# Charm hadron production in fixed-target collisions at the LHC

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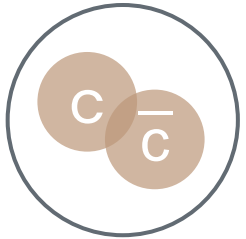
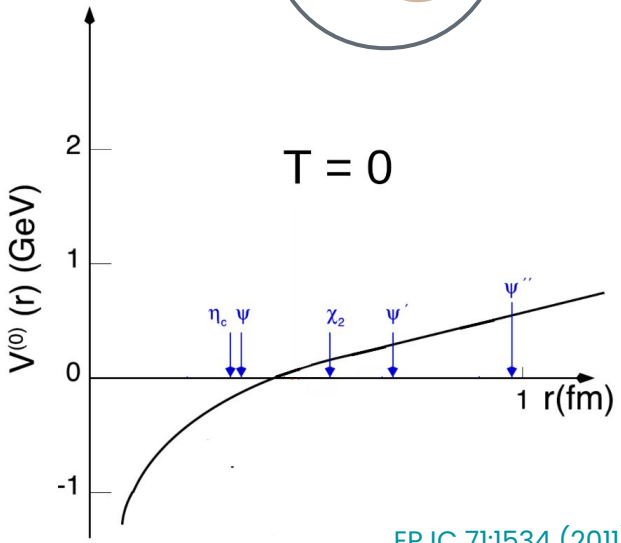
EuNPC 2025 – September 23

# Charmonium as probe of deconfinement

- Signatures of deconfinement → key research area in heavy-ion physics.
- Charmonium → model system to study color charge interaction at:
  - T=0 (vacuum).
  - Finite temperature (in medium).
- Charmonium suppression → historical probe of deconfinement in heavy-ion collisions.
- Non-primordial production → additional sign of deconfinement.




EPJC 71:1534 (2011)

# Total $c\bar{c}$ cross section as baseline for charmonia modification

- Charm is conserved in QGP → charm reservoir.
- Total $c\bar{c}$ cross section → natural normalization for charmonia modification.
- Contributions from different mesons and baryons.
- Extensive measurement program needed.

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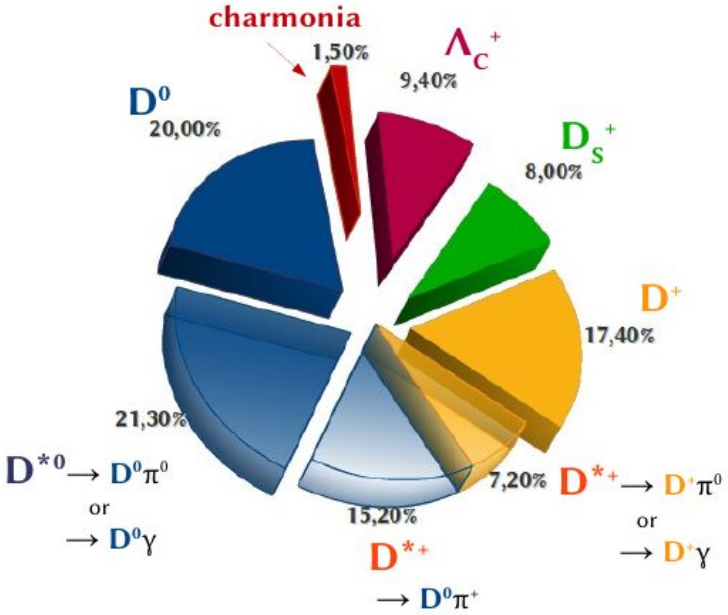
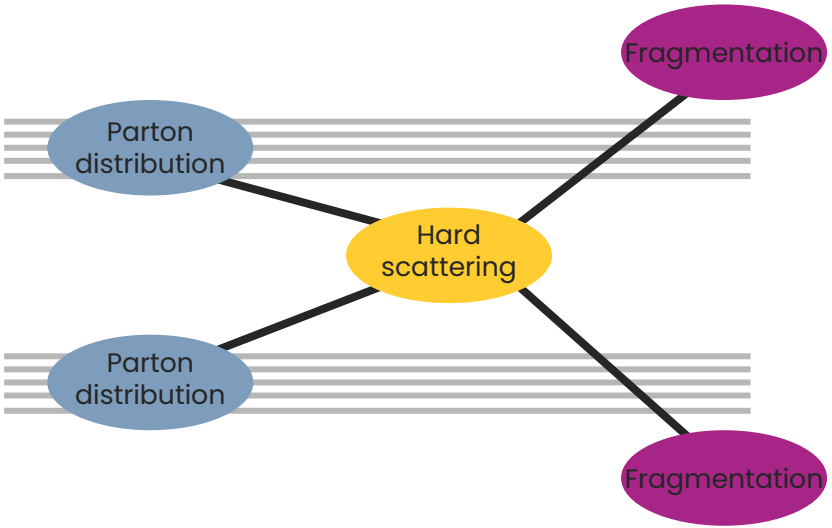


