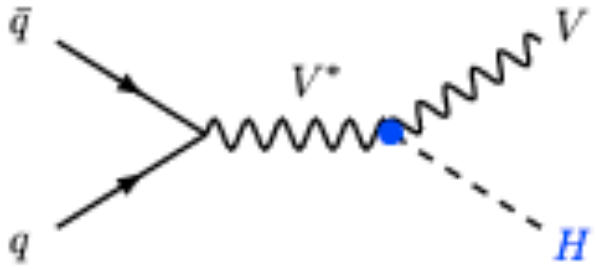
Triboson Results ATLAS

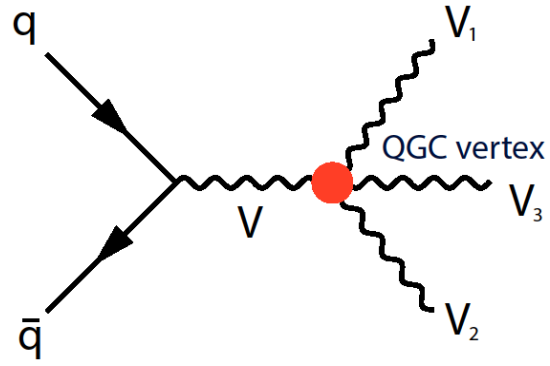
Duong Nguyen
Argonne National Laboratory

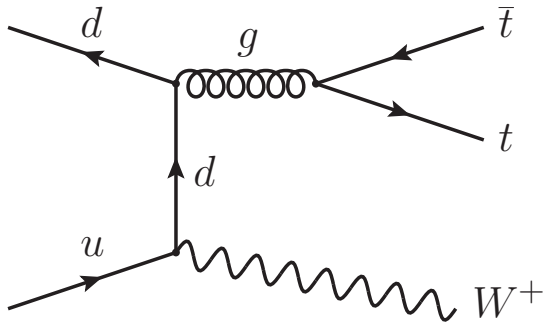
Multi-Boson Interactions Workshop
Brookhaven National Laboratory, Oct. 28-30, 2014

Introduction

- Triboson signature can be used to investigate:
  - Higgs physics in VH channels
  - SM triboson production: test SM quartic couplings and anomalous quartic couplings (aQGC), background to Higgs and new physics
  - Production of gauge bosons in association with top quarks: background to Higgs and new physics







Tribosons in VH search

ATLAS-CONF-2013-075

- HV channel provides information about coupling of Higgs to gauge bosons V (W and Z)
  - Expected cross section around 1.5 fb and 0.3 fb for WH and ZH (m_H = 125 GeV)
- Two analyses in fully leptonic channel (e, μ):
  - 3-lepton analysis (lvlvlv): targeting WH
  - 4-lepton analysis (lllvlv): targeting ZH
- Background in 3-lepton analysis:
  - Dibosons (WZ, ZZ), tribosons, tt+V
  - Fake lepton: Z+jets, tt, Wt
- Background in 4-lepton analysis: triboson, ttZ, fake leptons (dibosons).
- Leptons from Higgs decays are closer to each other than leptons from W decays are -> used to reject irreducible background.

VH analysis: 3-lepton selections

- 3-lepton analysis:
  - Pre-selection: 3 leptons with Σq = ±1
  - 2 samples: Z-enriched (with at least 1 SFOS pair) and Z-depleted (no SFOS pair)
  - Z-enrich contains ¾ signal but higher background (WZ backgrounds). Z-delepted contains ¼ signal but less backgrounds

Cut	*Z-enriched*	*Z-depleted*
Jet multiplicity	$N_{\text{jet}} \leq 1$	
b-veto	$N_{b-\text{tag}} = 0$	
$E_{\text{T,rel}}^{\text{miss}}$ cut	$E_{\text{T,rel}}^{\text{miss}} > 40$ GeV	$E_{\text{T,rel}}^{\text{miss}} > 25$ GeV
Dilepton mass cuts	$\lvert m_{\ell\ell} - m_Z \rvert > 25$ GeV and $m_{\ell\ell} > 12$ GeV	$m_{\ell\ell} > 12$ GeV
Angular cut	$\Delta R_{\ell_0\ell_1} < 2.0$	

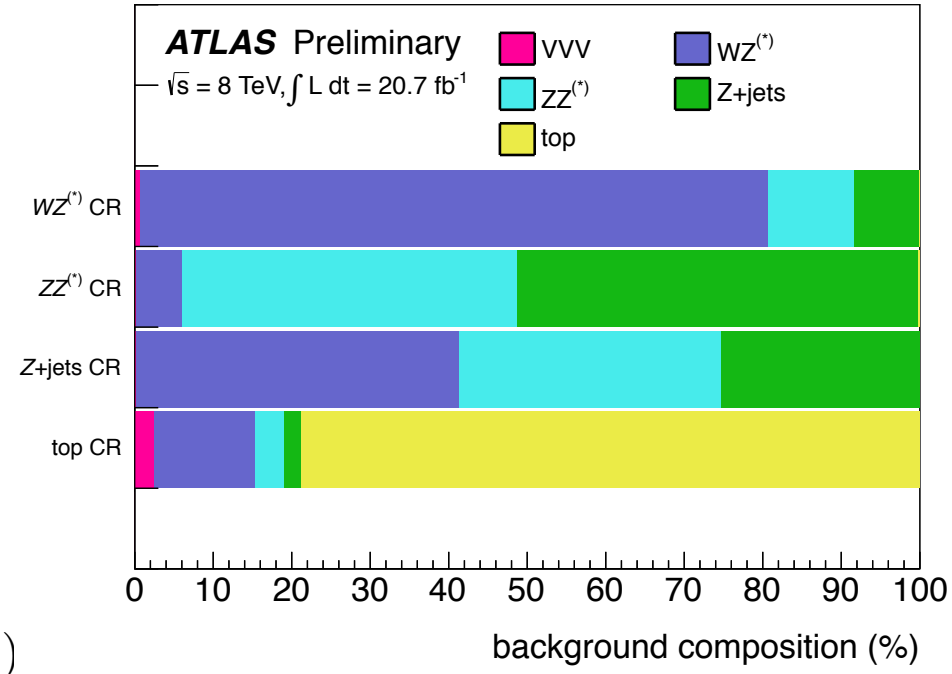
VH analysis: 4-lepton selections

- Basic signature: 4-lepton with total charge = 0 and a pair of leptons with $m_{ll} \sim m_Z$

Cut		
$E_{\mathrm{T}}^{\mathrm{miss}}$ cut	$E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV	
p_{T}^{ℓ} cuts	highest p_{T} lepton: $p_{\mathrm{T}} > 25$ GeV second highest p_{T} lepton: $p_{\mathrm{T}} > 20$ GeV third highest p_{T} lepton: $p_{\mathrm{T}} > 15$ GeV fourth highest p_{T} lepton: $p_{\mathrm{T}} > 10$ GeV	
Jet multiplicity	$N_{\mathrm{jet}} \leq 1$	
b-veto	$N_{b-\mathrm{tag}} = 0$	
Mass cuts	$\lvert m_{\ell_2\ell_3} - m_Z \rvert < 10$ GeV 10 GeV $< m_{\ell_0\ell_1} < 65$ GeV	
Angular cut	$\Delta\phi_{01}^{\mathrm{boost}} < 2.5$	
Channel separation	2SFOS	1SFOS
$p_{\mathrm{T}4\ell}$ cut	$p_{\mathrm{T}4\ell} > 30$ GeV	
$m_{4\ell}$ cut	$m_{4\ell} > 130$ GeV	

VH search: background estimation

- Background are estimated using MC simulation and normalizations are found using a set of CRs for major backgrounds



$$\chi^2 = \sum_{all\ samples,\ all\ CRs} (N^{data} - N^{MC})$$

- SM triboson backgrounds: Madgraph (LO) + k-factor = 1.5 (T. Binoth et al., arXiv: 0804.0350 [hep-ph])

$W(Z/\gamma^*)$ (*Z-enriched*)	$0.92 \pm 0.03 \pm 0.02$
$ZZ^{(*)}$ (*Z-enriched*)	$2.33 \pm 0.30 \pm 0.10$
Z+jets (*Z-enriched*, electrons)	$0.72^{+0.1}_{-0.03} \pm 0.04$
Z+jets (*Z-enriched*, muons)	$0.76 \pm 0.80 \pm 0.04$
Top (*Z-enriched*)	$1.15 \pm 0.70 \pm 0.03$

VH search: background estimations results and uncertainties

ATLAS-CONF-2013-075

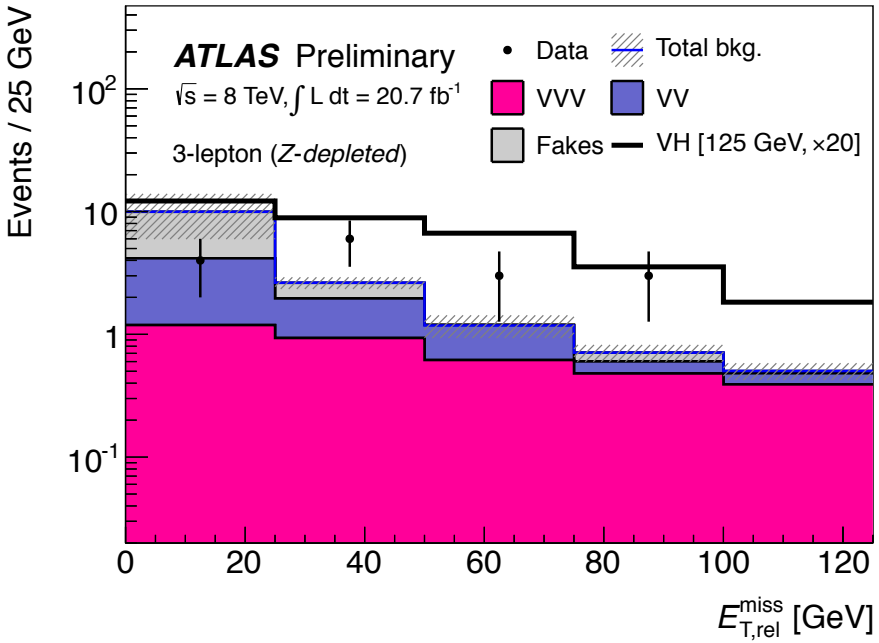
	VV	VVV	Fake	Total bkgr.	VH(125)	Data
Z-enriched (eee+μμμ)	8.7 ± 0.5	0.63 ± 0.06	4 ± 4	14 ± 4	0.42 ± 0.03	8
Z-enriched (eeμ+eμμ)	10.1 ± 0.6	1.56 ± 0.11	0.5 ± 0.2	12.2 ± 0.7	1.04 ± 0.04	16

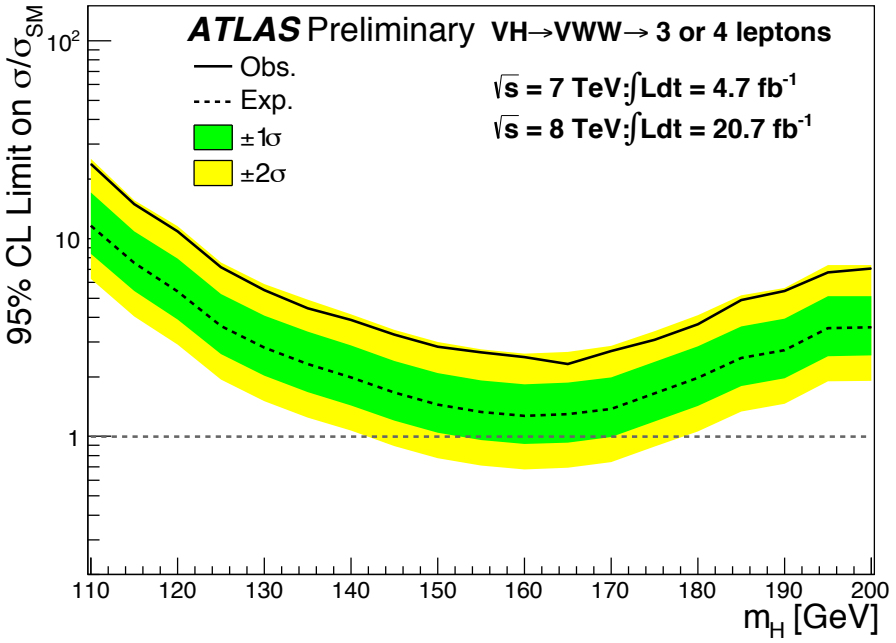
	ZZ	VVV	Fake	Total bkgr	VH (125)	Data
1 SFOS	0.23 ± 0.04	0.08 ± 0.01	0.00 ± 0.01	0.32 ± 0.05	0.18 ± 0.01	2
2 SFOS	0.70 ± 0.07	0.10 ± 0.01	0.04 ± 0.02	0.84 ± 0.08	0.17 0.01	0

