Future prospects for Higgs measurements with CMS

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On behalf of the CMS Collaboration

CERN

PASCOS 2013 - Higgs Parallel session

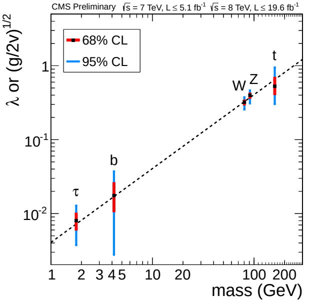
Introduction

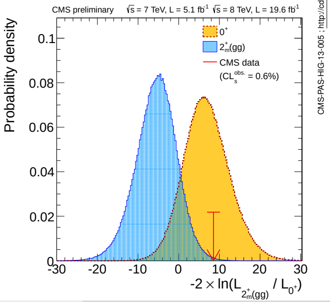
We have found one Higgs boson...

- Current tests: couplings and spin/parity consistent with the Standard Model

What next?

- No other new particles discovered@LHC so far...
- Properties of the new boson
- Self-coupling (EWK processes)
- Additional Higgs bosons?
- Exotic Higgs decays?



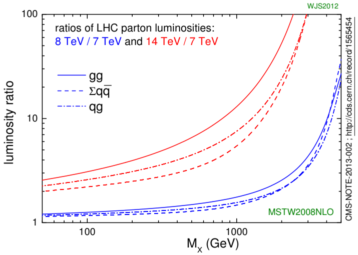


Future plans for the LHC

- Of the future accelerator options currently under study, the Large Hadron Collider is the only facility currently operating.

Period		$\sqrt{s}$ (TeV)	$\int L$ (fb^{-1})	L ($cm^{-2}s^{-1}$)	$< pu >$	BX (ns)
2009-2012	Run 1	7 and 8	25	7×10^{33}	21	50
2013-2014	LS1	"Phase 1" upgrades				
2015-2017	Run 2	13	-	10^{34}	25	25
2018-2019	LS2	"Phase 1" upgrades				
$\approx$ 2021	Run 3	-	300	-	50	-
2022-2023	LS3	"Phase 2" upgrades				
$\approx$ 2024	HL-LHC	-	3000	5×10^{34}	128	-

	σ (pb)	$\sqrt{s} = 14$ TeV, $\int L = 3000$ fb^{-1} Events	$\sqrt{s} = 8$ TeV, $\int L = 30$ fb^{-1} Events
ggH	50.4	150M	600K
VBF	4.2	13M	48K
WH	1.5	4.5M	21K
ZH	0.9	2.6M	12K
ttH	0.6	1.8M	4K



Phase I upgrades (1)

CMS public webpage

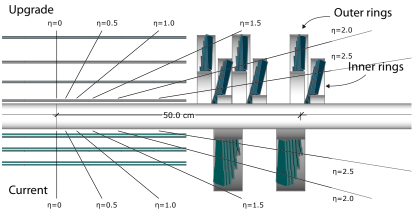
LS1: Already on-going

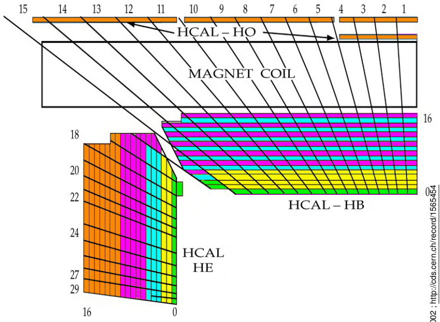
- Pixel: repairs, pilot blades
- Tracker: lower temperatures
- ECAL: repairs, crystal monitoring
- HCAL: new photo-diodes
- Muons systems:
  - DT: repairs, trigger boards
  - RPC: installation of the 4th disk
  - CSC: prep. for new electronics
- DAQ upgrade
- TDRs... and other "future studies"!

