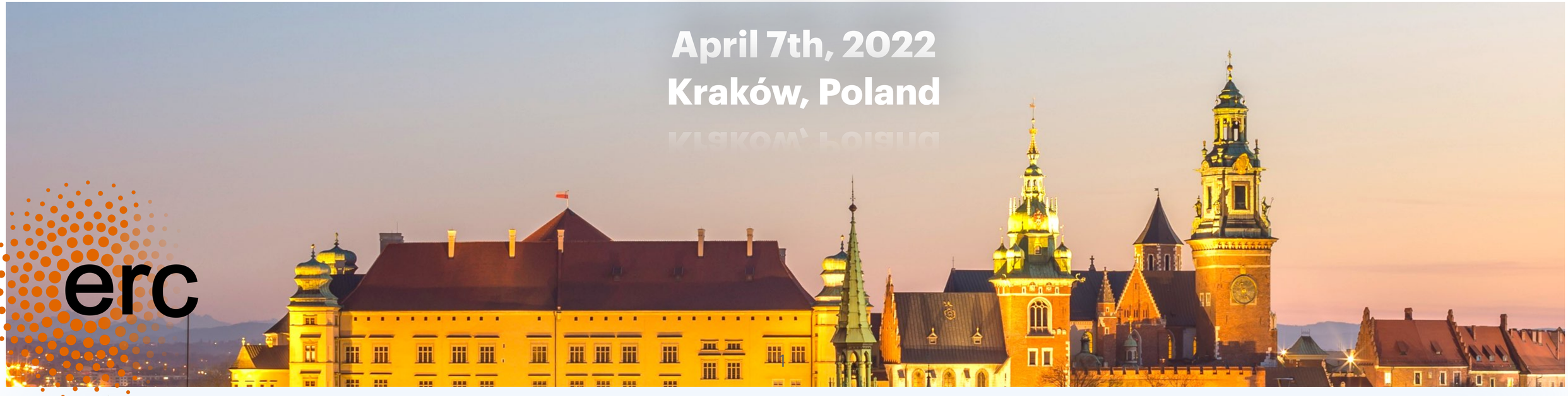
New measurements in fixed-target collisions at LHCb

Jiayin Sun for the LHCb collaboration
INFN Cagliari

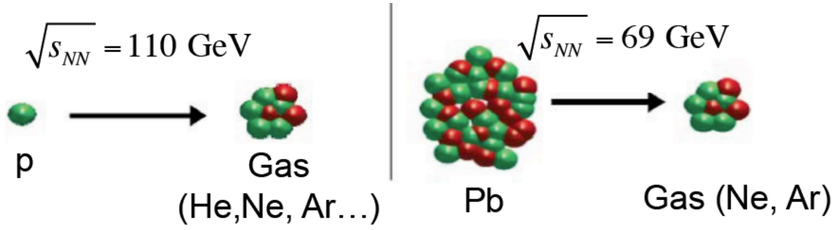


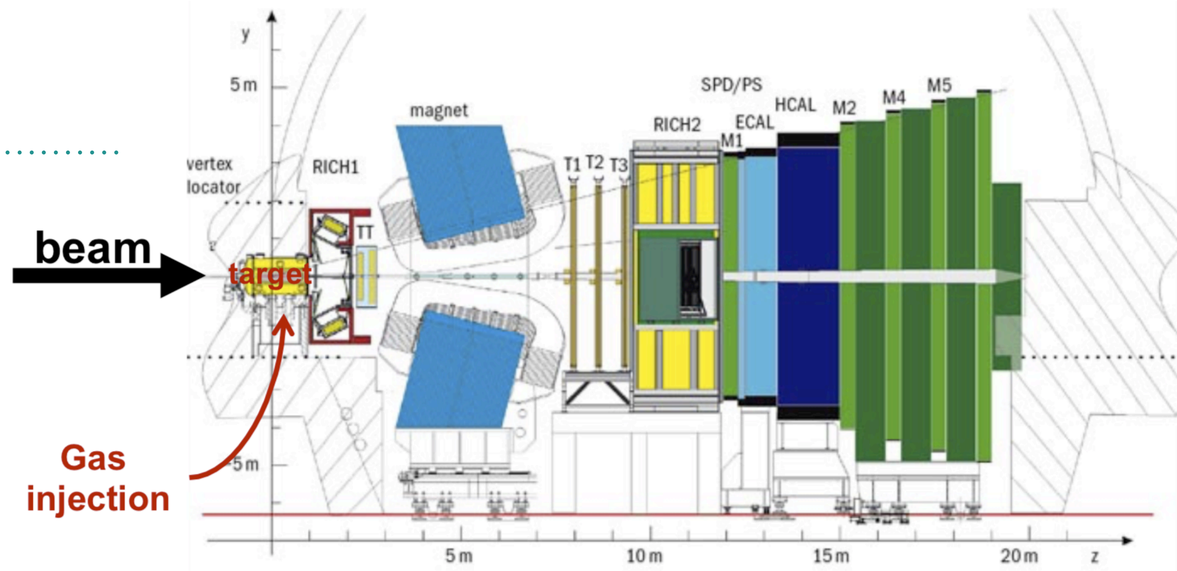
Outline

- The LHCb fixed-target program: SMOG
- ***New SMOG results:***
  - Charmonia production in pNe collisions at $\sqrt{s_{\mathrm{NN}}} = 68.5$ GeV LHCb-PAPER-2022-014
  - D^0 and J/ψ production in PbNe collisions at $\sqrt{s_{\mathrm{NN}}} = 68.5$ GeV LHCb-PAPER-2022-012
  - Detached antiproton production in pHe collisions at $\sqrt{s_{\mathrm{NN}}} = 110$ GeV LHCb-PAPER-2022-006
- SMOG2 upgrade for Run3

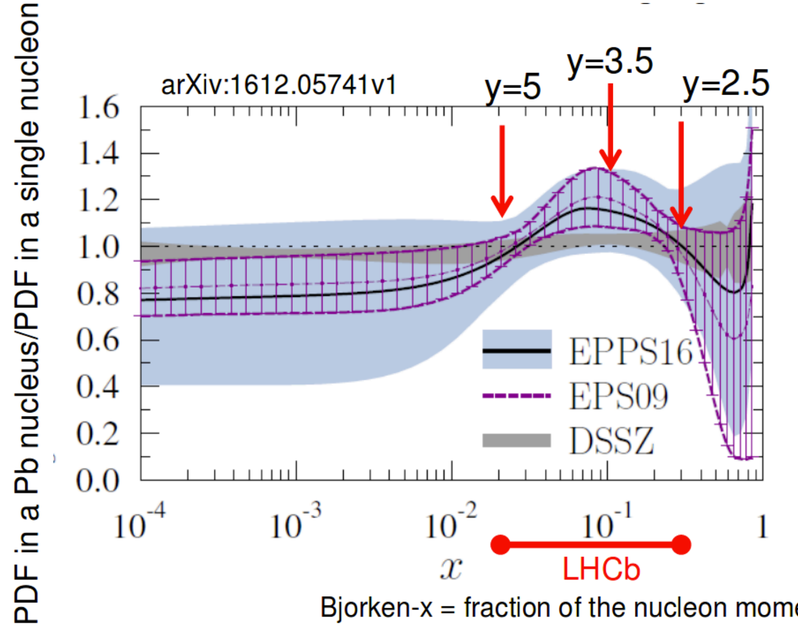
SMOG

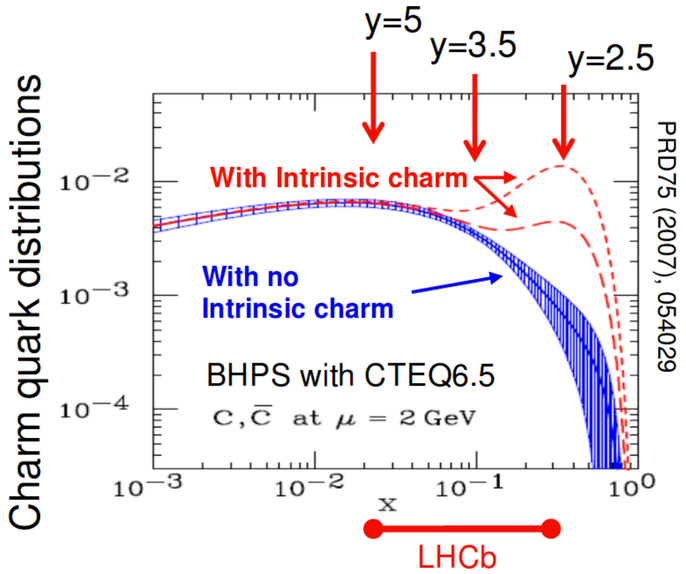
Fixed target mode

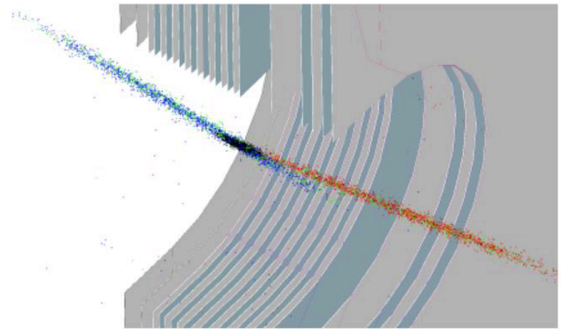




- SMOG: System for Measuring Overlap with Gas
- A noble gas (He, Ne, Ar) at ~2×10^{-7} mbar pressure injected into the LHC vacuum around the LHCb interaction region
- Originally used to determine luminosity, since 2015 started to collect fixed-target collision data





