Forward Physics at LHCb

Murilo Rangel
on behalf of the LHCb Collaboration

Outline

→ **Recent Results at LHCb**

p-p collisions

+ Measurements of W/Z bosons
+ Heavy quark jets associated with W/Z
+ Top quark production
+ Exclusive Υ production

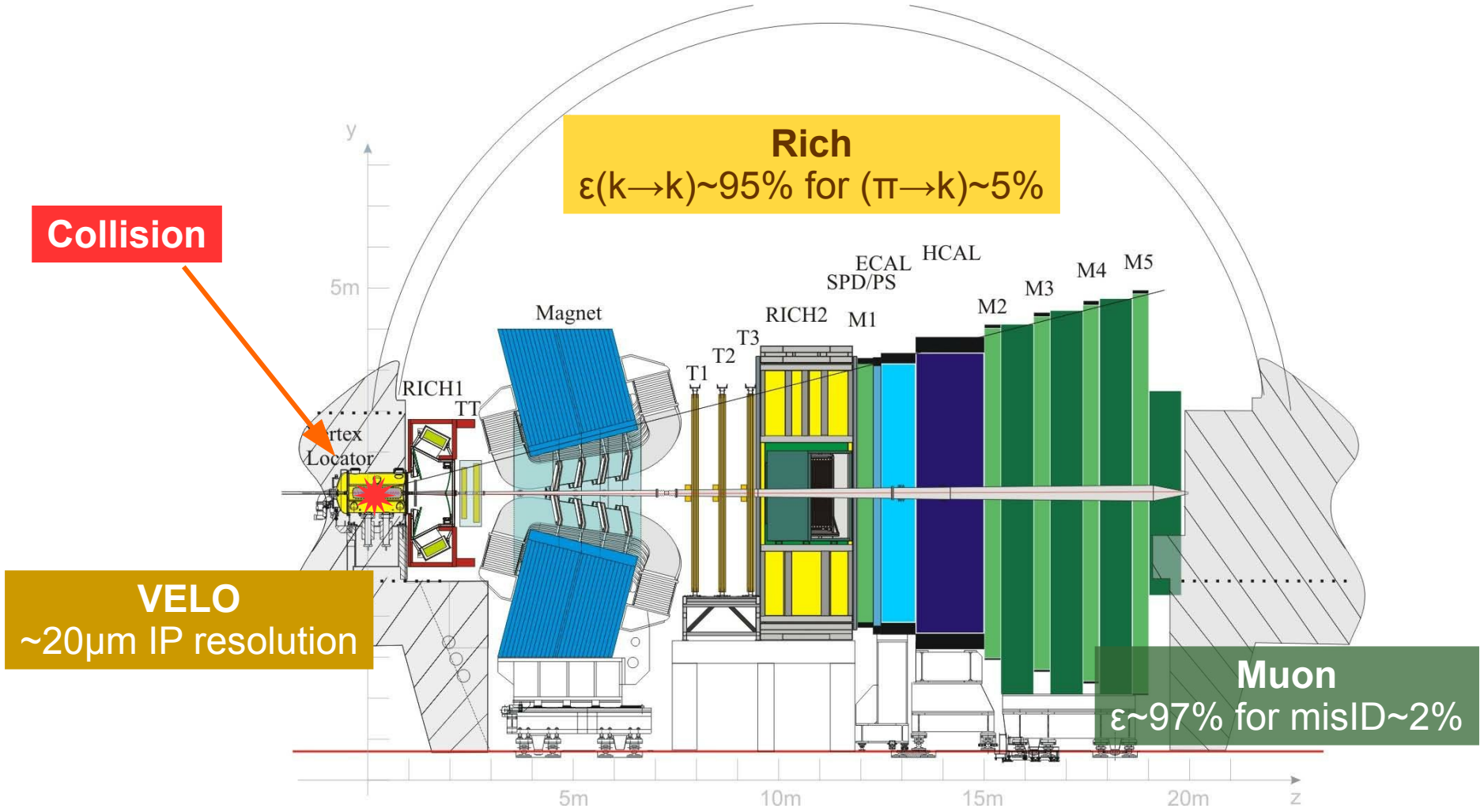
Not covered in this talk:

Pb-p collisions

+ J/ψ and Υ production (JHEP 07 (2014) 094)
+ Z production (JHEP 09 (2014) 030)
+ Two particle angular correlation (LHCB-CONF-2015-004)

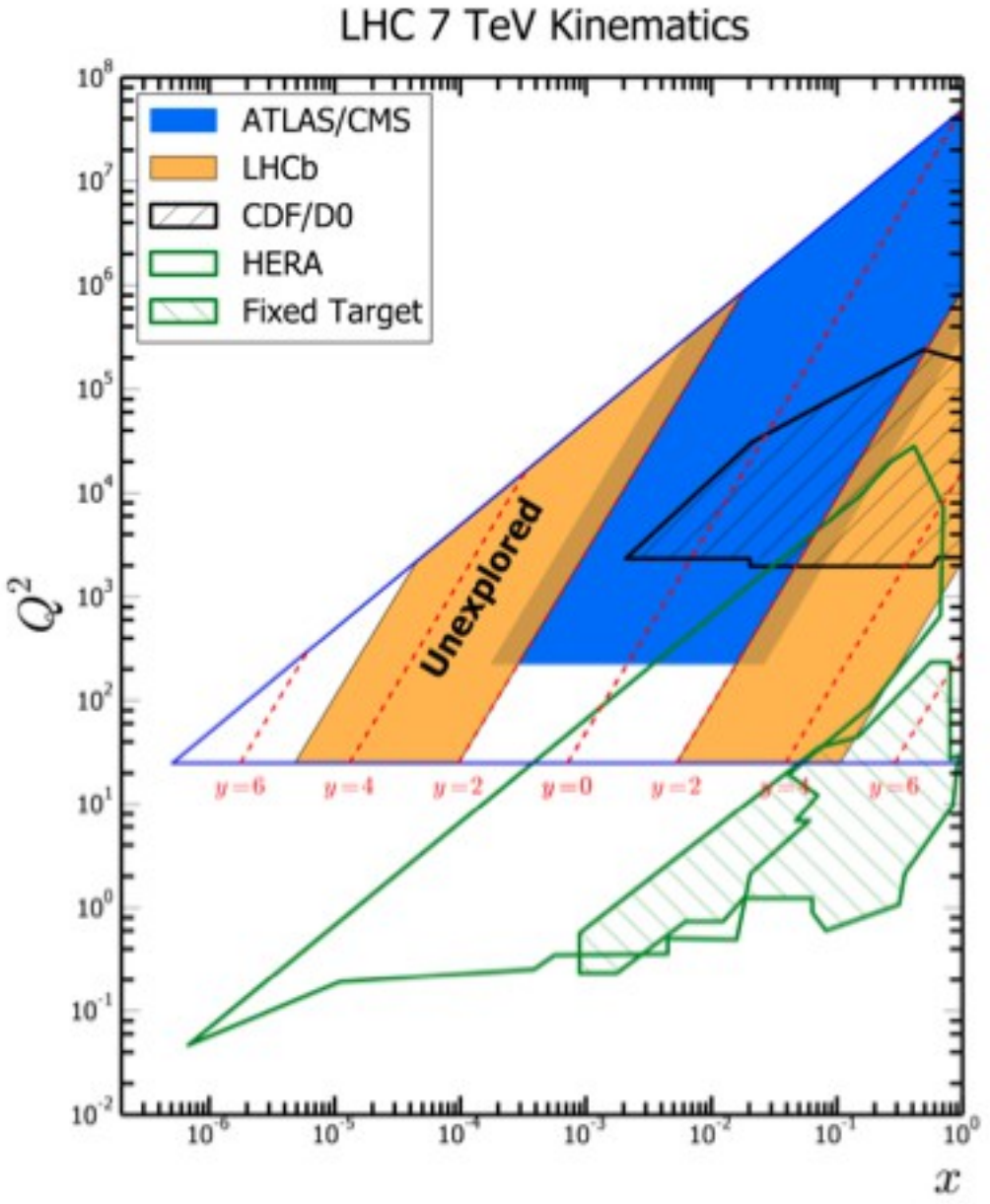
See Xabier's talk for direct searches on Weds (05/08 – 16:00).

LHCb is a single arm spectrometer fully instrumented in the forward region (2.0<η<5.0)
Designed for heavy flavour physics ↔ Explored for general purpose physics



LHCb Measurements

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



LHCb measurements:

1) are sensitive to previously unexplored regions of low x and high Q^2 phase space.

2) can be used to constrain PDFs.

3) probe the standard model when PDF errors are not relevant (ratios)

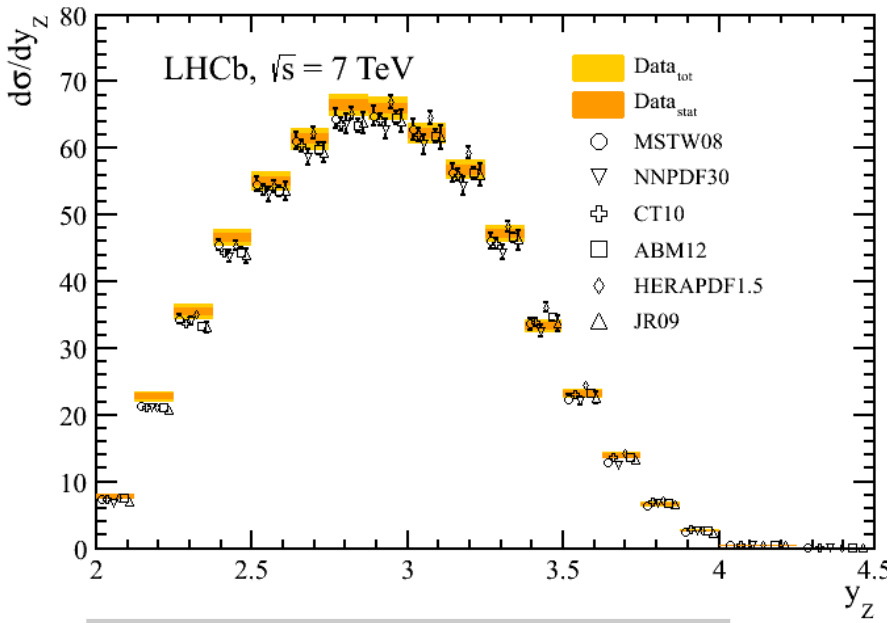
Z→μμ and W→μν production

arXiV:1505.07024

Data: 1/fb at 7 TeV

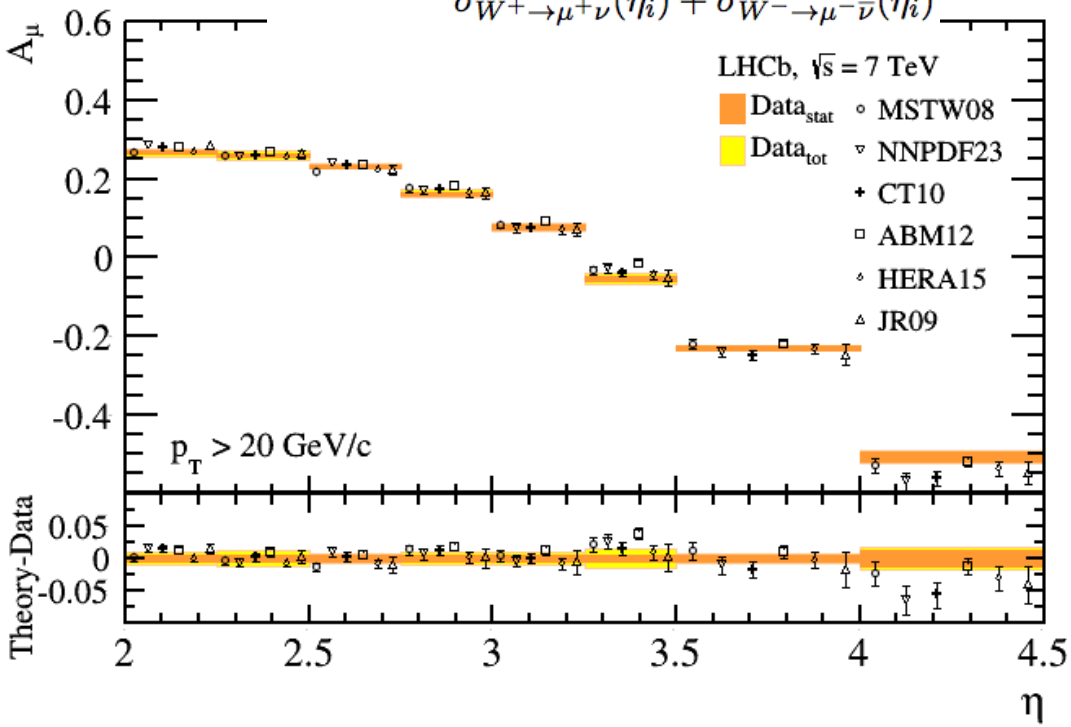
Fiducial acceptance: $2.0<\eta(\mu)<4.5$, $p_T(\mu)> 20$ GeV

$60<M(\mu\mu)/\text{GeV}<120$ for Z



Good agreement with NNLO
Sensitive to PDF variation

$$A_\mu(\eta_i) = \frac{\sigma_{W^+\to\mu^+\nu}(\eta_i) - \sigma_{W^-\to\mu^-\bar{\nu}}(\eta_i)}{\sigma_{W^+\to\mu^+\nu}(\eta_i) + \sigma_{W^-\to\mu^-\bar{\nu}}(\eta_i)}$$



