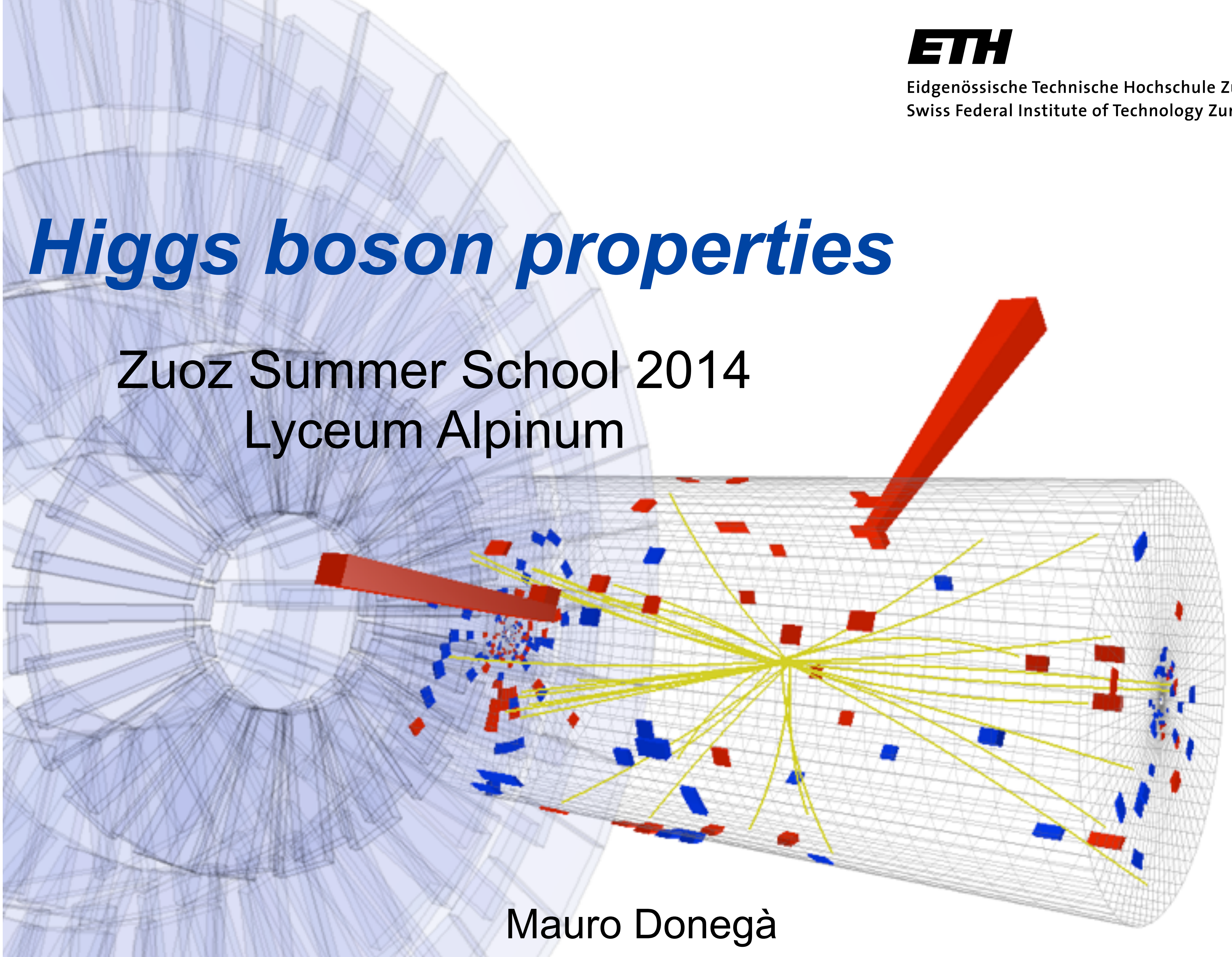
ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Higgs boson properties

Zuoz Summer School 2014
Lyceum Alpinum



Mauro Donegà

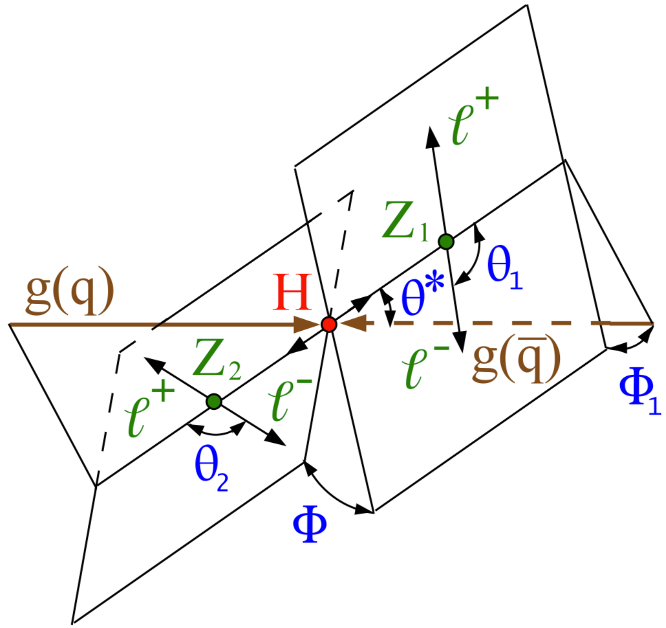
Lecture 2

Detectors
BDT
Statistics
Dissect one analysis
Main decay channels
top/Higgs
Coupling measurements
Differential measurements
Mass measurements
Width measurements
Spin structure

Not covered: searches and a lot more…

H→ZZ

Analysis takes advantage of the full kinematics of the event: 5 angles + m_{4l} + m_{Z1} + m_{Z2}
(Z_1 is the closest to the nominal Z mass)



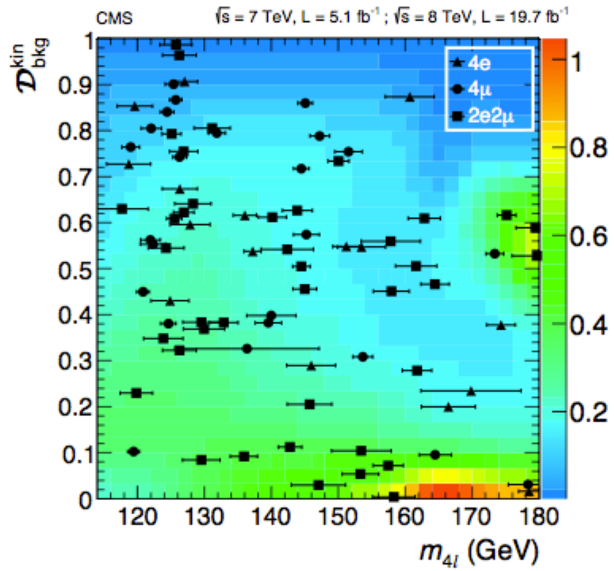
Build pdf using matrix elements (MELA):

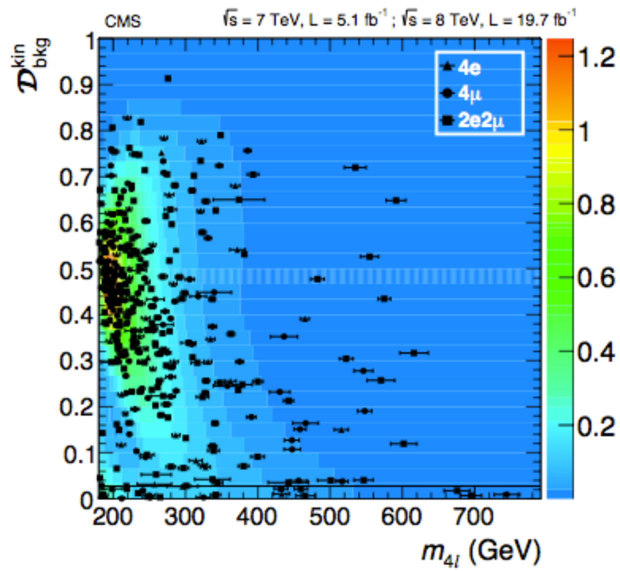
$$\mathcal{P}_{\rm bkg} = \mathcal{P}^{\rm kin}_{\rm bkg}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell}) \times \mathcal{P}^{\rm mass}_{\rm bkg}(m_{4\ell}),$$

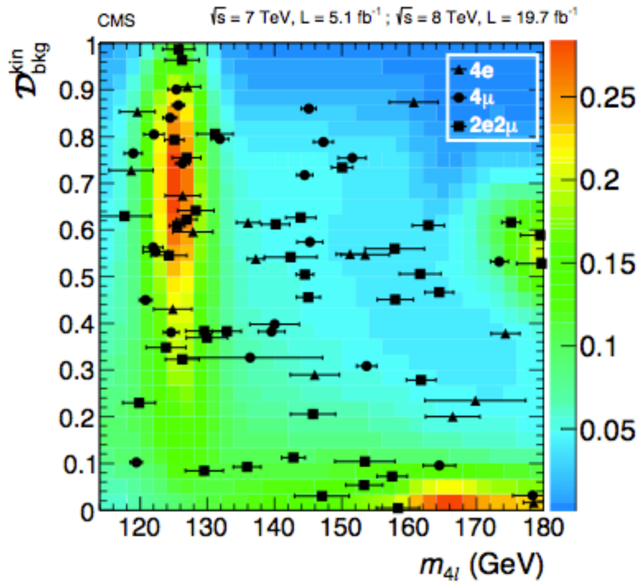
$$\mathcal{P}_{J^P} = \mathcal{P}^{\rm kin}_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell}) \times \mathcal{P}^{\rm mass}_{\rm sig}(m_{4\ell}|m_{\rm H}),$$

and from these build kinematic discriminants
(this is one, later for the spin we'll see others)

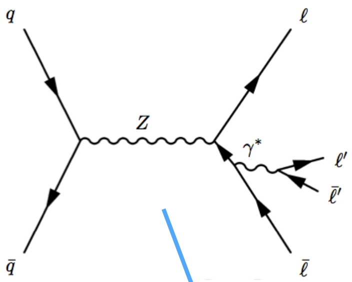
$$\mathcal{D}^{\rm kin}_{\rm bkg} = \frac{\mathcal{P}^{\rm kin}_{0^+}}{\mathcal{P}^{\rm kin}_{0^+} + \mathcal{P}^{\rm kin}_{\rm bkg}} = \left[1 + \frac{\mathcal{P}^{\rm kin}_{\rm bkg}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}^{\rm kin}_{0^+}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

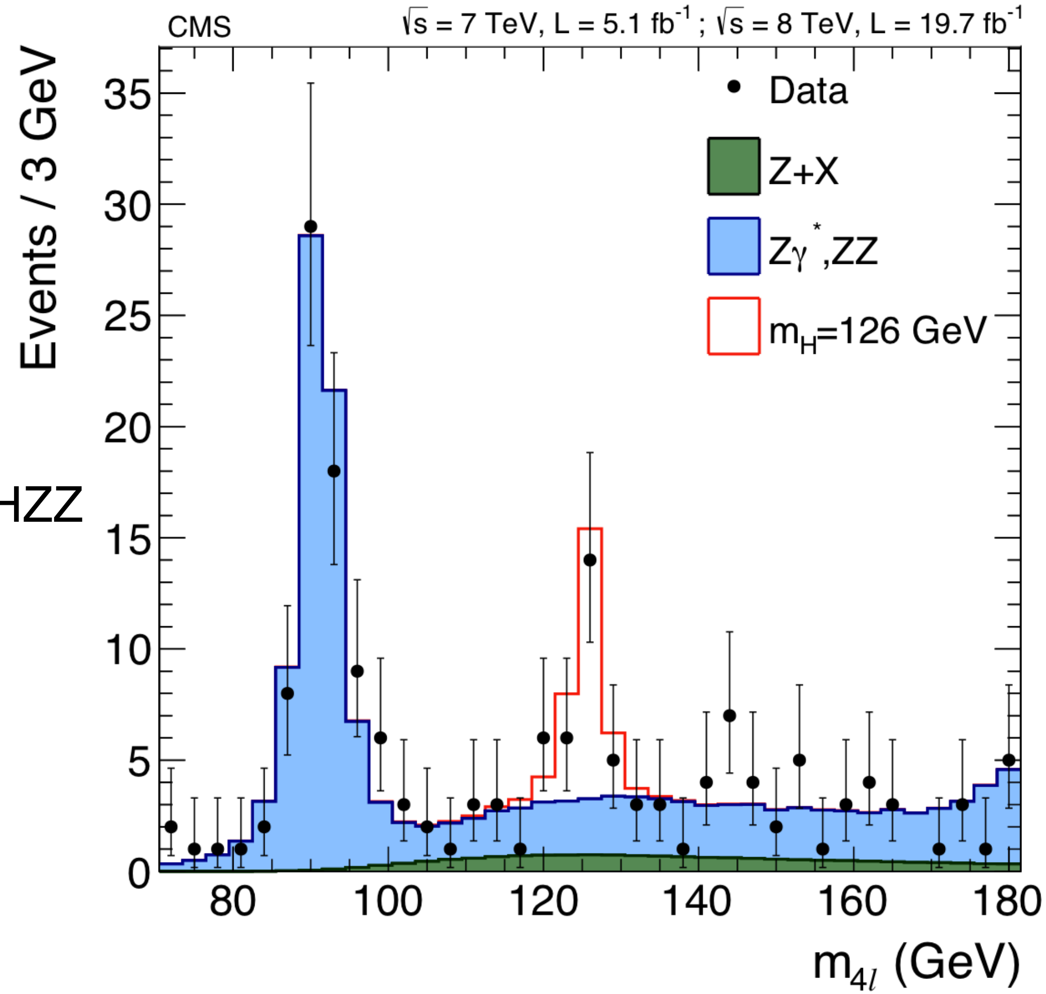


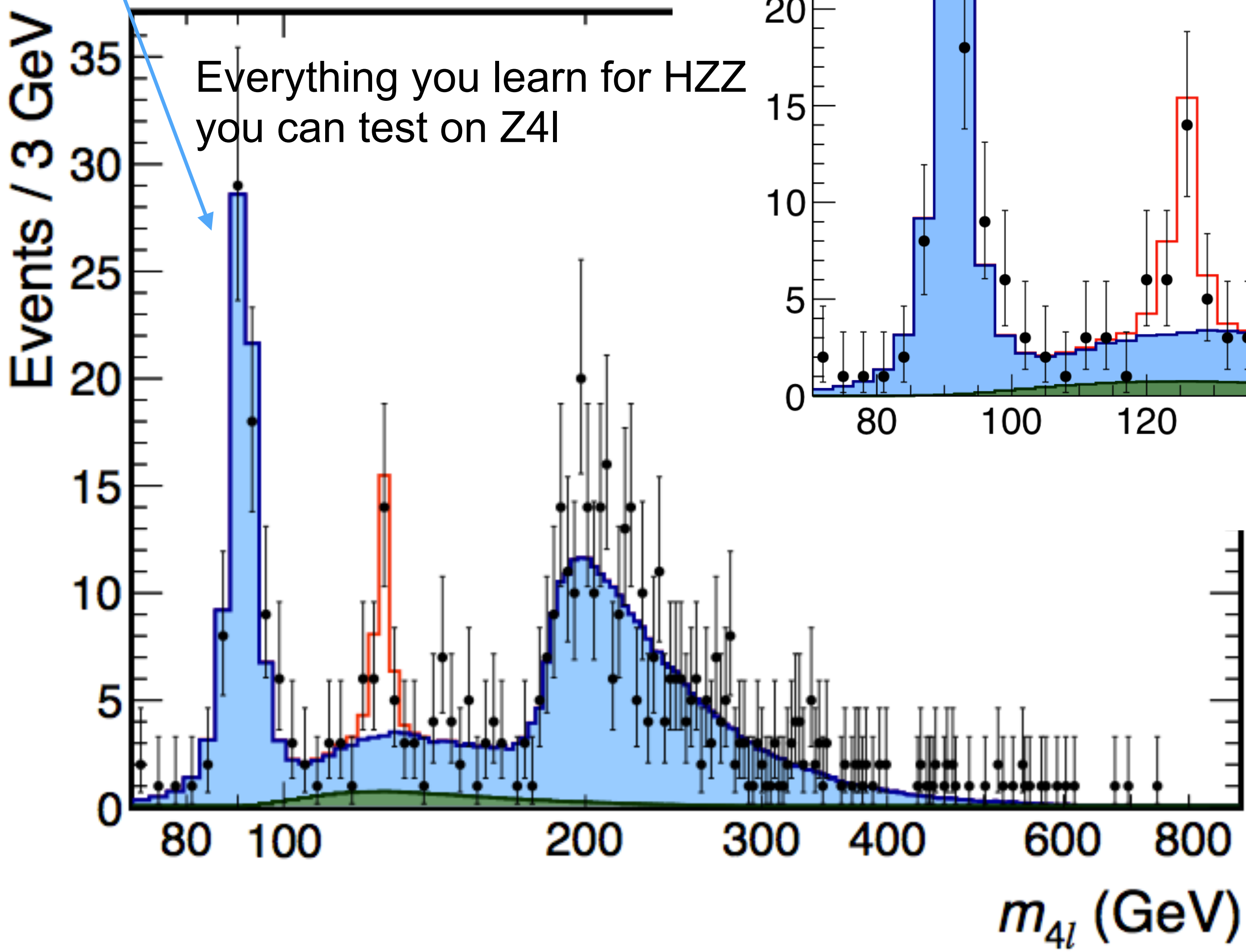




H→ZZ







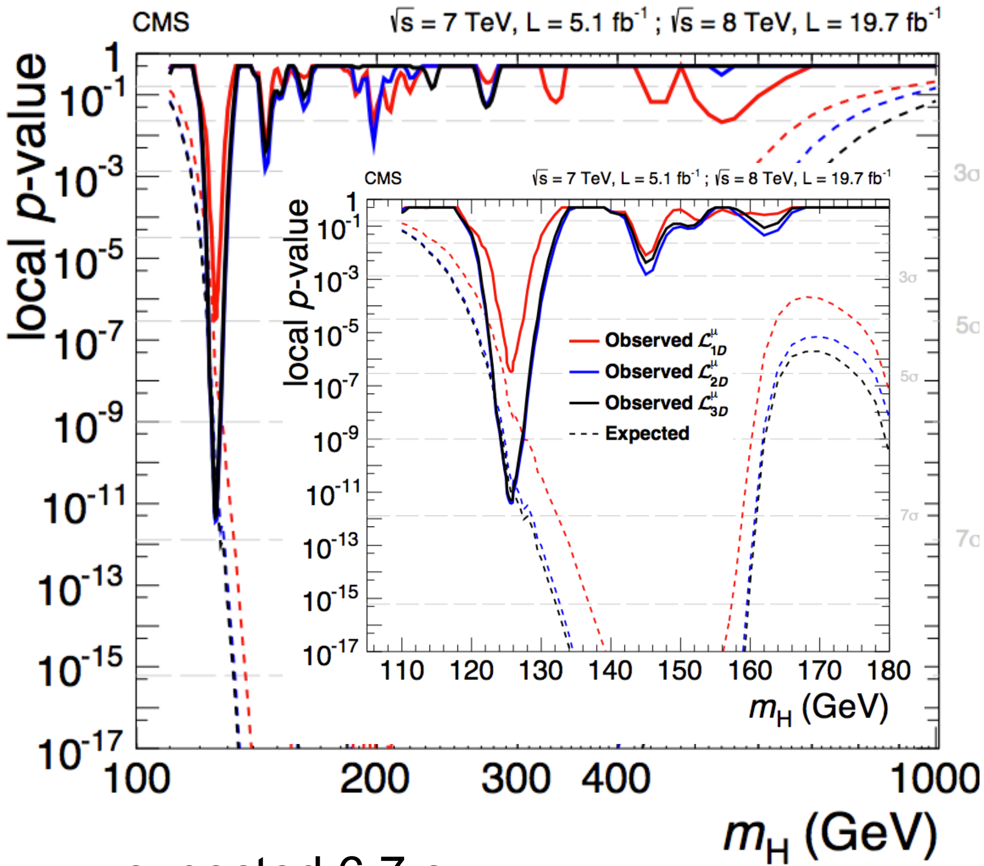
Everything you learn for HZZ
you can test on Z4l

H→ZZ

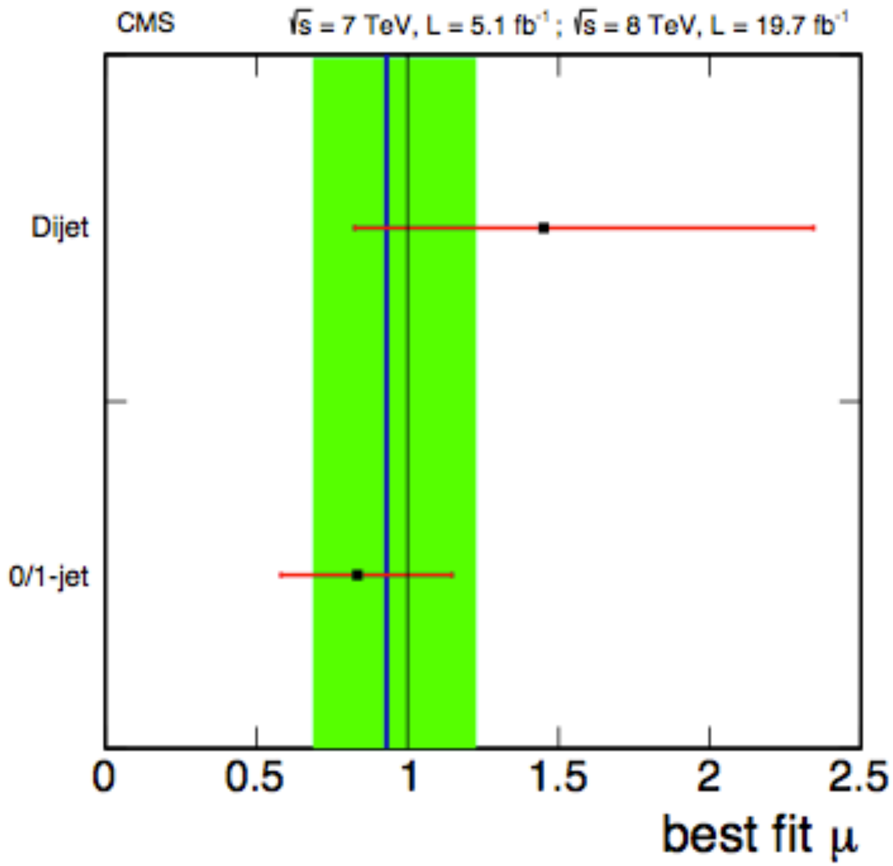
$$\mathcal{L}^{\mu}_{1D} \equiv \mathcal{L}^{\mu}_{1D}(m_{4\ell})$$

$$\mathcal{L}^{\mu}_{2D} \equiv \mathcal{L}^{\mu}_{2D}(m_{4\ell}, \mathcal{D}^{\text{kin}}_{\text{bkg}})$$

$$\boxed{\mathcal{L}^{\mu,0/1\text{-jet}}_{3D}(m_{4\ell}, \mathcal{D}^{\text{kin}}_{\text{bkg}}, p_{\text{T}}^{4\ell}) \text{ and } \mathcal{L}^{\mu,\text{dijet}}_{3D}(m_{4\ell}, \mathcal{D}^{\text{kin}}_{\text{bkg}}, \mathcal{D}_{\text{jet}})}$$



expected 6.7 σ
observed 6.8 σ @ 125.6 GeV



$$\mu = \sigma/\sigma_{SM} = 0.93^{+0.26}_{-0.23}\,(\text{stat.})^{+0.13}_{-0.09}\,(\text{syst.})$$

@ 125.6 GeV

H→WW

No mass peak because of the neutrinos in the final state

Signature:

2 oppositely charged isolated leptons

(e/mu min pT 20/10 GeV)

Missing Transverse Energy from neutrinos (>20GeV)

jets pT > 30 GeV (veto b-jets)

Main backgrounds:

non resonant WW, tt, Drell-Yan (same Flavour)

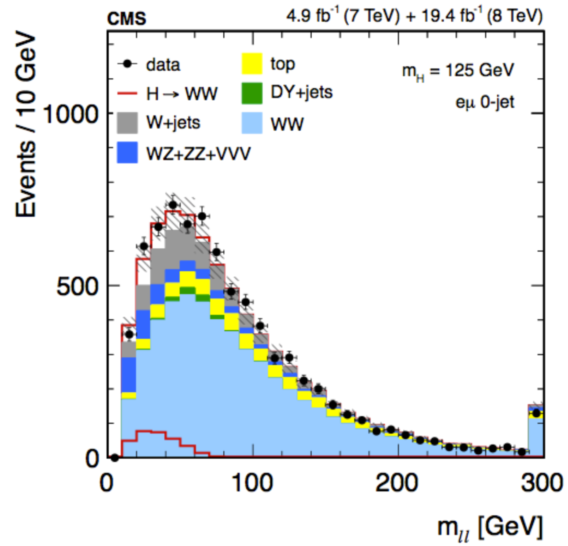
Discriminating variables:

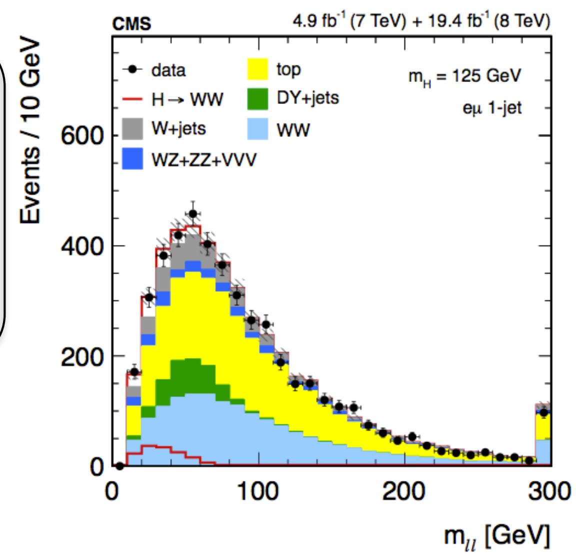
invariant mass of the dilepton system m_{ll}

opening in phi of the dilepton system $\Delta\phi$

transverse mass $m_{\mathrm{T}}^2 = 2p_{\mathrm{T}}^{\ell\ell} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\Delta\phi(\ell\ell, \vec{E}_{\mathrm{T}}^{\mathrm{miss}}))$

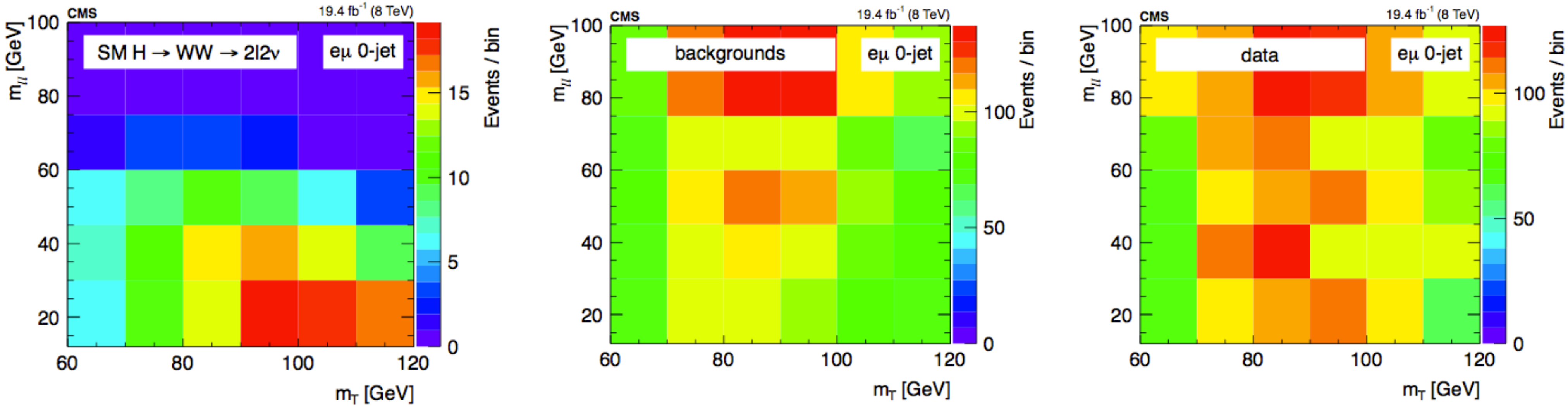
Categorize in number of jets (0,1, / >=2)

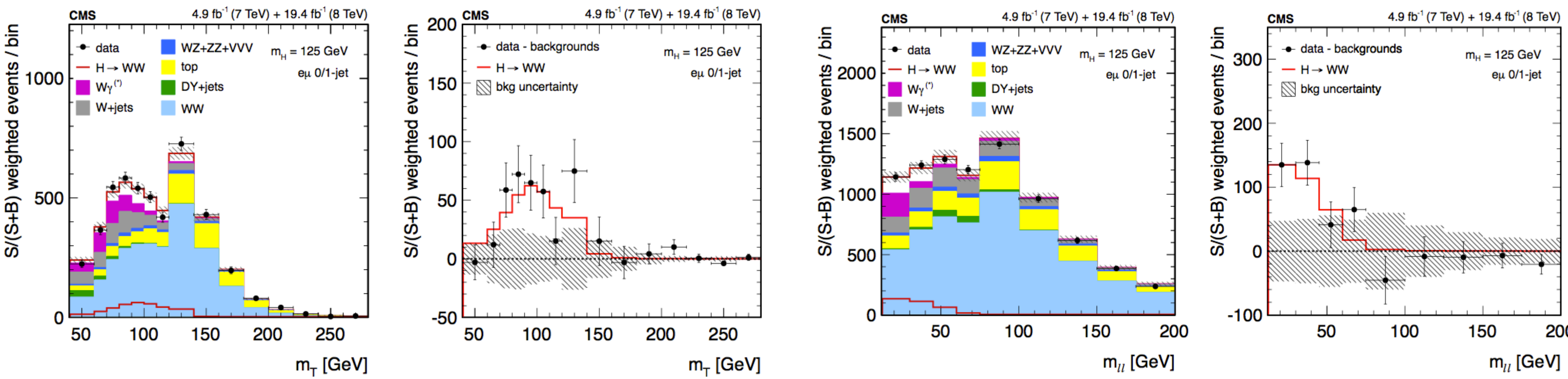




H→WW 0/1 jet bins

2D template fit on m_{ll} m_T
exe 0 jet bin



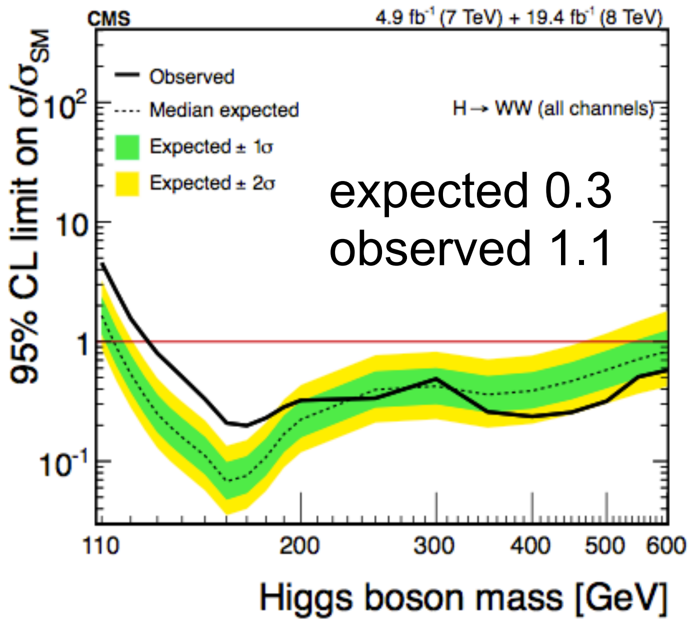


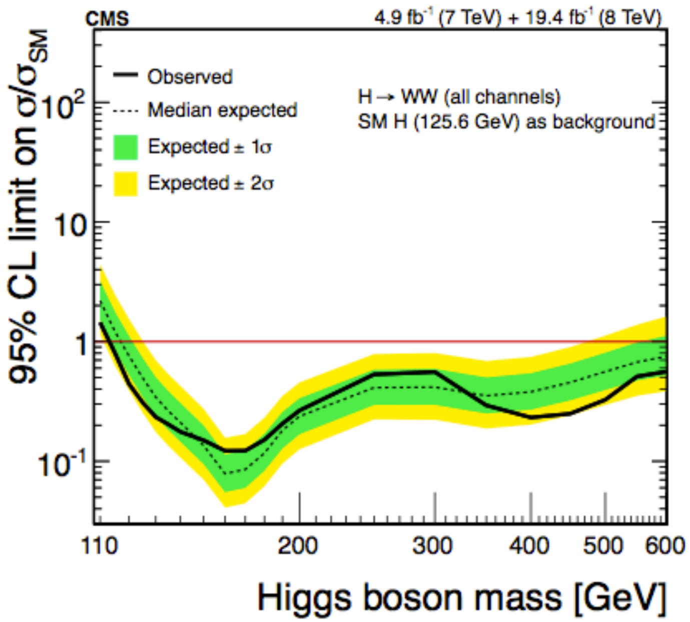
significance: expected 5.2 σ
observed 4.0 σ