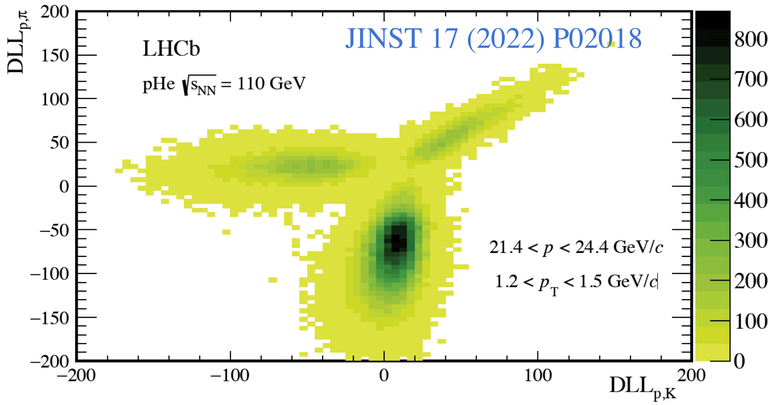


- $\sqrt{s_{NN}}$ = 69-110 GeV between SPS & RHIC
- $-3.0 < y^* < 0$
- Access nPDF anti-shadowing region
- Probe intrinsic charm content in the nucleon
- Inputs to astrophysics

SMOG datasets and results

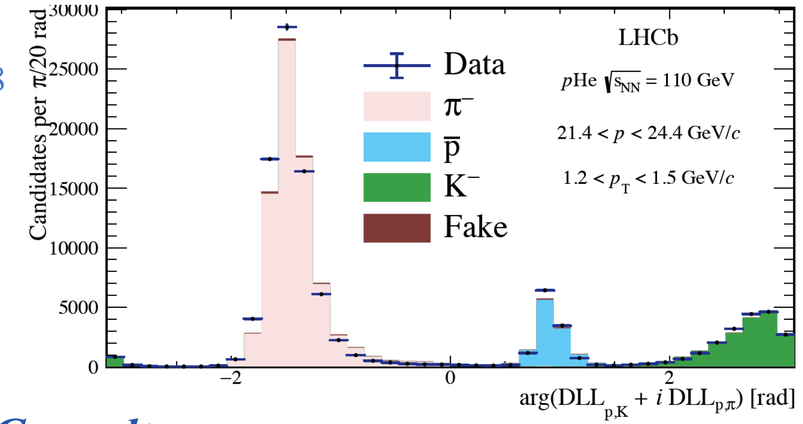
New results:

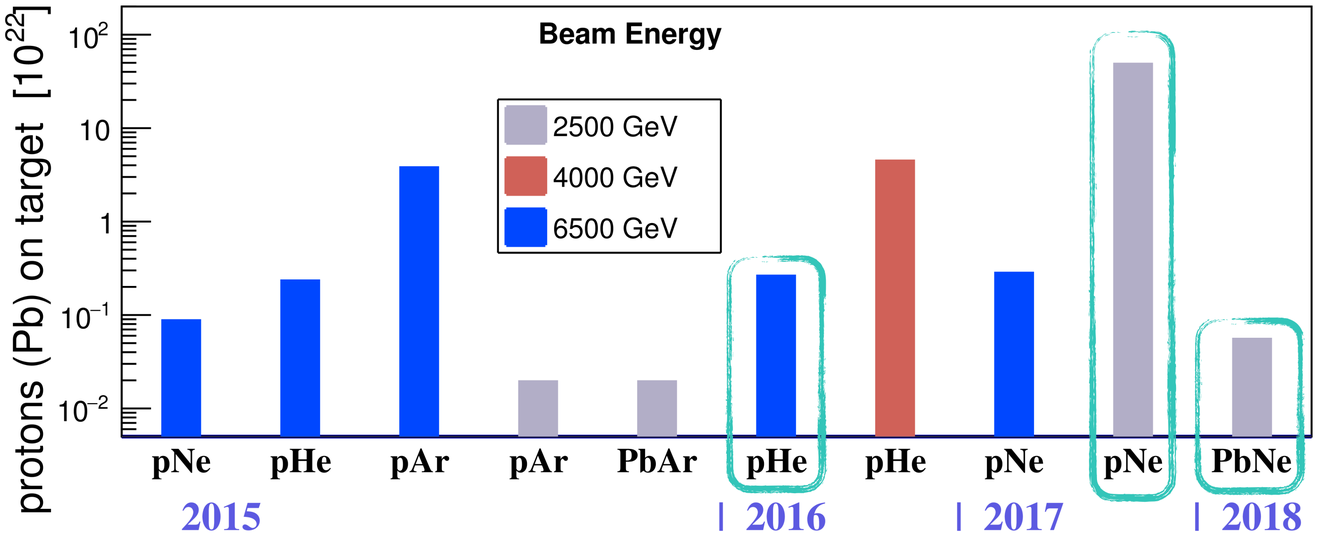
- Charmonia production in *p*Ne collisions at 68.5 GeV
- J/ψ and D^0 production in PbNe collisions at 68.5 GeV
- Detached antiproton production in *p*He collisions at 110 GeV



New technical publication:

- A Neural-Network-defined Gaussian Mixture Model for PID with SMOG data JINST 17 (2022) P02018
- Centrality determination in heavy-ion collisions with the LHCb detector arXiv:2111.01607





Previous SMOG results:

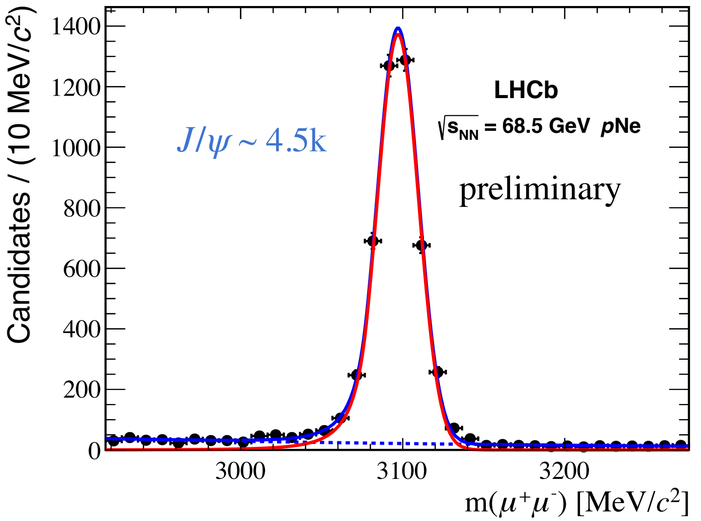
- Charm production in *p*Ar, *p*He collisions
  Phys. Rev. Lett. 122 (2019) 132002
- Prompt antiproton in *p*He collisions at 110 GeV
  Phys. Rev. Lett. 121 (2018) 222001

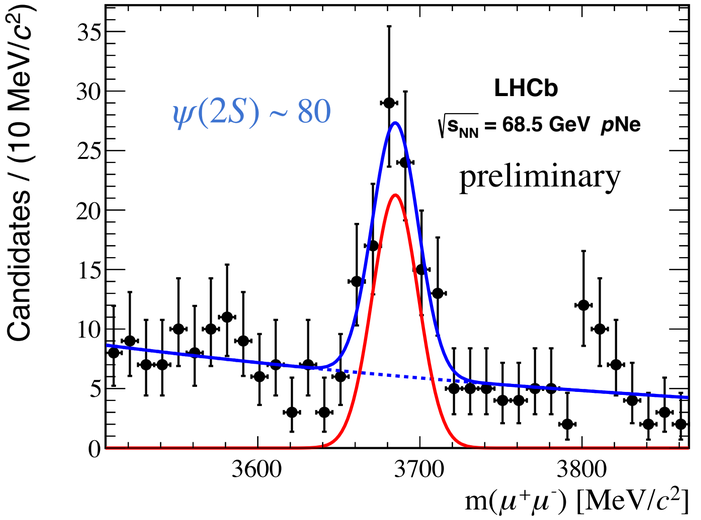
Charmonia in *p*Ne collisions at 68.5 GeV

LHCb-PAPER-2022-014
In preparation

- Charmonium production modified by initial and final state effects in proton-nucleus collisions
  - Modification of PDFs inside nuclei, CGC
  - Nuclear absorption, multiple scattering, energy loss
  - Comovers

- Dataset: collisions of 2.5 TeV protons and neon nuclei at rest ==> $\sqrt{s_{\mathrm{NN}}} = 68.5$ GeV
- Luminosity $21.7 \pm 1.4\ nb^{-1}$
- Center-of-mass rapidity coverage: $-2.3 < y^{*} < 0$

