# Measurements with electroweak gauge bosons and searches for Higgs-like particles at LHCb

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on behalf of the LHCb collaboration

PASCOS 2013

November 21st, 2013


# Outline

# Introduction to LHCb

# LHCb detector

- LHCb is a single-arm spectrometer with forward angular coverage from 10 mrad to 300 (250) mrad in the bending (non-bending) plane

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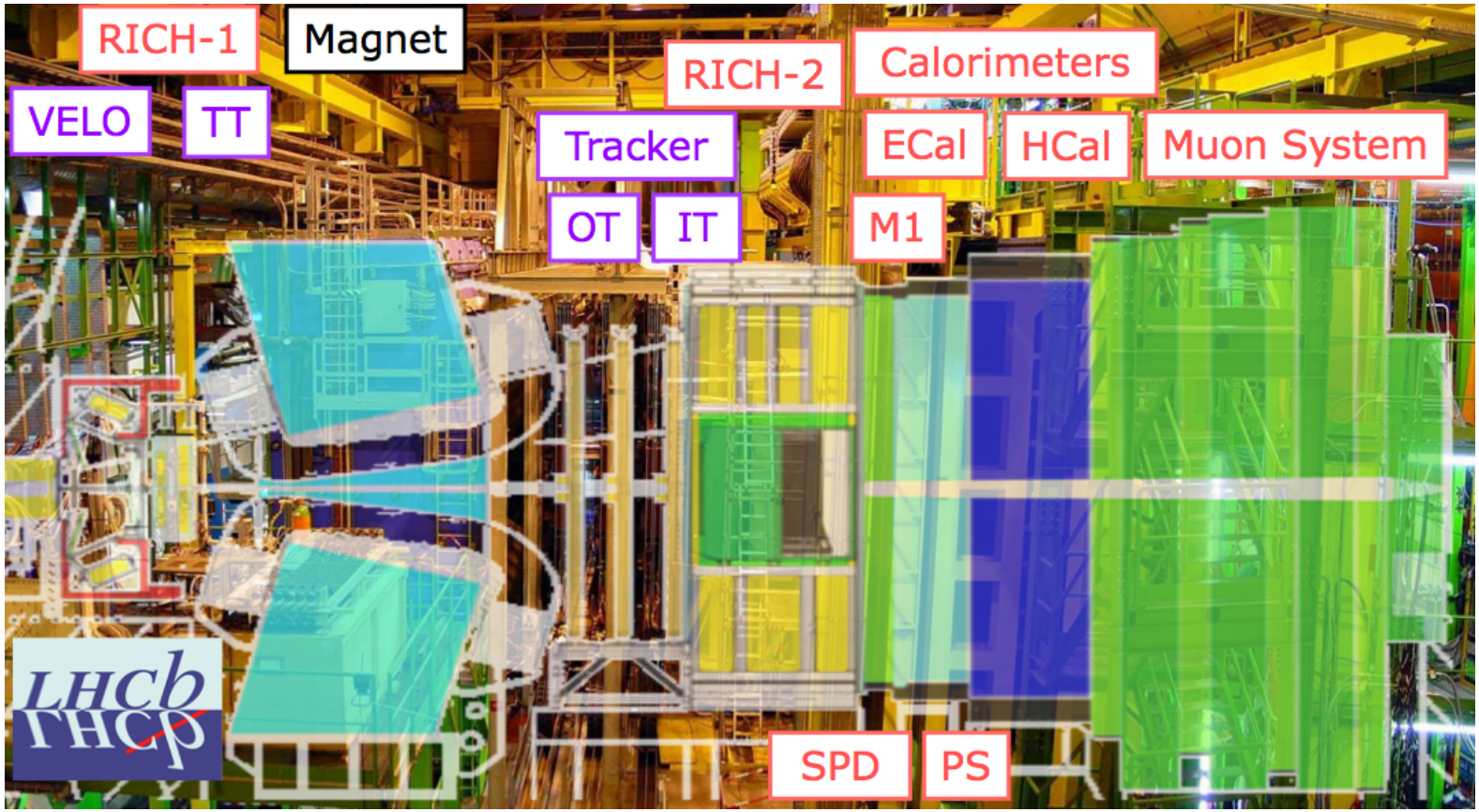


# LHCb detector

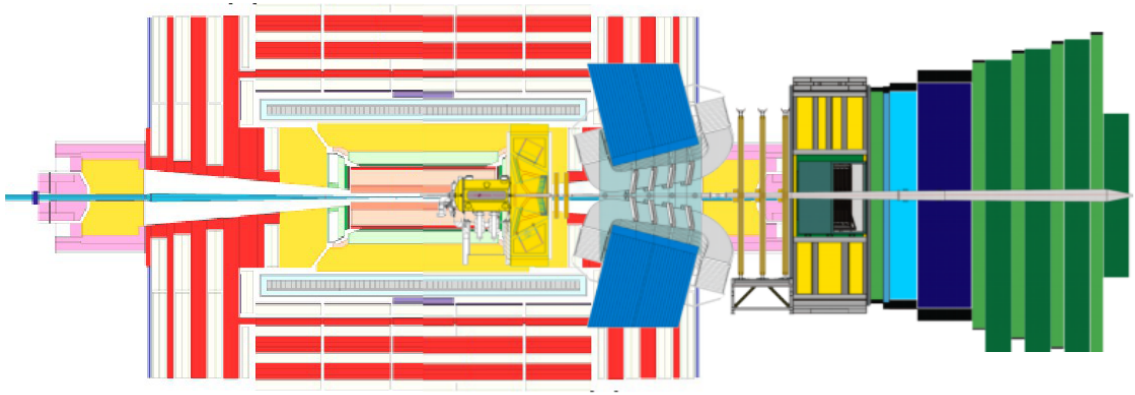
- LHCb is a single-arm spectrometer with forward angular coverage from 10 mrad to 300 (250) mrad in the bending (non-bending) plane

- Initially conceived for *b*-physics, current physics goals have been widely extended

- LHCb strong points:
  - → PID
  - → Vertexing and IP
  - → Momentum and mass resolution
  - → Unique coverage in $\eta$!

