Physics at run 2: prospects and opportunities

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some questions for run 2
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  • how much more can we learn about its properties, about EW symmetry breaking?
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→ how much richer and broader can the physics programme become? which new surprises?
some examples, off the beaten path of higgs, susy etc
LHC & CRs

R. Engel (KIT)
LHCf, fwd photon energy spectra, 
arXiv:1104.5294

LHCf, fwd neutron energy spectra, 
arXiv:1503.03505
Tuning CR MCs with LHC data (mostly from the first few pb$^{-1}$ ....)
Uncertainty on \(<X_{\text{max}}\) reduced from \(~50 \text{ g/cm}^2\) to \(~20 \text{ g/cm}^2\) ([proton – iron]~100 g/cm²)
Uncertainty on $\langle X_{\text{max}} \rangle$ reduced from ~50 g/cm$^2$ to ~20 g/cm$^2$ ([proton – iron]~100 g/cm$^2$)

$\langle X_{\text{max}} \rangle$ as measured by the Pierre Auger (left) and Telescope Array (right) Collaboration [2, 3]. The colored lines denote predictions of air shower simulation (note that different models are shown in the left and right panel, only Sibyll2.1 is the same). The black line on the right panel is a straight-line fit to the TA data.
J/ψ – azimuthal anisotropy in AA ($v_2$)

- Heavy-quark and quarkonium in-medium thermalization and medium (transport) properties: flow of J/ψ, D-mesons, HF-leptons
- In-medium parton energy loss: open-charm, HF-lepton suppression
  - $R_{AA}$: new reach at low-$p_T$ (down to $p_T < 1$ GeV/c) and high-$p_T$
- Multiple-parton interactions in pp and pA (via high-multiplicity events)

Present measurement: Indication of J/ψ flow

Projection for Run-2: >5σ measurement
Charged hadron $R_{pPb}$

- Two pronged approach min. bias and high-$p_T$ triggers:
  - Higher statistics in $pPb$ (up to $\times$ 5)
  - Reference pp measurement at 5 TeV (few $10^6$ events; 1/pb)

Discrepancy between ALICE and CMS (+ATLAS)

Need $O(1/pb)$ for conclusive measurement

$R_{pPb}$ vs $p_T$ (GeV/c)

Green: p-Pb Run2 (5x), current pp ref.
Red: p-Pb Run2 (5x), 1 pb$^{-1}$ pp 5 TeV

Additional $O(10^3)$ MB for EMCal trig correction
Glueballs

Run 1, evidence of sensitivity to $f_0(1710) \rightarrow \rho^0 \rho^0$ from 3nb$^{-1}$ joint CMS/TOTEM

- $f_0(1710), 0^{++}$ glueball candidate
- No info on production rate in gg channel
- Conflicting knowledge (B factories, Zeus) on:
  - mass
  - decay BRs to $u/d$ vs strange mesons (crucial to assess consistency with glueball interpretation): $\pi\pi, \rho\rho, KK$
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Run 2 projections:
0.05pb$^{-1}$ for discovery, $O(1\text{pb}^{-1})$ for BR measurements and first angular analysis, $O(5\text{pb}^{-1})$ for partial wave analysis in full mass range (40 MeV bins)

- $f \rightarrow \rho\rho \rightarrow 2\pi+2\pi$, acceptance modelled
- $J = 0$ generated, $J = 0$ and $J = 2$ fitted

![Graph showing mass distribution and significance level](image)
Status of BSM

• Until few yrs ago, we had a benchmark model, MSSM, expected to deliver the following:
  • low-mass Higgs $h^0$, no heavier than $\sim 130$ GeV
  • $\sim \text{TeV}$ scale squarks and gluinos, to be seen rapidly at the LHC
    • $\Rightarrow$ solution to the naturalness problem
  • extra Higgses ($A^0 / H^0 / H^\pm$) observed at the LHC
  • candidate for DM, confirmed by direct detection
  • interesting flavour phenomenology
    • explanation of $(g-2)_\mu$
    • sizable deviations from SM in $B(B_s \to \mu^+ \mu^-)$
    • $\mu \to e\gamma$ observed at MEG, consistent with SUSY neutrino masses induced at the GUT scale
  • CPV in the Higgs or squark/gluino sector, to explain BAU
  • electric dipole moments ($e, n$) measured, consistent with previous point
• Given our knowledge 4-5 yrs back, all of this could have happened by now.
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Even models alternative to SUSY (extra dim, little Higgs, SILH, ...) had the potential of matching the “natural” predisposition of SUSY to solve problems and to provide rich phenomenological consequences across the fields (LHC, flavour, astro/cosmo)
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• The above scenario may still happen, with a few-year delay, perhaps stretching a bit the “naturalness”.
• This expectation is still high, and well justified
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• Whether to keep believing in the MSSM or other specific BSM theories after LHC@8TeV is a matter of personal judgement. But the broad issue of *naturalness will ultimately require an understanding.*
The observation of the Higgs where the SM predicted it would be, its SM-like properties, and the lack of BSM phenomena up to the TeV scale, make the naturalness issue as puzzling as ever.

