Highlights from the CMS experiment

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for the CMS collaboration

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Physics goals & methods

Completing our picture
Physics goals & methods

How?

- New ideas for trigger, data processing, and analysis:

  continue improving analyses in terms of precision and sensitivity independently of increases in luminosity and collision energy
Physics goals & methods

“Scouting”

- Avoid bandwidth limitations in order to access lower $p_T$ and mass regions where trigger rates are (too) high
  - reduction of event size to $O(10\text{kB})$ allows trigger rates of several kHz
- Reconstruct at the High Level Trigger (HLT) stage, drop RAW data and analyse using the HLT objects
  - needs adequate calibration at the HLT level and validation against full reconstruction
- Example: search for low-mass n-jet resonances
Physics goals & methods

“Parking”

- Avoid CPU limitations in prompt reconstruction
- Store additional datasets and delay processing to times of lower load on the computing system
  - needs careful planning taking into account data taking schedule and MC production

- Example: B-physics

Use lower trigger rates at end of fill to store events at a rate of up to 6kHz
- displaced muon trigger $\rightarrow$ sample of unbiased B decays
- 12B events recorded
Physics goals & methods

Machine learning

- Use full power of multiple variables and reduce need for manual tuning
- Wide range of state-of-the-art algorithms used for solving combinatoric problems, regression, and classification
  - needs adequate control regions for performance measurements and (typically) large MC samples

![Diagram of neural network architecture](image)
CMS data in Run 2

Excellent data quality

- Reminder: Run 2 data taken with an evolving detector configuration, in particular
  - upgrade of the pixel detector to 4 layers
  - upgrade of the HCAL readout (long. segmentation)

- 2018: largest dataset collected so far
  - uses nearly complete CMS Phase-1 configuration
  - pileup conditions similar to 2017
Properties of the Higgs boson
Higgs boson properties

Continuous work toward a global picture

• LHC Run 1 led to discovery using decays to bosons
• LHC Run 2 directly established couplings to 3rd generation fermions
• LHC Run 3 will extend sensitivity to physics beyond the SM
• HL-LHC will allow to probe the Higgs self-coupling

Production and decay modes covered by recent CMS results

<table>
<thead>
<tr>
<th>H → ZZ</th>
<th>ggH</th>
<th>VBF</th>
<th>VH</th>
<th>ttH</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → ττ</td>
<td>HIG-16-044, ‘16</td>
<td>HIG-16-016, 16+17</td>
<td>HIG-18-030, ‘16+’17</td>
<td></td>
</tr>
<tr>
<td>H → bb</td>
<td>HIG-17-019, ‘16</td>
<td>HIG-18-031, ‘16</td>
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<tr>
<td>H → μμ</td>
<td>HIG-17-023, ’16</td>
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<tr>
<td>H → cc</td>
<td></td>
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<tr>
<td>H → inv</td>
<td></td>
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</tr>
</tbody>
</table>
An illustration of progress in the past years: $H \rightarrow ZZ$

**PLB 716 (2012) 30**
Run 1

**JHEP 11 (2017) 47**
Run 1

**CMS**

Run 1

**CMS**

Run 2

**JHEP 04 (2016) 5**
Run 1

**HIG-19-001**
Decays to 3rd generation fermions

$ttH (H \rightarrow bb)$

- Covers 0, 1, and 2l decay modes
- Improvements in particular for MVA techniques and b-jet identification

Achieved evidence for decays to $bb$ based on $ttH$ only:
obs (exp) significance = 3.9 (3.5) s.d.

$\mu_{comb} = 1.15^{+0.32}_{-0.29}$

HIG-18-030 NEW!

