Highlights from CMS and LHCb

Shahram Rahatlou

On behalf of the CMS and LHCb collaborations
LHC AFTER HIGGS DISCOVERY

• Intense scrutiny of Higgs and Yukawa sector

\[ \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} D\psi + \left| D_\mu \phi \right|^2 - V(H) + Y_{ij} \psi_i \psi_j \phi + h.c. \]

• While keeping a wide open eye on new phenomena

New light and heavy particles
Lepton flavour universality violation
Leptoquarks
SUSY
Long-lived particles
Dark matter

Precision Electroweak and QCD
Higgs properties
Higgs self interaction
Higgs coupling to bosons and fermions
CKM matrix and CP Violation

Shahram Rahatlou, Roma Sapienza & INFN
CMS and LHCb have produced more than 100 results in a year

- A lot more known about Higgs than just 2 years ago
- Extensive and precise probe of CKM paradigm
- Rich and diverse results at low energy in charm and beauty physics
- Extensive search program at high mass for new phenomena
- Differential measurements with top quark, Higgs, W and Z bosons
- Probe of QCD in proton-proton and heavy ion collisions

A taste of CMS and LHCb programs and prospects for data to be collected starting in 2021 (Run3)

Special thanks to operations and accelerator teams of the LHC for sustained stellar performance

See tomorrow’s talks covering these results

New Results: http://cms.cern/news/ICHEP-2018
**LHC PERFORMANCE**

- LHC to provide $150 \text{ fb}^{-1}$ to CMS and more than $5 \text{ fb}^{-1}$ to LHCb in Run2
  
  More data and challenges for operation and physics analysis
  - increased number of simultaneous interactions

- Improved analysis techniques and operations key for successful program
• Excellent tracking and superb particle identification key for flavor physics
  – Relative production ratio: \( B_d/B_u/B_s/B_c/b\)-baryons 4:4:1:0.01:1
**CMS Evolution**

**Pixel Tracker**
- 2018: replaced DCDC converters and 6 modules
- 2017: new detector with 4 layers
- Run1: 3 layers

**Si strip Tracker**
- 2018: lower operating temperature

**Electromagnetic Calorimeter**
- 2018: New DAQ links

**Hadron Endcap Calorimeter**
- 2018: Upgraded HPDs → SiPMs in Endcaps
- 2017: Upgraded HPDs → SiPMs in one 20º readout

**Hadron Forward Calorimeter**
- 2017: Upgraded readout

**Muon Detectors**
- Drift tubes (VME → µTCA ROS)
- Resistive Plate chambers;
- Cathode strip chambers;
- GEM slice test (GE1/1)

**3 slightly different detectors in 3 years**

**One more challenge for multi-year analysis**
Reconstructed dielectron invariant mass in 2016-17 data. Selection described in the following slide.

Zee invariant mass comparing 2018 with 2016/17 data.

<table>
<thead>
<tr>
<th></th>
<th>2016 Data</th>
<th>2017 Data</th>
<th>2018 Prompt Data</th>
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<tbody>
<tr>
<td>2016/2017 Data normalized to 2018 number of events</td>
<td>CMS Preliminary</td>
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</table>

Events with two tight electrons with $p_T > 35$ (25) and $|\eta| < 2.5$

$M(\mu^+\mu^-) = 9.44955 \pm 0.00010$ GeV (statistical error only)

CMS Collaboration

Plots with 2018 data - 13 TeV

$\sigma = 82$ MeV

$p_T(\mu^+\mu^-) > 12$ GeV

$|y(\mu^+\mu^-)| < 1.4$
pp → t¯tH

Y_{ij}ψ_iψ_jφ

CMS Preliminary 35.9 fb⁻¹ (13 TeV)

HIGGS
FROM DISCOVERY TO PRECISION

pp → t¯tH

→ ττ → e⁻+ν_e+ν_τ+τ_τ⁺+ν_τ

→ bW⁻ → b+μ⁻+ν_μ

→ bW⁺ → b+q+q

μ⁻

jet

b-jet

e⁻

τ⁺}

Higgs boson's couplings

pp → ttH

μ⁻

jet

b-jet

e⁻

τ⁺
• Observation of direct coupling of Higgs to top by CMS in April
  – Observation of $H \rightarrow \tau\tau$ by CMS in 2017 Phys. Lett. B 779 (2017) 283

• Establishes direct tree-level coupling to up-type quarks
  – Additional data to be used for coupling to $b$ quarks

\[
\sigma_{t\bar{t}H}/\sigma_{SM} = 1.26^{+0.31}_{-0.26} = 1.26^{+0.16}_{-0.16} \text{(stat.)} \pm 0.17 \text{(exp.)} + 0.14 \text{(bkg th.)} + 0.15 \text{(sig th.)}
\]
Total of 250 even categories

\[ BF(H \to \text{inv.}) < 22\% @ 95\% \text{ C.L.} \]

- Nearing theory-limited territory with just 2016 data
$Y_{ij} \psi_i \psi_j \phi$

CP VIOLATION

$72.2^{+5.3}_{-5.8}$
**MOST PRECISE γ**

- Dalitz analysis of decays $B^- \rightarrow DK^-$
  - both kaons and pions
  - Intervals of $D^0$-$\bar{D}^0$ strong phase to maximise sensitivity
    - strong phase measured by CLEO-c

$$\gamma = (80^{+10}_{-9})^\circ$$

- Run2 data critical for this measurement
**MEASUREMENT OF $\gamma$ AT LHCb**

- Combination of 16 measurements from LHCb
  - 4 updated and 3 new measurements
  - 98 observables with 40 free parameters

- Some tension between different decay modes

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**Figure 4:** Profile likelihood contours of $\gamma$ vs $\delta$ for the GLW/ADS analysis of $B^+ \to D^{*+} K^+$, alongside the Run 1 (brown) and Run 2 (pink) GGSZ analyses of $B^+ \to D^{*+} K_0^{*+}$.

**Figure 5:** $1-\Delta L$ plots, using the profile likelihood method, for combinations split by the initial $B$ meson flavour: (orange) $B^0_s$ initial states, (yellow) $B^0$ initial states, (blue) $B^+$ initial states, and (green) the full combination.

<table>
<thead>
<tr>
<th>Coverage</th>
<th>$\gamma$ (degree)</th>
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<tbody>
<tr>
<td>68.3%</td>
<td>$(74.0^{+5.0}_{-5.8})$</td>
</tr>
<tr>
<td>95.5%</td>
<td>$(73.5^{+4.2}_{-5.1})$</td>
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</tbody>
</table>

**Table 4:** Coverage of the best fit point.
Lepton Flavor Universality

Indirect New Physics

Motivation

B-physics anomalies,

LQ phenomenology

Leptoquarks possible solution

Muon AMM

Mass could be $O(1)$

decay to lepton + quark via unknown coupling

Standard Model

New Physics

Lepton Flavor Universality

Indirect New Physics
ANOMALIES AT TREE LEVEL

- Extending study of tree-level anomalies to B_c sector with J/psi

\[ R(D^*) = \frac{\text{BF}(B \rightarrow D^* \tau \nu)}{\text{BF}(B \rightarrow D^* \mu \nu)} \]

SM prediction: 0.25-0.28

\[ \mathcal{R}(J/\psi) = \frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)} = 0.71 \pm 0.17 \text{(stat)} \pm 0.18 \text{(syst)} \]

\[ B_c^+ \rightarrow J/\psi \text{ form factors} \]

PRD 97 (2018) 072013, PRL 120 (2018) 121801, Run 1, 3 fb^{-1}
ANOMALIES IN PENGUINS

Discrepancies in $b \to s l^+l^-$ transitions at BaBar, Belle, and LHCb
  - Differential branching fractions

Analysis with Run2 data underway at LHCb
  - challenging precision analysis over multi-year data sample
  - Also adding new final states, e.g. $B_s \to \phi l^+l^-$

Plan to perform measurement at CMS with improved low-momentum electron reconstruction

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ANOMALIES IN ANGULAR DISTRIBUTIONS

\[ B^0 \rightarrow K^* (K^+ \pi^-) \mu^+ \mu^- \]

• Some discrepancy observed also in angular distributions
  – Not as compelling as in rates
  – Very large uncertainties
  – Requires full Run2 statistics

• Dedicated triggers in CMS in 2017 to increase statistics for analysis at end of Run2
Tree-level explanation of B anomalies with preferred coupling to 2nd and 3rd generations

- Pair- and single-production of leptoquarks
- Also with DM candidate emission
**Light Z’ Boson**

- Search for new gauge boson below the Z mass
  - New ideas taking advantage of 2017 data

**EXO-18-008**

![Graph showing distribution of reconstructed four-muon invariant mass and a comparison to predicted q\(q/gg\) background. Different Z\(Z'\) signal hypotheses are also shown.](image)

**CMS Preliminary**

- 77.3 fb\(^{-1}\) (13 TeV)
- Data
- \(Z\gamma^*\rightarrow4\mu\)
- \(m(Z') = 5\text{ GeV, } g_\mu = 0.008\)
- \(m(Z') = 15\text{ GeV, } g_\mu = 0.01\)
- \(m(Z') = 30\text{ GeV, } g_\mu = 0.01\)
- Background syst. uncer.

**EXO-18-008**

![Graph showing distributions of reconstructed \(m(Z_1)\) and \(m(Z_2)\) observables and a comparison to predicted q\(q/gg\) background. Different Z\(Z'\) signal hypotheses are also shown.](image)

**CMS Preliminary**

- 77.3 fb\(^{-1}\) (13 TeV)
- Neutrino Trident mixing
- \(s = 7\text{ and } 8\text{ TeV}\)
- \(\mu^4\rightarrow\mu\mu Z'\rightarrow\text{CMS: } Z\text{ (exp.)}\)
- \(\mu^4\rightarrow\mu\mu Z'\rightarrow\text{CMS: } Z\text{ (exp.)}\)
- Altmannshofer, et. al.
- JHEP12(2016) 106
- \(b\rightarrow\mu^+\mu^-\) anomaly explanation allowed

**EXO-18-008**

![Graph showing distribution of coupling g\(\mu\) vs. \(m(Z')\) with different hypotheses.](image)

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- JHEP12(2016) 106
- \(b\rightarrow\mu^+\mu^-\) anomaly explanation allowed
The impact on the bin contents are fluctuated within their uncertainties. The standard deviation of these backgrounds (with data) comes from random combinations of decay $[\Omega^0_c]$.

In summary, we use the method for background subtraction uses the decay-time spectra in both $\Omega^0_c \rightarrow pK^-K^+\pi^+$ and $\Omega^0_c \rightarrow \pi^+\pi^-\pi^0\pi^0$ decay. The results of the fits described below. The decrease in the signal yield as the decay time.

The decay-time signal model, a sideband subtraction of the decay-time spectra are obtained using the $\mu\nu\mu X$.

$\tau_{\Omega^0_c} = 0.258 \pm 0.023 \pm 0.010$

$\tau_{\Omega^0_c} = 268 \pm 24 \pm 10 \pm 2 \text{ fs}$

Measurement 4 times larger than PDG average

- 69 ±12 fs
- dominated by FOCUS experiment

Measurement of $\Omega^0_c$ lifetime with respect to well measured $D^+$ lifetime

- copious reference sample $B \rightarrow D^+(\rightarrow K^-\pi^+\pi^+)\mu\nu\mu X$
- measurement with $\Omega^0_b \rightarrow \Omega^0_c(\rightarrow pK^-K^-\pi^+)\mu\nu\mu X$
- Critical role of particle identification
• Kinetic mixing of Dark Photon and a virtual photon
• Clean experimental signature
  – Prompt bump or displaced di-muon pair
• Great potential with data collected in 2017
  – dedicated low-mass triggers for increased sample
  – Addition of di-electron final state
SEARCHES

• Biggest jump in mass limits with increased energy at start of Run2
  – Assuming maximal coupling to SM particles
  – Most searches published with 36 fb⁻¹ of data

• With full Run2 data focus on exploring weakly coupled phenomena
  – Expect new publications with 150 fb⁻¹
SUPERSYMMETRY

- Higgs now used to probe electroweak production of supersymmetry
  - In just 6 years from discovery to Higgs tagging

\[ pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^+, \ pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^0, \ pp \rightarrow \tilde{\tau} \tilde{\tau} \]

July 2018

CMS Preliminary

35.9 fb\(^{-1}\) (13 TeV)

- Expected
- Observed

\[ m_{\tilde{\chi}_0^0} = m_{\tilde{\chi}_1^0} [\text{GeV}] \]

\[ m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^0} [\text{GeV}] \]
Inclusive W and Z

WW, WZ, ZZ

top pair
tt+X

Higgs self interaction

Vector boson scattering

Triple and Quartic Gauge Coupling

SUSY

SUSY Higgs self interaction

Triple and Quartic Gauge Coupling

Vector boson scattering

All results at: http://cern.ch/go/pNj7

STANDARD MODEL

NEW PHYSICS THROUGH PRECISION
• Quartic gauge couplings known exactly in SM and sensitive to new physics contributions
  – Disentangle QCD and EW contribution through jet kinematics

• Observed significance: 1.9σ
  – expected 2.7σ

\[ \frac{\sigma}{\sigma_{SM}} = 0.64^{+0.45}_{-0.37} \]

• Important milestone for Run2 and longterm LHC program towards study of WW scattering
  – Evidence for same-sign WW already published in 2017

**Phys. Rev. Lett. 120, 081801**

\[ \sigma_{EWZ}^{EWK} = 1.5 \text{ fb} \]
Towards High Luminosity with Upgraded Detectors

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<tr>
<th></th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
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<tr>
<td>HL-LHC</td>
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<td>Run 4</td>
<td>LS4</td>
<td>Run 5</td>
<td>LS4</td>
<td>Run 5</td>
<td>LS4</td>
<td>Run 5</td>
<td>LS4</td>
<td>Run 5</td>
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x5 Run1  
x2 Run2  
x10 Run3
LFUV with $B^0_s \rightarrow K^{*0} \mu^+\mu^-$

- Heavily suppressed $b \rightarrow dll$ transition in Standard Model
  - complementary to $b \rightarrow sll$ transitions in $B^0_d$ decays
- Evidence of $3.4\sigma (38 \pm 12$ events$)$ consistent with prediction

$$B(B^0_s \rightarrow \overline{K}^{*0}\mu^+\mu^-) = [2.9 \pm 1.0 \text{ (stat)} \pm 0.2 \text{ (syst)} \pm 0.3 \text{ (norm)}] \times 10^{-8}$$

- Angular analysis with upgraded LHCb detector
  - Sensitivity with Run3 possibly better than current $B_d$ measurement

[Graph showing the variation of log-likelihood with significance of the same final state but constrained to the wrong dimuon mass and becomes a broad signal-like neural network response bins for each data-taking period has been combined.]

[Graph of $m(K^-\pi^+\mu^+\mu^-)$ vs Candidates / (10.0 MeV/c$^2$) with fitting data points, fit line, and contributions from various processes like $B^0_s \rightarrow \overline{K}^{*0}\mu^+\mu^-$, $B^0 \rightarrow \overline{K}^{*0}\mu^+\mu^-$, $B^0 \rightarrow pK^-\mu^+\mu^-$, and comb. bkg.]
RARE HIGGS DECAYS

- Already tackling $H \rightarrow \mu\mu$ thanks to excellent detector performance
  - Looking forward to updated result with 150 fb$^{-1}$

- First results now also on more challenging decay modes
  - Higgs to $Z\gamma$

- Run3 and HL-LHC needed for first evidence of rare decays
  - Higgs to charm

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Higgs Self-Interaction

- Understanding Higgs sector requires measurement of its self-interaction

Standard Model

New Physics

- Promising for Run3 and HL-LHC
  - currently limited by statistics
  - room for even more sophisticated analysis techniques
OUTLOOK

• CMS getting close to establishing Yukawa interaction for third generation fermions
  – Run 2 data should provide first hint for 2nd generation
  – First results paving the way for Run3 and HL-LHC program

• LHCb entering precision measurement territory for angle $\gamma$
  – Also extending systematic study of CP violation to rare B decays
  – Tremendous advancement also in charm and beauty spectroscopy

• Both experiments investigating intriguing flavor anomalies
  – Adding new final states at low mass
  – Tackling possible sources of anomalies at high mass

• Run2 an opportunity to bridge the gap between Searches and Standard Model physics
  – Precision top and electroweak measurements sensitive to new physics

• Upgraded detectors key for a successful physics program at high luminosity
Extra Material
LHCb UPGRADE FOR RUN 3 IN A SNAPSHOT

All sub-detectors read out at 40 MHz for a **fully software trigger**

**Upgraded detector**

- New silicon upstream tracker (UT)
- New scintillating fibre tracker (SciFi)
- New RICH optics and photodetectors
- New PIXEL vertex detector (VELO)
- New electronics for muon and calorimeter systems
CMS Phase II Upgrade

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193
- Tracks in L1-Trigger at 40 MHz for 750 kHz PFlow-like selection rate
- HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- New GEM/RPC 1.6 < |η| < 2.4
- Extended coverage to |η| ≈ 3

Calorimeter Endcap
https://cds.cern.ch/record/2293646
- Si, Scint+SiPM in Pb-W-SS
- 3D shower topology with precise timing

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to |η| ≈ 3.8

MIP Timing Detector
https://cds.cern.ch/record/2296612
- ≈ 30 ps resolution
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes