Is the Higgs boson natural?

What experiments can tell us.

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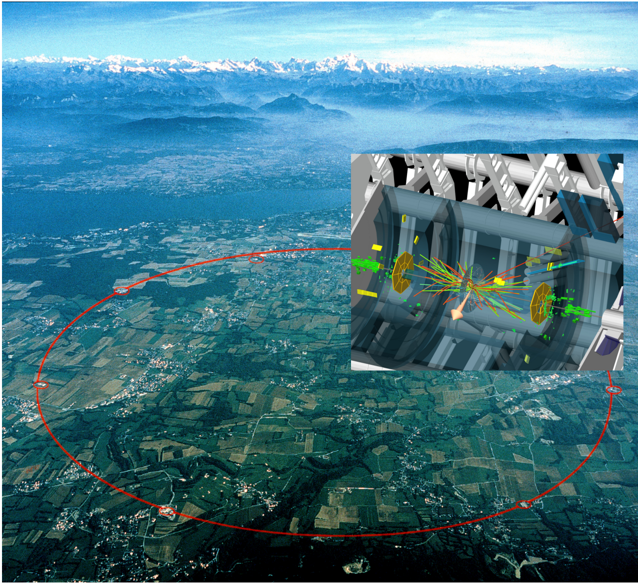
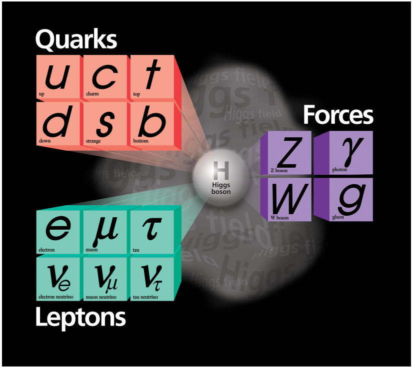
March 4, 2014



- Standard Model and Higgs boson
- LHC and ATLAS detector
- Higgs boson decays to gauge bosons
- Higgs boson couplings to fermions
- Future experimental outlook

The Standard Model

- Standard Model is renormalizable quantum field theory of 12 fermions with 3 forces mediated by spin-1 gauge bosons
- Electroweak Symmetry is spontaneously broken by Brout-Englert-Higgs mechanism with 4 scalar fields
- Predicts new particle: Higgs boson
- Very successful description of particle interactions



"[The Higgs boson is] a particle needed for theories to work" - Gerard 't Hooft

The Standard Model

Higgs discovery seminar
at CERN on July 4th, 2012

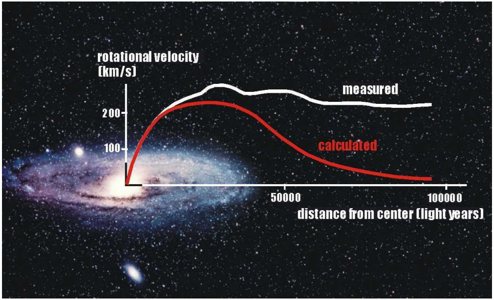
2013 Nobel Physics Prize
to Englert and Higgs

The Higgs boson discovery completes the SM,
making the theory self-consistent up to very high energy scale.

Some of open questions

- Dark matter and dark energy
- Matter antimatter asymmetry

Rotation curves of the Andromeda Galaxy

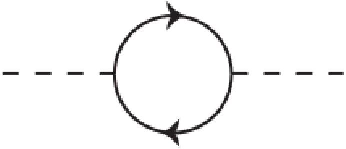


Gravitational lensing - "bullet cluster"

Some of open questions

- Higgs boson mass is sensitive to scale of new physics
- Gravity and cosmological constant problem

Quantum corrections to the Higgs boson mass term

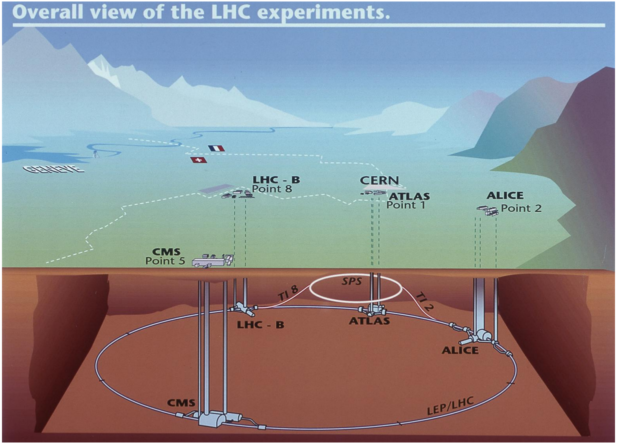


$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}[\Lambda_{\rm UV}^2 + ...].$$

- Broad experimental program underway to search for new physics
- SM precisely predicts all Higgs boson properties for fixed m_H
- Any deviations can represent signs of new physics

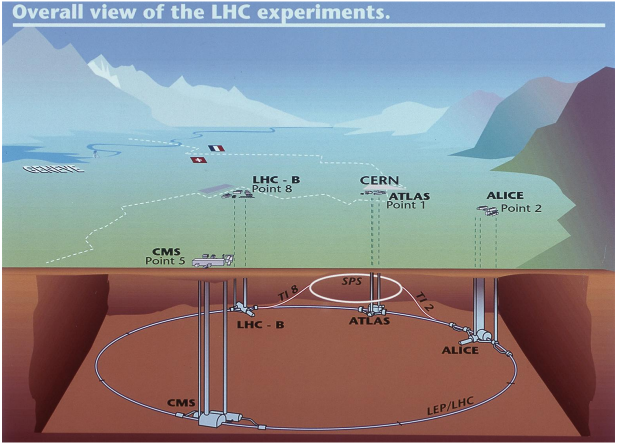
Road to the discovery

- 27 km tunnel LHC
- 1232 superconducting dipoles at 1.9 K
- Proton-proton, proton-ion and ion-ion collisions
- 7-8 TeV pp collisions in 2011 and 2012
- LHC will restart in 2015 at $\sim$ 14 TeV



4 large detectors to study:

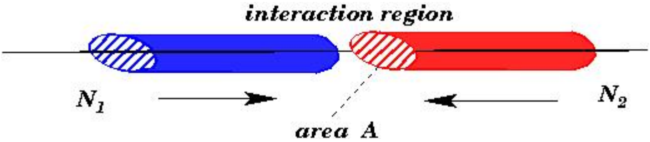
- Electroweak Symmetry Breaking
- Standard Model
- Searches for new physics
- Matter-antimatter asymmetry
- New states of matter



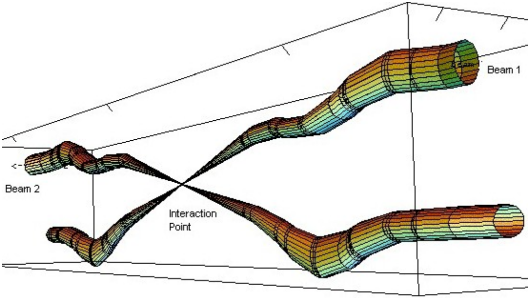
Colliding bunches:

$$\mathcal{L} = \frac{n_b \cdot N_1 \cdot N_2 \cdot f_{rev}}{A}$$

Area $A = 4\pi \cdot \beta \cdot \epsilon$



- n_b - number of bunches
- $N_{1,2}$ - number of protons per bunch ($\sim 1.15 \times 10^{11}$)
- f_{rev} - revolution frequency (11kHz)
- β and ϵ determined by interaction region focusing and injectors
- Run 1 - 1380 bunches at 50 ns: $\mathcal{L}_{2012} = 0.77 \times 10^{34} cm^{-2}s^{-1}$
- Design - 2808 bunches at 25 ns: $\mathcal{L}_{design} = 1.0 \times 10^{34} cm^{-2}s^{-1}$



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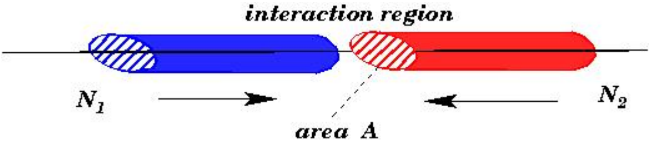

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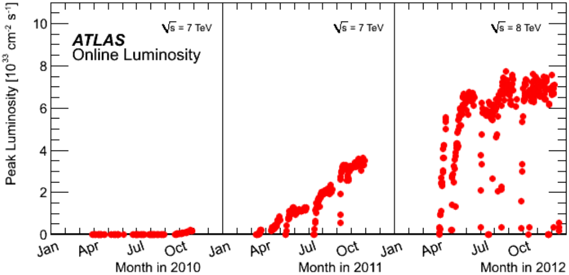
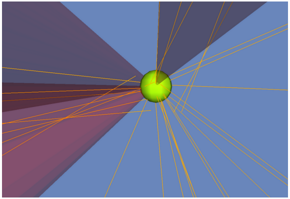


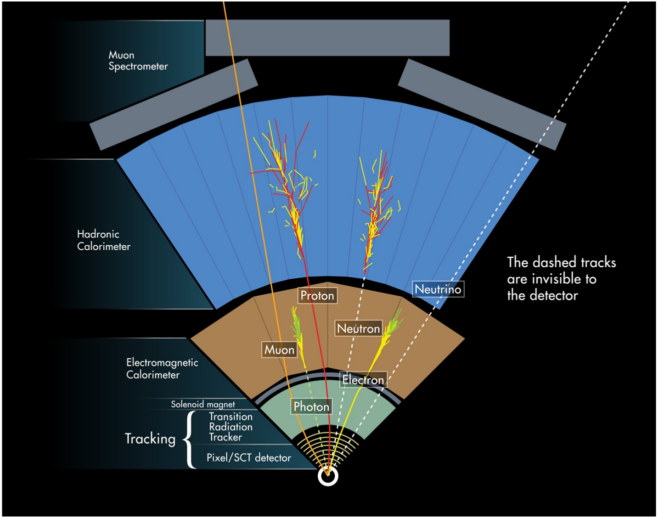
More than 3000 scientists from 38 countries

Particle reconstruction and identification

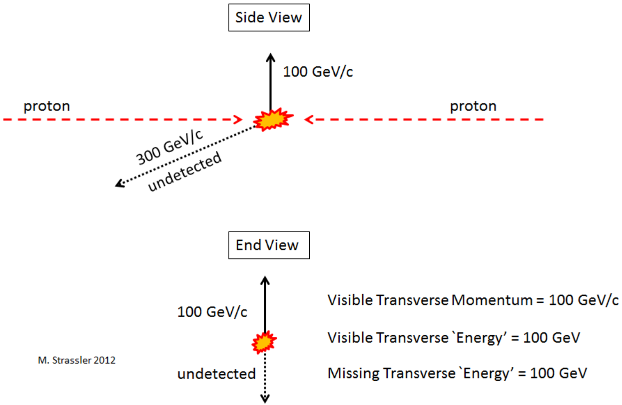
- Hermetic detector
- Almost all particles are reconstructed
- Miss neutrinos and particles traveling very near beam axis

Displaced b-hadron vertex





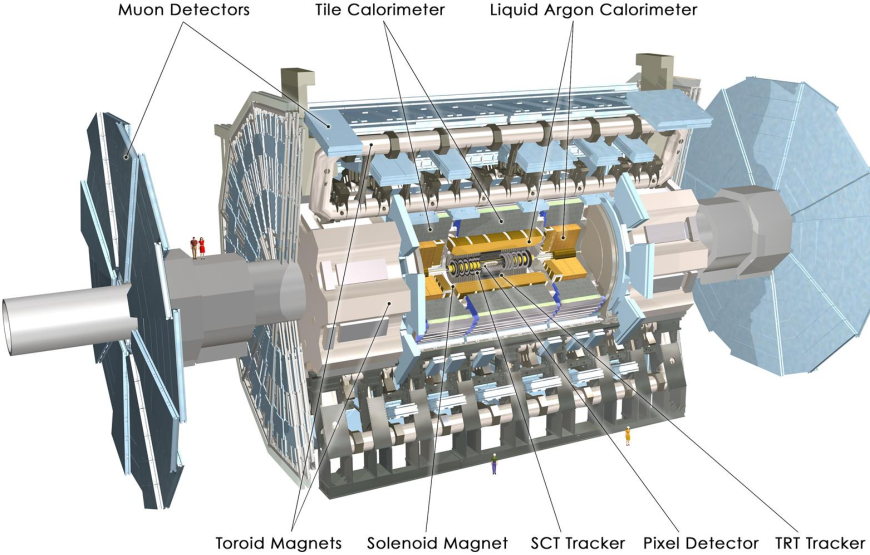
Missing transverse energy



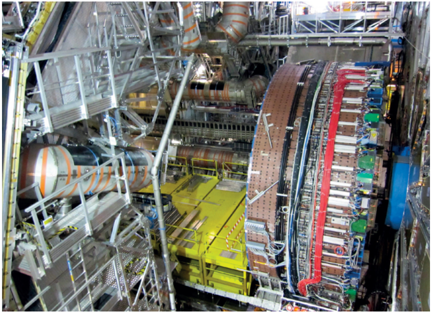
- Momentum is conserved only in transverse plane
- Missing transverse energy:

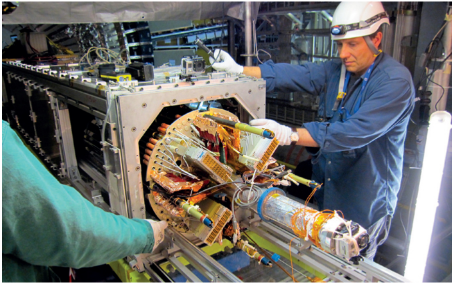
$$E_{T,miss} = -\sum_{jets} E_T - \sum_{leptons} p_T - \sum_{photons} E_T - \sum_{clusters} E_T$$

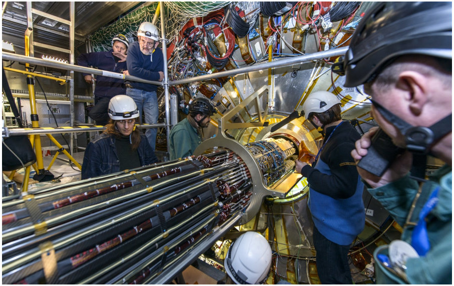
ATLAS detector

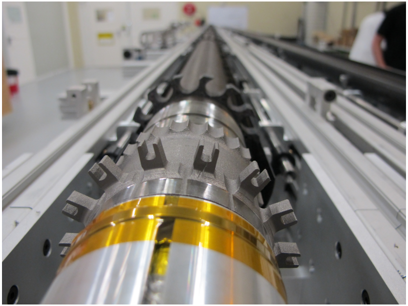


ATLAS pixel detector



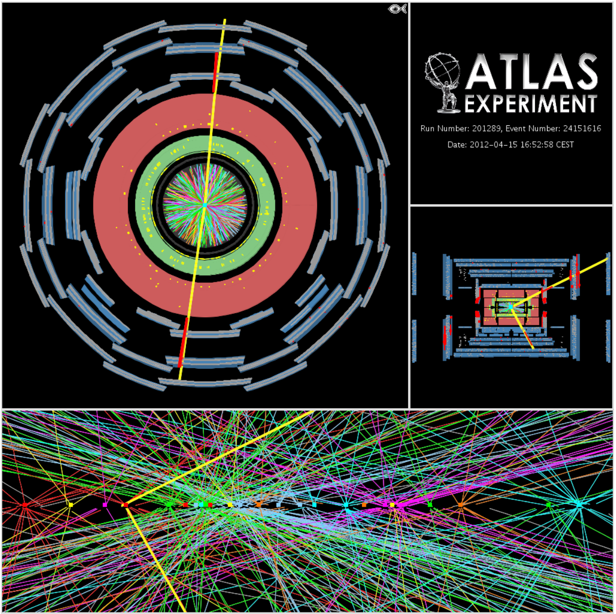




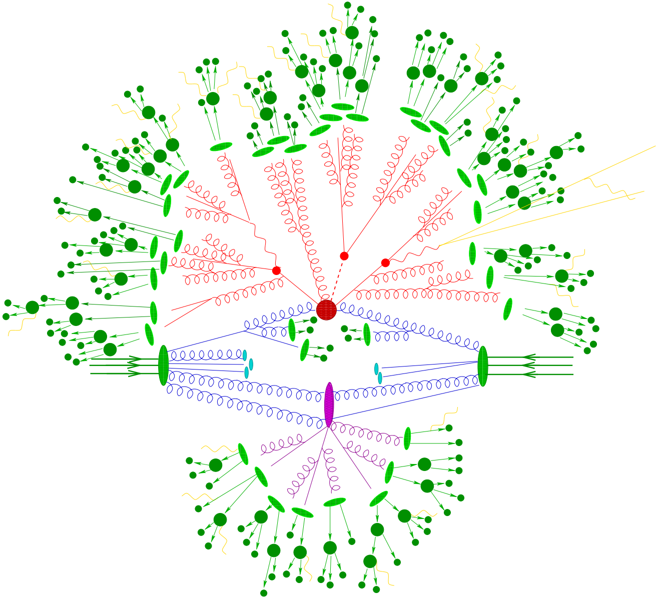


$Z \to \mu\mu$ with 25 vertexes

- Design ≈ 25 interactions at 25 ns
- Pileup deposits significant amount of energy in calorimeters
- Results in degraded performance - mostly compensated by reconstruction algorithms
- $E_{T,miss}$ resolution degrades



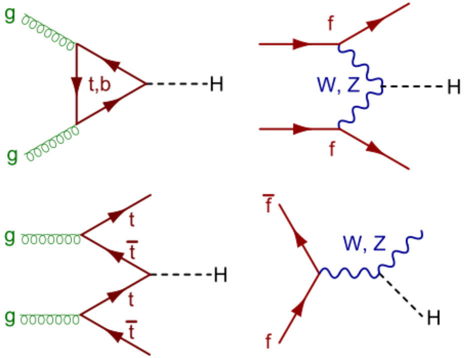
pp collisions from Sherpa's point of view



Higgs boson production at the LHC

Higgs boson properties are fixed once m_H is known

- Gluon-gluon fusion (ggF)
  - Fermion couplings in the loop
- Vector boson fusion (VBF)
  - Two forward separated jets
- WH/ZH associated production:
  - Tag W/Z to reduce backgrounds
- ttH associated production:
  - Direct ttH coupling



Cross-sections and theory uncertainties for $m_H = 126\ GeV$ at 8 TeV:

	ggF	VBF	WH/ZH	$t\bar{t}$H
σ (pb)	19.0	1.6	1.1	0.13
QCD scale	$\pm 8\%$	$\pm 1\%$	$\pm 1\%$	$+4\% \ -9\%$
PDF+α_S	$\pm 8\%$	$\pm 4\%$	$\pm 4\%$	$\pm 8\%$

