Rare and Non-Standard Model Decays of the Higgs Boson

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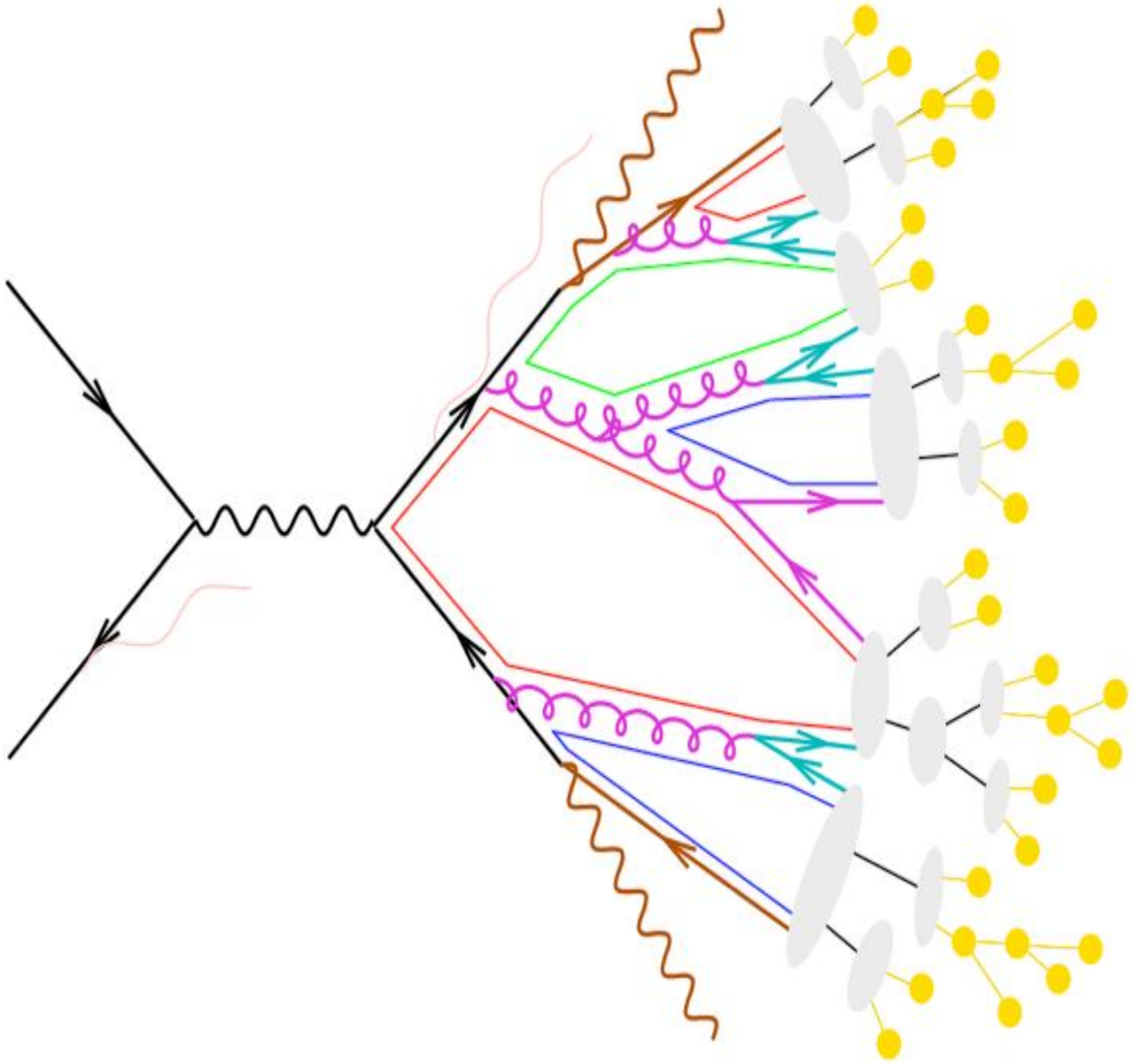
Outline

- Basics of pp Collider Physics.
- Particles Produced at the pp collider.
- Rare and Non-Standard Model decays of Higgs Boson.
- Charged Higgs Boson Decay in SUSY Models.
- Conclusions.



- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \to bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster $\to$ hadrons
- hadronic decays

pp collisions

cross- sectional area σ.

n is the number of particle per unit volume of the target, A is the geometrical area of the target

Probability of scattering from the target is

$$dp = \frac{n(Adx)\sigma}{A} = n\sigma dx$$

Number of particles hitting on the target be N_t

Number of scattered particles $N_s = N_t\, dp = n\sigma dx N_t$

Cross sectional area $\sigma = \frac{N_s}{ndxN_t}$

Differential cross section $\frac{d\sigma}{d\Omega} = \frac{1}{ndxN_t}\frac{dN_s}{d\Omega}$

Inclusive cross section $\sigma(H) = \frac{N(pp->H+others)}{ndxN_t}$

Exclusive cross section $\sigma(H) = \frac{N(pp->ppH)}{ndxN_t}$

Unit of cross section area 1b=10^{-24} cm^2 = 10^{-28} cm^2

Some common cross sectional area are

Proton-proton inelastic collision at LHC 50 mb
at 7 TeV

Higgs Boson production at Large Hadron Collider
(LHC) 20 pb

Heavy nuclei cross section 1 b

W/Z boson production at LHC 50 nb

Collider luminosity $$L = \frac{N_1 N_2}{A} f \quad cm^{-2} s^{-1}$$

Integrated Luminosity $$\int L dt \quad b^{-1}$$

Bunch crossing frequency f

Number of particles in beam 1 and 2 are N_1 and N_2

A is the geometrical area of the beam.

Rapidity $$Y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$$

Rapidity for massless particles $$Y = -\ln[\tan(\theta/2)]$$

Pseudorapidity $$\eta = -\ln[\tan(\theta/2)]$$

Particles after collision

neutrinos
electron
muon
tau
u, d, s, c, b quarks and gluons hadronizes to give jets of colorless bound states, hadrons which are

$\pi, K^+, K^-, K_L, proton, neutron$

top quark decays before it hadronizes
W, Z, H decays instantly

Basics of Statistics at LHC

Signal strength μ

Test statistic q

Excess quantification

p-value

Significance

Best fit value of μ or $\hat{\mu}$

Lack of excess quantification

CL_s value and CL

Limit on μ

Expected background rate b, expected signal rate s_0, observed events n_{obs}

p=P($n \geq n_{obs} | b$) is the p-value

p-value	0.16	0.023	1.3×10^{-3}	3.2×10^{-5}	2.9×10^{-7}
Z	1	2	3	4	5

Standard model Higgs boson event rate s_0, higgs boson event rate $s=\mu s_0$, μ is the signal strength modifier, L likelihood of observation

Likelihood of observation

$$L = \frac{(b+\mu s_0)^{n_{obs}}}{n_{obs}!} e^{-b-\mu s_0} \quad CL_s = \frac{P(n \leq n_{obs} \mid b+\mu s_0)}{P(n \leq n_{obs} \mid b)} = 1 - CL$$

Maximizing the likehood

$$\hat{\mu} = \frac{n_{obs} - b}{s_0}$$

CL: Confidence level when no excess found

Test statistics for Higgs searches

$$q_0 = 2 \ln \frac{L(data; b+\hat{\mu}s)}{L(data; b)}$$

$$Z = \sqrt{q_0^{\,obs}}$$

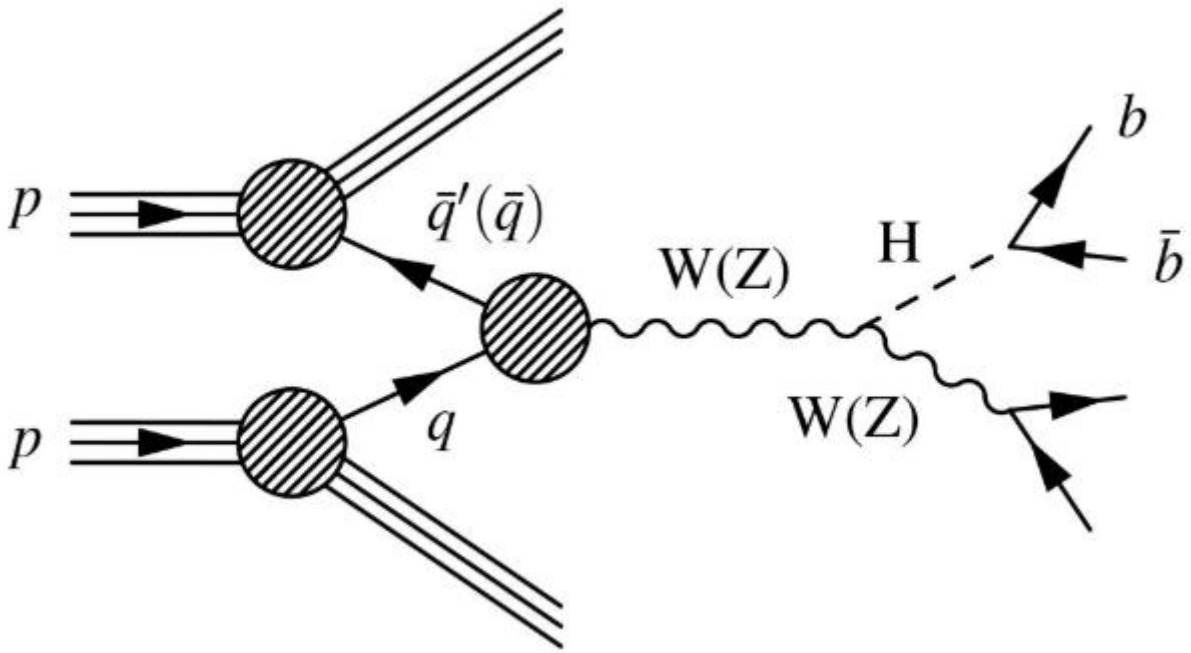
$$q_0 = 2 \ln \frac{\frac{(b+\hat{\mu}s)^{n_{obs}} e^{-b-\hat{\mu}s}}{n_{obs}!}}{\frac{b^{n_{obs}} e^{-b}}{n_{obs}!}} = 2 n_{obs} \ln\left(\frac{n_{obs}}{b}\right) - 2(n_{obs} - b)$$

CMS Experiment Trigger Table

Trigger	**Theshold Energy (GeV)**	**Rate (kHz)**
Single μ	14	7
Single e/γ	20	13
e/γ+μ	12,3.5	3
Single jet	128	1.5
Quad jet	36	5
E_T^{miss}	40	8

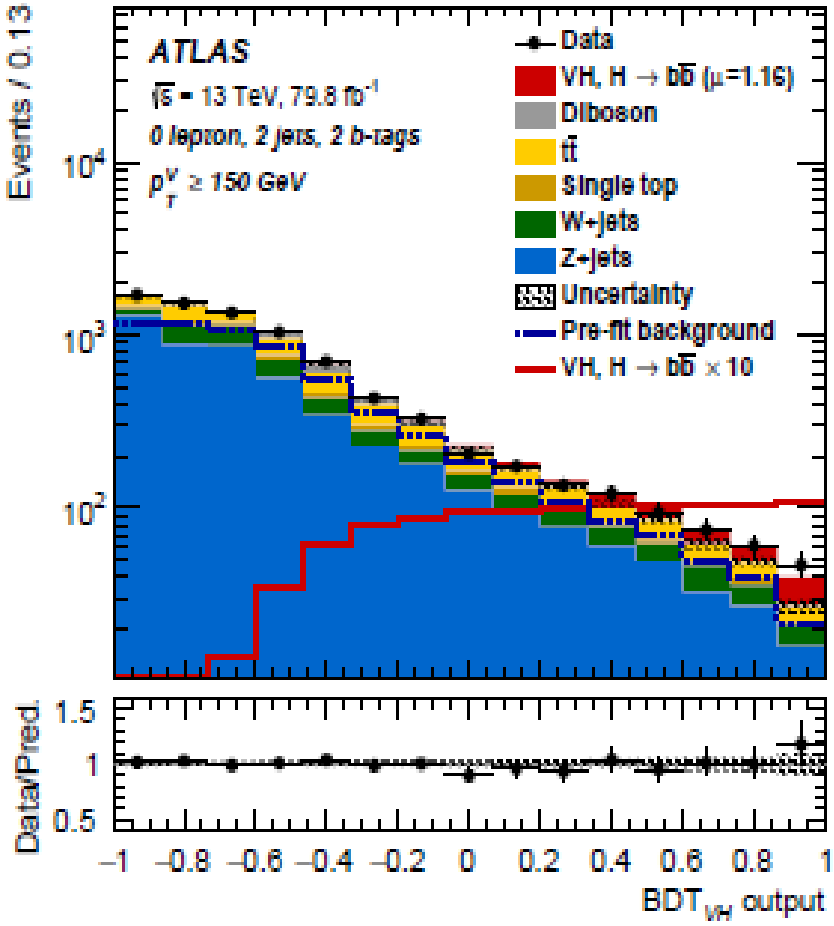
Particle	**Transverse momentum and trigger frequency**
μ	p_T>24 (44 Hz)
e	p_T>27 (72 Hz)
ee	p_T>17/8 (15 Hz)
eμ/μe	p_T>17/8 (15 Hz)
γγ	p_T>48 (7 Hz)
Single jet	p_T>400 (3 Hz)

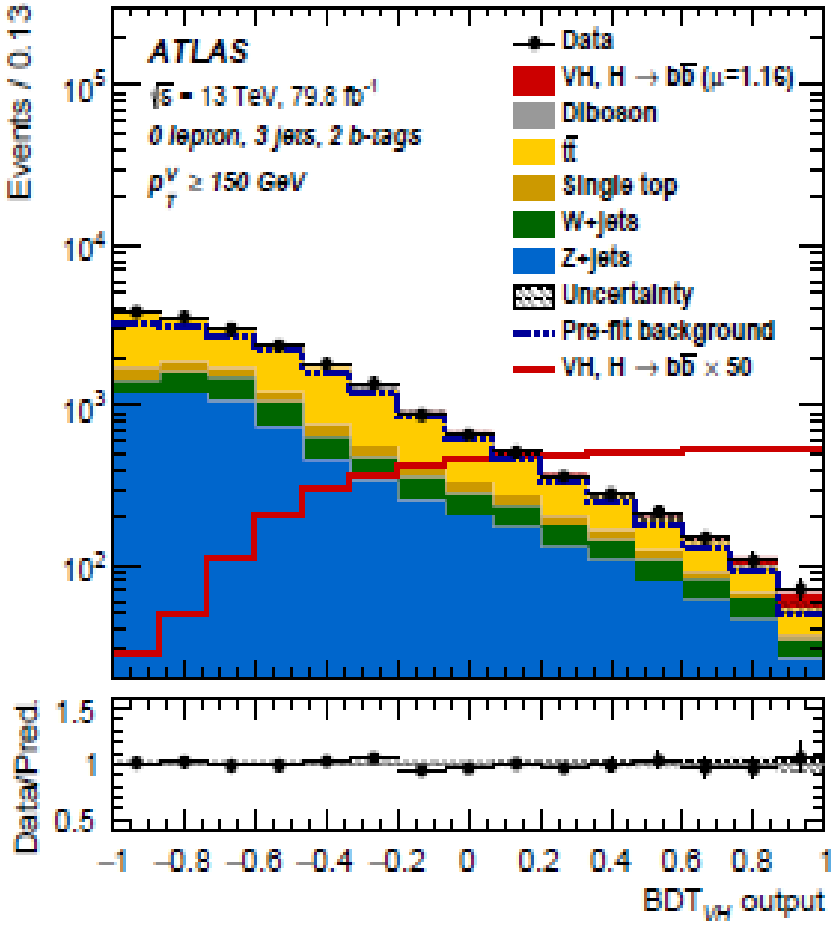
H-> $b\bar{b}$ with W or Z boson

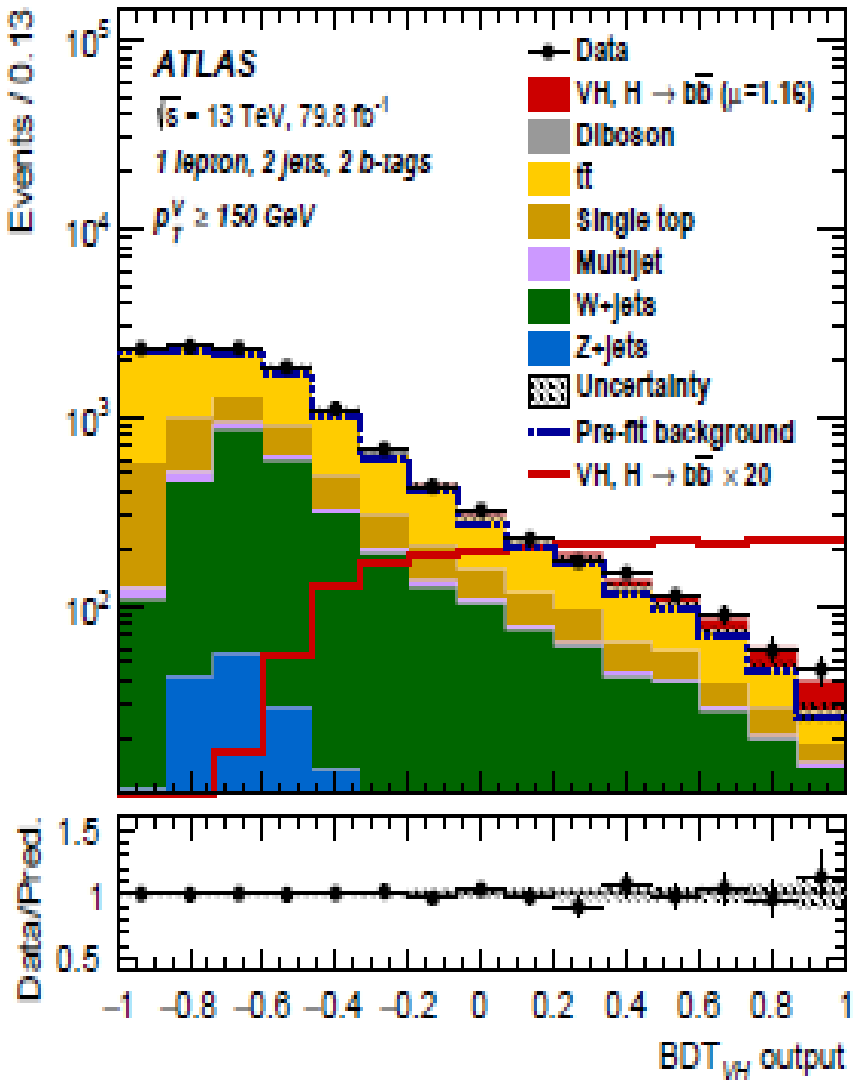


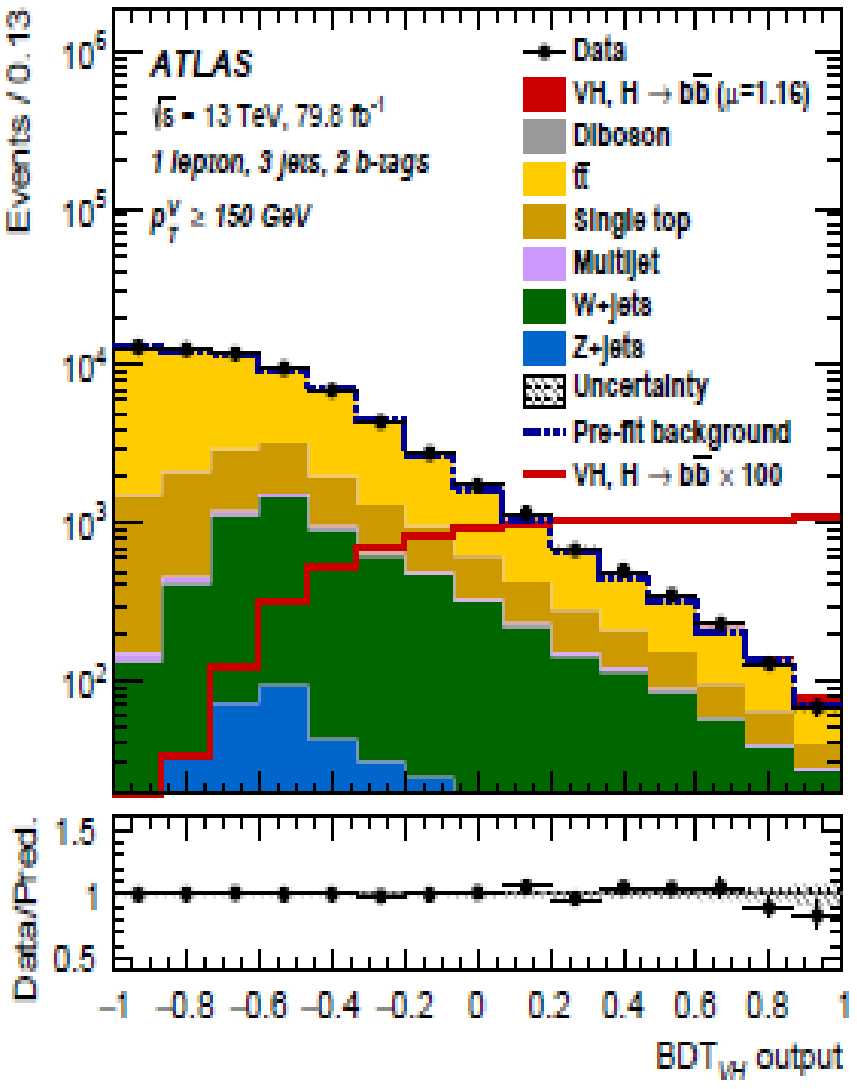
Higgs boson production in association with a vector boson V (a W or Z particle), a weak interaction process known as VH(bb)

