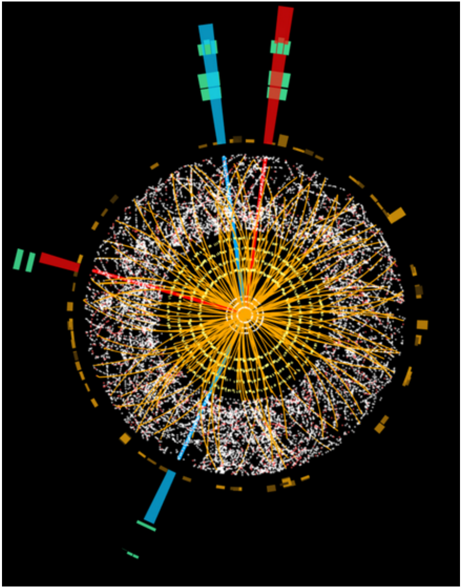


Higgs (decays and properties)

11th ICFA Seminar on Future Perspectives in High-Energy Physics

Oct 28, 2014

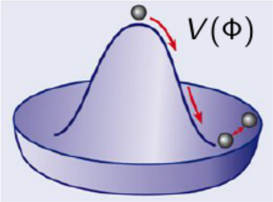
Kerstin Tackmann (DESY)

Thanks to my colleagues from CMS, ATLAS, CDF, D0, the LC, FCC and CEPC for plots, discussions, feedback, ...

Outline

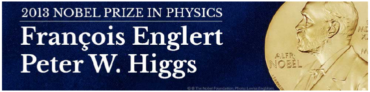
1. The Higgs boson in the SM
2. What do we know today?
3. What else will the LHC tell us?
4. What can we learn from an e^+e^- collider?
5. Summary

The Higgs boson.



The Higgs boson plays a special role

- "1/3 of the Standard Model": Higgs field breaks electroweak symmetry and gives rise to particle masses
- The only fundamental spin-0 particle

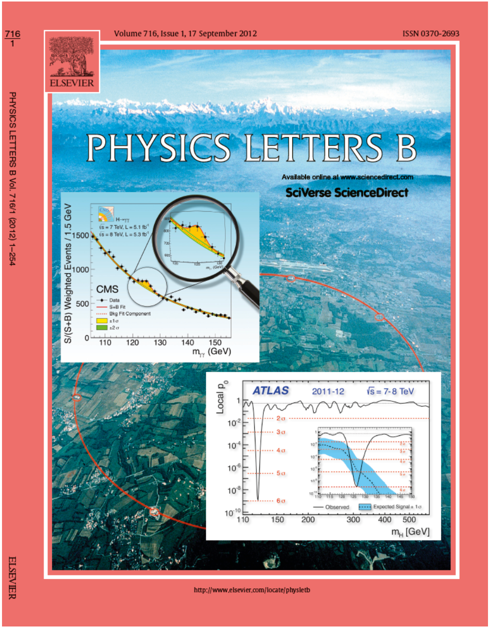


Nobel prize for F. Englert and P. Higgs after discovery of a new particle consistent with the Higgs boson by CMS and ATLAS

Discovery of a Higgs boson brings questions and opportunities

- Detailed measurement of properties: consistent with SM predictions?
- Many extensions of the SM predict additional Higgs bosons
  - ⋆ Models often contain one SM-like Higgs boson → need precision measurements of the properties of the new particle
  - ⋆ Finding an additional Higgs boson would be an unequivocal sign of new physics

July 2012: discovery of a new particle.



With the data taken 2011, and $\sim$ 5 fb^{-1} of data taken during 2012, the CMS and ATLAS experiments clearly discover the new particle with $\geq 5\ \sigma$ sigificance

- Driven by decays to boson pairs: $\gamma\gamma$, ZZ, WW

Focus since summer 2012:

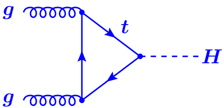
- Study of the properties of the new particle
- Search for decays into fermion pairs
  - ⋆ First evidence from Tevatron in 2012

What do we know today?
Measurements at hadron colliders

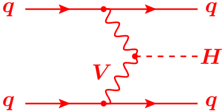
I will show examples for results from one (or two) experiment(s), in general results from CMS, ATLAS and Tevatron are in good agreement.

The Higgs boson at the LHC.

