Measurement of properties of the Higgs boson in the diboson channels using the ATLAS detector

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Introduction

Higgs to diboson searches in ATLAS

- ***Jul. 2012:*** **$\gamma\gamma$ + $ZZ^{(*)}\rightarrow 4l$ + $WW^{(*)}\rightarrow l\nu l\nu$** **combined discovery of resonance**
- ***Today***: moving from discovery mode to **Higgs property measurements**
  → **Higgs boson mass** / exclusive **production processes** / **couplings to bosons and fermions** / **J^P properties**

Presenting analysis update of diboson channels

Channel	Property	2011 (7 TeV)	2012 (8 TeV)	Reference
$\gamma\gamma$	Mass/Couplings	**4.8 fb^{-1}**	**20.7 fb^{-1}**	ATLAS-CONF-2013-012
	Spin	-	**20.7 fb^{-1}**	ATLAS-CONF-2013-029
$ZZ^{(*)}\rightarrow 4l$	Mass/Couplings/Spin	**4.6 fb^{-1}**	**20.7 fb^{-1}**	ATLAS-CONF-2013-013
$WW^{(*)}\rightarrow l\nu l\nu$	Couplings	**4.6 fb^{-1}**	**20.7 fb^{-1}**	ATLAS-CONF-2013-030
	Spin	-	**20.7 fb^{-1}**	ATLAS-CONF-2013-031
Combination	Mass ($\gamma\gamma$+$ZZ^{(*)}\rightarrow 4l$)	**4.8 fb^{-1}**	**20.7 fb^{-1}**	ATLAS-CONF-2013-014
	Couplings	**4.8 fb^{-1}**	Up to 20.7 fb^{-1}	ATLAS-CONF-2013-034
	Spin	Up to 4.8 fb^{-1}	**20.7 fb^{-1}**	ATLAS-CONF-2013-040

H→γγ analysis overview

Background

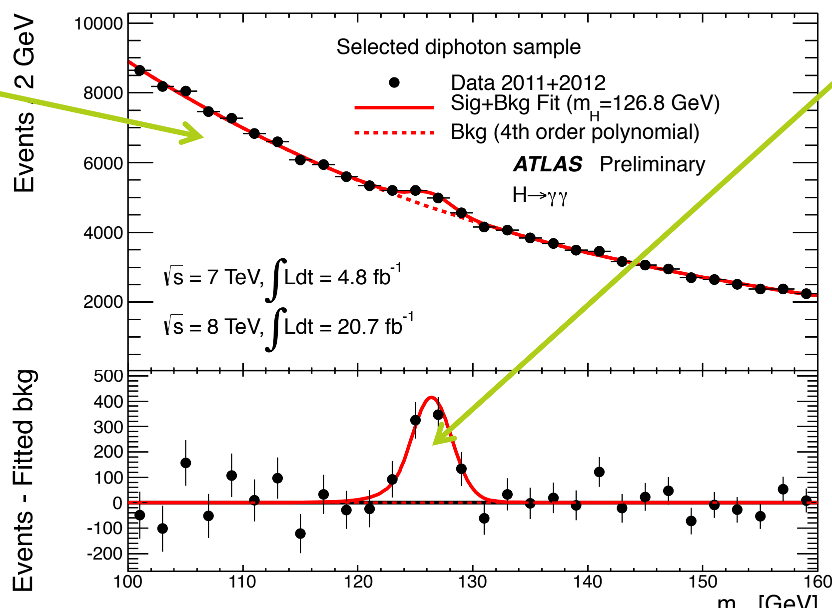
- γγ
- γj+jj fake(s)

✧ **Rejection** of huge bkg using tight photon identification and isolation

- **H→γγ = most sensitive channel at low masses + full mass reconstruction**
- **Topology**: two high pT photons
- **S/B of 3% @ 125 GeV in window containing 90% of signal**
- **118893 (23788) H→γγ candidates @ 8 TeV (7 TeV)**

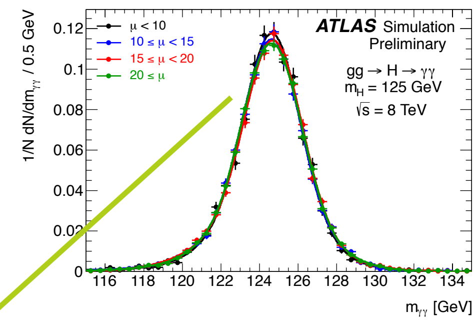
✧ **Mγγ model**: fit on data

✧ Background composition using data-driven techniques:
  - γγ (~75%)
  - γj+jj (~25%)



Signal

✧ Acceptance/ efficiency predicted by MC, yields normalized to theory



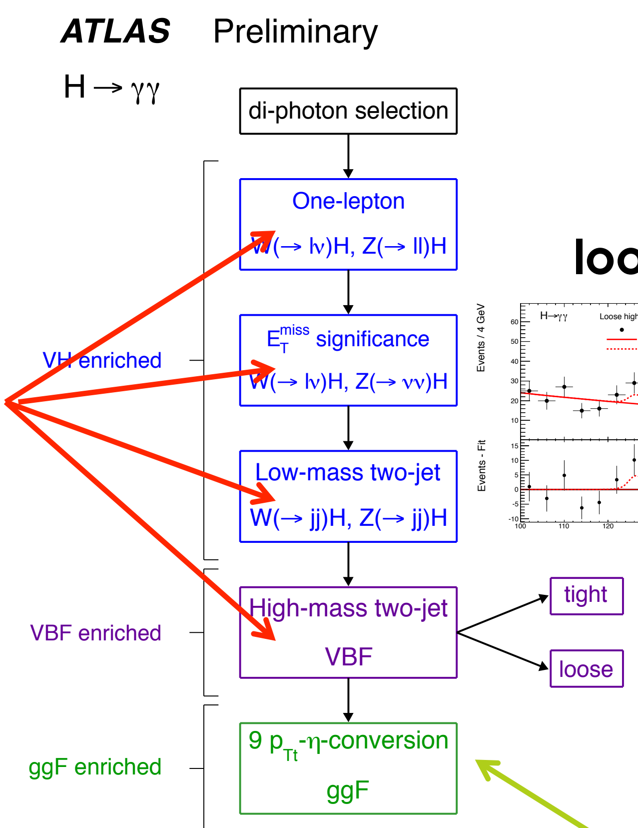
✧ Higgs Mγγ resolution model: fit on MC

✧ Overall resolution 1.7 GeV (~pileup independent)

H→γγ categories

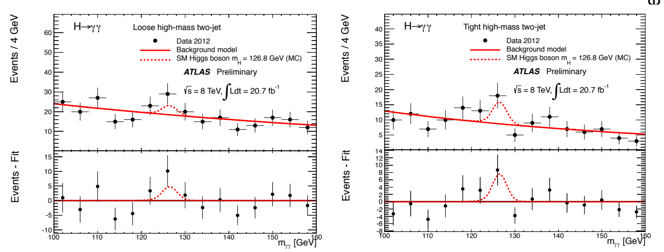
- **Categorization aimed at improving sensitivity:**
  - → **14 categories with different S/B (1%→60%) and resolutions (1.4→2.5 GeV)**
  - → **Enriched purity in VBF and VH in dedicated categories**

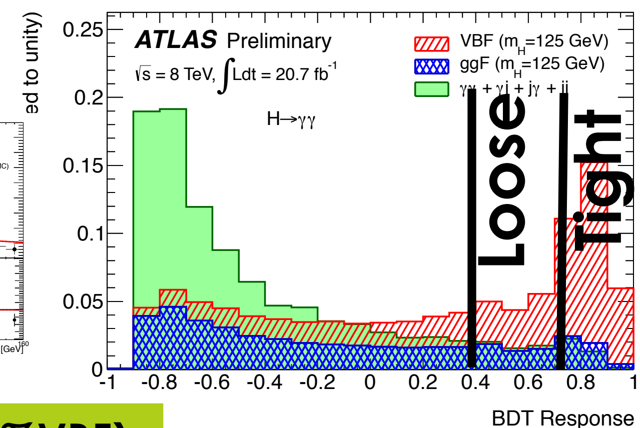
Exclusive VH/VBF processes targeted categories



- **VH production mode** (3 targeted categories)
  Leptonic, Et/miss, hadronic
- **VBF production mode** (2 targeted categories)
  MVA-based

loose **tight**





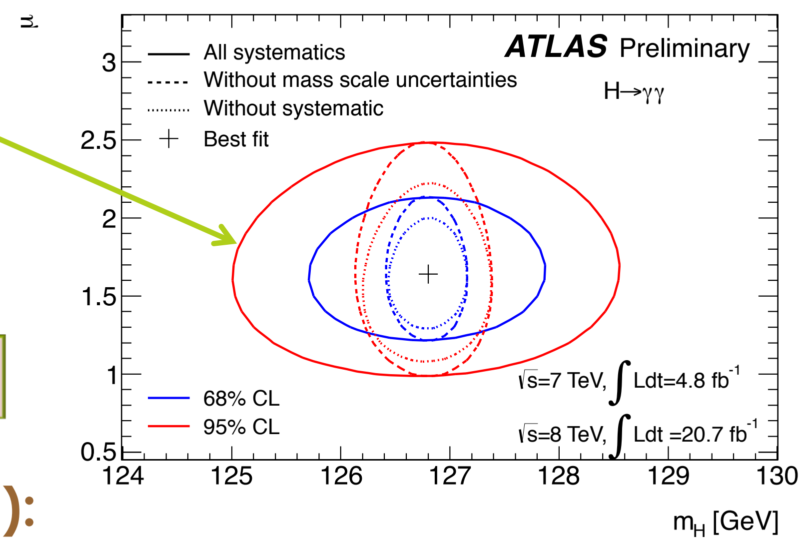
Category	Signal (%VBF)
Loose	4.8 (54%)
Tight	7.3 (76%)

- **Different $M_{\gamma\gamma}$ signal resolution categories**
  → ***Improve expected significance***

$H \rightarrow \gamma\gamma$ mass and signal strength

- **Excess wrt background-only hypothesis:**
  - **Observed 7.4σ @ M_H = 126.5 GeV (minimal p_0)**
    (expected 4.1σ for SM Higgs)
- **Best-fit mass:**
  - **M_H = 126.8 ± 0.2 (stat.) ± 0.7 (syst.) GeV**
  - ***Systematics dominated*** – highly dominated by photon energy scale
- **Signal strength $\mu = N_{obs}/N_{SM}$ @ M_H = 126.8 GeV**
  - **μ = 1.65 ± 0.24 (stat.) $^{+0.25}_{-0.18}$ (syst.)**

2.3σ from SM [Higgs + bkg] hypothesis



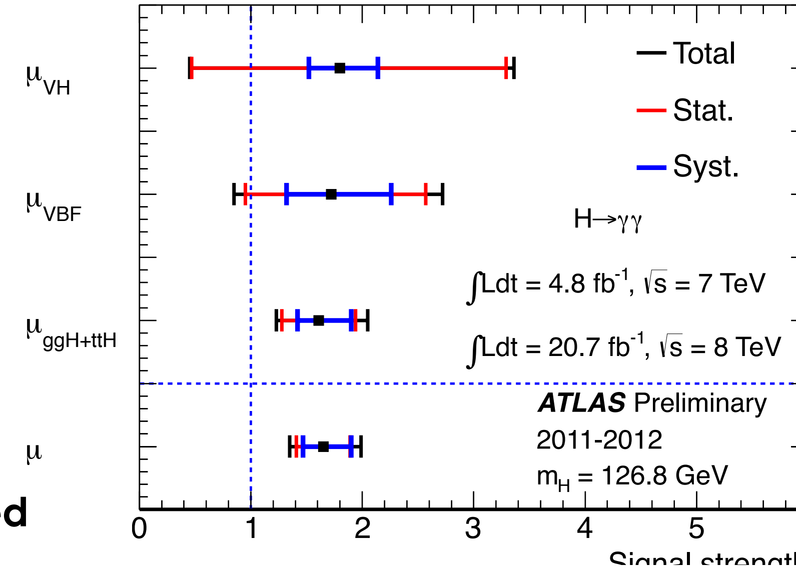
- **Fiducial cross-section (inclusive/8TeV):**
  - **σ_{fid} x BR = 56.2 ± 12.5 fb**

[in phase-space: $|\eta|$<2.37, $E_{\gamma 1}^{T}$> 40 GeV and $E_{\gamma 2}^{T}$> 30 GeV]

H→γγ signal strengths by processes

Fit 3 signal strengths

- $\mu_{VH} \times B/B_{SM} = 1.8^{+1.5}_{-1.3}\ (\text{stat.})^{+0.3}_{-0.3}\ (\text{syst.})$
- $\mu_{VBF} \times B/B_{SM} = 1.7^{+0.8}_{-0.8}\ (\text{stat.})^{+0.5}_{-0.4}\ (\text{syst.})$
- $\mu_{ggF+ttH} \times B/B_{SM} = 1.6^{+0.3}_{-0.3}\ (\text{stat.})^{+0.3}_{-0.2}\ (\text{syst.})$

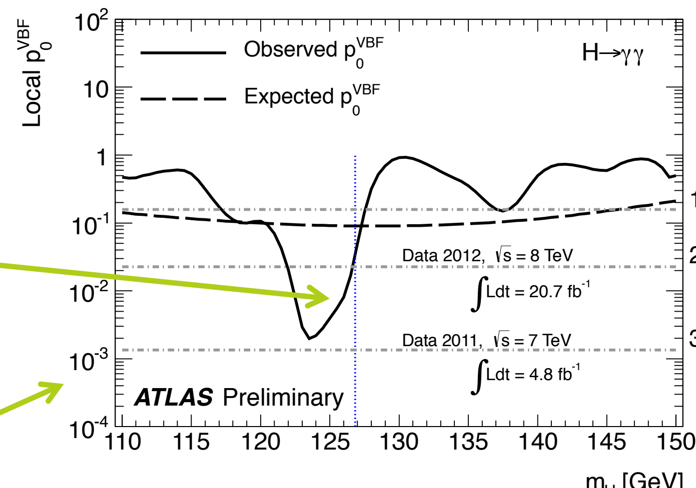


- **Measurement of signal strengths has been improved**
- At constant luminosity, the improvement is:
  - **32% on the measure of μ_{VBF}**
  - **27% on the measure of μ_{VH}**

  } w.r.t. previous result from dec.

- **Excess in γγ VBF**

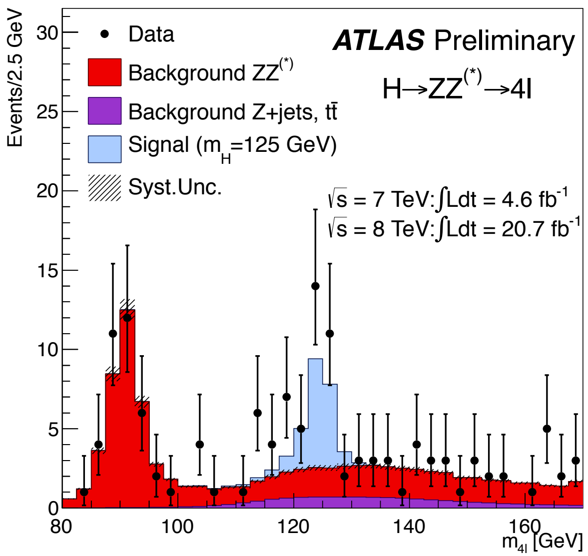
  (2σ @ M_H = 126.8 GeV)
  - **Significance almost fully driven by MVA-based high-mass 2-jet categories**



p_0 = probability that the background fluctuates to the observed data (or higher)

H→ZZ$^{(*)}$→4l analysis overview

- **ZZ$^{(*)}$→4l: golden channel**
- **In m_{4l} = [100, 160] GeV, expected for m_H = 125 GeV**
  - 4μ = 5.8
  - 2μ2e = 7.0
  - 4e = 2.9
- → **35 H→4l candidates observed in m_{4l}=[120,130] GeV**

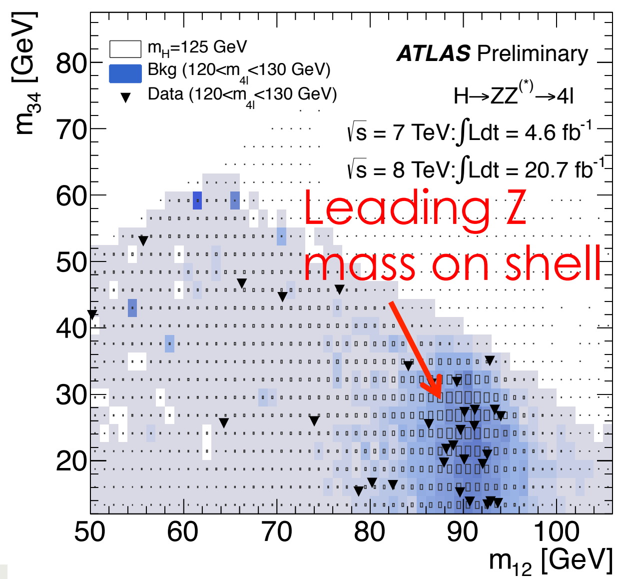


Background

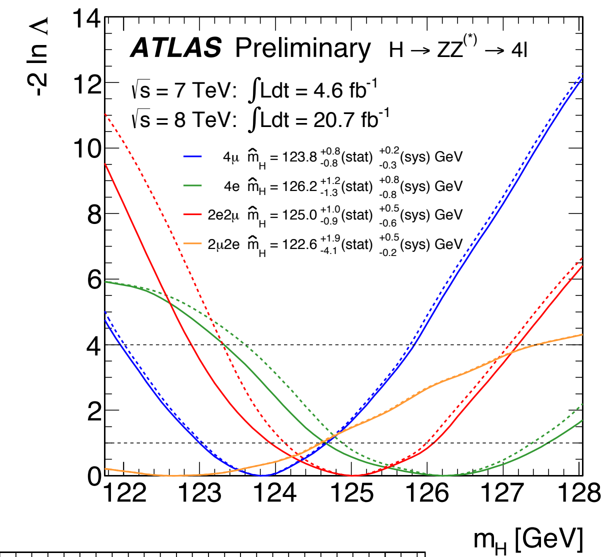
- Mainly from:
  - → Non resonant **ZZ$^{(*)}$ continuum**
  - → **Z+jets, ttbar**
- **Rejected** using isolation and impact parameter
- **Expectation**: extracted from data control regions (Z+jets/ ttbar) and MC (ZZ$^{(*)}$)

Signal reconstruction

- **Maximize acceptance** using lepton reco/ID down to low p_T of 6/7 GeV [ε=~40/20% for 4μ/4e]
- **Mass resolution from MC** using a fit that constrains the leading dilepton pair to the Z mass [σ_M/M=1.3/1.9% for 4μ/4e]
- **Energy scale/ID efficiency** for leptons from **data-driven** techniques using J/ψ or Z or W leptonic decays

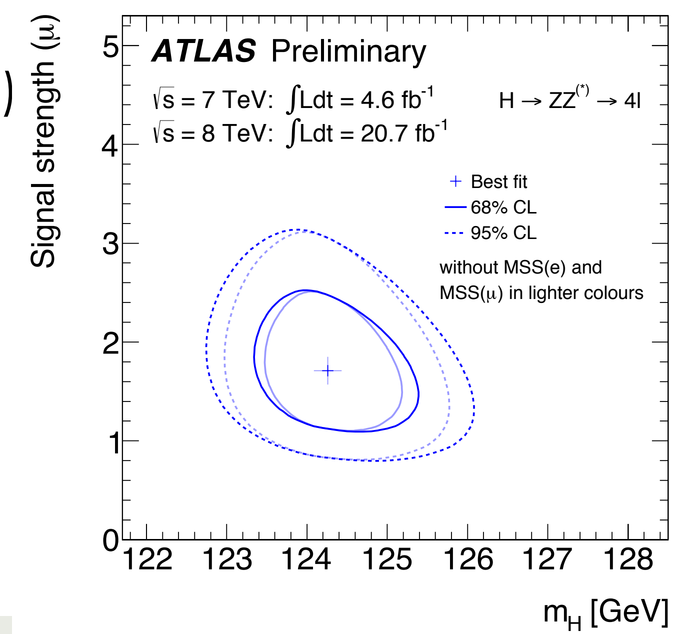


$H \to ZZ^{(*)} \to 4l$ mass and signal strength



- **Excess wrt background-only hypothesis:**
  - **Observed 6.6σ @ M_H =124.3 GeV**
    (expected 4.4σ for SM Higgs)
- **Best-fit mass:**
  - **$M_H = 124.3^{+0.6}_{-0.5}$ (stat.) $^{+0.5}_{-0.3}$ (syst.) GeV**
  - ***Statistically dominated***
  - ***Dominated by 4μ***

