Latest results with ATLAS detector

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CEPC 物理分析及探测器优化培训

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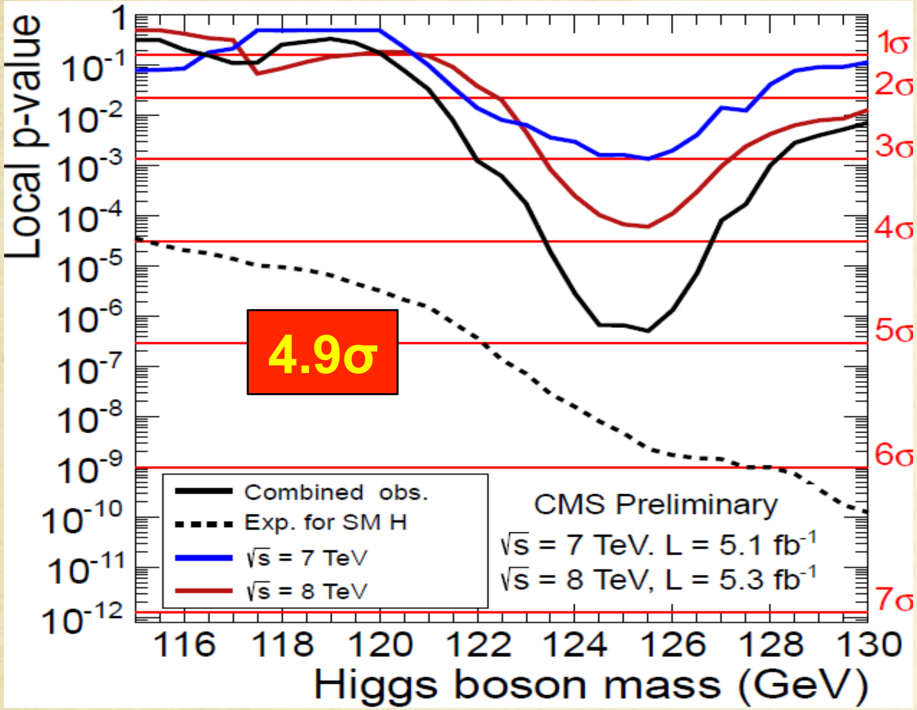
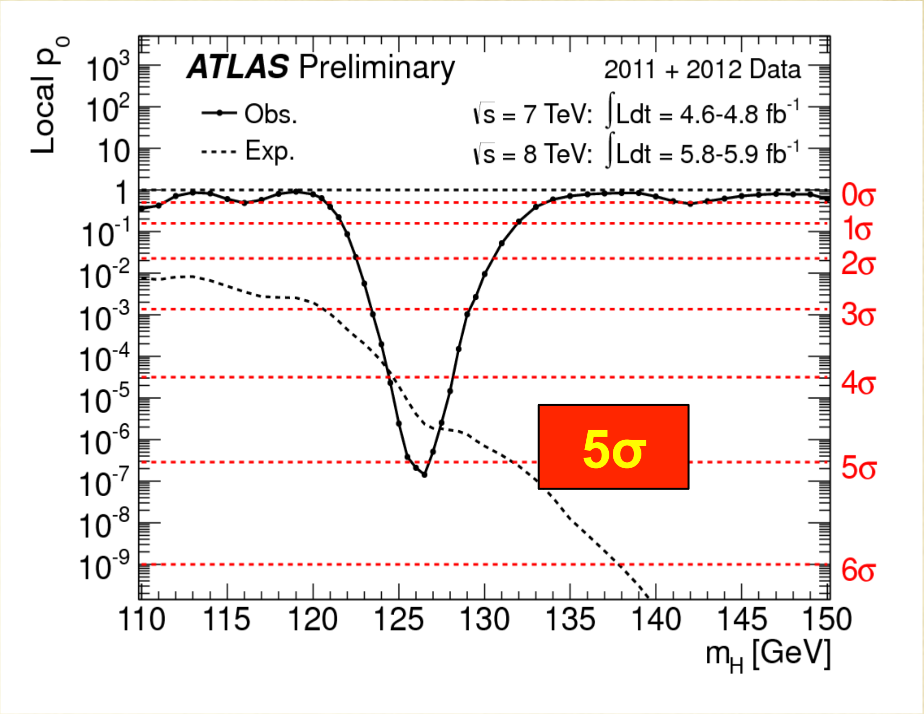
Motivation of the study after the discovery

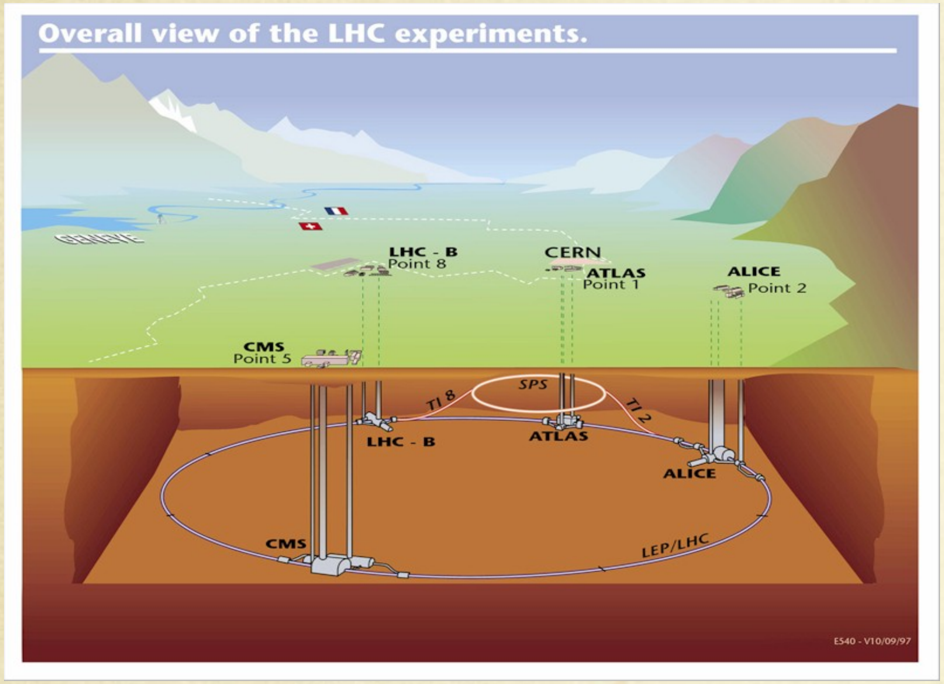


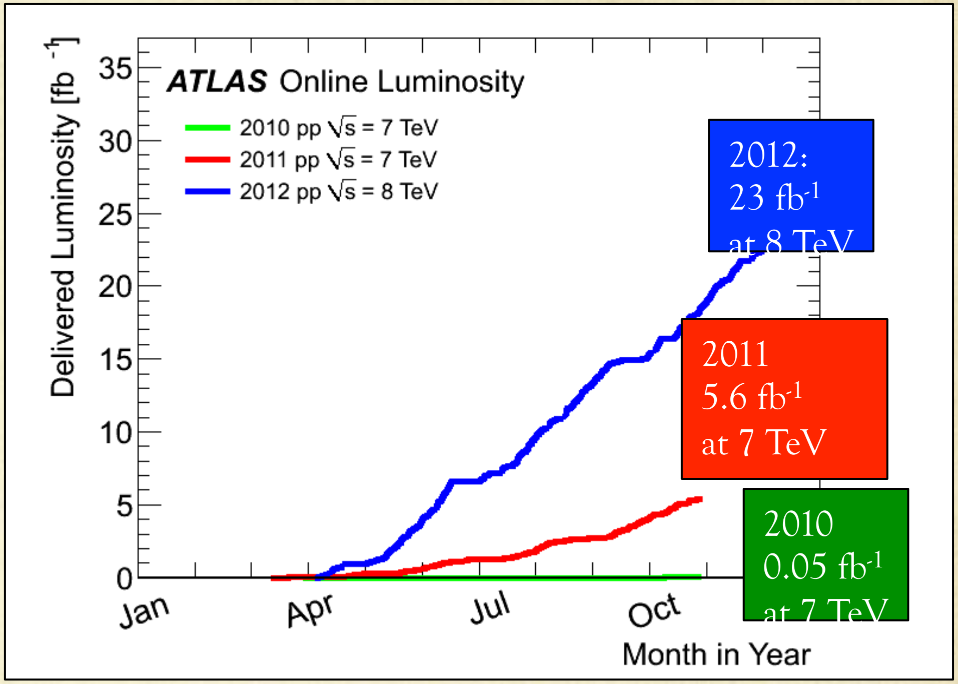


A milestone discovery announced in July, 2012.

- *Both ATLAS and CMS observed a new particle with ~5σ evidence .*
- *Will the signal be Standard Model (SM) Higgs?*
- *Properties such as mass measurement, spin-parity, rate, couplings etc….*

LHC machine and data collection with ATLAS detector

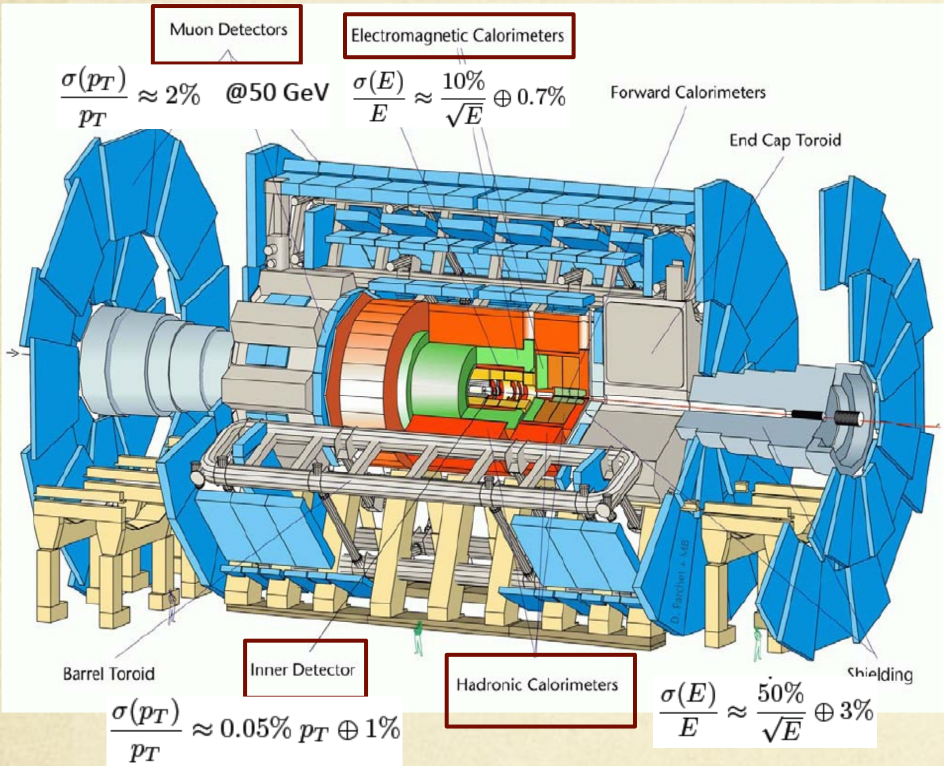


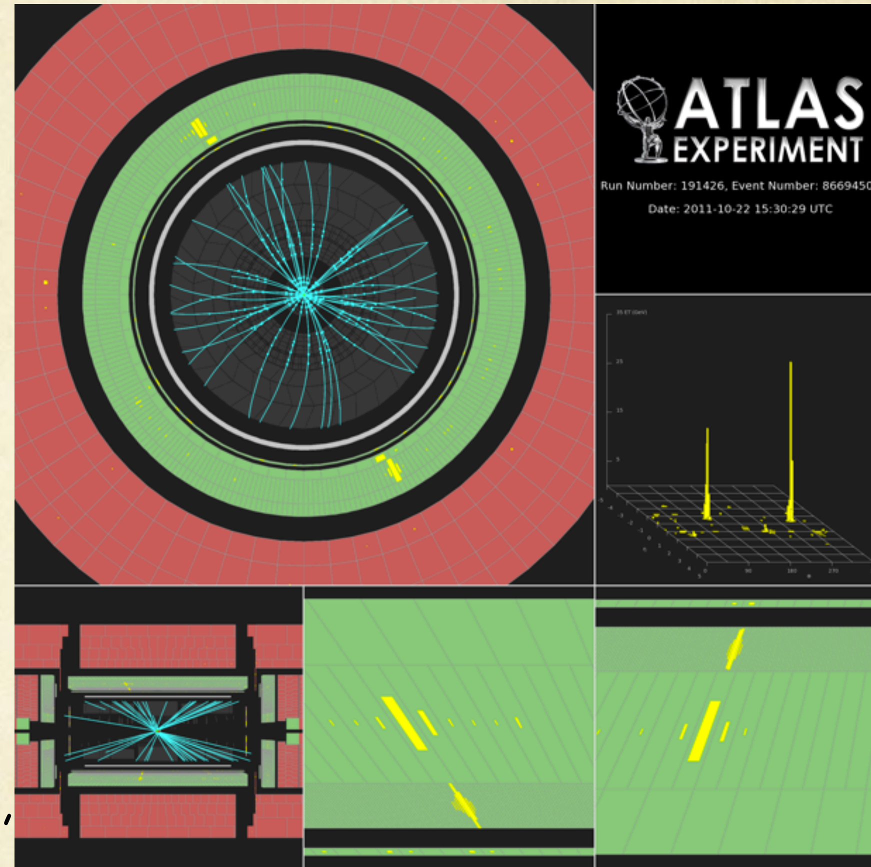


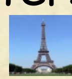
- ❑ 100 meters underground, 27 km ring .
- ❑Four experiments : ATLAS, CMS, ALICE, LHCb
- ❑ CM energy : 2012, 8 TeV; 2011, 7 TeV
- ❑Physics goal: Higgs, SUSY, dark matter, TeV scale weak interaction…
- ❑LHC has a successful run in the past three years (600K higgs)

