Higgs Prospects for future (HL)LHC runs

based on public ATLAS and CMS prospects studies (but likely biased towards showing more ATLAS material)

\[ L \]

3000 fb^{-1}

O. Arnaez
CERN
Introduction

- **Search and discovery** of the Brout-Englert-Higgs-Guralnik-Hagen-Kibble boson, a.k.a. “Higgs” boson and the initial **measurements** of its properties with the LHC Run-I data.

- Expected to collect up to $\sim 300 \text{ fb}^{-1}$ of data with the LHC and 3000 fb$^{-1}$ with the upgraded HL-LHC.

- This talk: expected precision from ATLAS and CMS on Higgs property measurements and on sensitivities to direct new physics searches in the Higgs sector at the HL-LHC.

**LHC / HL-LHC Plan**

- **LS1**: splice consolidation button, collimators, R2E project.
  - 2012: 8 TeV.
  - 2015: 13-14 TeV.

- **EYETS**: SPS CO.

- **LS2**: injector upgrade, cryogenics, Point 4, dispersion, suppression, collimation.
  - 2012: 25 fb$^{-1}$.
  - 2019: 100 fb$^{-1}$.

- **LS3**: HL-LHC installation.
  - 2023-2025: 5 to 7 x nominal luminosity.
  - 2025: 3000 fb$^{-1}$.

**Parameter Value**

- $\kappa_{V} \leq 1$
Introduction (2)

- HL-LHC Benchmark scenario:
  - LHC approved for running to deliver 300 fb\(^{-1}\) by \(~2021\)
  - Post-LS3 operation at 5\times10^{34} \text{ cm}^{-2}\text{s}^{-1} (lumi leveling)
    - 25 ns bunch spacing
    - 140 events per bunch crossing
    - 3000 fb\(^{-1}\) over 10 years
  - Detector upgrades needed to cope with radiation damage and pileup
    - aim to maintain/enhance physics performance

LHC / HL-LHC Plan

- LS1
  - splice consolidation button collimators
  - R2E project
- EYETS
  - 8 TeV
- SPS CC
- LS2
  - injector upgrade cryogenics Point 4
  - dispersion suppression collimation
- LS3
  - HL-LHC installation
  - 5 to 7 x nominal luminosity
- 2012
- 2013
- 2014
- 2015
- 2016
- 2017
- 2018
- 2019
- 2020
- 2021
- 2022
- 2023
- 2024
- 2025
- 2035

nominal luminosity 75%

Rencontres du Vietnam 2014

25 fb\(^{-1}\)

100 fb\(^{-1}\)

300 fb\(^{-1}\)

3000 fb\(^{-1}\)
Performance and methodology

- Experimental environment is degraded at high number of interactions per bunch-crossing, $\mu$, because of pile-up in the subdetectors

- Higgs prospects are studied by refining current analyses or designing new ones

- CMS assumes that the upgraded detector will compensate the effects of higher pile-up and extrapolates event rates from existing Run I-like selections or using DELPHES (fast simulation with uniform magnetic field and particle smearing)

- ATLAS evaluated the performance using full-simulation studies (sometimes similar, sometimes worse than today) and most often smeared truth-level info with efficiencies/resolution

- Different scenarios usually considered for what concerns the reduction of systematic uncertainties (in particular the signal theoretical ones: 'current', 'best guess', 'halved', 'none')
Performance and methodology (2)

- Full simulation studies help to get an idea of the future detector's performance under high-luminosity conditions.

**Photon selection**

$H(400 \text{ GeV}) \rightarrow \mu\mu$

$\sqrt{s}=14 \text{ TeV}$

$<\mu>=80$

$\Sigma E_T [\text{GeV}]$

$E_{\text{miss}}$ Resolution

**ATLAS Simulation Preliminary**

- 25 ns bunch spacing
- Parametrisation
- $Z' \rightarrow t\bar{t}, <\mu>=140, \sigma_{\text{pile-up}}^{\text{lead}} (\mu=140), \text{calib.}$
- MinBias, $<\mu>=140, \sigma_{\text{pile-up}}^{\text{lead}} (\mu=140), \text{calib.}$
- J3, $<\mu>=140, \sigma_{\text{pile-up}}^{\text{lead}} (\mu=140), \text{calib.}$

