Standard Model precision measurements
Misure di precisione del modello standard

Lesson 4: Higgs

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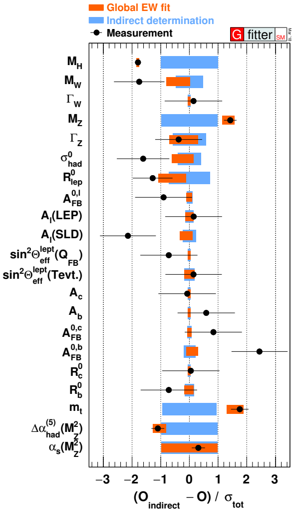
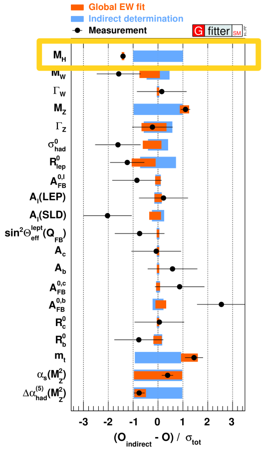


- Higgs mass (5)
  - LHC
- W mass and width (3)
  - LEP2, Tevatron
- Z-pole observables (1)
  - LEP1, SLD
  - M_Z, Γ_Z
  - σ_0^{had}
  - $\sin^2\theta_{eff}^{lept}$
  - Asymmetries (2)
  - BR $R^0_{lep,b,c} = \Gamma_{had}/\Gamma_{\ell\ell,b\bar{b},c\bar{c}}$
- top mass (4)
  - Tevatron, LHC
- other:
  - $\alpha_s(M_Z^2)$, $\Delta\alpha_{had}(M_Z^2)$

Input to global EWK fit

(in parenthesis the order followed in these lessons)



- Higgs mass (5)
  - LHC
- W mass and width (3)
  - LEP2, Tevatron
- Z-pole observables (1)
  - LEP1, SLD
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- top mass (4)
  - Tevatron, LHC
- other:
  - $\alpha_s(M_Z^2)$, $\Delta\alpha_{had}(M_Z^2)$

Outline

1. Z-pole observables
   - Standard Model
   - Z lineshape
2. Asymmetries
3. W mass and width
4. Top mass
5. Higgs mass and features
6. Global ElectroWeak fit

Outline

1. Z-pole observables
2. Asymmetries
   - Forward-Backward Asymmetries
   - Left-Right Asymmetries
   - Tau polarization
3. W mass and width
4. Top mass
5. Higgs mass and features
6. Global ElectroWeak fit

Outline

1. Z-pole observables
2. Asymmetries
3. W mass and width
   - Motivation
   - At LEP II
   - At Tevatron and LHC
4. Top mass
5. Higgs mass and features
6. Global ElectroWeak fit

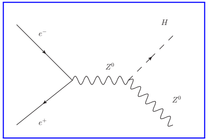
Outline

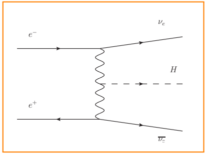
1. Z-pole observables
2. Asymmetries
3. W mass and width
4. Top mass
   - General technique
   - Lepton plus jets
   - Dileptons
5. Higgs mass and features
6. Global ElectroWeak fit

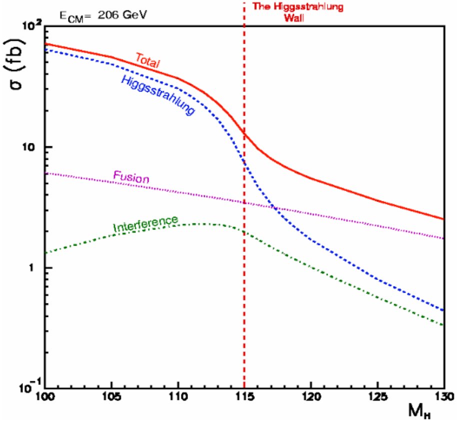
Outline

1. Z-pole observables
2. Asymmetries
3. W mass and width
4. Top mass
5. Higgs mass and features
   - Searches and Discovery
   - Mass
   - Width
   - Spin
   - Coupling

- Dominating production mode at LEP (I and II) was the Higgs-stralung.
- Direct production $ee \to H$ possible
  - H coupling to fermion $\propto m_f$
  - $\to$ negligible to $e^{\pm}$
- Second process is WW fusion
- Higgstralhung drops when the available $\sqrt{s} > M_Z + M_H$:
  - $\sqrt{s} = 206\ GeV$
  - $M_H \leq 115\ GeV$
  - Higgstralhung wall
- dominant H decay into $H \to b\bar{b}$





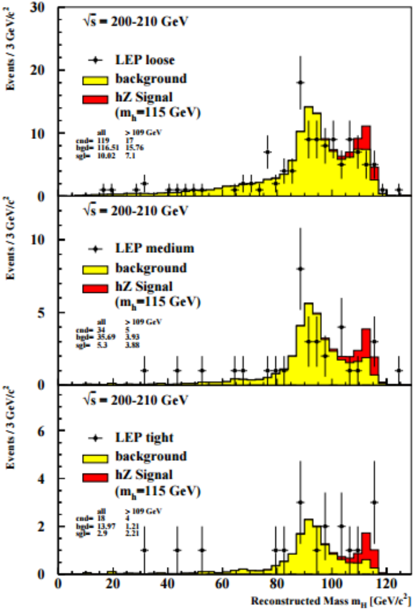


Final states considered: *ZH*

- $H \to b\bar{b}$,
- $Z \to q\bar{q}$, high BR
- $Z \to \ell\ell$, clean, low BR
- $Z \to \nu\nu$, invisible Z

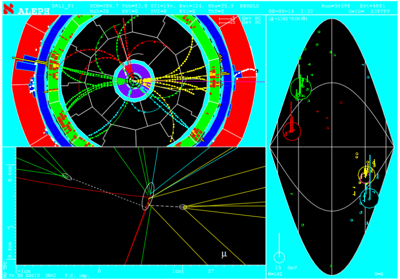
Analysis based on $H \to bb$ invariant mass, b-tagging, NN, $\mathcal{L}$, ...

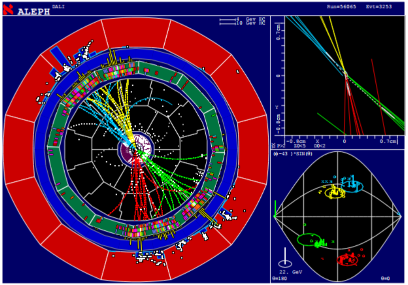
- For $M_H = 115$
- seen 17 events
  - (with $S/B > 0.2$)
- expected background 15.8
  - SM higgs signal 8.4

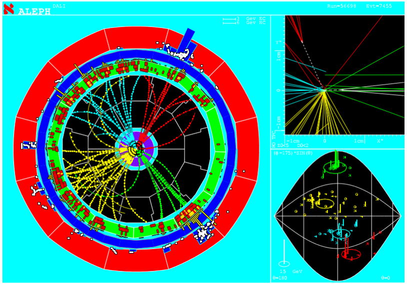


Most significant events

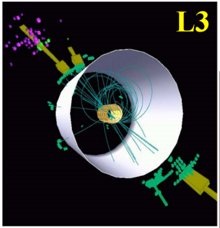
Including ALEPH 4 jets







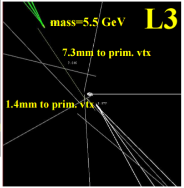
most significant Hνν candidate

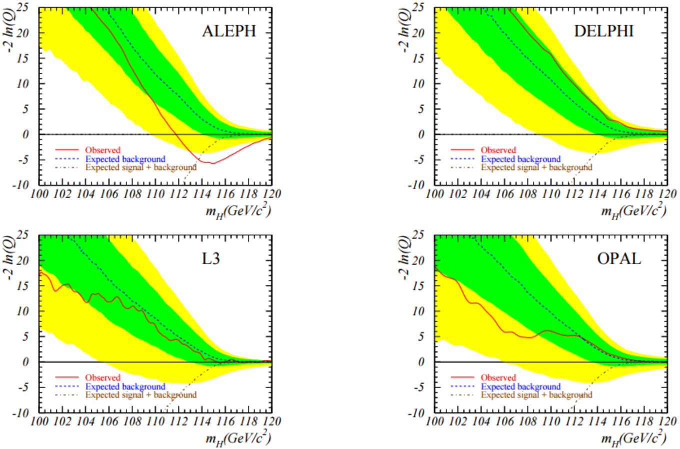


measured H mass=115 GeV

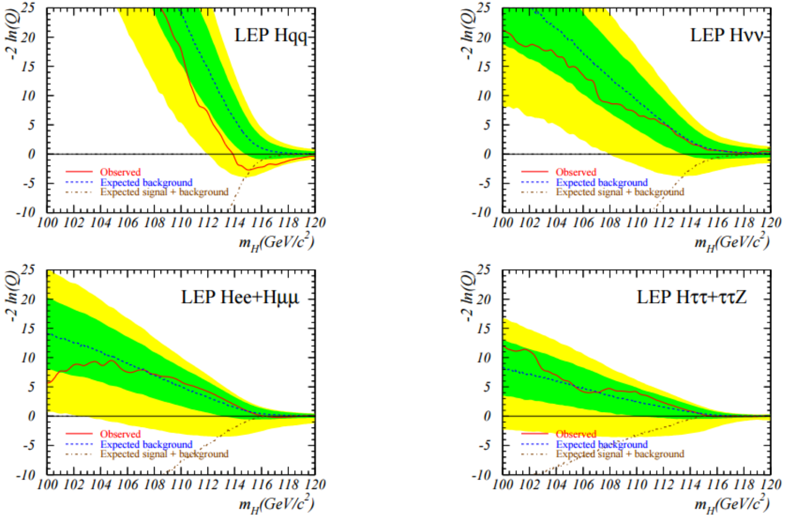
H mass resolution ~3 GeV

Secondary vtx's view

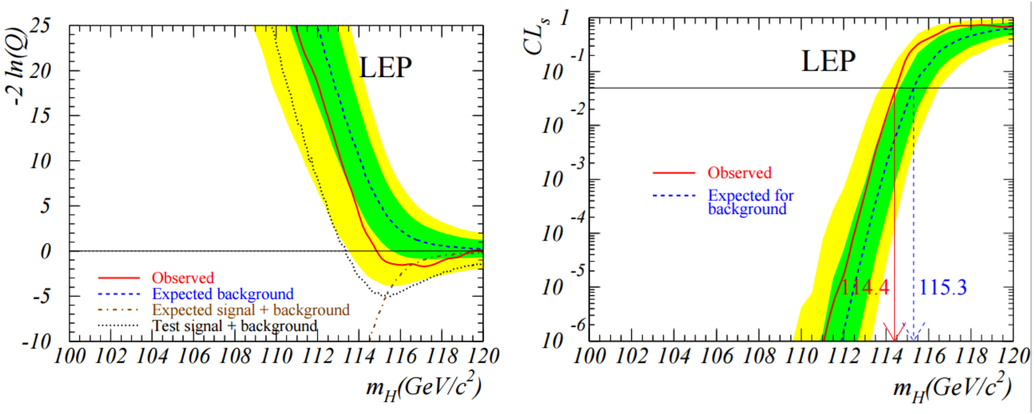




$Q = \frac{\mathcal{L}(data|s+b)}{\mathcal{L}(data|b)}$, $-2\ln Q$ negative means that (s+b) preferred (ALEPH)


LEP Hqq
LEP Hνν
LEP Hee+Hμμ
LEP Hττ+ττZ
Observed
Expected background
Expected signal + background
-2 ln(Q)
$m_H(GeV/c^2)$
25
20
15
10
5
0
-5
-10
100 102 104 106 108 110 112 114 116 118 120

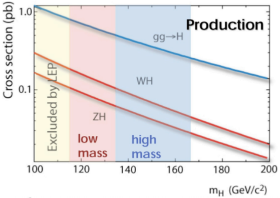
LEP final results

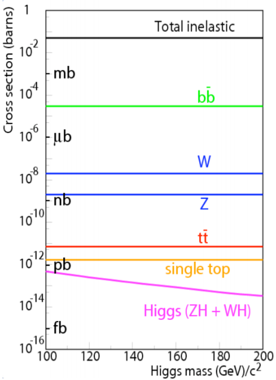


LEP II excludes a SM Higgs Boson with $M_H \leq 114.4\ GeV$ 95% CL (expected 115.3 GeV)
LEP I excluded up to 65 GeV

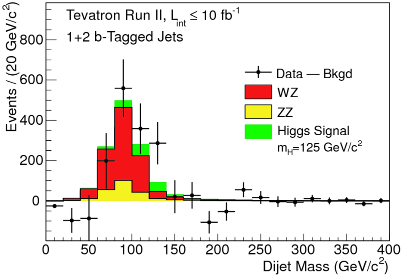
Searches at Tevatron

- Main production modes:
  - gluon fusion ($gg \to H$);
  - associated production (Higgstralhung) $Z/W \to Z/WH$;
- Searches in associated production for additional tagging;
- final states
  - $WH \to e/\mu + bb$
  - $ZH \to ee/\mu\mu + bb$
  - $ZH \to \nu\nu + bb$
  - $gg \to H \to WW \to e\nu e\nu/\mu\nu\mu\nu/e\nu\mu\nu$
- b-tagging, multivariate technique, similar to LHC;

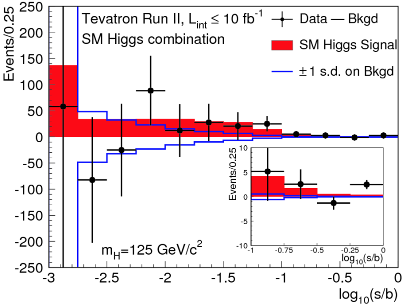




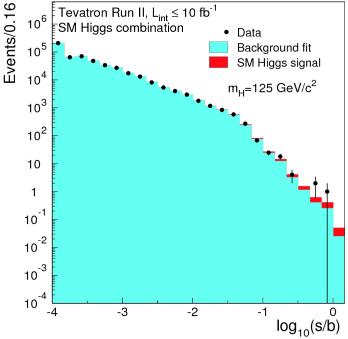
Background subtracted M_{bb} (CDF+D0)



Background subtracted discriminant for all channels

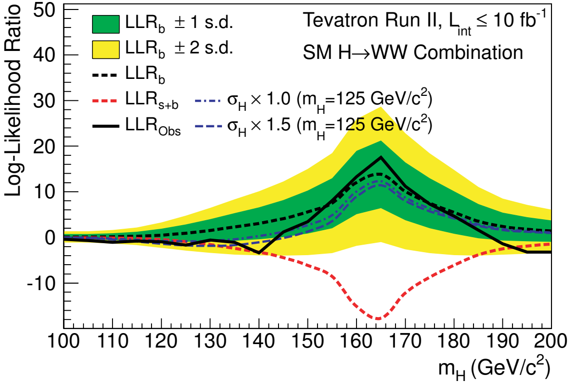


Background an signal vs S/B for all Higgs channel

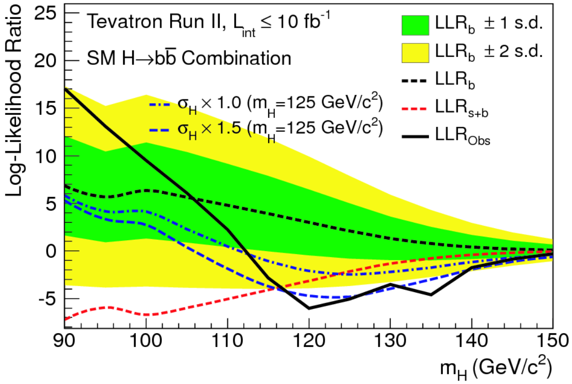


Tevatron results per channel

ln $\mathcal{L}$ for $H \to WW$



ln $\mathcal{L}$ for $H \to bb$

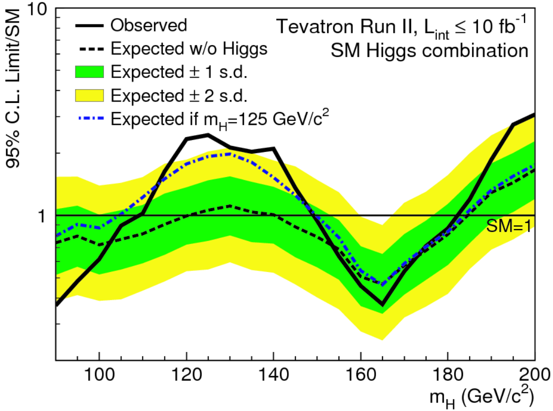


LLR_b: background-only; LLR_{s+b}: signal+background;