ATLAS detector and one example of an event display

A Toroidal LHC ApparatuS



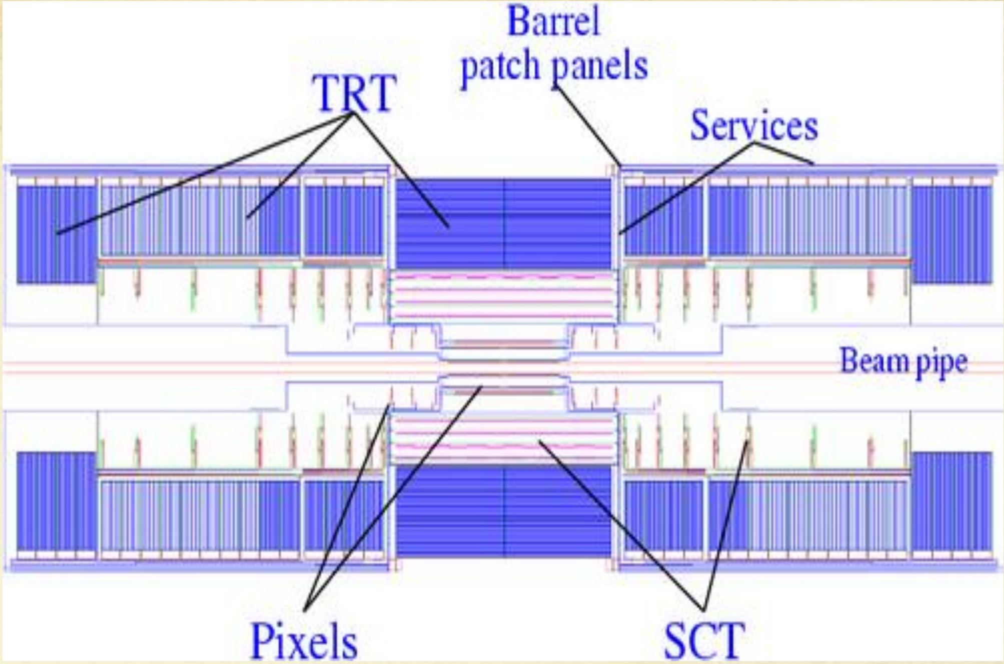


- Length: 44 meters，12.5 meters in radius, ~7000 tons. (One Eiffel tower ).
- Magnets (2T in the central region)

Muon Spectrometer, Hadronic Calorimeter, Electromagnetic (EM) Calorimeter， Inner Detector

One $H \rightarrow \gamma\gamma$ candidate event:
E_T=64.2 GeV, η=-0.34,
E_T=61.4 GeV, η= -0.61,
$M_{\gamma\gamma}$ = 126.6 GeV

Inner Detector



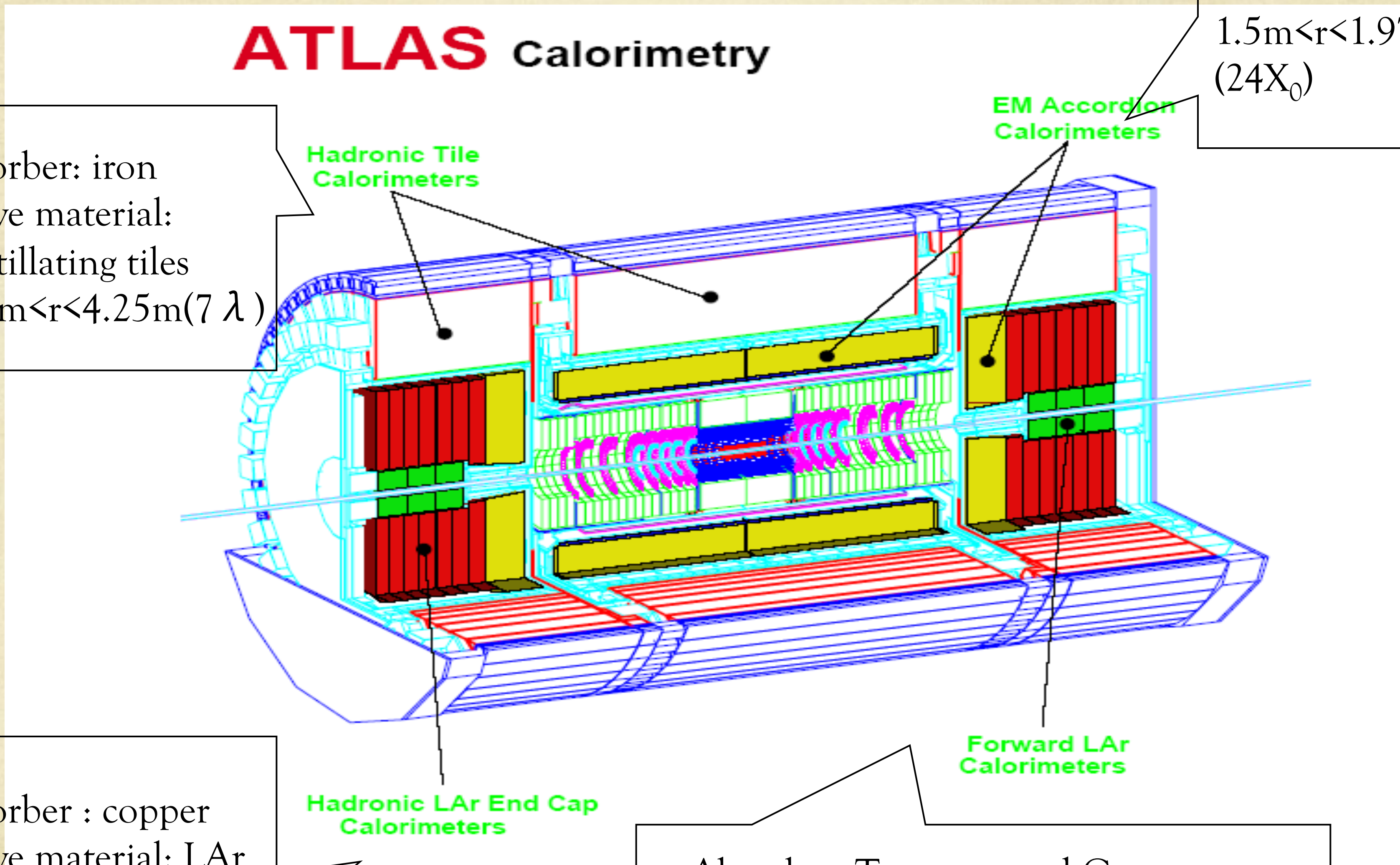
- Pixel detector
  - 3 high-precision measurement per track
    - 3 disks at each end(9-15cm)
    - 3 barrels (~5,9,12cm)
- Semiconductor Tracker
  - 8 precision measurements per track
  - 6.2 million readout channels
  - Spatial resolution 16μm in RΦ and 580μm in z
- Transition Radiation Tracker
  - straw detectors
    - 50000 straws in the barrel
    - End cap includes 32000 radial straws
  - Xenon gas in straws and radiator in region between straws: electron identification

- Out radius 1.15m
- Length 7m
- magnetic field of 2T

- Momentum of charged particles
- Vertex position

Absorber: Lead
Active material: LAr
1.5m<r<1.97m ($24X_0$)

Absorber: iron
Active material: Scintillating tiles
2.28m<r<4.25m(7λ)

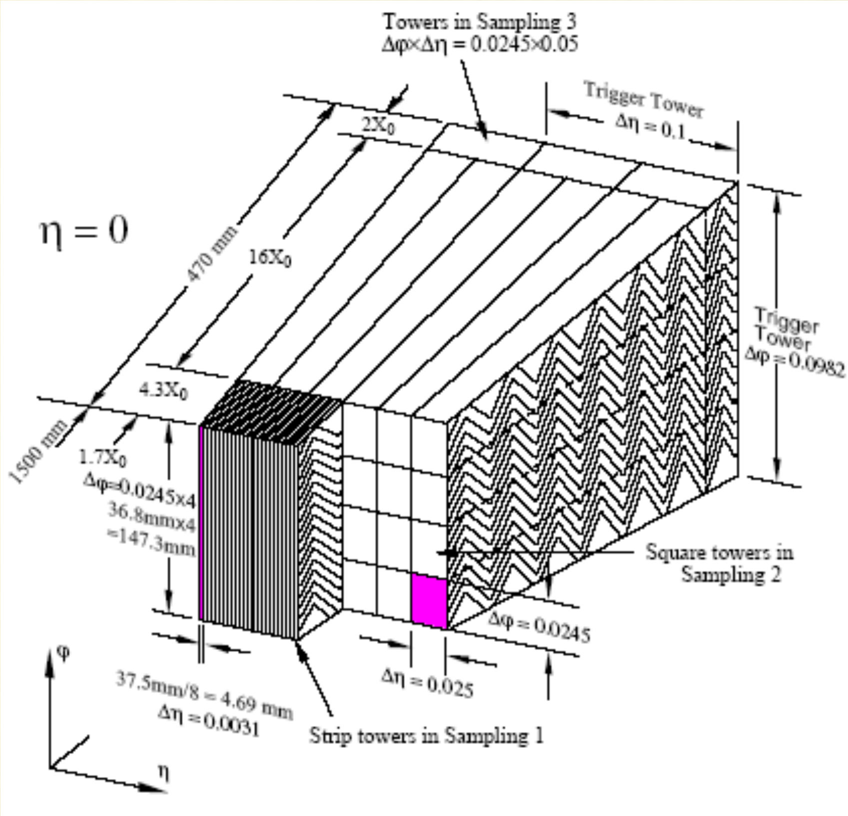


Absorber : copper
Active material: LAr
Out radius: 2.03m

Absorber: Tungsten and Copper
Active material: LAr

EM Calorimeter

- Three layers with accordion geometry (full azimuthal acceptance without dead zone)
- Presampler in front of the strip to correct the energy loss in material upstream of the EMC.
- Thin strip towers in Sampling 1 help to decide the direction of the photon.



Calibration Algorithm for π^0

$|\eta| < 1.47$

For track-matched clusters we apply electron based calibration:

$$E_{rec} = \lambda\left(b + W_0 E_{pres} + E_1 + E_2 + W_3 E_3\right)$$

For un-matched clusters we apply photon based calibration:

$$E_{rec} = \lambda_\gamma\left(W_{\gamma 0} E_{pres} + E_1 + E_2 + W_{\gamma 3} E_3\right)$$

Use $H \rightarrow \gamma\gamma$ generated with MC@NLO, $M_H = 130$ GeV

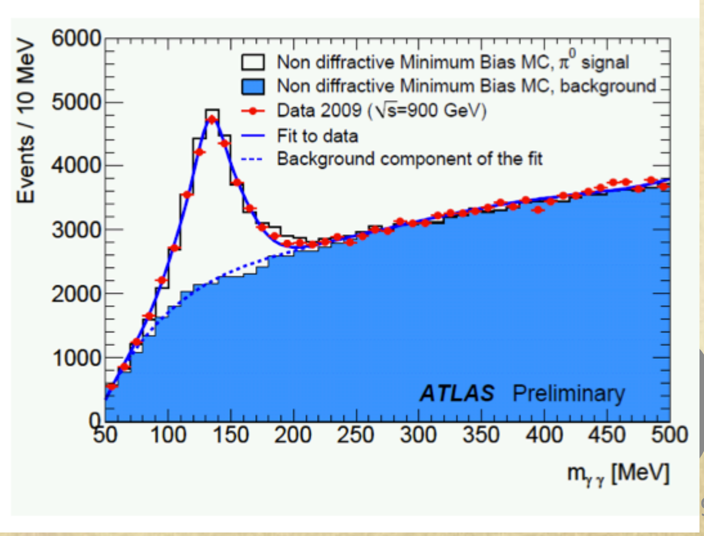
procedure

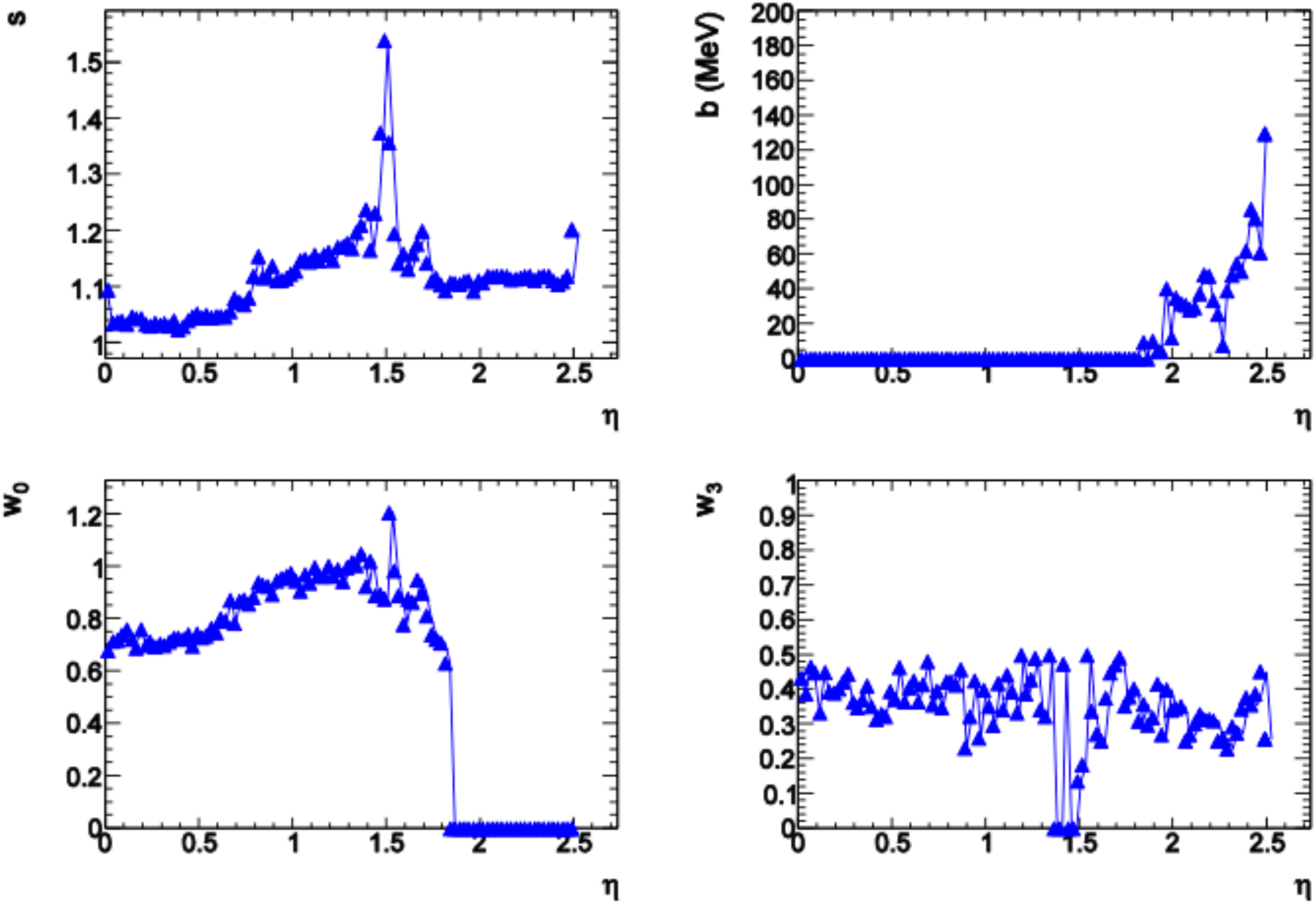
- This is a MC based calibration and apply the constants to data.
- Step:
  - Perform calibration with photons from π^0 ($p_{T\gamma}$>0.4 GeV, fixwin 35 with topo seed is used); the photons are binned with η (center) from 0.0125 to 2.4875 at a step of 0.025.
  - Perform the minimization of a function:

$$\sum \frac{(E_{rec} - E_{true})^2}{\sigma^2}$$

for all clusters belonging to a specific η bin.