- Theoretical uncertainties on cross section is a few percent.
- The VVV uncertainty on k-factor is 50%
- Experimental uncertainties: 5-9% dominated by lepton identification efficiency and JES

VH analysis: Results

ATLAS-CONF-2013-075



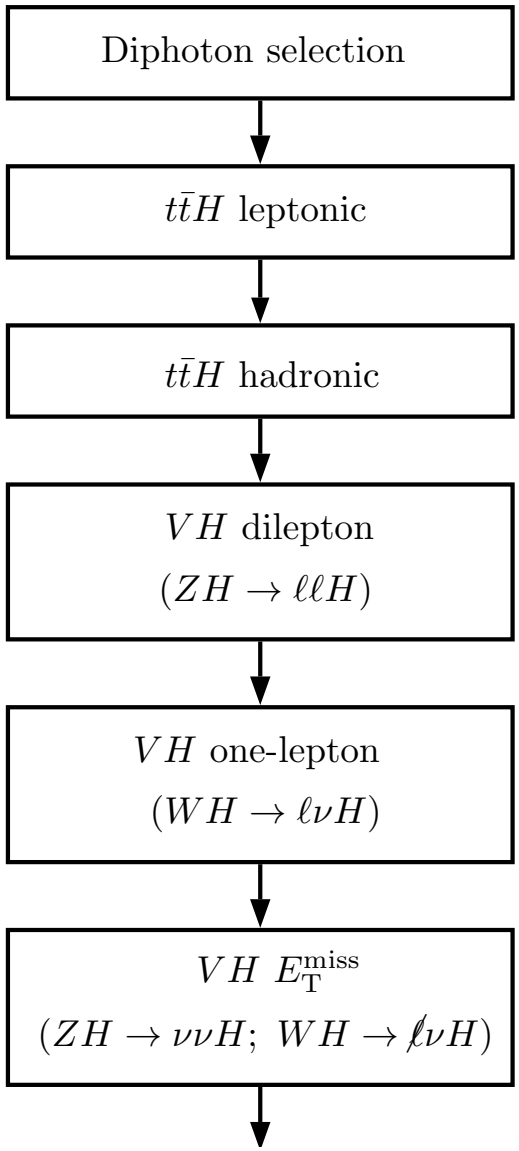


- Data are compatible with background-only hypothesis 2.0 sigma (p_0 = 2.1%)
- Fitted signal strength is $3.7^{+1.9}_{-2.1}$ times the expected SM Higgs boson signal

Tribosons in H(γγ)V measurement

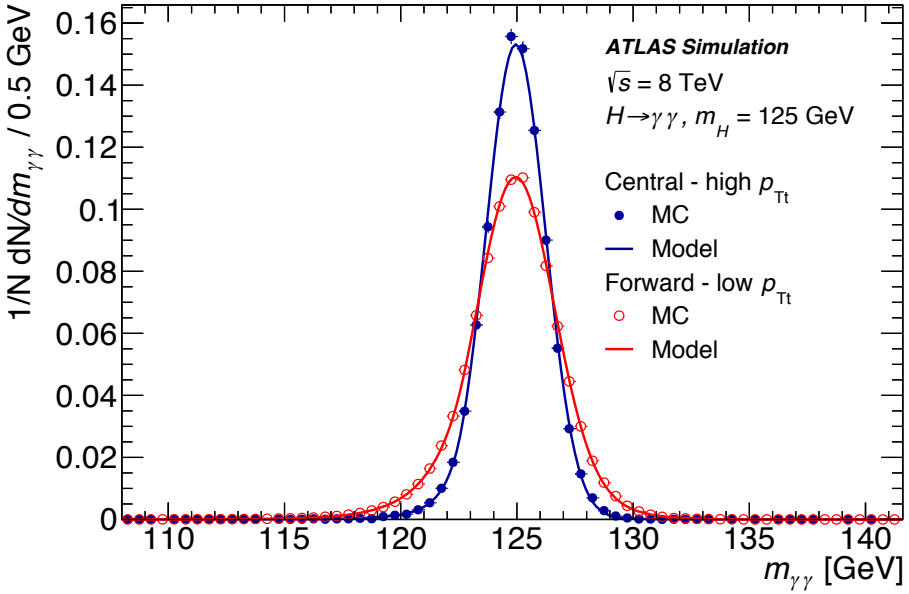
arXiv:1408.7084v2

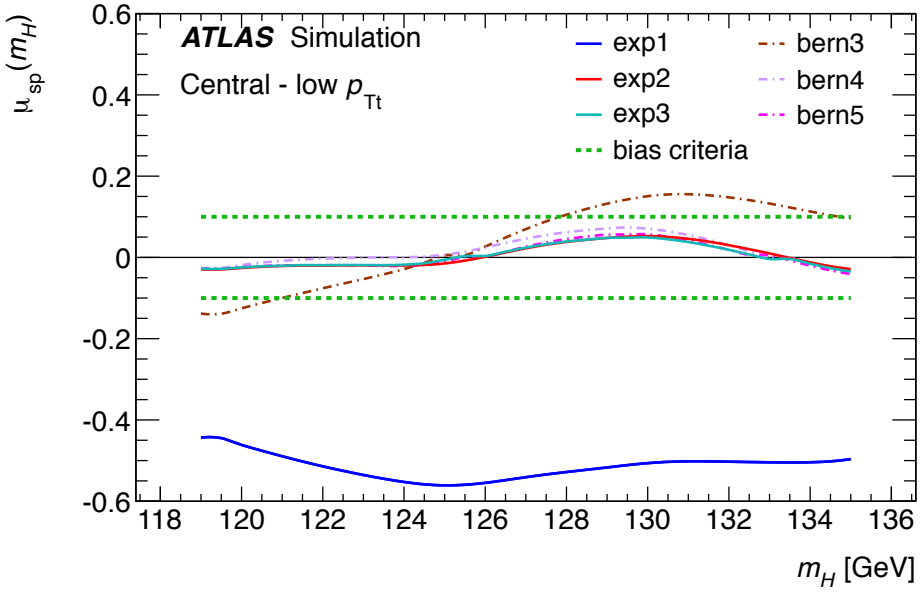
- Study the production modes using H(γγ) final state
- VH are exclusive categories in H->γγ selection chain
- VH selections:
  - Diphoton selection: $|\eta| < 2.37$, $E_T/m_{\gamma\gamma} > 0.35$ (0.25) for leading (sub-leading) photon
  - Lepton: $p_T > 15$ GeV (10 GeV) for electron (muon)
  - Significance of $E_T^{miss} > 1.5$ (one-lepton)
  - 70 GeV < M(ll) < 110 GeV (dilepton)
- VH dilepton targets WH (contains 89.8% WH)
- VH one lepton target ZH (contains 99.1% ZH)
- VH signal efficiency is small (1.3% for VH dilepton and 4.8% for VH one lepton)



H(γγ): Signal and background modeling

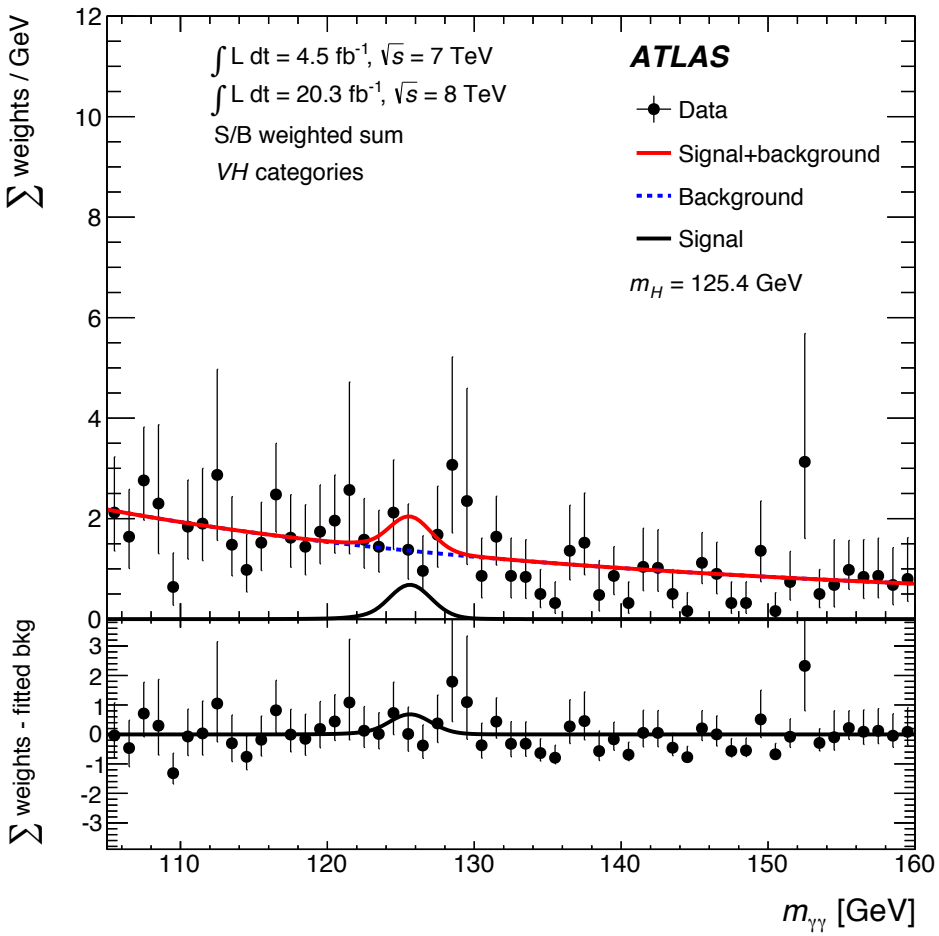
arXiv:1408.7084v2



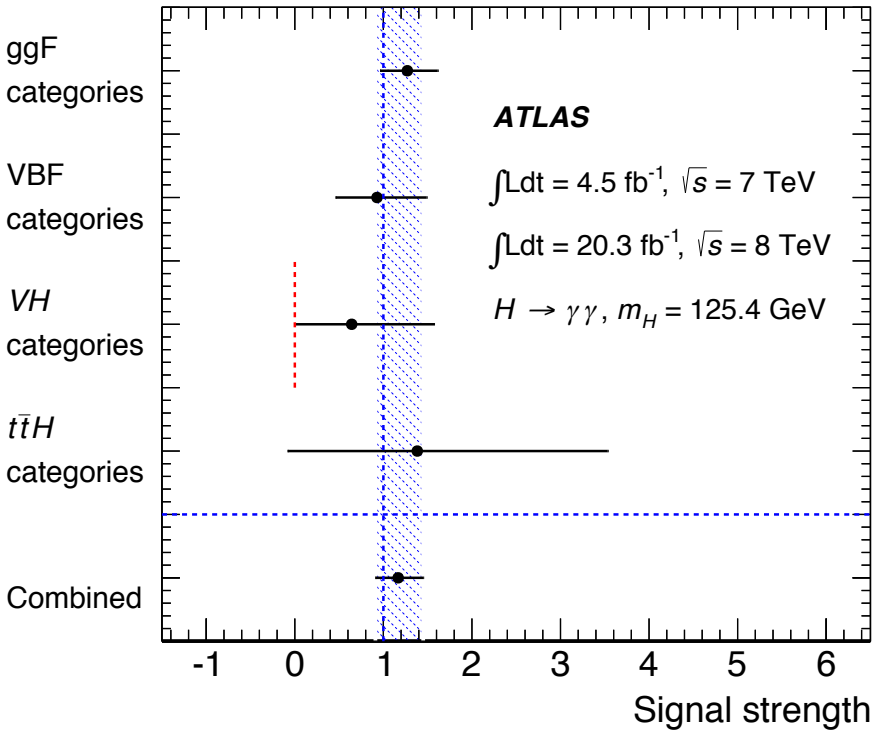


- Signal model: Crystal Ball + Gaussian
- Background model: parameterization are test in MC samples with a mixture of gg, gj and jj)
- Selection of parameterization: number of signal from a fit of signal + background

H(γγ): Signal strength



arXiv:1408.7084v2

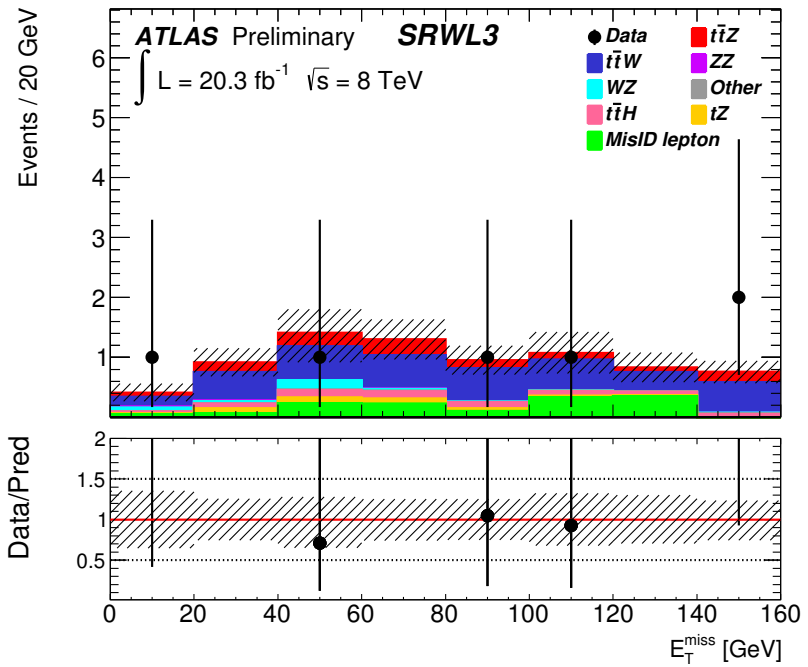


- Consistent with SM expectation

ttV measurements

ATLAS-CONF-2014-038

- Channels: SS and trilepton, opposite signed dilepton
- Use neural network analysis to separate ttW, ttZ from backgrounds



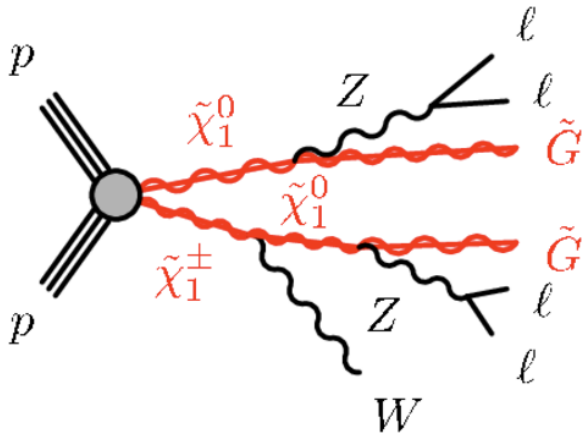
	Summary of combined simultaneous fit results		
Process	Measured cross-sections	Observed σ	Expected σ
$t\bar{t}Z$	$150^{+58}_{-54}(\text{total}) = 150^{+55}_{-50}(\text{stat.}) \pm 21(\text{syst.})$ fb	3.1	3.7
$t\bar{t}W$	$300^{+140}_{-110}(\text{total}) = 300^{+120}_{-100}(\text{stat.})^{+70}_{-40}(\text{syst.})$ fb	3.1	2.3

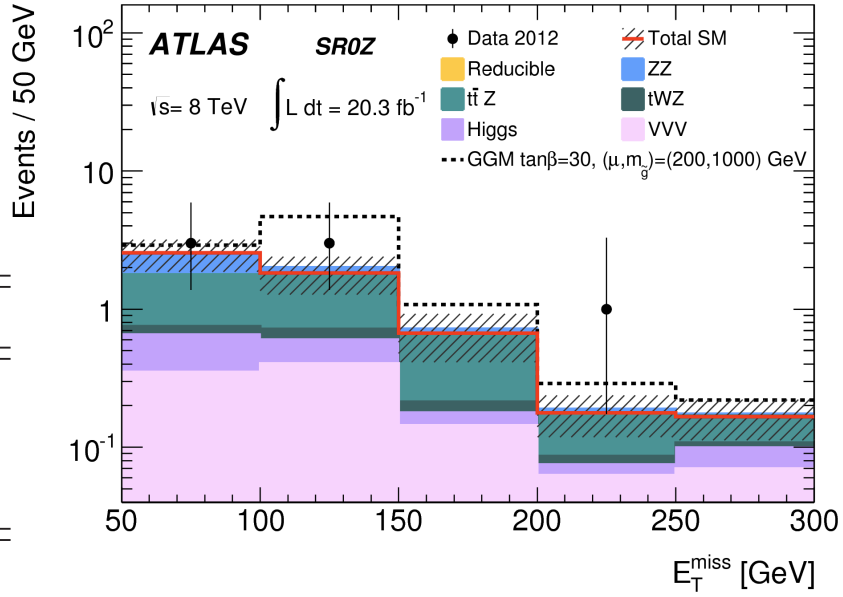
Signal strengths are $\mu_{ttZ} = 0.71^{+0.28}_{-0.26}$ and $\mu_{ttW} = 1.30^{+0.59}_{-0.48}$

Example of tribosons backgrounds in SUSY search

arXiv:1405.5086v2

- VVV are taken into account in SUSY searches in multilepton and same-signed lepton channels
- VVV estimation:
  - Generate at LO using Madgraph +PYTHIA (CTEQ6L1), k-factor = 1.5 for NLO correction (F. Campanario et. al. Phys. Rev. D78 (2008) 094012, arXiv: 0809.0790)
  - Cross section uncertainty 100% (to take into account for acc. Unc.)
  - Contribution is about a few percent





Process	σ [pb]	k-factor	$\int \mathcal{L}dt$ [fb^{-1}]
WWW (167006)	5.10	1.5	9800
ZWW (167007)	1.55	1.5	32250
ZZZ (167008)	0.33	1.5	151500

aQGC

- Effective field theory to describe the aQGC effect

$$\mathcal{L}_{\mathcal{EFT}} = \mathcal{L}_{SM} + \sum_{d>4} \sum_{i} \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i$$

- The higher-order terms break gauge invariance -> unitarity scheme (dipole form factor)
- Dimension-8 operators: lowest order linear realization of pure aQGC
  - Some can be translated to dimension-6 operators in non-linear realization
- Many dimension-8 operators are built and can be probed using tribosons final states (arXiv:hep---ph/0606118, Eboli et al.)

Zγγ at HL-LHC

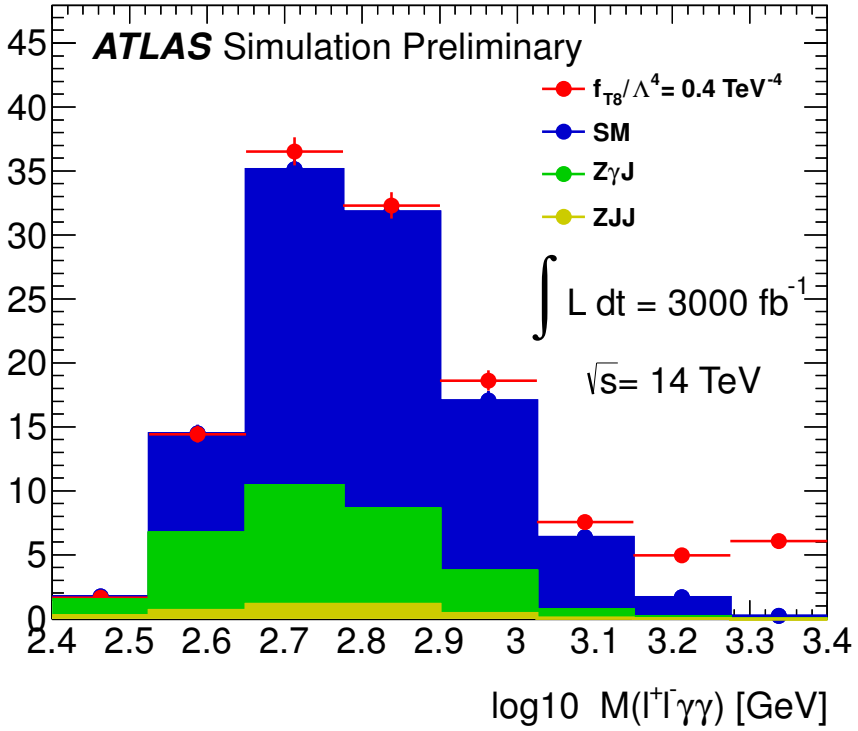
- Simulations:
  - LO MADGRAPH generator, CTEQ6L1 PDF. Particle showering is simulated by PYTHIA
  - Jets are reconstructed using anti-kT R=0.4 algorithm from truth level particles.
  - Use parameterization of ATLAS detector performance at high pile-up conditions to smear particle-level output.
- Triboson Zgg:
  - Two leptons (p_T > 25 GeV, $|\eta|$ < 2, $|m_{ll}$ - 91| < 10 GeV) and one gamma (p_T > 160 GeV)
  - Lepton photon separation ΔR > 0.4.
- Parameterization:

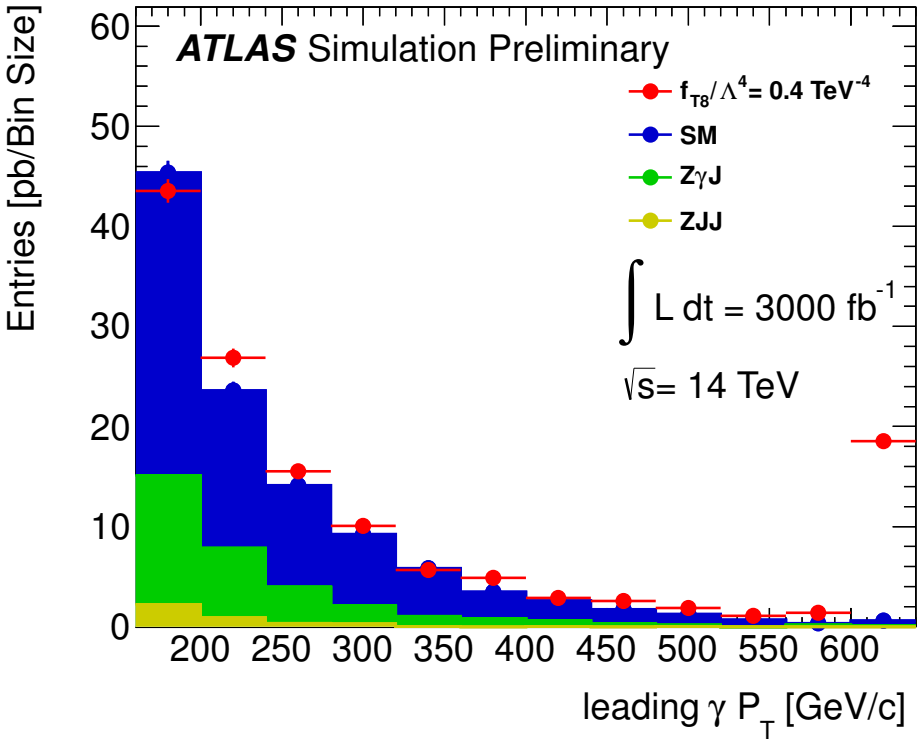
$$\mathcal{L}_{T,8} = \frac{f_{T8}}{\Lambda^4} B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$