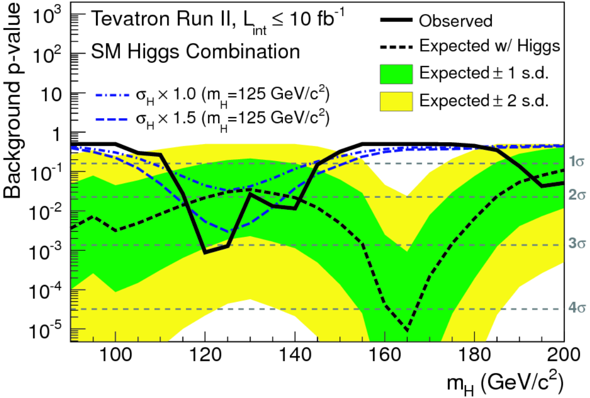
σ_H: LLR espected if SM σ for $M_H = 125\,\text{GeV}$

$H \to WW$ most sensitive to $M_H \sim 2M_W \sim 165\,\text{GeV}$, $H \to bb$ lower mass, no contribution from $H \to \gamma\gamma/\tau\tau$

Expected and observed CL limit

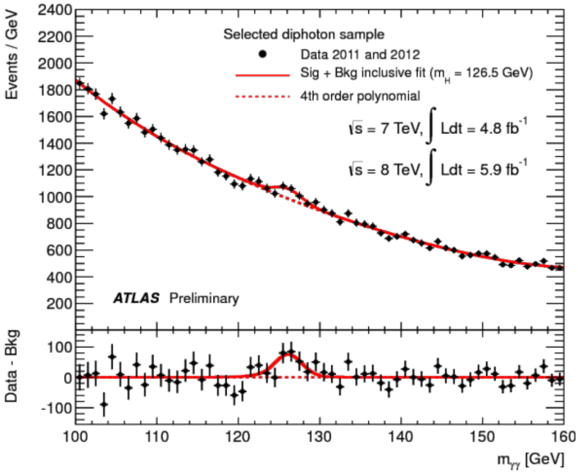


p-value

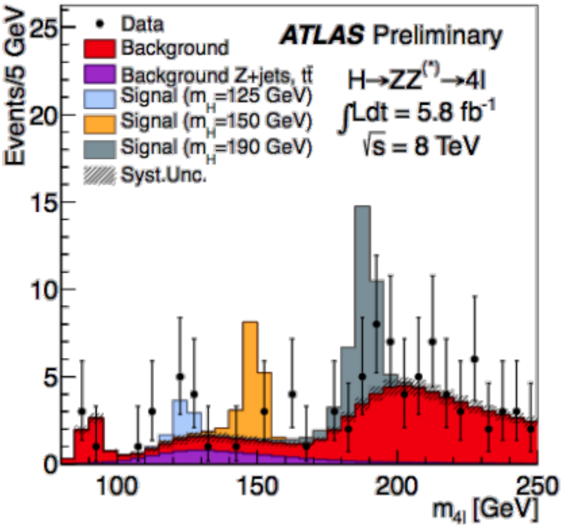


$p-$value is probability that the data observed is due only to a fluctuation of the expected background. Lower p-value is 3σ

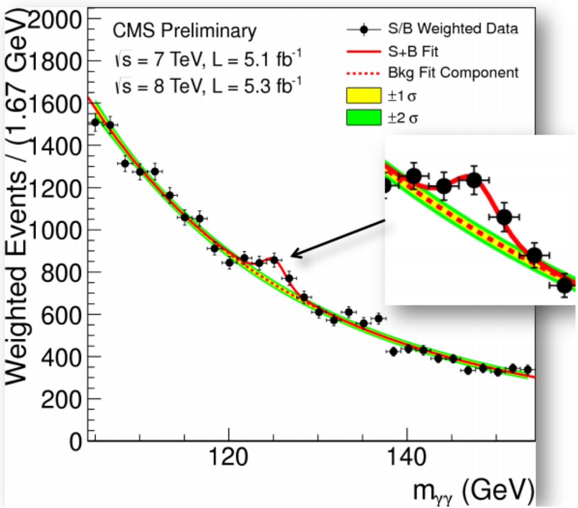
$H \to \gamma\gamma$



$H \to ZZ \to 4\ell$



$H \to \gamma\gamma$



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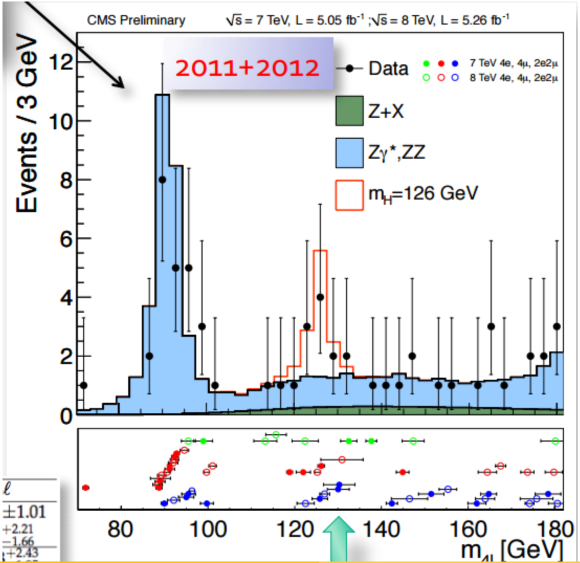
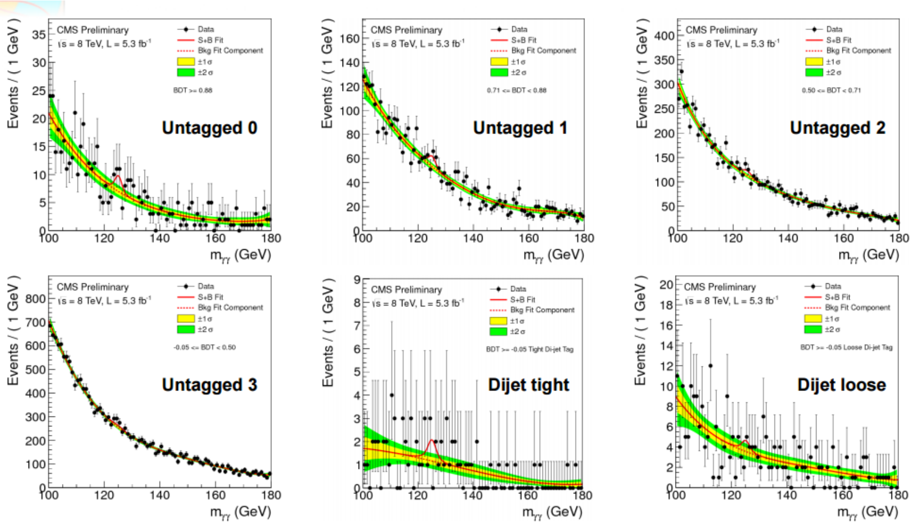
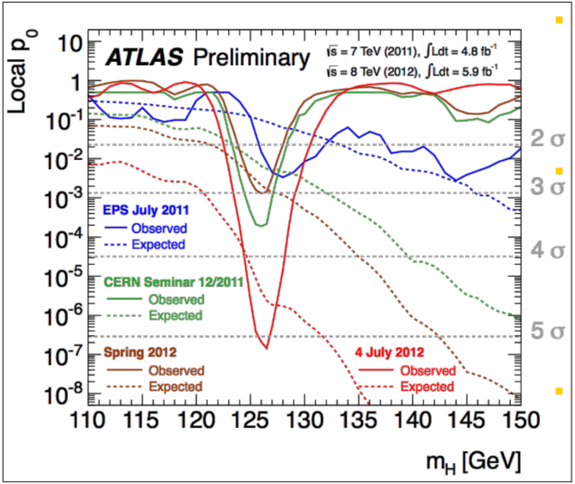
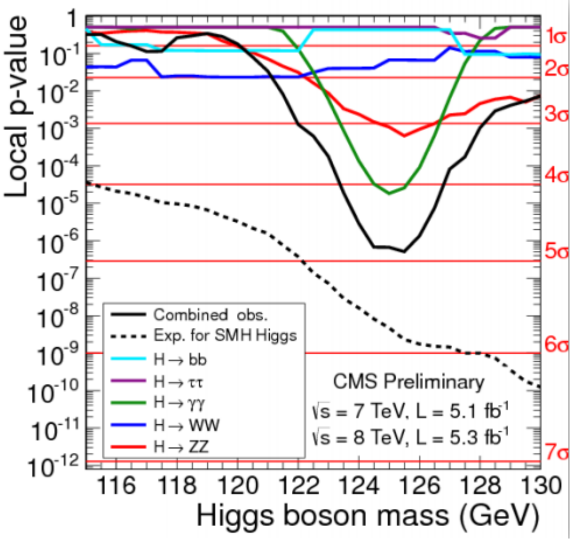



CMS Preliminary
√s = 8 TeV, L = 5.3 fb-1
Data
S+B Fit
Bkg Fit Component
±1σ
±2σ
BDT >= 0.88
Untagged 0
0.71 <= BDT < 0.88
Untagged 1
0.50 <= BDT < 0.71
Untagged 2
-0.05 <= BDT < 0.50
Untagged 3
BDT >= -0.05 Tight Di-jet Tag
Dijet tight
BDT >= -0.05 Loose Di-jet Tag
Dijet loose
Events / (1 GeV)
mγγ (GeV)



ATLAS Preliminary
√s = 7 TeV (2011), ∫Ldt = 4.8 fb⁻¹
√s = 8 TeV (2012), ∫Ldt = 5.9 fb⁻¹
Local p0
EPS July 2011
Observed
Expected
CERN Seminar 12/2011
Observed
Expected
Spring 2012
Observed
Expected
4 July 2012
Observed
Expected
2 σ
3 σ
4 σ
5 σ
mH [GeV]



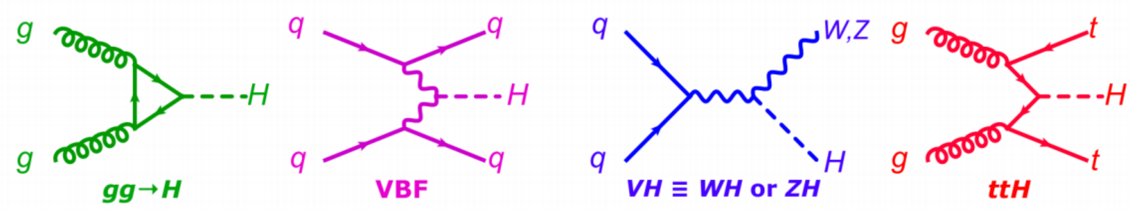
Local p-value
Combined obs.
Exp. for SMH Higgs
H → bb
H → ττ
H → γγ
H → WW
H → ZZ
CMS Preliminary
√s = 7 TeV, L = 5.1 fb⁻¹
√s = 8 TeV, L = 5.3 fb⁻¹
1σ
2σ
3σ
4σ
5σ
6σ
7σ
Higgs boson mass (GeV)

Moving on

Today dicovery of the Higgs boson is established w/o doubt
major effort it to establish/measure Higgs properties:
Is it **the** SM Higgs or not?

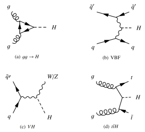
- Mass
- Width
- Spin
- Coupling to fermions/bosons

Exploit all possible production and decay channels

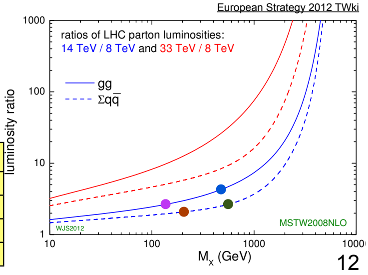


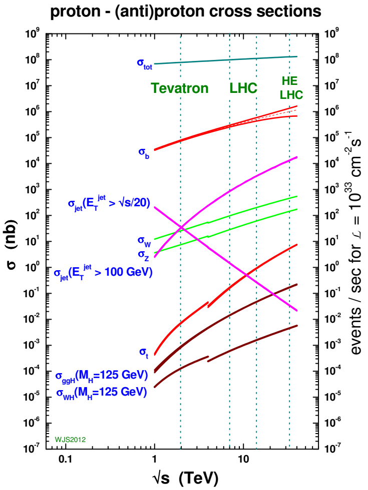
- *gg* $\rightarrow$ *H* gluon fusion:
  - Highest cross-section but "isolated" production, no associated objects.
- *VBF* vector boson fusion:
  - Presence of two forward-backward associated jets;
- *VH* associated with vector boson:
  - Clear signature from $V = Z/W$ decay;
- *ttH*/ *bbH* top-associated production:
  - Rich experimental signature, but low cross-section.

$\sqrt{s}$ / Process	7 TeV	8 TeV (σ [pb])	13 TeV
$gg \to H$	15.13	19.27	43.92
VBF	1.222	1.578	3.748
WH	0.5785	0.7046	1.380
ZH	0.3351	0.4153	0.8696
ttH	0.08632	0.1293	0.5085
bbH	0.1558	0.2035	0.5116

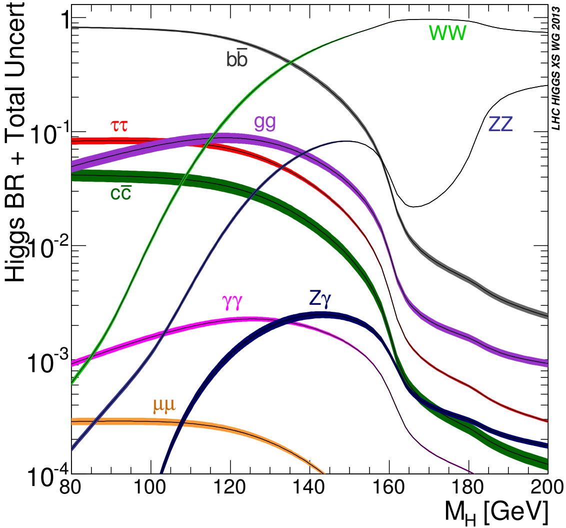


	σ(14TeV)/σ(8TeV)
gg→H	2.6 (M_X=M_H)
qq→qqH	2.6 (probes high M_X)
qq→VH	2.1 (M_X=M_V+M_H)
gg→ttH	4.7 (phase space+M_X)

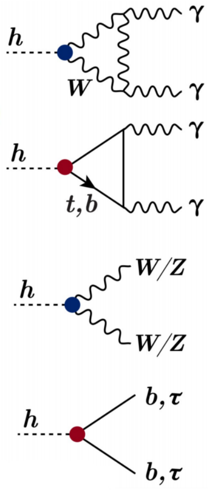




M_H =125 GeV is a gift from nature: many different decay channels are available



- $H \to bb$ $\mathcal{B} = 57.7\%$
  - very difficult for QCD b background;
- $H \to \tau\tau$ $\mathcal{B} = 6.3\%$
  - marginally better;
- $H \to WW$ $\mathcal{B} = 21.5\%$
  - $W \to \ell\nu$ easy, but 2 ν in the final state;
- $H \to ZZ$ $\mathcal{B} = 2.6\%$
  - $Z \to 2\ell$: golden channel;
- $H \to \gamma\gamma$ $\mathcal{B} = 0.228\%$
  - via loop, low BR, but $M_{\gamma\gamma}$ peak visible;
- $H \to invisible$ $\mathcal{B} = 0\%$
  - visible only in associated production;

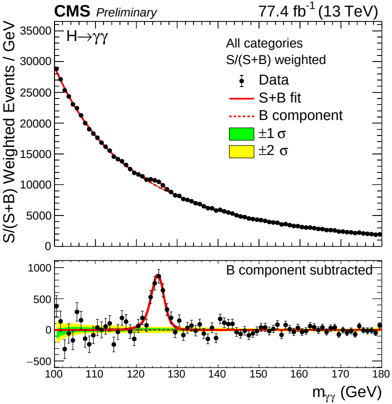


$H \rightarrow$	$\gamma\gamma$	ZZ	WW	bb	$\tau\tau$	$\mu\mu$	inv.
$gg \rightarrow H$	✓	✓	✓	✓	✓	✓	✓
VBF	✓	✓	✓	✓	✓	✓	✓
VH	✓	✓	✓	✓	✓	✗	✓
ttH	✓	✓	✓	✓	✗	✗	✗