Comparison with HL-LHC projections
- already improved w.r.t. basis for projection
- large further potential for full HL-LHC luminosity

For reference:
Observation of $H \rightarrow bb$ by both ATLAS and CMS in 2018

FTR-18-011
Decays to 3rd generation fermions

\[ H \rightarrow \tau \tau \]

- Covers the e\(\mu\), eth, \(\mu \tau h\), and \(\tau \tau h\) channels
- New: use of NN classification to distinguish background and different signal categories

\[ \mu_{\text{incl}} = 0.75^{+0.18}_{-0.17} \]

Includes detailed results on kinematic properties
(simplified template cross section stage 1 prescription)
Moving to the 2nd generation

First CMS result on VH, H→cc

- highly challenging due to low cross section and need for c-tagging
  - categorisation according to lepton multiplicity of V decays
  - addressing resolved (2 c jets) and merged (1 cc jet) cases
  - use of ML and jet substructure for tagging and classification

BDT output for one category
(resolved jets, p_T(V)>150GeV)

Jet mass for the high-purity category
(merged jets)
Moving to the 2nd generation

First CMS result on VH, H→cc

• final results from combination of resolved & merged jet analyses

Combined results on signal strength:
• Obs (exp) exclusion: 70 (37)
• $\mu(VH, H \rightarrow c\bar{c}) = 36^{+20}_{-19}$

Validation using VZ production:
• $\mu(VZ, Z \rightarrow c\bar{c}) = 0.55^{+0.86}_{-0.84}$

For reference: current CMS results on H→$\mu\mu$
signal strength (data from 2016)
• obs (exp) exclusion: 2.92 (2.16)
• obs (exp) significance: 0.9 (1.0) s.d.

PRL 122 (2019) 021801
Rare SM processes
VBS: EWK $Z\gamma$ production with two jets

Vector boson scattering directly probes EWK SM gauge structure

- Selection reduces contribution from strong production
- Signal extracted from 2D fit to properties of the djet system: $m_{jj}$ and $\Delta\eta_{jj}$

Obs (exp) significance
- this analysis: 3.9 (5.2) s.d.
- combination with 8TeV: 4.7 (5.5) s.d.

Signal strength (fid. region): $0.64^{+0.23}_{-0.21}$

Limits on anomalous QGC parameters:
- the analysis sets the most stringent limits to date on two of these parameters ($F_{T,8}/\Lambda^4$ and $F_{T,9}/\Lambda^4$)
Other VBS measurements

Anomalous EWK VV production with two jets
- Using the WW, WZ, and ZZ channels
- Interpretation in EFT or as limits on $H^\pm$ production

For reference:
Observation of EWK production of $W^\pm W^\pm$

PRL 120 (2018) 081801

Estimate ultimate precision of ~3% at HL-LHC:

FTR-18-005

Ultimate goal: investigation of $Z_L$ scattering → HL-LHC

<table>
<thead>
<tr>
<th>$\eta$ coverage</th>
<th>significance</th>
<th>VBS $Z_L Z_L$ fraction uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 2.5(2.4)$</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 3.0(2.8)$</td>
</tr>
<tr>
<td>$</td>
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</table>
Double parton scattering

Evidence for the DPS process in same-sign WW events

• Absence of extra jets @ LO can be used as a handle to distinguish DPS and single hard scattering
• Two multivariate classifiers discriminate signal from WZ backgrounds and events with mis-identified leptons

\[ \sigma_{DPS} = \frac{n}{2} \frac{\sigma_A \sigma_B}{\sigma_{eff}} \]

First evidence for DPS WW production
• Significance = 3.9 s.d.
SM precision measurements
Precision measurements: Z+jets

Differential cross section measurement

• Measured as function of $p_T(Z)$, $\eta(Z)$, and $\Phi^*$
• Incl. cross section agrees with NNLO predictions
• Uncertainty on absolute cross section dominated by luminosity component for low $p_T(Z)$

Achieves 0.5% uncertainty on normalised cross sections for $\Phi^*$<0.5 and $p_T(Z)$<50GeV
Measurement of $m(\text{jet})$ in top quark decays

Jet mass in decays of boosted top quarks

- Alternative approach to measuring $m(t)$: jet mass of highly boosted top quarks ($p_T>400\text{GeV}$)
- Reconstruction of large ($R=1.2$) jets, and 3 subjets / jet using the XCone algorithm
  - one leptonic top decay is required, and jet with max. distance to lepton is chosen

