$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$
$$- \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H.$$

Eilam Gross, Weizmann Institute of Science

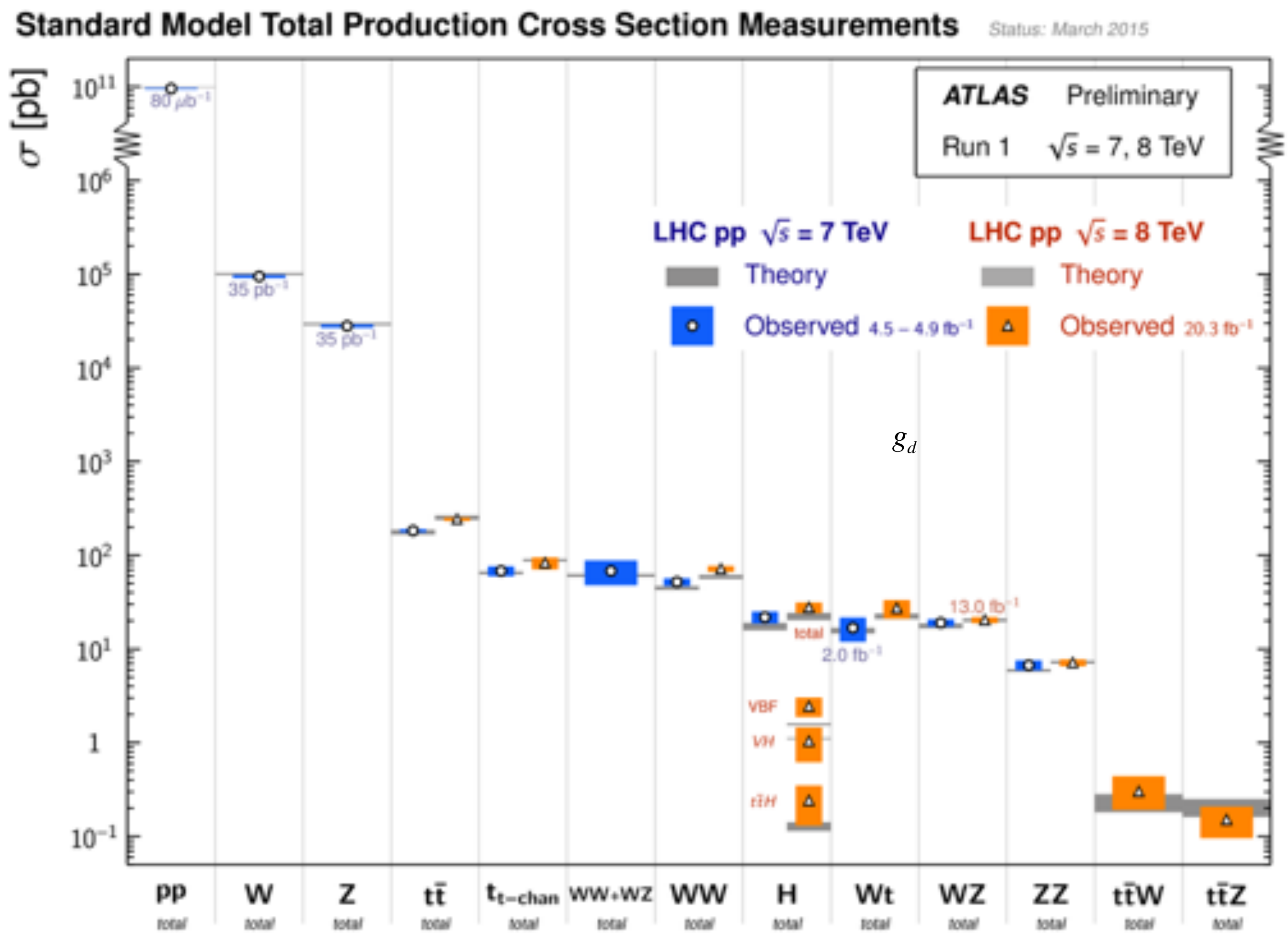
A Pedagogic Introduction to Higgs Measurements

Examples are taken mainly from ATLAS

V 2.0 20150606

The Best Introduction and Conclusion Ever

The "second creation" is close to perfect with unprocessed level of accuracy of both MC simulation and measurement



ATLAS have collected

$$Z \to \ell\ell \quad \sim 10M$$
$$W \to \ell\nu \quad \sim 100M$$
$$tt \to \ell + X \quad \sim 0.5M$$

These events can serve
as standard candles to calibrate the detector

Introduction

The mass of the Higgs Boson is not predictable by the SM.

Knowing the mass of the Higgs Boson all its SM couplings are predictable.

If we could order

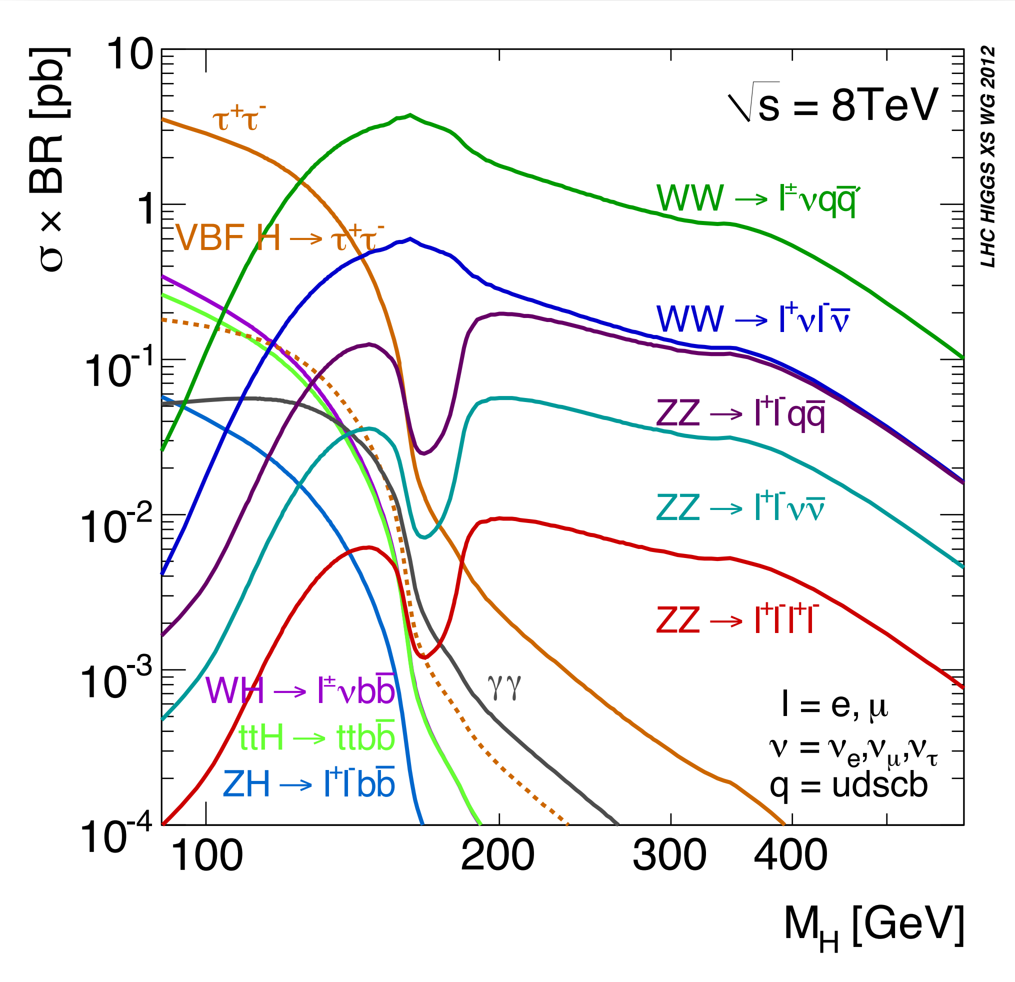
a mass,

we would order

m_H=120-130 GeV

At this mass we have access to all decay modes!

WE WERE LUCKY



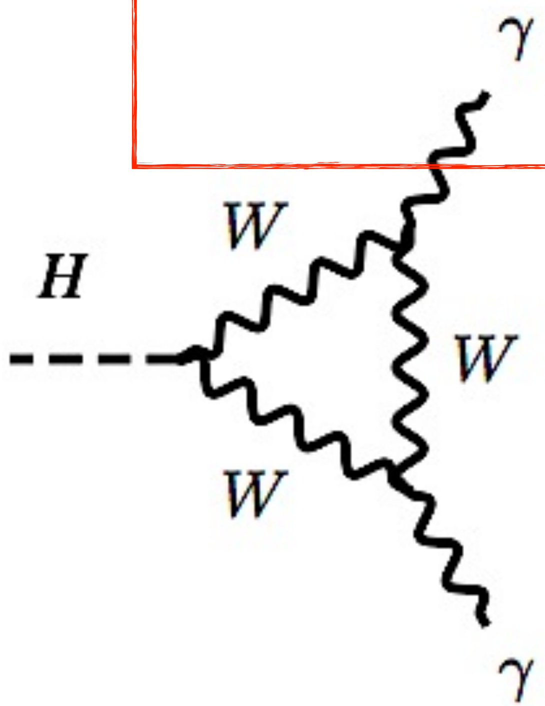
Discovery Channels

	BR@ m_H=125 GeV	~σ(m)/m
$\mathbf{H \to bb}$	**57.7%**	**10%**
$\mathbf{H \to WW \to 2l2}\nu$	**0.756%**	**20%**
$\mathbf{H} \to \tau\tau$	**6.32%**	**10-20%**
$\mathbf{H} \to \gamma\gamma$	**0.228%**	**1-2%**
$\mathbf{H \to ZZ \to 4l}$	**0.0276%**	**1-2%**
$\mathbf{H \to Z}\gamma \mathbf{\to ll}\gamma$	**0.01%**	**1-2%**
$\mathbf{H} \to \mu\mu$	**0.0219%**	**1-2%**

The Discovery Channels

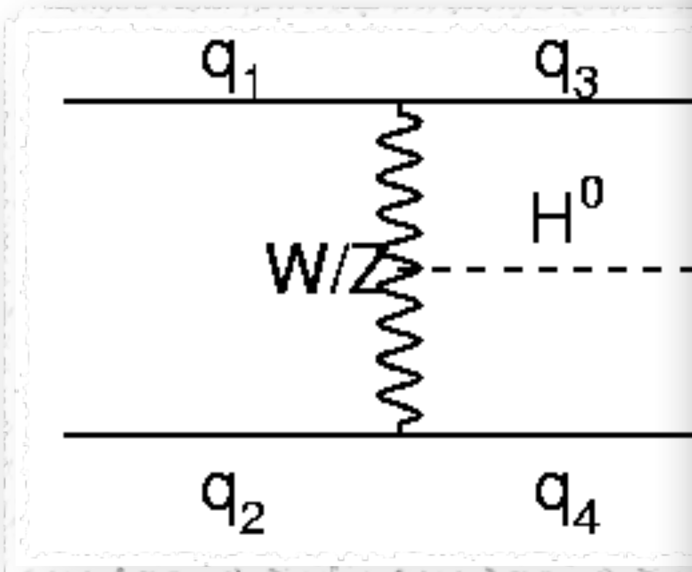
$$H \to \gamma\gamma$$

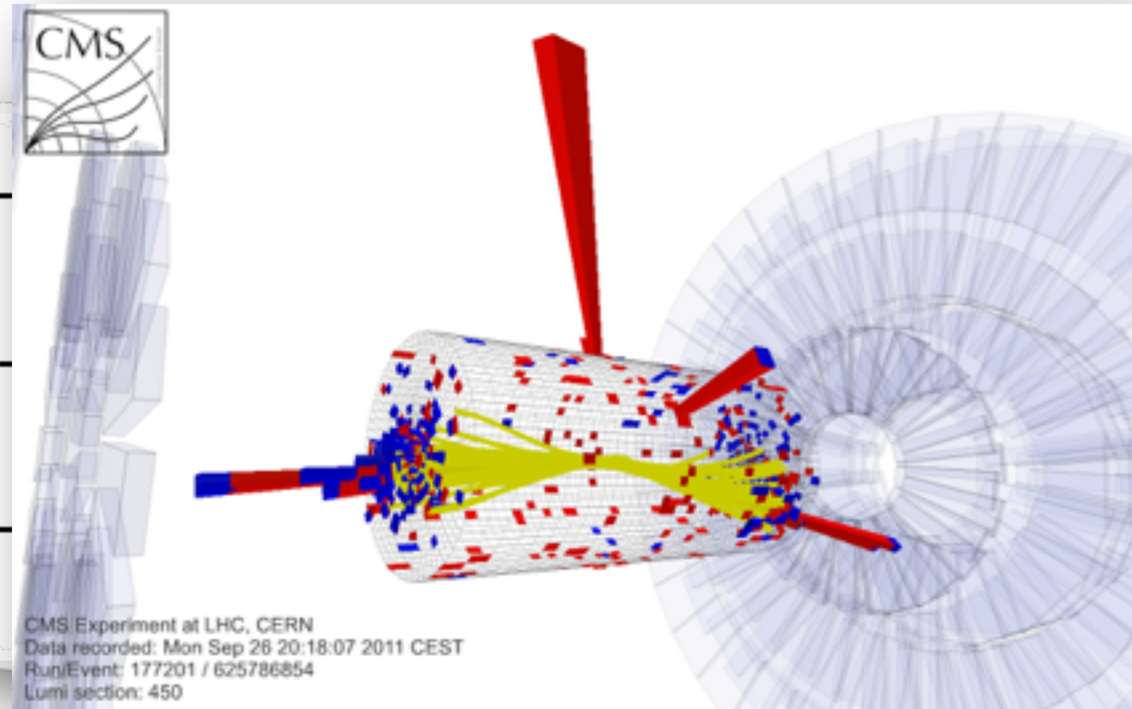
$$BR(H \to \gamma\gamma)(m_H \sim 125 GeV) \sim 2.3 \cdot 10^{-3}$$



Higgs Discovery Channels

Higgs decays to a pair of Photons has a very clear signature





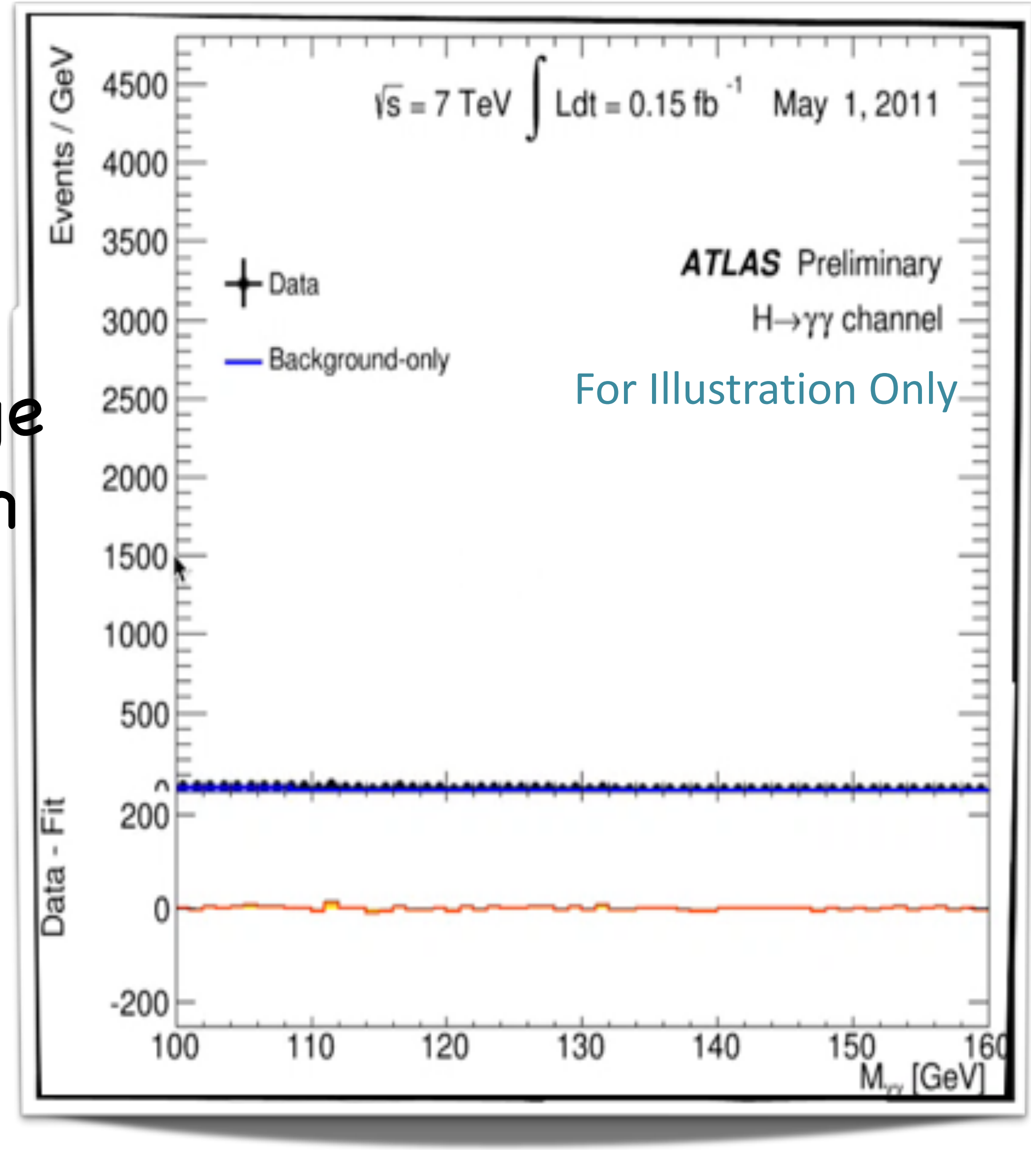
VBF $$qq' \rightarrow qq'H \rightarrow qq'\gamma\gamma$$

Follow the di-photon

As you accumulate statistics, the signal becomes apparent

The background is huge and comes mainly from

$$pp \to \gamma\gamma + jets$$



Follow the di-photon

$$pp \rightarrow \gamma\gamma + jets$$

A simplification to get the significance is by counting

$$B_{exp} = 7916$$

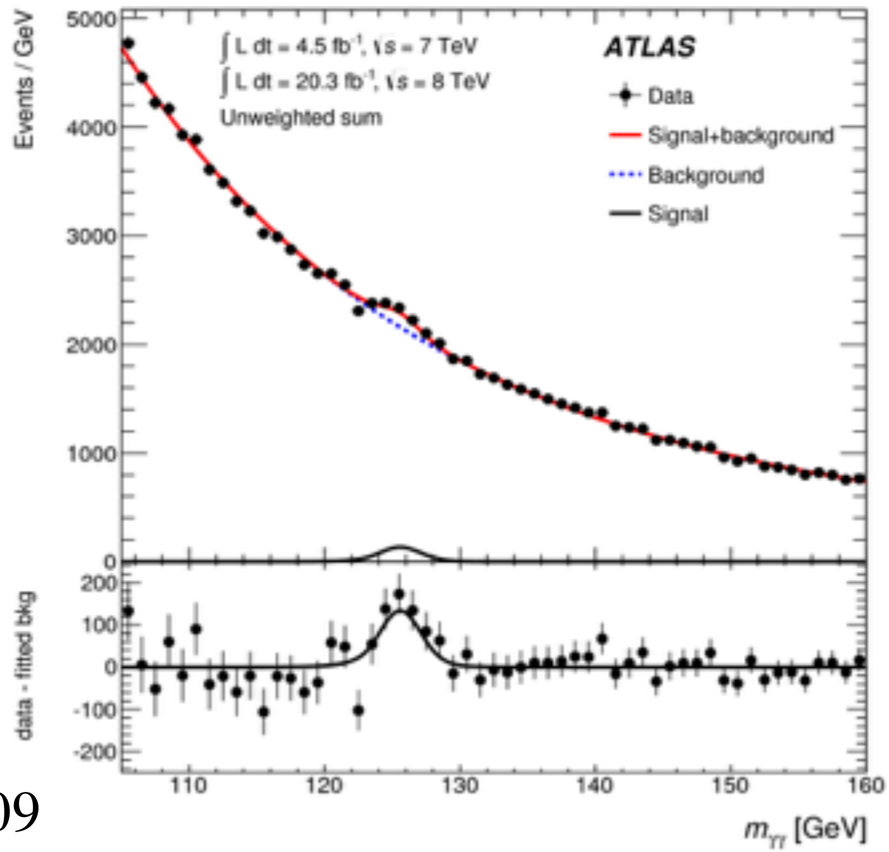
$$N_s = N_{obs} - B_{exp} = 468$$

$$\sigma_{obs} \sim \frac{s}{\sqrt{b}} = \frac{468}{\sqrt{7916}} = 5.2$$

$$N_{s,exp}^{\gamma\gamma} \sim \sigma(pp \rightarrow H \rightarrow \gamma\gamma) \cdot L \cdot \epsilon \cdot A \approx 409$$

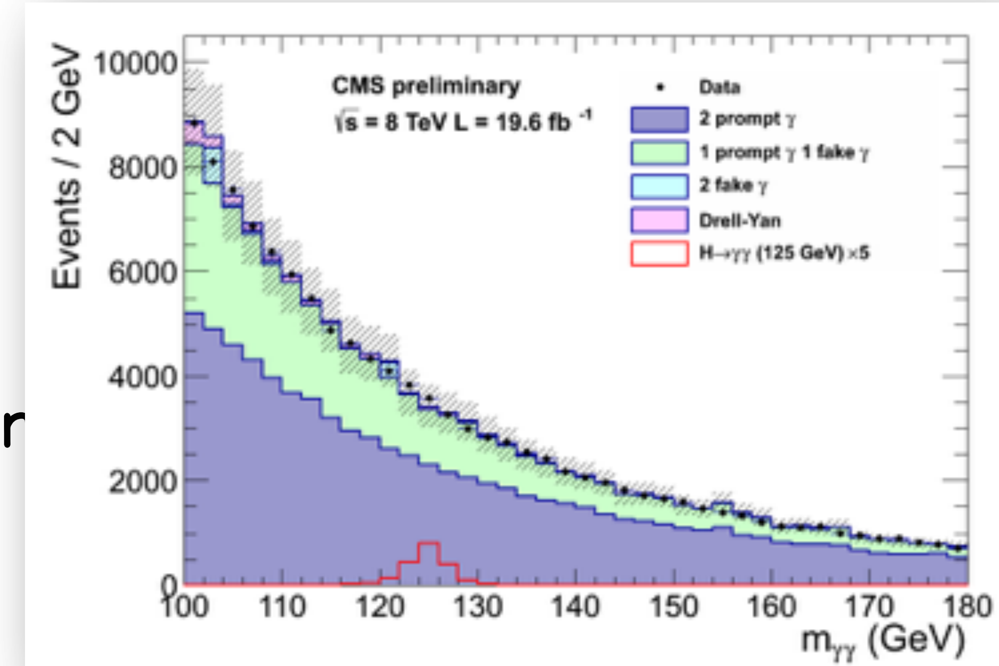
$$\sigma_{exp} = \frac{409}{\sqrt{7916}} \approx 4.6$$

$$\mu^{\gamma\gamma} = \frac{\sigma(pp \rightarrow H \rightarrow \gamma\gamma)_{obs}}{\sigma(pp \rightarrow H \rightarrow \gamma\gamma)_{exp}} \sim \frac{468}{409} \approx 1.17 \pm 0.27$$



Follow the di-photon

As you accumulate statistics, the signal becomes apparent



The background is huge and comes mainly from

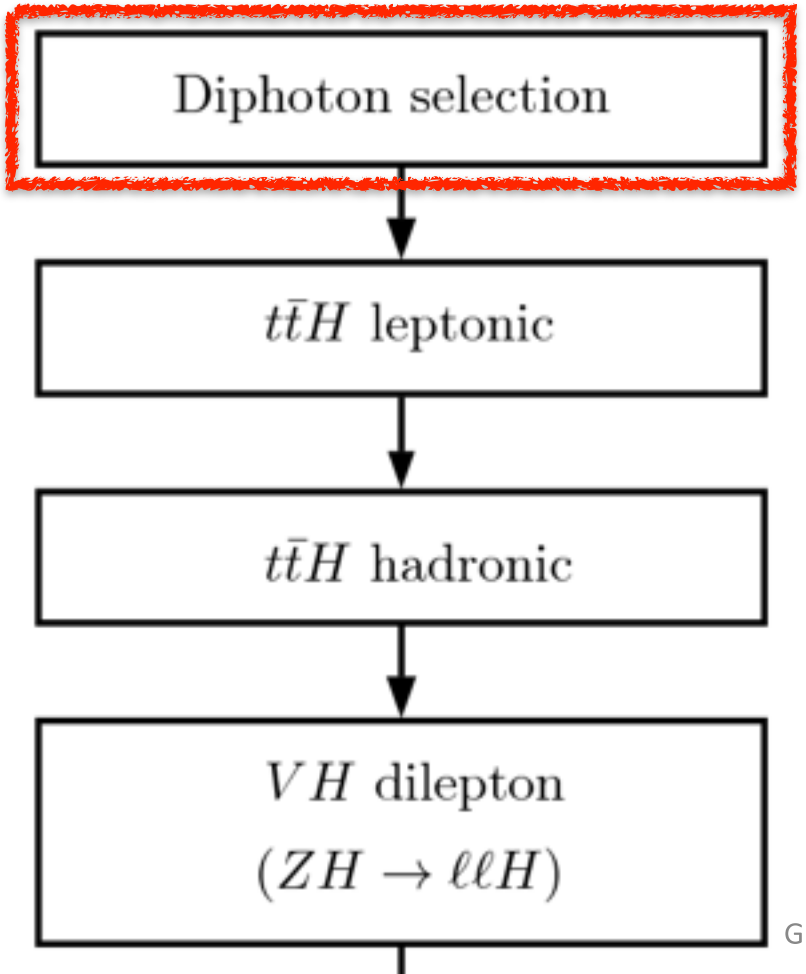
$$pp \rightarrow \gamma\gamma + jets$$

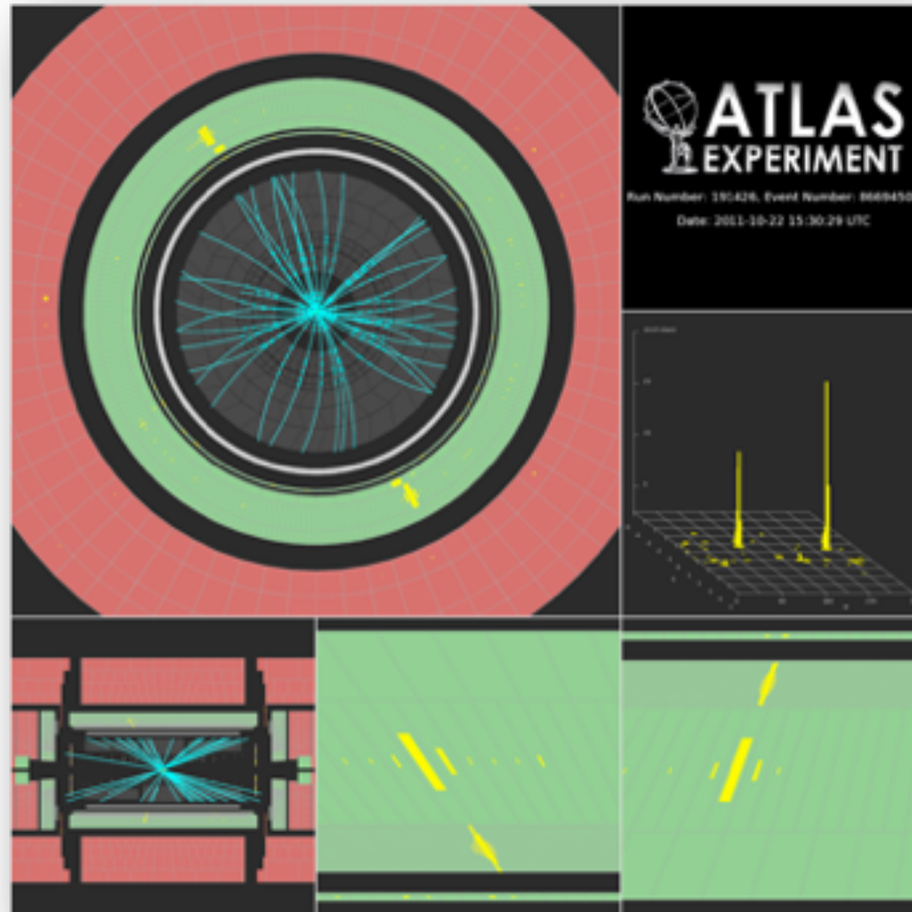
Need to separate the Background from the Signal, otherwise you will be swamped by the Background

Categorization to improve sensitivity

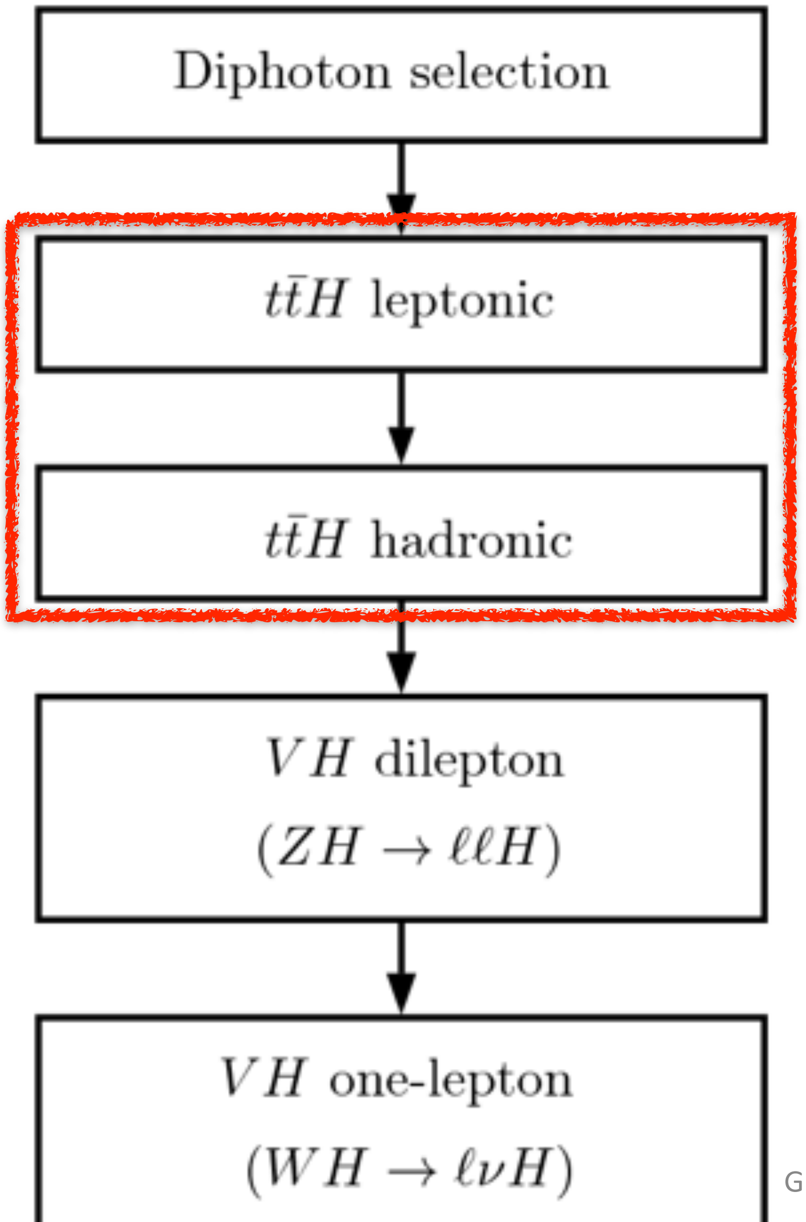
Two energetic isolated photons

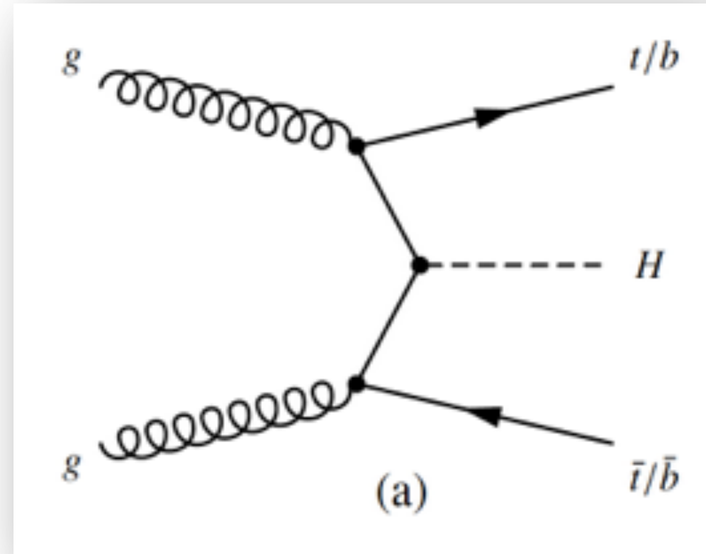
Photons: High p_T (~60 GeV) well isolated





Categorization to improve sensitivity





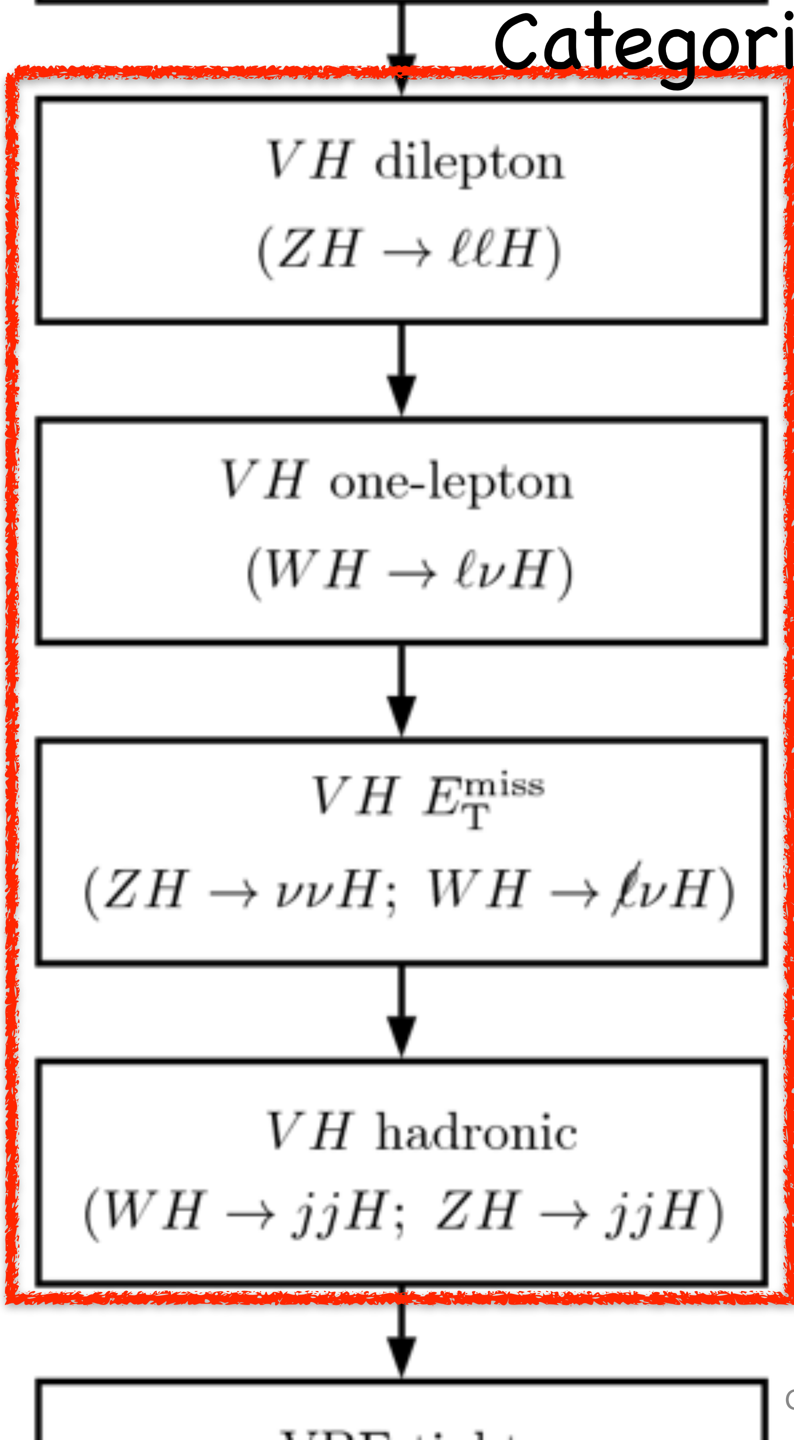
ttH with at least one top with a semileptonic decay

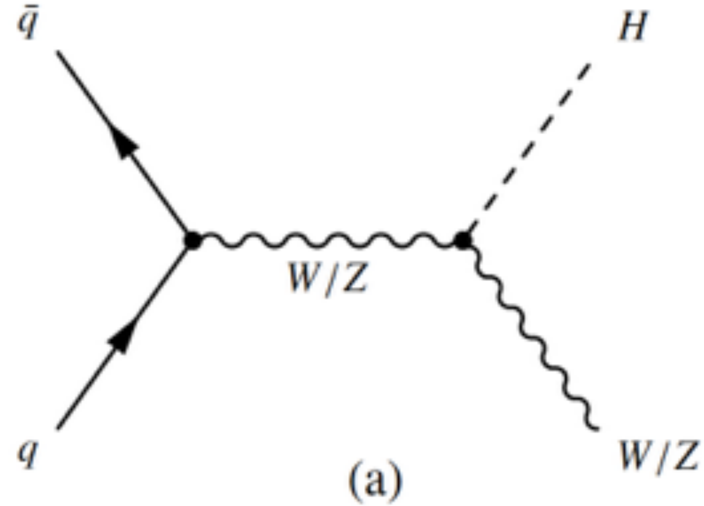
$$ttH \to b\ell\nu bWH$$

ttH with both tops decay Hadronically

$$ttH \to bW_{had}bW_{had}H$$

Categorization to improve sensitivity





VH targeting

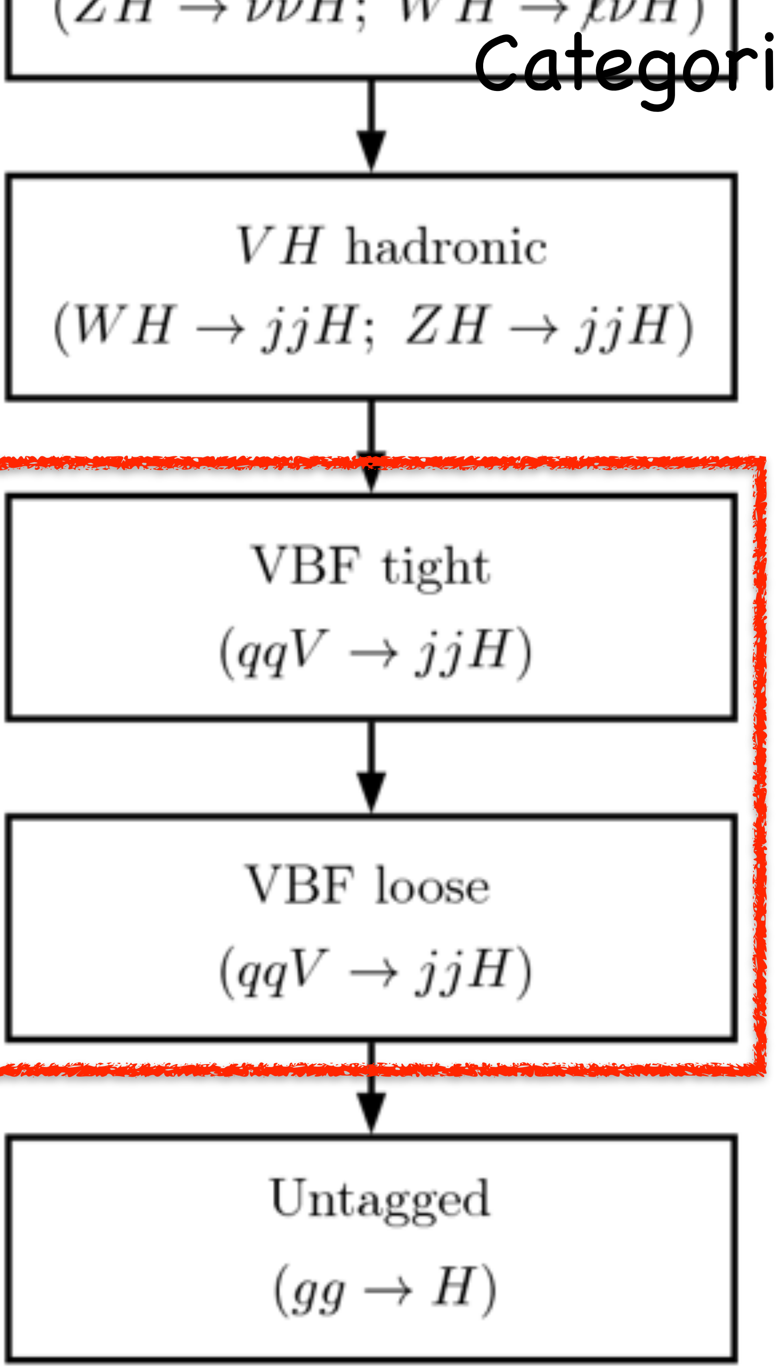
$ZH \to \ell\ell H$ $\gamma\gamma$+di-lepton

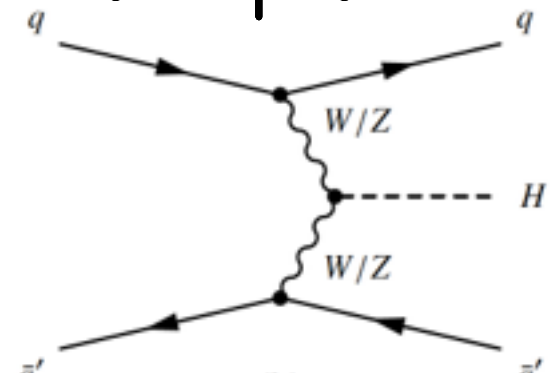
$WH \to \ell\nu H$ $\gamma\gamma$+one lepton

$ZH \to \nu\nu H$ $\gamma\gamma$+missing energy

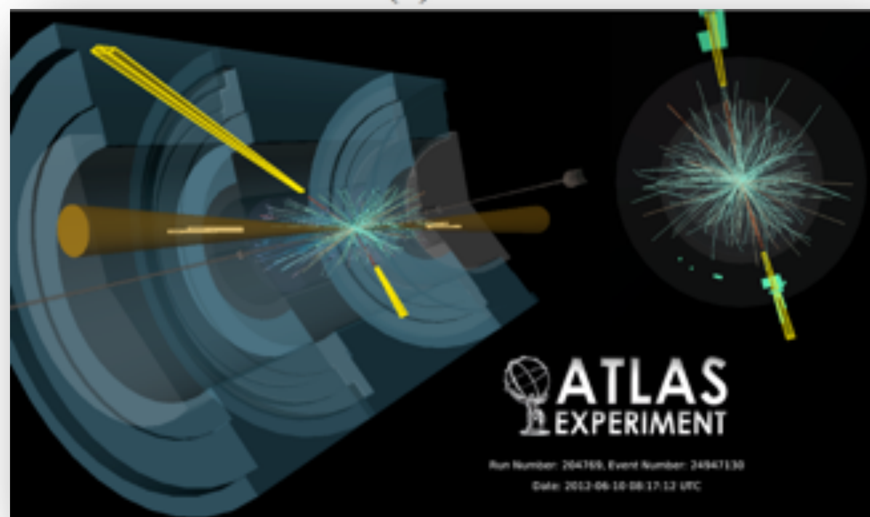
$W/ZH \to jjH$ $\gamma\gamma$+jets

Categorization to improve sensitivity



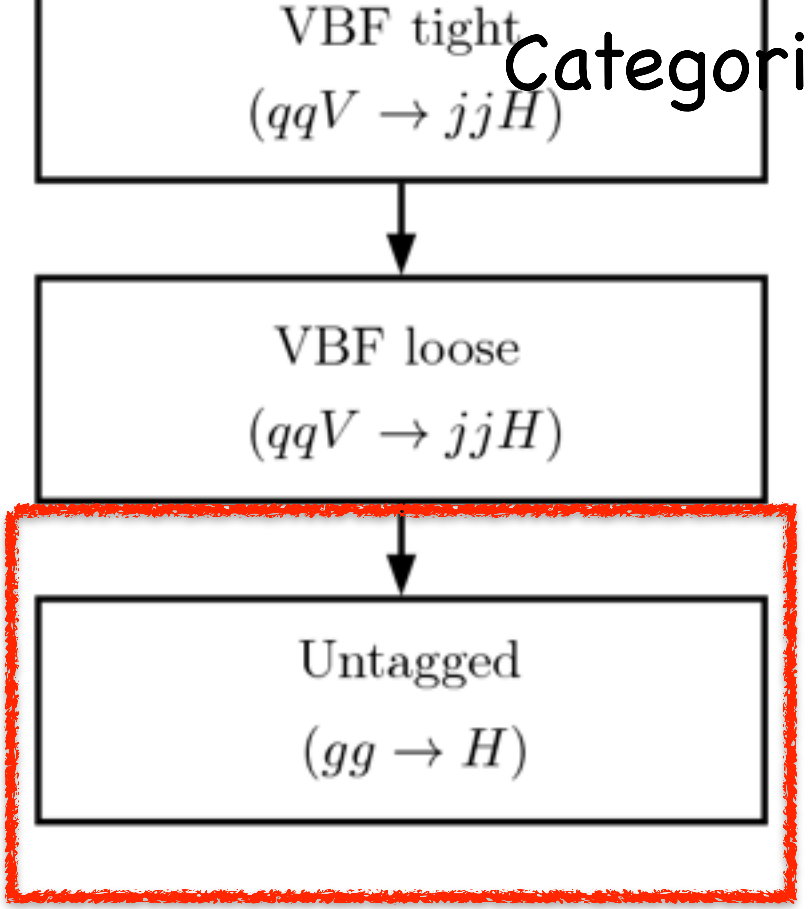


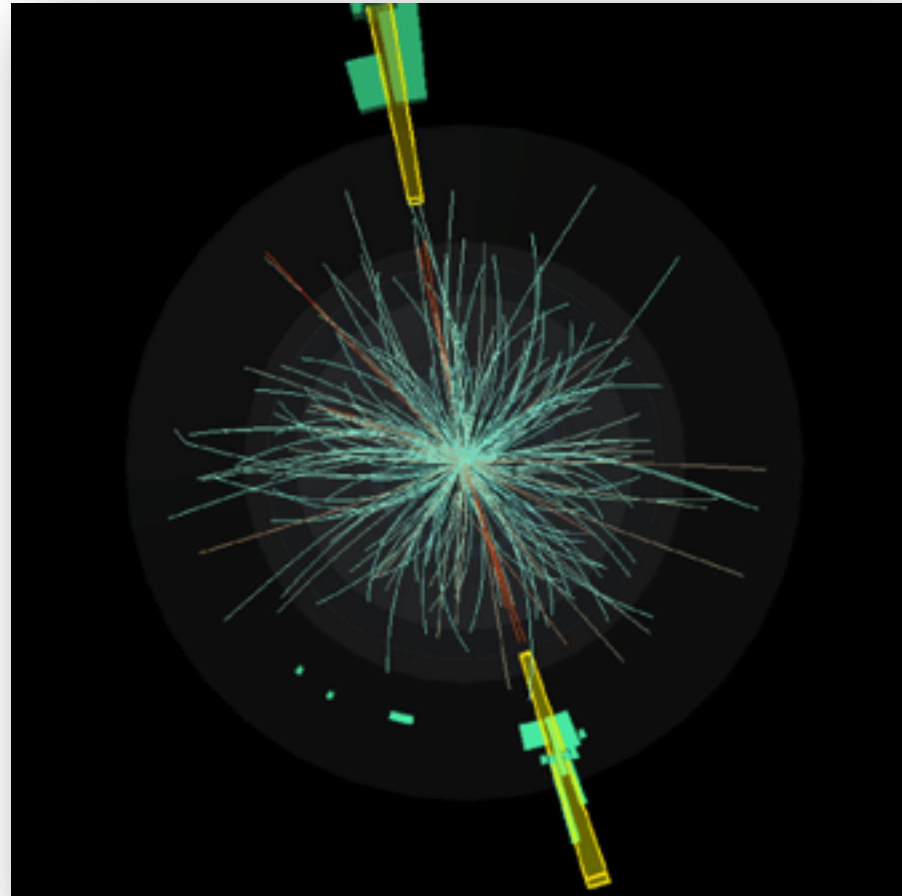
(b)



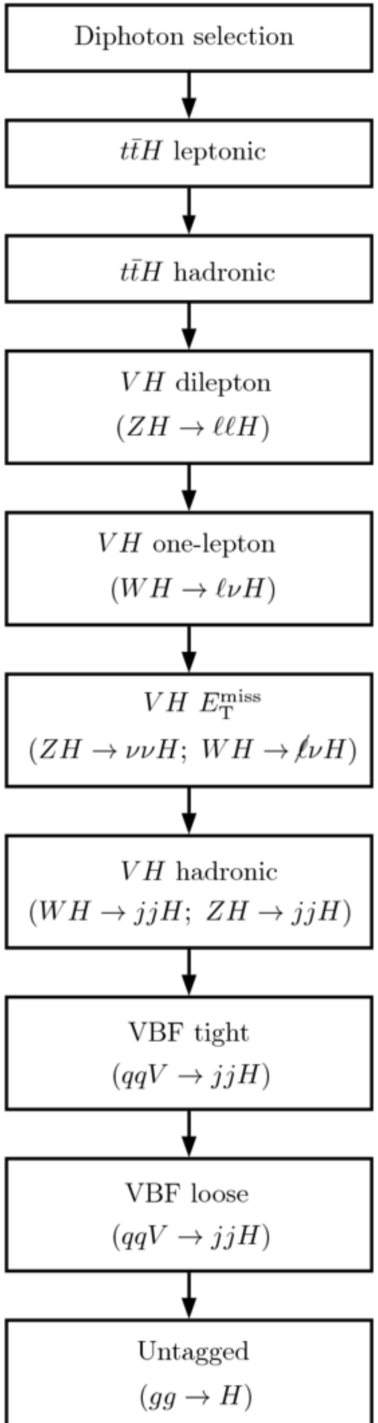
2 back to back forward jets with no additional activity (but di-photon, in the central region)

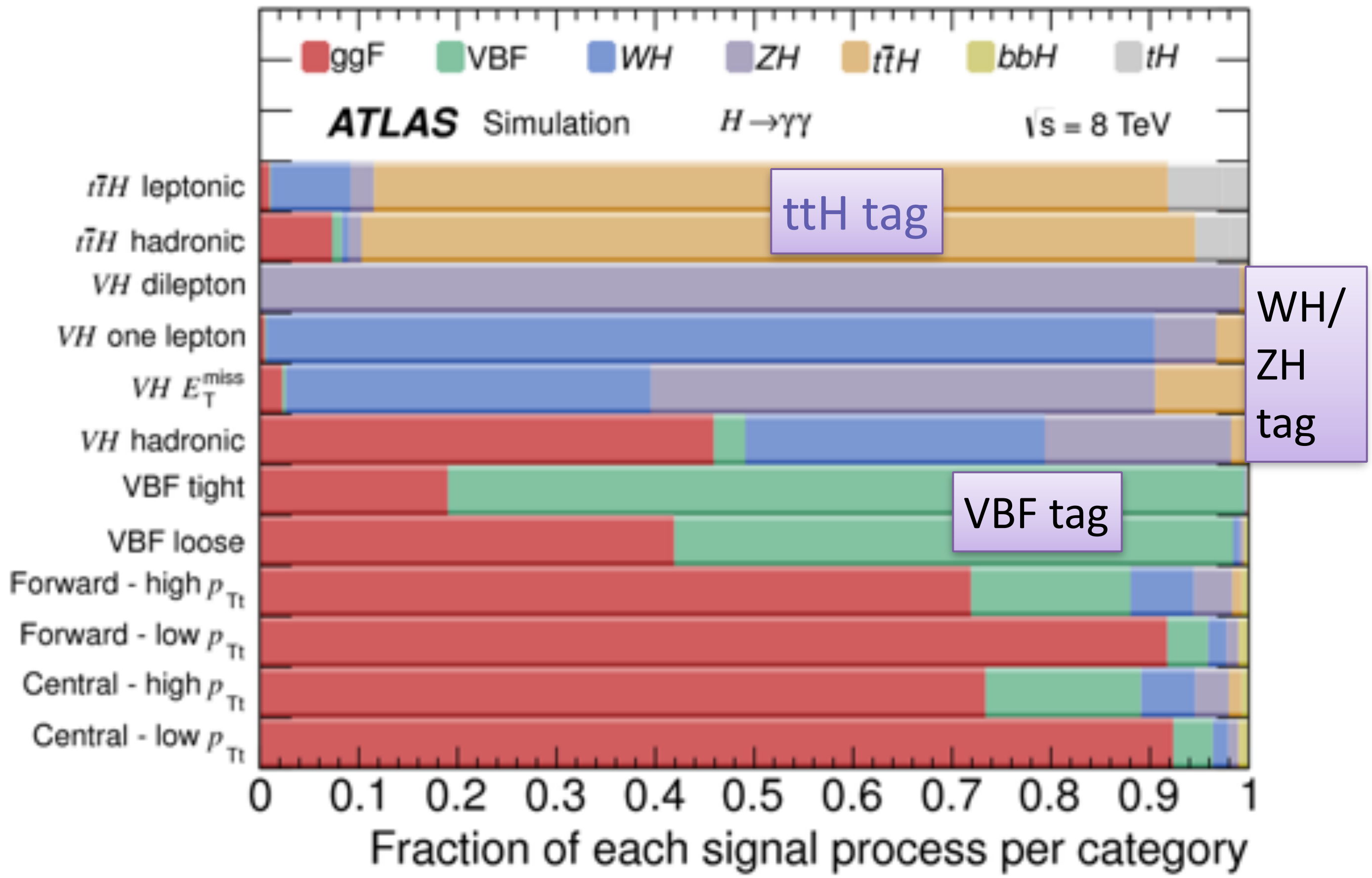
Categorization to improve sensitivity





Categorization to improve sensitivity

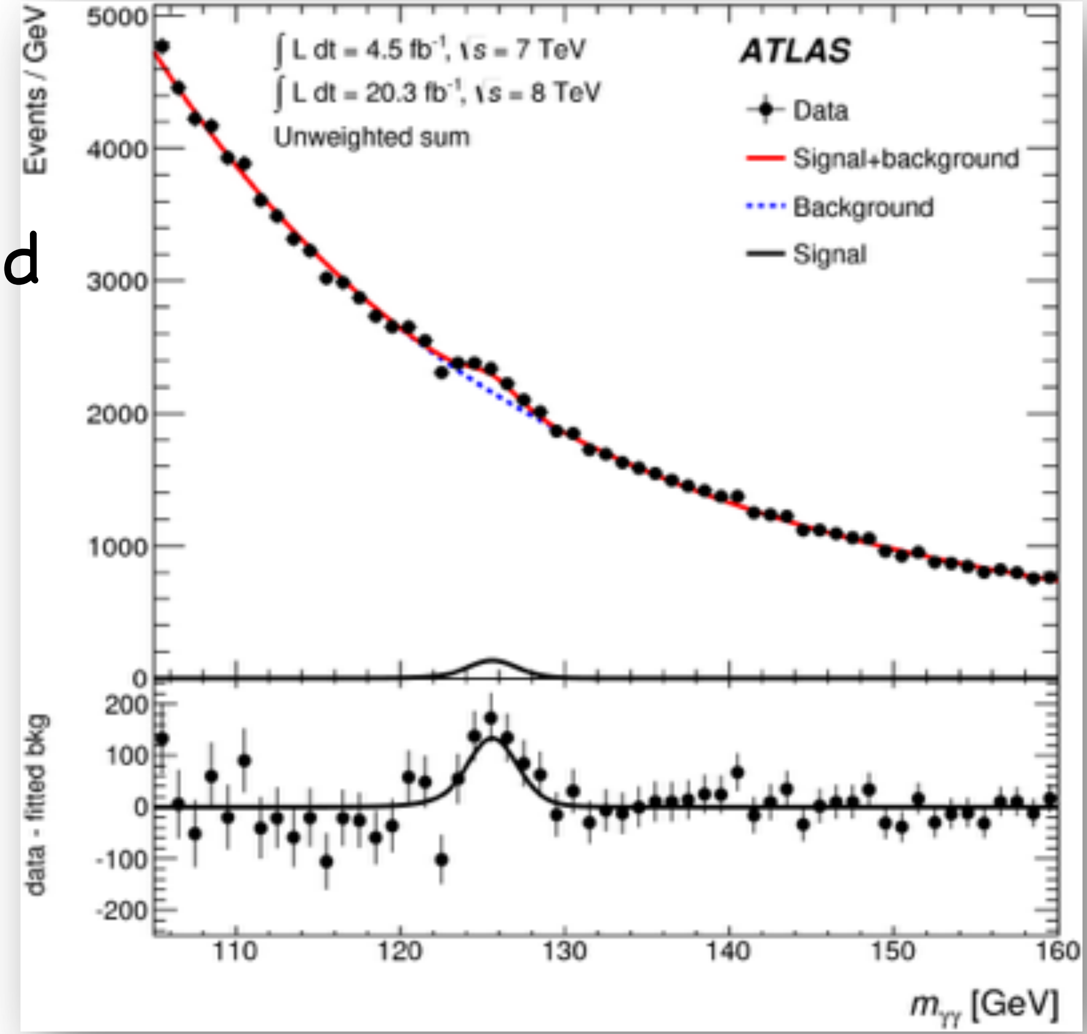




Follow the di-photon Categories

$$pp \rightarrow \gamma\gamma + jets$$

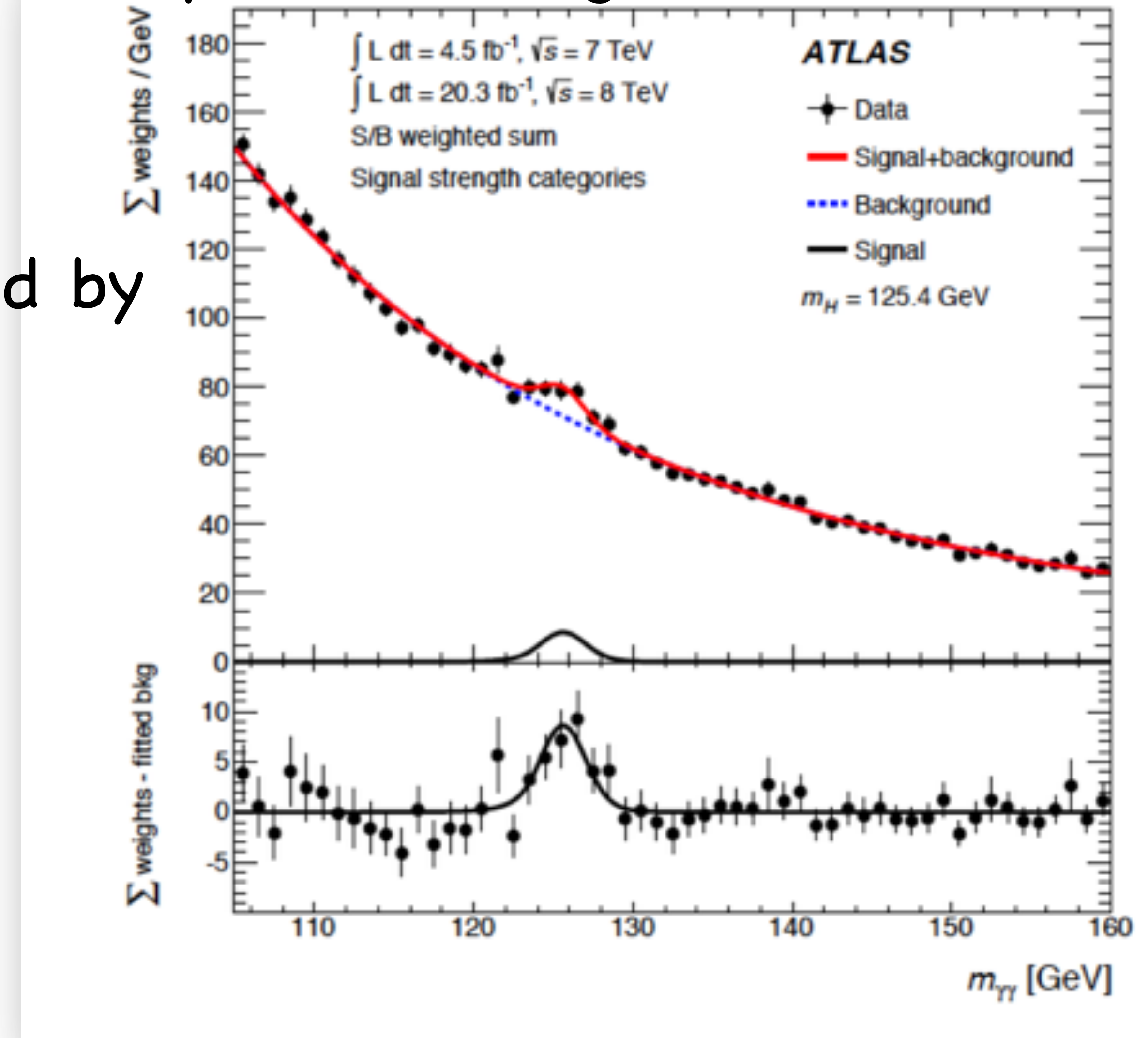
No weights are applied

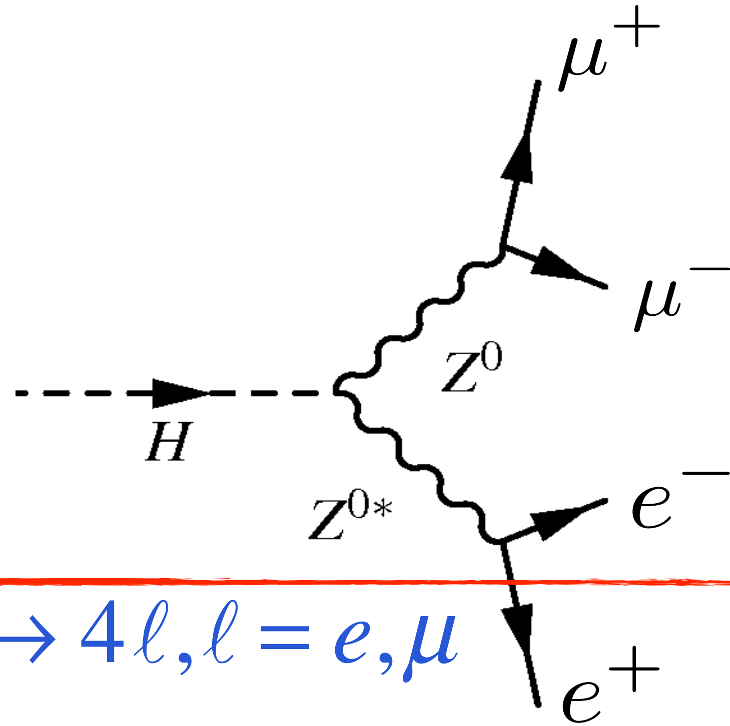


Follow the di-photon Categories

$$pp \to \gamma\gamma + jets$$

Events are weighted by 1+s/b





$$H \to ZZ^* \to 4\ell, \ell = e, \mu$$

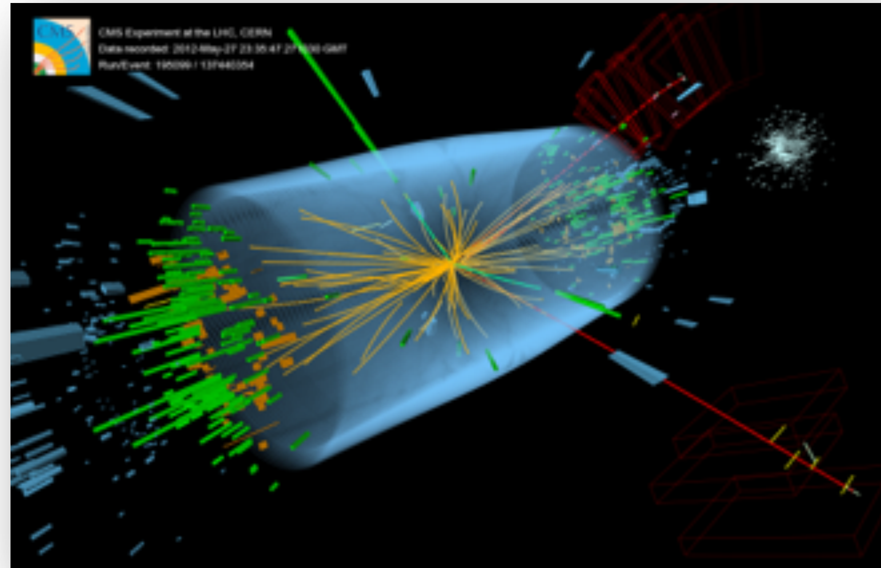
$$BR(H \to ZZ^*)(m_H \sim 125 GeV) \sim 3\%$$

$$BR(H \to 4\ell)(m_H \sim 125 GeV) \sim 0.011\%$$

Higgs Discovery Channels

Higgs decays to a pair of Z Bosons which deac into a pair of leptons each (lepton=Muon or Electron) has a very clear signature.

Actually this channel is fully reconstructed!



$$gg \to H \to ZZ^* \to e^+e^-\mu^+\mu^-$$

$4\ channels: ee\mu\mu, \mu\mu ee, eeee, \mu\mu\mu\mu$

$categories:$

$VBF \qquad m_{jj} > 130GeV$

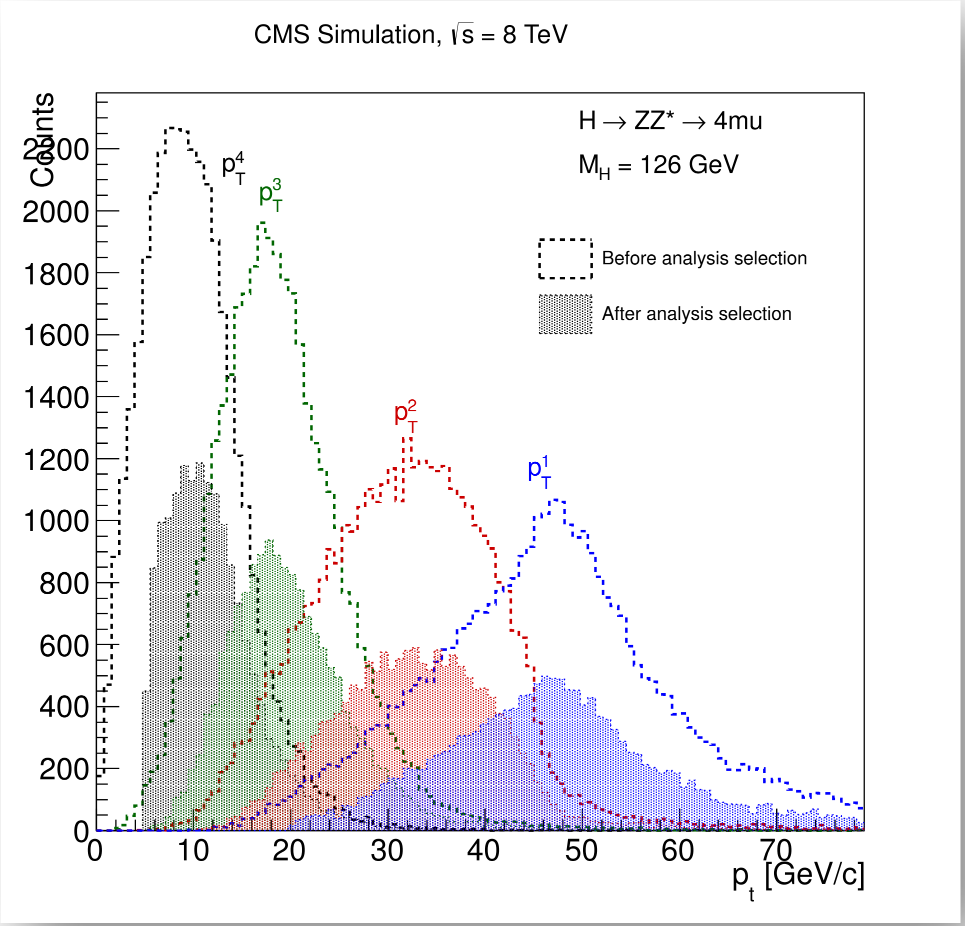
$VH_{had} \qquad 40 < m_{jj} < 130$

$VH_{lep} \qquad additional\ \ \ell$

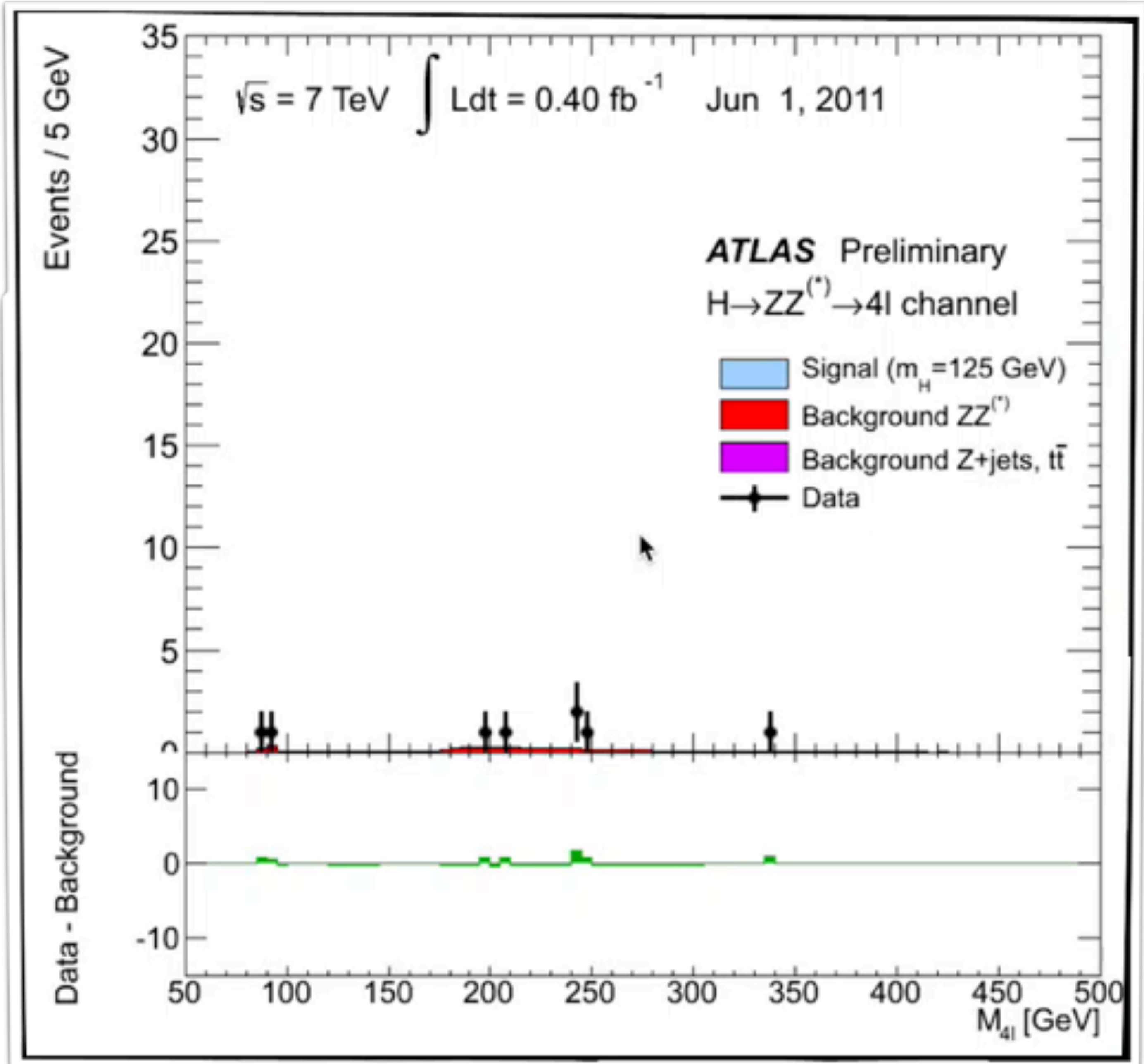
ggF

Higgs Discovery Channels

Due to one Z being off-shell, Z*, needs to control energy/momentum to very low values!

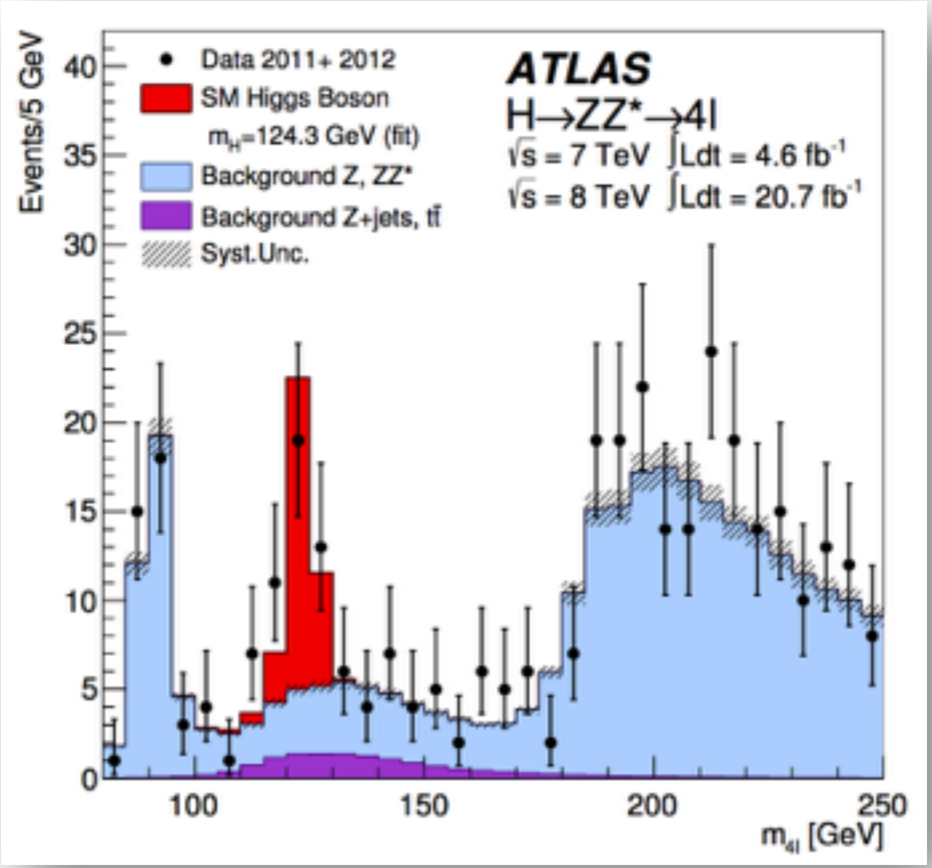


Discovery Animation



Follow the 4 leptons

Educated Simplification



$$B_{exp} = 21$$

$$N_s^{obs} = N_{obs} - B_{exp} = 37$$

$$\sigma_{obs} \sim \frac{s}{\sqrt{b}} = \frac{37}{\sqrt{21}} = 8.1$$

$$N_{s,exp}^{4\ell} \sim \sigma(pp \to H \to ZZ^* \to 4\ell) \cdot L \cdot \epsilon \cdot A \approx 28$$

$$\sigma_{exp} = \frac{28}{\sqrt{21}} \approx 6.2$$

$$\mu^{4\ell} = \frac{\sigma(pp \to H \to 4\ell)_{obs}}{\sigma(pp \to H \to 4\ell)_{exp}} \sim \frac{37}{28} \approx 1.44 \pm 0.35$$

$$H \rightarrow WW^{*} \rightarrow \ell\nu\ell'\nu$$

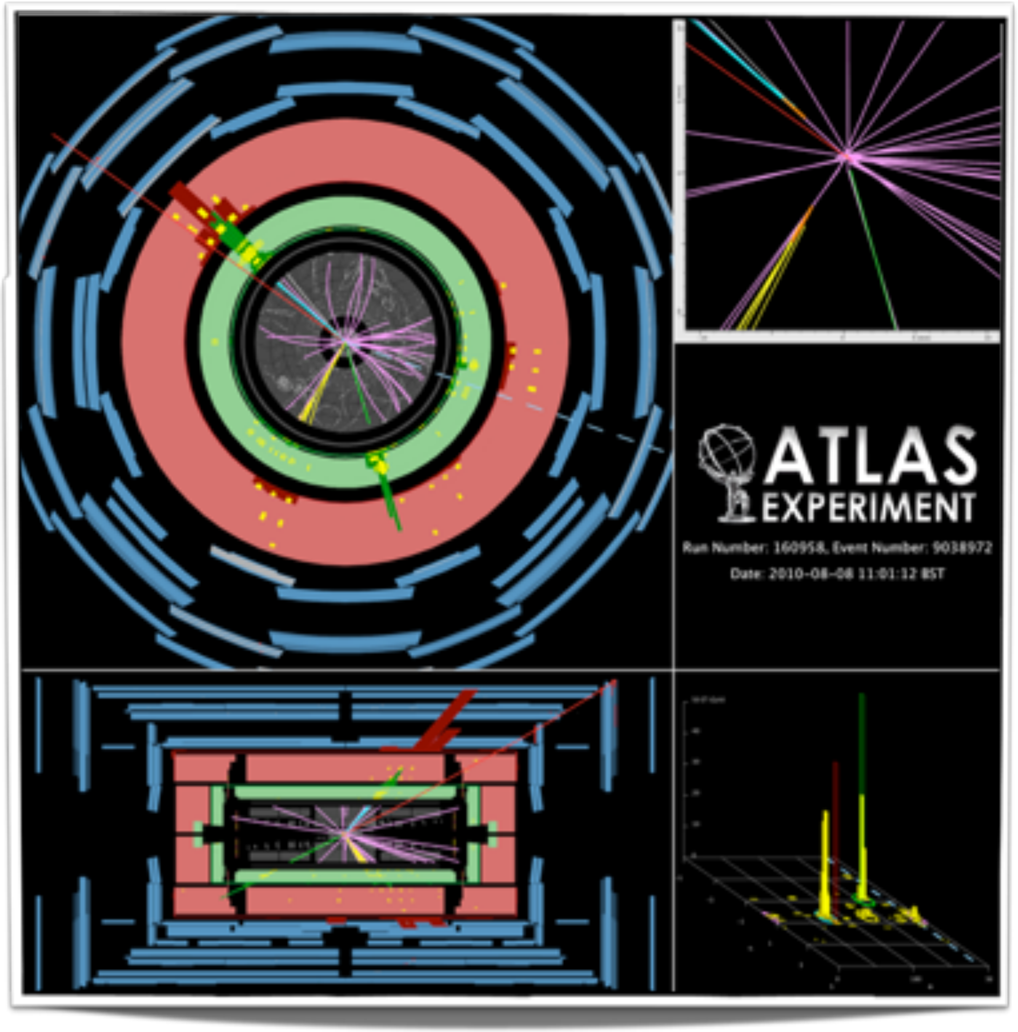
$$BR(H \rightarrow WW^{*})(m_H \sim 125GeV) \sim 22\%$$

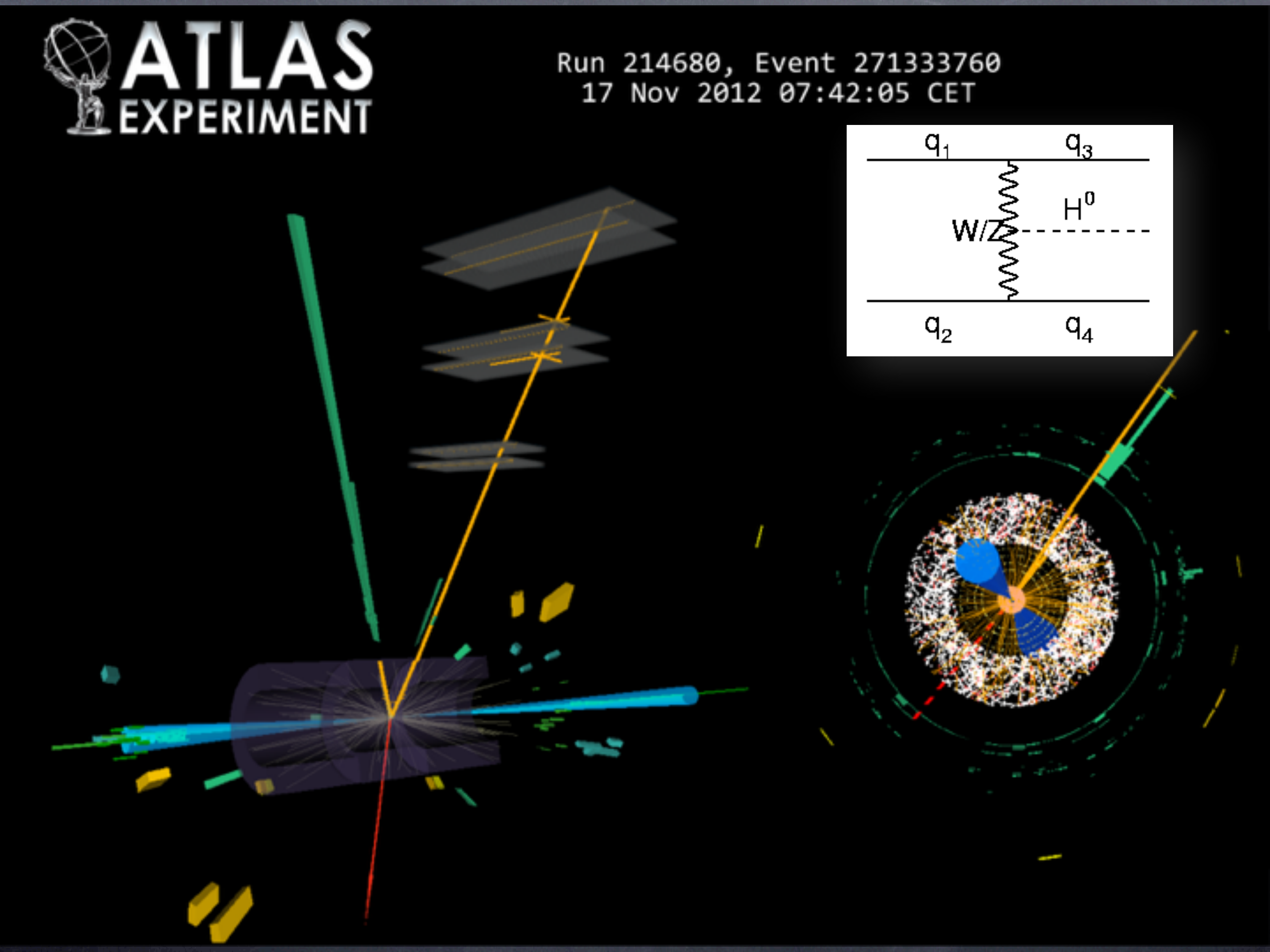
$$BR(H \rightarrow \ell\nu\ell\nu)(m_H \sim 125GeV) \sim 0.76\%$$

WW top Background (contains b quark)

$$t\bar{t} \rightarrow bb + \ell\ell'$$

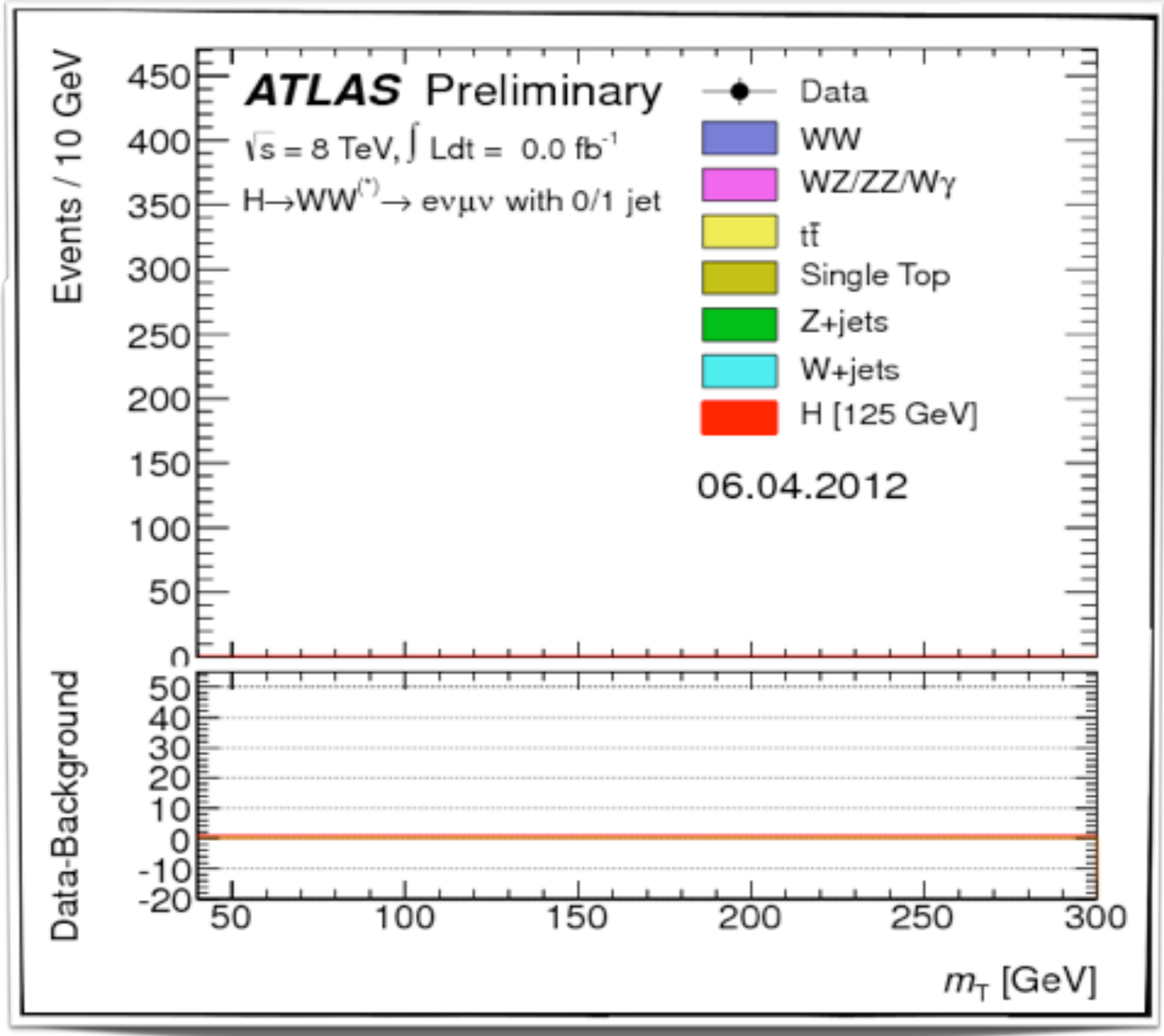
Use anti b tag
Angular separation
between leptons




ATLAS
EXPERIMENT
Run 214680, Event 271333760
17 Nov 2012 07:42:05 CET
q1
q3
H0
W/Z
q2
q4

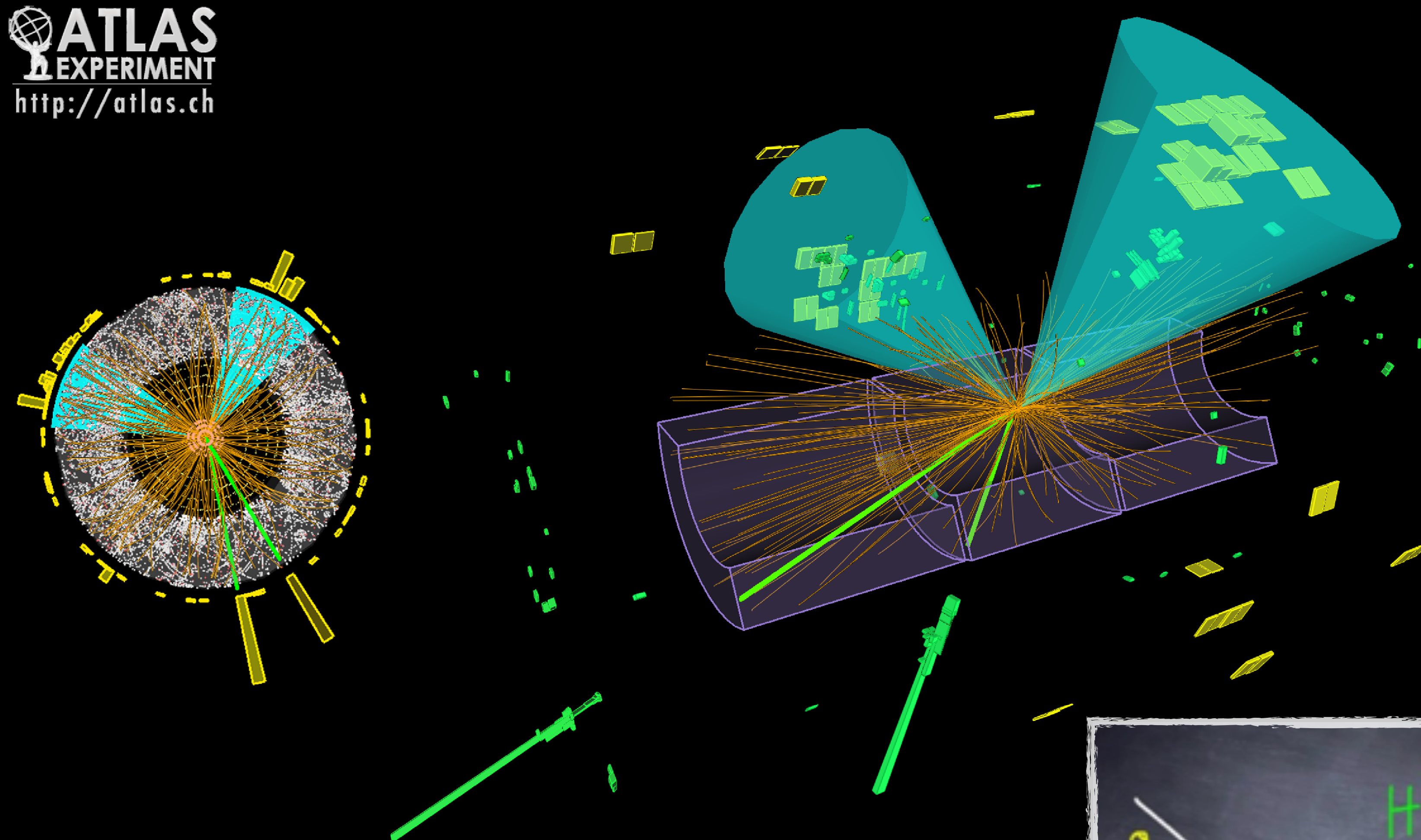
$$\sigma_{obs} = 6.5\sigma$$

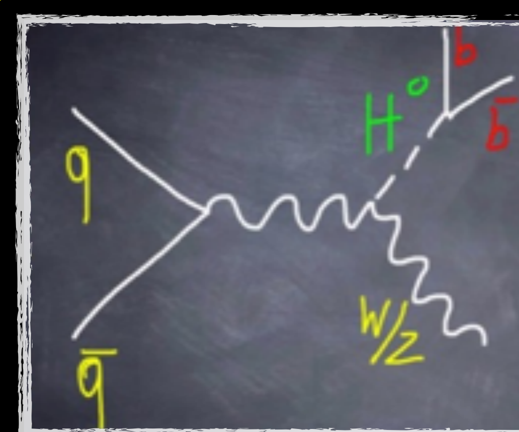
$$\sigma_{exp} = 5.9\sigma$$



H->bb: W/ZH->W/Zbb

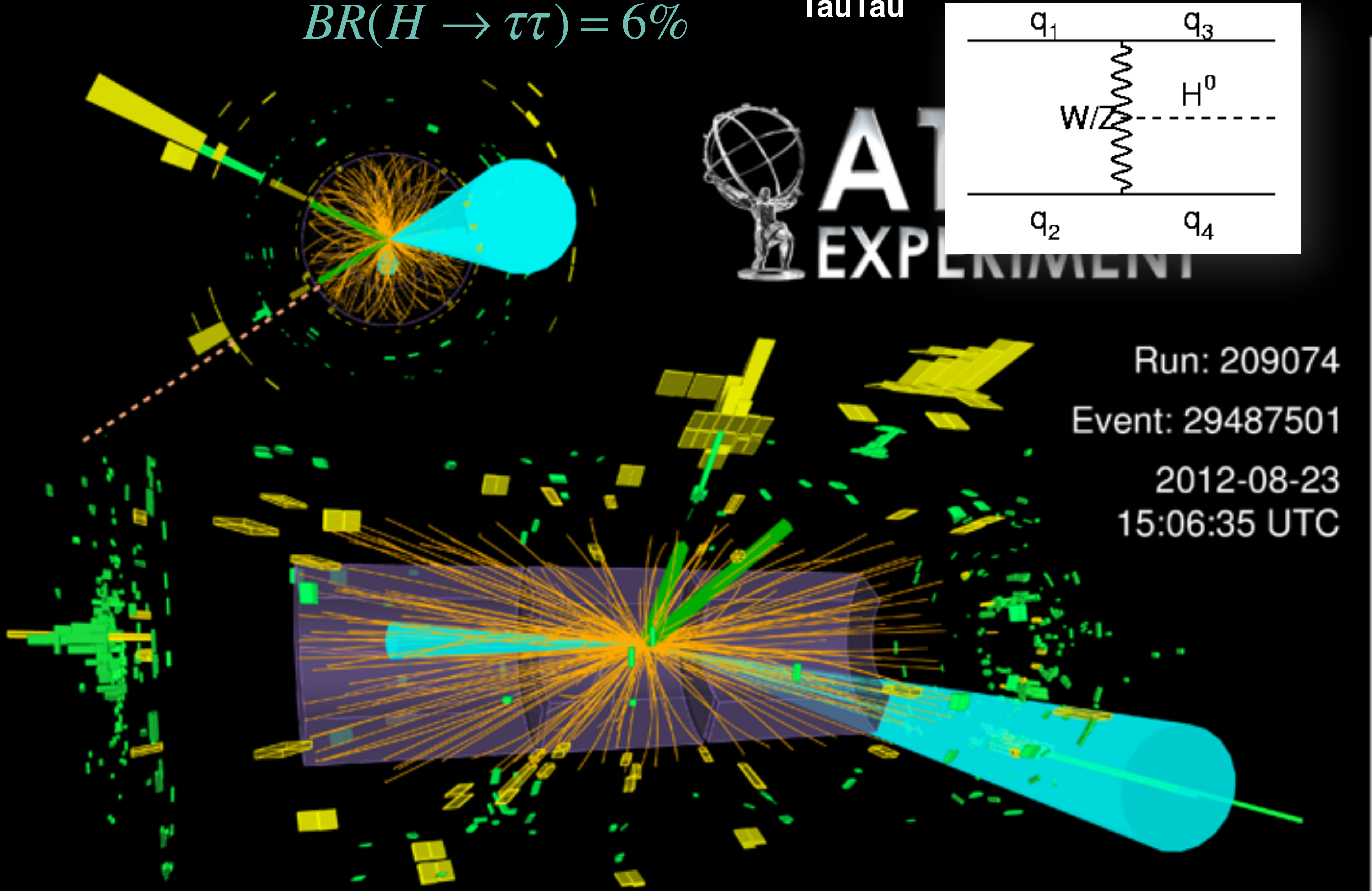
$BR(H \to bb) = 57\%$





$$BR(H \to \tau\tau) = 6\%$$

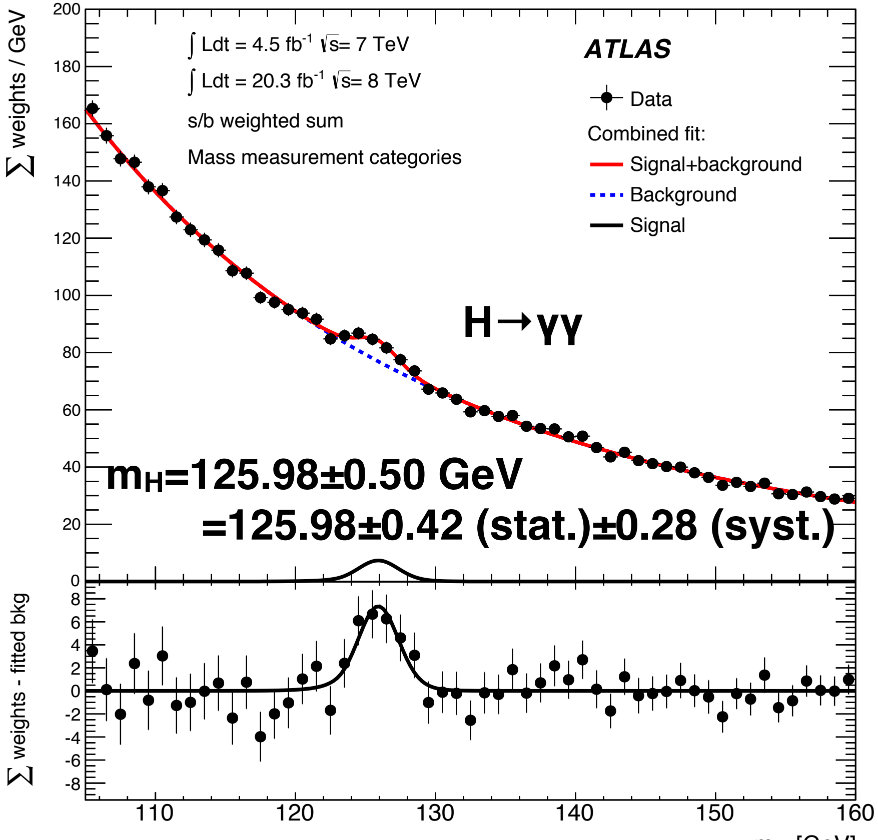
TauTau

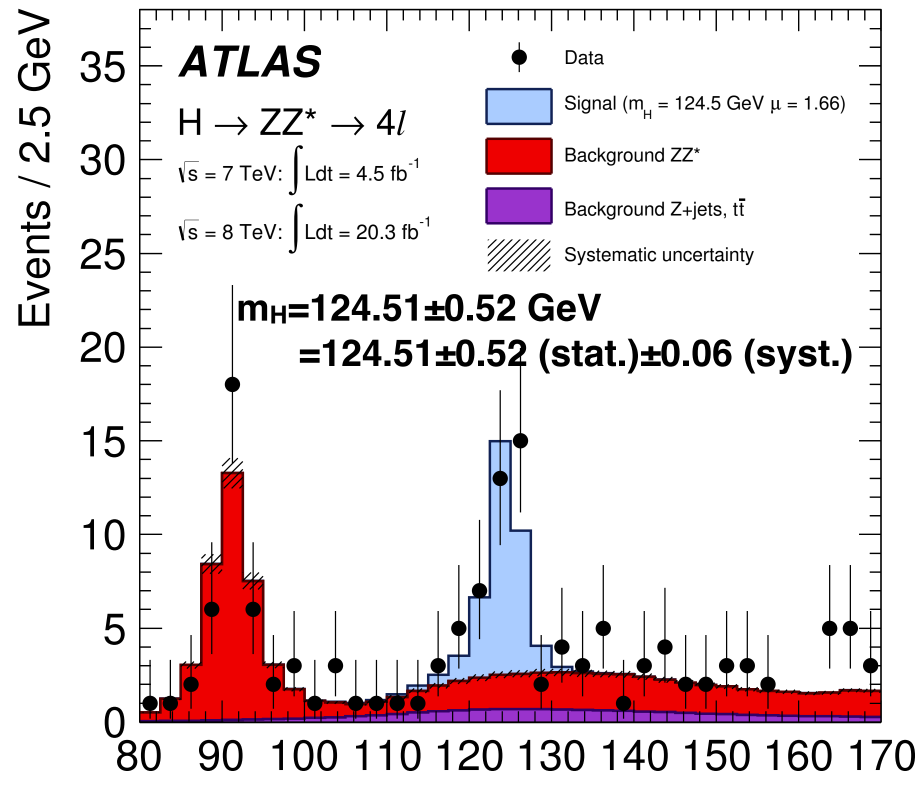


Mass Measurement Results

ATLAS Published analyses

[Phys. Rev. D. 90, 052004 (2014)](#)



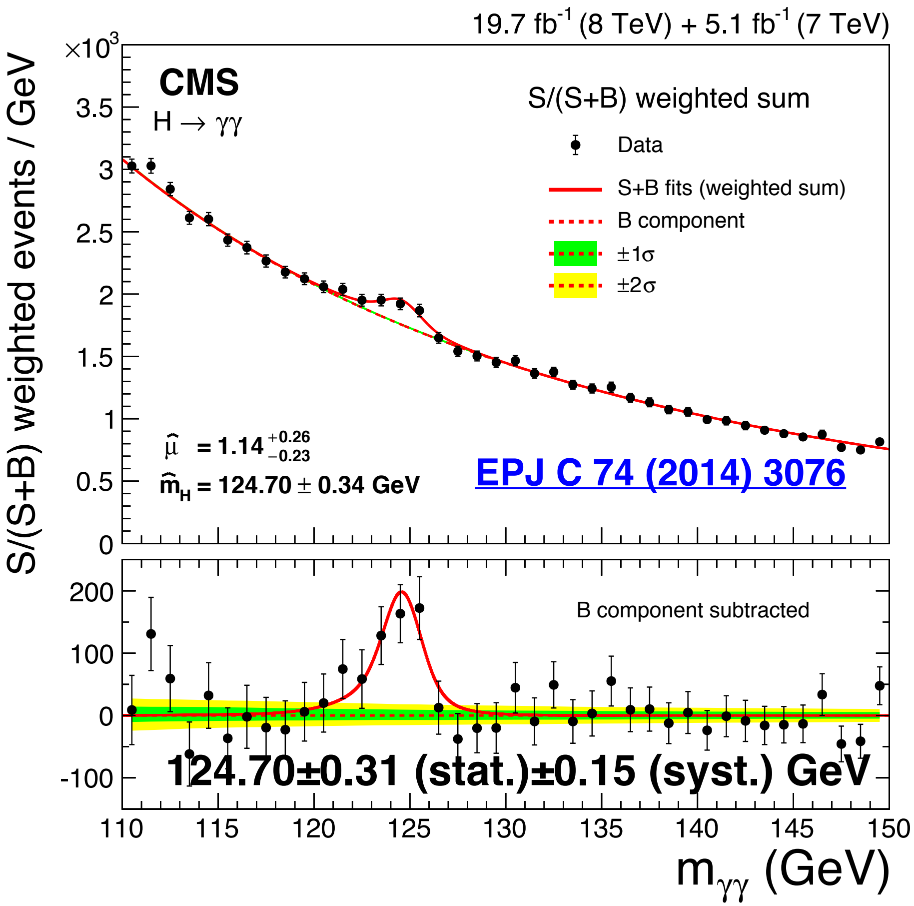


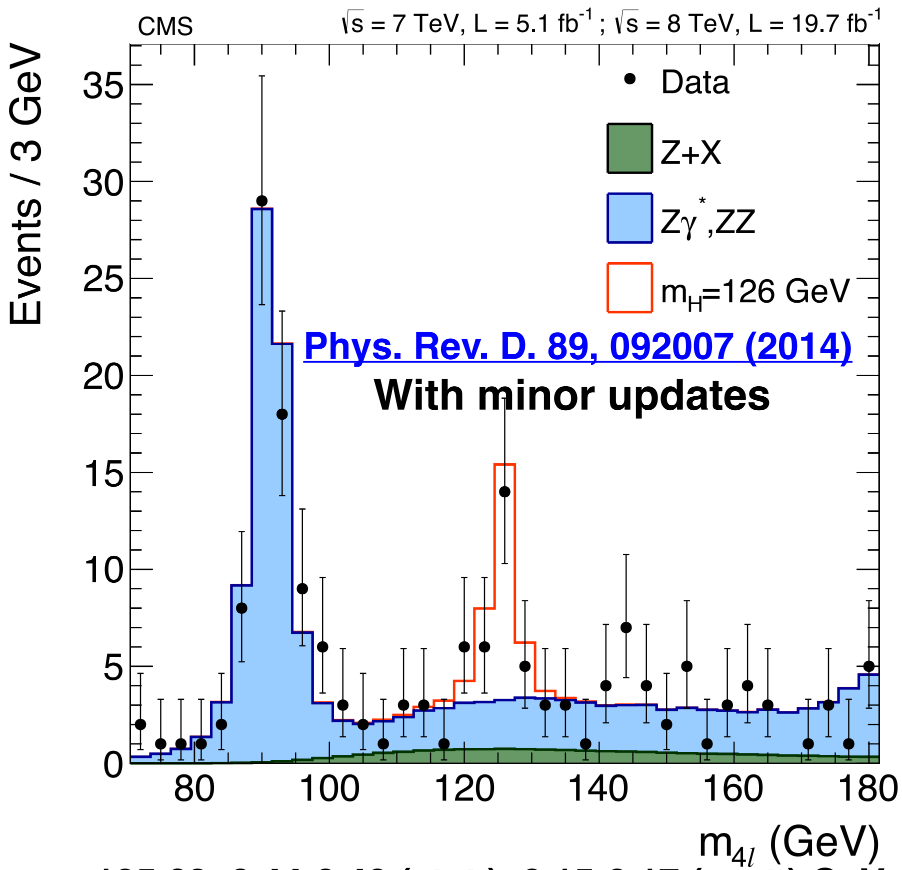
ATLAS Combined: **m_H=125.36±0.41 GeV** (symmetrized uncertainties)

=**125.36±0.37** (stat.)±**0.18** (syst.) **GeV**

CMS Published analyses

arXiv:1412.8662 (submitted to EPJ C)





125.63+0.44-0.40 (stat.)+0.15-0.17 (syst.) GeV

CMS Combined: **m_H=125.02+0.29-0.31 GeV**

=125.02+0.26-0.27 (stat.)+0.14-0.15 (syst) GeV

Couplings

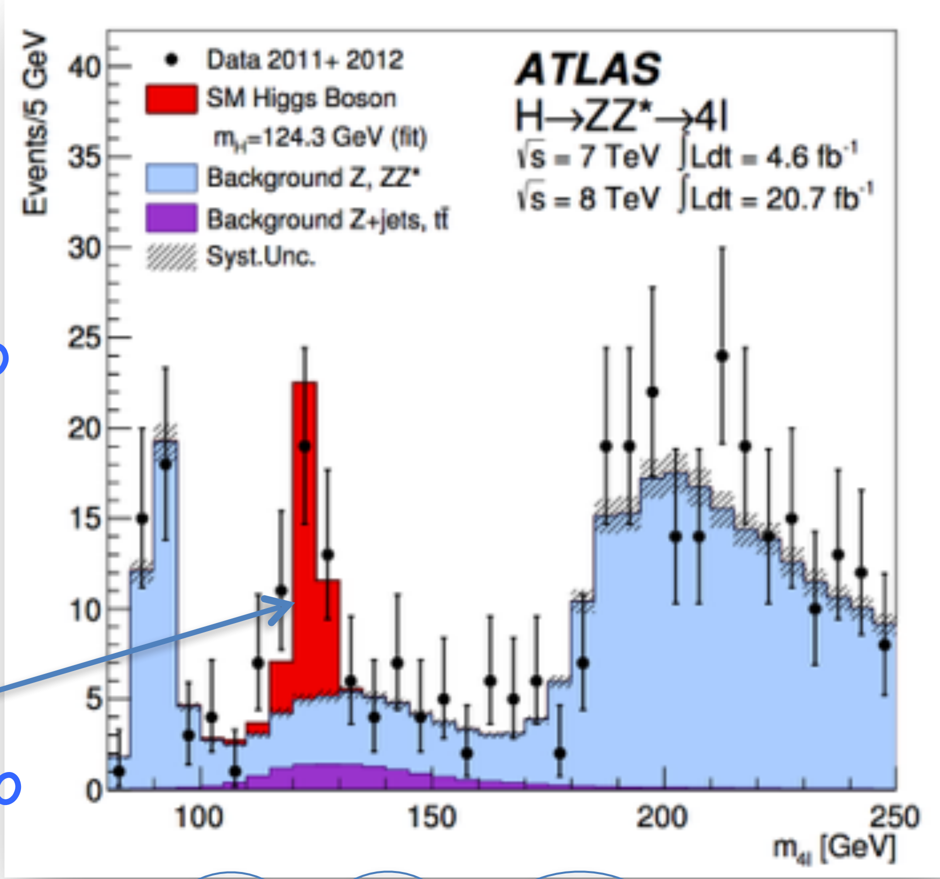
What do we measure

We measure event yields

We want to derive couplings and signal strengths

The first thing we want to measure is the the "signal strength" per channel

The analysis is using discriminators (usually reconstructed mass related) to increase S/B



$$n_s^f = \mu^f \times \sum_i (\sigma^i \times Br^f)_{SM} \times A_i^f \times \varepsilon_i^f \times Lumi$$

$i \in (ggF, VBF, VH, ttH)$ $\qquad$ $f \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$

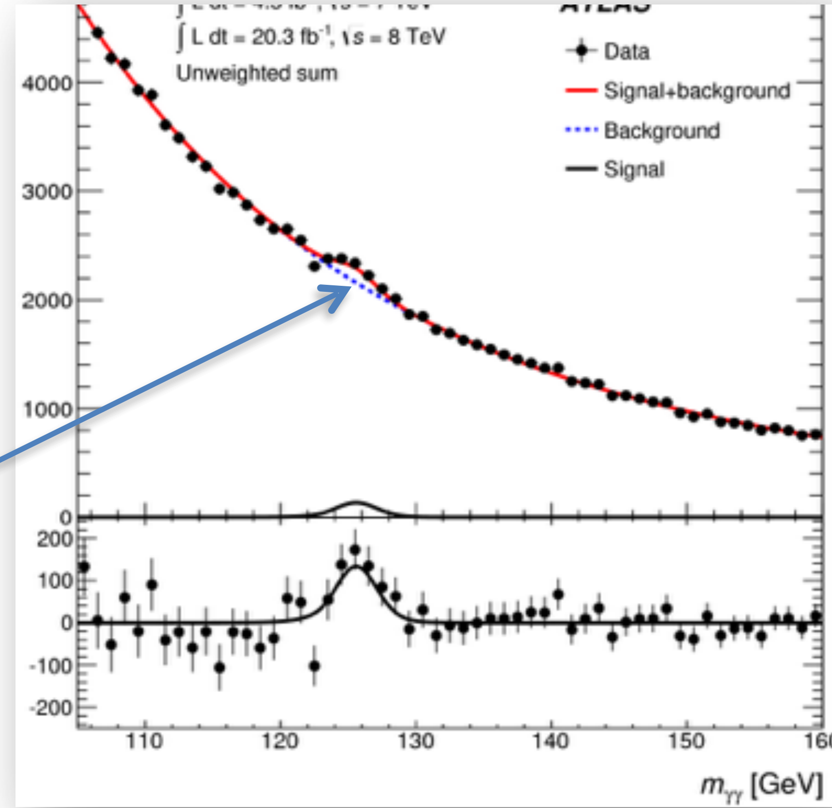
What do we measure

We measure event yields

We want to derive couplings and signal strengths

The first thing we want to measure is the the "signal strength" per channel

The analysis is using discriminators (usually reconstructed mass related) to increase S/B

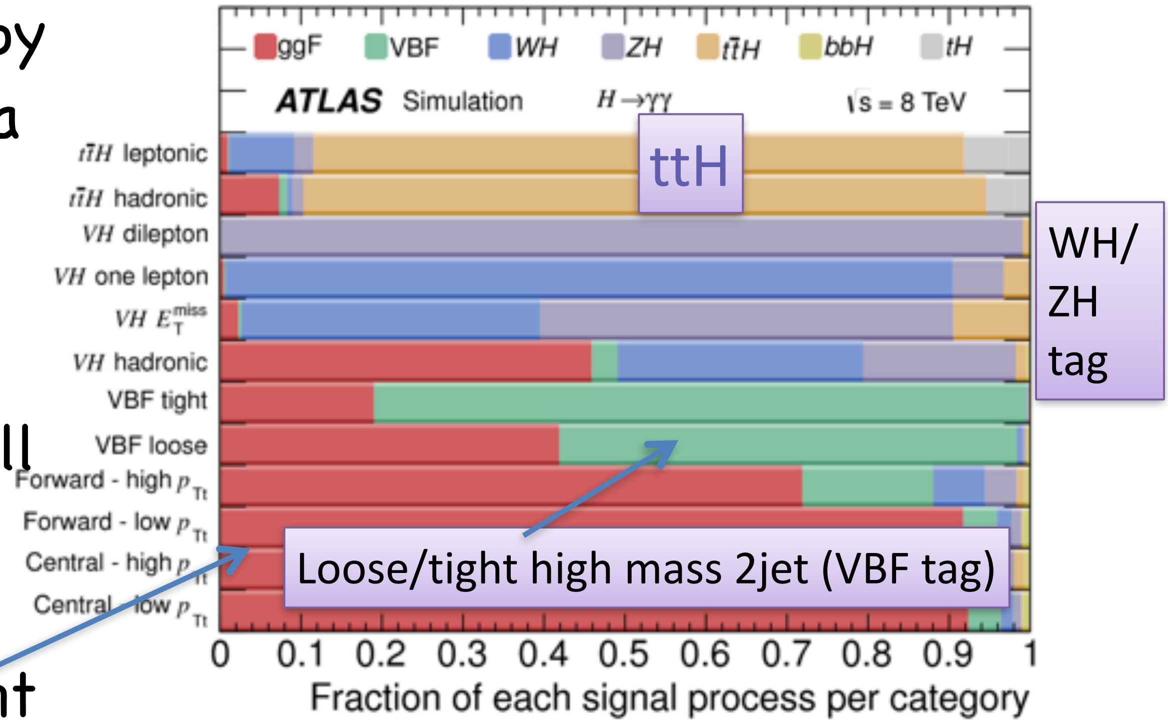


$$n_s^f = \mu^f \times \sum_i (\sigma^i \times Br^f)_{SM} \times A_i^f \times \varepsilon_i^f \times Lumi$$

$i \in (ggF, VBF, VH, ttH)$ $\qquad f \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$

What do we measure

We increase sensitivity by classifying the events via categories and measure the signal strength per category and then combining them taking all the sytematic and statistical errors uncertainties into account



$$n_s^{f,c} = \mu^{f,c} \times \sum_i (\sigma^i \times Br^f)_{SM} \times A_i^{f,c} \times \varepsilon_i^{f,c} \times Lumi$$

$$i \in (ggF, VBF, VH, ttH) \qquad f \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

Probe the Production Modes

Define $\mu_i^f \equiv \left[\mu_i \rho_{BR}^f\right]$ $\rho_{BR}^f \equiv \frac{BR^f}{BR_{SM}^f}$

Parameterize with explicit production modes and decays

$$n_s^{f,c} = \mu^{f,c} \times \sum_i (\sigma^i \times Br^f)_{SM} \times A_i^{f,c} \times \varepsilon_i^{f,c} \times Lumi$$

Note: ONE CAN ONLY FIT THE PRODUCT $\mu_i^f \equiv \left[\mu_i \rho_{BR}^f\right]$

We cannot fit simultaneously the cross section and the BR

Not knowing possible invisible,undetected Higgs decay modes inhibit measurement of the Higgs Width!

The categories allow us to fit specific production modes WITH their dedicated decays, but

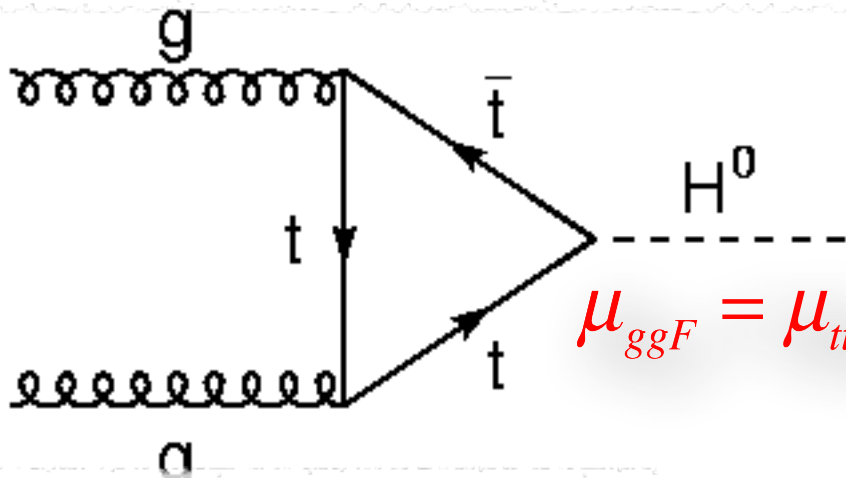
no combination is possible unless we make assumptions on the BR

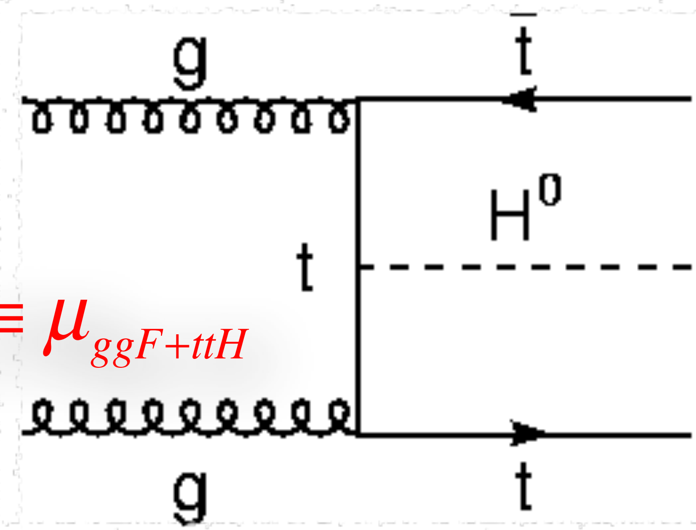
VBF+VH, ggF+ttH

It is plausible to assume (for increasing statistics with the loss of discriminating power)

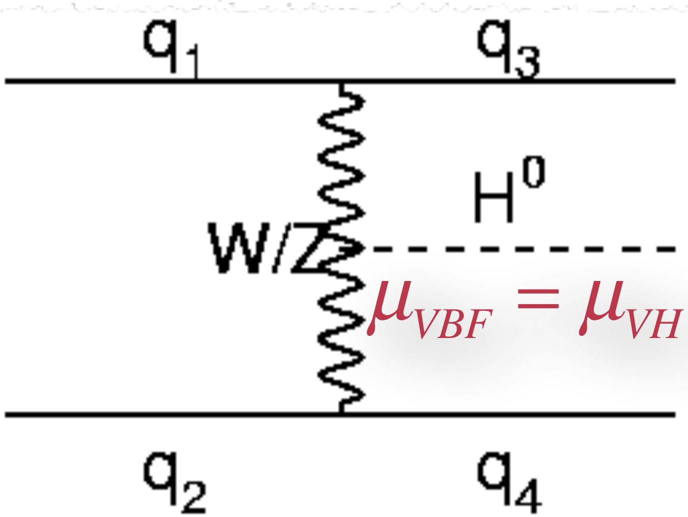
$$\mu_{VBF} = \mu_{VH} \equiv \mu_{VBF+VH}$$

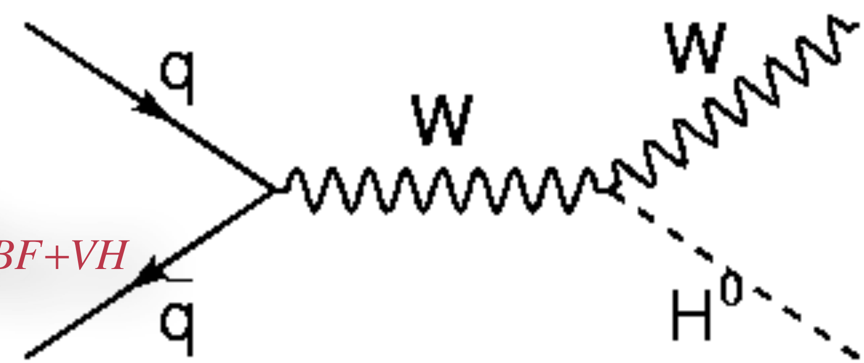
$$\mu_{ggF} = \mu_{ttH} \equiv \mu_{ggF+ttH}$$





$$\mu_{ggF} = \mu_{ttH} \equiv \mu_{ggF+ttH}$$





$$\mu_{VBF} = \mu_{VH} \equiv \mu_{VBF+VH}$$

Probe the Production Modes

$$\mu_i^f = \left[\mu_i \times \rho^f\right] \qquad \rho^f = \frac{BR^f}{BR_{SM}^f}$$

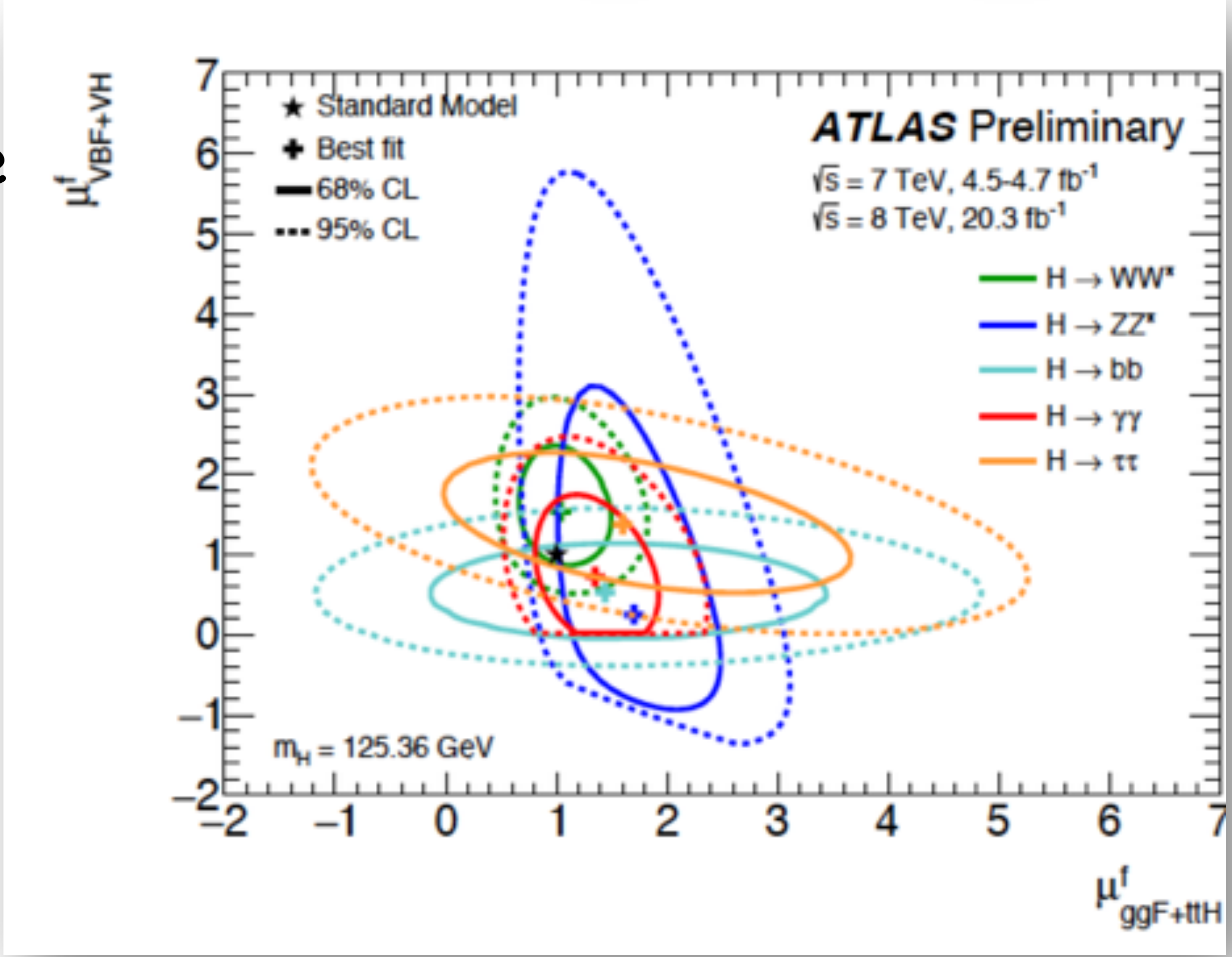
$$\mu_{VBF} = \mu_{VH} \equiv \mu_{VBF+VH}$$

$$\mu_{ggF} = \mu_{ttH} \equiv \mu_{ggF+ttH}$$

No combination is possible unless we assume BRs are that expected by the SM —>

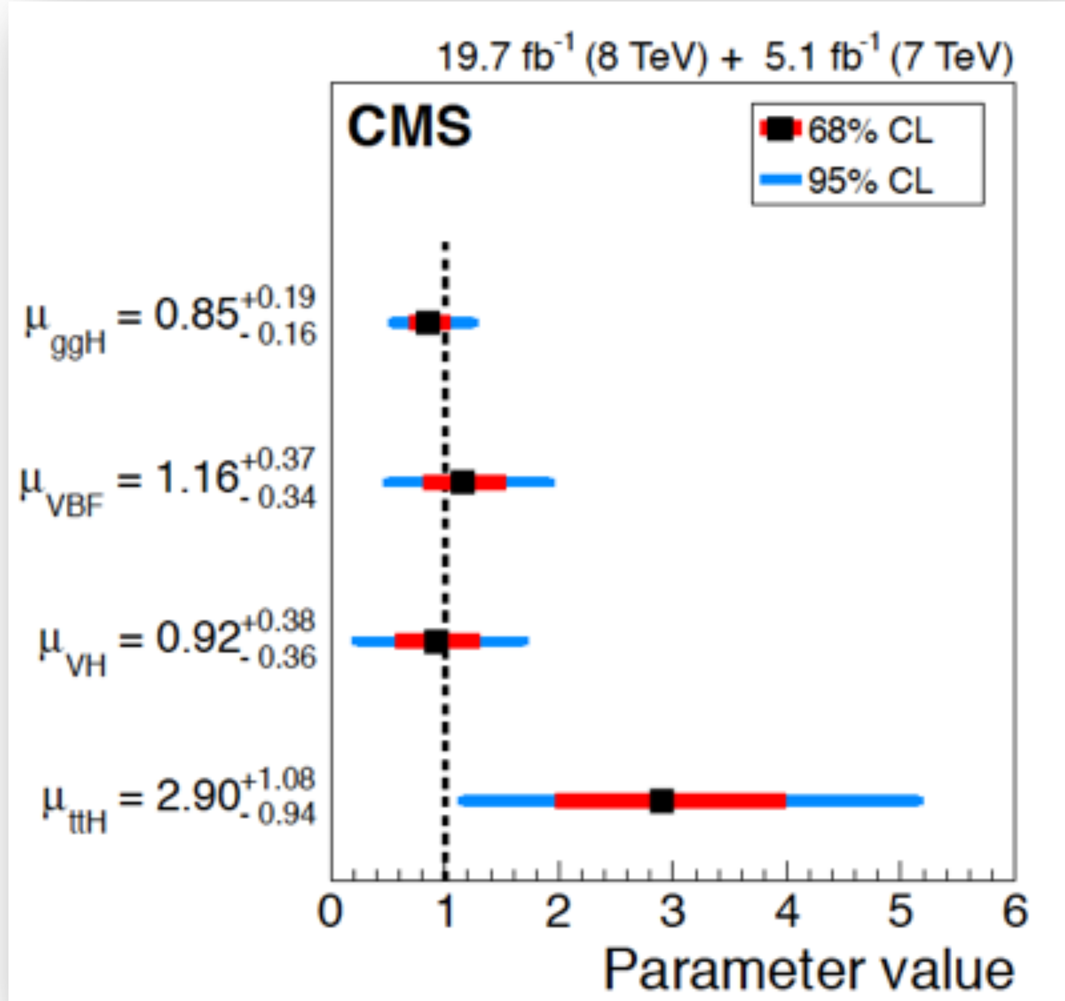
$$\rho^f = \frac{BR^f}{BR_{SM}^f} = 1$$

$$\mu_i^f = \mu_i$$



Probing the Higgs Production Modes

Within the SM (assuming SM decay rates) one can measure the production modes with respect to those expected from the SM



Ratios can be Measured!

Though we cannot separate production from decay in a model independent way, we can measure ratios is a model independent way.

Ratios also have the advantage of common uncertainties cancellation between the numerator and the denominator

$$\mu_i^f = \left[\mu_i \times \rho^f\right] \qquad \rho^f = \frac{BR^f}{BR^f_{SM}}$$

$$\frac{\mu^f_{VBF}}{\mu^f_{ggF}} = \frac{\mu_{VBF} \times \rho^f}{\mu_{ggF} \times \rho^f} = \frac{\mu_{VBF}}{\mu_{ggF}}$$

Ratios can be Measured!

$$n_{ggF}{}^{\gamma\gamma} \sim \sigma_{ggF} * BR(H \to \gamma\gamma) \sim \mu_{ggF}^{\gamma\gamma}$$

$$n_{VBF}{}^{\gamma\gamma} \sim \sigma_{VBF} * BR(H \to \gamma\gamma) \sim \mu_{ggF}^{\gamma\gamma} \frac{\mu_{VBF}^{\gamma\gamma}}{\mu_{ggF}^{\gamma\gamma}} = \mu_{ggF}^{\gamma\gamma} \frac{\mu_{VBF}}{\mu_{ggF}}$$

$$\begin{aligned}
\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\gamma\gamma} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\gamma\gamma} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H} \\
\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to ZZ^{(*)}} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to ZZ^{(*)}} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H} \\
\sigma(gg \to H) * \mathrm{BR}(H \to WW^{(*)}) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to WW^{(*)}} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to WW^{(*)}) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to WW^{(*)}} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H} \\
\sigma(gg \to H) * \mathrm{BR}(H \to \tau\tau) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\tau\tau} \\
\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \tau\tau) &\sim \mu_{\mathrm{ggF}+t\bar{t}H;H\to\tau\tau} \cdot \mu_{\mathrm{VBF}+VH}/\mu_{\mathrm{ggF}+t\bar{t}H}
\end{aligned}$$

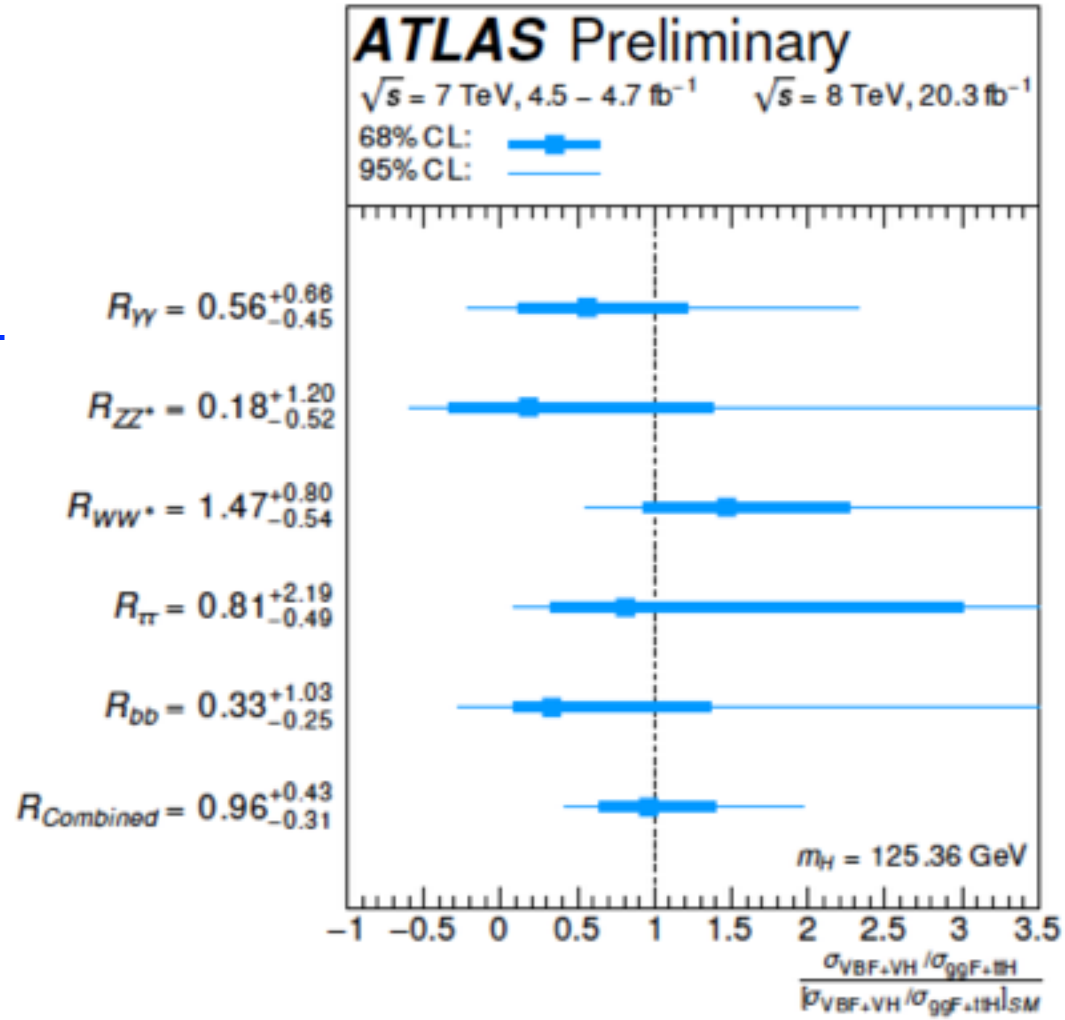
The ratios are measured with a fit profiling all the other parameters (such as μ_{ggF}^{f}) and systematics related parameters.

The ratios are channel independent so we can combine the measurements

Ratios can be Measured!

$$R_f \equiv \frac{\mu_{ggF}^f}{\mu_{VBF}^f} = \frac{\mu_{ggF}}{\mu_{VBF}}$$

Combination



Model Independent Ratios; A way to go

$$\sigma_i \cdot BR^f = \left(\sigma_{ggF} \cdot BR^{WW}\right) \cdot \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \cdot \left(\frac{BR^f}{BR^{WW}}\right)$$

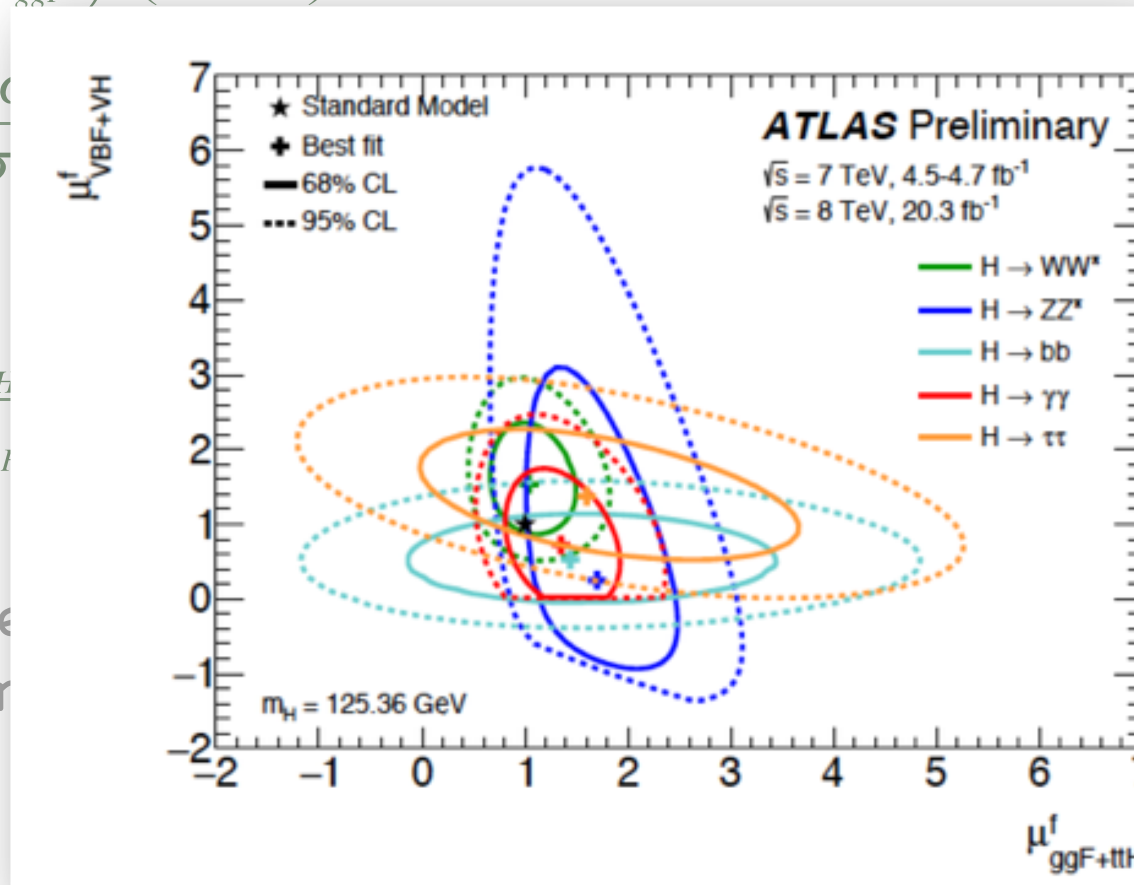
$$\sigma_i \cdot BR^f = \left(\sigma_{ggF} \cdot BR^{WW}\right) \cdot \left(\frac{\sigma}{\sigma}\right.$$

9 parameters fit:

$$\left(\sigma_{ggF} \cdot BR^{WW}\right), \left(\frac{\sigma_{VBF}}{\sigma_{ggF}}\right), \left(\frac{\sigma_{WH}}{\sigma_{ggF}}\right.$$

These parameters of inte

free of theoretical error



$\left(\sigma_{ggF} \cdot BR^{WW}\right)$ has the best resolution

Model Independent Ratios

$$\sigma_i \cdot BR^f = \left(\sigma_{ggF} \cdot BR^{WW}\right) \cdot \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \cdot \left(\frac{BR^f}{BR^{WW}}\right)$$

$$\sigma_i \cdot BR^f = \left(\sigma_{ggF} \cdot BR^{WW}\right) \cdot \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \cdot \left(\frac{\Gamma_f}{\Gamma_{WW}}\right)$$

9 parameters fit:

$$\left(\sigma_{ggF} \cdot BR^{WW}\right), \left(\frac{\sigma_{VBF}}{\sigma_{ggF}}\right), \left(\frac{\sigma_{WH}}{\sigma_{ggF}}\right), \left(\frac{\sigma_{ZH}}{\sigma_{ggF}}\right), \left(\frac{\sigma_{ttH}}{\sigma_{ggF}}\right), \left(\frac{\Gamma_{\gamma\gamma}}{\Gamma_{WW}}\right), \left(\frac{\Gamma_{ZZ}}{\Gamma_{WW}}\right), \left(\frac{\Gamma_{\tau\tau}}{\Gamma_{WW}}\right), \left(\frac{\Gamma_{bb}}{\Gamma_{WW}}\right)$$

These parameters of interest are model independent and relatively free of theoretical errors

Measuring Higgs Couplings

$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H$$
$$+ \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H$$
$$- \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\overline{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\overline{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\overline{f} \right) H.$$

Define the normalized coupling constants (w.r.t. the SM couplings)

$$k_i^2 = \frac{\Gamma_i}{\Gamma_I^{SM}}$$

Couplings

$$k_f^2 = \frac{\Gamma_f}{\Gamma_H}$$

$$\Gamma_H = \Sigma_f \Gamma_f + \Gamma_{i,u} \quad i = invisible, u = undetected$$

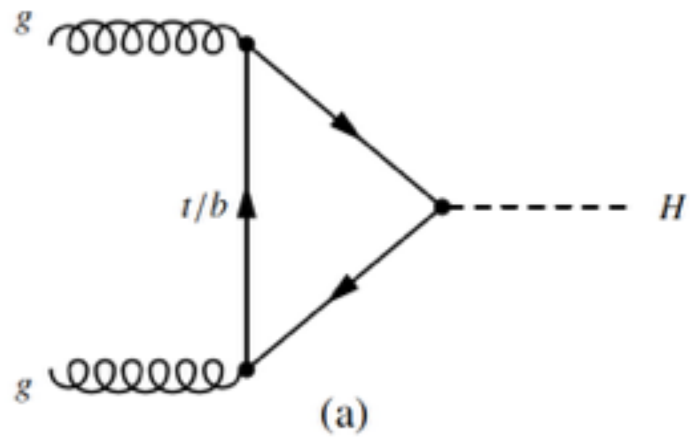
$$k_H^2 = \frac{\Gamma_H}{\Gamma_H^{SM}} = \sum_f \frac{\Gamma_f}{\Gamma_H^{SM}} + \frac{\Gamma_{i,u}}{\Gamma_H^{SM}} = \sum_f \frac{\Gamma_f}{\Gamma_f^{SM}} \frac{\Gamma_f^{SM}}{\Gamma_H^{SM}} + \frac{\Gamma_{i,u}}{\Gamma_H} \frac{\Gamma_H}{\Gamma_H^{SM}}$$

$$k_H^2 = \sum_f k_f^2 BR_f^{SM} + BR_{i,u} k_H^2$$

$$k_H^2 = \frac{\sum_f k_f^2 BR_f^{SM}}{1 - BR_{i,u}}$$

Hgg Effective Coupling

Higgs does not couple to Gluons and Photons leading order



The production of the Higgs Boson and its discovery are due to a pure quantum loop

$$k_g^2 \approx 1.06 k_t^2 + 0.01 k_b^2 - 0.07 k_t k_b$$

Hgg Approximate Calculation

Why a NEGATIVE interference term?

$$\sigma_{\rm LO}(gg \to h) = \sigma_0^h m_h^2 \delta(\hat{s} - m_h^2)$$

$$\sigma_0^h = \frac{G_f \alpha_s^2}{288\sqrt{2}\pi} \left| \frac{3}{4} \sum_q A_{1/2}^H(\tau_q) \right|^2$$

$$\tau_q = 4m_q^2/m_h^2$$

$\tau_t = 7.65$ and $\tau_b = 2 \times 10^{-3}$ for $m_b(m_h) \approx 2.8\,\text{GeV}$.

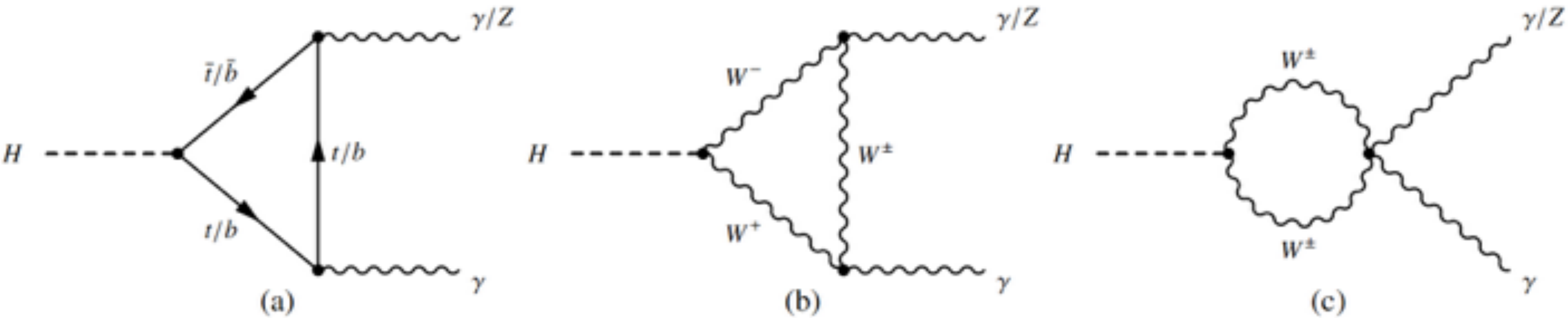
$$A_{1/2}^H(\tau) = 2\tau\left[1 + (1-\tau)f(\tau)\right] ,$$

$$f(\tau) = \begin{cases} -\frac{1}{4}\left[\log\left(\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}}\right) - i\pi\right]^2 & \tau < 1 \\ \arcsin^2(1/\sqrt{\tau}) & \tau \geq 1 \end{cases}$$

$$A_{1/2}^H = \begin{array}{ll} \tau \gg 1: & 4/3 \\ \tau \ll 1: & 2\tau\left[1 - \frac{1}{4}\left(\log\frac{\tau}{4} + i\pi\right)^2\right] \approx -\frac{\tau}{2}\left(\log\frac{\tau}{4}\right)^2 \end{array}$$

$$\frac{\sigma_0^h}{[\sigma_0^h]_{\rm SM}} = \left| \frac{\kappa_t A_{1/2}^H(\tau_t) + \kappa_b A_{1/2}^H(\tau_b)}{A_{1/2}^H(\tau_t) + A_{1/2}^H(\tau_b)} \right|^2 = \kappa_t^2 1.09 - 0.09\kappa_b\kappa_t + 0.0021\kappa_b^2$$

$H\gamma\gamma, H\gamma Z$ Effective Coupling



W/t interference

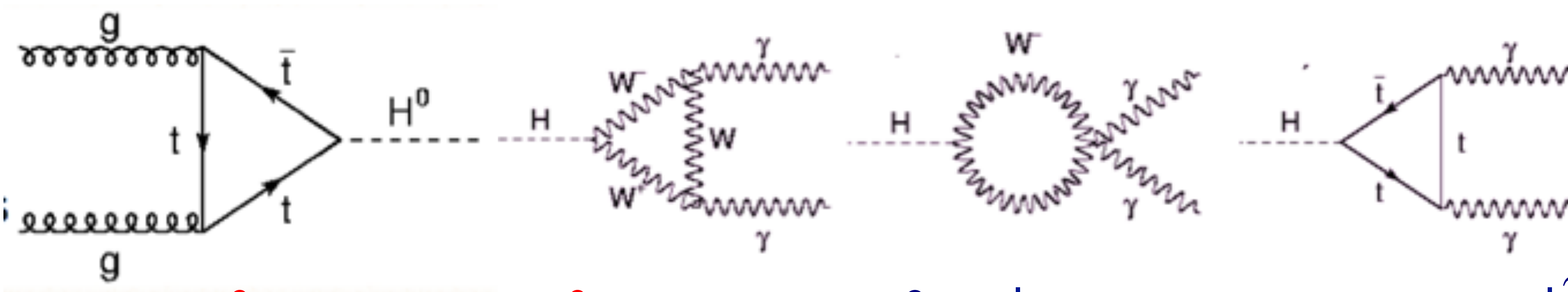
$$\kappa_\gamma^2 \sim \quad 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$$

$$k_\gamma^2 = \left|1.28 k_W - 0.28 k_t\right|^2$$

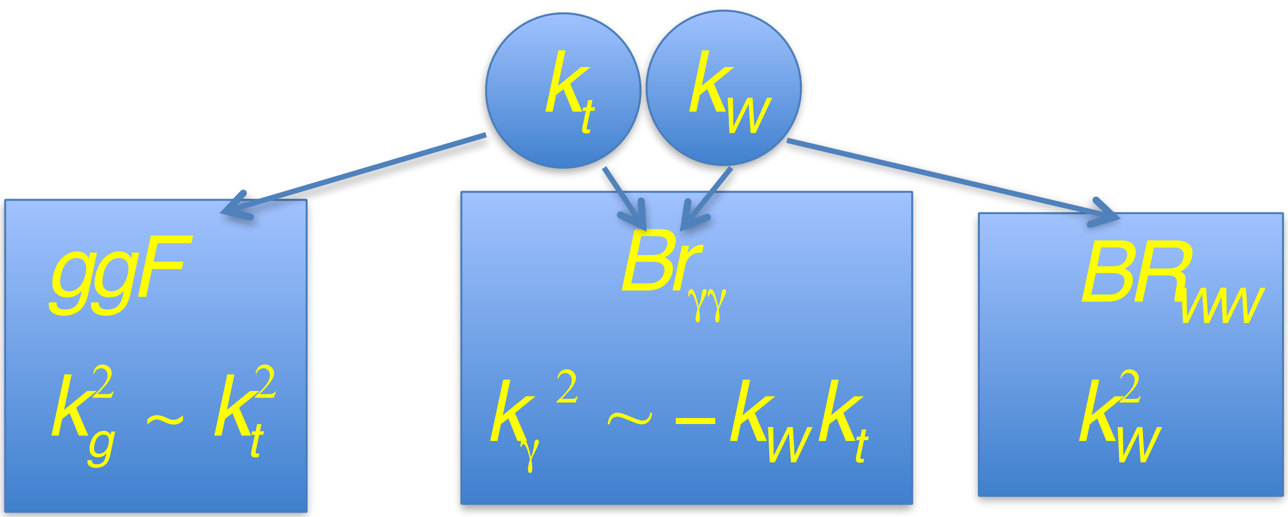
$$\kappa_{Z\gamma}^2 \sim \quad 1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_t^2 - 0.12 \cdot \kappa_W \kappa_t$$

A comment on Interference

is



$$n_s^{\gamma\gamma} \sim k_g^2(k_t, k_b) \times k_\gamma^2(k_t, k_W) \qquad k_\gamma^2 = \left|1.28 k_W - 0.28 k_t\right|^2$$



If k_t=-1 ggF slightly affected

WW unaffected

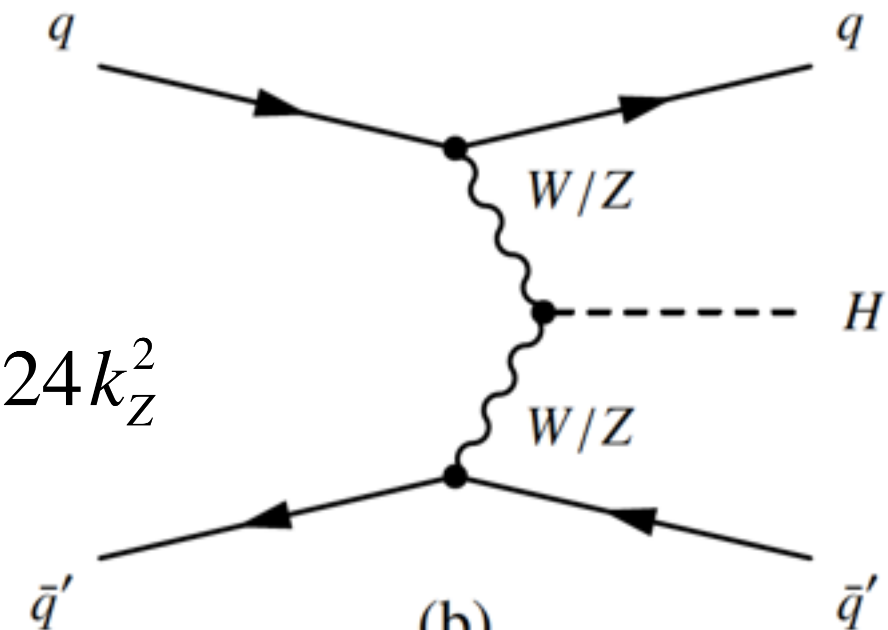
γγ increases

Testing negative k_t is extremely important

VBF Composition

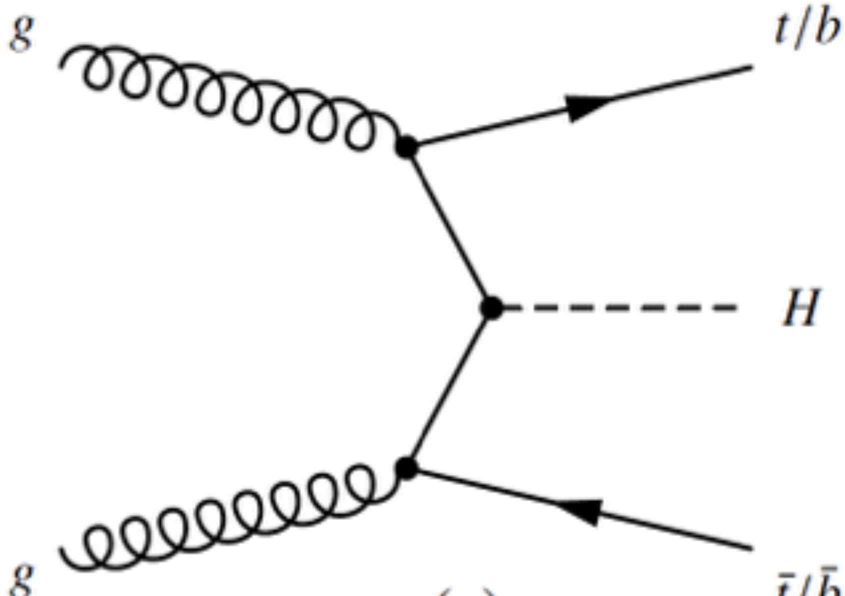
$$q\overline{q}' \to q\overline{q}'H$$

$$\mu_{VBF} = k_{VBF}^2 \approx 0.74 k_W^2 + 0.24 k_Z^2$$



(b)

ttH



(a)

$$gg \to ttH\ ,bbH$$

$$\mu_{ttH} = k_t^2$$

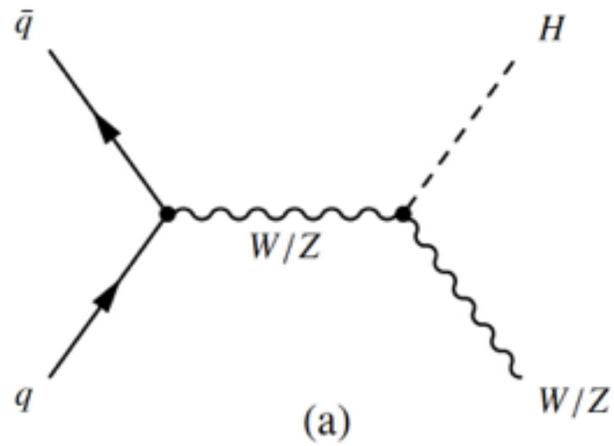
$$\mu_{bbH} = k_b^2$$

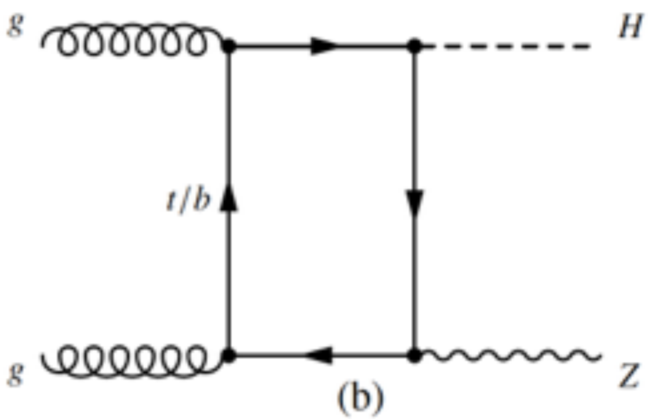
ZH Production

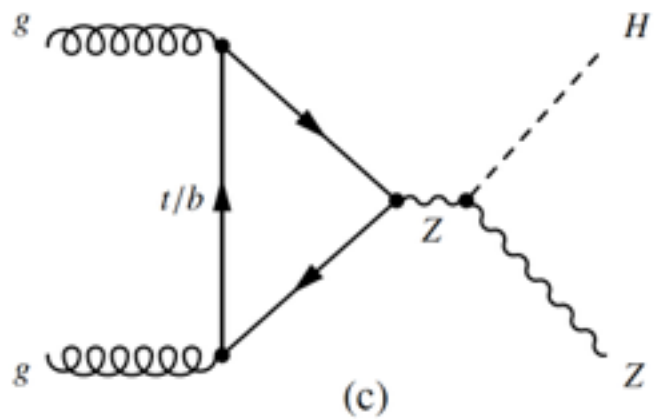
$$\sigma(q\bar{q} \to ZH) \sim k_Z^2$$

$$\sigma(q\bar{q} \to WH) \sim k_W^2$$

$$\sigma(gg' \to ZH) \sim k_{ggZH}^2$$



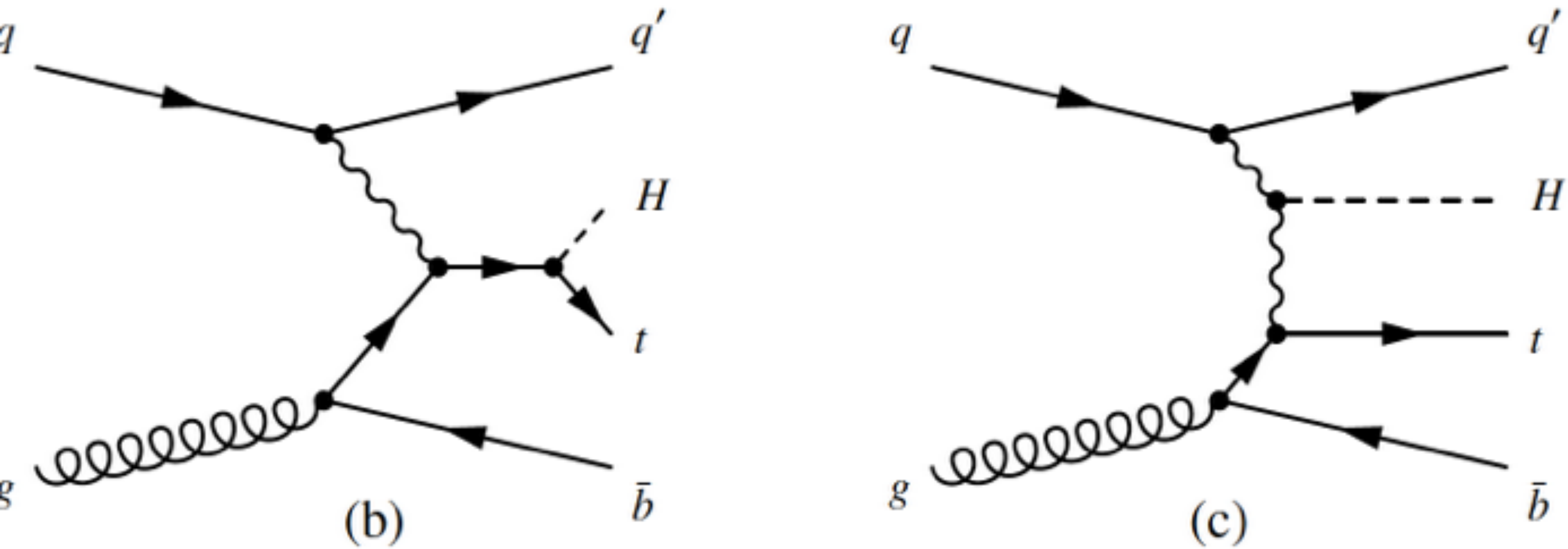




(Q:Why not gWH?)

$$\kappa_{ggZH}^2 \sim \quad 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$$

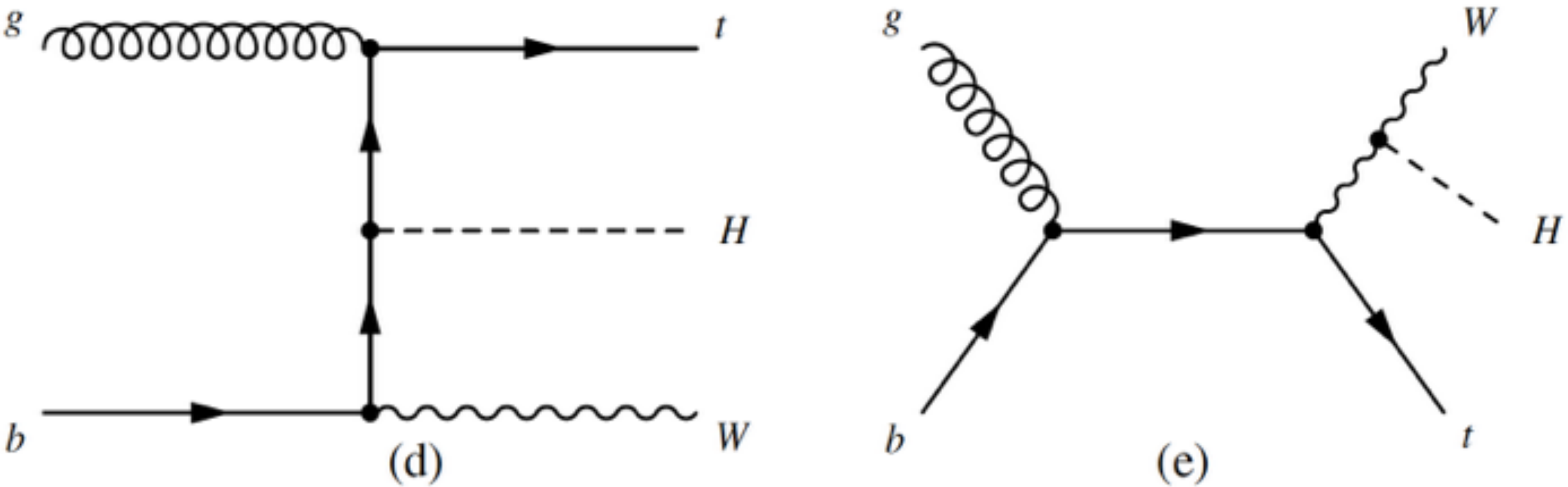
tHq composition (W,t) interference



(b) (c)

$$\sigma\left(qg \rightarrow tHq'(b)\right) \sim \quad 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$$

WtH composition



$$\sigma(gb \to tHW) \sim \quad 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$$

The Seven Decay Modes Probes

$$\Gamma_{b\bar{b}} \sim k_b^2$$

$$\Gamma_{\tau\tau} \sim k_\tau^2$$

$$\Gamma_{WW} \sim k_W^2$$

$$\Gamma_{ZZ} \sim k_Z^2$$

$$\Gamma_{\mu\mu} \sim k_\mu^2$$

$$\kappa_{Z\gamma}^2 \sim \quad 1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_t^2 - 0.12 \cdot \kappa_W \kappa_t$$

$$\kappa_\gamma^2 \sim \quad 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$$

$$k_H^2 = \sum_f k_f^2 BR_f^{SM}$$

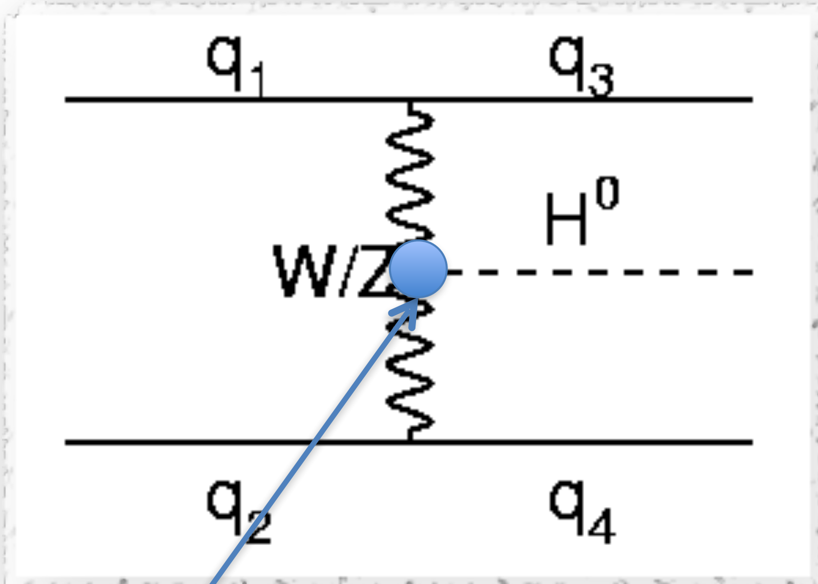
$$\kappa_H^2 \sim \quad \begin{array}{l} 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + \\ 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + \\ 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2 \end{array}$$

Resolving Degeneracy

Can we resolve the degeneracy, disentangle $\mu_i^{\ f} = \left[\mu_i \times \rho^f \right]$ $\rho^f = \frac{BR^f}{BR^f_{SM}}$

The degeneracy can be broken by parameterize the strength parameters with couplings and introduce constraints which reduce the number of p.o.i. and allow reasonable fits.

Disentangling The Couplings

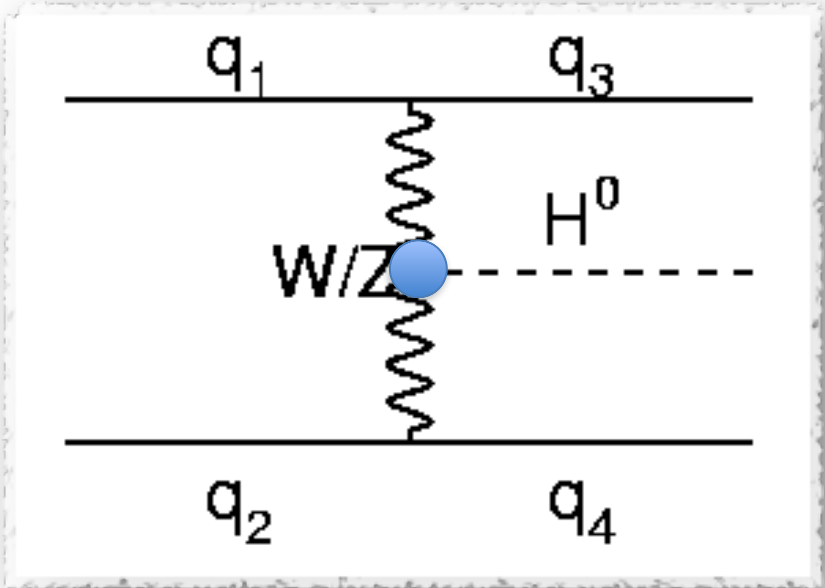


$$\rho^{WW}_{BR} = \frac{BR_{WW}}{BR^{SM}_{WW}} = \frac{\Gamma_{WW} / \Gamma_{H}}{\Gamma^{SM}_{WW} / \Gamma^{SM}_{H}} = \frac{k_W^2}{k_H^2}$$

$$\mu_{VBF} = k^2_{VBF} = k_w^2 BR^{WW}_{SM} + k_Z^2 BR^{ZZ}_{SM}$$

$$\mu^{WW}_{VBF} = [\mu_{VBF}\rho^{WW}_{BR}] = \left(k_W^2 BR^{SM}_{WW} + k_Z^2 BR^{SM}_{ZZ}\right) \cdot \frac{k_W^2}{k_H^2}$$

Disentangling The Couplings

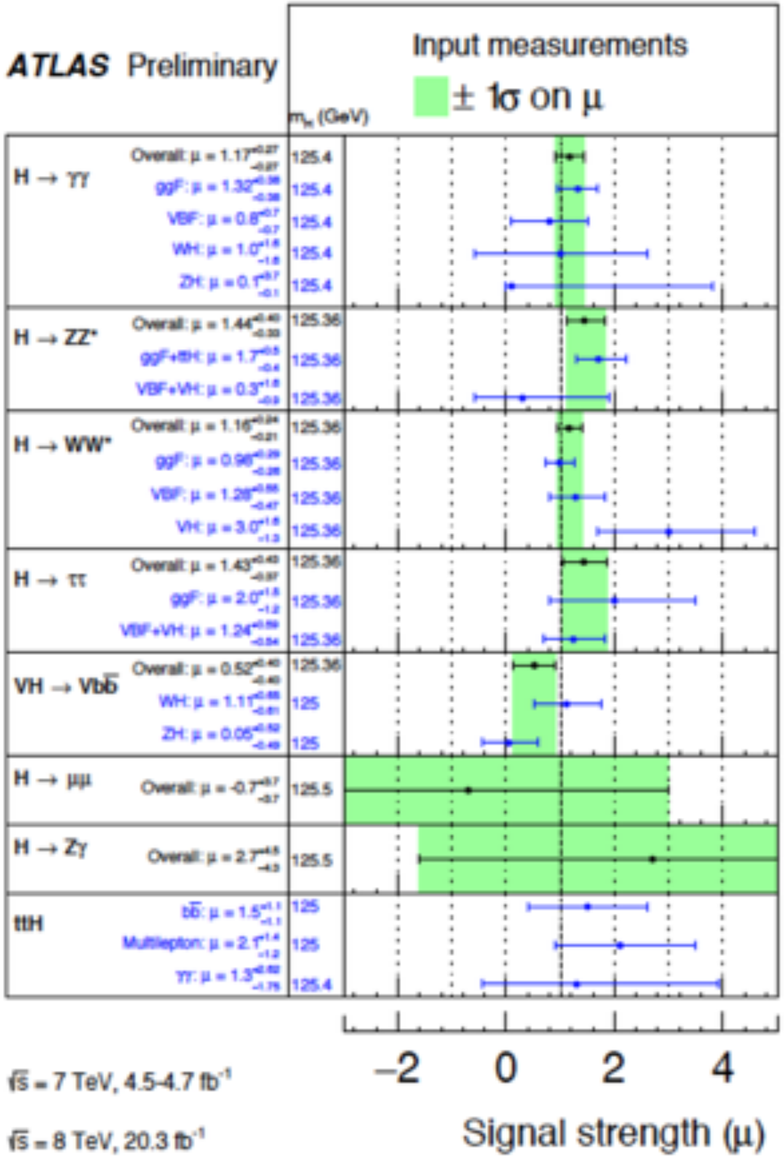


$$\mu^{WW}_{VBF} = [\mu_{VBF}\rho^{WW}_{BR}] = \left(k_W^2 BR^{SM}_{WW} + k_Z^2 BR^{SM}_{ZZ}\right)\cdot\frac{k_W^2}{k_H^2}$$

The simplest non-trivial model is ($k_{F,}$ k_V) where all Fermion couplings are set to k_F and all Boson couplings to k_V

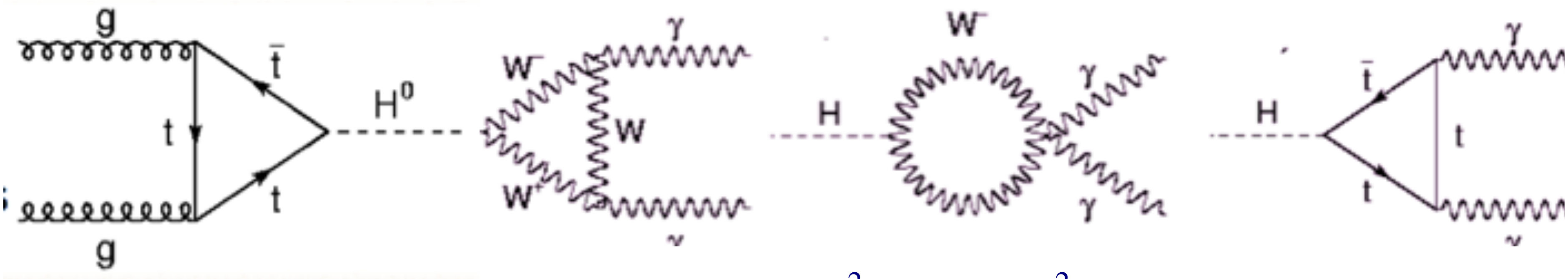
$$\mu^{WW}_{VBF} = [\mu_{VBF}\rho^{WW}_{BR}] = \frac{k_V^2\cdot k_V^2}{0.76k_F^2 + 0.24k_V^2}$$

The Measurements



$$\mu_i^f = \left[\mu_i \times \rho^f \right] \qquad \rho^f = \frac{BR^f}{BR^f_{SM}}$$

Disentangling The Couplings



$$(\sigma \cdot BR)(gg \to H \to \gamma\gamma) \sim \frac{k_g^2(k_b, k_t) \cdot k_\gamma^2(k_b, k_t, k_\tau, k_W)}{k_H^2(k_Z, k_W, k_\tau, k_t, k_b)}$$

Note, couplings are dependent on the Higgs mass

In the (k_F, k_V) benchmark:

$$\sigma(ggF) \times BR(H \to \gamma\gamma) \sim \frac{k_F^2 \cdot k_\gamma^2(k_F, k_F, k_F, k_V)}{0.74 k_F^2 + 0.26 k_V^2}$$

$$\sigma(VBF) \times BR(H \to \gamma\gamma) \sim \frac{k_V^2 \cdot k_\gamma^2(k_F, k_F, k_F, k_V)}{0.74 k_F^2 + 0.26 k_V^2}$$

$$\sigma(ggF) \times BR(H \to WW, ZZ) \sim \frac{k_F^2 \cdot k_V^2}{0.75 k_F^2 + 0.25 k_V^2}$$

$$\sigma(VBF) \times BR(H \to WW, ZZ) \sim \frac{k_V^2 \cdot k_V^2}{0.74 k_F^2 + 0.26 k_V^2}$$

$$\sigma(VBF, VH) \times BR(H \to \tau\tau, bb) \sim \frac{k_V^2 \cdot k_F^2}{0.74 k_F^2 + 0.26 k_V^2}$$

Coupling Benchmarks

To make reasonable fits we introduce physics motivated scenarios.

Testing the compatibility of the discovered Higgs with the SM is to test also where is it NOT compatible, spotting where NP might sneak in.

NP can appear in either the Higgs width and/or in the loops.

$$k_H^2 = \frac{\sum\limits_{j=Z,W,t,b,\tau} k_j^2 \Gamma_j^{SM} + k_\gamma^2 \Gamma_\gamma^{SM} + k_g^2 \Gamma_g^{SM}}{\Gamma_H^{SM}}$$

$$\Gamma_H = k_H^2 \Gamma_H^{SM} + BR_{\mathrm{i,u}} \Gamma_H$$

Γ_H	k_γ	k_g	Scenario	Comments
$\Gamma_H = k_H^2 \Gamma_H^{SM}$	$K_\gamma(k_t, k_W)$	$K_g(k_t, k_b)$	SM	only SM particles in loops
$\Gamma_H = k_H^2 \Gamma_H^{SM} + BR_{\mathrm{i,u}} \Gamma_H$	k_γ	k_g	$NP <$	m_{NP} could be $< \frac{m_H}{2}$
$\Gamma_H = k_H^2 \Gamma_H^{SM}$	k_γ	k_g	$NP >$	$m_{NP} > \frac{m_H}{2}$
$\Gamma_H = k_H^2 \Gamma_H^{SM} + BR_{\mathrm{i,u}} \Gamma_H$	$K_\gamma(k_t, k_W)$	$K_g(k_t, k_b)$	NP_{NL}	NP (not in the loops) neither charged nor coloured

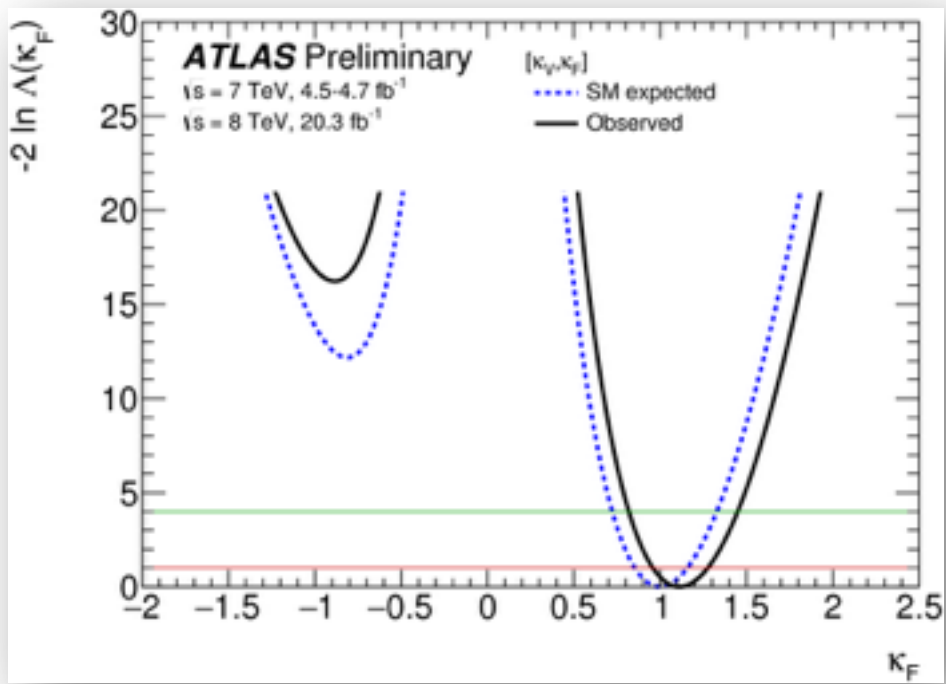
Vector and Fermion Couplings

HERE WE ASSUME ONLY SM PARTICLES ARE CONTRIBUTING TO THE LOOP AND ALL FERMION COUPLINGS EQUAL AND ALL VECTOR COUPLINGS EQUAL

$$k_\gamma^2 = |1.28\, k_W - 0.28\, k_t|^2$$

The $\gamma\gamma$ loop induces some sensitivity to the relative sign between k_t and k_W

The high observed $H \rightarrow ZZ$ pulls k_W up, allowing high $\gamma\gamma$ rate and keeps k_t positive



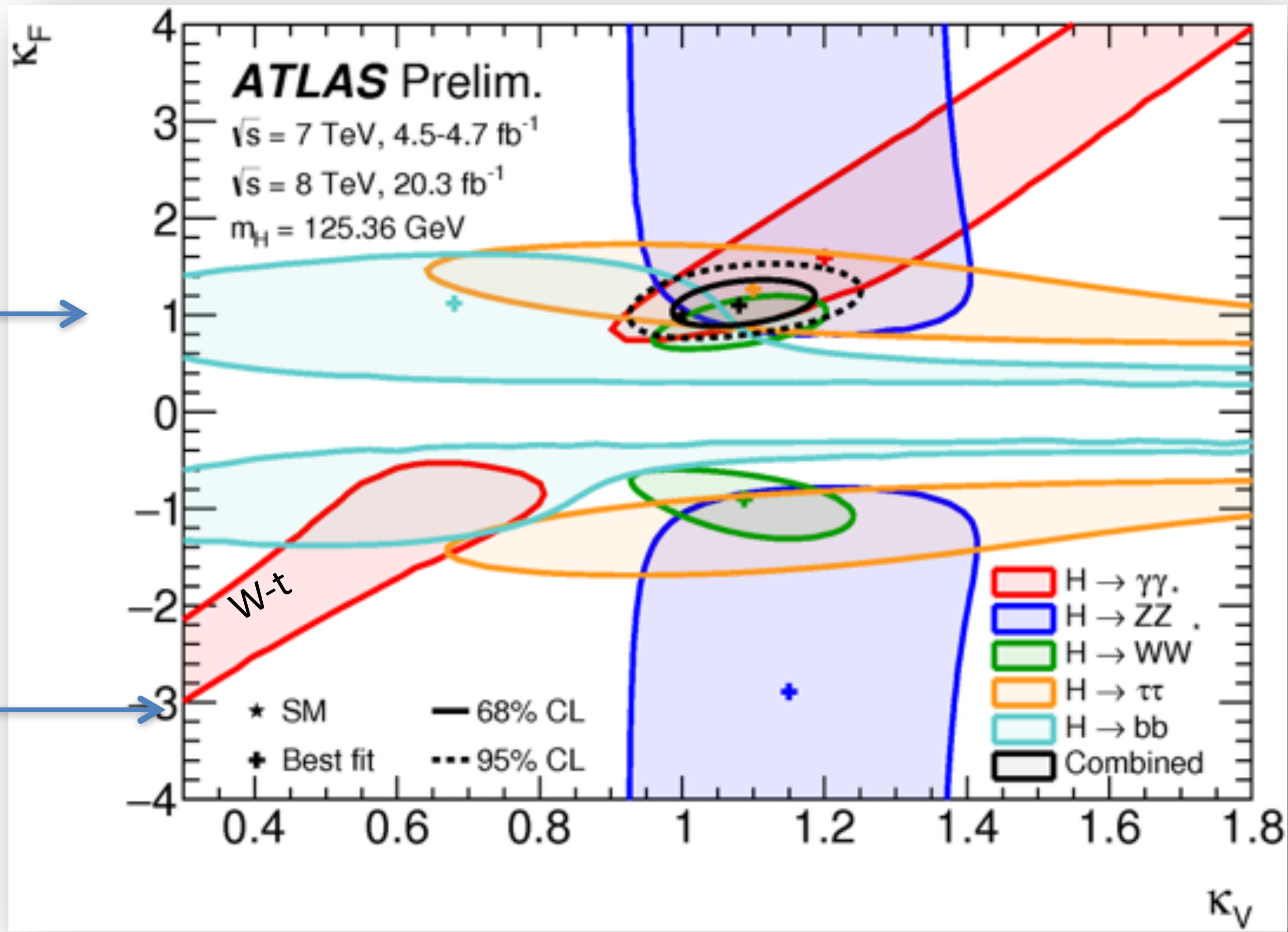
ATLAS: 2D compatibility with SM 10%

Vector and Fermion Couplings

This plot tells a story:

SM –
No Tension

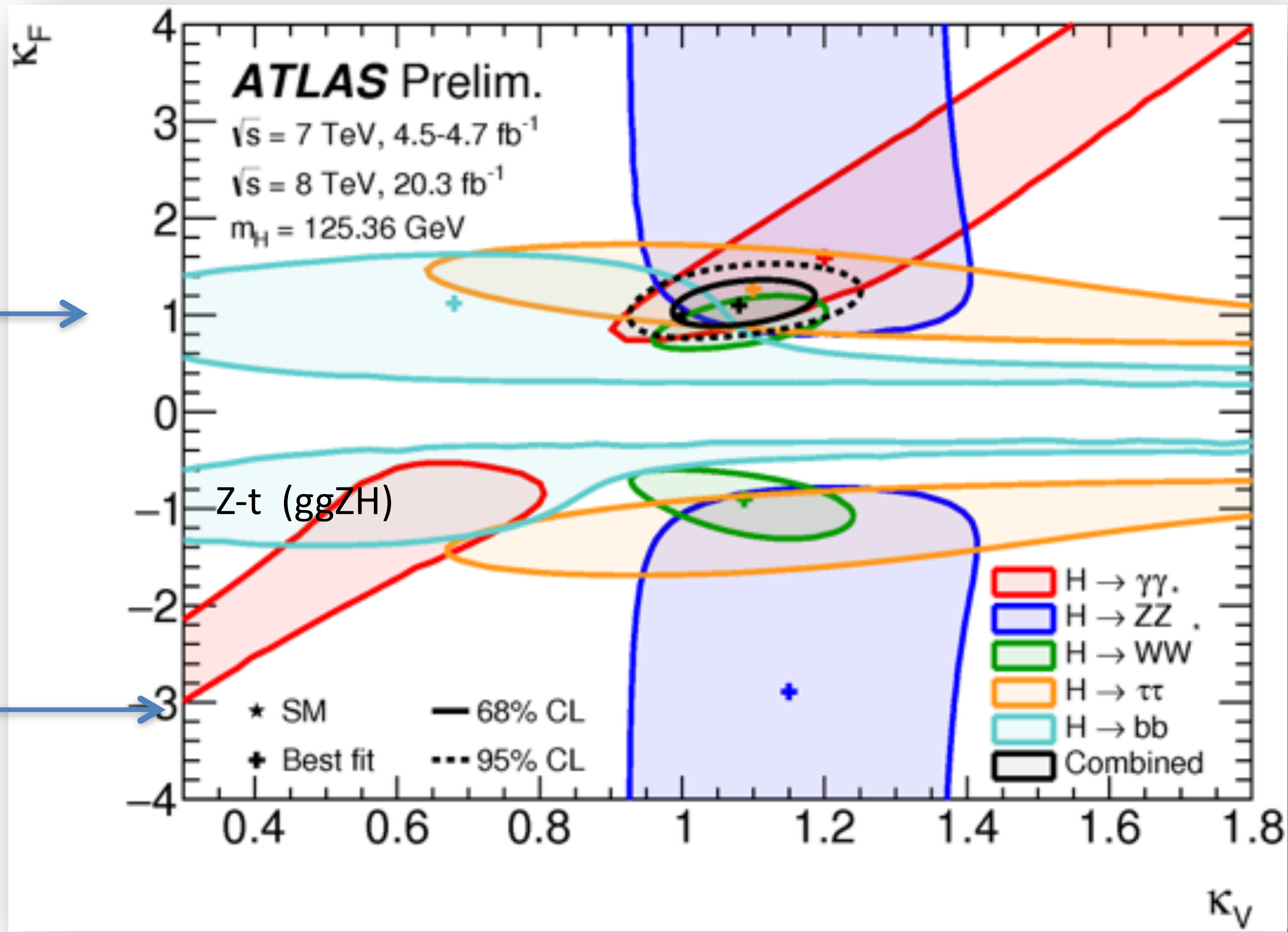
Tension
Drifting
apart



Vector and Fermion Couplings

This plot tells a story:

SM –
No Tension



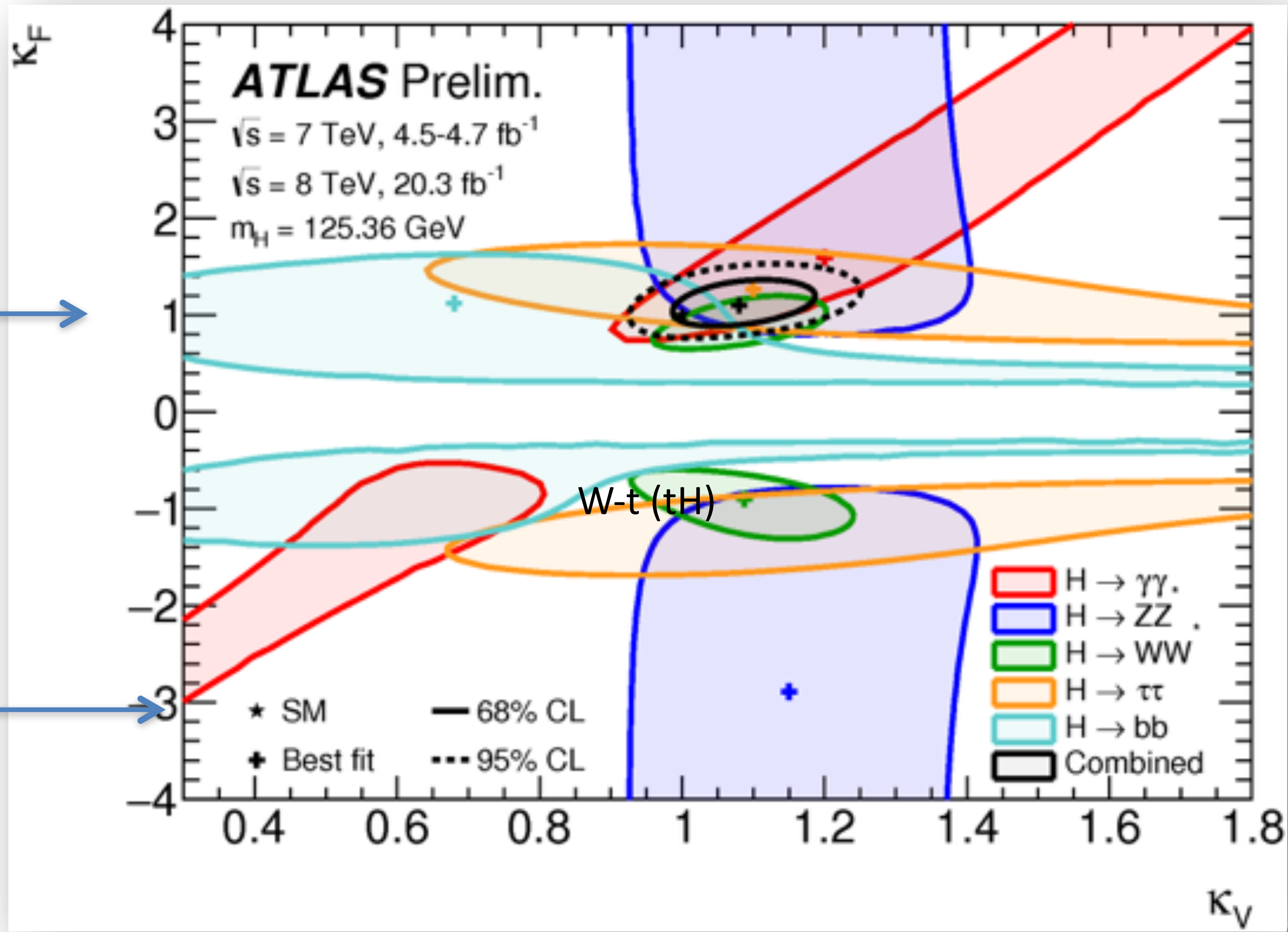
Tension
Drifting
apart

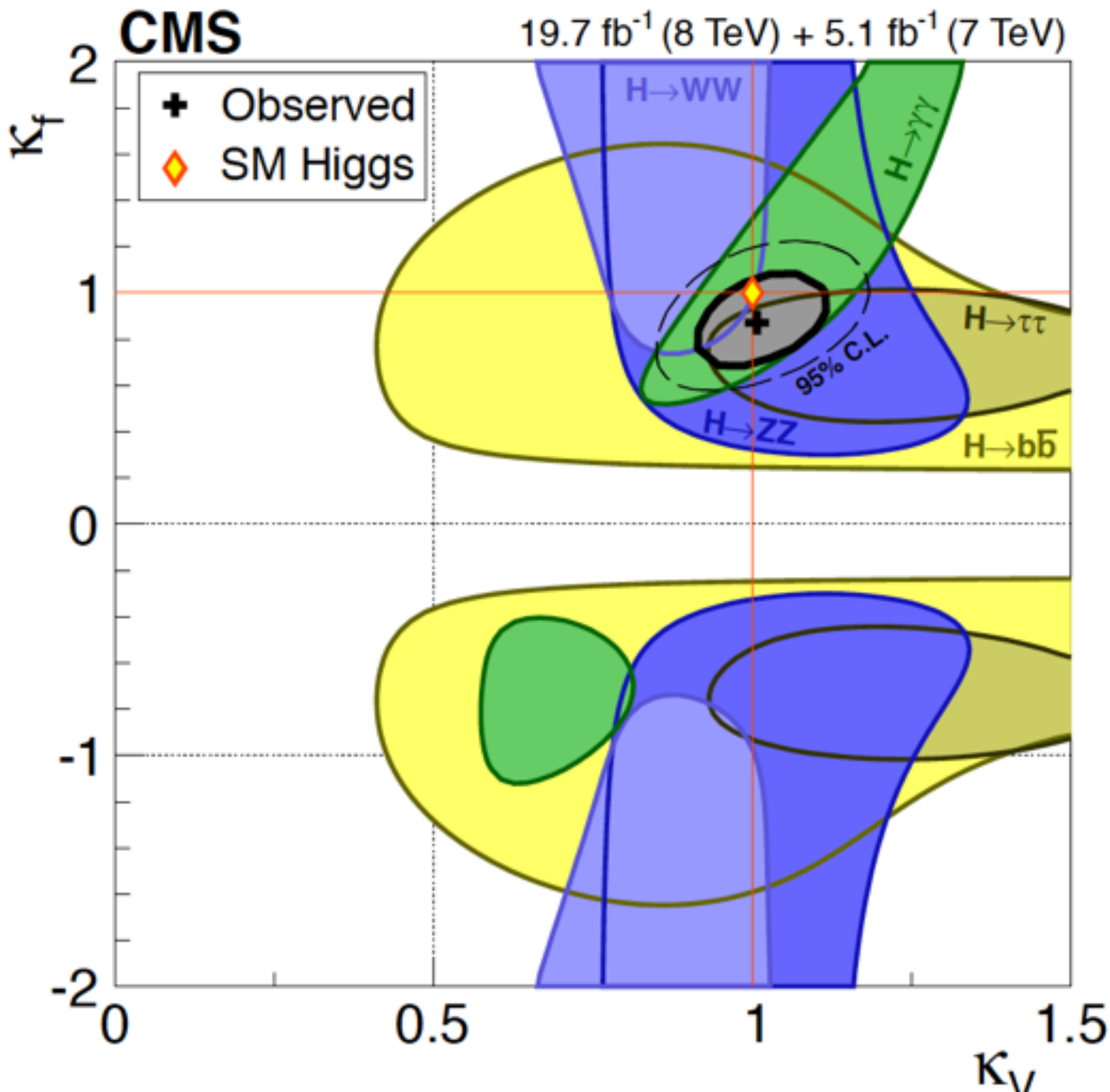
Vector and Fermion Couplings

This plot tells a story:

SM –
No Tension

Tension
Drifting
apart




CMS
19.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)
Observed
SM Higgs
H→WW
H→γγ
H→ττ
95% C.L.
H→ZZ
H→bb̄
κf
κV
2
1
0
-1
-2
0
0.5
1
1.5

Vector and Fermion Couplings

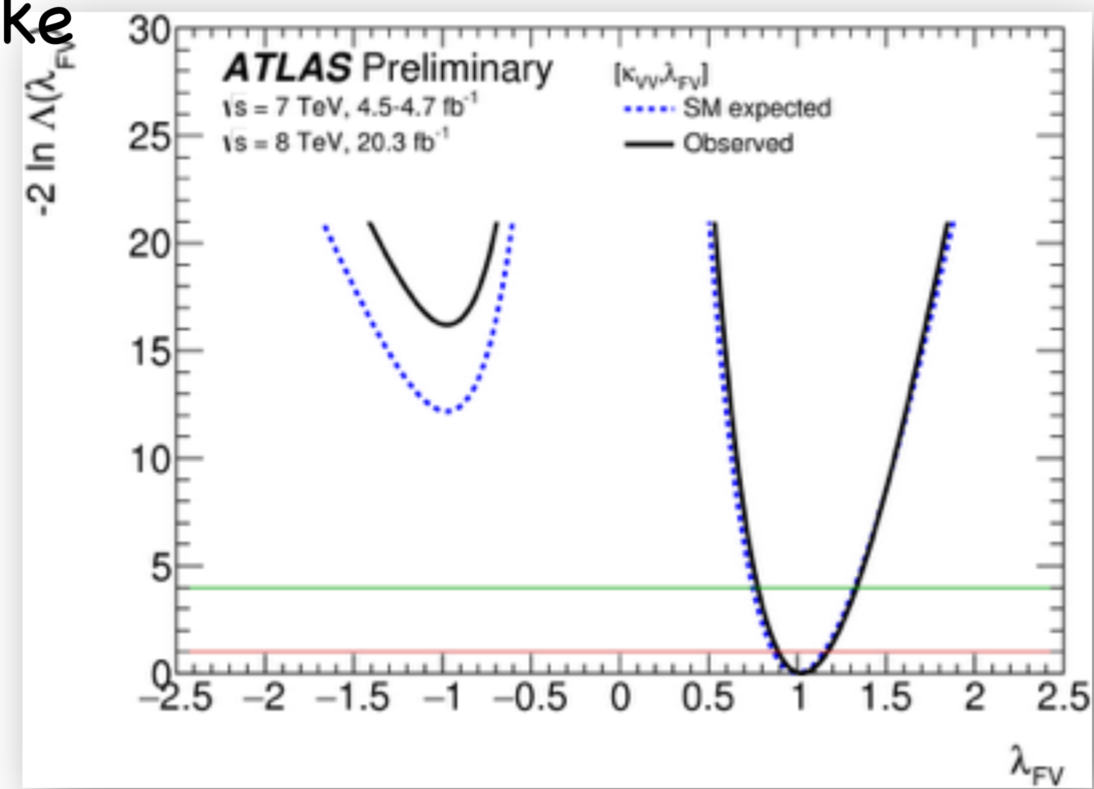
NO ASSUMPTION ON TOTAL WIDTH

Here we need to go to ratios (we cannot take advantage of total width)

p.o.i. are λ_{FV}

$$k_{VV} = k_V \cdot k_V / k_H$$

$$\lambda_{FV} = 1.02 \pm 0.14$$



Probing Custodia Symmetryu

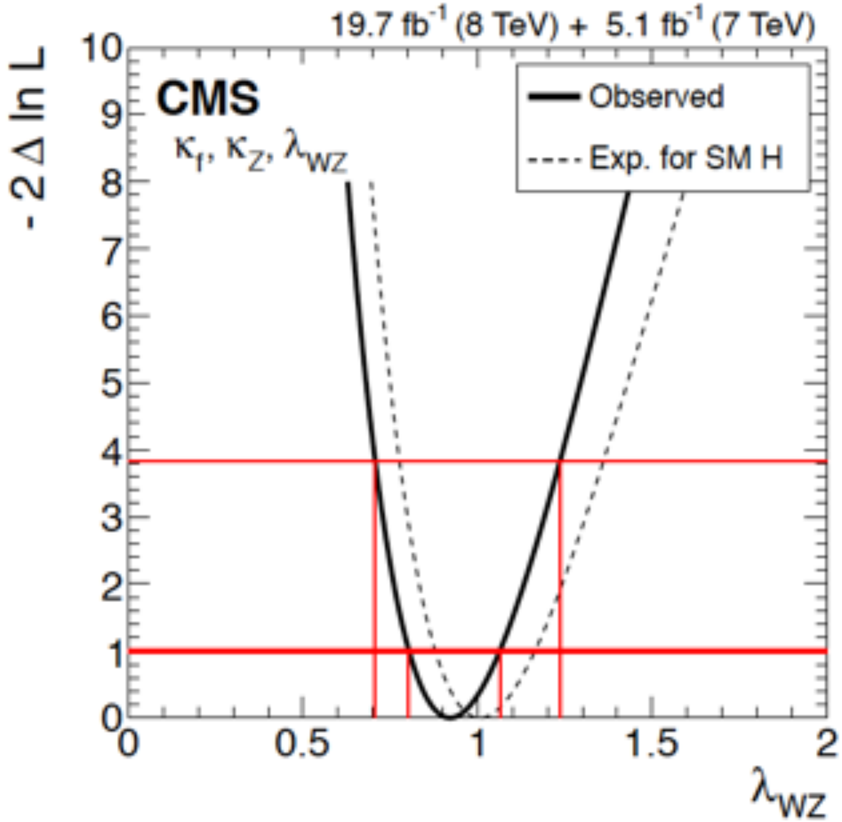
Identical coupling scale factors for the W- and Z-boson are required within tight bounds by the SU(2)L custodial

symmetry and the ρ parameter measurements at LEP (~1)

$$\rho = \frac{m_W}{m_Z cos\theta_W}$$

$$\lambda_{WZ} = \frac{k_W}{k_Z}$$

Assume no invisible width



NP>mH/2

Here NP will enter in the loop and will not contribute to BRi,u

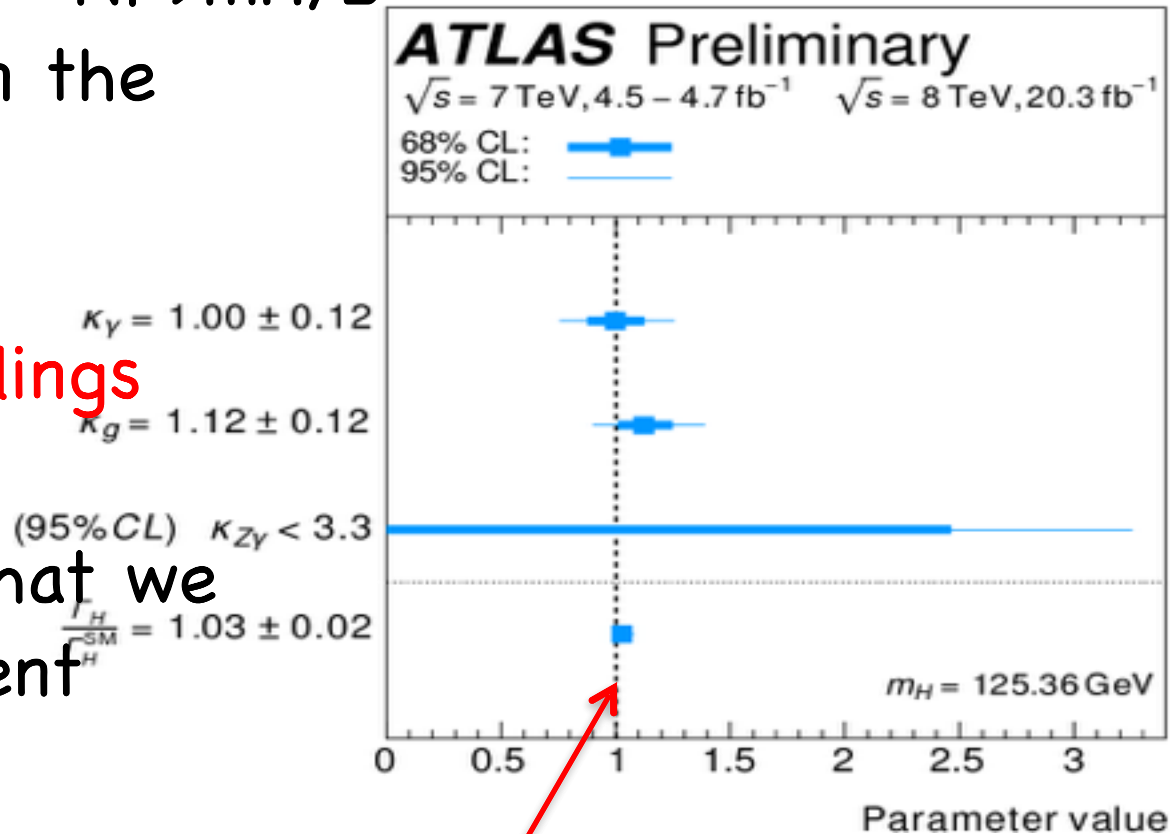
We assume SM couplings for all particles

We cannot assume that we know the loops content

So we introduce

$$k_\gamma, k_g, k_{Z\gamma}$$

$$\Gamma_H(\kappa_j, BR_{i.,u.}) = \frac{\kappa_H^2(\kappa_j)}{(1 - BR_{i.,u.})}\Gamma_H^{SM}$$



Constraint on the width is obtained by Replacing kg by kH

$$k_f^2 = \frac{\Gamma_f}{\Gamma_f^{SM}} \qquad k_H^2 = \frac{\sum k_f^2 \Gamma_f^{SM}}{\Gamma_H^{SM}}$$

NP<mH/2

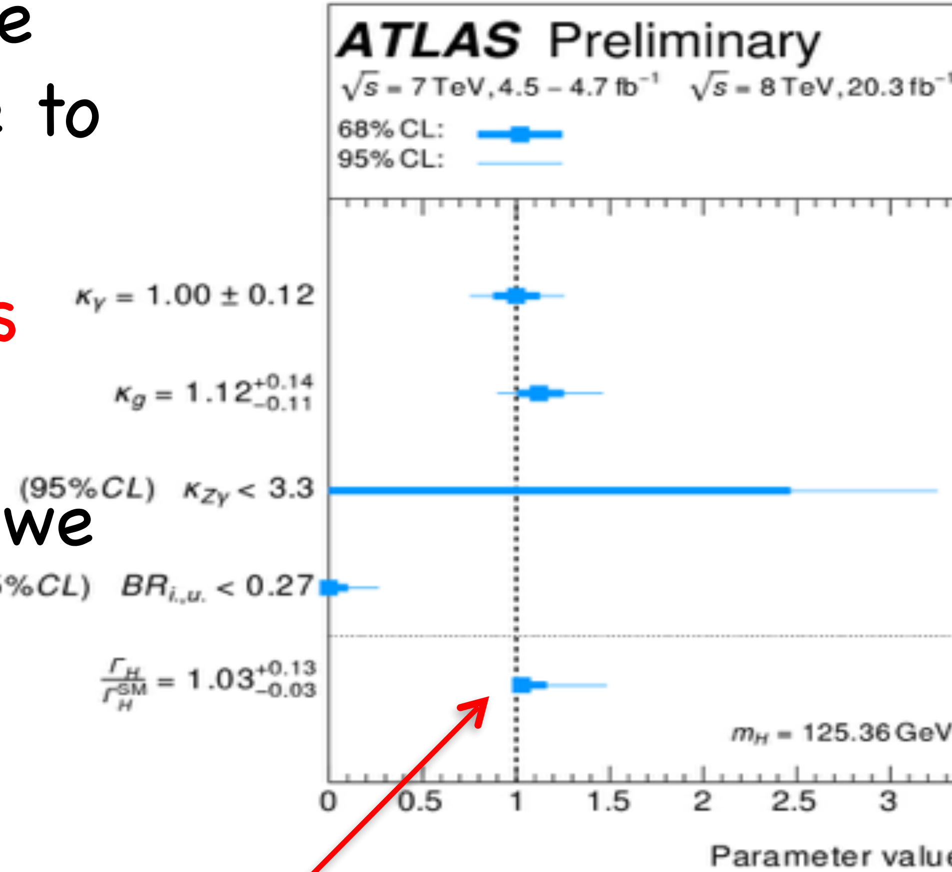
Here NP will enter in the loop and will contribute to BRi,u

We assume SM couplings for all particles

We cannot assume that we know the loops content

So we introduce

$$k_\gamma, k_g, k_{Z\gamma}$$



Constraint on the width is obtained by Replacing kg by kH

$$\Gamma_H(\kappa_j, BR_{i.,u.}) = \frac{\kappa_H^2(\kappa_j)}{(1 - BR_{i.,u.})}\Gamma_H^{SM}$$

$$k_f^2 = \frac{\Gamma_f}{\Gamma_f^{SM}} \qquad k_H^2 = \frac{\sum k_f^2 \Gamma_f^{SM}}{\Gamma_H^{SM}}$$

Generic Model

Remember the 9 Observables Fit?

$$\sigma_i \cdot BR^f = \left(\sigma_{ggF} \cdot BR^{WW}\right) \cdot \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \cdot \left(\frac{BR^f}{BR^{WW}}\right)$$

$$\sigma_i \cdot BR^f = \left(\sigma_{ggF} \cdot BR^{WW}\right) \cdot \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \cdot \left(\frac{\Gamma_f}{\Gamma_{WW}}\right)$$

9 parameters fit:

$$\left(\sigma_{ggF} \cdot BR^{WW}\right), \left(\frac{\sigma_{VBF}}{\sigma_{ggF}}\right), \left(\frac{\sigma_{WH}}{\sigma_{ggF}}\right), \left(\frac{\sigma_{ZH}}{\sigma_{ggF}}\right), \left(\frac{\sigma_{ttH}}{\sigma_{ggF}}\right), \left(\frac{\Gamma_{\gamma\gamma}}{\Gamma_{WW}}\right), \left(\frac{\Gamma_{ZZ}}{\Gamma_{WW}}\right), \left(\frac{\Gamma_{\tau\tau}}{\Gamma_{WW}}\right), \left(\frac{\Gamma_{bb}}{\Gamma_{WW}}\right)$$

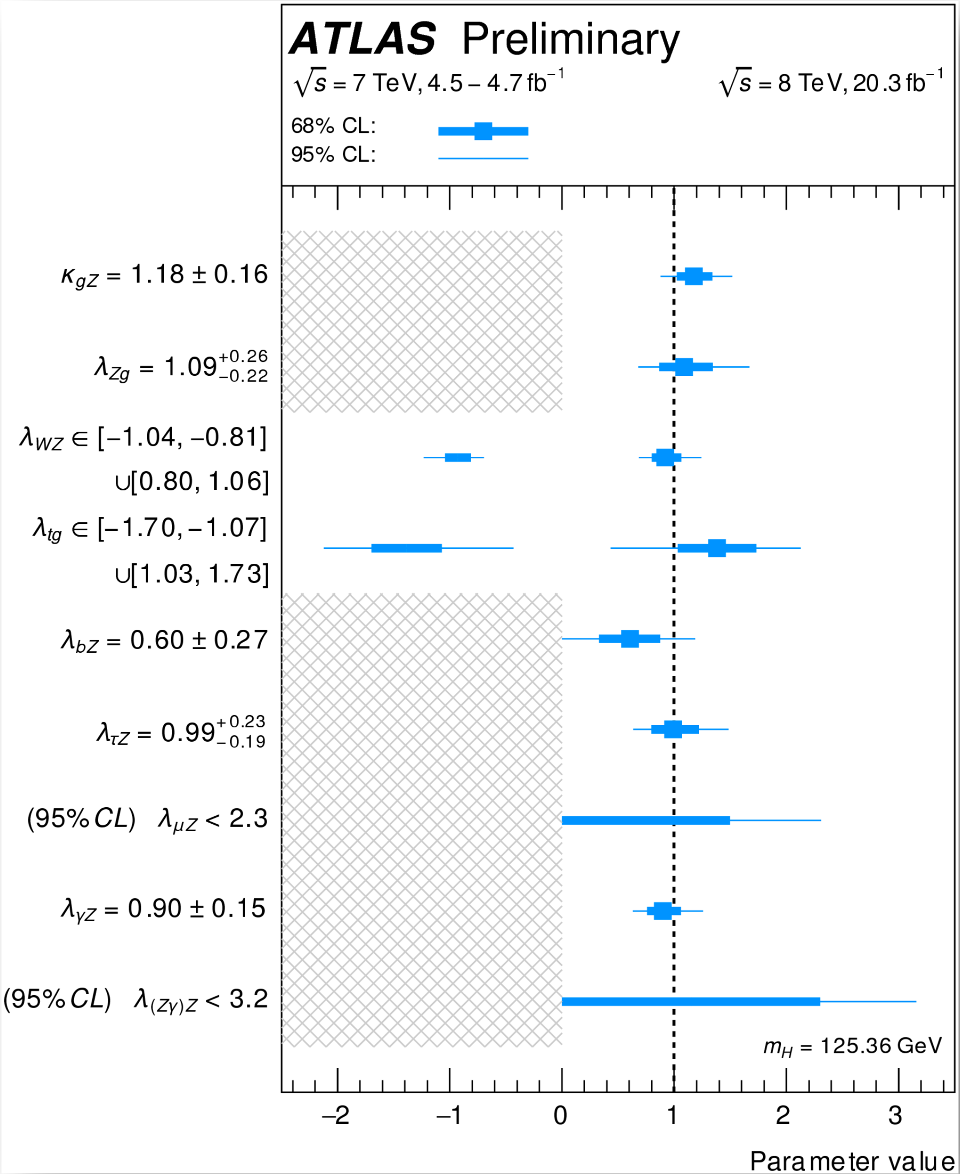
Generic Model – The mother of all fits

An alternative fit is

a fit to ratios of couplings without any assumption on total width or new physics

$$
\begin{aligned}
\kappa_{gZ} &= \kappa_g \cdot \kappa_Z/\kappa_H \\
\lambda_{Zg} &= \kappa_Z/\kappa_g \\
\lambda_{WZ} &= \kappa_W/\kappa_Z \\
\lambda_{tg} &= \kappa_t/\kappa_g \\
\lambda_{bZ} &= \kappa_b/\kappa_Z \\
\lambda_{\tau Z} &= \kappa_\tau/\kappa_Z \\
\lambda_{\mu Z} &= \kappa_\mu/\kappa_Z \\
\lambda_{\gamma Z} &= \kappa_\gamma/\kappa_Z \\
\lambda_{(Z\gamma)Z} &= \kappa_{Z\gamma}/\kappa_Z .
\end{aligned}
$$

Generic Model – The mother of all fits



$$
\begin{aligned}
\kappa_{gZ} &= \kappa_g \cdot \kappa_Z / \kappa_H \\
\lambda_{Zg} &= \kappa_Z / \kappa_g \\
\lambda_{WZ} &= \kappa_W / \kappa_Z \\
\lambda_{tg} &= \kappa_t / \kappa_g \\
\lambda_{bZ} &= \kappa_b / \kappa_Z \\
\lambda_{\tau Z} &= \kappa_\tau / \kappa_Z \\
\lambda_{\mu Z} &= \kappa_\mu / \kappa_Z \\
\lambda_{\gamma Z} &= \kappa_\gamma / \kappa_Z \\
\lambda_{(Z\gamma)Z} &= \kappa_{Z\gamma} / \kappa_Z .
\end{aligned}
$$

The SM Full Monty

Generic Model I (ATLAS)

All couplings to SM particles are fitted independently

Without loss of generality k_W assumed positive,

fit is sensitive to sign of k_t/k_W from $tH, H\gamma\gamma, HZ\gamma$

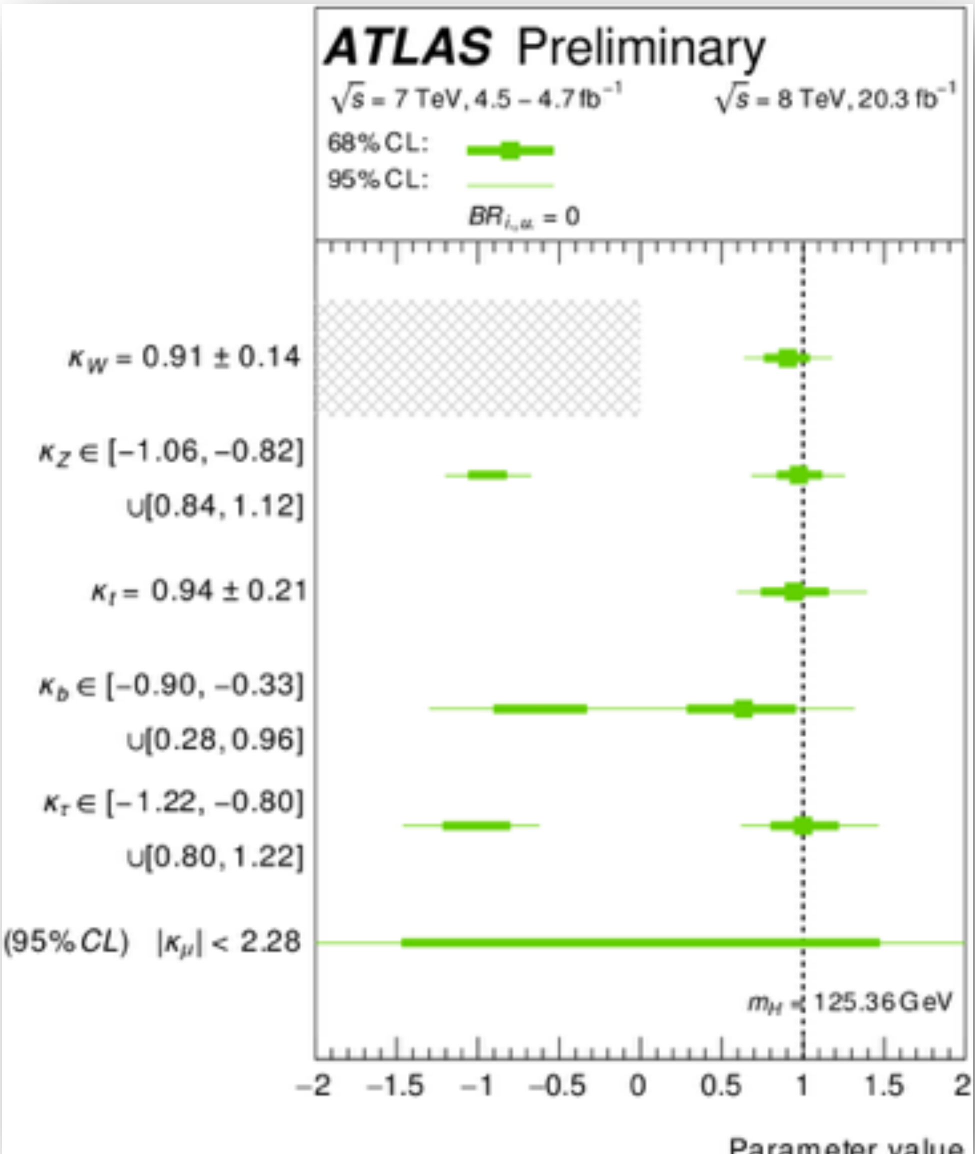
fit is sensitive to relative sign Z/t from gg—>ZH

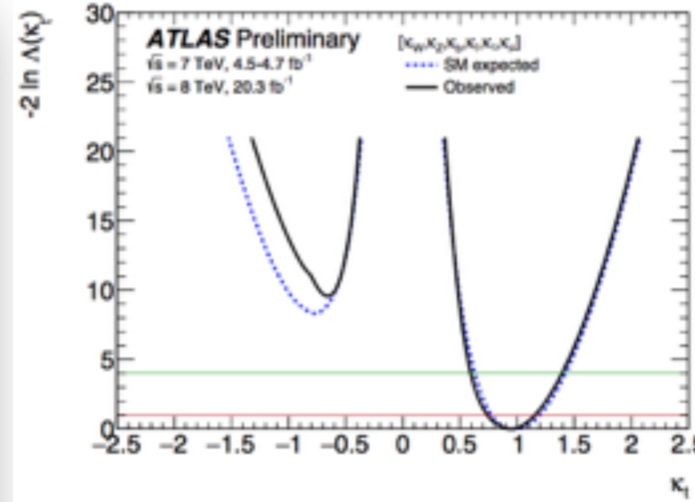
which gives indirect sensitivity to sign of W/Z

fit is also sensitive to relative signbetweem b/t (from ggF)

p.o.i	$k_W, k_Z, k_b, k_\tau, k_t, k_\mu$
Loop &	$k_g(k_b, k_t)$ $\mathrm{k}_\gamma(k_b, k_t, k_\tau, k_W)$
Width	
Constrains	$k_H^2(k_b, k_t, k_\tau, k_W, k_Z) = \frac{\sum k_j^2 \Gamma_j^{SM}}{\Gamma_H^{SM}}$

The SM Full Monty





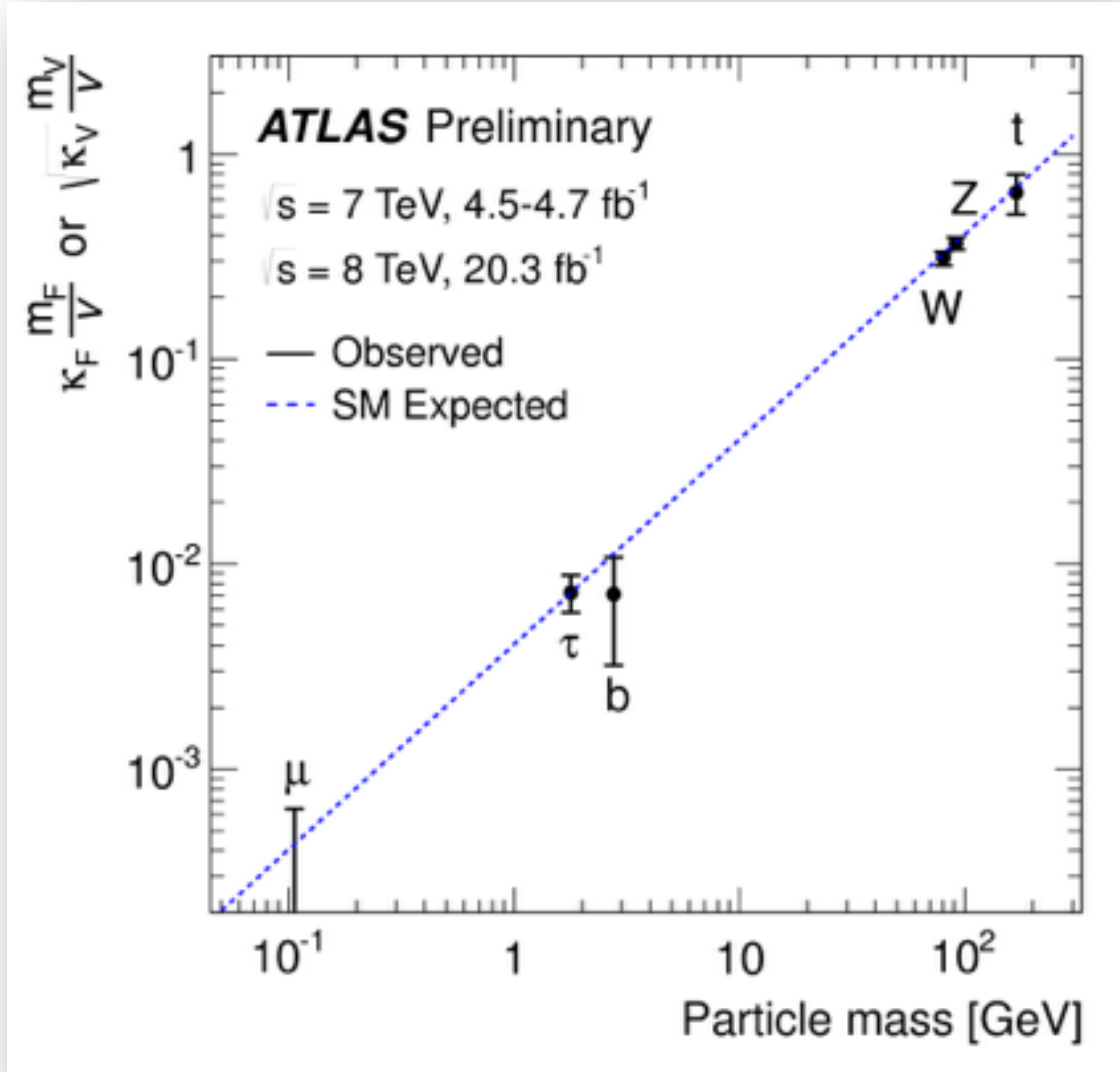
The SM Full Monty PR plot

$$Y_F = \frac{Y_F}{Y_F^{SM}} Y_F^{SM} = k_F \frac{m_F}{v}$$

$$\frac{g_{HVV}^{SM}}{v} = \frac{m_V^2}{v^2}$$

$$\sqrt{\frac{g_{HVV}}{v}} = \sqrt{k_V g_{HVV}^{SM}} =$$

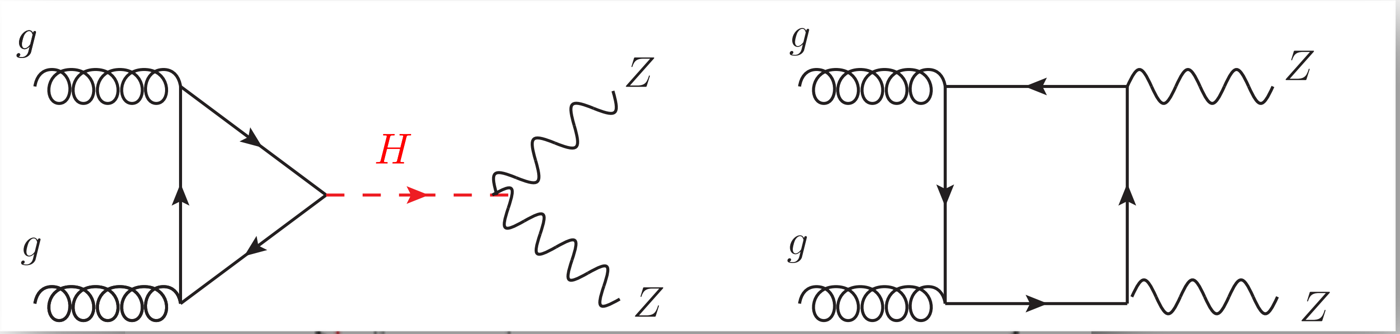
$$\sqrt{k_V}\,\frac{m_V}{v}$$



Higgs Width

OffShell in a NutShell

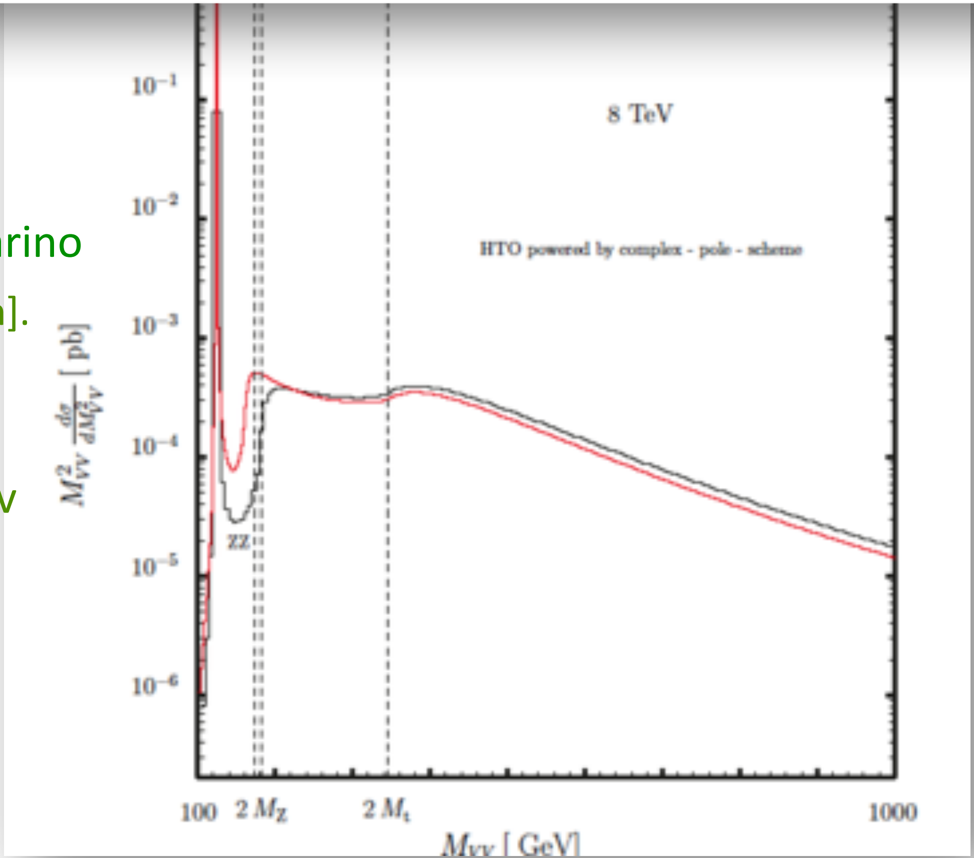
OffShell in a NutShell



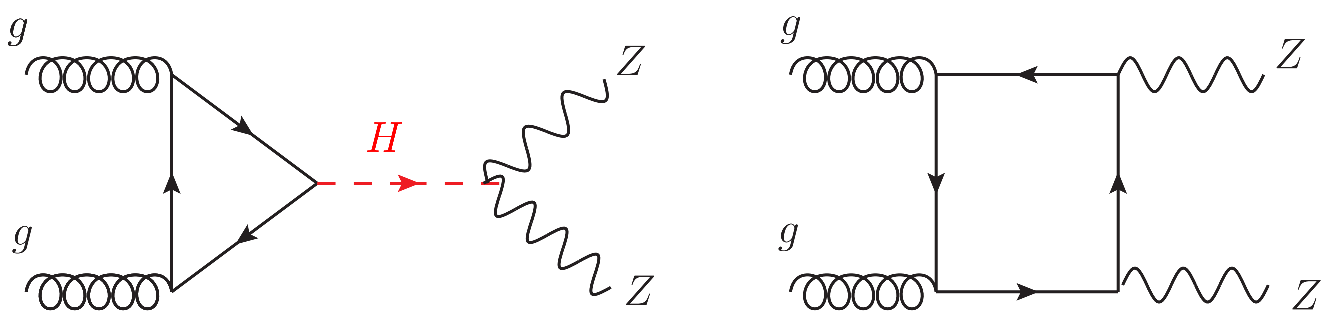
N. Kauer and G. Passarino
arXiv:1206.4803 [hep-ph].

F. Caola and K. Melnikov

C. Englert and
M. Spannowsky



OffShell in a NutShell



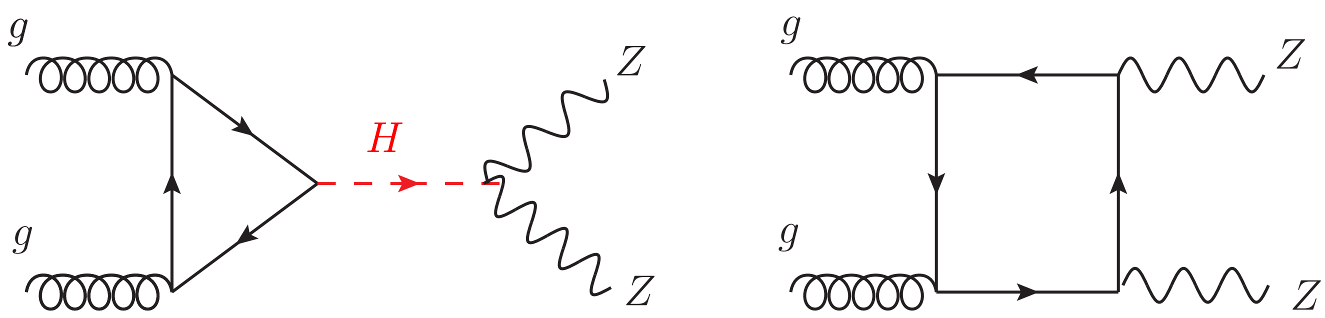
$$\mu_{OnShell} \equiv \frac{\sigma_{OnShell}(gg \to H \to ZZ^*)}{\sigma_{OnShell}(gg \to H \to ZZ^*)_{SM}} = \kappa_g^2 \kappa_Z^2 \frac{\Gamma_H^{SM}}{\Gamma_H}$$

$$\mu_{OffShell} \equiv \frac{\sigma_{OffShell}(gg \to H \to ZZ^*)(\sqrt{\hat{s}})}{\sigma_{OffShell}(gg \to H \to ZZ^*)_{SM}(\sqrt{\hat{s}})} \approx \kappa^2_{g,OffShell}(\sqrt{\hat{s}})\kappa^2_{Z,OffShell}(\sqrt{\hat{s}})$$

Assume the experimental resolution is not sensitive to the dependence on $\sqrt{\hat{s}}$

$$\frac{\mu_{OffShell}}{\mu_{OnShell}} = \frac{\kappa^2_{g,OffShell}\kappa^2_{Z,OffShell}}{\kappa_g^2 \kappa_Z^2 \frac{\Gamma_H^{SM}}{\Gamma_H}}$$

OffShell in a Nut Shell



$$\frac{\mu_{OffShell}}{\mu_{OnShell}} = \frac{\kappa^2_{g,OffShell}\kappa^2_{Z,OffShell}}{\kappa^2_g \kappa^2_Z \dfrac{\Gamma^{SM}_H}{\Gamma_H}}$$

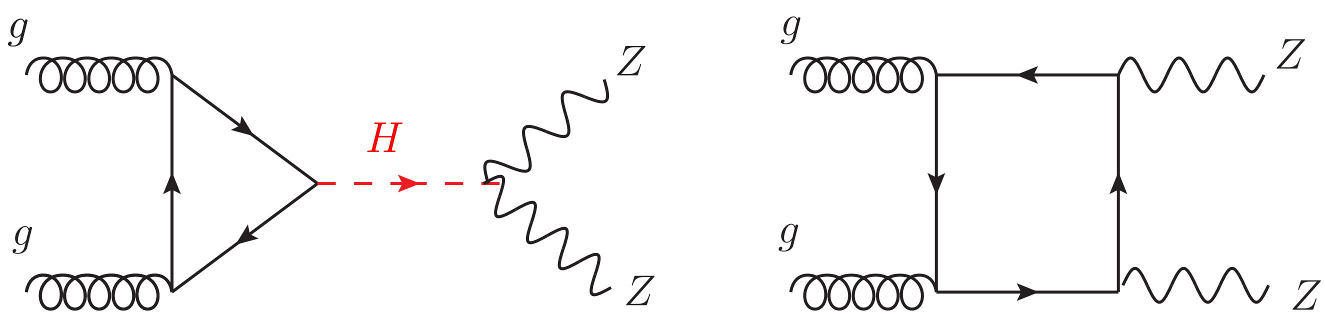
Caveats:

1. New Physics might enter into the calculation of the OffShell couplings, which we do not take into account

2. The Higgs signal K-factor is known , the gg–>ZZ K-factor is yet unknown

3. One has to take into account interference between the signal (gg–>H–>ZZ) and the background (gg–>ZZ)

OffShell in a Nut Shell



Interference term proportion to $\sqrt{\mu_{OffShell}} = k_{g,OffShell} \cdot k_{V,OffShell}$

New Physics can alter the running of the couplings so we assume $k_g \cdot k_v \le k_{g,OffShell} \cdot k_{V,OffShell}$

No higher QCD calculations exist for gg—> ZZ, though they exist for the signal.

WE DEFINE A RATIO OF K FACTORS:

$$R^B_{H^*} = \frac{K(gg \to VV)}{K(gg \to H^* \to VV)} = \frac{K^B(m_{VV})}{k^{H^*}(m_{VV})}$$

OffShell in a Nut Shell

Interference term proportion to $\sqrt{\mu_{OffShell}} = k_{g,OffShell} \cdot k_{V,OffShell}$

New Physics can alter the running of the couplings so we assume $k_g \cdot k_v \leq k_{g,OffShell} \cdot k_{V,OffShell}$

No higher QCD calculations exist for gg—> ZZ, though they exist for the signal.
WE DEFINE A RATIO OF K FACTORS:

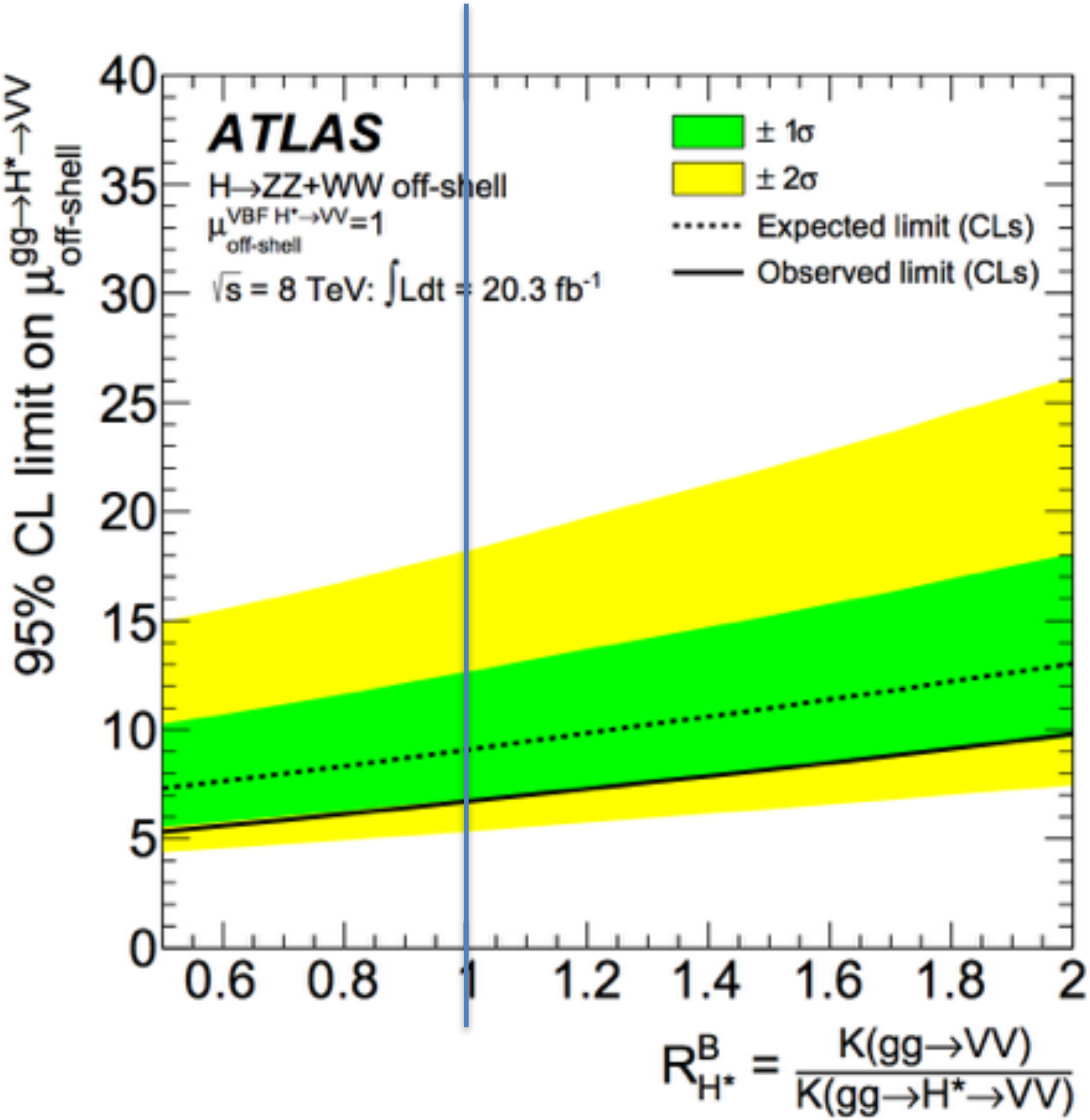
$$R^B_{H^*} = \frac{K(gg \to VV)}{K(gg \to H^* \to VV)} = \frac{K^B(m_{VV})}{K^{H^*}(m_{VV})}$$

$$\begin{aligned}\sigma_{gg\to(H^*\to)VV}(\mu_{\text{off-shell}}) &= \mathrm{K}^{H^*}(m_{VV}) \cdot \mu_{\text{off-shell}} \cdot \sigma^{\text{SM}}_{gg\to H^*\to VV} \\ &+ \sqrt{\mathrm{K}^{H^*}_{gg}(m_{VV}) \cdot \mathrm{K}^{\mathrm{B}}(m_{VV}) \cdot \mu_{\text{off-shell}}} \cdot \sigma^{\text{SM}}_{gg\to VV,\,\text{Interference}} \\ &+ \mathrm{K}^{\mathrm{B}}(m_{VV}) \cdot \sigma_{gg\to VV,\,\text{cont}} \,.\end{aligned}$$

Limit on OffShell signal strength

Agnostic to K factor

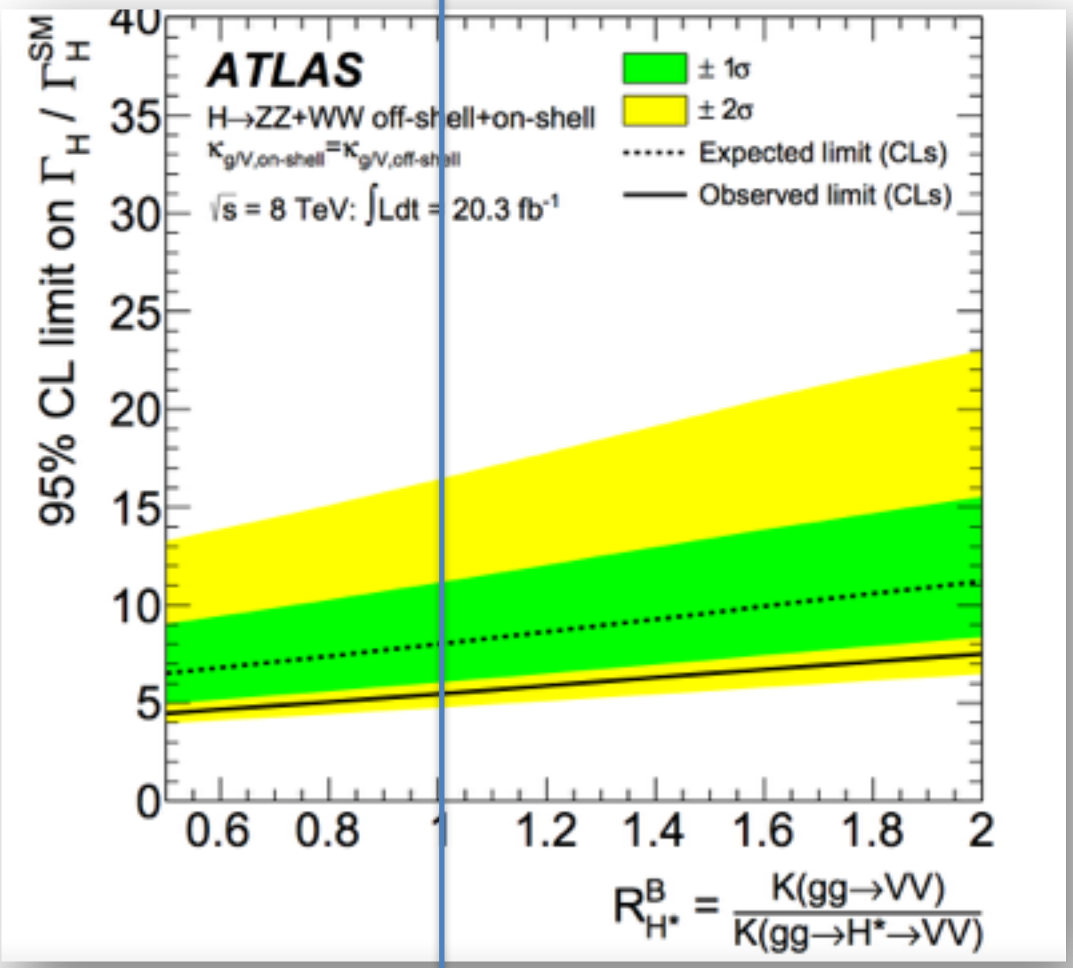
$\mu_{OffShell} < 6.9(7.9exp)$



$$\frac{\mu_{OffShell}}{\mu_{OnShell}} \geq \frac{\Gamma_H}{\Gamma_H^{SM}}$$

$$\Gamma_H \leq 5.5\Gamma_H^{SM}$$

$$\Gamma_H \leq 22.8\,MeV$$



	Observed			Median expected			Assumption
$R^B_{H^*}$	0.5	**1.0**	2.0	0.5	**1.0**	2.0	
Γ_H/Γ_H^{SM}	4.5	**5.5**	7.5	6.5	**8.0**	11.2	$\kappa_{i,\text{on-shell}} = \kappa_{i,\text{off-shell}}$
$R_{gg} = \kappa^2_{g,\text{off-shell}}/\kappa^2_{g,\text{on-shell}}$	4.7	**6.0**	8.6	7.1	**9.0**	13.4	$\kappa_{V,\text{on-shell}} = \kappa_{V,\text{off-shell}}, \Gamma_H/\Gamma_H^{SM}=1$

Spin and CP

Yang's Theorem (1948) and the Higgs Boson

Yang-Landau theorem states that a massive spin 1 particle cannot decay into two identical massless spin 1 particles.

The observation of $H \rightarrow \gamma\gamma$ can be taken as an evidence against a spin 1 nature of the Higgs.

The community concentrated on testing the spin $J^{PC}=0^{++}$ hypothesis of the Higgs against $J^{P}=0^{-}$ and spin 2 hypotheses.

Spin 0 Lagrangian

If the CP of the Higgs is a mixture of 0+ and 0- then the mass eigenstate is not a CP eigenstate.

In EFT the spin 0 Lagrangian of a scalar is given by $0^+ : SM$

$$L_0^V = \left\{ \frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu W^\mu \right\} X_0$$

$0^+ : 2HDM$

$$L_0^V = -\frac{1}{2}\frac{1}{\Lambda} \left\{ \frac{1}{2} Z_{\mu\nu} Z^{\mu\nu} + W_{\mu\nu} W^{\mu\nu} \right\} X_0$$

$0^- : 2HDM$

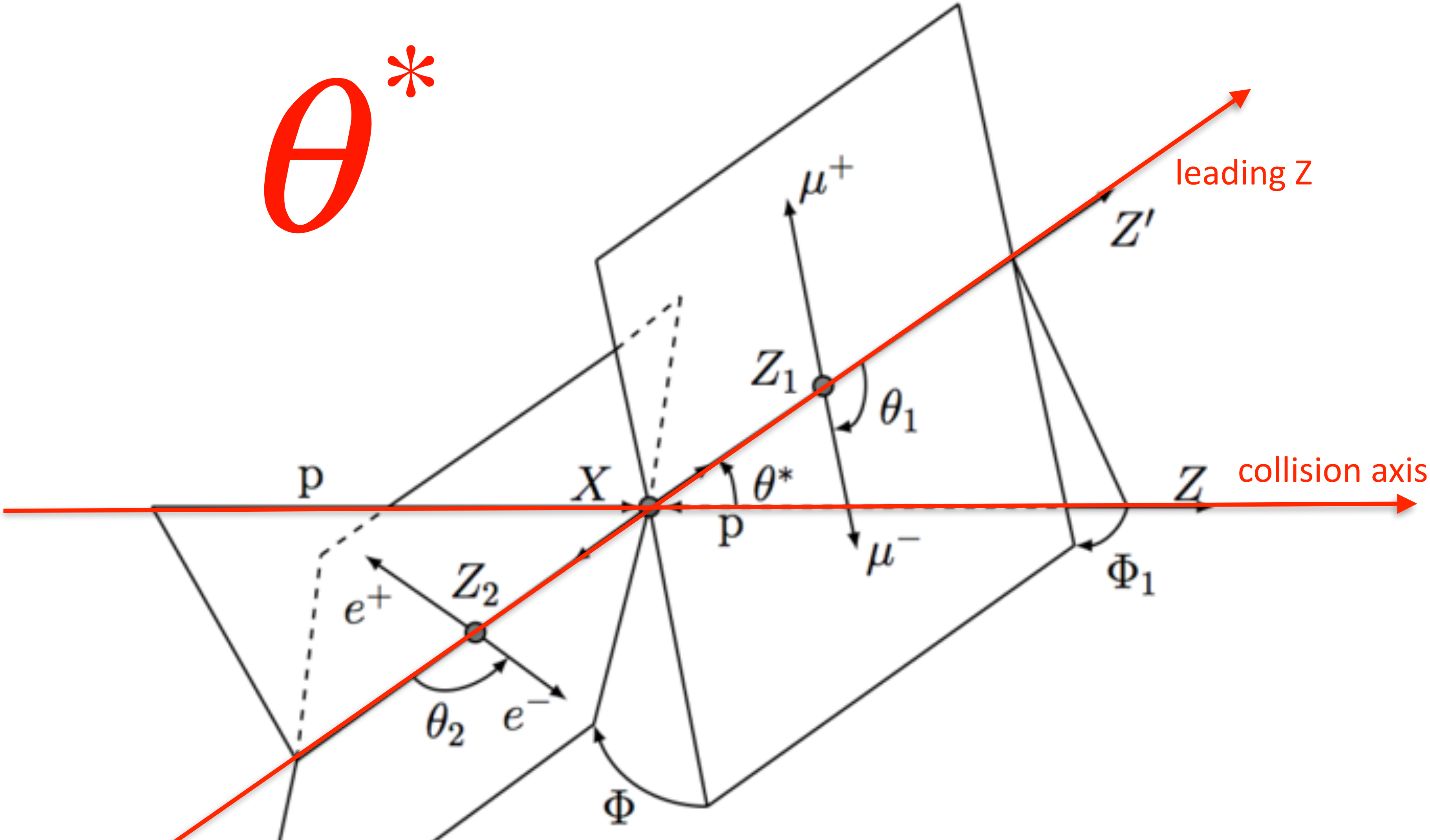
$$L_0^V = -\frac{1}{2\sqrt{2}}\frac{1}{\Lambda} \left\{ \frac{1}{2} Z_{\mu\nu} \tilde{Z}^{\mu\nu} + W_{\mu\nu} \tilde{W}^{\mu\nu} \right\} X_0 \qquad \tilde{V}^{\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} V_{\rho\sigma}$$

Spin 0 Lagrangian

$$\mathcal{L}_0^V = \Big\{c_\alpha \kappa_{\rm SM}\left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu}\right] - \tfrac{1}{4}\tfrac{1}{\Lambda}\left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] - \tfrac{1}{2}\tfrac{1}{\Lambda}\left[c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu}\right]\Big\} X_0.$$

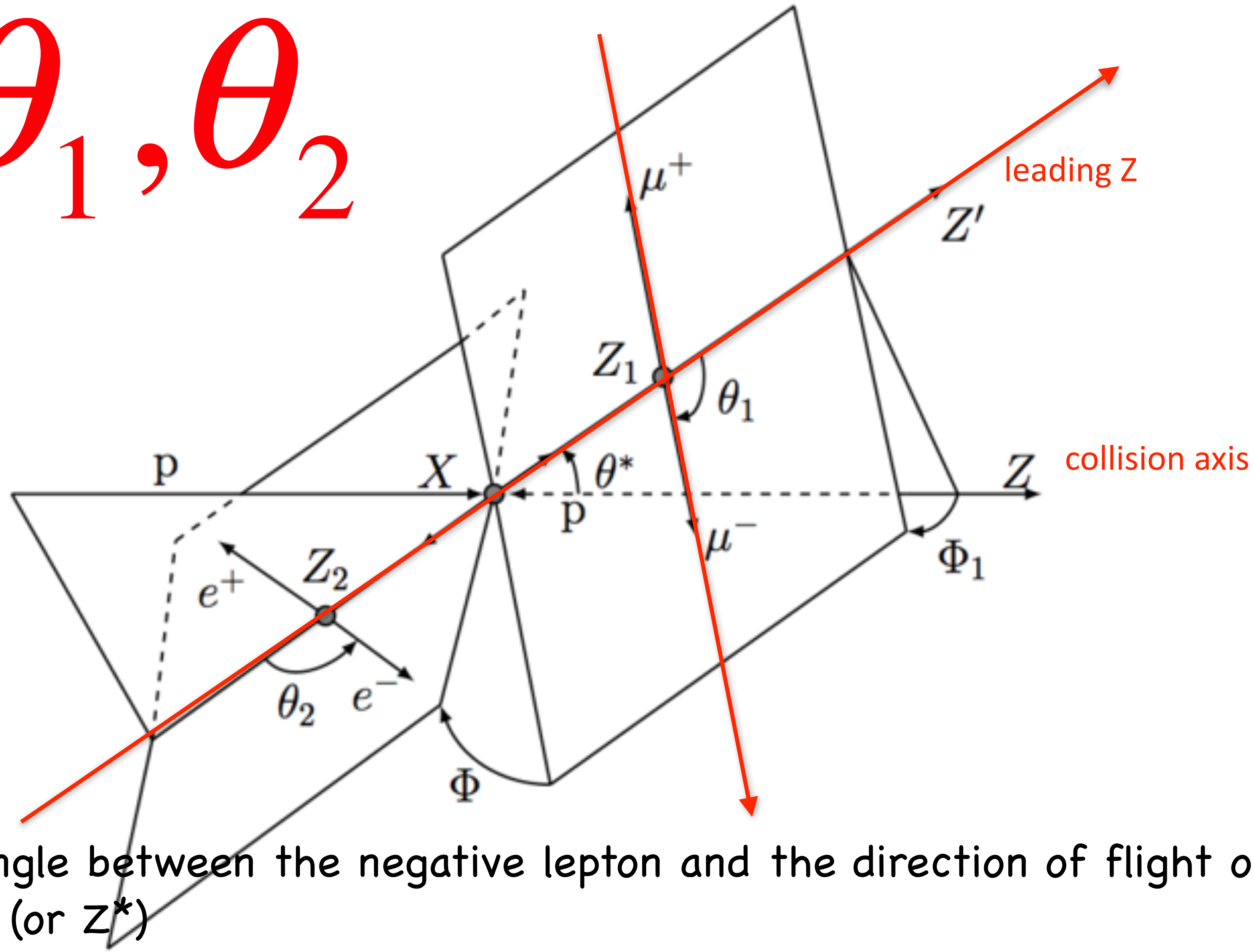
J^P	Model	Choice of tensor couplings			
		$\kappa_{\rm SM}$	κ_{HVV}	κ_{AVV}	α
0^+	Standard Model Higgs boson	1	0	0	0
0_h^+	BSM spin-0 CP-even	0	1	0	0
0^-	BSM spin-0 CP-odd	0	0	1	$\pi/2$

θ^*



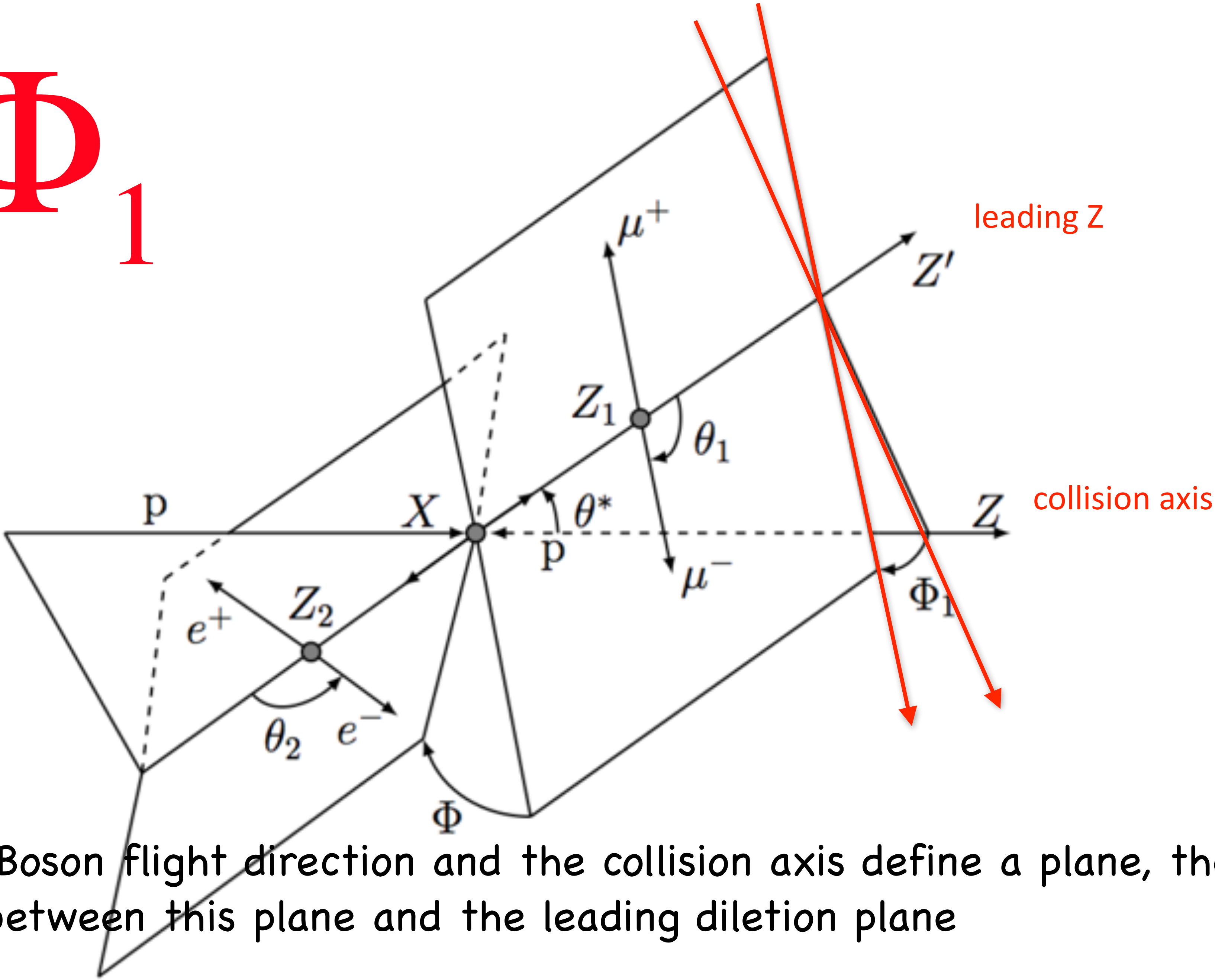
The angle between the leading Z (Z1) in the rest frame of the 4-l and the collision axis

θ_1, θ_2



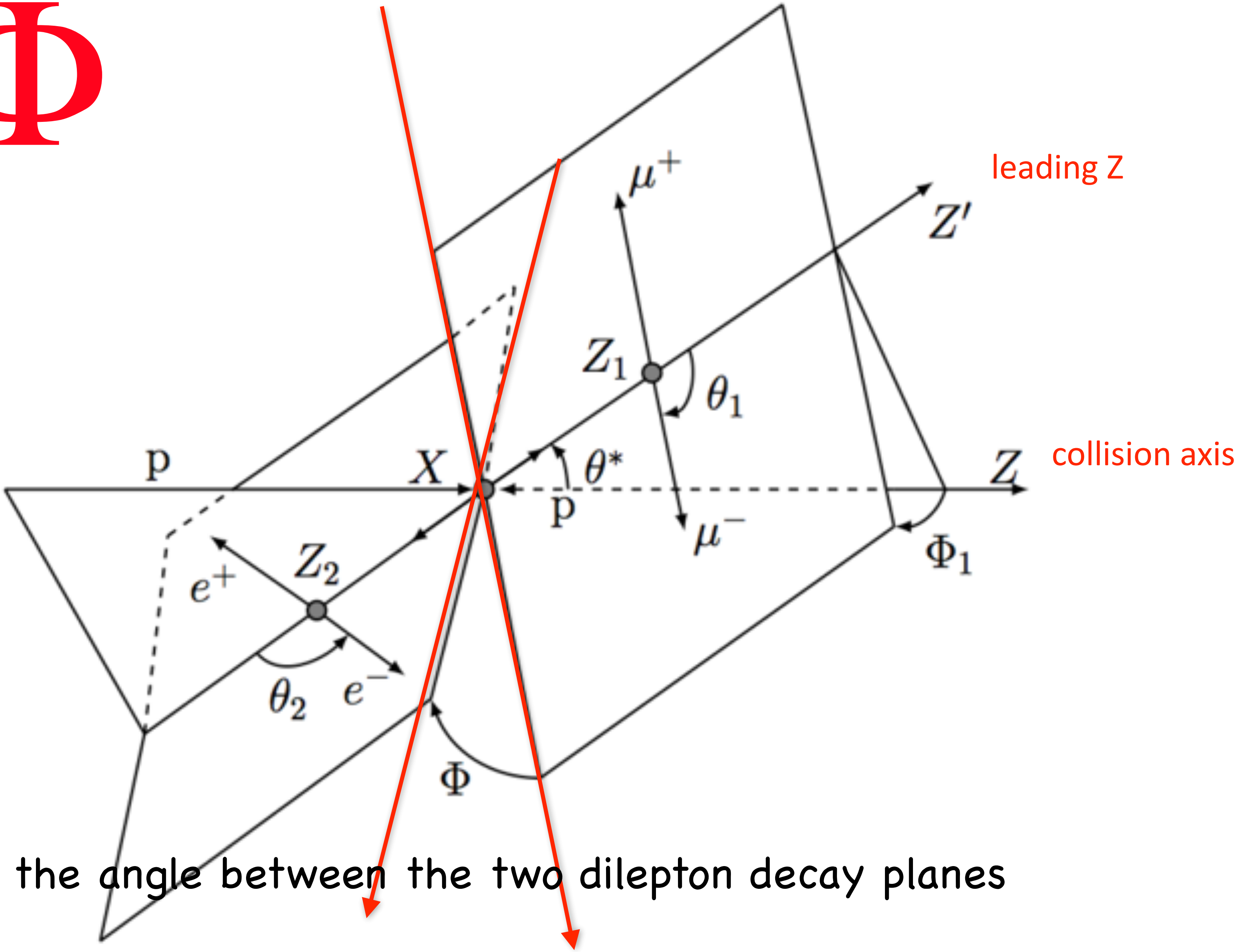
the angle between the negative lepton and the direction of flight of the Z (or Z*)

Φ_1



The Z Boson flight direction and the collision axis define a plane, the angle between this plane and the leading diletion plane

Φ



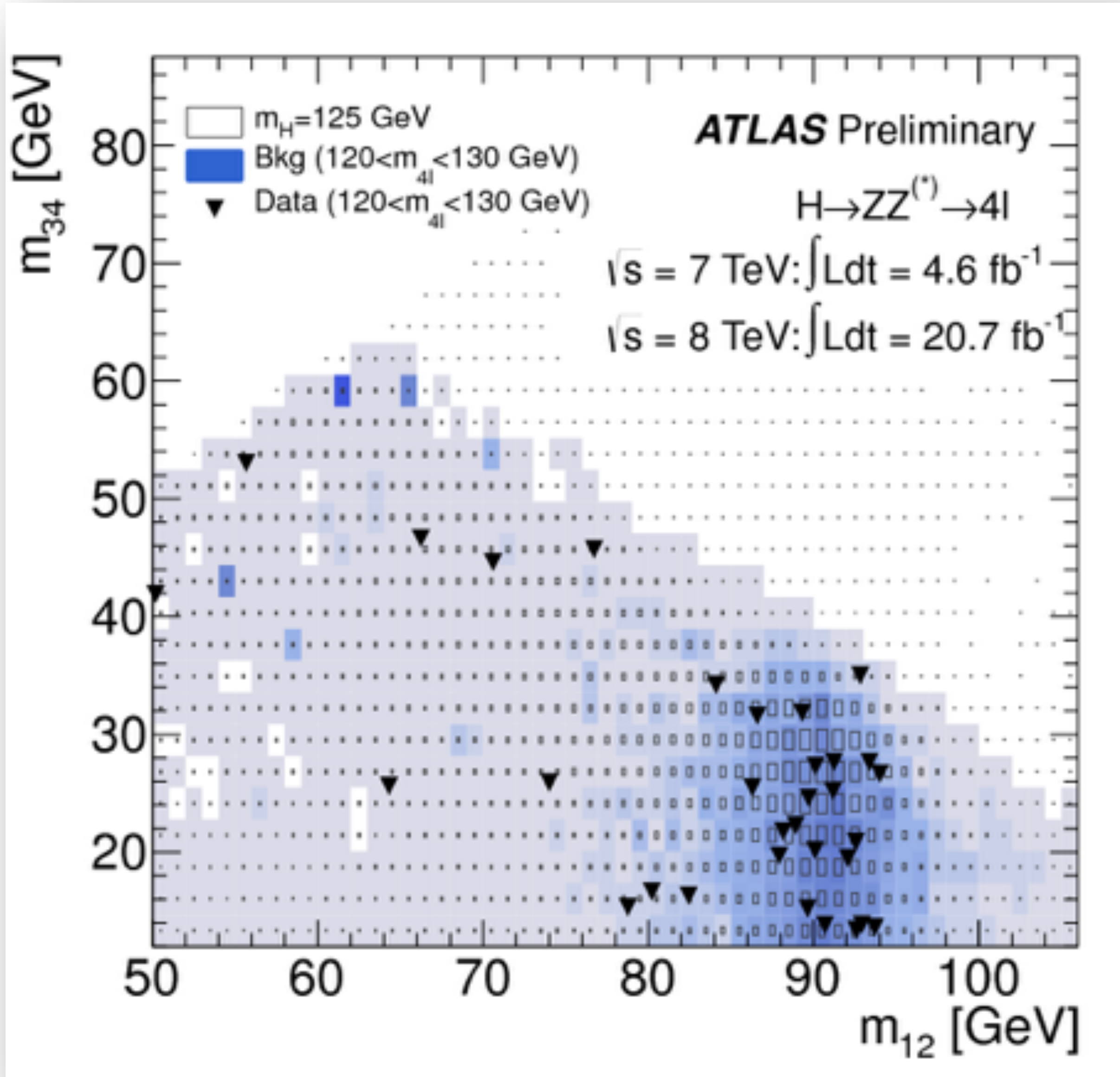
the angle between the two dilepton decay planes m12 -

leading deletion

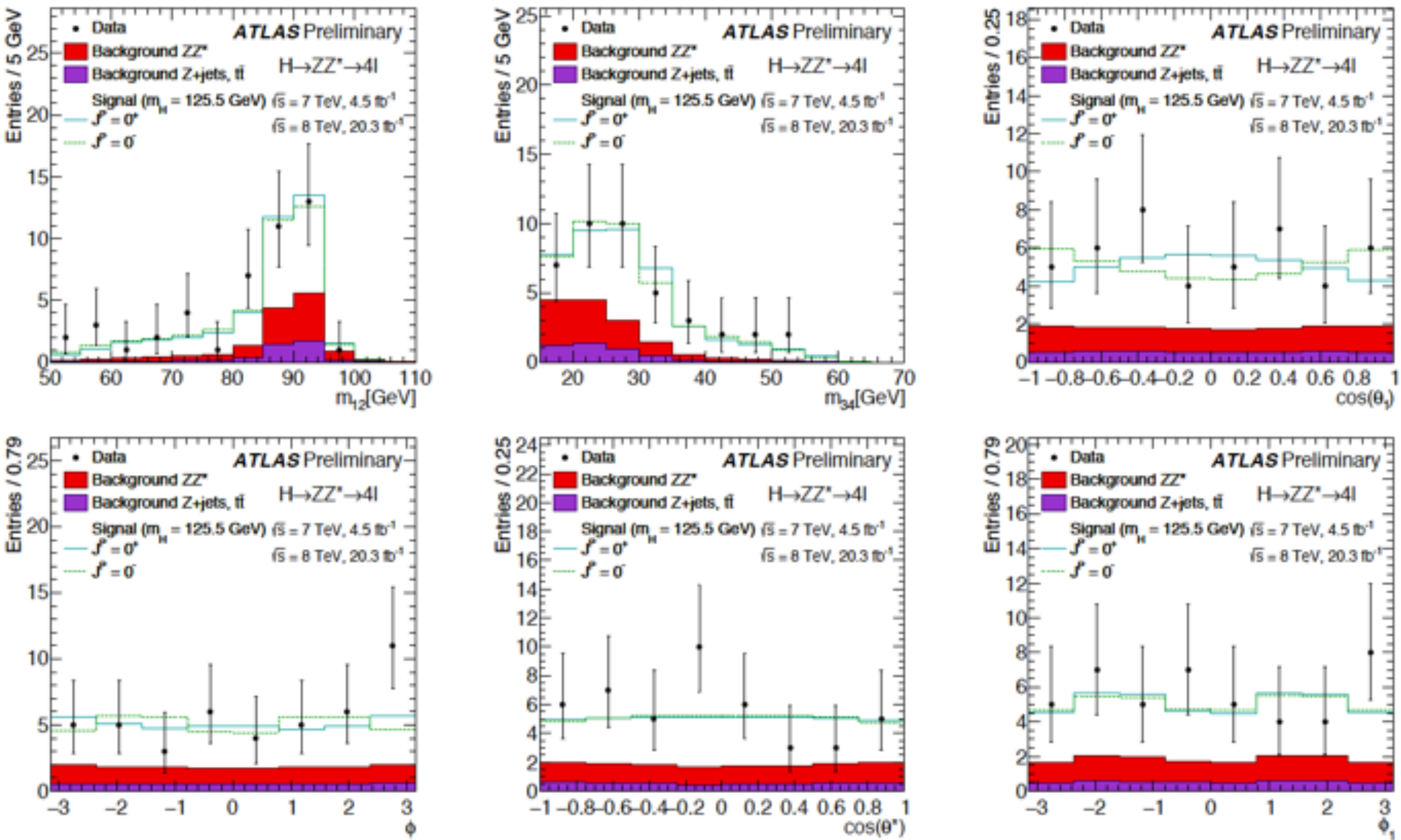
m34-

subleading

dilepton

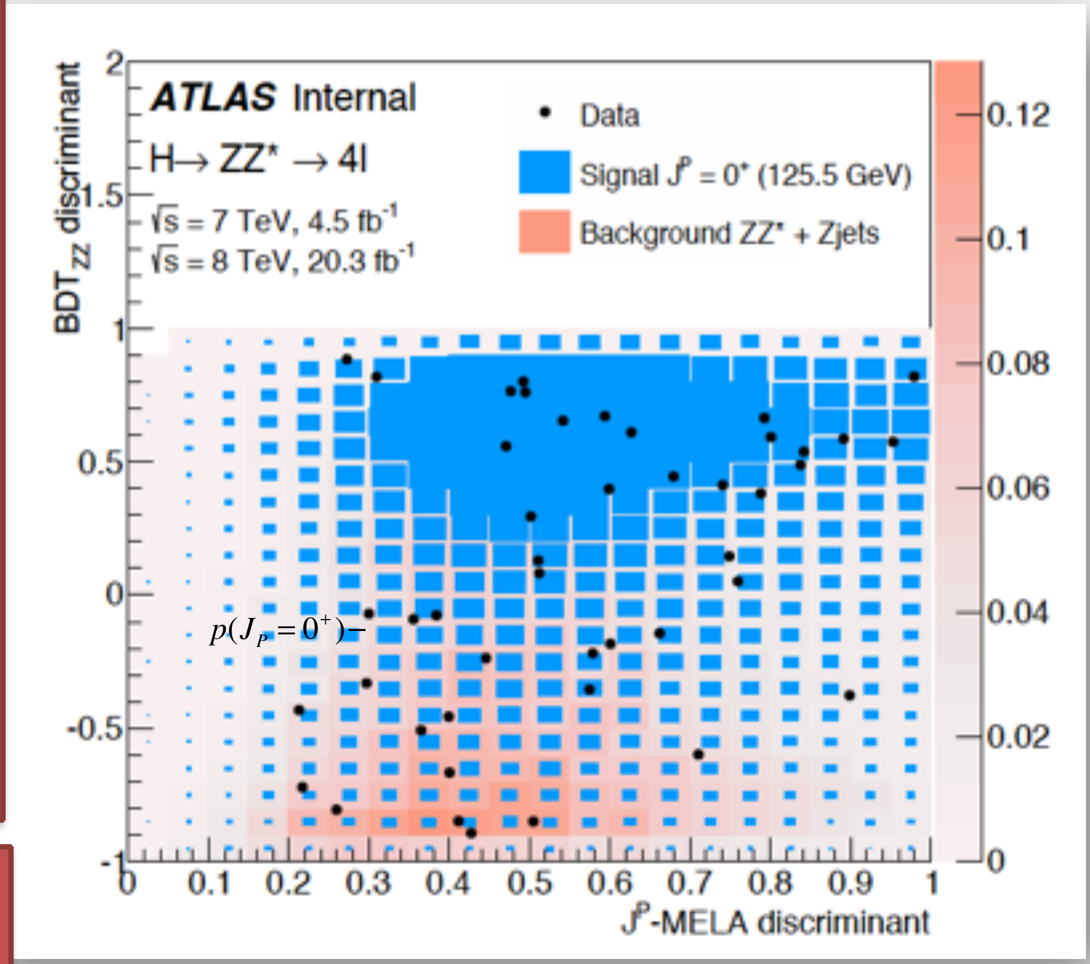


Discriminant Variables



BDT vs MELA

MELA
Use the theoretical differential decay rate for the parity sensitive final state observables, corrected for the detector acceptance and analysis selection, to construct a matrix element based likelihood ratio analysis, that is used as a discriminant between different spin and parity hypotheses, in this case 0^+ vs 0^-.



BDTzz is using 4-lepton system invariant mass, pseudo-rapidity,transverse momentum, and a matrix-element based kinematic discriminant.

The statistical treatment

Consider the di-photon,WW and ZZ channels.

Various distributions can serve as spin-parity discriminators (e.g. angles, Higgs momentum).

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

μ_j signal strength

θ Nuisance Pars

$S_{i,j}$ Signal

$B_{i,j}$ Background

Ttest Statistics q

$$q = \log \frac{\mathcal{L}(J^P_{\rm SM}, \hat{\mu}_{J^P_{\rm SM}}, \hat{\hat{\theta}}_{J^P_{\rm SM}})}{\mathcal{L}(J^P_{\rm alt}, \hat{\mu}_{J^P_{\rm alt}}, \hat{\hat{\theta}}_{J^P_{\rm alt}})}$$

Corrected via the CLs method to protect against insensitive measurements

$$\mathrm{CL_s}(J^P_{\rm alt}) = \frac{p(J^P_{\rm alt})}{1 - p(J^P_{\rm SM})}$$

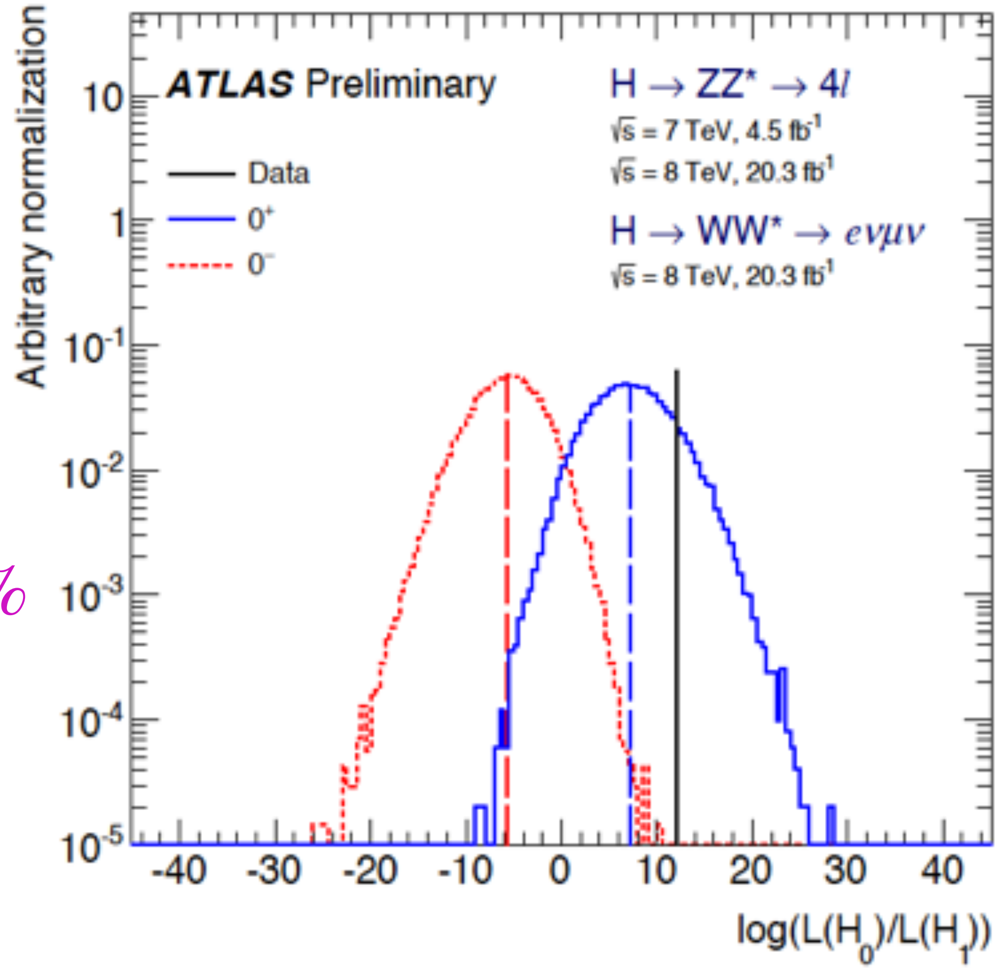
$$p_{obs} \leq 3.1 \cdot 10^{-5}$$

$$p_{obs}^{SM} = 0.88$$

$$CLs_{obs} = \frac{3.1 \cdot 10^{-5}}{1 - 0.88} =$$

$$= 2.6 \cdot 10^{-4} = 0.026\%$$

$$CL_{95} = 99.97\%$$



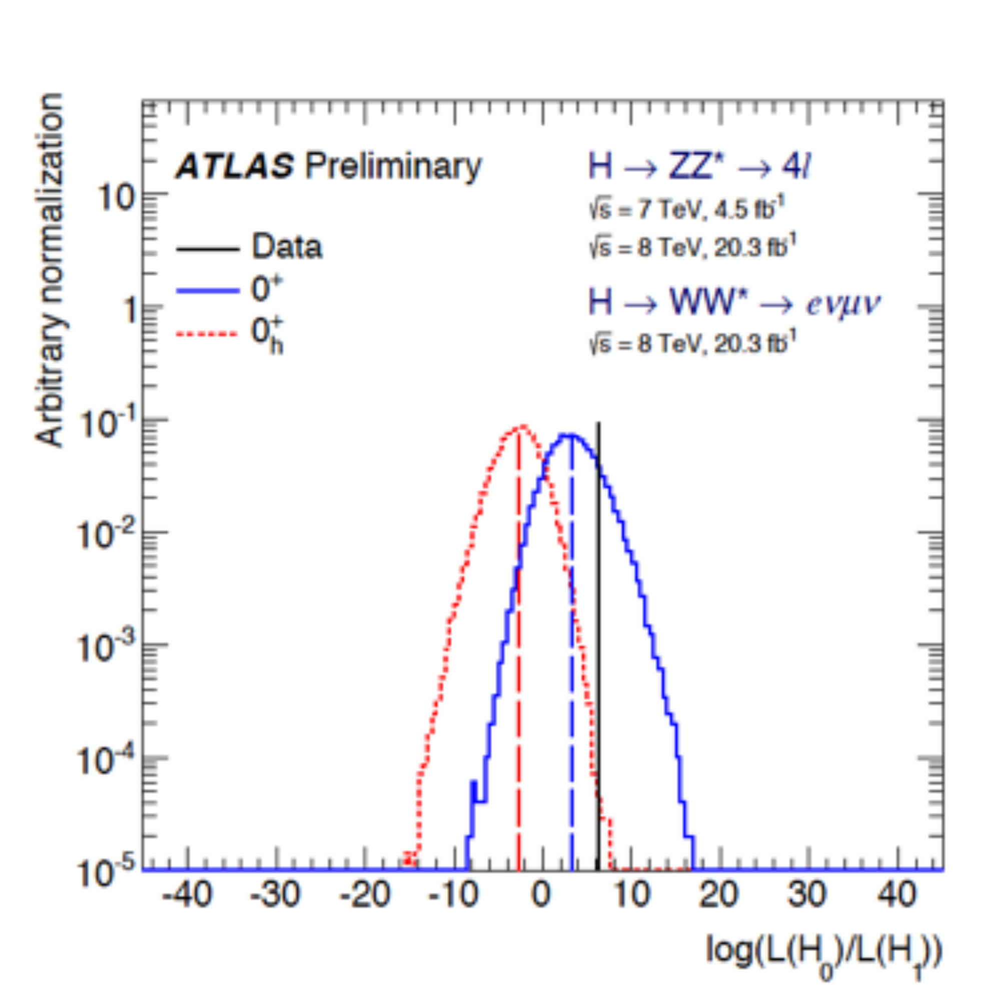
$$p_{obs} \approx 7.1 \cdot 10^{-5}$$

$$p_{obs}^{SM} = 0.85$$

$$CLs_{obs} = \frac{7.1 \cdot 10^{-5}}{1 - 0.85} =$$

$$= 4.7 \cdot 10^{-4} = 0.047\%$$

$$CL_{95} = 99.95\%$$



Spin Summary

Tested Hypothesis	$p^{ALT}_{exp,\mu=1}$	$p^{ALT}_{exp,\mu=\hat{\mu}}$	p^{SM}_{obs}	p^{ALT}_{obs}	Obs. CL_S (%)
0^+_h	$2.5 \cdot 10^{-2}$	$4.7 \cdot 10^{-3}$	0.85	$7.1 \cdot 10^{-5}$	$4.7 \cdot 10^{-2}$
0^-	$1.8 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$	0.88	$< 3.1 \cdot 10^{-5}$	$< 2.6 \cdot 10^{-2}$
2^+	$4.3 \cdot 10^{-3}$	$2.9 \cdot 10^{-4}$	0.61	$4.3 \cdot 10^{-5}$	$1.1 \cdot 10^{-2}$
$2^+(\kappa_q = 0;\ p_T < 300)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.52	$< 3.1 \cdot 10^{-5}$	$< 6.5 \cdot 10^{-3}$
$2^+(\kappa_q = 0;\ p_T < 125)$	$3.4 \cdot 10^{-3}$	$3.9 \cdot 10^{-4}$	0.71	$4.3 \cdot 10^{-5}$	$1.5 \cdot 10^{-2}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 300)$	$< 3.1 \cdot 10^{-5}$	$< 3.1 \cdot 10^{-5}$	0.28	$< 3.1 \cdot 10^{-5}$	$< 4.3 \cdot 10^{-3}$
$2^+(\kappa_q = 2\kappa_g;\ p_T < 125)$	$7.8 \cdot 10^{-3}$	$1.2 \cdot 10^{-3}$	0.80	$7.3 \cdot 10^{-5}$	$3.7 \cdot 10^{-2}$

LHC Higgs Mass combination

PHYSICAL REVIEW LETTERS

moving physics forward

Highlights Recent Accepted Authors Referees Search About

Accepted Paper

Combined measurement of the Higgs boson mass in pp collisions at \sqrt{s}=7 and 8 TeV with the ATLAS and CMS Experiments

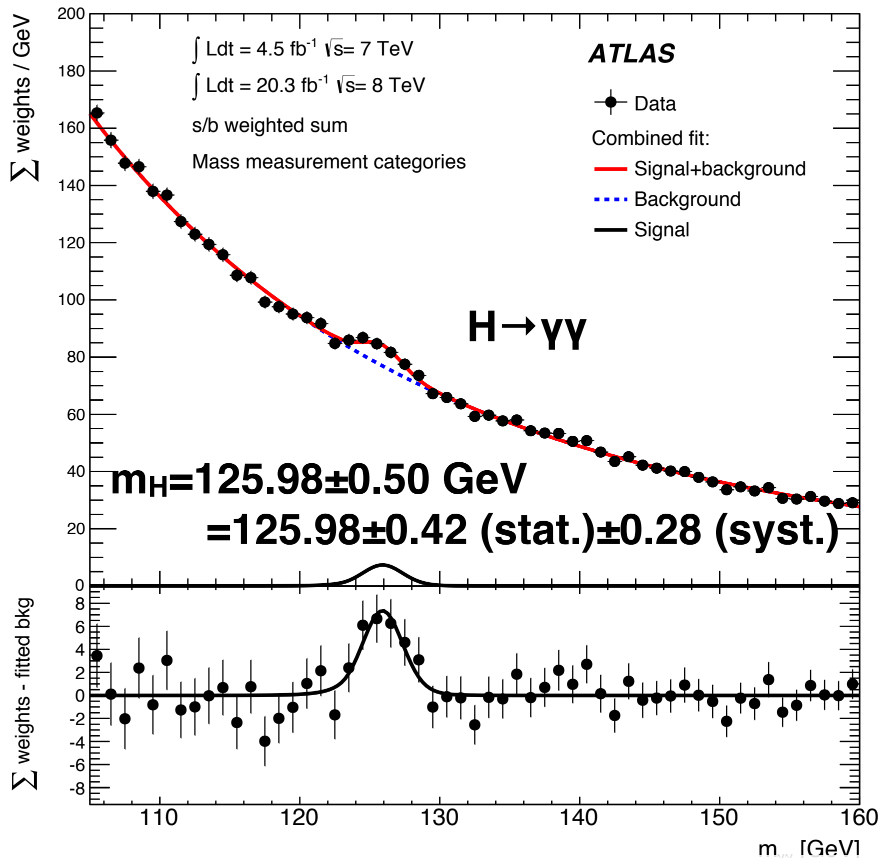
Phys. Rev. Lett.