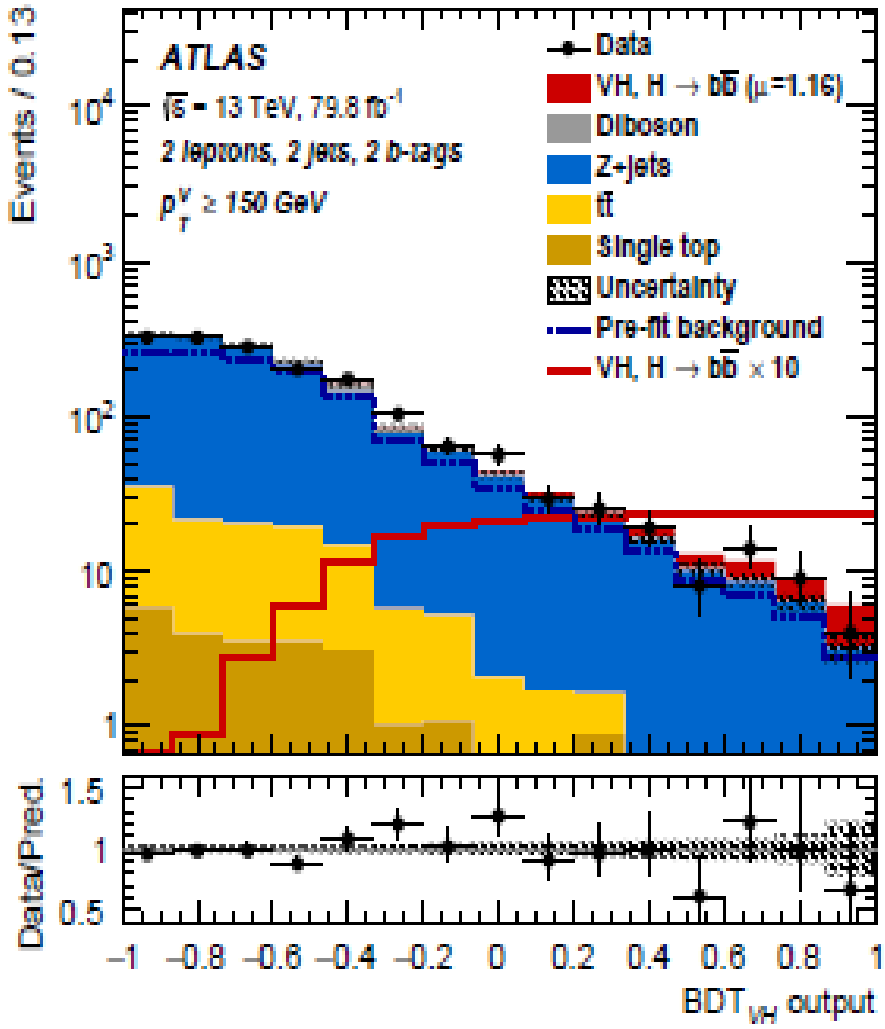
H-> $b\bar{b}$ with W or Z boson

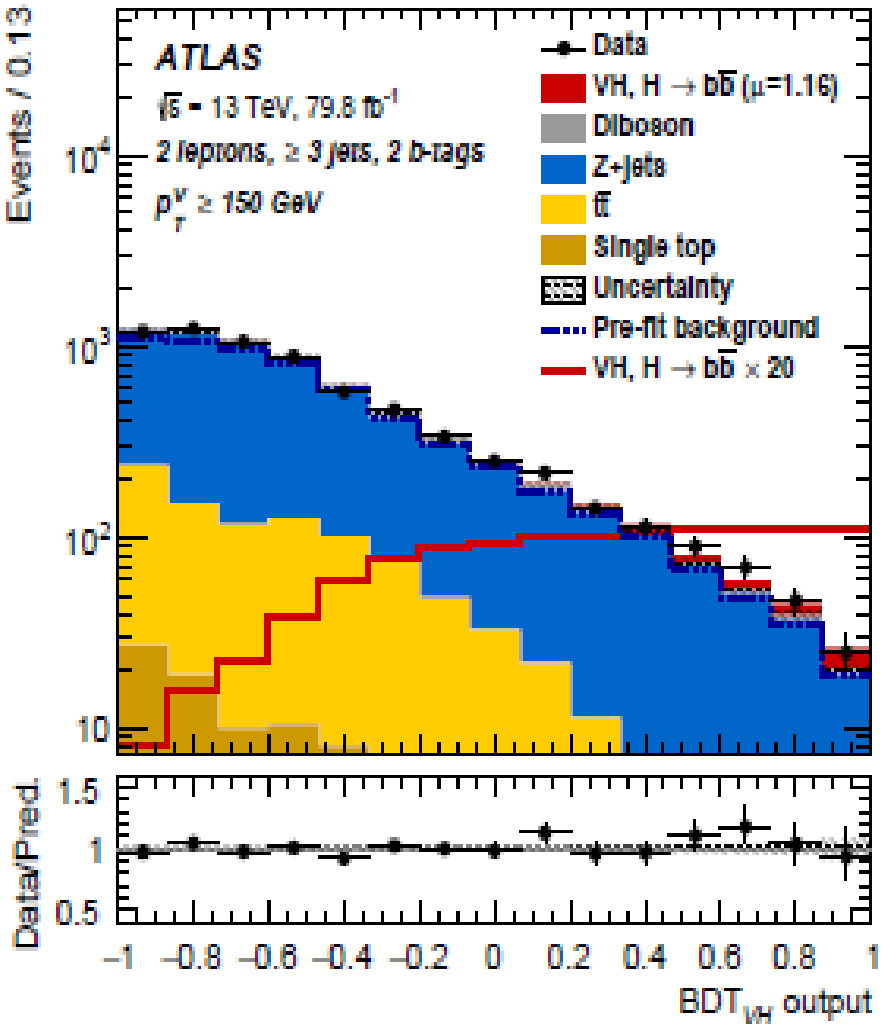


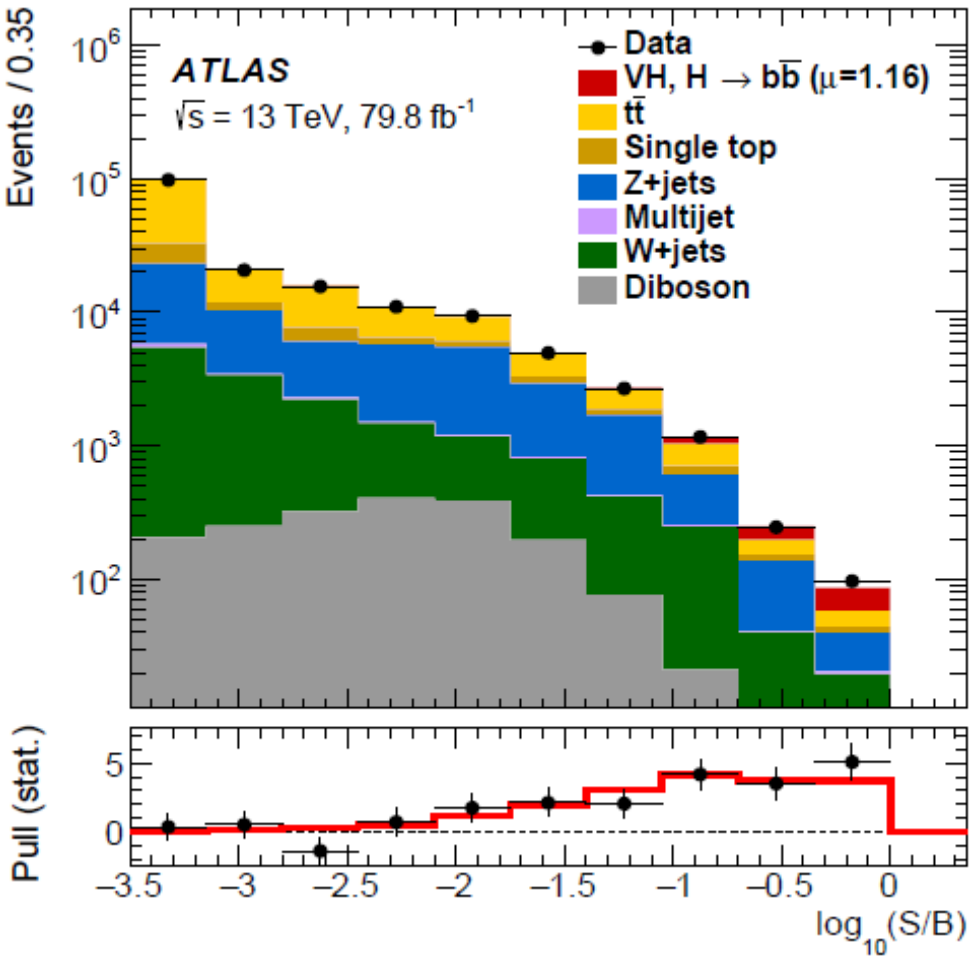


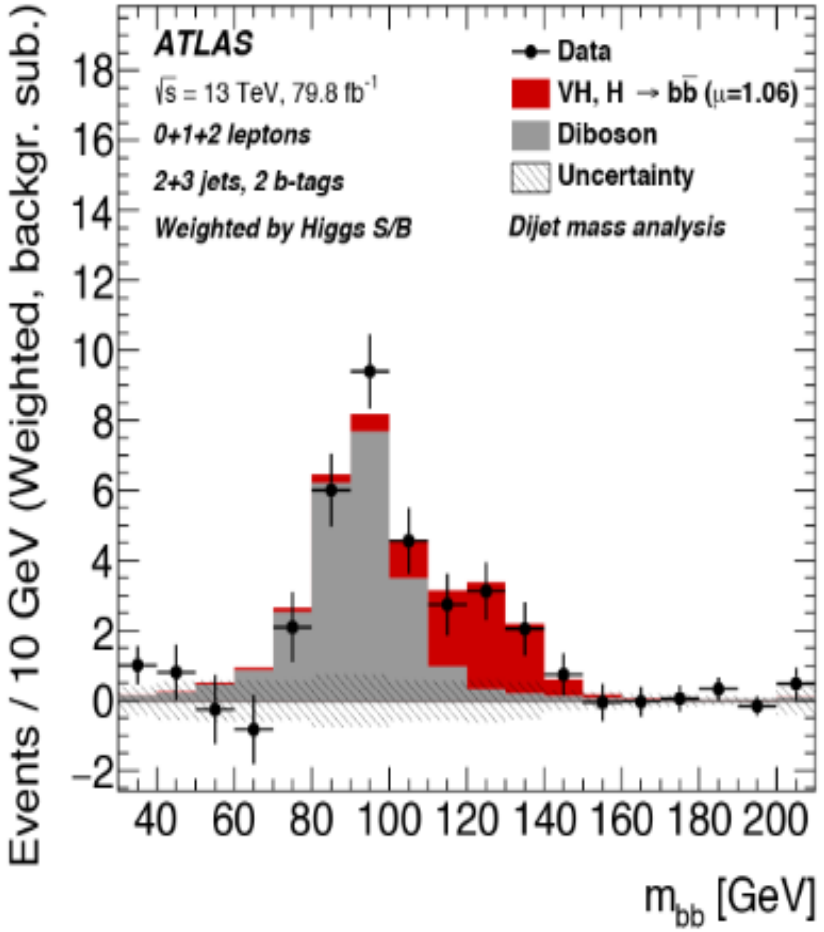

ATLAS
√s = 13 TeV, 79.8 fb-1
1 lepton, 2 jets, 2 b-tags
pTV ≥ 150 GeV
Data
VH, H → bb̄ (μ=1.16)
Diboson
tt̄
Single top
Multijet
W+jets
Z+jets
Uncertainty
Pre-fit background
VH, H → bb̄ × 20
Events / 0.13
Data/Pred.
BDTVH output