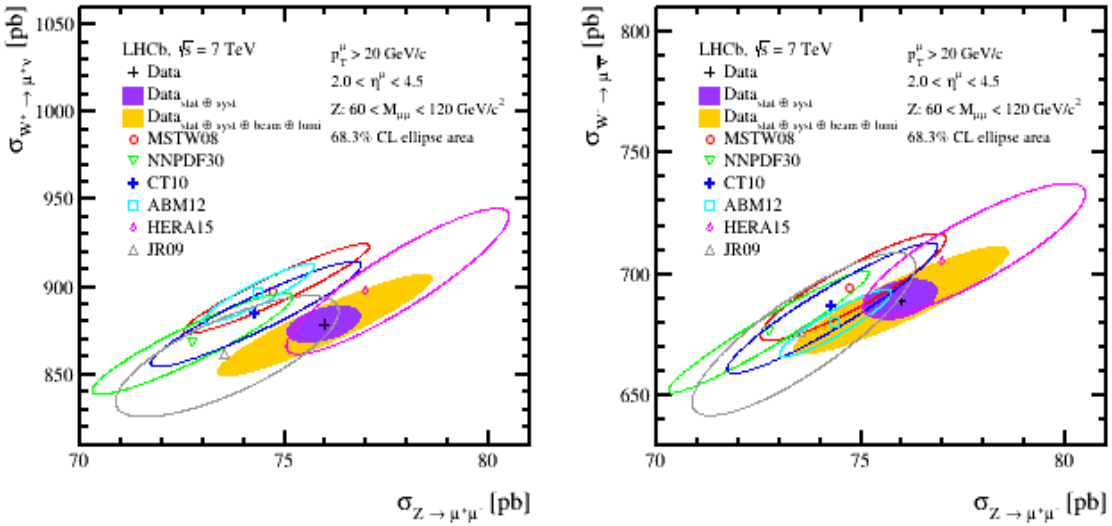
Lepton charge asymmetry - PDF
Good agreement with NNLO predictions

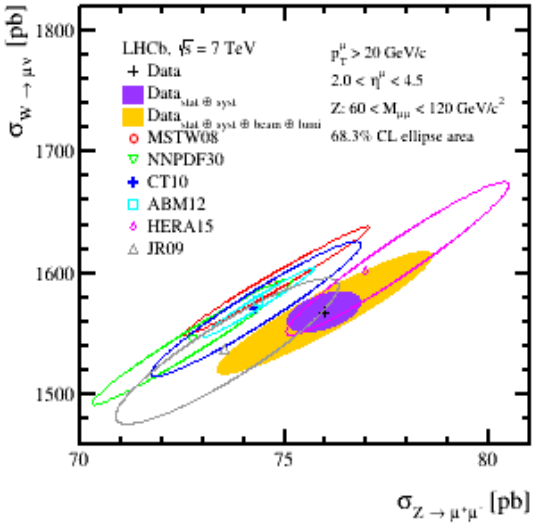
W and Z production ratios

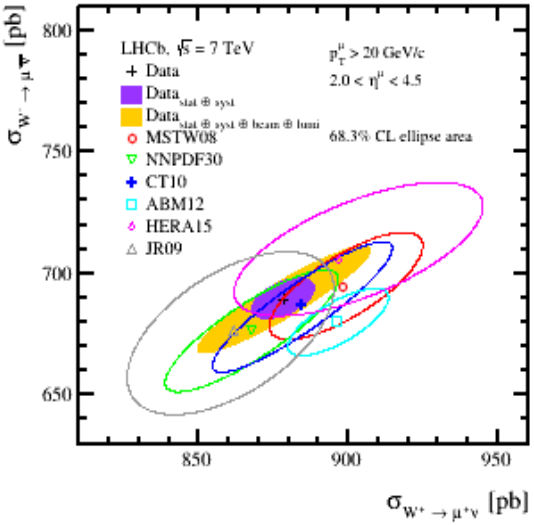
arXiV:1505.07024

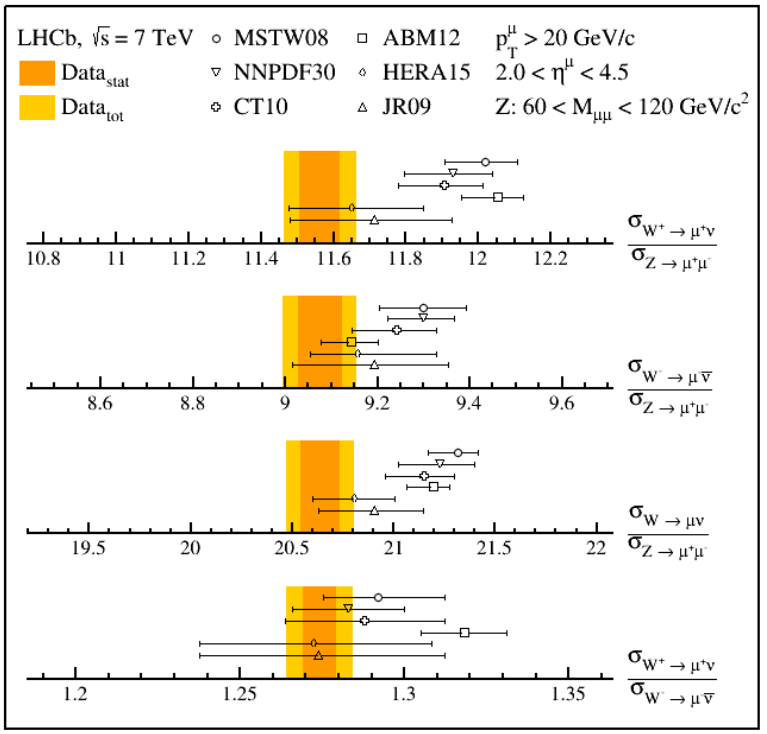
Data: 1/fb at 7 TeV

Analysis: Ratios cancel many scale uncertainties (mainly theoretical)









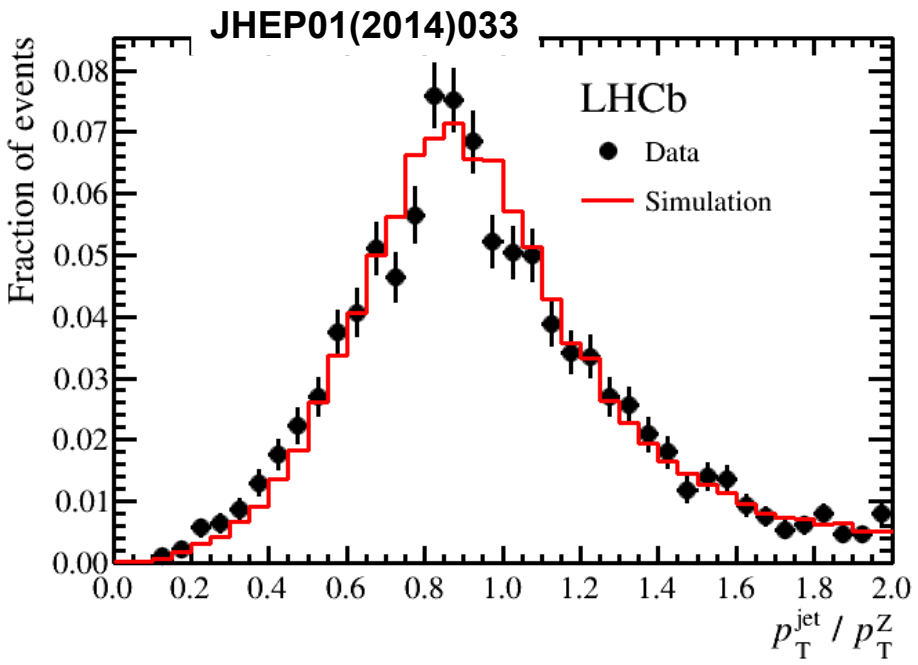
Tension between PDF sets

Z/W+jets

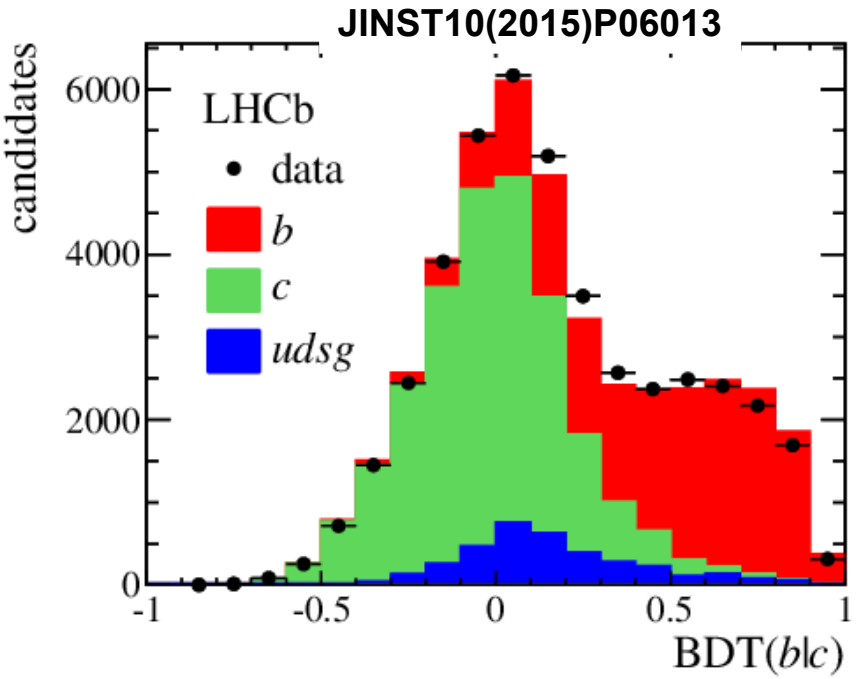
Data: 1/fb at 7 TeV

Analysis:

+ W/Z in muon decay channel
+ Jets reconstructed using anti-k_T R=0.5
+ Heavy quark identification using BDT



Good understanding of jet energy scale/resolution



Strong discrimination between b/c/l-jets

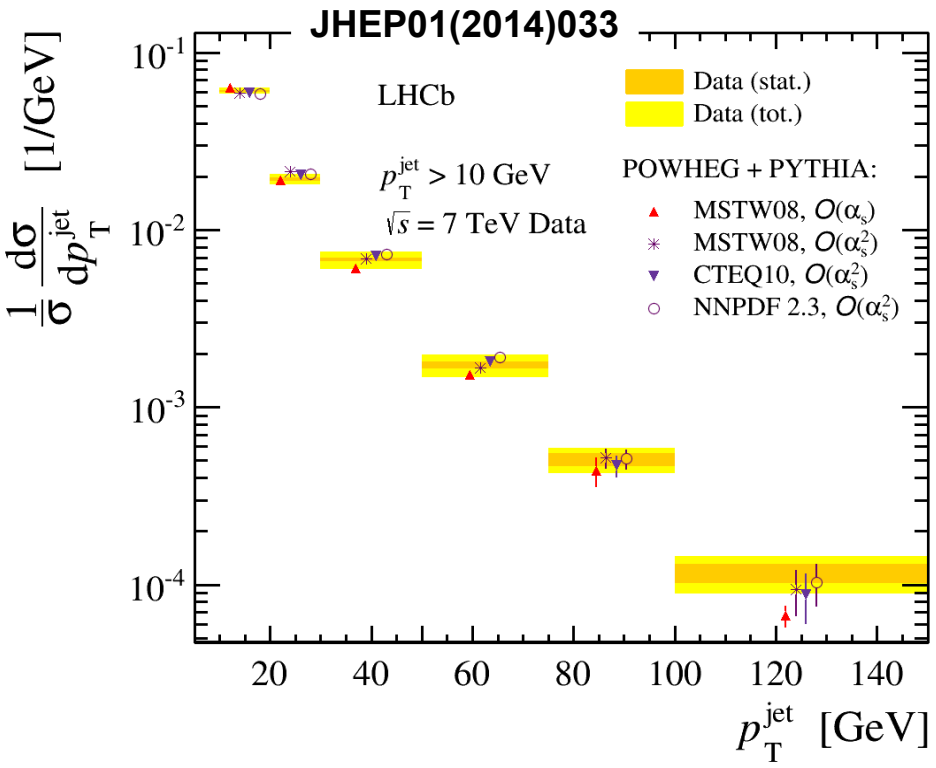
Z+jets and Z+b-jets

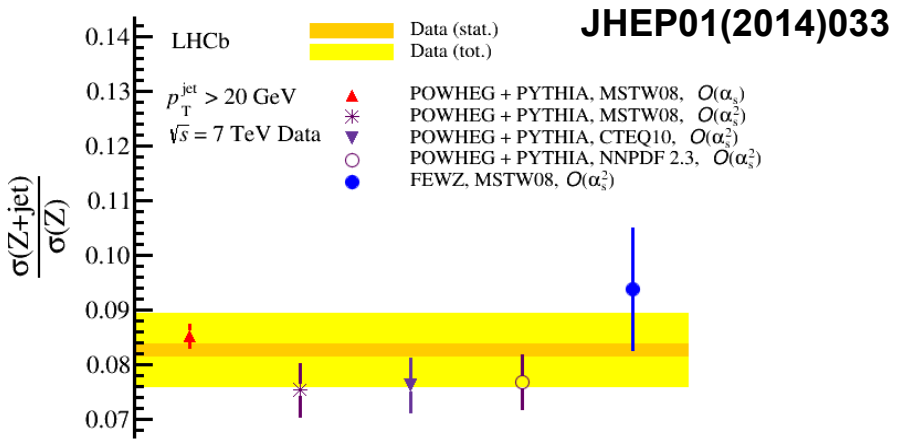
Data: 1/fb at 7 TeV

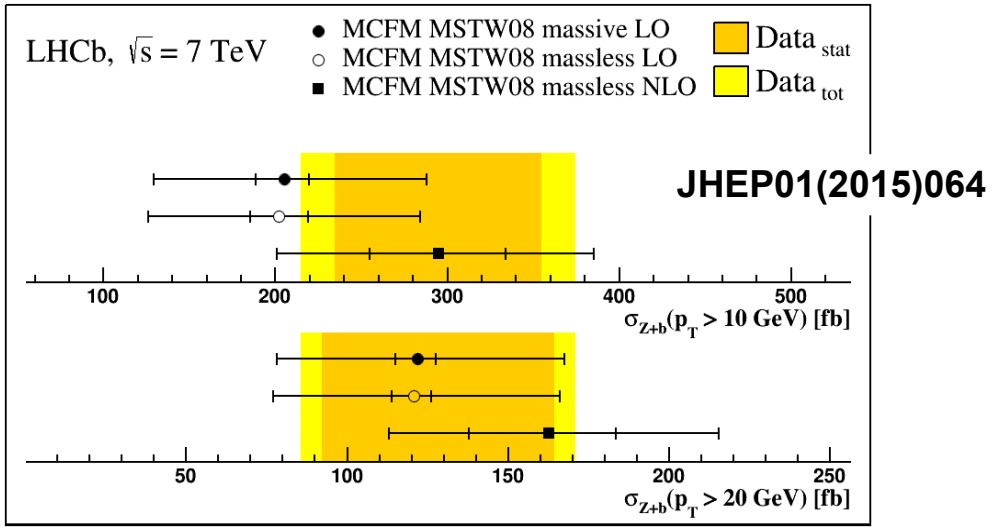
Analysis:

+ 2.0<η(jet)<4.5, pT(jet)> 20(10) GeV, ΔR(μ,jet)>0.4

+ b-jet yields extracted from template fit using SV mass







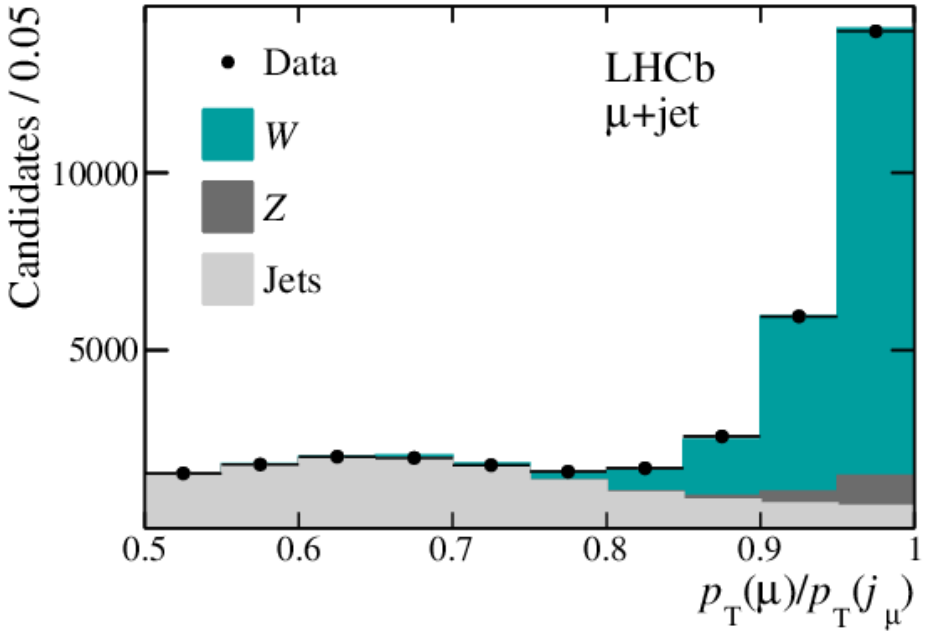
Good agreement with NLO predictions
Main uncertainty is related to jet

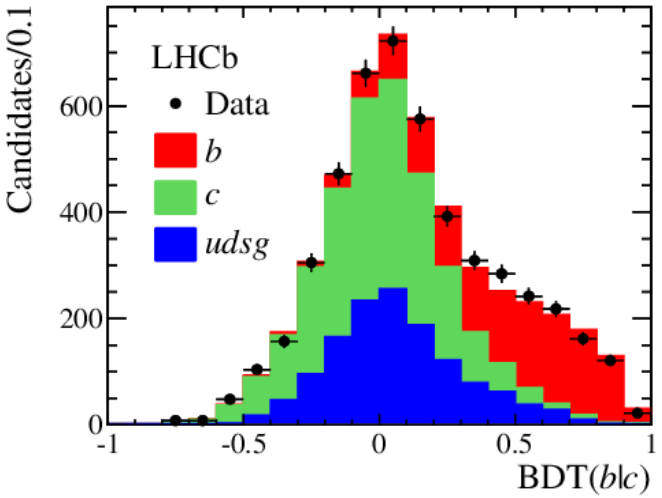
arXiv:1505.04051

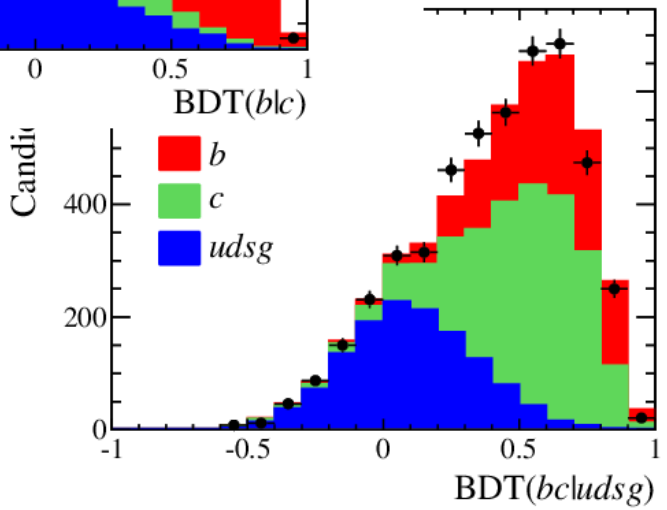
Data: 1/fb+2/fb at 7 TeV and 8 TeV

Analysis:

+ 2.2<η(jet)<4.2, p_T(jet)>20 GeV, ΔR(μ,jet)>0.5, p_T(μ+jet)>20 GeV
+ Muon isolation template fit used to extract W signal
+ Tagging BDT 2-D template fit used to estimate b/c yields

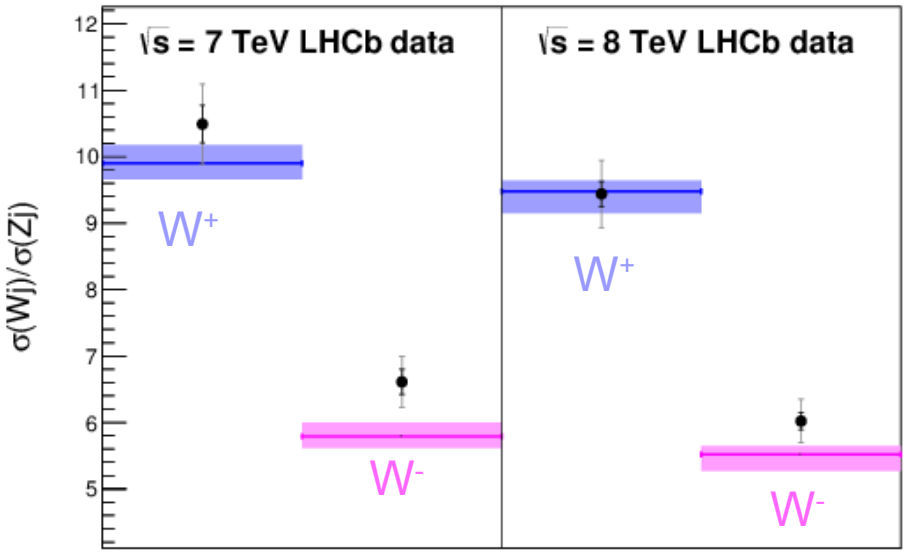


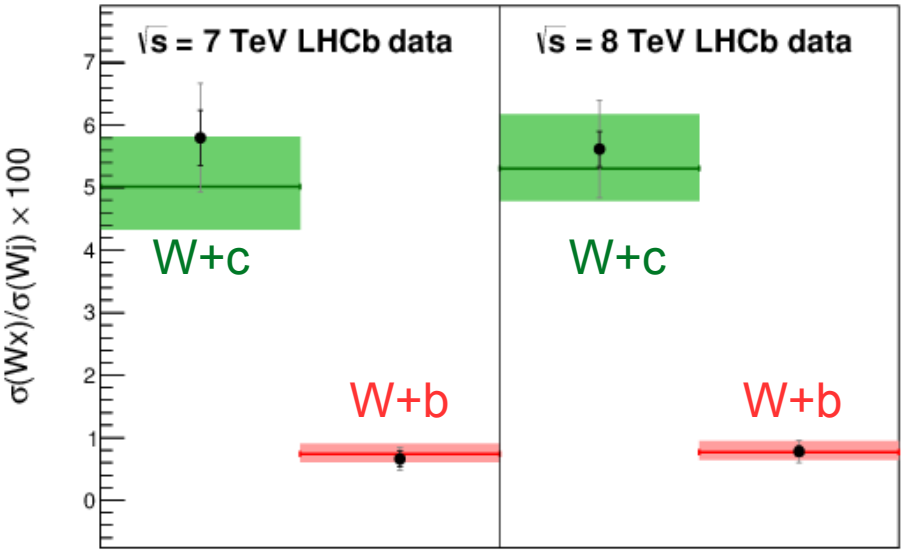




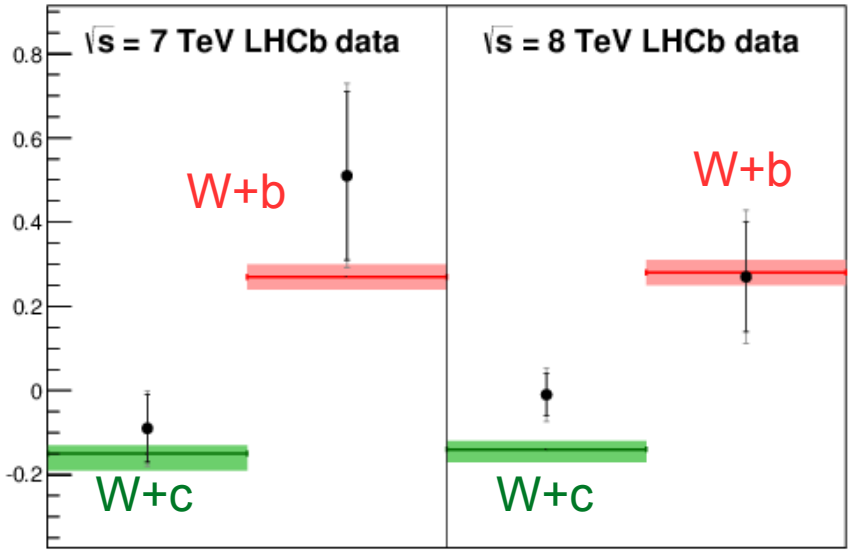
W+b-jets

arXiv:1505.04051





$$\mathcal{A}(Wq) \equiv \frac{\sigma(W^+q) - \sigma(W^-q)}{\sigma(W^+q) + \sigma(W^-q)}$$



Measurements are in good agreement with CT10 NLO p-QCD predictions

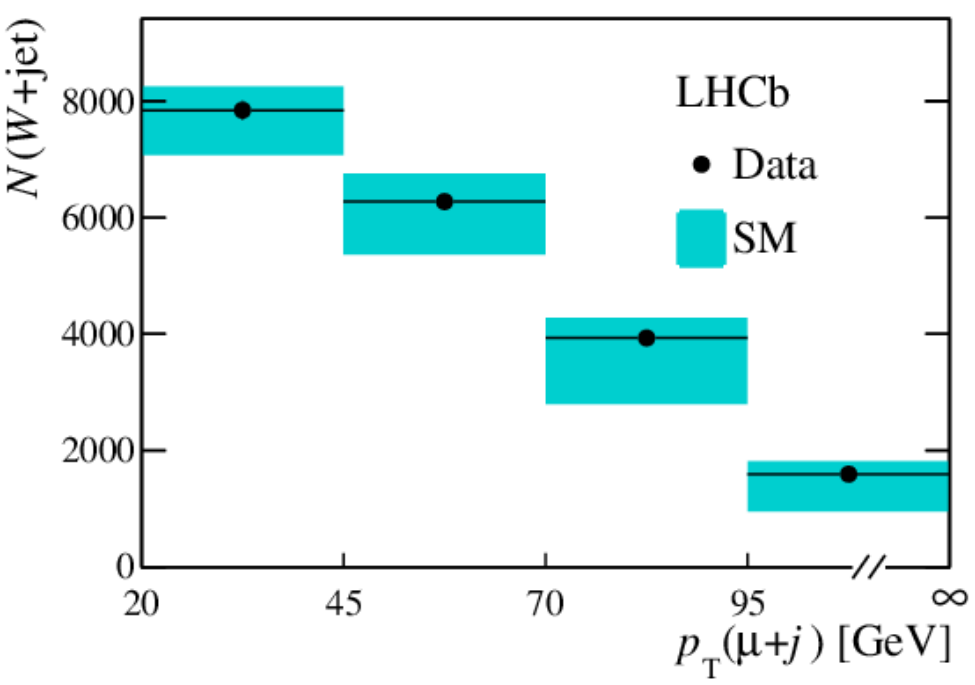
Top Observation in the forward region

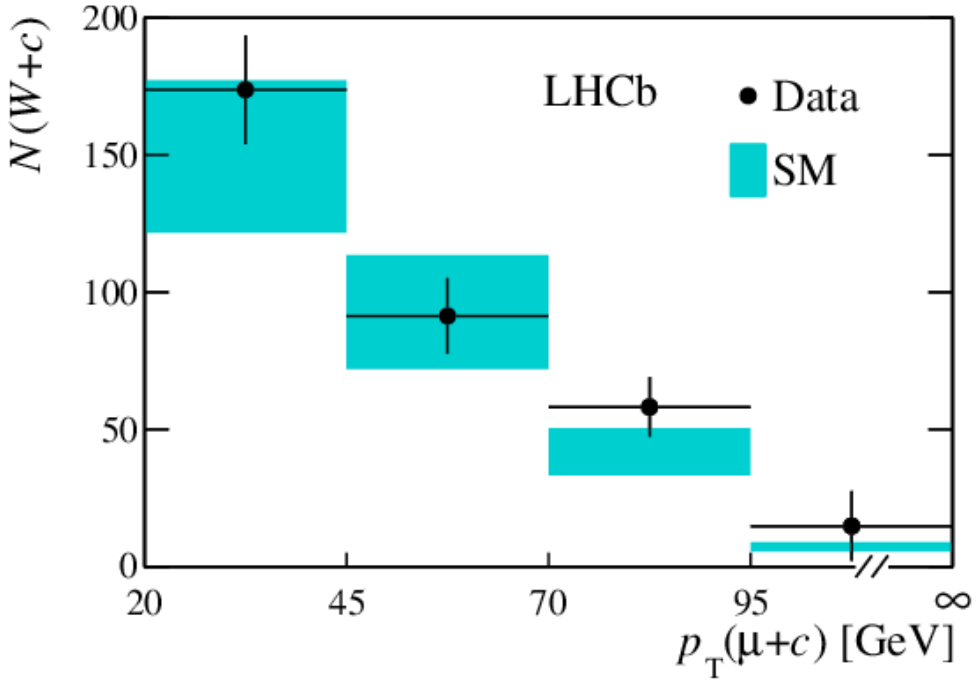
arXiv:1506.0090

Data: 1/fb+2/fb at 7 TeV and 8 TeV

Analysis:

+ Same same as W+b with p_T(jet)>50 GeV
+ W+jet yields extracted to estimate W+b-jet
+ W+c measurement used to validate analysis strategy



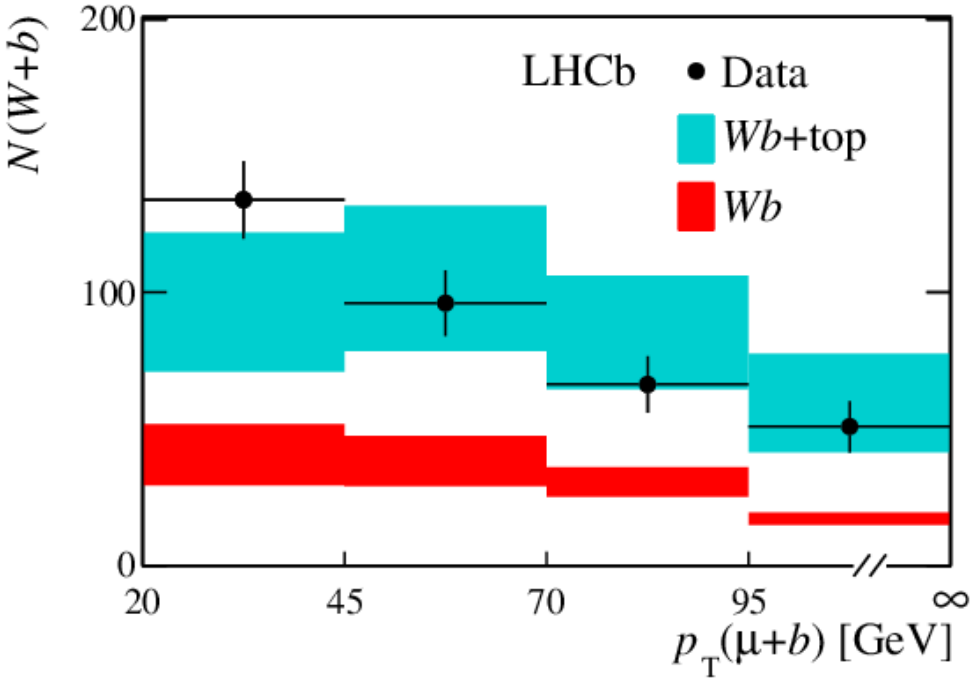


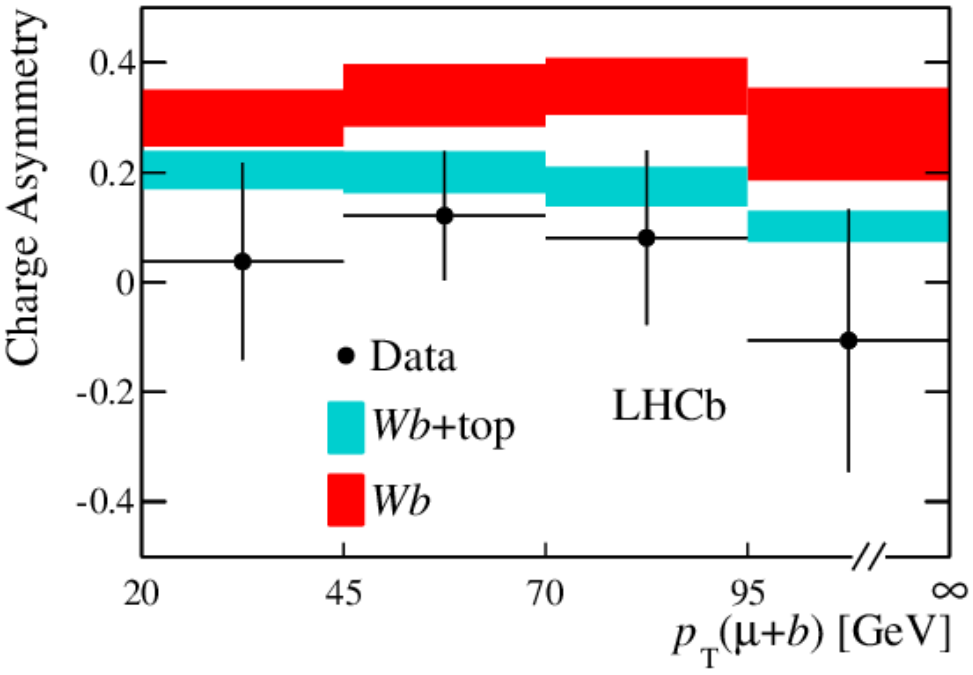
Good understanding of W+jet and W+c production

Top Observation in the forward region

arXiv:1506.0090

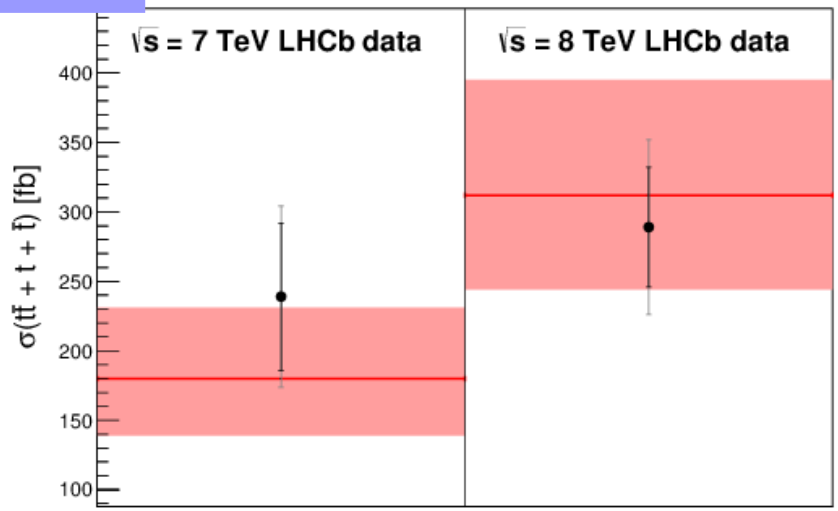
W+b-jet yield extracted and not explained only by direct production of W+b





Using Wilks theorem, top is observed with 5.4 σ

$$\sigma(\text{top})[7\,\text{TeV}] = 239 \pm 53\,(\text{stat}) \pm 38\,(\text{syst})\,\text{fb}$$
$$\sigma(\text{top})[8\,\text{TeV}] = 289 \pm 43\,(\text{stat}) \pm 46\,(\text{syst})\,\text{fb}$$

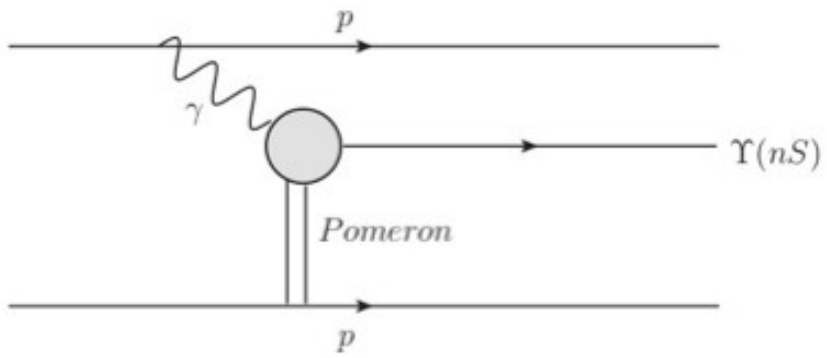


Exclusive Y production

arXiv:1505.08139

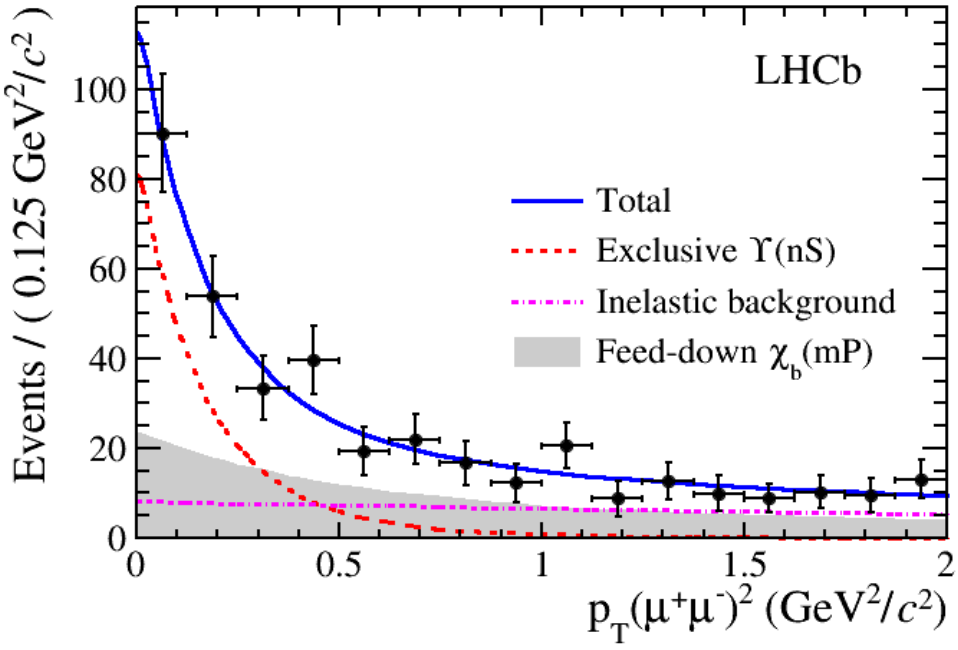
Data: 1/fb+2/fb at 7 TeV and 8 TeV

Motivation: sensitive to low-x gluon PDF ($x \sim 10^{-5}$) – "clean" enviroment



Analysis:

+ Analysis strategy similar to previous CEP publications
+ One primary vertex events considered
+ No backward tracks
+ Two muons in the event
  – veto on extra tracks
+ Non-resonant background estimated from fit

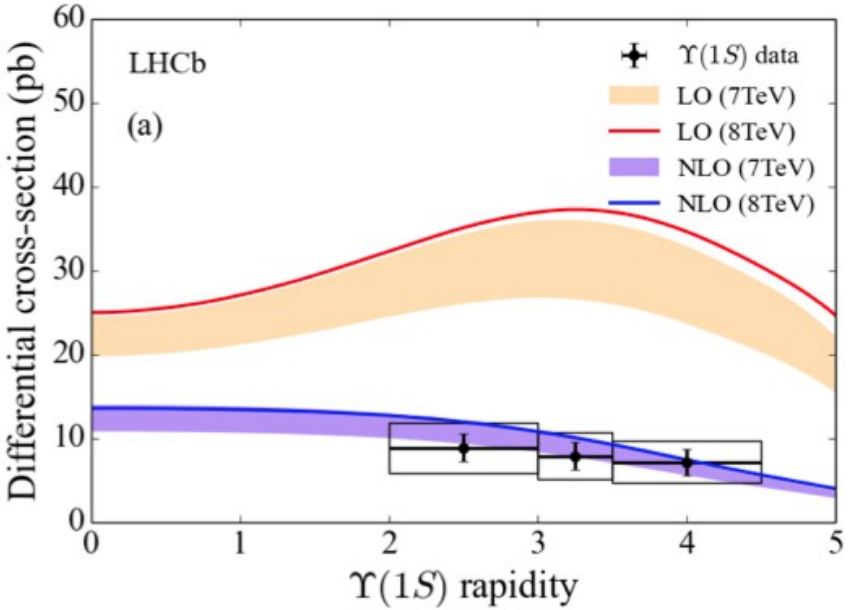


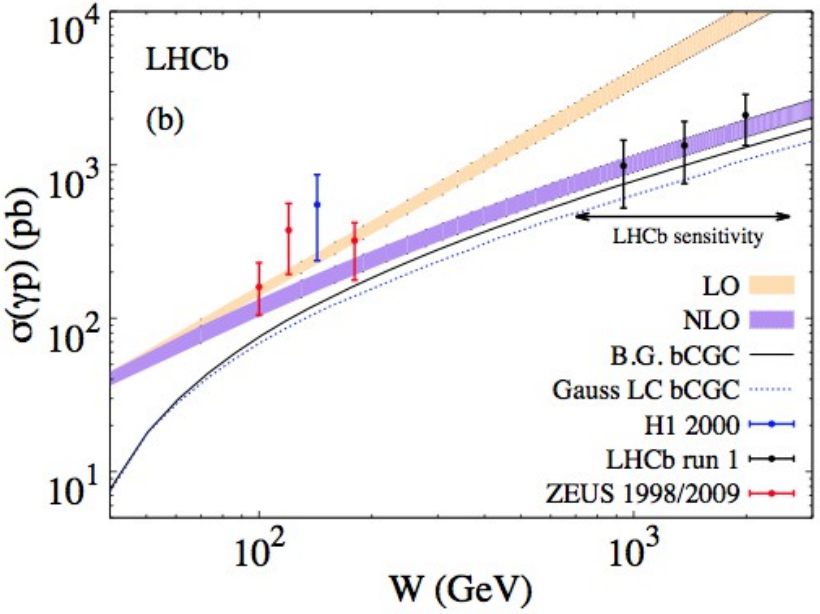
p_T^2 distribution extracted from sWeights is used to estimate the exclusive Y production

