Current Highlights and Future Prospects from CMS

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Kyungpook National University for the CMS Collaboration

Light Cone 2021
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Jeju Island, South Korea
Status at CMS

Run2 measurements & searches in a huge diversity of physics channels:

- Target most challenging and interesting signatures.
- Innovative analysis methods, e.g. extensive use of machine learning.
- More refined use of detector capabilities, e.g. searches with long-lived particles.

Run2 (2016-18):
- pp: 13 TeV, ~140 fb$^{-1}$,
- PbPb: 5.02 TeV/nucleon 2.26 nb$^{-1}$

Publications:
- >1100 total.
- > 500 on Run2 data.
General purpose detector capable of detecting different particles. Eligible for a wide range of physics studies.
Phase2 upgrade for the CMS detector

**Improved muon coverage and trigger**
- increased RPC coverage ($1.5 < |\eta| < 2.4$)
- new electronics

CMS-TDR-016

**New precision timing detector**
- Timing resolution of 30-40 ps for MIPs
- full coverage of $|\eta| < 3.0$

CMS-TDR-020

**New inner tracker**
- all silicon tracker
- 4 layers of pixels
- 5 layers of strips
- coverage to $|\eta| < 4$

CMS-TDR-014

**Beam Radiation Instrumentation and Luminosity Detectors**

CMS-TDR-023

**New endcap calorimeters**
- high granularity
- can reconstruct showers in 3D

CMS-TDR-019

**Updates to calorimeter and trigger**
- higher granularity
- electronics for trigger

CMS-TDR-015

**L1**
- CMS-TDR-021
- DAQ/HLT: CMS-TDR-022

**Upgrade to trigger and DAQ**
- L1 rate increased to 750 kHz
- High Level trigger rate to 7.5 kHz
- Track information at L1
Towards the HL-LHC

High Luminosity LHC outlook

• Center of mass energy: 14 TeV
• Instantaneous luminosity: $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
• Total luminosity to be delivered: 3-4 ab$^{-1}$
• Pileup: 140-200

Opportunities: More data, improved detector coverage, new detector features.

Challenges: High pile-up, high beam-induced backgrounds, high radiation.

Dedicated physics studies exploring full potential of the HL-LHC and upgraded detectors:

• Improve current searches, design new searches exploiting the new detector capabilities, and develop new analysis strategies.
• access scenarios with lower cross sections, lower acceptance and open new search channels.

Typical analysis flow

- Define final state describing the signal:
  - Analyses are mostly signature-based (designed around a given final state, e.g. dileptons, jets+$E_T^{miss}$, …). A final state often probes multiple models/scenarios.

- Apply trigger / online selection.
- Reconstruct, identify and select objects: electrons, muons, jets, boosted tops, …
- Apply an event selection to enhance signal and eliminate backgrounds.
  - Increased use of ML discriminants in Run2.
- Estimate backgrounds via data control regions and/or simulation.
- Apply systematic uncertainties.
- Do a blind analysis: validate analysis strategy before comparing data with background estimate in search regions.
- Perform statistical analysis.
- Interpret the results on relevant physics models.
Standard model physics

- CMS SM results: [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP)
- CMS top results: [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP)
- CMS heavy ion results: [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN)
SM cross sections

Measurements of total cross sections in various production channels.

Also performing measurements of differential cross sections.

Deviations from SM prediction may indicate new physics.
First measurement of the $Z \rightarrow \nu \nu$ (Z to invisible) width at a hadron collider. Based on 2016 data.

Ratio of $\Gamma_{\nu \nu} / \Gamma_{ll}$ from a simultaneous fit of $Z \rightarrow \nu \nu$, $Z \rightarrow ee$ and $Z \rightarrow \mu \mu$ enriched event categories.

$\Gamma_{Zinv} = 523 \pm 3$ (stat) $\pm 16$ (syst) MeV.

