Search for new SM Higgs production mechanisms and (B)SM decays

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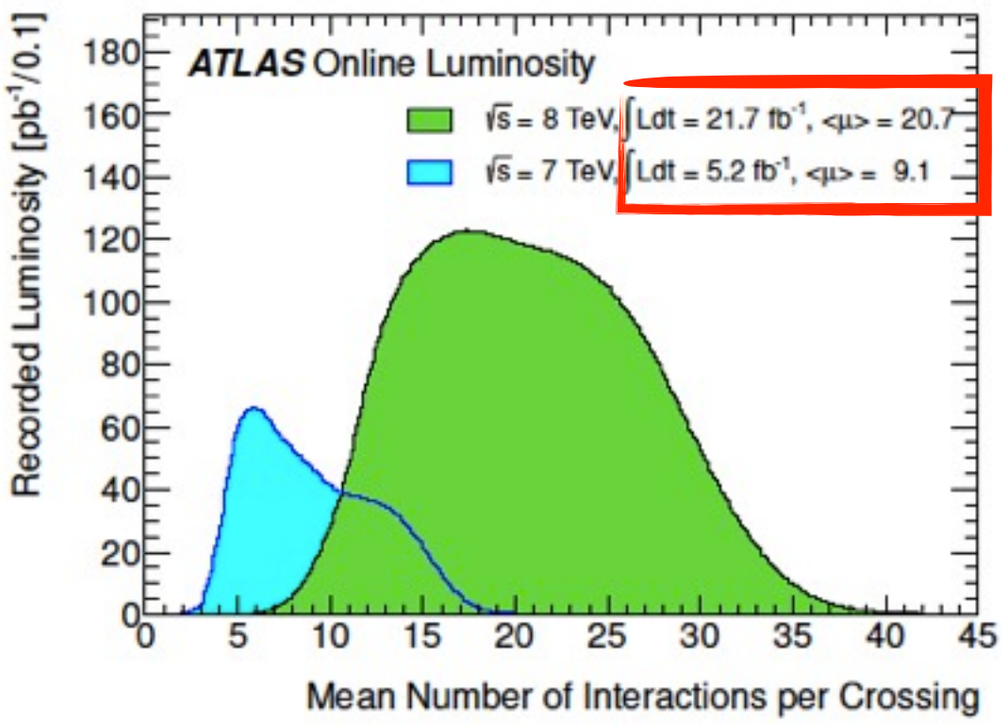
Outline

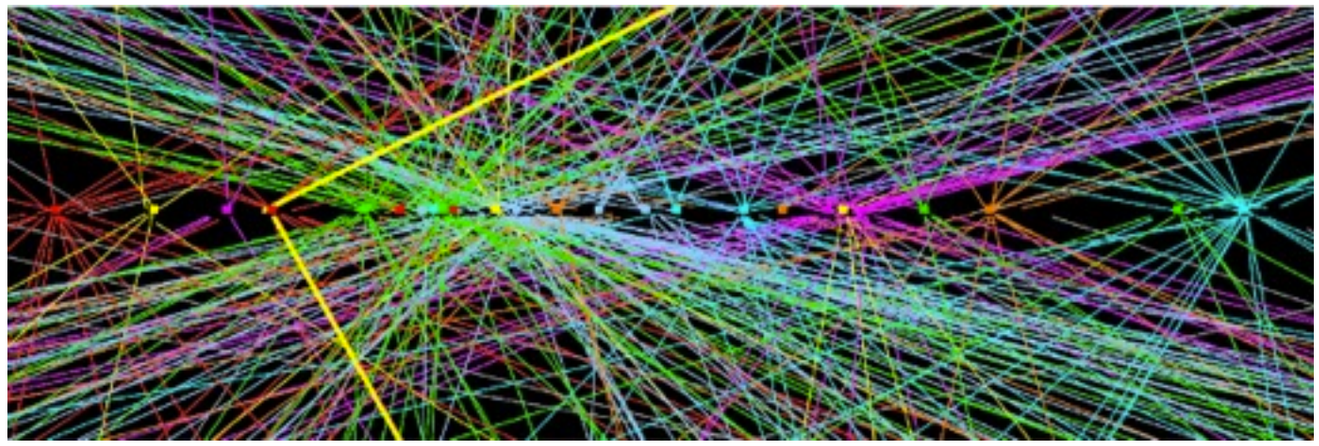
- ATLAS, LHC @ CERN
- rare Standard Model production mechanisms
  - latest results
- rare Standard Model decays
  - latest results
  - future projections
- (beyond Standard Model Higgs searches)

LHC, Run1

- Large Hadron Collider, Geneva (CH) - 26.7km
  - pp @ $\sqrt{s}$ = 7 (8) TeV in 2010 & 2011 (2012)
  - collisions every 50 ns (20 MHz)
  - 1368 bunches ~10^{11} protons -> **pile up**
    - **simultaneous interactions in one bunch crossing**
  - **integrated Luminosity (L) ~25 fb^{-1}**
- **ATLAS** - 4π detector, 44x25m, 7000t

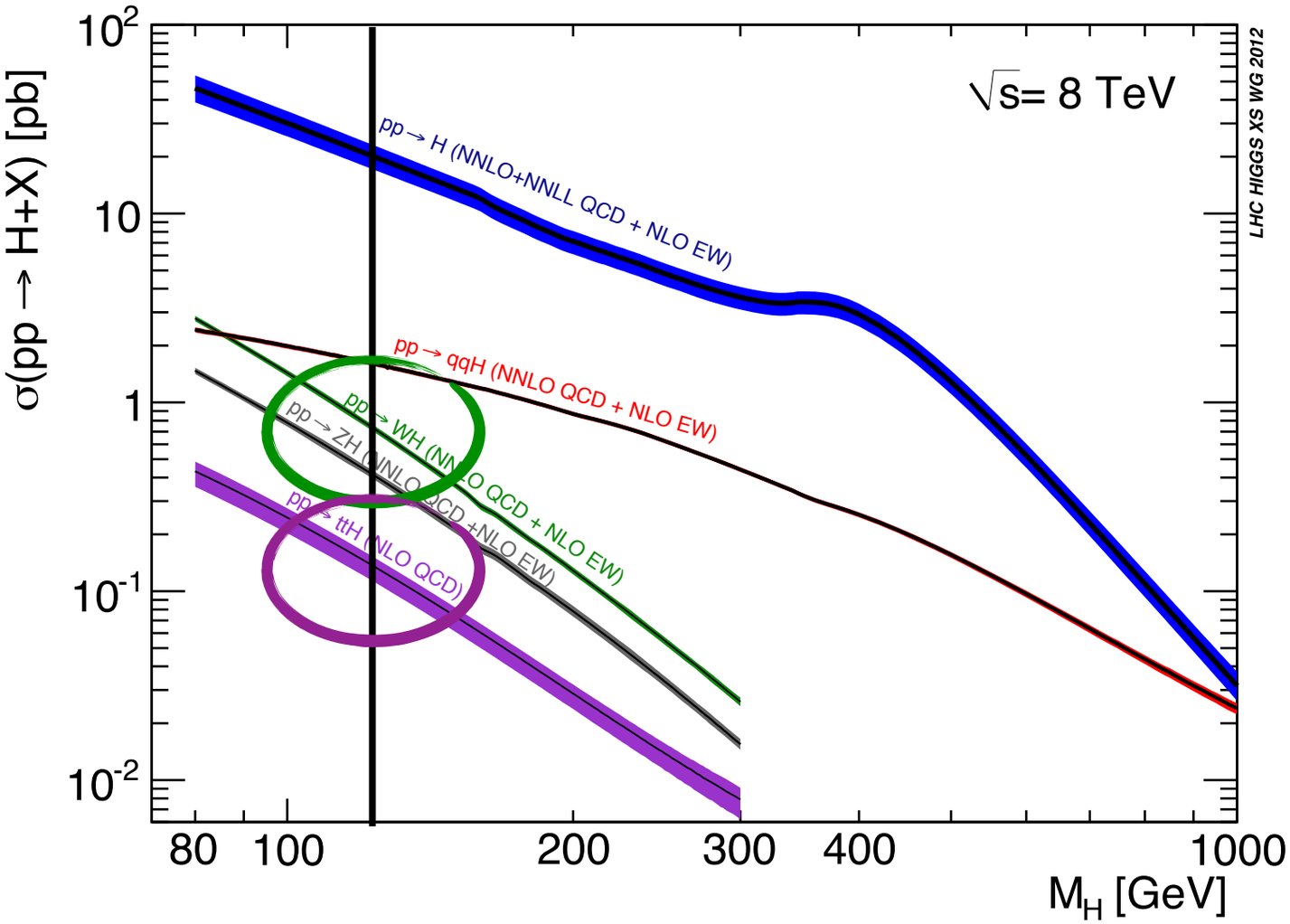
$$N = L * \sigma_{prod} * Br$$



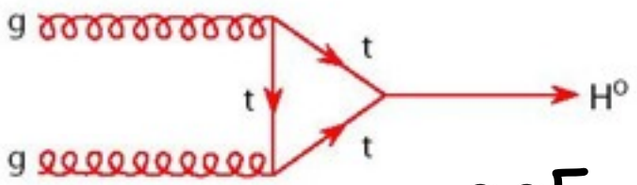


Higgs production

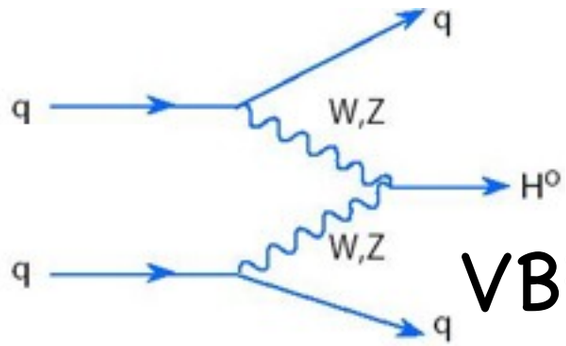
$$N = L * \sigma_{prod} * Br$$



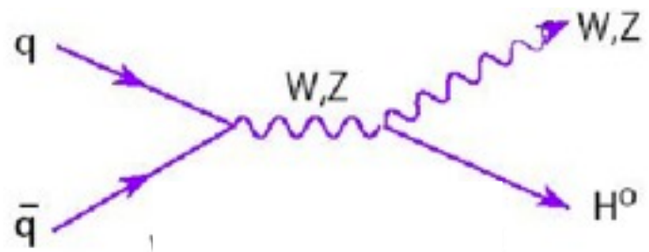
- main production modes:
  - gluon-gluon fusion (quark (top) loop) - ggF
  - vector boson fusion - VBF
- rare production modes:
  - vector boson associated production - VH
  - tt bar associated production - ttH



ggF



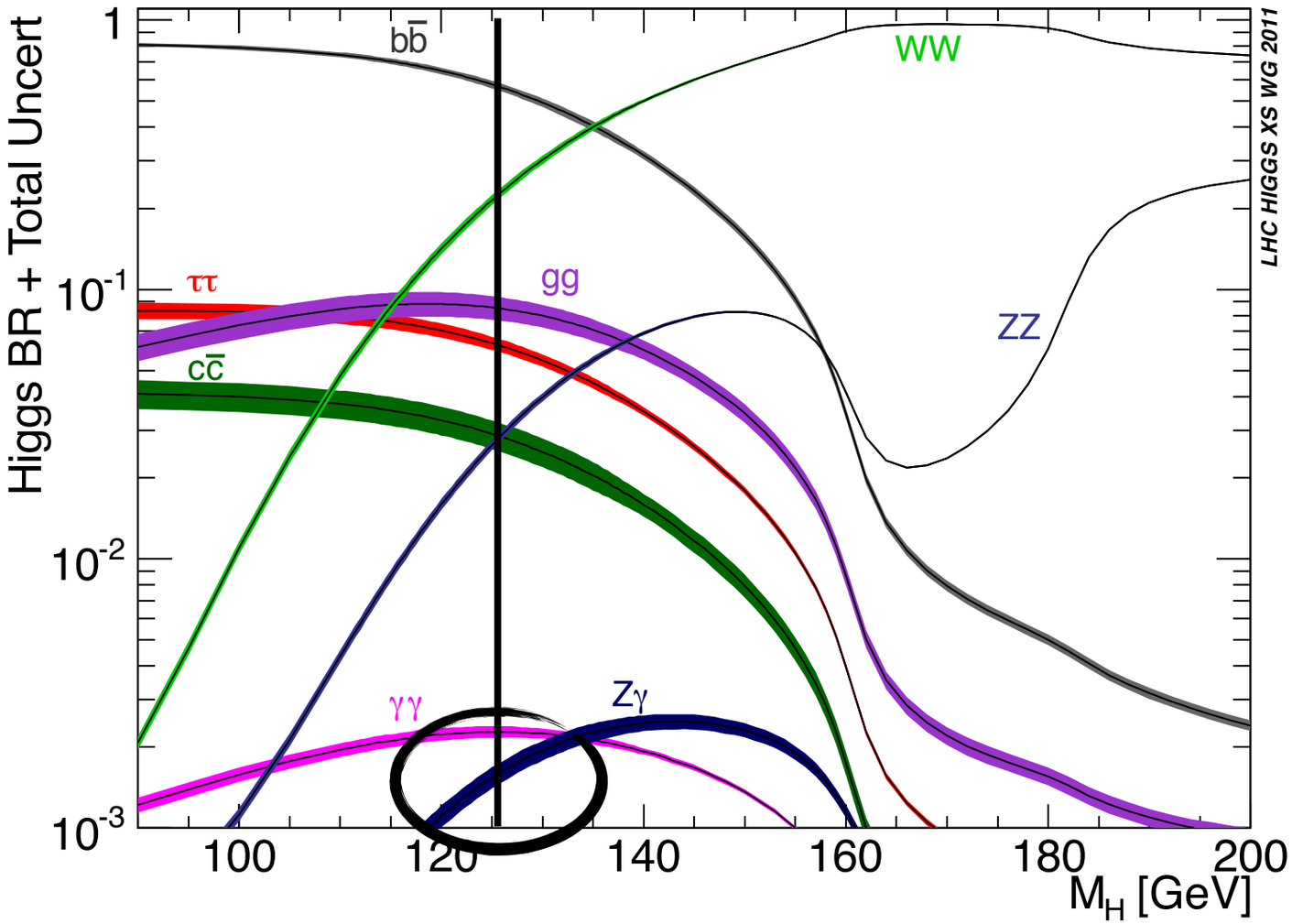
VBF



VH

Higgs decay

$$N = L^{*}\sigma_{prod}{}^{*}Br$$



- main decays:
  - H->bb .. 56.9%
  - H->WW .. 22.3%
  - H->gg .. 8.5%
  - H->ττ .. 6.2%
  - H->cc, ZZ .. ~3%
  - H->γγ .. 0.23%
- **rare decays:**
  - H->Zγ, J/Ψγ,Υγ
  - H->μμ
- double Higgs production -> Higgs self coupling