$$\mathcal{L}_{T,9} = \frac{f_{T9}}{\Lambda^4} B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

aQGC effects in Zγγ

ATLAS-PHYS-PUB-2013-006

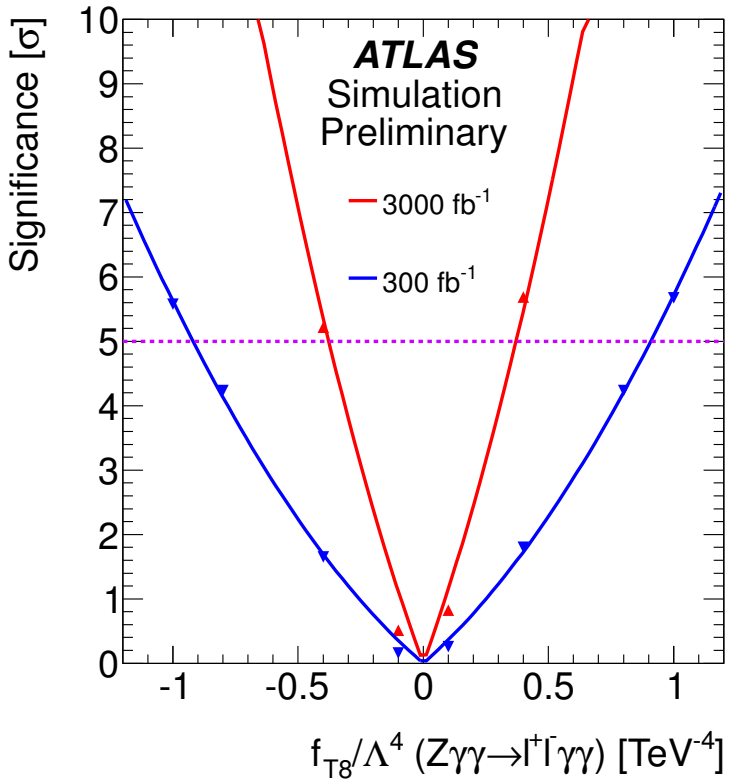


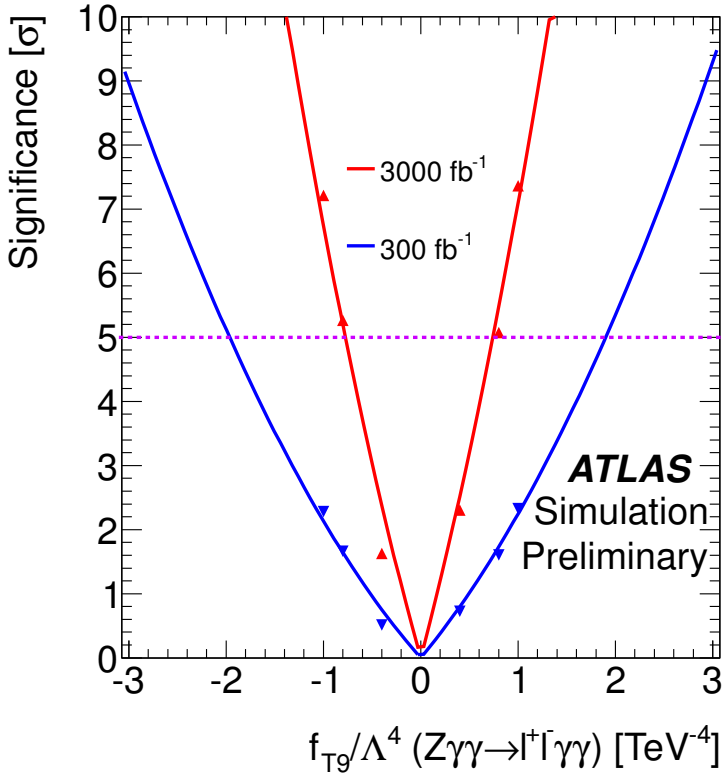


- aQGC effects are enhanced at high-end of invariant mass or photon p_T

Expected sensitivity in Zγγ at HL-LHC

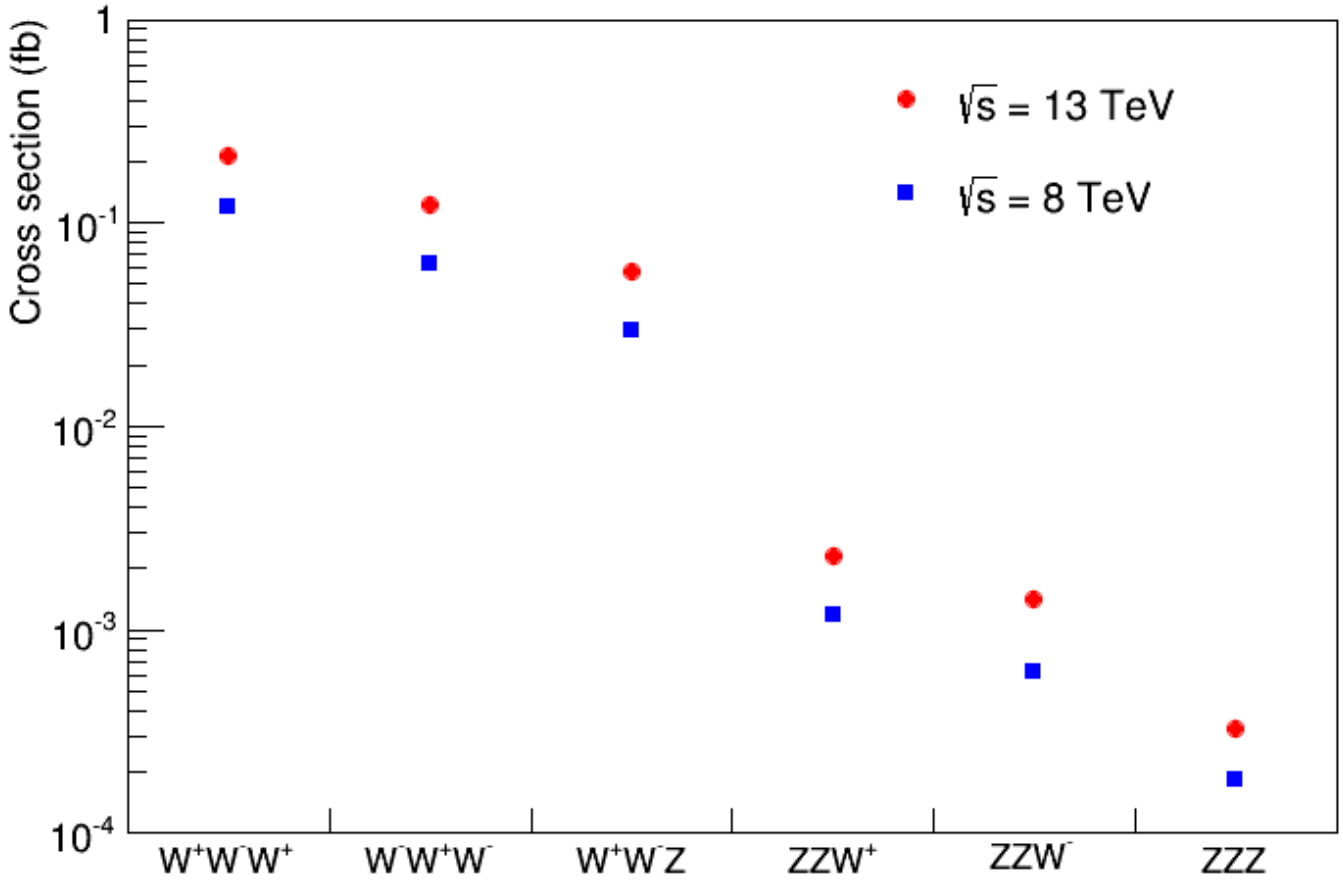
ATLAS-PHYS-PUB-2013-006





- Sensitivities increase dramatically with high luminosity

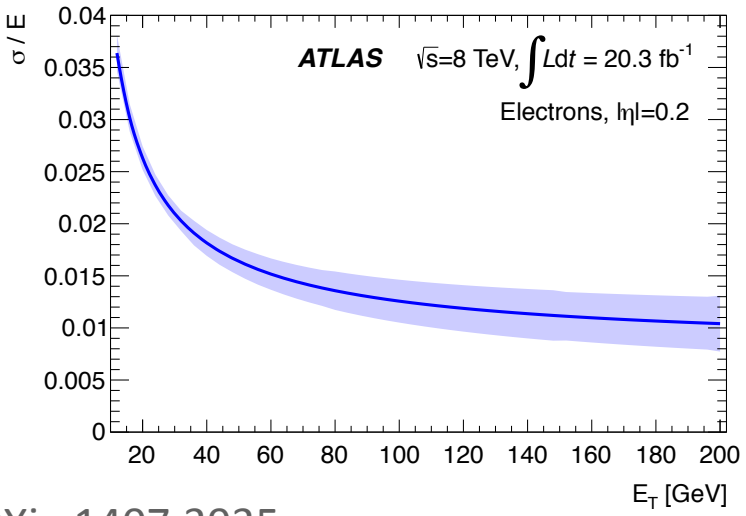
Prospect of VVV measurement in run II

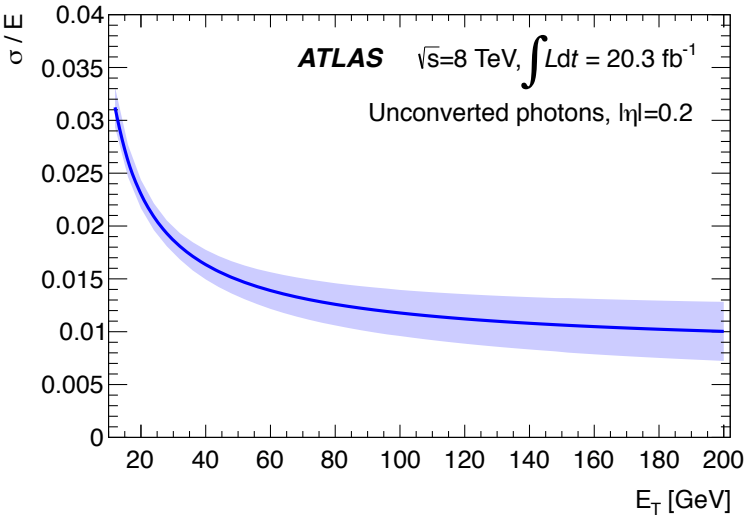


- Inclusive NLO cross section from VBFNLO (no Higgs. Bosons decay to electrons)