$\eta=0.2$

- ITK $\mu=80$
- ITK $\mu=140$
- ITK $\mu=200$
- ES

**b-tagging**

Jet $p_T [\text{GeV}]$

Mistag rate

**ATLAS Simulation Preliminary**

$\text{Entries / 2 GeV}$

H(400 GeV) $\rightarrow \mu\mu$

$\sim$ now vs Phase-II

- MS+ID
- MS+ITK

$\Delta m_{\mu\mu} - m_H [\text{GeV}]$
Extending the detectors

- Also looked at increase of the acceptance for some signals if using an extended tracker volume, here ATLAS H → tautau prospects:

<table>
<thead>
<tr>
<th>forward pile-up jet rejection</th>
<th>50%</th>
<th>75%</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>forward tracker coverage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run-I tracking volume</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 3.0$</td>
<td>0.18</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 3.5$</td>
<td>0.18</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 4.0$</td>
<td>0.16</td>
</tr>
</tbody>
</table>
Extending the detectors (2)

- Other example where H → ZZ events have served as benchmark to look at the different peak resolutions (ATLAS, left) obtained with forward tracking devices or acceptance gain (CMS, right).

**ATLAS Simulation Preliminary**

\[ \int L \, dt = 3000 \text{ fb}^{-1} \]

with Z mass constraint

**CMS Simulation 2013**

\[ s = 14 \text{ TeV} \]

\[ L = 3000 \text{ fb}^{-1} \]

Extending to \( |\eta| = 4 \) { }

<table>
<thead>
<tr>
<th>Pileup</th>
<th>Phase I detector</th>
<th>Full Simulation</th>
<th>Delphes</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td></td>
<td>35.87±0.48</td>
<td>35.68±0.48</td>
</tr>
<tr>
<td>70</td>
<td></td>
<td>35.65±0.48</td>
<td>34.69±0.48</td>
</tr>
<tr>
<td>140</td>
<td></td>
<td>34.74±0.48</td>
<td>36.05±0.48</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pileup</th>
<th>Phase II detector</th>
<th>Full Simulation</th>
<th>Delphes</th>
</tr>
</thead>
<tbody>
<tr>
<td>140 Configuration 3</td>
<td></td>
<td>37.88±0.49</td>
<td></td>
</tr>
<tr>
<td>140 Configuration 4</td>
<td></td>
<td>52.00±0.50</td>
<td></td>
</tr>
</tbody>
</table>
A peak! A cape! It's a peninsula!

- ZZ final states remain very clear channels
- The statistics allow to probe many production modes
- Total H production cross-section uncertainty can be constrained by ZZ events at O(few %)
- CMS showed that these channels could also benefit from a tracking system extended in rapidity (increase of acceptance)

<table>
<thead>
<tr>
<th>$\Delta \mu/\mu$</th>
<th>ATLAS</th>
<th>Total</th>
<th>Stat.</th>
<th>Expt. syst.</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production mode</td>
<td></td>
<td>300 fb$^{-1}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ggF</td>
<td>0.152</td>
<td>0.066</td>
<td>0.053</td>
<td>0.124</td>
<td></td>
</tr>
<tr>
<td>VBF</td>
<td>0.625</td>
<td>0.545</td>
<td>0.233</td>
<td>0.226</td>
<td></td>
</tr>
<tr>
<td>$WH$</td>
<td>1.074</td>
<td>1.064</td>
<td>0.061</td>
<td>0.085</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>0.535</td>
<td>0.516</td>
<td>0.038</td>
<td>0.120</td>
<td></td>
</tr>
<tr>
<td>Combined</td>
<td>0.125</td>
<td>0.042</td>
<td>0.044</td>
<td>0.108</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Production mode</td>
<td></td>
<td>3000 fb$^{-1}$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ggF</td>
<td>0.131</td>
<td>0.025</td>
<td>0.040</td>
<td>0.124</td>
<td></td>
</tr>
<tr>
<td>VBF</td>
<td>0.371</td>
<td>0.187</td>
<td>0.225</td>
<td>0.226</td>
<td></td>
</tr>
<tr>
<td>$WH$</td>
<td>0.390</td>
<td>0.375</td>
<td>0.061</td>
<td>0.085</td>
<td></td>
</tr>
<tr>
<td>ZH</td>
<td>0.532</td>
<td>0.526</td>
<td>0.038</td>
<td>0.073</td>
<td></td>
</tr>
<tr>
<td>$t\bar{t}H$</td>
<td>0.224</td>
<td>0.184</td>
<td>0.034</td>
<td>0.120</td>
<td></td>
</tr>
<tr>
<td>Combined</td>
<td>0.100</td>
<td>0.016</td>
<td>0.036</td>
<td>0.093</td>
<td></td>
</tr>
</tbody>
</table>

