Heavy-Ion results from LHCb

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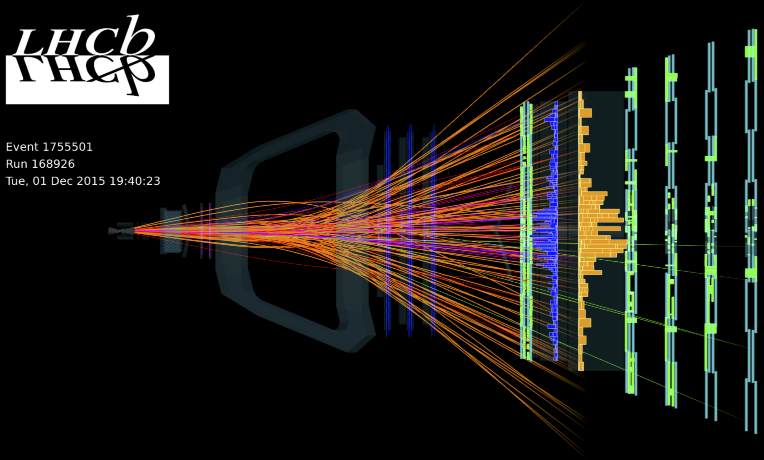
Outline

- nucleus-nucleus collisions in collider mode
- proton-nucleus collisions in collider mode
- proton-nucleus collisions in fixed-target mode
- Conclusions

Nucleus-nucleus collisions in collider mode

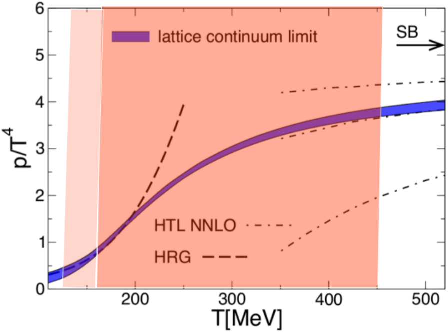


nucleus–nucleus (PbPb) event display with a J/ψ candidate

average multiplicity about 40 $\times$ average *pp* multiplicity

most central about 200 $\times$ average *pp* multiplicity: about ATLAS/CMS phase 2 for number of tracks per crossing
LHCb PbPb performance figures: https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015

PbPb 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

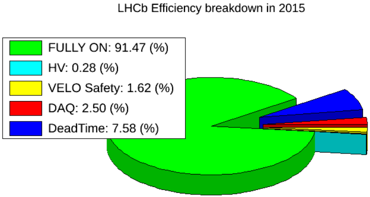
SB: Stefan-Boltzmann limit of non-interacting quarks and gluons

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

→ What can LHCb contribute in PbPb collisions?

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

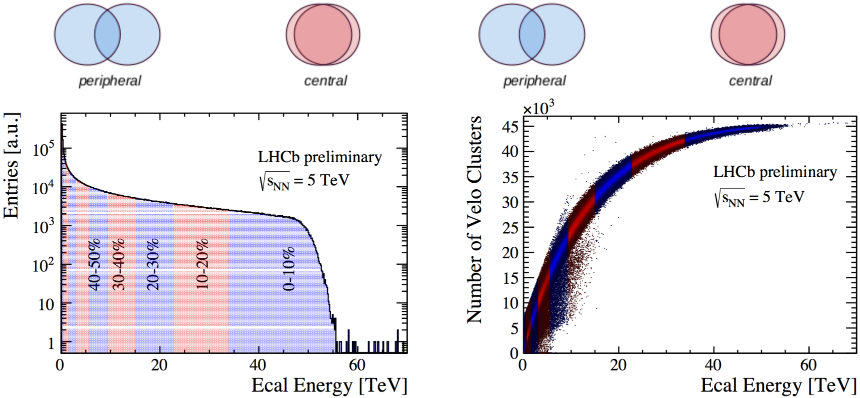


Experiment	2015 PbPb
ALICE central	150 mio MB evts. (0.02 nb^{-1})
ALICE muon	0.225 nb^{-1} analysed
CMS	0.464 nb^{-1} analysed
ATLAS	0.515 nb^{-1} analysed
LHCb	50 mio MB evts., 50-100% tracking

modified version in arXiv:1609.01135, references therein.

- first LHCb data in 2015: competitive for soft probes and charm in terms of event statistics in unique acceptance
- soft trigger requirement:
  $\rightarrow$ combined with LHCb PID capability: unique sample at the LHC including exclusive production studies from γ-induced processes
- envisage a factor 10 larger integrated PbPb-luminosity in 2018
  should be possible with change in β^* & doubling number of bunches
- 2017 0.4 $\approx \mu b^{-1}$ Xe-Xe collisions by LHCb

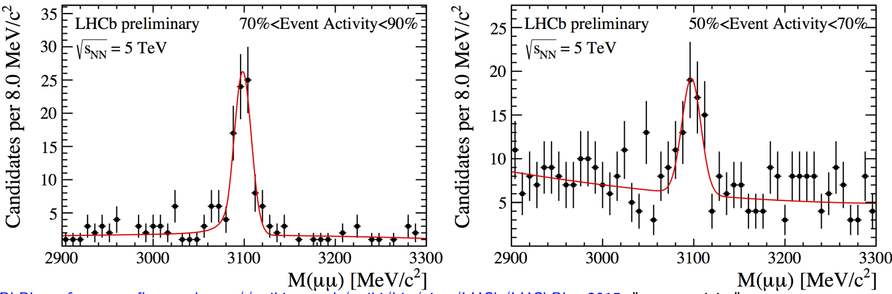
LHCb in PbPb collisions: centrality reach



