Hunting for new Physics at the LHC
Run 2 and Future Prospects

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European School of High Energy Physics
Évora, 6th - 19th Sep. 2017
• How did we arrive to the LHC?

• Where do we {stand, go}?

• Experimental signatures and challenges in the hunt for new physics
How did we arrive at the LHC?

Machine design and potential
General purpose detector design
Current performances
Lausanne (CH), 1984: 1 year past the W and Z discovery comes the LHC proposal

- LEP tunnel was chosen already in view of the highest energy possible @ the LHC
- excavation of the 27 km ± 1 cm ring is completed in February 1988
- first beams for LEP injected July 1989

1989: The race is ON!
After the LEP and SLC programmes ended

- SM tested to unprecedented precision
  - e.g. $\Gamma_Z$ => 3 families of active neutrino,
  - determination of $\alpha_s$ at N$^3$LO, …

![Graph showing $\sigma_{\text{had}}$ vs. $E_{cm}$ with 2v, 3v, 4v peaks]

$$N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_\ell} \left( \frac{\Gamma_\ell}{\Gamma_\nu} \right)_{\text{SM}} = 2.984 \pm 0.008$$
Particle physics at the dawn of the LHC I

- After the LEP and SLC programmes ended
  - SM tested to unprecedented precision
    e.g. $\Gamma_Z \Rightarrow 3$ families of active neutrino,
    determination of $\alpha_s$ at $N^3$LO, …
  - no strong tension between data and the SM
    modulo the forward-backward asymmetry under the Z pole, i.e. $A_{fb}^{0,b}$ …
After the LEP and SLC programmes ended

- SM tested to unprecedented precision
  e.g. $\Gamma_Z \Rightarrow$ 3 families of active neutrino,
  determination of $\alpha_s$ at $N^3LO$, …

- no strong tension between data and the SM
  modulo the forward-backward asymmetry
  under the $Z$ pole, i.e. $A_{f,b}^{0,1}$

- direct searches excluded $m_H < 114$ GeV at 95% CL…

Fermilab’s Tevatron ($pp$) : Run 2 is still on-going

- discovery of the top quark
- $m_t$ measured to $<1\%$ precision
Particle physics at the dawn of the LHC II

• Fermilab’s Tevatron (pp) : Run 2 is still on-going
  • discovery of the top quark
  • $m_t$ measured to <1% precision
  • not yet sensitive to Higgs (apart $m_H \sim 165$ GeV)
  • no hints of new physics (BSM) (but slight tensions in combined EWK fits)

• In addition, no hints of BSM from precision B-physics (Tevatron, Belle, BABAR)
Enters the LHC: a collider designed to test EWSB...

- Initially designed to uncover what happens at the TeV energy scale:
  - ensure coverage to produce a Higgs boson candidate
  - bridge LEP's $M_H > 114.4$ GeV @ 95%CL up to 1 TeV
  - maximal sensitivity below WW threshold (favored by indirect fits)

- What if no Higgs candidate? something should happen in $\sigma(W_L W_L)$

$$A(W^+W^- \rightarrow W^+W^-) \rightarrow \frac{1}{v^2} \left[ s + t - \frac{s^2}{s - m_H^2} - \frac{t^2}{t - m_H^2} \right]$$
...at the energy frontier...

- Replace electrons with protons
- scan partonic $s^{1/2}$ up to TeV scale
...at the energy frontier...

- Replace electrons with protons
  - scan partonic $s^{1/2}$ up to TeV scale
  - each collision is unique in energy and remnants
  - need knowledge on the PDF, UE, $\alpha_s$

(parton distribution functions / underlying event / strong coupling constant)

- Large total cross section: $O(100 \text{ mb})$

\[ M^2 = x_1 x_2 s \]
...at the energy frontier...

- Replace electrons with protons
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- Large total cross section: $O(100 \text{ mb})$

- Processes of interest are $O(10\text{pb})$
  - theory needs to cover $>14$ orders magnitude
  - experiments need online selection

Can it ever be precise enough?
...and breaking intensity records

• High integrated luminosity needed to produce the processes of interest
  
  • instantaneous luminosity $10^{34} \text{ cm}^{-2} \text{ s}^{-1} \Rightarrow 10^7 \text{ Hz/mb} \Rightarrow O(10^2-10^3 \text{ MHz})$ collision rate!
  
  • crossing rate $>10^3$ larger than LEP with $\sim$25 interactions/crossing

• Challenging for detectors: front-end, trigger and data acquisition systems
Main endpoint of the CERN accelerator complex

1. LINAC 2 (50 MeV)
2. BOOSTER (1.4 GeV)
3. PS (26 GeV)
4. SPS (450 GeV)
5. LHC (7 TeV)
Luminosity is the key ingredient

- Master formula for the event rate expected:
  \[ \dot{N} = \mathcal{L} \cdot \sigma \]

- Depends on the flux of particles in the beam
  - results from the convolution of the two beam densities
  - simplest case: heads-on collisions, gaussian profiles,…

\[
\mathcal{L} = \frac{2 \cdot N_p N_p \int N_b}{(\sqrt{2\pi})^6 \sigma_x^2 \sigma_y^2} \int \int \int \int \int e^{-\frac{x^2}{\sigma_x^2}} e^{-\frac{y^2}{\sigma_y^2}} e^{-\frac{s^2}{\sigma_s^2}} e^{-\frac{s_0^2}{\sigma_s^2}} \, dx \, dy \, ds \, ds_0
\]

\[
= \frac{1}{4\pi} \left( f N_b N_p \right) \frac{N_p}{\sigma_x \sigma_y}
\]