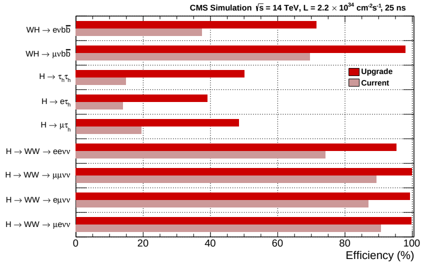
Phase I upgrades (2)

LS2: being finalized

- Pixel detector upgrade
  - Fourth layer, b-tagging
- Hadron calorimeter upgrade
  - improved readout, longitudinal segm. (PF)
- L1 trigger upgrade
  - Use HCAL/ECAL granularity
  - Flexibility and scalability







Phase II upgrades

Beyond LS2: radiation damage, aging, higher *L*

- New tracker:less material, improved tracking in dense charged particles environment, L1trigger
- Replacement of electromagnetic and hadronic calorimeters in the endcap region
- Extension of tracking beyond $\eta = 2.5$?
- Precision timing integrated into an EM preshower detector ?
- TDR with full-simulation studies anticipated for 2014

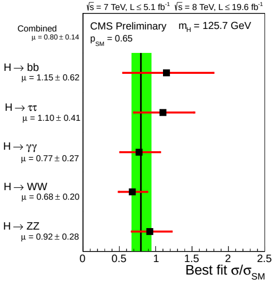
Now, let's start **extrapolating**

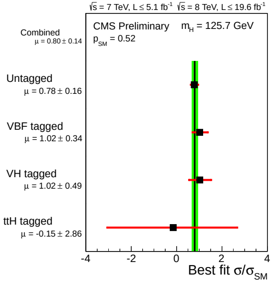
- **Keep in mind that changes are happening**, changes are planned, some still in design choice, detector is aging
- Dataset of 300 or 3000 fb^{-1}: 10 to 100 times what we have today!
- Evolution of systematic uncertainties (exp. and th.)?

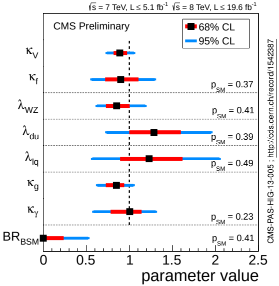
Menu

- Higgs coupling projections with 300 to 3000 fb^{-1}
- Upgrade layouts: $H \to ZZ^* \to 4\mu$
- Extending the search for (2HDM) neutral Higgses
- Probing EWK symmetry breaking: vector boson scattering and quartic gauge couplings
- Rare decays: $H \to \mu\mu$
- (SUSY: chargino-neutralino production with decays to a Higgs boson: cf. Snowmass report)
- (Exotics: Higgs production via vector-like quarks: cf. CMS-FTR-13-026)
- (Exotics: double Higgs production / Higgs self-couplings: no public projection)
- (Exotics: $H \to \text{invisible}$, MET hard to extrapolate to $< pu >= 140$)

Higgs couplings projections: starting point



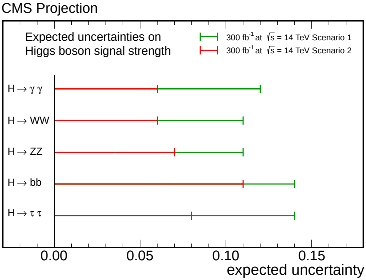


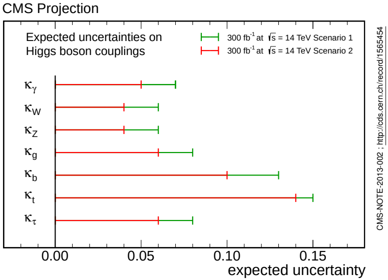


Discovery of a Higgs boson

- Analyzed 5.1 fb^{-1} at 7 TeV and 19.6 fb^{-1} at 8 TeV
- Mass $m_H = 125.7 \pm 0.4$ GeV
- Signal strength $\mu = \frac{\sigma}{\sigma_{SM}} = 0.80 \pm 0.14$

Higgs couplings projections





Strategy

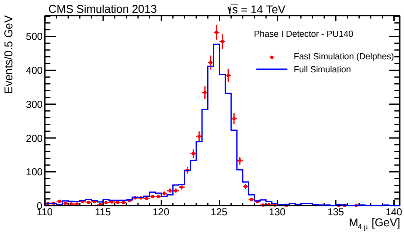
- Scale signal and bkg event yields to 300 fb^{-1} at $\sqrt{s} = 13$ TeV
- Assume 2012 CMS performance (no optimization)
- Scenario 1: systematic uncertainties unchanged
- Scenario 2: th. unc. scaled by $1/2$, exp. unc. scaled by $\sqrt{\int L}$