Extracted value for $m(t) = 172.56 \pm 2.47 \text{ GeV}$

Uncertainty similar to the ones from threshold production!
Long-lived particles
Delayed jets

Jet timing using ECAL

• Long-lived gluinos give rise to jets from displaced vertex
  - Delay due to differences in velocity and in path length
• uses median time of all ECAL cells in the jet cone

median time of ECAL cells in cone - background jets

main backgrounds from cosmics & satellite bunches

significant extension of sensitivity w.r.t. tracker-based searches

arXiv:1906.06441
Delayed photons

Photon timing using ECAL

- Long-lived neutralinos decay to a photon and a graviton
- requires precise calibration of ECAL timing and resolution

Spectra for prompt and delayed selections, and signal

Substantial improvement w.r.t. early Run 1 search

W. Adam: Highlights from the CMS experiment
(High-mass) direct searches
Classical high-mass resonance search

- can be interpreted in a wide range of BSM models predicting particles decaying to gg, gq, or qq
- keep to improve analysis with new techniques:
  - replace parameteric background shape by measurement in data sideband region
  - consistent predictions, higher sensitivity for masses > 3TeV

Resonant decays to two jets

EXO-19-012

NEW!
Resonant decays to jets (boosted)

But no strong indications at high masses

- investigate low mass range in more detail:
  - here: looking for light vector resonances coupling to quark pairs
- need to overcome trigger restrictions; two approaches:
  - “scouting” for masses between 450 and 1000 GeV
  - here: use a hard ISR jet → boosted di-jet systems
- use of large-radius jets and jet substructure leads to an extension of sensitivity up to 450 GeV
Recent searches for strongly produced SUSY particles in R-parity conserving scenarios

- Generic search for pair production of gluinos and squarks, stable (undetected) lightest SUSY particle - striking multijet + MET signature
- Targeted search for top squark production - single-lepton channel

Sensitivity in terms of mass limits in simplified model interpretations increased by ~150 GeV for gluinos and ~200 GeV for top squarks.

Optimization for long-lived scenarios (disappearing tracks) leads to largely enhanced mass reach.

W. Adam: Highlights from the CMS experiment
And many more ...
Observation of two excited $B_s^+$ states and measurement of the $B_s^+$ (2S) mass in pp collisions at $\sqrt{s} = 13$ TeV

Measurement of the $t\bar{t}b\bar{b}$ production cross section in the all-jet final state in pp collisions at $\sqrt{s} = 13$ TeV

Production of $\Lambda_c^+$ baryons in proton-proton and lead-lead collisions at $\sqrt{s}_{NN} = 5.02$ TeV

Observation of single top quark production in association with a $Z$ boson in proton-proton collisions at $\sqrt{s} = 13$ TeV

Measurement of the associated production of a $W$ boson and a charm quark at $\sqrt{s} = 8$ TeV

Search for charged Higgs bosons decaying into a top quark and a bottom quark in the fully hadronic final state at 13 TeV

Search for anomalous couplings in semileptonic WW and WZ decays at $\sqrt{s} = 13$ TeV

Measurement of total and differential cross sections of central exclusive $\pi^+\pi^-$ production in proton-proton collisions at 5.02 and 13 TeV

Search for the resonant production of a pair of Higgs bosons decaying to the $b\bar{b}ZZ$ final state
First LHC paper using the full Run 2 dataset!

CMS has published almost 900 papers based on LHC collision data!

Measurement of the dependence of inclusive jet production cross sections on the anti-$\Lambda$ distance parameter in proton-proton collisions at $\sqrt{s} = 13$ TeV.

Production of $A^+$ baryons in proton-proton and lead-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

CMS has published almost 900 papers based on LHC collision data!

First observation of $t\bar{t}Zq$ production in association with a $Z$ boson in proton-proton collisions at $\sqrt{s} = 13$ TeV.

