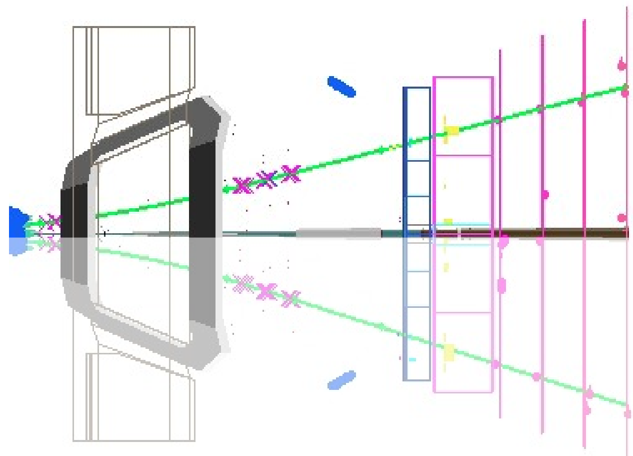
Electroweak and central exclusive measurements in the forward region at LHCb



Seminar, Heidelberg, July 8, 2014

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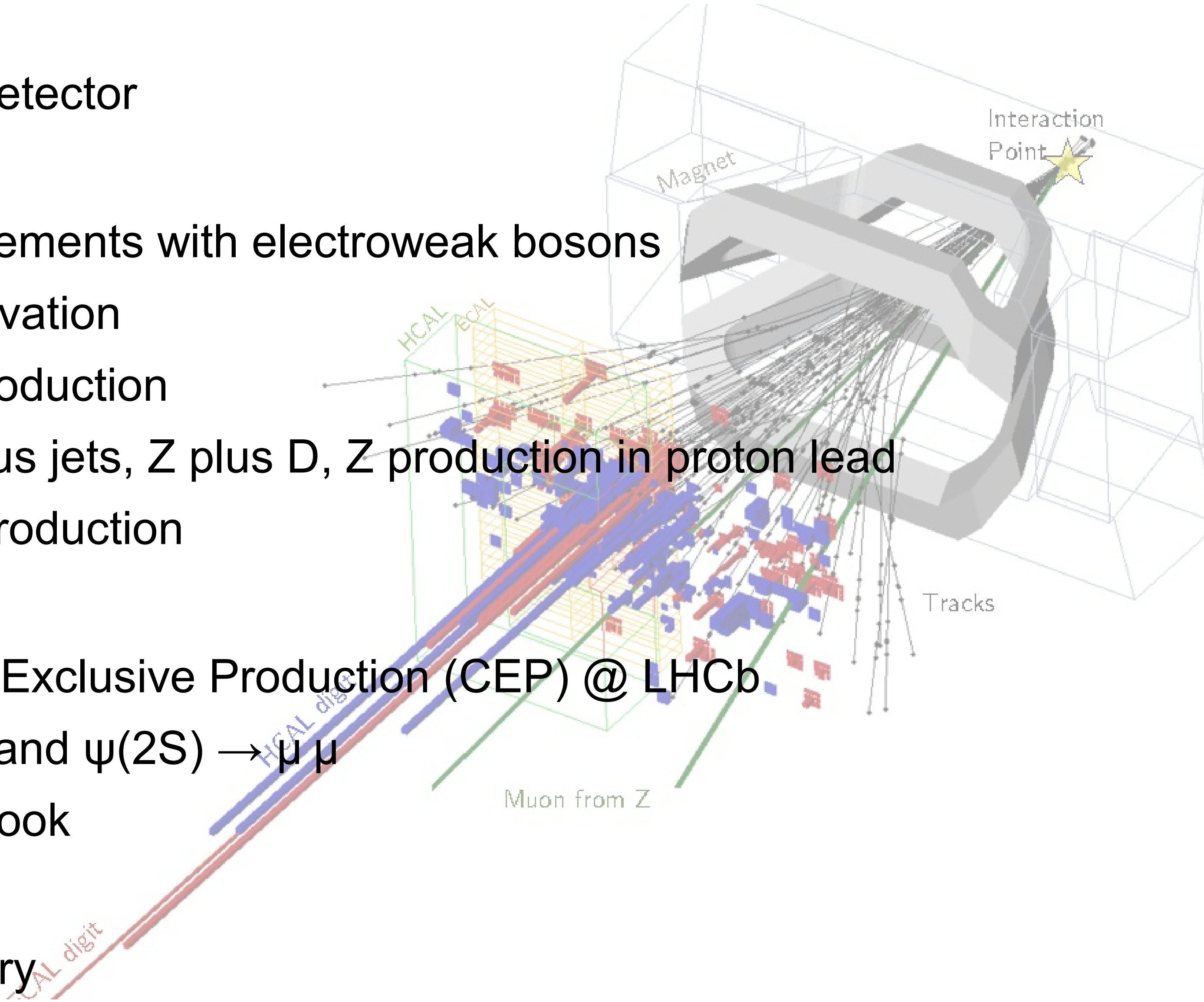
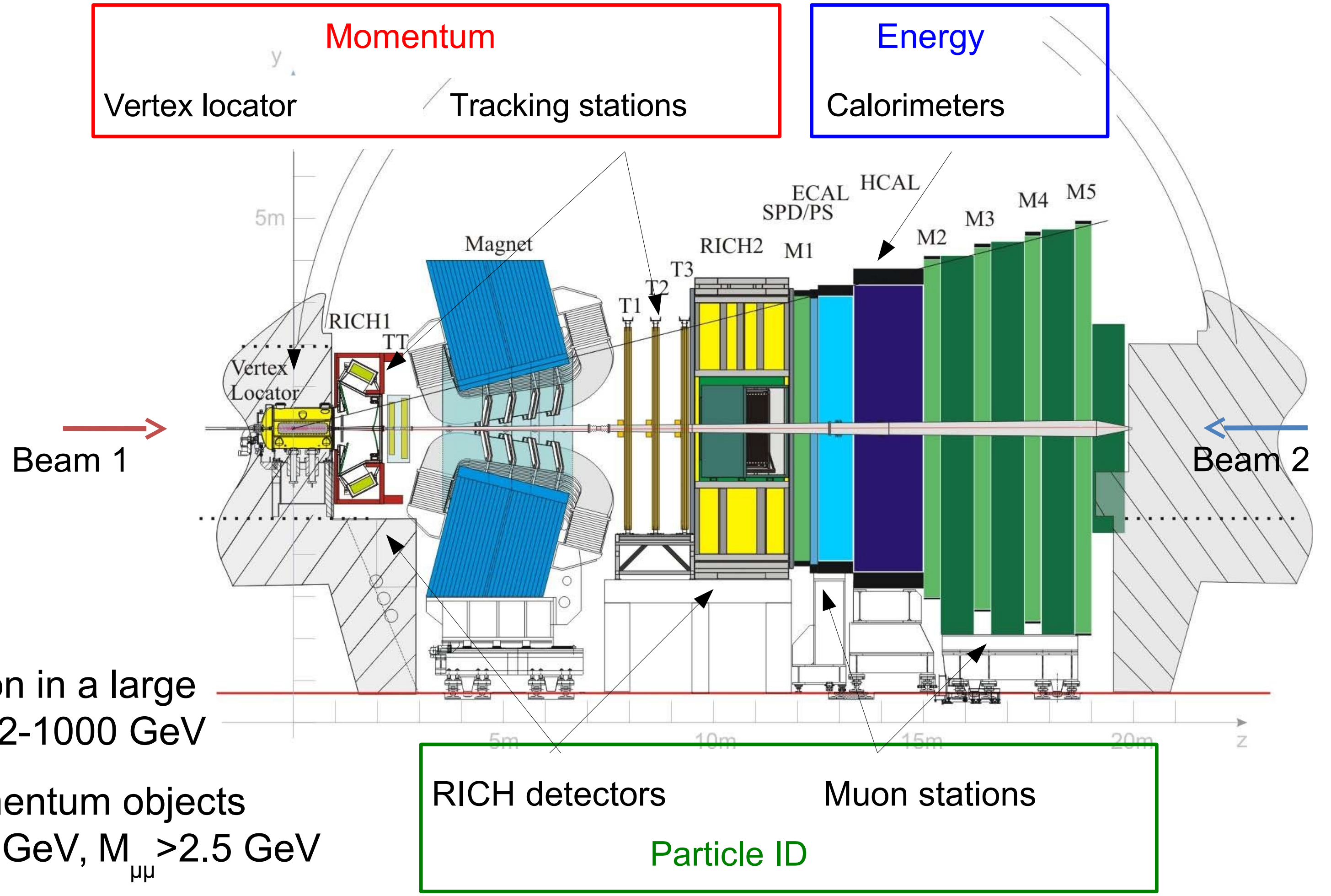
Outline

- LHCb detector
- Measurements with electroweak bosons
  - Motivation
  - Z production
  - Z plus jets, Z plus D, Z production in proton lead
  - W production
- Central Exclusive Production (CEP) @ LHCb
  - J/ψ and ψ(2S) → μ μ
  - Outlook
- Summary



LHCb Detector – more than a beauty detector

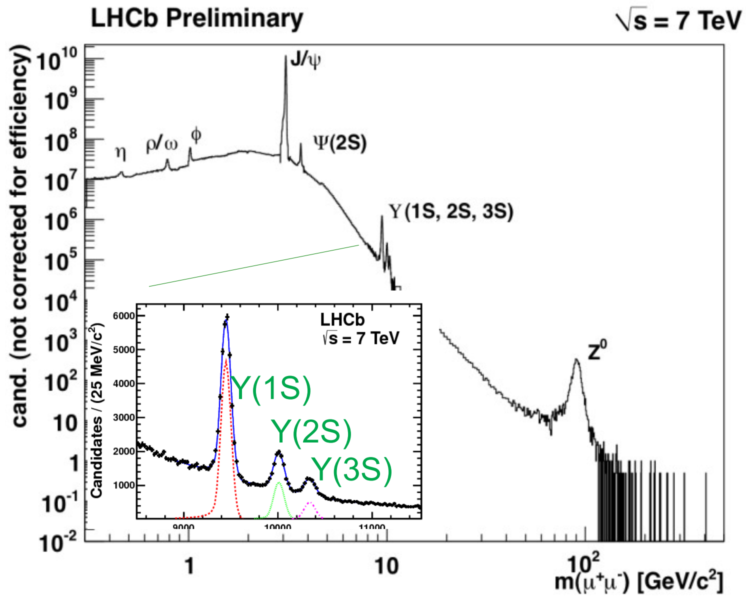
Fully instrumented in the forward region ($2 < \eta < 5$)
some detection capability in backward region ($-3.5 < \eta < -1.5$)
→ LHCb is a general purpose high resolution spectrometer



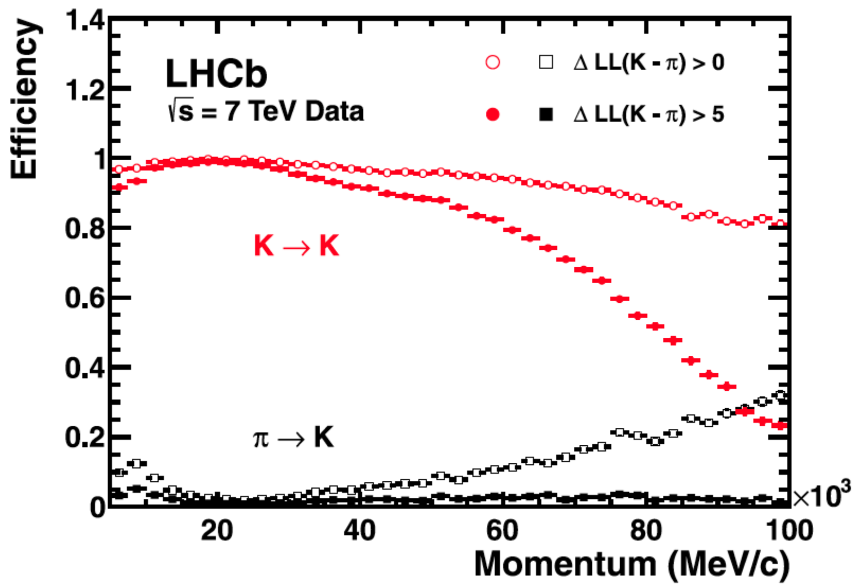
- excellent tracking
- particle identification in a large momentum range: 2-1000 GeV
- trigger on low momentum objects
  $p_\mu > 3$ GeV, $p_T^\mu > 0.5$ GeV, $M_{\mu\mu} > 2.5$ GeV

LHCb Performance

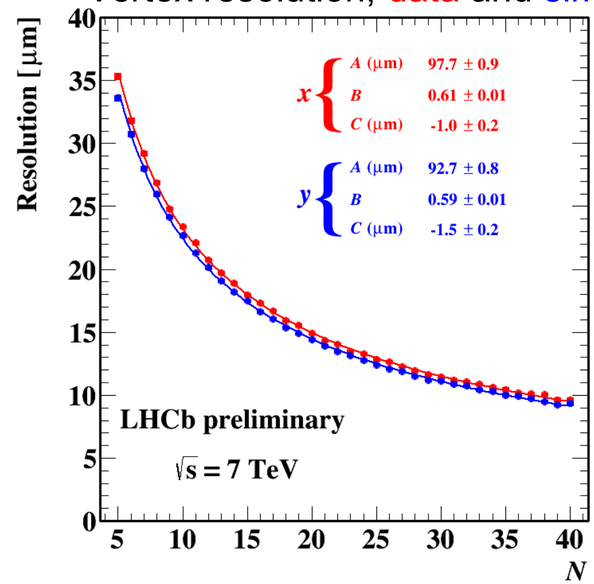
- Momentum resolution:
  0.4% at 5 GeV to 0.6% at 100 GeV
- Vertex resolution:
  σ_{xy}:10-50 μm, σ_z: 100-300 μm
- Track impact parameter resolution:
  13 -20 μm
- Particle ID:
  Muon ID ε=97%; mis-id: 0.7%
  Kaon ID ε=90%; π mis-id< 5%



Kaon identification



Vertex resolution, data and simulation



LHCb running

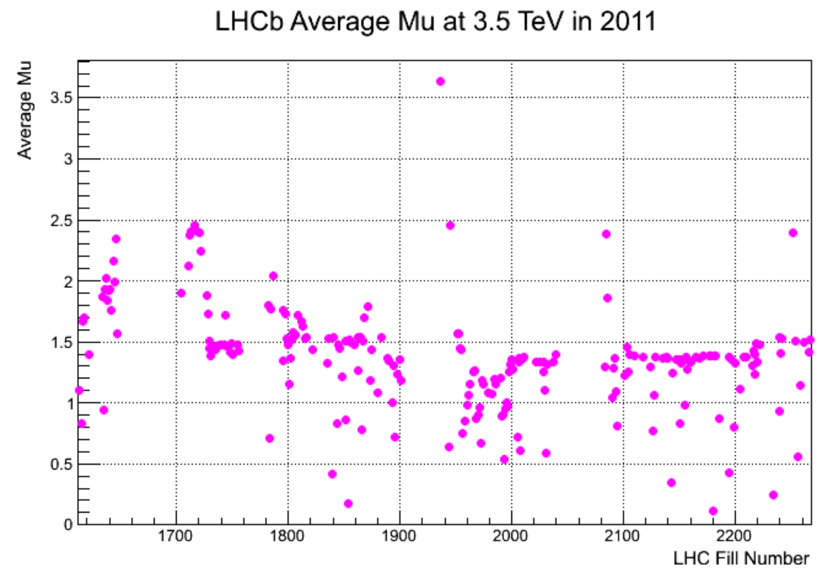
2010 36 pb^{-1} @ 7 TeV

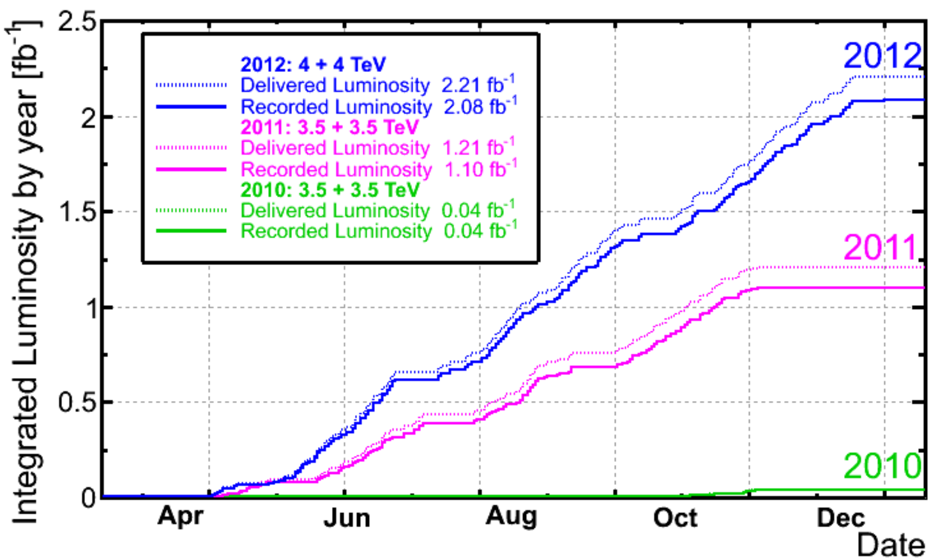
2011 1 fb^{-1} @ 7 TeV

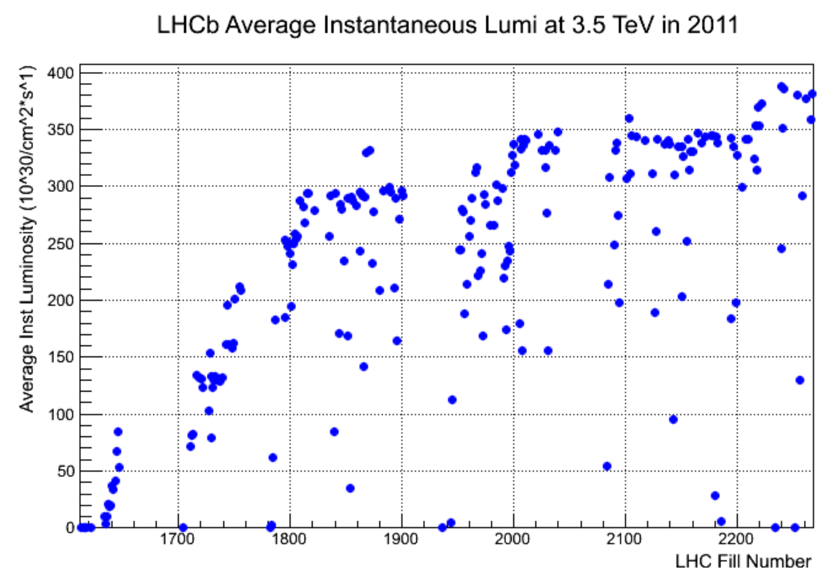
2012 2 fb^{-1} @ 8 TeV

2013 2 nb^{-1} @ 5 TeV proton-lead

Since 2011: Luminosity levelling:
Continuous adjusting of beam overlap
→ roughly constant luminosity
→ stable running conditions
High data taking efficiency:>90%



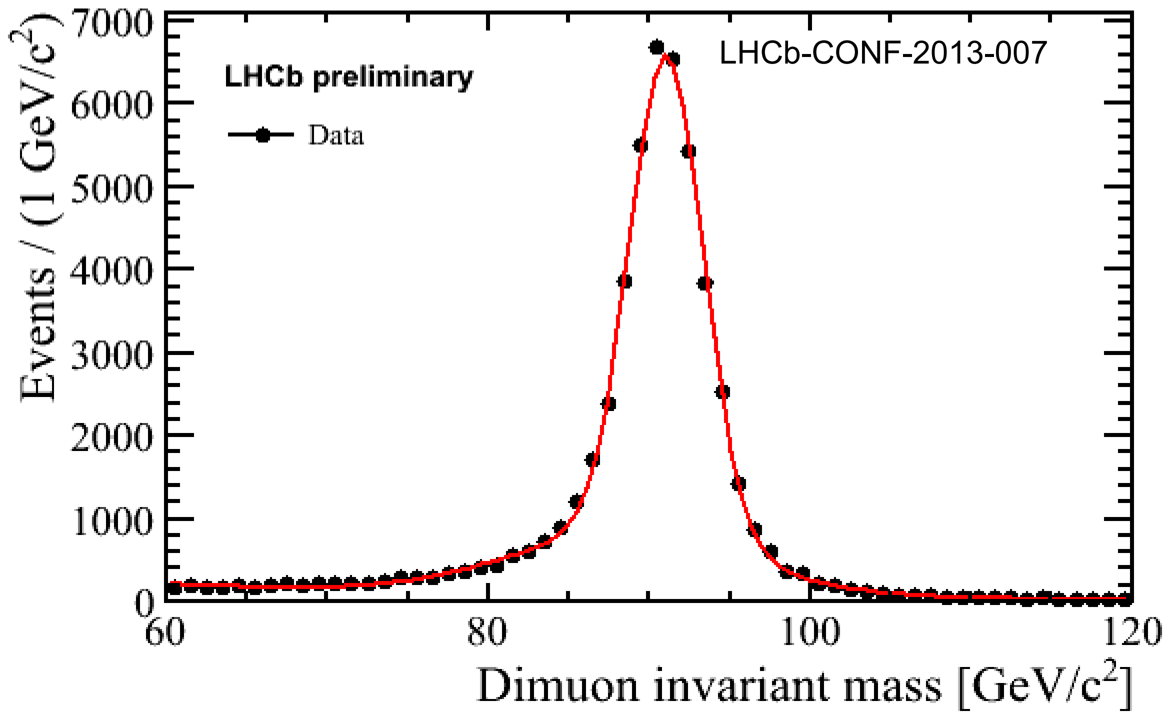




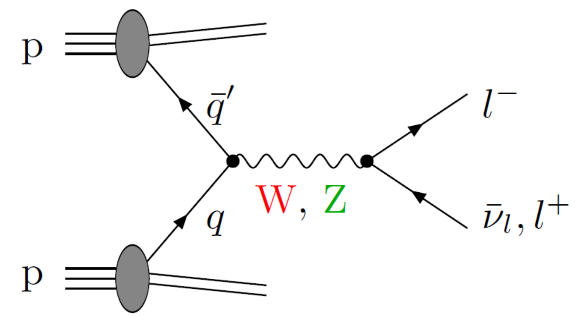
Measurements with electroweak bosons

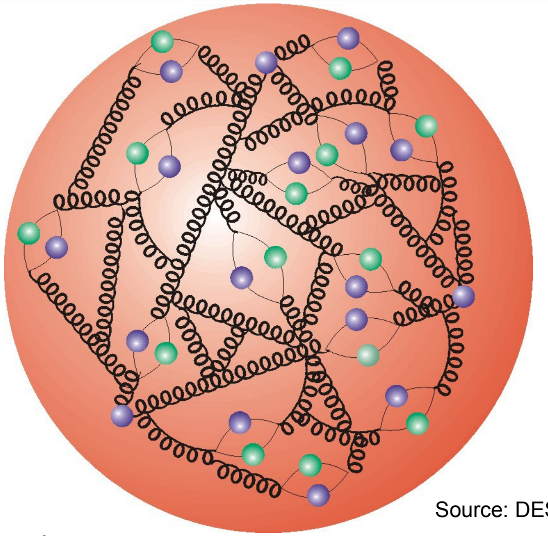
Introduction
Z production
- Z plus jet
- Z plus D
- in proton-ion collisions