$\mu = \sigma / \sigma_{SM}$
Diphoton channels

- Similarly, significance in $\gamma\gamma$ decay channels grows up with clear peaks on top of smooth background shapes.

  ![Graph showing significance growth](ATL-PHYS-PUB-2014-012)

- Diphoton channels is powerful for H-t Yukawa coupling measurements.

- Measurements limited by current signal uncertainties.

- Reaching the $\sim$3.5% level of precision on the combined signal strength (without th. uncertainties).

<table>
<thead>
<tr>
<th>Production mode</th>
<th>Total</th>
<th>Statistical</th>
<th>Experimental</th>
<th>Theoretical</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}H$</td>
<td>+21</td>
<td>+13</td>
<td>+5</td>
<td>+17</td>
</tr>
<tr>
<td>$WH$</td>
<td>+26</td>
<td>+21</td>
<td>+13</td>
<td>+10</td>
</tr>
<tr>
<td>$ZH$</td>
<td>+35</td>
<td>+32</td>
<td>+7</td>
<td>+12</td>
</tr>
<tr>
<td>$ggF$</td>
<td>+19</td>
<td>+3</td>
<td>+1</td>
<td>+19</td>
</tr>
<tr>
<td>$VBF$</td>
<td>+29</td>
<td>+18</td>
<td>+1</td>
<td>+23</td>
</tr>
</tbody>
</table>

11 mars 2015
O. Arnaez - FCC
Going from 8 to 14 TeV, $t\bar{t}$ increases $\sim 1.7x$ faster than the signal; jet counting affected by pile-up conditions → in general, current categories have a largely degraded S/B → HL-LHC studies require dedicated optimizations

Large stat → diff measurements?

$\tau\tau$ expectations on the signal strength precision are 8(5)% with current (/2) theory uncertainties

11 mars 2015

O. Arnaez - FCC
Rare channels

- Rare decays are the ones benefiting the most from the large HL-LHC dataset
- $Z\gamma$ sensitive to potential new particles in loop
  - $\sim 20-30\%$ precision on signal strength ($\sim 4\sigma$) expected by CMS/ATLAS
    (Currently limits are at $\sim 10\times$ the SM prediction)
- $\mu\mu$ sensitive to the 2$^\text{nd}$ generation couplings
  - 7-8$\sigma$ and $\Delta\mu/\mu \sim 20\%$ expected, ttH($\mu\mu$) observable
- $H\to e^+e^-$, $H\to cc$ decays and $bbH$ productions observable?
  (H$\to J/\psi\gamma$ at $O(500)x$SM in Run-I)
Channels summary

**CMS Projection**

Expected uncertainties on Higgs boson signal strength

- Scenario 1: 300 fb\(^{-1}\) at \(\sqrt{s} = 14\) TeV
- Scenario 2: 300 fb\(^{-1}\) at \(\sqrt{s} = 14\) TeV

Scenario 2: TH unc. Scaled by 1/2, exp by \(\sqrt{L}\)

**ATLAS Simulation Preliminary**

\(\sqrt{s} = 14\) TeV: \(\int L dt = 300\) fb\(^{-1}\); \(\int L dt = 3000\) fb\(^{-1}\)

- H\(\rightarrow\gamma\gamma\)
  - (comb.)
  - (0j)
  - (1j)
  - (VBF-like)
  - (WH-like)
  - (ZH-like)
  - (ttH-like)

- H\(\rightarrowZZ\)
  - (comb.)
  - (VH-like)
  - (ttH-like)
  - (VBF-like)
  - (ggF-like)

- H\(\rightarrowWW\)
  - (comb.)
  - (0j)
  - (1j)
  - (VBF-like)

- H\(\rightarrowZ\gamma\)
  - (incl.)