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

- designed for low "pile-up" pp collisions: running in pp at average number of visible collisions of 1.0
- occupancy limitation in PbPb collisions:
  current tracking algorithms up to 50% in centrality

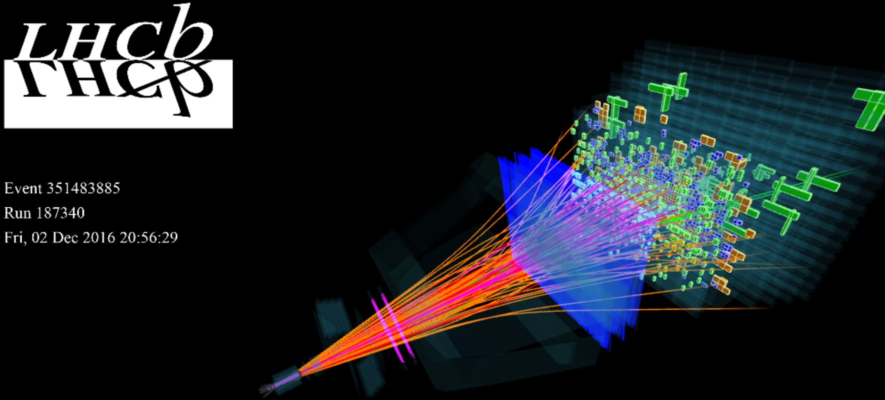
LHCb in PbPb collisions: J/ψ signal



PbPb performance figures: https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlots2015, "event-activity" corresponds to centrality percentiles.

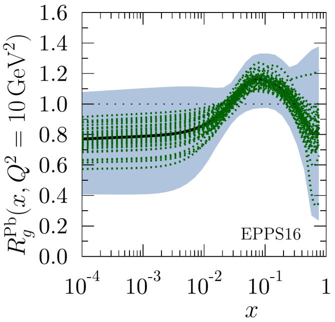
- clear signal up to edge of occupancy limit thanks to similar resolutions as in pp collisions
- data-driven efficiency determinations challenging
- prompt J/ψ pilot analysis knowledge will be combined with other analyses for publication

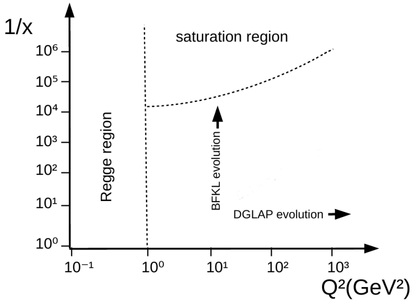
p–nucleus collisions in collider mode



2016 p–nucleus (pPb) event display
mean charged particle multiplicity per collision: about 3-4 $\times$ pp

p–nucleus: control & limits of collinear factorisation





left: taken from arXiv:1612.05741; right: modified version of graphic in "QCD and collider physics", Ellis, Stirling, Webber

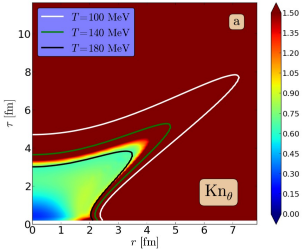
- **no HERA equivalent for lepton-nuclei**: parton flux **unconstrained** for LHC heavy-ion low-p heavy-quark production

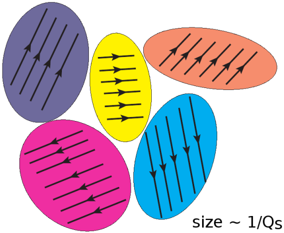
  total charm, beauty production in p-nucleus vital input for AA

- **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

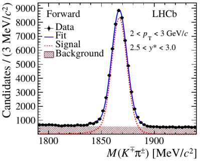


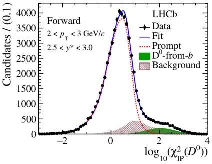


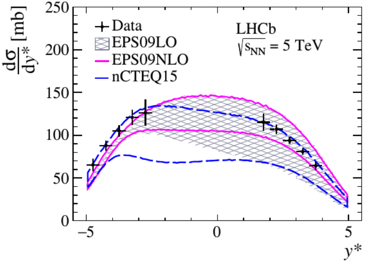
Left: taken from arXiv:1404.7327 $Kn = L_{micro}/L_{macro}$, already dN/dη =270! Right: taken from arXiv:1611.00329.

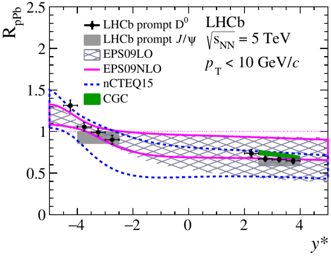
- correlations & bulk production@low-p_{T} & large multiplicity: **'same' patterns as in PbPb**, where sign for locally thermalised system
- **hydro** in large multiplicity pPb: set-up as in PbPb **describing data** despite **precondition doubts** arXiv:1705.03177
- colour glass condensate & color reconnections explanations not ruled out arXiv:1607.02496, arXiv:1705.00745
- alternative explanations via interference of multi-parton scatterings arXiv:1708.08241, string interactions arxiv:1710.09725

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





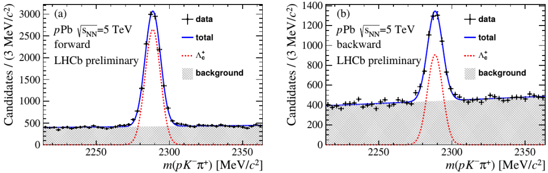


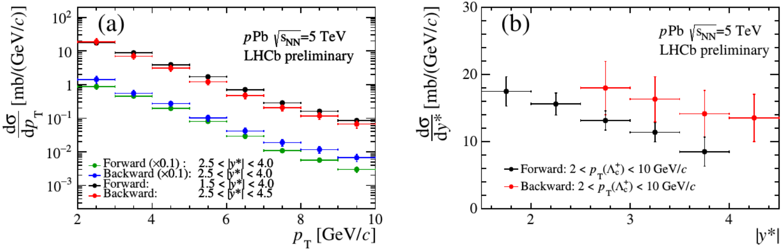


arXiv:1707.02750, JHEP 1710 (2017) 090.

