Electroweak, top and exotics physics at LHCb: present and future

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on behalf of the LHCb collaboration

Flavor and top physics @ 100 TeV workshop

March 6th, 2015

Outline

Introduction to LHCb

Electroweak physics

- Z and W production at LHCb
- Z+X

Exotics physics

- Limits on $H^0 \rightarrow \tau^+\tau^-$ production
- H^0 decays to long-lived particles
- A_C in $b\bar{b}$

Future

- Prospects on EW
- How about top?
- Towards $H^0 \rightarrow b\bar{b}$

Conclusions

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 [equivalent to 2$< \eta <$5]

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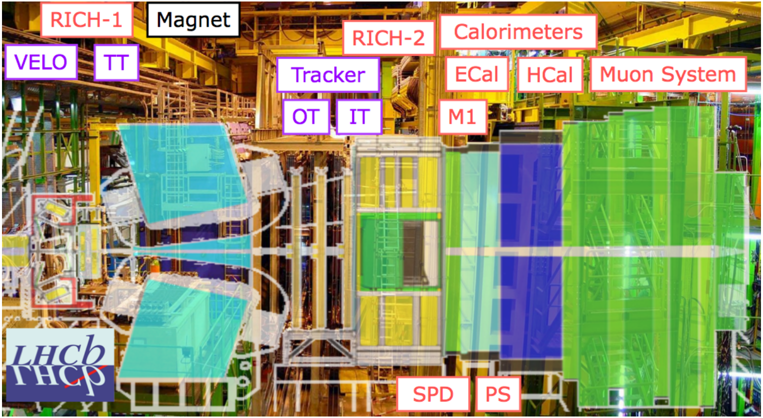

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LHCb detector

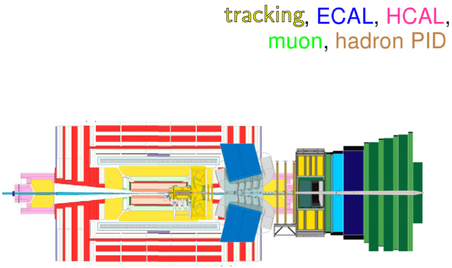
- LHCb is a single-arm spectrometer with forward angular coverage from 10 mrad to 300 (250) mrad in the bending (non-bending) plane [equivalent to 2$< \eta <$5]

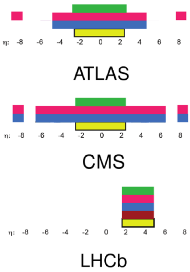
- Initially conceived for *b*-physics, current physics goals have been widely extended

- LHCb strong points:
  - $\to$ Particle identification (including K/π separation)
  - $\to$ Vertexing and IP
  - $\to$ Momentum and mass resolution
  - $\to$ Unique coverage in η!

- More details about LHCb (and its upgrade): see talks by **V. Vagnoni** and **M. Gersabeck**!

LHCb complementarity



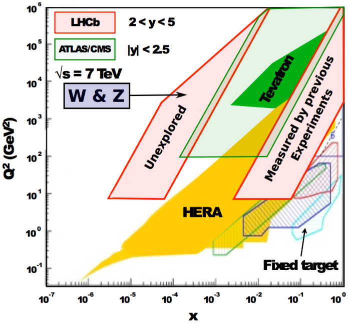


η coverage

- LHCb can offer unique coverage at the LHC
- However b physics imposes dealing with lower luminosities
  - $\rightarrow$ 2010: 37 pb^{-1} at $\sqrt{s} = 7$ TeV
  - $\rightarrow$ 2011: 1 fb^{-1} at $\sqrt{s} = 7$ TeV
  - $\rightarrow$ 2012: 2 fb^{-1} at $\sqrt{s} = 8$ TeV
- As a benefit, very stable conditions in terms of trigger/luminosity (luminosity leveling)

Electroweak physics

New regions to probe



where

x	parton longitudinal momentum fraction
Q^2	momentum transfer

- LHCb EW production measurements probe two Bjorken $x - Q^2$ regions
  - $\rightarrow$ Low x, high Q^2 previously unexplored
  - $\rightarrow$ LHCb produces W/Z by collisions between low-x and high-x partons
  - $\rightarrow$ Overlap region allows direct ATLAS/CMS comparison