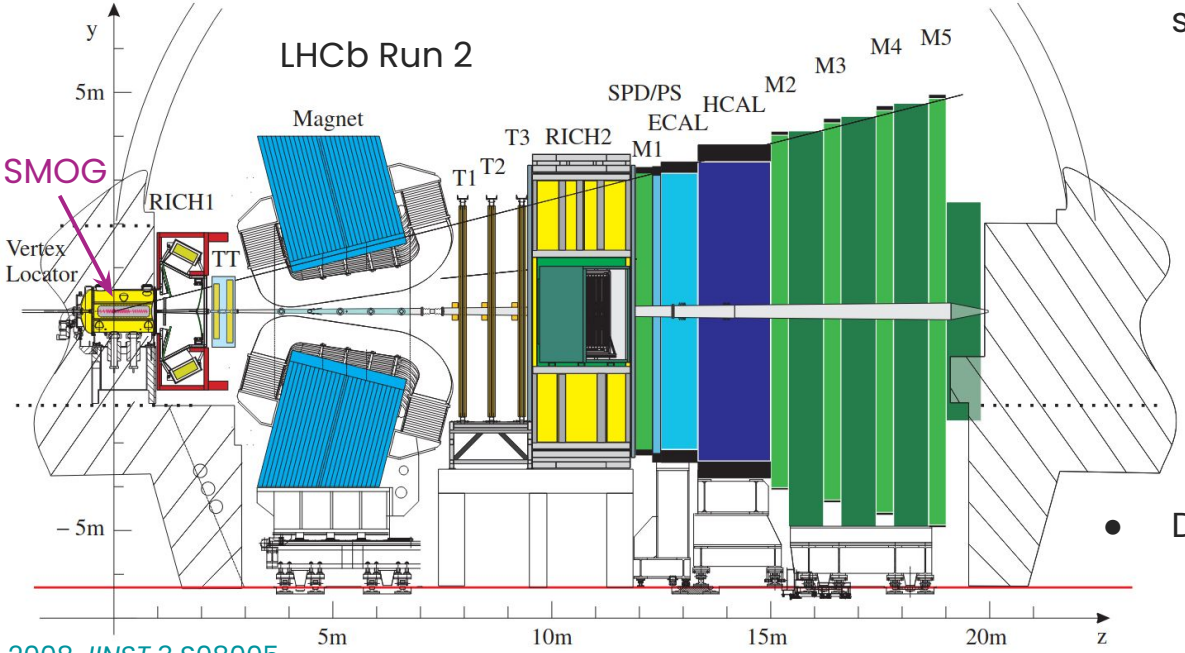

Charm fragmentation fractions from e+e- annihilation and lepton-nucleon DIS.

# Charm fragmentation universality




- Simplest assumption, fragmentation universal:
  - No energy dependence
  - No colliding system dependence ($e^+e^-$, pp, ep, …)
  - No production process dependence (photoproduction, DIS, …)
- Total $c\bar{c}$ cross section measurement:
  - ➢ $D^0$ measurement.