  - Obtain the coefficients (s, b, w0, w3) after the minimization

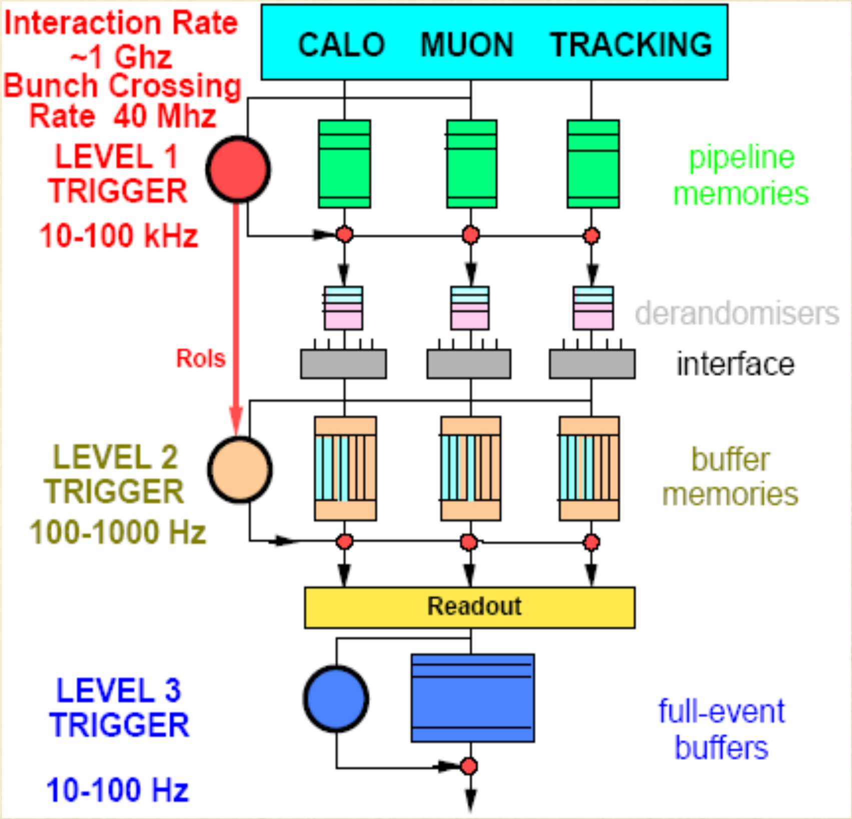




s
1.5
1.4
1.3
1.2
1.1
1
0
0.5
1
1.5
2
2.5
η
b (MeV)
200
180
160
140
120
100
80
60
40
20
0
0
0.5
1
1.5
2
2.5
η
w_0
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
η
w_3
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.5
1
1.5
2
2.5
η

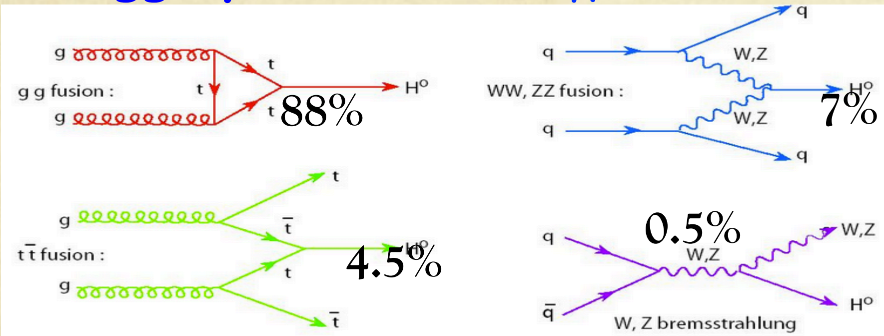
Trigger system at ATLAS

- Level 1:calorimeter and muon triggers which pass Region of Interest (ROI) data to Level 2
  - Two isolated EM Clusters $E_{TEMcluster}$>20GeV for H→γγ
- Level 2: refine the analysis of LVL1 across different detectors
  - Refine γ isolation cut for H→γγ
- Level 3: analysis data in the full detector and do more complicated physics analysis



How to know the discovered particle is the SM Higgs?

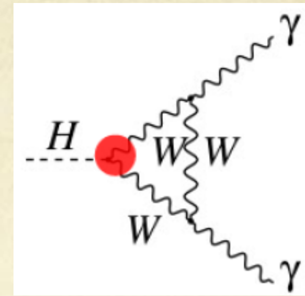
- **Higgs production (m_H = 125.5 GeV)**

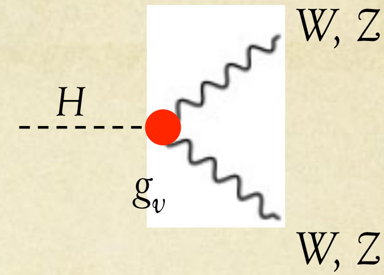


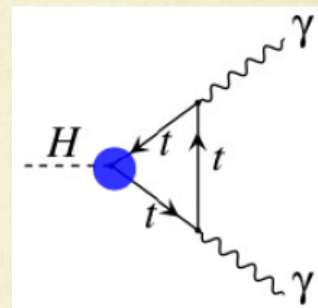
Separation of different production modes

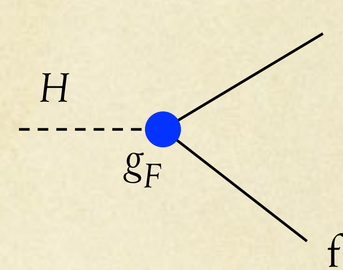
- Reconstruction higgs mass after the selections suppressing bkg with high s/b
- Additional selections: two forward jet tagging (VBF) lepton(s)/missing transverse momentum (VH)

Higgs decay









m_H=125.5 GeV	BR(%)
H→γγ	0.23
H→ZZ	2.8
H→WW	22
H→ττ	6.2
H→bb	57

- **Signal strength**

Measure and compare with the SM prediction

- **Couplings**

Coupling to fermion : $g_F = \sqrt{2}\frac{m_F}{v}$

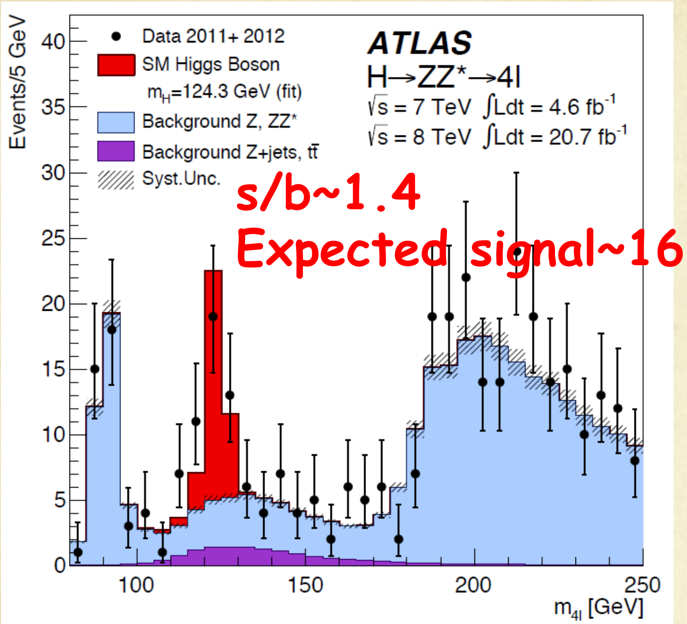
Coupling to gauge boson : $g_v = 2\frac{m_v^2}{v}$

(ν is the vacuum expectation value)

- **Spin-Parity**

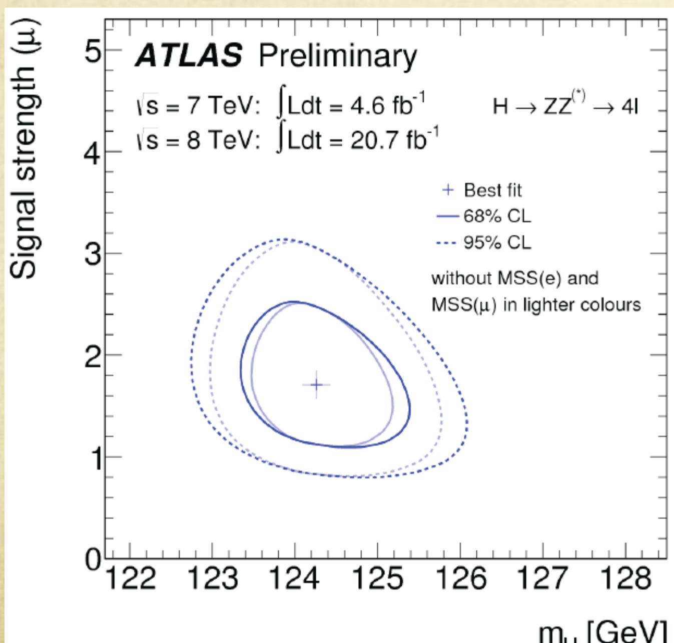
The Standard Model Higgs : $J^P = 0^+$

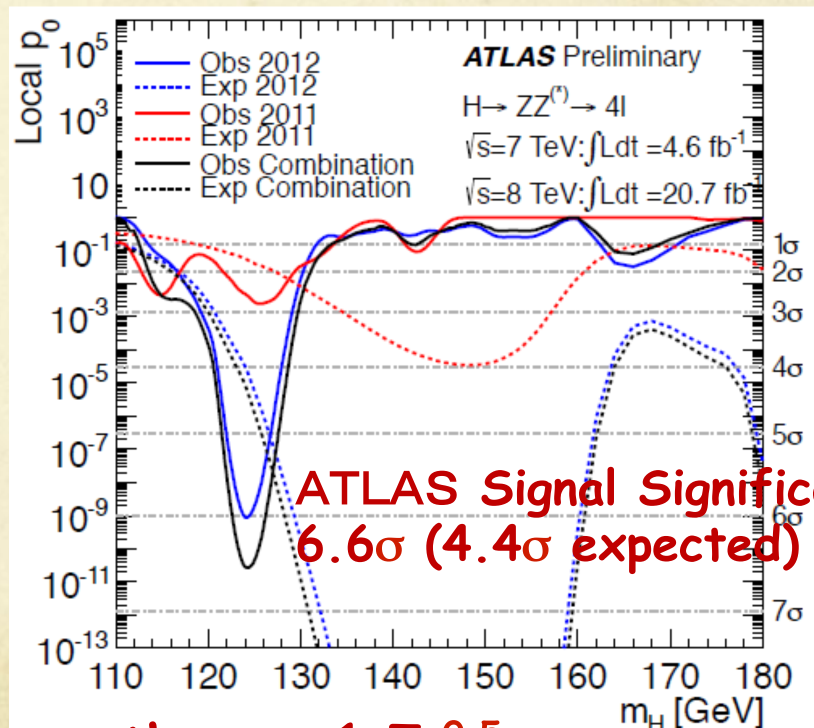
H→ ZZ*→ 4l



s/b~1.4
Expected signal~16

- Event Signature: 4-lepton events with p_T>20,15,10,7(6) GeV; pair 4l,m_{l1l2} (mass closest to Z) and m_{l3l4} (off-shell);
- Events in 3 categories: VBF(jets), VH(lepton) and ggF-like (the rest)



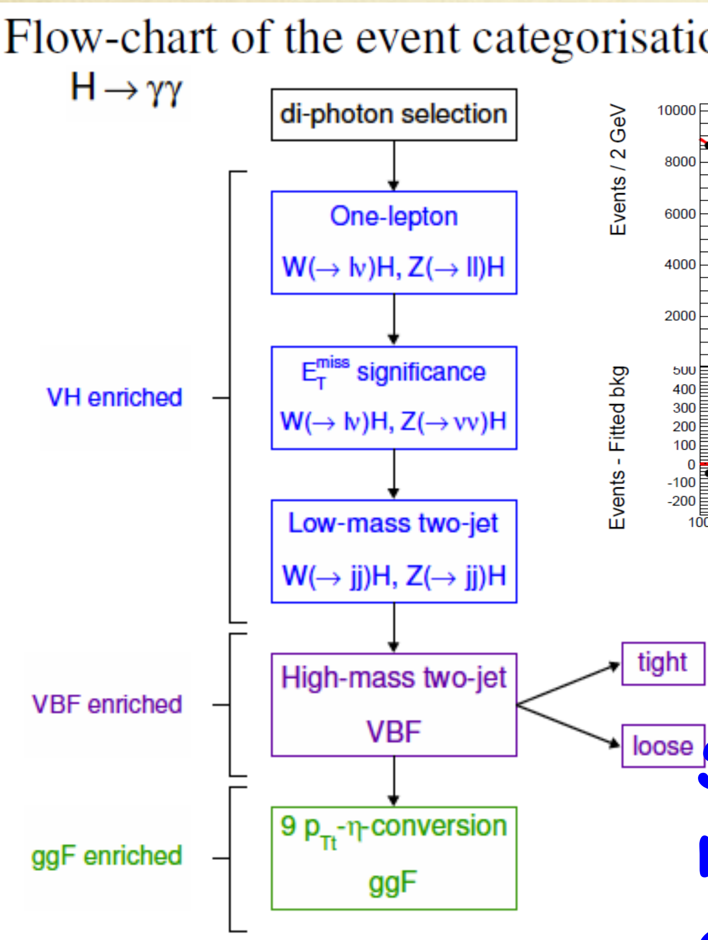


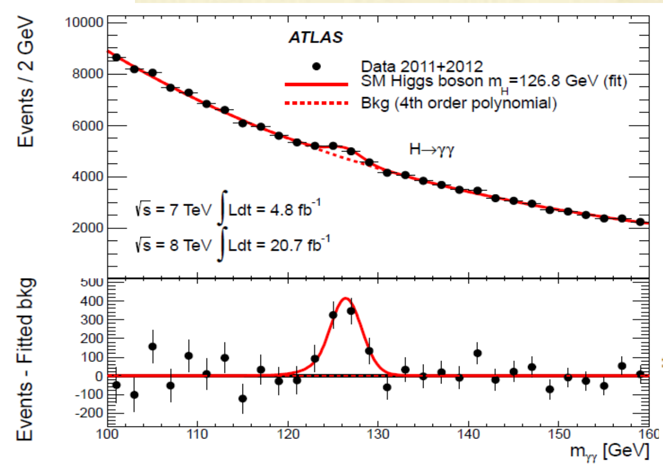
ATLAS Signal Significance : 6.6σ (4.4σ expected)

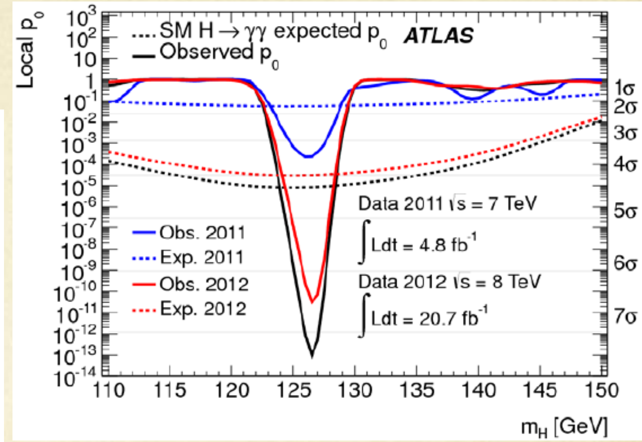
Strength: $\mu = 1.7^{+0.5}_{-0.4}$
Signal at mass = $124.3^{+0.6}_{-0.5}{}^{+0.5}_{-0.3}$ GeV

H→γγ

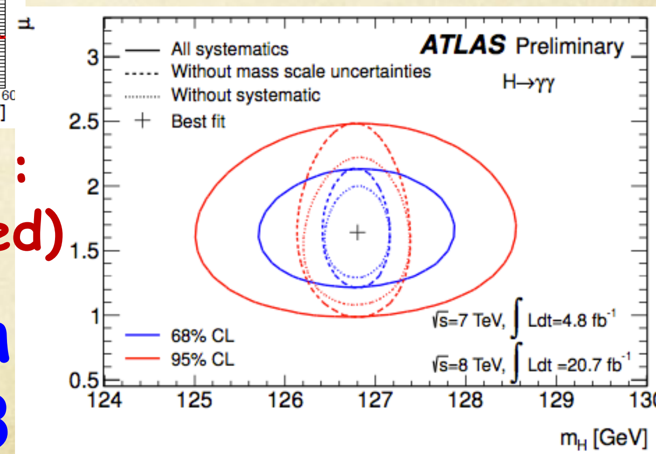
- Event Signature: 2-photon events reconstructed in EM calorimeter with p_T>40,30 GeV.
  - Thanks to good photon ID+isolation and reducible bkgs suppression.
- Categorize events w.r.t different productions and kinematics.