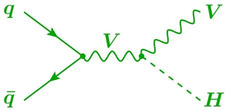
Higgs boson production



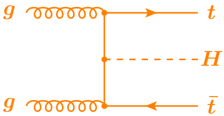
Main production channel



2 forward jets, little hadronic activity in between

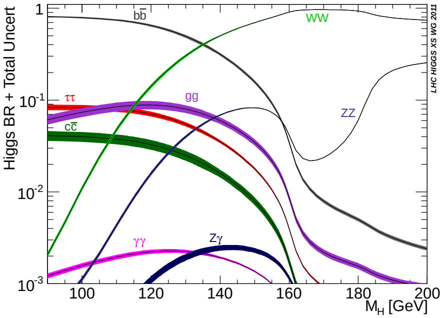


Tag W and Z leptonic and hadronic decays



Tag 2 top quarks

Higgs boson decays



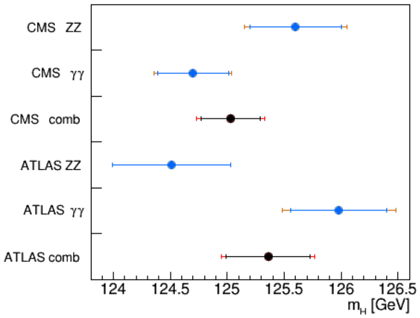
5 main decay channels at LHC

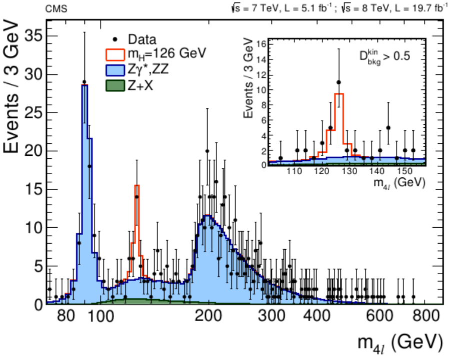
Decay branching fractions @ $m_H =$ 125 GeV

$H \to b\bar{b}$	57.7%
$H \to WW^*$	21.5%
$H \to \tau\tau$	6.3%
$H \to ZZ^*$	2.6%
$H \to \gamma\gamma$	0.23%

Mass measurement.

- Measured in high resolution channels $H \to \gamma\gamma$ and $H \to 4\ell$
- Careful calibration of electromagnetic calorimeters and muon momentum scale



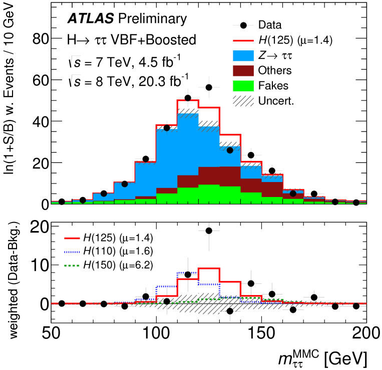


- Precise mass measurement is an important input to couplings measurements
  - ⋆ E.g. $\Delta m_H = 0.2$ GeV shifts prediction for BR($H \to ZZ$) by 2.5%

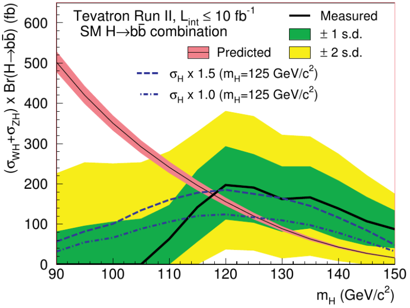
Decays to fermions.

- More challenging to observe than decays to bosons, but important to understand coupling of Higgs to SM particles

$H \to \tau\tau$



$H \to b\bar{b}$



Important channel to constrain total width due to large BR

CMS

$\mu_{\tau\tau} = 0.8 \pm 0.3$ 3.2 σ (3.7 σ exp)

$\mu_{bb} = 1.0 \pm 0.5$ 2.1 σ (2.3 σ exp)

ATLAS

$\mu_{\tau\tau} = 1.4 \pm 0.4$ 4.5 σ (3.5 σ exp)

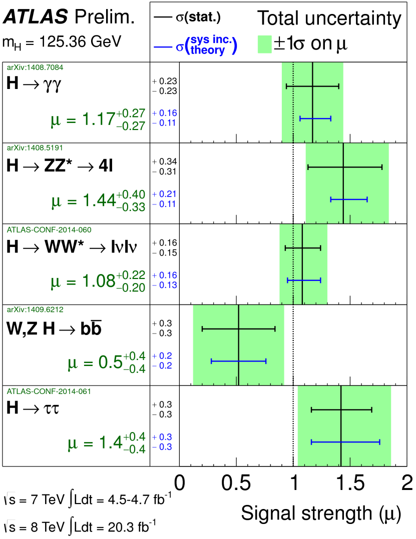
$\mu_{bb} = 0.5 \pm 0.4$ 1.4 σ (2.6 σ exp)

$$\mu = \frac{\sigma_{\text{meas}}}{\sigma_{\text{SM}}}$$

Tevatron

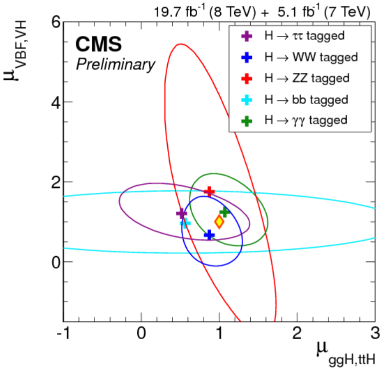
$\mu_{bb} = 1.6 \pm 0.7$

Measurements of production and decays.



Signal strength $\mu = \sigma_{\mathrm{meas}}/\sigma_{\mathrm{SM}}$

- Separate production modes by their specific signatures



Consistent with SM predictions within current uncertainties

Couplings to (SM) particles.

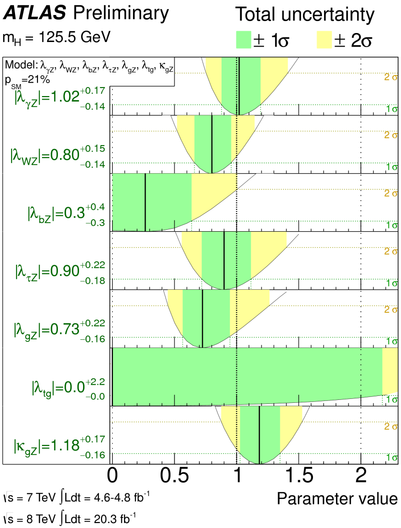
Introduce coupling modifiers κ_i

- Assumes no other differences to SM (single state, narrow, 0^+, only modification of couplings)
- Without further assumptions, LHC can measure ratios: $\lambda_{ij} = \kappa_i/\kappa_j$, $\kappa_{ij} = \kappa_i\kappa_j/\kappa_H$
  - ⋆ κ_H width scale factor

Most generic fit from LHC

- Free couplings to SM particles
- Allow for BSM contributions in loops ($gg \to H$, $H \to \gamma\gamma$)
- Allow for invisible and undetected final states

Consistent with SM predictions within current uncertainties



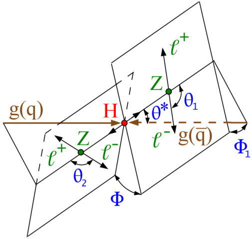
Combination not yet updated to newest measurements

[ATLAS-CONF-2014-009]

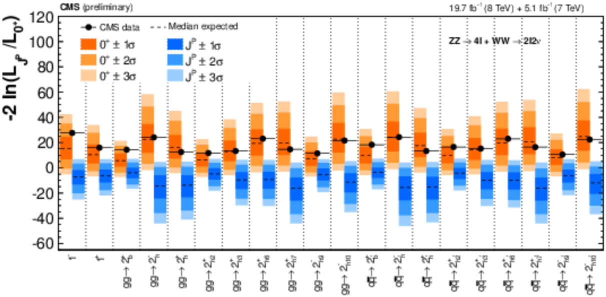
Probing Higgs boson quantum numbers.

SM: $J^P = 0^+$

Angular distributions sensitive to J^P



Test of alternative J^P hypotheses in WW and ZZ

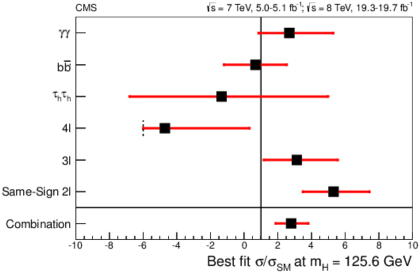


- All tested alternative models excluded at $>$99.9% CL
- Higgs boson very SM-like
- Does not exclude admixture of CP-odd state to SM-like 0^+

...and more.

$t\bar{t}H$ production

Combining measurements in several decay channels



- Direct access to top Yukawa coupling

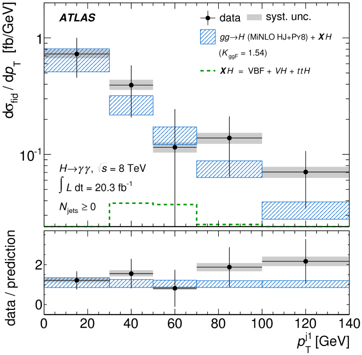
CMS

3.4 σ (2.3 σ exp.) significance

$$\mu_{t\bar{t}H} = 2.8 \pm 1.0$$

(Compatibility with SM $\sim$ 2%)

Differential cross sections

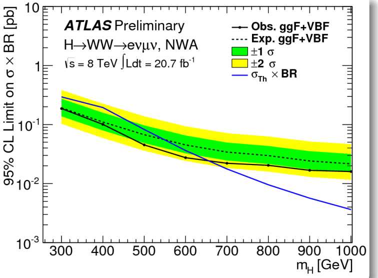


- Model-independent measurement of production and decay kinematics
- Can be compared to precision predictions

Searches for non-SM Higgs bosons.

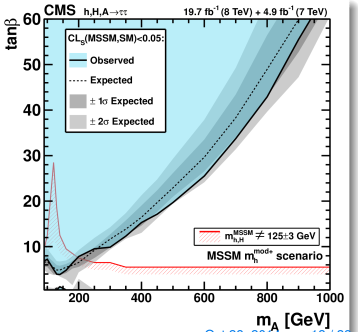
Search for narrow high mass states

- SM-like couplings of the Higgs at 125 GeV imply suppressed couplings of potential heavy Higgs boson to W and Z (in many models)
- Limits for decays of a heavy state into WW, ZZ and $\gamma\gamma$



$h, H, A \to \tau\tau$

- Important search channel for MSSM
- Need to ensure tested models are compatible with signal at 125 GeV
  - ⋆ Interpreted as light Higgs h in this scenario
- Large regions of parameter space excluded



What else will the LHC tell us? Projections for 300 fb^{-1} and High-Luminosity LHC

CMS

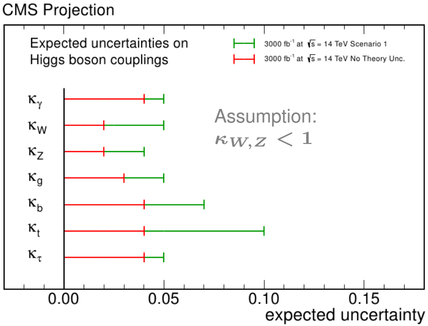
Scale signal and background yields of current analyses

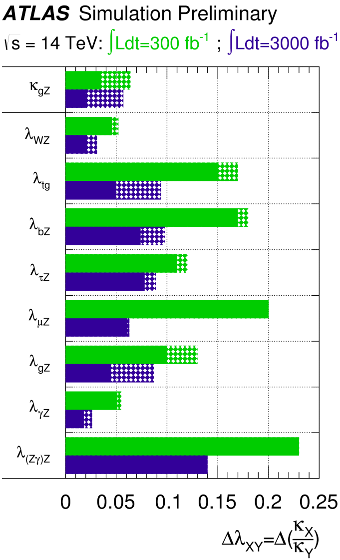
- Unchanged systematic and theoretical uncertainties
- Systematic and theoretical uncertainties scaled with $1/\sqrt{L}$ and 1/2

ATLAS

Efficiency and resolution parametrizations derived from simulation

Coupling measurements.





- Coupling ratios can be measured at several %-level with 3000 fb^{-1}
- HL-LHC will improve experimental precision by a factor 2-3

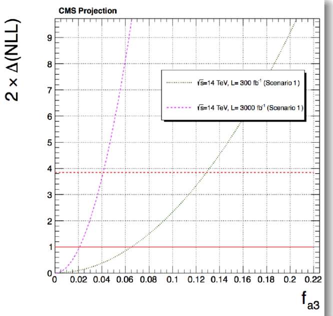
Projections done as coupling (ratios) in Run1, but will more likely be done in a more general framework going beyond a simple rescaling of couplings: effective field theory approaches, form factor parametrizations, ...

CP and $t\bar{t}H$.

CP-odd admixture

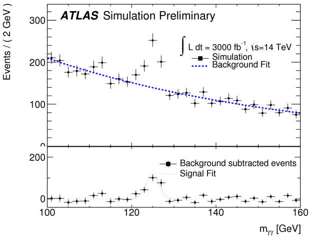
$$A(H \to ZZ) = v^{-1}\left(a_1 m_Z^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

- Constrain CP-odd cross-section contribution $f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_3|^2\sigma_3}$ from kinematics in $H \to 4\ell$
- Even large admixture of CP-odd state would not lead to large cross-section contribution (loop suppressed)(snowmass target: 10^{-5})
- 95% CL at 3000 fb^{-1} $f_{a3} < 0.04$



$t\bar{t}H$ in $H \to \gamma\gamma$

- 8.2 σ at 3000 fb^{-1} combining leptonic and semileptonic $t\bar{t}$
- $\Delta\mu/\mu \sim 20\%$ from $H \to \gamma\gamma$
  - ⋆ $\Delta\mu/\mu \sim 16\%$ when combined with $H \to 4\ell$ and $H \to \mu\mu$ ($\Delta\mu/\mu \sim 10\%$ without theoretical uncertainties)

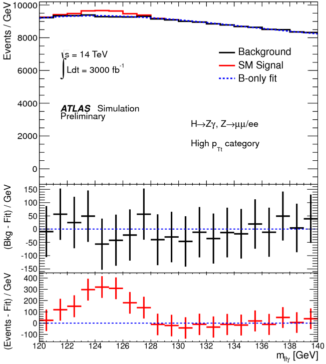


Rare decay modes.

CMS/ATLAS put limits ($\sim$7 and $\sim$11$\times$SM) on $H \to \mu\mu$ and $H \to Z\gamma$

$H \to Z\gamma$

Sensitive to new particles in decay loop

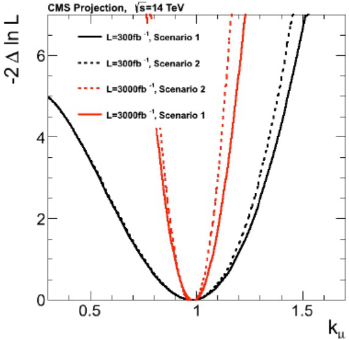


CMS	300 fb^{-1}	3000 fb^{-1}
$\Delta\mu/\mu$	62%	20-24%

ATLAS	300 fb^{-1}	3000 fb^{-1}
Significance		3.9 σ

$H \to \mu\mu$

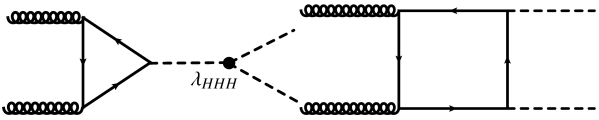
Sensitive to couplings to 2nd generation



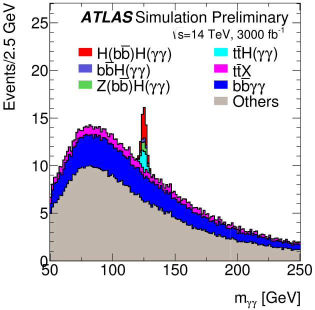
CMS	300 fb^{-1}	3000 fb^{-1}
$\Delta\mu/\mu$	40-42%	20-24%

ATLAS	300 fb^{-1}	3000 fb^{-1}
Significance	2.3 σ	7 σ
$\Delta\mu/\mu$	46%	21%

Higgs pair production (3000 fb^{-1}).



Small event yield due to small cross section: Expect 320 events for SM $H(\to b\bar{b})H(\to \gamma\gamma)$

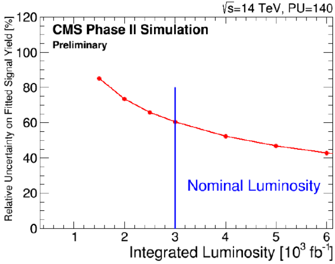


Significance for HH production

CMS $\sim 2\ \sigma$

ATLAS $\sim 1.3\ \sigma$

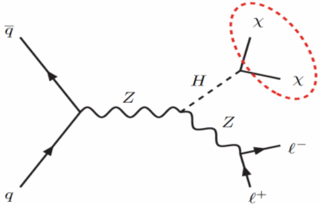
from cut-based analyses



2d fit of $m_{\gamma\gamma}$ and $m_{b\bar{b}}$

- Differences between CMS and ATLAS being discussed
- Measurement of self-coupling from HH production needs measurement of dependence on kinematic variables and will require combination of several channels

Search for non-SM decays.

