Searches for leptoquarks and other leptonic final states

Halil Saka (University of Cyprus) on behalf of the CMS Collaboration
May 23, 2023
LQs in BSM landscape

- Leptoquarks are colored states with both baryon and lepton quantum numbers
  - models with larger symmetry groups / unification of matter ( leptons ↔ quarks )
    - GUTs → Vector LQs may emerge as gauge bosons
    - → Scalar LQs may emerge in the symmetry breaking sector
  - compositeness theories (LQs may emerge as bound states)
  - LQ-like states also appear in the MSSM Lagrangian with R-parity violating terms
  - allowed in SM Lagrangian when extended to all renormalizable interactions

- At the LHC, novel lepton+jet resonances, among other signatures.

  Low energy bounds, including proton decay, can be avoided by:
  - couplings to one generation of leptons/quarks
  - couplings to third generation fermions (generally weaker constraints)
  - approximate alignment of couplings with SM Yukawa couplings

  Simultaneous violation of these may lead to QLFV
Searches with full Run2 data from CMS cover:

- **off-diagonal** couplings in flavor
- **non-QCD production** modes → indirect signatures
- **non-minimal models** with more than one coupling (motivated by tensions in LFU)
- emphasis on couplings with **third generation fermions** today!

*all with Run 2 dataset*
LQ-\(\tau\)-b / LQ-\(\tau\)-q

- First search for LQ using lepton-quark collisions!
  - possible due to recent advances in precision of lepton PDFs

- Event selection:
  - single lepton (c, \(\mu\), \(\tau\)_\(\nu\)) + high \(p_T\) jet
  - veto events with additional leptons

(complementarity to single/pair production)

- Two categories/models based on “b-tag” of leading jet
  - probes both \(\lambda_{rb}\) and \(\lambda_{rq}\)

- Unambiguous “LQ” resonance:
  - require \(p_T^{\text{miss}}\) to be aligned with \(\tau\) lepton

NEW RESULT! EXO-22-018

A crucial aspect which prevented so far to fully explore the phenomenology offered by lepton initiated processes is the lack of a precise determination of the lepton densities

\[\text{[Bertone,Carranza,Pagani,Zaro, JHEP 11 (2019) 194]}\]

1994 paper: very interesting, but almost forgotten...

[Slide borrowed from L. Buonocore et al.](https://indico.cern.ch/event/921962/)

LQ-τ-b / LQ-τ-q

- Single-lepton + high $p_T$ jet selection → $W+bb$ background.
  - Normalization is obtained from data in a dedicated selection (≈7% unc.)
- Other irreducible backgrounds are from simulation, with theoretical cross-sections.
- Data driven estimate of misidentified lepton candidates (10-30% unc.)

**BDT** for model-specific event selection:
- Angles between physics objects
- Ratios of object $p_T$'s with respect to each other, or w.r.t. collinear mass
  - Limited dependency on LQ mass

**Collinear mass** is the final discriminant (resonance at the LQ mass)
- $\gtrsim$10% resolution over the range of probed couplings
Constraints on $\text{LQ} - \tau - b$ coupling, complementary to the dilepton searches (next)

Differences due to the quark content of the proton PDF

First direct limits on $\text{LQ} - \tau - q$ couplings with light flavored quarks (similar acceptance)

Probing multi-TeV LQ phase-space otherwise inaccessible for direct production at the LHC
**LQ-τ-q / ν-q**

- Benchmark analysis for a "heavy W-like" signature, with high $p_T$ lepton and $p_T^{\text{miss}}$
  - traditionally interpreted for $W'$ of SSM (broad enhancement in $M_T$)

- Event selection:
  - one high $p_T$ hadronic tau lepton candidate ($p_T > 130/190$ GeV)
  - require $p_T^{\text{miss}}$ to be back to back with $\tau$ lepton, compatible in magnitude
  - veto events with additional electrons or muons

- Dominant background is $W$+jets:
  - estimated by MC (corrected to NNLO QCD + NLO EW)
  - mass dependent uncertainty (5-20%)
  - PDF uncertainties dominate at high $m_T$ (50% beyond 1.8 TeV, from NNPDF3.1)

