Studies of production in the forward region with LHCb

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– on behalf of the LHCb collaboration –

Outline

- The LHCb experiment
- Energy flow and multiplicities
- Identified particles
- Nuclear effects
- Summary and outlook

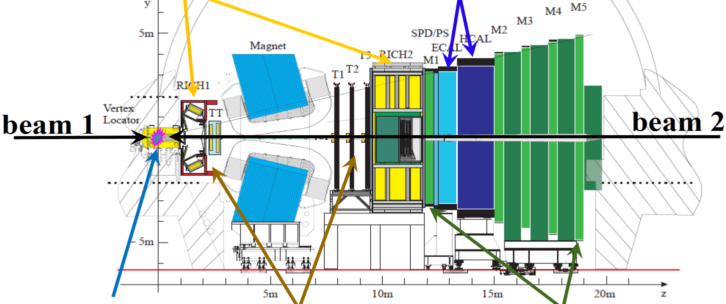
1. The LHCb Experiment

JINST 3 (2008) S08005

Pseudorapidity acceptance
$2 < \eta < 5$

RICH1 & RICH2
$\epsilon(K \to K) \sim 95\%$
$\pi \to K$ **mis-id:** $\sim 5\%$

Calorimeters
ECAL: $\sigma_E/E \sim 1\% + 10\%/\sqrt{E[\text{GeV}]}$

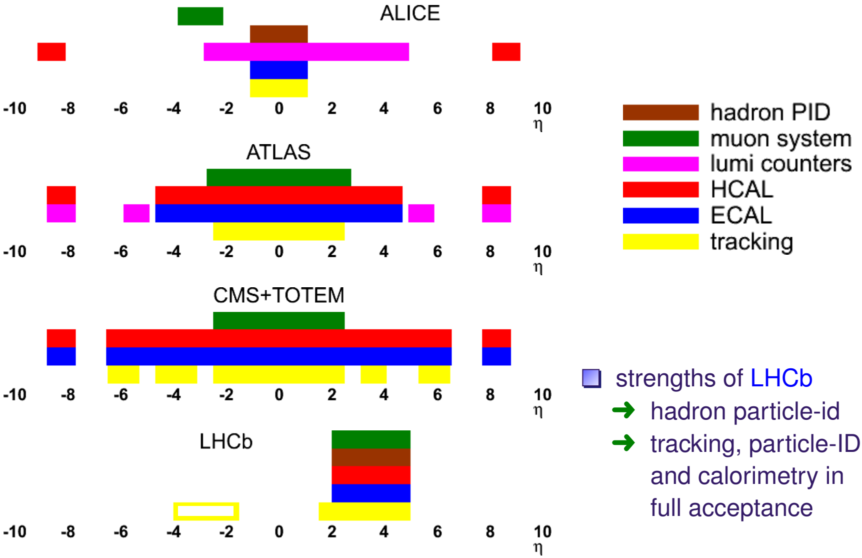


VELO
$\sigma_{IP} \sim 20\ \mu\text{m}$
for high-p_T **tracks**
bwd acc. $-4 < \eta < -1.5$

Tracking System
$\Delta p/p = 0.4\%@5\ \text{GeV}/c$
to $0.6\%@100\ \text{GeV}/c$

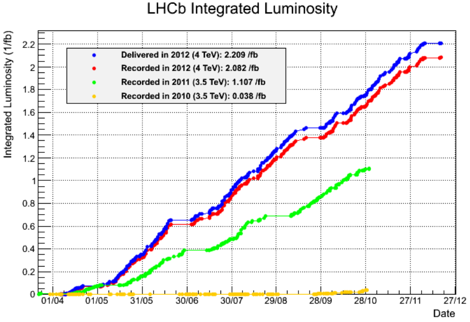
Muon System
$\epsilon(\mu \to \mu) \sim 97\%$
$\pi \to \mu$ **mis-id:** $1 \sim 3\%$

Angular coverage of the LHC experiments



- strengths of LHCb
  - ➜ hadron particle-id
  - ➜ tracking, particle-ID and calorimetry in full acceptance

Data taking history



year	int.luminosity	E[TeV]
2009	6.8 μb^{-1}	0.9
2010	0.3 nb^{-1}	0.9
2010	37 pb^{-1}	7
2011	0.1 pb^{-1}	2.76
2011	1 fb^{-1}	7
2012	2 fb^{-1}	8
2013	1.3 nb^{-1}	5 (pA)
2013	0.6 nb^{-1}	5 (Ap)
2013	3 nb^{-1}	2.76