ATLAS
√s = 13 TeV, 79.8 fb-1
1 lepton, 3 jets, 2 b-tags
pTV ≥ 150 GeV
Data
VH, H → bb̄ (μ=1.16)
Diboson
tt̄
Single top
Multijet
W+jets
Z+jets
Uncertainty
Pre-fit background
VH, H → bb̄ × 100
Events / 0.13
Data/Pred.
BDTVH output

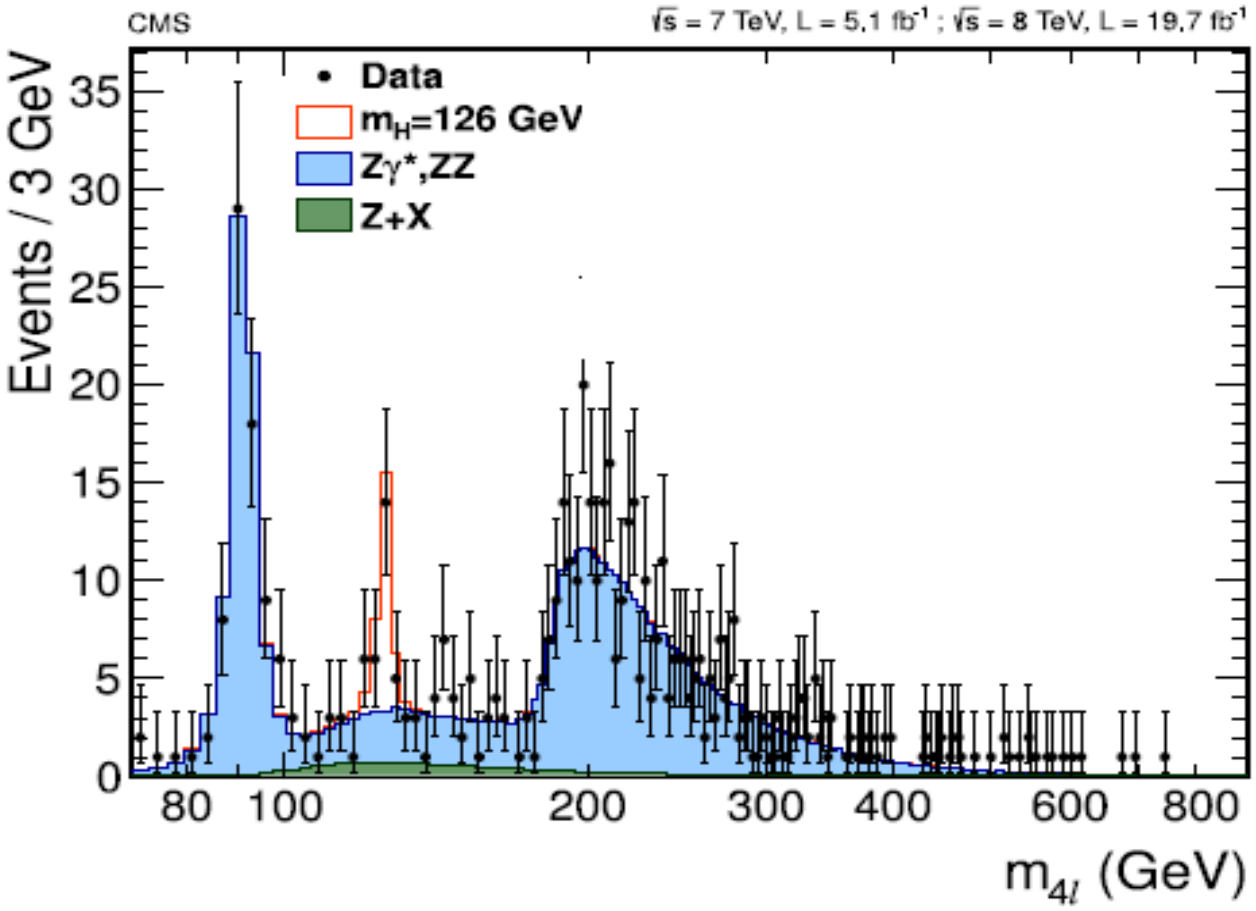

ATLAS
√s = 13 TeV, 79.8 fb⁻¹
2 leptons, 2 jets, 2 b-tags
p_T^V ≥ 150 GeV
Data
VH, H → bb̄ (μ=1.16)
Diboson
Z+jets
tt̄
Single top
Uncertainty
Pre-fit background
VH, H → bb̄ × 10
Events / 0.13
Data/Pred.
BDT_VH output

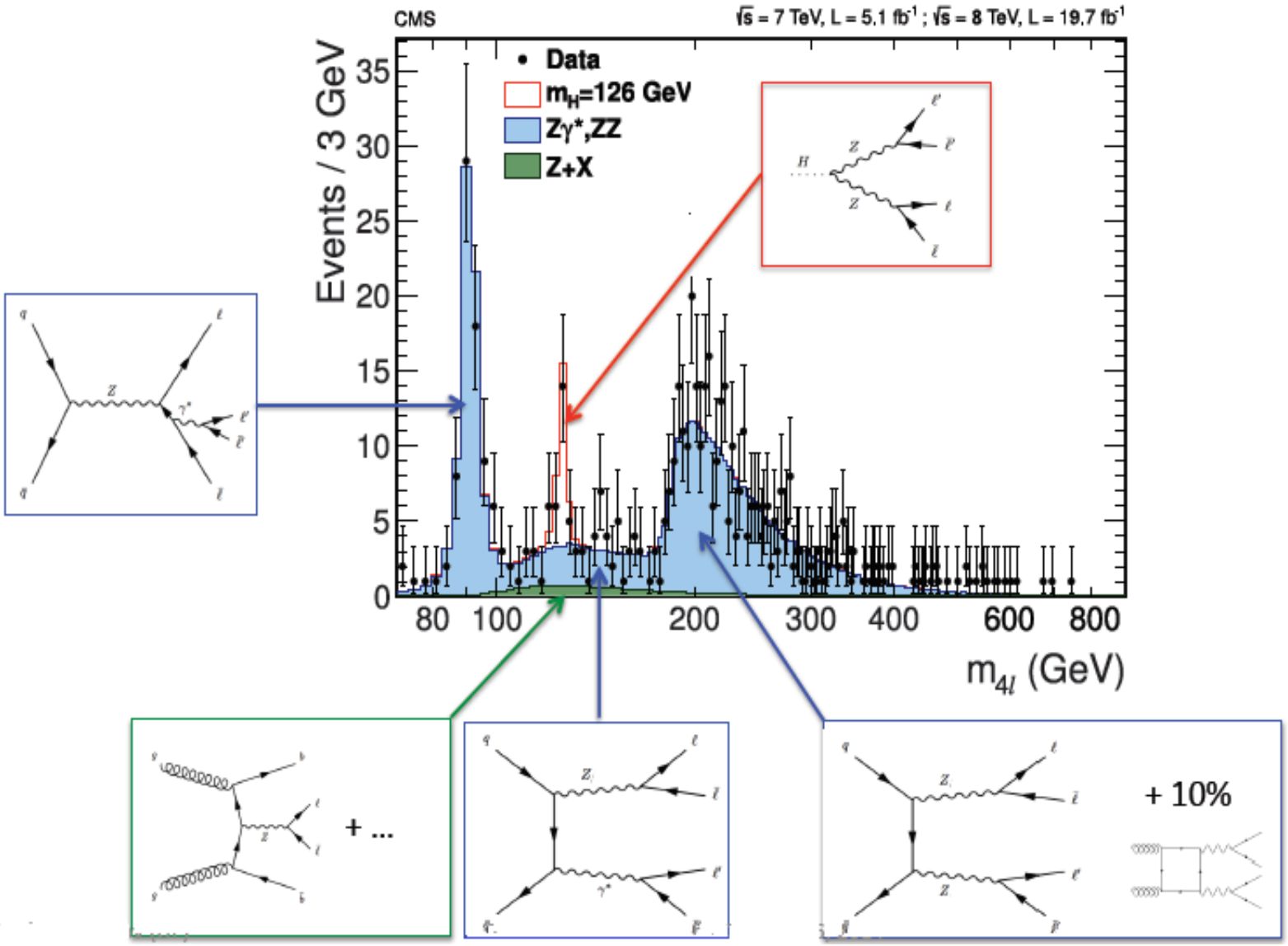

ATLAS
√s = 13 TeV, 79.8 fb⁻¹
2 leptons, ≥ 3 jets, 2 b-tags
p_T^V ≥ 150 GeV
Data
VH, H → bb̄ (μ=1.16)
Diboson
Z+jets
tt̄
Single top
Uncertainty
Pre-fit background
VH, H → bb̄ × 20
Events / 0.13
Data/Pred.
BDT_VH output


ATLAS
√s = 13 TeV, 79.8 fb-1
Data
VH, H → bb̄ (μ=1.16)
tt̄
Single top
Z+jets
Multijet
W+jets
Diboson
Events / 0.35
Pull (stat.)
log10(S/B)

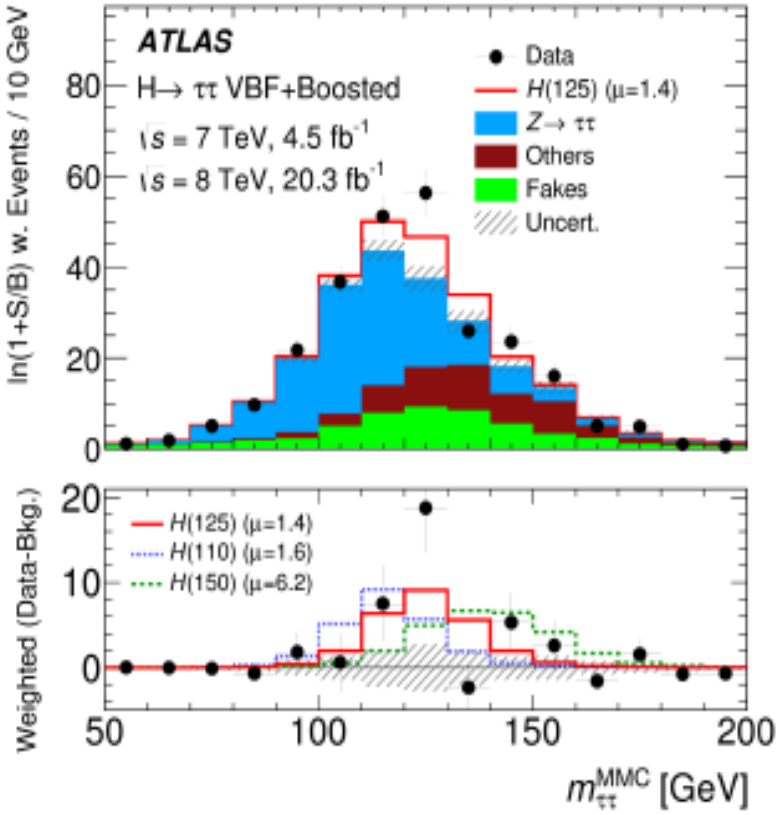

ATLAS
√s = 13 TeV, 79.8 fb-1
0+1+2 leptons
2+3 jets, 2 b-tags
Weighted by Higgs S/B
Data
VH, H → bb̄ (μ=1.06)
Diboson
Uncertainty
Dijet mass analysis
Events / 10 GeV (Weighted, backgr. sub.)
mbb [GeV]