- More details about LHCb: **plenary talk by Eduardo Rodrigues**!

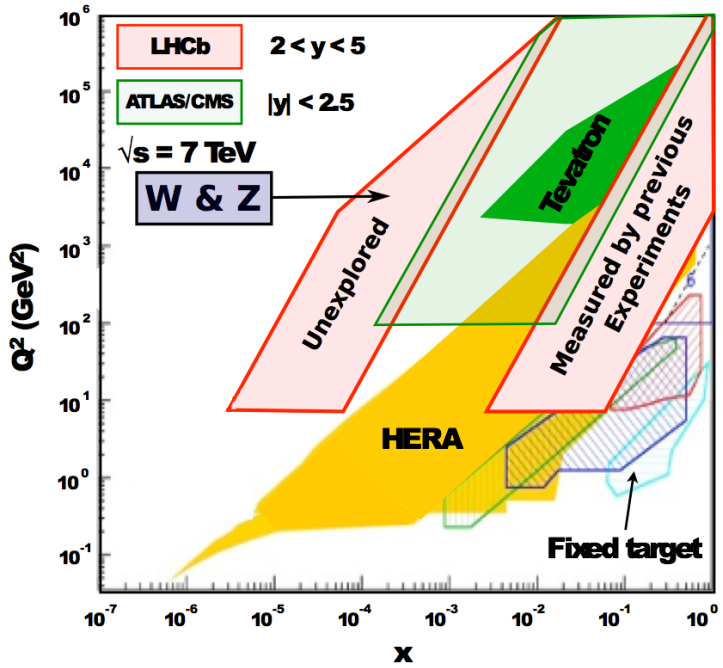
# LHCb complementarity



- LHCb can offer an unique coverage at the LHC
- However $b$ physics imposes dealing with lower luminosities
  - $\to$ 2010: 37 pb$^{-1}$ at $\sqrt{s} = 7$ TeV
  - $\to$ 2011: 1 fb$^{-1}$ at $\sqrt{s} = 7$ TeV
  - $\to$ 2012: 2 fb$^{-1}$ at $\sqrt{s} = 8$ TeV

# Measurements with electroweak gauge bosons

# New regions to probe




- LHCb EW production measurements probe two Bjorken $x - Q^2$ regions
  - $\rightarrow$ Low $x$, high $Q^2$ previously unexplored
  - $\rightarrow$ Overlap region allows direct ATLAS/CMS comparison

# Analyses produced at LHCb

- LHCb has measured the cross sections of Z and W using 2010 and 2011 datasets

  → $Z \to e^- e^-$ (2011 dataset):
  *JHEP* **1302** (2013) 106, [arXiv:1212.4620]

  → $Z \to \mu^+\mu^-$ (2011 dataset):
  *LHCb-CONF-2013-007*

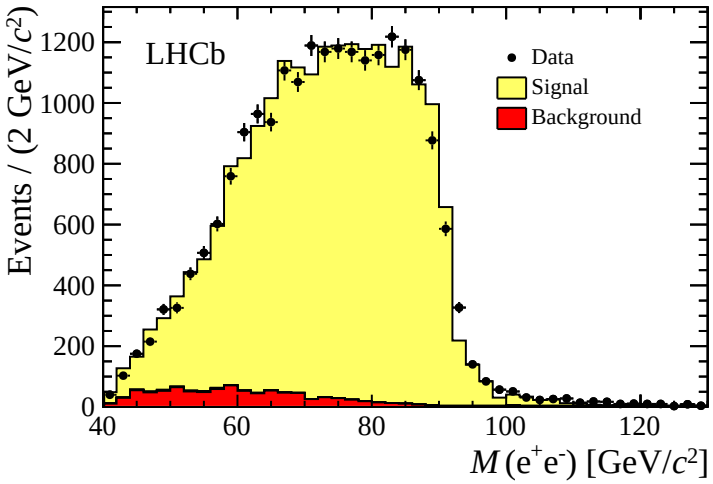
  → $Z \to \tau^+\tau^-$ (2011 dataset):
  *JHEP* **1301** (2013) 111, [arXiv:1210.6289]

  → $W \to \mu\nu_\mu$ (2010 dataset):
  *JHEP* **1206** (2012) 058, [arXiv:1204.1620]

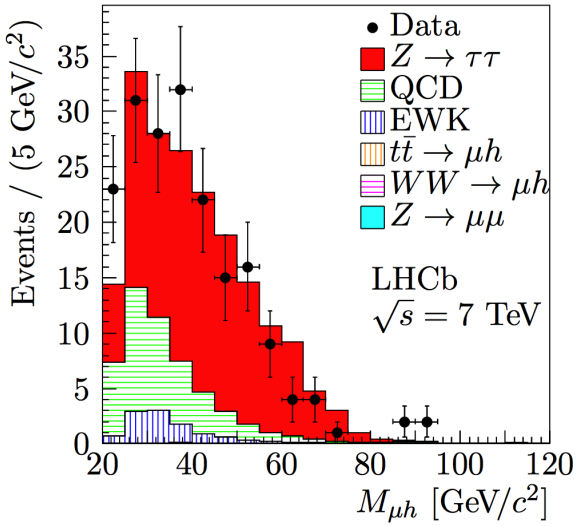
- We have also compared our cross sections to ATLAS and CMS:
  *LHCb-CONF-2013-005*

# Yields

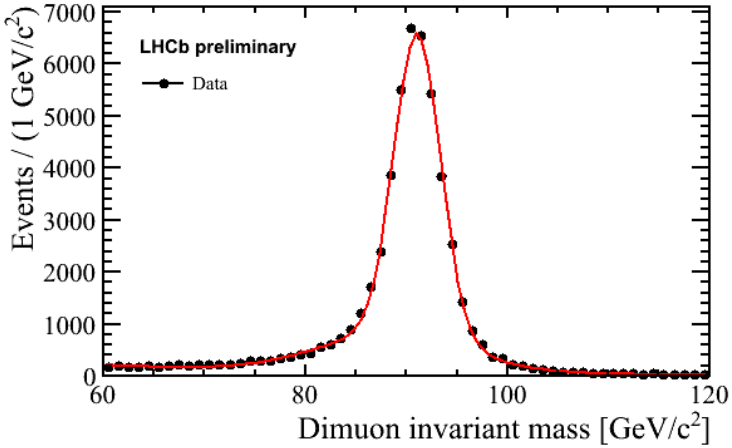
## $Z \to e^- e^-$



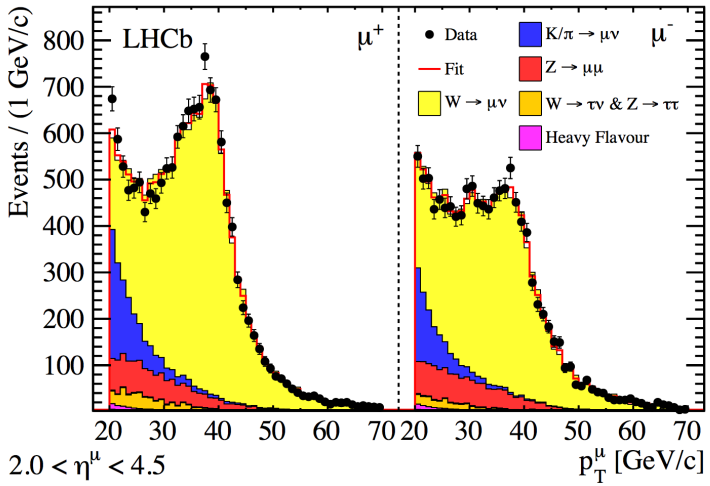

## $Z \to \tau^+\tau^-$ (example: $\mu h$ mode)




## $Z \to \mu^+\mu^-$

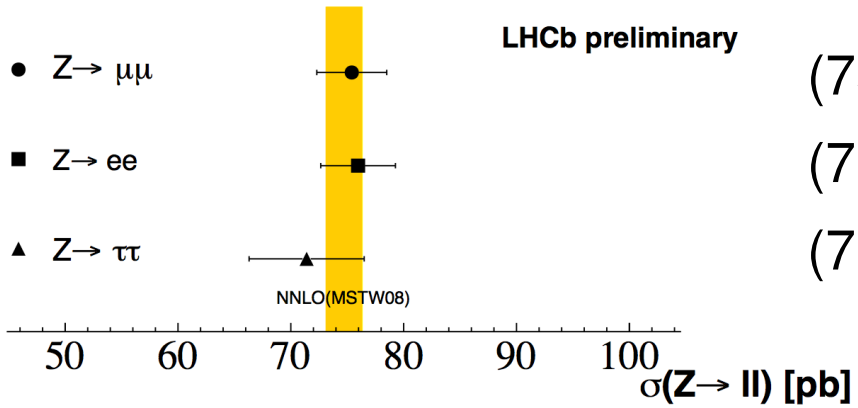



## $W \to \mu\nu_\mu$



# Z cross section

## Results agree with NNLO[a] and for all final states

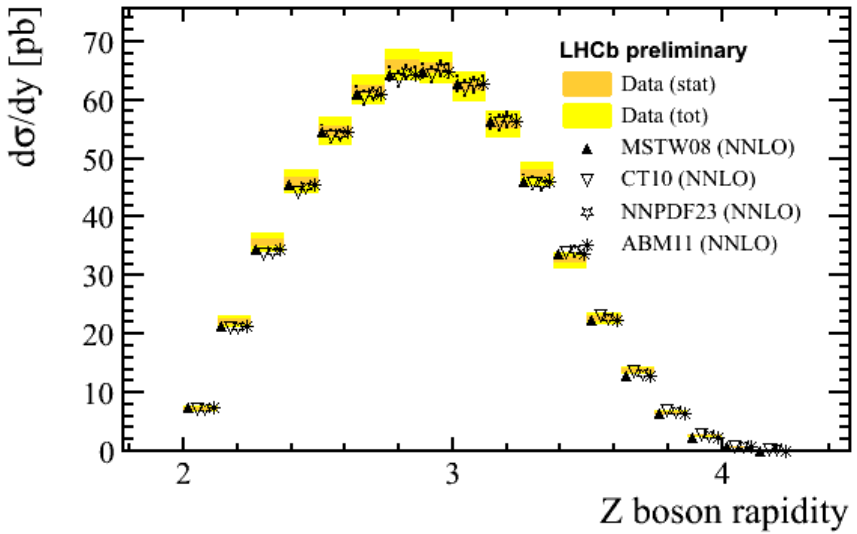



stat. – sys. – lumi.

