# Charm production with SMOG at LHCb

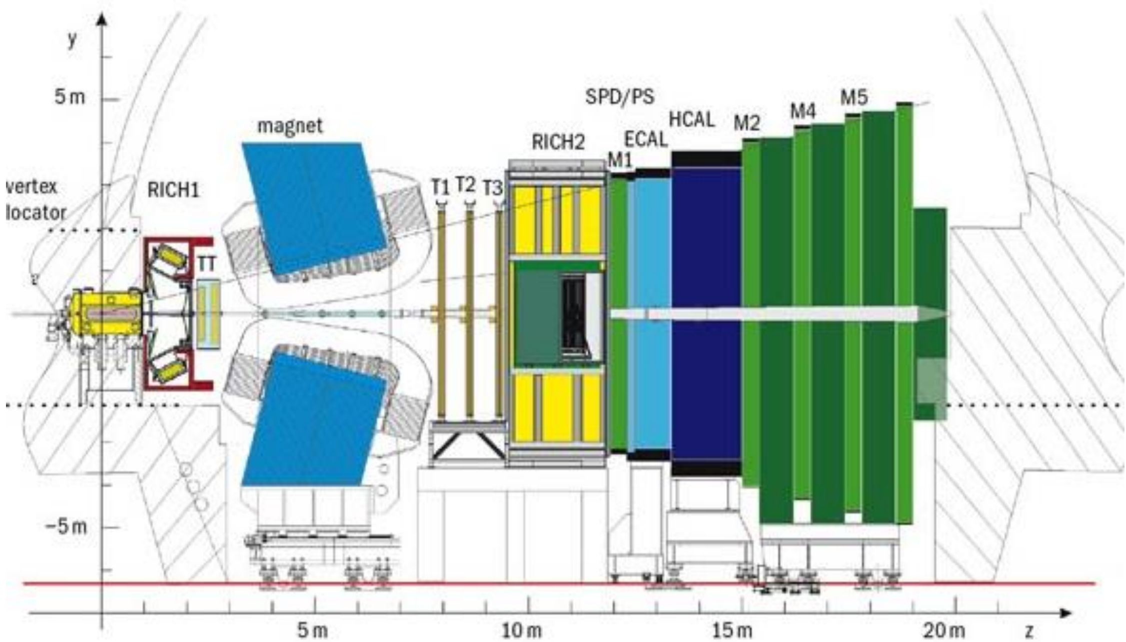
Running LHCb in a fixed-target mode

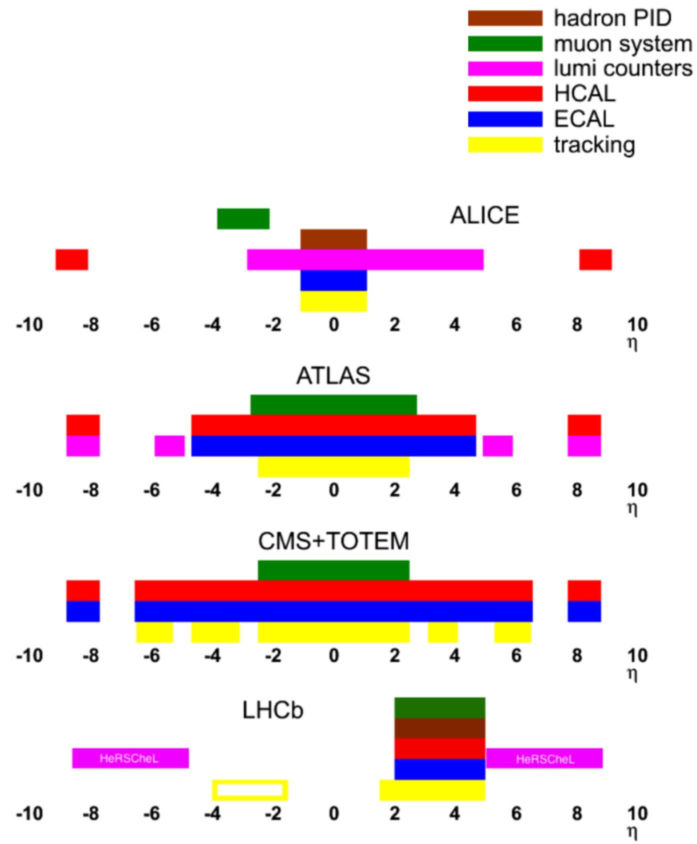
Heavy flavor production in Heavy Ion collisions

F. Fleuret on behalf of the LHCb collaboration

# LHCb detector

- Designed for heavy flavor physics
- Single arm spectrometer, fully instrumented in $2 < y < 5$




Excellent vertex, IP and decay time resolution

$\sigma(IP) \approx 20\mu m$

Very good momentum resolution

$\delta p/p \approx 0.5-1\%$ for $0<p<200$ GeV/c

Particle identification

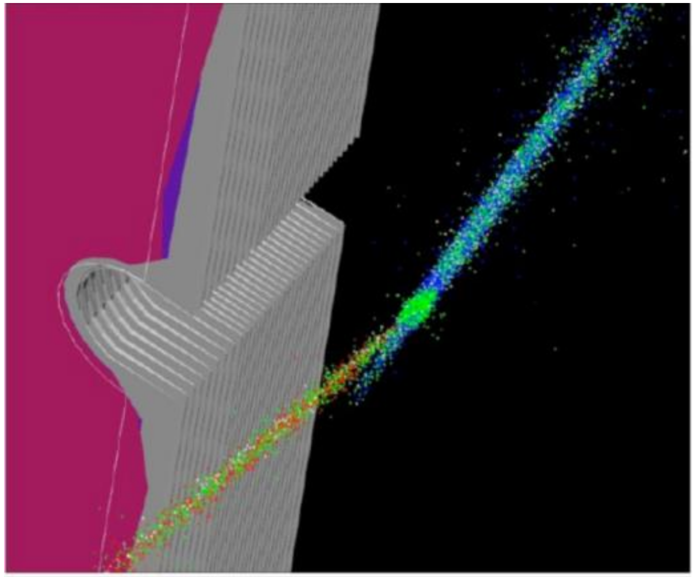
$\varepsilon_{K\to K} \approx 95\%$ for $\varepsilon_{\pi\to K} \approx 5\%$ up to 100 GeV/c

$\varepsilon_{\mu\to\mu} \approx 97\%$ for $\varepsilon_{\pi\to\mu} \approx 1-3\%$

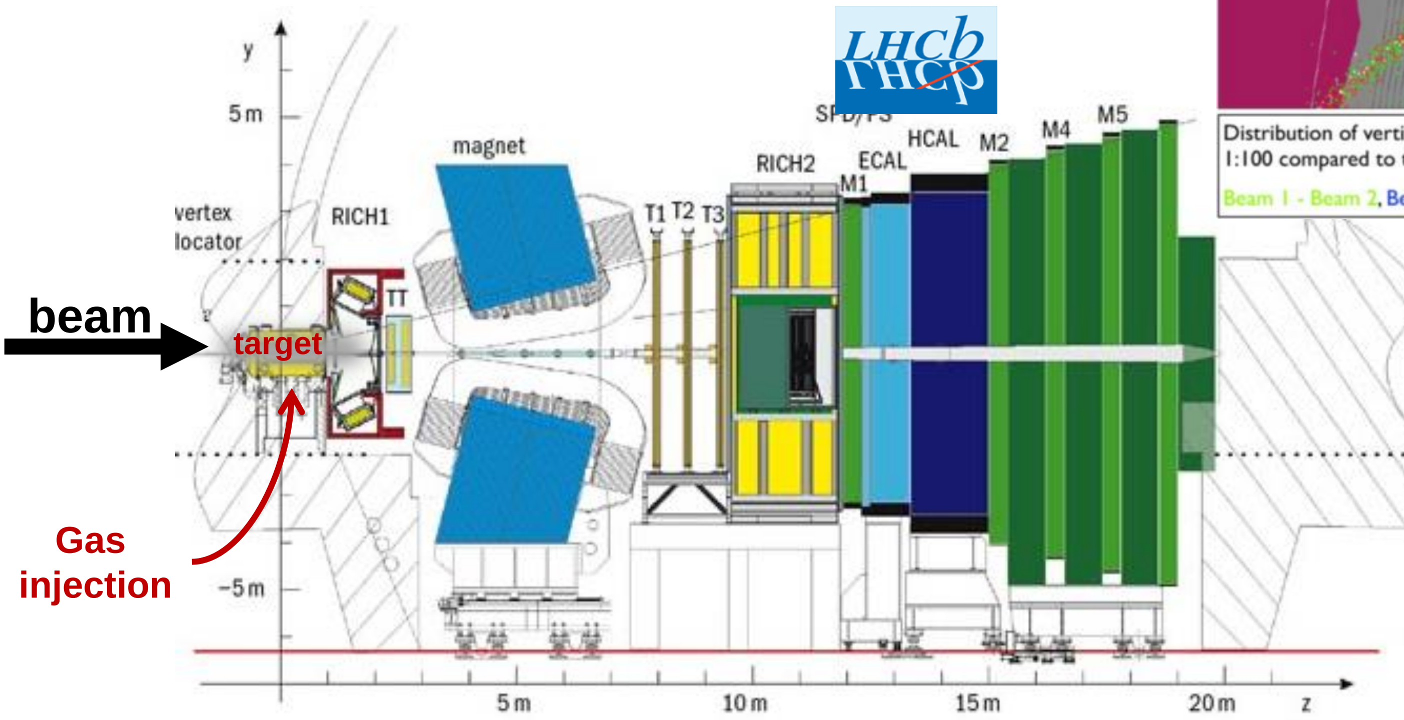
JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022