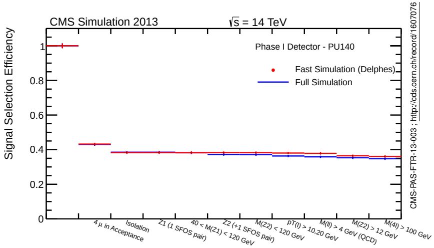
Phase II geometry: $H \rightarrow ZZ^* \rightarrow 4\mu$ (1)

Assumptions

- $\sqrt{s} = 14$ TeV ; $< pu >= 140$
- Configuration 3: new central tracker + new forward EM calorimeter (but no acceptance change)
- Configuration 4: extension from $|\eta| < 2.4$ to $|\eta| < 4.0$ of central tracking, EM and Had. calorimeters, muon detectors
- Only irreducible background considered (non-resonant SM $ZZ \rightarrow 4\mu$)
- No analysis reoptimization

Phase II geometry: $H \to ZZ^* \to 4\mu$ (2)

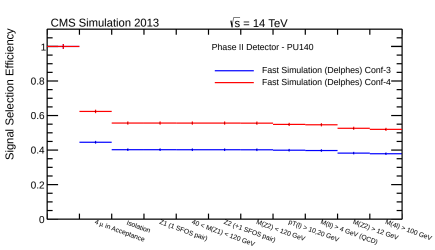


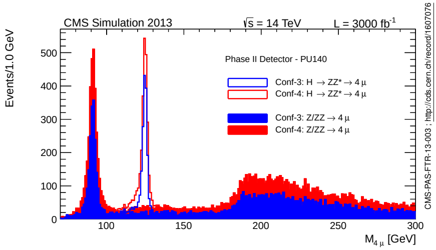


Delphes tuning

- Full- and Fast-sim samples in "2017" detector geometry
  - a.k.a. Pixel Phase I upgrade but no HCAL upgrade
- Compare signal and irr. bkg. for $< pu >= 70$ and $< pu >= 140$
  - muon reconstruction efficiencies, single muon momentum resolution, muon isolation, $m_{4\mu}$, cut-flow, etc.
- **Only then**, trust Delphes to simulate Phase II geometry

Phase II geometry: $H \to ZZ^* \to 4\mu$ (3)





- Configuration 3 shows similar selection efficiency as with Phase I detector simulation
- Configuration 4: η acceptance increase signal acceptance (40 % relative!), slightly degraded mass resolution
- Accuracy of future measurements dominated by signal yields... but reducible background yet to be studied

Extending the search of the Higgs sector: 2HDM (1)

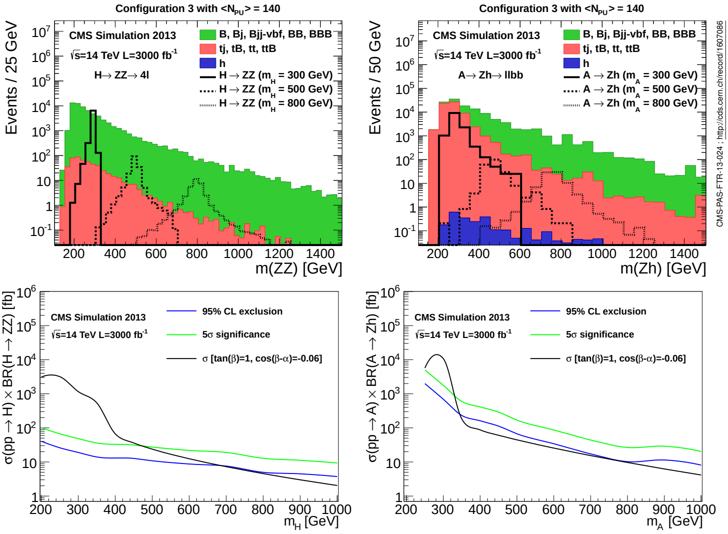
2 Higgs Doublet Model (2HDM)

- EWK symmetry breaking sector need not be minimal (i.e. SM)
- 5 physical Higgs bosons: 2 CP-even scalars H and h, CP-odd pseudo-scalar $\mathcal{A}$, a charged pair $H^{\pm}$
- Constrains: 2HDMs may be parametrized by 9 variables
  - m_h, m_H, $m_{\mathcal{A}}$, $m_{H^{\pm}}$, CP-even mixing angle α, ratio of Higgs vaccuum expectation values $\tan\beta$, three scalar couplings λ_5, λ_6, λ_7
  - Will assume here λ_5, λ_6, $\lambda_7 = 0$ (tree-level MSSM values)