- sensitive to gluons down to $x = 10^{-6}$
- consistency between colour glass condensate and nuclear PDF predictions: to be investigated
- assuming no other effect, constraining nPDFs in unexplored area: first fit and consistency with prompt and non-prompt J/ψ-data from LHCb at 8 TeV, see arxiv:1712.07024

Λ_C in pPb at $\sqrt{s_{NN}}$ =5 TeV

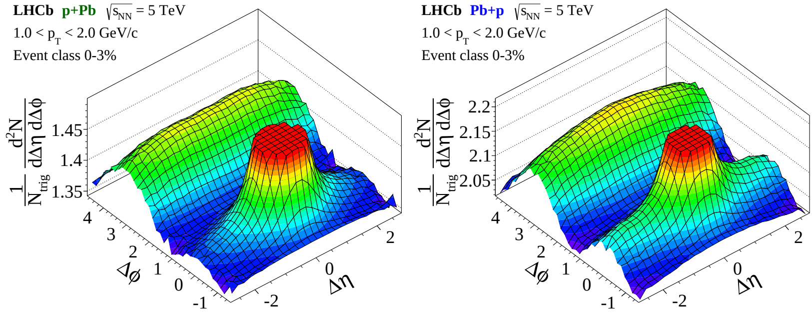




LHCb-CONF-2017–05.

- test of charm fragmentation in pPb: crucial input for hadronisation phenomenology

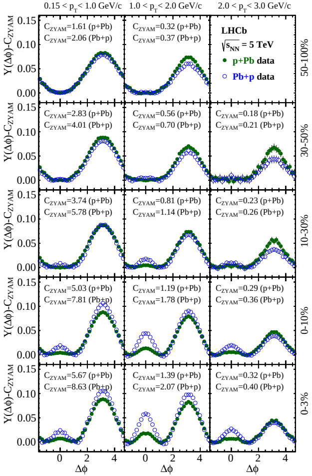
LHCb di-hadron correlations in pPb collisions

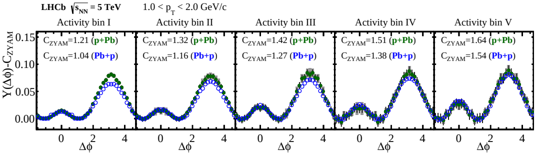


PLB 762 (2016) 473.

- unique forward acceptance with full tracking compared to other experiments
- 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





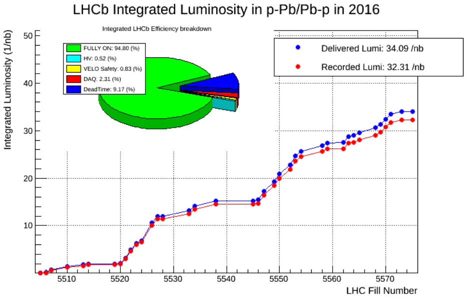
PLB 762 (2016) 473.

- increase of near-side correlation towards larger multiplicities and lower $p_{\rm T}$ 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 model comparison: kinematics favourable for application of saturation-based models

LHCb pPb collisions: 2016 run

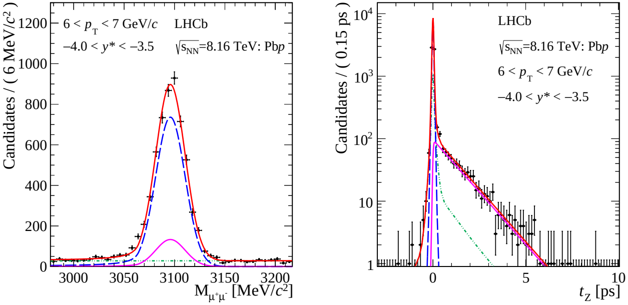
about 30 nb^{-1} at 8.16 TeV with Hadron PID and precision tracking/vertexing down to low-p_{T}: a factor 20 more than at 5 TeV in 2013
$\rightarrow$ unique opportunity to constrain nuclear effects in highly asymmetric system bridging between pp and pPb

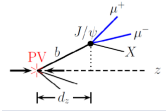
- ψ(2S) precision close to the one of J/ψ in 2013: confirm factorisation breaking, measure χ_c
- open charm and J/ψ: comparison with Drell-Yan
- double charm production and $c\bar{c}(c)$- correlations
- fully reconstructed open beauty and Υ family



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

First 2016 pPb result: prompt/non-prompt J/ψ



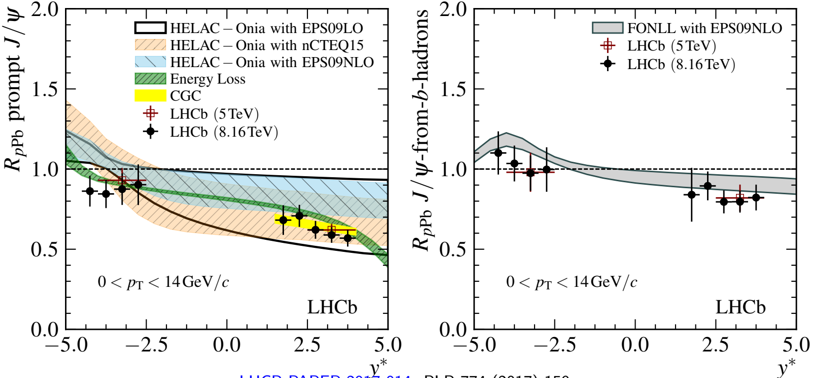


LHCB-PAPER-2017-014: PLB 774 (2017) 159.

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

- 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

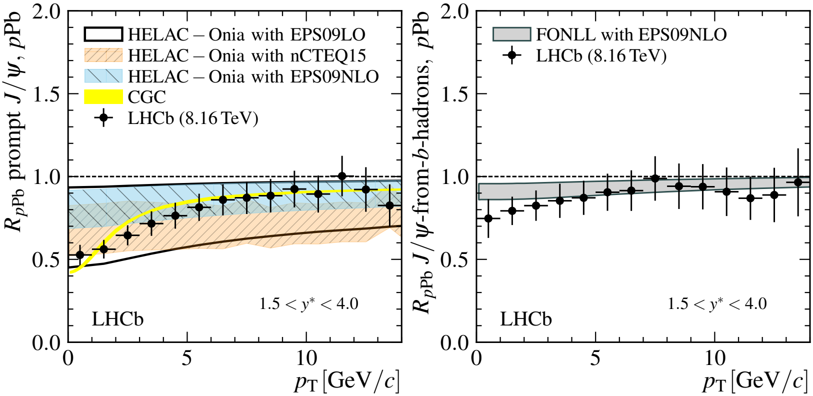
Prompt/nonprompt J/ψ in pPb at $\sqrt{s_{NN}}$ =8.16 TeV



LHCB-PAPER-2017-014: PLB 774 (2017) 159.

- collinear factorisation with HELAC-Onia arXiv:1610.05282, color glass condensate arXiv:1503.02789, coherent energy loss arXiv:1212.0434
- first precise B-production measurement in pPb down to $0p_{\mathrm{T}}$: crucial input for PbPb phenomenology
- consistent and similar powerful constraint on nPDF than D^0 at 5 TeV: arxiv:1712.07024

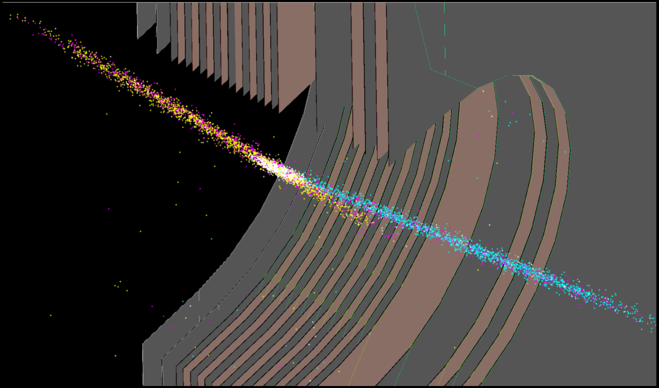
Prompt/nonprompt J/ψ in pPb at $\sqrt{s_{NN}} = 8.16$ TeV



LHCB-PAPER-2017-014: PLB 774 (2017) 159, $R_{pPb} = \sigma_{pPb,J/\psi}/(208 \cdot \sigma_{pp,J/\psi})$

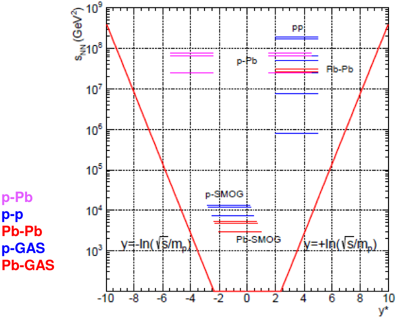
- collinear factorisation with HELAC-Onia arXiv:1610.05282, color glass condensate arXiv:1503.02789, coherent energy loss arXiv:1212.0434
- similar as at 5 TeV: no decision based on data possible
- for the first time precise B-production measurement in pPb

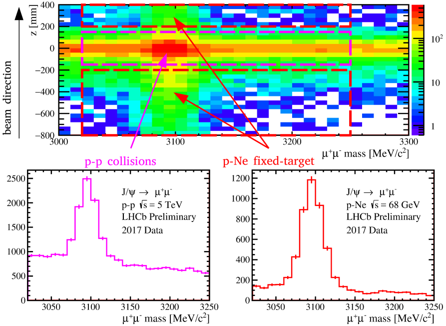
LHCb fixed-target



beam–gas & beam-beam vertices imaging both LHC beams
≈ 100 lower centre-of-mass energy than in collider mode

