CMS Overview

Physics Highlights

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on behalf of the CMS Collaboration

National Centre for Nuclear Research
NCBJ – Warsaw, Poland

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Outline

- **LHC** short intro
- **CMS Detector** status
  - Subdetector upgrades for data-taking in 2017
    - New: Pixel detector, L1 Trigger, HF calorimeter readout
    - 2017 Performance

- **CMS Physics highlights** with full 2016 $36/fb$ $13$ TeV data
  - 79 new results in 2017 realised at:
    - Moriond’17 – 39 publications
    - LHCP’17 – 22
    - EPS-HEP’17 – 20
  - In this talk – only selected *fresh* proton-proton results
    - during this conference – other 22 presentations and 4 posters
Introduction

Large Hadron Collider at CERN
LHC schedule

- LHC past, present, and future

- LHC proton-proton data delivered to CMS till yesterday
  - Run 2: ~60/fb
    - 2016: 41/fb
    - 2017: 17/fb
CMS DETECTOR
- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

STEEL RETURN YOKE
- 12,500 tonnes

SILICON TRACKERS
- Pixel (100x150 μm) ~16 m^2 ~66M channels
- Microstrips (80x180 μm) ~200 m^2 ~9.6M channels

SUPERCONDUCTING SOLENOID
- Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PREShOWER
- Silicon strips ~16 m^2 ~137,000 channels

FORWARD CALORIMETER
- Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
- ~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
- Brass + Plastic scintillator ~7,000 channels

CMS collaboration
- 199 institutes
- 46 countries
- x 3500 scientists, engineers, and students
CMS upgrades in 2016/17

- **New CMS Pixel detector:**
  - 3 layers (barrel) / 2 disks (endcaps) $\rightarrow$ 4 layers / 3 disks
    - Improved readout electronics
    - Innermost barrel layer closer to the interaction point
    - Lower material budget
  - Very good efficiency up to 99% for all pixel detector at $L=1.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$
- Expected improvements in tracking, vertexing and b-tagging

![Barrel Pixel layers and Forward Pixel disks diagram]

- **Hit Efficiency:** 99%
CMS upgrades in 2016/17

- Full upgrade of **L1 trigger** system
to manage with high inst. luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ and high pile-up

- **L1 electron/photon** trigger re-optimization
- better resolution $\rightarrow$ sharper turnON
- 20% rate reduction
- 15% gain in efficiency (keeping almost no PU dependence)

- **L1 muon** trigger
  new track finders
- Improved L1 muon track finding and $p_T$ resolution, and efficiency
- Lowest unprescaled threshold 25 GeV in 2017
First illustration of di-muon spectrum taken with inclusive and dedicated muon trigger paths
CMS data-taking efficiency > 85%

Some time was dedicated for testing the new Pixel detector

Successful restart of the LHC

Reaching inst. luminosity of $1.7 \times 10^{34}$ cm$^{-2}$s$^{-1}$
Data in 2016 → new results

- Excellent performance of the CMS detector
  - Efficiency of data-taking (41/fb) for:
    - 38/fb, recording > 92%
    - 35.9/fb, good for physics > 87%

![CMS Integrated Luminosity, pp, 2016, $\sqrt{s} = 13$ TeV](image1)

Data included from 2016-04-22 22:48 to 2016-10-27 14:12 UTC

![CMS Peak Luminosity Per Day, pp, 2016, $\sqrt{s} = 13$ TeV](image2)

Data included from 2016-04-22 22:48 to 2016-10-27 14:12 UTC

"CMSLumi2016"
Run 1&2 legacy – Nature is SM-like

- Theoretical description of high-$Q^2$ processes is with high agreement with LHC data
Run 2 continues – opened perspective

- **Higgs boson** and **precise SM measurements**
  - new possibilities for deciphering the properties opened up

![Graph showing luminosity ratios for different processes at different LHC energies](WJS2013)

