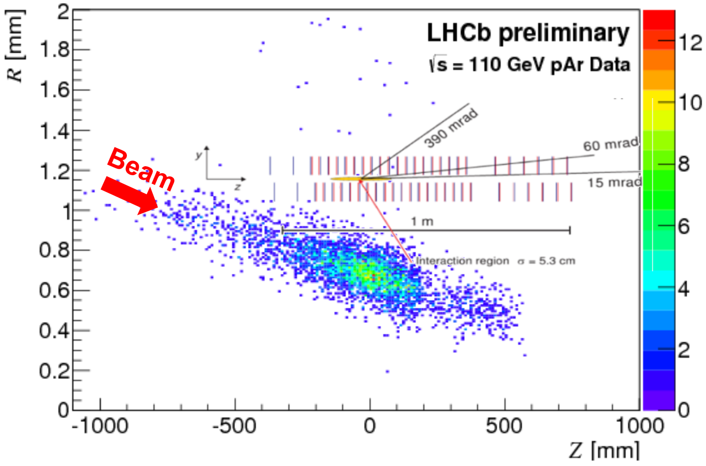
Charm production in fixed-target mode at LHCb



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On behalf of the LHCb collaboration

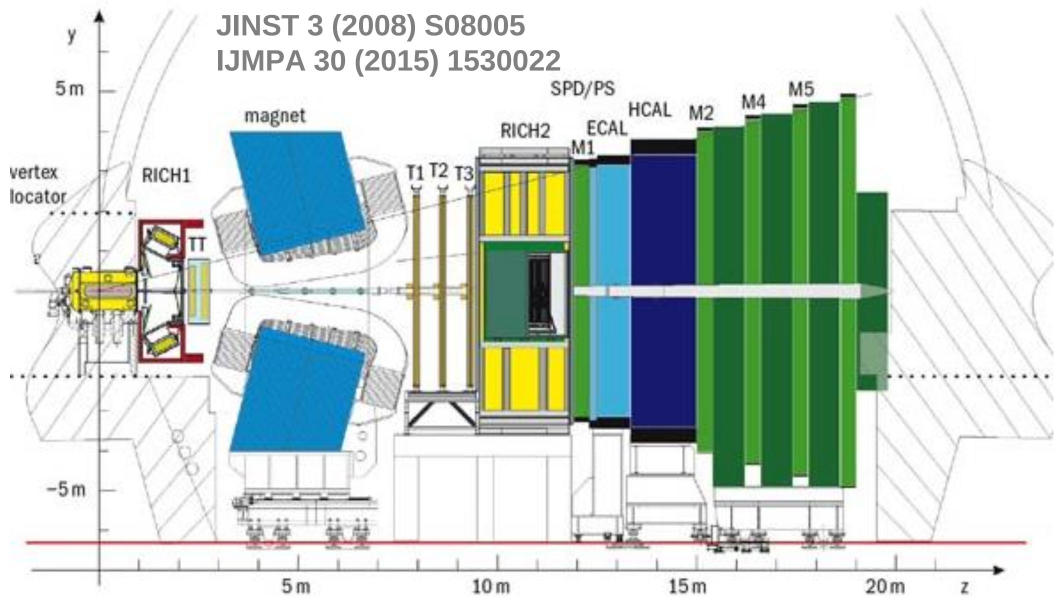
Hard Probes
Aix-les-bains, 2018

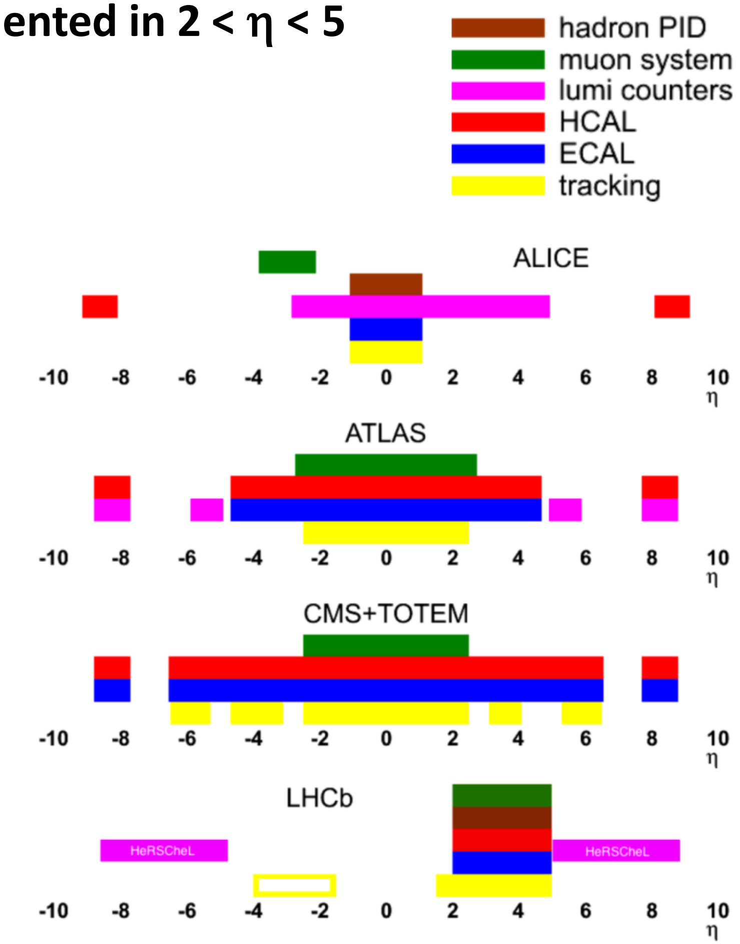
04/10/2018

The LHCb detector

Single arm spectrometer, *designed for heavy flavor physics in pp collisions*

the only LHC experiment fully instrumented in 2 < η < 5





Excellent vertex, IP and decay time resolution

σ(IP)≈20 μm

Very good momentum resolution

δp/p≈0.5−1% for 0<p<200 GeV/c

Particle identification

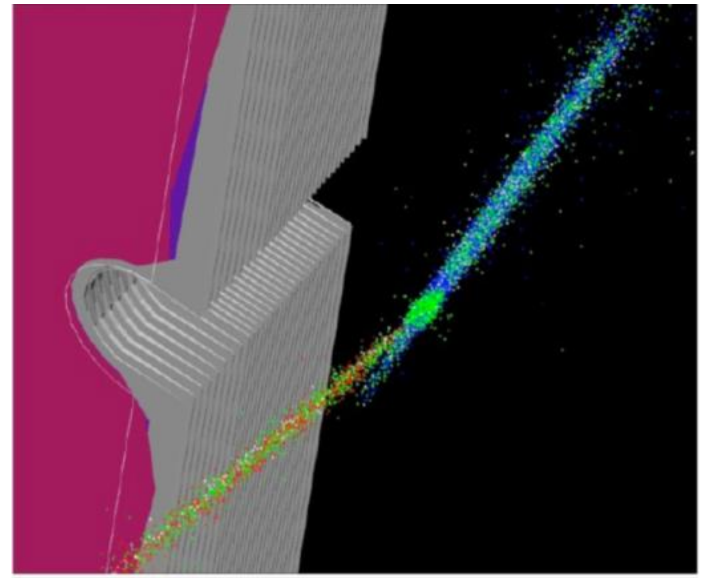
$\varepsilon_{K\to K}$≈95% for $\varepsilon_{\pi\to K}$≈5% up to 100 GeV/c