Signal Significance : 7.4σ (4.3σ expected)

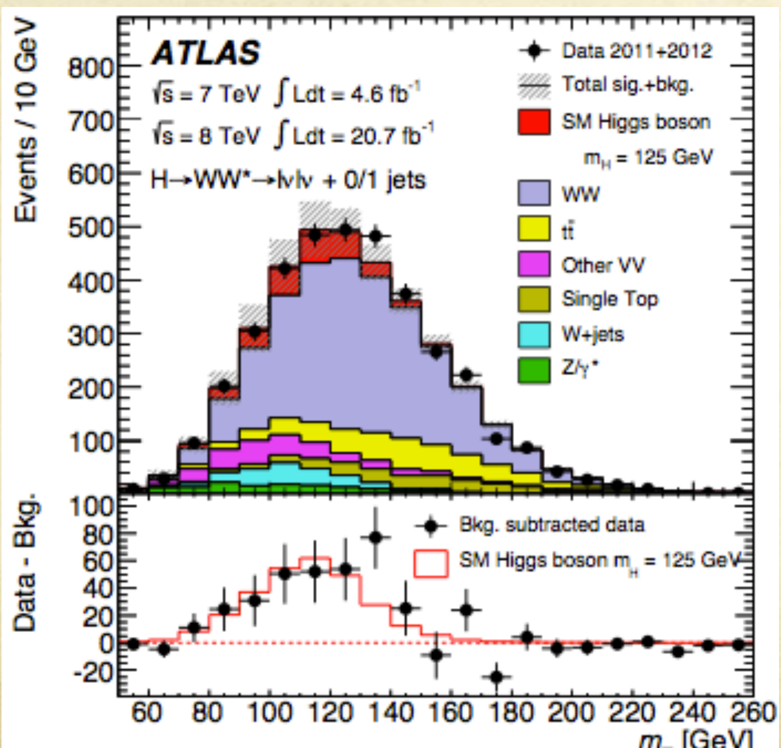


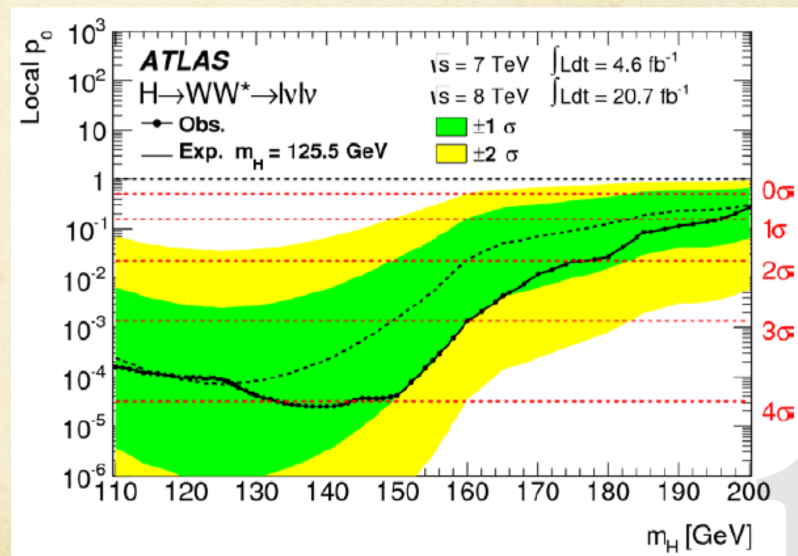
Signal strength
m = 1.57±0.33
at mass = 126.8±0.7 GeV

H→WW(→lνlν):

- Two isolated opposite-sign leptons, large missing transverse energy (E^{miss}_T) due to undetected neutrinos yield.
- Divide events into different categories according to jet multiplicities.
- No mass peak can be observed due to E^{miss}_T. Instead :

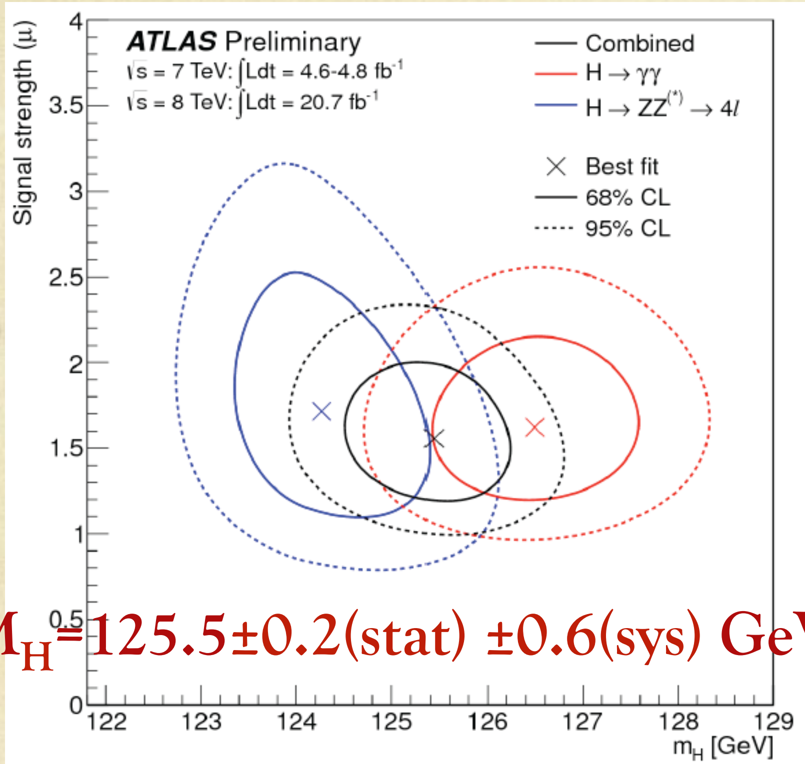
$$M_T = \sqrt{2 p_T^{\ell\ell} E_T^{\rm miss} (1 - \cos \Delta\phi_{E_T^{\rm miss}\ell\ell})}$$



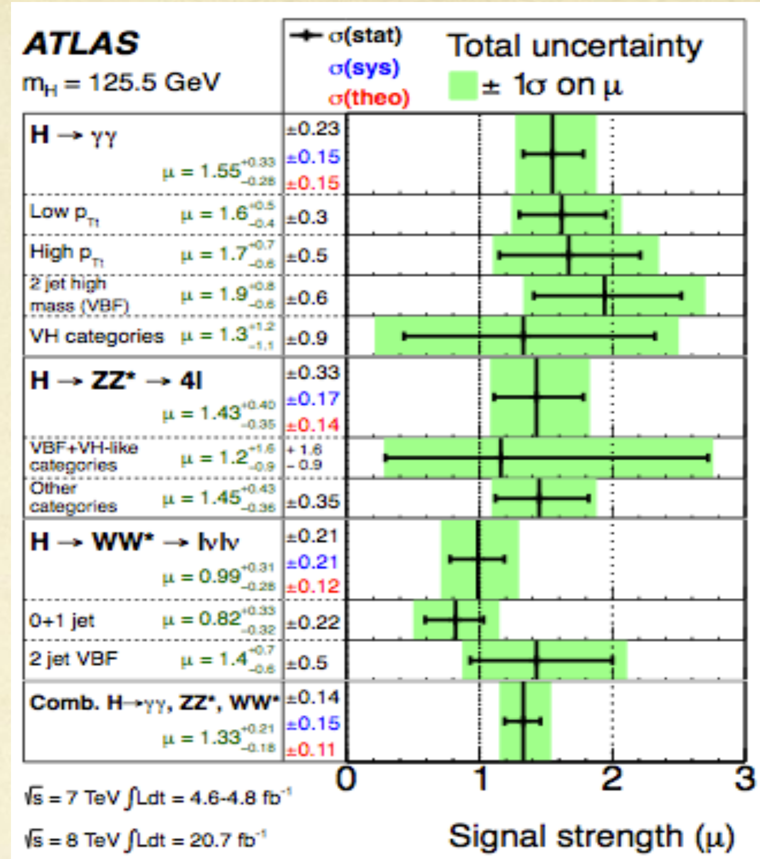


ATLAS: 3.8σ (3.8σ expected at 125.5 GeV)

Combination: Mass and rate



M_H=125.5±0.2(stat) ±0.6(sys) GeV

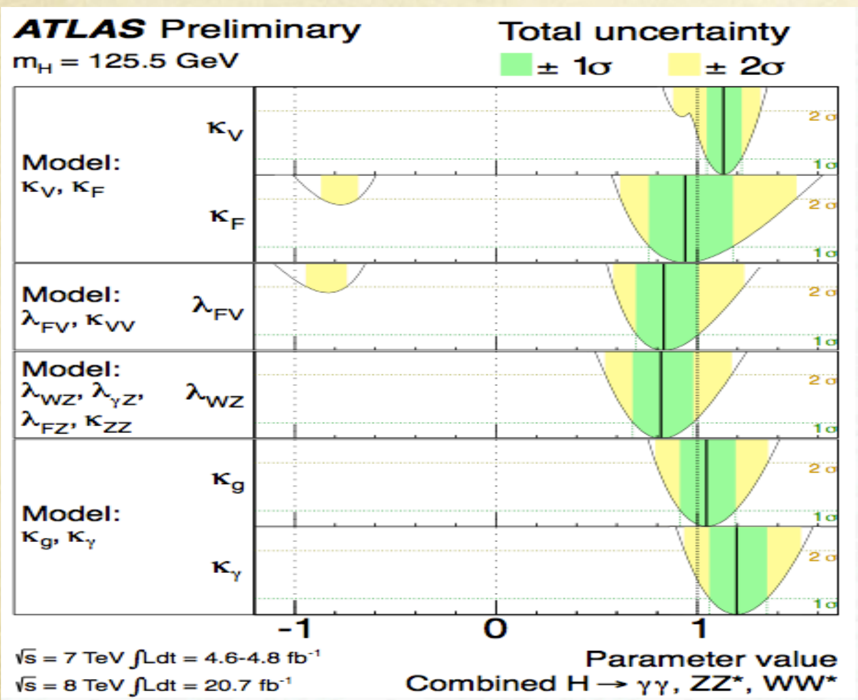


- Since WW doesn't provide the peak to reconstruct the mass, only di-photon and ZZ are included for mass combination.
- Signal strength $\mu = 1.33^{+0.21}_{-0.16}$ consistent with SM prediction within 2σ.

Coupling Measurements

Measure the ratios of the couplings to the those of the Standard Model.

Model	Probed couplings	Parameters of interest	Functional assumptions κ_V	κ_F	κ_g	κ_γ	κ_H	Example: $gg \to H \to \gamma\gamma$
1	Couplings to fermions and bosons	κ_V, κ_F	√	√	√	√	√	$\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)/\kappa_H^2(\kappa_F, \kappa_V)$
2		$\lambda_{FV}, \kappa_{VV}$	√	√	√	√	-	$\kappa_{VV}^2 \cdot \lambda_{FV}^2 \cdot \kappa_\gamma^2(\lambda_{FV}, \lambda_{FV}, \lambda_{FV}, 1)$
3	Custodial symmetry	$\lambda_{WZ}, \lambda_{FZ}, \kappa_{ZZ}$	-	√	√	√	-	$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \kappa_\gamma^2(\lambda_{FZ}, \lambda_{FZ}, \lambda_{FZ}, \lambda_{WZ})$
4		$\lambda_{WZ}, \lambda_{FZ}, \lambda_{\gamma Z}, \kappa_{ZZ}$	-	√	√	-	-	$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2 \cdot \lambda_{\gamma Z}^2$
5	Vertex loops	κ_g, κ_γ	=1	=1	-	-	√	$\kappa_g^2 \cdot \kappa_\gamma^2/\kappa_H^2(\kappa_g, \kappa_\gamma)$



Agree with SM within 2σ.