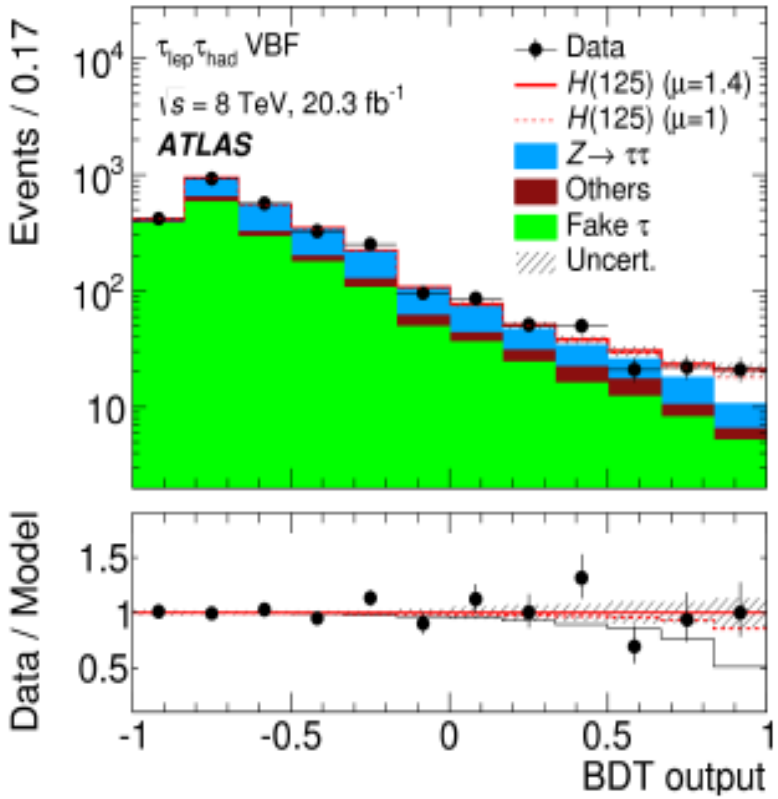
H->ZZ*->*llll*


CMS
√s = 7 TeV, L = 5.1 fb⁻¹ ; √s = 8 TeV, L = 19.7 fb⁻¹
Data
m_H=126 GeV
Zγ*,ZZ
Z+X
Events / 3 GeV
0
5
10
15
20
25
30
35
80
100
200
300
400
600
800
m_4l (GeV)

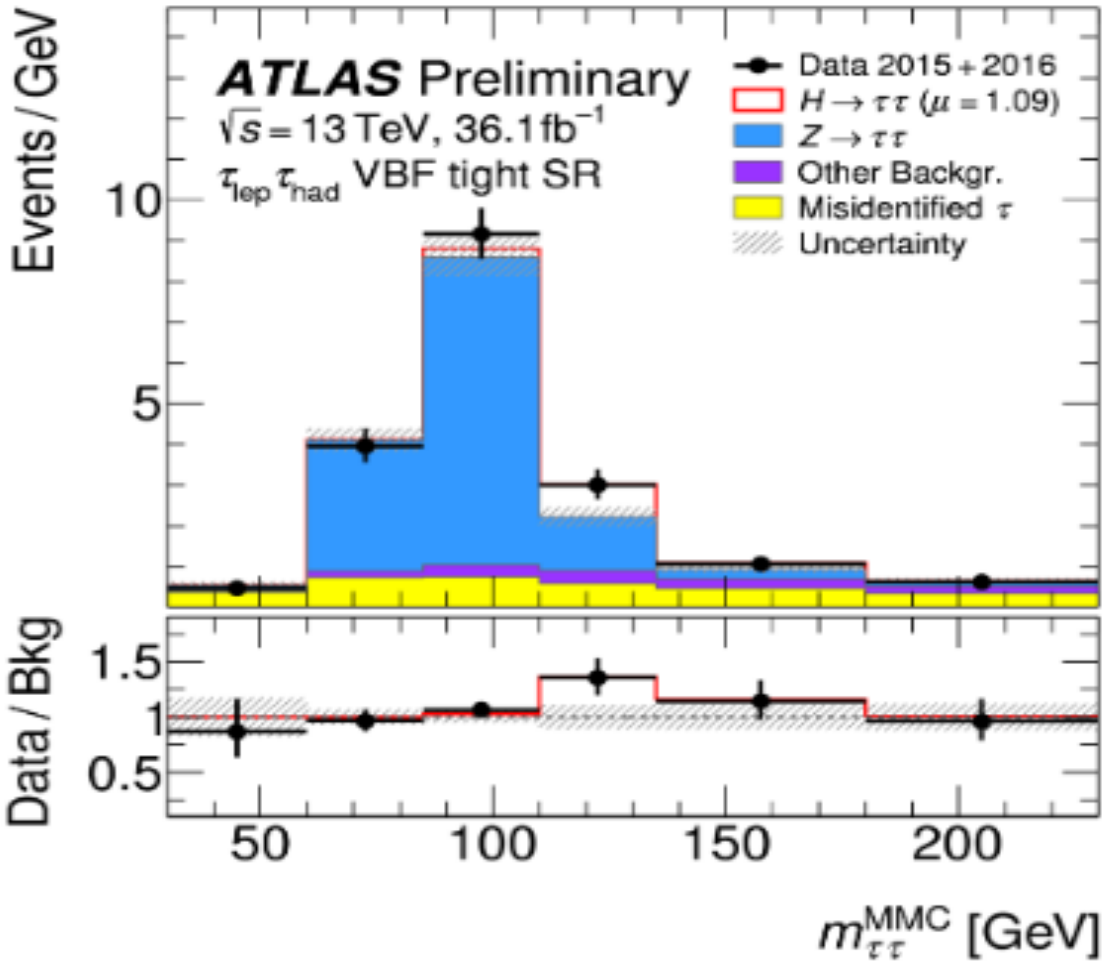

CMS
√s = 7 TeV, L = 5.1 fb-1 ; √s = 8 TeV, L = 19.7 fb-1
Data
mH=126 GeV
Zγ*,ZZ
Z+X
Events / 3 GeV
0
5
10
15
20
25
30
35
80
100
200
300
400
600
800
m4l (GeV)
+ ...
+ 10%

H->ττ


ATLAS
H→ ττ VBF+Boosted
√s = 7 TeV, 4.5 fb-1
√s = 8 TeV, 20.3 fb-1
Data
H(125) (μ=1.4)
Z→ ττ
Others
Fakes
Uncert.
ln(1+S/B) w. Events / 10 GeV
Weighted (Data-Bkg.)
H(125) (μ=1.4)
H(110) (μ=1.6)
H(150) (μ=6.2)
mMMC ττ [GeV]

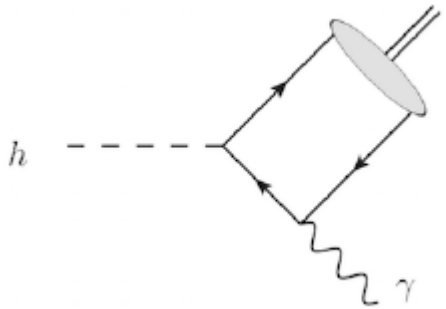

τlep τhad VBF
√s = 8 TeV, 20.3 fb-1
ATLAS
Data
H(125) (μ=1.4)
H(125) (μ=1)
Z→ ττ
Others
Fake τ
Uncert.
Events / 0.17
Data / Model
BDT output

Mass estimator on x-axis with events on y-axis

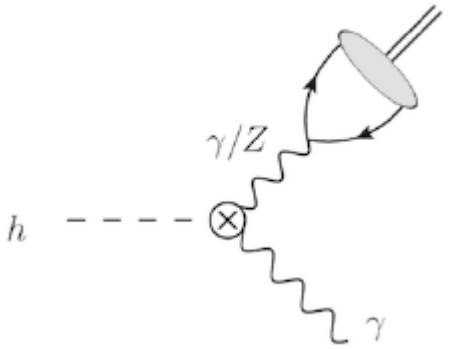


H->My

H: Higgs Boson, M is meson and y is photon

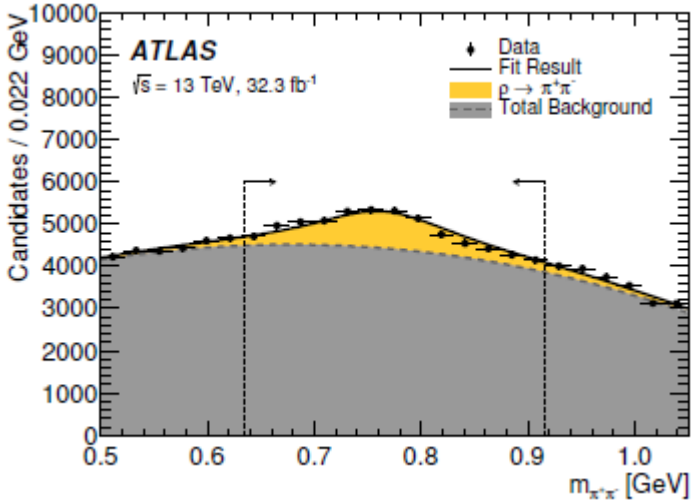


Direct Decay

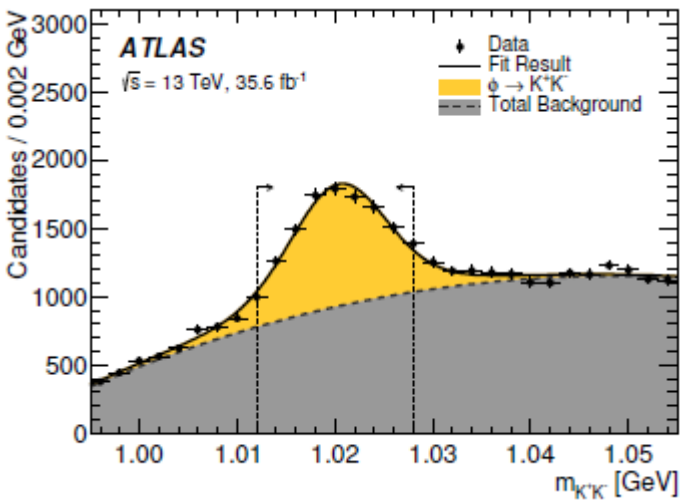


Indirect Decay

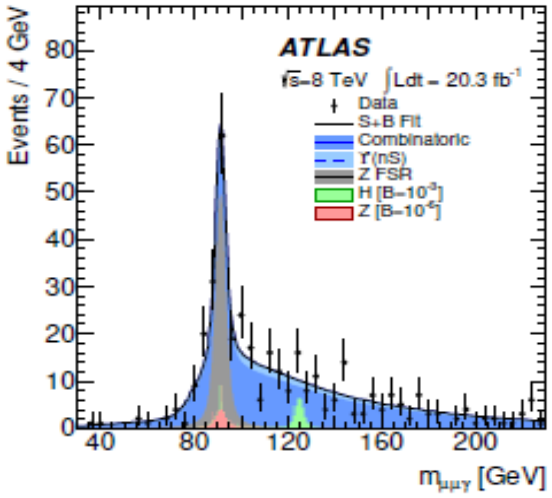
Meson	**Branching ratio(BR_{SM}) (H->M y)**	**Decay mode of meson**
ρ	1.7×10^{-5}	$\rho \rightarrow \pi^+\pi^-$
ϕ	2.3×10^{-6}	$\phi \rightarrow \mu^+\mu^-$
J/Ψ	2.8×10^{-6}	$J/\Psi \rightarrow \mu^+\mu^-$
Υ(1S,2S,3S)	$6.1, 2.0, 2.4 \times 10^{-10}$	$\Upsilon \rightarrow \mu^+\mu^-$



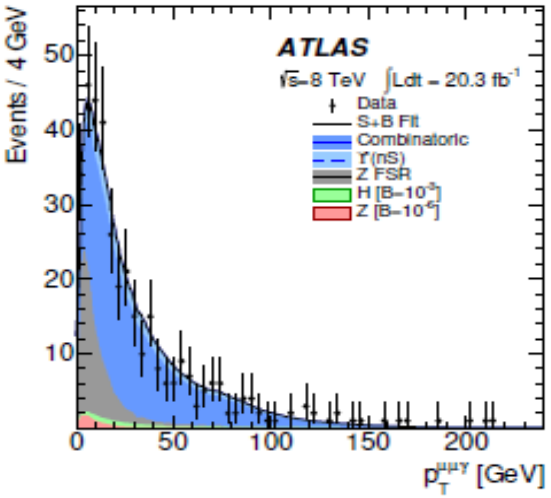
ρ->$\pi^+\pi^-$



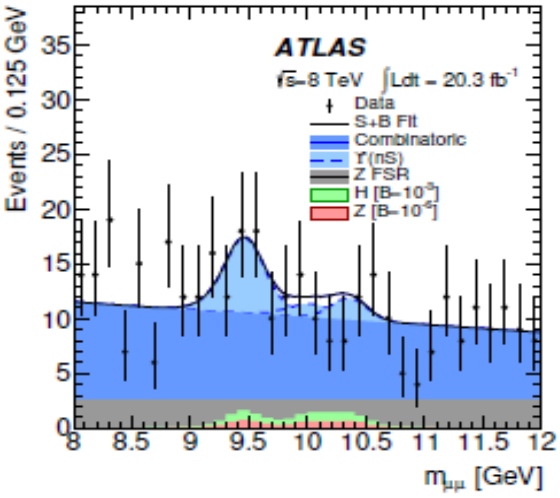
ϕ ->K^+K^-



$m_{\mu\mu\gamma}$

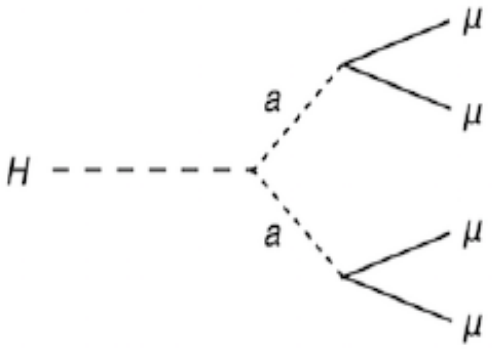


$p_T^{\mu\mu\gamma}$

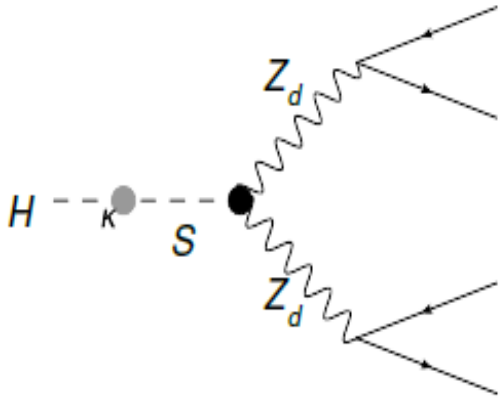


$m_{\mu\mu}$

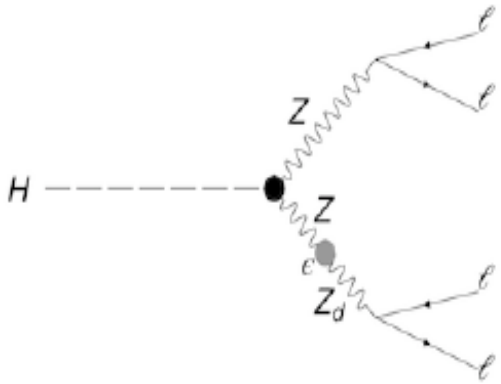
H->a^0a^0 and Z_dZ_d-> *llll*



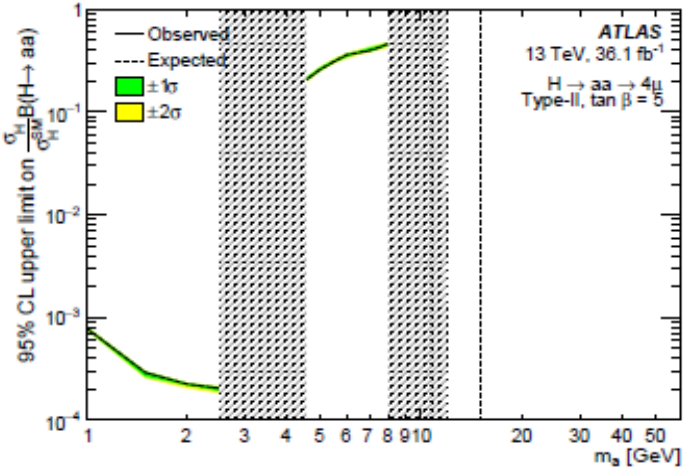
a^0a^0



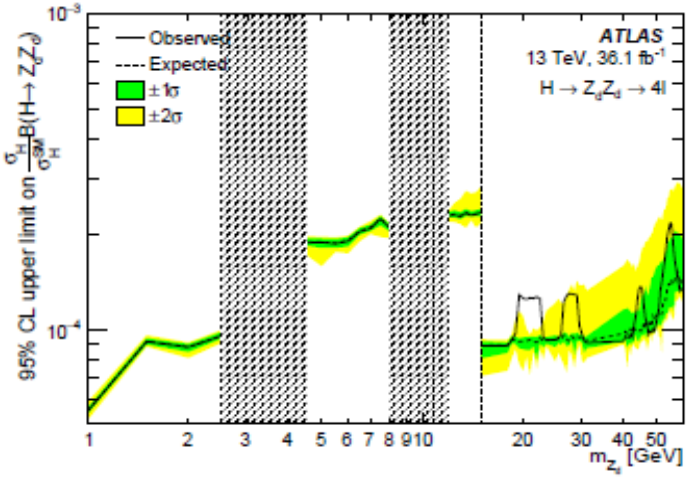
Z_dZ_d



ZZ_d



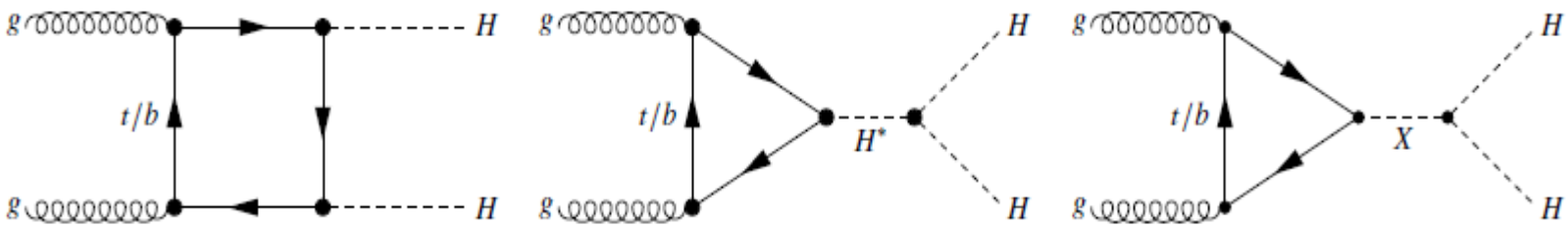
BR (H->a^0a^0)



BR (H->Z_dZ_d)

Higgs pair production and decay HH-> $b\bar{b}b\bar{b}$, HH->b$\bar{b}$ γγ, HH->WW* γγ

Higgs pair production using gluon-gluon fusion

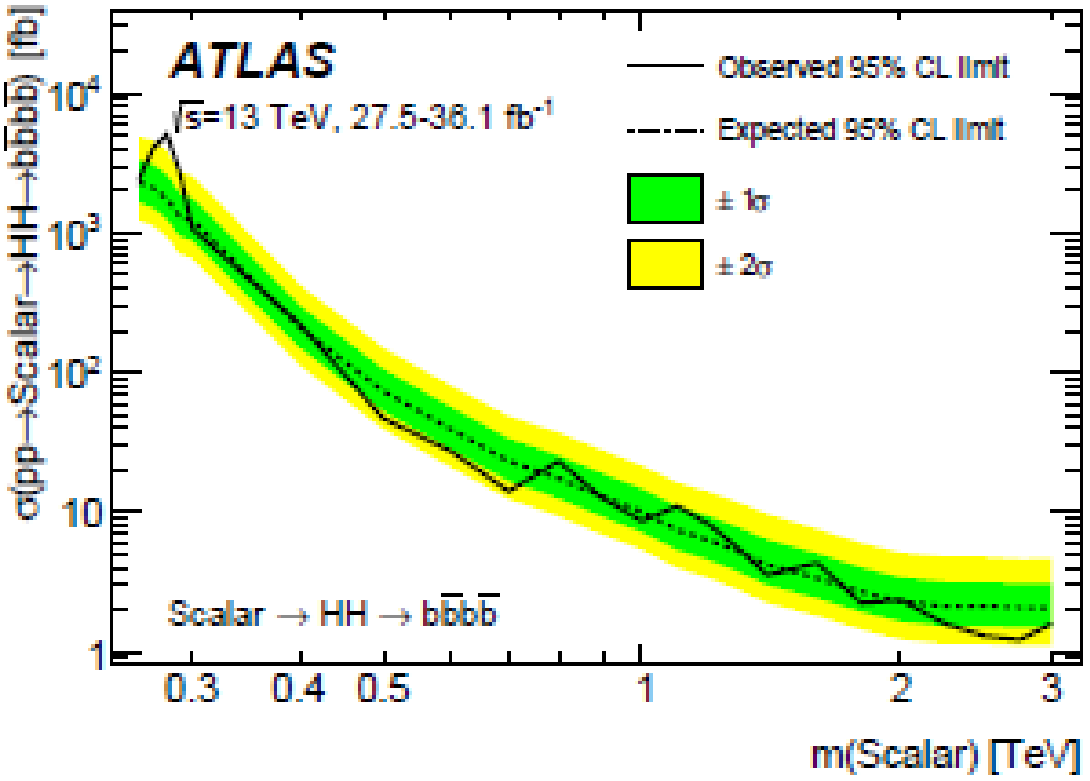


Heavy quark loop

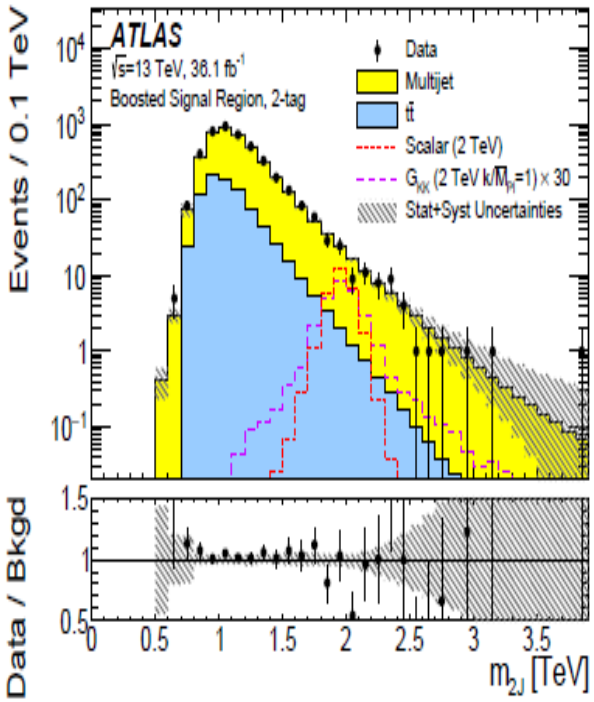
Higgs self-coupling in standard model

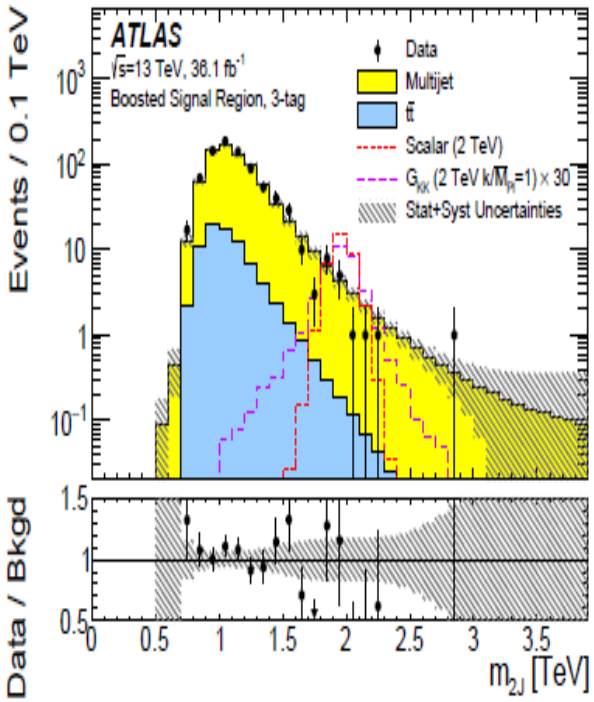
Intermediate resonance X

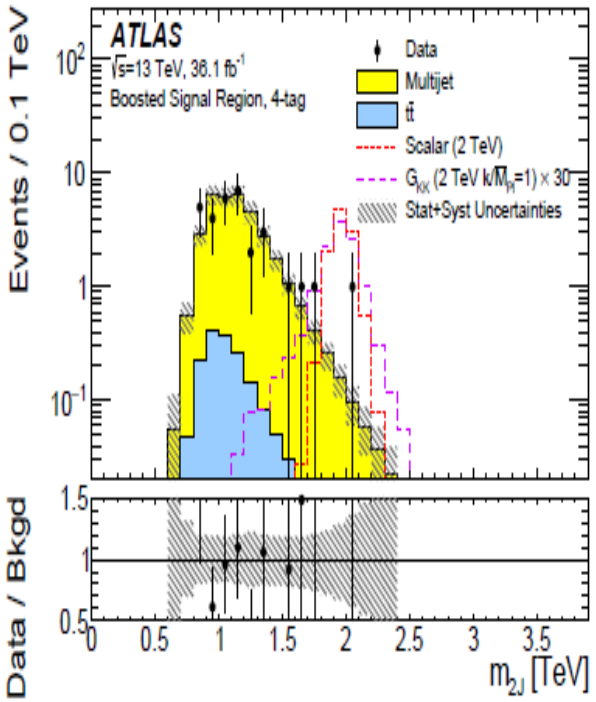
HH -> $b\bar{b}b\bar{b}$



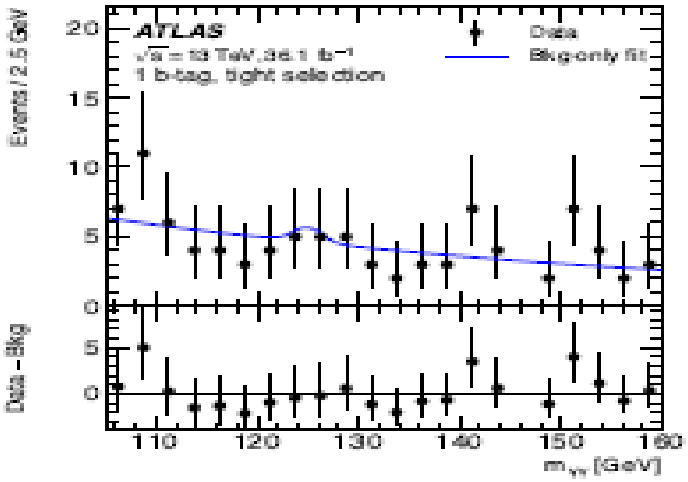
Invariant mass of two $b\bar{b}$ split by b-tags