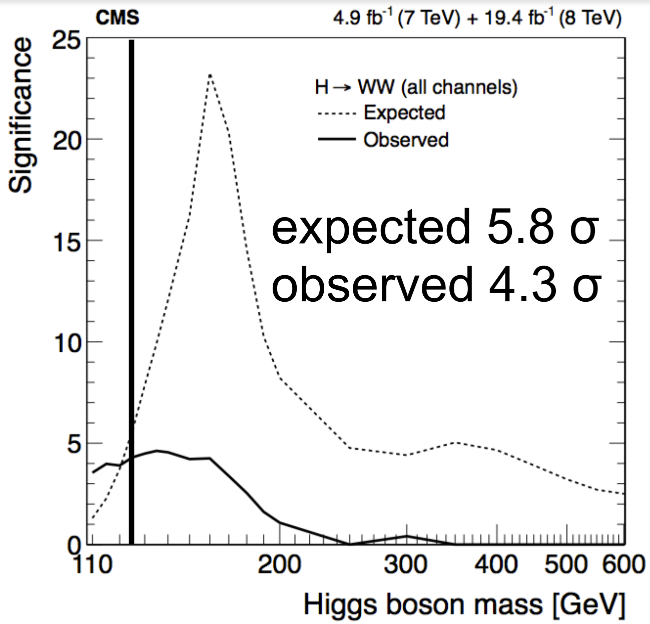
$\hat{\mu}$ = 0.76 ± 0.21

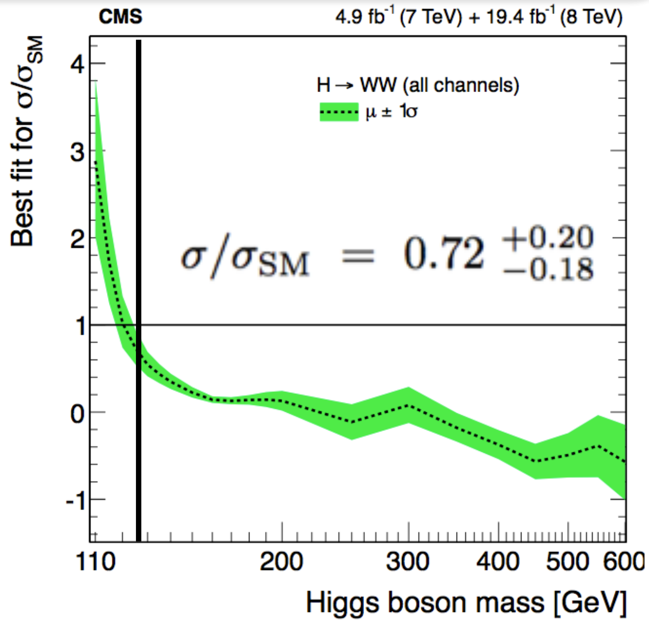
H→WW results

@ 125.6 GeV

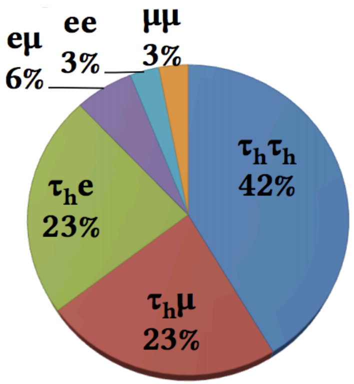


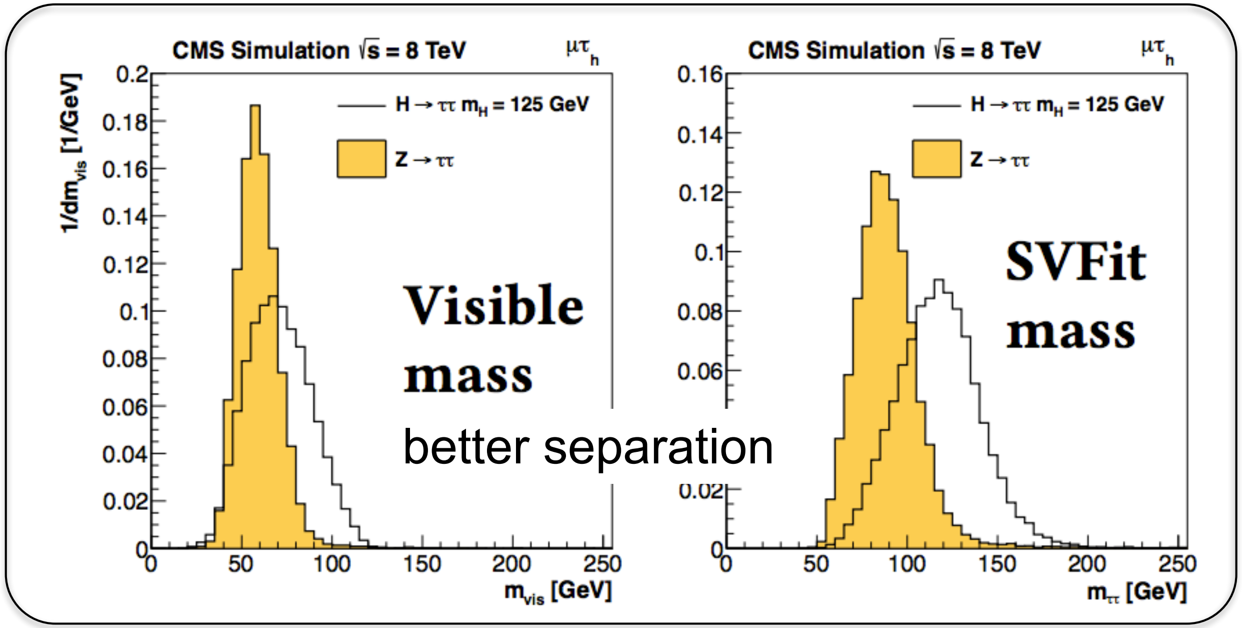






H→ττ





Look for all 6 decays

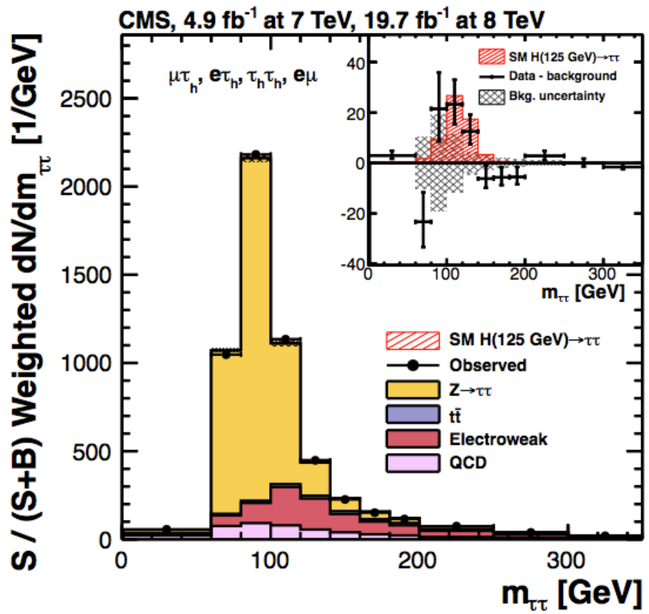
Observable: invariant mass

resolution ~10-20%

But τ have neutrinos in the final state !!

Use a Maximum Likelihood fit using the

ττ decay products and the missing energy



Categories

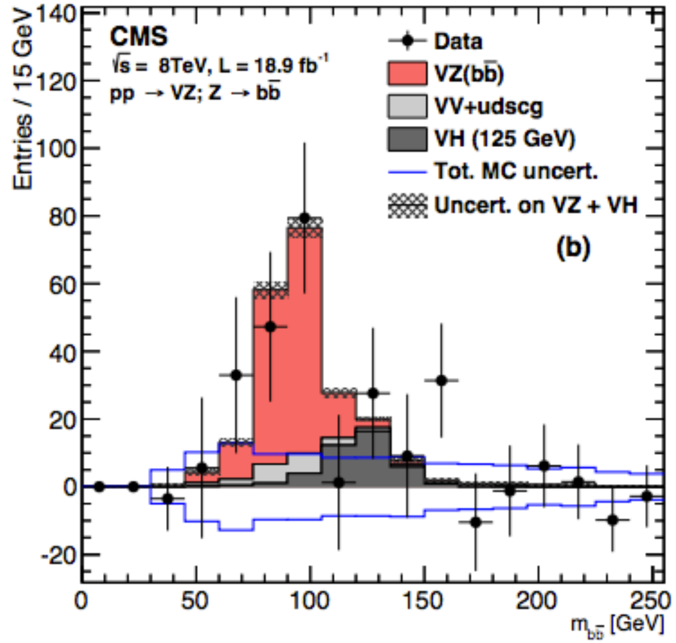
0j,1j (ggF), 2j (VBF)

l+ττ ll+ττ (VH)

and further lepton p_T, ττ pT,jet properties

H→bb

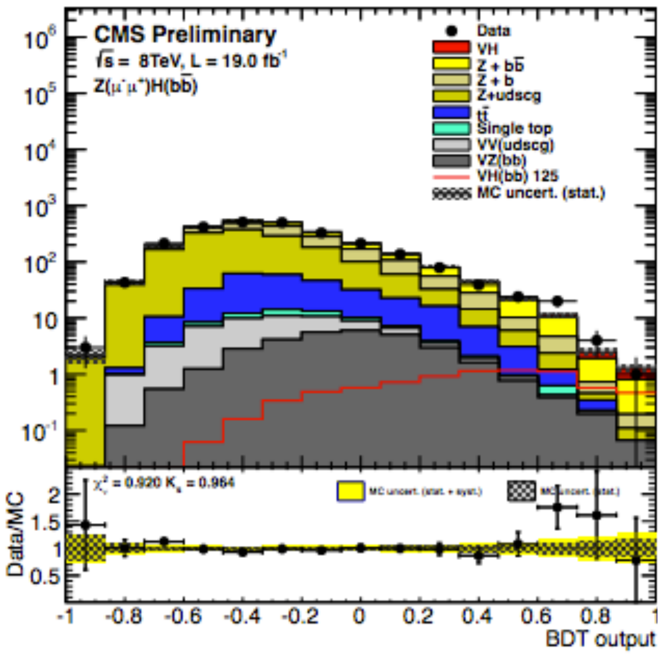
Everything you learn for Hbb
you can test on Vbb



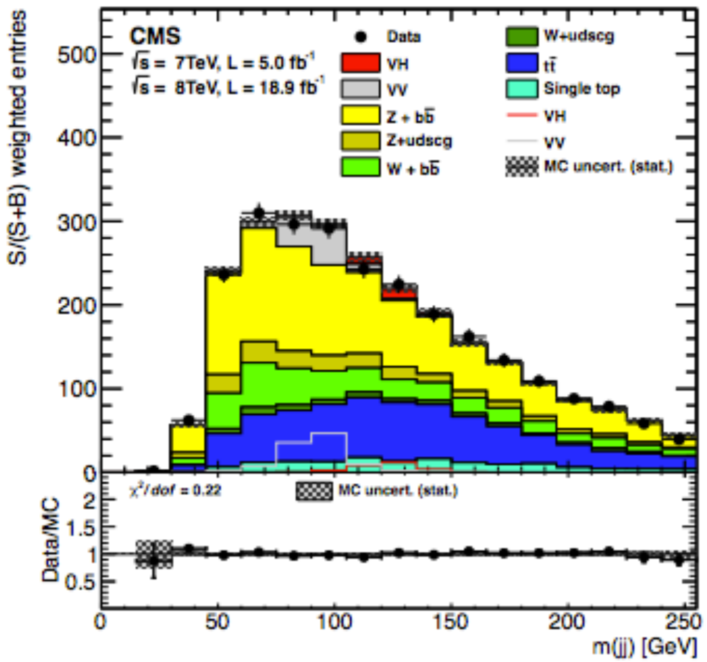
Largest BR (~58%) mass resolution ~ 10%
Can't look for it in ggF too much background
(10^7 times larger)

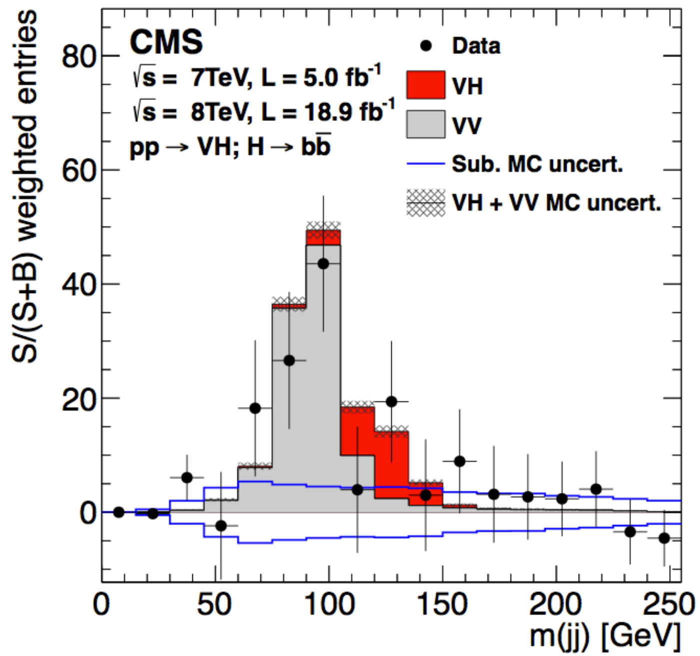
Idea: look for boosted VH production (>100GeV):
multijet bkg reduced + better mass resolution
Main backgrounds: Z+bb, tt, W+bb, single-t b

BDT shape (14 categories)

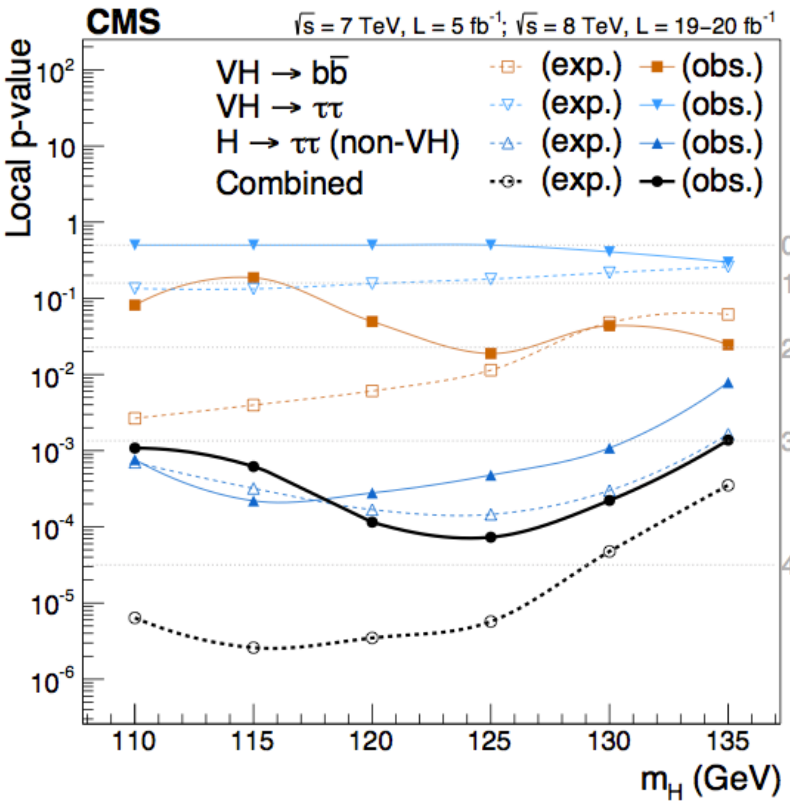


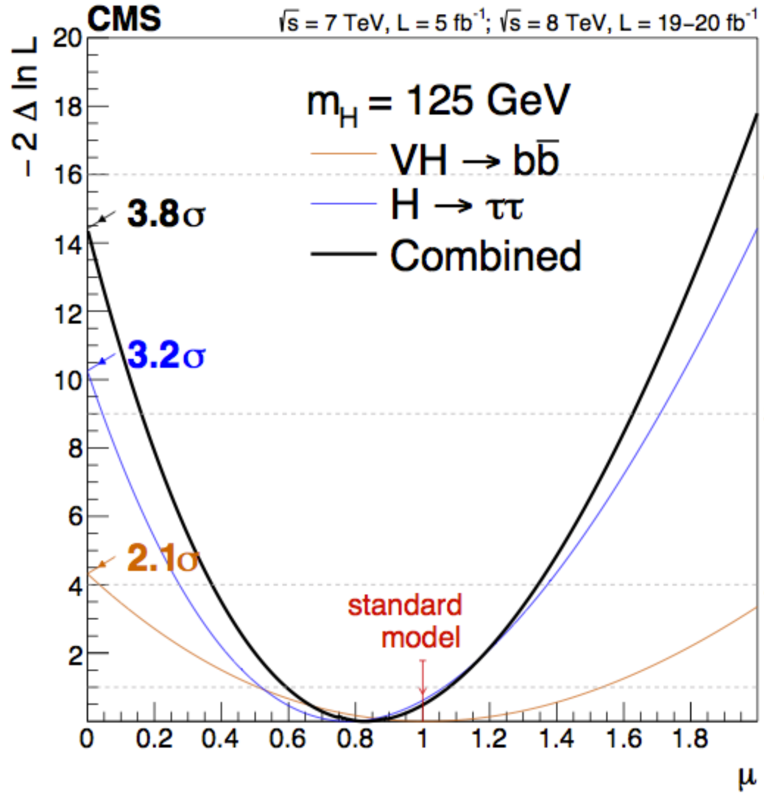
mjj (xcheck analysis)





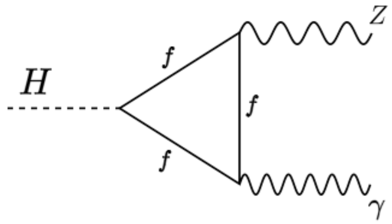
Higgs to fermion evidence



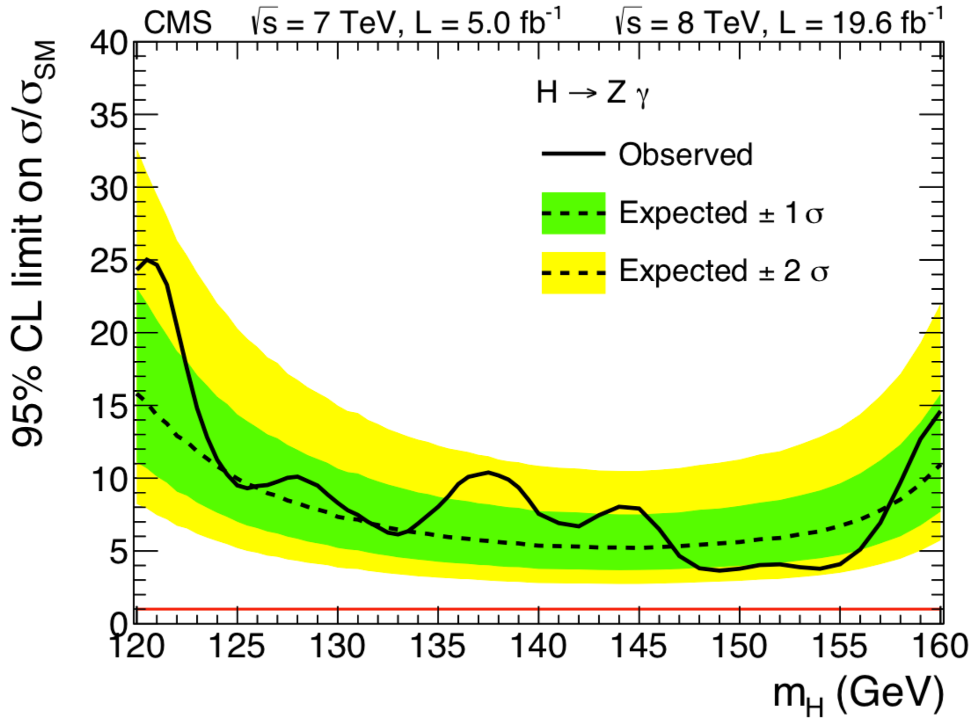


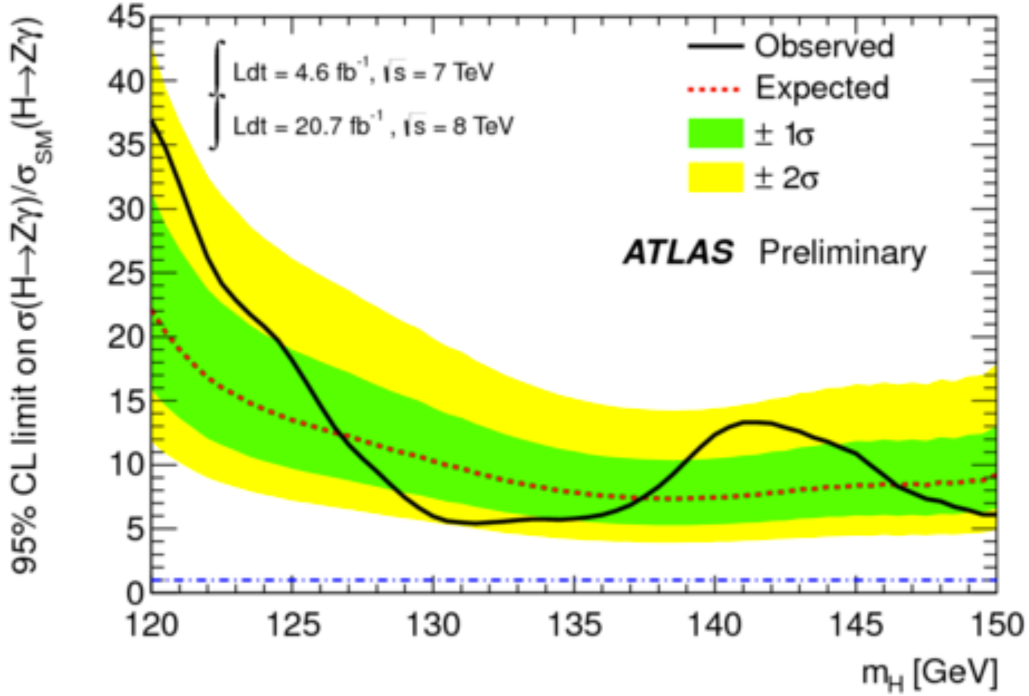
Channel ($m_{\mathrm{H}} = 125\,\mathrm{GeV}$)	Significance (σ) Expected	Significance (σ) Observed	Best-fit μ
$\mathrm{VH} \to \mathrm{b\bar{b}}$	2.3	2.1	1.0 ± 0.5
$\mathrm{H} \to \tau\tau$	3.7	3.2	0.78 ± 0.27
Combined	4.4	3.8	0.83 ± 0.24

H→Zγ



"Spin-off" of the H→γγ analyses (background treatment)

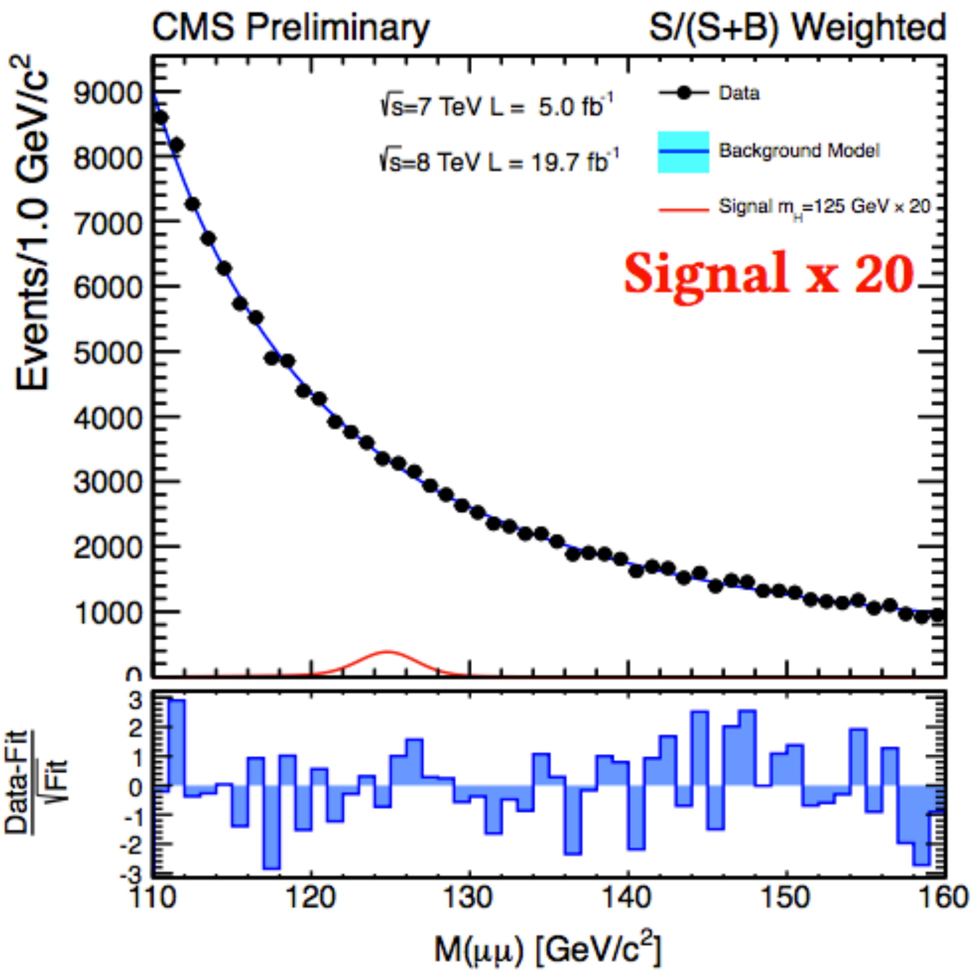


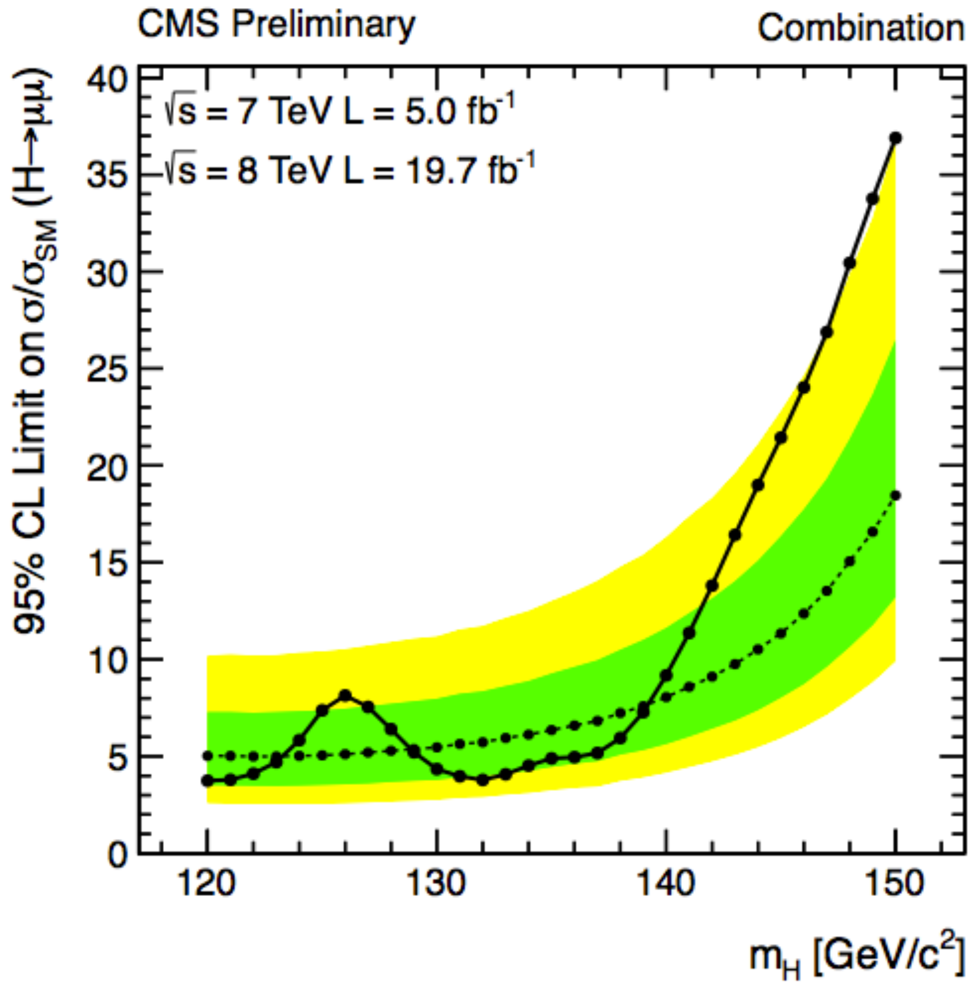


fit $m_{Z\gamma}$

fit ($m_{Z\gamma}$ - m_Z)

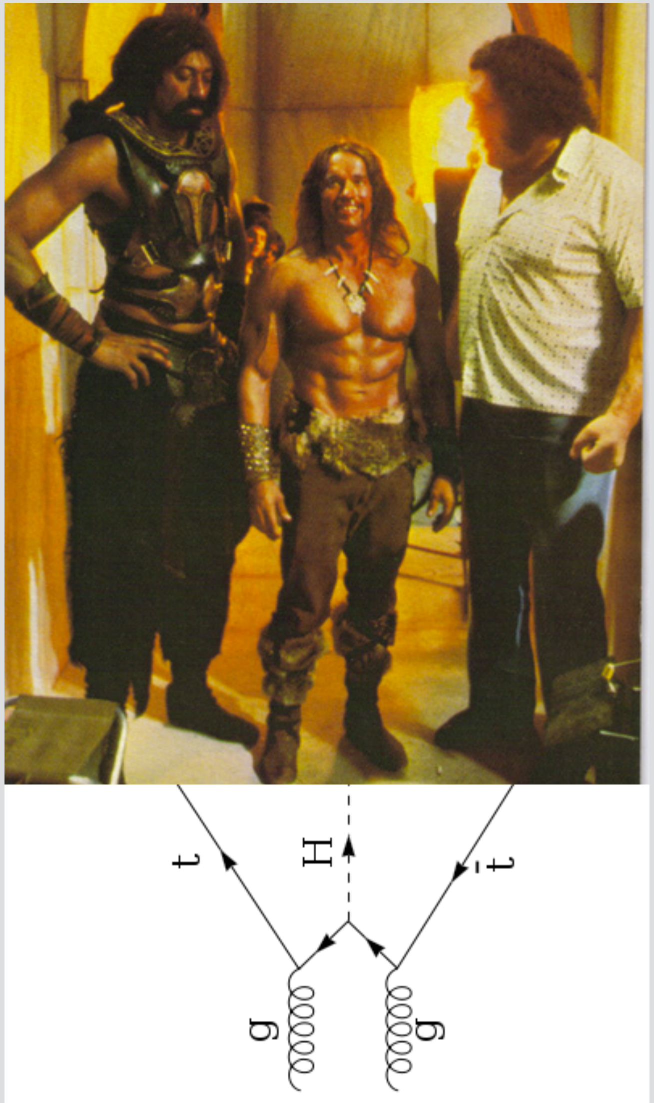
H→μμ





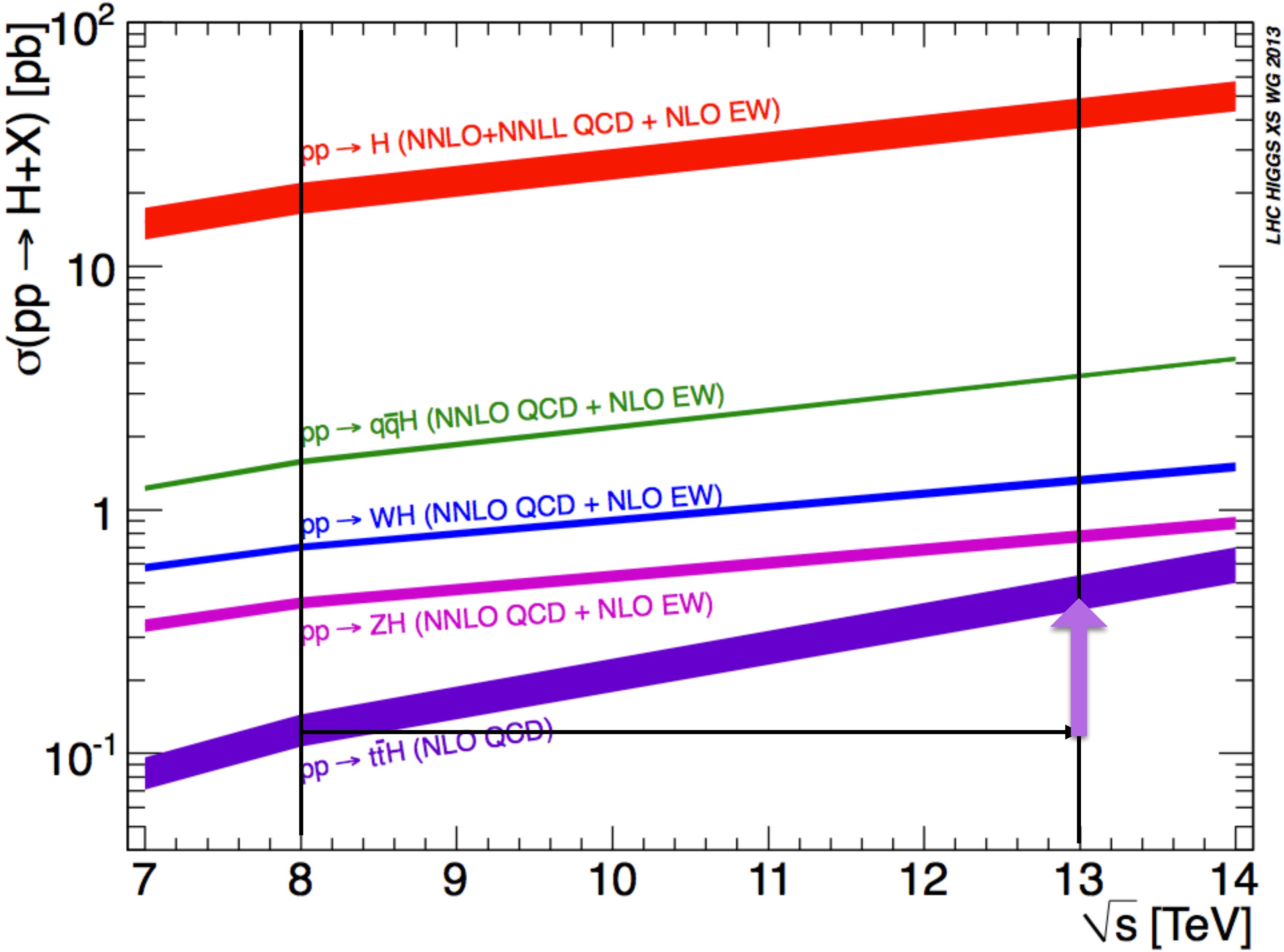
95% CL limit on $\mu(H\to\mu\mu)$ = 7.4 x SM observed
5.1 x SM expected

Similar results are obtained for H→ee and from ATLAS



top/Higgs

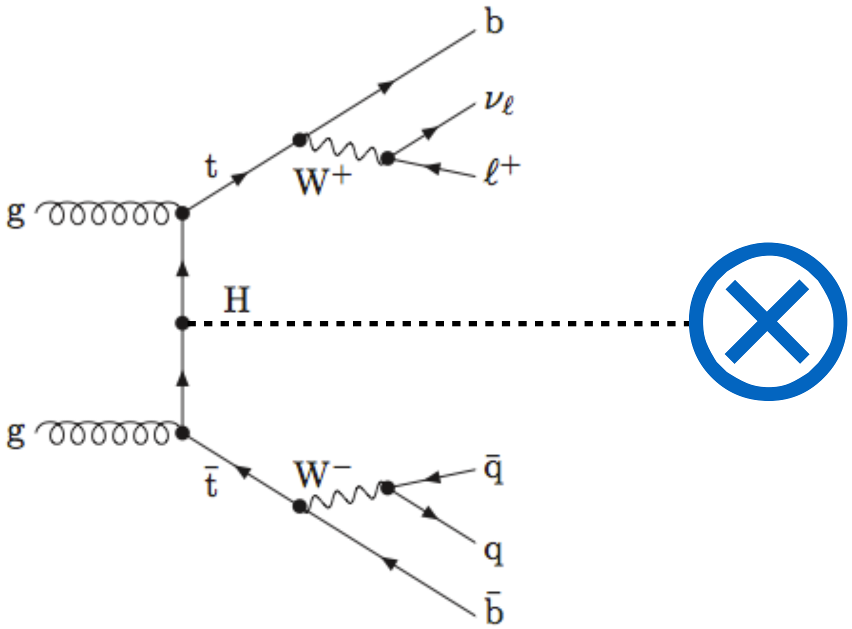
13 TeV

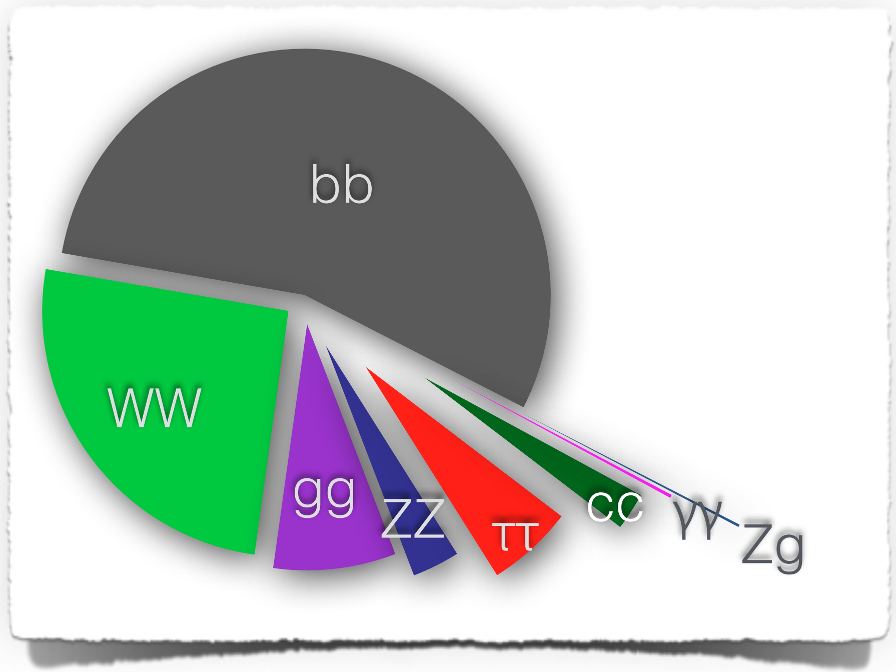


σ(pp → H+X) [pb]
10^2
10
1
10^{-1}
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qq̄H (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD + NLO EW)
pp → tt̄H (NLO QCD)
LHC HIGGS XS WG 2013
7
8
9
10
11
12
13
14
√s [TeV]

ttH

H + top quark(s) sensitive to the Yukawa coupling Yt at tree-level





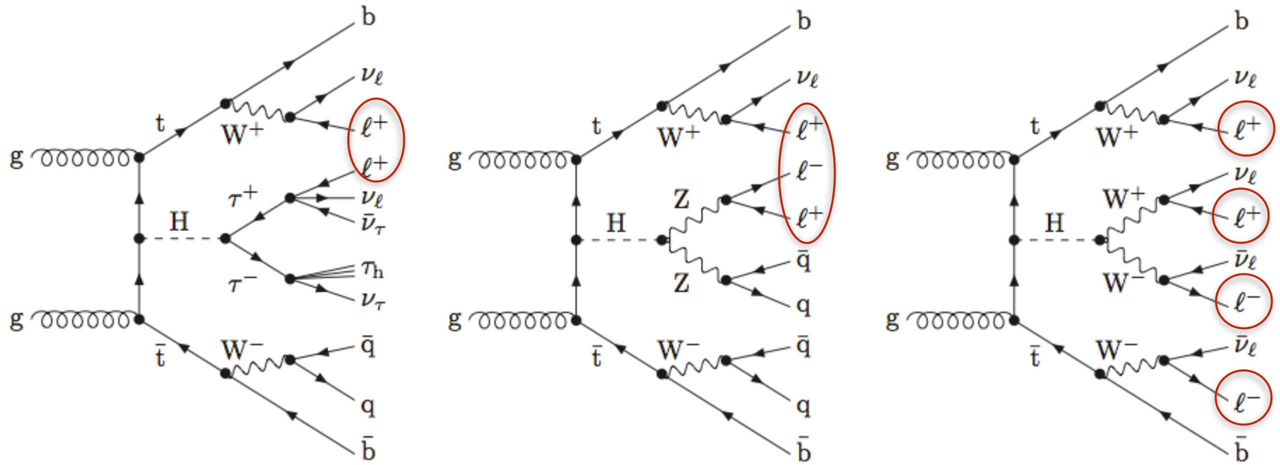
eventually the full zoology

ttH multi leptons

Consider:

$H \to ZZ^*, H \to WW^*, H \to \tau\tau$

tt : lepton + jets or dilepton



Signature:

2 same sign leptons + b-jets

3 leptons + b-jets

4 leptons + b-jets

Main backgrounds:

ttV, VV, reducible (at least one lepton not originating from W/Z/H)

Analysis strategy:

Use BDT to:

select high purity objects

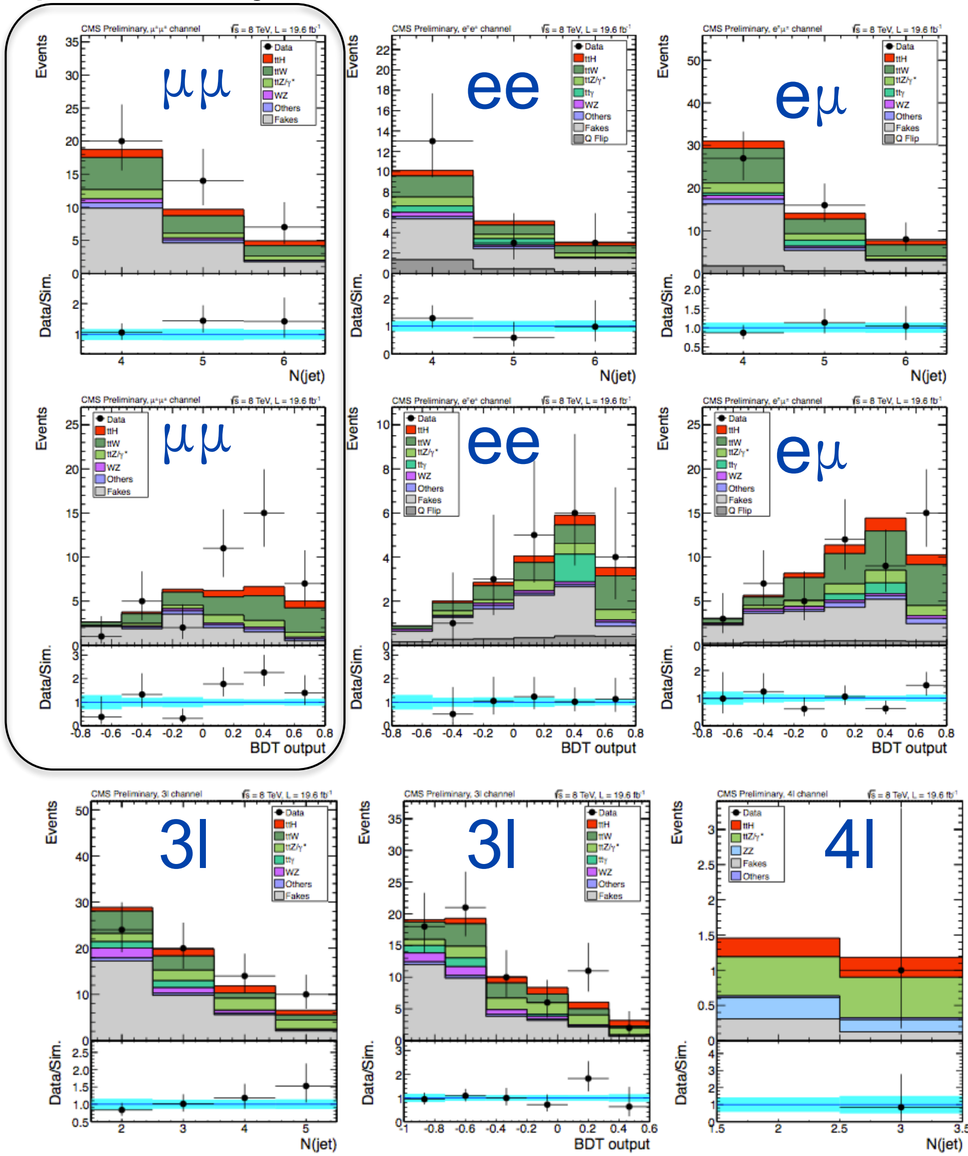
distinguish ttH (sig) from tt-jets (bkg)

All final states fit simultaneously on a BDT output

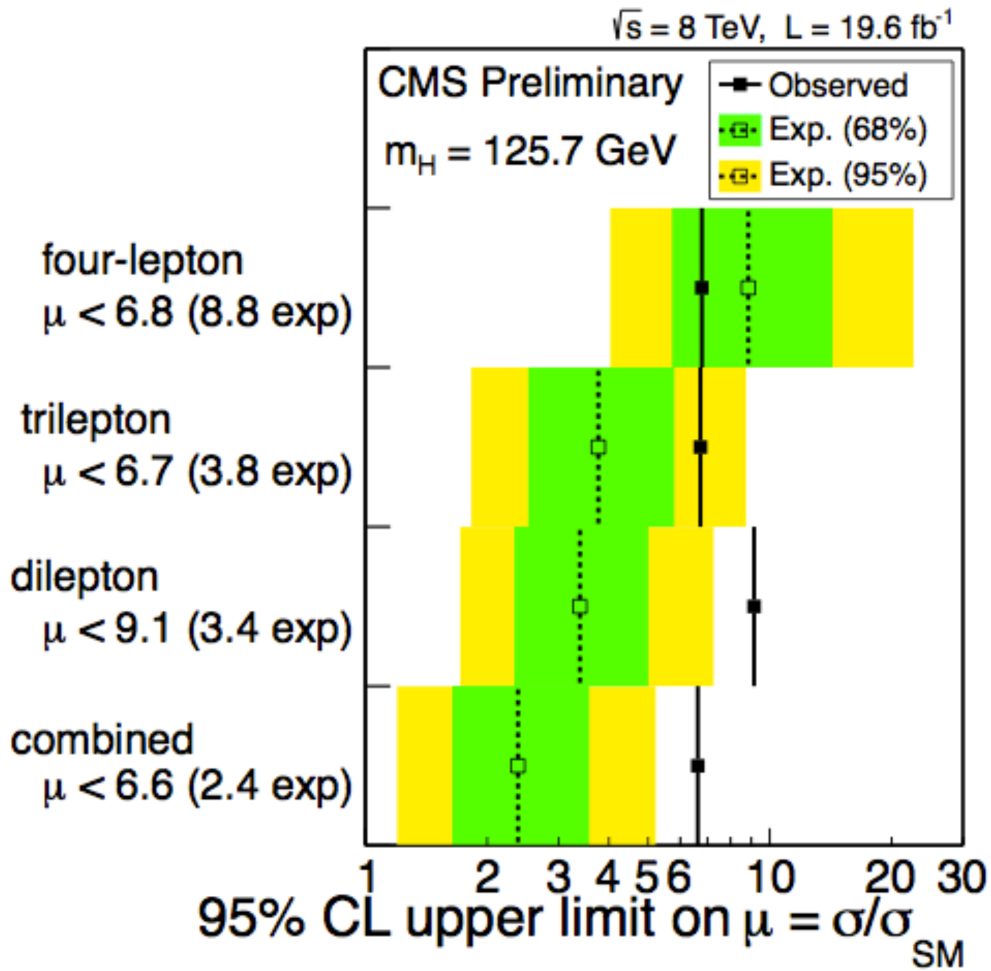
Similar machinery used for H4l

ttH multi leptons

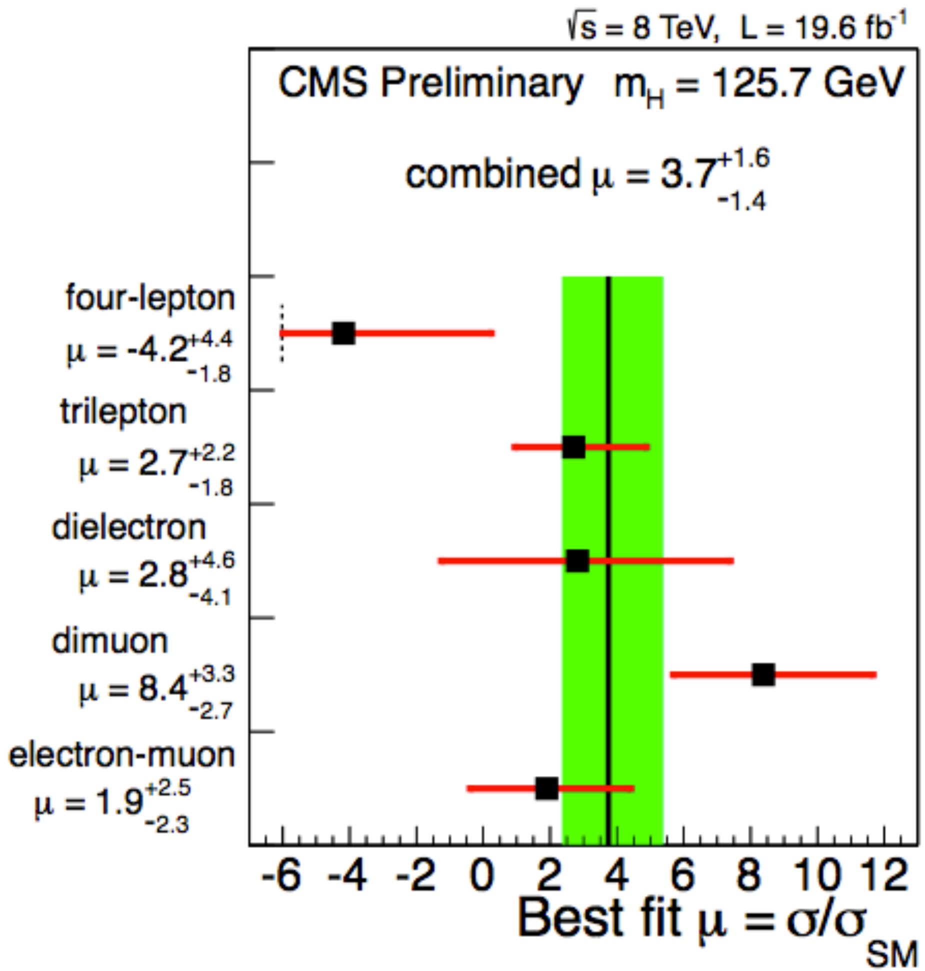
example: 2 same sign leptons + b-jets



ttH multi leptons

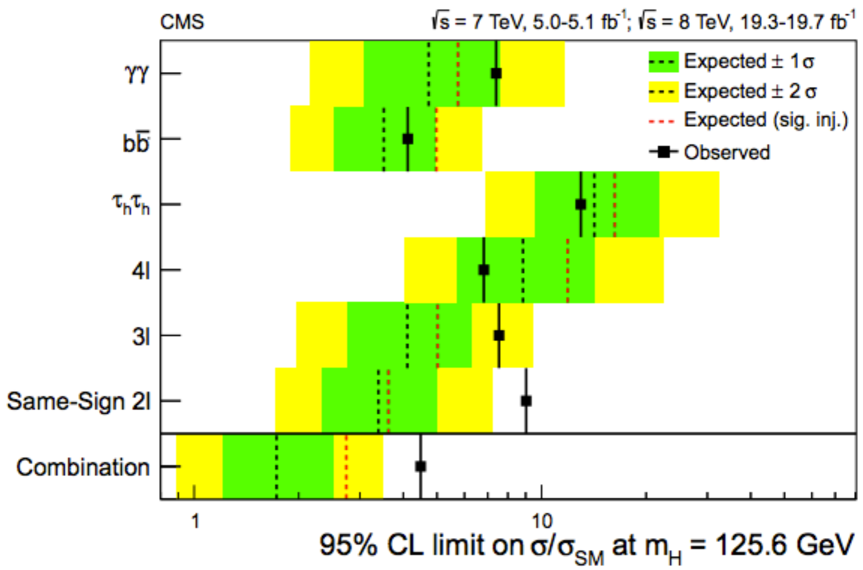


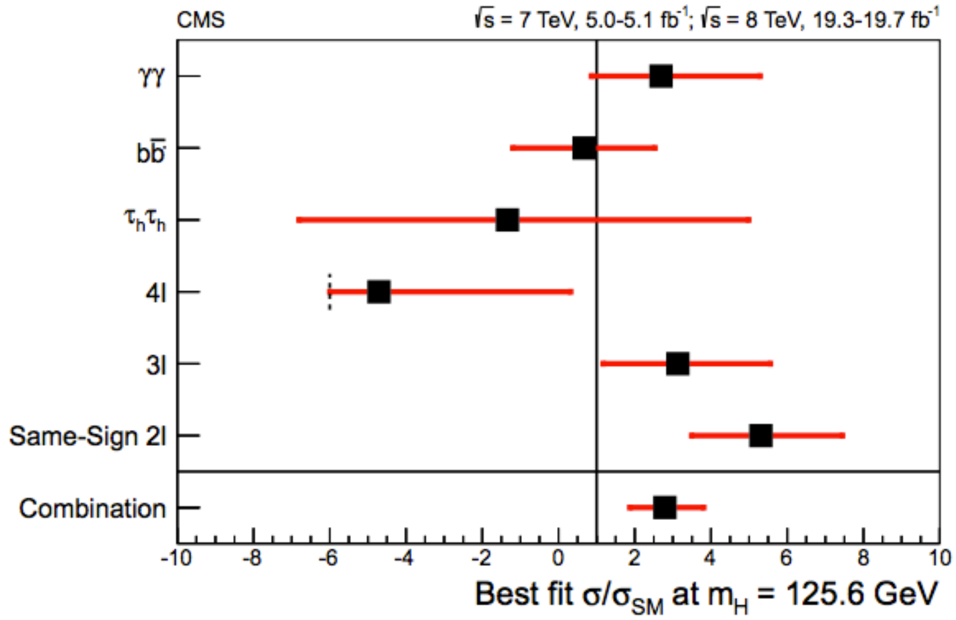
expected 2.4
observed 6.6

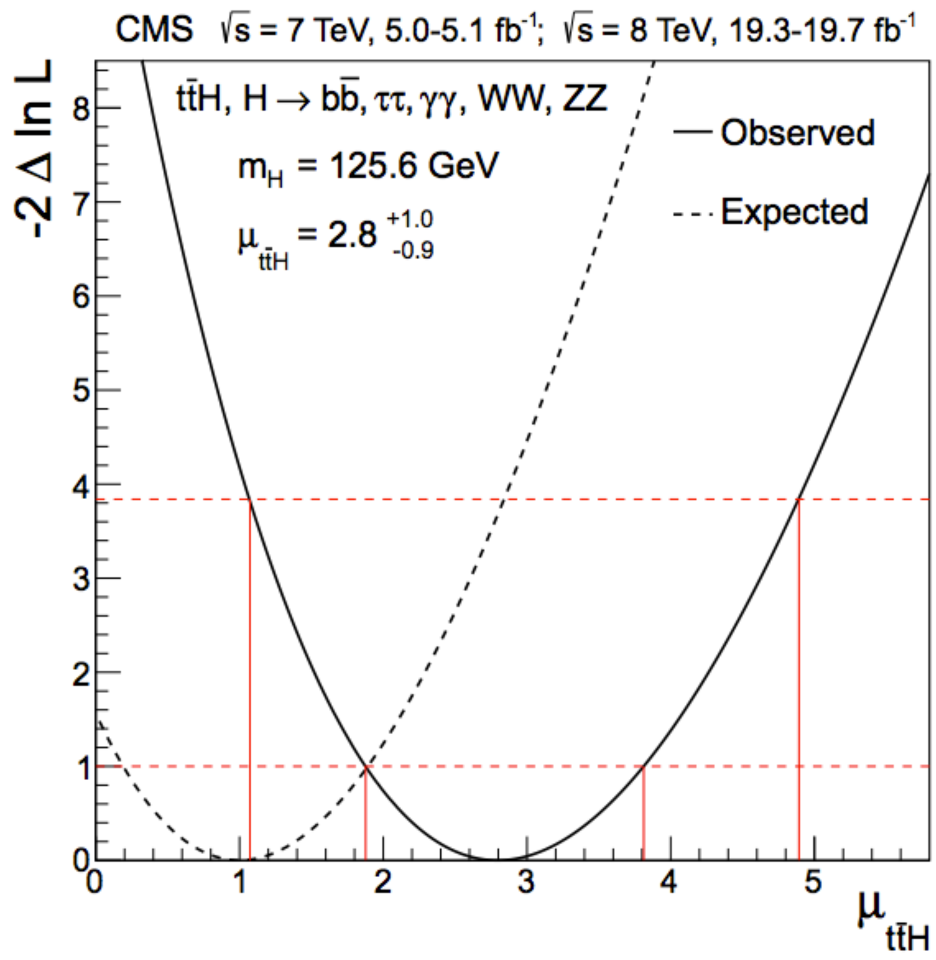


$$\mu = 3.7^{+1.6}_{-1.4}$$

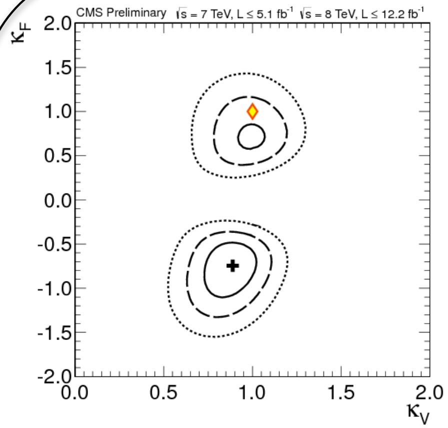
ttH combined



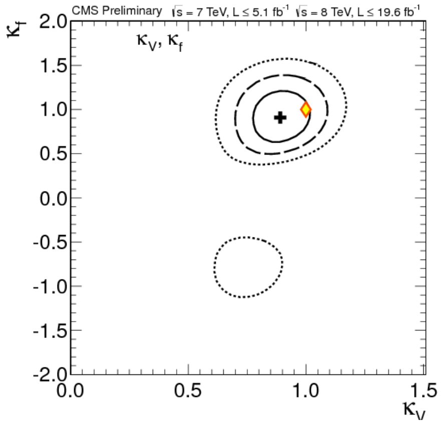




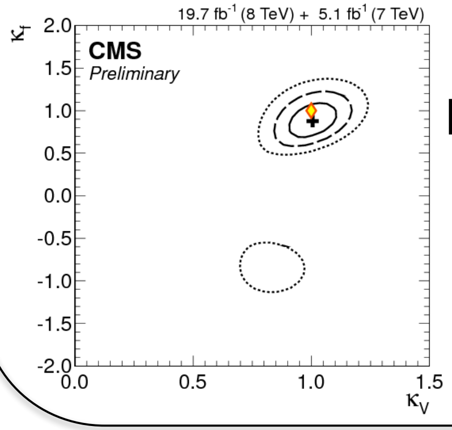
tqH→γγ



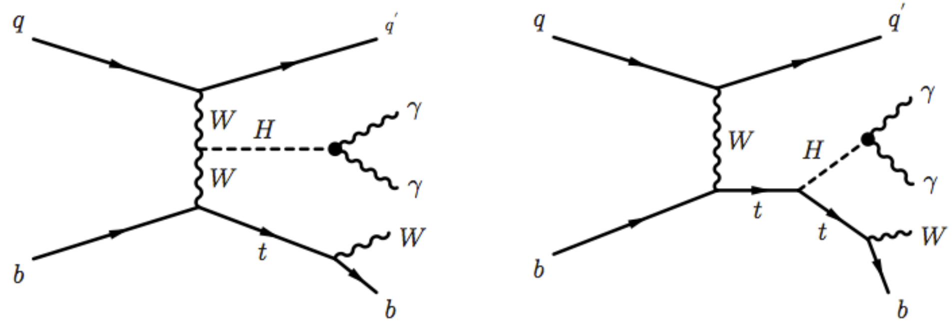
H→γγ enhancement 12.2/fb



Full dataset

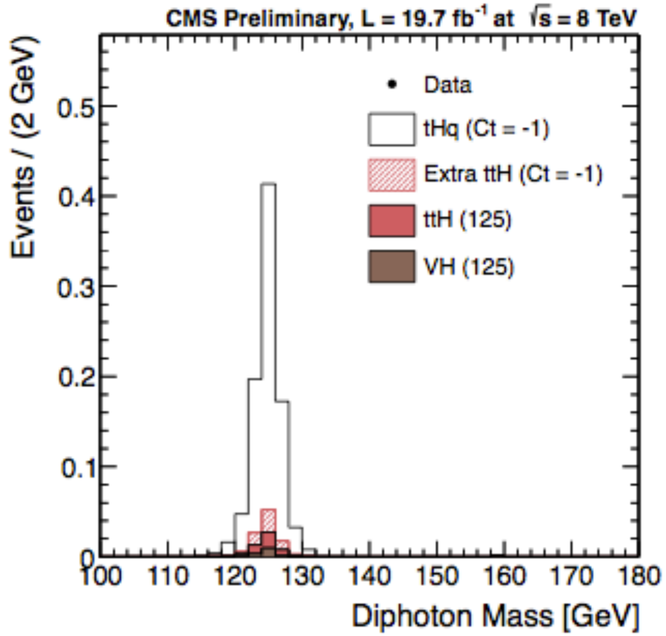


Legacy result



ttH→γγ now is resonant background

+ usual non resonant γγ



No sensitivity yet.

95% UL = 4.1 x the expected section assuming $C_t = -1$

Coupling measurements

Single channels inputs

Combine in one monster likelihood everything we measured about the Higgs:

207 categories
2519 nuisances
+ n parameters depending on the measurement

The event samples selected by the different analyses are mutually exclusive.
(not always true: When results are grouped according to decay/production tag, each individual category is assigned to the decay mode group that, in the SM, is expected to dominate the sensitivity in that channel.)

Test statistics
$$q(a) = -2\,\Delta \ln \mathcal{L} = -2 \ln \frac{\mathcal{L}(\text{data} \mid s(a) + b, \hat{\theta}_a)}{\mathcal{L}(\text{data} \mid s(\hat{a}) + b, \hat{\theta})}$$

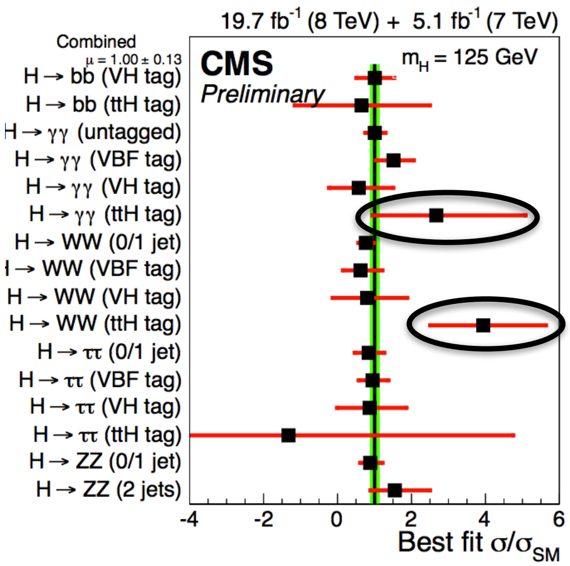
Channel grouping	Significance (σ)	
	Observed	Expected
$\mathrm{H} \to \mathrm{ZZ}$ tagged	6.5	6.3
$\mathrm{H} \to \gamma\gamma$ tagged	5.6	5.3
$\mathrm{H} \to \mathrm{WW}$ tagged	4.7	5.4
Grouped as in Ref. [17]	4.3	5.4
$\mathrm{H} \to \tau\tau$ tagged	3.8	3.9
Grouped as in Ref. [19]	3.9	3.9
$\mathrm{H} \to \mathrm{bb}$ tagged	2.0	2.3
Grouped as in Ref. [16]	2.1	2.3

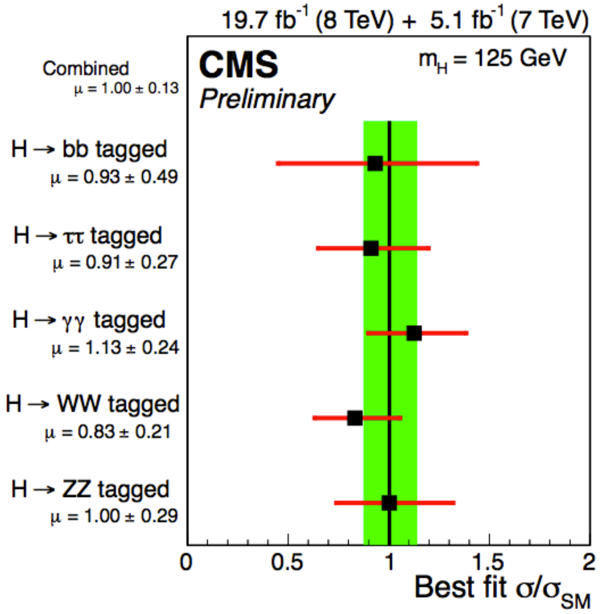
Signal strength

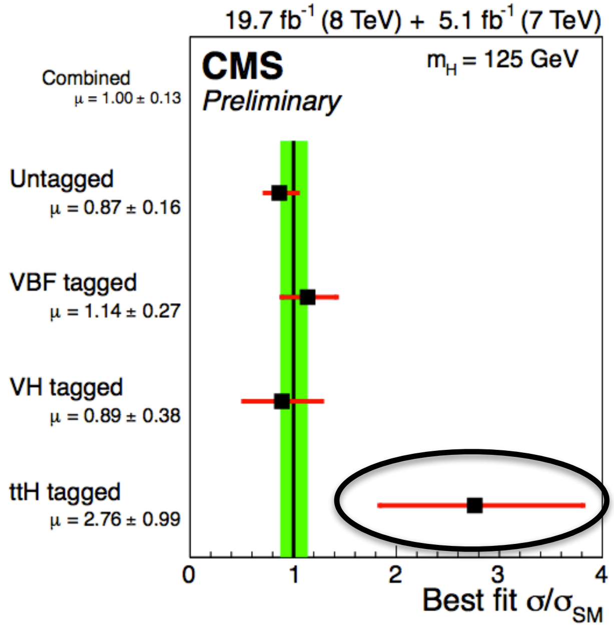
$\hat{\mu}$ is allowed to become negative if the observed number of events is smaller than the expected yield for the background-only hypothesis.