# The LHCb detector

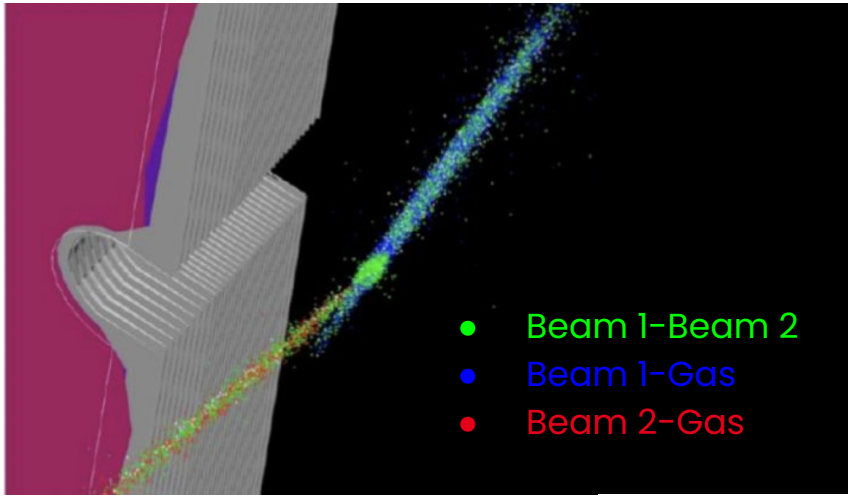


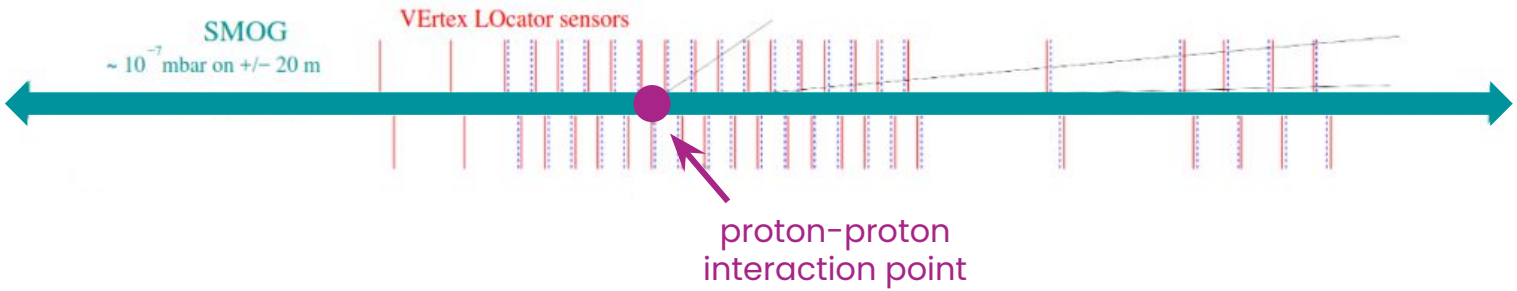

2008 *JINST* 3 S08005
Int. J. of Mod. Phys. A 2015 30:07

- Single arm ($2<\eta<5$), fully instrumented spectrometer.
  - $p$, $K^+$, $\pi^+$ separation
    - ➢ Ring Imaging CHerenkov (RICH).
  - Primary vertex reconstruction
    - ➢ VErtex LOcator (VELO)
  - Tracking
    - ➢ Silicon strip + straw tubes.
  - Hardware trigger
    - ➢ Calorimeters + muon system.
- Designed for heavy-flavour.
  - Physics program vastly expanded throughout the years.
  - Fixed-target program → SMOG.