$(75.4 \pm 0.3 \pm 1.9 \pm 2.6)$ pb

$(76.0 \pm 0.8 \pm 2.0 \pm 2.6)$ pb

$(71.4 \pm 3.5 \pm 2.8 \pm 2.5)$ pb

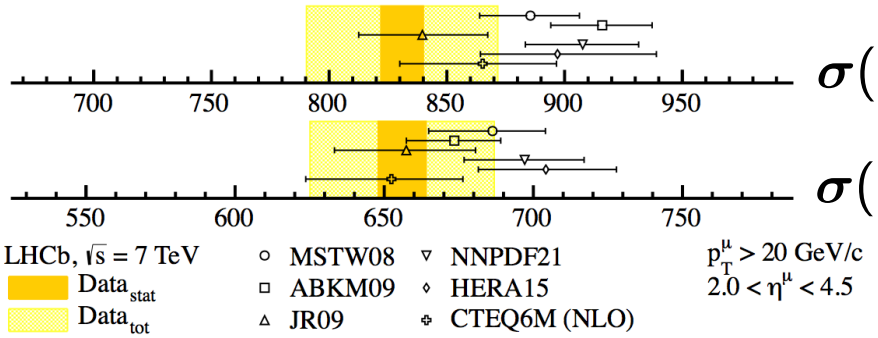



Agreement also as a function of $\eta^Z$ (from $Z \to \mu^+\mu^-$)

[a] Click here for theory references

# W cross section

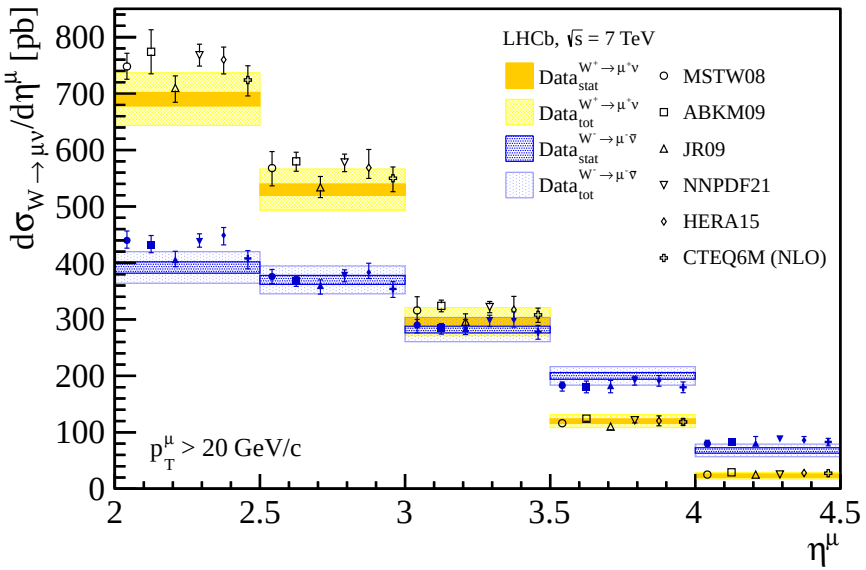
## Results also in agreement with NNLO[b]




stat. – sys. – lumi.

$\sigma(W^+)$ $(831 \pm 9 \pm 27 \pm 29)$ pb

$\sigma(W^-)$ $(656 \pm 8 \pm 19 \pm 23)$ pb

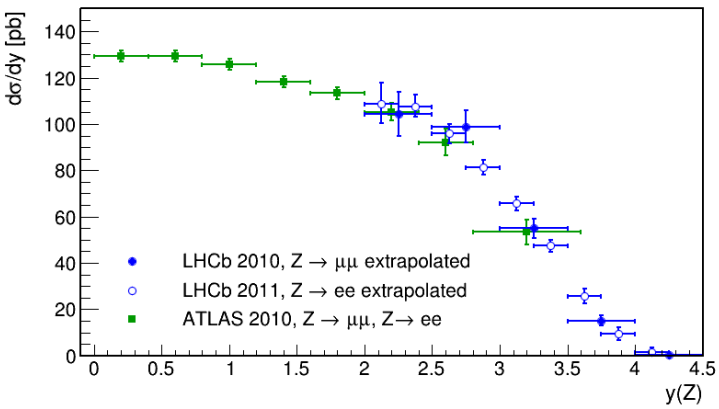



NNLO agreement as a function of $\eta^\mu$

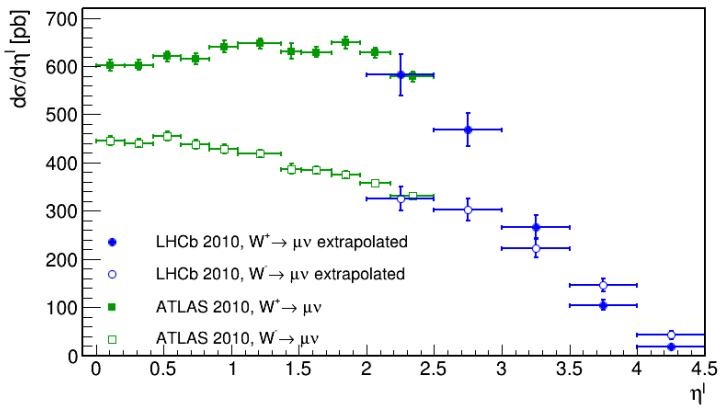
[b]Click here for theory references

# Comparison to ATLAS

- We have compared our differential cross sections to those of ATLAS in the overlapping region
  - $\rightarrow$ LHCb results extrapolated to the fiducial volume of the ATLAS measurements[c]




