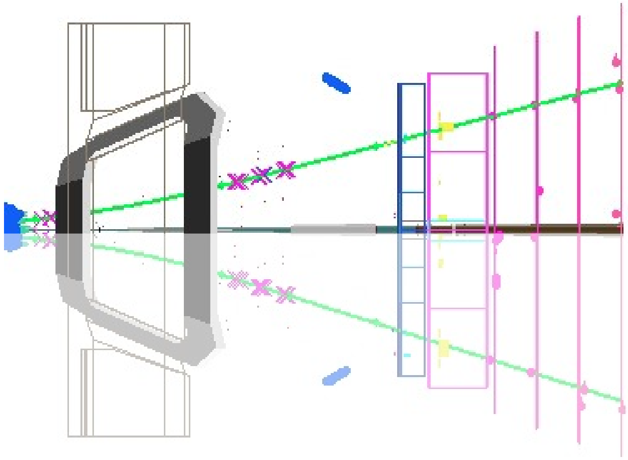
QCD and electroweak measurements in the forward region at LHCb

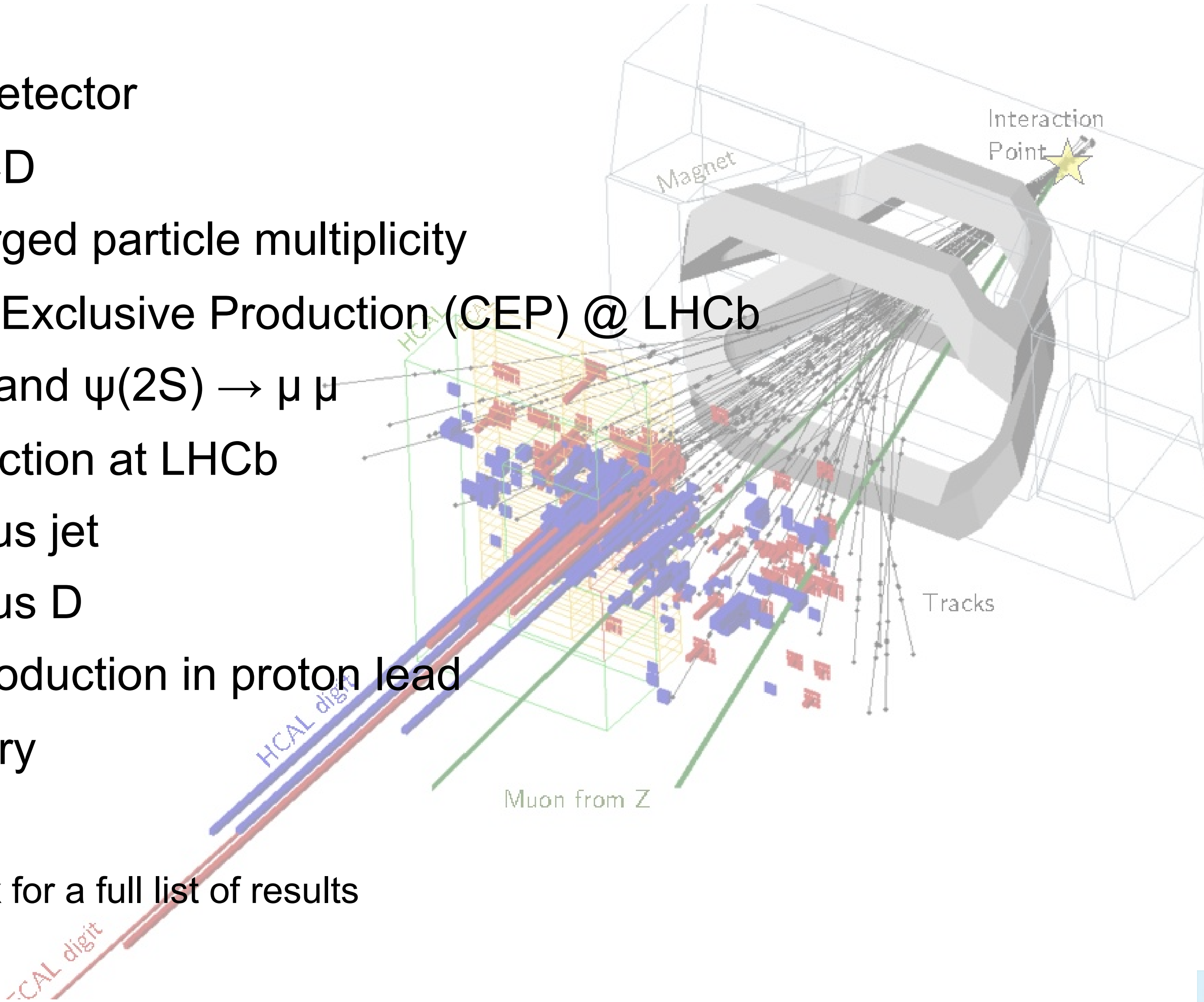


Rencontres de Blois, 18-23 May 2014

Katharina Müller
on behalf of the LHCb collaboration

University of Zurich[UZH]
Department of Physics

- LHCb detector
- Soft QCD
  - charged particle multiplicity
- Central Exclusive Production (CEP) @ LHCb
  - J/ψ and ψ(2S) → μ μ
- Z production at LHCb
  - Z plus jet
  - Z plus D
  - Z production in proton lead
- Summary

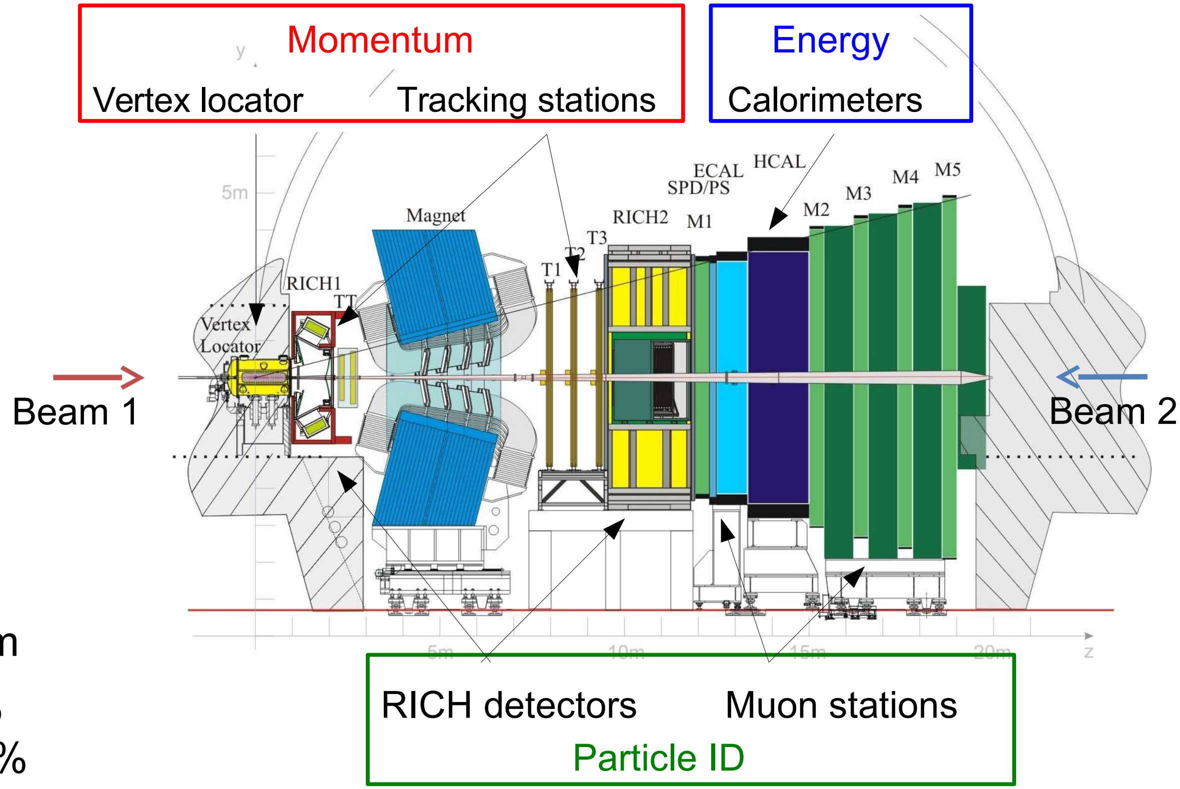


See appendix for a full list of results

LHCb Detector

JINST3 (2008) S08005

Fully instrumented in the forward region (2 < η < 5)
some detection capability in backward region (-3.5 < η < -1.5)



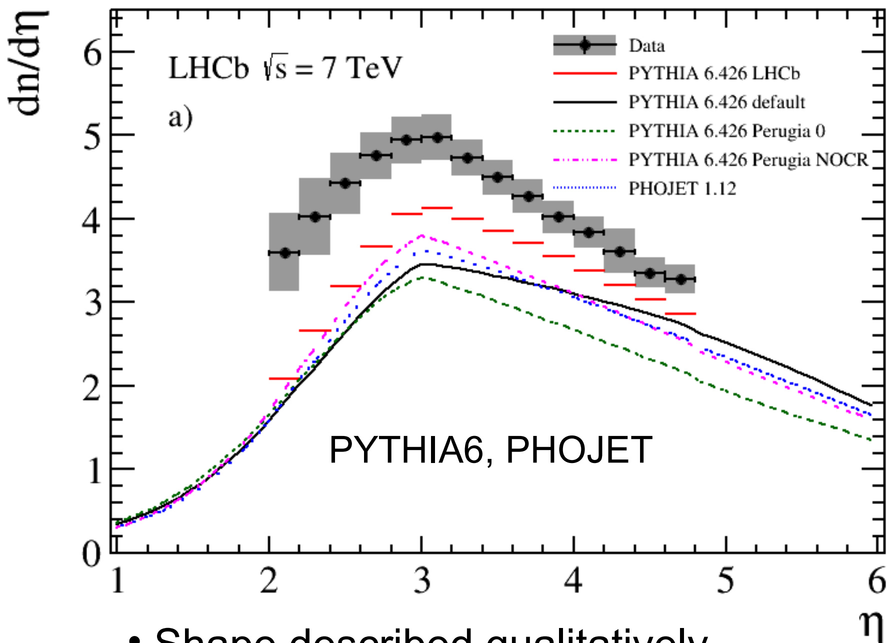
- Tracking: $\sigma_p/p \sim 0.4\text{-}0.6\%$
- Vertex resolution:
  $\sigma_{xy} \sim 15\mu m$, $\sigma_z \sim 80\mu m$
- Muon ID ε=97%; mis-id: 0.7%
- Kaon ID ε=90%; π mis-id< 5%

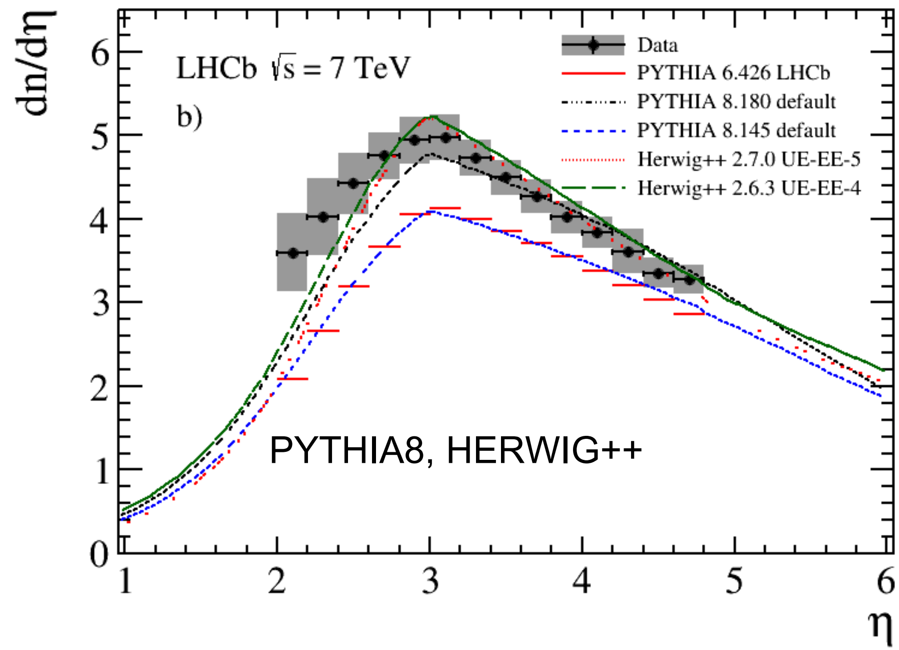
- Analyses based on
  - 2010 @ 7 TeV low multiplicity runs: charged particle multiplicity
  - 2011 1 fb^{-1} @ 7 TeV: CEP, Z plus jet, Z plus D
  - 2013 proton-lead runs 2 nb^{-1} @ 5 TeV: Z in proton lead

Tracks: p_T>0.2 GeV, p>2 GeV, 2.0<η<4.8

supersedes Eur. Phys. J. C 72 (2012) 1947: now measurement of momentum
minimum bias sample at √s=7 TeV (2010), low multiplicity run
low pile-up contribution: <4%
systematic uncertainties 1-10%, dead material description dominant

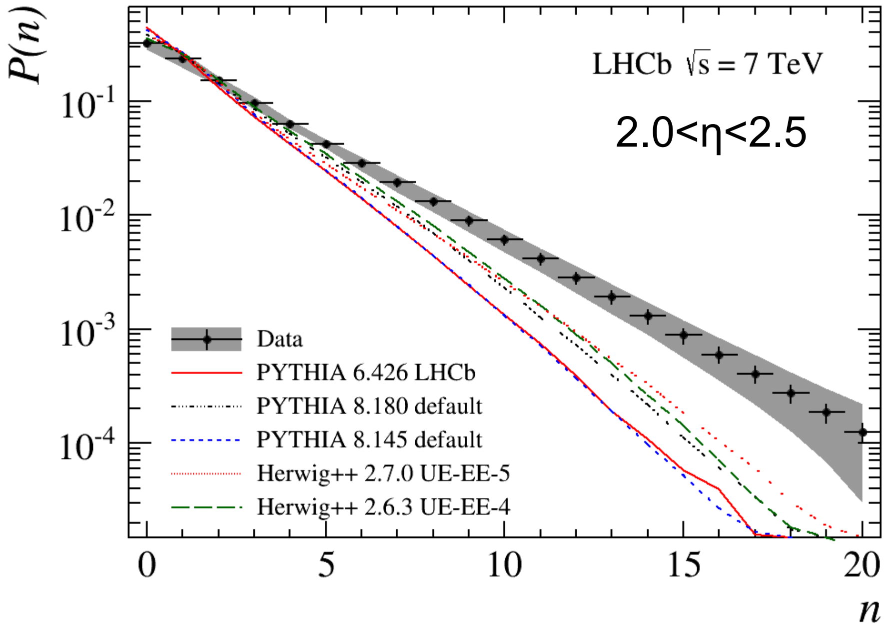
Charged particle density as a function of η





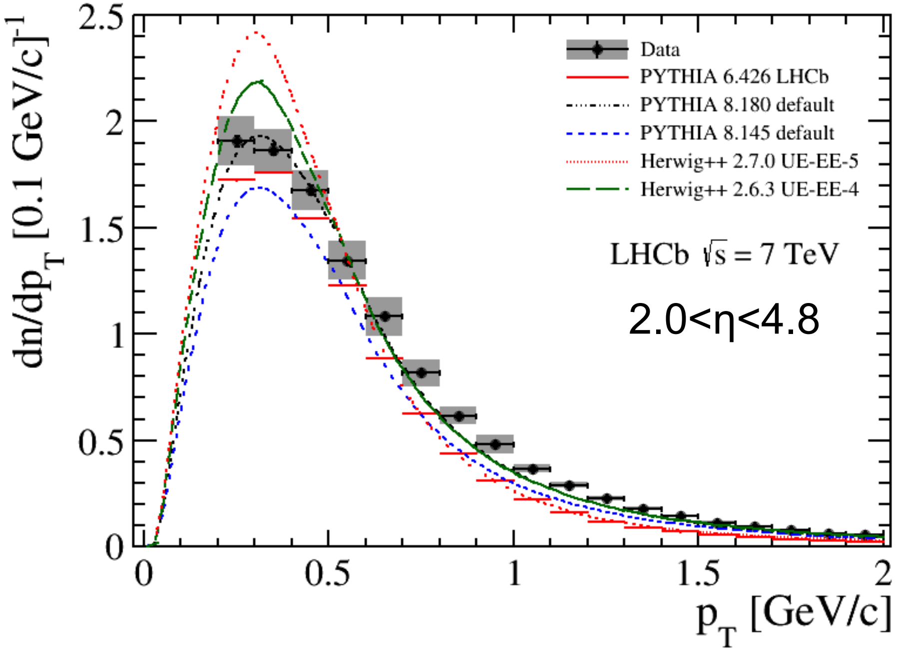
- Shape described qualitatively
- PYTHIA 6 and PHOJET (not tuned to LHC) underestimate particle density
- PYTHIA 8.180 (tuned to LHC) and HERWIG++ give best description

Charged particle multiplicities and densities



Charged particle multiplicity

- in bins of p_T and η
- models underestimate at low η and p_T (see backup)
- models tuned to central LHC data, are in better agreement (HERWIG++, PYTHIA8)



Charged particle density vs p_T

- PYTHIA6: too low
- good description by PYTHIA 8.180
- HERWIG++ problems describing shape: over(under)shoots at low (high) p_T
- none of the models describes all aspects → valuable input for tuning

Central exclusive production (CEP) of J/Ψ and Ψ(2S)

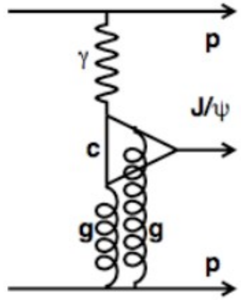
Exchange of a colourless object: γ, |

→ two muons + rapidity gaps

→ protons undetected

Bjorken x down to ~$5 \cdot 10^{-6}$

→ sensitive to gluon PDF and saturation effects

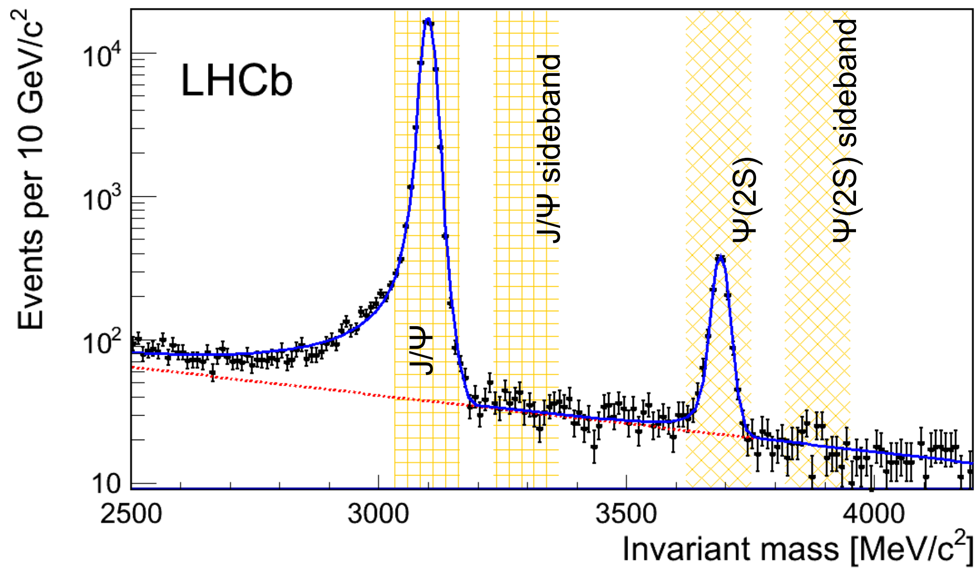


J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002

Selection

- event with one interaction: 24% of total luminosity
- precisely two forward muons
- no backward tracks
- no photons
- p_T^2 (μμ)< 0.8 GeV^2
- M(μμ) within 65 MeV of nominal mass

→ 55985 J/ψ and 1565 ψ(2s) candidates



Backgrounds

- non resonant: small (0.8±0.1)% for J/ψ and (17.0±0.3)% ψ(2s)
- feed down: J/ψ: (7.6 ± 0.9)% from χ_c and (2.5 ± 0.2)% from ψ(2s)

  ψ(2s): (2.0 ± 2.0)% from X(3872)
- dominant: inelastic background with extra particles out of LHCb acceptance

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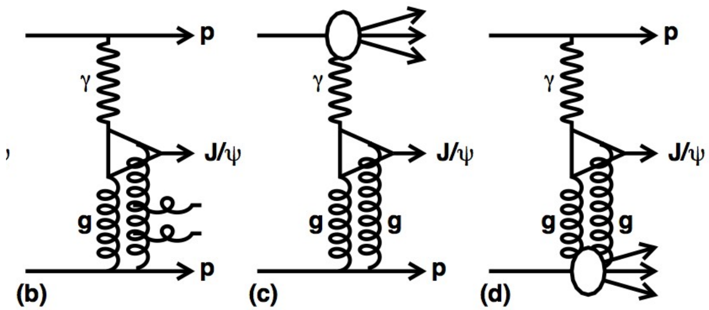
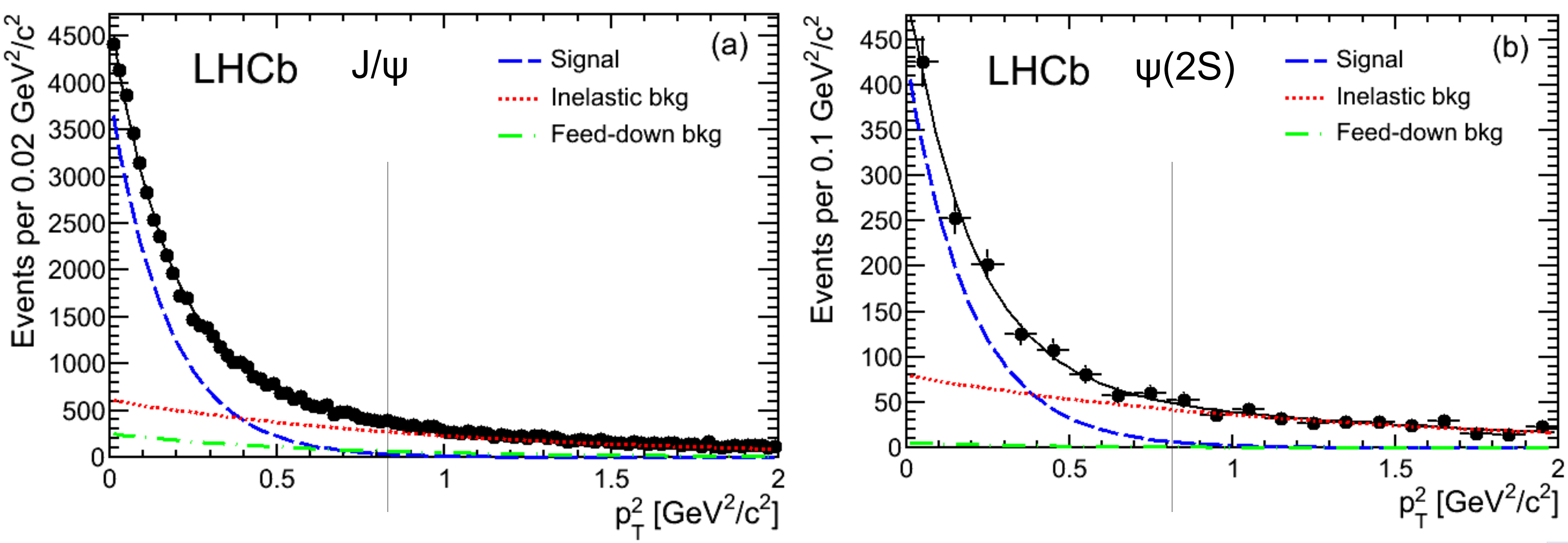


