Results of the search for an A boson decaying to Zh

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Overview

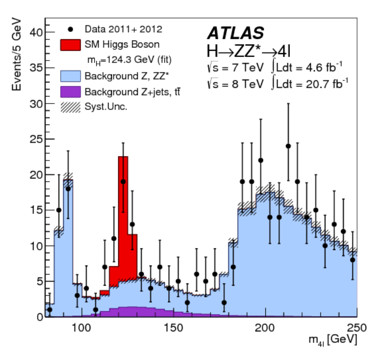
- Introduce 2HDMs and the 5 Higgs bosons
- Show where we look for 2HDM models (reducing parameters)
- Look at published results
- Motivate and introduce the $A \rightarrow Zh$ analysis
- Touch on some of the details of $\tau_{had}\tau_{had}$
- Results...

Higgs discovery at CMS and ATLAS

- 2012: New boson discovered by CMS + ATLAS
- 2013: Mass and spin-parity studies revealed

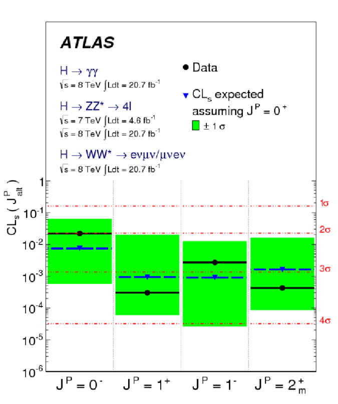
$m_H \approx 125.5$ GeV

CERN-PH-EP-2013-103



$J^P = 0^+$ compatible

CERN-PH-EP-2013-102



No deviations from SM

- σ, BR and couplings of H show no deviation from SM within uncertainties
- Higgs doublet responsible for EW symmetry breaking?
- **Is Higgs sector minimal or extended? (BSM)**

Beyond the SM: 2HDMs

- SM Higgs sector has experimental constrains:

$$\rho \equiv m_W/(m_Z \cos\theta_W) \to 1$$

- 2HDM: Simple extension by adding complex Higgs doublet, SU(2).
- **Assumptions**:
  - CP-conservation
  - Softly broken $\mathcal{Z}_2$ symmetry ($\Phi_1 = -\Phi_1$)
  - Electroweak symmetry breaking, and $v_1 v_2 \neq 0$

8 fields

3 give mass to $W^{\pm}$ and Z bosons, 5 physical **scalar ("Higgs") fields**

The Big Five

Five most **difficult** *and* **elusive** *animals in Africa to hunt.*

h H

CP-even
$J^P = 0^+$

The Big Five

Five most **difficult** *and* **elusive** *animals in Africa to hunt.*




h H H^+ H^-

CP-even
$J^P = 0^+$

Charged

The Big Five

Five most **difficult** *and* **elusive** *animals in Africa to hunt.*

h H H^+ H^- A

CP-even
$J^P = 0^+$

Charged

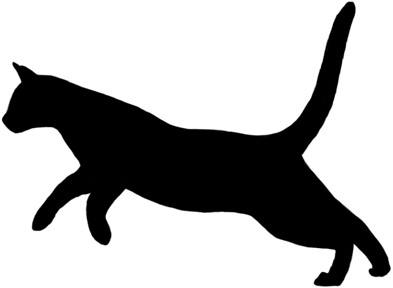
CP-odd
pseudoscalar
$J^P = 0^-$

Five most **difficult** *and* **elusive** *animals in Africa to hunt.*

h

H

CP-even
$J^P = 0^+$



Discovered Higgs is a cat.

Reducing 2HDM phasespace

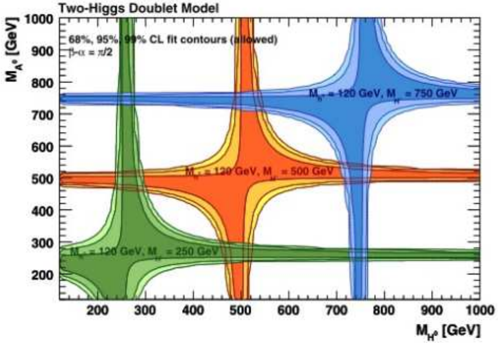
Degrees of freedom

m_h m_H m_A m_{H^+} m_{H^-} $tan\beta$ $\cos(\beta-\alpha)$

Possible coupling

	1^{st} doublet	2^{nd} doublet
Type-I	bosons	fermions
Type-II	q^{up}	$q^{dn}+\ell$
Type-III	Lepton Specific	
Type-IV	Flipped	