Inclusive W production



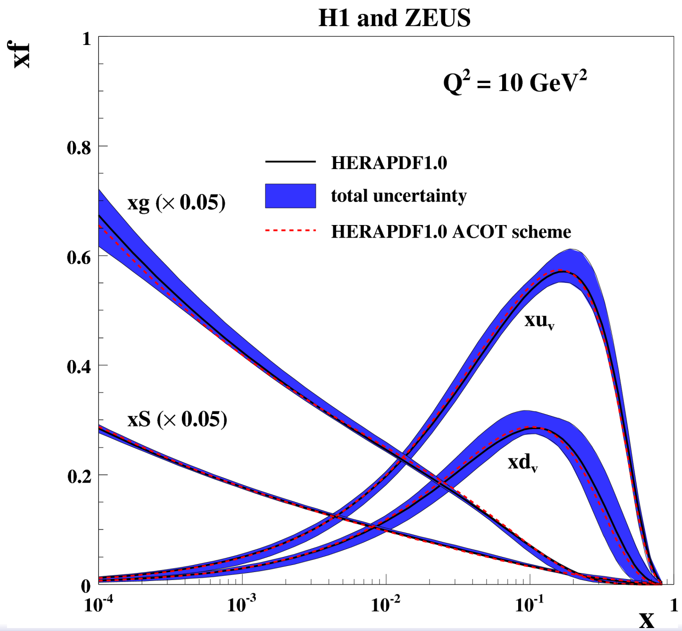
Theoretical motivation





Source: DESY, Hamburg

W and Z production at LHCb
LHCb forward kinematics:
@ first order, collision of a sea and a valence quark
→ asymmetry in production rate for W^+ and W^-
→ sensitivity to structure of the proton: parton distribution functions (PDF)



JHEP 1001 (2010) 109
arXiv:0911.0884 [hep-ex]

PDF : $f_q(x,Q^2)$
probability, that proton contains a parton q
with momentum fraction x
Q: invariant mass of parton interaction

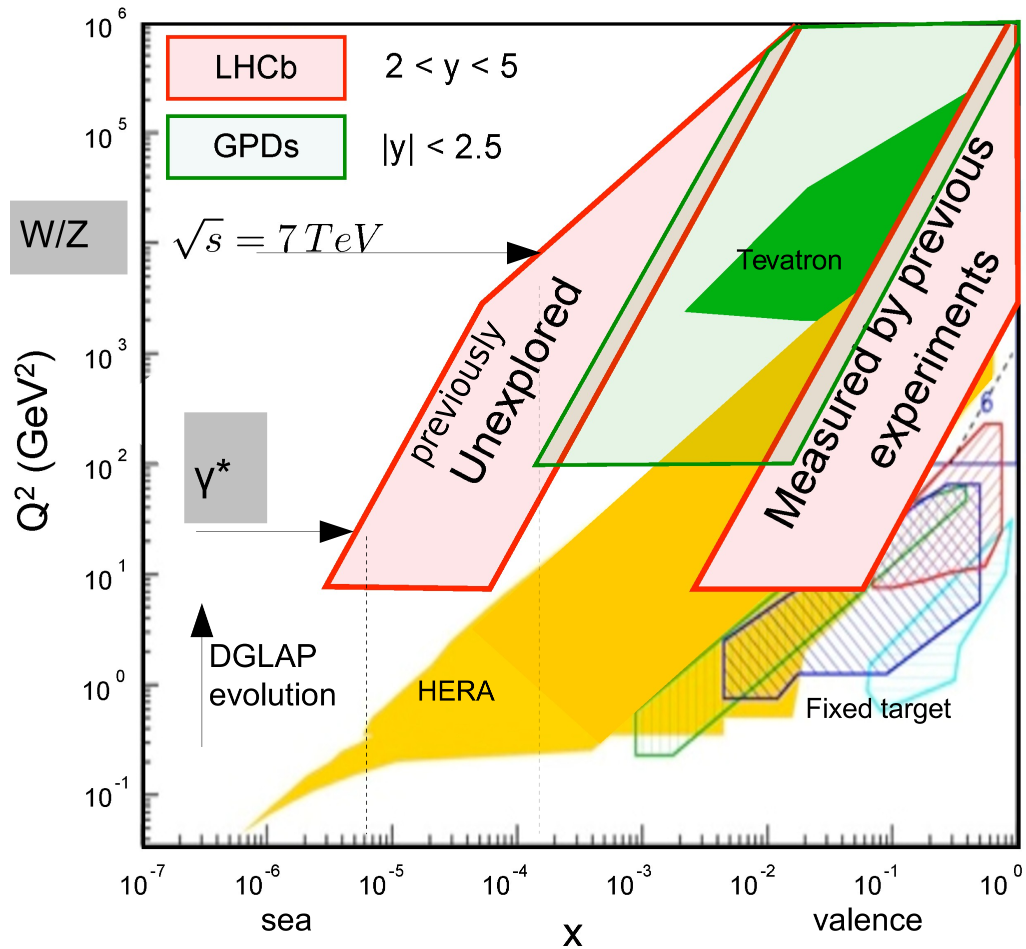
Measurements with electroweak bosons

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

Unique region at low x

- W, Z production:
  x= $1.7\cdot10^{-4}$
- complementary to ATLAS/CMS
- low mass Drell-Yan production
  x= $8\cdot10^{-6}$ at m=5 GeV

→ valuable input for the extraction of PDF

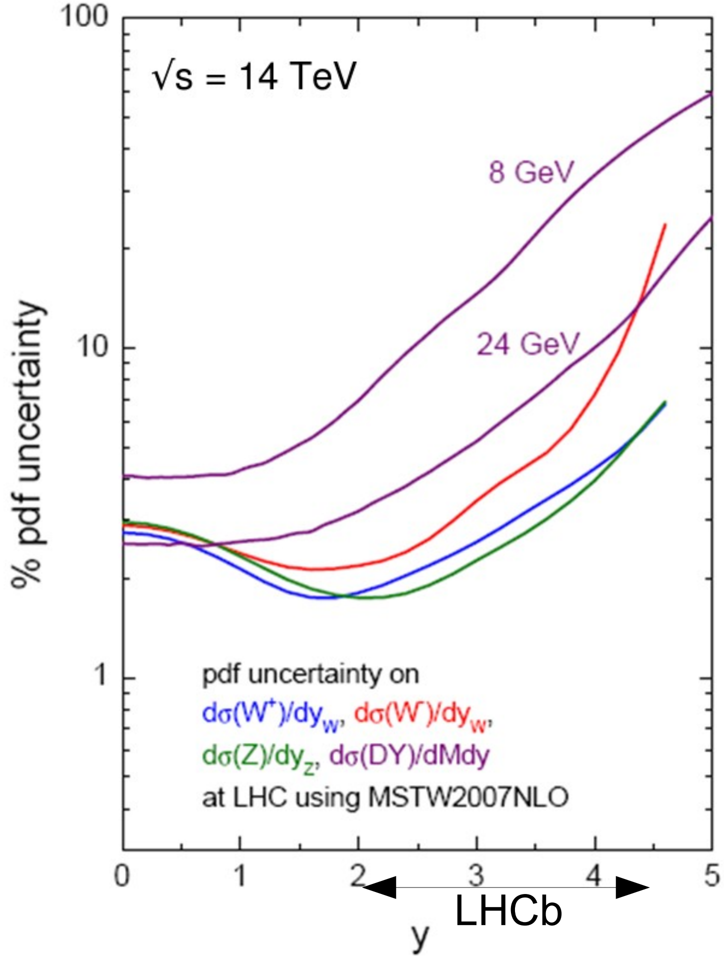


Theoretical uncertainties due to PDF

$$\underbrace{\sigma\left(x,Q^2\right)}_{hadronic\ x-sec.} = \sum_{a,b}\int_0^1 dx_1\, dx_2 \underbrace{f_a\left(x_1 Q^2\right) f_b\left(x_2 Q^2\right)}_{PDFs\ 2-8\%} \underbrace{\hat{\sigma}\left(x_1, x_2, Q^2\right)}_{partonic\ x-sec.:\ NNLO\ 1\%}$$

Theoretical predictions:

- cross-sections known at NNLO to %-level
- PDF uncertainty dominates at large rapidities
  3% at y <2, 6-8% at y~5
- low masses: uncertainties much larger



Plot from Thorne et al. (arXiv:0808.1847)

Theoretical uncertainties due to PDF

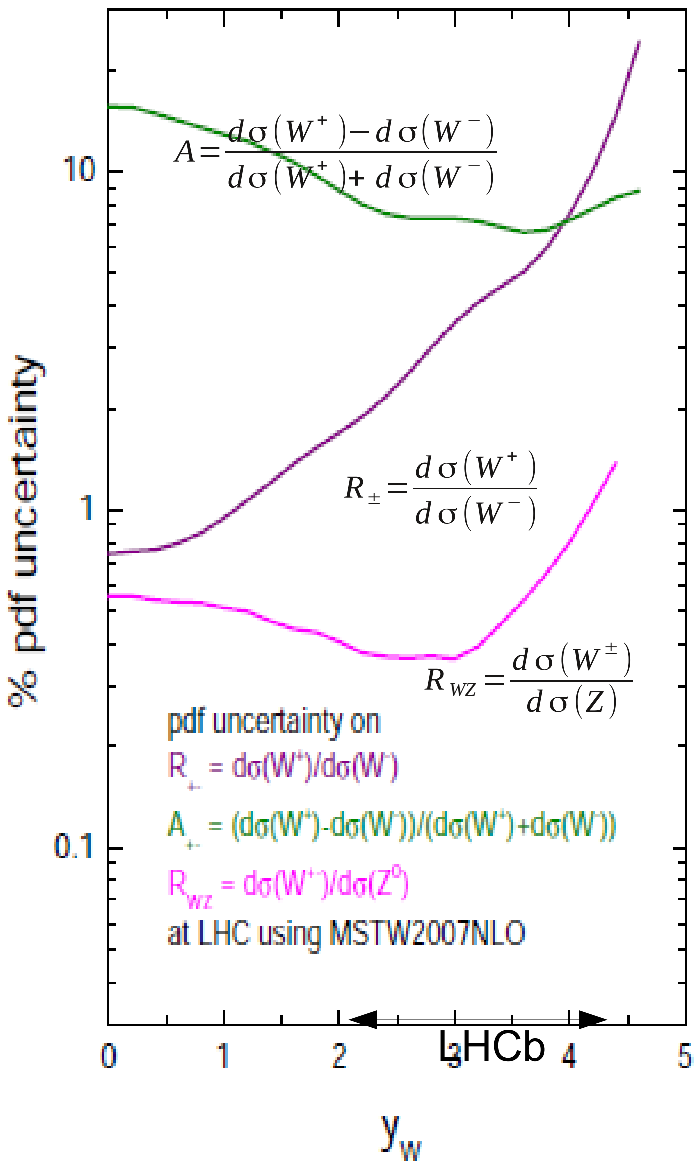
Cancel or highlight PDF uncertainties with ratios

- many systematic uncertainties cancel
- theoretical uncertainties partially cancel
- $A_W = (d\sigma(W^+)-d\sigma(W^-))/(d\sigma(W)+d\sigma(W^-))$

  tests valence quarks: difference btw. u_V and d_V
- $R_{+-}=d\sigma(W^+)/d\sigma(W^-)$

  tests valence quarks: u_V/d_V ratio
- $R_{WZ} = d\sigma(W^{+-})/d\sigma(Z)$

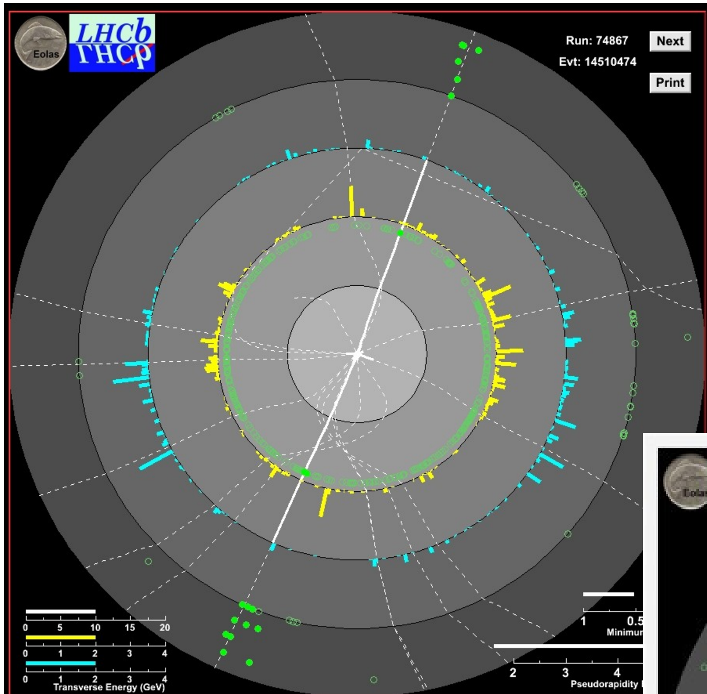
  almost insensitive to PDFs
  precise test of SM



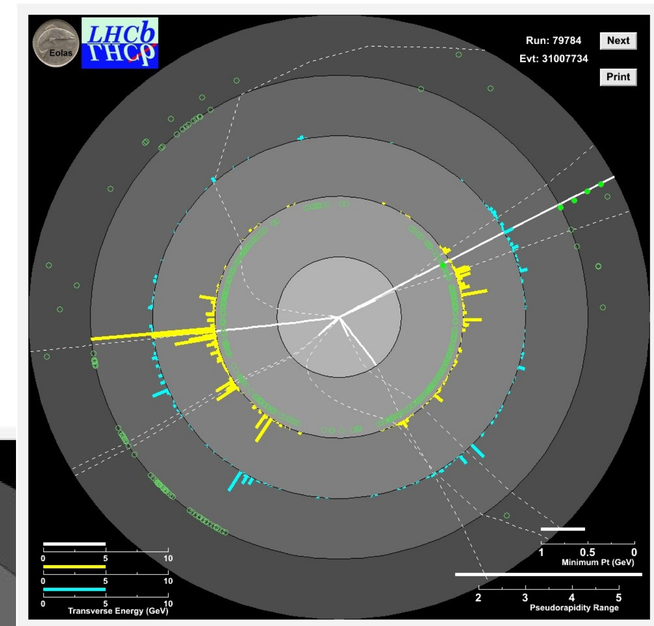
Plot from Thorne et al. (arXiv:0808.1847)

Inclusive Z measurements

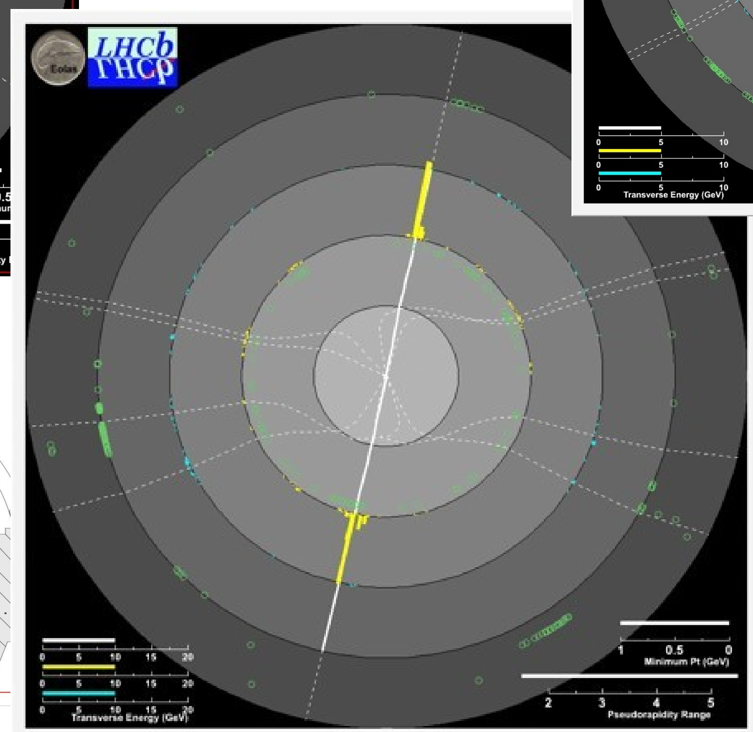
$Z \rightarrow \mu\mu$



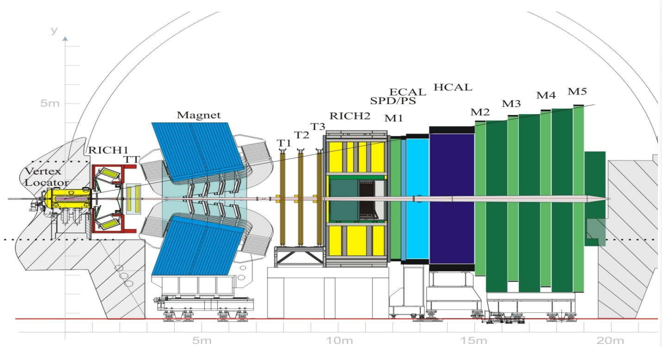
$Z \rightarrow \tau\tau \rightarrow e\mu$



$Z \rightarrow ee$



φ-z view (Radius=z)

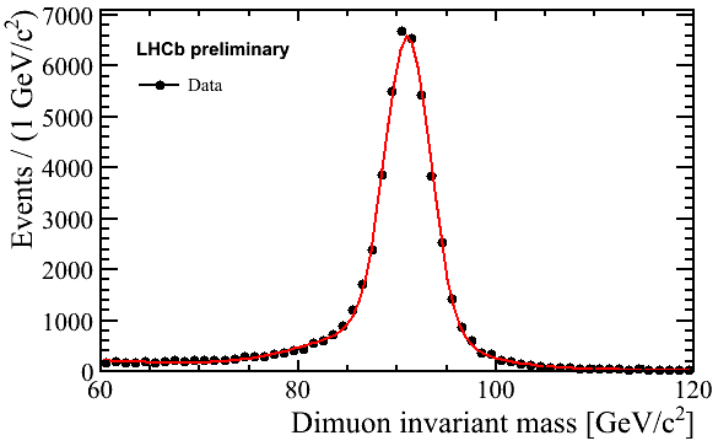


Inclusive Z measurements at 7 TeV

LHCb-CONF-2013-007

$Z \rightarrow \mu\mu$

LHCb-CONF-2013-007



$Z \rightarrow \tau\tau \rightarrow e\mu$

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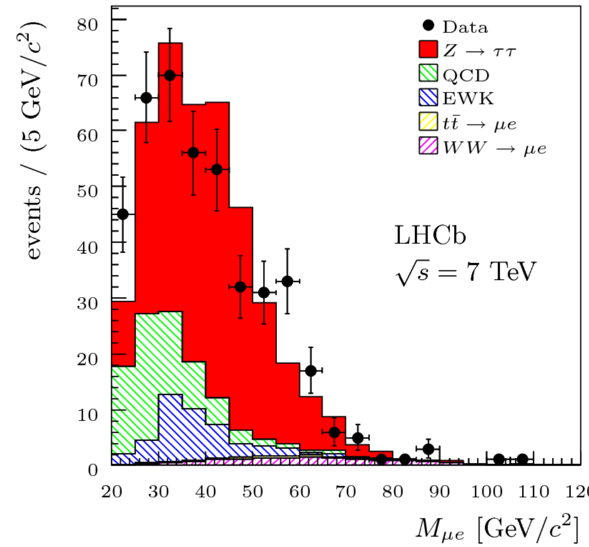

$Z \rightarrow ee$

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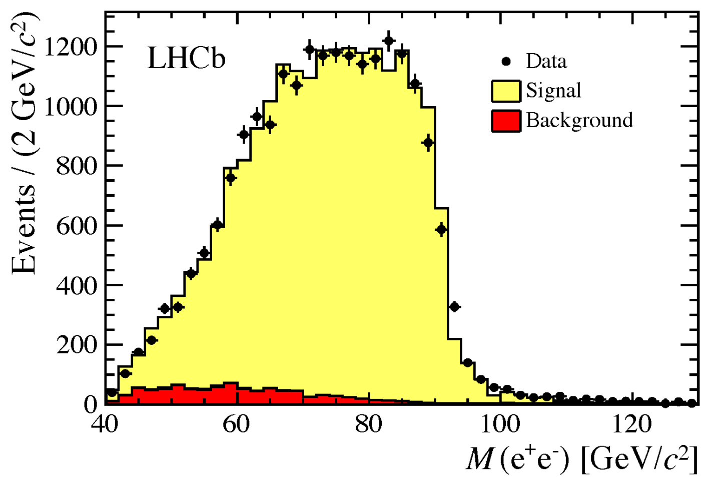