Coupling strengths k_i & ratio:

$\kappa_F = g_F/g_{F,SM}$, (the ratio of the coupling to fermions)

$\kappa_V = g_V/g_{V,SM}$, (the ratio of the coupling to bosons)

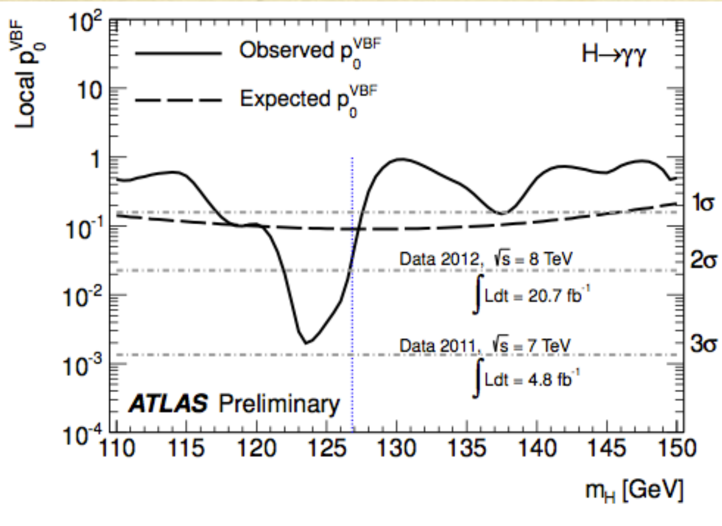
$\lambda_{ij} = \kappa_i / \kappa_j$

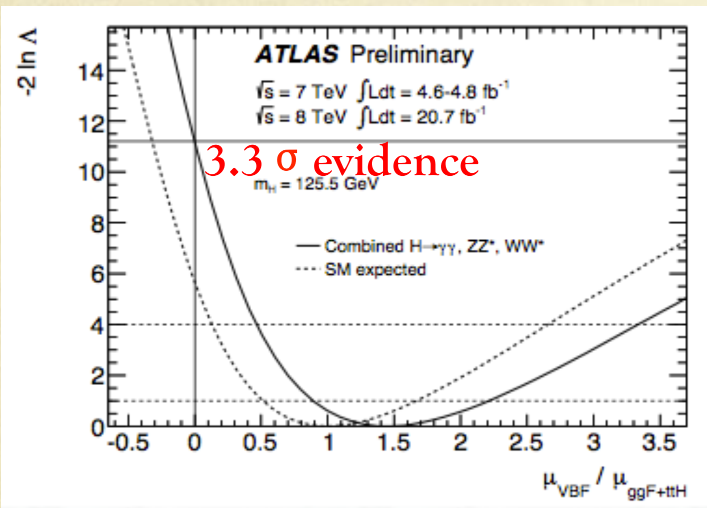
$\kappa^2_H = \Gamma_H/\Gamma^{SM}_H$ (Γ_H *is the total Higgs boson width*)

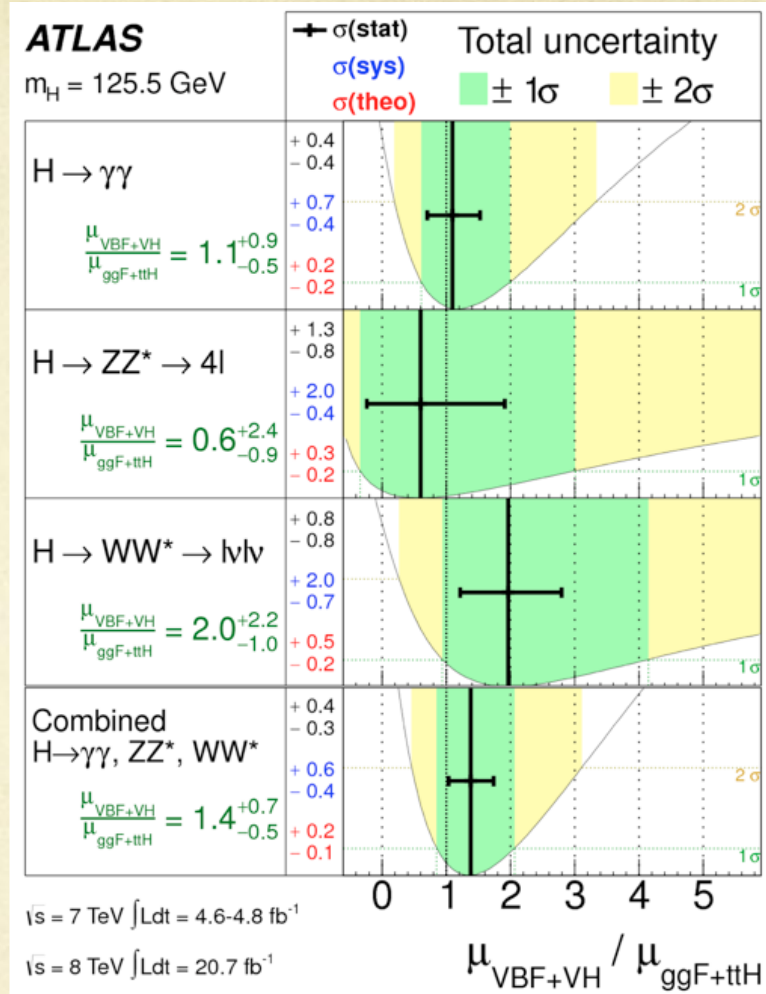
For example, gg→H→γγ process can be written as

$$\frac{\sigma \cdot B(gg \to H \to \gamma\gamma)}{\sigma_{SM}(gg \to H) \cdot B_{SM}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Evidence for VBF Higgs Production







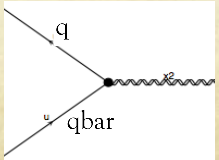
- First 3σ VBF Higgs evidence has been seen with ATLAS detector.
- The most important contribution to the 125.5 GeV VBF Higgs is from H→ γγ.
- The ratio of VBF+VH and ggF+ttH is consistent with standard model prediction within 1σ.

Spin and parity

Spin/parity models and MC

	0^-	$1^{+/-}$	2^+
$H\rightarrow\gamma\gamma$	No	Disfavored by L-Y theorem	Yes
$H\rightarrow WW$	No	Yes	Yes
$H\rightarrow ZZ$	Yes	Yes	Yes (2- too)
combined	No	No	Yes

- JHU[1]+PYTHIA8 is used as the spin1/2 MC's. q
- For the SM Higgs (0^+), we use POWHEG[2]+PYTHIA8/HqT.
- For spin 2 model, the most general amplitude of the decay has 10 coupling complex constants $g_1,..g_{10}$. Only a graviton like one with minimal coupling constants ($g_1=g_5=1$) 2^+_m is tested.
  - "Gravition-like" models with wrapped extra dimensions are greatly disfavored with observed high WW(ZZ)/γγ ratios.
- For 2^+_m , different fractions of qqbar production are tested.
  - Can be produced with gg Fusion and/or P-wave quark-antiquark annihilation.



1. JHU: a dedicated generator including full spin and polarization correlations for the processes pp -> X -> VV
2. POWHEG: The POWHEG BOX is a general computer framework for implementing NLO calculations in shower Monte Carlo programs

Statistical methods

- Construct the likelihood function corresponding to different spin-parity assumptions:

$$\mathcal{L}(J^P, \mu, \theta) = \prod_j^{N_{\text{chann.}}} \prod_i^{N_{\text{bins}}} P(N_{i,j} \mid \mu_j \cdot S_{i,j}^{(J^P)}(\theta) + B_{i,j}(\theta)) \times \mathcal{A}_j(\theta)$$

  - $S_{i,j}^{J^P}(\theta)$ and $B_{i,j}(\theta)$ are the expectations for the signal and background respectively.
  - N_{ij} is the observed events, μ_j is the signal rate (one nuisance parameter), $\mathcal{A}_j(\theta)$ is the auxiliary Measurements.
- The test statistic q (likelihood ratio) is used to distinguish the spin0 and the alternative hypothesis for the signal.

$$q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{\text{alt}}, \hat{\hat{\mu}}_{J^P_{\text{alt}}}, \hat{\hat{\theta}}_{J^P_{\text{alt}}})}$$

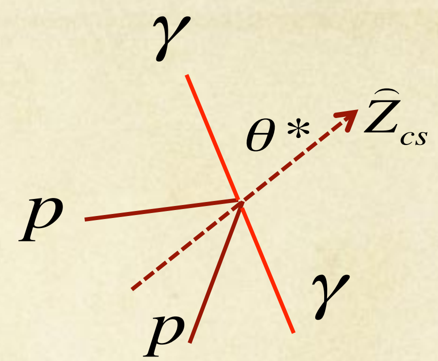
- The exclusion of the alternative hypothesis is evaluated with CL_s

$$\text{CL}_s(J^P_{\text{alt}}) = \frac{p_0(J^P_{\text{alt}})}{1 - p_0(0^+)}$$

Spin study with H→γγ

- Variable $|\cos(\theta^*)|$ is used as a discriminating variable

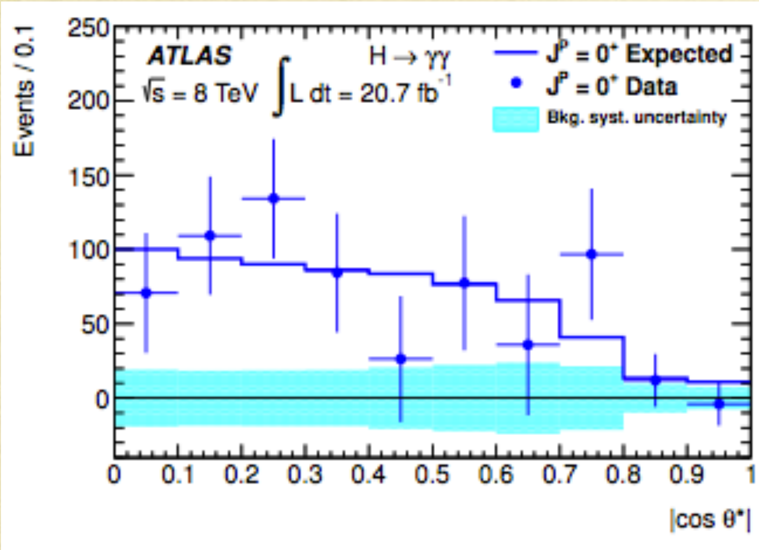
$$\cos\theta^* = \frac{\sinh(\eta_{\gamma_1} - \eta_{\gamma_2})}{\sqrt{1 + \left(p_T^{\gamma\gamma}/m_{\gamma\gamma}\right)^2}} \cdot \frac{2 p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$



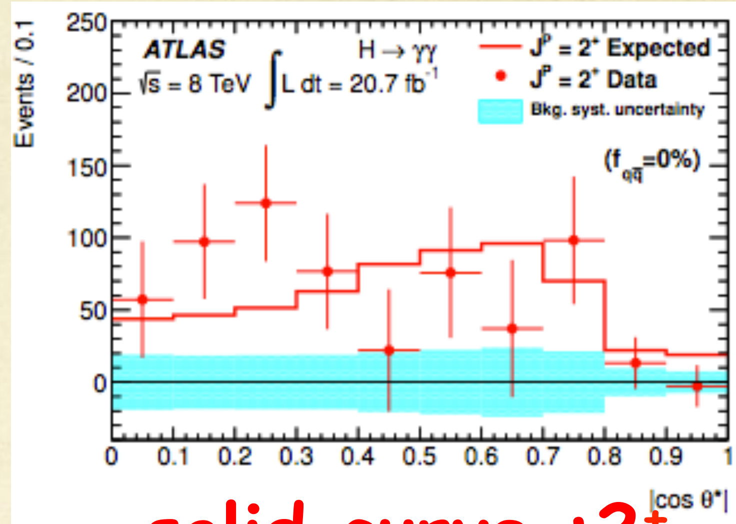
- Di-photon rest frame ;
- Z_{CS} bisects angle between the momenta of colliding hadrons

- In addition to kinematic cuts, $p_{T\gamma 1}/m_{\gamma\gamma} > 0.35$, $p_{T\gamma 2}/m_{\gamma\gamma} > 0.25$ to reduce the correlation between $\cos(\theta^*)$ and $m_{\gamma\gamma}$.
- Background shapes from mass sideband

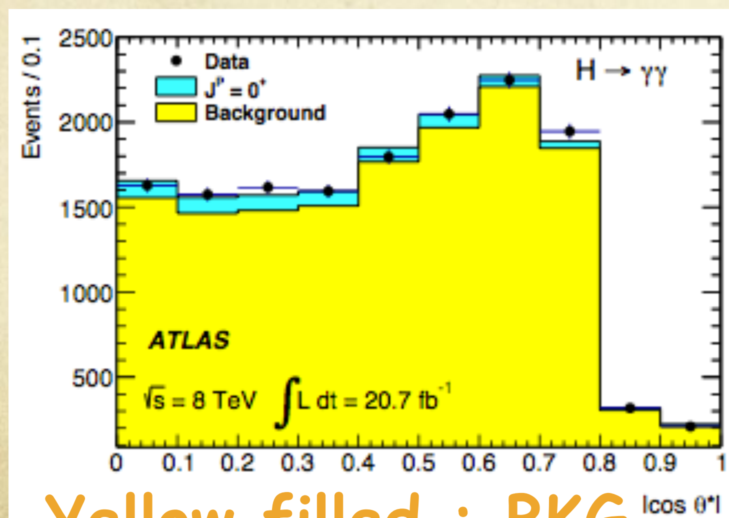
Spin study with H→γγ (cont.)



solid curve: 0⁺



solid curve :2⁺



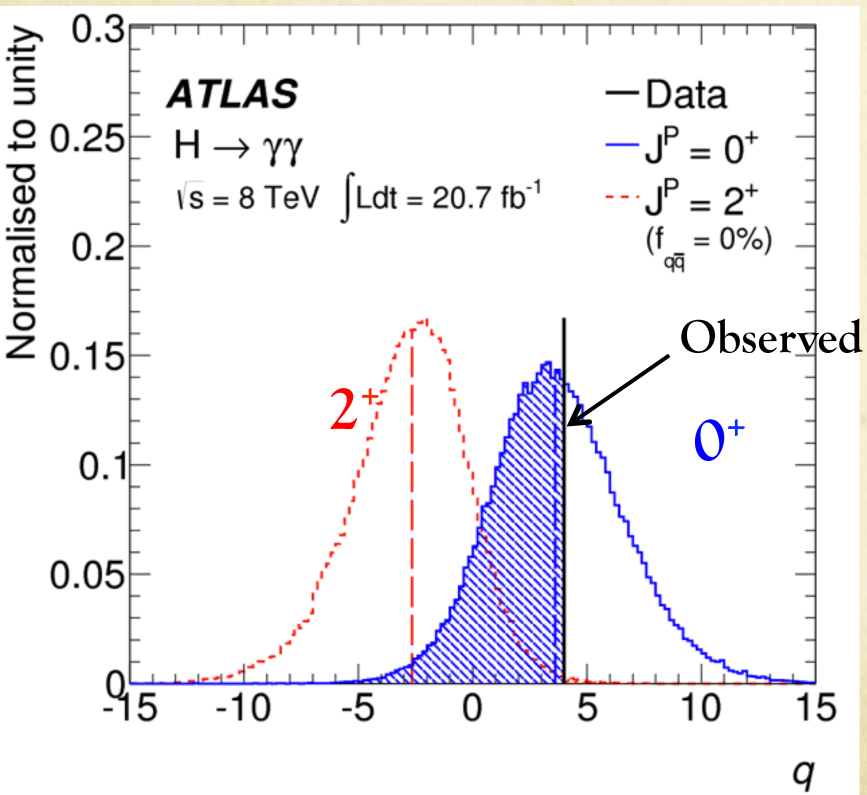
Yellow filled : BKG

- The top two plots show the distribution of $|\cos(\theta^*)|$ after the background is subtracted.
- The yellow filled histogram in the bottom plot shows the distribution for the background.

Spin study with H→γγ (cont.)