$\varepsilon_{\mu\to\mu}$≈97% for $\varepsilon_{\pi\to\mu}$≈1−3%

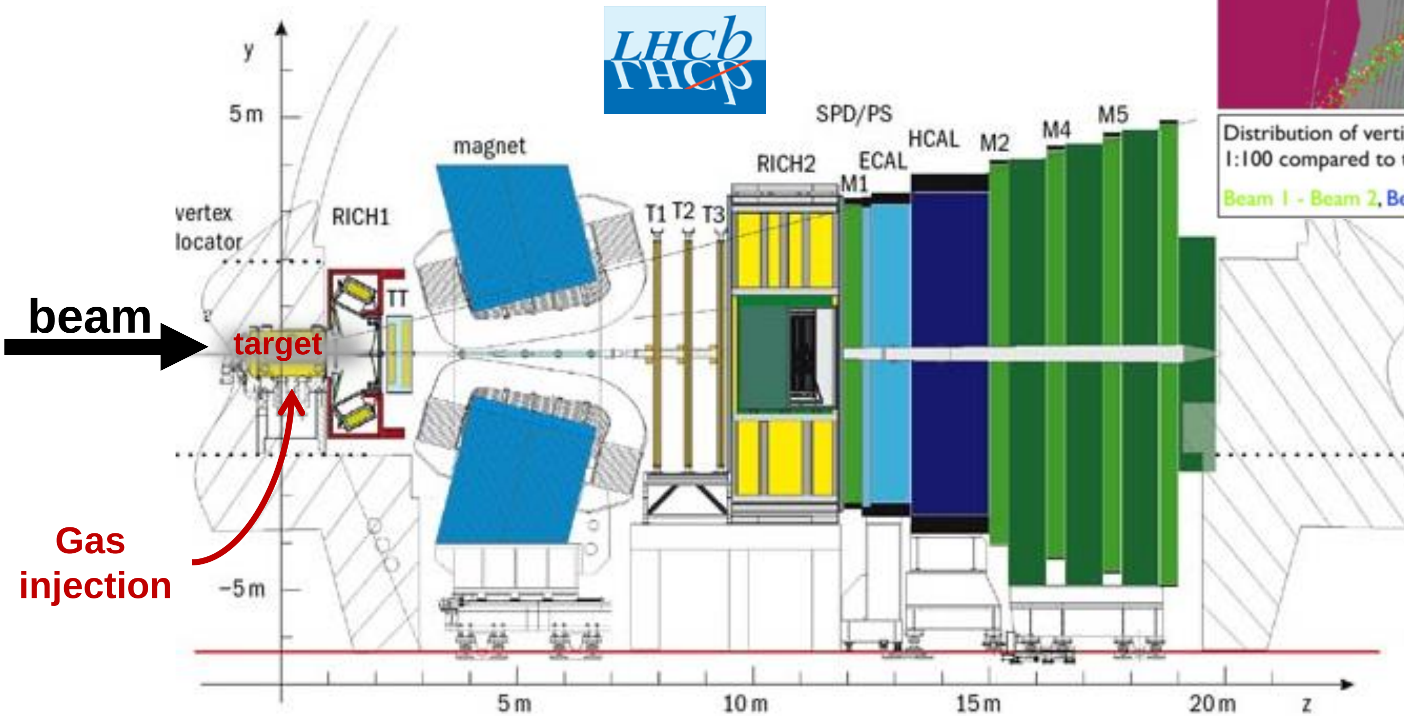
LHCb can also operate *p*-Pb and Pb-Pb collisions

The LHCb detector

- **Can also operate in fixed-target mode: unique at LHC**
  - Injecting gas in the LHCb VErtex LOcator (VELO) tank, originally done to perform 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)

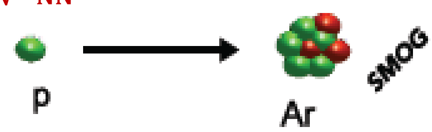
He, Ne, Ar, …
A = 4, 20, 40

Gas pressure:
10^{-7} to 10^{-6} mbar

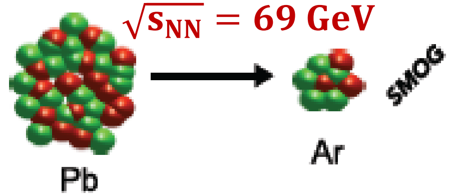
LHCb operations for heavy ion physics

- **The LHCb fixed-target program fills the gap between SPS and RHIC energies**

$\sqrt{s_{NN}} = 69$ to 110 GeV



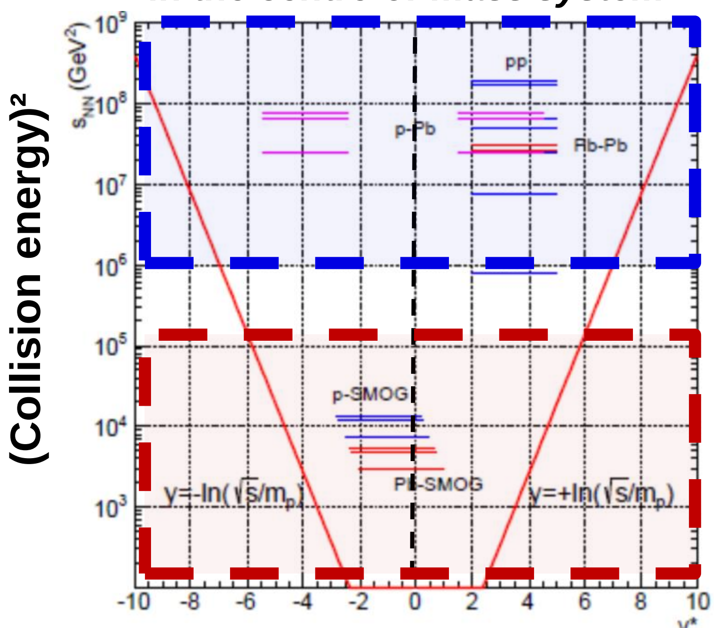
$\sqrt{s_{NN}} = 69$ GeV



$\sqrt{s}_{NN}^{SPS} \sim 20$ GeV
$\sqrt{s}_{NN}^{LHCb-FT} \sim 70$ GeV
$\sqrt{s}_{NN}^{RHIC} = 200$ GeV
$\sqrt{s}_{NN}^{LHC} = 5$ TeV