**New Physics**
- no sign, but….
  - Large increase in signal cross sections for heavy particles from 8→13 TeV
  - Strong gluino pair production privileged
CMS Physics Highlights

CMS pp Physics (in this talk):

- **Standard Model**
  - Electroweak Physics
- **Higgs**
- **Top Physics**
- **Searches:**
  - **SUSY**
  - **Exotica**
    - Dark Matter

639 collider data papers submitted as of 2017-08-11
Electroweak precise measurements

- Challenging Standard Model predictions
**EWK Gauge Couplings**

- **Diboson and W/Zjj processes** extensively studied
- **Vector-boson scattering** is the ideal testbench to study of the EWK sector

First **5.5σ observation** of EWK **same-sign WWjj** production

- Evts: two leptons of the same charge, moderate MET, 2 jets with large rapidity separation and large dijet mass
- Bkg: non-prompt leptons and the WZ → 3ℓν

**First measurement of VBS in the ZZjj channel** at the LHC

- Evts: fully leptonic (4ℓ) final state
- **EWK ZZjj** is measured with sign. of **2.7 (1.6) σ**

![Graph1](image1.png)

**Limitations:**

- CMS-SMP-17-004
- CMS-SMP-17-006
Electroweak mixing angle at 8 TeV

- Precise measurement with the forward-backward asymmetry $A_{FB}$ of Drell-Yan (ee and $\mu\mu$) events at 8 TeV
  Improved lepton momentum calibration, angular event weighting, and additional PDF constraints
- $\sin^2\theta$ extraction by fitting $A_{FB}$ inv. mass and rapidity bins
- Most precise measurement of $\sin^2\theta$ at the LHC
- Allows to constrain PDFs

\[
\sin^2 \theta_{\text{eff}} = 0.23101 \pm 0.00036(\text{stat}) \pm 0.00018(\text{syst}) \pm 0.00016(\text{theory}) \pm 0.00030(\text{pdf})
\]
EWK boson measurements

- Good agreement with SM to date
- Precision will be improved with increased luminosity

March 2017

<table>
<thead>
<tr>
<th>CMS measurements vs. NNLO (NLO) theory</th>
<th>CMS Preliminary</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td>7 TeV CMS measurement (stat,stat+sys)</td>
</tr>
<tr>
<td>$W\gamma$ (NLO th.)</td>
<td>8 TeV CMS measurement (stat,stat+sys)</td>
</tr>
<tr>
<td>$Z\gamma$ (NLO th.)</td>
<td>13 TeV CMS measurement (stat,stat+sys)</td>
</tr>
<tr>
<td>$WW+WZ$</td>
<td>1.06 ± 0.01 ± 0.12 5.0 fb$^{-1}$</td>
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<tr>
<td>$WW$</td>
<td>1.16 ± 0.03 ± 0.13 5.0 fb$^{-1}$</td>
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<tr>
<td>$WW$</td>
<td>0.98 ± 0.01 ± 0.05 5.0 fb$^{-1}$</td>
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<tr>
<td>$WW$</td>
<td>0.98 ± 0.01 ± 0.05 19.5 fb$^{-1}$</td>
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<tr>
<td>$WW$</td>
<td>1.01 ± 0.13 ± 0.14 4.9 fb$^{-1}$</td>
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<tr>
<td>$WW$</td>
<td>1.07 ± 0.04 ± 0.09 4.9 fb$^{-1}$</td>
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<tr>
<td>$WW$</td>
<td>1.00 ± 0.02 ± 0.08 19.4 fb$^{-1}$</td>
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<tr>
<td>$WW$</td>
<td>0.96 ± 0.05 ± 0.08 2.3 fb$^{-1}$</td>
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<td>1.05 ± 0.07 ± 0.06 4.9 fb$^{-1}$</td>
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<tr>
<td>$WZ$</td>
<td>1.02 ± 0.04 ± 0.07 19.6 fb$^{-1}$</td>
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<tr>
<td>$WZ$</td>
<td>0.80 ± 0.06 ± 0.07 2.3 fb$^{-1}$</td>
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<tr>
<td>$WZ$</td>
<td>0.97 ± 0.13 ± 0.07 4.9 fb$^{-1}$</td>
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<tr>
<td>$ZZ$</td>
<td>0.97 ± 0.06 ± 0.08 19.6 fb$^{-1}$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>1.10 ± 0.04 ± 0.05 35.9 fb$^{-1}$</td>
</tr>
</tbody>
</table>

