Experimental summary

Alain Blondel
Physics session

Warnings:

1. Physics was not the primary goal of the workshop.

2. Report claimed precisions based on claimed performances without critical evaluation of the difficulty of reaching them.
The Higgs Boson Discovery

Discovered Higgs-like Boson: C1

Is this the SM one? From searches to measurements

- observed: 6.9; expected: 7.8

November 14, 2012
LHC has done better than projected:

here is a plot from ATLAS in 2005, expected 3-4σ with 10fb-1 at 14TeV
The questions (Young-Kee-Kim):

Is this the Standard Model Higgs?
A Higgs beyond the SM?

Measure the properties of this new particle with high precision

your Banker's question:
What precision is needed to see something interesting?
Once the Higgs boson mass is known, the Standard Model is entirely defined. -- with the notable exception of neutrino masses, nature & mixings ***the only new physics there is*** but we expect these to be almost completely decoupled from Higgs observables. (true?)

Does $H(125.9)$
Fully accounts for EWSB ($W, Z$ couplings)?
Couples to fermions?
Accounts for fermion masses?
Fermion couplings $\propto$ masses?
Are there others?
Quantum numbers?
SM branching fractions to gauge bosons?
Decays to new particles?
All production modes as expected?
Implications of $MH \approx 126$ GeV?
Any sign of new strong dynamics?

your Banker's question:
What precision is needed to see something interesting?
The theorists (Chris Quigg) answer:
Some guidance from other theorists

New physics affects the Higgs couplings

SUSY
\[
\frac{g_{hbb}}{g_{h_{\text{SM}}bb}} = \frac{g_{h_{\tau\tau}}}{g_{h_{\text{SM}}\tau\tau}} \approx 1 + 1.7\% \left( \frac{1 \text{ TeV}}{m_A} \right)^2 , \quad \text{for } \tan\beta = 5
\]

Composite Higgs
\[
\frac{g_{h_{ff}}}{g_{h_{\text{SM}}ff}} \approx \frac{g_{h_{VV}}}{g_{h_{\text{SM}}VV}} \approx 1 - 3\% \left( \frac{1 \text{ TeV}}{f} \right)^2
\]

Top partners
\[
\frac{g_{h_{gg}}}{g_{h_{\text{SM}}gg}} \approx 1 + 2.9\% \left( \frac{1 \text{ TeV}}{m_T} \right)^2 , \quad \frac{g_{h_{\gamma\gamma}}}{g_{h_{\text{SM}}\gamma\gamma}} \approx 1 - 0.8\% \left( \frac{1 \text{ TeV}}{m_T} \right)^2
\]

Other models may give up to 5% deviations with respect to the Standard Model

Sensitivity to “TeV” new physics needs per-cent to sub-per-cent accuracy on couplings for 5 sigma discovery

LHC discoveries/(or not) at 13 TeV will be crucial to understand the strategy for future collider projects

The LHC is a Higgs Factory!

1M Higgs already produced - more than most other Higgs factory projects.
15 Higgs bosons / minute - and more to come (gain factor 3 going to 13 TeV)

Difficulties: several production mechanisms to disentangle and significant systematics in the production cross-sections $\sigma_{\text{prod}}$.
Challenge will be to reduce systematics by measuring related processes.

$$\sigma_{i\rightarrow f}^{\text{observed}} \propto \sigma_{\text{prod}} \left( g_{Hi} \right)^2 \left( g_{Hf} \right)^2 \frac{\Gamma_i}{\Gamma_f} \quad \text{if } i=f \text{ as in } WZ \text{ with } H \rightarrow ZZ \rightarrow \text{absolute normalization}$$

HF2012 summary  Physics-- Alain Blondel  16-11-2012 Fermilab
## Conclusions

### Approved LHC 300 fb\(^{-1}\) at 14 TeV:
- Higgs mass at 100 MeV
- Disentangle Spin 0 vs Spin 2 and main CP component in ZZ*  
- Coupling rel. precision/Exper.
  - Z, W, b, \(\tau\)  10-15\%
  - t, \(\mu\)  3-2 \(\sigma\) observation
  - \(\gamma\gamma\) and gg  5-11\%

### HL-LHC 3000 fb\(^{-1}\) at 14 TeV:
- Higgs mass at 50 MeV
- More precise studies of Higgs CP sector
- Couplings rel. precision/Exper.
  - Z, W, b, \(\tau\), t, \(\mu\)  2-10\%
  - \(\gamma\gamma\) and gg  2-5\%
  - H\(\rightarrow\)HH \(>3\ \sigma\) observation (2 Exper.)

