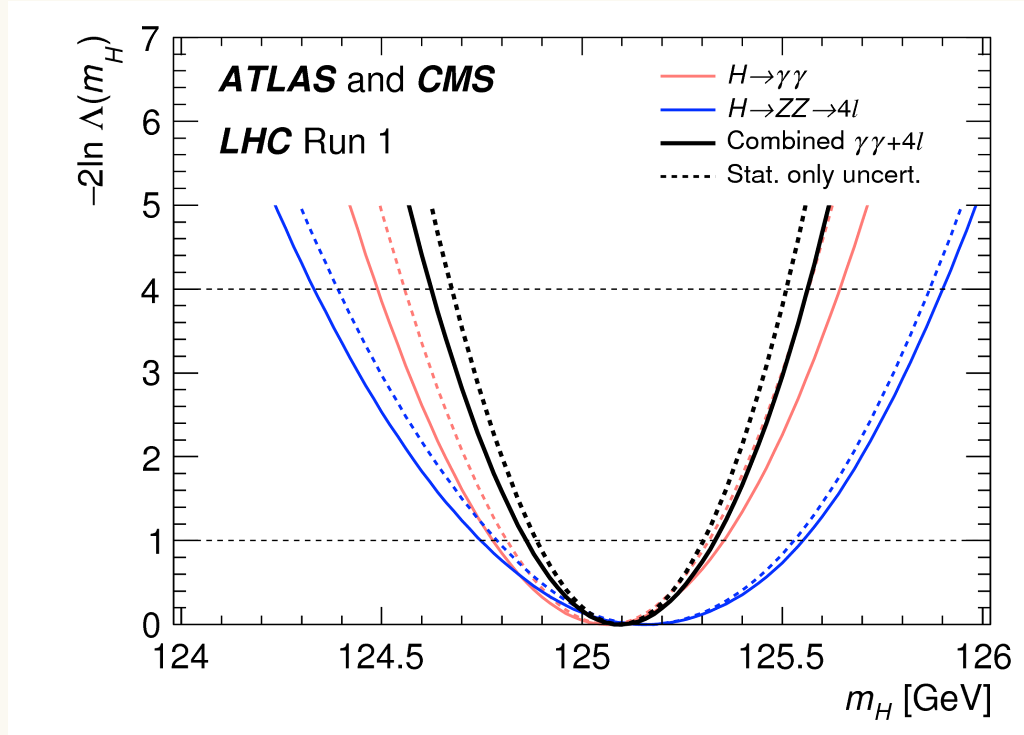
Eilam Gross, Weizmann Institute of Science

HIGGS COUPLINGS
A PEDAGOGIC INTRODUCTIOM

First LHC Higgs Combination Paper

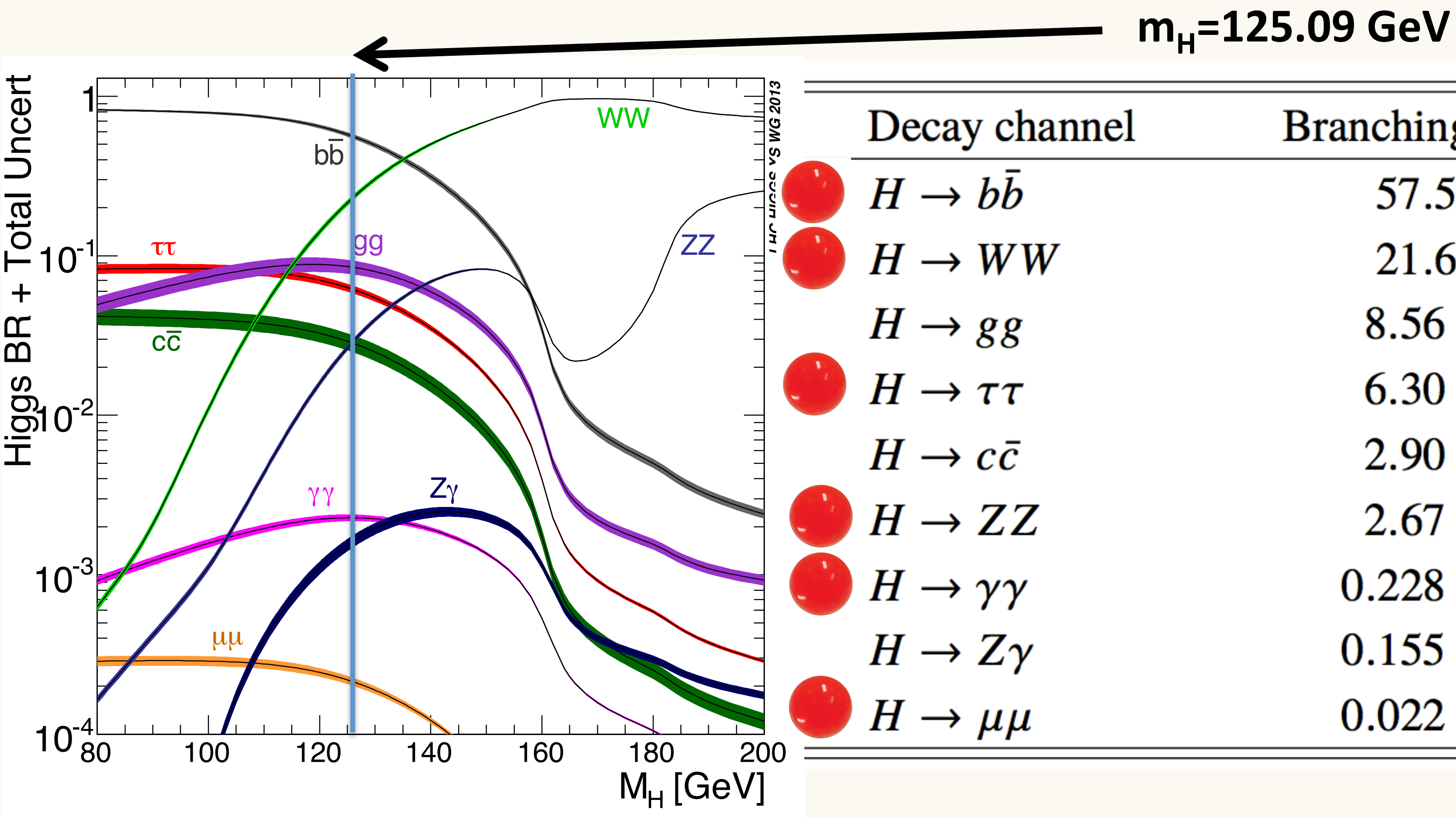


$M_H = 125.09 \pm 0.24$ GeV

$= \pm 0.21$ (stat.) ± 0.11(syst.) GeV

Published May 2015

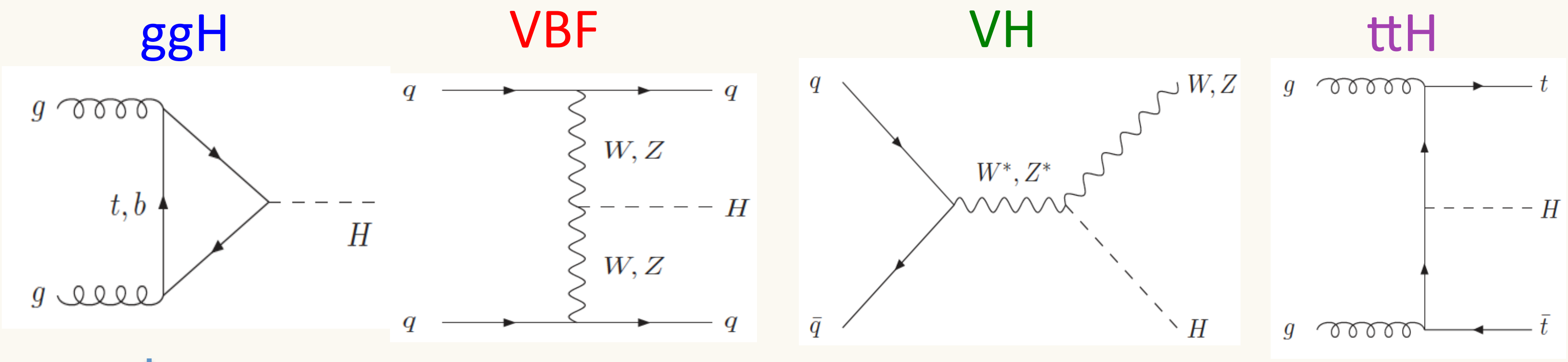
Theory Inputs : Higgs Decays

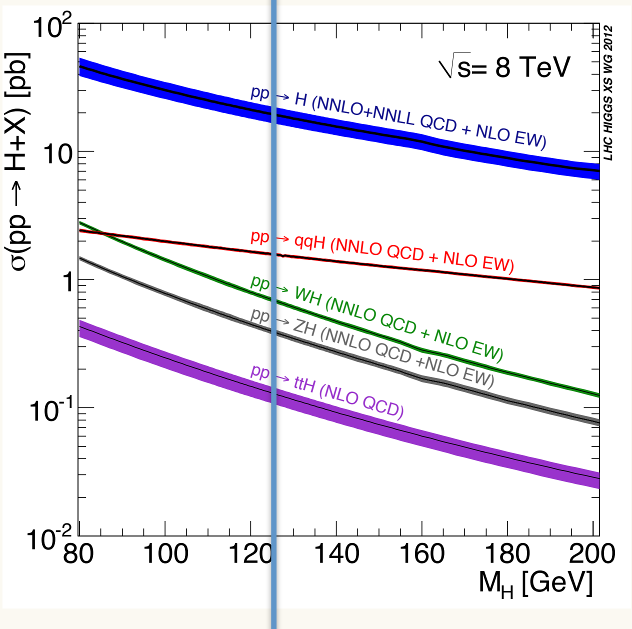


Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

The natural width of the Higgs boson is expected to be very small, 4.1 MeV (<< resolution)

Theory Inputs : Production Modes



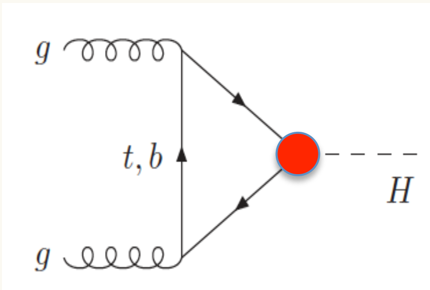


Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	Cross section [pb] $\sqrt{s} = 8$ TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)
$[ggZH]$	0.023 ± 0.007	0.032 ± 0.010	NLO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

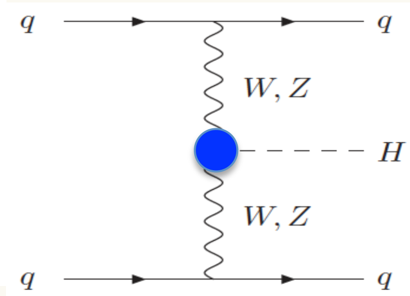
SM ggF, ttH, bbH theory uncertainty: ~10%
VBF, VH, ZH: 2-3%

Theory Inputs : Production Modes

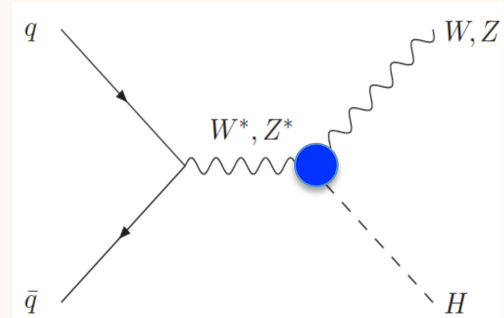
ggH



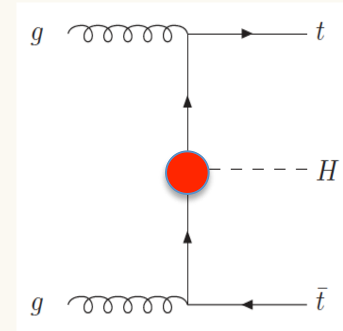
VBF

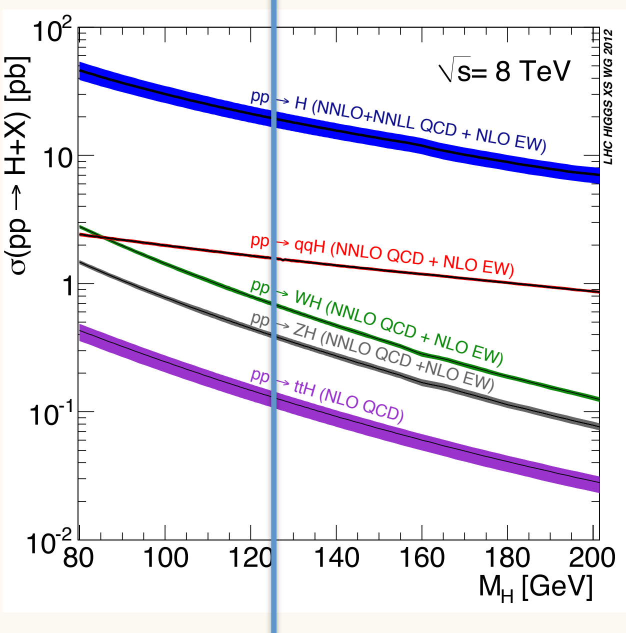


VH



ttH





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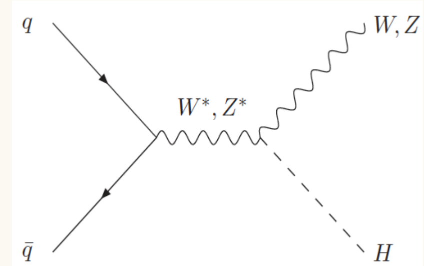
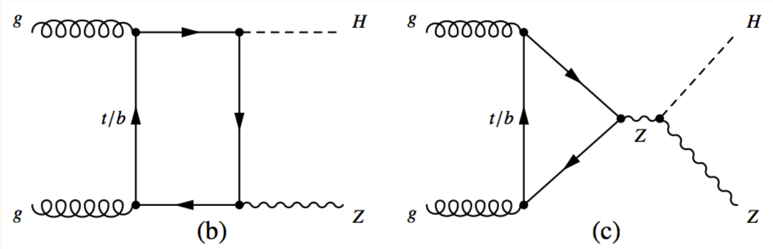
Theory Inputs: Other Production Modes



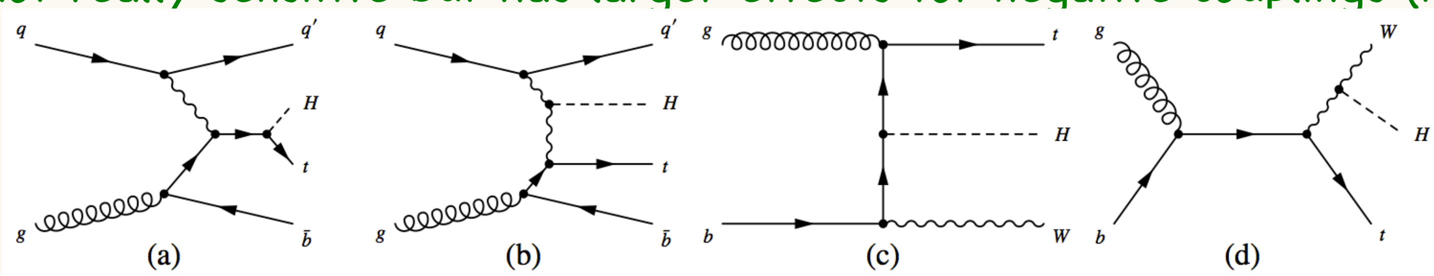
ggZH:

O(10%) effect on VHbb in SM, higher p_T than qqZH



tHq + tHW

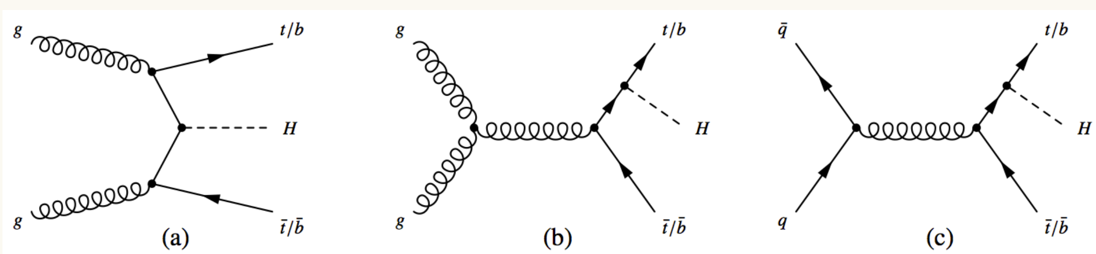
Not really sensitive but has larger effects for negative couplings (kF,kV)



bbH

bbH is ~1% of total HXSC.

Similar to ttH but not really distinguishable from ggF



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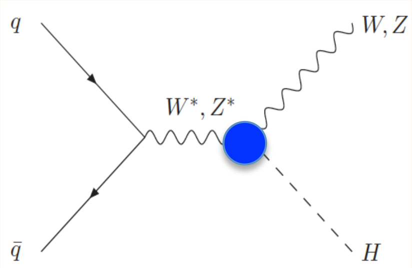

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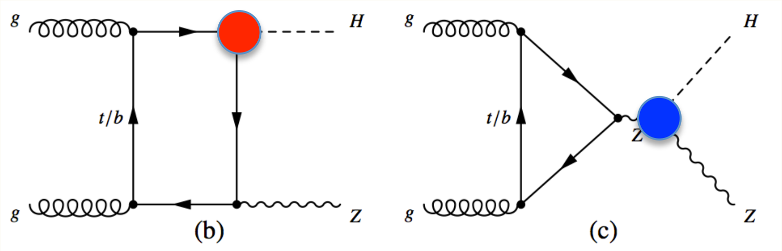

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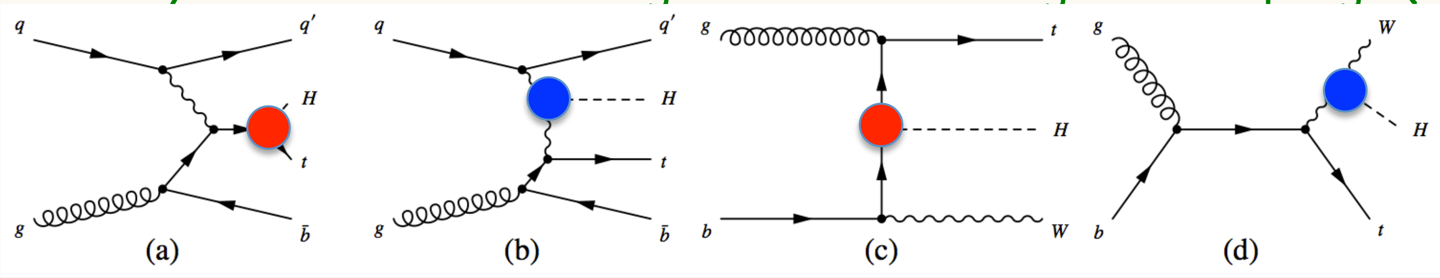

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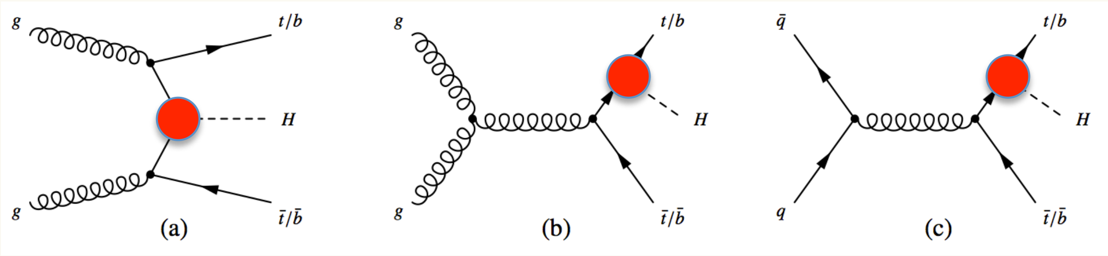
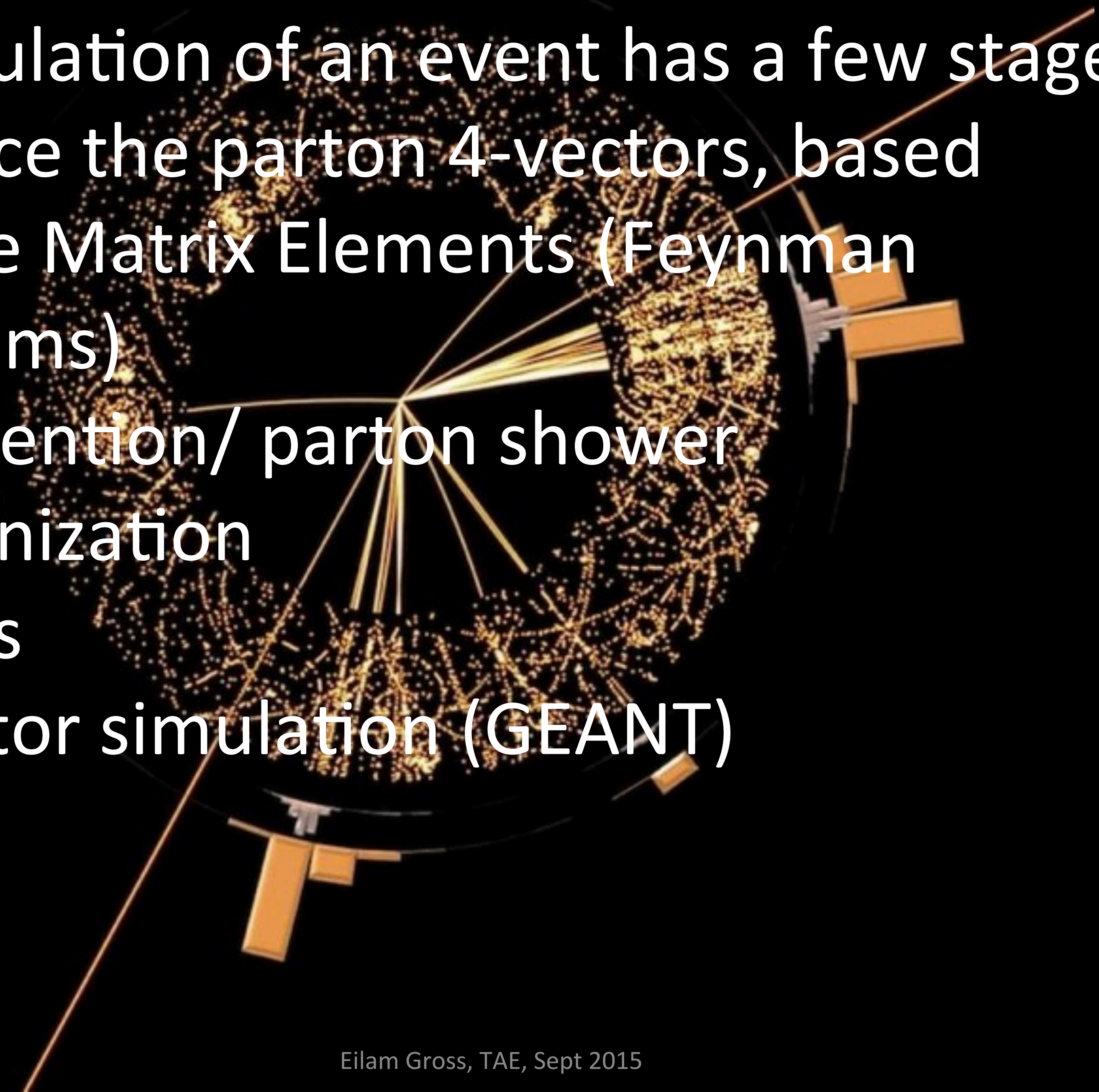