The combined signal strength is: $\hat{\mu} = 1.00 \pm 0.13$

$$1.00 \pm 0.09\,(\text{stat.})\,^{+0.08}_{-0.07}\,(\text{theo.}) \pm 0.07\,(\text{syst.})$$





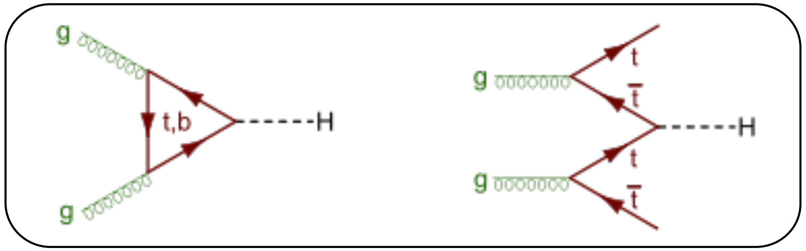


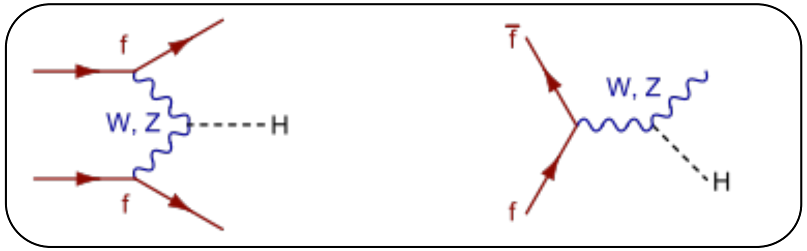
This is driven by the ttH-gg and the ttH multilepton

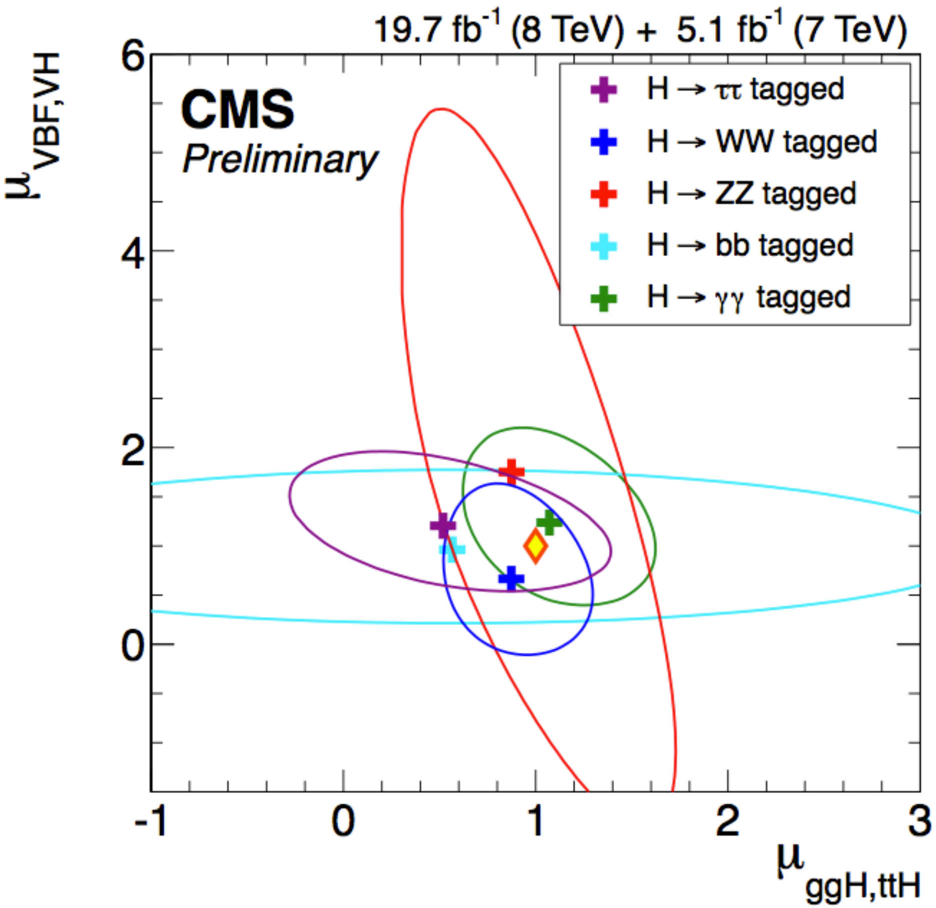
ATLAS $\mu = 1.30 \pm 0.12\,(\text{stat})\,^{+0.14}_{-0.11}\,(\text{sys})$

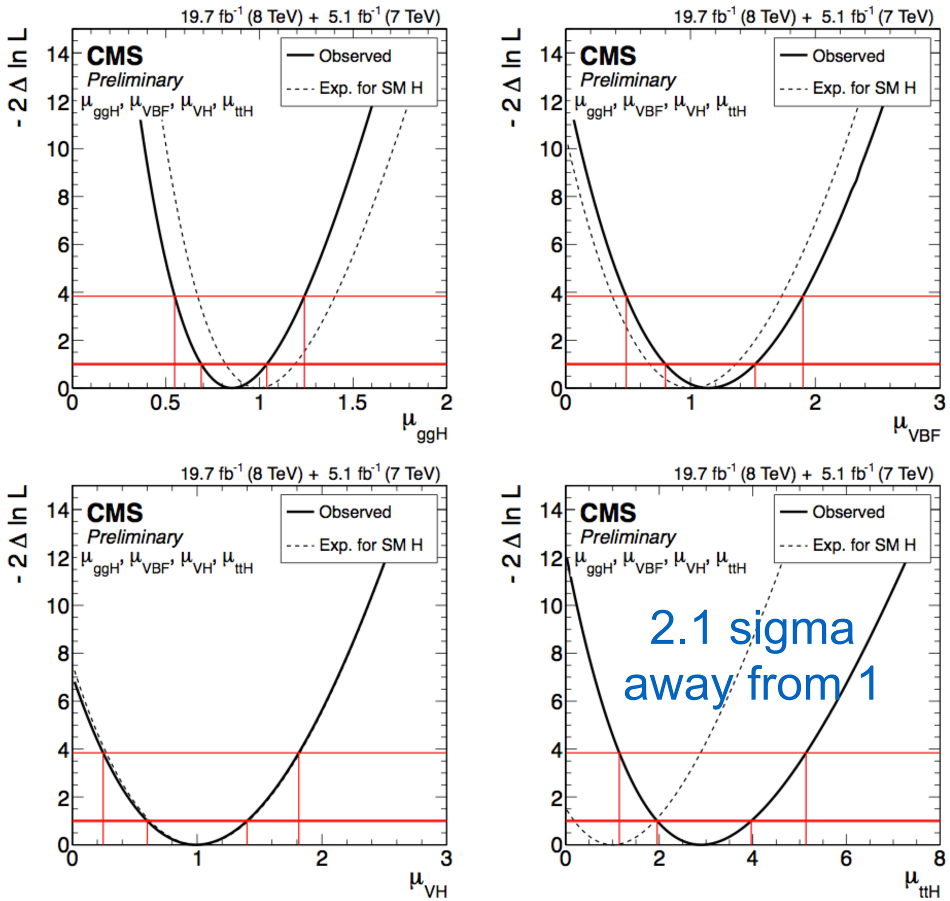
signal strength in combinations

Production mechanism associated to fermions (ggH + ttH) or bosons (VBF+VH)









assumes SM BR for decays

Hp testing on couplings

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

Coupling modifiers: κ_i

Deviation from 1
indicates New Physics

i = V, (same modifier for W and Z)
W, Z,
f, (same modifier for all fermions)
l, q, (one modifier for all leptons and another one for all quarks)
u-type quarks, d-type quarks,
b, top, g, γ,τ

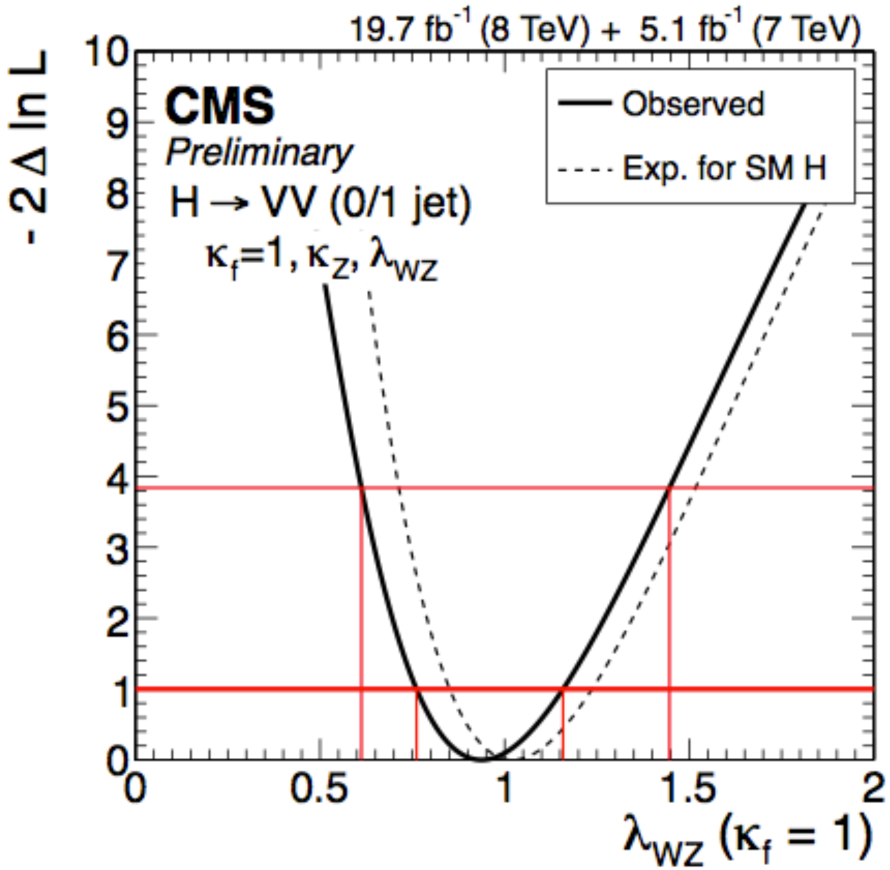
(in particular k_g (gluon) in *production* means not resolving the top loop
k_γ (photon) in *decay* means not resolving the top/W loop)

$$(\sigma \cdot \mathcal{B})(x \to \mathrm{H} \to ff) = \frac{\sigma_x \cdot \Gamma_{ff}}{\Gamma_{\mathrm{tot}}}$$

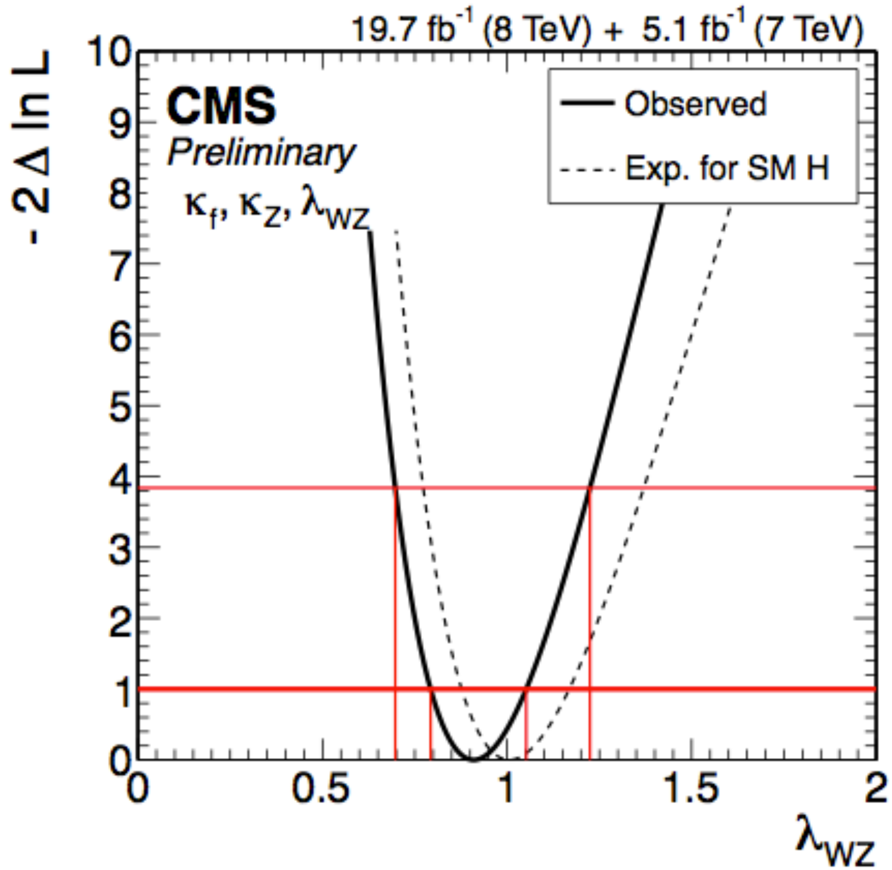
σ_x = production cross section (ggH, VBF, VH, ttH)
Γ_{ff} = partial decay width into final state ff: WW, ZZ,γγ,bb,ττ
Γ_{tot} = total width accounting for a possible BSM partial decay width

$$\Gamma_{\mathrm{tot}} = \sum \Gamma_{ff} + \Gamma_{\mathrm{BSM}}$$

Custodial symmetry $\lambda_{WZ} = \kappa_W / \kappa_Z$

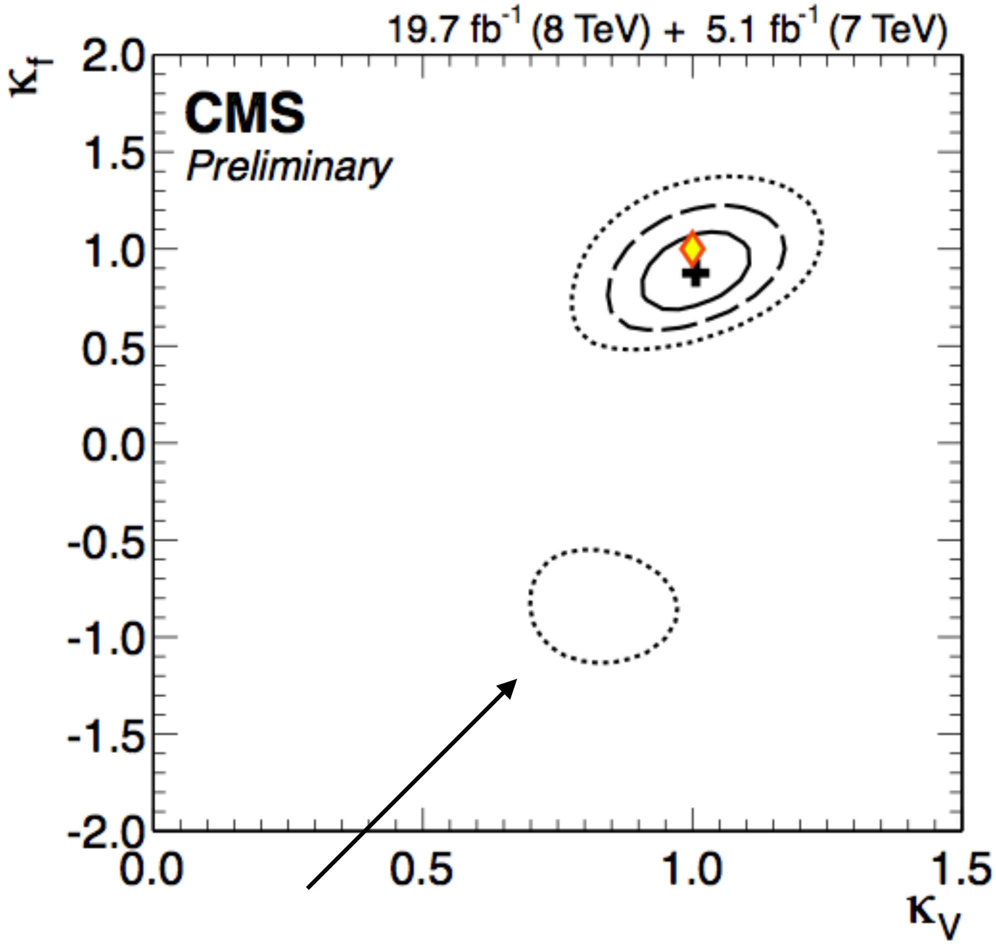


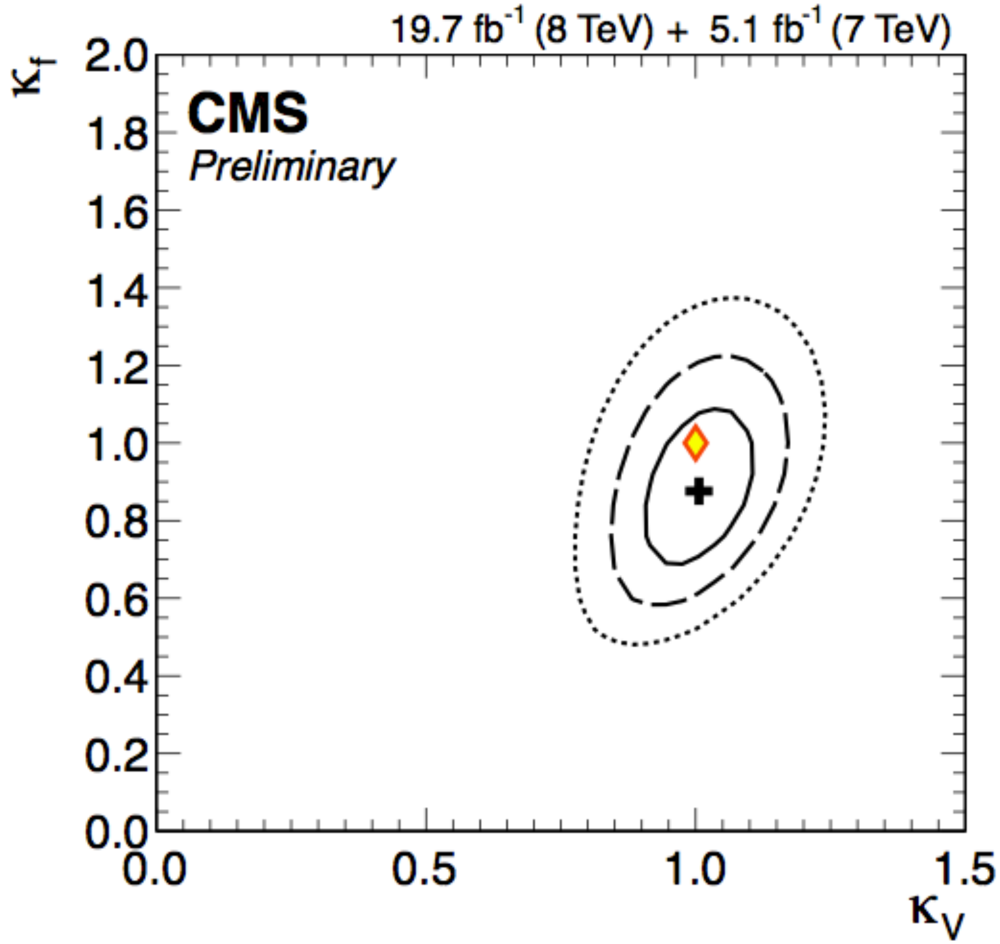
SM fermion couplings



fermion coupling modifier profiled

Couplings to fermions and bosons

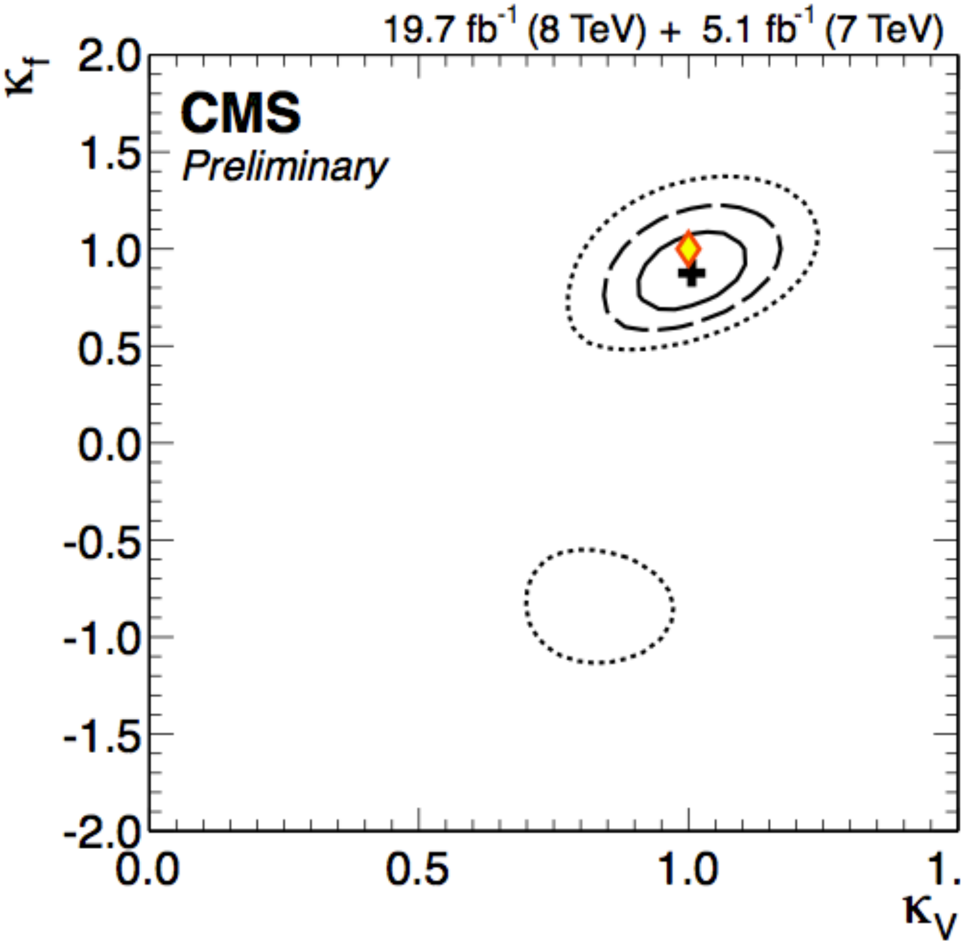


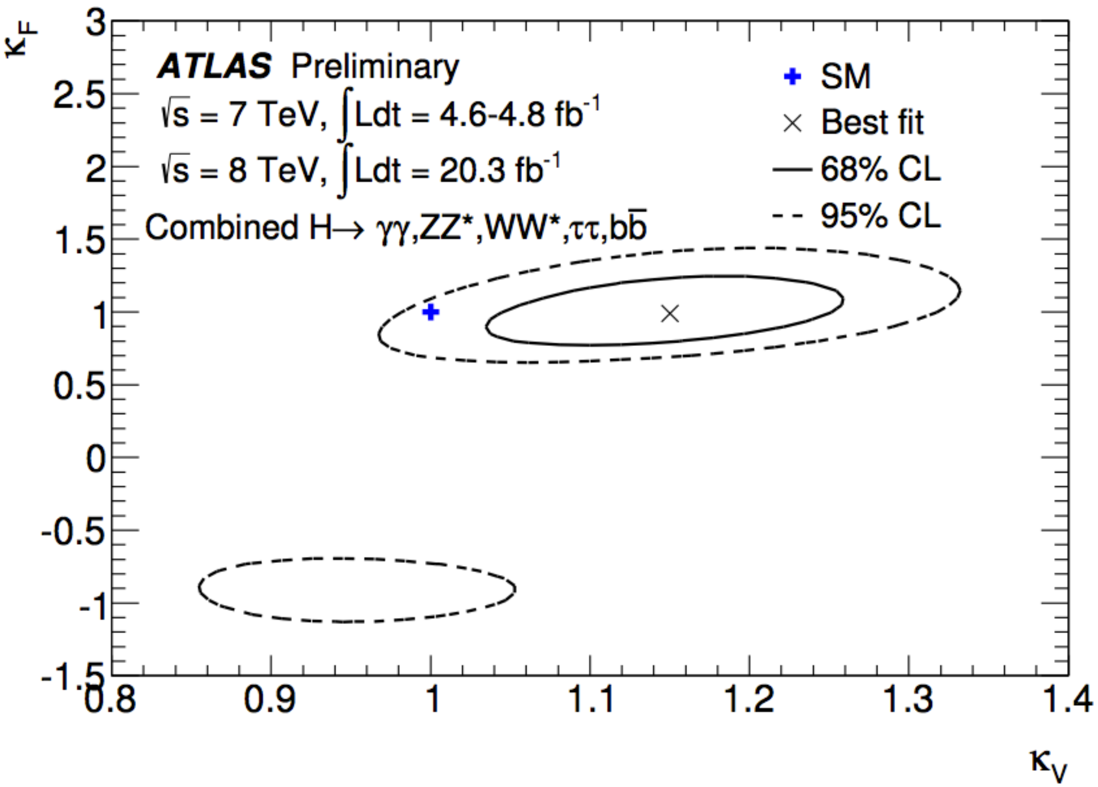


This would flip the interference
in the W/top decay loop in $\gamma\gamma$
Not favoured by data $\gamma\gamma$

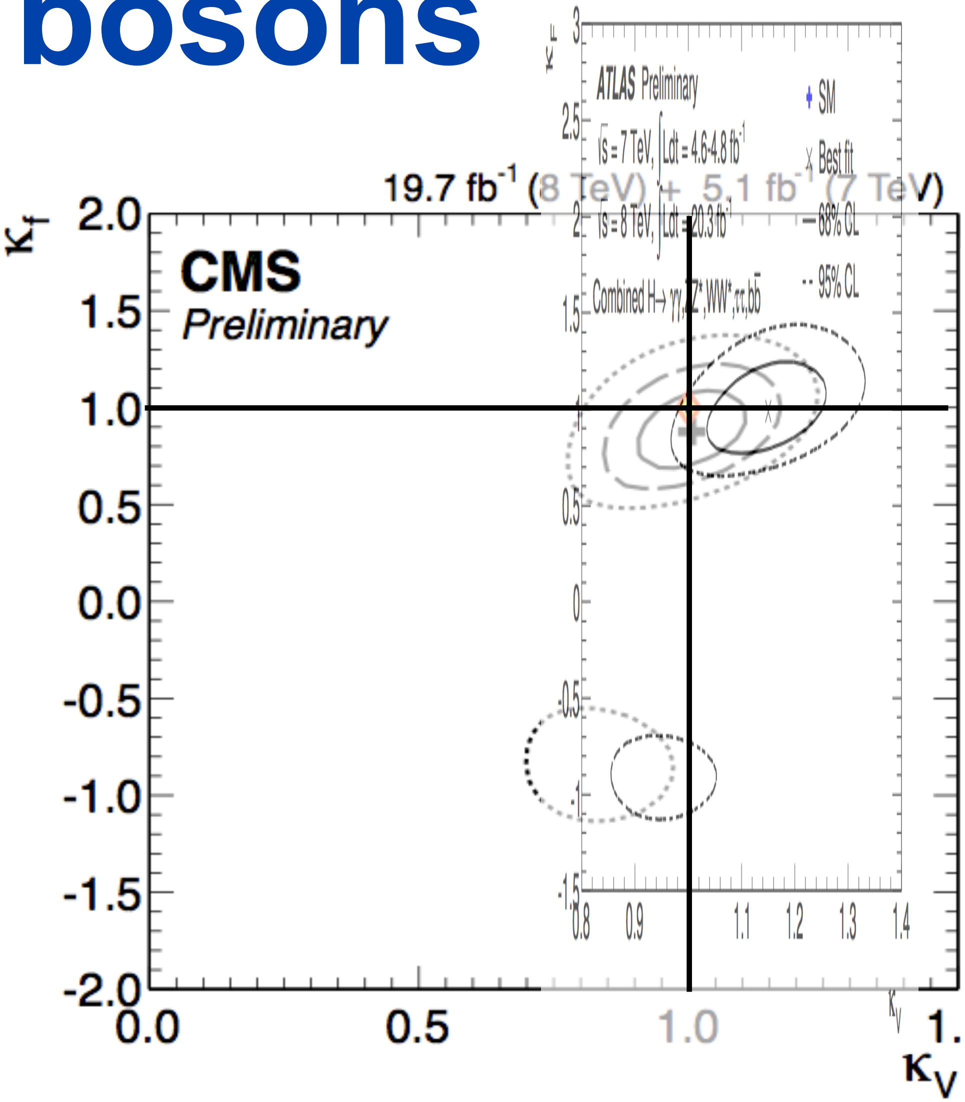
Constraint to be both positive:
the contour is slightly different

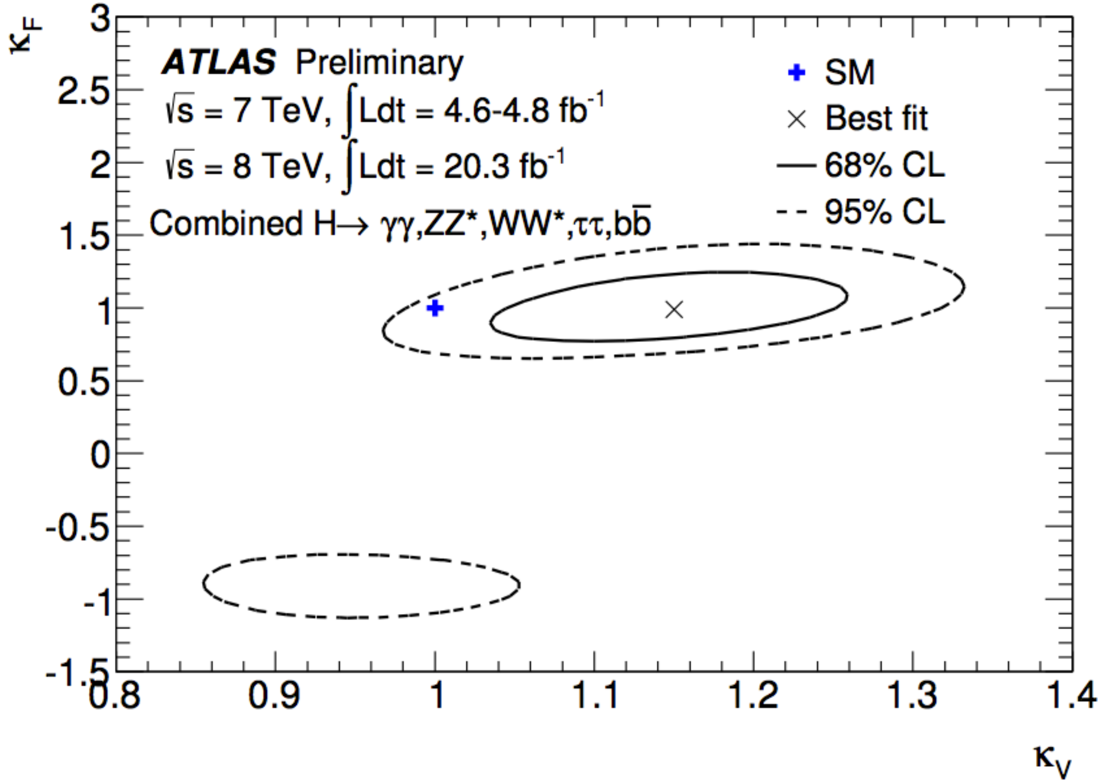
Couplings to fermions and bosons



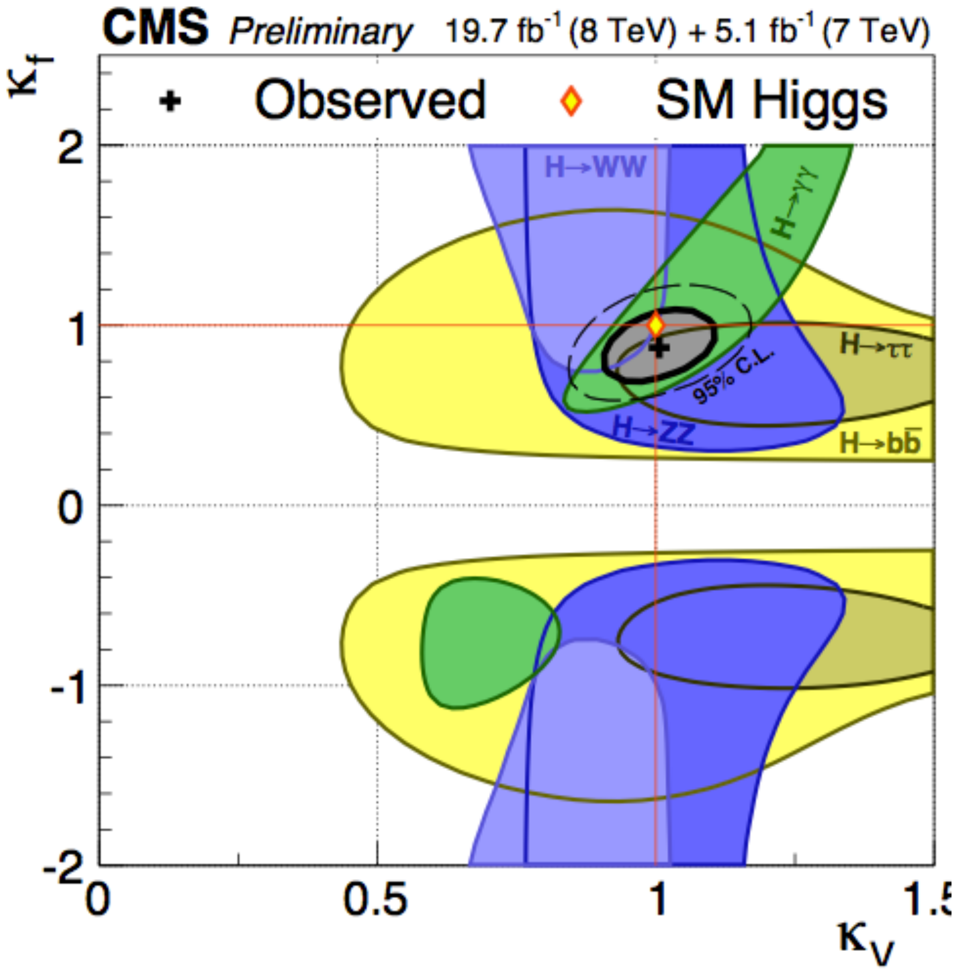


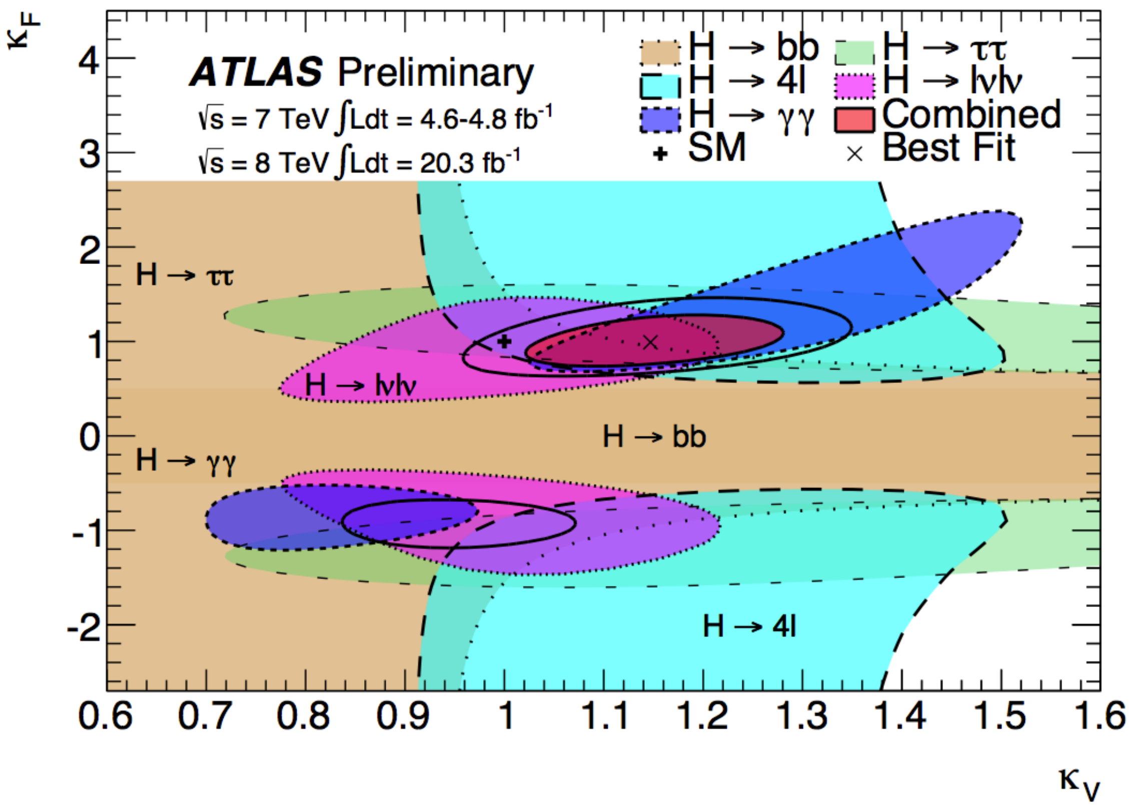
Couplings to fermions and bosons





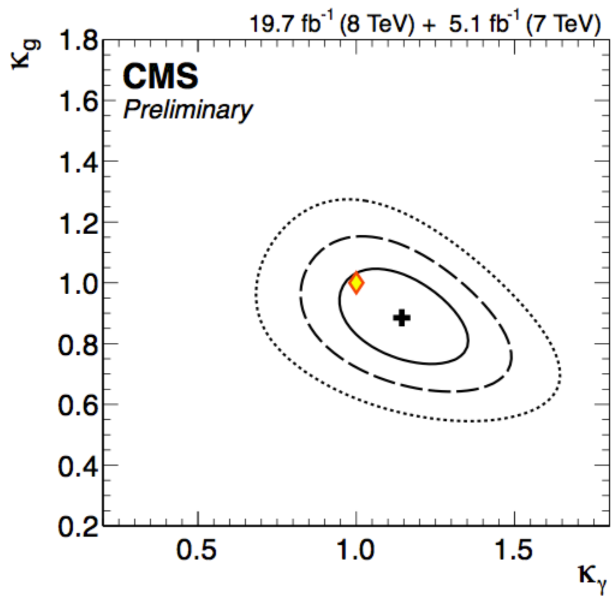
Couplings to fermions and bosons

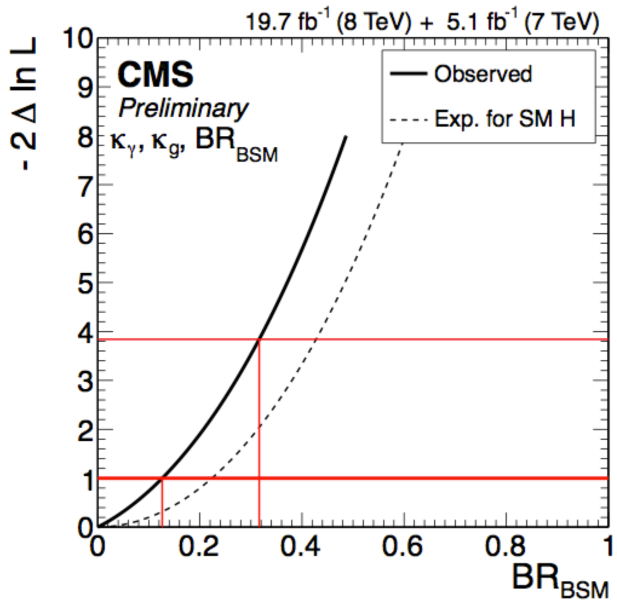


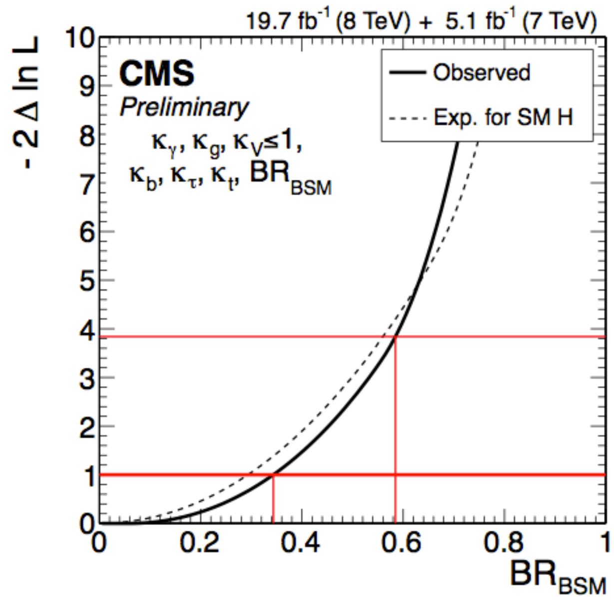


Test for BSM physics

Processes with loops: ggH H$\gamma\gamma$ (fit the modifier without resolving the loop)







