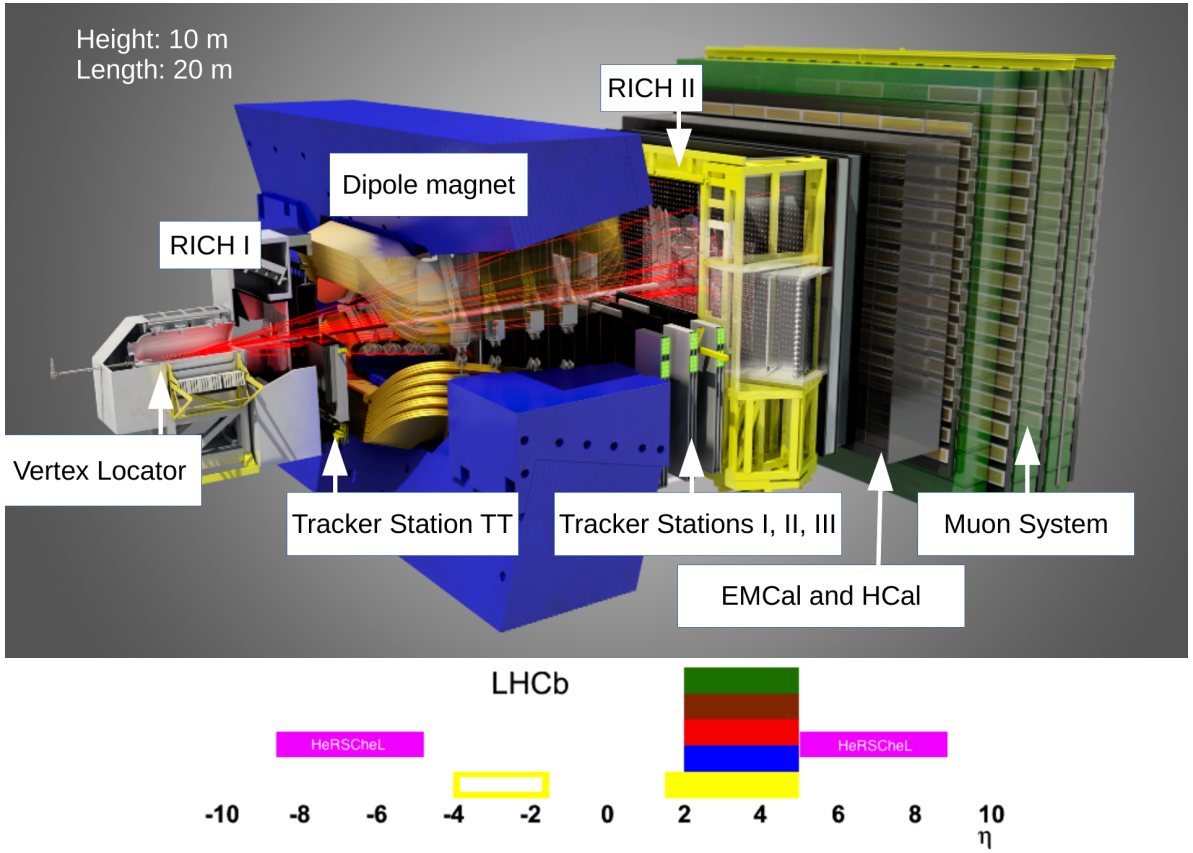
Fixed-target & heavy-ion collision results from LHCb

Michael Winn on behalf of the LHCb collaboration

Laboratoire de l'Accélérateur Linéaire, Orsay

LHC seminar, CERN, 21.08.2018

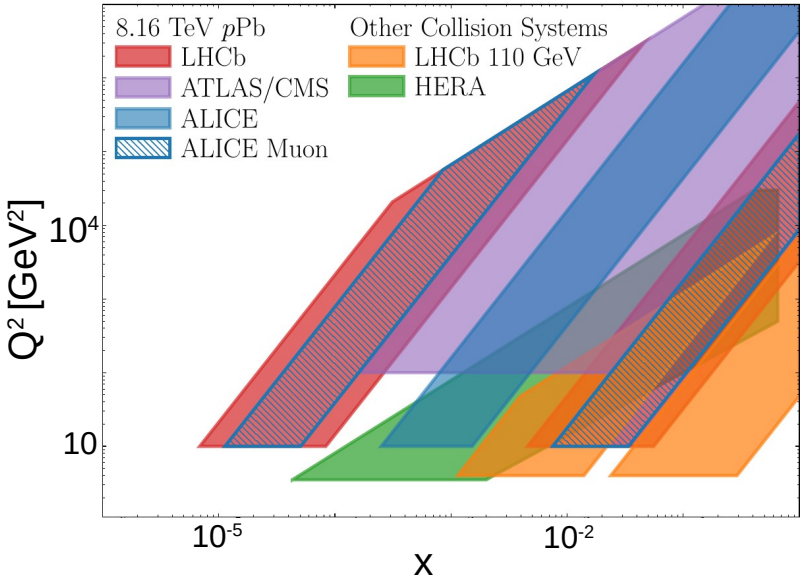
The LHCb detector

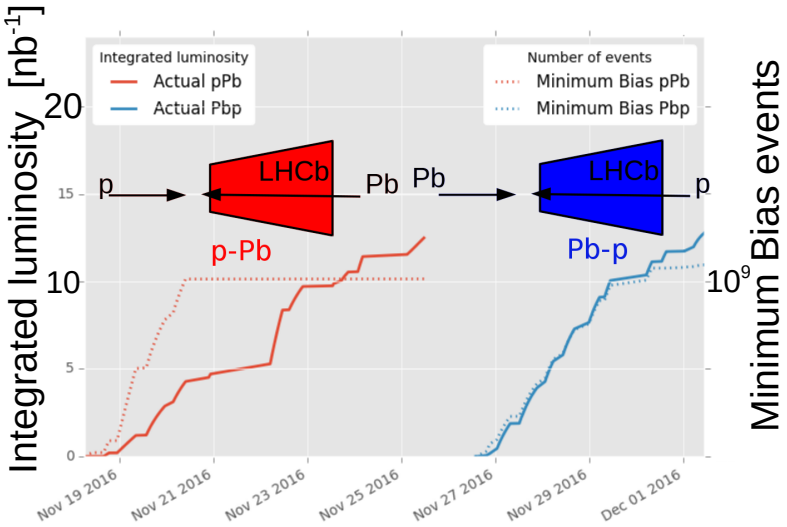


JINST 3 (2008) S08005.

- precise tests of the Standard Model in the flavour sector
- spectacular QCD spectroscopy and precision EW measurements
- flexible trigger down to low-p_T with high rates in fixed-target geometry
- High-Energy Physics eagerly waiting for news from lepton universality
  ... LHCb is even more than this!

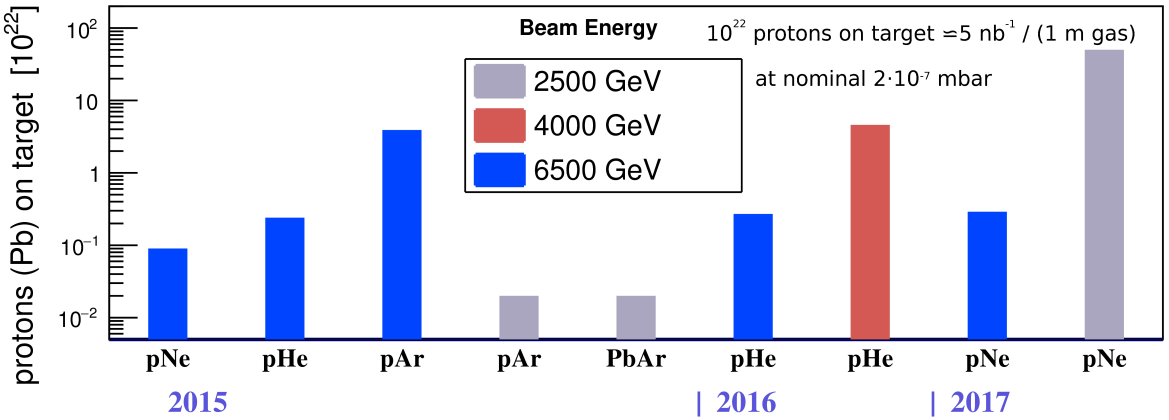
Unique forward kinematics in heavy-ion collider mode

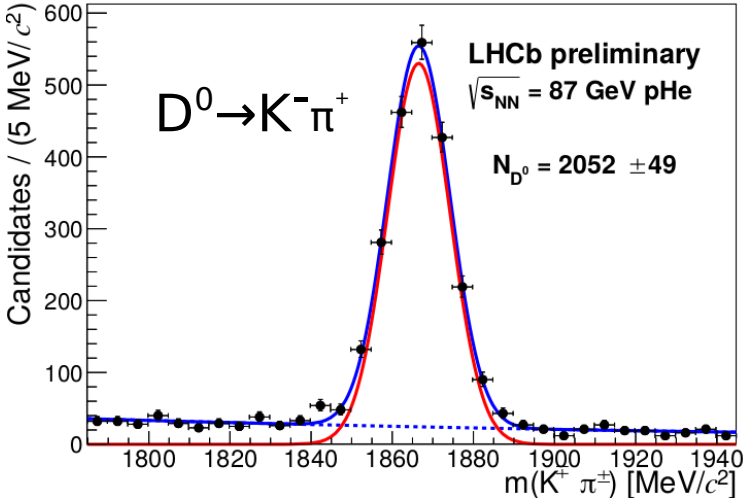


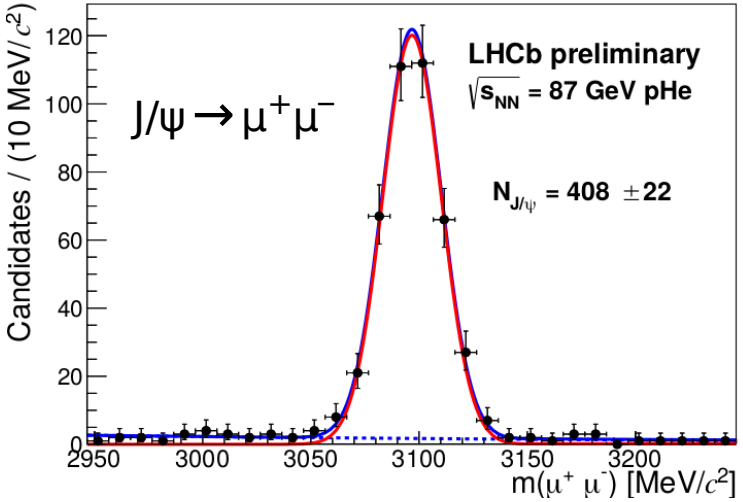


- 2016 pPb run at $\sqrt{s_{NN}} = 8.16$ TeV:
  - 10^9 minimum bias collisions in pPb and Pbp mode
  - $34\,\mathrm{nb}^{-1}$ in pPb+Pbp for heavy-flavour/other probes processed in HLT:
  ≈ 0.5 million J/ψ in pPb, Pbp each
- Ion-ion: 10 μb^{-1} PbPb and 0.4 μb^{-1} XeXe
  $\rightarrow$ 2018 PbPb aiming for a factor 10 more
- heavy-ion and low-x with inclusive and exclusive production channels

Unique fixed target mode at the LHC







- **S**ystem for **m**easuring **O**verlap with **G**as: most precise LHC luminosity
  LHCb-PAPER-2014-047, JINST 9 (2014) no.12
- used as internal gas target for physics parasitic to collider data taking
- cosmic ray and heavy-ion related physics with He, Ne and Ar targets

Today's selection

- $\bar{p}$-production in pHe fixed-target collisions:
  reference for direct cosmic rays

  Final results at $\sqrt{s_{NN}} = 110$ GeV LHCb-PAPER-2018-031, arXiv:1808.06127

- charm production in fixed-target collisions in $p\ ^4\mathrm{He}/^{40}\mathrm{Ar}$:
  intermediate/large-x & reference for ion-ion collisions

  D^0 and J/ψ production LHCb-PAPER-2018-023, in preparation

- heavy-flavour and quarkonium production in pPb:
  low-x, energy loss tests & reference for ion-ion collisions

  New Λ_c^+ at $\sqrt{s_{NN}} = 5$ TeV & Υ(nS) at $\sqrt{s_{NN}} = 8.16$ TeV
  LHCb-PAPER-2018-021, in preparation. & LHCb-PAPER-2018-035, in preparation.
  J/ψ at $\sqrt{s_{NN}} = 8.16$ TeV LHCb-PAPER-2017-014, PLB 774 (2017) 159

  D^0 at $\sqrt{s_{NN}} = 5$ TeV LHCb-PAPER-2017-015, JHEP 10 (2017) 090

- exclusive photonuclear J/ψ production in ultra-peripheral PbPb collisions:
  probe low-x and nuclear shadowing