- $m_h = 125$ **GeV**.
- $m_A = m_H = m_{H^\pm}$



Eur. Phys. J. C (2012) 72:2003

Figure : Constraints in the 2HDM

Reducing 2HDM phasespace

Degrees of freedom

m_h m_H m_A m_{H^+} m_{H^-} $tan\beta$ $\cos(\beta-\alpha)$

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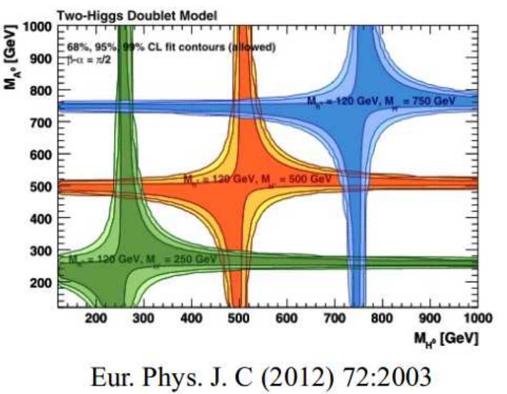


Figure : Constraints in the 2HDM

Reducing 2HDM phasespace

Constrains on new physics via Higgs coupling:ATLAS-CONF-2014-010

Coupling ratios $\frac{2HDM}{SM}$ cast as functions of β and α

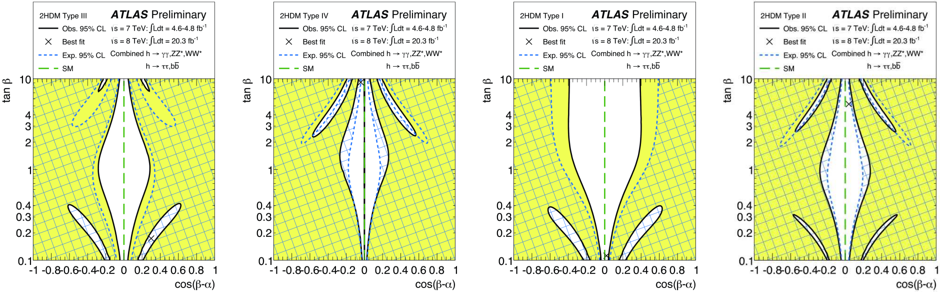
Coupling scale factor	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

The coupling scale factor of the Higgs boson h to vector bosons, up and d quark, and lepton of each type expressed as ratios relative to the SM-Higgs couplings.

Reducing 2HDM phasespace

Constrains on new physics via Higgs coupling:ATLAS-CONF-2014-010

Coupling ratios $\frac{2HDM}{SM}$ cast as functions of β and α



Reducing 2HDM phasespace

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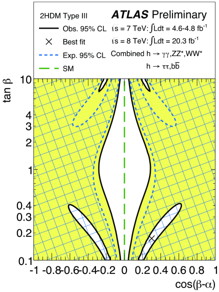
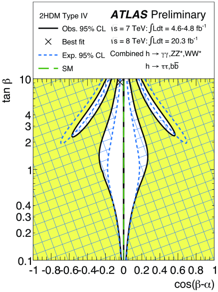
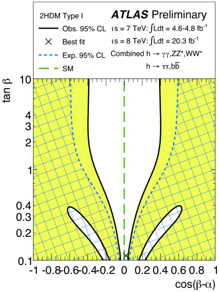
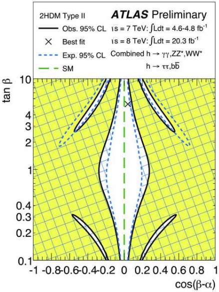


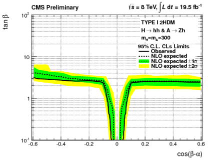


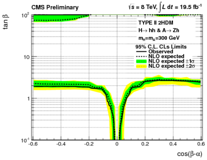


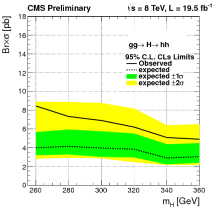


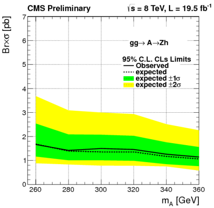
CMS Note on BSM search results: CMS-PAS-HIG-13-025

Search for extended Higgs sectors in the $H \rightarrow hh$ and $A \rightarrow Zh$