*Assuming sizeable reduction of theory errors*

---

LHC experiments entered the Higgs properties measurement era: this is just the beginning! LHC Upgrade crucial step towards precision tests of the nature of the newly-discovered boson
HL-LHC's evaluation today:

LHC will measure couplings between 2-10% for Z, W, gluon, γ, b, tau, and muon and the Higgs self-coupling to about 30%

-- Total width (and invisible width by difference with expected one)
-- CP properties
will be investigated

-- detailed line shape will *not* be measured

Caveat:
1. HL-LHC not approved yet
2. systematic errors will go down (how much?)
3. theory errors will reduce (how much?)

History has shown that smart people working hard usually do better than expected (ex: W mass at Tevatron etc...
S. Henderson

Linear Colliders
- ILC
- CLIC
- SLC-type
- Adv. Concepts

Circular e^+e^- Colliders
- LEP3
- TLEP
- Super-Tristan
- FNAL Site-filler
- IHEP, + ...

Higgs Factories

SAPPHIRE, CLICHÉ, + ...

γ-γ Colliders

Muon Colliders

HF2012 summary  Physics-- Alain Blondel  16-11-2012 Fermilab
ILC in a Nutshell

Ring to Main Linac (RTML) (inc. bunch compressors)

Damping Rings

Polarised electron source

Polarised positron source

Beam Delivery System (BDS) & physics detectors

not too scale
CLIC Layout at 3 TeV

**Goal:** Lepton energy frontier

- **Drive Beam Generation Complex**
  - 819 klystrons
  - 15 MW, 142 µs
  - Drive beam accelerator
    - 2.4 GeV, 1.0 GHz
  - 2.5 km
  - 240 ns
  - 140 µs train length - 24 × 24 sub-pulses
  - 4.2 A - 2.4 GeV - 60 cm between bunches

- **Main Beam Generation Complex**
  - Circumferences
    - CR1 293 m
    - CR2 439 m
  - 4.2 A - 2.4 GeV – 60 cm between bunches
  - 24 pulses – 101 A – 2.5 cm between bunches

D. Schulte, CLIC, HF 2012, November 2012
**Linear $e^+e^-$ Collider as a Higgs Factory**

- **Advantages:**
  - Extensive design and prototyping work have been done
  - Big investment have been made. Key technologies are in hand.
  - There exist well-organized international collaborations led respectively by the ILC GDE and CLIC Collaboration (to be combined under the Linear Collider Director appointed by ICFA)
  - Important step towards high energy $e^+e^-$ collisions
  - Polarized beams ($e^- 80\%$, $e^+ 30\%$)
  - A front runner (in terms of readiness)

- **Challenges:**
  - High cost

- **Specific issues:**
  - ILC
    - FFS (goal emittance has not yet been achieved at ATF2)
    - Positron source works only for $E_{e^-} > 350$GeV
    - Industrialization of SRF
    - For Higgs factory: Need 10 Hz for e+ production, or use unpolarized e+ beam as a backup scheme
  - CLIC
    - Accelerating structure
    - Industrialization of major components
    - From CDR to TDR
Many studies performed using full Geant-based MC

Integrated luminosity and numbers of events expected for initial 5 years running at each value of $E_{cm}$