# SMOG: fixed-target at the LHC

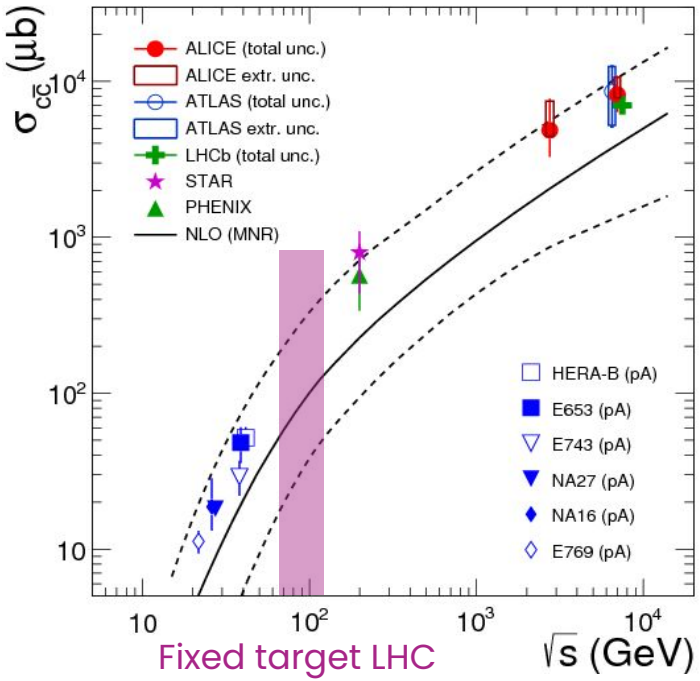
- System for Measuring Overlap With Gas.
  - Started 2015
- Unique opportunity at the LHC: fixed-target collisions.
- Gas injection inside the LHC vacuum around LHCb's interaction point.
- Gas extends ±20m along beam pipe.
- Vacuum pressure raised $10^{-9} \rightarrow 10^{-7}$ mbar.



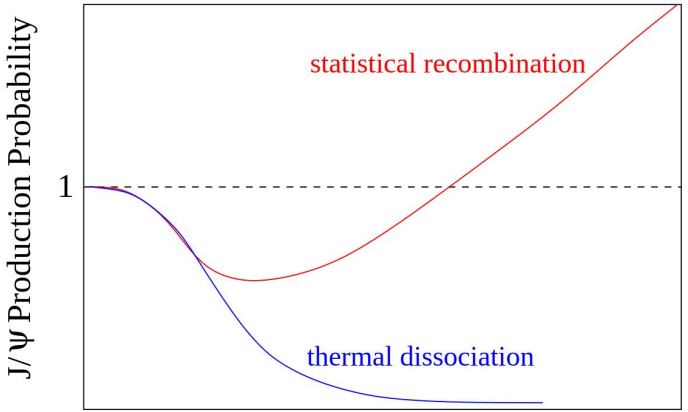



# Recombination at fixed-target LHC energies

Phys. Rev. C 94, 054908 (2016)




- Opportunity to test deconfinement at:
  - Expected lower energy density.
  - Expected lower charm quark density.
- Recombination of $c\bar{c}$ into charmonium expected to be lower than at LHC energies.