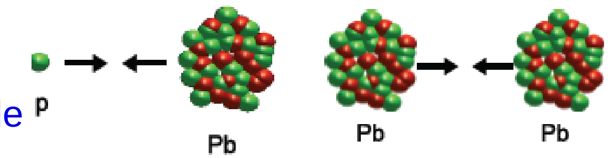
- **Gives access to the large Bjorken-x region in the target**

LHCb rapidity coverage in the centre-of-mass system



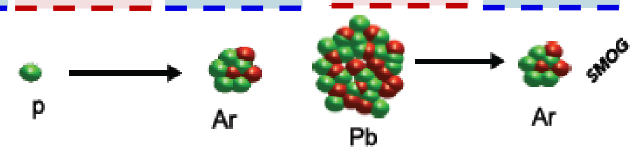
Mid-rapidity

Colliding beam mode



E_{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

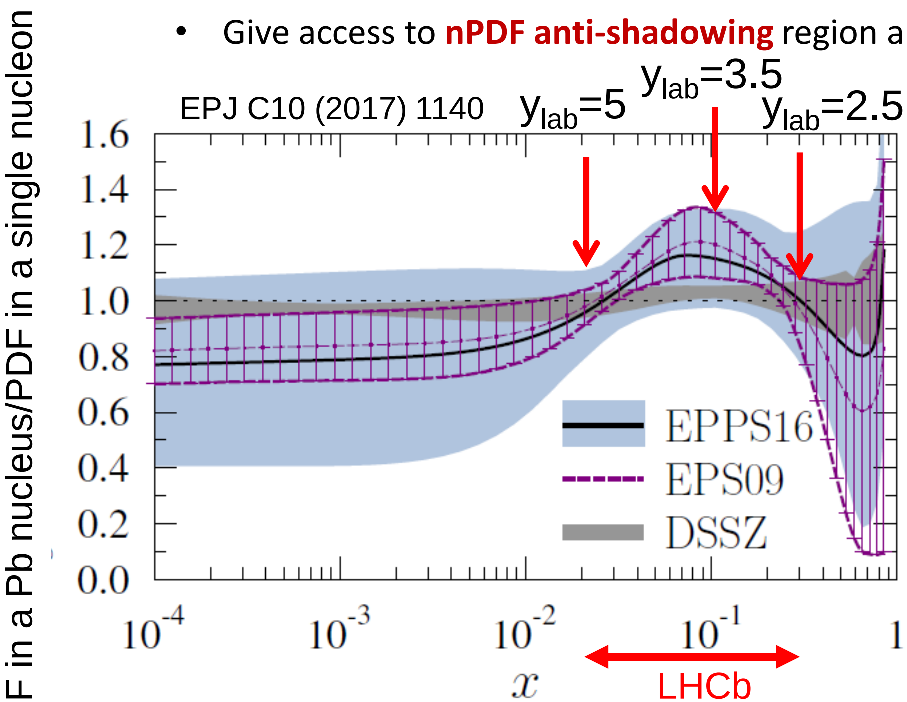
Fixed-target mode

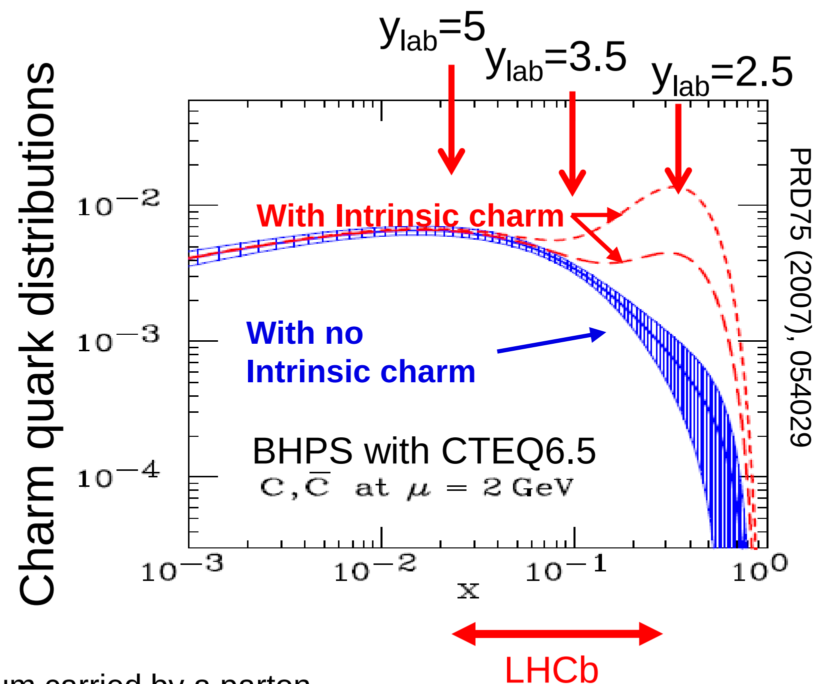


At $\sqrt{s_{NN}} = 110$ GeV $y^* = y_{lab} - 4.77$

Charm in fixed-target pA and AA collisions

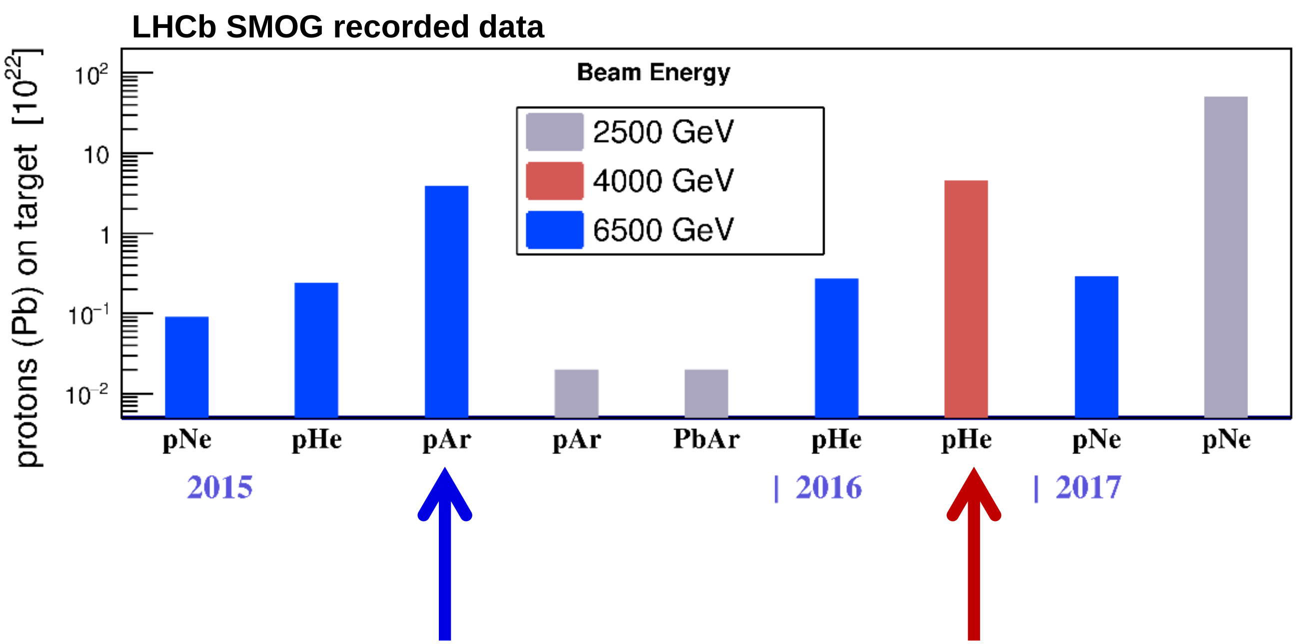
- **Nucleus-nucleus collisions : 2.5 TeV Pb beam on fixed target → $\sqrt{s_{NN}}$~69 GeV**
  - **No** secondary quarkonium production via **regeneration** at 70 GeV ($\sigma_{c\bar{c}}^{70\text{ GeV}} \sim \frac{1}{100}\sigma_{c\bar{c}}^{5\text{ TeV}}$)
  - Investigate the **Quark Gluon Plasma (QGP) color screening/phase transition**
  - Thanks to **unique capabilities**, LHCb offers **new opportunities** for charm: J/ψ, ψ′, χ_c, D^0, $D^{+/-}$, D^*, Λ_c…