Single most precise direct measurement of the Z to invisible width competitive with the direct LEP result.
Observation of VVV production

Triple vector boson (VVV, V=W,Z) final state is sensitive to new particles coupling to V or modifying SM couplings.

VVV observed for the first time in 2020 (search in clean leptonic final states).

Compatible with the SM.
First observation of triple J/ψ meson production

Contributions from single (SPS), double (DPS) and triple (TPS) parton scattering final states:

Significance > 5σ. Measured the fiducial cross section:

$$\sigma(pp \rightarrow J/\psi J/\psi J/\psi X) = 272^{+141}_{-104}\text{(stat)} \pm 17\text{ (syst)} \text{ fb}$$

Measured process dominated by DPS and TPS contributions.

Extracted $$\sigma_{eff,DPS}$$: DPS-associated effective cross section parameter. Consistent with measurements in other processes.

Candidate channel for first observation of TPS.
First observation of $B_{C}^{+}$ meson in PbPb collisions

Observation in $B_{C}^{+} \rightarrow J/\psi (\rightarrow \mu \mu) \mu \nu$ decay channel in pp and PbPb collisions with $>5\sigma$:

- 3 displaced muons final state.
- $B_{C}^{+}$ is the only meson containing both $b$ and $c$ quark: bridge between charmonia, bottomonia and open heavy mesons.
- Provides unique insight into the interplay between suppression and recombination (at low $p_T$).
- Measured cross section and nuclear modification factor in two bins of trimuon $p_T$ and in two ranges of collision centrality.

CMS-PAS-HIN-20-004
Top quark measurements

Top rare decays at Run2: Observed upper limits above the SM predictions. A good probe for new physics.

4-tops production at HL-LHC: Expect 10-30% uncertainty.
Currently only projections done for Phase2. Expect dedicated analyses with sophisticated methods for Phase2.
Higgs physics

• CMS Higgs results
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults

• CMS exotic Higgs results:
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
SM Higgs boson: LHC production and decay

- Higgs boson can be produced via several processes and decay into several final states.
- Observed mass 125 GeV presents a particular diversity of decay channels.  
  → multiple probes for studying the Higgs!

<table>
<thead>
<tr>
<th>process</th>
<th>13 TeV</th>
</tr>
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<tbody>
<tr>
<td>ggF</td>
<td>49 pb</td>
</tr>
<tr>
<td>VBF</td>
<td>3.8 pb</td>
</tr>
<tr>
<td>VH</td>
<td>2.3 pb</td>
</tr>
<tr>
<td>ttH</td>
<td>0.51 pb</td>
</tr>
</tbody>
</table>

- SM Higgs branching ratios

- cc, 2.9
- WW, 21.5
- ZZ, 2.6
- gg, 8.6
- Zγ, 0.2
- γγ, 0.2
SM Higgs: Mass and couplings

Run2 Higgs mass measurements:

Run2 Higgs coupling strength measurements:

CMS

<table>
<thead>
<tr>
<th>Run 1: 5.1 fb⁻¹ (7 TeV) + 19.7 fb⁻¹ (8 TeV)</th>
<th>Run 1: 5.1 fb⁻¹ (7 TeV) + 19.7 fb⁻¹ (8 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016: 35.9 fb⁻¹ (13 TeV)</td>
<td>2016: 35.9 fb⁻¹ (13 TeV)</td>
</tr>
</tbody>
</table>

