Patricia Rebello Teles
on behalf of CMS Collaboration

IIP2017

*LHC Chapter II: The Run for New Physics*

6th-17th November 2017, Natal (Brazil)
Science, Art & Outreach
25 years

CMS turns twenty-five!

CMS Virtual visits:
almost 23 000 people from 40 countries
http://cms.cern/engage-with-cms/virtual-visits

About art@CMS
“Science discovers, art creates”
John Opie

Letter of intent for CMS submitted to the LHCC October 1st, 1992

https://cms25.web.cern.ch/

CMS Public Website: https://cms.cern/

Photo by Michael Roch
https://artcms.web.cern.ch/artcms/
LHC & CMS Performance

On track for 150 fb⁻¹ @13TeV by the end of 2018

LHC reached 2017 lumi target (45 fb⁻¹) 19 days ahead of schedule

Luminosity leveling deployed to limit pile up average at 35
Detector Update for the 14TeV (from Phase-0 to Phase I)

- Doubled number of channels and active area (2m²)
- Number of layers increased from 3 to 4 in barrel (BPix) and 2 to 3 in endcaps (FPix)
- Innermost layer closer to beam pipe (4.4cm to 2.9cm)
- New readout chips allows higher rates and less dynamic inefficiency at high instantaneous luminosity
- DC-DC conversion powering system and CO₂ cooling
- Significant reduction of material
- Commissioning of the detector was challenging

Credits: Markus Klute

Run3: after LS2 (2020) <PU> ~50

GEM: Gas Electron Multiplier

https://goo.gl/sVdcWB
The Future: High-Luminosity LHC (Phase II)

Workshop on the physics of HL-LHC and perspectives at HE-LHC

https://indico.cern.ch/event/647676
CMS Upgrades for Phase II

- Phase-II upgrades aim to fully exploit HL-LHC program (after LS3 => 2025; <PU> ~140 )
- Exciting new detector concepts
- Documenting projects in Technical Design Report (TDR) or interim reports

TDR
https://goo.gl/CrMybU
CMS Publications

671 collider data papers published as of 2017-10-28

700 papers submitted!!

CMS public results: https://goo.gl/LECjSq

Interesting results from Heavy Ions, Forward Physics, among others, not covered in this talk!
Excrutinizing the SM

All XS measurements are in excellent agreement

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsCombined
Updated Higgs properties measurements in
H → 4 leptons

- the most important channel for studies of the Higgs boson’s properties: large signal-to-background ratio due complete reconstruction of the final state decay products and excellent lepton momentum resolution;

- studies performed targeting all the production modes using 35.9 fb⁻¹ of CMS data @13TeV

- “New Physics: anomalous HVV couplings exclusion limits (see CMS-HIG-17-011), including the CP-violation one”

- Main systematics:
  - reducible background estimation: 36%-43%;
  - uncertainty in the 4l mass resolution 20%;
  - renormalization and factorization scales, PDF set, and the modeling of the fragmentation, hadronization and underlying event 4–20% for the signal and 3–20% for the background.

No events observed with m₄l > 1 TeV

#expected back and signal events and #observed candidate events after the full selection for m₄l > 70 GeV

<table>
<thead>
<tr>
<th>Channel</th>
<th>4e</th>
<th>4μ</th>
<th>2e2μ</th>
<th>4l</th>
</tr>
</thead>
<tbody>
<tr>
<td>qq → ZZ</td>
<td>193±19</td>
<td>360±25</td>
<td>471±33</td>
<td>1024±69</td>
</tr>
<tr>
<td>gg → ZZ</td>
<td>41.2±6.3</td>
<td>69.0±9.5</td>
<td>102±14</td>
<td>212±29</td>
</tr>
<tr>
<td>Z+X (Data)</td>
<td>21.1±8.5</td>
<td>34±14</td>
<td>60±22</td>
<td>115±32</td>
</tr>
<tr>
<td>Sum of backgrounds</td>
<td>255±24</td>
<td>463±32</td>
<td>633±44</td>
<td>1351±86</td>
</tr>
<tr>
<td>Signal</td>
<td>12.0±1.3</td>
<td>23.6±2.1</td>
<td>30.0±2.6</td>
<td>65.7±5.6</td>
</tr>
<tr>
<td>Total expected</td>
<td>267±26</td>
<td>487±33</td>
<td>663±46</td>
<td>1417±89</td>
</tr>
<tr>
<td>Observed</td>
<td>293</td>
<td>505</td>
<td>681</td>
<td>1479</td>
</tr>
</tbody>
</table>
Updated Higgs properties measurements in $H \to 4$ leptons