Higgs decays

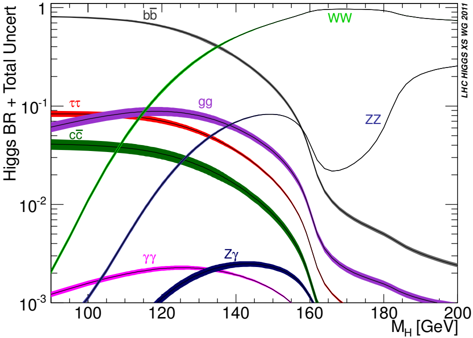
- $\Gamma_H = 4.1$ MeV - observed signal width is determined by detector resolution
- WW and ZZ dominate when kinematically allowed
- 7 channels accessible at the LHC for $m_H = 126$ GeV:

$$\begin{aligned} &H \to bb \\ &H \to WW \\ &H \to \tau\tau \\ &H \to ZZ \\ &H \to \gamma\gamma \\ &H \to Z\gamma \\ &H \to \mu\mu \end{aligned}$$

- $H \to \gamma\gamma$ and $H \to Z\gamma$ decay via loops - sensitive to new physics

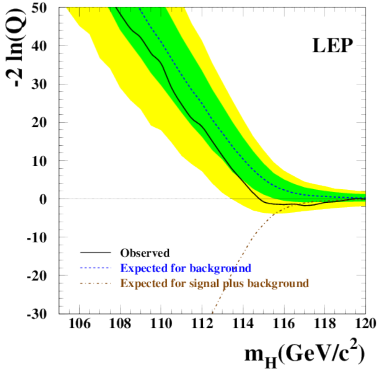
Fermion couplings $\propto \frac{m_f}{\nu}$

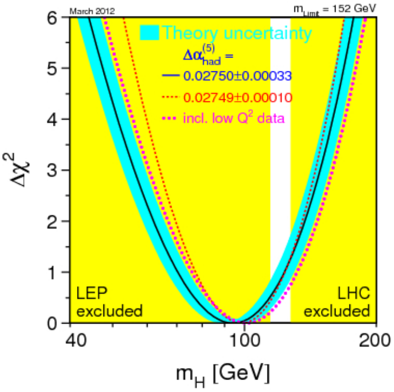
Gauge boson couplings $\propto \frac{2m_V^2}{\nu}$



Higgs boson before LHC

- LEP excluded Higgs boson with $m_H < 114.4$ GeV
- Tevatron excluded m_H in 160-170 GeV
- Precision Electroweak fits imply $m_H \lesssim 200$ GeV
- $W_L W_L$ scattering violates unitarity for $m_H \gtrsim 1$ TeV
- LHC was designed to find or rule out Higgs boson with $m_H \lesssim 1$ *TeV*

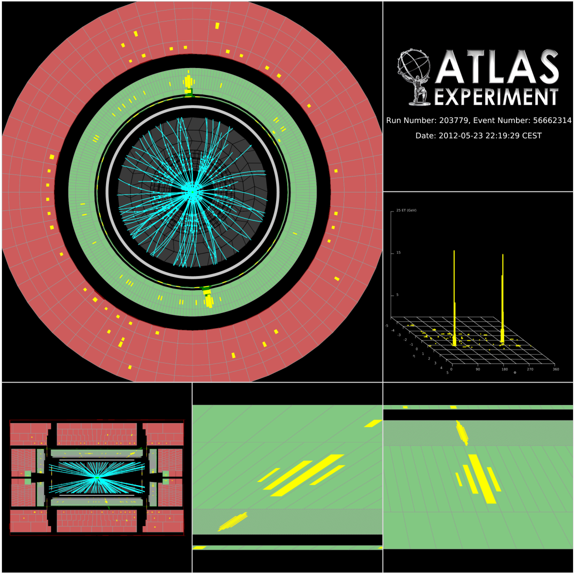




$H \to \gamma\gamma$

$m_H = 125$ GeV: $\sigma \times BR \approx 0.05\ pb$

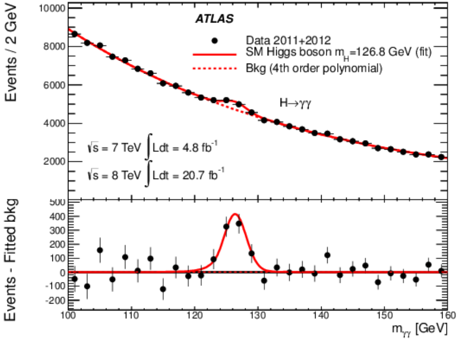
≈ 1000 events at 8 TeV before selection

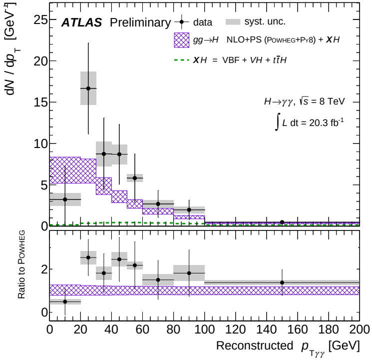


- Fine η granularity in the strip layer to reject π^0
- $\varnothing(8000)$ jet rejection at $\sim 85\%$ photon efficiency
- Longitudinal segmentation for shower direction: $m^2_{\gamma\gamma} = 2E_1E_2(1 - cos\alpha)$

$H \to \gamma\gamma$: analysis strategy

- Rare decay mode but clear signature: 2 isolated γ with $p_T > 40, 30$ GeV
- Full Higgs boson mass reconstruction - search for a narrow resonance
- Dominant backgrounds - continuum $\gamma\gamma$ and $\gamma + jet$
- 14: categories: different Higgs boson production modes and S/B
- Backgrounds are fitted from sidebands: $PDF_{BKG} + \mu \times PDF_{SIG}$
- Observed 7.4σ excess (expected 4.3σ) with $m_H \sim 126.5$ GeV



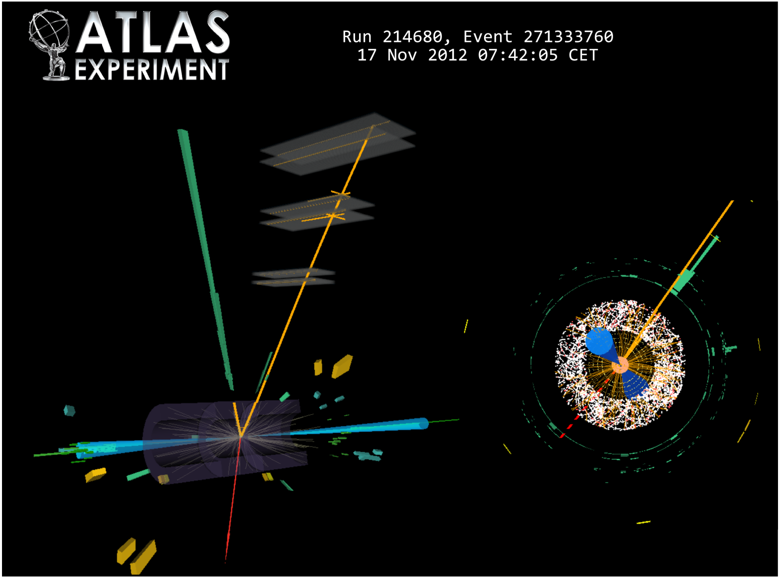


View from the summit

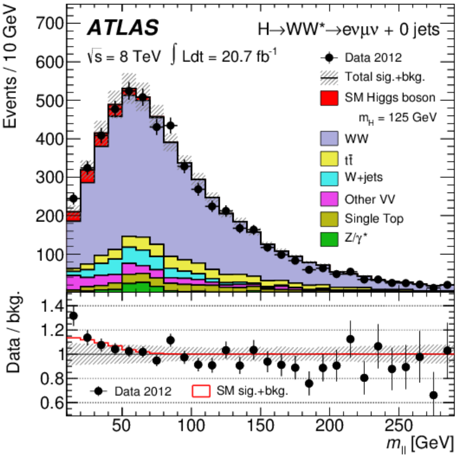
$H \to WW \to l\nu l\nu$

$\sigma \times BR \approx 0.24\ pb$ for $m_H = 126$ GeV

≈ 4800 events at 8 TeV before selection



$H \to WW$: analysis strategy



$H \to WW \to l\nu l\nu$:

- 2 opposite sign leptons + E_T^{miss}
- Only electrons and muons
- High rate, clean final state
- No mass peak because of ν

Irreducible background:

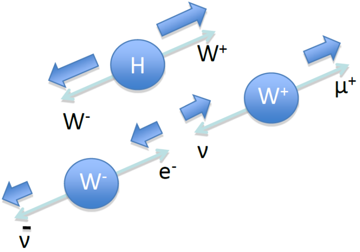
- Non-resonant WW
- Normalized from data

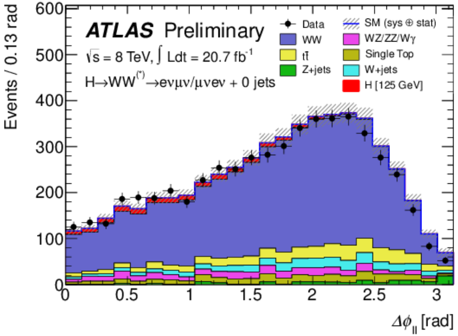
Other backgrounds:

- Top quark
- Z+jets
- W+jets
- Di-bosons: WZ, ZZ, $W\gamma^{(*)}$
- Normalized/validated from data

$H \to WW \to l\nu l\nu$: Spin-0 Higgs boson

- Irreducible non-resonant WW background: $\sigma_H / \sigma_{WW} \approx 3\%$
- Spin-0: small opening angle for 2 charged leptons:
  - $|m_{ll}| < 50\ GeV$
  - $|\Delta\phi_{ll}| < 1.8$





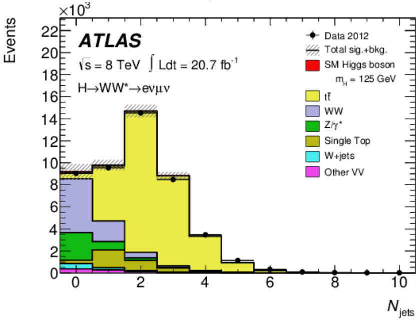
"... for the weak interactions parity conservation is so far only an extrapolated hypothesis unsupported by experimental evidence." - Lee and Yang, 1956.

$H \rightarrow WW \rightarrow l\nu l\nu$: jet multiplicity

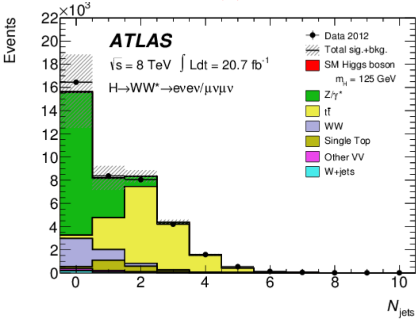
Categories based on number of jets and lepton flavor:

- Veto events with b-jets to reduce top quark background
- Improve S/B because of different background composition
- Increase sensitivity to VBF production mode (+)
- Increase theory and experimental uncertainties (-)

$e\mu$:

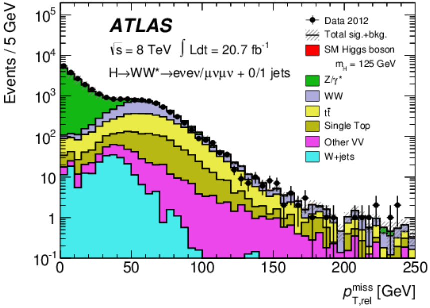


$ee + \mu\mu$:

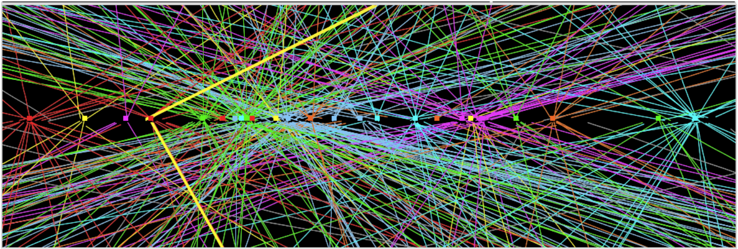


$H \to WW \to l\nu l\nu$: $p_{T,miss}$ performance

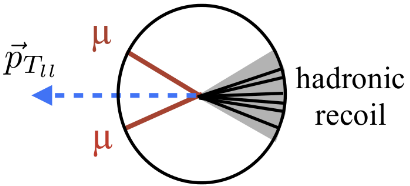
- Missing transverse momentum: $p_{T,miss} = -\sum_{charged\ \ particle} p_T$
- Use reconstructed charged particle tracks matching primary vertex - does not depend on pileup
- Miss neutral particles
- Suppress $Z \to ll$ by factor of ~ 5