*Z*




*W*

Agreement as a function of $\eta$ is good

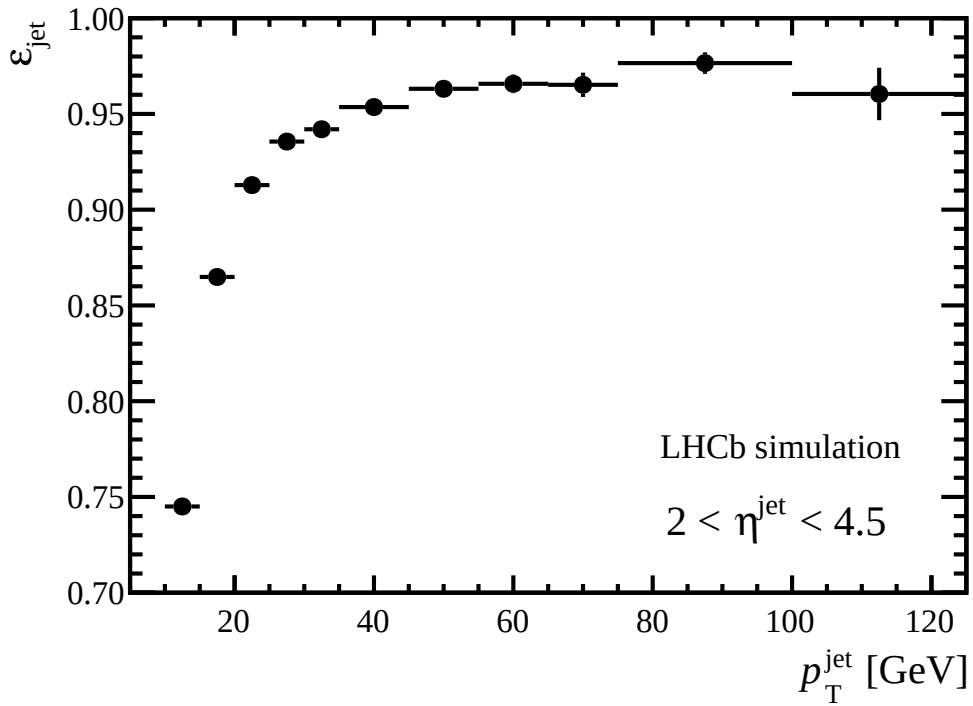
[c] Click here for the reference

# Z+jets overview

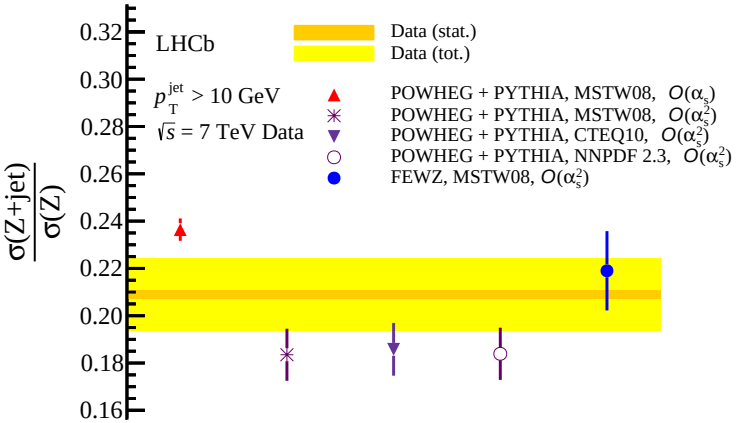
- Brand new paper, just submitted to JHEP, includes 2011 dataset:

  arXiv:1310.8197

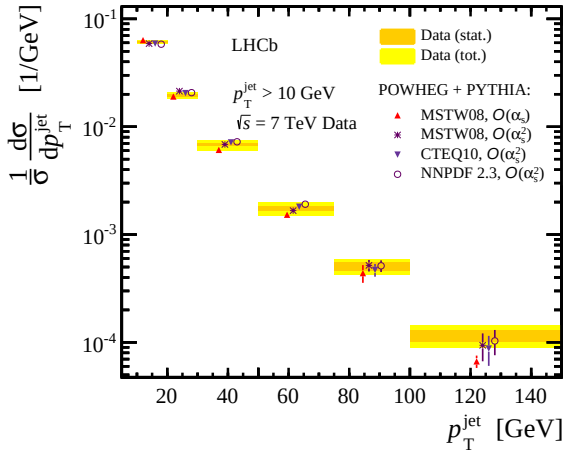
- $Z$ reconstructed in $\mu^+\mu^-$ mode
- Nice test of LHCb capabilities with jets
  - → Use of *anti-kt* algorithm with R=0.5
  - → Jet reconstruction efficiency reasonably high:



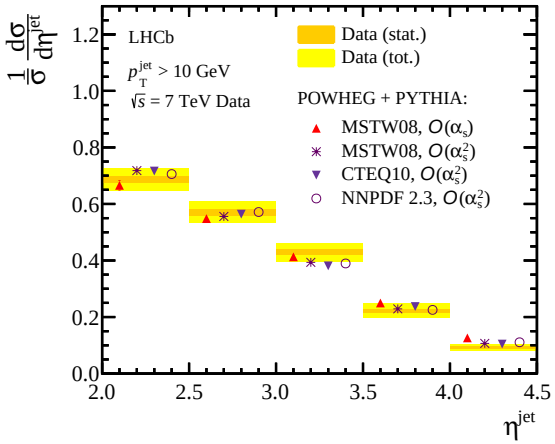
# Z+jets cross section results




$Z$+jets cross section normalized to $Z$ cross section vs. different theory[d] predictions




Cross section as a function of the jet $p_T$




Cross section as a function of the jet $\eta$

[d] Click here for theory references

# Searches for Higgs-like particles at LHCb

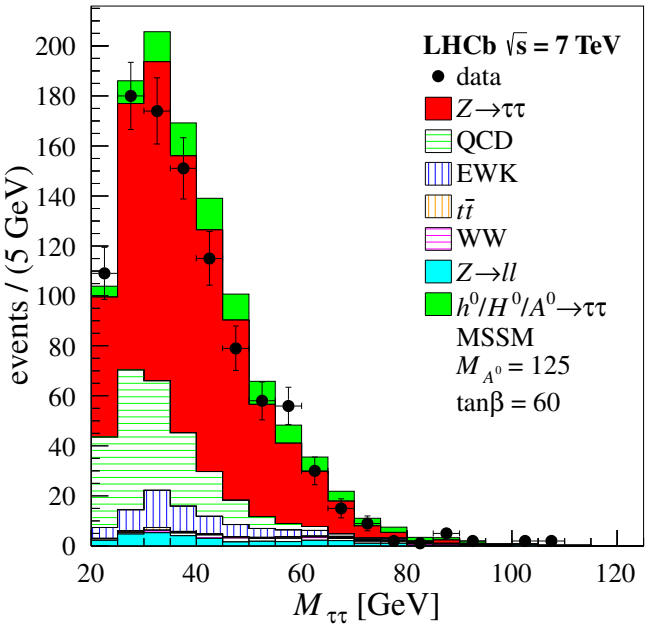
# Limits on $H^0 \to \tau^+\tau^-$: Analysis overview