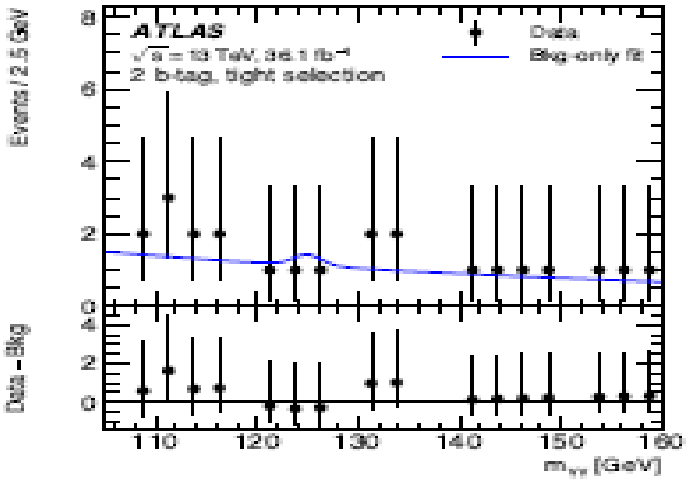




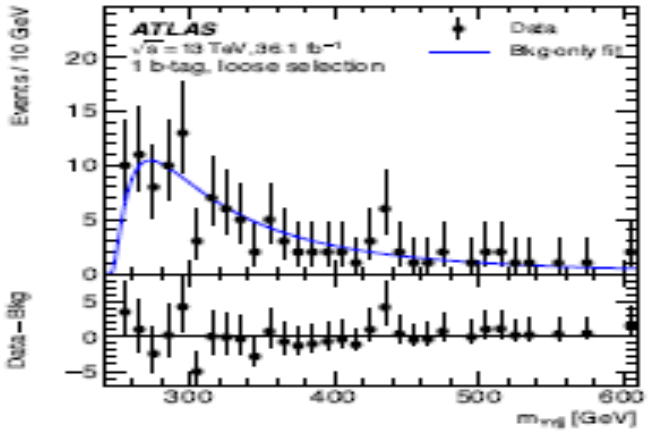


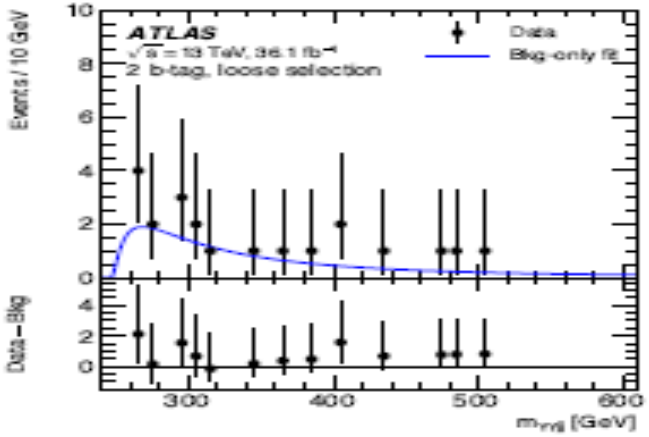
HH -> $b\bar{b}$ yy





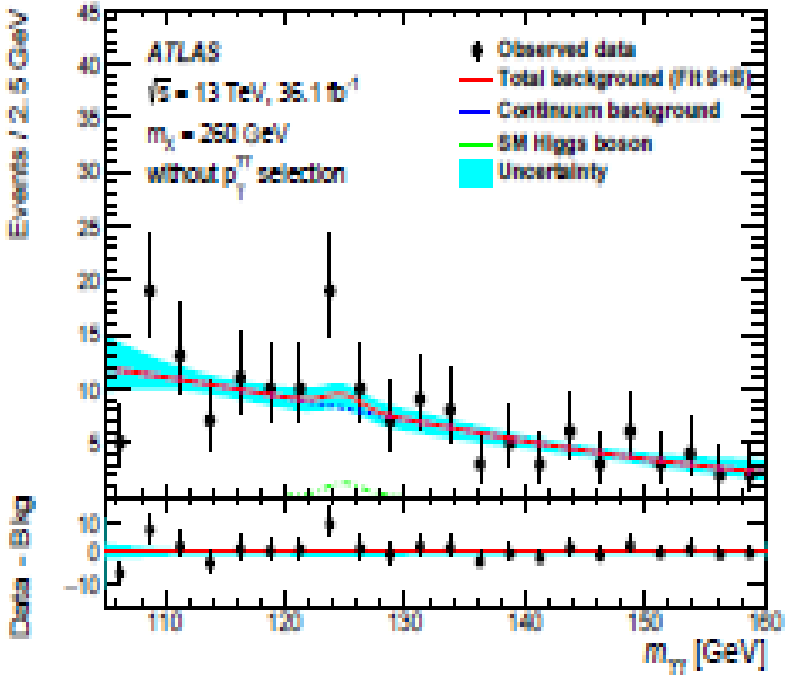
Non-resonant production

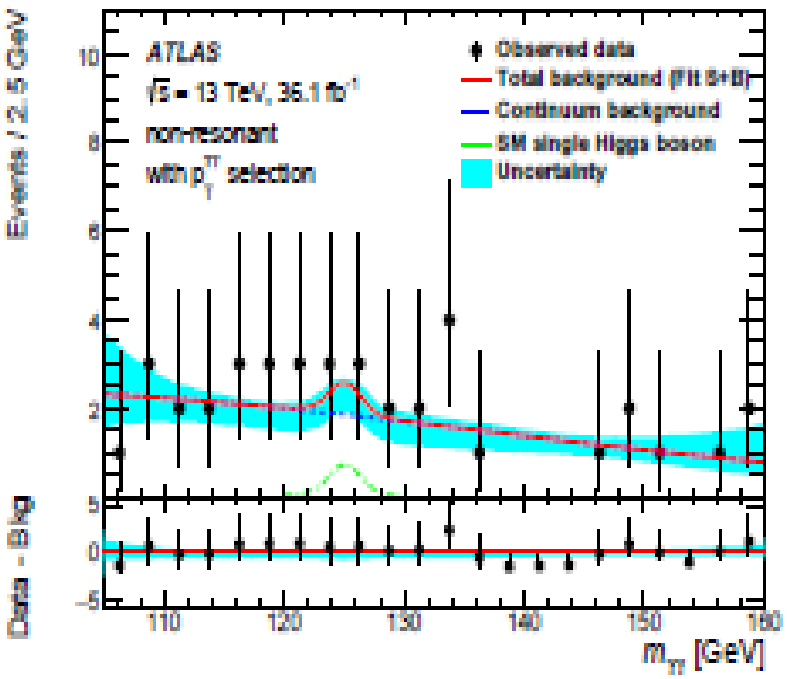




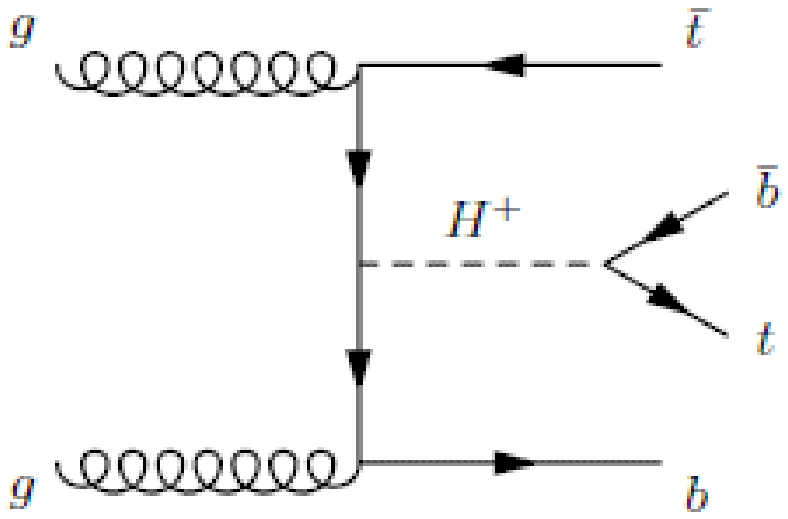
Resonant production

HH -> WW* yy

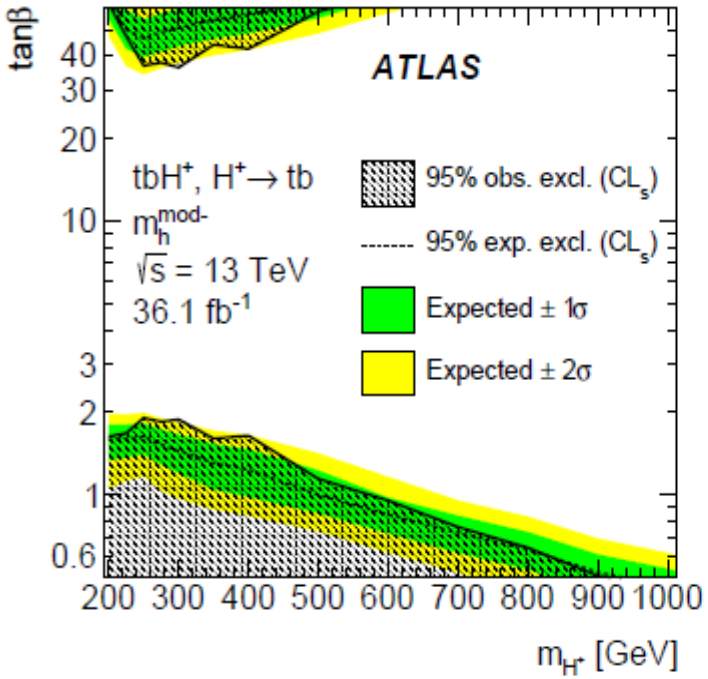

ATLAS
√s = 13 TeV, 36.1 fb⁻¹
m_X = 260 GeV
without p_T^γγ selection
Observed data
Total background (Fit S+B)
Continuum background
SM Higgs boson
Uncertainty
Events / 2.5 GeV
Data - Bkg
m_γγ [GeV]

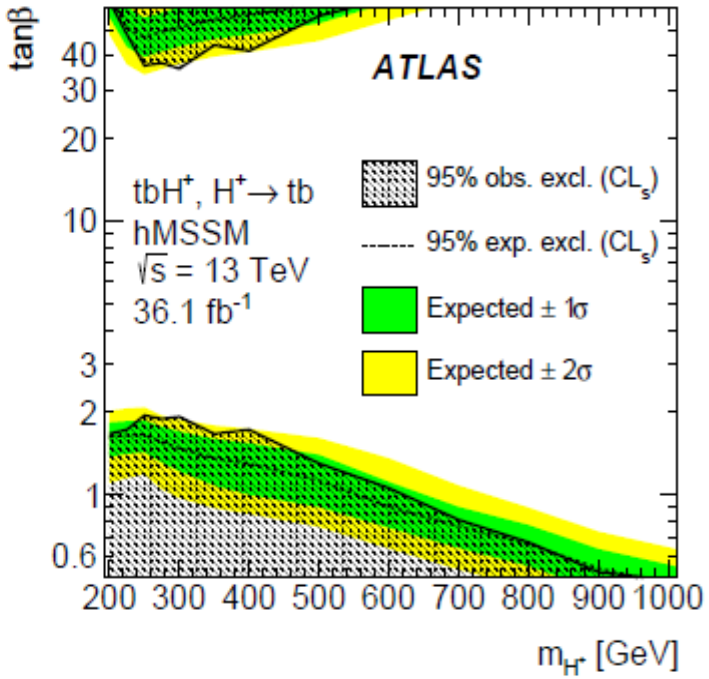

ATLAS
√s = 13 TeV, 36.1 fb⁻¹
non-resonant
with p_T^γγ selection
Observed data
Total background (Fit S+B)
Continuum background
SM single Higgs boson
Uncertainty
Events / 2.5 GeV
Data - Bkg
m_γγ [GeV]

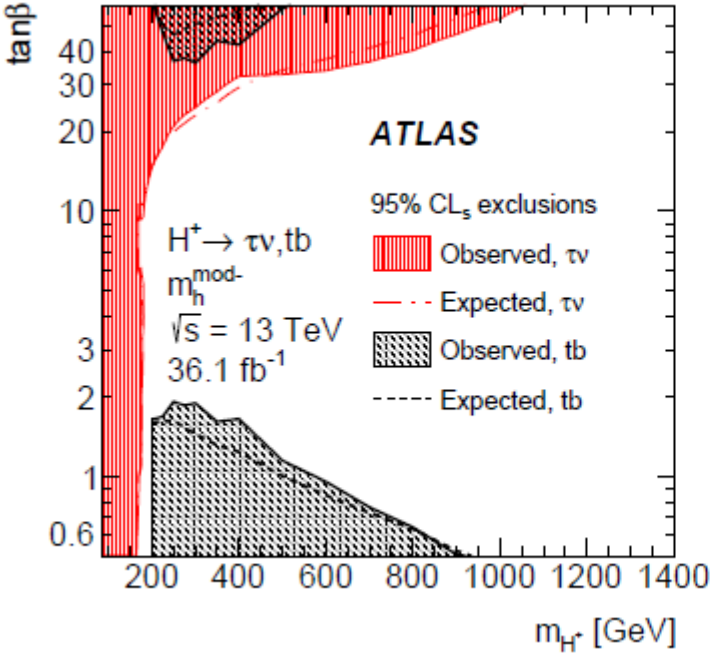
Charged Higgs Boson Decay

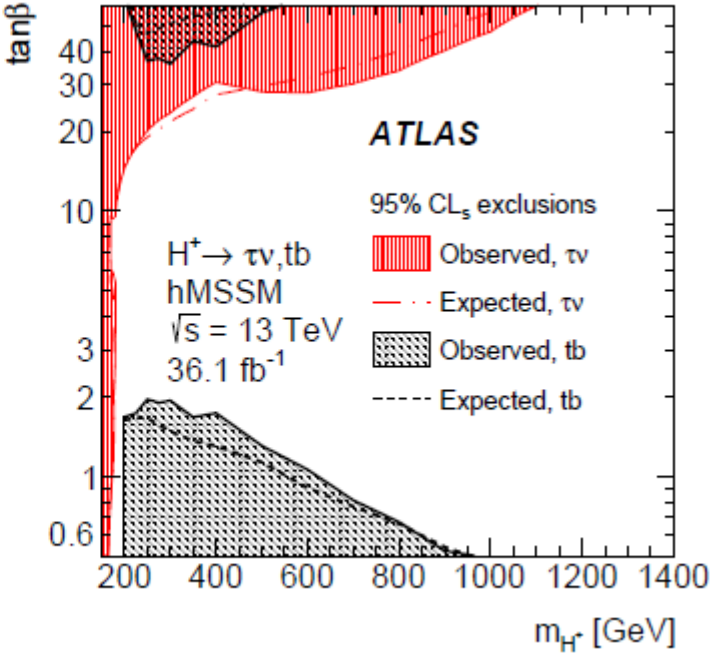


Leading order Feynman Diagram for Charged Higgs Boson decay to top and anti-bottom quark


ATLAS
tbH+, H+→ tb
m_h^mod-
√s = 13 TeV
36.1 fb-1
95% obs. excl. (CLs)
95% exp. excl. (CLs)
Expected ± 1σ
Expected ± 2σ
tanβ
mH+ [GeV]


ATLAS
tbH+, H+→ tb
hMSSM
√s = 13 TeV
36.1 fb-1
95% obs. excl. (CLs)
95% exp. excl. (CLs)
Expected ± 1σ
Expected ± 2σ
tanβ
mH+ [GeV]


ATLAS
H+→ τν,tb
m_h^mod-
√s = 13 TeV
36.1 fb-1
95% CLs exclusions
Observed, τν
Expected, τν
Observed, tb
Expected, tb
tanβ
mH+ [GeV]


ATLAS
H+→ τν,tb
hMSSM
√s = 13 TeV
36.1 fb-1
95% CLs exclusions
Observed, τν
Expected, τν
Observed, tb
Expected, tb
tanβ
mH+ [GeV]

Conclusions

- Higgs Boson decay to meson and a photon is vital to be probed at HL-LHC for H-> J/Ψ γ.
- Cross –section of H-> J/Ψ γ will be $15\sigma_{SM}$ at HL-LHC.
- Cross section of SM Higgs pair production is 33.41 fb at 13 TeV with decay modes HH->$b\bar{b}b\bar{b}$ HH->$b\bar{b}\gamma\gamma$, HH->WW* γγ.
- The limit on non-resonant Higgs boson pair cross section is 0.223 pb at 95 % CL which is 6.7 σ_{SM} and Higgs boson self-coupling to SM coupling at 95 % CL is $-5 < \kappa_\lambda < 12$.

- Higgs boson can decay to $b\bar{b}$ pair and it can be produced with W or Z boson at 13 TeV, 79.8 fb^{-1} significance 4.9 standard deviation, signal strength $\mu^{bb}_{VH} = 1.16 \pm 0.16(stat.)^{+0.21}_{-0.19}(syst.)$

- Higgs Boson can decay to bottom quarks H->bb, H->ττ leptons, H-> $b\bar{b}$ and H->ZZ*->4l.

- Mass estimates of positively charged Higgs Boson is 40-100 GeV for LEP, 80-150 GeV for CDF DØ and 180-600 GeV for CMS.

The End

Thank you!