Proton dissociation or gluon radiation
→ estimated from data: fit p_T^2 distribution

- Signal and inelastic background: exponential
- Feed-down: shape from data $\chi_c \to J/\psi\gamma$ and $\psi(2S) \to J/\psi\pi\pi$
- Fit slope and normalization of signal and background
  slope agrees well with expectation from HERA



Purity p_T^2<0.8 GeV²: 0.59±0.01 for J/ψ and 0.52±0.07 for ψ(2S)

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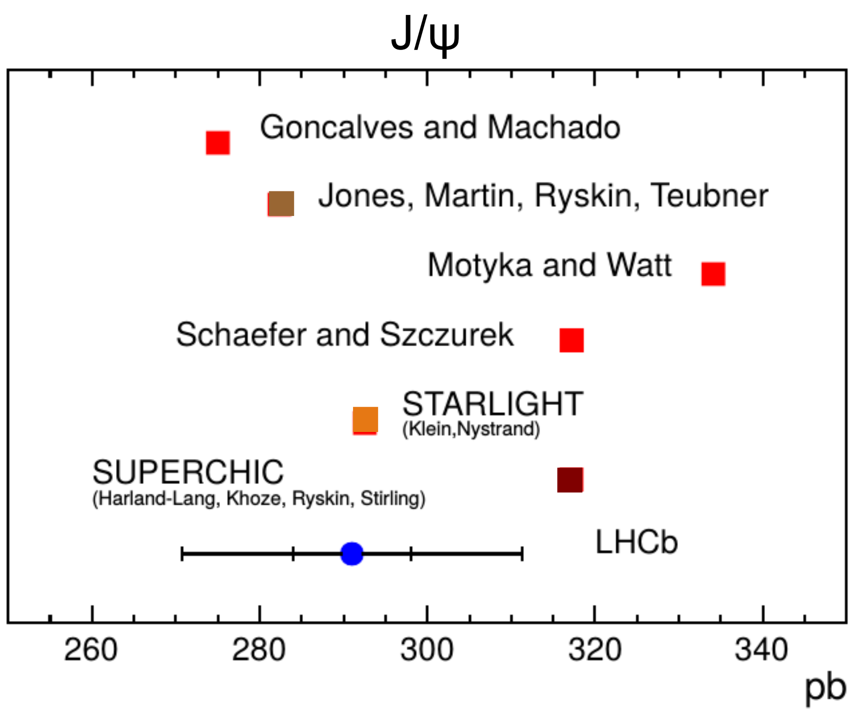
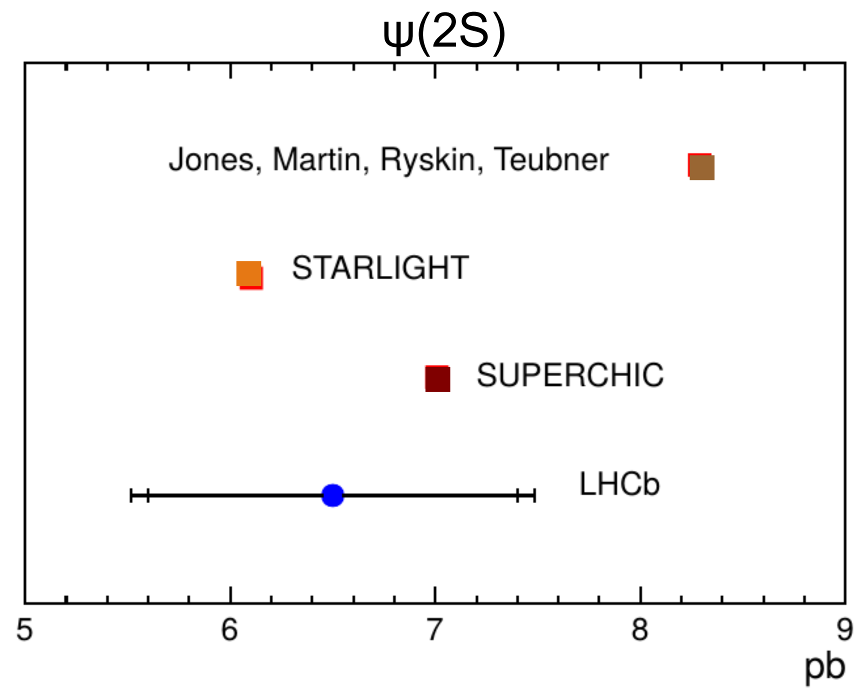




Cross section times BF to two muons with $2.0 < \eta < 4.5$

$\sigma(J/\psi) = 291 \pm 7(\text{stat}) \pm 19(\text{syst})$ pb

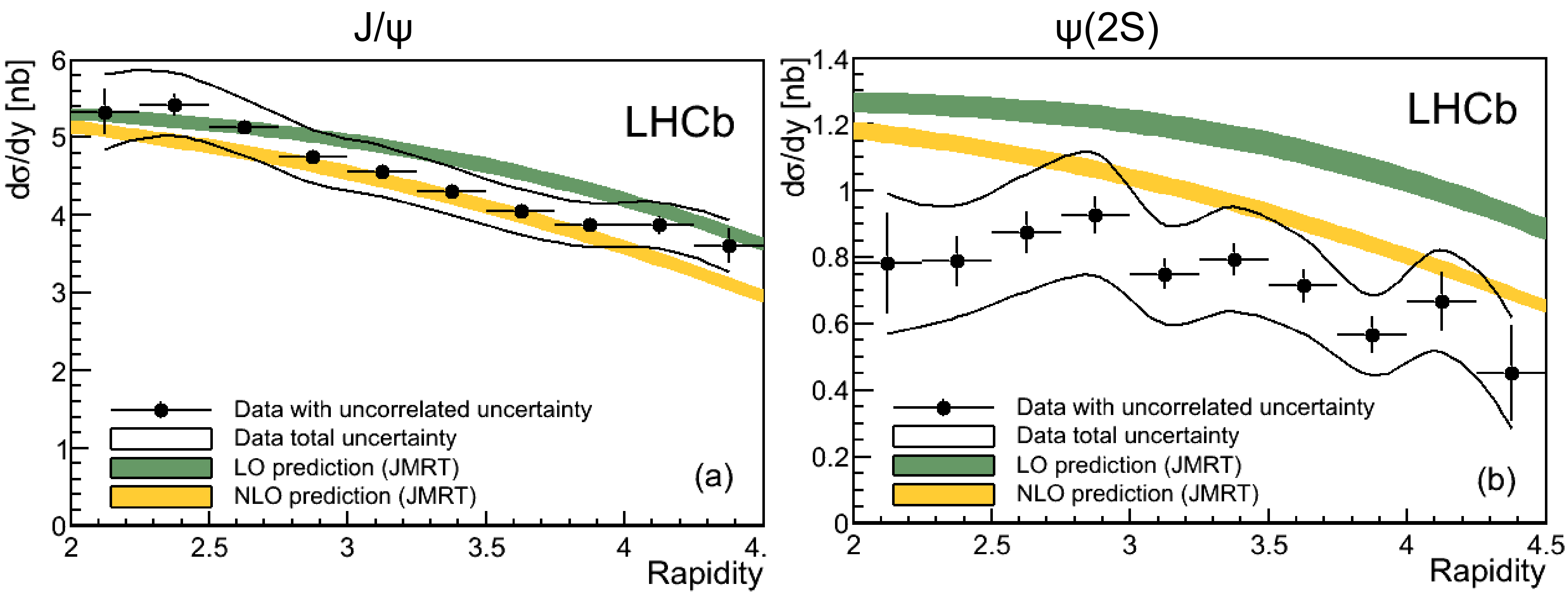
$\sigma(\psi(2S)) = 6.5 \pm 0.9(\text{stat}) \pm 0.4(\text{syst})$ pb

in good agreement with predictions

G&M: Phys. Rev. C84 (2011) 011902
JRMT: JHEP 1311 (2013) 085
M&W:Phys. Rev. D78 (2008) 014023
Sch&SPhys. Rev. D76 (2007) 094014
Starlight: Phys. Rev. Lett. 92 (2004) 142003
Superchic: Eur. Phys. J. C65 (2010) 433

CEP: differential cross section

J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002



- Prediction from Jones, Martin, Ryskin and Teubner arXiv:1307.7099
- Shape better described by NLO prediction
- Also well described by saturation model predictions (arXiv:1305.4611, PhysRevD.78.014023) (→ backup)