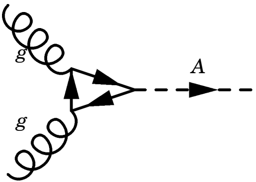




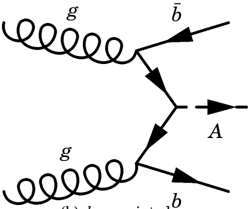


Cross section × Branching ratio of A boson

- Gluon-fusion is dominant
- b-associated important for Type-II and Type-IV at large $\tan\beta$

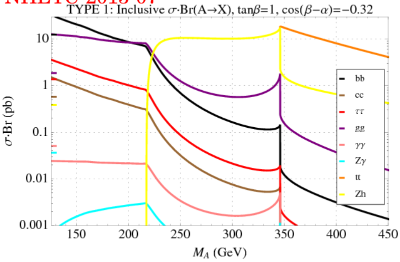


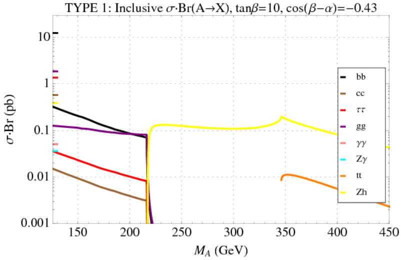
(a) gluon-fusion



(b) b-associated

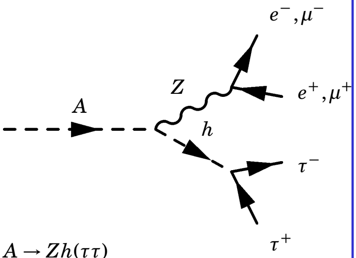
RU-NHETC-2013-07





$A \to Zh$ analysis

- $A \to Zh$ analysis searching for $m_A \in (220, 1000)$ GeV at 8TeV pp collisons with 20 fb^{-1}.



- $A \to Zh(\tau\tau)$
  -
  -
  -

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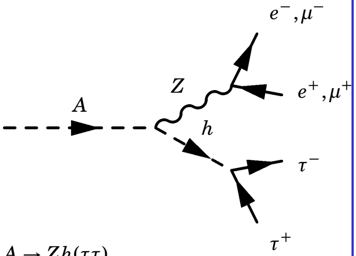
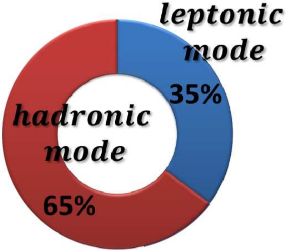


- $A \to Zh(\tau\tau)$
  - $\to \ell\ell\tau_\ell\tau_\ell$
  - $\to \ell\ell\tau_{had}\tau_\ell$
  - $\to \ell\ell\tau_{had}\tau_{had}$

τ Decays:



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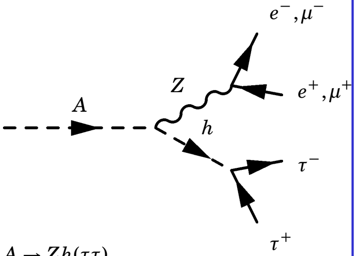

- $A \to Zh(\tau\tau)$
  - $\to \ell\ell\tau_\ell\tau_\ell$
  - $\to \ell\ell\tau_{had}\tau_\ell$
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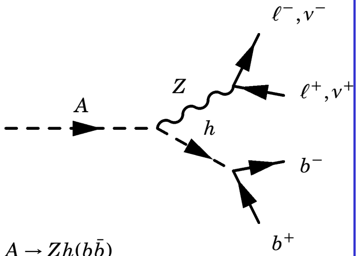
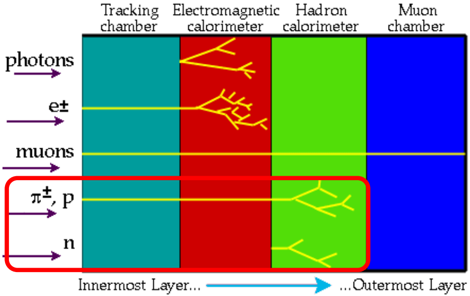


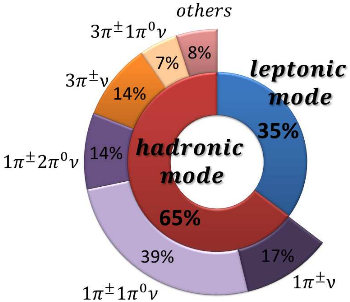
- $A \to Zh(b\bar{b})$
  - $\to \ell\ell b\bar{b}$
  - $\to \nu\nu b\bar{b}$