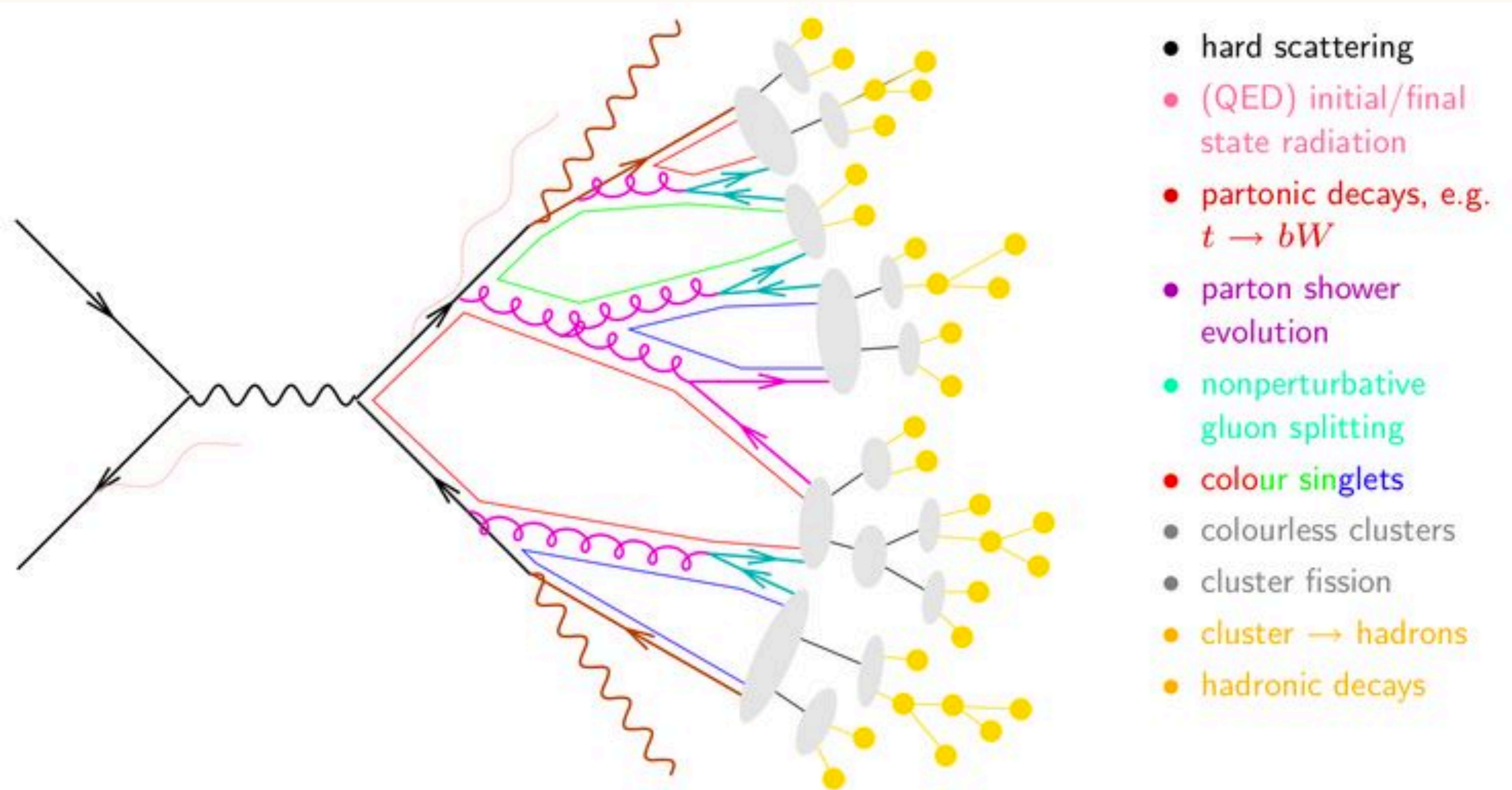
Event (MC) Simulation

The simulation of an event has a few stages:

1. Produce the parton 4-vectors, based on the Matrix Elements (Feynman Diagrams)
2. Fragmention/ parton shower
3. Hadronization
4. Decays
5. Detector simulation (GEANT)

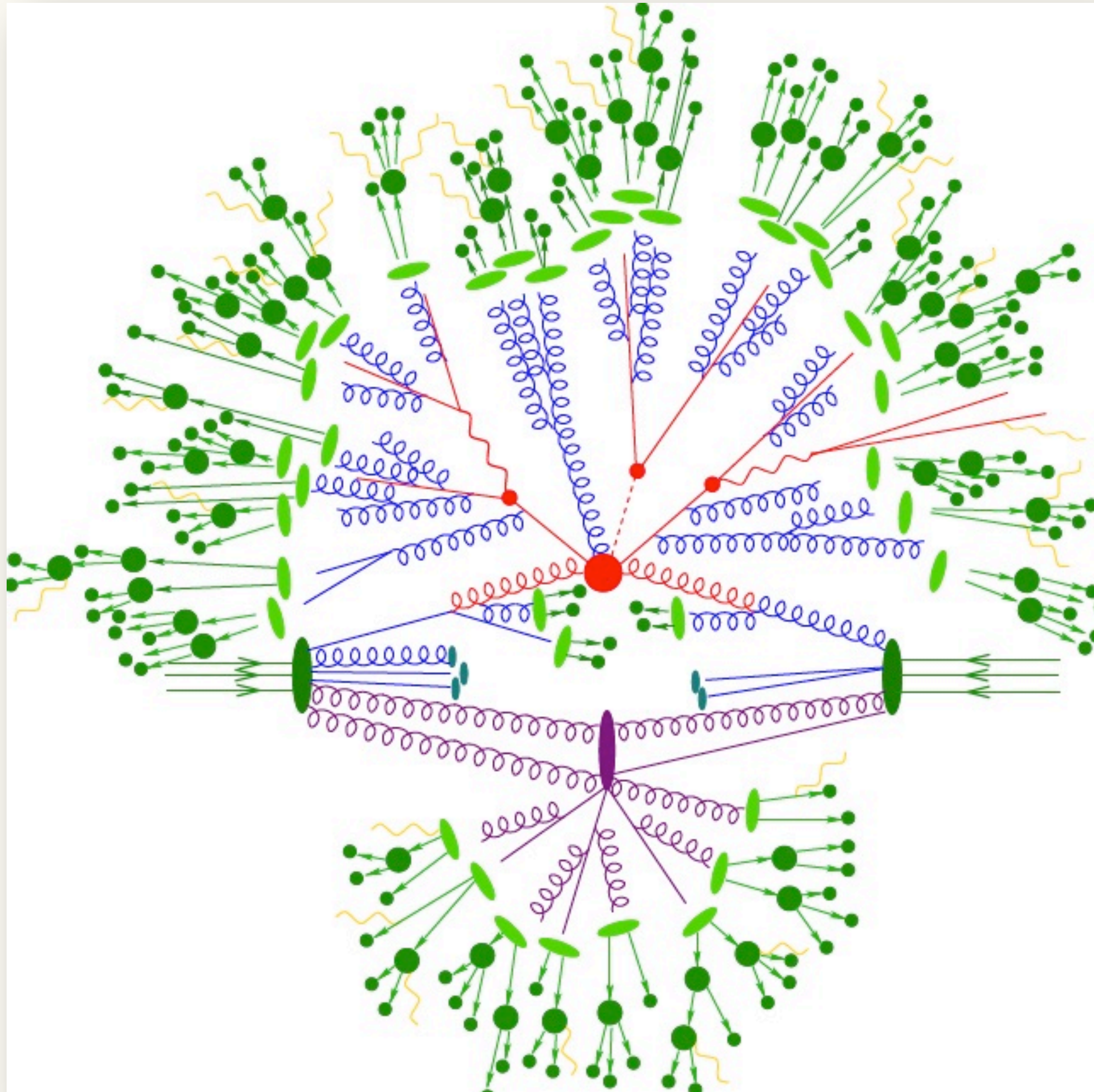


Simulation (MC Generators)

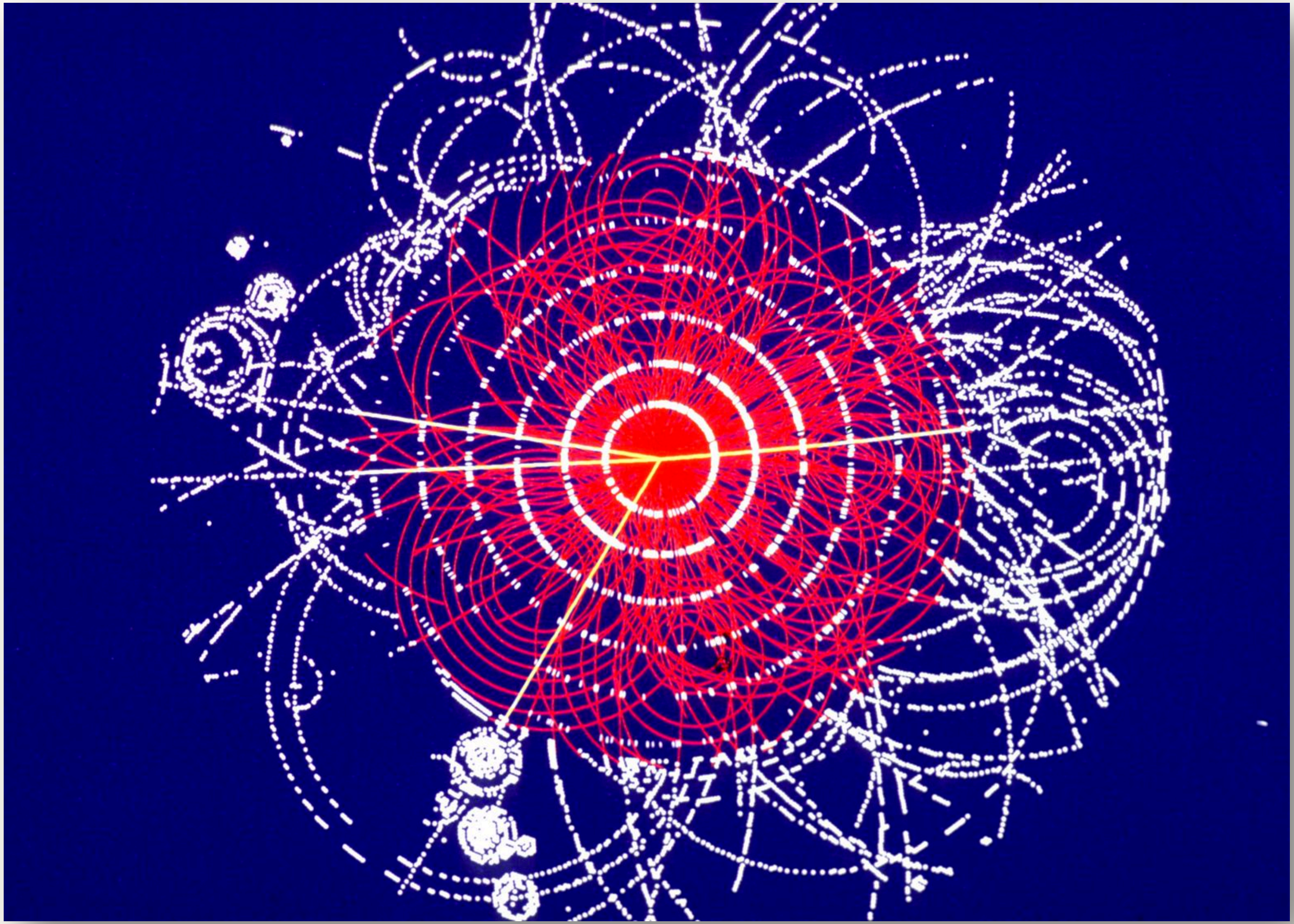


Simulation (MC Generators)

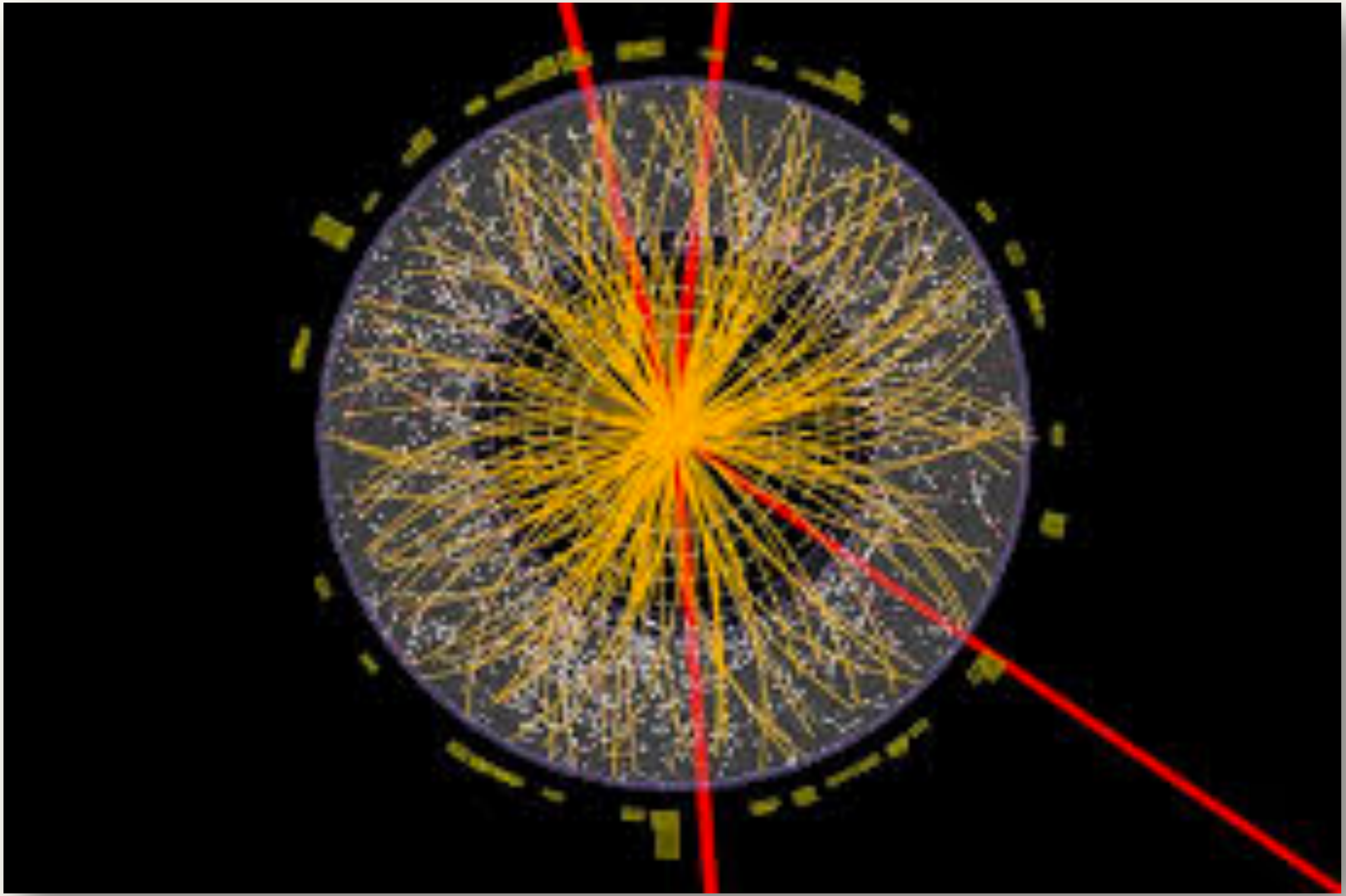
Partons
Fragmentation
Multiple interactions
Hadronization
Decays



EVENT SIMULATION

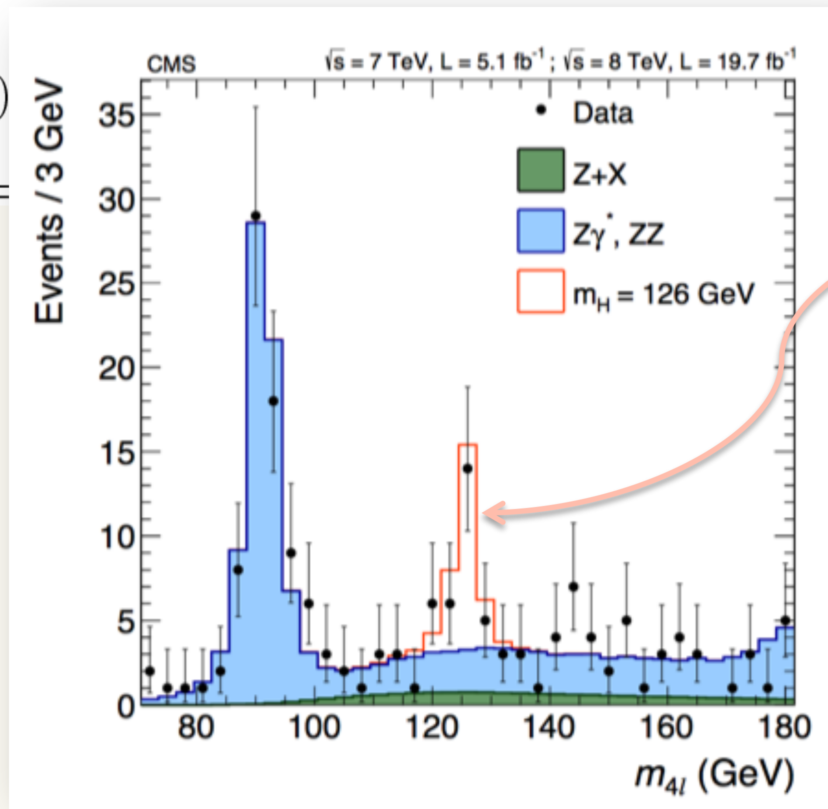


REAL EVENT



Theory Input : Event (MC) Generators

Production process	Event generator ATLAS	Event generator CMS
ggF	POWHEG [30,31,32,33,34]	POWHEG
VBF	POWHEG	POWHEG
WH	PYTHIA8 [35]	PYTHIA6.4 [36]
ZH ($qq \to ZH$ or $qg \to ZH$)	PYTHIA8	PYTHIA6.4
$ggZH$ ($gg \to ZH$)	POWHEG	See text
ttH	POWHEL [44]	PYTHIA6.4
tHq ($qb \to tHq$)		aMC@NLO [29]
tHW ($gb \to tHW$)		aMC@NLO
bbH		PYTHIA6, aMC@NLO



What do we measure (observables)

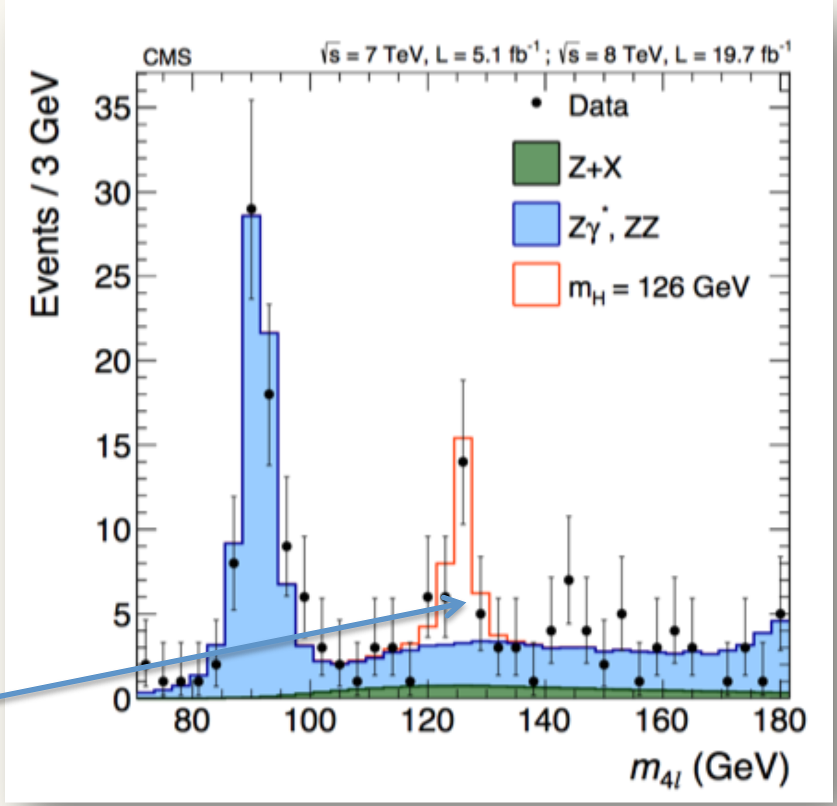
A simplified view:

We measure event yields

(in bins, i.e. shapes)

We want to derive couplings and signal strengths

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



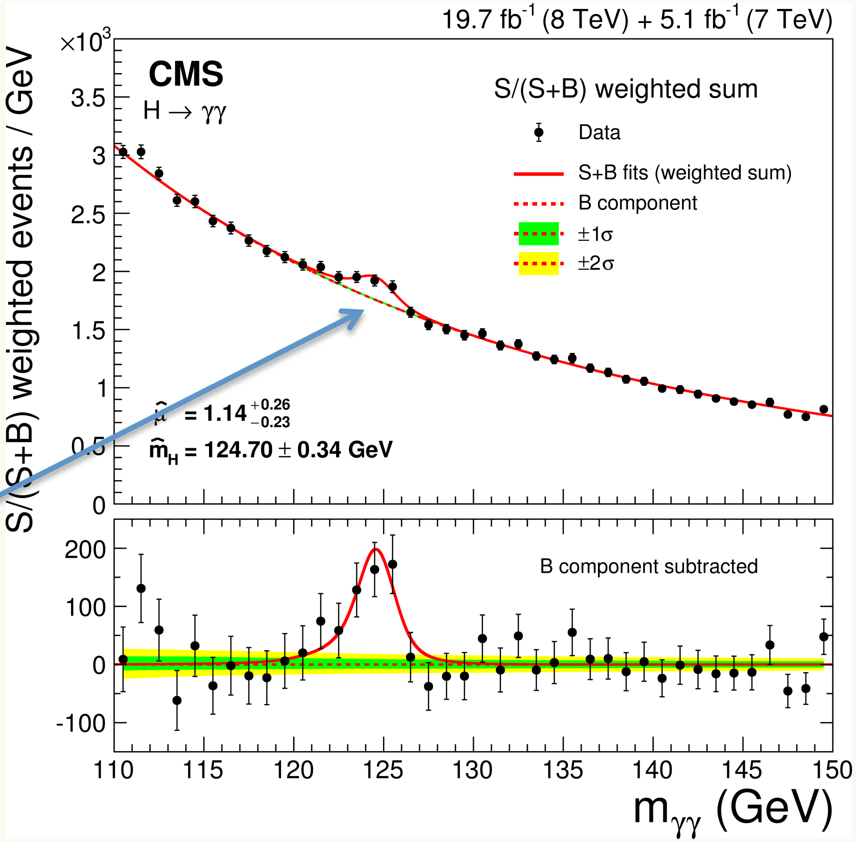
$$n_s(i \to f) = \mu^i \mu^f \times \sum_i (\sigma^i \times Br^f)_{SM} \times A_p^i \times \varepsilon_p^i \times Lumi$$

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

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}} \quad \text{and} \quad \mu^f = \frac{\mathrm{BR}^f}{(\mathrm{BR}^f)_{SM}}$$

What do we measure (observables)

A simplified view:



We measure event yields

(in bins, i.e. shapes)

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

$$n_s(i \to f) = \mu^i \mu^f \times \sum_i (\sigma^i \times Br^f)_{SM} \times A_p^i \times \varepsilon_p^i \times Lumi$$

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

PO

$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

What do we Measure?