#expected back and signal events, and #observed candidate events after the full selection for $118 \text{ GeV} < m_{4l} < 130 \text{ GeV}$, for different production modes

<table>
<thead>
<tr>
<th>Event category</th>
<th>Untagged</th>
<th>VBF-1j</th>
<th>VBF-2j</th>
<th>VH-hadr.</th>
<th>VH-lept.</th>
<th>$E_T^{miss}$</th>
<th>tH</th>
<th>Inclusive</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q\bar{q} \to ZZ$</td>
<td>19.18</td>
<td>2.00</td>
<td>0.25</td>
<td>0.30</td>
<td>0.27</td>
<td>0.01</td>
<td>0.01</td>
<td>22.01</td>
</tr>
<tr>
<td>$gg \to ZZ$</td>
<td>1.67</td>
<td>0.31</td>
<td>0.05</td>
<td>0.02</td>
<td>0.04</td>
<td>0.01 &lt;0.0</td>
<td>2.09</td>
<td></td>
</tr>
<tr>
<td>$Z+X$</td>
<td>10.79</td>
<td>0.88</td>
<td>0.78</td>
<td>0.31</td>
<td>0.17</td>
<td>0.30</td>
<td>0.27</td>
<td>13.52</td>
</tr>
<tr>
<td>Sum of backgrounds</td>
<td>31.64</td>
<td>3.18</td>
<td>1.08</td>
<td>0.63</td>
<td>0.49</td>
<td>0.32</td>
<td>0.28</td>
<td>37.62</td>
</tr>
</tbody>
</table>

| gg → H | 38.78 | 8.31 | 2.04 | 1.41 | 0.08 | 0.02 | 0.10 | 50.74 |
| VBF   | 1.08  | 1.14 | 2.09 | 0.09 | 0.02 | <0.01 | 0.02 | 4.44  |
| WH    | 0.43  | 0.14 | 0.05 | 0.30 | 0.21 | 0.03 | 0.02 | 1.18  |
| ZH    | 0.41  | 0.11 | 0.04 | 0.24 | 0.04 | 0.07 | 0.02 | 0.93  |
| tH    | 0.08  | <0.01| 0.02 | 0.03 | 0.02 | <0.01 | 0.35 | 0.50  |
| Signal | 40.77 | 9.69 | 4.24 | 2.08 | 0.38 | 0.11 | 0.51 | 57.79 |
| Total expected | 72.41 | 12.88 | 5.32 | 2.71 | 0.86 | 0.43 | 0.79 | 95.41 |
| Observed    | 73    | 13    | 4     | 2     | 1     | 1     | 0     | 94    |

**Signal strength modifier $\mu$:** production XS of the Higgs boson times its BR to four leptons relative to the SM expectation.