First measurement of the $t\bar{t}bb$ production cross section in the hadronic channel at $\sqrt{s} = 13$ TeV.

Observation of two exclusive final states at $\sqrt{s} = 13$ TeV.

CMS has published almost 900 papers based on LHC collision data!
### Overview of CMS long-lived particle searches

<table>
<thead>
<tr>
<th>Process</th>
<th>Energy (TeV)</th>
<th>Luminosity (fb⁻¹)</th>
<th>Cross Section (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dilepton</td>
<td>13</td>
<td>35.9</td>
<td>0.54 ± 0.35</td>
</tr>
<tr>
<td>Lepton+jets</td>
<td>13</td>
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<tr>
<td>CMS Run 1 legacy</td>
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<td>0.61 ± 0.07</td>
</tr>
<tr>
<td>Dilepton</td>
<td>8</td>
<td>18.2</td>
<td>0.32 ± 0.02</td>
</tr>
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### CMS Preliminary

**Overview of CMS B2G results**

- **Tevatron**: 4.0 TeV (L = 8.8 fb⁻¹)
- **LHC Run 1**: 13 TeV (L = 5 fb⁻¹)
- **LHC Run 2**: 13 TeV (L = 27.4 fb⁻¹)
- **CMS Preliminary May 2019**

- CMS in CATS, Dilepton (L = 5 fb⁻¹)
- CMS in CATS, Lepton+jets (L = 5 fb⁻¹)
- CMS in CATS, All-jets (L = 5 fb⁻¹)
- CMS Run 1 legacy in CATS, All-jets (L = 5 fb⁻¹)

**All results at https://atlas.cern.ch**

**Selection of observed exclusion limits at 95% CL (other uncertainties are not included)**

- **Tevatron**: 4.0 TeV (L = 8.8 fb⁻¹)
- **LHC Run 1**: 13 TeV (L = 5 fb⁻¹)
- **LHC Run 2**: 13 TeV (L = 27.4 fb⁻¹)

**CMS Preliminary**

**Tevatron combination**

- ATLAS, CDF, CMS, D0

**World combination**

- ATLAS, CDF, CMS, D0

**CMS Preliminary**

**Dilepton**

- jHEP 07 (2011) 049, 38 ps⁻¹
- EPJC 72 (2013) 2032, 5.0 fb⁻¹
- PRD 93 (2016) 072004, 19.7 fb⁻¹
- EPJC 79 (2019) 368, 35.9 fb⁻¹

**Lepton+jets**

- jHEP 12 (2012) 105, 5.0 fb⁻¹
- PRD 93 (2016) 072004, 19.7 fb⁻¹
- EPJC 78 (2018) 891, 35.9 fb⁻¹
- EPJC 79 (2019) 313, 35.9 fb⁻¹

**All-jets**

- EPJC 72 (2013) 2032, 5.0 fb⁻¹
- PRD 93 (2016) 072004, 19.7 fb⁻¹
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**CMS Preliminary May 2019**

**Inclusive tt cross section (pb)**

- CMS Run 1 legacy
- CMS Run 2
- Tevatron
- LHC Run 1
- LHC Run 2

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**Data and MC**

- ATLAS, CDF, CMS, D0
- Tevatron, Fiesler, Minw. PRL 110 (2013) 252004
- NNLO+NNLL (pp)
- pNNLO+NNLL (pCzakon, Fiedler, Mitov, PRL 110 (2013) 252004)
- NNPDF3.0
- MMHT14
- CT14
- ABM12

**Z**

- M₃ s= 172.5 GeV, top
- NNPDF3.0, m¹³ [TeV]

**Stat. ± Syst.**

- 1.43 GeV ± 0.43 ± 172.50
- 1.22 GeV ± 0.19 ± 172.82
- 0.98 GeV ± 0.43 ± 173.49
- 1.21 GeV ± 0.09 ± 172.22
- 0.43 ± 170.89