Zγ .. 0.16%, μμ .. 0.022%

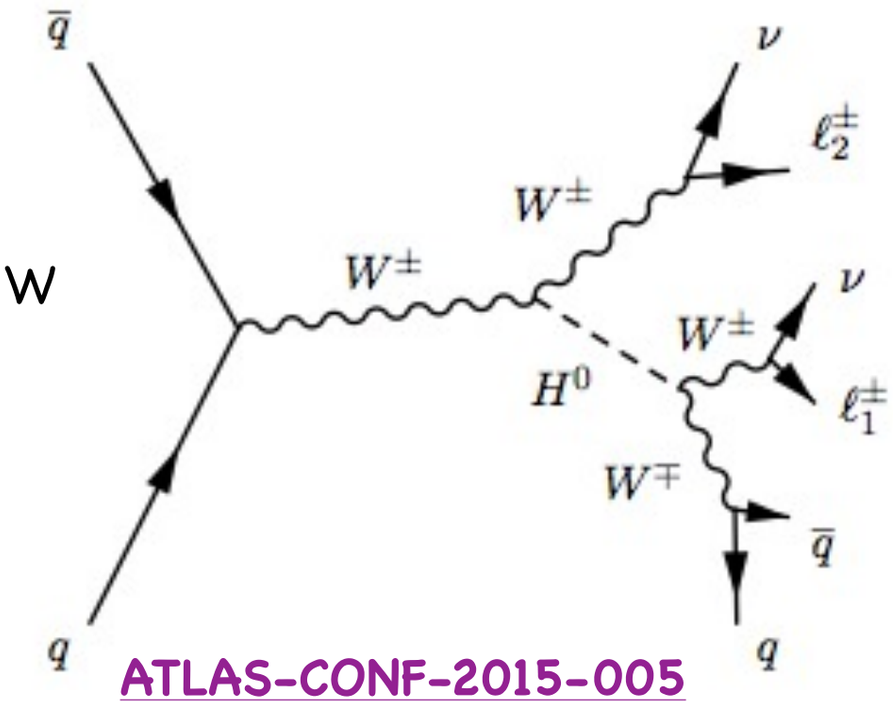
J/Ψγ .. 2.8×10^{-4}%,Υγ .. 1.5×10^{-7}%

Higgs Glossary

- Z_0 ... expected significance (importance of observation of an excess above background), discovery = 5σ
- μ ... signal strength in units of Standard Model, $\mu = 1$ for rates consistent with SM
  - $\Delta\mu$ ... uncertainty on μ
- κ, λ ... coupling constants (strength) defining interaction of particles
- κ_f - coupling of Higgs with fermions
- λ_{ttH} - coupling between Higgs and two top quarks
- "event classification" ... due to different amount of signal and backgrounds in different regions of phase space, events are categorized

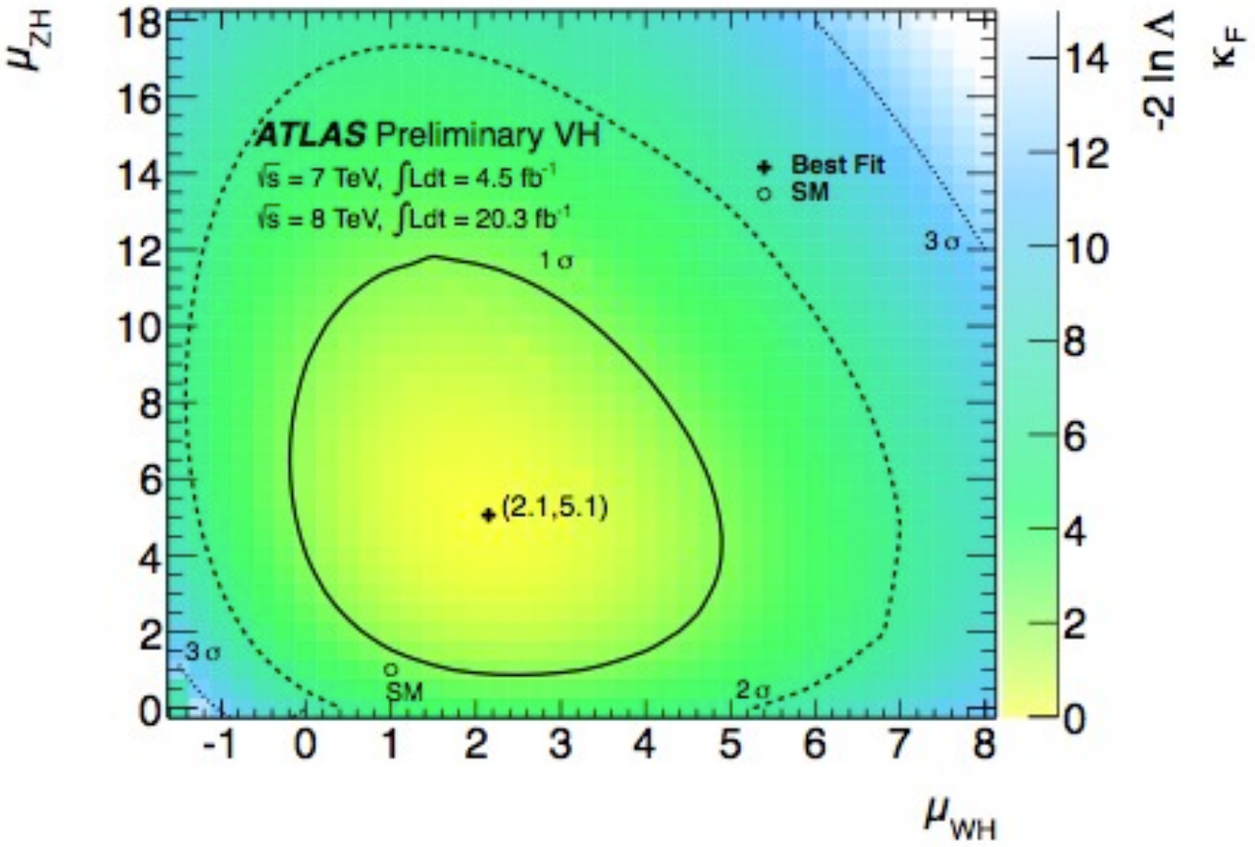
VH(->WW)

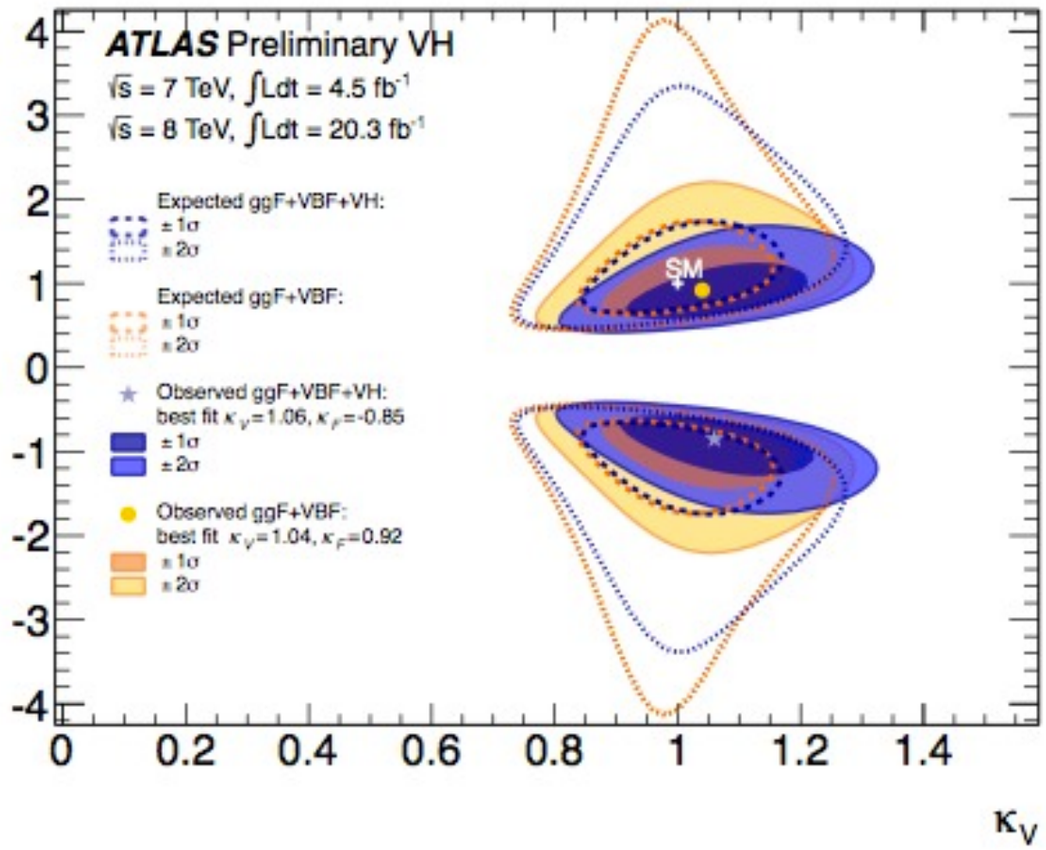
- sensitive only to gauge boson couplings, WH only to W (W->lν or qq)
- categories: 4l, 3l, 2l(+qq) - opp sign and same sign
- 7+8TeV analyses



ATLAS-CONF-2015-005

N^{sig}_{exp} ~ 10.5 evts





Z0 (ggF+VBF) ~6.1σ->

Z0 (ggF+VBF+VH) = 6.5σ

big improvement through VH in the coupling contour

ttH multilepton

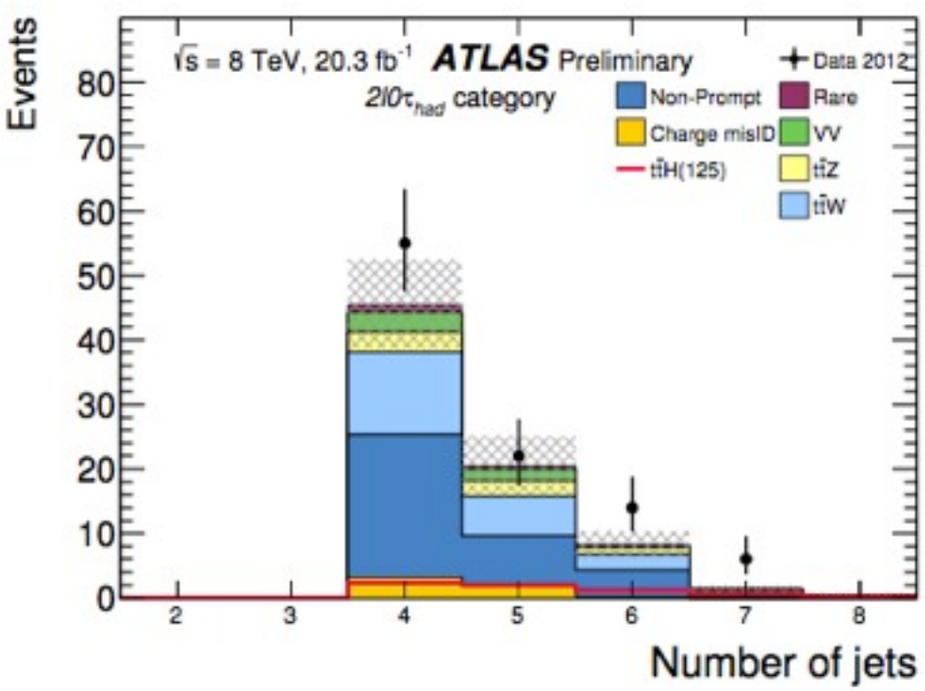
ATLAS-CONF-2015-006

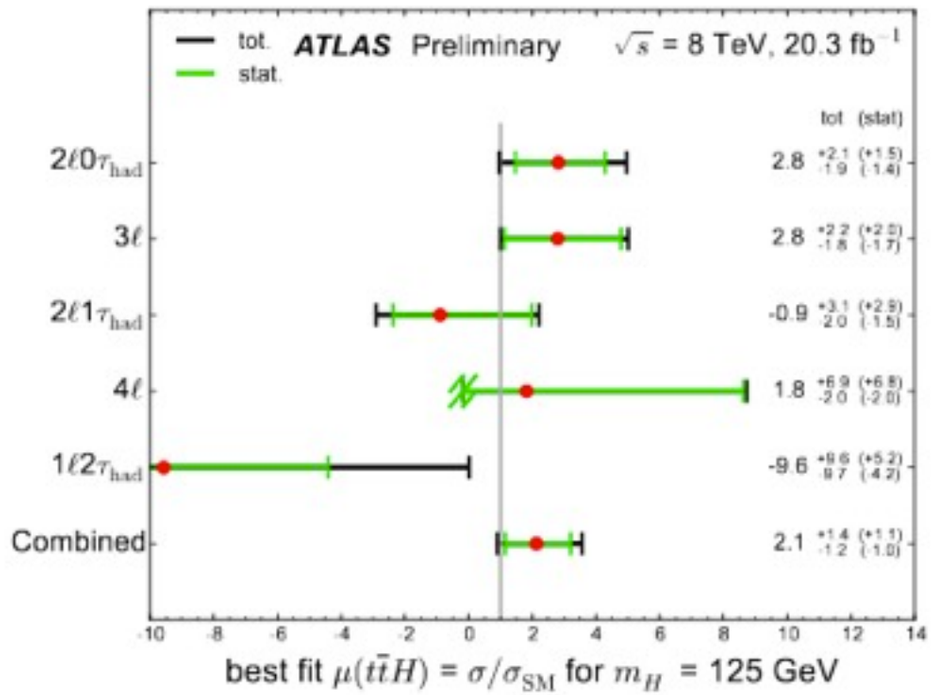
tree level measurement of λ_{ttH} with clean final states

- combination of direct & loop level measurements allows to search for new physics
- final states:
  - -> primary H decay targets are WW and ττ, together with the tt decays: WWWWbb/ττWWbb
    - -> bkg suppression of tt primarily (ttV, tZ, tt+jets; various lepton isolation and jet multiplicity/tagging criteria)
  - 8TeV analysis; event classification:
    - 2 $l^{\pm}l^{\pm}$ + 0/1 τ_{had}, lll, llll, l + 2 τ_{had}; l .. e/μ (p_T > 10 GeV)

Category	Higgs boson decay mode WW^*	$\tau\tau$	ZZ^*	Other
$2\ell 0\tau_{had}$	80%	15%	3%	2%
3ℓ	74%	15%	7%	4%
$2\ell 1\tau_{had}$	35%	62%	2%	1%
4ℓ	69%	14%	14%	4%
$1\ell 2\tau_{had}$	4%	93%	0%	3%