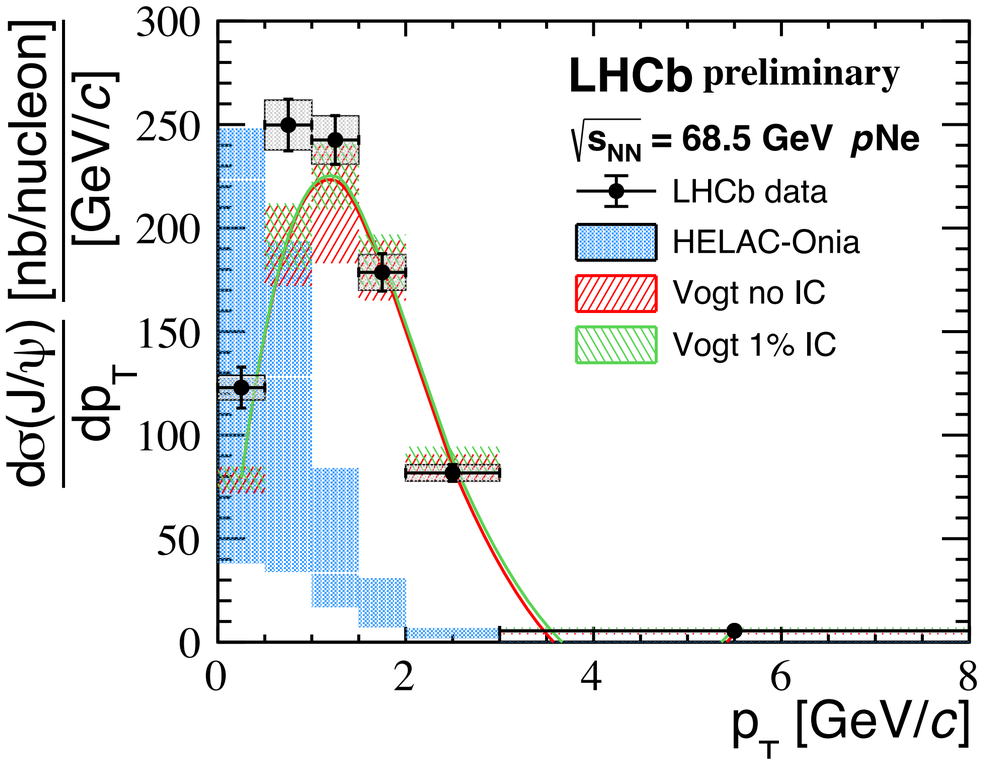


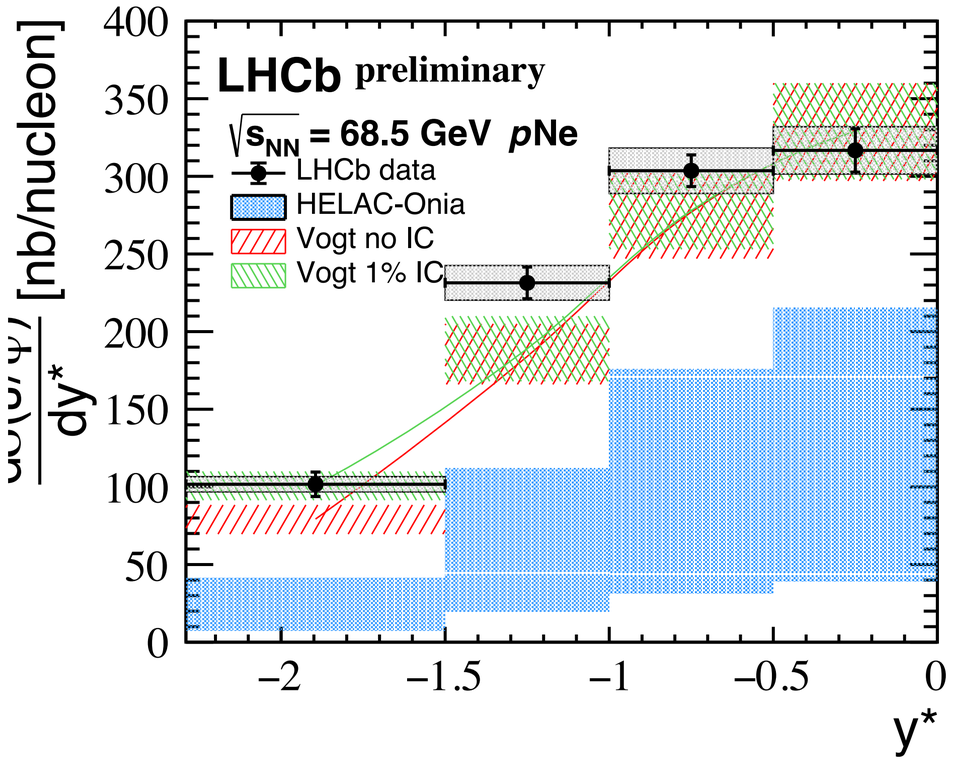


Charmonia in *p*Ne collisions at 68.5 GeV

LHCb-PAPER-2022-014
In preparation

Differential J/ψ production cross-section

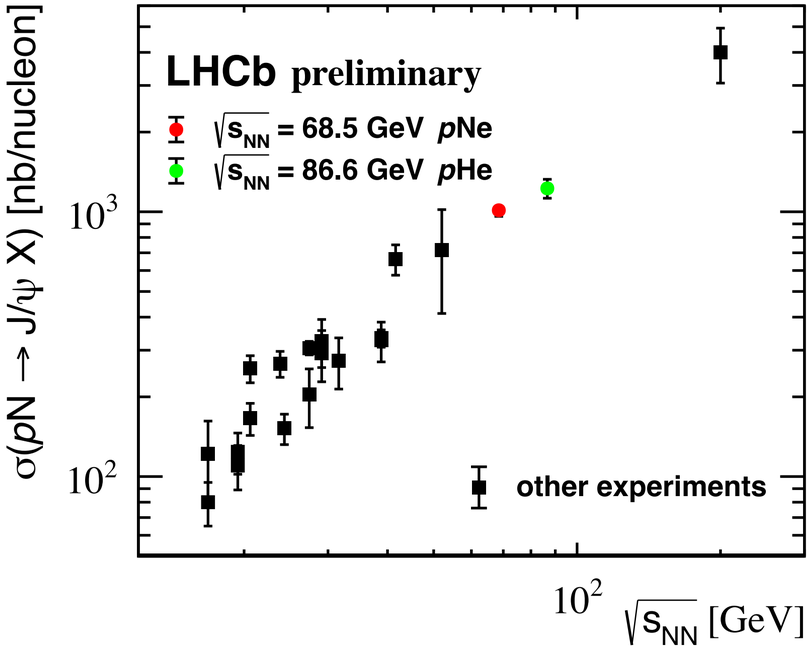


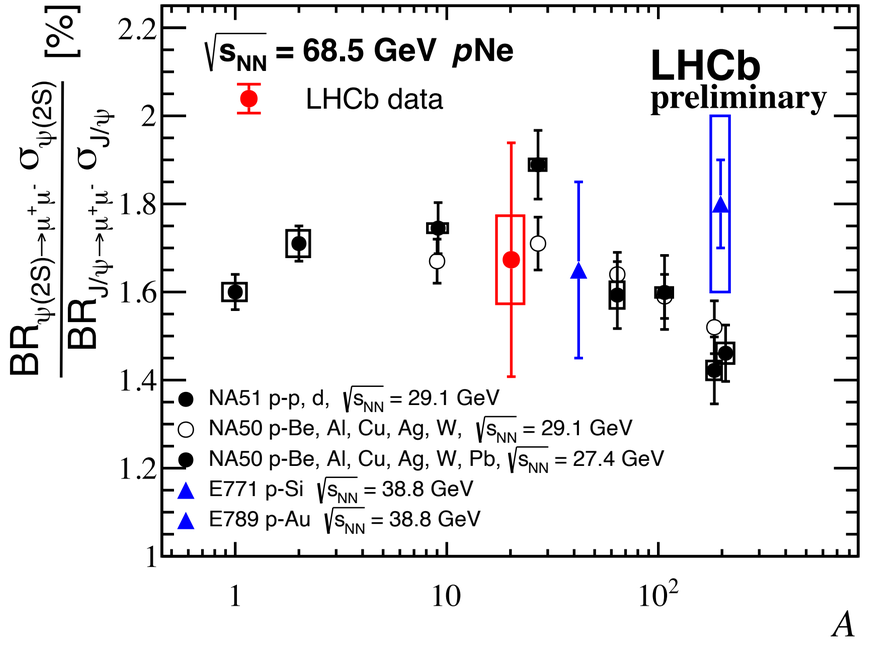


- HELAC-ONIA using CT14NLO and nCTEQ15 under predicts the data
- Good agreement with predictions with (1%) and without an Intrinsic Charm contribution [PRC103 (2021) 035204]