  LHCb-CONF-2018-003

$\bar{p}$ from space: indirect search for the unknown

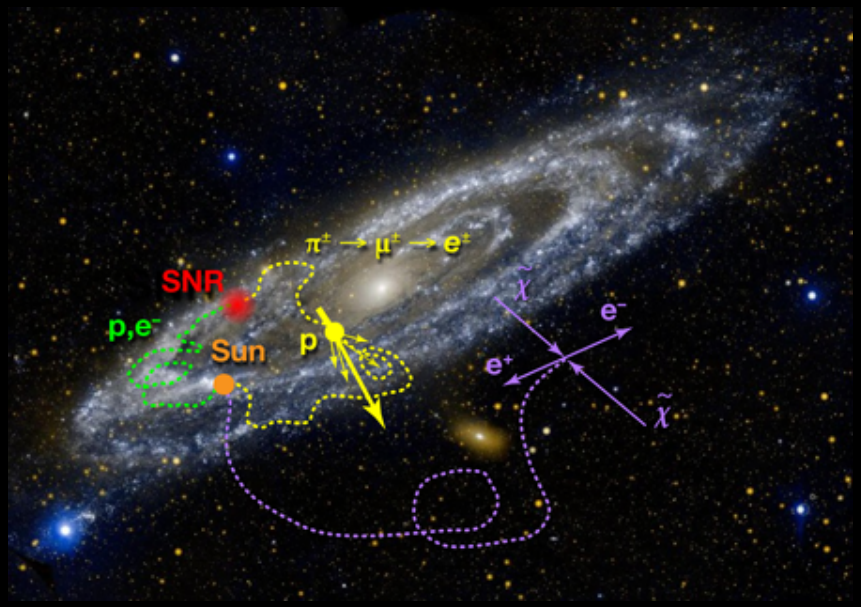
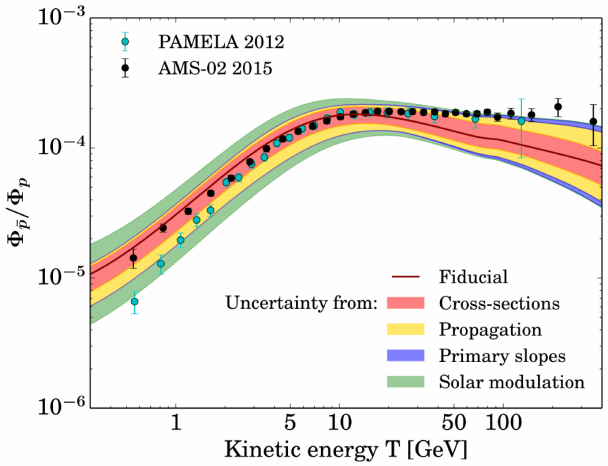


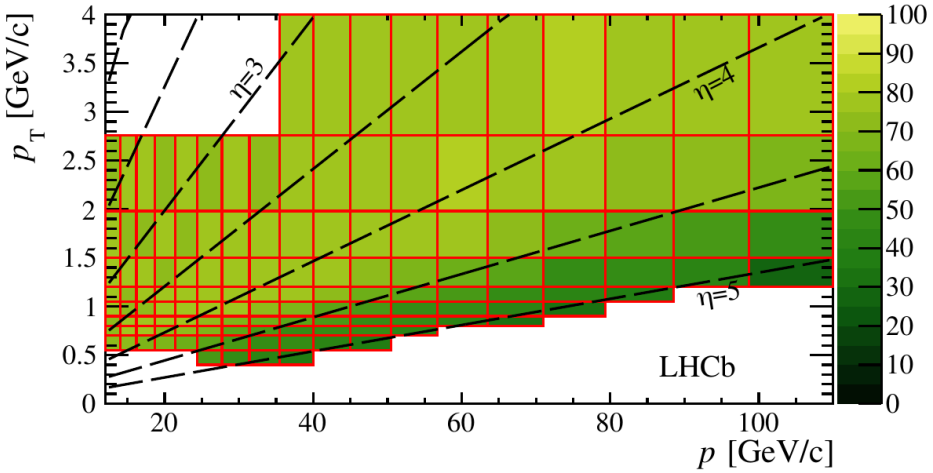
Image: GALEX, JPL-Caltech, NASA; Drawing: APS/Alan Stonebraker.

- matter:
  primary cosmic rays from Supernovae Remnants (SNR) and other sources
- possible exotic **antimatter** sources in space: dark matter annihilations
- irreducible **background**: primary cosmic rays hitting interstellar medium, **Hydrogen and Helium**, producing secondary cosmic rays containing $\bar{p}$
- direct charged cosmic ray detection in space:
  precision data with Pamela and AMS

Production cross sections in pHe: a crucial missing piece



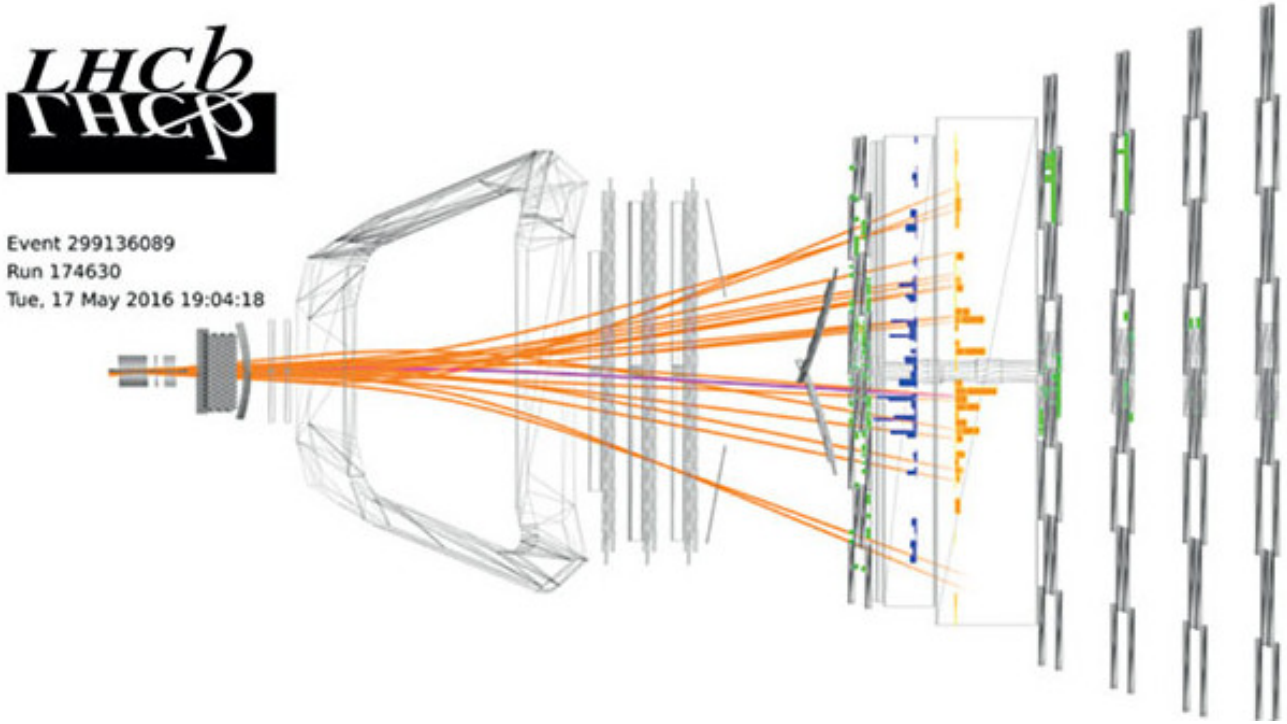
comparsion with AMS data JCAP 1509 (2015) no.09, 023



$\bar{p}$-measurement kinematics, z-axis ϵ_{rec}.

- flux prediction uncertainties in 10-100 GeV kinetic energy range: dominated by production cross sections uncertainties
- $\bar{p}$-production in pHe collisions never directly measured
- LHCb in fixed-target mode: pioneer with well suited kinematics
- publication submitted to PRL, LHCb-PAPER-2018-031, arXiv:1808.06127

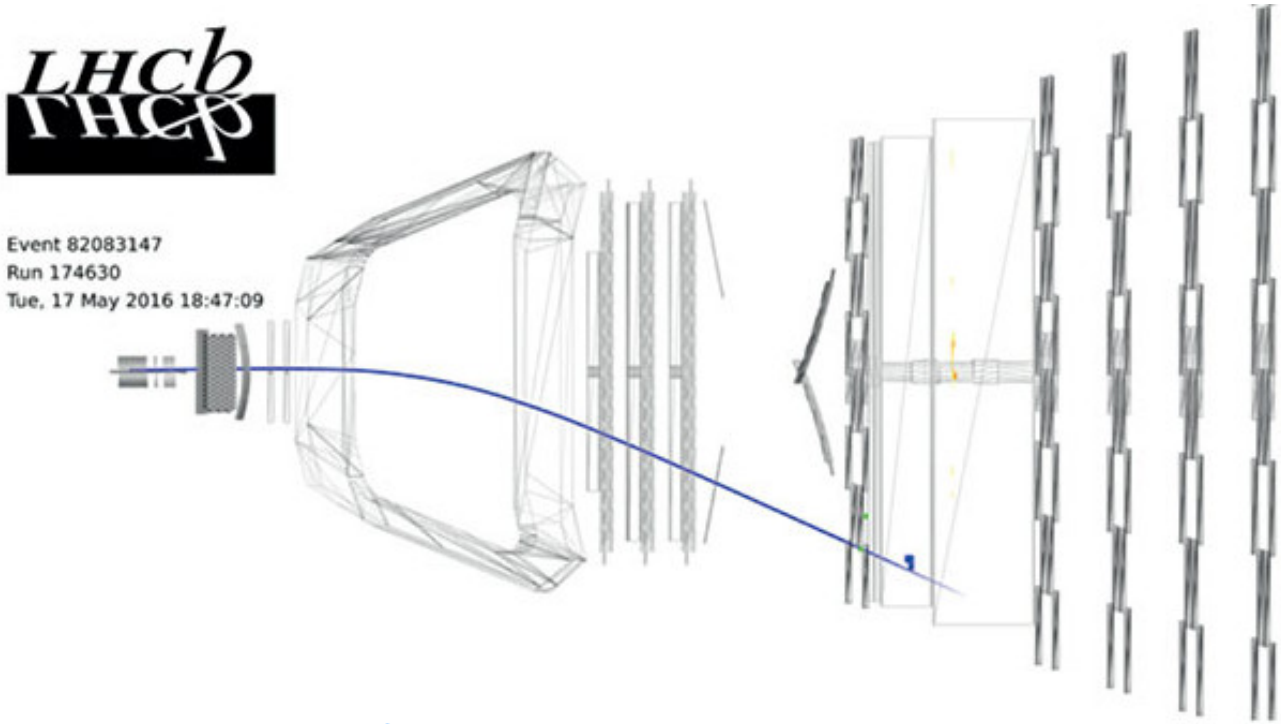
Prompt $\bar{p}$-production in pHe collisions at $\sqrt{s_{NN}} = 110$ GeV



LHCb-PAPER-2018-031, arXiv:1808.06127

- proton beam 1 hits He-gas pressure $O(10^{-7})$ mbar
- $\bar{p}$ momentum: 12-110 GeV/c $\bar{p}$ transverse momentum: 0.4-4 GeV/c
  lower bound: RICH K^--threshold
- prompt: excluding weak hyperon decays
- trigger: activity in scintillator + $\geqslant$ 1 track at software stage
- event vertex: -700$< z <$ 100 mm
- simulation: minimum bias EPOS LHC PRC 92, 034906 (2015)

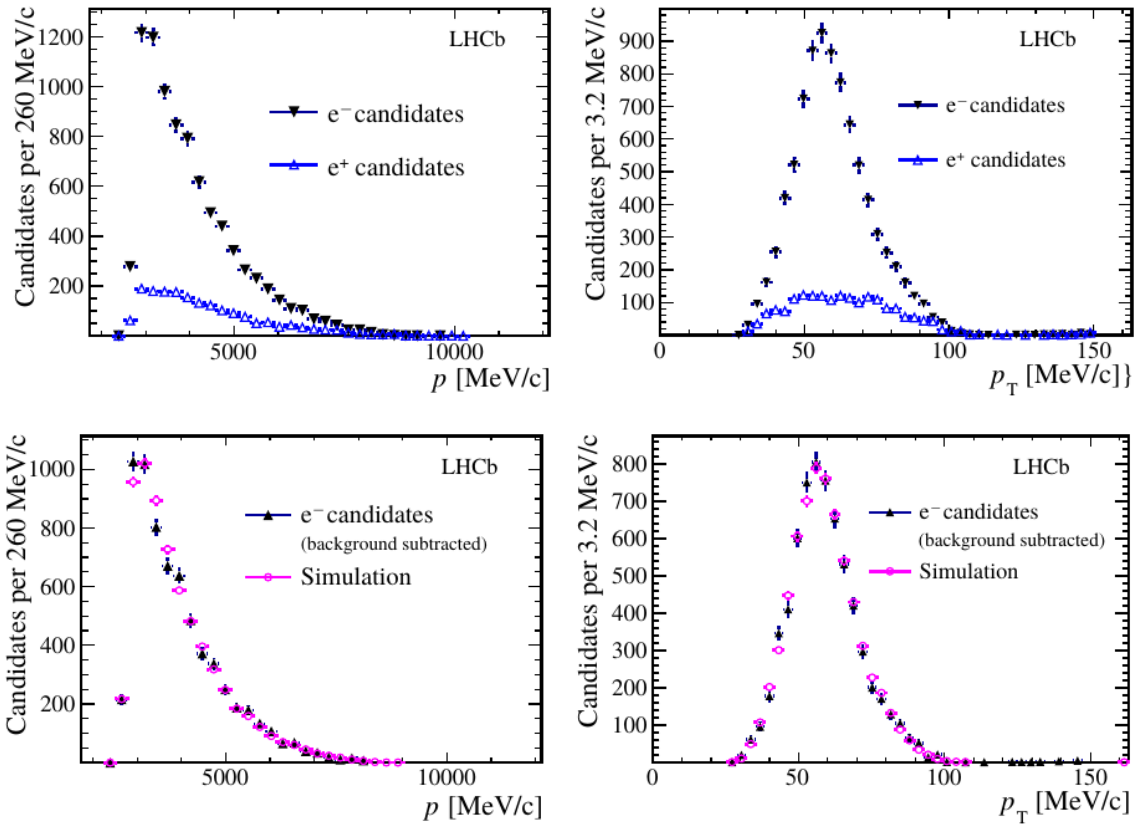
$\bar{p}$-production in pHe collisions: luminosity determination