Assume $\Gamma_{\mathrm{BSM}} = 0$

$$(\sigma \cdot \mathcal{B})\,(x \to \mathrm{H} \to ff) = \frac{\sigma_x \cdot \Gamma_{ff}}{\Gamma_{\mathrm{tot}}}$$

i.e. $\Gamma_{\mathrm{tot}} = \sum \Gamma_{ff}$

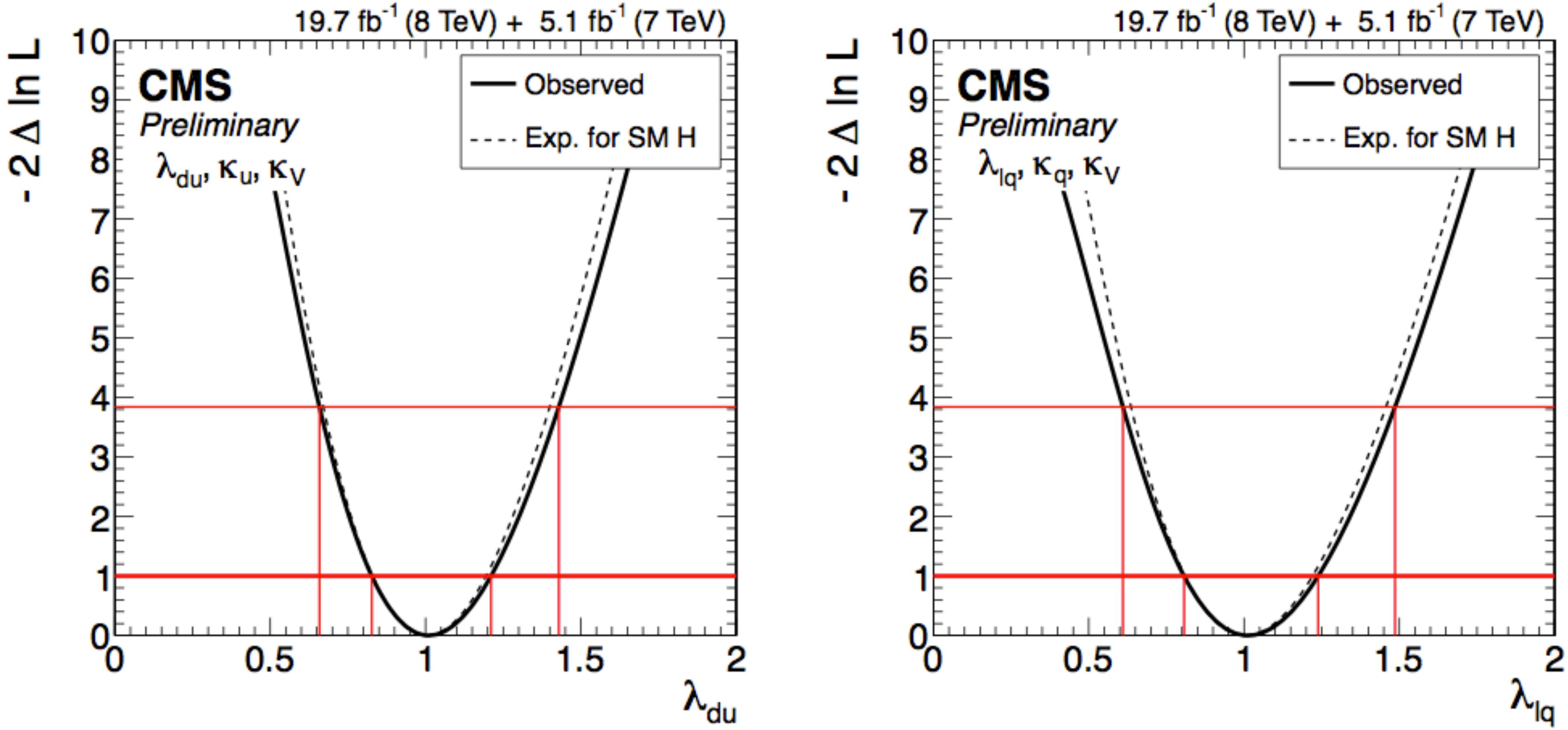
Profile κ_γ, κ_g,
leave all the tree level as SM
and scan $\mathrm{BR_{BSM}}$

all modifiers profiled
only $\kappa_V \leq 1$

$\mathrm{BR_{BSM}}$ in [0,0.32] at 95% CL

$\mathrm{BR_{BSM}}$ in [0,0.58] at 95% CL

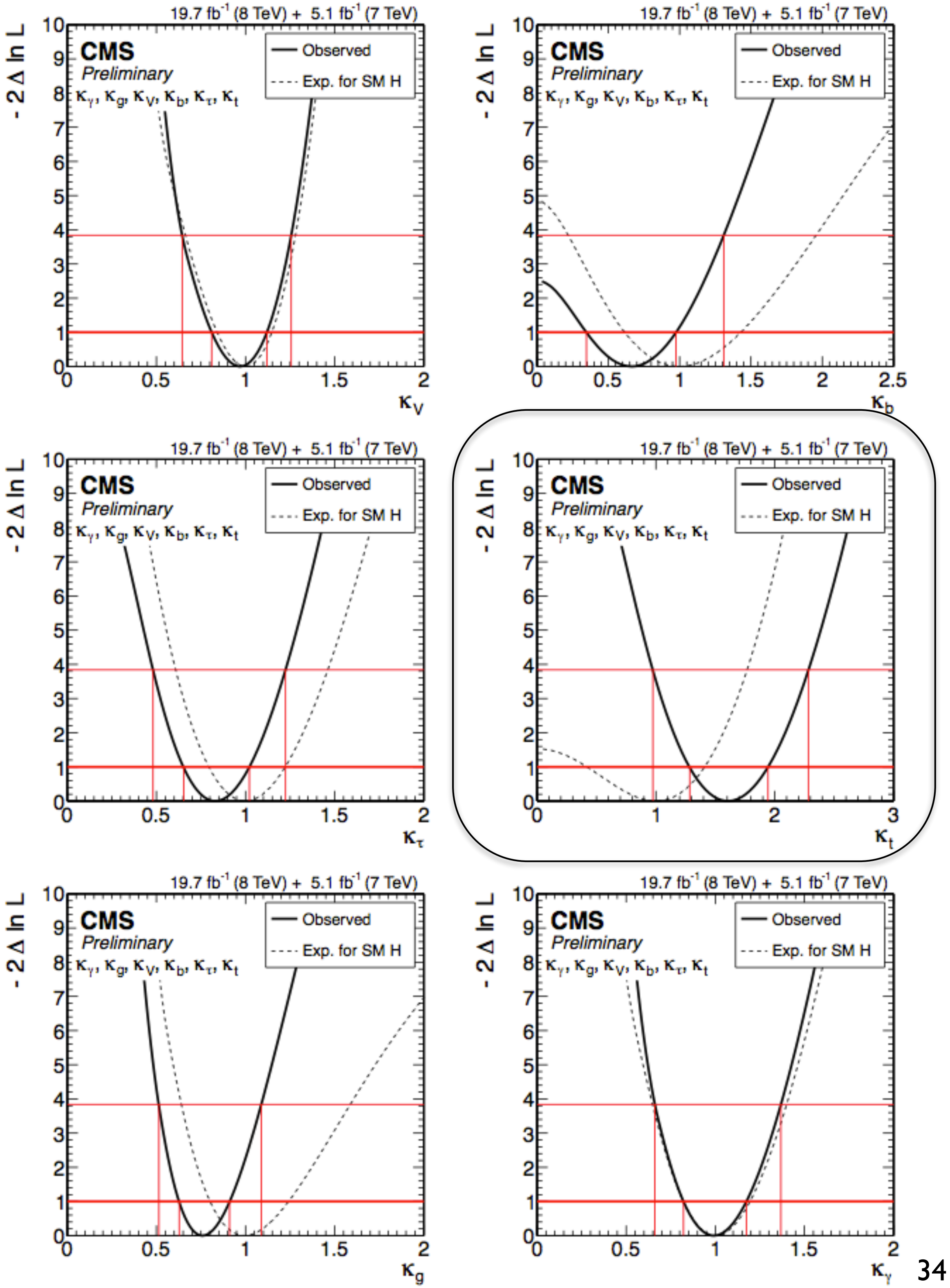
lepton/quark - u-type/d-type asymmetries



Six scaling factors

- W and Z bosons scaled by a common factor κ_V;
- third generation fermions scaled independently by κ_t, κ_b, and κ_τ;
- first and second generation fermions are equal to those for the third;
- gluons and photons, induced by loop diagrams, are given independent scaling factors κ_g and κ_γ,
- Γ_{BSM} = zero

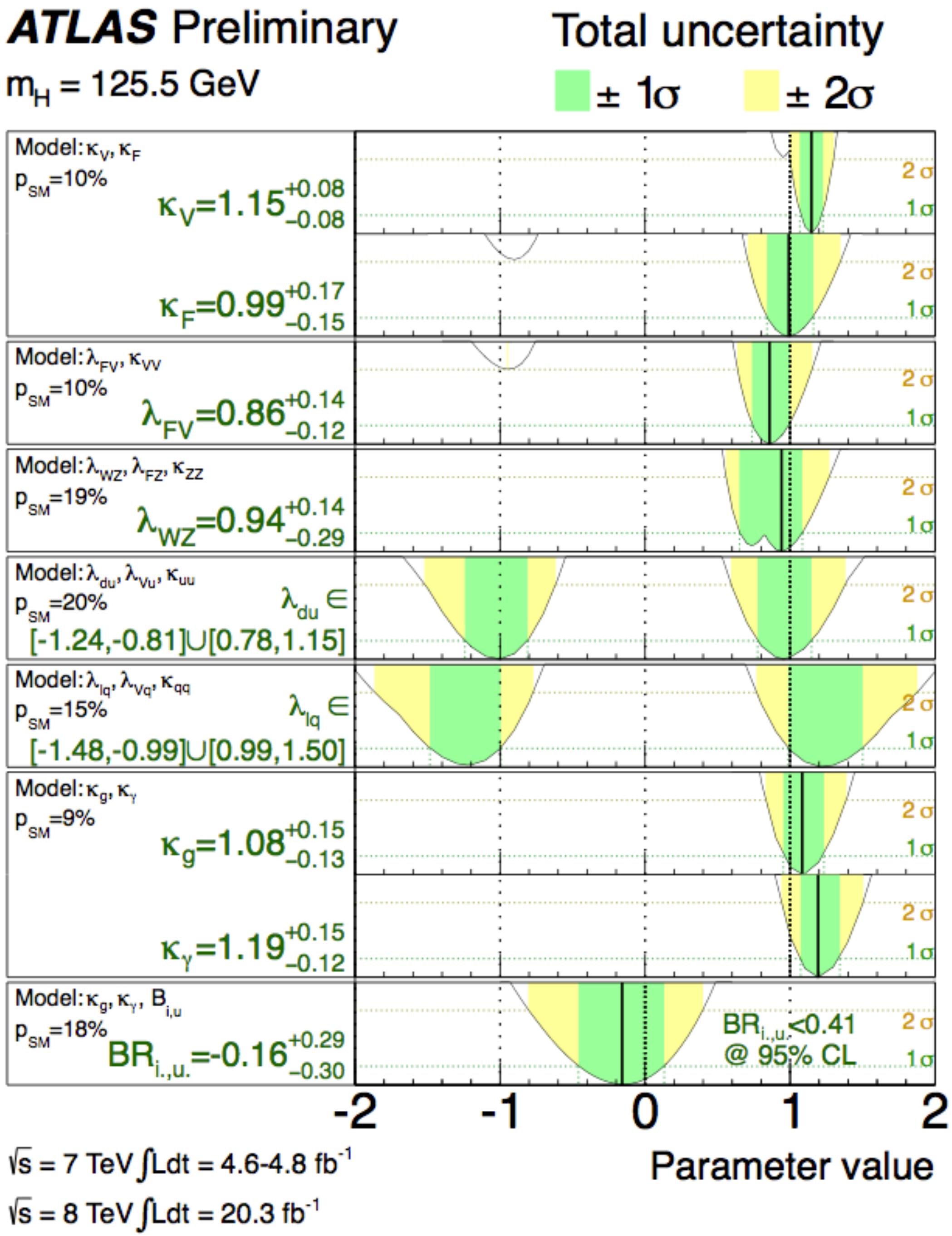
The maximum number of parameters you can fit (valid for ANY fit) depends on how much statistics you have



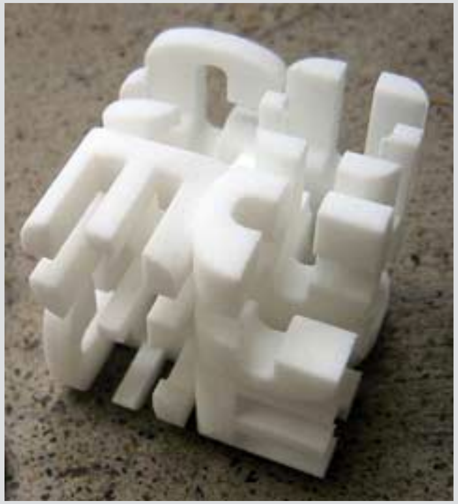
Compatibility summary CMS

Model Parameters	Best-fit result Parameter	68% CL	95% CL	Comment
κ_Z, λ_{WZ} (κ_f =1)	λ_{WZ}	$0.94^{+0.22}_{-0.18}$	[0.61,1.45]	$\lambda_{WZ} = \kappa_W/\kappa_Z$ using ZZ and 0/1-jet WW channels.
$\kappa_Z, \lambda_{WZ}, \kappa_f$	λ_{WZ}	$0.91^{+0.14}_{-0.12}$	[0.70,1.22]	$\lambda_{WZ} = \kappa_W/\kappa_Z$ from full combination.
κ_V, κ_f	κ_V	$1.01^{+0.07}_{-0.07}$	[0.88,1.15]	κ_V scales couplings to W and Z bosons.
	κ_f	$0.89^{+0.14}_{-0.13}$	[0.64,1.16]	κ_f scales couplings to all fermions.
κ_g, κ_γ	κ_g	$0.89^{+0.10}_{-0.10}$	[0.69,1.10]	Effective couplings to gluons (g) and photons (γ).
	κ_γ	$1.15^{+0.13}_{-0.13}$	[0.89,1.42]	
$\kappa_g, \kappa_\gamma, BR_{BSM}$	BR_{BSM}	≤ 0.13	[0.00,0.32]	Branching fraction for BSM decays.
$\kappa_V, \lambda_{du}, \kappa_u$	λ_{du}	$1.01^{+0.20}_{-0.19}$	[0.66,1.43]	$\lambda_{du} = \kappa_u/\kappa_d$, relating up-type and down-type fermions.
$\kappa_V, \lambda_{\ell q}, \kappa_q$	$\lambda_{\ell q}$	$1.02^{+0.22}_{-0.21}$	[0.61,1.49]	$\lambda_{\ell q} = \kappa_\ell/\kappa_q$, relating leptons and quarks.
$\kappa_g, \kappa_\gamma, \kappa_V,$ $\kappa_b, \kappa_\tau, \kappa_t$	κ_g	$0.76^{+0.15}_{-0.13}$	[0.51,1.09]	
	κ_γ	$0.99^{+0.18}_{-0.17}$	[0.66,1.37]	
	κ_V	$0.97^{+0.15}_{-0.16}$	[0.64,1.26]	
	κ_b	$0.67^{+0.31}_{-0.32}$	[0.00,1.31]	Down-type quarks (via b).
	κ_τ	$0.83^{+0.19}_{-0.18}$	[0.48,1.22]	Charged leptons (via τ).
	κ_t	$1.61^{+0.33}_{-0.32}$	[0.97,2.28]	Up-type quarks (via t).
as above plus BR_{BSM} and $\kappa_V \leq 1$	BR_{BSM}	≤ 0.34	[0.00,0.58]	

Compatibility summary ATLAS



i.u. = invisible undetected



Differential measurements

Differential cross sections

Begin to dissect the Higgs boson, measure the differential production cross section.
Still largely dominated by statistical uncertainties, but a good preparatory exercise for Run 2.

Final goal combine the fits of the coupling modifiers with the full kinematics information.

exe: pT spectrum constrains the operators with derivative of the field.
=>Multiply the combination likelihood with likelihood that fits the pT

$\boxed{\begin{array}{c} p_{\mathrm{T}}^{\gamma\gamma} \\ |y_{\gamma\gamma}| \end{array}}$ perturbative-QCD modelling ggF (dominant) gluon fusion production mechanism and PDFs

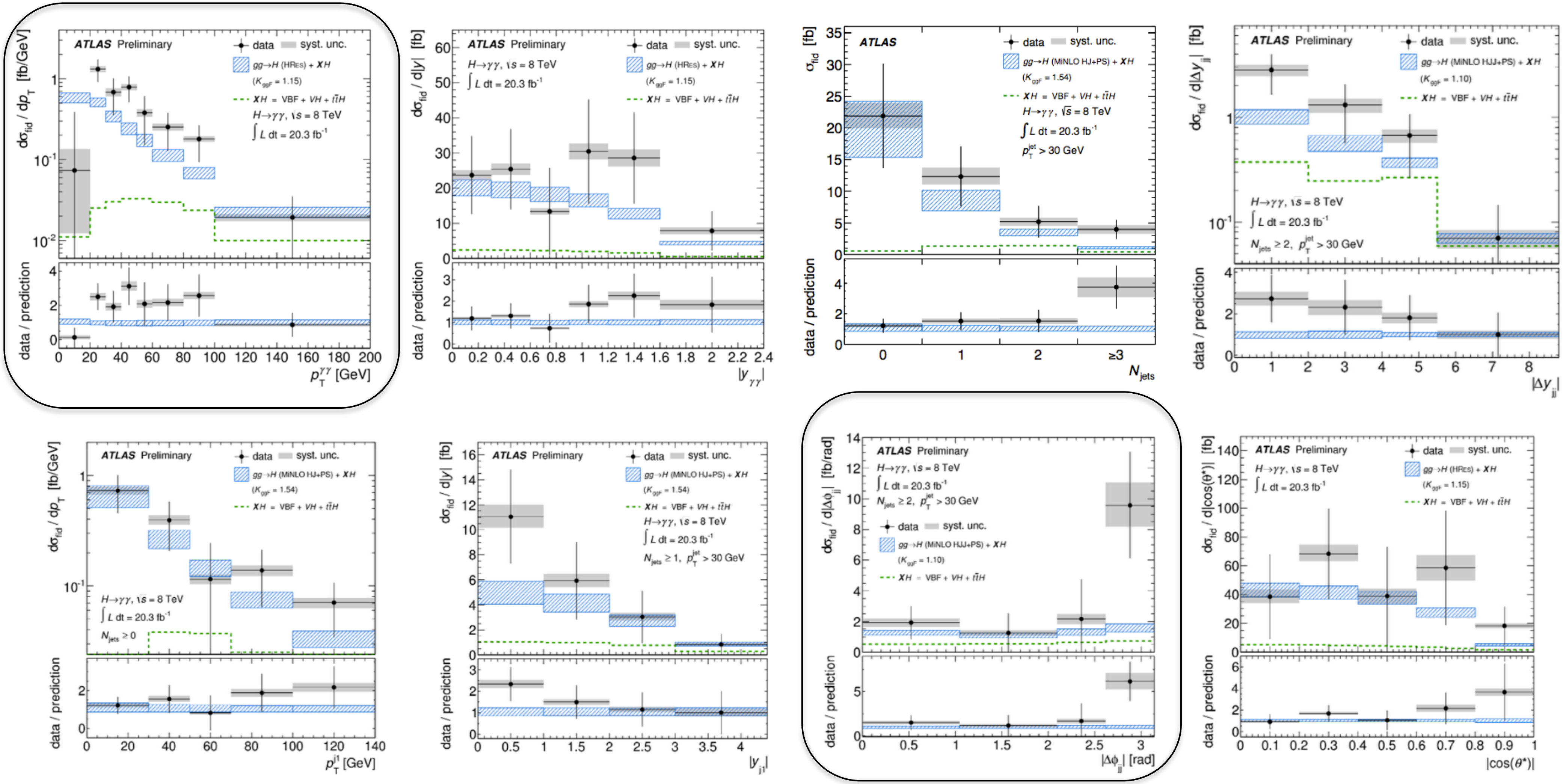
$\boxed{\begin{array}{cc} p_{\mathrm{T}}^{j_1} & |y_{j_1}| \\ p_{\mathrm{T}}^{j_2} & H_{\mathrm{T}} \\ |\Delta y_{jj}| & |\Delta\phi_{\gamma\gamma,jj}| \end{array}}$ production mechanisms

$\boxed{|\cos\theta^*| \; |\Delta\phi_{jj}|}$ spin/CP

cos(θ*) cosine of the angle between the beam axis and the photons in the Collins–Soper frame of the Higgs boson

Differential H→γγ

$$\mathcal{L}(m_{\gamma\gamma}, \nu^{\mathrm{sig}}, \nu^{\mathrm{bkg}}, m_H) = \prod_i \left\{ \frac{e^{-\nu_i}}{n_i!} \prod_j^{n_i} \left[\nu_i^{\mathrm{sig}} \mathcal{S}_i(m_{\gamma\gamma}^j; m_H) + \nu_i^{\mathrm{bkg}} \mathcal{B}_i(m_{\gamma\gamma}^j) \right] \right\} \times \prod_k G_k$$



sensitive to CP

$$A_{\Delta\phi} = 0.72\,^{+0.23}_{-0.29}\,(\mathrm{stat.})\,^{+0.01}_{-0.02}\,(\mathrm{syst.})$$

$$A_{\Delta\phi}^{\mathrm{SM}} = 0.43 \pm 0.02$$

Differential H→ZZ

Handful of events !

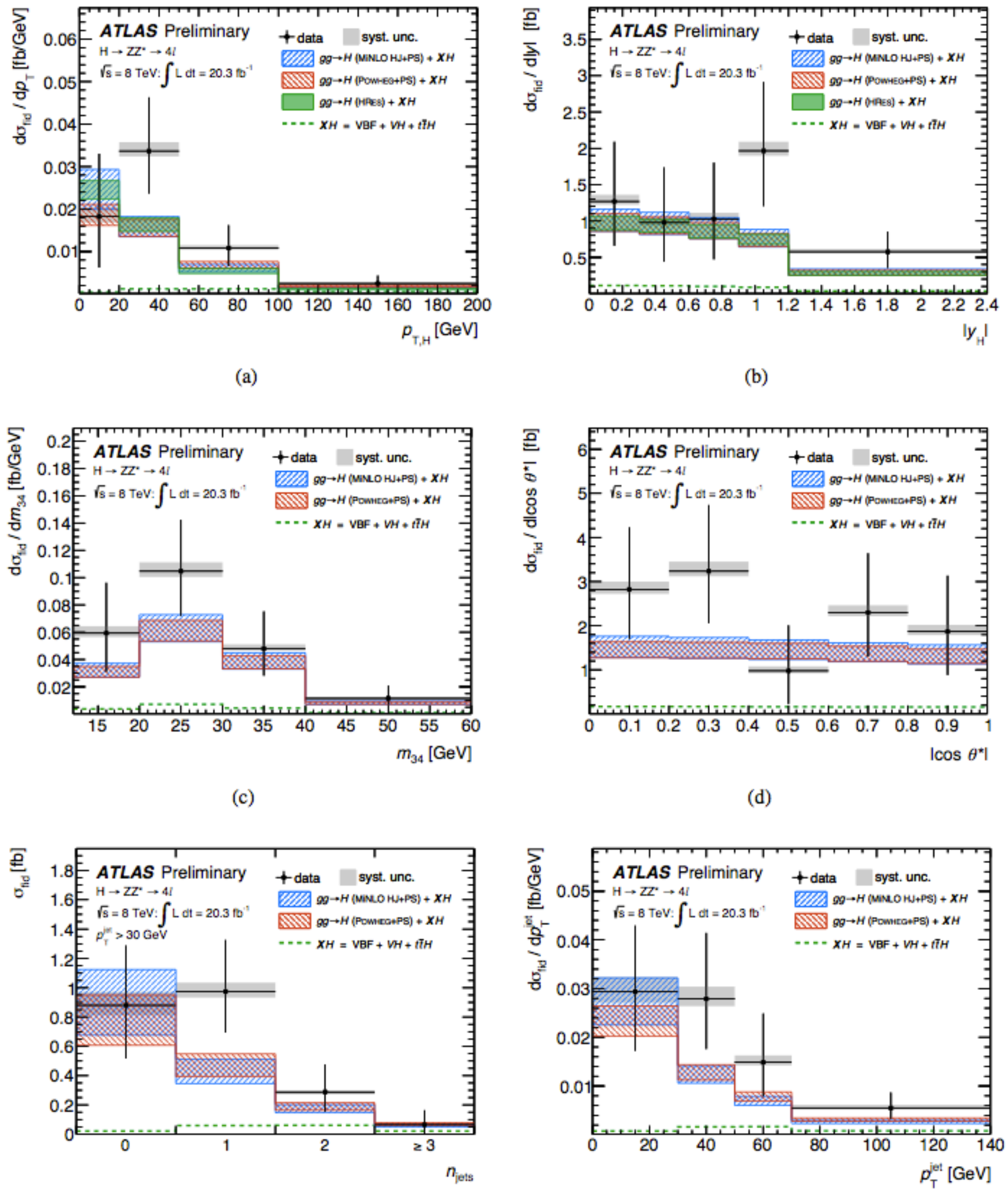
Fiducial region defined on bare leptons
(i.e. no final state radiation added - dressed), difference ~0.5%
muons (electrons) p_T > 6 (7) GeV
|η| < 2.7 (2.47)

@ 125.4GeV

$$\sigma^{\text{fid}}_{\text{tot}} = 2.11^{+0.53}_{-0.47}(\text{stat})^{+0.08}_{-0.08}(\text{syst})\ \text{fb}$$

$$\sigma_{SM} = 1.30 \pm 0.13\ \text{fb}$$

all p-values ~30%



(a) (b) (c) (d) (e) (f)

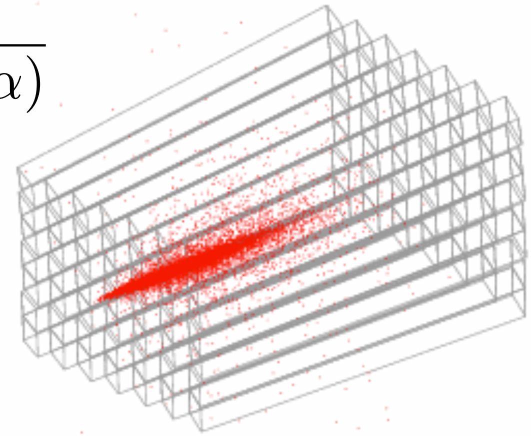
Mass measurements

H→γγ CMS

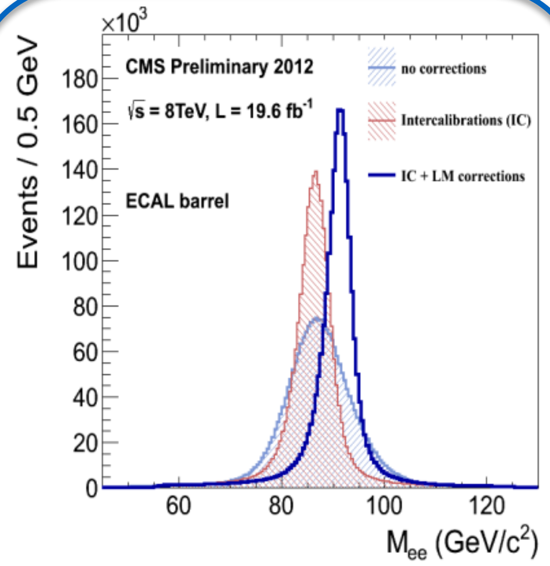
$$m_{\gamma\gamma} = \sqrt{2E_1E_2(1-\cos\alpha)}$$

It's all about energy calibrations
It's all about how well you know your detector

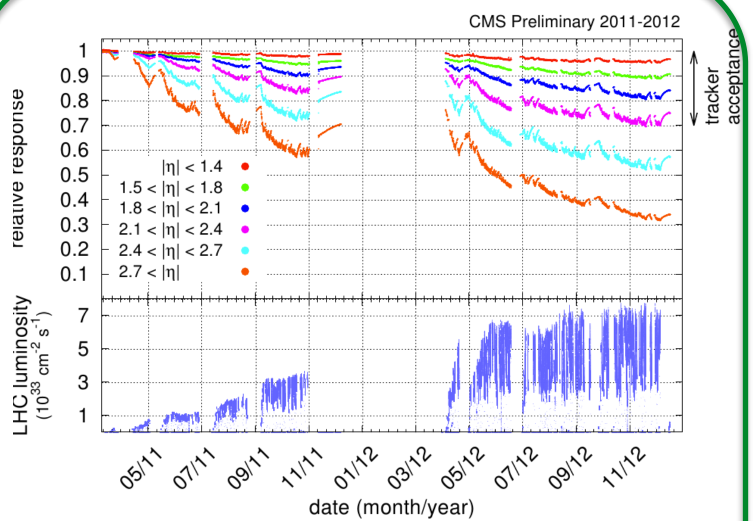
electromagnetic shower



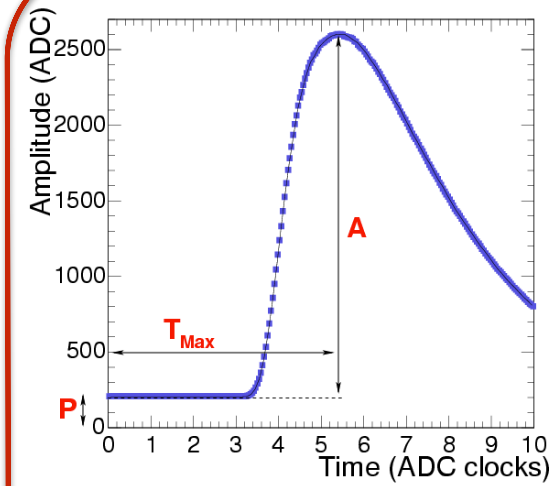
$$\tilde{E}_{SuperCluster} = \sum_{xtal} [\boxed{IC_{xtal}} \cdot \boxed{LC_{xtal}(t)} \cdot \boxed{A_{xtal}}]$$



InterCalibrations flatten the response of ECAL vs eta/phi



crystal transparency changes during the LHC run
Measured every 20 minutes



electronics pulse from an ECAL channel

The final energy correction is obtained through a regression BDT using as input several shower shapes variables and information about the pileup in the event (ρ, #vtx)
Finally: the energy scale of the data is set to MC the resolution of the MC is set on data on Zee

 …but these are electrons! No high mass usable diphoton resonance yet…

H→γγ CMS

Source of uncertainty	Uncertainty in $\hat{m}_H$ (GeV)
Imperfect simulation of electron-photon differences	0.10
Linearity of the energy scale	0.10
Energy scale calibration and resolution	0.05
Other	0.04
All systematic uncertainties in the signal model	0.15
Statistical	0.31
Total	0.34

BOOST 90 → 125 (high pT Z)