Charmonia in *p*Ne collisions at 68.5 GeV

LHCb-PAPER-2022-014
In preparation



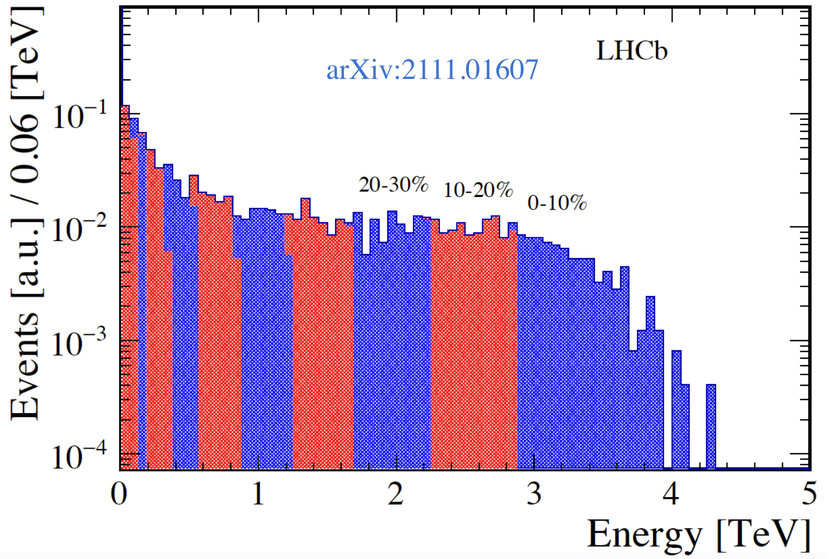


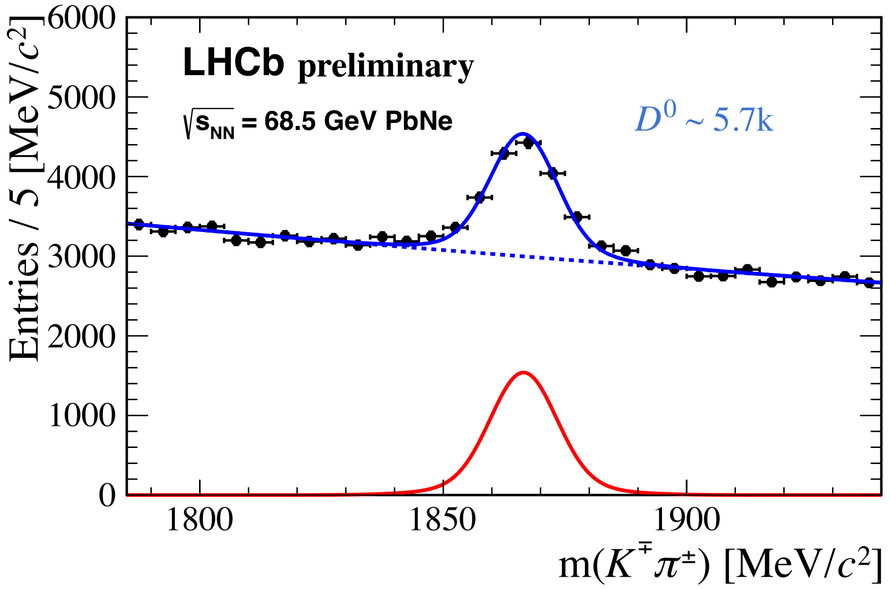
- Total J/ψ cross-section: extrapolation to full phase space using Pythia8+CT09MCS PDF, assuming forward-backward symmetry.
  - shows a power-law dependency with the center-of-mass energy $\sqrt{s_{\mathrm{NN}}}$
- $\psi(2S)$ to J/ψ production ratio in good agreement with other proton-nucleus measurements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

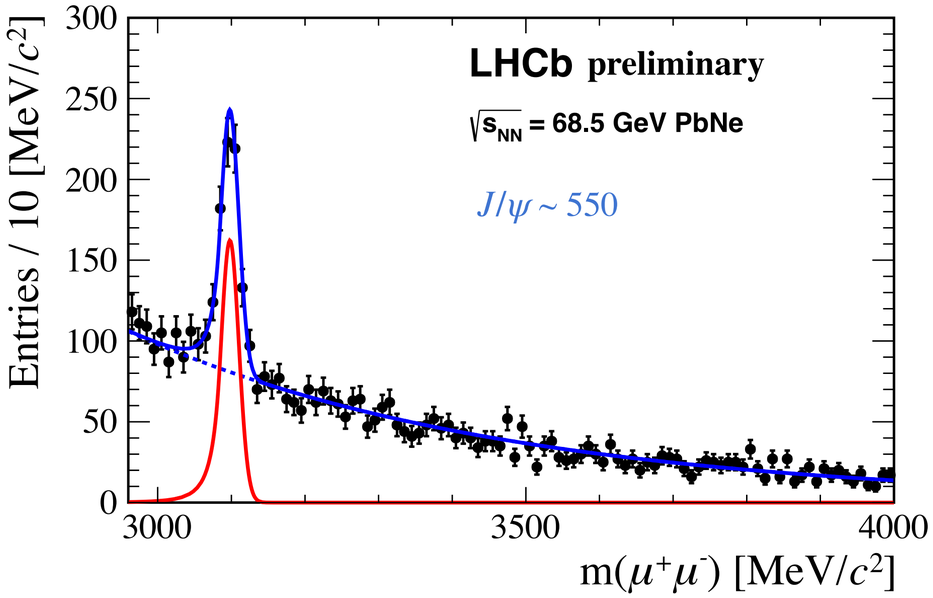
D^0 and J/ψ in PbNe collisions at 68.5 GeV

LHCb-PAPER-2022-011, in preparation

- The first measurement of J/ψ and D^0 production in fixed-target nucleus-nucleus collisions at the LHC
- Search for the potential formation of quark-gluon plasma. Look for the onset of the transition from ordinary hadronic matter to the QGP.
- Suppression of charmonium $c\bar{c}$ bound states due to presence of the hot and dense medium
- Dataset: 2.5 TeV lead ions incident on neon nuclei ==> $\sqrt{s_{\mathrm{NN}}} = 68.5$ GeV
- PbNe centrality determined by energy in ECal



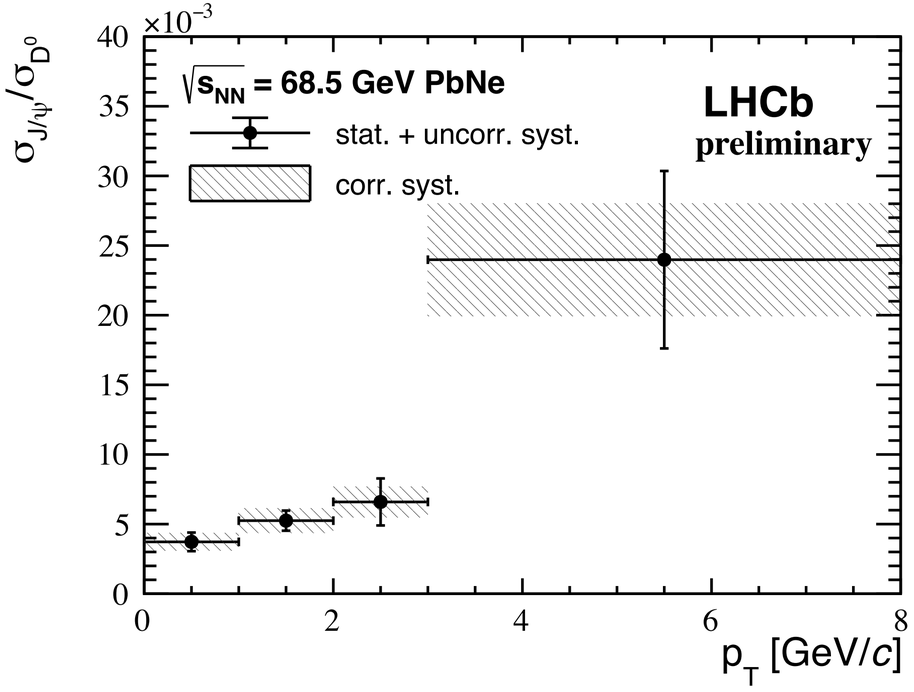




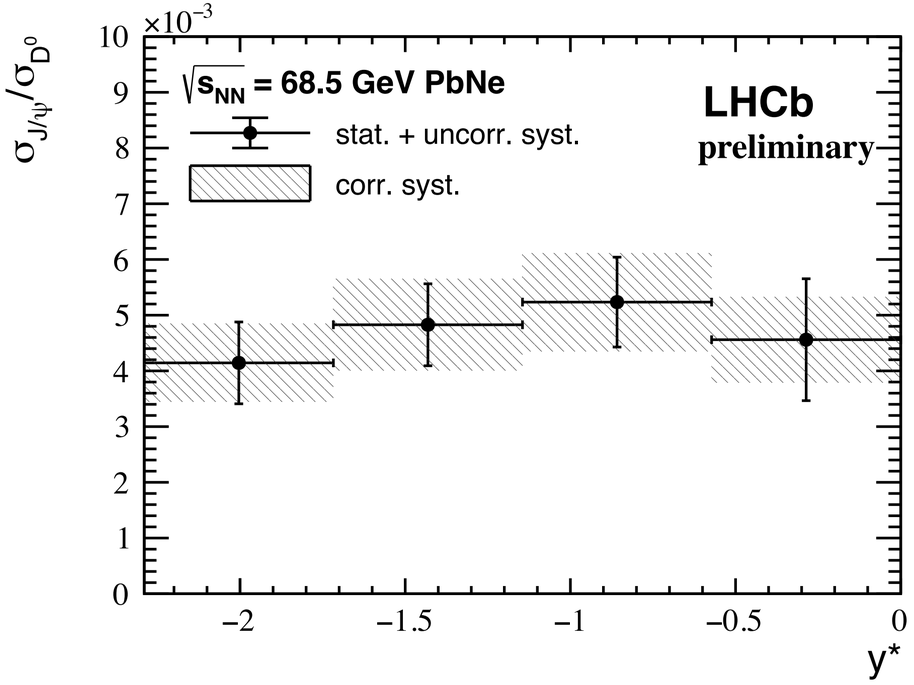
D^0 and J/ψ in PbNe collisions at 68.5 GeV

LHCb-PAPER-2022-011
In preparation

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



- Depends strongly on p_T



- Compatible with no dependence on rapidity

- Suppression of $c\bar{c}$ bound states: measure charmonium together with the overall charm quark production
- The production of D^0 mesons reflects a large fraction of the overall charm quark production
- D^0 acts as a reference for studying quarkonium modification inside nuclear medium