LHCb-PAPER-2018-031, arXiv:1808.06127

- gas pressure not precisely known
  $\rightarrow$ indirect luminosity measurement
- elastic scattering of proton beam with atomic e^- of He-gas:
  $\rightarrow$ QED and proton form factors
- simulation: ESEPP for e^- scattering J. Phys. G41 (2014) 115001

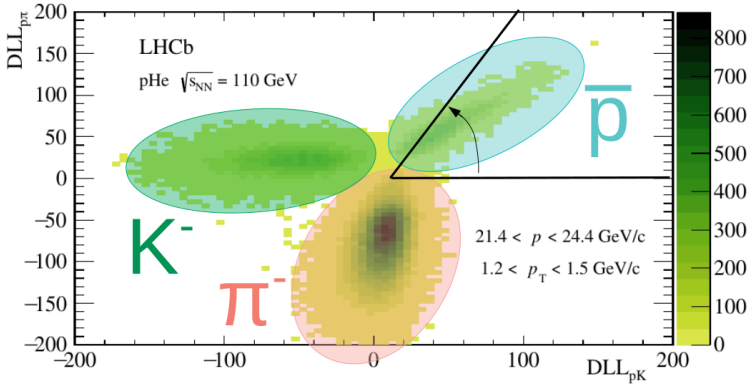
$\bar{p}$-production in pHe collisions: luminosity determination

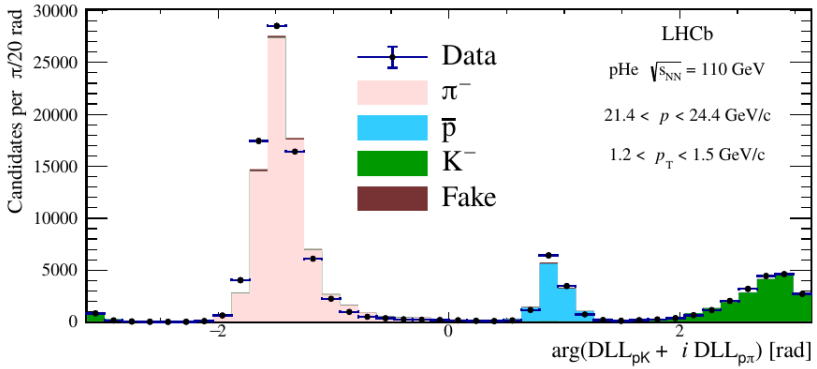


LHCb-PAPER-2018-031, arXiv:1808.06127

- single soft e^- in $11 < \Theta < 21$ mrad: $< \epsilon_{rec} >= 16.3\%$
- loose e^-/e^+-ID via energy in ECal
- background charge symmetric: e^+ as background proxy from data
- BDT-based selection on geometry, kinematics + exclusivity: $\epsilon = 96$ %
- main uncertainty low $< \epsilon_{rec} >$: 5 % relative uncertainty

$\bar{p}$-production in pHe collisions: particle identification

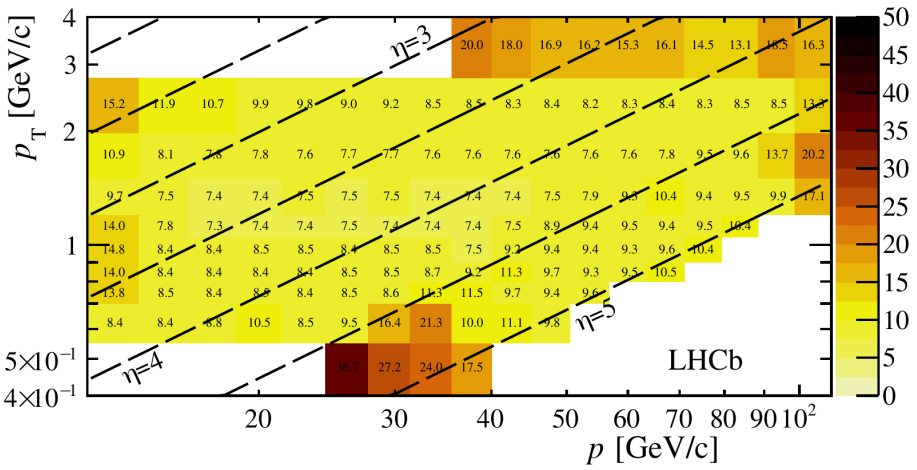




LHCb-PAPER-2018-031, arXiv:1808.06127

- negatively charged tracks: π^-, K^- and $\bar{p}$; 1.7 % fakes (simulation)
- PID with 2 RICH detectors
- 3 set of templates:
  - pHe simulation (default)
  - pHe data: tracks from weakly decaying light-flavour and $\phi \to KK$
  - pp data: as in pHe and D-meson decays
- 2 methods:
  - 2-dimensional binned extended-max. likelihood fit
  - cut & count

Prompt $\bar{p}$-production in pHe collisions: uncertainties

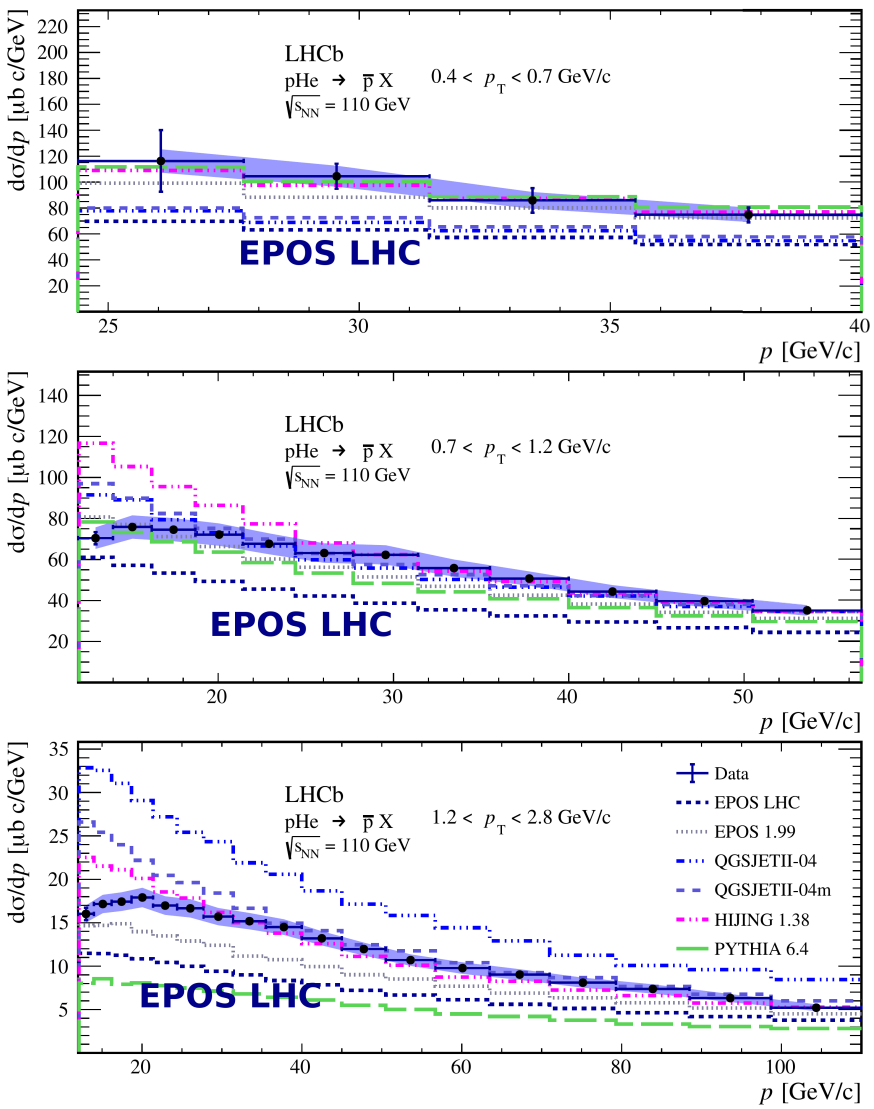


Statistical	
$\bar{p}$ yields	$0.5 - 11\%$ ($< 2\%$ for most bins)
Luminosity	$1.5 - 2.3\%$
Correlated systematic	
Luminosity	6.0%
Event and PV selection	0.3%
PV reconstruction	$0.4 - 2.9\%$
Tracking	$1.3 - 4.1\%$
Non-prompt background	$0.3 - 0.5\%$
Target purity	0.1%
PID	$3.0 - 6.0\%$
Uncorrelated systematic	
Tracking	1.0%
IP cut efficiency	1.0%
PV reconstruction	1.6%
PID	$0 - 36\%$ ($< 5\%$ for most bins)
Simulated sample size	$0.4 - 11\%$ ($< 2\%$ for most bins)

LHCb-PAPER-2018-031, arXiv:1808.06127

- luminosity and PID dominating uncertainties
- **uncertainties below 10%** for most kinematic bins

Prompt $\bar{p}$-production cross section results in pHe collisions



LHCb-PAPER-2018-031, arXiv:1808.06127

EPOS LHC, EPOS 1.99, QGSJET-II, QGSJETII-04m, Hijing, PYTHIA 6.4, ICRC '17: difference summary by T. Pierog

- uncertainties **smaller than model spread**

  differ by hadronisation & parton model+dynamics

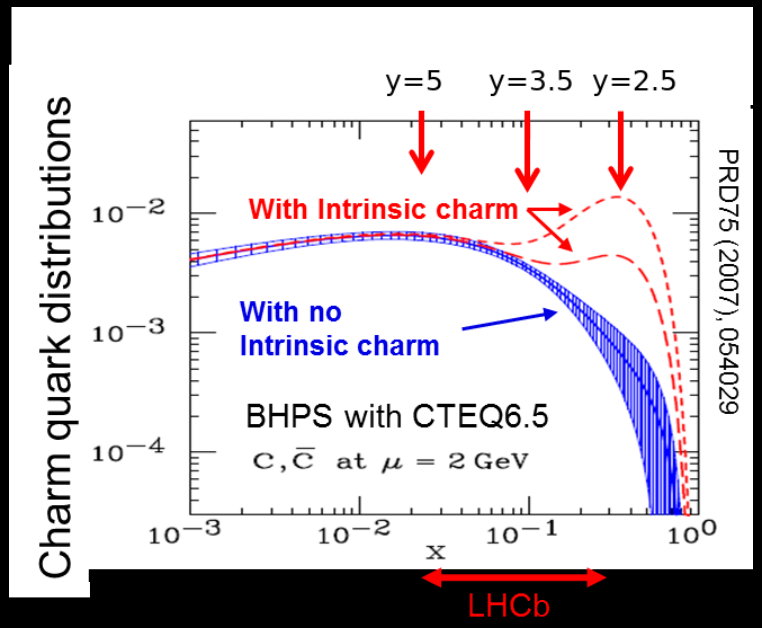
- **EPOS LHC** tuned on LHC collider data **underestimates** $\bar{p}$-production

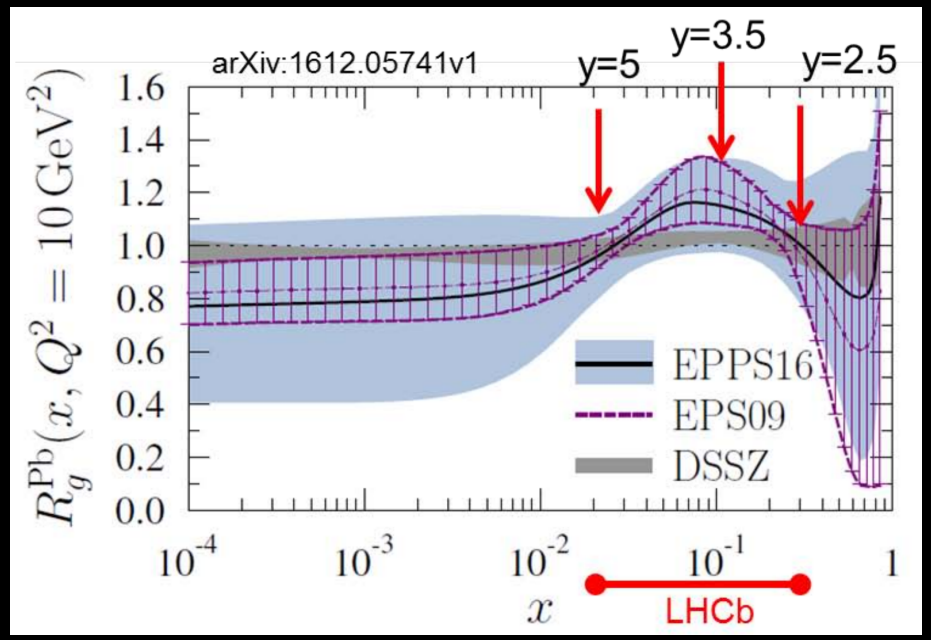
- $\sigma_{vis}^{LHCb} / \sigma_{vis}^{EPOS-LHC}$
  $= 1.08 \pm 0.07(lumi) \pm 0.03(primary\ vertex)$
  $\rightarrow$ discrepancy: $\bar{p}$ yield/event

- **unique and precise**:
  decisive contribution to shrink background uncertainties in dark matter searches in space

- natural pHe extensions:
  - inclusive $\bar{p}$ with hyperon decays
  - charged π, K, p spectra
  - $\sqrt{s_{NN}} = 87$ GeV data

Charm production in fixed-target *p*He and *p*Ar



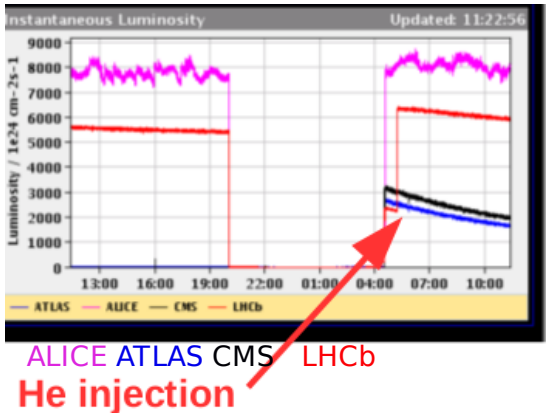


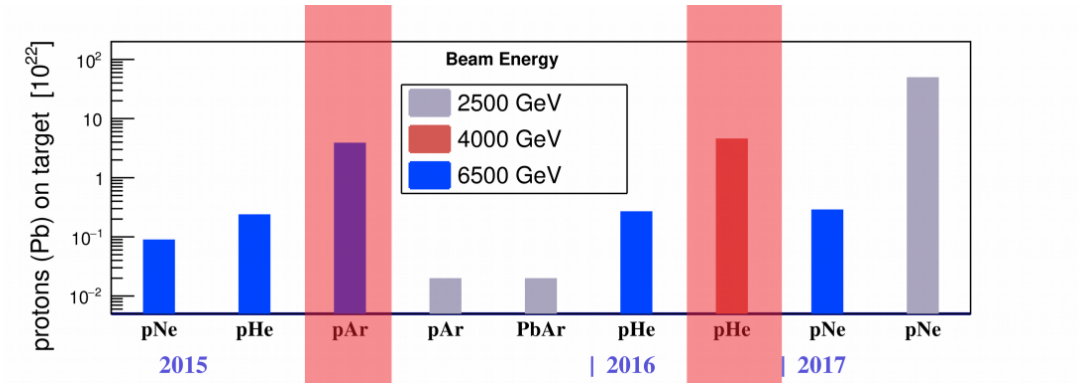
PRD 75 (2007) 054029

EPJC 77 (2017), 163.

- nuclear modification of parton distribution function
- 'valence-like' intrinsic charm via backward rapidity coverage
- reference for future Pb–A fixed target studies for Quark-Gluon Plasma:
  $\rightarrow$ quarkonium suppression patterns and open charm:
  intermediate $\sqrt{s}$ between SPS & top RHIC energy

Charm production in fixed-target configuration: data sets

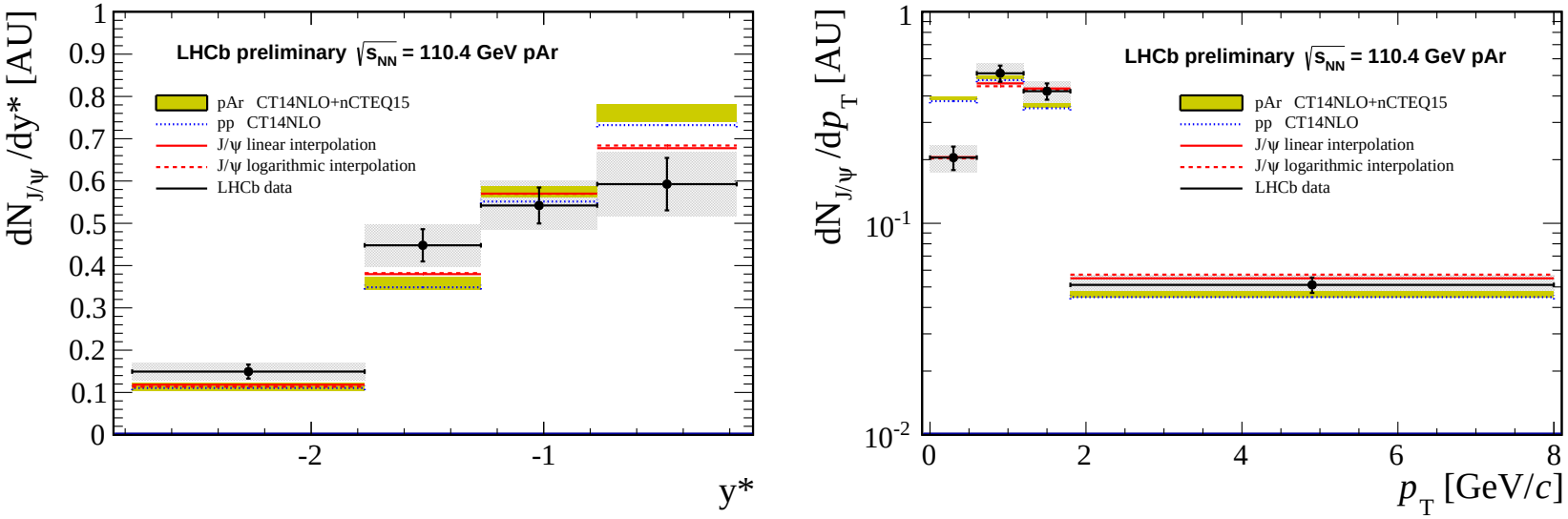




- bridging the gap:
  - Tevatron/HERA fixed-target up to $\sqrt{s_{NN}} = 42$ GeV
  - RHIC at $\sqrt{s_{NN}} = 200$ GeV
- pHe at 87 GeV: luminosity as for 110 GeV $\bar{p}$-analysis
- indirect luminosity not available for 2015 pAr

System	$\sqrt{s_{NN}}$	Protons on target	Target A	L_{int}
pAr	110 GeV	$4 \cdot 10^{22}$	40	-
pHe	87 GeV	$5 \cdot 10^{22}$	4	7.58 ± 0.47 nb^{-1}

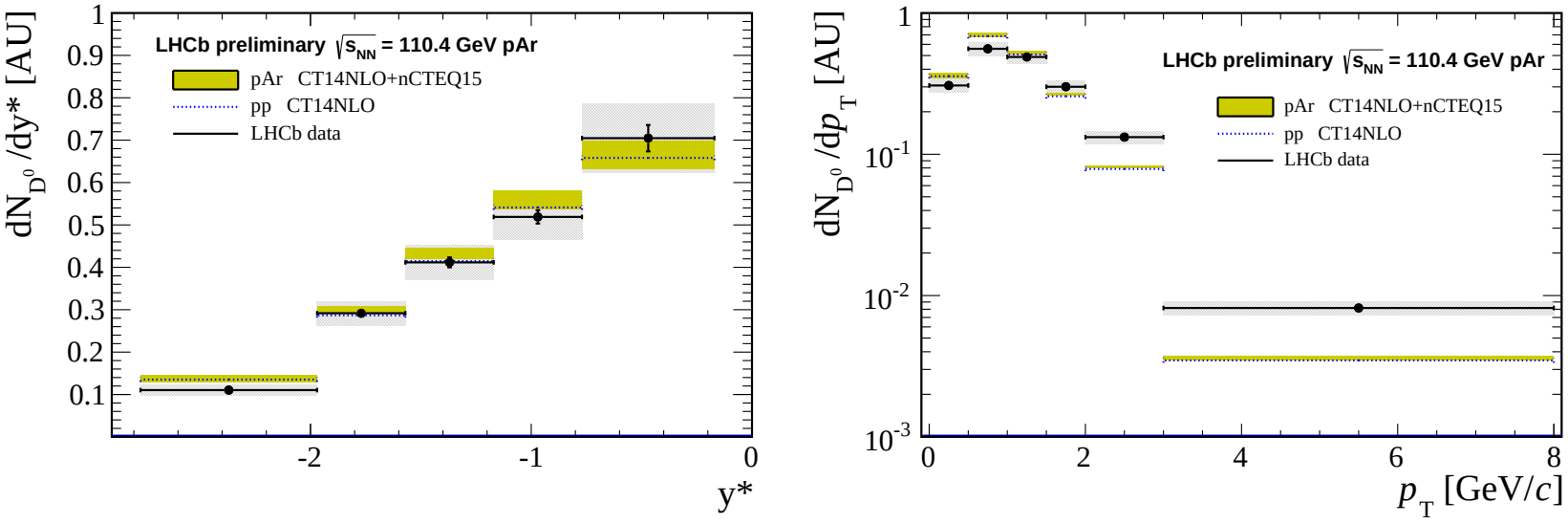
J/ψ production in pAr collisions at $\sqrt{s_{NN}} = 110$ GeV



LHCb-PAPER-2018-022, in preparation.

- backward hemisphere in centre-of-mass probing Bjorken-x: 0.02-0.16
  estimate: $x = 2m_c/\sqrt{s_{NN}} \cdot e^{-y*}$
- shape in agreement for rapidity with phenomenological parametrisation
  JHEP 1303 (2013) 122
- HELAC-onia model EPJC 77 (2017) designed and tuned for collider data
  reasonable for rapidity, not working very well for p_T

D^0 production in pAr collisions at $\sqrt{s_{NN}} = 110$ GeV



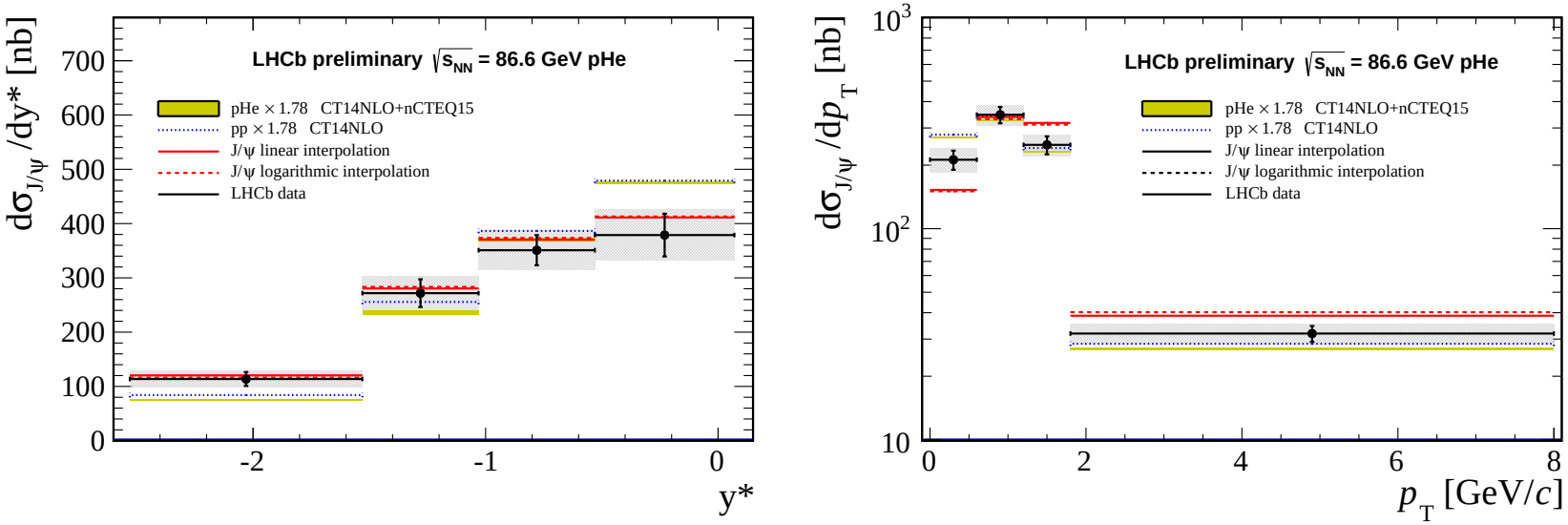
LHCb-PAPER-2018-023, in preparation.

- probing Bjorken-x: 0.02-0.16

  estimate: $x = 2m_c/\sqrt{s_{NN}} \cdot e^{-y*}$

- HELAC-onia model EPJC 77 (2017) designed for collider data reasonable for rapidity, not working very well for p_T

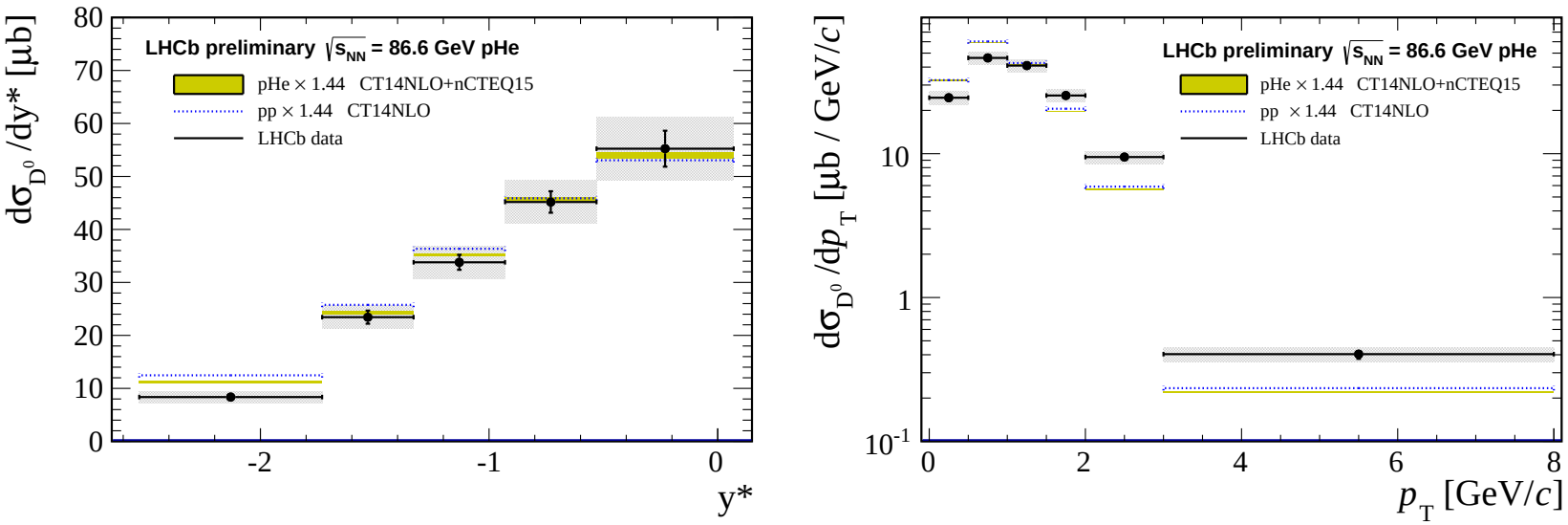
J/ψ production in pHe collisions at $\sqrt{s_{NN}} = 87$ GeV



LHCb-PAPER-2018-023, in preparation.

- probing Bjorken-x: 0.03-0.37
  estimate: $x = 2m_c/\sqrt{s_{NN}} \cdot e^{-y*}$
- in agreement for rapidity, tension for p_T with phenomenological parametrisation JHEP 1303 (2013) 122
- HELAC-onia model designed for collider data reasonable for rapidity, not working well for p_T and requiring scale factor of 1.78 EPJC 77 (2017)

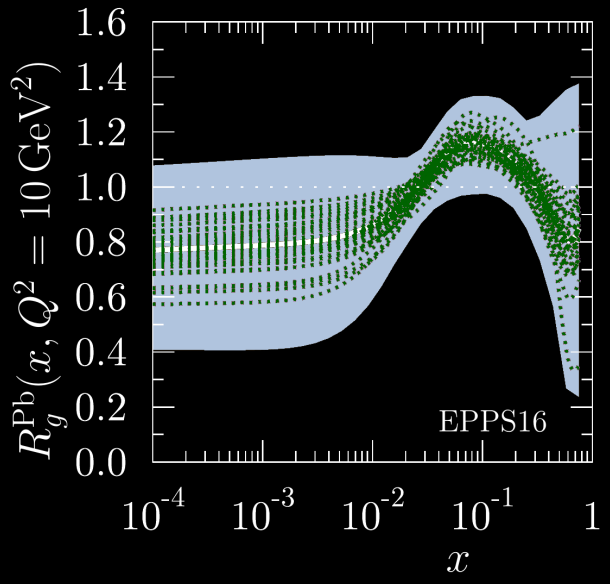
D^0 production in pHe collisions at $\sqrt{s_{NN}} = 87$ GeV

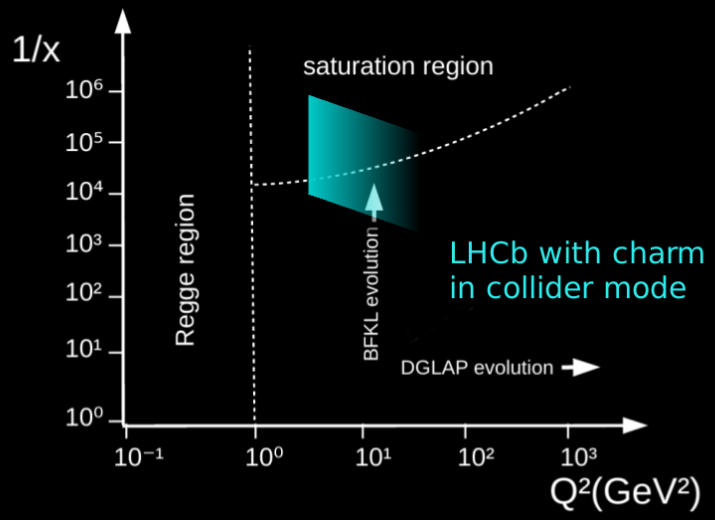


LHCb-PAPER-2018-023, in preparation.

- probing Bjorken-x: 0.03-0.37
  estimate: $x = 2m_c/\sqrt{s_{NN}} \cdot e^{-y*}$
- HELAC-onia model designed and tuned for collider reasonable for rapidity, not working well for p_T and requiring a scale factor of 1.44 EPJC 77 (2017)
- no indication of visible valence-like intrinsic charm in rapidity distribution
- starting point for more detailed p-ion and future ion-ion collisions: open charm & charmonium down to 0 p_T at $\sqrt{s_{NN}} = 69$ GeV on Neon targets

p–nucleus collider: control & limits of collinear factorisation



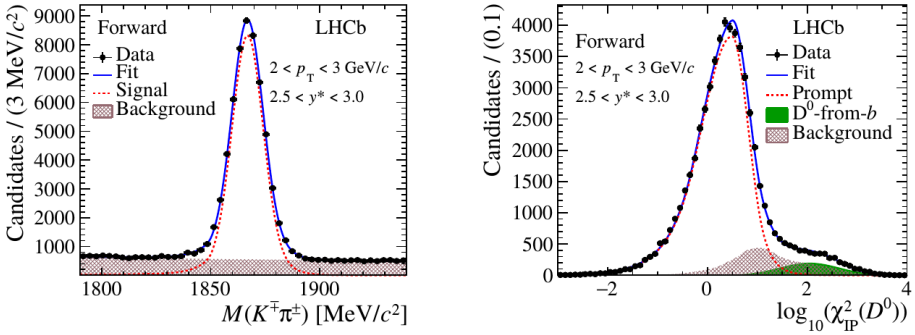


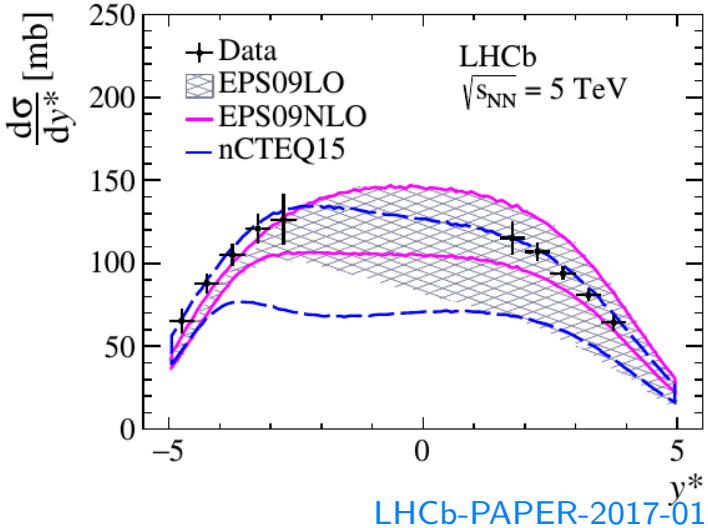
Eur.Phys.J. C77 (2017) no.3, 163 modified from "QCD and collider physics", Ellis, Stirling, Webber

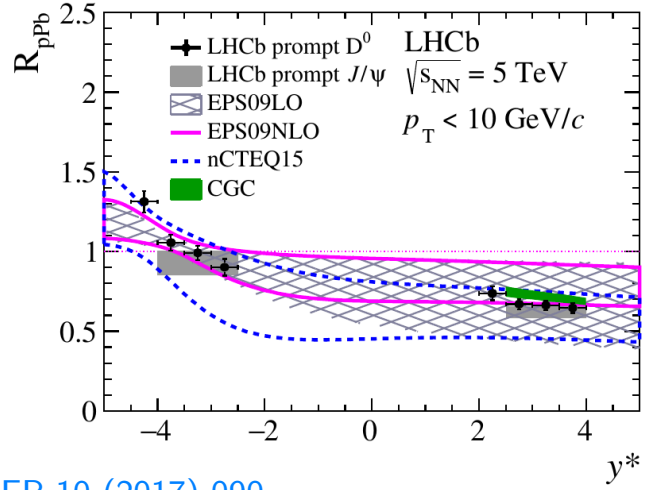
- **no HERA equivalent for lepton-nuclei**:
  partons largely **unconstrained** for LHC heavy-ions
- **saturation** scale $Q_s^2 \propto A_{nucleus}^{1/3}$ $\rightarrow$ linear parton evolution break-down?
  Color glass condensate Ann.Rev.Nucl.Part.Sci.60:463-489,2010?
- Other effects?

  as coherent energy loss by enhanced small-angle gluon radiation JHEP 1303 (2013) 122
- LHCb: forward acceptance + heavy-flavour
  $\rightarrow$ low, but perturbatively amenable Q^2 to reach low-x

D^0 production in pPb collisions at 5.02 TeV: precision data





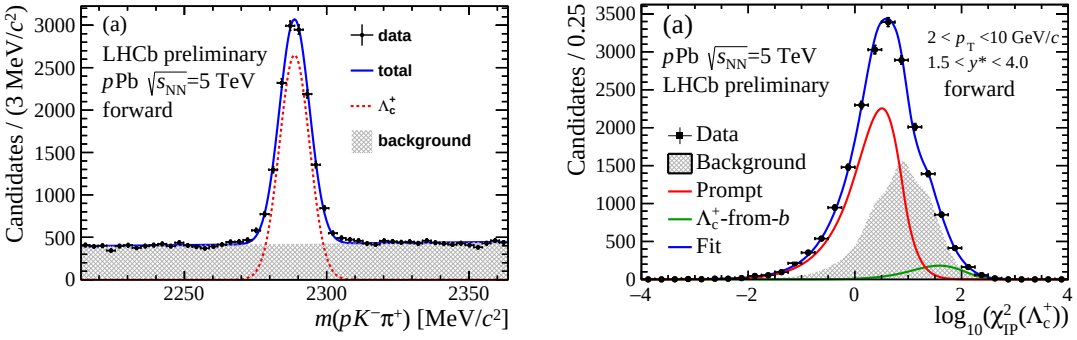


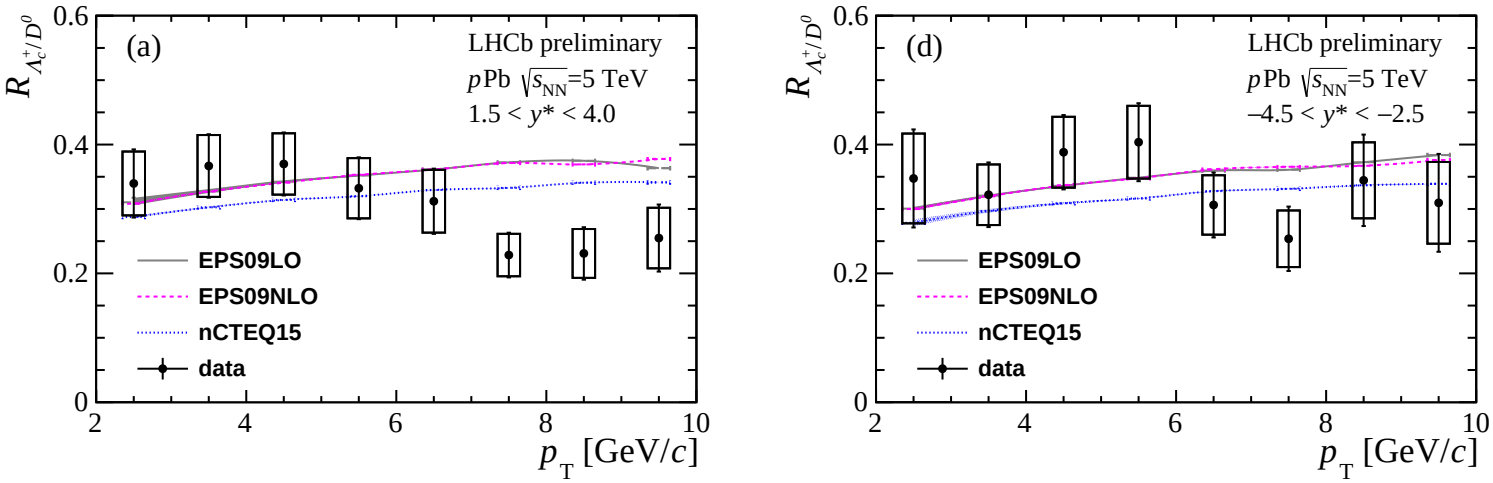
LHCb-PAPER-2017-015, JHEP 10 (2017) 090.