- H\(\rightarrowbb\)
  - (comb.)
  - (WH-like)
  - (ZH-like)

- H\(\rightarrow\tau\tau\)
  - (VBF-like)

- H\(\rightarrow\mu\mu\)
  - (comb.)
  - (incl.)
  - (ttH-like)

Dashed band = adding current Theo. unc.
Combination

- Inputs from ATLAS and CMS concerning the individual channels are very similar although techniques to obtain those prospects are quite different.

- As for run-I data, those channels prospects can be combined to obtain precision on couplings measurements.

- One very simple model consists in fitting scale factors for fermions on one hand and bosons on the other hand:
Couplings fit

- $\kappa$-framework to scale couplings or their ratios to get rid of total width assumptions
  - Which precision do we need to go? $< \frac{5\% \times (\frac{1}{\Lambda})^2}{\Lambda}$?

**ATLAS** Simulation Preliminary

$\sqrt{s} = 14$ TeV: $\int dt = 300$ fb$^{-1}$; $\int L dt = 3000$ fb$^{-1}$

CMS

Assumption = no BSM particle

- In the future, use of EFT for more general model fits

ATLAS combined results do not include yet the new information for $Z\gamma$, $VH(\gamma\gamma)$, $ttH(\gamma\gamma)$ and $VH(bb)$
Missing partial decay width?

- Using Z-tagging, direct search for invisible branching fraction in ZH events can be carried out.

<table>
<thead>
<tr>
<th>BR(H→inv.) limits at 95% (90%) CL</th>
<th>300 fb⁻¹</th>
<th>3000 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Realistic scenario</td>
<td>23% (19%)</td>
<td>8.0% (6.7%)</td>
</tr>
<tr>
<td>Conservative scenario</td>
<td>32% (27%)</td>
<td>16% (13%)</td>
</tr>
</tbody>
</table>

- Through the coupling fit, CMS expects to constrain the BR(inv) to better than 11%.
- Limits on the invisible branching fraction can be interpreted as bounds on the strength of the interaction between the dark matter and the Higgs boson.

**ATLAS Simulation**

- Preliminary
- ZH → e⁺e⁻/μ⁺μ⁻ invisible
- s=14 TeV, ∫L dt = 3000 fb⁻¹

**ATLAS Simulation Preliminary**

- ZH → ll invisible
- Zs = 14 TeV, ∫L dt = 3000 fb⁻¹

**Higgs-portal Model**

- DM-Nucleon cross section [cm²]
- DM Mass [GeV]

References:

- ATLAS
- ATL-PHYS-PUB-2013-014
- arXiv:hep-ph0605188
- arXiv:1109.4398
- arXiv:1112.3299
- arXiv:1203.2064
Total width

- Interference of the $H \rightarrow \gamma\gamma$ signal with respect to the continuum diphoton background ($gg \rightarrow \gamma\gamma$ box diagrams)
  
  - Causes $p_T(H)$-dependent apparent shift in mass
  - Looking at the mass difference between $p_T(H)$ categories

- New techniques based on off-shell measurements have not been extrapolated yet to high-luminosity datasets:
  - Current limits at 5-10x $\Gamma_{SM}$
  - Almost already theoretical uncertainties-limited
  - mu_off vs mu_on → refined differential measurements could help?
Probing the coupling structure

- ZZ events provide the full angular information
- Very sensitive to non-SM (0\(^+\)) contributions

\[ A(H \rightarrow ZZ) = v^{-1} \left( a_1 m_Z^2 e_1^* e_2^* + a_2 f_{\mu\nu}^{(1)} f^{* (2), \mu\nu} + a_3 f_{\mu\nu}^{(1)} f^{* (2), \mu\nu} \right) \]

- Fit fraction of events discriminant distributions
  \[ f_{\alpha_i} = \frac{|a_i|^2 \sigma_i}{|a_1|^2 \sigma_1 + |a_i|^2 \sigma_i} \]

\[ \text{CMS-FTR-13-013, arXiv:1307.7135} \]