# SMOG (System for Measuring Overlap with Gas)

- **Injecting gas in LHCb Vertex Locator (VELO) region**
  - Primary role : luminosity measurement
  - Can be used as an **internal gas target**
  - Allows measurement of p-gas and ion-gas interactions



Distribution of vertices overlaid on detector display. z-axis is scaled by 1:100 compared to transverse dimensions to see the beam angle.
Beam 1 - Beam 2, Beam 1 - Gas, Beam 2 - Gas.




**Noble gas only :**
(very low chemical reactivity)

He, Ne, Ar, Kr, Xe
A = 4, 20, 40, 84, 131

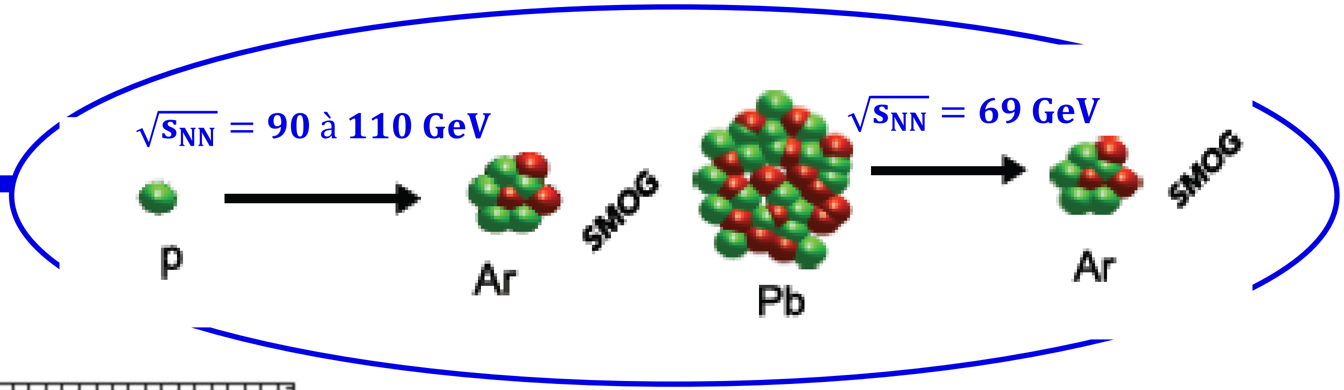
Gaz pressure:
$10^{-7}$ to $10^{-6}$ mbar

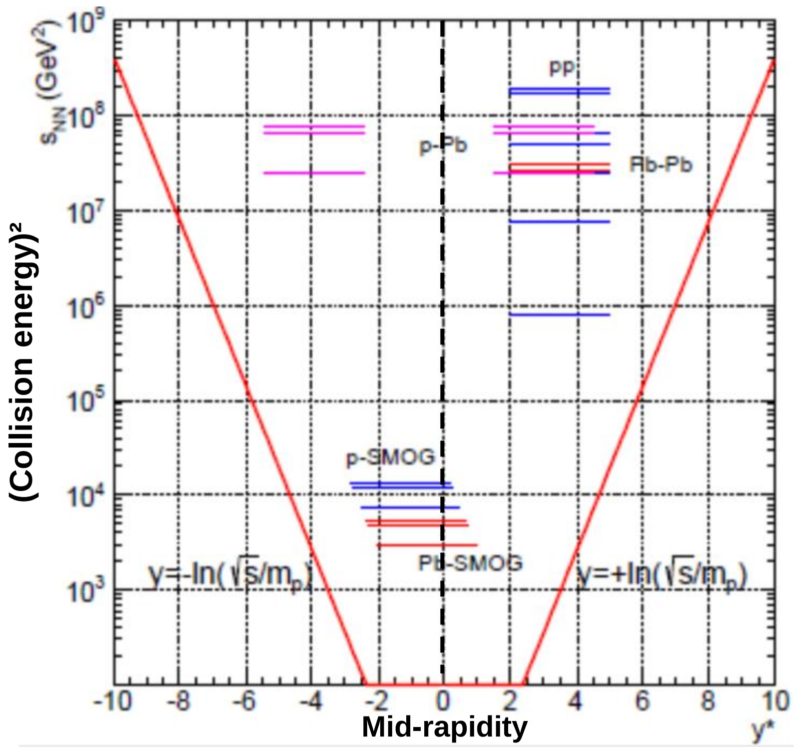
# Fixed-target program

$\sqrt{s_{NN}^{SPS}}$ ~ 20 GeV

$\sqrt{s_{NN}^{RHIC}}$ = 200 GeV

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




LHCb rapidity coverage in the center-of-mass system

Colliding mode (forward rapidity)

| $E_{\text{beam}}$(p) | pp | p-SMOG | p-Pb/Pb-p | Pb-SMOG | Pb-Pb |
|---|---|---|---|---|---|
| 450 GeV | 0.90 TeV | | | | |
| 1.38 TeV | 2.76 TeV | | | | |
| 2.5 TeV | 5 TeV | 69 GeV | | | |
| 3.5 TeV | 7 TeV | | | | |
| 4.0 TeV | 8 TeV | 87 GeV | 5. TeV | 54 GeV | |
| 6.5 TeV | 13 TeV | 110 GeV | 8.2 TeV | 69 GeV | 5.02 TeV |
| 7.0 TeV | 14 TeV | 115 GeV | 8.8 TeV | 72 GeV | 5.5 TeV |

Fixed-target mode (backward rapidity)

At $\sqrt{s_{NN}}$ = 110 GeV y* = $y_{lab}$ - 4.77

Give access to the target large Bjorken-x region

# Nucleus-Nucleus collisions

- **Physics case**
  - 2.75 TeV Pb beam on fixed target ➔ $\sqrt{s_{NN}}$~71 GeV (close to the 17 GeV regime reached at SPS)
    - Investigate the **Quark Gluon Plasma (QGP) phase transition**
    - Thanks to **unique capabilities**, LHCb offers **new opportunities** in the charm sector: $J/\psi$, $\psi'$, $\chi_c$, $D^0$, $D^{+/-}$, $D^*$, $\Lambda_c$… *(in the 90's the NA50/SPS experiment measured only $J/\psi$ and $\psi'$ in PbPb @ 17 GeV)*

- **Accessing similar energy density regime (than SPS): operate PbAr@71 GeV**
  - Particle multiplicity is related to event centrality and center-of-mass energy
  - Particle multiplicity can be used to compare different A+B collisions at different $\sqrt{s_{NN}}$

| System \ centrality | 60 – 100% | 50 – 60% | 40 – 50% | 30 – 40% | 20 – 30% | 10 – 20 % | 0 – 10% |
|---|---|---|---|---|---|---|---|
| PbNe – 71 GeV | 108.6 | 254.4 | 392.5 | 588.0 | 814.5 | 1086.0 | 1494.9 |
| **PbAr – 71 GeV** | **123.6** | **308.8** | **496.5** | **806.6** | **1228.3** | **1711.9** | **2372.7** |
| PbKr – 71 GeV | 196.9 | 533.6 | 919.1 | 1451.2 | 2205.5 | 2986.6 | 4084.3 |
| **PbPb – 17 GeV** | **124.2** | **331.6** | **605.9** | **919.6** | **1338.7** | **2035.8** | **2980.5** |