**CMS Preliminary May 2019**

- 3.17 fb⁻¹ (8, 13 TeV)

**Tevatron combined**

- 1.96 TeV (L = 135 fb⁻¹)
- 0.72 GeV ± 0.66 ± 0.24 ± 172.33

**World combination**


- CMS, Fiesler, Minw. PRL 110 (2013) 252004
- NNLO+NNLL (pp)
- pNNLO+NNLL (pCzakon, Fiedler, Mitov, PRL 110 (2013) 252004)
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**World combination**

Upgrades
“Phase-1” upgrades of CMS

- Majority of the upgrades have been done in the past years
- Last step: **HCAL barrel**
  - install new 5Gbps readout

**Pixel**
- replace layer 1 and all DCDC converters

**Muon system (phase-2)**
- GEM GE1/1 chambers
- Upgrade CSC front-end electronics

**New beam pipe (phase-2)**

*small* selection of activities in long shutdown 2 (2019/2020)
The road to high luminosity

LHC / HL-LHC Plan

Run 1 | Run 2 | Run 3 | Run 4 - 5...

LS1
splice consolidation
button collimators
R2E project

13 TeV

7 TeV


EyETS

LS2
INJECTOR UPGRADE
TDIS absorber
11T dipole & collimator
Civil Eng. P1-P5

14 TeV

14 TeV

8 TeV

experiment beam pipes

nominal luminosity

2 x nom. luminosity

2.5 x nominal luminosity

30 fb⁻¹

5 to 7 x nominal luminosity

ATLAS - CMS
upgrade phase 1

ALICE - LHCb
upgrade

ATLAS - CMS
upgrade phase 2

300 fb⁻¹

3000 fb⁻¹

nominal luminosity

75% nominal luminosity

EPS-HEP 2019
Upgrades for HL-LHC

**Trigger**
- incl. tracker at 40MHz
- increase max. rate to 750kHz (L1) / 7.5kHz (HLT)

**Calorimeter endcaps**
- Si-based high-granularity calorimeter
- 3D shower measurement + timing

**Barrel calorimeters**
- ECAL crystal-granularity readout @ 40MHz
- new ECAL&HCAL backend boards

**Tracker**
- increased granularity & extension to $|\eta|=3.8$
- tracking @ L1

**MIP timing detector**
- Precision timing for barrel & endcaps

**Muon detectors**
- new GEM & RPC fwd. detectors
- extended coverage to $|\eta|=3$
- upgraded readout for CSC, DT, RPC
Upgrades for HL-LHC

**Trigger**
- incl. tracker at 40MHz
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---

Many new & Innovative elements!
Phase-2 upgrade starts now!
Upgrades for HL-LHC

What are the benefits? Some examples

Endcap calorimeters
  • fine segmentation provides powerful discriminating variables for e-ID

Muon system
  • L1 trigger on delayed signals with upgraded RPC readout

MIP timing detector
  • Improved efficiency of the isolation selection for leptons

CERN-LHCC-2017-023
CERN-LHCC-2017-012
CERN-LHCC-2019-003
Summary
Summary

Continuing the harvest based on the LHC Run 2 dataset

• Many results using the full dataset of 137fb\(^{-1}\) have been shown
  - currently mainly focusing on searches and rare processes
  - can expect many more results in the next months
• Also progressing in precision measurements
  - currently using early data
  - full Run 2 results will use ultimate calibrations with a legacy reconstruction of Run 2 datasets

Preparing for the future

• First round of upgrades is terminating now
• Starting first extensions and modifications in view of HL-LHC
• Current results show that we are on track for Run 3 and beyond
  - HL-LHC projections show the large gains expected with the upgraded detector and an integrated luminosity of 3ab\(^{-1}\)
Additional material
Preparing for LHC Run 3 ...