H decay fractions

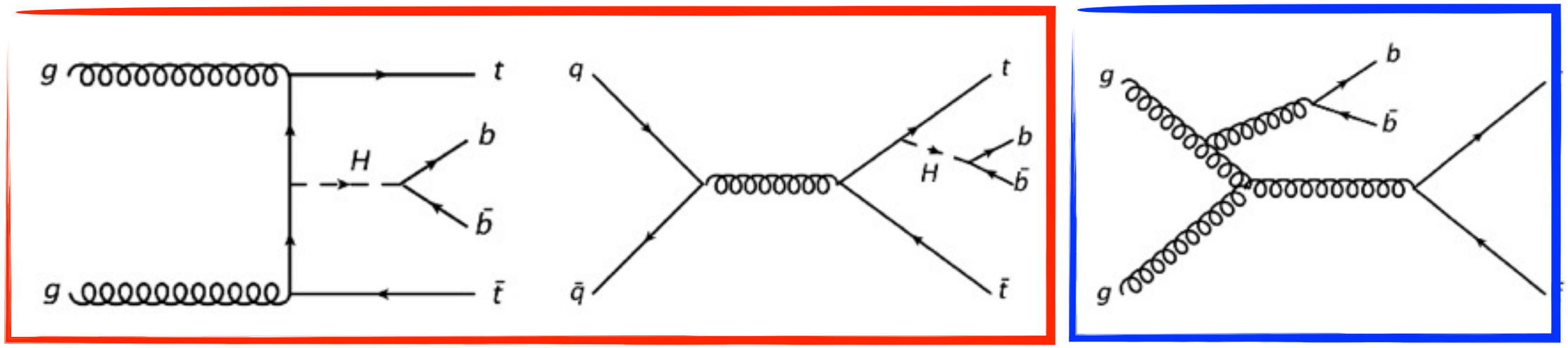




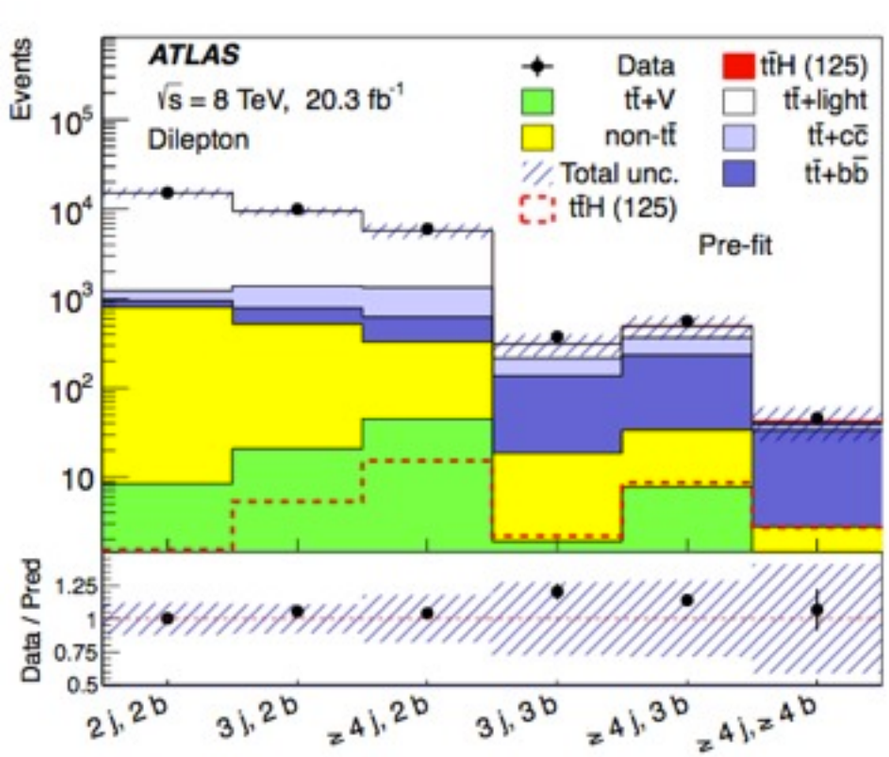
$\mu(ttH) = 2.1^{+1.4}_{-1.2}$

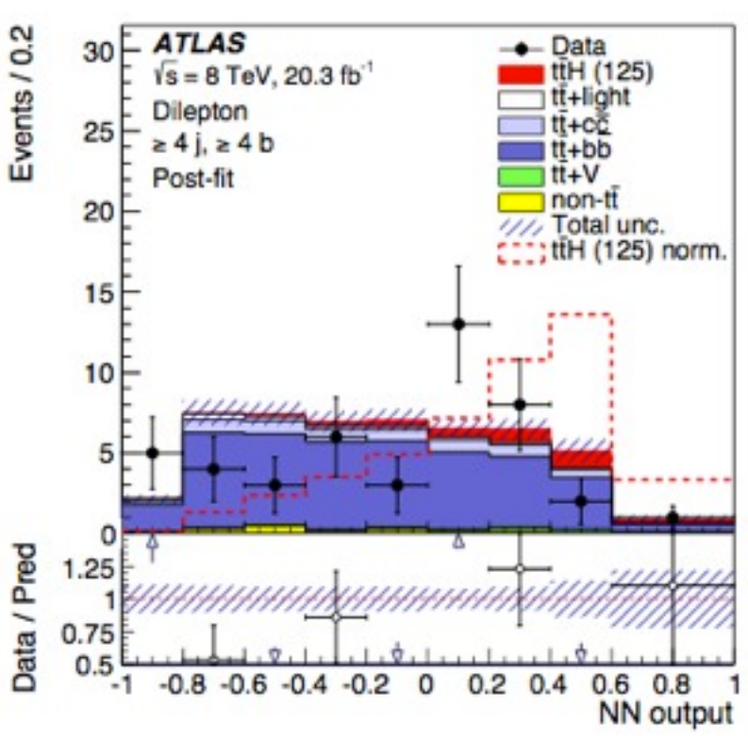
ttH(->bb)

arXiv:1503.05066



- tree level measurement of λ_{ttH} with strongest decay channel (H->bb)
- 8TeV dataset, main bkg: tt+bb, tt+light, tt+cc
- Neural Network (NN, based on Σp_T), #light and bjets make the classification



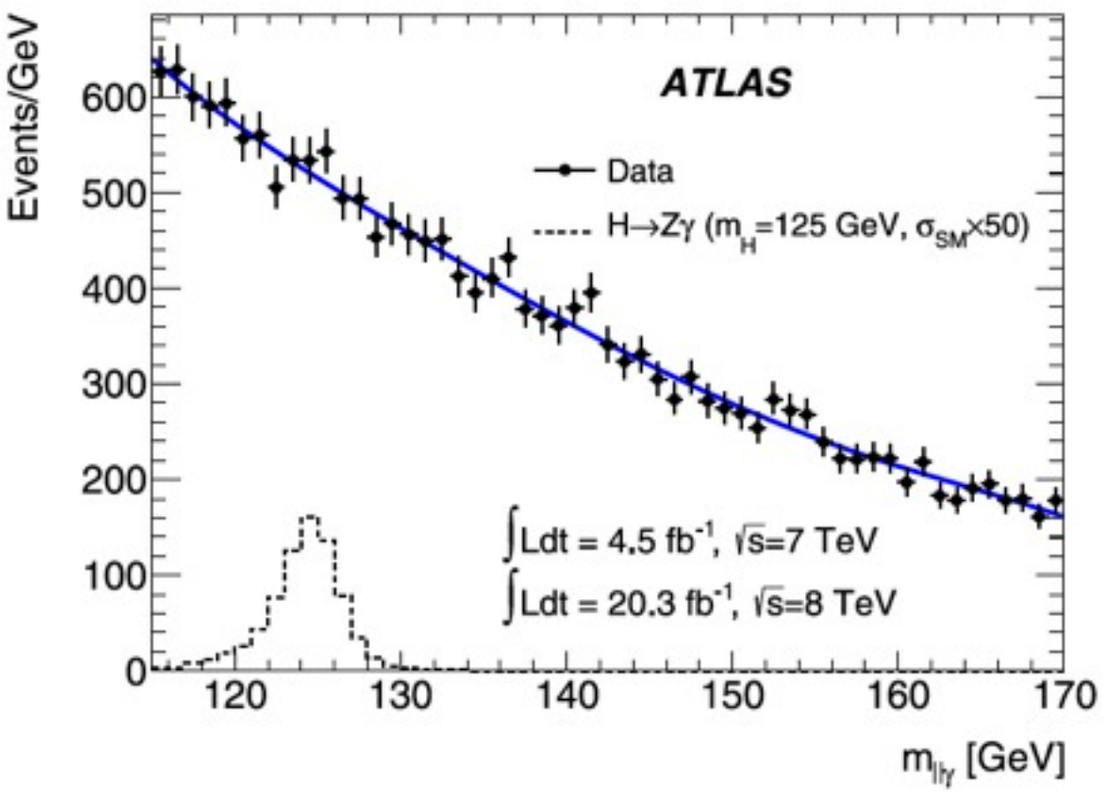


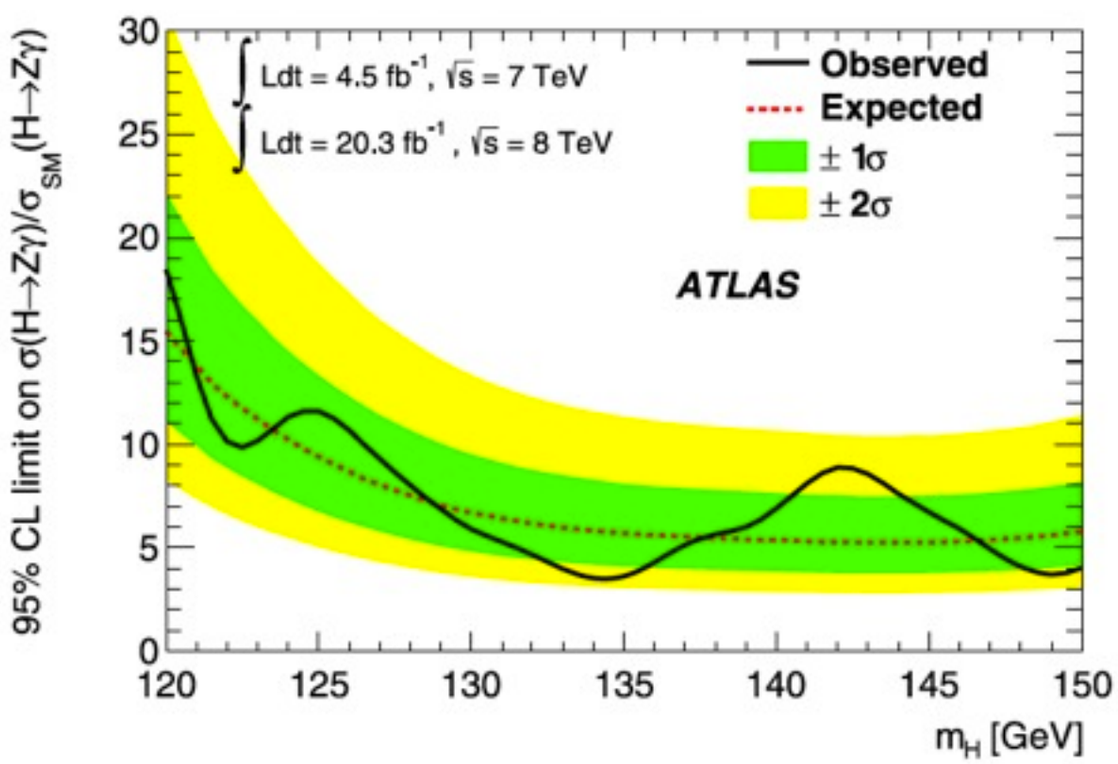
$\mu(ttH) = 1.5 \pm 1.1$

H->Zγ

arXiv:1402.3051

- loop-induced decay, sensitive to BSM physics
- 7&8 TeV; not "rare" per-se, but through Br(Z->ll) - 6.7% (to kill bkg).. ee and $\mu\mu$ categories (7 and 8 TeV) => 4 categories
- p_{Tl} > 10 GeV, $p_{T\gamma}$ > 15 GeV, isolation and m_{ll} cuts
- bkg: continuum Zγ, radiative Z->llγ, Z->ll+jets





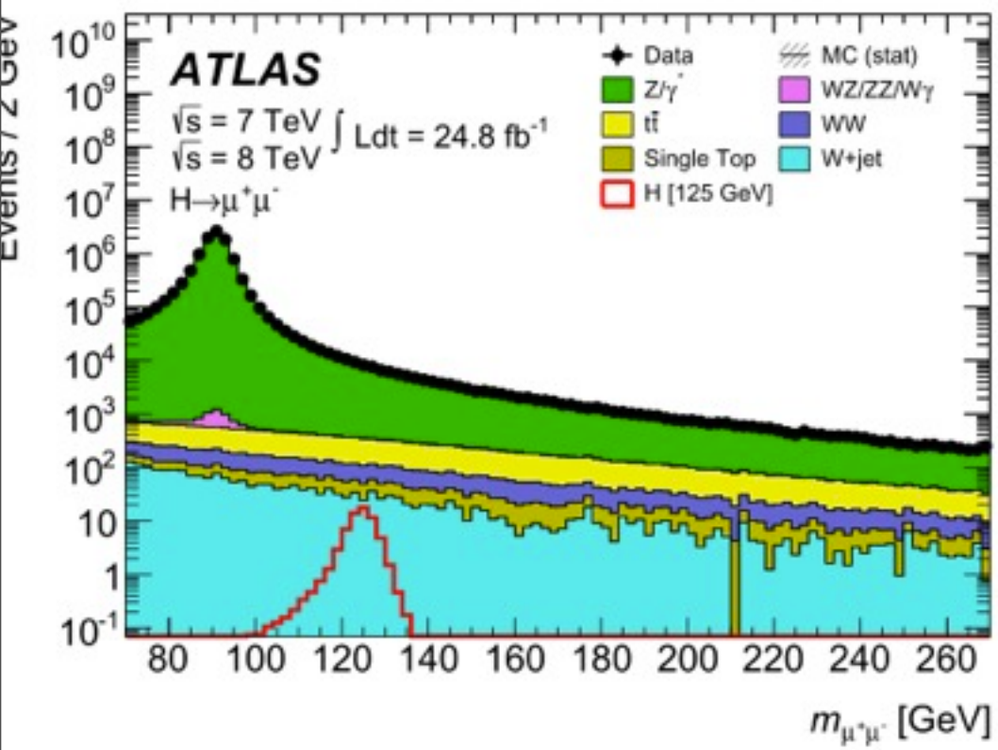
@125.5 GeV, limit 9x (11x) SM expected (observed)