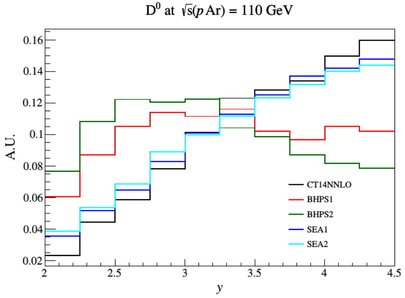
LHCb fixed target

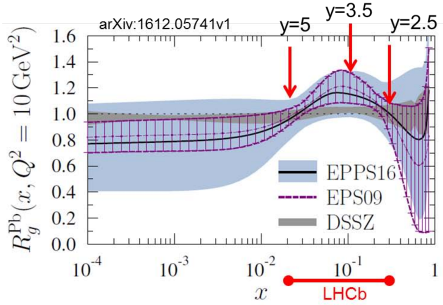




- noble gas injections with pressures 10^{-6}-10^{-7} mbar introduced for improved luminosity measurements
- used as internal gas target for p-gas and ion-gas collisions: He(A=4), Ne(A=20), Ar(A=40) used so far
- LHCb acceptance reaches close to midrapidity
- 2017 first parallel running of high-intensity pp data taking at 5 TeV and fixed-target mode: very successful, about a factor 10 higher luminosity than previous fixed-target runs in *p*Ne

Charm production in fixed-target collisions: unique constraints



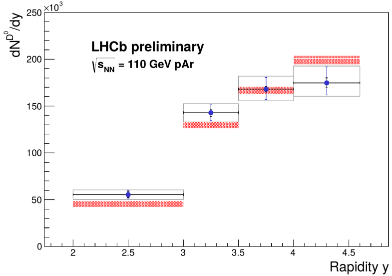


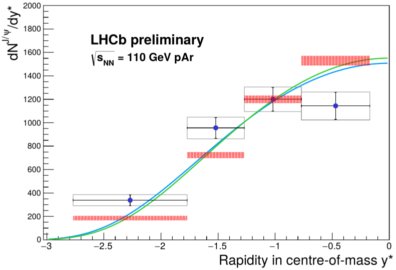
Left: figure by Philip Ilten link, considered pdf models based on CT14 from: Phys. Rev. D 93, 074008; right: figure from talk by Emilie Maurice at QM 2017

- sensitive to nuclear modification of parton distribution function & intrinsic charm
- relevant also to estimate μ-production in cosmic ray air showers

Charm production in fixed target collisions: first results

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

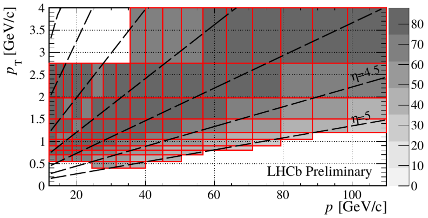


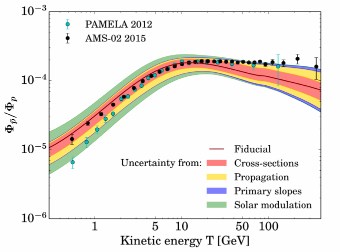


LHCb-CONF-2017-001, data in blue points, Pythia 8 with CT09MCS pdf, world-data parameterisation by Arleo et al. for charmonium.

- compared with normalised distributions from Pythia 8 with CT09MCS and from parameterisation of world-data by Arleo et al. for charmonium

Soft particle production in fixed-target

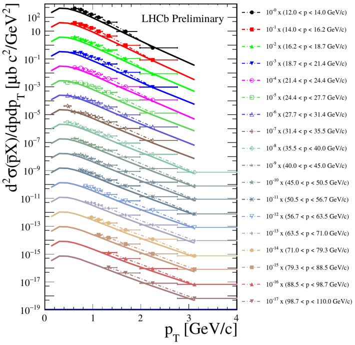




Left: kinematic bins of $\bar{p}$-cross section measurement in pHe LHCb-CONF-2017-002; right: arXiv:1504.04276.

- forward spectrometer geometry allows low p measurements at moderate track momenta
- in fixed-target mode: production studies close to midrapidity well suited for cosmic-ray physics references
- examplary application: constrain $\bar{p}$ production in pHe
  $\rightarrow$ important uncertainty for interpretation of AMS results in view of dark matter

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

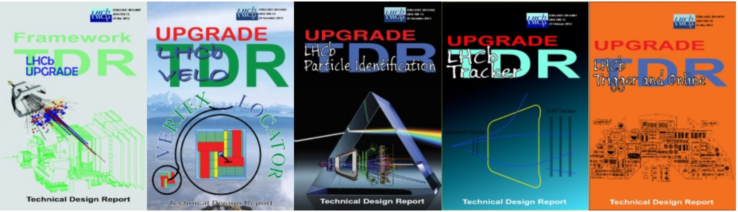


Statistical:	
Yields in data and PID calibration	0.7 – 10.8% (< 3% for most bins)
Normalization	2.5%
Correlated Systematic:	
Normalization	6.0%
Event and PV requirements	0.3%
PV reco	0.8%
Tracking	2.2%
Nonprompt background	0.3 – 0.7%
Residual vacuum background	0.1%
Uncorrelated Systematic:	
Tracking	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

LHCb upgrade and heavy-ion physics



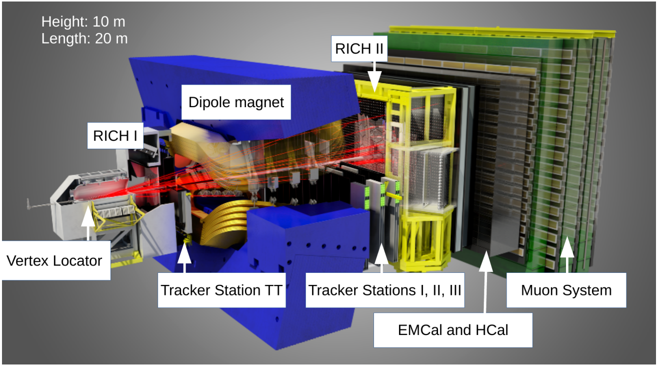
Framework TDR,Velo TDR, PID TDR,Tracker TDR,Trigger & Online TDR