- Data driven estimate of misidentified $\tau_h$ candidates (10-30%)
  - developed in $\ell\tau_h$ events
  - normalization constrained in the fit (100% prefit uncertainty)
Probing phase-space favored by an LQ fit of the charged-current B decay anomalies

\[ \beta_L = \begin{pmatrix} 0 & 0 & \beta_L^{\tau} \\ 0 & \beta_L^{\mu} & \beta_L^{\tau} \\ 0 & \beta_L^{\mu} & 0 \end{pmatrix}, \quad \beta_R = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \beta_R^{\tau} \end{pmatrix} \]

\[ J_{\mu}^L = \beta_L^{\tau} \left( \overline{q}_L \gamma_{\mu} \ell_L^\tau \right) + \beta_L^{\mu} \left( \overline{d}_R \gamma_{\mu} \ell_R^\tau \right) \]

<table>
<thead>
<tr>
<th>Model</th>
<th>Parameter</th>
<th>Expected Limit</th>
<th>Observed Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>LQ best-fit LH+RH, ( g_U = 1.0 )</td>
<td>( m_{1Q} )</td>
<td>645 GeV</td>
<td>515 GeV</td>
</tr>
<tr>
<td>LQ best-fit LH+RH, ( g_U = 2.5 )</td>
<td>( m_{1Q} )</td>
<td>3.0 TeV</td>
<td>2.5 TeV</td>
</tr>
</tbody>
</table>

https://arxiv.org/abs/2103.16558
95% CL upper limits, 16% signal eff.
- Observed
- Median expected
- 68% expected
- 95% expected

Signal efficiency includes the branching fraction of hadronic $\tau$ lepton decays and experimental efficiencies for the signal.

Valid for models with **back-to-back topology** of $\tau_h$ and $p_T^{\text{miss}}$
LQ-τ-b

- Targets three production modes simultaneously, with τ – b couplings

- Resonant channels: $S_{\text{T}}^{\text{MET}}$
  Nonresonant channel: $\chi$

- Event selection:
  - dilepton signal regions ($e\tau_h, \mu\tau_h, \tau_h\tau_h$) with(out) a high $p_T$ jet
  - light-flavored final states ($e\mu, \mu\mu$) used as control selections

- Main categories:
  - b-tagged jet multiplicity (resonant ch.)
  - visible mass $m_{\text{vis}}$ (200-400, 400–600, >600 GeV) (nonresonant ch.)

- Irreducible backgrounds are estimated by MC methods
  - normalized to theoretical cross-sections.

- Data driven estimate of misidentified lepton candidates (10-30%)
  - W+jets and QCD multijet contributions
**LQ-τ-b**

- **Angular χ variable** is used to probe **nonresonant** signal: \( \chi \equiv \exp \left( |y(\tau_1) - y(\tau_2)| \right) \)
- **LQ Yukawa coupling** dominate sensitivity at **large mass**

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**Events / 2**

- CMS Preliminary
- 137 fb\(^{-1}\) (13 TeV)

- \( \tau_\ell \tau_\ell \), 400 < \( m_{\text{vis}} \) < 600 GeV

**Obs. / Bkg.**

- Small excess, with contributions from multiple dilepton channels

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**CMS Preliminary**

- LQ, 2000 GeV, \( \lambda=2.5 \), \( \beta=1 \), \( \kappa=1 \)
- Z \rightarrow \tau_\ell \tau_\ell
- τ and single top
- τ \rightarrow τ \_ fakes
- Drell-Yan with \( l \rightarrow \tau_\ell \)
- Diboson
- Bkg. unc.