**Inclusive**

| Expected | $1.00^{+0.15}_{-0.14}$ (stat) $^{+0.10}_{-0.08}$ (syst) |
| Observed | $1.05^{+0.15}_{-0.14}$ (stat) $^{+0.11}_{-0.09}$ (syst) |
Updated Higgs properties measurements in $H \rightarrow 4$ leptons

https://goo.gl/ewsK6x

1D likelihood scans as a function of mass for the different final states and the combination of all final states

Observed and expected likelihood scan of $\Gamma_H$ using the signal range $105 \text{ GeV} < m_{4l} < 140 \text{ GeV}$

$m_H = 125.26 \pm 0.20 \text{ (stat)} \pm 0.08 \text{ (syst)} \text{ GeV}$

$\Gamma_H < 1.10 \text{ GeV}$ @95% CL
Updated Higgs properties measurements in \( H \rightarrow 4 \) leptons

Definition of the fiducial phase space

<table>
<thead>
<tr>
<th>Lepton kinematics and isolation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading lepton ( p_T )</td>
</tr>
<tr>
<td>Subleading lepton ( p_T )</td>
</tr>
<tr>
<td>Additional electrons (muons) ( p_T )</td>
</tr>
<tr>
<td>Pseudorapidity of electrons (muons)</td>
</tr>
<tr>
<td>Sum ( p_T ) of all stable particles within ( \Delta R &lt; 0.3 ) from lepton</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Event topology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existence of at least two same-flavor OS lepton pairs, where leptons satisfy criteria above</td>
</tr>
<tr>
<td>Invariant mass of the ( Z_1 ) candidate</td>
</tr>
<tr>
<td>Invariant mass of the ( Z_2 ) candidate</td>
</tr>
<tr>
<td>Distance between selected four leptons</td>
</tr>
<tr>
<td>Invariant mass of any opposite-sign lepton pair</td>
</tr>
<tr>
<td>Invariant mass of the selected four leptons</td>
</tr>
</tbody>
</table>

Differential and fiducial XS measurement

No events observed with \( p_T(H) > 200 \text{ GeV} \)

\[
\sigma_{\text{fid}} = 2.92^{+0.48}_{-0.44} \text{ (stat)} +0.28_{-0.24} \text{ (syst)} \text{ fb}
\]

\[
\sigma_{\text{SM}}^{\text{fid}} = 2.76 \pm 0.14 \text{ fb}
\]
Prospects for differential measurements (impact of 100 times larger dataset)

- Showing this only to give you a flavor
- $H\to ZZ$ channel shows 4-10% uncertainty (stat.)
- Experimental results will challenge theoretical precision (magenta)
- Other channels will be exploited
- Sensitivity to NP

https://goo.gl/oHduyy
Updated Higgs properties measurements in $H \rightarrow \gamma\gamma$

Fiducial and differential XS measurements

Definition of the fiducial phase space:

- both photons within $|\eta_{1,2}| < 2.5$ and $p_T / m_{\gamma\gamma} > 1/3(1/4)$ for the leading (subleading) photon.

- Fiducial and differential XS measurements

\[ \hat{\sigma}_{\text{fid}} = 84^{+13}_{-12} \text{ fb} \]

Diphoton mass spectrum weighted by the ratio $S/(S+B)$
New resonances searches in \( H \to \gamma\gamma \)

- First LHC results to appear for a search for new resonances in the diphoton final state in the mass range between 70 and 110 GeV.

- 8 TeV plus 13 TeV combination yields an excess with approximately 2.8\( \sigma \) local (1.3\( \sigma \) global) significance for the same hypothesis mass as for the 13 TeV dataset alone, 95.3 GeV.

Expected and observed exclusion limits (95\% CL) on the production cross section times branching ratio into two photons in the asymptotic CLs approximation.
Observation of $H \rightarrow \tau \bar{\tau}$

- gluon fusion, vector boson fusion, and boosted (events with one jet and events with several jets that fail the specific requirements of previous categories) categories are exploited.
- $5.9\sigma$ in combination of 7, 8, and 13 TeV results

First single experiment observation of Higgs-boson Yukawa coupling to $\tau$-leptons

Combined observed and predicted $m_{\tau\tau}$ distributions
Observation of $H \rightarrow \tau \bar{\tau}$

- Coupling modifiers to bosons and fermions tested.
- Couplings will be fully explored in combination with other Higgs studies.