- First LHCb paper on search for neutral Higgs in the forward direction

  *JHEP* **1305** (2013) 132, [arXiv:1304.2591]

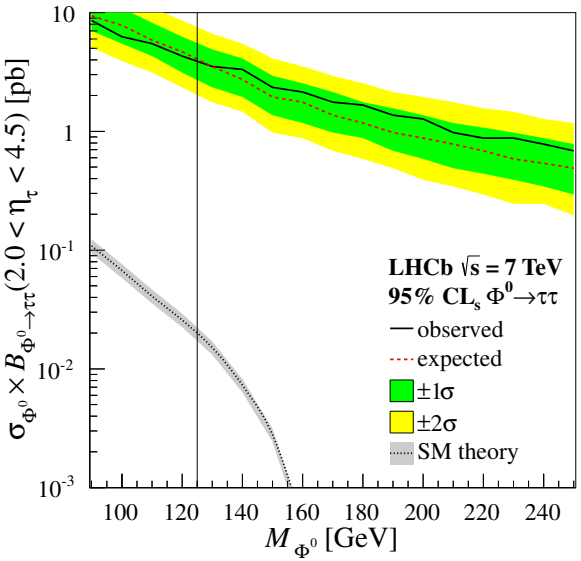
- Using 2011 dataset Search using different $\tau$ decay modes: $\tau_\mu\tau_\mu$, $\tau_\mu\tau_e$, $\tau_e\tau_\mu$, $\tau_\mu\tau_h$, $\tau_e\tau_h$
- Discrimination based on having isolated leptons, lifetime of the $\tau$ and back-to-back objects

Yields using all samples combined

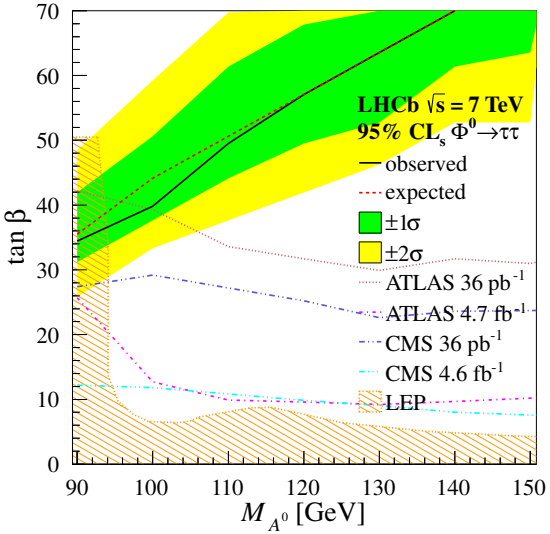


# Limits on $H^0 \to \tau^+\tau^-$

- No excess found $\to$ limits set for both in a model independent way (as a function of $m_H$) and in one particular realization of MSSM
  - $\to$ Limits set using $CL_S$ method at 95% CL




Model independent limit in terms of $\sigma_H \times BR(H \to \tau^+\tau^-)$[e]




MSSM limit compared to ATLAS, CMS and LEP in the $m(h^0)_{max}$ scenario[e]

[e] Click here for theory references

# $H^0$ decays to long-lived particles

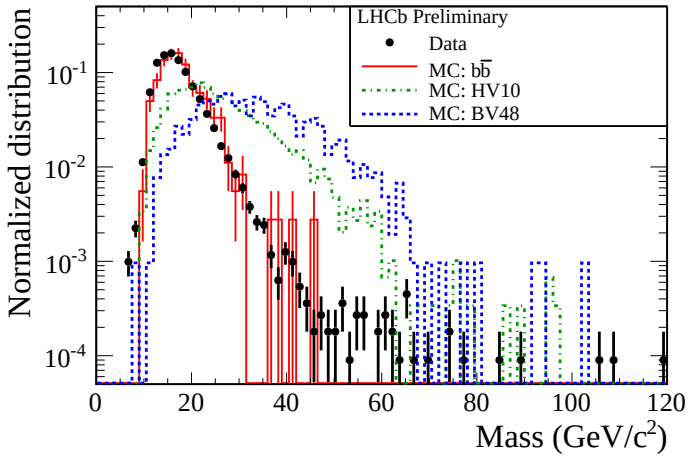
- Search for Higgs decaying to Long Lived massive Particles (LLP), predicted by many BSM theories, using 2010 LHCb dataset *LHCb-CONF-2012-014*

→ SUSY with RPV through Baryon number Violation (BV)[f]

- $h^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0$, with $\tilde{\chi}_1^0$ neutralino long-lived, $\tilde{\chi}_1^0 \to$ 3 quarks

→ Some Hidden Valley models (HV)[f]

- $h^0 \to \pi_V^0\pi_V^0 \to$4 displaced $b$ quarks




→ No excess above $b\bar{b}$ (main source of background)

→ Limits set in different regions of the BSM models phase space

→ Complementary searches by ATLAS and CMS[f]

