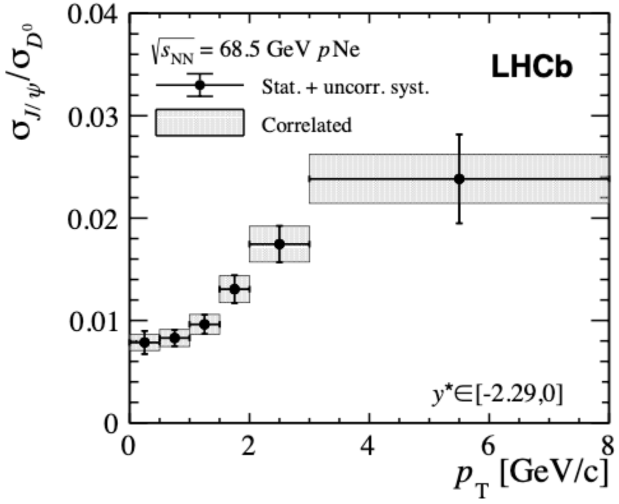
- No evident y^* dependence
- Significant p_T dependence
- $\psi(2S)$ to J/ψ ratio $= (1.67 \pm 0.27 \pm 0.10)\%$

Comparing charm production in pNe and PbNe @ $\sqrt{s_{NN}} = 68.5$ GeV

[arXiv:2211.11645]

pNe





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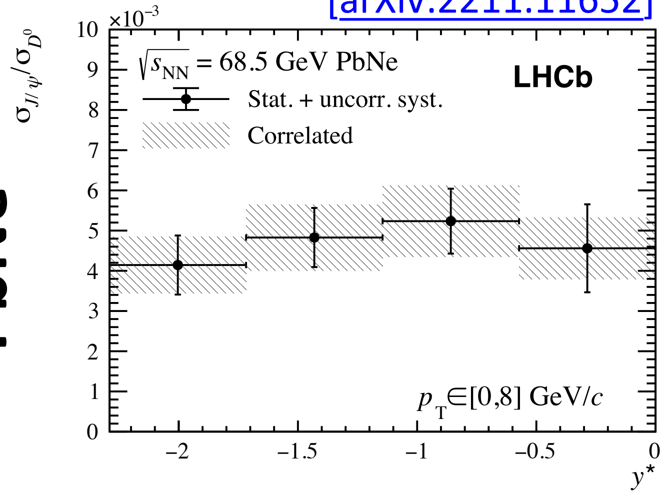
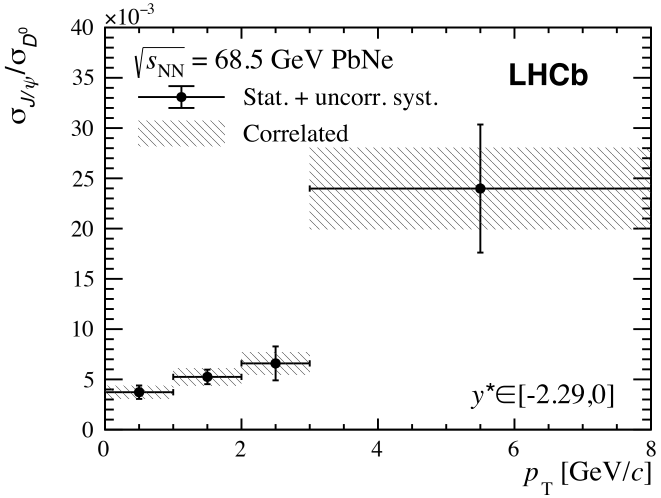
PbNe





- No evident y^* dependence, but **strong p_T dependence!**

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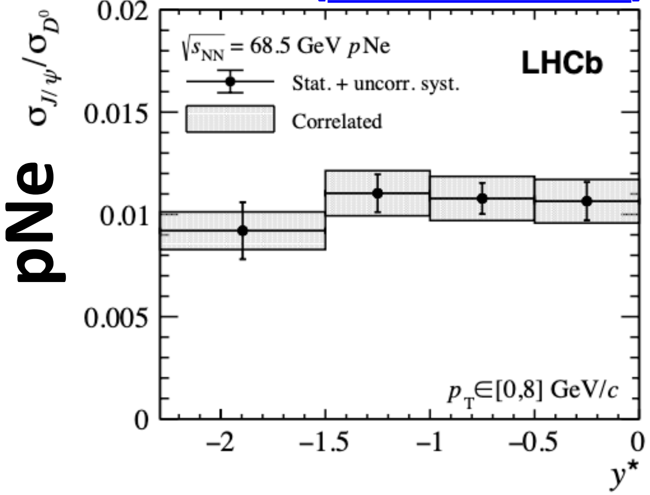
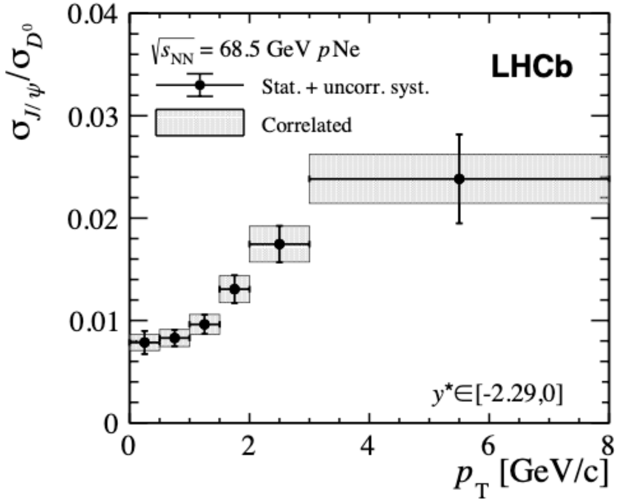
[arXiv:2211.11645]

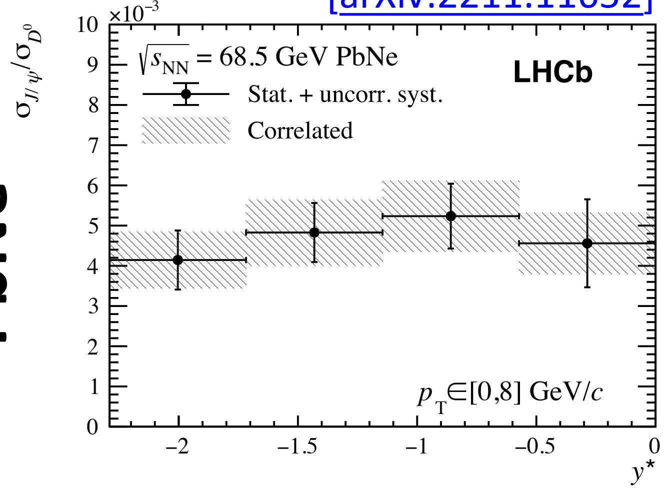
pNe

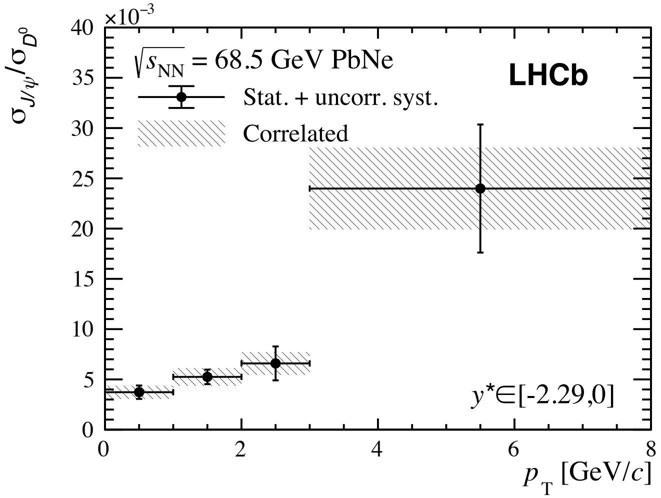




[arXiv:2211.11652]

PbNe





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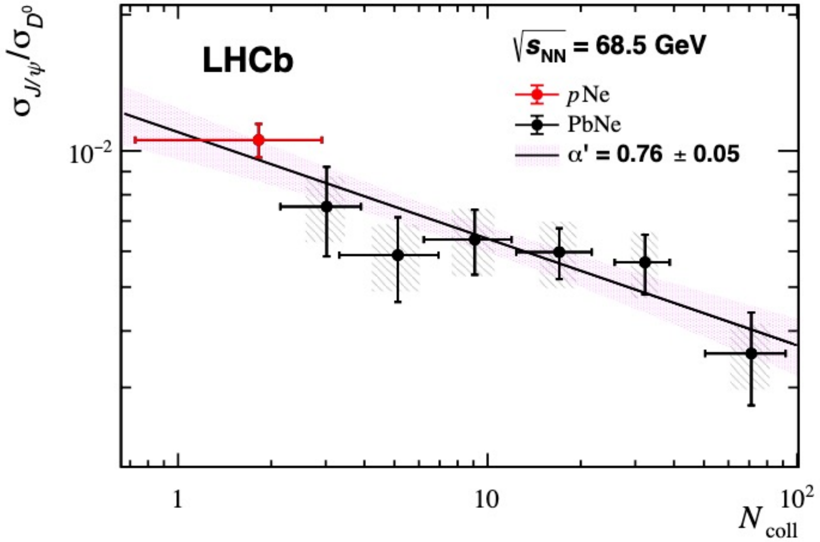


- **No evidence of anomalous suppression that could indicate QGP formation**

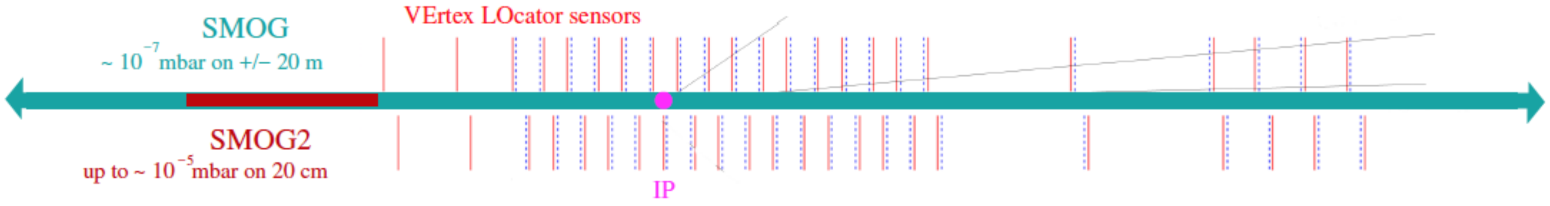
The SMOG2 upgrade

[SMOG2 TDR]

Project approved in Nov. 2019

Main hardware implementations:

- 20 cm **storage cell** for the target gas installed upstream of the VELO
- Brand new, more flexible and sophisticated **Gas Feed System** (GFS)



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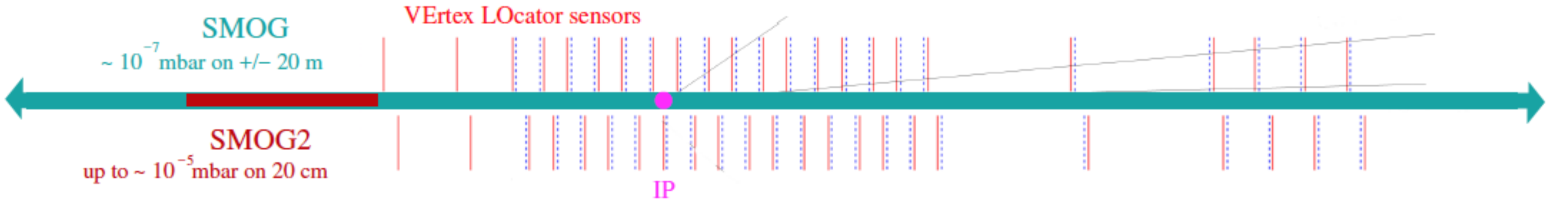
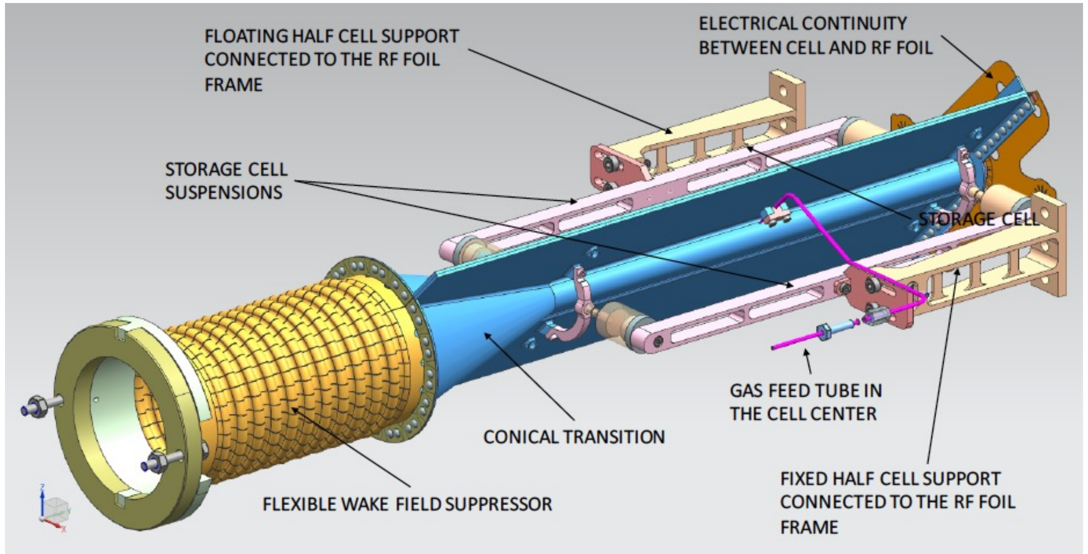


SMOG2 vs. SMOG:

- ✓ Well **defined interaction region** upstream of the collider IP (limited to cell length/position: $-541 < z < -341$ mm)
- ✓ **Increase of target density (luminosity)** by factor 8-35 using the same gas load
- ✓ Possibility to inject **more gas species**: $H_2, D_2, He, N_2, O_2, Ne, Ar, Kr, Xe$
- ✓ New Gas Feed System allows to **measure target density (→ luminosity) with much higher precision** (few % uncert.)
- ✓ Well displaced int. regions: possibility to **run in parallel with collider mode**