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**Nonresonant channel: \( \chi \)**

- \( \lambda = 1 \)
- 137 fb\(^{-1}\) (13 TeV)

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**λ = 2.5**

- 95% CL upper limit on \( σ_{\text{scalar}} \) [pb]

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**λ = 1**

- 95% CL upper limit on \( σ_{\text{scalar}} \) [pb]

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Hall Saka (University of Cyprus)

Searches for leptoquarks and other leptonic final states at CMS - LHCP 2023
Probing phase-space favored by an LQ fit of the charged-current B decay anomalies

CMS Preliminary
137 fb⁻¹ (13 TeV)

95% CL upper limits
- Observed
- Expected
Scalar, \( \beta = 1 \)

68% expected

Coupling strength \( \lambda \)

Leptoquark mass [GeV]

~3.5 \( \sigma \) excess at large coupling values

→ details are to appear in a paper soon!
- not signal-like in the strict sense of the probed LQ model
- mostly insensitive to interference effects, and systematic uncertainties

CMS Preliminary
137 fb⁻¹ (13 TeV)

95% CL upper limits
- Observed
- Expected
Vector, \( \beta = 1, \kappa = 0 \)

68% expected

Coupling strength \( \lambda \)

Leptoquark mass [GeV]
- A broad BSM search targeting **multilepton** events
  - Type-III seesaw heavy fermions
  - Vector-like leptons
  - **Leptoquarks** (top-philic)

- Event selection:
  - **three/four lepton** signatures \((e, \mu, \tau_h)\) with minimum \(p_T\) of 10-20 GeV.
  - events are categories based on **lepton charge, mass, and flavor** characteristics.

- Irreducible bckg. processes are taken from simulation
  - WZ, ZZ, t\(\bar{t}\)Z, Z\(\bar{g}\), (normalized to data)

- **Data driven** estimate of events with **misid. lepton**
  - jet \(\rightarrow e, \mu, \tau_h\) (matrix method)
Inclusive categories

Selection-based, ST binning

CMS Advanced S, Table [3L 1S]

Events / Bin

CMS Advanced S, Table [3L 2B]

Events / Bin

BDT-based binning

CMS

LQ-M \( H_{L} + H_{L} = 1 \) BDT regions [3L,2L1T,1L2T]

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

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

Signal discrimination via dual approach:
- selection based approach with \( L_T, p_T^{\text{miss}}, H_T, S_T \) (transverse momentum variables), and \( N_f, N_b \)
- machine learning based (BDT) discriminator is built for LQ signal (transverse or angular variables of physics objects)
Limits on pair-production mode: \( \text{LQ} - e/\mu - t \sim 1.4 \text{ TeV} \)
\( \text{LQ} - \tau - t \sim 1.1 \text{ TeV} \)
Summary

- **Leptoquarks** are among the plausible/desirable extensions of the SM boson sector:
  - matter unification
  - revival due to observed tensions in the flavor sector
  - provide appealing detector signatures

- A multi-prong LQ search program at CMS:
  - lepton+jet & neutrino+jet
    final states are both being targeted
  - models with third generation fermion couplings

- Breaking tradition with the most minimal models:
  - non-QCD production modes
  - flavor off-diagonal couplings
  - simultaneous nonzero couplings
  - LQs with other BSM particles

*Stay tuned!*
Backup
Overview of CMS LQ search program

CMS Summary Plots

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included.)

Scalar   Vector(k=0)   Vector(k=1)

Halli Saka (University of Cyprus)

Searches for leptoquarks and other lepton final states at CMS - LHCP 2023
Run1+2+3 pp collisions at a glance

Total integrated luminosity (fb⁻¹)

Date (UTC)

Recorded luminosity (fb⁻¹/10)

