Physics at run 2: prospects and opportunities

FRONTIER DETECTORS FOR FRONTIER PHYSICS
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Key outcomes of 3 yrs at the LHC: # one

I: The Higgs signal has been detected through sharp mass peaks in several channels

II: Its production and decay rates are consistent with the SM expectation, at the +/- 20% level ....
Key outcomes of 3 yrs at the LHC: # one

I: The Higgs signal has been detected through sharp mass peaks in several channels

II: Its production and decay rates are consistent with the SM expectation, at the $\pm 20\%$ level

... How far can we push the accuracy of these tests, and probe the mechanism of EWSB?
Key outcomes of 3 yrs at the LHC: # two

The theoretical description of high-$Q^2$ processes at the LHC is very good ....
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The theoretical description of high-$Q^2$ processes at the LHC is very good ....

.... Can “precision” become a discovery tool?
Key outcomes of 3 yrs at the LHC: # three

No sign of BSM, in any of the places the experiments have searched .....

CMS EXOTICA 95% CL Exclusion Limits (TeV)

Heavy Resonances

q^* (qg), dijet pair
q^* (qW)
q^* (qZ)
q^*, dijet pair
q^*, boosted Z
e^*, \Lambda = 2 TeV
\mu^*, \Lambda = 2 TeV

Z'sSM (ee, \mu\mu)
Z'sSM (\tau\tau)
Z' (tt hadronic) width=1.2%
Z' (tt lep+jet) width=1.2%
Z'sSM (ll) fbb=0.2
G (dijet)
G (ttbar hadronic)
G (jet+MET) k/M = 0.2
G (\gamma\gamma) k/M = 0.1
G (Z(lilZ(qq))) k/M = 0.1
W' (lv)
W' (dijet)
W' (tq)
W'\rightarrow WZ(lep)
W'\rightarrow WZ(lep)
W'\rightarrow WZ(lep)
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W'\rightarrow WZ(lep)
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Compositeness

LQ1, \beta=0.5
LQ1, \beta=1.0
LQ2, \beta=0.5
LQ2, \beta=1.0
LQ3 (pv), Q=\pm 1/3, \beta=0.0
LQ3 (bt), Q=\pm 2/3 or \pm 4/3, \beta=1.0
stop (bt)

LeptoQuarks

b' \rightarrow tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' \rightarrow tW, l+jets
B' \rightarrow bZ (100%)
T' \rightarrow Iz (100%)
t' \rightarrow bW (100%), l+jets
t' \rightarrow bW (100%), l+l

4th Generation

C.I. \Lambda, X analysis, \Lambda+ LL/RR
C.I. \Lambda, X analysis, \Lambda- LL/RR
C.I., \mu\mu, destructive LLM
C.I., \mu\mu, constructive LLM
C.I., incl. jet, destructive
C.I., incl. jet, constructive

Contact Interactions

Ms, \gamma\gamma, HLZ, nED = 3
Ms, \gamma\gamma, HLZ, nED = 6
Ms, ll, HLZ, nED = 3
Ms, ll, HLZ, nED = 6
MD, monojet, nED = 3
MD, monojet, nED = 6
MD, mono-\gamma, nED = 3
MD, mono-\gamma, nED = 6
MBH, rotating, MD=3TeV, nED = 2
MBH, non-rot, MD=3TeV, nED = 2
MBH, boil. remn., MD=3TeV, nED = 2
MBH, stable remn., MD=3TeV, nED = 2
MBH, Quantum BH, MD=3TeV, nED = 2

Extra Dimensions & Black Holes

MS, \gamma\gamma, HLZ, nED = 3
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MS, ll, HLZ, nED = 3
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Key outcomes of 3 yrs at the LHC: # three

No sign of BSM, in any of the places the experiments have searched …..

Where is everybody (DM, solution to the naturalness problem, sources of CPV, ...) ???

How do we access regions of parameters of BSM models where the search sensitivity is low?
Status of BSM

• Until few yrs ago, we had a benchmark model, MSSM, expected to deliver the following:
  • low-mass Higgs $h^0$, no heavier than $\sim 130$ GeV
  • $\sim$TeV scale squarks and gluinos, to be seen rapidly at the LHC
    • $\Rightarrow$ solution to the naturalness problem
  • extra Higgses ($A^0 / H^0 / H^\pm$) observed at the LHC
  • candidate for DM, confirmed by direct detection
  • interesting flavour phenomenology
    • explanation of $(g-2)_\mu$
    • sizable deviations from SM in $B(B_s \rightarrow \mu^+ \mu^-)$
    • $\mu \rightarrow e\gamma$ observed at MEG, consistent with SUSY neutrino masses induced at the GUT scale
  • CPV in the Higgs or squark/gluino sector, to explain BAU
  • electric dipole moments (e, n) measured, consistent with previous point
Given our knowledge 4-5 yrs back, all of this could have happened by now.
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• Even models alternative to SUSY (extra dim, little Higgs, SILH, ...) had the potential of matching the “natural” predisposition of SUSY to solve problems and to provide rich phenomenological consequences across the fields (LHC, flavour, astro/cosmo)
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• The above scenario may still happen, with a few-year delay, perhaps stretching a bit the “naturalness”.
• This expectation is still high, and well justified
Naturalness
Naturalness is not a recent “fashion”: it’s an original sin of the SM itself ... See e.g.
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As we will see, naturalness will put the severest restriction on the occurrence of scalar particles in renormalizable theories. In fact we conjecture that this is the reason why light, weakly interacting scalar particles are not seen.

Pursuing naturalness beyond 1000 GeV will require theories that are immensely complex compared with some of the grand unified schemes.

A remarkable attempt towards a natural theory was made by Dimopoulos and Susskind \(^2\). These authors employ various kinds of confining gauge forces to obtain scalar bound states which may substitute the Higgs fields in the conventional schemes. In their model the observed fermions are still considered to be elementary.

Most likely a complete model of this kind has to be constructed step by step. One starts with the experimentally accessible aspects of the Glashow-Weinberg-Salam-Ward model. This model is natural if one restricts oneself to mass-energy scales below 1000 GeV. Beyond 1000 GeV one has to assume, as Dimopoulos and Susskind do, that the Higgs field is actually a fermion-antifermion composite field. Coupling this field to quarks and leptons in order to produce their mass, requires new scalar fields that cause naturalness to break down at 30 TeV or so.

We’re finally there, at 1 TeV, facing the fears about a light SM Higgs anticipated long ago.
• The observation of the Higgs where the SM predicted it would be, its SM-like properties, and the lack of BSM phenomena up to the TeV scale, make the *naturalness issue as puzzling as ever*
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Whether to keep believing in the MSSM or other specific BSM theories after LHC@8TeV is a matter of personal judgement. But the broad issue of *naturalness will ultimately require an understanding*. 
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• Naturalness remains a guiding principle to drive the search of new phenomena at the LHC
Possible reasons for the lack of signals ...
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- BSM particles are already being created at the LHC, but are hiding well:
  - compressed spectra: low MET, low ET, long lifetime heavy particles, ...
  - RPV
  - ....
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- BSM is less “conventional”, fine-tuning or direct search constraints less tight
  - NMSSM
  - non-degenerate squarks
  - ....
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- The scale at which naturalness is restored is higher than the TeV: acceptable, but becoming less and less “natural” as the scale grows ....

- Naturalness is an ill guided principle $\Rightarrow$ Anthropic principle
Example of ways out: explore less constrained SUSY models

Fraction of excluded models in the pMSSM (19 parameters MSSM)

Dark Matter

Our thinking has shifted

From a single, stable weakly interacting particle ..... (WIMP, axion)

$M_p \sim 1 \text{ GeV}$

Standard Model

...to a hidden world with multiple states, new interactions

K. Zurek, Aspen 2014

ASPEN 2014: https://indico.cern.ch/event/276476/
Evidence building up for self-interacting DM