For the scan above, the $pp \rightarrow H \rightarrow WW$ contribution is treated as a signal process.
Evidence of $H \to b \bar{b}$

- Exploring ZH and WH production modes
- 0-, 1-, and 2-lepton categories are exploited
- Signal extracted from combined fit to signal and control regions

$Z(\nu\nu)H$, $W(\mu\nu)H$, $W(e\nu)H$, $Z(\mu\mu)H$, and $Z(ee)H$

Weighted dijet invariant mass distribution for events in all channels combined

Combination of all channels into a single event BDT distribution

The best fit value of the signal strength $\mu$

<table>
<thead>
<tr>
<th>Data used</th>
<th>Significance expected</th>
<th>Significance observed</th>
<th>Signal strength observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run 1</td>
<td>2.5</td>
<td>2.1</td>
<td>0.89$^{+0.44}_{-0.42}$</td>
</tr>
<tr>
<td>Run 2</td>
<td>2.8</td>
<td>3.3</td>
<td>1.19$^{+0.40}_{-0.38}$</td>
</tr>
<tr>
<td>Combined</td>
<td>3.8</td>
<td>3.8</td>
<td>1.06$^{+0.31}_{-0.29}$</td>
</tr>
</tbody>
</table>
Boosted $H \rightarrow b \bar{b}$

W, Z, and Higgs bosons identified as a large jet containing two b-quarks, highly boosted ($p_T > 450$ GeV) identified using jet substructure** and dedicated b-tagging techniques.

First observation of $Z \rightarrow bb$ in the single-jet topology.

** "soft-drop grooming" to reduce jet mass ($m_{SD}$): removes soft and wide-angle radiation produced by parton shower activity, pileup interactions, and the underlying event from the jet.

https://arxiv.org/abs/1402.2657
Probes of $H(\gamma\gamma)H(bb)$ pair production

https://goo.gl/8JzkGM

- Resonant (investigated in the mass range 200-900 GeV) and nonresonant production mechanisms of the Higgs boson pair
- Study of H self coupling very challenging at the LHC

**modified SM Lagrangian**

$$\Delta L = \kappa_\lambda \lambda_{SM} \nu H^3 - \frac{m_t}{v} (v + \kappa_t H + \frac{c_2}{v} H^2) (t_L t_R + h.c.) + \frac{1}{4} \frac{\alpha_s}{3\pi v} (c_g H - \frac{c_2}{2v} H^2) G^{\mu\nu} G_{\mu\nu}$$

- BSM: existence of heavy particles that can couple to a pair of Higgs bosons; induce changes in Higgs boson’s fundamental couplings wrt SM values.

Contact interactions between the H boson and gluons, and of two H bosons with top quarks

- WED models predict both spin-0 (radions), and spin-2 (gravitons) new states that can be directly detected at the LHC experiments => bulk RS model as benchmark model.
- 2HDM to induce resonant HH enhancements in which a second complex scalar doublet field is added to the SM scalar sector.
Probes of $H(\gamma\gamma)H(b\bar{b})$ pair production

https://goo.gl/8JzkGM

The observed limits exclude the radion (spin-0) signal hypothesis, assuming $\Lambda_R=3$ TeV, for all mass points below $m_X = 550$ GeV, and exclude the graviton (spin-2) hypothesis, assuming $\kappa/M_{Pl} =1.0$, for the mass points above $m_X = 280$ GeV and below 900 GeV.
Probes of $H(\gamma\gamma)H(bb)$ pair production

Non-resonant production $\text{XS} = 1.67$ fb at 95% C.L.

Below left: upper limits for the BSM models with varying $\kappa_\lambda$ parameter, while the others are fixed to their SM value.

Below right: exclusion regions for models with varying $\kappa_\lambda$ and $\kappa_t$ parameters, while the others are fixed to their SM values.

Exclusion region for the effective Higgs self-coupling $\kappa_\lambda > -8.82$ and $\kappa_\lambda < 15.04$
The observed (expected) best fit $t\bar{t}H$ yield is $1.5^{+0.5}_{-0.5} \times (1.0^{+0.5}_{0.4})$ times the SM prediction, corresponding to a significance of $3.3\sigma (2.5\sigma)$. 