Fiducial volume

leptons: p_T>20 GeV, 2<η<4.5

mass: 60<M_{ll}<120 GeV^2

Background

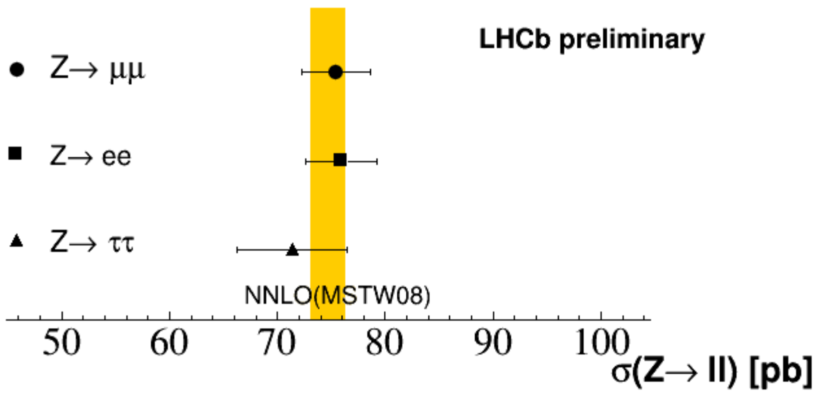
muon < 0.3%

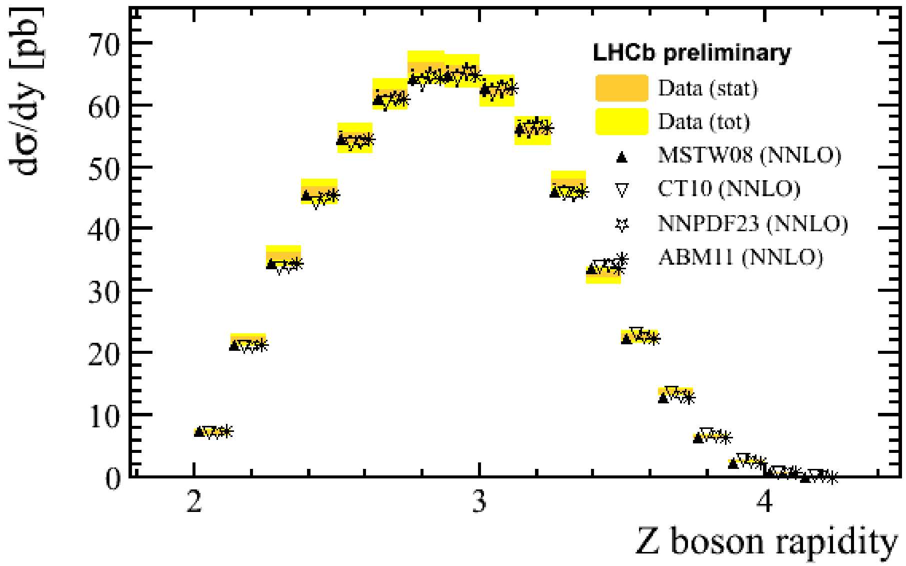
electron ~ 4.5%

tau 28-37

→ the following analyses are all based on the di-muon final state

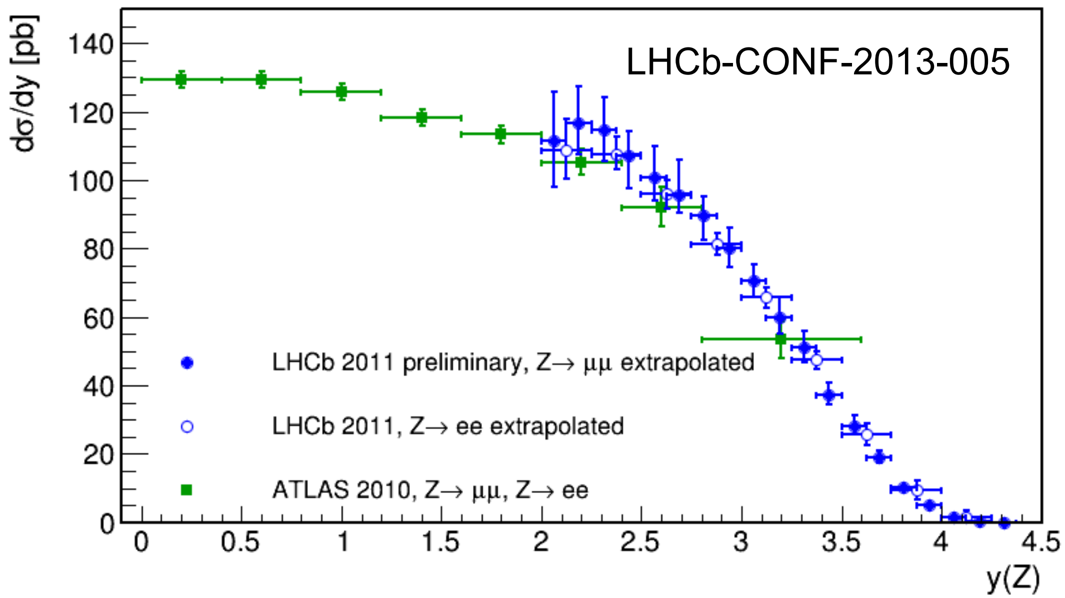
Inclusive Z measurements



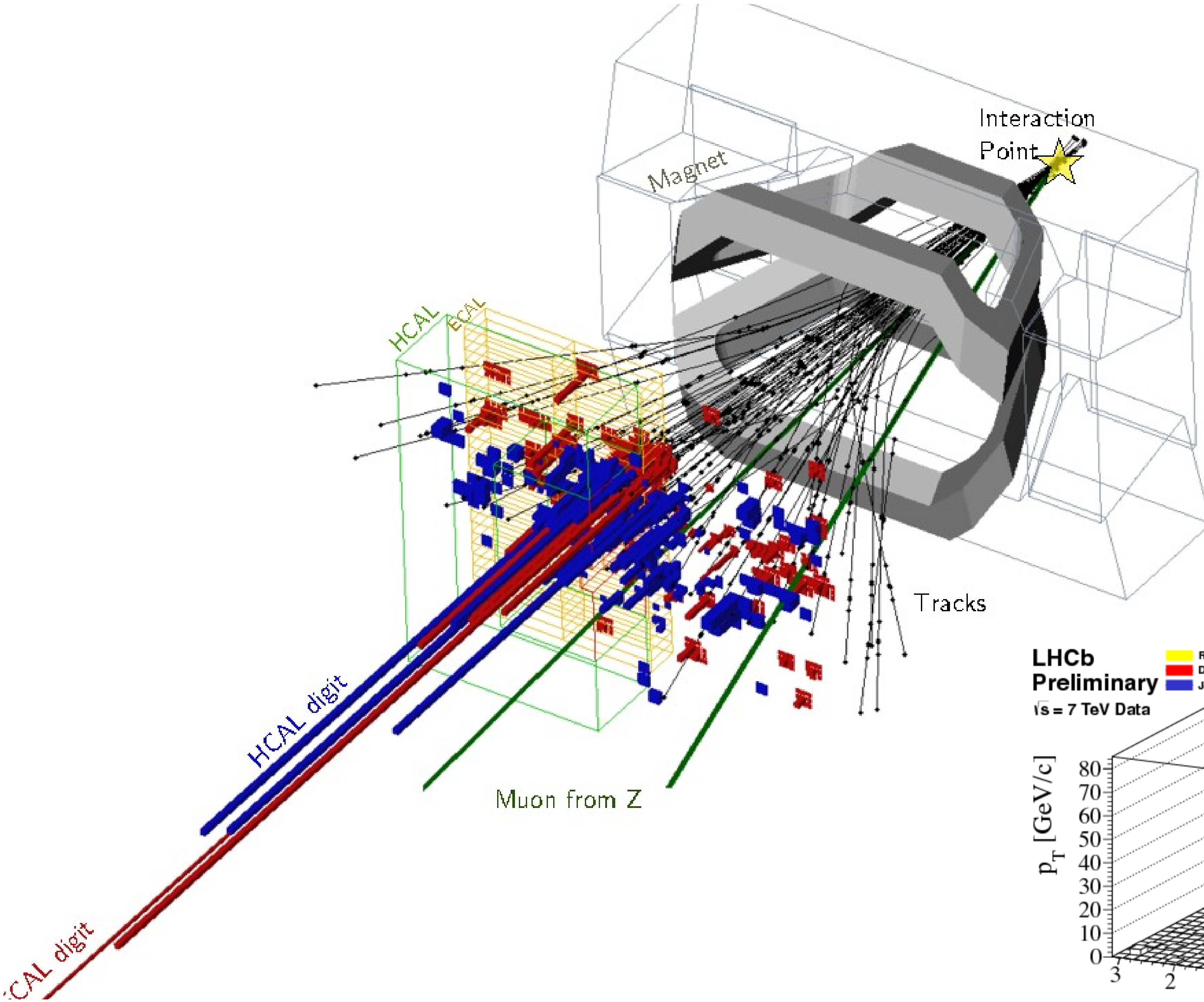


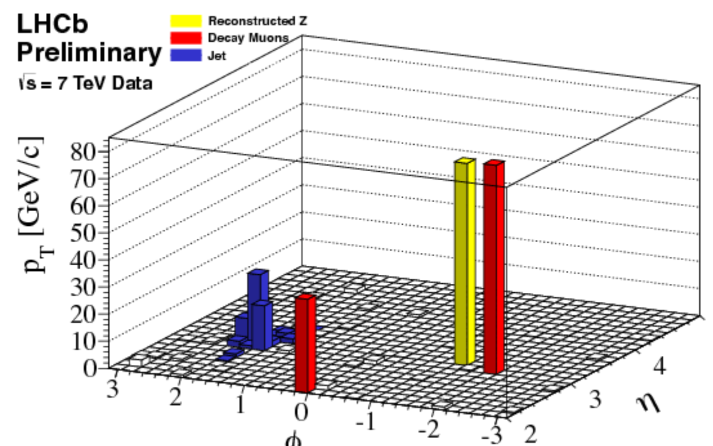
Good agreement
- between different channels
- with NNLO predictions
- with ATLAS in overlap region

extrapolation to ATLAS:
accounts for acceptance of
the leptons and a different mass window



Z plus jet production





LHCb-CONF-2012-016

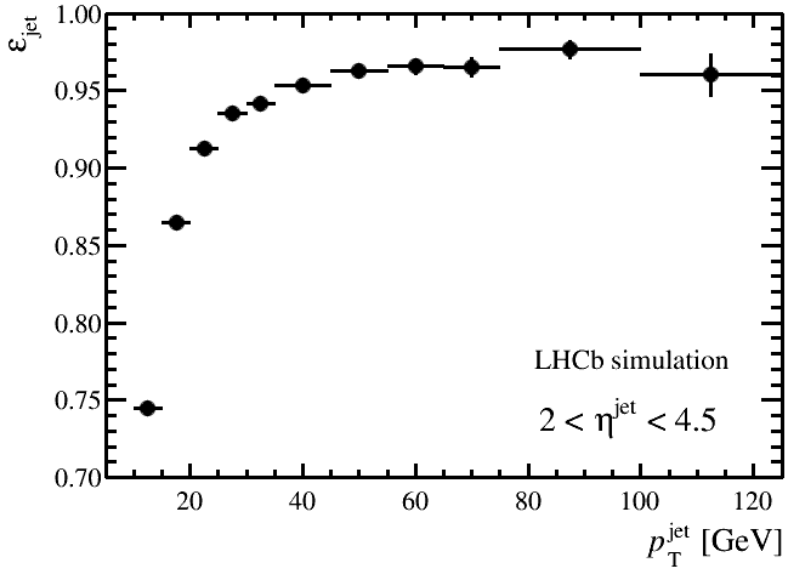
Z plus jet

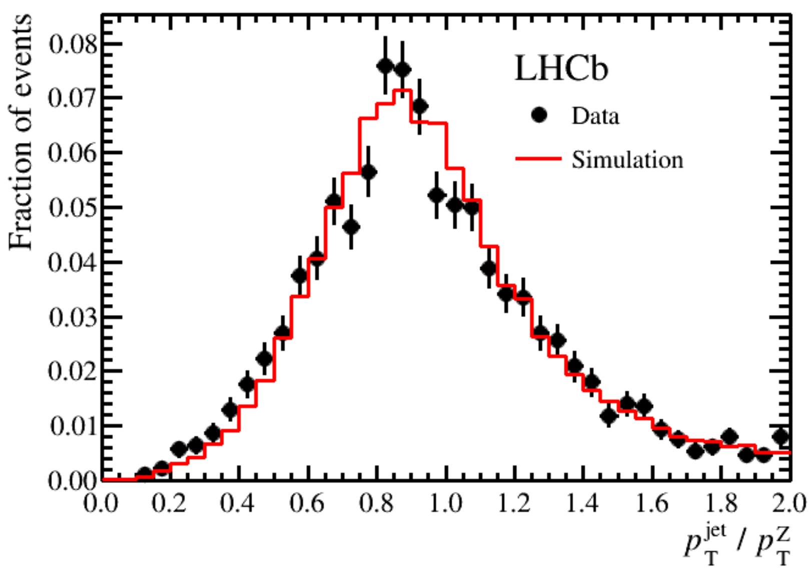
Jet reconstruction
- anti-k_T algorithm(R=0.5)
- particle-flow objects:
  charged tracks and neutral clusters

Z plus jet selection
- standard selection for the Z
- jet $2<\eta<4.5$, $p_T>10$ (20 GeV)
- jet-muon separation: $\Delta r(\text{jet},\mu)>0.4$

Jet energy correction
- from simulation: 0.9-1.1
- validated in data: Z plus 1 jet events
- simulation describes data well

Dominant systematic uncertainties
- jet energy scale and resolution
- jet reconstruction efficiency





Z plus jet production

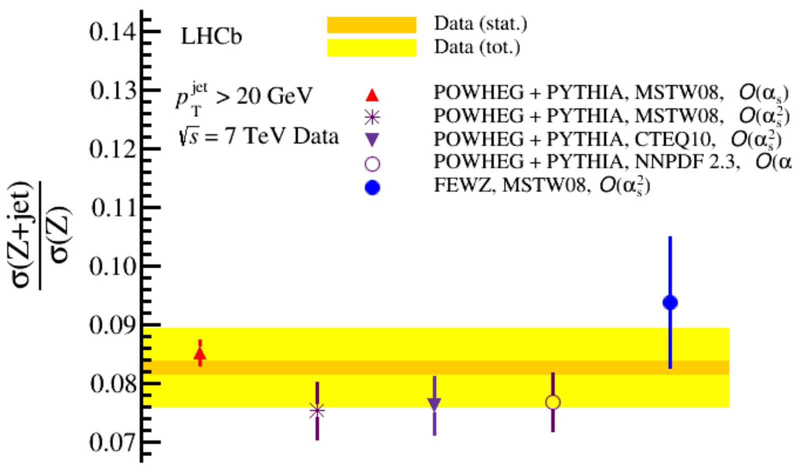
Jets: anti-k_T (R=0.5), $2<\eta<4.5$, $p_T>10$ (20 GeV), $\Delta r(\text{jet},\mu)>0.4$

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

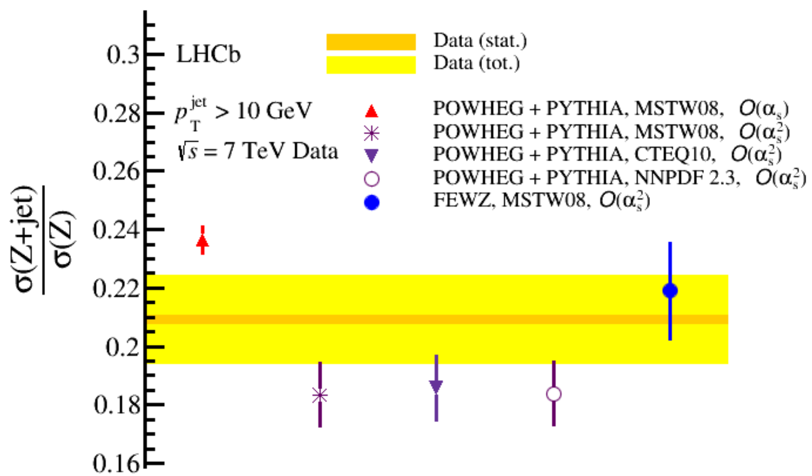
$p_{T(jet)}>10$ GeV: $\sigma = 16.0 \pm 0.2(\text{stat}) \pm 1.2(\text{syst}) \pm 0.6(\text{lumi})$ pb

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

$p_{T(jet)}>20$ GeV



$p_{T(jet)}>10$ GeV



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

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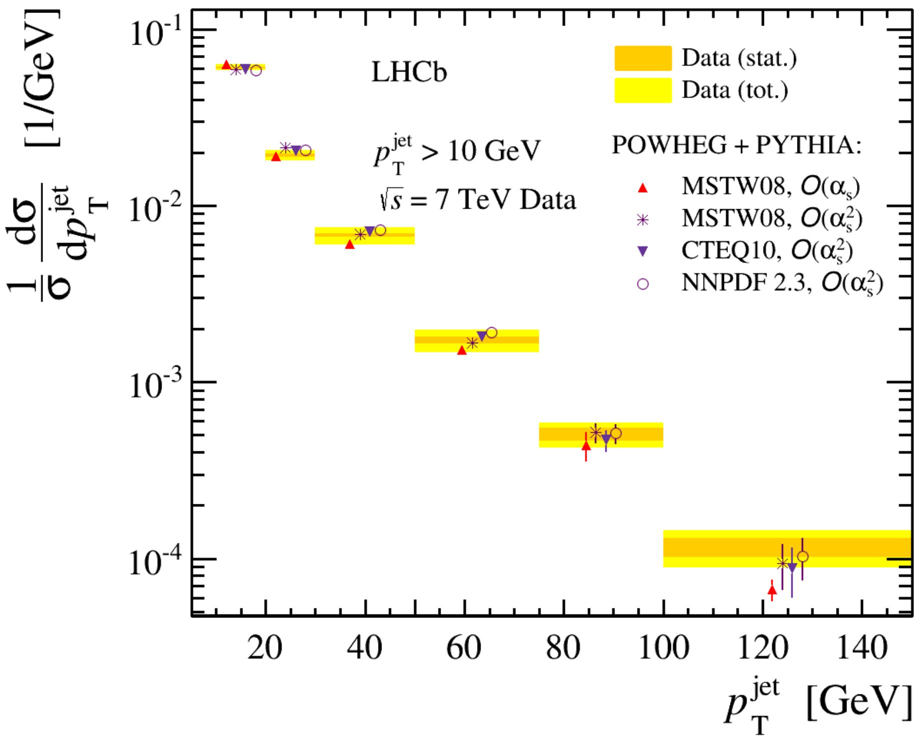
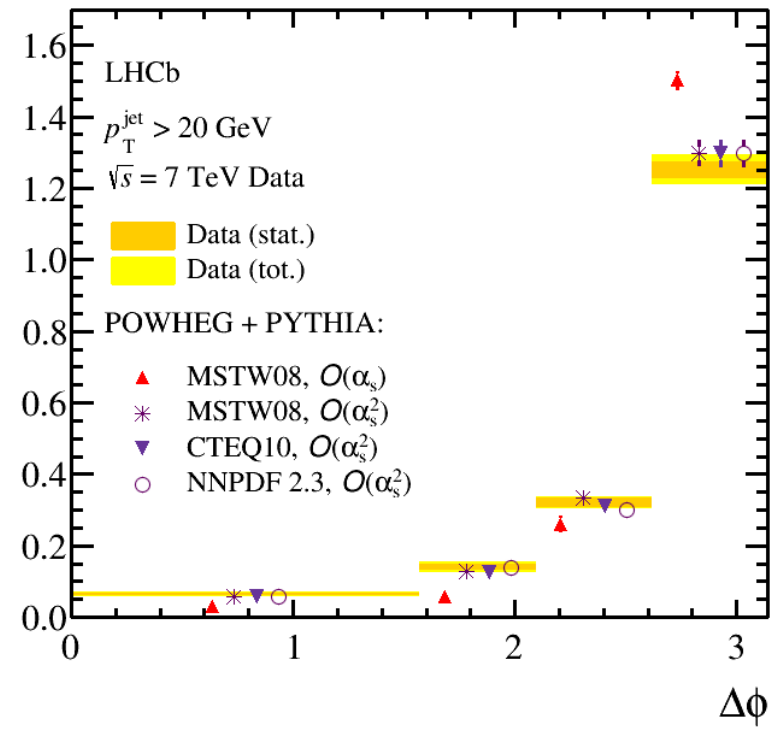




Shapes well described by NLO predictions

LO fails to describe Δφ(Z,jet)

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

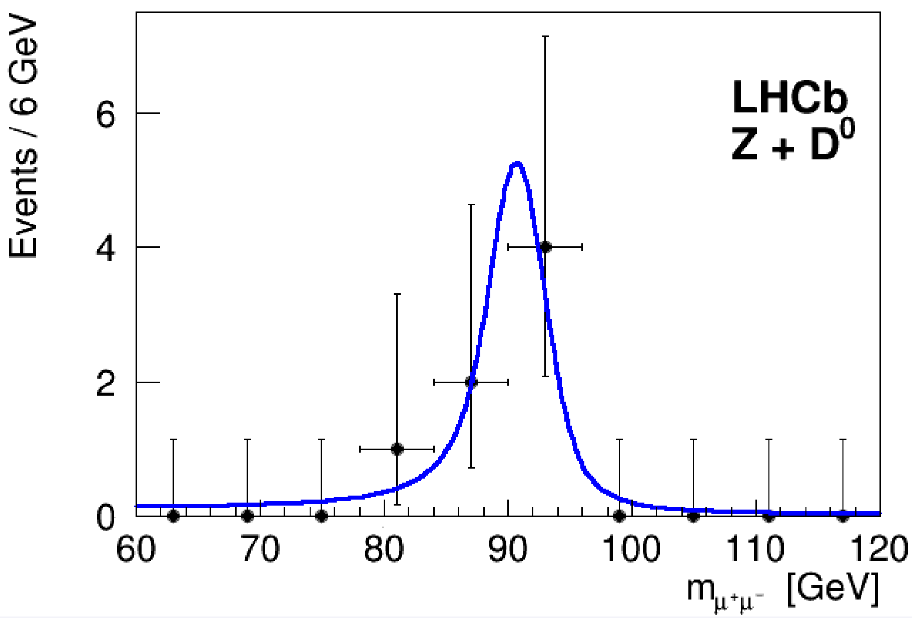
Selection

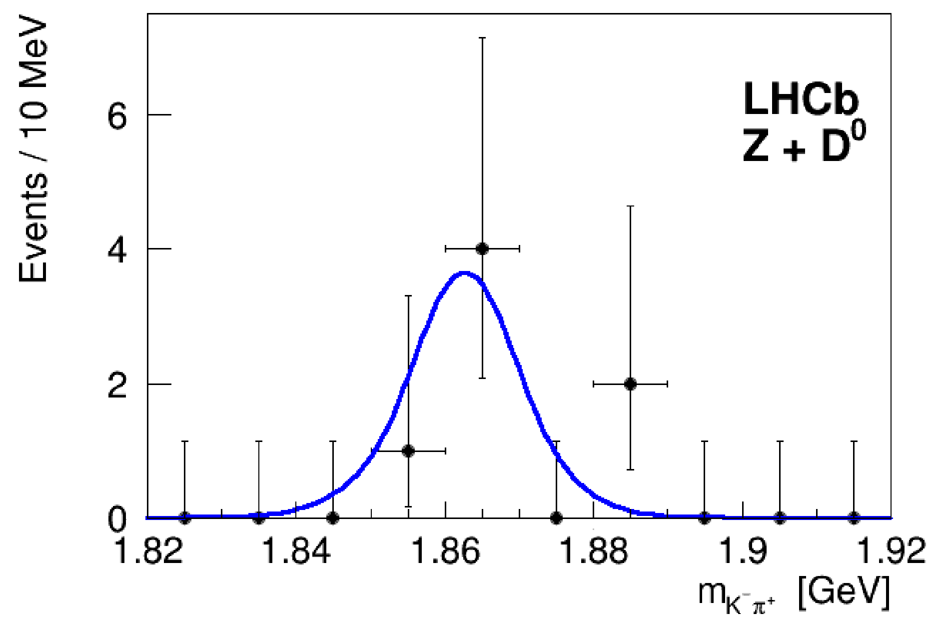
standard Z selection
$D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+\pi^+$
$2 < p_T^D < 12$ GeV
$2 < \eta^D < 4$
Z and D from same vertex