- **Run 1 H → γγ**
  - Total: 124.70 ± 0.34 (± 0.31) GeV
  - Stat. Only: 124.70 ± 0.34 (± 0.31) GeV
- **Run 1 H → ZZ → 4l**
  - Total: 125.59 ± 0.46 (± 0.42) GeV
  - Stat. Only: 125.59 ± 0.46 (± 0.42) GeV
- **Run 1 Combined**
  - Total: 125.07 ± 0.28 (± 0.26) GeV
  - Stat. Only: 125.07 ± 0.28 (± 0.26) GeV
- **2016 H → γγ**
  - Total: 125.78 ± 0.26 (± 0.18) GeV
  - Stat. Only: 125.78 ± 0.26 (± 0.18) GeV
- **2016 H → ZZ → 4l**
  - Total: 125.26 ± 0.21 (± 0.19) GeV
  - Stat. Only: 125.26 ± 0.21 (± 0.19) GeV
- **2016 Combined**
  - Total: 125.46 ± 0.16 (± 0.13) GeV
  - Stat. Only: 125.46 ± 0.16 (± 0.13) GeV
- **Run 1 + 2016**
  - Total: 125.38 ± 0.14 (± 0.11) GeV
  - Stat. Only: 125.38 ± 0.14 (± 0.11) GeV

**Ratio to SM**

- Vector bosons
- 3rd generation fermions
- Muons
- Dashed line: SM Higgs boson
SM Higgs: Evidence for Higgs to $\mu\mu$

First evidence for $H \rightarrow \mu\mu$:  

- SM BR($H \rightarrow \mu\mu$) = $2.18 \times 10^{-4}$. Challenging signature.  
- Analysis done for all 4 Higgs production channels.  
- Backgrounds suppressed due to forward jets, leading to highest sensitivity in the vector boson fusion channels.  

- $3\sigma$ excess.  
- The most recent discovery.  
- Run1+Run2 results combined to obtain the best sensitivity.
SM Higgs: Higgs to invisible

H → invisible: SM BR ~0.1%. Powerful probe for BSM, e.g. light DM coupling to Higgs.

- Measure in conjunction with a taggable object: Z, forward jets, high p_T jet, etc.
- Most sensitive channel is vector boson fusion: 2 forward jets + E_T^{miss}. Challenging due to soft E_T^{miss}.

Run2 analyses exclusion limits summary:
Current limit: ~20-25%

HL-LHC: Optimized VBFH analysis.
m_{jj} > 2500 GeV.
Exclusion limits on BH(H → inv) vs. minimum E_T^{miss} threshold.

Can be interpreted in various DM models.
SM Higgs: diHiggs and Higgs self coupling

HH allows to measure trilinear H self coupling $\lambda_{HHH} = m_H^2/2v \rightarrow$ constrain H potential shape, nature of EWSB. Also sensitive to BSM physics.

Combinations with Run2 2016 measurements reach $\sigma/\sigma_{SM} = 10$.

Full Run2 measurements in progress.

Observation requires HL-LHC and combining all channels. Expect $4\sigma$ from ATLAS+CMS for ggH. Most sensitive decay channels: $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$.

$V(\Phi) = m^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$

Coupling modifier:

$\kappa_\lambda = c_{hh} = \lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$

Run2 2016 combination

HL-LHC projections

ATLAS and CMS

3000 fb$^{-1}$ (14 TeV)

HL-LHC prospects

ATLAS

CMS

Combination

Stat. uncertainty
BSM Higgses: Heavy Higgses in 2HDM

Extend SM with 2 Higgs doublets. Doublets couple to SM fermions in 4 different ways.

→ Results in 5 Higgs bosons: CP-even h (~h_{125}), neutral H, charged H^±, CP-odd A.

MSSM is a Type II 2HDM: One doublet couples to up-type, other couples to down-type fermions.

→ Higgs sector determined at tree level by 2 parameters: \( m_A \) and \( \tan\beta = v_1/v_2 \).

Look for excess in invariant mass (for H/A/H^± → visible) or transverse mass (H/A/H^± → visible + neutrino).

Run2 direct searches for heavy H/A.

HL-LHC search for H/A → ττ (\( τ_{lep}τ_{had} + τ_{had}τ_{had} \) channels). Increased sensitivity wrt Run2.
BSM Higgses: 2HDM+S

MSSM Higgs sector + singlet field ← Motivated by next-to-MSSM Higgs sector.

7 Higgs bosons: \( h_1, h_2, H_3, A_2, a_1, H^\pm \). \( h_{125} \rightarrow aa \) possible in NMSSM, where \( a \) is pseudoscalar or scalar.

Many final states analyzed by varying \( m_a \) up to \( m_{h_{125}}/2 \). Low \( m_a \) → boosted a decay products.

Search for excess in 4 object invariant mass (\( aa \rightarrow \text{visible} \)) or transverse mass (\( aa \rightarrow \text{vis + invis} \)).

HL-LHC search for \( H \rightarrow aa \rightarrow bb\tau\tau, \mu\mu\tau\tau \) (hadronic and leptonic \( \tau \) decays). Sensitivity of the order of SM \( h_{125} \) cross section.
BSM Higgses: Charged Higgs in Higgs triplet models

VBF production of charged and doubly-charged Higgses $H^{±±}$, $H^{±}$, decaying to vector bosons. $H^{±±}$, $H^{±}$ mass degenerate

- 2 same charge leptons or 3 leptons + 2 VBF jets.

CMS-HIG-20-017

Extract signal via maximum likelihood fit to $m_{jj}$ & $m_{VV}$.

No excess.

Interpreted in Georgi-Machacek (GM) model.

Exclude $m_{H^{±±}} < ~2.4$ TeV

$m_{H^{±}} < ~1.6$ TeV.
BSM physics

- CMS SUSY results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults
- CMS Exotica results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
- CMS Beyond 2 Generations results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G
Supersymmetry (SUSY): Overview

SUSY is a symmetry between bosons and fermions.

- Every SM particle has a superpartner with a different spin.
- SUSY is a broken symmetry: SUSY particles are heavier than SM particles.
- SUSY offers solutions to deficiencies of the SM.

$O(100)$ free parameters $\rightarrow$ different sparticle masses, cross sections, branching ratios $\rightarrow$ rich phenomenology and a broad set of signatures.

LHC searches:

- Large diversity of searches targeting many flavors of SUSY and mass spectra.
- Interpreted using simplified models: Effective Lagrangian descriptions defined by sparticle masses, production and decay processes.
- Set upper limits on cross sections.
**SUSY: Characteristic signatures**

- **R parity conserving SUSY:** Sparticle pair production, lightest SUSY particle is stable (dark matter candidate.)
- **High missing transverse energy** $E_T^{\text{miss}}$ (or momentum $p_T^{\text{miss}}$), **high object multiplicities, high visible transverse momentum**...

**RPV, compressed SUSY:** multiple particles; small mass differences between sparticles $\rightarrow$ **low** $E_T^{\text{miss}}$. 
Gluino, top squark and chargino/neutralino vs. neutralino mass limits: Decay BRs = 1 unless stated.

- Searches in diverse final states with jets, leptons, photons, giving complementary sensitivity.
- Multiple disjoint search regions defined by object multiplicities and kinematic variables.

Gluino vs NT1:

Top squark vs NT1:

CH1/NT2 vs NT1:

At HL-LHC, exclusion limits are expected to increase by ~O(few 100 GeV) - 1TeV.
Compositeness models: Leptons and quarks are composite objects made of more fundamental constituents.

- Postulate excited states of quarks and leptons.
- New interactions occur above compositeness scale $\Lambda$.

Excited $b^*$ search via dijet resonances with at least one jet coming from a $b$ quark.

- Energetic $b$ quarks in jets identified by a deep neural network.
- Look for excess in dijet inv. mass over fit to BG.

Exclude $m_{b^*} < 4$ TeV.

(Also interpreted for $Z'$ in sequential standard model.)
New bosons: Resonances with vector bosons

Search for heavy resonances X decaying to ZW. ZZ pairs:
- \( Z \rightarrow \nu \nu, \text{boosted } Z/W \rightarrow jj \): Merged jets + \( E_{T}^{\text{miss}} \) + forward jets.
- Extract signal in a fit to transverse mass of merged jet + \( E_{T}^{\text{miss}} \). No excess.