- DAQ efficiency $\approx$ 95%
- instantaneous luminosity up to $L = 4 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$
  - ➜ twice design value at double the nominal bunch spacing
  - ➜ luminosity leveling for LHCb by beam steering
- a total of about 2×10^{14} pp-collisions scrutinized

Published results on forward production

- global event properties of pp collisions
  - ➜ EPJC72(2012)1947 — Measurement of charged particle multiplicities at $\sqrt{s} = 7$ TeV
  - ➜ EPJC73(2013)2124 — Measurement of the forward energy flow at $\sqrt{s} = 7$ TeV
- light quarks and strangeness in pp collisions
  - PLB693(2010)69 — Prompt K_S^0 production in pp collisions at $\sqrt{s} = 0.9$ TeV
  - PLB703(2011)267 — Measurement of the inclusive ϕ cross-section at $\sqrt{s} = 7$ TeV
  - JHEP08(2011)034 — Measurement of V^0 production ratios at $\sqrt{s} = 0.9$ and 7 TeV
  - ➜ EPJC72(2012)2168 — Prompt hadron production ratios at $\sqrt{s} = 0.9$ and 7 TeV
- proton-lead collisions at $\sqrt{s_{\mathrm{NN}}} = 5$ TeV
  - ➜ arXiv:1308.6729 — Study of J/ψ production and cold nuclear matter effects
- open charm and charmonium in pp collisions
  - NPB871(2013)1 — Prompt charm production in pp collisions at $\sqrt{s} = 7$ TeV
  - EPJC71(2011)1645 — J/ψ production in pp collisions at $\sqrt{s} = 7$ TeV
  - EPJC72(2012)2100 — $\psi(2S)$ meson production in pp collisions at $\sqrt{s} = 7$ TeV
  - JHEP02(2013)041 — J/ψ production in pp collisions at $\sqrt{s} = 2.76$ TeV
  - JHEP06(2013)064 — Production of J/ψ and Υ mesons in at $\sqrt{s} = 8$ TeV
  - JPG40(2013)045001 — Exclusive J/ψ and $\psi(2S)$ production at 7 TeV

2. Energy Flow and Multiplicities

➜ *Energy Flow: energy emitted per event into a given η-interval*

Energy Flow: $$\frac{1}{N_{int}}\frac{dE}{d\eta} = \frac{1}{\Delta\eta}\left(\frac{1}{N_{int}}\sum_{i=1}^{N_{part,\eta}} E_{i,\eta}\right)$$

- ➜ part of underlying event
- ➜ sensitive to multi-parton interactions & parton radiation
- ➜ comparison to PYTHIA and cosmic-ray event generators

❖ analysis for different event classes:

- inclusive minimum bias: ≥ 1 track in $1.9 < \eta < 4.9$ and $p > 2\,\mathrm{GeV}/c$
- hard scattering: ≥ 1 track in $1.9 < \eta < 4.9$ and $p_T > 3\,\mathrm{GeV}/c$
- diffractive enriched: no tracks in $-3.5 < \eta < -1.5$ (rapidity gap)
- non-diffractive enriched: ≥ 1 tracks in $-3.5 < \eta < -1.5$ (no gap)

Energy Flow: data vs PYTHIA

➜ *total EF = (charged+neutral)EF*

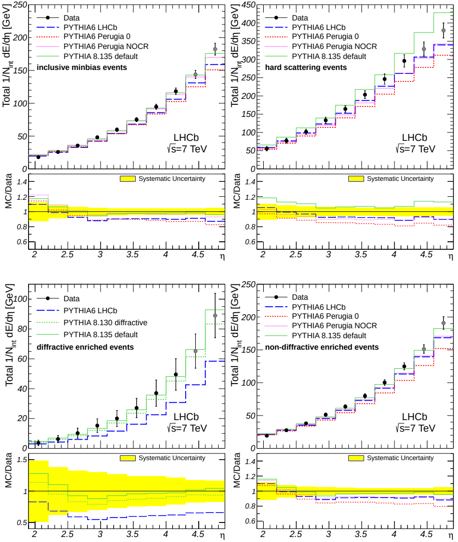
- Energy Flow increases with momentum transfer

  $$EF_{diff} < EF_{incl} < EF_{ndiff} < EF_{hard}$$

- highest sensitivity at large η
- uncertainties:
  - ➜ dominated by systematics
  - ➜ smallest at large η