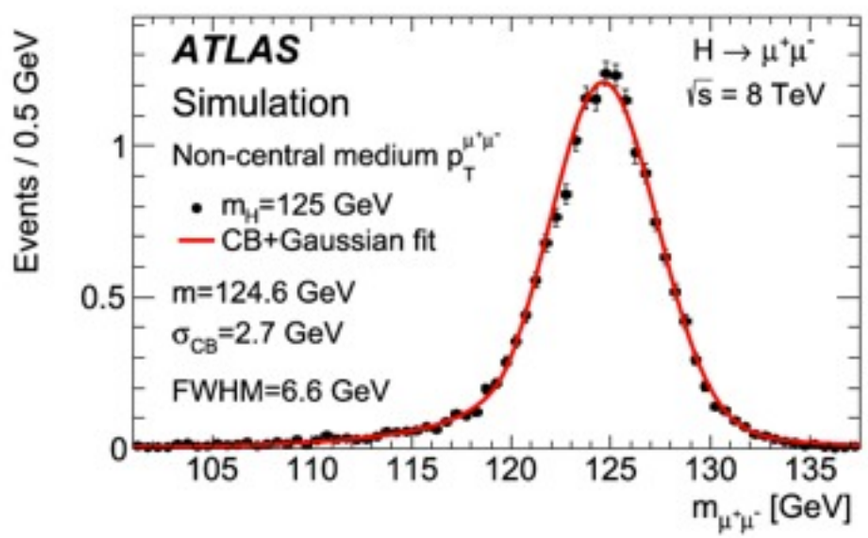
limit on σxBr @125.5 GeV is 0.33 (0.45) pb for 8TeV

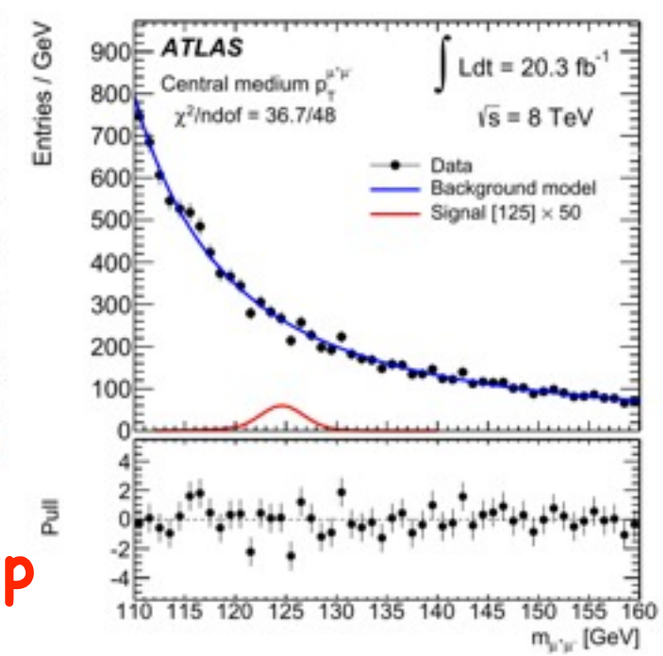
H->μμ

arXiv:1406.7663

- unique opportunity to measure $\lambda_{H\mu\mu}$
- clean signature but overwhelming background, 7+8 TeV dataset
- irreducible Z/y* -> μμ background by 3 orders of magnitude higher -> S/B ~0.4%
- 7 categories based on $p_{T\mu\mu}$ and $|\eta_\mu|$ + VBF



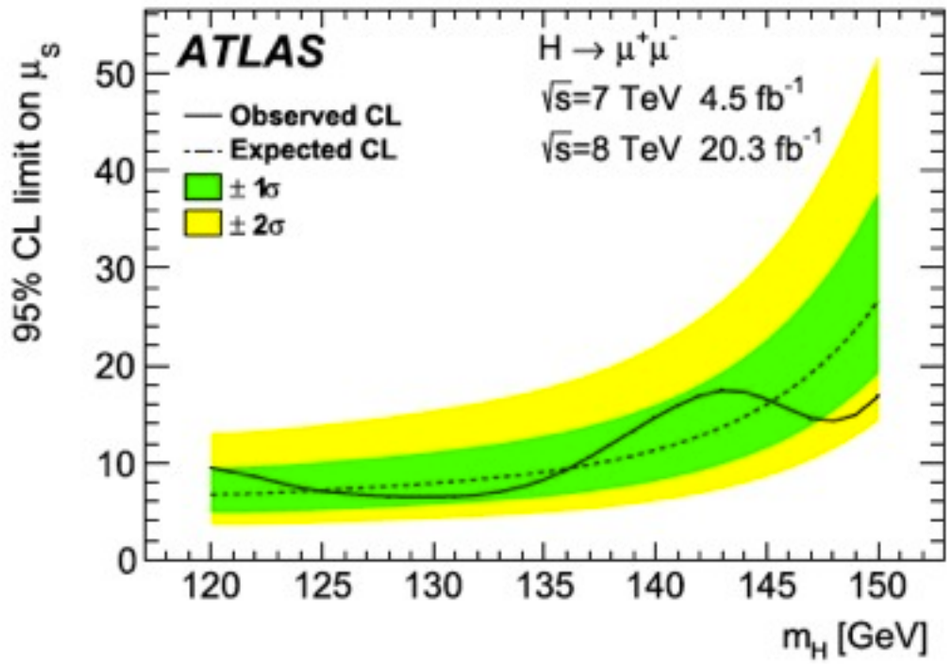




Breit-Wigner x Gauss + exp

Observed and expected 95% CL upper limits on the $H \to \mu^+\mu^-$ signal strength μ_S for different values of m_H.

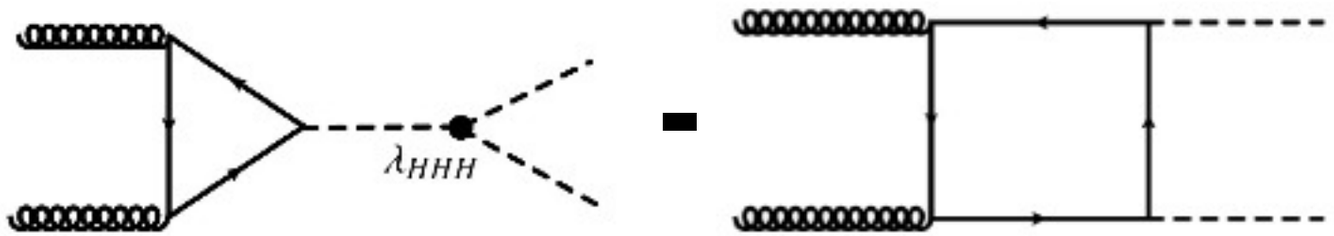
m_H [GeV]	120	125	130	135	140	145	150
Obs.	9.5	7.1	6.5	8.3	14.7	16.5	16.8
Exp.	6.7	7.2	7.9	9.1	11.3	16.0	26.6

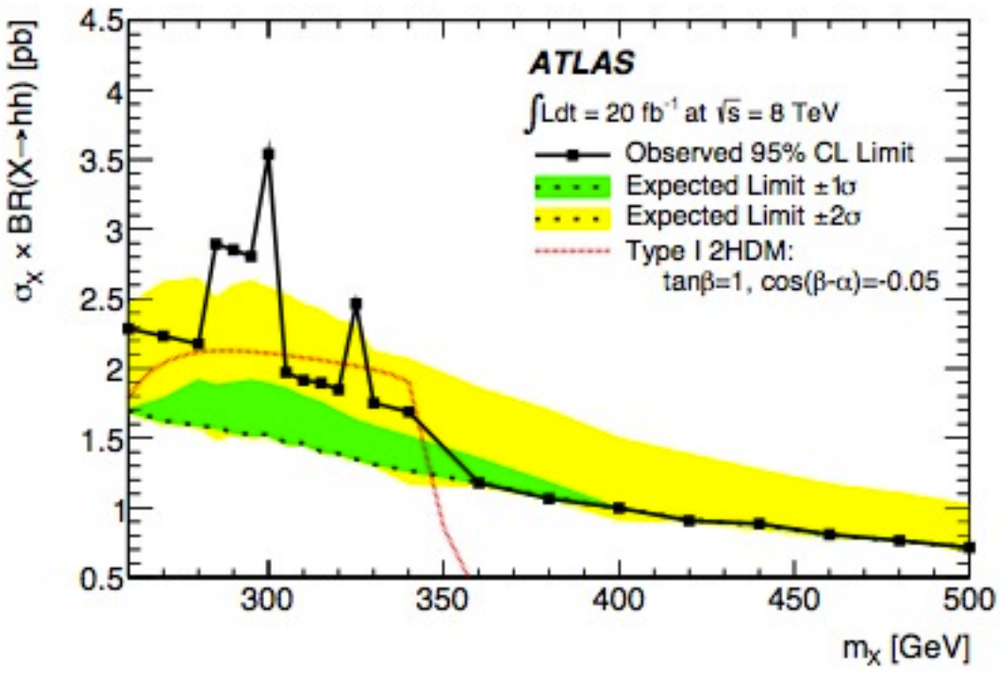


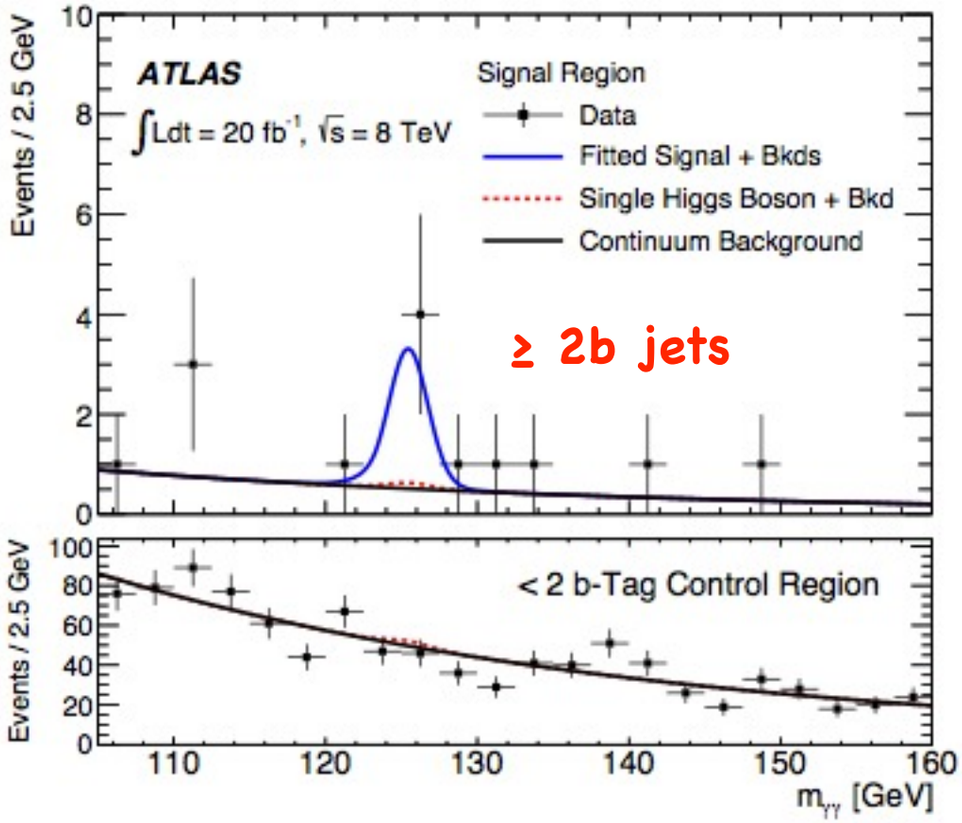
HH->bbyy

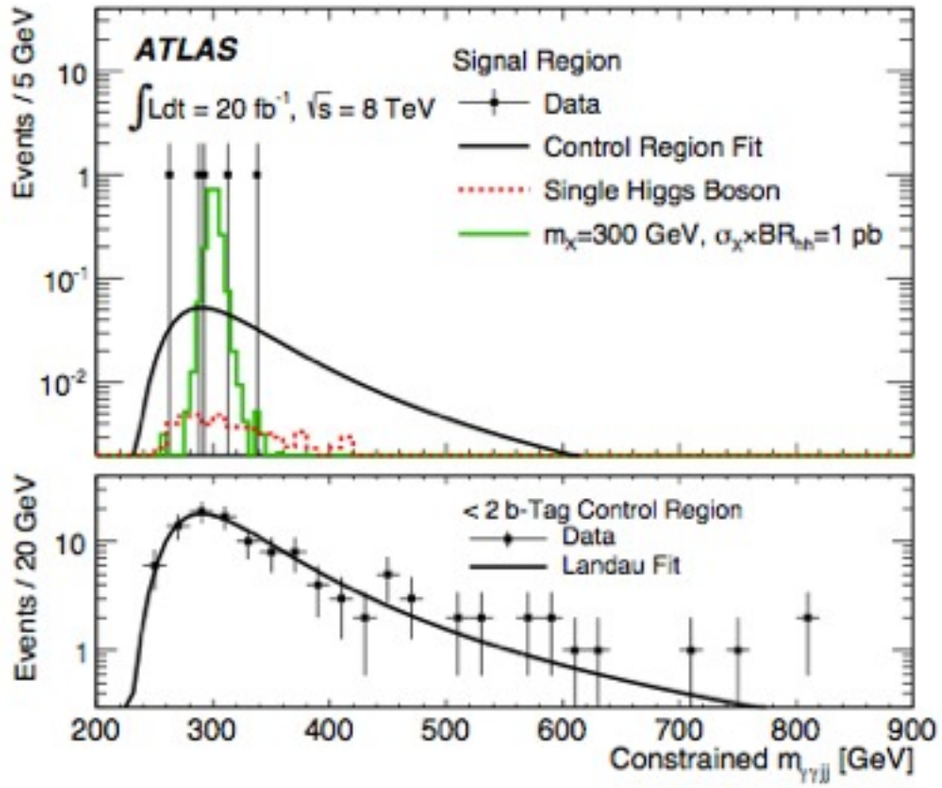
arXiv:1406.5053

- chance to measure Higgs self-coupling!
- problem - negative interference with non-resonant HH
- very promising for new physics (σ_{HH}(DarkMatter) ~1pb)
- large H->bb BR, clean H->γγ signal
  - Higgs-less background taken from data
- $m_{\gamma\gamma}$ spectrum: Crystal BallxGaussian+exponential