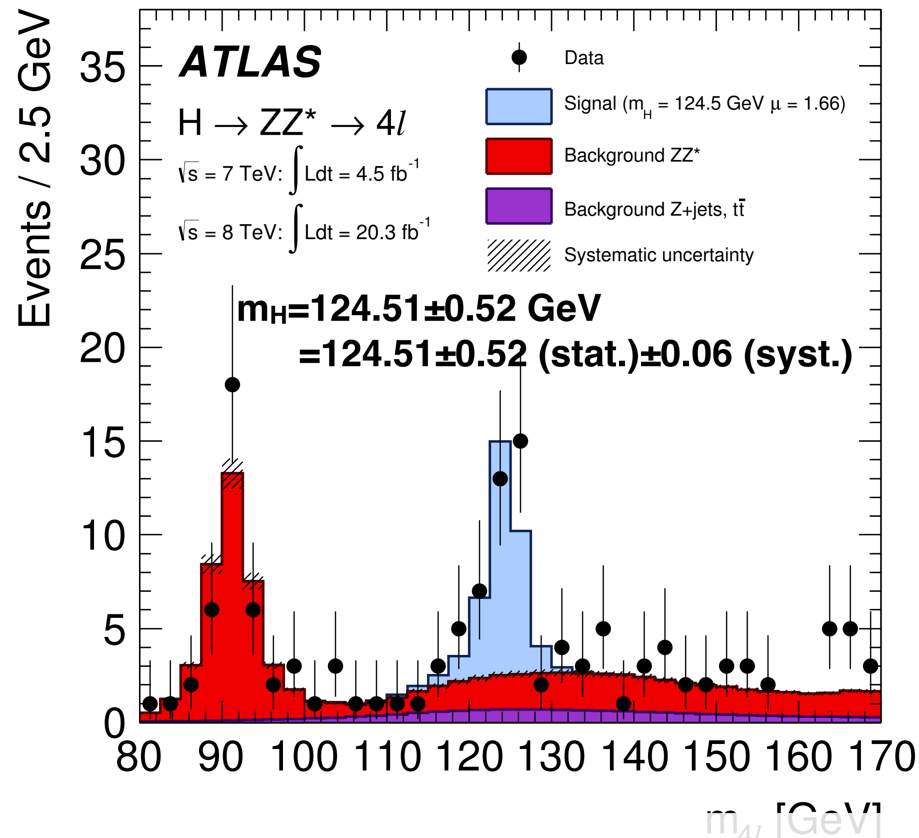
G. Aad et al.

Accepted 16 April 2015

ATLAS Published analyses

[Phys. Rev. D. 90, 052004 (2014)](#)



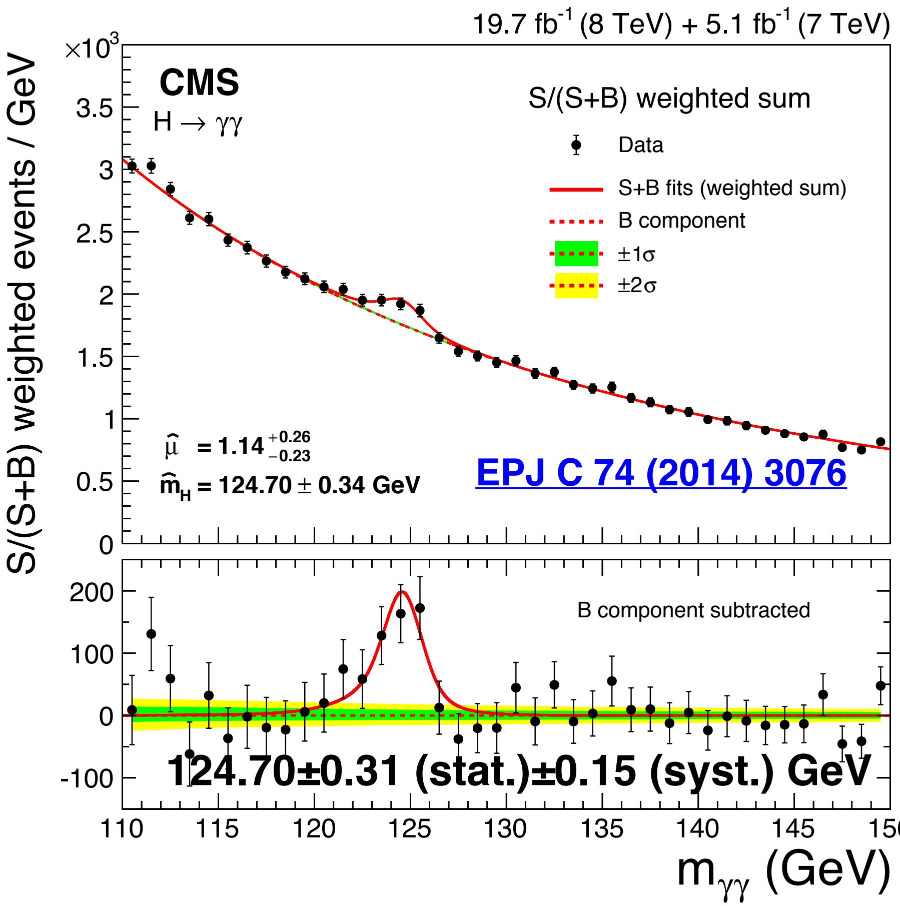


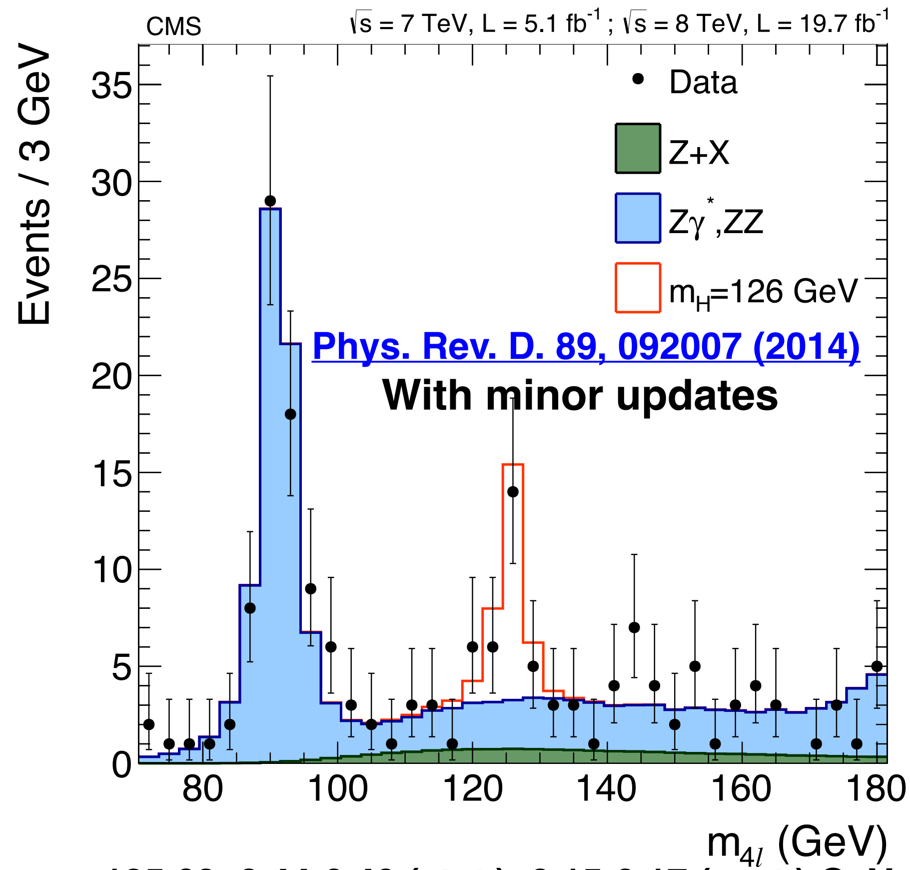
- **ATLAS**

=125.36±0.37 (stat.)±0.18 (syst.) GeV

CMS Published analyses

arXiv:1412.8662 (submitted to EPJ C)





125.63+0.44-0.40 (stat.)+0.15-0.17 (syst.) GeV

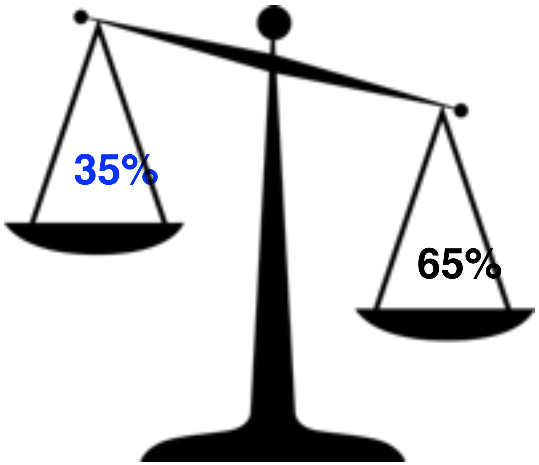
- CMS Combined: $\mathbf{m_H}$=**125.02+0.29-0.31 GeV**

=**125.02+0.26-0.27 (stat.)+0.14-0.15 (syst) GeV**

- **ATLAS**

=125.36±0.37 (stat.)±0.18 (syst.) GeV

- **CMS**



CMS Weight

$$\frac{\frac{1}{\sigma^2_{CMS}}}{\frac{1}{\sigma^2_{CMS}}+\frac{1}{\sigma^2_{ATLAS}}}=\frac{\frac{1}{0.30^2}}{\frac{1}{0.30^2}+\frac{1}{0.40^2}}\approx 65\%$$

Profile Likelihood in a Nut Shell

$$n = \mu s + b \qquad H_0 = BG\ only \qquad H_\mu = Signal\ with\ strength\ \ \mu$$

$$L(\mu) = \Pr ob(data \mid \mu) \sim e^{-\frac{(\mu-\hat{\mu})^2}{2\sigma_{\hat{\mu}}^2}} \Rightarrow \frac{L(\mu)}{L(\hat{\mu})} = e^{-\frac{(\mu-\hat{\mu})^2}{2\sigma_{\hat{\mu}}^2}}$$

$$\log \frac{L(\mu)}{L(\hat{\mu})} = -\frac{(\mu-\hat{\mu})^2}{2\sigma_{\hat{\mu}}^2}$$

$$-2\log \frac{L(\mu)}{L(\hat{\mu})} = \frac{(\mu-\hat{\mu})^2}{\sigma_{\hat{\mu}}^2} = Z^2 \ \text{(Z is the significance)}$$

$$\Lambda(\mu) \equiv -2\log \frac{L(\mu)}{L(\hat{\mu})} \qquad \text{Z}=\sqrt{\Lambda(\mu)}$$

Profile Likelihood in a Nut Shell

$n = \mu s + b \qquad H_0 = BG\ only \qquad H_\mu = Signal\ with\ strength\ \ \mu$

$$\Lambda(\mu) \equiv -2\log\frac{L(\mu)}{L(\hat{\mu})} \qquad \mathrm{Z}=\sqrt{\Lambda(\mu)}$$

Let θ_i *be n Nuisance Parameters*

$$\Lambda(\mu) \equiv -2\log\frac{\max\limits_{\theta_i} L(\mu,\theta_i)}{\max\limits_{\mu,\theta_i} L(\mu,\theta_i)} \equiv -2\log\frac{L(\mu,\hat{\hat{\theta}}_i)}{L(\hat{\mu},\hat{\theta}_i)}$$

Wilks Theorem $\quad \Lambda(\mu) \equiv -2\log\dfrac{L(\mu,\hat{\hat{\theta}}_i \mid H_\mu)}{L(\hat{\mu},\hat{\theta}_i)H_\mu)} \sim \chi_1^2$

Jargon: The Nuisance Parameters are Profiled

Mass Measurement Parameterisation

Nominal fit: which μ to profile?

- The nominal fit has four common parameters:

$$m_H \quad \mu^{\gamma\gamma}_{ggH+ttH} \quad \mu^{\gamma\gamma}_{VBF+VH} \quad \mu^{ZZ}$$

$$\mu_i^f = \mu_i \cdot \rho^f$$

$$\mu^{\gamma\gamma}_{ggF} = \mu_{ggF} \cdot \rho^{\gamma\gamma} = \frac{\sigma_{ggF}}{\sigma^{SM}_{ggF}} \cdot \frac{BR(H \to \gamma\gamma)}{BR(H \to \gamma\gamma)^{SM}}$$

Nominal fit: which μ to profile?

- The nominal fit has four common parameters:

$$m_H \quad \mu^{\gamma\gamma}_{ggH+ttH} \quad \mu^{\gamma\gamma}_{VBF+VH} \quad \mu^{ZZ}$$

- The combined mass of ATLAS+CMS is therefore given by the following profile likelihood test statistic

$$\Lambda(m_H) = \frac{L(m_H\,,\,\hat{\hat{\mu}}^{\gamma\gamma}_{ggF+ttH}(m_H)\,,\hat{\hat{\mu}}^{\gamma\gamma}_{VBF+VH}(m_H)\,,\,\hat{\hat{\mu}}_{4\ell}(m_H)\,,\,\hat{\hat{\boldsymbol{\theta}}}(m_H))}{L(\hat{m}_H,\hat{\mu}^{\gamma\gamma}_{ggF+ttH}\,,\hat{\mu}^{\gamma\gamma}_{VBF+VH},\hat{\mu}_{4\ell},\hat{\boldsymbol{\theta}})}$$

- Systematics is modeled with ~300 Nuisance Parameters
- 100 for shape parameters and normalization in Hγγ Background model (unconstrained)
- Most of the remaining ones, correspond to experimental or theory (constrained)

The Fit Model

$$\lambda^{exp} = \frac{\mu^{CMS}}{\mu^{ATLAS}} \quad \lambda_{RV}^{exp} = \frac{\mu_{VBF+VH}^{CMS}}{\mu_{VBF+VH}^{ATLAS}} \quad \lambda_{RF}^{exp} = \frac{\mu_{ggF+ttH}^{CMS}}{\mu_{ggF+ttH}^{ATLAS}} \quad \lambda_{ZZ}^{exp} = \frac{\mu_{ZZ}^{CMS}}{\mu_{ZZ}^{ATLAS}}$$

- ATLAS is the other experiment

$$\mu^{CMS} = \mu \quad \mu^{ATLAS} = \mu\lambda^{exp}$$

		$H \to \gamma\gamma$	$H \to ZZ^{(*)} \to \ell\ell\ell\ell$
ATLAS	Mass	$m_H + \Delta m_{\gamma Z} + \Delta m^{exp.}$	$m_H + \Delta m^{exp.}$
	$ggF, t\bar{t}H$	$\mu\lambda^{exp.} \cdot \mu_{ggF+t\bar{t}H(+b\bar{b}H)}^{\gamma\gamma}\lambda_{RF}^{exp.}$	$\mu\lambda^{exp.} \cdot \mu^{ZZ}\lambda_{ZZ}^{exp.}$
	VBF, VH	$\mu\lambda^{exp.} \cdot \mu_{VBF+VH}^{\gamma\gamma}\lambda_{RV}^{exp.}$	
CMS	Mass	$m_H + \Delta m_{\gamma Z}$	m_H
	$ggF, t\bar{t}H$	$\mu \cdot \mu_{ggF+t\bar{t}H(+b\bar{b}H)}^{\gamma\gamma}$	$\mu \cdot \mu^{ZZ}$
	VBF, VH	$\mu \cdot \mu_{VBF+VH}^{\gamma\gamma}$	

Systematics

Correlations

Correlated Sytematics

- The experiments are different;
  Different detectors and different methodology for systematic evaluation
    - Experimental systematics on γ, e and μ (energy/momentum scale/resolution, efficiencies etc.) are **uncorrelated**
- Only common theoretical uncertainties (QCD scale, PDF, BR) and partial luminosity were **correlated**
    - It should be noted that the effect of these uncertainties is mainly normalisation so the effect on the mass is negligible (<10 MeV)

PDF and QCD scale uncertainties

Correlation rather straightforward:
PDF uncertainties in ATLAS 4l analysis is uncorrelated between signal and background because the correlation is expected to be small. But in LHC combination they have been correlated to be consistent with CMS 4l treatment

Source	Affected Processes	Typical uncertainty
PDFs+α_s (cross sections)	ggF, $t\bar{t}H$, $b\bar{b}H$, $gg \to ZZ$	$\pm 7\,\%$
	VBF, VH, $qq \to ZZ$	$\pm 3\,\%$
Higher-order uncertainties on cross sections	ggF	$\pm 8\,\%$
	VBF	$\pm 0.2\,\%$
	VH	$\pm 1\,\%$
	$t\bar{t}H$	$^{+4\,\%}_{-9\,\%}$
	$b\bar{b}H$	$^{+13\,\%}_{-23\,\%}$
	$qq \to ZZ$	±3%
	$gg \to ZZ$	±30%

BR Uncertainties

- Uncertainties below 0.3% were neglected
- We were left with 5 NPs

Decay widths	Parametric uncertainty on α_S(varies with decay)	$\pm 1\,\%$
	Parametric uncertainty on m_b(varies with decay)	$\pm 2\,\%$
	Theoretical uncertainty on $\Gamma(H \to VV)$	$\pm 0.4\,\%$
	Theoretical uncertainty on $\Gamma(H \to q\bar{q})$	$\pm 1\,\%$
	Theoretical uncertainty on $\Gamma(H \to \gamma\gamma)$	$\pm 1\,\%$

Luminosity Uncertainties

- Naturally part of the Luminosity uncertainty is common to ATLAS and CMS
  - 0.5% (0.6%) of ATLAS (CMS) Lumi @ 7 TeV
  - 1.1% (2.1%) of ATLAS (CMS) Lumi @ 8 TeV
- Effect is negligible

7 TeV	ATLAS	CMS
Total	1.8%	2.2%
100% correlated between ATLAS and CMS	$< 0.5\%$	$< 0.6\%$
Uncorrelated between ATLAS and CMS	$> 1.7\%$	$> 2.1\%$

8 TeV	ATLAS	CMS
Total	2.8%	2.6%
100% correlated between ATLAS and CMS	$< 1.1\%$	$< 2.1\%$
Uncorrelated between ATLAS and CMS	$> 2.5\%$	$> 1.5\%$

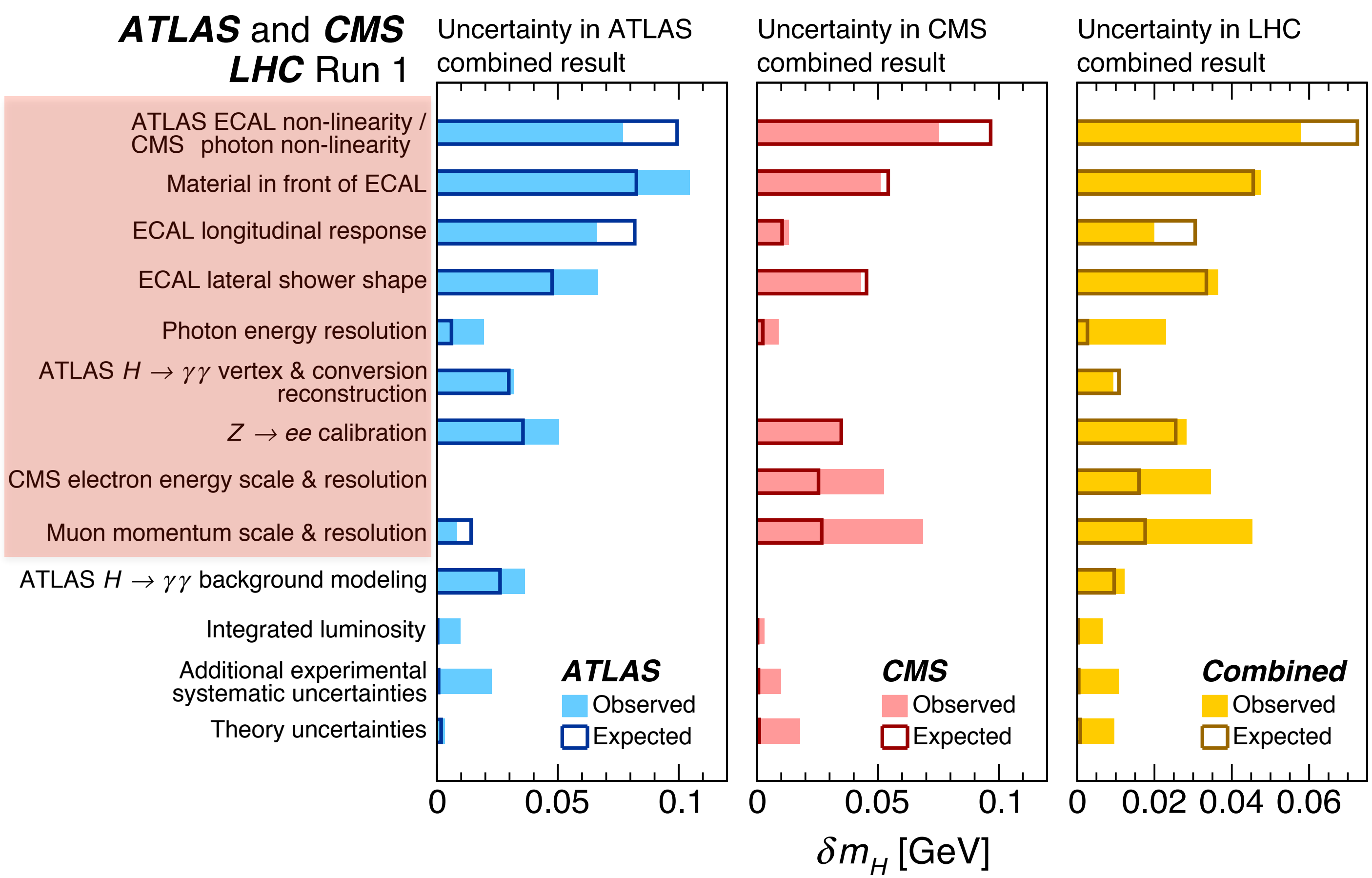
Other NPs

- Other NPs are the individual experiments NP
- Main impact comes from those related to Calibration/Energy/Momentum/Scale and Resolution
- The correlation of the calibration based on Z—>ee energy scale in both experiments turns out to be negligible

Impact of Systematics

Systematic uncertainties

Energy/momentum scale and resolution of μ, e and γ dominate systematic uncertainty

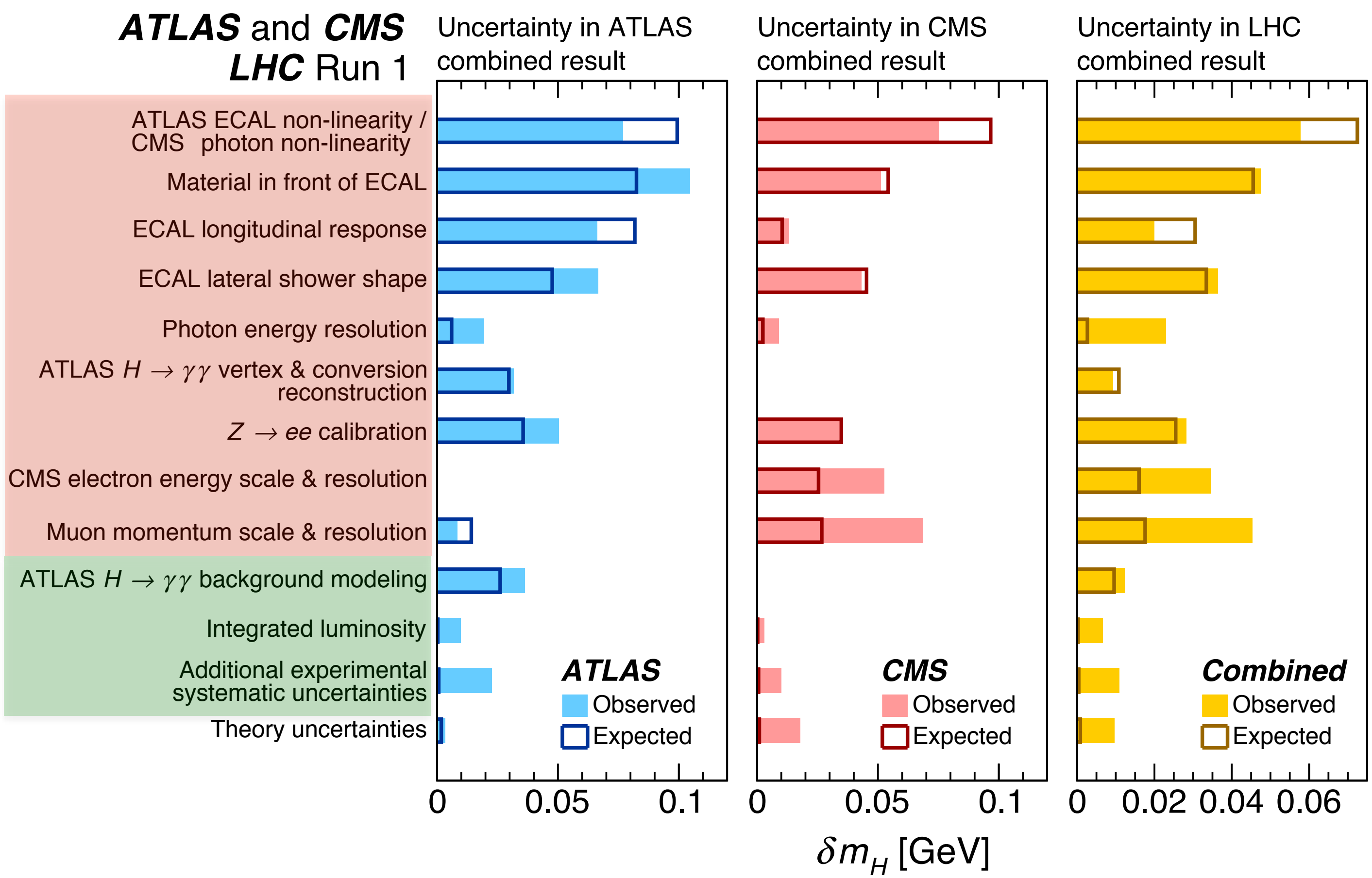


Systematic uncertainties

Energy/momentum scale and resolution of μ, e and γ dominate systematic uncertainty

Other experimental uncertainties (eff, JES, luminosity…)

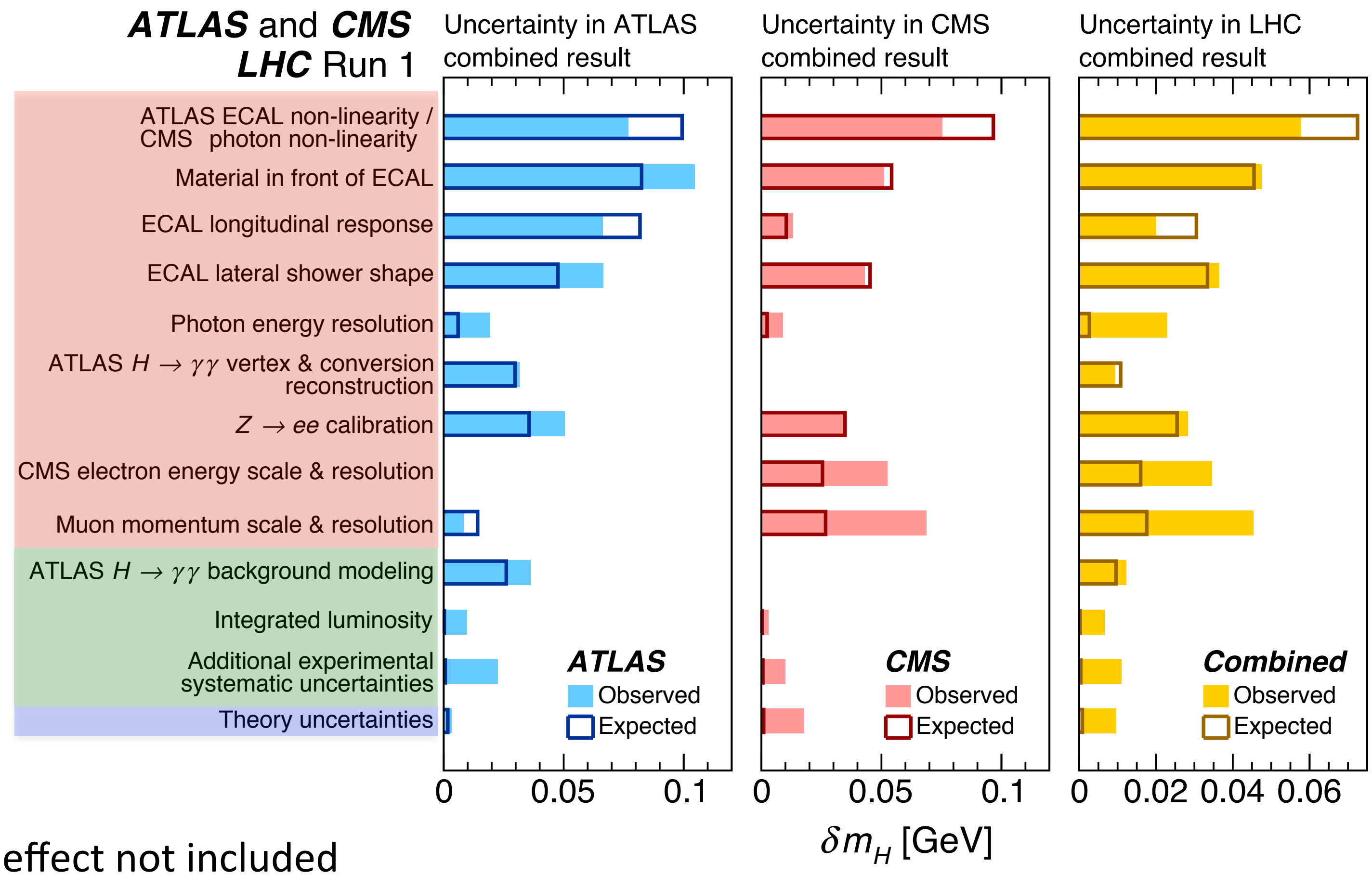
All experimental uncertainties uncorrelated between experiments except luminosity (partial correlation)



Systematic uncertainties

Theoretical uncertainties (QCD scales, pdf, BR…*) 100% correlated between experiments

Almost no impact on mass measurement (as expected)!



*Interference effect not included

Systematic uncertainties

Systematic contribution evaluated sequentially "freezing" nuisance parameter groups to their best values and re-scanning the likelihood ratio…

$$\mathbf{m_H = 125.09 \pm 0.21\ (stat)}$$

$$\mathbf{\pm 0.11\ (scale)}$$

$$\mathbf{\pm 0.02\ (other)}$$

$$\mathbf{\pm 0.01\ (theory^{*})}$$

$$\mathbf{GeV}$$

Uncertainty is mostly statistical

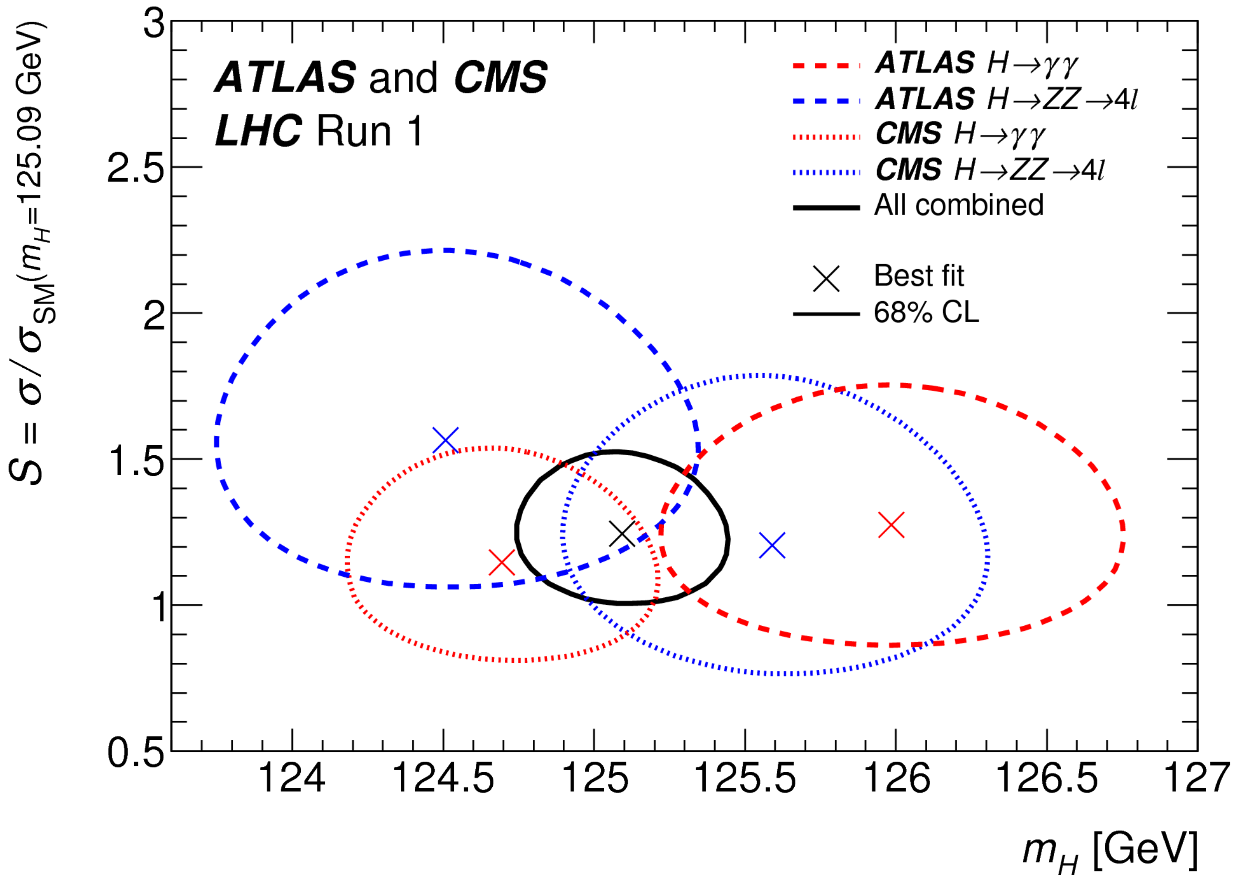
Scale uncertainties dominate systematic

→ But we can expect that to improve with more data!

*Interference effect not included

Results

m_H vs. μ contours



The best fit mH in contour (×) is not identical as m_H measured

Some Examples

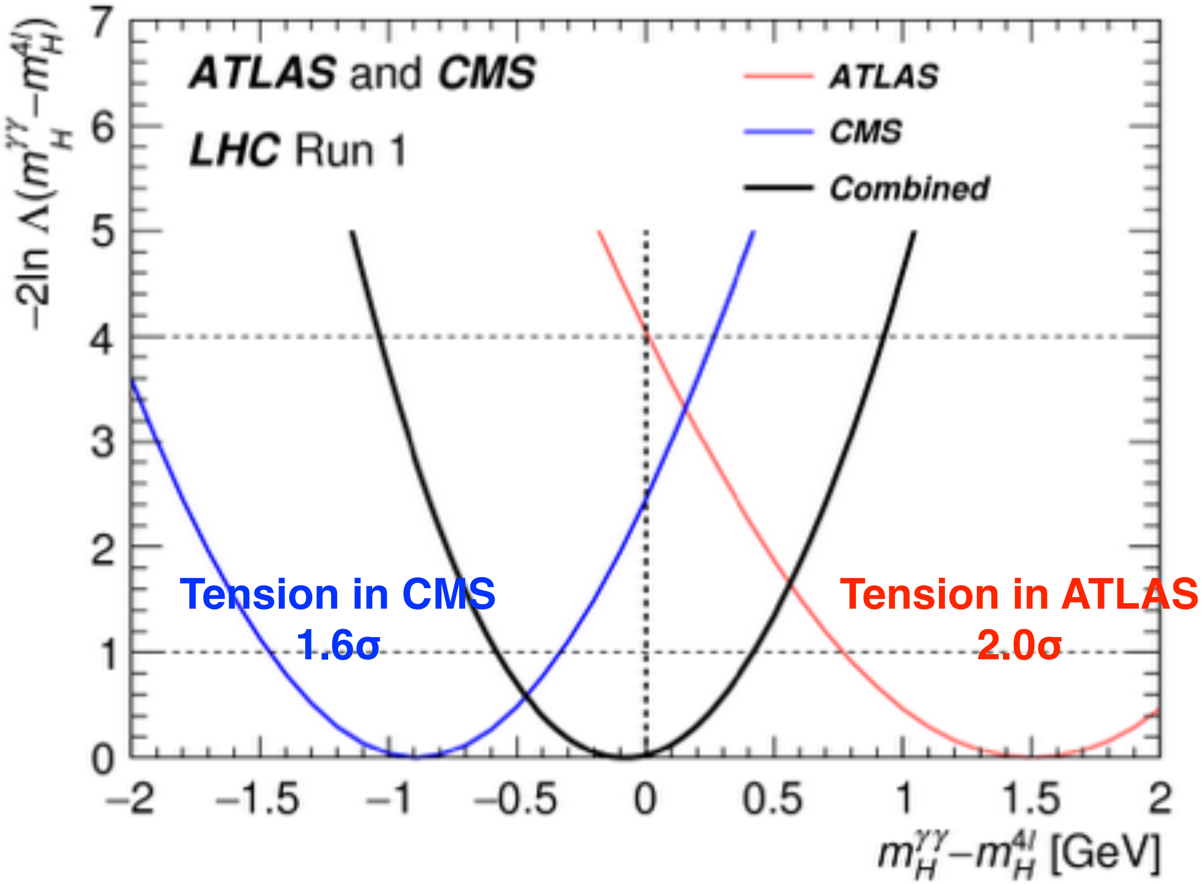
- Asses the tension between channels $\Delta m_H(\gamma\gamma\text{-}4l)$

$$\Lambda(\Delta m_{\gamma Z}) = \frac{L(\Delta m_{\gamma Z}, \hat{\hat{m}}_H, \hat{\hat{\mu}}^{\gamma\gamma}_{ggF+ttH}, \hat{\hat{\mu}}^{\gamma\gamma}_{VBF+VH}, \hat{\hat{\mu}}_{4\ell}, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\Delta} m_{\gamma Z}, \hat{m}_H, \hat{\mu}^{\gamma\gamma}_{ggF+ttH}, \hat{\mu}^{\gamma\gamma}_{VBF+VH}, \hat{\mu}_{4\ell}, \hat{\boldsymbol{\theta}})}$$

- Asses the tension between experiments Δm_H(ATLAS-CMS)

$$\Lambda(\Delta m^{exp}) = \frac{L(\Delta m^{exp}, \hat{\hat{m}}_H, \hat{\hat{\mu}}^{\gamma\gamma}_{ggF+ttH}, \hat{\hat{\mu}}^{\gamma\gamma}_{VBF+VH}, \hat{\hat{\mu}}_{4\ell}, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\Delta} m^{exp}, \hat{m}_H, \hat{\mu}^{\gamma\gamma}_{ggF+ttH}, \hat{\mu}^{\gamma\gamma}_{VBF+VH}, \hat{\mu}_{4\ell}, \hat{\boldsymbol{\theta}})}$$

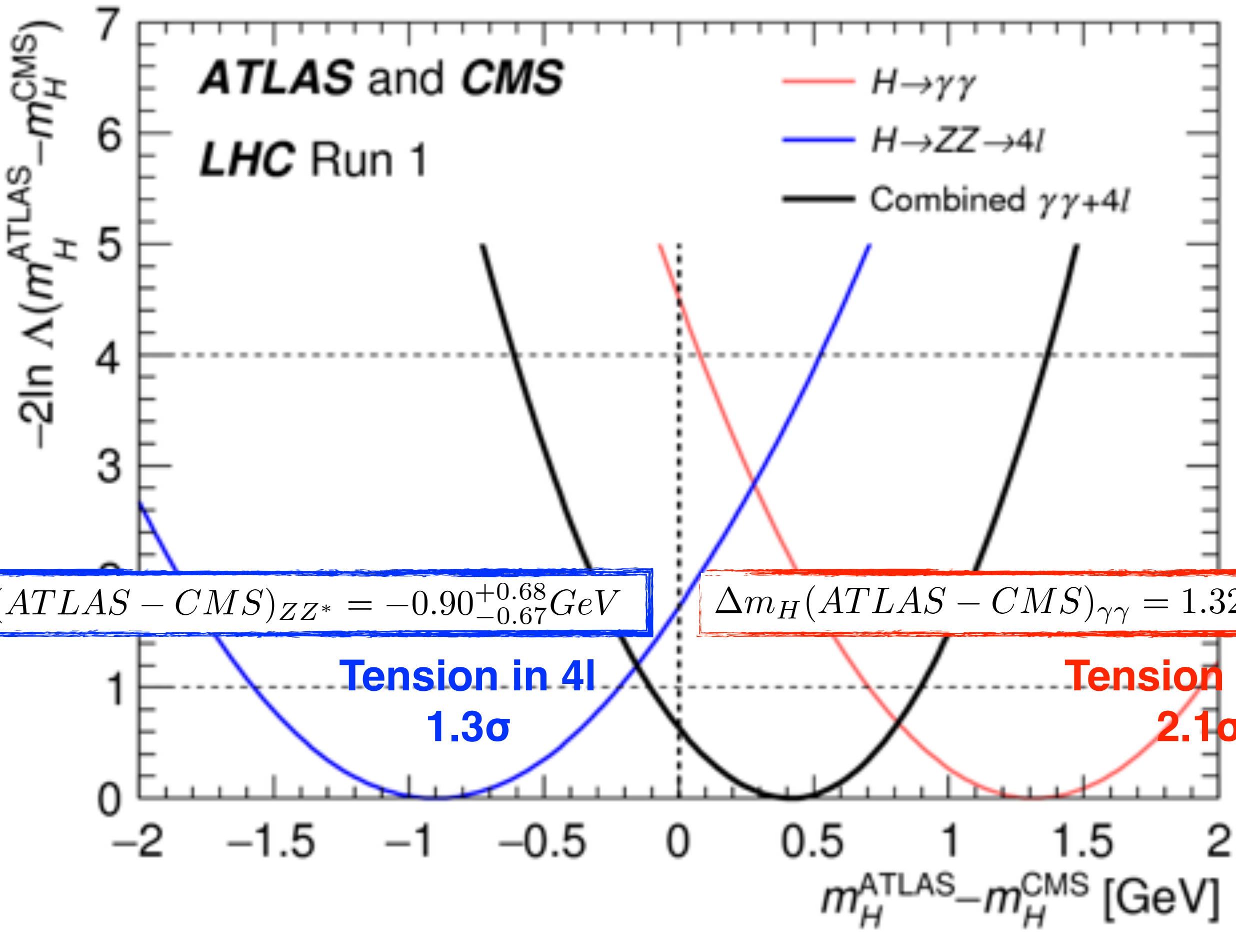
Tension in m_H between decay channels



$$\Delta m_H(\gamma\gamma - ZZ^*) = -0.08^{+0.50}_{-0.49}\ \text{GeV}$$

No observed tension in combined

Tension in m_H between experiments



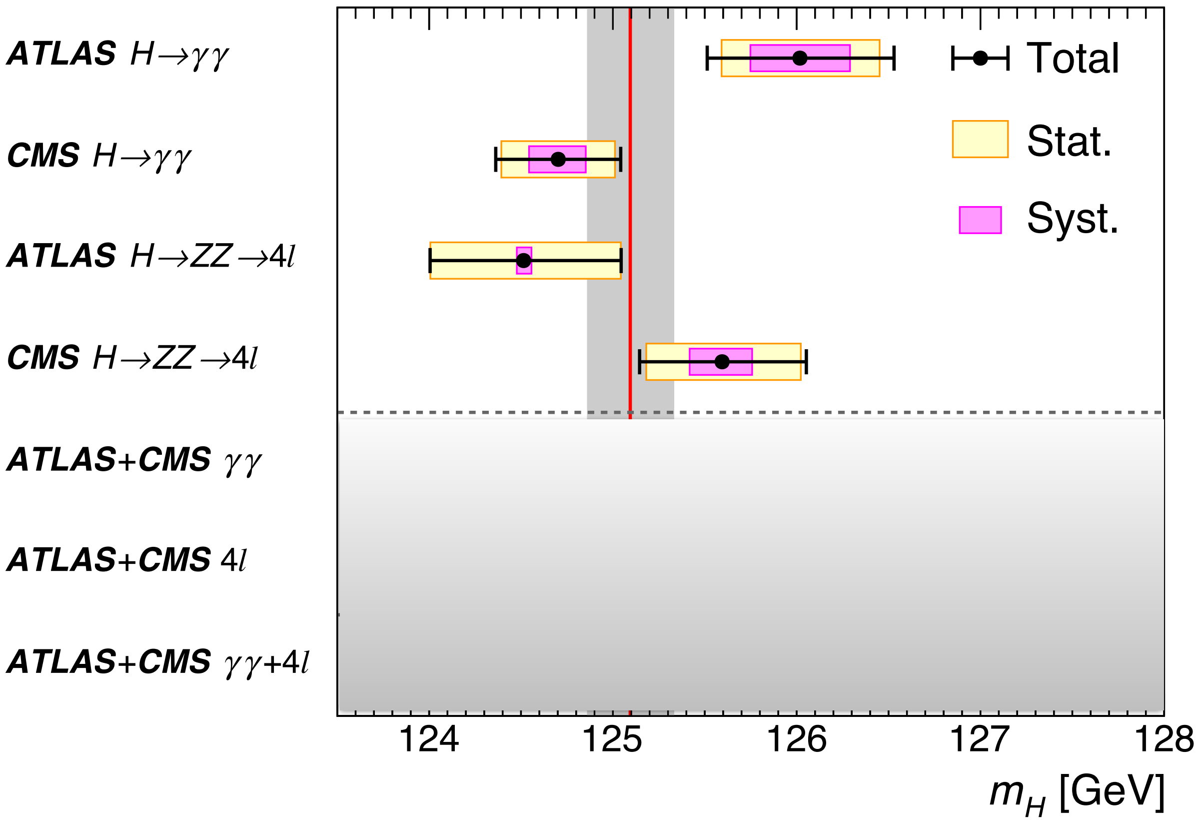
$\Delta m_H(ATLAS - CMS)_{ZZ^*} = -0.90^{+0.68}_{-0.67} GeV$

$\Delta m_H(ATLAS - CMS)_{\gamma\gamma} = 1.32^{+0.62}_{-0.61} GeV$

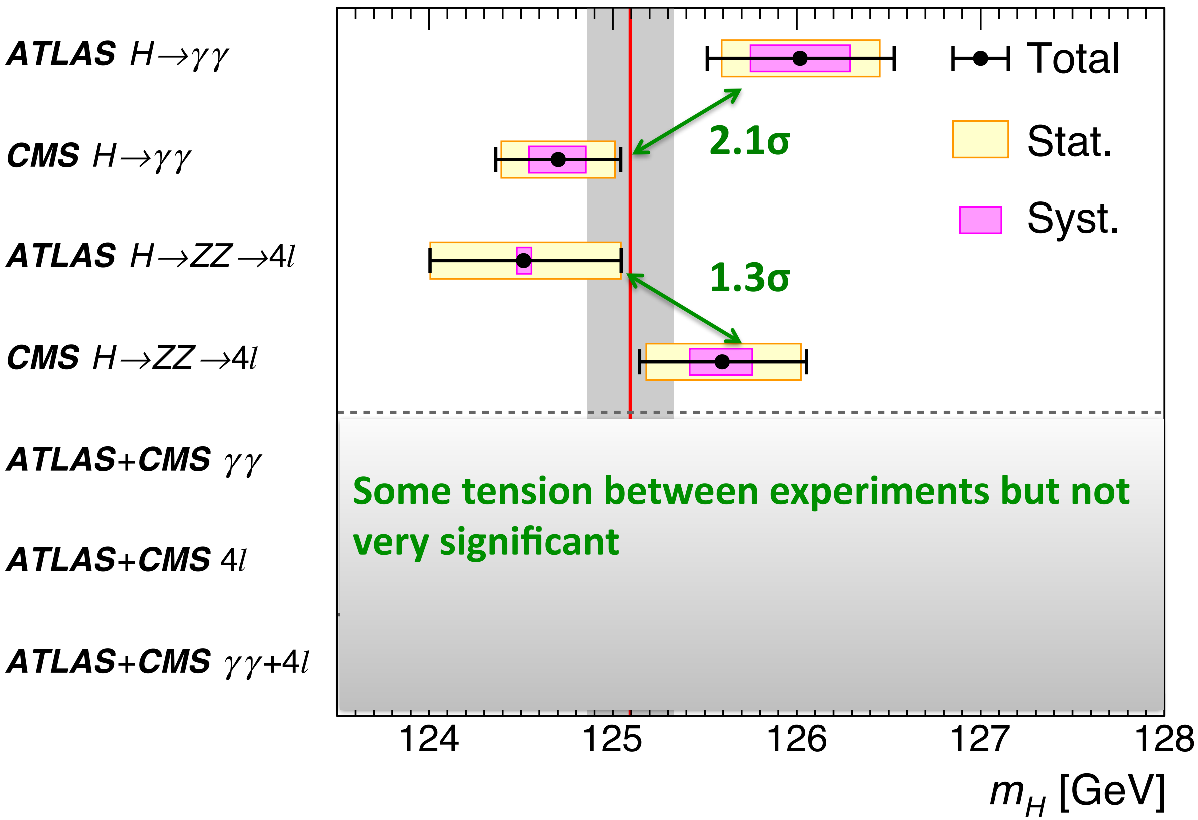
$\Delta m_H(ATLAS - CMS) = 0.41^{+0.48}_{-0.52}$ GeV

No observed tension in combined measurements between experiments

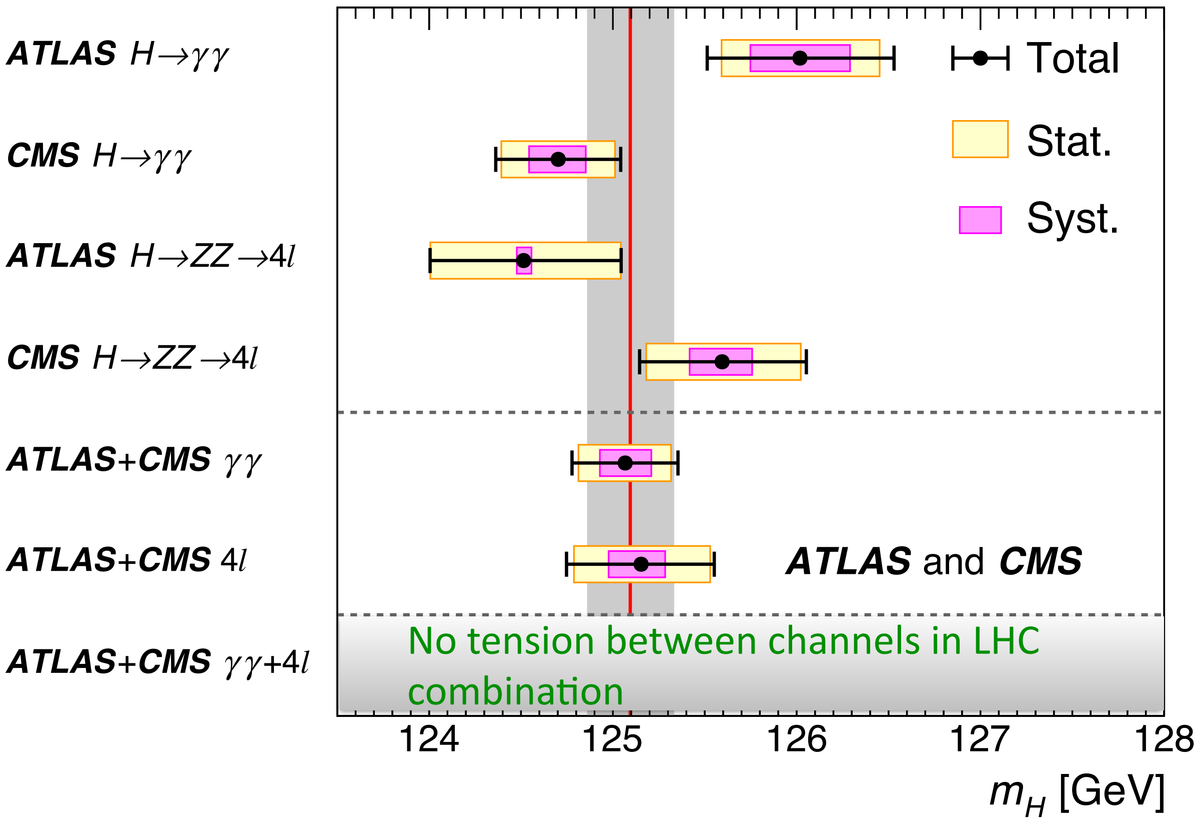
Reproduce Published results



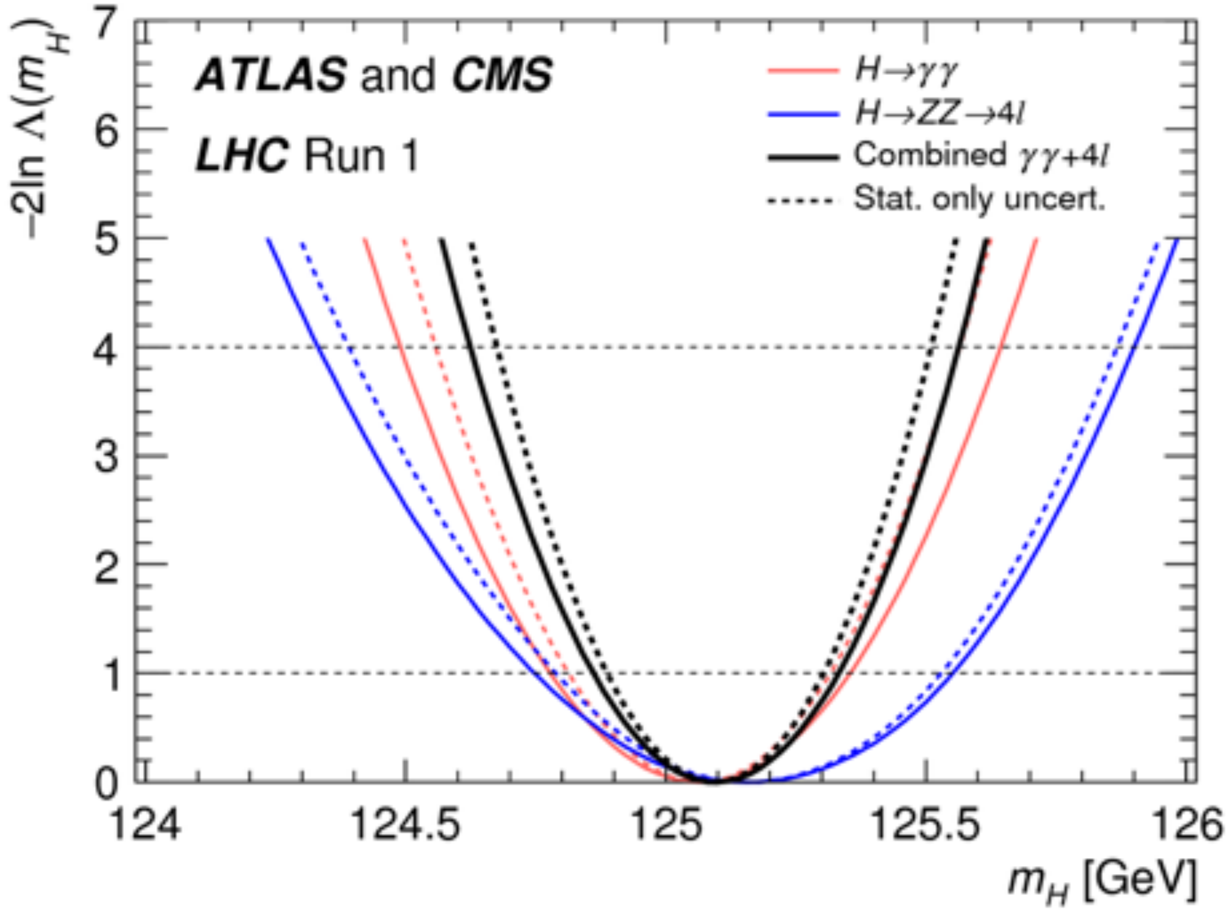
Tension Between Experiments



No Tension Between Combined Channels



Fine Final Scan

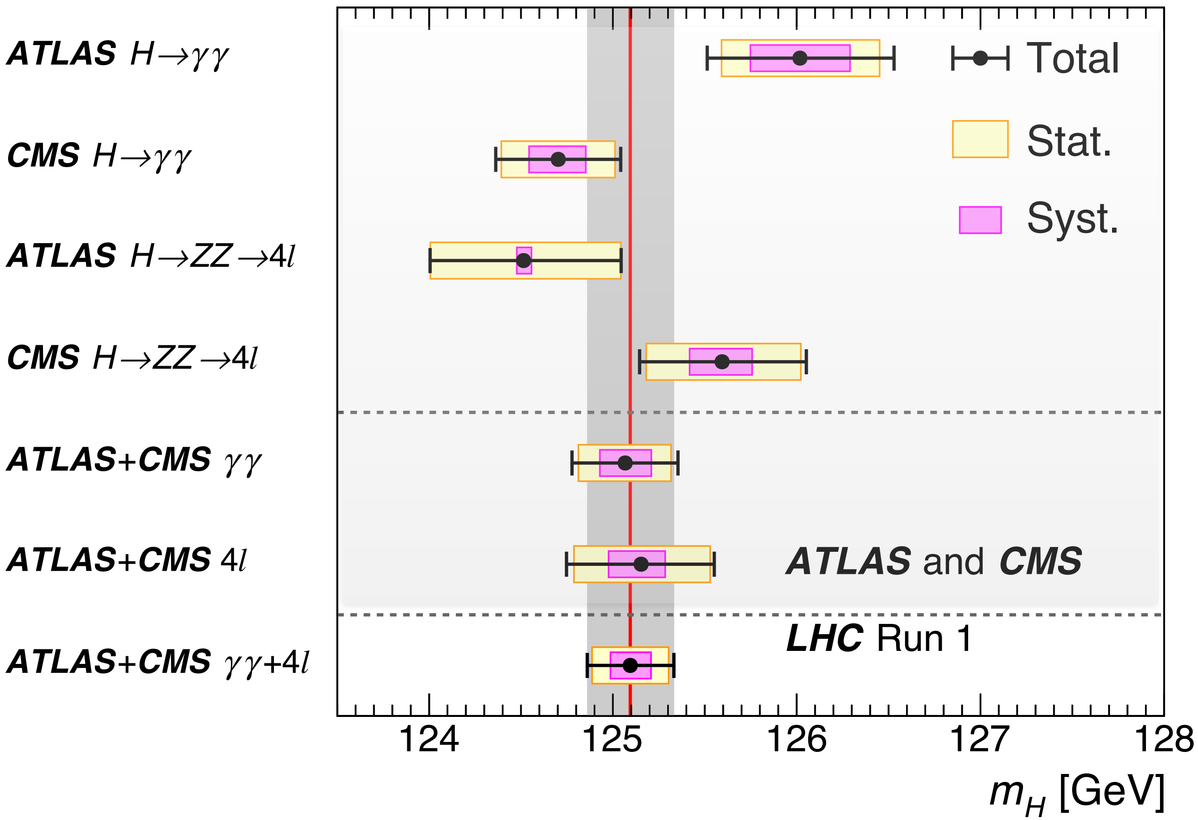


$$-2\ln\Lambda = 1 \Rightarrow \sigma$$

$$\sqrt{\sigma_{tot}^2 - \sigma_{Stat}^2} = \sigma_{syst}$$

$$m_H = 125.09 \pm 0.21(stat) \pm 0.11(syst)GeV$$

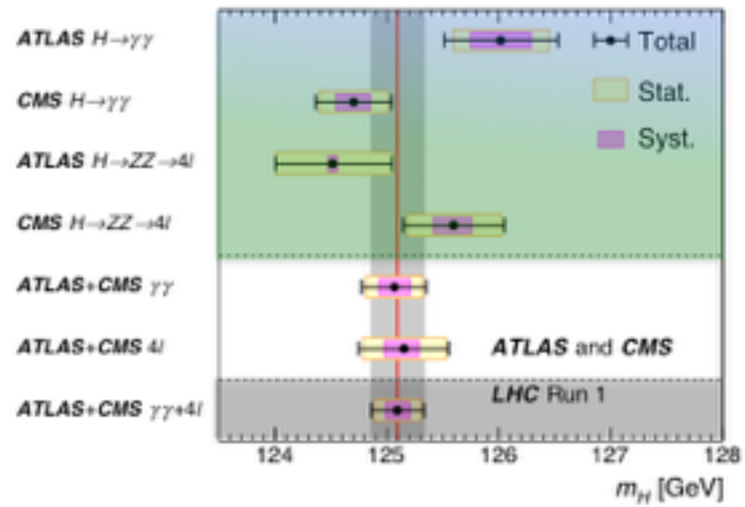
Combined Mass

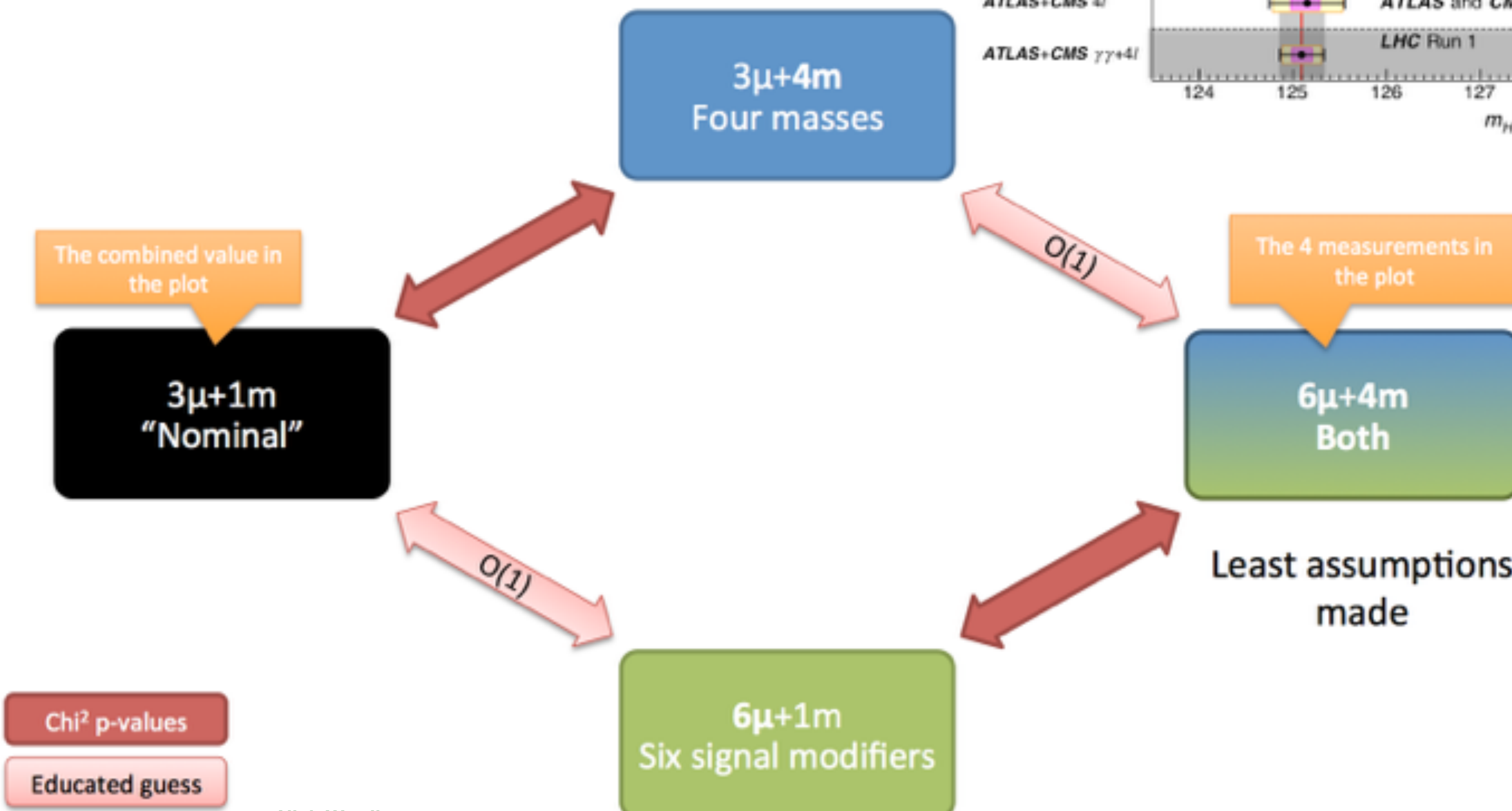


$$m_H = 125.09 \pm 0.21(stat) \pm 0.11(syst) GeV$$

Compatibility

A number of different models to check compatibility of the result …



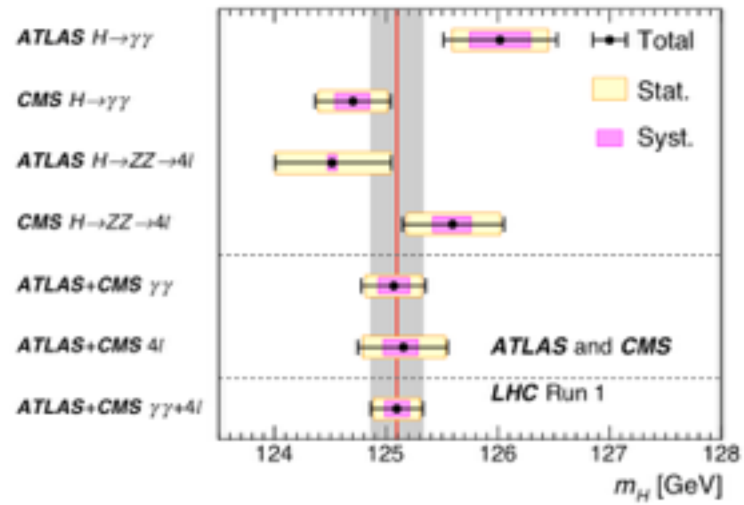


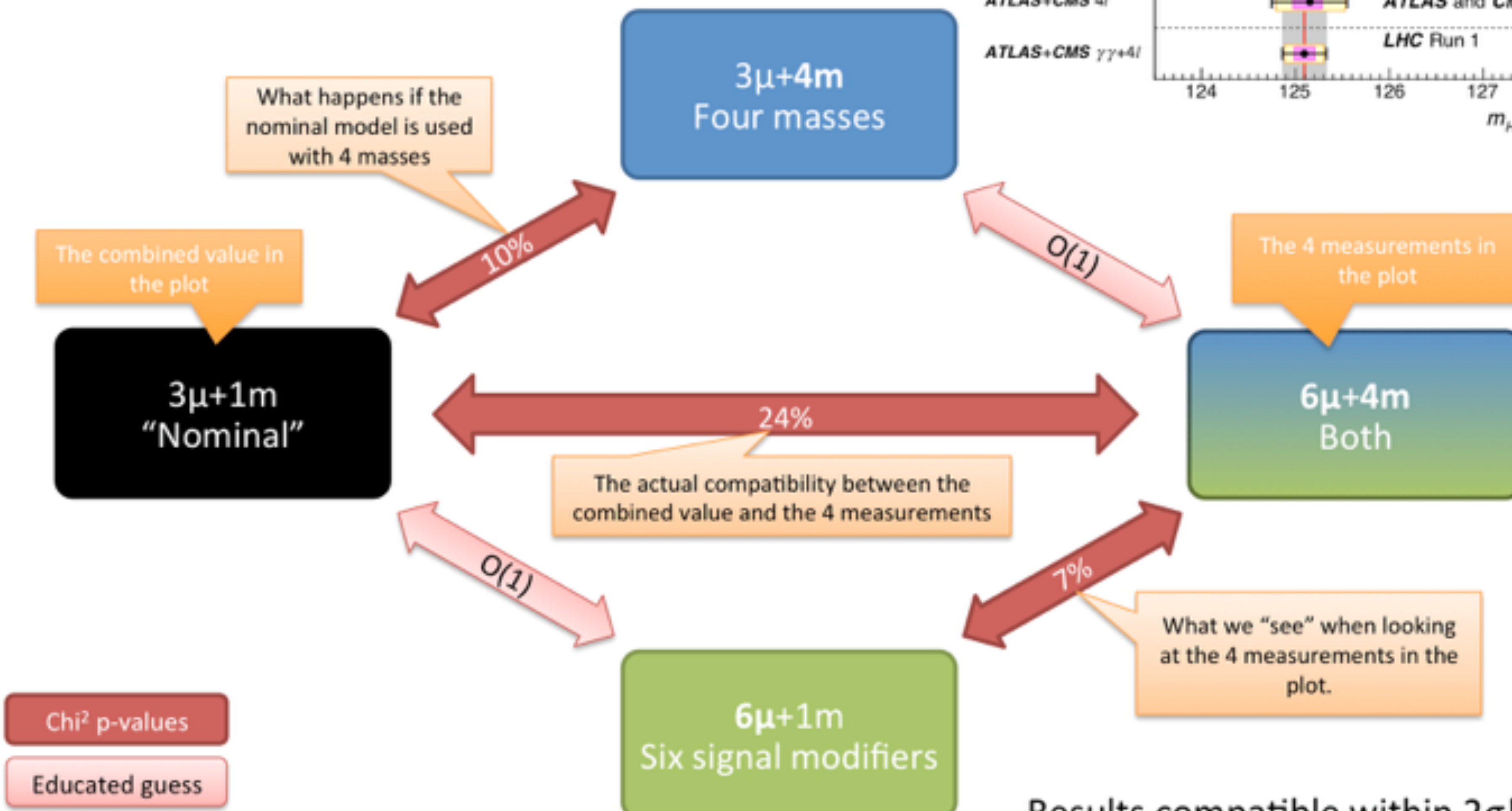
Least assumptions made

Nick Wardle

Compatibility

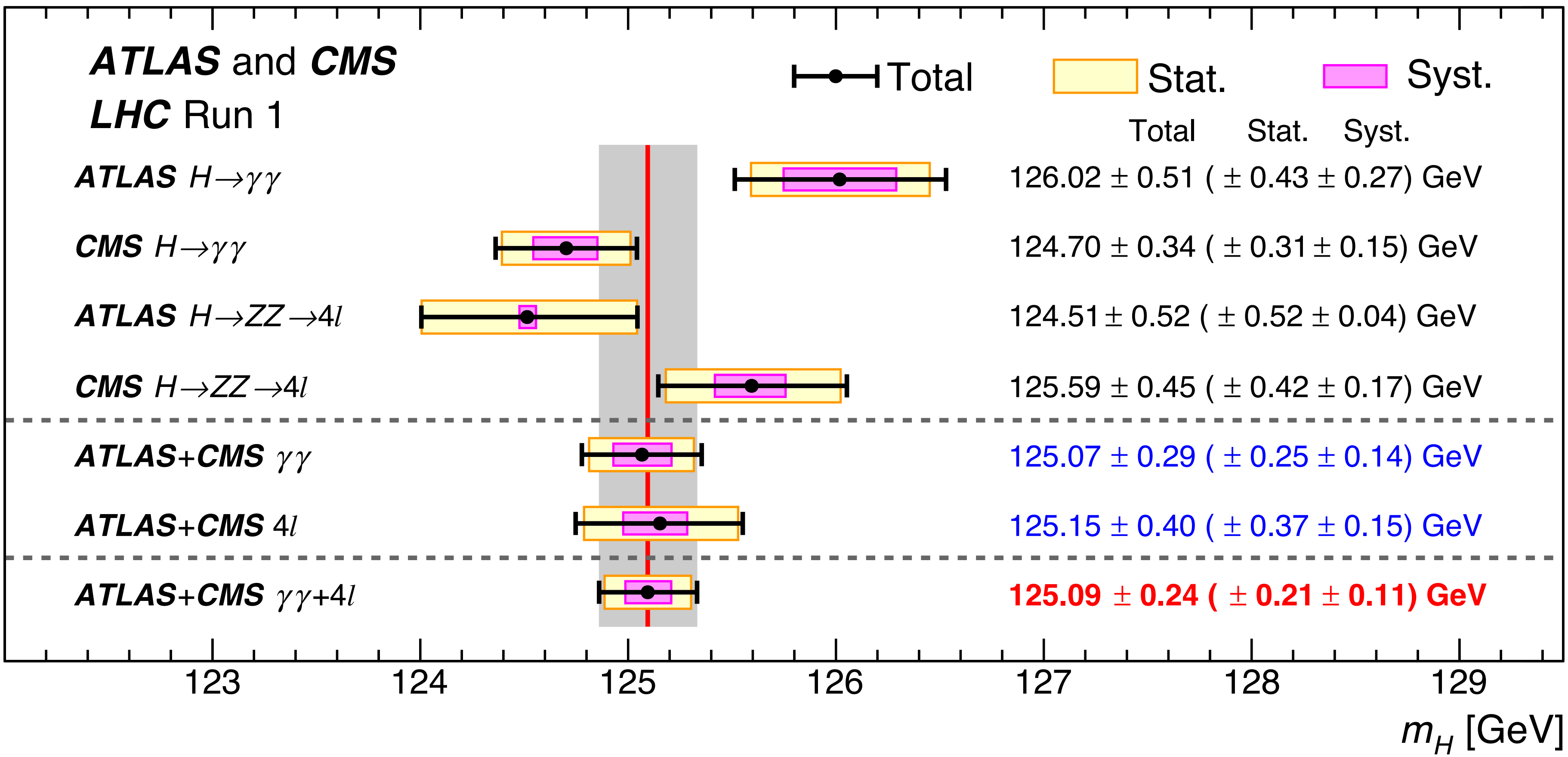
A number of different models to check compatibility of the result …

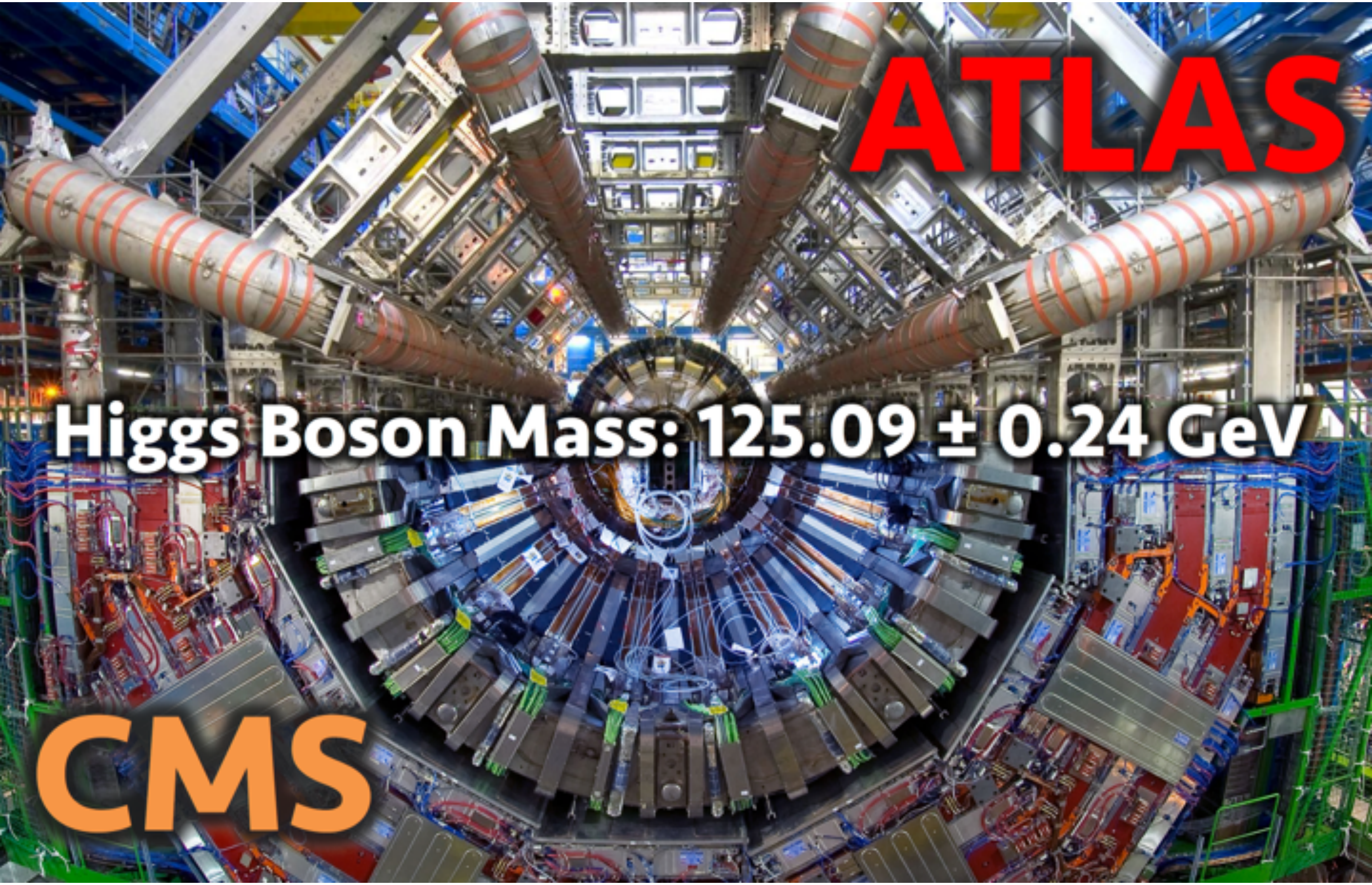




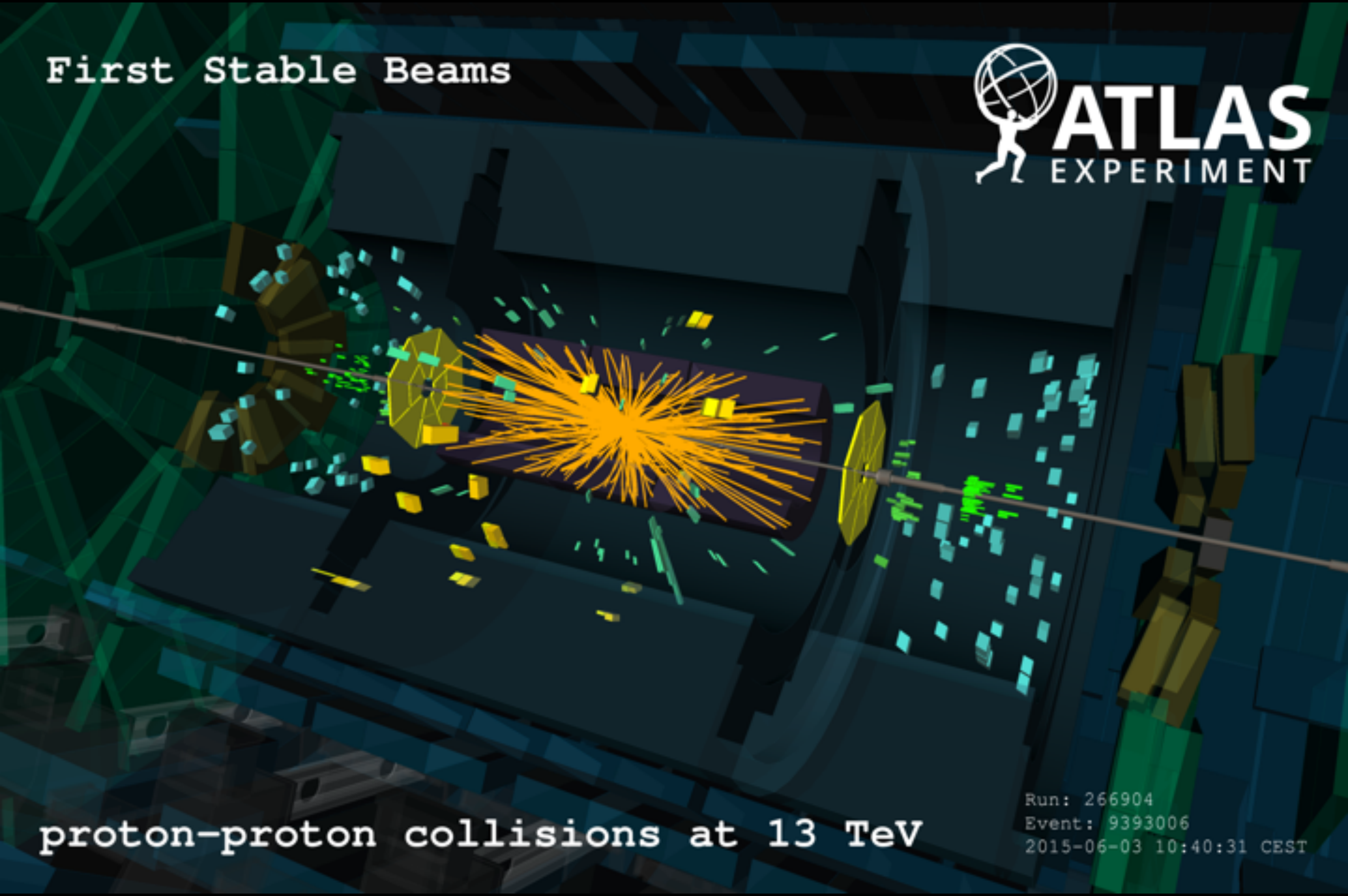
Results compatible within 2σ!

Conclusion

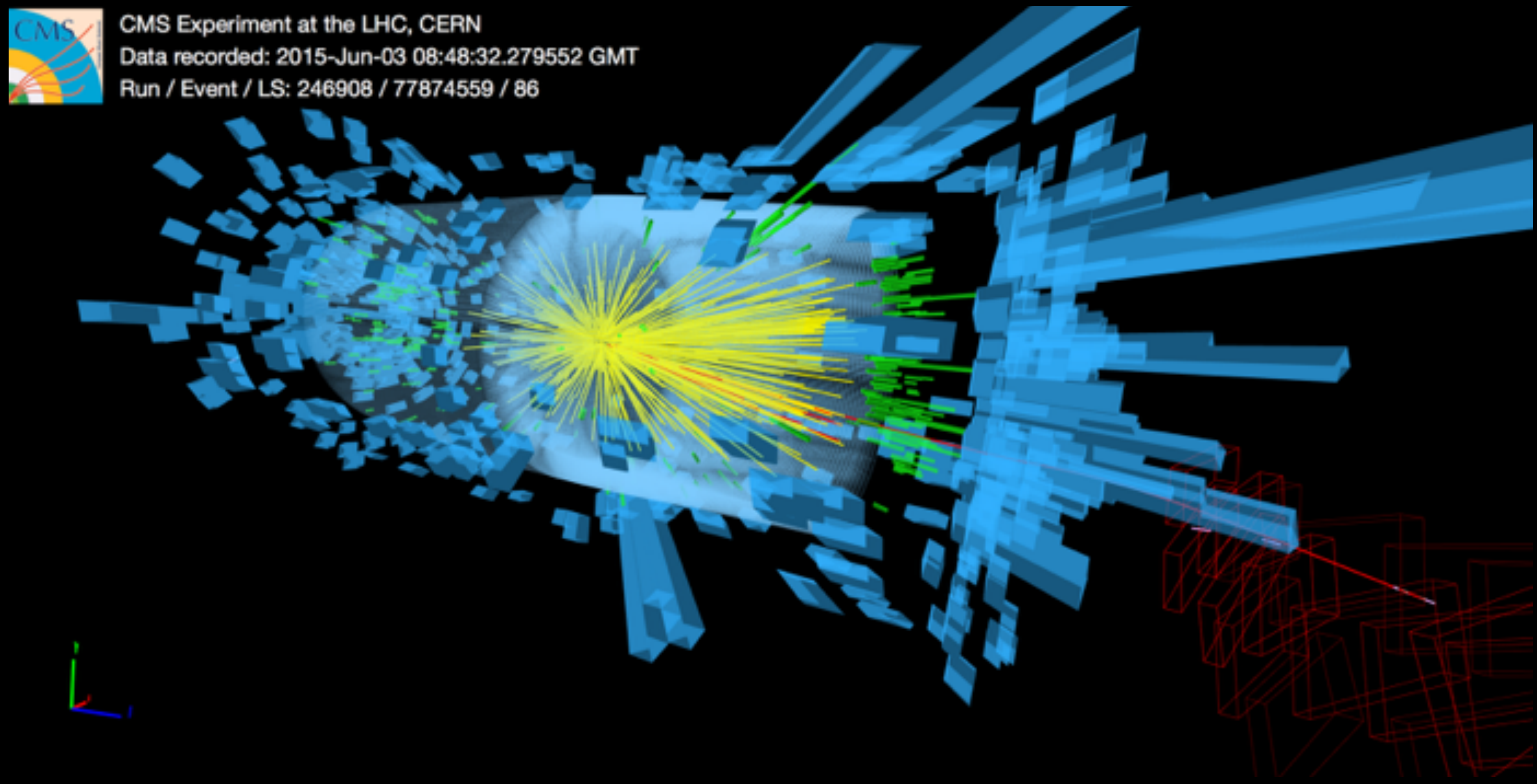

ATLAS and CMS
LHC Run 1
Total
Stat.
Syst.
Total Stat. Syst.
ATLAS H→γγ
126.02 ± 0.51 (± 0.43 ± 0.27) GeV
CMS H→γγ
124.70 ± 0.34 (± 0.31 ± 0.15) GeV
ATLAS H→ZZ→4l
124.51 ± 0.52 (± 0.52 ± 0.04) GeV
CMS H→ZZ→4l
125.59 ± 0.45 (± 0.42 ± 0.17) GeV
ATLAS+CMS γγ
125.07 ± 0.29 (± 0.25 ± 0.14) GeV
ATLAS+CMS 4l
125.15 ± 0.40 (± 0.37 ± 0.15) GeV
ATLAS+CMS γγ+4l
125.09 ± 0.24 (± 0.21 ± 0.11) GeV
123
124
125
126
127
128
129
m_H [GeV]


ATLAS
Higgs Boson Mass: 125.09 ± 0.24 GeV
CMS

The Return of the LHC



The Return of the LHC



Conclusions

In almost three years the "discovery of a scalar particle compatible with a SM Higgs Boson" made a clear phase transition into "precsion measurements"

The Higgs moved from the "search" regime to the "SM" regime

The more luminosity collected (so far) it does not reveal a new face, it is remarkably compatible with a SM Higgs

The Higgs revolution has just begun and we look forward to better measurements and new searches that will reveal hopefully either new particles or significant deviations from the SM. But life is becoming more demanding……

We thank the LHC machine team that enabled us to experience a once in a physicist's lifetime experience!

BACKUP

Eilam Gross, NExT Abingdon 2015