[f]Click here for references

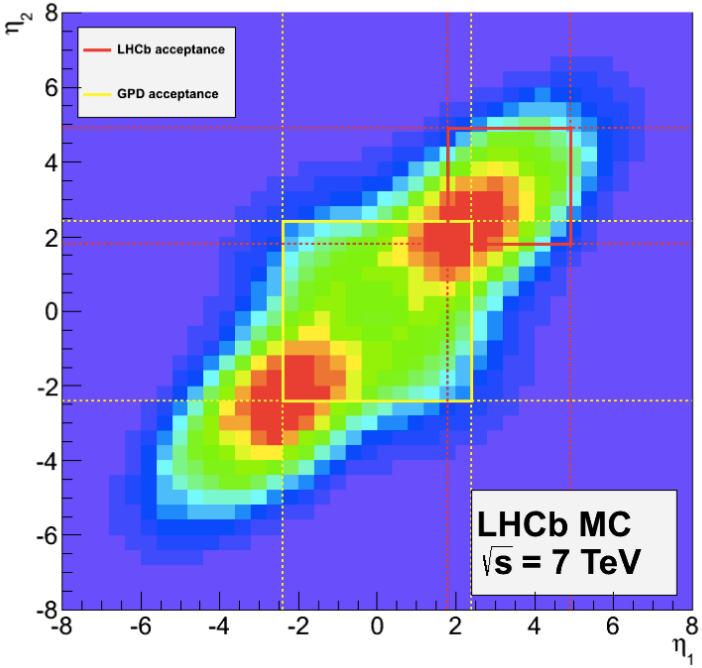
# Towards $H^0 \to b\bar{b}$

- LHCb is also on its way to perform a search for $H^0 \to b\bar{b}$

→ Interest: Higgs coupling to fermions!

→ Probability to have both $b$ quarks in LHCb acceptance: ∼5% at 7 TeV

→ Our jet reconstruction has been tested to work successfully. Work ongoing for $b$-jet tagging.




- Benchmark analyses done:
  - → Measurement of the central forward $b\bar{b}$ asymmetry *LHCb-CONF-2013-001*
  - → Measurement of $\sigma(b\bar{b})$ with inclusive final states *LHCb-CONF-2013-002*

# $A_{FC}$ in $b\bar{b}$

- Result using 2011 LHCb dataset
- Related to $t\bar{t}$ asymmetry from Tevatron:

$$A_{FC}^{b\bar{b}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \qquad \Delta y = |y_b| - |y_{\bar{b}}|$$

$\to$ Results found are consistent with SM[g]

$\to$ Asymmetry is not significant, although points to be larger at higher $b\bar{b}$ invariant mass[h] (where new effects could be expected)

$$A_{FC}^{b\bar{b}} = [0.5 \pm 0.5\ (\text{stat}) \pm 0.5\ (\text{syst})]\%$$

$$A_{FC}^{b\bar{b}}(M_{b\bar{b}} > 100\ \text{GeV/c}^2) = [4.3 \pm 1.7\ (\text{stat}) \pm 2.4\ (\text{syst})]\%$$

[g] Click here for theory references

[h] Mass unfolding yet to be done

# Conclusions

# Conclusions

- LHCb has been shown to be competitive also in measurements not directly related to flavour
- We offer an unique phase-space coverage

  $\to$ Results in EW physics
  - Cross sections measured for $Z$ and $W$ in different decay modes
  - Brand new measurement in $Z$+jets

  $\to$ Also, searches for Higgs-like particles in the forward direction
  - First LHCb paper on Higgs searches: $H^0 \to \tau^+\tau^-$
  - Advantage reconstructing long lived particles
  - Progress towards $H^0 \to b\bar{b}$

# Thanks!

# Backup

# Z and W production references

- Z and W
  - → MSTW08: *Eur.Phys.J.* **C63** (2009) 189–285, [arXiv:0901.0002]
  - → ABKM09: *Phys.Rev.* **D81** (2010) 014032, [arXiv:0908.2766]
  - → JR09: *PoS* **DIS2010** (2010) 038, [arXiv:1006.5890]
  - → NNPDF: *Nucl.Phys.* **B867** (2013) 244–289, [arXiv:1207.1303]
  - → HERA15: **H1 and ZEUS Collaboration** Collaboration *JHEP* **1001** (2010) 109, [arXiv:0911.0884]
  - → CTEQ6m: *Phys.Rev.* **D78** (2008) 013004, [arXiv:0802.0007]
  - → DYNNLO: *Phys.Rev.Lett.* **103** (2009) 082001, [arXiv:0903.2120]
  - → FEWZ: *Comput.Phys.Commun.* **182** (2011) 2388–2403, [arXiv:1011.3540]

# Z and W production references

- Z and W
  - → POWHEG: *JHEP* **1101** (2011) 095, [arXiv:1009.5594]
  - → PYTHIA: *JHEP* **0605** (2006) 026, [hep-ph/0603175]
  - → RESBOS 1: *Phys.Rev.* **D50** (1994) 4239, [hep-ph/9311341]
  - → RESBOS 2: *Phys.Rev.* **D56** (1997) 5558–5583, [hep-ph/9704258]
  - → RESBOS 3: *Phys.Rev.* **D67** (2003) 073016, [hep-ph/0212159]
- ATLAS paper for comparison:
  - → *Phys.Rev.* **D85** (2012) 072004, [arXiv:1109.5141]

# Z+jet production references

- Z+jets
  - → POWHEG: *JHEP* **1101** (2011) 095, [arXiv:1009.5594]
  - → PYTHIA: *JHEP* **0605** (2006) 026, [hep-ph/0603175]
  - → MSTW08: *Eur.Phys.J.* **C63** (2009) 189–285, [arXiv:0901.0002]
  - → CTEQ10: *Phys.Rev.* **D82** (2010) 074024, [arXiv:1007.2241]
  - → NNPDF: *Nucl.Phys.* **B867** (2013) 244–289, [arXiv:1207.1303]
  - → FEWZ: *Comput.Phys.Commun.* **182** (2011) 2388–2403, [arXiv:1011.3540]

