(Selected) Experimental Summary

- Introduction and a look back
- Selected Highlights from LHC and the present
- Prospects at LHC and beyond
Where do we come from, What are we, Where are we going?

The blue idol represents “The Beyond”

D'où Venons Nous / Que Sommes Nous / Où Allons Nous

Paul Gauguin
S. Glashow (2009): Highlights from 1964 - 50 years ago

- **January:** Gell-Mann suggested quarks as hadron constituents, but not specifying whether they were mathematical fictions or real particles.

- **February:** Nick Samios discovered the $\Omega$ particle, whose existence and properties Murray had predicted.

- **July:** Fitch, Cronin et al. discovered CP violation in kaon decay, an effect that was entirely unanticipated.

- **August:** James Bjorken and I proposed the existence of a fourth (charmed) quark to establish lepton-quark symmetry.

- **October:** Oskar Greenberg proposed the additional quark attribute that would evolve to become quark color.

- **And in August, October and November:** Three seminal papers appeared in Volume 13 of the Physical Review Letters. Taken together, they established what is now known as the Higgs mechanism.

BEH
Harvest from the 1st few months of LHC Run 1


\[ (q\bar{q}) \text{ composites} \]

50 years of Particle Physics

CMS Preliminary 2010

\[ \sqrt{s} = 7 \text{ TeV}, \quad L_{\text{int}} = 40 \text{ pb}^{-1} \]

Di-muons

fundamental spin-1 boson
## Peak performance through the years

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch spacing [ns]</td>
<td>150</td>
<td>50</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>No. of bunches</td>
<td>368</td>
<td>1380</td>
<td>1380</td>
<td>2808</td>
</tr>
<tr>
<td>beta* [m] ATLAS and CMS</td>
<td>3.5</td>
<td>1.0</td>
<td>0.6</td>
<td>0.55</td>
</tr>
<tr>
<td>Max bunch intensity [protons/bunch]</td>
<td>$1.2 \times 10^{11}$</td>
<td>$1.45 \times 10^{11}$</td>
<td>$1.7 \times 10^{11}$</td>
<td>$1.15 \times 10^{11}$</td>
</tr>
<tr>
<td>Normalized emittance [mm.mrad]</td>
<td>~2.0</td>
<td>~2.4</td>
<td>~2.5</td>
<td>3.75</td>
</tr>
<tr>
<td>Peak luminosity [cm$^{-2}$s$^{-1}$]</td>
<td>$2.1 \times 10^{32}$</td>
<td>$3.7 \times 10^{33}$</td>
<td>$7.7 \times 10^{33}$</td>
<td>$1.0 \times 10^{34}$</td>
</tr>
</tbody>
</table>

M. Lamont
Run I: Integrated Luminosity

2010-2012 (Run 1): LHC integrated luminosity

3 Memorable Years

2010: 0.04 fb$^{-1}$
7 TeV CoM
Commissioning

2011: 6.1 fb$^{-1}$
7 TeV CoM
... exploring limits

2012: 23.3 fb$^{-1}$
8 TeV CoM
... production

7 TeV and 8 TeV in 2012
Up to 1380 bunches
with $1.5 \times 10^{11}$ protons
The LHC Accelerator and Experiments Have Performed Exceedingly Well
Good Performance under Ferocious Conditions

Leptons and MET: almost insensitive to pileup
Good performance expected even under more ferocious conditions of Run 2

MET resolution is only slightly affected by pileup when using the most advanced reconstruction method.

With the improvements performance expected to be similar or better than in Run 1

C. Delaear

M. Nagel

A. Bocci
Why do we care about QCD

of these 21 papers, 19 are QCD: the common denominator at LHC

today’s progress = tomorrow’s workhorse

No real understanding of LHC physics is possible without sophisticated QCD calculations!
Wide range of measurements have shown that SM predictions for known physics have been essentially spot on.

This is a tribute to a large amount of work done by our theory colleagues along with the results from the other collider experiments at LEP, Tevatron, HERA, b-factories etc.

- **Two caveats:**
  - despite the success of the LHC programme during run-1, we are still learning how to do precision measurements in ATLAS and CMS
  - this is why we have not digested fully yet to the best of our understanding, neither our detector performance nor how well we can constrain the theoretical uncertainties (eg PDFs) from our own data.

Le meilleur est encore à venir!
anti-triplet as anti-quarks \( \bar{q} \). Baryons can now be constructed from quarks by using the combinations \((q q q), (q q q \bar{q}), \text{etc.}\), while mesons are made out of \((q \bar{q}), (q q \bar{q} \bar{q}), \text{etc.}\). It is assuming that the lowest

**Exotic State** \( Z^+(4430) \)

Must contain \( c-c \) bar quarks \((Z^+ \rightarrow \psi(2S) \pi^+)\) but also \( u \) and \( d \) quarks (it is charged).

Is it a **tetra-quark** state?
EVIDENCE FOR THE $2\pi$ DECAY OF THE $K_{s}^{0}$ MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

$\Delta m_{S} = 17.768 \pm 0.023\text{(stat)} \pm 0.006\text{(syst)} \text{ ps}^{-1}$

$B_{s}^{0} - \bar{B}_{s}^{0}$ oscillation frequency

$\sigma_{t} \sim 45 \text{ fs}$
Study of charmless B decays (interesting as dominated by penguin diagrams)

Raw asymmetries

First 5σ observation of direct CPV in $B_s$ decays

$B_s$ is the 4th particle known to show direct CP violation after $K^0$ [1964], $B^0$ [2000] and $B^\pm$ [2012]

Stringent test of SM $A_{CP}$ (Lipkin)

\[
\Delta = \frac{A_{CP}(B^0 \to K^+ \pi^-)}{A_{CP}(B_s^0 \to K^- \pi^+)} + \frac{B(B_s^0 \to K^- \pi^+)}{B(B^0 \to K^+ \pi^-)} \tau_d = -0.02 \pm 0.05 \pm 0.04.
\]

PRL 110 (2013) 221601
Rare Decays: $B \rightarrow \mu \mu$
Rare Decays: $B \to \mu \mu$

In Standard Model:

$B(B_d \to \mu \mu) = (0.10 \pm 0.01) \times 10^{-9}$

$B(B_s \to \mu \mu) = (3.2 \pm 0.2) \times 10^{-9}$


Sensitive to New Physics, can be strongly enhanced in SUSY with scalar H exchange

Sensitive probe for MSSM with large $\tan\beta$:

$B(B_S \to \mu^+ \mu^-) \sim \tan\beta^6 / M_A^4$
Observation of $B_S \rightarrow \mu\mu$

$\mathcal{B}(B_S^0 \rightarrow \mu^+ \mu^-) = (2.9 \pm 0.7) \times 10^{-9}$

$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = \left(3.6^{+1.6}_{-1.4}\right) \times 10^{-10}$
Take account generally of these measurements in building “acceptable” SUSY models
Rich Future: Flavour Physics

Observing $B^0 \rightarrow \mu^+\mu^-$
Following $B^0 \rightarrow \mu^+\mu^-$ observation, challenge now is to observe for $B^0 \rightarrow \mu^+\mu^-$
In the SM suppressed by $|V_{ts}|^2/|V_{td}|^2 \sim 25$
New physics not following this pattern may manifest itself as a higher $B^0 \rightarrow \mu^+\mu^-$ rate
Lower rate and peaking backgrounds now a real issue

CMS
$BF < 1.1 \times 10^{-9}$

LHCb
$BF < 0.7 \times 10^{-9}$

Determination of CP angle $\gamma$

Need to understand relative signal yield in the different final states
Statistical reach for Belle-II is $2^\circ$, for LHCb upgrade $1^\circ$
Physics Reach of Belle II and LHCb Upgraded

<table>
<thead>
<tr>
<th>Observable</th>
<th>Expected th. accuracy</th>
<th>Expected exp. uncertainty</th>
<th>Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>CKM matrix</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>V_{us}</td>
<td>[K \rightarrow \pi \ell \nu]$</td>
<td>**</td>
</tr>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>[B \rightarrow X_c \ell \nu]$</td>
<td>**</td>
</tr>
<tr>
<td>$</td>
<td>V_{ub}</td>
<td>[B_d \rightarrow \pi \ell \nu]$</td>
<td>*</td>
</tr>
<tr>
<td>$\sin(2\phi_1) [v e K^0_S]$</td>
<td>***</td>
<td>$8 \cdot 10^{-3}$</td>
<td>Belle II/LHCb</td>
</tr>
<tr>
<td>$\phi_2$</td>
<td>***</td>
<td>$1.5^\circ$</td>
<td>Belle II</td>
</tr>
<tr>
<td>$\phi_3$</td>
<td>***</td>
<td>$3^\circ$</td>
<td>LHCb</td>
</tr>
<tr>
<td>CPV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S(B_s \rightarrow \psi \phi)$</td>
<td>**</td>
<td>0.01</td>
<td>LHCb</td>
</tr>
<tr>
<td>$S(B_s \rightarrow \phi \phi)$</td>
<td>**</td>
<td>0.05</td>
<td>LHCb</td>
</tr>
<tr>
<td>$S(B_d \rightarrow \phi K)$</td>
<td>**</td>
<td>0.05</td>
<td>Belle II/LHCb</td>
</tr>
<tr>
<td>$S(B_d \rightarrow \eta' K)$</td>
<td>**</td>
<td>0.02</td>
<td>Belle II</td>
</tr>
<tr>
<td>$S(B_s \rightarrow \phi^* K)$</td>
<td>***</td>
<td>0.03</td>
<td>Belle II</td>
</tr>
<tr>
<td>$S(B_d \rightarrow K^*(\rightarrow K^0_S \pi^0 \pi^0))$</td>
<td>***</td>
<td>0.05</td>
<td>Belle II</td>
</tr>
<tr>
<td>$S(B_d \rightarrow \phi \gamma)$</td>
<td>***</td>
<td>0.15</td>
<td>Belle II</td>
</tr>
<tr>
<td>$S(B_d \rightarrow \rho \gamma)$</td>
<td>0.001</td>
<td>LHCb</td>
<td></td>
</tr>
<tr>
<td>$A_{SL}^d$</td>
<td>***</td>
<td>0.001</td>
<td>LHCb</td>
</tr>
<tr>
<td>$A_{SL}^s$</td>
<td>***</td>
<td>0.005</td>
<td>Belle II</td>
</tr>
<tr>
<td>$A_{CP}(B_d \rightarrow s \gamma)$</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>rare decays</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B(B_s \rightarrow \tau \nu)$</td>
<td>**</td>
<td>3%</td>
<td>Belle II</td>
</tr>
<tr>
<td>$B(B \rightarrow D \tau \nu)$</td>
<td>**</td>
<td>3%</td>
<td>Belle II</td>
</tr>
<tr>
<td>$B(B_d \rightarrow \mu \nu)$</td>
<td>**</td>
<td>6%</td>
<td>Belle II</td>
</tr>
<tr>
<td>$B(B_s \rightarrow \mu \nu)$</td>
<td>***</td>
<td>10%</td>
<td>LHCb</td>
</tr>
<tr>
<td>zero of $A_{FB}(B \rightarrow K^\pm \mu \nu)$</td>
<td>**</td>
<td>0.05</td>
<td>LHCb</td>
</tr>
<tr>
<td>$B(B \rightarrow K^\pm (\rightarrow K^\mp \nu \nu))$</td>
<td>***</td>
<td>30%</td>
<td>Belle II</td>
</tr>
<tr>
<td>$B(B \rightarrow s \gamma)$</td>
<td>**</td>
<td>4%</td>
<td>Belle II</td>
</tr>
<tr>
<td>$B(B \rightarrow \gamma \gamma)$</td>
<td>0.25 $\cdot 10^{-6}$</td>
<td>Belle II (with 5 ab$^{-1}$)</td>
<td></td>
</tr>
<tr>
<td>$B(K \rightarrow \tau \nu)$</td>
<td>**</td>
<td>10%</td>
<td>K-factory</td>
</tr>
<tr>
<td>$B(K \rightarrow e \nu)/(B(K \rightarrow \mu \nu))$</td>
<td>***</td>
<td>0.1%</td>
<td>K-factory</td>
</tr>
<tr>
<td>charm and $\tau$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B(\tau \rightarrow \mu \nu)$</td>
<td>***</td>
<td>$3 \cdot 10^{-9}$</td>
<td>Belle II</td>
</tr>
<tr>
<td>$</td>
<td>q/p</td>
<td>_D$</td>
<td>***</td>
</tr>
<tr>
<td>$\arg(q/p)</td>
<td>_D$</td>
<td>***</td>
<td>$1.5^\circ$</td>
</tr>
</tbody>
</table>

Rencontres de Vietnam 2014 tsv
Remarks: Heavy Flavours

If CKM unitarity is violated Belle 2, with 50 ab\(^{-1}\) will reveal it.

Look out for significant deviations from SM in loop processes.

Pay attention to:
Measurement of angle $\gamma$ with and without penguin contributions
$B \rightarrow \tau \nu, \mu \nu$

Top – “the new Flavour Frontier” [G. Hou] e.g. $t \rightarrow c h^0$

$B_s, B_d \rightarrow \mu \mu$ – precise measurements. Need help from Belle 2 – precise and absolute measurements of some BR

<table>
<thead>
<tr>
<th>$L$ (fb(^{-1}))</th>
<th>No. of $B^0_S$</th>
<th>No. of $B^0$</th>
<th>$\delta B / B(B^0_s \rightarrow \mu^+ \mu^-)$</th>
<th>$\delta B / B(B^0 \rightarrow \mu^+ \mu^-)$</th>
<th>$B^0$ sign.</th>
<th>$\delta B(B^0 \rightarrow \mu^+ \mu^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>16.5</td>
<td>2.0</td>
<td>35%</td>
<td>&gt;100%</td>
<td>0.0–1.5 $\sigma$</td>
<td>&gt;100%</td>
</tr>
<tr>
<td>100</td>
<td>144</td>
<td>18</td>
<td>15%</td>
<td>66%</td>
<td>0.5–2.4 $\sigma$</td>
<td>71%</td>
</tr>
<tr>
<td>300</td>
<td>433</td>
<td>54</td>
<td>12%</td>
<td>45%</td>
<td>1.3–3.3 $\sigma$</td>
<td>47%</td>
</tr>
<tr>
<td>3000</td>
<td>2096</td>
<td>256</td>
<td>12%</td>
<td>18%</td>
<td>5.4–7.6 $\sigma$</td>
<td>21%</td>
</tr>
</tbody>
</table>
Standard Model and Electroweak Physics

Standard Model Production Cross Section Measurements

ATLAS Preliminary
Run 1 $\sqrt{s} = 7, 8$ TeV

LHC pp $\sqrt{s} = 7$ TeV
LHC pp $\sqrt{s} = 8$ TeV

- $W$ fiducial
- $Z$ fiducial
- $t\bar{t}$ total
- $W$ total
- $Z$ total
- $t\bar{t}$ fiducial
- $W\gamma$ fiducial $n_{jet}=0$
- $Z\gamma$ fiducial $n_{jet}=0$
- $Zjj$ EWK fiducial $n_{jet}=0$
- $t\bar{t}s$-channel total
- $t\bar{t}Z$ total

Data points and theoretical predictions are depicted in the diagram.
October 1964: Oskar Greenberg proposed the additional quark attribute that would evolve to become quark color.
Quark and Gluon Interactions - Jets

\[ M_{jj} = 4.04 \text{ TeV} \]
\[ P_T^1 = 1850 \text{ GeV}, \; \eta = 0.32 \]
\[ P_T^2 = 1840 \text{ GeV}, \; \eta = -0.53 \]
Routinely and successfully analyse physics at the high energy frontier in terms of quarks and gluons!

Double Differential Di-jet cross section

\[ \frac{d^2\sigma}{d m_{12} \, d y^*} \] [pb/TeV]

\( y^* \leq 0.5 \times 10^3 \)
\( 0.5 \leq y^* \leq 1.0 \times 10^3 \)
\( 1.0 \leq y^* \leq 1.5 \times 10^3 \)
\( 1.5 \leq y^* \leq 2.0 \times 10^3 \)
\( 2.0 \leq y^* \leq 2.5 \times 10^3 \)
\( 2.5 \leq y^* \leq 3.0 \times 10^3 \)

\( \Lambda_{\text{compositeness}} \geq 7 \text{ TeV} \)

\( m_{12} \text{ [TeV]} \)

E. Torregrosa

The strong coupling constant

\[ \alpha_s(Q) \]

\[ \alpha_s(M_Z) = 0.1185^{+0.0065}_{-0.0041} \]

Excellent description by QCD

Asymptotic freedom: \( \alpha_s \) runs
The most complex SM signal: the Top

**QUARK MASSES**

For each quark, the diagram displays the mass in GeV. The quarks are categorized as:

- **up**: Mass range 0.25 to 4.05 GeV
- **down**: Mass range 0.15 to 4.05 GeV
- **strange**: Mass range 0.15 to 4.05 GeV
- **charm**: Mass range 0.15 to 4.05 GeV
- **bottom**: Mass range 4.05 to 175 GeV
- **top**: Mass range 175 to 200 GeV

**muon+jets event**

- **Muon**:
  - $p_T = 64.4$ GeV/c, $\eta = 1.38$
  - Missing $E_T$: 65.9 GeV
- **Jet**:
  - $p_T = 61.7$ GeV/c, $\eta = 0.29$
  - $p_T = 135.9$ GeV/c, $\eta = 0.79$
  - $p_T = 51.5$ GeV/c, $\eta = -0.12$

**electron+muon event**
Top Studies: e.g. cross sections

108'000 events in 19.5 fb\(^{-1}\) at 8 TeV selected
(2'500 at Tevatron)
Mass of the Top Quark

World combination of $m_{\text{top}}$

- An impressive 0.44% precision
- Some of the most precise measurements non included yet, e.g.
  - D0 full statistics, matrix element method, arXiv:1405.1756, $m_t=174.98\pm0.76$
  - CMS $t+\text{jets}$ at 8 TeV, $L=19.6$ fb$^{-1}$ CMS-TOP-2014-001, $m_t=172.04\pm0.77$
Search for non-SM couplings of top in FCNC decays

A. Iorio

- FCNC can give $t \rightarrow u/c + g/z/\gamma$: Can be searched for in events with 2 tops

- Several BSM theories can be parametrised through similar dimension-6 operators.

- CMS and Atlas look for events with 3 leptons, 2 of which generating a Z boson resonance.

\[ \text{BR}(t \rightarrow Zq) < 0.73\% \text{ (Atlas)} / \]
\[ < 0.05\% \text{ (CMS)} \]

PLB 716 (2012) 142-159
PRL 112 (2014) 171802
High precision top mass:
A fundamental input to the understanding of the SM
(fateful cosmological implications?)

\[ \mu \frac{d}{d\mu} \lambda \approx \frac{1}{16\pi^2} \left( 24\lambda^2 - 6y_t^4 \right) \]
W and Z at 7/8 TeV: (still) clean and beautiful

Z → e^+e^-

W → e ν

Electrons p_T = 34.0, 31.9 GeV/c
Inv. mass = 91.2 GeV/c^2
Standard Model: VBF production of Z bosons

Important reaction in order to establish whether the newly found Higgs boson is fully responsible for unitarization of VV scattering (background and techniques).

CMS – 7 TeV: Bkg. Hypothesis excluded at 2.6 $\sigma$

ATLAS Observation of EW production of Z+jets at $>5\sigma$

$\sigma_{\text{EW}}(m_{jj}>1\text{TeV}) = 10.7 \pm 0.9\,(\text{stat}) \pm 1.9\,(\text{syst}) \pm 0.3\,(\text{lumi})$ fb

cf POWHEG: 9.5 $\pm 0.4$ fb

S. C. Hsu
## Di-boson Production

### Diboson Cross Section Measurements

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Status: July 2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\text{fid}}(\gamma\gamma)[\Delta R_{\gamma\gamma} &gt; 0.4]$</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{fid}}(W\gamma \rightarrow e\gamma)$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma$ [pb]</th>
<th>Theory</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{\text{total}}(pp \rightarrow WW)$</td>
<td>$51.9 \pm 2.0 \pm 4.4$</td>
<td>MCFM</td>
<td>JHEP 01, 086 (2013)</td>
</tr>
<tr>
<td>$\sigma_{\text{fid}}(WW \rightarrow ee)$</td>
<td>$71.4 \pm 5.5 - 4.9$</td>
<td>MCFM</td>
<td>PRD 87, 112303 (2013)</td>
</tr>
<tr>
<td>$\sigma_{\text{fid}}(WW \rightarrow \mu\mu)$</td>
<td>$56.4 \pm 6.8 \pm 10.0$</td>
<td>MCFM</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{fid}}(WW \rightarrow e\mu)$</td>
<td>$73.9 \pm 5.9 \pm 7.5$</td>
<td>MCFM</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{total}}(pp \rightarrow WZ)$</td>
<td>$19.0 \pm 1.4 - 1.3$</td>
<td>MCFM</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{fid}}(WZ \rightarrow \ell\nu\ell\ell)$</td>
<td>$20.3 \pm 0.8 \pm 0.7 - 1.4 - 1.3$</td>
<td>MCFM</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{total}}(pp \rightarrow ZZ)$</td>
<td>$6.7 \pm 0.7 \pm 0.5 - 0.4$</td>
<td>MCFM</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{fid}}(ZZ \rightarrow 4\ell)$</td>
<td>$99.2 \pm 3.8 - 3.0 \pm 6.6 - 6.2$</td>
<td>MCFM</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{fid}}(ZZ^* \rightarrow 4\ell)$</td>
<td>$12.7 \pm 3.1 - 2.9 \pm 1.8$</td>
<td>MCFM</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{fid}}(ZZ^* \rightarrow \ell\ell\nu\nu)$</td>
<td>$29.7 \pm 13.1 - 12.1 \pm 8.7$</td>
<td>MCFM</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{theory}}(\ell\ell\nu\nu)$</td>
<td>$29.8 \pm 3.8 - 3.5 - 2.1 - 1.9$</td>
<td>Powheg/Pythia</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{theory}}(ZZ^*)$</td>
<td>$12.7 \pm 3.1 - 2.9 \pm 1.8$</td>
<td>Powheg/Pythia</td>
<td></td>
</tr>
</tbody>
</table>

**Data/Theory Ratio**

<table>
<thead>
<tr>
<th>Data/Theory Ratio</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
<th>1.2</th>
<th>1.4</th>
<th>1.6</th>
<th>1.8</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>stat + syst</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>stat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>syst</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Reference

- JHEP 01, 086 (2013)
- PRD 87, 112303 (2013)
Completing the SM: A Higgs boson

August 1964


These papers on the spontaneous symmetry breaking mechanism attracted very little attention at the time. The boson attracted even less interest (T. Kibble, 2011).
Completing the particle content of SM 
A Higgs boson is Born

July 4th 2012

First observations of a new particle in the search for the Standard Model Higgs boson at the LHC

www.elsevier.com/locate/physletb
Final Legacy Results: H Decays to bosons

H→ 2γ Channel

H→Z→4l Channel

Sign/Exp  | Exp  | Obs
---|---|---
ATLAS  | 4.1σ | 7.1σ
CMS  | 4.2σ | 5.7σ

H→Z→4l Channel

Sign/Exp  | Exp  | Obs
---|---|---
ATLAS  | 4.4σ | 6.6σ
CMS  | 6.7σ | 6.8σ
Higgs boson Decays to Fermions

**ATLAS: H→ττ Channel**

**CMS: H→ττ, bb Channels**

### Significance

<table>
<thead>
<tr>
<th></th>
<th>Exp</th>
<th>Obs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATLAS (ττ)</strong></td>
<td>3.2σ</td>
<td>4.1σ</td>
</tr>
<tr>
<td><strong>Tevatron:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>exp (2.1σ), obs (3.0σ)</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### CMS Channels

- **H→ττ Channel**
  - CMS (ττ) 3.4σ 3.2σ
- **H→bb Channel**
  - CMS (bb) 2.1σ 2.1σ

**Graphical Representations**

- ATLAS Preliminary
- CMS
- Tevatron: exp (2.1σ), obs (3.0σ)

---

**Notes**

- CMS arXiv:1401.6527
- ATLAS CONF-2013-108

---

**Graph Details**

- ATLAS: 
  - H→ττ VBF+Boosted
  - ∫L dt = 20.3 fb⁻¹
  - √s = 8 TeV

- CMS:
  - m_H = 125 GeV
  - VH → bb
  - Combined

---

**ATLAS CONF-2013-108**
Properties: Spin-Parity – $0^+$ Favoured

ATLAS

$H \rightarrow \gamma\gamma$
1s = 8 TeV $\mid$ Ldt = 20.7 fb$^{-1}$

$H \rightarrow ZZ^* \rightarrow 4l$
1s = 7 TeV $\mid$ Ldt = 4.6 fb$^{-1}$
1s = 8 TeV $\mid$ Ldt = 20.7 fb$^{-1}$

$H \rightarrow WW^* \rightarrow e\mu\nu/\mu\nu$eν
1s = 8 TeV $\mid$ Ldt = 20.7 fb$^{-1}$

Alternative hypotheses disfavoured at >97.8% CL

CMS: $H \rightarrow Z \rightarrow 4l$ Channel

All alternative spin-1 (spin-2) hypotheses tested are excluded at 99% (95) CL or higher
Higgs boson: Couplings

\[ m_{\text{CMS}} = 1.00 \pm 0.09 \text{ (stat)} \pm 0.08 \text{ (theo)} \pm 0.07 \text{ (syst)} \]

\[ m_{\text{ATLAS}} = 1.30 \pm 0.12 \text{ (stat)} \pm 0.10 \text{ (theo)} \pm 0.09 \text{ (syst)} \]
Mass and Couplings

\[ m_H^{(\text{CMS})} = 125.03 \pm 0.26 \text{ (stat)} \pm 0.13 \text{ (syst)} \text{ GeV} \]

\[ m_H^{(\text{ATLAS})} = 125.36 \pm 0.37 \text{ (stat)} \pm 0.18 \text{ (syst)} \text{ GeV} \]
Mass and Couplings

\[ M_H^{(CMS)} = 125.03 \pm 0.26 \text{ (stat)} \pm 0.13 \text{ (syst)} \text{ GeV} \]

\[ M_H^{(ATLAS)} = 125.36 \pm 0.37 \text{ (stat)} \pm 0.18 \text{ (syst)} \text{ GeV} \]
Exotic Decays of the Higgs boson: $H \rightarrow \mu \tau$?

- $\mu \tau_e$  
- $\mu \tau_{\text{had}}$

- $\tau$ lepton flavor violation not as well constrained as $\mu e$ (MEG).
- Based on SM $H \rightarrow \tau \tau$ analysis. Different kinematics allows good SM $H$ rejection.
- $\text{BR}(H \rightarrow \mu \tau) < 1.57\%$ at 95\%CL (expected limit of 0.75\%)
Exotic Decays of the Higgs boson: $H \to \mu \tau$?

<table>
<thead>
<tr>
<th>CMS preliminary</th>
<th>19.7 fb$^{-1}$, $\sqrt{s} = 8$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_\tau$ had 0 Jets</td>
<td></td>
</tr>
<tr>
<td>2.35% (exp.)</td>
<td>2.94% (obs.)</td>
</tr>
<tr>
<td>$\mu_\tau$ had 1 Jet</td>
<td></td>
</tr>
<tr>
<td>2.10% (exp.)</td>
<td>2.11% (obs.)</td>
</tr>
<tr>
<td>$\mu_\tau$ had 2 Jets</td>
<td></td>
</tr>
<tr>
<td>1.95% (exp.)</td>
<td>3.26% (obs.)</td>
</tr>
<tr>
<td>$\mu_\tau$ lep 0 Jets</td>
<td></td>
</tr>
<tr>
<td>1.32% (exp.)</td>
<td>2.04% (obs.)</td>
</tr>
<tr>
<td>$\mu_\tau$ lep 1 Jet</td>
<td></td>
</tr>
<tr>
<td>1.66% (exp.)</td>
<td>2.38% (obs.)</td>
</tr>
<tr>
<td>$\mu_\tau$ lep 2 Jets</td>
<td></td>
</tr>
<tr>
<td>3.77% (exp.)</td>
<td>3.84% (obs.)</td>
</tr>
<tr>
<td>$h \to \mu \tau$</td>
<td></td>
</tr>
<tr>
<td>0.75% (exp.)</td>
<td>1.57% (obs.)</td>
</tr>
</tbody>
</table>

- **BR** ($H \to \tau \mu$) < 1.57% @ 95 CL observed
  (expected $B(H \to \mu \tau) < (0.75 \pm 0.38)\%$)
  
  **Best fit:** $B(H \to \mu \tau) = (0.89 \pm 0.40)\%$

- Mild excess in data at the level of 2.5\(\sigma\) → still compatible with the SM

**Constraint on $B(H \to \mu \tau)$ interpreted in terms of LFV Higgs Yukawa couplings**

**Promising future in the LFV Yukawa sector**

**Significant improvement** (4.4x) wrt. indirect measurements

- **Best limits on $\tau$ anomalous Yukawa couplings to date**
  - Previous best limit from $\tau \to \mu \gamma$:
    \[
    \sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\tau}|^2} < 0.16
    \]
  - Observed limit:
    \[
    \sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\tau}|^2} < 0.0036
    \]
Vector Boson Scattering $W_L W_L \rightarrow W_L W_L$

Several models predict SM-like Higgs but different physics at high energy.

Direct access to EW theory in the unbroken regime ($\sqrt{s} \gg v = 246$ GeV) is a crucial closure test of the SM.

- Does $H(125)$ regularize the theory?
- Or is there any new dynamics: anomalous quartic couplings or resonances?

$V_L V_L \rightarrow V_L V_L$ violates unitarity at TeV scale without Higgs exchange diagram.

10% precision on the SM VBS cross-section (discovery if NP observed at 1 TeV) can be reached with HL-LHC.

Evidence 3.6 $\sigma$ for EW VBS having 2 same-sign leptons and 2 high mass forward jets.
When LHC started Operating .....  

Prior to LHC startup there was much “theoretical” anticipation of new physics. No evidence has yet been found.

e.g. No sight of SUSY has led to a change of perspective

It is quite conceivable that SUSY will make an appearance at 13-14 TeV?
Phenomenology of SUSY

- **R-parity conserved (RPC)**
  - SUSY particles created in pairs
  - Stable lightest SUSY particle (LSP)
  - Expect large MET from escaping LSPs

- **R-parity violated (RPV)**
  - RPC pair-production, but decaying LSP
  - Loss of MET, but large object multiplicity and resonances

- **Long Lived (LL) particles (in both RPC and RPV)**
  - Meta-stable LSP due to small RPV coupling
  - Compressed spectra
  - Metastable / collider stable sparticles
Seeking SUSY!

\[ \sigma_{\text{tot}}[\text{pb}]: \text{pp} \rightarrow \text{SUSY} \]
\[ \sqrt{S} = 8 \text{ TeV} \]

- \( \bar{q} \bar{g} \)
- \( \bar{q} q \)
- \( \bar{q} q^* \)
- \( g g \)

100 produced events

- EWK-inos expected sensitivity up to 0.5 TeV
- Stop expected sensitivity up to 0.7 TeV
- Squarks-gluino sensitivity up expected up to 1.2 TeV

A. Canepa
Seeking SUSY

Overview search limits
Fall 2013

Direct squark

\[ m_{SUSY} = m_{\tilde{q}} \]

\[ \tilde{q} \rightarrow q\chi_1^0 \text{CMS-PAS-SUS-12-028} \]

\[ \tilde{u}_L \rightarrow u\chi_1^0 \text{CMS-PAS-SUS-12-028} \]

\[ \tilde{b} \rightarrow b\chi_1^0 \text{ATLAS-CONF-2013-053} \]

\[ \tilde{t} \rightarrow t\chi_1^0 \text{ATLAS-CONF-2013-037} \]

Direct stop in “gap”

\[ m_{SUSY} = m_{\tilde{t}} \]

\[ \tilde{t} \rightarrow c\chi_1^0 \text{ATLAS-CONF-2013-068} \]

\[ \tilde{t} \rightarrow Wb\chi_1^0 \text{CMS-PAS-SUS-13-011} \]

Direct slepton

\[ m_{SUSY} = m_{\tilde{L}} \]

\[ \tilde{l}_L \rightarrow l^\pm \chi_1^0 \text{ATLAS-CONF-2013-049} \]

\[ \tilde{l}_R \rightarrow l^\pm \chi_1^0 \text{ATLAS-CONF-2013-049} \]

Gluino mediated

\[ m_{SUSY} = m_{\tilde{g}} \]

\[ \tilde{g} \rightarrow q\bar{q}\chi_1^0 \text{ATLAS-CONF-2013-047} \]

\[ \tilde{g} \rightarrow b\bar{b}\chi_1^0 \text{CMS-PAS-SUS-12-024} \]

\[ \tilde{g} \rightarrow t\bar{t}\chi_1^0 \text{ATLAS-CONF-2013-061} \]

BR=100%

all limits are observed nominal
95% CLs limits
RP conserved

DM Searches: Collider vs. Direct detection O. Buchmüller

\[ m_{SUSY} \text{ [GeV]} \]

\[ 0 \quad 250 \quad 500 \quad 750 \quad 1000 \quad 1250 \quad 1500 \]

\[ m_{\tilde{L}} \text{ [GeV]} \]

\[ 0 \quad 250 \quad 500 \quad 750 \quad 1000 \quad 1250 \quad 1500 \]
“Stop”- Supposed Key to Naturalness: Exploring Corridors

- cross section is suppressed, 10pb to 1fb from 200 to 900 GeV stops
- sensitivity highly dependent on the decay mode, the mass hierarchy of “sparticles” participating (and to some extent on the stop “handiness”)
# Beyond the Standard Model: SUSY

## ATLAS SUSY Searches - 95% CL Lower Limits

### Status: ICHEP 2014

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell+\mu$, $\tau\gamma$ Jets</th>
<th>$E_{\text{T}}^\text{miss}$</th>
<th>$\mathcal{L}$ (ab fb$^{-1}$)</th>
<th>Mass limit, TeV</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUGRA/CMSSM</td>
<td>0</td>
<td>2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.2 TeV</td>
</tr>
<tr>
<td>MSUGRA/CMSSM</td>
<td>1</td>
<td>2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.7 TeV</td>
</tr>
<tr>
<td>MSUGRA/CMSSM</td>
<td>2</td>
<td>2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.1 TeV</td>
</tr>
<tr>
<td>$\tilde{b}_1, \tilde{b}_2 \to b\tilde{\chi}_1^0$</td>
<td>0</td>
<td>2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>850 GeV</td>
</tr>
<tr>
<td>GMSB (L NLSP)</td>
<td>1-2 $\tau + 0-1$</td>
<td>0-2 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.3 TeV</td>
</tr>
<tr>
<td>GGM (bino NLSP)</td>
<td>2</td>
<td>2-jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.26 TeV</td>
</tr>
<tr>
<td>GGM (bino NLSP)</td>
<td>1</td>
<td>2-4 jets</td>
<td>No</td>
<td>20.3</td>
<td>1.26 TeV</td>
</tr>
<tr>
<td>GGM (higgsino-bino NLSP)</td>
<td>1</td>
<td>1-2 $\tau + 0$</td>
<td>Yes</td>
<td>20.3</td>
<td>1.6 TeV</td>
</tr>
<tr>
<td>GGM (higgsino-bino NLSP)</td>
<td>2</td>
<td>2-4 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.8 TeV</td>
</tr>
<tr>
<td>Gravitino LSP</td>
<td>0</td>
<td>mono-jet</td>
<td>Yes</td>
<td>20.3</td>
<td>1.25 TeV</td>
</tr>
<tr>
<td>$2-6\tilde{b}$</td>
<td>0</td>
<td>3-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.34 TeV</td>
</tr>
<tr>
<td>$2-6\tilde{t}$</td>
<td>0</td>
<td>2-4 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>1.34 TeV</td>
</tr>
<tr>
<td>$2-6\tilde{b}$</td>
<td>0</td>
<td>1-2 $\mu$</td>
<td>Yes</td>
<td>20.3</td>
<td>1.25 TeV</td>
</tr>
<tr>
<td>$2-6\tilde{t}$</td>
<td>0</td>
<td>1-2 $\mu$</td>
<td>Yes</td>
<td>20.3</td>
<td>1.25 TeV</td>
</tr>
</tbody>
</table>

### Inclusive Searches

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell+\mu$, $\tau\gamma$ Jets</th>
<th>$E_{\text{T}}^\text{miss}$</th>
<th>$\mathcal{L}$ (ab fb$^{-1}$)</th>
<th>Mass limit, TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>0</td>
<td>1-2 $\mu$</td>
<td>Yes</td>
<td>20.3</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>0</td>
<td>1-2 $\mu$</td>
<td>Yes</td>
<td>20.3</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>0</td>
<td>1-2 $\mu$</td>
<td>Yes</td>
<td>20.3</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>0</td>
<td>1-2 $\mu$</td>
<td>Yes</td>
<td>20.3</td>
</tr>
</tbody>
</table>

### EW Direct

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell+\mu$, $\tau\gamma$ Jets</th>
<th>$E_{\text{T}}^\text{miss}$</th>
<th>$\mathcal{L}$ (ab fb$^{-1}$)</th>
<th>Mass limit, TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}\tilde{t}$</td>
<td>0</td>
<td>1-2 $\mu$</td>
<td>Yes</td>
<td>20.3</td>
</tr>
</tbody>
</table>

### Long-lived particles

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell+\mu$, $\tau\gamma$ Jets</th>
<th>$E_{\text{T}}^\text{miss}$</th>
<th>$\mathcal{L}$ (ab fb$^{-1}$)</th>
<th>Mass limit, TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell\rightarrow\tilde{t}^\pm\tilde{t}^\mp$</td>
<td>0</td>
<td>1-2 $\mu$</td>
<td>Yes</td>
<td>20.3</td>
</tr>
</tbody>
</table>

### RPP

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell+\mu$, $\tau\gamma$ Jets</th>
<th>$E_{\text{T}}^\text{miss}$</th>
<th>$\mathcal{L}$ (ab fb$^{-1}$)</th>
<th>Mass limit, TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell\rightarrow\tilde{t}^\pm\tilde{t}^\mp$</td>
<td>0</td>
<td>1-2 $\mu$</td>
<td>Yes</td>
<td>20.3</td>
</tr>
</tbody>
</table>

### Other

<table>
<thead>
<tr>
<th>Model</th>
<th>$\ell+\mu$, $\tau\gamma$ Jets</th>
<th>$E_{\text{T}}^\text{miss}$</th>
<th>$\mathcal{L}$ (ab fb$^{-1}$)</th>
<th>Mass limit, TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalar gluon pair</td>
<td>0</td>
<td>4-jets</td>
<td>Yes</td>
<td>14.3</td>
</tr>
<tr>
<td>Scalar gluon pair</td>
<td>0</td>
<td>4-jets</td>
<td>Yes</td>
<td>14.3</td>
</tr>
</tbody>
</table>

### Mass scale [TeV]

- $\sqrt{s} = 7$ TeV: full data
- $\sqrt{s} = 8$ TeV: partial data
- $\sqrt{s} = 8$ TeV: full data

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.*

---

50
Prospects

“The Beyond”

+ “The Crystal Ball”
Physics Outlook: Questions for the LHC

1. SM contains too many apparently arbitrary features - presumably these should become clearer as we make progress towards a unified theory.

2. Clarify the e-w symmetry breaking sector
SM has an unproven element: the generation of mass
Higgs mechanism ->? or other physics?
Answer will be found at LHC energies

3. SM gives nonsense at LHC energies
Probability of some processes becomes greater than 1!! Nature’s slap on the wrist!
Higgs mechanism provides a possible solution

4. Identify particles that make up Dark Matter
Even if the Higgs boson is found all is not completely well with SM alone:
next question is “Why is (Higgs) mass so low”?
If a new symmetry (Supersymmetry) is the answer, it must show up at O(1TeV)

5. Search for new physics at the TeV scale
SM is logically incomplete – does not incorporate gravity
Superstring theory ➔ dramatic concepts: supersymmetry, extra space-time dimensions?
Physics Outlook: Using P5 Science Drivers

1. SM contains too many apparently arbitrary features - presumably these should become clearer as we make progress towards a unified theory.

2. Clarify the e-w symmetry breaking sector
   - Use the Higgs boson as a new tool for discovery

   Answer will be found at LHC energies

3. SM gives nonsense at LHC energies
   Probability of some processes becomes greater than 1!! Nature’s slap on the wrist!
   *Higgs mechanism provides a possible solution*

4. Identify particles that make up Dark Matter
   - Identify the new physics of dark matter

   *If a new symmetry (Supersymmetry) is the answer, it must show up at O(1 TeV)*

5. Search for new physics at the TeV scale
   - Explore the unknown: new particles, interactions, and physical principles.
Frontiers of Particle Physics (PP)

$\mathbf{m_{11} \simeq 125\text{GeV}, \bar{\mu} \simeq 1}$

Precision measurements and reaching higher energy are the Frontiers of PP

$B(\bar{B} \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$

No evidence of NP in range 200-3000 GeV depending on its type

Data strongly favor the scalar $0^+$ hypothesis

S. Ganjour

Physics Motivations for Future Machines
Ample observational evidence for physics Beyond the SM.
Neutrino masses (oscillations), dark matter, matter-antimatter asymmetry, (Low Higgs boson mass?)

Previously theory “always” showed a nearby new physics scale
Next scale could be anywhere between 1 TeV and very high scale ($10^{12}-10^{15}$ GeV)

The new physics scale can be much lower than the scale $\Lambda$ that we measure through precision physics
Flavour violation $1 - 10^5$ TeV
EDMs $1 - 100$ TeV
Neutrino masses $1 - 10^{12}$ TeV

Precision BEH boson physics is particularly interesting and promising:
This is a new world.
Excellent portal to new physics.

K. Choi
Propelled by surprising discoveries from a series of pioneering experiments, neutrino physics has progressed dramatically over the past two decades.

Many aspects of neutrino physics are puzzling:
- What are the origin of neutrino mass?
- What are the masses?
- How are the masses ordered (mass hierarchy)?
- Do neutrinos and antineutrinos oscillate differently? (CP)
- Are there additional neutrino types or interactions?
- Are neutrinos their own antiparticles?
Can neutrinos bring more surprises?

Completeness of the SM?

Large neutrino mass $\sim M$

In a large part of the interesting region expect displaced vertices. $l+\text{jets}, l^++l^+$, $l+\tau$

Search in ATLAS/CMS? $3000\text{fb}^{-1} \rightarrow 10^{11}-5.10^{11} (Z/W)$
Past, Present

Comparison of Colliders at the Energy Frontier

- ISR
- CESR
- Tevatron
- HERA
- LEP2
- LEP, SLC
- Tristian
- PETRA
- PEP
- SpS
- Hadron colliders

- HERA
- LHC
- KEK-B
- PEP-II
- DAFNE
- VEP-1
- VEP-2
- ACO
- DAFNE
- SuperKEKB

Year of First Physics


Constituent Center-of-Mass Energy [GeV]

10^{-1} 1 10 10^{2} 10^{3}

N. Walker ICHEP14
• Target energy: 6.5 TeV  
  – to be confirmed at end of powering tests
• Bunch spacing: 25 ns  
  – strongly favored by experiments (pile-up limit around 50)
• Beta*: 80 to 40 cm

Energy
• Lower quench margins
• Lower tolerance to beam loss
• Lower intensity set-up beams
• Hardware closer to maximum (beam dumps, power converters etc.)

25 ns
• E-cloud, UFOs
• More long range collisions
• Larger crossing angle, higher beta*
• Higher total beam current
• Higher intensity per injection
LHC: 10 year plan

- Long years – 13 weeks Christmas stop
- Interspersed with long shutdown every 3 to 4 years
- Ions very much part of the plan

Run 2: 13 to 14 TeV c.m. with peak luminosity of $\sim 1.7 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

Run 3: 14 TeV c.m. with peak luminosity of $\sim 2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

---

### Schedule

**2015 – 2018**
- **EYETS** ~5 months
  - Extended year end technical stop (CMS)

**2019 – 2022**
- **LS2**: 18 months
  - Connection of LINAC4
  - LHC Injectors Upgrade

**2023 – 2025**
- **LS3**: 30 months
  - High Luminosity
  - LHC

---

**LS3 2.5 years to mid 2025**
HL-LHC

- 3000 fb\(^{-1}\) delivered in the order of 10 years
- High “virtual” luminosity with levelling anticipated
- Challenging demands on the injector complex
  – major upgrades foreseen

\[ L \left[ 10^{34} \text{ cm}^{-2}\text{s}^{-1} \right] \]

- no leveling w peak \(2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}\)
- leveling at \(5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}\)
- nominal

\[ 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \text{ levelled luminosity} \]
- Pile-up \(~140\
- 3 fb\(^{-1}\) per day
- \(~250 \text{ fb}^{-1} /\text{year}\)
LHC roadmap to achieve full potential

2009
LHC startup, √s 900 GeV

2010
√s=7+8 TeV, L ~6x10^{33}cm^{-2}s^{-1}, bunch spacing 50ns

Run 1
~25 fb^{-1}

2011
Go to design energy, nominal luminosity - Phase 0

2012
√s=13~14 TeV, L~1x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns

Run 2
~75-100 fb^{-1}

2013

Run 3
~350 fb^{-1}

2014
LS1
Injector + LHC Phase I upgrade to ultimate design luminosity

2015
√s=14 TeV, L~2x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns

2016
Phase II upgrade: Interaction Region, crab cavities?

2017
√s=14 TeV, L~5x10^{34}cm^{-2}s^{-1}, luminosity levelling

2018
LS2
...

2019
LS3

2020

2021

2022

2023

2024

2025

2035?

Last update - December 2013

Rencontres de Vietnam 2014 tsv
14 TeV vs 8 TeV – Gain Factors

Use parton luminosities to illustrate the gain of 14 vs 8 TeV

**Higgs:**

\[ pp \rightarrow H, \ H \rightarrow WW, \ ZZ \text{ and } \gamma\gamma \]

mainly gg: Factor \(\sim 2\)

**SUSY – 3rd Generation:**

Mass scale \(\sim 500 \text{ GeV}\)

qq and gg: Factor \(\sim 8\)

**SUSY – Squarks/Gluino:**

Mass scale \(\sim 2.0 \text{ TeV}\)

qq, gg, qg: Factor \(\sim 300\)

**Z’:**

Mass scale \(\sim 5 \text{ TeV}\)

qq: Factor \(\sim 1000\)

For the searches increase in energy will help a lot!
Looking Ahead to Phase 1

Runs II and III

• Conduct detailed studies of the properties of the found Higgs boson. Run II will produce > 5M Higgs bosons
• Search for exotic decays of Higgs boson?

<table>
<thead>
<tr>
<th>Exp.</th>
<th>$\kappa_\gamma$</th>
<th>$\kappa_W$</th>
<th>$\kappa_Z$</th>
<th>$\kappa_g$</th>
<th>$\kappa_b$</th>
<th>$\kappa_t$</th>
<th>$\kappa_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS</td>
<td>[8, 13]</td>
<td>[6, 8]</td>
<td>[7, 8]</td>
<td>[8, 11]</td>
<td>N/a</td>
<td>[20, 22]</td>
<td>[13, 18]</td>
</tr>
<tr>
<td>CMS</td>
<td>[5, 7]</td>
<td>[4, 6]</td>
<td>[4, 6]</td>
<td>[6, 8]</td>
<td>[10, 13]</td>
<td>[14, 15]</td>
<td>[6, 8]</td>
</tr>
</tbody>
</table>

• Couplings Precision ~ 5-15%

Effect of New Physics on couplings:

\[ \Delta g_{HXX} / g_{HXX} \leq 5\% \times \left( \frac{1}{\text{TeV}} \right)^2 \]

• Search for new physics: resonances, supersymmetry, exotica, yet unknown.
It is conceivable that we find new heavy particle(s) in Phase 1.

• Look for deviations from the standard model – precision SM measurements
Past, Present, Future

Comparison of Colliders at the Energy Frontier

Starting in 60's with $e^+e^-$ at about 1GeV
Factor 4 every 10 years...

Coiliders
Hadron colliders
HL-LHC
LHC
Running

Constituent Center-of-Mass Energy [GeV]
10^{-1}
10
10^2
10^3

Year of First Physics

Tevatron, HERA, LEP2, LEP, SLC, Tristam, PETRA, PEP, ISR, SpS, SPEAR, Doris2, Doris, Adone, SPPS, PEP, DAFNE, VEP-2, VEP-1, ACO, KEK-B, PEP-II, SuperKEKB, HERA, LHeC, LHC, HL-LHC

Running
HL-LHC aka SLHC

EP-TH Faculty Meeting

Challenges for pp GPDs
- LHC design luminosity,
  \( L \sim 10^{35} \text{ cm}^{-2}\text{s}^{-1}, \)
- Higher c.o.m energy

Implications for Detector R&D
- LHC design energy and luminosity - Upgrades (~ 2009)
  \( L \sim 10^{35} \text{ cm}^{-2}\text{s}^{-1} \)
- Major Upgrades (~ 2012)
- Higher energy – next generation of detectors (20??)

Conclusions

EP-TH Faculty 17 Jan 01
Looking Further Ahead to Phase 2 (HL-LHC)

Topmost Priority – exploitation of the full potential of the LHC
High luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design

Conduct detailed studies of the properties of the found Higgs boson. How much does it contribute to restoring unitarity in VBF, rare decays (e.g. $H\rightarrow\mu\mu$), and treat the Higgs boson as today we treat the b-quark $LHC \rightarrow HL-LHC$ (HL-LHC will be a Higgs factory! 100M produced $3ab^{-1}$)

Couplings Precision ~ 2-10%, H self coupling ~30% (further study)

Continue searching for new physics. If new physics has been found by the end of Phase 1, associated particle(s) will be heavy. Then conduct detailed studies in Phase 3 (HL-LHC).
**Direct squark**

\[ m_{SUSY} = m_{\tilde{q}} \]

\[ \tilde{t} \rightarrow t\chi_1^0 \]  
ATLAS-CONF-2013-037

**Direct slepton**

\[ \tilde{l}_R \rightarrow l^\pm \chi_1^0 \]  
ATLAS-CONF-2013-049

**Direct**

\[ \chi_1^\pm / \chi_2^0 \]

\[ \chi_1^\pm \chi_2^0 \text{(heavy } \tilde{t} \text{)} \]

CMS-PAS-SUS-13-006

\[ m_{SUSY} = m_{\chi_1^\pm} = m_{\chi_2^0} \]

---

**Example of “difficult” SUSY channels!**

Assume ATLAS and CMS detector performance remains the same

---

BR=100%

all limits are observed nominal
95% CLs limits
RP conserved
\[ m_{\text{LSP}} \ [\text{GeV}] \]

**Direct squark**
\[
m_{\text{SUSY}} = m_{\tilde{q}}
\]
\[
\tilde{t} \rightarrow t\chi_1^0 \text{ ATLAS-CONF-2013-037}
\]

**Direct slepton**
\[
\tilde{l}_R \rightarrow l^\pm \chi_1^0 \text{ ATLAS-CONF-2013-049}
\]

**Direct** \[ \chi_1^\pm / \chi_2^0 \]
\[
\chi_1^\pm \chi_2^0 (\text{heavy } \tilde{t})
\]

CMS-PAS-SUS-13-006
\[
m_{\text{SUSY}} = m_{\chi_1^\pm} = m_{\chi_2^0}
\]

---

BR=100%  
all limits are observed nominal  
95% CLs limits  
RP conserved

LHC: 8 TeV 20 fb^{-1}

LHC: 14 TeV 300 fb^{-1}
**Direct squark**

\[ m_{SUSY} = m_{\tilde{q}} \]

\[ \tilde{t} \rightarrow t\chi_1^0 \] ATLAS-CONF-2013-037

---

**Direct slepton**

\[ \tilde{l}_R \rightarrow l^\pm \chi_1^0 \] ATLAS-CONF-2013-049

**Direct** \[ \chi_1^\pm / \chi_2^0 \]

---

\[ \chi_1^\pm \chi_2^0 \text{(heavy } \tilde{t} \text{)} \]

---

CMS-PAS-SUS-13-006

\[ m_{SUSY} = m_{\chi_1^\pm} = m_{\chi_2^0} \]

---

**LHC: 8 TeV 20 fb^{-1}**

**LHC: 14 TeV 300 fb^{-1}**

**HL-LHC: 14 TeV 3000 fb^{-1}**

---

BR=100%

all limits are observed nominal 95% CLs limits
RP conserved
**Direct squark**

\[ m_{SUSY} = m_{\tilde{q}} \]

\[ \tilde{t} \rightarrow t\chi_1^0 \text{ ATLAS-CONF-2013-037} \]

**Direct slepton**

\[ \tilde{l}_R \rightarrow l^\pm \chi_1^0 \text{ ATLAS-CONF-2013-049} \]

**Direct** \[ \chi^\pm_1 / \chi_2^0 \]

\[ \chi^\pm_1 \chi^0_2 \text{(heavy \tilde{t})} \]

CMS-PAS-SUS-13-006

\[ m_{SUSY} = m_{\chi^\pm_1} = m_{\chi^0_2} \]

---

**BR=100%**

All limits are observed nominal 95% CLs limits

RP conserved

- LHC: 8 TeV 20 fb\(^{-1}\)
- LHC: 14 TeV 300 fb\(^{-1}\)
- HL-LHC: 14 TeV 3000 fb\(^{-1}\)
Future Accelerators

Possible High Energy Frontier Machines

- **Next generation linear collider in Japan**
  - **International Linear Collider-ILC:**
    - $e^+e^-$ collisions up to 1 TeV

- **Post-LHC accelerator projects at CERN**
  - **Future Circular Collider-FCC:**
    - FCC-hh (100 TeV), FCC-$e^+e^-$ (350 GeV), possibly ep
  - **Compact Linear Collider-CLIC:**
    - $e^+e^-$ collisions up to 3 TeV

- **Circular Collider project in China**
  - **Circular Electron Positron Collider-CEPC:**
    - CEPC $e^+e^-$ (250 GeV), SppC pp collider (70-90 TeV)
  - **Muon collider ≤5 TeV, US (Neutrino Factory first step)**
Electron-Positron Colliders

<table>
<thead>
<tr>
<th></th>
<th>Size (km)</th>
<th>√s (GeV)</th>
<th>RF (MV/m)</th>
<th>L per IP (10^34 cm^2 s^-1)</th>
<th>Bunch/train x-ing rate (Hz)</th>
<th>σ_x (μm)</th>
<th>σ_y (nm)</th>
<th>Lumi within 1% of √s</th>
<th>Polarisation e^-/e^+</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEPC</td>
<td>54</td>
<td>240</td>
<td>20</td>
<td>1.8</td>
<td>4x10^5</td>
<td>74</td>
<td>160</td>
<td>&gt;99%</td>
<td>considered</td>
</tr>
<tr>
<td>FCC-ee</td>
<td>100</td>
<td>240</td>
<td>20</td>
<td>6</td>
<td>2x10^7</td>
<td>22</td>
<td>45</td>
<td>&gt;99%</td>
<td>considered</td>
</tr>
<tr>
<td>ILC</td>
<td>31</td>
<td>250</td>
<td>14.7</td>
<td>0.75</td>
<td>5</td>
<td>0.7</td>
<td>7.7</td>
<td>87%</td>
<td>80%/30%</td>
</tr>
<tr>
<td>ILC</td>
<td>500</td>
<td>31.5</td>
<td>1.8</td>
<td>5</td>
<td>0.5</td>
<td>0.5</td>
<td>5.9</td>
<td>58%</td>
<td>80%/30%</td>
</tr>
<tr>
<td>CLIC</td>
<td>48</td>
<td>3000</td>
<td>100</td>
<td>6</td>
<td>50</td>
<td>0.04</td>
<td>1</td>
<td>33%</td>
<td>80%/considered</td>
</tr>
</tbody>
</table>

FCC-ee v. high statistics e.g. expected statistical uncertainty:
- m_{top} = 10 MeV
- Γ_{top} = 11 MeV
- λ_{top} = 13%
### Hadron Colliders

<table>
<thead>
<tr>
<th></th>
<th>Ring (km)</th>
<th>Magnets (T)</th>
<th>$\sqrt{s}$ (TeV)</th>
<th>L ($10^{34}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC</td>
<td>27</td>
<td>8.3</td>
<td>14</td>
<td>up to 5</td>
</tr>
<tr>
<td>HE-LHC</td>
<td>27</td>
<td>16-20</td>
<td>26-33</td>
<td>5</td>
</tr>
<tr>
<td>SppC-1</td>
<td>50</td>
<td>12</td>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td>SppC-2</td>
<td>70</td>
<td>19</td>
<td>90</td>
<td>2.8</td>
</tr>
<tr>
<td>FCC-hh</td>
<td>100</td>
<td>16</td>
<td>100</td>
<td>$\geq 5$</td>
</tr>
</tbody>
</table>

More parameters of 100 TeV FCC-hh:

<table>
<thead>
<tr>
<th></th>
<th>HL-LHC</th>
<th>FCC-hh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch spacing</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>N. of bunches</td>
<td>2808</td>
<td>10600</td>
</tr>
<tr>
<td>Pile-up</td>
<td>140</td>
<td>170</td>
</tr>
<tr>
<td>$E_{\text{loss}}$/turn</td>
<td>7 keV</td>
<td>5 MeV</td>
</tr>
<tr>
<td>SR power/ring</td>
<td>3.6 kW</td>
<td>2.5 MW</td>
</tr>
<tr>
<td>Interaction Points</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Stored beam energy</td>
<td>390 MJ</td>
<td>8.4 GJ</td>
</tr>
</tbody>
</table>

5 ns also considered to mitigate e-cloud
How precisely do we need to know the Higgs boson couplings?

Scenarios with no new particles observable at LHC

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$\kappa_V$</th>
<th>$\kappa_b$</th>
<th>$\kappa_\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singlet Mixing</td>
<td>$\sim 6%$</td>
<td>$\sim 6%$</td>
<td>$\sim 6%$</td>
</tr>
<tr>
<td>2HDM</td>
<td>$\sim 1%$</td>
<td>$\sim 10%$</td>
<td>$\sim 1%$</td>
</tr>
<tr>
<td>Decoupling MSSM</td>
<td>$\sim -0.0013%$</td>
<td>$\sim 1.6%$</td>
<td>$&lt; 1.5%$</td>
</tr>
<tr>
<td>Composite</td>
<td>$\sim -3%$</td>
<td>$\sim -(3-9)%$</td>
<td>$\sim -9%$</td>
</tr>
<tr>
<td>Top Partner</td>
<td>$\sim -2%$</td>
<td>$\sim -2%$</td>
<td>$\sim -3%$</td>
</tr>
</tbody>
</table>

Integrated luminosities correspond to 3-5 years of running at each $\sqrt{s}$ for $e^+e^-$ and 5 years with 2 experiments for pp

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$\sqrt{s}$ (TeV)</th>
<th>L (ab$^{-1}$)</th>
<th>$N_H$ ($10^6$)</th>
<th>$N_{ttH}$</th>
<th>$N_{HH}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC-ee*</td>
<td>$0.24\pm0.35$</td>
<td>10</td>
<td>2</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>ILC</td>
<td>$0.25\pm0.5$</td>
<td>0.75</td>
<td>0.2</td>
<td>1000</td>
<td>100</td>
</tr>
<tr>
<td>ILC$_{1\text{TeV}}$</td>
<td>$0.25\pm0.5\pm1$</td>
<td>1.75</td>
<td>0.5</td>
<td>3000</td>
<td>400</td>
</tr>
<tr>
<td>CLIC</td>
<td>$0.35\pm1.4\pm3$</td>
<td>3.5</td>
<td>1.5</td>
<td>3000</td>
<td>3000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$\sqrt{s}$ (TeV)</th>
<th>L (ab$^{-1}$)</th>
<th>$N_H$ ($10^6$)</th>
<th>$N_{ttH}$</th>
<th>$N_{HH}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>bb$\ell\ell$</td>
<td>14</td>
<td>3</td>
<td>180</td>
<td>3600</td>
<td>250</td>
</tr>
<tr>
<td>HL-LHC</td>
<td>100</td>
<td>6</td>
<td>5400</td>
<td>12000</td>
<td>20000</td>
</tr>
</tbody>
</table>

$N_{ttH}$ and $N_{HH}$ run are same with 2 experiments.

$<10\%$ of events usable

Rencontres de Vietnam 2014 tsv
### Precision of the Higgs couplings

<table>
<thead>
<tr>
<th>Facility</th>
<th>LHC 14,000</th>
<th>HL-LHC 14,000</th>
<th>ILC500 250/500</th>
<th>ILC500-up 250/500</th>
<th>ILC1000 250/500/1000</th>
<th>ILC1000-up 250/500/1000</th>
<th>CLIC 350/1400/3000</th>
<th>TLEP (4 IPs) 240/350</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$ (GeV)</td>
<td>14,000</td>
<td>14,000</td>
<td>250/500</td>
<td>250/500</td>
<td>250/500/1000</td>
<td>250/500/1000</td>
<td>350/1400/3000</td>
<td>240/350</td>
</tr>
<tr>
<td>$\int L,dt$ (fb$^{-1}$)</td>
<td>300/expt</td>
<td>3000/expt</td>
<td>250+500</td>
<td>1150+1600</td>
<td>250+500+1000+1500+2000</td>
<td>10,000+2600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\kappa_\gamma$</td>
<td>5 – 7%</td>
<td>2 – 5%</td>
<td>8.3%</td>
<td>4.4%</td>
<td>3.8%</td>
<td>2.3%</td>
<td>–</td>
<td>1.45%</td>
</tr>
<tr>
<td>$\kappa_t$</td>
<td>6 – 8%</td>
<td>3 – 5%</td>
<td>2.0%</td>
<td>1.1%</td>
<td>1.1%</td>
<td>0.67%</td>
<td>3.6/0.79/0.56%</td>
<td>0.79%</td>
</tr>
<tr>
<td>$\kappa_W$</td>
<td>4 – 6%</td>
<td>2 – 5%</td>
<td>0.39%</td>
<td>0.21%</td>
<td>0.21%</td>
<td>0.2%</td>
<td>1.5/0.15/0.11%</td>
<td>0.10%</td>
</tr>
<tr>
<td>$\kappa_Z$</td>
<td>4 – 6%</td>
<td>2 – 4%</td>
<td>0.49%</td>
<td>0.24%</td>
<td>0.50%</td>
<td>0.3%</td>
<td>0.49/0.33/0.24%</td>
<td>0.05%</td>
</tr>
<tr>
<td>$\kappa_L$</td>
<td>6 – 8%</td>
<td>2 – 5%</td>
<td>1.9%</td>
<td>0.98%</td>
<td>1.3%</td>
<td>0.72%</td>
<td>3.5/1.4/1&lt;1.3%</td>
<td>0.51%</td>
</tr>
<tr>
<td>$\kappa_d = \kappa_b$</td>
<td>10 – 13%</td>
<td>4 – 7%</td>
<td>0.93%</td>
<td>0.60%</td>
<td>0.51%</td>
<td>0.4%</td>
<td>1.7/0.32/0.19%</td>
<td>0.39%</td>
</tr>
<tr>
<td>$\kappa_u = \kappa_t$</td>
<td>14 – 15%</td>
<td>7 – 10%</td>
<td>2.5%</td>
<td>1.3%</td>
<td>1.3%</td>
<td>0.9%</td>
<td>3.1/1.0/0.7%</td>
<td>0.69%</td>
</tr>
</tbody>
</table>

Theory uncertainties need to be improved to match expected good experimental precision and sensitivity to new physics.
New Physics e.g. $Z'$: Mass Reach

### ATLAS projections

<table>
<thead>
<tr>
<th>model</th>
<th>300 fb^{-1}</th>
<th>1000 fb^{-1}</th>
<th>3000 fb^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z'_{SSM} \rightarrow ee$</td>
<td>6.5</td>
<td>7.2</td>
<td>7.8</td>
</tr>
<tr>
<td>$Z'_{SSM} \rightarrow \mu\mu$</td>
<td>6.4</td>
<td>7.1</td>
<td>7.6</td>
</tr>
</tbody>
</table>

![CMS Simulation 2013, $\sqrt{s}=14$ TeV, L = 3000 fb^{-1}](image)

The Detector Challenge: Phase II

Detector Challenge: Maintain/improve on detector performance achieved in Phase I, under more hostile conditions.