PYTHIA 6: Energy Flow is
- ➢ overestimated at small η
- ➢ underestimated at large η

PYTHIA 8.135 default:
- ➢ except for hard scattering the Energy Flow is well described for all samples

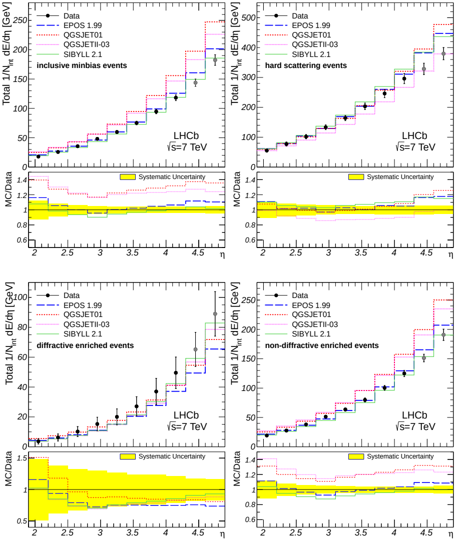


Eur.Phys.J.C73(2013)2124

Energy Flow: data vs cosmic ray models

➜ *models not tuned to LHC(b)*

- ➢ EPOS & SYBILL:
  good description of EF for inclusive and non-diffractive events
- ➢ QGSJET models:
  overestimated EF for inclusive and non-diffractive events; good description of hard scattering
- ➢ best description by SYBILL
- ➢ all models underestimate the EF of diffractive events



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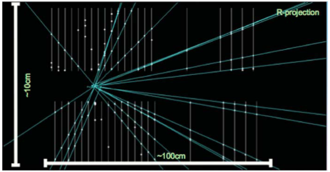
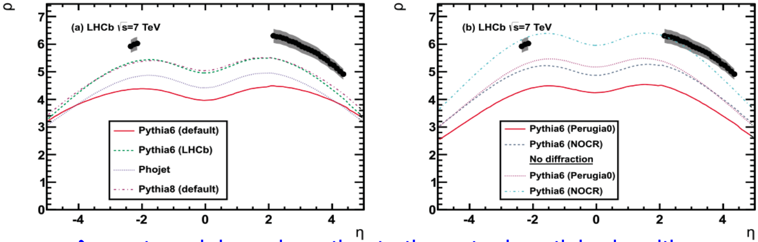
Charged particle multiplicities

➜ *VELO based measurement*

- no magnetic field
  - ➜ only measurement of direction
  - ➜ tracks as a function of η
- events with ≥ 1 tracks in forward acceptance
  - ➜ inclusive minimum bias interactions
  - ➜ hard interactions with ≥ 1 track with $p_T > 1\,\mathrm{GeV}/c$



❖ charged particle density per events vs η

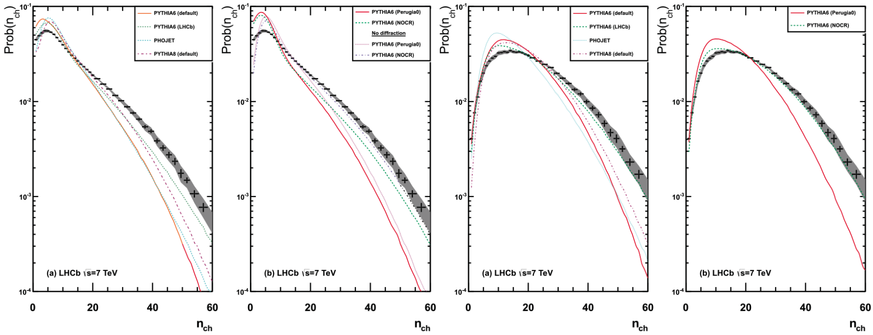


Eur.Phys.J.C72(2012)1947

➜ most models underestimate the actual particle densities

Multiplicity distributions for $2.0 < \eta < 4.5$

inclusive minimum bias	hard interactions



Eur.Phys.J.C72(2012)1947

- none of the models studied is fully able to describe the distributions
- models underestimate multiplicity in the forward region
- agreement better for hard interactions

➜ *particle production ratios as a function of y and p_T*

- antiparticle/particle ratios and ratios of different particle species

$$\frac{\pi^-}{\pi^+}\,,\ \frac{K^-}{K^+}\,,\ \frac{\bar{p}}{p} \quad \text{and} \quad \frac{p+\bar{p}}{\pi^+ + \pi^-}\,,\ \frac{K^+ + K^-}{\pi^+ + \pi^-}\,,\ \frac{p+\bar{p}}{K^+ + K^-}$$

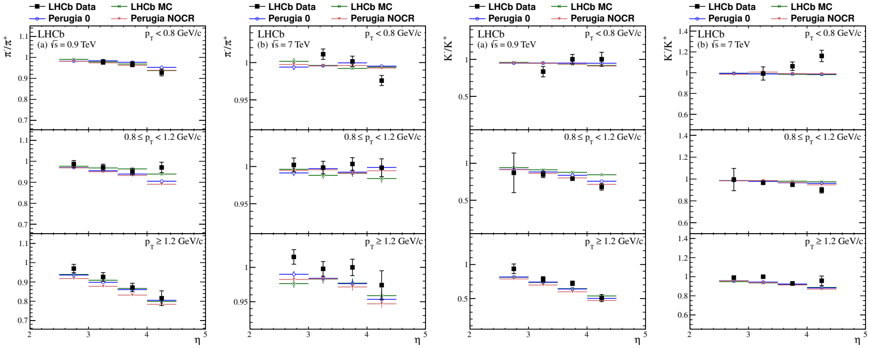
- many systematic uncertainties cancel
- lots of information about the hadronization process, for example:
  - ➜ baryon number transport from $\bar{p}/p$
  - ➜ baryon suppression from baryon/meson ratios
  - ➜ strangeness suppression from kaon/pion ratios

❖ experimental aspects:

- ➢ results based on 0.3 nb^{-1} at $\sqrt{s} = 0.9$ TeV and 1.8 nb^{-1} at $\sqrt{s} = 7$ TeV
- ➢ PID efficiencies from $K_S^0 \to \pi^+\pi^-$, $\Lambda \to p\pi^-$, $\bar{\Lambda} \to \bar{p}\pi^+$ and $\phi \to K^+K^-$
- ➢ dominant uncertainties from PID due to limited size of calibration sample

Antiparticle/particle ratios

π^-/π^+		K^-/K^+	
$\sqrt{s} = 0.9\,\mathrm{TeV}$	$\sqrt{s} = 7\,\mathrm{TeV}$	$\sqrt{s} = 0.9\,\mathrm{TeV}$	$\sqrt{s} = 7\,\mathrm{TeV}$

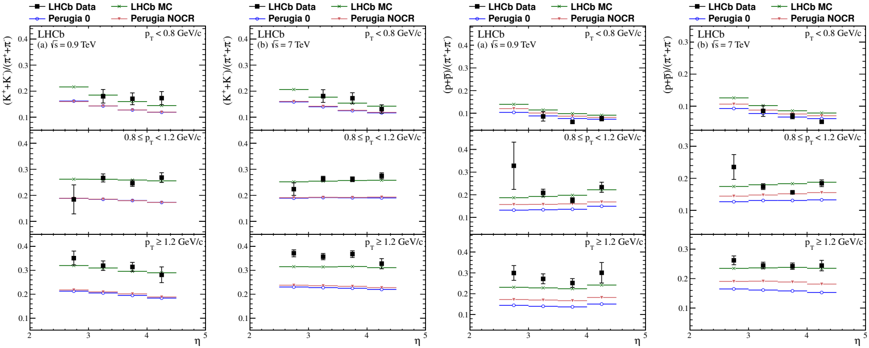


Eur.Phys.J.C72(2012)2168

- ➜ charge ratio drops towards larger rapidities (proton beam)
- ➜ effect more pronounced at higher p_T
- ➜ general behaviour reproduced by PYTHIA tunes

Ratios between particle species

$(K^+ + K^-)/(\pi^+ + \pi^-)$		$(\bar{p} + p)/(\pi^+ + \pi^-)$	
$\sqrt{s} = 0.9\,\text{TeV}$	$\sqrt{s} = 7\,\text{TeV}$	$\sqrt{s} = 0.9\,\text{TeV}$	$\sqrt{s} = 7\,\text{TeV}$