\( N_p \) = number of particles in bunch

\( \sigma \) = beam current

\( \sigma \) = beam xy width

\( \mathcal{L} \) = luminosity

\( \sigma \) = cross section
Luminosity in real life

- At the LHC the beams have however:
  - a crossing angle \( \varphi \approx 300 \text{ rad} \)
  - distance-dependent profile (aka hourglass effect)
  - non-gaussianities, offsets,…
- Usually becomes expressed as:
  \[
  L = \frac{1}{4\pi} \left( f N_b N_p \right) \frac{N_p}{\varepsilon N} \frac{\gamma}{\beta^*} R(\phi, \beta^*, \varepsilon, \sigma_z)
  \]

Online tool to estimate it is provided by the CERN LPC - [link](#)
**Pileup: one side-product of instantaneous luminosity**

- High instantaneous luminosity does not come for free
  - The average number of events per crossing is currently
    \[
    \frac{\sigma \cdot \mathcal{L}}{f \cdot N_b} = \frac{80 \text{ mb} \cdot 10 \text{ nb s}^{-1}}{11245 \text{ s}^{-1} \cdot 2808} \approx 25
    \]
  - Expected to increase by a factor of 6 at the HL-LHC

An extreme event recorded in 2012 with 78 simultaneous collisions
Radiation levels: a challenge for detectors and electronics

- Activation of materials, impurities, loss of transparency/response, spurious hits …
- Additional shielding/moderators needed to limit radiation impact in the detectors
Parton distribution functions are crucial at the LHC

- How effectively can the beam energy be converted in physics?
- The cross section is determined by:
  - short-distance interaction between the proton constituents
    (Feynman rules for the process will determine its strength)
  - parton distribution functions (PDFs)
    (parametrize probability of constituent carrying a fraction of the energy)
  - Valid in all pQCD orders, up to power corrections $\sim p_n(\Lambda_{QCD}/Q)^n$

$$\sigma = \sum_{i,j} \int_0^1 dx_1 dx_2 f_i(x_1, \mu^2) f_j(x_2, \mu^2) \hat{\sigma}_{ij}(\frac{Q^2}{\mu^2})$$

- PDF for species $i$
- Factorization scale: separates hard-process from soft-process
- Scale of the hard scattering process: e.g. $m_H$, $m_{top}$
PDF coverage

13 TeV LHC parton kinematics

- Usually expressed in the \((x,Q^2)\)-plane
- Previous measurements from HERA/fixed target covered only a portion of what needs to be explored at the LHC
Parton luminosities

• A convenient way to write $\sigma$ is:

\[
\sigma = \sum_{(i,j)} \int_{\tau_0}^{1} \frac{1}{\tau} \frac{dL_{ij}}{s} \frac{d\tau}{d\tau} \hat{s}\hat{\sigma}_{ij}\left(\frac{Q^2}{\mu^2}\right)
\]

sum over possible parton pairs  \(\tau=x_1x_2\) : energy fraction converted in the hard process  Parton luminosity  \(\hat{s}=\tau s\) : partonic center-of-mass energy

• The parton luminosity results from the integration of the PDFs

\[
\tau \frac{dL_{ij}}{d\tau} = \frac{1}{1+\delta_{ij}} \int_0^1 dx_1 dx_2 [x_1 f_i(x_1, \mu^2)x_2 f_j(x_2, \mu^2) + (1 \leftrightarrow 2)] \delta(\tau-x_1x_2)
\]

• We can use this compact definition almost as a look-up-table to evaluate

  • cross sections (starting from an already existing partonic cross section value)
  • the reach of a hadron collider
Dijet rate at the LHC as an example

- Consider the production of two gluon jets with $p_T > 0.5$ TeV: $\sigma(pp \rightarrow gg, p_T^g > 0.5$ TeV)

$$\sigma = \sum_{(i,j)} \int_{\tau_0}^{1} \frac{d\tau}{\tau} \frac{1}{s} \frac{dL_{ij}}{d\tau} \hat{s} \hat{\sigma}_{ij} \left( \frac{Q^2}{\mu^2} \right)$$

- Multiplying all the factors we get $\sigma = 10 \text{pb}$

For $L=10^{34}$ cm$^{-2}$ s$^{-1}$ that is

$O(1 \text{ event / 1s})$ at the LHC
Expected cross sections and rates in hadron colliders

- Strong processes dominate

- Higgs: $O(5 \text{ Hz})$ production rate
  - Need to reject $10^9$ orders of magnitude to find the “golden” events!

- New physics <$\text{Hz}$ production rate
  - Need to collect high statistics: $O(ab^{-1} = 10^6 \text{ pb}^{-1})$
Collider reach

- Use parton luminosities to estimate reach
  - ratio at different $s^{1/2}$ estimates the gain in $\sigma$
  - use to find the (mass,luminosity)-equivalent
- Example:
  - during the 8 TeV run (20 fb$^{-1}$) we have a sequential $Z'$ up to $M \approx 2.8$ TeV
  - this would correspond @ 14 TeV to
    
    \[
    \begin{array}{ccc}
    \text{Mass [TeV]} & 4.2 & 5.7 & 7.0 \\
    \text{Luminosity [fb]} & 20 & 300 & 3000 \\
    \end{array}
    \]

- Useful online tool is available
  
  @ collider-reach
Collisions at the LHC: a summary

10^{34} \text{ cm}^{-2}\text{s}^{-1} \text{ luminosity}
2835 \text{ Bunches/beam}
10^{11} \text{ protons/bunch}

7 \text{ TeV Proton Proton colliding beams}

Bunch Crossing \quad 4 \times 10^7 \text{ Hz}
Proton Collisions \quad 10^9 \text{ Hz}
Parton Collisions
New Particle Production (Higgs, SUSY, ...)

scan down to <10^{-5} \text{ Hz}

Need to select 1 / 10^{13} \text{ events produced and reject pileup!}
LHC Run 2 performance overview

- Run 2 of the LHC at 13 TeV surpasses completely in luminosity Run 1 (7 and 8 TeV)
  - >2 times more luminosity than initially expected in 2016
  - total number of bunches not yet at maximum allowed: peak lumi. reaching $\sim 1.4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
  - also successful 570 $\mu$b$^{-1}$ PbPb (2015) and 180 nb$^{-1}$ pPb (2016) runs
The general-purpose detectors concept