The SMOG2 target Cell



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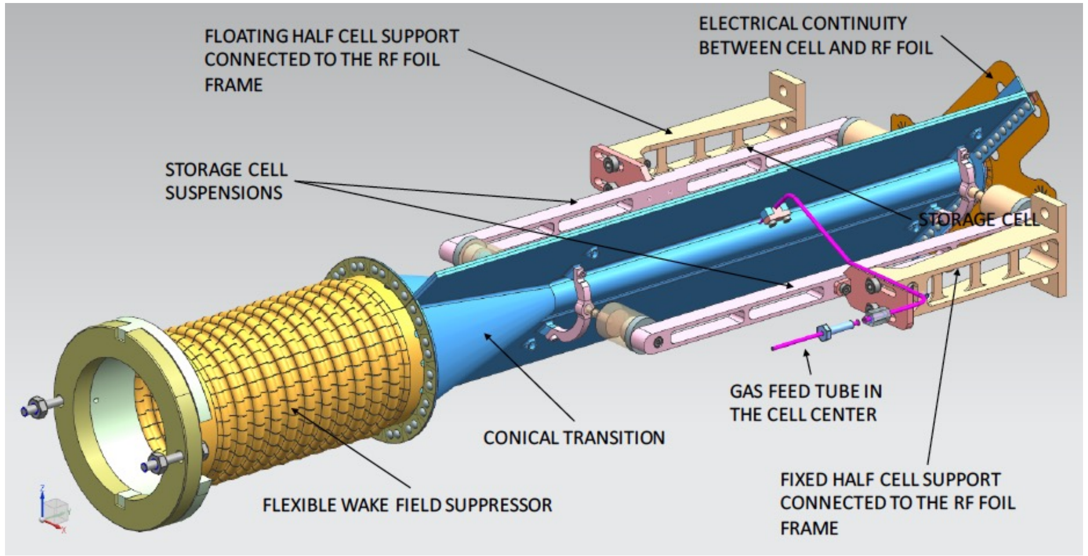

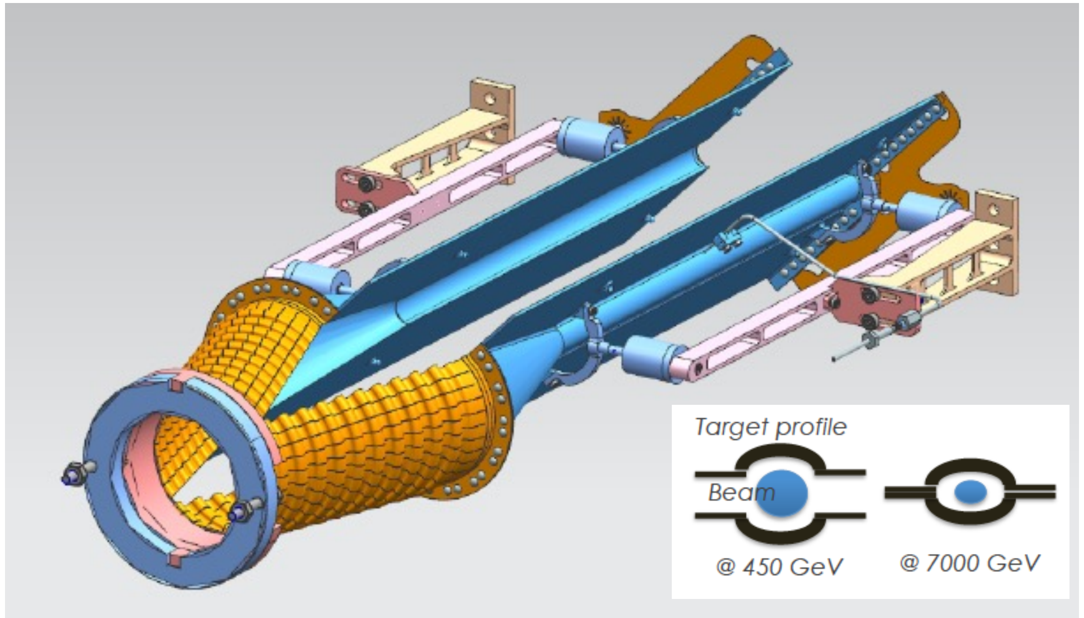

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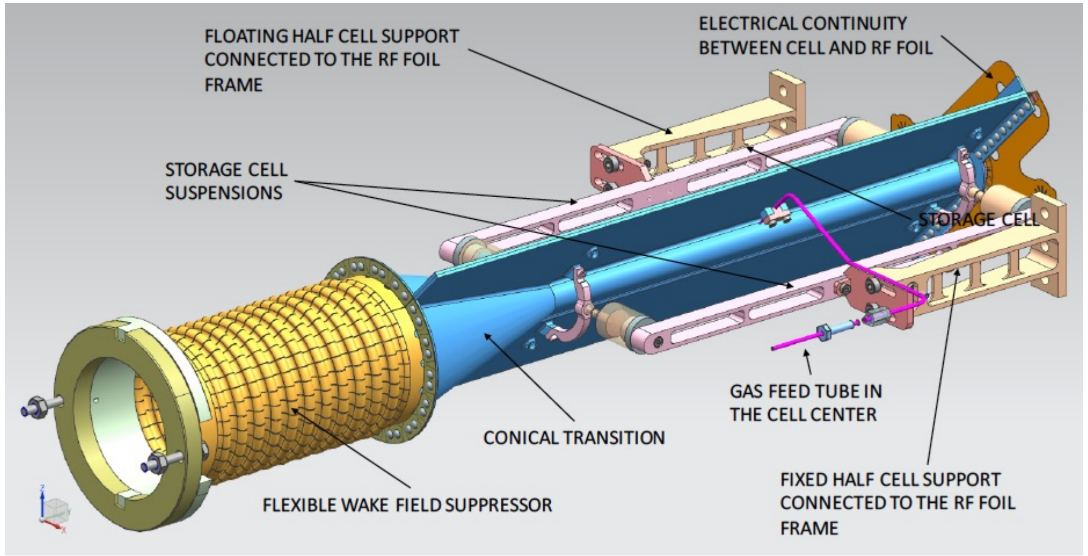
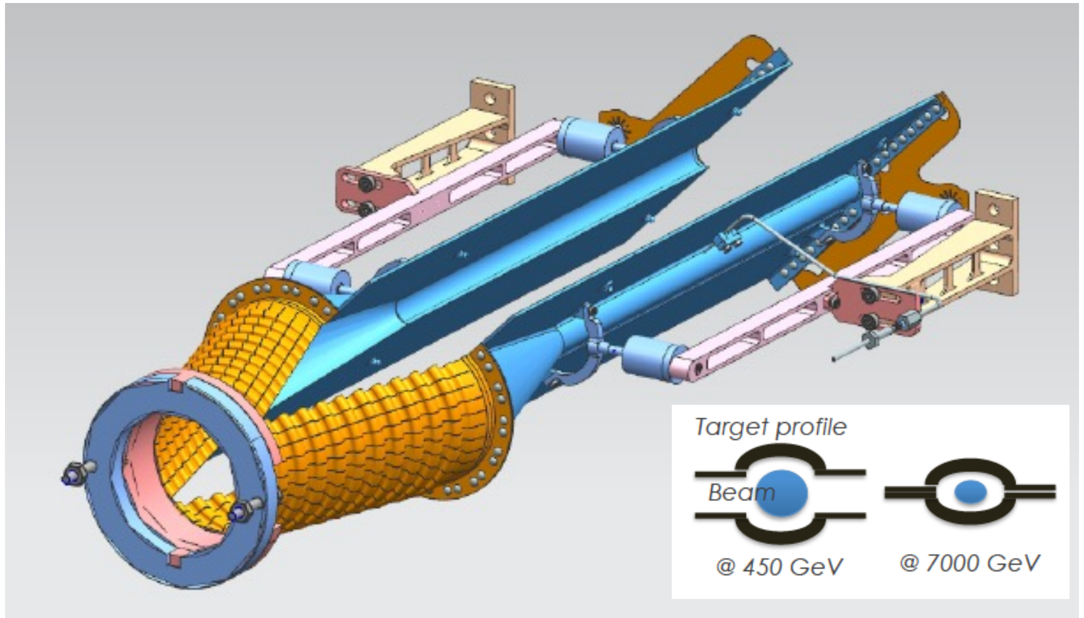
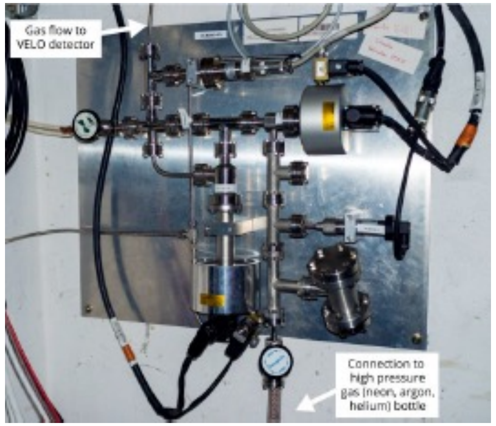




The SMOG2 gas feed system



SMOG Gas Feed System

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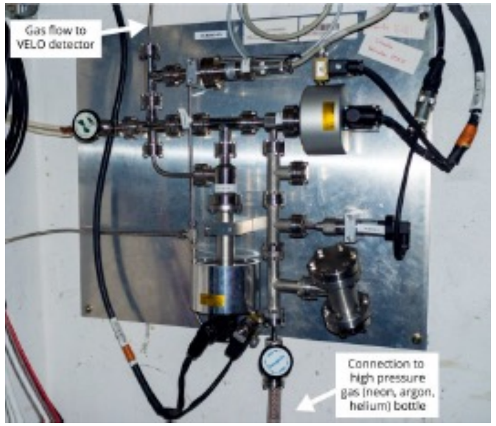

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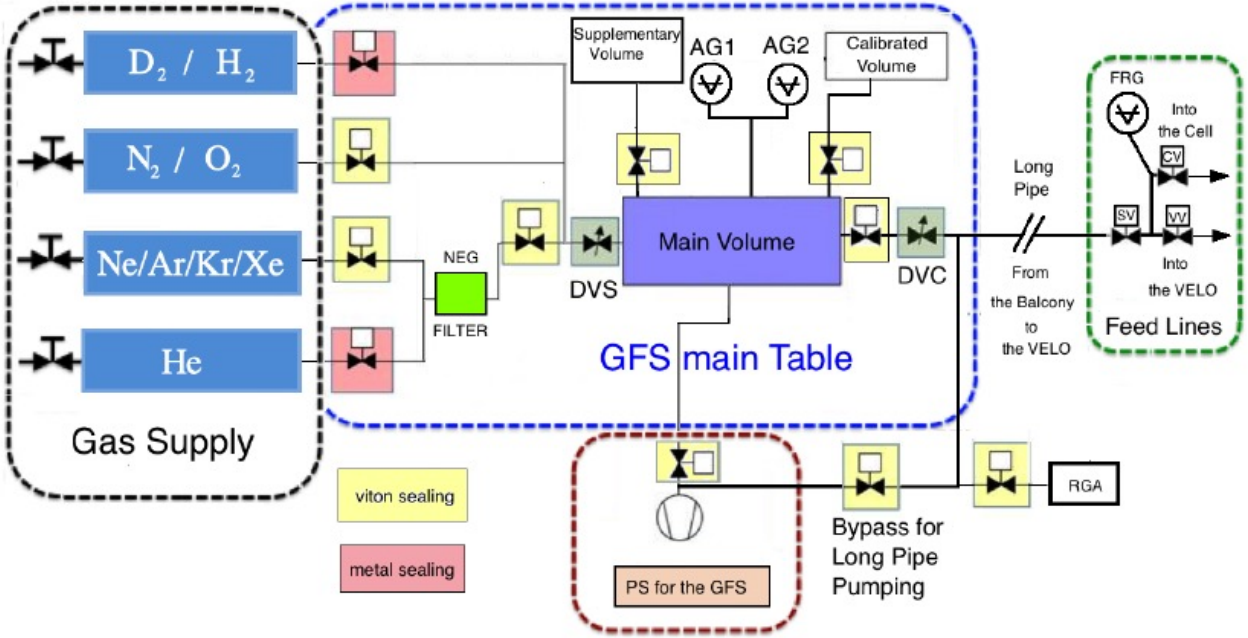
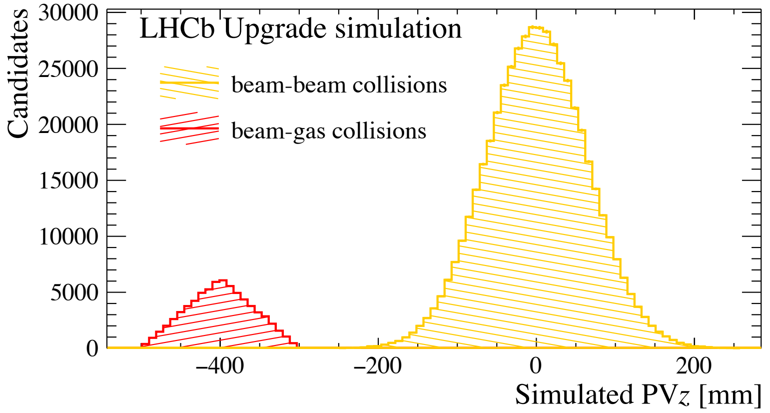


SMOG2 expected performance

- **Beam-beam and beam-gas interaction regions well detached**



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- Full reconstruction efficiency (PV + Tracking) retained in beam-gas interaction region despite the distance from the VELO and the different event topology
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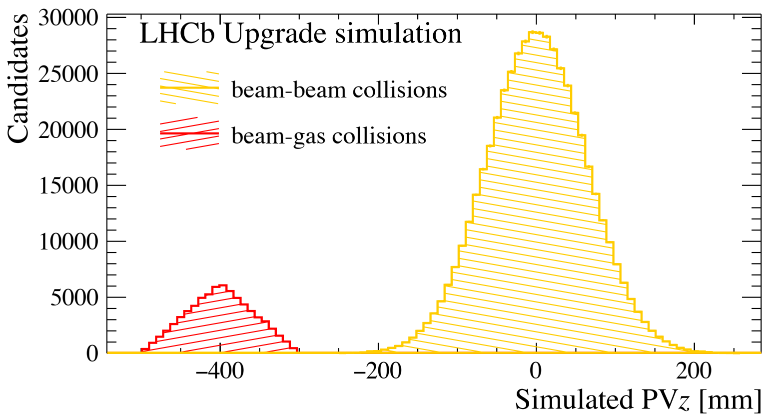