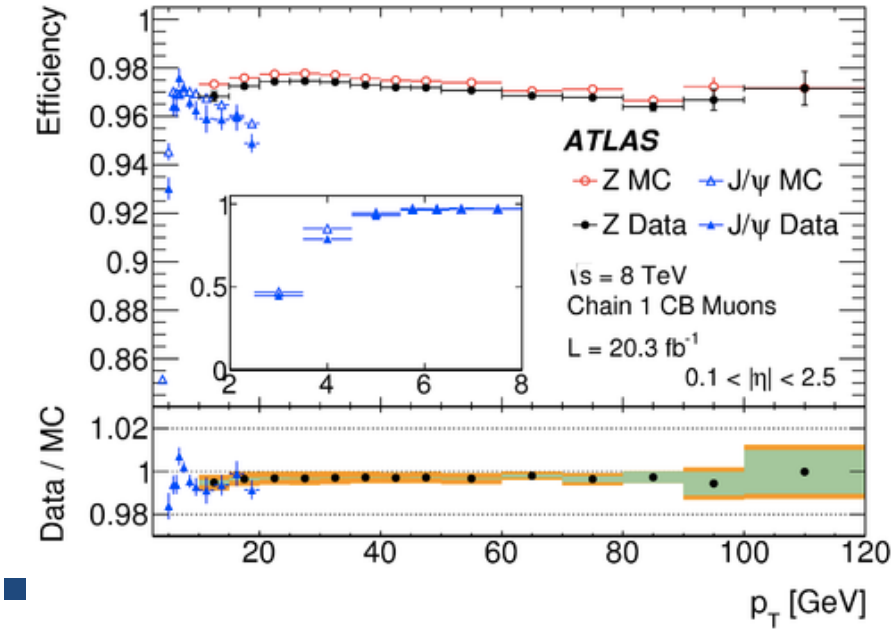
Run I performances

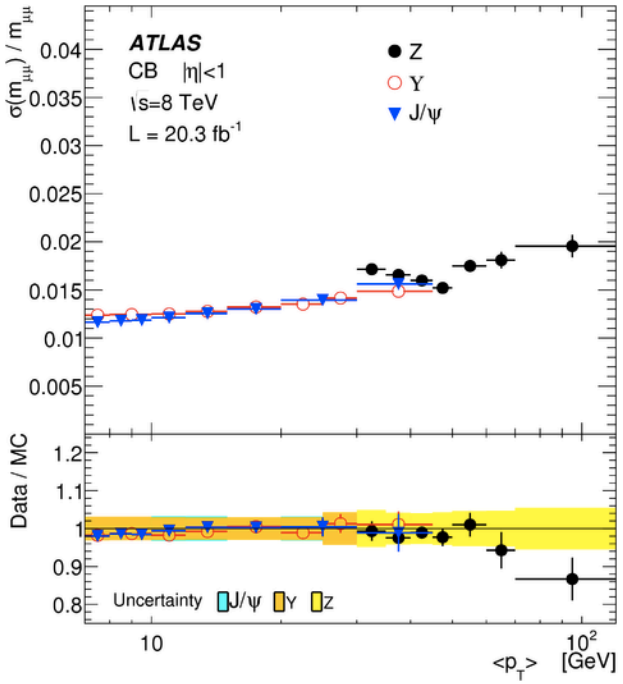
arXiv:1407.5063





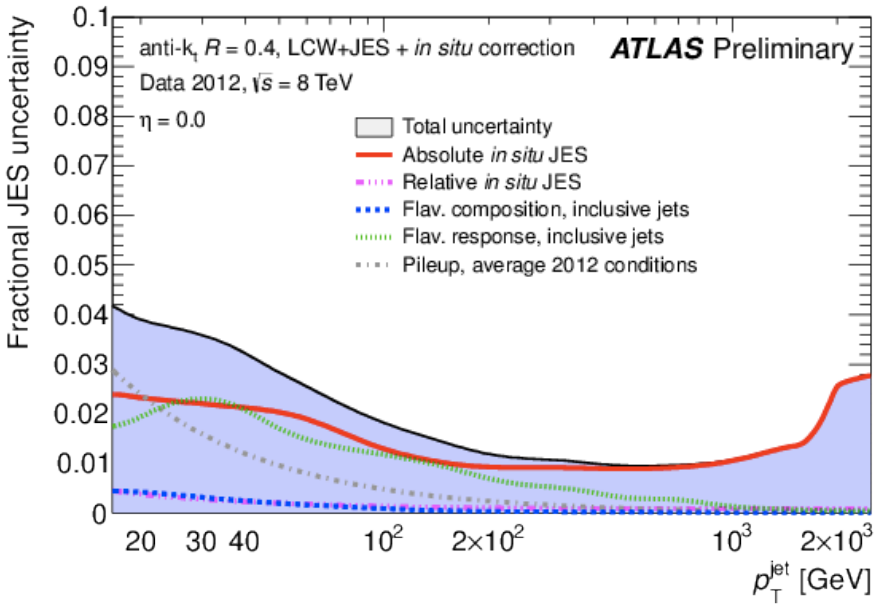
arXiv:1407.3935

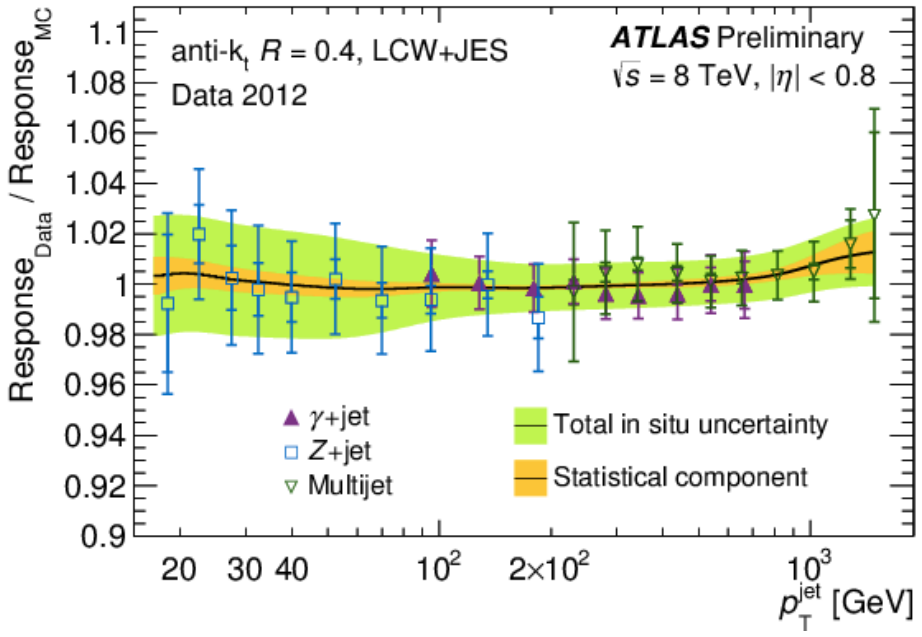




Run I performances (cont.)

ATLAS-CONF-2013-083





- Run I performance remarks:
  - High object reconstruction efficiency (90% or higher)
  - Good resolution (percent level)
  - Controlled ow uncertainties
  - Well modeled MC simulations (scale factor ~1)
- Run II outlook: pile-up robustness, improved identifications and selection menus, extending the kinematic ranges of performances

Conclusions

- Search for VH production in VVV channel and study of the Higgs production mode in VH(gg) has been conducted at ATLAS.
  - The signal strength in VVV search is 3.7 of SM
  - No deviation from the SM prediction in Higgs production mode is found.
- The ttV and VVV backgrounds have small contributions in Higgs and new physics search. However, future precision Higgs measurement requires to understand these backgrounds well.
- A few SM triboson productions can be accessible at early run II and they can be fully measured at higher luminosity.
- The preparation for run II are developing based on excellent performance in run I.
- The HL-LHC scenario can be very sensitive for new physics in aQGC.

Backgrounds in SUSY 4-lepton search

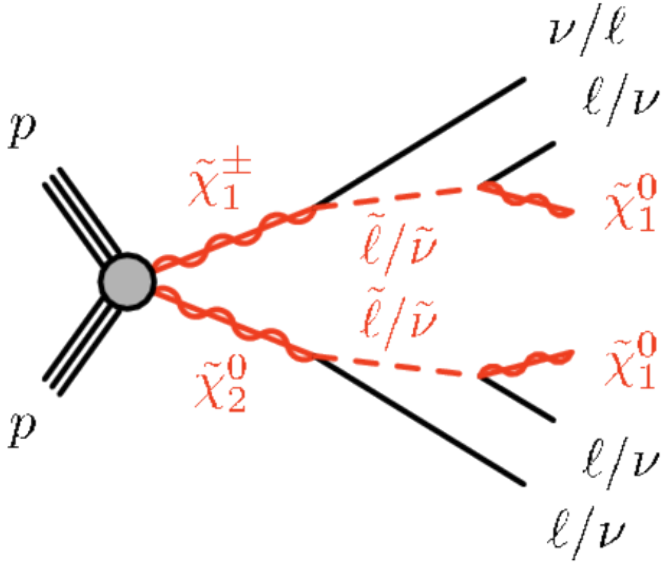
arXiv:1405.5086v2

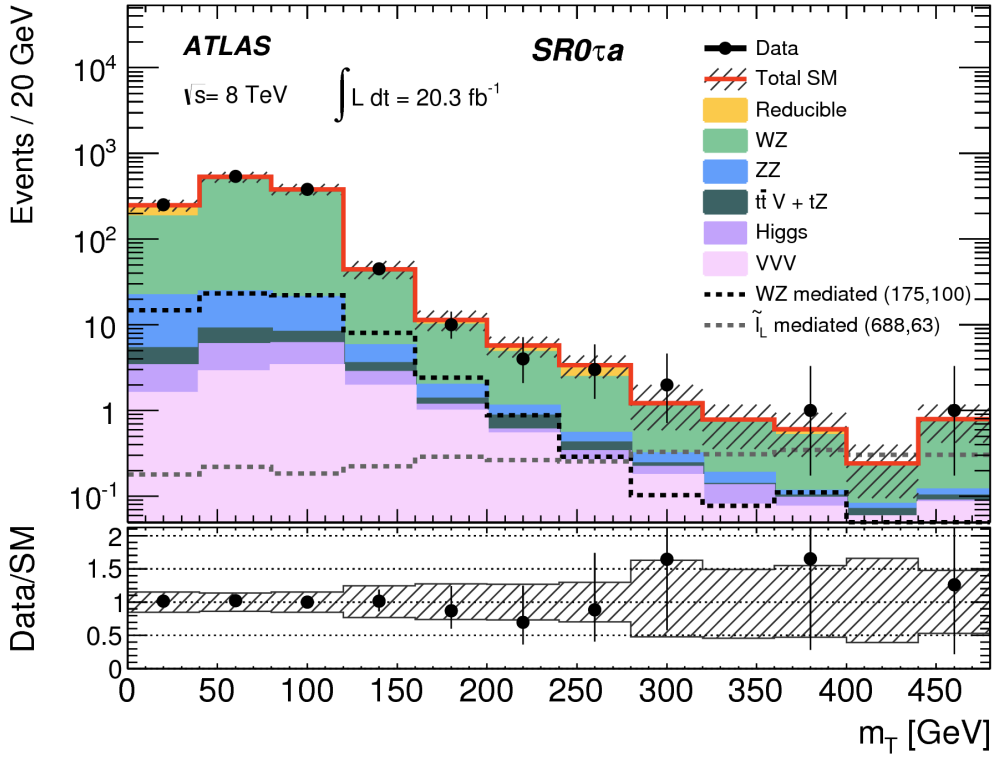
	$ZZ/Z\gamma^*$	tWZ	$t\bar{t}+Z$	VVV	Higgs	Reducible	Σ SM	Data
SR0noZa	0.29 ± 0.08	0.067 ± 0.033	0.8 ± 0.4	0.19 ± 0.09	0.27 ± 0.23	$0.006^{+0.164}_{-0.006}$	1.6 ± 0.5	3
SR1noZa	0.52 ± 0.07	0.054 ± 0.028	0.21 ± 0.08	0.14 ± 0.07	0.40 ± 0.33	$3.3^{+1.3}_{-1.1}$	$4.6^{+1.3}_{-1.2}$	4
SR2noZa	0.15 ± 0.04	0.023 ± 0.012	0.13 ± 0.10	0.051 ± 0.024	0.20 ± 0.16	3.4 ± 1.2	$4.0^{+1.2}_{-1.3}$	7
SR0noZb	0.19 ± 0.05	0.049 ± 0.024	0.68 ± 0.34	0.18 ± 0.07	0.22 ± 0.20	$0.06^{+0.15}_{-0.06}$	1.4 ± 0.4	1
SR1noZb	$0.219^{+0.036}_{-0.035}$	0.050 ± 0.026	0.17 ± 0.07	0.09 ± 0.04	0.30 ± 0.26	$2.1^{+1.0}_{-0.9}$	$2.9^{+1.0}_{-0.9}$	1
SR2noZb	$0.112^{+0.025}_{-0.024}$	0.016 ± 0.009	$0.27^{+0.28}_{-0.27}$	0.040 ± 0.018	0.13 ± 0.12	$2.5^{+0.9}_{-1.0}$	3.0 ± 1.0	6
SR0Z	$1.09^{+0.26}_{-0.21}$	0.25 ± 0.13	2.6 ± 1.2	1.0 ± 0.5	$0.60^{+0.22}_{-0.21}$	$0.00^{+0.09}_{-0.00}$	5.6 ± 1.4	7
SR1Z	$0.59^{+0.11}_{-0.10}$	0.042 ± 0.022	0.41 ± 0.19	0.22 ± 0.11	0.14 ± 0.05	1.0 ± 0.5	2.5 ± 0.6	3
SR2Z	$0.70^{+0.12}_{-0.11}$	0.0018 ± 0.0015	0.035 ± 0.024	0.039 ± 0.014	$0.14^{+0.04}_{-0.05}$	0.9 ± 0.5	1.8 ± 0.5	1