- A really large scattering cross section!  
  \[ \sigma \sim 1 \text{cm}^2 \frac{(m_x/g)}{2 \times 10^{-24} \text{cm}^2 (m_x/\text{GeV})} \]

For a WIMP:  
\[ \sigma \sim 10^{-38} \text{cm}^2 \frac{(m_x/100 \text{ GeV})}{1} \]

SIDM indicates a new mass scale

Hai-BoYu, ASPEN 2014:  
https://indico.cern.ch/event/276476/

More in general, interest is growing in scenarios for EWSB with rich sectors of states only coupled to the SM particles via weakly interacting “portals”
Anomalies left over from run 1, some examples

\[ Br[h \rightarrow \mu \tau] = (0.89^{+0.40}_{-0.37}) \% \]

\[ R(K) = \frac{B \rightarrow K\mu^+\mu^-}{B \rightarrow Ke^+e^-} = 0.745^{+0.090}_{-0.074} \pm 0.036 \]

• \( B \rightarrow K\mu^+\mu^- \) anomaly

For possible interpretation within a single BSM model see e.g. Crivellin, D’Ambrosio, Heeck, arXiv:1501.00993 (2HDM w. gauged \( L_\mu - L_\tau \))

CMS-PAS-HIG-14-005

LHCb, arXiv:1406.6482

Anomalies left over from run 1, some examples

Dileptons + jets + MET (SUSY searches)


\[ N_{\text{jets}} (p_T > 40 \text{ GeV}) \geq 2, \quad E_T^{\text{miss}} > 150 \text{ GeV} \]

or

\[ N_{\text{jets}} (p_T > 40 \text{ GeV}) \geq 3, \quad E_T^{\text{miss}} > 100 \text{ GeV} \]

low mass: \( m_{ll} = (20–70) \text{ GeV} \)

On-Z: \( m_{ll} = (81–101) \text{ GeV} \)

\[ N_{\text{jets}} (p_T > 35 \text{ GeV}) \geq 2, \quad E_T^{\text{miss}} > 225 \text{ GeV} \]

\[ H_T > 600 \text{ GeV} \]

On-Z: \( m_{ll} = (81–101) \text{ GeV} \)
Anomalies left over from run 1, some examples


<table>
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</tr>
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<td>Central</td>
<td>Forward</td>
</tr>
<tr>
<td>Observed</td>
<td>860</td>
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</tr>
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<td>Flavor-symmetric</td>
<td>722 ± 27 ± 29</td>
<td>155 ± 13 ± 10</td>
</tr>
<tr>
<td>Drell–Yan</td>
<td>8.2 ± 2.6</td>
<td>2.5 ± 1.0</td>
</tr>
<tr>
<td>Total estimated</td>
<td>730 ± 40</td>
<td>158 ± 16</td>
</tr>
<tr>
<td>Observed – estimated</td>
<td>130^{+48}_{-49}</td>
<td>5^{+20}_{-20}</td>
</tr>
<tr>
<td>Significance</td>
<td>2.6 σ</td>
<td>0.3 σ</td>
</tr>
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⇒ 2.6 σ

... no signal on-peak

σ(350 GeV) ratio 13TeV/8TeV ∼ 4.5
Anomalies left over from run 1, some examples

**CMS,** http://arxiv.org/abs/1502.06031

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$\Rightarrow 2.6 \sigma$

... no signal on-peak

$\sigma(350 \text{ GeV})$ ratio $13\text{TeV}/8\text{TeV} \sim 4.5$

**ATLAS,** http://arxiv.org/abs/1503.03290

<table>
<thead>
<tr>
<th>Channel</th>
<th>SR-Z $ee$</th>
<th>SR-Z $\mu\mu$</th>
<th>SR-Z same-flavour combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>16</td>
<td>13</td>
<td>29</td>
</tr>
<tr>
<td>Expected background events</td>
<td>$4.2 \pm 1.6$</td>
<td>$6.4 \pm 2.2$</td>
<td>$10.6 \pm 3.2$</td>
</tr>
<tr>
<td>Flavour-symmetric backgrounds</td>
<td>$2.8 \pm 1.4$</td>
<td>$3.3 \pm 1.6$</td>
<td>$6.0 \pm 2.6$</td>
</tr>
<tr>
<td>$Z/\gamma^* + \text{jets}$ (jet-smearing)</td>
<td>$0.05 \pm 0.04$</td>
<td>$0.02^{+0.03}_{-0.02}$</td>
<td>$0.07 \pm 0.05$</td>
</tr>
<tr>
<td>Rare top</td>
<td>$0.18 \pm 0.06$</td>
<td>$0.17 \pm 0.06$</td>
<td>$0.35 \pm 0.12$</td>
</tr>
<tr>
<td>WZ/ZZ diboson</td>
<td>$1.2 \pm 0.5$</td>
<td>$1.7 \pm 0.6$</td>
<td>$2.9 \pm 1.0$</td>
</tr>
<tr>
<td>Fake leptons</td>
<td>$0.1^{+0.7}_{-0.1}$</td>
<td>$1.2^{+1.3}_{-1.2}$</td>
<td>$1.3^{+1.7}_{-1.3}$</td>
</tr>
</tbody>
</table>

$\Rightarrow 3.0 \sigma$  $\Rightarrow 1.6 \sigma$

... but no signal off-peak

$\sigma(800 \text{ GeV})$ ratio $13\text{TeV}/8\text{TeV} \sim 8.5$

Already more than 10 TH interpretation papers on arXiv ....
How long before run 2 extends the discovery reach of run 1?
Rate comparison 8 vs 13 TeV: dijet production

Dijet production

$|\eta_{\text{jet}}|<2.5$

$\sigma(M_{jj}>M_{\text{min}})$ [fb]

$\sqrt{S}=8$ TeV

$100 \text{ ev} \Rightarrow \sim 100 \text{ pb}^{-1}$

$\sqrt{S}=13$ TeV

$1 \text{ ev} \Rightarrow 10 \text{ pb}^{-1}$

$100 \text{ ev/20 fb}^{-1}$

$1 \text{ ev/20 fb}^{-1}$
Remarks

• Large statistics of jets with $E_T$ in the multi-TeV range =>
  • start measurements of large EW effects
\[ \frac{\sigma(jj+W)}{\sigma(jj)} \] with
\[ E_T, \text{leading jet} > E_T^{\text{min}} \]

- Dotdashes: $\sigma(jj)$ in the denominator replaced by $\sigma(jj, \text{no } gg \rightarrow gg)$

- Substantial increase of $W$ production at large energy: over 10% of high-ET events have a $W$ or $Z$ in them!
- It would be interesting to go after these $W$ and $Z$s, and verify their emission properties
Rate comparison 8 vs 13 TeV: \( t \bar{t} \) production

\[ \text{fb} \]

\[ \sigma(M_{tt}>M_{\text{min}}) \text{ [fb]} \]

\( |\eta_{\text{top}}| < 2.5 \)

1 ev \( \Rightarrow 0.2 \text{ fb}^{-1} \)

\( \sqrt{S}=8 \text{ TeV} \)

\( \sqrt{S}=13 \text{ TeV} \)

1 ev/20 fb\(^{-1} \)
Remarks

• After $\sim 20 \text{ fb}^{-1}$ top quark $E_T$ probed above 2-3 TeV $\Rightarrow$
  • Lorentz factor $\gamma$ larger than 10:
    • top jet $\sim b$ jet at LEP!
  • all top decay products within a cone with $R<0.1$
    • “hyper”-boosted regime for top tagging ...
Rate comparison 8 vs 13 TeV: Drell-Yan production

\[ \text{DY production (} e^+\mu^- \text{)} \]
\[ |\eta_{lep}| < 2.5 \]
\[ \sigma(M_{ll} > M_{\text{min}}) \text{ [fb]} \]

\[ \sqrt{s} = 13 \text{ TeV} \]
\[ \sqrt{s} = 8 \text{ TeV} \]

1 ev \Rightarrow 2 fb^{-1}

1 ev/20 fb^{-1}
13 TeV luminosity required to match BSM sensitivity reached so far (20 fb$^{-1}$) at 8 TeV

See also http://collider-reach.web.cern.ch, by Salam and Weiler
Remarks

• Large statistics of jets with $E_T$ in the multi-TeV range =>
  • start measurements of large EW effects

• Further studies at high energy/luminosity should not just focus on pushing the high mass end, but also on exploring low-couplings at low mass
Current $g_B$ vs. $M_{Z'}$ limits: $Z'_B$ dijet resonance

**ATLAS projections for early discovery in run 2**

**Dijet resonances:** ATL-PHYS-PUB-2015-004

### Discovery reach vs $\int L$

![Diagram showing discovery reach vs $\int L$](image)

**SUSY:** ATL-PHYS-PUB-2015-005

### Exclusion reach vs $\int L$

<table>
<thead>
<tr>
<th>Integrated Luminosity [fb$^{-1}$]</th>
<th>$m_{q^*}$ [TeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>4.0</td>
</tr>
<tr>
<td>1</td>
<td>5.0</td>
</tr>
<tr>
<td>5</td>
<td>5.9</td>
</tr>
<tr>
<td>25</td>
<td>6.6</td>
</tr>
<tr>
<td>300</td>
<td>7.4</td>
</tr>
<tr>
<td>3000</td>
<td>8.0</td>
</tr>
</tbody>
</table>

![Diagram showing exclusion reach vs $\int L$](image)
Remarks

• For what concerns the extension of the discovery reach, nothing in the future of the LHC programme will match the step forward from 20 fb$^{-1}$ at 8 TeV to 100 fb$^{-1}$ at 13 TeV
Higgs rates, 8 vs 13 TeV

(Discussion of Higgs physics status, issues and prospects in Toni Pich’s talk)

<table>
<thead>
<tr>
<th>Process</th>
<th>σ(8 TeV)</th>
<th>σ(13 TeV)</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>gg→H</td>
<td>19.3</td>
<td>43.9</td>
<td>2.3</td>
</tr>
<tr>
<td>VBF</td>
<td>1.58</td>
<td>3.75</td>
<td>2.4</td>
</tr>
<tr>
<td>WH</td>
<td>0.70</td>
<td>1.38</td>
<td>2.0</td>
</tr>
<tr>
<td>ZH</td>
<td>0.42</td>
<td>0.87</td>
<td>2.1</td>
</tr>
<tr>
<td>ttH</td>
<td>0.13</td>
<td>0.51</td>
<td>3.9</td>
</tr>
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</table>

From Higgs Cross Section WG, @m_H = 125 GeV

⇒ run 2 statistics ~10-20 times larger than run 1
run 1 H statistics in perspective

Most recent updates of Higgs results at CERN PH LHC seminars:

CMS H studies: P. Musella, http://indico.cern.ch/event/360238/
ATLAS/CMS $m_H$: N. Wardle, http://indico.cern.ch/event/360243/

**Mass:**

$$m_H = 125.09 \pm 0.21\,\text{(stat)} \pm 0.11\,\text{(syst)}\,\text{GeV}$$

**Rate** ($\mu=\text{data}/\text{SM for }\sigma\cdot\text{BR}$):

$$\mu_{\text{ATLAS}} = 1.18 \pm 0.10\,\text{(stat)} \pm 0.07\,\text{(expt)} \pm 0.08\,\text{(theory)}$$

$$\mu_{\text{CMS}} = 1.00 \pm 0.09\,\text{(stat)} \pm 0.07\,\text{(expt)} \pm 0.08\,\text{(theory)}$$
H @ run 2 in perspective
Run 1 → Run 2 will mark the transition from statistics-limited to systematics-dominated Higgs physics

• of course not in all channels ..... for ttH production and \( H \rightarrow bb \) decays the goal is still confirmation of the signal
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Higher stat will allow

- more systematic studies of systematics, particularly theoretical modeling of signals and backgrounds in fiducial regions
- to fragment studies into more signal regions, with complementary systematics and sensitivity to signal properties
Run 1 $\rightarrow$ Run 2 will mark the transition from statistics-limited to systematics-dominated Higgs physics

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  - to fragment studies into more signal regions, with complementary systematics and sensitivity to signal properties

- Run 2 will prepare the ground for the work needed to fully exploit the ultimate HL-LHC luminosity in terms of Higgs physics, and will give us a much more clear picture of what the ultimate precision targets can be
Example: ATLAS, arXiv:1504.05833

**Total and Differential Higgs Cross Sections from $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$**

$$\sigma(pp\to H) = 33.0 \pm 5.3\,(\text{stat}) \pm 1.6\,(\text{syst})\,\text{pb}$$

$$= 33.0 \pm 5.5\,(\text{tot run 1})\,\text{pb}$$

**NB** Most of the TH vs data discrepancy comes from final states with $\geq 1$ jet, which in other analyses ($WW^*$) are left out ....
ATLAS, arXiv:1504.05833

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\]
\[
= 33.0 \pm 5.5 \text{(tot run 1)} \text{ pb}
\]

\(\times \) 10 statistics \(\Rightarrow\)

\[
\sigma(pp \rightarrow H) = XX \pm 2.3 \text{ pb}
\]

NB Most of the TH vs data discrepancy comes from final states with $\geq 1$ jet, which in other analyses ($WW^*$) are left out ....
Not quite for run 2: Higgs selfcoupling: $HH \rightarrow bb\gamma\gamma$

- Measurement of the Higgs pair production to probe the trilinear coupling and thus the Higgs potential
- Negative interference between the box and s-channel leading to suppression of event yield

### ATLAS Simulation Preliminary

<table>
<thead>
<tr>
<th>process</th>
<th>Expected events in 3000 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM $H H \rightarrow b b\gamma\gamma$</td>
<td>8.4 ± 0.1</td>
</tr>
<tr>
<td>$b b\gamma\gamma$</td>
<td>9.7 ± 1.5</td>
</tr>
<tr>
<td>$c c\gamma\gamma$, $b b j$, $b b j j$, $j j\gamma\gamma$</td>
<td>24.1 ± 2.2</td>
</tr>
<tr>
<td>top background</td>
<td>3.4 ± 2.2</td>
</tr>
<tr>
<td>$t t H (\gamma\gamma)$</td>
<td>6.1 ± 0.5</td>
</tr>
<tr>
<td>$Z(b b)H (\gamma\gamma)$</td>
<td>2.7 ± 0.1</td>
</tr>
<tr>
<td>$b b H (\gamma\gamma)$</td>
<td>1.2 ± 0.1</td>
</tr>
<tr>
<td>Total background</td>
<td>47.1 ± 3.5</td>
</tr>
<tr>
<td>$S/VB$ (barrel+endcap)</td>
<td>1.2</td>
</tr>
<tr>
<td>$S/VB$ (split barrel and endcap)</td>
<td>1.3</td>
</tr>
</tbody>
</table>

3ab$^{-1}$: 60% precision on signal yield (SM coupling)

$\rightarrow$ 40% with 2 expts

$\rightarrow$ 30% including other channels?

$\rightarrow$ 25% with experience?

$\rightarrow$ ?? %

must be optimistic!
Not to be forgotten: continued improvement in the measurement of SM parameters and dynamics:

- \( m_{\text{top}} \), \( m_W \), \( \sin^2 \theta_W \), CKM and flavour
- PDFs
- spectroscopy:
  - heavy-flavoured hadrons (esp baryons)
  - meson spectroscopy in exclusive central production: \( pp \rightarrow pp X \) (to explore e.g. nature of \( 0^{++} \) glueball candidates like \( f_0(1710) \) (TOTEM/CMS, ATLAS/AFP))
- very forward physics of relevance to cosmic ray shower modeling (LHCf)
- elastic, diffractive, total cross sections (all expts)
- HI collisions, including pA
- ....
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