Fixed target results from LHCb for cosmic rays physics

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on behalf of the LHCb collaboration

EDS Blois 2017

17th International Conference on Elastic and Diffractive Scattering

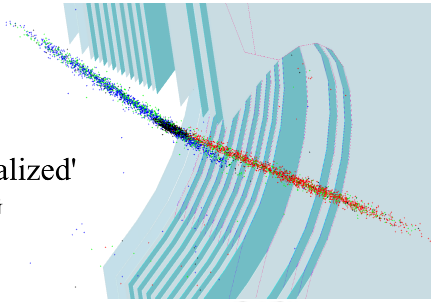
Prague, Czech Republic, 26-30 June 2017

Fixed Target at LHCb with SMOG

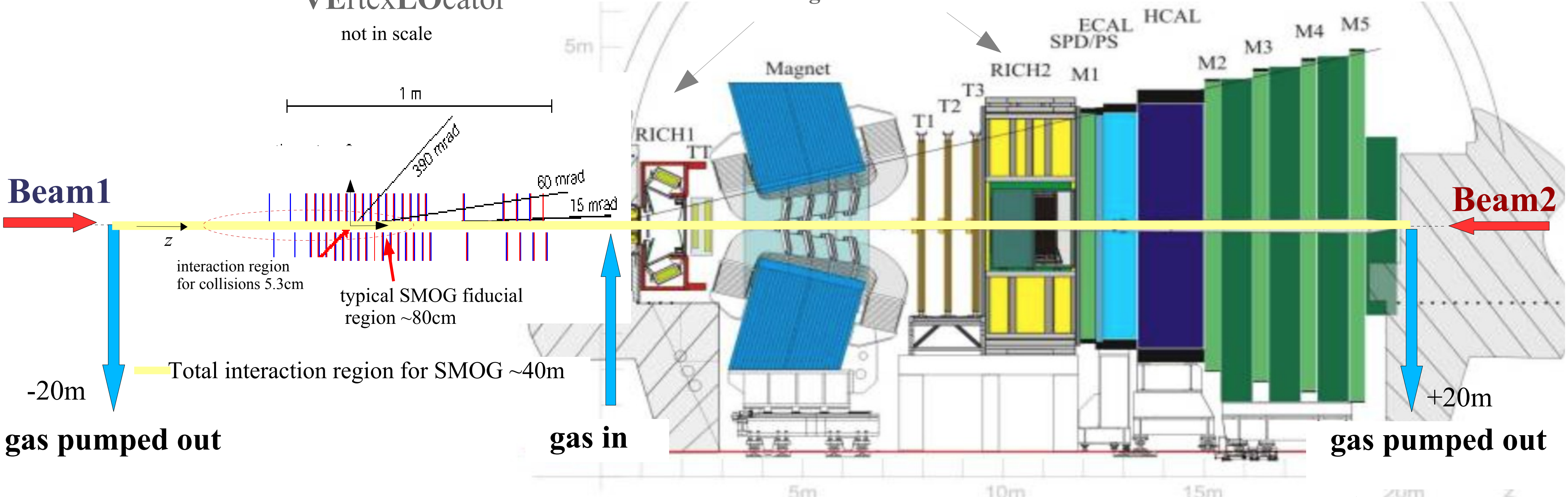
- **SMOG** (**S**ystemfor**M**easuringthe**O**verlapwith**G**as)

  initially used for the measurements of the overlap of colliding beams:

  $\mathcal{L}=N_1N_2\ f/(4\pi\sigma_x\sigma_y)$ (*arxiv.1410.0149*)



colliding
beams 'visualized'
with SMOG



LHCb, JINST 3 S08005 2008

Projectile:

Beam1 forward (Beam2 backward)

Particles: **p (Pb)**

Energy: **6.5 (Pb 2.5) TeV**

bunch intensity: **~ 10^{11} p**

10-700 non colliding bunches
(in addition to colliding)

Target:

inert gas: **He4, Ne20, Ar40, Kr84,Xe131**

beam pipe vacuum: **~10^{-9} mbar**

SMOG gas pressure: **~2×10^{-7} mbar**

expected instant luminosity in VELO acceptance(1m) $\mathcal{L}$: **~ 0.5 mb $^{-1}$s^{-1}**

per non colliding bunch

LHCb Detector: **$\eta \approx 2-5$**

- **Vertex:** VELO $\sigma_{\text{ImpactPar.}}$ ~20 µm
- **Particle Identification:** p/K/π

	η	P(*K*)	P($\bar{p}$)
RICH1	**2.0-4.4**	**>18 GeV/c**	**>30 GeV/c**
RICH2	**3.0-5.0**	**>10 GeV/c**	**>16 GeV/c**

Fixed target event selection

- **SMOG Event Selection:**

➔ Minimum bias trigger for inclusive p,π,K,...
or dedicated trigger for resonances

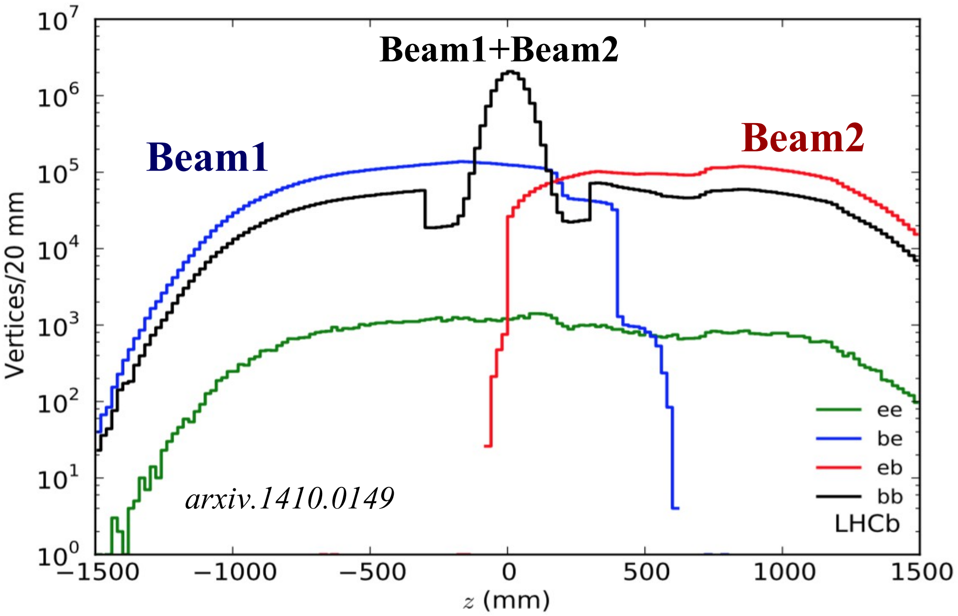
➔ Select non-colliding bunches from Beam1 using LHC bunchID

➔ Remove Beam2 interaction with 'ghost' charge*) and upstream/downstream interactions.
use tracks and VELO hits topologies, require N of backward tracks <5

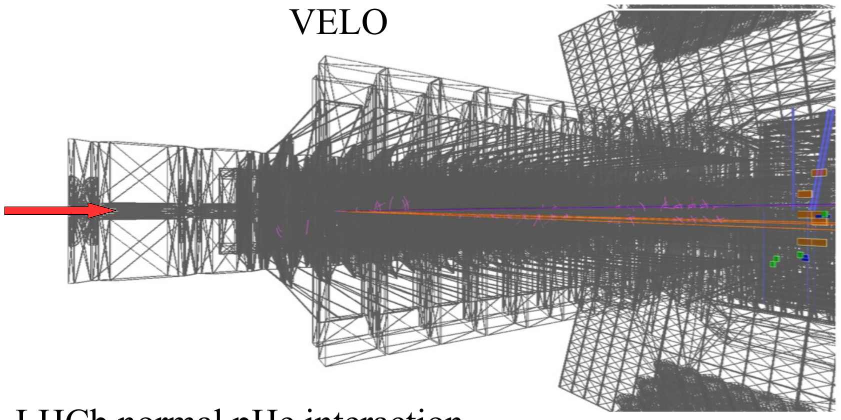
➔ At least one good primary vertex in the fiducial region

Fiducial region is defined by the primary vertex reconstruction efficiency in VEL0, which is >75% in [-700,100] mm.
For resonances [-200,200] mm region is used.

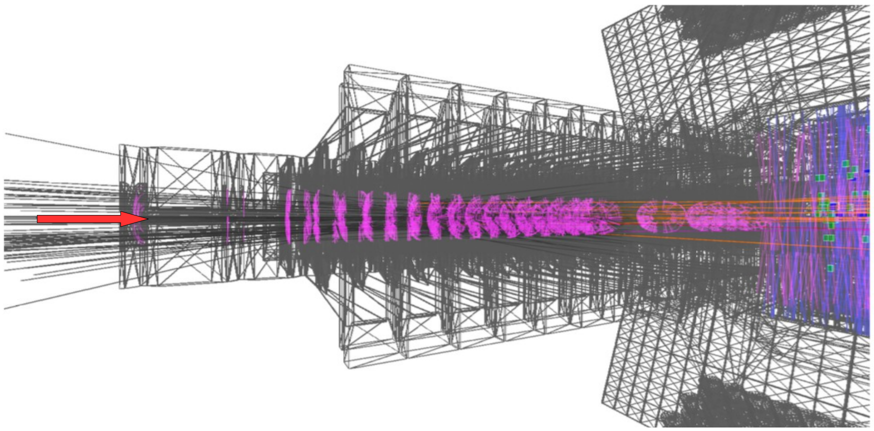
Primary vertex z reconstructed with Beam1(be), Beam2(eb), Collisions(bb), and without beams(ee)



gas is spread far upstream/downstream →
have to suppress these interactions



LHCb normal pHe interaction



LHCb 'splash' events
(interactions with high multiplicity and with
the fake reconstructed vertex in the fiducial region)

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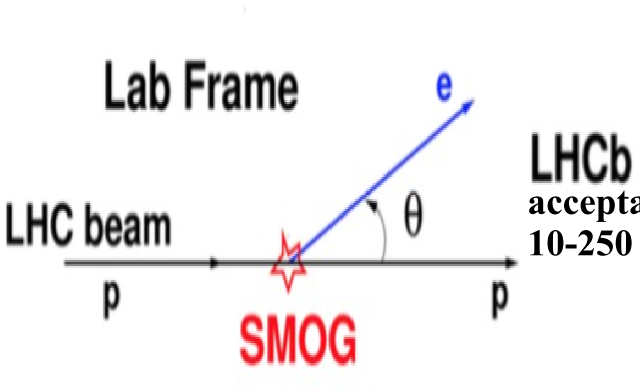
*) LHC beam 'ghost' charge: beam particles migrated from one bunch to another

Luminosity measurements

No precise measurements of the gas density in SMOG along the pipe → use elastic pe$^-$ scattering



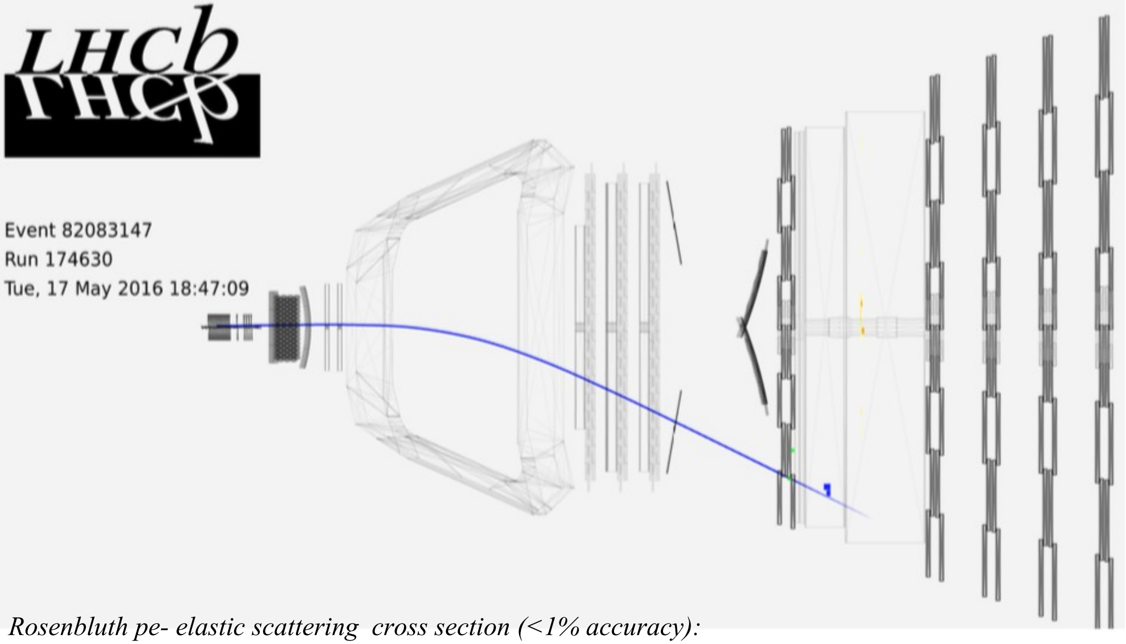
acceptance
10-250 mrad

- single e$^\pm$ track with p>2 GeV/c → $\theta < 22$mrad, no hadron activity
- residual background is charge symmetric and can be subtracted $N_{e-} = N_{pe-} - N_{pe+}$
- residual vacuum is corrected from LHCb run without gas $N_e = N_e$ - nogas(pe$^-$ - pe$^+$) <1%