- **The likelihood function can be written as the following assuming |cosθ*| and $m_{\gamma\gamma}$ have low correlation.**

$$-\ln\mathcal{L} = (n_S + n_B) - \sum_{\text{events}} \ln\left[n_S \cdot f_S(|\cos\theta^*|) \cdot f_S(m_{\gamma\gamma}) + n_B \cdot f_B(|\cos\theta^*|) \cdot f_B(m_{\gamma\gamma})\right]$$



- **The distributions of test q for 0+ (blue curve) and 2+ with 0% fraction of qqbar (red curve) hypotheses are plotted.**

$$q = \ln\frac{\mathcal{L}_0(\hat{\hat{\theta}}_0)}{\mathcal{L}_2(\hat{\hat{\theta}}_2)}$$

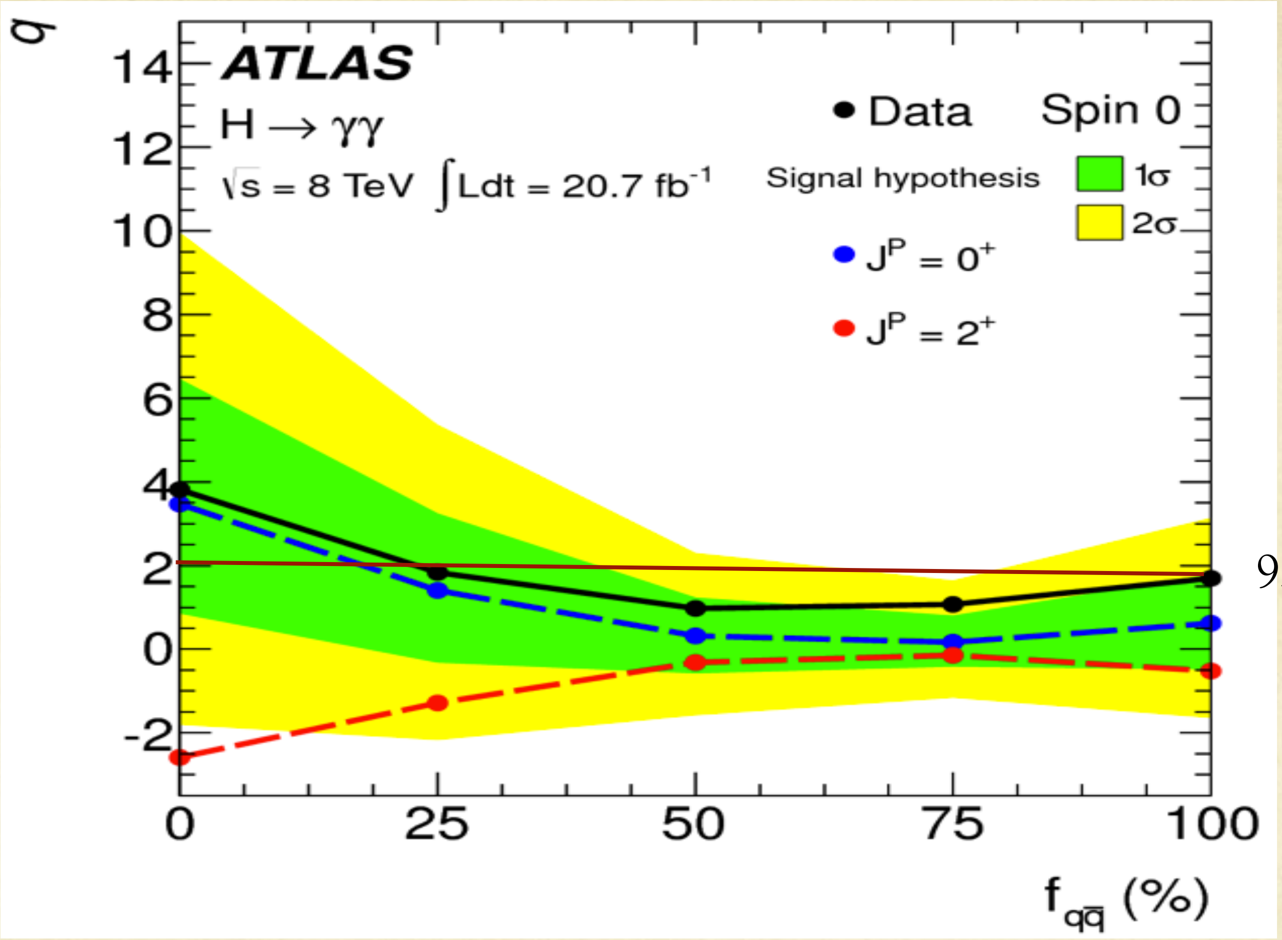
- The observed CLs limit

$$1 - CL_S(2^+) = 1 - \frac{p(2^+)}{1 - p(0^+)}$$

3% (p(2⁺)), 58.8% (p(0⁺))

which is **99.3%**

Result for H→γγ with different configurations of qqbar/gg fraction

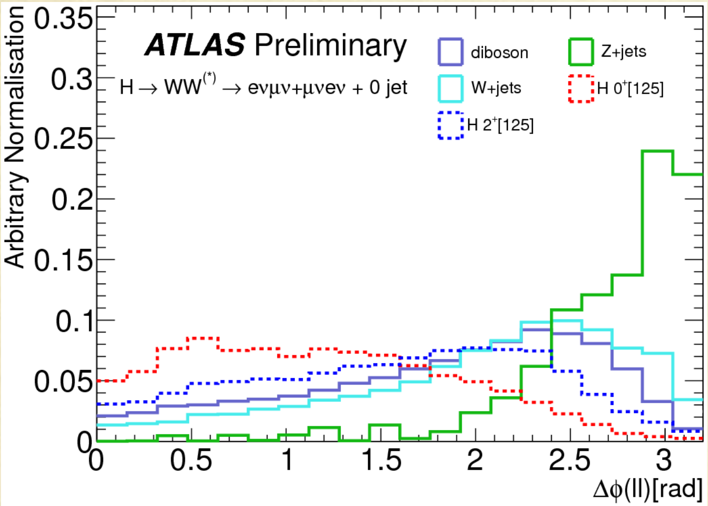


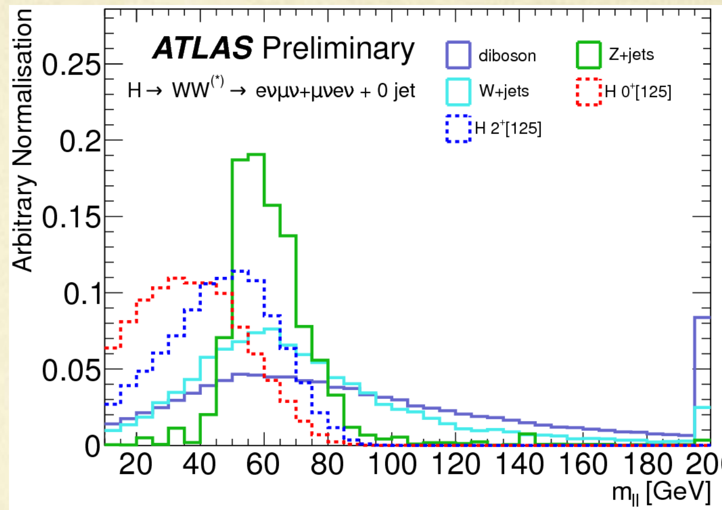
95% CL

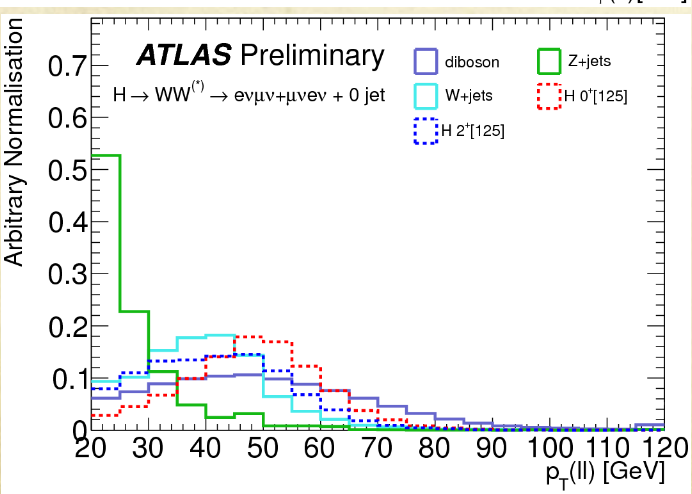
- From the plot, the highest exclusion of 2+ hypothesis is at the f_{qqbar}=0%. The smallest expected separation happens at 25% gg+75% qqbar due to the sum pdf of |cos(θ*)| with this admixture is closet to the one of Spin-0.
- For the fraction of qqbar above or equal to 25%, the exclusion is not higher than 95% CL.

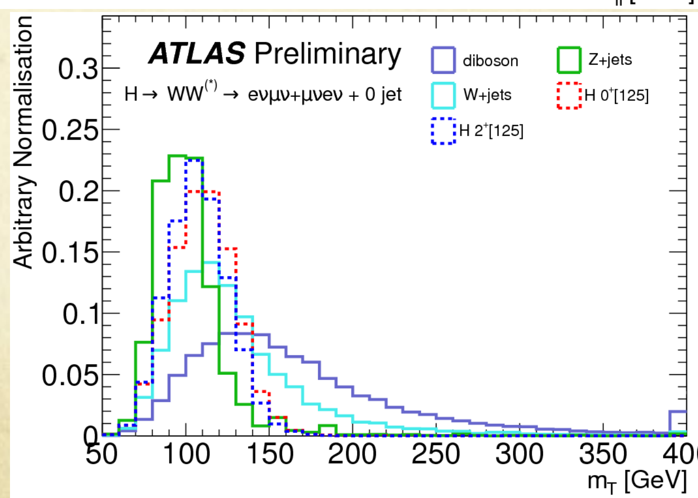
Spin study with H→WW

- In addition to the object selection, the pre-selection E^{T}_{rel}>20 GeV, p^{ll}_{T} >20 GeV, $\Delta\phi_{ll}$<2.8 mll<80 GeV and 0jet defines the signal region
- Boost Decision Tree (BDT) analysis using these four variables are introduced to maximize the separation between Spin0 and Spin2 mode





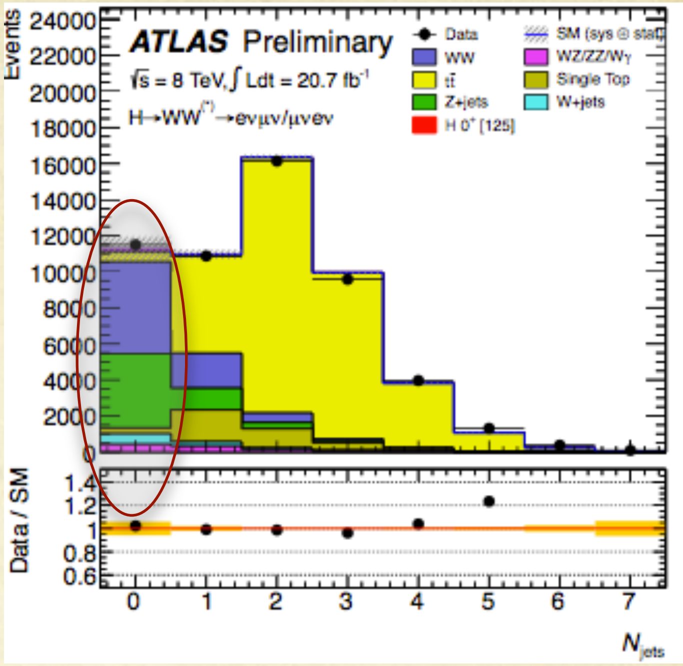




In general, the shapes for spin2 variables are closer to those of backgrounds.

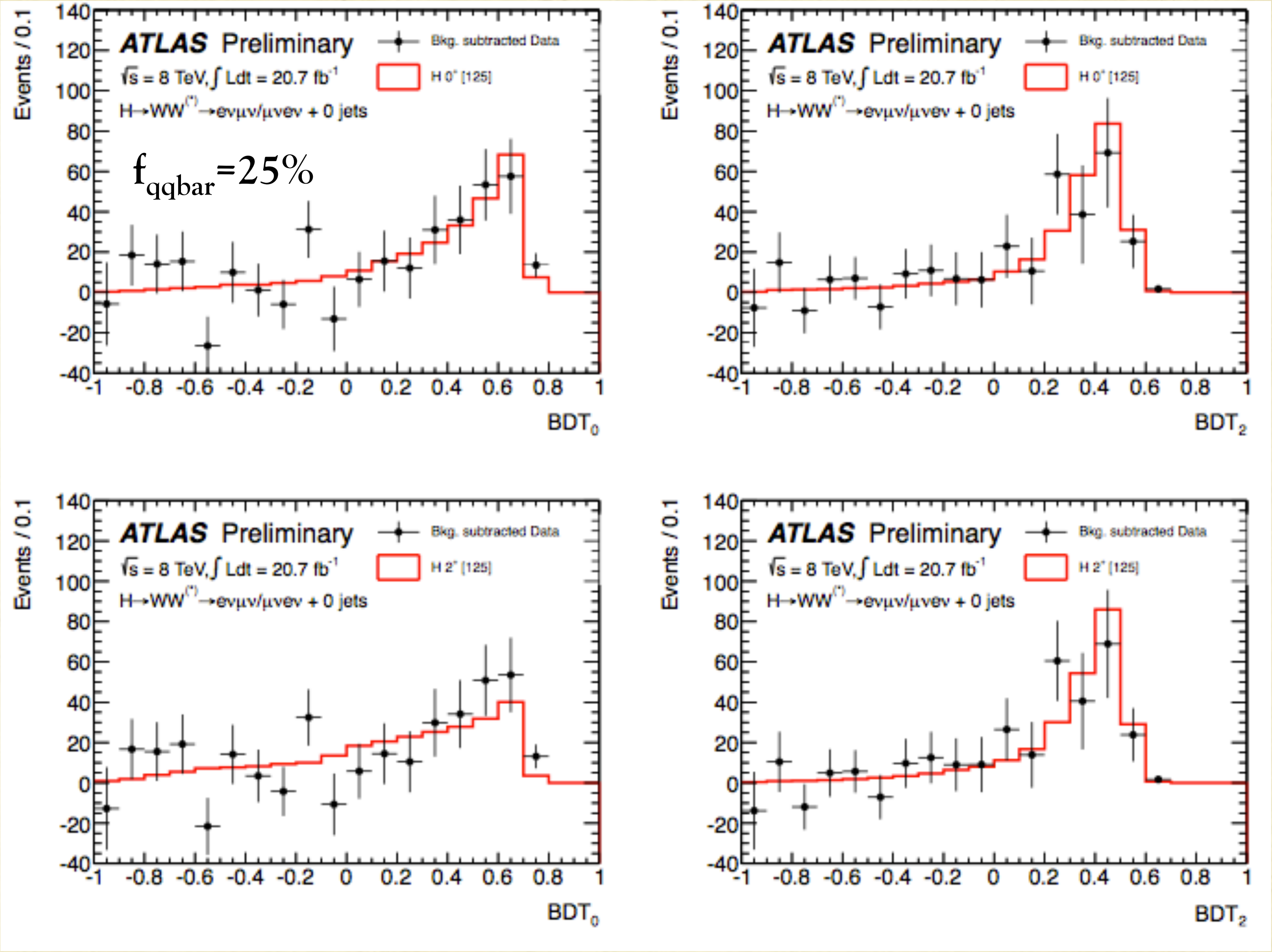
Control region of the background for H→WW

- The bkg shape and normalization for Wjet is fully data-driven.
- The contributions from other bkgs are obtained from MC with a normalization factors estimated from control region.