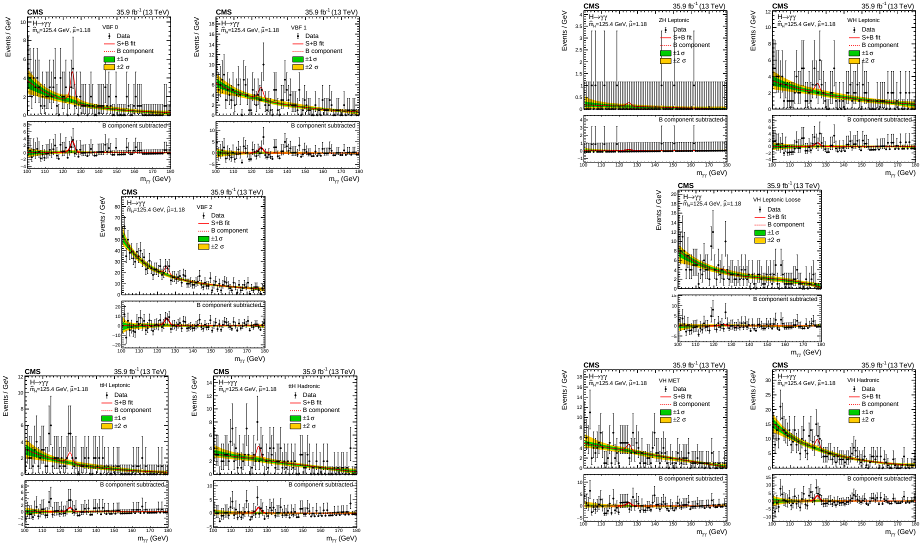
- Basically all possible production/decay channels have been used;
- Some (eg $H \rightarrow \mu\mu$) has expected yield $\ll 1$ with current luminosity;

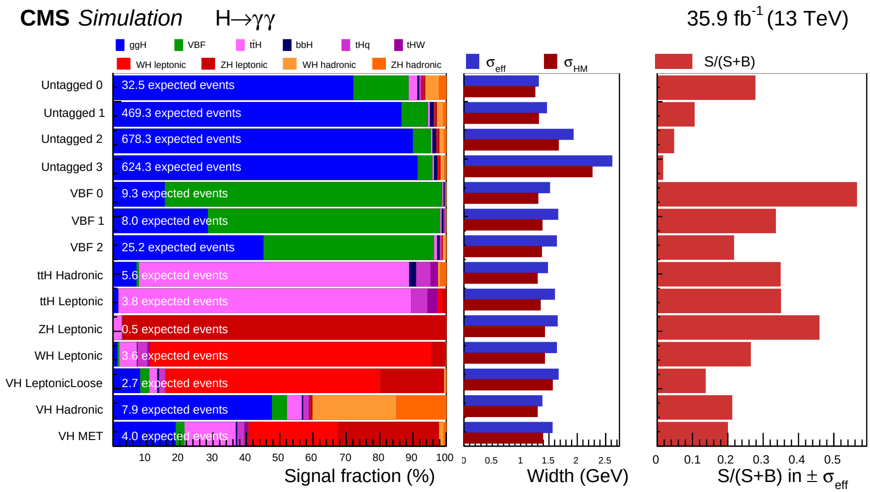
- Small peak over rapidly falling continuous background;
- key element is ECAL resolution and stability;
  - Use $Z \to ee$ sample to calibrate and monitor ECAL response;
  - CMS has $1 - 1.7\ X_0$ in front of ECAL: γ conversion reconstruction is crucial;
  - BDT γ-jet to identify γ
- vertex identification;
  - problematic with high PU;
  - combine info on tracking recoiling against $\gamma\gamma$ system
  - and γ conversion pointing direction.
- Many event categories
  - according to γ ID (MVA)
  - production channel (kineamtics)
    - tH, VH, ttH, VBF, untagged;
  - associated object decay: leptonic, hadronic, MET

weighted ($w = S/(S+B)$) sum of all categories.



Many categories . . . (run I [1])





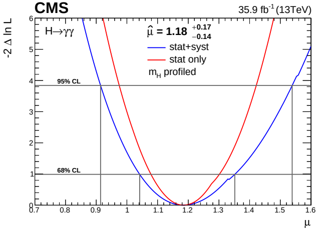
Different categories have different $M_{\gamma\gamma}$ resolution, $S/(S+B)$, and are sentitive to different production mechanism (small to bbH)

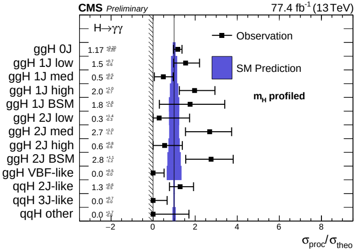
individual prod channel significance:

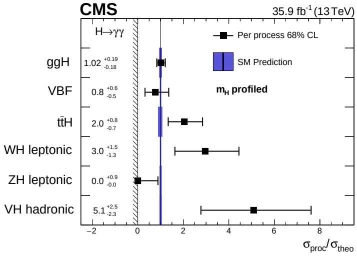
$ggH \gg 5\sigma$, VBF 1.1σ, ttH 3.3σ, VH 2.5σ

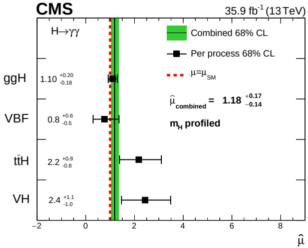
$\mu = 1.16 \pm 0.11(stat) \pm 0.09(syst) \pm 0.06(th) = 1.16^{+0.15}_{-0.14}$

(was ± 0.25 at $7+8$ TeV)

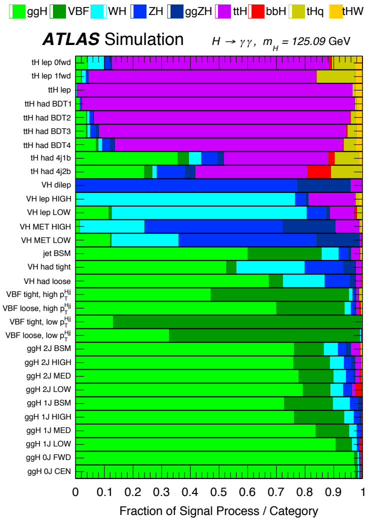




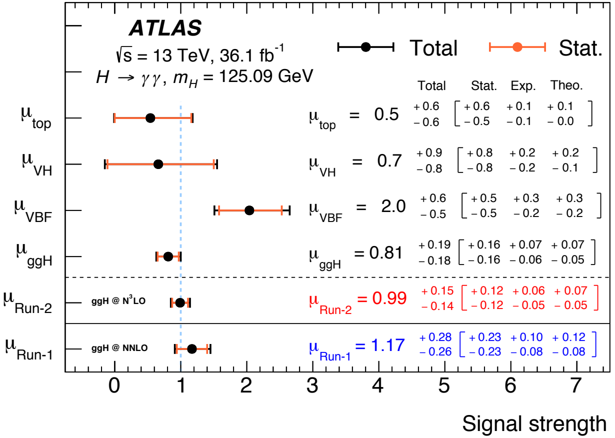




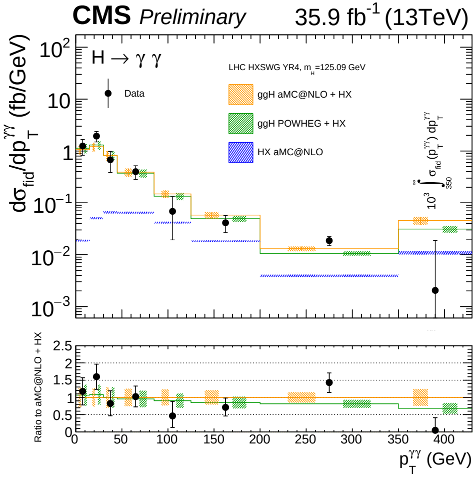
$H \to \gamma\gamma$: ATLAS results [3]

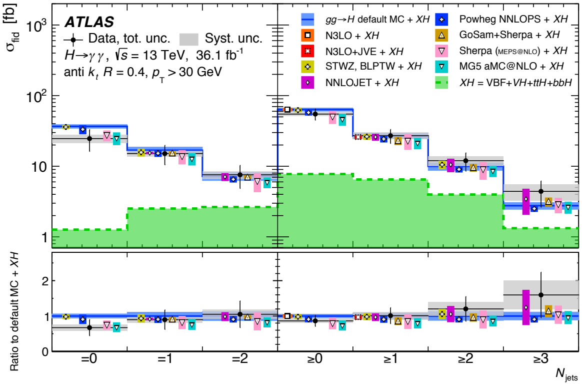


similar analysis, even more categories (32), sensitive to different prod. channel

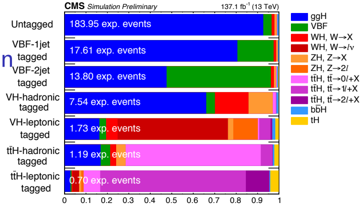


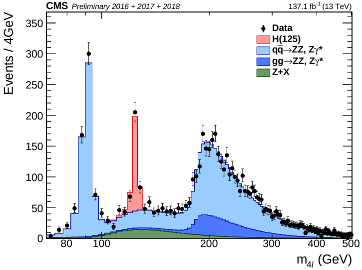
Signal so clean that differential $d\sigma/dp_T$,$d\sigma/N_{jets}$ possible

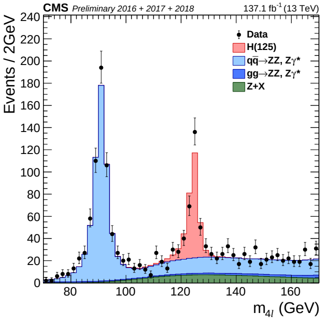


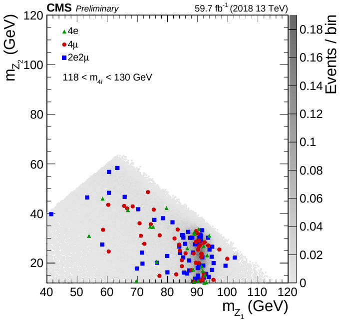


- four ℓ, high p_T, isolated: $eeee$, $ee\mu\mu$, $\mu\mu\mu\mu$
  - narrow peak ($M_{\ell\ell\ell\ell}$, $\sigma \sim 1-2\%$)
  - handy $Z \to 4\ell$ peak to calibrate lepton scale and resolution
  - one Z on-shell (other $Z^\star$)
  - (small) background from ZZ and $Z+X$
- use also $p_T^{4\ell}$ and angular correlations between ℓ
- ggF, VBF, VH

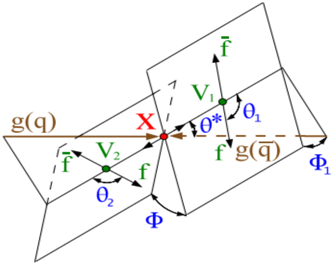


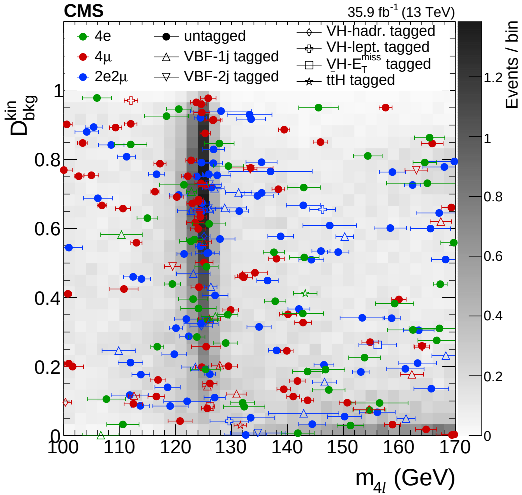




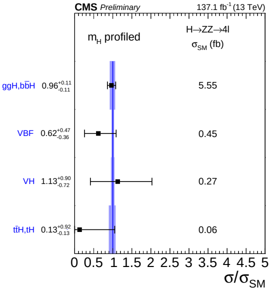


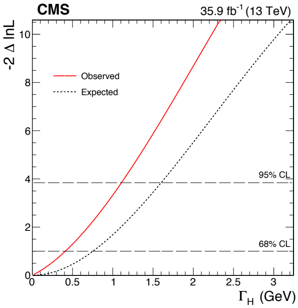
- Fully use the polarization information of the $H \to ZZ^{\star} \to \ell\ell + \ell\ell$ decay;
- define 5 uncorrelated angles which fully determines the decay kinematics;
- using ME build probabily for S and B (ZZ)
- then build likelihood-ratio discriminant $\mathcal{D}^{kin}$
- very sensitive to J^P of initial state

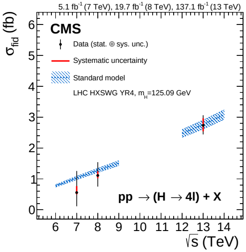


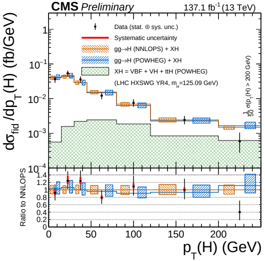


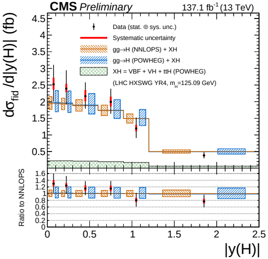
- $\mu = 0.94 \pm 0.07(\text{stat.}) \pm 0.08(\text{syst.})$
- differential cross section
  - vs $\sqrt{s}$, p_T^H, N_{jets}, p_T^{jet}
- also direct limit on $\Gamma_H < 1.1$ GeV @95% CL

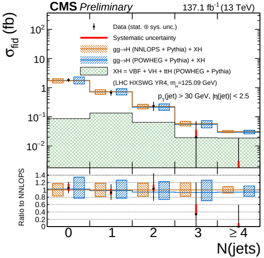






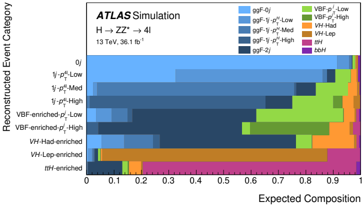


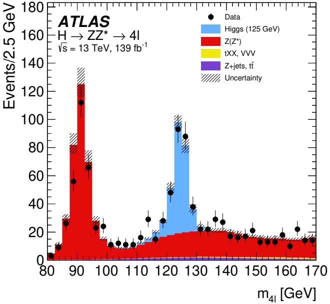


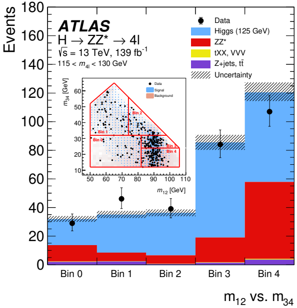


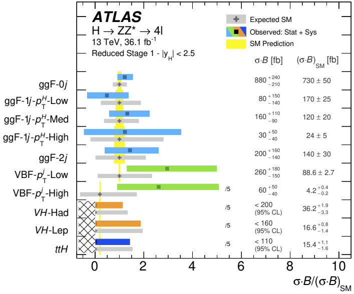
$H \to ZZ$: ATLAS [6, 7]

- Very similar analysis
- mostly sensitive to ggF
- differential cross section also measured
- tensor structure of SM studied (2HDM)
- $\mu = 1.29 \pm 0.18 \pm 0.8$ (μ_{VBF} is a bit high)

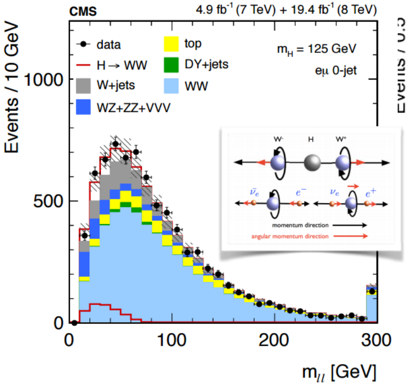






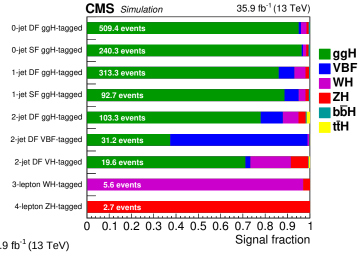


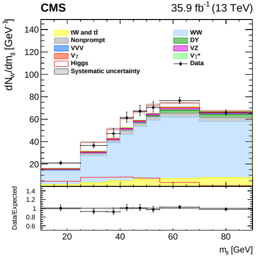
- Large $\mathcal{B}$, consider $W \to \ell\nu$ ($\mathcal{B}$ =10%)
- prod: gg/VBF/VH $\sim$ 25/1/1.4;
- clean final state, but with 2 ν.
  - No M_{WW} reconstruction possible
  - reconstruct $M_{\ell\ell}$ mass
  - and $M_T = \sqrt{2p_T^{\ell\ell}E_T^{miss}(1-\cos\Delta\phi)}$
- large background
- Selection
  - Opposite charge ℓ, MET
  - Use W polarization from H decay to reduce WW background
  - control regions for background normalization
- categories for 0,1,2 jets, additional ℓs

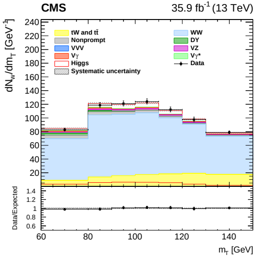


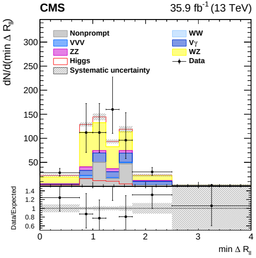
- Signal extraction based on M_T, $M_{\ell\ell}$ or $\Delta R_{\ell\ell}^{min}$ (ZH)
- many categories, as usual...
- significance 9.1σ (7.1 expected):
- $\mu = 1.28 \pm 0.18$

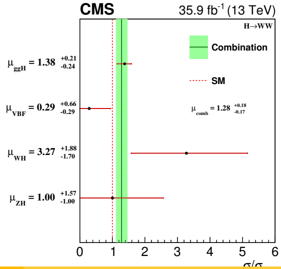
Ch vs Prod







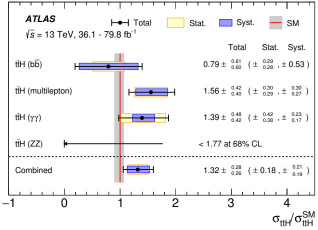


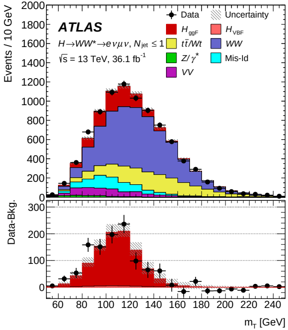


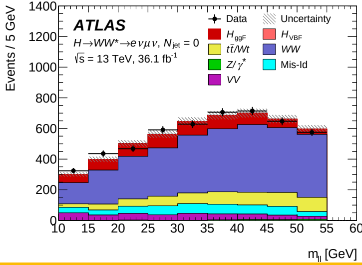
$H \rightarrow WW$: ATLAS results [5]

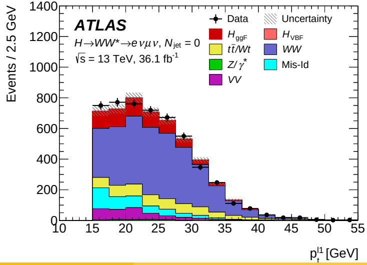
- $WW \rightarrow e\nu\mu\nu$, categories: N jets$= 0, 1, \geq 2$
- measured ggF as well as VBF cross section;
- sensitive variable are: $M_{\ell\ell}, M_T$ and $p_T^{sublead}$ (2^{nd} ℓ)
- significance: ggF 6.3σ (7.1 expected) - VBF 1.9 (2.7)
- $\mu_{ggF} = 1.21 \pm 0.22$, $\mu_{VBF} = 0.62 \pm 0.36$,

ggF vs VBF

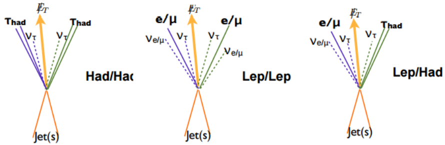


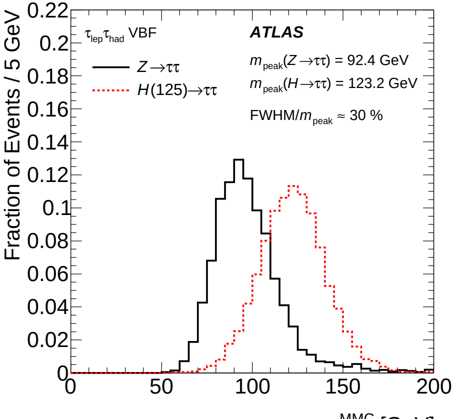




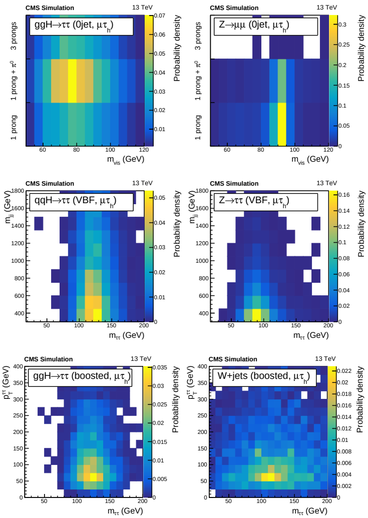


- Direct probe of coupling to fermions;
- sizeable $\mathcal{B}$
  - use all τ decay channel
  - leptonic and hadronic
- most powerful variable $M_{\tau\tau}$ $\sigma_M \sim 10\%$
  - M_H =125 GeV close to M_Z =91 GeV
  - use kinematic fit of $M_{\tau\tau}$ using visible products and MET
  - $Z \to \tau\tau$ background estimated via $Z \to \mu\mu$ and replacing $\mu \leftrightarrow \tau$
- many categories according to production mechanism
  - additional ℓ (VH);
  - additional F-B jets (VBF);
  - boosted topology;
  - 0/1 jets;





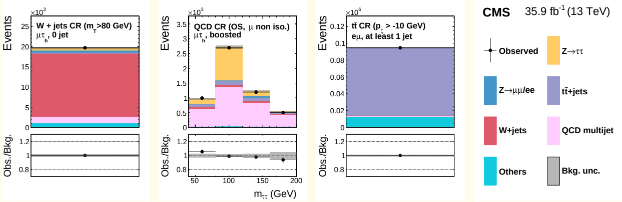
$H \to \tau\tau$: CMS Observables [9]



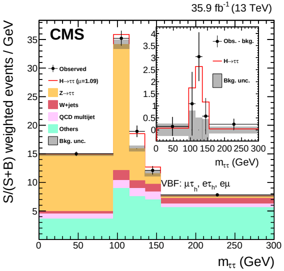
Distribution for signal (left) and background (right) in $\mu\tau_h$ final state:

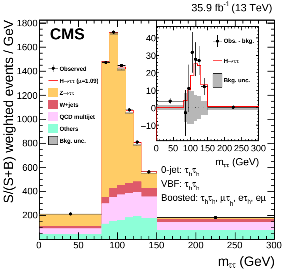
- M_{vis} in 0-jet category (visible $\tau\tau$ mass)
  - 1 prong
  - 1 prong $+\pi^0$
  - 3 prongs
- $M_{\tau\tau}$ in VBF category ($\tau\tau$ using kin fit)
- $M_{\tau\tau}$ in boosted categoty

Several control samples with enriched W+jets, QCD, $t\bar{t}$

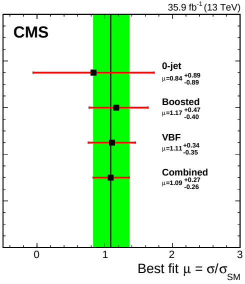


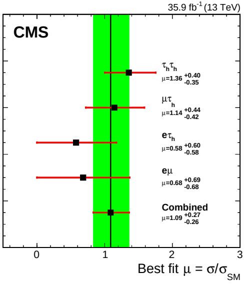
$H \to \tau\tau$: CMS results [9]





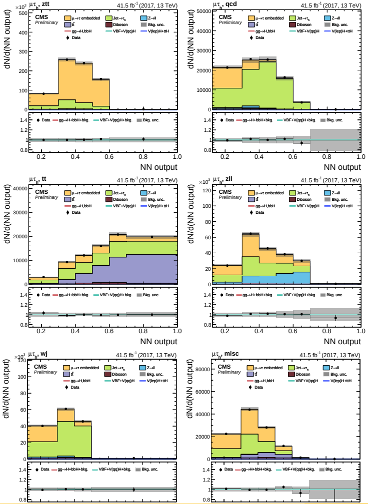
- signal searched in *ggH*, boosted, VBF, and VH (not separately)
  - significance 4.7σ 13 TeV.
  - 3.2σ at 7+8 TeV
- Combined: 5.9σ
- $\mu = 1.07 \pm 0.20(stat) \pm 0.15(syst)$

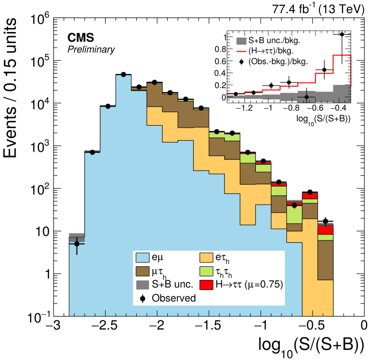


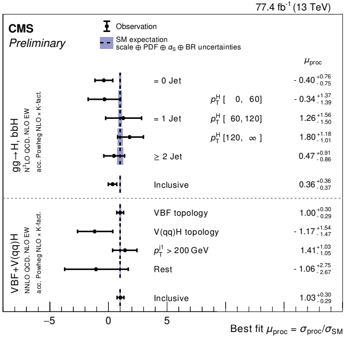


$H \to \tau\tau$: CMS results [10]

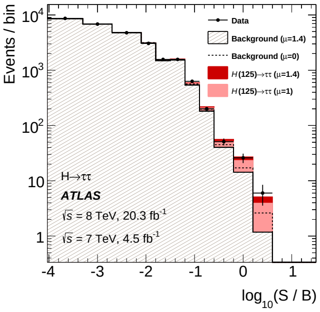
New analysis (using 77.4 fb^{-1}) fully based on Neural Network, condidering different final state and different production mechanism, each quite pure, to extract the full information.

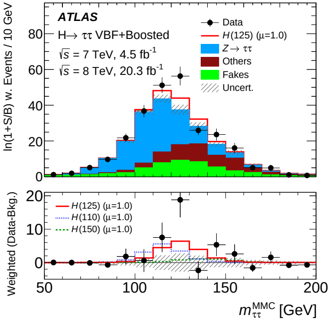


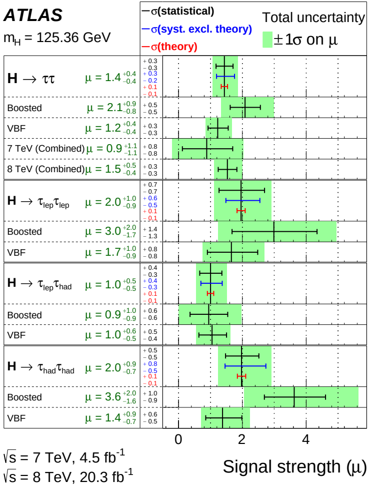




- Similar analyisis
  - boosted, VBF
  - $\tau \to h' s\nu, e\nu\nu, \mu\nu\nu$
- significance at 7+8 TeV: 4.3σ (3.4 expected)
- $\mu = 1.4 \pm 0.4$ (VBF 1.2 ± 0.4, boosted 2.1 ± 0.9)

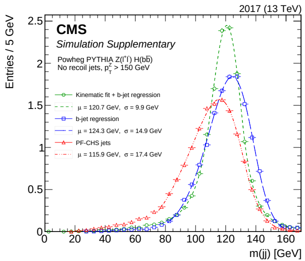


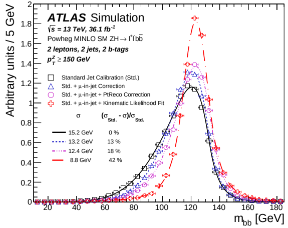




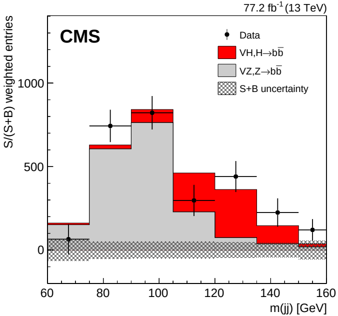
$H \to bb$ CMS [12], ATLAS [13]

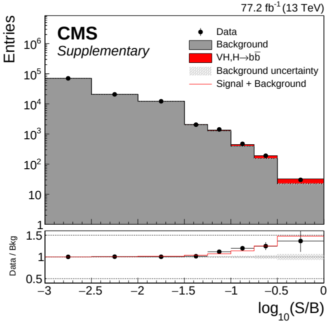
- Mostly in associated production: VH, ttH, bbH
  - $W/Z + H \to \ell\nu/\ell\ell/\nu\nu + bb$
  - Selection: two central b-tag jets
  - 0,1,2 ℓ (different prod mechanism)
  - MVA for final selection
  - also gg in boosted regime
- Key element is M_{bb} resolution
  - Use b-jet regression and kin fit to improve it
  - in 35% b jet has a ν: bJES different from light-JES
  - Use MVA calibration
    - ★ trained with GenJets on MC
    - ★ use jet-related and event variables:
    - ★ p_T, η jet composition (charged/neutral/em/μ/...), b-tag, soft-lepton, MET, ...
    - ★ plus kin fit
    - ★ σ : 17 $\to$ 10 GeV
- Background $WZ + light$, $W/Z + bb$, $t\bar{t}$

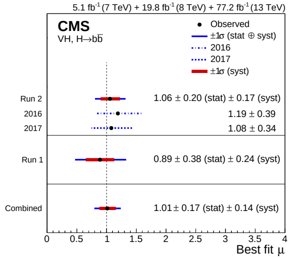




- final states considered: $Z(\nu\nu/ee/\mu\mu)H(b\bar{b}),\ W(e/\mu\nu)H(b\bar{b})$
- background: $VZ(b\bar{b})$, peaks are not resolved, and V+jets



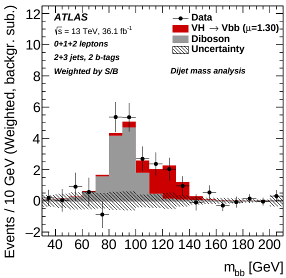


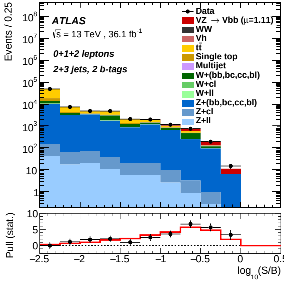


	Significance (σ)		
Data set	Expected	Observed	Signal strength
2017			
0-lepton	1.9	1.3	0.73 ± 0.65
1-lepton	1.8	2.6	1.32 ± 0.55
2-lepton	1.9	1.9	1.05 ± 0.59
Combined	3.1	3.3	1.08 ± 0.34
Run 2	4.2	4.4	1.06 ± 0.26
Run 1 + Run 2	4.9	4.8	1.01 ± 0.23

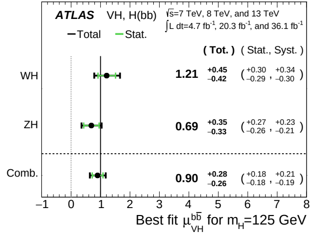
$H \to bb$ ATLAS VH results [13]

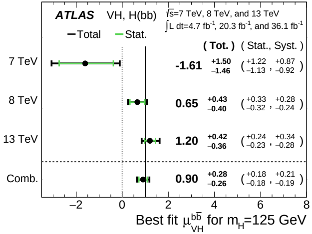
Analysis similar to CMS
VH (Z/W+H), 0,1,2 ℓ, categories





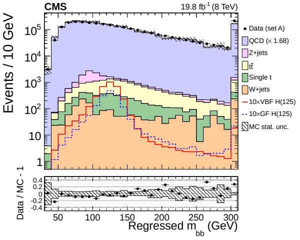
Significance 4.9 (4.3)σ



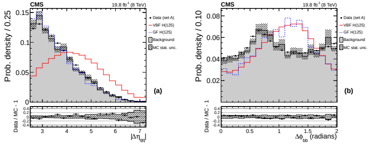


$H \to bb$ CMS VBF [14]

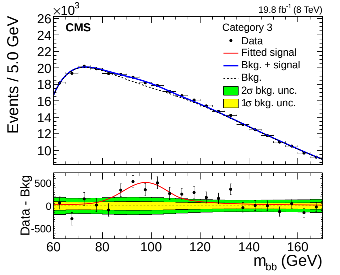
Final state $qqb\bar{b}$, large QCD background, then Z+jets, tt.



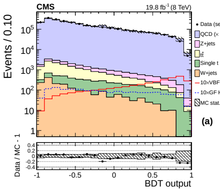
- Selection using topology (fwd/bwk qq jets), $\Delta\phi_{bb}$, BDT
- Separation of VBF from gg from $\Delta\phi/\eta_{bb}$

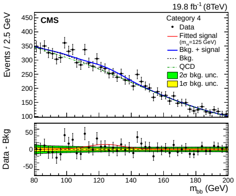


Important benchmark is extraction of $Z \to b\bar{b}$ signal



7 category, this is the best one



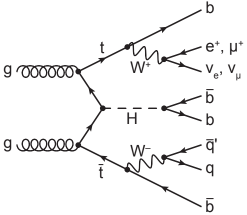


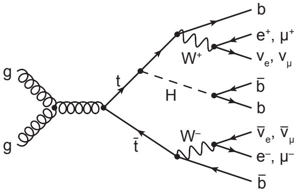
Fitting all together

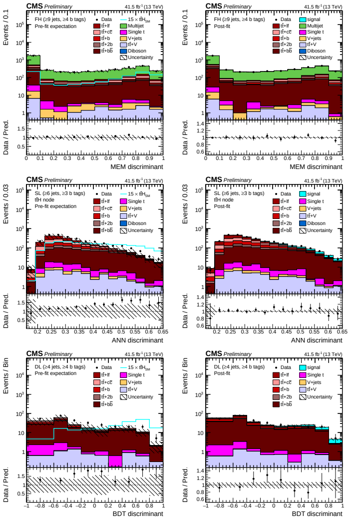
$H \to b\bar{b}$ Channel	Best fit (68% CL) Observed	Upper limits (95% CL) Observed	Upper limits (95% CL) Expected	Signal significance Observed	Signal significance Expected
VH	0.89 ± 0.43	1.68	0.85	2.08	2.52
$t\bar{t}H$	0.7 ± 1.8	4.1	3.5	0.37	0.58
VBF	$2.8^{+1.6}_{-1.4}$	5.5	2.5	2.20	0.83
Combined	$1.03^{+0.44}_{-0.42}$	1.77	0.78	2.56	2.70

$ttH \to bb$ CMS [15, 16]

Rich but terrific final state







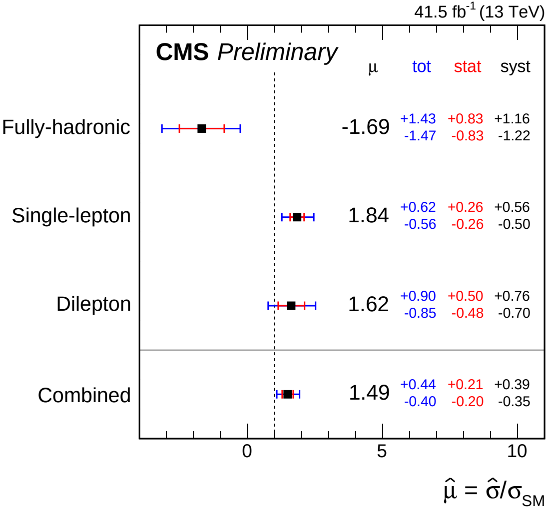
- Extremely complex analysis fully based on MVA techniques;
- categories based on N jets and N b-jets;

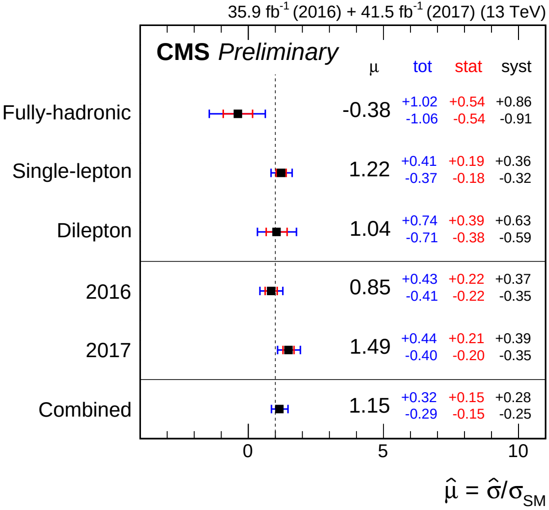
2ℓ "Standard" MVA:ANN, BDT and, MEM;

1ℓ Deep Neural Network (DNN) [one of the first usage in CMS];

- Combined significance 3.9σ (3.5 expected)

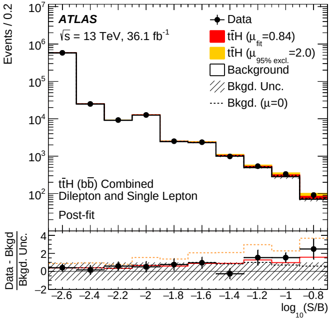
$ttH \to bb$ CMS [16]: results

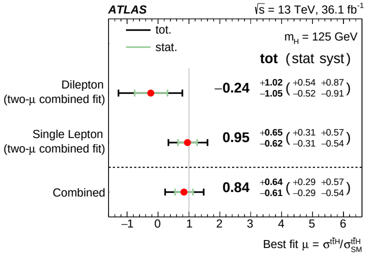


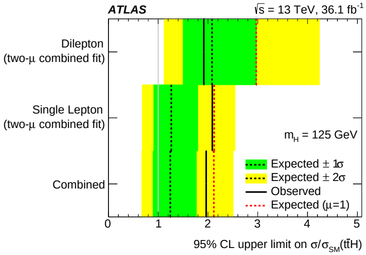


$ttH \to bb$ ATLAS [17]

- Also heavily MVA based, no DNN;
- Categorization based on N jets and b-tagging classifier ;
- Single and double lepton final state.





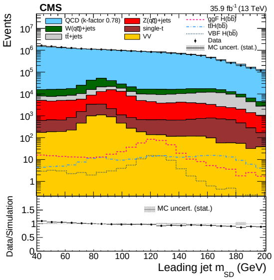


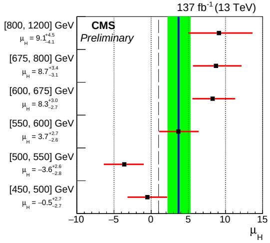
Significance 1.4σ (1.6 expected)

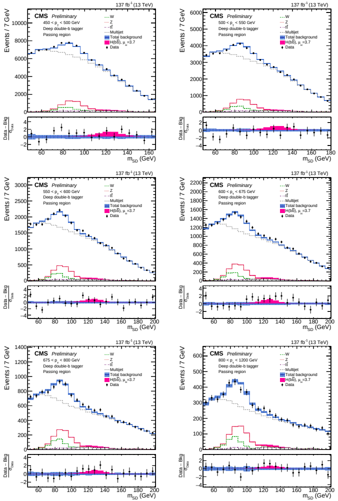
post fit results:

$H \to bb$ boosted [18, 19]

- Search for $gg \to H \to bb$ $\sim 2.54\sigma$ (0.7 expected)
- Boosted regime: $p_T > 450$, single "fat" jet topology, look at fat-jet inv mass
  - signal region is double b-tagged fat jets
  - data driven QCD background from fat jets w/o double b-tag (also $W \to qq$ present)
- method validated with $Z \to bb$: clear signal!

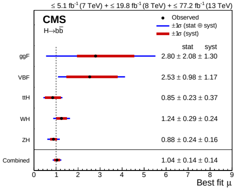






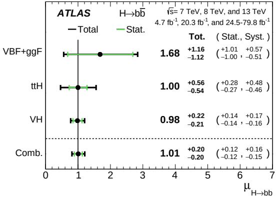
- CMS, using all $H \to bb$ searches:
  - VH (4.8σ) [12]
  - VBF (2.56σ) [14]
  - ttH (3.9σ) [15, 16] (new)
  - gg (boosted topology) (1.5σ) [18]

signal significance is $5.6(5.5)\sigma$ (not updated)

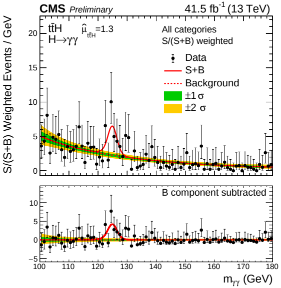


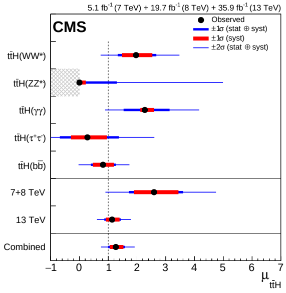
- Same for ATLAS
- no gg

Channel	Significance Exp.	Significance Obs.
VBF+ggF	0.9	1.5
$t\bar{t}H$	1.9	1.9
VH	5.1	4.9
$H \to b\bar{b}$ combination	5.5	5.4

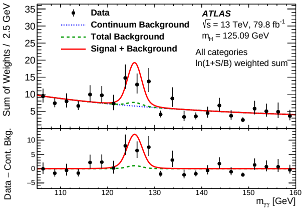


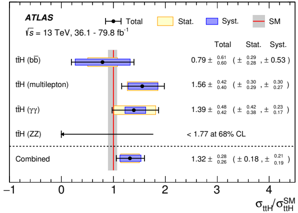
CMS: ttH $H \to \gamma\gamma$
categories by BDT and $0, \geq 1\ell$





significance: $5.2(4.2)\sigma$, $\mu = 1.26^{+0.31}_{-0.26}$

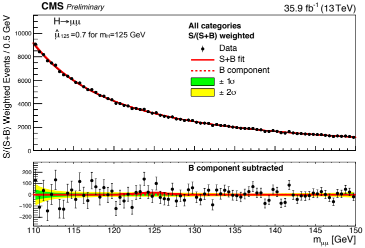


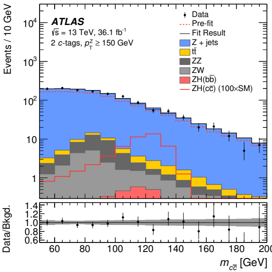


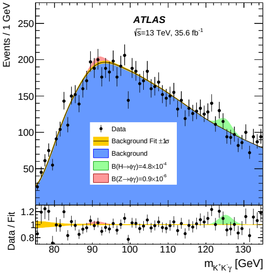
significance: $6.3(5.1)\sigma$, $\mu = 1.32^{+0.28}_{-0.26}$

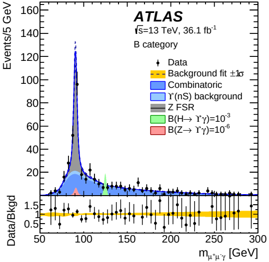
Other channels

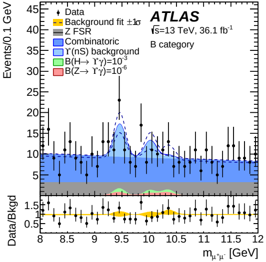
- $H \to \mu\mu \;\; \mu < 2.6 - 2.8$ [23, 24]
- $H \to Z\gamma \;\; \mu < 3.9 - 6.0$ [25, 26, 27]
- $H \to invisible \;\; \Gamma_{inv} < 28 - 26\%$ [28, 29]
- $H \to c\bar{c} \;\; \mu \lesssim 150/70$ [30, 31]
- $H/Z \to (\phi/\rho)\gamma \;\; BR(H \to (\phi/\rho)) \lesssim (4.8/8.8)10^{-4}$ [32]
- $H/Z \to (J/\psi/\psi'/\Upsilon(nS))\gamma \;\; BR \lesssim (3.5/0.2/5)10^{-4}$ [33]





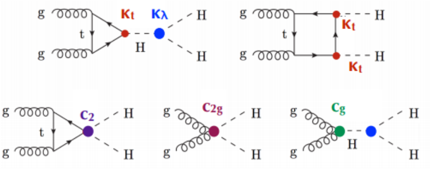


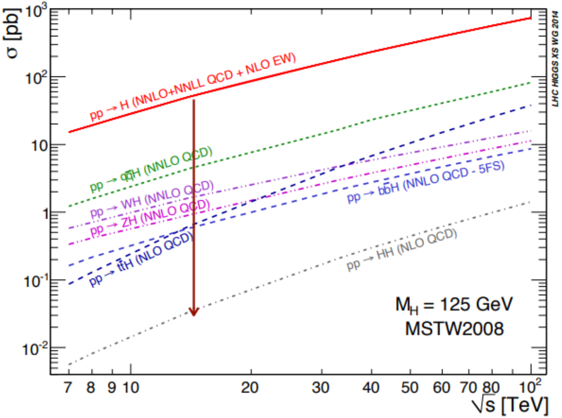




double Higgs production

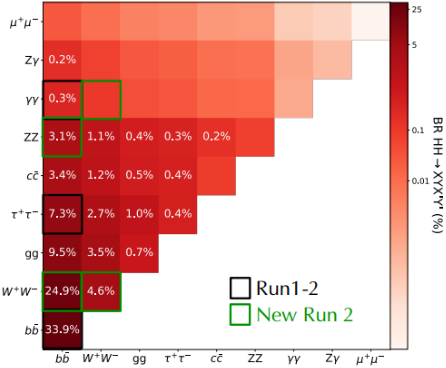
- probe shape of H potential in $\mathcal{L}_{SM}$
- destructive interference: small rate $\sigma_{SM} = 33\ fb$ at 13 TeV
- sensitive to BSM: $\lesssim 20\%$ precision to probe BSM
- Effective Field Theory approach



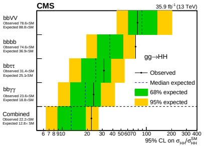


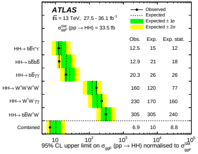
Many searches

- one $H \to bb$ for large BR,
- other H for signal/background separation ($\gamma\gamma, ZZ, WW, \tau\tau$)



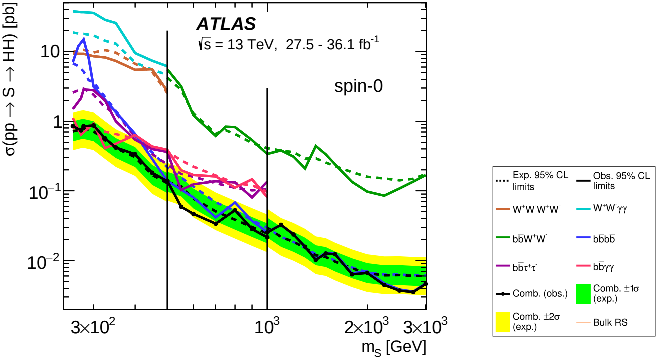
$HH \to$	Limits on μ Obs (exp)	L fb^{-1}
$bbbb$ [34, 35]	37,13	36
$bb\gamma\gamma$ [36, 37]	24,22	36
$bb\tau\tau$ [38, 39]	30,12.7	36
$bbWW/ZZ$ [40, 41]	79, 190	36
$WWWW$ [42]	160	36
$WW\gamma\gamma$ [40, 43]	80,230	36

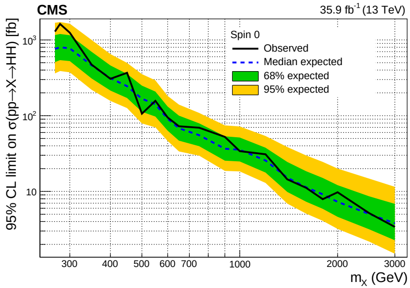




Combination probes $\mu \lesssim 10$ [44, 45] and $k_\lambda (= \lambda_{HHH}/\lambda_{SM}) \in [-2.3, 10.1]$ [46]

Search for hig mass resonant HH: summary



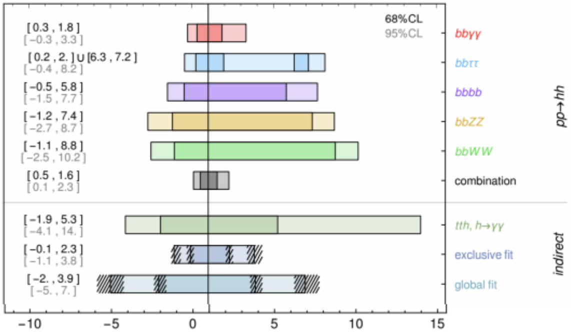


$HH \to bbbb$ most sensitive for high M_x, $HH \to bb\gamma\gamma$ complementary at low mass

Perspectives for HH at HL-LHC [47]

- Estimates of the sensitivity to HH at HL-LHC are based on:
  - extrapolations from Run-2 analyses
  - dedicated studies with smeared/parametric detector response, corresponding to pile-up of 200
- A combined significance to the **SM HH process of 4σ** can be achieved with all systematic uncertainties

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined		Combined	
	4.5		4.0	

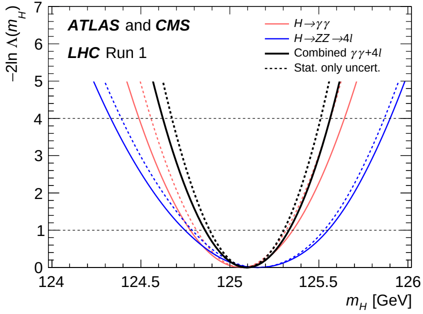


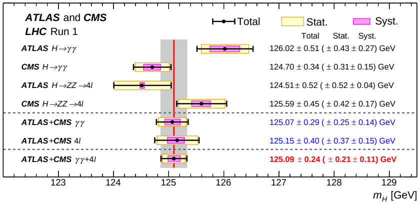
Mass: 8 TeV combined CMS+ATLAS results [48]

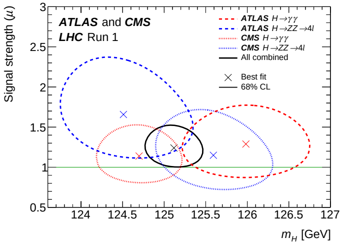
Mass resolution

- $H \to \gamma\gamma$ $\sigma_M \sim 1 - 2\%$
- $H \to ZZ \to 4\ell$ $\sigma_M \sim 1 - 2\%$
- $H \to WW$ $\sigma_M \sim 20\%$
- $H \to \tau\tau$ $\sigma_M \sim 10 - 20\%$
- $H \to bb$ $\sigma_M \sim 10\%$
- $H \to \mu\mu$ $\sigma_M \sim 1 - 2\%$

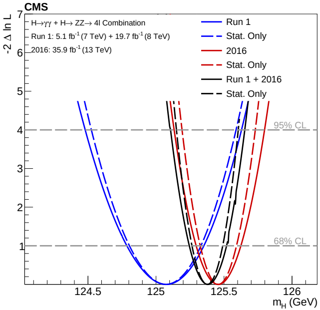
$M_H = 125.09 \pm 0.21(stat) \pm 0.11(syst)$ GeV

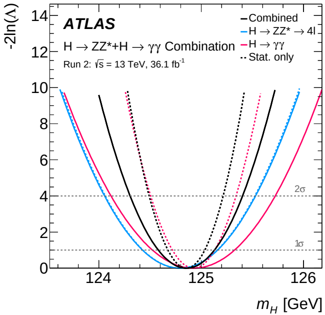




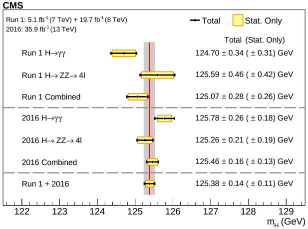


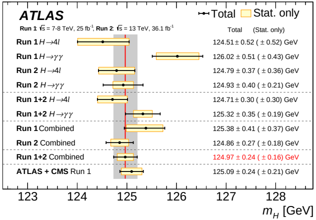
Mass: 13 TeV results. CMS [5, 4, 49], ATLAS [50]





exp	Run	Mass ±(stat) ±(syst) [GeV]
LHC	1	125.09 ± 0.21 ± 0.12
CMS (4ℓ)	2	125.26 ± 0.20 ± 0.08
CMS ($\gamma\gamma$)	2	125.78 ± 0.26 ± 0.18
CMS	2	125.46 ± 0.16 ± 0.13
CMS	1+2	125.38 ± 0.14 ± 0.11
ATLAS (4ℓ)	2	124.79 ± 0.37 ± 0.36
ATLAS ($\gamma\gamma$)	2	124.93 ± 0.40 ± 0.21
ATLAS	2	124.86 ± 0.27 ± 0.18
ATLAS	1+2	124.97 ± 0.16 ± 0.18
PDG	2020	125.10 ± 0.14

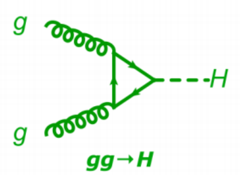




How to measure Γ_H

- Expected (SM) $\Gamma_H = 4\ MeV$ for $M_H = 125$ GeV
- Direct measurement
  - highest resolution channels ($\gamma\gamma$ and 4ℓ) has a M resolution few GeV;
  - direct upper limit $\Gamma_H \lesssim 1\ GeV$ at 95% C.L. (from $H \to 4\ell$ decay);
  - direct lower limit $\Gamma_H \gtrsim 3.5 \cdot 10^{-12}\ GeV$ at 95% C.L. (from $H \to 4\ell$ vertex lifetime);
- Indirect limit
  - Invariant mass distribution governed by Higgs propagator

$$\frac{d\sigma_{pp\to H\to ZZ}}{dM^2_{4\ell}} \propto \frac{g^2_{Hgg}g^2_{HZZ}}{(M^2_{4\ell}-m^2_H)^2+m^2_H\Gamma^2_H}$$



On-shell

$$M_{4\ell} - m_H \lesssim \Gamma_H$$

$$\sigma^{on-shell}_{gg\to H\to ZZ^*} \propto \frac{g^2_{Hgg}g^2_{HZZ}}{m^2_H\Gamma^2_H}$$

Off-shell

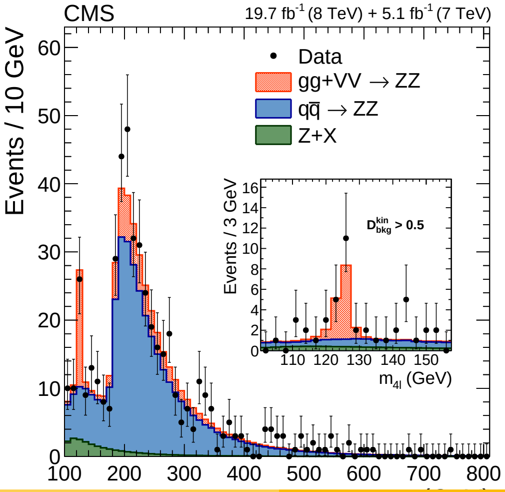
$$M_{4\ell} > 2m_Z,\ M_{4\ell} - m_H \gg \Gamma_H$$

$$\sigma^{off-shell}_{gg\to H^*\to ZZ} \propto \frac{g^2_{Hgg}g^2_{HZZ}}{2m_Z}$$

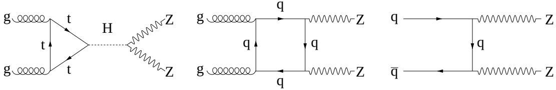
Ratio of off-shell/on-shell production is sensitive to Γ_H

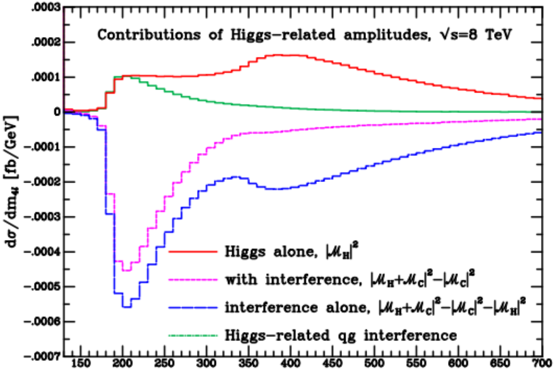
Width

Off-shell cross-section increases when the two Z are produced on-shell



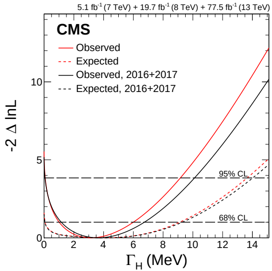
Must consider interference effect among different diagram with same final state:





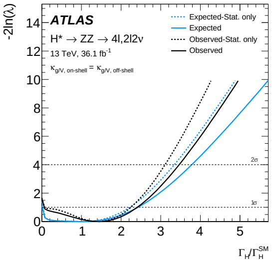
CMS: use $ZZ \to 4\ell$ and $ZZ \to 2\ell 2\nu$

2D $\mathcal{L}$ fit to $M_{4\ell}$ (or M_T) vs MELA



Parameter	Observed	Expected
Γ_H (MeV)	$3.2^{+2.8}_{-2.2}$ [0.08, 9.16]	$4.1^{+5.0}_{-4.0}$ [0.0, 13.7]

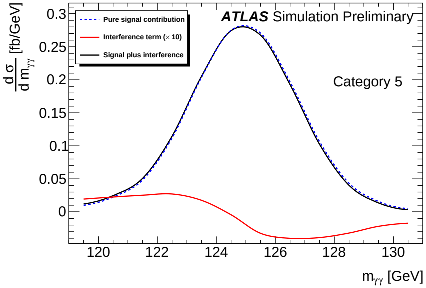
ATLAS [51]:



		Observed	Expected		
			Median	$\pm 1\ \sigma$	$\pm 2\ \sigma$
$\mu_{\text{off-shell}}$	$ZZ \to 4\ell$ analysis	4.5	4.3	[3.3, 5.4]	[2.7, 7.1]
	$ZZ \to 2\ell 2\nu$ analysis	5.3	4.4	[3.4, 5.5]	[2.8, 7.0]
	Combined	3.8	3.4	[2.7, 4.2]	[2.3, 5.3]
Γ_H/Γ_H^{SM}	Combined	3.5	3.7	[2.9, 4.8]	[2.4, 6.5]
R_{gg}	Combined	4.3	4.1	[3.3, 5.6]	[2.7, 8.2]

Limit on Γ_H at 95% C.L.: CMS $\Gamma_H < 9.16$ MeV, ATLAS: $\Gamma_H < 14.4$ MeV

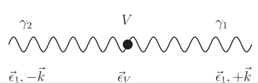
- In $H \to \gamma\gamma$, interference between $gg \to H \to \gamma\gamma$ and $gg \to \gamma\gamma$ change on-shell cross section. [53, 54]
  - shift of $M_{H\to\gamma\gamma}$ estimated 35 ± 9 MeV [55] which depends on Γ_H;
  - possible to measure Γ_H
  - with $3\,\text{ab}^{-1}$, upper limit on $\Gamma_H \sim 200$ MeV
- also cross section changes due to interference
  - combined with previous 95% C.L. on $\Gamma_H \sim 60$ MeV with $3\,\text{ab}^{-1}$
- using on-shell vs off-shell cross section measurement [56]
  - with $3\,\text{ab}^{-1}$ expected results at 95% C.L. $\Gamma_H = 4.1^{+0.7}_{-0.8}$ MeV.



Spin: is it really a 0^+?

Detection of $H \to \gamma\gamma$ rules out the $J = 1$ state (Landau-Yang theorem)

Landau-Yang theorem



$M(\vec{\epsilon}_1, \vec{\epsilon}_2, \vec{\epsilon}_V, \vec{k})$ is a scalar.

For γ: $\vec{\epsilon}_{1,2} \cdot \vec{k} = 0$. So two possibilities:

$M \propto (\vec{\epsilon}_1 \times \vec{\epsilon}_2) \cdot \vec{\epsilon}_V \qquad (J^P = 1^-)$

$M \propto (\vec{\epsilon}_1 \cdot \vec{\epsilon}_2)(\vec{\epsilon}_V \cdot \vec{k}) \qquad (J^P = 1^+)$

But γ obeys to BE statistics

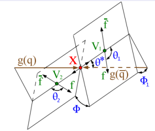
$$M(\gamma_1, \gamma_2) = M(\gamma_2, \gamma_1)$$

$(\vec{\epsilon}_2 \times \vec{\epsilon}_1) \cdot \vec{\epsilon}_V = -(\vec{\epsilon}_1 \times \vec{\epsilon}_2) \cdot \vec{\epsilon}_V$ NO

$(\vec{\epsilon}_2 \cdot \vec{\epsilon}_1)(\vec{\epsilon}_V \cdot (-\vec{k})) = -(\vec{\epsilon}_1 \cdot \vec{\epsilon}_2)(\vec{\epsilon}_V \cdot \vec{k})$ NO

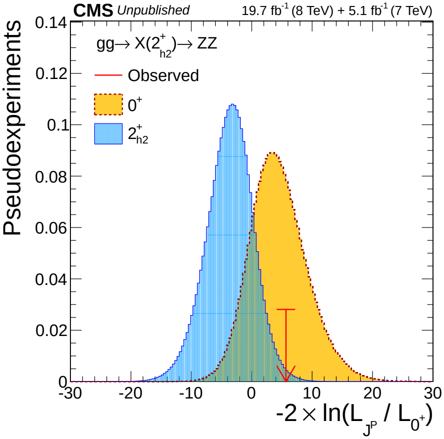
More states can be tested using the angular information from

- $H \to ZZ \to 4\ell$
  - angles from MELA analysis are very powerful

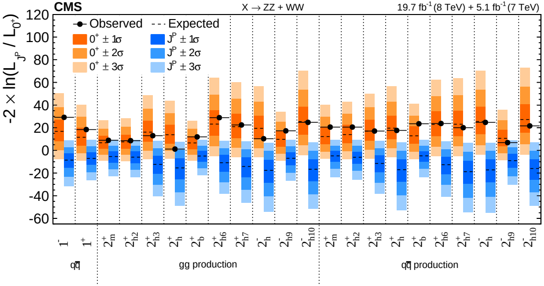


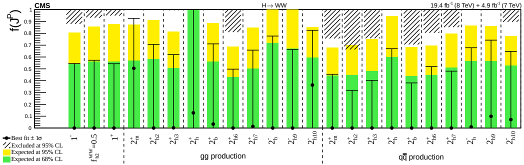
- $H \to WW \to 2\ell 2\nu$
  - $\Delta\phi_{\ell\ell}$
- $H \to \gamma\gamma$
  - $p_T^{\gamma\gamma}$
  - $|\cos\theta^*|$

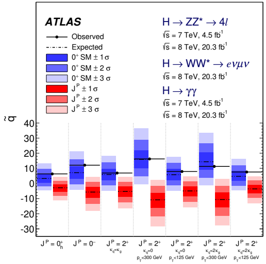
- A $\mathcal{L}$ is build for SM 0^+ hypotesis
- and exotic one J^P
- using all variables sensitive to Higgs spin/parity (angles, $\Delta\phi_{\ell\ell}$, $p_T^{\gamma\gamma}$, $|\cos\theta^*|$)
- A $\mathcal{L}$ ratio is used to compare the two hypotesis
- pseudo-experiment to build the two $\mathcal{L}$ distributions:
- Positive $-2\ln\mathcal{L}_{J^P}/\mathcal{L}_{0^+}$ means that J^P is less likely than 0^+
- Many different and exotic possiblities are checked: $0^-, 1^\pm, 2^\pm$

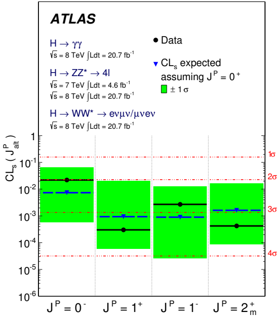


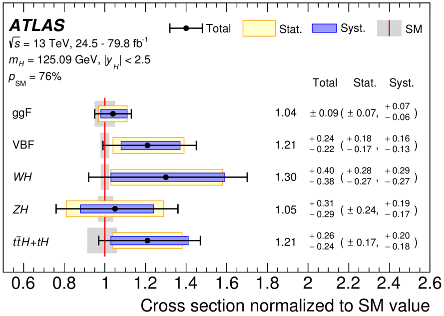
Spin results: CMS [57], ATLAS [58, 59]

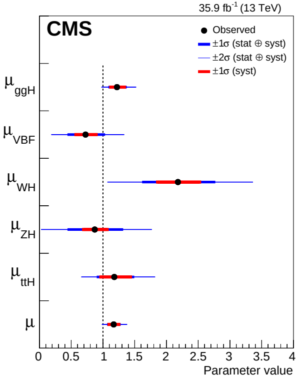






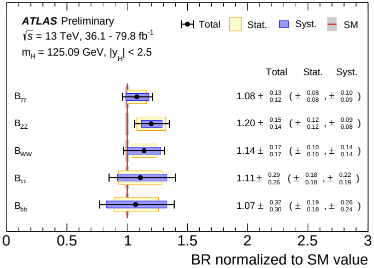


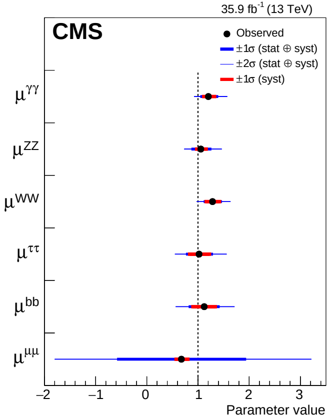


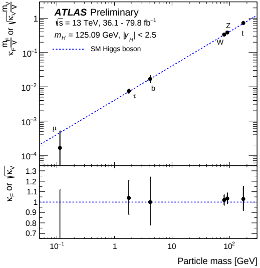


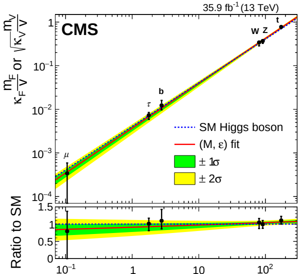
All main production modes have been observed. Global signal strength: $\mu = 1.13 \pm 0.09 / 1.11 \pm 0.09$ CMS/ATLAS

Higgs Coupling: by final state [60, 62]

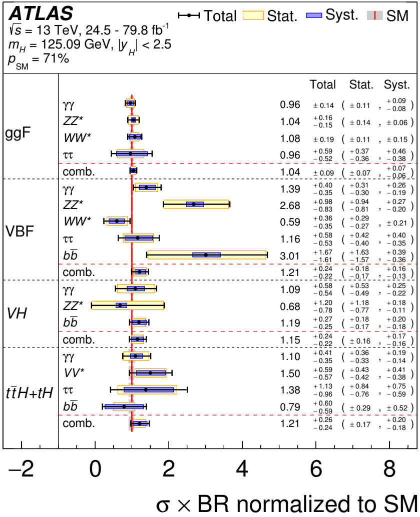


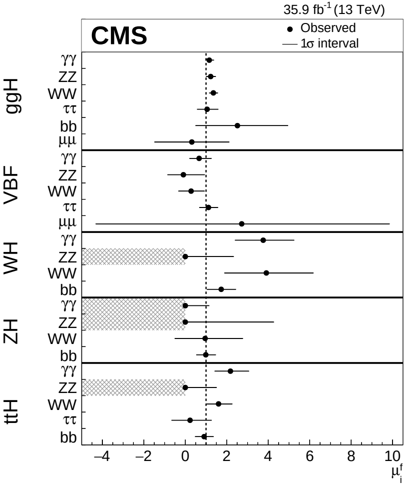






Coupling by final state/production mechanism [60, 62]

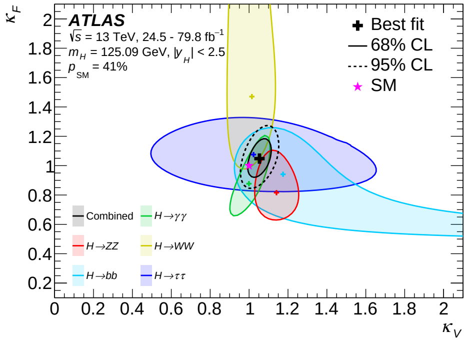


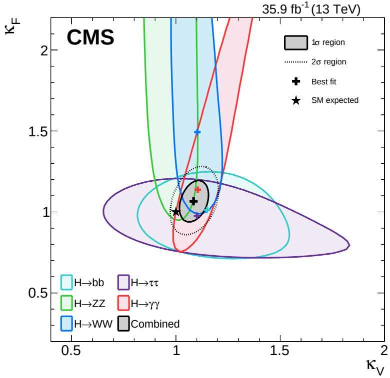


$\kappa_{F,V}$: scaling factor of Yukawa coupling of fermions and bosons (= 1 in SM)

- Fermions: $g_F = \kappa_F \sqrt{2} m_F / \nu$
- Bosons: $g_V = \kappa_V 2 m_V^2 / \nu$

$H \to \gamma\gamma$ distinguish up-down quadrant, thanks to top and W loop origin





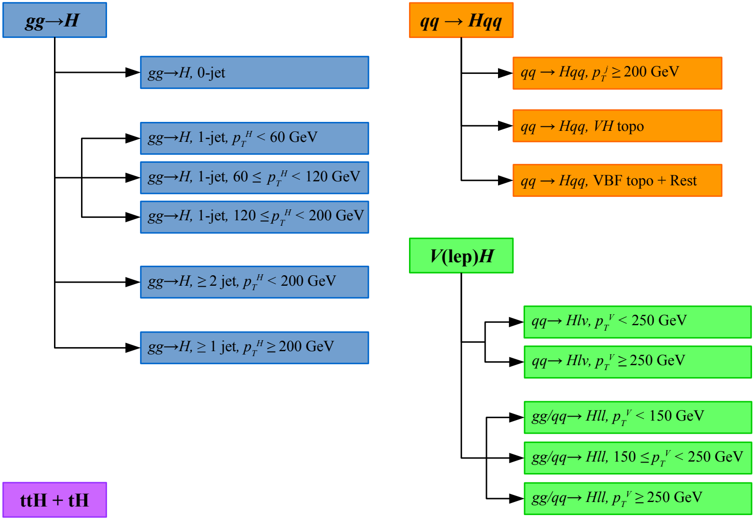
- intepretation of Higgs coupling in term of Wilson coefficient of effective Lagrangian, alternative to k-framwork [63] than $k_f^2 = \Gamma_f/\Gamma_f^{SM}$
- Effective Lagrangian approach for Higgs

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \Sigma_i \frac{C_i^{(d)}}{\Lambda^{(d-4)}} \mathcal{O}_i^{(d)} \quad \text{for } d > 4$$

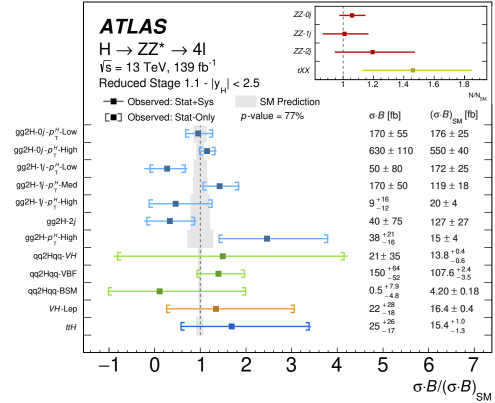
- Possible to define a common event categorization (CMS/ATLAS) with corresponding sensitiveness to different C_i

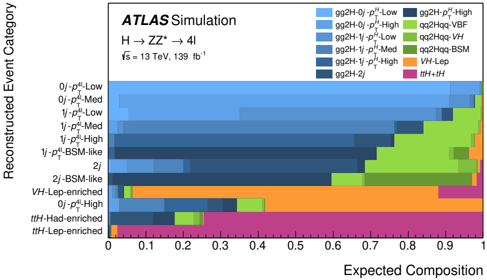
CP-even			CP-odd			Impact on	
Operator	Structure	Coeff.	Operator	Structure	Coeff.	production	decay
O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	c_{uH}	O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	$c_{\tilde{u}H}$	ttH	-
O_{HG}	$HH^\dagger G^A_{\mu\nu} G^{\mu\nu A}$	c_{HG}	$O_{H\tilde{G}}$	$HH^\dagger \tilde{G}^A_{\mu\nu} G^{\mu\nu A}$	$c_{H\tilde{G}}$	ggF	Yes
O_{HW}	$HH^\dagger W^l_{\mu\nu} W^{\mu\nu l}$	c_{HW}	$O_{H\widetilde{W}}$	$HH^\dagger \widetilde{W}^l_{\mu\nu} W^{\mu\nu l}$	$c_{H\widetilde{W}}$	VBF, VH	Yes
O_{HB}	$HH^\dagger B_{\mu\nu} B^{\mu\nu}$	c_{HB}	$O_{H\tilde{B}}$	$HH^\dagger \tilde{B}_{\mu\nu} B^{\mu\nu}$	$c_{H\tilde{B}}$	VBF, VH	Yes
O_{HWB}	$HH^\dagger \tau^l W^l_{\mu\nu} B^{\mu\nu}$	c_{HWB}	$O_{H\widetilde{W}B}$	$HH^\dagger \tau^l \widetilde{W}^l_{\mu\nu} B^{\mu\nu}$	$c_{H\widetilde{W}B}$	VBF, VH	Yes

STXS example of categorization [65]



STXS example sensitiveness [65]





- It exists!
- $M_H = 125.09 \pm 0.24\ GeV$
- $\Gamma_H < 10\ MeV$ ($\Gamma_H^{SM} = 4\ MeV$)
- $J^P = 0^+$
- coupling to fermions and gauge boson as expected from SM
  - Including direct evidence of coupling to third generation quarks
- all production mechanism seen,
- only missing item is di-Higgs production: task for HL-LHC

As Standard-Model-Higgs-particle as it can be

Outline

1 Z-pole observables

2 Asymmetries

3 W mass and width

4 Top mass

5 Higgs mass and features

6 Global ElectroWeak fit
- Future prospective

Electroweak sector given by 3 parameters

- once v, g, g' are known, all other parameters are fixed

$$M_W = \frac{v|g|}{2}$$

$$M_Z = \frac{v\sqrt{g^2 + g'^2}}{2}$$

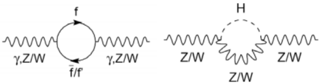
$$\cos\theta_W = \frac{M_W}{M_Z}$$

Use the three most precise parameters

- $\alpha : \Delta\alpha/\alpha = 3\times10^{-10}$
- $G_F : \Delta G_F/G_F = 5\times10^{-7}$
- $M_Z : \Delta M_Z/M_Z = 2\times10^{-5}$
- measure more than the minimal set of parameters to test the theory!

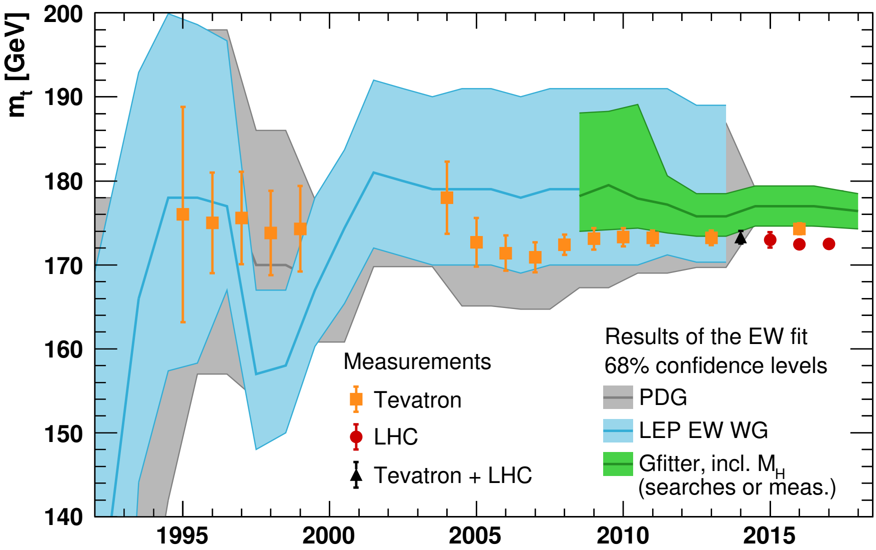
$$M_W^2 = \frac{M_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha}{G_F M_Z^2}}\right)$$

Radiative corrections



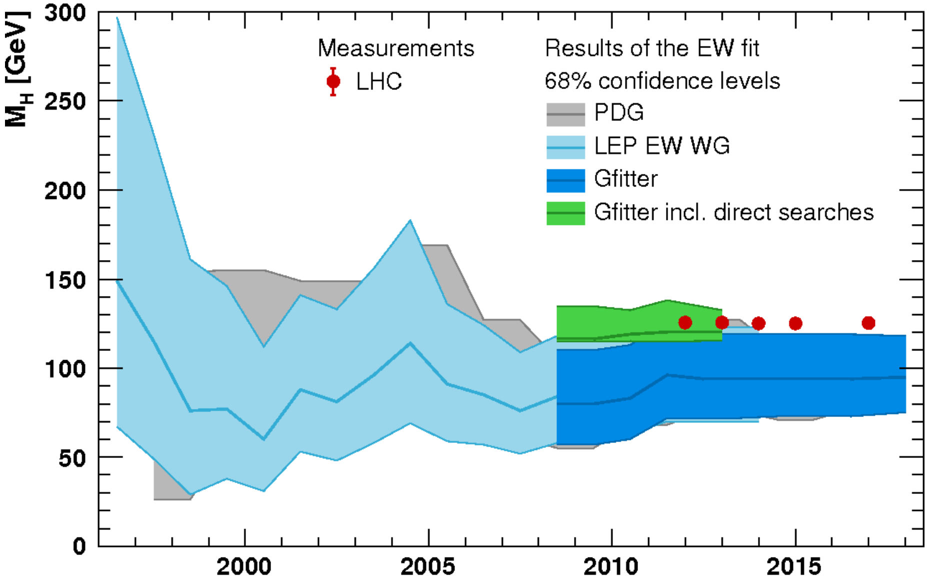
- modification of propagators and vertices
- electroweak form factors ρ, κ, Δr
  - depend on all parameters of the theory (m_t, M_H, α_s...)

$$M_W^2 = \frac{M_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha(1 + \Delta r)}{G_F M_Z^2}}\right)$$



m_t [GeV]
200
190
180
170
160
150
140
1995
2000
2005
2010
2015
Measurements
Tevatron
LHC
Tevatron + LHC
Results of the EW fit
68% confidence levels
PDG
LEP EW WG
Gfitter, incl. M_H
(searches or meas.)