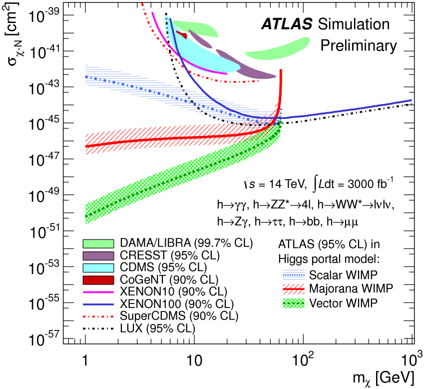


ATLAS	300 fb^{-1}	3000 fb^{-1}
$ZH \to \ell\ell$+invisible	23-32%	8-16%
Coupling fits	22%	13%

Two approaches (with comparable sensitivity)

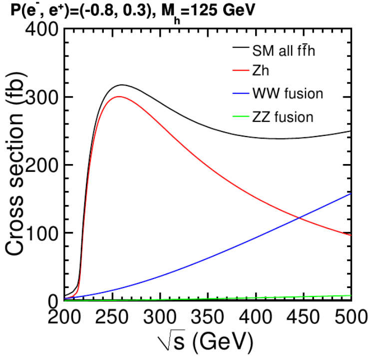
1. Direct search in $ZH \to \ell\ell$+invisible
2. Indirect constraints from coupling measurements
   - ★ Assumptions: no undetectable decays, tree-level couplings $\kappa_i = 1$

- Interpretation in terms of dark matter particles coupling to Higgs boson (assume no other $H \to$inv)
  - ★ Excellent sensitivity for low-mass dark matter particles

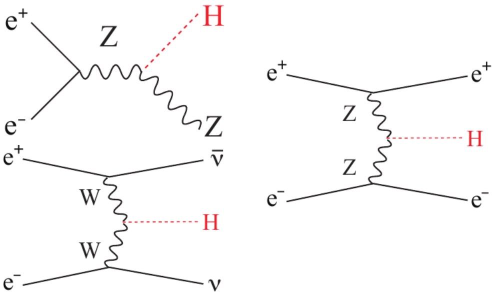


What can we learn from an e^+e^- collider? Higgs physics at a Linear Collider

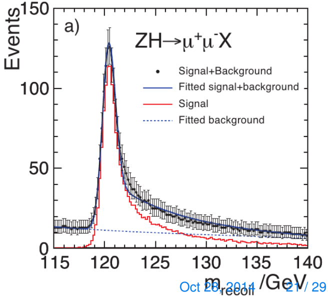
Higgs at ILC.



Higgs production

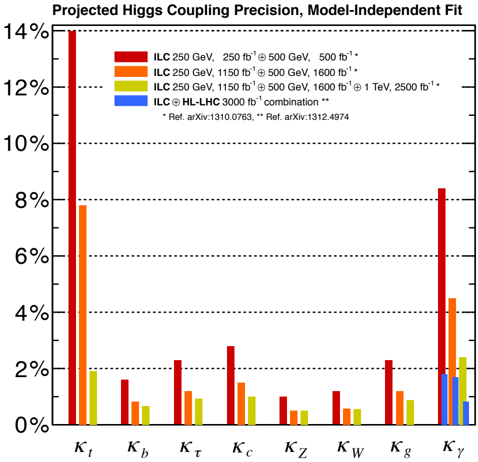


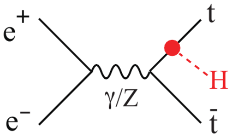
- Total Higgs production cross section σ can be measured from recoil mass
  - ⋆ 2.5% uncertainty at $\sqrt{s}$=250 GeV, 250 fb^{-1}
  - ⋆ Inclusive measurement, independent of Higgs decay
- Higgs mass can be measured to $\sim$30 MeV (statistical)



Coupling measurements.

- Increased cross section for $e^+e^- \rightarrow H\nu\bar{\nu}$ at $\sqrt{s} =$ 350 GeV allows for improved measurement of total width Γ_H
- Knowledge of σ and Γ_H allows for model-independent coupling measurements
- Direct measurement of $H \rightarrow c\bar{c}$ and $H \rightarrow gg$
- Measurement of top coupling improved by $\sim \times 2$ by running at 550 GeV (instead of baseline 500 GeV)
- %-level measurements of Higgs couplings

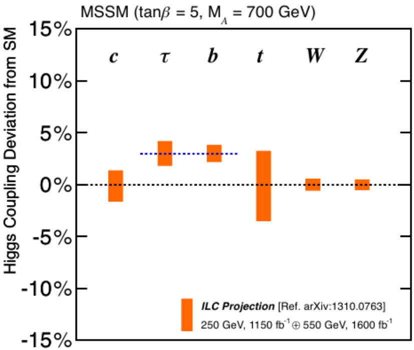




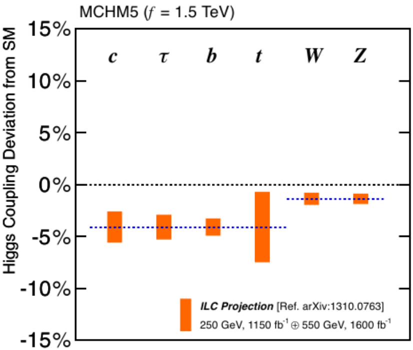
How well do we need to measure the couplings?