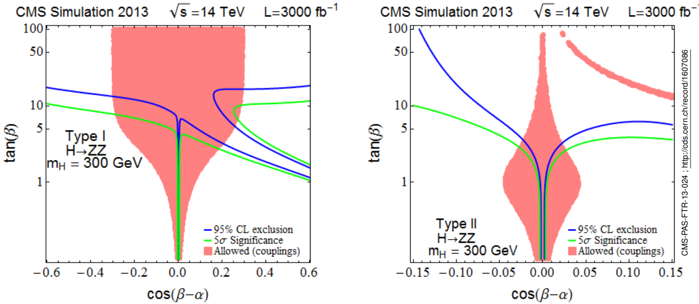
Scope of the study

- Heavy scalar H boson: $H \rightarrow ZZ \rightarrow llll$
- Pseudo-scalar $\mathcal{A}$ boson: $\mathcal{A} \rightarrow Zh \rightarrow llbb$
- Figures done for $\tan\beta = 1$ and $\cos(\beta - \alpha) = -0.06$

Extending the search of the Higgs sector: 2HDM (2)



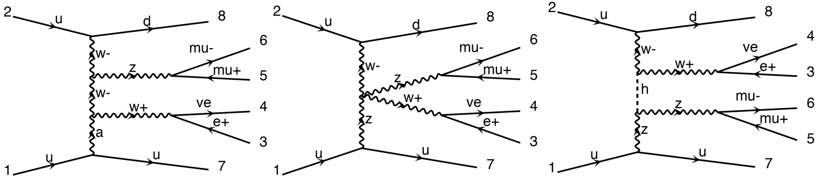
Extending the search of the Higgs sector: 2HDM (3)



Conclusion

- There is some phase space still allowed where exclusion or discovery of either *H* or $\mathcal{A}$ is possible
- Constraints coming from *h* boson couplings measurement
- Coverage of parameter space by the two strategies are **complementary** at low masses

Probing EWK symmetry breaking: QGC (1)



WZ scattering (leptonic decays)

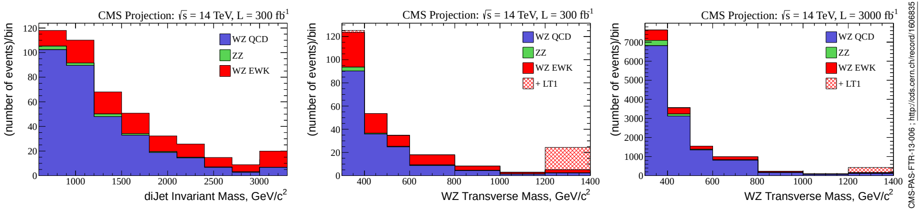
- Double TGC, QGC, t-channel Higgs boson scattering
- Strong interference, σ_{NLO} predicted (Higgs boson mass)
- Scattering topology $\rightarrow$ new physics in the EWKSB sector

σ_{NLO} (fb)	WZ EWK	WZ QCD	ZZ	L_{T1} ($f_{T1}/\Lambda^4 = 1.0$)
Total	7.7	270	16	3.1
Fiducial (2.4)	0.69	0.96	0.038	0.57
Fiducial (4.0)	1.3	1.6	0.0016	0.58

Probing EWK symmetry breaking: QGC (2)

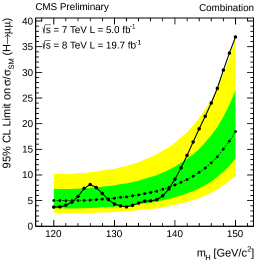
EFT approach

- EFT for modelling aQGCs (no new physics (yet) at the LHC)
- Operator: $L_{T1} = (f_{T1}/\Lambda^4) Tr[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] Tr[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}]$



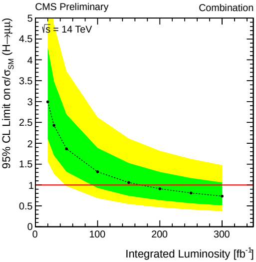
Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}
f_{T1}/Λ^4 at 300 fb^{-1} f_{T1}/Λ^4 at 3000 fb^{-1}	0.8 TeV^{-4} 0.45 TeV^{-4}	1.0 TeV^{-4} 0.55 TeV^{-4}