Higgs Mass from Loop Effects



- Most from e^+e^- collider
- Many from hadrons one too;
  - M_Z: 0.002%
  - M_{top}: 0.4%
  - M_W: 0.016%
  - M_H: 0.16%
- requires procise calculation on theory side
  - M_W: full EW 1 and 2-loop plus 4-loop QCD correction;
  - $\sin^2\theta^{lept}_{eff}$: as M_W;
  - Γ_f 2-loop for all flavours;
  - Radiator N^3LO
  - Γ_W: only 1-loop EW (negligible in fit)
  - all: 1 and 2-loop QCD

M_H [GeV]	125.1 ± 0.2	LHC
M_W [GeV]	80.379 ± 0.013	Tev.+LHC
Γ_W [GeV]	2.085 ± 0.042	Tev.+LHC
M_Z [GeV]	91.1875 ± 0.0021	LEP
Γ_Z [GeV]	2.4952 ± 0.0023	LEP
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	LEP
R^0_ℓ	20.767 ± 0.025	LEP
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	LEP
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	LEP, SLD
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	LEP
$\sin^2\theta^\ell_{\rm eff}$(TEV)	0.23148 ± 0.00033	Tev. (+LHC?)
A_c	0.670 ± 0.027	SLD
A_b	0.923 ± 0.020	SLD
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	LEP
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	LEP
R^0_c	0.1721 ± 0.0030	LEP, SLD
R^0_b	0.21629 ± 0.00066	LEP, SLD
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$	2760 ± 9	low E
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	low E
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	low E
m_t [GeV]$^{(\triangledown)}$	172.47 ± 0.68	Tev.+LHC

Experimental and Theoretical input

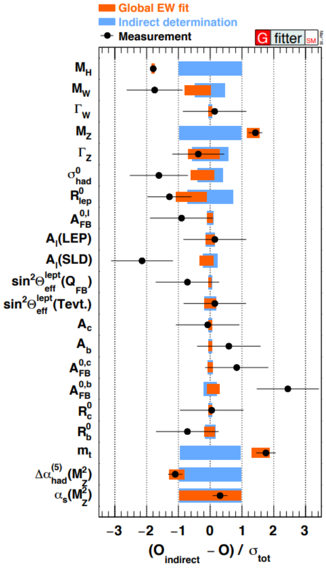
- Most from e^+e^- collider
- Many from hadrons one too;
  - M_Z: 0.002%
  - M_{top}: 0.4%
  - M_W: 0.016%
  - M_H: 0.16%
- requires procise calculation on theory side
  - M_W: full EW 1 and 2-loop plus 4-loop QCD correction;
  - $\sin^2\theta_{eff}^{lept}$: as M_W;
  - Γ_f 2-loop for all flavours;
  - Radiator N^3LO
  - Γ_W: only 1-loop EW (negligible in fit)
  - all: 1 and 2-loop QCD

Comparison of important contributions exp. vs theo. uncertainties

important

Observable	Exp. error	Theo. error
M_W	15 MeV	4 MeV
$\sin^2\theta^l_{\rm eff}$	$1.6 \cdot 10^{-4}$	$0.5 \cdot 10^{-4}$
Γ_Z	2.3 MeV	0.5 MeV
$\sigma^0_{\rm had}$	37 pb	6 pb
R^0_b	$6.6 \cdot 10^{-4}$	$1.5 \cdot 10^{-4}$
m_t	0.76 GeV	0.5 GeV

new in fit

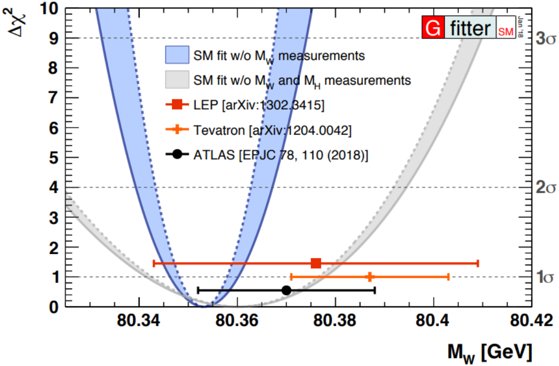


SM Fit Results

- χ^2_{min} = **18.6** Prob(χ^2_{min}, 15) = **23%**
  - χ^2_{min}(old m_t) = 17.3
  - χ^2_{min}(old M_W) = 19.3
- M_W: −1.5σ (−1.4σ previously)
  - central value smaller by 4 MeV
  - uncertainty reduced by 1 MeV
- m_t: 0.5σ (unchanged)
  - central value: 177 → 176.4 GeV
  - uncertainty reduced by 0.3 GeV
  - can reach ±0.9 GeV with perfect knowledge of M_W
- largest deviations in b-sector:
  - $A^{0,b}_{FB}$ with 2.5σ

[Gfitter, 1803.01853]

Predicting M_W

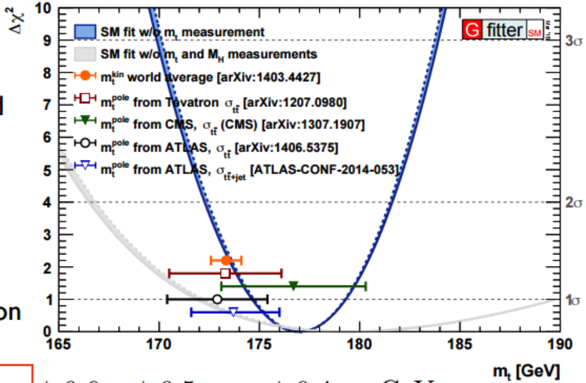


$$\begin{aligned} M_W &= 80.3535 \pm 0.0027_{m_t} \pm 0.0030_{\delta_{\rm theo} m_t} \pm 0.0026_{M_Z} \pm 0.0026_{\alpha_S} \\ &\quad \pm 0.0024_{\Delta\alpha_{\rm had}} \pm 0.0001_{M_H} \pm 0.0040_{\delta_{\rm theo} M_W} \ \text{GeV}\,, \\ &= 80.354 \pm 0.007_{\rm tot}\ \text{GeV} \end{aligned}$$

(exp: ± 0.013 GeV)

$\Delta\chi^2$ profile vs m_t

- determination of m_t from Z-pole data (fully obtained from rad. corrections $\sim m_t^2$)
- alternative to direct measurements
- M_H allows for significantly more precise determination of m_t

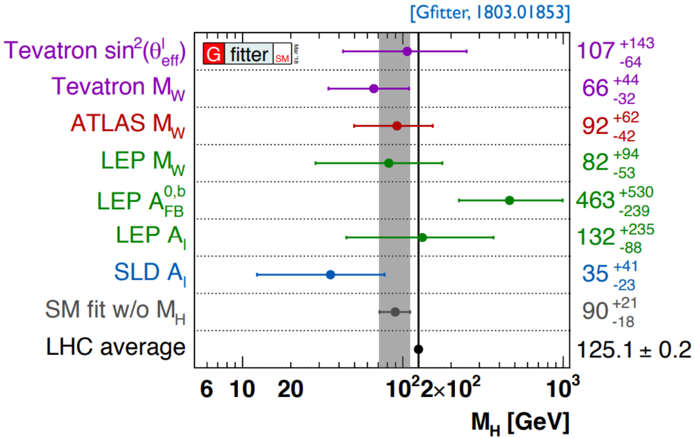


$$m_t = 177.0 \pm 2.3_{M_W,\, \sin^2\theta^f_{\rm eff}} \pm 0.6_{\alpha_s} \pm 0.5_{\Delta\alpha_{\rm had}} \pm 0.4_{M_Z}\ \mathrm{GeV}$$

$$= 177.0 \pm 2.4_{\rm exp} \pm 0.5_{\rm theo}\ \mathrm{GeV}$$

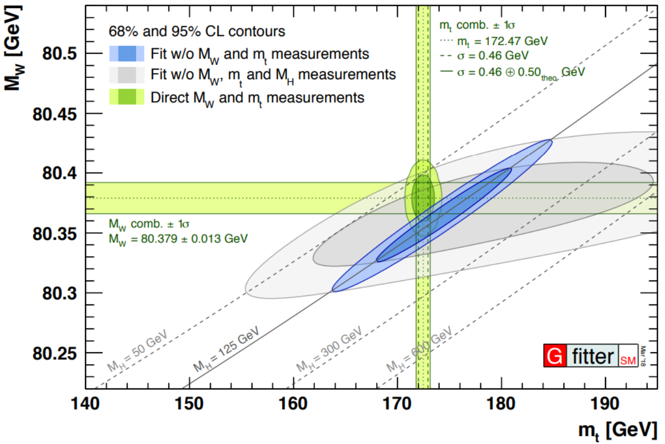
- similar precision as determination from $\sigma_{t\bar{t}}$, good agreement
- dominated by experimental precision

Predicting M_H

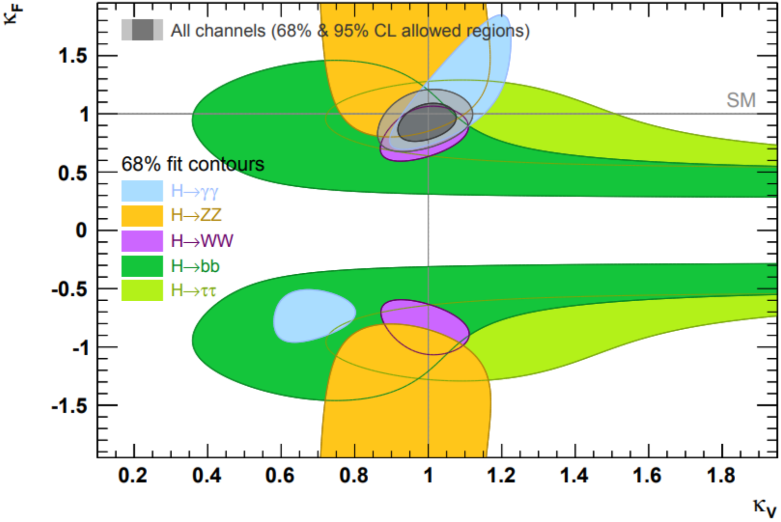


SM: Incredibly Healthy!

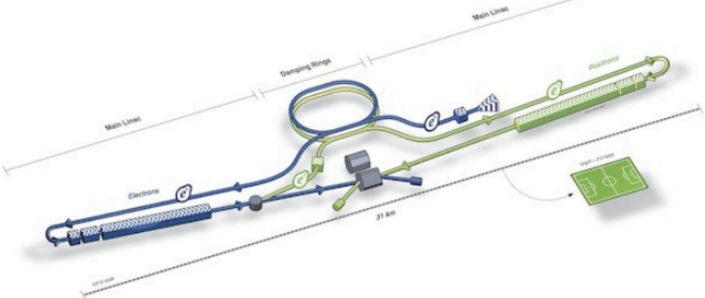
[Gfitter, 1803.01853]



Higgs coupling



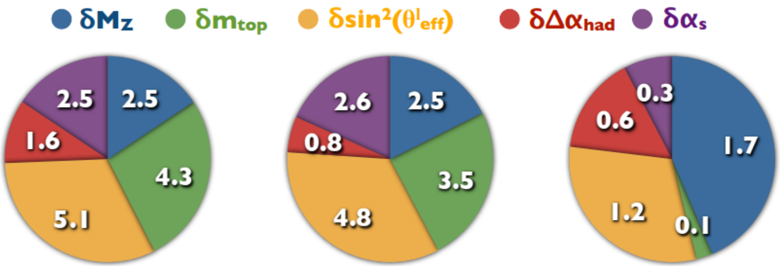
The Future


Main Linac
Damping Rings
Main Linac
Positrons
Electrons
31 km

Parameter	Present		LHC		ILC/GigaZ	
M_H [GeV]	0.2	→	< 0.1		< 0.1	
M_W [MeV]	15	→	8	→	5	WW threshold
M_Z [MeV]	2.1		2.1		2.1	
m_t [GeV]	0.8	→	0.6	→	0.1	$t\bar{t}$ threshold scan
$\sin^2\theta^\ell_{\rm eff}$ $[10^{-5}]$	16		16	→	1.3	$\delta A^{0,f}_{LR}$: $10^{-3} \rightarrow 10^{-4}$
$\Delta\alpha^5_{\rm had}(M^2_Z)$ $[10^{-5}]$	10	→	5		5	low energy data, better α_s
R^0_l $[10^{-3}]$	25		25	→	4	high statistics on Z-pole
κ_V (λ = 3 TeV)	0.05	→	0.03	→	0.01	direct measurement of BRs

- theoretical uncertainties reduced by a factor of 4 (esp. M_W and $\sin^2\theta^l_{\rm eff}$)
  - implies three-loop EW calculations!
  - exception: $\delta_{\rm theo}\, m_t$ (LHC) = 0.25 GeV (factor 2)

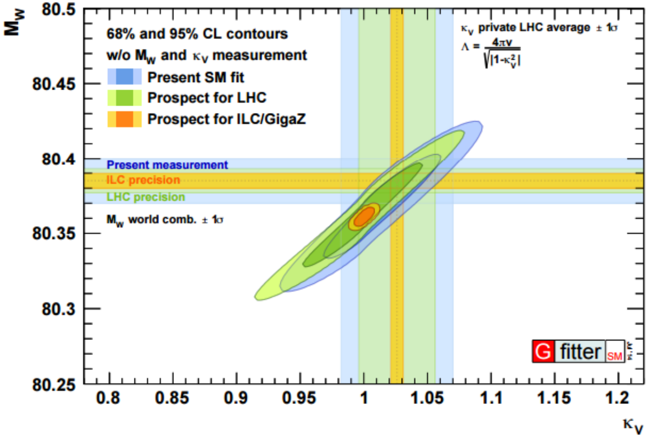
Today	LHC-300	ILC/GigaZ
δ_{meas} = 15 MeV	δ_{meas} = 8 MeV	δ_{meas} = 5 MeV
δ_{fit} = 8 MeV	δ_{fit} = 6 MeV	δ_{fit} = 2 MeV



Impact of individual uncertainties on δM_W in fit (numbers in MeV)

- ILC/GigaZ: impact δM_Z of will become important again!

Prospects of EW Fit



- competitive results between EW fit and Higgs coupling measurements!
  - precision of about 1%
- ILC/GigaZ offers fantastic possibilities to test the SM and constrain NP

The end

Data speaks and it's telling:
Standard Model, Standard Model, Standard Model
but we have ν oscillations, P_5', $R(K^{(*)})$, $R(D^{(*)})$, Dark Matter, Dark Energy . . .

Data speaks and it's telling:
Standard Model, Standard Model, Standard Model
but we have ν oscillations, P_5', $R(K^{(*)})$, $R(D^{(*)})$, Dark Matter, Dark Energy . . .
More at 13 TeV? NO

[1] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Measurements of Higgs boson properties in the diphoton decay channel in proton-proton collisions at $\sqrt{s} = 13$ TeV," *JHEP* **11** (2018) 185, arXiv:1804.02716 [hep-ex].

[2] **CMS** Collaboration, "Measurements of Higgs boson production via gluon fusion and vector boson fusion in the diphoton decay channel at $\sqrt{s} = 13$ TeV,".

[3] **ATLAS** Collaboration, "Measurements of Higgs boson properties in the diphoton decay channel with 36 fb^{-1} of *pp* collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector," arXiv:1802.04146 [hep-ex].

[4] C. Collaboration, "Measurement of inclusive and differential higgs boson production cross sections in the diphoton decay channel in proton-proton collisions at $\sqrt{s} = 13$ *tev*," *Journal of High Energy Physics* **2019** no. 1, (Jan, 2019) 183. https://doi.org/10.1007/JHEP01(2019)183.

[5] **CMS** Collaboration, "Measurements of properties of the Higgs boson decaying into the four-lepton final state in pp collisions at $\sqrt{s} = 13$ TeV," *JHEP* **11** (2017) 047, arXiv:1706.09936 [hep-ex].

[6] **ATLAS** Collaboration, "Measurement of inclusive and differential cross sections in the $H \to ZZ^* \to 4\ell$ decay channel in *pp* collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector," *JHEP* **10** (2017) 132, arXiv:1708.02810 [hep-ex].

[7] **ATLAS** Collaboration, G. Aad *et al.*, "Measurements of the Higgs boson inclusive and differential fiducial cross sections in the 4ℓ decay channel at $\sqrt{s} = 13$ TeV," arXiv:2004.03969 [hep-ex].

[8] **CMS Collaboration** Collaboration, "Measurements of properties of the Higgs boson decaying to a W boson pair in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$," Tech. Rep. CMS-PAS-HIG-16-042, CERN, Geneva, 2018. https://cds.cern.ch/record/2308255.

[9] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Observation of the Higgs boson decay to a pair of τ leptons with the CMS detector," *Phys. Lett.* **B779** (2018) 283–316, arXiv:1708.00373 [hep-ex].

[10] **CMS** Collaboration, "Measurement of Higgs boson production and decay to the $\tau\tau$ final state,".

[11] **ATLAS** Collaboration, "Evidence for the Higgs-boson Yukawa coupling to tau leptons with the ATLAS detector," arXiv:1501.04943 [hep-ex].

[12] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Observation of Higgs boson decay to bottom quarks," *Phys. Rev. Lett.* **121** no. 12, (2018) 121801, arXiv:1808.08242 [hep-ex].

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