Mean number of interactions per crossing

Hall Saka (University of Cyprus)
Leptoquark representations in mBRW

<table>
<thead>
<tr>
<th>Leptoquark</th>
<th>Spin</th>
<th>F</th>
<th>SU(3) (<em>{C} \otimes) SU(2) (</em>{L} \otimes) U(1) (_{Y}) representation</th>
<th>(Q_{EM})</th>
<th>Coupling</th>
<th>Decay mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>(S_{1})</td>
<td>0</td>
<td>2</td>
<td>(3,1,–2/3)</td>
<td>–1/3</td>
<td>(\lambda_{L,R}(u,e_{L,R})), (-\lambda_{L}(d,\nu_{e}))</td>
<td>(t\nu), (b\nu)</td>
</tr>
<tr>
<td>(\tilde{S}_{1})</td>
<td>0</td>
<td>2</td>
<td>(3,1,–8/3)</td>
<td>–4/3</td>
<td>(\lambda_{R}(d,e_{R}))</td>
<td>(b\tau)</td>
</tr>
<tr>
<td>(S_{2})</td>
<td>0</td>
<td>0</td>
<td>(3,2,–7/3)</td>
<td>–2/3</td>
<td>(\lambda_{L}(u,\nu_{e}))</td>
<td>(\tilde{t}\nu), (b\tau)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>–5/3</td>
<td>(\lambda_{L,R}(u,e_{L,R}))</td>
<td>(t\tau)</td>
</tr>
<tr>
<td>(\tilde{S}_{2})</td>
<td>0</td>
<td>0</td>
<td>(3,2,–1/3)</td>
<td>+1/3</td>
<td>(\lambda_{L}(d,\nu_{e}))</td>
<td>(b\nu)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>–2/3</td>
<td>(\lambda_{L}(d,e_{L}))</td>
<td>(b\tau)</td>
</tr>
<tr>
<td>(S_{3})</td>
<td>0</td>
<td>2</td>
<td>(3,3,–2/3)</td>
<td>+2/3</td>
<td>(\sqrt{2}\lambda_{L}(u,\nu_{e}))</td>
<td>(t\nu)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>–1/3</td>
<td>(-\lambda_{L}(u,e_{L}))</td>
<td>(t\tau), (b\nu)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>–4/3</td>
<td>(-\sqrt{2}\lambda_{L}(d,e_{L}))</td>
<td>(b\tau)</td>
</tr>
<tr>
<td>(\nu_{1})</td>
<td>1</td>
<td>0</td>
<td>(3,1,4/3)</td>
<td>–2/3</td>
<td>(\lambda_{L,R}(d,e_{L,R})), (\lambda_{L}(u,\nu_{e}))</td>
<td>(b\tau), (\tilde{t}\nu)</td>
</tr>
<tr>
<td>(\tilde{\nu}_{1})</td>
<td>1</td>
<td>0</td>
<td>(3,1,–10/3)</td>
<td>–5/3</td>
<td>(\lambda_{R}(u,e_{R}))</td>
<td>(\tilde{t}\tau)</td>
</tr>
<tr>
<td>(\nu_{2})</td>
<td>1</td>
<td>2</td>
<td>(3,2,–5/3)</td>
<td>–1/3</td>
<td>(\lambda_{L}(d,\nu_{e}))</td>
<td>(b\nu), (t\tau)</td>
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<td>(\lambda_{L,R}(d,e_{L,R}))</td>
<td>(b\tau)</td>
</tr>
<tr>
<td>(\tilde{\nu}_{2})</td>
<td>1</td>
<td>2</td>
<td>(3,2,1/3)</td>
<td>+2/3</td>
<td>(\lambda_{L}(u,\nu_{e}))</td>
<td>(t\nu)</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td>–5/3</td>
<td>(-\sqrt{2}\lambda_{L}(u,e_{L}))</td>
<td>(t\tau)</td>
</tr>
</tbody>
</table>

Table 2.1: Scalar and vector LQs as defined in the mBRW model. Representations under the SM gauge group are labelled by the dimensions of SU(3)\(_{C}\) and SU(2)\(_{L}\) representations, and the U(1)\(_{Y}\) hypercharge Y, respectively. Fermion number is defined as \(F = 3B + L\), and electric charge, \(Q_{EM} = T^{3} + Y/2\), is in units of proton charge, |e|, where \(T^{3}\) is the third eigenvalue component of the SU(2) representation. Decay mode is provided assuming third generation LQs only.
The flavor issue: $R(D^{(*)})$, $R(K^{(*)})$