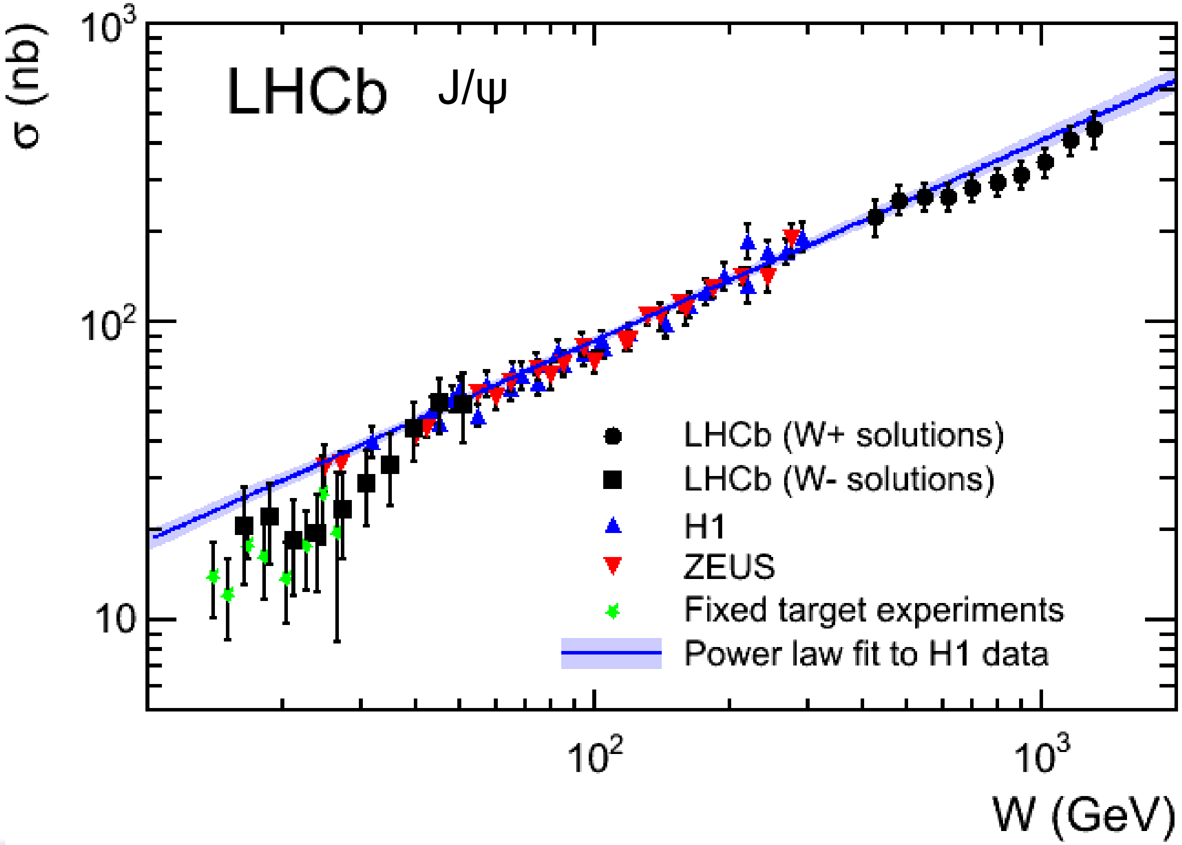
CEP: γp cross-section

Compare to HERA γp data using known photon flux for a photon (energy k)

$$\underbrace{\frac{d\sigma}{dy}_{pp\to pVp}}_{\text{measured}} = r(y)\left[k_{+}\frac{dn}{dk_{+}}\underbrace{\sigma_{\gamma p\to Vp}(W^{+})}_{\text{extracted}} + k_{-}\frac{dn}{dk_{-}}\underbrace{\sigma_{\gamma p\to Vp}(W^{-})}_{\text{extracted}}\right]$$

gap survival

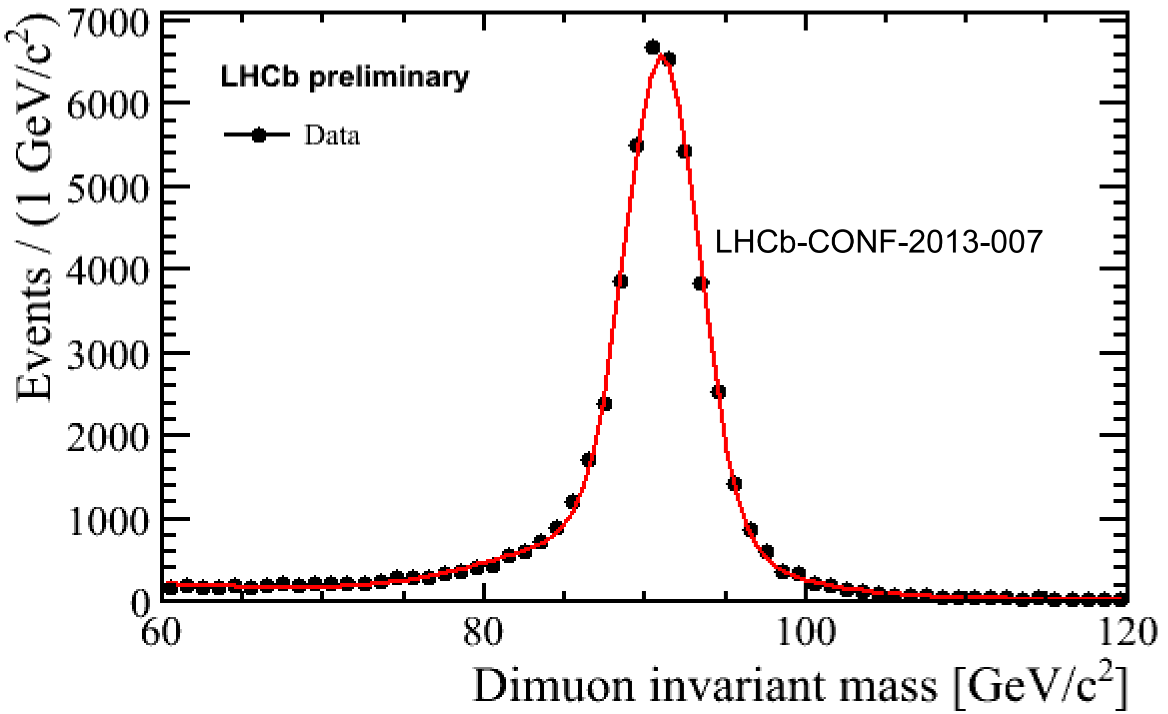
photon flux



→ two correlated points for each measurement (W^{+}, W^{-}) in y

Deviation from power law:
- higher order
- saturation effects

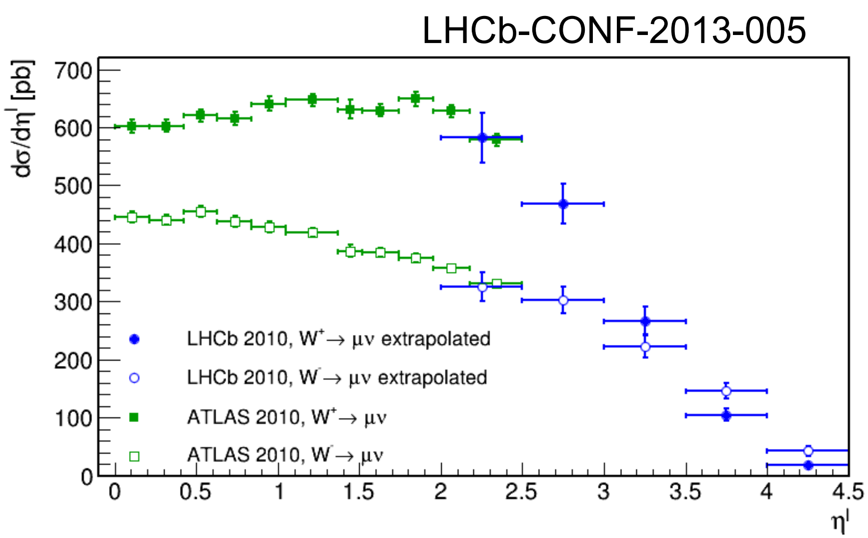
Measurements with Z bosons

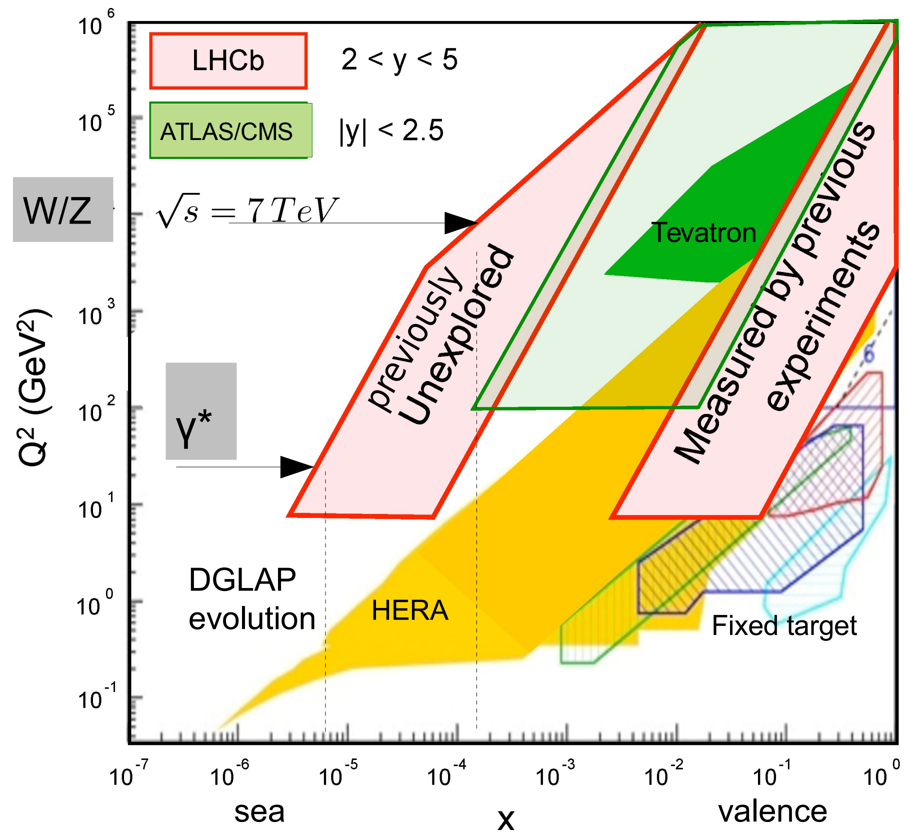


LHCb probes two distinct regions in x-Q²: $x_{1,2}=(Q/\sqrt{s})\,e^{\pm y}$

Unique region at low x

- W, Z production: $x= 1.7\cdot10^{-4}$
- complementary to ATLAS/CMS





Z → μμ selection

- muons: p_T>20 GeV, 2<η<4.5
- mass: 60<M(μμ)<110 GeV²
- background <0.3%

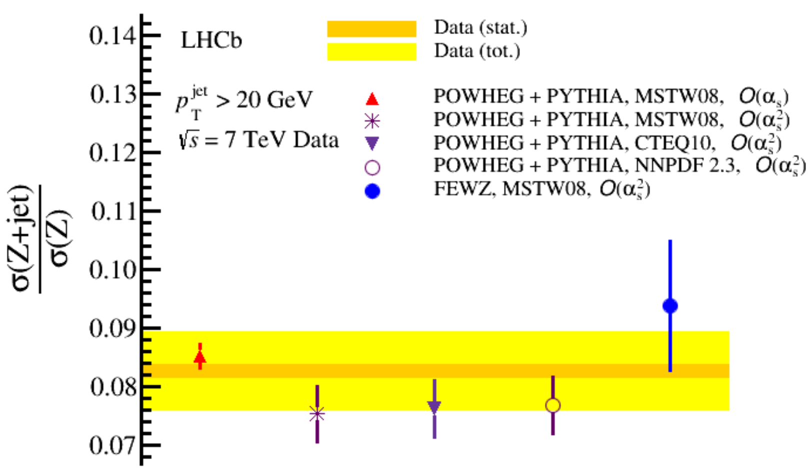
Z plus jet Production

Jets: anti-kT (R=0.5), $2<\eta<4.5$, $p_T>10$ (20 GeV), $\Delta r(\text{jet},\mu)>0.4$

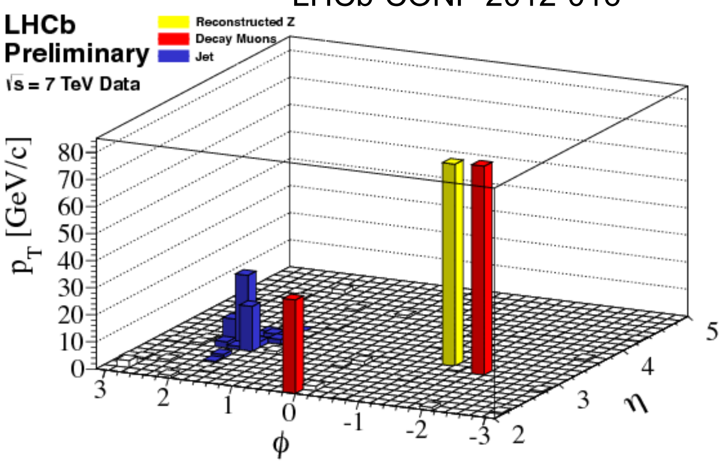
Dominant uncertainties: jet energy scale and resolution, jet reconstruction efficiency

$p_{T(\text{jet})}>10$ GeV: $\sigma = 16.0 \pm 0.2(\text{stat}) \pm 1.2(\text{syst}) \pm 0.6(\text{lumi})$ pb

$p_{T(\text{jet})}>20$ GeV: $\sigma = 6.3 \pm 0.1(\text{stat}) \pm 0.5(\text{syst}) \pm 0.2(\text{lumi})$ pb



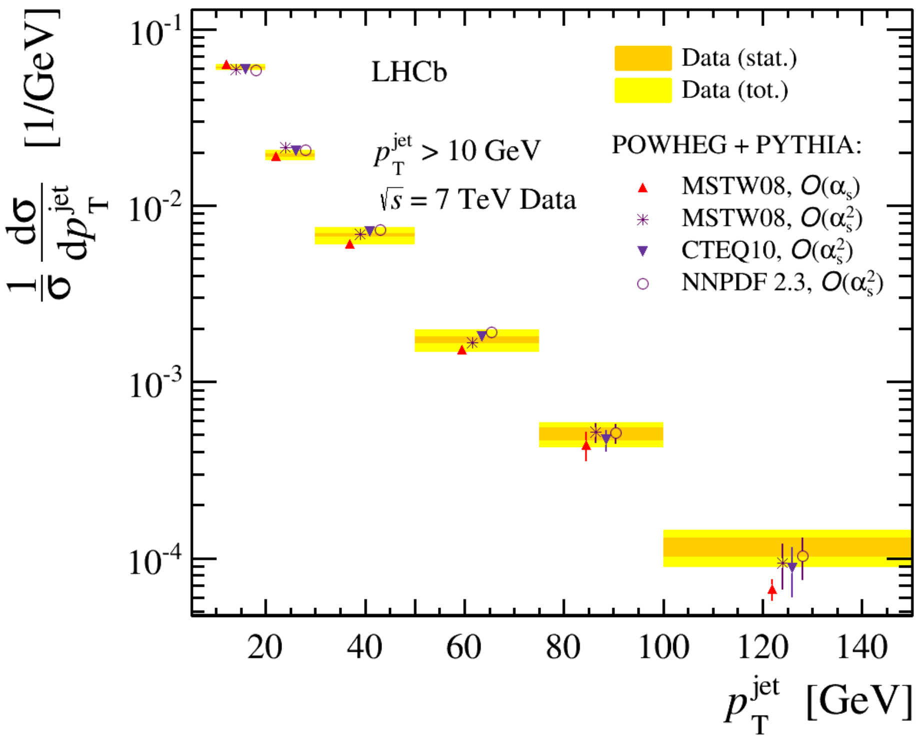
LHCb-CONF-2012-016

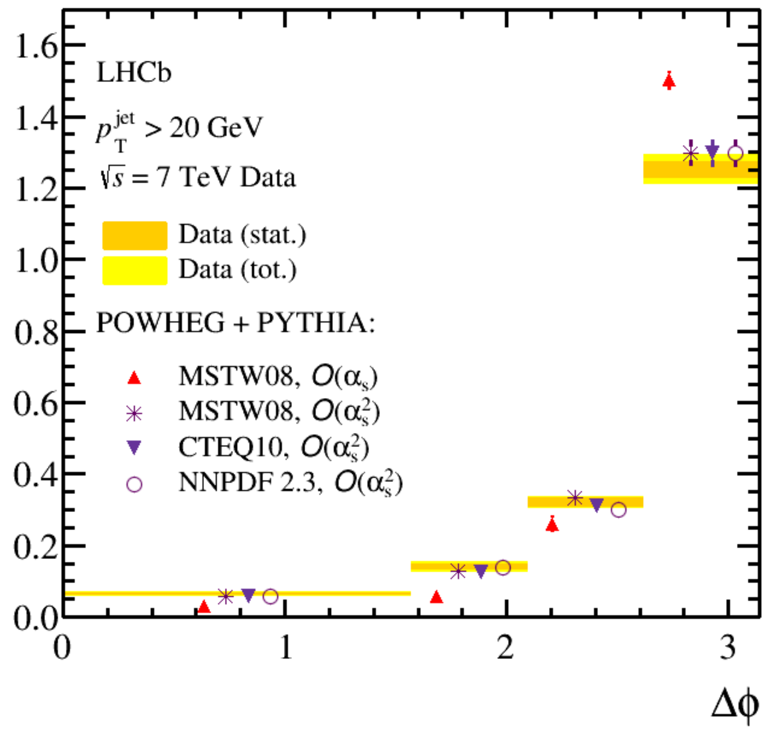


Predictions:

- POWHEG+PYTHIA at $O(\alpha_s)$ and $O(\alpha_s^2)$ and different PDF sets
- FEWZ $O(\alpha_s^2)$ not corrected for hadronisation and underlying event

Z plus jet: differential cross sections





Shapes well described by NLO predictions

LO fails to describe Δφ(Z,jet)

Z plus D

Yields information on charm PDF and charm production mechanisms
Contribution from single-(SPS) and double-parton scattering (DPS)

Selection

standard Z selection
$D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+\pi^+$
Z and D from same vertex

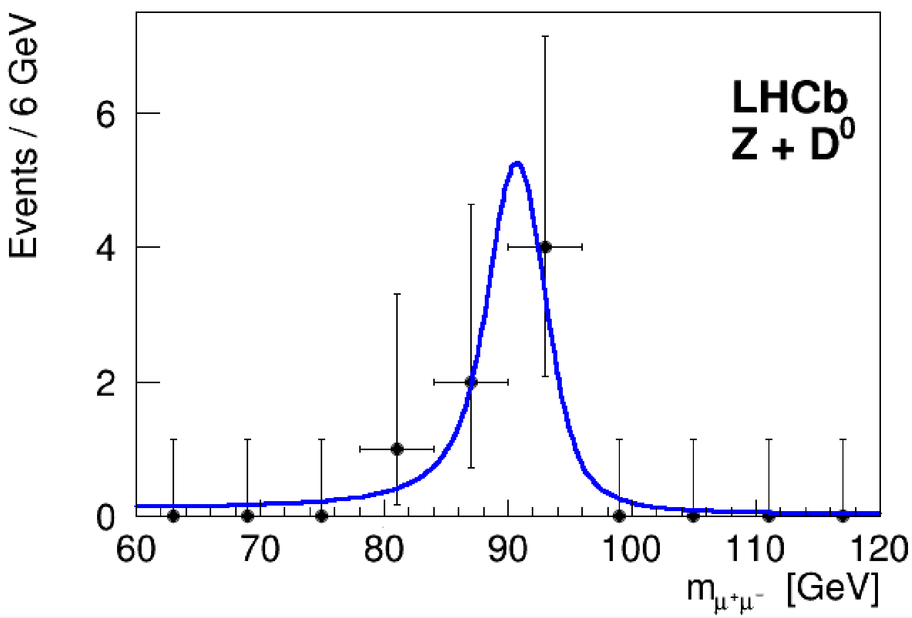
Purity: 0.95:

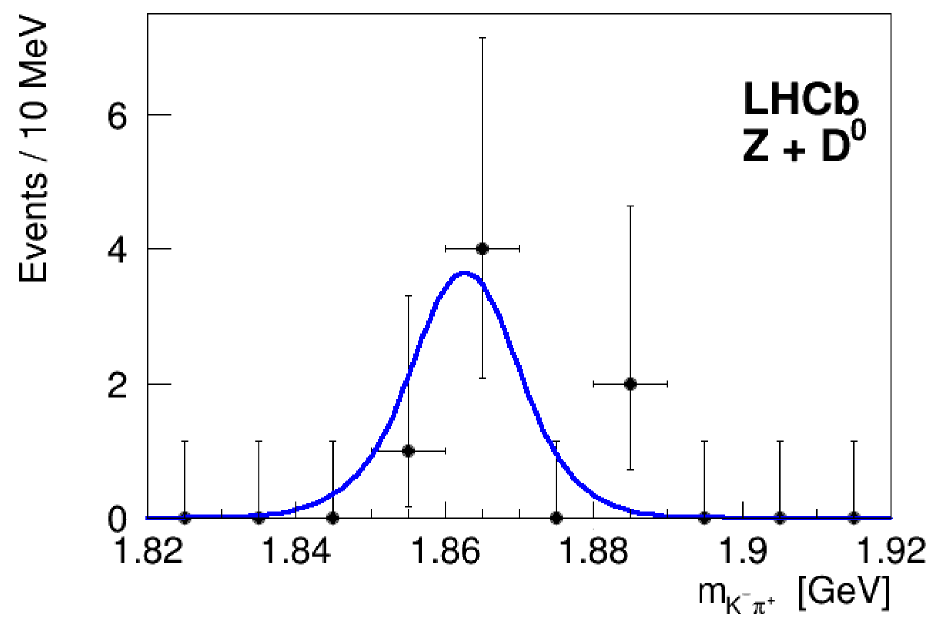
charmed hadrons from B-decays,
real Z and D from different vertices
combinatorial background

7 Z plusD^0 and 4 Z plus D^+ candidates

combined significance: 5.1 σ

no $\Lambda_c^+ \rightarrow pK\pi$, $D_s^+ \rightarrow \Phi\pi^+$

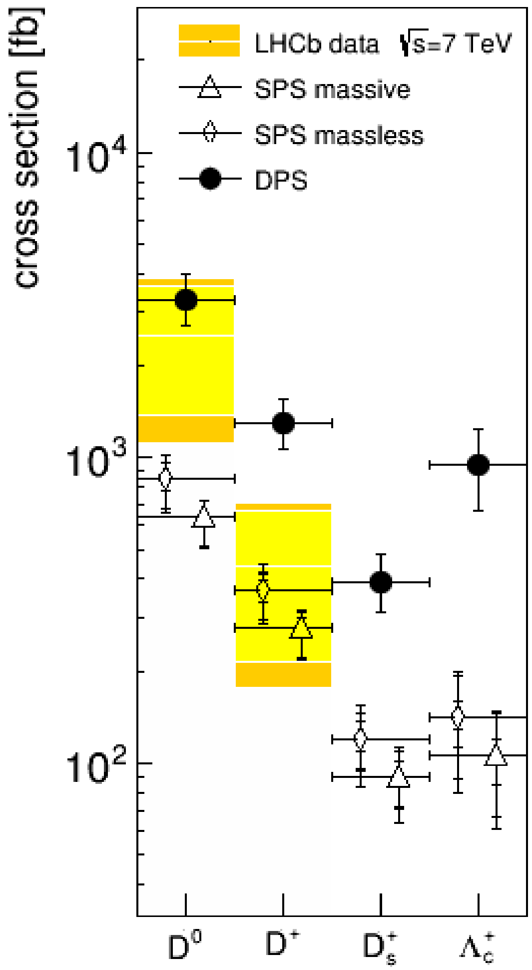




Z plus D: Results

$\sigma(Z\to\mu\mu,D^0) = 2.50 \pm 1.12(\text{stat}) \pm 0.22(\text{syst})$ pb

$\sigma(Z\to\mu\mu,D^+) = 0.44 \pm 0.23(\text{stat}) \pm 0.03(\text{syst})$ pb



Predictions

Single parton scattering (SPS) from MCFM

Double parton scattering (DPS):

$\sigma(\text{DPS})=(\sigma(Z\to\mu\mu)\,\sigma(D))/\sigma_{\text{eff}}$

$\sigma_{\text{eff}} = 14.5 \pm 1.7\ ^{+1.7}_{-2.5}$ mb (CDF)

Sum of SPS and DPS expected to describe signal

- consistent for Z plus D^0
- Z plus D^+ below expectation

→ differential measurements with high statistics will allow to disentangle SPS and DPS contributions

MCFM: J. M. Campbell and R. K. Ellis, Nucl. Phys. Proc. Suppl. 205-206 (2010) 10, arXiv:1007.3492.

Z production in proton-lead

Forward: pA collisions

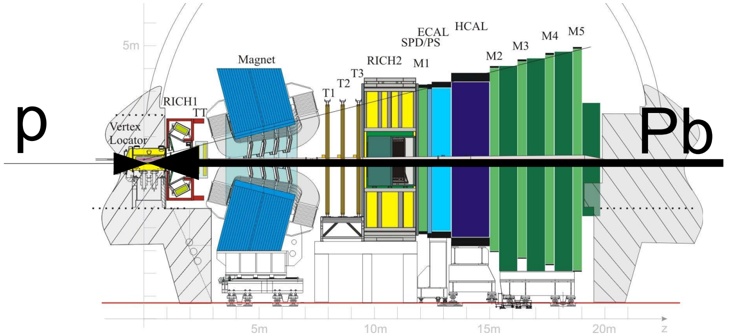
proton beam: E_p = 4 TeV

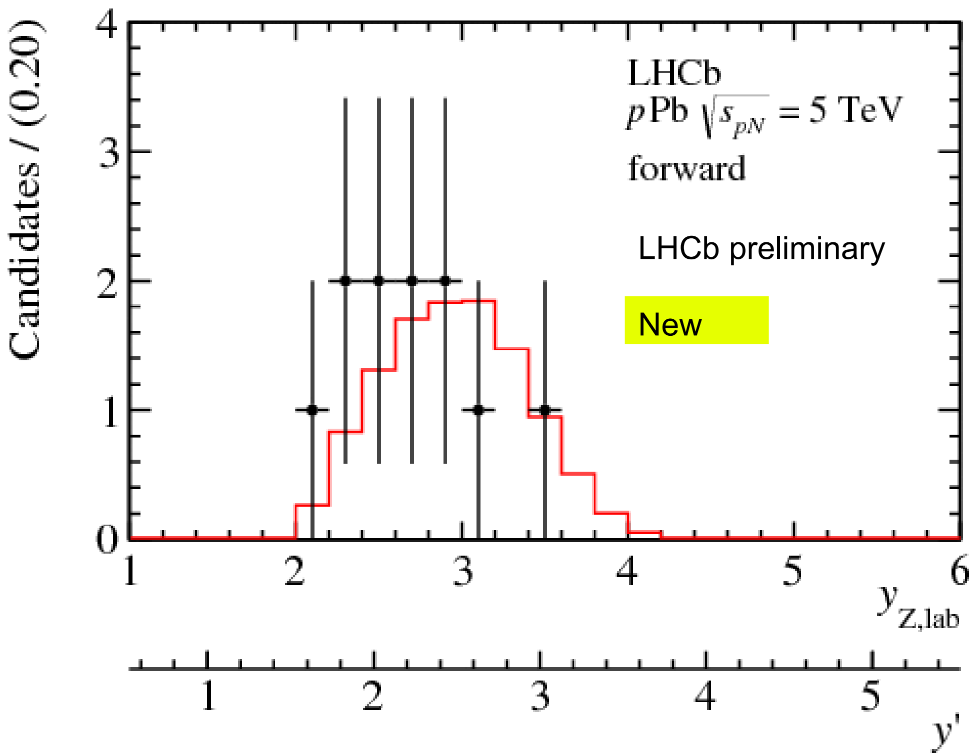
$^{208}_{82}$Pb beam: $E_N = Z\,E_p \approx 1.58$ TeV

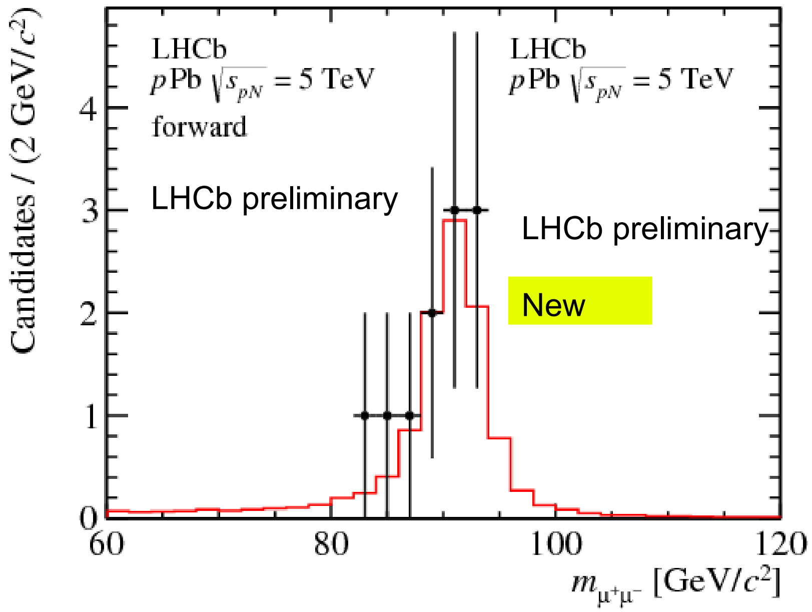
cms energy: $\sqrt{s_{pN}} \approx 5.02$ TeV

shift in rapidity: $\Delta y = -2 \ln Z/A \approx -0.47$

11 candidates







Z production in proton-lead

Backward: Ap collisions

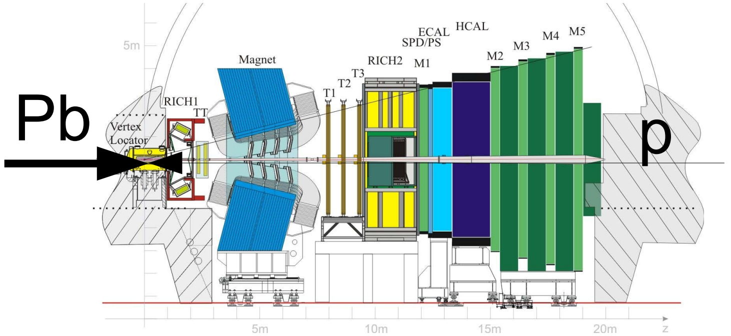
proton beam: E_p = 4 TeV

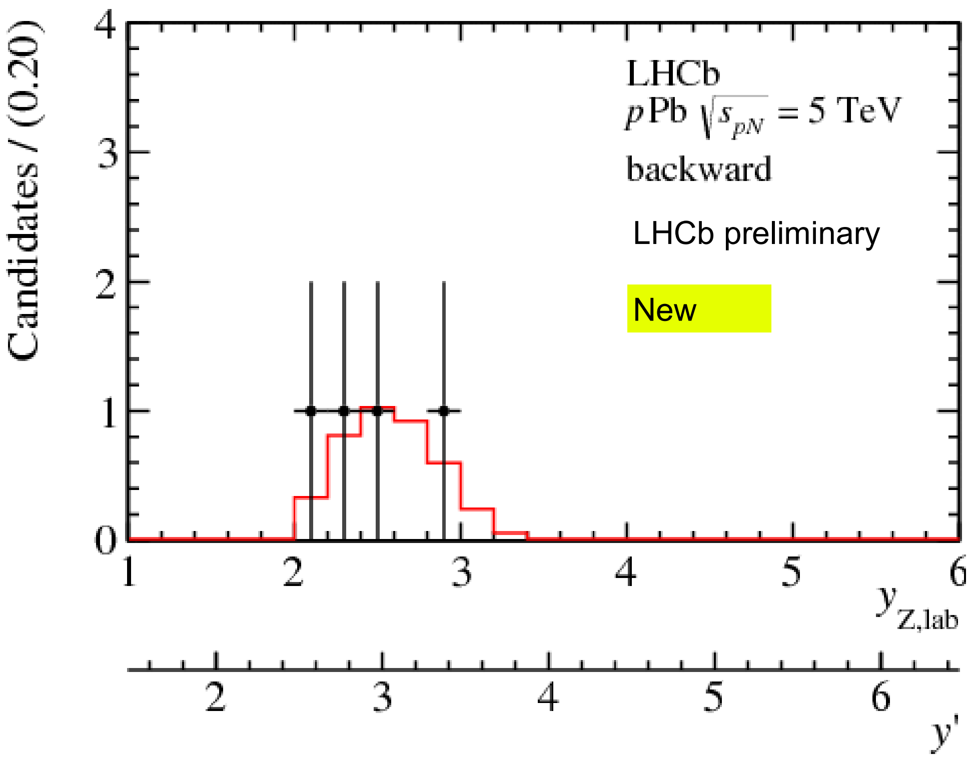
$^{208}_{82}$Pb beam: $E_N = Z\,E_p \approx 1.58$ TeV

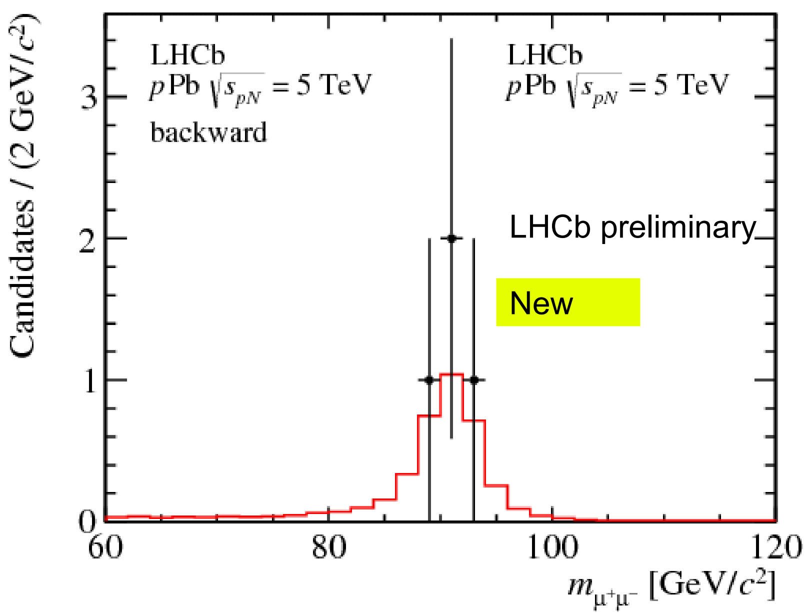
cms energy: $\sqrt{s_{pN}} \approx 5.02$ TeV

shift in rapidity: $\Delta y = +2 \ln Z/A \approx +0.47$

4 candidates





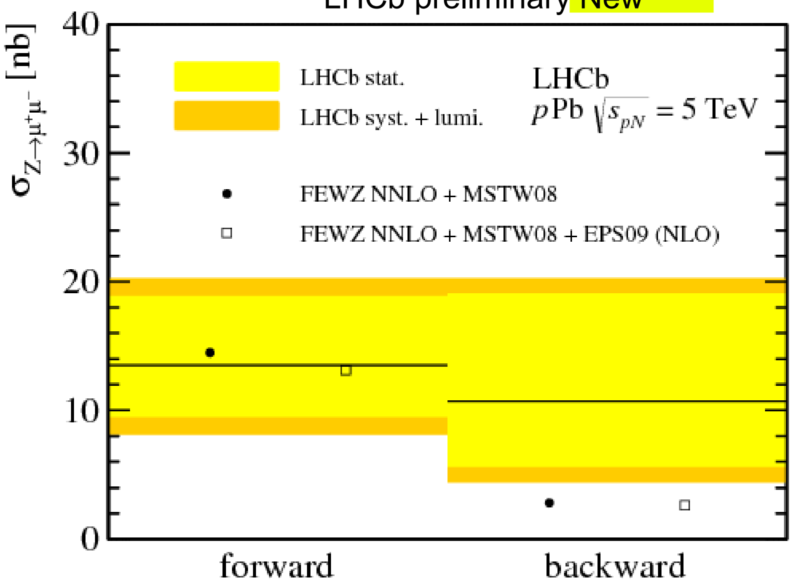


Z production in proton-lead

Efficiencies, purity from data (purity >0.995)
Cross sections:

forward: $\sigma_{Z(\rightarrow\mu+\ \mu-)} = 13.5^{+5.4}_{-4.0}$ (stat.) ± 1.1(syst.) ± 0.3(lumi.) nb
backward: $\sigma_{Z(\rightarrow\mu+\mu-)} = 10.7^{+8.4}_{-5.1}$ (stat.) ± 0.9(syst.) ± 0.2(lumi.) nb