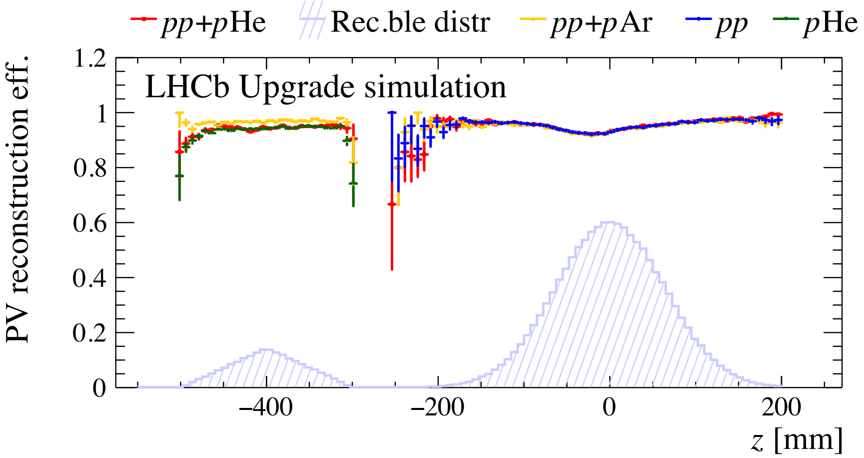

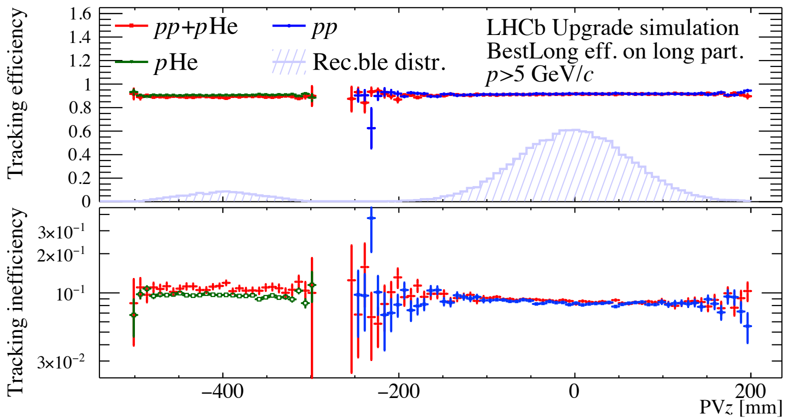

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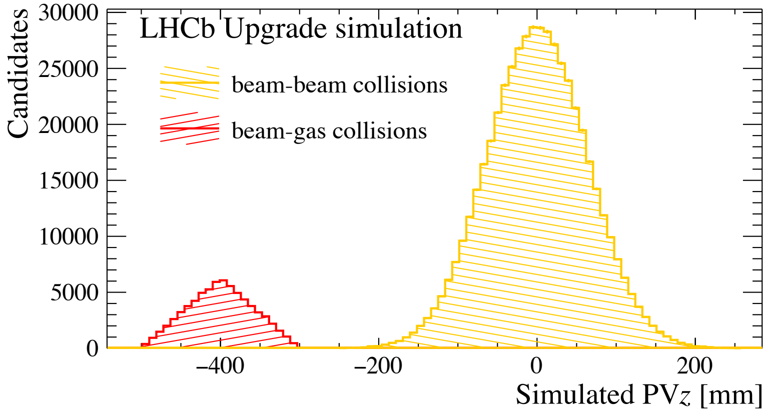
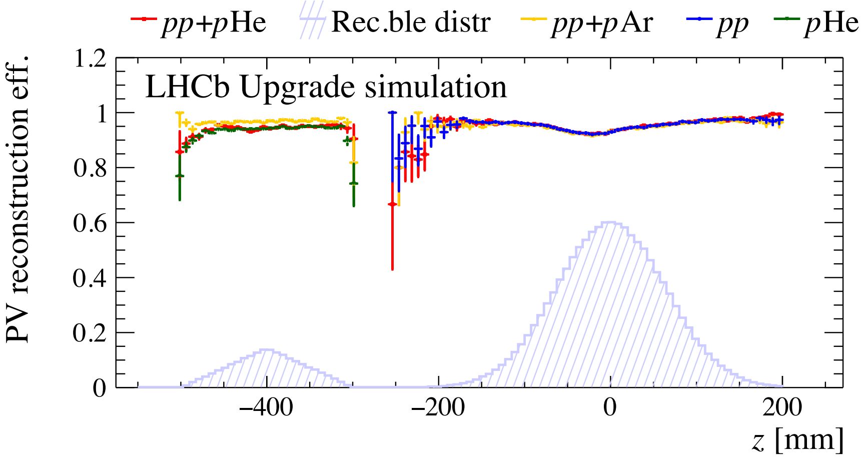
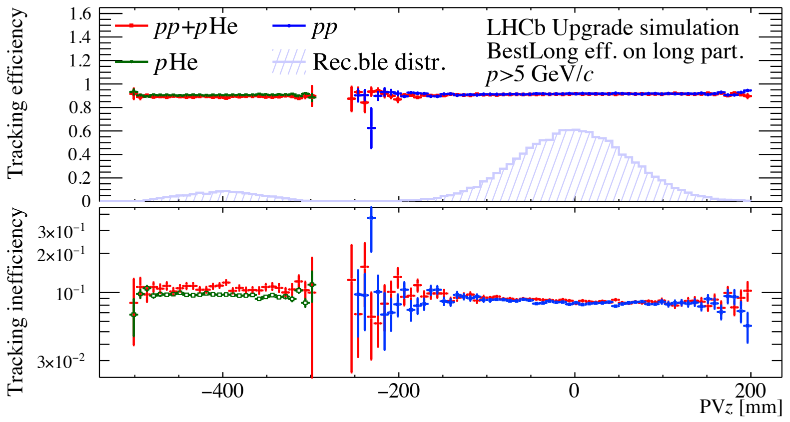
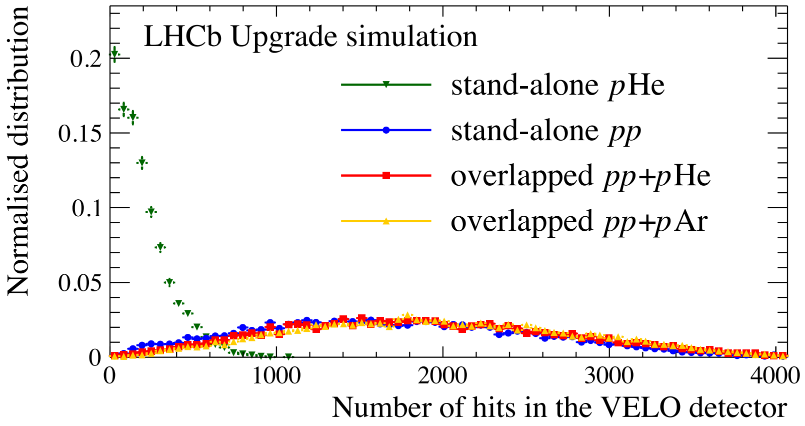






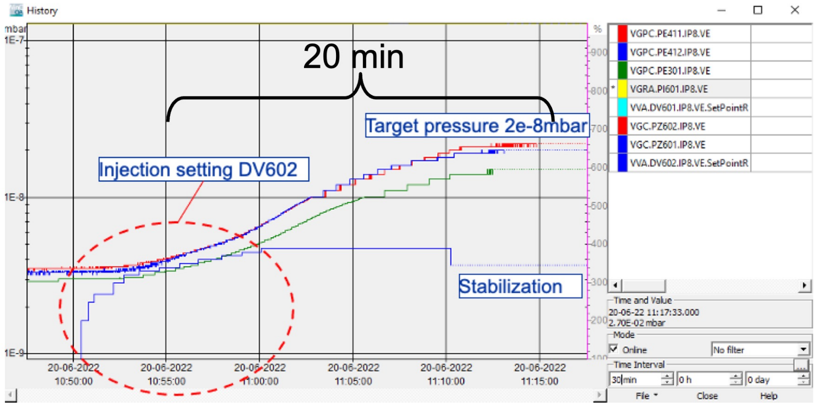


- In case of simultaneous data-taking, beam-gas collisions cause a negligible increase in the detector occupancy
- The gas target provides a negligible impact on beam life-time (e.g. a relative loss of 0.4% is expected for pAr in 10 h [SMOG2 TDR])

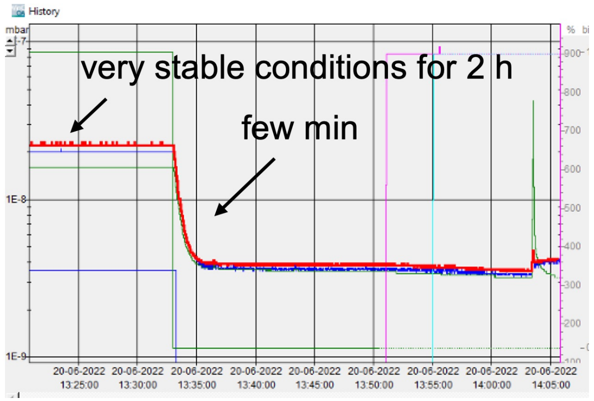
SMOG2 commissioning

First gas injection in RUN3 (June 22): low pressure Ne injection with cell OPEN, circulating beams

Pressure increase into the primary vacuum



Vacuum recovery after the gas injection stop



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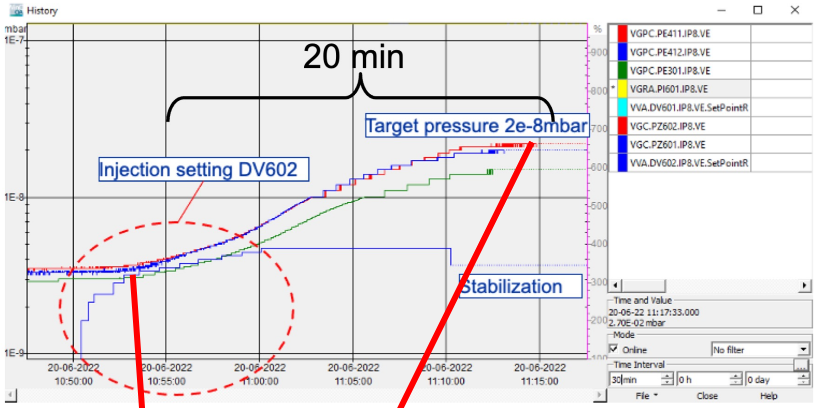

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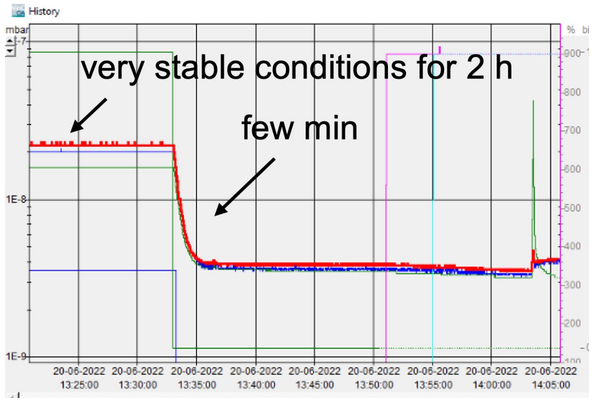

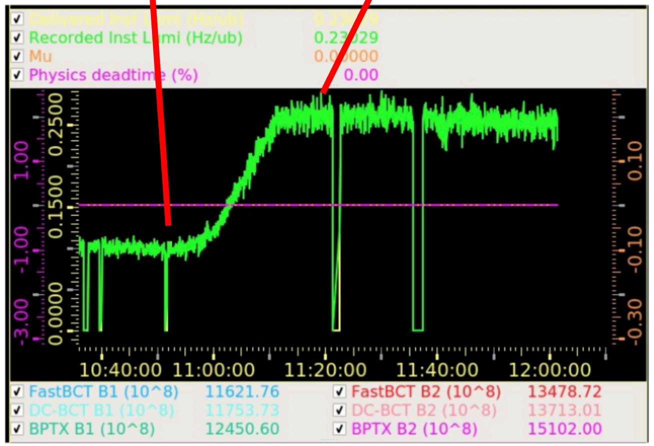

- ✓ Luminosity increase seen by the LHCb luminometer Plume
- ✓ CALO, RICH and Muon systems recorded activity

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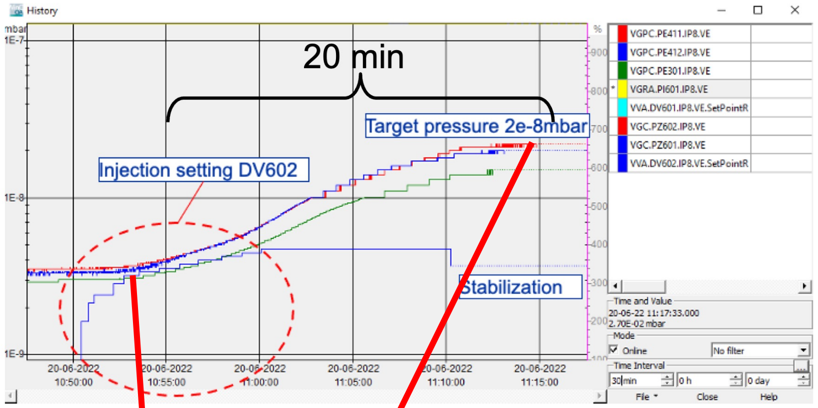

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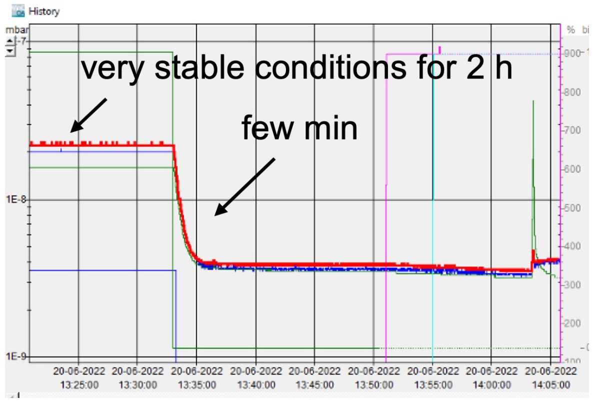