Recent published search by CMSCMS-PAS-HIG-14-011

Tau Reconstruction

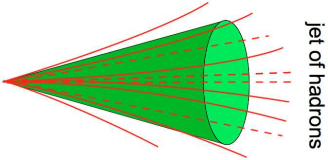
Different decays in ATLAS detector:



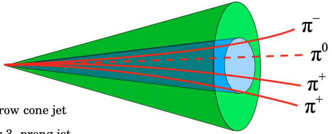


Taus never make the inner-detector (can only look at decays) ATLAS-CONF-2013-064

Non-Tau Jet



Tau Jet

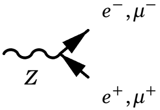


- Narrow cone jet
- 1- or 3- prong jet
- BDT and e-veto

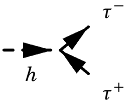
Preselection of HadHad channel

Event Preselection for hadronic channel:

- Single lepton triggers.
- Leptons: 2 loose ℓ SF, OS
  Z mass window: $80 < m_{ll} < 100$ GeV
  Isolation:
  ptcone40/$p_{\mathrm{T}} < 0.2$ and etcone20/$p_{\mathrm{T}} < 0.2$



- Taus: 2 loose τ_{had}
  muon and electron vetos
  H mass window: $75 < m_{ll} < 175$ GeV.
- Events with additional light leptons or $\tau_{\mathrm{had-vis}}$ are discarded.



Background Monte Carlo:

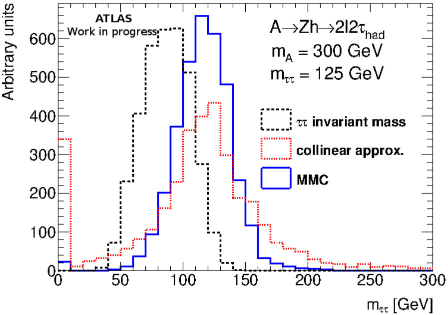
- Z+jets (DY)
- Diboson: ZZ,WZ,WW
- Tribozon: WWW*,ZWW*,ZZZ*
- Top: t$\bar{t}$, tW, tℓ, t$\bar{t}$Z
- SM assosiated Higgs production: ZH

10 Signal Mass points (in GeV):
220,240,260,300,340,350,400,500,800,1000

The Missing Mass Calculator

$m_{\tau\tau}$ reconstruction uses **Missing Mass Calculator**
Assume non-zero angle between τs and νs
System of equations with 6-8 unknowns
Most likely solution chosen (likelihood)

Nucl. Instrum. Methods,A654,p481-489



Used in $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$

Data estimated background

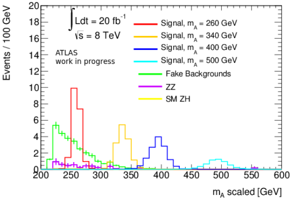
- Blind in signal region.
- Data can boost BKG predictions.
- Bkgs with fake taus estimated using template.

Template Method

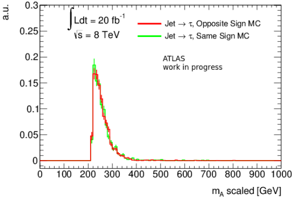
- Define 3 control regions populated with fakes:

OS — loose τ	**SS — loose τ**
OS — !loose τ	**SS — !loose τ**

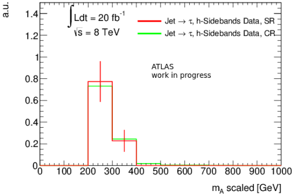
- Bkg shape extrapolated from CR to SR
- Bkg normalized using m_A sideband



- Important assumptions:
  - Template m_A shape is good in SR.



- and
  - Normalisation in h-sideband describes m_h window

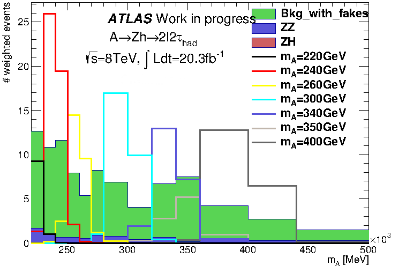


Full selection for Hadhad channel

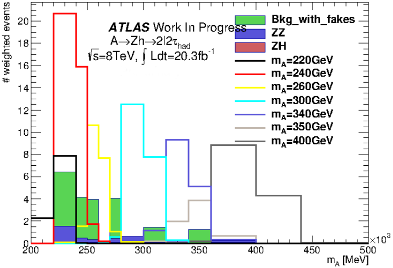
Full Selection

- The leading $\tau_{\text{had-vis}}$ is required to have $E_t > 35$ GeV
- For events with $m_A <= 400$ GeV, $Z\ p_{\text{T}} > (0.64m_A$ - 131) GeV.
- For events with $m_A > 400$ GeV, $Z\ p_{\text{T}} > 125$ GeV.