We measure event yields

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\text{SM}}} \quad \text{and} \quad \mu^f = \frac{\text{BR}^f}{(\text{BR}^f)_{\text{SM}}}$$

Pseudo Observables

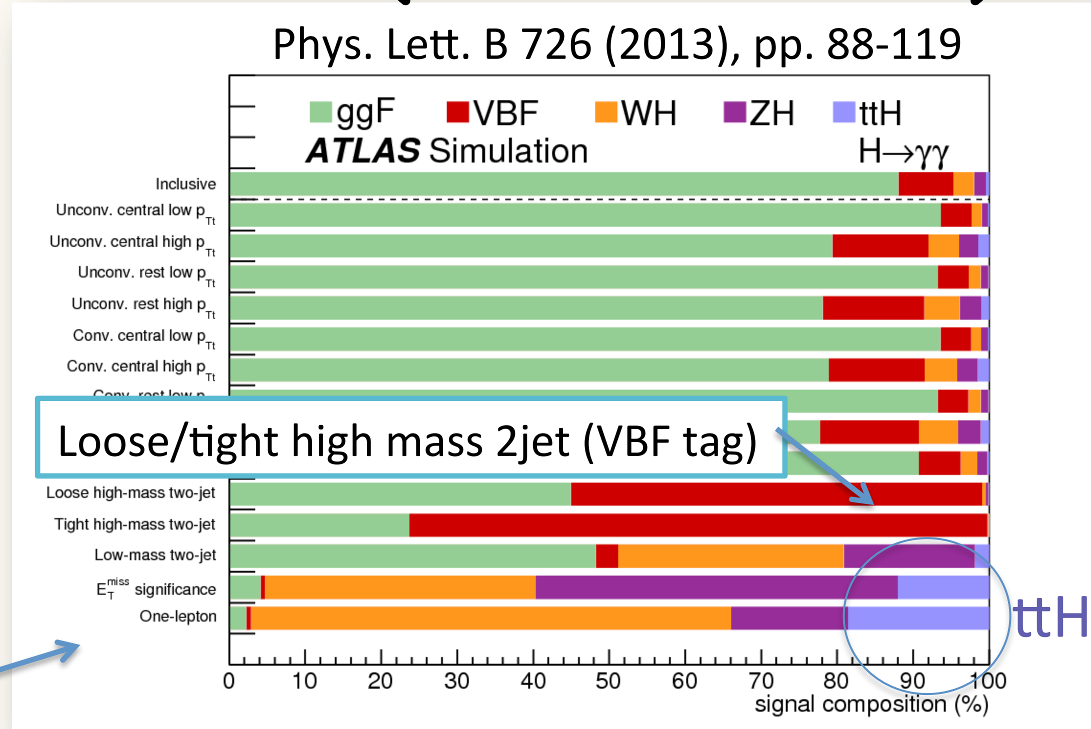
$$\mu_i^f = \frac{\sigma_i \cdot \text{BR}^f}{(\sigma_i)_{\text{SM}} \cdot (\text{BR}^f)_{\text{SM}}} = \mu_i \times \mu^f$$

$$n_s(i \to f) = \mu^i \mu^f \times \sum_i (\sigma^i \times Br^f)_{SM} \times A_p^i \times \varepsilon_p^i \times Lumi$$

Observable | PO | Theory | Experiment | Accelerator & Experiment

What do we measure (observables)

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



The categories are also sensitive to different production modes, allowing the measurement of the couplings

$$n_s^c(i \rightarrow f) = \mu^i \mu^f \times \sum_{i,c} (\sigma^i \times Br^f)_{SM} \times A_p^{i,c} \times \varepsilon_p^{i,c} \times Lumi$$

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

PO

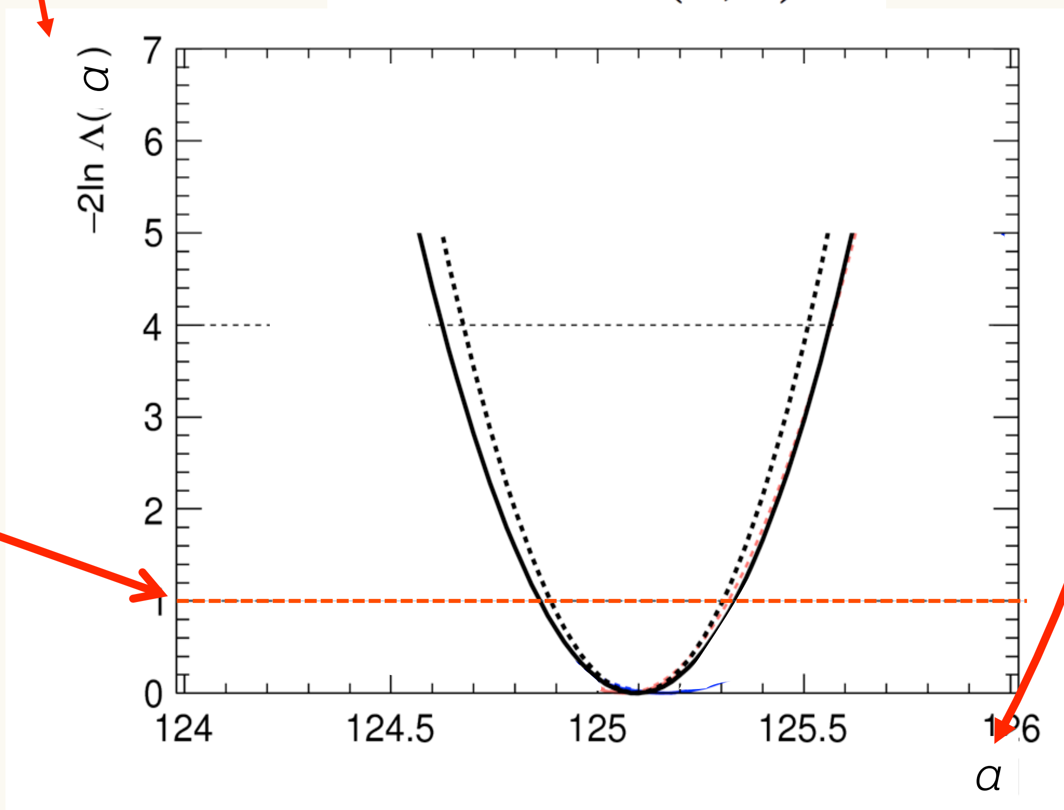
$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

Statistical treatment – profile likelihood

From L(ATLAS+CMS) construct the **profile likelihood** for a statement on the parameter(s) of interest α

$$\Lambda(\vec{\alpha}) = \frac{L(\vec{\alpha}, \hat{\hat{\vec{\theta}}}(\vec{\alpha}))}{L(\hat{\vec{\alpha}}, \hat{\vec{\theta}})}$$

Θ: vector of ~4200 nuisance parameters



68% Confidence interval defined by a rise of 1 unit in $\Lambda(\alpha)$ (asymptotic limit)

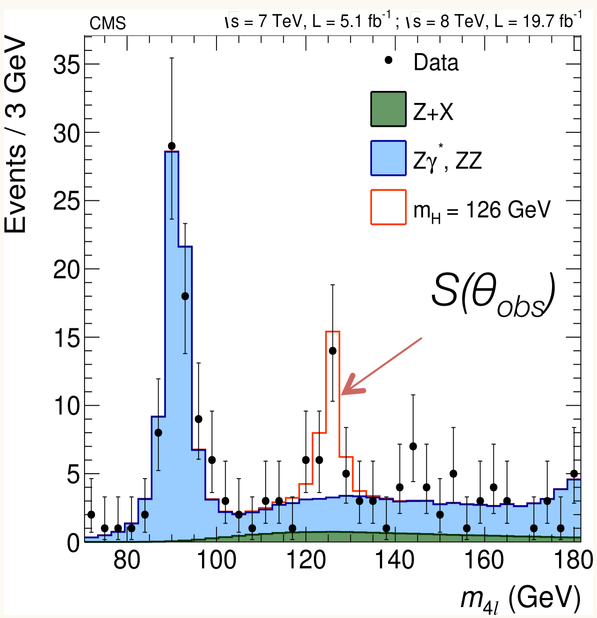
Systematics and Nuisance Parameters

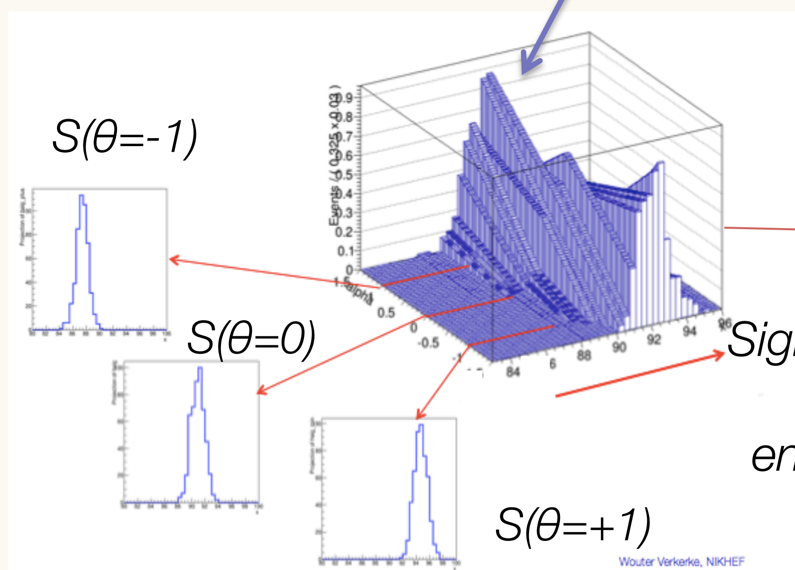
Profile likelihood ratio test statistics:

The signal/background distributions can *describe distribution under a wide range of parameters* for which the true values are unknown (energy scales, QCD scales…)

Illustration: modeling of energy scale uncertainty

$$n_{s+b}(i \to f) = \mu^i \mu^f \times s_i^f(\theta) + b$$



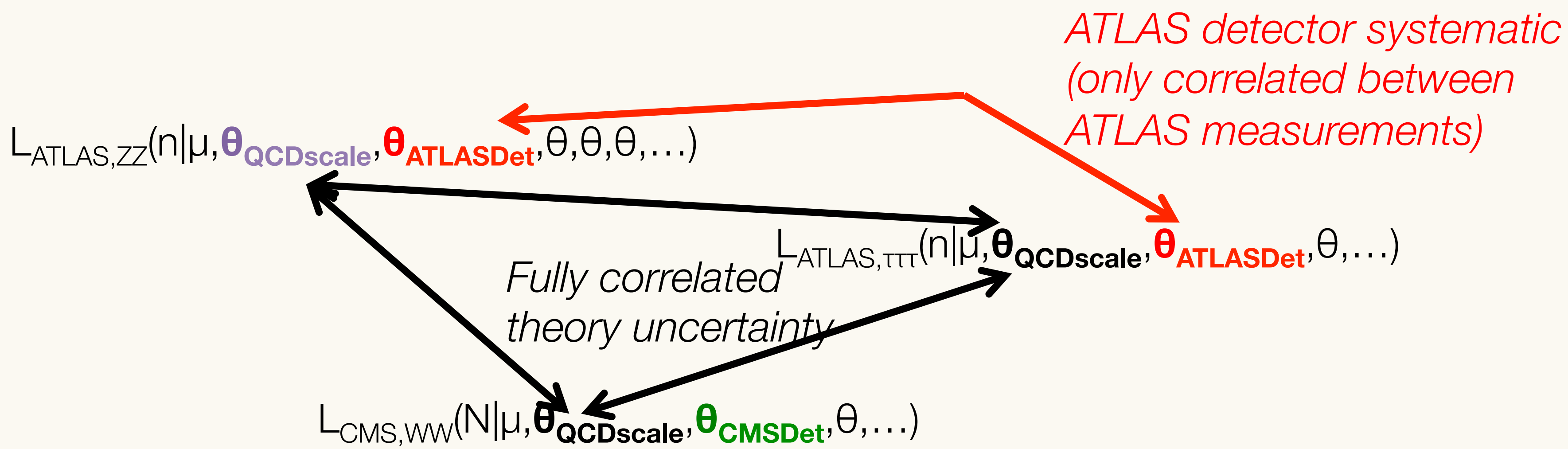


S(N|θ)

Signal Probability model for any value of energy scale param θ

Correlating Experiments and Channels

The PDF uncertainties on the inclusive rates for different Higgs boson production processes are correlated between the two experiments for the same channel but are treated as uncorrelated between different channels, except in two cases:

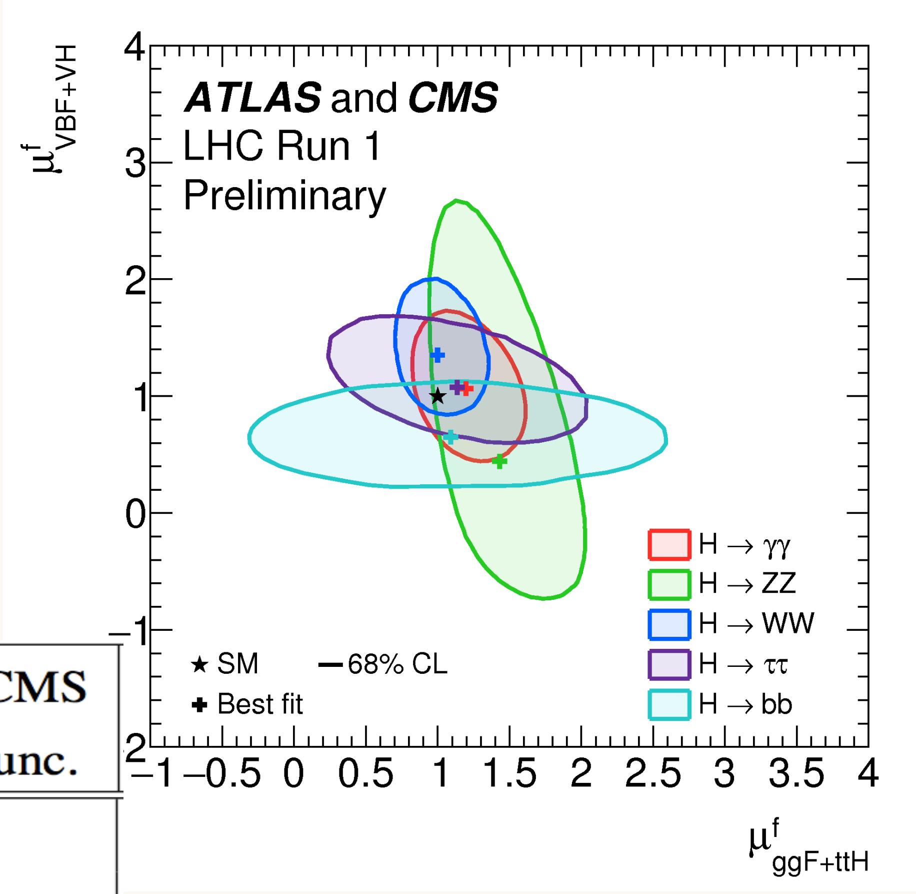


Measuring Signal Strengths

$$\frac{\mu_V^f}{\mu_F^f} = \frac{\mu_V \times BR^f}{\mu_F \times BR^f} = \frac{\mu_V}{\mu_F}$$

μ_V/μ_F can be measured in the different decay channels and combined:

$$\mu_V/\mu_F = 1.06^{+0.35}_{-0.27}$$



Parameter	ATLAS+CMS observed	ATLAS+CMS expected unc.
μ_V/μ_F	$1.06^{+0.35}_{-0.27}$	$^{+0.34}_{-0.26}$
$\mu_F^{\gamma\gamma}$	$1.13^{+0.24}_{-0.21}$	$^{+0.21}_{-0.19}$
μ_F^{ZZ}	$1.29^{+0.29}_{-0.25}$	$^{+0.24}_{-0.20}$
μ_F^{WW}	$1.08^{+0.22}_{-0.19}$	$^{+0.19}_{-0.17}$
$\mu_F^{\tau\tau}$	$1.07^{+0.35}_{-0.28}$	$^{+0.32}_{-0.27}$
$\mu_F^{b\bar{b}}$	$0.65^{+0.37}_{-0.28}$	$^{+0.45}_{-0.34}$

SM p-value
72% (6p)

Measuring Production Signal Strengths

Assuming SM BR we can measure the signal production strengths.

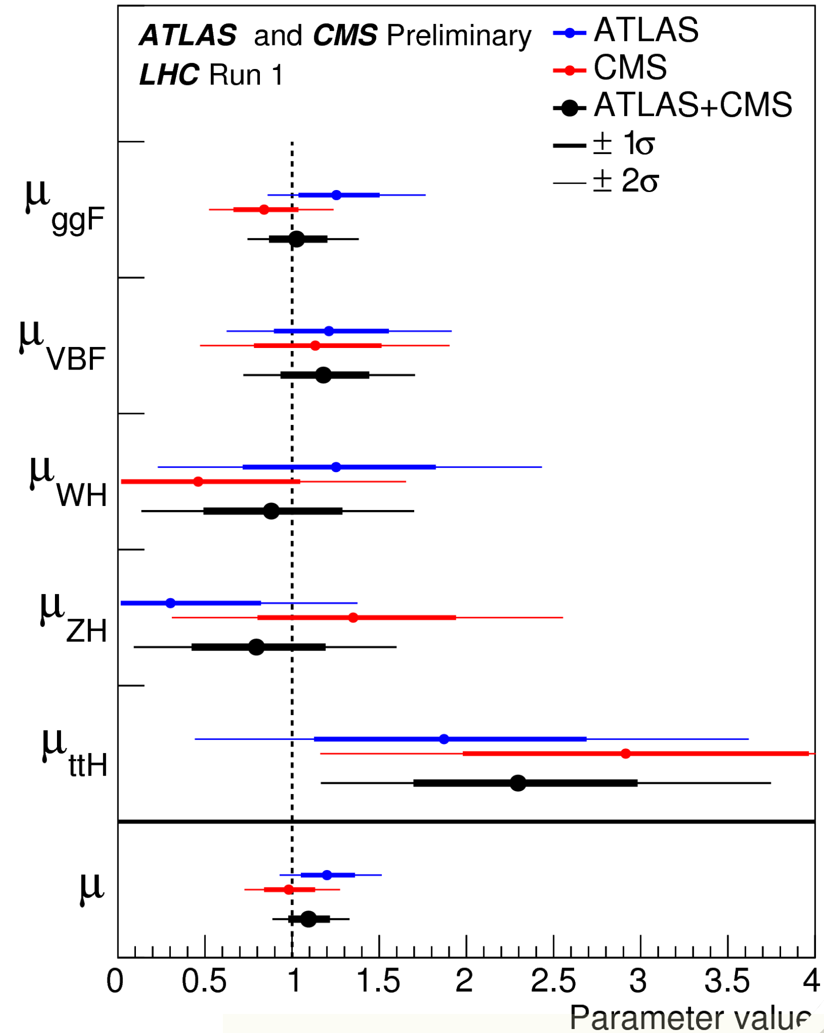
Production process	ATLAS+CMS
μ_{ggF}	$1.03^{+0.17}_{-0.15}$
μ_{VBF}	$1.18^{+0.25}_{-0.23}$
μ_{WH}	$0.88^{+0.40}_{-0.38}$
μ_{ZH}	$0.80^{+0.39}_{-0.36}$
μ_{ttH}	$2.3^{+0.7}_{-0.6}$

SM p-value 24% (5p)

A subtlety:
Assume signal strengths are equal @ 7 and 8 TeV

Largest difference in ttH: 2.3σ excess with respect to SM

Over 5 sigma in VBF



Main uncertainty from ggF xsc

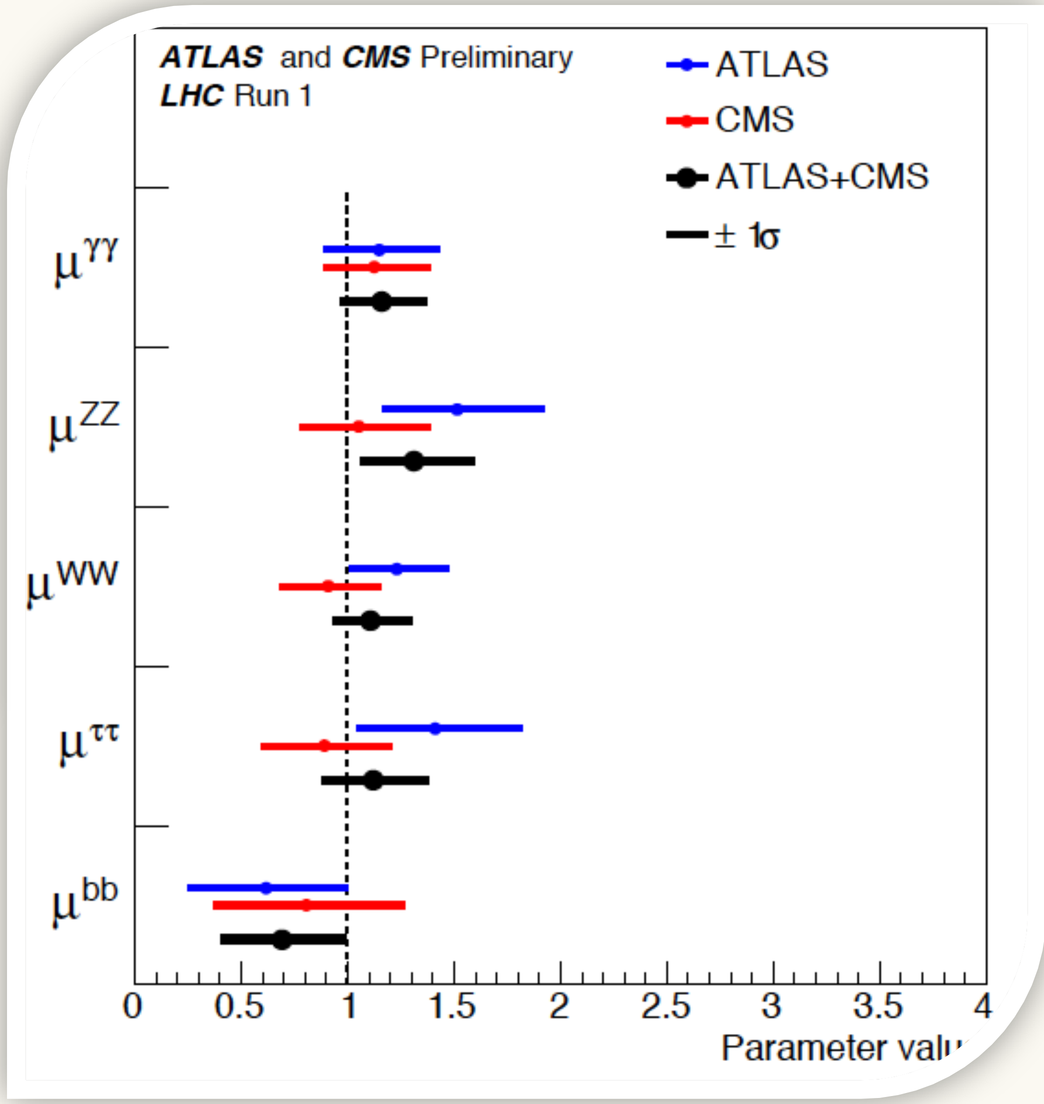
$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\ (\text{stat})\ ^{+0.04}_{-0.04}\ (\text{expt})\ ^{+0.03}_{-0.03}\ (\text{thbgd})^{+0.07}_{-0.06}\ (\text{thsig})$$

Measuring the Higgs Decay Modes

Assuming SM signal production strengths, we can measure the Higgs Decay BRs

Decay channel	ATLAS+CMS
$\mu^{\gamma\gamma}$	$1.16^{+0.20}_{-0.18}$
μ^{ZZ}	$1.31^{+0.27}_{-0.24}$
μ^{WW}	$1.11^{+0.18}_{-0.17}$
$\mu^{\tau\tau}$	$1.12^{+0.25}_{-0.23}$
μ^{bb}	$0.69^{+0.29}_{-0.27}$

Over 5 sigma in ττ



Significance in the different channels

Comparing likelihood of the best-fit with μ_{prod}=0 and μ^{decay}=0 we obtain:

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \rightarrow \tau\tau$	5.5	5.0
$H \rightarrow bb$	2.6	3.7

Combination largely increases the sensitivity

VBF and H→ $\tau\,\tau$ now established at over 5 σ.
Same as ggF and H→ZZ, $\gamma\,\gamma$, WW from single experiments

Model Independent Ratios (Generic I)

One can fit the data with ONE channel specific measurement (i→H→f) , 4 ratios of cross sections and 4 ratios of BRs

$$\sigma_x \times BR^y = \sigma(i \to H \to f)\left(\frac{\sigma_x}{\sigma_i}\right)\cdot\left(\frac{BR^y}{BR^f}\right)$$

$9\ pars$

$ref: \sigma_i \cdot BR^f,\ e.g.\ \sigma_{ggH} \cdot BR^{ZZ}$

$\frac{\sigma_{VBF}}{\sigma_{ggH}}$

$\frac{\sigma_{WH}}{\sigma_{ggH}}$

$\frac{\sigma_{ZH}}{\sigma_{ggH}}$

$\frac{\sigma_{ttH}}{\sigma_{ggH}}$

$\frac{BR^{\gamma\gamma}}{BR^{ZZ}}$

$\frac{BR^{WW}}{BR^{ZZ}}$

$\frac{BR^{\tau\tau}}{BR^{ZZ}}$

$\frac{BR^{bb}}{BR^{ZZ}}$

This way, we make no assumptions on the Higgs boson total width, which can freely vary, **provided the narrow width approximation is still valid.**

Furthermore, many theoretical and experimental systematic uncertainties cancel in these ratios. In particular, they are not subject to the dominant signal theoretical uncertainties on the inclusive cross sections for the various production processes.