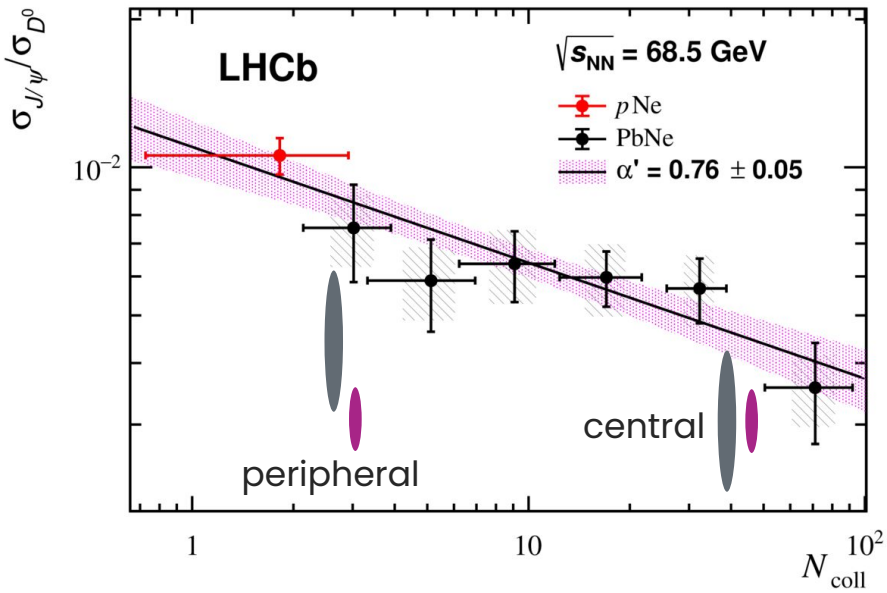



arXiv:0901.3831

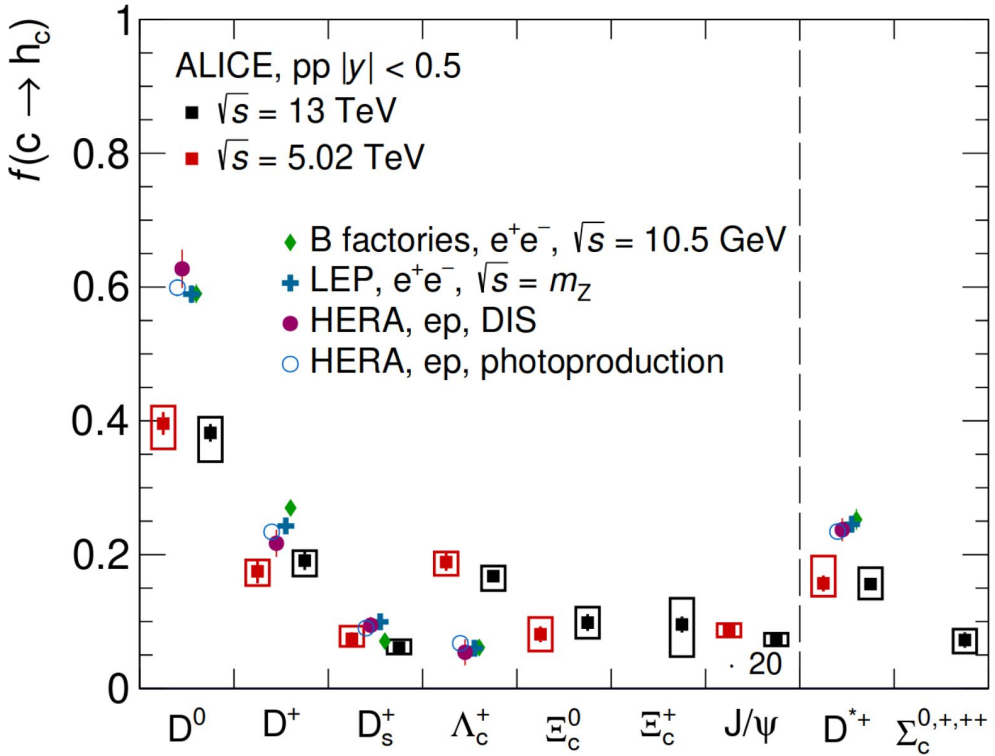
# $D^0$ as proxy for total $c\bar{c}$ cross section

- $J/\psi$ over $D^0$ ratio measured:
  - Fixed-target *p*Ne.
  - Fixed-target PbNe
- PbNe data splitted in several centrality bins and matched to the number of binary nucleon-nucleon collisions ($N_{coll}$).
- Assume scaling:
  - $\sigma_{J/\psi} \propto \langle N_{coll} \rangle^{\alpha'}$.
  - $\sigma_{D^0} \propto \langle N_{coll} \rangle \rightarrow$ $D^0$ as proxy for total $c\bar{c}$ production.
- No hint of anomalous $J/\psi$ suppression.
- Assumed charm fragmentation fractions universality.