Spin-2 bulk graviton < 1.8 TeV
Radion < 3.1 TeV
Graviton < 1.2 TeV
W' < 3.0 TeV
W' < 4.0 TeV

Search for heavy resonances X decaying to WW, WZ, WH pairs:
- \( W \rightarrow l\nu, \text{boosted } W/Z/H \rightarrow jj \): Lepton + merged jet final state. Dedicated VBF selection via forward jets.
- Extract signal in 2D fit to \( m_{jj} \) vs \( m_{\text{diboson}} \). No excess.

Spin-2 bulk graviton < 1.8 TeV
Radion < 3.1 TeV
Z' < 3.9 TeV
W' < 4 TeV
W' < 3.9 TeV
Some BSM models predict long-lived particles decaying away from the interaction point.

- Leads to unique and challenging signatures.
- Measure timing or displacement information for an object.

Many searches at Runs 1&2.

At HL-LHC, new Phase2 tracking and timing detectors, along with extended detector coverage and sensitivity will allow a wider diversity and reach.
LLPs: SM Higgs decays to long-lived BSM particles

Complementarity of different LLP searches for SM Higgs decays to LL BSM particles. Different searches sensitive to different LLP proper lifetime ranges.
LLPs: Phase2 timing detectors

CMS MIP Timing Detector: MIP timing with 30ps precision. Acceptance of $|\eta| < 3$ for $p_T$, $p < 0.7$ GeV in barrel/endcap.

Displaced photons from GMSB (gauge-mediated SUSY breaking models): $\tilde{\chi}_0 \rightarrow G + \gamma$

Use time of arrival of photons to MTD to discriminate signal $\rightarrow$ determine neutralino time of flight.

Increased sensitivity with MTD to short $c\tau$ and high masses.

Heavy charged stable particles:

Long-lived GMSB stau:

Measure particle velocity $\beta$.

MTD improves time resolution.

Discriminate signals, extract mass.
• ~1000 SM measurements and new physics searches available with Run1/Run2 CMS data covering a large diversity of models and signatures.
  • Many precision measurements; no significant BSM signal observed.
• Preparations for Run3 ongoing.
• HL-LHC will offer unprecedented physics opportunities:
  • All technical design reports for Phase2 are ready.
  • Physics projections are ongoing.

“Data are coming! Data are coming!”

Summary and outlook
Extra slides
## HL-LHC exotic particles reach summary

### Model

<table>
<thead>
<tr>
<th>Model</th>
<th>spin</th>
<th>95% CL Limit (solid), 5 σ Discovery (dash)</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>KK → 4b</td>
<td>2</td>
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<td>6.1.1</td>
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<tr>
<td>HVT → VV</td>
<td>1</td>
<td></td>
<td>6.4.4</td>
</tr>
<tr>
<td>G_RS → W⁺W⁻</td>
<td>1</td>
<td></td>
<td>6.4.6</td>
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<tr>
<td>G_RS → t̅t̅</td>
<td>1</td>
<td></td>
<td>6.2.2</td>
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<tr>
<td>Z_TC2 → t̅t̅</td>
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<td></td>
<td>6.2.3</td>
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<tr>
<td>Z_SSM → tt</td>
<td>1</td>
<td></td>
<td>6.2.4</td>
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<td>Z_SSM → t̅t̅</td>
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<td>Z_SSM → τ⁺τ⁻</td>
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<tr>
<td>W_SSM → τν</td>
<td>1</td>
<td></td>
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<tr>
<td>W_SSM → ν̅ν̅</td>
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<td>6.2.7</td>
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<tr>
<td>W_R → t̅b → b̅b̅ν</td>
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### Additional Models