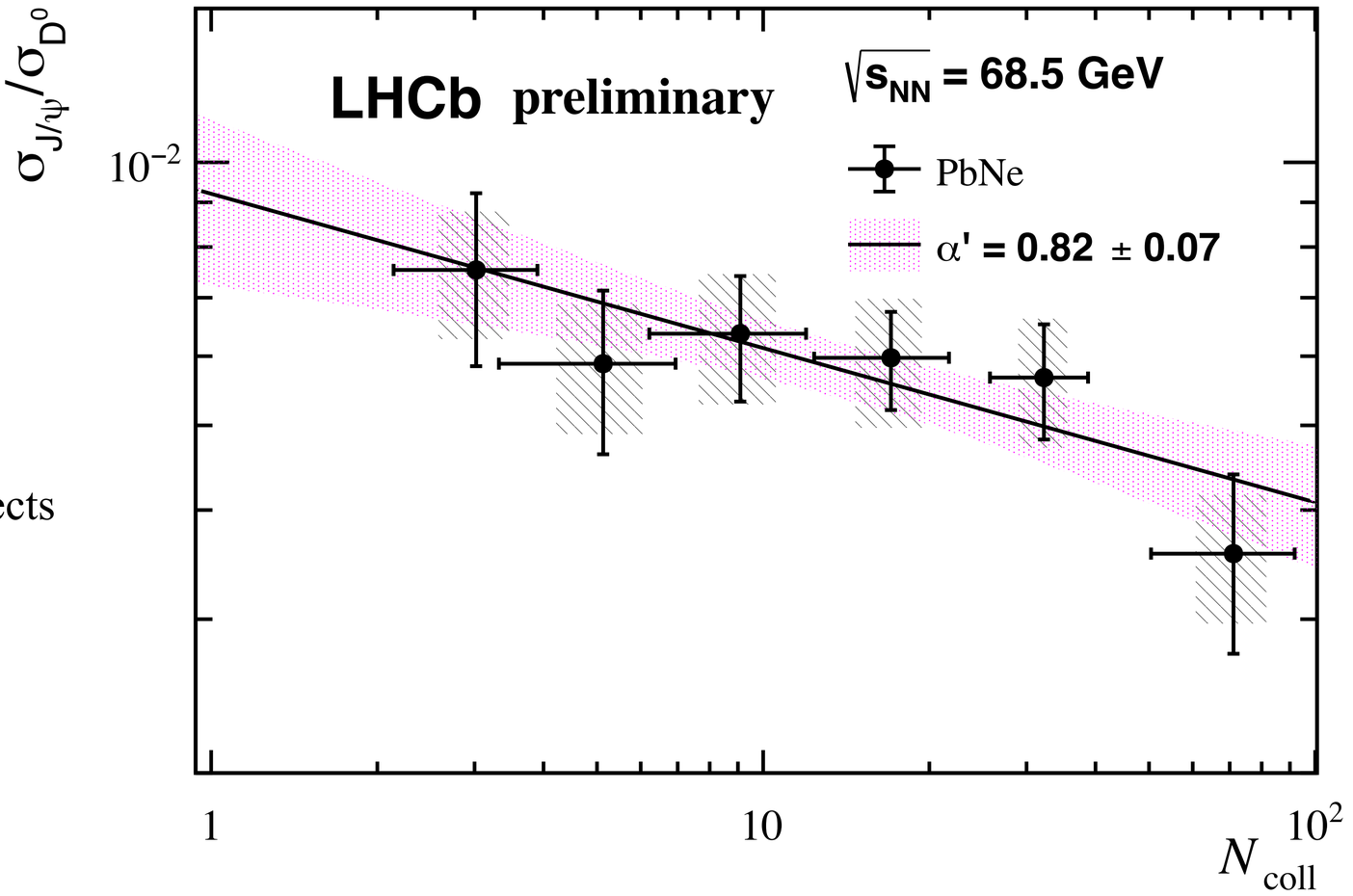
D^0 and J/ψ in PbNe collisions at 68.5 GeV

LHCb-PAPER-2022-011
In preparation

J/ψ / D^0 ratio as a function of N_{coll}

- Assuming $\sigma_{J/\psi} \propto \langle N_{coll} \rangle^{\alpha'}$ and $\sigma_{D^0} \propto \langle N_{coll} \rangle$

  ==> $\sigma_{J/\psi}/\sigma_{D^0} \propto \langle N_{coll} \rangle^{\alpha'-1}$
- $\alpha' = 0.82 \pm 0.07$
- Agree with measurements from proton-nucleus collisions by NA50 Phys. Lett. B 410 (1997) 337
- J/ψ production affected by additional nuclear effects compared to D^0
- No anomalous J/ψ suppression is observed that could indicate the formation of QGP

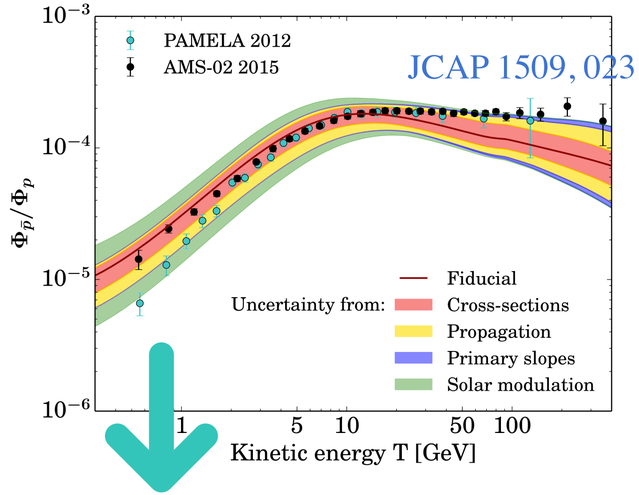


Detached antiproton in pHe collisions at 110 GeV

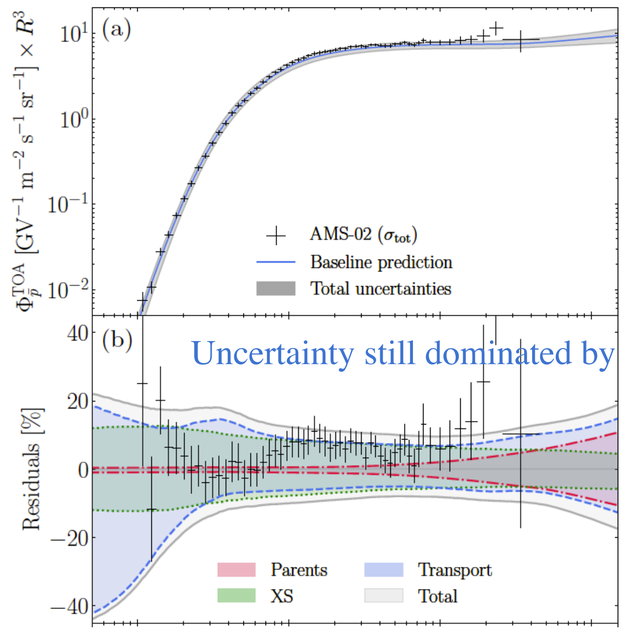
SMOG input to astrophysics

LHCb-PAPER-2022-006, in preparation

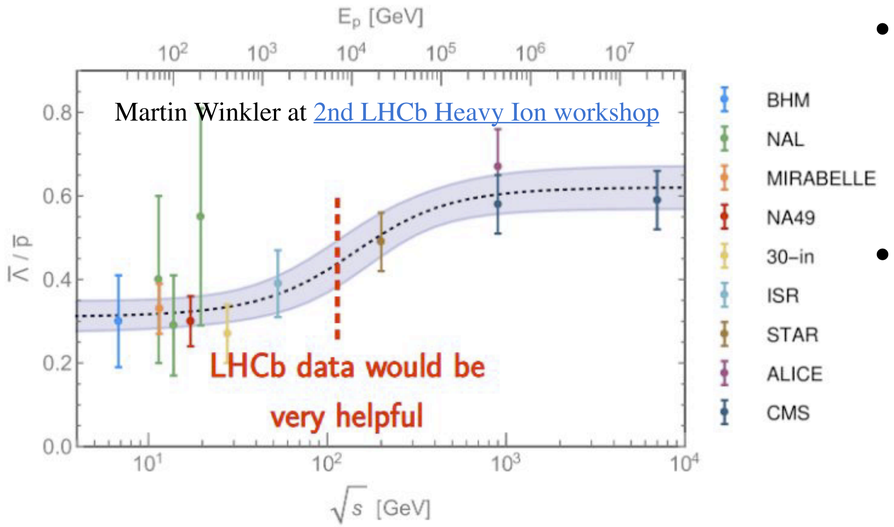
- PAMELA and AMS-02 measurements of $\bar{p}/p$ in cosmic rays sensitive to a possible dark matter contribution
- Interpretation of $\bar{p}/p$ measurements require precise $\bar{p}$ production cross-section in spallation of cosmic rays in the interstellar medium (H and He)
- A first measurement of prompt $\bar{p}$ production in pHe collisions at 110 GeV using SMOG PRL 121 (2018) 222001
- Extending the first measurement: antiproton from anti-hyperon decays (detached $\bar{p}$)



JCAP 1509, 023 (2015)



Uncertainty still dominated by XS



- Detached $\bar{p}$ can be distinguished from prompt $\bar{p}$ in LHCb by the separation of their original vertex and the primary pHe collision vertex.
- Study strangeness production enhancement at $\sqrt{s} \sim 100$GeV

Phys. Rev. Research 2, 023022 (2020)