All results at: http://cern.ch/go/pNj7
EWK boson measurements

- **Good agreement with SM to date**
- **Precision will be improved with increased luminosity**

### CMS EWK measurements vs. Theory

<table>
<thead>
<tr>
<th>Process</th>
<th>CMS EWK Measurement</th>
<th>7 TeV CMS Measurement (stat,stat+sys)</th>
<th>8 TeV CMS Measurement (stat,stat+sys)</th>
<th>13 TeV CMS Measurement (stat,stat+sys)</th>
</tr>
</thead>
<tbody>
<tr>
<td>qqW</td>
<td>0.84 ± 0.08 ± 0.18</td>
<td>0.93 ± 0.14 ± 0.32</td>
<td>0.84 ± 0.07 ± 0.19</td>
<td>1.02 ± 0.03 ± 0.10</td>
</tr>
<tr>
<td>qqZ</td>
<td></td>
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<tr>
<td>γγ→WW</td>
<td>1.74 ± 0.00 ± 0.74</td>
<td>1.77 ± 0.67 ± 0.56</td>
<td>1.74 ± 0.00 ± 0.74</td>
<td>19.7 fb⁻¹</td>
</tr>
<tr>
<td>qqWγ</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ss WW</td>
<td>0.69 ± 0.38 ± 0.18</td>
<td>0.90 ± 0.16 ± 0.08</td>
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<td>0.90 ± 0.16 ± 0.08</td>
</tr>
<tr>
<td>ss WW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>qqZγ</td>
<td>1.48 ± 0.65 ± 0.48</td>
<td></td>
<td>1.48 ± 0.65 ± 0.48</td>
<td>19.7 fb⁻¹</td>
</tr>
<tr>
<td>qqZZ</td>
<td>1.38 ± 0.64 ± 0.38</td>
<td></td>
<td>1.38 ± 0.64 ± 0.38</td>
<td>35.9 fb⁻¹</td>
</tr>
</tbody>
</table>

All results at: [http://cern.ch/go/pNj7](http://cern.ch/go/pNj7)

Production Cross Section Ratio: \( \sigma_{\text{exp}} / \sigma_{\text{theo}} \)
QCD stress tests

- Jet production at 13 TeV with full 2016
- Measurements of the normalized inclusive 2-jet, 3-jet, and 4-jet xSec. differential in $\Delta \phi_{1,2}$
  - Observations emphasize the need to improve predictions for multijet production
- $\alpha_s(M_Z)$ inferred from a fit of the ratio of the 3-jet over 2-jet event xSec

$$\alpha_s(M_Z) = 0.1150 \pm 0.0010 \text{ (all except scale)} + 0.0050 - 0.0000 \text{ (scale)}$$

4-jet xSec. in $\Delta \phi_{1,2}$ for $8 p_T^{\text{max}}$ regions
Top quark

LHC is a top quark factory

- ~10 top pairs every second @ $10^{34}$ cm$^{-2}$s$^{-1}$ inst. luminosity
- Wide and detailed studies under top quark
- Testing SM and BMS physics

$m_{\text{top}} = 177$ GeV
\[ p_T = 613 \text{ GeV} \]
3 sub-jets

$m_{\text{top}} = 176$ GeV
\[ p_T = 488 \text{ GeV} \]
3 sub-jets
Top quark production

- **New xsec** (69.5 ± 8.4 pb) for tt pair prod. @ 5 TeV (special short run in 2016, L=27.4/pb)
- Evts: 1 muon and at least 4jets, 2b-tag

### Table: \( \sqrt{s} \) vs \( \sigma(tt) \) [pb] vs L [fb⁻¹]

<table>
<thead>
<tr>
<th>( \sqrt{s} ) (TeV)</th>
<th>( \sigma(tt) ) [pb]</th>
<th>L [fb⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>~70</td>
<td>0.03</td>
</tr>
<tr>
<td>7</td>
<td>~170</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>~250</td>
<td>19.7</td>
</tr>
<tr>
<td>13</td>
<td>~800</td>
<td>2.3</td>
</tr>
</tbody>
</table>
Top quark mass

- Great accuracy (~0.3%) in the CMS top mass measurement from Run 1
- First top mass measurement from $\mu +$jets with 13 TeV with only 2.2/fb

$$M_{\text{top}} = 172.62 \pm 0.38 \pm 0.70 \text{ GeV}$$
Rare top processes

- **Top pair prod. with W/Z**
  
  Same same-sign dilepton, 3- and 4-lepton final states where the jet and b-jet multiplicities are exploited to enhance the signal-to-bkg ratio

- **Measured xSec. are in agreement with SM predictions**
  
  $\sigma(ttZ) = 1.00^{+0.09}_{-0.08} \text{(stat.)}^{+0.12}_{-0.10} \text{(sys.)} \text{ pb}$
  
  $\sigma(ttW) = 0.80^{+0.12}_{-0.11} \text{(stat.)}^{+0.13}_{-0.12} \text{(sys.)} \text{ pb}$

- **Four top production**
  
  Single-lepton +jets and the opposite-sign +jets channels
  
  Boosted decision trees to combine information on the global event and jet properties to distinguish between $tt\bar{t}t\bar{t}$ and $tt\bar{t}t$ production

- **Upper limit on xSec.**
  
  Combined with same-sign dilepton search
  
  $\sigma(tttt) < 69 \text{ fb} @ 95\% \text{ C.L.} (7.4\times\text{SM})$

![Diagram showing CMS Preliminary results for $\sigma(ttZ)$ and $\sigma(ttW)$](image1)

![Diagrams showing CMS Preliminary results for $\sigma(tttt)$](image2)
5th anniversary of the Higgs boson

4th July 2012
Higgs boson production

- New measurement at 13 TeV in $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$
- Discovery channels despite small BF of $\sim 0.013\% (4\ell)$, $\sim 0.23\% (\gamma\gamma)$
- Consistent with SM

$H \rightarrow ZZ^* \rightarrow 4\ell$

$H \rightarrow \gamma\gamma$

CMS Preliminary

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

$H \rightarrow \gamma\gamma$

$\hat{m}_H = 125.4$ GeV, $\hat{\mu} = 1.16$

Data

S+B fit

B component

\[\pm 1 \sigma\]

\[\pm 2 \sigma\]

CMS-HIG-16-040

CMS-HIG-16-041

M. Kazana

CMS Overview ICNFN2017 Crete 21.08.2017
Higgs mass and xSec

- Mass measurement in golden channel: $H \rightarrow ZZ^* \rightarrow 4\ell$
  via ggH, VH, VBF
  $m_H = 125.26 \pm 0.20 \text{(stat.)} \pm 0.08 \text{(sys.) GeV}$

- As good as the world average of the ATLAS+CMS combination from Run 1
  $m_H = 125.09 \pm 0.21 \text{ (stat.)} \pm 0.11 \text{ (syst.) GeV}$
Higgs couples to $\tau$ lepton

- **First observation** of $H\rightarrow\tau\tau$ at CMS with the full 2016 dataset using excellent CMS tau tagging

- Tau semi-hadronic & leptonic decay channels
  - 4 final states ($\tau\tau$, $\mu\tau$, $e\tau$, $e\mu$)
  - 3 categories (0-jet, VBF, Boosted)