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

combined significance: 5.1 σ

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

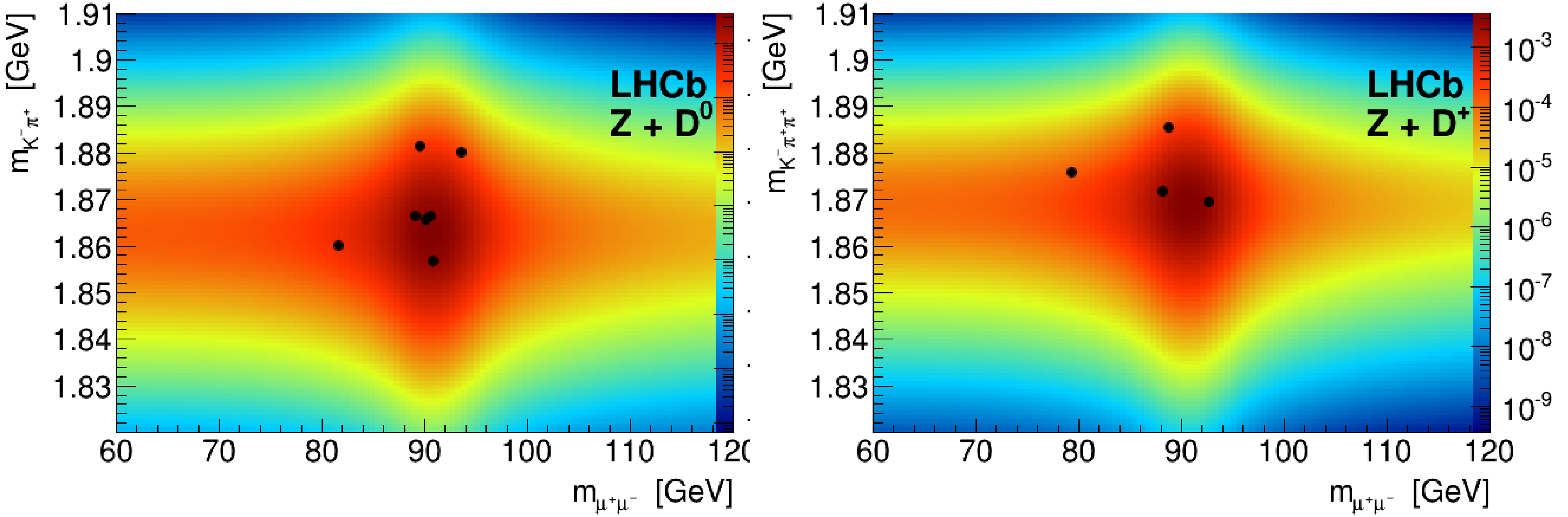




Z plus D: backgrounds

- charmed hadrons from B-decays (dominant)
- real Z and D from different vertices
- combinatorial background: from 2d fit to mass distributions

2D mass distribution with PDF for signal and background

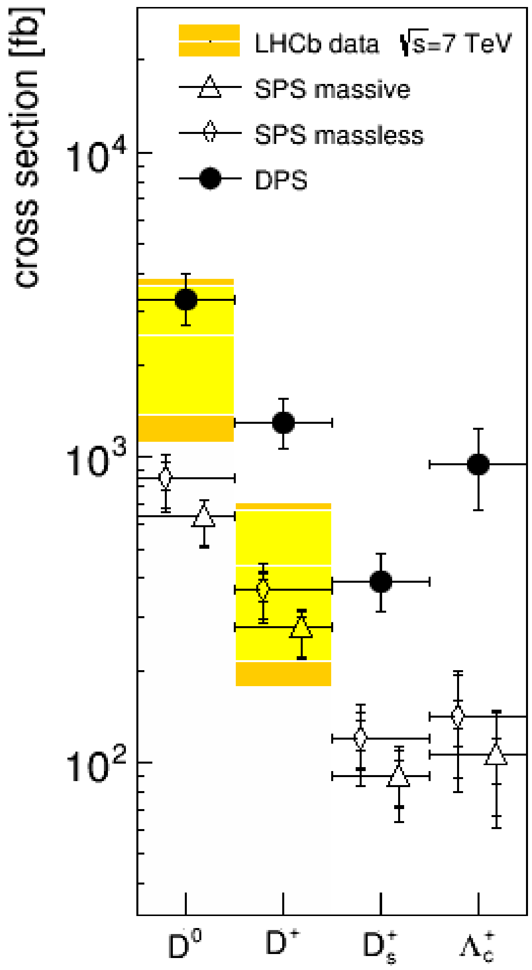


- purity is high about 95%

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):

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

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

Sum of SPS and DPS expected to describe signal

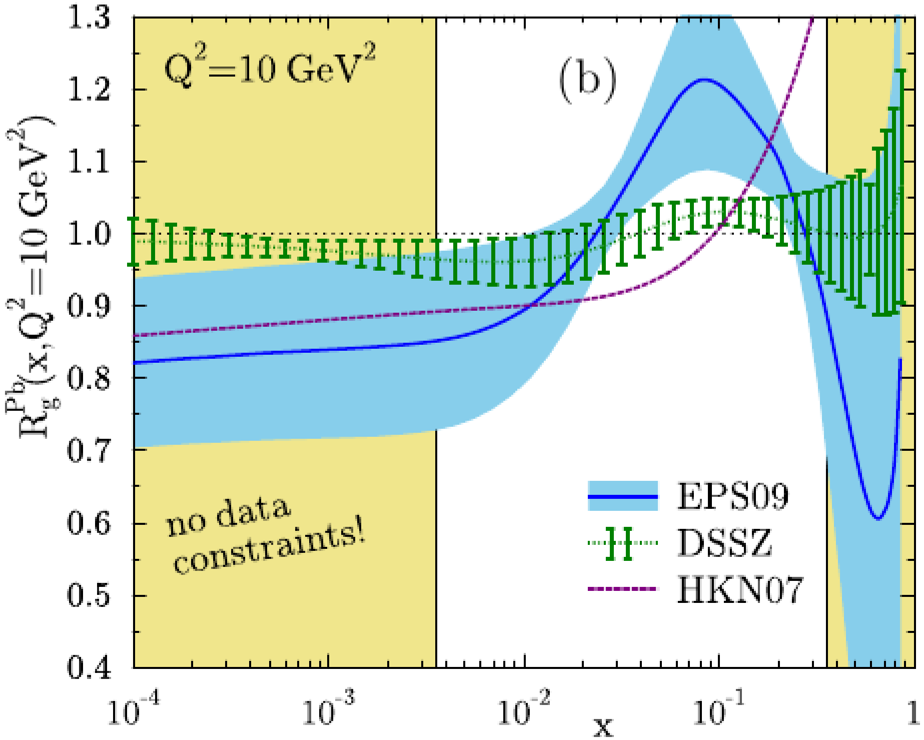
- consistent for Z plus D^0
- Z plus D^+ below expectation

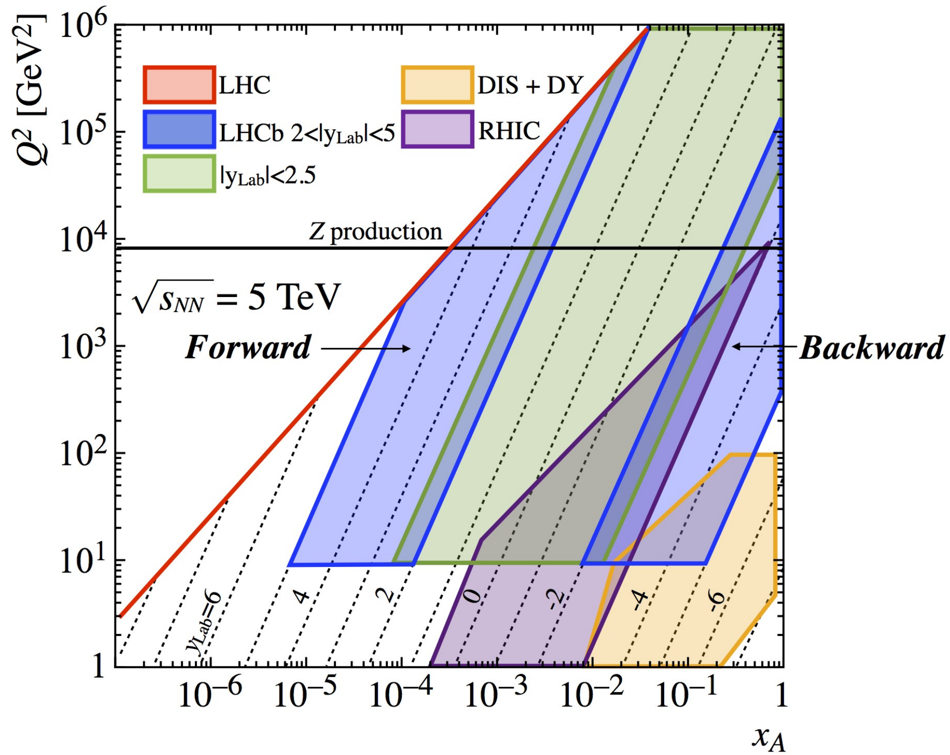
→ differential measurements with high statistics will allow to disentangle SPS and DPS contributions

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

Z production in pA

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





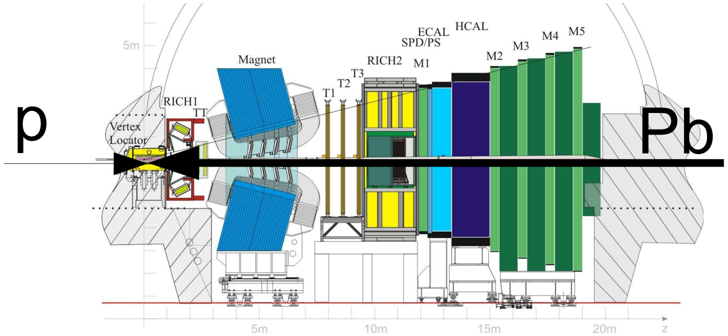
Nuclear PDF (nPDF) poorly constrained at high and low x_A, where measurements at LHCb have a good sensitivity.

x_A:momentum fraction of a parton inside the nucleon

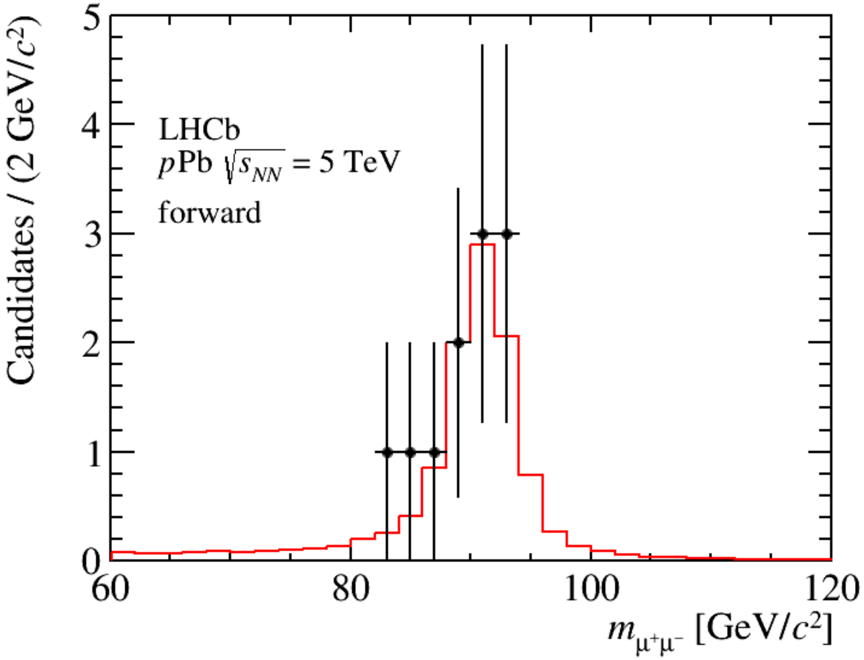
Forward: proton beam in LHCb direction, backward: lead beam in LHCb direction arXiv:1406.2885

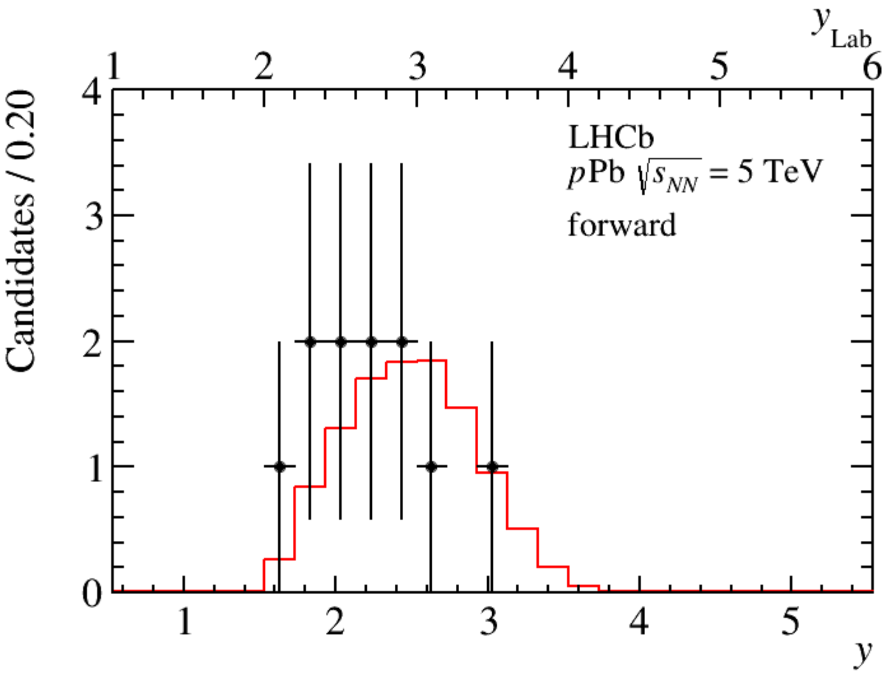
Forward: pA collisions

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:	$\Delta y = - 1/2 \ln Z/A \approx 0.47$
Luminosity:	$1.099 \pm 0.021\ nb^{-1}$



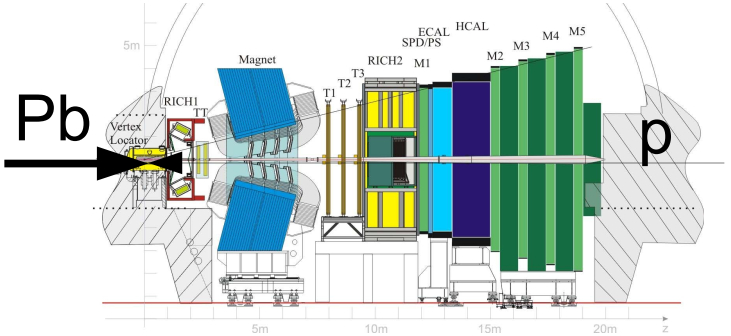
11 candidates





Z production in proton-lead

Backward: Ap collisions



proton beam: E_p = 4 TeV

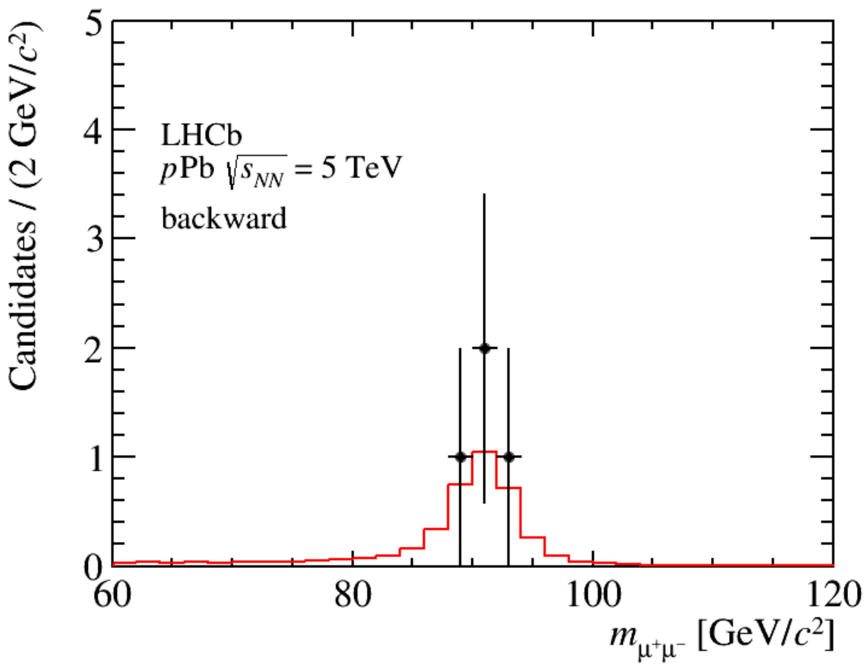
$^{208}_{82}$Pb beam: $E_N = Z\,E_p \approx 1.58$ TeV

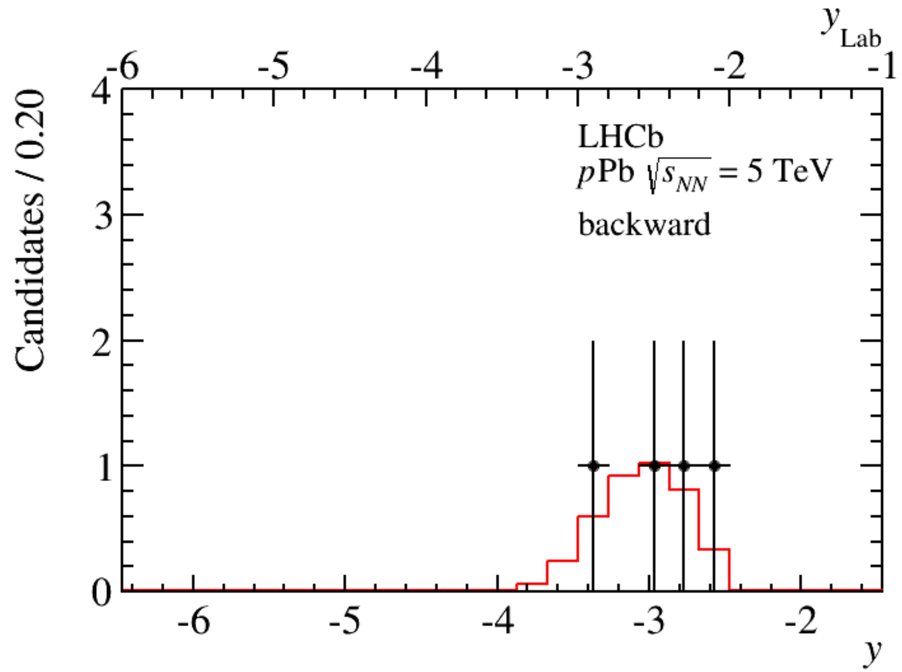
cms energy: $\sqrt{s_{pN}} \approx 5.02$ TeV

shift in rapidity: $\Delta y = -\,1/2 \ln Z/A \approx 0.47$

Luminosity: $0.521 \pm 0.011\ \mathrm{nb}^{-1}$

4 candidates





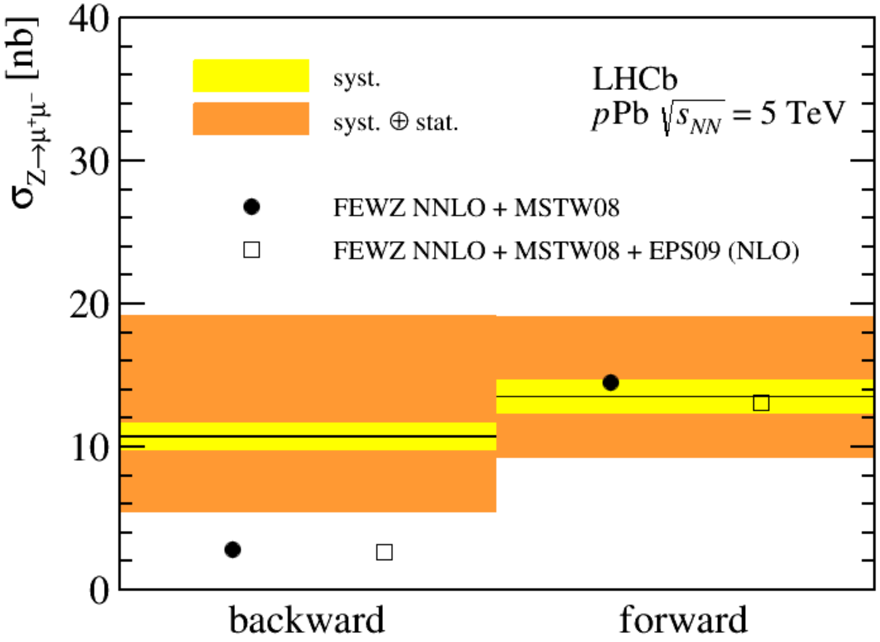
Z production in proton-lead

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

forward: $\sigma_{Z(\rightarrow\mu+\mu-)} = 13.5^{+5.4}_{-4.0}$ (stat.) ± 1.2(syst.)
backward: $\sigma_{Z(\rightarrow\mu+\mu-)} = 10.7^{+8.4}_{-5.1}$ (stat.) ± 1.0(syst.)

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

future higher statistics measurements will provide important information on nuclear PDFs

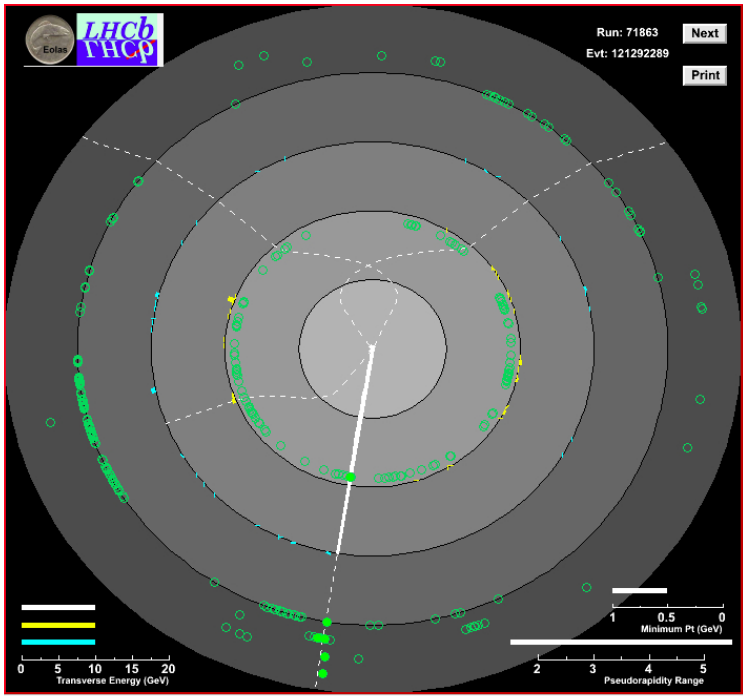


Fiducial volume
muons: p_T>20 GeV, 2<η<4.5
mass: 60<M(μμ)<120 GeV^2

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.

