Charm production in LHCb fixed-target mode

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Nagasaki (Japan)

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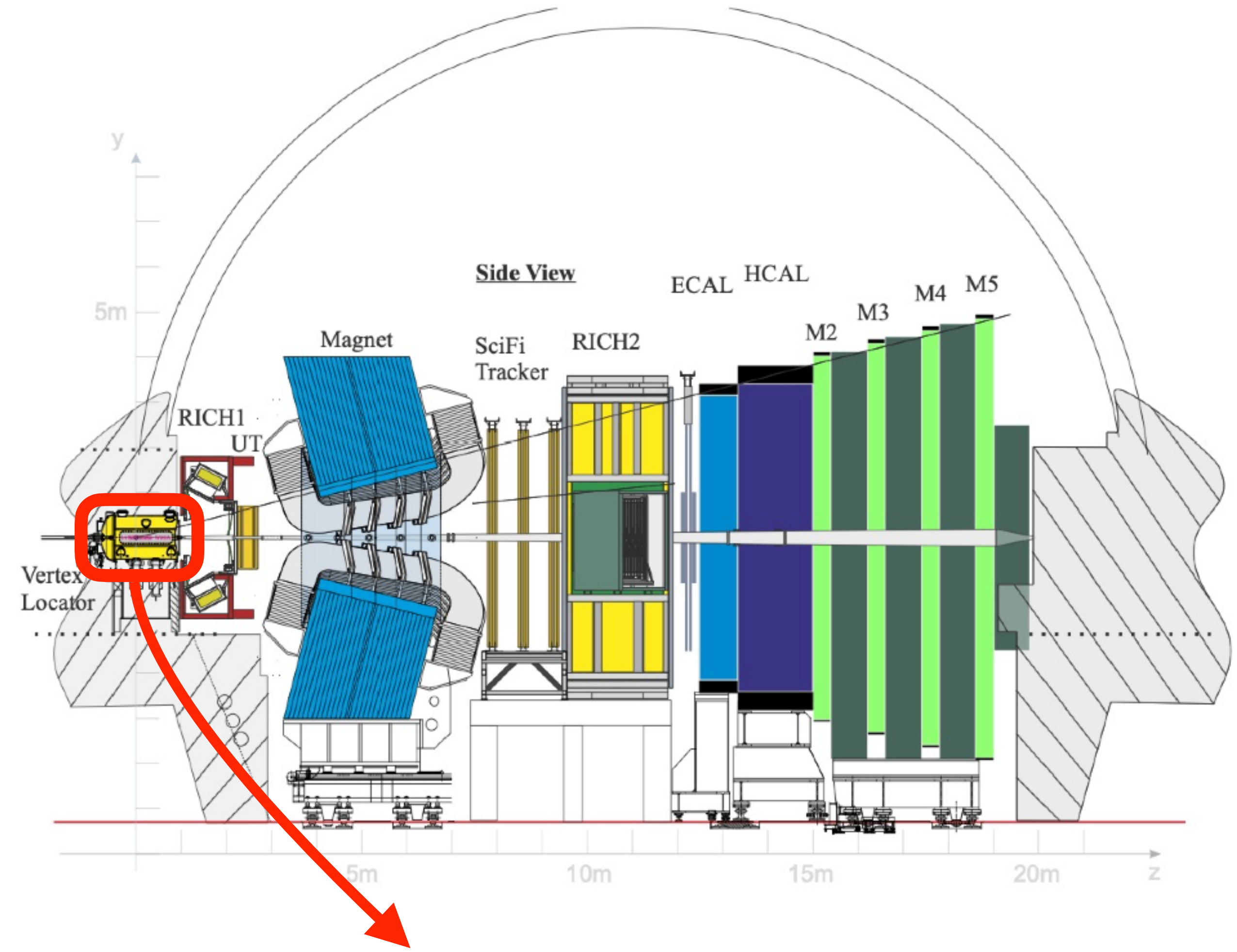
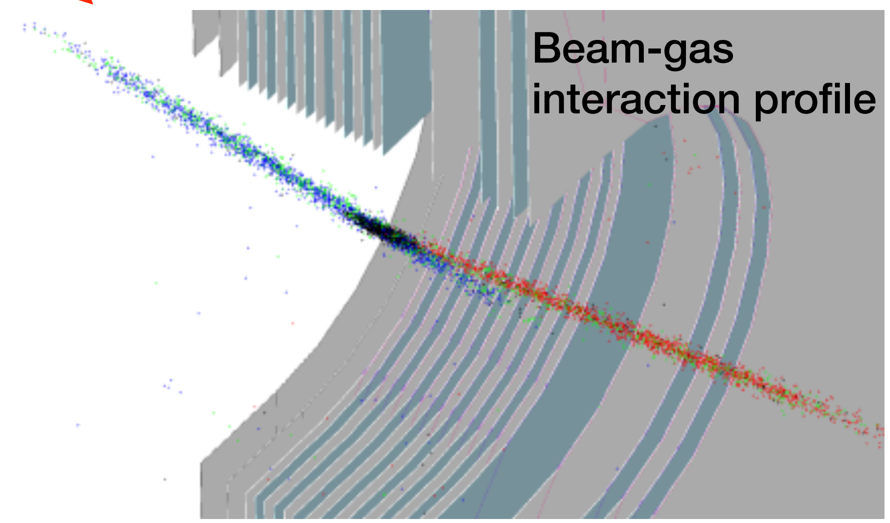
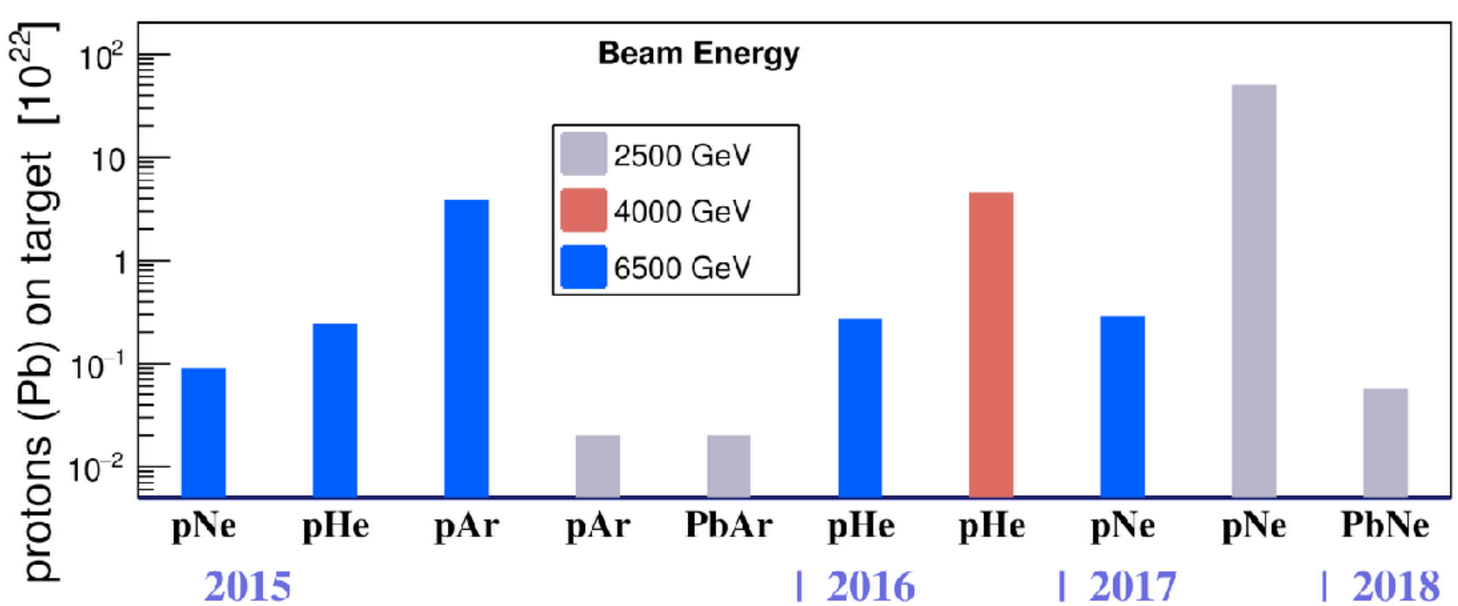
LHCb in fixed-target configuration

- One-arm spectrometer at LHC fully instrumented in $2 < \eta < 5$
- **Unique fixed-target configuration at LHC**:
  - Gas injection into LHC primary vacuum thanks to SMOG system
  - Circulating LHC beams produce pA or PbA collisions
  - Achieve collisions at $\sqrt{s_{\mathrm{NN}}} \sim 100\,\mathrm{GeV}$
    - ✳ Relatively unexplored energy range
  - Covers $-2.5 \lesssim y^* < 0$ in center-of-mass system





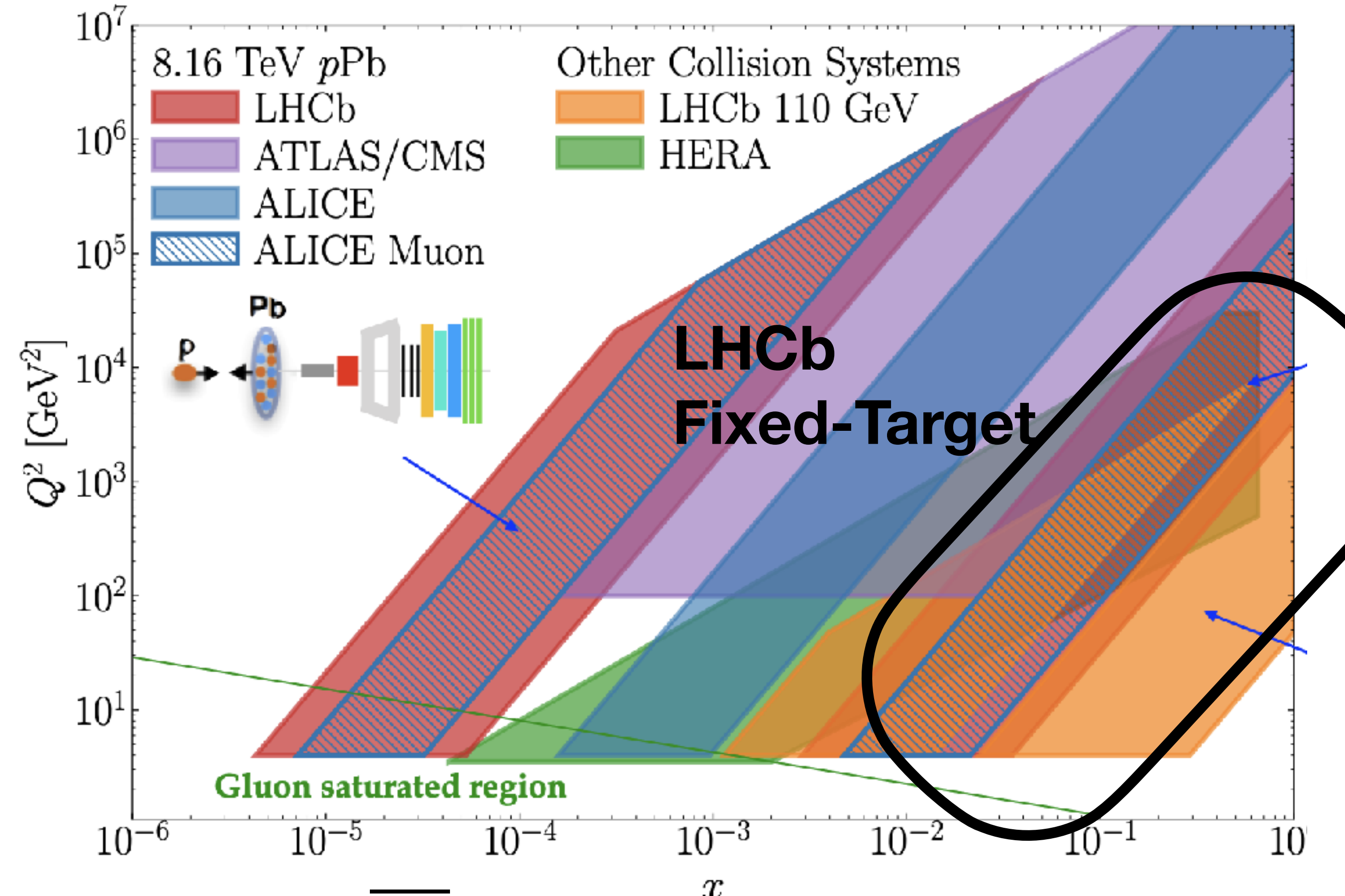
Samples collected in during Run 2:



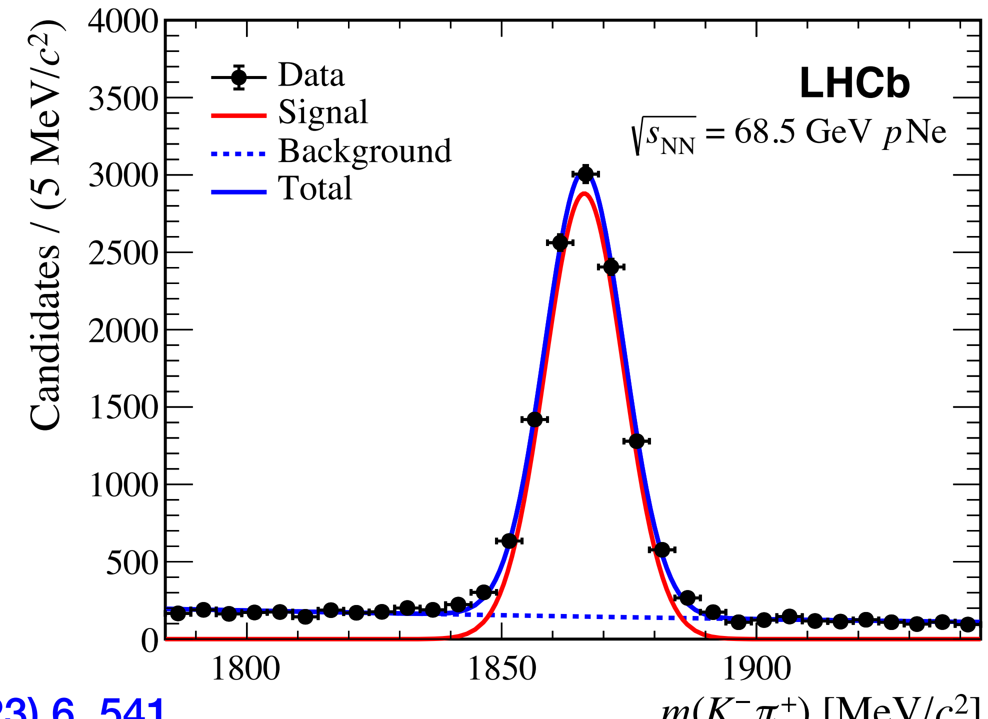
LHCb Run 1/2 detector: JINST 3, S08005 (2010), Int.J.Mod.Phys.A 30 (2015) 07, 1530022
LHCb Upgrade I (Run 3): JINST 19 (2024) P05065

Probing nuclear structure with charm

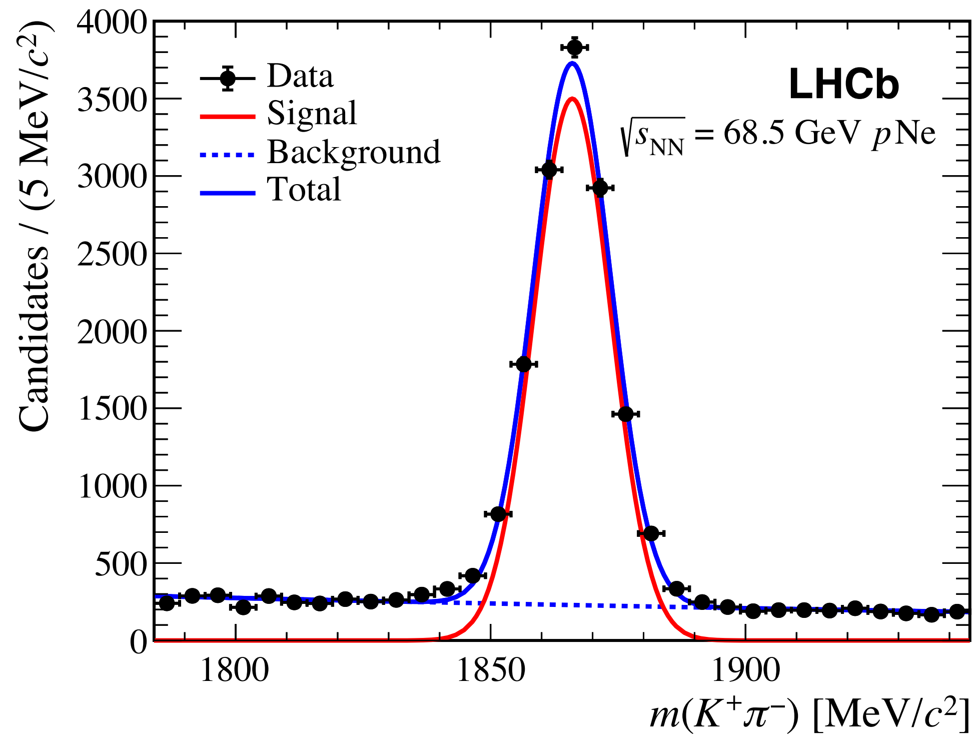
- Open charm: produced at early stage of the collision → Access nuclear parton structure
- Probing Bjorken-$x \approx 0.02 - 0.3$:
  - Significant valence quark contribution → test charm hadronisation mechanisms
  - Medium dependence
  - Probe intrinsic charm in the nucleon
- Most recent open-charm measurement with largest Run 2 sample of pNe collisions: $\mathcal{L}_{p\mathrm{Ne}} = 21.7 \pm 1.4\,\mathrm{nb}^{-1}$