- CMS observed $H\rightarrow\tau\tau$ at $4.9\,\sigma$ wrt $4.7\,\sigma$ expected
- Run 1 + Run 2’16 result: $5.9\,\sigma$
Higgs Physics: $H \to bb$

- Dominant H decay channel (58.1%), but with huge QCD $bb$ background
- Presence of the vector boson (leptons, MET) supresses highly QCD

- **Sig:** 2b-tag jets + 2 lep (+1 leptMET), (+MET) extracted via a simultaneous fit of all control regions and signal regions
- **Bkg:** fitted in simultaneous fit for V+jets and ttbar

- Analysis validated for $Z \to bb$
  - 5.0 σ observation

- For $m_H = 125$ GeV,
  Run 1&2 excess of events observed
  with local sig. of
  3.8 σ (3.8 σ SM exp.)

- Signal strength
  \[ \mu = \frac{\sigma}{\sigma_{SM}} = 1.06^{+0.31}_{-0.29} \]
Higgs – top production

- Direct test of **H-t coupling** using ttH and tHq channels
- H decaying to WW*, ZZ* or ττ
  - 2 same-sign leptons or at least 3 leptons, and b-tag jets

**Evidence for ttH signal**

3.3σ obs. (2.5σ exp.) comb. 2015 & 2016

**Upper limit on** $\sigma^{tH+ttH} \times \text{BR}$

0.64 pb obs. (0.32 exp.)

Single top in the t-channel – unique opportunity to study the relative sign of the coupling
LHC is a unique place to search for new particles

- **directly** and
- **indirectly**
  - precise SM measurements
**Strong SUSY**

- Gluino or squark \((gg, qq, gq)\) production
- **Sig.:** Jets+MET
  
  \[ +N_{\text{jet}} + N_{\text{b-tag jet}} \]
- Experimental search based on **signatures**
- and kinematical variable sensitive to SUSY
- Multiple signal regions and searches in bins of different variables
- **No SUSY particles detected**

**Run 2'16 at 13 TeV:** Limits on gluino mass up to \(~2\) TeV
Electroweak SUSY

- Electroweak SUSY production and decays of **chargino** and **neutralino**
- Statistical combination of several searches
  - Improvement of 40 GeV on the limit mass
- Optimized analysis with 2- and 3-leptons

\[ pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \]

**CMS Preliminary**

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

- SUS-16-039, 2l SS + \(\geq 3l\) (WH)
- SUS-16-043, 1l (WH)
- SUS-16-045, \(H \rightarrow \gamma\gamma\) (WH)
- SUS-16-034, 2l OS (WZ)
- This result, 3l (WZ)
- SUS-16-048, soft 2-lep (WZ)
SUSY R-parity violation

- R-parity can be not conserved!
- Minimal flavour violation, $\lambda_{tbs}, g \rightarrow t \bar{t} \rightarrow t b s$
- **Signature:** single lepton, large jet multiplicity, and large q-quark jet multiplicity, NO requirement on MET
- Signal extraction through shape fit to $N_b$ in bins of $N_{\text{jet}}$ and $M_J$

Gluino mass > 1610 GeV (95% C.L.)
Gauge Mediated SUSY

- **Search for BSM with at least 1 photon, large MET, and large $H_T$**
- **Sig:** strongly produced GMSB with $N1 \rightarrow \gamma G$
- **New limits** depending $m_{\text{neutralino}}$ & BR:
  - $m_{\text{gluino}}$ up to 1.5-2.0 TeV
  - $m_{\text{squark}}$ up to 1.3-1.65 TeV

- **Complementary searches:**
  - $\gamma V$, $\gamma\gamma$, $\gamma+$lepton, multi-lepton
  - Provide weaker limits