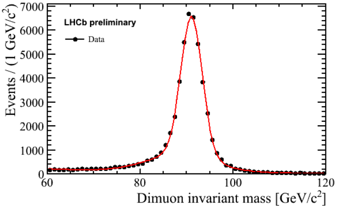
Z/W cross sections analyses

- LHCb has measured the cross sections of Z and W using 2010, 2011 and 2012 datasets
  - → Z and W, μ decays (2010):
    7 TeV *JHEP* **1206** (2012) 058, [arXiv:1204.1620]
  - → $Z \to e^+e^-$:
    7 TeV *JHEP* **1302** (2013) 106, [arXiv:1212.4620]
    8 TeV arXiv:1503.0963 (submitted to JHEP)
  - → $Z \to \mu^+\mu^-$:
    LHCb-CONF-2013-007
  - → $Z \to \tau^+\tau^-$:
    JHEP **1301** (2013) 111, [arXiv:1210.6289]
  - → $W \to \mu\nu_\mu$:
    JHEP **1412** (2014) 079, [arXiv:1408.4354]

Yields

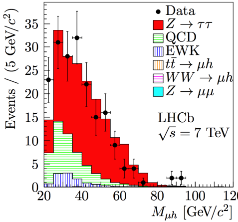
$Z \to \mu^+\mu^-$

LHCb-CONF-2013-007



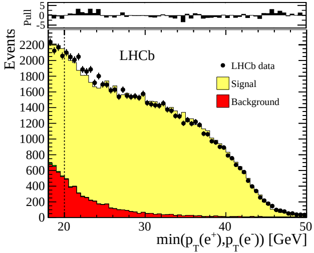
$Z \to \tau^+\tau^-$ (example: μh mode)

JHEP **1301** (2013) 111, [arXiv:1210.6289]



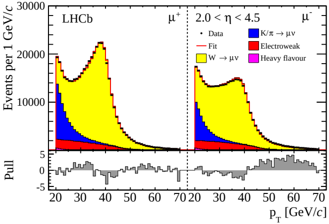
$Z \to e^+e^-$

8 TeV, arXiv:1503.0963 (submitted to JHEP)



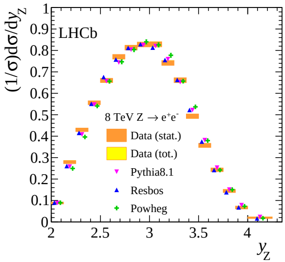
$W \to \mu\nu_\mu$

JHEP **1412** (2014) 079, [arXiv:1408.4354]



Z cross section

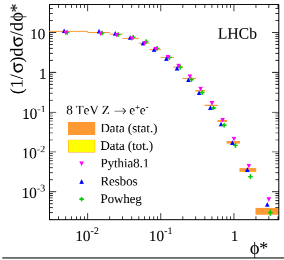
Results agree with NNLO[a] and for all final states. Examples from $Z \to e^+e^-$ at 8 TeV, arXiv:1503.0963



Agreement as a function of η^Z

$*$ different NNLO PDF sets shown

$*$ e^- and e^+ should satisfy $2.0 < \eta < 4.5$; $p_T > 20\ \mathrm{GeV}/c$; $60 < m_{e^+e^-} < 120\ \mathrm{GeV}/c^2$



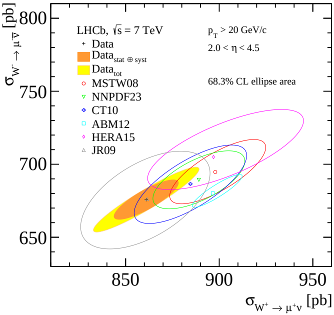
and also as a function of Φ^*

[a] Click here for theory references

W cross section

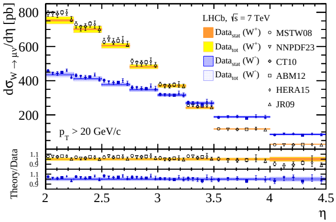
Results also in agreement with NNLO[b]

JHEP **1412** (2014) 079, [arXiv:1408.4354]



	stat. – sys. – lumi.
$\sigma(W^+)$	$(861.0 \pm 2.0 \pm 11.2 \pm 14.7)$ pb
$\sigma(W^-)$	$(675.8 \pm 1.9 \pm 8.8 \pm 11.6)$ pb