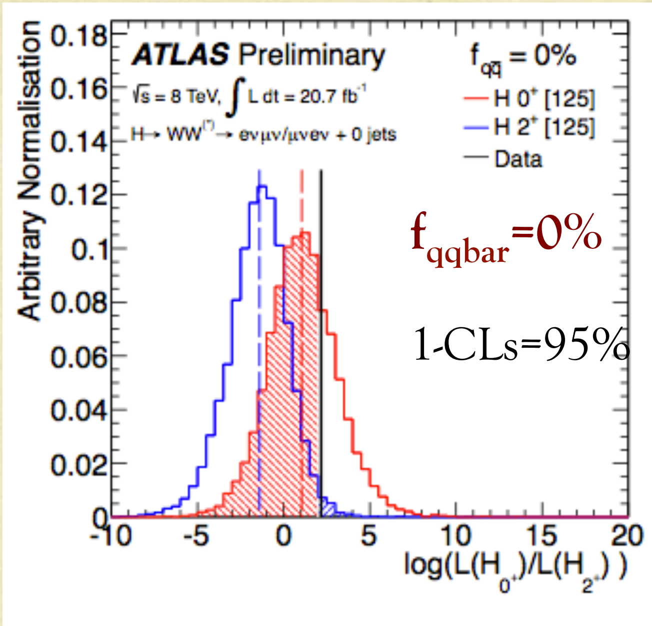
- **Wjet**
  - anti-leptons passing loose lepton id, failing tight lepton id.
- **Z→ττ**
  - M_{ll}<80 GeV & $\Delta\phi_{ll}$>2.8 with the subtraction of other bkgs from MC expectation.
- **Top quark**
  - Remove 0jet requirement from preselection and require at least one b-tagged jet. This control region is used to estimate jet veto efficiency.
  - The kinematic efficiency from MC.
  - Contamination from the bkg from MC except Wjet.
- **WW**
  - Remove the selection of $\Delta\phi_{ll}$ and require m_{ll}>80 GeV.

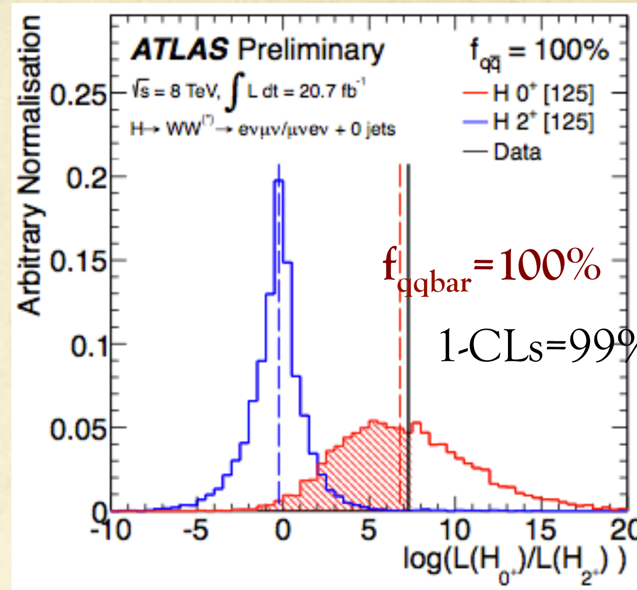
BDT for the spin study of H→WW

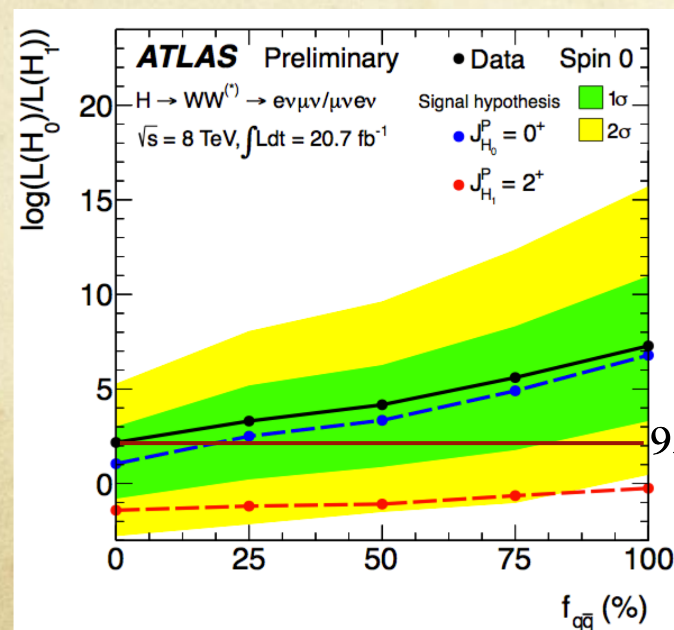


- Two BDTs using SM (BDT_0) and alternative 2^+_m (BDT_2) signals as the training sample to separate SM Higgs and bkg from alternative hypothesis.
- The figures show the BDT distributions with two BDTs from data after backgrounds are subtracted and fitted with best fitted signal (SM and 2^+_m) model.

Results for the spin study for H→WW



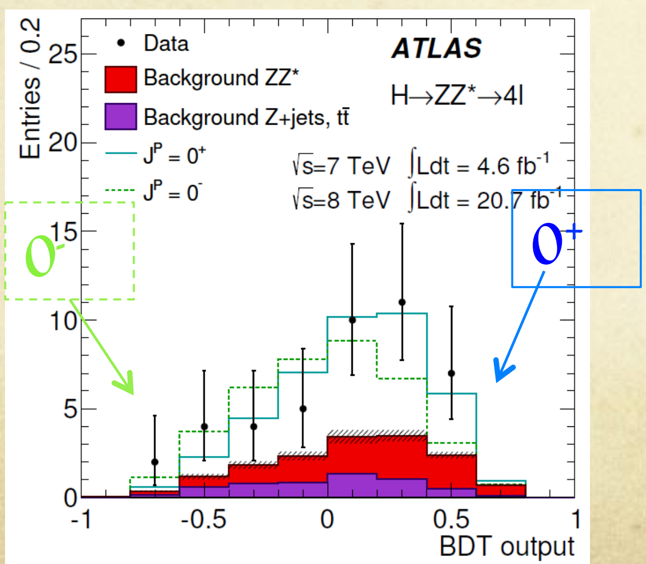


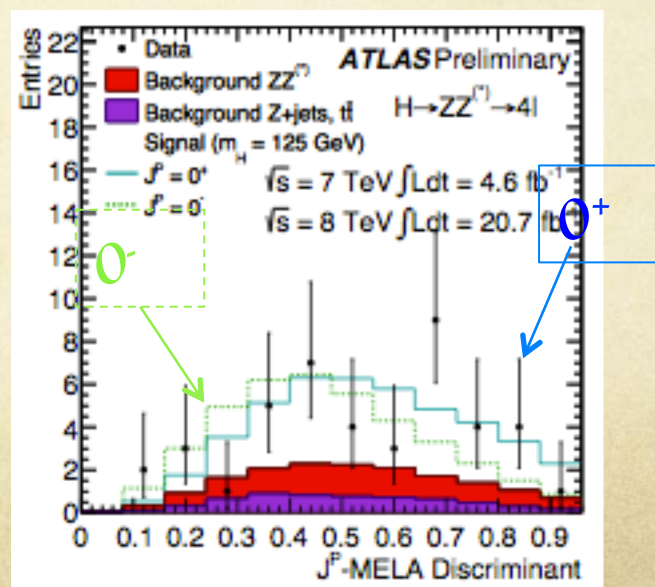


- For different configurations of the fraction of qqbar, 2^+_m is excluded at least 95% CL.
- 1^+ and 1^- are excluded with 92% and 98% CL respectively.

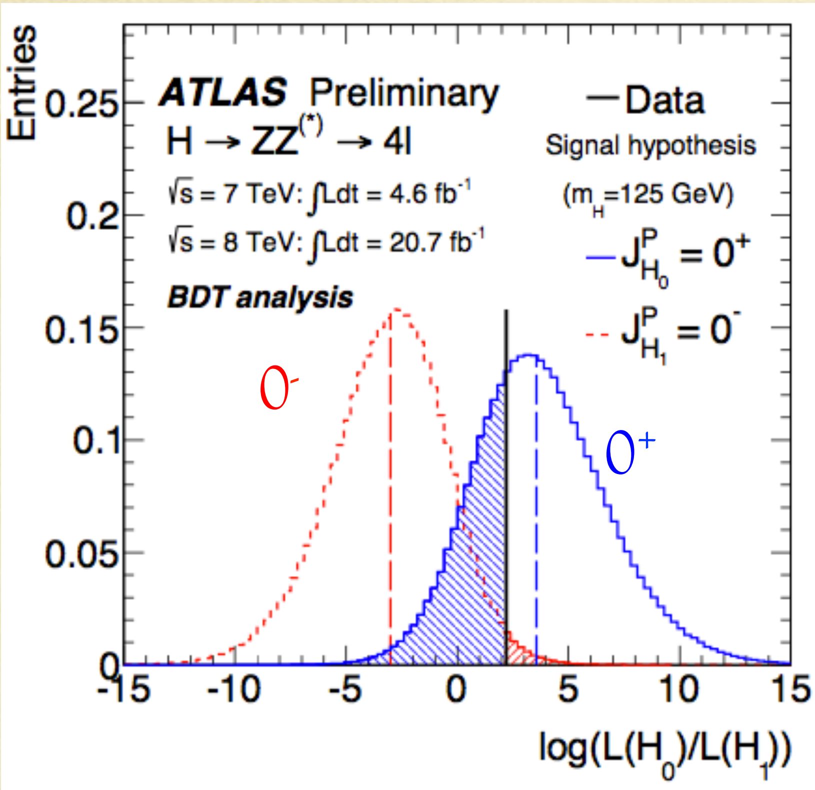
Spin study for H→ZZ

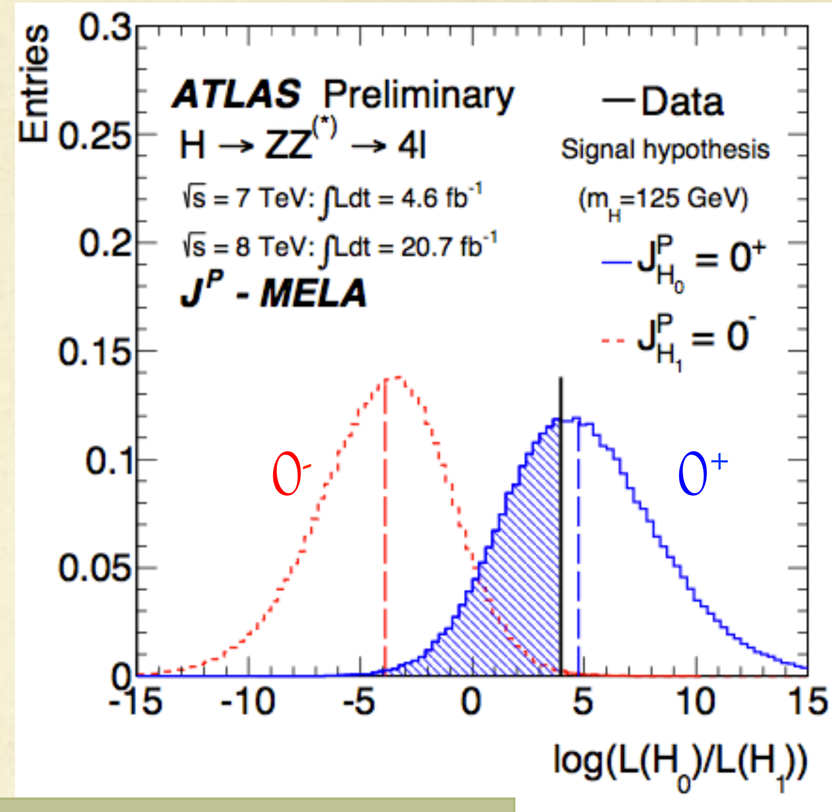
- BDT and Matrix Element Likelihood Analysis (MELA) are used for the spin analysis (up to 6 variables) : m_{l1l2}, m_{l3l4} and 4 other angular variables.
- Events in the rage $115<m_{4l}<130$ GeV are selected and divided into low and high mass bins according to different S/B ratio.
- Both 7 TeV and 8 TeV data are considered.
- Train separated BDT/MELA for each of 0^- $1^\pm$, $2^\pm$ hypotheses.