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Long-lived particles

**LLPs** are foreseen by many BSM models

- Small coupling, small mass splitting, hidden sector

- **Signature depends on lifetime**
LLP: stopped particles

- LLP (gluino or $|Q|=2e$) is **stopped inside the detector** and decay to muons from rest after unknown time (sensitivity to lifetimes between $0.1 \mu s$ and $10^6$ s)
- Events recorded **out-of-time with collisions** with the custom trigger

**No events** observed

- 13 orders of magnitude of the lifetime tested
- Excluded gluinos with mass between 400 and 970 GeV, assuming 100% BF to muons
Heavy resonance searches

- Many BSM models predict narrow **di-X resonances**
- **X** – many object in the final state analysed
- **Di-jets** (from Axigluons, colorons, W'/Z' bosons, color octet scalars, string resonances, RS, etc)

![Graph showing di-jet resonance analysis up to 7.7 TeV](image)
Dark Matter

Indirect searches → direct searches

**Vector** and **scalar** interactions → **spin-independent (SI)** DM-nucleon interactions

**Axial-vector** interactions → **spin-dependent (SD)** DM-nucleon interactions
Dijet searches

- Used for the DM interpretation
- New 36/fb upper limit on mass of mediator 2.6 TeV extends previously reported limits in the dijet channel (2.0 TeV @13/fb)

Used for the DM interpretation

New 36/fb upper limit on mass of mediator 2.6 TeV extends previously reported limits in the dijet channel (2.0 TeV @13/fb)
Mono-object searches for DM

- Searching for **excess on MET** with mono-jet or mono-V

Bkg. evaluated with combined fit to the data in control samples
No significant excess of events is observed with respect to the SM backgrounds
Mono-object search results

- Limits* for simplified models in which DM production is mediated by spin-1 (vector or vec-axial) or spin-0 (scalar, pseudo-scalar) particles

* strongly depend on the chosen couplings and model scenario

Boson as a mediator
Obs. (exp.) 95% C.L. upper limit of 0.53 (0.40) on the invisible BR of SM-like 125 GeV Higgs
Dark Matter searches

- Dijet angular correlation search probes interactions between quarks and DM particles
- Also constrains models of
  - quark contact inter. \((\text{scale}^\text{limit}_{\text{CI}} = 13.1 - 17.4 \text{ TeV})\)
  - ExDim \((\text{mass}^\text{limit}_{\text{graviton}} = 10.6 \text{ TeV})\)
  - quantum black holes \((\text{mass}^\text{limit}_{\text{BH}} = 6.3 - 8.0 \text{ TeV})\)

\[\begin{align*}
\text{Vector} & \\
g_q = 1, g_{\text{DM}} = 1
\end{align*}\]

DM mediator excluded \(2.5 - 5 \text{ TeV}\)
CMS Highlights summary

- **Excellent performance** of LHC and the CMS detector resulting in **publications with the 13 TeV data of Run 2’16**

- **Precise measurement of Higgs and Standard Model** starting with the increase of luminosity
  - **Higgs is very SM-like**
    - the observation of decays to taus and an evidence for decays to b-quarks
  - **New Physics can be discovered** if it exists at the TeV scale
    - ~3 times more data (150/fb) till end of 2018 than now (>50/fb)
    - and ~3 orders of magnitude (3000/fb) more for HL-LHC

**References:**

- **Next CMS presentations during the conference**
  Details and much more about the CMS physics, its performance, and the future

- All CMS public results: [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults)
Thank you!

Supported in part by the NCN grant: 2014/039982014/15/B/ST2/03998
BACKUP
Higgs

19.7 fb\(^{-1}\) (8 TeV) + 5.1 fb\(^{-1}\) (7 TeV)

CMS

\(\lambda_f \) or \((g_f/2\lambda_f)^{1/2}\)

- 68% CL
- 95% CL
- SM Higgs

\((M, \epsilon)\) fit
- 68% CL
- 95% CL

Particle mass (GeV)
High Pt event in 2017

2017 highest di-muon mass candidate with mass = 2.4 TeV