<table>
<thead>
<tr>
<th></th>
<th>$250$ GeV</th>
<th>$350$ GeV</th>
<th>$500$ GeV</th>
<th>$1$ TeV</th>
<th>$1.5$ TeV</th>
<th>$3$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(e^+e^- \rightarrow ZH)$</td>
<td>240 fb</td>
<td>129 fb</td>
<td>57 fb</td>
<td>13 fb</td>
<td>6 fb</td>
<td>1 fb</td>
</tr>
<tr>
<td>$\sigma(e^+e^- \rightarrow H\nu\bar{\nu})$</td>
<td>8 fb</td>
<td>30 fb</td>
<td>75 fb</td>
<td>210 fb</td>
<td>309 fb</td>
<td>484 fb</td>
</tr>
<tr>
<td>Int. $\mathcal{L}$</td>
<td>250 fb$^{-1}$</td>
<td>350 fb$^{-1}$</td>
<td>500 fb$^{-1}$</td>
<td>1000 fb$^{-1}$</td>
<td>1500 fb$^{-1}$</td>
<td>2000 fb$^{-1}$</td>
</tr>
<tr>
<td># ZH events</td>
<td>60,000</td>
<td>45,500</td>
<td>28,500</td>
<td>13,000</td>
<td>7,500</td>
<td>2,000</td>
</tr>
<tr>
<td># $H\nu\bar{\nu}$ events</td>
<td>2,000</td>
<td>10,500</td>
<td>37,500</td>
<td>210,000</td>
<td>460,000</td>
<td>970,000</td>
</tr>
</tbody>
</table>

HF2012 summary  Physics-- Alain Blondel  16-11-2012 Fermilab
How can one increase over LEP 2 (average) luminosity by a factor 500 without exploding the power bill?

Answer is in the B-factory design: a very low vertical emittance ring with higher intrinsic luminosity

electrons and positrons have a much higher chance of interacting
  ➔ much shorter lifetime (few minutes)
  ➔ feed beam continuously with a ancillary accelerator
**LEP3, TLEP**

\[(e^+e^- \to ZH, \ e^+e^- \to W^+W^-, \ e^+e^- \to Z, [e^+e^- \to t\bar{t}])\]

**key parameters**

<table>
<thead>
<tr>
<th></th>
<th>LEP3</th>
<th>TLEP</th>
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<tbody>
<tr>
<td>circumference</td>
<td>26.7 km</td>
<td>80 km</td>
</tr>
<tr>
<td>max beam energy</td>
<td>120 GeV</td>
<td>175 GeV</td>
</tr>
<tr>
<td>max no. of IPs</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>luminosity at 350 GeV c.m.</td>
<td>$5 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
<td>$2.5 \times 10^{35}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>luminosity at 240 GeV c.m.</td>
<td>$2 \times 10^{35}$ cm$^{-2}$s$^{-1}$</td>
<td>$10^{36}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>luminosity at 160 GeV c.m.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>luminosity at 90 GeV c.m.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

at the $Z$ pole repeating LEP physics programme in a few minutes...
prefeasibility assessment for an 80km project at CERN
John Osborne and Caroline Waijer ESPP contr. 165
TLEP tunnel in the KEK area?

SuperTRISTAN in Tsukuba: 40 km ring

Proposal by K. Oide, 13 February 2012
80 km ring in KEK area
105 km tunnel near FNAL

H. Piekarz, “... and ... path to the future of high energy particle physics,” JINST 4, P08007 (2009)

(+ FNAL plan B from R. Talman)
Circular $e^+e^-$ Collider as a Higgs Factory

- **Advantages:**
  - At 240 GeV, potentially a higher luminosity to cost ratio than a linear one
  - Based on mature technology and rich experience
  - Some designs can use existing tunnel and site
  - More than one IP
  - Tunnel of a large ring can be reused as a pp collider in the future

- **Challenges:**
  - Beamstrahlung limiting beam life time requires lattice with large momentum acceptance
  - RF and vacuum problem from synchrotron radiation
  - A lattice with low emittance
  - Efficiency of converting wall power to synchrotron radiation power
  - Limited energy reach
  - No comprehensive study; design study report needed.
The main point of the workshop was to understand whether the performance of circular machines could be as high as advertised, because they offer a potentially better luminosity/cost ratio than the linear ones and the possibility to have several Ips.

There is lots of experience with e+e- storage ring colliders.