  (*notably* systematics of 0.2% on pT scale)
- **Signal strength $\mu = N_{obs}/N_{SM}$**
  @ M_H = 124.3 GeV
  - **$\mu = 1.7^{+0.5}_{-0.4}$**



H→WW$^{(*)}$→lvlv analysis overview

Various backgrounds

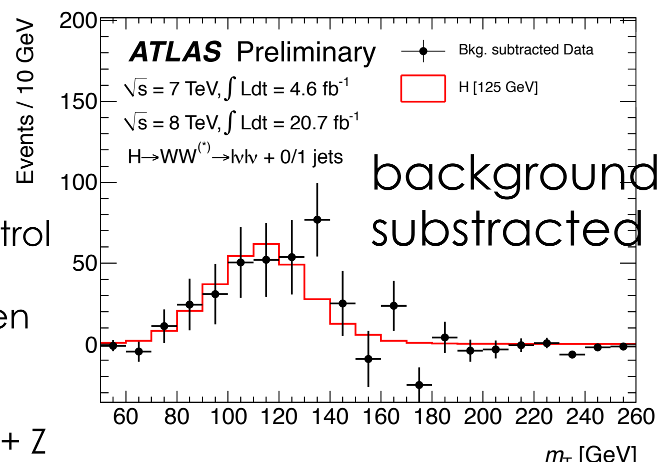
Backgrounds
WW
ttbar + single top
Z/γ*→ττ
Z/γ*→ ll
W + jets
WZ/ZZ/Wγ

Estimated:

- **WW, top, Z/γ*→ττ:** data control region
- **Z/γ*→ ll, W + jets:** fully datadriven
- **WZ/ZZ/Wγ**: MC

Rejected: using lepton ID + isolation + Z mass veto + MET cuts + m_{ll} < 50 GeV + b-veto + $\Delta\phi(ll)$ < 1.8

- **WW$^{(*)}$→lvlv = highest cross-section diboson channel, sensitive in a wide mass region**
- **Poor Higgs mass reconstruction**
- **Signature: 2 opposite sign leptons with high pT + MET**



Analysis done in 3 jet bins:

- **N_{jets} = 0, N_{jets} = 1**
- **$N_{jets} \geq 2$ (targeting VBF)**

Signal reconstruction

- **Using cuts + mT as final discriminating variable**

$$m_T = \sqrt{\left(E_T^{ll} + E_T^{miss}\right)^2 - \left|\vec{p}_T^{\,ll} + \vec{E}_T^{miss}\right|^2}$$

- **Challenge: MET resolution dependence on pileup**
  - Addressed using pileup suppression methods based on tracks
  - ~Pileup independence of σ(MET)

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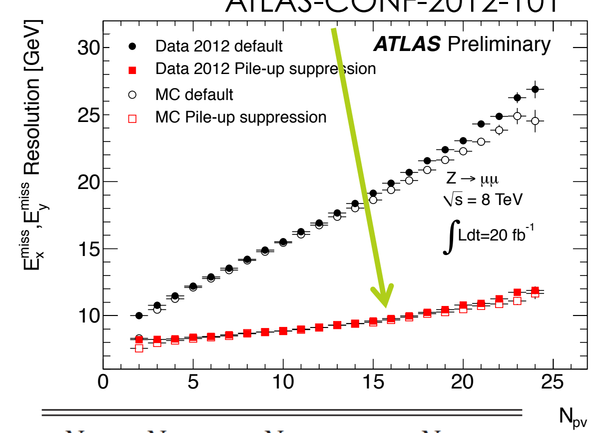
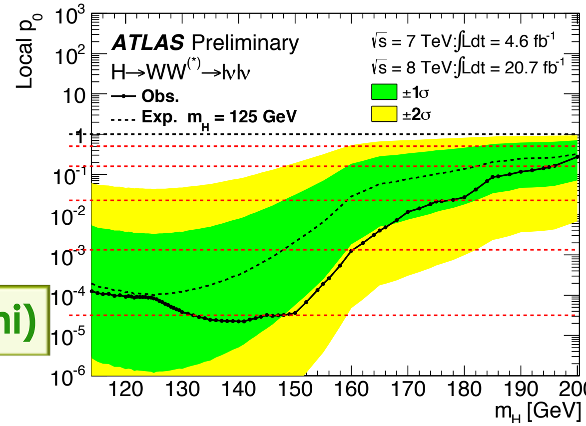
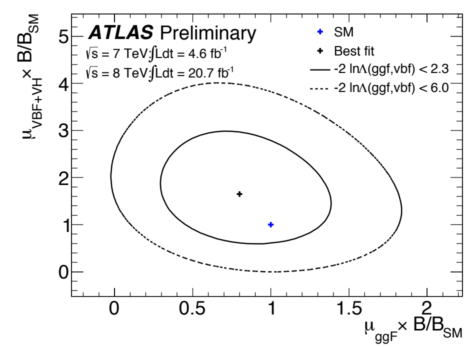


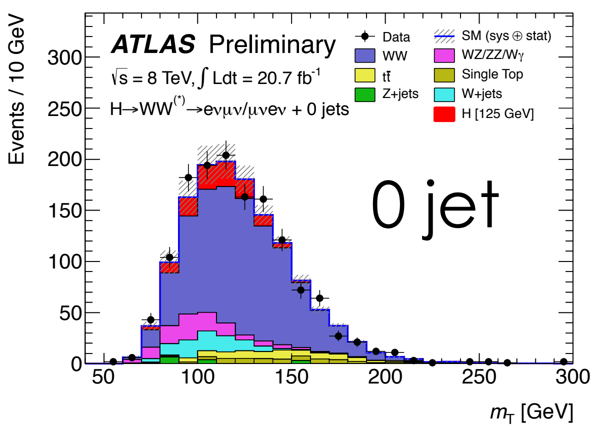
$N_{\rm jet}$	$N_{\rm obs}$	$N_{\rm bkg}$	$N_{\rm sig}$
= 0	831	739 ± 39	97 ± 20
= 1	309	261 ± 28	40 ± 13
≥ 2	55	36 ± 4	10.6 ± 1.4

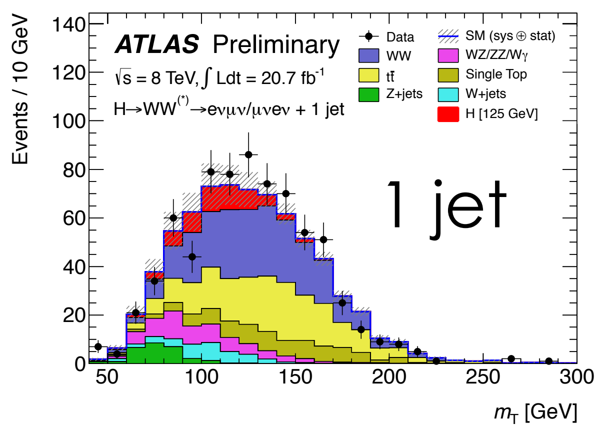
H→WW$^{(*)}$→lνlν signal strengths

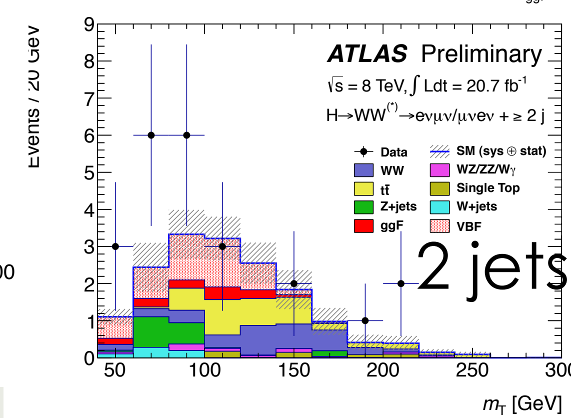
- **Broad excess wrt background-only hypothesis. At m_H = 125 GeV:**
  - **Observed 3.8σ** (expected ~3.7σ for SM Higgs)
- **Best fitted signal strength**
  - $\mu = 1.01 \pm 0.21$ (stat) ± 0.19 (theo) ± 0.12 (expt) ± 0.04 (lumi) ($\mu = 1.01 \pm 0.31$)
- **Fit 2 signal strengths**
  - $\mu_{VBF+VH} \times B/B_{SM} = 1.66 \pm 0.67$ (stat.) ± 0.42 (syst.
  - $\mu_{ggF+ttH} \times B/B_{SM} = 0.82 \pm 0.24$ (stat.) ± 0.28 (syst.)







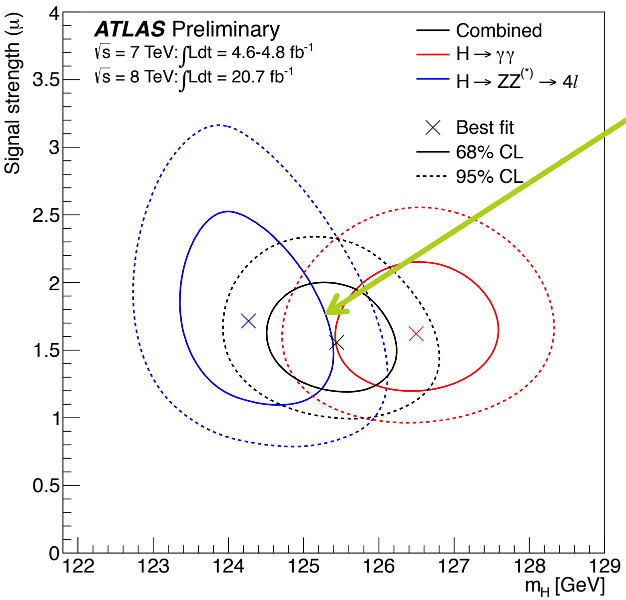




Combination: mass/signal strength

- **Only the $\gamma\gamma$ and $ZZ^{(*)} \rightarrow 4l$ are combined here**

$$M_H = 125.5 \pm 0.2\,(\text{stat.})\,^{+0.5}_{-0.6}\,(\text{syst.})\ \text{GeV}$$



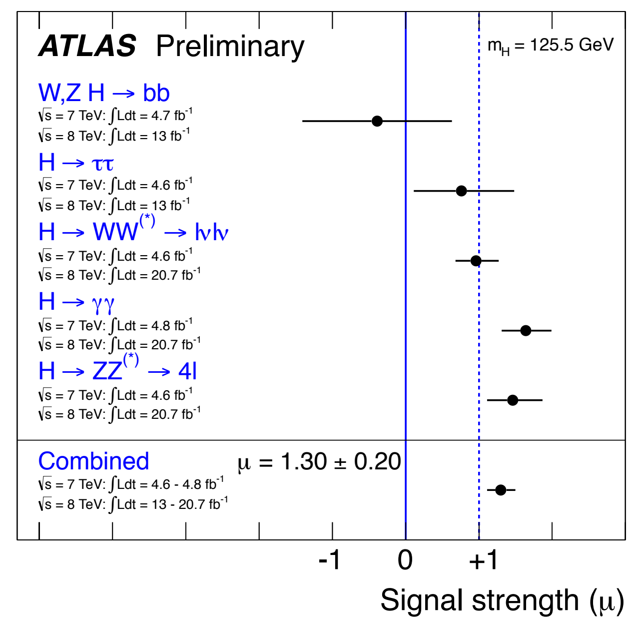
Two masses are consistent within 2.5σ (1.5% probability, 8% with a more conservative implementation of systematics)

	Source	$H \to \gamma\gamma$	$H \to 4l$
e/γ	Absolute Energy scale calibration from Z	±0.3%	±0.4%
	Upstream material simulation inaccuracies	±0.3%	-
	Presampler energy scale	±0.1%	-
	Energy scale calibration for low transverse energy electrons	-	±0.2%
	Additional sources of uncertainties	±0.35%	-
μ	Muon momentum scale	-	±0.2%
	Total	±0.6%	±0.4%

- **Combined signal strength across all channels:**

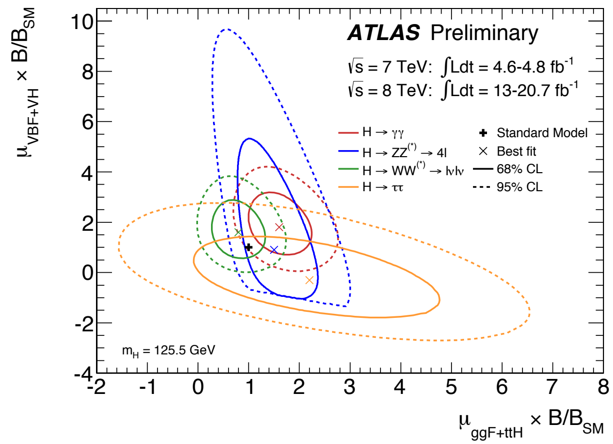
$$\mu = 1.30 \pm 0.20$$

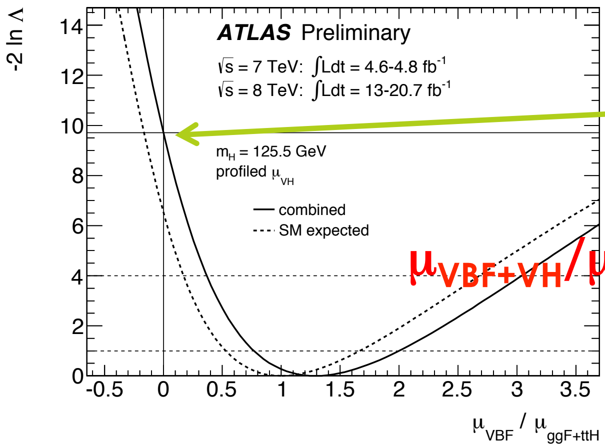
@ M_H = 125.5 GeV



Combination: processes and couplings

- **Processes signal strenghts μ_{VBF+VH} versus $\mu_{ggF+ttH}$**
- **Global picture**
  - **compatibility between channels**
  - **combination compatible with the SM**





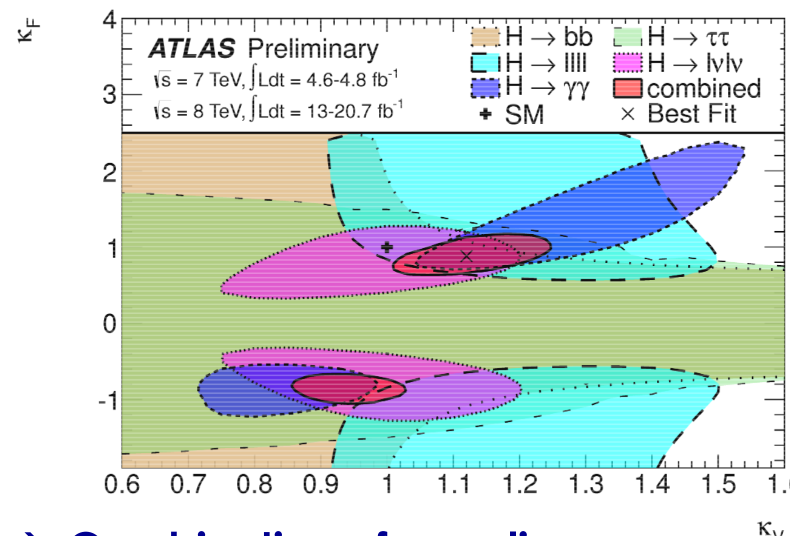
- **Evidence for VBF production at 3.1σ level:**

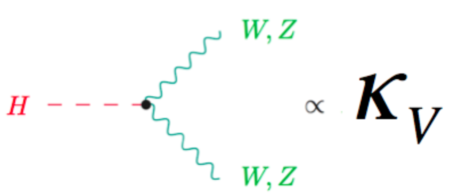
$$\mu_{VBF+VH}/\mu_{ggF+ttH} = 1.2^{+0.7}_{-0.5}$$

- **Couplings** (asssuming single narrow resonance, no BSM)

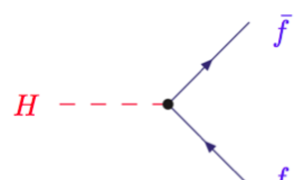
$$\kappa_i^2 = \frac{\Gamma_i}{\Gamma_{i(SM)}} \Rightarrow$$

σ_i and the partial decay widths Γi associated with the SM particle i scale with the factor κ_i^2





$\propto \kappa_V$



$\propto \kappa_F$

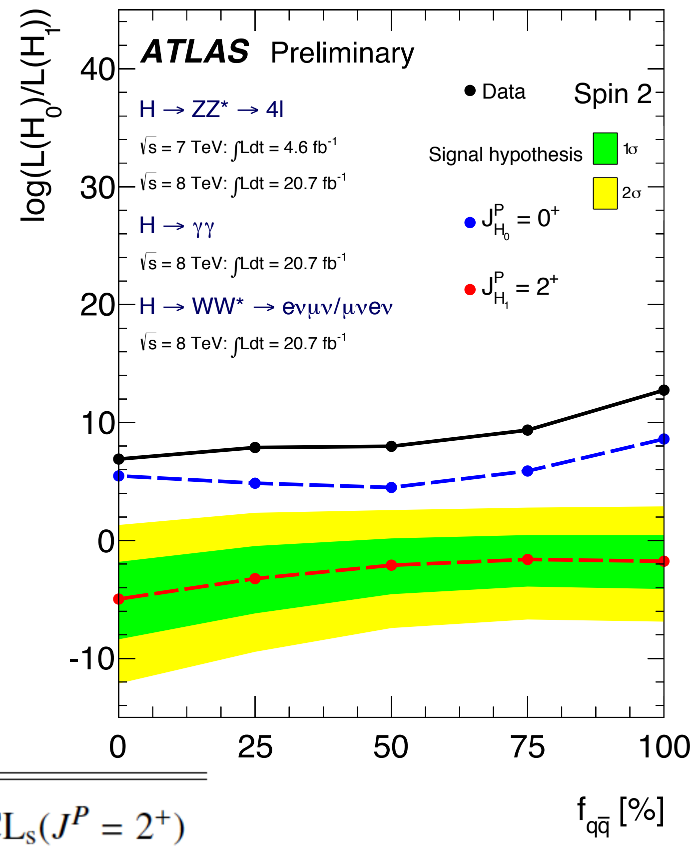
Same κ_V for W,Z, same κ_f for fermions, SM tensor structure

→ **Combination of couplings compatible with SM at 8% level** (assuming no new physics)

Spin measurements

- SM predicts J^P(Higgs)=0^+
- $H\to\gamma\gamma$ strongly disfavors spin 1 (Yang-Landau's theorem)
- Tested hypothesis: could the resonance be $J^P=2^+$? → Combining $\gamma\gamma$, $ZZ^{(*)}$, $WW^{(*)}$
- Many spin 2 models: choice – graviton-like spin 2 model with minimal couplings to SM particles → f_{qq} denotes the fraction of Higgs production through qq annihiliation

- $\gamma\gamma$ channel
  - sensitive through cos(θ*) = angular distribution of photons in the resonance rest frame
- $ZZ^{(*)}$ channel
  - sensitive through many angular variables (θ*,ϕ1,Φ, θ1, θ2) + Z masses
  - 43 events in 115<M(4l)<130 used
- $WW^{(*)}$ channel
  - Restricted to eνμν or μνeν final states
  - No reconstruction of angles due to neutrinos
  - Sensitive through other kinematic variables: m(ll), p_T(ll), ΔΦ(ll), mT → into multivariate analysis



$f_{q\bar{q}}$	$CL_s(J^P = 2^+)$
100%	$0.2 \cdot 10^{-4}$
75%	$2.1 \cdot 10^{-4}$
50%	$6.0 \cdot 10^{-4}$
25%	$5.3 \cdot 10^{-4}$
0%	$4.0 \cdot 10^{-4}$

- **Spin 2+ excluded at all qq fractions with > 99.9% C.L. (>3σ)**

Conclusion

- **Updated Higgs analysis for $\gamma\gamma$, $ZZ^{(*)} \rightarrow 4l$, $WW^{(*)} \rightarrow l\nu l\nu$ on full 2011+2012 dataset**
- **Individual channels**
  - **The excess is seen in the three channels with consistent signal strengths**

$\gamma\gamma$	$ZZ^{(*)}$	$WW^{(*)}$
7.4σ (m_H=126.5 GeV)	6.6σ (m_H=124.3 GeV)	3.8σ (m_H=125.0 GeV)

Combined μ = **1.30 ± 0.20** **(@ m_H = 125.5 GeV)**

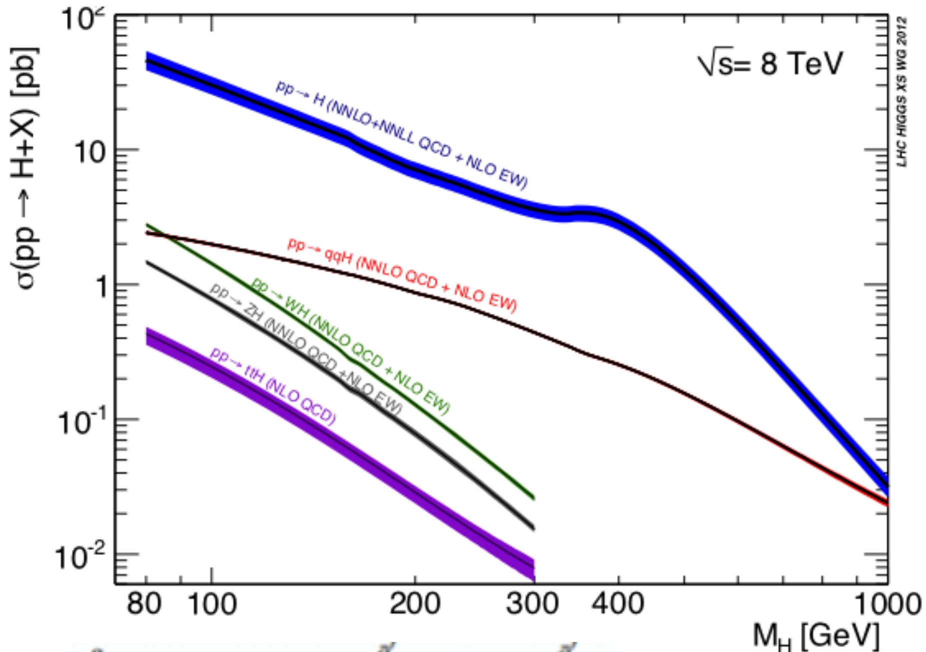
- **Evidence for VBF production** is seen (3.1σ)
- **Higgs properties**
  - **Combined** $\gamma\gamma/ZZ^{(*)}$ **mass: m_H = 125.5 ± 0.2 (stat.) $^{+0.5}_{-0.6}$ (syst.) GeV**
  - **Couplings to vector bosons, fermions** were tested (other combined tests performed & not shown here: sign of k_V x k_F custodial symmetry = W,Z universality, BSM contributions, etc.)
  - **Spin parity** measurements **pointing** strongly towards **0^+ (> 3σ)**

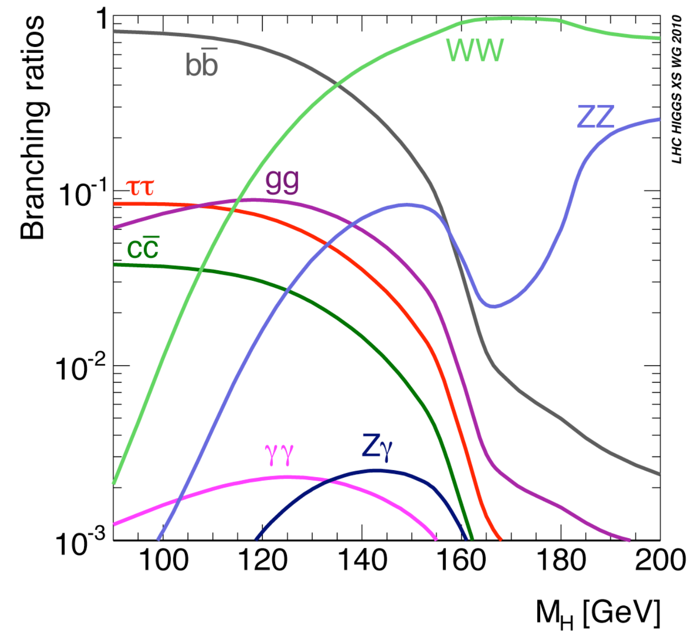
→ Properties: no significant deviation with respect to SM expectations

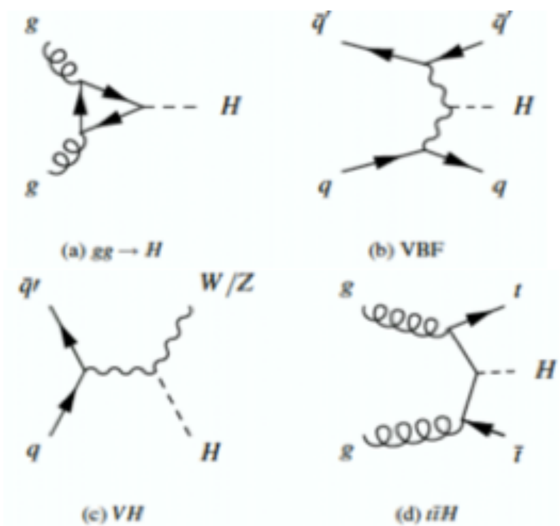
Thank you for your attention!

Backup

Higgs production and decay







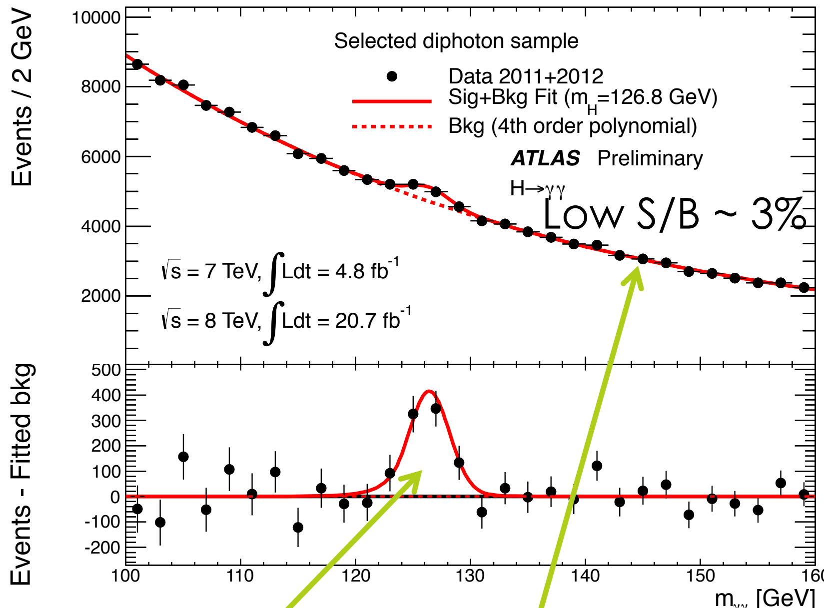
In the mass range M_H=[100,160] GeV, the total cross-section for Higgs production is ~10 pb
→ ~87% of gluon fusion
→ ~7% of vector boson fusion
→ ~6% of associated VH/tt production

H→γγ: Event selection, signal/bkg models

Event selection

(based on 20.7 fb-1 of 8 TeV and 4.8 fb-1 of 7 TeV data)

- Diphoton trigger
- *Tight* photons identification criteria
- Isolation requirements
- p_T(leading γ) > 40 GeV, p_T(subleading γ) > 30 GeV
- $M_{\gamma\gamma}$ > 100 GeV and $M_{\gamma\gamma}$ < 160 GeV



118893 (23788) H→γγ candidates @ 8 TeV (7 TeV)

Mass reconstruction

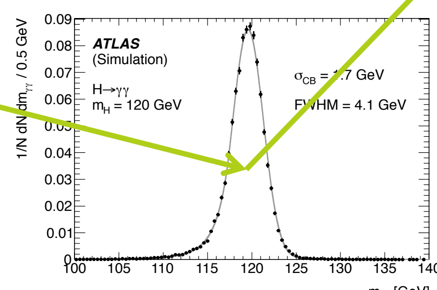
- Calorimetric energies
- Direction measurement

Background modelling

- Fit of $M_{\gamma\gamma}$ in data
- Functional form motivated by MC studies

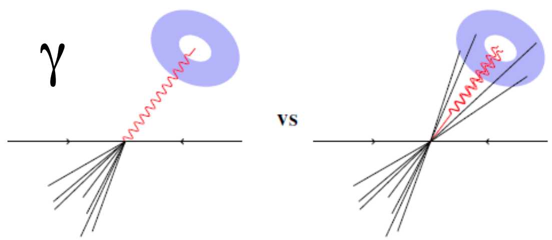
Signal $M_{\gamma\gamma}$ resolution

- Fit of MC Higgs signal
- Crystal Ball + Gaussian



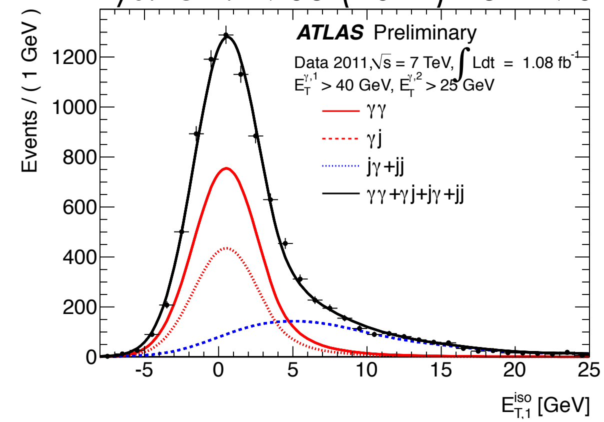
H→γγ: Data composition

- **Photon isolation**



$\pi^0 \rightarrow \gamma\gamma$
(in jets)

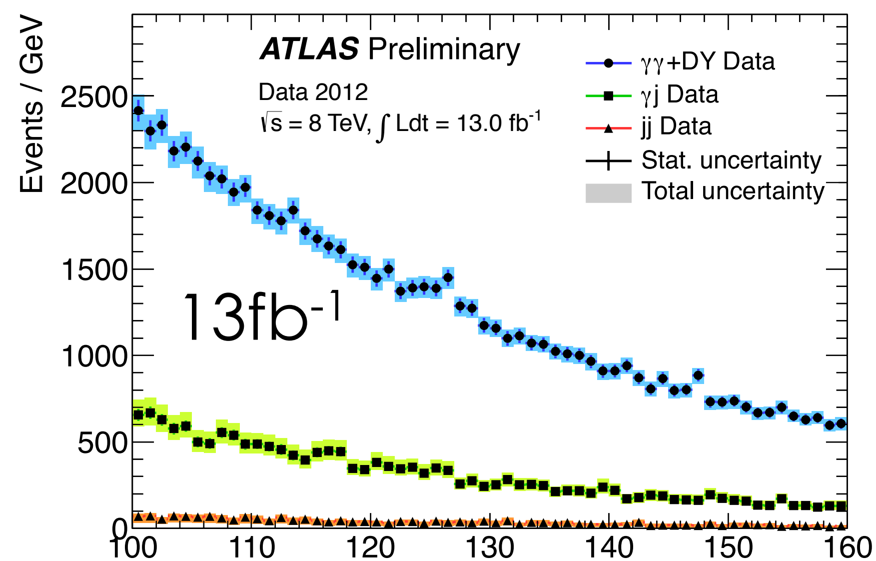
Phys.Lett. B705 (2011) 452-470



- **Sample composition**
  - → **extracted using data driven techniques**

Component	Fraction
γγ	75%
γj+jγ	22%
jj	3%
Drell-Yann	<1%

- → **Gives confidence on bkg rejection**
- → **Helps the understanding of background shapes**



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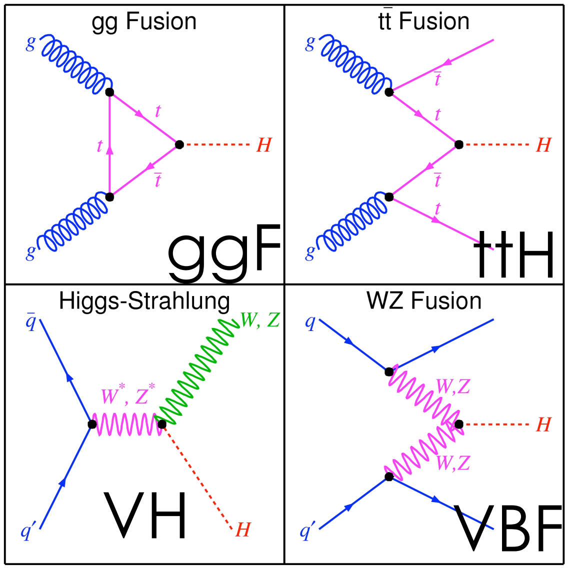
H→γγ: Exclusive categories

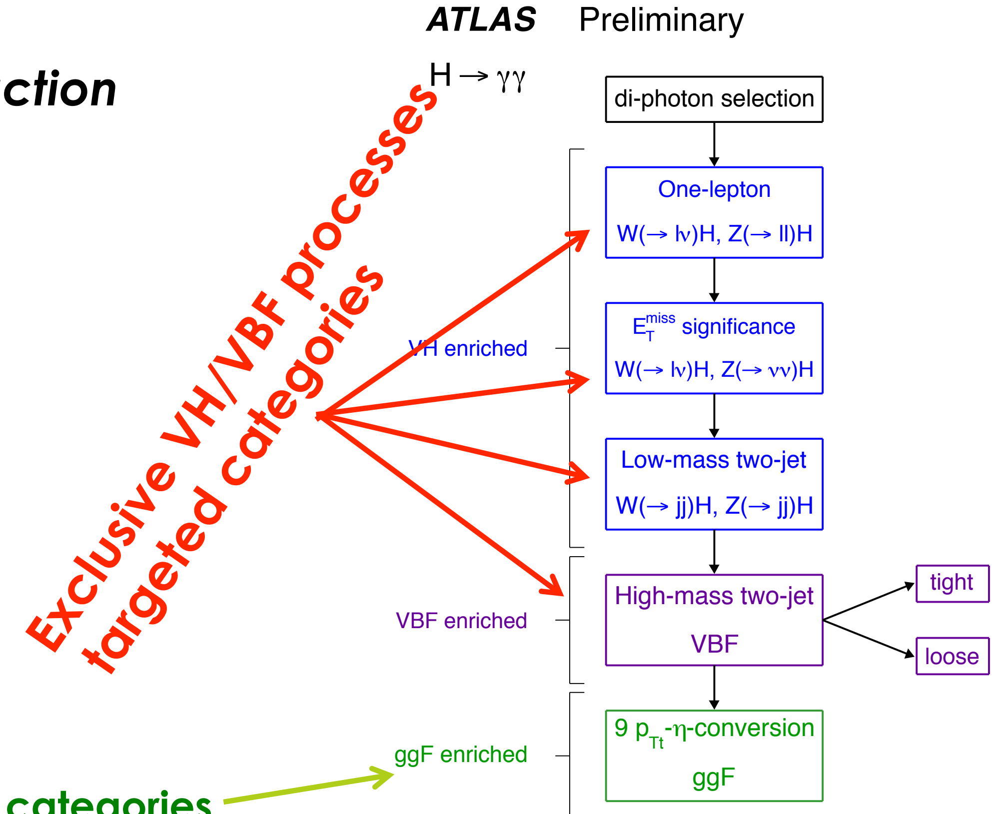
- **Different event topologies**

→ ***Sensitive to different Higgs production mechanisms → Higgs couplings***

87% 1%



5% 7%

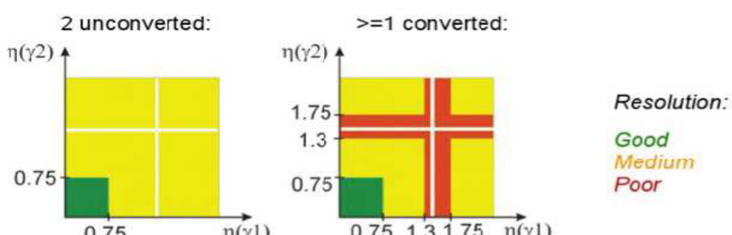


- **Different $M_{\gamma\gamma}$ signal resolution categories**

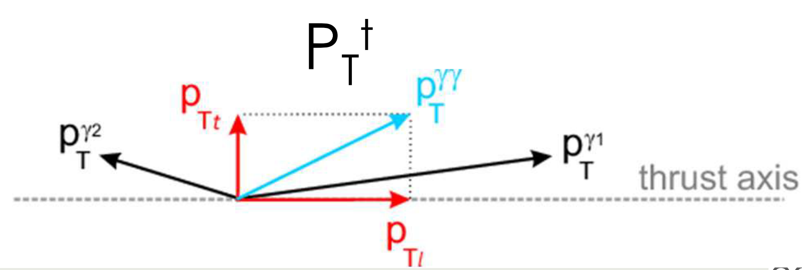
→ ***Improve expected significance***

Both unconverted:
- Central
- Rest

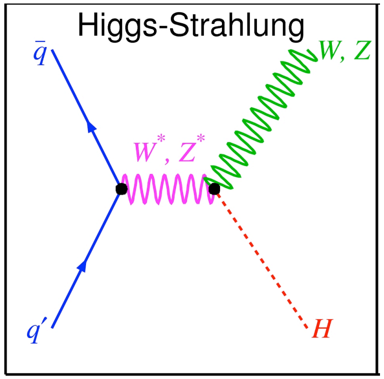
At least one converted:
- Central
- Transition
- Rest



Detector resolution



H→γγ: VH enriched categories



- **Associate production with a vector boson [W or Z]**
  - **Boosted Higgs → γγ**
  - **Leptonic (lepton/MET) or hadronic (jj) decay of the vector boson**

Selection

Electron pT > 15 GeV or muon pT > 10 GeV

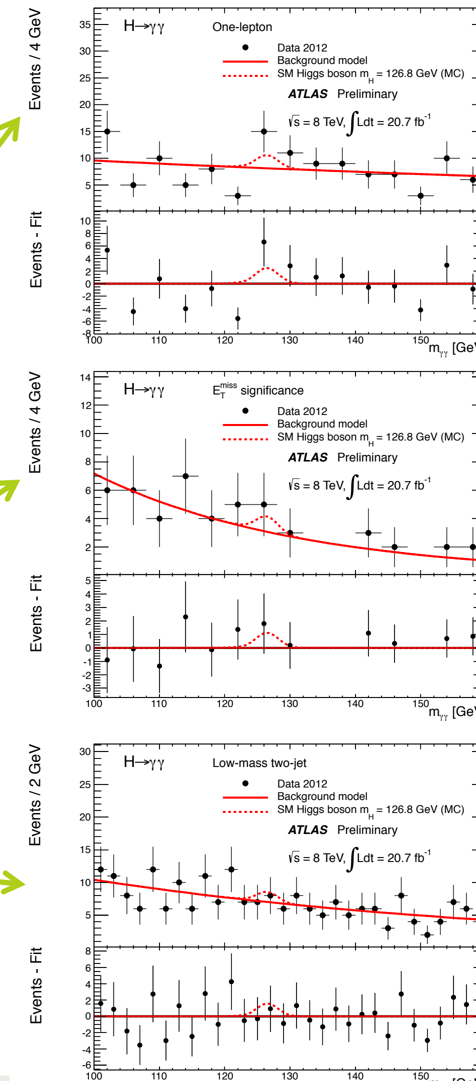
MET Significance > 5

$$\sigma_{E_T^{miss}} = 0.67\left[GeV^{1/2}\right]\sqrt{\Sigma E_T}$$

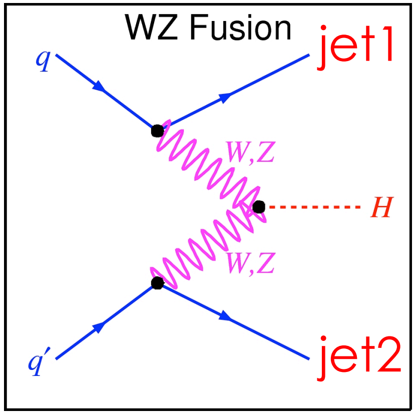
M(jj) in [60,110] GeV
P_T^t > 70 GeV

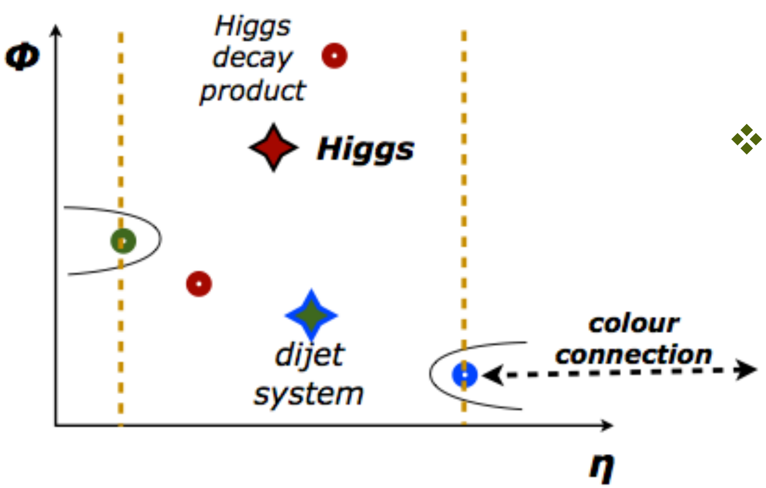
di-photon selection
→ One-lepton: W(→ lν)H, Z(→ ll)H
→ E_T^{miss} significance: W(→ lν)H, Z(→ νν)H
→ Low-mass two-jet: W(→ jj)H, Z(→ jj)H

$\sqrt{s}$	8 TeV				
Category	σ_{CB}(GeV)	Observed	N_S	N_B	N_S/N_B
Low-mass two-jet	1.62	21	3.0	21	0.14
E_T^{miss} significance	1.74	8	1.1	4	0.24
One-lepton	1.75	19	2.6	12	0.20



H→γγ: VBF enriched categories (1/3)





- **Vector boson fusion topology**
  - ***No colour exchange at the vertex***
    → *Suppressed central jet activity*
  - ***Forward jets – central photons***
  - ***Boosted Higgs → γγ***

→ ***Discrimination wrt to background and other signals***

- **8 variables: P_T^t, ΔΦ(γγ-jj), jets |η|, η gap between the jets, dijet mass, η* = |η[γγ-(j1+j2)/2]| ΔR^{min}(jet/photon)**

8 discriminating variables chosen to train *Boosted Decision Trees (BDT)*

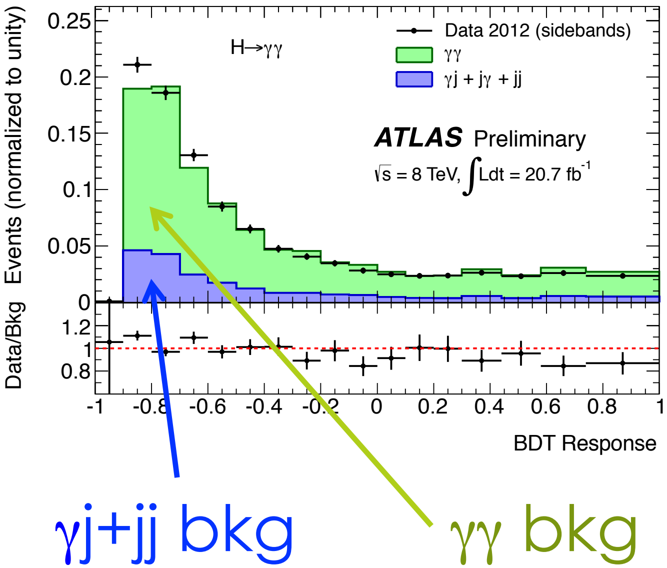
Signal: Vector Boson Fusion MC

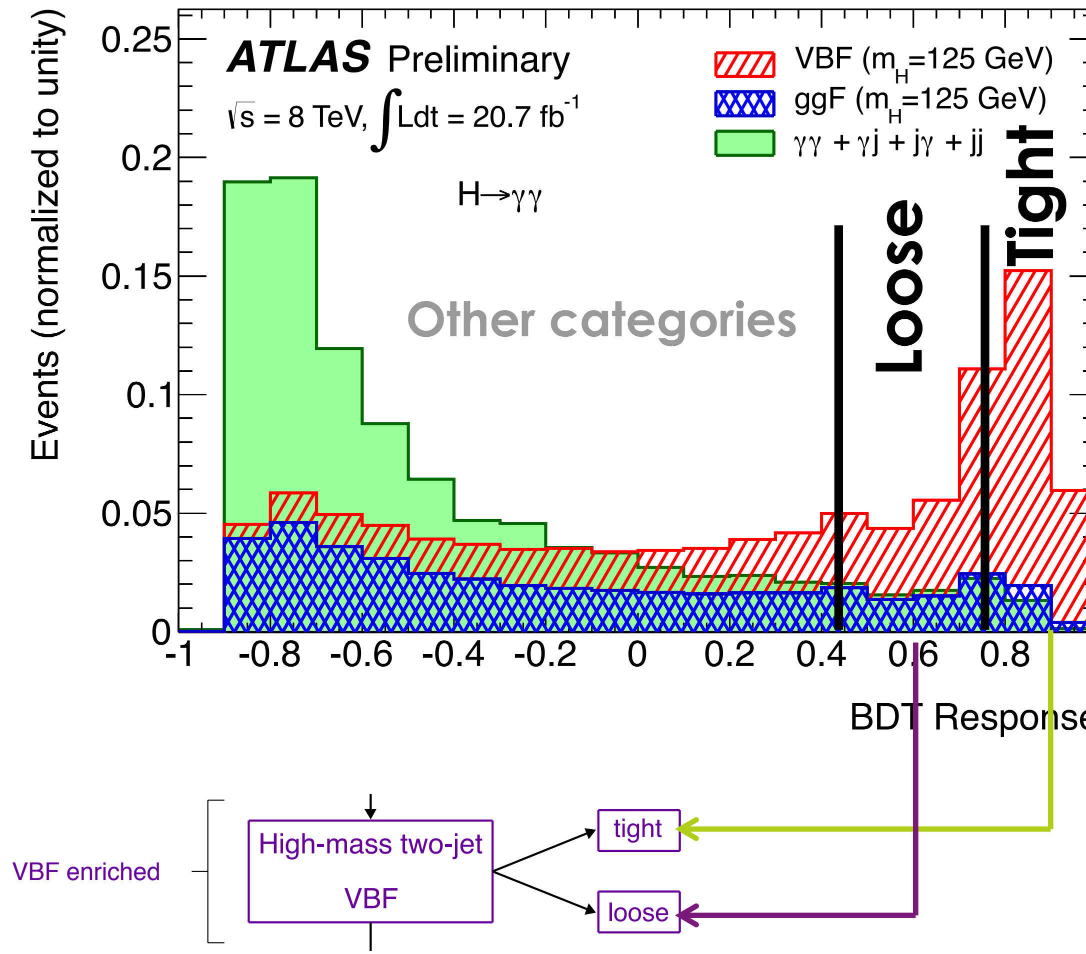
Background:

- γγ MC
- reversed isolation sidebands gj + jj

H→γγ: VBF enriched categories - definition (2/3)

Two categories based on multivariate analysis response



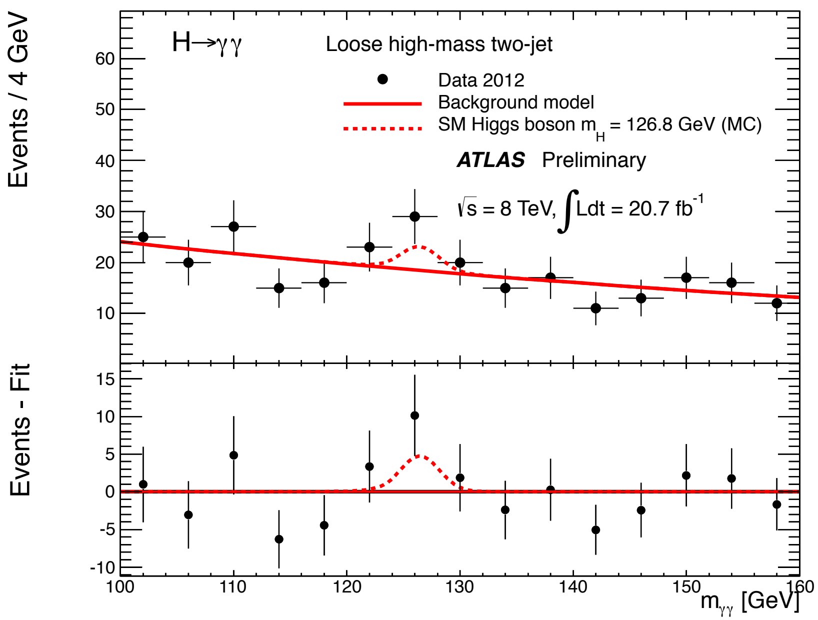


- **BDT discriminant:**
  - **VBF/bkg separation**
  - **VBF/ggF separation**

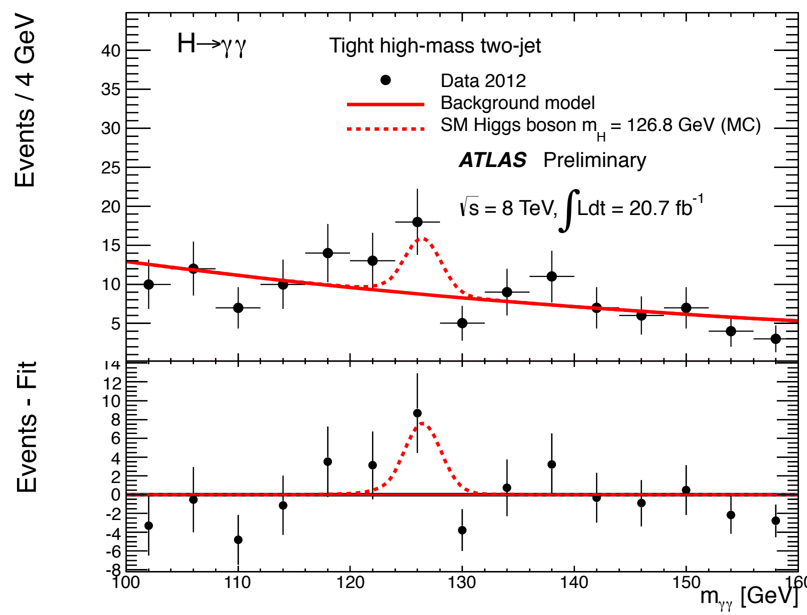
Category	Signal (%VBF)
Tight	7.3 (76%)
Loose	4.8 (54%)

H→γγ: VBF enriched categories (3/3)

Loose high mass 2-jet

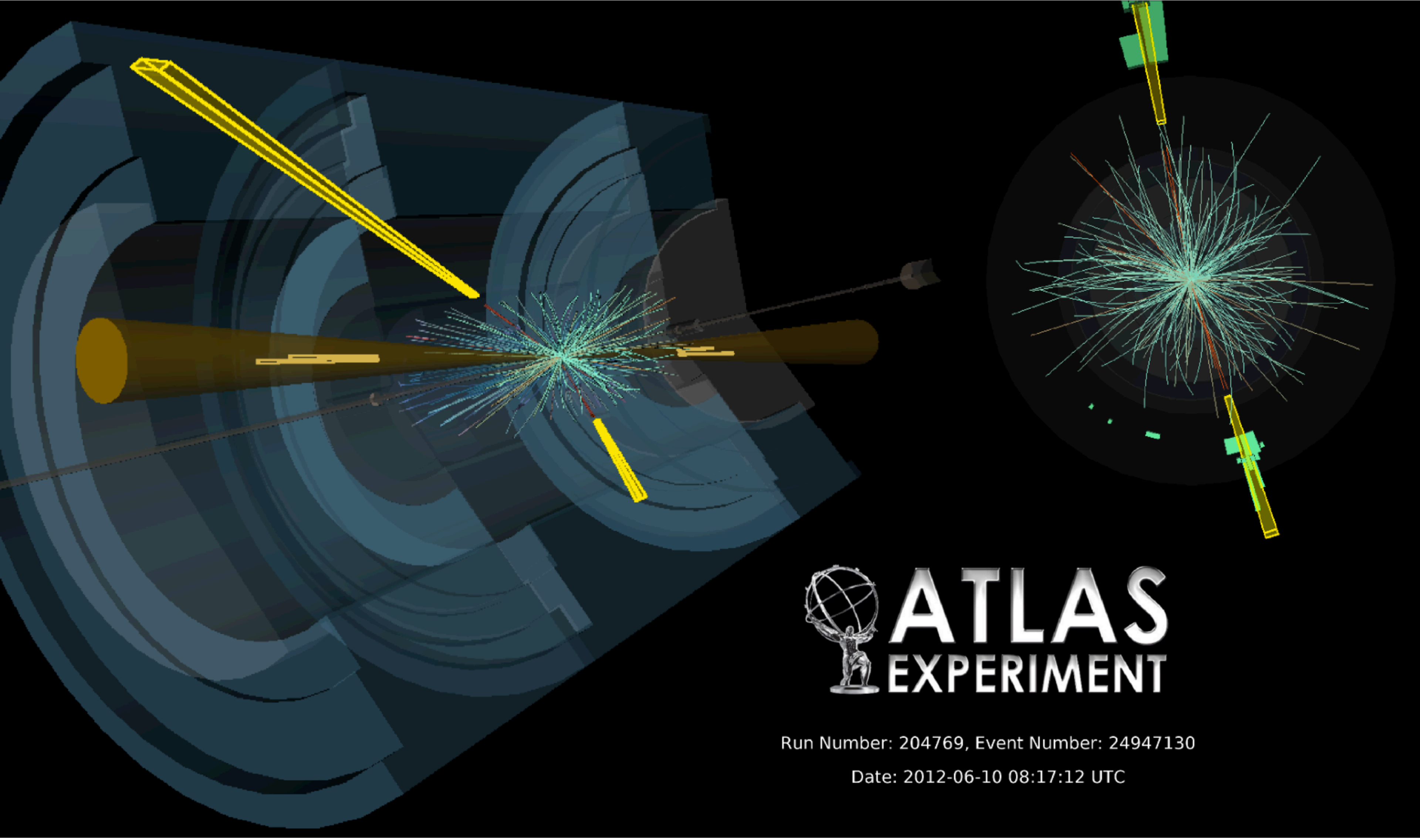


Tight high mass 2-jet



$\sqrt{s}$	8 TeV				
Category	σ_{CB}(GeV)	Observed	N_S	N_B	N_S/N_B
Loose High-mass two-jet	1.71	40	4.8	28	0.17
Tight High-mass two-jet	1.64	24	7.3	13	0.57

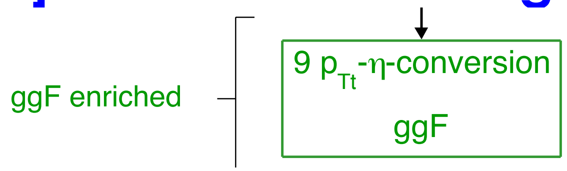
Favorable S/B

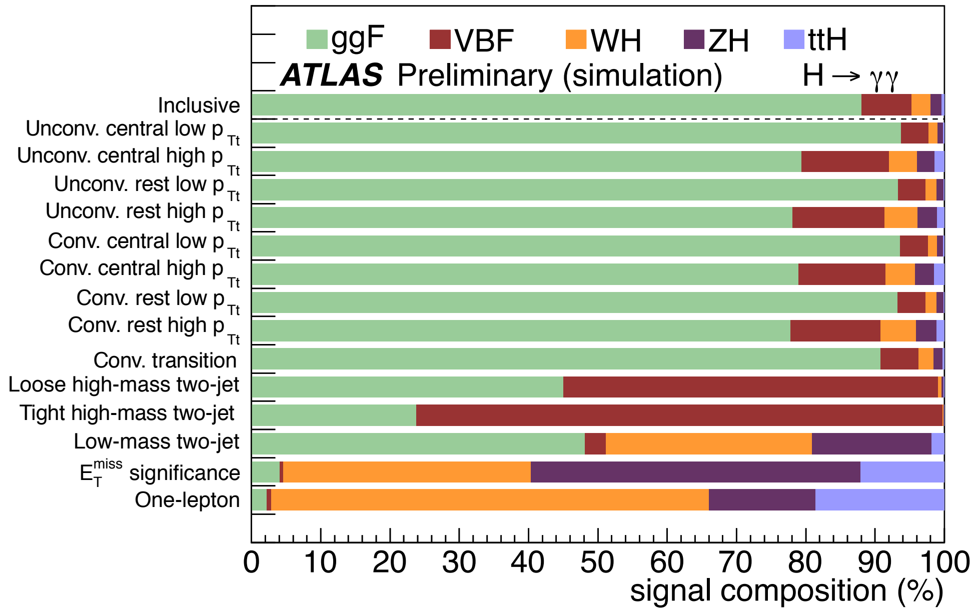


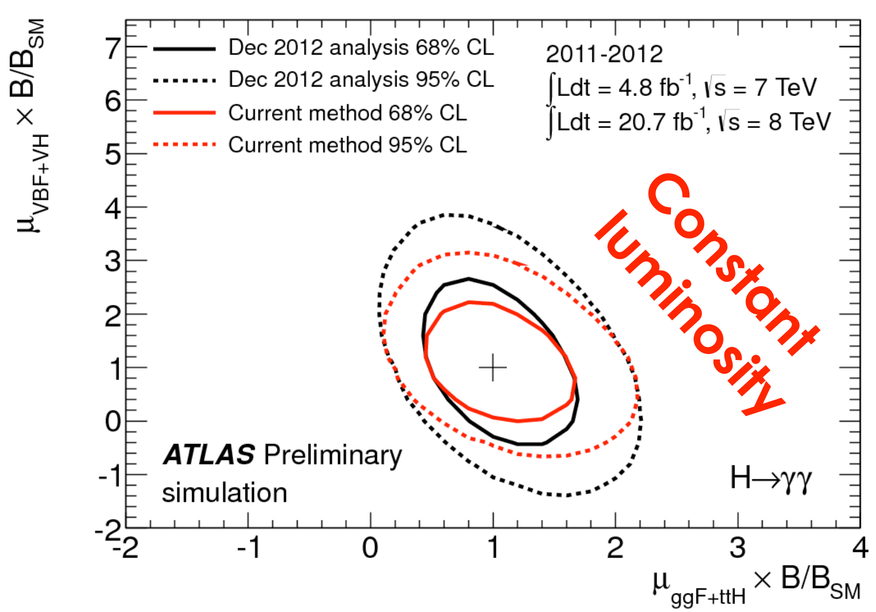
Event display of a VBF H→γγ candidate @ √s=8TeV.
$M_{\gamma\gamma}$ = 126.9 GeV.
M(jj) = 1.67 TeV
$\Delta\eta$(jj) = 5.62
$\Delta\,\phi$ (gg-jj) = 2.90.

$H \to \gamma\gamma$: processes along categories

- **The remaining events [ggF enriched] are classified using the 9 P_{Tt}-η-conversion categories**







14 categories for 8 TeV data

Sensitive improvement from from revisited exclusive VH/ VBF categories

H→γγ: systematic uncertainties

- **All the uncertainties, except luminosity, are taken as fully correlated between 7 and 8 teV. 7 TeV systematics are unchanged wrt latest result*, except luminosity uncertainty which has been updated (now ±1.8%)**

*ATLAS-CONF-2012-091

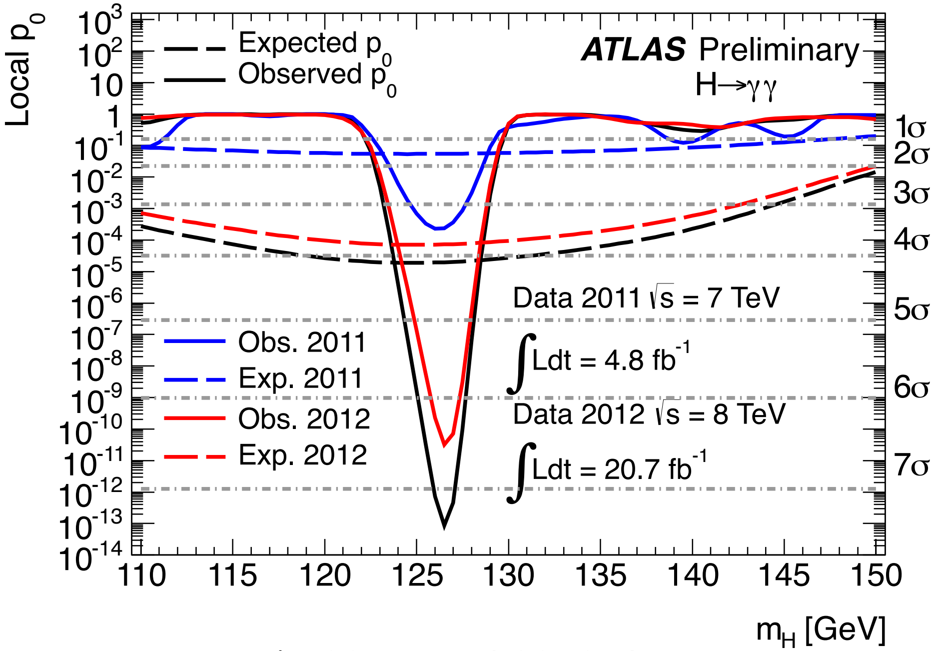
- **Main uncertainty on signal yield (8 TeV)**

Source of uncertainty	Level
Theory (PDF, scale, α_S)	~12% (average) (up to ~50% for 2-jet categories)
Photon ID	2.4%
Background model	~3% (average)
Luminosity	3.6%

- **Main uncertainties on assignment to categories – migration (8 TeV)**

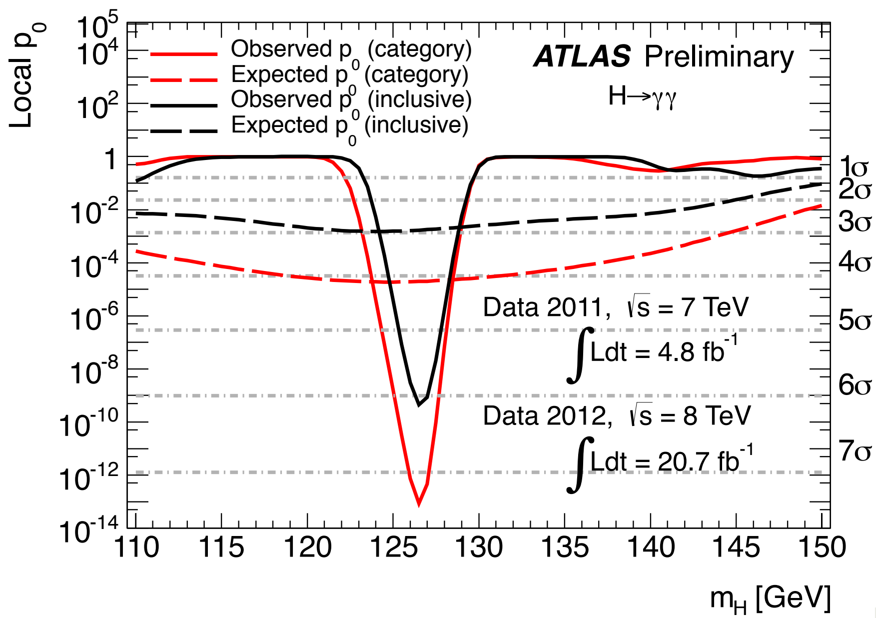
Source of uncertainty	Level
Higgs pT modelling	Up to ~10%
JES	Up to ~20%
Underlying event	Up to ~13%
Material in front of calo	~4%

H→γγ: p0 - significance



Excess in 2011 and 2012 data

Observed: 6σ for inclusive analysis



H→γγ: background composition (1/2)

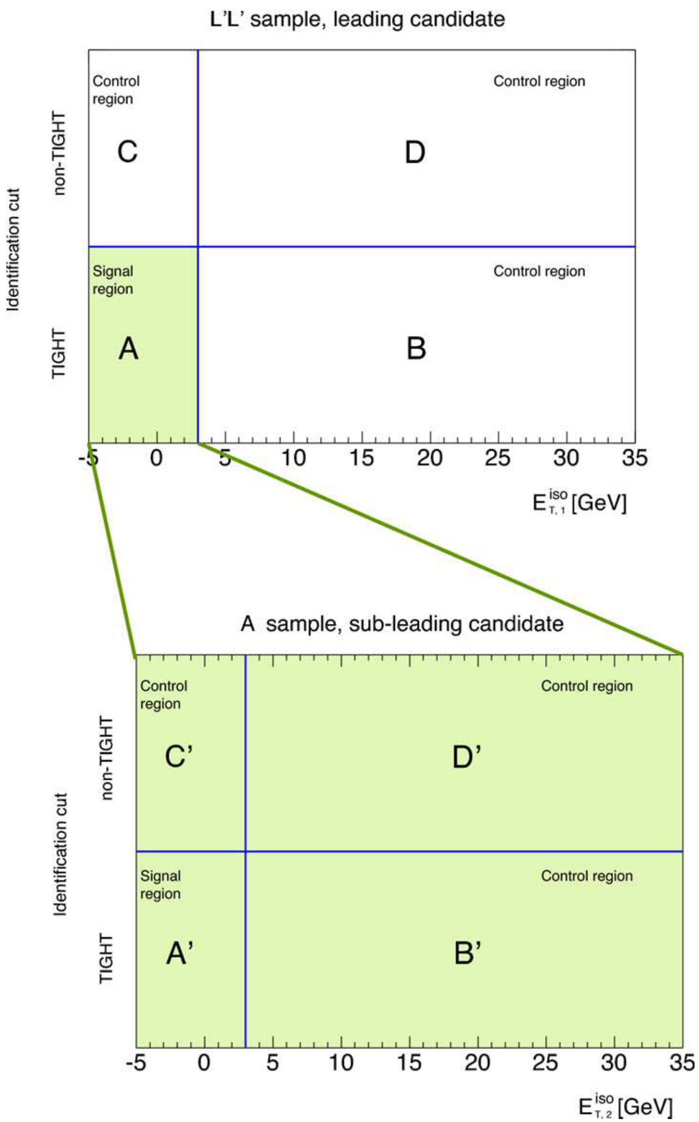
2x2D (ABCD) method

- Extension of the 2D method to the diphoton candidates case
- Preselect events passing the loose section
- Determining number of true leading photons N_A^{sig} from $N_A/N_B = N_C/N_D$

$$N_A^{sig} = N_A - \left[(N_B - c_1 N_A^{sig}) \frac{N_C - c_2 N_A^{sig}}{N_C - c_1 c_2 N_A^{sig}} \right] R^{bkg}$$

- If leading photon is in region A, apply same method to subleading photon, giving the number of true diphoton pairs:

$$N_{\gamma\gamma}^{TITI} = \frac{\varepsilon' \left(\alpha f' N_A^{sig} + (\alpha - 1) N_A^{sig}{}' \right)}{(\alpha - 1)\varepsilon' + \alpha f'}$$



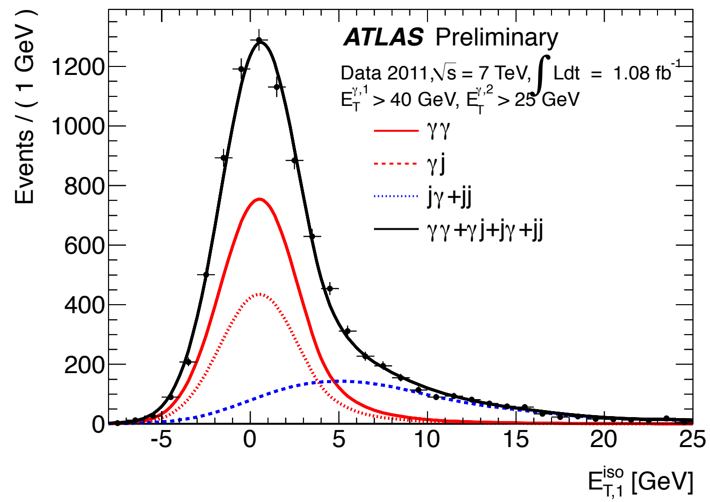
H→γγ: background composition (2/2)

Isolation template fit method

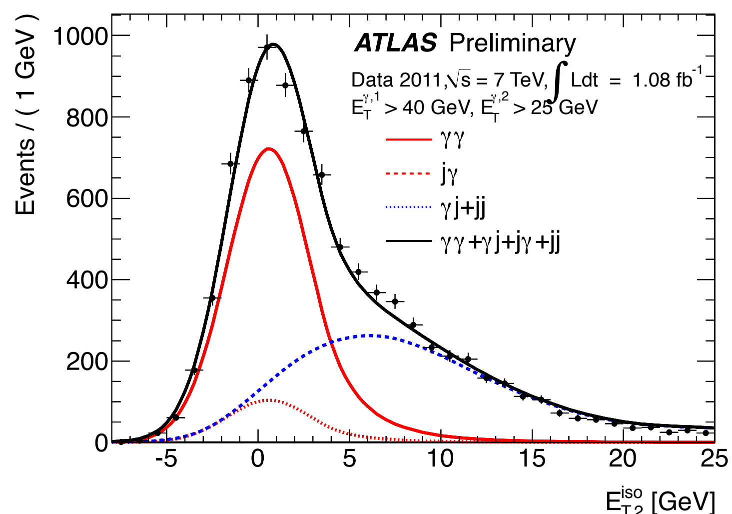
- **2D simultaneous fit of the isolation distributions for leading and subleading photons**
  - → 4 fractions of (γγ/γj/jγ/jj)
  - → Different component PDFs
  - → Correlations taken into account

- **PDFs shapes extracted from control regions (reversing photon ID variables) or MC**

- **Gives compatible results with 2x2D**



Phys.Lett. B705 (2011) 452-470



Phys.Lett. B705 (2011) 452-470

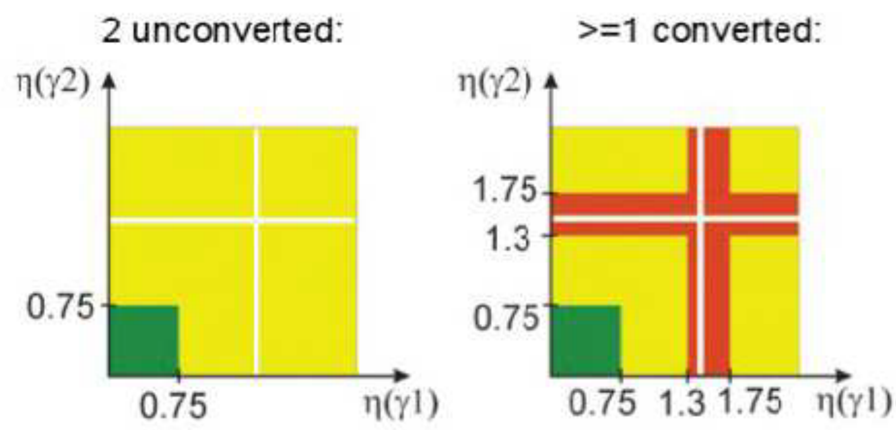
H→γγ: PTt eta-conv categories

Both unconverted:

- Central
- Rest

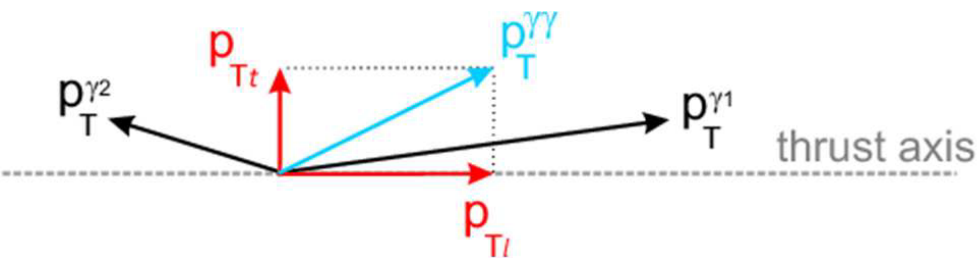
At least one converted:

- Central
- Transition
- Rest



Resolution:

Good
Medium
Poor



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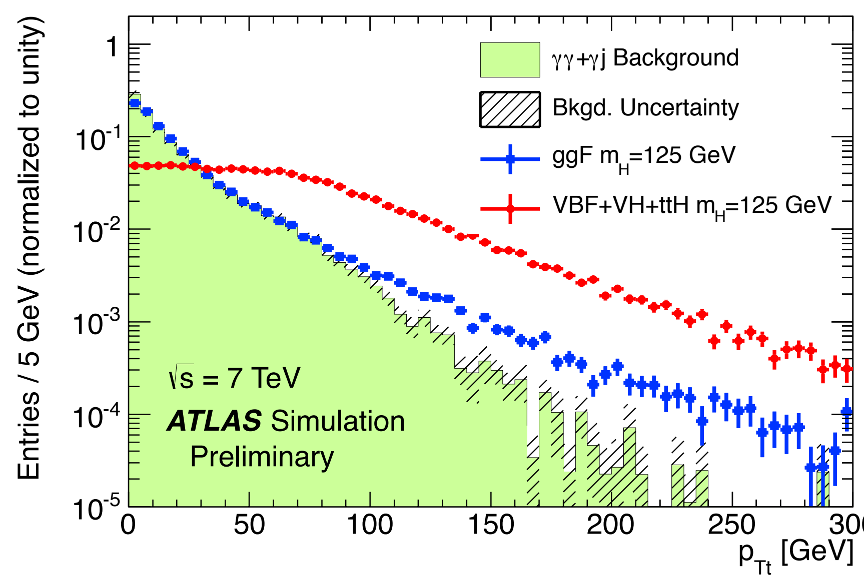
Diphoton momentum perpendicular to the thrust axis



ATLAS-CONF-2012-091

H→γγ: VBF enriched categories – MVA details

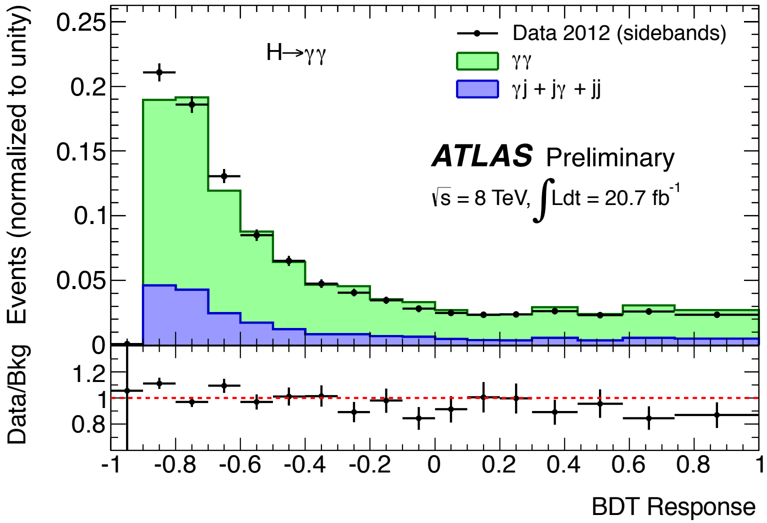
- **New: multivariate analysis (MVA) of the VBF Higgs → γγ searches**

- **Strategy:**
  - **Focus on the <u>2-jet signature and topology</u> of the VBF Higgs events**
    → Jets: reconstructed with anti-kT algorithm
  - ***Primary goal*** – build a MVA response which discriminates Higgs signal versus non-resonant backgrounds **(increase S/B)**
  - ***Good side effect*** – discrimination against resonant ggF Higgs*
    (increase VBF purity)
    ****QCD Higgs production with kinematics close to non-resonant backgrounds***
  - **Build exp. significance optimized event categories based on the MVA response**

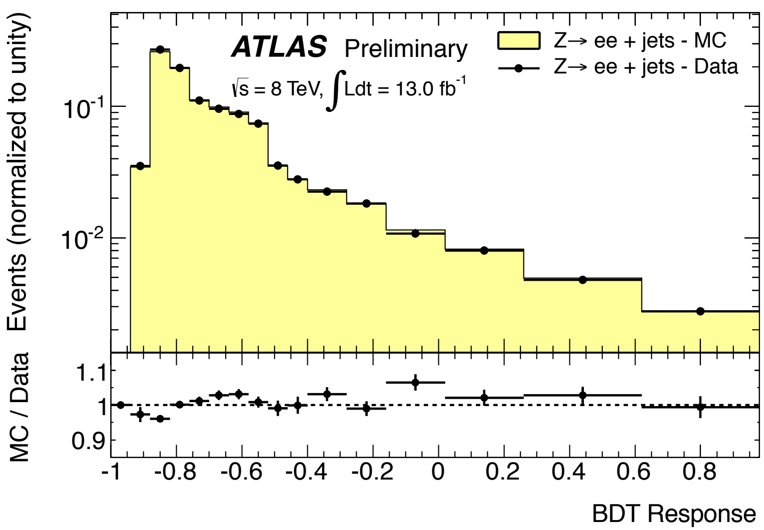
- **MVA training:**
  - **8 discriminating vars.: P_T^t, Δη(jj), M(jj), η(jet1), η(jet2), ΔΦ(γγ-jj), ΔR^{min}(g,j), η***
  - **Signal:** PYTHIA VBF Higgs @ 125 GeV
  - **Background:** MC Sherpa γγ + reversed isolation sidebands to emulate γj + jγ + jj reducible backgrounds
    irreducible and reducible backgrounds weighted to fractions measured in data
  - **Boosted Decision Tree (BDT)**

$H \to \gamma\gamma$: MVA checks

- **Check the MVA response consistency:**



- **Data sidebands** (excluding $M_{\gamma\gamma}$ signal region) **vs. background sample** (as used in the training)
  → Reasonable agreement
  [NB: the background yield is not extracted from the training sample but from data]



- High statistics $Z \to e^+e^-$
  Data vs. Simulation
  → Reasonable agreement
  [Z->ee is background-like]

H→γγ: categorization summary

$\sqrt{s}$	8 TeV				
Category	σ_{CB}(GeV)	Observed	N_S	N_B	N_S/N_B
Unconv. central, low p_{Tt}	1.50	911	46.6	881	0.05
Unconv. central, high p_{Tt}	1.40	49	7.1	44	0.16
Unconv. rest, low p_{Tt}	1.74	4611	97.1	4347	0.02
Unconv. rest, high p_{Tt}	1.69	292	14.4	247	0.06
Conv. central, low p_{Tt}	1.68	722	29.8	687	0.04
Conv. central, high p_{Tt}	1.54	39	4.6	31	0.15
Conv. rest, low p_{Tt}	2.01	4865	88.0	4657	0.02
Conv. rest, high p_{Tt}	1.87	276	12.9	266	0.05
Conv. transition	2.52	2554	36.1	2499	0.01
Loose High-mass two-jet	1.71	40	4.8	28	0.17
Tight High-mass two-jet	1.64	24	7.3	13	0.57
Low-mass two-jet	1.62	21	3.0	21	0.14
E_T^{miss} significance	1.74	8	1.1	4	0.24
One-lepton	1.75	19	2.6	12	0.20
Inclusive	1.77	14025	355.5	13280	0.03

In a $M_{\gamma\gamma}$ window containing 90% of the signal

118893 (23788) H→γγ candidates @ 8 TeV (7 TeV)

- S/B ratio changes along categories
- Resolution is different along categories

→ **Gives better expected significance than inclusive analysis**

H→γγ: background modelling

Category	Parametrisation	Uncertainty [N_{evt}] $\sqrt{s}$ = 7 TeV	Uncertainty [N_{evt}] $\sqrt{s}$ = 8 TeV
Inclusive	4th order pol.	7.3	12.0
Unconverted central, low p_{Tt}	Exp. of 2nd order pol.	2.1	4.6
Unconverted central, high p_{Tt}	Exponential	0.2	0.8
Unconverted rest, low p_{Tt}	4th order pol.	2.2	11.4
Unconverted rest, high p_{Tt}	Exponential	0.5	2.0
Converted central, low p_{Tt}	Exp. of 2nd order pol.	1.6	2.4
Converted central, high p_{Tt}	Exponential	0.3	0.8
Converted rest, low p_{Tt}	4th order pol.	4.6	8.0
Converted rest, high p_{Tt}	Exponential	0.5	1.1
Converted transition	Exp. of 2nd order pol.	3.2	9.1
Loose high-mass two-jet	Exponential	0.4	1.1
Tight high-mass two-jet	Exponential	-	0.3
Low-mass two-jet	Exponential	-	0.6
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	Exponential	-	0.1
One-lepton	Exponential	-	0.3

H→γγ: signal and background modeling

Signal modeling

- Higgs natural width small along studied mass range (~100 MeV)
- Dominated by detector resolution

→ **Fit on MC of the $M_{\gamma\gamma}$ resolution using a Crystal Ball + Gaussian model**

→ **Resolution is almost pileup independent**

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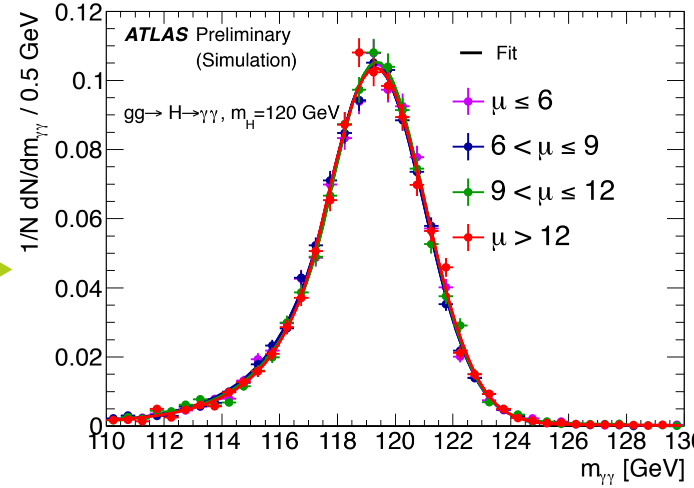