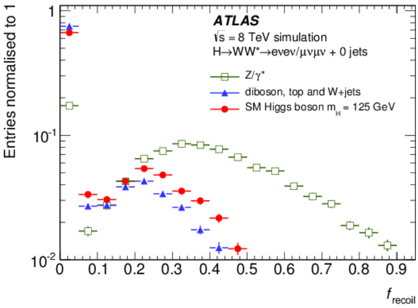


$Z \to \mu\mu$ with 25 vertexes



$H \to WW \to l\nu l\nu$: soft hadronic recoil veto





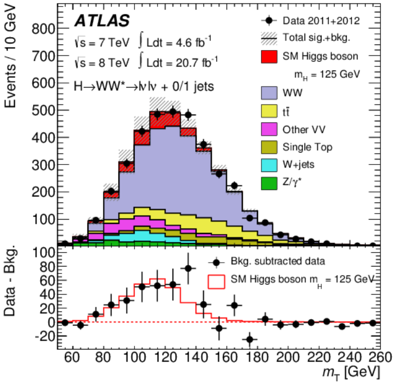
- Require that di-lepton system is boosted: $p_{T,ll} > 30$ GeV
- Soft hadronic recoil fraction: $f_{recoil} = E_{T,recoil} / p_{T,ll}$
- $H \to WW \to l\nu l\nu$ - recoil carried away by neutrinos
- $Z \to ll$ - boost requires hadronic recoil
- $Z \to ll$ estimated from regions with high f_{recoil} and Z peak
- Suppress $Z \to ll$ by factor of ~ 5

$H \to WW \to l\nu l\nu$: results

$$m_{\mathrm{T}} = \sqrt{\left(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left|\mathbf{p}_{\mathrm{T}}^{\ell\ell} + \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}$$

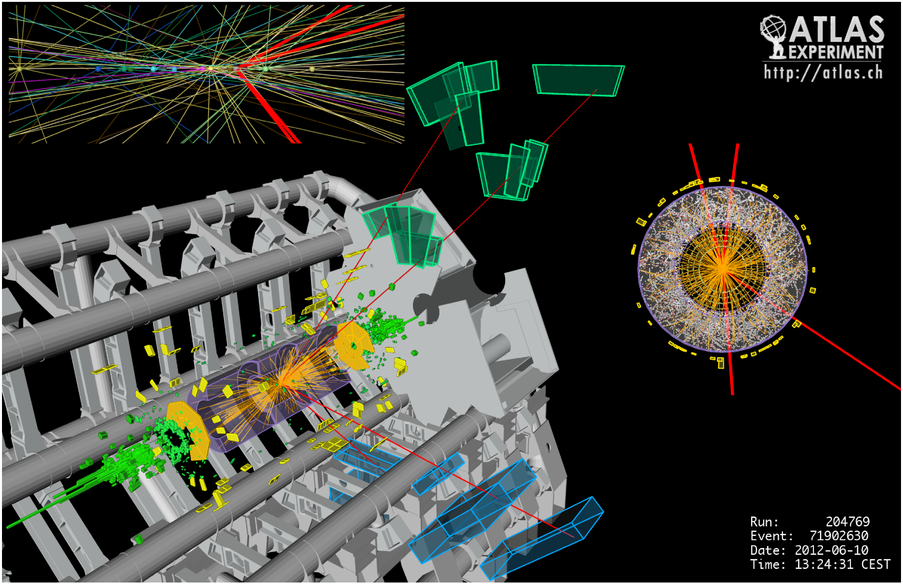
- Probe transverse mass distribution
- Observed 3.8 σ excess for $m_H = 125$ GeV (expected 3.8 σ)

Category	Source	Uncertainty, up (%)	Uncertainty, down (%)
Statistical	Observed data	+21	−21
Theoretical	Signal yield ($\sigma \cdot \mathcal{B}$)	+12	−9
Theoretical	WW normalisation	+12	−12
Experimental	Objects and DY estimation	+9	−8
Theoretical	Signal acceptance	+9	−7
Experimental	MC statistics	+7	−7
Experimental	W+jets fake factor	+5	−5
Theoretical	Backgrounds, excluding WW	+5	−4
Luminosity	Integrated luminosity	+4	−4
Total		+32	−29



$H \to ZZ \to 4l$

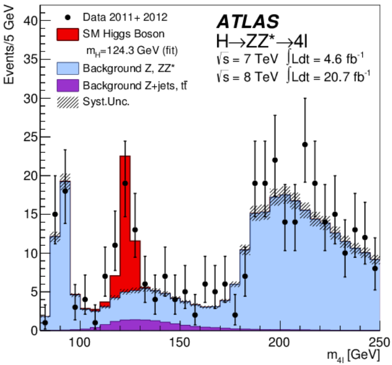
$\sigma \times BR \approx 3$ fb for $m_H = 126$ GeV
≈ 56 events at 8 TeV before selection



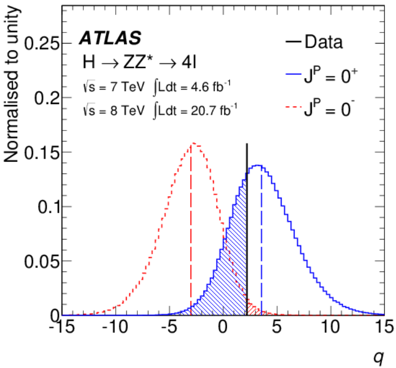
$H \to ZZ \to 4l$

- Four isolated electrons or muons
- Hard work on improving efficiency and momentum resolution
- 4 resolution categories: $4e$, $2e2\mu$, $2\mu 2e$, 4μ
- Observed 27 events (expected 9 background only) in 115-135 GeV range
- $m_H = 124.3 \pm 0.6(stat) \pm 0.4(syst)$ GeV
- $J^P = 0^+$ strongly favored - other modes excluded at $> 95\%$ CL