W production in pp @ 7 TeV



W selection: one (isolated) muon

Muon: one muon
$20 < p_T < 70$ GeV/c, $2.0 < \eta_\mu < 4.5$

Isolation $E_T^{cone} < 2$ GeV (Cone R<0.5 around μ)
$p_T^{cone} < 2$ GeV/c

Cuts against background:

- from semi-leptonic decays of heavy flavour
  Impact parameter < 40 μm
- γ*/Z: No other muon with $p_T > 2$GeV
- K/π punch through
  E(Calorimeter)/p<0.04

Main background:
kaon, pion decay in flight
γ*/Z→μμ, one muon in acceptance

W production

Purity from fit to p_T distribution

simultaneously in 8 η bins and both charges

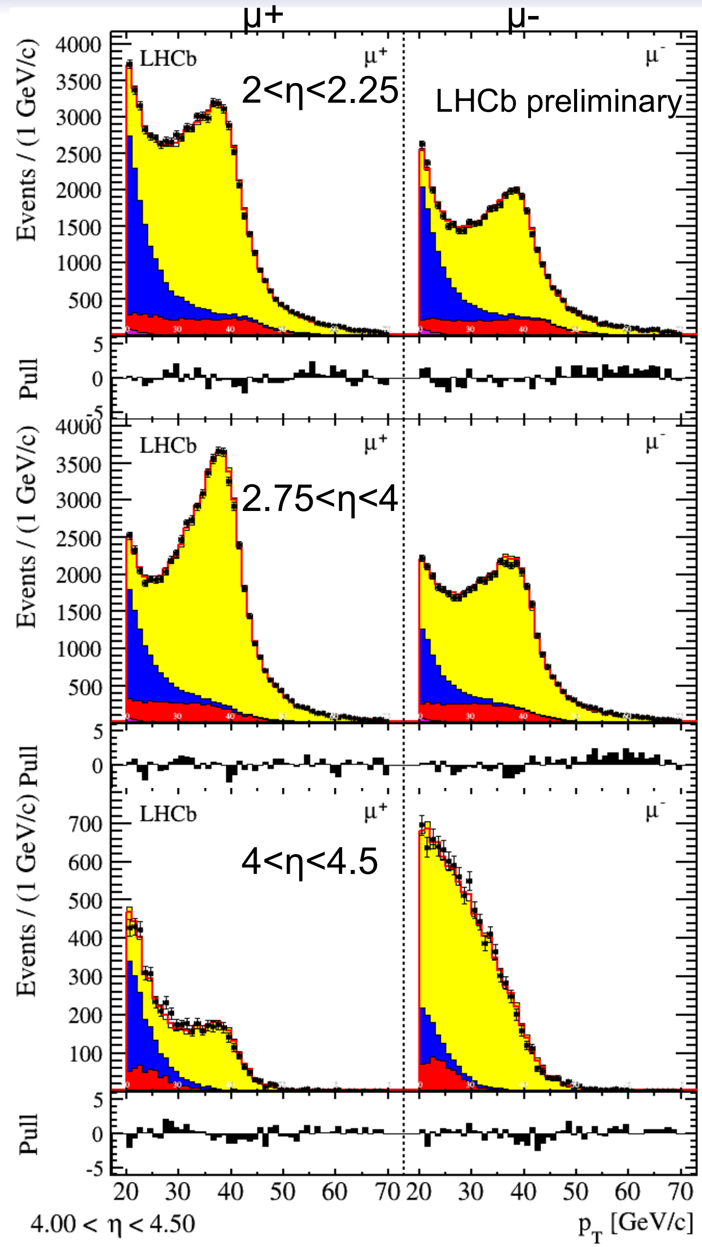
	Shape	Norm.
W →μν	simulation	fit
K/π decay in flight	ata	fit
γ*/Z→μμ	simulation	fixed
W→τν , Z→ττ	simulation	fixed
Heavy Flavour	data	fixed

Normalisation

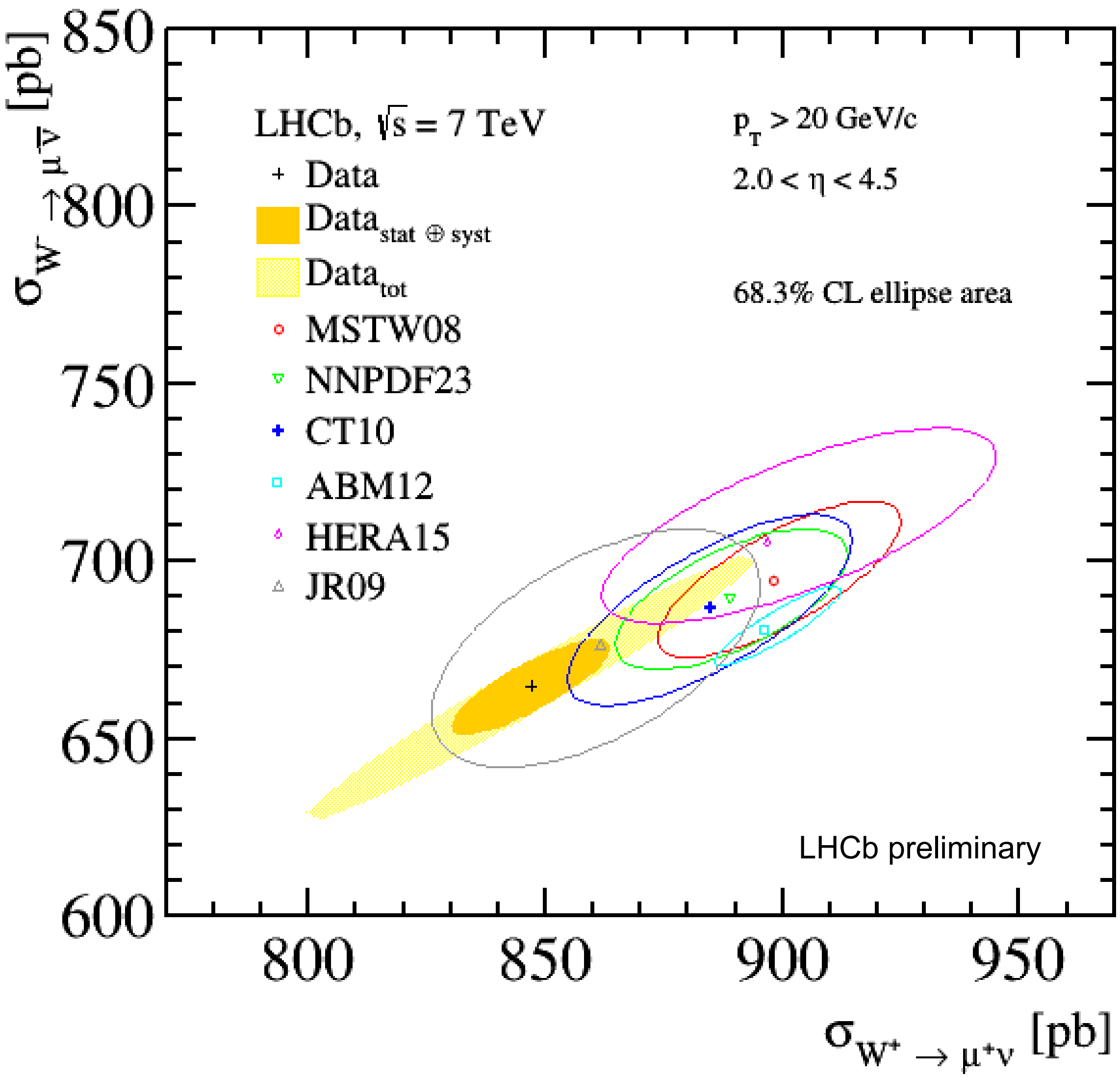
- signal and decay in flight: fitted
- others : fixed from data

Purity: (77.17 ± 0.19)% for W^+

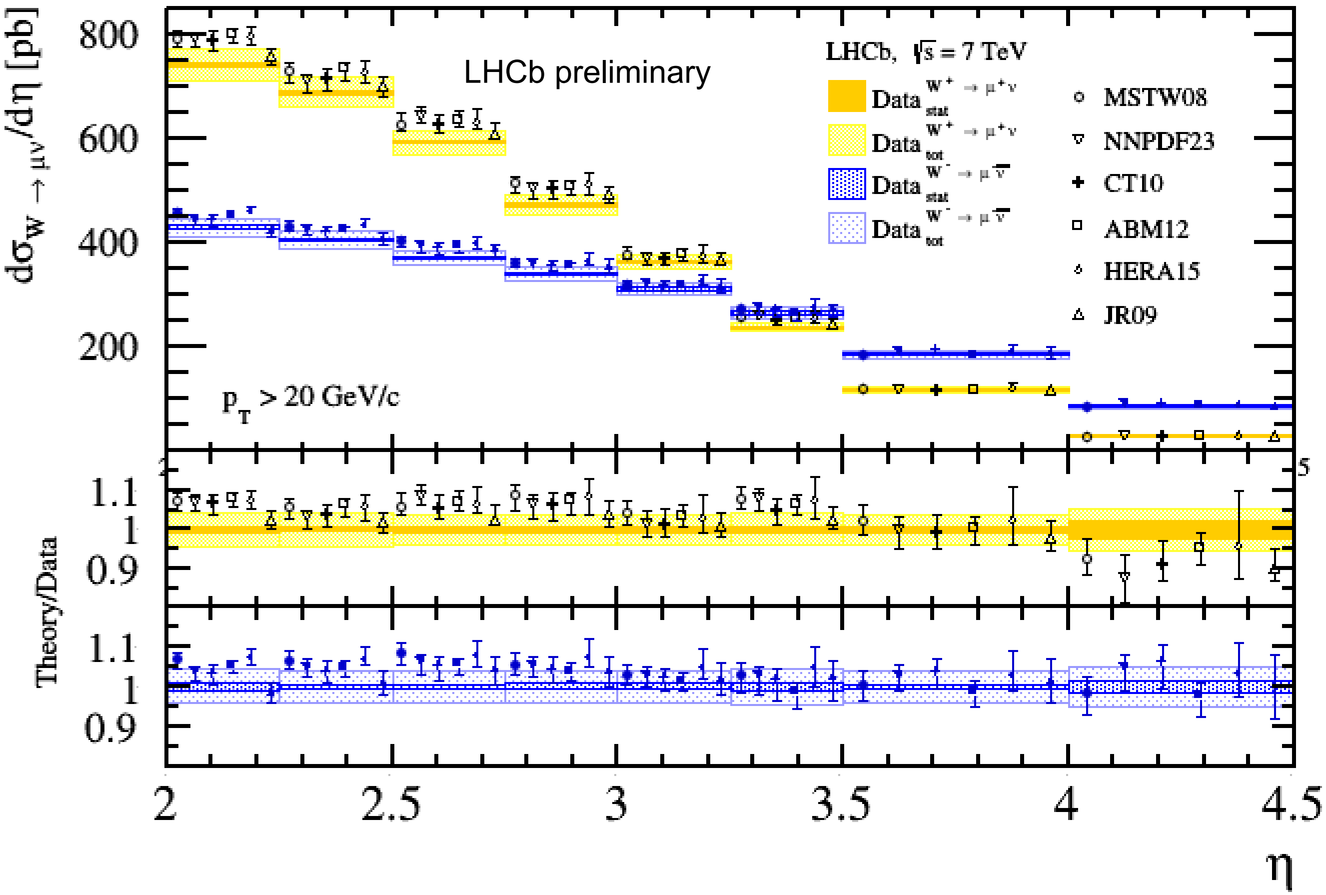
(77.40 ± 0.23)% for W^-



W production

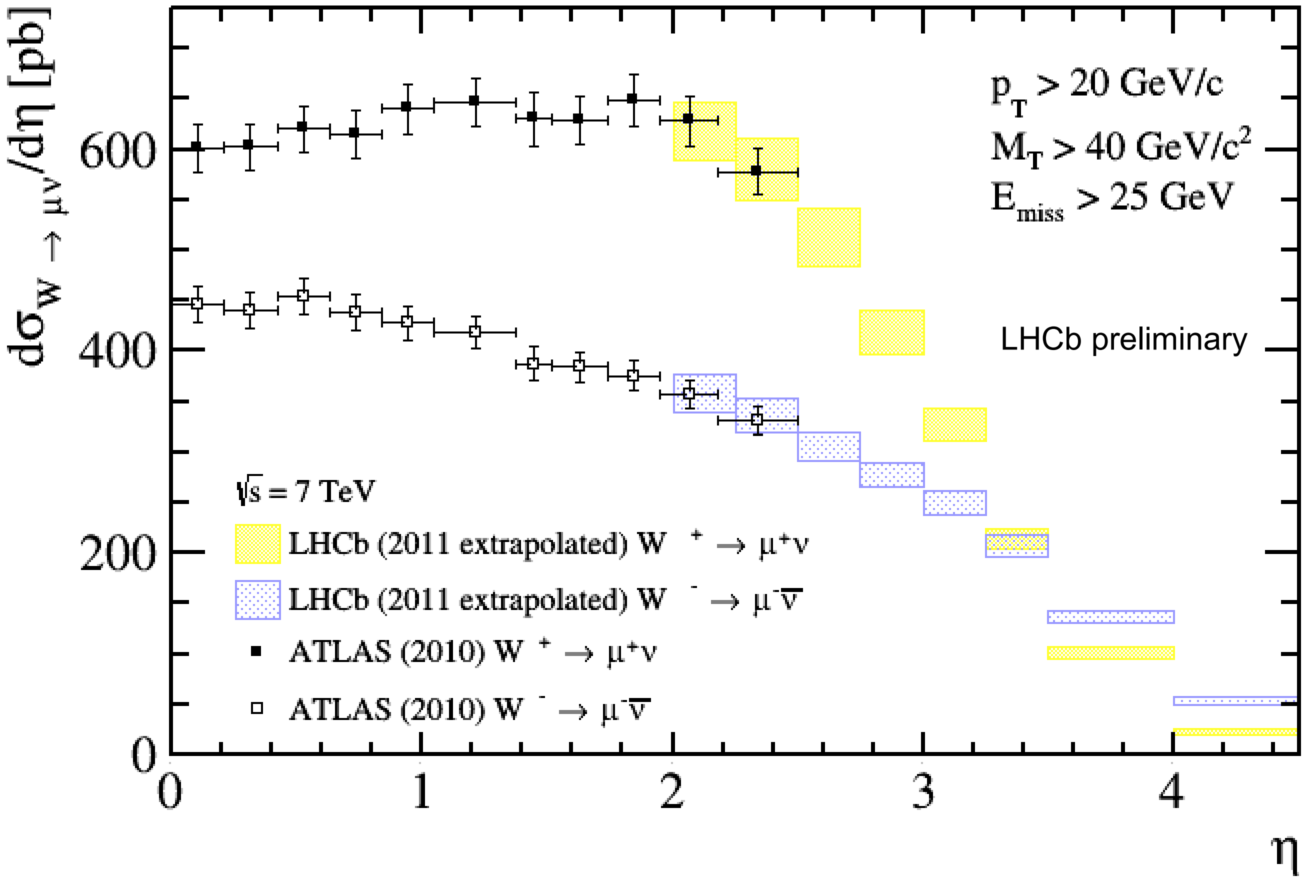


W cross section



Comparison to NNLO predictions with six different PDF sets

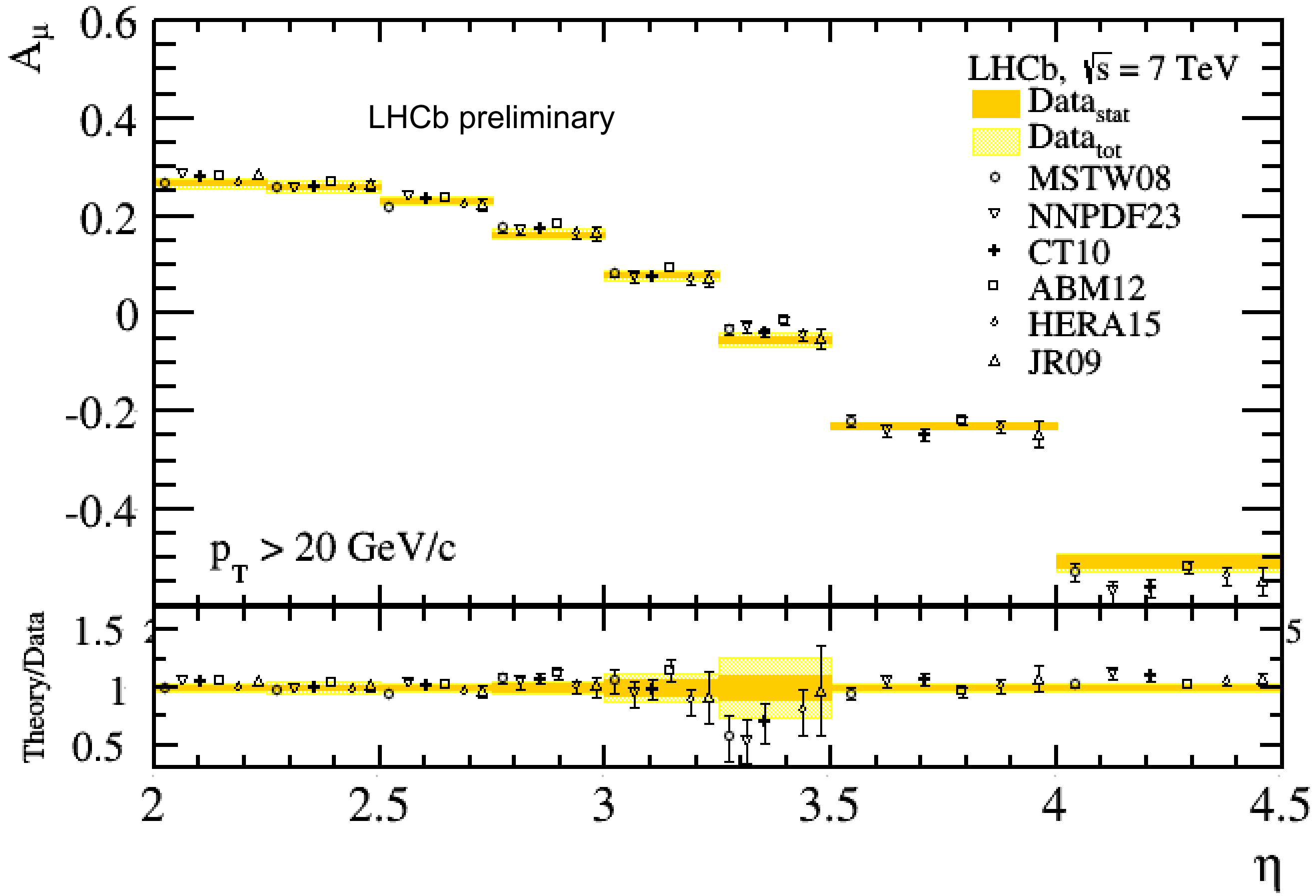
W cross section – comparison to ATLAS



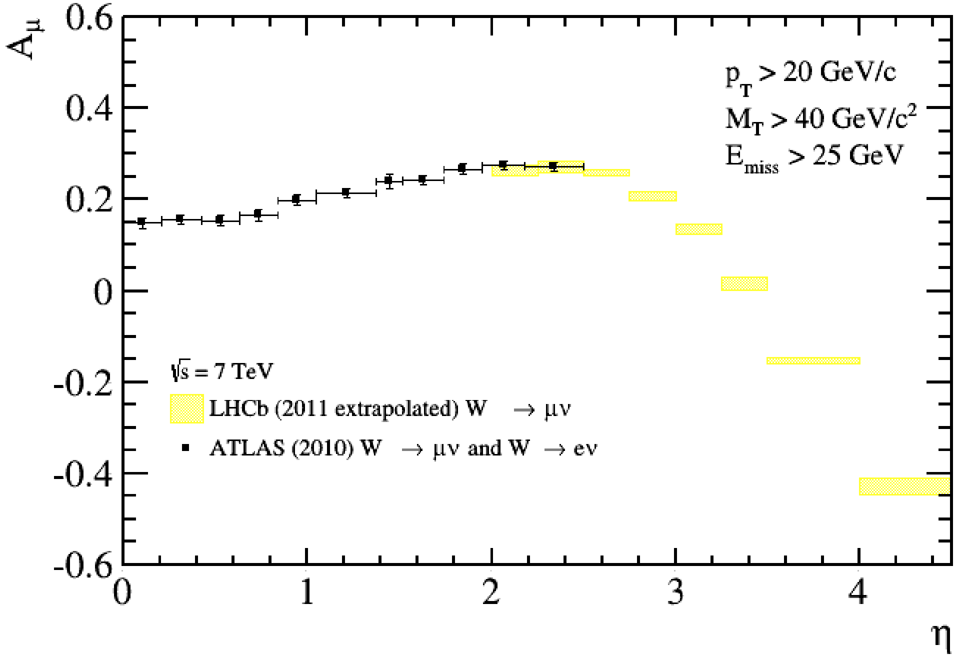
Comparison to ATLAS: LHCb measurements corrected to account for the additional cuts: E_{Tmiss}>25 GeV, M_T>40 GeV

→ good agreement in overlap region

W: lepton charge asymmetry

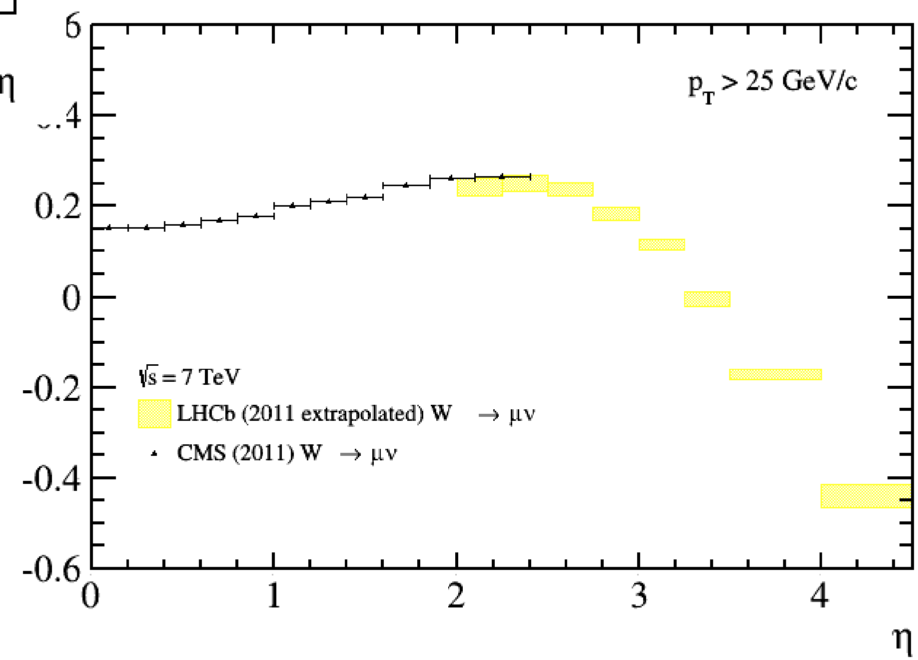


W: lepton charge asymmetry



Comparison to ATLAS for p_T>20 GeV corrected for cut on M_T>40 GeV and $E_{T,miss}$>25 GeV