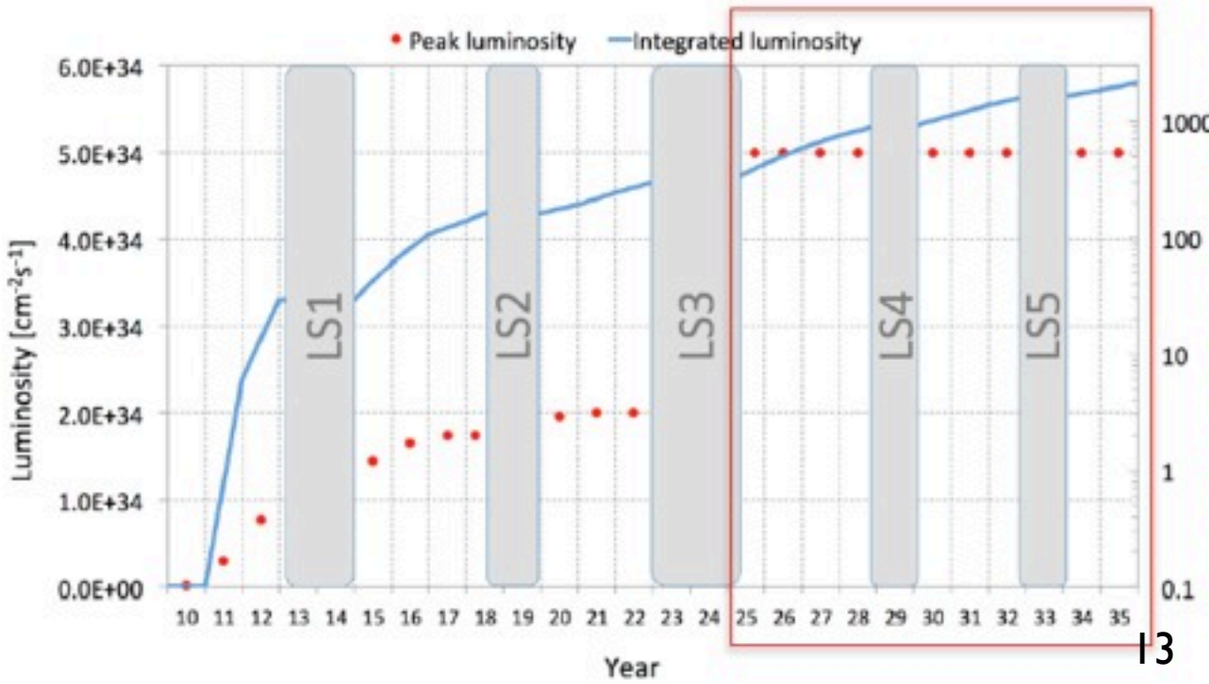


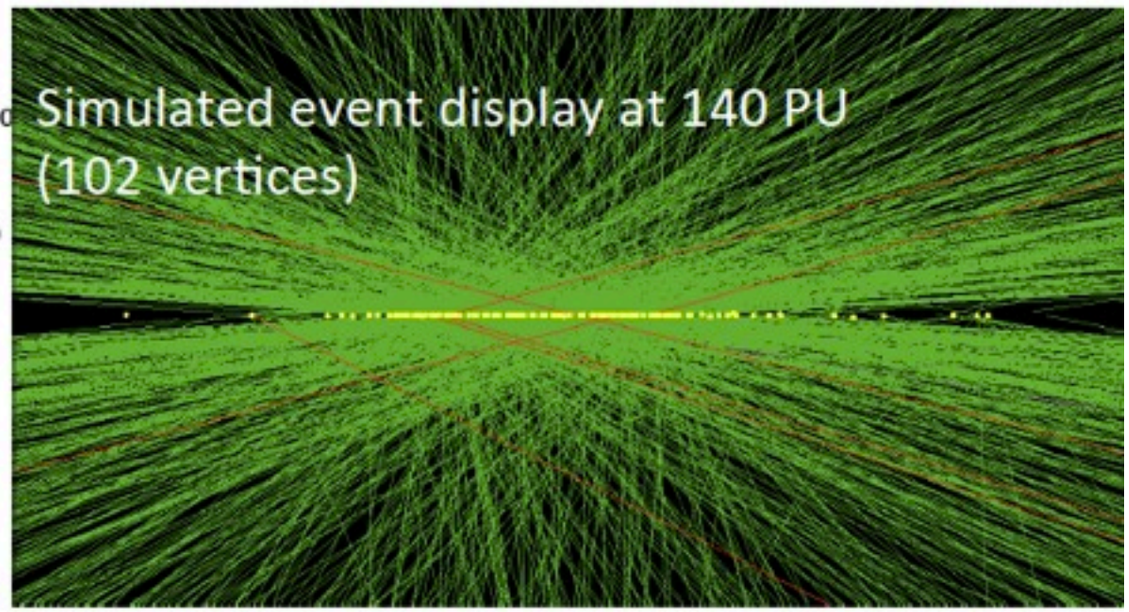
biggest excess @ 300 GeV

locally 3.0σ, globally 2.1σ

Future Prospects

- Run3 finishes in 2022 with expected collected luminosity of ~300 fb^{-1} and average pile-up conditions of $<\mu>=80$
- Phase2 Upgrade for High Luminosity LHC (2025-2035, HL-LHC) works with scenario of 3000 fb^{-1} and $<\mu>=140$
  - may change towards higher values depending on LHC capabilities (up to $<\mu>=200$)
- analyses performed on truth level with smearing functions applied
  - parametrized future detector response in terms of smearing p_T and energy and
  - parametrized expected trigger efficiencies
  - generally higher p_T thresholds applied especially on objects which are pile-up sensitive (such as jets)
- general cross section scaling 8->14 TeV: 2.6 (gg and VBF), 2.1 (VH), 4.7 (ttH)





Prospects for H->Zγ

- p_{Tl} > 10 GeV, $p_{T\gamma}$ > 15 GeV, isolation and mll cuts (as Run1)
- smeared Higgs signal @ 14 TeV
- for bkg, Zγ shape is taken from MC and normalization from σ(14TeV)/ σ(8TeV)[=1.82]*3000/20[=150]
- signal from fit to $m_{ll\gamma}$, categories in $p_T^{Z\gamma}$, $|\Delta\eta^{Z\gamma}|$

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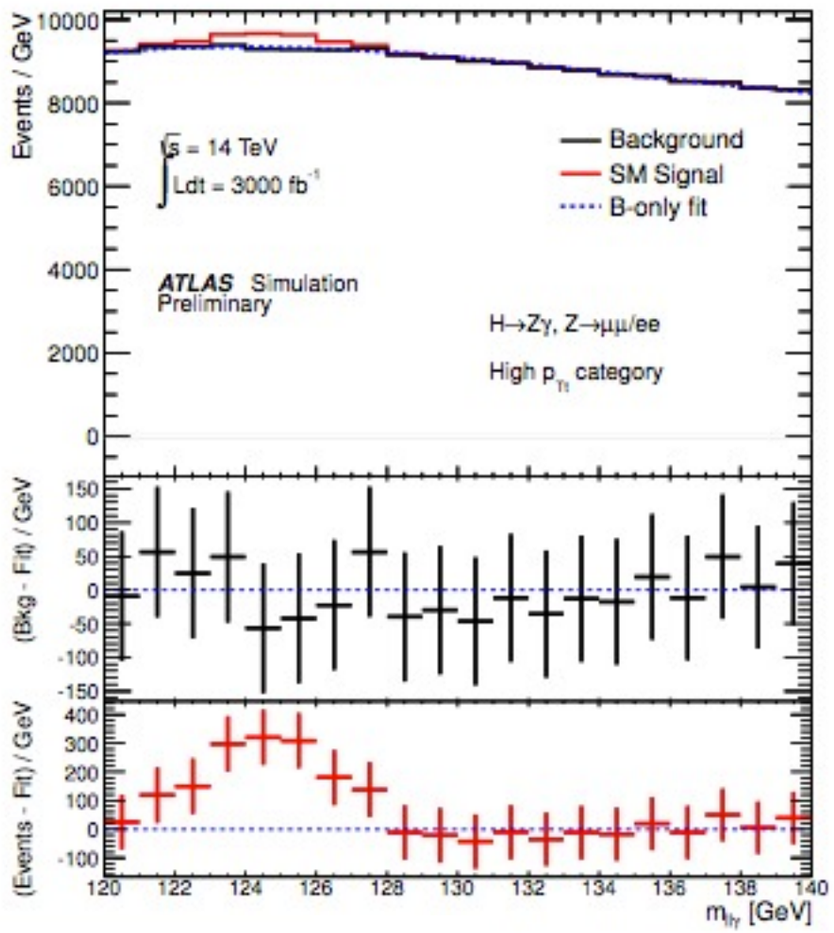


Category	high p_{Tt}		low p_{Tt} low $\lvert\Delta\eta_{Z\gamma}\rvert$		low p_{Tt} high $\lvert\Delta\eta_{Z\gamma}\rvert$	
Final states	$ee\gamma$	$\mu\mu\gamma$	$ee\gamma$	$\mu\mu\gamma$	$ee\gamma$	$\mu\mu\gamma$
S	602	721	703	839	138	165
B	$2.56 \cdot 10^4$	$3.05 \cdot 10^4$	$1.09 \cdot 10^5$	$1.30 \cdot 10^5$	$2.56 \cdot 10^4$	$3.06 \cdot 10^4$
S/B (%)	2.4	2.4	0.64	0.64	0.54	0.54
$S/\sqrt{B}$	3.8	4.1	2.1	2.3	0.86	0.94

Table 4: Summary of number of expected signal and background events in each channel and signal to (square root) background ratios for 3000 fb^{-1} and $122 < m_{ll\gamma} < 128$ GeV

Z_0 from fit to mlly = 3.9σ

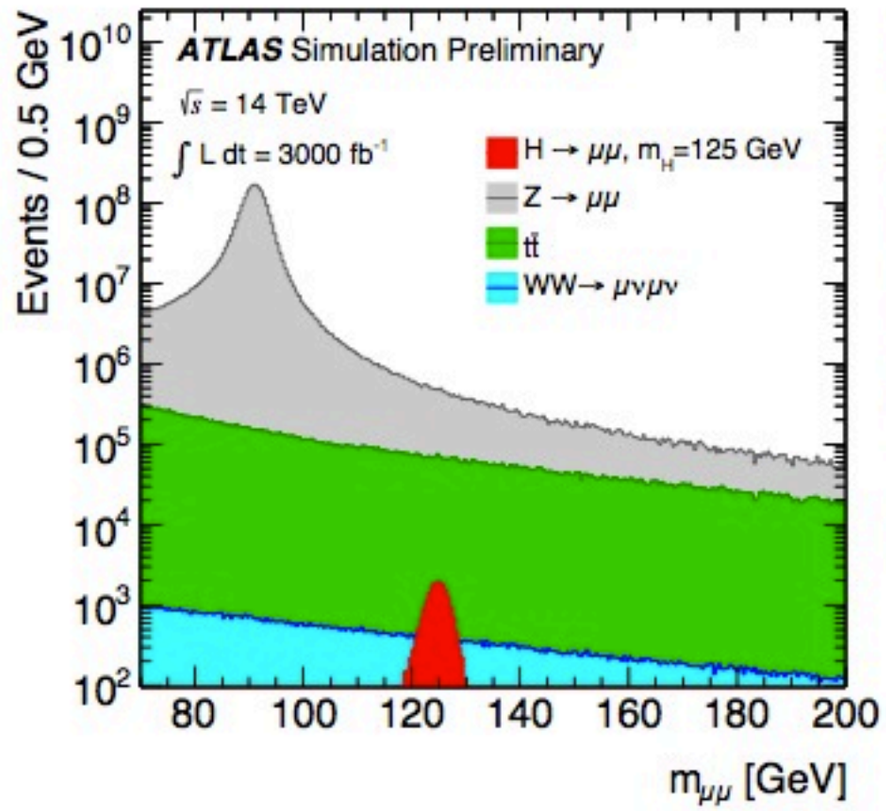
$\Delta\mu$ = ±0.25 (stat) ±0.16(sys)

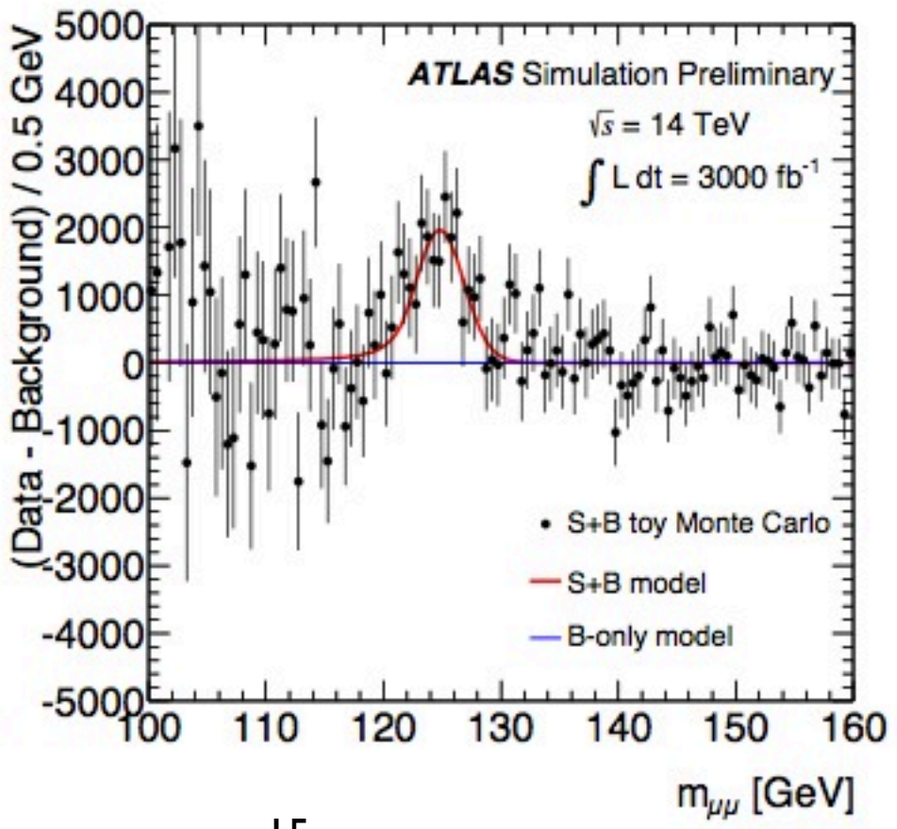
Prospects for H->μμ

- all samples 14 TeV truth smeared to pseudo-reconstructed level
- 2 OS muons p_T > 25/20 GeV
- BW+exp for fit -> pseudo-experiments corresponding to the luminosity

$m_H \pm 3$GeV

$\mathcal{L}$ [fb^{-1}]	300	3000
N_{ggH}	1510	15100
N_{VBF}	125	1250
N_{WH}	45	450
N_{ZH}	27	270
N_{ttH}	18	180
N_{Bkg}	564000	5640000
Δ^{sys}_{Bkg} (model)	68	110
Δ^{sys}_{Bkg} (fit)	190	620
Δ^{stat}_{S+B}	750	2380
Signal significance	2.3σ	7.0σ
$\Delta\mu/\mu$	46%	21%





ATL-PHYS-PUB-2013-014

Z_0 (@3ab^{-1}) = 7.0σ

$\Delta\mu$ = ±0.21

HL-LHC Di-Higgs Factory

Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b} + b\bar{b}$	33%	40,000
$b\bar{b} + W^+W^-$	25%	31,000
$b\bar{b} + \tau^+\tau^-$	7.3%	8,900
$ZZ + b\bar{b}$	3.1%	3,800
$W^+W^- + \tau^+\tau^-$	2.7%	3,300
$ZZ + W^+W^-$	1.1%	1,300
$\gamma\gamma + bb$	0.26%	320
$\gamma\gamma + \gamma\gamma$	0.0010%	1.2