Background modeling

- Background is **extracted** in each category **by fitting the $M_{\gamma\gamma}$ spectra**
- The fitting function is determined on high statistics background MC
- The functional form is chosen as to minimize the corresponding systematic uncertainty

H→γγ: systematics (signal yields)

Systematic uncertainties	Value(%)			Constraint
Luminosity	±3.6			
Trigger	±0.5			
Photon Identification	±2.4			Log-normal
Isolation	±1.0			
Photon Energy Scale	±0.25			
Branching ratio	±5.9% – ±2.1% (m_H = 110 - 150 GeV)			Asymmetric Log-normal
Scale	ggF: $^{+7.2}_{-7.8}$ ZH: $^{+1.6}_{-1.5}$	VBF: $^{+0.2}_{-0.2}$ ttH: $^{+3.8}_{-9.3}$	WH: $^{+0.2}_{-0.6}$	Asymmetric Log-normal
PDF+α_s	ggF: $^{+7.5}_{-6.9}$ ZH: ±3.6	VBF: $^{+2.6}_{-2.7}$ ttH: ±7.8	WH: ±3.5	Asymmetric Log-normal
Theory cross section on ggF	Tight high-mass two-jet: ±48 Loose high-mass two-jet: ±28 Low-mass two-jet: ±30			Log-normal

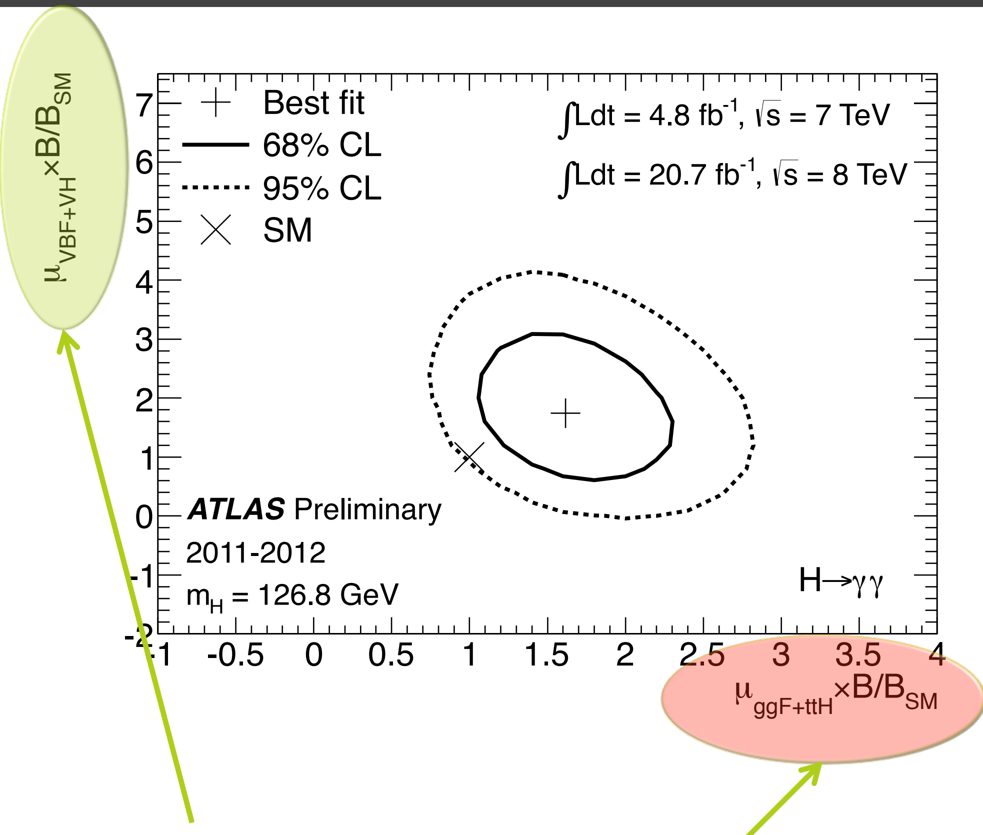
H→γγ: systematics (migrations 1/2)

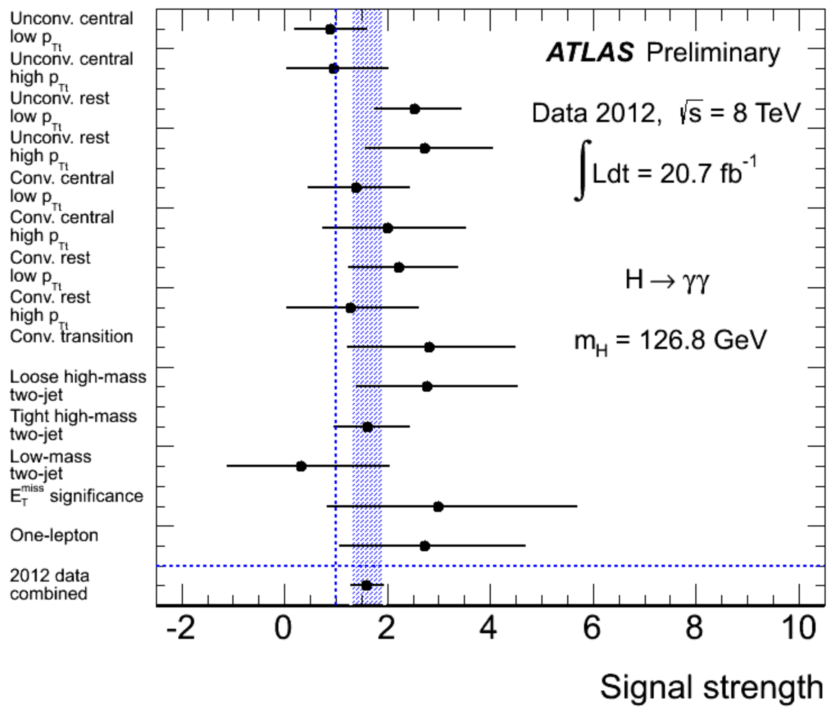
Systematic uncertainties	Category	Value(%)			Constraint
Underlying Event	Tight high-mass two-jet	ggF: ±8.8	VBF: ±2.0	VH, ttH: ±8.8	Log-normal
	Loose high-mass two-jet	ggF: ±12.8	VBF: ±3.3	VH, ttH: ±12.8	
	Low-mass two-jet	ggF: ±12	VBF: ±3.9	VH, ttH: ±12	
Jet Energy Scale	Low p_{Tt}	ggF: −0.1	VBF: −1.0	Others: −0.1	Gaussian
	High p_{Tt}	ggF: −0.7	VBF: −1.3	Others: +0.4	
	Tight high-mass two-jet	ggF: +11.8	VBF: +6.7	Others: +20.2	
	Loose high-mass two-jet	ggF: +10.7	VBF: +4.0	Others: +5.7	
	Low-mass two-jet	ggF: +4.7	VBF: +2.6	Others: 1.4	
	E_T^{miss} significance	ggF: 0.0	VBF: 0.0	Others: 0.0	
	one-lepton	ggF: 0.0	VBF: 0.0	Others: −0.1	
Jet Energy Resolution	Low p_{Tt}	ggF: 0.0	VBF: 0.2	Others: 0.0	Gaussian
	High p_{Tt}	ggF: −0.2	VBF: 0.2	Others: 0.6	
	Tight high-mass two-jet	ggF: 3.8	VBF: −1.3	Others: 7.0	
	Loose high-mass two-jet	ggF: 3.4	VBF: −0.7	Others: 1.2	
	Low-mass two-jet	ggF: 0.5	VBF: 3.4	Others: −1.3	
	E_T^{miss} significance	ggF: 0.0	VBF: 0.0	Others: 0.0	
	one-lepton	ggF: −0.9	VBF: −0.5	Others: −0.1	
η^* modelling		Tight high-mass two-jet: +7.6			Gaussian
		Loose high-mass two-jet: +6.2			
Dijet angular modelling		Tight high-mass two-jet: +12.1			Gaussian
		Loose high-mass two-jet: +8.5			

H→γγ: systematics (migrations 2/2)

Higgs p_T		Low p_{Tt}: +1.3 High p_{Tt}: −10.2 Tight high-mass two-jet: −10.4 Loose high-mass two-jet: −8.5 Low-mass two-jet: −12.5 E_T^{miss} significance: −2.0 one-lepton : −4.0			Gaussian
Material Mismodelling		Unconv: −4.0	Conv: +3.5		Gaussian
JVF	Loose High-mass two-jet	ggF: −1.2	VBF: −0.3	Others: −1.2	Gaussian
	Low-mass two-jet	ggF: −2.3	VBF: −2.4	Others: −2.3	
E_T^{miss}	E_T^{miss} significance	ggF: +66.4	VBF: +30.7	VH, ttH: +1.2	Gaussian
e reco and identification		one-lepton: < 1			Gaussian
e Escale and resolution		one-lepton: < 1			Gaussian
μ reco, ID resolution		one-lepton: < 1			Gaussian
μ spectrometer resolution		one-lepton: 0			Gaussian

H→γγ: signal strength [V,t and by category]





VBF+VH

ggF+ttH

→ compatible with SM within 2σ

H→γγ: fiducial cross-section

Fiducial cross-section

- N_S extracted from signal + background fit on the inclusive $M_{\gamma\gamma}$ spectrum
- Uncertainties are statistical + systematics (mass resolution, background model)

$$\sigma_{fid} \cdot BR = \frac{N_{signal}}{\varepsilon \cdot L_{\mathrm{int}}}$$

- Luminosity uncertainty +/- 3.6%
- ε: acceptance/reconstruction efficiency factors

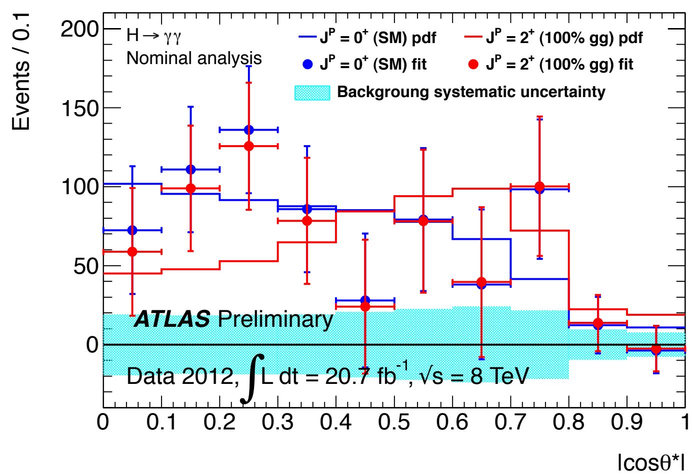
$$\Rightarrow \sigma_{fid} \cdot BR = 56.2 \pm 12.5 \text{ fb}$$

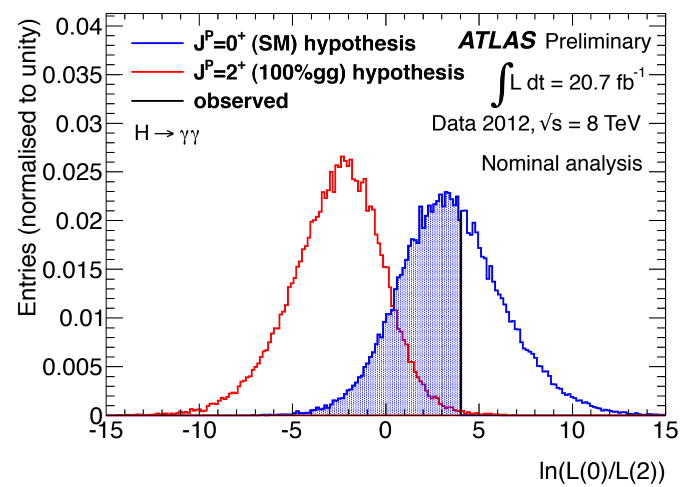
γγ spin measurement

- **SM predicts J^P(Higgs)=0^+**
- **Observation in γγ strongly disfavors spin 1 (Yang-Landau's theorem)**
- **Tested hypothesis: could the resonance be $J^P=2^+$? → Combining γγ, $ZZ^{(*)}$, $WW^{(*)}$**
- **Many spin 2 models: choice goes for graviton-like spin 2 model with minimal couplings to SM particles →in this model, f_{qq} denotes the fraction of Higgs production through qq annihiliation**

γγ channel

- **sensitive through cos(θ*) = angular distribution of photons in the resonance rest frame**

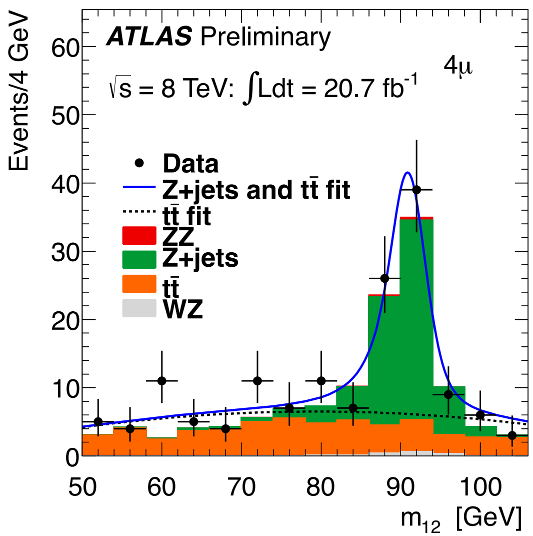


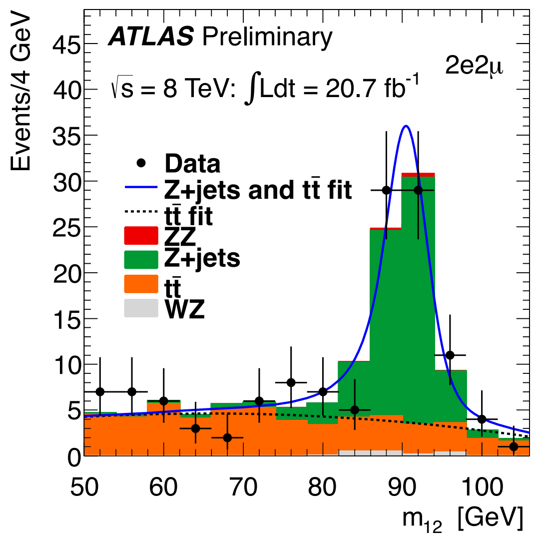


- **Excludes spin 2^+ hypothesis at >99% C.L. when f_{qq}=0%**

$ZZ^{(*)}$ background estimation

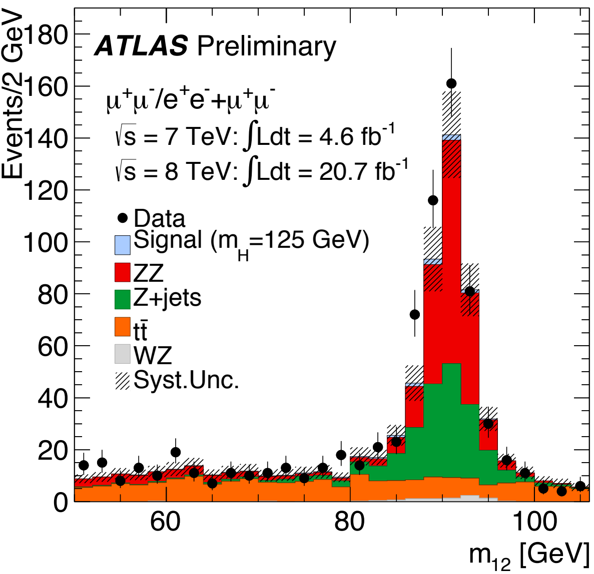
- **Irreducible $ZZ^{(*)}$**: MC-based
- **Reducible ll + μμ**: data-driven – from control region removing isolation requirement on subleading pair and asking at least one of the subleading leptons to fail the impact parameter significance cut
→ extrapolated to signal region using MC efficiencies

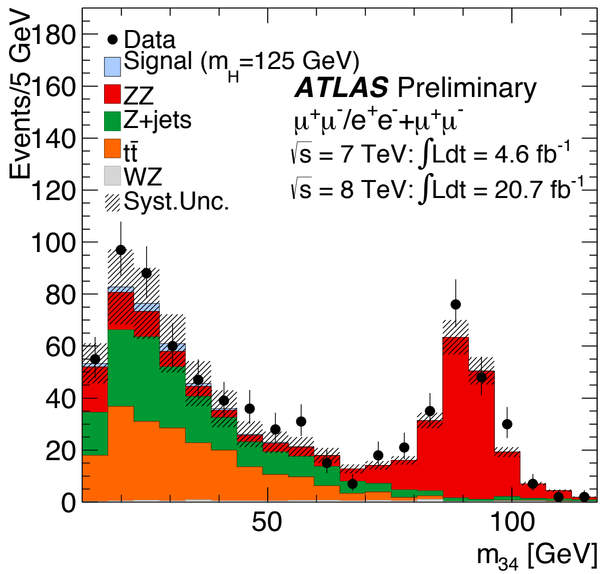




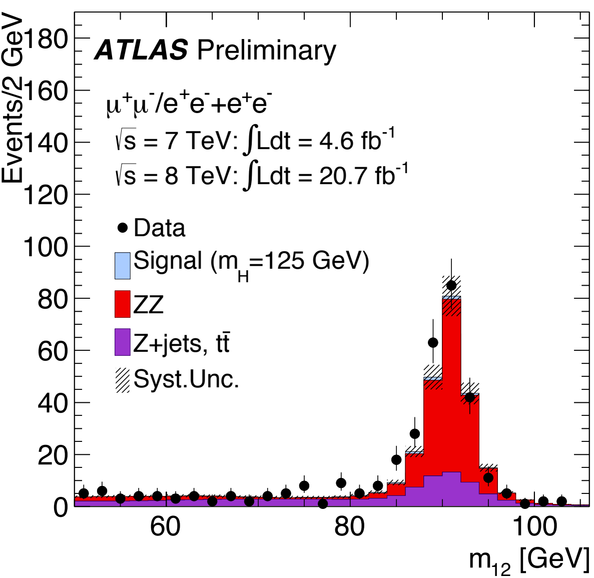
- **Reducible ll + ee**: data-driven – from control region relaxing identification criteria on the electrons
→ extrapolated to signal region using MC efficiencies

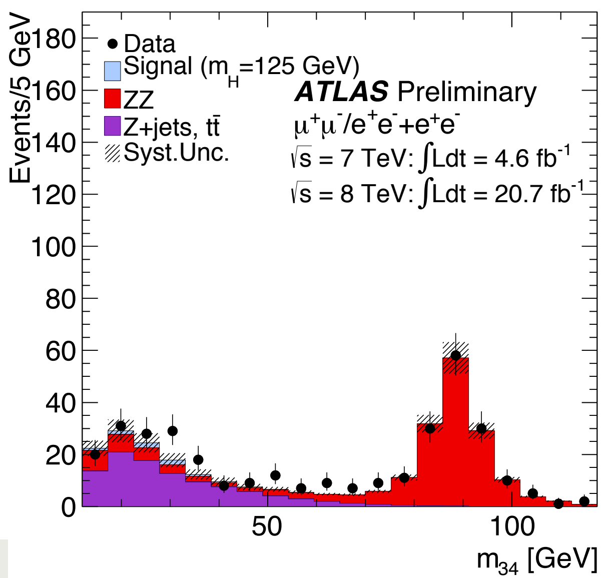
$ZZ^{(*)}$ background checks in control regions





ll + μμ backgrounds





ll + ee backgrounds

$ZZ^{(*)}$ events

Excess seen in all 4l channels

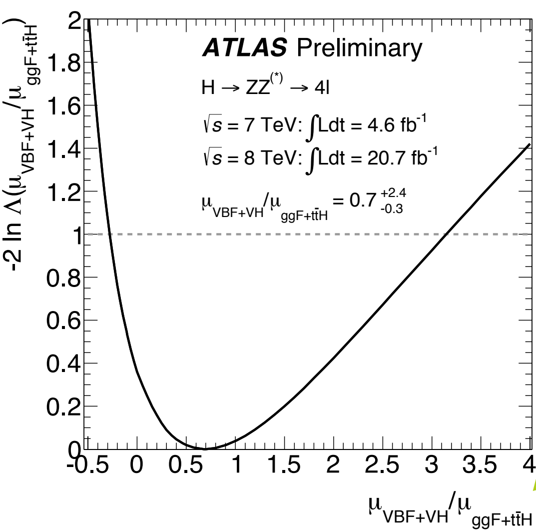
	4μ		$2\mu 2e/2e2\mu$		$4e$	
	low mass	high mass	low mass	high mass	low mass	high mass
$\sqrt{s} = 8$ TeV integrated luminosity 20.7 fb^{-1}						
$ZZ^{(*)}$	12.4 ± 0.6	92.6 ± 6.7	14.7 ± 0.9	144 ± 11	5.4 ± 0.5	55.9 ± 4.5
Z, $Zb\bar{b}$, and $t\bar{t}$	1.9 ± 0.6	0.5 ± 0.2	6.1 ± 1.5	1.5 ± 0.4	2.5 ± 0.6	0.6 ± 0.2
total background	14.3 ± 0.8	93.1 ± 6.7	20.8 ± 1.8	145 ± 11	8.0 ± 0.8	56.5 ± 4.5
data	27	93	28	169	13	55
$m_H = 123$ GeV	4.4 ± 0.6		5.4 ± 0.8		2.2 ± 0.4	
$m_H = 125$ GeV	5.8 ± 0.7		7.0 ± 0.9		2.9 ± 0.4	
$m_H = 127$ GeV	6.7 ± 0.9		8.4 ± 1.2		3.4 ± 0.5	