- $*$ different NNLO PDF sets shown
- $*$ μ should satisfy $2.0 < \eta < 4.5$ and $p_T > 20$ GeV/c



NNLO agreement as a function of η^μ

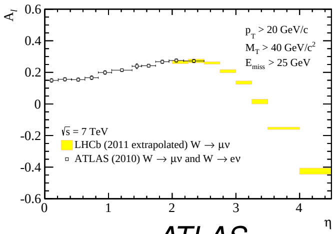
[b] Click here for theory references

W: comparison to ATLAS and CMS

- We have compared our differential cross sections to those of ATLAS/CMS in the overlapping region with 2010 and 2011 datasets
  - $\rightarrow$ LHCb charge asymmetry results extrapolated to the fiducial volume of the ATLAS/CMS measurements
  - $\rightarrow$ Results in term of charge asymmetry:

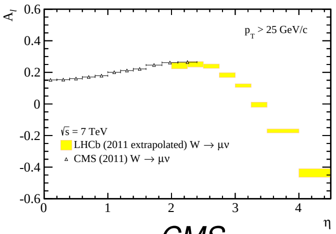
$$A_l = \frac{\mathrm{d}\sigma/\mathrm{d}\eta(W^+ \rightarrow l^+\nu) - \mathrm{d}\sigma/\mathrm{d}\eta(W^- \rightarrow l^-\bar{\nu})}{\mathrm{d}\sigma/\mathrm{d}\eta(W^+ \rightarrow l^+\nu) + \mathrm{d}\sigma/\mathrm{d}\eta(W^- \rightarrow l^-\bar{\nu})}$$

JHEP **1412** (2014) 079, [arXiv:1408.4354]



ATLAS

Phys.Rev. **D85** (2012) 072004, [arXiv:1109.5141]



CMS

Phys.Rev. **D90** (2014), no. 3 032004, [arXiv:1312.6283]

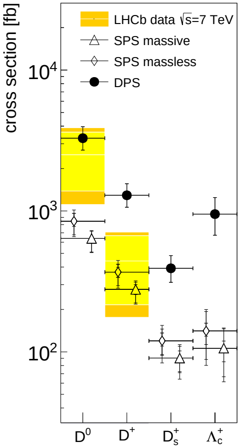
Agreement as a function of η is good

Z+X analyses

- LHCb has measured the cross sections of associated Z production also using 2011 dataset.
- Z reconstructed in $\mu^+\mu^-$ mode in all cases

- $Z+$ D mesons:
  - $\rightarrow$ *JHEP* **1404** (2014) 091, [arXiv:1401.3245]
- $Z+$ jets:
  - $\rightarrow$ *JHEP* **1401** (2014) 033, [arXiv:1310.8197]
- $Z+b$ jets:
  - $\rightarrow$ *JHEP* **1501** (2015) 064, [arXiv:1411.1264]

Results: Z+D



$Z+$ D meson cross section vs. different theory[c] contributions

JHEP **1404** (2014) 091, [arXiv:1401.3245]

Interesting to address the charm parton distribution inside the proton and the charm production mechanism: single- (SPS) and double-parton scattering (DPS)

D decay modes used:

$D \to K^-\pi^+$

$D^+ \to K^-\pi^+\pi^+$

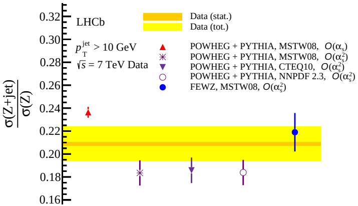
DPS dominates, while SPS negligible. Big uncertainty for now, will be very interesting in the future.

$*$ μ^- and μ^+ should satisfy $2.0 < \eta < 4.5$; $p_T > 20$ GeV/c; $60 < m_{\mu^+\mu^-} < 120$ GeV/c^2

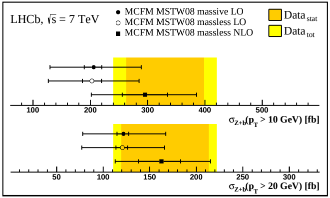
Standard cuts for D selection

[c]Click here for theory references

Z+ (b) jets



Z+jets cross section normalized to Z cross section



$Z + b$ jets cross section

Z+jets
JHEP **1401** (2014) 033, [arXiv:1310.8197]