- The Higgs mass is not fixed in the SM: different signatures to be expected
- $4\pi$-hermetic general purpose detectors are needed covering: leptons, photons, jets

<table>
<thead>
<tr>
<th>Detector component</th>
<th>Required resolution</th>
<th>$\eta$ coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Measurement</td>
</tr>
<tr>
<td>Tracking</td>
<td>$\sigma_{p_T}/p_T = 0.05% \ p_T \oplus 1%$</td>
<td>$\pm 2.5$</td>
</tr>
<tr>
<td>EM calorimetry</td>
<td>$\sigma_E/E = 10% /\sqrt{E} \oplus 0.7%$</td>
<td>$\pm 3.2$</td>
</tr>
<tr>
<td>Hadronic calorimetry (jets) barrel and end-cap forward</td>
<td>$\sigma_E/E = 50% /\sqrt{E} \oplus 3%$</td>
<td>$\pm 3.2$</td>
</tr>
<tr>
<td></td>
<td>$\sigma_E/E = 100% /\sqrt{E} \oplus 10%$</td>
<td>3.1 &lt; $</td>
</tr>
<tr>
<td>Muon spectrometer</td>
<td>$\sigma_{p_T}/p_T=10% \ at \ p_T = 1 \ TeV$</td>
<td>$\pm 2.7$</td>
</tr>
</tbody>
</table>

ATLAS performance goals from *JINST 3 S08003*
The two general purpose detectors

- Standalone measurement of $p(\mu)$
- Resolution is flat in $\eta$ and independent of pileup
- Two complementary $p(\mu)$ measurements
- Tracks point to primary vertex
The magnet is the heart of an experiment

- **Goal:** measure 1 TeV muons with $\delta p_T/p_T = 10\%$ without charge error
  
  \[
  \frac{\sigma_{p_T}}{p_T} = \frac{8}{0.3} \frac{p_T}{B l^2} \sigma_s
  \]
  
  this implies $\sim 50\mu m$ uncertainty in measuring $s$

- either use “continuous tracking” or “extreme field”

- **From Ampere’s theorem:**
  
  \[
  \int \vec{B} \cdot d\vec{s} = \mu_0 I \Rightarrow B = \mu_0 n I.
  \]
  
  \(\Rightarrow n = 2168 \ (120)\) turns per coil in CMS (ATLAS)

- special design needed for superconducting cable in CMS

- size limited by magnetic pressure ($P \approx 6.4 \text{ MPa}$)
The magnet is the heart of an experiment II

<table>
<thead>
<tr>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>B</strong></td>
<td>0.6T (8 coils, 2x2x30 turns)</td>
</tr>
</tbody>
</table>

**Challenges**
- spatial/alignment precision over large surface
- 1.5GJ energy stored
- design and winding of the cable
- 2.7GJ energy stored

**Drawbacks**
- limited pointing capabilities
- non-trivial B
- additional solenoid (2T) needed for tracking
- space needed
- limits space available for calorimetry
- no photomultipliers for calorimeters
- multiple scattering in iron core
- poor bending at large angles
Si-based trackers

- **General requirements:**
  - 0.5% (10%) $p_T$ resolution at 1 GeV (TeV)
  - allow lepton charge at $p \sim 2$ TeV
  - keep narrow signals narrow ($H \rightarrow 4\mu, Z \rightarrow \ell\ell$)
  - keep $Z'\rightarrow \ell\ell$ searches competitive

- **Continuous tracking (ATLAS) or few accurate points (CMS)?**

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{in}$ [cm]</td>
<td>5</td>
<td>4.4</td>
</tr>
<tr>
<td>$R_{out}$ [m]</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Length [m]</td>
<td>5.4</td>
<td>5.8</td>
</tr>
<tr>
<td>$B$ [T]</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>$X_0 \ @ \eta \approx 0$ (1.4)</td>
<td>0.3 (2.3)</td>
<td>0.4 (1.8)</td>
</tr>
<tr>
<td>$\sigma p_T/p_T \ @ 1$ (100) GeV</td>
<td>1.3% (3.8%)</td>
<td>0.7% (1.5%)</td>
</tr>
<tr>
<td>“outer” $\sigma_{r\phi}$</td>
<td>130 $\mu$m/straw</td>
<td>35 $\mu$m/strip</td>
</tr>
</tbody>
</table>
Refurbished pixels in Run 2

CMS

ATLAS

CMS Simulation preliminary

13 TeV

<table>
<thead>
<tr>
<th></th>
<th>2016</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
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<tr>
<td>3</td>
<td></td>
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</tr>
</tbody>
</table>

CMS-TDR-011

ATLAS Preliminary

0.4 < p_T < 0.5 [GeV]

Data 2012, √s = 8 TeV

Data 2015, √s = 13 TeV

2017 TRK performance

CMS-TDR-011
Calorimeters

- Di-object invariant mass performance is often the figure of merit

\[ m_{\alpha\alpha'} = \sqrt{2E_{\alpha}E_{\alpha'}(1 - \cos \zeta)} \Rightarrow \frac{\delta m_{\alpha\alpha'}}{m_{\alpha\alpha'}} \propto \frac{\delta E_{\alpha}}{E_{\alpha}} \oplus \sin \zeta \cdot \delta \zeta \]

<table>
<thead>
<tr>
<th>Particle</th>
<th>( \sigma_{E/E} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma )</td>
<td>(~3-10%/E^{1/2})</td>
</tr>
<tr>
<td>hadrons</td>
<td>(~50-100/E^{1/2})</td>
</tr>
</tbody>
</table>

Pileup mitigation from pointing and timing capabilities + fast charge integration

Fine segmentation to resolve \( \pi^0 \rightarrow \gamma \gamma \), jet substructure
CMS calorimetry system

**HCAL**
- Brass and scintillator
- Si photomultipliers (Run 2)

**ECAL**
- PbWO$_4$ crystals
- Avalanche photodiodes
- Projective geometry

**Forward HCAL**
- Quartz fibers and steel
- Multi-anode photomultipliers
**ATLAS calorimetry overview**

**ATLAS Preliminary**

- Data 2016, $\sqrt{s} = 13$ TeV
- $Z \to ee$, 8.5 fb$^{-1}$

**ECAL**
- Lead and liquid Argon
- accordion geometry

**HCAL**
- Steel and scintillating tiles
- WLS readout by PMTs

**Forward HCAL**
- Copper/W and liquid Argon
Jet performance: Run I vs Run II

- **Jet energy scale**
  - **Pileup:** 25ns (Run I) vs 50ns (Run II) more work needed to mitigate out-of-time pileup contribution
  - **Absolute/relative scale:** more data needed in Run II

- **Jet energy resolution**
  - similar performance (driven by single particle resolutions)
Muons reconstruction

- External tracking for muons is used in both detectors
  - mostly based on gaseous ionization chambers used
  - provide easy id at high integrated luminosities
  - good momentum resolution for level-1 trigger
    (significantly improved in CMS after matching to tracker)
- $\delta$-rays, punch-throughs, $n$ may trick pattern recognition
- lower $p_T$ $b,c \rightarrow \mu$ decays have high trigger rates
Field integral and particle flow

- Particle flow algorithms benefit from larger B.R
  - well separated tracks
  - reconstruct conversions, nuclear interactions, $V^0$ decays
  - easier to link with calorimeter deposits
  - dedicated calibrations from identified $\pi^+, K^0, e, \gamma, \mu$
Particle flow performance

- >80% of the jet components are reconstructed using high resolution detectors
  - *tracking*: $\pi^+, K^+$ and other charged hadrons are approximately $O(60\%)$
  - *ECAL*: by isospin symmetry $\pi \rightarrow \gamma \gamma$ contribute in second place with $O(20\%)$
Trigger is the brain of the experiment

- Ultimately decides what is experimentally accessible at the LHC
  - ADCs must be in synch with beam crossings @ 40 MHz
  - can only use a sub-set of information (coarser granularity)

- Intermediate buffers are the trick
  - de-randomize incoming event rate
  - decouple slow readout from fast front-end

- L1/L2 trigger implemented in hardware
  - combine information from sub-detectors
  - accept @ 100kHz

- HLT implemented in a CPU farm
  - partial or full reconstruction from raw data
  - ultimate decision if data goes to tape @300Hz
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Road ahead for detector upgrades

Consolidate detectors, address operational issues, prepare for high pileup
- complete muon coverage, improve muon trigger, new smaller radius beam pipes
- CMS: Replace HCAL forward PMTs and outer HPD → SiPM
- ATLAS: Diamond beam monitor, additional pixel layer 2013-2014 2018-2019

Mantain / improve performance at high pileup
- CMS: new pixels, HCAL SiPMs, electronics, and L1-Trigger
- ATLAS: L1 trigger improvement, fast track trigger at L2, new muon small wheels

Mantain / improve performance at extreme pileup : sustain rate + radiation doses
- New inner detector, new calorimeter electronics, muon extension, trigger and DAQ upgrade
- CMS: track trigger, replace endcap calorimeters
- ATLAS: replace inner tracker, new forward calorimeter
Detector strategies to mitigate pileup at HL-LHC

- Use fine granular detectors
  - *transverse*: reduce flux per calorimeter cell, resolve fine structures
  - *longitudinal*: absorb low energy pileup in the first layers
  - *3D reconstruction+timing*: associate deposits to primary vertices

- Example: $H \rightarrow \gamma\gamma$ association to primary vertex
  - loose 30% in resolution with “tracker only” informat
    $\Rightarrow$ up to 20% larger uncertainty in cross section
Example of detector challenges ahead

- **High granular calorimeter for CMS endcap**
  - $>10^6$ channels measuring: $E$, $t$ and $x,y,z$
  - Trigger (data) flow @ 40 MHz (up to 750 kHz)
  - Keep intercalibration unc. below 3%
  - Clock distribution for timing capabilities (30ps/cell)
  - Cooling, mechanics,…

- **Tracker**
  - Extend to higher rapidities and reduce material budget
  - Reduce hit merging (improve track separation)
  - Provide robust, fast pattern recognition (for L1 and HLT)
Future of Trigger and DAQ systems?

- To sustain the HL-LHC rates refined information is needed: track trigger, crystal level
Future of Trigger and DAQ systems?

- Unavoidable increase in bandwidth: up to ~7.5x higher at L1 and HLT
- Storage throughput increasing by ~10x ⇒ 42Gb/s @ HL-LHC
Where do we \{stand, go\}?

\(O(4\%)\) of the pieces identified
\(O(96\%)\) to be found

(c) Todd McLellan
With the Higgs boson the SM is now complete

- Run I discovery behaving like the SM Higgs
  - not all couplings are yet measured
  - no coupling is measured to the % level
  - still a large room for BSM contributions
Some highlights from Higgs in Run 2

ATLAS Preliminary

Δσ/σ ~ 30%

re-discovering recent friends at new $s^{1/2}$:

ATLAS twiki
Some highlights from Higgs in Run 2

programme of differential measurements gaining thrust: fiducial measurements comparing to state-of-the-art MC: fair agreement with predictions
Some highlights from Higgs in Run 2

Observation for $ttH$? Maybe, if combined…
…but missing a flagship final state.

from G. Petrucciani @ Moriond EW'17
Some highlights from Higgs in Run 2

**Observation for $H \rightarrow \tau\tau$**

- **4.9$\sigma$ significance in Run II**
- **5.9$\sigma$ significance combining with Run I**

**Evidence for $VH \rightarrow bb$**

- **3.5$\sigma$ significance in Run II**
- **3.6$\sigma$ significance combining with Run I**

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**Graphs and Data**

- **ATLAS**
  - Total vs. Stat.
  - Significances:
    - 7 TeV: -1.61 (Stat.)
    - 8 TeV: 0.65 (Stat.)
    - 13 TeV: 1.20 (Stat.)
    - Combined: 0.90 (Stat.)

- **CMS**
  - Significances:
    - 0-jet: 0.84
    - Boosted: 1.17
    - VBF: 1.11
    - Combined: 1.09

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[arXiv:1708.00373]
[arXiv:1708.03299]
With the Higgs the SM is now **incomplete**

**Corrections to Higgs mass from loops:**

un-natural balance with the top quark in the SM

\[ m_H^2 \approx (125 \text{ GeV})^2 = \]

\[ m_{H0}^2 + \frac{1}{16\pi^2} \lambda_H^2 \Lambda^2 - \frac{3}{8\pi^2} \lambda_t^2 \Lambda^2 + \frac{9}{64\pi^2} g^2 \Lambda^2 \]

⇒ part of the clues are in the Higgs self-interaction and \( m_t \)
Tracing back from the early universe

- A phase transition must occur for $T_{EW} (~10^{-10}$s after the big bang)
  - strong first order transition is possible if $<\phi_c> > T_{EW}$
  - in the SM this implies that $m_H < 80$ GeV but experimental evidence contradicts this
    
    $m_H \sim 125$ GeV and cosmological remnants from the electroweak epoch exist

$\Rightarrow$ new physics coupling to H at the TeV scale?
Testing the origin of $M_H$ at the LHC

- Measuring the self-couplings of the Higgs at the LHC will require the HL-LHC
  - HH production: low cross sections, non-trivial backgrounds and competition with $(y_t)^2$
  - nevertheless new physics may be contributing to it resonantly or not
  - current Run2 testing $O(20-30)\times$ the SM expectations for triple H couplings

\[
\Delta \mathcal{L} = \kappa_\lambda \lambda_{SM} v H^3 \]
\[
- \frac{m_t}{v} \left( v + \kappa_t + \frac{c_2}{v} H^2 \right) (\bar{t}_L t_R + h.c.) 
+ \frac{\alpha_S}{12\pi v} \left( c_g H - \frac{c_{2g}}{2v} H^2 \right) G^{\mu\nu} G_{\mu\nu} 
\]
Where are we aiming for regarding the Higgs couplings?

- Establishing the Higgs couplings to bosons and fermions
  - <5-10% (<10-15%) level end of HL-LHC (Run 2)
  - $H \rightarrow \mu \mu$ measured with 5-8% uncertainty
- Higgs self-couplings long road ahead
  - $HH @ 3\sigma$ after combinations?

Theory needs to accompany - how far can we get?
• Running $\lambda$ and $m_H$ to the Planck scale: some tension regarding the vacuum stability

  • experimentally $\delta M_H \sim 100$ MeV is within reach (10x smaller than theory prediction)

  • how far can we get in the experimental sources: top quark mass and $\alpha_s$?
Testing further the SM consistency through $m_H$

- The top mass uncertainty is the most significant blocker to untie this situation
  - $\delta m_W \sim 0.02\%$: unlikely to see a 0.5% shift in future measurements?
  - $\delta m_t \sim 0.4\%_{\text{exp}} + 0.4\%_{\text{interpretation}}$: can reference MCs be calibrated to pole mass?
  - how far can we push $m_W$ and $m_t$ at the LHC?
**Direct $m_t$ measurements circa 2017**

<table>
<thead>
<tr>
<th>ATLAS+CMS Preliminary LHCtopWG</th>
<th>$m_{	ext{top}}$ summary, $\sqrt{s} = 7$-8 TeV</th>
<th>May 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>World Comb. Mar 2014, [7]</strong></td>
<td>$m_{\text{top}} = 173.34 \pm 0.76 (0.36 \pm 0.67)$ GeV</td>
<td></td>
</tr>
<tr>
<td>stat</td>
<td>total uncertainty</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATLAS, $t$+jets (*)</td>
<td>$172.31 \pm 1.55 (0.75 \pm 1.35)$</td>
<td>7 TeV [1]</td>
</tr>
<tr>
<td>ATLAS, dilepton (*)</td>
<td>$173.09 \pm 1.63 (0.64 \pm 1.50)$</td>
<td>7 TeV [2]</td>
</tr>
<tr>
<td>CMS, $t$+jets</td>
<td>$173.49 \pm 1.06 (0.43 \pm 0.97)$</td>
<td>7 TeV [3]</td>
</tr>
<tr>
<td>CMS, dilepton</td>
<td>$172.50 \pm 1.52 (0.43 \pm 1.46)$</td>
<td>7 TeV [4]</td>
</tr>
<tr>
<td>CMS, all jets</td>
<td>$173.49 \pm 1.41 (0.69 \pm 1.23)$</td>
<td>7 TeV [5]</td>
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<tr>
<td><strong>LHC comb. (Sep 2013)</strong></td>
<td>$173.29 \pm 0.95 (0.35 \pm 0.88)$</td>
<td>7 TeV [6]</td>
</tr>
<tr>
<td>World comb. (Mar 2014)</td>
<td>$173.34 \pm 0.76 (0.36 \pm 0.67)$</td>
<td>1.96-7 TeV [7]</td>
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<tr>
<td>ATLAS, $t$+jets</td>
<td>$172.33 \pm 1.27 (0.75 \pm 1.02)$</td>
<td>7 TeV [8]</td>
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<tr>
<td>ATLAS, dilepton</td>
<td>$173.79 \pm 1.41 (0.54 \pm 1.30)$</td>
<td>7 TeV [8]</td>
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<tr>
<td>ATLAS, all jets</td>
<td>$175.1 \pm 1.8 (1.4 \pm 1.2)$</td>
<td>7 TeV [9]</td>
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<tr>
<td>ATLAS, single top</td>
<td>$172.2 \pm 2.1 (0.7 \pm 2.0)$</td>
<td>8 TeV [10]</td>
</tr>
<tr>
<td>ATLAS, dilepton</td>
<td>$172.99 \pm 0.85 (0.41 \pm 0.74)$</td>
<td>8 TeV [11]</td>
</tr>
<tr>
<td>ATLAS, all jets</td>
<td>$173.72 \pm 1.15 (0.55 \pm 1.01)$</td>
<td>8 TeV [12]</td>
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<tr>
<td><strong>ATLAS comb. (June 2016)</strong></td>
<td>$172.84 \pm 0.70 (0.34 \pm 0.61)$</td>
<td>7+8 TeV [11]</td>
</tr>
<tr>
<td>CMS, $t$+jets, dil.</td>
<td>$172.35 \pm 0.51 (0.16 \pm 0.48)$</td>
<td>8 TeV [13]</td>
</tr>
<tr>
<td>CMS, dilepton</td>
<td>$172.82 \pm 1.23 (0.19 \pm 1.22)$</td>
<td>8 TeV [13]</td>
</tr>
<tr>
<td>CMS, all jets</td>
<td>$172.32 \pm 0.64 (0.25 \pm 0.59)$</td>
<td>8 TeV [13]</td>
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<tr>
<td>CMS, single top</td>
<td>$172.95 \pm 1.22 (0.77 \pm 0.95)$</td>
<td>8 TeV [14]</td>
</tr>
<tr>
<td>CMS comb. (Sep 2015)</td>
<td>$172.44 \pm 0.48 (0.13 \pm 0.47)$</td>
<td>7+8 TeV [13]</td>
</tr>
</tbody>
</table>

(*) Superseded by results shown below the line

- LHC rapidly caught up with precise mass measurements
- 500 MeV (0.3%) level
- ambiguity at the level of $\Lambda_{\text{QCD}}$
- calibrated to a simulation

$M_{\text{exp}}^2 = \left( \sum_{i=1,\ldots,n} p_i \right)^2$

\[ \Rightarrow \text{npQCD + parton shower} \]

Translate precisely to $m_t^{\text{pole}}$?
First $W$ mass at the LHC!

- Several ingredients involved
  - Lepton calibration: $J/\psi$, $Z$ data
  - Modelling of the recoil: $Z$ data
  - $W_pT$: calibrate predictions on $Z_pT$
  - but also angular distributions and FSR
  - PDFs: sea/valence quark ratios

Breakdown of uncertainties:
- FSR/EWK: 13%
- $W_pT/QCD$: 19%
- PDFs: 21%
- Backgrounds: 10%
- Lepton: 15%
- Recoil: 7%
- Statistics: 16%
- Theory: challenging
- Experiment: challenging

$\text{Free of ambiguities: decay products are pure EWK}$
But calibration involves non-trivial QCD predictions
Latest on the weak mixing angle

- **Forward-Backward asymmetry in** $Z/\gamma^* \rightarrow \ell \ell$
  - sensitive to the weak mixing angle $\sin^2 \theta_W = 1 - \frac{M_Z^2}{M_W^2}$
  - still room for improvement at the LHC
- common theory/PDF uncertainties with W mass

$$\sin^2 \theta_{eff}^{lept} = 0.23101 \pm 0.00036_{stat} \pm 0.00018_{syst} \pm 0.00016_{th} \pm 0.00030_{pdf}$$
What are we aiming for with $m_t$, $m_W$?

- $m_W$: fresh start! Uncertainty already competitive with Tevatron
  - Recoil estimate from data becomes harder in more recent and future datasets due to pileup
  - Benefit from higher statistics for higher $p_T$ W's evading the npQCD uncertainties
  - ~5-10 MeV (may be optimistic?)

- $m_t$: $\Lambda_{QCD}$ within experimental reach using classic techniques
  - Combination with alternative methods
  - Evolve towards differential $m_t$
  - But theory needs to accompany interpretation
  - 200 MeV

In both cases: rich programme of experimental and theory challenges ahead!
With the Higgs the SM is now **incomplete** - reprise

$$m_H^2 \approx (125 \text{ GeV})^2 =$$

\[m_{H^0}^2 + \frac{1}{16\pi^2} \lambda_H^2 \Lambda^2 - \frac{3}{8\pi^2} (\lambda_t^2 - \lambda_{t'}^2) \Lambda^2 + \frac{9}{64\pi^2} g^2 \Lambda^2\]

⇒ a top quark partner at the TeV scale?
**Selected CMS SUSY Results** - SMS Interpretation

**CMS Preliminary**

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

\[ L = 12.9 \text{ fb}^{-1} \quad L = 35.9 \text{ fb}^{-1} \]

For decays with intermediate mass, 

\[ m_{\text{Intermediate}} = x \cdot m_{\text{Mother}} + (1-x) \cdot m_{\text{LSP}} \]

*Observed limits at 95% C.L. - theory uncertainties not included*

Only a selection of available mass limits. Probe *up to* the quoted mass limit for \( m_{\text{LSP}} = 0 \) GeV unless stated otherwise.
Desperately searching for SUSY?

- Although nothing striking is above the standard model expectations
  - we have only analysed ~2% of the data to come
  - still room to find a stop quark in a “moderate fine-tuned scenario”
- Intensity/precision frontier : common challenges with Higgs, EWK, flavour
Vector-like quarks I

- Extra fermion partners may contribute to cancel divergences in $m_H$
  - unlike SM fermions have left- and right-handed charged currents
  - Yukawa-type coupling to SM fermions
  - reach signatures with bottoms/tops and bosons in the final state
- Typical of composite Higgs, little Higgs-like theories, extra dimensions
Uncharted territory - leave no stone unturned

- cover all possible final states and scan the couplings
# ATLAS Exotics Searches - 95% CL Upper Exclusion Limits

Status: July 2017

\[ \int L \, dt = (3.2 - 37) \, fb^{-1} \]

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

<table>
<thead>
<tr>
<th>Model</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( E_{\text{miss}}/\tau )</th>
<th>( \int L , dt [fb^{-1}] )</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD ( g_{KK} + g'/\eta )</td>
<td>0, e, ( \mu )</td>
<td>1 - 4</td>
<td>( \pm 1 )</td>
<td>36.1</td>
<td>1.6 TeV</td>
<td>ATLAS-CONF-2017-060</td>
</tr>
<tr>
<td>ADD non-resonant ( g' g' )</td>
<td>2, ( \gamma )</td>
<td>-</td>
<td>-</td>
<td>36.7</td>
<td>1.6 TeV</td>
<td>ATLAS-CONF-2017-060</td>
</tr>
<tr>
<td>ADD DBH</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>37.0</td>
<td>1.6 TeV</td>
<td>ATLAS-CONF-2017-060</td>
</tr>
<tr>
<td>ADD BH high ( \Sigma_{\Delta T} )</td>
<td>( \geq 1 ), ( \mu ), ( \geq 2 )</td>
<td>-</td>
<td>-</td>
<td>3.2</td>
<td>1.6 TeV</td>
<td>ATLAS-CONF-2017-060</td>
</tr>
<tr>
<td>ADD BH multijet</td>
<td>-</td>
<td>3, 4</td>
<td>-</td>
<td>3.6</td>
<td>1.6 TeV</td>
<td>ATLAS-CONF-2017-060</td>
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<tr>
<td>RSI ( g_{KK} \rightarrow \gamma \gamma )</td>
<td>2, ( \gamma )</td>
<td>-</td>
<td>-</td>
<td>36.7</td>
<td>1.6 TeV</td>
<td>ATLAS-CONF-2017-060</td>
</tr>
<tr>
<td>Bulk RS ( g_{KK} \rightarrow WW \rightarrow qq\nu\nu )</td>
<td>1, ( e, \mu )</td>
<td>( 1 )</td>
<td>-</td>
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<td>1.6 TeV</td>
<td>ATLAS-CONF-2017-060</td>
</tr>
<tr>
<td>2UED / RPP</td>
<td>1, ( e, \mu )</td>
<td>( \geq 2, \geq 3 )</td>
<td>-</td>
<td>13.2</td>
<td>1.6 TeV</td>
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<table>
<thead>
<tr>
<th>Gauge bosons</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( E_{\text{miss}}/\tau )</th>
<th>( \int L , dt [fb^{-1}] )</th>
<th>Limit</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSM ( Z' \rightarrow t \ell )</td>
<td>2, ( e, \mu )</td>
<td>-</td>
<td>-</td>
<td>36.1</td>
<td>1.6 TeV</td>
<td>ATLAS-CONF-2017-060</td>
</tr>
<tr>
<td>SSM ( Z' \rightarrow \tau \tau )</td>
<td>2, ( \tau )</td>
<td>-</td>
<td>-</td>
<td>36.1</td>
<td>1.6 TeV</td>
<td>ATLAS-CONF-2017-060</td>
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<tr>
<td>Leptophobic ( Z' \rightarrow bb )</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>3.2</td>
<td>1.6 TeV</td>
<td>ATLAS-CONF-2017-060</td>
</tr>
<tr>
<td>Leptophobic ( Z' \rightarrow tt )</td>
<td>1, ( e, \mu ), ( \geq 1 ), ( \geq 1 )</td>
<td>-</td>
<td>-</td>
<td>3.2</td>
<td>1.6 TeV</td>
<td>ATLAS-CONF-2017-060</td>
</tr>
<tr>
<td>SSM ( W' \rightarrow \ell \nu )</td>
<td>1, ( e, \mu )</td>
<td>-</td>
<td>-</td>
<td>36.1</td>
<td>1.6 TeV</td>
<td>ATLAS-CONF-2017-060</td>
</tr>
<tr>
<td>HVT ( V' \rightarrow WW \rightarrow qqqq )</td>
<td>2, ( e, \mu )</td>
<td>-</td>
<td>-</td>
<td>36.1</td>
<td>1.6 TeV</td>
<td>ATLAS-CONF-2017-060</td>
</tr>
<tr>
<td>HVT ( V' \rightarrow WH/ZH model B )</td>
<td>Multi-channel</td>
<td>-</td>
<td>-</td>
<td>36.1</td>
<td>1.6 TeV</td>
<td>ATLAS-CONF-2017-060</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>LRS model</th>
<th>( W_3^L \rightarrow \ell \nu )</th>
<th>Jets</th>
<th>( E_{\text{miss}}/\tau )</th>
<th>( \int L , dt [fb^{-1}] )</th>
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<tr>
<td>LRS model</td>
<td>( W_3^L \rightarrow \ell \nu )</td>
<td>( 2, \ell, \nu )</td>
<td>-</td>
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<td>LRS model</td>
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<thead>
<tr>
<th>CI</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( E_{\text{miss}}/\tau )</th>
<th>( \int L , dt [fb^{-1}] )</th>
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<tr>
<td>CI</td>
<td>( \ell, \gamma )</td>
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<thead>
<tr>
<th>DM</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( E_{\text{miss}}/\tau )</th>
<th>( \int L , dt [fb^{-1}] )</th>
<th>Limit</th>
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<tbody>
<tr>
<td>DM</td>
<td>( \ell, \gamma )</td>
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<td>DM</td>
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<thead>
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<th>Scalar</th>
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<th>( \int L , dt [fb^{-1}] )</th>
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<tr>
<td>Scalar</td>
<td>( \ell, \gamma )</td>
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<tr>
<th>Heavy quarks</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( E_{\text{miss}}/\tau )</th>
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<tr>
<th>Excited fermions</th>
<th>( \ell, \gamma )</th>
<th>Jets</th>
<th>( E_{\text{miss}}/\tau )</th>
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<thead>
<tr>
<th>LRSM Majorana</th>
<th>( \ell, \gamma )</th>
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<td>1.6 TeV</td>
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</tr>
</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown.

\( ^\dagger \) Small-radius (large-radius) jets are denoted by the letter j (J).
Should the new physics scale be at the LHC reach?

- $K^0, D^0, B^0, B_0^s$ mass splittings yield tight constraints on new physics contributions

$$
\delta L = \frac{Z_{qq'}}{\Lambda^2} \left( \bar{q}_L \gamma_\mu q'_L \right)^2 \Rightarrow \frac{\Delta m_h}{m_h} \sim \left| \frac{Z_{qq'}}{3} \right| \left( \frac{f_h}{\Lambda} \right)^2
$$

- If flavour structure is trivial ($z \sim 1$)

$$
\Lambda \approx O(100 \text{ TeV})
$$

⇒ only glimpses of NP observed at the LHC?

- If $\Lambda \sim O(1 \text{ TeV})$

NP flavour structure is far from trivial

⇒ flavour measurements are good probe of NP

Both cases ⇒ higher precision at the LHC
Searching for subtle NP effects in data

• If the energy probed does not yet resolve the mass of the new particles
  • look for deviations induced by Fermi-like interactions

\[ \delta \mathcal{L} = \sum \frac{c_i}{\Lambda^2} \mathcal{O}_i + \mathcal{O}\left(\frac{1}{\Lambda^4}\right) \Rightarrow \delta \sigma = \sum \frac{c_i^2}{\Lambda^2} \sigma_i + \sum \frac{c_i c_j}{\Lambda^4} \sigma_{ij} + \ldots \]

interference with the SM expectations
pure NP contribution although suppressed by \(1/\Lambda^4\) may be non-negligible!

• Several start moving in the direction of a global scan of allowed NP contributions
Higgs as a portal

- Still a (experimental) large room for invisible Higgs decays: BR<0.24 @ 95%CL
  - significant changes in this BR could be due to new neutral particles: dark matter?
- It may also be that the Higgs sector is more complex and accompanied by partners
  - resonant associated (VH) and hh production, high-mass diboson resonances, ....
Dark matter and Higgs

• The limits on the invisible BR of the Higgs can be re-casted to limits dark matter production

\[
\begin{align*}
\sigma_{S-N}^{SI} &= \frac{4 \Gamma_{inv} f_N^2}{m_H^2 v^2 \beta (M_X + m_N)^2}, \\
\sigma_{V-N}^{SI} &= \frac{16 \Gamma_{inv} M_X^4}{m_H^2 v^2 (m_X^2 - 4M_X^2 m_H^2 + 12M_X^4) (M_X + m_N)^2}, \\
\sigma_{T-N}^{SI} &= \frac{8 \Gamma_{inv} M_X^2}{m_H^2 v^2 \beta^2 (M_X + m_N)^2}.
\end{align*}
\]

\(m_N\) - nucleon mass ~0.939 GeV
\(v=246/\sqrt{2}\) GeV (vev)
\(f_N\sim0.326\) central value for coupling (from lattice*)
\(\beta = \sqrt{1 - 4M_X^2/m_H^2}\).
\(\Gamma_{inv} = \Gamma_{SM \ BR_{inv}}/(1-BR_{inv})\)


• Latest re-interpretations in terms of mediator-WIMP mass (see CERN-LPCC-2016-001)
Dark matter at the LHC

- Wide range of searches for associated production of dark matter: mono-\(X\), jet+ISR, top, H
  - spin-dependent re-interpretation is unavoidable
  - nevertheless, nicely complements direct searches from dedicated experiments
Data, models, what is the nature of BSM?

- Experimentalists rely on this type of model landscape to gauge their findings
  - but the point is not so much what we plot/quote as limit
  - we want to fill in the puzzle by leaving no stone unturned
Outstanding questions - LHC dawn

Electroweak symmetry breaking
• does the Higgs boson exist?

Dark matter
• composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ...
• one type or more?
• only gravitational or other interactions?

Neutrinos
• $\nu$ masses, their origin - Higgs role?
• Majorana or Dirac?
• CP violation
• additional species?
• sterile $\nu$?

Quarks and leptons
• why 3 families?
• masses and mixing
• CP violation in the lepton sector
• matter and antimatter asymmetry
• baryon and charged lepton number violation

Physics at the highest E-scales:
• how is gravity connected with the other forces?
• do forces unify at high energy?

Neutrinos

Universe’s accelerated expansion:
• primordial: is inflation correct? which (scalar) fields? role of quantum gravity?
• today: dark energy (why is $\Lambda$ so small?) or gravity modification?
Electroweak symmetry breaking
- $m_H$ natural or fine-tuned?
- if natural: what new physics/symmetry?
- does it regularize the divergent $V_L V_L$ cross-section at high $M(V_L V_L)$? new dynamics?
- elementary or composite Higgs?
- is it alone or are there other Higgs bosons?
- origin of couplings to fermions
- coupling to dark matter?
- does it violate CP?
- cosmological EW phase transition

Quarks and leptons
- why 3 families?
- masses and mixing
- CP violation in the lepton sector
- matter and antimatter asymmetry
  - baryon and charged lepton number violation
- CP violation in the lepton sector
- additional species?
- sterile $\nu$?

Neutrinos
- $\nu$ masses, their origin - $H(125)$ role?
- Majorana or Dirac?
- CP violation
- additional species?
- sterile $\nu$?

Dark matter
- composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ...
- one type or more?
- only gravitational or other interactions?

Universe’s accelerated expansion:
- primordial: is inflation correct? which (scalar) fields? role of quantum gravity?
- today: dark energy (why is $\Lambda$ so small?) or gravity modification?

Physics at the highest E-scales:
- how is gravity connected with the other forces?
- do forces unify at high energy?

adapted from I. Shipsey @ ICHEP2016
be happily unsettled and search for new physics