- **Proton-nucleus collisions**
  - Serve as a baseline for nucleus-nucleus collisions, study of nuclear PDF (nPDF), nuclear absorption, …
  - With LHCb, large rapidity coverage (~3 rapidity units) at large Bjorken-x in the target (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

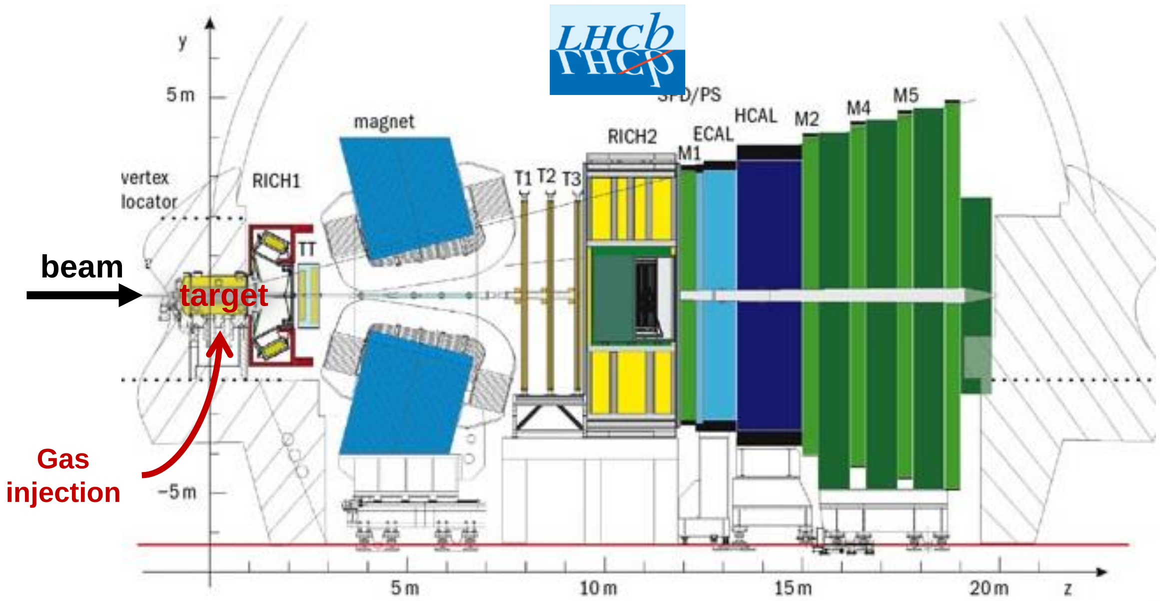
- **Data samples: two data sets presented here**



$\sqrt{s_{NN}}$ = 110 GeV proton-Ar interactions 2015
~ 4×10^{22} Protons On Target (17h)

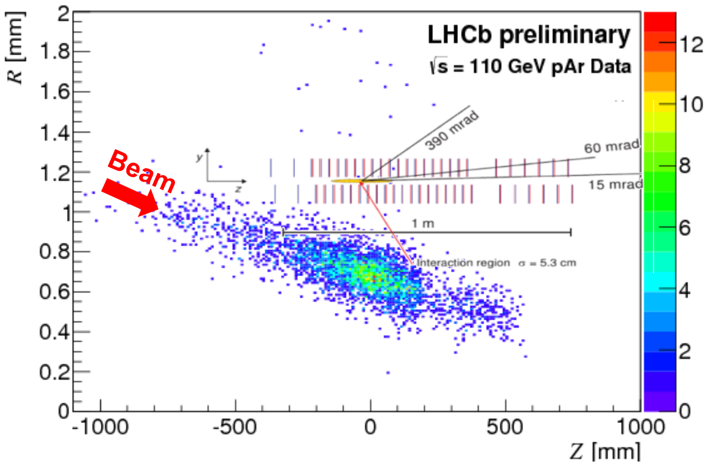
$\sqrt{s_{NN}}$ = 86.6 GeV proton-He interactions 2016
~ 4×10^{22} POTs (87h)
$\mathcal{L}_{pHe} = 7.6 \pm 0.5\ \text{nb}^{-1}$

- **Beam-gas events**



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

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



– Select events with Beam 1 only at interaction point

– **Select events with Z_{vertex} inside VELO** $Z_{vertex} \in$ [-20 cm, 20 cm]