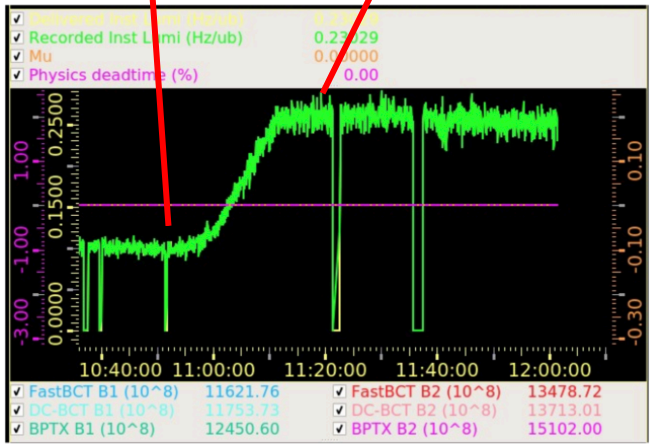

- ✓ Luminosity increase seen by the LHCb luminometer Plume
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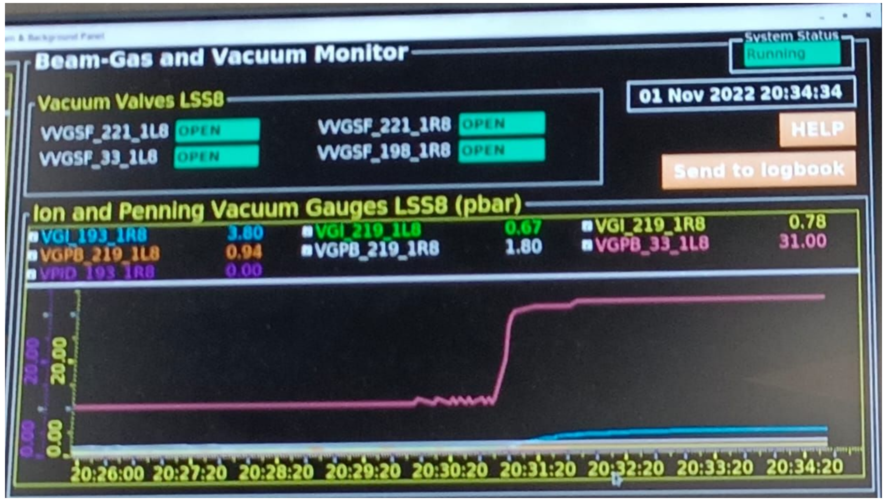
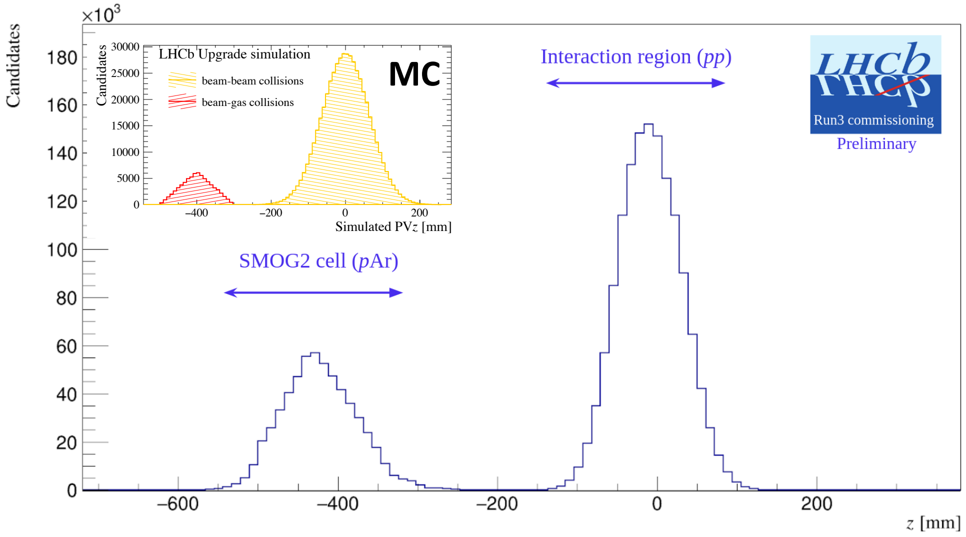
First gas injection with closed VELO and SMOG2 cell, with circulating beams (Nov. 22)



- Injected **Ar at $1.6{\times}10^{-8}$ mbar** (a factor 6.5 lower than SMOG, but density x5.5 higher)
- A steep increase of pressure followed by a stable plateau
- **Simultaneous beam-beam and beam-gas data taking with full LHCb detector ON and running**

First SMOG2 data from commissioning



- The two interaction regions are clearly visible and well separated!
- PV distributions consistent with simulations
- **LHCb is now the first (unique) LHC experiment with two simultaneous interaction regions!**

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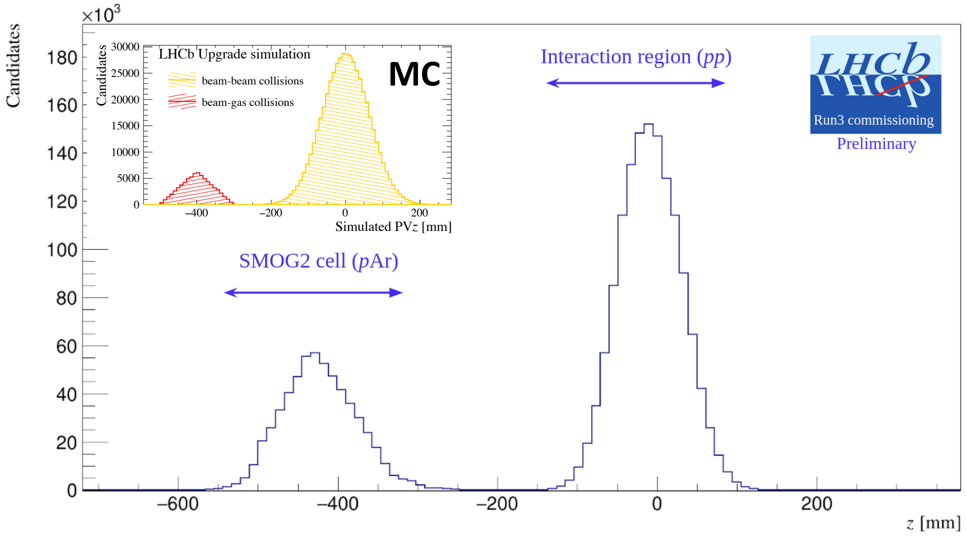

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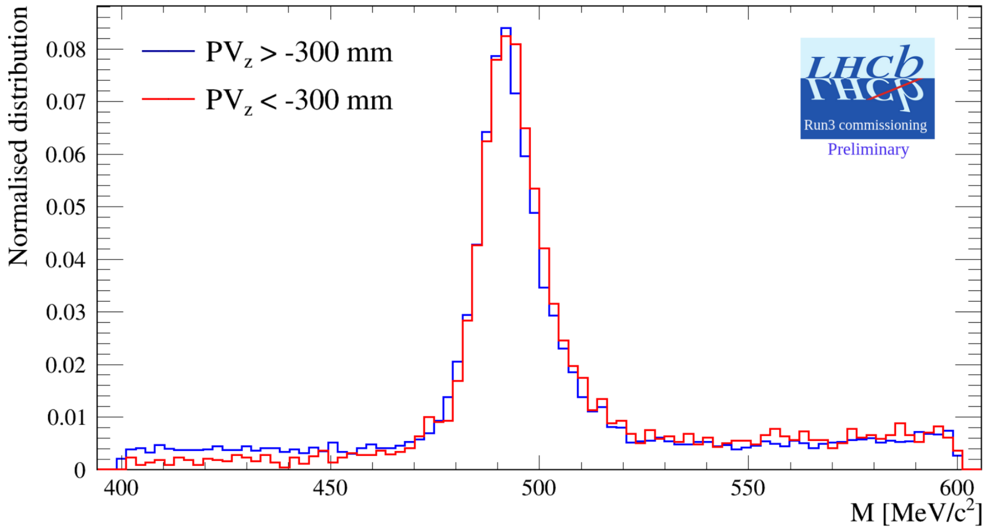
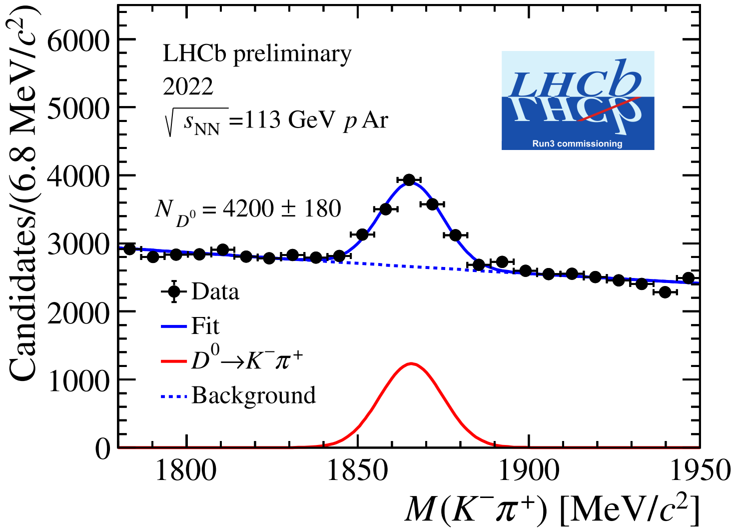
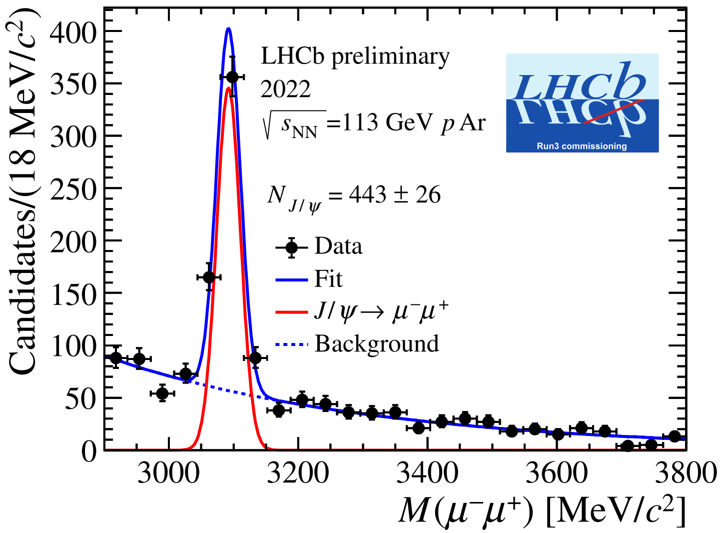


- K_S^0 mass reconstructed using pp (blue) and p-Ar collisions (red)
- Mass resolution found to be comparable!

First SMOG2 data from commissioning

- Data collected for the SMOG2 commissioning in short periods ($\sim$ 20 min) of gas injection
- Clean D^0 and J/ψ samples obtained in just 18 min of data taking with p-Ar collisions at $\sqrt{s_{NN}} = 113\ GeV$





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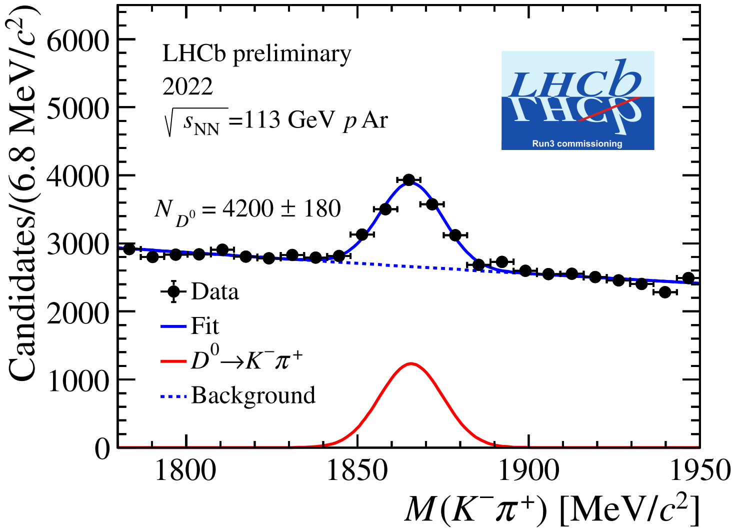
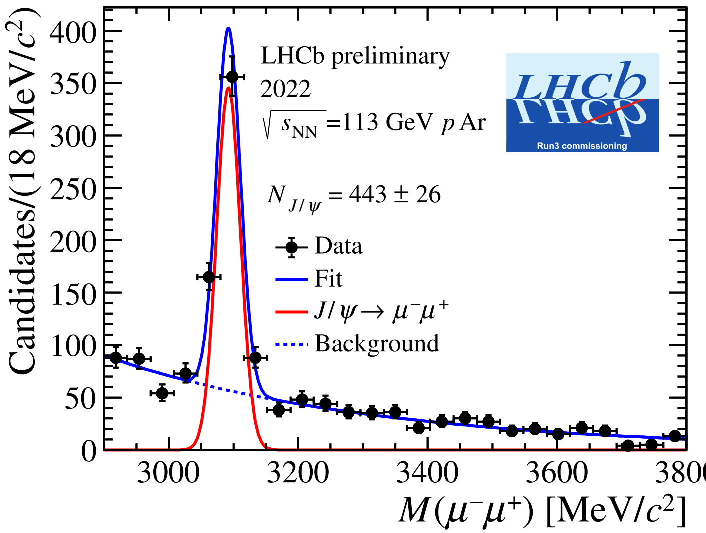
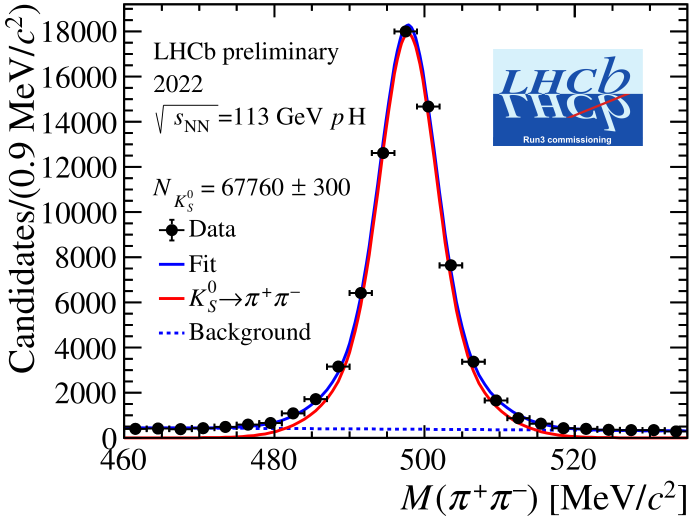
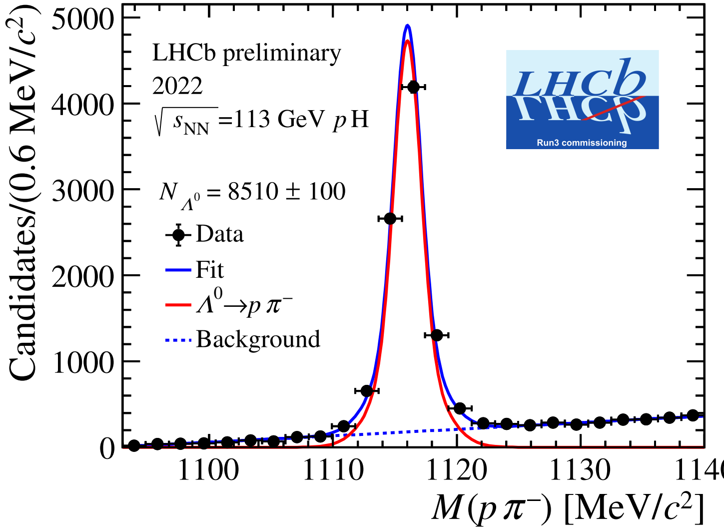




- First data from p-H collisions at $\sqrt{s_{NN}} = 113\ GeV$
- Very well reconstructed K_S^0 and Λ^0 masses





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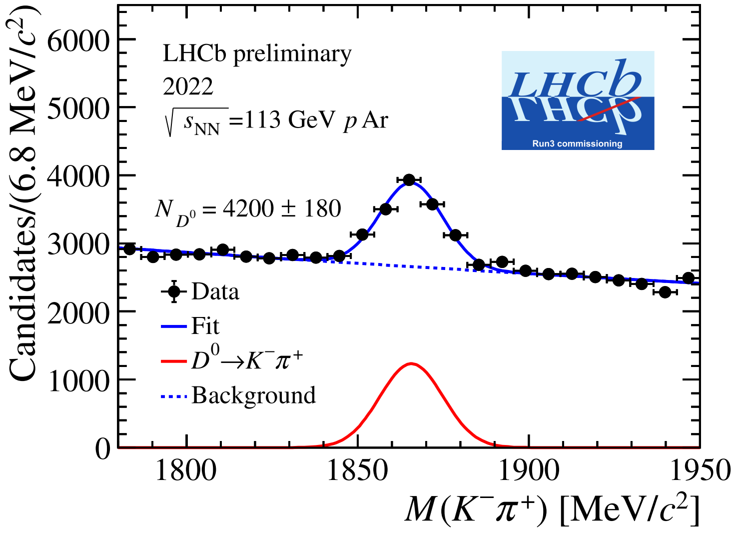