Comparison to CMS for p_T>25 GeV

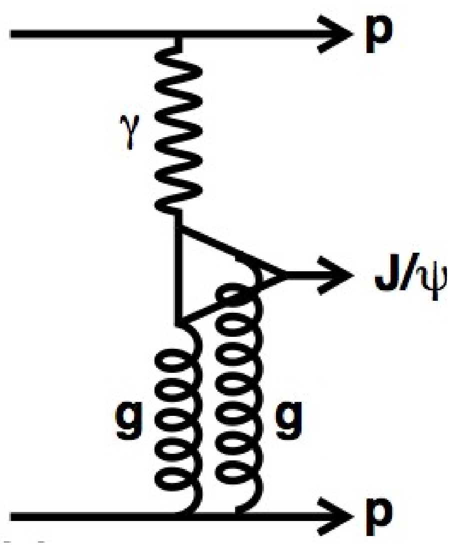


Central Exclusive Production (CEP)

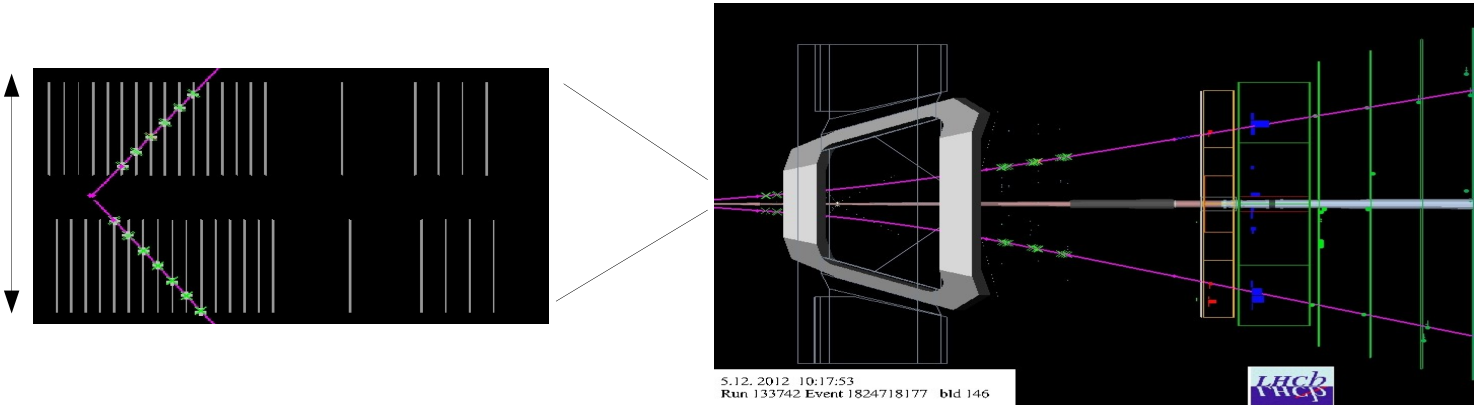
Introduction

J/Ψ, Ψ(2S) $\rightarrow \mu\mu$

Outlook



VELO
8.4 cm



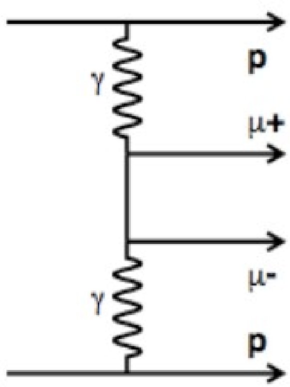
CEP: Introduction

Exchange of a colourless object: γ, pomeron

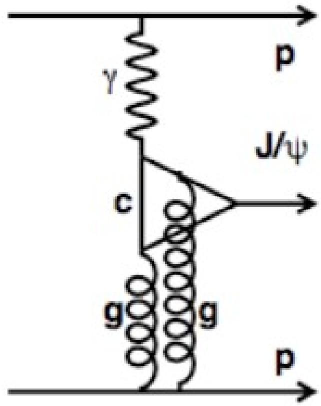
→ two muons (+ photon) + rapidity gaps

→ protons escape undetected in beampipe

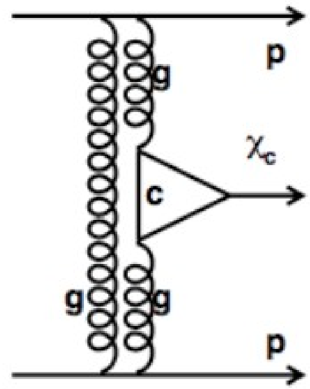
Non-resonant di-muon (di-γ fusion)



di-μ from J/Ψ, Ψ(2S) (γ-pomeron fusion)



di-μ from $\chi_c \rightarrow J/\Psi\ \gamma$ (di-pomeron exchange)



LPAIR
A.G.Shamov and V.I.Telnov, NIM A 494 (2002) 51

Starlight
S.R.Klein and J.Nystrand, Phys. Rev. Lett. 92 (2004) 142003

SuperChiC: MC for CEP
L.A.Harland-Lang, V.A.Khoze, M.G.Ryskin, W.J.Stirling, arXiv:0909.4748[hep-ph]

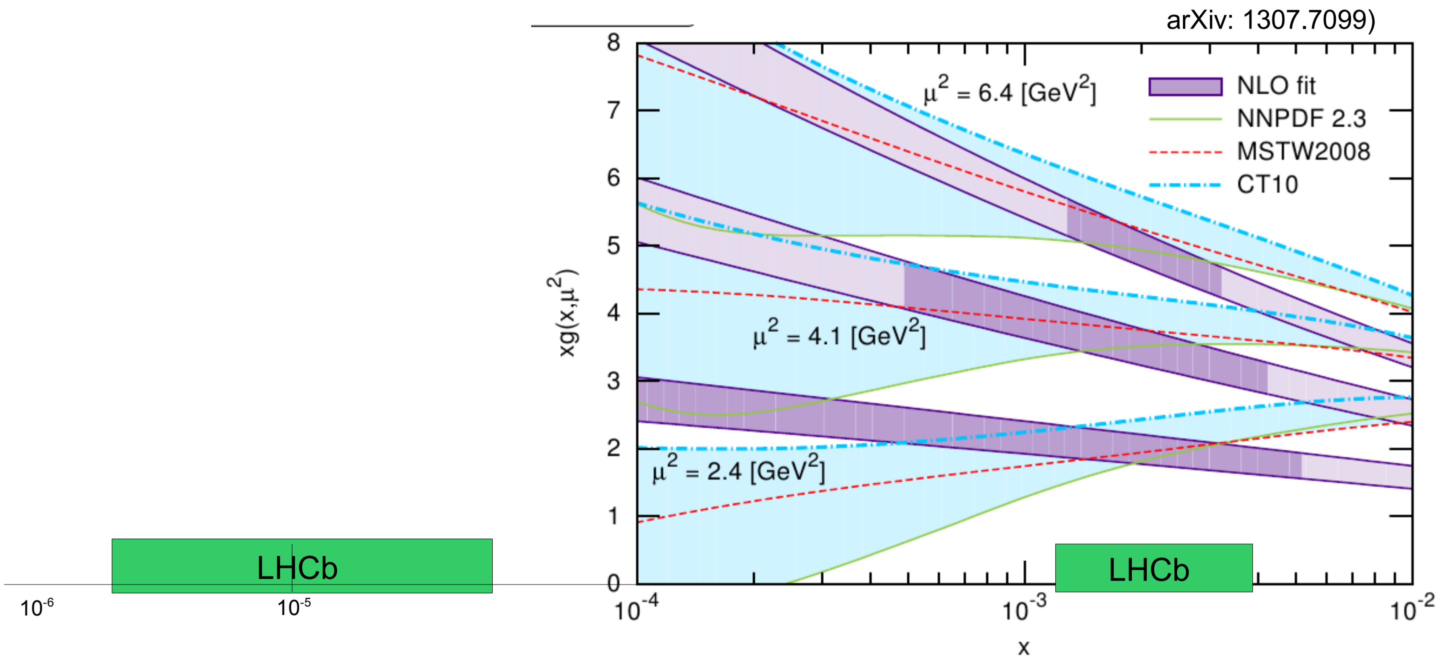
Resonant production

→ sensitivity to gluon distribution at low Bjorken-x ($5 \cdot 10^{-6}$)

Non-resonant production: pure QED process, precisely known

→ could be used for luminosity measurement

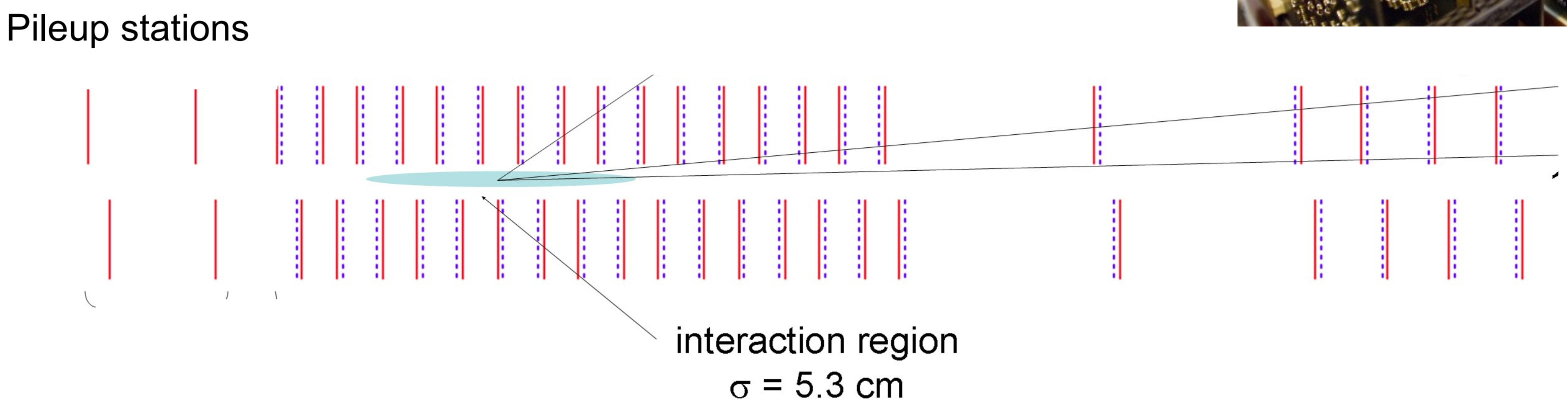
CEP: sensitivity to gluon PDF

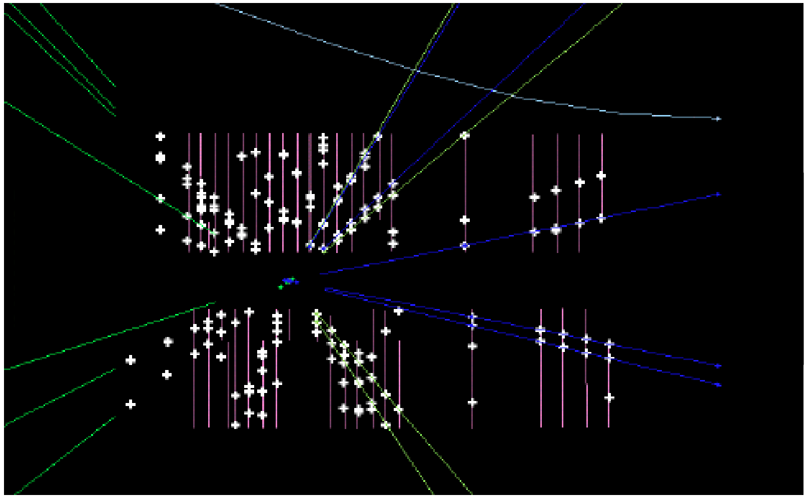


Sensitivity to gluon PDF in a region which is poorly constrained

LHCb Vertex locator (VELO)

Silicon strip vertex detector
R and φ sensors



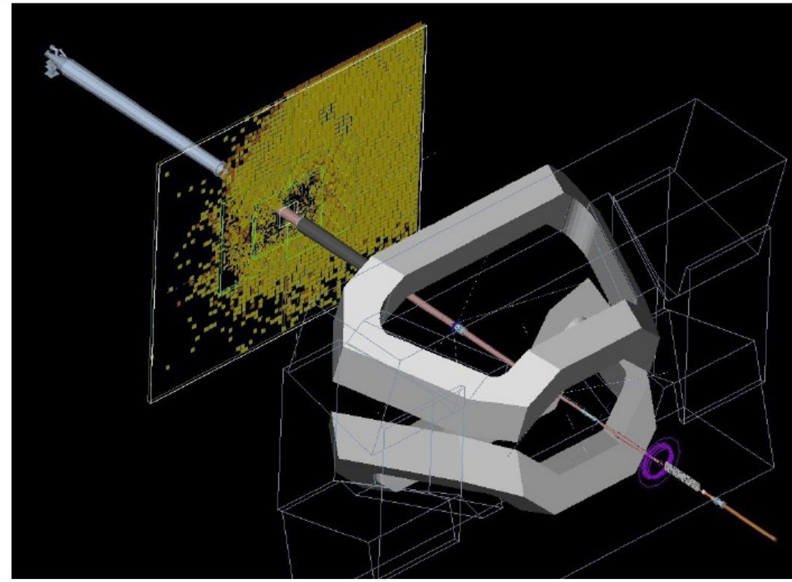


Forward: $1.5 < \eta < 5.0$
Backward: $-3.5 < \eta < -1.5$

Backwards tracks re-constructable
(no momentum information)

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

CEP with di-muons: J/Ψ, Ψ(2S)



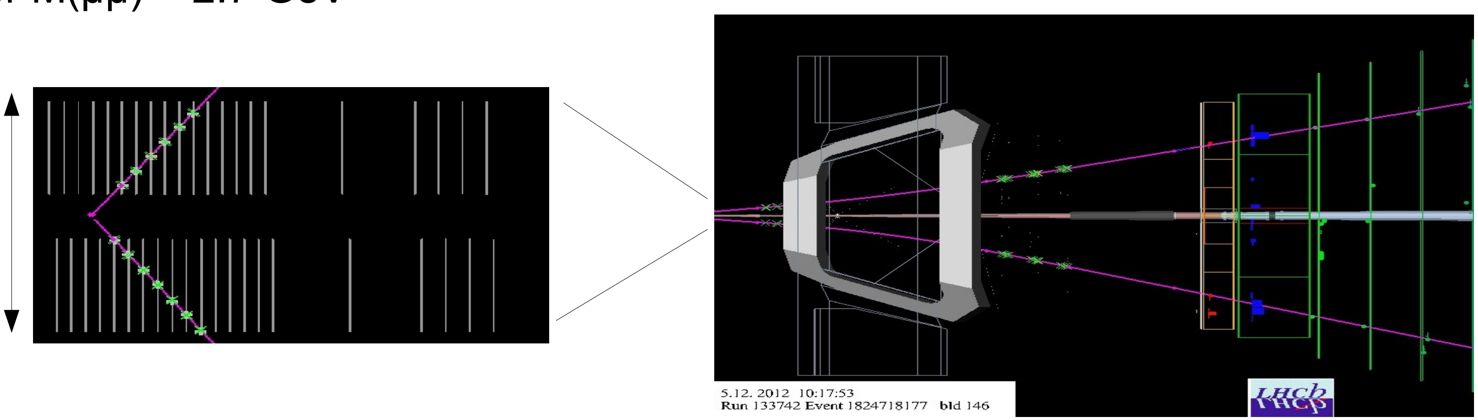
Signature

- Two muons
- No other activity in event
- di-muon system: low p_T

Trigger:

- Hardware:
  one μ (p_T> 400 MeV)
  or two μ (p_T> 80 MeV)
  low multiplicity in scintillator pad detector in front of calorimeter
- Software:
  di-μ candidate with p_T< 900 MeV
  or M(μμ) > 2.7 GeV

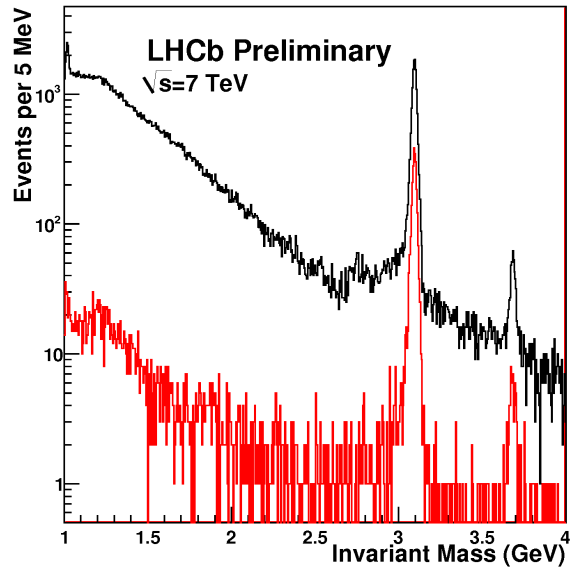
VELO
8.4 cm

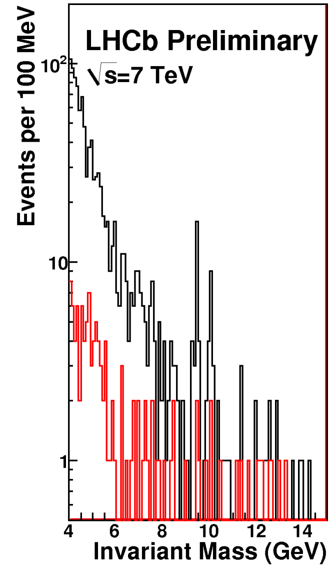


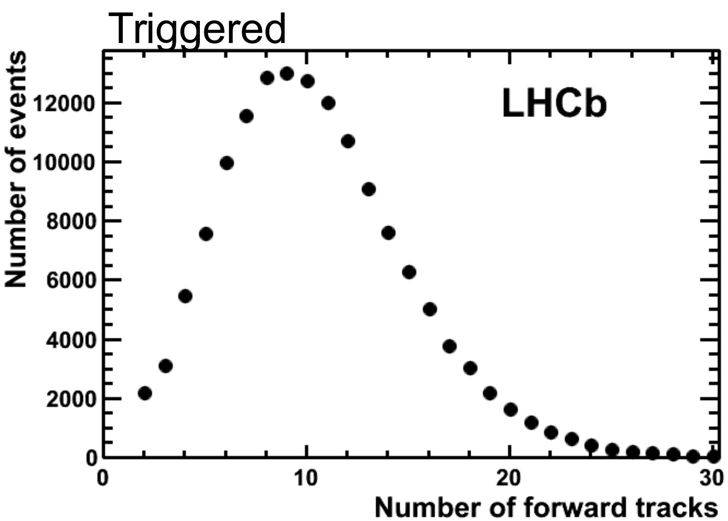
Exclusive di-muon selection

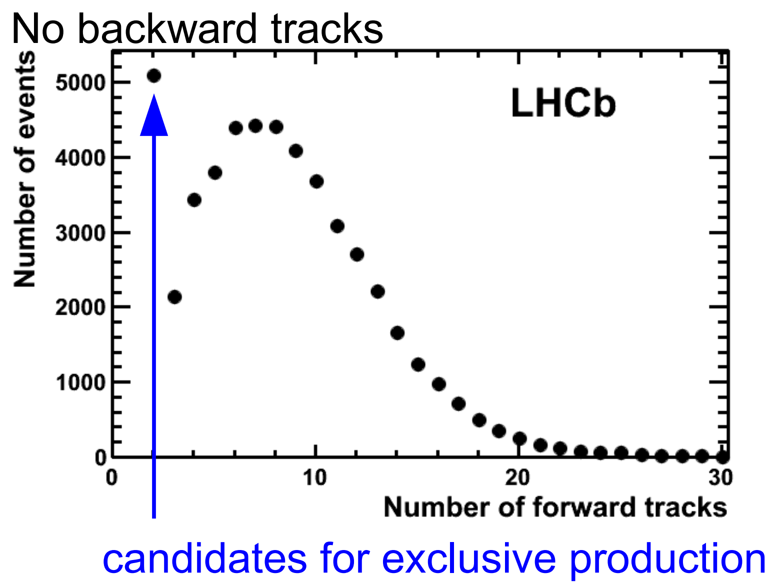
Triggered:
two μ, little activity in calorimeter

Exclusive:
two forward, no backward tracks









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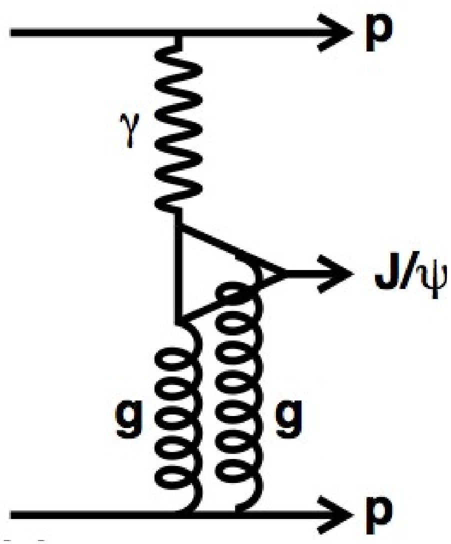
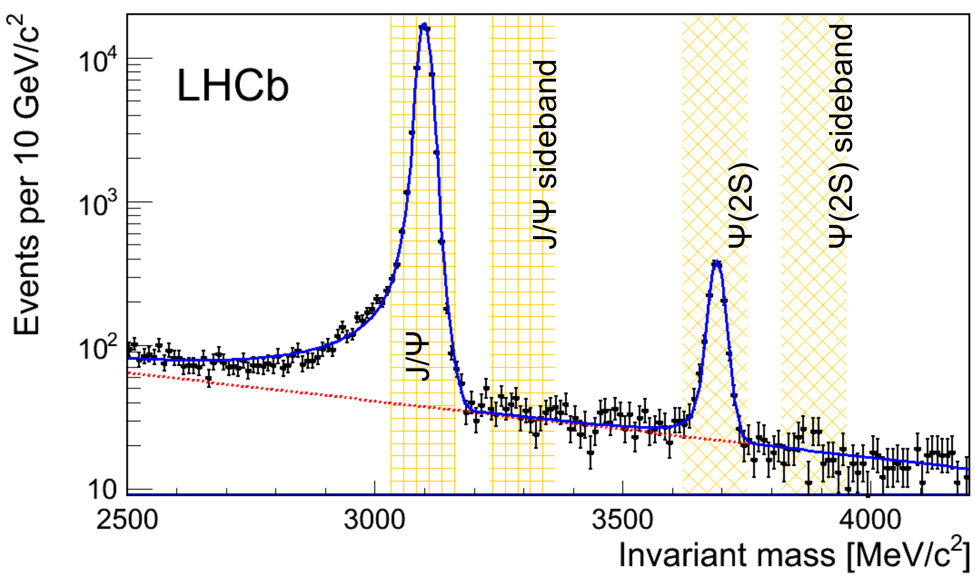
Selection