The high energy ones considered here involve very small $\beta^*$
  -- leading to strong beamstrahlung that requires large momentum acceptance 4% for LEP3, 3% for TLEP that requires
  1) extra RF
  2) special design of the optics which has not been demonstrated
  -- a possible way out is to reduce the vertical emittance to obtain luminosity with less current/ bunch

and very large synchrotron radiation
  -- what is the wall to beam power transmission efficiency?
  -- detail beam pipe design is challenging -- high critical energy (>1MeV)

There was no obvious show stopper found but a rather long to-do list!

In the following I assume that the performance could be achieved
The Higgs at a Linear e^+e^- Collider has been studied for many years. The community is large and well organized.

At a given $E_{cm}$ and luminosity, the physics has marginally to do with the fact that the collider is linear.

--specifics: +-- $e^-$ polarization is easy at the source for ILC (not critical for Higgs)
- -- Beam energy calibration at $Z$ peak (perhaps $WW$) for rings
- -- EM backgrounds from beam disruption in linear
- -- one IP in linear vs several IPs in circular.
Higgs production mechanism

Assuming that the Higgs is light, in an $e^+e^-$ machine it is produced by the “higgstrahlung” process close to threshold.
Production $\sigma$ section has a maximum at near threshold $\sim 200$ fb.
$10^{34}/cm^2/s \Rightarrow 20'000$ HZ events per year.

$Z$ - tagging by missing mass

For a Higgs of $125$ GeV, a centre of mass energy of $240$ GeV is sufficient
$\Rightarrow$ kinematical constraint near threshold for high precision in mass, width, selection purity
Figure 5: The Higgs boson production cross section as a function of the centre-of-mass energy. The red curve corresponds to the Higgsstrahlung process only, $e^+e^- \rightarrow HZ$, and the blue curve includes the WW and ZZ fusion processes as well, together with their interference with the Higgsstrahlung process. The right graph is a zoom of the left graph around the maximum of the cross section.

Prospective Studies for LEP3 with the CMS Detector

Patrizia Azzis, Colin Bernet1, Cristina Botta1, Patrick Janet1, Markus Klute2, Piergiulio Lenz1, Luca Malgeri1, and Marco Zanetti2

1 CERN, Geneva
2 Massachusetts Institute of Technology
3 INFN, Sezione di Padova

best for tagged ZH physics:
$E_{cm} = m_H + 111 \pm 10$
W. Lohmann et al LCWS/ILC2007

take 240 GeV.
Z - tagging by missing mass

total rate \propto g_{HZZ}^2
ZZZ final state \propto g_{HZZ}^4/\Gamma_H

\Rightarrow measure total width \Gamma_H
empty recoil = invisible width
'funny recoil' = exotic Higgs decay
easy control below threshold

HF2012
Higgs Physics with high-energy $e^+e^-$ colliders

1. Similar precisions to the 250/350 GeV Higgs factory for $W, Z, b, g, \tau, \text{charm, gamma and total and invisible width}$

2. $ttH$ coupling possible with similar precision as HL-LHC (8-10%)

3. Higgs self coupling also very difficult... precision 20-30% similar to HL-LHC

I have to conclude that on the basis of the study of $H(126)$ alone is concerned, the high energy $e^+e^-$ collider is not compelling

Reversely, the Higgs physics can be done with CLIC at high energy

CLIC can work at 250 GeV onwards
- can it be brought down to the $Z$ pole?
# Machines considered:

## #1 Light Higgs Factory: CLICHE, ILC (TESLA) & SAPPHiRE

<table>
<thead>
<tr>
<th>Machine</th>
<th>$E_{e^+e^-}$ (GeV)</th>
<th>$M_{h_{SM}}$ (GeV)</th>
<th>Yield/year</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLICHE</td>
<td>150</td>
<td>115</td>
<td>22.5k</td>
<td>hep-ex/0110056</td>
</tr>
<tr>
<td>TESLA</td>
<td>160</td>
<td>120</td>
<td>23.6k</td>
<td>Correct for $\Gamma_{\gamma\gamma}$</td>
</tr>
<tr>
<td>SAPPHiRE</td>
<td>160</td>
<td>120</td>
<td>21.0k</td>
<td>hep-ex/0101056</td>
</tr>
<tr>
<td>$e^+e^-$</td>
<td>$350_{\text{TESLA}}(500_{\text{NLC}})$</td>
<td>120</td>
<td>3.5k(20k) Tag(Raw)</td>
<td>1208.2827</td>
</tr>
</tbody>
</table>