- strong suppression at forward rapidity, modification factor at backward rapidity close to 1, increasing in most backward bins
- nuclear PDFs EPJC 77 (2017) & color glass condensate calculation PRD91 (2015) no.11, 114005 accounting for observations

  coherent energy-loss JHEP 1303 (2013) 122 qualitatively similar expectation
- assuming no other effect:
  constraining nPDFs in unexplored area at low-x, see PRL 121, 052004 (2018)

Λ_c production in pPb collisions at 5.02 TeV: test of charm fragmentation

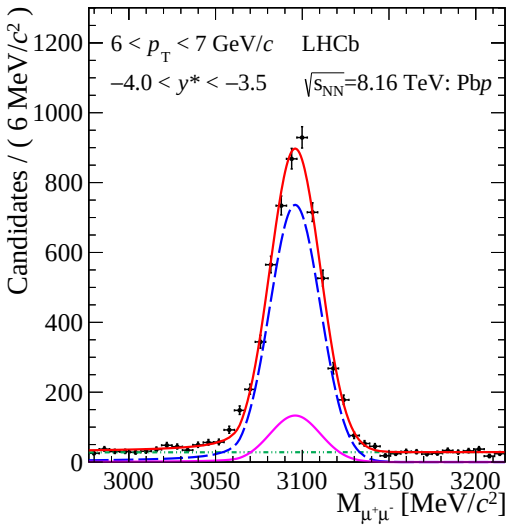


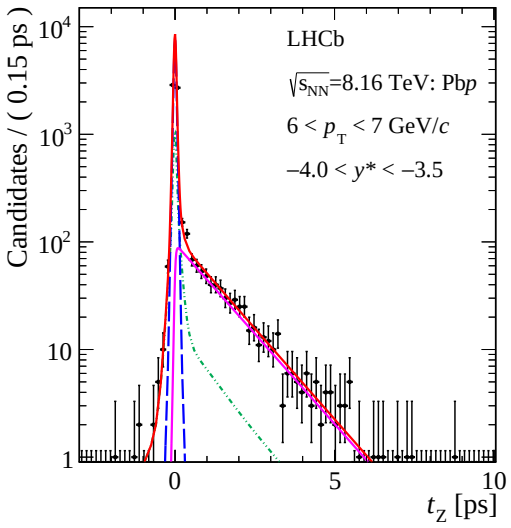


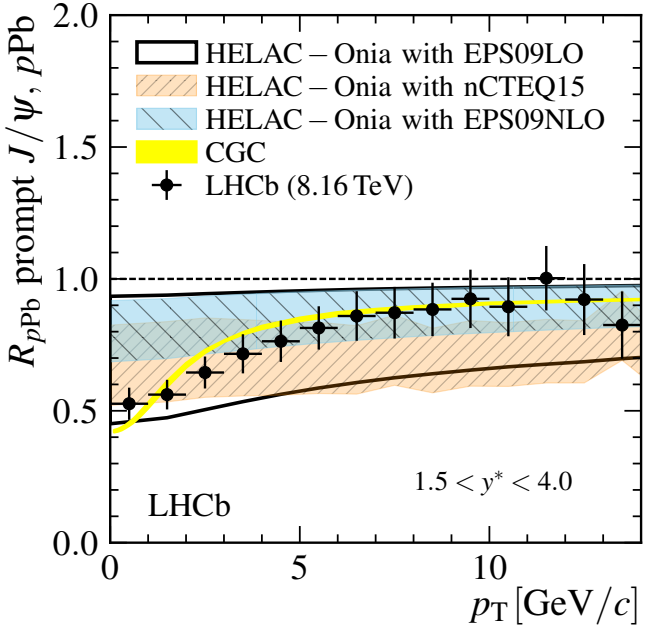
LHCb-PAPER-2018-021, in preparation.

- input for hadronisation phenomenology: crucial comparison with other collision systems
- hadronisation pattern of $c\bar{c}$ similar to model tuned to pp

Prompt J/ψ production in pPb collisions at 8.16 TeV: precision nuclear modification





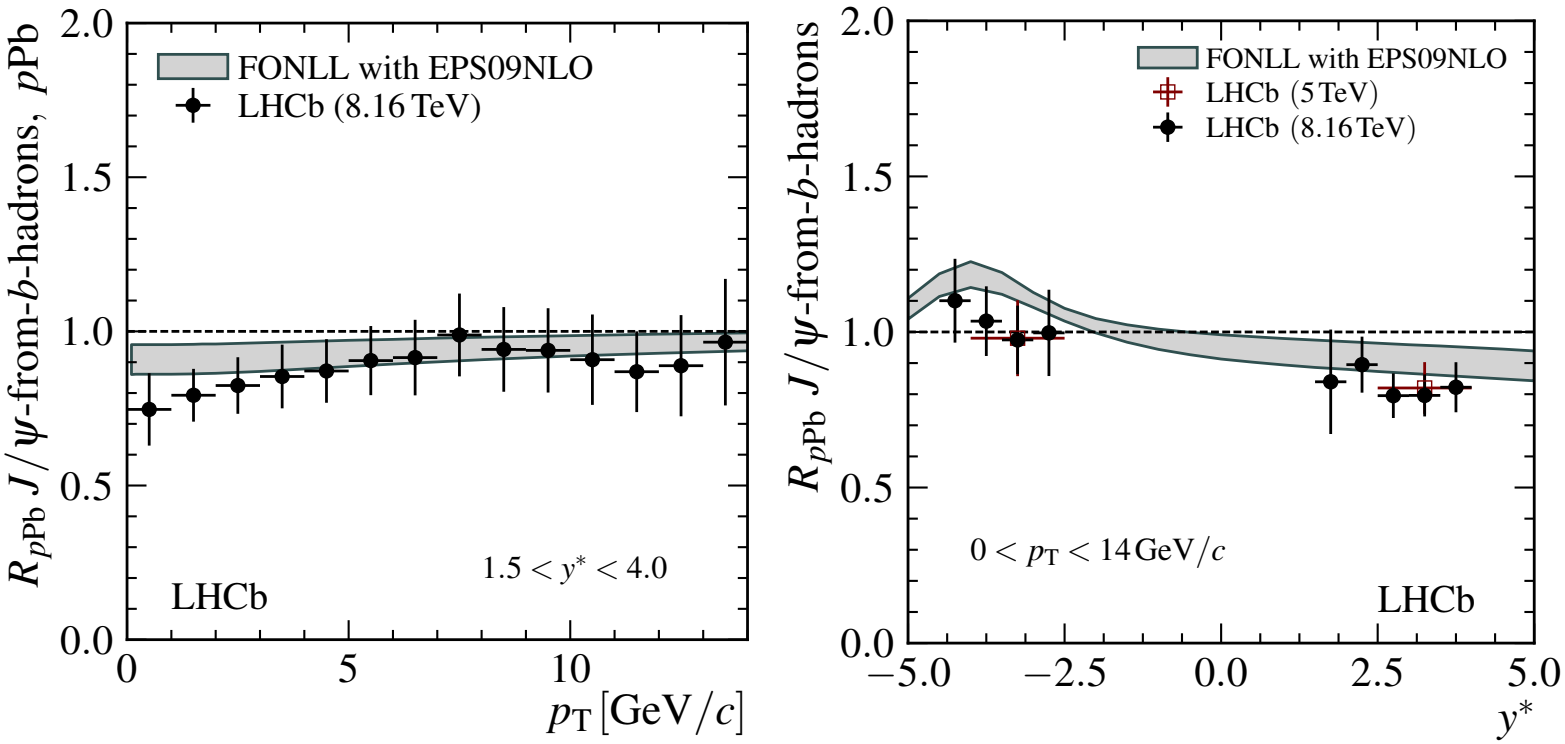


LHCb-PAPER-2017-014,PLB 774 (2017) 159.

- strong suppression at forward rapidity: increasing from 0.5 at lowest p_T reaching 1 at highest p_T
- nuclear PDFs EPJC77 (2017) 1 & Color Glass Condensate calculations PRD91 (2015) no.11, 114005 accounting for observations

  coherent energy-loss JHEP 1303 (2013) 122 accounting for rapidity dependence
- assuming no other effect:
  constraining nPDFs in unexplored area at low-x, see PRL 121, 052004 (2018)

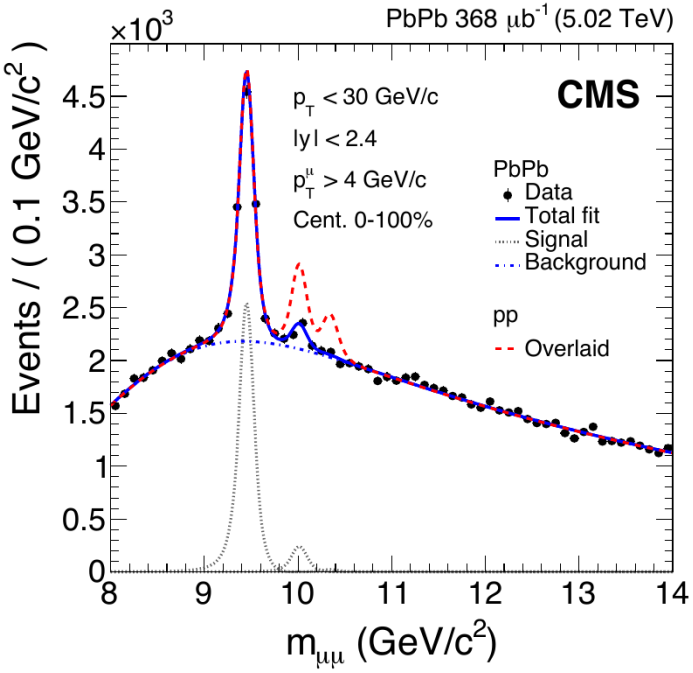
Non-prompt J/ψ production in pPb collisions at 8.16 TeV: precision data on beauty



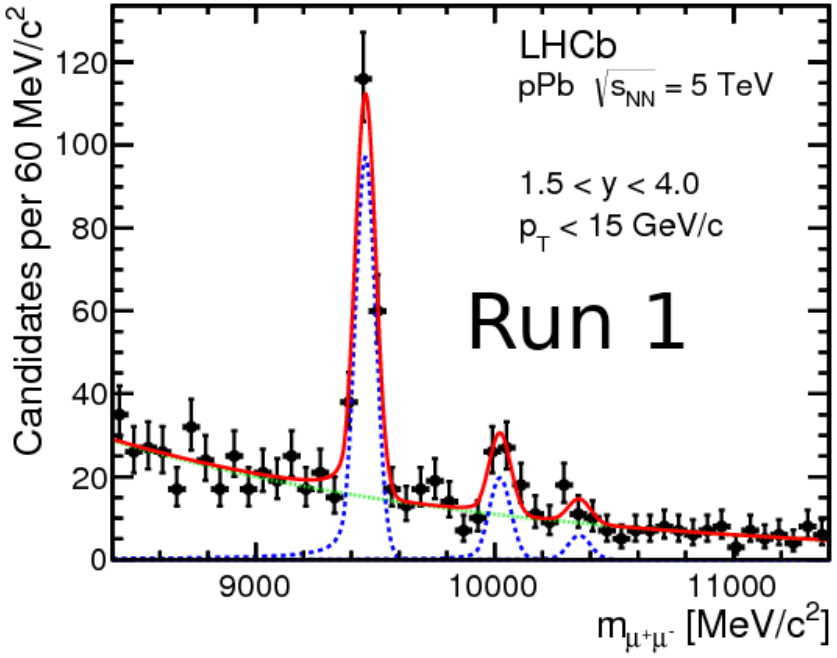
LHCb-PAPER-2017-014, PLB 774 (2017) 159.

- suppression at forward rapidity, modification factor at backward rapidity close to 1
- first precise b-production measurement in pPb down to 0 p_{T}
- crucial input for PbPb phenomenology
- assuming no other effect:
  constraining nPDFs in unexplored area at low-x, see PRL 121, 052004 (2018)

Υ(nS) in heavy-ions: probe of deconfinement



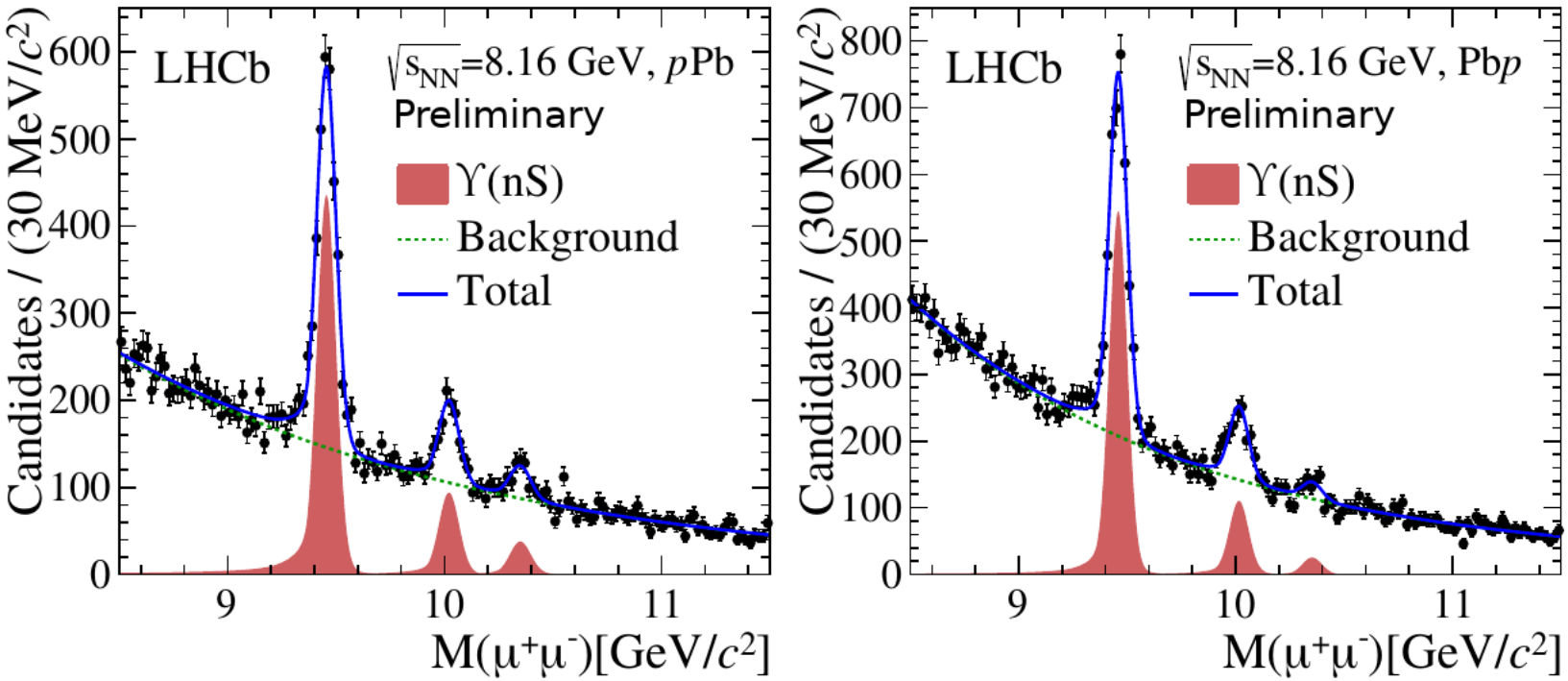
PRL 120 (2018) 142301



LHCb-PAPER-2014-015, JHEP 1407 (2014) 094

- quarkonium: QCD hydrogen atom $\rightarrow$ probe deconfinement in PbPb
- Υ(nS) suppression patterns in PbPb by CMS and ALICE
- observed additional suppression of ψ(2S) and Υ(2S,3S) at low-p_T also in pPb/Pbp by LHC collaborations in Run 1
- LHCb Run 1 Υ(nS) in pPb/Pbp statistically limited

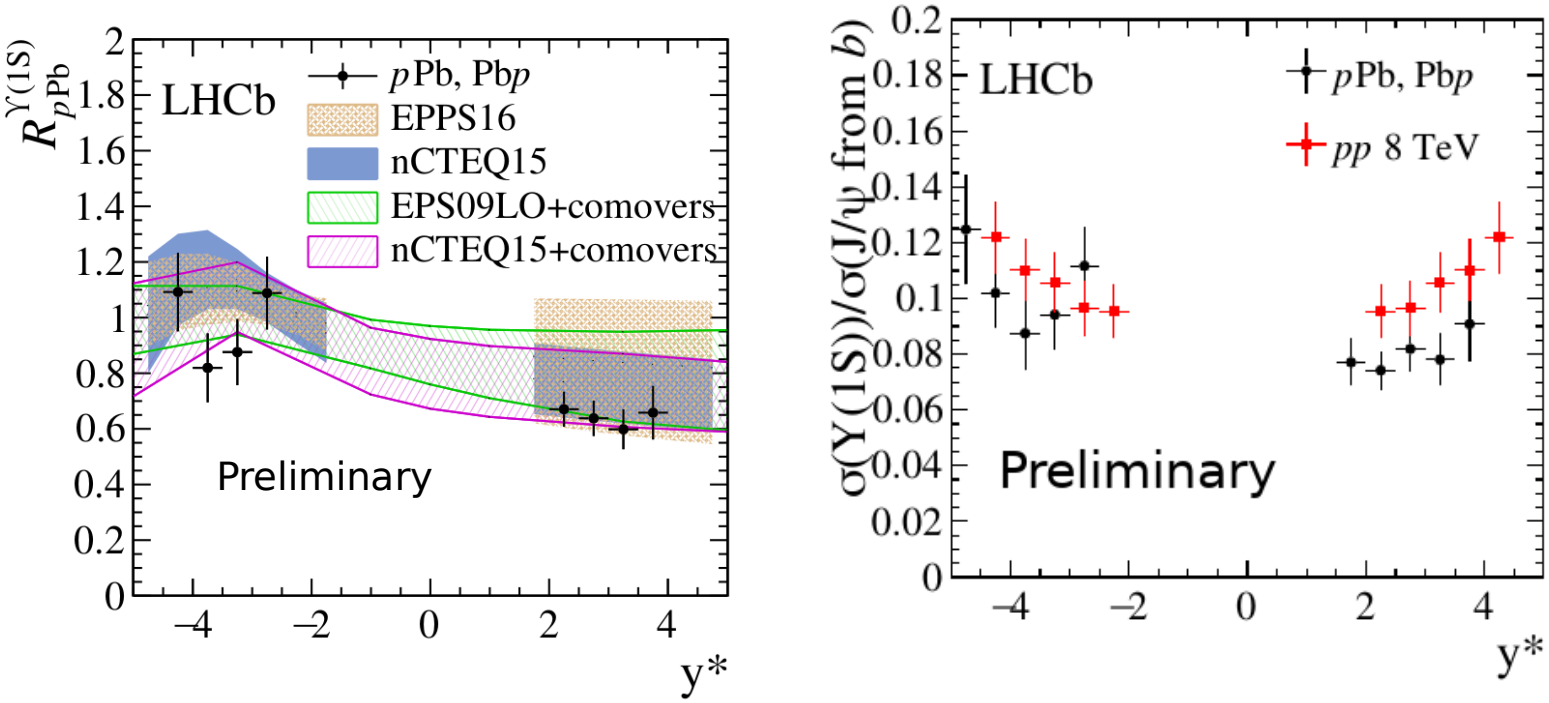
Υ(nS) production in pPb and Pbp collisions with LHCb



LHCb-PAPER-2018-035, in preparation.

- LHCb: factor 20 more luminosity in 2016 than in Run 1 to scrutinize the situation
  $\rightarrow$ fully profitting thanks to resolution and excellent μ-PID

$\Upsilon(1S)$ in pPb and Pbp collisions at $\sqrt{s_{NN}} = 8.16$ TeV



LHCb-PAPER-2018-035, in preparation.

- $\Upsilon(1S)$: suppressed forward, compatible with unity backward $\rightarrow$ within nPDF uncertainties
- p_T-integrated $\Upsilon(1S)/J/\psi$-from-b similar in pp & in pPb/Pbp:
  $\rightarrow$ naive approximate expectation in pure nuclear PDF & coherent energy-loss
  $\rightarrow$ 'additional' suppression limited for ground state
  $\rightarrow$ new observable:
  proxy for 'natural' normalisation by total $b\bar{b}$ with same final state

Υ(nS) suppression patterns in pPb and Pbp collisions at $\sqrt{s_{NN}} = 8.16$ TeV

$$R(p\mathrm{Pb}/pp)[\Upsilon(2S)] = 0.86 \pm 0.15$$

$$R(p\mathrm{Pb}/pp)[\Upsilon(3S)] = 0.81 \pm 0.15$$

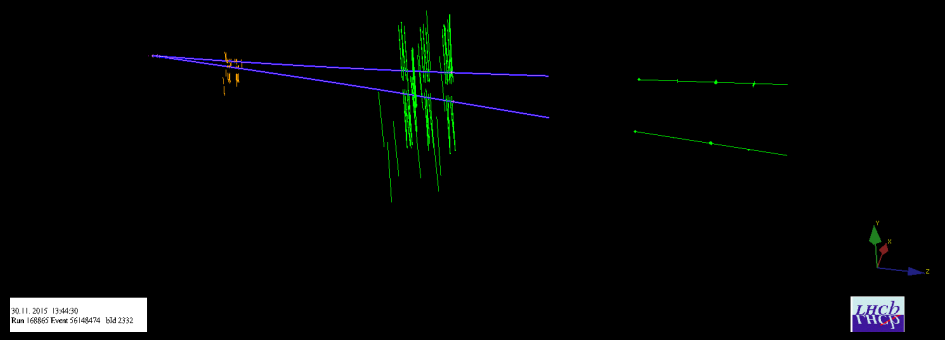
$$R(\mathrm{Pb}p/pp)[\Upsilon(2S)] = 0.90 \pm 0.21$$

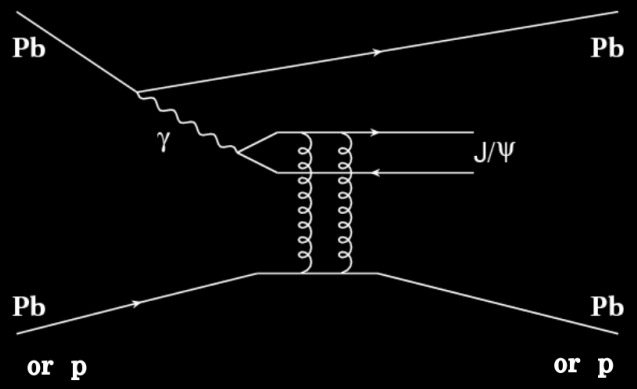
$$R(\mathrm{Pb}p/pp)[\Upsilon(3S)] = 0.44 \pm 0.15$$

LHCb preliminary LHCb-PAPER-2018-035, in preparation.

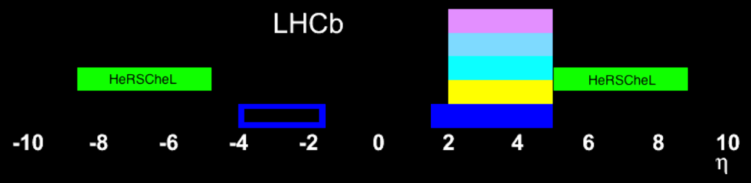
- additional suppression of excited states observed in inclusive collisions: significant for $\Upsilon(3S)$ in Pbp
  $\rightarrow$ factorisation with respect to final state broken
- in qualitative agreement with models invoking late time interactions in pPb/Pbp
  PLB749 (2015) 98-103, NPA 943 (2015) 147-158, PRC 97, 014909 (2018)
- comprehensive understanding: ingredient for ion-ion collisions
  $\rightarrow$ upcoming prompt ψ(2S) LHCb measurement at 8.16 TeV will contribute

Ultra-peripheral PbPb collisions: γ-probe of the nucleus



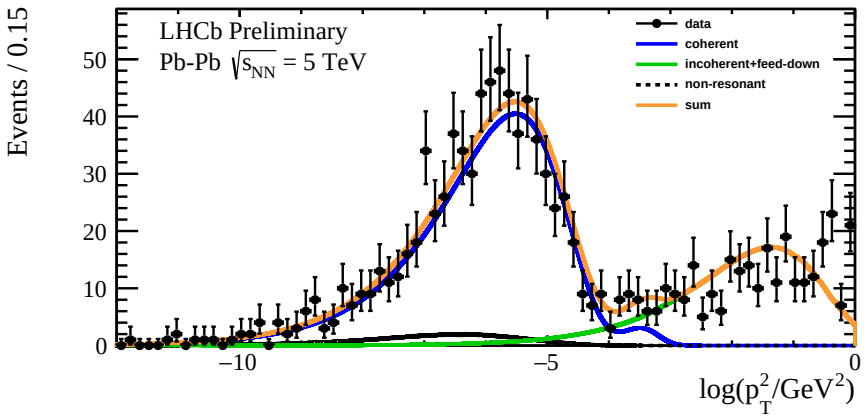


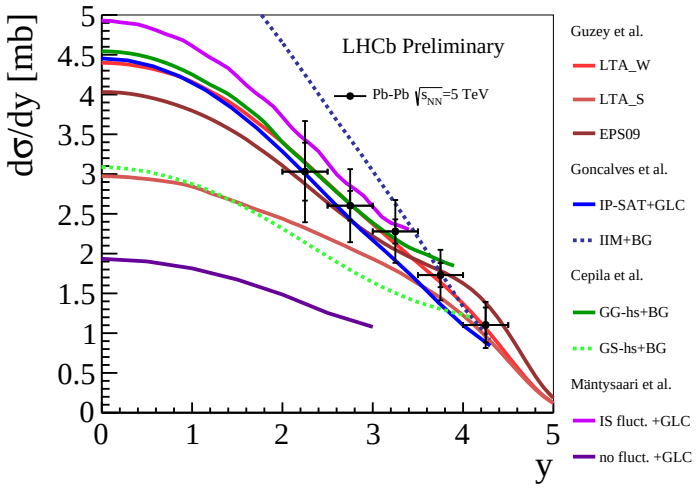
- exclusive vector meson production via γ-pomeron scattering
- sensitive to generalised gluon distributions for Bjorken-$x \in 10^{-2}$-10^{-5}
- for small $q\bar{q}$ at leading twist, leading $\ln(1/x)$, t$\rightarrow$0: $\sigma \propto$ (gluon PDF)^2
  PRD50 (1994) 3134-3144
- LHCb well suited for exclusive production studies with Pb-beams: resolution, PID & very forward detector HerSCheL



- LHCb experience: unique γ-p production studies in pp with quarkonium
  LHCb-PAPER-2018-011, arXiv:1806.04079; JHEP 1509 (2015) 084, LHCb-PAPER-2015-011; J. Phys. G41 (2014) 055002, LHCb-PAPER-2013-059; J. Phys. G40 (2013) 045001, LHCb-PAPER-2012-044