For **pHe** in the fiducial region[-700,100] mm
Ne ≈7000 events:

$\mathcal{L} = 0.443 \pm 0.01(\mathrm{stat}) \pm 0.027(\mathrm{sys})\ \mathrm{nb}^{-1}$

~ 6% systematic in fix target luminosity
(~1.5% in pp collisions)



Rosenbluth pe- elastic scattering cross section (<1% accuracy):

$$\frac{d\sigma_{p-e^-}}{dcos\vartheta_s} = \pi\left(\frac{Z_p\alpha}{E_e}\right)^2 \frac{(1+\cos(\vartheta_s))}{(1-\cos(\vartheta_s))^2}\frac{E_{ef}}{E_e}\left[\frac{G_E^2(Q^2)+\tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan\left(\frac{\vartheta_s}{2}\right)^2\right]$$

$$\Rightarrow \boxed{\mathcal{L} = \frac{N_e}{Z_{He}\times\sigma_{p-e^-}\times\epsilon}}$$

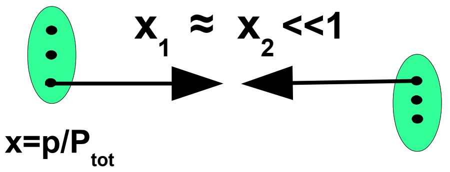
Z=2 for He
ε ~10-30% efficiency from MC

corresponds to the pressure in the beam pipe :
$p_{He} = \mathcal{L}\, kT/n_p \Delta z$ ~ 1.7- 2.5× 10^{-7} mbar
(n_p-total number of protons on target ~3 10^{21}, Δz=80cm)
in agreement with pressure measurements

Kinematics

collisions

$\sqrt{s}$ ~ 7-13 TeV



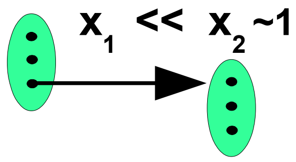
$x_1 \approx x_2 << 1$

$x = p/P_{tot}$

$y^* \approx 0$

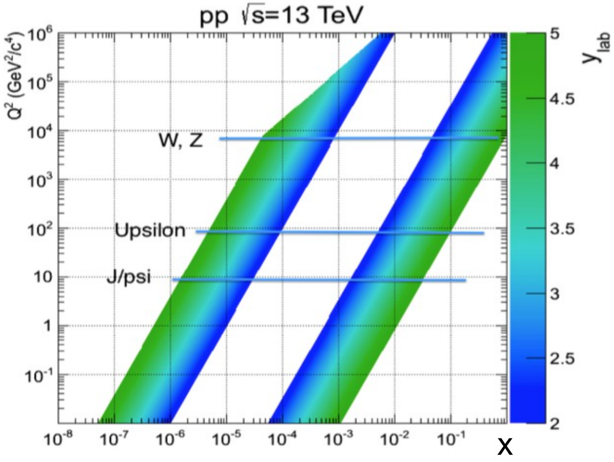
fixed target

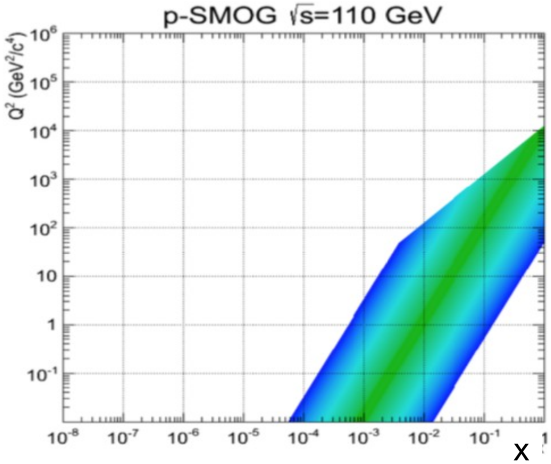
$\sqrt{s}$ ~ 70-110 GeV



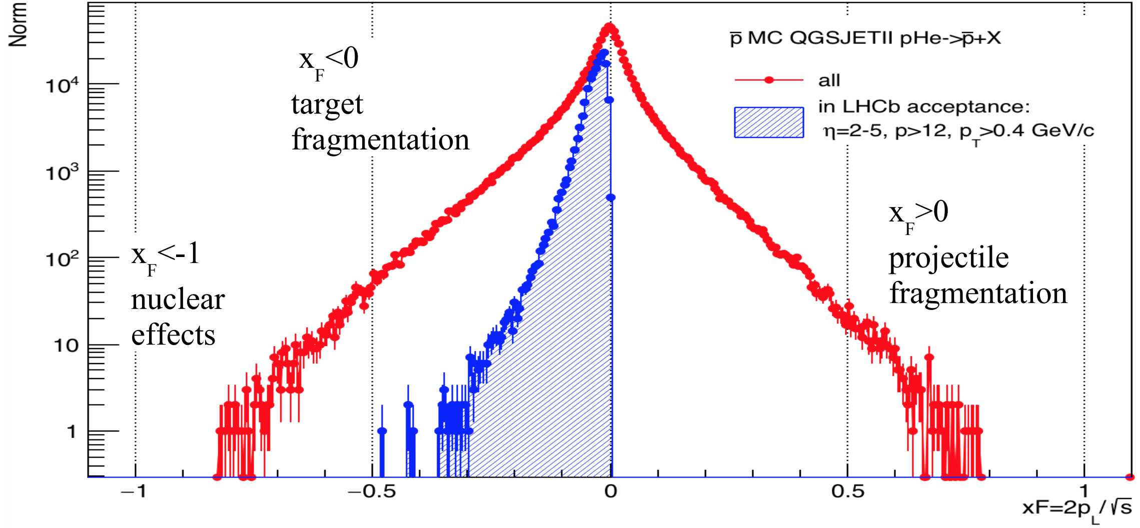
$x_1 << x_2 \sim 1$

$y^* = y - y_{beam}(\approx 4.8) < 0$





$x_F = 2p_L^*/\sqrt{s} = x_1 - x_2$ $\quad x = e^{\pm y} Q/\sqrt{s}$

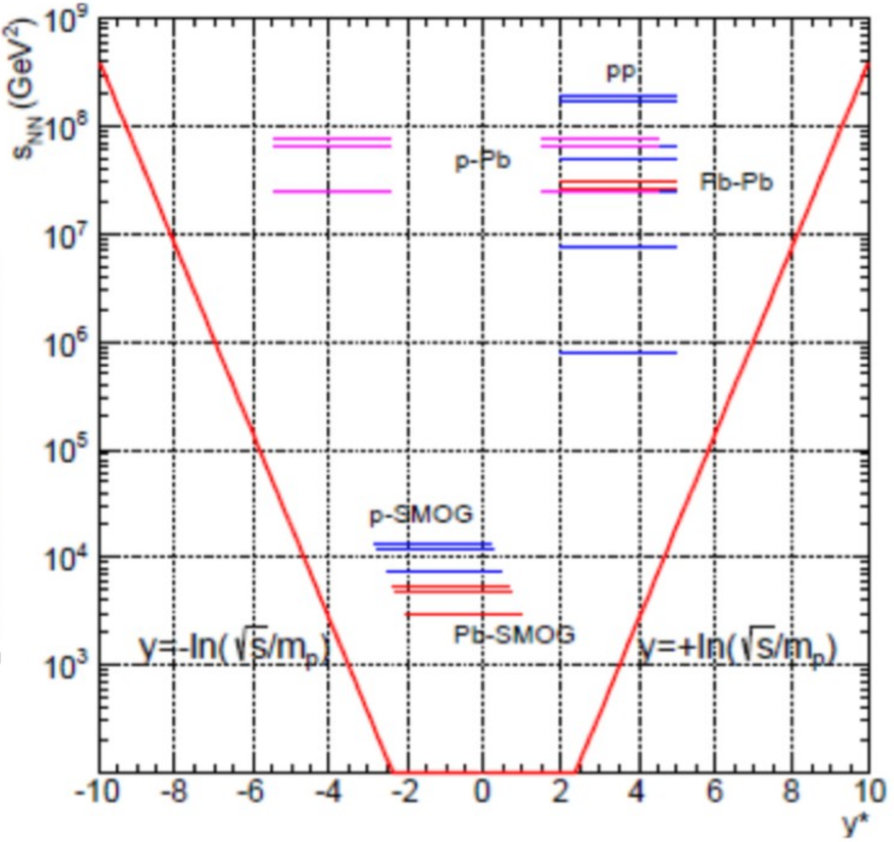


$x_F < 0$
target
fragmentation

$x_F < -1$
nuclear
effects

$x_F > 0$
projectile
fragmentation

LHCb y coverage for different beam setups*



Access to different kinematic regions with the same detector

Data samples LHCb SMOG

SMOG runs in 2015-2016

	Ebeam	√ s	duration	p/target
pHe	**6.5 TeV**	**110.4 GeV**	**18h**	**30×10^{20}**
pHe	4.0 TeV	86.6 GeV	87h	400×10^{20}
pNe	6.5 TeV	110.4 GeV	12h	10×10^{20}
pAr	**6.5 TeV**	**110.4 GeV**	**17h**	**400×10^{20}**
pAr	2.5 TeV	68.5 GeV	11h	2×10^{20}
pNe	6.5 TeV	110.4 GeV	12h	10×10^{20}
PbAr	2.5 TeV	68.5 GeV	100h	2×10^{20}

more runs with pHe, Ar, Ne in 2017-18
may try heavier targets at the end....

First results:

LHCb-CONF-2017-002
Measurements of antiproton production in pHe collisions at $\sqrt{s}_{NN}$=110 GeV

LHCb-CONF-2017-001
Measurements of J/Ψ and D_0 production in pAr collisions at $\sqrt{s}_{NN}$=110 GeV

→ Ongoing studies for other samples and other subjects

Compare with other measurements

experiment	interactions	√s, GeV	Ebeam,GeV	η
SPS(NA49,NA61)	pH, pC	6.3-17.3	20-158	$\|\eta\|<4$
RHIC(STAR ,PHENIX)	pp,dAu,CuCu,AuAu	62, 200	-	$\|\eta\|<1$
LHC(ALICE,CMS)	pp, pPb, PbPb	900-13000	-	$\|\eta\|<2.4$*)
LHCf (mostly γ)	pp, pPb	900-7000	-	[8.5-11]
LHCb SMOG	p(Pb) He,Ne,Ar,...	69-110	6500(2500)	[2-5]
LHCb collisions	pp, pPb	900-13000	-	[2-5]

Covers a gap in the region of the scaling violation

*) also instrumented in forward region

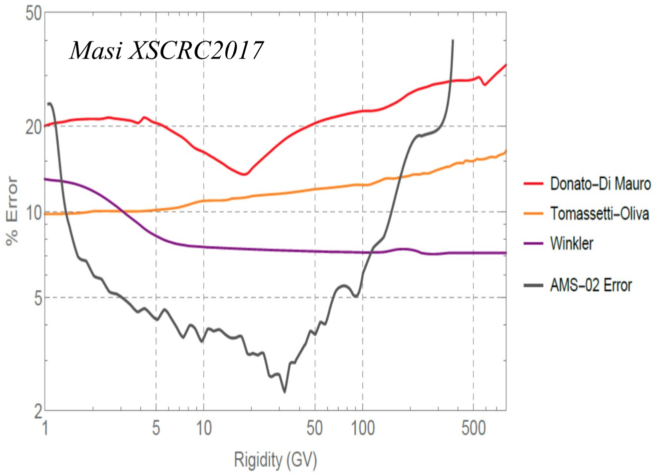
Physics cases

I. Antiprotons $pA\to\bar{p}+X$

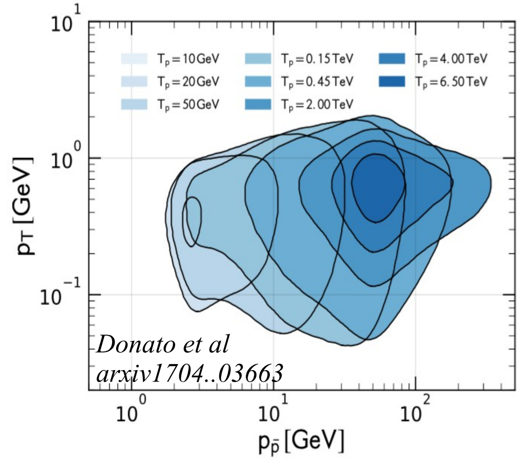
- precise (~5%) AMS02 results on antiproton flux(PRL117,091103,2016), constrain indirect DM searches
- other AMS02 measured fluxes (p,He,B,C,Be..) allow to reduce propagation uncertainties to ~10%, making the nuclear uncertainties dominant.
- interpretation of various indirect HEP data can bring nuclear uncertainties to ~10% , but using assumptions on:
  - scaling violation
  - multiplicities
  - nuclear effects (nPDF, CNM)
  - hyperon productions
  - isospin violation
  - ...

Winkler arxiv1701.04866
Kachelriess et al. arxiv1502.04
Feng et al. arxiv1612.08520
Donato et al. arxiv1704.03663
Boschini et al. arxiv1704.06337
Giesen et al. arxiv1504.04276
etc...

Nuclear cs uncertainties from different studies, and AMS02 errors



Antiprotons pT-p range in fix target pHe required to constrain the cs uncertainties



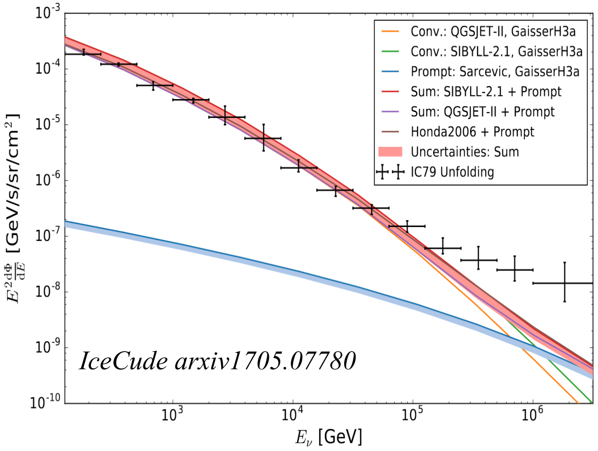
Direct measurements of $pHe\to\bar{p}+X$ using SMOG LHCb in the AMS02 kinematic region

II. Intrinsic charm

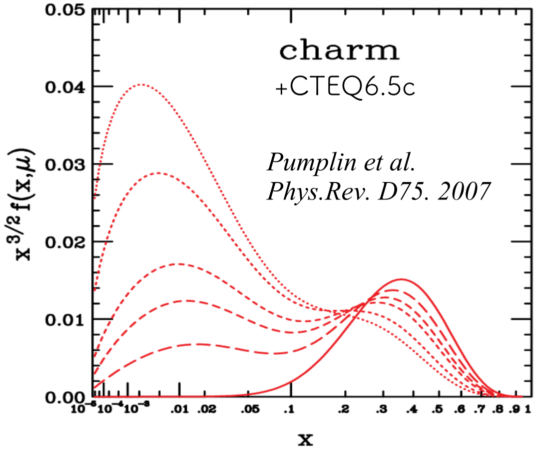
- IceCube neutrino flux shows astrophysics component(AJ833,2016)
- Atmospheric neutrino from open charm (D, Λc) $c\to\nu lX$ is the dominant background at high energy
- open charm production is measured in collisions at xF~0, but large contribution from |xF|~1 is expected from the **intrinsic charm (IC)**
- have to separate the IC from nuclear effects

Halzen, Wille, arxiv1605.01409
Brodsky et al. arxiv1504.06287
Laha, Brodsky. arxiv1607.08240
Dulat et al, arxiv1309.0025
etc...

IceCube neutrino flux and simulations (without intrinsic charm)



BPHS model with intrinsic charm, consistent with experiments



Can measure $pA\to D/\Lambda c$ production down to $xF\approx -0.4$

more is possible with SMOG: forward and ions physics related to CR

Antiproton production in pHe at $\sqrt{s}$=110 GeV

Analysis is similar to LHCb (*arxiv1206.5160)* in pp collisions at $\sqrt{s}$=0.9, 7 TeV with some complications:

- Primary Vertex(PV) is distributed in SMOG along *z* , have to check sensitivity to PVz for all parameters
- Occupancies are different, can change the efficiencies
- Use template fit of PID likelihoods in addition to cut-based selection used in former study

- **Particle Identification(PID) at LHCb with two RICHs using Likelihoods:**

RICH thresholds define the p_T-p acceptance:

12 < p < 110 GeV/c
p_T > 0.4 GeV/c

- **Acceptance and Efficiencies:**

$$\varepsilon = \varepsilon_{acc} \times \varepsilon_{trg} \times \varepsilon_{PV} \times \varepsilon_{trk} \times \varepsilon_{PID}$$

ε_{acc} geometrical acceptance: from MC simulation

ε_{trg} trigger(minbias): ~100% from data

ε_{PV} PV reconstruction [-700,100]mm: >75%
from MC simulation

ε_{trk} tracking efficiency: 60-70%
from MC , validated with pHe and pp data

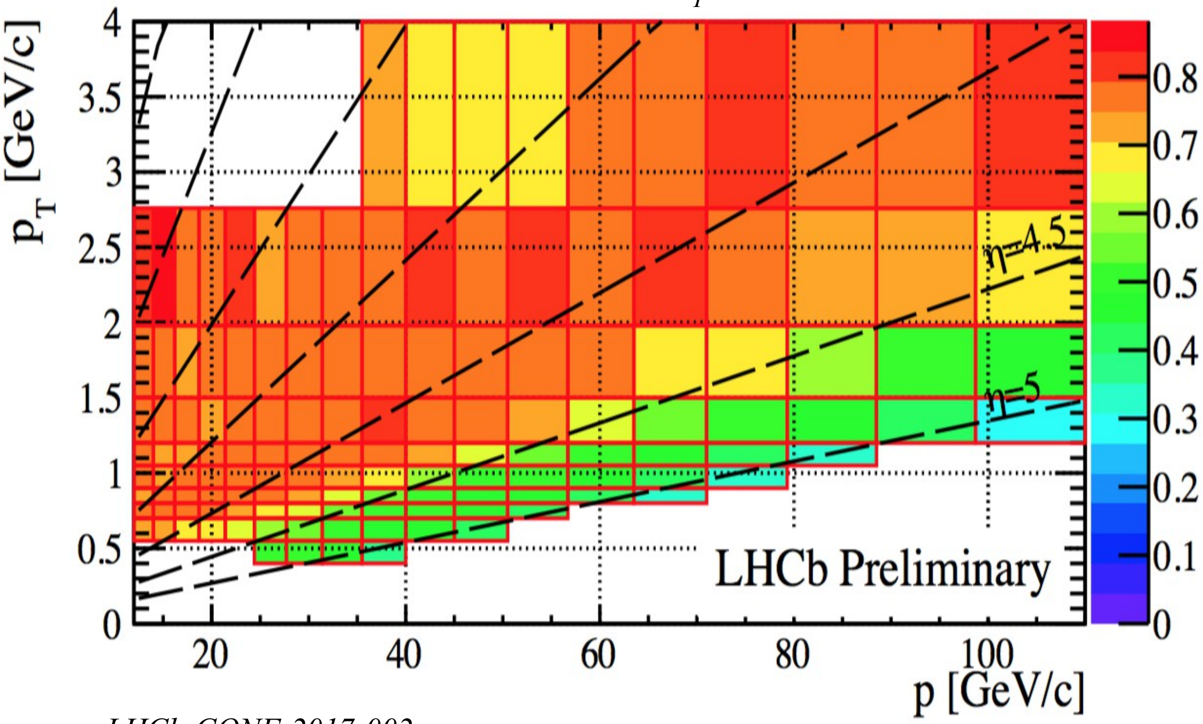
ε_{PID} PID, combination of MC and data(pHe and pp)

- **Feed-down correction**:

Only prompt particle selection (suppress Λ,Ξ,.. <3%)
use impact parameter to PV to suppress hyperons

Efficiencies and statistic define the binning
individual analysis for each p_T- p bin

Total selection efficiency in p_T- p bins

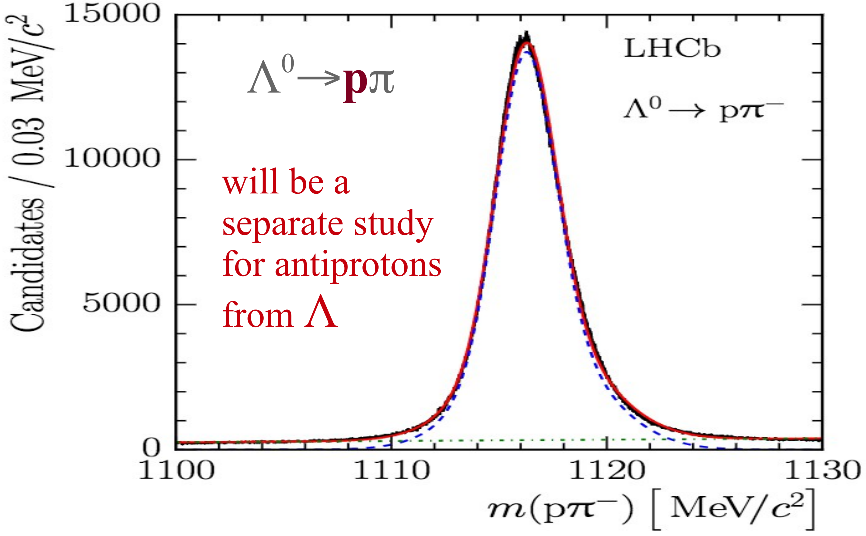


LHCb-CONF-2017-002

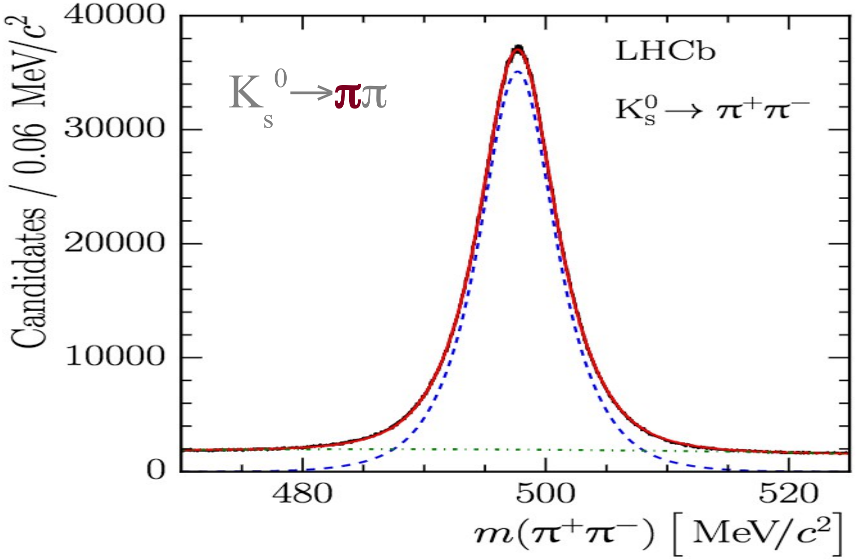
Data-Driven calibration

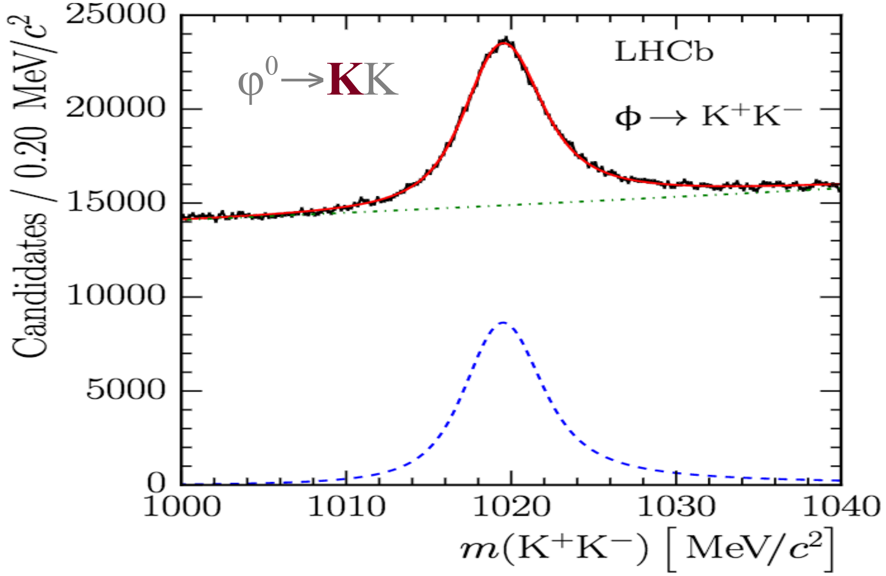
- **Calibration samples from pp collisions and pHe interactions with hadronic decays of:** Λ, K_s, φ, D reconstructed without PID requirement or loose track selection are used for estimation of the PID and tracking efficiencies

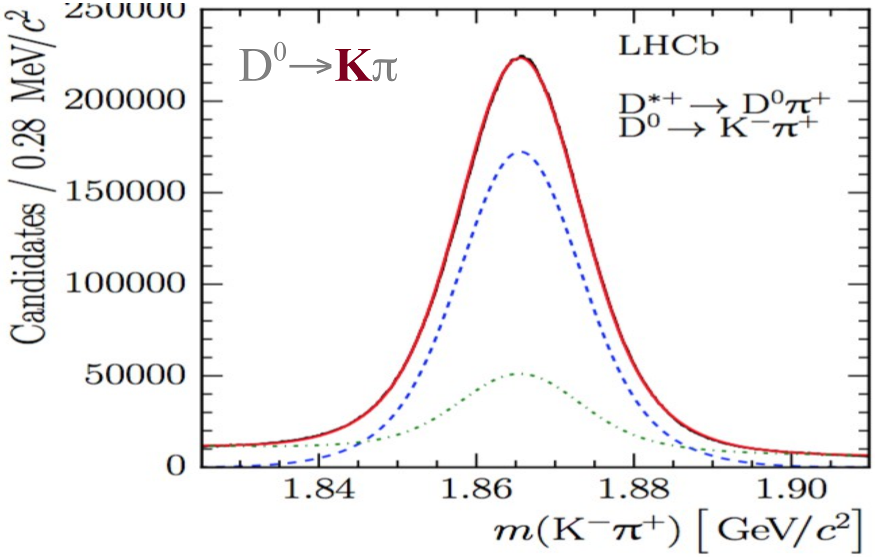
LHCb-PUB-2016-005



will be a separate study for antiprotons from Λ







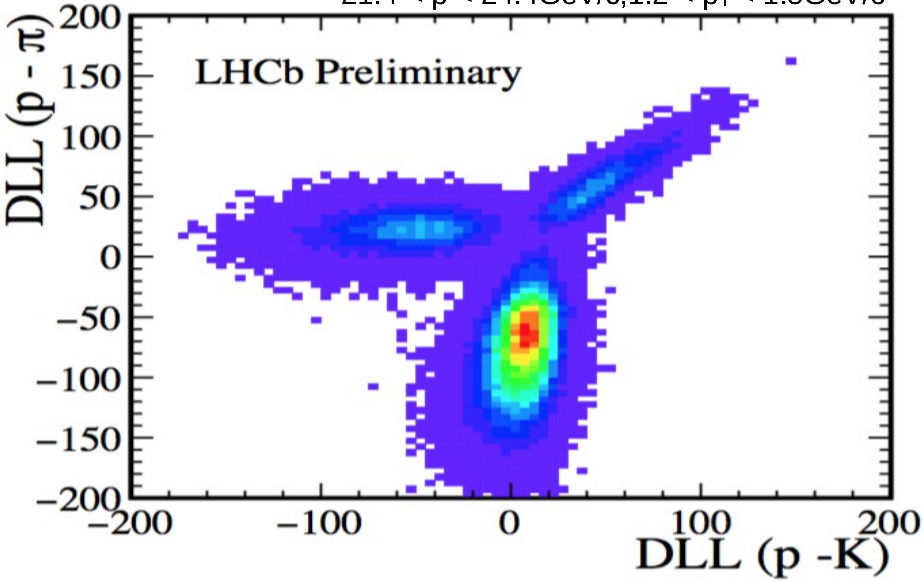
PID template fit

- **Use 2D PID templates from calibration samples and simulations to extract $p^{\pm}$, $\pi^{\pm}$, $K^{\pm}$ and ghost*) track contributions for each p_T-p bin**

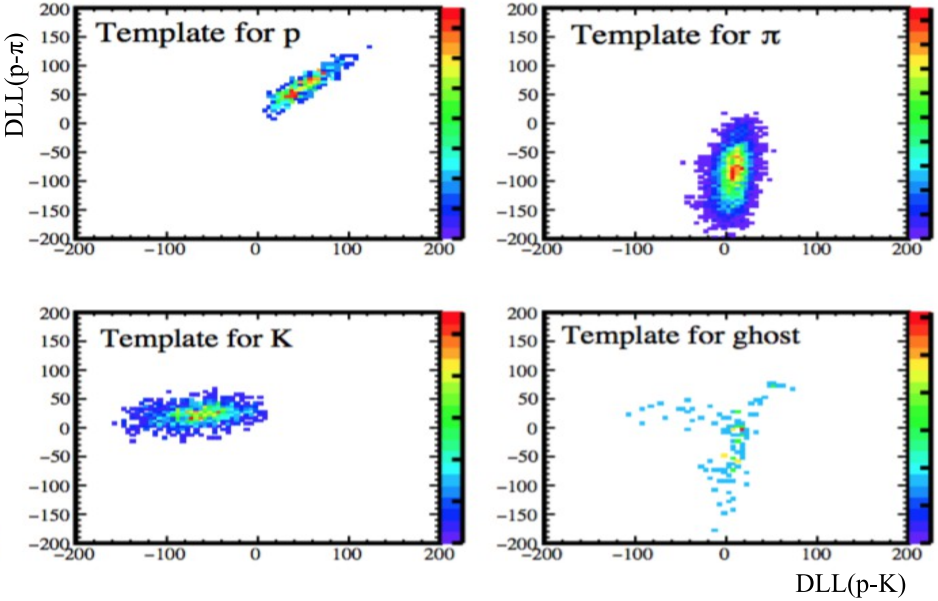
DLL(p-π)=LogLikelihood(p)-LogLikelihood(π), DLL(p-K)=LogLikelihood(p-π)-LogLikelihood(K−π)

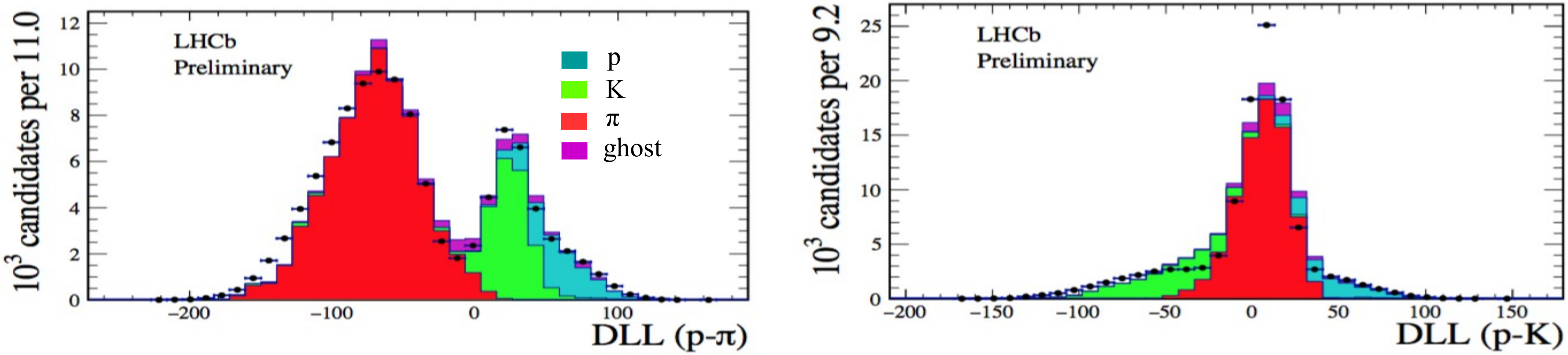
DLL(p-π) vs DLL(p-K)

21.4 < p < 24.4GeV/c,1.2 < p_T < 1.5GeV/c



LHCb-CONF-2017-002



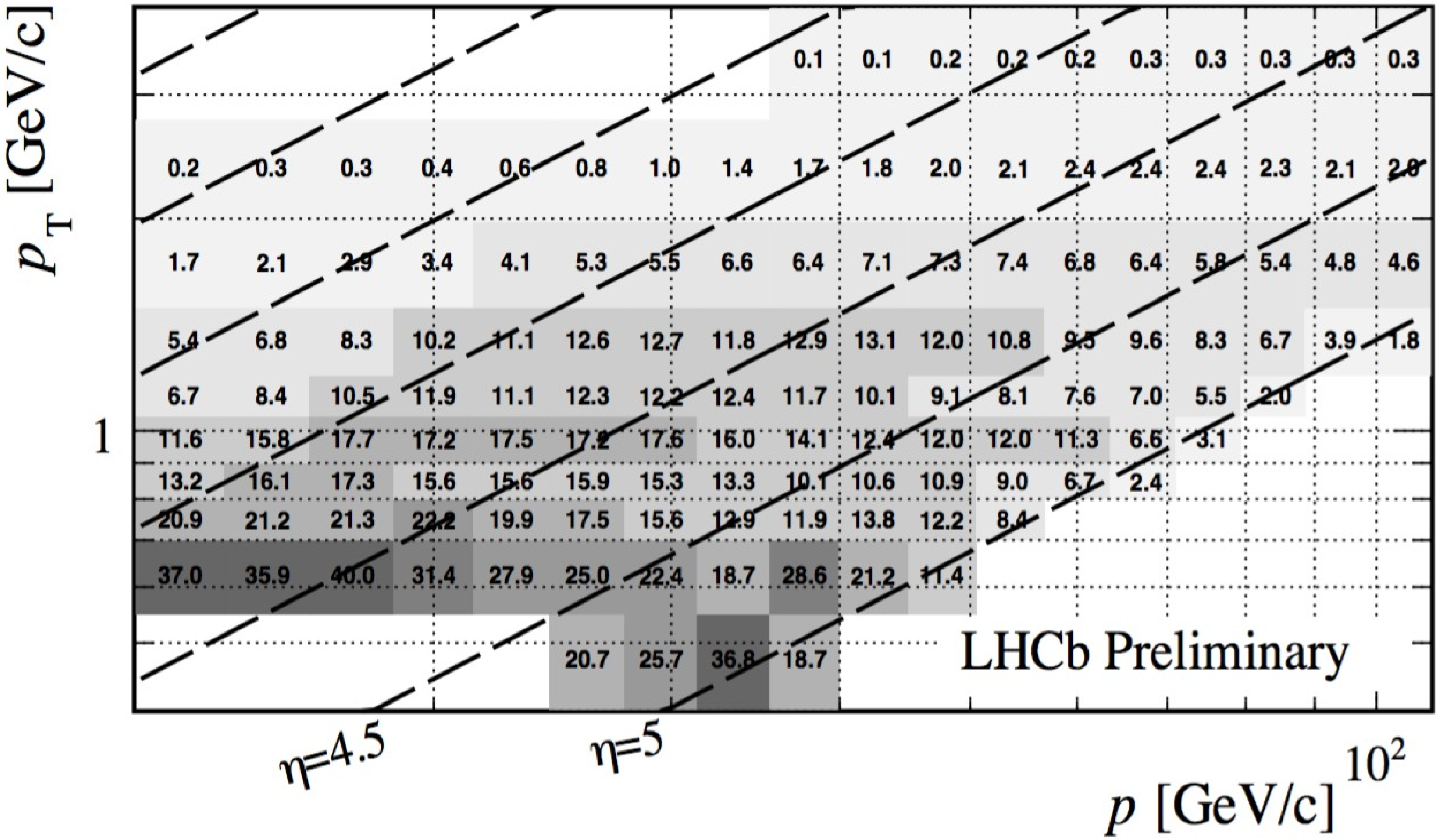


*) ghost tracks are reconstructed using hits from different particles, <2% estimated from simulations

Raw yields

Number of antiprotons (×10 ^{3}) extracted from the fit per p_T-p bin before efficiency corrections

LHCb-CONF-2017-002



$N_{tot}(\bar{p})$ ~1.4×10^6 antiprotons in ~3.5×10^7 selected events from ~0.7×10^9 registered

also the p, $\pi^\pm$ and $K^\pm$ contributions are extracted, ongoing work

Uncertainties

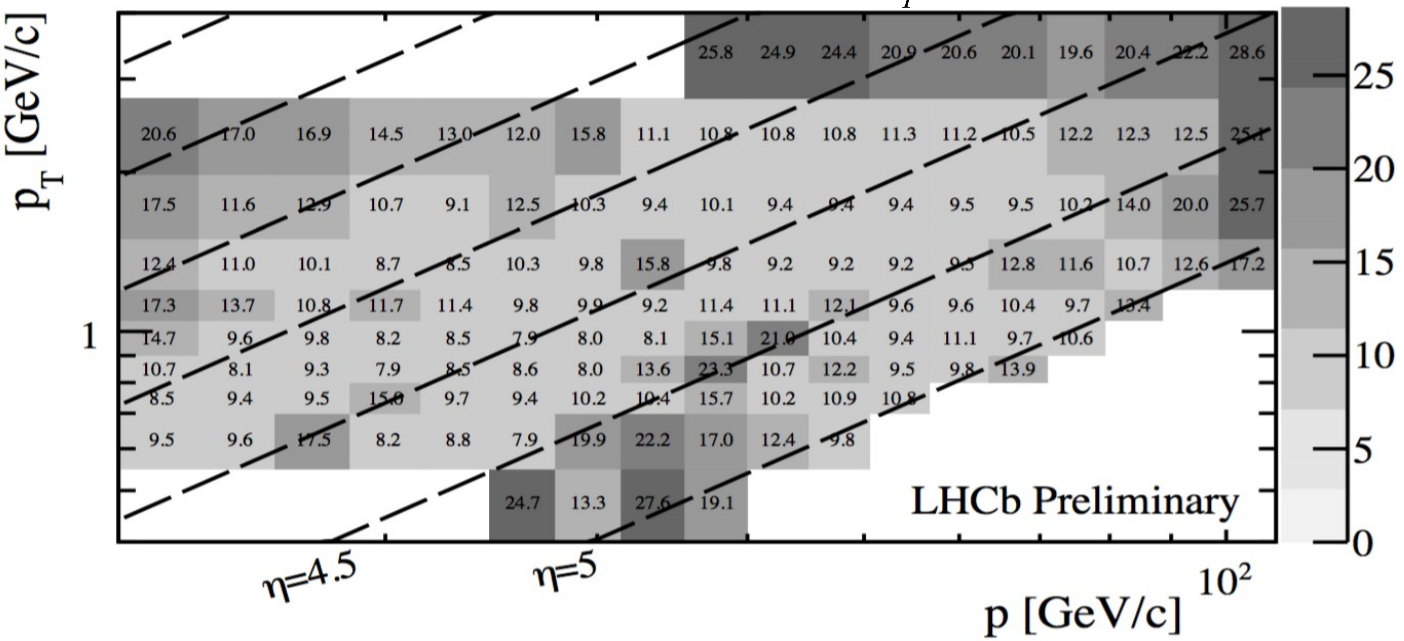
LHCb-CONF-2017-002

Statistical:	
Yields in data and PID calibration	0.7 – 10.8% (< 3% for most bins)
Normalization	2.5%
Correlated Systematic:	
Normalization	6.0%
Event and PV requirements	0.3%
PV reco	0.8%
Tracking	2.2%
Nonprompt background	0.3 – 0.7%
Residual vacuum background	0.1%
PID	1.2 – 5.0%
Uncorrelated Systematic:	
Tracking	3.2%
IP cut efficiency	1.0%
PID	0 – 26% (< 10% for most bins)
Simulated sample size	0.8 – 15% (< 4% for $p_T < 2$ GeV/c)

common for all p_T-p bins, dominated by luminosity measurements

for each p_T-p bin, dominated by the PID uncertainties, mostly in boundary bins

Total relative uncertainties in p_T-p bins

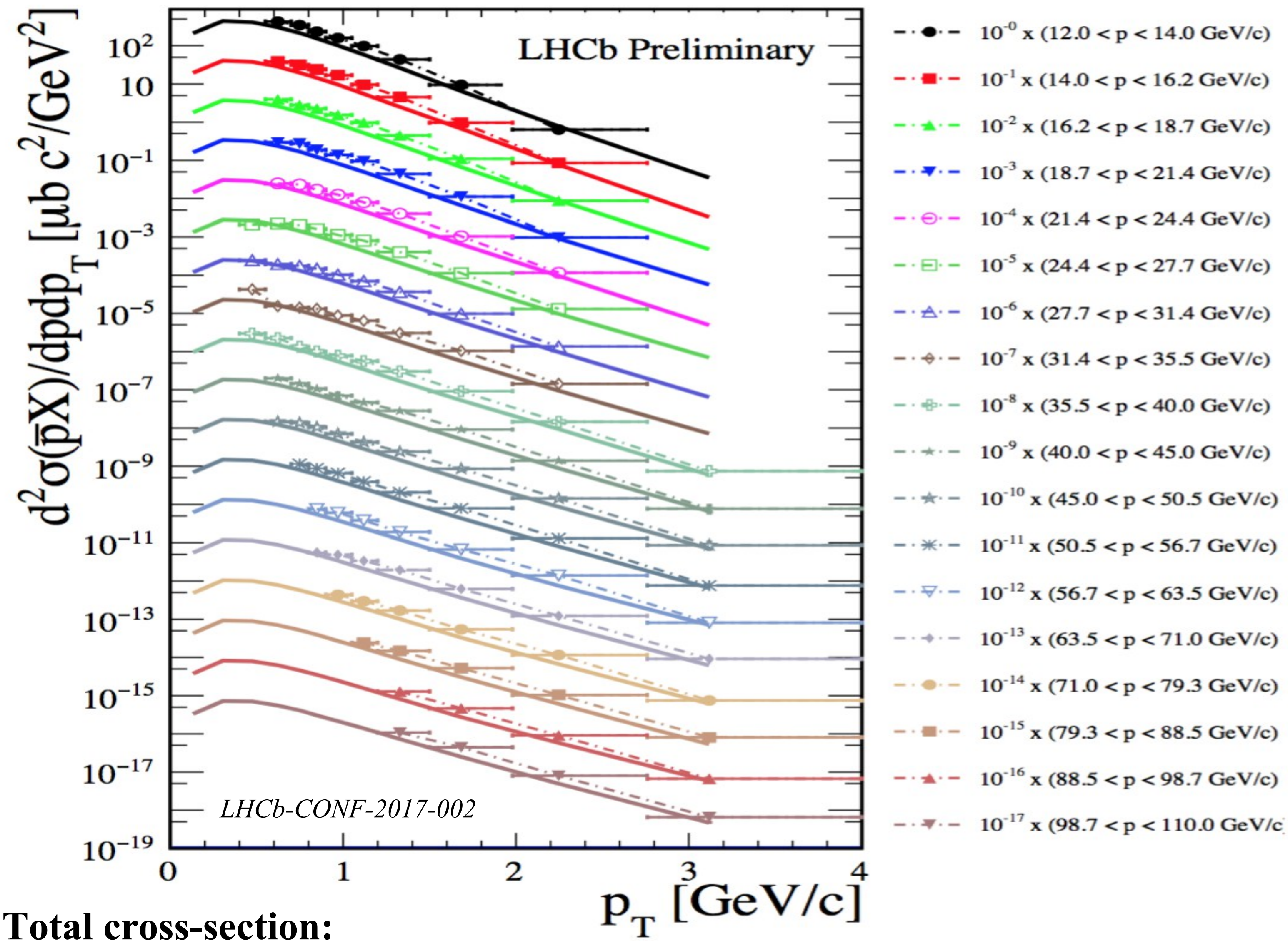


use the PID cut based counting for cross-check and estimation of systematic uncertainties

Results pHe→$\bar{p}$+X

Differential cross section in comparison with EPOSLHC) (solid line)*

*) from CRMC 1.5.6



Total cross-section:

$$\sigma_{\rm inel}^{\rm LHCb}({\rm pHe}, \sqrt{s_{\rm NN}} = 110\,{\rm GeV}) = (140 \pm 10)\ {\rm mb}$$

EPOS-LHC = 118 mb (used for acceptance)

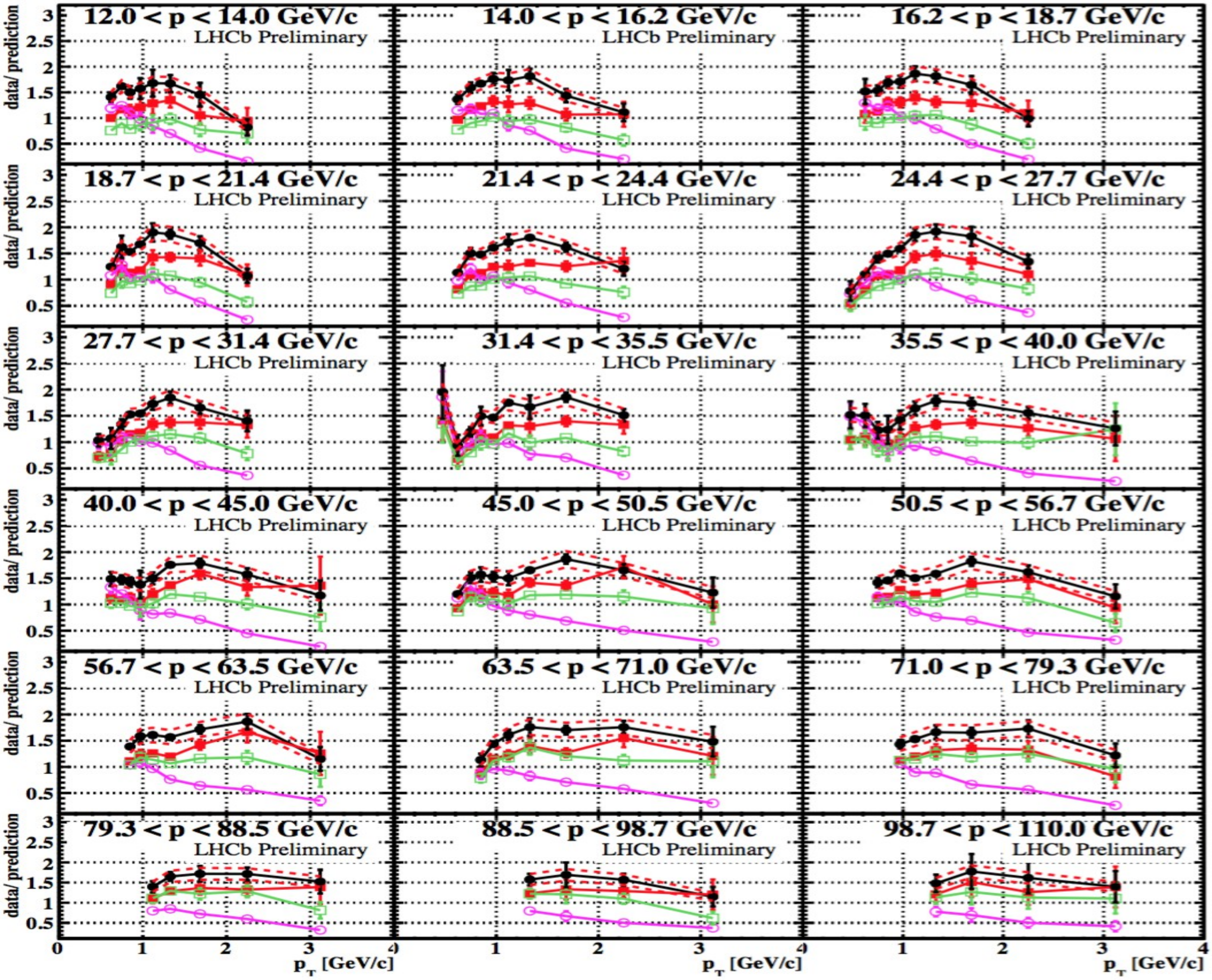
QGSJETII = 127 mb

×1.5 larger differential cross section

×1.2 larger total cross section

Data/MC

LHCb-CONF-2017-002



CRMC:

EPOSLHC
EPOS1.99
QGSJETII-04
HIJING 1.38

EPOSLHC and QGSJETII are bracketing the Data

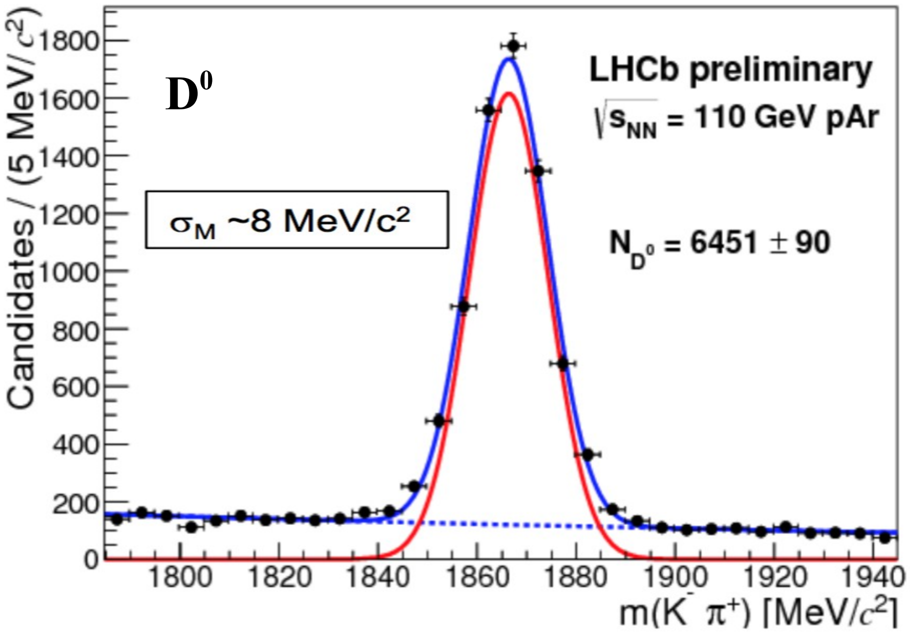
QGSJETIIm arxiv1502.04158 good agreement (see backup)

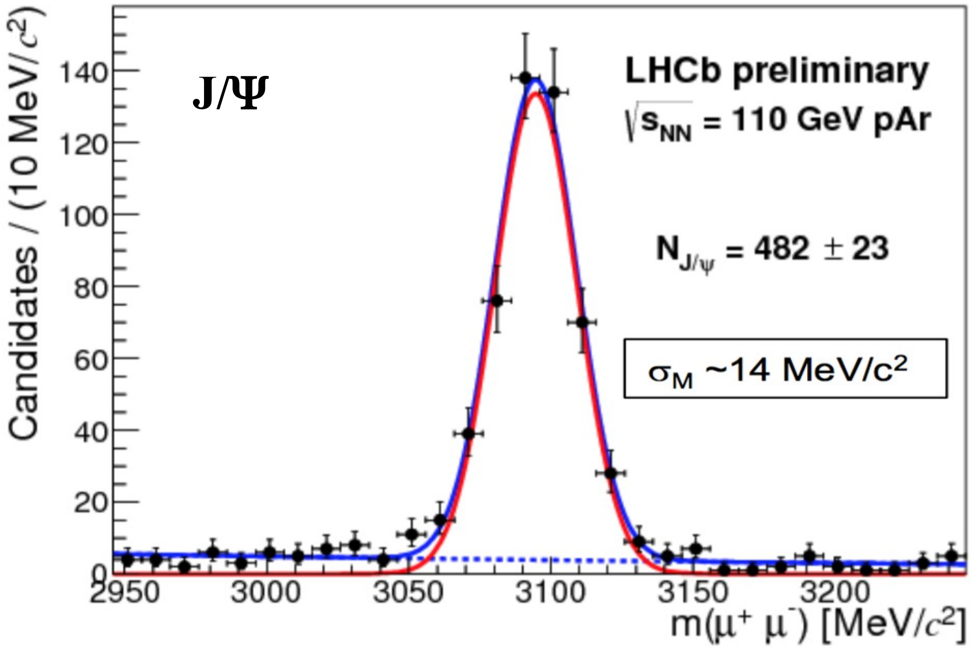
Charm production in pAr at $\sqrt{s}$=110 GeV

- **Measure open charm $D^0 \rightarrow K\pi$ and charmonium $J/\Psi \rightarrow \mu\mu$ yields in distributions: p_T, y, x_2, x_F**

  - no luminosity measurement for pAr yet, no absolute cross sections

LHCb-CONF-2017-001





- **Acceptance and Efficiencies:**

$\varepsilon = \varepsilon_{acc} \times \varepsilon_{trg} \times \varepsilon_{sel} \times \varepsilon_{PV} \times \varepsilon_{trk} \times \varepsilon_{PID}$	D^0	J/Ψ
acc-acceptance	75%	70%
trg- trigger	79%	77%
sel- selection	14%	90%
PV- Primary Vertex	59%	61%
trk- tracking	57%	87%
PID-ParticleIdentification	70-85%	80-85%
	1.8-2.5%	**21.7-22.8%**

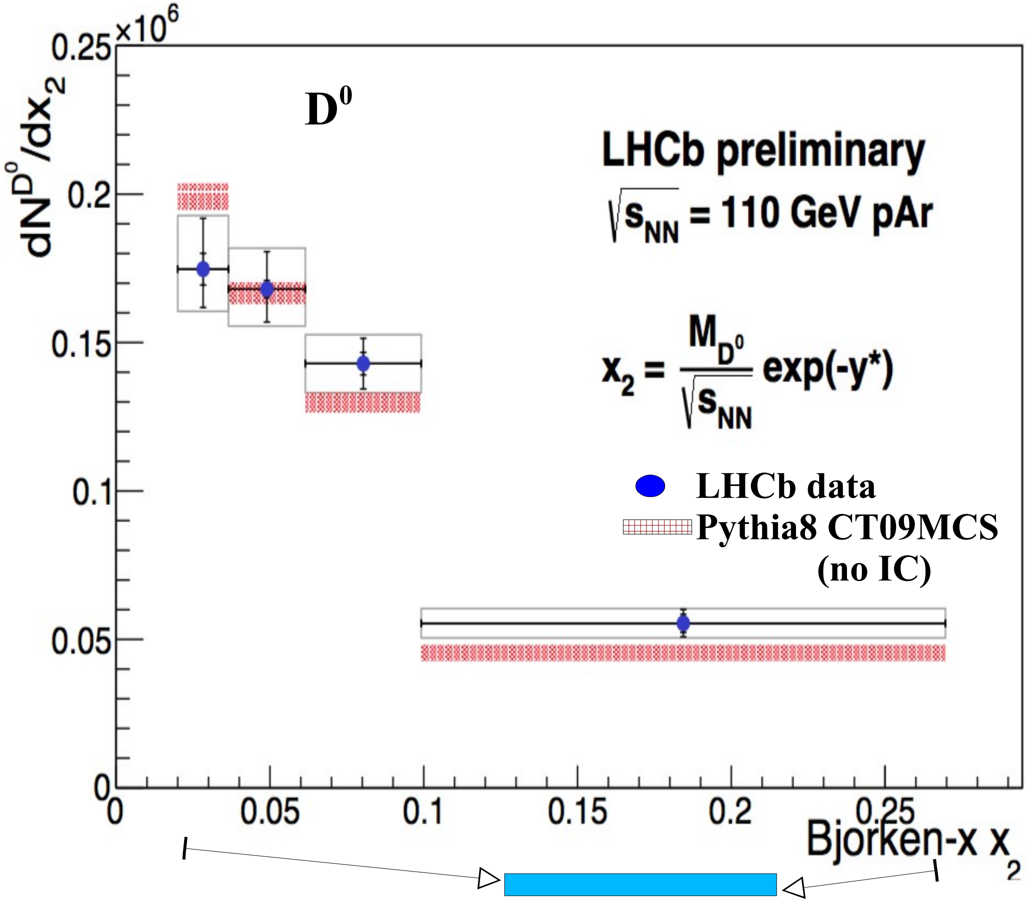
- **Uncertainties**

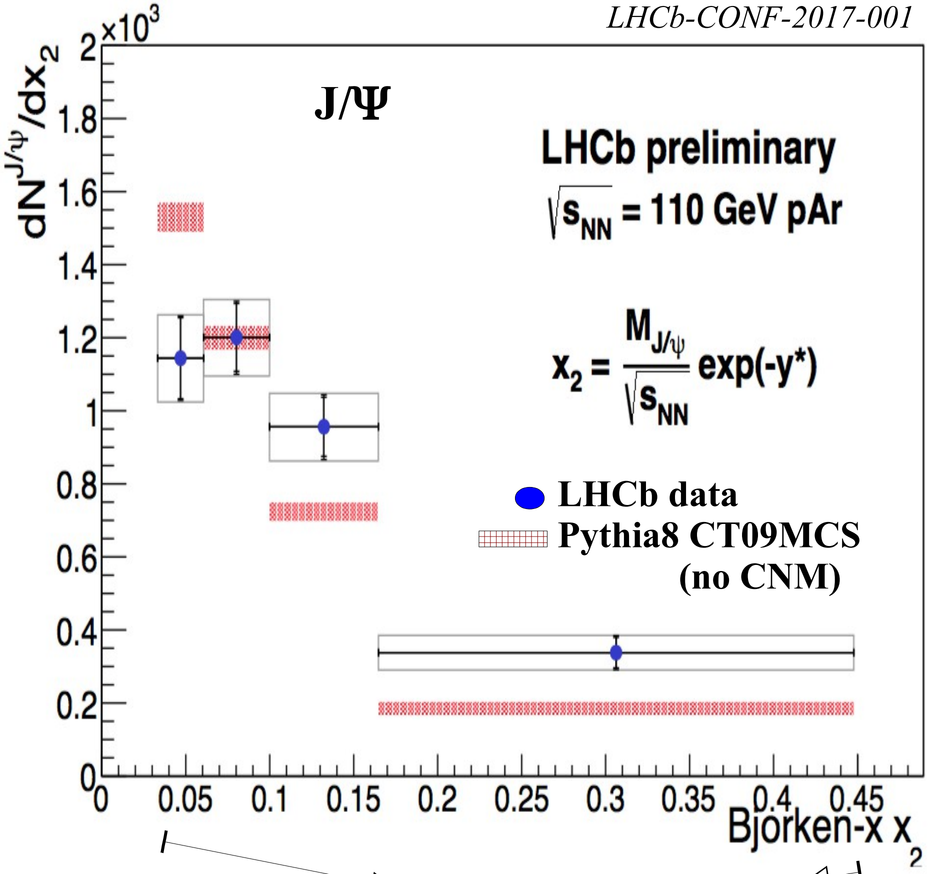
Source	J/ψ y	J/ψ p_T	D^0 y	D^0 p_T
Correlated between bins				
Signal selection	1.4%	1.4%	2.2%	2.2%
Signal extraction	2.3%	2.3%	2.3%	2.7%
Uncorrelated between bins				
MC sample	(1.2 – 2.6)%	(0.9 – 1.4)%	(1.0 – 1.9)%	(1.0 – 1.5)%
Tracking	(2.2 – 4.8)%	(2.2 – 2.9)%	(2.7 – 4.0)%	(2.8 – 3.6)%
PID	(0.2 – 2.7)%	(0.1 – 2.0)%	(4.1 – 8.8)%	(4.8 – 6.9)%
Statistical uncertainties	(7.7 – 12.5)%	(7.8 – 13.6)%	(0.7 – 3.7)%	(0.6 – 3.4)%

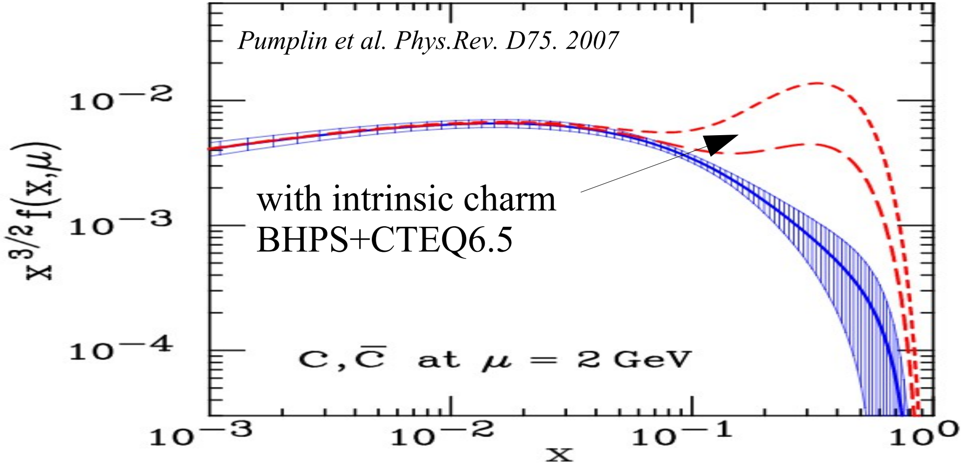
Contributions from b-decays: D^0 <1%, J/Ψ>0.03%