SPS|←LHC→|

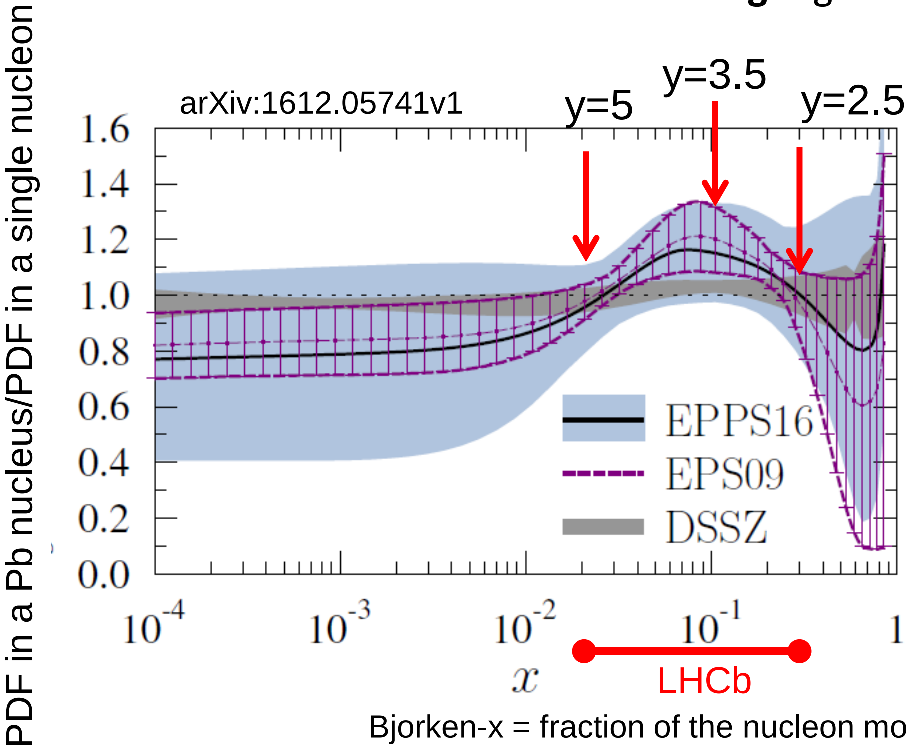
(based on EPOS-LHC-v3400)

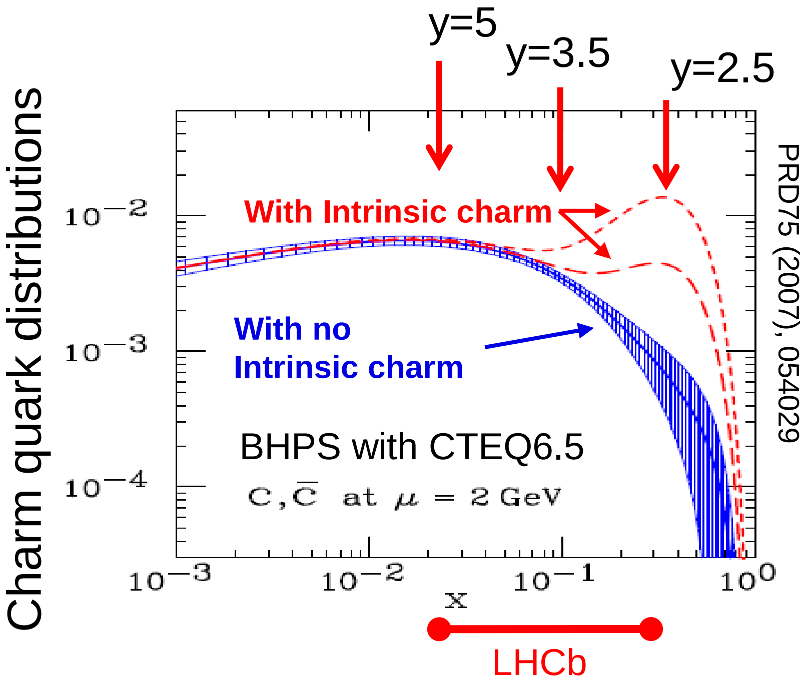
  - PbAr @ 71 GeV multiplicity ≡ PbPb@17 GeV multiplicity

    ➔ **PbAr @ 71 GeV is a good starting point to compare with NA50 (SPS)**

# Proton-Nucleus collisions

- Serve as a **baseline** for nucleus-nucleus collisions
- **Specific proton-nucleus physics program:**
  - Precision cross-section measurement for cosmic ray physics (see G. Graziani's talk)
  - Nuclear parton distribution function (nPDF), saturation, energy loss, nuclear absorption, …
- With SMOG, LHCb offers a large rapidity coverage (~3 rapidity units) at **large Bjorken-x $x_2$**
  - Give access to **nPDF anti-shadowing** region and **intrinsic charm** content in the nucleon




Bjorken-x = fraction of the nucleon momentum carried by a parton

# LHCb fixed-target mode

- **Data recorded**
  - Gas pressure in the VELO: ~ 1 – 2×10$^{-7}$ mbar

| System | Duration | CMS energy | Protons on target |
|---|---|---|---|
| ***2015*** | | | |
| pHe | 7h | 110 GeV | $2\times10^{21}$ |
| pNe | 12h | 110 GeV | $1\times10^{21}$ |
| **pAr** | **17h** | **110 GeV** | $\mathbf{4\times10^{22}}$ |
| pAr | 11h | 69 GeV | $2\times10^{20}$ |
| PbAr (To be analyzed) | 100h | 69 GeV | $2\times10^{20}$ |
| ***2016*** | | | |
| *pHe (see G. Graziani's talk)* | *18h* | *110 GeV* | $3\times10^{21}$ |
| pHe (to be analyzed) | 87h | 87 GeV | $4\times10^{22}$ |

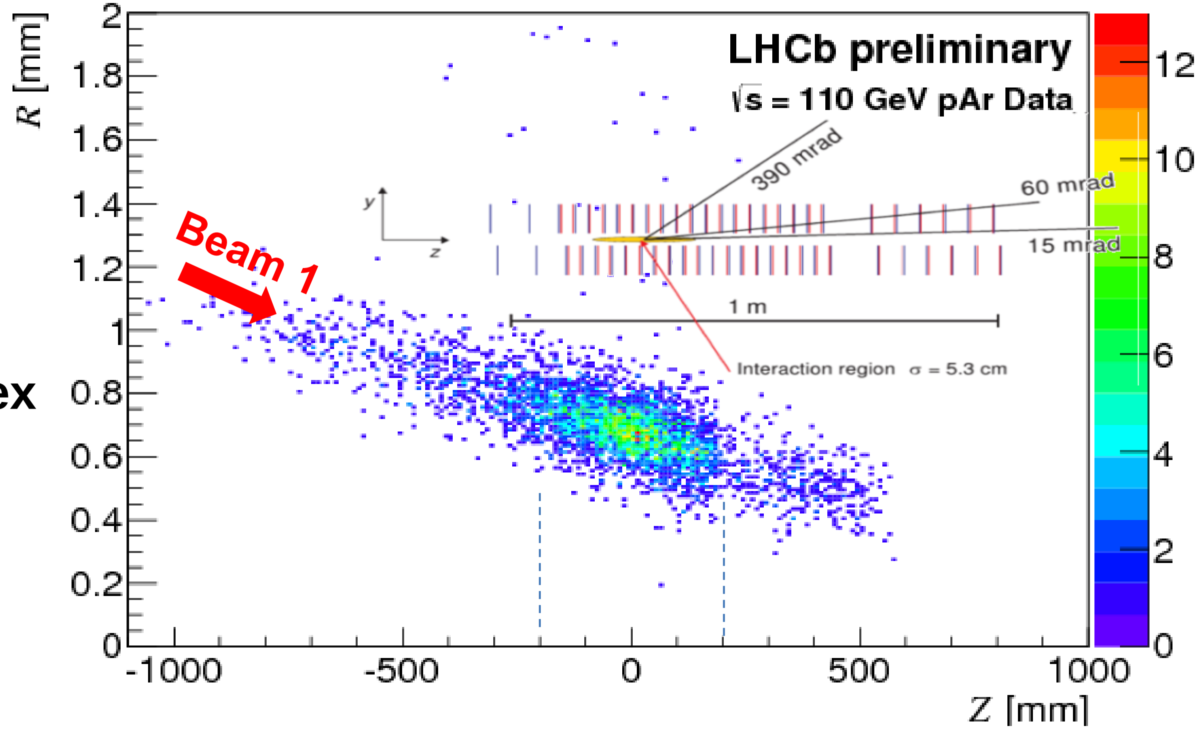
- **Presented here : pAr @ 110 GeV (LHCb-CONF-2017-001)**
  - Preliminary results on heavy flavor production with SMOG
  - **Study J/ψ and D$^0$ production in $\sqrt{s_{NN}}$=110 GeV proton-argon collisions**
    - Demonstration of feasibility of the heavy- flavor LHCb fixed-target program