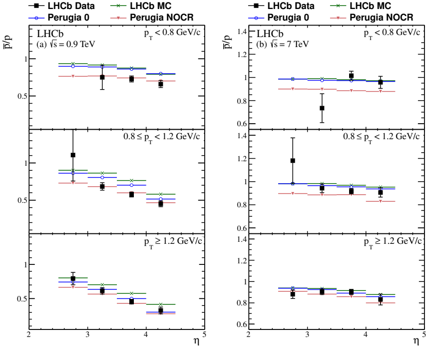
Eur.Phys.J.C72(2012)2168

- ➜ strangeness suppression very similar to baryon suppression
- ➜ less suppression at larger p_T
- ➜ data best described by LHCb-tune of PYTHIA

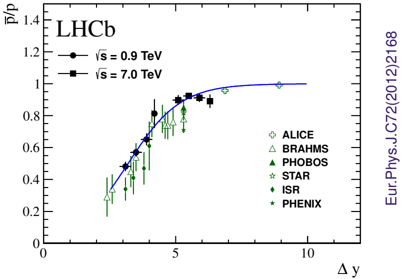
Baryon number transport

$\bar{p}/p$

$\sqrt{s} = 0.9\,\text{TeV}$ $\sqrt{s} = 7\,\text{TeV}$



➜ *study also p_T-integrated ratios:*

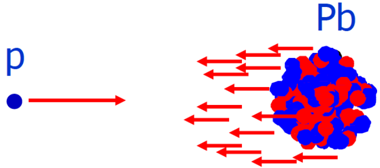


rapidity loss: $\Delta y = y_{\text{beam}} - y$

$y_{\text{beam}} = 8.9(6.9)$ at $\sqrt{s} = 7(0.9)$ TeV

- ➜ scaling behaviour as a function of rapidity loss
- ➜ fit to LHCb&ALICE data based in *Regge-model* of baryon transport

→ *measure J/ψ production in pA and compare to pp*



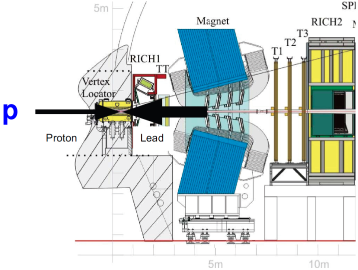
- pA collisions are an ideal laboratory to probe cold nuclear effects
- needed for the interpretation of quark-gluon-plasma signatures in heavy-ion collisions
- use J/ψ mesons to probe the hadronic environment
- differentiate between prompt J/ψ and J/ψ from b
  - → possible handle to disentangle shadowing and energy loss

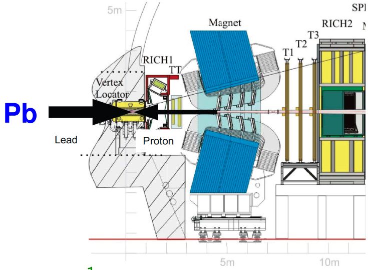
→ cross-section ratios:

nuclear modification factor: $$R_{pA}(y) = \frac{1}{A} \cdot \frac{d\sigma_{pA}/dy}{d\sigma_{pp}/dy}$$

forward-backward asymmetry: $$R_{FB}(y) = \frac{R_{pA}(+|y|)}{R_{pA}(-|y|)}$$

- positive rapidity in direction of the proton
- pp cross-section cancels in R_{FB}
- exploit asymmetric layout of LHCb to measure forward and backward

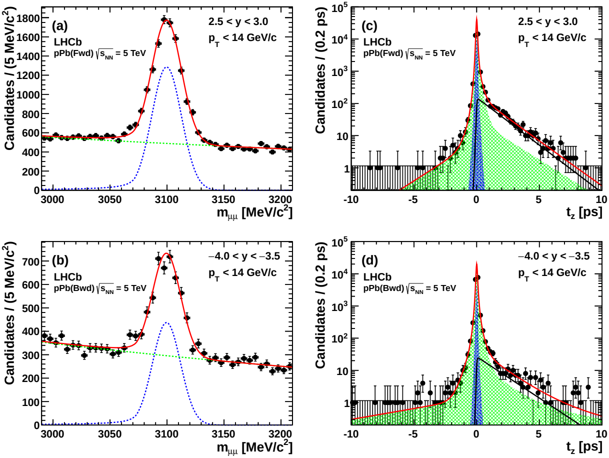




results from 1.6 nb^{-1} pPb-data recorded in 2013 →

Separating prompt and delayed components

❖ simultaneous fit of mass and pseudo-proper-time $t_z = (z_{J/\psi} - z_{PV}) \cdot M_{J/\psi}/p_z$



