Highlights from EPS HEP 2015

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Karlsruhe Institute of Technology
Excellent conference with many beautiful results presented in talks and posters

- 41 plenary talks
- 425 talks in 36 parallel session
- 194 posters

Selection of some highlights cannot do justice to all the great physics discussed during the past week
Outline

• The Higgs and its friends
• Resonance searches
• First results from run 2 of the LHC
• The ridge
• NLO and the NNLO revolution
• Cosmology
• Heavy flavors
• ... and more
Higgs Production at the LHC

<table>
<thead>
<tr>
<th>process</th>
<th>8 TeV</th>
<th>13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>19 pb</td>
<td>44 pb</td>
</tr>
<tr>
<td>VBF</td>
<td>1.6 pb</td>
<td>3.7 pb</td>
</tr>
<tr>
<td>VH</td>
<td>1.1 pb</td>
<td>2.2 pb</td>
</tr>
<tr>
<td>ttH</td>
<td>0.13 pb</td>
<td>0.51 pb</td>
</tr>
<tr>
<td>tH</td>
<td>~20 fb</td>
<td>~90 fb</td>
</tr>
</tbody>
</table>

SM Production Modes
($M_H = 125$ GeV)
The SM does not predict the Higgs boson mass: we need to measure it.

Given a mass, we can make predictions* for the production cross section and decay rates.

Higgs mass measurements (GeV):
- ATLAS: $125.36 \pm 0.37 \text{ (stat)} \pm 0.18 \text{ (syst)}$
- CMS: $125.02 \pm 0.27 \text{ (stat)} \pm 0.15 \text{ (syst)}$

**LHC combination:**
$125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst)}$

**Precision measurement:** <0.2%

* a lot of progress by theory community, LHCXSWG. Improvements continue…
**Signal Strength for Decay Modes**

**ATLAS**

$m_H = 125.36 \text{ GeV}$

- $H \rightarrow \gamma \gamma$
  - $\mu = 1.17^{+0.28}_{-0.26}$
- $H \rightarrow ZZ^*$
  - $\mu = 1.46^{+0.40}_{-0.34}$
- $H \rightarrow WW^*$
  - $\mu = 1.18^{+0.24}_{-0.21}$
- $H \rightarrow \tau \tau$
  - $\mu = 1.44^{+0.45}_{-0.37}$
- $H \rightarrow bb$
  - $\mu = 0.63^{+0.39}_{-0.37}$
- $H \rightarrow \mu \mu$
  - $\mu = -0.7^{-3.7}_{+5.7}$
- $H \rightarrow Z\gamma$
  - $\mu = 2.7^{+4.6}_{-4.5}$

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

**CMS**

$m_H = 125 \text{ GeV}$

- $H \rightarrow \gamma \gamma$ tagged
  - $\mu = 1.12 \pm 0.24$
- $H \rightarrow ZZ$ tagged
  - $\mu = 1.00 \pm 0.29$
- $H \rightarrow WW$ tagged
  - $\mu = 0.83 \pm 0.21$
- $H \rightarrow \tau \tau$ tagged
  - $\mu = 0.91 \pm 0.28$
- $H \rightarrow bb$ tagged
  - $\mu = 0.84 \pm 0.44$

ATLAS: individual $\mu$ values from combination of channels
CMS: individual $\mu$ values from tagged analyses
Searches for rare decays performed in various channels

Observation of these decays in Run 1 would signal BSM physics

Non-universal coupling of Higgs to leptons:

- $\mu\mu$ signal would be 280 times larger than SM if $\mu$ coupling was equal to that of $\tau$

<table>
<thead>
<tr>
<th>Process</th>
<th>limit (times SM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu\mu$ (ATLAS)</td>
<td>7.0</td>
</tr>
<tr>
<td>$\mu\mu$ (CMS)</td>
<td>7.4</td>
</tr>
<tr>
<td>$Z\gamma$ (ATLAS)</td>
<td>11</td>
</tr>
<tr>
<td>$Z\gamma$ (CMS)</td>
<td>9</td>
</tr>
<tr>
<td>$\gamma\gamma^*$ (CMS)</td>
<td>7.7</td>
</tr>
<tr>
<td>$J/\psi\gamma$ (ATLAS)</td>
<td>540</td>
</tr>
<tr>
<td>$J/\psi\gamma$ (CMS)</td>
<td>540</td>
</tr>
<tr>
<td>ee (CMS)</td>
<td>$10^5$</td>
</tr>
</tbody>
</table>
A $\rightarrow \tau\tau$ (Low/High Mass)

Search for pseudoscalar (A) boson decaying to $\tau$ leptons

- Sensitive in high $\tan(\beta)$ regime

Searches performed at high and low mass

Results interpreted in the context of SUSY scenarios. Limits given on $\sigma \times \text{BR}$
Search for heavy, narrow resonances

Many channels
• Dijets
• Photon pairs
• Lepton Pairs
• Pairs of heavy bosons
Di-jets

- Classical bump search – narrow resonance: up to widths 20-30% of the mass
- Simple – Data-driven, background parameterized by smooth function
- Powerful – generic search, many interpretations, high mass reach

Excluded resonances with masses of 2 – 5 TeV depending on model
Di-photons

- Sensitive to spin 2 (RS graviton) or spin 0 (heavy Higgs) resonances
- Clean topology with well understood SM $\gamma\gamma$ background (Higgs searches)
- Challenge is the photon reconstruction and ID at high energies

- Limits on RS graviton mass 1- 2.7 TeV (sensitivity similar to di-lepton)

Mikulec
Di-bosons

- Search for resonance decaying to pairs of $W$, $Z$, $H$
- Challenging topology:
  - At resonance masses above 1 TeV the decay products of bosons overlap due to strong boost
- Needs dedicated techniques to reconstruct objects
  - Specific lepton isolation
  - Grooming techniques (cleaning pileup and noise)
  - Boson tagging (jet substructure, jet mass)
The background is estimated by filling the data.

Additional cuts to reduce QCD (with substantialness).

Independent

Overlapping signal regions non statistically events whose one of the jets is poorly measured

ATLAS: $|\eta| > 1.2$, $p_T$ accepted > 0.15 to reject

Select events with $M_W$ within the W/Z mass window

(only boosted region considered) Low mass QCD

ATLAS: Trigger on a jet with $p_T > 200$ GeV CMS: Trigger

$\Delta Y < 4.99$
Di-bosons – excess?

- Moderate excesses observed in some channels around 1.8 – 2 TeV
  - Global significance 2 – 2.5 $\sigma$
  - Small excesses also in di-jets...
- Excesses of 2$\sigma$ not unusual, but ATLAS + CMS at similar place = excitement

**CMS: PAS EXO-14-010**

**ATLAS: arXiv 1506.00962**

- Not in all channels...
- Will know more after a few first fb$^{-1}$ of Run 2 data
LHC has started run 2 and is delivering

Luminosities @ CMS

- **Total delivered**: 106/pb
- **Total recorded**: 83.5/pb
- **Total recorded @ 3.8T**: 61.8/pb
- **Results @ EPS presented up to**: 43/pb
13 TeV: 37 pb⁻¹, M_{jj} ≤ 5 TeV, 8 TeV: 19.7 fb⁻¹, M_{jj} ≤ 5.15 TeV

Close to Run 1 limit ➔ interesting times ahead of us 😊
### 13 TeV / 8 TeV inclusive \( pp \) cross-section ratio

<table>
<thead>
<tr>
<th>Event Type</th>
<th>Cross-section Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum bias</td>
<td>1.2</td>
</tr>
<tr>
<td>W(\ln)</td>
<td>1.6</td>
</tr>
<tr>
<td>Z(\ell\ell)</td>
<td>1.7</td>
</tr>
<tr>
<td>ZZ</td>
<td>2.0</td>
</tr>
<tr>
<td>t (s-channel)</td>
<td>2.2</td>
</tr>
<tr>
<td>t (t-channel)</td>
<td>2.5</td>
</tr>
<tr>
<td>WH</td>
<td>2.0</td>
</tr>
<tr>
<td>H (ggF)</td>
<td>2.3</td>
</tr>
<tr>
<td>H (VBF)</td>
<td>2.4</td>
</tr>
<tr>
<td>tt</td>
<td>3.3</td>
</tr>
<tr>
<td>ttZ</td>
<td>3.6</td>
</tr>
<tr>
<td>ttH</td>
<td>3.9</td>
</tr>
<tr>
<td>A(0.5 TeV, ggF+bbA)</td>
<td>4.0</td>
</tr>
<tr>
<td>stop pair (0.7 TeV)</td>
<td>8.4</td>
</tr>
<tr>
<td>gluino pair (1.5 TeV)</td>
<td>10</td>
</tr>
<tr>
<td>Z' SSM (3 TeV)</td>
<td>56</td>
</tr>
<tr>
<td>Q' (4 TeV)</td>
<td>370</td>
</tr>
<tr>
<td>QBH (5 TeV)</td>
<td>9000</td>
</tr>
<tr>
<td>QBH (6 TeV)</td>
<td>9000</td>
</tr>
</tbody>
</table>

At \(10^{34} \text{ cm}^{-2} \text{ s}^{-1} \) & 13 TeV, \( pp \) the LHC produces:
- 200 Hz W → lν
- 19 Hz Z → ll
- 8 Hz top pair
- 0.5 Hz Higgs
Reach very high mass $t\bar{t}$bar pairs

- **Top – jet 1:**
  - $m = 177$ GeV, $p_T = 613$ GeV

- **Di-top jet Mass:** 2491 GeV

- **Top – jet 2:**
  - $m = 176$ GeV, $p_T = 488$ GeV

Borras
Top-antitop production at 13 TeV

Extraction of top-pair cross section

$\sigma_{tt} (13 \text{ TeV}) = 825 \pm 49 \, \text{(stat)} \pm 60 \, \text{(syst)} \pm 83 \, \text{(lumi)} \, \text{pb}$
Properties of inelastic pp collisions at 13 TeV

Key input to pileup and underlying event modelling, uses low-µ data

Average charged-particle multiplicity per unit of rapidity for \( \eta = 0 \) vs CM energy

For comparison, the strange baryon contribution is included at 13 TeV (1.5% correction factor)
Two-charged-particle correlations

Near-side ($\Delta \phi \sim 0$) “ridge” shape in $\Delta \eta$–$\Delta \phi$ seen in $pp$, pPb and PbPb collisions

Unexpected effect of collective dynamics. Increases with particle multiplicity and moderate $p_T$

CMS, pp at 7 TeV:
$N_{ch} > 110$, $1.0 < p_T < 3.0$ GeV

ATLAS, pPb at 5.02 TeV:
$N_{ch} > 220$, $1.0 < p_T < 3.0$ GeV

ATLAS, PbPb at 2.76 TeV:
Centrality 0–5%, largest 10% $q_2$

[ CMS, 1009.4122 ]
[ ATLAS, 1212.5198 ]
[ ATLAS, 1504.01289 ]

[ Enhancement found to be also present at $\Delta \phi \sim \pi$, when subtracting hard scattering contributions ]
How does the pp ridge evolve with CM energy?

- Trigger on MBTS (97M events) & high charged multiplicity (9.5M)
- Exploit work on tracking systematics from minimum bias analysis
- Unfold to particle level
- Extract two-particle correlation function
  \[ C(\Delta \eta, \Delta \phi) = \frac{S(\Delta \phi, \Delta \eta)}{B(\Delta \phi, \Delta \eta)} \]
- Background from mixed data events
Higher order calculations [Grazzini]

The NLO automation

- Unitarity and on-shell methods
  - MadGraph5_aMC@NLO
  - BlackHat+Sherpa
  - NJet
  - GoSam+Sherpa
  - Helac-NLO

- Numerical off-shell methods
  Combine efficiency of the numerically stable tensor integral reduction with the automation made possible by a completely recursive approach
  - OpenLoops+Sherpa
  - Recola

The final goal is really automatic NLO calculations
Specify process (input card), define cuts/distributions → run and get the results

The problem is “in principle” solved

see also Van Hameren (2009)
The NNLO revolution

NNLO calculations important for:

1) Benchmark processes measured with high accuracy
   - $e^+e^- \rightarrow 3$ jets
   - $pp \rightarrow W, Z$
   - $pp \rightarrow t\bar{t}$bar and single top
   - $pp \rightarrow 2$ jets (towards completion)

2) Processes with large NLO corrections
   - $pp \rightarrow H$
   - $pp \rightarrow H$+jet
   - $pp \rightarrow HH$
   - Even N$^3$LO known now

3) Important backgrounds for Higgs and NP searches
   - $pp \rightarrow \gamma\gamma$
   - $pp \rightarrow W\gamma, Z\gamma$
   - $pp \rightarrow WW$
   - $pp \rightarrow ZZ$
   - $pp \rightarrow WZ$
   - $pp \rightarrow W(Z)$+jet

It is essential to provide fiducial cross sections and distributions with which the data can be directly compared

(for more processes see also Les Houches 2013 NNLO wish list)
Comparison to measured WW cross section

**Signature**

\[ e^+e^-, \mu^+\mu^-, \text{ or } e^\pm\mu^\mp + 0,1 \text{ jets} + \text{MET} \]

**Previous Measurements**

[CMS-PAS-SMP-12-013]

- 8 TeV, 3.5 fb\(^{-1}\), found \(\sigma(WW \rightarrow \ell\ell\nu\nu) = (22\pm13)\%\) higher than NLO prediction
Reanalysis of WW cross section by CMS

**Signature**
\[ e^+e^-, \mu^+\mu^- , \text{ or } e^\pm\mu^\mp + 0,1 \text{ jets } + \text{MET} \]

**Previous Measurements**

CMS-PAS-SMP-12-013
- 8 TeV, 3.5 fb\(^{-1}\), found \( \sigma(\text{WW} \rightarrow 2\ell 2\nu) = (22\pm13)\% \) higher than NLO prediction

New CMS: 60.1 ± 4.8 pb
Cosmology, dark matter and cosmic rays

• Many nice talks in parallel sessions
• Great reviews on Tuesday morning
  Volansky, Monroe, Hoffmann, Halzen, Ganga, Lahav, Binetruy
Dark Energy Survey (DES) (talk by Ofer Lahav)

Goal: weak lensing effects on 300 million galaxies provide dark matter map

DM distribution (center) tracks luminous matter distribution of galaxies (left)

Chang, Vikram, Jain et al. (PRL) 1M Background sources @ z ~0.8
Vikram, Chang, Jain et al. (PRD) 1M Foreground lenses @ z ~ 0.3
Improved low mass WIMP bounds by CRESST
Few anomalies in B sector

Tension in $P'_5$ is confirmed with 3fb$^{-1}$

$B \rightarrow K^* \mu^+ \mu^-$

LHCb preliminary

SM from DHMV

[arXiv:1503.03328]

Test of lepton universality using $B^+ \rightarrow K^+ \ell^+ \ell^-$ decays

$LHCb$

$R_K = 0.745^{+0.090}_{-0.074}$ (stat) $\pm 0.036$ (syst)

Summary for $B \rightarrow D^{(*)}\ell\nu$

BaBar

$R(D) = 0.440 \pm 0.058 \pm 0.042$

$R(D^*) = 0.332 \pm 0.024 \pm 0.018$

Belle

$R(D) = 0.375 \pm 0.064 \pm 0.026$

$R(D^*) = 0.293 \pm 0.038 \pm 0.015$

LHCb

$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

average

$R(D) = 0.391 \pm 0.041 \pm 0.028$

$R(D^*) = 0.322 \pm 0.018 \pm 0.012$

Karim Trabelsi

= difference with SM predictions is at $3.9\sigma$ level
New anomaly in $\varepsilon'/\varepsilon$: direct CPV in $K_L \rightarrow \pi\pi$

- Highly BSM-sensitive observable, precisely measured
  $$(\varepsilon'/\varepsilon)_{\text{exp}} = (16.6 \pm 2.3) \times 10^{-4} \quad \text{world average (KTeV & NA48)}$$
- Major driver of flavour theory in 1990’s
  Buras-Buchalla-Lautenbacher; Buras-Jamin-Lautenbacher-Weisz; Bosch-Buras-Gorbahn-Jaeger-Jamin-Lautenbacher-Silvestrini; Bertolini et al; Ciuchini et al; Pallante-Pich; Cirigliano et al; ... situation murky due to uncertain hadronic matrix elements (nonperturbative)
- @ EPS 2015: first complete lattice calculation (tour de force; evaluation of 20 hadronic matrix elements in isospin limit)
  $$(\varepsilon'/\varepsilon)_{\text{SM}} = (1.4 \pm 7.0) \times 10^{-4}$$
  RBC-UKQCD collaboration [Z Bai et al]; talk A Soni at this conference
- @ EPS 2015: impose Delta I=1/2 to reduce number of independent hadronic matrix elements; isospin and NNLO corrections; corroborate lattice with new large-N relations (and vice versa)
  $$\varepsilon'/\varepsilon = (2.2 \pm 3.7) \times 10^{-4} \quad \text{3.3}\sigma \text{ from expt}$$
  Buras, Gorbahn, Jaeger, Jamin; Buras and Gerard; talk A Buras at this conference

Excellent prospects as BSM probe if theory errors are confirmed/further reduced

Big improvements on hadronic matrix elements for B-physics, talk R. van de Water
Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b^0 \rightarrow J/\psi K^- p$ decays

Best fit with $J^P = (3/2^-, 5/2^+)$
(also $(3/2^+, 5/2^-)$ and $(5/2^+, 3/2^-)$)

<table>
<thead>
<tr>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>fit fraction (%)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>4380±8±29</td>
<td>205±18±86</td>
<td>8.4±0.7±4.2</td>
<td>9 $\sigma$</td>
</tr>
<tr>
<td>4449.8±1.7±2.5</td>
<td>39±5±19</td>
<td>4.1±0.5±1.1</td>
<td>12 $\sigma$</td>
</tr>
</tbody>
</table>
...and another real highlight of the conference
A big thank you to the organizers for making this a great conference!