Eur. Phys. J. C83 (2023) 658



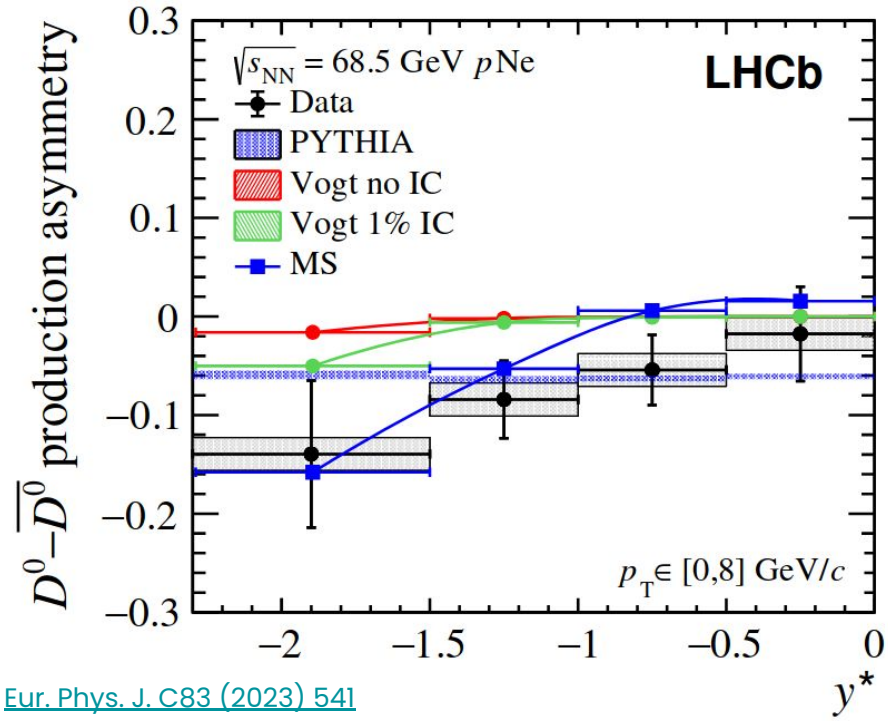
# Charm fragmentation results in *pp*




JHEP 12 (2023) 086

- Significant enhancement of charm baryon contribution to the $c\bar{c}$ cross-section compared to $e^+e^-$ and *ep* data.
- Need measurement of all ground state open charm hadrons.

# $D^0$ production asymmetry in *p*Ne

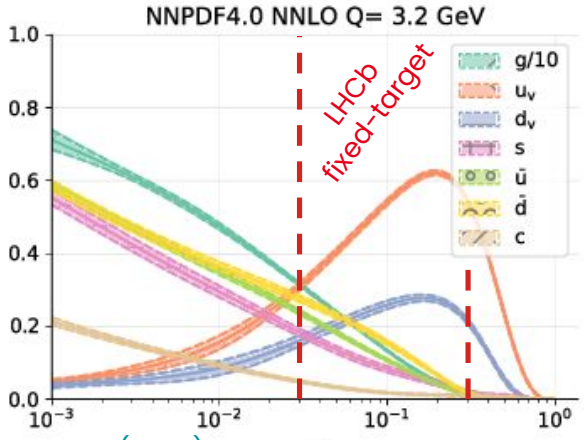



Eur. Phys. J. C83 (2023) 541

- Open charm charge asymmetry tendency in fixed-target *p*Ne at LHCb.
- Additional fragmentation fraction non universality.
- Sensitive to intrinsic charm.
- Needs confirmation with other open charm hadrons and colliding systems.

$$A = \frac{N(c\bar{q}) - N(\bar{c}q)}{N(c\bar{q}) + N(\bar{c}q)}$$

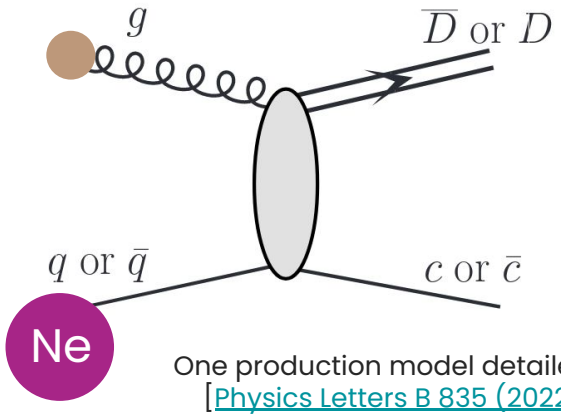
# Qualitative explanation




EPJC 82 (2022) 428

- Coalescence of charm with target valence quark.
- Valence region dominated by u and d quarks.
  - ➢ Negative asymmetry increasing at backward rapidity.