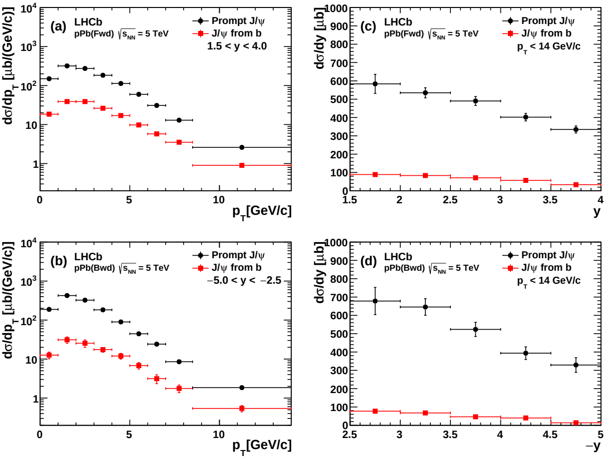
pA collisions:
forward hemisphere
$2.5 < y < 3.0$
$p_T < 14\,\mathrm{GeV}/c$

Ap collisions:
backward hemisphere
$-4.0 < y < -3.5$
$p_T < 14\,\mathrm{GeV}/c$

arXiv:1308.6729

Single differential cross-sections

❖ center-of-mass energy $\sqrt{s} = 5\,\text{TeV}$, transverse momentum $0 < p_T < 14\,\text{GeV}/c$



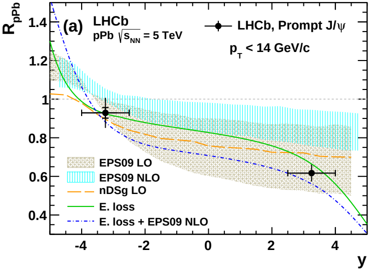
arXiv:1308.6729

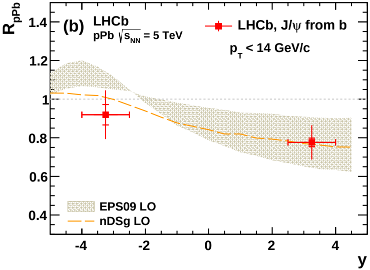
pA collisions:
forward hemisphere
$1.5 < y < 4.0$

Ap collisions:
backward hemisphere
$-5.0 < y < -2.5$

Results: nuclear modification factors

➜ *common range of forward and backward acceptance:* $2.5 < |y| < 4.0$



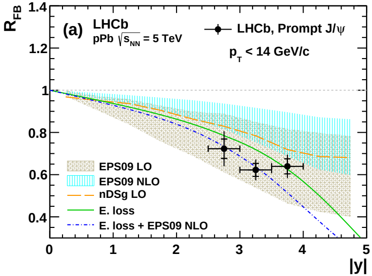


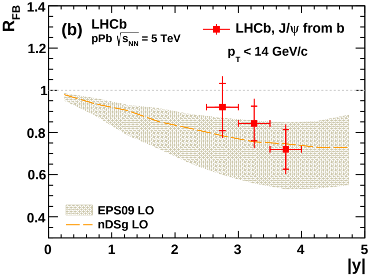
arXiv:1308.6729

- results require interpolation of pp cross-section to $\sqrt{s} = 5\,\text{TeV}$
- $R_{pPb} \neq 1$: the nucleus is not a loose collection of independent nucleons
- B-mesons less affected than prompt J/ψ: smaller systems less affected
- energy loss and shadowing are about equally important
- J/ψ data agree with "energy loss + NLO shadowing"

Results: forward-backward asymmetries

➜ *interpolated pp cross-section not required*





arXiv:1308.6729

- differential measurement in $|y|$
- same conclusions as for R_{pPb}
  - ➜ $R_{FB} \neq 1$: the nucleus is not a loose collection of independent nucleons
  - ➜ B-mesons less affected than prompt J/ψ: smaller systems less affected
  - ➜ energy loss and shadowing are about equally important
  - ➜ J/ψ data agree with "energy loss + NLO shadowing"

5. Summary and Outlook

➜ *LHCb also has a very wide QCD-related physics program. . .*

- studies of global event properties
  - ➜ forward energy flow and multiplicities not well described by PYTHA6
  - ➜ cosmic ray models appear to do better
- production ratios of identified particles
  - ➜ antiparticle/particle ratios generally well described
  - ➜ strangeness and baryon suppression too strong in many models
  - ➜ scaling of baryon number transport with rapidity difference
- study of proton-ion collisions probes cold nuclear effects
  - ➜ data show clear evidence for energy-loss and shadowing
  - ➜ $c\bar{c}$ and $b\bar{b}$ results may be able to disentangle the two contributions
- many subjects not covered here
  - ➜ cross-sections for identified particles, Drell-Yan production, CEP, . . .