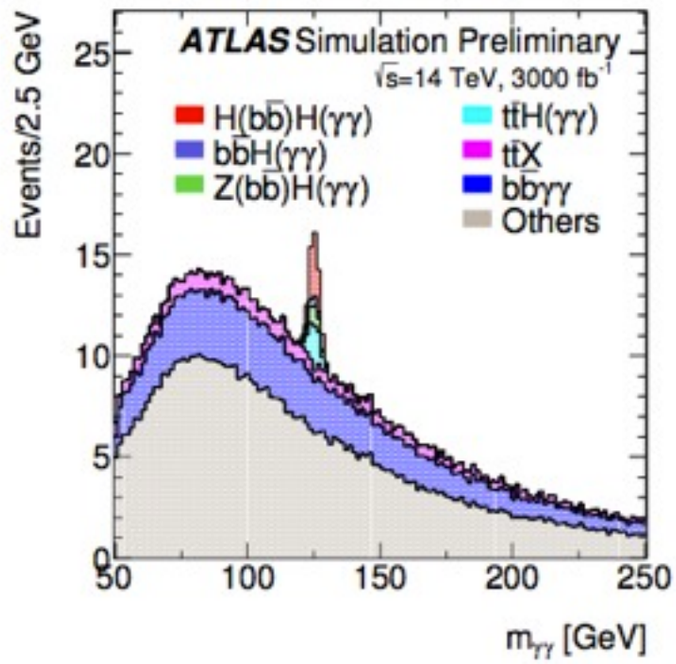
only analysis public so far, more coming

- many interesting channels
  - especially in high pile-up, some objects quite challenging for reconstruction
- prospects for rare decays may change the analyses from limit setting to (at least) observations

HH->bbγγ

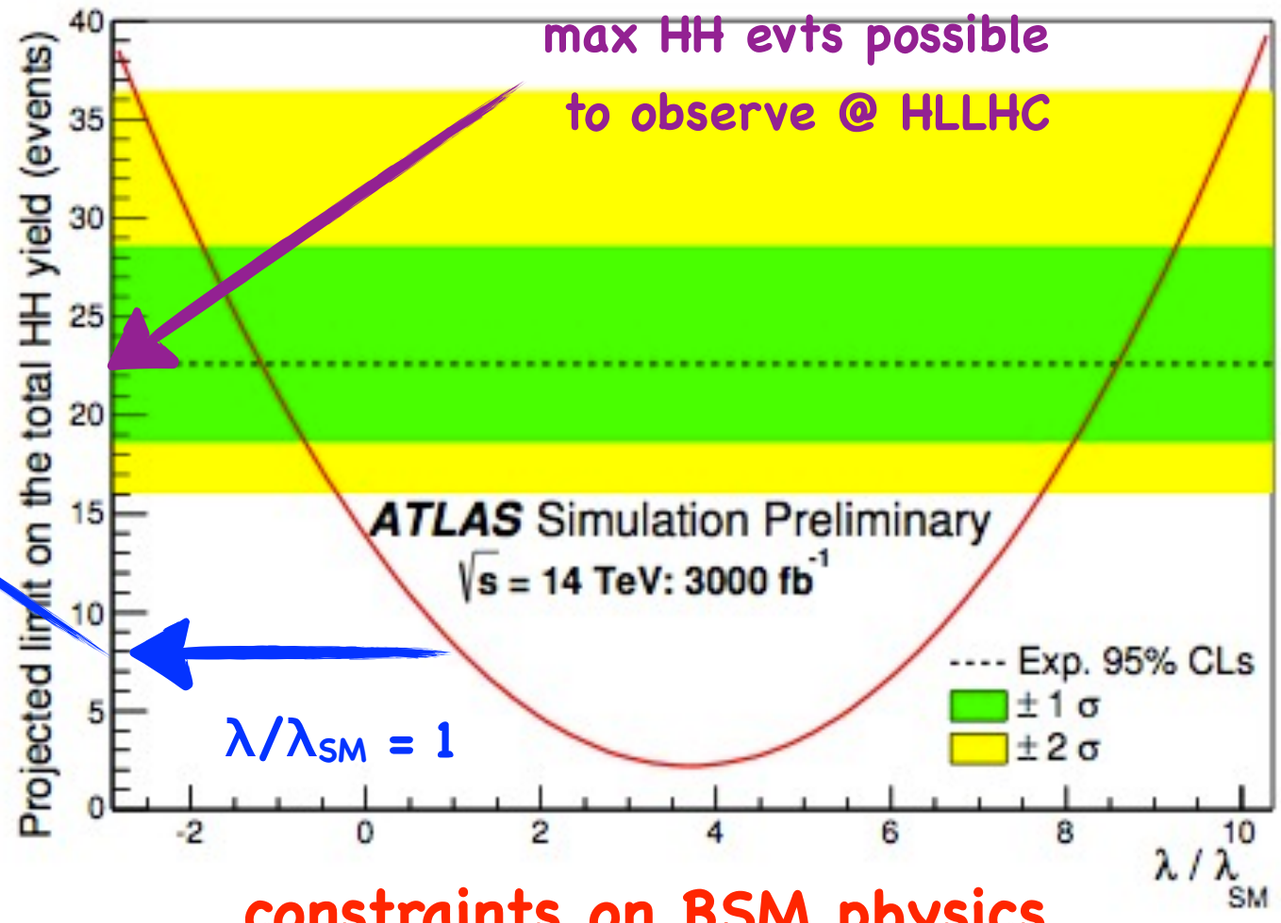
ATL-PHYS-PUB-2014-019

- jets p_T > 40/25 leading/subleading, > 30 GeV, mimicked bTagging
- 2 categories of photons: barrel and EC
- BSM scenarios explored ($\lambda/\lambda_{SM} \neq 1$)



Expected yields (3000 fb^{-1}) Samples	Total	Barrel	End-cap
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=1)$	8.4±0.1	6.7±0.1	1.8±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=0)$	13.7±0.2	10.7±0.2	3.1±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=2)$	4.6±0.1	3.7±0.1	0.9±0.1
$H(b\bar{b})H(\gamma\gamma)(\lambda/\lambda_{SM}=10)$	36.2±0.8	27.9±0.7	8.2±0.4
$b\bar{b}\gamma\gamma$	9.7±1.5	5.2±1.1	4.5±1.0
$c\bar{c}\gamma\gamma$	7.0±1.2	4.1±0.9	2.9±0.8
$b\bar{b}\gamma j$	8.4±0.4	4.3±0.2	4.1±0.2
$b\bar{b}jj$	1.3±0.2	0.9±0.1	0.4±0.1
$jj\gamma\gamma$	7.4±1.8	5.2±1.5	2.2±1.0
$t\bar{t}$(≥ 1 lepton)	0.2±0.1	0.1±0.1	0.1±0.1
$t\bar{t}\gamma$	3.2±2.2	1.6±1.6	1.6±1.6
$t\bar{t}H(\gamma\gamma)$	6.1±0.5	4.9±0.4	1.2±0.2
$Z(b\bar{b})H(\gamma\gamma)$	2.7±0.1	1.9±0.1	0.8±0.1
$b\bar{b}H(\gamma\gamma)$	1.2±0.1	1.0±0.1	0.3±0.1
Total Background	47.1±3.5	29.1±2.7	18.0±2.3
$S/\sqrt{B}(\lambda/\lambda_{SM}=1)$	1.2	1.2	0.4

1.3σ combined



constraints on BSM physics

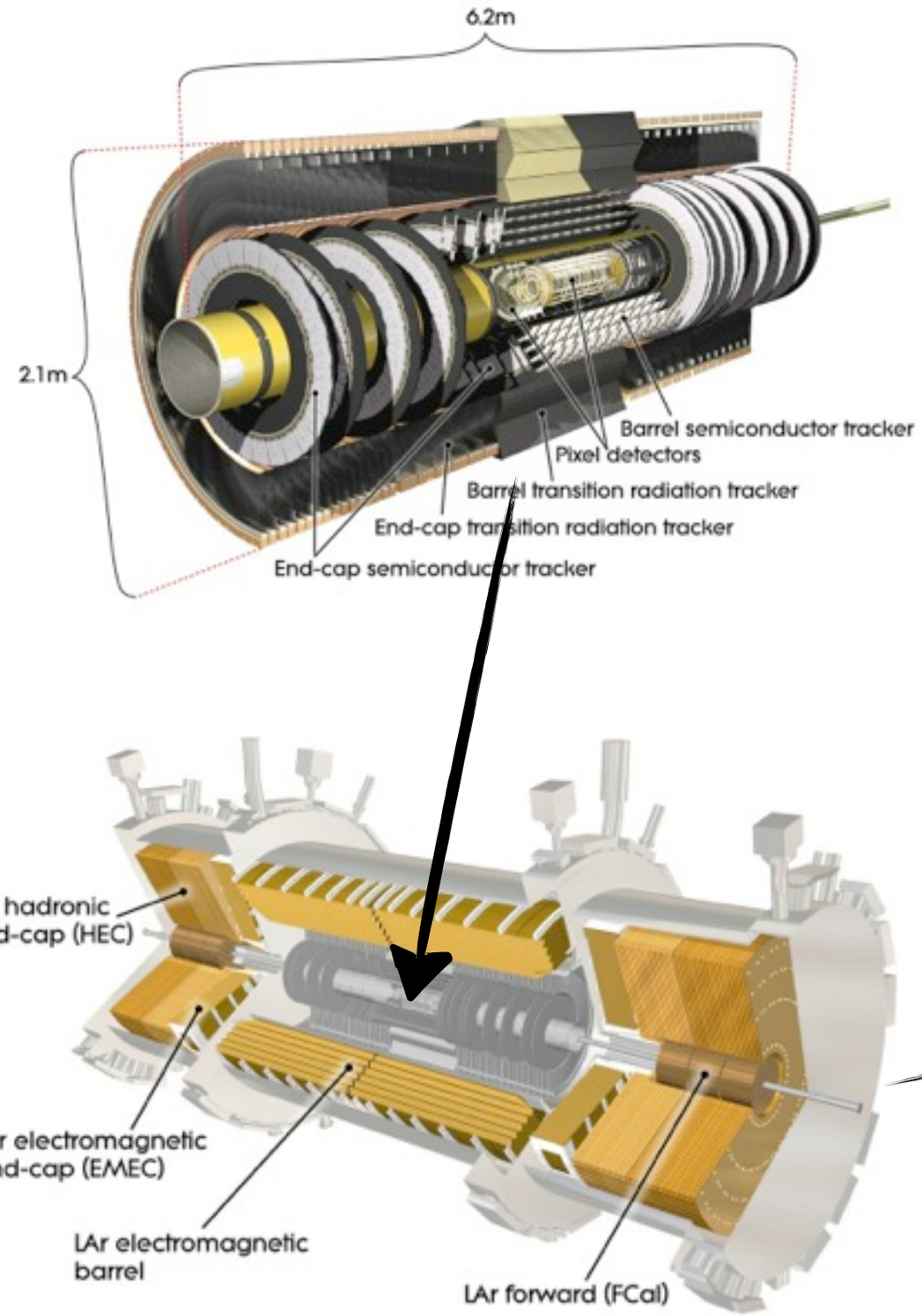
for λ/λ_{SM} < -13 and > 8.7

Summary

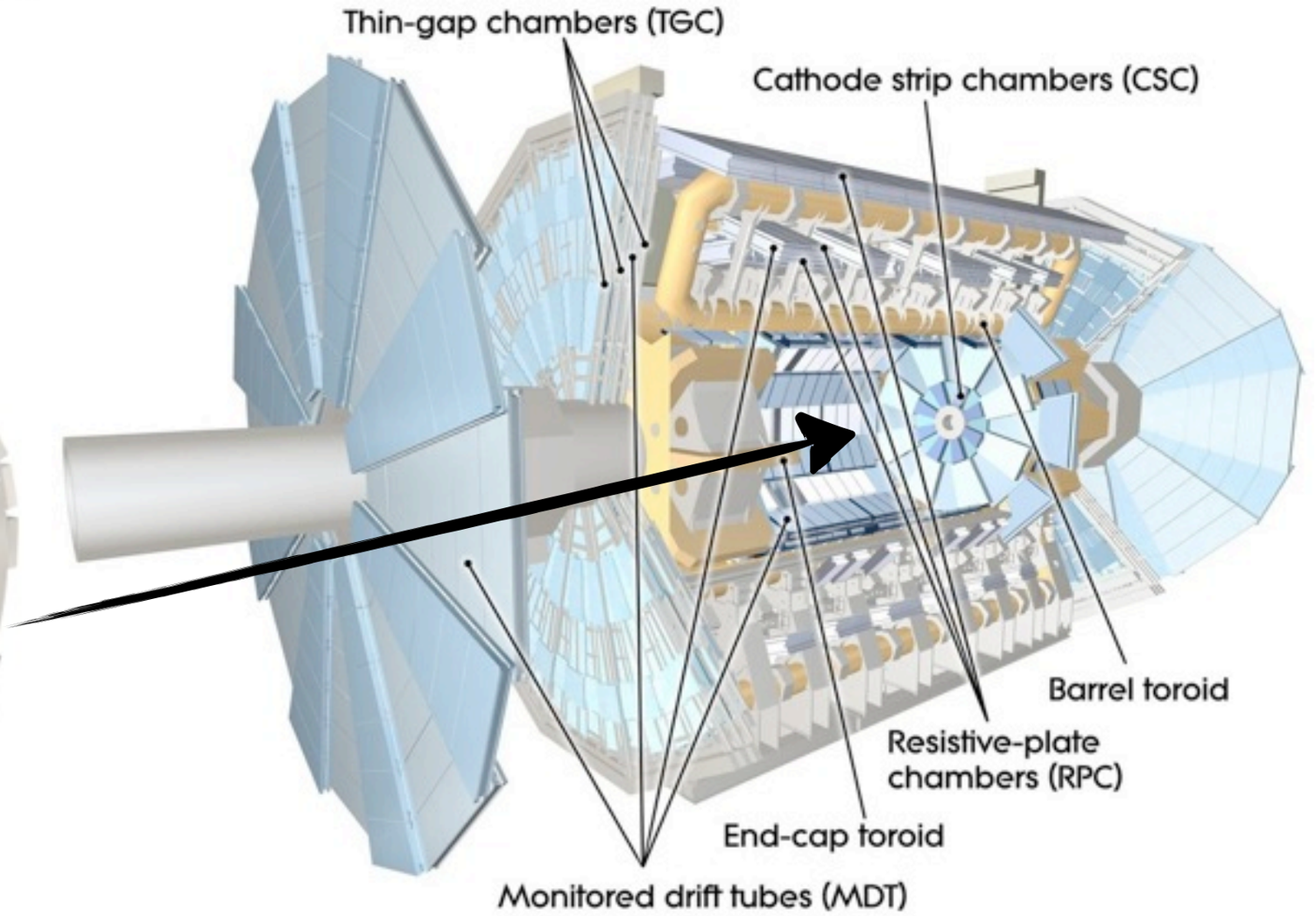
- ATLAS performed a wide range of Higgs measurements
- with increasing statistics, more and more rare processes can be analyzed, that are sensitive to new physics (through coupling constants)
  - Run1
    - first indications of rare productions modes such as VH and ttH
    - rare decays - mostly setting limits, some promising results such as 3σ excess in the HH->bbγγ analysis
  - HL-LHC
    - rare decays can reach up to discovery potential with 7σ expected significance

backup

ATLAS @ LHC



- 4π detector, 44x25m, 7000t
- ID (PIX, SCT, TRT) -> solenoid magnet (2T) -> Calo (LAr - EM, TileCal/LAr - Had) -> toroid magnets (4T) -> muon system (MDT, CSC, RPC, TGC)