<table>
<thead>
<tr>
<th>Model</th>
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<th>95% CL Limit (solid), 5 σ Discovery (dash)</th>
<th>Section</th>
</tr>
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<td>Q → jj</td>
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<tr>
<td>ν_Heavy</td>
<td>1</td>
<td></td>
<td>5.1.1</td>
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<tr>
<td>ℓ → γ</td>
<td>1</td>
<td></td>
<td>6.3.1</td>
</tr>
</tbody>
</table>

- **HE-LHC**
  - $\sqrt{s} = 27$ TeV, $L = 15$ ab⁻¹
  - 5.2.3 5.2.4

- **HL-LHC**
  - $\sqrt{s} = 14$ TeV, $L = 3$ ab⁻¹
  - 5.1.1 5.1.1

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*arXiv:1812.07831*
CMS Run2 long-lived particles reach summary

### Overview of CMS long-lived particle searches

<table>
<thead>
<tr>
<th>CMS Preliminary</th>
<th>3 - 140 fb⁻¹ (8, 13 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPV UDD, ( g \to t \bar{b} s ), ( m_t = 2500 ) GeV</td>
<td>140 fb⁻¹ (13 TeV)</td>
</tr>
<tr>
<td>RPV UDD, ( g \to t \bar{b} s ), ( m_t = 2500 ) GeV</td>
<td>132 fb⁻¹ (13 TeV)</td>
</tr>
<tr>
<td>RPV UDD, ( g \to t \bar{b} s ), ( m_t = 1600 ) GeV</td>
<td>140 fb⁻¹ (13 TeV)</td>
</tr>
<tr>
<td>RPV UDD, ( t \to g b ), ( m_t = 1600 ) GeV</td>
<td>132 fb⁻¹ (13 TeV)</td>
</tr>
<tr>
<td>RPV LQD, ( t \to b l ), ( m_t = 600 ) GeV</td>
<td>36 fb⁻¹ (13 TeV)</td>
</tr>
<tr>
<td>RPV LQD, ( t \to b l ), ( m_t = 600 ) GeV</td>
<td>3 fb⁻¹ (13 TeV)</td>
</tr>
<tr>
<td>RPV LQD, ( t \to b l ), ( m_t = 1600 ) GeV</td>
<td>132 fb⁻¹ (13 TeV)</td>
</tr>
<tr>
<td>GMSB, ( g \to q \bar{q} Z ), ( m_Z = 2450 ) GeV</td>
<td>132 fb⁻¹ (13 TeV)</td>
</tr>
<tr>
<td>GMSB, ( g \to q \bar{q} G ), ( m_g = 2100 ) GeV</td>
<td>137 fb⁻¹ (13 TeV)</td>
</tr>
<tr>
<td>Split SUSY, ( g \to q \bar{q} Z ), ( m_Z = 1300 ) GeV</td>
<td>36 fb⁻¹ (13 TeV)</td>
</tr>
<tr>
<td>Split SUSY (HSCP), ( f_0 = 0.1 ), ( m_{\chi^0} = 1600 ) GeV</td>
<td>133 fb⁻¹ (13 TeV)</td>
</tr>
<tr>
<td>mGMSB (HSCP) ( \tan \beta = 10 ), ( \mu &gt; 0 ), ( m_{\chi^0} = 247 ) GeV</td>
<td>13 4fb⁻¹ (13 TeV)</td>
</tr>
<tr>
<td>Stopped ( g \to q \bar{q} g ), ( m_{q \bar{q}} = 700 ) GeV</td>
<td>39 fb⁻¹ (13 TeV)</td>
</tr>
<tr>
<td>Stopped ( g \to q \bar{q} g ), ( f_0 = 0.1 ), ( m_{\chi^0} = 1300 ) GeV</td>
<td>39 fb⁻¹ (13 TeV)</td>
</tr>
<tr>
<td>Stopped ( g \to q \bar{q} g ), ( \mu &gt; 0 ), ( m_{\chi^0} = 940 ) GeV</td>
<td>39 fb⁻¹ (13 TeV)</td>
</tr>
<tr>
<td>AMSB, ( \chi^{\pm} \to \chi^0 \pi^\pm ), ( m_{\chi^0} = 700 ) GeV</td>
<td>140 fb⁻¹ (13 TeV)</td>
</tr>
<tr>
<td>GMSB+SPSB, ( \chi^{\pm} \to \chi^0 \bar{g} ), ( m_{\chi^0} = 400 ) GeV</td>
<td>77 fb⁻¹ (13 TeV)</td>
</tr>
</tbody>
</table>