Exclusive Υ production

arXiv:1505.08139

$$\sigma(pp \to p\Upsilon(1S)p) = 9.0 \pm 2.1 \pm 1.7 \text{ pb}$$
$$\sigma(pp \to p\Upsilon(2S)p) = 1.3 \pm 0.8 \pm 0.3 \text{ pb}$$

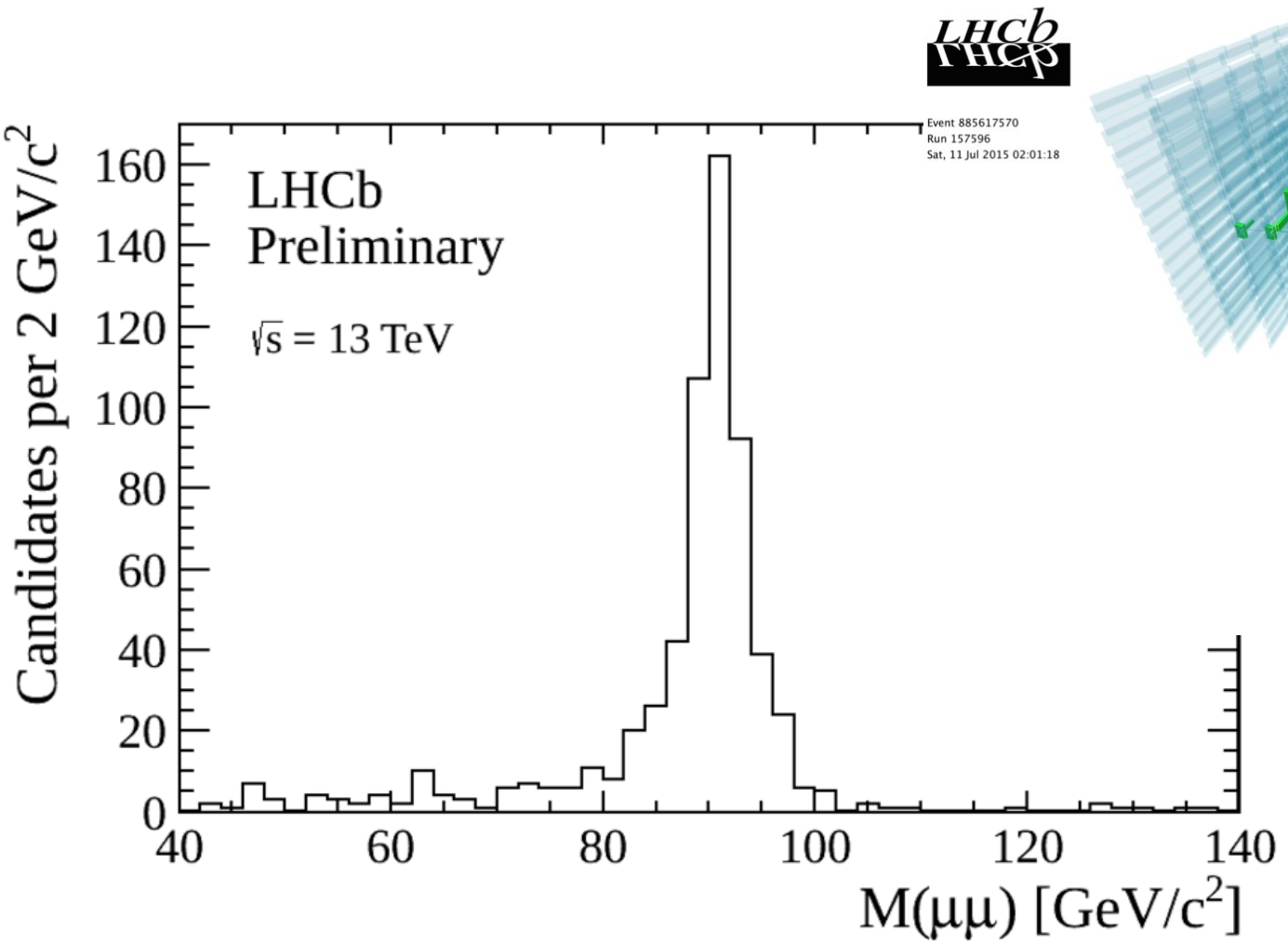


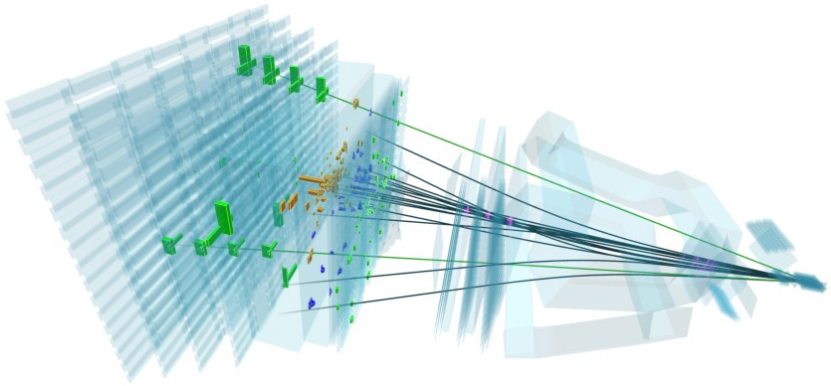


Rapidity dependence in agreement with NLO calculation

Photon-proton cross-section extrapolated from measurement can be compared with different phenomenological models

First look at 13 TeV





Summary

→ LHCb probes a unique coverage in η and low p_T reach at LHC

→ Measurements are in agreement with theoretical prediction and can be used to constrain PDF

→ Great b-tagging performance and ability to tag charm jets

→ Exclusive Y production studies test
RunII data have dedicated CEP triggers
with new forward sub-detector (Herschel)

→ Many other results not covered in this talk are available here
LHCb Results

→ 13 TeV first data are very promising!!

Back up

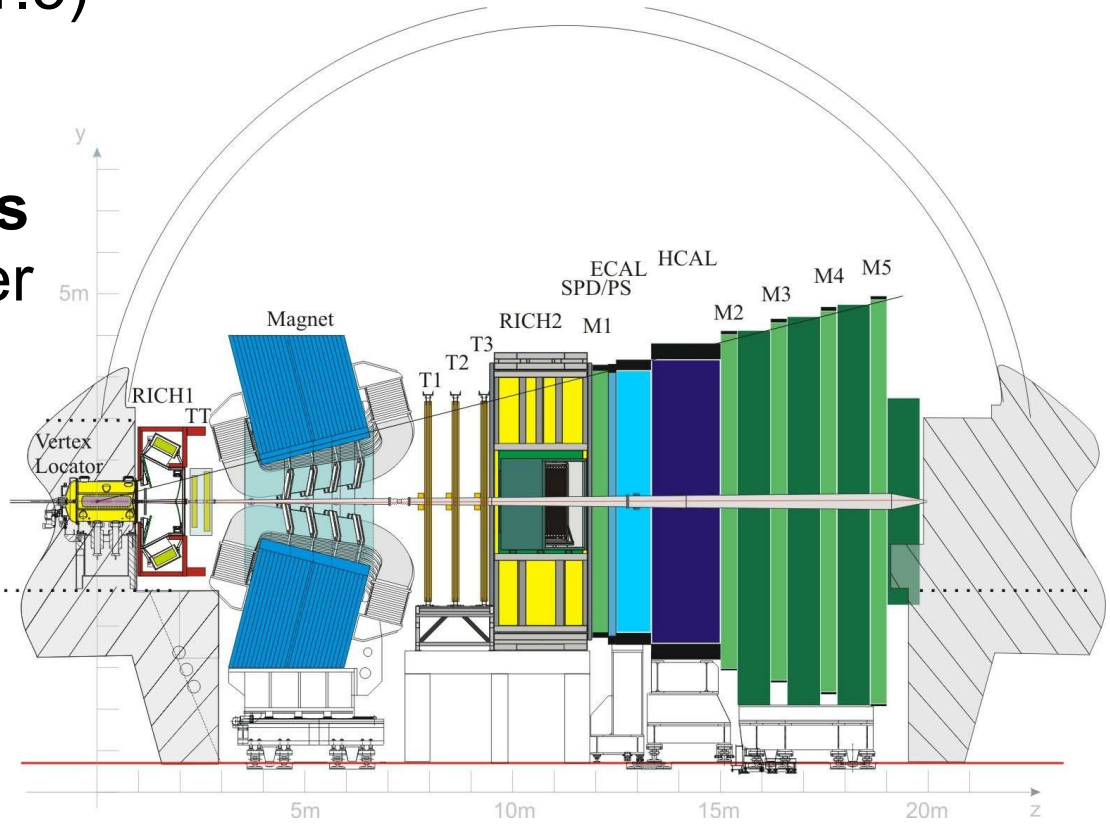
The detector is a single arm spectrometer fully instrumented in the forward region ($2.0 < \eta < 5.0$) → Unique coverage at LHC

Excellent Vertex Resolution and Tracking
→ Vertex Locator (also for $\eta < -1.5$)
→ Tracking Stations

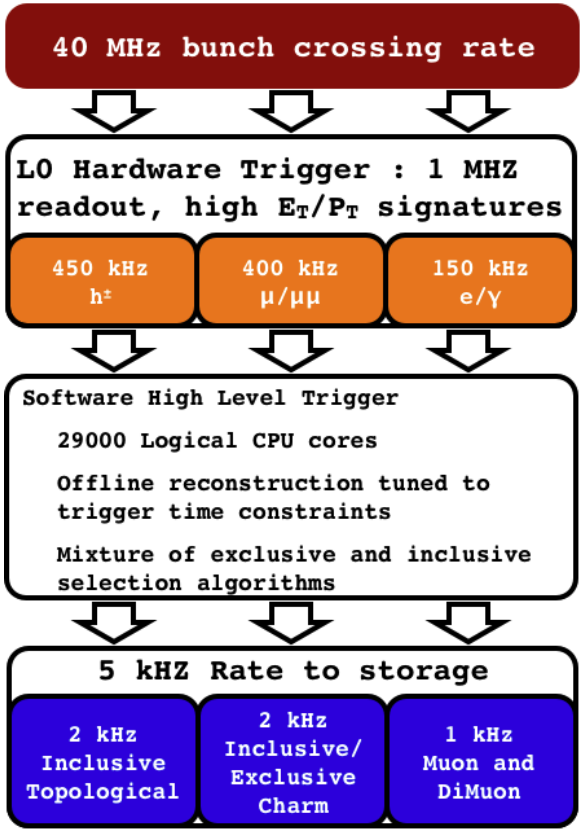
Neutral Energy Measurements
→ EM and Hadronic Calorimeter

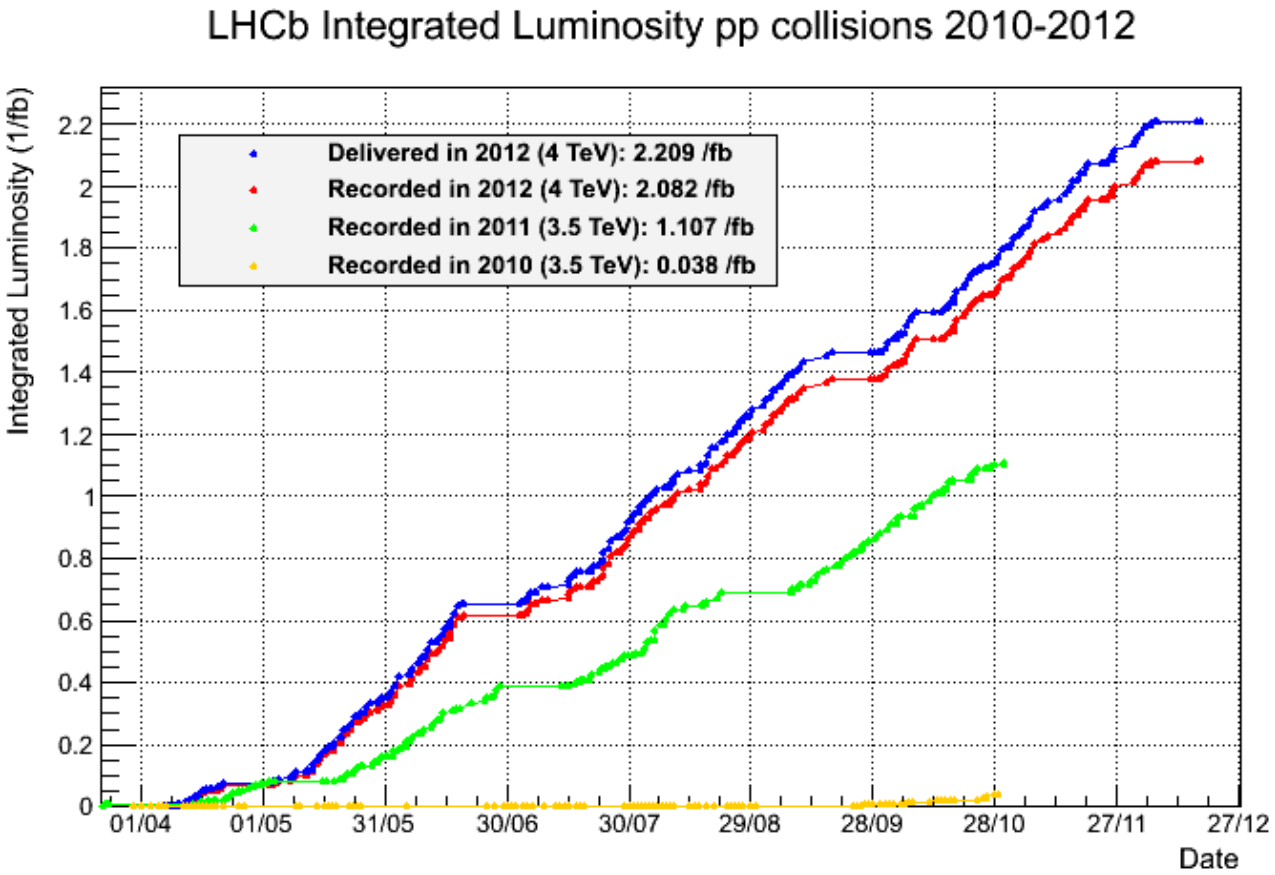
Particle Identification
→ Rich detectors
→ Muon Stations