# $H^0 \to \tau^+\tau^-$ references

- SM prediction
  - → hep-ph/9510347
  - → *Comput.Phys.Commun.* **124** (2000) 76–89, [hep-ph/9812320]
- $m(h^0)_{max}$ scenario: *Eur.Phys.J.* **C26** (2003) 601–607, [hep-ph/0202167]
- ATLAS on $H \to \tau^+\tau^-$:
  - → *Phys.Lett.* **B705** (2011) 174–192, [arXiv:1107.5003]
  - → *JHEP* **1302** (2013) 095, [arXiv:1211.6956]
- CMS on $H \to \tau^+\tau^-$:
  - → *Phys.Rev.Lett.* **106** (2011) 231801, [arXiv:1104.1619]
  - → *Phys.Lett.* **B713** (2012) 68–90, [arXiv:1202.4083]
- LEP on $H \to \tau^+\tau^-$: *Eur.Phys.J.* **C47** (2006) 547–587, [hep-ex/0602042]

# Other Higgs references

- $H \rightarrow LLP$
  - → BV model: *Phys.Rev.Lett.* **99** (2007) 211801, [hep-ph/0607204]
  - → HV model: *Phys.Lett.* **B651** (2007) 374–379, [hep-ph/0604261]
  - → Complementary search by ATLAS: *Phys.Rev.Lett.* **108** (2012) 251801, [arXiv:1203.1303]
  - → Complementary search by CMS: *CMS-PAS-EXO-12-038*
- SM Predictions for $A_{FC}^{b\bar{b}}$
  - → *Phys.Rev.* **D59** (1999) 054017, [hep-ph/9807420]
  - → *JHEP* **1201** (2012) 069, [arXiv:1108.3301]
  - → *Phys.Rev.Lett.* **111** (2013) 062003, [arXiv:1302.6995]

# How we measure the cross sections

$$\sigma = \frac{\rho \times N \times f_{FSR}}{\epsilon \times \mathcal{A} \times \mathcal{L}}$$

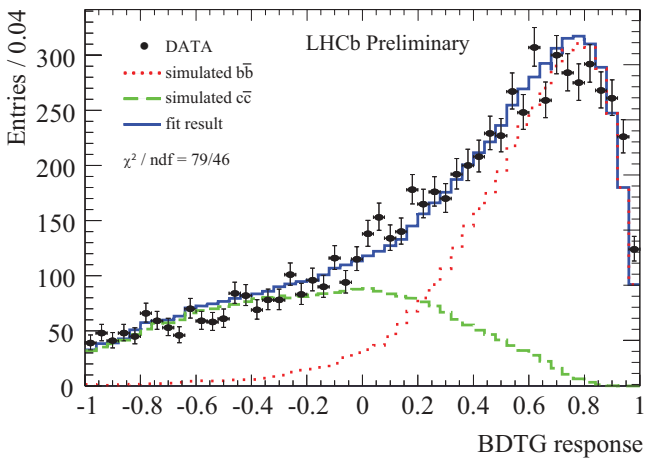
- $N$: Number of observed candidates
- From simulation
  - $\rightarrow$ $f_{FSR}$: final state radiation correction
  - $\rightarrow$ $\mathcal{A}$: acceptance
- Data driven
  - $\rightarrow$ $\rho$: purity
  - $\rightarrow$ $\epsilon$: efficiency
  - $\rightarrow$ $\mathcal{L}$: integrated luminosity

# ATLAS, CMS and LHCb on $H^0 \rightarrow$LLP

- ATLAS and CMS: Two triggering approach
  - $\rightarrow$ Displaced vertex object dedicated trigger ATLAS $\rightarrow$ sensitivity to low masses not to low proper time ($c\tau_{min} \sim 1$ m) *Phys.Rev.Lett.* **108** (2012) 251801, [arXiv:1203.1303]
  - $\rightarrow$ Inclusive jet trigger in CMS $\rightarrow$ sensitivity to low proper time not to low masses *CMS-PAS-EXO-12-038*
- Displaced vertex object dedicated trigger at LHCb
  - $\rightarrow$ Region of sensitivity $\rightarrow$ complementary to GPDs: low mass ($20 < \pi^0_V < 50$ GeV/$c^2$) and low proper time ($c\tau \sim$ O cm)
  - $\rightarrow$ Trigger strategy for semi-leptonic and fully leptonic decay of LLP in place too.

# Measurement of $\sigma(b\bar{b})$ with inclusive final states

- Measurement with a fraction of 2010 data
- Use of $b$ seeding technique




$\rightarrow$ Measurement of cross sections done with a fit of the shape of a multivariate discriminant, built to isolate $b\bar{b}$ from $c\bar{c}$ events (shapes from simulation)

- Results for $2.5 < \eta < 4$ and $p_T > 5$ GeV/$c$:

$$\sigma(b\bar{b}) = [7.7 \pm 0.1\ (\text{stat}) \pm 0.8\ (\text{syst})]\ \text{pb}$$
$$\sigma(c\bar{c}) = [104.6 \pm 2.7\ (\text{stat}) \pm 11.4\ (\text{syst})]\ \text{pb}$$

# Summary of systematics and backgrounds

| **Channel** | **Dominant background** | **Main systematics** |
|---|---|---|
| $Z \to e^- e^-$ | Had. misID | $\mathcal{L}$ |
| $Z \to \mu^+ \mu^-$ | H. flavour | $\mathcal{L}$ |
| $Z \to \tau^+ \tau^-$ | QCD | $\mathcal{L}$ |
| $W \to \mu \nu_\mu$ | Had. misID<br>$Z \to \mu^+ \mu^-$ | $\mathcal{L}$ |
| $Z+$ jets | H. flavour | Jet-energy scale, resolution and rec. |
| $H^0 \to \tau^+ \tau^-$ | $Z \to \tau^+ \tau^-$ | Exp. bkg. |
| $H^0 \to$ LLP | $b\bar{b}$ | $\epsilon^{TRIGGER}$ |
| $A_{FB}^{b\bar{b}}$ | – | Flav. tagging |
| $\sigma(b\bar{b})$ | $c\bar{c}$ | Simulation sample size |