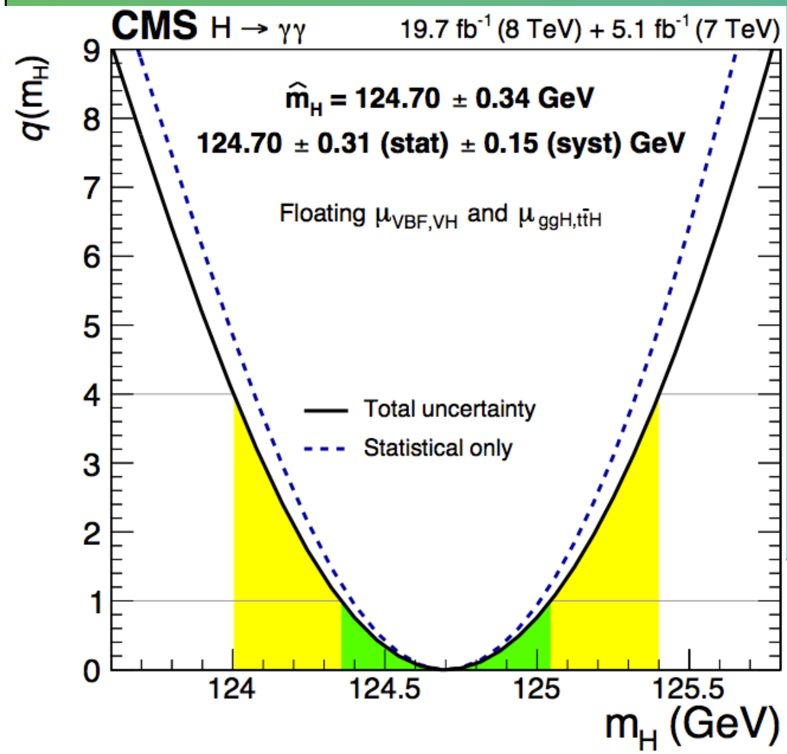
Z→ee
- Z-scale energy
- Electrons

Systematics:
- energy scale/resolution
- ±50 MeV

H→ee
- H-scale energy
- Electrons

Systematics:
- Non-linearity
- ±100 MeV

ELECTRONS → PHOTONS (MC)



H→γγ
- H-scale energy
- Photons

Systematics:
- Electron/photon differences
- ±100 MeV

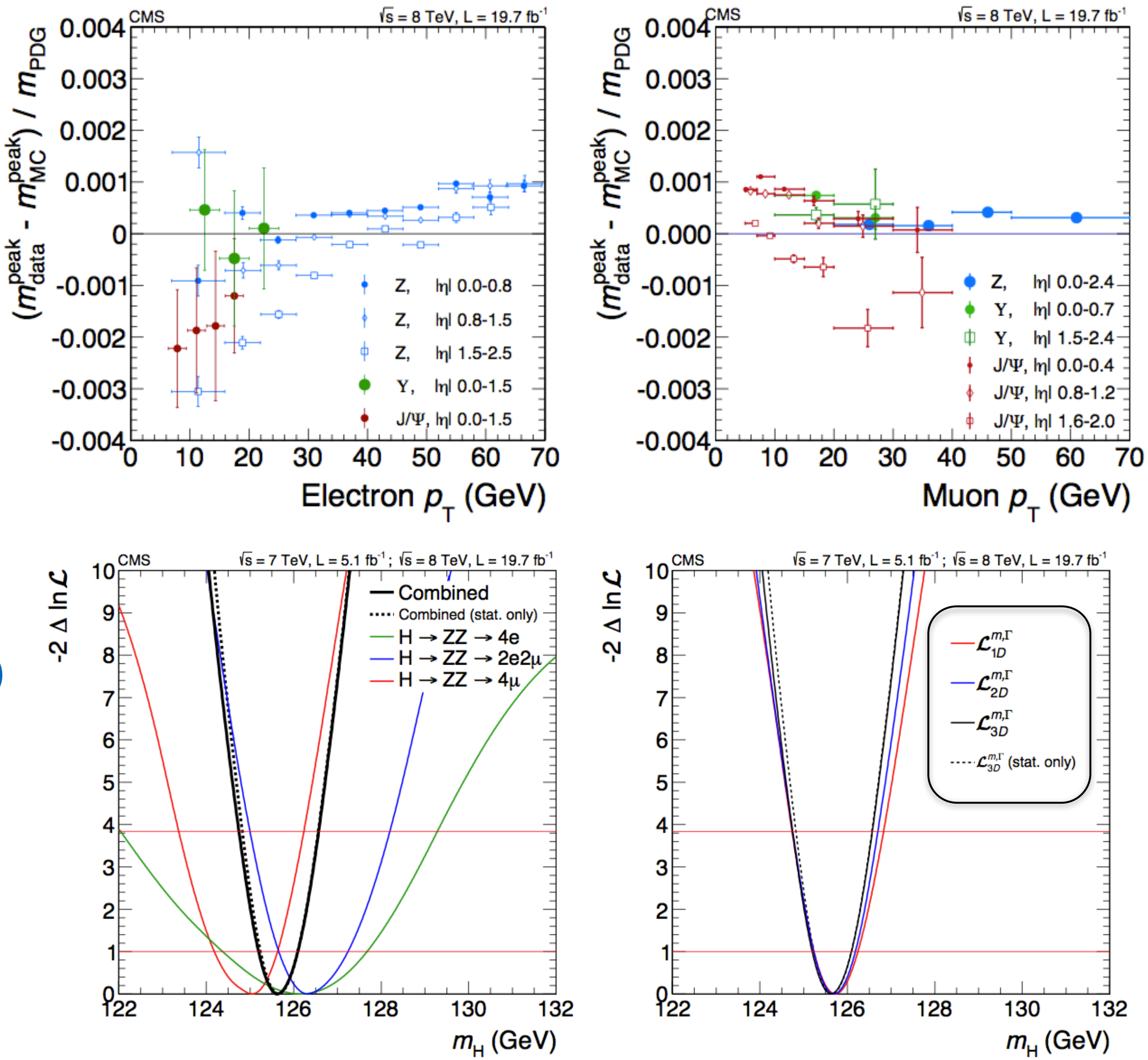
Get the statistical uncertainty by fixing the nuisance to their best values

H→ZZ CMS

Electrons MVA
(use ECAL and tracker info)

Scale data, smear MC

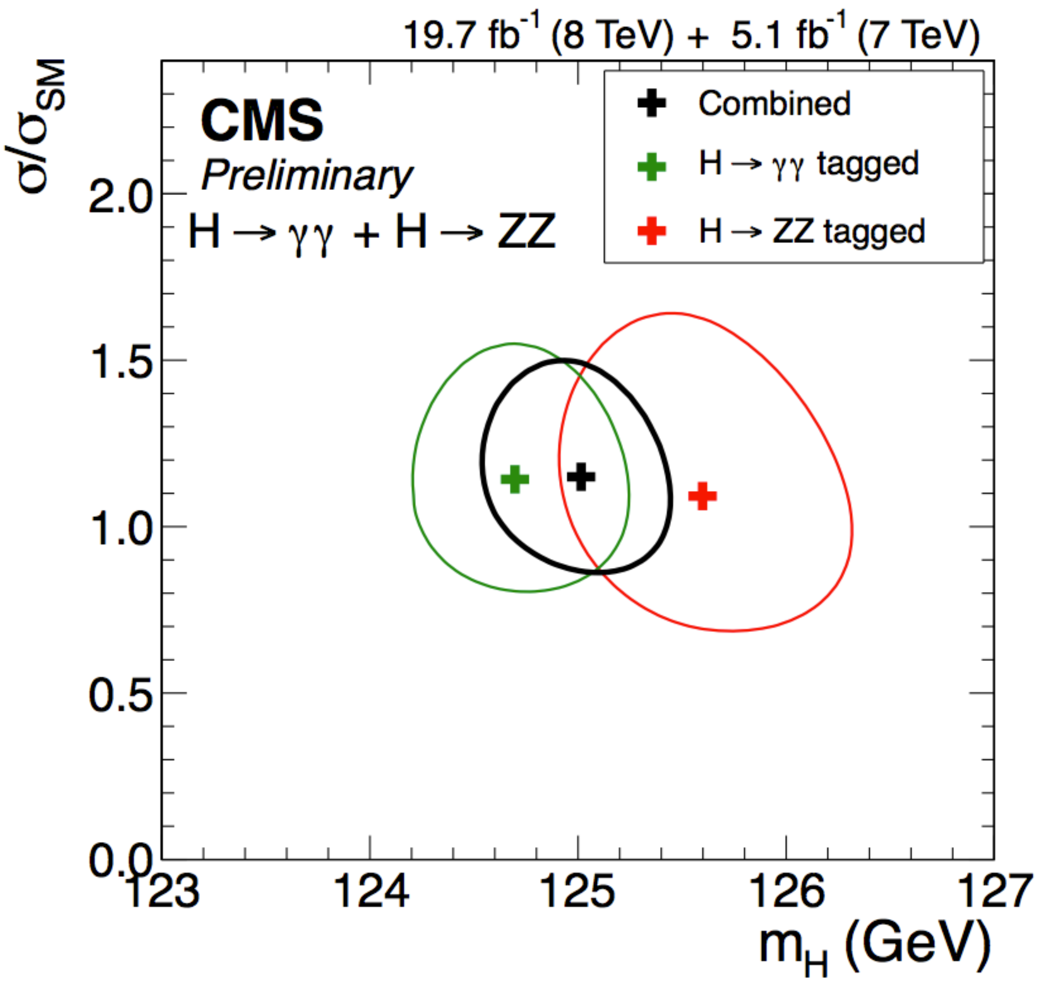
Muons
(multiple scattering in the tracker)

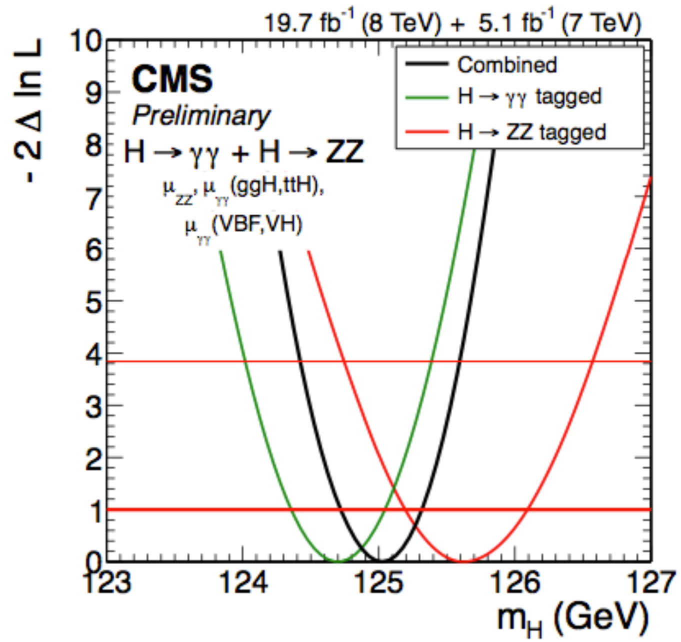


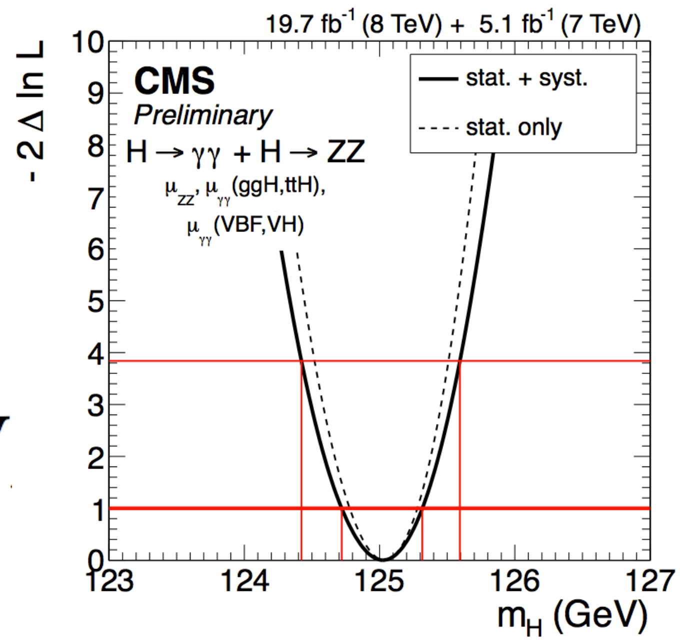
$$m_{\mathrm{H}} = 125.6 \pm 0.4\,(\mathrm{stat.}) \pm 0.2\,(\mathrm{syst.})\ \mathrm{GeV}$$

CMS combined mass

(~1.6σ difference)

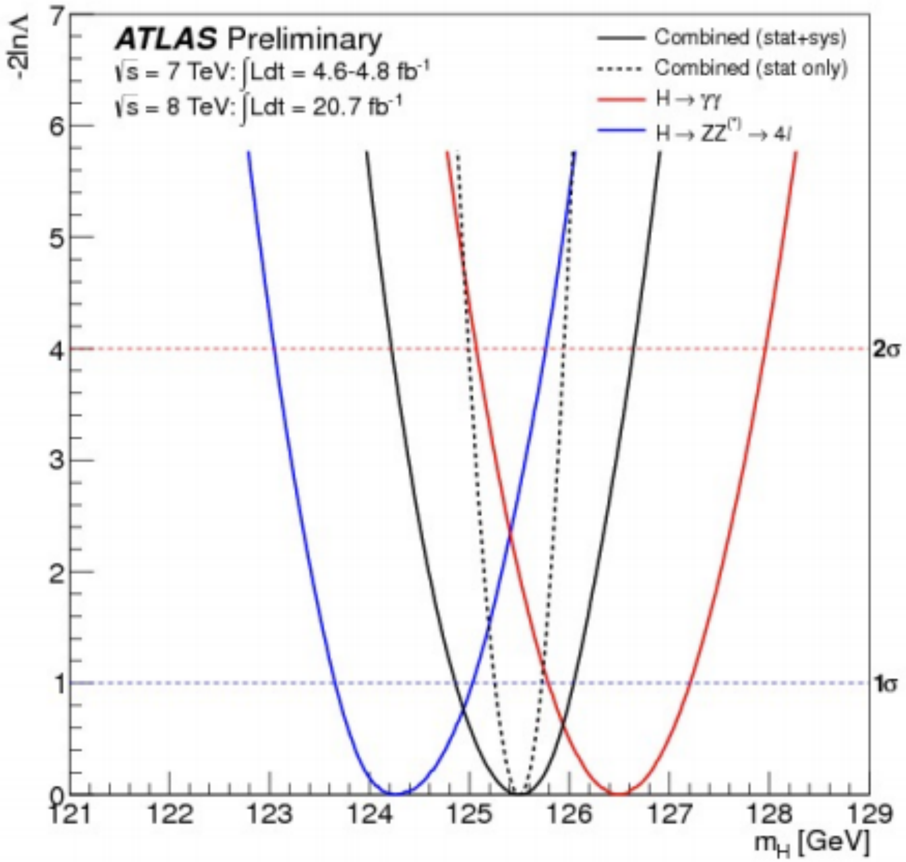


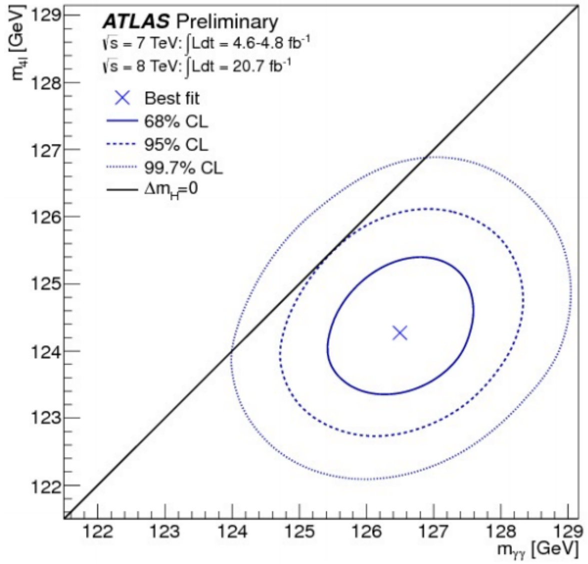


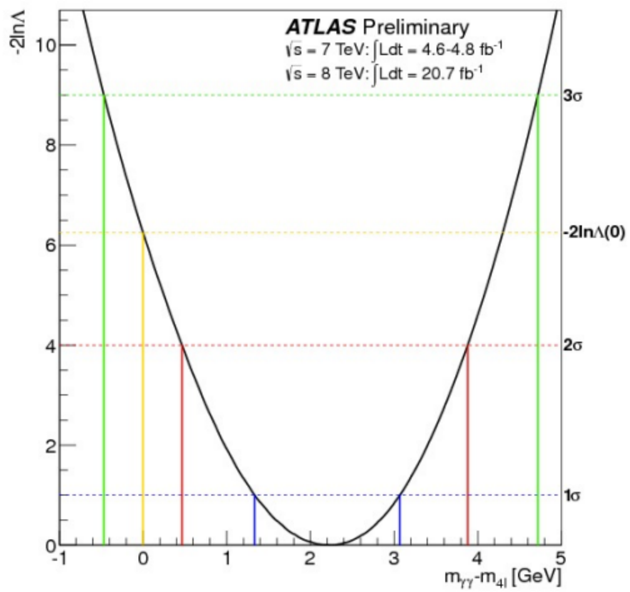


$$125.03\ ^{+0.26}_{-0.27}\ (\text{stat.})\ ^{+0.13}_{-0.15}\ (\text{syst.})\ \text{GeV}$$

ATLAS mass old results







Statistical fluctuation or systematic effect ?

$H\to\gamma\gamma$ 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV

$H\to ZZ$ 124.3 $^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (syst) GeV

combined = 125.5 ± 0.2 (stat) $^{+0.5}_{-0.6}$ (sys) GeV

$\Delta m_H = 2.3\ ^{+0.6}_{-0.7}$ (stat) ± 0.6 (sys) GeV

2.4 σ from $\Delta m_H = 0$ (p = 1.5%)

$H\to\gamma\gamma$ ATLAS

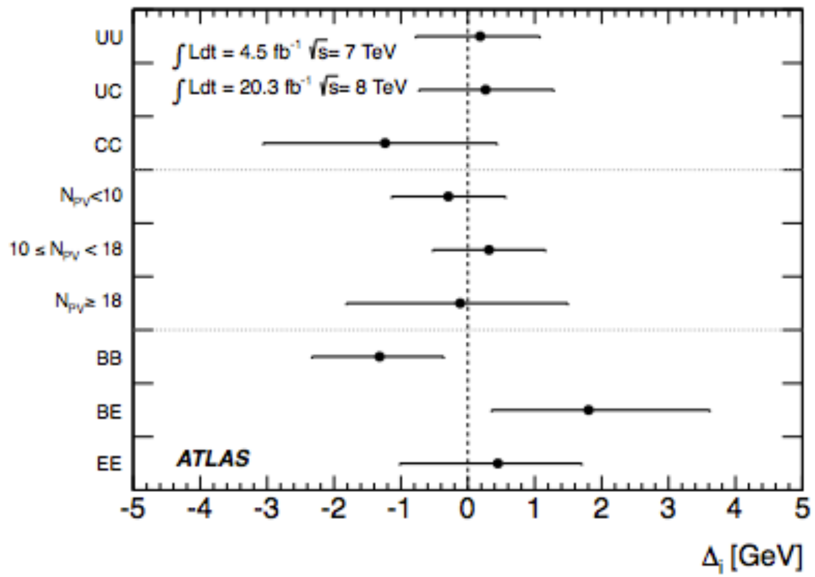
Huge amount of work went in the electron/photon calibration:

- use a BDT energy regression
- new inter calibration EM layers 1,2 with muons
- new tracker material description
- new assessment of EM calorimeter stability
- new energy/resolution calibrations from Zee

Systematic uncertainties reduced by 2.5

And on the analysis side:

- new bkg modelling
- new categorisation



E = endcap
B = barrel
U = unconverted
C = converted
Npv = # primary vtx (Pile Up)

old: 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV

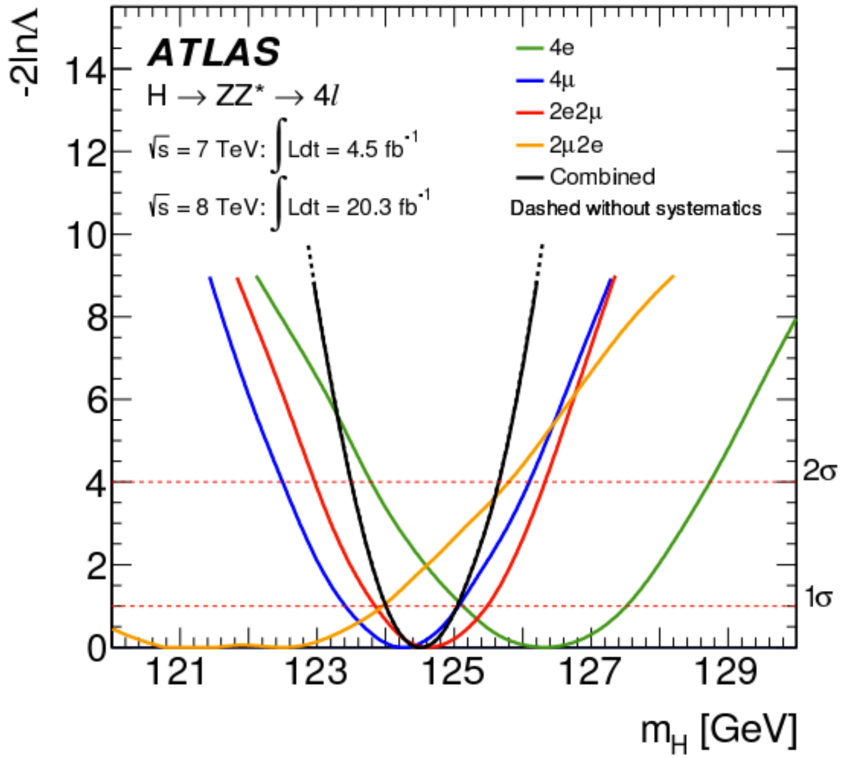
mH = 125.98 ± 0.42(stat) ± 0.28(sys) GeV
= 125.98 ± 0.50 GeV (μ = 1.29 ± 0.30)

H→ZZ ATLAS

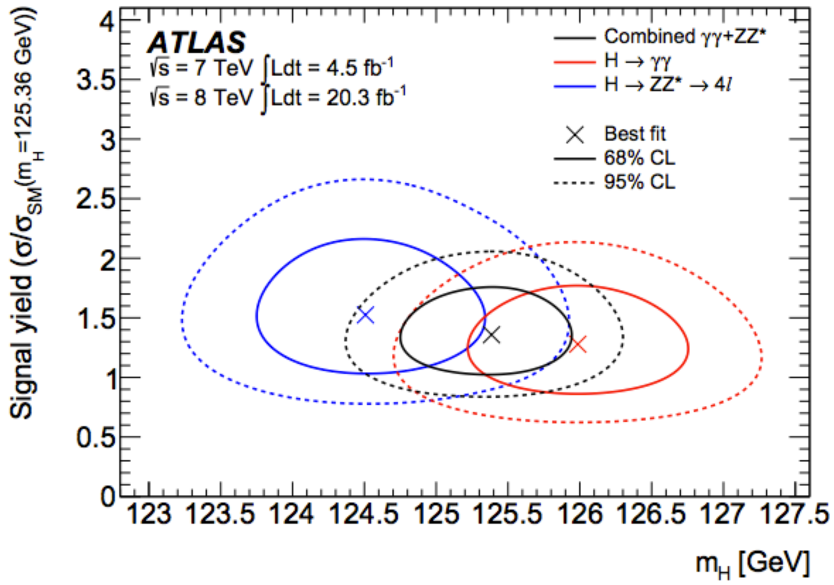
New electron ID (BDT)
(new EM calibrations)
new BDT to separate ZZ from bkg
new muon pT corrections
Total systematic uncertainty down by ~6

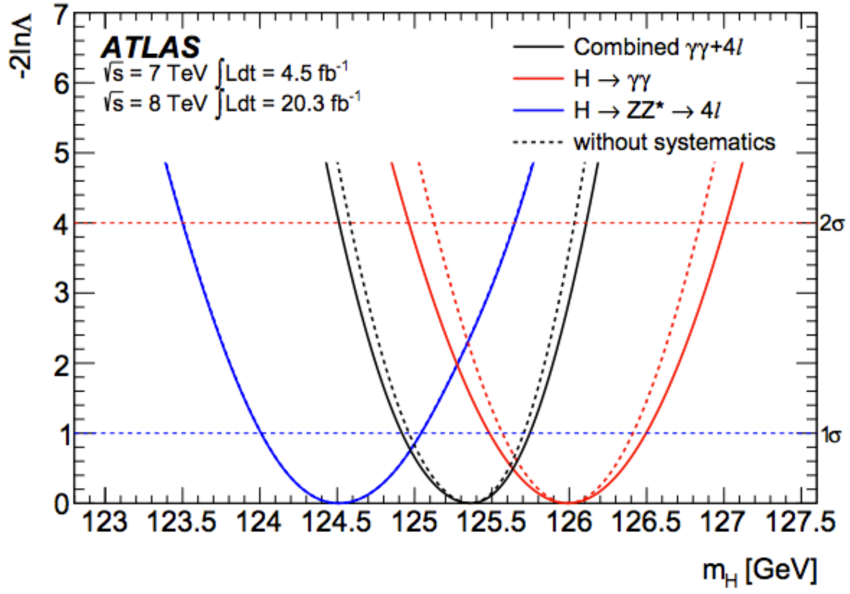
old: H→ZZ 124.3 $^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (syst) GeV

$$m_H = 124.51 \pm 0.52(\text{stat}) \pm 0.06(\text{sys})\ \text{GeV}$$
$$= 124.51 \pm 0.52\ \text{GeV} \quad (\mu = 1.66^{+0.45}_{-0.38})$$



ATLAS combined mass





combined = 125.5 ± 0.2 (stat) $^{+0.5}_{-0.6}$ (sys) GeV

mH = 125.36 ± 0.37(stat) ± 0.18(sys) GeV
= 125.36 ± 0.41 GeV

Total uncertainty reduced by ~ 40%
Systematic uncertainties reduced by factor ~ 3
Compatibility between channels:
2.0σ (4.8%) for observed μ_{4l} and $\mu_{\gamma\gamma}$,
1.6σ for μ = 1 (previous compatibility 2.5σ)

Width measurements

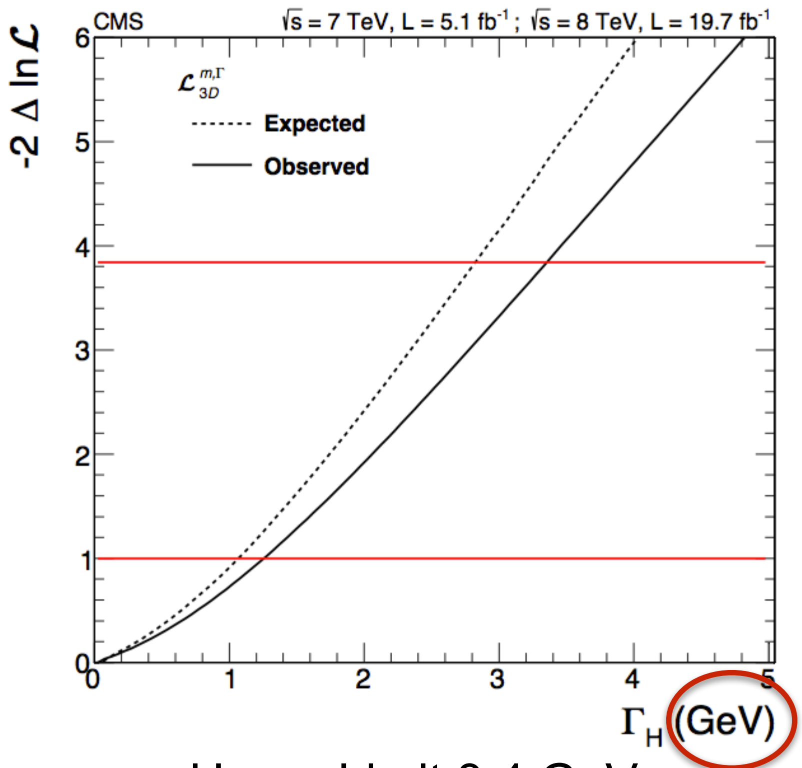
Direct measurement

SM width ~4 MeV

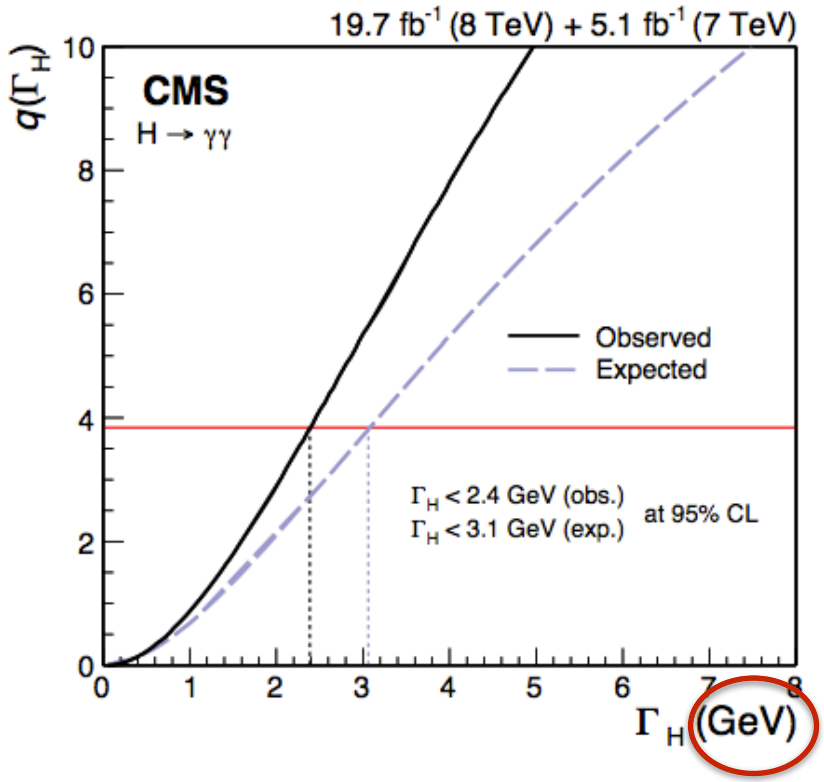
Strongly limited by the mass (energy/momentum) resolution of the detector

Scanning the $\gamma\gamma$, ZZ(3D) likelihood vs. the width parameter

$$\Gamma_H = 0.0^{+1.3}_{-0.0}\,\mathrm{GeV}$$



Upper Limit 3.4 GeV
(exp 2.8 GeV)



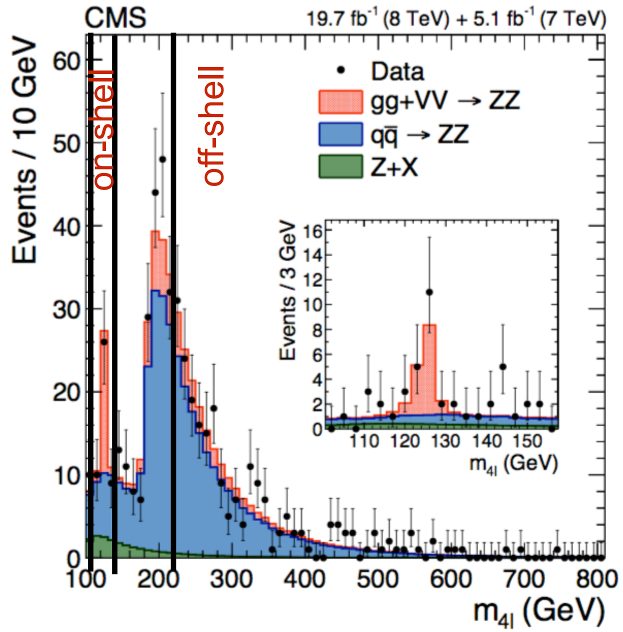
off-shell ZZ production: method

The assumption behind “production cross section are compatible with the SM”, is that width is the SM one. You can get the same cross sections by rescaling simultaneously couplings and width:

Caola-Melnikov 1307.4935

$$i \to H \to f \qquad \sigma_{i\to H\to f} \sim \frac{g_i^2 g_f^2}{\Gamma_H}$$

In general: $$\frac{d\sigma_{pp\to H\to ZZ}}{dM_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$



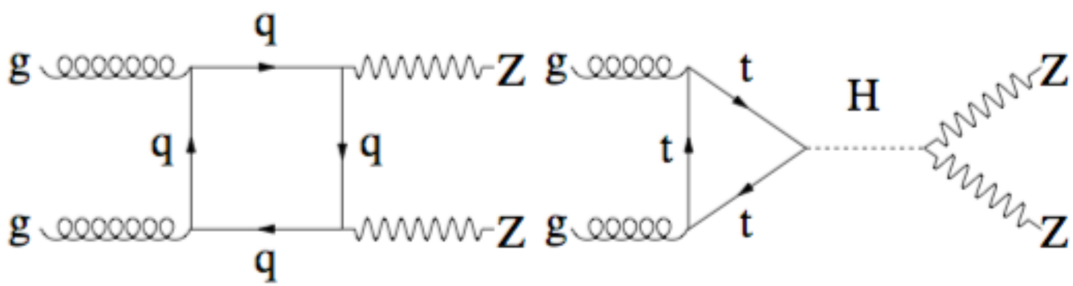
Away from the peak it becomes independent from the width

Important to estimate correctly the k-factors !