Charm production in fixed-target proton-nucleus collisions

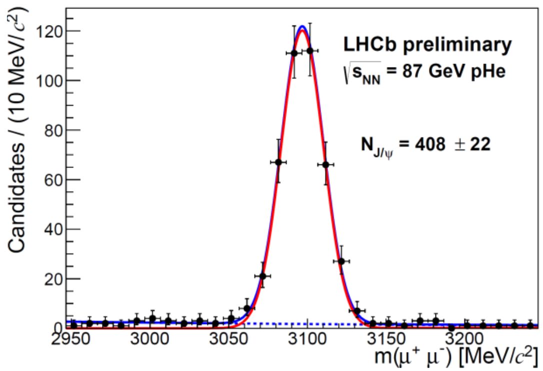
New results

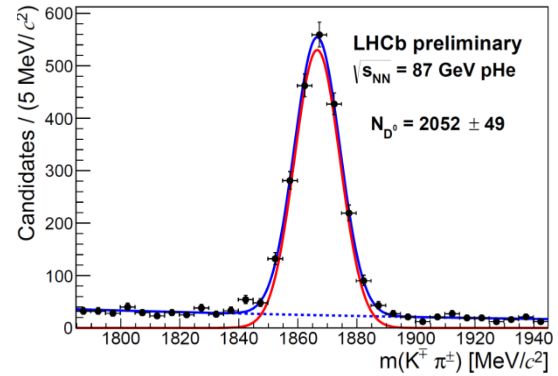
- **$J/\psi \to \mu^+\mu^-$ and $D^0 \to K^\mp\pi^\pm$ inclusive cross sections in *p*He @86.6 GeV**

LHCb-PAPER-2018-023
in preparation

J/ψ ←

→ D⁰



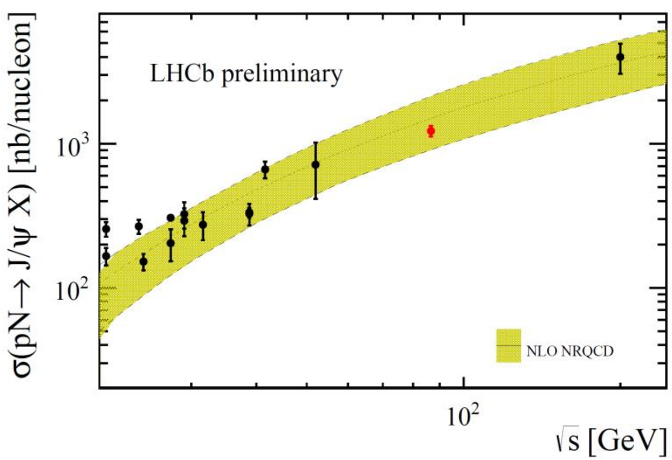


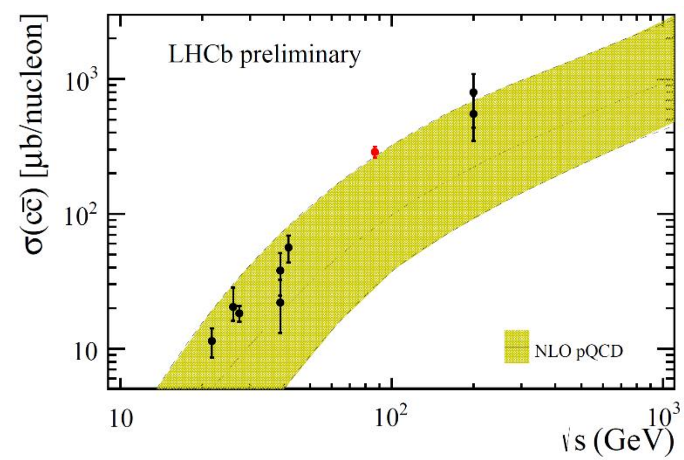
$\sigma_{J/\psi} = 1225.6 \pm 62.0\ (\text{stat}) \pm 81.6\ (\text{syst})\ \text{nb/nucleon}$

$\sigma_{D^0} = 156.0 \pm 4.6\ (stat) \pm 12.3\ (syst)$ μb/nucleon

with fraction ($c \to D^0$) = 0.542±0.024

$\sigma_{c\bar{c}} = 287.8 \pm 8.5\ (stat) \pm 25.7\ (syst)$ μb/nucleon





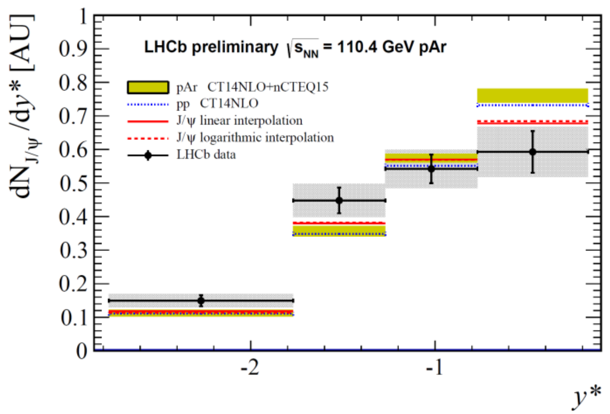
LHCb result in good agreement with NRQCD fit and other measurements

LHCb result in reasonable agreement with NLO pQCD (MNR) predictions and other measurements

Charm production in fixed-target proton-nucleus collisions

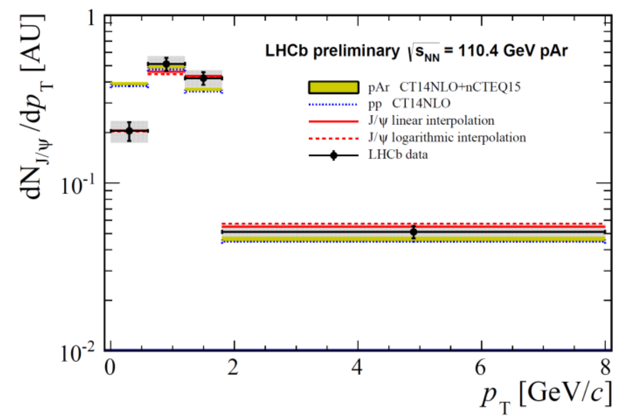
New results

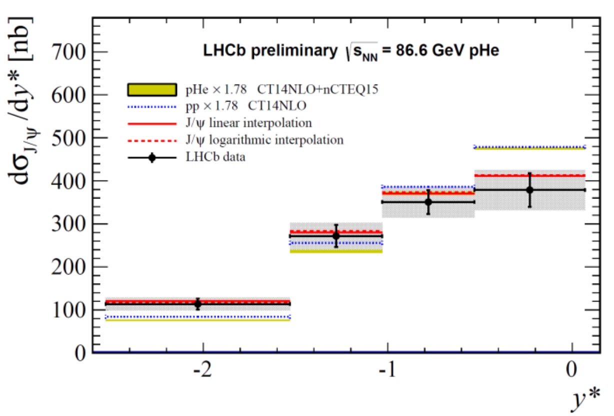
- **J/ψ differential yields (pAr@110 GeV) and cross sections (pHe@86.6 GeV)**
  - Plain and dashed **red lines**, **phenomenological parametrization**: JHEP 05 (2013) 155
  - **HELAC-ONIA** predictions for pp (blue lines) and pA (yellow boxes): EPJC(2017) 77:1