- Want to disentangle various possible extensions (SUSY, composite Higgs, ...) of the SM, and their parameters
- Requires %-level accuracy in measurements of couplings of SM-like Higgs

Supersymmetry
(MSSM)



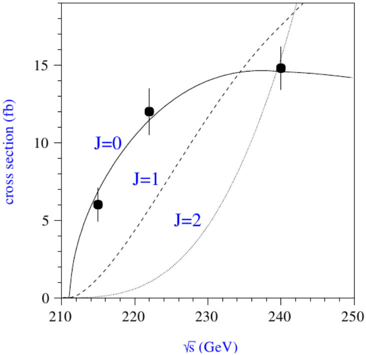
Composite Higgs
(MCHM5)

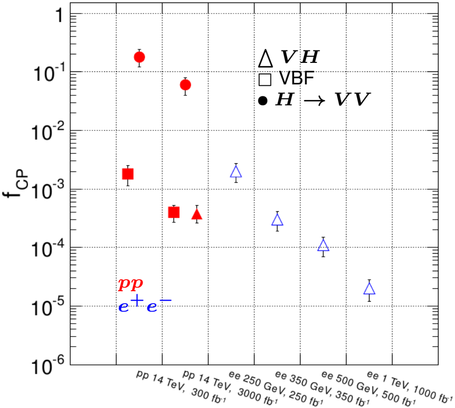


ILC 250+550 LumiUP

Spin and CP studies.

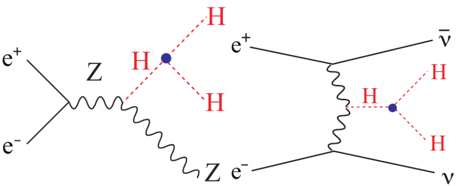
- Model-independent measurement of spin from ZH threshold behavior
- 3 points in $\sqrt{s}$ of 20 fb^{-1}

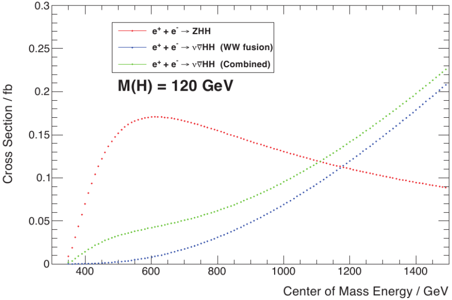




- CP-odd coupling suppressed by loop
- Target precision for f_{CP} (snowmass report): 10^{-5}
  - ⋆ Corresponds to 10% admixture of CP-odd state

Higgs self-coupling.





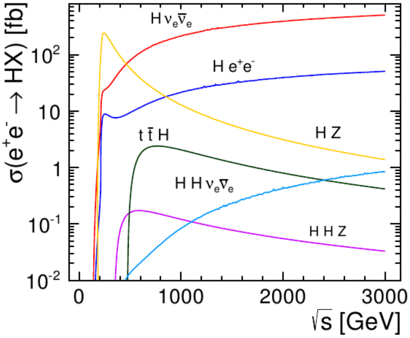
- Difficult measurement due to very small rate and sizable backgrounds
- Sensitivity much improved at 1 TeV with $e^+e^- \to HH\nu\bar{\nu}$
  - ⋆ Contributions from background diagrams not sensitive to self-coupling smaller than for $e^+e^- \to ZHH$ at 500 GeV

$\sqrt{s}$ (GeV)	500	500	500+1000	500+1000
L (fb^{-1})	500	1600	500+1000	1600+2500
$\Delta\lambda/\lambda$	83%	46%	21%	13%

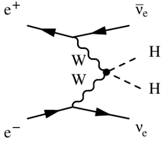
Going to higher energies.

- CLIC offers possibility to go to higher energies

$\sqrt{s}$	350-375 GeV	1.4 TeV	3 TeV
L	500 fb^{-1}	1.5 ab^{-1}	2 ab^{-1}

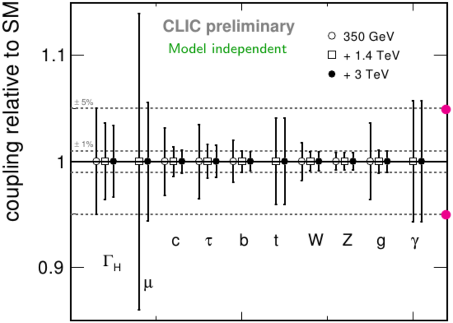


- %-level uncertainties for coupling measurements



- Improved sensitivity for rare decays

Measurement	Observable	Statistical precision 1.4 TeV 1.5 ab^{-1}	3.0 TeV 2.0 ab^{-1}
$\sigma(HH\nu_e\bar{\nu}_e)$	g_{HHWW}	7% (prel.)	3% (prel.)
$\sigma(HH\nu_e\bar{\nu}_e)$	λ	32%	16%
with 80% e^- polarisation	λ	24%	12%



What can we learn from an e^+e^- collider? Higgs physics at an e^+e^- circular collider

Coupling measurements at FCC-ee.