These measurements will therefore remain valid, for example when improved theoretical calculations of Higgs boson production cross sections will become available. The remaining theoretical uncertainties are reduced to those related to the acceptances and selection efficiencies in the various categories.

This is the most generic parameterisation considered, and from the results in terms of their central values and the full error covariance matrix, it is possible, assuming the asymptotic approximation, to derive other results of signal strength parameterisations

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$9\ pars$

$ref: \sigma_i \cdot BR^f,\ e.g.\ \sigma_{ggH} \cdot BR^{ZZ}$

$\frac{\sigma_{VBF}}{\sigma_{ggH}}$

$\frac{\sigma_{WH}}{\sigma_{ggH}}$

$\frac{\sigma_{ZH}}{\sigma_{ggH}}$

$\frac{\sigma_{ttH}}{\sigma_{ggH}}$

$\frac{BR^{\gamma\gamma}}{BR^{ZZ}}$

$\frac{BR^{WW}}{BR^{ZZ}}$

$\frac{BR^{\tau\tau}}{BR^{ZZ}}$

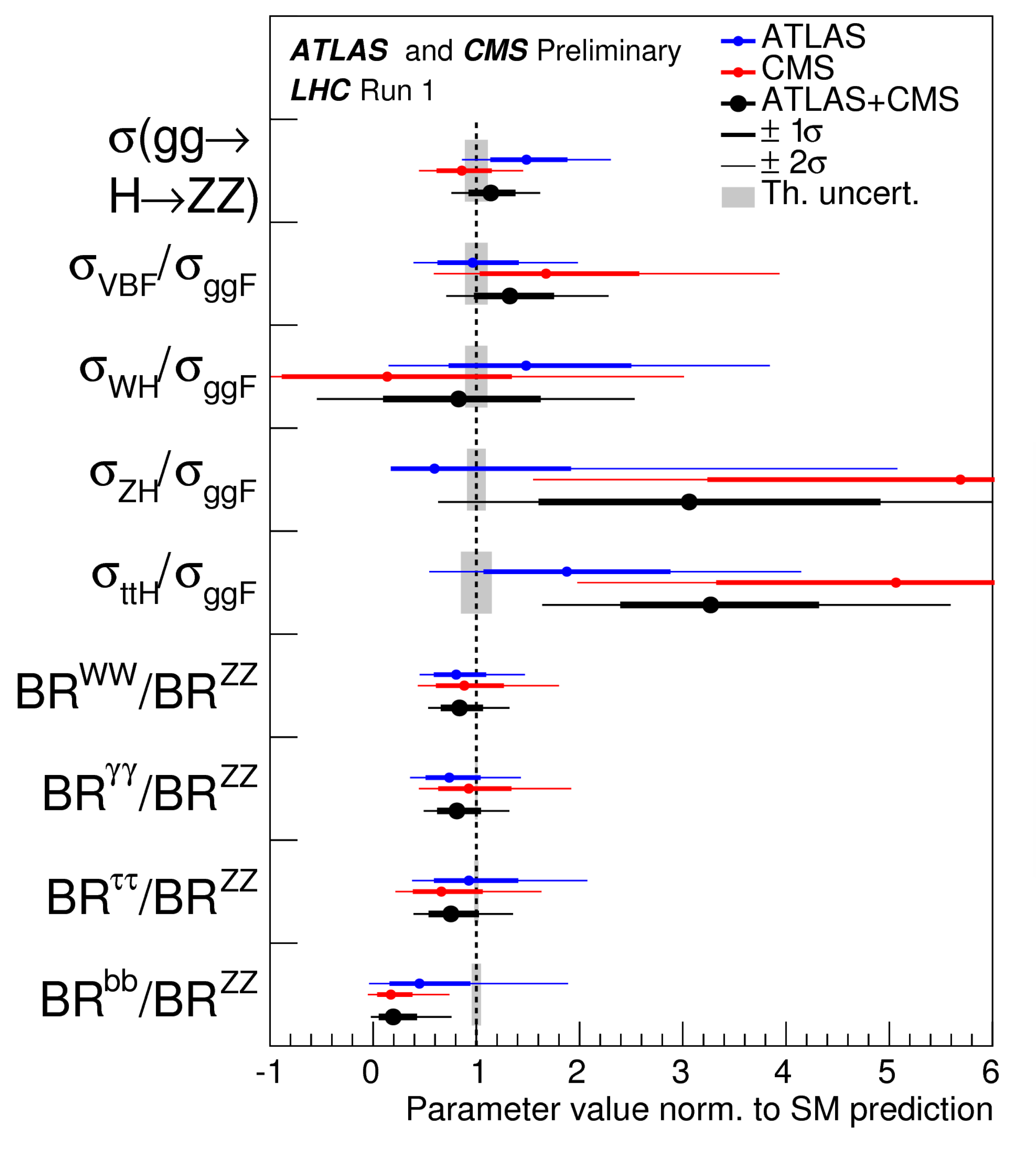
$\frac{BR^{bb}}{BR^{ZZ}}$

reference process: $i \to f$

$e.g.\quad \text{ref=gg} \to H \to ZZ$

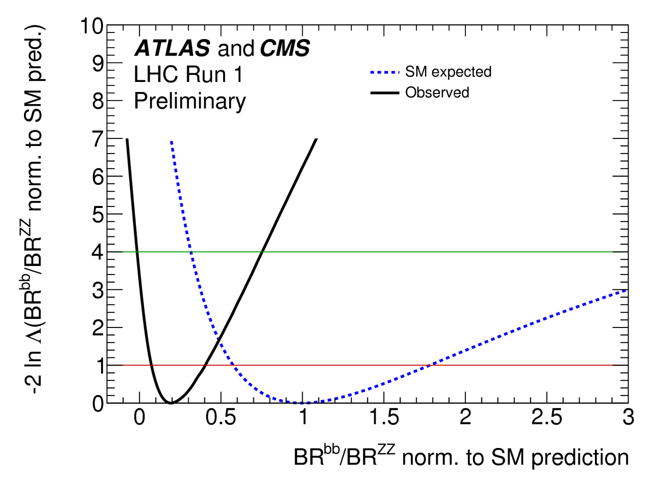
$$\mu_{ZH}^{bb} = \left[\frac{\mu_{ZH}}{\mu_{ggH}}\right] \cdot \mu_{ggH}^{ZZ} \cdot \left[\frac{\mu_{bb}}{\mu_{ZZ}}\right]$$

Model Independent Ratios (Generic I)

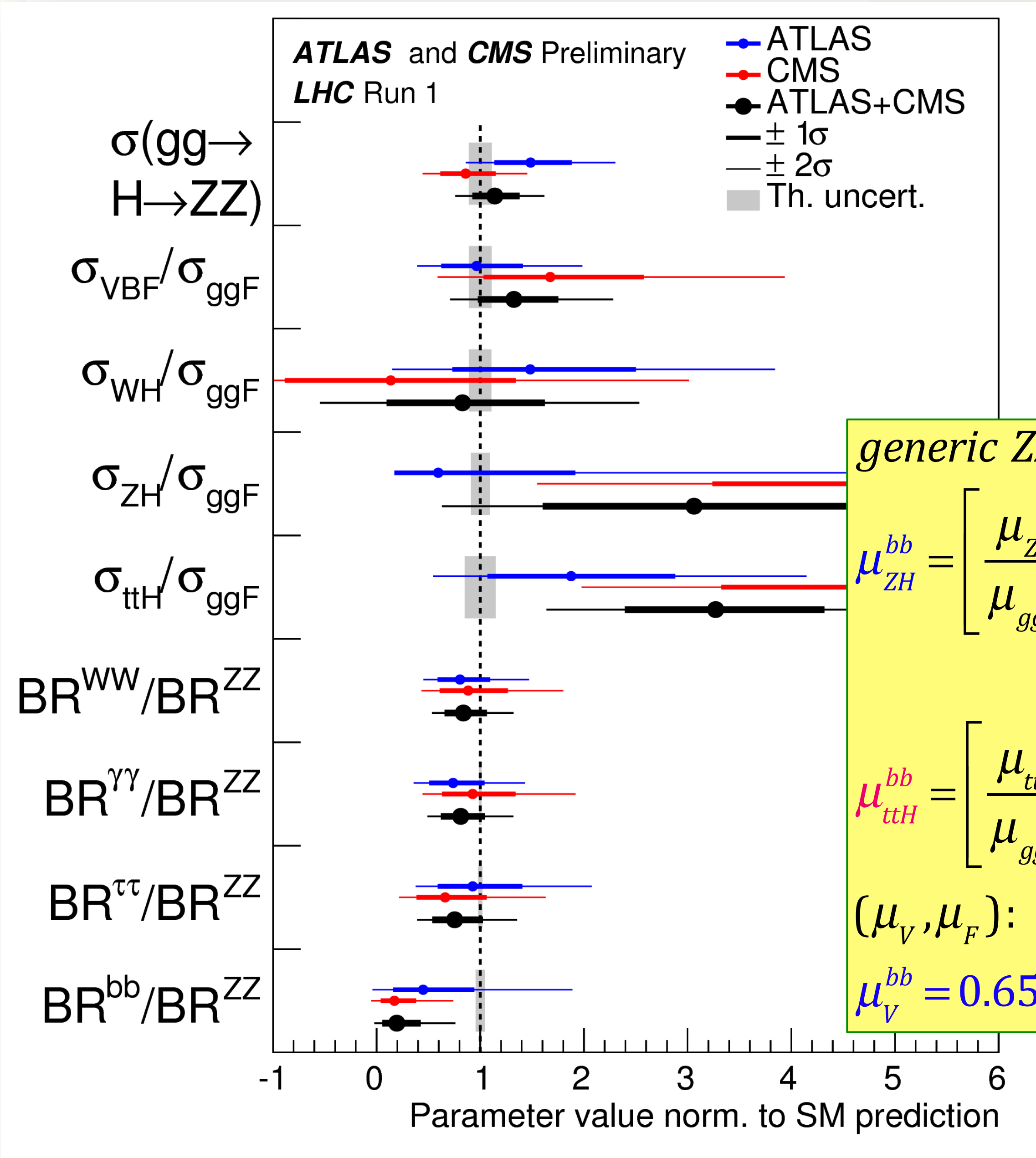


Largest deviationfrom SM is seen in BR^{bb}/BR^{ZZ}, at the level of 2.4 σ

Effect mainly coming from large ZH and ttH (both ratios σ_i / σ_{ggF} ~ 3)



Model Independent Ratios (Generic I)



Largest deviationfrom SM is seen in BR^{bb}/BR^{ZZ}, at the level of 2.4 σ

Effect mainly coming from large ZH and ttH (both ratios σ_i/σ_{ggF} ~ 3)

generic ZZ :

$$\mu^{bb}_{ZH} = \left[\frac{\mu_{ZH}}{\mu_{ggH}}\right] \cdot \mu^{ZZ}_{ggH} \cdot \left[\frac{\mu_{bb}}{\mu_{ZZ}}\right] \approx 3.1 \cdot 1.14 \cdot 0.2 = 0.7$$

$$\mu^{bb}_{ttH} = \left[\frac{\mu_{ttH}}{\mu_{ggH}}\right] \cdot \mu^{ZZ}_{ggH} \cdot \left[\frac{\mu_{bb}}{\mu_{ZZ}}\right] \approx 3.3 \cdot 1.14 \cdot 0.2 = 0.8$$

(μ_V, μ_F):

$$\mu^{bb}_V = 0.65, \mu^{bb}_F = 1.09$$

Couplings

The κ –framework

$$k_f^2 = \frac{\Gamma_f}{\Gamma_H} \qquad \Gamma_{i,u} = \Gamma_{BSM}$$

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

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

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

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

Measuring Higgs Couplings

$$n_s(i \to f) = \mu^i \mu^f \times \sum_i (\sigma^i \times Br^f)_{SM} \times A_p^i \times \varepsilon_p^i \times Lumi$$

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

Can we resolve the degeneracy, disentangle $\left[\mu_i^f \equiv \mu^i \mu^f\right]$

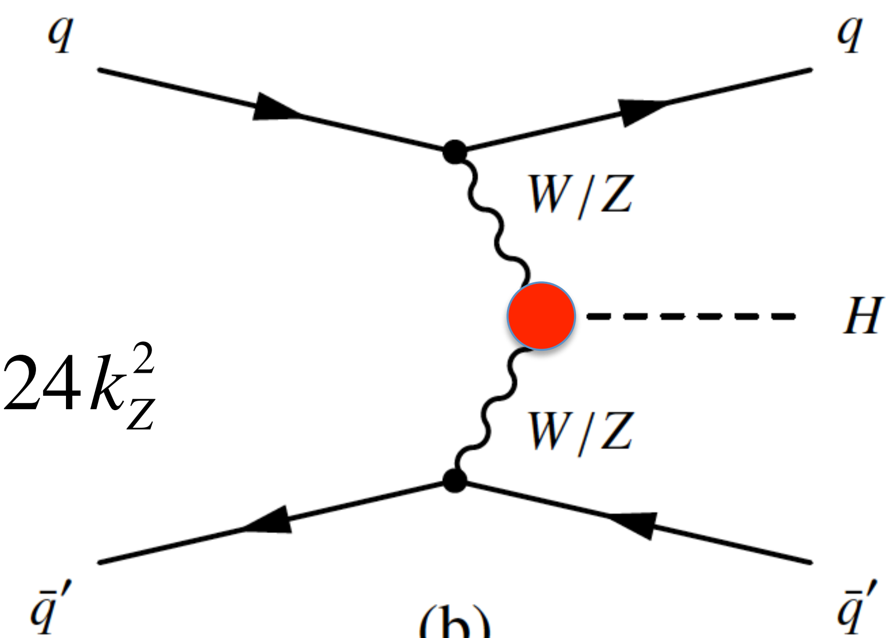
The degeneracy can be broken by parameterize the strength parameters with couplings and introduce constraints which reduce the number of p.o.i. and allow reasonable fits.

$$k_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}, \frac{\sigma_j}{\sigma_j^{SM}} \quad k_H^2 = \frac{\sum k_j^2 \Gamma_j^{SM}}{\Gamma_H^{SM}} = \sum k_j^2 BR_j^{SM}$$

VBF Composition

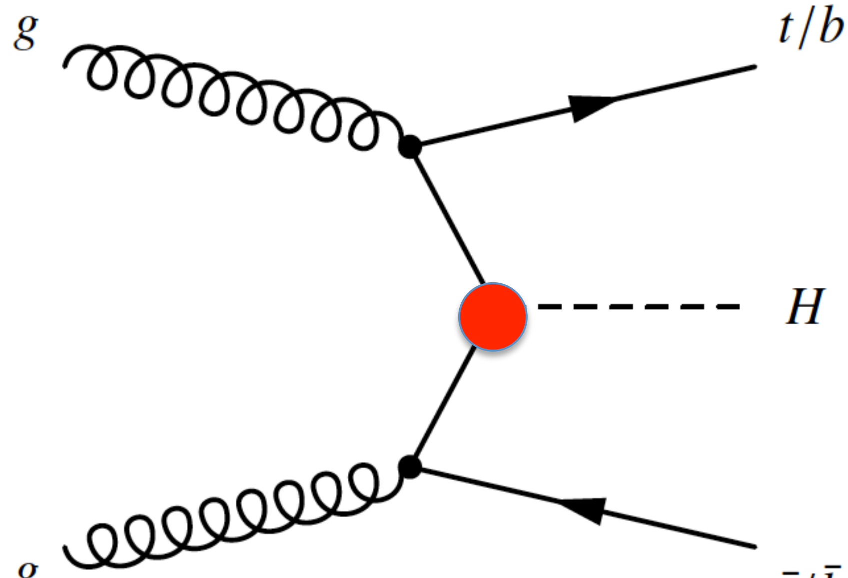
$$q\overline{q}' \rightarrow q\overline{q}'H$$

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



(b)

ttH

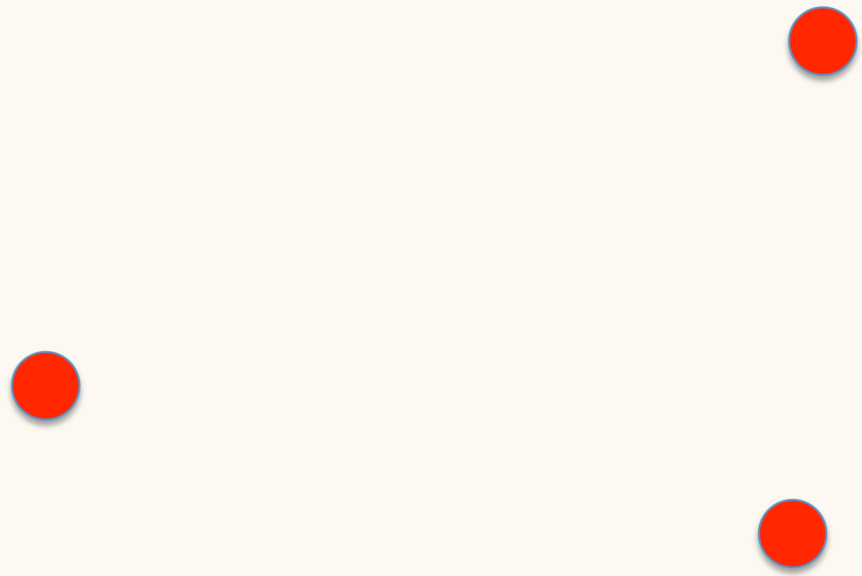


(a)

$$gg \to ttH, bbH$$

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

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

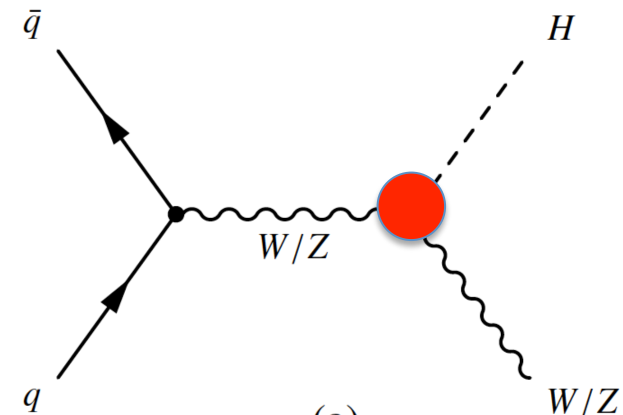


ZH Production

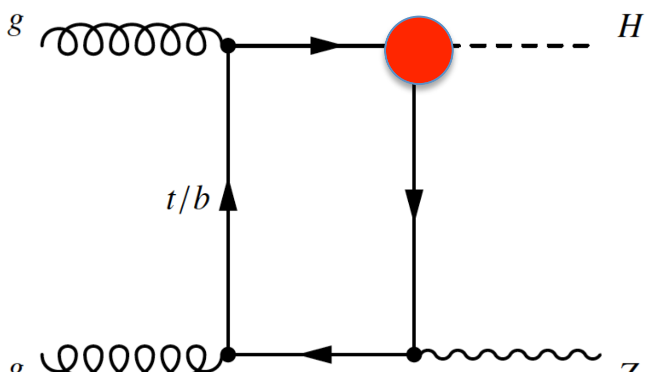
$$\sigma(q\bar{q} \to ZH) \sim k_Z^2$$

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

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



(a)



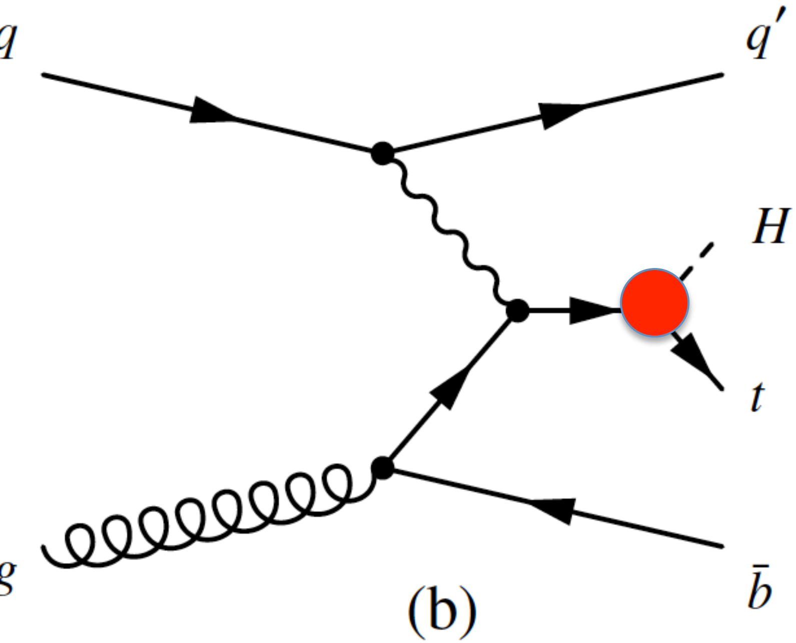
(b) (c)

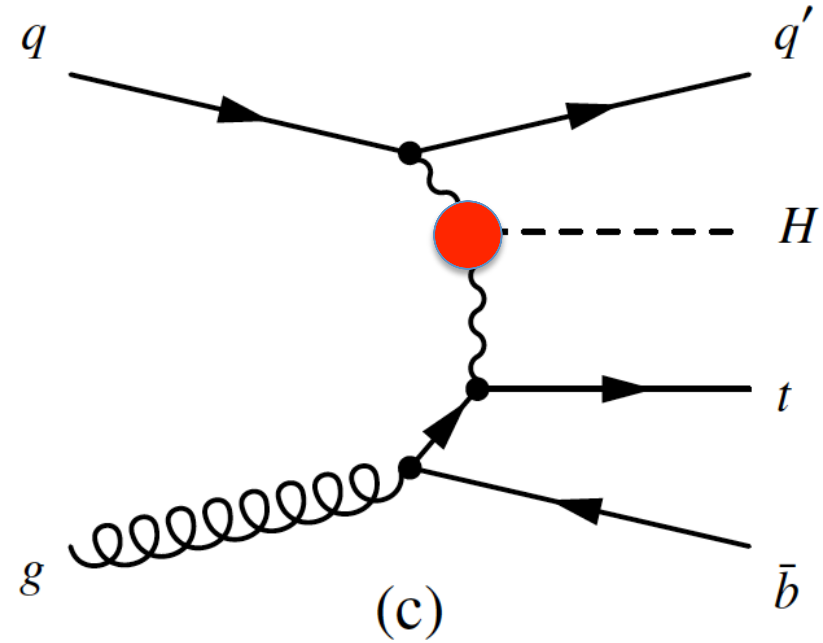
(Q:Why not gWH?)