- LHCb detector upgrade in 2019/2020
- run at $L_{inst} = 2 \times 10^{33}$ cm^{-2} s^{-1}: about a factor 5 larger than now
  $\rightarrow$ on average 5.2 visible pp collisions per bunch crossing instead ≈ 1 now
- process full pp input rate in HLT without hardware trigger
- tracker fully replaced: increased granularity
- silicon vertex locator from strip to pixel detector
- beneficial for heavy-ion related collision systems
- Pb–Pb centrality reach: studies ongoing in view of HL-LHC yellow report

Conclusions

- LHCb: fully instrumented spectrometer with unique kinematics with flexible trigger system
- nucleus-nucleus and proton-nucleus collisions in collider and fixed-target modes
- important *p*Pb and fixed-target results:
  - unique constraints on partonic content of nucleons & nuclei
  - soft & collective particle production
- much more to come

Back-up: LHCb designed as heavy-flavour precision experiment

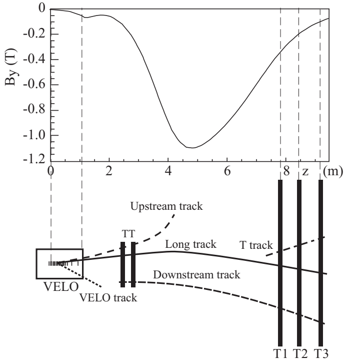


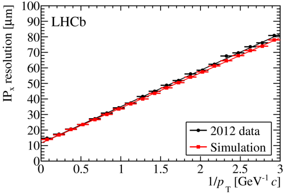
JINST 3 (2008) S08005.

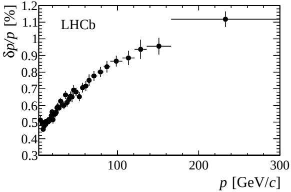
- collect large number of B-hadrons in small angular acceptance: about 27% of b-quarks within acceptance in pp collisions

Example: first observation of rare $B_S \to \mu^+\mu^-$ decay together with CMS Nature 522 (2015) 68, most precise single experiment measurement of the γ angle in the CKM matrix JHEP 12 (2016) 087

Back-up: LHCb tracking



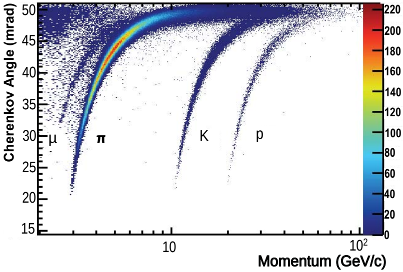


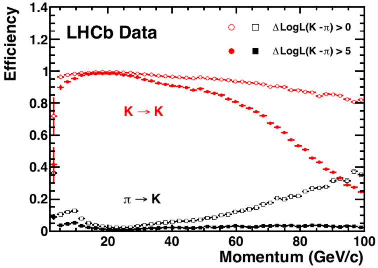


Int. J. Mod. Phys. A 30 1530022.

- VELO: silicon strip telescope down to radial distance to beam $r = 0.8\ cm$
- VELO+RICH1+silicon strip+ 4Tm dipole + straw tubes/silicon strips
- tracker with $\approx 30\%\ X_0$
- momentum resolution below 1% in wide range
- topological ID of charm and beauty hadrons down to 0 p_T: longitudinal boost

Back-up: LHCb particle identification

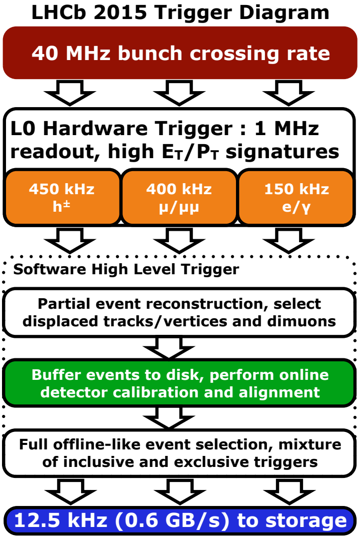




JINST 3 (2008) S08005

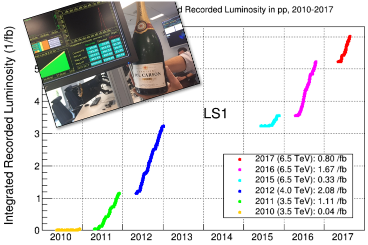
- 2 RICH systems with 2 radiators for charged track PID
- muon-ID behind calorimetry: $\varepsilon_{\mu\to\mu} \approx 97\%$ for $\varepsilon_{\pi\to\mu} \approx$ 1-3 % Mis-ID
- photon measurement & electron/photon-ID with calorimetry and preshower
  $\Delta m(\mu^+\mu^-, \mu^+\mu^-\gamma)$-resolution: 5 MeV$/c^2$ from $\chi_{c1,c2} \to J/\psi + \gamma$-decay with calorimeter

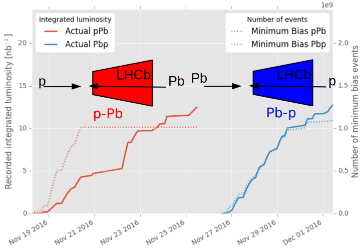
LHCb trigger system, data acquisition and calibration