Apply lessons from the past – finish a directed programme of R&D and prototyping before starting construction.

HL-LHC: High-level Summary

Inner Trackers Replacement

Endcap/Forward Calorimeters Replacement

Level-1 Trigger: using a “good” set is of utmost importance
Keep thresholds Low, Increase Accept Rate, Bring in tracking info

Changes to Front-end Electronics to allow high L1 accept rate.
CMS Phase 2 Upgrades

**Trigger/DAQ**
- L1 (hardware) with tracks and rate up $\sim 500$ kHz to 1 MHz
- Latency $\geq 10$ µs
- HLT output up to 10 kHz

**New Tracker**
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to $\eta \sim 4$

**New Endcap Calorimeters**
- Radiation tolerant - high granularity
- Investigate coverage up to $\eta \sim 4$

**Barrel ECAL**
- Replace FE electronics

**Muons**
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to $\eta \sim 4$

D. Abbaneo
ATLAS: Phase 2 Upgrades

Muon spectrometer
- New Small Wheel
- Additional BMG chambers sectors 12&14
- BIS 7-8 RPCs in transition region
- Replacement of read-out electronics
- MDT-based trigger

Calorimeter system
- New L1 trigger (Super Cells)
- LAr and Tile electronics replacement
- Replacement of HEC cold electronics, FCAL?

Inner Detector (ID)
- Fast Tracker for L2 trigger
- New All-Silicon Inner Tracker

Two Level Trigger system
- L0: 1MHz, 6/10μs latency
- L1: 300-400kHz, 30/60μs latency

M. Hagel
LHCb: Upgrades

- VErteX LOcator: new (silicon pixels)
- RICH detectors: new photon detectors (SiPM); improve RICH1 optics
- Muon system: new off-detector electronics

Tracking system: new (silicon strips, scintillating fibres)
Calorimeters: new readout electronics

readout full detector at 40 MHz
full software trigger with 20 kHz output rate
“Reconstructing the Universe”

Session and Discussions on Future Accelerators

at Guggenheim, New York
Remarks from Discussions on Future Accelerators 1

- Where does our Science stand today?
- We have made a major discovery - a Higgs boson – a particle like no other. And we have no evidence for BSM physics at the LHC.
- The only established new physics beyond the SM has been seen arguably in the neutrino sector, BAU, in the form of dark matter and dark energy… BUT what scale(s)?

IF new physics (or strong indications) is discovered at the LHC14 – then it is likely to be the lowest of coloured states or the lowest of a series of resonant states – and will be quite heavy. This implies the full spectrum will have even heavier particles and the only sure way to explore that spectrum will to go to a high energy hadron collider (e.g. 100 TeV pp collider – (R.Aleksan- LHC magnets in a 100 km tunnel already gives ~ 55 TeV).

IF NO new physics (beyond the Higgs boson) is found (e.g. in Run 2) then we must continue searching and looking for cracks in the SM in all areas (HL-LHC, neutrinos, EDM, dark matter,…). The found Higgs boson and the associated field are new to fundamental physics. It behoves us to study it in depth and its implications (some of which may go beyond particle physics).

Where does it point us? What tools/experiments do we have today: HL-LHC, neutrino experiments, rare processes experiments, dark matter searches, etc.
Remarks from Discussions on Future Accelerators

- **HL-LHC** – full exploitation of the potential of LHC
  (Note: the GPD Upgrades funding is not secured yet – and we must make the upgrades a success)
  - The LHC provides a broad platform for performing Higgs (studies) and other precision measurements. It is a b-quark, W/Z, top-quark, Higgs factory – the only one we have for the foreseeable future (+ Belle2). Should aim to keep the doubling time short: below ~ one (longish) LHC run. So at some suitable integrated luminosity perhaps push the LHC accelerator and the experiments to the limit \(\Rightarrow\) design upgrades beyond \(3\text{ab}^{-1}\) (say \(5\text{ab}^{-1}\))?

- **Crucial to have a wide range of (unprejudiced) experimental programme (Y. Nomura)**

- **Neutrinos**
  - Through experiments probing their nature, the origin of their masses and hierarchy, leptonic CP violation, the unitarity of the PMNS matrix and whether there are additional species.
  - The US-P5 report provides an opportunity to shape a global neutrino programme with possibly complementary long-baseline experiments. Can the world afford two such experiments (e.g. in US and Japan)? The potential physics payoff seems to point that way.

- **Other complementary experiments** (astroparticle, neutrinoless \(\beta\)-decay, EDM, dark matter, etc)
Any new (high energy) accelerator will require substantial resources (human and financial).

**Need**
1) Scientifically persuasive (better still - compelling) case – compare with what is projected to be known in ~ 2030 from the upgraded HL-LHC and elsewhere. And secure consensus/buy-in by most of our community (as was the case for the LHC)
2) Support/understanding from other scientific disciplines
3) Probably international sharing of cost
4) Public support
Electron-positron colliders
The LHC results already limit the sub-TeV colliders mostly to a justification based on precision studies of the Z, W, Higgs boson and ttH. (TeV or multi-TeV accelerators?)

ILC in Japan: √s=0.5 TeV: Await decision in Japan. The report of the Japanese Science Council (K. Yokoya) requested a 2-3 year study to provide:
- Clearer and more persuasive arguments – including the relation with the (upgraded) LHC
- A “budget” framework that does not …..stagnate… progress in other academic fields
- International cost sharing
- Public support

CepC: Recent article in Nature (S. Chattopaday) – China is a candidate to build 250 GeV electron–positron collider. Yifang Wang – “You can’t just talk about a project which is 20 years from now”. Proposing to use international participation to increase radius/energy (ee/pp).

Can one of these accelerators be built without support from all regions? Does this imply substantial supplementary funding beyond existing resources?
Remarks from Discussions on Future Accelerators

- **Hadron colliders**
  Today these seem to be the only reasonable way to probe energy scales some 5-10 times higher than the LHC.

- There is a need to proceed vigorously with R&D on affordable high field SC dipole magnets.

- The development of 16-20T magnets in the next decade opens up options. The possibility of going for HE-LHC or a truly global collider (e.g. pp-FCC). (As already noted current LHC magnets in an FCC already gives 55 TeV).
The next large accelerator?

- A case can be made for an e^+e^- accelerator on the basis of precision measurements (searching for deviations and/or checking the self-consistency of SM) but appears to require a high luminosity and broad energy reach - from Z mass upwards.

- A discovery at LHC/HL-LHC would make a compelling for a high energy hadron collider (with $\sim \sqrt{s_{LHC}} \times 5-10$). However, a case can always be made on the basis of unknowns/searches at the next frontier for an energy frontier accelerator.

- The path to follow will depend on the strength of the scientific case, that takes account of results from LHC14, including HL-LHC, and other experiments seeking cracks in the SM, the accelerator’s technical, cost and schedule, the regional and global context/involvement, and the longevity of scientific exploitation.

- Great care, patience, thought and wisdom will be needed to reach a correct and consensual decision within our community, that can be well explained further afield.
At the LHC, after twenty years of design and construction we are firmly in the 2\textsuperscript{nd} half of the journey – the extraction of the science.

A “massive” discovery has been made – a Higgs boson. The boson appears just to be the one predicted by the SM.

No evidence found yet of physics BSM. The Standard Model with a single “elementary” scalar doublet seems to work well (too well)

The start of Run 2 will be just as exciting as the original startup. We must be well prepared.

We must fully exploit the potential of the HL-LHC and so must make a success of the HL-LHC – our future may well depend on this.
The “novelty” and the “lightness” of this Higgs boson calls for its in-depth studies, and beyond, at the HL-LHC and the circular and linear e^+e^- colliders (with differing pros and cons).

Must take a holistic view of particle physics – whether we find BSM physics at the LHC or not – and select the path to follow in a prudent manner.

- Precision measurements (not only of the new boson, and not only at the LHC)
- Searches for new particles and phenomena, and their in-depth study if found

Above all we hope that new physics appears in Run II at 13-14 TeV.