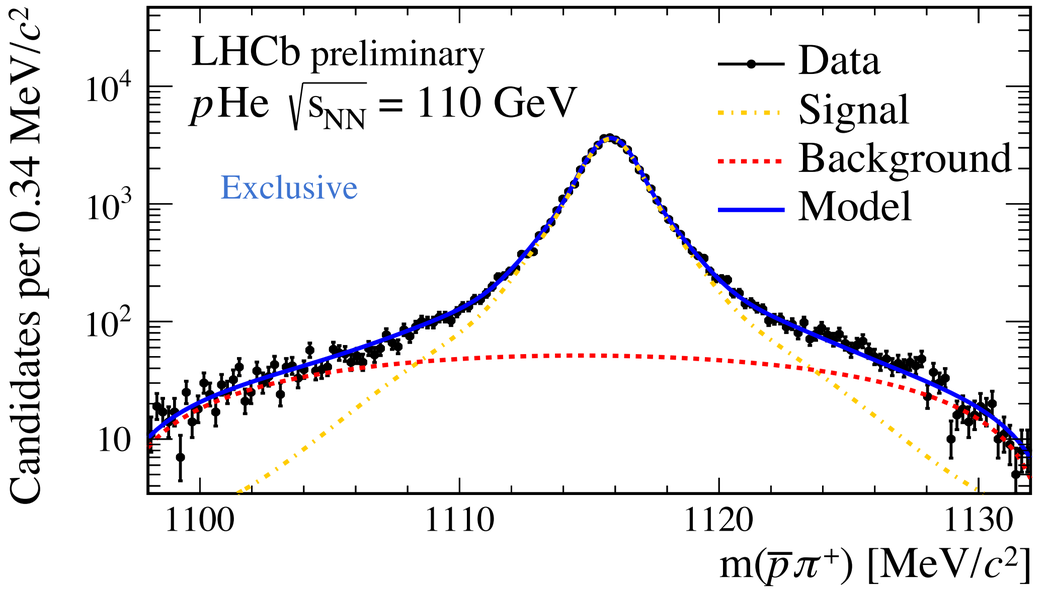
Detached antiproton in *p*He collisions at 110 GeV

LHCb-PAPER-2022-006, in preparation

Exclusive measurement:

- Dominant anti-hyperon contribution from $\overline{\Lambda}$ exclusively reconstructed
- $\overline{\Lambda} \to \bar{p}\pi^+$: $(50.7 \pm 0.3) \times 10^3$ candidates

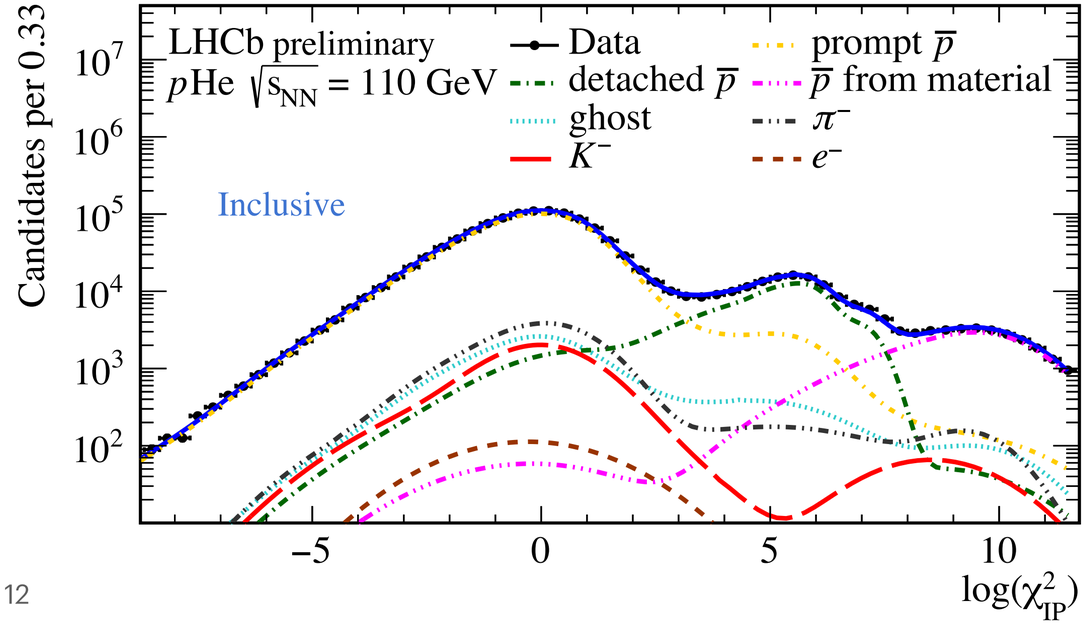
$$R_{\bar{\Lambda}} \equiv \frac{\sigma(p\mathrm{He} \to \bar{\Lambda} X \to \bar{p}\pi^+ X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}} X)}$$



Inclusive measurement:

- Anti-hyperon $\overline{H} = \overline{\Lambda}, \overline{\Sigma}, \overline{\Xi}, \overline{\Omega}$
- template fit of $\bar{p}$ impact parameter:
  - Prompt, detached, secondary collisions from materials

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

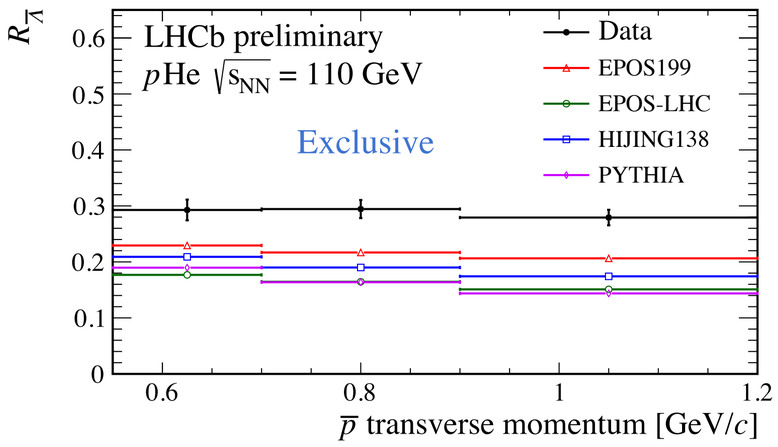


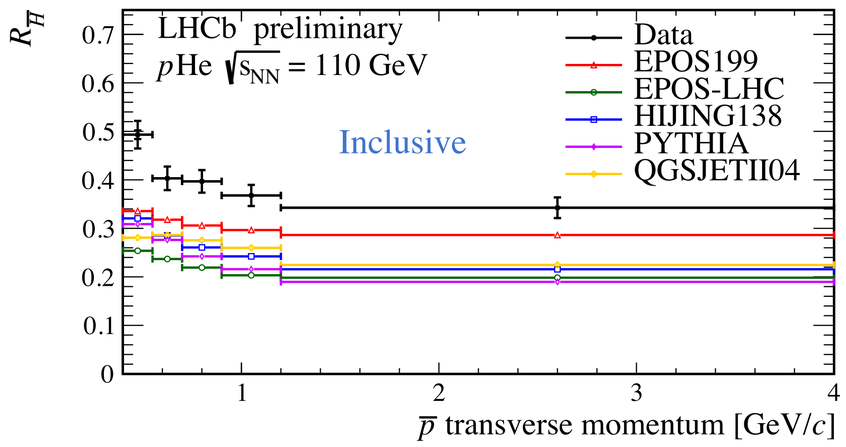
LHCb-PAPER-2022-006
In preparation

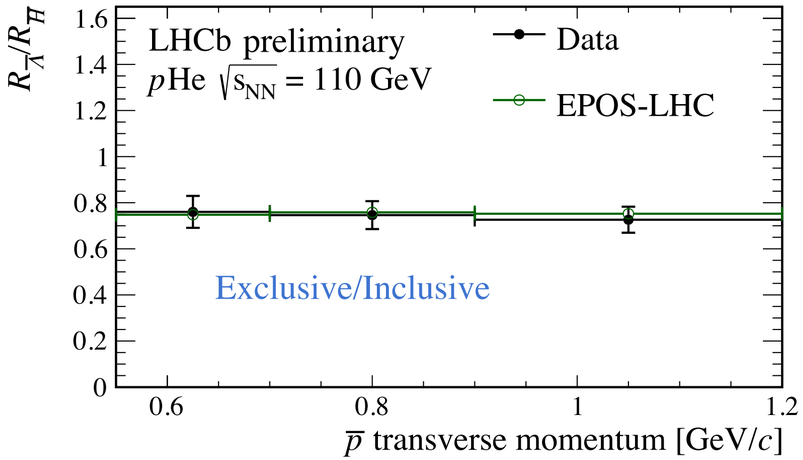
Detached antiproton in *p*He collisions at 110 GeV

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

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







Exclusive

- All considered generators significantly underestimate the $\bar{\Lambda}$ contribution to the $\bar{p}$ production

Inclusive

- Generators underestimate the anti-hyperon contribution to $\bar{p}$ production

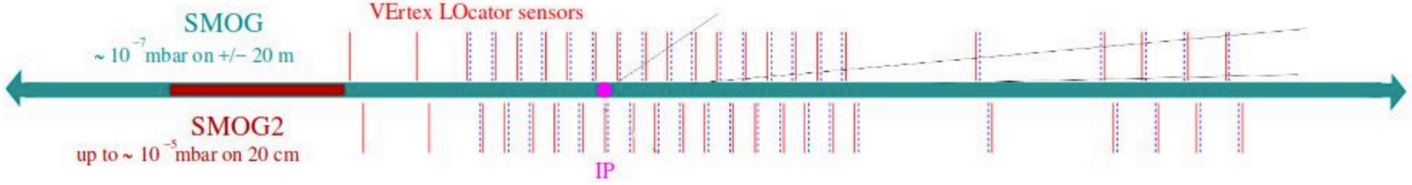
Exclusive / Inclusive

- Well reproduced by EPOS-LHC
- Mutual validation of the two complementary approaches

- The results confirm an increased $\bar{H}$ contributions compared to $\sqrt{s_{\mathrm{NN}}} \sim 10$ GeV
- Indicate a sizable underestimation of detached $\bar{p}$ contribution in most hadronic production models used in cosmic ray physics

SMOG2

More details: talk by S. Mariani
06/04, 11:30

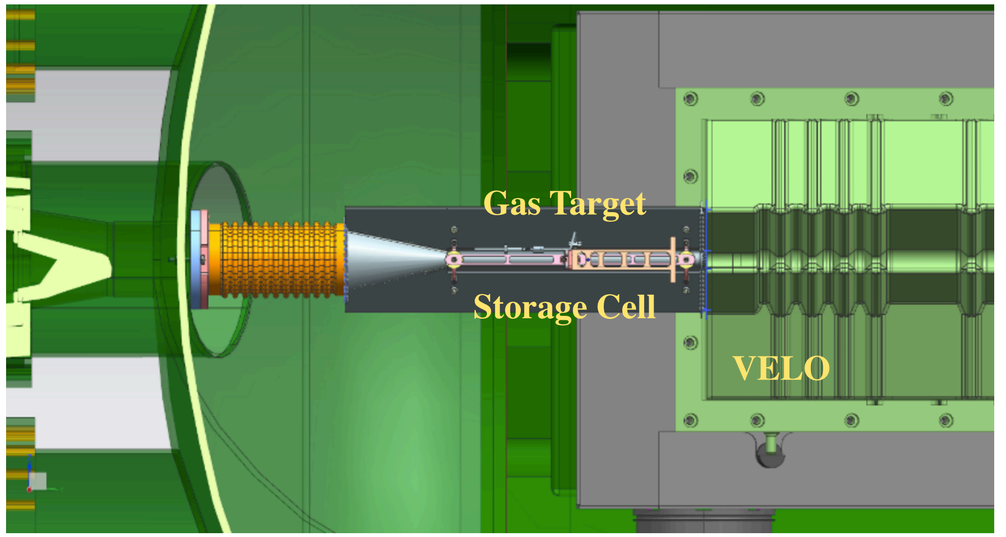


- SMOG2: Storage Cell for the gas upstream of the nominal IP (z in [-500, -300] mm) and precisely calibrated Gas Feed System.
  - Gas density increased by up to two orders of magnitude ==> much higher luminosity
  - More gas targets: H_2, D_2, He, N_2 , O_2, Ne, Ar, Kr, Xe
- beam-beam and beam-gas separate luminous regions:

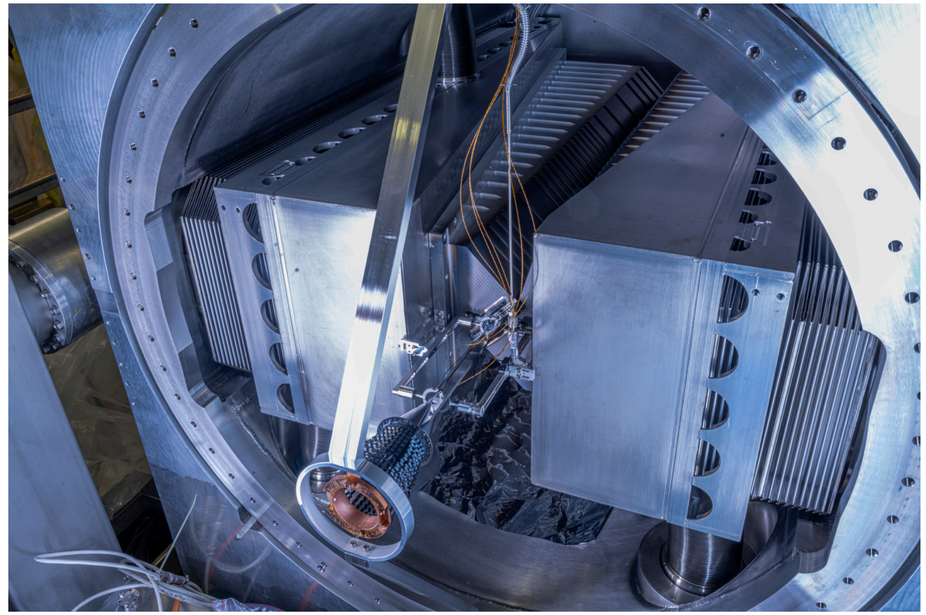
  ==> simultaneous *pp*-SMOG2 data-taking

  ==> large statistics
- Physics:

  No centrality limitation!
  - Intrinsic heavy-quark
  - p-Gas collisions: nPDFs, gluon anti-shadowing at large x, cold nuclear matter effects
  - Pb-Gas collisions: QGP formation, rapidity scan at lower energy, quarkonium sequential suppression
  - Astrophysics



LHCb-TDR-020



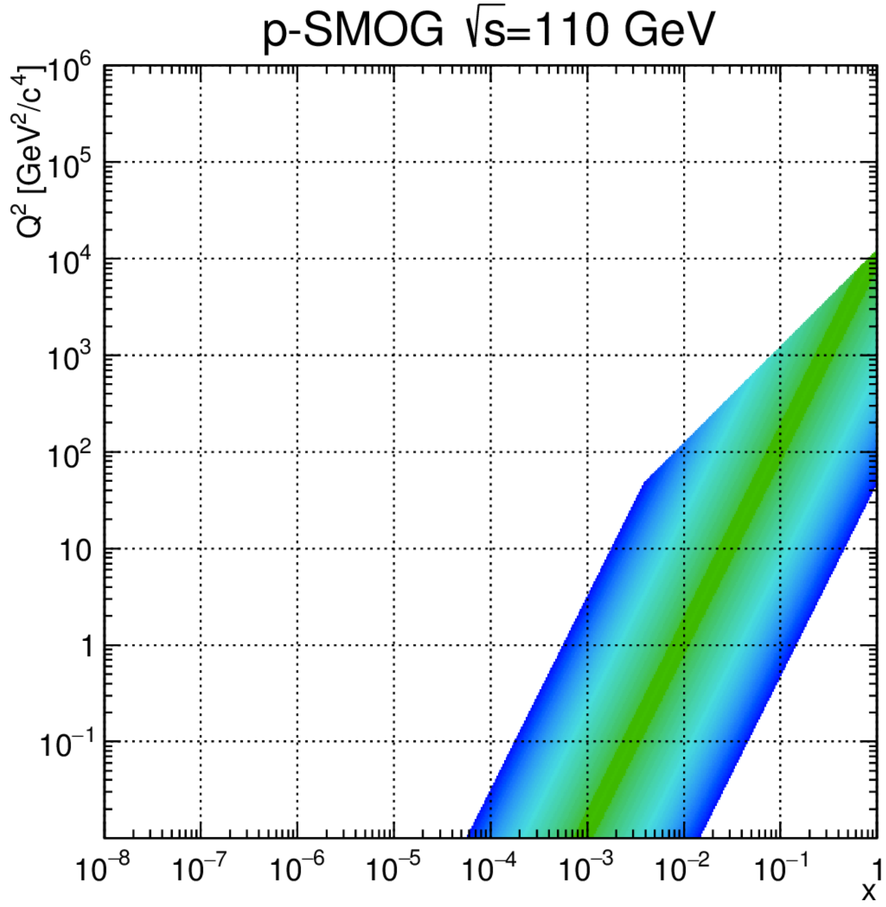
Conclusion

Thanks for your attention!

- The LHCb fixed-target program SMOG offers rich physics opportunities
- New results from SMOG data:
  - Charmonia production in pNe at 68.5 GeV: first $\psi(2S)$ result from SMOG
  - D^0 and J/ψ production in PbNe collisions at 68.5 GeV: first result from SMOG AB collisions
  - Detached $\bar{p}$ production in pHe at 110 GeV: key inputs to astrophysics
- Promising SMOG2 upgrade in Run3
- And much more to come from the SMOG/SMOG2

Backups

	nSPDHits	$\langle N_{\mathrm{coll}} \rangle$	RMS(N_{coll})
p**Ne**		1.81	1.10
PbNe	0-200	3.02	0.88
	200-300	5.13	1.81
	300-446	9.09	2.87
	446-715	17.04	4.67
	715-960	32.26	6.51
	960-1700	71.12	20.70