Trigger
→ Ability to go low in muon p_T



LHCb Data





>90% data taking efficiency

>99% DQ efficiency

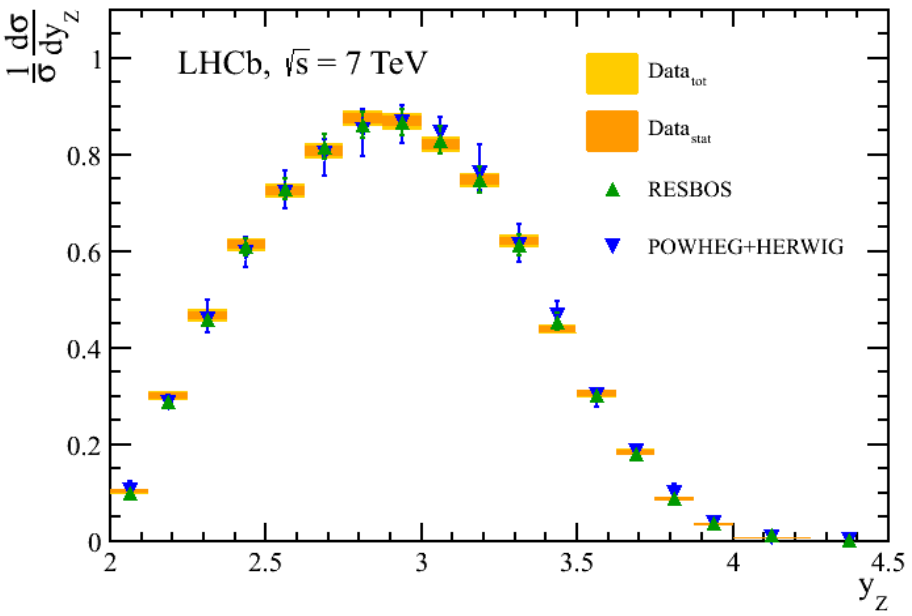
2010 → 37/pb at $\sqrt{s}$ = 7 TeV

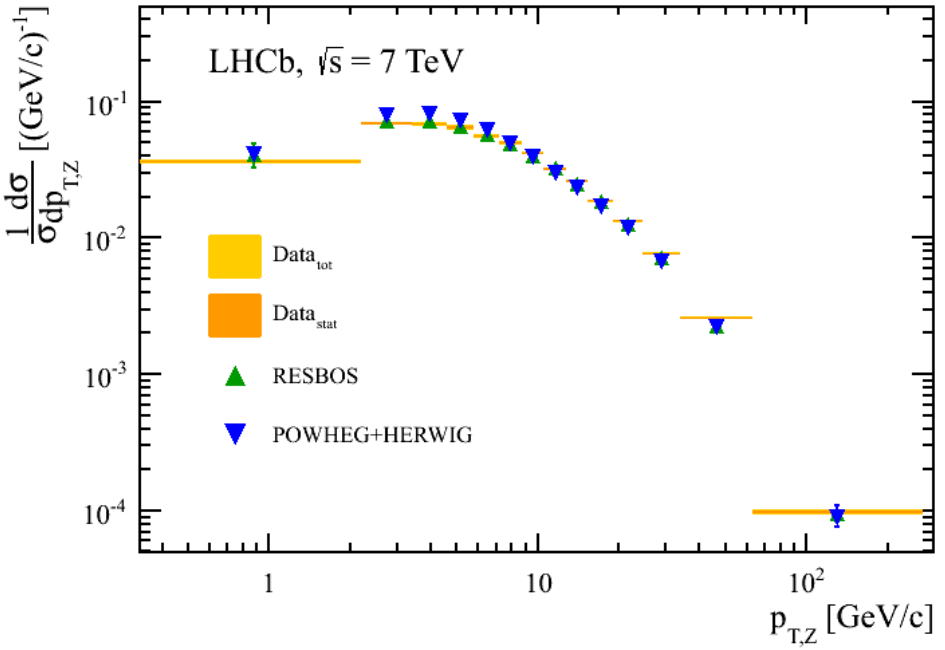
2011 → 1.0/fb at at $\sqrt{s}$ = 7 TeV

2012 → 2/fb at at $\sqrt{s}$ = 8 TeV

Z→μμ production

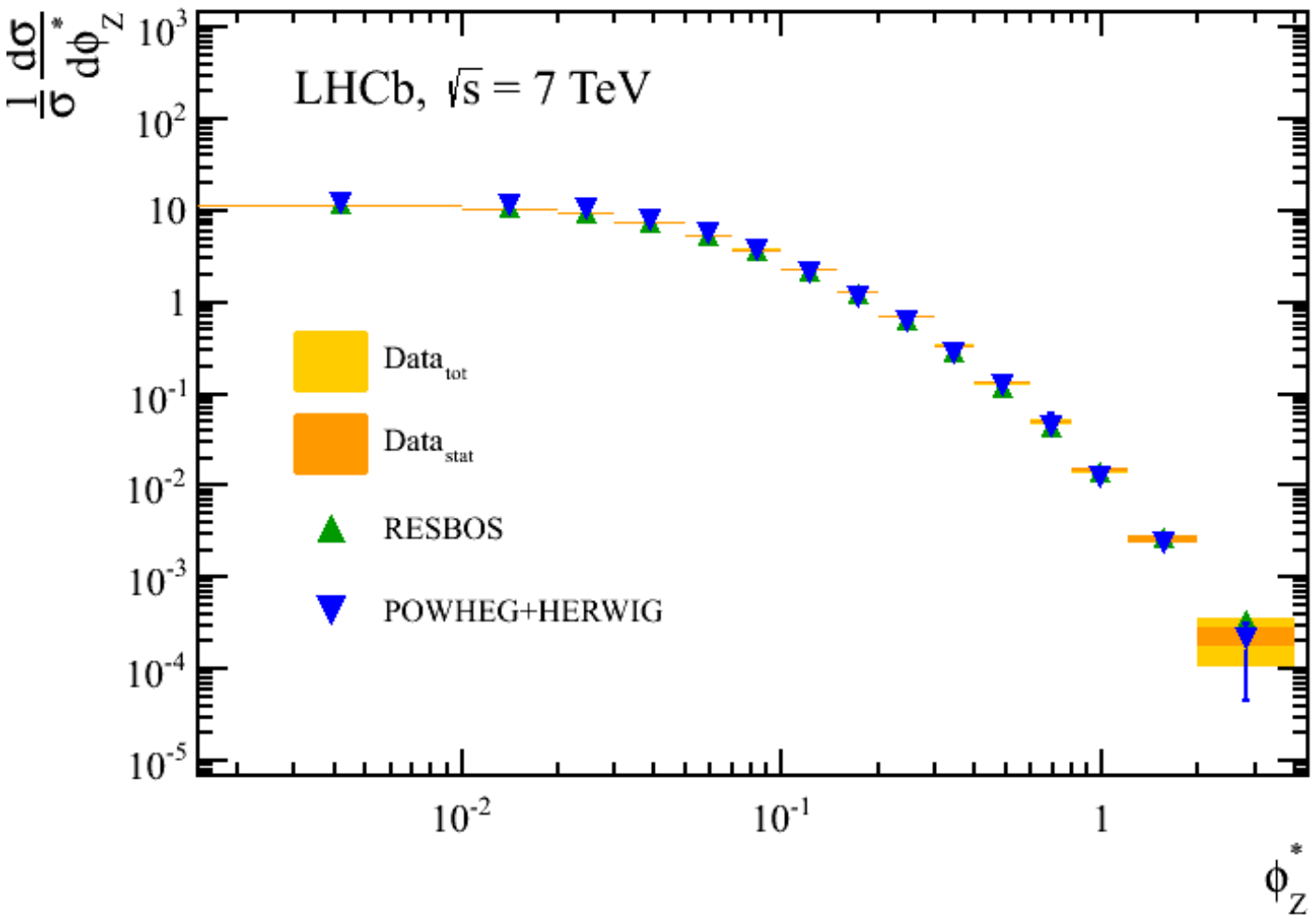
arXiV:1505.07024





Source	Uncertainty (%)
Statistical	0.39
Trigger efficiency	0.07
Identification efficiency	0.23
Tracking efficiency	0.53
FSR	0.11
Purity	0.22
GEC efficiency	0.26
Systematic	0.68
Beam energy	1.25
Luminosity	1.72
Total	2.27

arXiV:1505.07024



$$\phi^* \equiv \tan\left(\frac{\phi_{\text{acop}}}{2}\right) \Big/ \cosh\left(\frac{\Delta\eta}{2}\right) \approx \frac{p_{\text{T}}}{Mc}$$

Z→ee production

JHEP05(2015)109

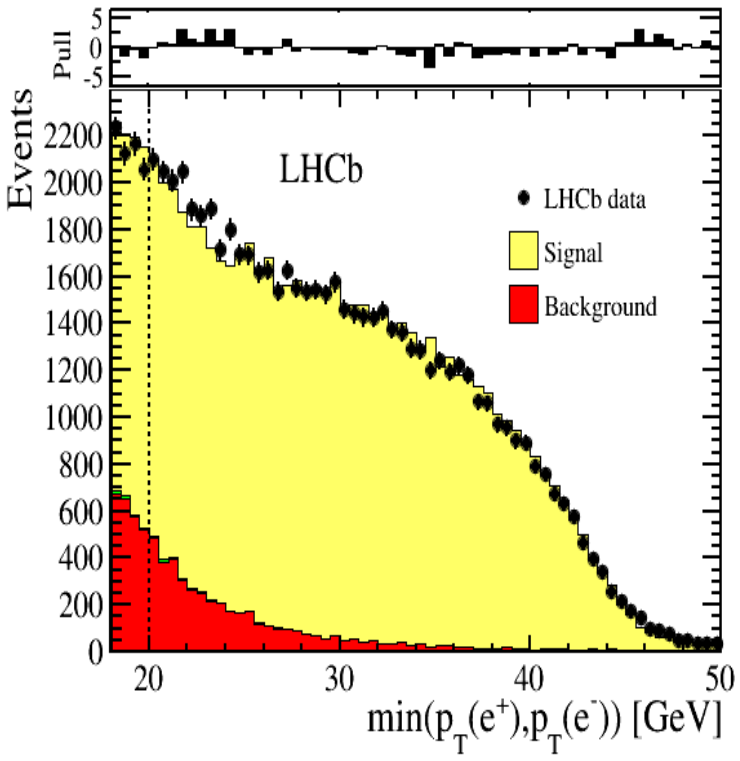
Data: 2/fb at 8 TeV

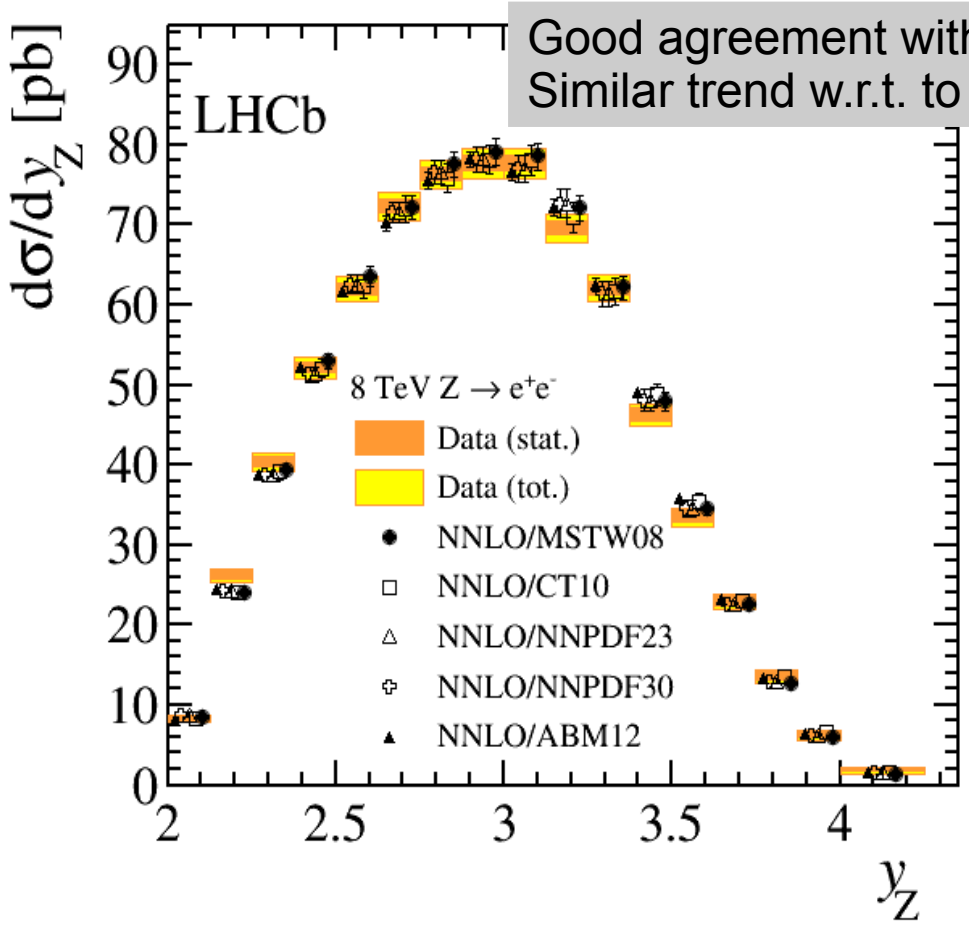
Fiducial acceptance: $2.0<\eta(e)<4.5$, $p_T(e)> 20$ GeV, $60<M(ee)/GeV<120$

Analysis:

Calorimeter information used to identify the electron

~90% purity – main background is electron mis-identification





Good agreement with NNLO
Similar trend w.r.t. to PDF variation

Z→ee production

JHEP05 (2015) 109

Data: 2/fb at 8 TeV

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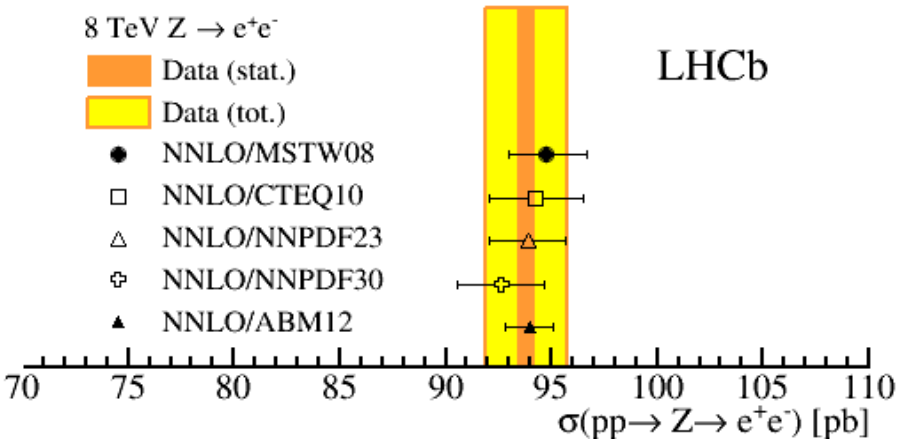

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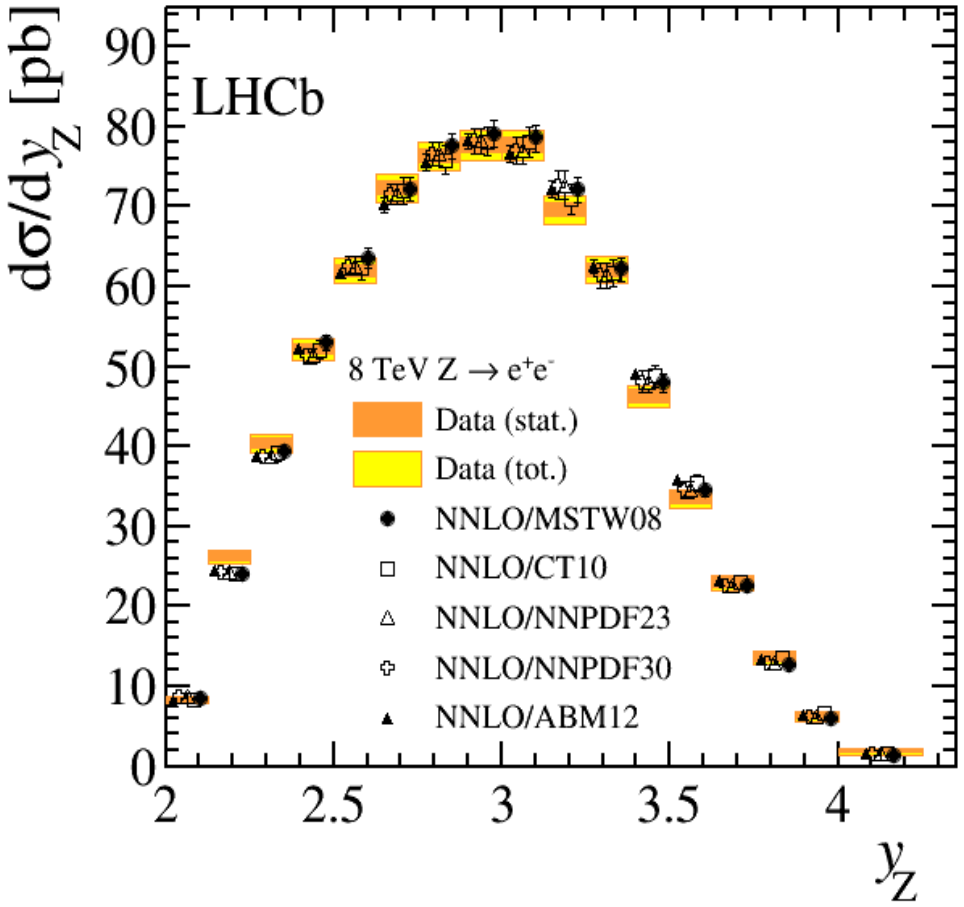


Z→μμ production

arXiV:1505.07024

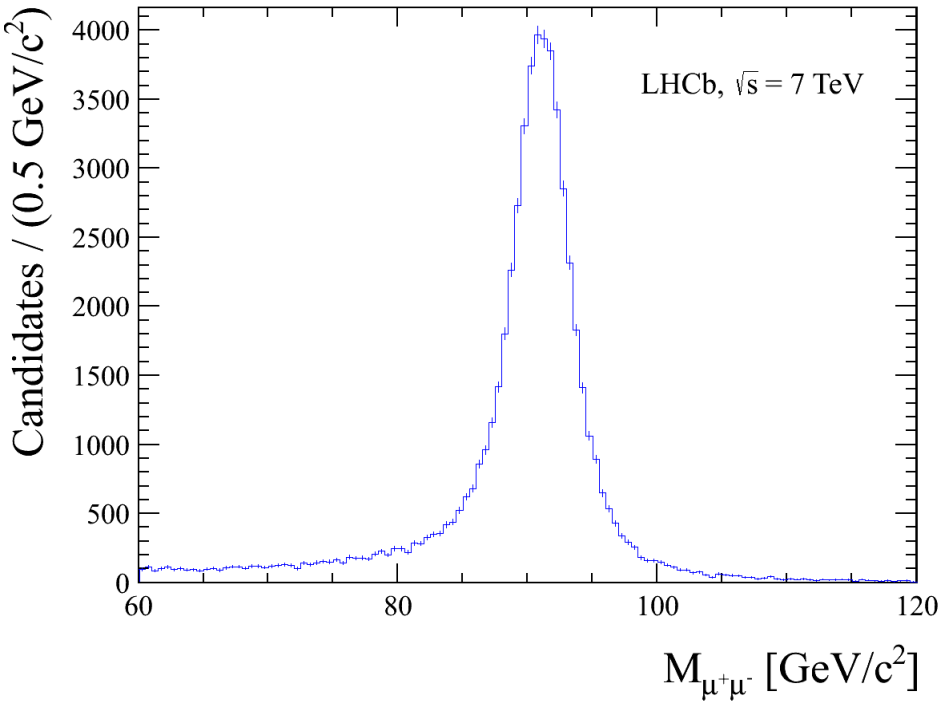
Data: 1/fb at 7 TeV

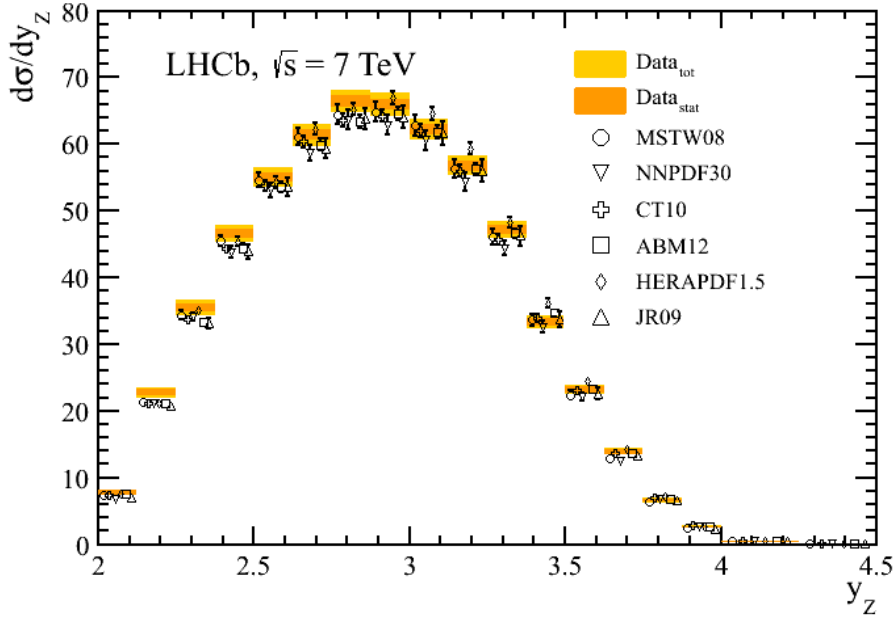
Fiducial acceptance: $2.0<\eta(\mu)<4.5$, $p_T(\mu)> 20$ GeV, $60<M(\mu\mu)/\text{GeV}<120$

Analysis:

Efficiency derived from data: tag-and-probe method

~99% purity – main systematic errors are lumi. and beam energy





Good agreement with NNLO
Sensitive to PDF variation

W→μν production

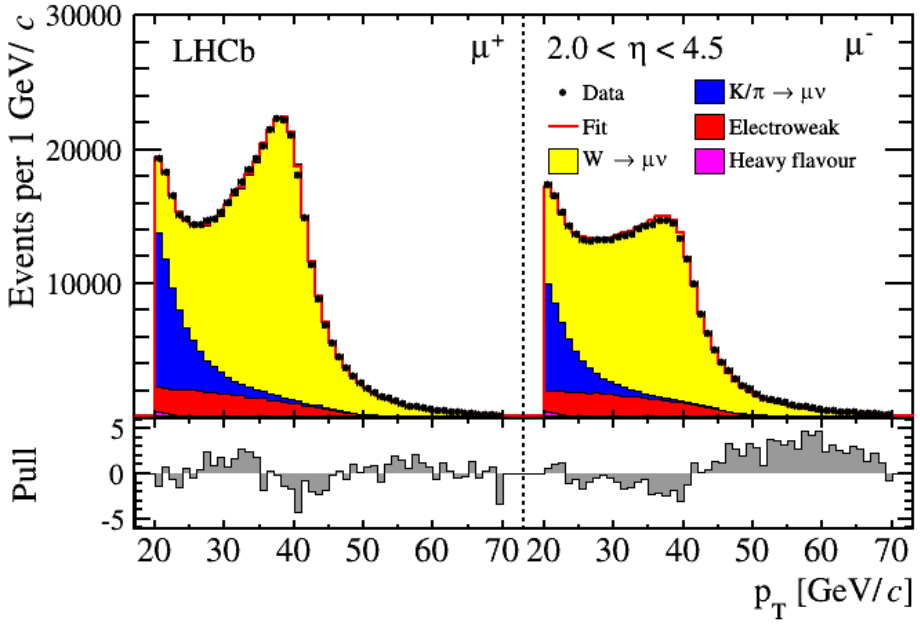
JHEP12(2014)079

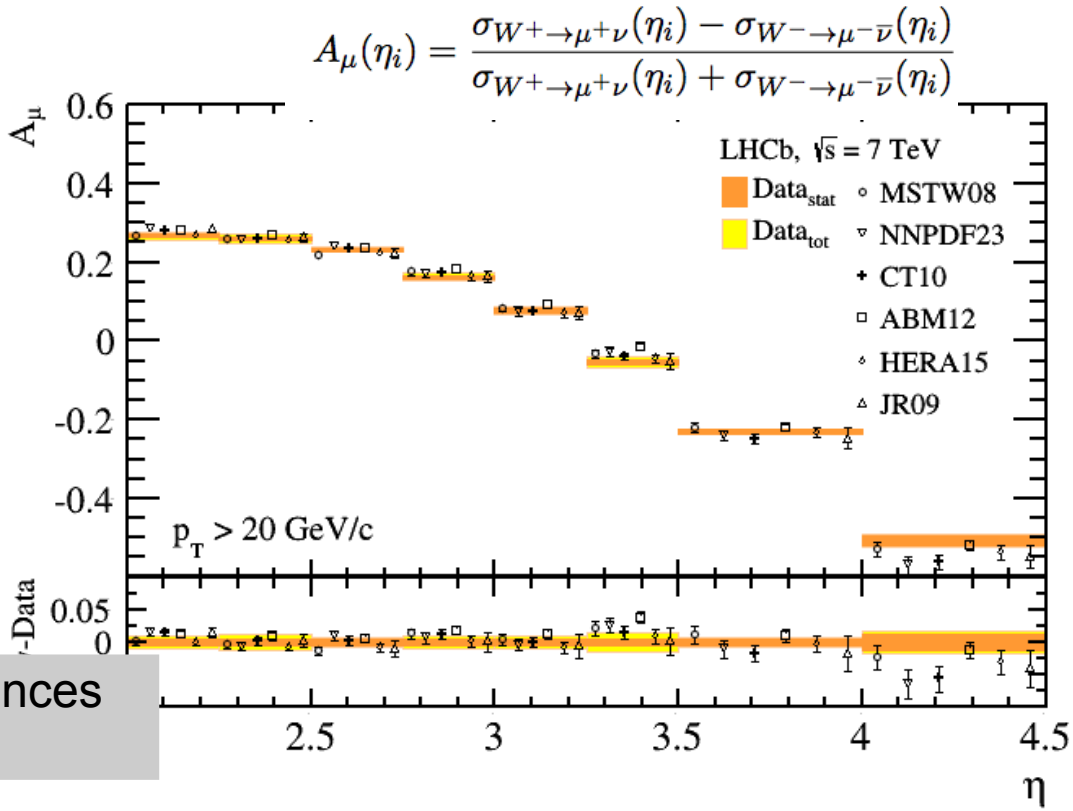
Data: 1/fb at 7 TeV

Fiducial acceptance: $2.0<\eta(\mu)<4.5$, $p_T(\mu)> 20$ GeV

Analysis:

+ Signal extracted with template fit of $p_T(\mu)$
+ ~77% purity
+ Cross-section and charge lepton asymmetry vs η(μ)

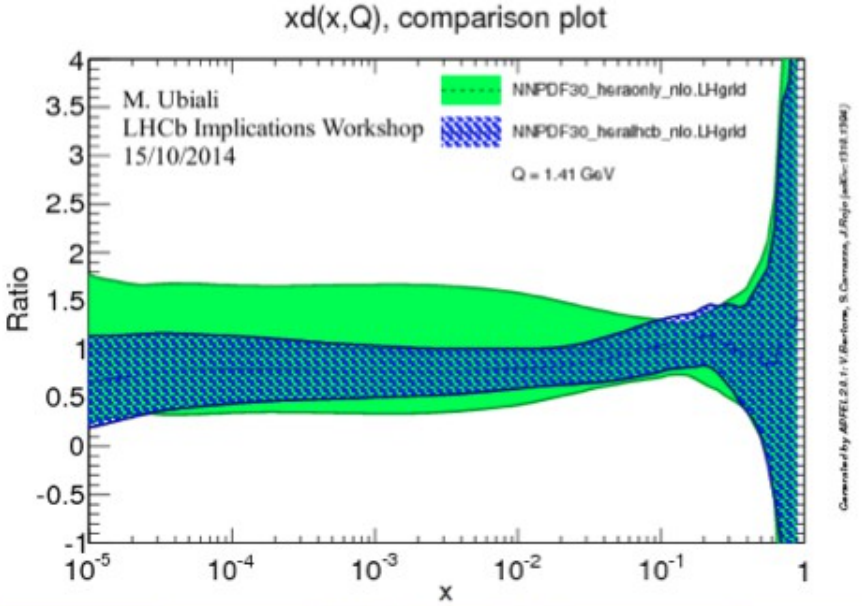




Lepton charge asymmetry probes PDF differences
Good agreement with NNLO predictions

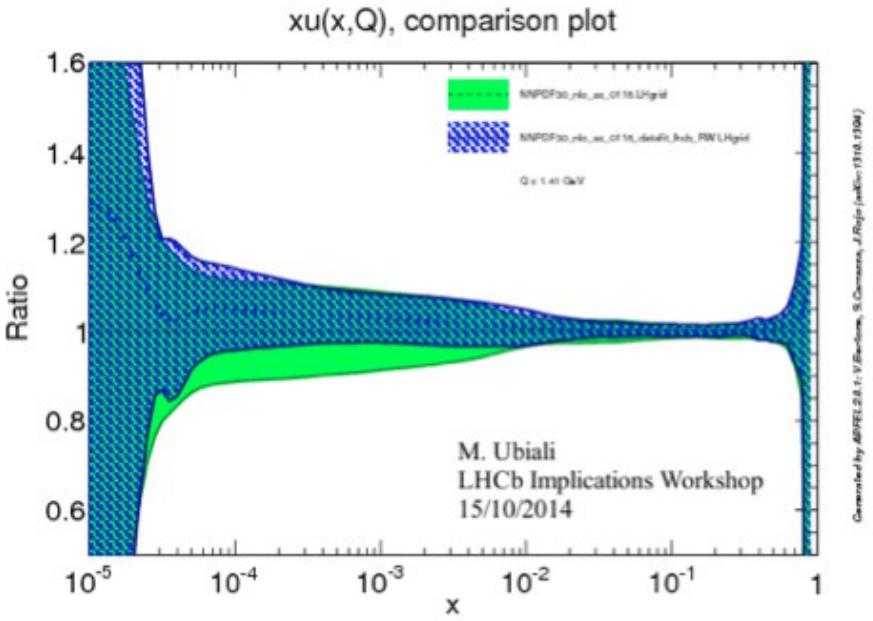
Impact of LHCb results on PDFs

- Many LHCb run 1 results on electroweak boson production now included in PDF fits.
- Large impact on pre-LHC PDF knowledge.
- Shown here NNPDF down quark PDF and uncertainties (normalised so central value pre-LHC is unity):
  - Green: PDF fit using pre-LHC data
  - Blue: PDF fit using pre-LHC data and LHCb data



Impact of LHCb results on PDFs

- Even when results from other LHC experiments are included in PDF fits, LHCb still noticeably reduces PDF uncertainties.
- Shown here NNPDF up quark PDF and uncertainties:
  - Green: PDF fit with LHC data (but no LHCb data)
  - Blue: PDF fit with LHC data (including LHCb data)



arXiv:1505.04051

Data: 1/fb+2/fb at 7 TeV and 8 TeV

Analysis:

+ 2.2<η(jet)<4.2, p_T(jet)>20 GeV, ΔR(μ,jet)>0.5, p_T(μ+jet)>20 GeV
+ Muon isolation template fit used to extract W signal
+ Tagging BDT template fit used to estimate b/c yields

Source	$\frac{\sigma(Wb)}{\sigma(Wj)}$	$\frac{\sigma(Wc)}{\sigma(Wj)}$	$\frac{\sigma(Wj)}{\sigma(Zj)}$	$\mathcal{A}(Wb)$	$\mathcal{A}(Wc)$
Muon trigger and selection	–	–	2%	–	–
GEC	1%	1%	1%	–	–
Jet reconstruction	2%	2%	–	–	–
Jet energy	2%	2%	1%	0.02	0.02
(b, c)-tag efficiency	10%	10%		–	–
SV-tag BDT templates	5%	5%		0.02	0.02
$p_T(\mu)/p_T(j_\mu)$ templates	10%	5%	4%	0.08	0.03
Top quark	13%	–	–	0.02	
$Z \to \tau\tau$	–	3%	–	–	–
Other electroweak	–	–	–	–	–
$W \to \tau \to \mu$	–	–	1%	–	–
Total	20%	13%	5%	0.09	0.04

arXiv:1506.0090

source	uncertainty
GEC	2%
$p_{\mathrm{T}}(\mu)/p_{\mathrm{T}}(j_{\mu})$ templates	5–10%
jet reconstruction	2%
SV-tag BDT templates	5%
b-tag efficiency	10%
trigger & μ selection	2%†
jet energy	5%†
$W \to \tau \to \mu$	1%†
luminosity	1–2%†

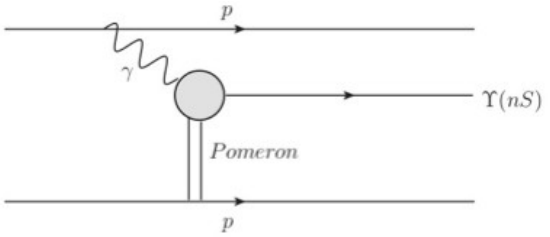
Exclusive Υ production

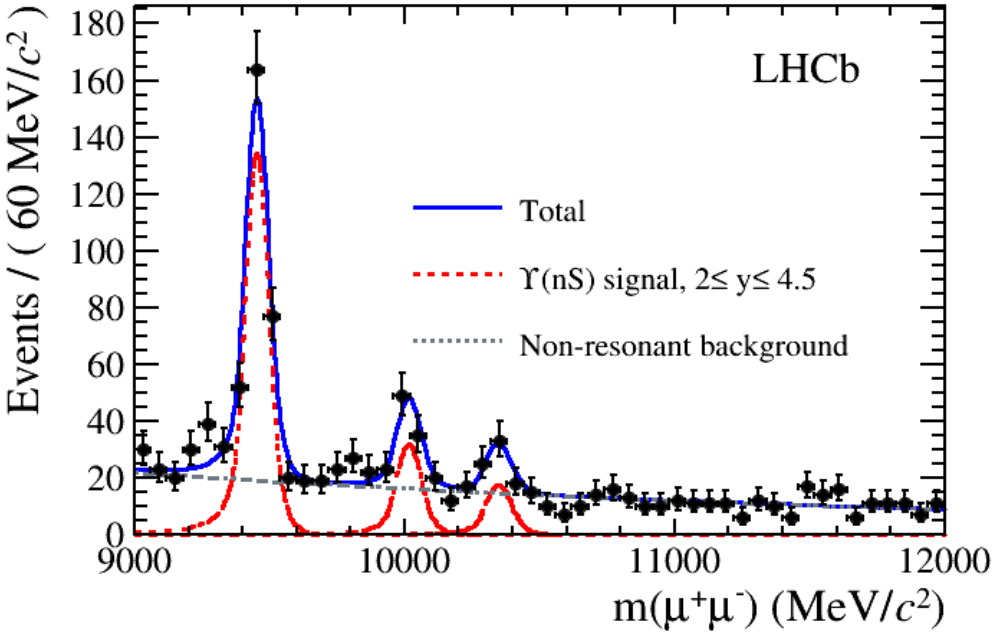
arXiv:1505.08139

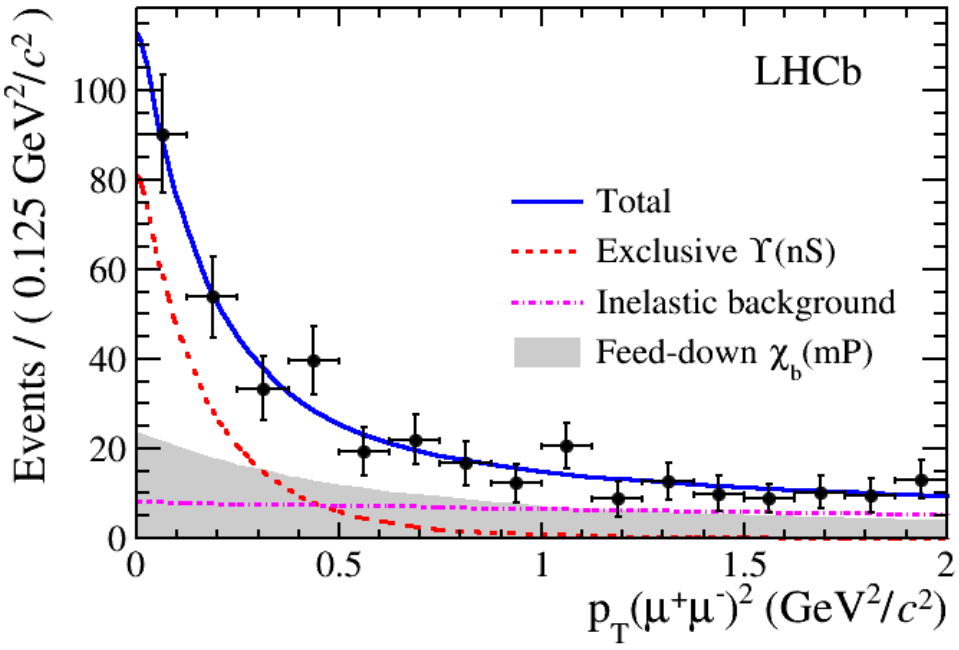
Data: 1/fb+2/fb at 7 TeV and 8 TeV

Analysis:

+ Analysis strategy similar to previous CEP publications
+ One primary vertex events considered
+ Two muons in the event – veto on extra tracks
+ Non-resonant background estimated from fit







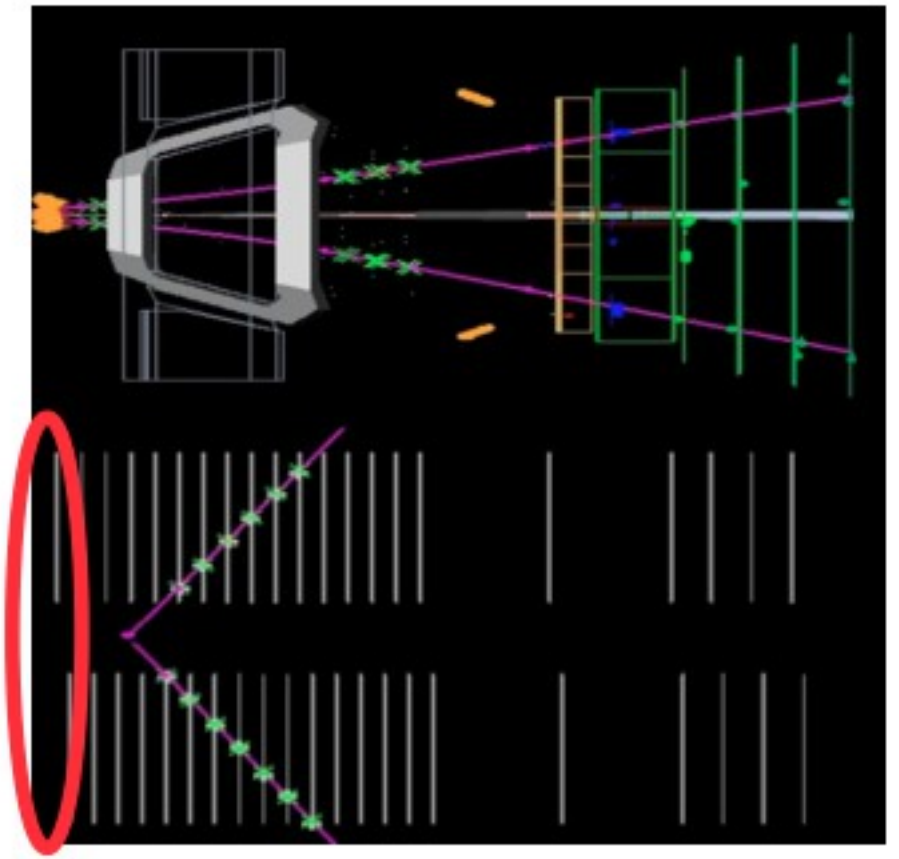
p_T^2 distribution extracted from sWeights is used to estimate the exclusive Υ production

Exclusive Υ production

arXiv:1505.08139

	$2 < y < 3$ $\Upsilon(1S)$	$3 < y < 3.5$ $\Upsilon(1S)$	$3.5 < y < 4.5$ $\Upsilon(1S)$	$2 < y < 4.5$ $\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Purity fit	14.2	14.2	14.2	13.7	13.7	13.7
Feed-down b.g.	12.2	12.2	12.3	12.2	14.6	12.5
Υ' feed-down	4.0	4.3	5.4	4.5	11.1	–
Mass fit	2.2	2.8	2.9	2.1	2.8	3.6
Luminosity	2.3	2.3	2.3	2.3	2.3	2.3
$\mathcal{B}(\Upsilon \to \mu^+\mu^-)$	2.0	2.0	2.0	2.0	8.8	9.6
Total	19.5	19.7	20.0	19.3	24.8	21.4

CEP-like event: 2muons



VELO acceptance

cross section at $x=0$: