LHCb Heavy-ion results

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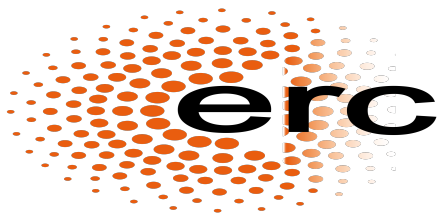
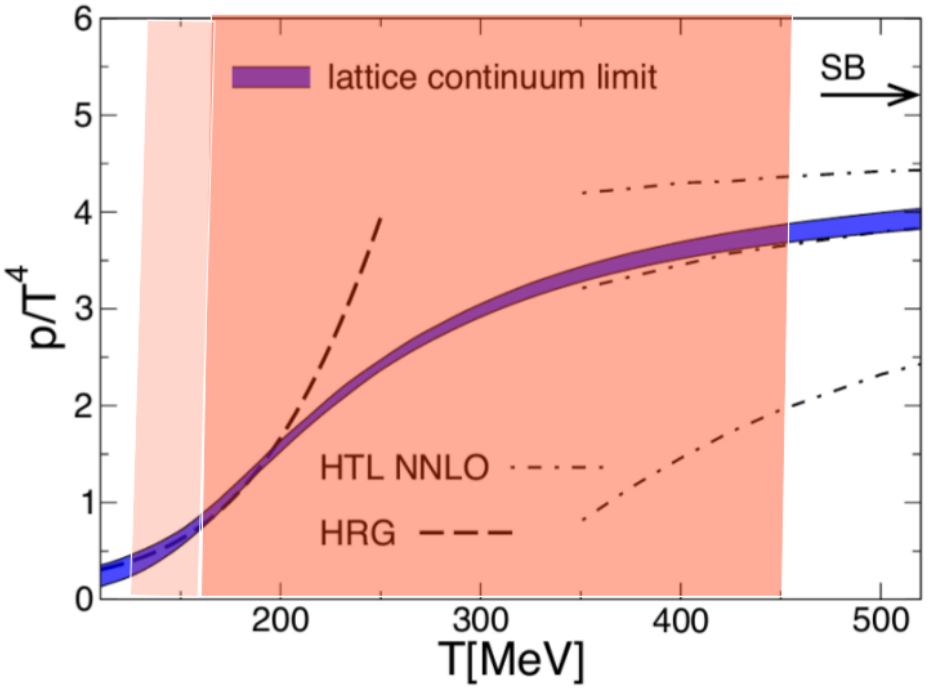


Étretat, 09.10.2017

Outline

- Introduction
- PbPb plans
- pPb results and plans
- Conclusions

QGP physics at the LHC



T-range probed at the LHC according to hydrodynamic models

Figure taken from PLB 370 (2014), T-range from PRC 89, 044910 (2 014)

p/T^4: pressure over temperature^4

HRG: Hadron Resonance Gas

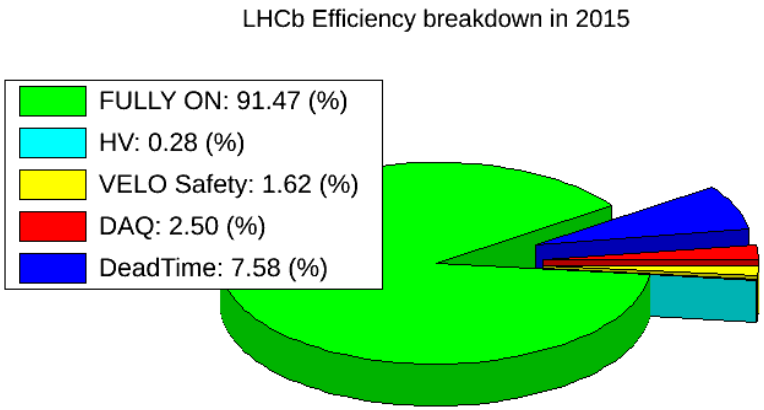
HTL: Hard thermal loop

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

- 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

$\rightarrow$ What can LHCb contribute in AA and *p*A collisions?

LHCb in PbPb collisions at $\sqrt{s_{NN}} = 5$ TeV

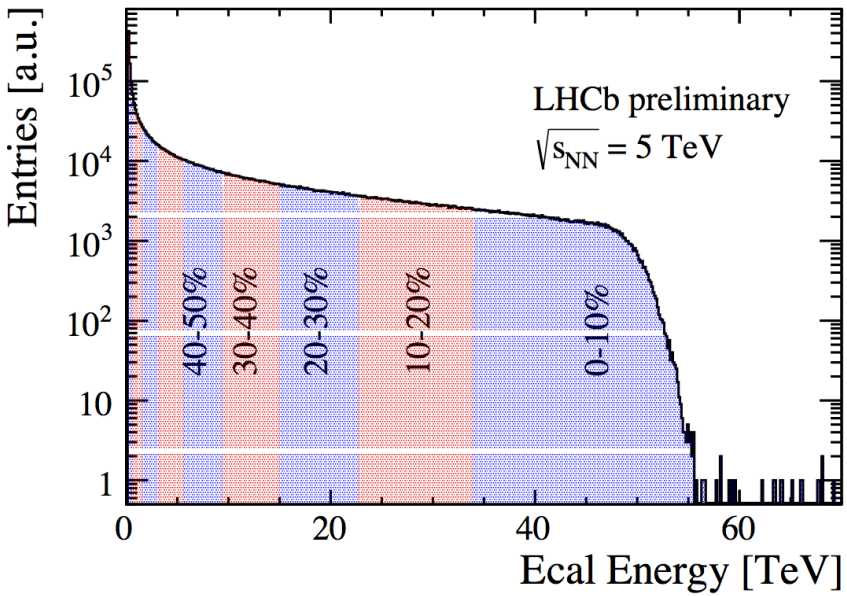


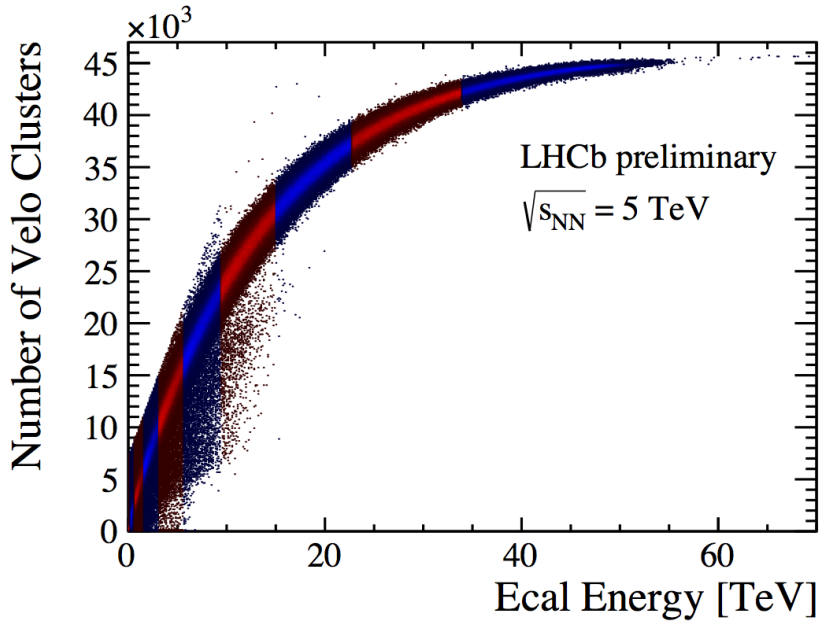
Experiment	2015 PbPb
ALICE central	150 mio MB evts. (0.02 nb^{-1})
ALICE muon	0.225 nb^{-1} analysed
CMS	0.464 nb^{-1} analysed
ATLAS	0.515 nb^{-1} analysed
LHCb	50 mio MB evts., 50-100% tracking

modified version in arXiv:1609.01135, references therein.

- 2015 first data taking in most challenging environment for LHCb
- competitive data sample for soft probes and charm in terms of event statistics in unique acceptance
- very soft trigger requirement:
  $\rightarrow$ combined with LHCb PID capability: unique sample at the LHC!

LHCb in PbPb collisions: centrality reach

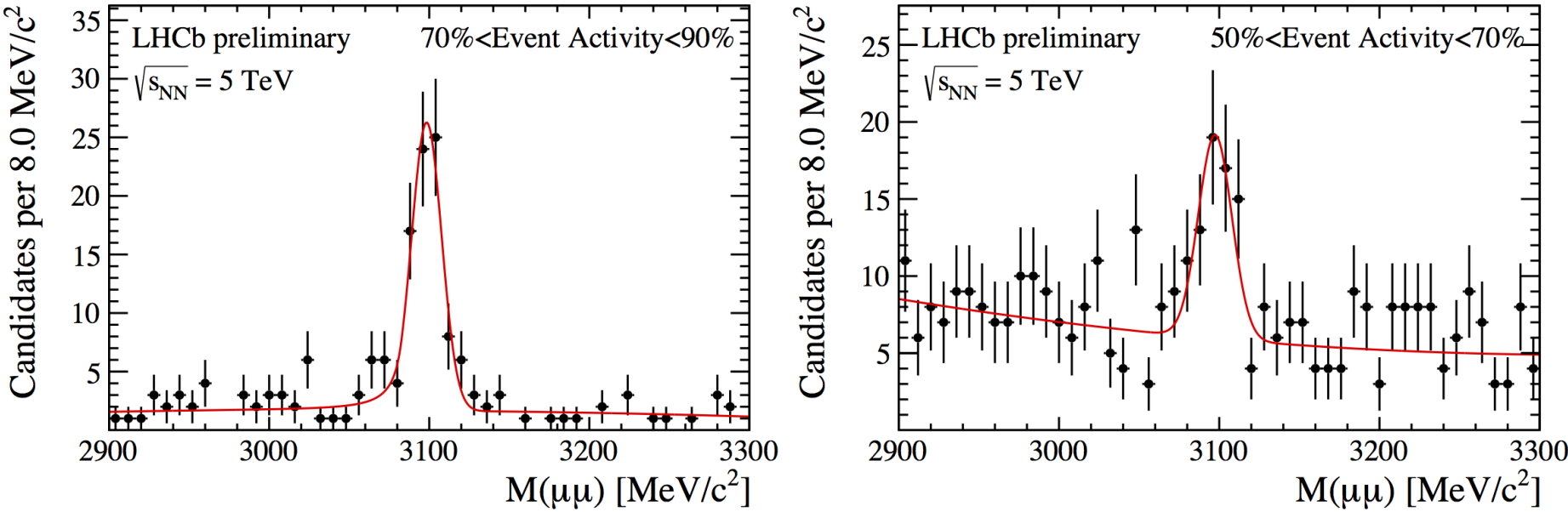




PbPb performance figures: https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015

- designed for low pile-up pp collisions: running in pp at $\mu \approx 1$
- occupancy limitation in PbPb collisions:
  current tracking algorithms up to 50% in centrality

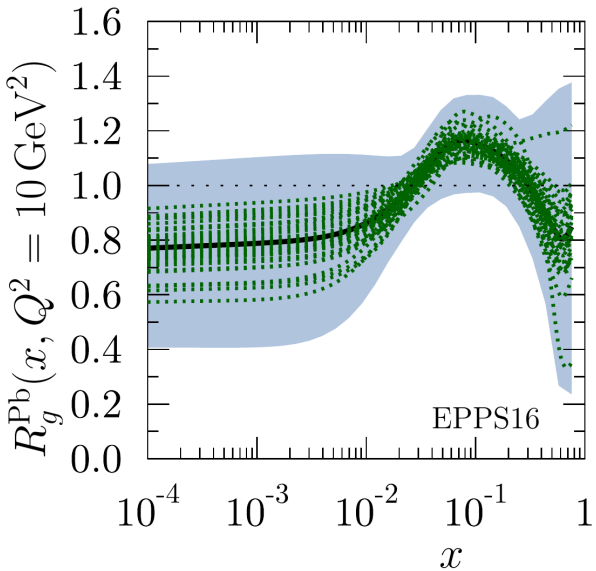
LHCb in PbPb collisions: J/ψ signal

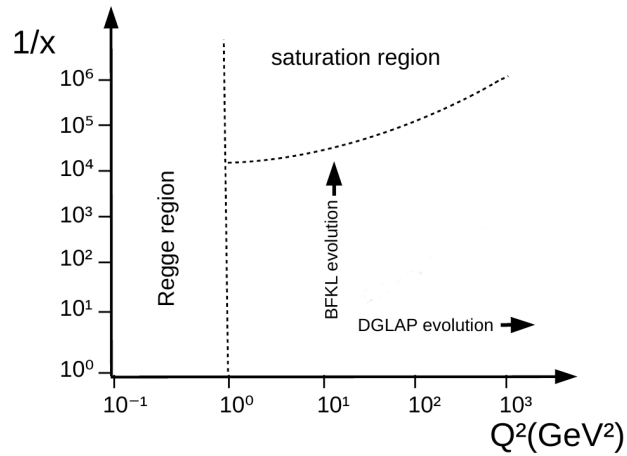


PbPb performance figures: https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015.

- clear signal up to edge of occupancy limit thanks to similar resolutions as in pp collisions
- data-driven efficiency determinations challenging
- prompt J/ψ analysis as pilot analysis in Pb-Pb will be combined with other analysis for publication

p–nucleus collisions: control & limits of collinear factorisation



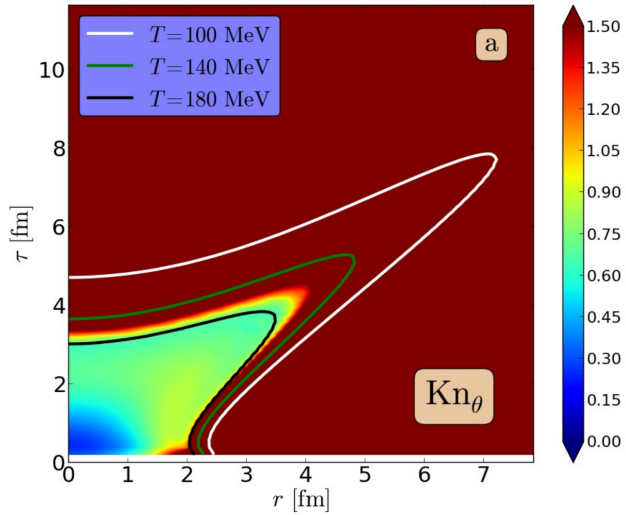


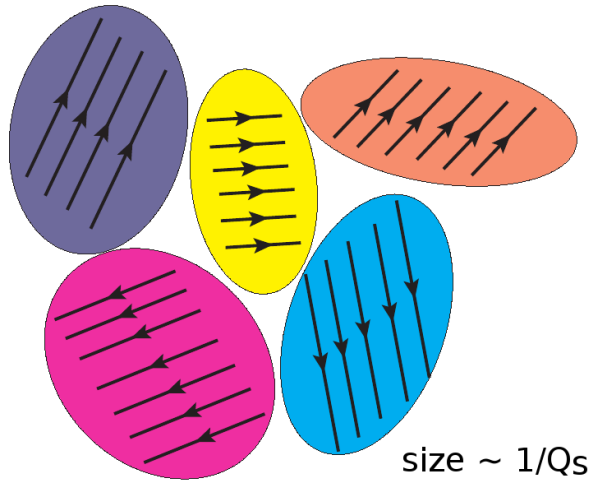
RHS: taken from arXiv:1612.05741, LHS: modified version of graphic in "QCD and collider physics", Ellis, Stirling, Webber

- **no HERA equivalent for lepton-nuclei**: parton flux **unconstrained** for LHC heavy-ion low-p_T heavy-qu ark production

  total charm, beauty production in p-nucleus vital input for AA
- **saturation** scale $Q_s^2 \propto A_{nucleus}^{1/3}$ $\rightarrow$ linear parton evolution break-down?
- Which framework if collinear factorisation no longer valid? color glass condensate arXiv:1002.0333?
- Are there further effects like energy loss by enhanced small-angle gluon radiation arXiv:1212.0434 ?

p-nucleus/pp high multiplicity events: interesting questions

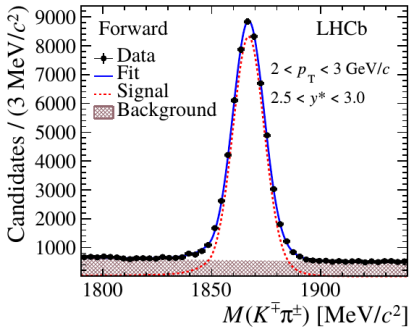


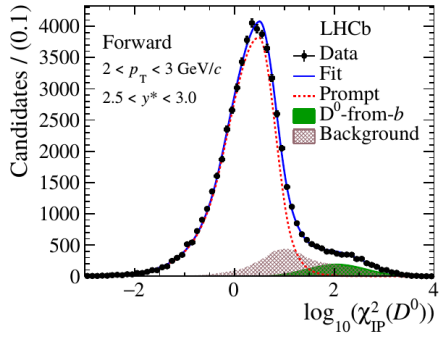


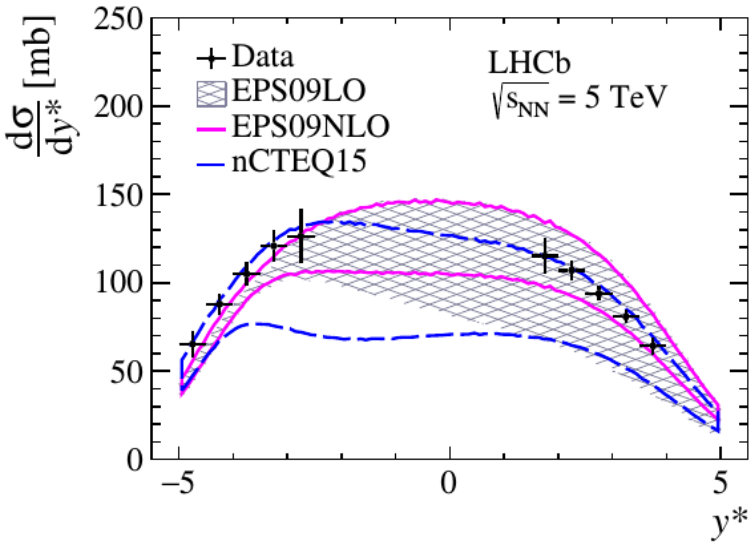
Left: taken from arXiv:1404.7327 $Kn = L_{micro}/L_{macro}$, already $dN/d\eta$ =270! Right: taken from arXiv:1611.00329.

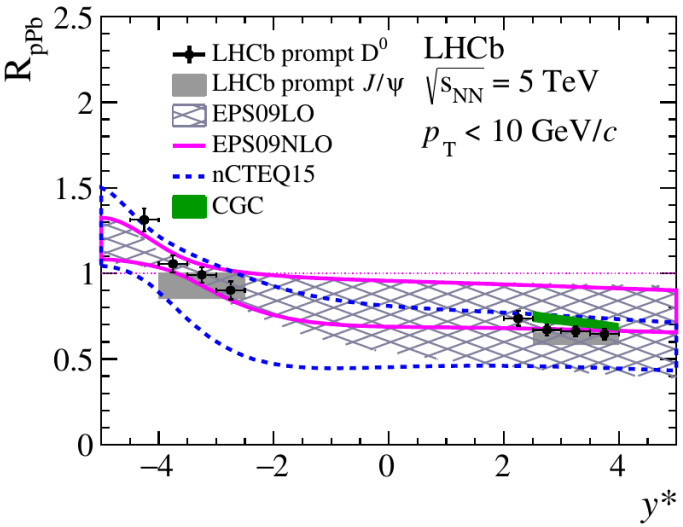
- correlations & bulk production@low-p_T & large multiplicity: **'same' patterns as in PbPb**, where sign for locally thermalised system
- **hydro** in large multiplicity pPb: set-up as in PbPb **describing data** despite **precondition doubts** arXiv:1705.03177
- colour class condensate & color reconnections explanations not ruled out arXiv:1607.02496, arXiv:1705.00745
- recently explanation via interference of multi-parton scatterings arXiv:1708.08241

D^0 in pPb:
$\sqrt{s_{NN}} = 5$ TeV





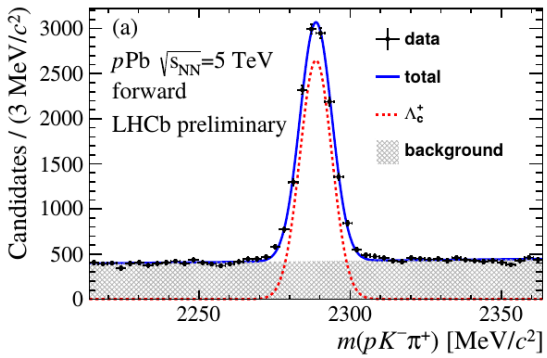


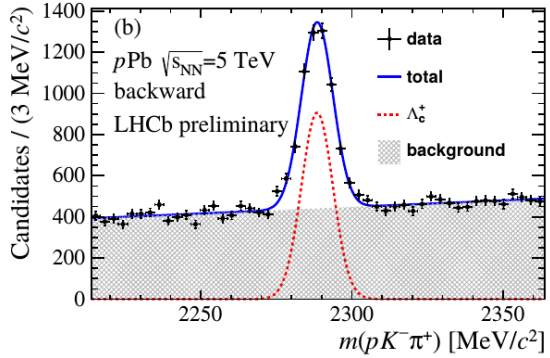


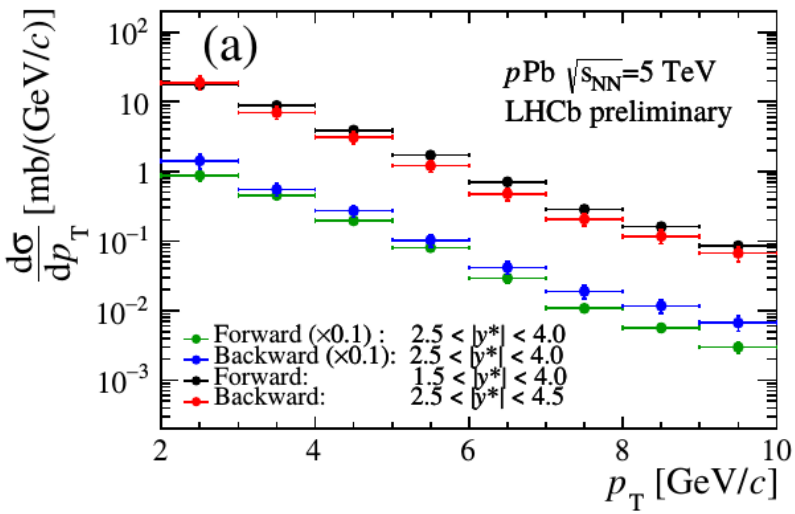
arXiv:1707.02750, accepted by JHEP.

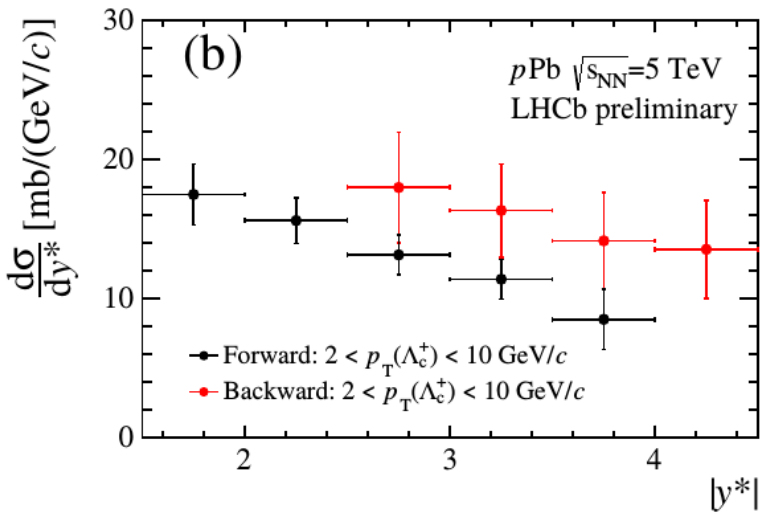
- sensitive to gluons down to $x = 10^{-6}$
- consistency between colour glass condensate and nuclear PDF predictions: to be investigated
- more precise than present nPDF-based calculations: looking forward for global fit and consistency tests with prompt and non-prompt J/ψ-data from LHCb arXiv:1706.07122, accepted by PLB
- see also talk by Yanxi

Λ_C: $\sqrt{s_{NN}}$ =5 TeV





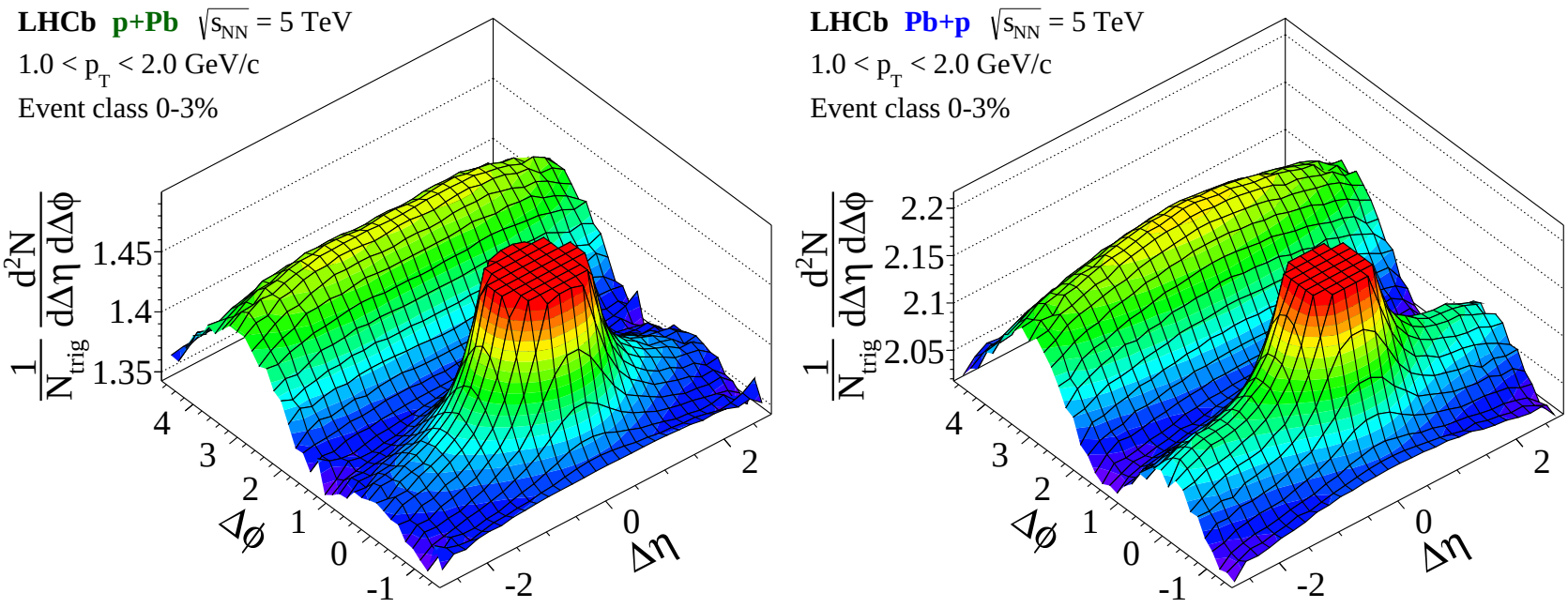




LHCb-CONF-2017–05.

- test of fragmentation in pPb
- to be complemented with a pp measurement at same $\sqrt{s_{NN}}$ for publication
- see also talk by Yanxi

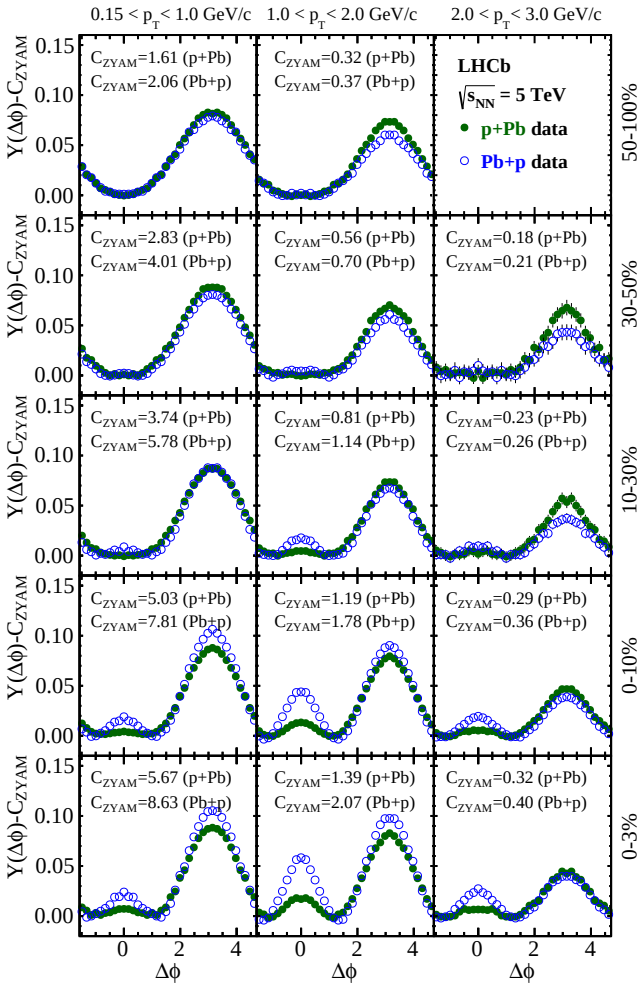
LHCb di-hadron correlations in pPb collisions

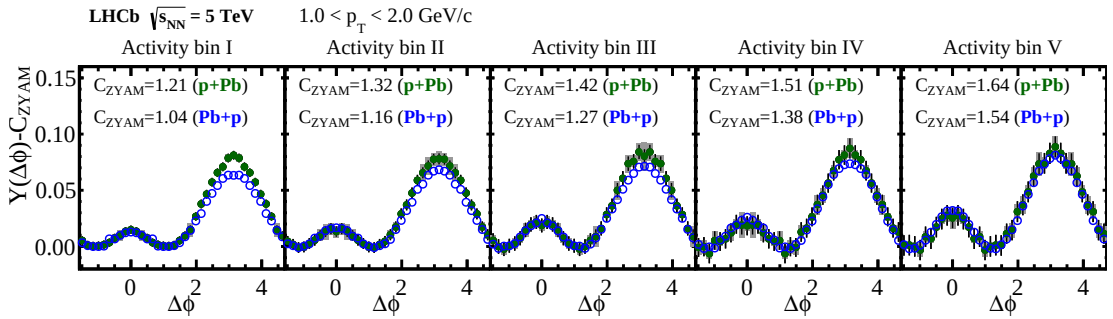


Phys. Lett. B 762 (2016) 473-483.

- unique forward acceptance with full tracking
- qualitative agreement with mid-rapidity findings by ALICE, ATLAS and CMS in high multiplicity events
- significant difference between lead and proton fragmentation side, when comparing same fraction of events based on multiplicity in experimental acceptance $2.0 < \eta < 4.9$

LHCb di-hadron correlations in pPb collisions





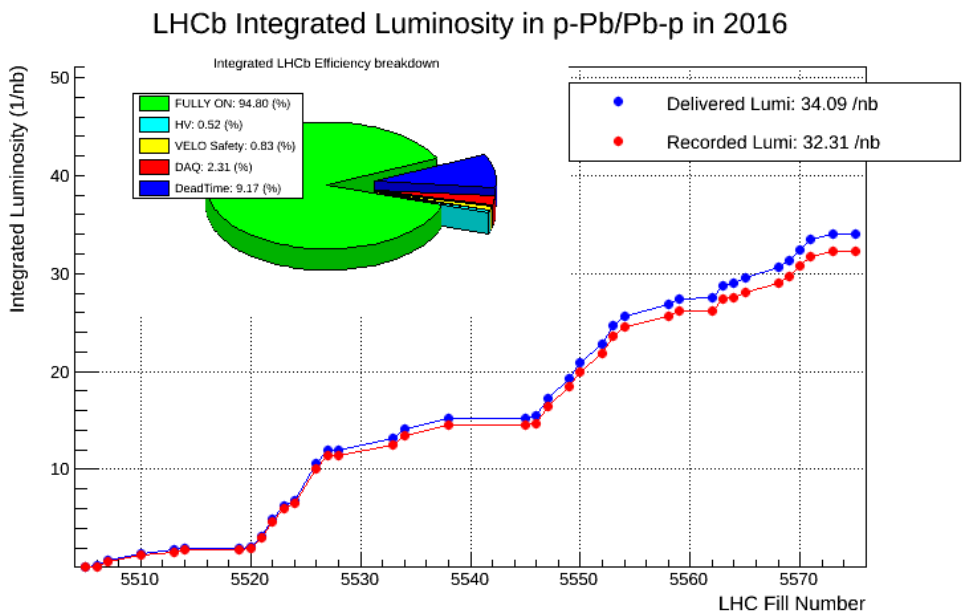
Phys. Lett. B 762 (2016) 473-483.

- increase of near-side correlation towards larger multiplicities and lower p_T after pedestal subtraction
- results at forward and backward rapidity at same estimated absolute multiplicity in acceptance: similar results of correlation strength after pedestal subtraction
- looking forward to phenomenological models: kinematics should be favourable for better control in CGC calculations
- pp measurement ongoing

LHCb pPb collisions: 2016 run

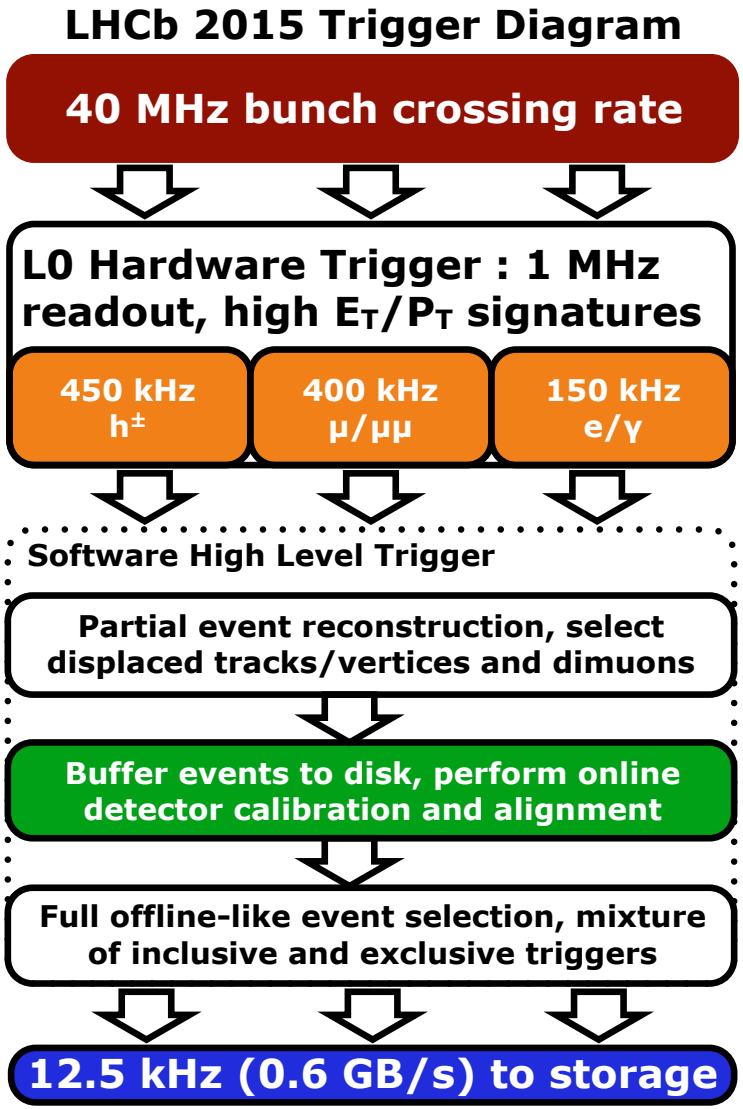
request 10 nb^{-1} per beam direction at 8 TeV:
Hadron PID and precision tracking/vertexing down to low-p_T

- ψ(2S) precision close to the one of J/ψ in 2013 by 10-40 times higher statistics
- comparison with Drell-Yan
- double charm production and $c\bar{c}(c)$- correlations
- fully reconstructed open beauty and Υ family



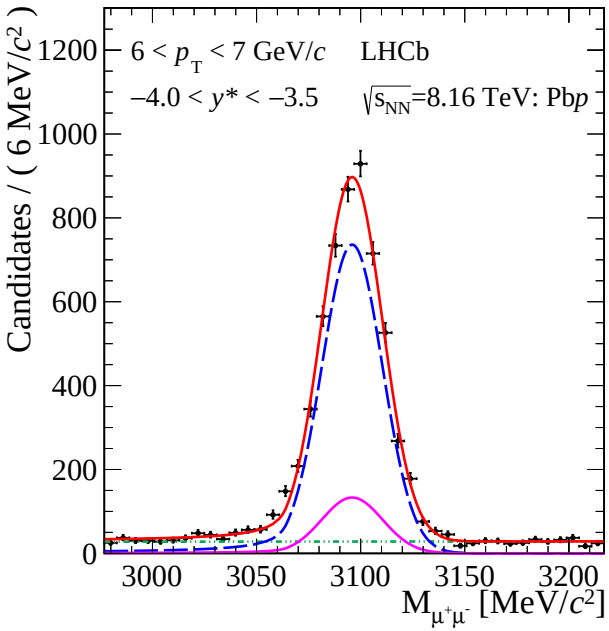
13.6±0.3 nb^{-1} in pPb
20.8±0.5 nb^{-1} in Pbp
≈10^9 minimum events in both configurations

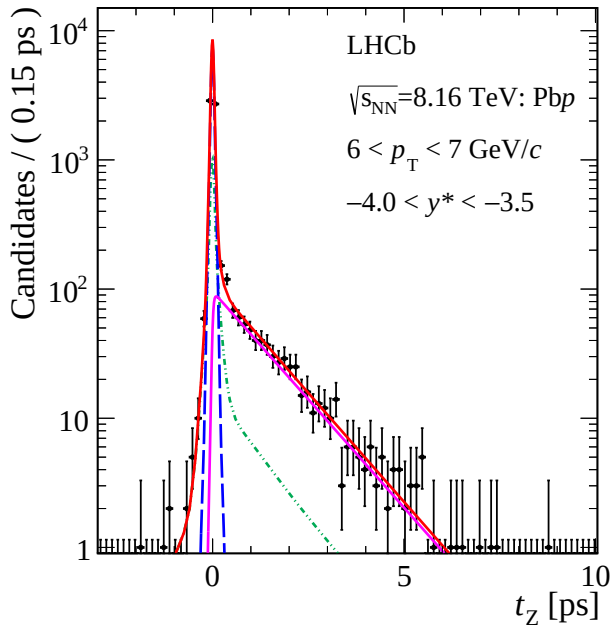
2016: pPb trigger set-up, data acquisition and calibration

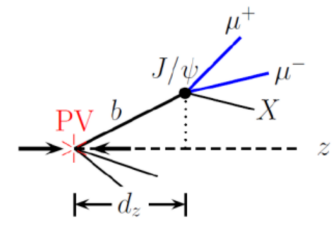


- offline quality at the software trigger level
- analysis hot off the press with dedicated stream optionally including full event info: TURBO++
- trigger system 'overdesigned' for pPb: O(100 kHz) vs. 40 Mhz interaction rate, 25 ns vs. 200 ns bunch-bunch spacing
- TURBO++ heavily used for pPb: more open cuts than in pp at L0 and HLT1 level
- 10^9 minimum bias lines taken with **no bias from L0**, just require 1 Velo-track at HLT1!

2016 pPb run: prompt/non-prompt J/ψ: FIRST result!







LHCB-PAPER-2017-014: accepted by PLB.

$$t_z = \frac{(z_{J/\psi} - z_{PV}) \times M_{J/\psi}}{p_z}$$

- about 0.5 $\cdot 10^6$ J/ψ candidates in final selection for pPb and Pbp each
- signal extraction with 2-dimensional log-likelihood fit of pseudoproper time and mass

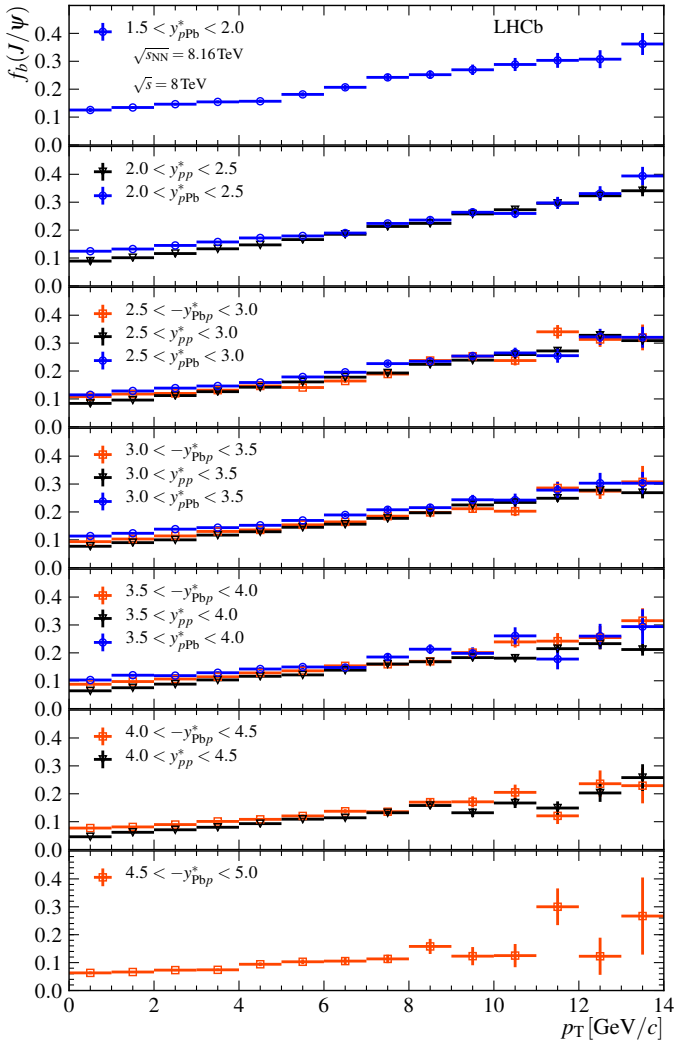
2016 pPb run: J/ψ result uncertainties

Source	pPb	Pbp	Comment
Signal model	1.3%	1.3%	correlated
Muon identification	2.0% – 11.0%	2.1% – 15.3%	correlated
Tracking	3.0% – 8.0%	5.9% – 26.5%	correlated
Hardware trigger	1.0% – 10.9%	1.0% – 7.4%	correlated
Software trigger	2.0%	2.0%	correlated
Simulation statistics	0.4% – 7.0%	0.4% – 26.2%	uncorrelated
$\mathcal{B}(J/\psi \to \mu^+\mu^-)$	0.05%	0.05%	correlated
Luminosity	2.6%	2.5%	correlated
Polarisation	–	–	not considered

LHCB-PAPER-2017-014: accepted by PLB.

- quoted for double differential results in this table
- pPb for most phase space several sources of similar size
- dominated by tracking in Pbp: statistical limitation of data-driven correction tables data vs. simulation (worse S/B as in pPb)

Prompt/nonprompt J/ψ: baseline for future



$$f_b = \frac{\sigma_{J/\psi-\mathrm{from}-b}}{\sigma_{J/\psi-\mathrm{from}-b} + \sigma_{J/\psi-\mathrm{from}-b}}$$

LHCB-PAPER-2017-014: accepted by PLB.

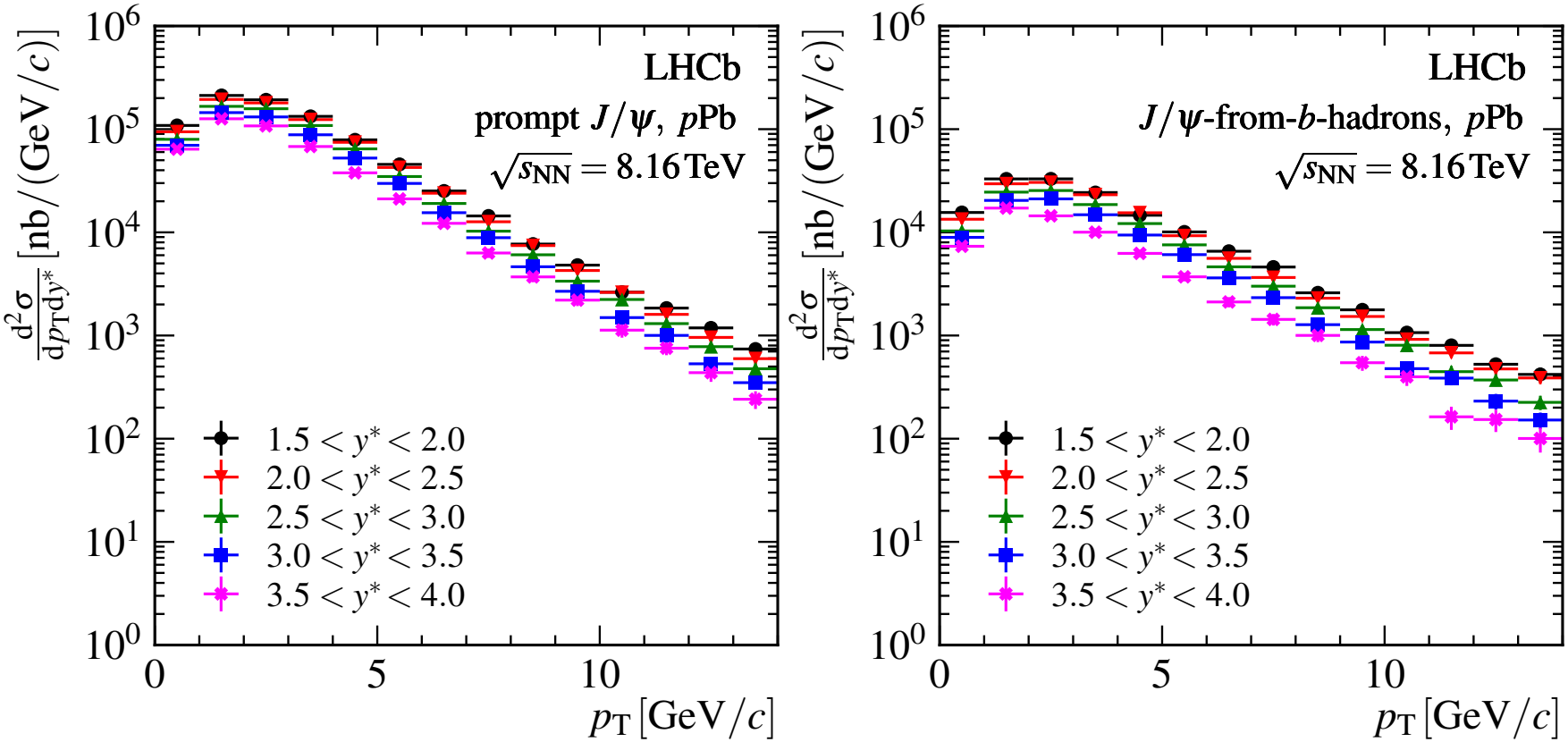
pp@8TeV

***p*Pb**@8.16TeV

Pb*p*@8.16TeV

- large *p*Pb statistics enable detailed double-differential comparison between 3 systems
- different fraction from *B* hadrons shows already different nuclear modification of prompt and non-prompt component

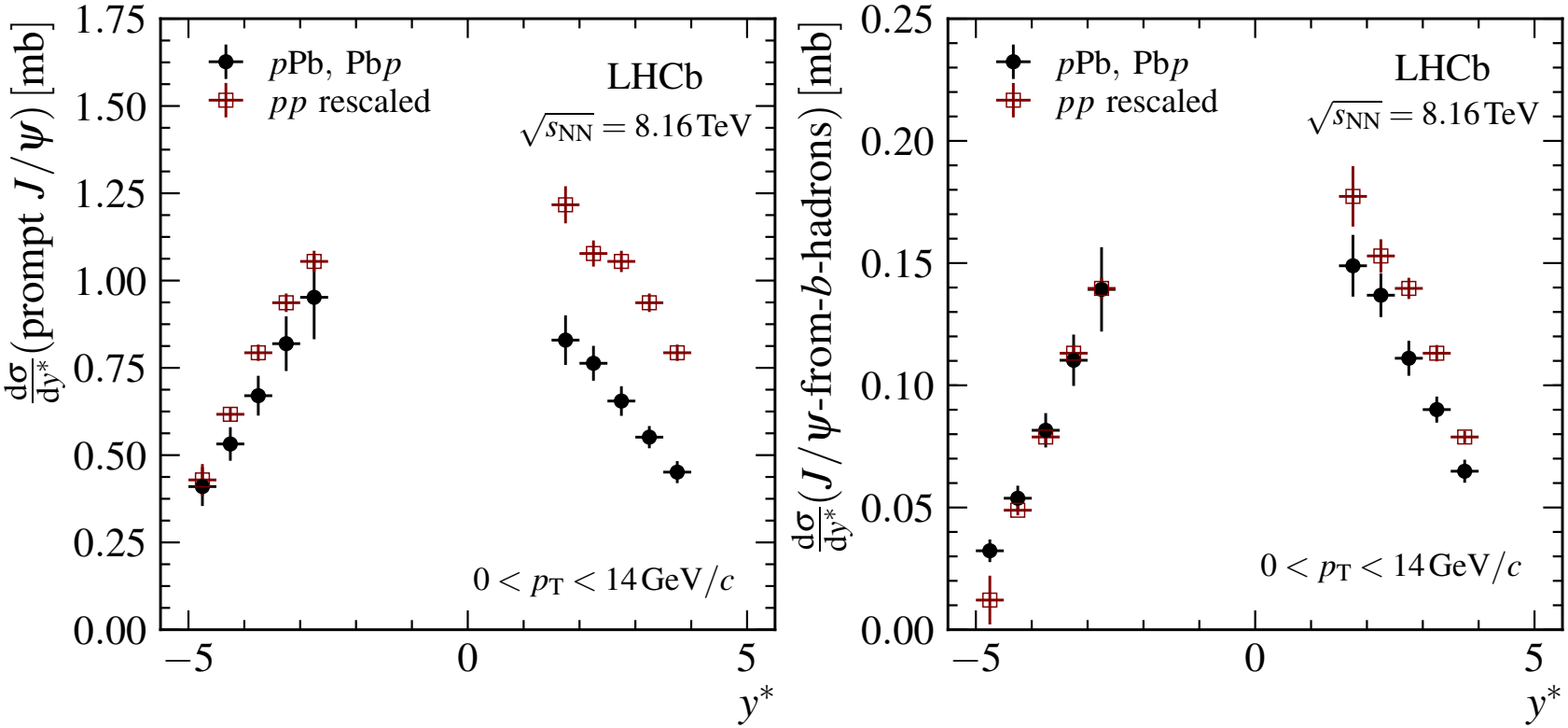
Prompt/nonprompt J/ψ: baseline for future



LHCB-PAPER-2017-014: accepted by PLB.

- precise double differential measurements

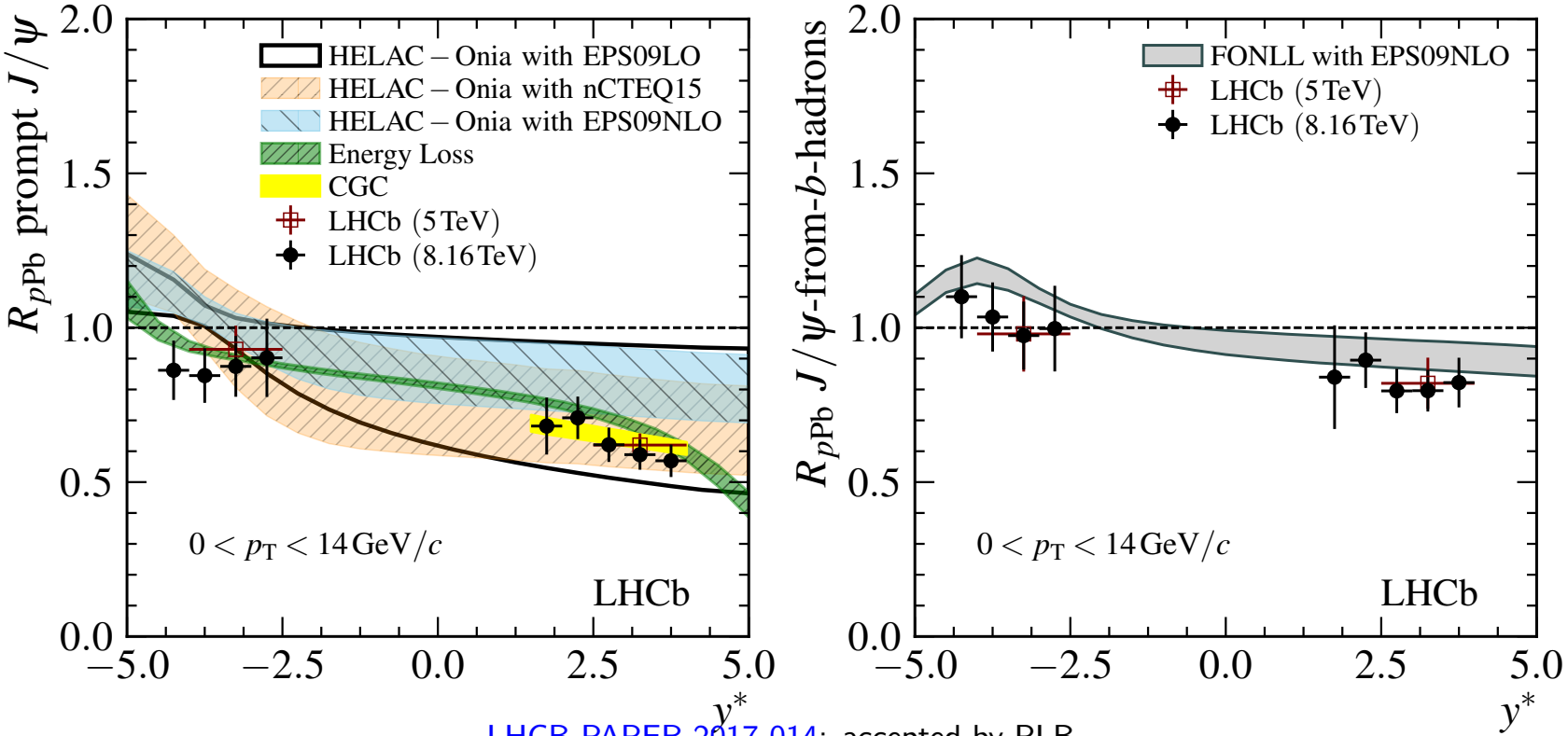
Prompt/nonprompt J/ψ: baseline for future



LHCB-PAPER-2017-014: accepted by PLB.

- pp reference cross section from inter- (in energy) and extrapolation (in rapidity) of measurements at $\sqrt{s_{NN}} = 7, 8, 13$ TeV
- comparison of pPb cross section at $\sqrt{s_{NN}}$ =8.16 TeV and $pp \times 208$ cross section
- strong modifications for prompt J/ψ
- modifications smaller for large Q^2 (J/ψ-from-b-hadrons)

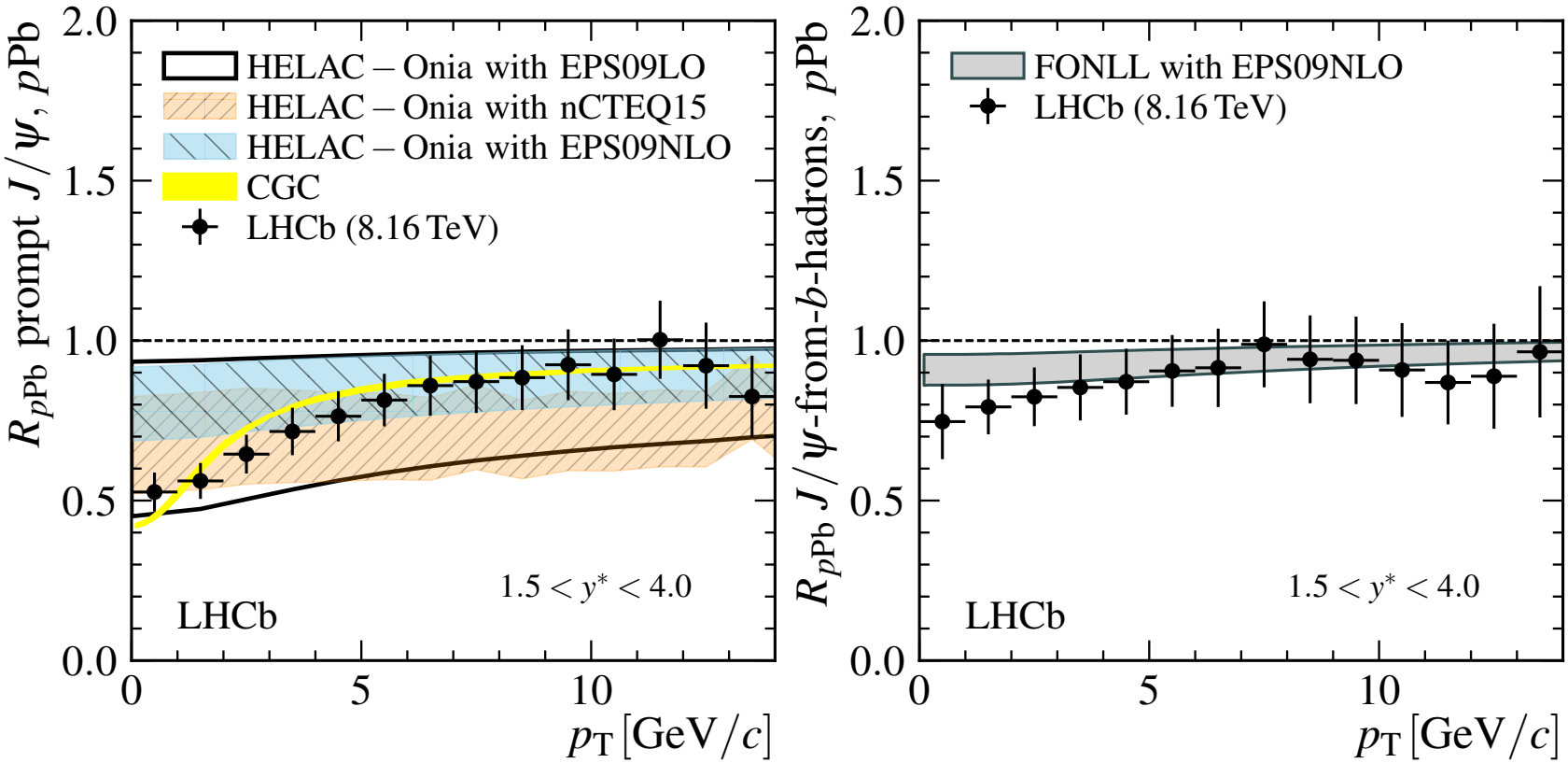
Prompt/nonprompt J/ψ: baseline for future



LHCB-PAPER-2017-014: accepted by PLB.

- collinear factorisation with HELAC-Onia arXiv:1610.05282, color glass condensate arXiv:1503.02789, coherent energy loss arXiv:1212.0434
- similar as at 5 TeV: no decision based on data possible
- remarkable that at very backward rapidity rise seen in D-meson data and in nuclear PDF not seen here in prompt and nonprompt J/ψ
- for the first time precise B-production measurement in pPb down to 0p_T: crucial input for PbPb phenomenology

Prompt/nonprompt J/ψ: baseline for future



LHCB-PAPER-2017-014: accepted by PLB, $R_{pPb} = \sigma_{pPb,J/\psi}/(208 \cdot \sigma_{pp,J/\psi})$

- collinear factorisation with HELAC-Onia arXiv:1610.05282, color glass condensate arXiv:1503.02789, coherent energy loss arXiv:1212.0434
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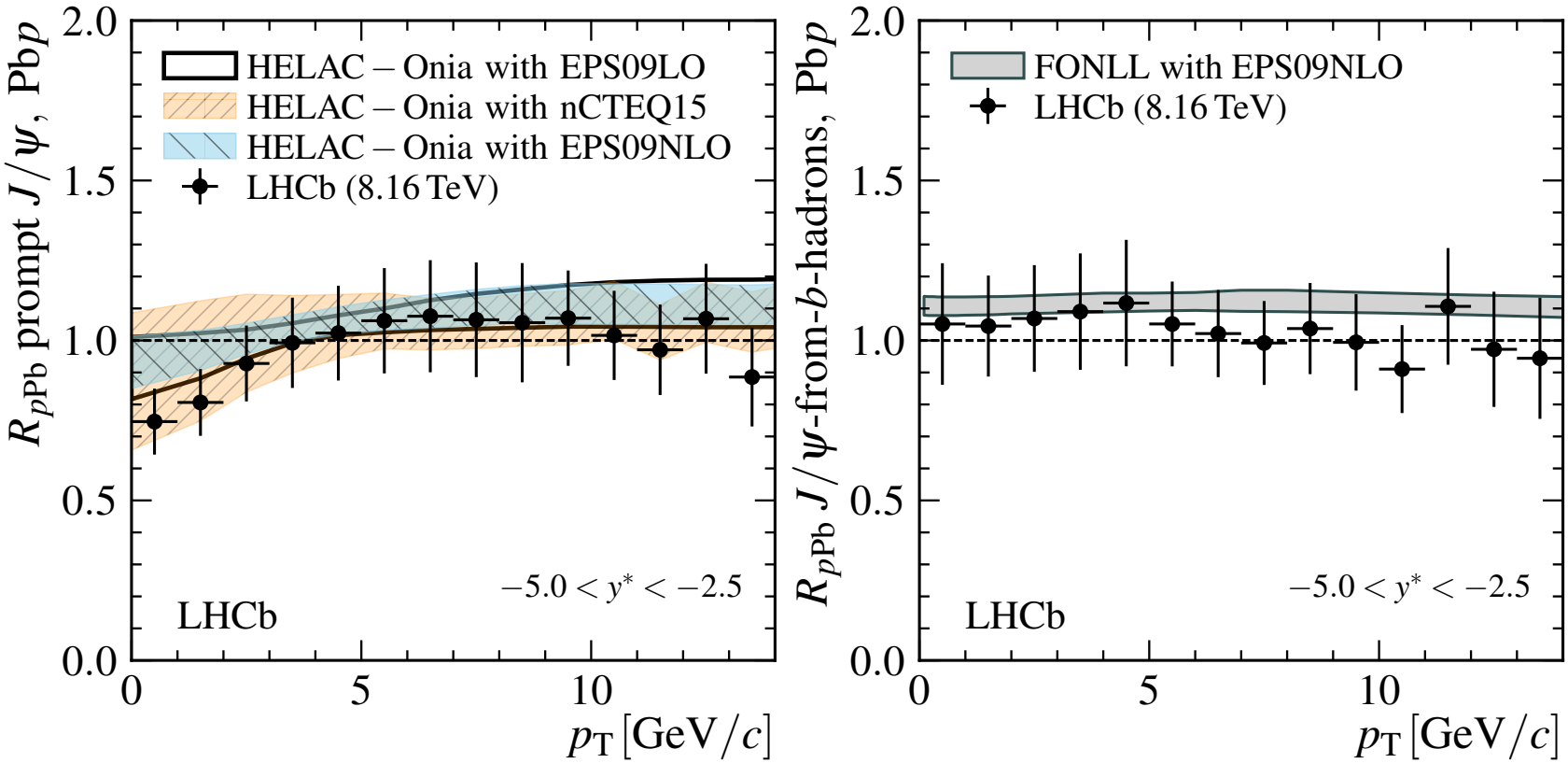
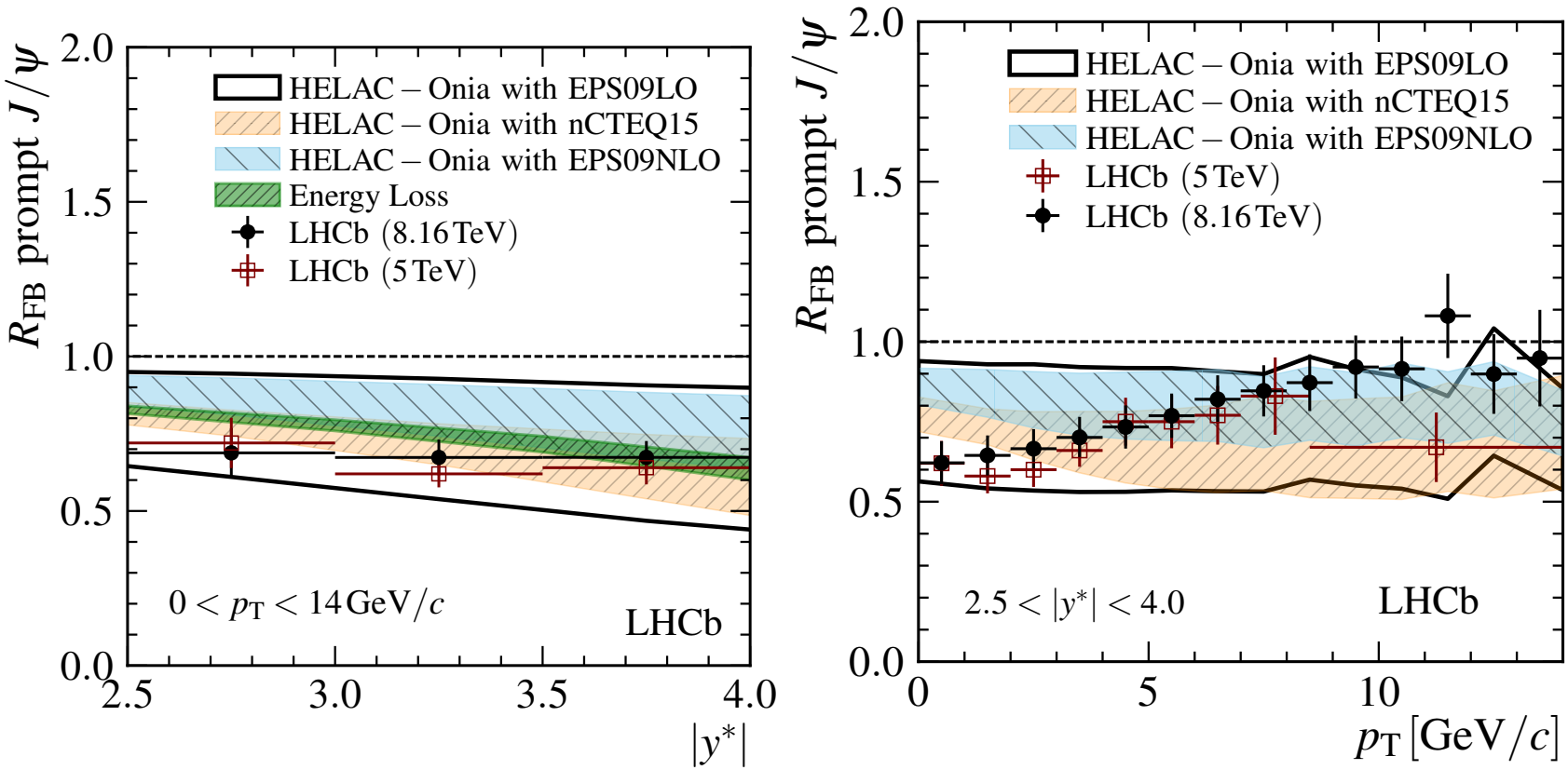


LHCB-PAPER-2017-014: accepted by PLB, $R_{pPb} = \sigma_{pPb,J/\psi}/(208 \cdot \sigma_{pp,J/\psi})$

- collinear factorisation with HELAC-Onia: arXiv:1610.05282, color glass condensate arXiv:1503.02789, coherent energy loss: arXiv:1212.0434
- similar picture as at 5 TeV: no decision based on data possible with higher granularity and precision
- for the first time precise B-production measurement in pPb

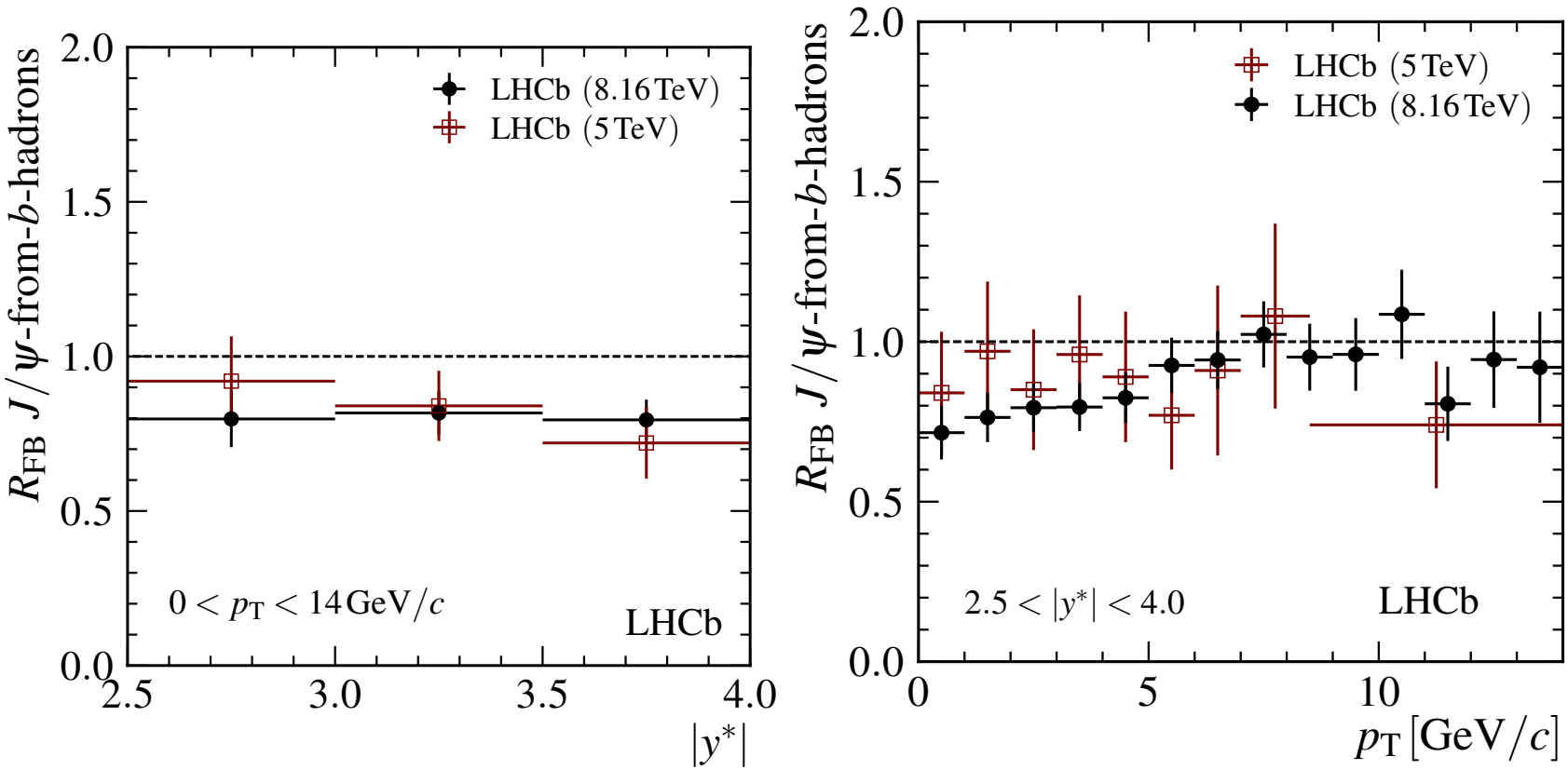
Prompt/nonprompt J/ψ: baseline for future



LHCB-PAPER-2017-014: results from paper draft, $R_{FB} = \sigma_{pPb}/\sigma_{Pbp}$

- forward-backward ratio: more precise, no *pp* reference involved
- slight tension with coherent energy loss model and with nuclear PDF

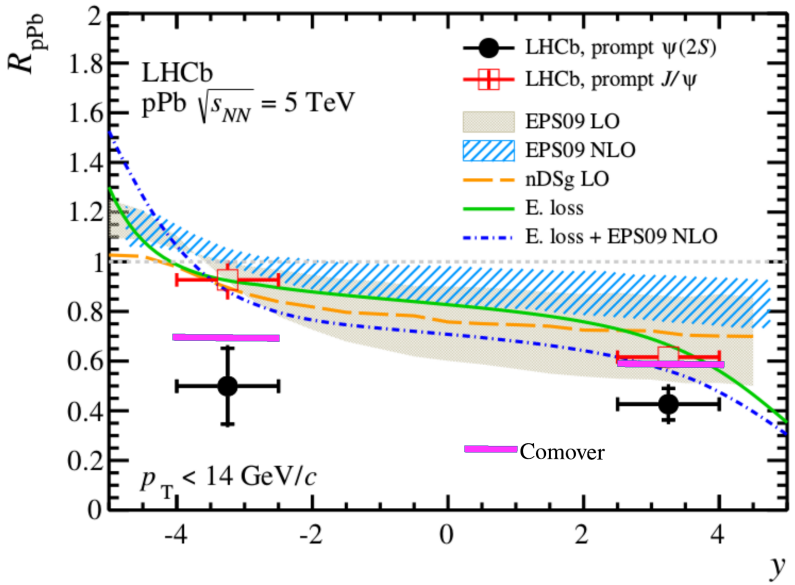
Prompt/nonprompt J/ψ: baseline for future

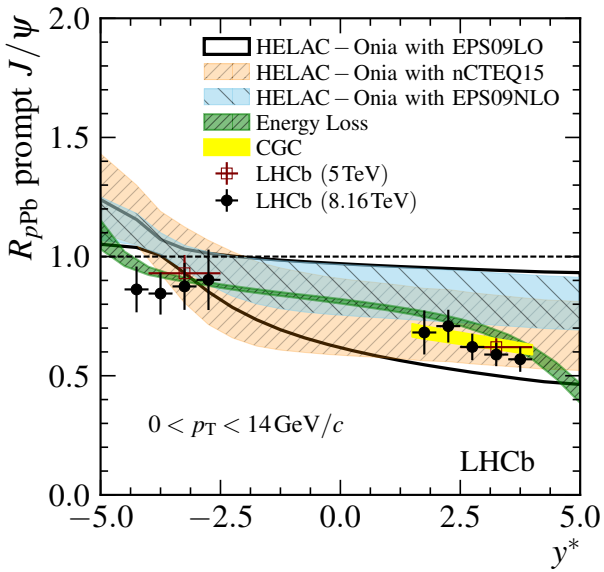


LHCB-PAPER-2017-014: results from paper draft. $R_{FB} = \sigma_{pPb}/\sigma_{Pbp}$

- forward-backward ratio: more precise, no *pp* reference involved
- unique test of B-production

Investigate break-down of factorisation in nuclear collisions with $\psi(2S)$

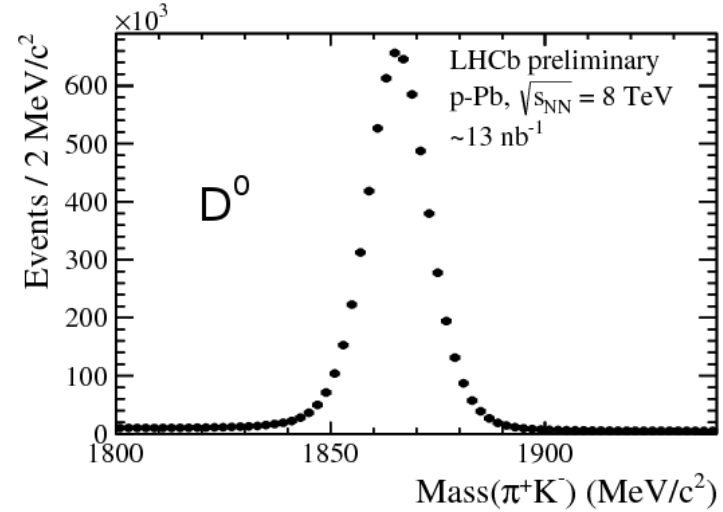


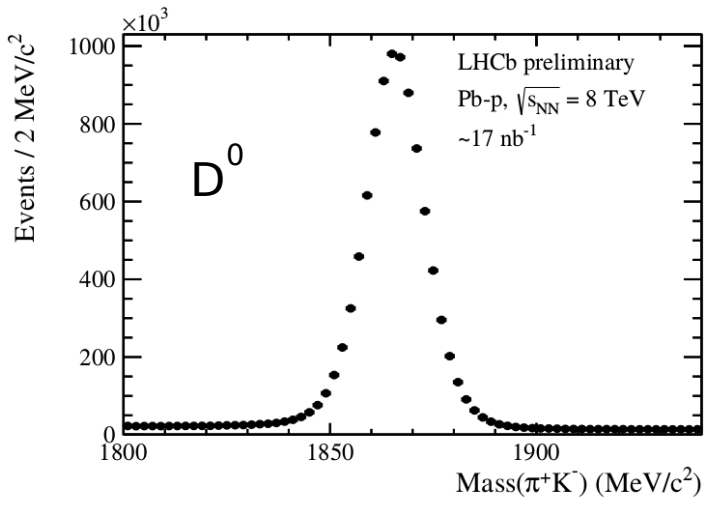


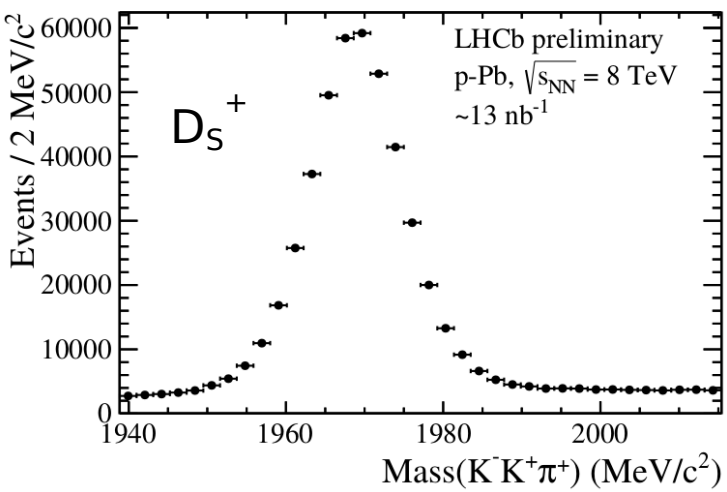
5 TeV: JHEP 02 (2014) 072, JHEP 1603 (2016) 133; 8.16 TeV arxiv:1706.07122, accepted by PLB.

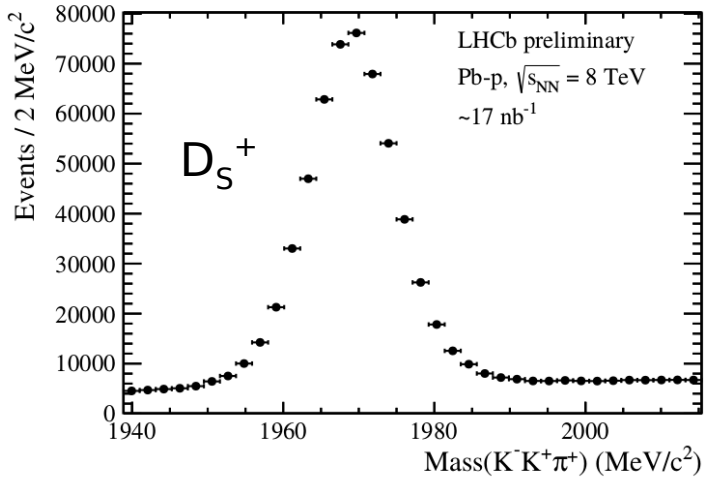
- additional suppression for $\psi(2S)$ not explained by nuclear PDFs nor by coherent energy loss
- 'comover' model with no precisely specified secondary interaction Phys.Lett. B749 (2015) 98-103: additional suppression also with hadron resonance gas + QGP ansatz by Du & Rapp Nucl.Phys. A 943 (2015)
- calculation from gluon-kicks estimated with Color Glass Condensate approach and colour evaporation model can explain the data arXiv:1707.07299
- double-differential measurement ongoing at 8 TeV: in preparation

2016 *p*Pb run: open charm



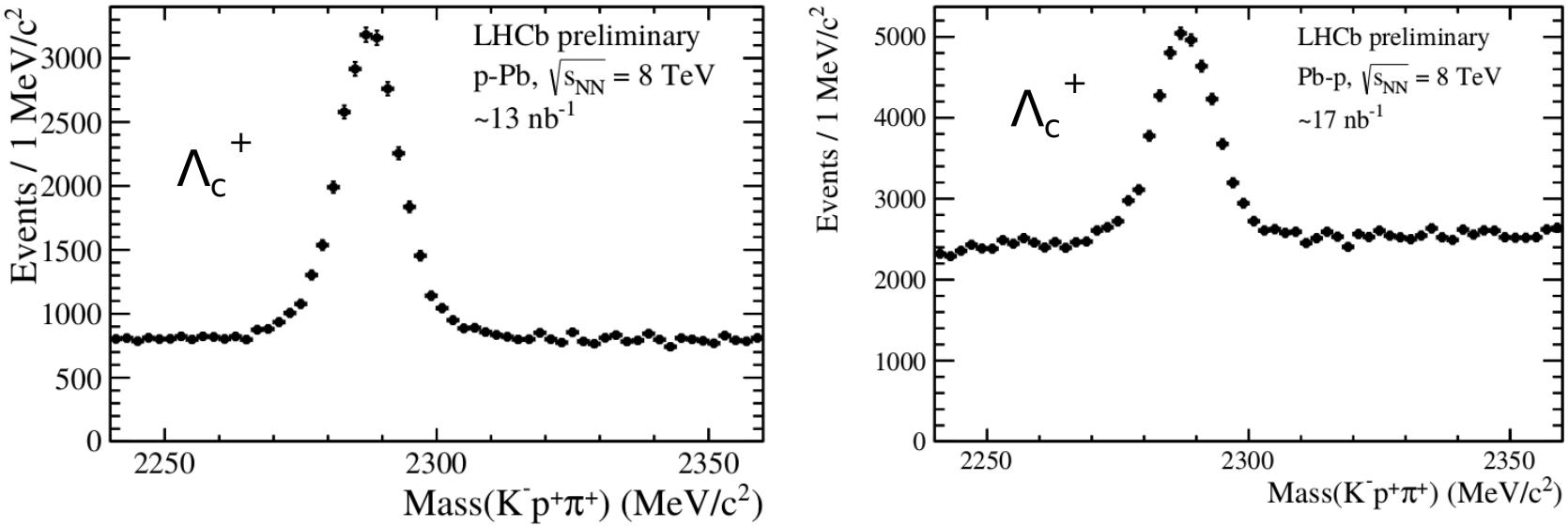






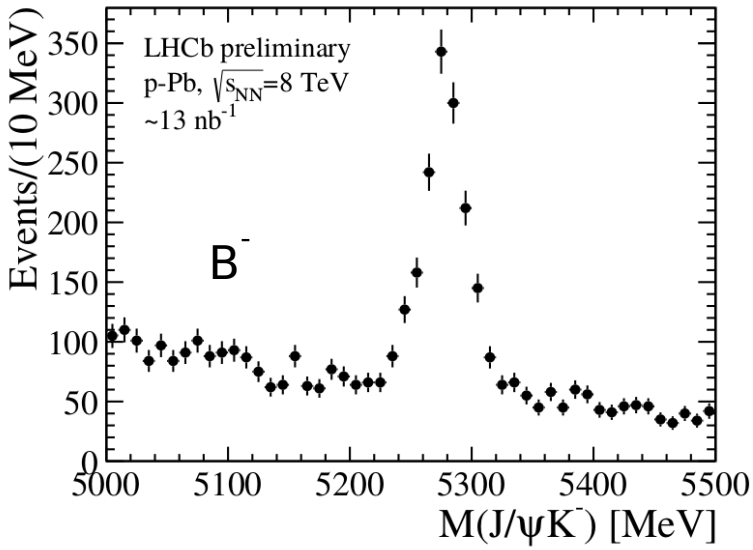
- unique heavy-flavour data samples to be exploited
- both in *p*Pb (left) as well as in Pb*p* (right)
- also large statistics for double charm production studies

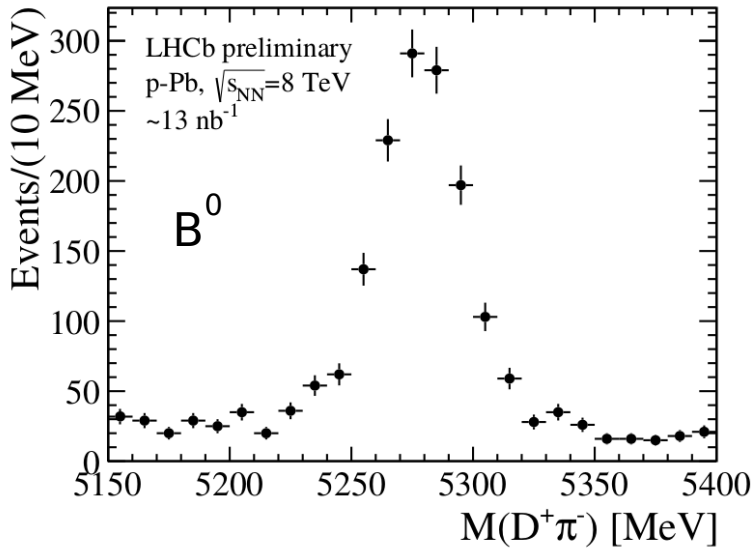
2016 pPb run: open charm baryons

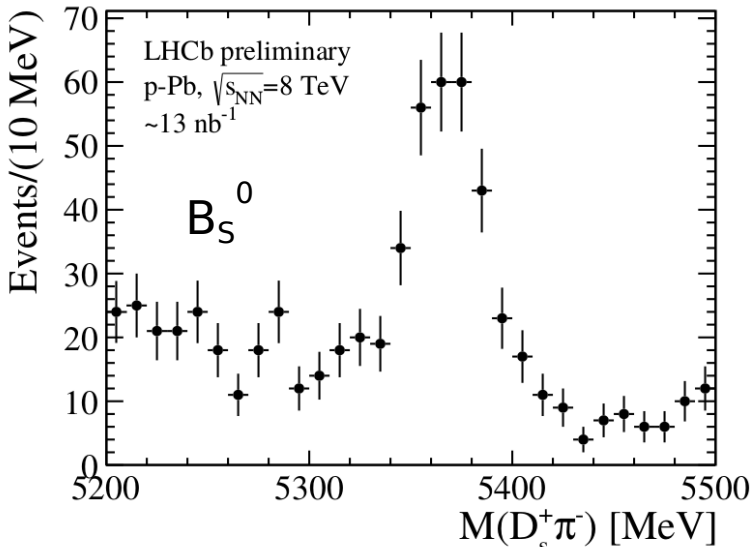


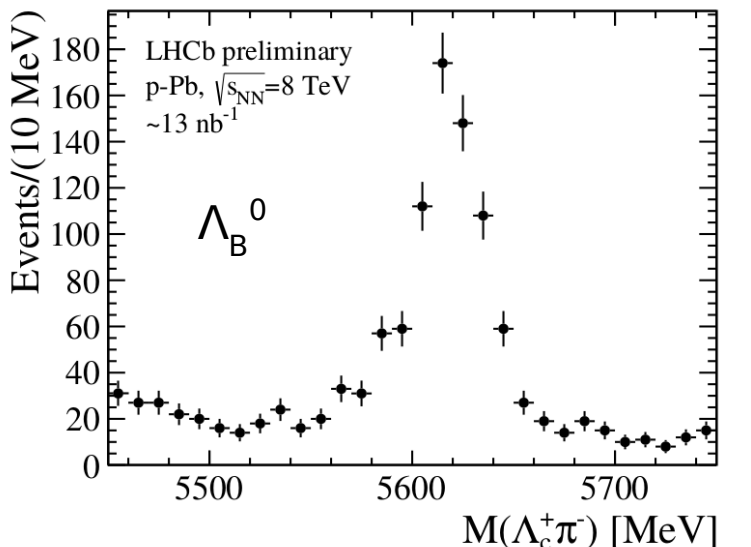
- large data sample down to $p_T = 0$ both in pPb (left) and Pbp (right)

2016 pPb run: open beauty



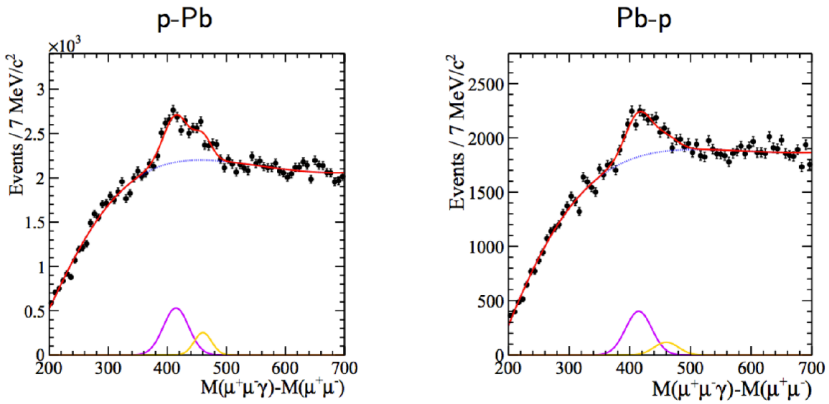




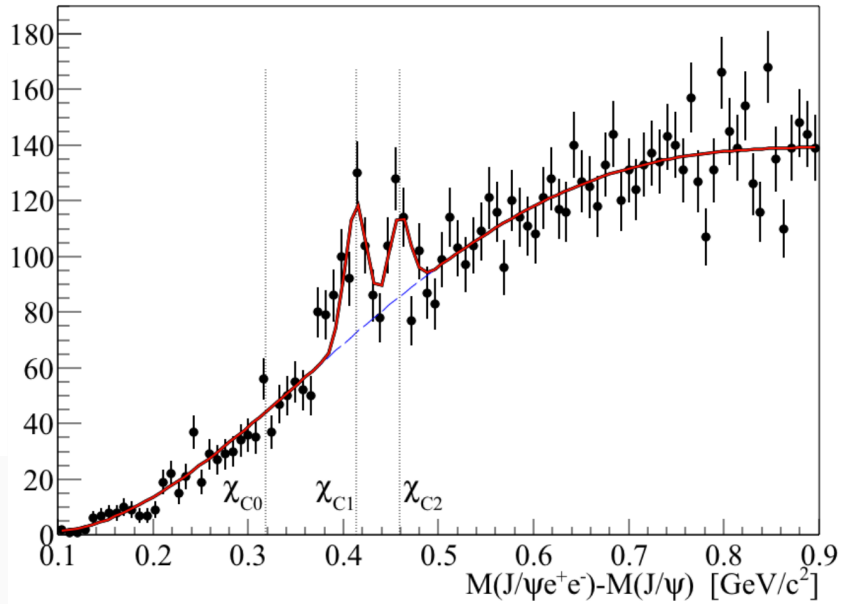


- significant samples of beauty meson & baryons down to $p_T = 0$, analysis started

2016 pPb run: χ_c

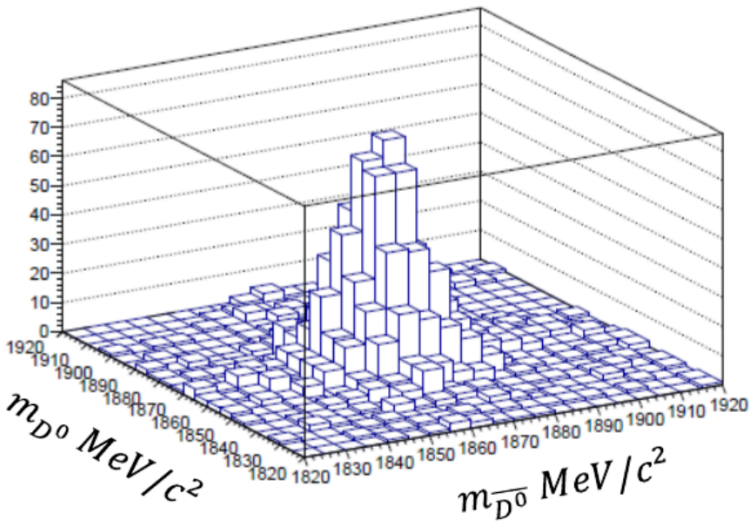


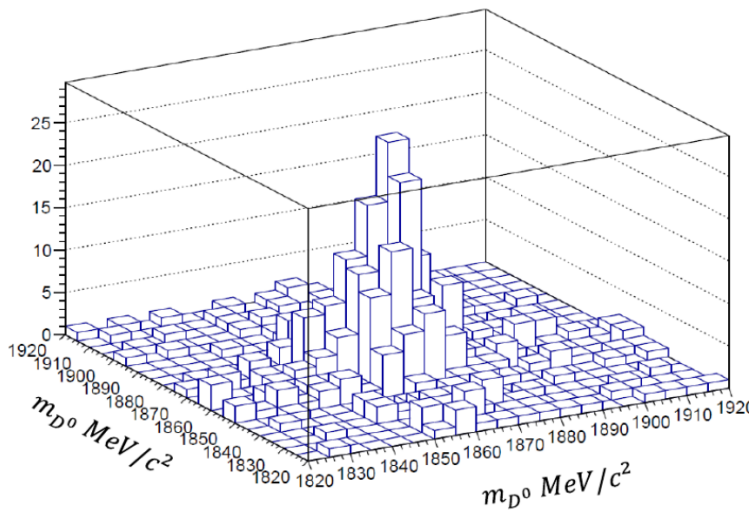
χ_c	$p_T > 3$ GeV/c
J/ψ	$3.04 < MM[GeV/c^2] < 3.16$
μ	$p_T > 0.75$ GeV/c, PROBNN$\mu > 0.5$
non-converted γ	$p_T > 0.6$ GeV/c, $p > 5$ GeV/c, CL>0.5



- first look
- clarify factorisation break-down further after $\psi(2S)$ measurement

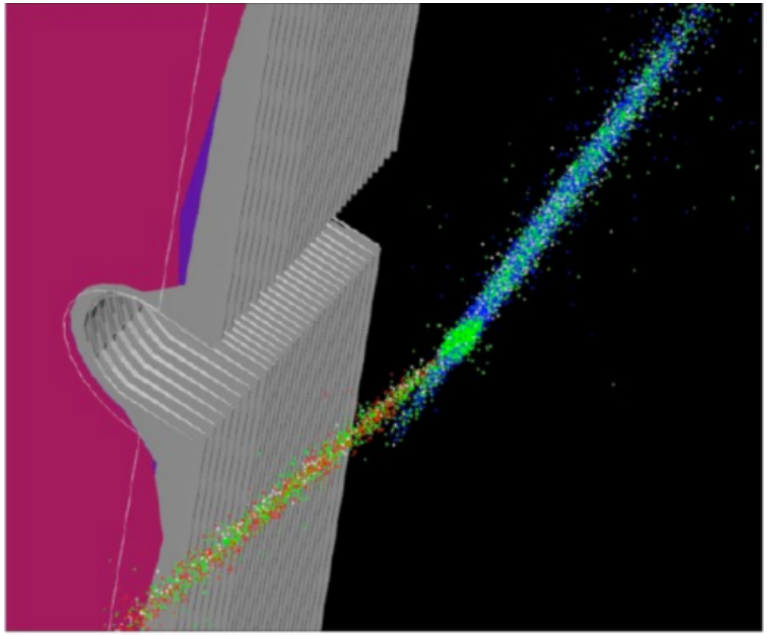
2016 pPb run: double charm production





- first look with bachelor student
- check DPS and correlations in pPb

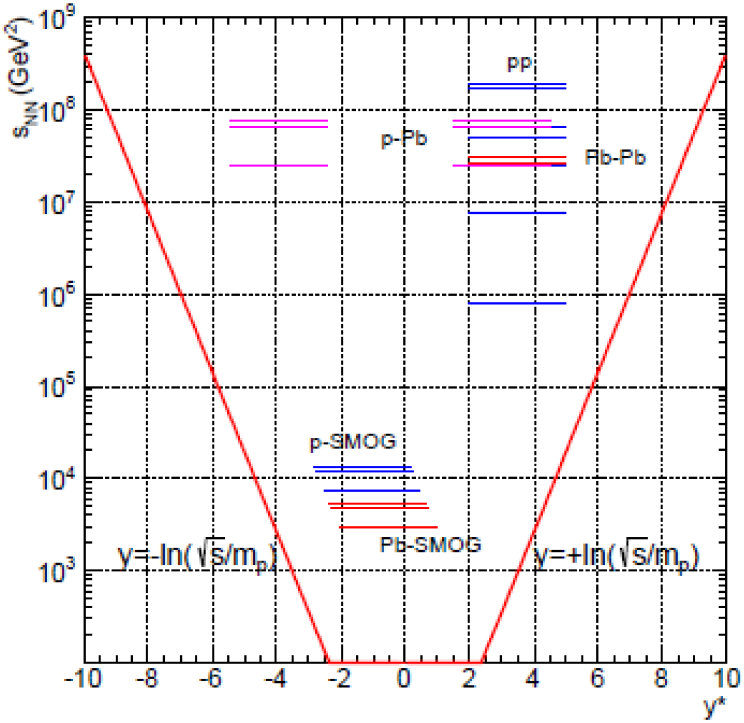
LHCb fixed target



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

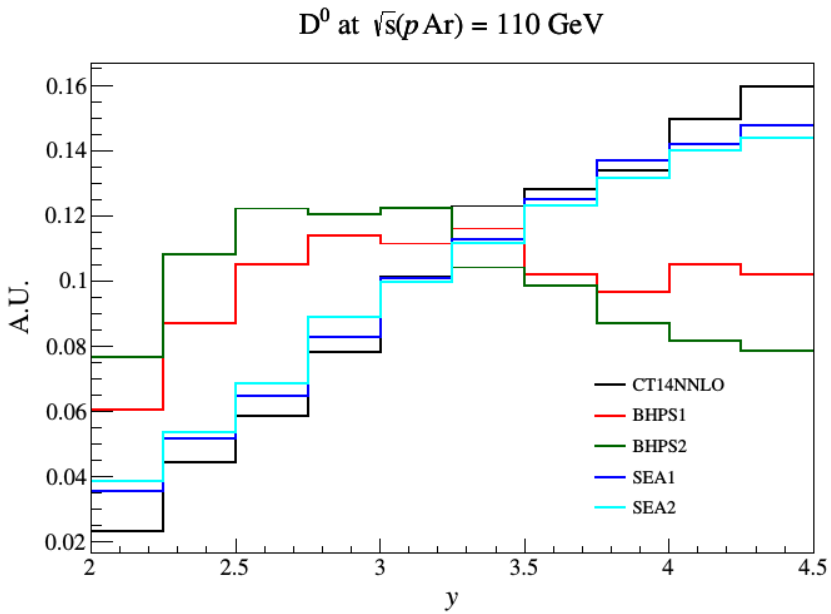
Beam 1 - Beam 2, Beam 1 - Gas, Beam 2 - Gas.

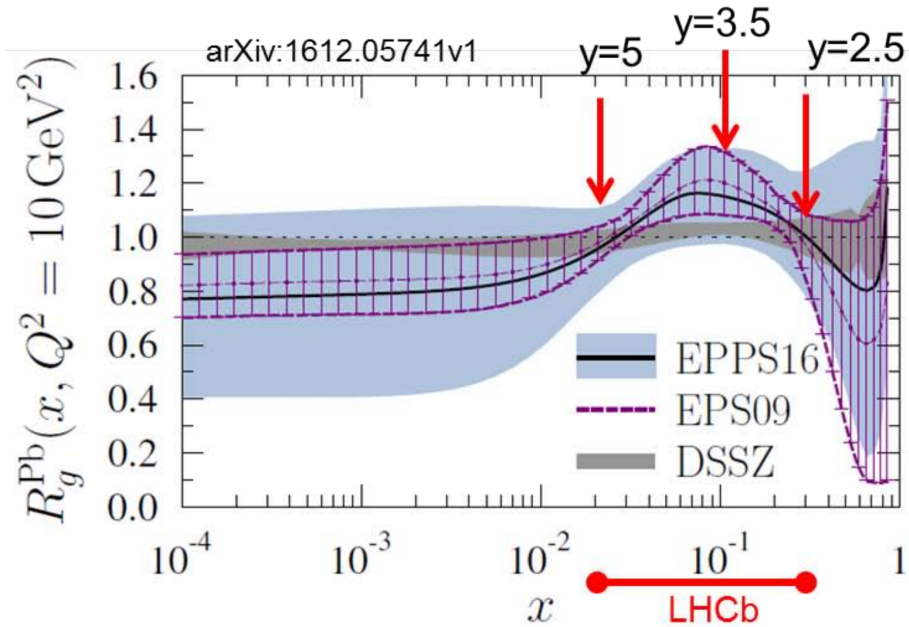
p-Pb
p-p
Pb-Pb
p-GAS
Pb-GAS



- noble gas injections with pressures 10^{-6}-10^{-7} mbar introduced for improved luminosity measurements olorredgive relation of highest multiplicity in PbAr vs. PbPb
- used as internal gas target for p-gas and ion-gas collisions: He(A=4), Ne(A=20), Ar(A=40) used so far
- LHCb acceptance reaches close to midrapidity
- first preliminary measurements in pAr and in pHe collisions from Run2

Charm production in fixed-target collisions: unique constraints



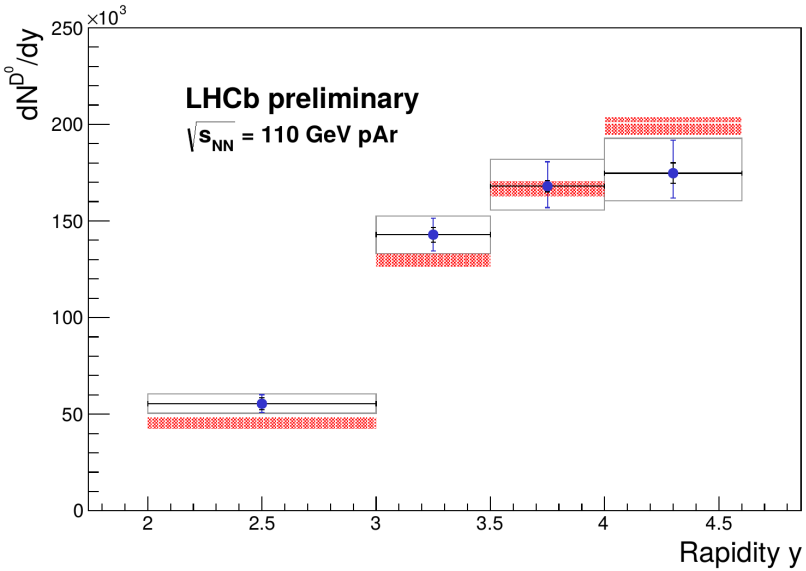


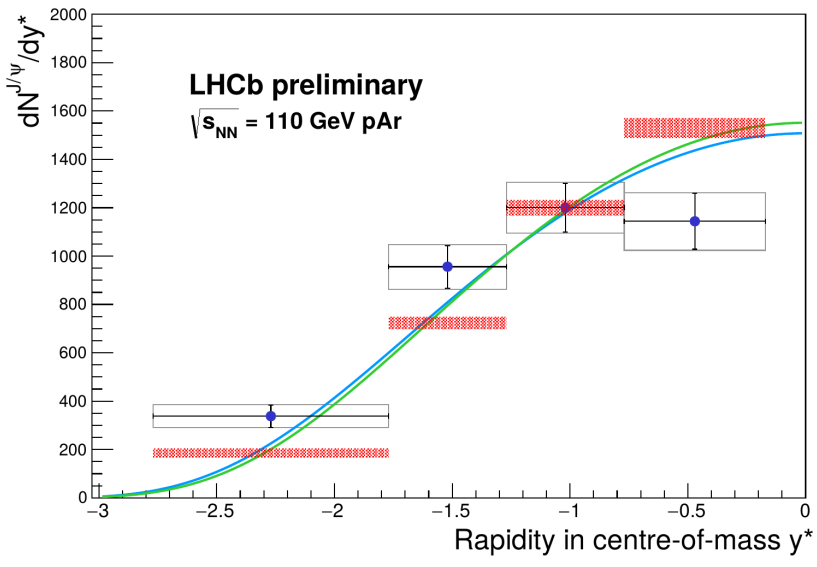
Left: figure by Philip Ilten link, considered pdf models based on CT14 from: Phys. Rev. D 93, 074008; right: figure from talk by Emilie Maurice at QM 2017

- sensitive to nuclear modification of parton distribution function & intrinsic charm on 2015 data shown at Quark Matter 2017: first public physics result from SMOG data

Charm production in fixed target collisions: first results

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

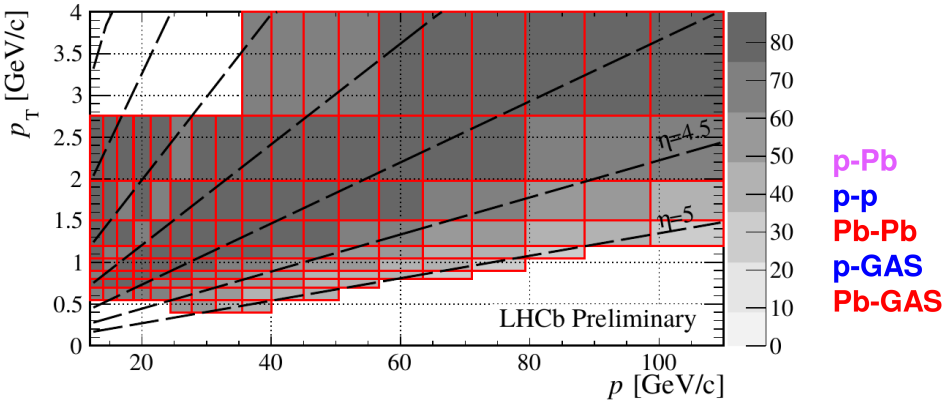


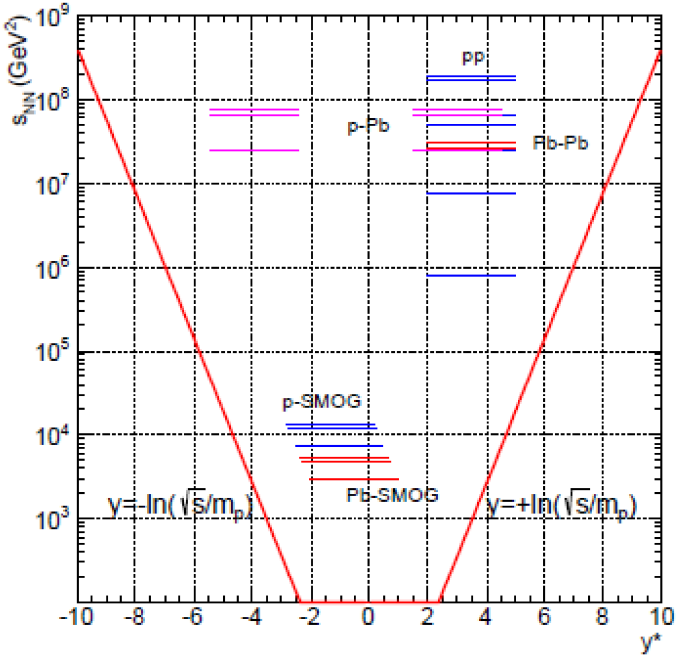


LHCb-CONF-2017-001

- normalised distributions compared with Pythia 8 with CT09MCS and with parameterisation of world-data by Arleo et al. for charmonium
- final analysis together with *p*He result soon

Soft and collective particle production

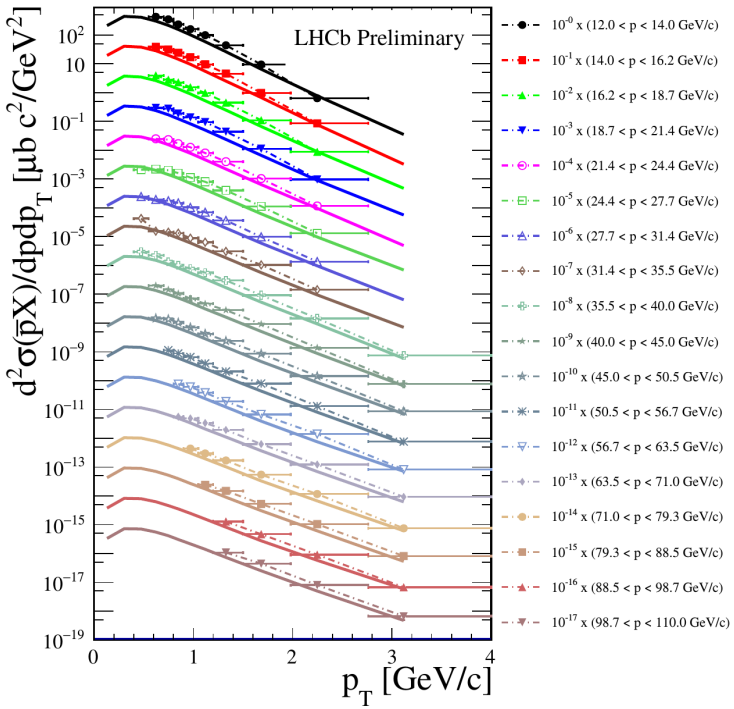




Left kinematic bins of $\bar{p}$-cross section measurement in pHe LHCb-CONF-2017-002

- forward spectrometer geometry allows low p_T measurements at moderate track momenta
- in fixed-target mode: production studies close to midrapidity well suited for cosmic-ray physics references

$\bar{p}$-production in pHe collisions



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%
Uncorrelated Systematic:	
Tracking	3.2%
IP cut efficiency	1.0%
PID	$2.0 - 28\%$ ($< 10\%$ for most bins)
Simulated sample size	$0.8 - 15\%$ ($< 4\%$ for $p_T < 2$ GeV/c)

LHCb-CONF-2017-002, EPOS in solid lines.

- precise measurement demonstrates the feasibility of primary particle spectra measurements in fixed-target events
- luminosity determined via elastic e-proton scattering
- EPOS-LHC underestimates the cross sections by about 50 %
- starting point for comparative studies for other particle species and collision systems

Conclusions

- LHCb: fully instrumented spectrometer with unique kinematics with flexible trigger system in collider and fixed-target mode
- PbPb: first understanding achieved
- important pPb results to constrain gluons at low-x and much more to come
- upgrade in talk on Wednesday