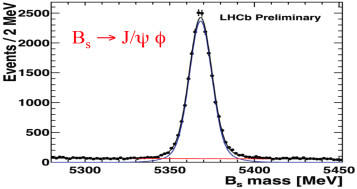
BACKUP

References to cosmic ray models

- T. Pierog and K.Werner,
  EPOS model and ultra high energy cosmic rays,
  Nucl. Phys. Proc. Suppl. 196 (2009) 102,
  arXiv:0905.1198.
- S. Ostapchenko,
  Status of QGSJET,
  AIP Conf. Proc. 928 (2007) 118,
  arXiv:0706.3784.
- E.-J. Ahn et al.,
  Cosmic ray interaction event generator SIBYLL 2.1,
  Phys. Rev. D80 (2009) 094003,
  arXiv:0906.4113.

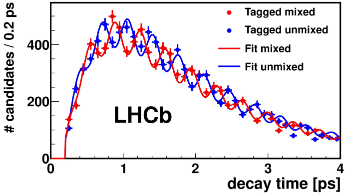
Physics performance

- excellent particle-ID and mass resolution for complex decays



➜ B-mass resolution:
$\sigma(m_B) = 8\,\mathrm{MeV}/c^2$
for $B_s \to J/\psi X$
with J/ψ mass constraint

- excellent particle-ID, vertex- and proper-time resolution

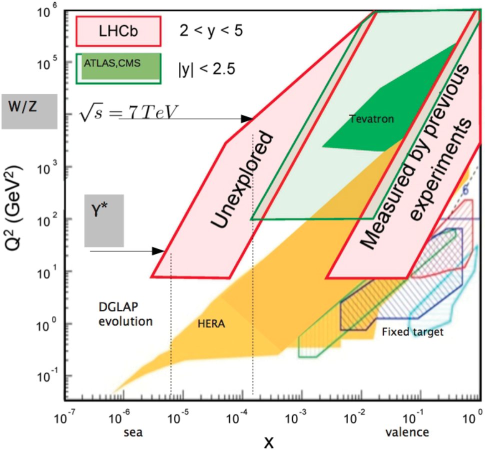


➜ proper time resolution:
$\sigma_t \sim 45\,\mathrm{fs}$
for B_s-mixing

❖ polarity switching of dipol magnet allows to control systematics

Drell-Yan Production

➜ LHCb physics reach



❖ kinematics

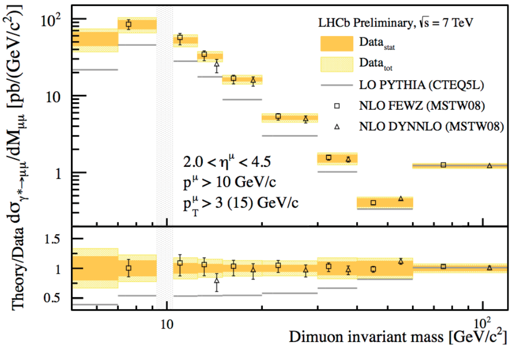
$$x_1 x_2 = \frac{m^2}{s} \quad \text{and} \quad \frac{x_1}{x_2} = e^{2y}$$

➜ small masses test small x

➜ forward rapidity means large asymmetries in x and thus sensitivity to even smaller values

❖ LHCb allows to probe PDFs in a completely unexplored regime!

→ Drell-Yan di-muon cross-section vs invariant mass (LHCb-CONF-2012-013)



- $q\bar{q} \rightarrow \gamma^* \rightarrow \mu^+\mu^-$
- $37\,\mathrm{pb}^{-1}$ recorded in 2010
- $5 < M_{\mu\mu} < 120\,\mathrm{GeV}/c^2$
- isolated high-p_T muons

- leading order predictions systematically too low
- NLO predictions in good agreement with the data