### 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.

**Moriond 2021**
HL-LHC SUSY reach summary

<table>
<thead>
<tr>
<th>Model</th>
<th>$\xi, \mu, \tau, \gamma$</th>
<th>Jets</th>
<th>Mass limit</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gluino</td>
<td>0</td>
<td>4 jets</td>
<td>2.9 (3.2) TeV</td>
<td>2.1.1</td>
</tr>
<tr>
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<td>0</td>
<td>4 jets</td>
<td>5.2 (6.7) TeV</td>
<td>2.1.1</td>
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<tr>
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<td>0</td>
<td>Multi</td>
<td>2.3 (2.5) TeV</td>
<td>2.1.3</td>
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<tr>
<td></td>
<td>0</td>
<td>Multi</td>
<td>2.4 (2.6) TeV</td>
<td>2.1.3</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>Multi</td>
<td>5.5 (5.9) TeV</td>
<td>2.4.2</td>
</tr>
</tbody>
</table>

| Stop | 0 | Multi | 1.4 (1.7) TeV | 2.1.2, 2.1.3 |
| | 0 | Multi | 0.6 (0.8) TeV | 2.1.2 |
| | 0 | Multi | 3.1 (3.6) TeV | 2.4.2 |

| Eggi or Higgsino | 2 c, μ | 0 | 0.56 (0.64) TeV | 2.1.2 |
| | 3 c, μ | 0 | 0.92 (1.1) TeV | 2.2.2 |
| | 1 c, μ | 2.3 jets | 1.08 (1.26) TeV | 2.2.3 |
| | 2 c, μ | - | 0.9 TeV | 2.4.2 |

| Eggi or Higgsino | 2 c, μ | 1 jet | 0.25 (0.36) TeV | 2.2.5.1 |
| | 2 c, μ | 1 jet | 0.42 (0.55) TeV | 2.2.5.1 |
| | 2 c, μ | 1 jet | 0.21 (0.35) TeV | 2.2.5.2 |

| WW | 2 c, μ | 0 | 0.86 (1.08) TeV | 2.4.2 |

| Site | 2 c, μ | - | 0.53 (0.73) TeV | 2.3.1 |
| | 2 c, μ | - | 0.47 (0.65) TeV | 2.3.2 |
| | 2 c, μ | - | 0.81 (1.15) TeV | 2.3.4 |

| Long-lived particles | Disapp. trk. | 1 jet | 0.9 (1.1) TeV | 4.1.1 |
| | Disapp. trk. | 1 jet | 0.4 (0.5) TeV | 4.1.1 |
| | Disapp. trk. | 1 jet | 0.88 (0.9) TeV | 4.1.3 |
| | Disapp. trk. | 1 jet | 2.0 (2.1) TeV | 4.1.3 |
| | Disapp. trk. | 1 jet | 0.28 (0.3) TeV | 4.1.3 |
| | Disapp. trk. | 1 jet | 0.55 (0.6) TeV | 4.1.3 |
| | R-hadron, $\xi \to \gamma$ | 0 | 3.4 TeV | 4.2.1 |
| | R-hadron, $\xi \to \gamma$ | 0 | 2.6 TeV | 4.2.1 |
| | GMSB $p \to \gamma$ | - | 0.2 TeV | 4.2.2 |

Simulation Preliminary

$\sqrt{s} = 14, 27$ TeV

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