- offline quality at the software trigger level since 2015
- analysis directly with trigger reconstruction output
- used for e.g. charm cross section measurement at 13 TeV JHEP 10 (2015) 172, JHEP 03 (2016) 159
- pPb/Pbp conditions: able to process all events in HLT
- PbPb conditions: recorded all events on tape; tracking up to ≈ 50 % centrality
- pAr, pHe fixed target: able to process all events in HLT

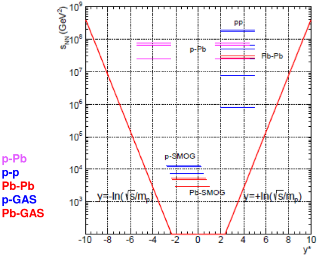
Back-up: Collision systems and running conditions in collider mode

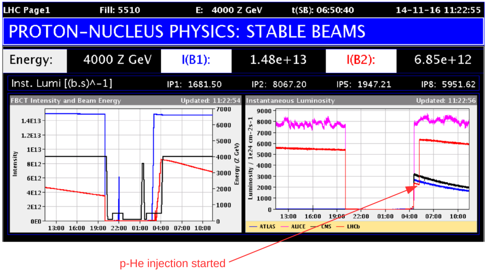




- luminosity levelling with ≈ 1 visible collisions per beam-beam encounter every 25 ns in pp: $L \approx 4 \times 10^{32}$ cm^{-2} s^{-1}
- 6 fb^{-1} from 2010-now at $\sqrt{s}$ =0.9,2.76,5,**7,8,13** TeV
- pPb/Pbp 2016: running at $\lesssim$ 200 kHz interaction rate with $\lesssim$ 0.1 visible collisions per beam-beam encounter: 34.4 nb^{-1} in two beam configurations at $\sqrt{s_{NN}}$ =8.16 TeV, 0.5 nb^{-1} at $\sqrt{s_{NN}} = 5$ TeV in one configuration
- 1.6 nb^{-1} at $\sqrt{s_{NN}} = 5$ TeV in both beam configurations accumulated in 2013
- in PbPb 2015: luminosity equivalent to about 50 million hadronic minimum bias collisions

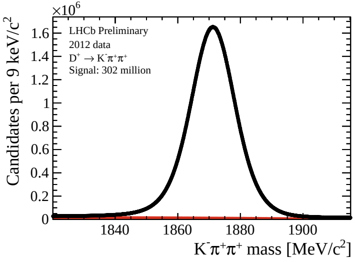
Back-up: Collision systems and running conditions in fixed-target collisions

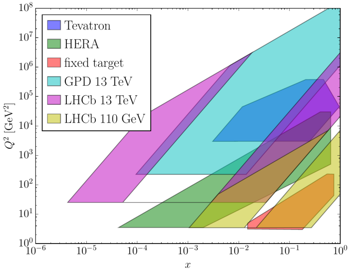




- noble gas injected in interaction region:
  improve luminosity measurement by beam imaging J. Instrum. 9 (2014) P12005
- residual gas pressure in beam pipe increased by 2 orders of magnitude: $O(10^{-7})$ mbar
- used for fixed target with proton and Pb beams: LHCb ≈ midrapidity rapidity coverage at lower collision energies
- *p***He,** *p***Ar**, *p*Ne, *Pb*Ne and *Pb***Ar** data samples available
- *p*Ar and *p*He $O(\text{nb}^{-1})$ integrated luminosities

Why QCD studies with LHCb?

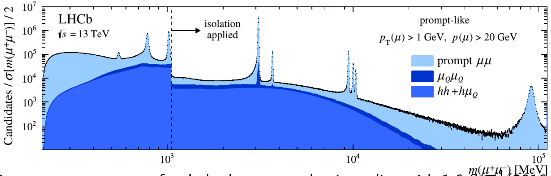


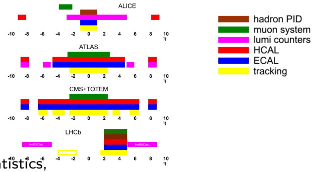


Left: LHCb-CONF-2016-005.

- largest recorded c, b-hadron yields – hard quark mass scale as opportunity for QCD studies:
  - effective field theory for bound state properties
  - test diagrammatic approaches & factorisation schemes as low as possible in Q^2
- forward acceptance at the LHC: unique kinematics in $Q^2 - x$-plane
- the only fixed-target programme at the LHC: unique kinematics

Back-up: Why QCD studies with LHCb?

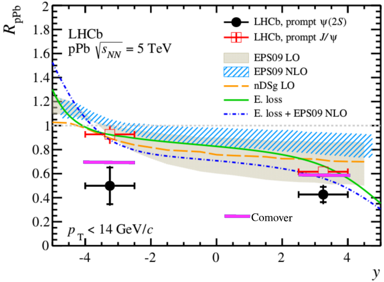


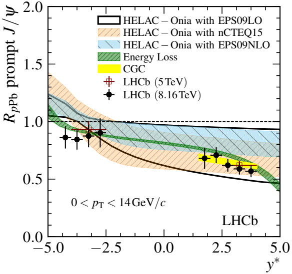


dimuon mass spectrum for dark photon search trigger line with 1.6 fb^{-1} (2016 statistics, https://arxiv.org/abs/1710.02867), accepted by PRL without comment.

- highest software trigger rate at the LHC: flexible high-rate selections down to low p_T
- only detector at the LHC with charged hadron-id, muon-id and calorimeters in same acceptance
- about 1 collision per bunch crossing in pp: clean events also for low-Q^2 & possibility of exclusive production studies
- "overdesigned" trigger for heavy-ion beam rates

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

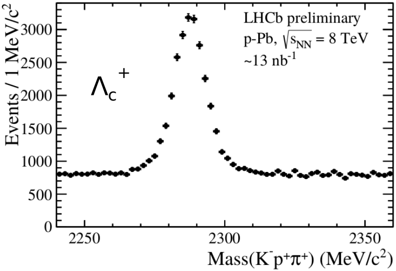


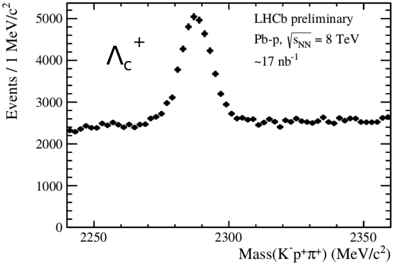


5 TeV: JHEP 02 (2014) 072, JHEP 1603 (2016) 133; 8.16 TeV arxiv:1706.07122 PLB 774 (2017) 159.

- 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

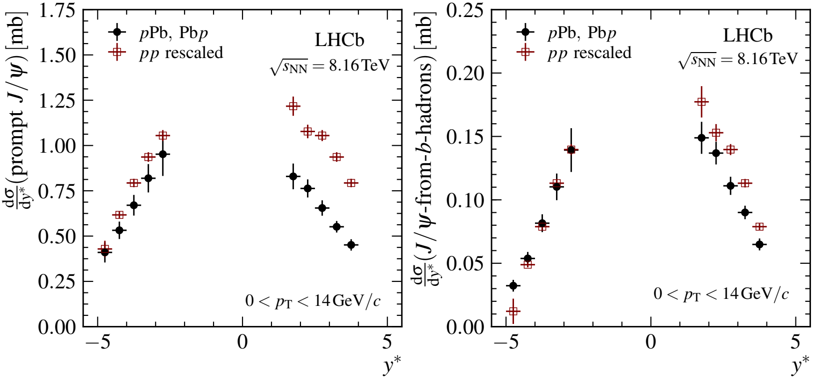
Back-up: 2016 *p*Pb run: open charm baryons





- large data sample down to $p = 0$ both in *p*Pb (left) and Pb*p* (right)

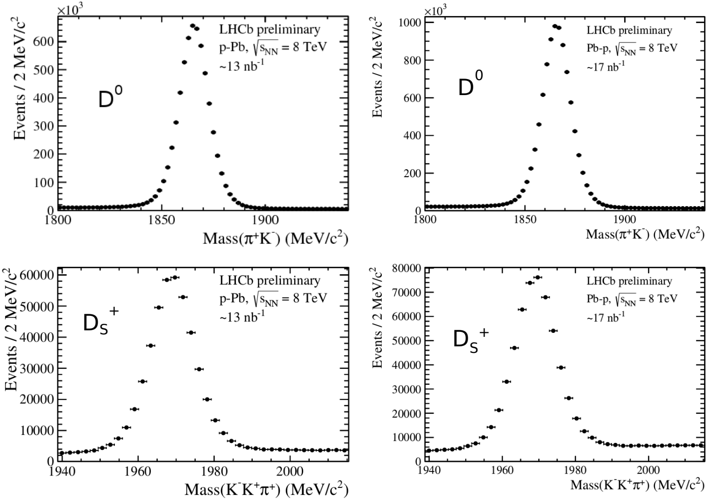
Back-up: Prompt/nonprompt J/ψ in pPb at $\sqrt{s_{NN}} = 8.16$ TeV



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

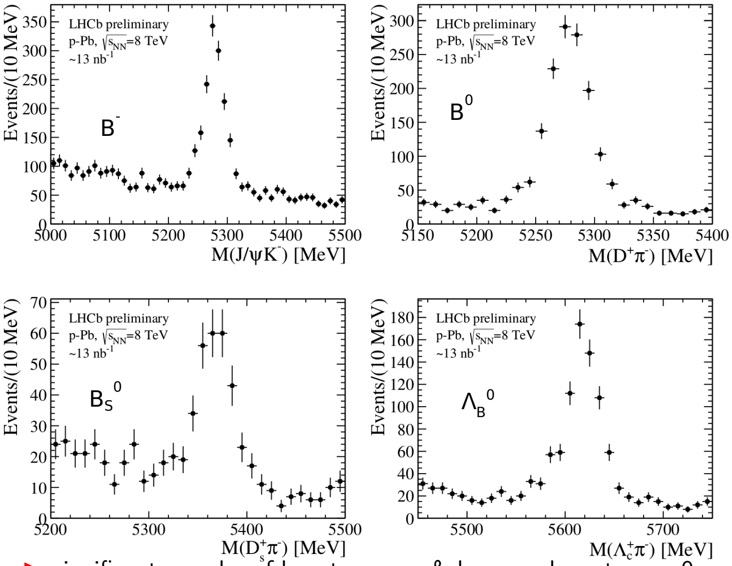
- pp reference cross section from inter- (in energy) and extrapolation (in rapidity) of measurements at $\sqrt{s_{NN}} = 7, 8, 13$ TeV
- comparison of pPb cross section at $\sqrt{s_{NN}}$ =8.16 TeV and $pp \times 208$ cross section
- strong modifications for prompt J/ψ
- modifications smaller for large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

Back-up: 2016 pPb run: open charm



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

Back-up: 2016 pPb run: open beauty



- significant samples of beauty meson & baryons down to $p = 0$
- publication in preparation