ATL-PHYS-PUB-2013-013

\[ 2 \times \Delta(\text{NLL}) \]

- Loop-induced CP-even contribution \( f_{g_2} \)
- CP-odd fraction limit \( f_{a_3} \)

\[ \text{ATLAS Simulation Preliminary} \]

3000 fb\(^{-1}\): 68%-95% CL
300 fb\(^{-1}\): 68%-95% CL

\[ 8D \text{ Fit} \]
2HDM models can be probed in $A \rightarrow Zh \rightarrow 2l2b$ selections.
2HDM expected sensitivity

\[ A \to Zh \to 2l2b \]  \hspace{1cm} \[ H \to ZZ \to 4l \]

\( m_{A/H} = 300 \text{ GeV} \)  \hspace{1cm} \( m_{A/H} = 500 \text{ GeV} \)
MSSM \(\mu\mu\) limits

- high tan \(\beta\) region complementary to \(A\to Zh\) for MSSM constraints
- High mass resolution at high dimuon mass
- Search for two production modes
  - gluon fusion
  - \(b\) associated production
FCNC top to Higgs

- FCNC processes are forbidden at tree level in the SM
- \( t \rightarrow cH \) observation in ttbar events would certainly be a sign of new physics

<table>
<thead>
<tr>
<th>Process</th>
<th>SM</th>
<th>QS</th>
<th>2HDM-III</th>
<th>FC-2HDM</th>
<th>MSSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t \rightarrow u\gamma )</td>
<td>( 3.7 \cdot 10^{-16} )</td>
<td>( 7.5 \cdot 10^{-9} )</td>
<td>—</td>
<td>—</td>
<td>( 2 \cdot 10^{-6} )</td>
</tr>
<tr>
<td>( t \rightarrow uZ )</td>
<td>( 8 \cdot 10^{-17} )</td>
<td>( 1.1 \cdot 10^{-4} )</td>
<td>—</td>
<td>—</td>
<td>( 2 \cdot 10^{-6} )</td>
</tr>
<tr>
<td>( t \rightarrow uH )</td>
<td>( 2 \cdot 10^{-17} )</td>
<td>( 4.1 \cdot 10^{-5} )</td>
<td>( 5.5 \cdot 10^{-6} )</td>
<td>—</td>
<td>( 10^{-6} )</td>
</tr>
<tr>
<td>( t \rightarrow c\gamma )</td>
<td>( 4.6 \cdot 10^{-14} )</td>
<td>( 7.5 \cdot 10^{-9} )</td>
<td>( \sim 10^{-6} )</td>
<td>( \sim 10^{-9} )</td>
<td>( 2 \cdot 10^{-6} )</td>
</tr>
<tr>
<td>( t \rightarrow cZ )</td>
<td>( 1 \cdot 10^{-14} )</td>
<td>( 1.1 \cdot 10^{-4} )</td>
<td>( \sim 10^{-7} )</td>
<td>( \sim 10^{-10} )</td>
<td>( 2 \cdot 10^{-6} )</td>
</tr>
<tr>
<td>( t \rightarrow cH )</td>
<td>( 3 \cdot 10^{-15} )</td>
<td>( 4.1 \cdot 10^{-5} )</td>
<td>( 1.5 \cdot 10^{-3} )</td>
<td>( \sim 10^{-5} )</td>
<td>( 10^{-5} )</td>
</tr>
</tbody>
</table>

- Event selection relies on diphoton Higgs decay for its clear signature

**Typical BRs of EW FCNC-top decays:**
Self-coupling & di-Higgs production

- The Higgs mechanism and the shape of its potential rely on the self-coupling term of the Lagrangian

\[ V(|\phi|^2) = \mu^2 |\phi|^2 + \lambda |\phi|^4. \]

\[ V(H^0) = 2\lambda v^2 \frac{(H^0)^2}{2} + 6\lambda v \frac{(H^0)^3}{3!} + 6\lambda \frac{(H^0)^4}{4!} - \frac{v^4 \lambda}{4}. \]

\[ \equiv m_H^2 \frac{(H^0)^2}{2} + \lambda_3 H \frac{(H^0)^3}{3!} + \lambda_4 H \frac{(H^0)^4}{4!} - \frac{v^4 \lambda}{4}. \]

- Origin of matter relies in baryon/anti-baryon asymmetry

- Electroweak baryogenesis: generate baryon asymmetry with particle mass generation at EW scale, under some conditions on the way the EWSB happens

- Inflation of the Universe usually modeled using a scalar field (inflaton): could this be related to the Higgs boson?