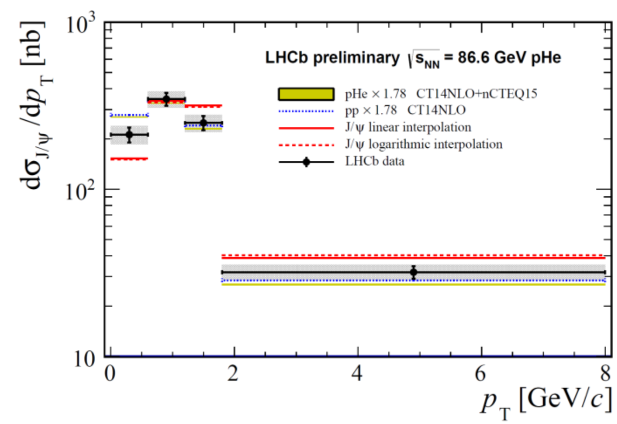
LHCb-PAPER-2018-021
in preparation

pAr @ 110 GeV
yields





pHe @ 86.6 GeV
Cross sections

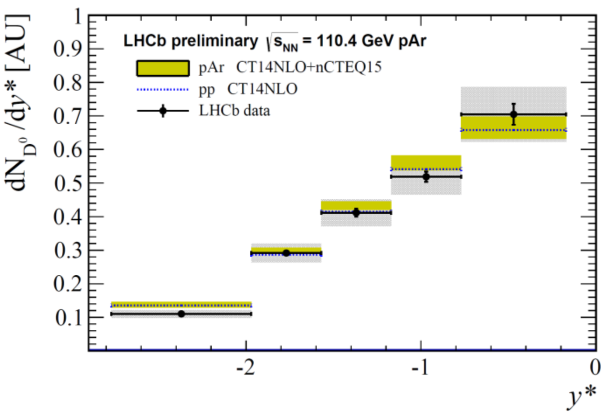


- **HELAC-ONIA underestimate the J/ψ cross section (pHe) by a factor 1.78**
- **Good shape agreement with phenomenological predictions**

Charm production in fixed-target proton-nucleus collisions

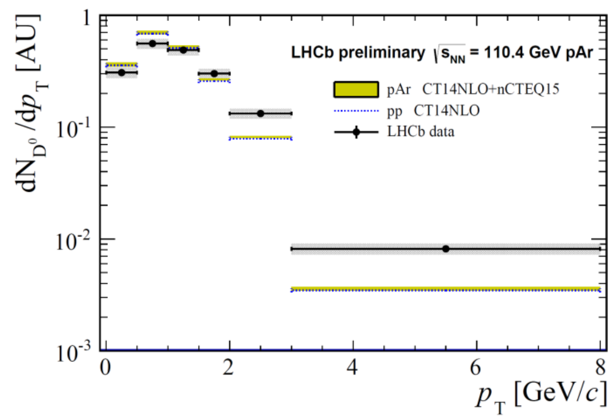
New results

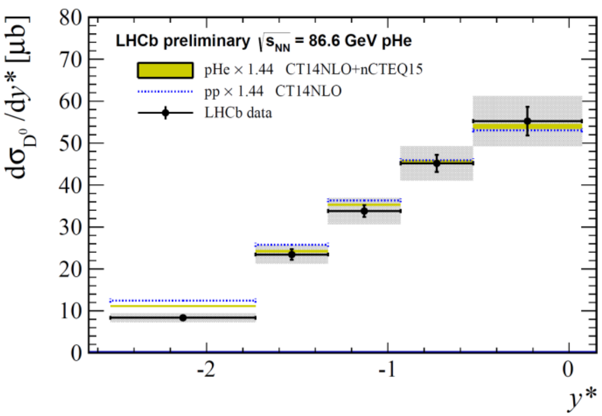
- **D^0 differential yields (pAr@110 GeV) and cross sections (pHe@86.6 GeV)**
  - **HELAC-ONIA** predictions for pp (blue lines) and pA (yellow boxes): EPJC(2017) 77:1



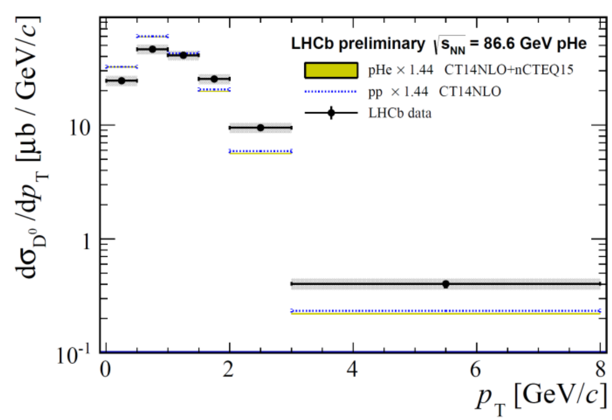
LHCb-PAPER-2018-021 in preparation

pAr @ 110 GeV yields





pHe @ 86.6 GeV Cross sections



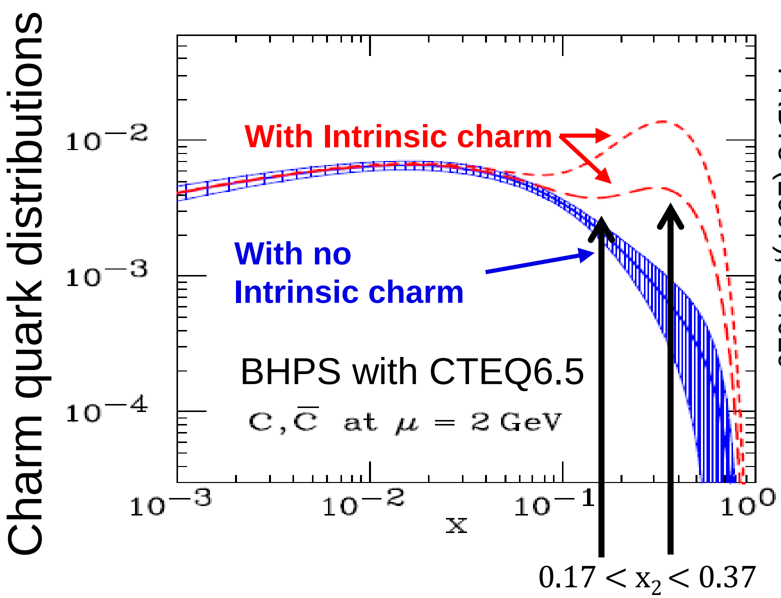
  - **HELAC-ONIA underestimate the D^0 cross section (pHe) by a factor 1.44**
  - **Good agreement in rapidity shapes between data and predictions**