Pre-selection



Full-selection



Systematics

Experimental systematics negligable when compared to template systematics.

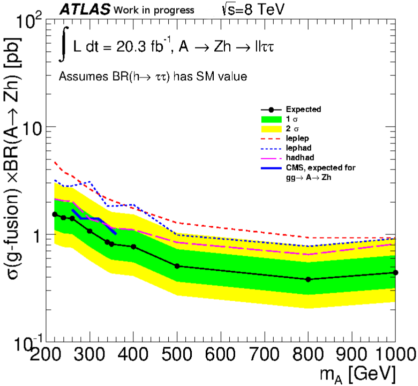
- Experimental
  - Electron, muon, tauID
  - Pile-up and Luminosity
  - Jet Energy Scale
  - Tau Energy Scale
  - Tau Energy Resolution
  - Tau Energy Scale
  - Missing Transverse Energy
  - Jet Vertex Fraction
- Theoretical cross sections used in the normalization

- Template method systematics:

  Changes in normalization and template due to different CR
  - Region 1 (R1): events with 2 loose τ that are of same sign charge,
  - Region 2 (R2): events with 2 τ, where one fails the loose τ ID, of opposite sign charge.
  - Region 3 (R3): events with 2 τ that fail the loose τ ID, of opposite sign charge.
  - Region 4 (R4): events with 2 τ, where one fails the loose τ ID, of same sign charge.
  - Region 5 (R5): events with 2 τ that fail the loose τ ID, of same sign charge.

Limits on $\sigma \times$ BR for $\tau\tau$ and bb

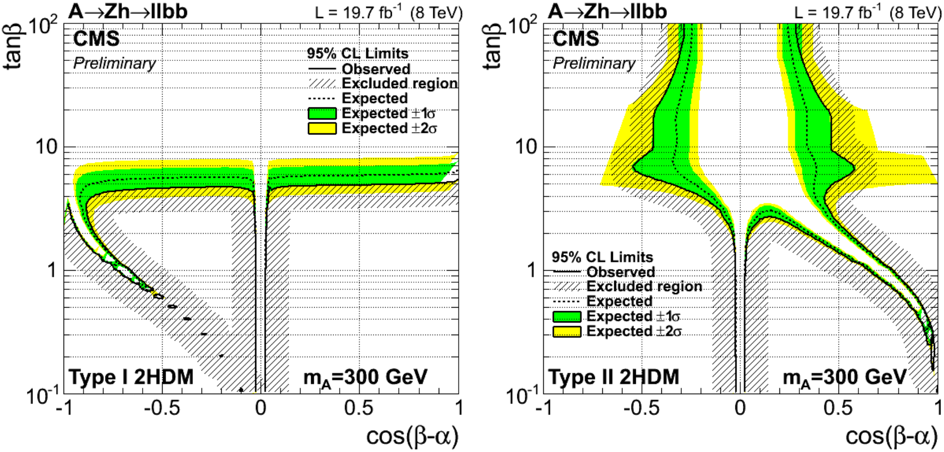
- Expected limits derived with asymptotic approximation
- Limits reject 95% CL
- Limits of each channel is combined



Exclusion plots for combined $\tau\tau$ and bb

Exclusion plots for combined $\tau\tau$ and bb

CMS-PAS-HIG-14-011



Conclusion

- Search for a neutral, CP-odd A-boson, predicted by 2HDMs, decaying to Zh in proton-proton collisions at the at the LHC is TBA.
- Gluon-fusion + b-associate considered in Type-II and Type-IV.
- Final States for combination:
  - $Z \to \ell\ell$ and h to either $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$ or $\tau_{had}\tau_{had}$. Focus was placed on the $\tau_{had}\tau_{had}$.
  - $A \to Zh \to ffb\bar{b}$ analysis, where $f = \nu, \ell$
- The background predictions and systematic and statistical uncertainties have been calculated.
- Direct expected 95% CL upper limits on the gluon-fusion and b-associated production.
- The resulting limits are interpreted in four 2HDM models.
- Paper will be ready SOON, aiming to submit to Phys. Lett B
- Analysis will continue in Run-II at higher luminosity.