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

Eilam Gross, TAE, Sept 2015

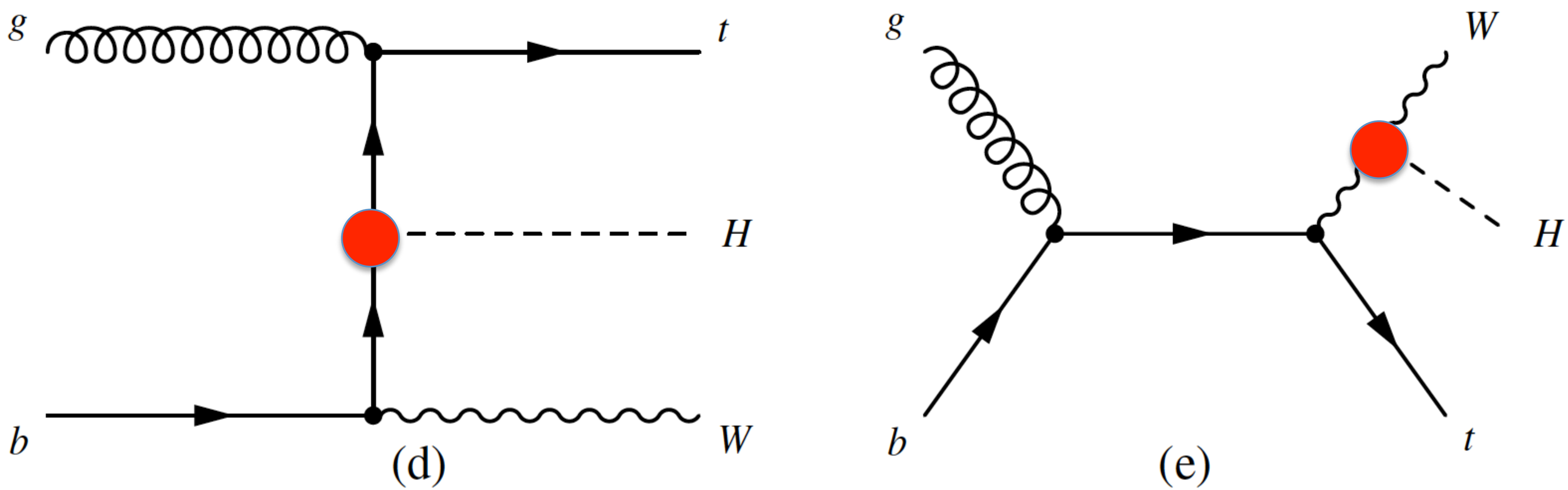
tHq composition (W,t) interference





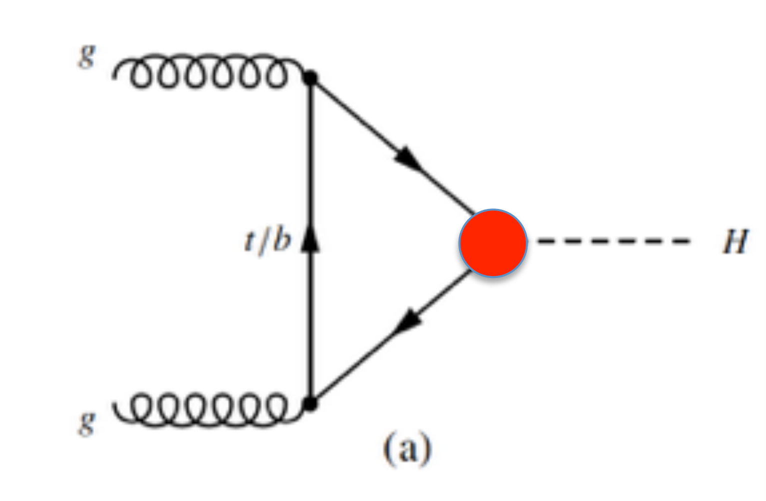
$$\sigma\left(qg \to tHq'(b)\right) \sim \quad 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$$

WtH composition



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

Higgs does not couple
to to Gluons and Photons
in 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?

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

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

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

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

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

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

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

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

The Seven Decay Modes Probes

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

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

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

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

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

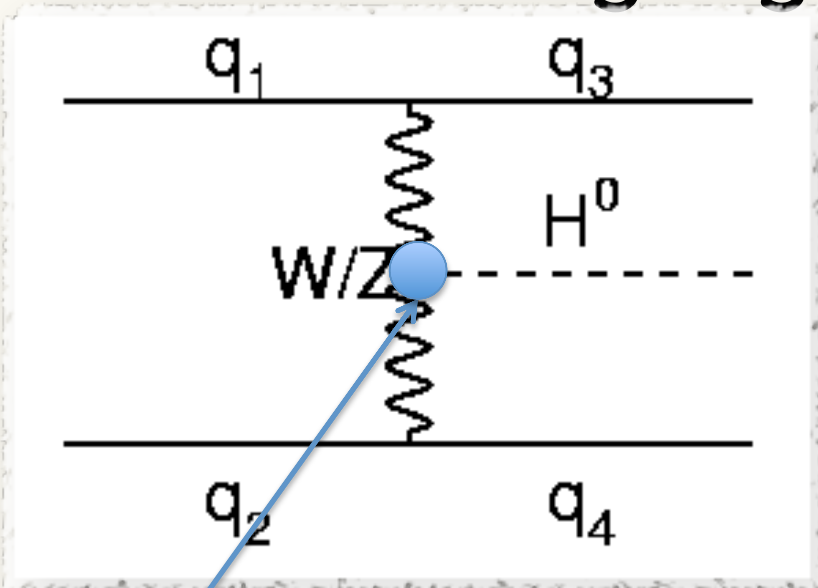
$$\kappa_{Z\gamma}^2 \sim 1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_t^2 - 0.12 \cdot \kappa_W \kappa_t$$

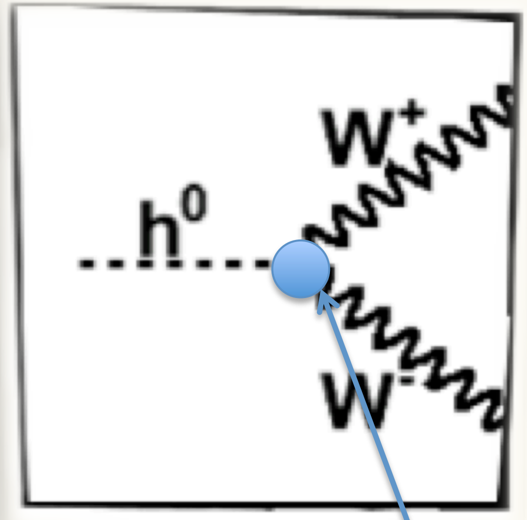
$$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$$

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

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

Disentangling The Couplings





$$\mu^{W}_{VBF} = [\mu_{VBF}\mu^{W}]$$

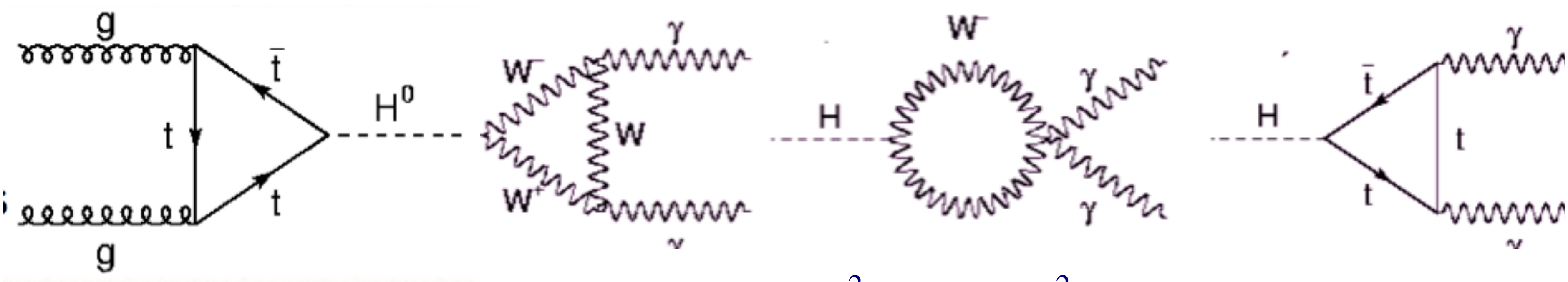
$$\mu^{W} = \frac{k_W^2}{k_H^2}$$

$$\mu_{VBF} = k_{VBF}^2 = k_w^2 BR_{SM}^{WW} + k_Z^2 BR_{SM}^{ZZ}$$

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

$$\frac{\sigma^{WW}_{VBF}}{\sigma^{WW}_{VBF}(SM)} = \frac{k_V^2 \cdot k_V^2}{0.75 k_F^2 + 0.25 k_V^2}$$

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:

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

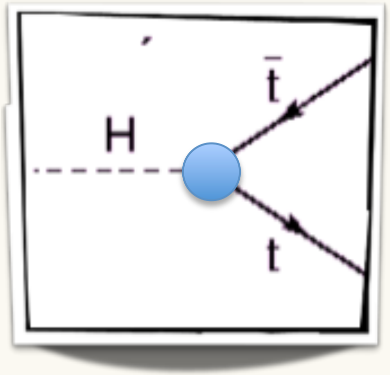
$$\sigma(VBF) \times BR(H \to \gamma\gamma) \sim \frac{k_V^2 \cdot \mathrm{k}_\gamma^2(k_F, k_F, k_F, k_V)}{0.74 k_F^2 + 0.26 k_V^2}$$

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

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

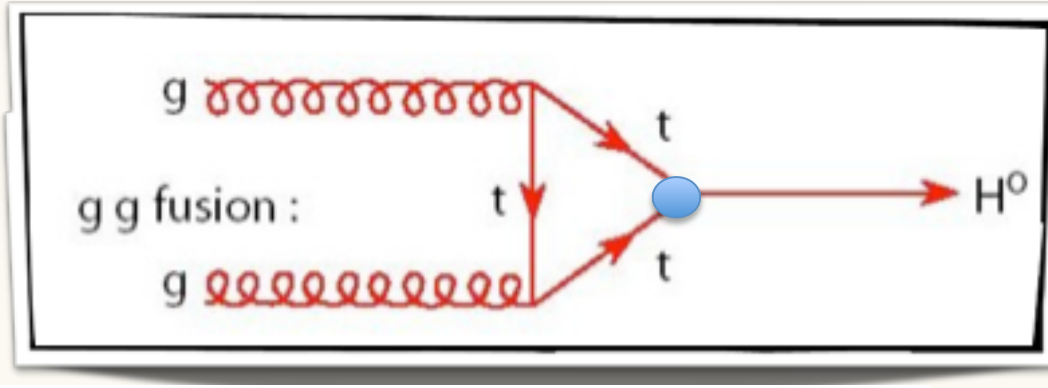
$$\sigma(VBF, VH) \times BR(H \to \tau\tau, bb) \sim \frac{k_V^2 \cdot \mathrm{k}_F^2}{0.74 k_F^2 + 0.26 k_V^2}$$

Indirect Sensitivity to Fermion Couplings



$$k_t^2 = \frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}}$$

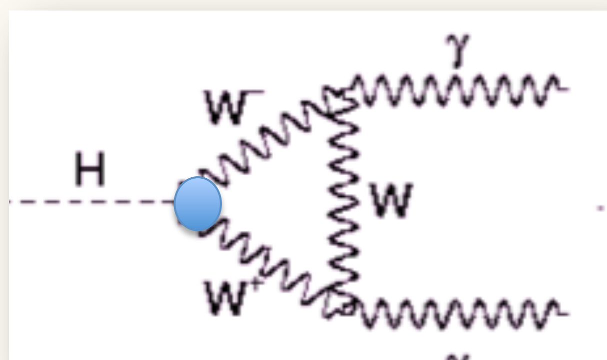
$$k_t^2 = \frac{g_t^2}{g_{t.SM}^2}$$



$$\kappa_g^2(\kappa_b, \kappa_t) = \frac{\kappa_t^2 \cdot \sigma_{ggH}^{tt} + \kappa_b^2 \cdot \sigma_{ggH}^{bb} + \kappa_t \kappa_b \cdot \sigma_{ggH}^{tb}}{\sigma_{ggH}^{tt} + \sigma_{ggH}^{bb} + \sigma_{ggH}^{tb}}$$

Note that if all fermion couplings are set to be equal, $k_g^2 = k_F^2$

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



Coupling Scenarios

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.

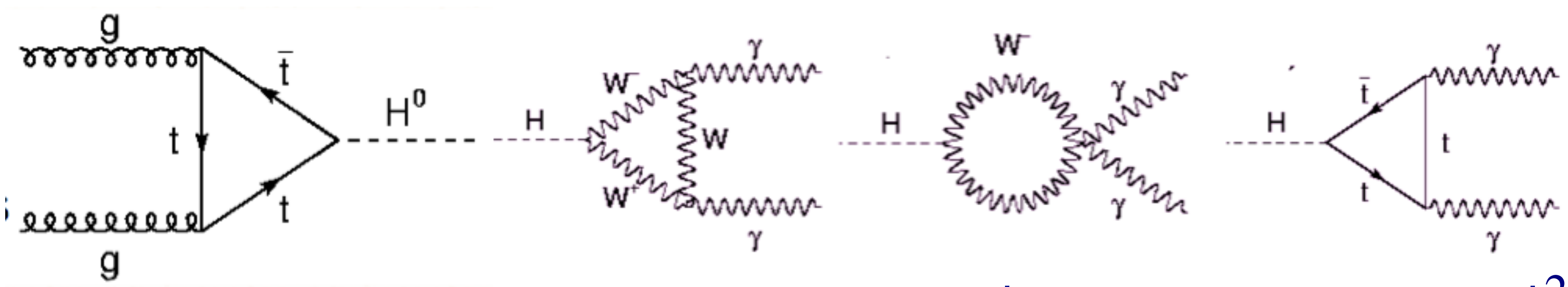
NP can appear in either the Higgs width and/or in the loops.

$$k_H^2 = \frac{\sum_{j=Z,W,t,b,\tau} k_j^2 \Gamma_j^{SM} + k_\gamma^2 \Gamma_\gamma^{SM} + k_g^2 \Gamma_g^{SM}}{\Gamma_H^{SM}} \qquad \Gamma_H = k_H^2 \Gamma_H^{SM} + BR_{\mathrm{i,u}} \Gamma_H$$

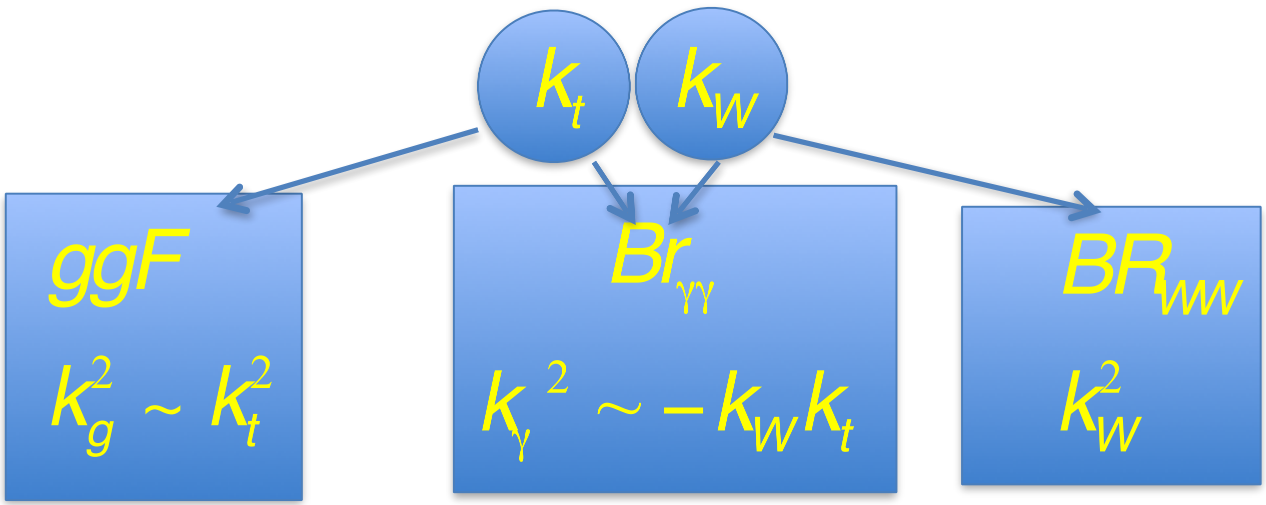
Γ_H	k_γ	k_g	Scenario
$\Gamma_H = k_H^2 \Gamma_H^{SM}$	$K_\gamma(k_t, k_W)$	$K_g(k_t, k_b)$	only SM particles in loops
$\Gamma_H = k_H^2 \Gamma_H^{SM} + BR_{\mathrm{i,u}} \Gamma_H$	k_γ	k_g	m_{NP} could be $< \frac{m_H}{2}$
$\Gamma_H = k_H^2 \Gamma_H^{SM}$	k_γ	k_g	$m_{NP} > \frac{m_H}{2}$
$\Gamma_H = k_H^2 \Gamma_H^{SM} + BR_{\mathrm{i,u}} \Gamma_H$	$K_\gamma(k_t, k_W)$	$K_g(k_t, k_b)$	NP (not in the loops)

Negative Couplings?

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

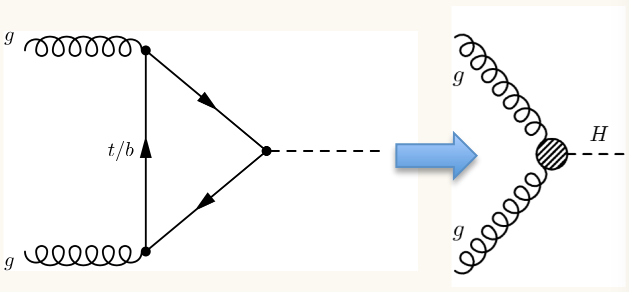
γγ increases

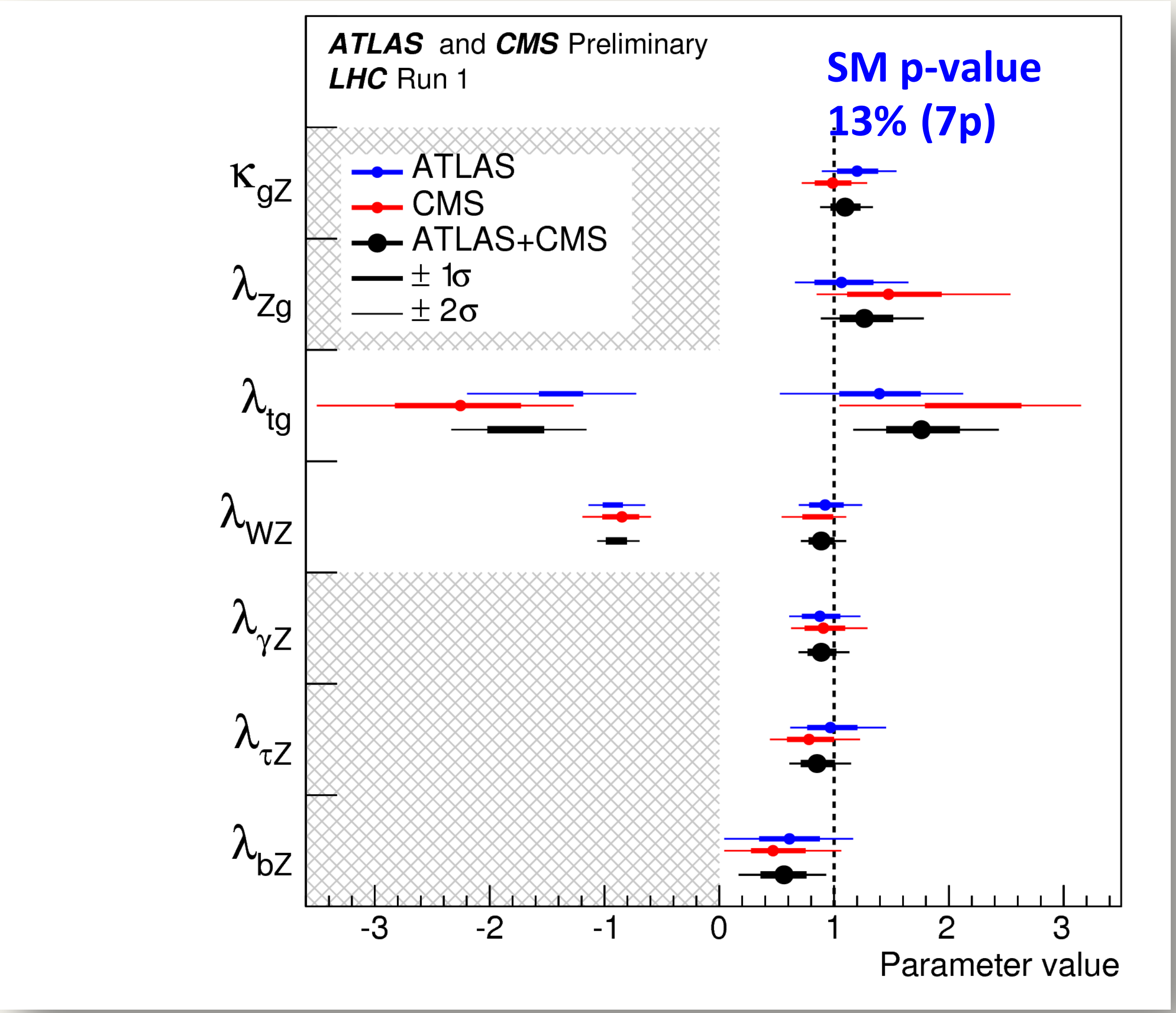
Testing negative k_t is extremely important

Couplings Generic Model

LHC is not able to measure the Higgs full width.