Exclusion for $H \rightarrow ZZ$ (f_{gg}=100%)

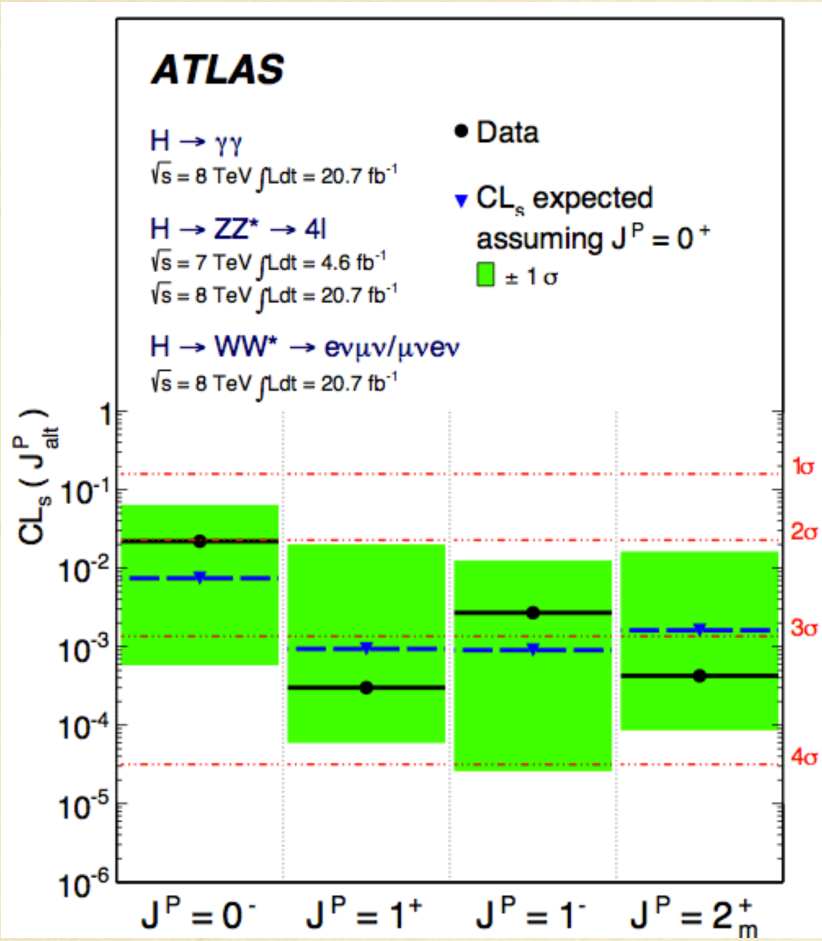




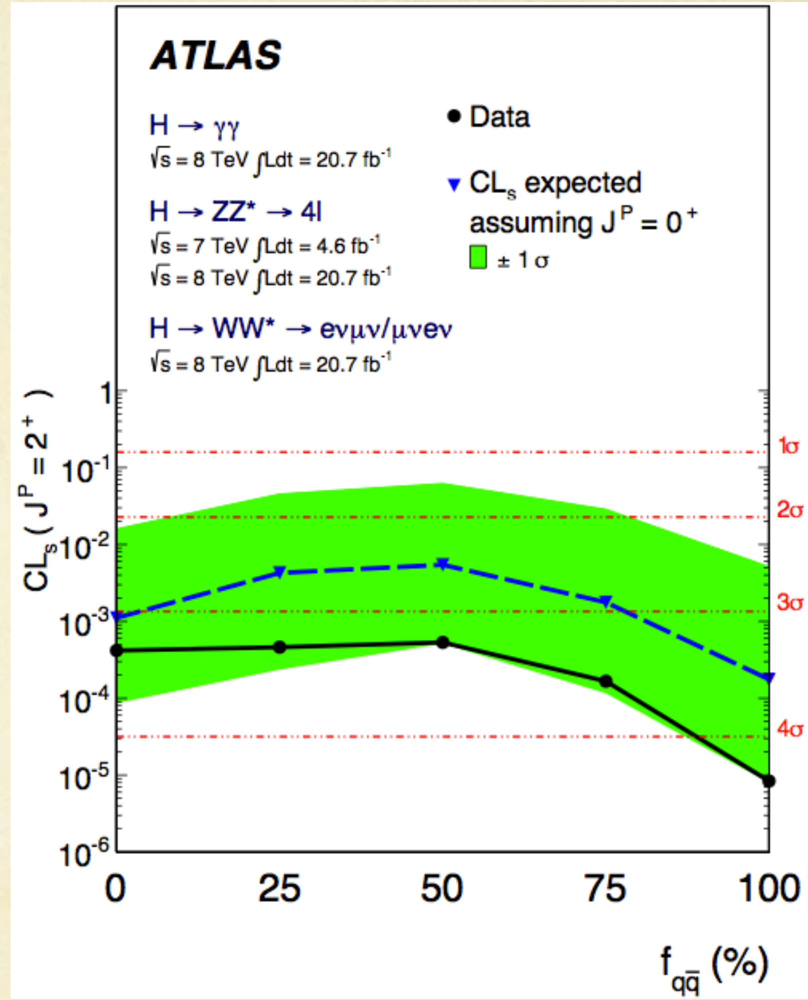
	0^-	1^-	1^+	2^-	2^+
BDT(%)	97.8	99.8	94.0	83.2	74.2
MELA(%)	99.6	99.4	96.9	81.8	88.4

The CL limits for BDT and MELA are comparable.
0^- and 1^- are excluded at least 95% CL

combined results for Spin study



1-CLs : 97.8% 99.97% 99.7% 99.96%



- Alternative models are excluded with 97.8-99.97%
- Spin-0 nature of the Higgs boson, with positive parity is strongly preferred.

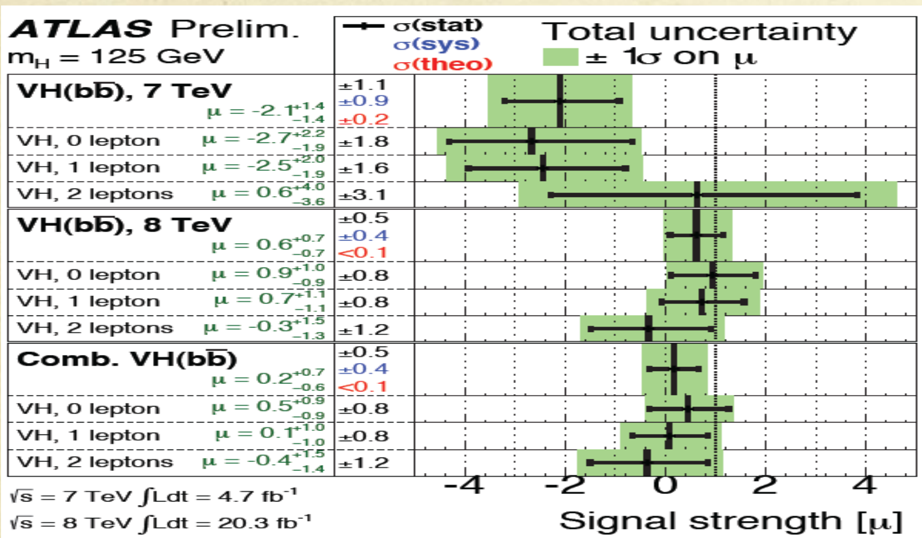
Conclusion

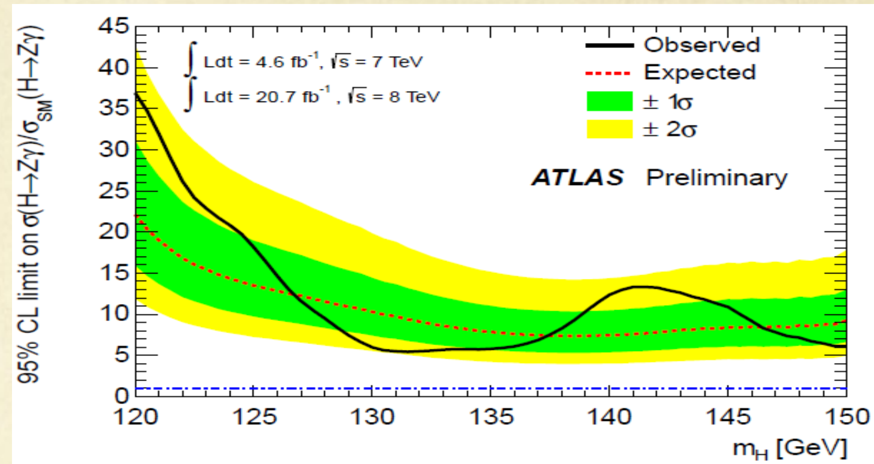
- Data collected at ATLAS with Run 1 are analyzed for the studies of Higgs properties.
  - Rate, coupling are briefly summarized.
  - The study of spin-parity is shown in detail.
- Everything is compatible with the Standard Model Higgs.
  - There is of course still some space for BSM scenarios.
- Need to prepare for Run 2 and more study such as VBF spin-parity can be done.

Backup slides

Other Higgs results

***H*→ ττ** : μ(125) = 0.7 ± 0.7
Significance (125): 1.1(1.7)σ obs.(exp)



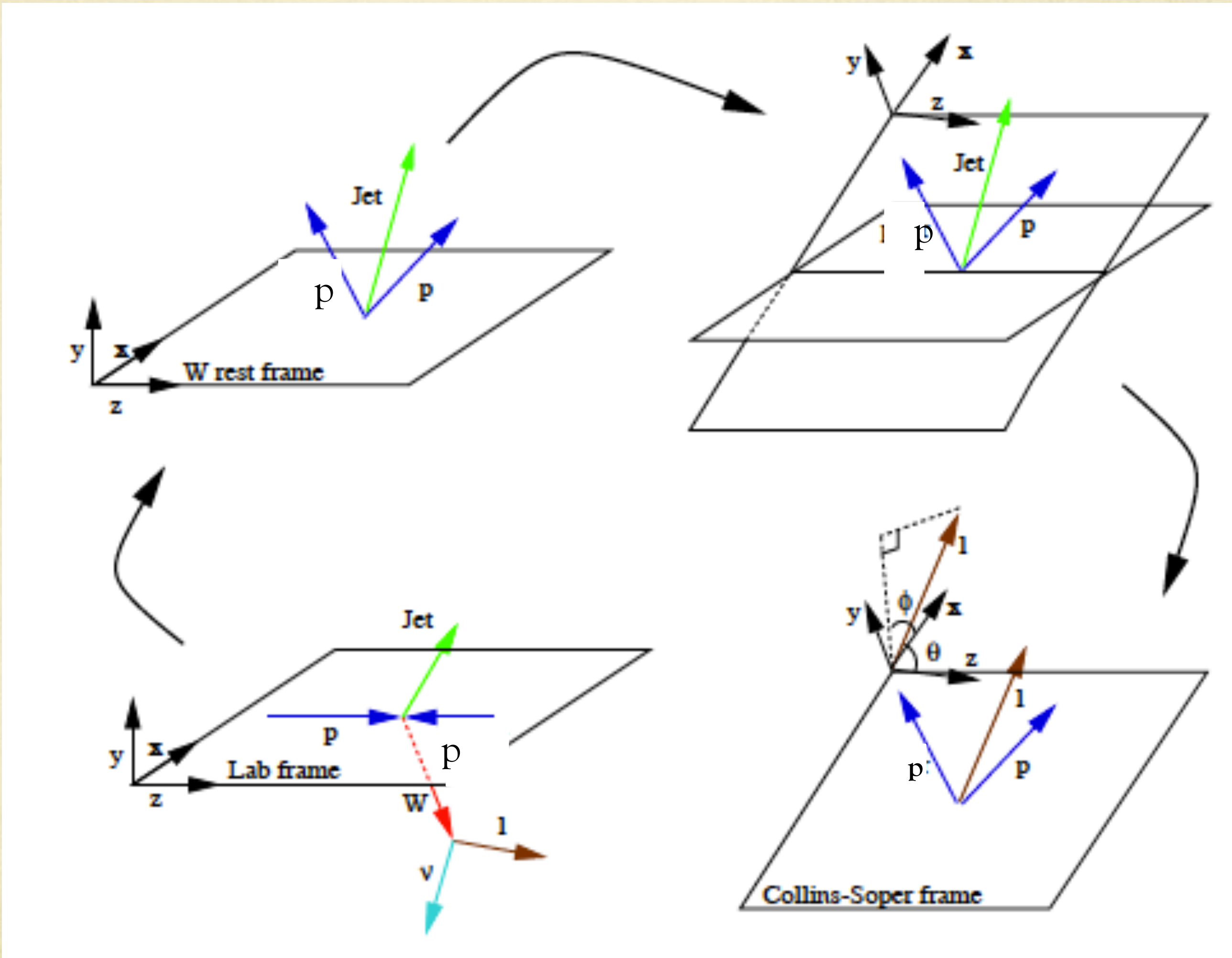


h→Z γ

Although not very sensitive, agree with SM within 2σ.

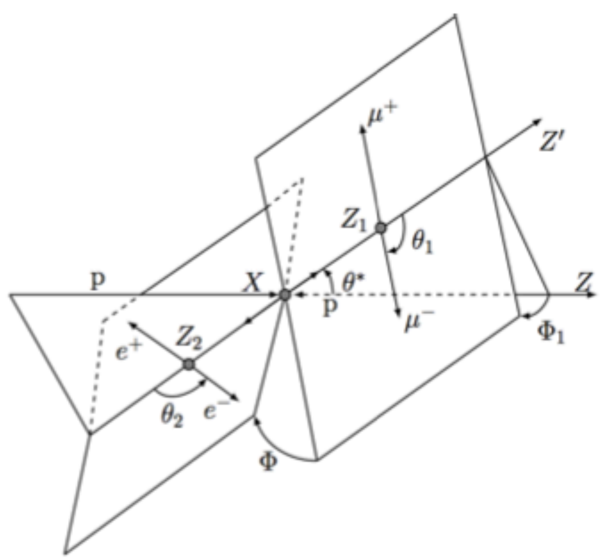
***H*→ bb**: μ (125 GeV) = 0.2 ± 0.5(stat) ± 0.4(syst)

Collins-Soper frame

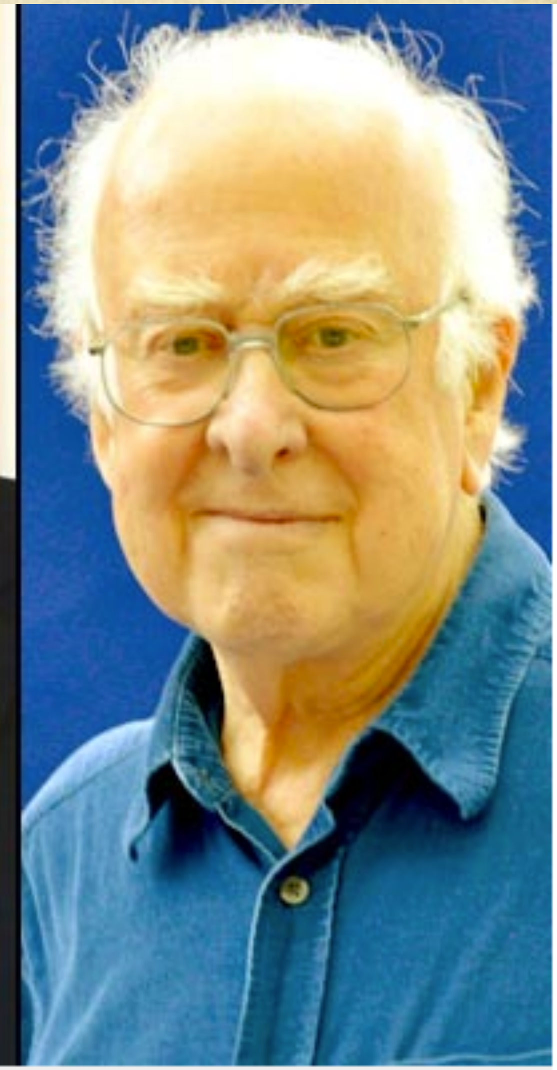


Angular variables for H->ZZ Spin study

- θ_1 (θ_2) is the angle between the negative final state lepton and the direction of flight of Z_1 (Z_2) in the Z rest frame.
- Φ is the angle between the decay planes of the four final state leptons expressed in the four lepton rest frame.
- Φ_1 is the angle defined between the decay plane of the leading lepton pair and a plane defined by the vector of the Z_1 in the four lepton rest frame and the direction of the parton following the positive z axis.
- θ^* is the production angle of the Z_1 defined in the four lepton rest frame.[2]



Breakthrough is awarded



Congratulations to Professors François Englert and Peter Higgs