Whether to keep believing in the MSSM or other specific BSM theories after LHC@8TeV is a matter of personal judgement. But the broad issue of naturalness will ultimately require an understanding.

Naturalness remains a guiding principle to drive the search of new phenomena at the LHC.
Anomalies / pending items from run 1, some examples

CMS-PAS-HIG-14-005

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

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

\text{ stat } \text{syst}

LHCb, arXiv:1406.6482

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


For possible interpretation within a single BSM model
see e.g. Crivellin, D’Ambrosio, Heeck, arXiv:1501.00993 (2HDM w. gauged \(L_\mu–L_\tau\))
CMS/LHCb $B_{(S)} \rightarrow \mu^+ \mu^-$

\[
\frac{\text{BR}(B \rightarrow \mu^+ \mu^-)}{\text{BR}(B_S \rightarrow \mu^+ \mu^-)} = 2.3\sigma \text{ high w.r.t. SM}
\]
$V_{ub}$ puzzle

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<thead>
<tr>
<th>PDG version</th>
<th>Exclusive</th>
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$|V_{ub}|$
**V_{ub} puzzle**

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**Λ_b → pμν at LHCb**

\[
\frac{\mathcal{B}(Λ_b \rightarrow pμ^−\bar{ν}_μ)_{q^2 > 15 GeV^2/c^4}}{\mathcal{B}(Λ_b \rightarrow Λcμν)_{q^2 > 7 GeV^2/c^4}} = (1.00 \pm 0.04(stat) \pm 0.08(syst)) \times 10^{-2}
\]

**LHCb**

\[|V_{ub}| = (3.27 \pm 0.15(exp) \pm 0.17(theory) \pm 0.06(|V_{cb}|)) \times 10^{-3}\]
Anomalies left over from run 1, examples at large Q

Dileptons + jets + MET (SUSY searches)


$N_{\text{jets}} (p_T > 40 \text{ GeV}) \geq 2$, $E_T^{\text{miss}} > 150 \text{ GeV}$
or

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

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

On-Z: $m_{ll} = (81–101) \text{ GeV}$


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

$H_T > 600 \text{ GeV}$

On-Z: $m_{ll} = (81–101) \text{ GeV}$
... no signal on-peak

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

<table>
<thead>
<tr>
<th></th>
<th>Low-mass</th>
<th>On-Z</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Central</td>
<td>Forward</td>
</tr>
<tr>
<td>Observed</td>
<td>860</td>
<td>487</td>
</tr>
<tr>
<td>Flavor-symmetric</td>
<td>722 ± 27 ± 29</td>
<td>355 ± 19 ± 14</td>
</tr>
<tr>
<td>Drell-Yan</td>
<td>8.2 ± 2.6</td>
<td>2.5 ± 1.0</td>
</tr>
<tr>
<td>Total estimated</td>
<td>730 ± 40</td>
<td>471 ± 32</td>
</tr>
<tr>
<td>Observed – estimated</td>
<td>130^{+48}_{-49}</td>
<td>16^{+37}_{-38}</td>
</tr>
<tr>
<td>Significance</td>
<td>2.6 \sigma</td>
<td>0.3 \sigma</td>
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\( \Rightarrow 2.6 \sigma \)

... no signal on-peak

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


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

\( \Rightarrow 3.0 \sigma \) \( \Rightarrow 1.6 \sigma \)

... but no signal off-peak

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

Already more than 10 TH interpretation papers on arXiv ....
Assessing the consistency/significance of such anomalies in view of the multitude and diversity of existing constraints, is becoming more and more difficult!

⇒ relevance of “recasting” frameworks and tools, “simplified models” approaches, proper documentation and archival of exptl results, ....
How long before run 2 extends the discovery reach of run 1?
Rate comparison 8 vs 13 TeV: dijet production

![Graph showing dijet production rate comparison]

- **Dijet production**
  - $|\eta_{\text{jet}}|<2.5$
  - $\sigma(M_{jj}>M_{\min})$ [fb]

- $\sqrt{S}=8$ TeV
  - $100 \text{ ev} \Rightarrow \sim 100 \text{ pb}^{-1}$
  - $1 \text{ ev} \Rightarrow 10 \text{ pb}^{-1}$

- $\sqrt{S}=13$ TeV
  - $100 \text{ ev/20 fb}^{-1}$
  - $1 \text{ ev/20 fb}^{-1}$
Remarks

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

- **Substantial increase of W production at large energy:** over 10% of high-ET events have a W or Z in them!
- **It would be interesting to go after these W and Zs, and verify their emission properties**

\[
\frac{\sigma(jj+W)}{\sigma(jj)} \quad \text{with} \quad E_{T, \text{leading jet}} > E_{T, \text{min}}
\]

\[
\frac{\sigma(jj+WW)}{\sigma(jj+W)}
\]

\[
\frac{\sigma(jj+WWW)}{\sigma(jj+WW)}
\]

\[
\frac{\sigma(jj+W)}{\sigma(jj)}
\]

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

- **pp @ 14 TeV**
Rate comparison 8 vs 13 TeV: t tbar production

\[ |\eta_{\text{top}}| < 2.5 \]
\[ \sigma(M_{tt} > M_{\text{min}}) \text{ [fb]} \]

1 ev \Rightarrow 0.2 \text{ fb}^{-1}
Remarks

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

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

DY production $(e+\mu)$

$|\eta_{lep}| < 2.5$

$\sqrt{S} = 13$ TeV

$\sqrt{S} = 8$ TeV

1 ev $\Rightarrow$ 2 fb$^{-1}$

$1$ ev/20 fb$^{-1}$

$M_{\text{min}}$ (TeV)
13 TeV luminosity required to match BSM sensitivity reached so far (20fb⁻¹) at 8 TeV

See also http://collider-reach.web.cern.ch, by Salam and Weiler
ATLAS/CMS projections for early discovery in run 2: dijet resonances

CMS, PHYS14 exercise
Remarks

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

• Further studies at high energy/luminosity should not just focus on pushing the high mass end, but also on exploring low-couplings at low mass
ATLAS/CMS projections for discovery in run 2: SUSY

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

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

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

From Higgs Cross Section WG, @m$_H = 125$ GeV

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

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

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

Mass:

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

Rate ($\mu =$data/SM for $\sigma \cdot BR$):

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

$\mu_{\text{CMS}} = 1.00 \pm 0.09\text{(stat)} \pm 0.07\text{(expt)} \pm 0.08\text{(theory)}$
\[ m_H = 125.36 \text{ GeV} \]

<table>
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<tr>
<th>Process</th>
<th>( \mu )</th>
<th>( \sigma_{\text{(stat.)}} )</th>
<th>( \sigma_{\text{(sys inc.)}} )</th>
<th>( \sigma_{\text{(theory)}} )</th>
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<tbody>
<tr>
<td>( H \rightarrow \gamma\gamma )</td>
<td>1.17^{+0.28}_{-0.25}</td>
<td>-0.23</td>
<td>0.16</td>
<td>0.08</td>
</tr>
<tr>
<td>( H \rightarrow ZZ^* )</td>
<td>1.46^{+0.40}_{-0.34}</td>
<td>0.35</td>
<td>0.19</td>
<td>0.11</td>
</tr>
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<td>( H \rightarrow WW^* )</td>
<td>1.18^{+0.24}_{-0.21}</td>
<td>0.16</td>
<td>0.08</td>
<td>0.09</td>
</tr>
<tr>
<td>( H \rightarrow bb )</td>
<td>0.63^{+0.39}_{-0.37}</td>
<td>0.31</td>
<td>0.23</td>
<td>0.09</td>
</tr>
<tr>
<td>( H \rightarrow \tau\tau )</td>
<td>1.44^{+0.42}_{-0.37}</td>
<td>0.30</td>
<td>0.23</td>
<td>0.10</td>
</tr>
<tr>
<td>( H \rightarrow \mu\mu )</td>
<td>-0.7^{+3.7}_{-3.7}</td>
<td>0.05</td>
<td>0.07</td>
<td>0.04</td>
</tr>
<tr>
<td>( H \rightarrow Z\gamma )</td>
<td>2.7^{+4.6}_{-4.5}</td>
<td>4.3</td>
<td>1.7</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td>1.18^{+0.15}_{-0.14}</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

 CMS

 Events / bin

 $\mu = 1.18^{+0.15}_{-0.14}$

 $\mu_{4\ell}$ (GeV)

 $\ell s = 7 \text{ TeV}, 4.5-4.7 \text{ fb}^{-1}$

 $\ell s = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}$
H @ run 2 in perspective
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  - of course not in all channels ..... for ttH production and $H\rightarrow bb$ decays the goal is still confirmation of the signal
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Run 2 will prepare the ground for the work needed to fully exploit the ultimate HL-LHC luminosity in terms of Higgs physics, and will give us a much more clear picture of what the ultimate precision targets can be
Example: ATLAS, arXiv:1504.05833

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

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

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

NB Most of the TH vs data discrepancy comes from final states with $\geq 1$ jet, which in other analyses ($WW^*$) are left out ....
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$$= 33.0 \pm 5.5\,(\text{tot run 1})\,\text{pb}$$

$x\ 10$ statistics $\Rightarrow$

$$\sigma(pp\rightarrow H) = XX \pm 2.3\,\text{pb}$$

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

Many channels
Nothing found yet ...

\[ h \rightarrow aa \rightarrow \tau\tau\mu\mu: \text{HIGG-2014-02} \]
\[ A \rightarrow Zh: \text{arxiv:1502.04478, sub. to PLB} \]
\[ H^+ \rightarrow WZ: \text{HIGG-2014-13, sub. to PRL} \]
\[ H^+ \rightarrow \tau\nu: \text{arxiv:1412.6663, acc. by JHEP} \]
\[ h \rightarrow (Z/Z_d)Z \rightarrow 4\ell: \text{ATLAS-CONF-2015-003} \]
Final remarks
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• Regardless of the emergence of direct BSM discoveries, LHC measurements will address the fundamental questions of our field, and the answers obtained from data will greatly extend our understanding of nature