The only way to get minimal assumptions measurement is using ratios, and use effective couplings for Gamma and Gluon

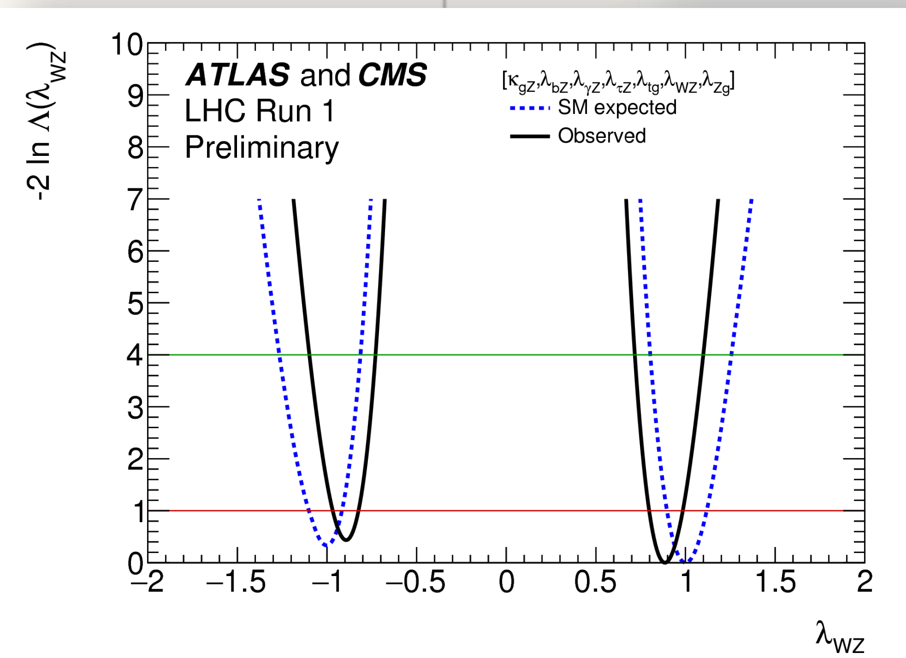


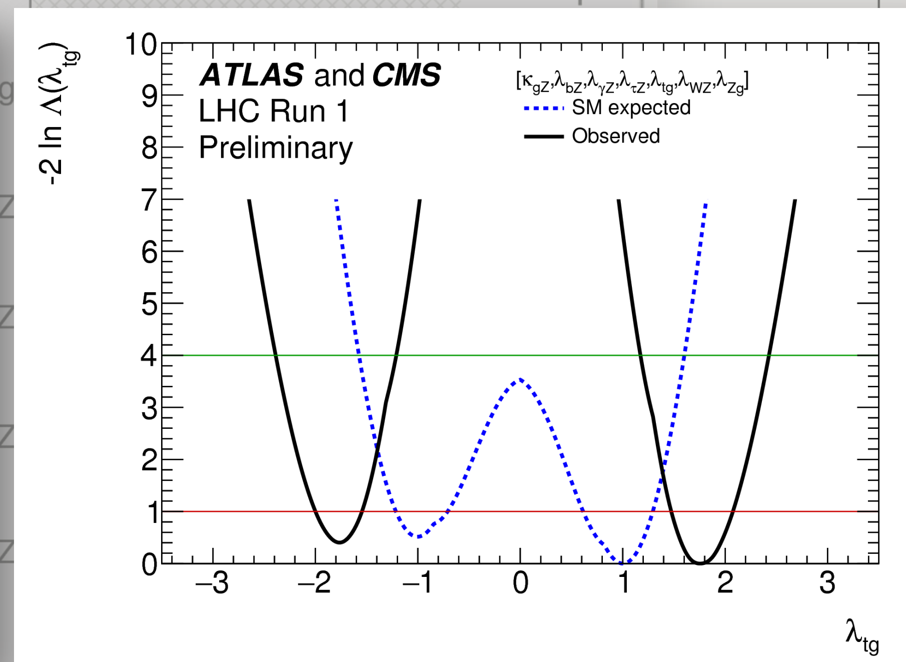


Couplings Generic Model

$ggZH$ and $tH \rightarrow$

possible solutions with negative λ_{tg} and λ_{WZ}





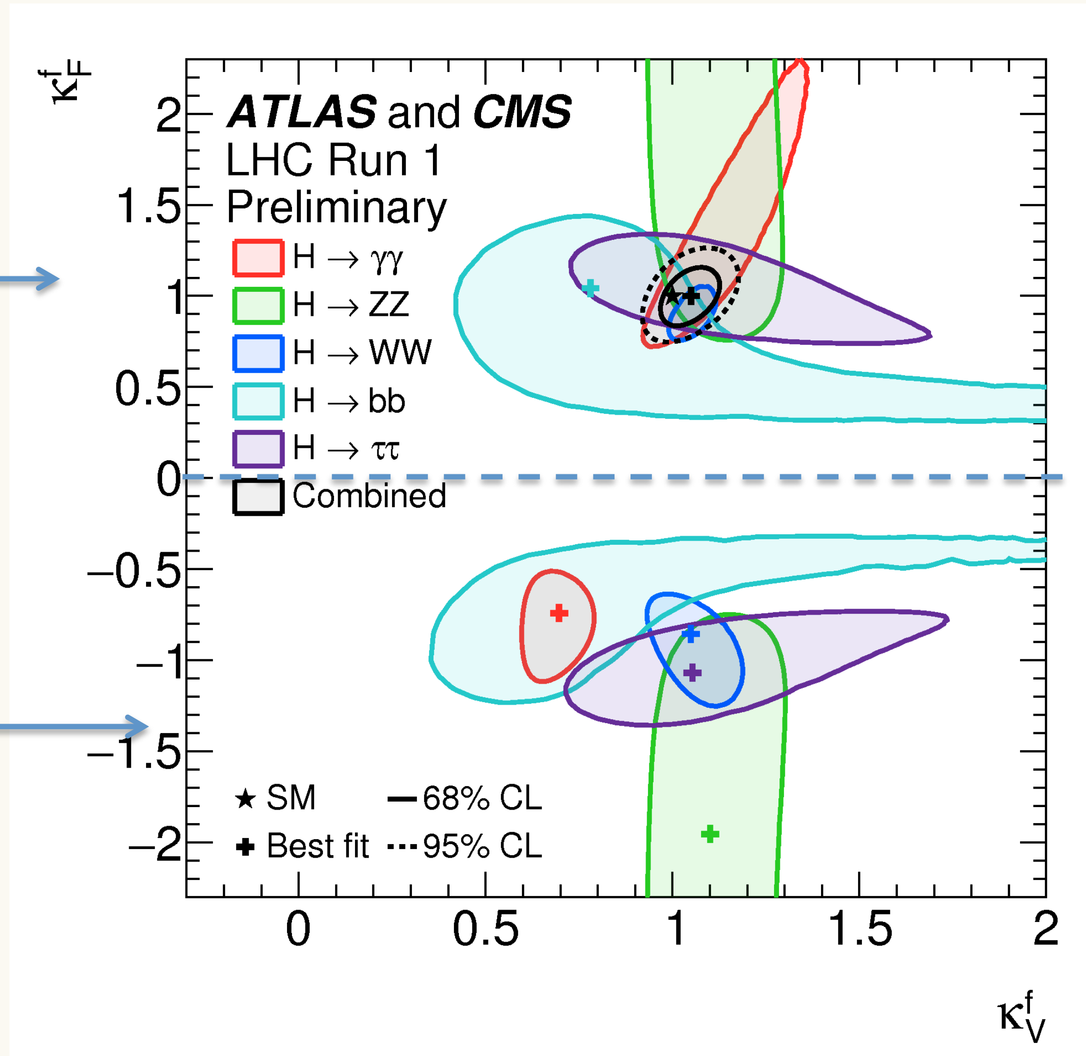
kV & kF: The pedagogic plot

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

~ 5σ exclusion of $k_F<0$

SM – No Tension

Tension Drifting apart

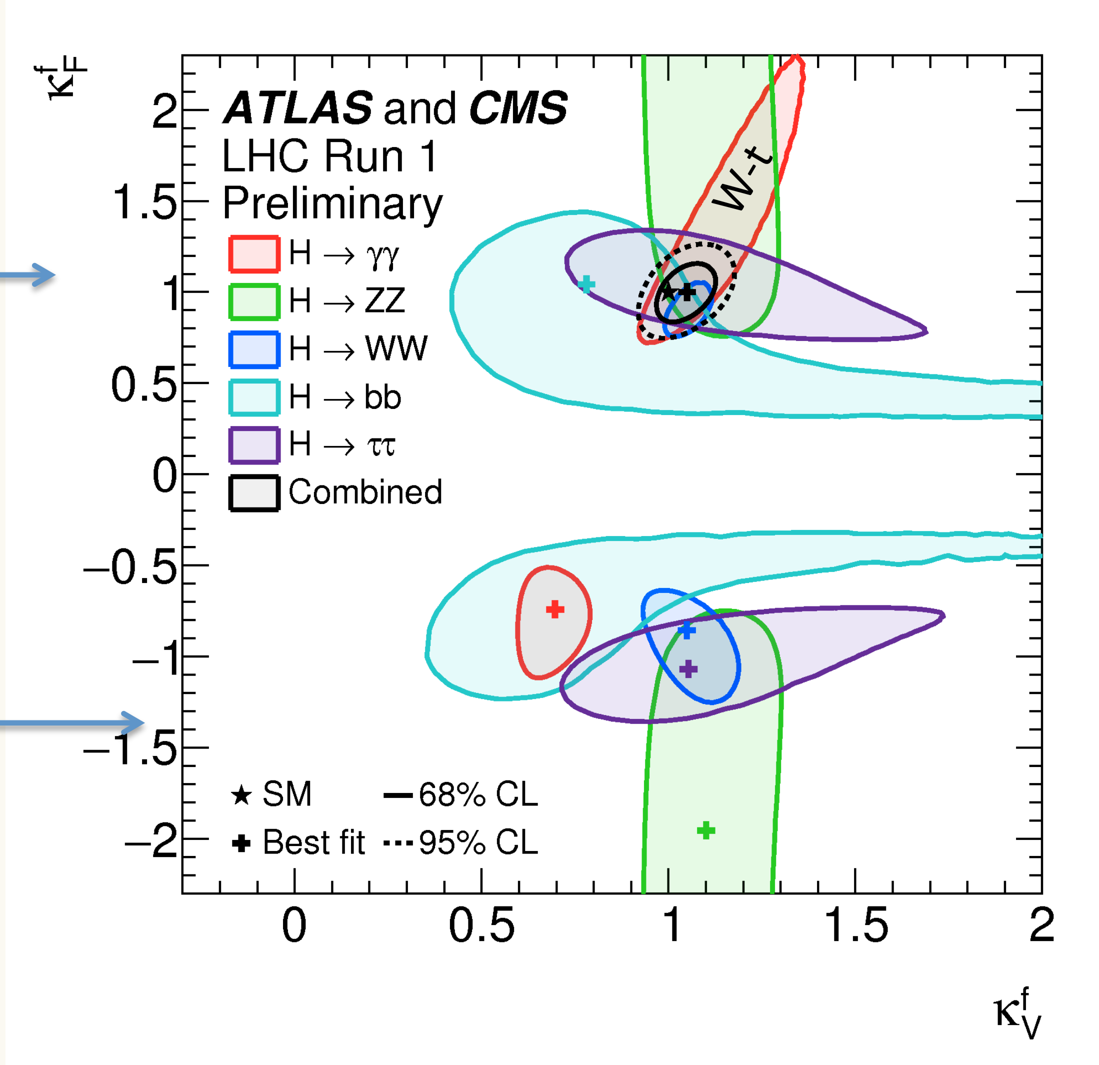


kV & kF: The pedagogic plot

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

SM –
No Tension

Tension
Drifting
apart



kV & kF: The pedagogic plot

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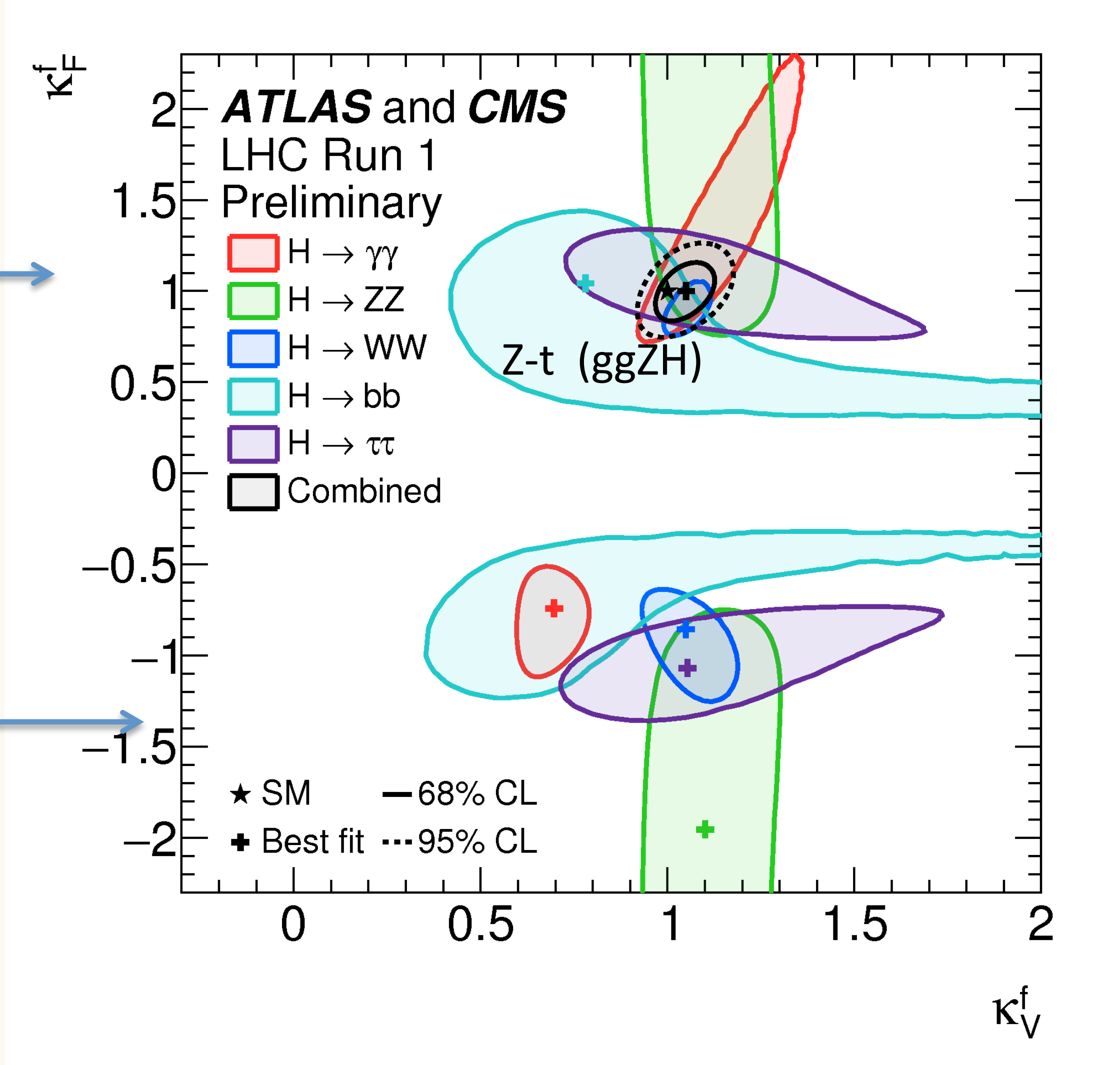
SM –
No Tension

Tension
Drifting
apart



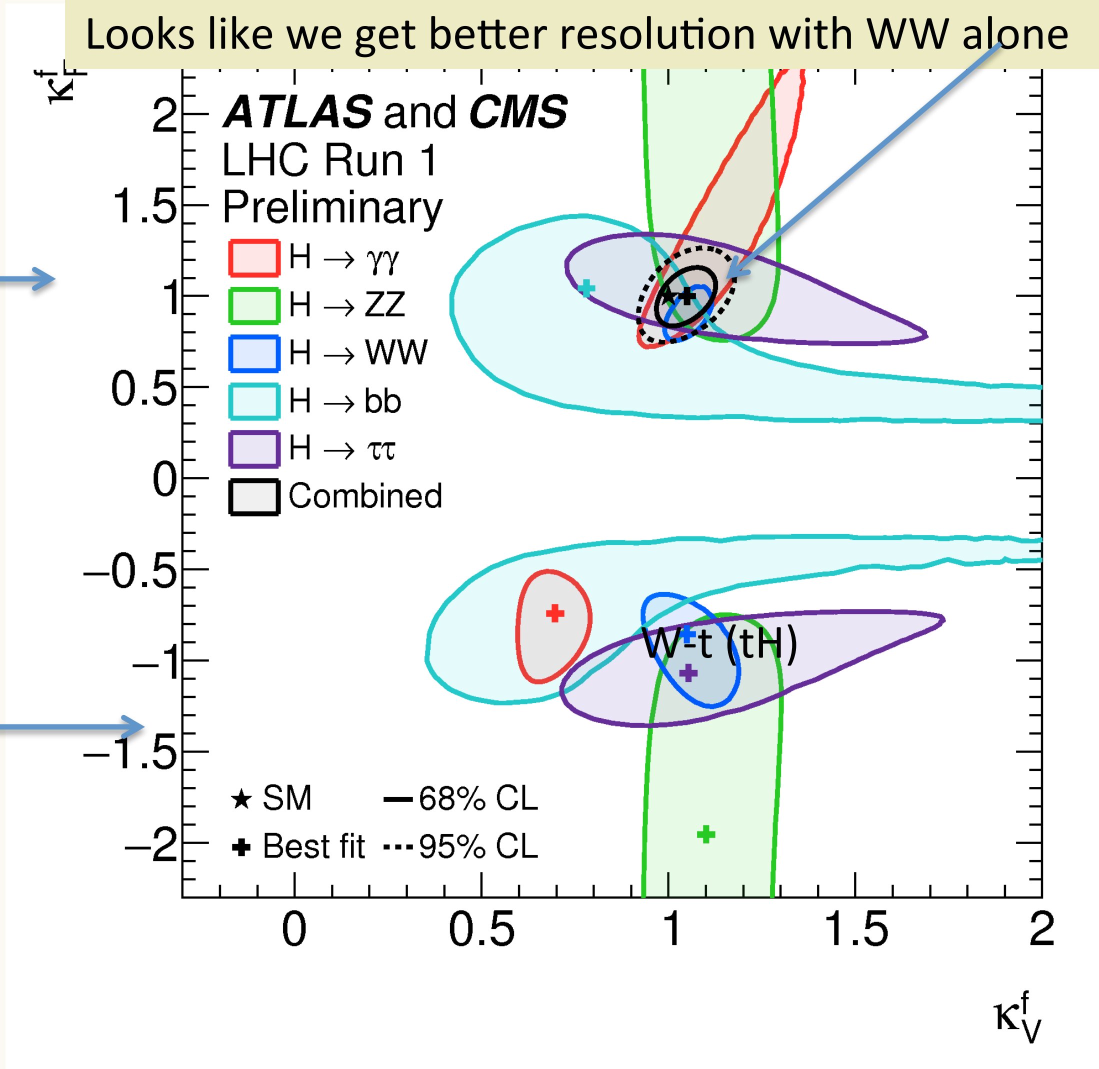
kV & kF: The pedagogic plot

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

Looks like we get better resolution with WW alone

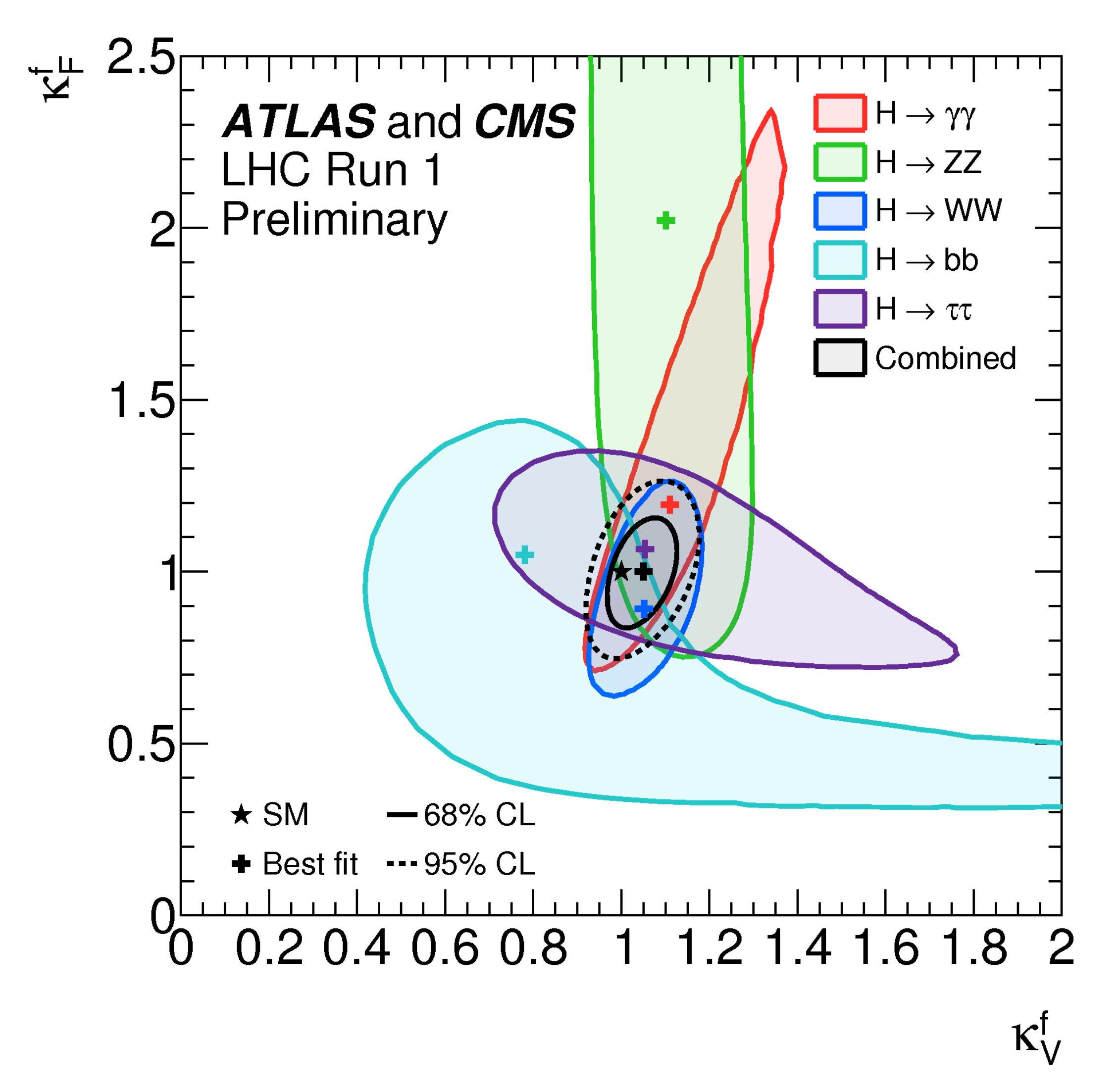
SM – No Tension

Tension Drifting apart



kV & kF: The pedagogic plot

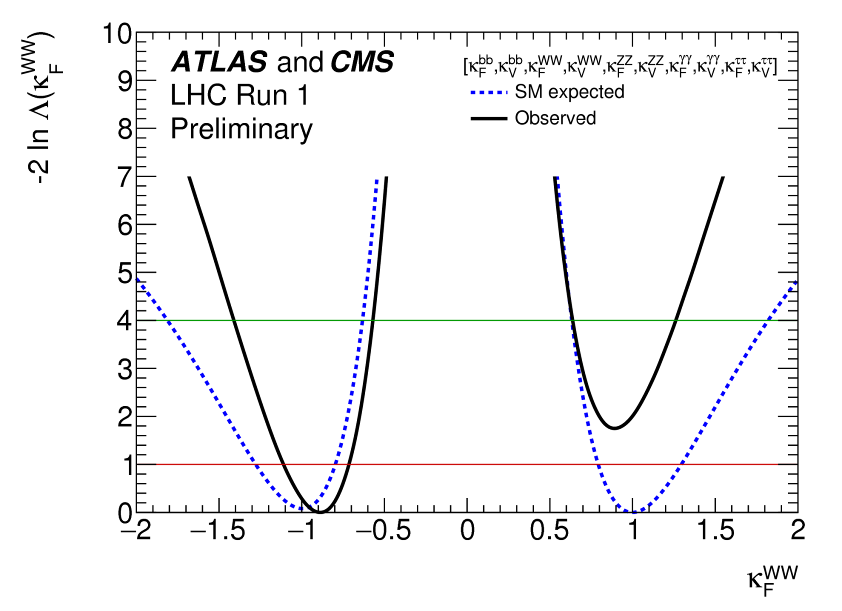
Fitting only positive Kappas, tautology resolved

