Discussion hooks
Hadron colliders session
25/7/2018

Thanks to Alessandro, Daniel, Pascal for sharing a preview of their slides!
Context and Caveats

I’m assuming a rather miopic view here:

• there will be only hadron colliders in the future (lepton colliders are discussed somewhere else)

• the physics we are interested in is only Higgs related, or BSM searches based on Higgs analyses

• given that I’m only given three slides and I’m using one for CAVEATS I have to oversimplify and try to be provocative (and add a couple of slides more, sorry!)

As a consequence, the discussion might be totally different in a bigger context.

General comment: many of the “projections” are in the process of being revisited for the HL/HE-LHC yellow report due in a few months. Many baseline assumptions already surpassed by Run2 results!
The goals

What are the main goals in Higgs physics for the future generations/colliders that will not be fully exploited by the LHC (up to Run3):

- **Higgs potential:**
  - self-coupling
  - vector boson scattering (in particular $W_L W_L$)
- **Couplings below 5% accuracy** (BSM territory)
- **High pT(H) regime** (BSM territory)

- HL-LHC (3ab$^{-1}$) will give us a glimpse on $\lambda_{HHH}$ and VBS (expect 1 to 2 sigma “evidence” in most optimistic scenarios)
- couplings (mu) will reach, and in a few cases will go below, the 5% level.
- will start to explore second generation couplings: $VH(cc) < 6 \text{ SM @95\%CL}$ (would be interesting to see experiments $\gamma_c$ projections from differential distributions!)
- The highest pT(H) regime that we will be able to probe is $O(100 \text{ GeV})$, probably not enough to be sensitive to new physics above 1 TeV scale (but it will not be syst. dominated!)
## Machines performance

<table>
<thead>
<tr>
<th></th>
<th>LHC / HL-LHC</th>
<th>HE-LHC (tentative)</th>
<th>FCC-hh Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cms energy [TeV]</td>
<td>14</td>
<td>27</td>
<td>100</td>
</tr>
<tr>
<td>Luminosity [$10^{34}$cm$^{-2}$s$^{-1}$]</td>
<td>1 / 5</td>
<td>16</td>
<td>5</td>
</tr>
<tr>
<td>Machine circumference</td>
<td>26.7</td>
<td>26.7</td>
<td>97.75</td>
</tr>
<tr>
<td>Arc dipole field [T]</td>
<td>8</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>1.15 / 2.2</td>
<td>2.2</td>
<td>1</td>
</tr>
<tr>
<td>Bunch distance [ns]</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Background events/bx</td>
<td>27 / 135</td>
<td>440</td>
<td>170</td>
</tr>
<tr>
<td>Bunch length [cm]</td>
<td>7.5</td>
<td>7.5</td>
<td>8</td>
</tr>
</tbody>
</table>
The questions

Let’s start with a fact: the HL-LHC (phase 2) is granted.

What is the gain, for Higgs physics, in going to HE-LHC (27 TeV)?
- $X_{\text{sec}} = 3 \times (14 \text{ TeV}), \ lumi(\text{and} \ PU!) = 2-4 \ times$,
- production rate is $\sim 5-10 \times$ (i.e. 1 year HE-LHC $\sim 5-10 \text{ years HL-LHC}$)
- Higgs yield $\sim 10-15 \times$ (uncertainties down by $\sim 3\times$)
- we might touch the 30% accuracy on Higgs self-coupling (not reachable by HL-LHC)
- BUT: uncertainties might hit the same “flooring” due to systematics (even though the enlarged phase space might help) !! (see next slide for discussion)

FCC-hh seems to be a clearer case:
- 200x more stats, $>5\times$ kinematical reach
- rare decays will be fully explorable
- Higgs self coupling (and VBS) will be studied at percent level
- percent precision also on $p_{T}(H) \sim 500 \text{ GeV}$
- no idea about systematics

ep versions (LHeC, FCC-eh)
- seems rather interesting options:
  - VBF (CC and NC) dedicated signatures
  - not far from pp reach for couplings, beat down the systematics and goes into the ILC regime (too good to be true?)
The questions

Systematics is one of the key points, if not THE point (current projected syst. effects ~10x statistics):

• we experimentalists don’t have much control on theoretical ones
  - can we bracket theory systematics directly from data? What about combined fits?

• how optimistic we can be with experimental systematics?
  - we know that despite detectors will not get much better analyser/analyses gets smarter and smarter
  - we might hit the floor before the 3ab^{-1} but what is the floor?
  - on the positive side we see first evidence of 1/sqrt(L) reduction of systematics (see P. Meridiani’s session and plot below) and even BETTER than 1/sqrt(L) (see L. Borgonovi)

New phase space (energy) might be beneficial in terms of S/B (HH→bbγγ)
BACKUP
### HL-LHC di-Higgs comparison (from R. Salerno)

<table>
<thead>
<tr>
<th></th>
<th>CMS</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>bbbb</td>
<td>$0.39\sigma$</td>
<td>$\mu &lt; 5.2 ,(1.5)^{(3)}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$-4.1 &lt; \lambda / \lambda_{SM} &lt; 8.7 ,(0.2 &lt; \lambda / \lambda_{SM} &lt; 7.0)$</td>
</tr>
<tr>
<td>bb$\tau \tau$</td>
<td>$0.39\sigma^{(1)} / \mu &lt; 1.6^{(2)}$</td>
<td>$\mu &lt; 4.3^{(4)}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$-4.0 &lt; \lambda / \lambda_{SM} &lt; 12$</td>
</tr>
<tr>
<td>bb$\gamma \gamma$</td>
<td>$1.43\sigma$</td>
<td>$1.5\sigma^{(3)}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$0.2 &lt; \lambda / \lambda_{SM} &lt; 6.9 ,(\text{stat only})$</td>
</tr>
<tr>
<td>bbVV</td>
<td>$0.45\sigma$</td>
<td></td>
</tr>
<tr>
<td>ttHH(bbbb)</td>
<td></td>
<td>$0.35\sigma$</td>
</tr>
</tbody>
</table>
Detectors for HL-LHC

- Extended coverage (VBF coverage and missing \( E_T \))
- Track trigger at early stage of trigger
- Timing capabilities @30ps

**Tracking**

**ATLAS Simulation**
- Z' (5 TeV) → \( \bar{t}t \), Inclusive jets
- I7k Inclined Duals
- \( <\mu> = 0 \)
- \( <\mu> = 200 \)

**CMS Phase-2 Simulation Preliminary**

14 TeV

- Run 2
- With HGC, 0 PU
- With HGC, 200 PU

VBF jet \( \eta \) distribution (a.u.)
Additional systematics comparison

**ATLAS Simulation Preliminary**

\[ \sqrt{s} = 14 \text{ TeV} ; \int dt = 300 \text{ fb}^{-1} ; \int dt = 3000 \text{ fb}^{-1} \]

- \( H \rightarrow \gamma\gamma \) (comb.)
- \( H \rightarrow ZZ \) (comb.)
- \( H \rightarrow WW \) (comb.)
- \( H \rightarrow Z\gamma \) (incl.)
- \( H \rightarrow b\bar{b} \) (comb.)
- \( H \rightarrow \tau\tau \) (VBF-like)
- \( H \rightarrow \mu\mu \) (comb.)

**CMS Projection**

**Projection from Run 1**

Snowmass 2013

arxiv:1307.7135

**Expected uncertainties on Higgs boson couplings**

- \( K_\gamma \)
- \( K_W \)
- \( K_Z \)
- \( K_g \)
- \( K_b \)
- \( K_t \)
- \( K_\tau \)

**ATLAS Preliminary**

\( \sqrt{s} = 14 \text{ TeV} ; L = 3000 \text{ fb}^{-1} \)

<table>
<thead>
<tr>
<th>Observable</th>
<th>Parameter</th>
<th>Precision (stat)</th>
<th>Precision (stat+syst)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu = \sigma(H) \times B(H \rightarrow \mu\mu) )</td>
<td>( \delta\mu/\mu )</td>
<td>0.5%</td>
<td>0.9%</td>
</tr>
<tr>
<td>( \mu = \sigma(H) \times B(H \rightarrow H \gamma \gamma) )</td>
<td>( \delta\mu/\mu )</td>
<td>0.1%</td>
<td>1%</td>
</tr>
<tr>
<td>( \mu = \sigma(H) \times B(H \rightarrow H \gamma \gamma) )</td>
<td>( \delta\mu/\mu )</td>
<td>0.2%</td>
<td>1.6%</td>
</tr>
<tr>
<td>( \mu = \sigma(H) \times B(H \rightarrow H \gamma \gamma) )</td>
<td>( \delta\mu/\mu )</td>
<td>1%</td>
<td>1.3%</td>
</tr>
<tr>
<td>( \mu = \sigma(H) \times B(H \rightarrow H \gamma \gamma) )</td>
<td>( \delta\mu/\mu )</td>
<td>3.5%</td>
<td>5.0%</td>
</tr>
<tr>
<td>( B = B(H \rightarrow H \gamma \gamma) \times B(H \rightarrow H \gamma \gamma) )</td>
<td>( \delta\mu/\mu )</td>
<td>0.1%</td>
<td>0.8%</td>
</tr>
<tr>
<td>( B = B(H \rightarrow H \gamma \gamma) \times B(H \rightarrow H \gamma \gamma) )</td>
<td>( \delta\mu/\mu )</td>
<td>0.6%</td>
<td>1.4%</td>
</tr>
</tbody>
</table>

**Table 1.2:** Target precision for the parameters relative to the measurement of various Higgs couplings, the Higgs self-coupling \( \lambda \), Higgs branching ratios \( B \) and ratios thereof. Notice that lagrangian couplings have a precision that is typically half that of what is shown here, since all rates and branching ratios depend quadratically on the couplings.