VH(->WW)

- sensitive only to gauge boson couplings, WH only to W
- categories: 4l, 3l, 2l(+qq) - opp sign and same sign
- 7+8TeV analyses

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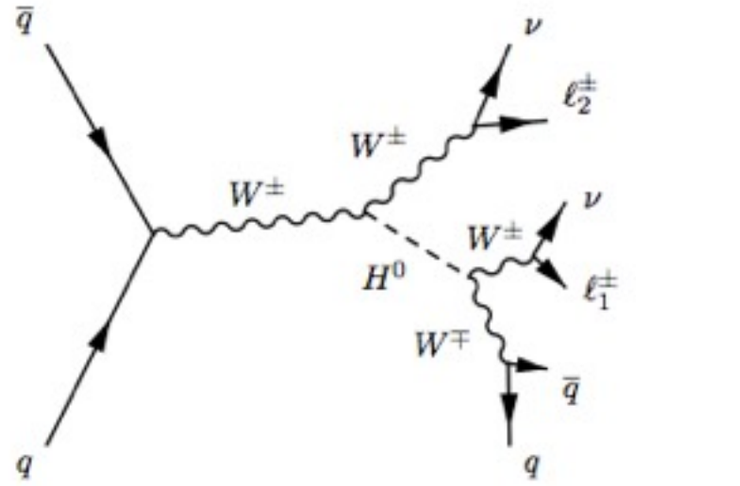
Channel	4ℓ		3ℓ			2ℓ		
Category	2SFOS	1SFOS	2SFOS	1SFOS	0SFOS	DFOS	SS2jet	SS1jet
Trigger	single lepton triggers		single lepton triggers			single & dilepton triggers		
Num. of leptons	4	4	3	3	3	2	2	2
Total lepton charge	0	0	±1	±1	±1	0	±2	±2
Num. of SFOS	2	1	2	1	0	0	0	0
Num. of jets	≤ 1	≤ 1	≤ 1	≤ 1	≤ 1	≥ 2	2	1
Num. of b-tagged jets	0	0	0	0	0	0	0	0
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 20	> 20	> 30	> 30	—	> 20	> 50	> 45
$p_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 15	> 15	> 20	> 20	—	—	—	—
$\lvert m_{\ell\ell} - m_Z \rvert$ [GeV]	< 10 ($m_{\ell_2\ell_3}$)	< 10 ($m_{\ell_2\ell_3}$)	> 25	> 25	—	—	> 15	> 15
Min. $m_{\ell\ell}$ [GeV]	> 10 ($m_{\ell_0\ell_1}$)	> 10 ($m_{\ell_0\ell_1}$)	> 12	> 12	> 6	> 10	> 12 ($ee, \mu\mu$) > 10 ($e\mu$)	> 12 ($ee, \mu\mu$) > 10 ($e\mu$)
Max. $m_{\ell\ell}$ [GeV]	< 65 ($m_{\ell_0\ell_1}$)	< 65 ($m_{\ell_0\ell_1}$)	< 200	< 200	< 200	< 50	—	—
$m_{4\ell}$ [GeV]	> 140	—	—	—	—	—	—	—
$p_{\mathrm{T},4\ell}$ [GeV]	> 30	—	—	—	—	—	—	—
$M_{\tau\tau}$ [GeV]	—	—	—	—	—	< 66.2	—	—
$\Delta R_{\ell_0\ell_1}$	—	—	< 2.0	< 2.0	—	—	—	—
$\Delta\phi_{\ell_0\ell_1}$ [rad]	< 2.5 ($\Delta\phi_{\ell_0\ell_1}^{\mathrm{boost}}$)	< 2.5 ($\Delta\phi_{\ell_0\ell_1}^{\mathrm{boost}}$)	—	—	—	< 1.8	—	—
m_{T} [GeV]	—	—	—	—	—	< 125	—	> 105 ($m_{\mathrm{T}}^{\mathrm{Lead}}$)
Min. $m_{\ell_1 j(j)}$ [GeV]	—	—	—	—	—	—	< 115	< 70
Min. $\phi_{\ell_1 j}$ [rad]	—	—	—	—	—	—	< 1.5	< 1.5
ΔY_{jj}	—	—	—	—	—	< 1.2	—	—
$\lvert m_{jj} - 85 \rvert$ [GeV]	—	—	—	—	—	< 15	—	—



(a) 8 TeV data analysis

Channel	4ℓ		3ℓ			2ℓ		
Category	2SFOS	1SFOS	2SFOS	1SFOS	0SFOS	DFOS	SS2jet	SS1jet
$WH\,(H \to WW^*)$	—	—	0.563	1.43	1.284	1.48	1.02	1.84
$ZH\,(H \to WW^*)$	0.208	0.235	0.168	0.179	0.145	0.668	0.017	0.195
$VH\,(H \to WW^*)$	0.208	0.235	0.731	1.62	1.428	2.15	1.04	2.04
(all categories)	9.44							

(b) 7 TeV data analysis

$WH\,(H \to WW^*)$	—	–	0.116	0.292	0.263	0.210
$ZH\,(H \to WW^*)$	0.023	0.021	0.013	0.033	0.028	0.075
$VH\,(H \to WW^*)$	0.023	0.021	0.129	0.325	0.291	0.285
(all categories)	1.073					

Table 3: Number of expected signal events, for m_H = 125 GeV, in the (a) 8 TeV and (b) 7 TeV da samples.

m_T lead - from E_T^{miss}+leading lepton p_T

N_{exp} ~ 10.5 evts

VH(->WW)

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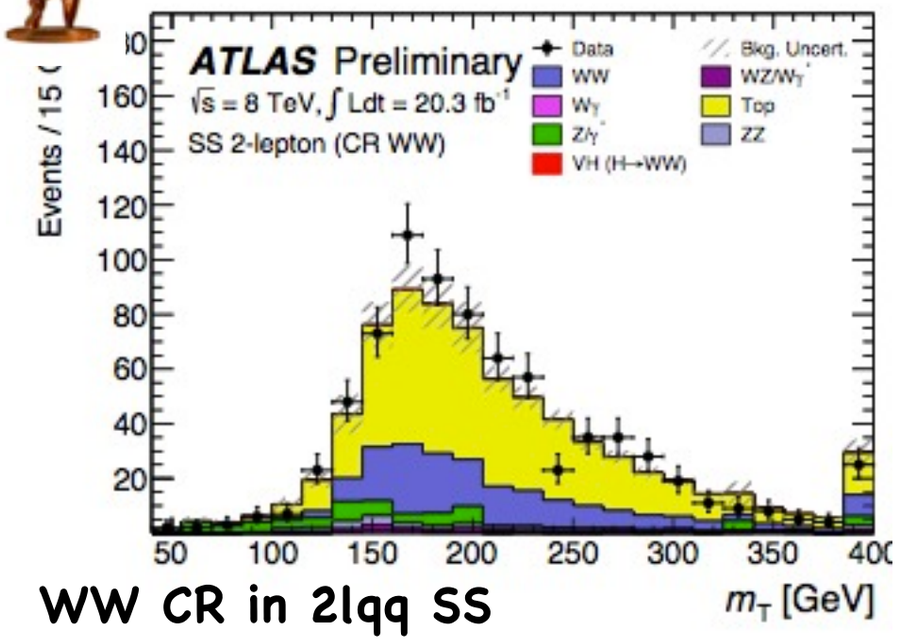
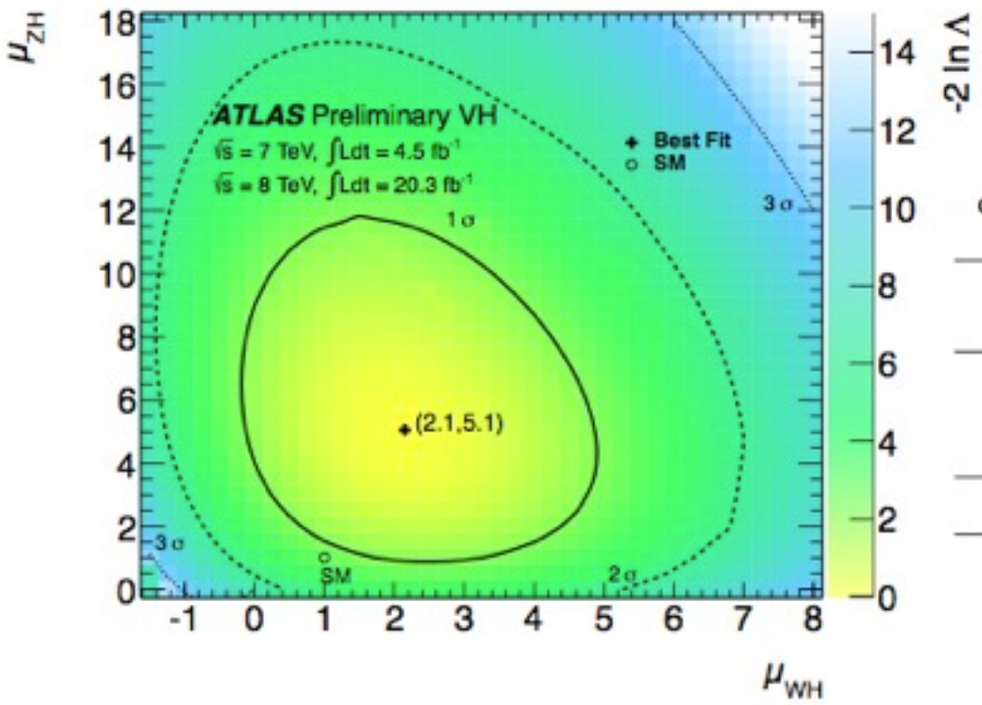


WW CR in 2lqq SS

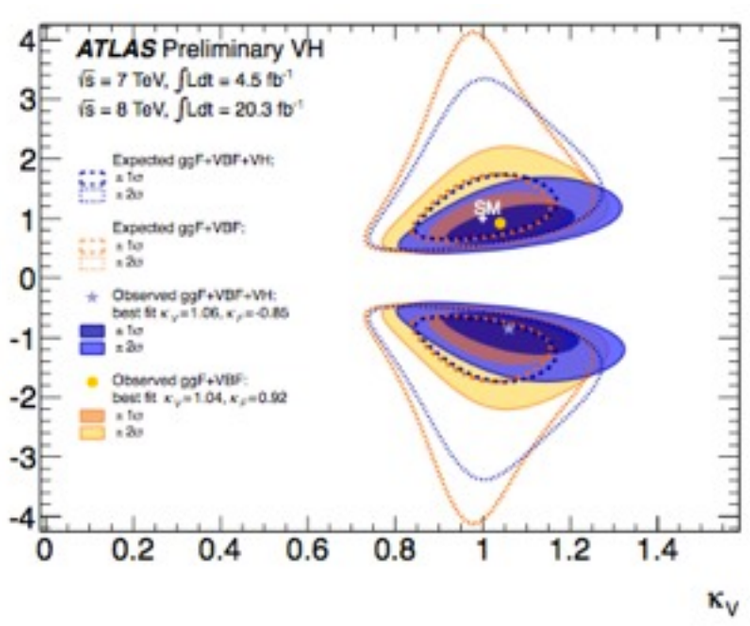
Category	Signal significance Z_0 Exp. Z_0	Obs Z_0	Obs. Z_0	Observed signal strength μ_{obs} μ	Tot. err. +	Tot. err. −	Syst. err. +	Syst. err. −	μ
4ℓ	0.44	1.9		4.9	4.6	3.1	1.2	0.35	
2SFOS	0.31	0		−5.9	6.8	4.1	0.33	0.72	
1SFOS	0.40	2.5		9.6	8.1	5.4	2.1	0.64	
3ℓ	0.84	0.66		0.72	1.3	1.1	0.42	0.27	
1SFOS and 2SFOS	0.57	0		−2.9	3.2	3.2	2.1	2.5	
0SFOS	0.69	1.2		1.6	1.9	1.4	0.51	0.29	
2ℓ	0.61	2.0		3.7	1.9	1.8	1.2	1.4	
DFOS	0.57	1.1		2.2	2.0	1.9	1.1	1.0	
SS2jet	0.24	1.4		7.7	6.0	5.5	3.2	3.3	
SS1jet	0.63	2.3		8.4	4.3	3.8	2.3	2.0	

$$\mu_{WH} = 2.1^{+1.5}_{-1.3}\,(\text{stat.})^{+1.2}_{-0.8}\,(\text{sys.}),\ \mu_{ZH} = 5.1^{+3.8}_{-3.0}\,(\text{stat.})^{+1.9}_{-0.9}\,(\text{sys.}),$$

$$\mu_{VH} = 3.0^{+1.3}_{-1.1}\,(\text{stat.})^{+1.0}_{-0.7}\,(\text{sys.})$$



Category	Signal significance Z_0 Exp. Z_0	Obs. Z_0	Obs. Z_0
ggF	4.4	4.2	
VBF	2.6	3.2	
VH	0.93	2.5	
WH only	0.77	1.4	
ZH only	0.30	2.0	
ggF+VBF+VH	5.9	6.5	