LHCb-PAPER-2022-006
In preparation

Detached antiproton in *p*He collisions at 110 GeV

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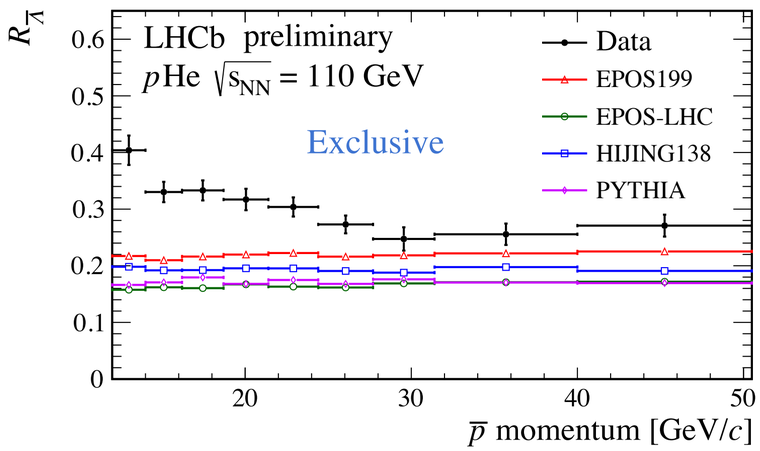
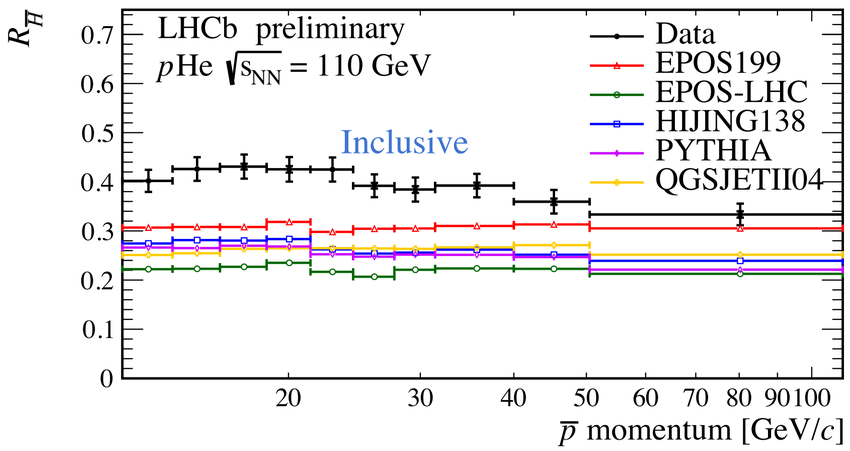
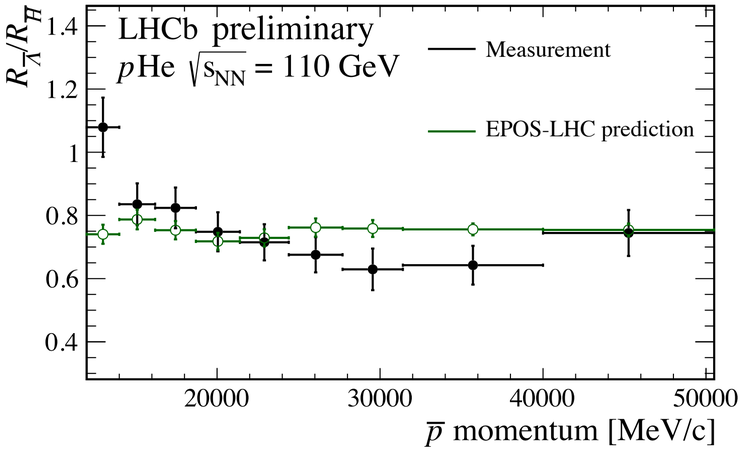
$$R_{\bar{H}} \equiv \frac{\sigma(p\mathrm{He} \to \bar{H} X \to \bar{p} X)}{\sigma(p\mathrm{He} \to \bar{p}_{\mathrm{prompt}} X)}$$

Exclusive/Inclusive







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Inclusive

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Exclusive / Inclusive

- Well reproduced by EPOS-LHC
- Mutual validation of the two complementary approaches

- A significant dependence on $\bar{p}$ momentum is observed.
- The results confirm an increased $\bar{H}$ contributions compared to $\sqrt{s_{\mathrm{NN}}} \sim 10$ GeV
- Indicate a sizable underestimation of detached $\bar{p}$ contribution in most hadronic production models used in cosmic ray physics

SMOG2: statistics in 1 year data taking

More details: talk by S. Mariani 06/04, 11:30

simultaneous *pp*-SMOG2 data-taking

Storage cell assumptions	gas type	gas flow (s^{-1})	peak density (cm^{-3})	areal density (cm^{-2})	time per year (s)	int. lum. (pb^{-1})
SMOG2 SC	He	1.1×10^{16}	10^{12}	10^{13}	3×10^{3}	0.1
	Ne	3.4×10^{15}	10^{12}	10^{13}	3×10^{3}	0.1
	Ar	2.4×10^{15}	10^{12}	10^{13}	2.5×10^{6}	80
	Kr	8.5×10^{14}	5×10^{11}	5×10^{12}	1.7×10^{6}	25
	Xe	6.8×10^{14}	5×10^{11}	5×10^{12}	1.7×10^{6}	25
	H_2	1.1×10^{16}	10^{12}	10^{13}	5×10^{6}	150
	D_2	7.8×10^{15}	10^{12}	10^{13}	3×10^{5}	10
	O_2	2.7×10^{15}	10^{12}	10^{13}	3×10^{3}	0.1
	N_2	3.4×10^{15}	10^{12}	10^{13}	3×10^{3}	0.1

SMOG2 pAr @ 115 GeV

Int. Lumi.		80/pb
Sys.error of J/Ψ	xsection	~3%
J/Ψ	yield	28 M
D^0	yield	280 M
Λ_c	yield	2.8 M
Ψ'	yield	280 k
$\Upsilon(1S)$	yield	24 k
$DY\ \mu^+\mu^-$	yield	24 k

Measurement ideas:

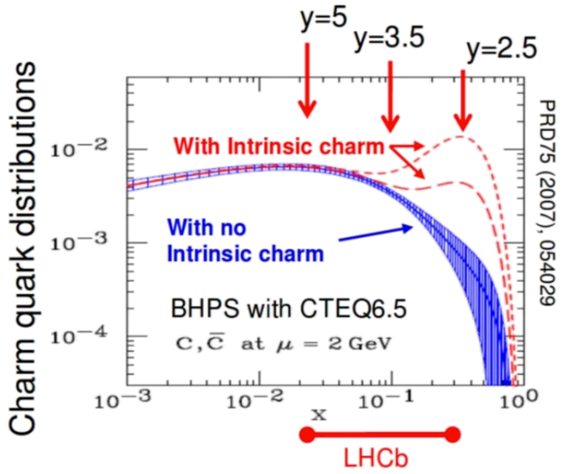
- Anti-proton production
- ρ in Central Exclusive Production
- $\psi(2S)$ / J/ψ ratio in pHe, pAr, pXe…
- Strangeness production in pHe, pAr, pXe…
- Λ_c^+ polarization and Λ_c^+/D^0 ratio in in pHe, pAr, pXe…
- X(3872)/$\psi(2S)$ ratio in pHe, pAr, pXe…
- Drell-Yan

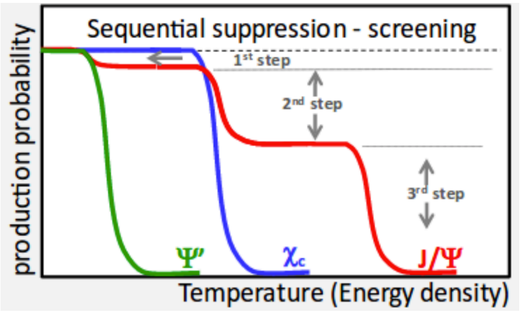
Physics programs and future measurements

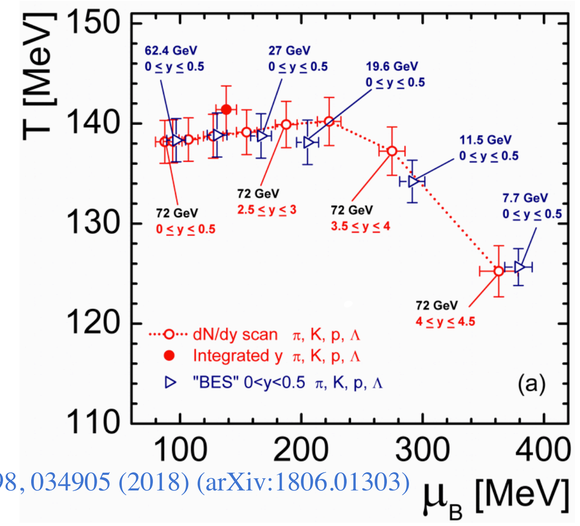
- **Fixed Target Mode: SMOG2**
- **Physics:**
  - **Intrinsic heavy-quark**
  - ***p*-Gas collisions**: nPDFs, gluon anti-shadowing at large *x*, cold nuclear matter effects
  - **Pb-Gas collisions**: QGP formation, rapidity scan at lower energy, quarkonium sequential suppression
- **Measurements:**

No centrality limitation!

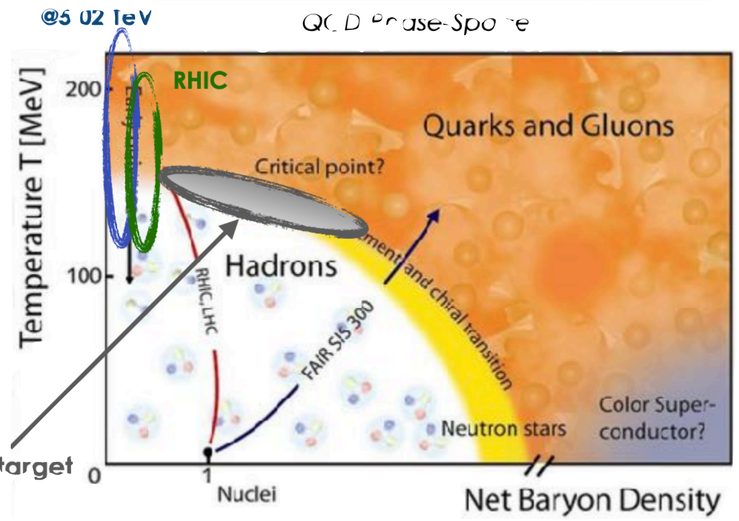
  - Anti-proton production
  - ρ in Central Exclusive Production
  - X(3872)/$\psi(2S)$ ratio in *p*He, *p*Ar, *p*Xe…
  - $\psi(2S)$ / J/ψ ratio in *p*He, *p*Ar, *p*Xe…
  - Strangeness production in *p*He, *p*Ar, *p*Xe…
  - Λ_c^+ polarization and Λ_c^+/D^0 ratio in in *p*He, *p*Ar, *p*Xe…
  - Drell-Yan







PRC 98, 034905 (2018) (arXiv:1806.01303)



- **Collider Mode**
  - **O-O collisions:** do not expect centrality limitation. Simultaneous with SMOG2?
  - ***p*-O collisions**: study elemental composition of high energy cosmic rays
    - Help understand the forward particle flux in hadron-nucleus interactions at TeV scale
    - Help resolve the Muon Puzzle in the cosmic-ray induced air showers.