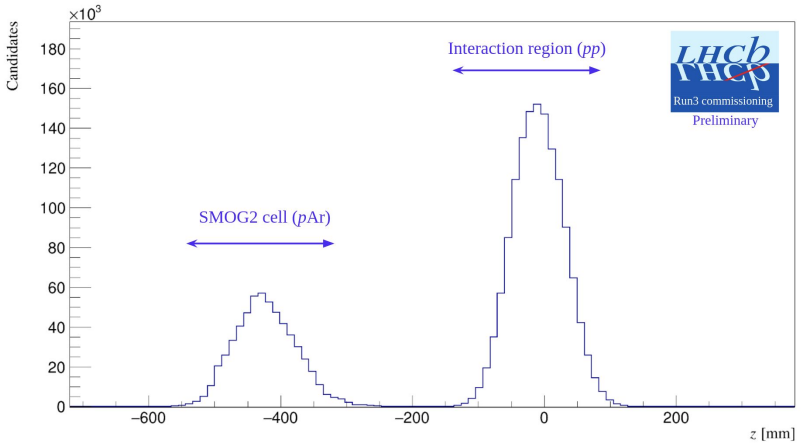
- Charm hadronization sensible to partonic environment.
- More statistics needed to confirm effect.
- Ideally use Hydrogen target → No nuclear effect.



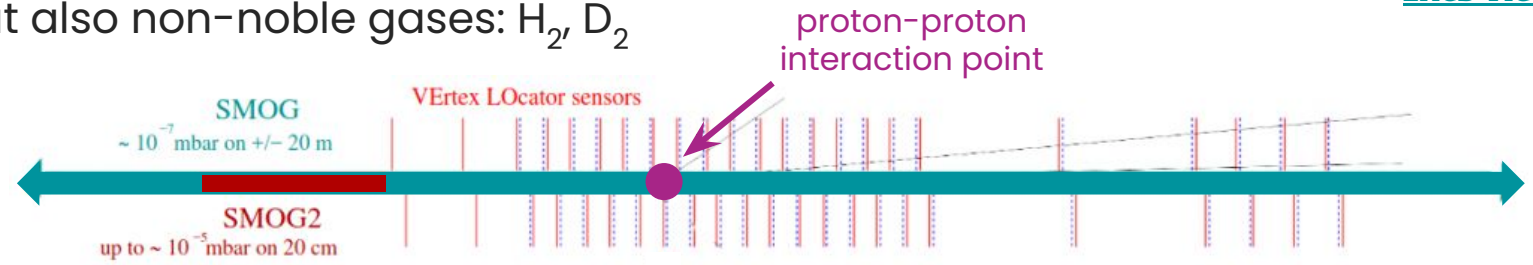

One production model detailed in [Physics Letters B 835 (2022)]

# SMOG2

- Gas storage cell upstream of the VELO.
  - Installed in 2022 → Taking data!
- Higher pressure than SMOG → x100
- Parallel running with collider mode.
- Dedicated open charm trigger lines for total $c\bar{c}$ cross section measurements.
- Numerous noble gases: $^{4}He$, $^{20}Ne$, $^{40}Ar$
- But also non-noble gases: $H_2$, $D_2$