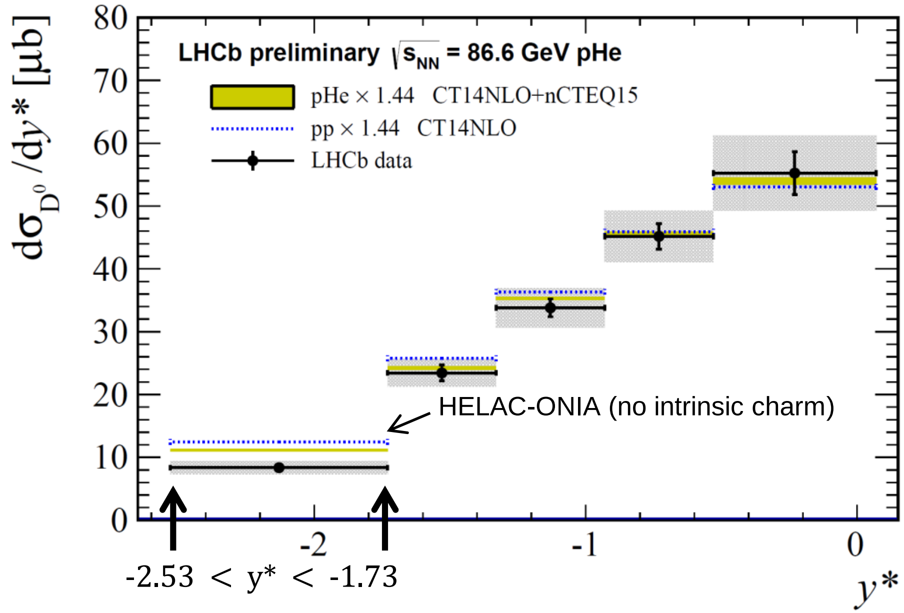
Charm production in fixed-target proton-nucleus collisions

New results

LHCb-PAPER-2018-021
in preparation

- **D^0 cross sections (pHe@86.6 GeV) .vs. Intrinsic charm**
  - **HELAC-ONIA** predictions for pp (blue lines) and pA (yellow boxes): EPJC(2017) 77:1
  - With $x_2 \simeq \frac{2 \times m_c}{\sqrt{s_{NN}}} \exp(-y^*)$ y*∈[-1.73, -2.53] ⟺ x_2 ∈[0.17, 0.37]





  - HELAC-ONIA does not contain intrinsic charm contribution
  - **No evidence of substantial valence-like intrinsic charm contribution**
  - Predictions for intrinsic charm welcome

Conclusions

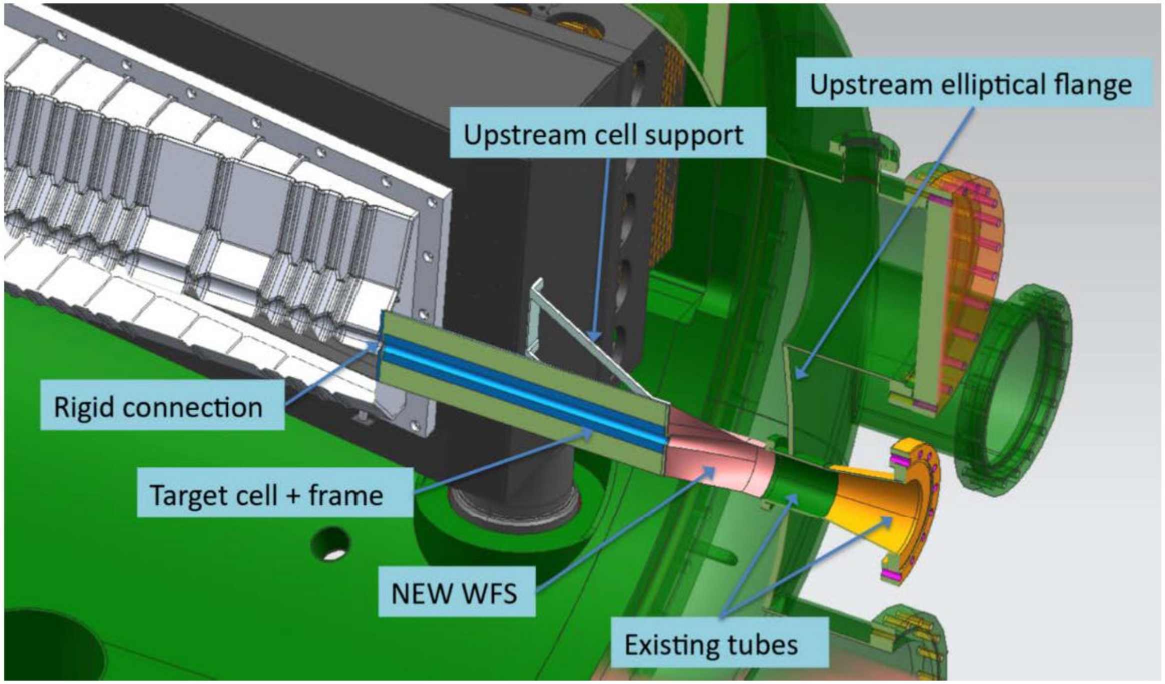
- **The LHCb detector**
  - Has unique capabilities for heavy flavor measurements at LHC
  - Can operate a **fixed-target program**, unique at LHC

- **Current results**
  - Performed J/ψ and D^0 measurements
    - in $\sqrt{s_{NN}}$ = **110 GeV *p*-Ar** collisions
    - in $\sqrt{s_{NN}}$ = **86.6 GeV *p*-He** collisions
  - ***No evidence of strong intrinsic charm contribution***

- **Short-term Future of fixed-target physics**
  - pNe data at 69 GeV (recorded in 2017): x10 more statistics than *p*Ar/*p*He
  - PbNe data at 69 GeV (to be recorded in 2018)

Conclusions

- **Middle-term future (starting 2021)**
  - Possible SMOG upgrade: SMOG2
  - Install a Storage Cell (SC) upstream of the vertex detector (length=20 cm, diameter=1 cm)
  - Increase the density of the target gas up to a factor 100
  - No overlap with pp collisions: reduced background and possibility for parallel running with pp collisions



F. Martinez Vidal, LHCP Bologna, 4 – 9 June 2018

R&D on SC at NIKHEF, INFN-Ferrara, INFN-Frascati

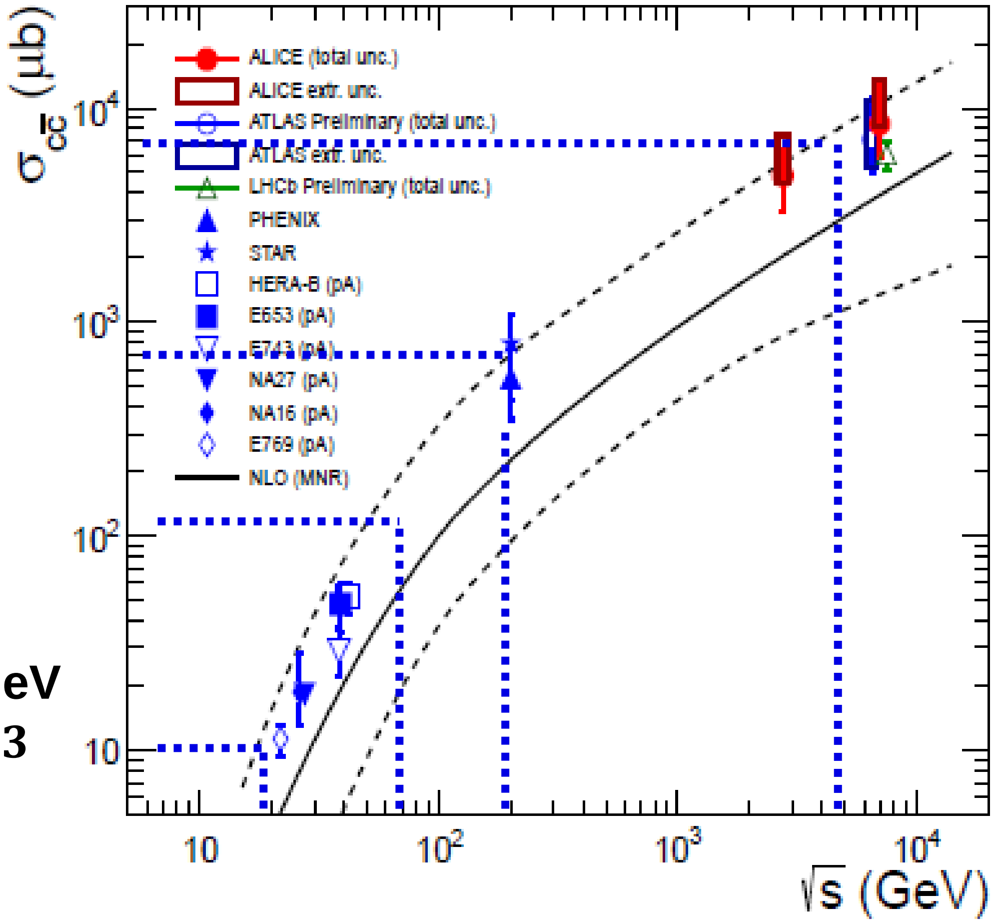
Supplemental material

Open charm production

TABLE I: Centrality bin, number of NN collisions, nuclear overlap function, charm cross section per NN collision, and total charm multiplicity per NN collision, in $\sqrt{s_{NN}}$ = 200 GeV Au+Au reactions.

Centrality	N_{coll}	T_{AA} (mb^{-1})	$\frac{1}{T_{AA}}\frac{dN_{c\bar{c}}}{dy}\|_{y=0}$ (μb)	$N_{c\bar{c}}/T_{AA}$ (μb)
min. bias	258±25	6.14±0.45	143±13±36	622±57 ±160
0–10 %	955±94	22.8±1.6	137±21±35	597±93 ±156
10–20 %	603±59	14.4±1.0	137±26±35	596±115±158
20–40 %	297±31	7.07±0.58	168±27±45	731±117±199
40–60 %	91±12	2.16±0.26	193±47±52	841±205±232
60–92 %	14.5±4.0	0.35±0.10	116±87±43	504±378±190

Phys. Rev. Lett. 94, 082301 (2005)



In central Au+Au collisions @ 200 GeV

$$N_{c\bar{c}} \sim 597 \cdot 10^{-3} mb \times 22.8\ mb^{-1} \sim 13$$

~0.1 $c\bar{c}$ @ 20 GeV
~1 $c\bar{c}$ @ 70 GeV
~10 $c\bar{c}$ @ 200 GeV
~100 $c\bar{c}$ @ 5500 GeV

$$\sigma_{c\bar{c}}^{5500\ GeV} \sim 10 \times \sigma_{c\bar{c}}^{200\ GeV} \sim 100 \times \sigma_{c\bar{c}}^{70\ GeV} \sim 1000 \times \sigma_{c\bar{c}}^{20\ GeV}$$

Fit of J/ψ cross section

- **NRQCD approach used to fit the data: Phys. Lett. B638 (2006) 202-208**

$$\sigma(pp \to H + X) = \sum_{i,j} \int dx_1 dx_2 f_{i/p} f_{j/p} \sum_n \hat{\sigma}(ij \to Q\bar{Q}[n] + x) \langle \mathcal{O}^H[n] \rangle, \quad (1)$$

  - The NRQCD matrix element are related to the nonperturbative transition probabilities from the QQ state to the quarkonium H

5. Conclusions

In this Letter we have collected all available data on J/ψ and $\psi(2S)$ production in hadron collisions (with the exception of data obtained in pion–nucleus collisions) and updated them in the light of the most precise determinations of nuclear effects. We have then presented their analysis in the context of NRQCD, using NLO predictions for the short-distance cross sections and fitting the color-octet non-perturbative matrix elements. In order to ease the comparison with the available determinations, we have chosen the values extracted at the Tevatron as our reference. We find sizeable systematic uncertainties associated both to the experimental data, which sometimes are marginally consistent among themselves, and to the fixed-order nature of theoretical predictions. Nevertheless, our results clearly indicate that the amount of color-octet contributions needed to explain fixed-target data is only about 10% of that fitted at the Tevatron. One can certainly argue that part of this discrepancy might be associated to the fact that the Tevatron analysis is based on LO calculations only. On the other hand, the difference is too large to be resolved by the inclusion of higher-order corrections. In addition, it is plausible to speculate that once the NLO corrections to the color-singlet production were computed and included in the analysis, there would be very little room left for color-octet contributions to fit the fixed-target experiments, in close analogy to what happens in photoproduction [5] and in agreement with the results in Ref. [49] where a different approach is used.