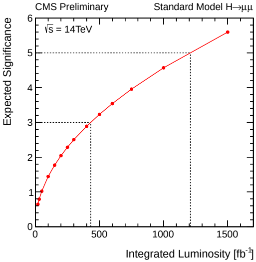
$H \to \mu\mu$

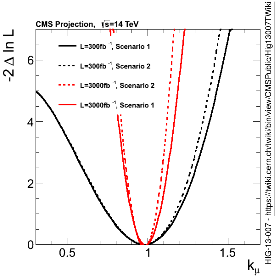


Excess at $m_H = 125$ GeV in the search for $H \to \mu\mu$

- Exclusion can be settled with < 200 fb^{-1}
- Evidence (discovery) can be settled with $< 500(1250)$ fb^{-1}





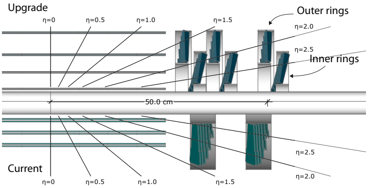


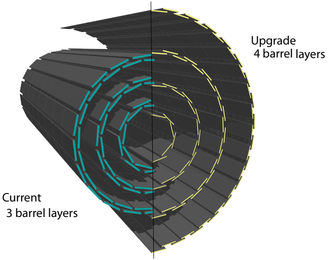
Conclusion

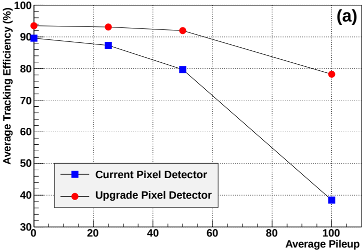
- A new particle (a Higgs boson) has been discovered with 30 fb^{-1} at LHC at $\sqrt{s} = 7, 8$ TeV
- Upgrade planned for $\sqrt{s} = 13$ TeV and $\int L = 300\ \mathrm{fb}^{-1}$
- Besides (directly) looking for new physics, Higgs and Higgs-related studies are priority
  - Couplings of the new boson
  - Other Higgses (2HDM)
  - EWK symmetry breaking sector (QGC, self-couplings)
  - Exotic Higgs decays ($H \to \mu\mu$, $H \to \mathrm{invisible}$)
  - Higgs with SUSY/Exotics (vector-like quarks, WED)
- Important interplay between upgrade plans and these studies

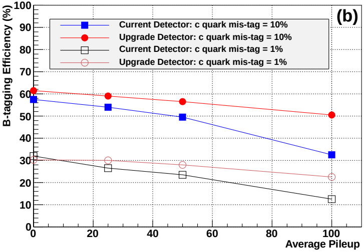
BACKUP

Pixel upgrade





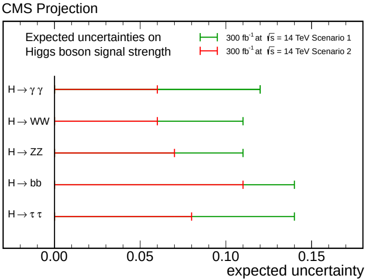


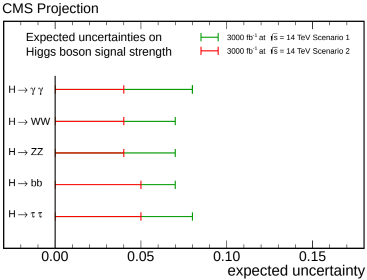


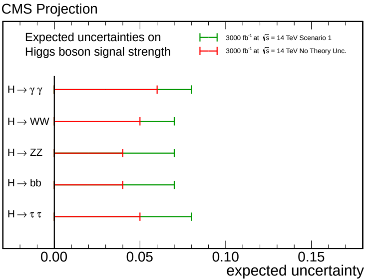
L1 trigger upgrade

- Improved electromagnetic object isolation using calorimeter energy distributions with pile-up subtraction;
- Improved jet finding with pile-up subtraction;
- Improved hadronic tau identification with a smaller fiducial area;
- Improved muon transverse momentum (p_{T}) resolution in difficult regions;
- Isolation of muons using calorimeter energy distributions with pile-up subtraction;
- Improved global Level-1 trigger menu with a greater number of triggers and with more sophisticated relations involving the input objects.