The deviation w.r.t. the SM at $3.2\sigma$ for the combination of $R(D)-R(D^*)$

https://hflav.web.cern.ch/content/semileptonic-b-decays
https://cds.cern.ch/record/2857546 (LHCb-PAPER-2022-052, for the most recent measurement)
Best-fit scenarios to ‘b anomalies’

\[
\beta_L = \begin{pmatrix}
0 & 0 & \beta_{d\tau}^L \\
0 & \beta_{s\mu}^L & \beta_{s\tau}^L \\
0 & \beta_{b\mu}^L & \beta_{b\tau}^L
\end{pmatrix}, \quad \beta_R = \begin{pmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & \beta_{b\tau}^R
\end{pmatrix}
\]

\[
J^U_{\mu} = \beta_{L}^{i\alpha} (\bar{q}^i_L \gamma_{\mu} e^\alpha_L) + \beta_{R}^{i\alpha} (\bar{d}^i_R \gamma_{\mu} e^\alpha_R)
\]

ex/ https://arxiv.org/abs/2103.16558

Best-fit LH couplings

\[
\beta_L = \begin{pmatrix}
0 & 0 & -0.04 \\
0 & 0.014 & 0.19 \\
0 & -0.15 & 1
\end{pmatrix}, \quad \beta_R = \begin{pmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{pmatrix}
\]

Best-fit LH+RH couplings

\[
\beta_L = \begin{pmatrix}
0 & 0 & -0.04 \\
0 & 0.03 & 0.21 \\
0 & -0.21 & 1
\end{pmatrix}, \quad \beta_R = \begin{pmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & -1
\end{pmatrix}
\]

Democratic couplings

\[
\beta_L = \begin{pmatrix}
1 & 1 & 1 \\
1 & 1 & 1 \\
1 & 1 & 1
\end{pmatrix}, \quad \beta_R = \begin{pmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{pmatrix}
\]
VLL / Type-III Seesaw

Doublet: $\tau', \nu'$

Singlet: $\tau'$

$\Sigma^+\Sigma^0$

**Limits on VLL doublet ~ 1 TeV**
singlet ~ around 125-170 GeV

**Limits on Type-III Seesaw heavy fermions:**
~890-1065 GeV (per flavor scenario)
Resonances in multilepton events

CMS Preliminary

$W\phi(\rightarrow \tau\tau)$, Pseudoscalar $\phi$

$Z\phi(\rightarrow ee)$, Pseudoscalar $\phi$

$t\phi(\rightarrow \mu\mu)$, Pseudoscalar $\phi$

95% CL upper limits
- Observed
- Median expected

68% expected
- Expected

95% expected
- Expected

Same machinery as in EXO-21-002
LQ-τ-b / ν-t

- "Third generation" vector leptoquarks
  - pair + single production mode, with $\beta = 0.5$
  - Couplings only to third generation fermions (bτ, tν or bν, tτ)

- Dilepton final state, with resolved/merged top quark decays $\rightarrow t\tau ν(b)$

---

Most stringent limits on LQ mass $\sim 1.4$ TeV for $\beta = 0.5$
- Targeting final states with **high hadronic activity** (jets and $p_T^{miss}$)
  - categories (b-tagged) jet multiplicity, and $H_T$
  - background estimated by data driven methods (lost lepton, QCD, $Z \rightarrow \nu\nu$)

**Constraints on $LQ \rightarrow q\nu$ decays for all quark flavors!**
Table 2: Best-fit LQ cross sections $\sigma$ for various masses and coupling strengths $\lambda$, and the corresponding significance $z$ (given in standard deviations) for different production modes individually, as well as their combination.

<table>
<thead>
<tr>
<th>Signal</th>
<th>$m_{LQ} = 1400,\text{GeV}$</th>
<th>$m_{LQ} = 2000,\text{GeV}$</th>
<th>$\sigma$ [pb]</th>
<th>$\sigma$ [fb]</th>
<th>$z$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scalar</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pair</td>
<td>$0.24^{+0.47}_{-0.45}$</td>
<td>$0.5$</td>
<td>$0.22^{+0.41}_{-0.39}$</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Single, $\lambda = 1$</td>
<td>$1.15^{+0.92}_{-0.68}$</td>
<td>$1.3$</td>
<td>$0.64^{+0.65}_{-0.65}$</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Single, $\lambda = 2.5$</td>
<td>$9.1^{+5.5}_{-5.3}$</td>
<td>$1.7$</td>
<td>$18^{+1}_{-11}$</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Nonres.</td>
<td>$70^{+23}_{-22}$</td>
<td>$3.4$</td>
<td>$63^{+20}_{-19}$</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>Total, $\lambda = 1$</td>
<td>$1.7^{+1.9}_{-1.8}$</td>
<td>$0.9$</td>
<td>$9.6^{+5.2}_{-5.9}$</td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>Total, $\lambda = 2.5$</td>
<td>$43^{+15}_{-16}$</td>
<td>$2.9$</td>
<td>$62^{+20}_{-19}$</td>
<td>3.4</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Resonant</th>
<th>Nonresonant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of jets, $p_T &gt; 50,\text{GeV}$</td>
<td>$\geq 1j$</td>
<td>$\geq 1j$</td>
</tr>
<tr>
<td>Number of $b$ tags, $p_T &gt; 50,\text{GeV}$, loose DeepCSV</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>DeepTaus2017v2p1VJet</td>
<td>Medium</td>
<td>VLoose</td>
</tr>
<tr>
<td>DeepTaus2017v2p1V8eSmu</td>
<td>VLoose</td>
<td></td>
</tr>
<tr>
<td>Extra lepton vetoes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Opposite charge</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>$p_T$ of decay candidates</td>
<td>$&gt; 50,\text{GeV}$</td>
<td></td>
</tr>
<tr>
<td>$m_{T\ell}$</td>
<td>$&gt; 100,\text{GeV}$</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>+</td>
</tr>
<tr>
<td>$\Delta\eta_T$</td>
<td>$&lt; 3$</td>
<td></td>
</tr>
<tr>
<td>Discriminating variable</td>
<td>$S_T^{\text{MET}}$</td>
<td>$\chi$</td>
</tr>
</tbody>
</table>
LQ-τ-b

- A broad search targeting **resonant and nonresonant ditau** signatures
  - **Vector leptoquark** with enhanced LQ-tau-b/s couplings (bb, bs, ss initiated production)

- **Event selection:**
  - **two lepton** final states (eμ, eτh, μτh, τhτh)
  - events with additional e/μs are vetoed
  - two categories: 0, >0 “b-tagged” jets
  - further categorization on lepton-\(p_{T}\)\(^{\text{miss}}\) based variables (e.g. \(m_{T}\))

- **“Tau-embedding”** for irreducible pp → ττ background
  - Muons in pp → μμ events are replaced with “simulated” tau lepton decays

- **Data driven** estimate of events with lepton misID
  - jet → e, μ, (same sign method), jet → τh (fake factor)
  - typical uncertainty are \(\mathcal{O}(10)\)%

- Other (irreducible) backgrounds are estimated by MC simulation

---

**Background composition:**

- 0 b-tagged jet: Z, jet → tau MisID (Loose-\(m_{T}\))
- >0 b-tagged jet: tt
\( \tau_h \tau_h + b \) tag

BM2: Bestfit LH+RH

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

CMS

SM interference → reduced sensitivity at high mass.

Signal discrimination:
- total transverse mass \( m_T^{\text{tot}} \) is used as the final discriminant.

\[
m_T^{\text{tot}} = \sqrt{m_T^2(p_T^{T_1}, p_T^{T_2}) + m_T^2(p_T^{\tau_1}, p_T^{\tau_1}) + m_T^2(p_T^{\tau_2}, p_T^{\tau_2})}
\]
**Tau embedding** ($pp \rightarrow \tau\tau$)

**Z → μμ Selection**

Simulate $\tau$ leptons with same kinematic properties as muons.

**Z → μμ Cleaning**

Remove energy deposits from muons.

**Z → ττ Simulation**

Merge simulated and cleaned event.

**Z → ττ Hybrid**

Embedding technique eliminates possible issues with underlying event description, pileup contributions, or production of associated jets.