*(small) selection of activities in long shutdown 2*(

(2019/2020)
Detector performance in 2018

Improved $\tau$ triggers
- Use of offline “HPS” algorithm
  - sharper turn-on
  - lower rates

Excellent muon performance
- Compatible with previous years
- MC reproduces data well
  - e.g., dimuon mass resolution

Tracker “radiography”
- Reconstructed hadronic interactions show structure of “Phase-1”, 4-layer pixel detector

Images: CMS Preliminary, 59 fb$^{-1}$ (13 TeV)
Heavy Ions

$\Lambda_c^+$ production in pp and PbPb at $\sqrt{s_{NN}}=5.02\text{TeV}$

- Ratio w.r.t. $D_0$ production
- pp: well described by model including colour reconnection
- pp and PbPb consistent with current precision

Performance in the 2018 PbPb run

- collected luminosity: $\sim 1.80 \text{nb}^{-1}$
- dataset includes $\sim 4.5 \times 10^8$ min. bias events
- transferring up to 7GB/s to offline
- excellent data quality

CMS DP–2018/060
Top-quark pairs + bb / jj

One of the main backgrounds for ttH(H→bb) measurement
• first measurement of \( \sigma(ttbb) \) in the hadronic channel

Predictions underestimate measured \( \sigma(ttbb) \)

TOP–18–011
SUSY searches

But we (can) do more!

- models with small mass differences between the two lightest sparticles predict long-lived, charged particles with an invisible decay:
  - disappearing tracks

- extension of a search for strong SUSY production leads to long-lived signatures leads lower backgrounds and increased sensitivity
  - for large $c\tau$, the mass limit for gluinos increases by up to 400GeV with respect to the standard search

**SUS-19-005**
Summary plots
Summary SM cross sections

March 2019

CMS Preliminary

Production Cross Section, $\sigma$ [pb]

- 7 TeV CMS measurement ($L \leq 5.0$ fb$^{-1}$)
- 8 TeV CMS measurement ($L \leq 19.6$ fb$^{-1}$)
- 13 TeV CMS measurement ($L \leq 137$ fb$^{-1}$)
- Theory prediction
- CMS 95%CL limits at 7, 8 and 13 TeV

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

W. Adam: Highlights from the CMS experiment
Summary SM cross sections

CMS measurements vs. NNLO (NLO) theory

- $\gamma\gamma$ (NLO th.): $1.06 \pm 0.01 \pm 0.12$ fb
- $W\gamma$ (NLO th.): $1.16 \pm 0.03 \pm 0.13$ fb
- $Z\gamma$ (NLO th.): $0.98 \pm 0.01 \pm 0.05$ fb
- $Z\gamma$ (NLO th.): $0.98 \pm 0.01 \pm 0.05$ fb
- $WW+WZ$: $1.01 \pm 0.13 \pm 0.14$ fb
- $WW$: $1.07 \pm 0.04 \pm 0.09$ fb
- $WW$: $1.00 \pm 0.02 \pm 0.08$ fb
- $WW$: $0.96 \pm 0.05 \pm 0.08$ fb
- $WZ$: $1.05 \pm 0.07 \pm 0.06$ fb
- $WZ$: $1.02 \pm 0.04 \pm 0.07$ fb
- $WZ$: $0.96 \pm 0.02 \pm 0.05$ fb
- $ZZ$: $0.97 \pm 0.13 \pm 0.07$ fb
- $ZZ$: $0.97 \pm 0.06 \pm 0.08$ fb
- $ZZ$: $1.06 \pm 0.02 \pm 0.04$ fb

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

Production Cross Section Ratio: $\sigma_{\text{exp}} / \sigma_{\text{theo}}$

7 TeV CMS measurement (stat,stat+sys)
8 TeV CMS measurement (stat,stat+sys)
13 TeV CMS measurement (stat,stat+sys)
Summary SM cross sections

March 2019

CMS EWK measurements vs. Theory

7 TeV CMS measurement (stat,stat+sys)
8 TeV CMS measurement (stat,stat+sys)
13 TeV CMS measurement (stat,stat+sys)

qqW
qqW
qqZ
qqZ
qqZ
γγ→WW
qqWγ
ss WW
ss WW
qqZγ
qqWZ
qqZZ

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

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

0.84 ± 0.08 ± 0.18  19.3 fb⁻¹
0.91 ± 0.02 ± 0.09  35.9 fb⁻¹
0.93 ± 0.14 ± 0.32  5.0 fb⁻¹
0.84 ± 0.07 ± 0.19  19.7 fb⁻¹
0.98 ± 0.04 ± 0.10  35.9 fb⁻¹
1.74 ± 0.00 ± 0.74  19.7 fb⁻¹
1.77 ± 0.67 ± 0.56  19.7 fb⁻¹
0.69 ± 0.38 ± 0.18  19.4 fb⁻¹
0.90 ± 0.16 ± 0.08  35.9 fb⁻¹
1.48 ± 0.65 ± 0.48  19.7 fb⁻¹
0.82 ± 0.47        35.9 fb⁻¹
1.38 ± 0.64 ± 0.38  35.9 fb⁻¹
Summary top quark cross sections

March 2019

CMS Preliminary

- 7 TeV CMS measurement (L < 5.0 fb⁻¹)
- 8 TeV CMS measurement (L < 19.6 fb⁻¹)
- 13 TeV CMS measurement (L < 137 fb⁻¹)
- Theory prediction
- CMS 95%CL limits at 7, 8 and 13 TeV

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

W. Adam: Highlights from the CMS experiment
Top-quark pair cross section summary

W. Adam: Highlights from the CMS experiment

CMS Preliminary

May 2019

NLO+NNLL (pp)
NLO+NNLL (pp)

Czakon, Fiedler, Mitov, PRL 110 (2013) 252004

NNPDF3.0, $m_{top} = 172.5$ GeV, $\alpha_s(M_Z) = 0.118 \pm 0.001$ [$\alpha_s(M_Z) = 0.113$]
Top-quark pair cross section summary

W. Adam: Highlights from the CMS experiment
## Overview of SUSY results: gluino pair production

<table>
<thead>
<tr>
<th>Process</th>
<th>Mass Scale [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{g} \rightarrow t\bar{t}$</td>
<td>500</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow t\bar{t}$</td>
<td>1000</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow t\bar{t}$</td>
<td>1500</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow t\bar{t}$</td>
<td>2000</td>
</tr>
</tbody>
</table>

Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probes up to the quoted mass limit for light LSPs unless stated otherwise. The quantities $\Delta M$ and $x$ represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP, respectively, unless indicated otherwise.
Overview of CMS long-lived particle searches

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.
Summaries vector-like quarks

**Vector-like quark single production**

- $\sigma(Qq) \times B(Q \to qW)$, $m = 1.0\text{ TeV}$
- $\sigma(Qq) \times B(Q \to qZ)$, $m = 1.0\text{ TeV}$
- $\sigma(Ybq) \times B(Y \to bW)$, $m = 1.5\text{ TeV}$
- $\sigma(Tbq) \times B(T \to bW)$, $m = 1.5\text{ TeV}$

**Vector-like quark pair production**

- $\sigma(X_{5/3}) \times B(X_{5/3} \to tW(LH))$, $m = 1.0\text{ TeV}$
- $\sigma(X_{5/3}) \times B(X_{5/3} \to tW(RH))$, $m = 1.5\text{ TeV}$
- $\sigma(Ybq) \times B(Y \to bW)$, $m = 1.0\text{ TeV}$
- $\sigma(Bbq) \times B(B \to bW)$, $m = 1.0\text{ TeV}$