# Data sample

- **pAr collisions @ 110 GeV**

$$R = \sqrt{X^2 + Y^2}$$

**(*R*,*Z*) position of the Primary Vertex**

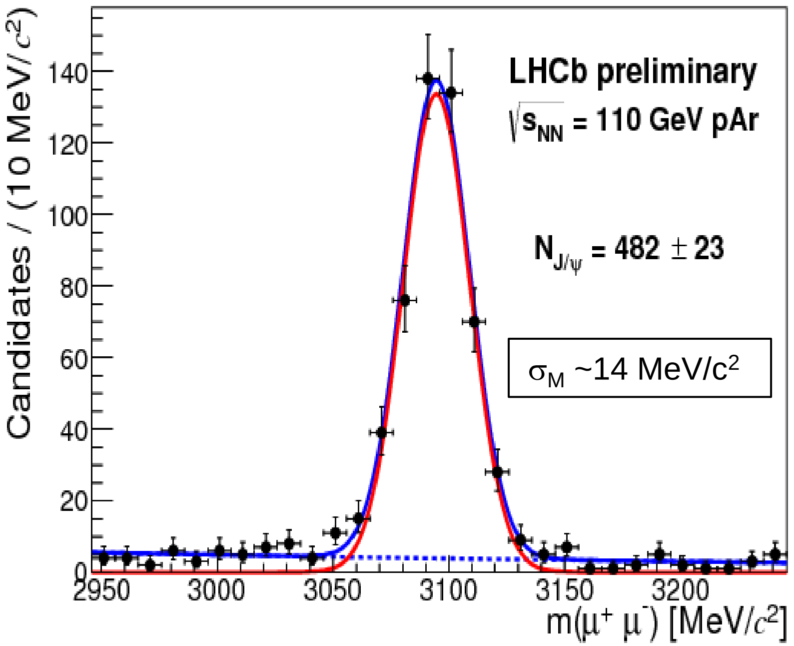


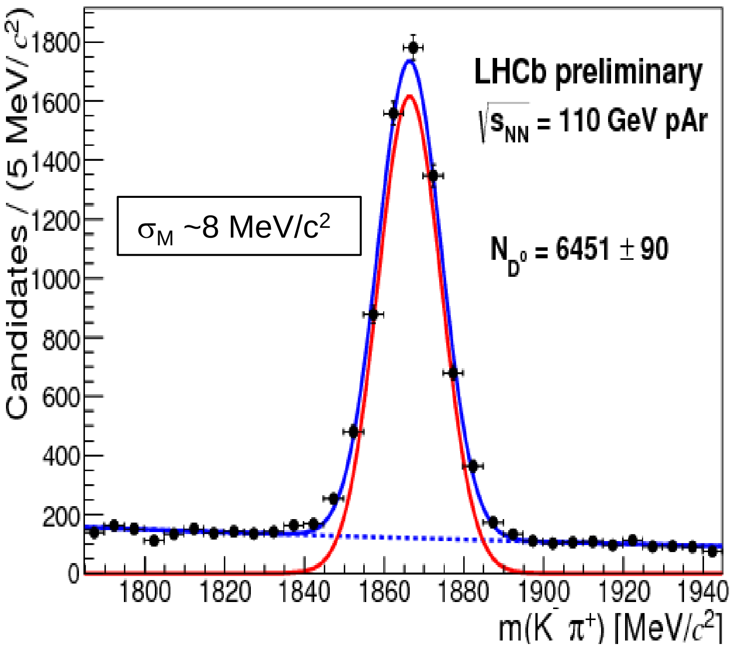

- 17h of pAr collisions with 685 non-colliding bunches: ~$4\times10^{22}$ protons on target
- Select events with Beam 1 only at interaction point
- Apply topological cuts to remove possible residual proton-proton collisions (ghost charge)
- **Select events with $Z_{vertex}$ inside VELO** $Z_{vertex} \in$ [-20 cm, 20 cm]

# Signal extraction

(LHCb-CONF-2017-001)

- **J/ψ and $D^0$ signal**
  - Overall data (17h) : ~500 J/ψ     ~6500 $D^0$



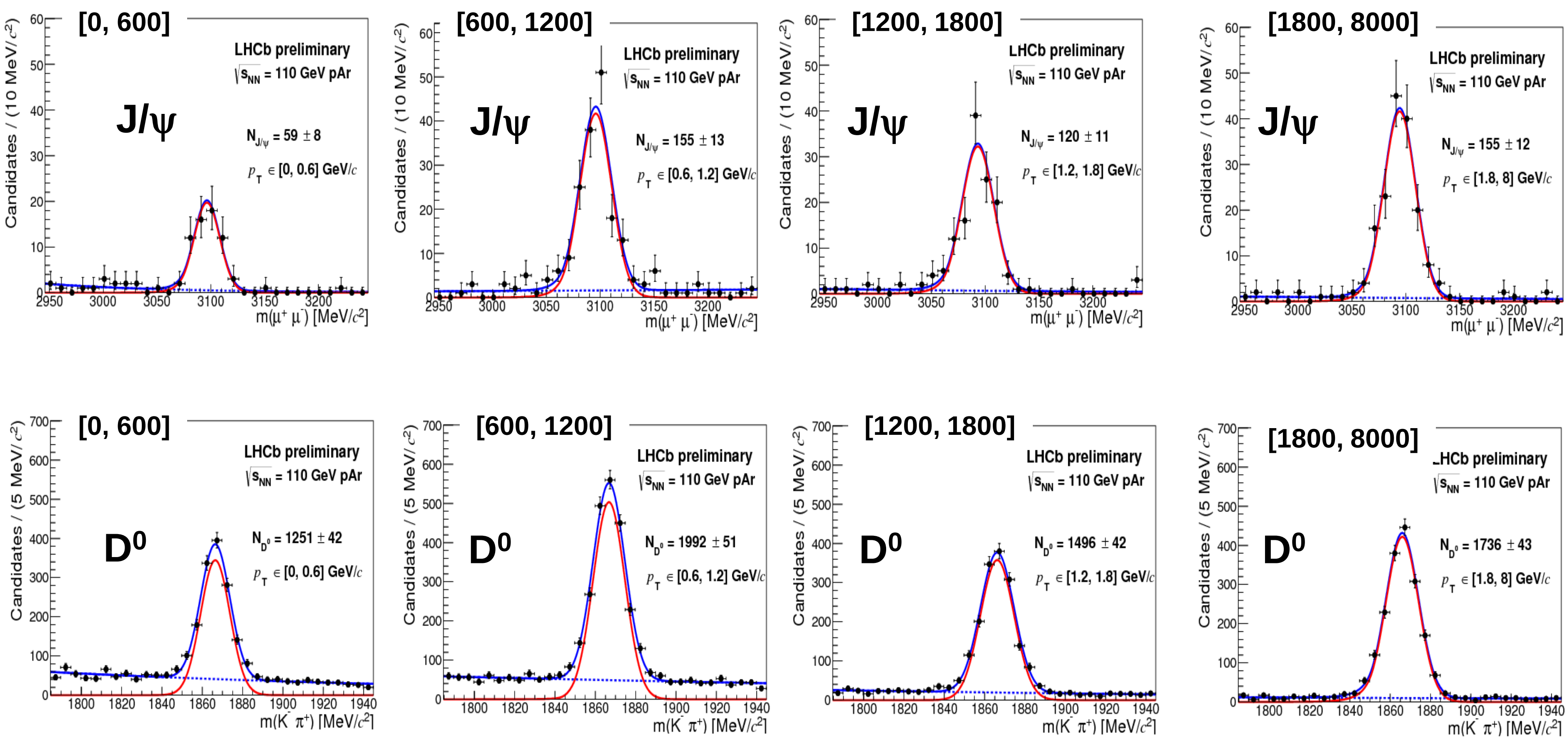




  - Very clear signal, very small background

# J/ψ and $D^0$ differential production

(LHCb-CONF-2017-001)