$H \rightarrow ZZ^{(*)} \rightarrow 4l$ signal strengths by processes

- **Coupling measurement helped by 2 dedicated categories:**

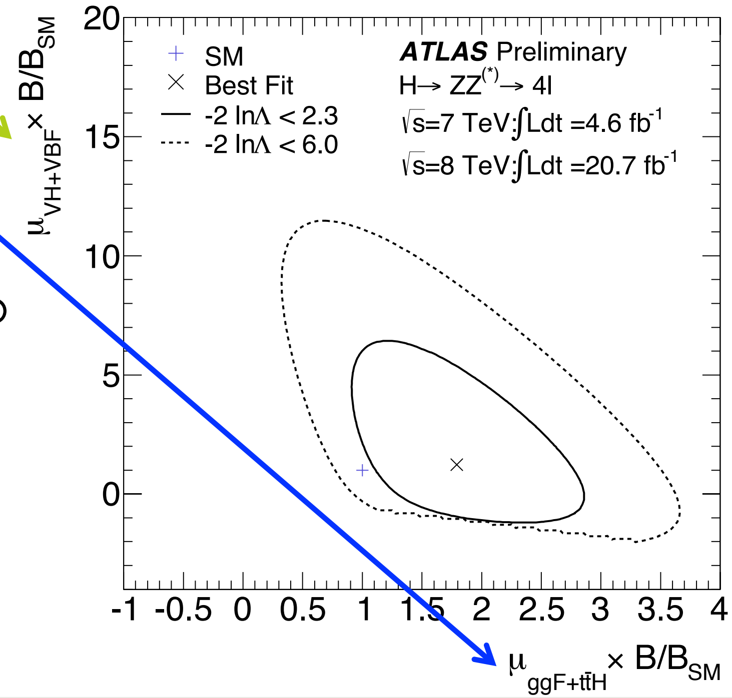
Category	Selection	Exp. Signal (mH=125 GeV)	Observed candidates
VBF-targeted (purity: 60%)	2jets with $\|\Delta\eta(jj)\|$ > 3 & m(jj) > 350 GeV	~0.71	1 (S/B=5) (with M~123.5 GeV)
VH-targeted (purity: 70%)	1 additional lepton with pT > 8 GeV	~0.20	0 (with M < 200 GeV)

- **Fit 2 signal strengths**
  - $\mu_{VBF+VH} \times B/B_{SM} = 1.2^{+3.8}_{-1.4}$ (stat.+syst.)
  - $\mu_{ggF+ttH} \times B/B_{SM} = 1.8^{+0.8}_{-0.5}$ (stat.+syst.)



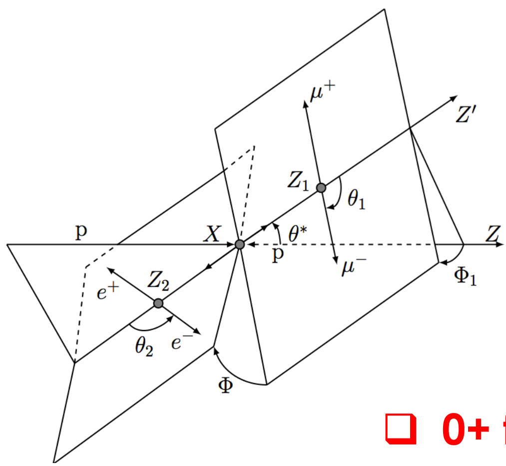
Remove dependence to branching ratio by computing the ratio:

$\mu_{VBF+VH}/\mu_{ggF+ttH} = 0.7^{+2.4}_{-0.3}$

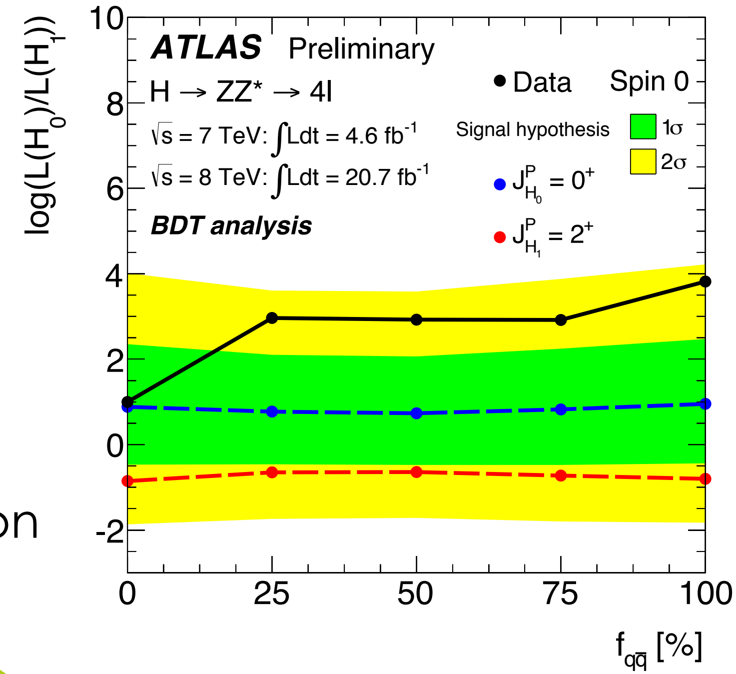


$ZZ^{(*)}$ spin measurement

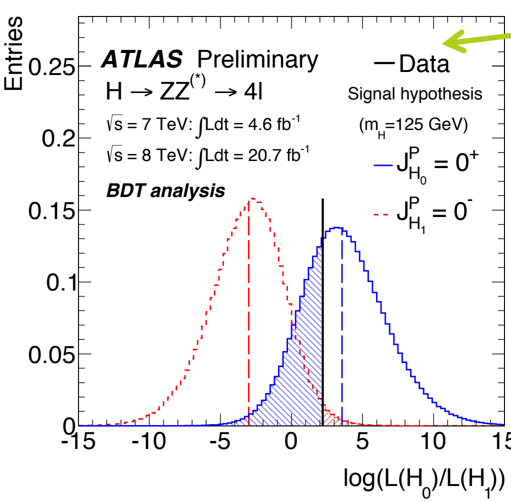
- **$ZZ^{(*)}$ channel**
  - **sensitive through many angular variables ($\theta^*, \phi_1, \Phi, \theta_1, \theta_2$) + Z masses → combined in BDT**
  - **43 events in 115<M(4l)<130 used**

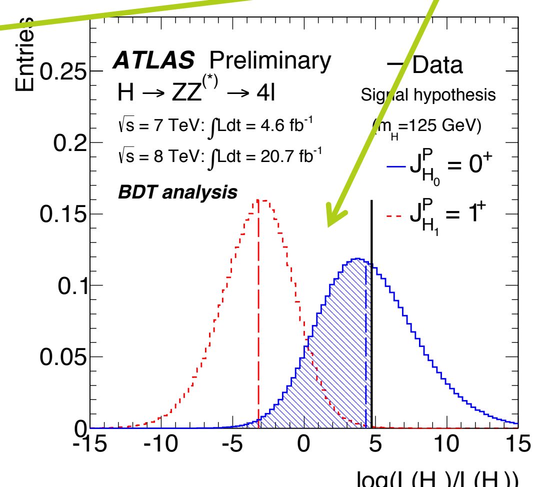


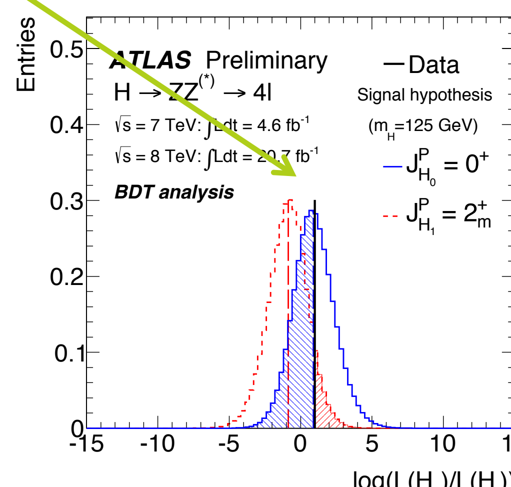
Separation with 2^+ ~constant with qq fraction



- **0+ favored against 0-, 1+, 2+**

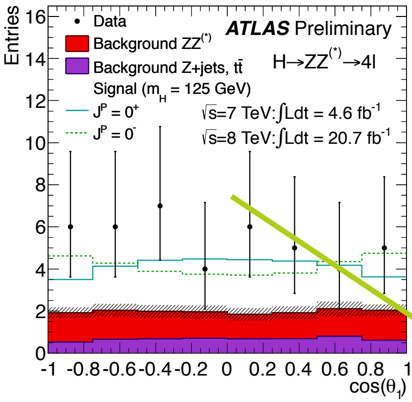


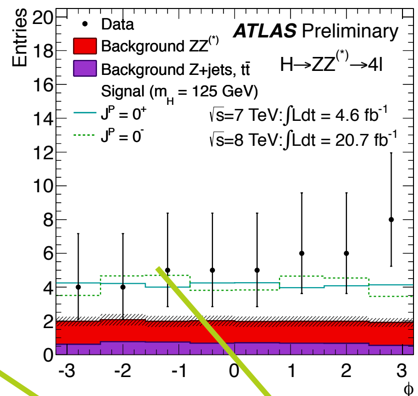


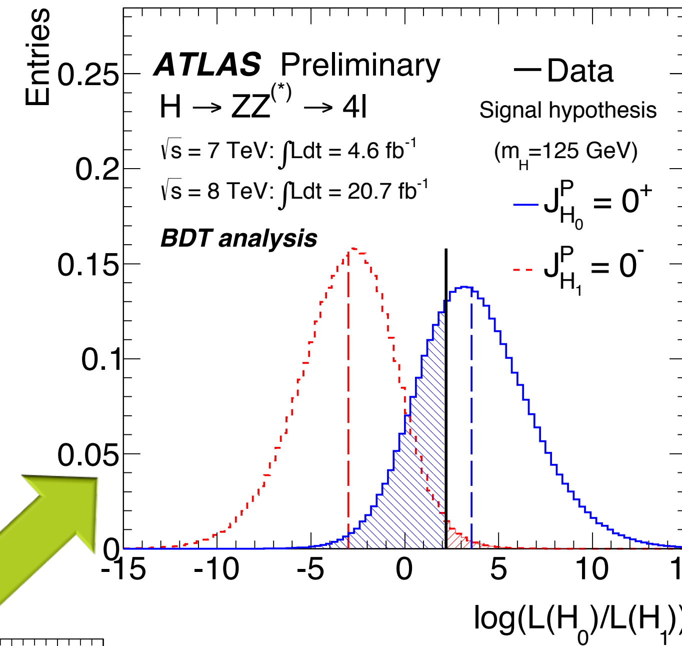


$ZZ^{(*)}$: 0^+ vs. 0^-

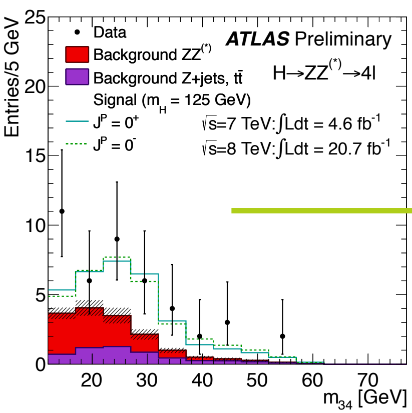
- **$ZZ^{(*)}$ channel**
  - **sensitive to 0^+ vs. 0^- parity through (Φ, $\theta1$, $\theta2$) + Z masses → combined into BDT**
  - **43 events in 115<M(4l)<130 used**

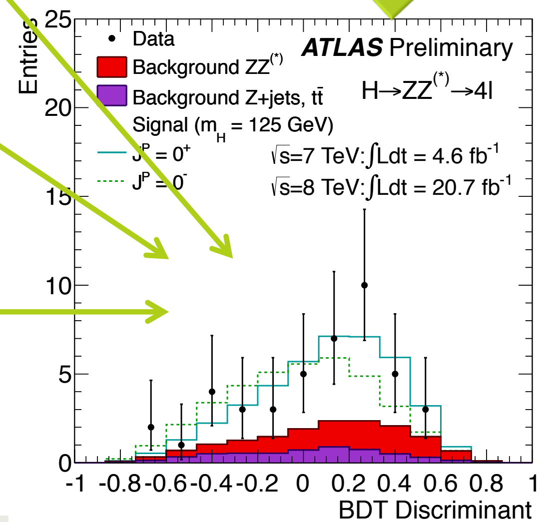






combined



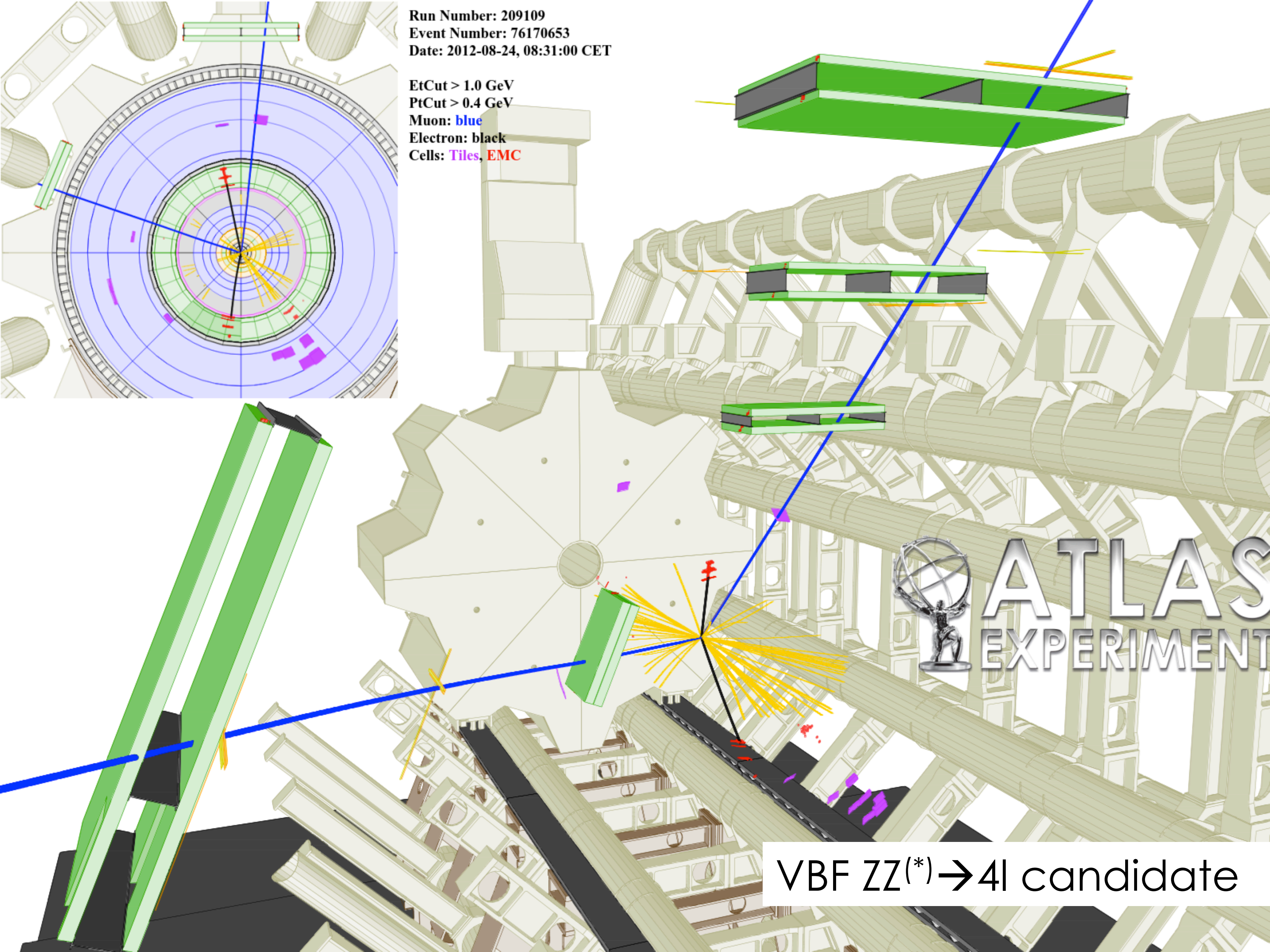


- **0+ favored against 0- @ 97.8% C.L.**

$ZZ^{(*)}$: spin/parity results

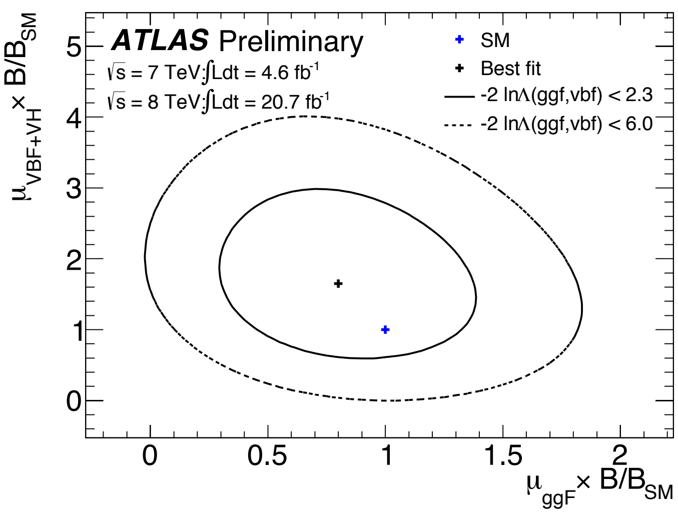
		BDT analysis				J^P-MELA analysis			
		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S	tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S
		expected	observed	observed*		expected	observed	observed*	
0^-	p_0	0.0037	0.015	0.31	0.022	0.0011	0.0022	0.40	0.004
1^+	p_0	0.0016	0.001	0.55	0.002	0.0031	0.0028	0.51	0.006
1^-	p_0	0.0038	0.051	0.15	0.060	0.0010	0.027	0.11	0.031
2^+_m	p_0	0.092	0.079	0.53	0.168	0.064	0.11	0.38	0.182
2^-	p_0	0.0053	0.25	0.034	0.258	0.0032	0.11	0.08	0.116

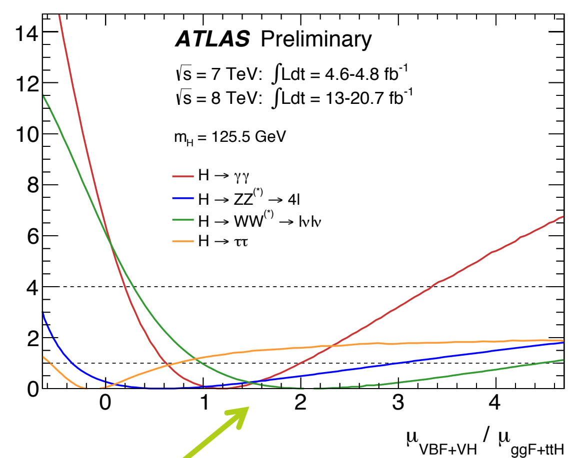
$CL_S = p_0(\text{alternative } J^P)/[1 - p0(0^+)]$