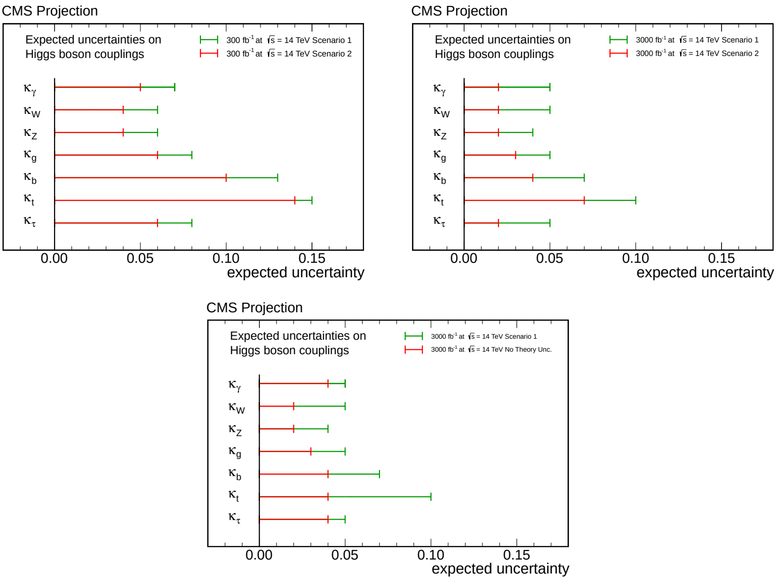
Higgs couplings projections (1)







Higgs couplings projections (2)



Inputs to the higgs projections

H decay	prod. tag	exclusive final states	cat.	res.
$\gamma\gamma$	untagged	$\gamma\gamma$ (4 diphoton classes)	4	1-2%
	VBF-tag	$\gamma\gamma + (jj)_{VBF}$	2	<1.5%
	VH-tag	$\gamma\gamma + (e, \mu, \mathrm{MET})$	3	<1.5%
	ttH-tag	$\gamma\gamma$ (lep. and had. top decay)	2	<1.5%
$ZZ \to 4\ell$	$N_{\mathrm{jet}} < 2$	$4e$, 4μ, $2e2\mu$	3	1-2%
	$N_{\mathrm{jet}} \geq 2$		3	
$WW \to \ell\nu\ell\nu$	0/1-jets	(DF or SF dileptons) $\times$ (0 or 1 jets)	4	20%
	VBF-tag	$\ell\nu\ell\nu + (jj)_{\mathrm{VBF}}$ (DF or SF dileptons)	2	20%
	WH-tag	$3\ell3\nu$ (same-sign SF and otherwise)	2	
$\tau\tau$	0/1-jet	$(e\tau_h, \mu\tau_h, e\mu, \mu\mu)\times$ (low or high p_T^{τ})	16	15%
	1-jet	$\tau_h\tau_h$	1	
	VBF-tag	$(e\tau_h, \mu\tau_h, e\mu, \mu\mu, \tau_h\tau_h) + (jj)_{\mathrm{VBF}}$	5	
	ZH-tag	$(ee, \mu\mu) \times (\tau_h\tau_h, e\tau_h, \mu\tau_h, e\mu)$	8	
	WH-tag	$\tau_h\mu\mu, \tau_h e\mu, e\tau_h\tau_h, \mu\tau_h\tau_h$	4	
bb	VH-tag	$(\nu\nu, ee, \mu\mu, e\nu, \mu\nu$ with 2 b-jets$)\times$x	13	10%
	ttH-tag	(ℓ with 4, 5 or $\geq$6 jets) $\times$ (3 or $\geq$4 b-tags);	6	
		(ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or $\geq$3 b-jets)	3	
$Z\gamma$	inclusive	$(ee, \mu\mu) \times (\gamma)$	2	
$\mu\mu$	0/1-jets	$\mu\mu$	12	1-2%
	VBF-tag	$\mu\mu + (jj)_{\mathrm{VBF}}$	3	
invisible	ZH-tag	$(ee, \mu\mu) \times (\mathrm{MET})$	2	