SUSY search in trilepton

ATLAS-CONF-2013-035

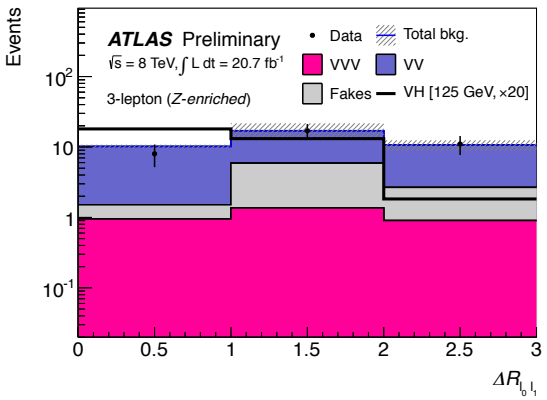
- Search for direct production of charginos and neutralinos in events with three leptons and missing transverse momentum

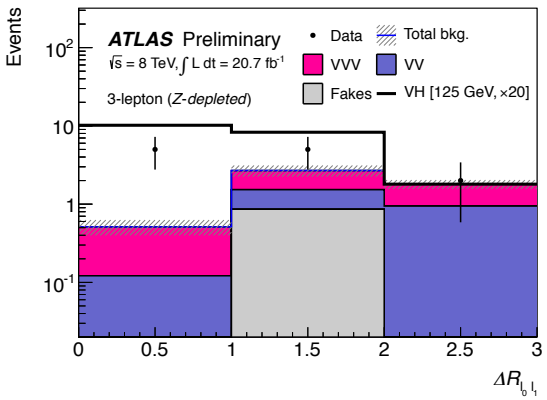


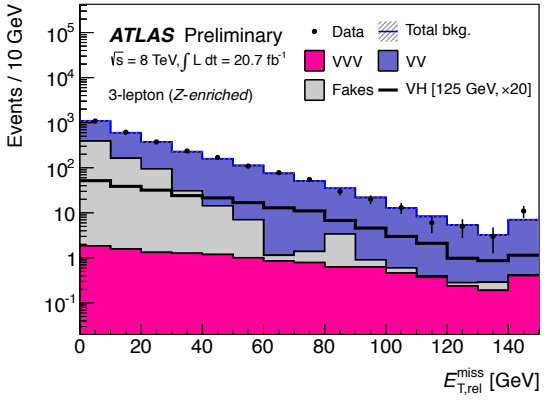


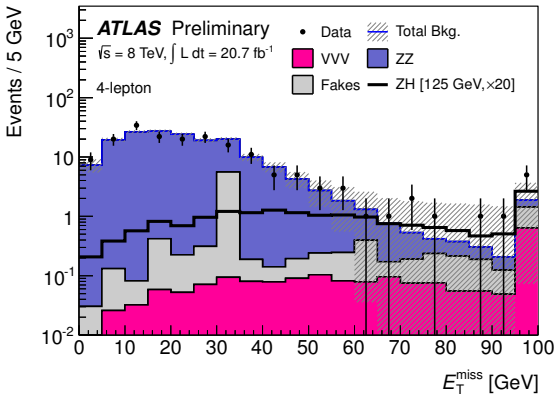
More control plots in VH->VWW analysis

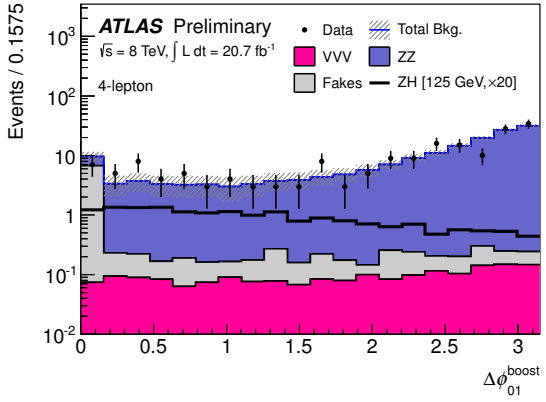
ATLAS-CONF-2013-075

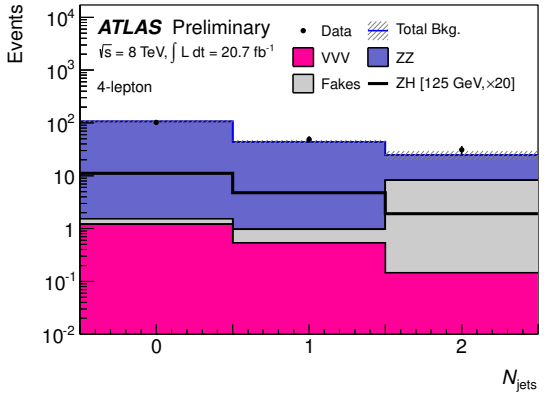












VH analysis: definition of CRs

- 3-lepton analysis

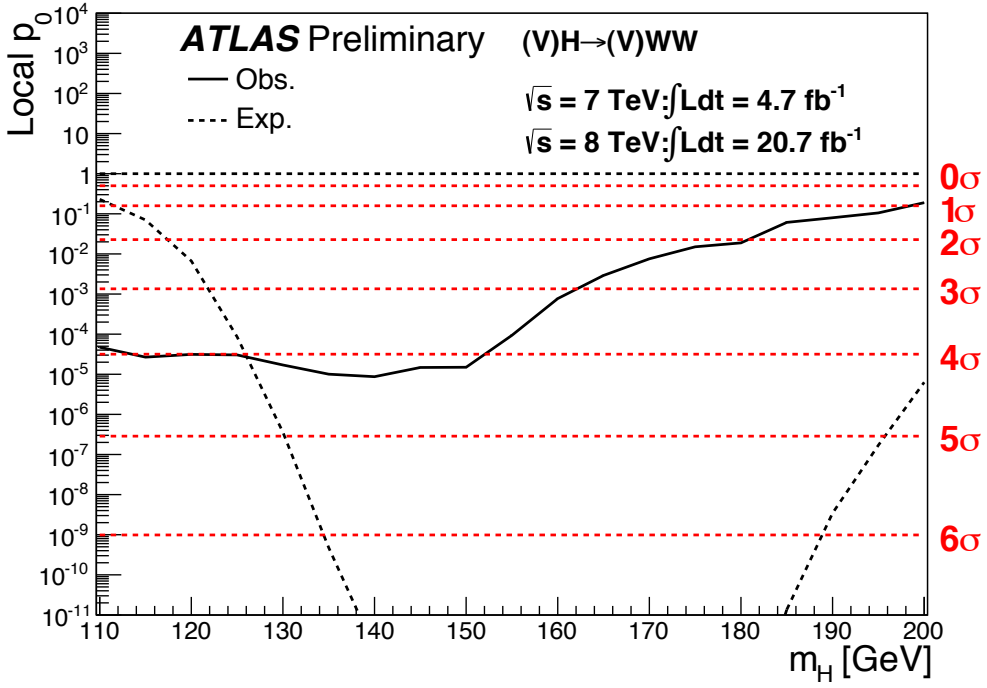
Control Region	Selections	
$W(Z/\gamma^*)$ CR	at most one jet with $p_{\mathrm{T}} > 25$ GeV;	$E_{\mathrm{T,rel}}^{\mathrm{miss}} > 25$ GeV at least one SFOS lepton pair with $\lvert m_{\ell\ell} - m_Z \rvert < 25$ GeV
$ZZ^{(*)}$ CR	no b-tagged jets with $p_{\mathrm{T}} > 25$ GeV;	$E_{\mathrm{T,rel}}^{\mathrm{miss}} < 40$ GeV $\lvert m_{\ell\ell\ell} - m_Z \rvert < 15$ GeV
Z+jets CR	$m_{\ell\ell,\mathrm{min}} > 12$ GeV; $\Delta R_{\ell_0\ell_1} < 2.0$	$E_{\mathrm{T,rel}}^{\mathrm{miss}} < 40$ GeV at least one SFOS lepton pair with $\lvert m_{\ell\ell} - m_Z \rvert < 25$ GeV
Top CR	at least one b-tagged jet with $p_{\mathrm{T}} > 25$ GeV $m_{\ell\ell,\mathrm{min}} > 12$ GeV; $\Delta R_{\ell_0\ell_1} < 2.0$	$E_{\mathrm{T,rel}}^{\mathrm{miss}} > 40$ GeV all SFOS lepton pairs with $\lvert m_{\ell\ell} - m_Z \rvert > 25$ GeV

- 4-lepton analysis

	Selection
ZZ CR	2 SFOS pairs of isolated leptons highest p_{T} lepton: $p_{\mathrm{T}} > 25$ GeV second highest p_{T} lepton: $p_{\mathrm{T}} > 20$ GeV third highest p_{T} lepton: $p_{\mathrm{T}} > 15$ GeV fourth highest p_{T} lepton: $p_{\mathrm{T}} > 10$ GeV at most one jet with $p_{\mathrm{T,jet}} > 25$ GeV no b–tagged jets with $p_{\mathrm{T}} > 25$ GeV $\lvert m_{\ell_2\ell_3} - m_Z \rvert < 10$ GeV $m_{\ell_0\ell_1} > 65$ GeV overlap removal with dilepton analysis

Significance of VH->VWW

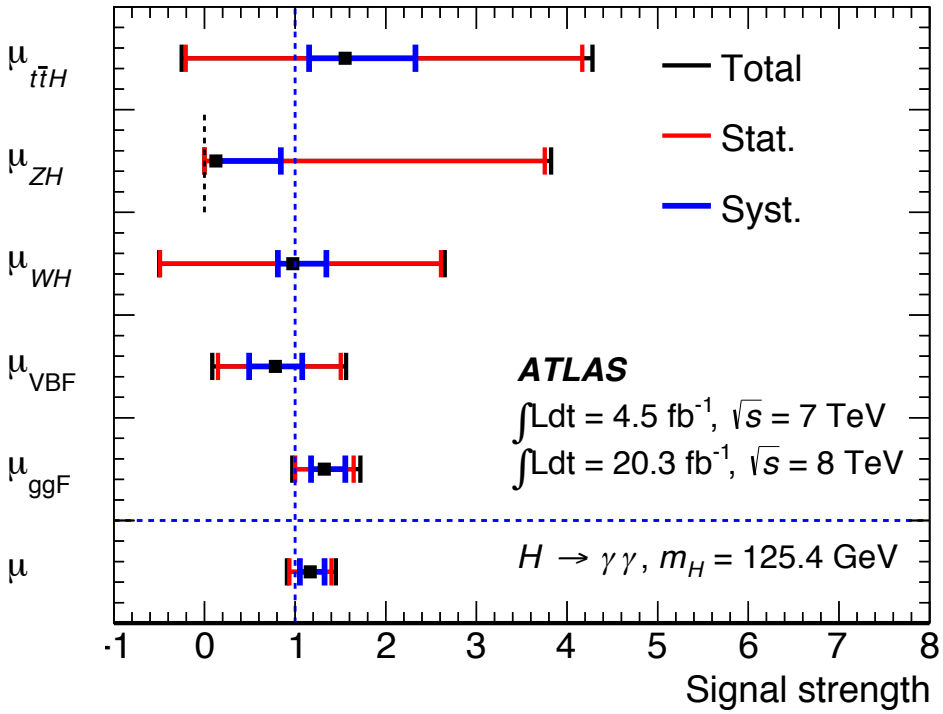
ATLAS-CONF-2013-075

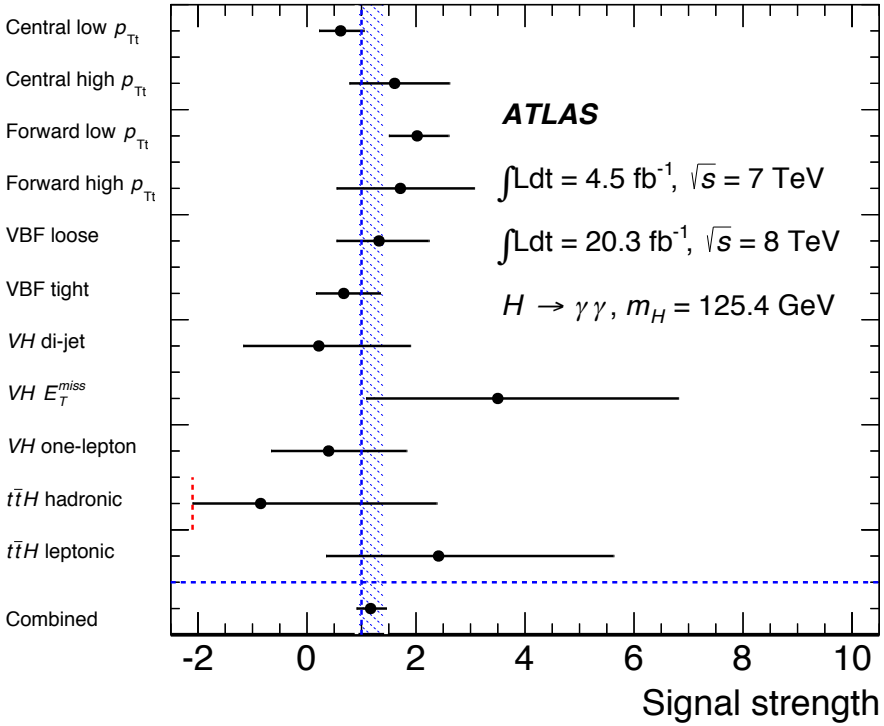


significance (σ)	VH	$H\rightarrow WW^{(*)}$ [6]	Combined
expected	0.7	3.7	3.8
observed	2.0	3.8	4.0

Signal strength in VH(gg) analysis

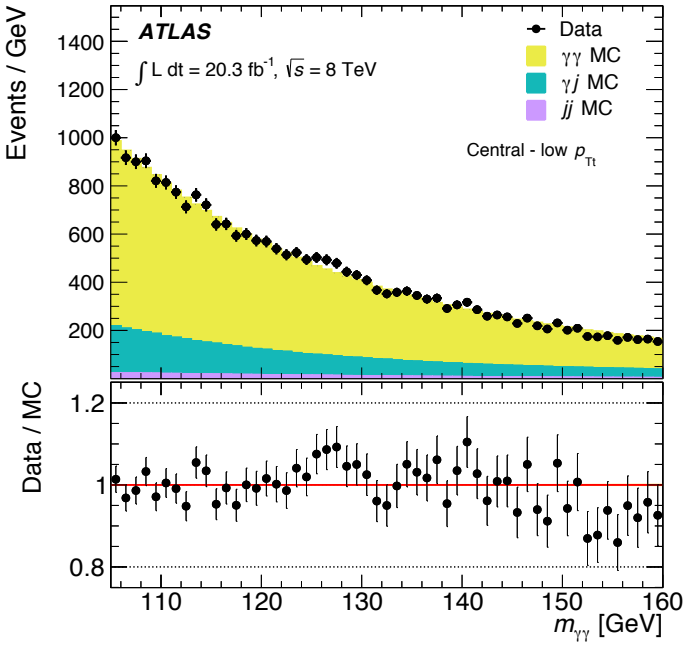
arXiv:1408.7084v2



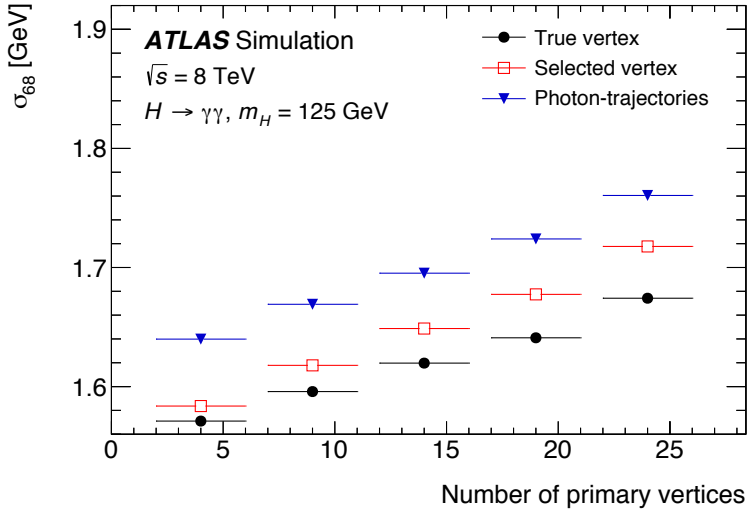


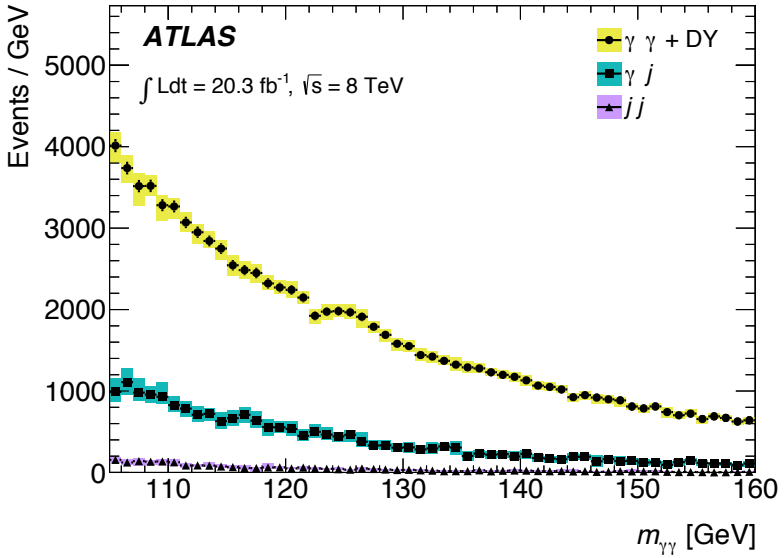
Photon fake background in H(gg)

arXiv:1408.7084v2



gg = 84 ± 8%,
gj = 15 ± 8 %
jj = 1 ± 1 %

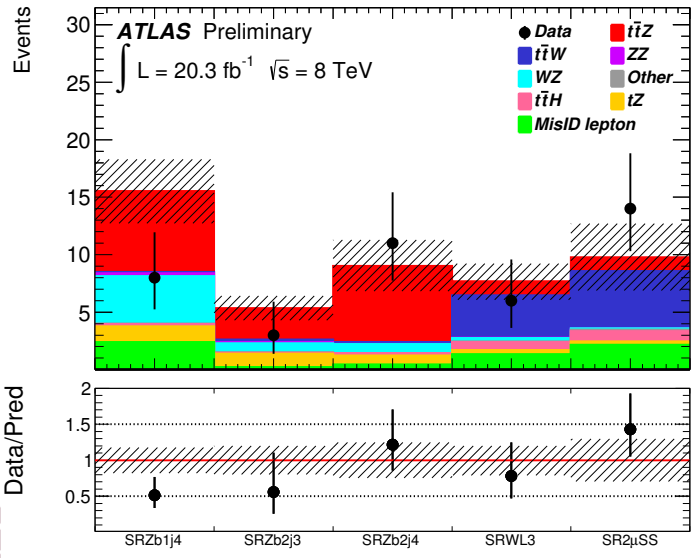


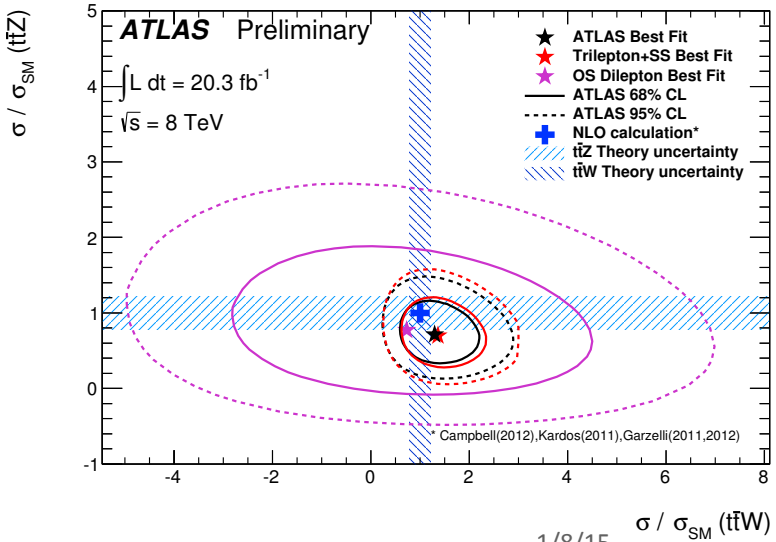


Additional ttV materials

ATLAS-CONF-2014-038

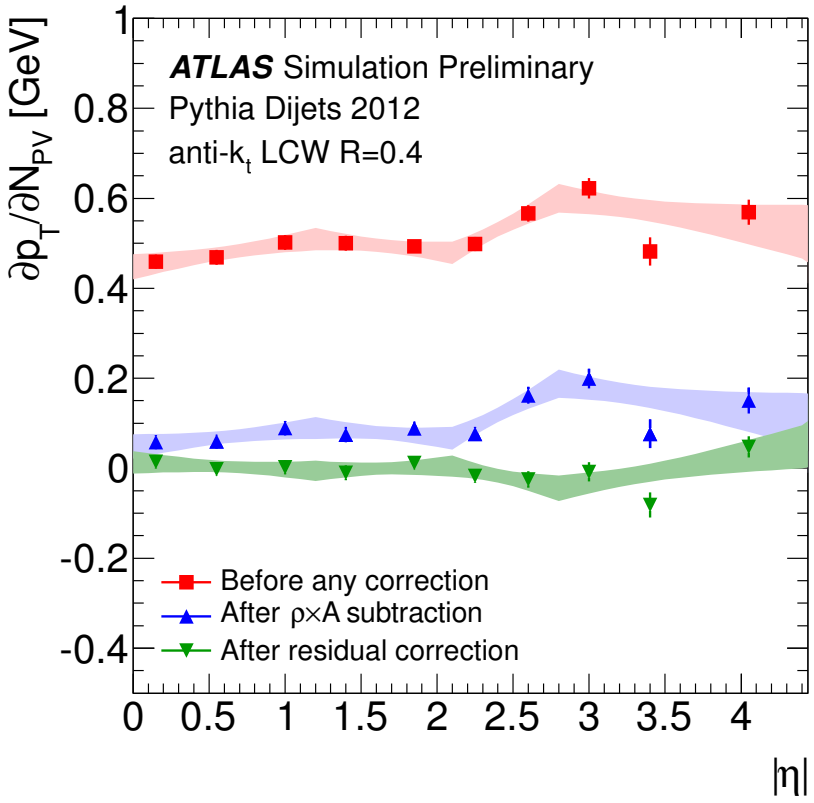
	Trilepton and same-sign dilepton			Opposite-sign dilepton	
Analysis strategy	comparable signal and background: cut and count			small signal in huge background multivariate techniques	
	3ℓZ	3ℓZveto	2μSS	2ℓOSZveto	2ℓOSZ
Z-mass selection	$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV	$\lvert m_{\ell\ell} - m_Z \rvert > 10$ GeV	-	$\lvert m_{\ell\ell} - m_Z \rvert > 10$ GeV	$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV
Additional selection			$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV $H_{\mathrm{T}} > 240$ GeV	$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV$_{(ee,\,\mu\mu)}$ $H_{\mathrm{T}} > 130$ GeV$_{(e\mu)}$ $\Delta R_{\mathrm{ave}}^{\mathrm{jj}} > 0.75$	$\Delta R_{\mathrm{ave}}^{\mathrm{jj}} > 0.75$
Lepton flavour Signal Main background	all trilepton $t\bar{t}Z$ tZ, WZ and fakes	all trilepton $t\bar{t}W$ dominated $t\bar{t}Z$, $t\bar{t}H$ and fakes	$\mu\mu$ $t\bar{t}W$ dominated $t\bar{t}Z$, $t\bar{t}H$ and fakes	all dilepton $t\bar{t}Z$ and $t\bar{t}W$ $t\bar{t}$+jets	ee, $\mu\mu$ $t\bar{t}Z$ dominated Z+jets
Validation regions	(3j + 2j + 1j, 1b) (CRZ)	(1b) (CRW)	$E_{\mathrm{T}}^{\mathrm{miss}} < 40$ GeV		
Regions in the fit (**Signal region**, control region)	**(≥ 4j, 1b) (SRB1J4)** **(3j, ≥ 2b) (SRB2J3)** **(≥ 4j, ≥ 2b) (SRB2J4)**	**(3j + 2j, ≥ 2b) (SRW3ℓ)**	**(≥ 2j, ≥ 2b) (SR2μSS)**	(3j, 1b + 2b) **(4j, 1b + 2b)** **(≥ 5j, 1b + 2b)**	(3j, 2b) (4j, 2b) **(≥ 5j, 2b)**