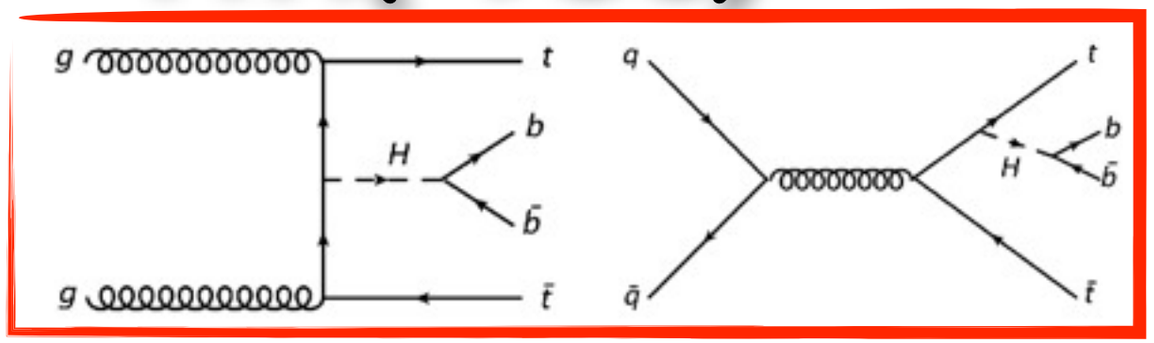
Z0 (ggF+VBF) ~6.1 ->

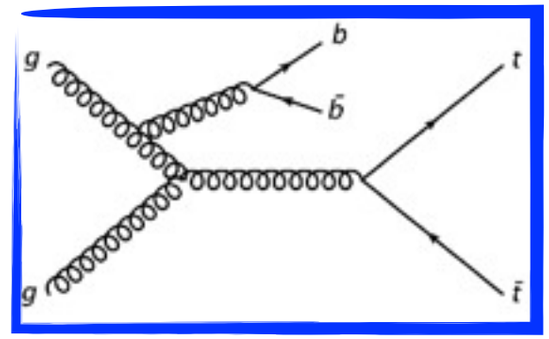
Z0 (ggF+VBF+VH) = 6.5

big improvement through VH in the coupling contour

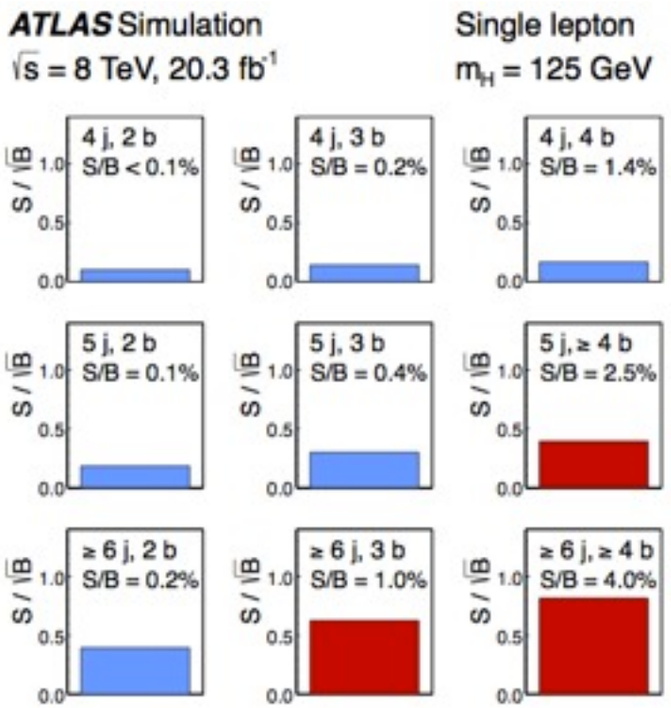
ttH(->bb)

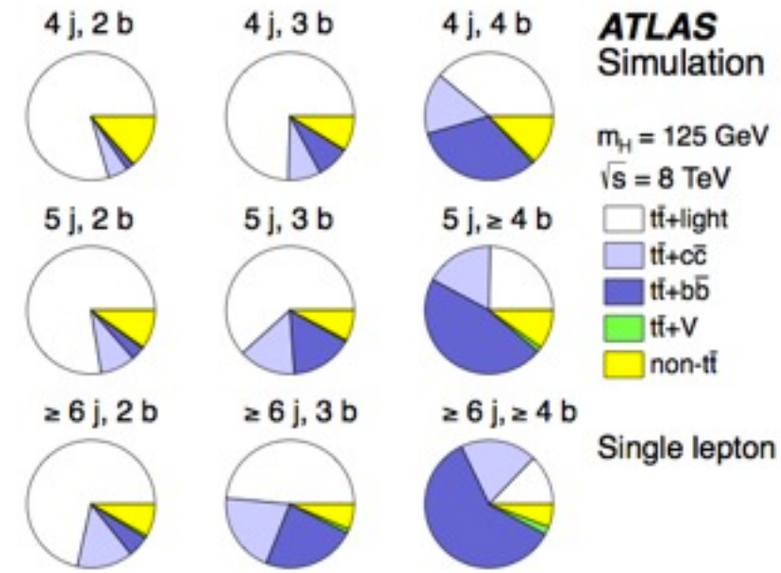
arXiv:1503.05066

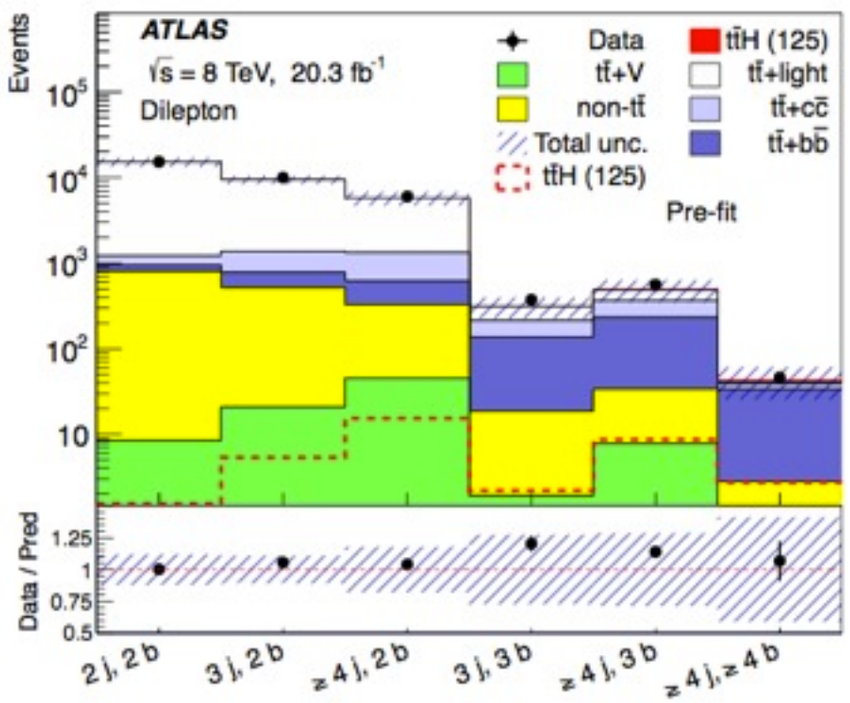


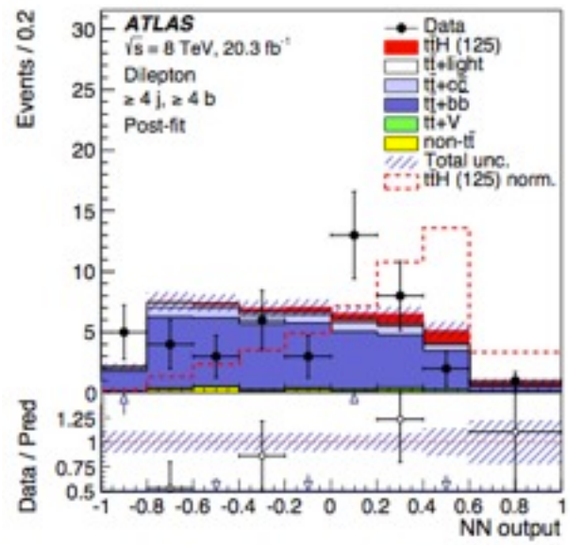


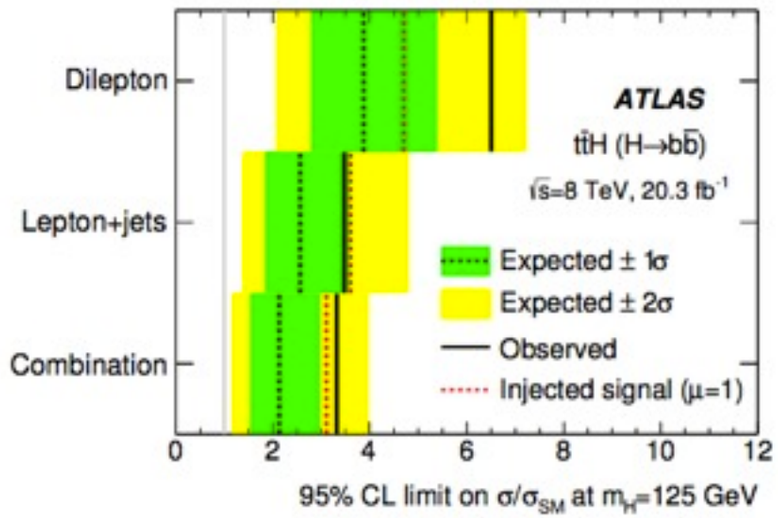
- tree level measurement of λ_{ttH} with strongest decay channel
- main bkg: tt+bb, tt+light, tt+cc
- Neural Network (H_T), #light and bjets make the classification
- 8 TeV









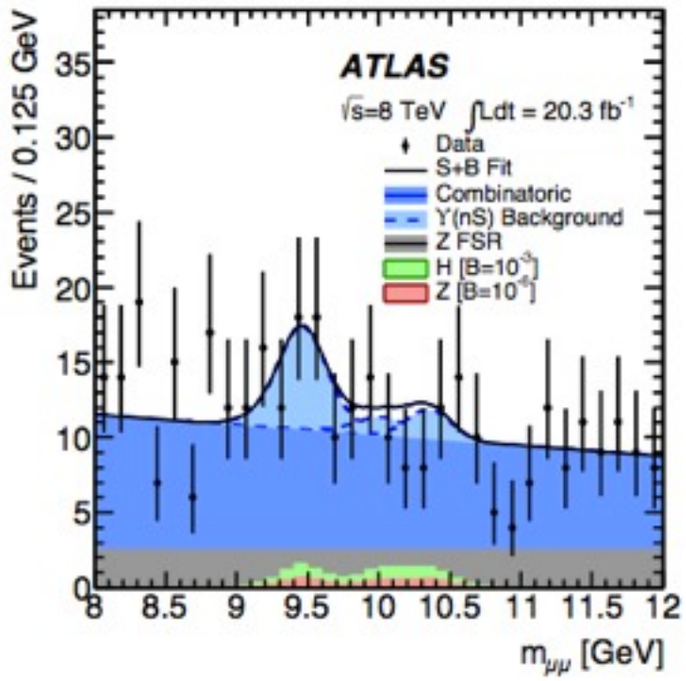


$\mu(ttH) = 1.5 \pm 1.1$

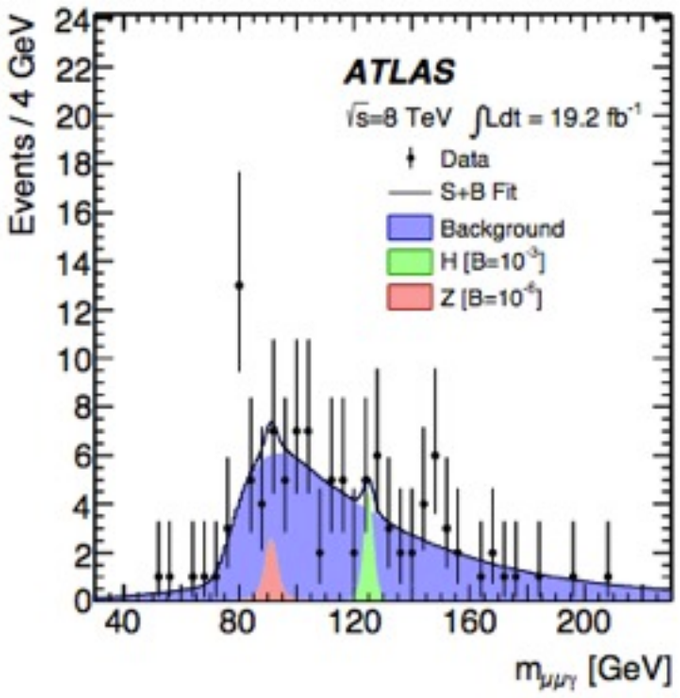
H/Z-> J/ΨΥ,ΥΥ

PLB 732 (2014) 8-27

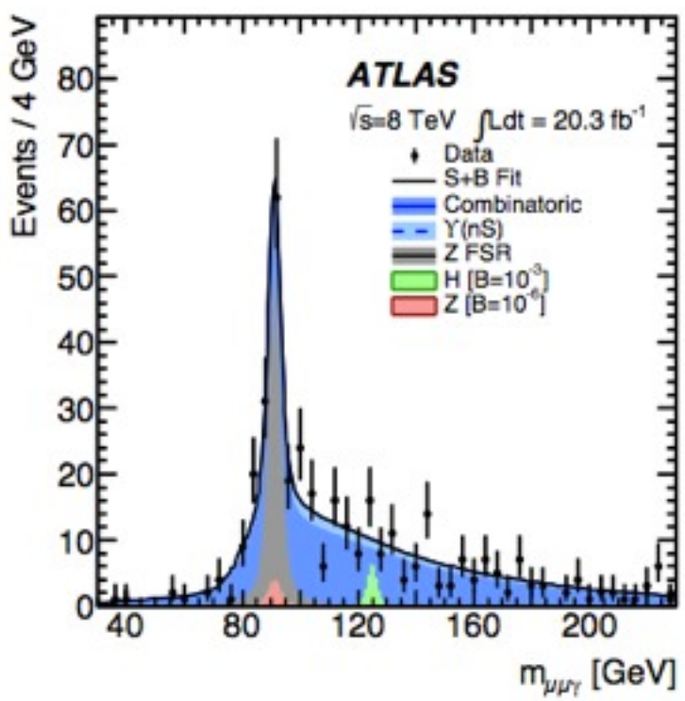
- 8TeV only, $\mu^+\mu^-\gamma$ final states measured
- unique access to λccH and λbbH
  - very challenging due to overwhelming QCD background & low mass of the system
  - association with photon in order to suppress QCD
  - very sensitive to new physics modifying heavy quarks couplings
- **first measurement ever!**



ΥΥ



J/ΨΥ



ΥΥ

unbinned likelihood fit

TABLE II. Expected and observed branching fraction limits at 95% CL for $\sqrt{s} = 8$ TeV. The $\pm 1\sigma$ fluctuations of the expected limits are also given. For the Higgs decay search, limits are also set on the cross section times branching fraction $\sigma(pp \to H) \times \mathcal{B}(H \to Q\gamma)$.

	95% CL Upper Limits				
	J/ψ	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\sum_n \Upsilon(nS)$
	$\mathcal{B}(Z \to Q\gamma)$ [10^{-6}]				
Expected	$2.0^{+1.0}_{-0.6}$	$4.9^{+2.5}_{-1.4}$	$6.2^{+3.2}_{-1.8}$	$5.4^{+2.7}_{-1.5}$	$8.8^{+4.7}_{-2.5}$
Observed	2.6	3.4	6.5	5.4	7.9
	$\mathcal{B}(H \to Q\gamma)$ [10^{-3}]				
Expected	$1.2^{+0.6}_{-0.3}$	$1.8^{+0.9}_{-0.5}$	$2.1^{+1.1}_{-0.6}$	$1.8^{+0.9}_{-0.5}$	$2.5^{+1.3}_{-0.7}$
Observed	1.5	1.3	1.9	1.3	2.0
	$\sigma(pp \to H) \times \mathcal{B}(H \to Q\gamma)$ [fb]				
Expected	26^{+12}_{-7}	38^{+19}_{-11}	45^{+24}_{-13}	38^{+19}_{-11}	54^{+27}_{-15}
Observed	33	29	41	28	44