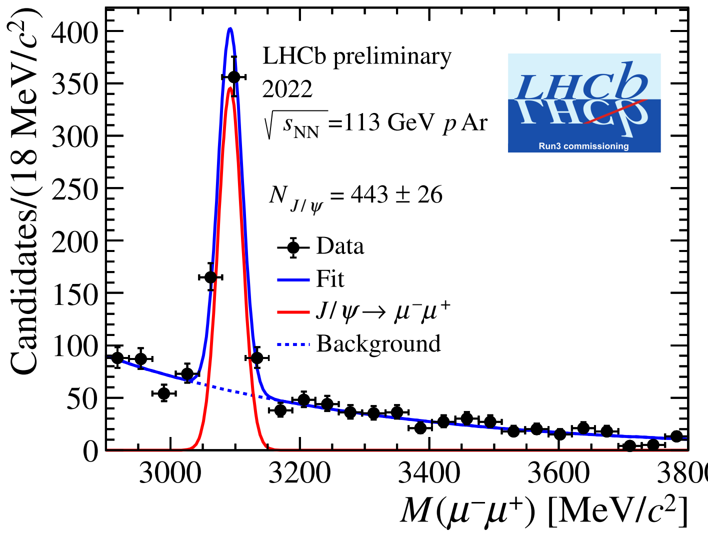

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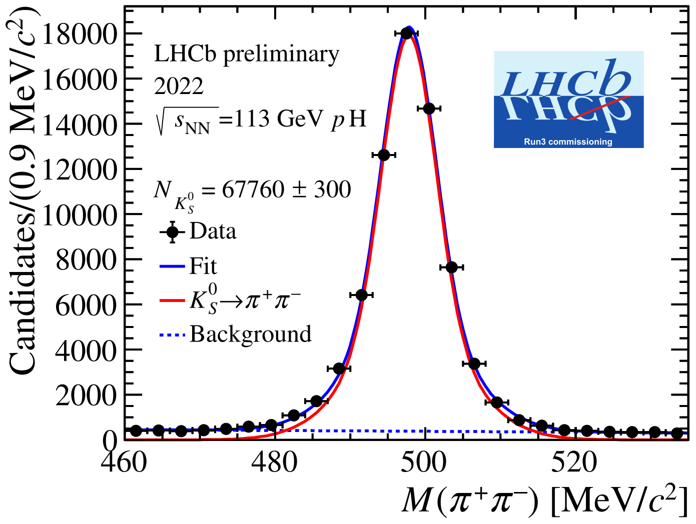
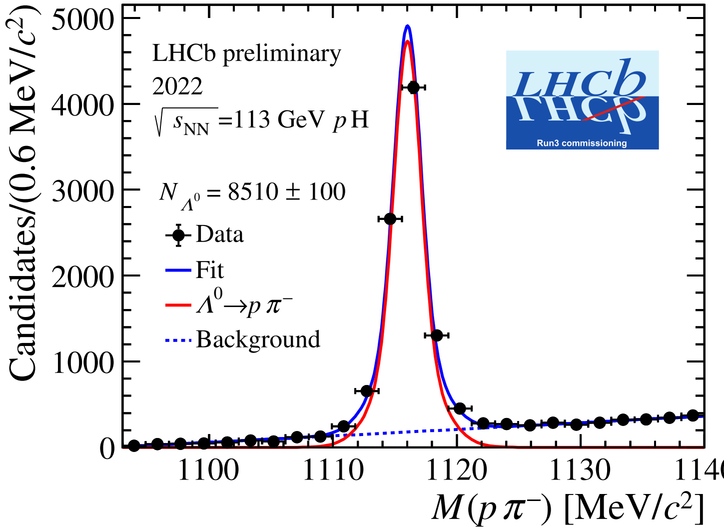
More details and commissioning figures:

- LHCb-FIGURE-2023-001
- LHCb-FIGURE-2023-008

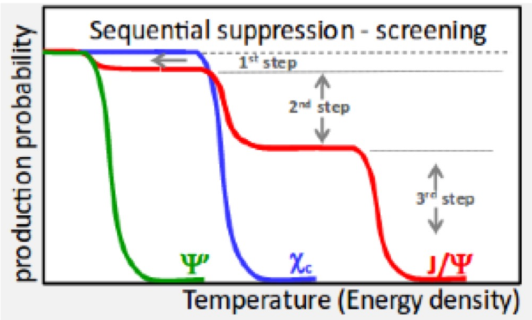




Future physics perspectives with SMOG2 (find more in backup slides!)

Heavy-ion physics:

- New measurements of prompt charm production in p-gas and Pb-gas collisions with a significantly increased statistical precision.
- Study of cold nuclear matter effects (baseline to understand QGP signals)
- Measurements of excited charmonium states (including $\psi(2S)$ and χ_c) relevant for studying the **sequential charmonia suppression** due to **color screening**.
- Possibility to measure also **charmed baryons** (Λ_c^+) as well as **prompt beauty production**
- Measurement of QGP-related flow observables and correlations in Pb-A collisions at $\sqrt{s_{NN}} \sim 70$ GeV



different binding energies lead to different dissociation temperatures
J.Phys.G32:R25,2006

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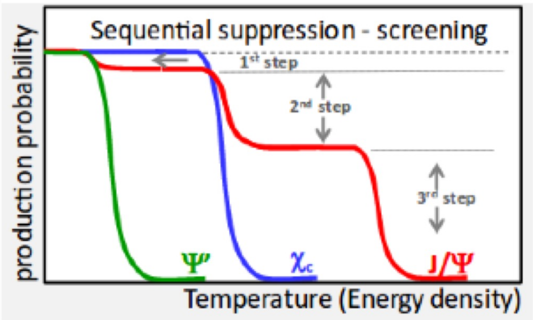

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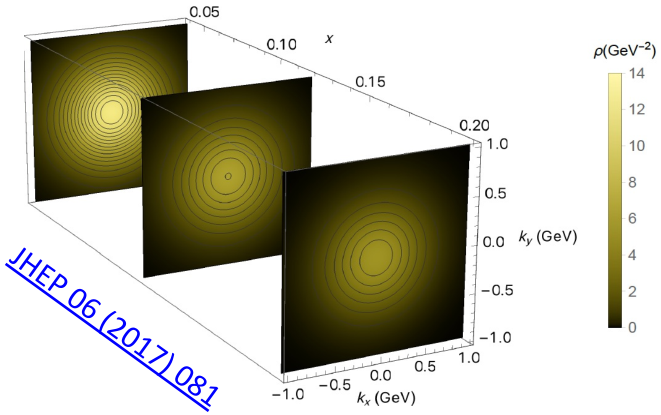
Nucleon structure:

- SMOG2 operated with H_2 and D_2 targets offers unique conditions to probe quark and gluon **PDFs in nucleons and nuclei**, especially at high-x and moderately-high Q^2, where present experimental data are largely missing.
- Measurements of **quark and gluon transverse-momentum-dependent (TMD) PDFs**, respectively in **Drell-Yan** and **inclusive production of quarkonia** (J/ψ, ψ', Υ, etc.), will significantly improve our understanding of the 3D structure of the nucleon.
- Possibility to precisely test contributions from **Intrinsic charm** in the proton at high-x.



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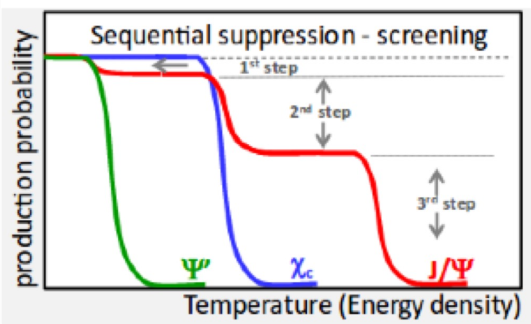
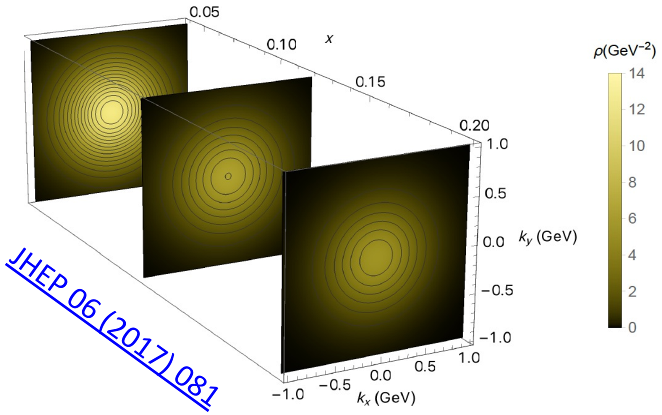
- Measurement of QGP-related flow observables and correlations in Pb-A collisions at $\sqrt{s_{NN}} \sim 70$ GeV



different binding energies lead to different dissociation temperatures
J.Phys.G32:R25,2006

Nucleon structure:

- SMOG2 operated with H_2 and D_2 targets offers unique conditions to probe quark and gluon **PDFs in nucleons and nuclei**, especially at high-x and moderately-high Q^2, where present experimental data are largely missing.
- Measurements of **quark and gluon transverse-momentum-dependent (TMD) PDFs**, respectively in **Drell-Yan** and **inclusive production of quarkonia** (J/ψ, ψ', Υ, etc.), will significantly improve our understanding of the 3D structure of the nucleon.
- Possibility to precisely test contributions from **Intrinsic charm** in the proton at high-x.



JHEP 06 (2017) 081

Cosmic-ray and DM physics: anti-hadrons production cross sections in p-H, p-D and p-He (see backup slides).

Conclusions

- **The Fixed-Target program at LHCb with SMOG, active since 2015, has already produced lots of interesting physics results:**
  - prompt and detached antiproton production in pHe collisions (→ cosmic-ray physics, DM search)
  - charm production in pHe, pAr, pNe and PbNe (→ heavy-ion physics, cold nuclear matter effects, QGP form.)

- Many ongoing analyses on different topics (CNM effects, strangeness and charm production, hyperon polarization, etc.)

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- Plenty of interesting fixed-target physics measurements at unique kinematic conditions are in program

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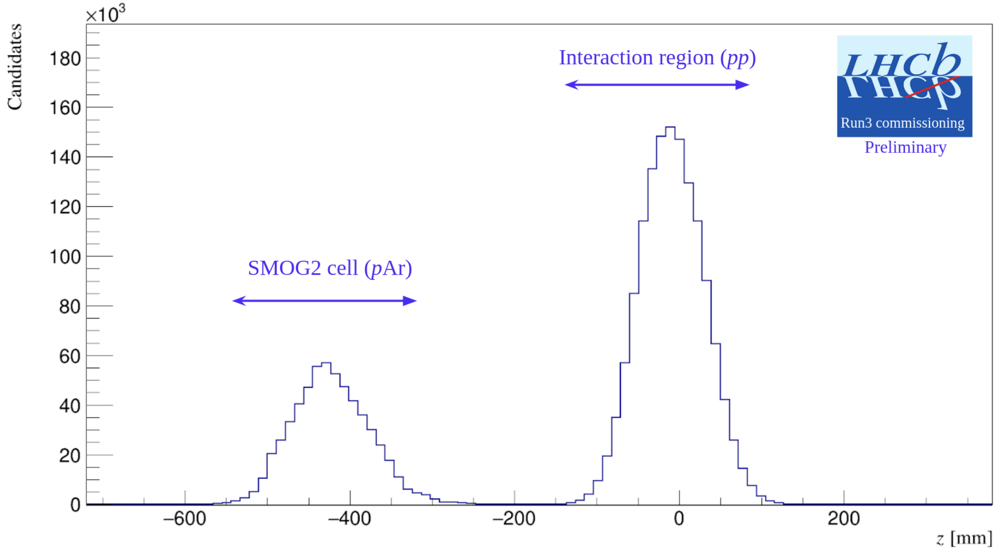
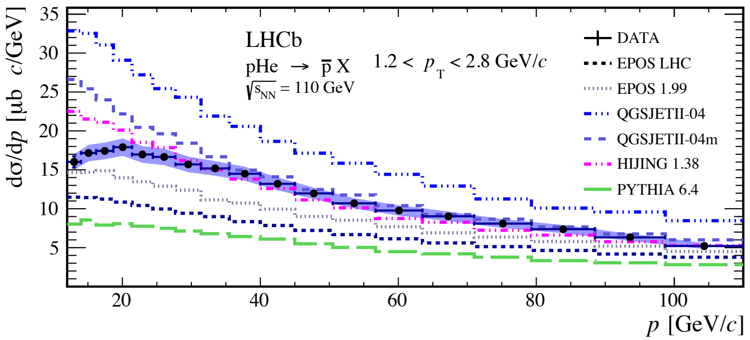
- **With SMOG2, LHCb has become the first experiment with two simultaneous interaction regions (fixed-target and collider modes), allowing for a new range of exploration at the LHC!**



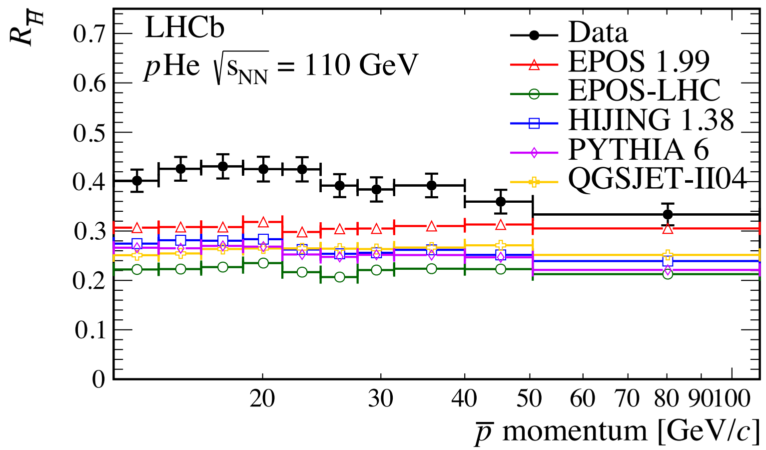
Backup

LHCb published analyses with SMOG

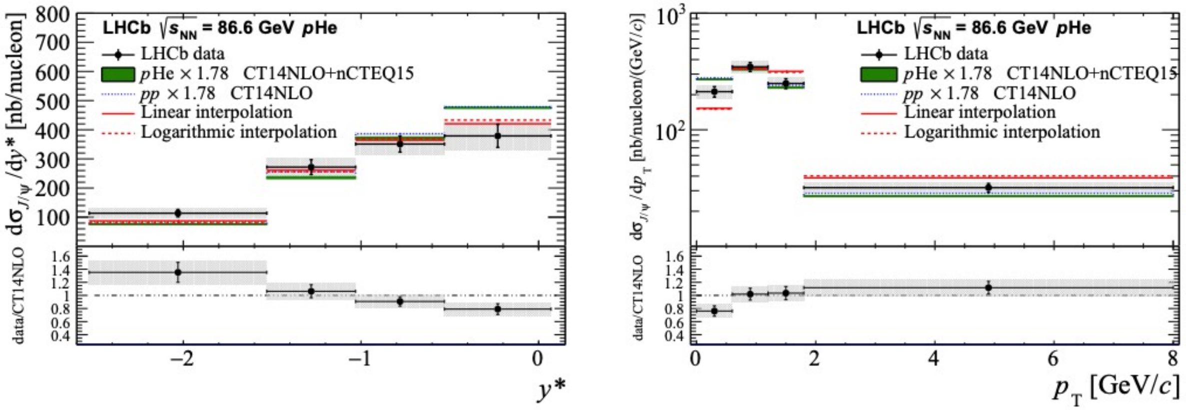
- ✓ Prompt antiproton production in pHe collisions at $\sqrt{s_{NN}} = 110$ GeV [Phys. Rev. Lett. 121 (2018) 222001]