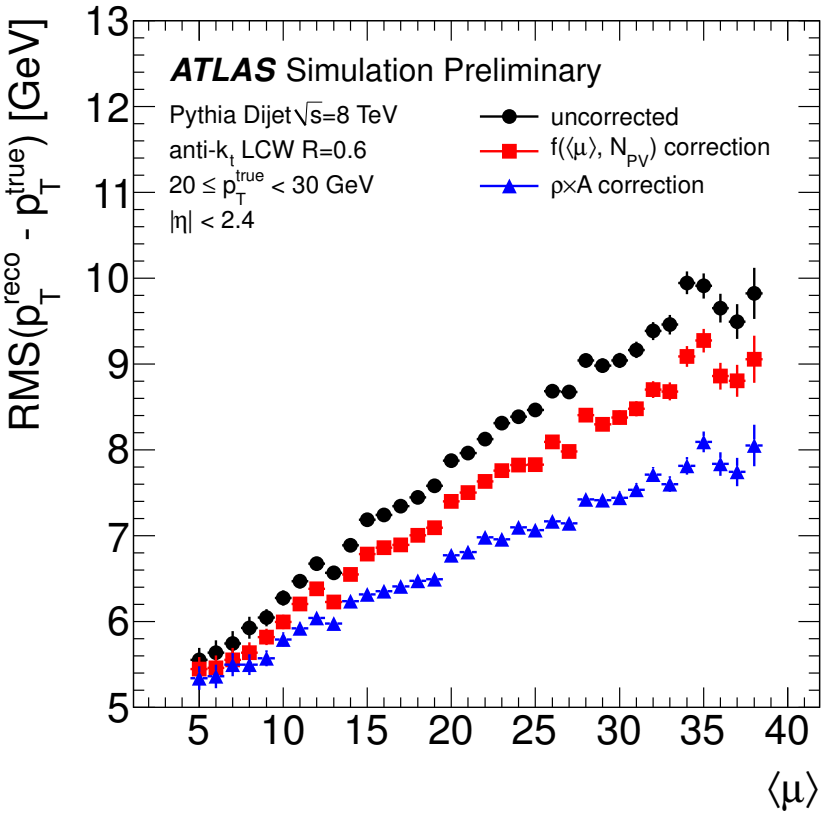




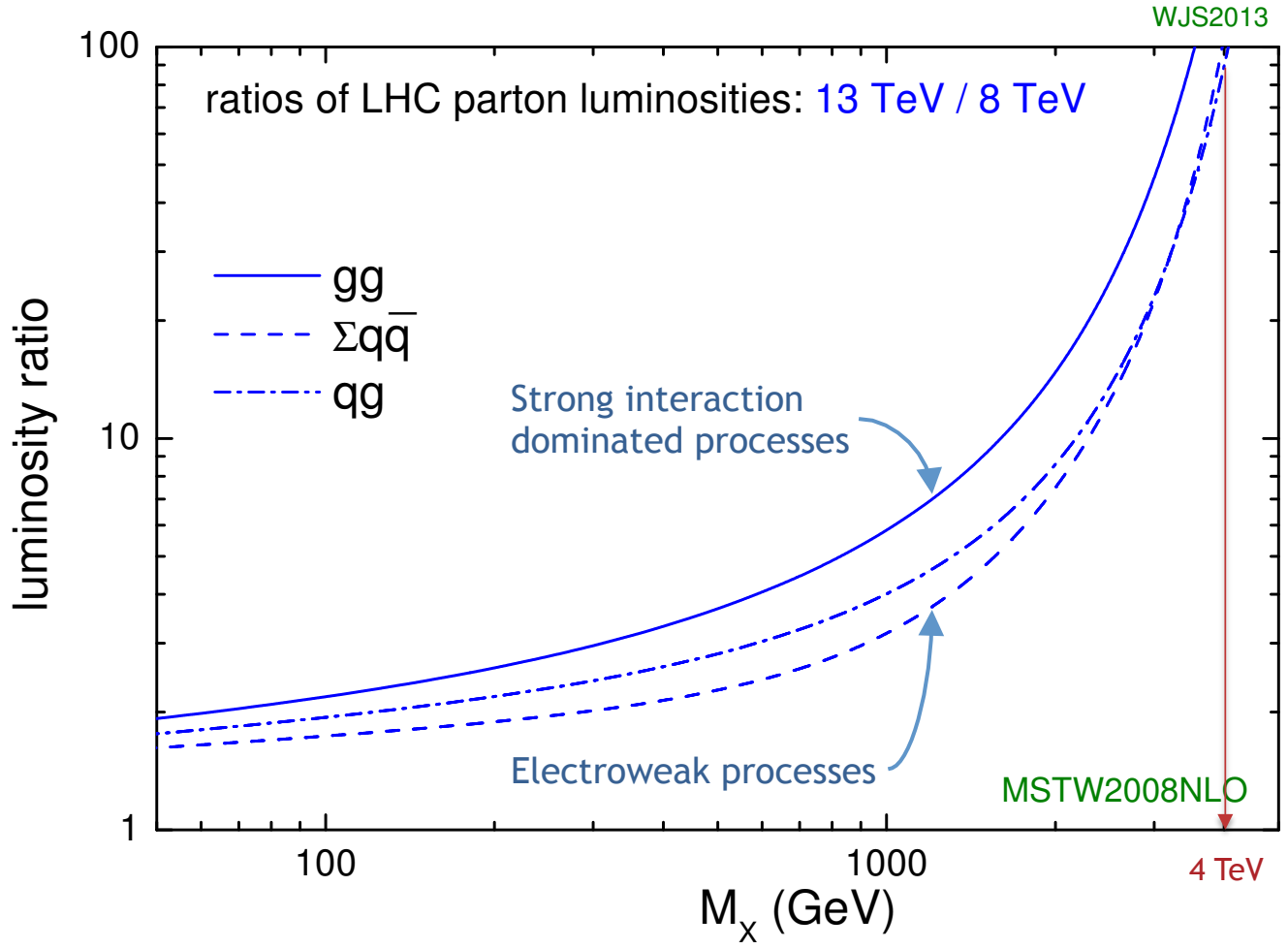
Jet pile-up subtractions

ATLAS-CONF-2013-083

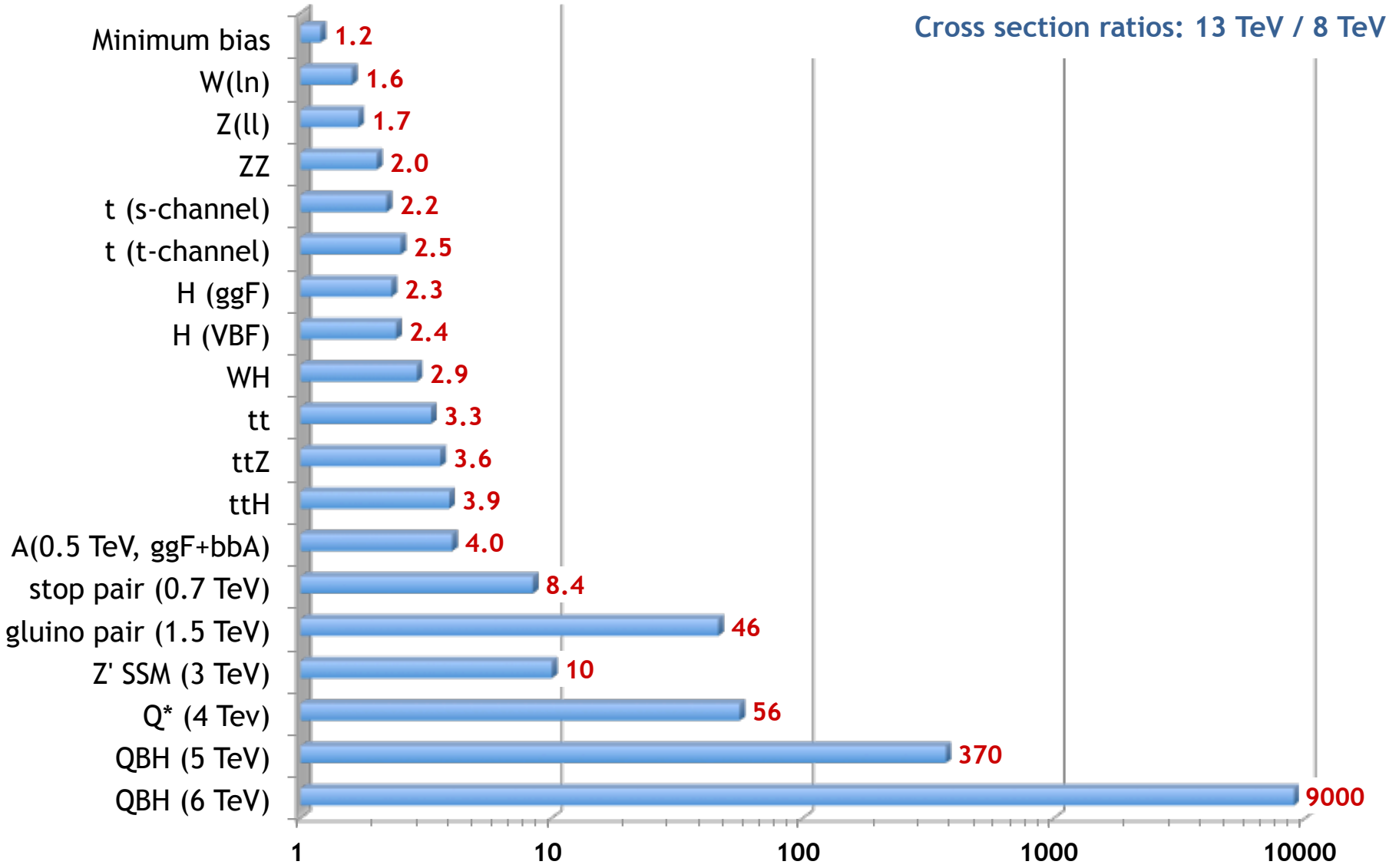




Luminosity scaling



Cross section ratio



Standard Model Production Cross Section Measurements

Status: July 2014