**Diagram:**
- Main linac
- Laser γ
- Detector
- Drive beam decelerator
- Drive beam
- Delay loop
- Combiner rings
- Drive beam accelerator
- 11-GeV linac
- 500 MeV e- injector
- Drive beam
- Tune-up dump
- 10, 30, 50, 70 GeV
- 0, 20, 40, 60 GeV
- 2.0 km
- Total circumference ~ 9 km
- Dump
- Final focus
- Final focus
- Final focus
- Dump
$h^0 \to b\bar{b}$ and $h^0 \to \gamma\gamma$  

2% measurement of $\{\Gamma_{\gamma\gamma} \times Br(h \to b\bar{b})\}$ within a year!

21% measurement of $\{\Gamma_{\gamma\gamma} \times Br(h \to \gamma\gamma)\}$ within a year!

150 MeV mass measurement in 0.5 year!  

Schmitt, Stenz & Velasco
A $\mu^+\mu^-$ collider can do things that an $e^+e^-$ collider cannot do

- Direct coupling to H expected to be larger by a factor $m_\mu/m_e$
  \[ \sigma(\mu^+\mu^- \rightarrow H) \approx 40000 \times \sigma(e^+e^- \rightarrow H), \sigma_{\text{peak}} = 70 \text{ pb at tree level} \]
- Can it be built + beam energy spread $\delta E/E$ be reduced to $3 \times 10^{-5}$?
  - 6D Cooling, no beamstrahlung, ~no bremsstrahlung
  - For $\delta E/E = 0.003\%$ (δE ~ 3.6 MeV, $\Gamma_H$ ~ 4 MeV)
    \[ \Rightarrow \text{Corresponding luminosity} \sim 10^{31} \text{ cm}^{-2}\text{s}^{-1} \]
    
    Expect 2300 Higgs events in 100 pb$^{-1}$/ year
- Using g-2 precession, beam energy and energy spectrum
  - Can be measured with exquisite precision (<100 keV)
    \[ \Rightarrow \text{From the electrons of muon decays} \]
- Then measure the lineshape of the Higgs at $\sqrt{s} \sim m_H$
  - Five-point scan, $50 + 100 + 200 + 100 + 50$ pb$^{-1}$
    \[ \Rightarrow \text{Precision from } H \rightarrow bb \text{ and } WW : \]

<table>
<thead>
<tr>
<th>$m_H$ (MeV)</th>
<th>$\sigma_{\text{Peak}}$ (pb)</th>
<th>$\Gamma_H$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>$10^{-6}$</td>
<td>2.5%</td>
<td>5%</td>
</tr>
</tbody>
</table>

Patrick Janot

HF2012 : Higgs beyond LHC (Experiments)
14 Nov 2012
MICE is one of the critical R&D experiments towards neutrino factories and muon colliders.

With the growing importance of neutrino physics and the existence of a light Higgs (125 GeV), physics could be turning this way very fast!

Cooling and more generally the initial chain capture, buncher, phase rotation and cooling rely on complex beam dynamics and technology, such as high gradient (~>16 MV/m) RF cavities embedded in strong (>2T) solenoidal magnetic field.

**MANY CHALLENGES!**

**MUON COOLING ➔ HIGH INTENSITY NEUTRINO FACTORY**

**HIGH LUMINOSITY MUON COLLIDER**
COOLING -- Principle is straightforward...

Longitudinal:

Emittance exchange involves ionization varying in space which cancels the dispersion of energies in the beam.

This can be used to reduce the energy spread and is of particular interest for

$$\mu^+ \mu^- \rightarrow H \ (125)$$

since the Higgs is very narrow (~4.2 MeV)
Similar to radiation damping in an electron storage ring: muon momentum is reduced in all directions. Emittance exchange involves ionization varying in space which cancels the dispersion of energies in the beam. This can be used to reduce the energy spread and is of particular interest for \( \mu^+ + \mu^- \rightarrow H \) since the Higgs is very narrow (~5MeV).

COOLING -- Principle is straightforward...

Transverse: muon momentum is reduced in all directions by going through liquid hydrogen absorbers, and restored longitudinally by acceleration in RF cavities. Thus transverse emittance is reduced progressively. Because of a) the production of muons by pion decay and b) the short muon lifetime, ionization cooling is only practical solution to produce high brilliance muon beams.

Practical realization is not!

MICE cooling channel (4D cooling)

6D candidate cooling lattices
Extension possibilities

1. LEP3 (C=27km) is limited to the ZH threshold at 240 GeV
   TLEP (C=80km) can reach 350 GeV.
   all rings can accept up to 4 collision points and run at the Z peak
   80km ring e+e- collider 1st step to O(100 TeV) pp collider
   400-500 GeV is the end limit to circular machines.

2. linear machines can be upgraded to energies up to ~1 or even 3 TeV

3. the time structure is very different between linear (pulsed)
   and circular (CW) which has impact on the detector design.
   The ILC detectors as presently designed would not work on a ring.

4. A muon collider remains the most promising option for the very high
   energy exploration with point-like particles.
Conclusions

-- The newly discovered H(126) candidate is a fascinating particle of a new nature (elementary scalar!) that deserves detailed measurements.

-- There is much more to understand about Higgs physics measurements and their potential to test physics beyond the SM. This should be discussed in a dedicated and detailed Higgs Physics workshop.

-- LHC is/will be an impressive Higgs factory. This must be taken into account in any future machine discussion!

-- The linear collider ILC can perform measurements at few% level for the Higgs invisible width, search for exotic decays, and improvement of bb, cc, W, Z couplings wrt LHC by factors 2-5
  -- for γγ, ττ, μμ, ttH, HHH, HL-LHC will do ~ as well or better

-- There is a strong motivation to investigate if one could do better
  -- more precise or/and cheaper

-- Now that the Higgs mass is known, a new round of precision EWRC measurements is strongly motivated. (Predicted \( m_{\text{top}} \), \( m_{\text{Higgs}} \), now sensitive inclusively to EW-coupled new physics)
Conclusions(2)
Alternate Higgs factories considered include
-- circular e+e- collider
-- $\gamma\gamma$ collider
-- $\mu\mu$ collider
In combination with HL-LHC the physics coverage of e+e- machines
is quite complete.

A $\gamma\gamma$ collider is a good add-on to linear collider
-- one should discuss carefully what can be done at $\gamma\gamma$ collider
that cannot be done between LHC and e+e- collider
-- the claim of uniqueness is 2% resolution on $\Gamma_{\gamma\gamma}$; very interesting
A study dedicated to the understanding of the feasibility of the machine
and of the specificity of the measurements would be worthwhile

A muon collider could do everything an e+e- could do if same luminosity
can be reached.
-- If an energy resolution of 0.003% can be achieved (4D and 6D cooling!)
s-channel Higgs production allows superb measurements of the
$H(126)$ line shape and 'fine structure' exploration
-- A muon collider is completely unique to study the $H/A$ system of
a Higgs doublet model
-- it remains the best way to reach $>3$ TeV energy collisions between
point like particles.
-- e+e- ring collider offer a potentially better luminosity/cost ratio than the linear one and the possibility to have several IPs.

-- Much progress has been brought about by the experience of LEP2 B factories and Synchrotron light sources.

-- The main point of the HF2012 workshop was to understand whether the performance of circular machines could be as high as advertised.

The answer is 'maybe' but there is lots of work to do to establish this. There are also ideas to push the luminosity further. This calls for a design study of circular e+e- Higgs Factory.

-- If the luminosities advertised can be reached, the resolutions on several Higgs couplings can be improved from a few % to below percent precisions, opening the possibility of discovery of TeV scale new physics.

-- Revisiting Z pole and W threshold is now a must. This can be done at both circular and linear machines with some differences regarding energy calibration and polarization.
CONCLUSION

With the discovery of H(126) a new chapter is open in Particle physics. It will take a long time and should be planned carefully.

This is all very exciting!
Higgs boson production at LHC

8 TeV

<table>
<thead>
<tr>
<th>$M_H$ (125 GeV)</th>
<th>$\sigma$ (fb)</th>
<th>$\delta_{<em>{\text{th}}}^{</em>{\text{TOT}}}$</th>
<th>$\delta_{<em>{\text{th}}}^{</em>{\text{QCD-Scale}}}$</th>
<th>$\delta_{<em>{\text{th}}}^{</em>{\text{PDF+as}}}$</th>
<th>$\delta\sigma/\delta M(0.5\text{GeV})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggH</td>
<td>$19.5 \times 10^3$</td>
<td>15%</td>
<td>8%</td>
<td>7%</td>
<td>0.8%</td>
</tr>
<tr>
<td>VBF</td>
<td>$1.58 \times 10^3$</td>
<td>3%</td>
<td>0.2%</td>
<td>3%</td>
<td>0.4%</td>
</tr>
<tr>
<td>WH</td>
<td>697</td>
<td>4%</td>
<td>0.5%</td>
<td>4%</td>
<td>1.3%</td>
</tr>
<tr>
<td>ZH</td>
<td>394</td>
<td>5%</td>
<td>1.5%</td>
<td>4%</td>
<td>1.3%</td>
</tr>
<tr>
<td>ttH</td>
<td>130</td>
<td>14%</td>
<td>7%</td>
<td>8%</td>
<td>1.9%</td>
</tr>
</tbody>
</table>

Theory systematics more relevant for ggH and ttH - Mass dependency very weak.
-- Important measurements at any moment depend on what is already known

What are the expected precisions from HL-LHC?

-- mass (125.9±0.4 GeV/c²) (my average)
-- spin parity (0+ preferred at 2.45σ -- CMS) →

Couplings:
-- H-Z and H-W (κᵥ to ~20%)
-- H-t,b,c (κₕ to ~20%)
-- H-τ, μ
green = today
-- H-invisible (dark matter candidates)
black = HL-LHC
-- H-exotic
red = no claim to
-- H-gluon, H-γ (20-30%)
be possible
-- H self coupling

-- CP violation
-- detailed line shape (more than one peak etc...)

κᵢ = gᵢ^{meas}/gᵢ^{SM}

(σ · BR)(gg → H → γγ) = σ_{SM}(gg → H) · BR_{SM}(H → γγ) · \frac{κ₂^g · κ₂^γ}{κ₂^H}
**Couplings at HL-LHC: ATLAS**

**MC Samples at 14 TeV from Fast-Sim.**
Truth with smearing: best estimate of physics objects dependency on pile up.
Validated with full-sim. up to \( \mu \sim 70 \)

**Analyses included in ATLAS study:**
- \( H \rightarrow \gamma \gamma \) 0-jet and VBF
- \( H \rightarrow \tau \tau \) VBF lep-lep and lep-had
- \( H \rightarrow ZZ \rightarrow 4l \)
- \( H \rightarrow WW \rightarrow l\nu l\nu \) 0-jet and VBF
- \( WH/ZH \rightarrow \gamma \gamma \)
- \( ttH \rightarrow \gamma \gamma \) (\( ttH \rightarrow \mu \mu \)) Direct top Y coupling
- \( H \rightarrow \mu \mu \) Second generation fermion coupling
- \( HH \rightarrow bb \gamma \gamma \) Higgs Self-Couplings

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**Graph:**
- **ATLAS Preliminary (Simulation)**
  - \( \sqrt{s} = 14 \text{ TeV} \)
  - \( \int L dt = 3000 \text{ fb}^{-1} \)

**Legend:**
- \( ttH \rightarrow \gamma \gamma \)
- \( HH \rightarrow bb \gamma \gamma \)
- \( WH/ZH \rightarrow \gamma \gamma \)
- \( HH \rightarrow \mu \mu \)
- \( ttH \rightarrow \mu \mu \)

**Statistics:**
- Very Robust channel
- Good S/B
- Statistically limited