- ✓ Antiproton production from antihyperon decays in pHe collisions at $\sqrt{s_{NN}} = 110$ GeV [arXiv:2205.09009] (acc. by EPJC)



- ✓ Charm Production in Fixed-Target pHe and pAr collisions [Phys. Rev. Lett. 122 (2019) 132002]



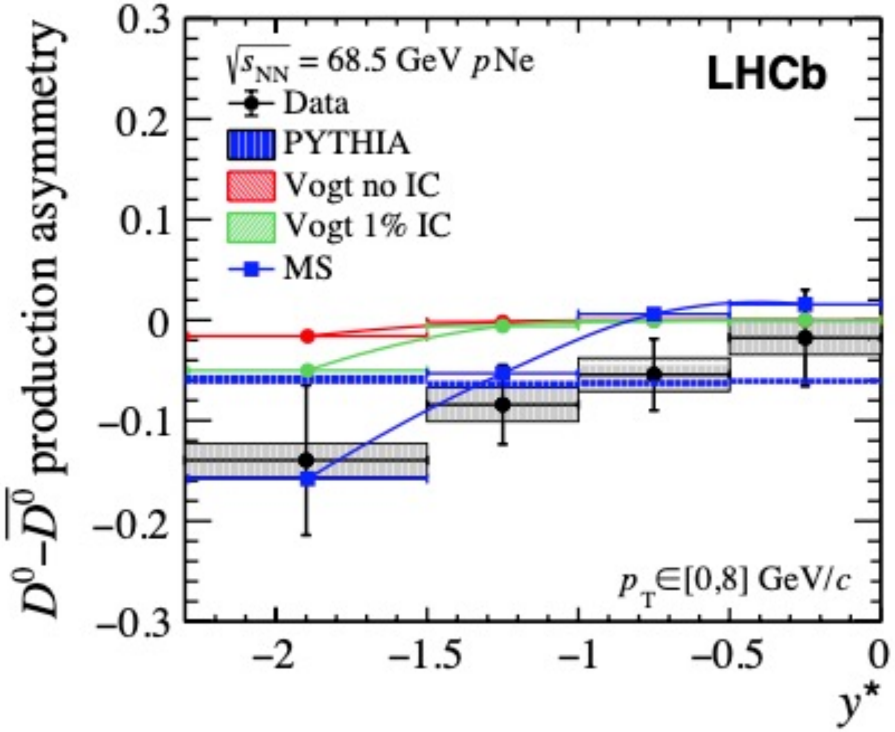
- ✓ Charmonium production in pNe collisions [arXiv:2211.11645]
- ✓ Open charm production in pNe collisions [arXiv:2211.11633]
- ✓ J/ψ and D^0 production in PbNe collisions [arXiv:2211.11652]

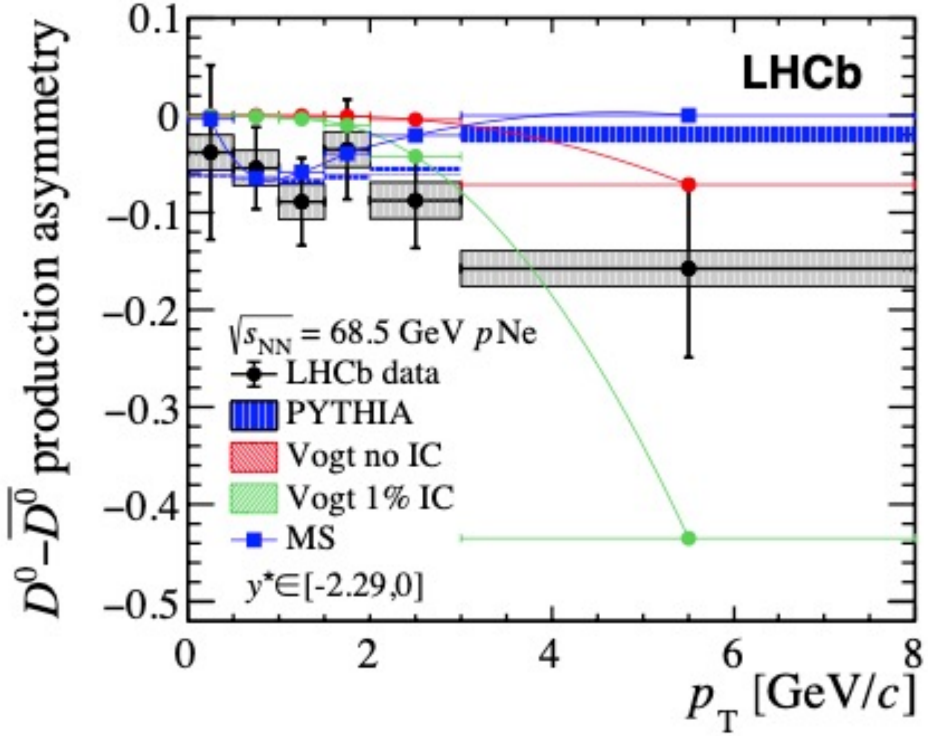
Relevant for

- Study of cold nuclear matter effects in pNe collisions (no QGP)
- Study of sequential suppression of charmonia states in PbNe as signal of QGP formation
- Cross section measurements in a unique kinematic domain

Charm production in pNe @ $\sqrt{s_{NN}} = 68.5$ GeV

[arXiv:2211.11633]

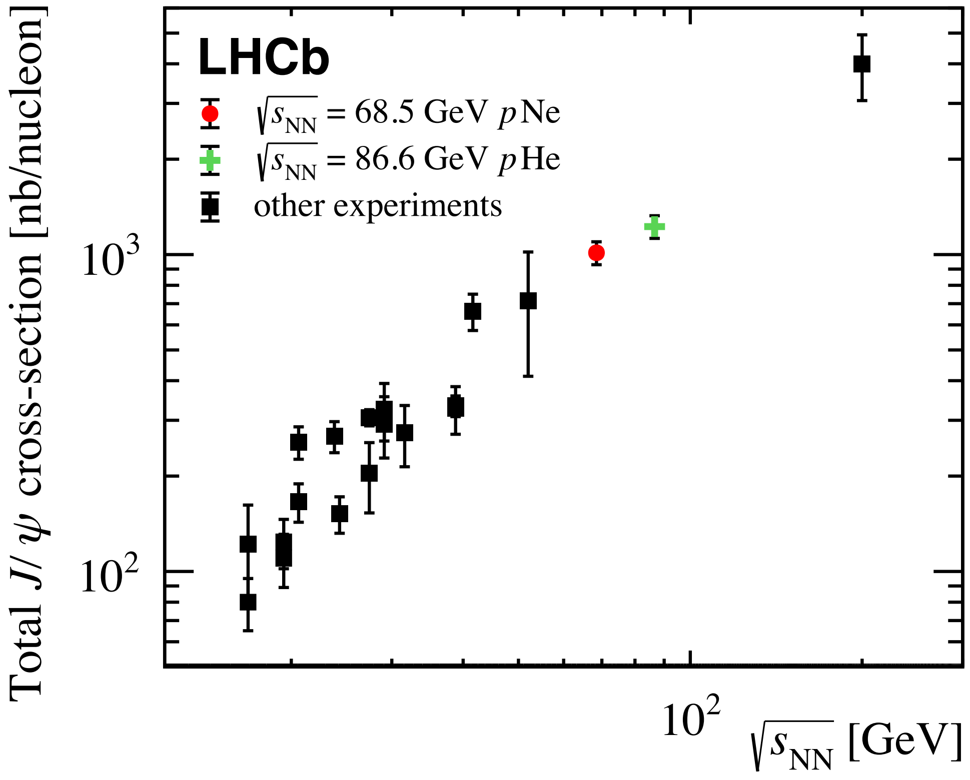


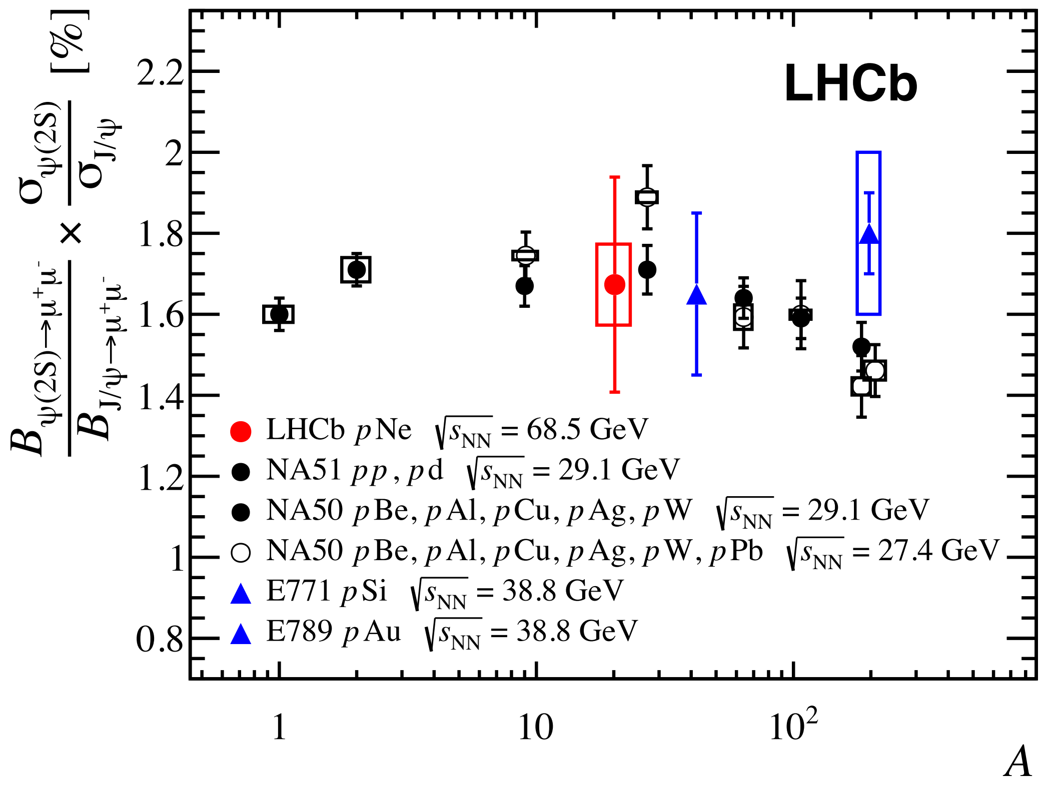


$$\mathcal{A}_{\text{prod}} = \frac{Y_{\text{corr}}(D^0) - Y_{\text{corr}}(\overline{D}^0)}{Y_{\text{corr}}(D^0) + Y_{\text{corr}}(\overline{D}^0)}$$

- Probe charm hadronization at high-x
- Asymmetry of $\sim 15\%$ in most negative y^* bin
- Available models fail to simultaneously describe y^* and p_T distributions

Charm production in pNe @ $\sqrt{s_{NN}} = 68.5$ GeV





SMOG2 projected performances for LHC Run3

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

	SMOG published result pHe@87 GeV	SMOG largest sample pNe@69 GeV	SMOG2 example pAr@115 GeV
Integrated luminosity	7.6 nb^{-1}	$\sim$ 100 nb^{-1}	$\sim$ 45 pb^{-1}
syst. error on J/ψ x-sec.	7%	6 - 7%	2 - 3 %
J/ψ yield	400	15k	15M
D^0 yield	2000	100k	150M
Λ_c^+ yield	20	1k	1.5M
$\psi(2S)$ yield	negl.	150	150k
$\Upsilon(1S)$ yield	negl.	4	7k
Low-mass Drell-Yan yield	negl.	5	9k

Opportunities with SMOG2: cosmic rays and DM

- Thanks to the possibility to use also a H_2 target, it will be possible to precisely measure the ratio:

$$\frac{\sigma(pHe \rightarrow \bar{p}X)}{\sigma(pH \rightarrow \bar{p}X)}$$

where many systematic uncertainties cancel

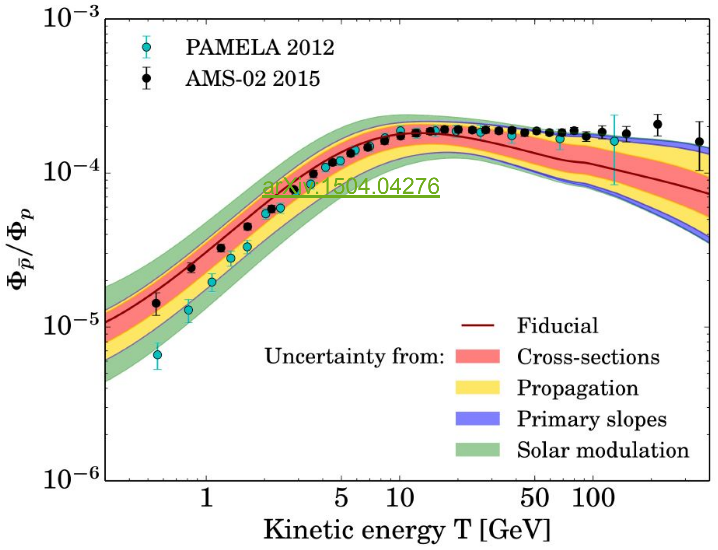
- By injecting H_2 and D_2 it will be possible to test isospin symmetry in the ratio:

$$\frac{\sigma(pD \rightarrow \bar{p}X)}{\sigma(pH \rightarrow \bar{p}X)}$$

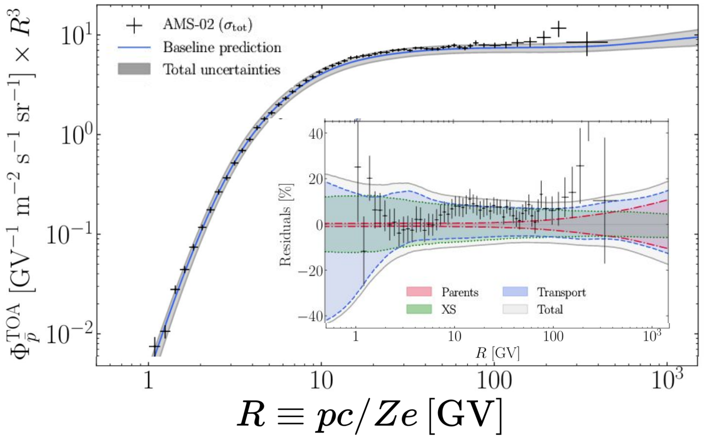
which can allow to put constraints on the unknown production ratio

$$\frac{\sigma(pH \rightarrow \bar{n}X)}{\sigma(pH \rightarrow \bar{p}X)}$$

- Possibility to measure cross sections at different CM energies
- Light anti-nuclei production: $pp,\ pHe\ \rightarrow\ \bar{d}\ ,\ \overline{H_e}$
- $pp,\ pHe\ \rightarrow\ \pi, K$ to model positron source term



M. Boudaud et. al., PoS (ICRC2019) 038

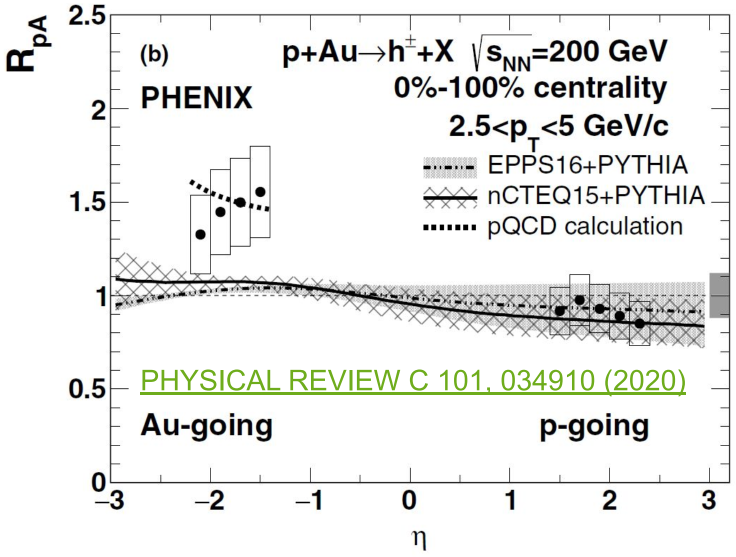


Opportunities with SMOG2: cold nuclear matter effects

Heavy Ions studies and Cold Nuclear Matter Effects

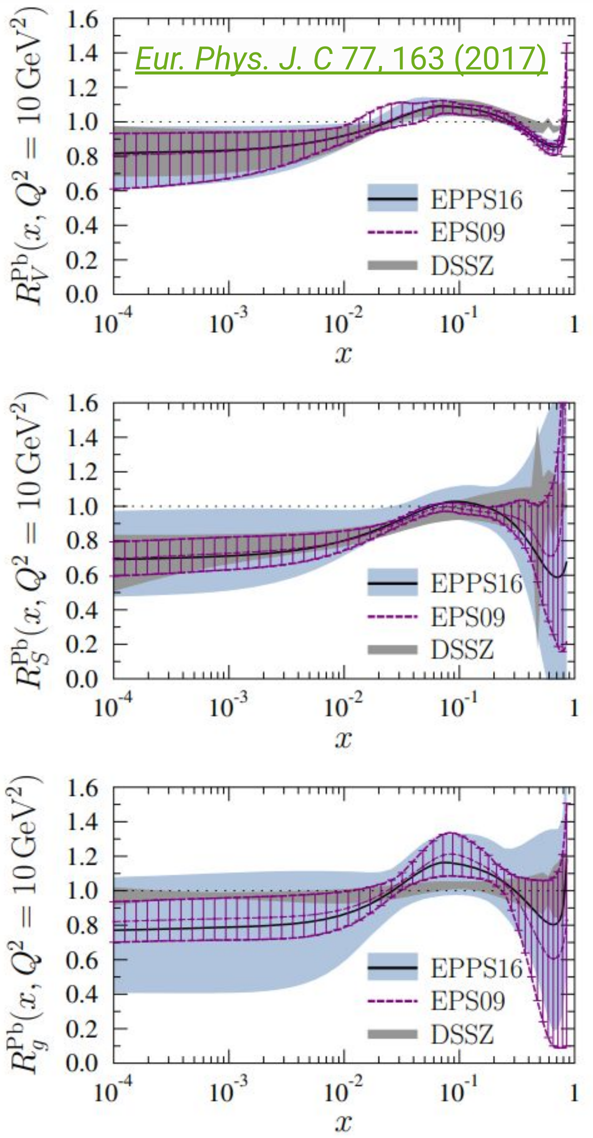
Study and disentangle effects arising from the structure of the initial state of the collision and medium-induced effects

- *Modification of the nucleon PDFs in nuclear matter*
- *High-x parton PDFs*
- *antishadowing, EMC effects*
- *Cronin effect*
- *nuclear absorption*

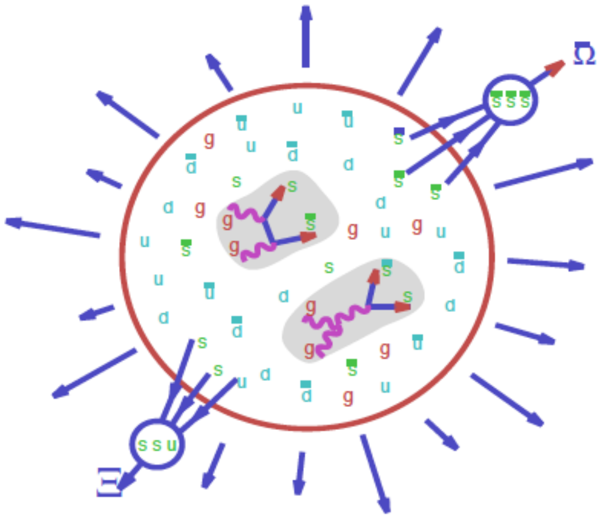


$$R_i^A(x,Q^2) = \frac{f_i^{p/A}(x,Q^2)}{f_i^{p}(x,Q^2)}$$

$$R_{pA} = \frac{dY^{pA}/dp_T d\eta}{dY^{pp}/dp_T d\eta} \cdot \frac{1}{\langle N_{coll}\rangle}$$



Opportunities with SMOG2: strangeness production in PbA vs. pA

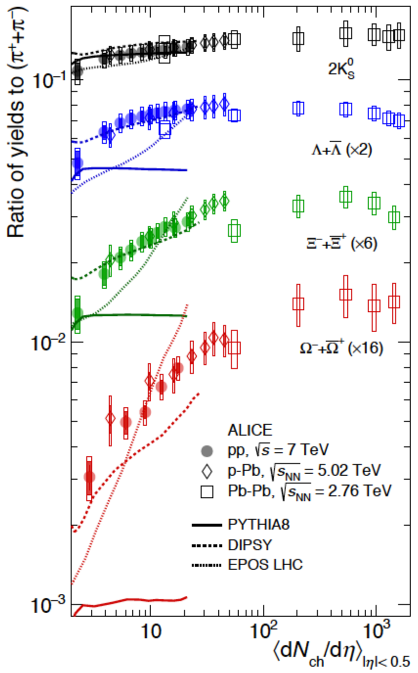


Strangeness enhancement is expected due to:

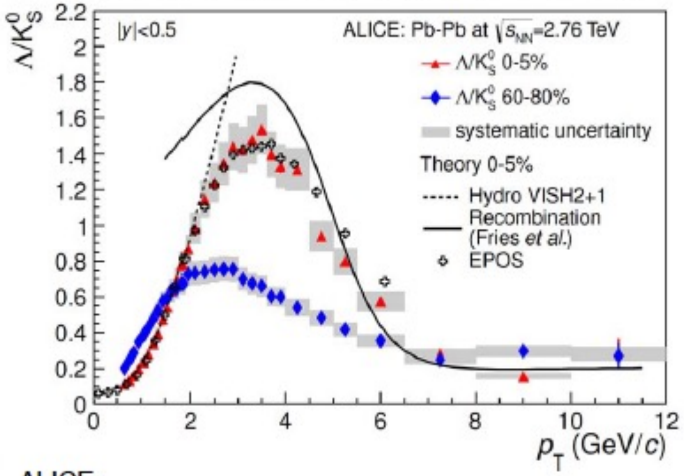
- high gluon density in the QGP
- dominance of the gluonic production channel for strangeness in the QGP ($gg \rightarrow s\bar{s}$)
- mass of the s quark being similar to the critical temperature T for the QCD phase transition ($\sim 150\ MeV$)
- strangeness formation time similar to the expected lifetime of the QGP. Therefore strangeness chemical equilibration in QGP is possible, leading to abundant strange quark density in QGP

Strange/non-strange hadron ratios vs. event multiplicity $\boldsymbol{p_T}$ and $\boldsymbol{\eta}$

- $(K^+ + K^-)/(\pi^+ + \pi^-)$
- $K_S^0/(\pi^+ + \pi^-)$
- $(\Lambda + \bar{\Lambda})/(\pi^+ + \pi^-)$
- $(\Xi^- + \bar{\Xi}^+)/(\pi^+ + \pi^-)$
- $(\Omega^- + \bar{\Omega}^+)/(\pi^+ + \pi^-)$



Baryon/meson ratios: $\boldsymbol{p/\pi, \Lambda/K, \Lambda/\phi, \Omega/\phi}$,…



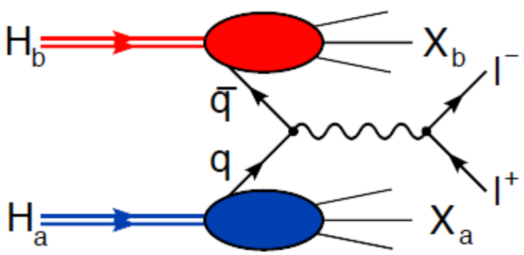
ALICE
PRL111, 222301 (2013)

Opportunities with SMOG2: quark TMDs

quark pol.

nucleon pol.	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

Unpolarized Drell-Yan

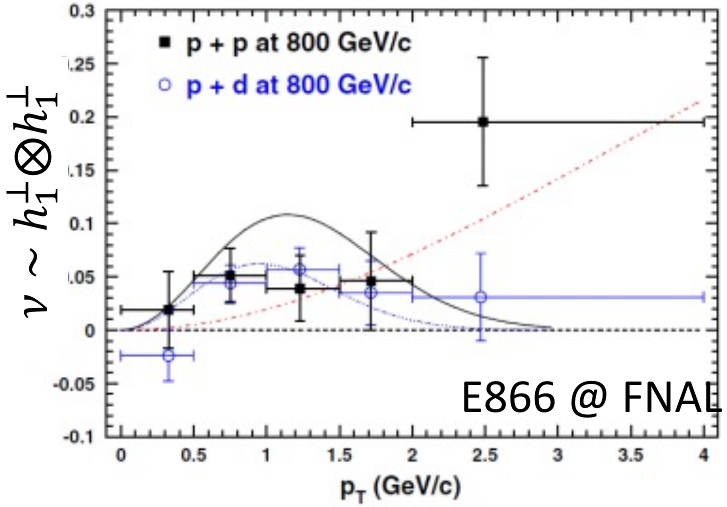


- Theoretically cleanest hard h-h scattering process
- LHCb has excellent μ-ID & reconstruction for $\mu^+\mu^-$
- **dominant**: $\bar{q}(x_{beam}) + q(x_{target}) \rightarrow \mu^+\mu^-$
- suppressed: $q(x_{beam}) + \bar{q}(x_{target}) \rightarrow \mu^+\mu^-$
- beam sea quarks probed at small x
- target valence quarks probed at large x

Sensitive to unpol. and BM TMDs for $q_T \ll M_{ll}$

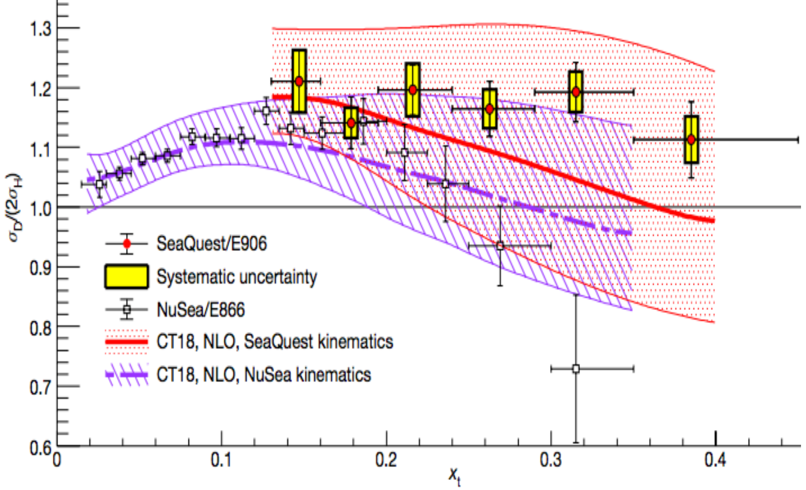
(violation of Lam-Tung relation)

$$d\sigma_{UU}^{DY} \propto f_1^{\bar{q}} \otimes f_1^q + \cos 2\phi\ h_1^{\perp,\bar{q}} \otimes h_1^{\perp,q}$$



[PRL 102 2009 182001]

[Nature 590, 561 (2021)]

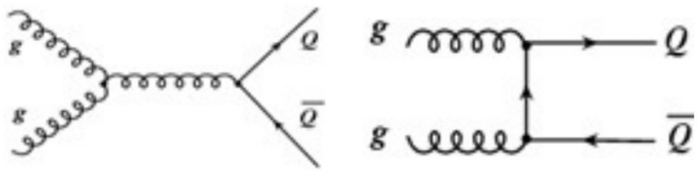


- Lattice QCD: $\bar{s}(x) \neq s\ (x)$ [arXiv:1809.04975]
- **proton sea more complex than originally thought!**
- **intrinsic heavy quarks**?
- Still a lot to be understood

- H & D targets allow to study the **antiquark content of the nucleon**
- SeaQuest (E906): $\bar{d}(x) > \bar{u}(x) \implies$ **sea is not flavour symmetric!**

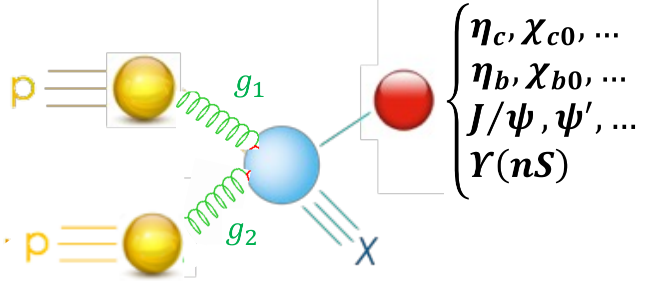
Opportunities with SMOG2: gluon TMDs

In high-energy hadron collisions, heavy quarks are dominantly produced through gg fusion:



The most efficient way to access the gluon dynamics inside the proton at LHC is to **measure heavy-quark observables**

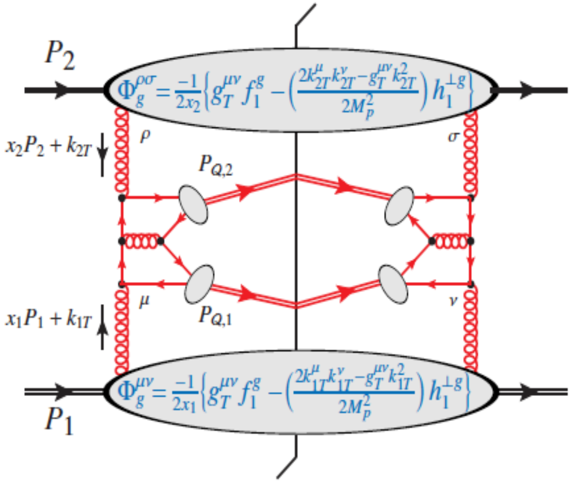
- **Inclusive quarkonia production in (un)polarized pp interaction** $(pp^{(\uparrow)} \to [Q\bar{Q}]X)$ turns out to be an ideal observable to access gTMDs (assuming TMD factorization)



- TMD factorization requires $q_T(Q) \ll M_Q$. Can look at **associate quarkonia production**, where only the relative q_T needs to be small:

E.g.: $pp^{(\uparrow)} \to J/\psi + J/\psi + X$

- Due the larger masses this condition is more easily matched in the case of **bottomonium**, where TMD factorization can hold at larger q_T (although very challenging for experiments!)