- All this may happen in some extended Higgs sector in which the trilinear coupling

\[ \lambda_{3H} = \frac{3m_H^2}{v} \] is modified

<table>
<thead>
<tr>
<th>Model</th>
<th>( \Delta g_{hhh}/g_{hhh}^{SM} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed-in Singlet</td>
<td>-18%</td>
</tr>
<tr>
<td>Composite Higgs</td>
<td>tens of %</td>
</tr>
<tr>
<td>Minimal Supersymmetry</td>
<td>-2%(^a) -15%(^b)</td>
</tr>
<tr>
<td>NMSSM</td>
<td>-25%</td>
</tr>
</tbody>
</table>
Di-Higgs boson production

- Di-Higgs boson production dominated by box diagram
- Negative interference with self-coupling diagrams
  ![Di-Higgs boson production diagram](image)
- Low cross-section
- Currently large theoretical uncertainties for the signal
- Many channels are now being explored in order to assess the potential for the di-Higgs boson observation and the sensitivity to the self-coupling at the HL-LHC
  - The simplest (ggF with decays into b pairs) might not be the most powerful
- Difficult (new!) analyses to develop
Self-coupling measurements?

- ATLAS and CMS have documented some prospects for the di-Higgs production measurements.

- Here the example of the -so far- “golden” channel: \( bb\gamma\gamma \).

- Very complicated analyses:
  - Often large background
    - Higgs its own background
    - Large contributions from top and/or fakes processes
    - Currently no good prediction for the continua (\( bb\gamma\gamma, bbjj, \ldots \))
  - Working in busy environment (high pile-up for hadrons colliders) where triggering will be an issue too

- So far, barely able to see with 3000 fb\(^{-1}\) the total HH production

- Measuring precisely the trilinear coupling will be very challenging!
Self-coupling measurements? (2)

- Every bit of acceptance will matter in this respect
- Performance not precisely known

- CMS presented projections of the performance in function of the assumed performance
Self-coupling measurements? (3)

- Uncertainties on the main background to the signal measurement are also unknown
  - When there are natural high-stats control regions uncertainties can sometimes be assumed to be negligible or to scale with luminosity
  - CMS also produced projections in function of the assumed background systematic uncertainty
    - Here for the ggF HH → bbWW prospects

- Some other channels have also been looked at by both collaborations but no public results yet.
  - What about the associated productions? VBF HH → 4b for instance?
  - Combining many channels is anyway interesting even if they're not 5σ channels...
Conclusions

- Prospects for the precision Higgs couplings measurements are very promising!
  - Often better than 10% for couplings
  - Probably enough for starting to probe new physics which would have not shown up elsewhere in the EWSB sector
- Also, great potential for direct evidence of new physics in
  - (Not so?) rare decays
  - 2DHM models-like signatures
  - FCNC
- Now working on
  - Adding more rare channels to this picture
  - Establishing the potential for di-Higgs bosons measurements and sensitivity to the self-coupling
  - Consolidating the detector designs and running conditions in order to achieve those goals
  - Writing the developments of this story
- More information about the performance assumptions at
BACKUP
Higgs total width (2)

- Higgs off-shell analysis searches for large Higgs couplings for the off-shell Higgs at large virtualities (mass) $m_{VV}$

- Use high mass channels $H^* \rightarrow ZZ \rightarrow 4l$, $H^* \rightarrow ZZ \rightarrow 2l2n$ and $H^* \rightarrow WW \rightarrow l\nu l\nu$

- Unknown QCD effects
  → all analysis done inclusive in jets
  → depending on the unknown K-factor for the $gg \rightarrow VV$ bkg

- Combination with on-shell analysis allows interpretation as measurement of $\Gamma_H$

- Assumes same on- & off-shell couplings

- $\Gamma_H < 22$ MeV

(95%CL limit on $\mu_{\text{off-shell}}$ between 5.1-8.6)