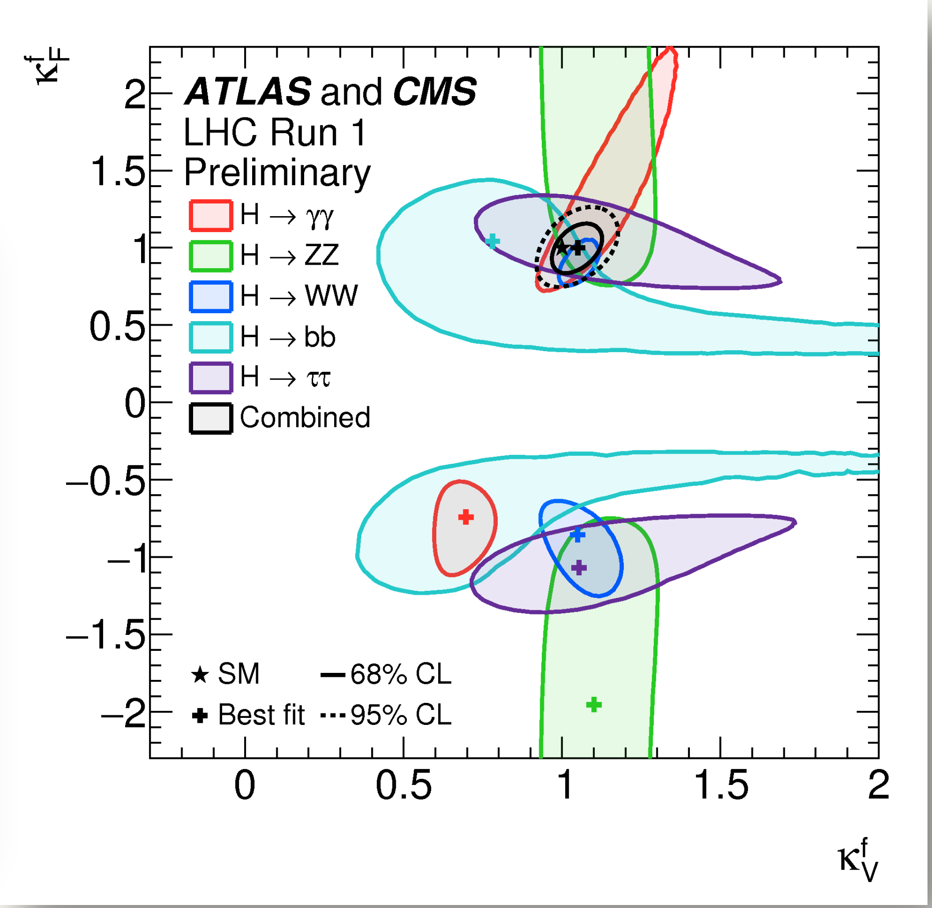


kV & kF: The pedagogic plot

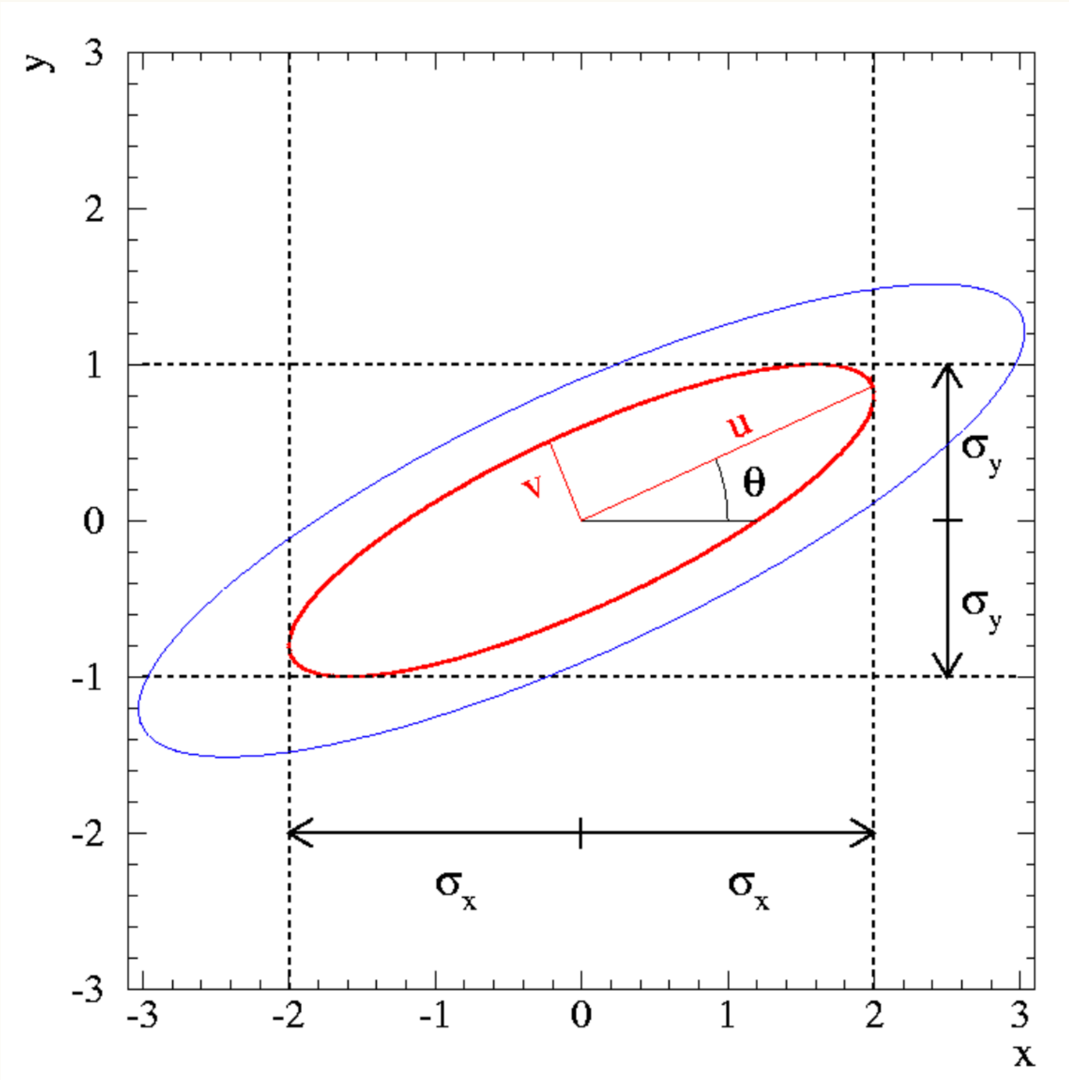
Another interesting point

Why in 1D we do not see a positive Confidence Interval for WW





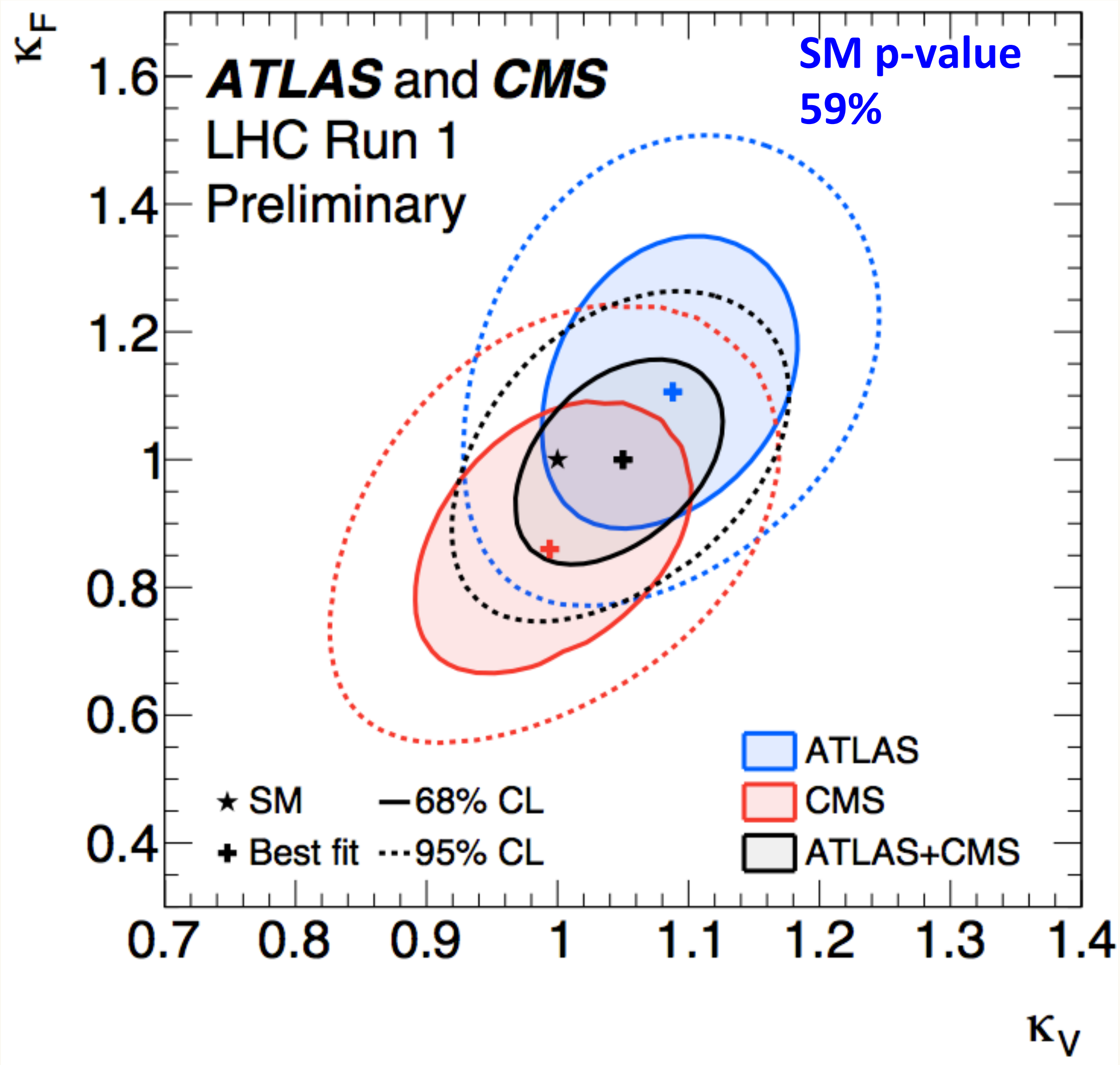
1D vs 2D Confidence Interval



$\Delta\chi^2 = 1$

$\Delta\chi^2 = 2.3 \;\; (68\%\ CL)$

The CERN Courier PR plot



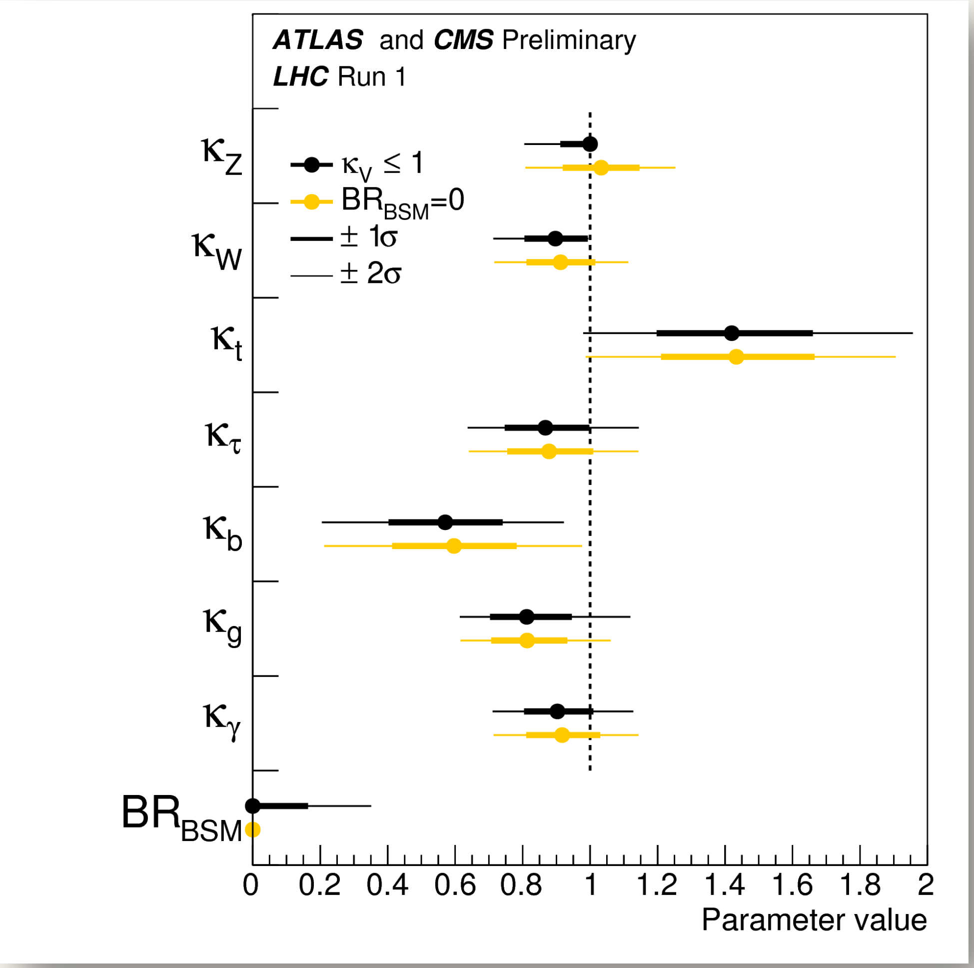
In the presence of NP

Here NP will enter in the loop and might contribute to BR_{BSM}

We introduce effective couplings k_γ, k_g

To be able to fit we need to constrain the width by either assume BR_{BSM}=0 (NP>mH/2)

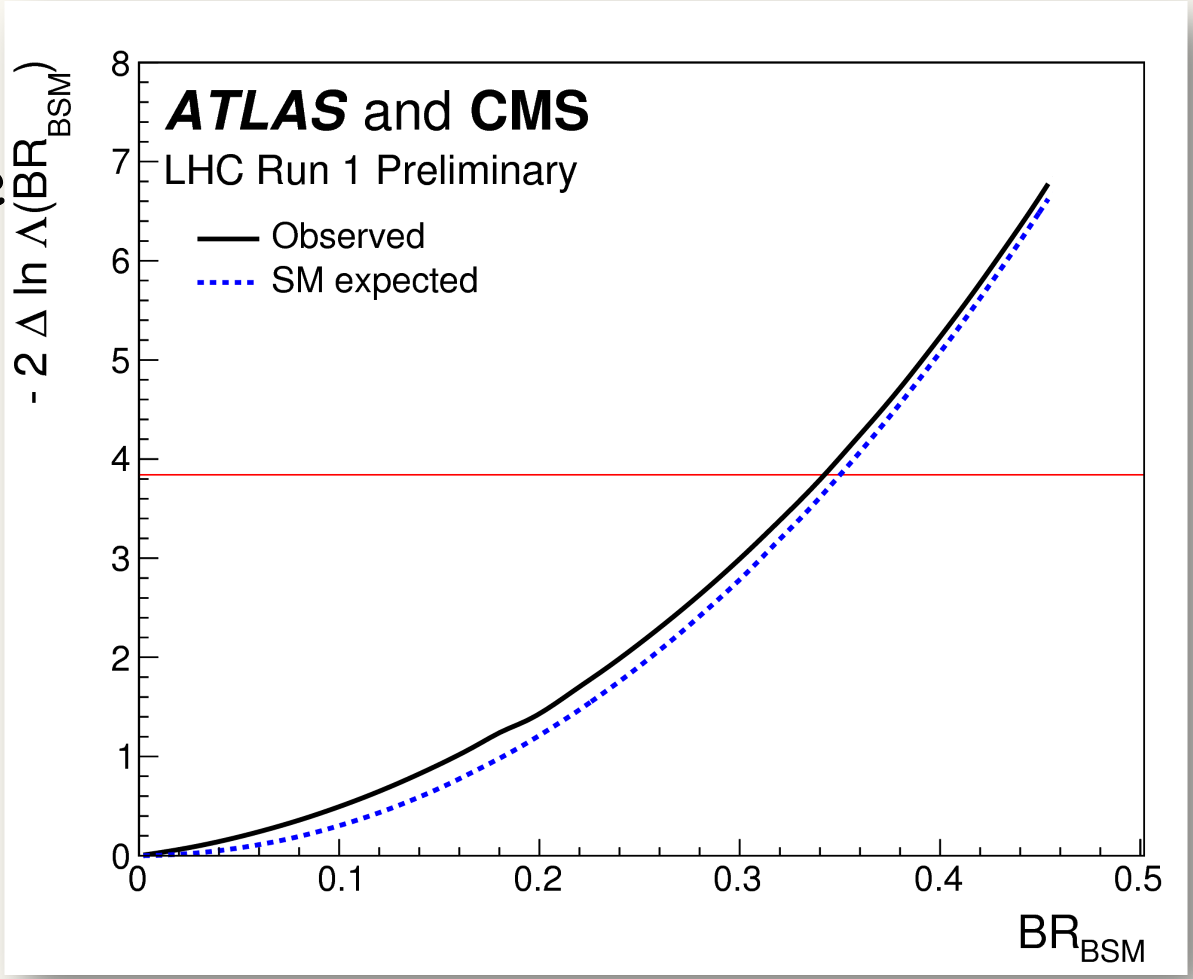
Or $k_V \leq 1$ and BR_{BSM}>0 (like in many BSM physics such as MSSM)



Bounds on BR_{BSM}

$BR_{BSM} < 0.34$ @ 95% CL

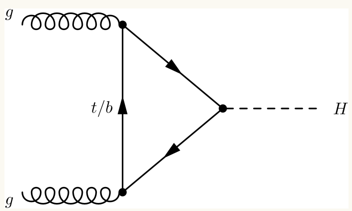
This is using the $\tilde{t}_\mu$ test statistics Which does not Allow negative BRs, leading to Possible Overcoverage (conservative)



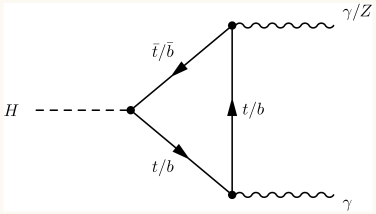
κ_g and κ_γ

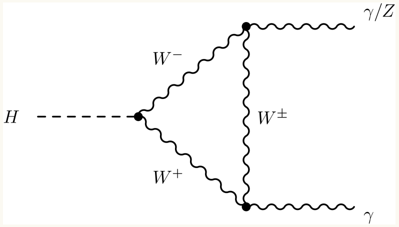
Assuming tree level couplings as in the SM and only modifications to the two main loops of ggF and $H \to \gamma\gamma$

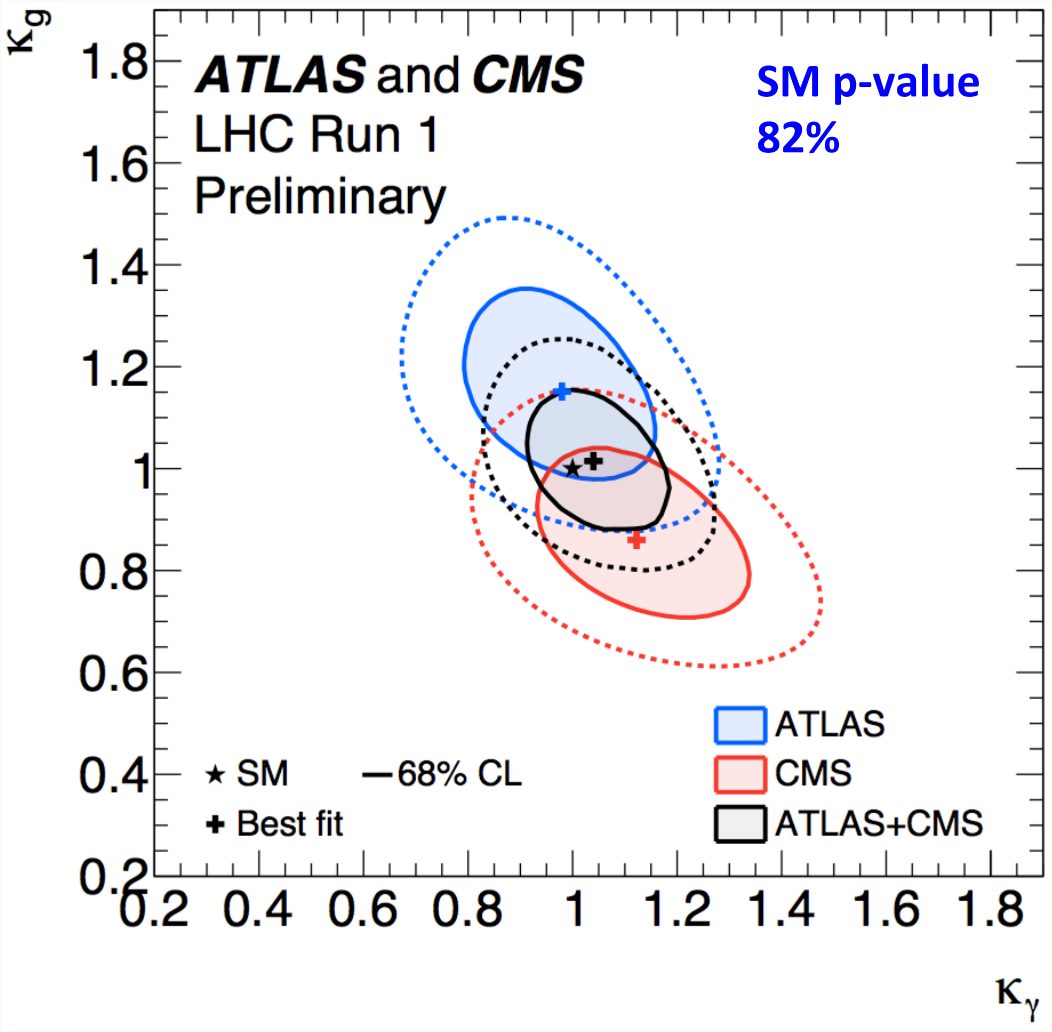
ggF loop



H→γγ loop





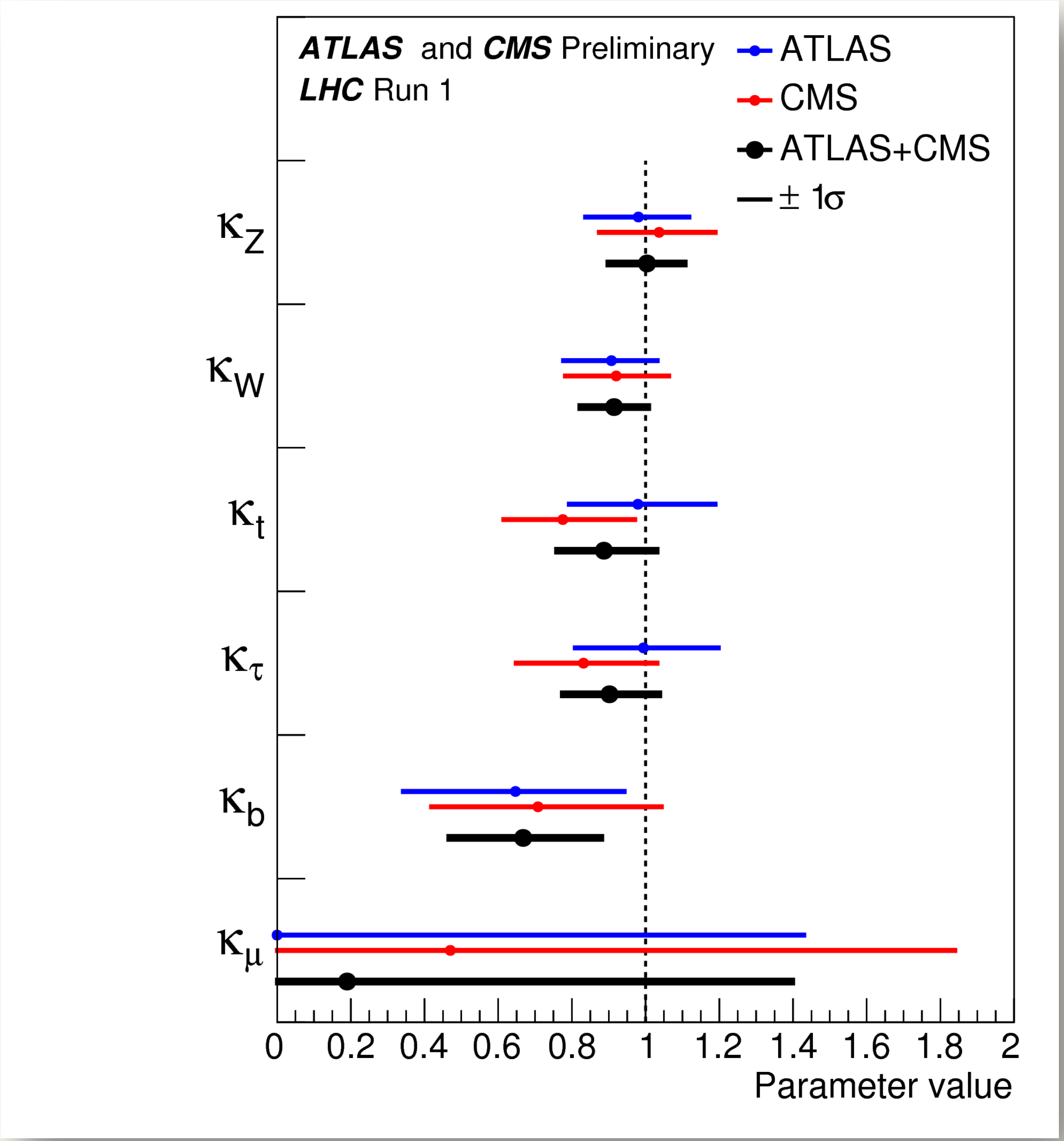


Additional heavy fermions or charged Higgs boson would modify the effective couplings

"SM" fit

This is the olny fit where the MuMu coupling was included in the 6p fit. Loops content was assumed (all loops resolved) and $BR_{BSM}=0$ was assumed.