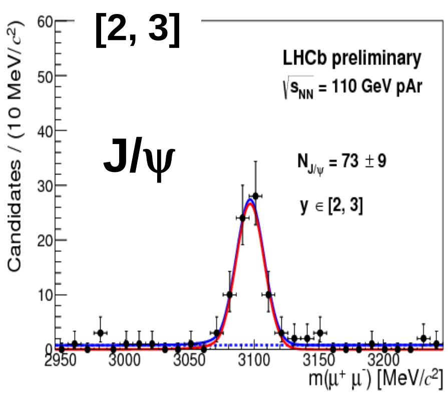
- **4 $p_T$ bins ∈ [0, 600] – [600, 1200] – [1200, 1800] – [1800, 8000] MeV/c**

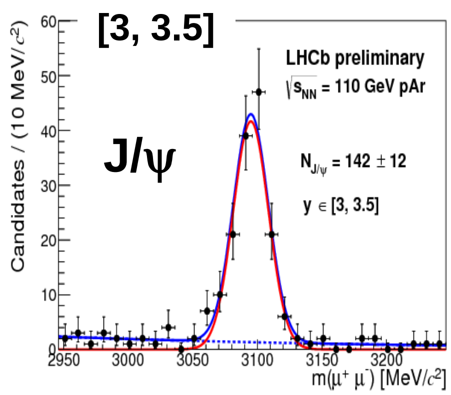


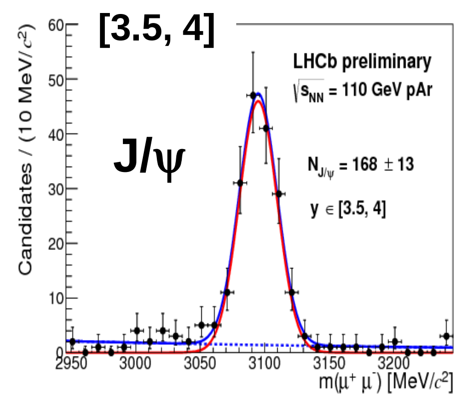
# J/ψ and $D^0$ differential production

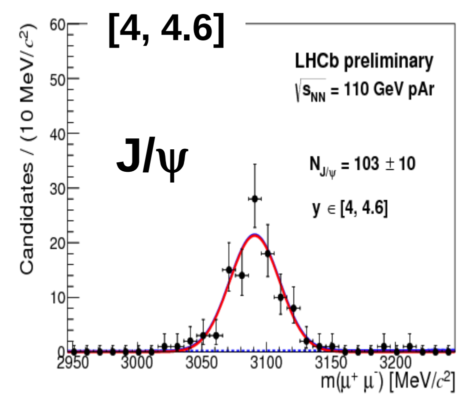
[(LHCb-CONF-2017-001)](LHCb-CONF-2017-001)

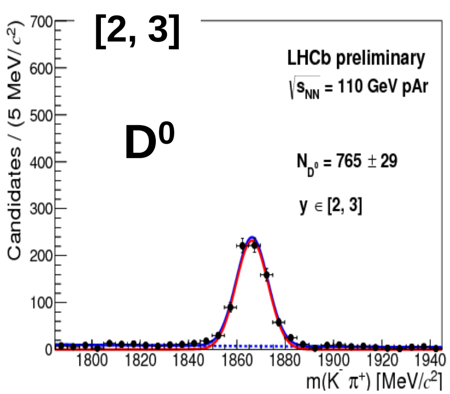
- **4 rapidity bins : [2, 3] – [3, 3.5] – [3.5, 4] – [4, 4.6]**

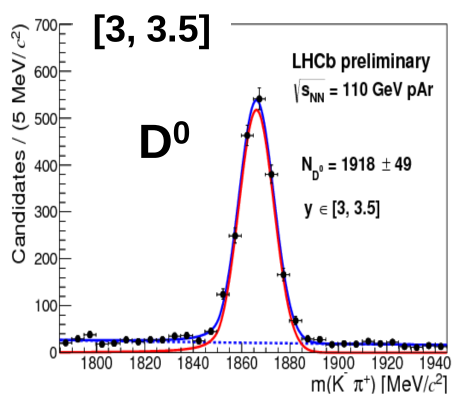


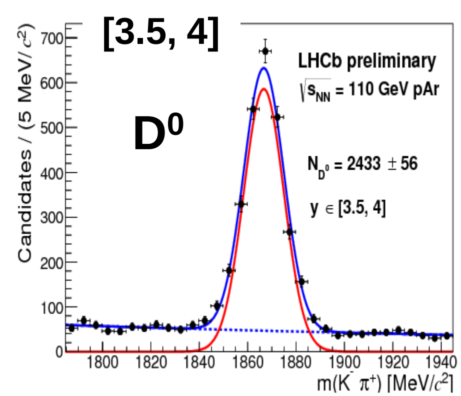



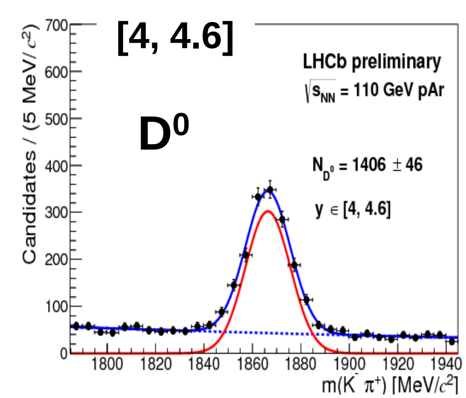



# Yield corrections and uncertainties

(LHCb-CONF-2017-001)

$$Y = \frac{Y^{measured}}{\varepsilon}$$

$Y^{measured}$ *extracted from mass fits are corrected for different efficiencies:*

$$\varepsilon = \varepsilon_{acc} \times \varepsilon_{trig} \times \varepsilon_{sel} \times \varepsilon_{reco} \times \varepsilon_{PID}$$

*geometrical acceptance, trigger, selection, reconstruction, particle identification*

Corrections are computed using pAr simulation samples and pp 13 TeV data

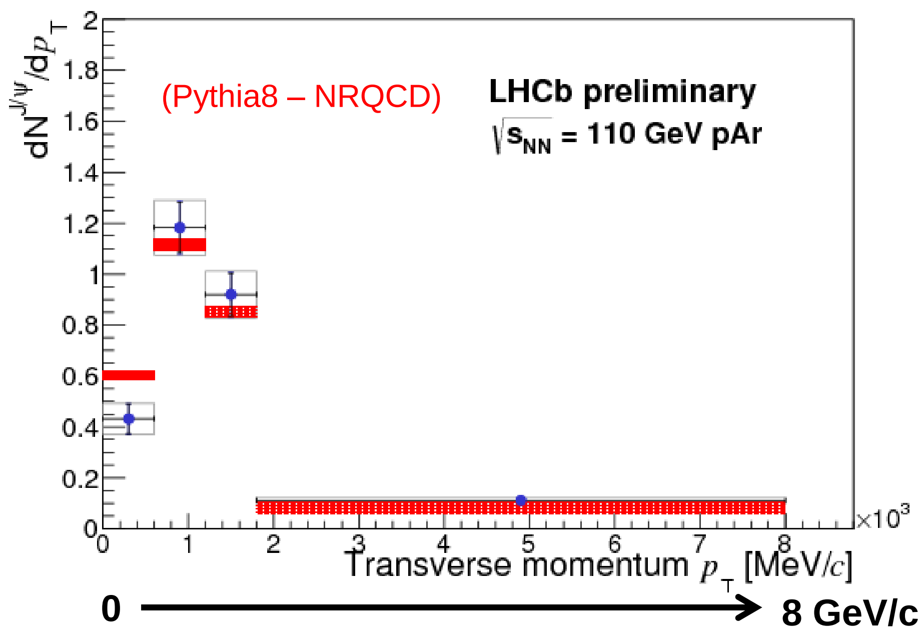
| Source of uncertainties | $J/\psi$ y | $J/\psi$ $p_T$ | $D^0$ y | $D^0$ $p_T$ |
|---|---|---|---|---|
| ***Corr. between bins*** | | | | |
| Signal selection | 1.4% | 1.4% | 2.2% | 2.2% |
| Signal extraction | 2.3% | 2.3% | 2.3% | 2.7% |
| ***Uncorr. between bins*** | | | | |
| MC smaple | (1.2 – 2.6)% | (0.9 – 1.4)% | (1.0 – 1.9)% | (1.0 – 1.5)% |
| Tracking | (2.2 – 3.7)% | (2.2 – 2.9)% | (2.7 – 3.4)% | (2.8 – 3.6)% |
| PID | (0.2 – 2.7)% | (0.1 – 2.0)% | **(4.1 – 8.8)%** | **(4.8 – 6.9)%** |
| ***Stat. uncertainties*** | ***(7.7 – 12.5)%*** | ***(7.8 – 13.6)%*** | *(0.7 – 3.7)%* | *(0.6 – 3.4)%* |