- 2L (same-sign), 3L and 4L channels
- 4L channel no kinematic discrimination is performed, because of its limited statistical power.

Combination of the BDT classifier outputs in the bins.

https://goo.gl/ijJZ5F
Flavor Violating Higgs decay

- Exploring off-diagonal Yukawa couplings
- Excitement in Run-I with 2.4σ excess
- Two different analysis techniques: $M_{col}$ and BDT
- New upper limits supersede Run-I results:

<table>
<thead>
<tr>
<th></th>
<th>$M_{col}$-fit</th>
<th>BDT-fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{</td>
<td>Y_{\mu \tau}</td>
<td>^2 +</td>
</tr>
<tr>
<td>$\sqrt{</td>
<td>Y_{e \tau}</td>
<td>^2 +</td>
</tr>
</tbody>
</table>

(a) Constraints on $|Y_{\mu \tau}| / |Y_{\tau \mu}|$

(b) Constraints on $|Y_{e \tau}| / |Y_{\tau e}|$

limits on the branching fraction

<table>
<thead>
<tr>
<th></th>
<th>Observed(Expected) limits (%)</th>
<th>Best fit branching fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M_{col}$-fit</td>
<td>BDT-fit</td>
</tr>
<tr>
<td>$H \rightarrow \mu \tau$</td>
<td>$&lt;0.51 \ (0.49)$ %</td>
<td>$&lt;0.25 \ (0.25)$%</td>
</tr>
<tr>
<td>$H \rightarrow e \tau$</td>
<td>$&lt;0.72 \ (0.56)$%</td>
<td>$&lt;0.61 \ (0.37)$%</td>
</tr>
</tbody>
</table>
Vector Boson Scattering

- Test of electroweak sector of the SM
- Sensitive to anomalous triple and quartic gauge couplings (aTGC & aQGC)
- Measurable key process linked with EWSB
- Diboson production plus back-forward jets
- Background to Higgs searches and BSM searches

**Leptonic final states:**
- $W^\pm W^\pm \rightarrow l^\pm l^\pm \nu$: reduced diagrams wrt $W^\pm W^{\mp}$
- $W^\pm W^{\mp} \rightarrow l^\pm l^{\mp} \nu$: relatively large top background
- $W^\pm Z \rightarrow 3l\nu$: clean channel with three leptons
- $ZZ \rightarrow 4l$: very clean, limited number of events
- $ZZ \rightarrow 2l2\nu$: challenging analysis, but relatively large branching fraction

**Semi-leptonic final states:** 😞
- $ZW^\pm$ (or $Z$) $\rightarrow lljj$ & $W^\pm W^{\mp}$ (or $Z$) $\rightarrow lvjj$
- More difficult due to larger backgrounds
- High $m_{VV}$ generates boosted jets which can be merged
Leptonic final state: two identified leptons (electrons or muons) of the same charge, moderate missing transverse momentum, and two jets with a large rapidity separation and a large dijet mass.

- Observation of EW production of same-sign W pairs
  - 5.5\(\sigma\) observed, 5.7\(\sigma\) expected
  - Fiducial XS measurement
  - Signal strength \(\mu = 0.90\pm0.22\)

- Limits on doubly-charged Higgs boson production (models with Higgs triplet field)
  - Model independent limits (left) and interpretation in Georgi-Machack model (right)
  - Limits aQGCs dim8 effective op.
  - factor of up to 6 times better than previous results

\[
\sigma_{\text{fid}}(W^{\pm}W^{\pm}jj) = 3.83 \pm 0.66(\text{stat}) \pm 0.35(\text{syst}) \text{ fb}
\]
Searches for DM

...if it couples at least weakly to Standard Model (SM) particles...