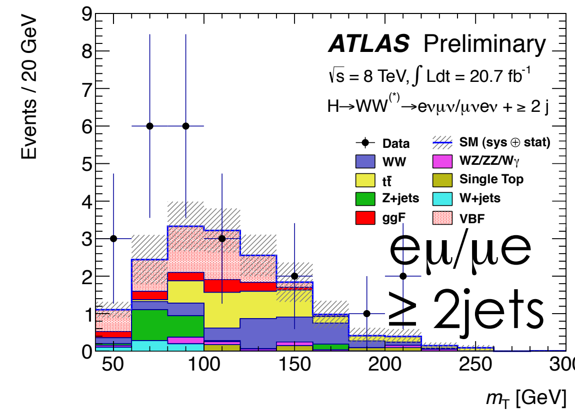

Run Number: 209109
Event Number: 76170653
Date: 2012-08-24, 08:31:00 CET
EtCut > 1.0 GeV
PtCut > 0.4 GeV
Muon: blue
Electron: black
Cells: Tiles, EMC
ATLAS
EXPERIMENT
VBF ZZ(*)→4l candidate

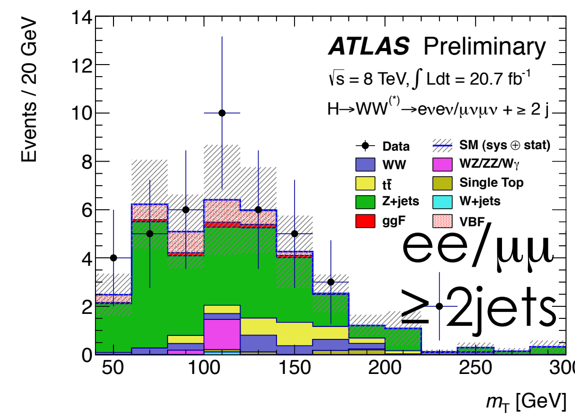
H→WW(*)→lνlν signal strengths by processes

- **Coupling measurement helped by VBF dedicated category**
- **Fit 2 signal strengths**
  - **$\mu_{VBF+VH} \times B/B_{SM} = 1.66 \pm 0.67\ (stat.) \pm 0.42\ (syst.)$**
  - **$\mu_{ggF+t\bar{t}H} \times B/B_{SM} = 0.82 \pm 0.24\ (stat.) \pm 0.28\ (syst.)$**









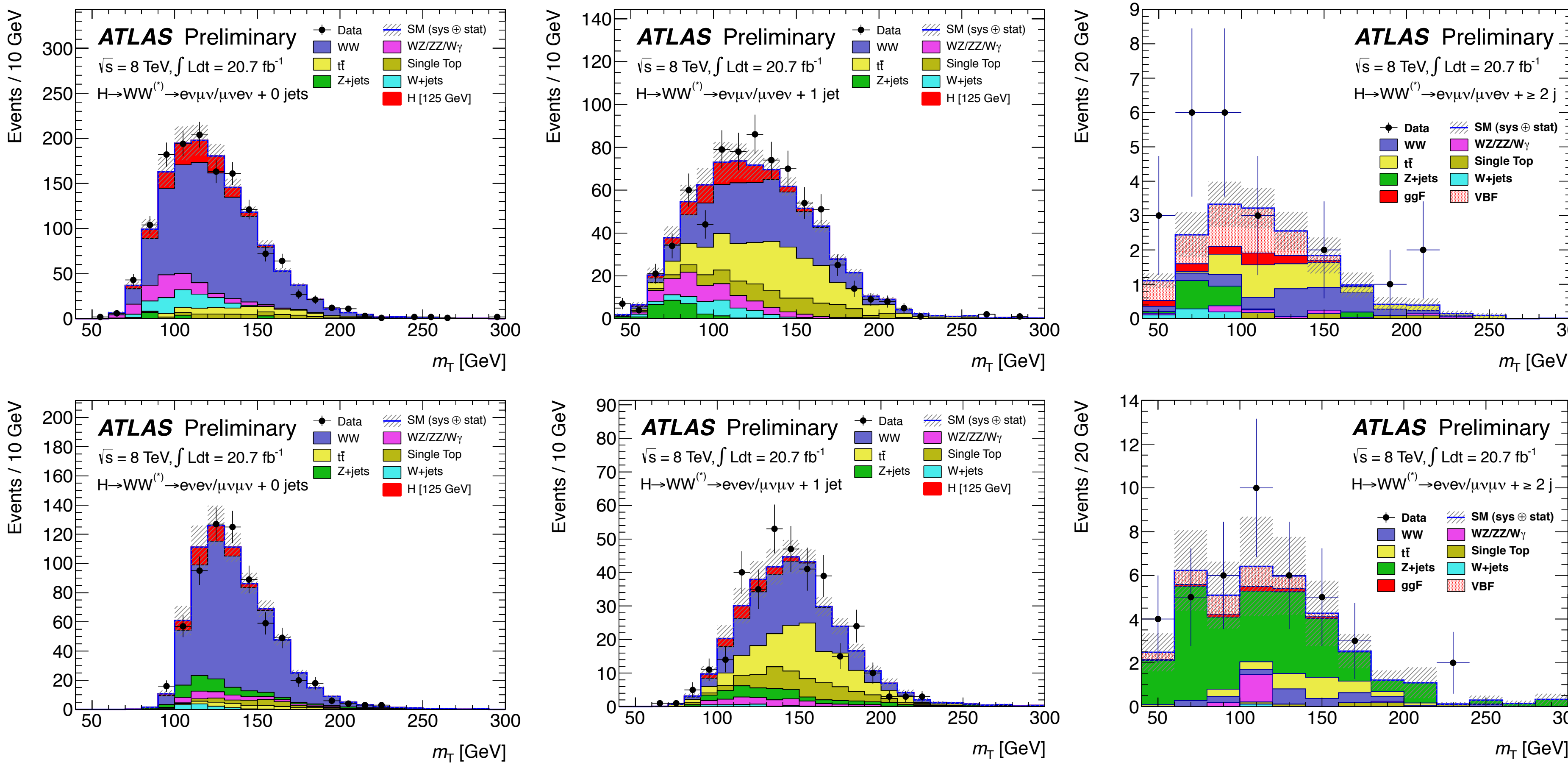
Remove dependence to branching ratio by computing the ratio:

$\mu_{VBF+VH}/\mu_{ggF+t\bar{t}H}$

H→WW$^{(*)}$→lνlν analysis selection

Category	$N_{\rm jet}=0$	$N_{\rm jet}=1$	$N_{\rm jet}\geq 2$
Pre-selection	Two isolated leptons ($\ell=e,\mu$) with opposite charge Leptons with $p_{\rm T}^{\rm lead}>25$ and $p_{\rm T}^{\rm sublead}>15$ $e\mu+\mu e$: $m_{\ell\ell}>10$ $ee+\mu\mu$: $m_{\ell\ell}>12$, $\lvert m_{\ell\ell}-m_Z\rvert>15$		
Missing transverse momentum and hadronic recoil	$e\mu+\mu e$: $E_{\rm T,rel}^{\rm miss}>25$ $ee+\mu\mu$: $E_{\rm T,rel}^{\rm miss}>45$ $ee+\mu\mu$: $p_{\rm T,rel}^{\rm miss}>45$ $ee+\mu\mu$: $f_{\rm recoil}<0.05$	$e\mu+\mu e$: $E_{\rm T,rel}^{\rm miss}>25$ $ee+\mu\mu$: $E_{\rm T,rel}^{\rm miss}>45$ $ee+\mu\mu$: $p_{\rm T,rel}^{\rm miss}>45$ $ee+\mu\mu$: $f_{\rm recoil}<0.2$	$e\mu+\mu e$: $E_{\rm T}^{\rm miss}>20$ $ee+\mu\mu$: $E_{\rm T}^{\rm miss}>45$ $ee+\mu\mu$: $E_{\rm T,STVF}^{\rm miss}>35$ -
General selection	- $\lvert\Delta\phi_{\ell\ell,MET}\rvert>\pi/2$ $p_{\rm T}^{\ell\ell}>30$	$N_{b\text{-jet}}=0$ - $e\mu+\mu e$: $Z/\gamma^*\to\tau\tau$ veto	$N_{b\text{-jet}}=0$ $p_{\rm T}^{\rm tot}<45$ $e\mu+\mu e$: $Z/\gamma^*\to\tau\tau$ veto
VBF topology	- - - -	- - - -	$m_{jj}>500$ $\lvert\Delta y_{jj}\rvert>2.8$ No jets ($p_{\rm T}>20$) in rapidity gap Require both ℓ in rapidity gap
$H\to WW^{(*)}\to\ell\nu\ell\nu$ topology	$m_{\ell\ell}<50$ $\lvert\Delta\phi_{\ell\ell}\rvert<1.8$ $e\mu+\mu e$: split $m_{\ell\ell}$ Fit $m_{\rm T}$	$m_{\ell\ell}<50$ $\lvert\Delta\phi_{\ell\ell}\rvert<1.8$ $e\mu+\mu e$: split $m_{\ell\ell}$ Fit $m_{\rm T}$	$m_{\ell\ell}<60$ $\lvert\Delta\phi_{\ell\ell}\rvert<1.8$ - Fit $m_{\rm T}$

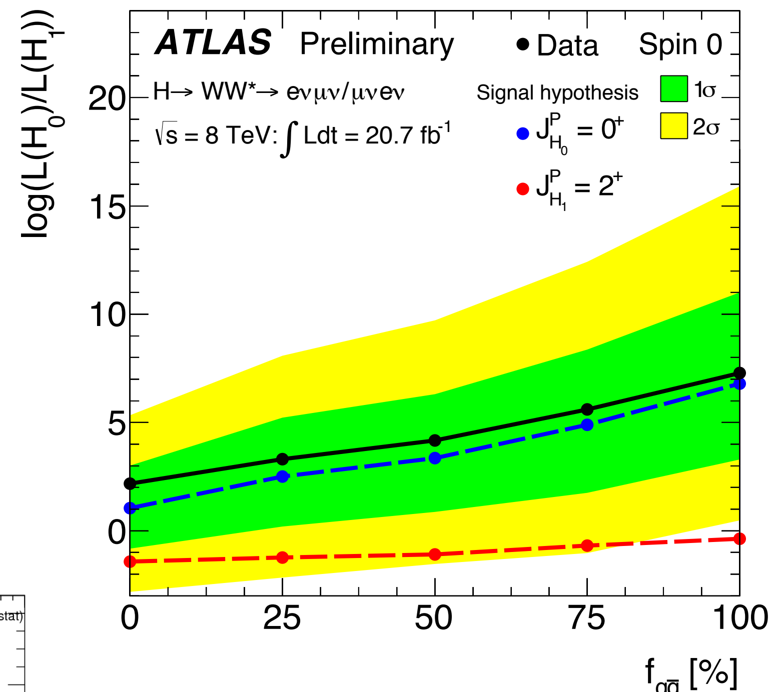
H→WW$^{(*)}$→lvlv mT plots

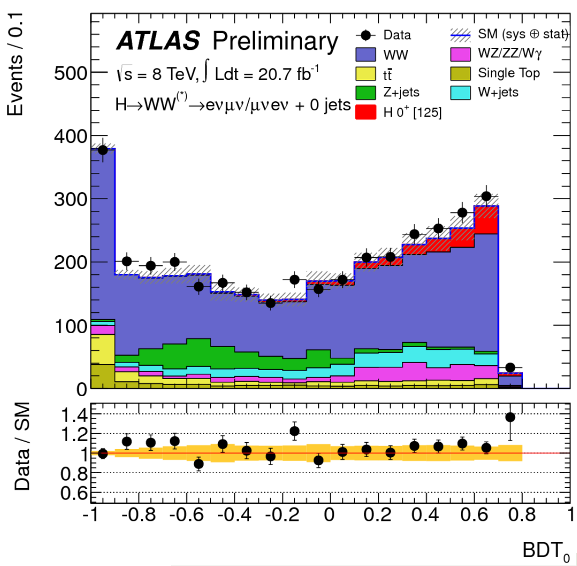


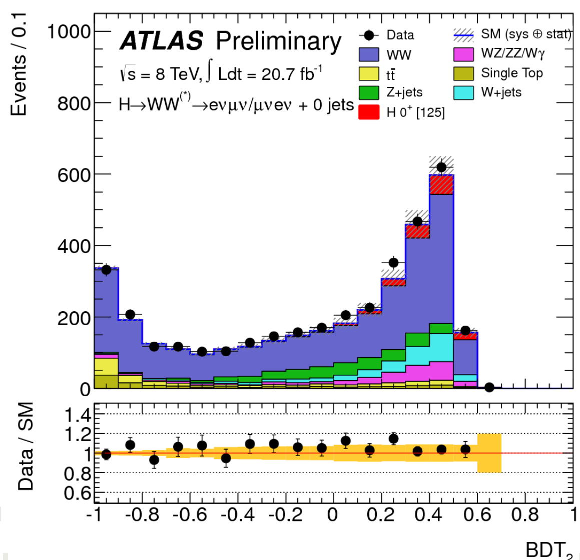
1 jet 0 jet 2 jets

$WW^{(*)}$ spin measurement

- **$WW^{(*)}$ channel**
  - Restricted to $e\nu\mu\nu$ or $\mu\nu e\nu$ final states
  - No reconstruction of angles due to neutrinos
  - Discriminating variables: m(ll), p_T(ll), $\Delta\Phi$(ll), mT
  - 2 multivariate analysis (BDTs): one trained to reject background, the other trained to discriminate 0^+ from 2^+
  - 2-dimensional (BDT_a,BDT_b) data distributions fitted to test compatibility with each hypothesis







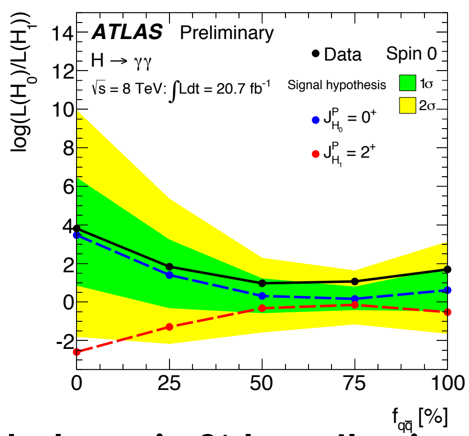
- **Excludes spin 2^+ hypothesis**
  - **at >99% C.L. when f_{qq}=100%**
  - **at >95% C.L. when f_{qq}=0%**

Spin measurements

- **SM predicts J^P(Higgs)=0^+**
- **H→γγ strongly disfavors spin 1 (Yang-Landau's theorem)**
- **Tested hypothesis: could the resonance be $J^P=2^+$? → Combining γγ, $ZZ^{(*)}$, $WW^{(*)}$**
- **Many spin 2 models: choice – graviton-like spin 2 model with minimal couplings to SM particles → f_{qq} denotes the fraction of Higgs production through qq annihiliation**

γγ channel

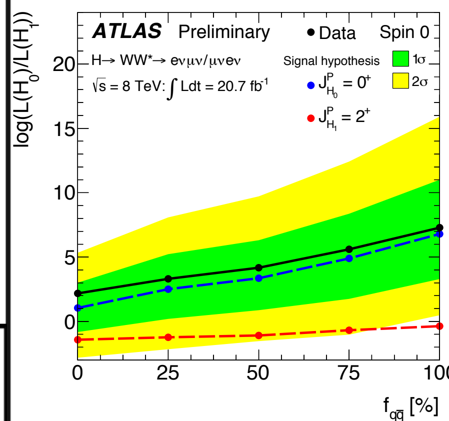
- **sensitive through cos(θ*) = angular distribution of photons in the resonance rest frame**



- **Excludes spin 2^+ hypothesis at >99% C.L. when f_{qq}=100%**

$WW^{(*)}$ channel

- **Restricted to eνμν or μνeν final states**
- **No reconstruction of angles due to neutrinos**

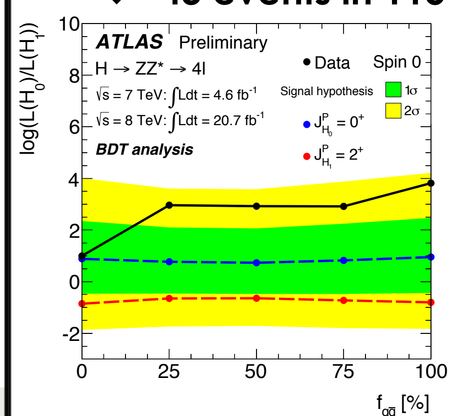


- **Sensitive through other kinematic variables:**
  m(ll), p_T(ll), ΔΦ(ll), mT
  → into multivariate analysis

- **Excludes spin 2^+ hypothesis**
  - **>99% C.L. when f_{qq}=100%**
  - **>95% C.L. when f_{qq}=0%**

$ZZ^{(*)}$ channel

- **sensitive through many angular variables (θ*,φ1,Φ, θ1, θ2) + Z masses**
- **43 events in 115<M(4l)<130 used**



- **Excludes spin 2^+ hypothesis**
  - **>95% C.L.**
  - **~ constant with f_{qq}**

Combination: mass/signal strength

- **Only the $\gamma\gamma$ and $ZZ^{(*)}\rightarrow 4l$ are combined here**
- **Done using the following likelihood ratio**

Tested m_H value

$$\Lambda(m_H) = \frac{L(m_H, \hat{\hat{\mu}}_{\gamma\gamma}(m_H), \hat{\hat{\mu}}_{4\ell}(m_H), \hat{\hat{\theta}}(m_H))}{L(\hat{m}_H, \hat{\mu}_{\gamma\gamma}, \hat{\mu}_{4\ell}, \hat{\theta})}$$

Conditionnal maximum likelihood estimates of μ/θ

Unconditionnal maximum likelihood estimates of $m_H/\mu/\theta$

θ are the nuisance parameters

- **Similar likelihood ratio for combined signal strength**

Combination: coupling results

- **Couplings: assuming a unique & narrow resonance with tensor structure of the SM Higgs, define effective couplings κ to Higgs boson from partial widths:**

$$\kappa_i^2 = \frac{\Gamma_i}{\Gamma_{i(SM)}} \Rightarrow$$

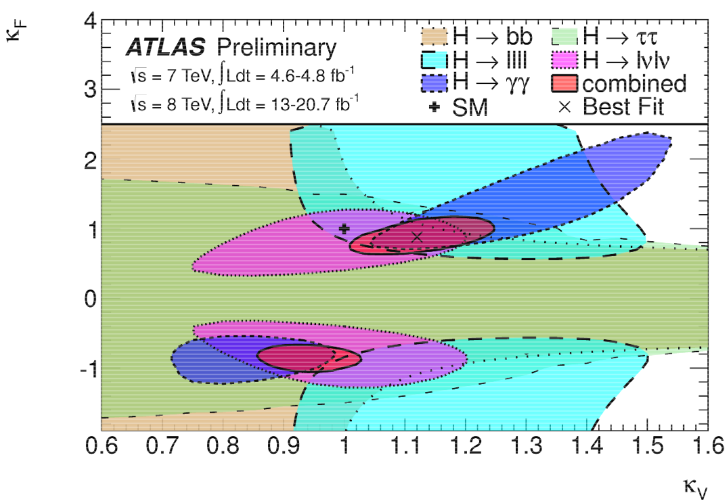
the cross sections σ_i and the partial decay widths Γi associated with the SM particle i scale with the factor κ_i^2

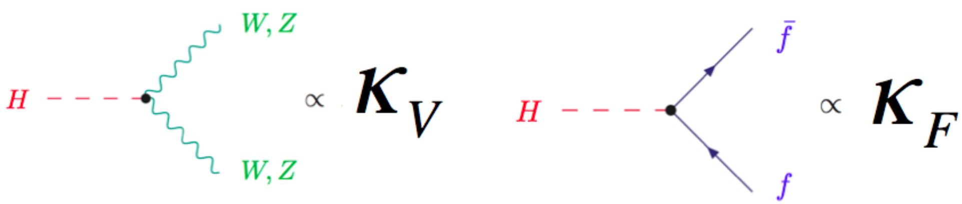
i = H (total width), f, V, W, Z, g, γ, etc.

- **Example for gluon gluon fusion Higgs decaying to diphoton:**

$$\sigma \times BR(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \times BR_{SM}(H \to \gamma\gamma) \times \frac{\kappa_g^2 \times \kappa_\gamma^2}{\kappa_H^2}$$

- **Typically assume same κ_V-scales for bosons and same κ_f-scales for fermions**





→ **Combination of couplings makes the measurement compatible with SM at 8% level**
(assuming no new physics)