LHCb preliminary New



Theoretical predictions:
NNLO calculations (FEWZ)
nuclear modification: EPS09(NLO)

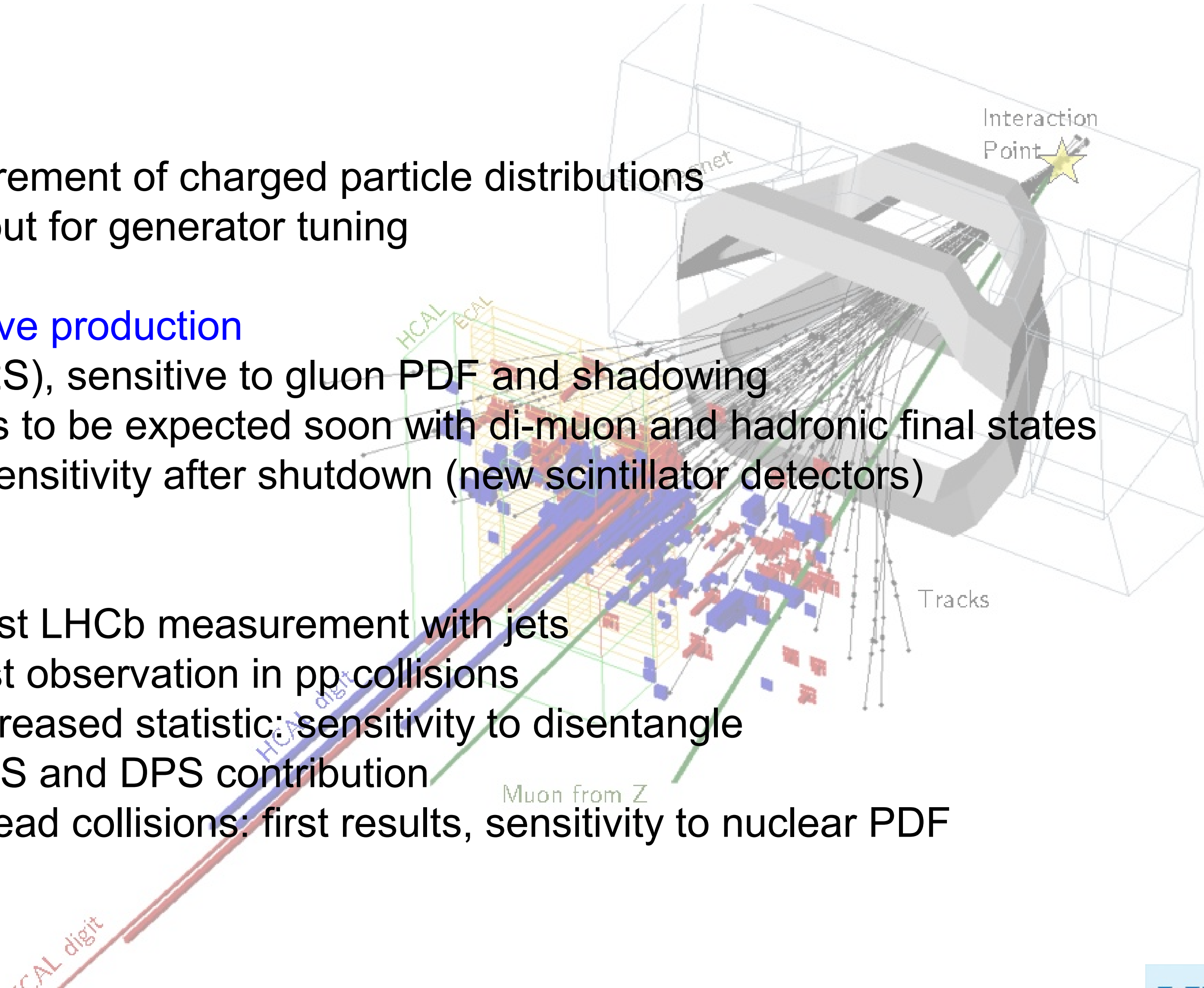
future higher statistics measurements will provide important information on nuclear PDFs

Fiducial volume
muons: p_T>20 GeV, 2<η<4.5
mass: 60<M(μμ)<110 GeV^2

FEWZ: Y. Li and F. Petriello, Phys. Rev. D86 (2012) 094034, arXiv:1208.5967.

EPS09: K. Eskola, H. Paukkunen, and C. Salgado, JHEP 04 (2009) 065, arXiv:0902.4154.

Conclusions



Soft QCD

new measurement of charged particle distributions
valuable input for generator tuning

Central exclusive production

J/ψ and $\psi(2S)$, sensitive to gluon PDF and shadowing
more results to be expected soon with di-muon and hadronic final states
increased sensitivity after shutdown (new scintillator detectors)

Z production

Z plus jet: first LHCb measurement with jets
Z plus D: first observation in pp collisions
increased statistic: sensitivity to disentangle SPS and DPS contribution
Z in proton-lead collisions: first results, sensitivity to nuclear PDF

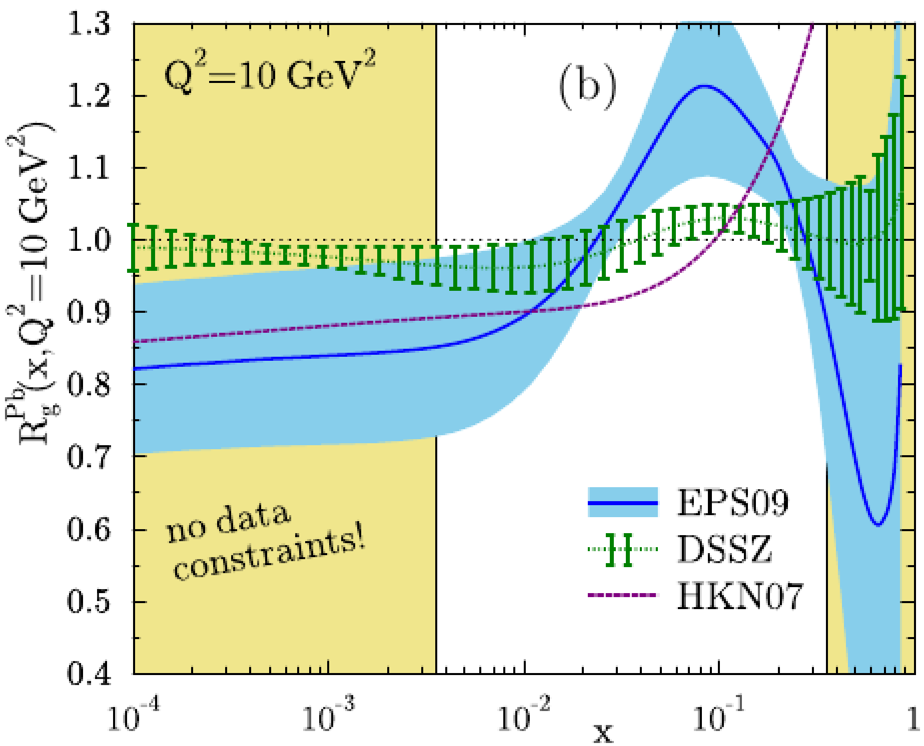
→ Many more interesting measurements to come!

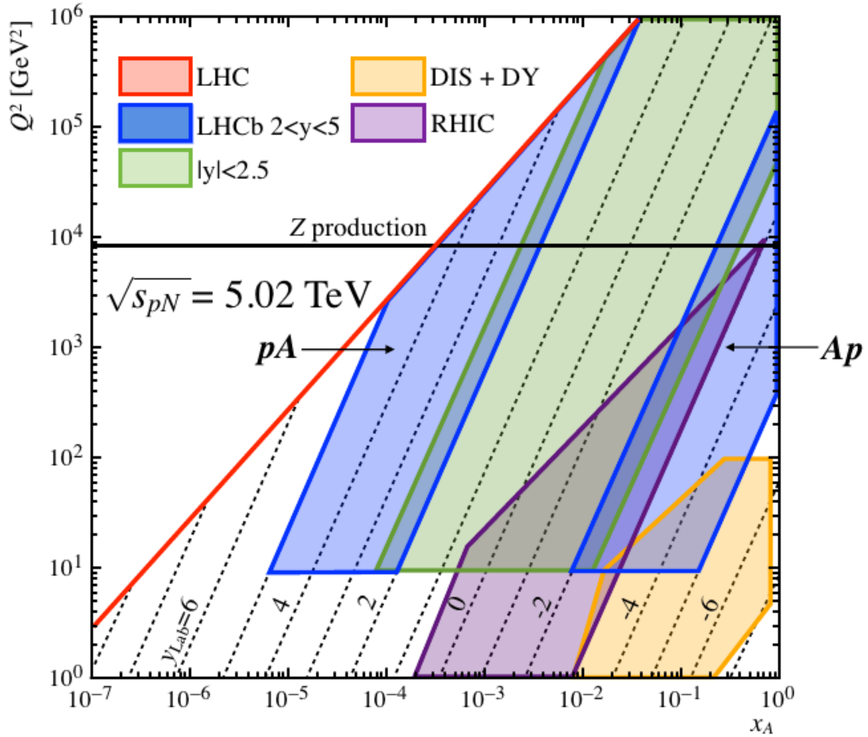
Backup slides

Full list of QCD results

Measurement of charged particle multiplicities and densities	arXiv:1402.4430
Prompt charm production at √s = 7 TeV	Nucl. Phys. B 871 (2013) 1-20
Measurement of the forward energy flow at √s = 7 TeV	Eur. Phys. J. C73 (2013) 2421
Measurement of Y production in pp collisions at √s = 2.76 TeV	accepted by EPJC arXiv:1402.2539
Measurement of V0 production ratios at √s = 0.9 and 7 TeV	Eur. Phys. J. C 72 (2012) 2168
Measurement of the B± production cross-section at √s=7 TeV	JHEP 04 (2012) 093
Measurement of the inclusive ϕ cross-section at √s = 7 TeV	Phys. Lett. B 703 (2011) 267
Prompt K0S production at √s = 0.9 TeV	Phys. Lett. B 693 (2010) 69
W&Z production studies at √s = 7 TeV	JHEP 06 (2012) 058
Z → tau tau production at √s = 7 TeV	JHEP 01 (2013) 111
Z →ee production at √s = 7 TeV	JHEP 02 (2013) 106
Z →μμ + jet production at √s = 7 TeV	JHEP 1401 (2014) 033
Z plus D production at √s = 7 TeV	JHEP 04 (2014) 91
Measurement of the cross-section for Z→μμ at s√=7 TeV	LHCb-CONF-2013-007
Low mass Drell Yan production at √s = 7 TeV	LHCb-CONF-2012-013
Graphical comparison of W and Z results with ATLAS and CMS	LHCb-CONF-2013-005
Exclusive J/Ψ and Ψ(2S) production in the dimuon channel √s = 7	J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002
Measurement of σ(bbbar) with inclusive final states	LHCb-CONF-2013-002
Inclusive jets and dijets	LHCb-CONF-2011-015