- DM particles invisible in detector
- total transverse momentum conserved
- select events with visible particles from Initial-State Radiation (ISR)
- look for ISR-object plus missing transverse momentum (missing $p_T$)
  - $E_T^{miss}$, “missing ET”, “MET”
  - → “mono-X” searches
    - $E_T^{miss} + X$ analyses: “something + nothing”
    - mono-jet, mono-photon, mono-Z, mono-W
- production in decay chains
  - SUSY cascades
  - Higgs portal

Mediator coupling

- spin-independent
  - scalar or vector coupling
  - scattering cross section: amplitude proportional to number of nucleons (i.e., mass of nucleus)
- spin-dependent
  - axial-vector or pseudo-scalar coupling
- very different sensitivities in direct-detection experiments
  - may differ by about six orders of magnitude

Contact interaction - effective field theory

- LHC Run 1 (<=2012): DM interpretation mostly in terms of Effective Field Theories
  - contact interaction, valid if mediator mass $>>$ momentum transfer
  - 7 and 8 TeV collision energy
  - invalid at high energy transfer
- LHC Run 2 (>=2015): use Simplified Models
  - 13 TeV collision energy
    - $\rightarrow$ higher momentum transfer possible
    - $\rightarrow$ EFT may become invalid
  - explicit definition of mediator particles
  - benchmark models
Mono-Jet & Mono-V

direct pair production of Dark Matter particles
- visible only with Initial State Radiation (ISR)
- “Mono-Jet” signature
- or Mono-Photon, Mono-V, (Mono-Z, Mono-W), Mono-Higgs, Mono-Top etc.

Main backgrounds:
- Z(vv) + jets
- W (ℓv) + jets
- WW / WZ / ZZ

Trigger:
- missing transverse momentum
  - missing $p_T = \text{“} E_T^{\text{miss}} \text{“}$
- using calorimeter only
  - no muons
  - all calorimeter objects ($E_T^{\text{miss}}$)
  - or jet sums only ($H_T^{\text{miss}}$)

Pseudoscalar mediators with masses up to 400 GeV are excluded at 95% C.L.

observed (expected) 95% C.L. upper limit of 0.53 (0.40) on the invisible BR of a SM-like 125 GeV Higgs from FermiLAT

from FermiLAT indirect detection**: stronger constraints for $m_{\text{DM}} < 200$ GeV (pseudoscalar)

no limits from direct-detection experiments: XS suppressed at non-relativistic velocities

**velocity averaged DM annihilation XS

Credits: Manfred Jeitler

https://goo.gl/PivcMd
Mono-Jet & Mono-V

@https://goo.gl/PivcMd

Credits: Manfred Jeitler

Translate limits from mass-mass plane to mass-cross section plane: compare to direct detection results
Di-Jets

- Search for low mass vector resonances;
- Utilizing boosted events with $p_T > 500$ GeV; jet mass groomed with the soft-drop algorithm;
- Excess at 115 GeV with $2.9\sigma$ ($2.2\sigma$) local (global)

Physics/Models: Leptophobic Z’ and DM

Combined DiJet on DM searches:

leptophobic vector mediator decaying to dijets excluded from 50 GeV to 300 GeV (red)

Di-Bosons

- Exhaustive list of signatures considered
- Exploring VBF and gluon fusion production modes
- Interpretations in various models

Bulk graviton ($k_{\ast} = 0.5$) XS limits
- CMS-PAS-B2G-16-023 (ZZ $\rightarrow$ 2l2ν)
- CMS-PAS-B2G-16-026 (HH $\rightarrow$ 4b)
- CMS-PAS-B2G-17-001 (WW/ZZ $\rightarrow$ 4q)
- CMS-PAS-B2G-17-005 (ZZ $\rightarrow$ 2q2v)

W' upper XS limits in the heavy vector triplet (HVT) model B
- CMS-PAS-B2G-17-005 (WZ $\rightarrow$ 2q2v)
- CMS-PAS-B2G-17-001 (WZ $\rightarrow$ 4q)
- CMS-PAS-B2G-17-002 (WH $\rightarrow$ 2q2b)
Vector-like quark single production