This is actually a SM fit which leads to the "Money Plot"

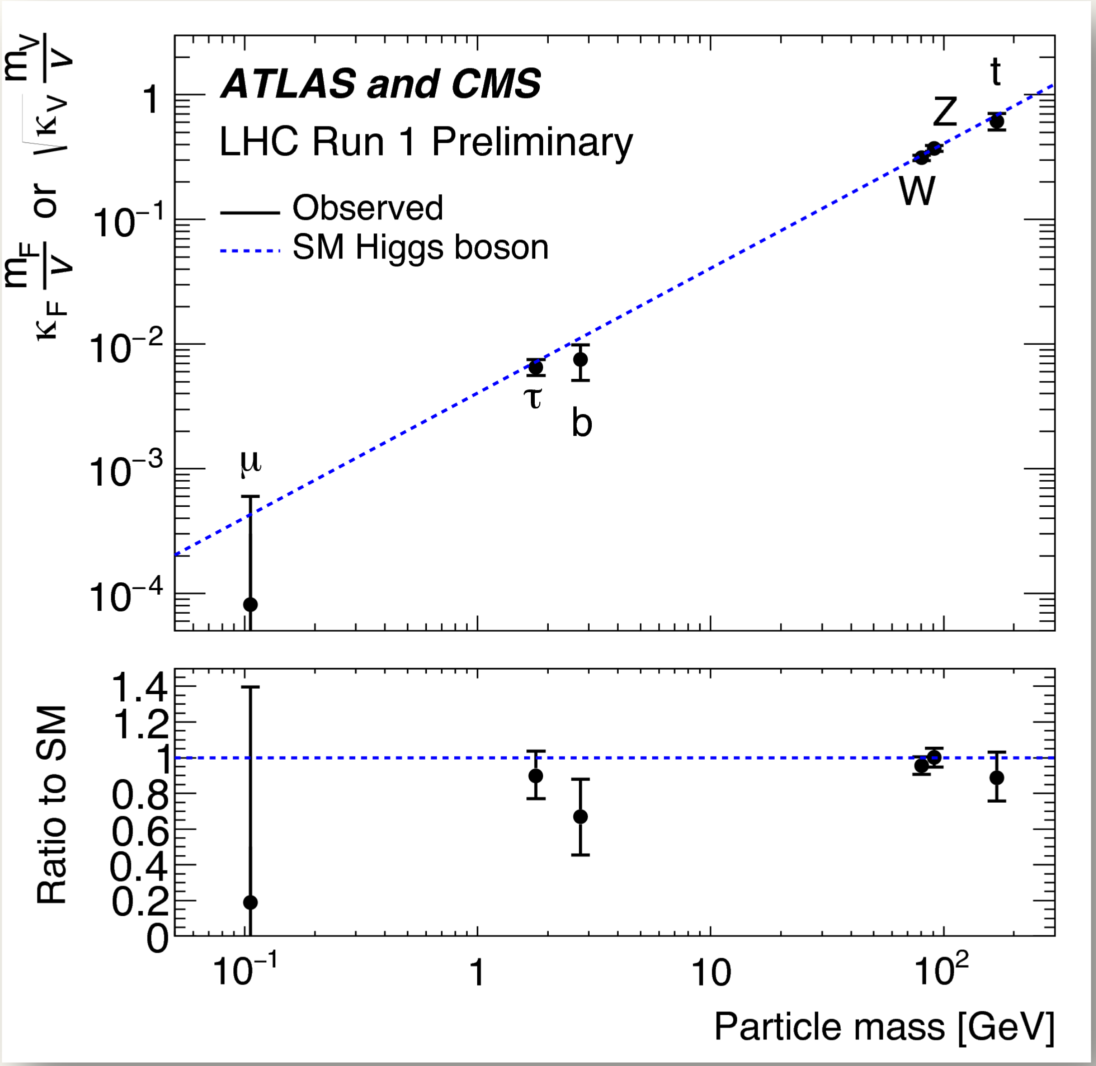


The PR Plot (an alternative version)

$$g_{Hff} = \frac{g_{Hff}}{g_{Hff}^{SM}} g_{Hff}^{SM} = \kappa_f g_{Hff}^{SM} \sim \kappa_f m_f$$

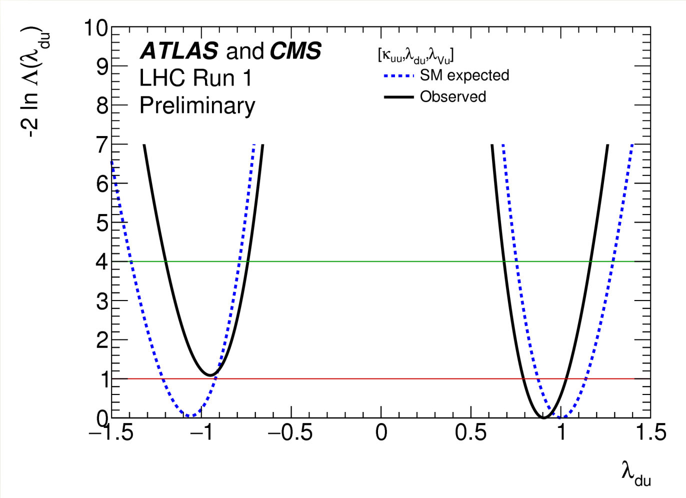
$$g_{HVV} = \frac{g_{HVV}}{g_{HVV}^{SM}} g_{HVV}^{SM} = \kappa_V g_{HVV}^{SM} \sim \kappa_V m_V^2$$

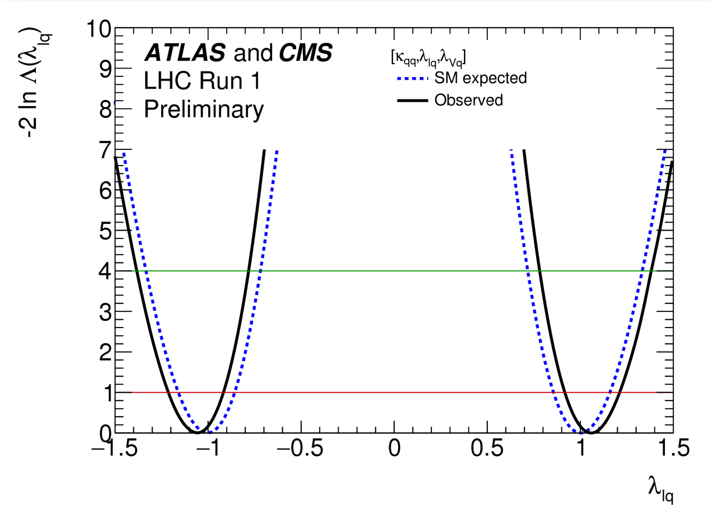
reduced coupling $\sqrt{g_{HVV}} \sim \sqrt{\kappa_V}\, m_V$



k_F or $\sqrt{k_V}$

lq and du





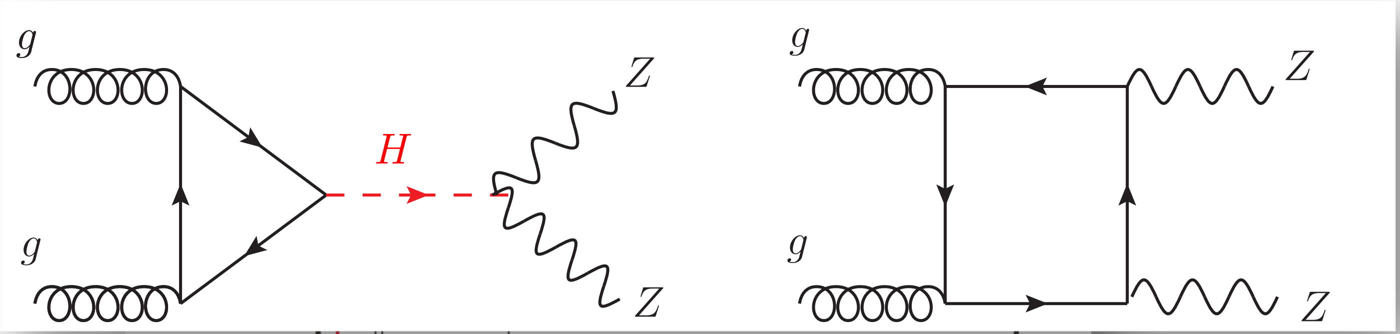
Parameter	ATLAS+CMS	
	observed	expected unc.
λ_{du}	$0.91^{+0.12}_{-0.11}$	$[-1.21, -0.92] \cup [0.87, 1.14]$
λ_{Vu}	$0.99^{+0.13}_{-0.12}$	$^{+0.20}_{-0.12}$
κ_{uu}	$1.09^{+0.22}_{-0.19}$	$^{+0.20}_{-0.27}$
λ_{lq}	$[-1.21, -0.92] \cup [0.92, 1.21]$	$[-1.16, -0.86] \cup [0.86, 1.16]$
λ_{Vq}	$1.09^{+0.14}_{-0.13}$	$^{+0.13}_{-0.11}$
κ_{qq}	$0.94^{+0.17}_{-0.15}$	$^{+0.18}_{-0.16}$

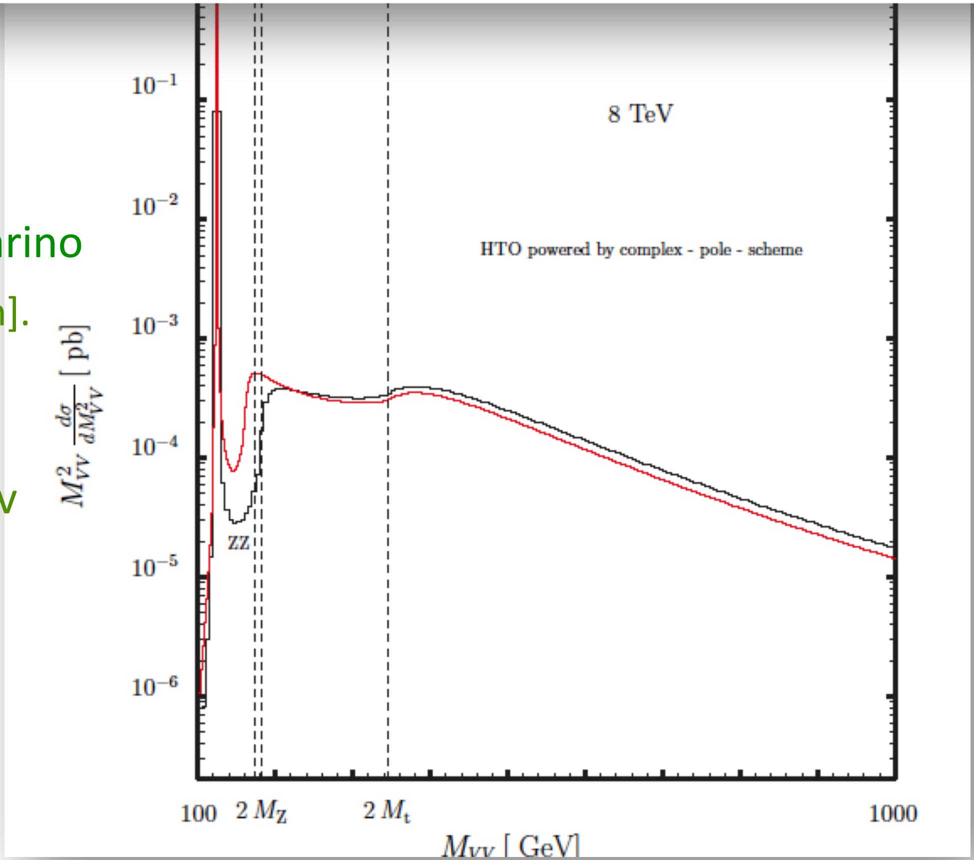
SM p-value 67%

SM p-value 78%

Higgs Width
OffShell in a NutShell

OffShell in a NutShell





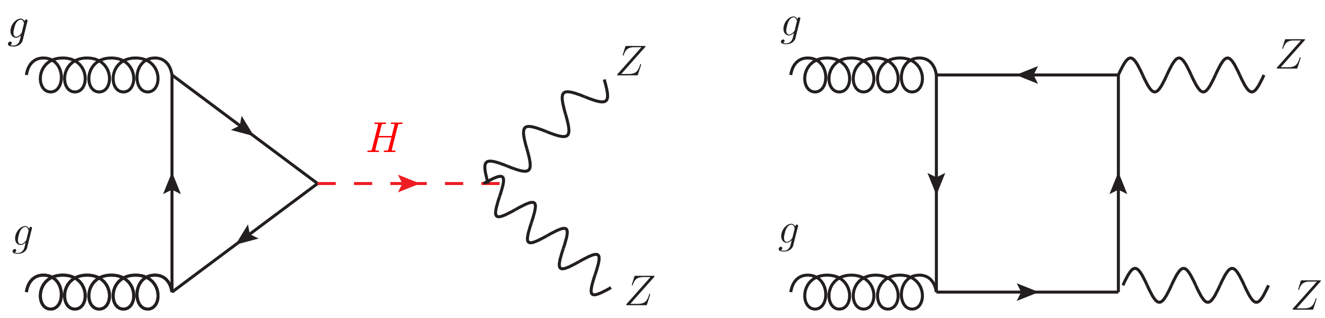
N. Kauer and G. Passarino

arXiv:1206.4803 [hep-ph].

F. Caola and K. Melnikov

C. Englert and
M. Spannowsky

OffShell in a NutShell



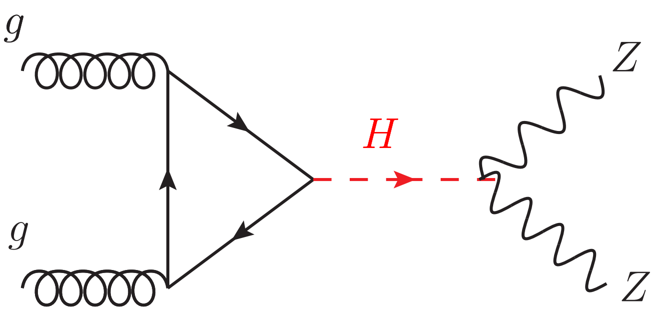
$$\mu_{OnShell} \equiv \frac{\sigma_{OnShell}(gg \to H \to ZZ^*)}{\sigma_{OnShell}(gg \to H \to ZZ^*)_{SM}} = \kappa_g^2 \kappa_Z^2 \frac{\Gamma_H^{SM}}{\Gamma_H}$$

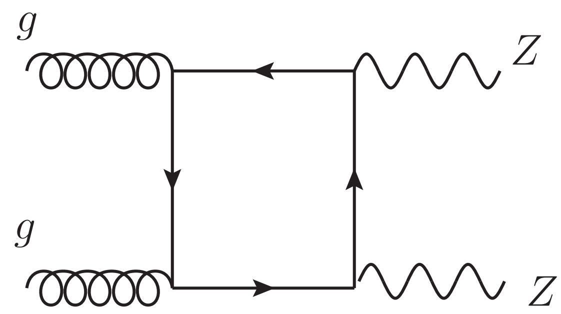
$$\mu_{OffShell} \equiv \frac{\sigma_{OffShell}(gg \to H^* \to ZZ)(\sqrt{\hat{s}})}{\sigma_{OffShell}(gg \to H^* \to ZZ)_{SM}(\sqrt{\hat{s}})} \approx \kappa^2_{g,OffShell}(\sqrt{\hat{s}})\kappa^2_{Z,OffShell}(\sqrt{\hat{s}})$$

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





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

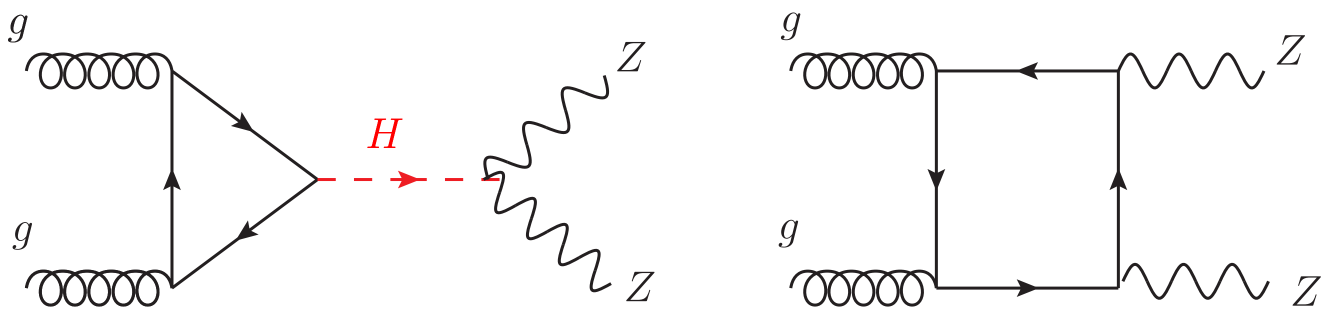
Caveats:

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:

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

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 $k_g \cdot k_v \le k_{g,OffShell} \cdot k_{V,OffShell}$

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

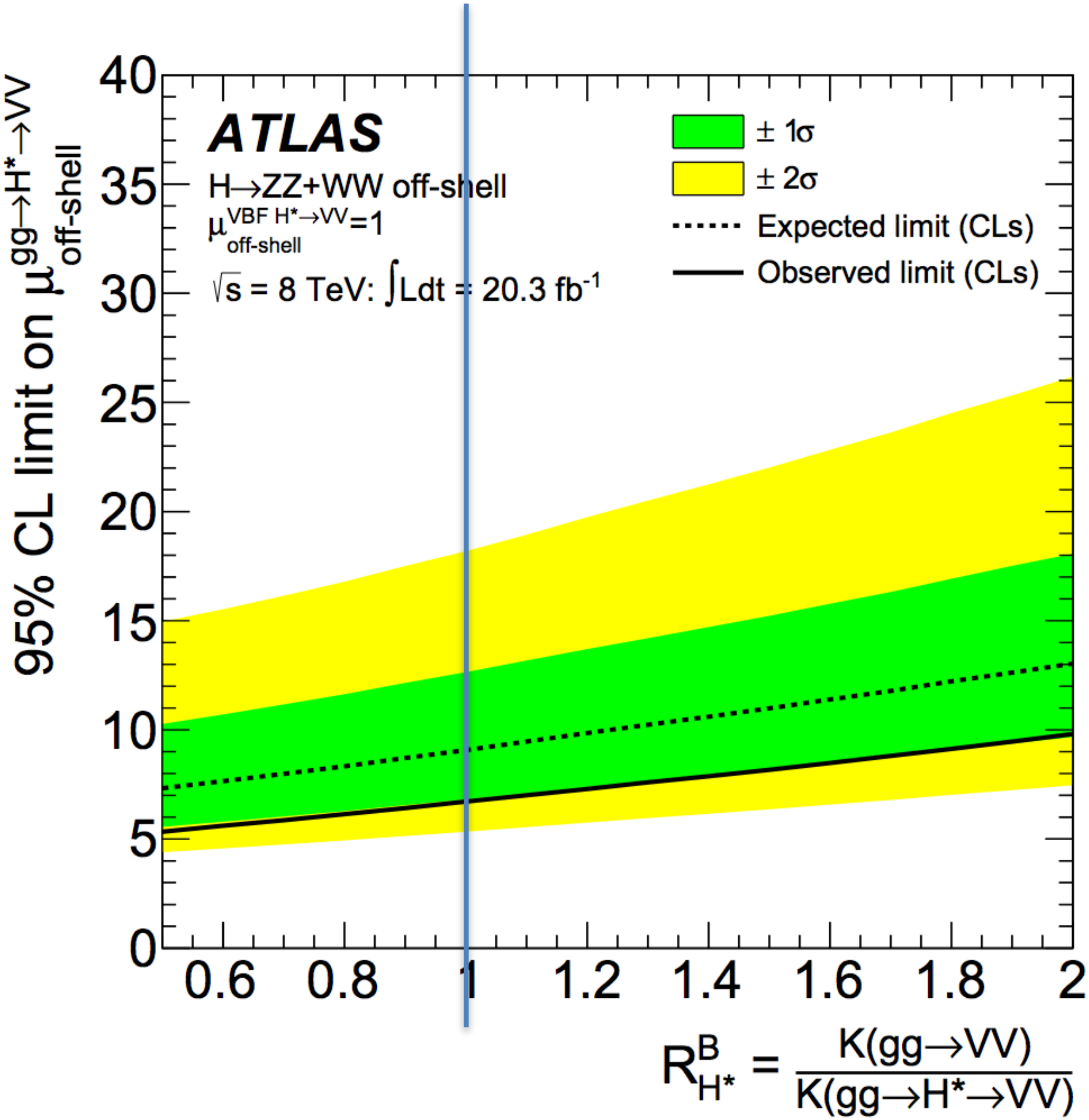
$$R_{H^*}^{B} = \frac{K(gg \to VV)}{K(gg \to H^* \to VV)} = \frac{K^{B}(m_{VV})}{K^{H^*}(m_{VV})}$$

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

Limit on OffShell signal strength

Agnostic to K factor

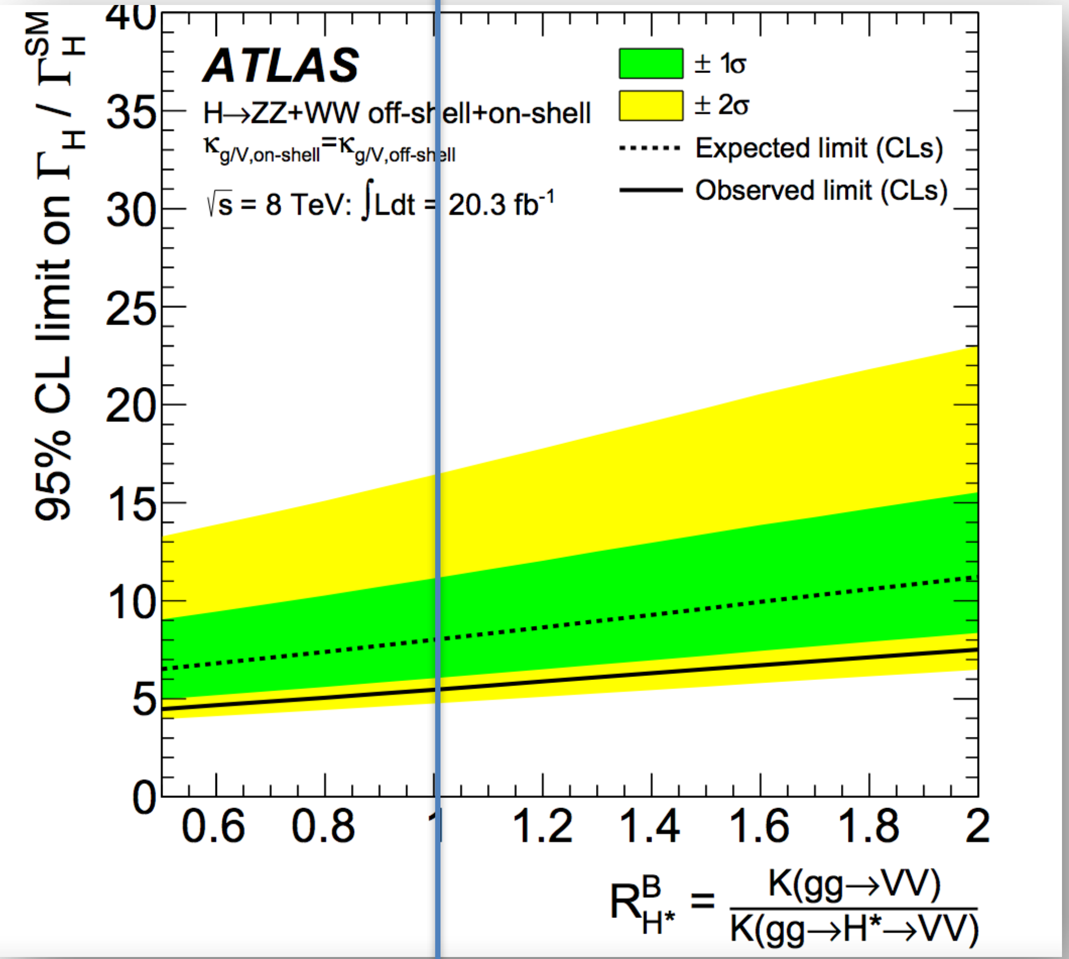
$\mu_{OffShell} < 6.9(7.9 exp)$



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

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

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



	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	$\kappa_{V,\text{on-shell}} = \kappa_{V,\text{off-shell}}, \Gamma_H/\Gamma_H^{SM}=1$

Instead of Conclusions

4 years ago, September 2011

The DG told us the

"not observing the Higgs is also a discovery, and we should prepare ourself for the press"

Look where we are today!

BACKUP