Back-up Slide: MC samples

Process	Dataset ID	Generator	Cross Section [pb]	k-factor	efficiency
		SM ZH production			
$ZH(125) \to \tau_{lep}\tau_{lep}$	161675	Pythia8			
$ZH(125) \to \tau_{lep}\tau_{had}$	161686	Pythia8	0.02491976	1	0.456192
$ZH(125) \to \tau_{had}\tau_{had}$	161697	Pythia8	0.02491976	1.0	0.4199
		$Z+$jets			
$Z \to ee + \mathrm{Np0}$	147105	Alpgen	718.97	1.18	1.0
$Z \to ee + \mathrm{Np1}$	147106	Alpgen	175.70	1.18	1.0
$Z \to ee + \mathrm{Np2}$	147107	Alpgen	58.875	1.18	1.0
$Z \to ee + \mathrm{Np3}$	147108	Alpgen	15.636	1.18	1.0
$Z \to ee + \mathrm{Np4}$	147109	Alpgen	4.0116	1.18	1.0
$Z \to ee + \mathrm{Np5}$	147110	Alpgen	1.2592	1.18	1.0
$Z \to \mu\mu + \mathrm{Np0}$	147113	Alpgen	719.16	1.18	1.0
$Z \to \mu\mu + \mathrm{Np1}$	147114	Alpgen	175.74	1.18	1.0
$Z \to \mu\mu + \mathrm{Np2}$	147115	Alpgen	58.882	1.18	1.0
$Z \to \mu\mu + \mathrm{Np3}$	147116	Alpgen	15.673	1.18	1.0
$Z \to \mu\mu + \mathrm{Np4}$	147117	Alpgen	4.0057	1.18	1.0
$Z \to \mu\mu + \mathrm{Np5}$	147118	Alpgen	1.2544	1.18	1.0
$Z \to \tau^+\tau^- + \mathrm{Np0}$	147121	Alpgen	719.18	1.18	1.0
$Z \to \tau^+\tau^- + \mathrm{Np1}$	147122	Alpgen	175.72	1.18	1.0
$Z \to \tau^+\tau^- + \mathrm{Np2}$	147123	Alpgen	58.862	1.18	1.0
$Z \to \tau^+\tau^- + \mathrm{Np3}$	147124	Alpgen	15.664	1.18	1.0
$Z \to \tau^+\tau^- + \mathrm{Np4}$	147125	Alpgen	4.0121	1.18	1.0
$Z \to \tau^+\tau^- + \mathrm{Np5}$	147126	Alpgen	1.2560	1.18	1.0

Back-up Slide: MC samples

Process	Dataset ID	Generator	Cross Section [pb]	k-factor	efficiency
		Di-boson			
WW	105985	Herwig	53.899	1	0.38212
WZ	105987	Herwig	22.258	1	0.30546
$ZZ \to 4e$	126937	Powheg	0.069	1	
$ZZ \to 2e2\mu$	126938	Powheg	0.145	1	
$ZZ \to 2e2\tau$	126939	Powheg	0.102	1	
$ZZ \to 4\mu$	126940	Powheg	0.070	1	
$ZZ \to 2\mu2\tau$	126941	Powheg	0.103	1	
$ZZ \to 4\tau$	126942	Powheg	0.008	1	
		Single top			
single top: $t-$channel $W \to e\nu$	117360	AcerMC	9.48	1	1
single top: $t-$channel $W \to \mu\nu$	117361	AcerMC	9.48	1	1
single top: $t-$channel $W \to \tau\nu$	117362	AcerMC	9.48	1	1
single top: $s-$channel $W \to e\nu$	108343	MC@NLO	0.606	1	1
single top: $s-$channel $W \to \mu\nu$	108344	MC@NLO	0.606	1	1
single top: $s-$channel $W \to \tau\nu$	108345	MC@NLO	0.606	1	1
single top: $Wt-$channel	108346	MC@NLO	22.37	1	1
		$t\bar{t}$			
$t\bar{t}$(no hadronic)	105200	MC@NLO	238.06	1	0.543
$t\bar{t}$(all hadronic)	105204	MC@NLO	238.06	1	0.457
$t\bar{t}Z$	119355	MadGraph	0.0677	1.34	1.0

Table : Details for the simulated background samples that are used in this analysis.