$D^0 \to K^-\pi^+$

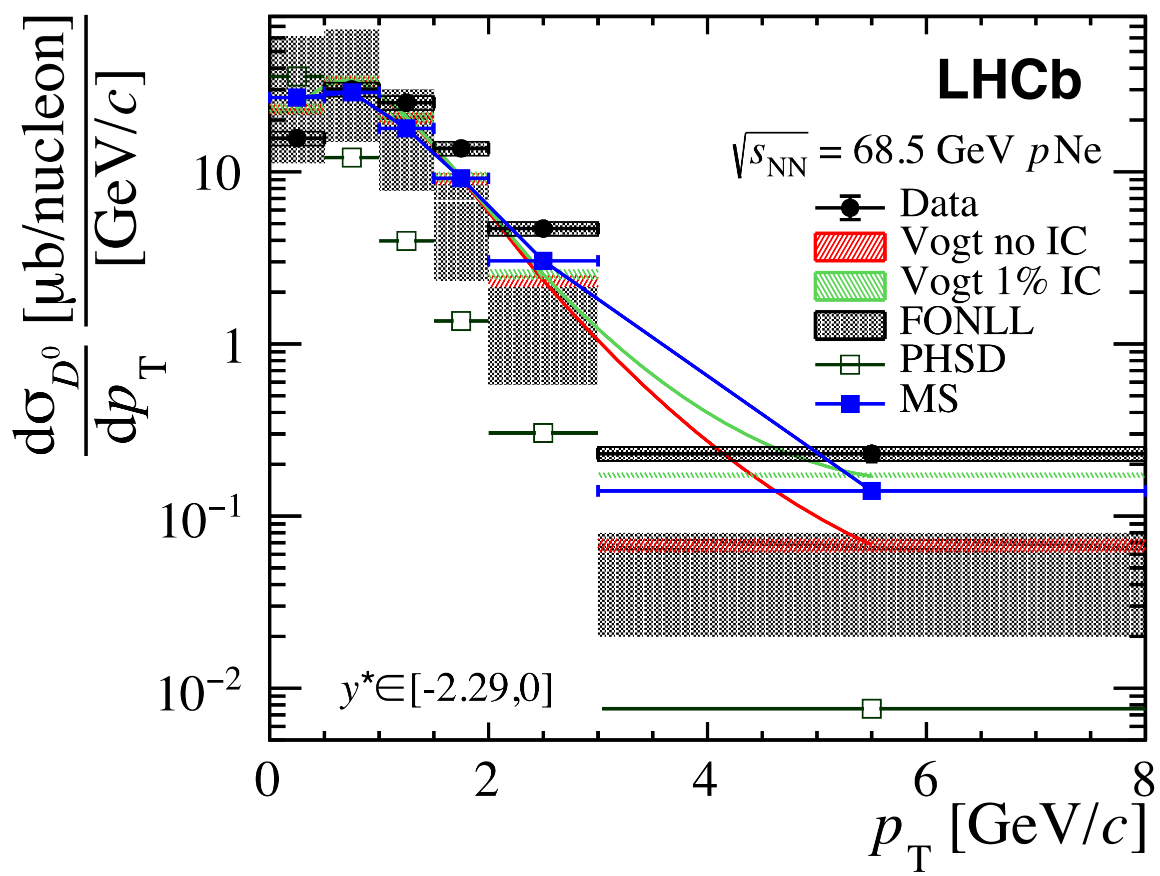


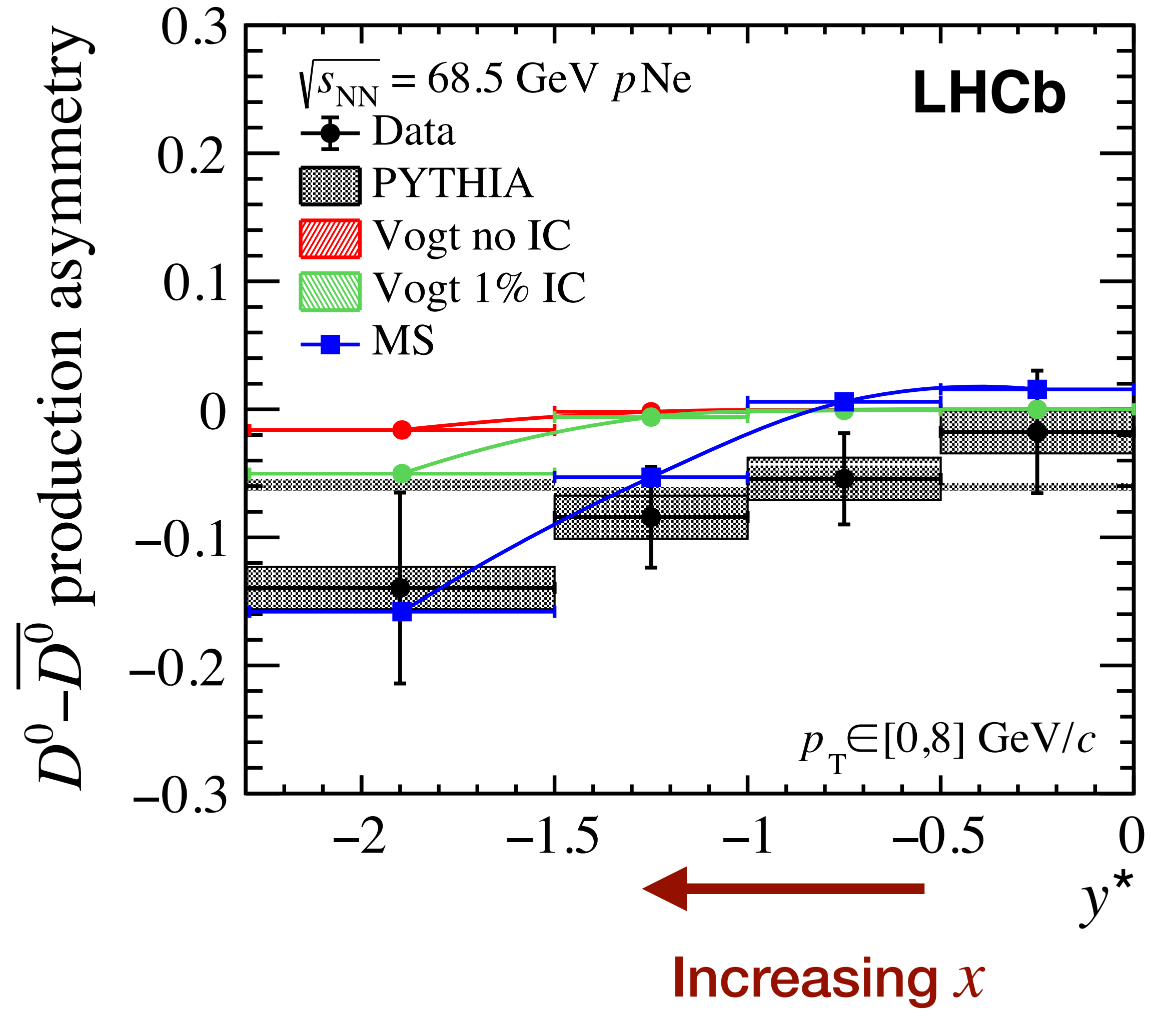
$\overline{D^0} \to K^+\pi^-$



EPJ C83 (2023) 6, 541

Open charm production and asymmetry





- Measure production and D^0, $\overline{D^0}$ production asymmetry
  - Probe of charm hadronization in the high-x region → $D^0(c\bar{u})$, $\overline{D^0}(\bar{c}u)$

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

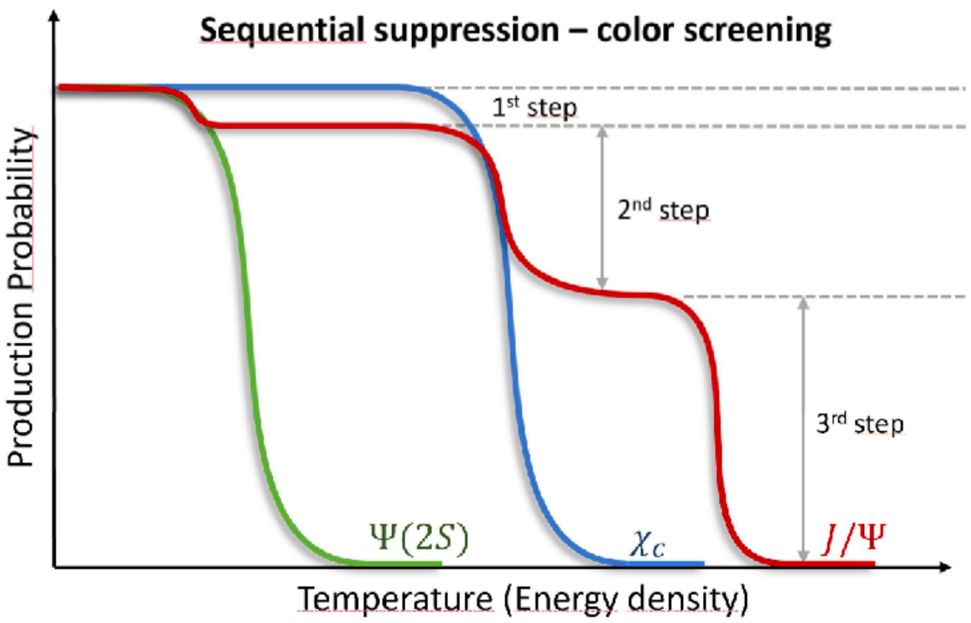
- Vogt predictions including and excluding intrinsic charm (IC)
- MS prediction including IC and recombination with valence quark
- **More statistics is needed for double-differential measurements**

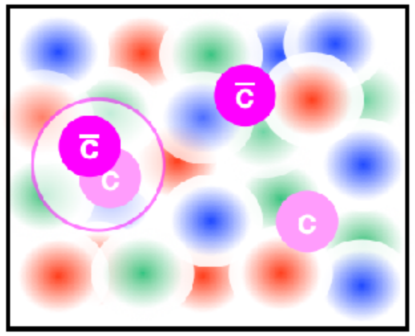
LHCb data: EPJ C83 (2023) 6, 541

Vogt: PRC 103 (2021) 035204 MS: PLB 835 (2022) 137530 PHSD: PRC 96 (2017) 014905 FONLL: PRL 95 (2005) 122001

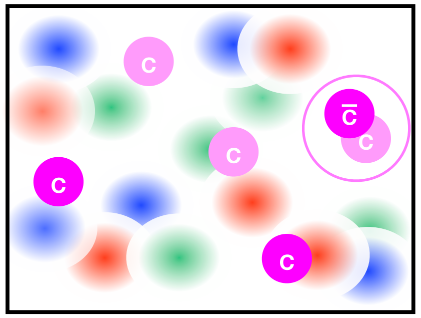
Quarkonium production in medium

- **Quarkonium dissociation** in Quark Gluon Plasma (QGP):
  - Need to measure **full spectra of charmonia states** ($J/\psi \to \chi_c \to \psi(2S)$) to correlate with feed-down contributions
- **Charmonia recombination**: expected at LHC energies and at low p_{T}, competes with dissociation

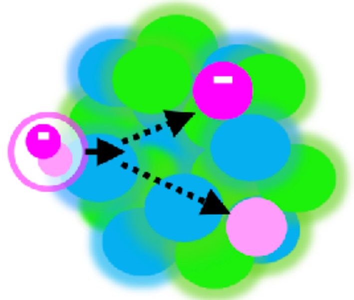




Dissociation in QGP

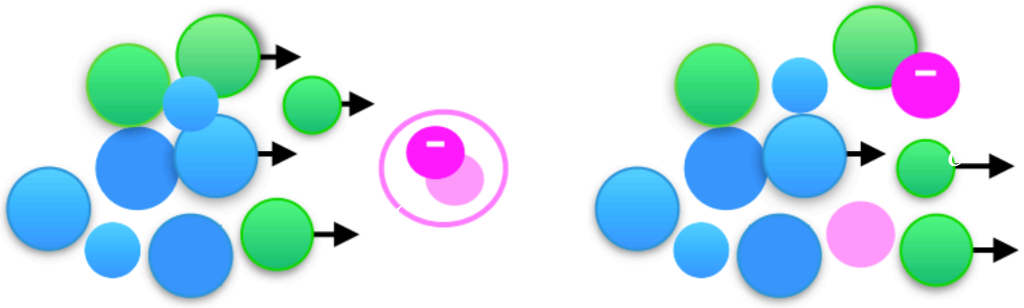


Recombination in QGP



Nuclear absorption

- **Non-QGP nuclear effects also play a role**, also expected in medium-size systems:
  - Initial and final-state effects
  - Excited-to-ground state suppression observed in medium size systems (proton-nucleus)
    - ✳ Final-state effects? Nuclear absorption, comover interaction or hot medium hypothesis

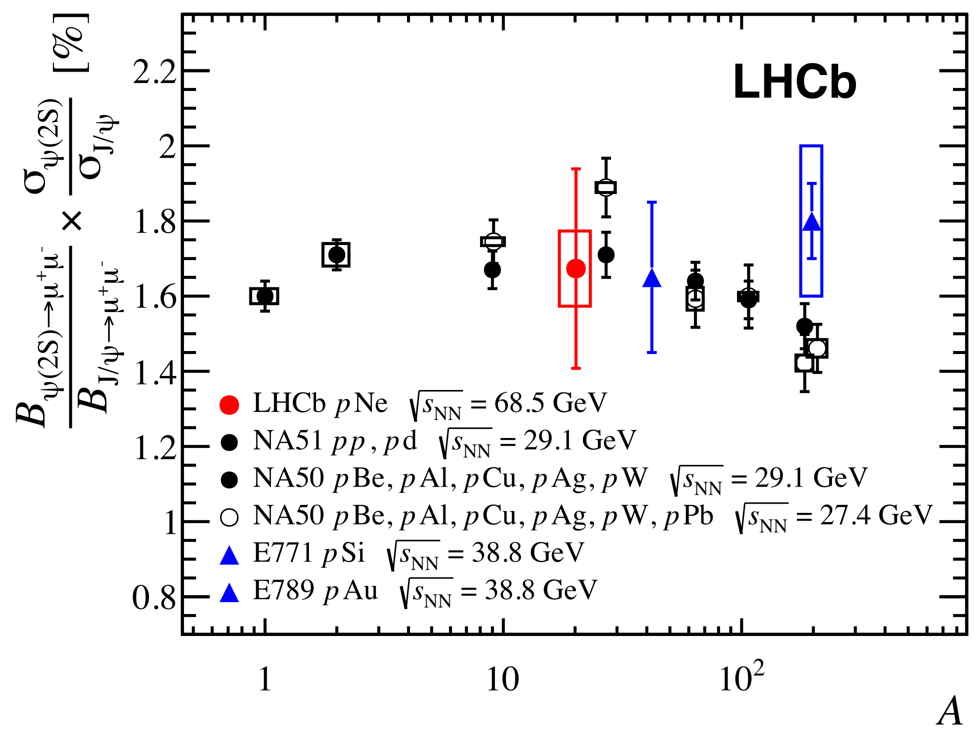


Breakup due to co-moving particles

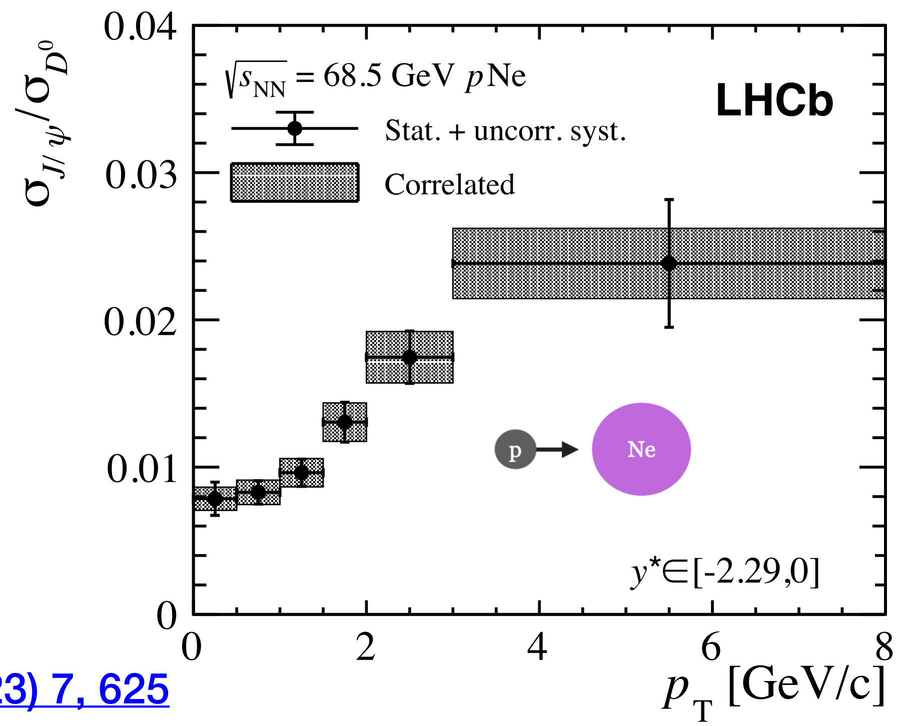
Quarkonia in pNe and PbNe collisions

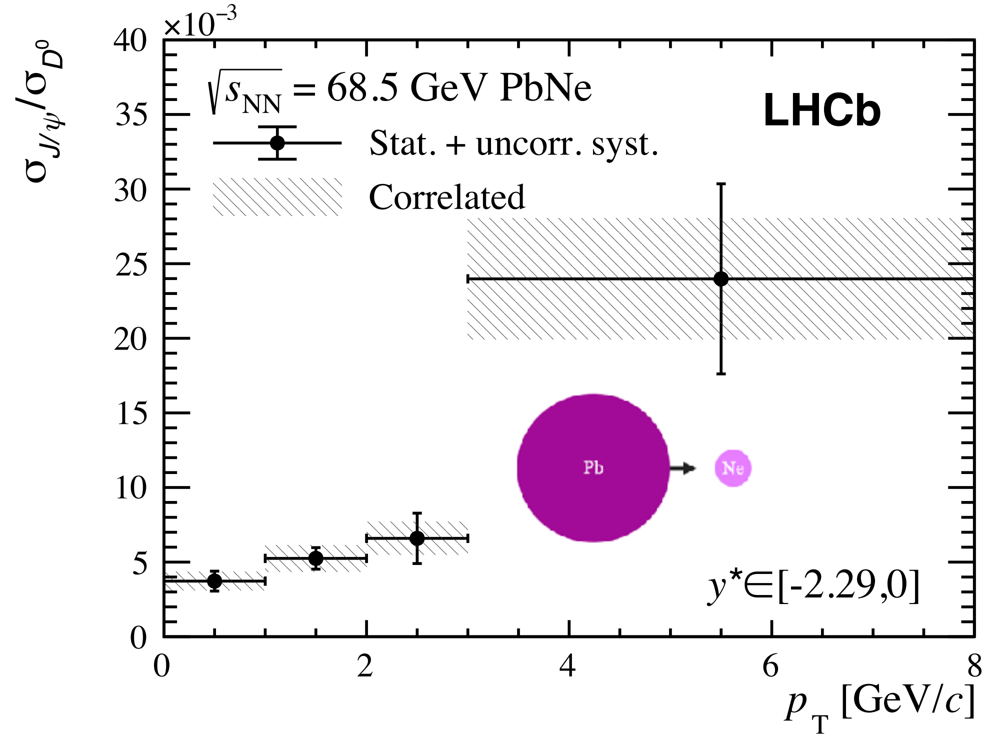
- $J/\psi, \psi(2S) \to \mu^+\mu^-$ in pNe and PbNe collisions at $\sqrt{s_{NN}} = 68.5\,\text{GeV}$
- $\psi(2S)/J/\psi$ ratio: key probe of final-state effects:
  - Limited by statistical uncertainties in pNe, unreachable in PbNe with Run 2 data
- $J/\psi/D^0$ production ratio in pNe and PbNe:
  - Used D^0 as a proxy of total charm cross-section
  - Significant p_T dependence $\to J/\psi$ experiences additional nuclear effects with respect to D^0

$\psi(2S)/J/\psi$ ratio:



$J/\psi/D^0$ ratio:





pNe: Eur.Phys.J.C 83 (2023) 7, 625
PbNe: Eur. Phys. J. C83 (2023) 658

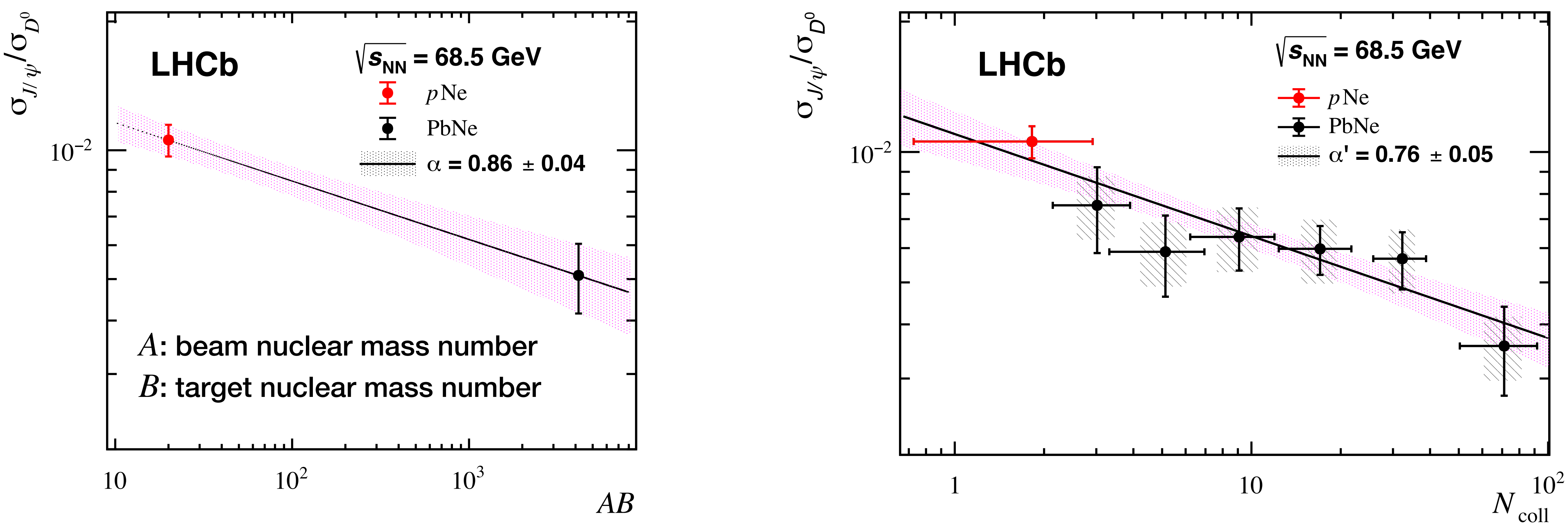
$J/\psi/D^0$ ratio in PbNe collisions

- Assuming: $\sigma^{AB}_{D^0} = \sigma^{pp}_{D^0} \times AB$ and $\sigma^{AB}_{J/\psi} = \sigma^{pp}_{J/\psi} \times AB^{\alpha}$:

$$\frac{\sigma^{AB}_{J/\psi}}{\sigma^{AB}_{D^0}} = \frac{\sigma^{pp}_{J/\psi}}{\sigma^{pp}_{D^0}} \times AB^{\alpha-1} = C \times AB^{\alpha-1}$$

(functional form expected from nuclear absorption)

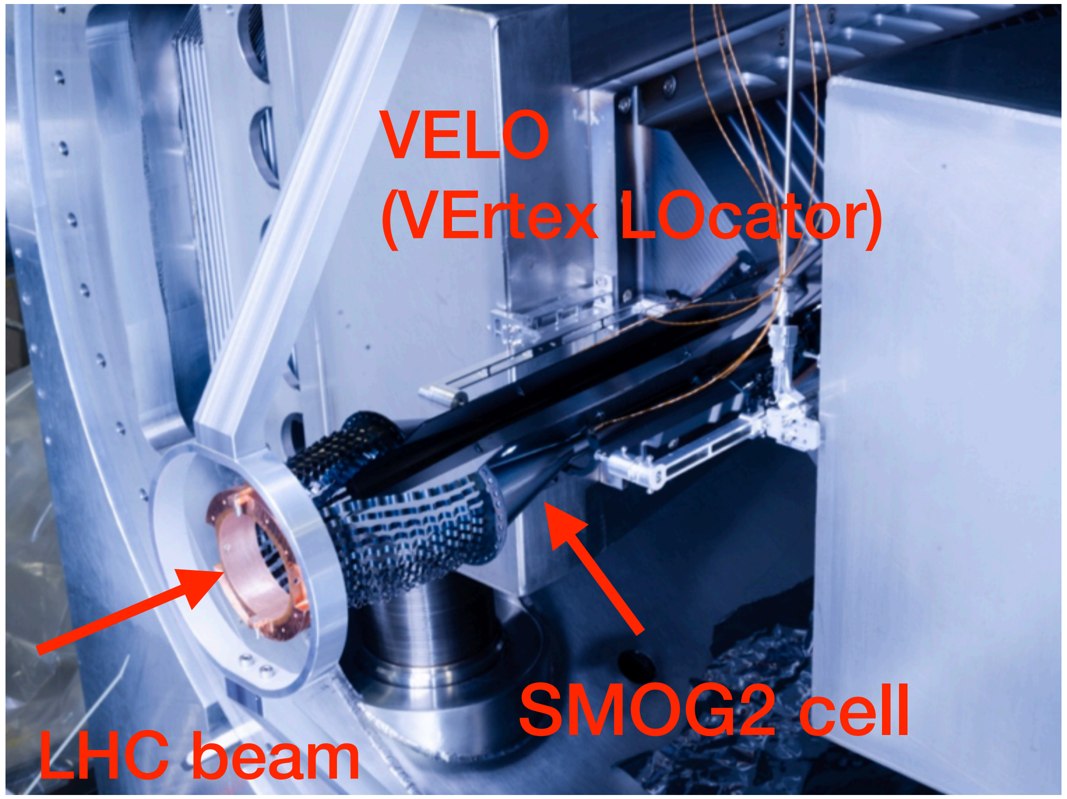
- $\alpha < 1 \implies J/\psi$ experiences additional nuclear effects with respect to D^0
  - α is compatible with NA50 values from proton-nucleus collisions (PLB 410 (1997) 337)
- Ratio with respect to $\langle N_{\text{coll}} \rangle$ does not show within current precision indications of **anomalous suppression in PbNe**
  - **Larger luminosities and larger system size are needed!**



Eur. Phys. J. C83 (2023) 658

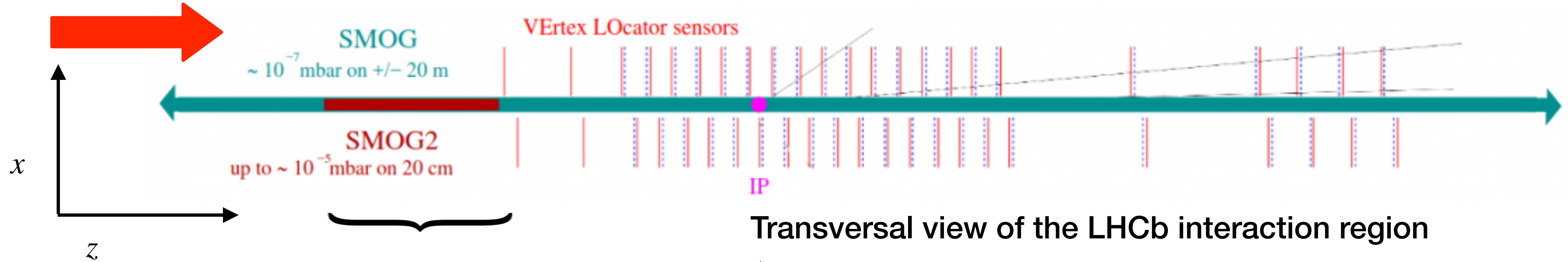
SMOG2: high-density gas target for Run 3

- New fixed-target device **SMOG2**
  - storage cell, increase effective luminosity with the same gas flow in a $20\,\mathrm{cm}$ wide region
  - gain in luminosity **up to $\times 100$ factor**
- Possibility to inject new gases: H_2 (R_{AB} reference), D_2 (isospin violation), O_2 and larger nuclei (Kr,Xe)
- Fast switch between gases, can be done during LHC operation



More SMOG2 details in poster by F. Fabiano

Proton beam direction



Transversal view of the LHCb interaction region

SMOG2 location

$z \in [-541, -341]\,\mathrm{mm}$

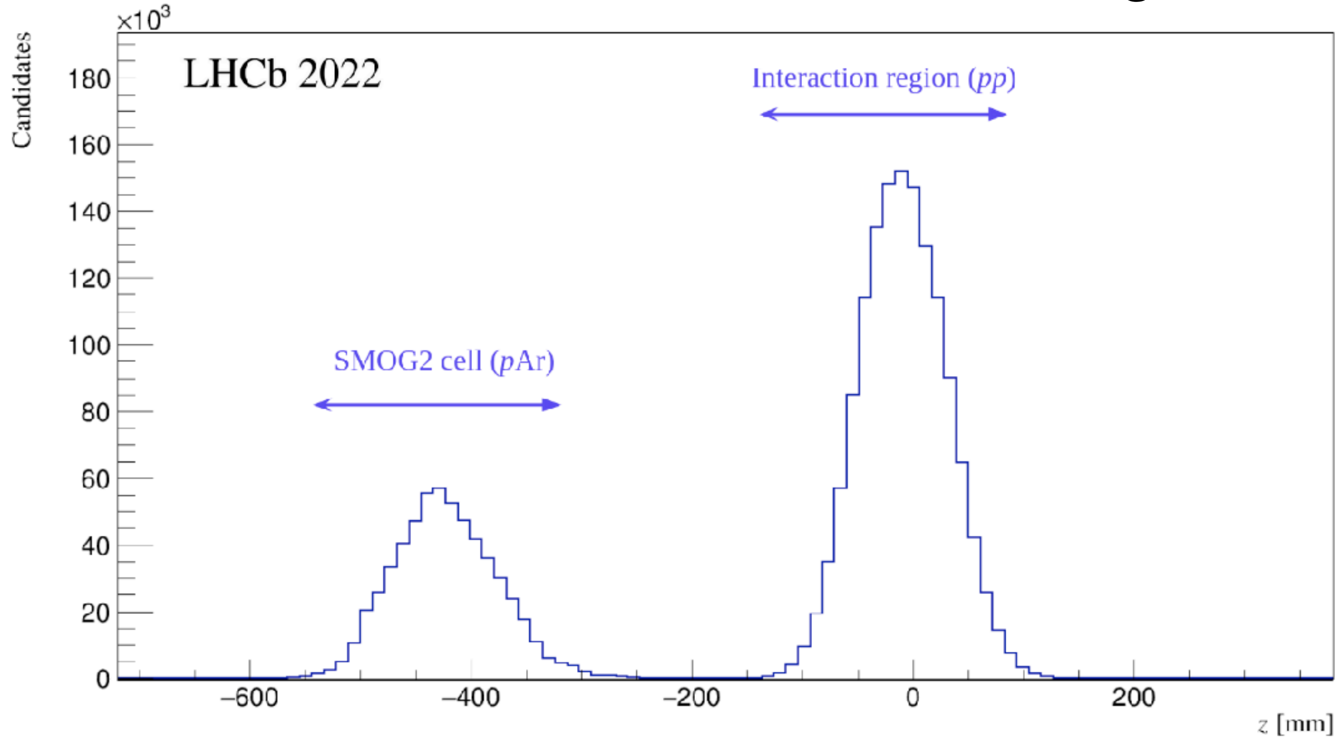
$z \approx 0$

arXiv:2407.14200

Two independent interaction regions

arXiv:2407.14200

z position of primary vertices in a beam-beam bunch crossing:



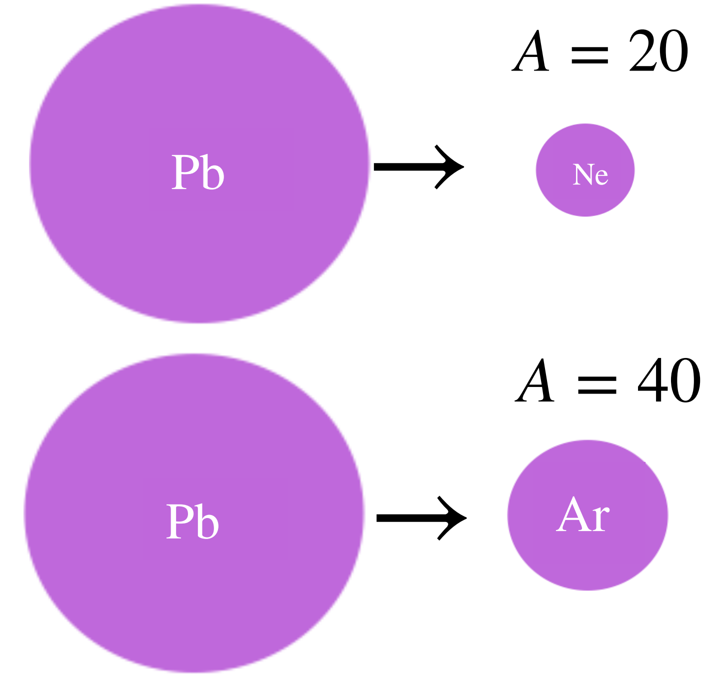
- Separate beam-beam and beam-gas interaction regions
  - Enables simultaneous data-taking with pp
  - **Massive increase in luminosity in fixed-target configuration**
- Precise luminosity determination: direct control of the gas density in storage cell
  - Aiming for $< 2\,\%$ systematic uncertainty

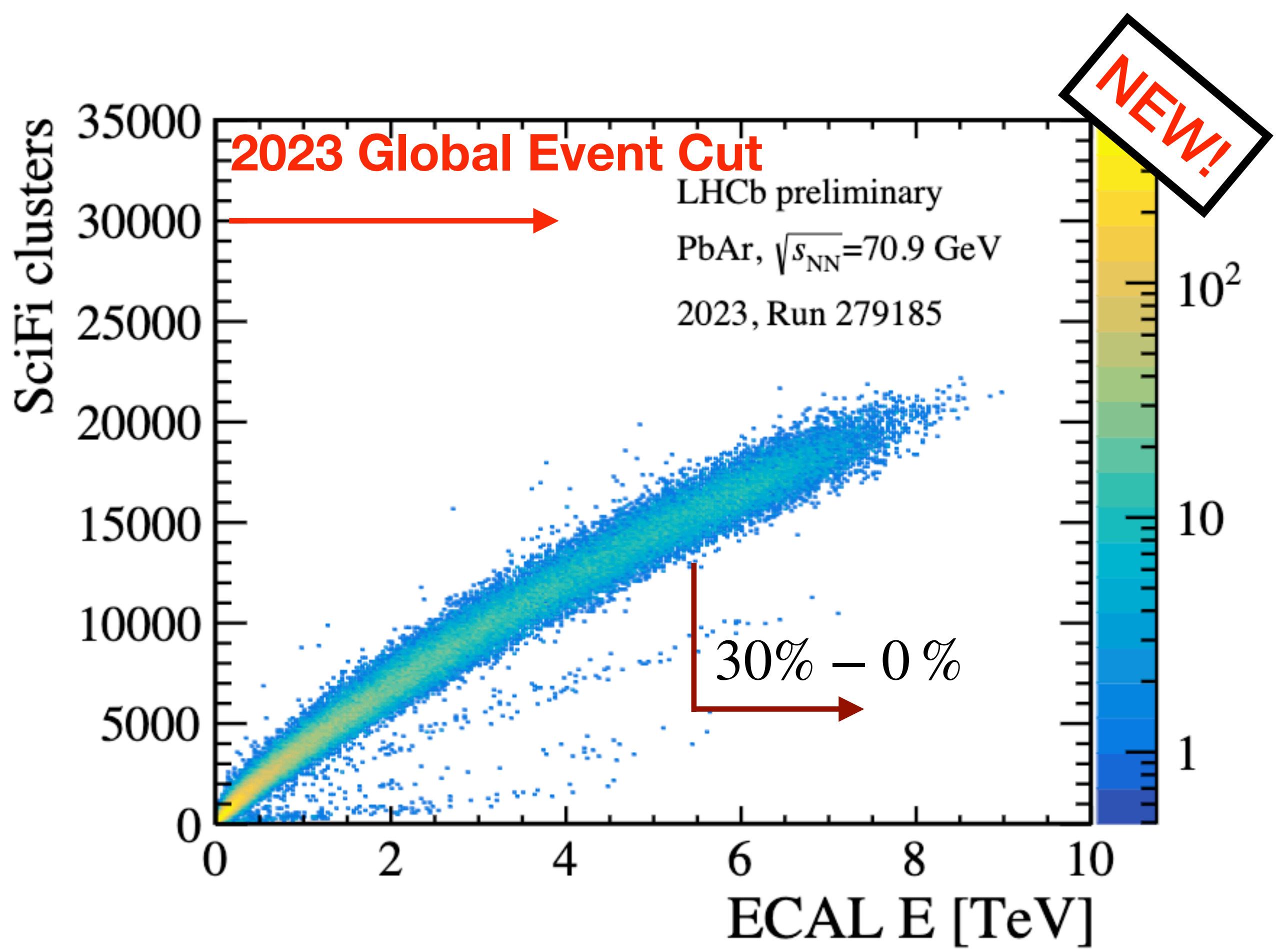
	SMOG largest sample pNe@69 GeV	SMOG2 example pAr@115 GeV
Integrated luminosity	$\sim 100\ \text{nb}^{-1}$	$\sim 45\ \text{pb}^{-1}$
syst. error on J/ψ x-sec.	6 - 7%	2 - 3 %
J/ψ yield	15k	15M
D^0 yield	100k	150M
Λ_c^+ yield	1k	1.5M
$\psi(2S)$ yield	150	150k
$\Upsilon(1S)$ yield	4	7k
Low-mass Drell-Yan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

Possible scenario for 3 year data-taking, from LHCb-PUB-2018-015

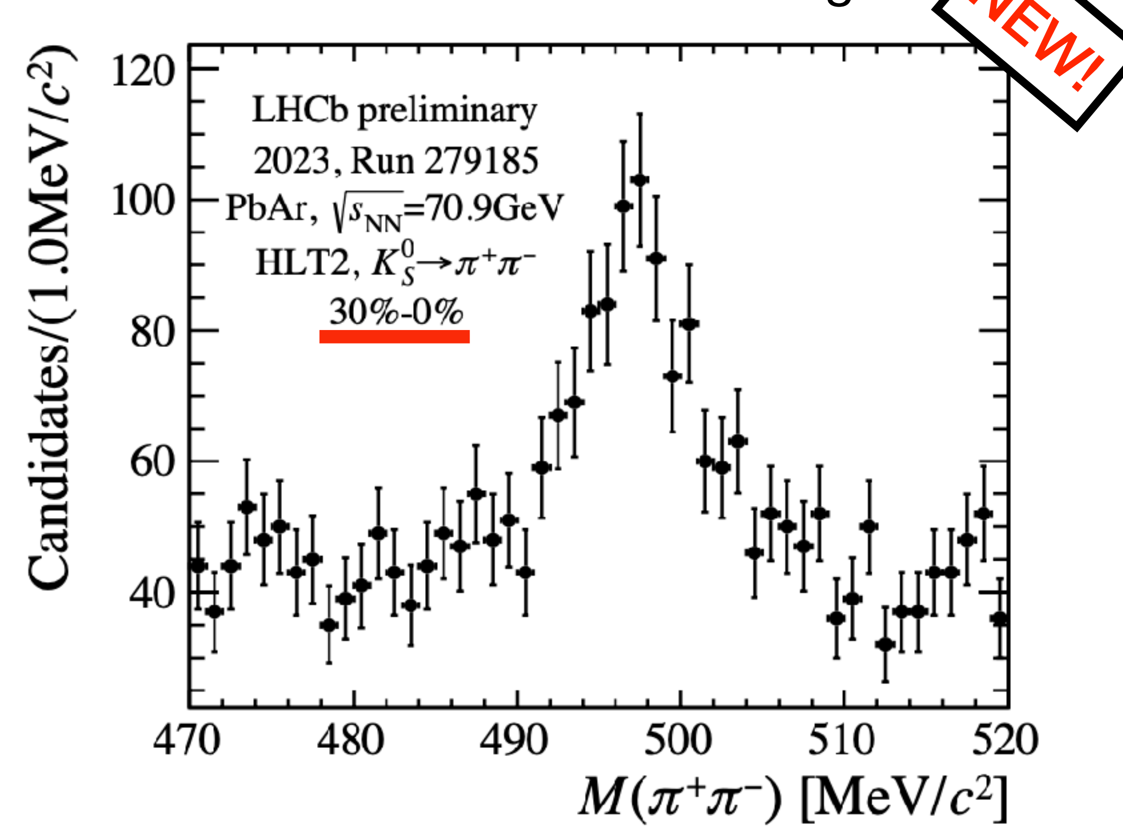
PbAr collisions from the 2023 ion run

- 2023 was a challenging year, LHC incident at VELO (vertex detector) vacuum:
  - VELO and gas-storage cell remained open → gas pressure at Run 2 levels, reduced tracking acceptance
- VELO issue successfully fixed and ready now for 2024 PbAr run
- Used 2023 run to evaluate performances of new tracking system at higher detector occupancies of PbAr collisions:
  - **Able to reconstruct tracks down to most central PbAr collisions**





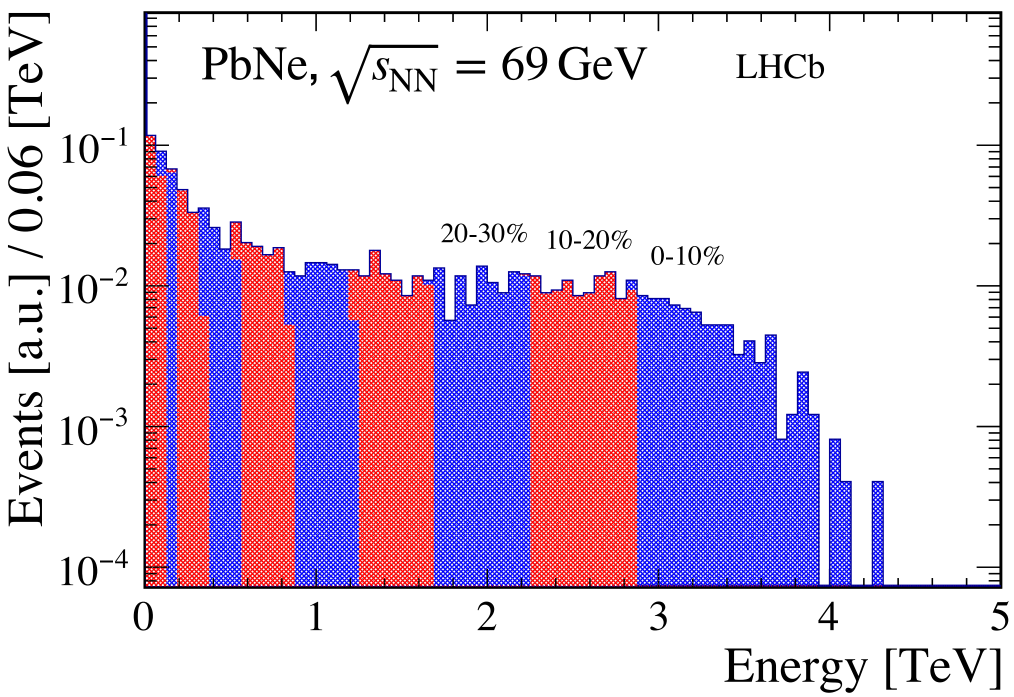
Data from 40 mins of data-taking:

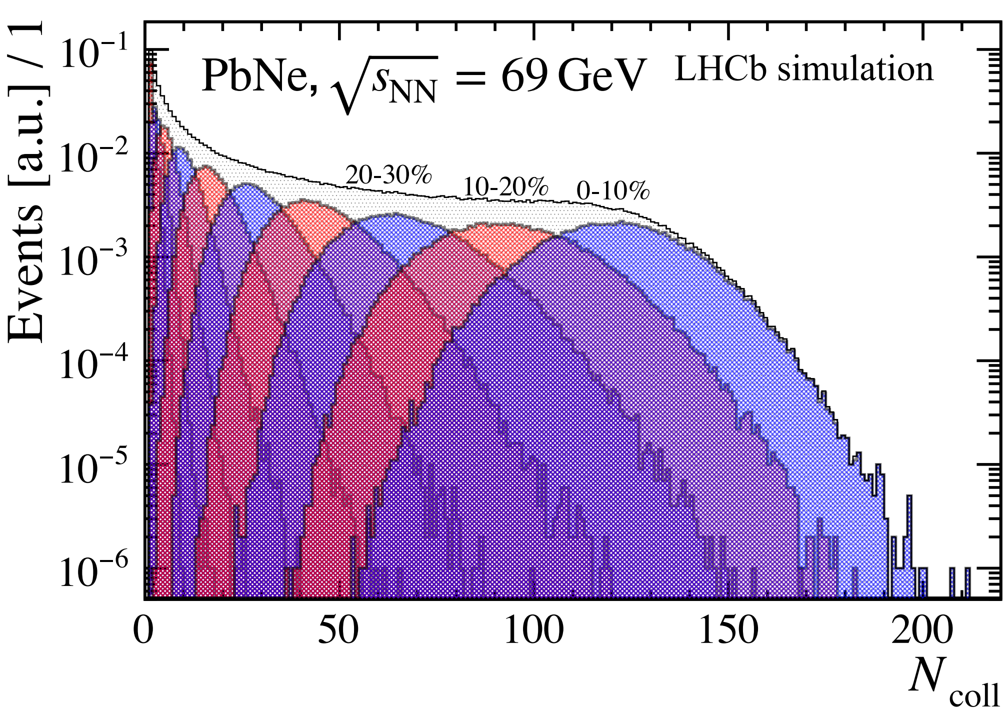


LHCb-FIGURE-2023-030

Centrality in PbNe and PbAr collisions

PbNe in Run 2

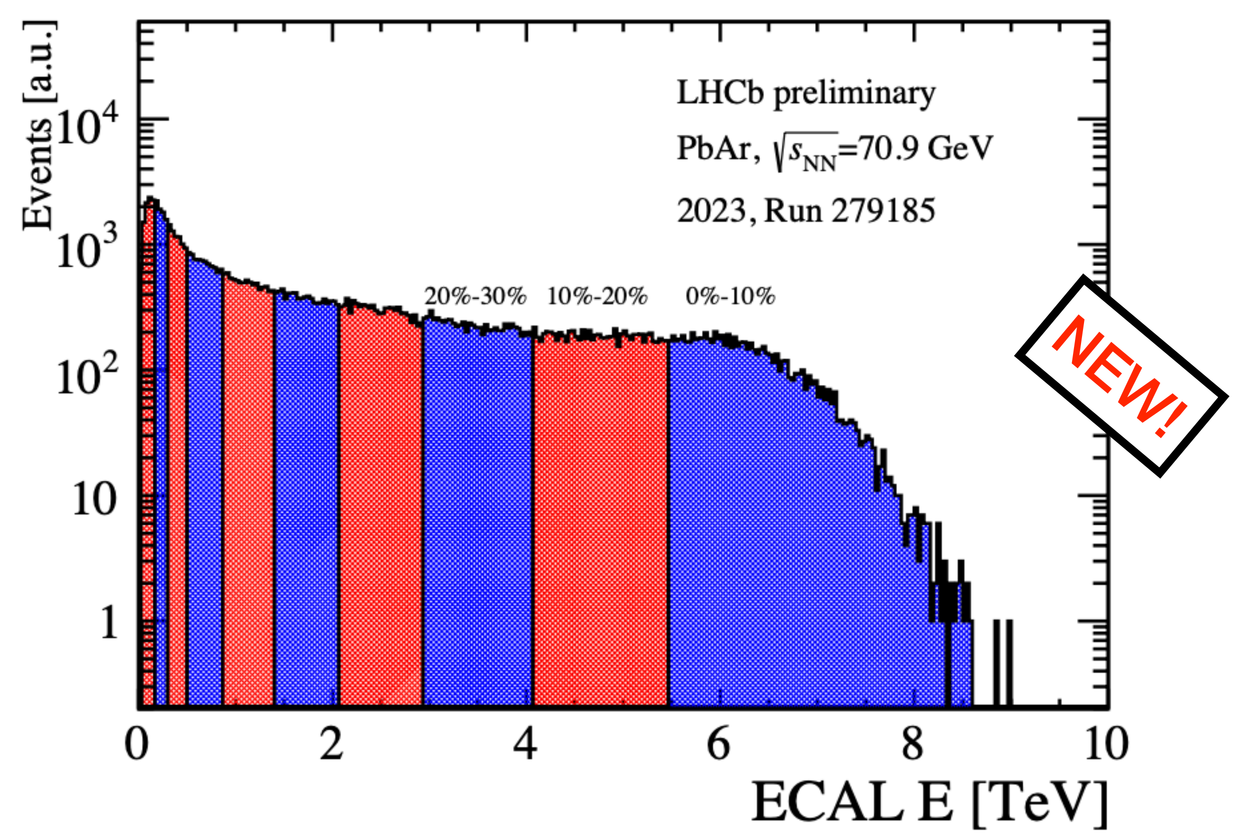




JINST 17 (2022) 05, P05009

- ECAL energy used to determine centrality at LHCb
- Maximum ECAL energy reach increased of a factor x2 with PbAr collisions with respect to PbNe

PbAr in 2023



Expect to reach an $N_{coll} \approx 350$ with PbAr

LHCb-FIGURE-2023-030

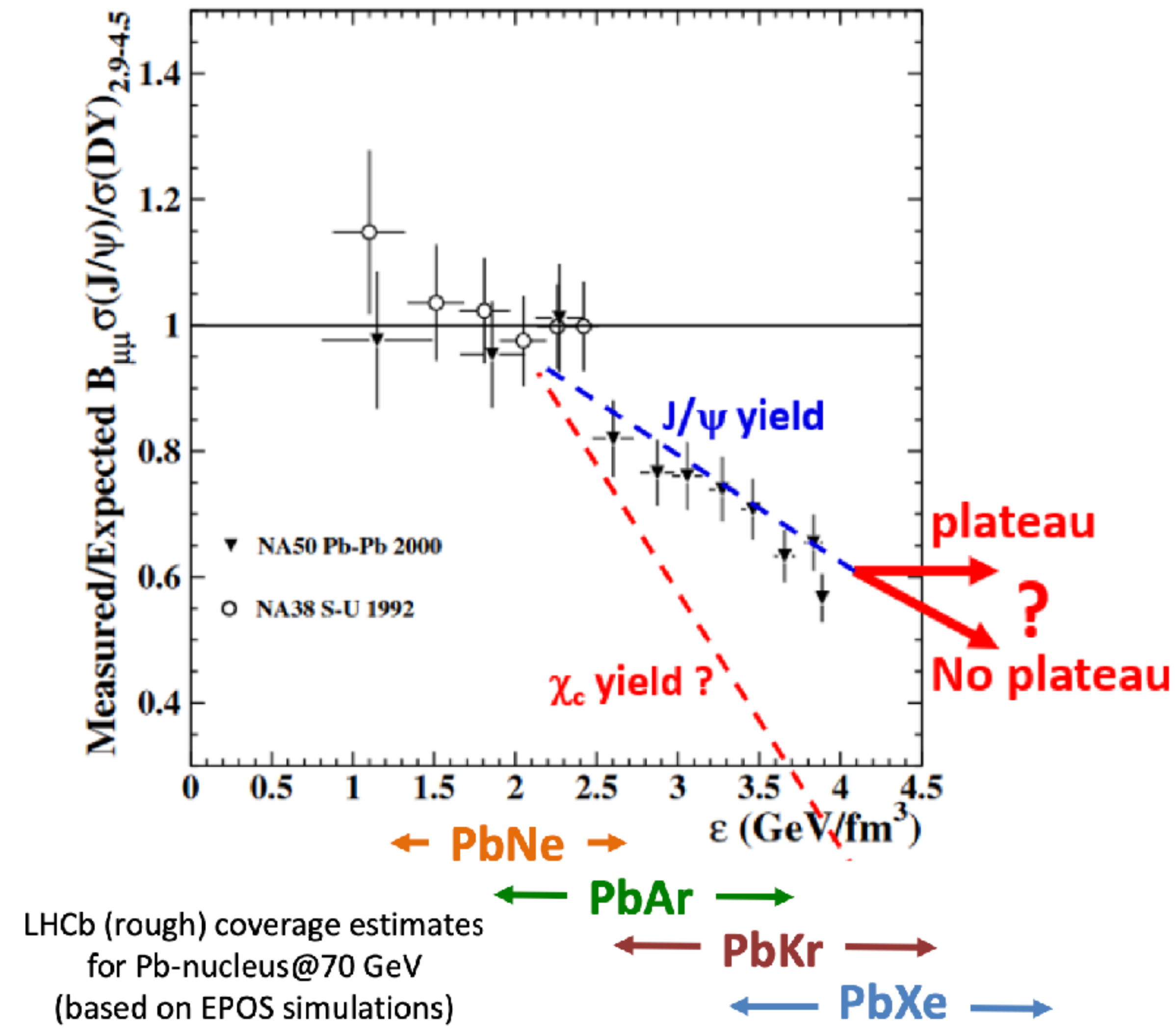
Studying quarkonia in QGP in PbAr

- Central PbAr collisions reach an energy density close to that of SPS fixed-target experiments
  → first indication of "anomalous" suppression
  - **Larger statistics** from SMOG2 and improved tracking efficiency with respect to Run 2
  - **Baseline** from pH_2 and pAr collisions
  - Expect **no significant charm recombination**

(At $\sqrt{s_{NN}} = 70.6\,\mathrm{GeV}$, only 1 $c\bar{c}$ pair produced per collision)

$$\sigma_{c\bar{c}}^{5.5\,\mathrm{TeV}} \approx 10 \times \sigma_{c\bar{c}}^{200\,\mathrm{GeV}} \approx 100 \times \sigma_{c\bar{c}}^{70\,\mathrm{GeV}} \approx 1000 \times \sigma_{c\bar{c}}^{20\,\mathrm{GeV}}$$

Unique setup to probe and understand quarkonia dissociation in the QGP

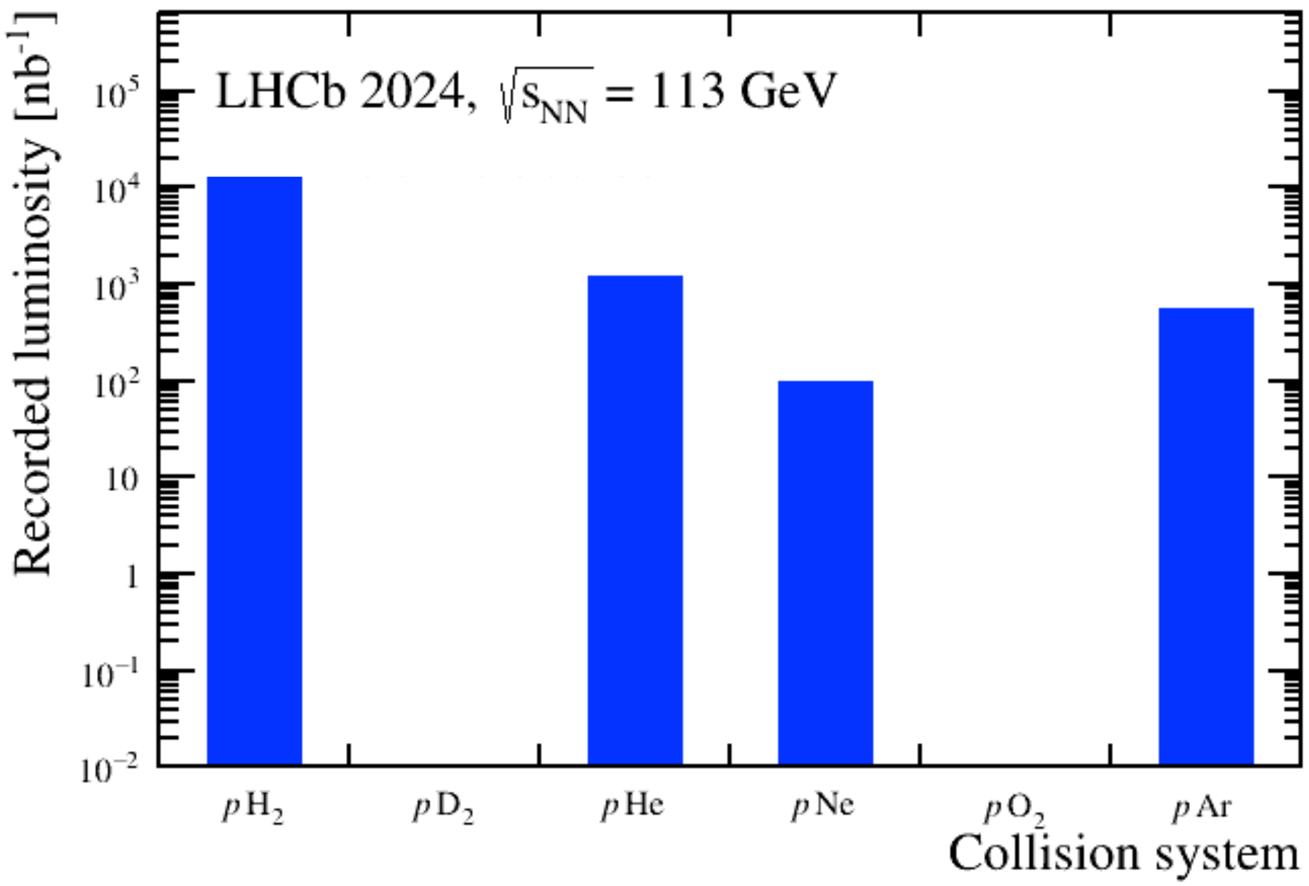


EPJC 39, (2005) 335-345
PRL 94, 082301 (2005)

SMOG2 data-taking in 2024

- **LHCb approaching nominal conditions**:
  - VELO fully closed, and all sub-detectors commissioned and integrated in the data-chain
  - Running at $\mu_{pp} = 4.4$ and with good DAQ efficiency
  - Gas injection in SMOG2 has become a routine operation at LHCb, injecting by default at almost every fill

SMOG2 data collected until 19/09

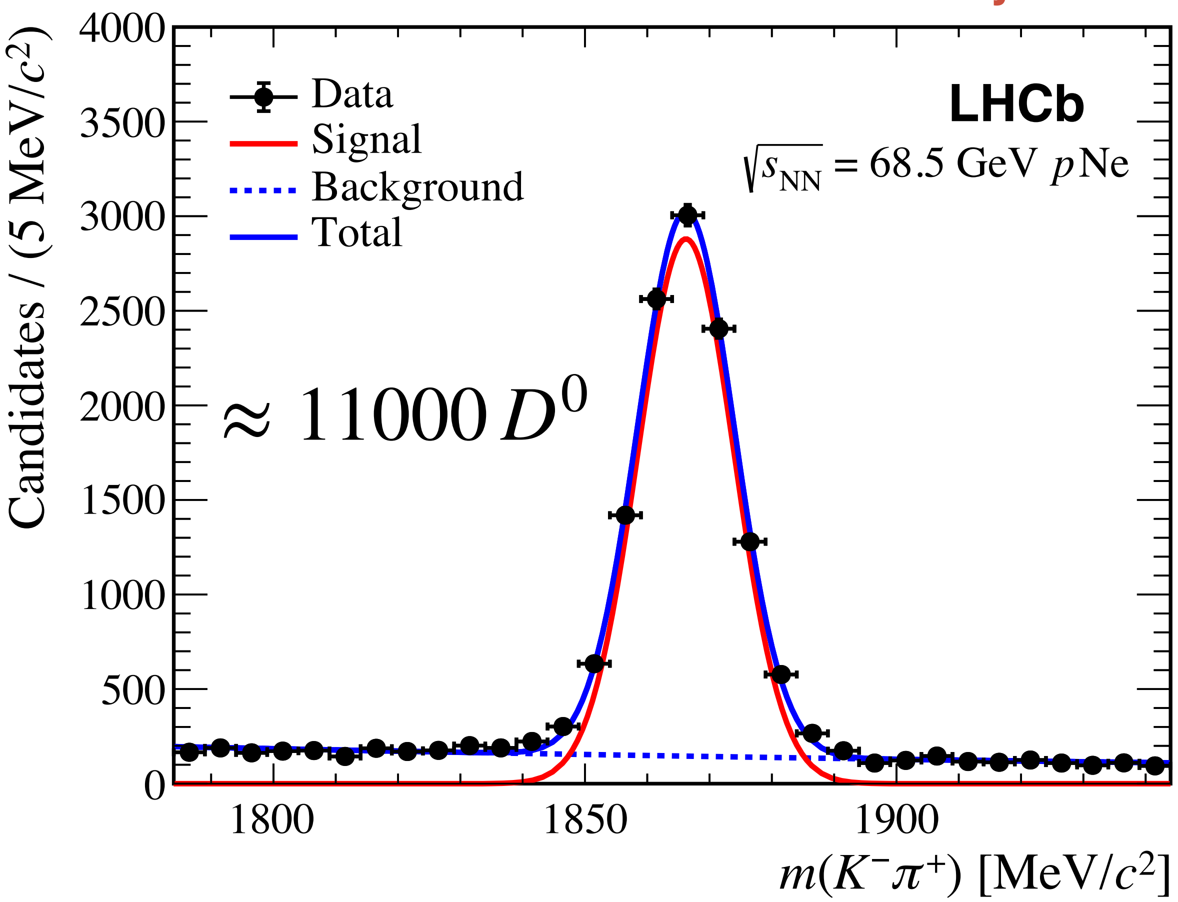


Open-charm in $p\mathrm{Ar}$ collisions from 2024

- Data from $p\mathrm{Ar}$ collisions collected this August with SMOG2
- Studying $D^0 \to K^-\pi^+$ decay channel for first production measurements:
  - Collected during nominal proton-proton physics run
  - Huge increase in statistics! **From 24K to 1.2M collected in half the time!**
  - Physics performance of 2024 data achieving that of Run 2

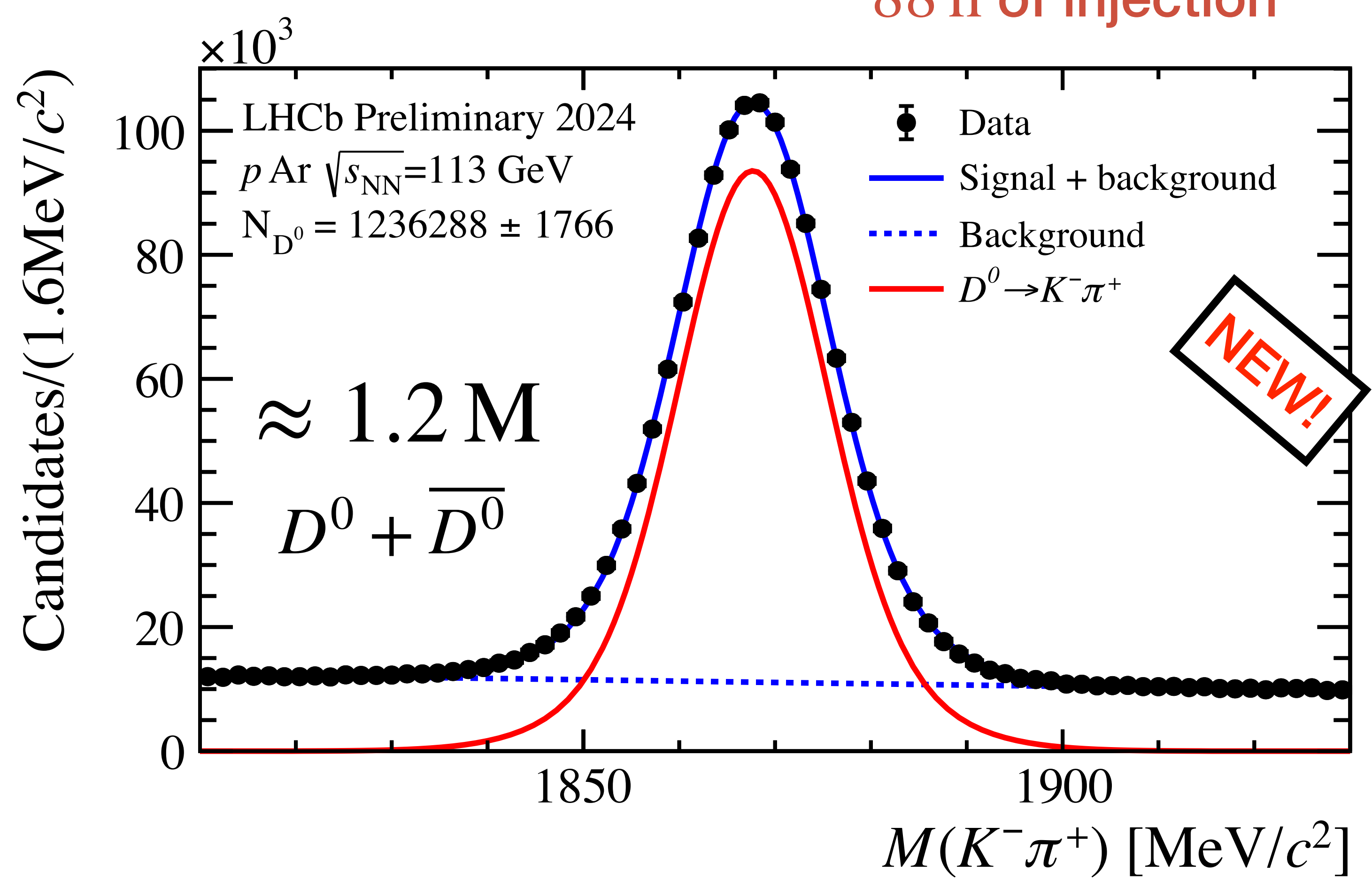
Run 2 largest sample - $p\mathrm{Ne}$

$167\,\mathrm{h}$ of injection



2024 August sample - $p\mathrm{Ar}$

$88\,\mathrm{h}$ of injection



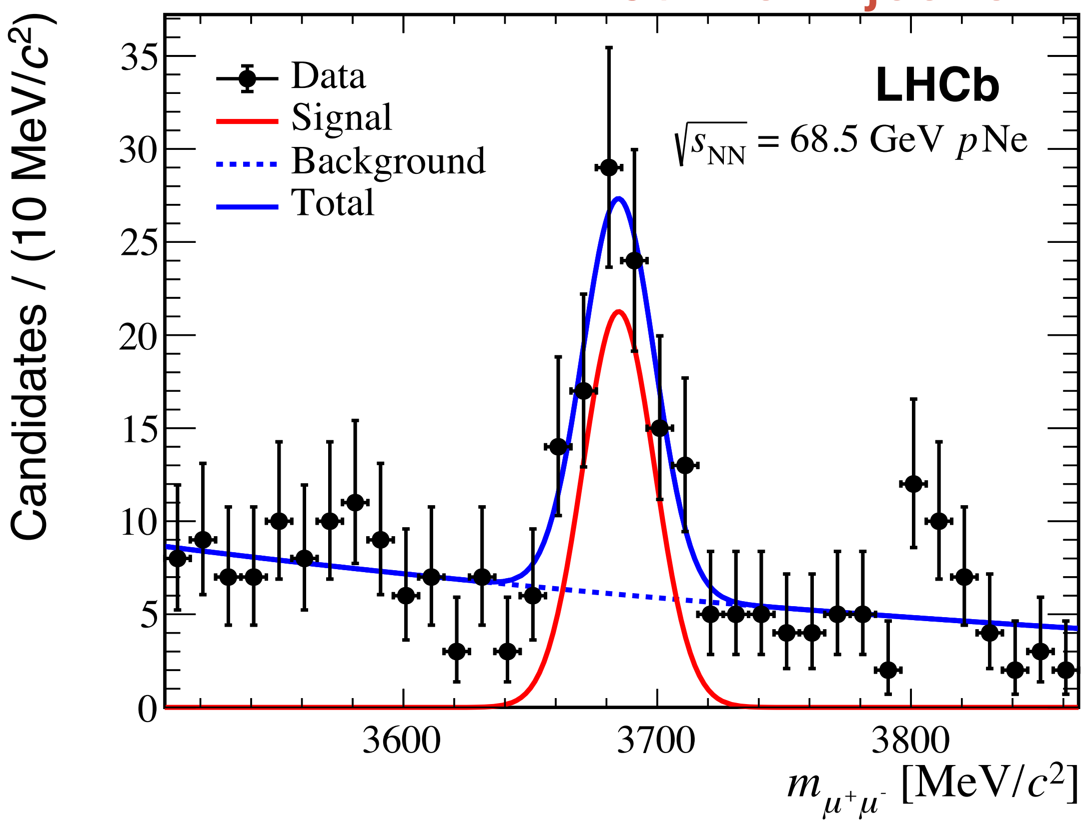
LHCb-FIGURE-2024-023

Quarkonia in $p\mathrm{H}_2$ collisions from 2024

- Collected also large samples of $p\mathrm{H}_2$ collision data!
  - Crucial for $R_{p\mathrm{A}}$ determinations
- Dimuon spectrum shows clean signals for $J/\psi \to \mu^+\mu^-$ and $\psi(2S) \to \mu^+\mu^-$!
  - Physics performances achieving those of Run 2
- Aiming for an early study the $\psi(2S)/J/\psi$ ratio to probe cold nuclear effects in different systems

Run 2 largest sample - $p\mathrm{Ne}$

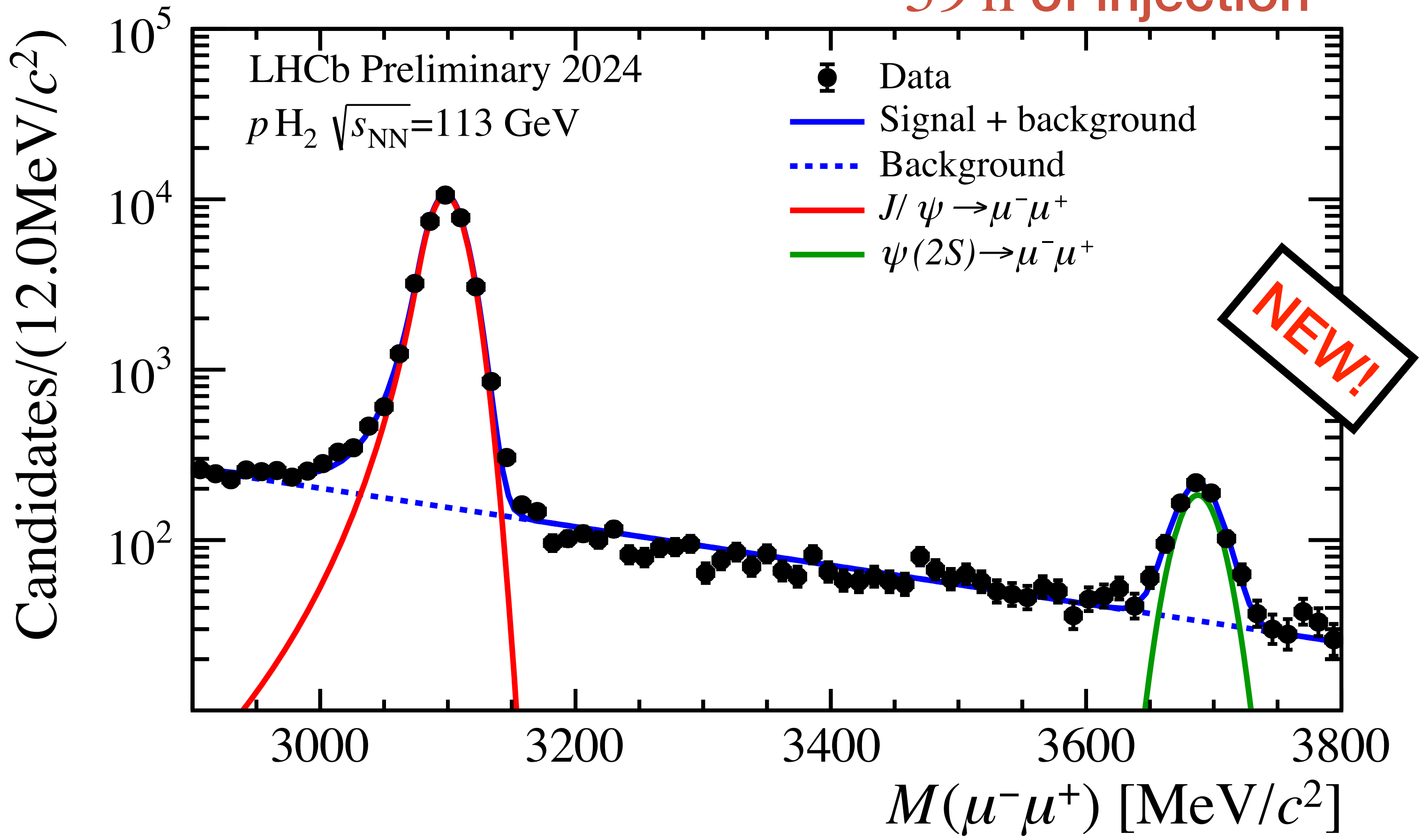
$167\,\mathrm{h}$ of injection



EPJC 83 (2023) 625

2024 August sample - $p\mathrm{H}_2$

$39\,\mathrm{h}$ of injection



LHCb-FIGURE-2024-023

Conclusions

- LHCb in its fixed-target mode provides a **unique environment to study charm production** in a variety of collision systems in an unexplored region of the phase-space
- Recent measurements with **Run 2 data** provide unique inputs:
  - D^0 and $\overline{D^0}$ production and asymmetry in $p\mathrm{Ne}$ collisions probes nuclear partonic structure and hadronisation in an unexplored regime
  - Charmonium production in $p\mathrm{Ne}$ and PbNe collisions tests the presence of nuclear effects and the presence of a hot nuclear medium
- The **new gas storage target SMOG2** is a huge step forward:
  - Allow for simultaneous data-taking with nominal proton-proton
  - Increase up to a factor $\times 100$ in statistics, higher precision
  - Allow for injection of new gases; a data sample with H_2 is already available
- **Highly successful LHCb operations in 2024**:
  - Demonstrated that we are able to run simultaneously with proton-proton operations
  - Physics performances in fixed-target collisions similar to those in proton-proton and achieving those of Run 2
  - We are ready for the ion run at the end of 2024 → Aiming to collect a **large** PbAr **sample**

Backup