- 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





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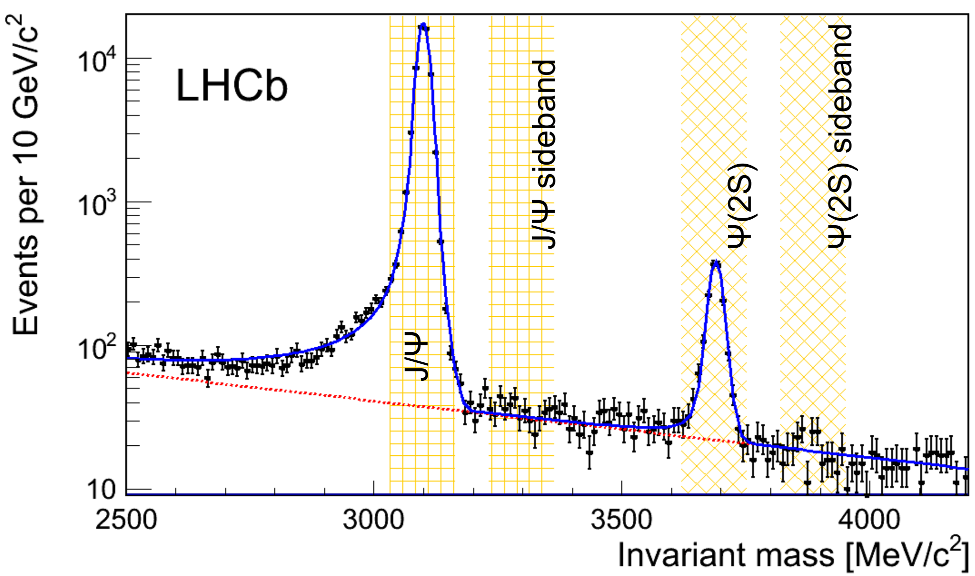
Backgrounds

- 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



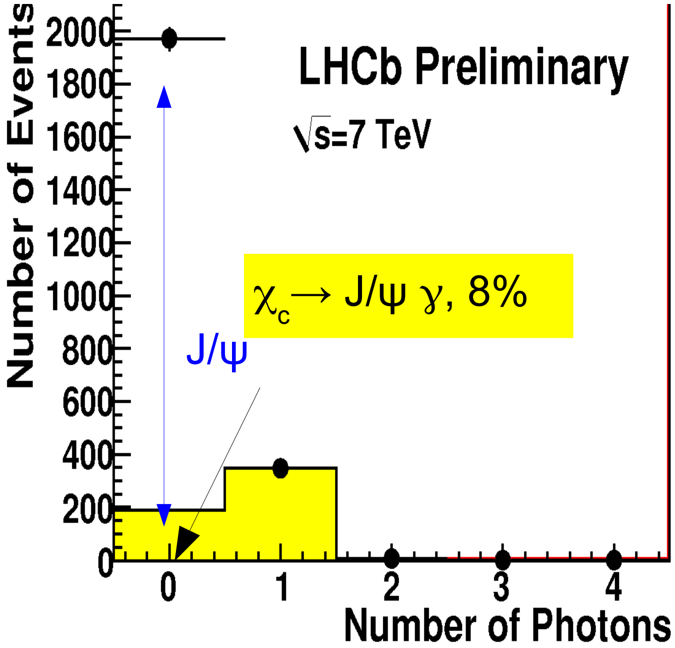
Backgrounds from feed down – J/ψ only

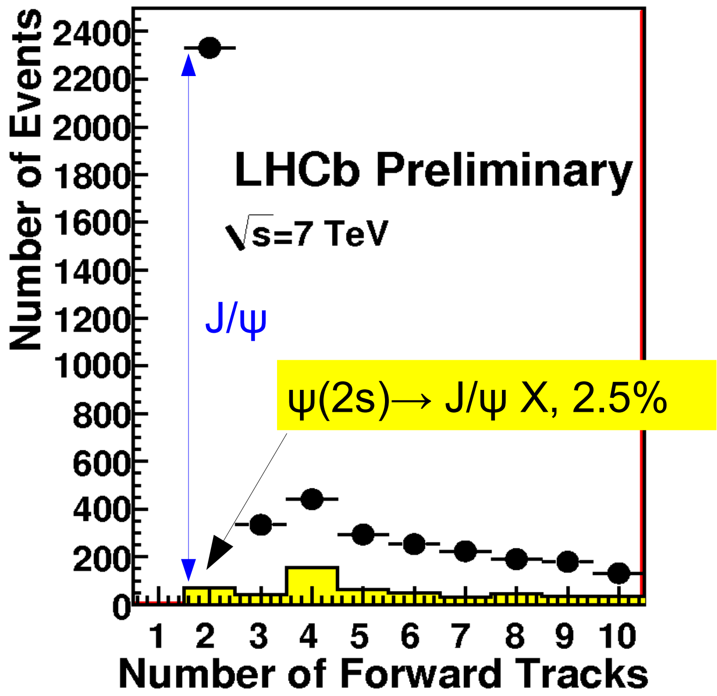
LHCb-CONF-2011-022

- From $\chi_c \rightarrow J/\psi\ \gamma$:

  suppressed: no photons
  estimate residual background from SuperChic, normalised to data

  contribution: (7.6 ± 0.9)%





- From $\psi(2s) \rightarrow J/\psi\ X$:

  suppressed: exactly two tracks
  estimated from scaling MC simulation to measured ratio

  contribution: (2.5 ± 0.2)%

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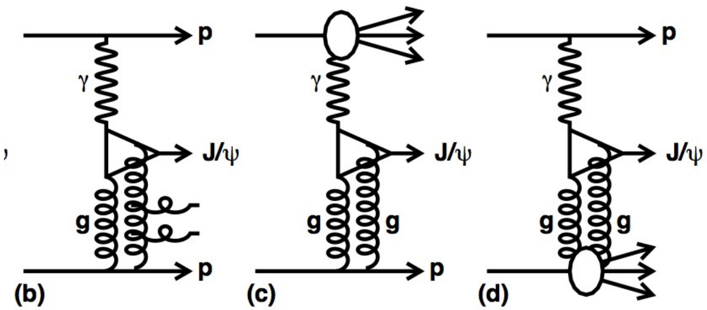
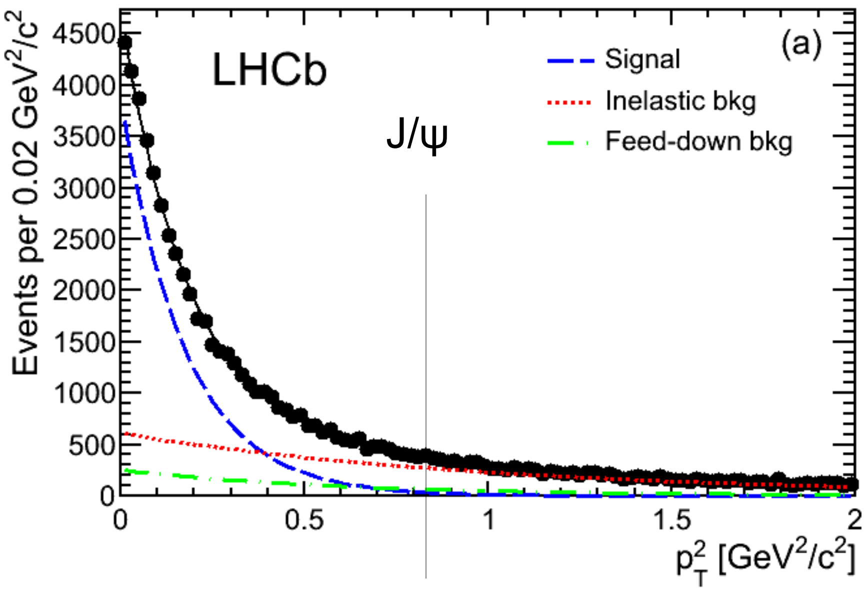


Proton dissociation or gluon radiation
→ estimated from data: fit p_T^2 distribution

- signal and inelastic background: exponential
- feed-down: shape from data $\chi_c \rightarrow J/\psi\gamma$ and $\psi(2S) \rightarrow J/\psi\pi\pi$
- fit slope and normalization of signal and background

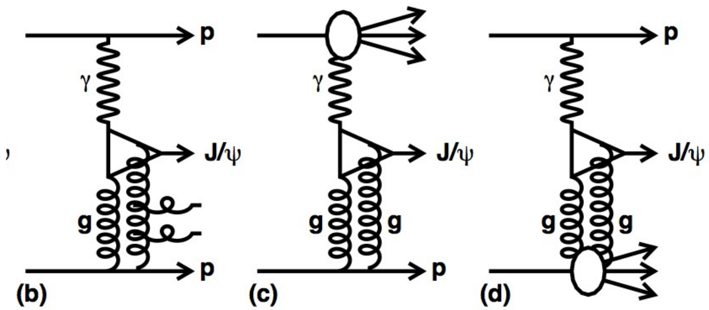


slope b agrees well with expectation from HERA:

LHCb expected from HERA
$b_s \sim 6$ GeV^{-2}
$b_b \sim 1$ GeV^{-2}

LHCb Fit:
$b_s = 5.70 \pm 0.11$ GeV^{-2}
$b_b = 0.97 \pm 0.04$ GeV^{-2}

CEP: Inelastic background



Proton dissociation or gluon radiation

→ estimated from data: fit p_T^2 distribution

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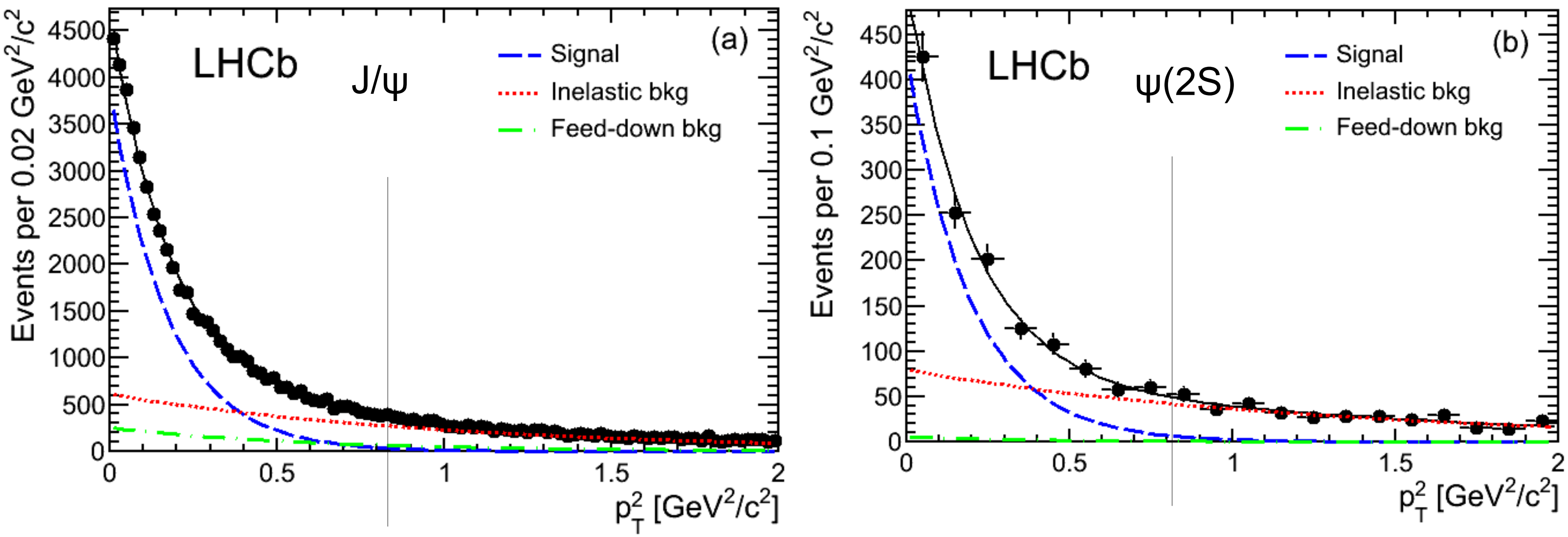
- feed-down: shape from data $\chi_c \to J/\psi\gamma$ and $\psi(2S) \to J/\psi\pi\pi$
- fit slope and normalization of signal and background



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

Cross section

ρ: purity

- feed down background (10% / 2%)
- non resonant background (1% / 17%)
- inelastic background (40% / 40%)

N: number of observed events

$$\sigma = \frac{\rho N}{\epsilon L}$$

ε: efficiency

- trigger, tracking, μ ID, selection (simulation)
- single interaction beam crossing

$P(n) = \mu^n \exp(-\mu)/n!$

n number of visible pp interactions
μ average number of visible interactions
efficiency 21.1%

L: luminosity

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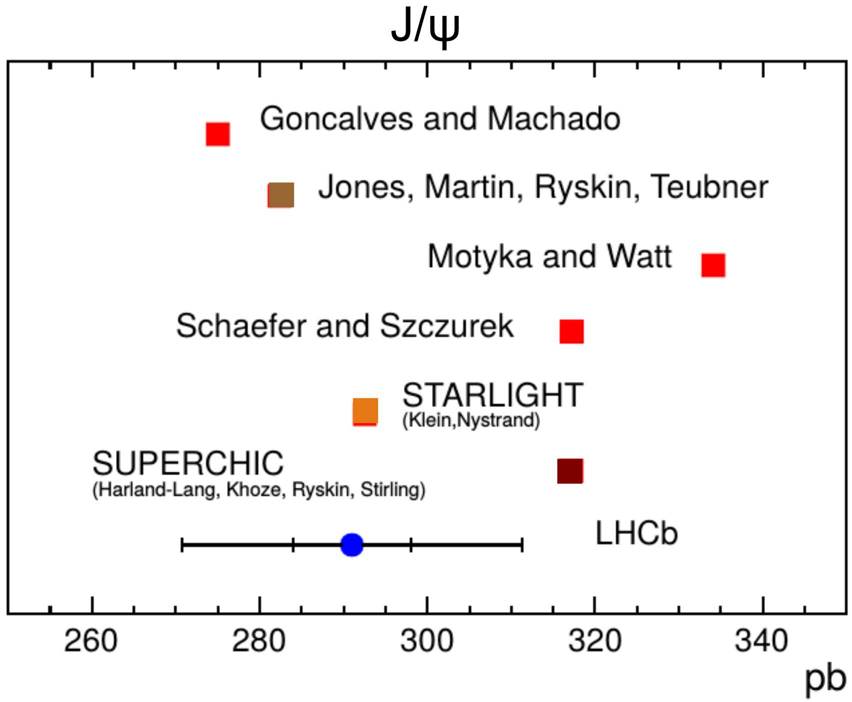
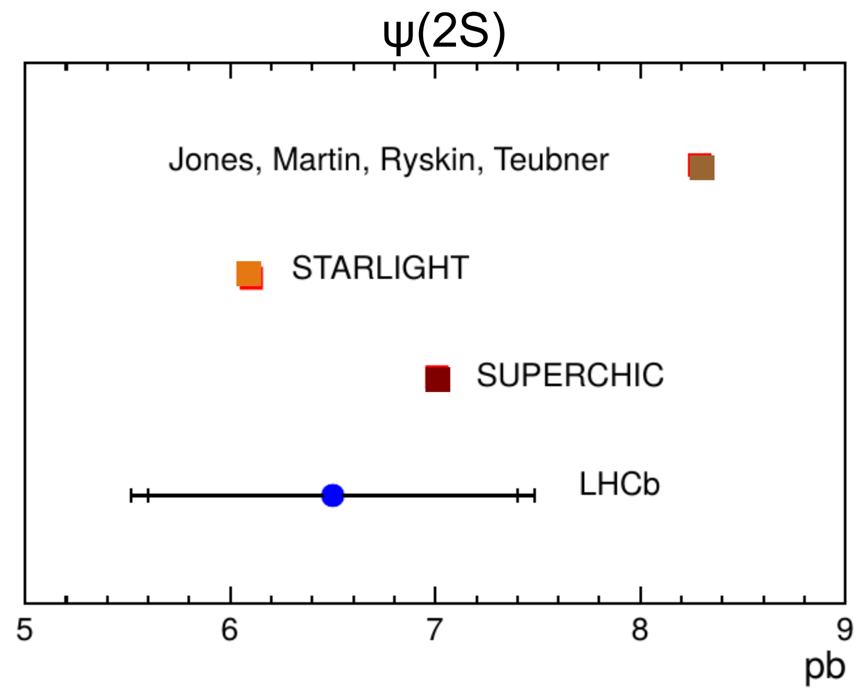




Cross section times BF to two muons with $2.0 < \eta < 4.5$

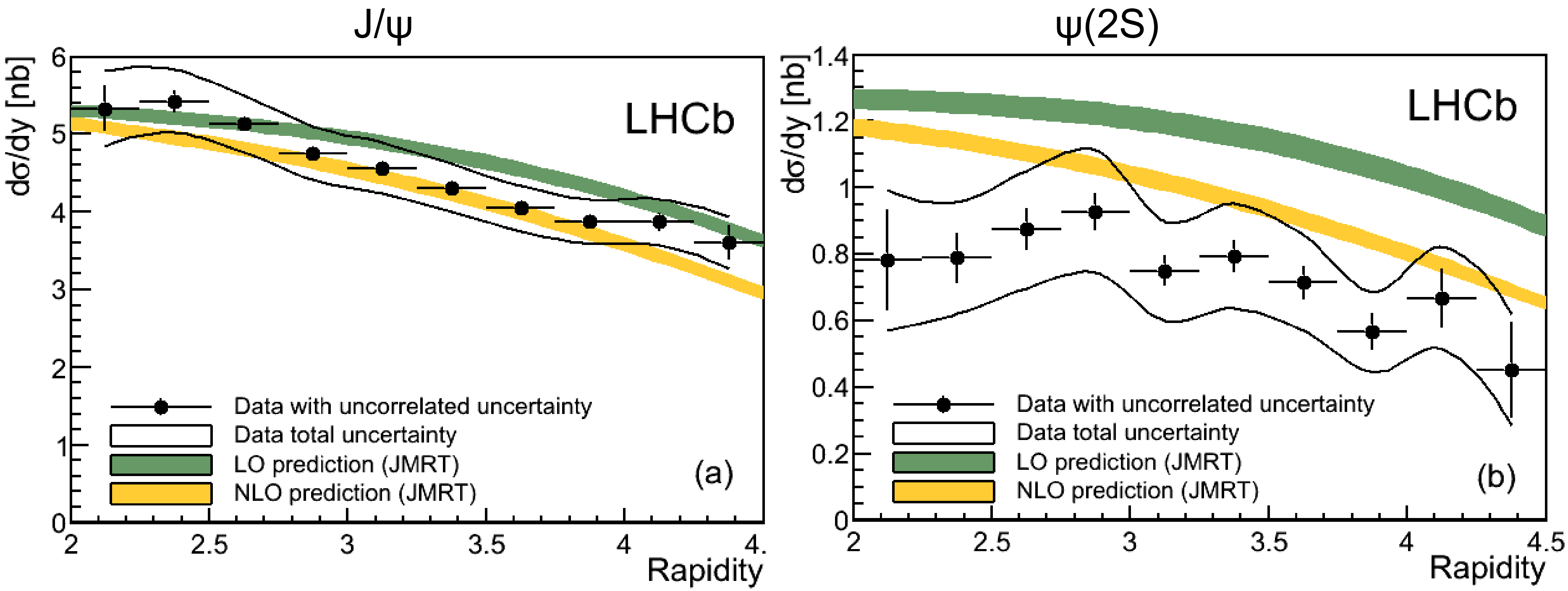
$\sigma(J/\psi) = 291 \pm 7(\text{stat}) \pm 19(\text{syst})$ pb

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



- prediction from Jones, Martin, Ryskin and Teubner arXiv:1307.7099
- shape better described by NLO prediction

CEP: Results

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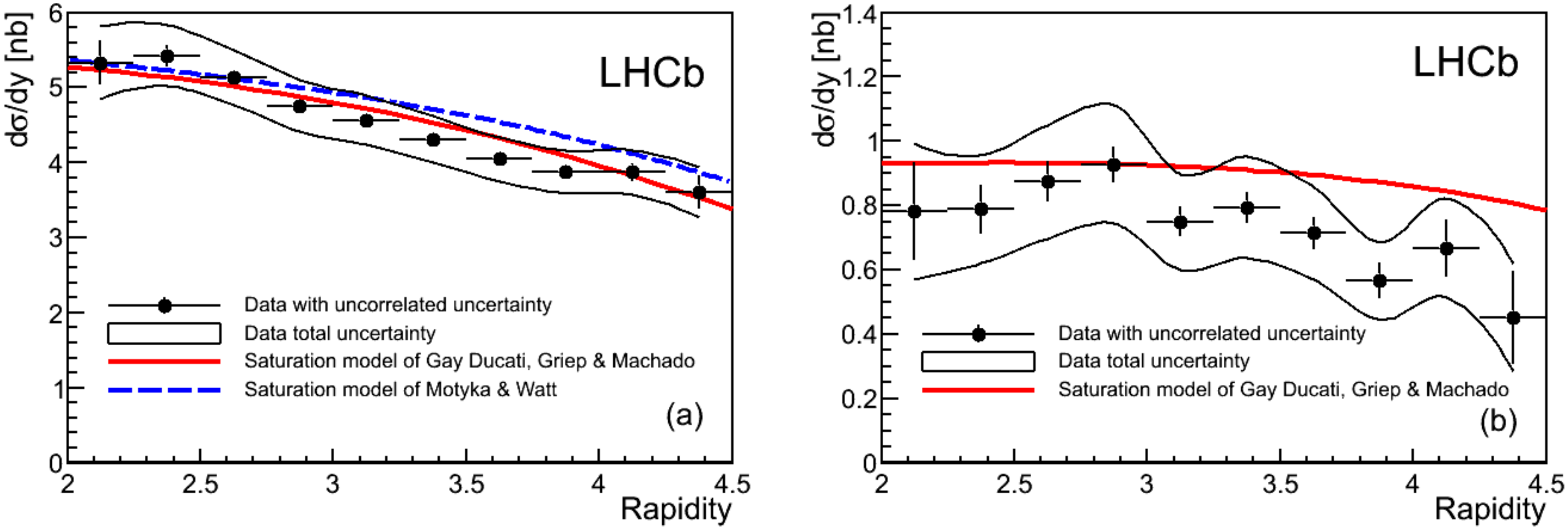


also described by models including saturation (arXiv:1305.4611, PhysRevD.78.014023)

J/ψ Photoproduction cross section

J. Phys. G: 41 (2014) 055002

J/Ψ production cross section measured as a function of rapidity (10 bins)
→ results can then be compared to H1/ZEUS data using
known photon flux for a photon of energy k
correcting for gap survival

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

$$r(y) = 0.85 - \frac{0.1|y|}{3} \quad \text{absorptive correction, gap survival}$$

$$\frac{dn}{dk} = \frac{\alpha_{cm}}{2\pi k}\left[1+\left(1-\frac{2k}{\sqrt{s}}\right)^{2}\right]\left(\log A - \frac{11}{6} + \frac{3}{A} - \frac{3}{2A^{2}} + \frac{1}{3A^{3}}\right) \quad \text{photon energy spectrum}$$

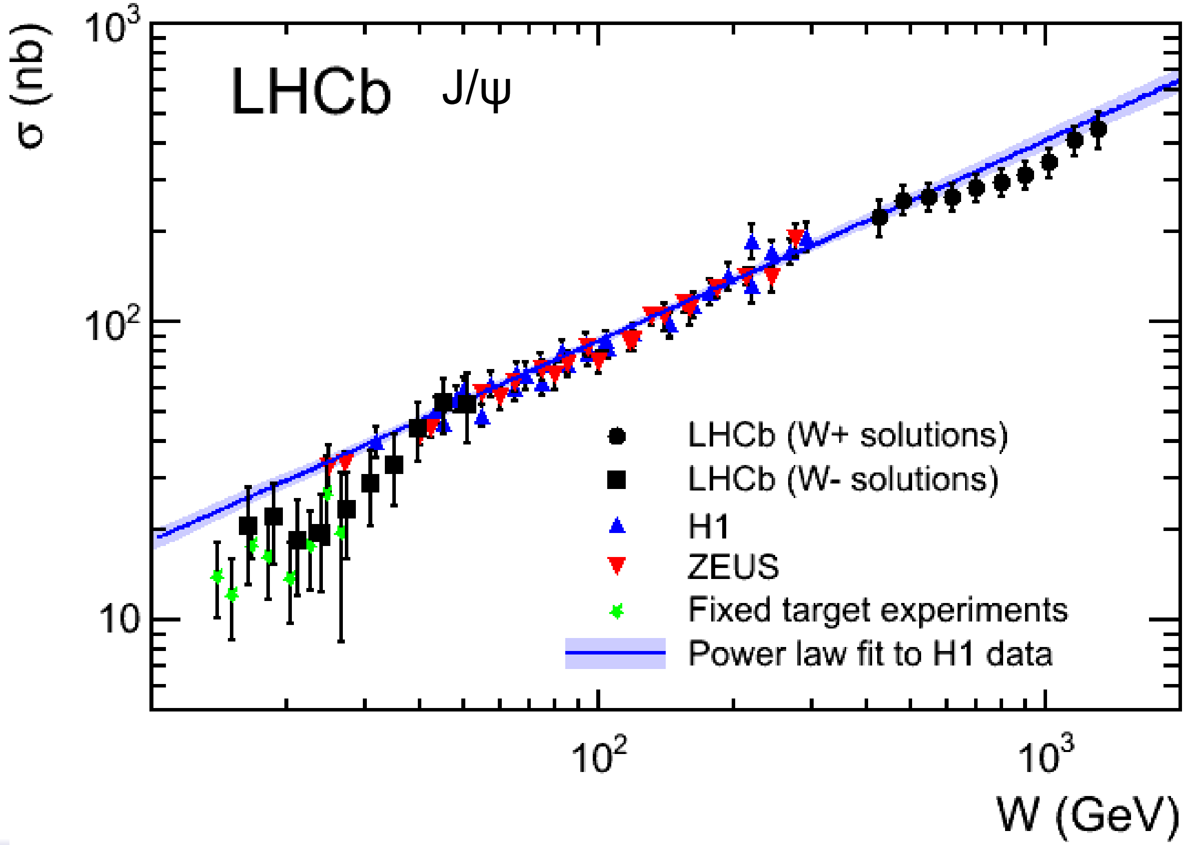
for each rapidity bin two solutions for W (photon-proton cm energy)

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

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

gap survival

photon flux



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

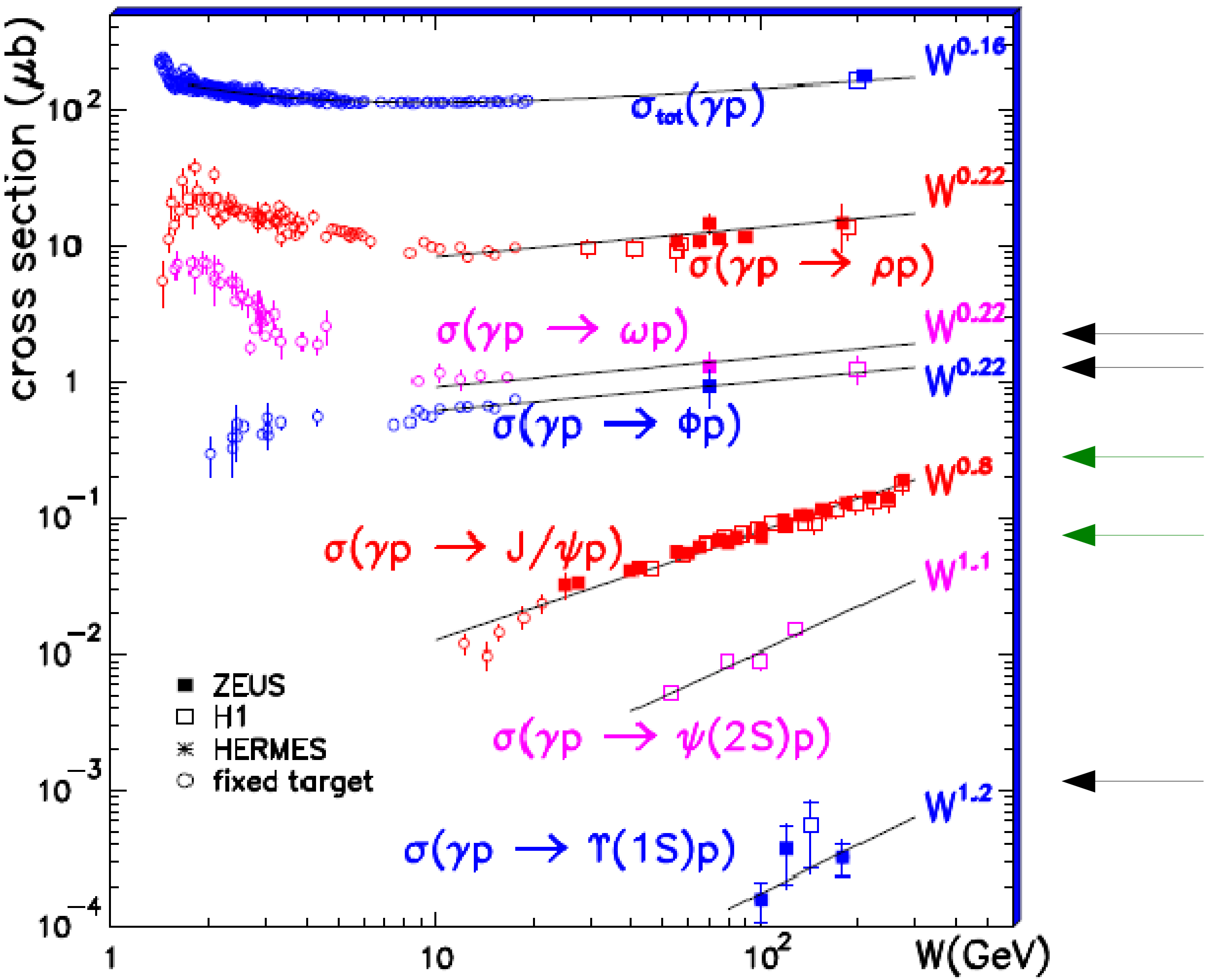
Deviation from power law:

- higher order
- saturation effects

CEP outlook

Work ongoing with other final states, also in hadronic channels

10.3204/DESY-PROC-2012-03/58



CEP outlook

Increase rapidity gap with scintillators in forward and backward region

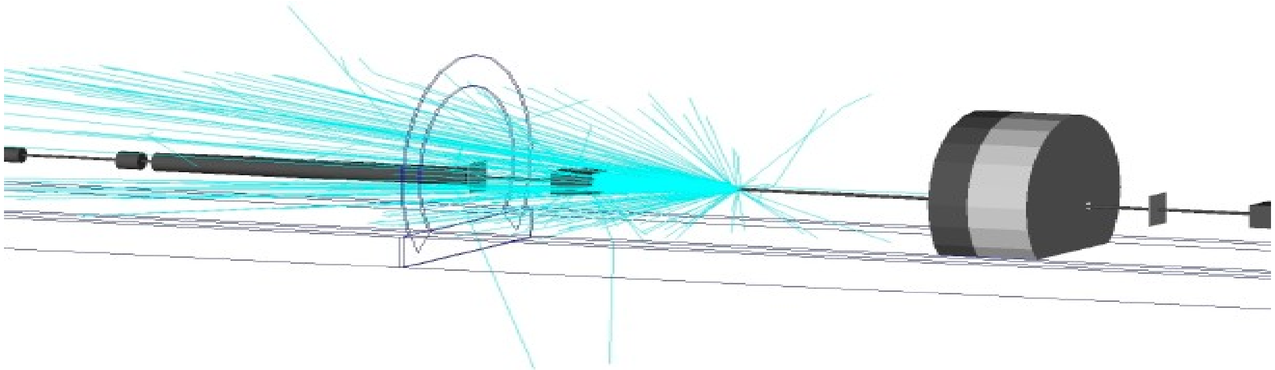
Detect showers from high rapidity particles interacting with beam pipe elements

→ improve veto on inelastic background

→ better control of the background

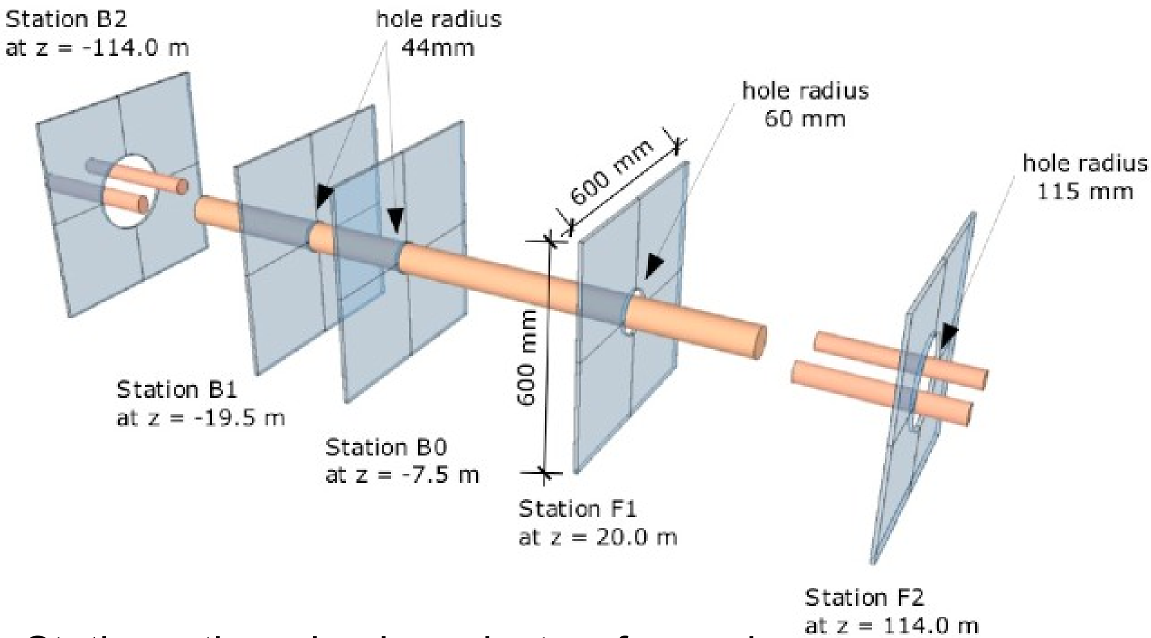
→ better precision

Simulations studies suggest veto region for charged and neutral particles can be extended to include $5<|\eta|<8$ - an extra 6 units in pseudorapidity.



CEP outlook

HeRSCheL: High Rapidity Shower Counters for LHCb



Five Stations: three backwards, two forward

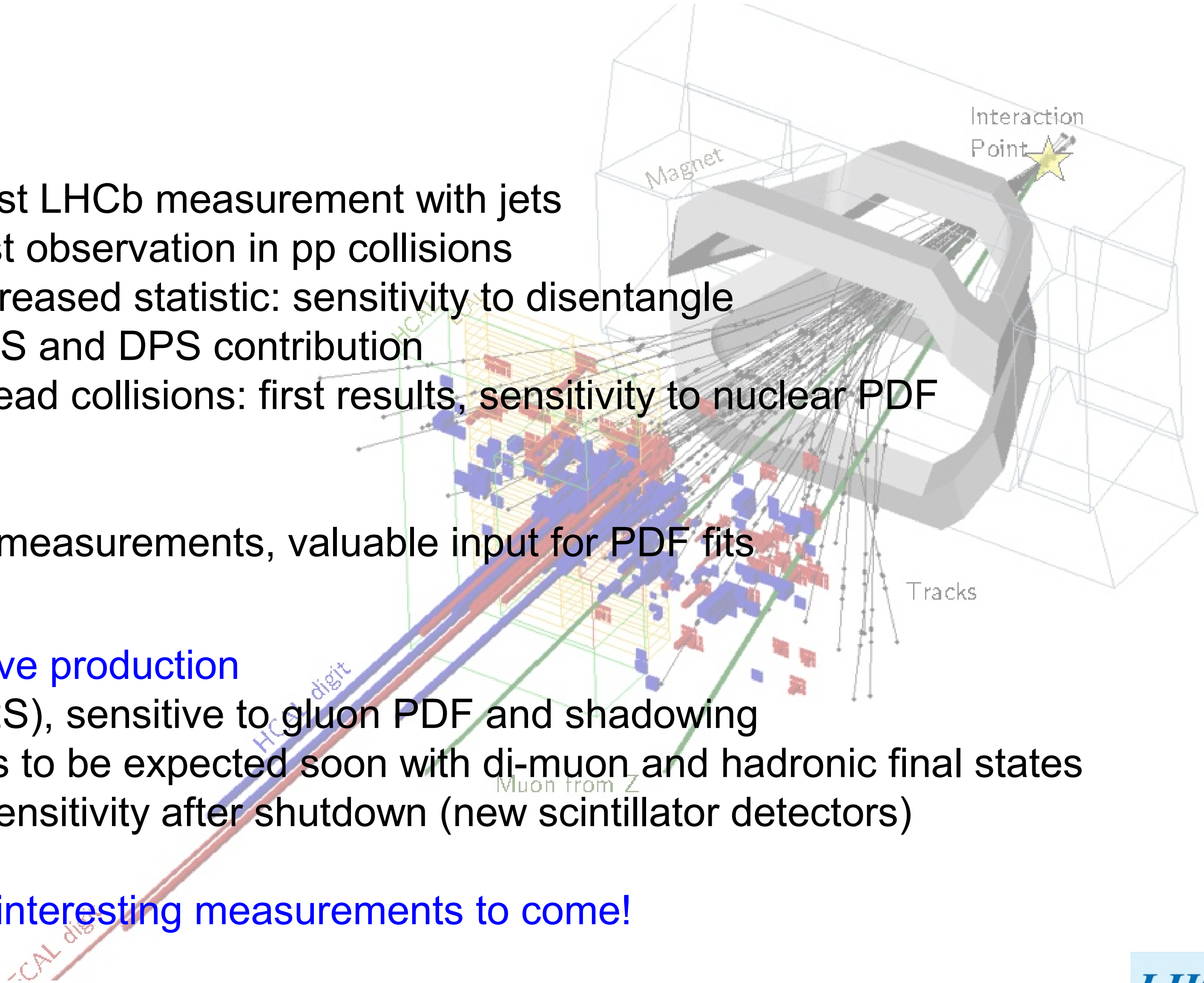
Detectors four plastic scintillator plates, 20 mm thick - retractable

Installation: starting in August

→ Expect improvements in triggering and background rejection

for CEP events for the run starting in 2015

Conclusions



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

W production

Precise new measurements, valuable input for PDF fits

Central exclusive production

J/ψ and ψ(2S), sensitive to gluon PDF and shadowing

more results to be expected soon with di-muon and hadronic final states

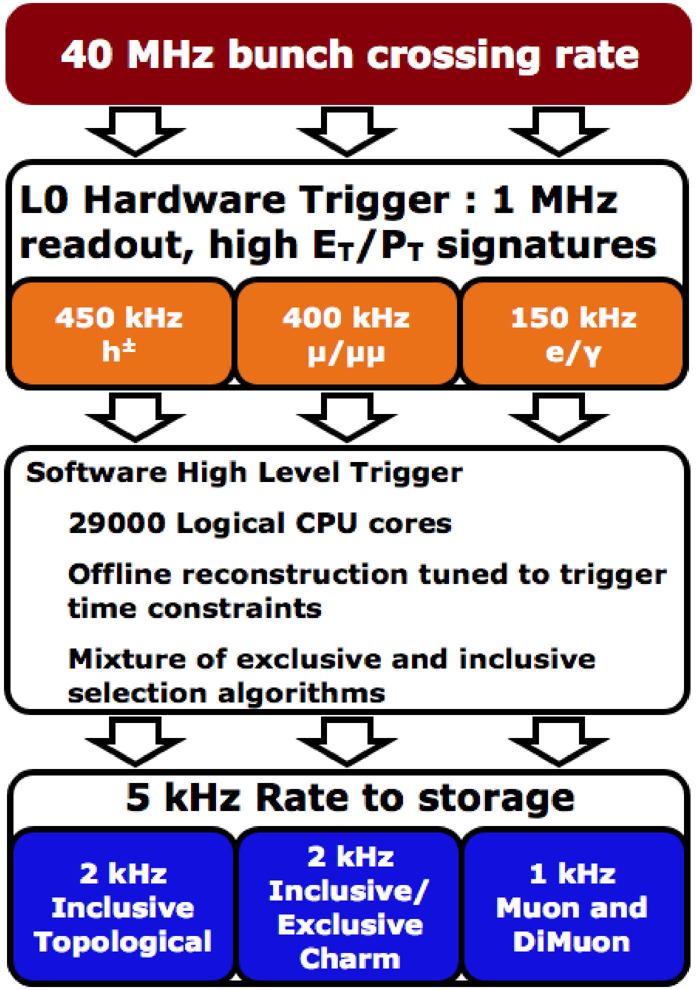
increased sensitivity after shutdown (new scintillator detectors)

→ Many more interesting measurements to come!

Backup slides

Flexible Trigger

- Hardware trigger: L0 40→14 MHz
  information from calorimeter and muon system
- Two software trigger stages
  14MHz →950 kHz
  950 →4.5 kHz
- Ability to trigger on low transverse momentum particles: $p_T^{\mu} > 1.5$ GeV
- Special triggers for low multiplicity events



Full list of QCD results

Measurement of charged particle multiplicities and densities	arXiv:1402.4430
Prompt charm production at $\sqrt{s}$ = 7 TeV	Nucl. Phys. B 871 (2013) 1-20
Measurement of the forward energy flow at $\sqrt{s}$ = 7 TeV	Eur. Phys. J. C73 (2013) 2421
Measurement of Y production in pp collisions at $\sqrt{s}$ = 2.76 TeV	accepted by EPJC arXiv:1402.2539
Measurement of V0 production ratios at $\sqrt{s}$ = 0.9 and 7 TeV	Eur. Phys. J. C 72 (2012) 2168
Measurement of the $B^{\pm}$ production cross-section at $\sqrt{s}$=7 TeV	JHEP 04 (2012) 093
Measurement of the inclusive ϕ cross-section at $\sqrt{s}$ = 7 TeV	Phys. Lett. B 703 (2011) 267
Prompt K0S production at $\sqrt{s}$ = 0.9 TeV	Phys. Lett. B 693 (2010) 69
W&Z production studies at $\sqrt{s}$ = 7 TeV	JHEP 06 (2012) 058
$Z \to$ tau tau production at $\sqrt{s}$ = 7 TeV	JHEP 01 (2013) 111
$Z \to ee$ production at $\sqrt{s}$ = 7 TeV	JHEP 02 (2013) 106
$Z \to \mu\mu$ + jet production at $\sqrt{s}$ = 7 TeV	JHEP 1401 (2014) 033
Z plus D production at $\sqrt{s}$ = 7 TeV	JHEP 04 (2014) 91
Measurement of the cross-section for $Z \to \mu\mu$ at s√=7 TeV	LHCb-CONF-2013-007
Low mass Drell Yan production at $\sqrt{s}$ = 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 $\Psi(2S)$ production in the dimuon channel $\sqrt{s}$ = 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

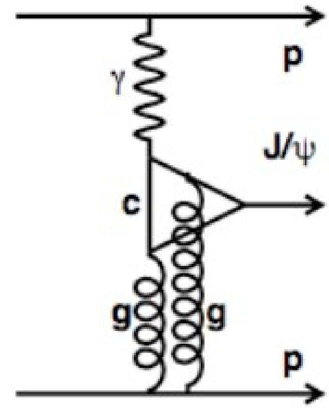
CEP of J/Ψ and Ψ(2S) → μμ

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 $5 \cdot 10^{-6}$

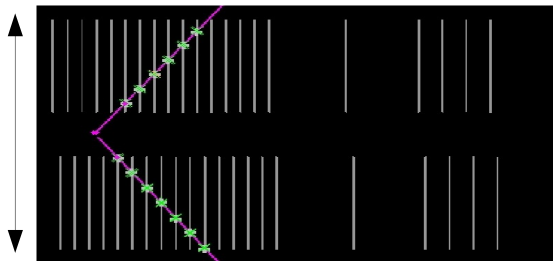
VELO acceptance

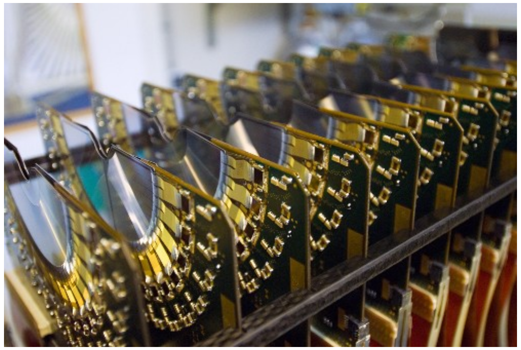
forward: $1.5 < \eta < 5.0$

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

CEP systematic uncertainties

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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%