- Q → qW: 20 fb
- T → tH: 35 fb
- T → tZ: 25 fb
- T → bW: 7 fb
- B → bH: 7 fb
- B → bZ: 35 fb
- B → tW: 9 fb
- X5/3 → tW: 4 fb
- X5/3 → tW: 300 fb
- T → bW: 60 fb

Observed limit 95%CL (TeV)

Vector-like quark pair production

- Q → qW: 20 fb
- T → tH: 35 fb
- T → tZ: 25 fb
- T → bW: 7 fb
- B → bH: 7 fb
- B → bZ: 35 fb
- B → tW: 9 fb
- X5/3 → tW: 4 fb
- X5/3 → tW: 300 fb
- T → bW: 60 fb

Observed limit 95%CL (TeV)

Resonances to heavy quarks

- Z'(1.2%) → tt: 8 fb
- Z'(10%) → tt: 15 fb
- gKK → tt: 40 fb
- W' → tb: 40 fb
- W' → tb M_W < M_R: 50 fb
- W' → tb M_W > M_R: 50 fb
- Z'(1%) → tt: 100 fb
- Z'(10%) → tt: 120 fb
- Z'(30%) → tt: 200 fb
- gKK → tt: 200 fb
- W' → tb: 400 fb
- Z' → Tt → tZt: 150 fb

Observed limit 95%CL (TeV)

Excited quarks

- t* → tg S=3/2: 80 fb
- t* → tg S=1/2: 500 fb
- b* → tW K_L=1: 70 fb
- b* → tW K_R=1: 60 fb
- b* → tW K_L,K_R=1: 70 fb

Observed limit 95%CL (TeV)

Resonances to dibosons

- radion → HH: 6 fb
- radion → HH: 600 fb
- W' → WH: 10 fb
- Z' → ZH: 13 fb
- G_{bulk} → WW: 20 fb
- G_{bulk} → ZZ: 30 fb
- W' → VW HVT(B): 28 fb
- W' → WH HVT(B): 40 fb
- Z' → VH HVT(B): 18 fb
- radion → HH: 20 fb

Observed limit 95%CL (TeV)

B2G new physics searches with heavy SM particles

B2G group in CMS covers models of new physics featuring the decay of new resonances to heavy standard model objects such as top, W, Z, or Higgs bosons
LONG-LIVED PARTICLES
the first search for stopped particles (long-lived particles - LLPs) that decay to muons at the LHC
If the LLP is colored, it will hadronize prior to traversing the detector, creating a R-hadron, which will eventually stop in the detector;
R-hadrons could then decay seconds, days, or even weeks after the proton-proton collision
the major background: cosmic rays (survive the 100 m trip through the earth to the CMS detector); looked for when there were no collisions in the detector, namely, during gaps between LHC beam crossings

Excluded:

Excluded: $400 \text{ GeV} < m_{\text{gluino}} < 970 \text{ GeV}$

$100 \text{ GeV} < m_{\text{champ}} < 410 \text{ GeV}$

for lifetimes between 10 $\mu$s and 1000 s:

Multiple charged massive particle ($m_{\text{champ}}$): modified Drell-Yan production of long-lived lepton-like fermions
Particles stopping in the Calorimeter

https://goo.gl/bmRvqb

- the strongest limits on stopped long-lived particles to date;
- cloud model of R-hadron interactions assumed;

\[ E_g > 130 \text{ GeV} \text{ and } BR(\tilde{g} \rightarrow g\tilde{\chi}^0) = 100\% \]
gluinos excluded with lifetimes from 10 \( \mu \)s to 1000s and mass \( m_{\tilde{g}} < 1385 \text{ GeV} \)

\[ E_\tilde{t} > 170 \text{ GeV} \text{ and } BR(\tilde{t} \rightarrow t\tilde{\chi}^0) = 100\% \]
stops excluded with lifetimes from 10 \( \mu \)s to 1000s and mass \( m_{\tilde{t}} < 744 \text{ GeV} \)
Electroweak Susy

Chargino-neutralino pair production with the chargino decaying to the W boson and the LSP and the neutralino decaying to either (left) a Z boson and the LSP or (right) a Higgs boson and the LSP.

Expected and observed yield comparison in the search regions

Exclusion contours at the 95% CL for each analysis

- Electroweak production of charginos ($\tilde{\chi}^\pm$) and neutralinos ($\tilde{\chi}^0$)
- Combination of several analyses

CMS SUSY results https://goo.gl/7d6foP
Top squarks & direct DM

- final states with two oppositely charged leptons (electrons or muons), jets (from b quarks) and missing transverse momentum

- large background from SM dilepton events

![CMS Supplementary 35.9 fb⁻¹ (13 TeV)](https://goo.gl/bDZT97)

T2tt model

- $\tilde{t}_1 < 800$ GeV
- $\chi_1^0 < 360$ GeV

T2tt excluded

T2bW model

- $\tilde{t}_1 < 750$ GeV
- $\chi_1^0 < 320$ GeV

T2bW excluded
Top squarks & direct DM

[Diagram of T8bbllνν model]

- More stringent limits if all-jet and single-lepton channels are combined

\[ m_\ell = x + (m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0}) + m_{\tilde{\chi}_1^0} \]

- DM ($M_{DM} = 1$ GeV) coupled to the top quark via a scalar or a pseudoscalar mediator

\[ M_{scalar} < 100 \text{ GeV} \]

\[ M_{pseudo} < 50 \text{ GeV} \]

https://goo.gl/bDZT97
signature of a single lepton, large jet multiplicity, and large bottom quark jet multiplicity, without a requirement on the missing transverse momentum in an event;

• limits on the parameter space for R-parity-violating supersymmetric extensions of the standard model using a benchmark model of gluino pair production in which each gluino decays promptly via $\tilde{g} \rightarrow tbs$;

• Gluinos with a mass below 1610 GeV are excluded at 95% confidence level

• This observed mass limit is slightly lower than the expected limit, $m_{\text{gluino}} < 1640$ GeV, because of the small observed excess in the $M_J > 1000$ GeV bins.
NEUTRINOS
Search for type-III seesaw heavy fermions in multilepton final states: strongest constraints to date on the mass of heavy fermions associated with the type-III seesaw mechanism, excluded at 95% C.L:

- lepton-flavor democratic scenario ($B_e = B_\mu = B_\tau$) with $M < 840$ GeV;
- $\tau$-phobic case ($B_e = B_\mu = B_\tau$) $M < 900$ GeV in the pure electron scenario to $M < 930$ GeV in the pure muon scenario;
- $e/\mu$-phobic case ($B_\tau = 1$, $B_e + B_\mu = 0$) $M < 390$ GeV.
Summary

• CMS celebrates its 25th Birthday in 2017 prepared for data taking and physics production in the next ~20 years.
• Phase-I upgrade: more challenging environment. Phase-II upgrades are well under way to address HL-LHC demands
• Large dataset provided by the LHC allows to probe smaller coupling and larger mass range
   Observing new SM processes and improving precision
   Higgs physics turning into precision program
   Stringent limits on Dark Matter, SUSY, and other Exotics as heavy fermions
   A few excesses to look out for in the next years
   Interesting results from Heavy Ions, Forward Physics among others not covered in this talk

Big expectations for 2018!!
Xe-Xe Collisions

Only eight hours run in LHC
ATLAS, ALICE, CMS and LHCb recorded xenon collisions for the first time

NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) experiment, which is also studying quark-gluon plasma, analyses will complement those carried out by the LHC experiments.

The large number of tracks emerging from the centre of the detector shows the many simultaneous nucleon-nucleon interactions that take place when two xenon nuclei, each with 54 protons and 75 neutrons, collide inside CMS.