$pp \to J/\psi\, J/\psi\, X$

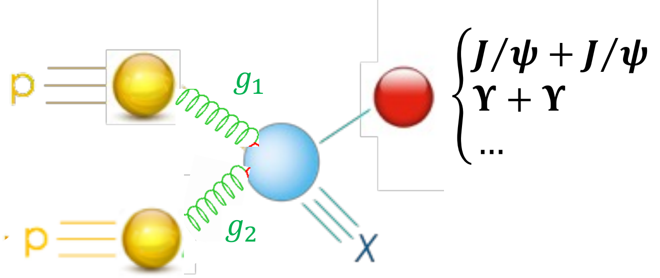
Opportunities with SMOG2: gluon TMDs

$$\frac{d\sigma}{dM_{QQ}dY_{QQ}d^2\boldsymbol{P}_{QQ_T}d\Omega} = \frac{\sqrt{M_{QQ}^2 - 4M_Q^2}}{(2\pi)^2 8s\, M_{QQ}^2}$$

$$\Big\{ F_1(M_{QQ},\theta_{CS})\, \mathcal{C}\Big[f_1^g f_1^g\Big](x_{1,2},\boldsymbol{P}_{QQ_T})$$

$$+F_2(M_{QQ},\theta_{CS})\, \mathcal{C}\Big[w_2 h_1^{\perp g} h_1^{\perp g}\Big](x_{1,2},\boldsymbol{P}_{QQ_T})$$

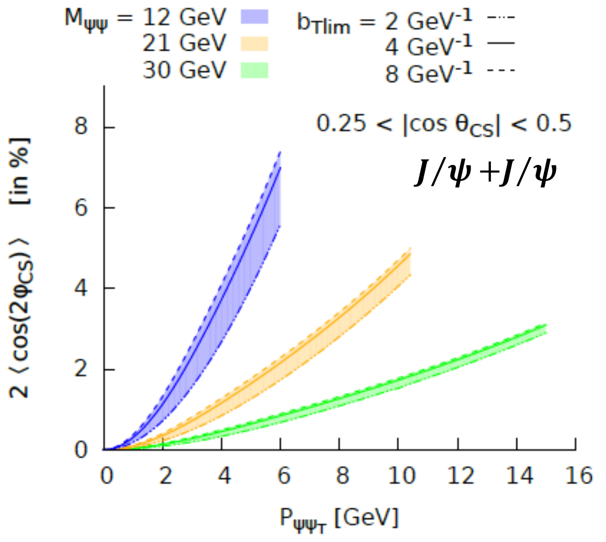
$$+\boxed{\Big(F_3(M_{QQ},\theta_{CS})\, \mathcal{C}\Big[w_3 f_1^g h_1^{\perp g}\Big](x_{1,2},\boldsymbol{P}_{QQ_T}) + F_3'(M_{QQ},\theta_{CS})\, \mathcal{C}\Big[w_3' h_1^{\perp g} f_1^g\Big](x_{1,2},\boldsymbol{P}_{QQ_T})\Big)\cos 2\phi_{CS}} \boxed{+F_4(M_{QQ},\theta_{CS})\, \mathcal{C}\Big[w_4 h_1^{\perp g} h_1^{\perp g}\Big](x_{1,2},\boldsymbol{P}_{QQ_T})\cos 4\phi_{CS}\Big\}}$$



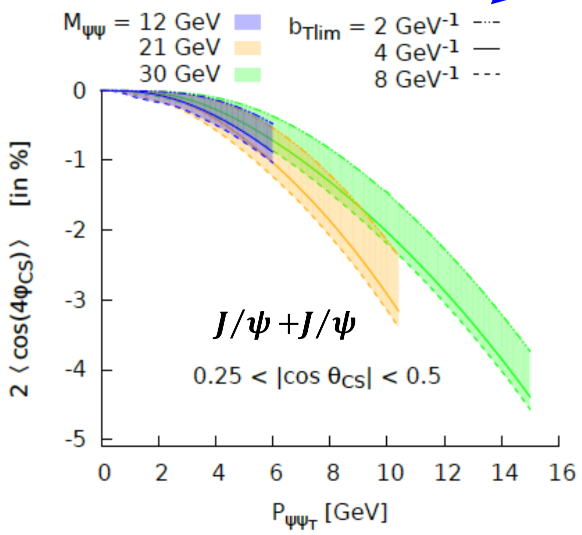
gluon pol.

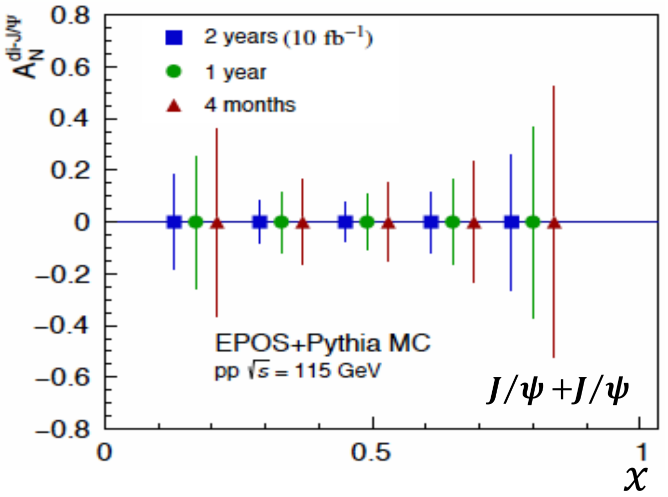
nucleon pol.	U	Circularly	Linearly
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	$h_1^g,\ h_{1T}^{\perp g}$

Predictions based on CSM + TMD evolution for $x_1 \sim x_2 \sim 10^{-3}$ at forward rapidity [EPJ C 80, 87 (2020)]



Azimuthal amplitudes $\sim 5\%$!



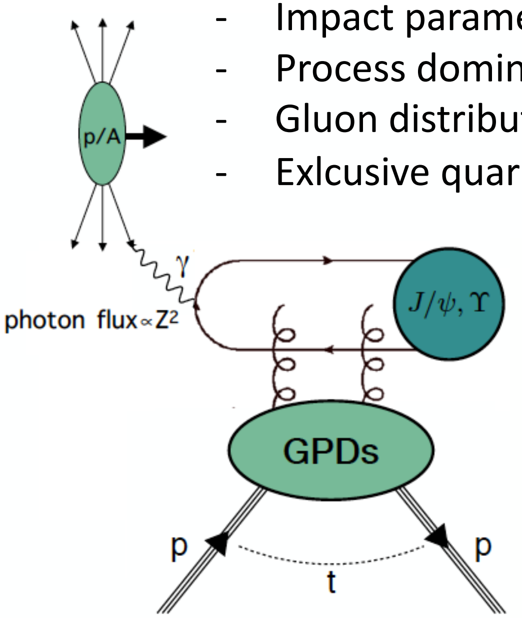


Opportunities with SMOG2: UPC and GPDs

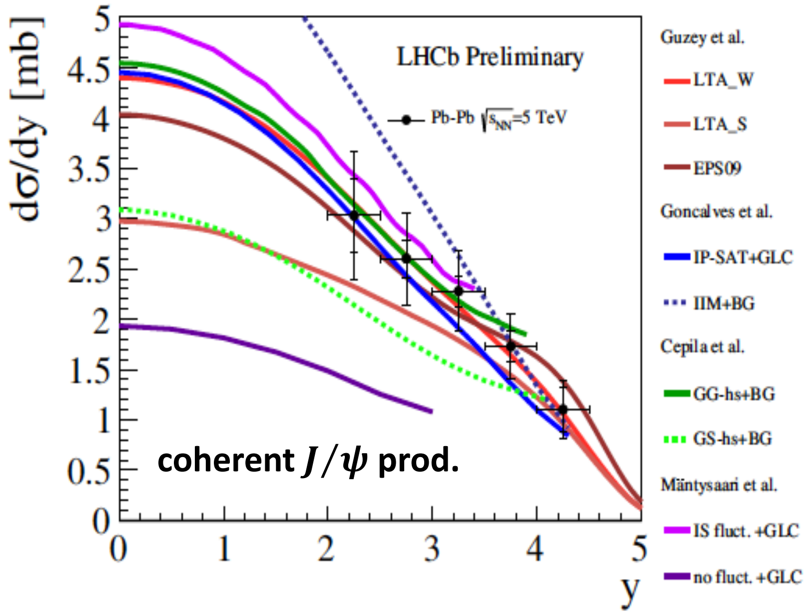
GPD	U	L	T
U	H		$\mathcal{E}_T$
L		$\tilde{H}$	$\tilde{E}_T$
T	E	$\tilde{E}$	$H_T,\ \tilde{H}_T$

Gluon GPDs can be accessed at LHC in **Ultra-Peripheral collisions (UPC)**

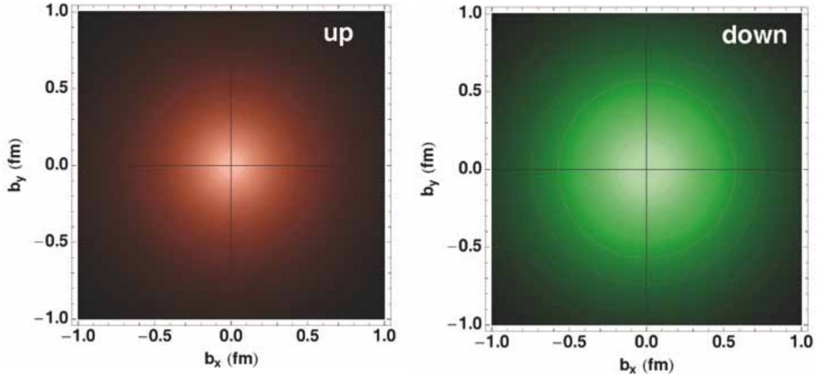
- Impact parameter larger than sum of radii
- Process dominated by EM interaction
- Gluon distributions probed by pomeron exchange
- Exlcusive quarkonia prod. sensitive to gluon GPDs [PRD 85 (2012), 051502]



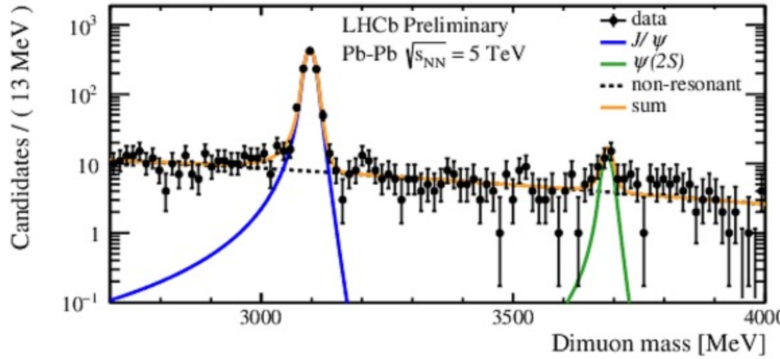
First results from LHCb in PbPb UPC



3D maps of parton densities in coordinate space



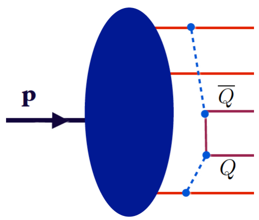
[NS 28 (2012), 1]



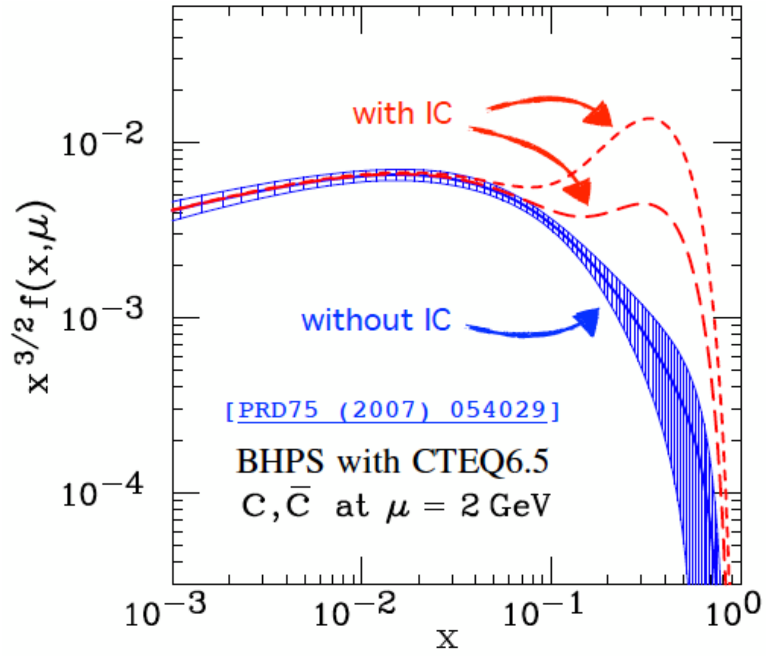
[NPA 982 (2019) 247]

Opportunities with SMOG2: intrinsic charm

Intrinsic heavy-quark
- 5-quark Fock state of the proton may contribute at high x!
- **charm PDFs** at large x could be larger than obtained from conventional fits



[PRD 75 (2007) 054029]



- **Significant contributions of IC expected at large x**

- First search performed with SMOG [PRL 122 (2019)]
- New intriguing LHCb results with pp collisions at large rapidity [arXiv:2109.08084]
- Still to be investigated!