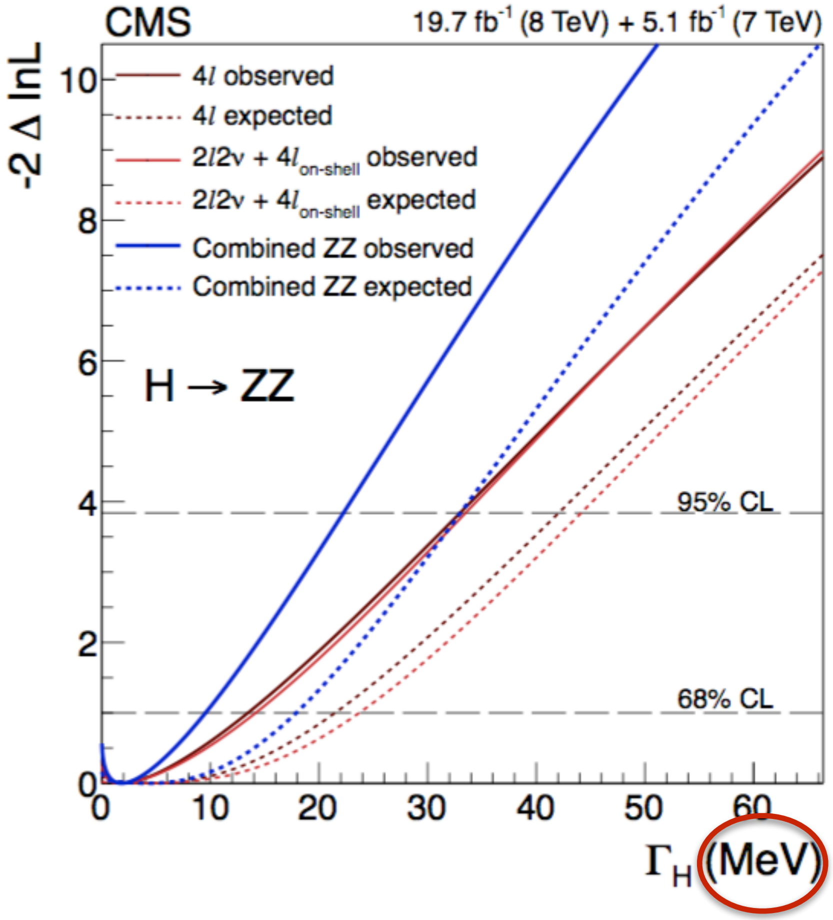
Off peak contributions:

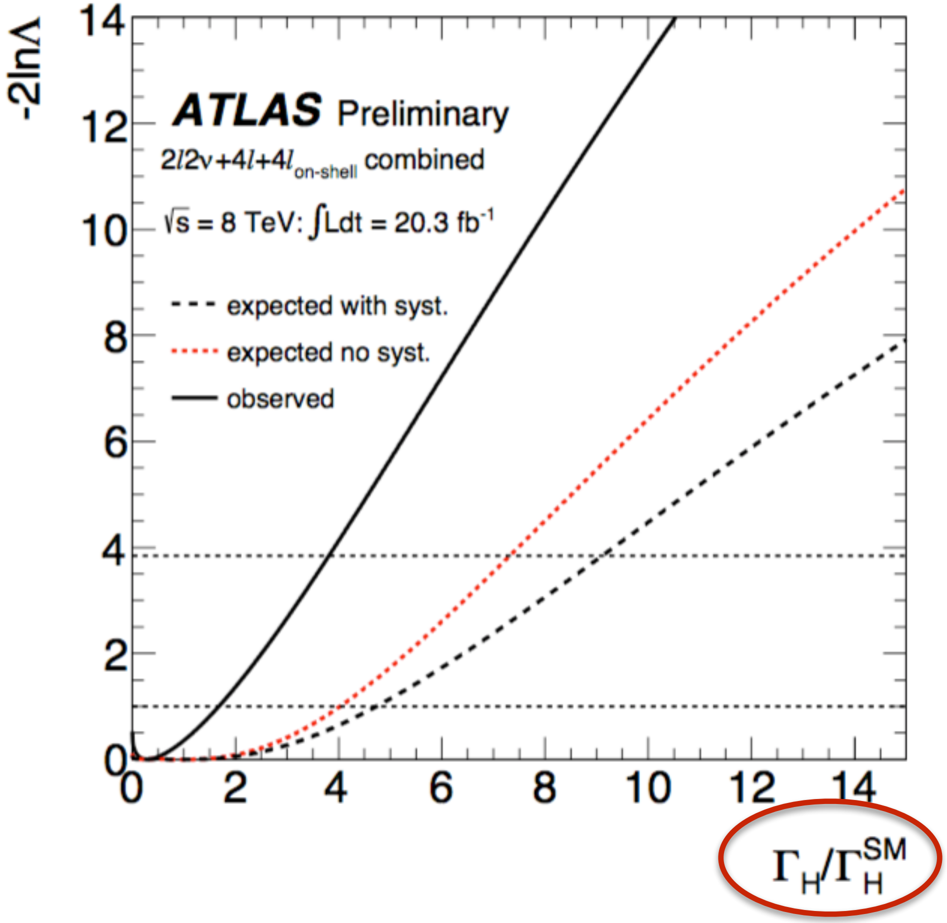
off-shell production: gg + VBF ~7%. No contribution from ttH,VH offshell

interference with the ZZ box production



off-shell ZZ production: results





Spin structure

Spin 0,1,2

For spin 0 we moved from the spin hypothesis testing to the parameters estimation.
Write the amplitudes for the decay and constrain its parameters through a ML fit

Presently H-ZZ-4l and HWW are included in the fits.

Consider also spin 1 despite the decay to gamma-gamma. The idea is to probe if the resonance is composed of 2 resonances one with spin1 and the other with spin ≠1 decaying to $\gamma\gamma$, close in mass no t to be resolved by the detectors, but far enough not to interfere

Spin 0

Amplitude parametrisation:

$$A(X_{J=0} \to V_1 V_2) \sim v^{-1}\left(\left[\boxed{a_1} - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{(\boxed{\Lambda_1})^2}\right] m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* \right.$$

$$\text{ZZ}\rightarrow \quad + \boxed{a_2} f_{\mu\nu}^{*(Z_1)} f^{*(Z_2),\mu\nu} + \boxed{a_3} f_{\mu\nu}^{*(Z_1)} \tilde{f}^{*(Z_2),\mu\nu}$$

$$\text{Z}\gamma\rightarrow \quad + \boxed{a_2^{Z\gamma}} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + \boxed{a_3^{Z\gamma}} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu}$$

$$\gamma\gamma\rightarrow \quad \left. + \boxed{a_2^{\gamma\gamma}} f_{\mu\nu}^{*(\gamma_1)} f^{*(\gamma_2),\mu\nu} + \boxed{a_3^{\gamma\gamma}} f_{\mu\nu}^{*(\gamma_1)} \tilde{f}^{*(\gamma_2),\mu\nu}\right)$$

Notation:

V1, V2 = ZZ*, Zγ*,γγ

a_1 = tree level SM interaction (CP-even)

a_2 = SM Z*gamma*, gamma*gamma* (CP-even)

a_3 = CP-odd

ai= form factors depending on kinematics invariants (mZ^2, $mV1^2$, $mV2^2$)

in general have a Re and Im part. Here considered kin <u>independent</u>

Λ_1 = scale for new physics affecting tree level coupling to ZZ

ε = polarisation vectors

q_i = Vi momentum

$f^{(i)\mu\nu} = \epsilon_i^\mu q_i^\nu - \epsilon_i^\nu q_i^\mu$ field strength tensor of V_i

SM: a1 = 2; a2 ~10-3 ; a3 ~0

Spin 0

What we really fit (more convenient) is a re-parametrisation in terms of effective fractions:

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1} / (\Lambda_1)^4} \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1} / (\Lambda_1)^4} \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right)$$

$$f_{\Lambda 1} = \frac{\tilde{\sigma}_{\Lambda_1} / (\Lambda_1)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1} / (\Lambda_1)^4} \qquad \phi_{\Lambda 1},$$

(consider H-ZZ-2e2mu to avoid taking into account the interference between same flavour final states)

Spin 1

Amplitude parametrisation mixture of 1^+ 1^-:

$$A(X_{J=1} \to V_1 V_2) \sim b_1 \left[\left(\epsilon^*_{V_1} q\right) \left(\epsilon^*_{V_2} \epsilon_X\right) + \left(\epsilon^*_{V_2} q\right) \left(\epsilon^*_{V_1} \epsilon_X\right) \right] + b_2 \epsilon_{\alpha\mu\nu\beta} \epsilon^{\alpha}_{X} \epsilon^{*\mu}_{V_1} \epsilon^{*\nu}_{V_2} \tilde{q}^{\beta}$$

b1 = pure vector
b2 = pure pseudo-vector

In terms of effective fractions:

$$f_{b2} = \frac{|b_2|^2 \sigma_2}{|b_1|^2 \sigma_1 + |b_2|^2 \sigma_2}$$

Consider only ZZ

Spin 2

Amplitude parametrisation ZZ only:

$$
\begin{aligned}
A(X_{J=2} \to V_1 V_2) \sim \Lambda^{-1} \Big[& 2\boxed{c_1} t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha} + 2\boxed{c_2} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu\beta} \\
& + \boxed{c_3} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha} \right) + \boxed{c_4} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta} \\
& + m_V^2 \left(2\boxed{c_5} t_{\mu\nu} \epsilon^{*\mu}_{V_1} \epsilon^{*\nu}_{V_2} + 2\boxed{c_6} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon^{*\nu}_{V_1} \epsilon^{*\alpha}_{V_2} - \epsilon^{*\alpha}_{V_1} \epsilon^{*\nu}_{V_2} \right) + \boxed{c_7} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon^{*}_{V_1} \epsilon^{*}_{V_2} \right) \\
& + \boxed{c_8} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + \boxed{c_9} t^{\mu\alpha} \tilde{q}_\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon^{*\nu}_{V_1} \epsilon^{*\rho}_{V_2} q^\sigma \\
& + \boxed{c_{10}} \frac{t^{\mu\alpha} \tilde{q}_\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon^{*\nu}_{V_1} (q \epsilon^{*}_{V_2}) + \epsilon^{*\nu}_{V_2} (q \epsilon^{*}_{V_1}) \right) \Big] ,
\end{aligned}
$$

ε = polarisation vectors
t = wave function of X
c_i = (as in spin 0) momentum independent form factors
    c1-c5 = minimal couplings (slang: 2m)
    c6-c10= higher orders
Here assume c_i momentum independent corresponding to the lowest order expansion in q_1^2 (V_1), q_2^2 (V_2)

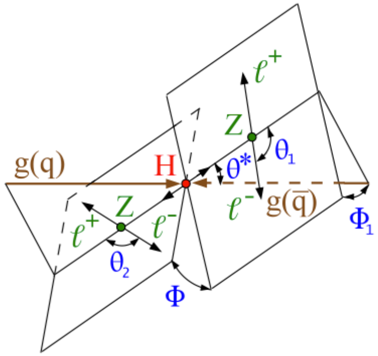
Analysis

Selection as in the standard analysis (Z_1 is the closest to the Z invariant mass, Z_2 the other)
Main backgrounds $q\bar{q} \to ZZ$ and $gg \to ZZ$

MC samples:

spin 0 = POWHEG (NLO) spin0 decayed through JHUGEN (for spin correlations)
spin 1, spin 2 = JHUGEN (LO)

(+Pythia +G4)

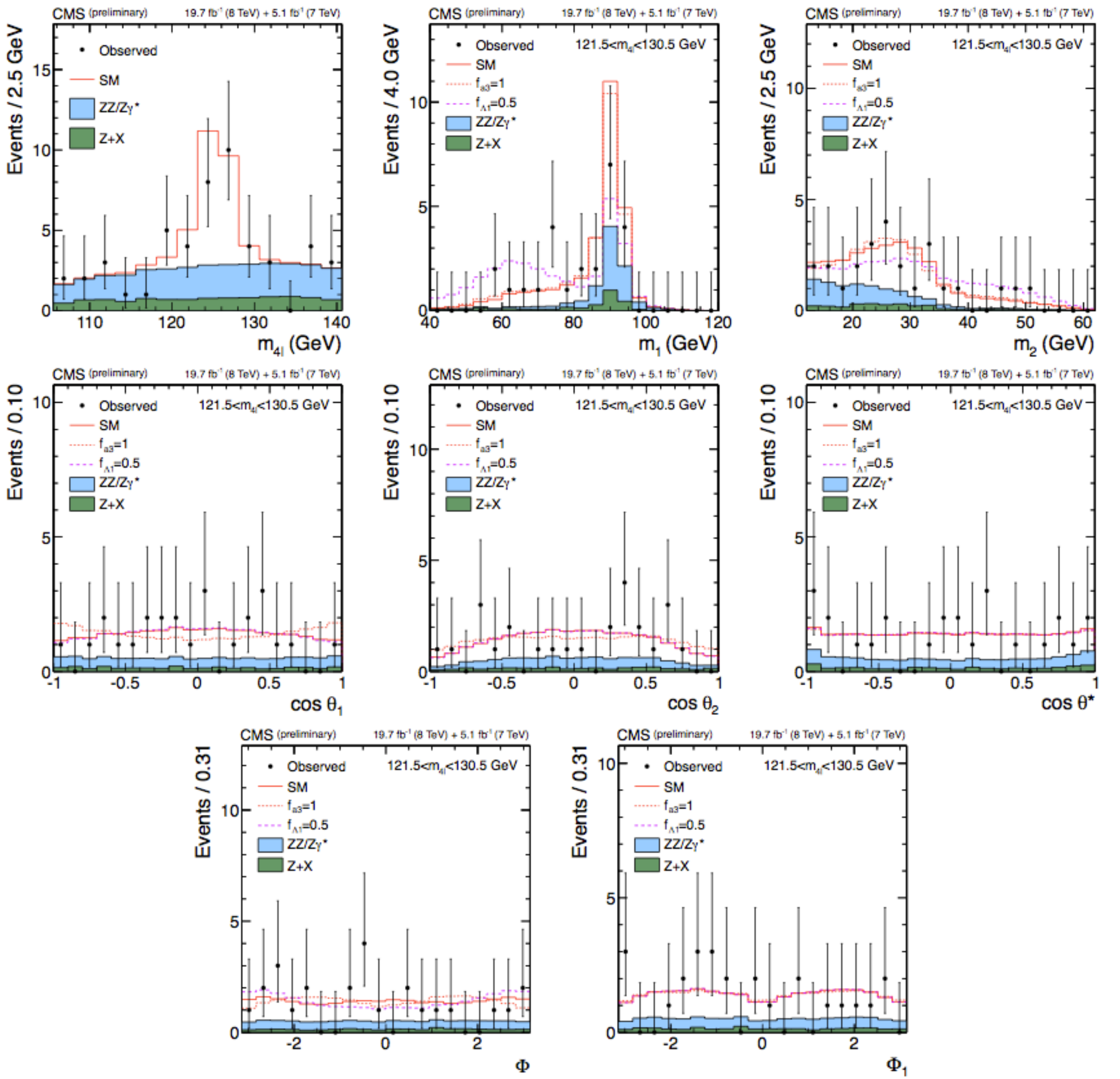


Observables: 5 angles + mZ1 + mZ2 + m4l

Used both for signal/background separation and for spin/parity extraction
Allow the relative yields to be used in the discriminant to distinguish various tensor structures but not the overall yield (more independence from the production mechanism).

Two approaches:
1) build kinematics discriminants and then do a ML fit
2) build the pdf of the ML directly on all 8 variables

The 8-variables



Discriminants

Use the LO matrix elements in MELA package.
For each event compute the probabilities

$$\mathcal{P}_{\rm SM} = \mathcal{P}^{\rm kin}_{\rm SM}(\vec{\Omega}, m_1, m_2 | m_{4\ell}) \times \mathcal{P}^{\rm mass}_{\rm sig}(m_{4\ell}|m_H)$$

$$\mathcal{P}_{\rm J^P} = \mathcal{P}^{\rm kin}_{\rm J^P}(\vec{\Omega}, m_1, m_2 | m_{4\ell}) \times \mathcal{P}^{\rm mass}_{\rm sig}(m_{4\ell}|m_H)$$

$$\mathcal{P}^{\rm kin}_{\rm interf} = \left(\mathcal{P}^{\rm kin}_{\rm SM+J^P}(\vec{\Omega}, m_1, m_2 | m_{4\ell}) - g_{J^P}\mathcal{P}^{\rm kin}_{\rm J^P}(\vec{\Omega}, m_1, m_2 | m_{4\ell}) - \mathcal{P}^{\rm kin}_{\rm SM}(\vec{\Omega}, m_1, m_2 | m_{4\ell})\right)$$

$$\mathcal{P}^{\rm kin}_{\rm interf\perp} = \left(\mathcal{P}^{\rm kin}_{\rm SM+J^P\perp}(\vec{\Omega}, m_1, m_2 | m_{4\ell}) - g_{J^P}\mathcal{P}^{\rm kin}_{\rm J^P}(\vec{\Omega}, m_1, m_2 | m_{4\ell}) - \mathcal{P}^{\rm kin}_{\rm SM}(\vec{\Omega}, m_1, m_2 | m_{4\ell})\right)$$

$$\mathcal{P}_{q\bar{q}ZZ} = \mathcal{P}^{\rm kin}_{q\bar{q}ZZ}(\vec{\Omega}, m_1, m_2 | m_{4\ell}) \times \mathcal{P}^{\rm mass}_{q\bar{q}ZZ}(m_{4\ell}),$$

And build different discriminants:

Separate:

$$\mathcal{D}_{\rm bkg} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + c \times \mathcal{P}_{\rm bkg}} = \left[1 + c(m_{4\ell}) \times \frac{\mathcal{P}^{\rm kin}_{\rm bkg}(m_1, m_2, \vec{\Omega}|m_{4\ell}) \times \mathcal{P}^{\rm mass}_{\rm bkg}(m_{4\ell})}{\mathcal{P}^{\rm kin}_{\rm SM}(m_1, m_2, \vec{\Omega}|m_{4\ell}) \times \mathcal{P}^{\rm mass}_{\rm sig}(m_{4\ell}|m_H)}\right]^{-1}$$

Sig/Bkg

$$\mathcal{D}^{\rm kin}_{J^P} = \frac{\mathcal{P}^{\rm kin}_{\rm SM}}{\mathcal{P}^{\rm kin}_{\rm SM} + c_{J^P} \times \mathcal{P}^{\rm kin}_{J^P}} = \left[1 + c_{J^P} \times \frac{\mathcal{P}^{\rm kin}_{J^P}(m_1, m_2, \vec{\Omega}|m_{4\ell})}{\mathcal{P}^{\rm kin}_{\rm SM}(m_1, m_2, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

SM/J^P

$$\mathcal{D}_{\rm Interf} = \frac{\left(\mathcal{P}^{\rm kin}_{\rm SM+J^P} - g_{J^P}\mathcal{P}^{\rm kin}_{\rm J^P} - \mathcal{P}^{\rm kin}_{\rm SM}\right)}{\mathcal{P}^{\rm kin}_{\rm SM} + c_{J^P} \times \mathcal{P}^{\rm kin}_{J^P}}.$$

SM+J^P/
their interference

(Production mechanism dependence removed integrating over the production angles)

The fits are then performed in 1D (one discriminant) 2D (2 discriminants simultaneously) or 3D (3 discriminants simultaneously).

Discriminants

	Observables used to test the spin-zero anomalous couplings	
ZZ	$\mathcal{D}_{\mathrm{bkg}}$	Discriminate SM Higgs boson against ZZ background, include $m_{4\ell}$
	$\mathcal{D}_{0-}$	Discriminate SM Higgs boson from Pseudoscalar (0^-)
	$\mathcal{D}_{0h+}$	Discriminate SM Higgs boson from BSM scalar with higher dim operators (0_h^+)
	$\mathcal{D}_{\Lambda 1}$	Discriminate SM Higgs boson from BSM scalar with higher dim operators (Λ_1)
	$\mathcal{D}_{CP}$	Discriminate pure states (SM, 0^-) from their interference (a_1, a_3)
	$\mathcal{D}_{\mathrm{int}}$	Discriminate pure states (SM, 0_h^+) from their interference (a_1, a_2)
Zgamma* gamma* gamma*	$\mathcal{D}_{a_2}^{Z\gamma}$	Discriminate between states SM_{ZZ} and $SM_{Z\gamma}$, a_1 vs $a_2^{Z\gamma}$
	$\mathcal{D}_{a_3}^{Z\gamma}$	Discriminate between states SM_{ZZ} and $0_{Z\gamma}^-$, a_1 vs $a_3^{Z\gamma}$
	$\mathcal{D}_{a_2}^{\gamma\gamma}$	Discriminate between states SM_{ZZ} and $SM_{\gamma\gamma}$, a_1 vs $a_2^{\gamma\gamma}$
	$\mathcal{D}_{a_3}^{\gamma\gamma}$	Discriminate between states SM_{ZZ} and $0_{\gamma\gamma}^-$, a_1 vs $a_3^{\gamma\gamma}$
	$\mathcal{D}_{\mathrm{int}}^{Z\gamma}$	Discriminate pure states $SM_{ZZ}, SM_{Z\gamma}$ from their interference (a_1, $a_2^{Z\gamma}$)
	$\mathcal{D}_{CP}^{Z\gamma}$	Discriminate pure states $SM_{ZZ}, 0_{Z\gamma}^-$ from their interference (a_1, $a_3^{Z\gamma}$)
	$\mathcal{D}_{\mathrm{int}}^{\gamma\gamma}$	Discriminate pure states $SM_{ZZ}, 0_{\gamma\gamma}^-$ from their interference (a_1, $a_2^{\gamma\gamma}$)
	$\mathcal{D}_{CP}^{\gamma\gamma}$	Discriminate pure states $SM_{ZZ}, 0_{\gamma\gamma}^-$ from their interference (a_1, $a_3^{\gamma\gamma}$)
		Additional observables used for the study of the exotic models
ZZ	$\mathcal{D}_{\mathrm{bkg}}^{\mathrm{dec}}$	Discriminate against ZZ background, include $m_{4\ell}$, exclude $\cos\theta^*$, Φ_1
	$\mathcal{D}_{1^-}^{\mathrm{dec}}$	Exotic vector (1^-), $q\bar{q} \to X$, decay only
	$\mathcal{D}_{1^+}^{\mathrm{dec}}$	Exotic pseudovector (1^+), $q\bar{q} \to X$, decay only
	$\mathcal{D}_{2_b^+}^{\mathrm{dec}}$	KK Graviton-like with SM in the bulk (2_b^+), $q\bar{q} \to X$, decay only
	$\mathcal{D}_{2_h^+}^{\mathrm{dec}}$	BSM tensor with higher dim operators (2_h^+), $q\bar{q} \to X$, decay only
	$\mathcal{D}_{2_h^-}^{\mathrm{dec}}$	BSM pseudotensor with higher dim operators (2_h^-), $q\bar{q} \to X$, decay only
	$\mathcal{D}_{2_{h2}^+}^{\mathrm{dec}}$	BSM tensor with higher dim operators ($2_{h_2}^+$), $gg \to X$, $q\bar{q} \to X$, decay only
	$\mathcal{D}_{2_{h3}^+}^{\mathrm{dec}}$	BSM tensor with higher dim operators ($2_{h_3}^+$), $gg \to X$, $q\bar{q} \to X$, decay only
	$\mathcal{D}_{2_{h6}^+}^{\mathrm{dec}}$	BSM tensor with higher dim operators ($2_{h_6}^+$), $gg \to X$, $q\bar{q} \to X$, decay only
	$\mathcal{D}_{2_{h7}^+}^{\mathrm{dec}}$	BSM tensor with higher dim operators ($2_{h_7}^+$), $gg \to X$, $q\bar{q} \to X$, decay only
	$\mathcal{D}_{2_{h9}^-}^{\mathrm{dec}}$	BSM pseudotensor with higher dim operators ($2_{h_9}^-$), $gg \to X$, $q\bar{q} \to X$, decay only
	$\mathcal{D}_{2_{h10}^-}^{\mathrm{dec}}$	BSM pseudotensor with higher dim operators ($2_{h_{10}}^-$), $gg \to X$, $q\bar{q} \to X$, decay only

Spin 0

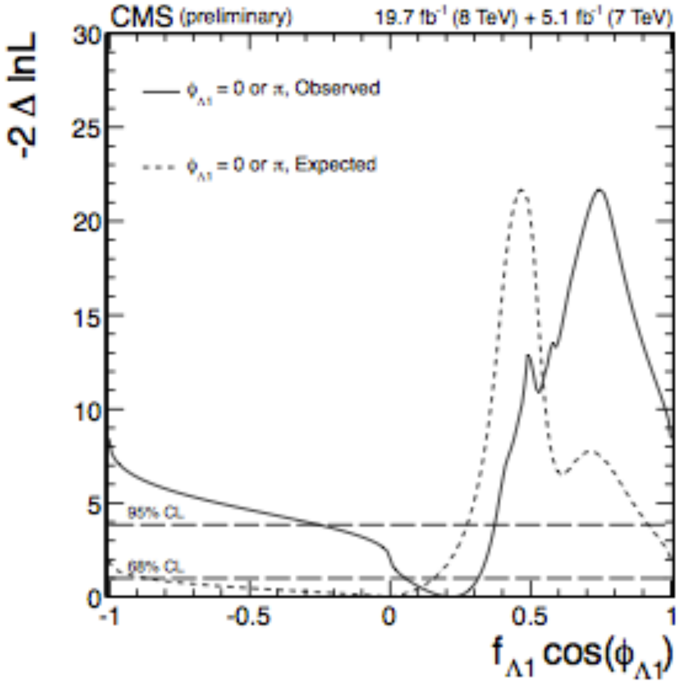
Spin 1,2

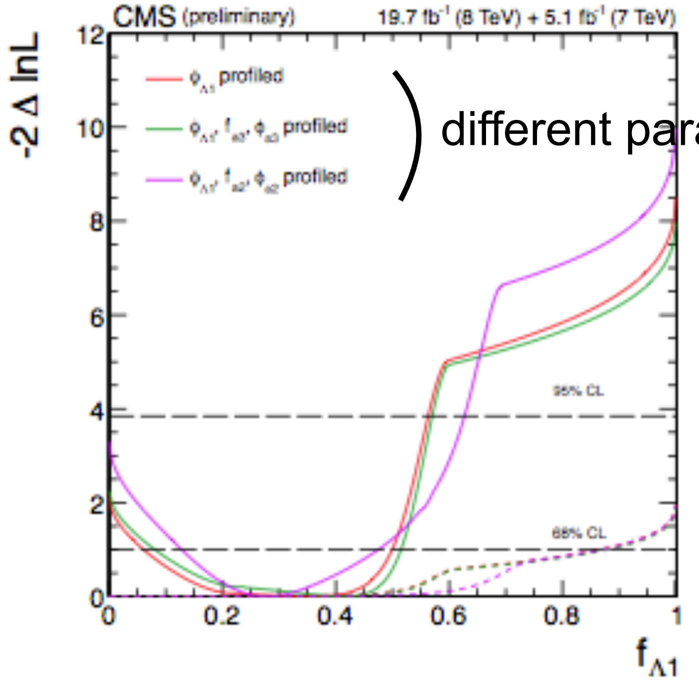
Results

Spin 0 allow for one anomalous coupling

(all other amplitudes fixed to the SM values)

Use the discriminants: $(\mathcal{D}_{\rm bkg}, \mathcal{D}_{\Lambda 1}, \mathcal{D}_{0h+})$





different parameters profiled

Amplitude constrained to be Real so: $\phi = 0$ or π

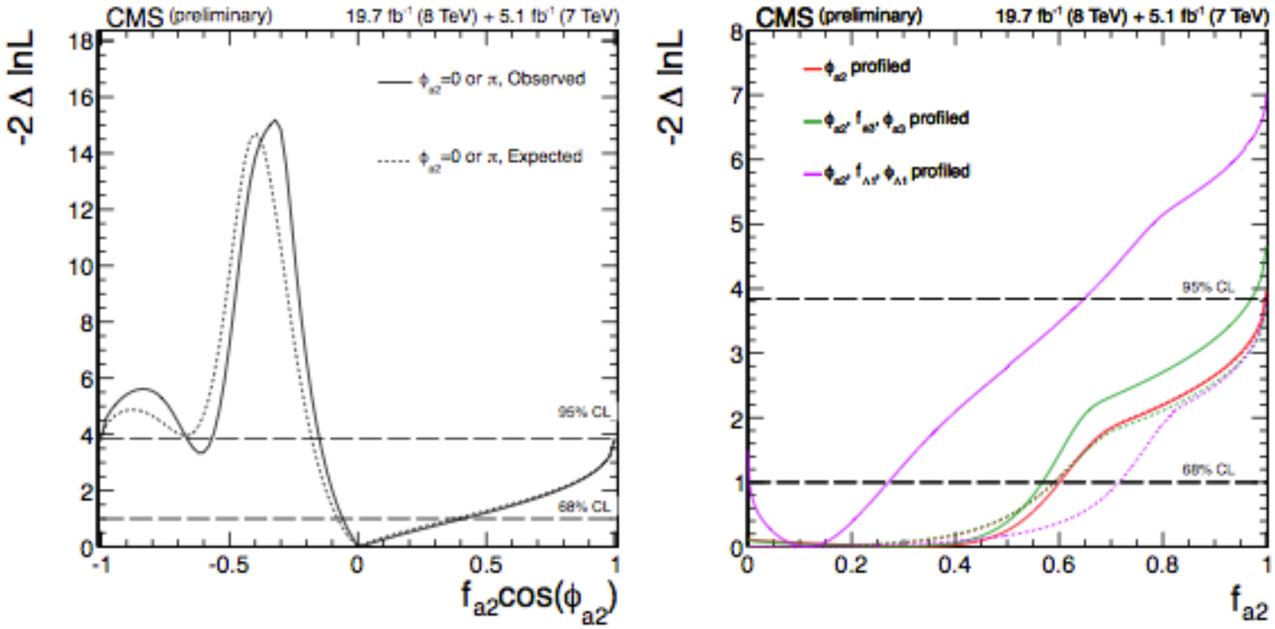
(positive/negative)

Amplitude NOT constrained to be real (i.e. any value of Φ): profile all the rest

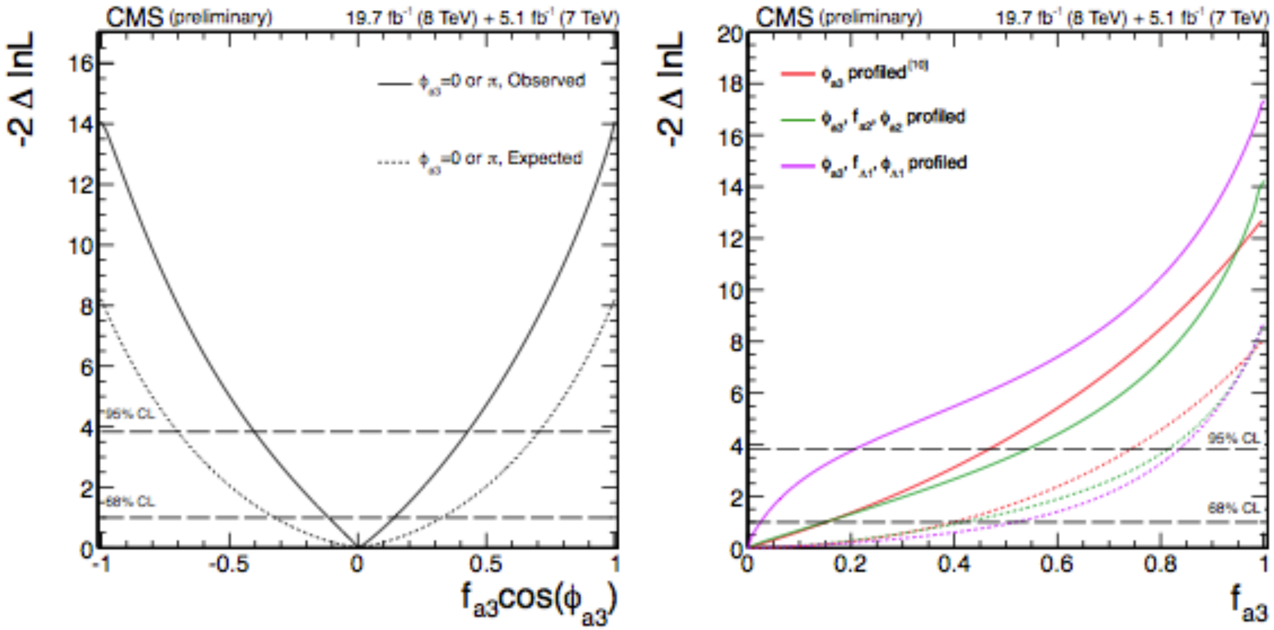
For the other parameters and depending on what is profiled we use different sets of discriminants

Results

Spin 0
one anomalous coupling



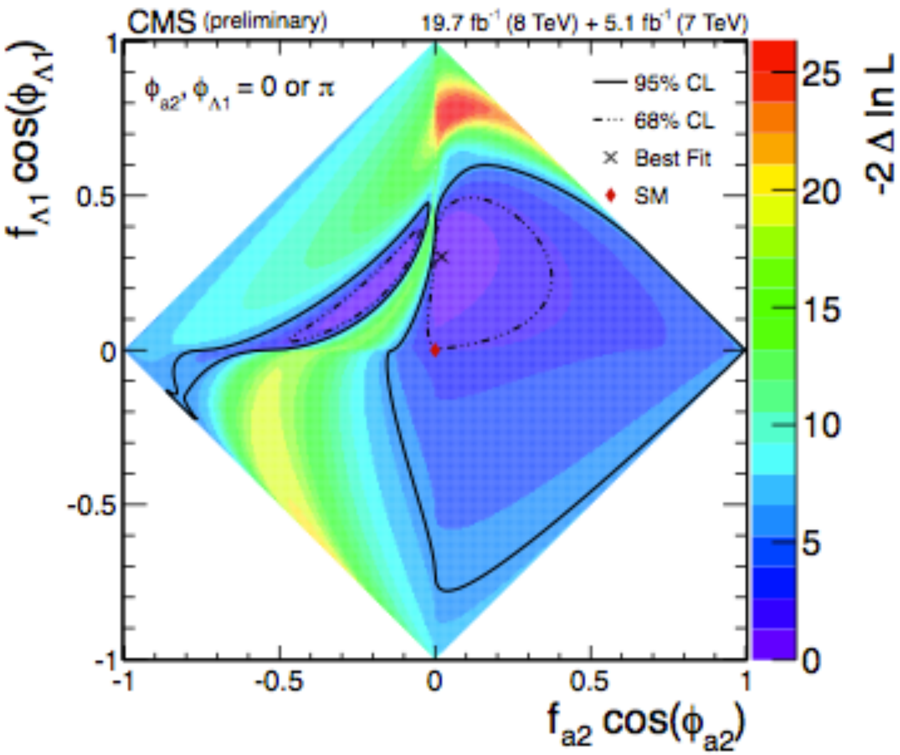
(c) (d)



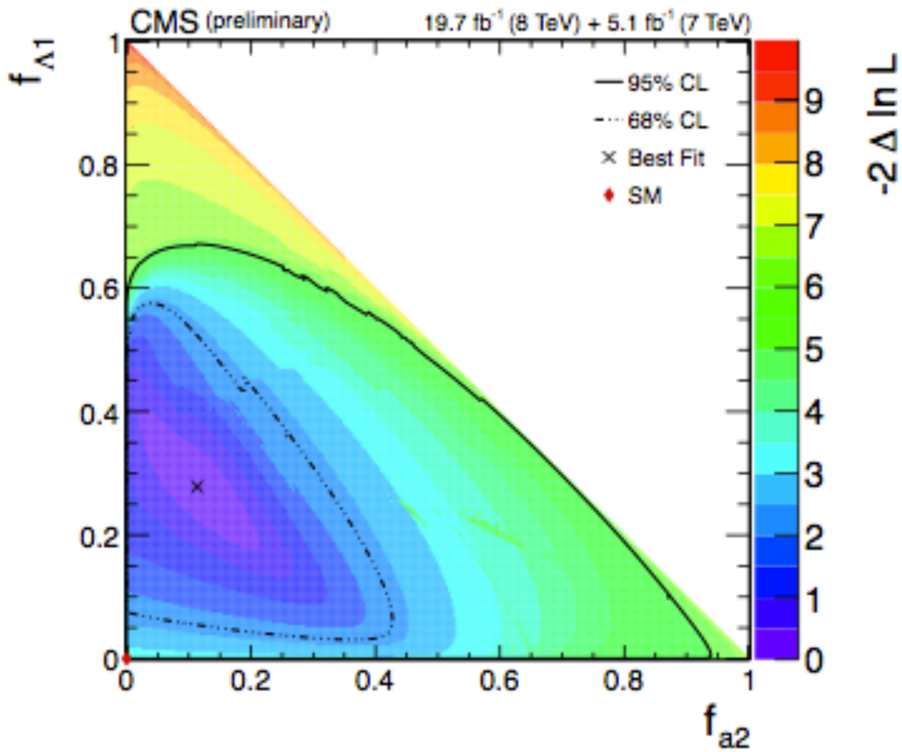
Results

Spin 0 allow for two anomalous couplings

(all other amplitudes fixed to the SM values)



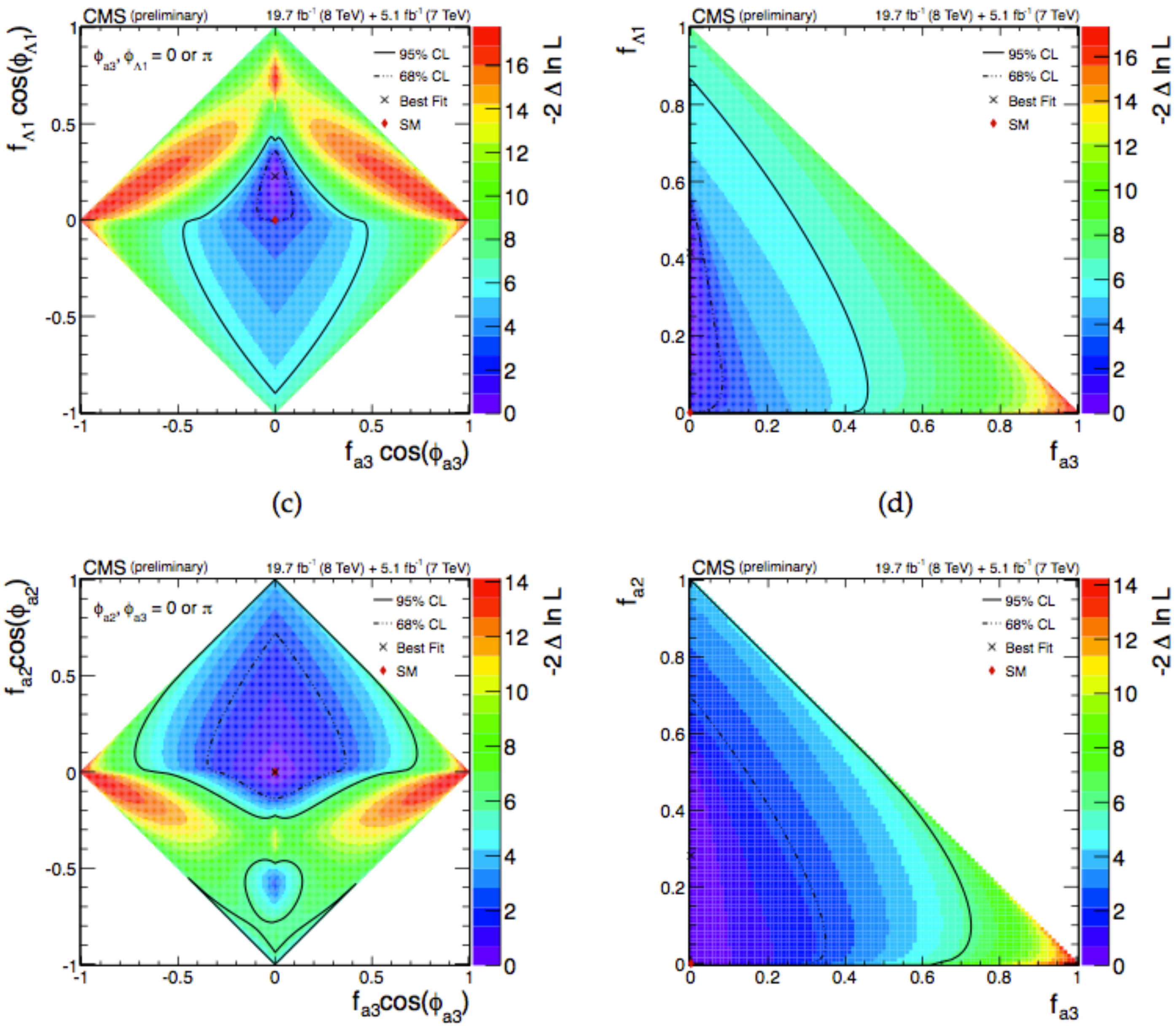
Assume that both discriminants are real



Profile both phases

Results

Spin 0
two anomalous couplings

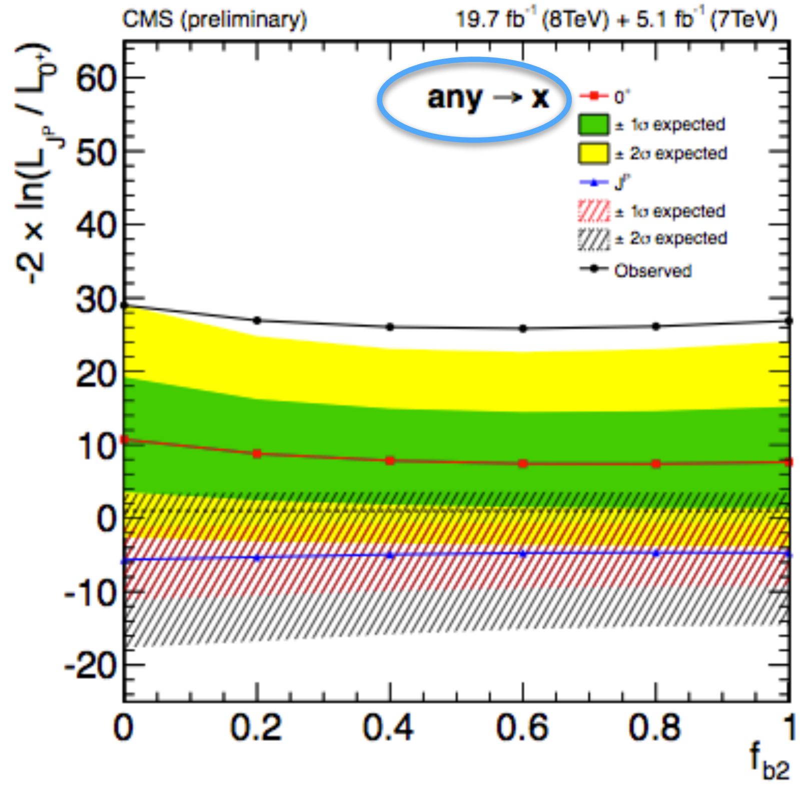


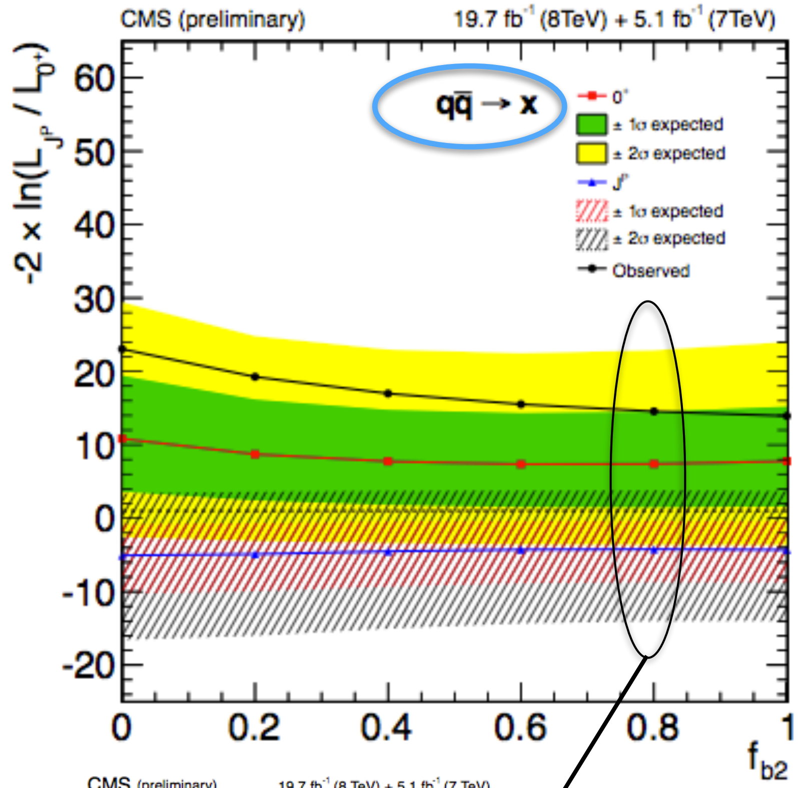
Results

Spin 1 use the 3D fit $(\mathcal{D}_{\rm bkg}, \mathcal{D}_{1^-}, \mathcal{D}_{1^+})$
Spin 2 use the 2D fit $(\mathcal{D}_{\rm bkg}, \mathcal{D}_{J^P})$

Spin 1

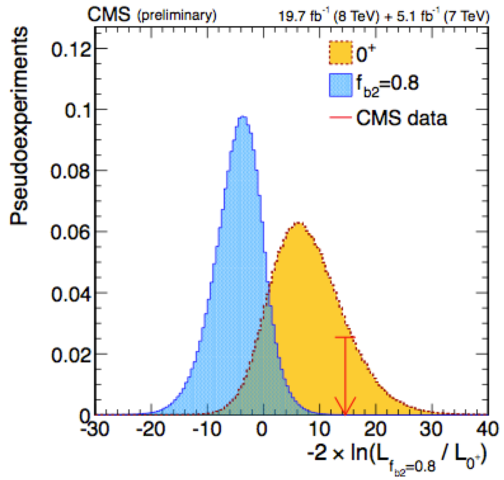
Test different fractions (f_{b2}) of mixture $1^+/1^-$ vs SM



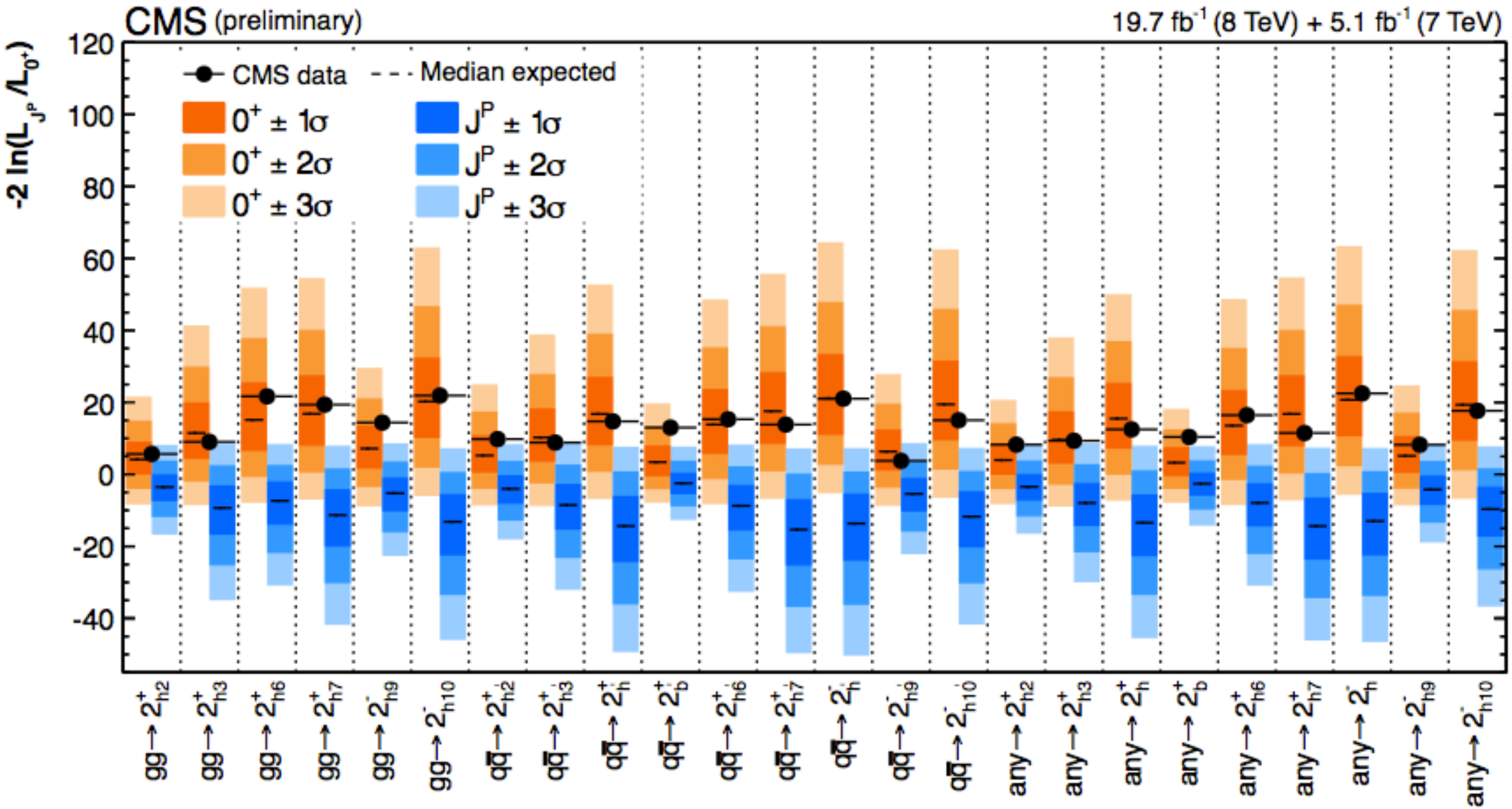


$$f_{b2} = \frac{|b_2|^2\sigma_2}{|b_1|^2\sigma_1 + |b_2|^2\sigma_2}$$

b_1 = pure vector
b_2 = pure pseudo-vector

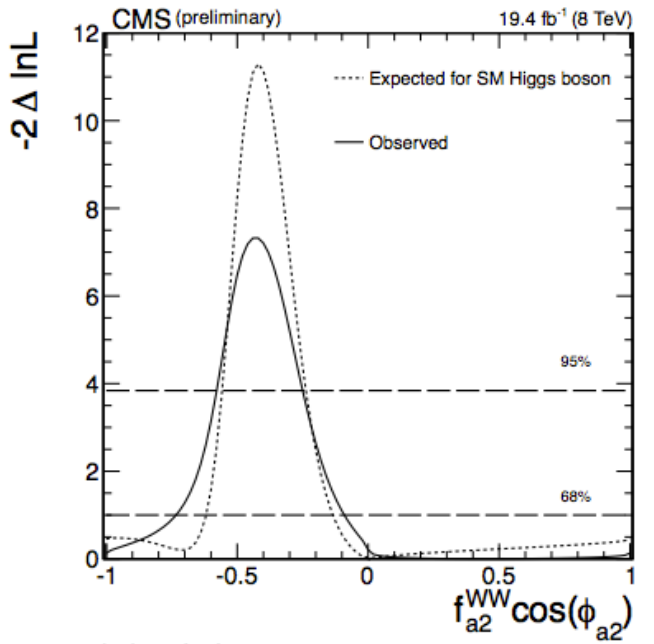


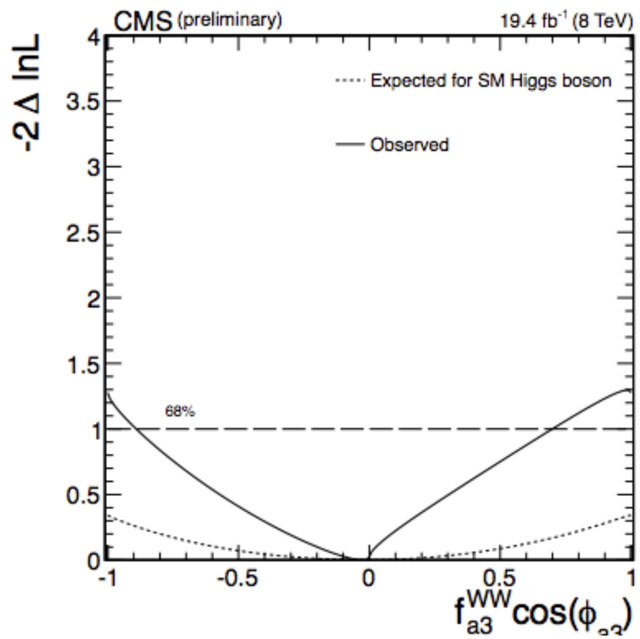
Results
Spin 2

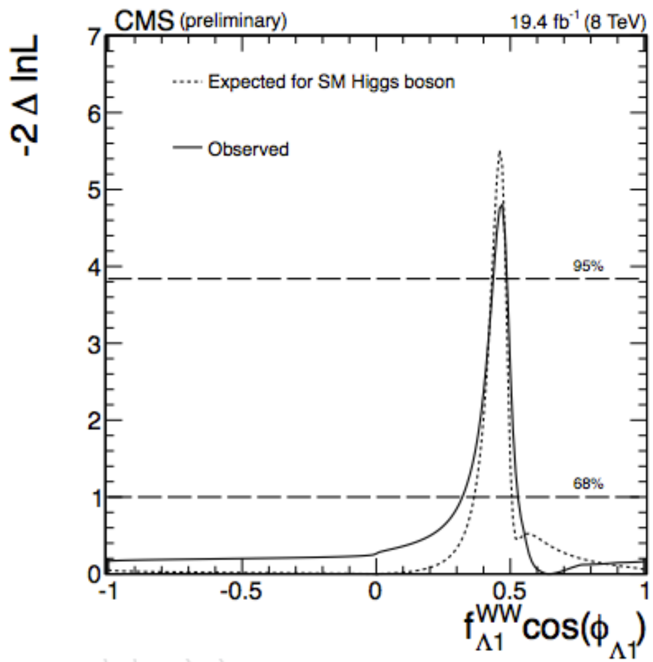


Now look at HWW: spin 0

Repeat the same analysis using the HWW decays: 2D fit (M_T, m_{ll}).
Less sensitivity because of the less constraint kinematics.



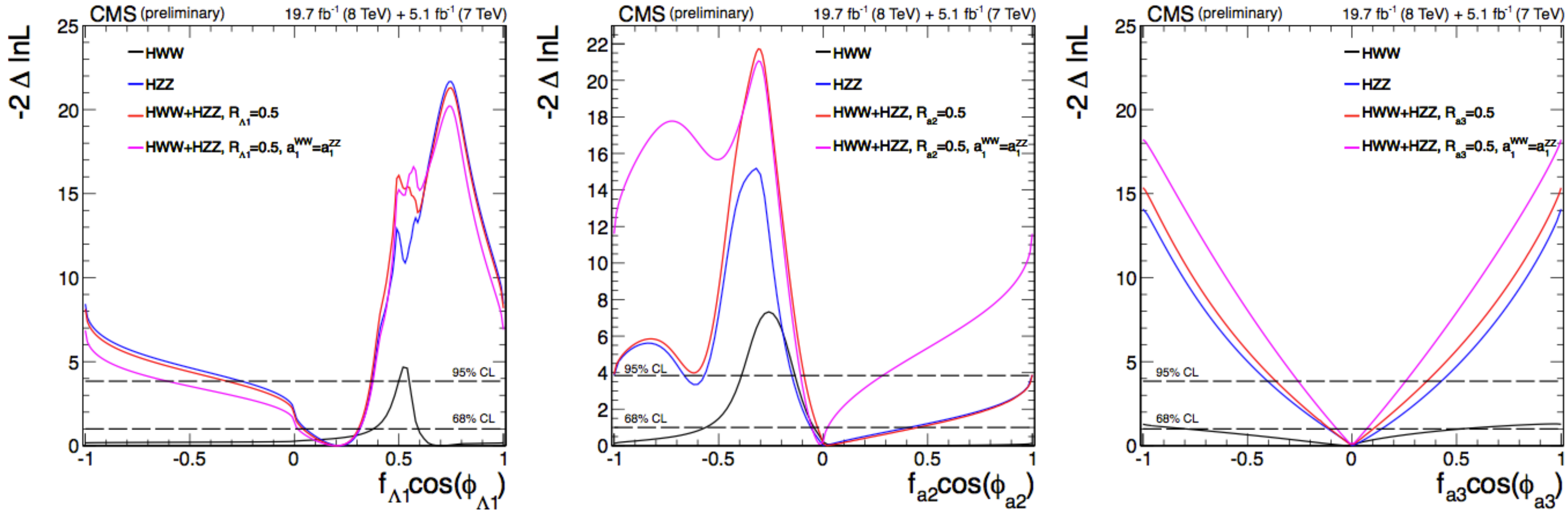




HZZ + HWW spin 0

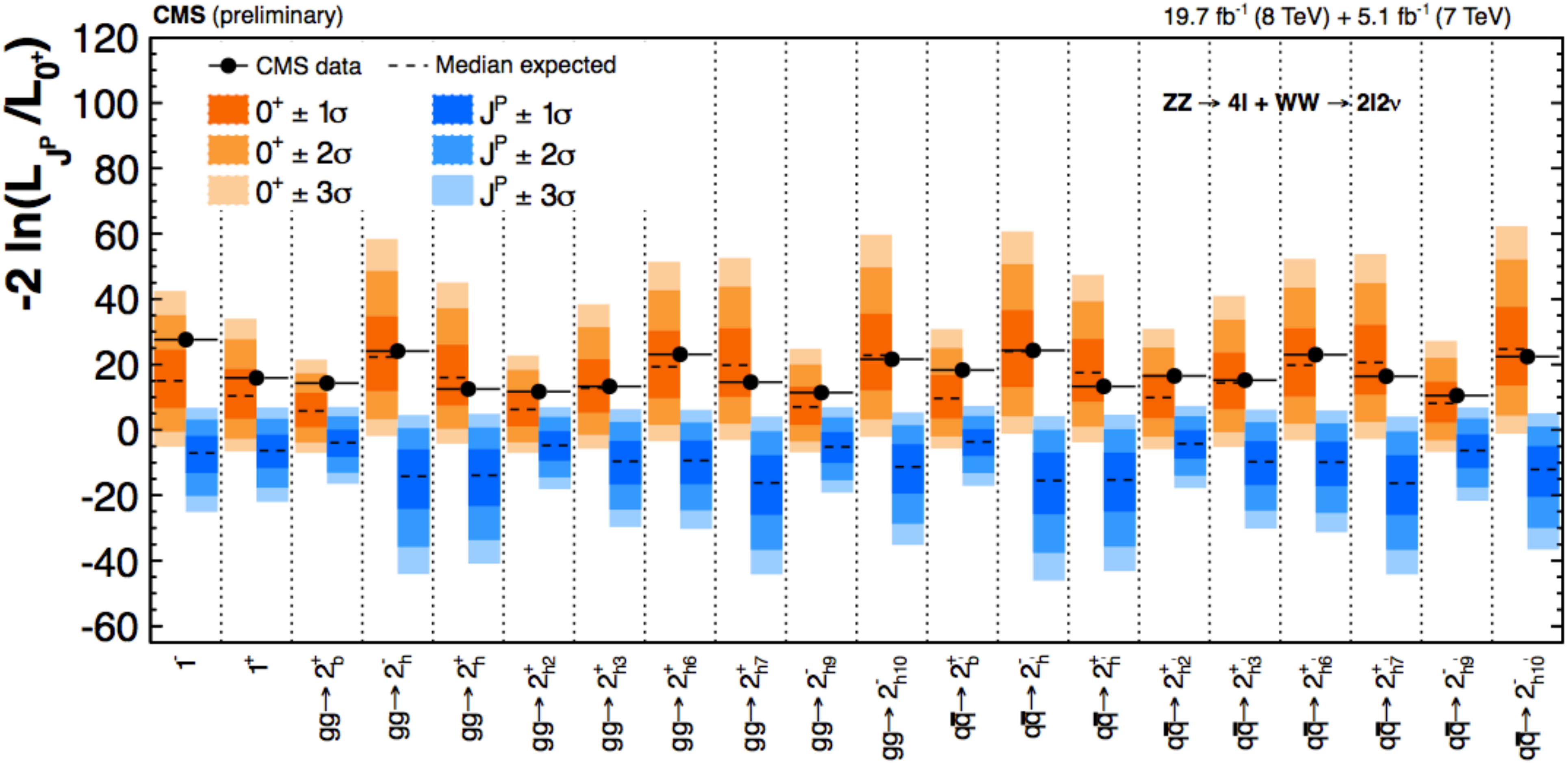
HZZ and HWW are combined under two hp:

- custodial symmetry ($a_1^{ZZ} = a_1^{WW}$)
- anomalous couplings parametrized through the ratio: $r_{ai} = a_i^{WW}/a_1^{WW} \,/\, a_i^{ZZ}/a_1^{ZZ}$
  (in practice implemented as $R_{ai} = r_{ai}|r_{ai}| / (1+r_{ai}^2)$ which is bounded in (-1,1))



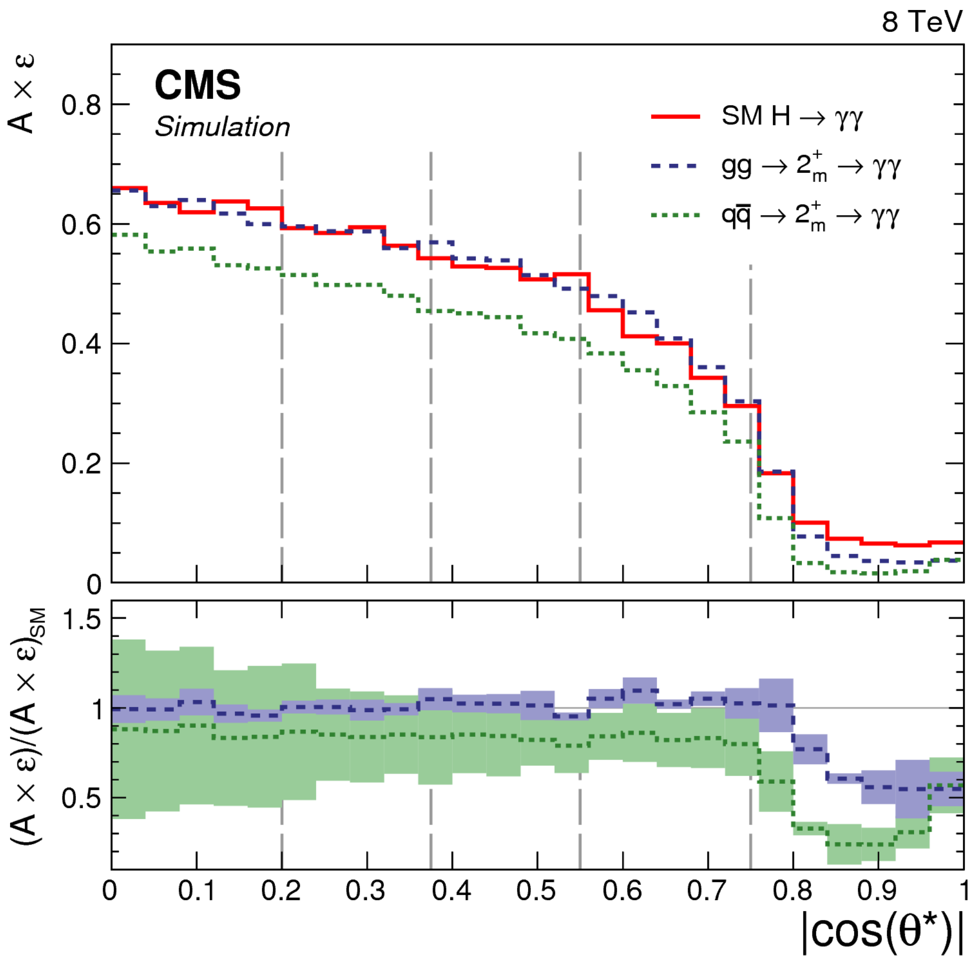
When adding the custodial symmetry ($a^{WW} = a^{ZZ}$) you get more sensitivity
(always true anytime you reduce the number of degrees of freedom)

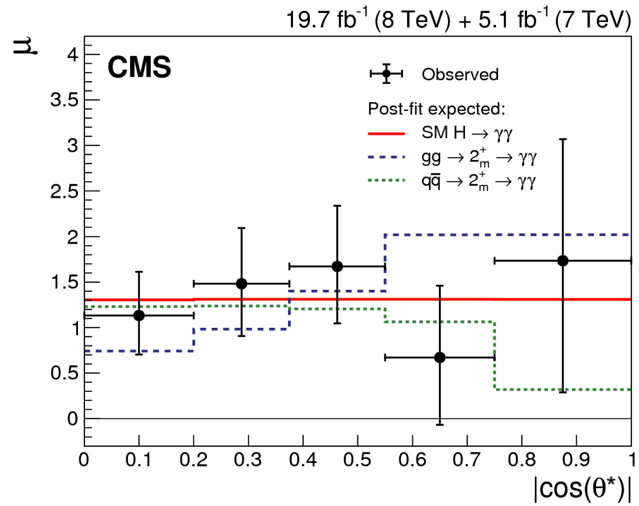
HZZ + HWW spin 1, spin 2

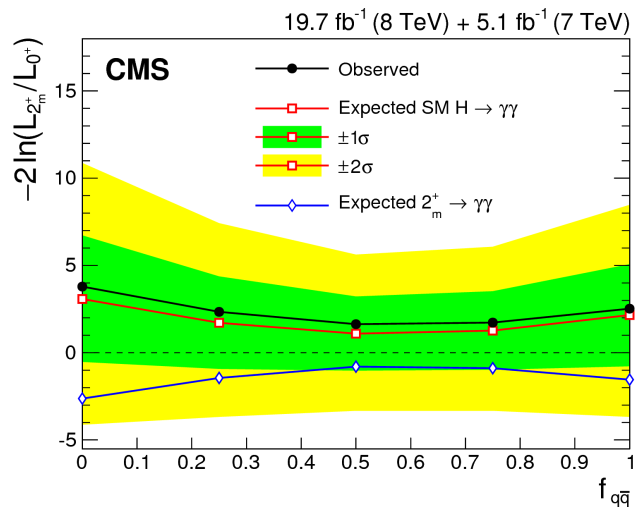


H→γγ

Use the Cut-in-Categories photon selection (less model dependent)
no exclusive tagged events used
Compute the signal strength in 5 bins in cos(theta*) use categories in 2 R9 x 2 eta bins
Test hypothesis



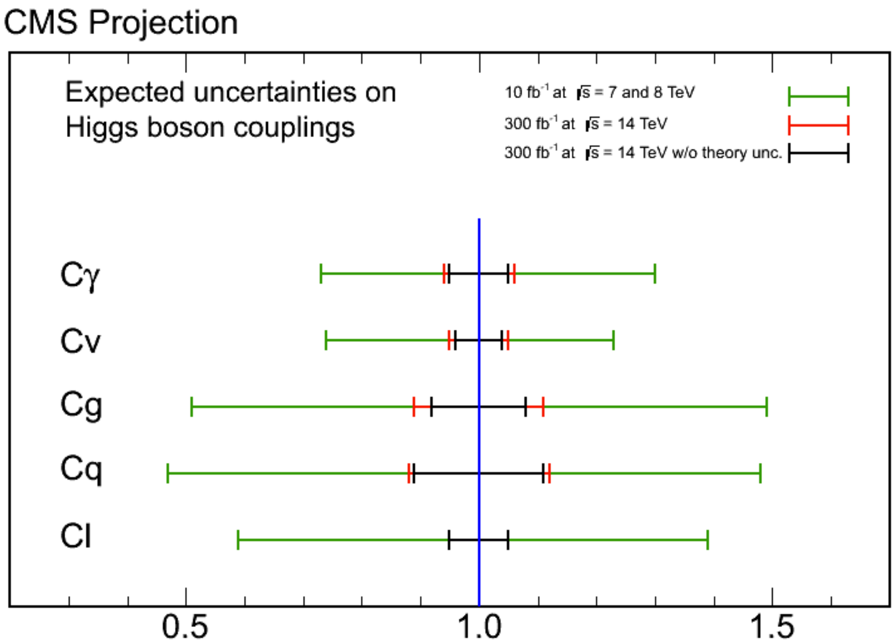


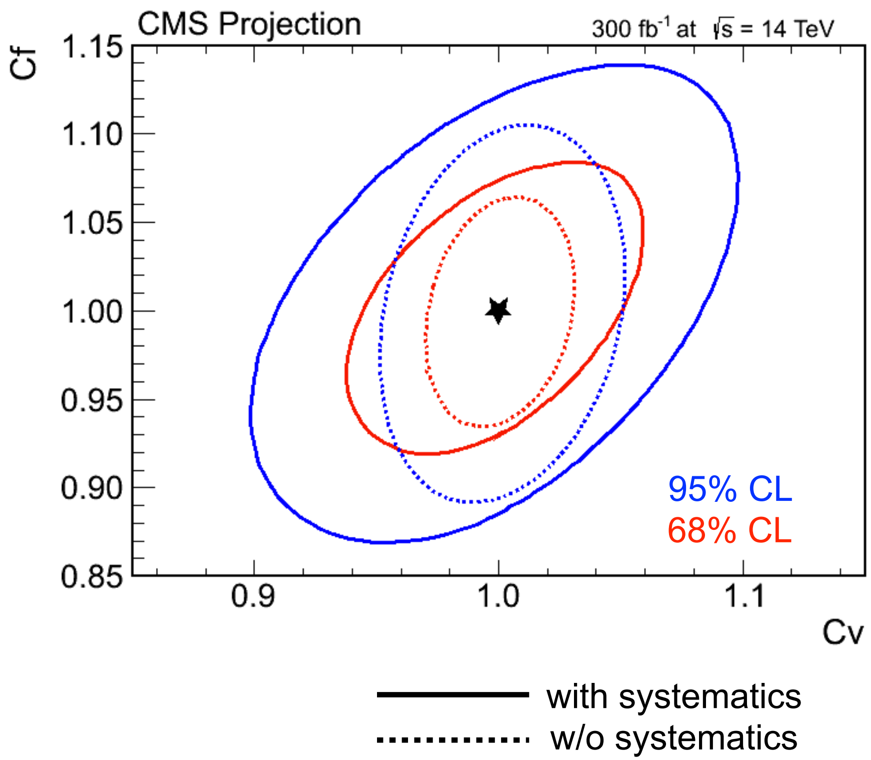


Prospects

Prospects

Just to give an idea of what to expect from 300/fb





Summary

Summary

The first big chunk of work is completed.
We learnt a lot and we got a lot of fun

We discovered a new boson and its properties are very close to what we expect from the SM Higgs boson…

Summary

The first big chunk of work is completed.
We learnt a lot and we got a lot of fun

We discovered a new boson and its properties are very close to what we expect from the SM Higgs boson…

…but sometimes things are not what they look like

Bibliography

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