Ratio of nPDF (gluon) for Pb to bare proton PDF
[arXiv:1401.2345]

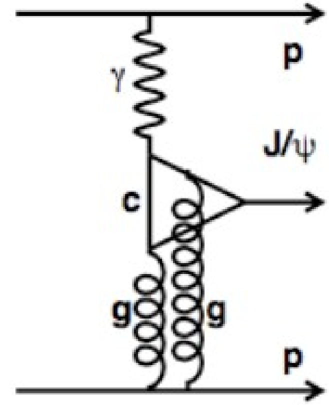




nPDF poorly constrained at high and low x_A, where measurements at LHCb have a good sensitivity

J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002

Exchange of a colourless object: γ, pomeron
→ two muons + rapidity gaps
→ protons escape undetected in beampipe

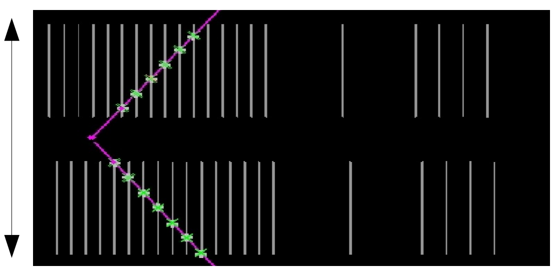


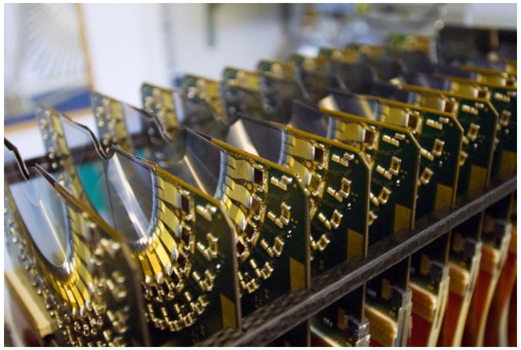
High rapidities 2-5
- complementary to ATLAS/CMS
- sensitivity to x values 5 $\cdot 10^{-6}$

VELO acceptance
forward: $1.5 < \eta < 5.0$
backward: $-3.5 < \eta < -1.5$ no momentum information

VELO surrounds beampipe

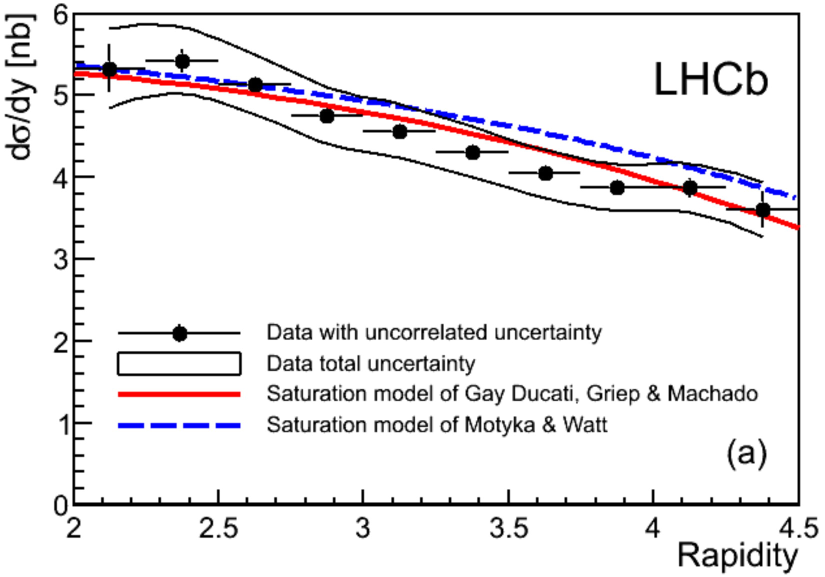
VELO
8.4 cm

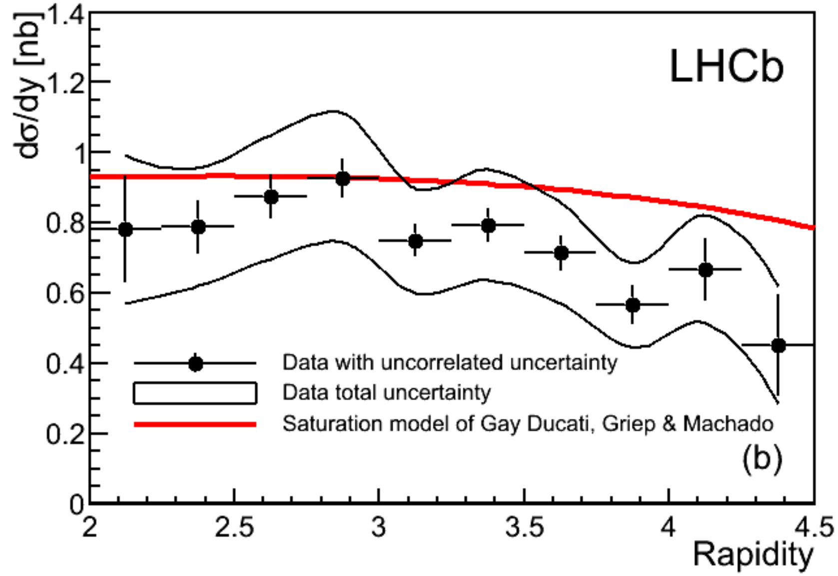




Rapidity gap coverage
forward: 2 gaps, sum of 3.5
backward: ~ 1-2 units, depending on z vertex position

J. Phys. G: Nucl. Part. Phys. 41 (2014) 055002





Saturation model predictions (arXiv:1305.4611, PhysRevD.78.014023)

CEP systematic uncertainties

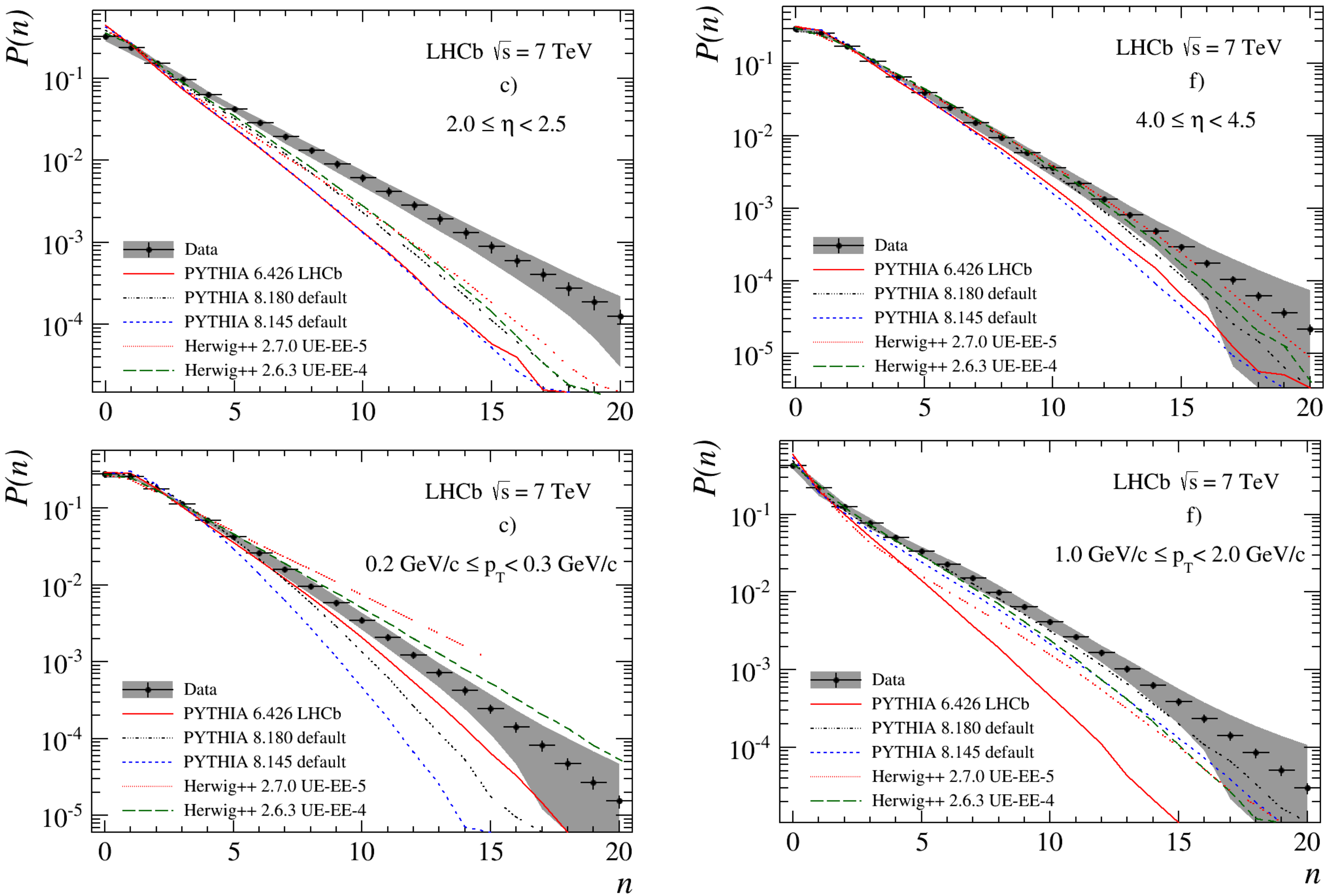
J. Phys. G40 (2013) 045001

Correlated uncertainties expressed as a percentage of the final result

ϵ_{sel}	1.4%
Purity determination (J/ψ)	2.0%
Purity determination ($\psi(2S)$)	13.0%
*ϵ_{single}	1.0%
*Acceptance	2.0%
*Shape of the inelastic background	5.0%
*Luminosity	3.5%
Total correlated statistical uncertainty (J/ψ)	2.4%
Total correlated statistical uncertainty ($\psi(2S)$)	13.0%
Total correlated systematic uncertainty	6.5%

Charged particle multiplicities

arXiv:1402.4430



Z plus D: backgrounds

- charmed hadrons from B-decays
- real Z and D from different vertices
- combinatorial background: from 2d fit to mass distributions
- purity is high about 95%