- Starting design studies for two projects: FCC-ee ($\sqrt{s} = 350$ GeV) and CEPC ($\sqrt{s} = 240$ GeV))
- Aiming for very high luminosity $\rightarrow$ couplings measured with high statistical precision
- No direct access to $t\bar{t}H$ and Higgs self-coupling

Projected statistical precision for a model-independent fit (some systematic uncertainty estimates included for ILC) [snowmass report]

Facility	ILC			ILC(LumiUp)	TLEP (4 IP)		CLIC		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
BR_{inv}	0.9%	< 0.9%	< 0.9%	0.4%	0.19%	< 0.19%			

Summary.

- We have come quite far during the last 3 years: from a textbook discovery to first detailed property measurements

- LHC will continue to improve the precision of Higgs measurements
  - ⋆ Access to rare decays $H \to \mu\mu$ and $H \to Z\gamma$
- ILC offers the possibility for more precise measurements
  - ⋆ Model-independent coupling measurements
  - ⋆ Measurement of Higgs self-coupling

- Higgs discovery was a major step for particle physics
- Understanding in detail the nature of the Higgs boson and its role in electroweak symmetry breaking and mass generation is one of the primary tasks for the next decades

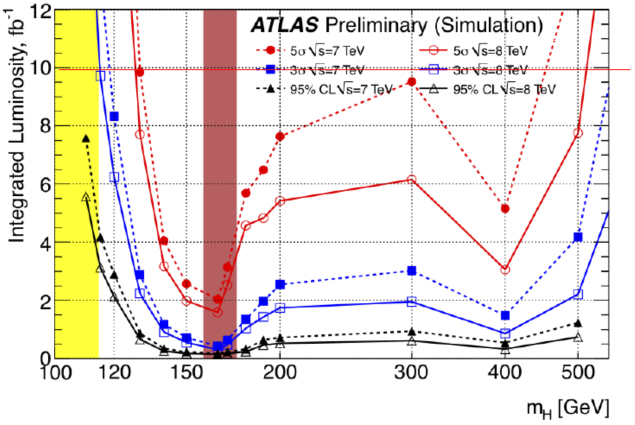
Backup

Sachio Komamiya at ICFA seminar at CERN 2011:

Prospects of Higgs discovery/studies at LHC

It is very hard to tell the future prospects without seeing Higgs.

Very short term (in the end of this year)



Integrated Luminosity in the end of 2011
~10 fb^{-1}
(CMS+ATLAS)

120 GeV SM Higgs can be seen with 3σ

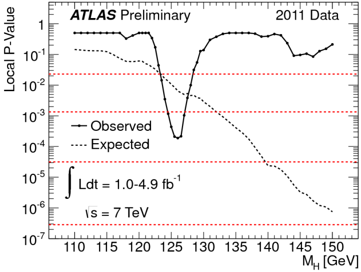
114-600 GeV with 3σ

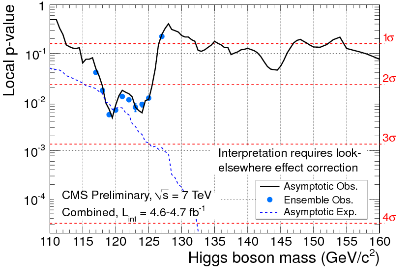
SPS 12.9.2011
F. Gianotti

18

Status end of 2011.

Close to $\sim 5\ \text{fb}^{-1}$ per experiment, combining several search channels





- Local significance 3.6 σ
- Taking into account "look-elsewhere effect" 2.3 σ

- Local significance 2.6 σ
- Taking into account "look-elsewhere effect" 0.9 σ

Interesting hints, but larger data set needed to be sure

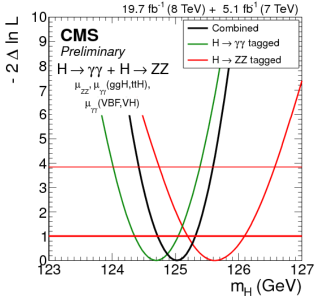
Mass measurement at LHC.

CMS

$$m_{4\ell} = 125.6 \pm 0.4\,(\mathrm{stat}) \pm 0.2\,(\mathrm{syst})\ \mathrm{GeV}$$
$$m_{\gamma\gamma} = 124.70 \pm 0.31\,(\mathrm{stat}) \pm 0.15\,(\mathrm{syst})\ \mathrm{GeV}$$

Compatible within 1.6 σ

$$m_H = 125.03 \pm 0.26\,(\mathrm{stat}) \pm 0.14\,(\mathrm{syst})\ \mathrm{GeV}$$

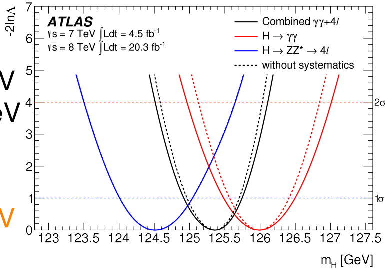


ATLAS

$$m_{4\ell} = 124.51 \pm 0.52\,(\mathrm{stat}) \pm 0.06\,(\mathrm{syst})\ \mathrm{GeV}$$
$$m_{\gamma\gamma} = 125.98 \pm 0.42\,(\mathrm{stat}) \pm 0.28\,(\mathrm{syst})\ \mathrm{GeV}$$

Compatible within 1.98 σ

$$m_H = 125.36 \pm 0.37\,(\mathrm{stat}) \pm 0.18\,(\mathrm{syst})\ \mathrm{GeV}$$



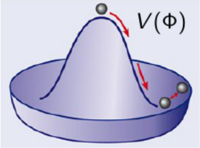
Higgs self-coupling.

Brout, Englert, Guralnik, Higgs, Hagen, Kibble

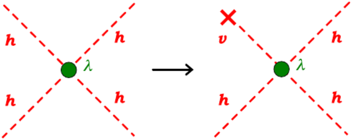
Introduce a scalar field with vaccum expectation value $v \neq 0$

$$\phi(x) = \begin{pmatrix} \phi^+(x) \\ \phi^0(x) \end{pmatrix} \rightarrow \langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \text{ (choose gauge)}$$

with potential $V(\phi) = -\mu^2 |\phi^\dagger \phi| + \frac{\lambda}{2} \left(|\phi^\dagger \phi| \right)^2$



- Measurement of triple Higgs couplings gives access to λ parameter of Higgs potential
- Direct evidence for vacuum condensate



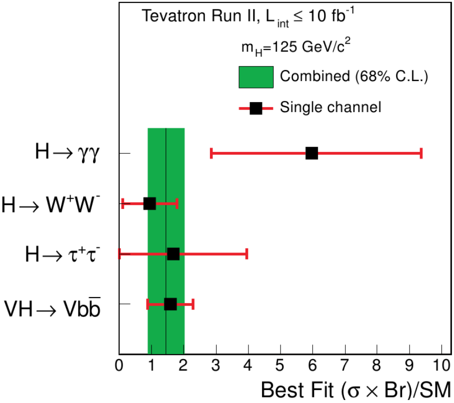
- Crucial (though difficult) test of Higgs mechanism

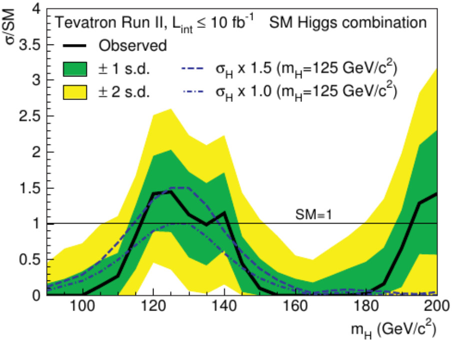
Higgh self-coupling: going to higher precision.

	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14000	500	500	500/1000	500/1000	1400	3000	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	500	$1600^{\ddagger}$	500+1000	$1600+2500^{\ddagger}$	1500	+2000	3000	3000
λ	50%	83%	46%	21%	13%	21%	10%	20%	8%

LHC	HL-LHC							
+ILC	+ILC-up	+(TLEP)			+ILC-up		+CLIC	
		+CLIC	+HE-LHC	+VLHC	+HE-LHC	+VLHC	+HE-LHC	+VLHC
21%	12.6%	15.2/9.8%	18.6%	7.9%	10.9%	6.8%	12.5/8.9%	7.2/6.2%

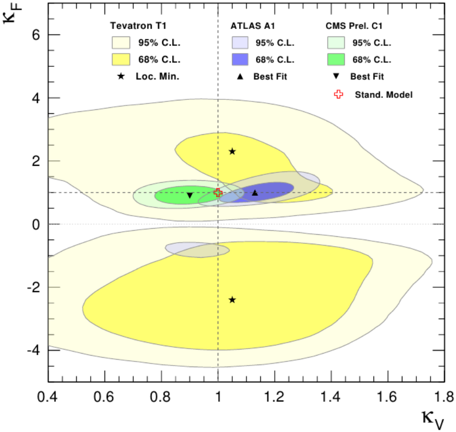
Higgs at Tevatron.





Final combination of all channels: 3 σ evidence at 125 GeV

Coupling measurements from LHC and Tevatron.



Common couplings scaling factor for all vector bosons (κ_V) and all fermions (κ_f)

Fair agreement with SM predictions

$H \to \gamma\gamma$ has sensitivity to relative sign of κ_V and κ_f through interference of W and t in the loop

Measurements from ATLAS and CMS have been superseeded by updated measurements

Coupling measurements comparison.

- 7-parameter constrained fit to compare hadron and lepton colliders on equal footing
  - ⋆ Assumes no non-SM production or decay modes
  - ⋆ Assumes generation universality

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%	$-/5.5/<5.5\%$	1.45%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%	1.3%	0.72%	$3.5/1.4/<1.3\%$	0.51%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

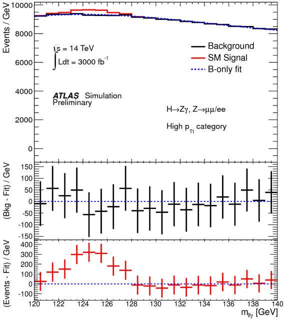
[snowmass report]

Rare decay modes.

LHC has put limits (7-11×SM) on $H \to \mu\mu$ and $H \to Z\gamma$

$H \to Z\gamma$

Sensitive to new contributions in decay loop

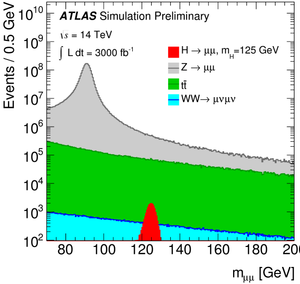


For 3000 fb^{-1}

- Expected significance 3.9 σ
- Expected limit in absence of signal 0.52×SM

$H \to \mu\mu$

Sensitive to couplings to 2nd generation



	300 fb^{-1}	3000 fb^{-1}
Significance	2.3 σ	7 σ
$\Delta\mu/\mu$	46%	21%