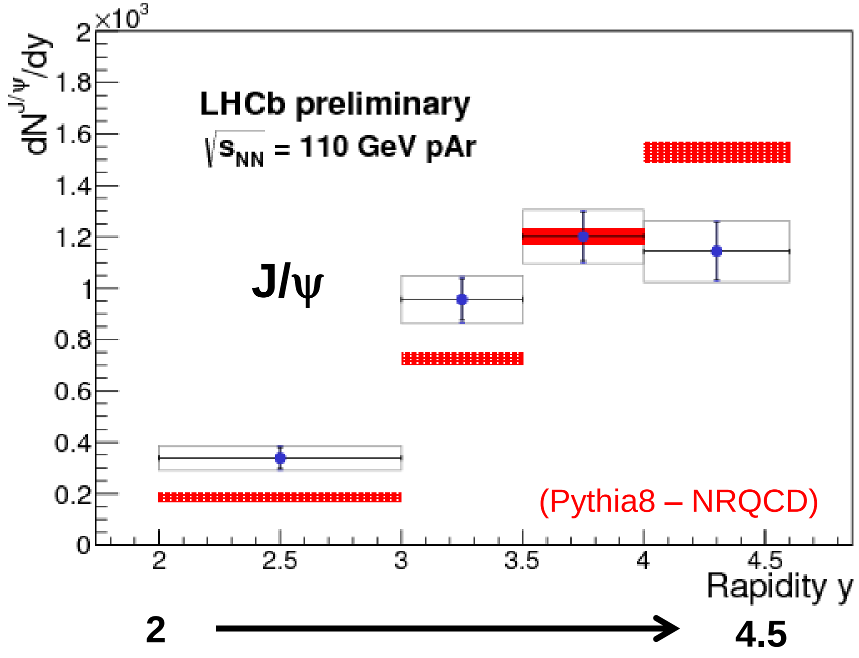
**$J/\psi$ uncertainties are dominated by statistical uncertainties**

# J/ψ corrected yields

(LHCb-CONF-2017-001)

- **J/ψ transverse momentum and rapidity distributions**
  - Box = quadractic sum of all uncertainties

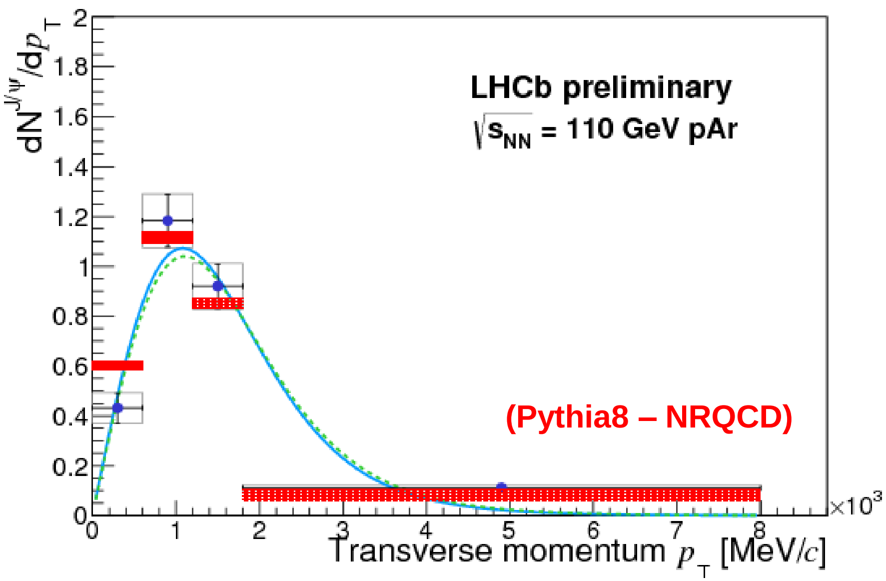


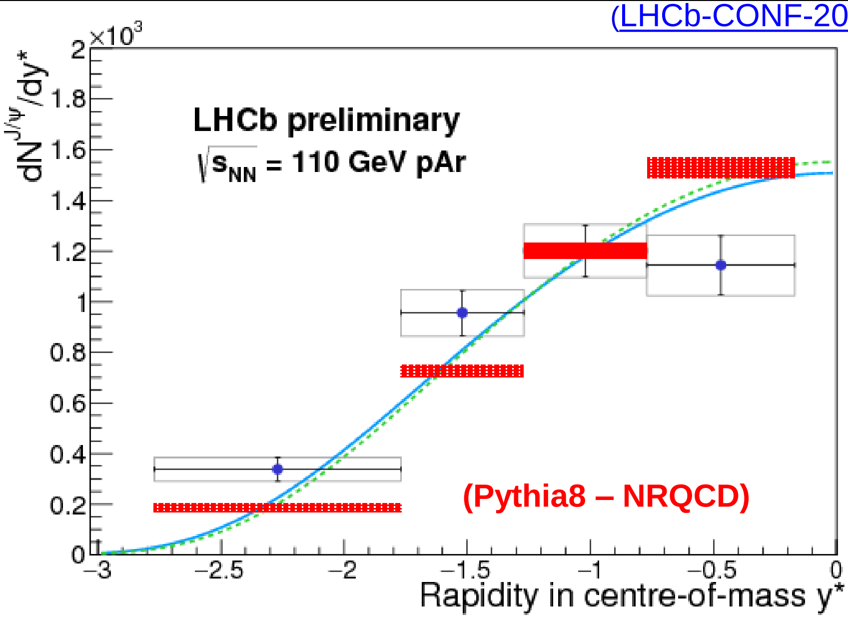




- Red boxes = MC
  - Pythia8-CT09MCS/NRQCD
  - Overall MC yields normalized to overal data yields

# J/ψ yields compared to phenomenological parametrizations

(LHCb-CONF-2017-001)