**95% CL Upper Cross Section Limits (pb)**

- $\sqrt{s} = 13\text{ TeV}$
- $\sqrt{s} = 8\text{ TeV}$

**95% CL Lower Mass Limits (TeV)**

- $\sqrt{s} = 13\text{ TeV}$
- $\sqrt{s} = 8\text{ TeV}$

**CMS, EPS-HEP 2019**

W. Adam: Highlights from the CMS experiment
Resonances to dibosons ($\sqrt{s} = 13$ TeV)

<table>
<thead>
<tr>
<th>Resonance Type</th>
<th>Upper Cross Section Limit [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W'$ (all final states)</td>
<td>0.3</td>
</tr>
<tr>
<td>$W' \rightarrow WZ (q:\bar{q}q\bar{q})$</td>
<td>1.5</td>
</tr>
<tr>
<td>$W' \rightarrow WZ (q:\bar{q}q\nu\bar{\nu})$</td>
<td>2.7</td>
</tr>
<tr>
<td>$W' \rightarrow WZ (\nu\bar{q}\nu\bar{q})$</td>
<td>6.0</td>
</tr>
<tr>
<td>$W' \rightarrow WZ (q:\bar{q}\nu\bar{\nu})$</td>
<td>3.6</td>
</tr>
<tr>
<td>$W' \rightarrow WZ (\nu\bar{q}\nu\bar{\nu})$</td>
<td>7.0</td>
</tr>
<tr>
<td>$W' \rightarrow WH (q\bar{\nu}\nu\nu)$</td>
<td>9.4</td>
</tr>
<tr>
<td>$Z' (all final states)$</td>
<td>0.6</td>
</tr>
<tr>
<td>$Z' \rightarrow WW (q:\bar{q}q\bar{q})$</td>
<td>6.0</td>
</tr>
<tr>
<td>$Z' \rightarrow ZH (\nu\bar{b}\nu\bar{b} + vv\bar{b}\bar{b})$</td>
<td>6.6</td>
</tr>
<tr>
<td>$Z' \rightarrow ZH (q\bar{b}q\nu\nu)$</td>
<td>25.0</td>
</tr>
<tr>
<td>HVT (all final states)</td>
<td>0.3</td>
</tr>
<tr>
<td>HVT $\rightarrow$ WW+ZH (q:\bar{q}qq\bar{q})</td>
<td>1.5</td>
</tr>
<tr>
<td>HVT $\rightarrow$ WH+ZH (q\bar{b}q\nu\nu)$</td>
<td>1.0</td>
</tr>
<tr>
<td>HVT $\rightarrow$ WH+ZH (q\bar{q}\nu\nu)$</td>
<td>5.1</td>
</tr>
<tr>
<td>HVT $\rightarrow$ WH+ZH (q\nu\nu)$</td>
<td>7.0</td>
</tr>
<tr>
<td>Bulk Graviton $k=0.5$ (all final states)</td>
<td>2.0</td>
</tr>
<tr>
<td>Bulk G $\rightarrow$ WW+ZZ (q:\bar{q}qq\bar{q})</td>
<td>0.5</td>
</tr>
<tr>
<td>Bulk G $\rightarrow$ WW (q:\bar{q}q\nu\nu)$</td>
<td>0.5</td>
</tr>
<tr>
<td>Bulk G $\rightarrow$ ZZ (q\bar{q}\nu\nu)$</td>
<td>0.5</td>
</tr>
<tr>
<td>Bulk G $\rightarrow$ ZZ (q\bar{q}qq\bar{q})</td>
<td>0.5</td>
</tr>
<tr>
<td>Bulk G $\rightarrow$ ZZ (q\bar{q}\nu\nu)$</td>
<td>1.5</td>
</tr>
<tr>
<td>Bulk G $\rightarrow$ HH (b\bar{b}b\bar{b})</td>
<td>4.4</td>
</tr>
<tr>
<td>Radion ($\lambda_{W} = 3$ TeV) $\rightarrow$ HH (b\bar{b}b\bar{b})</td>
<td>4.4</td>
</tr>
<tr>
<td>Radion ($\lambda_{W} = 3$ TeV) $\rightarrow$ HH (qq\bar{q}q\bar{q})</td>
<td>20.0</td>
</tr>
</tbody>
</table>

95% CL Lower Mass Limit [TeV] (Upper Cross Section Limit [fb])

**CMS, EPS-HEP 2019**

**HVT model B**