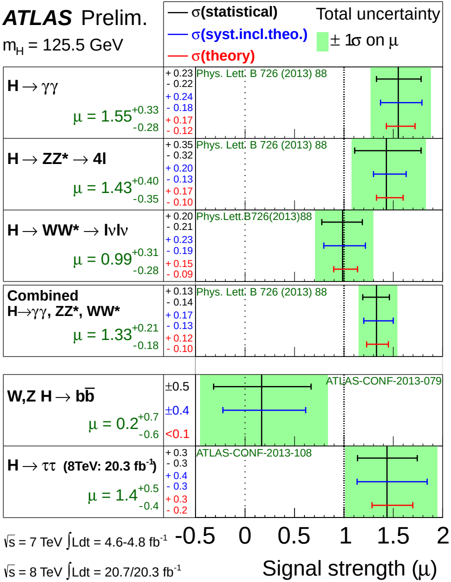
Observed 6.6σ excess



0^- excluded at 97.8% CL



Summary of Higgs boson measurements

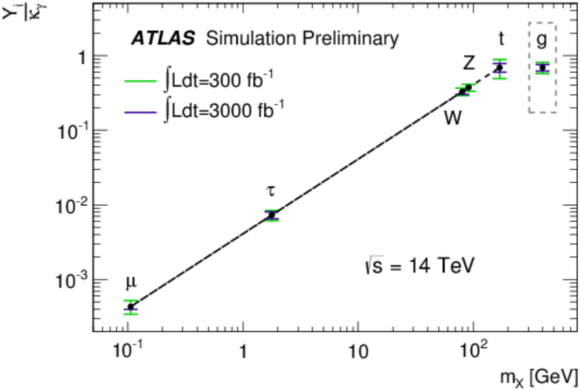


- Signal strength $\mu = \frac{\sigma \times BR}{\sigma_{SM} \times BR_{SM}}$
- Clear evidence for Higgs boson decays to gauge bosons with properties consistent with the SM predictions
- Strong evidence for $H \to \tau\tau$ decays

What's next?

Flavor puzzles: Higgs couplings to fermions at LHC

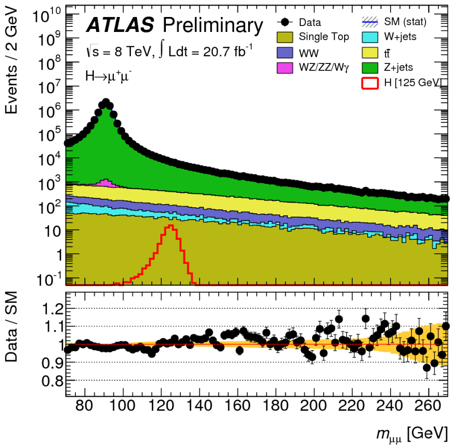
$$Y_f \sim m_f/v, \; Y_V \sim m_V/v, \; v = 246 \text{ GeV}$$



- Explore flavor physics in Higgs boson couplings to fermions
- $H \to \tau\tau$ and $t\bar{t}H$ test 3rd generation couplings
- $H \to \mu\mu$ tests 2nd generation coupling
- Is there CP violation at the Electroweak scale?

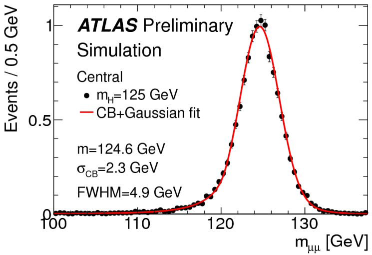
$H \to \mu\mu$ search

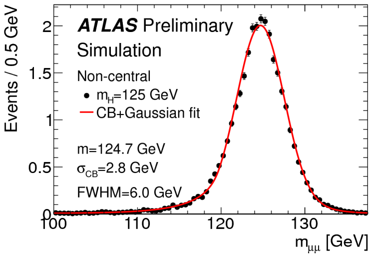
- $H \to \mu\mu$ probes directly SM Higgs coupling to 2nd generation fermions
- $B(H[125] \to \mu\mu) = 2.2 \times 10^{-4} \to 2.6$ events/fb^{-1} ($\approx$ 55% efficiency)
- Dominant irreducible background is Z+jet (also $t\bar{t}$ and di-bosons)

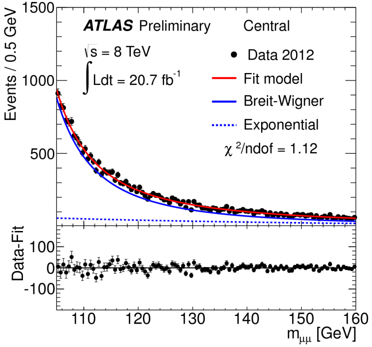


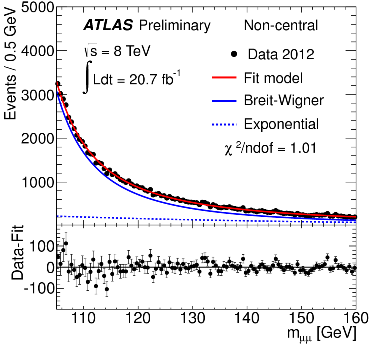
	$\lvert m_H - m_{\mu\mu}\rvert \leq 5$ GeV
Signal [125 GeV]	37.7 ± 0.2
WW	250 ± 4
$WZ/ZZ/W\gamma$	30 ± 1
$t\bar{t}$	1374 ± 13
Single Top	151 ± 5
Z+jets	15806 ± 125
W+jets	88 ± 6
Total Bkg.	17697 ± 126
Observed	17442

$H \rightarrow \mu\mu$: two resolution categories

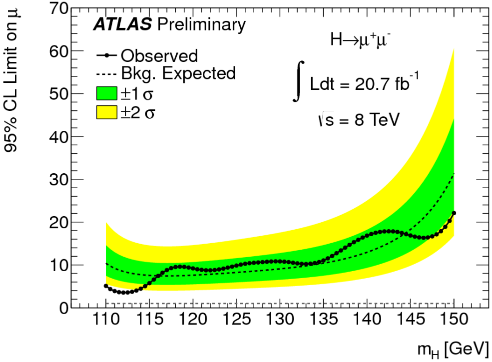








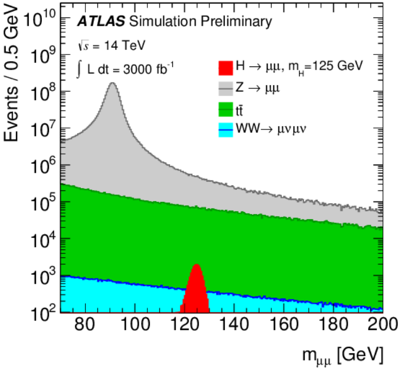
Results

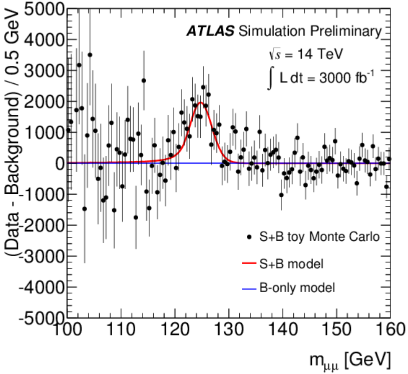


- No evidence of signficant enhancement in the $H \to \mu\mu$ production
- Observed (expected) limit at the 95% CL for the Higgs boson with a mass of 125 GeV is 9.8 (8.2) times the Standard Model prediction

$H \to \mu\mu$ at HL-LHC

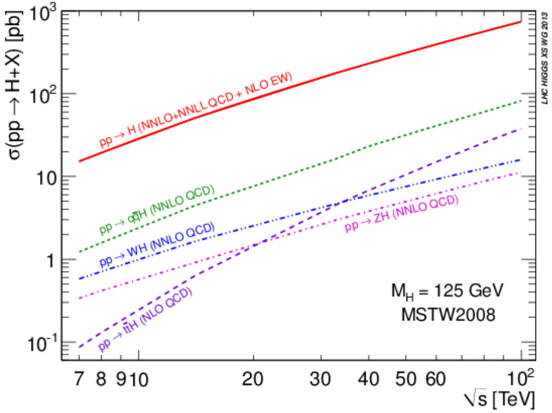
- High Luminosity LHC will provide up to 3000 fb^{-1}
- Extensive ATLAS detector upgrades
- Expand sensitivity of searches for new physics
- Expect $\sim 10\%$ statistical uncertainty on $H \to \mu\mu$ with HL-LHC





Higgs boson measurements at 14 TeV

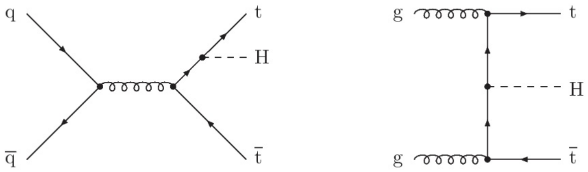
- Higher Higgs cross-section but challenging pileup conditions
- Expect $\approx 5 - 10\%$ statistical precision on Higgs boson couplings



	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)

$t\bar{t}H$ cross-section and branching ratios

- $t\bar{t}H$ allows to measure directly the top quark Yukawa coupling
- Probe for new physics contributions in $gg \to H$ and $H \to \gamma\gamma$ loops



Examples of LO Feynman diagrams for the partonic processes $\mathrm{q\overline{q}, gg \to t\bar{t}H}$.

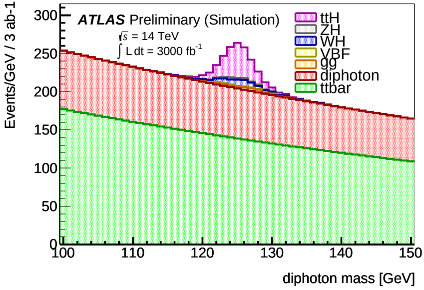
$t\bar{t}H, H \to bb$

- Dominant decay mode
- Large irreducible $t\bar{t} + bb$ QCD background
- Boosted techniques at 14 TeV

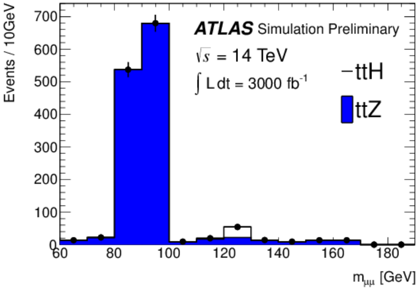
$t\bar{t}H$ at HL-LHC

- $\sim 20\%$ statistical precision on ttH coupling measurement in $H \to \mu\mu$, $H \to 4l$ and $H \to \gamma\gamma$ decay modes

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



$t\bar{t}H \to t\bar{t} + \mu\mu$



$t\bar{t}H \to$ *leptons*

ttH coupling measurement:

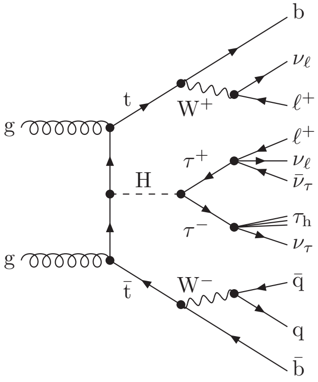
- $t\bar{t}H \to WbWb + WW$
- $t\bar{t}H \to WbWb + \tau\tau$
- Search for CP violation in $\tau\tau$

$t\bar{t}H \to$ *leptons*

- Multi-lepton final states to suppress $t\bar{t} + X$
- Main backgrounds:
  – $t\bar{t}W$ and $t\bar{t}Z$
  – $t\bar{t}$ + jets with non-prompt leptons

Potential channels

- $t\bar{t}H \to$ same sign 2-lepton + 6-jets
- $t\bar{t}H \to$ same sign 2-lepton + τ + 4-jets
- $t\bar{t}H \to$ 3-lepton + 4-jets
- $t\bar{t}H \to$ 4-lepton + 2-jets



Summary and outlook

- The Higgs boson discovery completes the SM
- Yet the SM does not explain full range of the observed phenomena
- Extensive searches at the LHC and other facilities so far have found no evidence for new physics
- Upcoming LHC runs will expand reach of new physics searches and allow precision measurements of Higgs boson properties
- Studies for future high energy colliders are underway
- SM precisely predicts all Higgs boson properties for fixed m_H
- Any deviations can represent signs of new physics

Is the Higgs boson natural?
Only future experiments can tell.