Z+ b jets
JHEP **1501** (2015) 064, [arXiv:1411.1264]

Both results are a nice test of LHCb potential with jets, use of *anti-kt* algorithm with $R = 0.5$

For Z+b, normalization to $Z+$ jets, show jet $b-$tagging capabilities

Results compatible with different NNLO PDF sets shown[d]

$*$ μ^- and μ^+ should satisfy $2.0 < \eta < 4.5$; $p_T > 20$ GeV$/c$; $60 < m_{\mu^+\mu^-} < 120$ GeV$/c^2$

Different p_T cuts for the (b) jets (starting at 10 GeV$/c$). Also $\Delta R(\mu, jet) > 0.4$

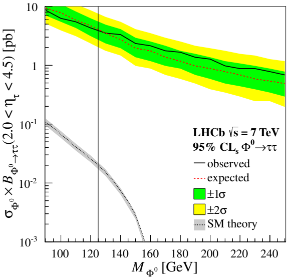
[d]Click here for theory references

Exotics physics

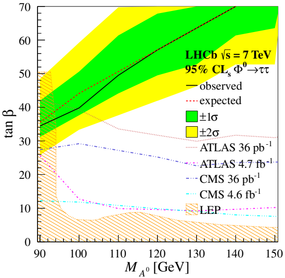
Limits on $H^0 \to \tau^+\tau^-$

- First LHCb paper on search for neutral Higgs in the forward direction *JHEP* **1305** (2013) 132, [arXiv:1304.2591]
- 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 $\mathrm{CL_S}$ 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: Overview

- Search for Higgs decaying to Long Lived massive Particles, predicted by many BSM theories, using 0.62 fb^{-1} of 2011 LHCb dataset

arXiv:1412.3021 (submitted to Eur. Phys. J. C)

- Examples of theory models predicting such particles:

→ SUSY models with Baryon number Violation (BV)

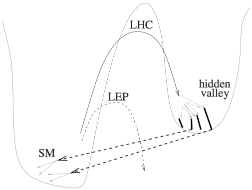
- $h^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0$, with $\tilde{\chi}_1^0$ neutralino long-lived, $\tilde{\chi}_1^0 \to$ 3 quarks

Phys.Rev.Lett. **99** (2007) 211801, [hep-ph/0607204]

→ Some Hidden Valley (HV) models

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

Phys.Lett. **B651** (2007) 374–379, [hep-ph/0604261]



H^0 decays to long-lived particles: LHCb analysis

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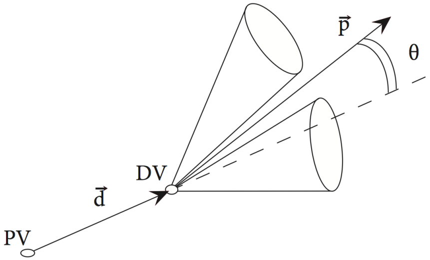
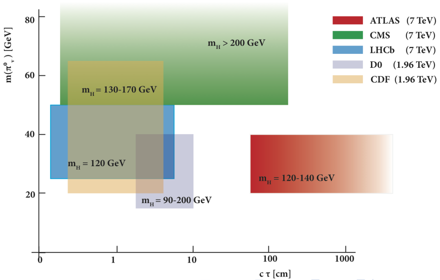
Experimental signature: displaced vertex with two associated jets. LHCb advantage thanks to Particle Identification, vertexing...



Important LHCb contribution, e.g., for HV models LHCb can look into a complementary phase space region with respect to ATLAS/CMS in terms of π^0_V lifetime and mass.



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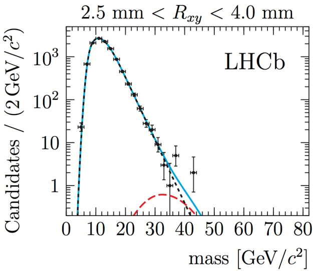
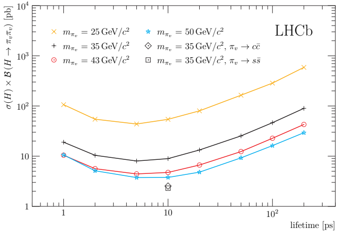
H^0 decays to long-lived particles: Results

arXiv:1412.3021 (submitted to Eur. Phys. J. C)



No excess above $b\bar{b}$ (main source of background). Example from one of the fits to different radial distances



Limits set in different regions of the BSM models phase space

- Complementary searches by ATLAS and CMS

ATLAS: *Phys.Rev.Lett.* **108** (2012) 251801, [arXiv:1203.1303]
CMS: *CMS-PAS-EXO-12-038*

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A_C in $b\bar{b}$: Overview

- Measurement of $b\bar{b}$ charge asymmetry (A_C) using 2011 LHCb dataset

Phys.Rev.Lett. **113** (2014), no. 8 082003, [arXiv:1406.4789]

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

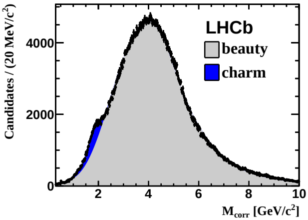
- Related to $t\bar{t}$ asymmetry from Tevatron, so that models to explain it predict also large A_C in $b\bar{b}$

JHEP **1201** (2012) 069, [arXiv:1108.3301]
Phys.Rev.Lett. **111** (2013) 062003, [arXiv:1302.6995]

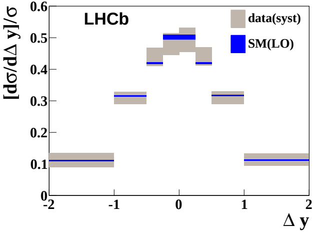
- Strategy:
  - $\rightarrow$ Reconstruct the $b\bar{b}$ as a pair of jets
  - $\rightarrow$ Use b-tagging to select jets and muon from semi-leptonic decays to determine their charge
  - $\rightarrow$ Measure asymmetry in bins of $M_{b\bar{b}}$

A_C in $b\bar{b}$: Results

Phys.Rev.Lett. **113** (2014), no. 8 082003, [arXiv:1406.4789]



Corrected mass distribution



Corrected Δy distribution, L0 SM from PYTHIA
JHEP **0605** (2006) 026, [hep-ph/0603175]

- Results in different mass regions (in GeV/c^2)

$$A_C^{b\bar{b}}(40,75) = 0.4 \pm 0.4(\mathrm{stat}) \pm 0.3(\mathrm{syst})\%$$
$$A_C^{b\bar{b}}(75,105) = 2.0 \pm 0.9(\mathrm{stat}) \pm 0.6(\mathrm{syst})\%$$
$$A_C^{b\bar{b}}(>105) = 1.6 \pm 1.7(\mathrm{stat}) \pm 0.6(\mathrm{syst})\%$$

$\rightarrow$ Asymmetry is not significant and the results found are consistent with SM (expected to be $O(1\%)$ from QCD with an extra $O(1\%)$ in the Z mass region)

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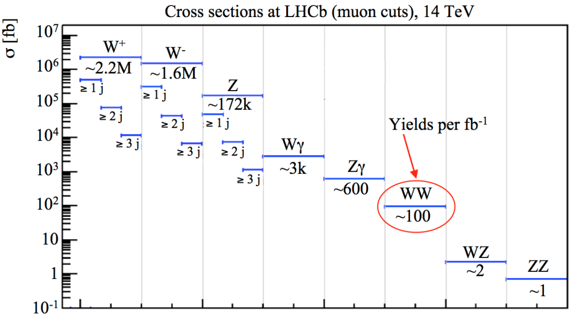
Prospects on EW

- An update is expected in many of the channels presented using the 2012 data sample at $\sqrt{s} = 8$ TeV
- Also, $W + j(l, c, b)$ production measurements will appear in the coming months
- For RUN II, di-boson production reachable, e.g., WW. Also, $\sim$10 times more W with Run II dataset (5 fb^{-1}) than in the 7 TeV measurements.



How about top?