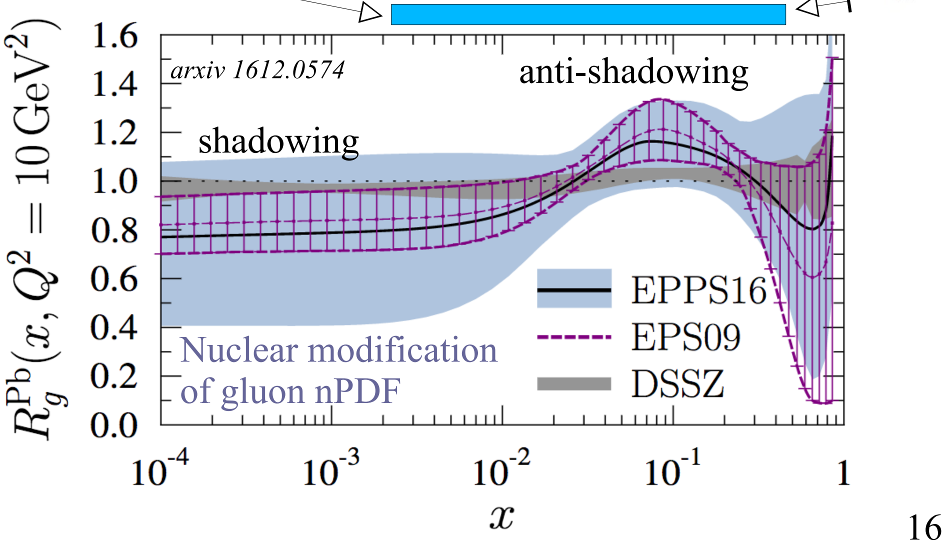
Results: Bjorken-x

LHCb-CONF-2017-001



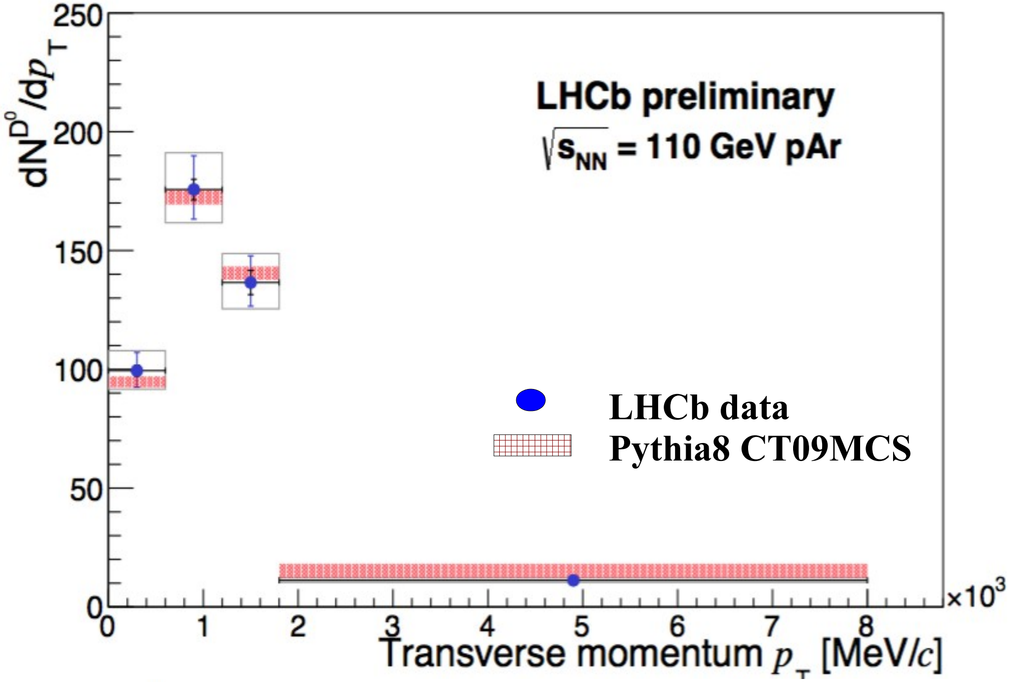



Pumplin et al. Phys.Rev. D75. 2007


arxiv 1612.0574

Results: p_T momentum and rapidity y

D^0



J/Ψ

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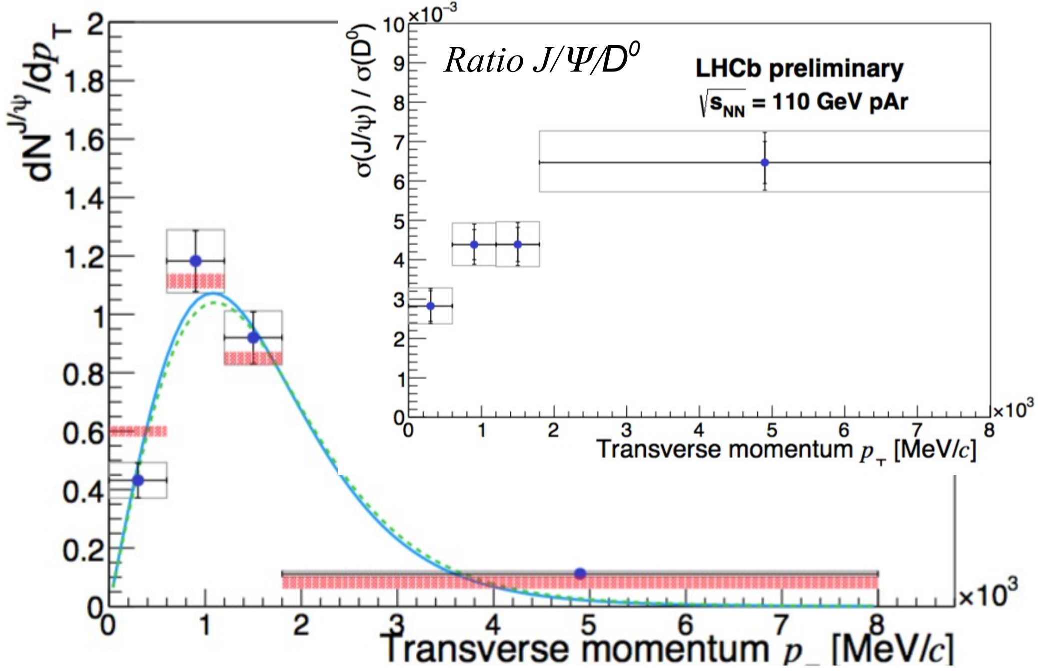
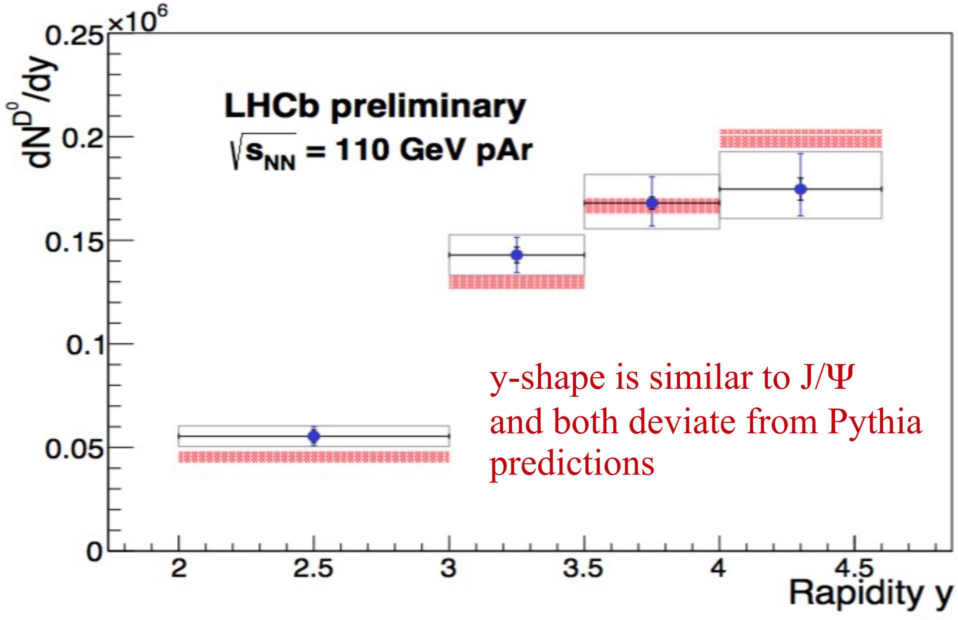
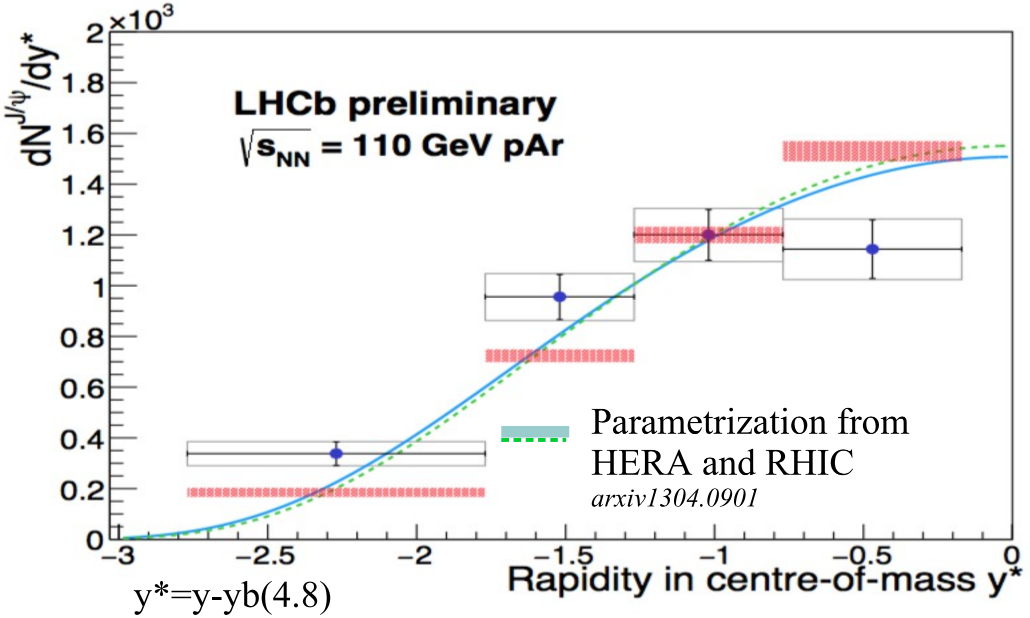




y-shape is similar to J/Ψ and both deviate from Pythia predictions



Parametrization from HERA and RHIC

arxiv1304.0901

$y^* = y - y_b(4.8)$

Perspectives on charm production

Other resonances in the same pAr SMOG data sample (data-taking 17h)

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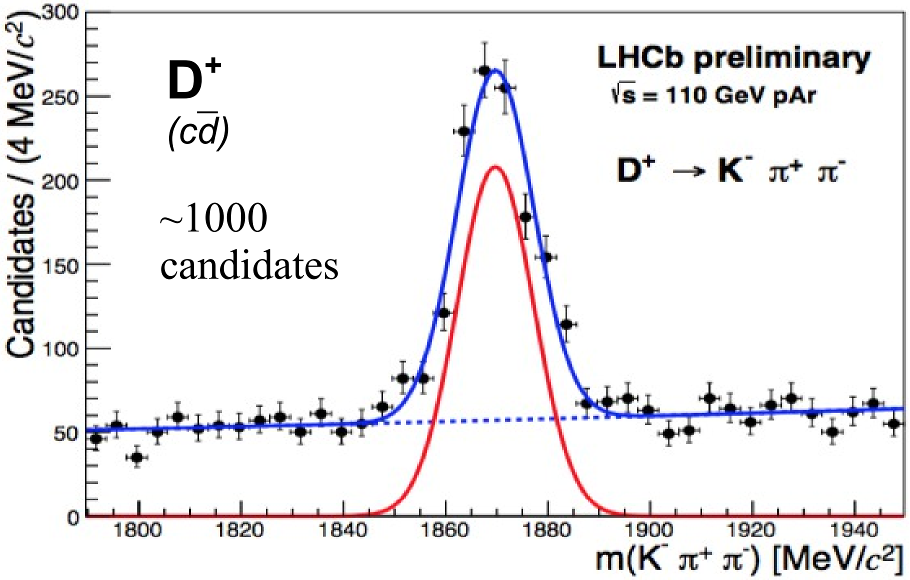
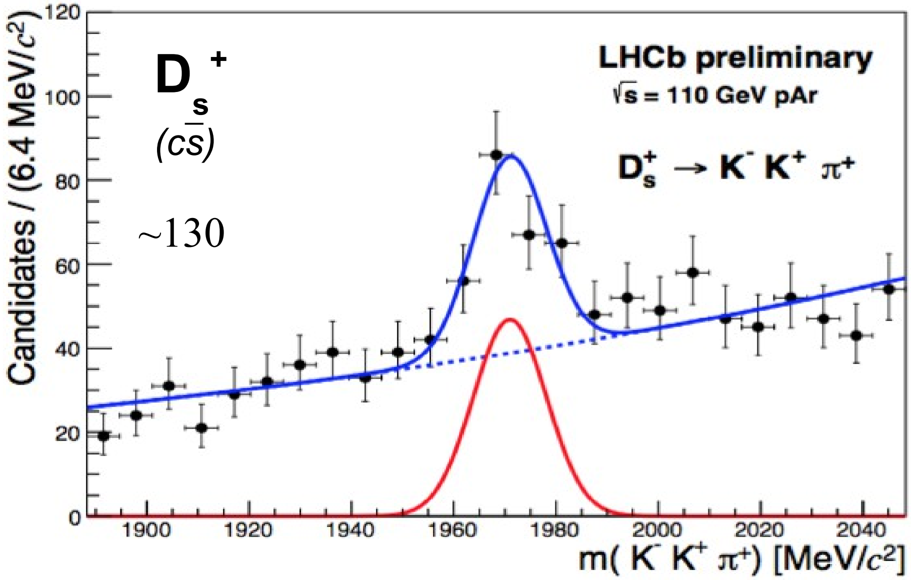
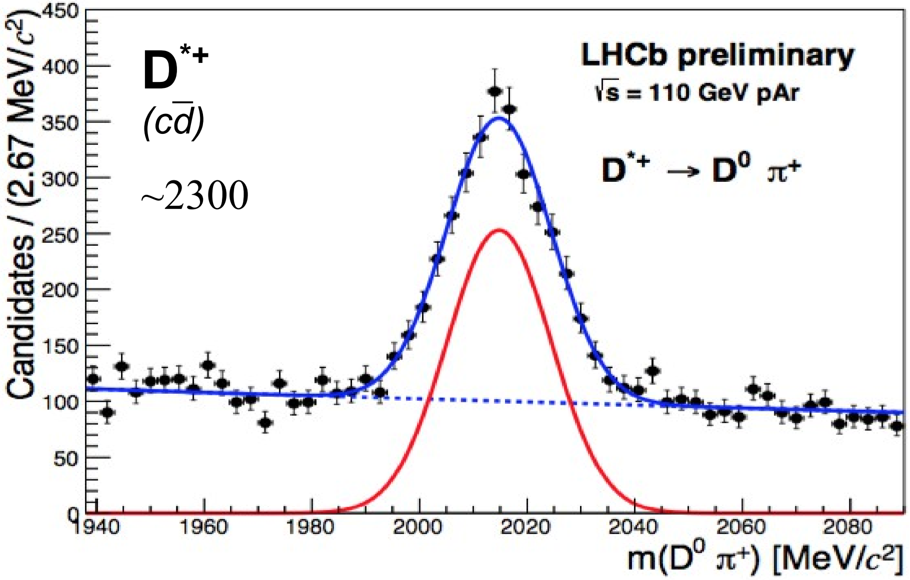


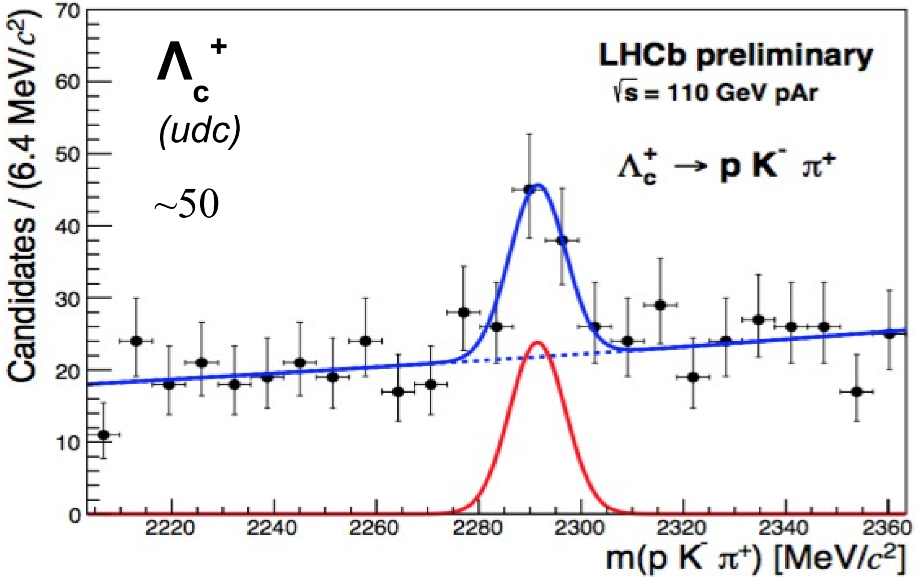
D^+
($c\bar{d}$)
~1000 candidates



D_s^+
($c\bar{s}$)
~130



D^{*+}
($c\bar{d}$)
~2300



Λ_c^+
(udc)
~50

need ×100 more statistics for Λ_c

Summary

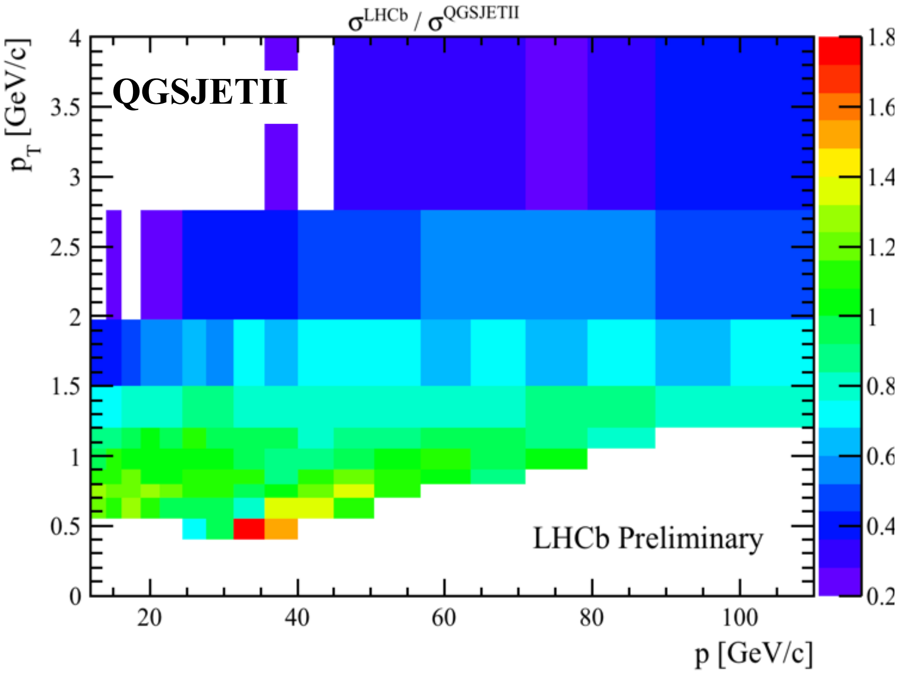
- Amazing possibility to measure hadron production in collisions and fixed target with the same detector and in the same run.
  First results are validation of the possibility, more will come.
  Different gas targets are possible, more complicated is to vary the energy.