Ultra-peripheral PbPb collisions at 5.02 TeV: first J/ψ results

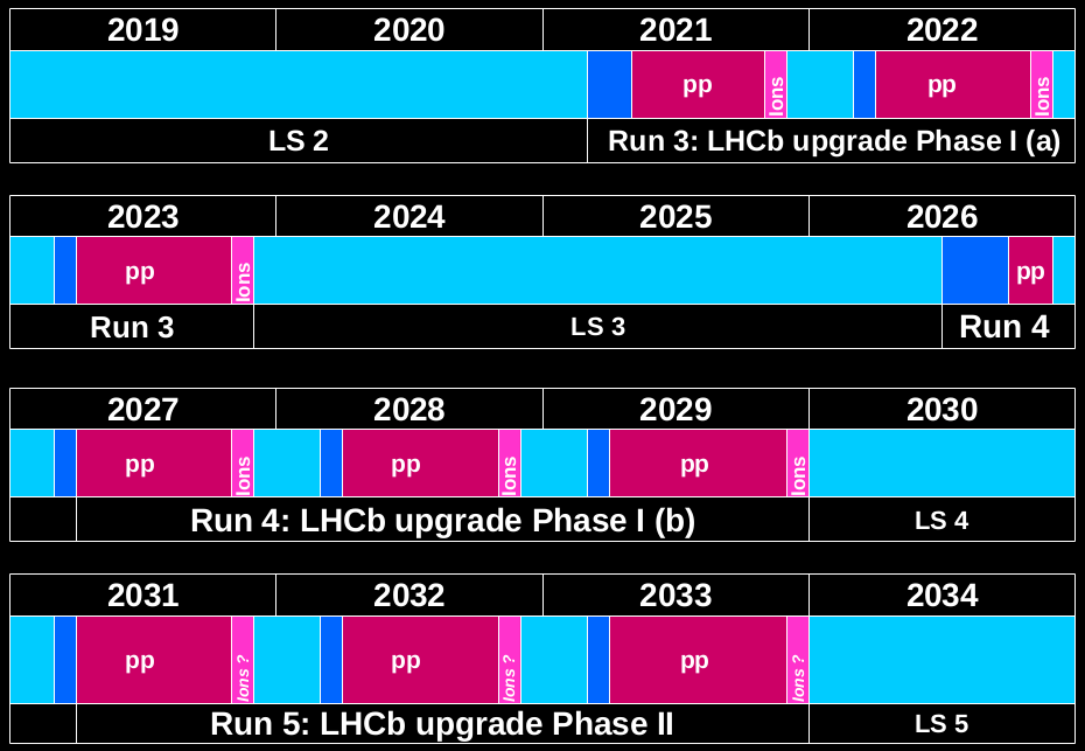




LHCb-CONF-2018-003.

- coherent J/ψ production can be well separated from incoherent part
- covered rapidity range and precision constraining model space:
  Cepila et al. PRC 97 024901 (2018), Goncalves et al.: PRD 96, 094027 (2017) Guzey et al.: PRC 93, 055206 (2016), Mäntysaari, PLB 772 (2017) 832-838
- heavy-ions: Mäntysaari-Schenke requires fluctuations to describe data as for v_n coefficients from particle correlations in pPb collisions
- final publication: include HerSchel information
- 2018 data waiting with 10$\times$ larger luminosity and exploiting other final states in exclusive γ-induced reactions

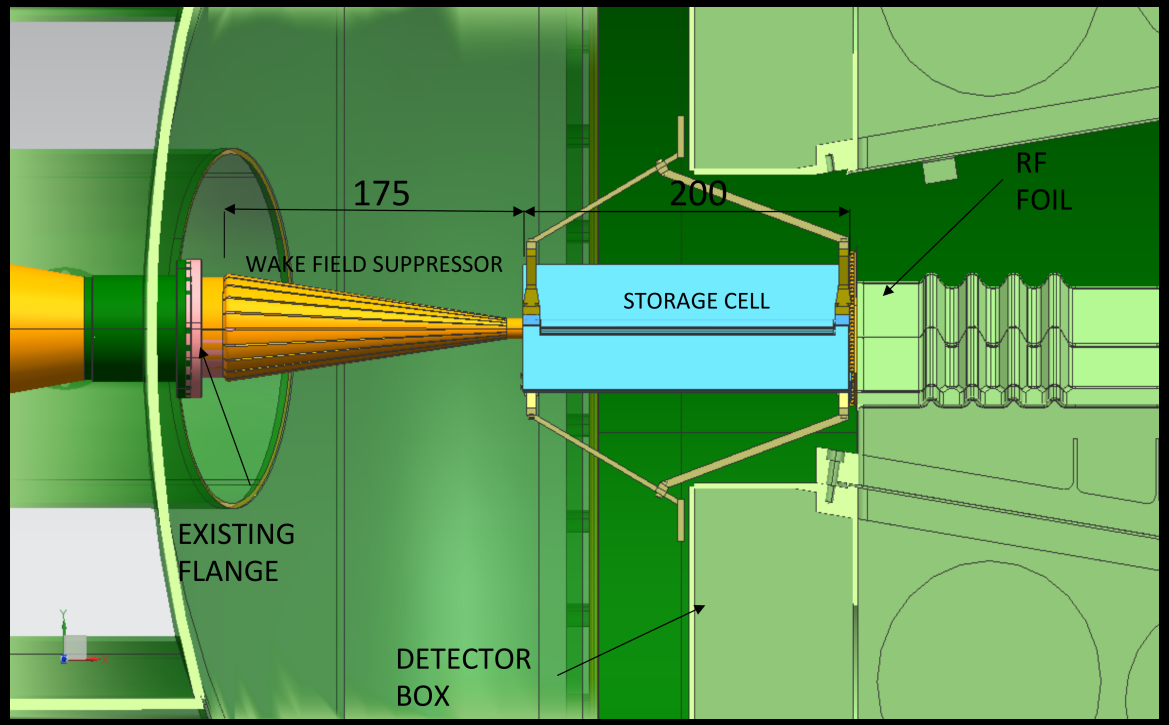
Outlook collider



- heavy-ion Run 2 data started to be exploited:
  $\rightarrow$ largest heavy-flavour statistics in pPb, forward acceptance & PID
- Phase I: $\approx 5 \times L_{inst}$(Run II) in pp LHCB-TDR-12 – 17
  - extend ion-ion capabilities
  - increase pA luminosity for low-x sector
- Phase II in design phase: $\approx 50 \times L_{inst}$(Run II) in pp
  $\rightarrow$ dream detector for heavy-ion physics

Physics case for an LHCb Upgrade II; CERN-LHCC-2018-026; LHCB-TDR-019

Outlook fixed target



- pNe data sample from 2017: $\approx 10 \times p\mathrm{He}/p\mathrm{Ar}$
- large PbNe sample in 2018
- Run 3: plan for storage cell upstream, allow for non-noble gas targets, in particular H^2 and D^2 as references
- 10-100 $\times$ larger instant. luminosity per unit length
- upgrades with crystal target for c-quark MDM, EDM
  polarised target further upstream & wire targets under discussion

Conclusions:
LHCb as versatile lab for heavy-ion & fixed-target collisions

- **fixed-target pHe**:
  reference for direct cosmic ray $\bar{p}$ measurements

  - uncertainties mostly < 10 %: improve baseline for darkmatter searches

- **fixed-target pA**:
  high-x tests: intrinsic charm & gluon pdfs at low scales

  - y & p_T-distributions with D^0 & J/ψ at backward y with A=4/40: y-dependence reproduced by models

- **pPb and PbPb collider**:
  tests of low-x with perturbative probes in gluon and γ-induced reactions

  - nuclear suppressions in pPb: up to 50% at low-p_T in pPb forward with charm and 20-30% for beauty
  - $d\sigma/dy$ of coherent J/ψ-production in PbPb collision constraining models

  test heavy-flavour bound state hadronisation & fragmentation down to low-p_T with Λ_C and Υ(nS)

Conclusions:
LHCb as versatile lab for heavy-ion & fixed-target collisions

A precision experiment at low/moderate Q^2:

Unique acceptance at a hadron collider
- the world of colour charges & hadrons

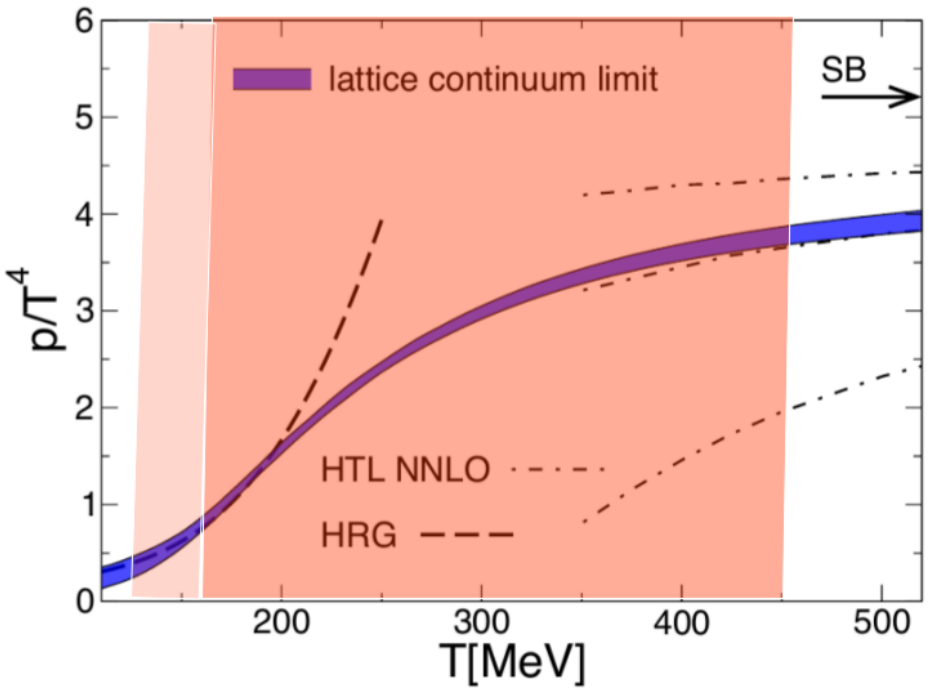
A chance:

- to measure soft QCD
- to probe the partonic content of nucleons and nuclei
- to investigate QCD many body systems

Thanks a lot for two exciting years!

Back-up

Heavy-ion collisions at the LHC as a probe of QCD matter



T-range probed at the LHC according to hydrodynamic models
PLB 370 (2014), T-range from PRC 89, 044910 (2014)

p/T^4: pressure over temperature^4

HRG: Hadron Resonance Gas

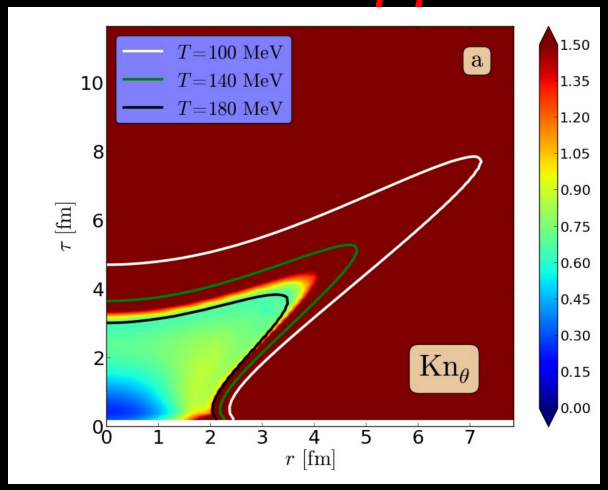
HTL: Hard thermal loop

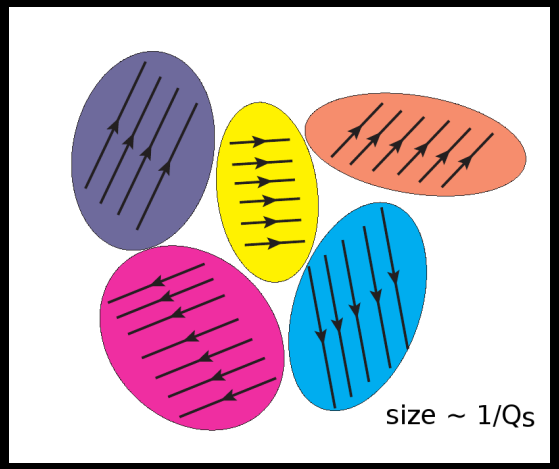
SB: Stefan-Boltzmann limit of non-interacting quarks and gluons

The QCD many-body system in the lab: nucleus-nucleus collisions

- measure equilibrium properties:
  deconfinement, chiral restoration, thermodynamic&transport properties
- quantify QCD properties:
  QCD radiation, hadronisation, phase transition characteristics
- understand non-equilibrium dynamics and relation to equilibrium

p-nucleus and pp as a test of the heavy-ion paradigm





Left: arXiv:1404.7327 $Kn = L_{micro}/L_{macro}$. Right: arXiv:1611.00329

- correlations & bulk production@low-p_{T} & large multiplicity: **'same' patterns as in PbPb** where assumption of local thermalisation
- **hydro** in large multiplicity pPb: set-up as in PbPb **describing data** despite **precondition doubts** PLB772 (2017) 681-686
- role of kinetic theory: to be quantified arXiv:1805.04081
- debate on saturation explanations of observed anisotropies arXiv:1808.01276 arXiv:1805.09342
- alternative: string interactions PLB779 (2018) 58-63
- LHCb: acceptance + heavy-flavour as hard scale: ideal testing ground