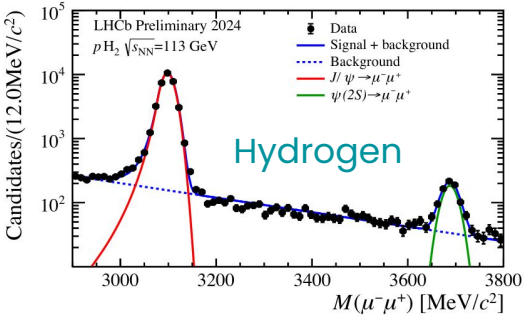


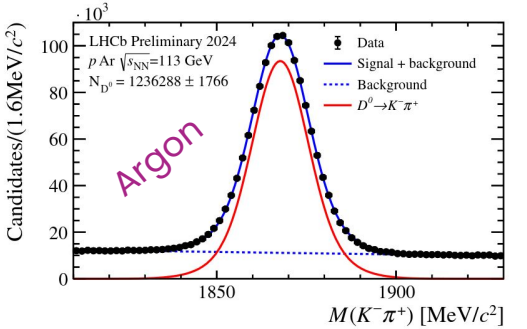

LHCB-FIGURE-2023-001



# Charm in SMOG2 – 2024 data-taking

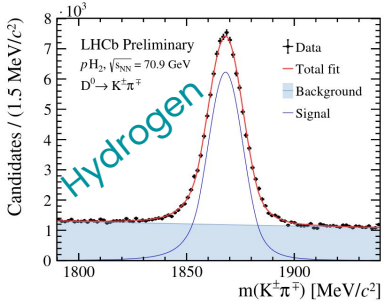
## Proton beam, $\sqrt{s_{NN}}$ = 113 GeV

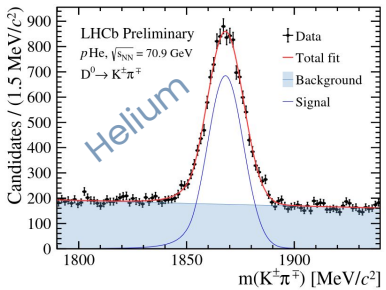


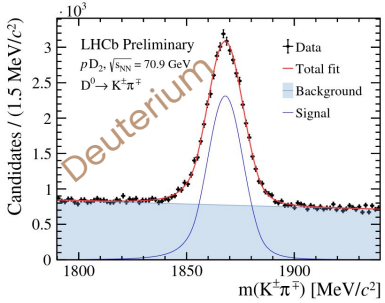



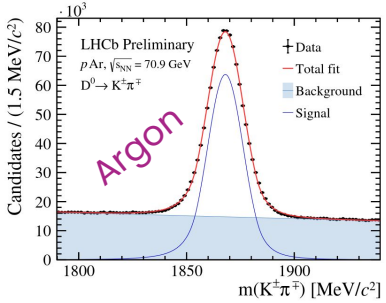

[LHCB-FIGURE-2024-023]

## Proton beam, $\sqrt{s_{NN}}$ = 70.9 GeV



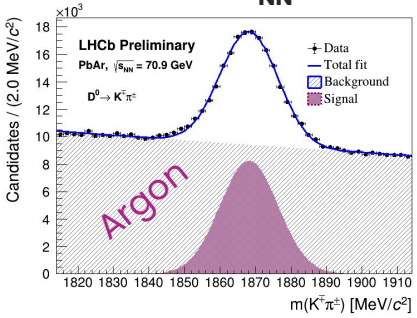



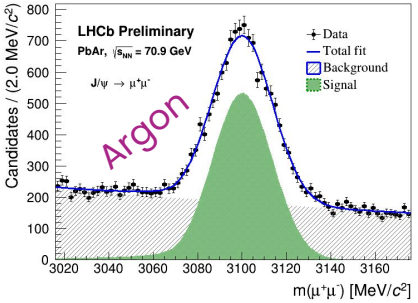




[LHCB-FIGURE-2025-013]

## Lead beam, $\sqrt{s_{NN}}$ = 70.9 GeV




[LHCB-FIGURE-2025-014]

## And more to come!

# Conclusions & outlook

- Unique environment to study charm.
  - Various colliding systems.
  - Unexplored phase-space region.
- Results from Run 2:
  - **Charmonium in *p*Ne and PbNe**
    - ➢ Nuclear effects, hot nuclear medium.
  - **Open charm charge asymmetry in *p*Ne**
    - ➢ Nuclear structure, hadronization.
- SMOG2:
  - Analyses with 2024 data ongoing.
  - 2025 data-taking at full-speed.
  - Possible future gases: $N_2$, $O_2$