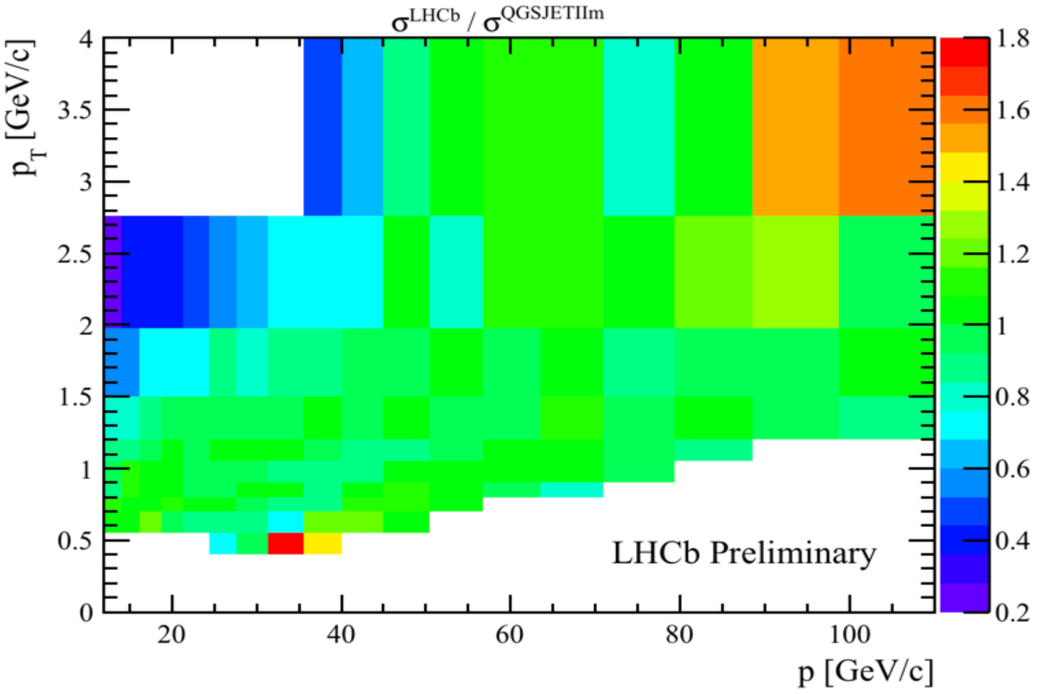
- Antiproton production $pHe \to \bar{p}X$ at $\sqrt{s}=110$ GeV shows some deviations from RTF MC (EPOS,QGSJETII) predictions. The accuracy of the absolute cross section is limited by uncertainties in the luminosity measurements(~6%), and systematic in particle identification.

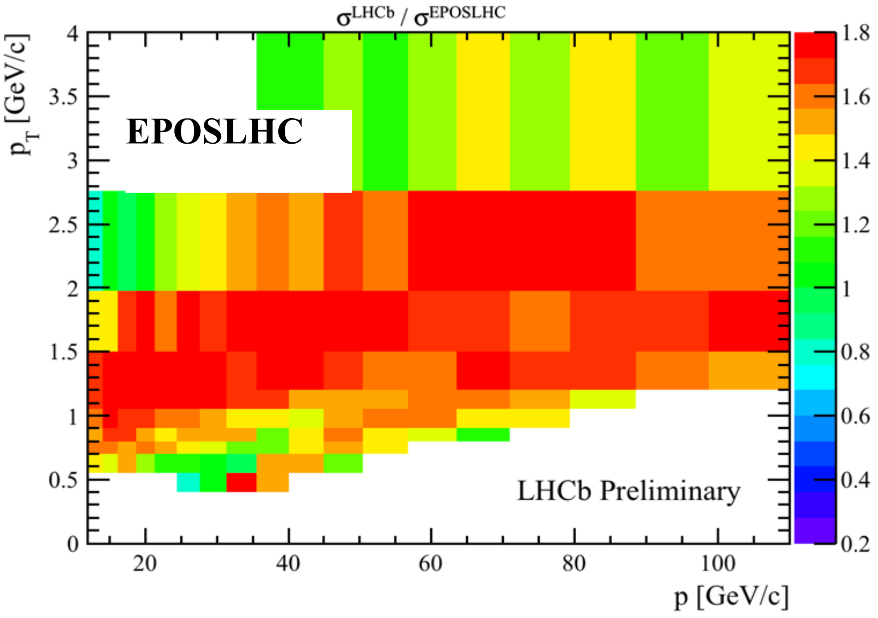
- The open charm D^0 and charmonium J/Ψ productions in pA marginally agree with the theory prediction (Pythia8). Significant (~30%) deviations in the Bjorken-x and rapidity-y distributions would require more theoretical investigation.

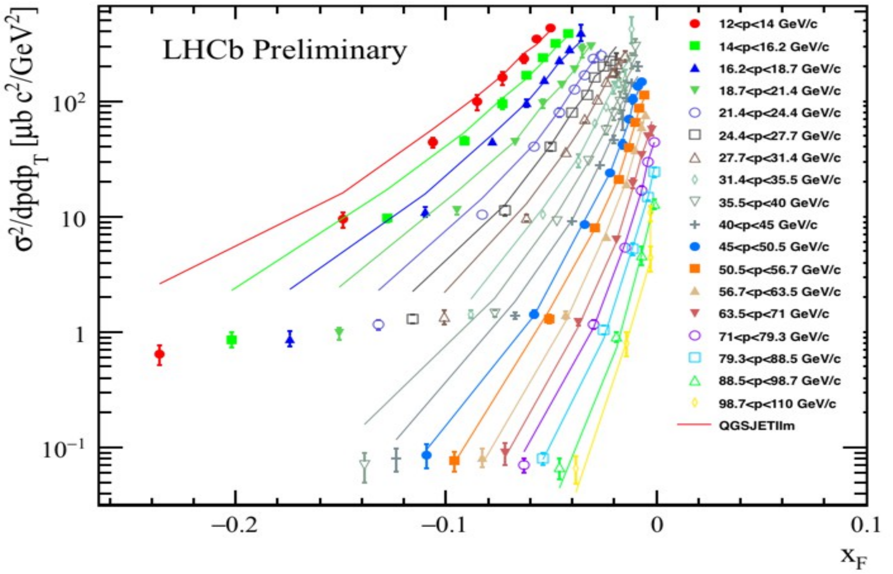
BACKUPs

Data/MC: $pA \rightarrow \bar{p} + X$



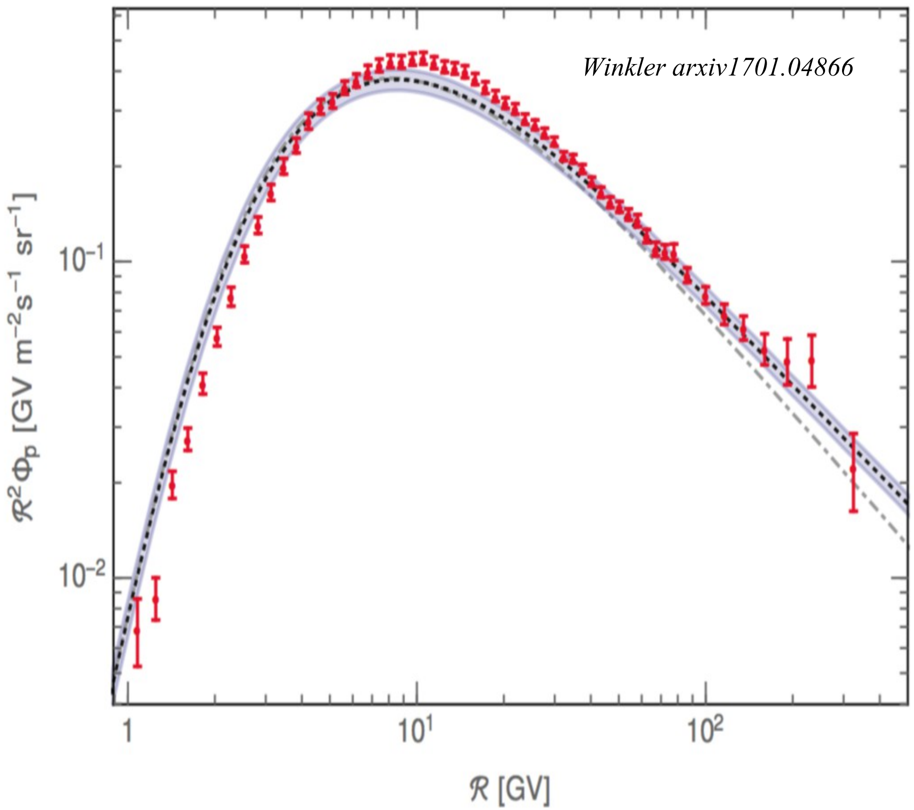




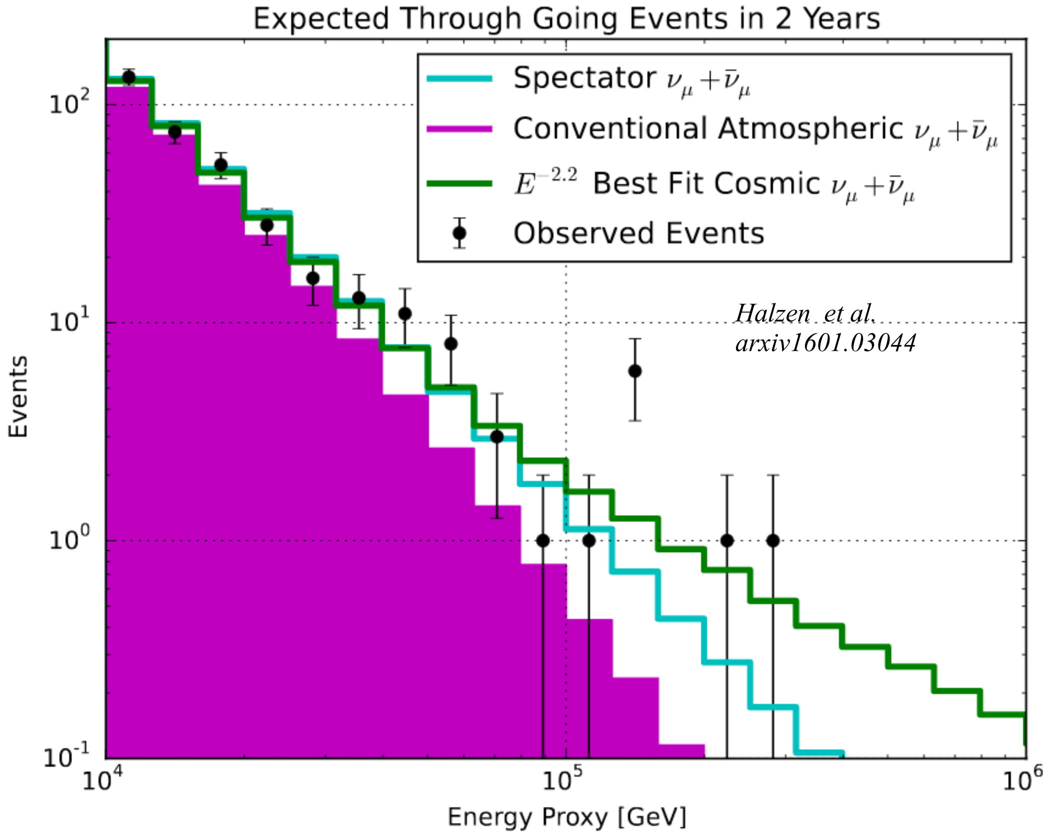


Increase of $\bar{p}$ σ_{inel} ×1.5 brings calculated flux closer to the AMS measured rates, accounting for hyperons ($\Lambda+\Xi/\bar{p}\sim0.4$) and neutrons ($\bar{n} \to \bar{p}X \sim 0.5$) can be enough to explain observation

The observed slight increase in D^0 at x>0.1 may not be enough to claim IC, and is not enough to explain the IceCube HE neutrino



Winkler arxiv1701.04866


Expected Through Going Events in 2 Years

Halzen et al. arxiv1601.03044