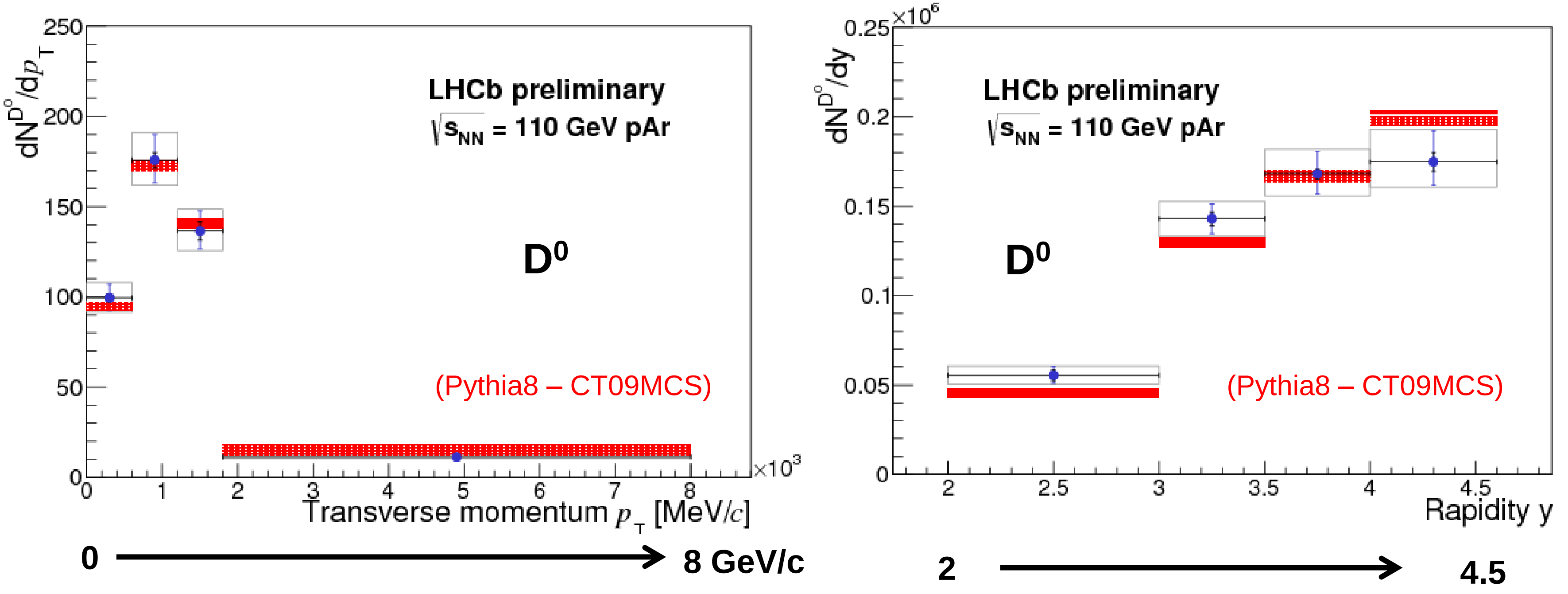

Rapidity in CMS: $y^* = y - 4.77$

- **Phenomenological parametrizations based on**
  - Arleo, F. and Peigné, S. J. High Energ. Phys. (2013) 2013:122
  - Arleo, F. et al., J. High Energ. Phys. (2013) 2013: 155
  - *MC and phenomenological distributions are normalized to data*
- **Phenomenological parameters**
  - extracted from linear (blue plain curve) and logarithmic (green dashed curve) interpolations between 41.5 GeV and 200 GeV measurements
- **No strong difference observed within uncertainties**

# $D^0$ corrected yields

(LHCb-CONF-2017-001)

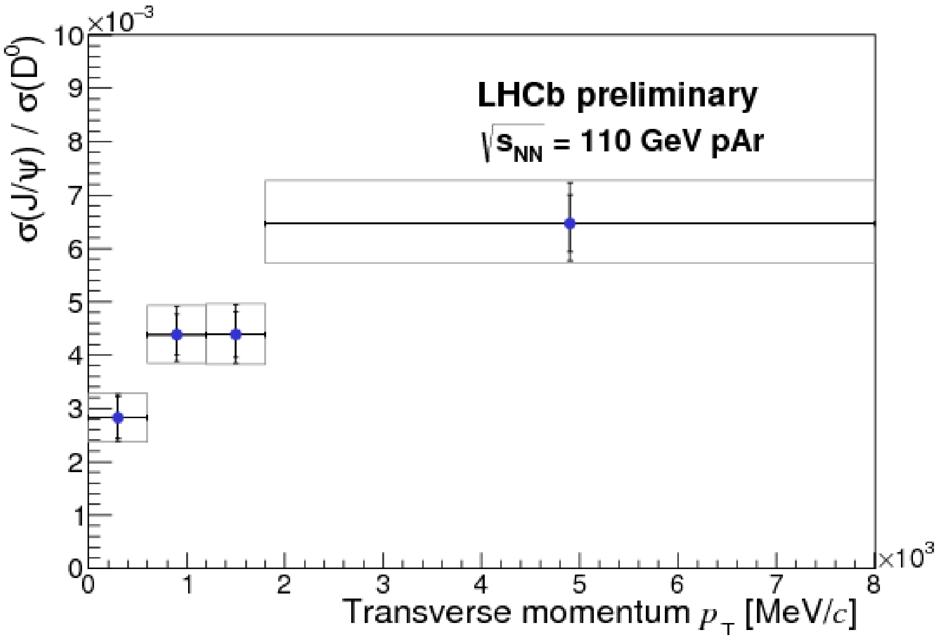
- **$D^0$ transverse momentum and rapidity distributions**
  - Box = quadractic sum of all uncertainties

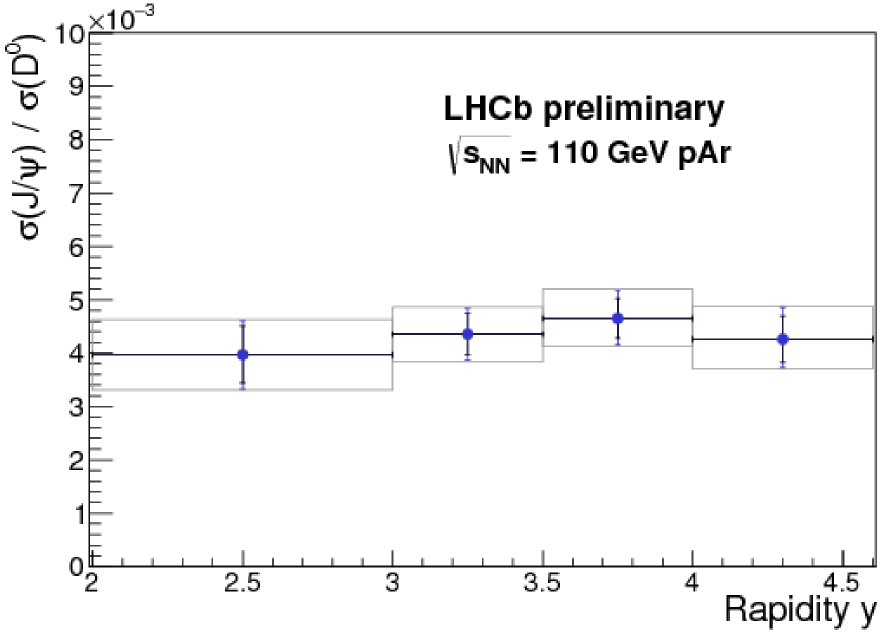



- Red boxes = MC
  - Pythia8-CT09MCS
  - Overall MC yields normalized to overal data yields

(LHCb-CONF-2017-001)

- **J/ψ / $D^0$ cross section ratio *vs.* $p_T$ and rapidity**

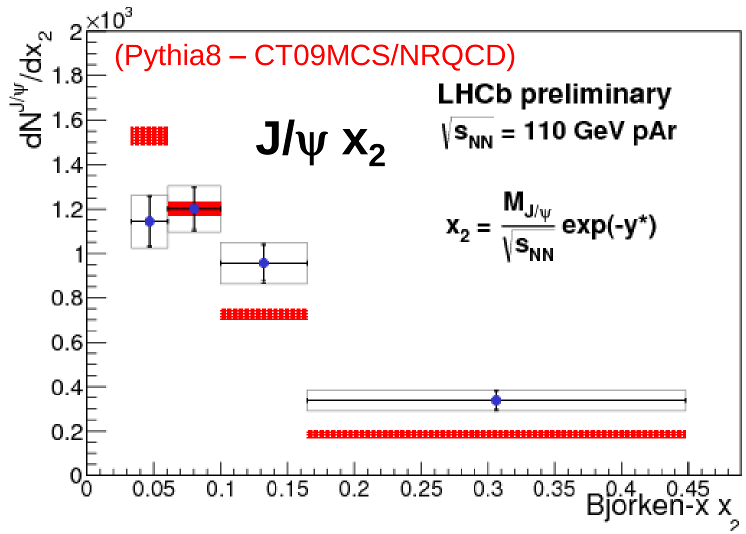


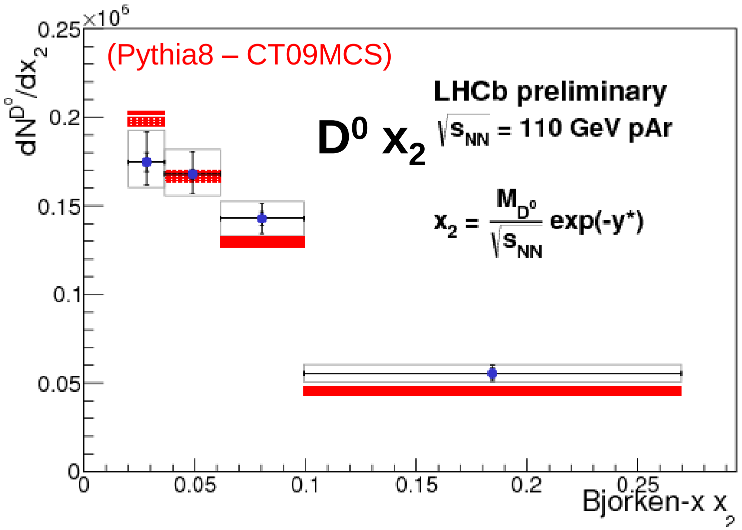




- Luminosity cancel out in the cross section ratio $\left(\frac{\sigma(J/\psi)}{\sigma(D^0)} = \frac{Y(J/\psi)}{\mathcal{L}} \times \frac{\mathcal{L}}{Y(D^0)}\right)$
- **No significant dependence** of σ(J/ψ)/σ($D^0$) with **rapidity**
- σ(J/ψ)/σ($D^0$) **ratio increases** with **transverse momentum**
- ***Need theoretical predictions !***

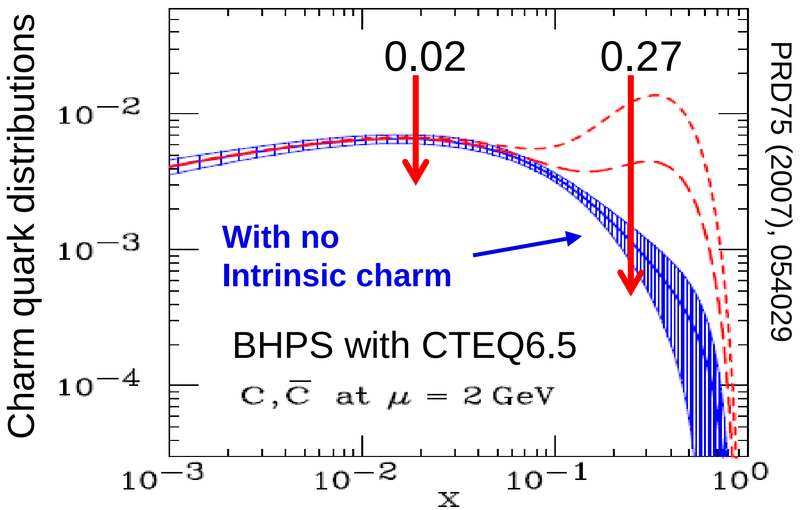
[(LHCb-CONF-2017-001)](LHCb-CONF-2017-001)

- **Definition used in this analysis:** $x_2 = \frac{M}{\sqrt{s_{NN}}} e^{-y^*}$ (Rapidity in CMS: y* = y – 4.77)
  - Overall MC yields normalized to overal data yields




- Bjorken-x range covered by the data
  - $J/\psi$ $x_2 \in [0.03, 0.45]$
  - $D^0$ $x_2 \in [0.02, 0.27]$

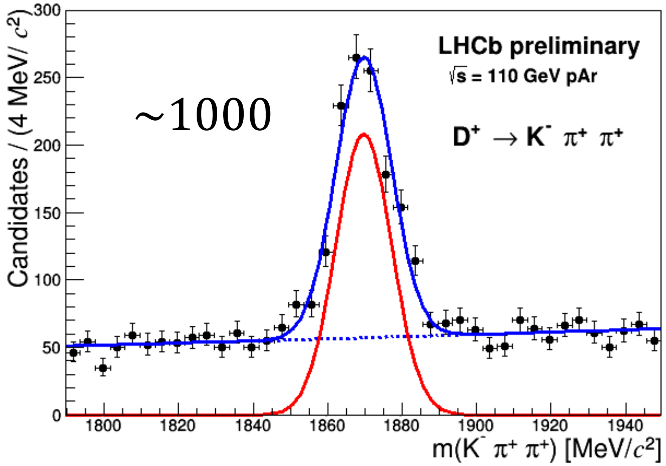


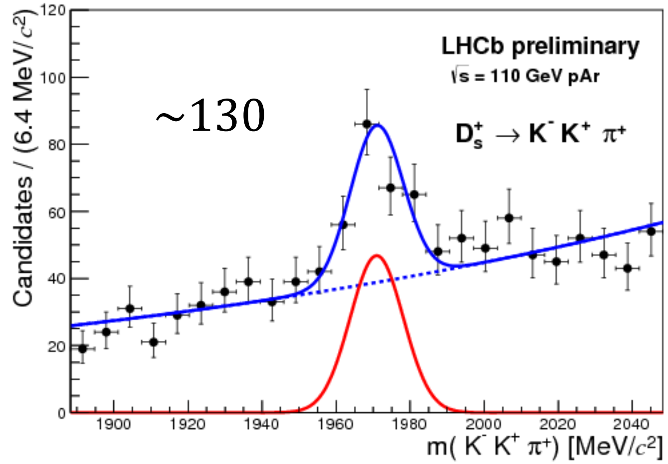

- **Access Intrinsic charm regime**
- ***Need theoretical predictions !***

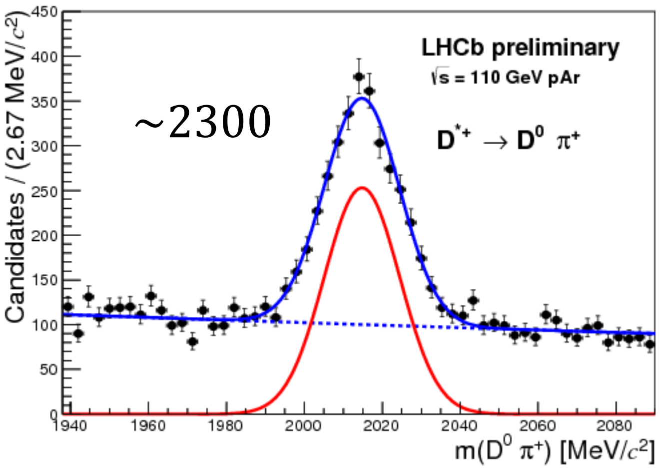
# Other charmed hadrons

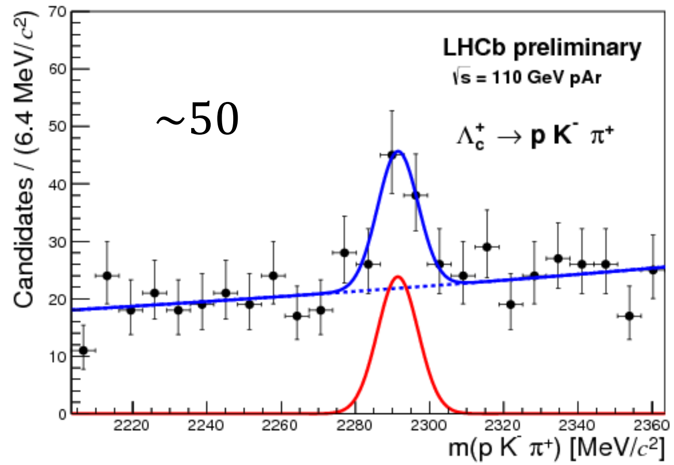
(LHCb-CONF-2017-001)

- **Other possible measurements: signals extracted from these pAr data**



# Conclusion

- **LHCb has been designed for heavy flavor studies**
  - Offers the capabilities to measure many charm hadrons in a wide rapidity range

- **LHCb is the only experiment at LHC capable of running in a fixed-target mode**
  - Operate at $\sqrt{s_{NN}} = 70$ GeV in lead-nucleus collisions
  - Operate at $\sqrt{s_{NN}} = 110$ GeV in proton-nucleus collisions

- **First measurement of heavy flavor production in fixed-target mode completed**
  - Measured ~500 $J/\psi$ and 6500 $D^0$, other charm hadrons observed
  - Theoretical predictions needed for $J/\psi$ / $D^0$ ratio (nPDF) and $D^0$ yield (Intrinsic Charm)
  - *Demonstrate the feasibility of a heavy-flavor fixed-target program with LHCb*

- **Future**
  - (Close) Analyse PbAr@69 GeV and pHe@87 GeV data samples
  - Record larger statistics (10 to 100 times) to access $\chi_c$ and $\psi'$ ($\psi'$ yield ~2% $J/\psi$ yield)