- Measurements on top production, also close to become a reality
- Yields expected in the LHCb acceptance

Phys.Rev.Lett. **107** (2011) 082003, [arXiv:1103.3747]

JHEP **1402** (2014) 126, [arXiv:1311.1810]

$d\sigma$(fb)	7 TeV	8 TeV	14 TeV
lb	285 ± 52	504 ± 94	4366 ± 663
lbj	97 ± 21	198 ± 35	2335 ± 323
lbb	32 ± 6	65 ± 12	870 ± 116
$lbbj$	10 ± 2	26 ± 4	487 ± 76
l^+l^-	44 ± 9	79 ± 15	635 ± 109
l^+l^-b	19 ± 4	39 ± 8	417 ± 79

- LHCb measurement will be very useful to reduce the uncertainty on the high-x gluon PDFs
- Possibility to measure the $t\bar{t}$ asymmetry also under study

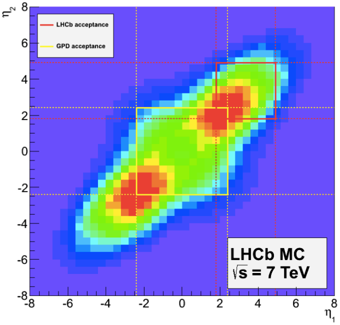
Towards $H^0 \to b\bar{b}$

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

$\to$ Interest: Higgs coupling to quarks

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

$\to$ Our jet reconstruction has been tested to work successfully. Substantial progress in b-jet tagging.



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

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

$\rightarrow$ Results in EW physics

- Z and W cross sections in different decay modes
- Associated Z production

$\rightarrow$ Also, relevant exotica results

- First LHCb paper on Higgs searches: $H^0 \rightarrow \tau^+\tau^-$
- Long lived particles decaying to jets
- Charge asymmetry in $b\bar{b}$

$\rightarrow$ And an exciting future ahead of us...

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]
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Z+X production references

- Z+X
  - $\rightarrow$ POWHEG: *JHEP* **1101** (2011) 095, [arXiv:1009.5594]
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  - $\rightarrow$ FEWZ: *Comput.Phys.Commun.* **182** (2011) 2388–2403, [arXiv:1011.3540]
  - $\rightarrow$ MCFM: *Nuclear Physics B - Proceedings Supplements* **205 - 206** (2010), no. 0 10 – 15

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

- SM prediction
  - $\to$ hep-ph/9510347
  - $\to$ *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 $H \to \tau^+\tau^-$:
  - $\to$ *Phys.Lett.* **B705** (2011) 174–192, [arXiv:1107.5003]
  - $\to$ *JHEP* **1302** (2013) 095, [arXiv:1211.6956]
- CMS on $H \to \tau^+\tau^-$:
  - $\to$ *Phys.Rev.Lett.* **106** (2011) 231801, [arXiv:1104.1619]
  - $\to$ *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]

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More references

How we measure the cross sections

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

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

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

Summary of systematics and backgrounds

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
  - $\to$ f_{FSR}: final state radiation correction
  - $\to$ $\mathcal{A}$: acceptance
- Data driven
  - $\to$ ρ: purity
  - $\to$ ϵ: efficiency
  - $\to$ $\mathcal{L}$: integrated luminosity

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

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

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

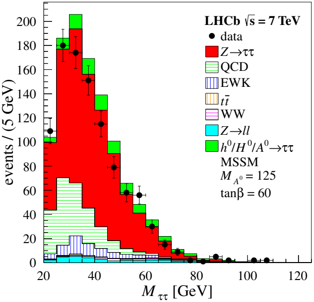
- First LHCb paper on search for neutral Higgs in the forward direction

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

- Using 2011 dataset
  Search using different τ 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 τ and back-to-back objects

Yields using all samples combined



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

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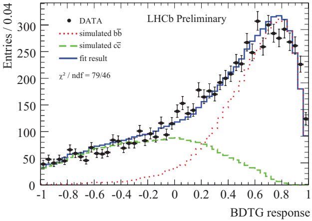
- Measurement with a fraction of 2010 data
- Use of *b* seeding technique



$\rightarrow$ 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 $p_T > 5\ \mathrm{GeV}/c$:

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

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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 $Z \to \mu^+\mu^-$	$\mathcal{L}$
$Z + D$	B semil.	Efficiency
$Z+$ jets	H. flavour	Jet-energy scale, resolution and rec.
$Z + b$ jets	$Z + l/c$ jets	M_{corr} template and b-tagging
$H^0 \to \tau^+\tau^-$	$Z \to \tau^+\tau^-$	Exp. bkg.
$H^0 \to$ LLP	$b\bar{b}$	$\epsilon^{TRIGGER}$ SV reconstruction
$A_C^{b\bar{b}}$	–	Flav. tagging
$\sigma(b\bar{b})$	$c\bar{c}$	Simulation sample size