Cornering natural SUSY with $\sqrt{s} = 13$ TeV data

Les Rencontres de Moriond
*EW Interactions and Unified Theories*
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*On behalf of the ATLAS and CMS collaborations*

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Supersymmetry and Naturalness

The most studied extension of the SM among any BSM theory. Advantages:

- Could solve the hierarchy problem through the one loop stop correction;
- Could unify the fundamental interactions of nature;
- Could provide a dark matter candidate, if R-Parity is conserved;

- Naturalness requirement by the tree-level relation in MSSM:
  \[
  \frac{-m_Z^2}{2} = |\mu|^2 + m_{H_u}^2
  \]

- stops expected to be light (\(<\sim 1 \text{ TeV})
- higgsinos with masses below 350 GeV;
- a not too heavy gluino;

Overview

Analyses covered

- $\tilde{t}\tilde{t}$
- $\tilde{b}\tilde{b}$
- $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$

Compressed spectra

$(\Delta m = m_{\tilde{\chi}_1^\pm}/m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} < 30 \text{ GeV})$

**ATLAS**

- $\tilde{t}$ 0-lepton ([ATLAS-CONF-2017-020])
- $\tilde{t}_2 \rightarrow \tilde{t}_1 \ Z/H$ ([ATLAS-CONF-2017-013])
- $\tilde{t}$ 1-lepton R-Parity Violation ([ATLAS-CONF-2017-013])

**CMS**

- $\tilde{t}$ 0-lepton ([SUS-16-049])
- $\tilde{t}$ 2-leptons ([SUS-17-001])
- 2-soft-leptons ([SUS-16-042])
- $HH \rightarrow 4b$ ([SUS-16-044])
- $\tilde{b}$ 0-lepton ([SUS-16-032])
- $\tilde{b} \ h \rightarrow \gamma\gamma$ ([SUS-16-045])

Link to ATLAS public results

Link to CMS public results

A. Petridis
... from stops ...

... to sbottoms ...
The stop searches: $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$

- **High mass region**
  \( \Delta m > m_t \)
  - boosted topologies

- **Intermediate region**
  \( \Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m_t \)
  - Examine “3-body-decays”

- **Compressed region**
  \( \Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m_W + m_b \)
  - Examine “4-body-decays”
  - Challenging region due to the soft products of the decays
  - high background rates
  - $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ challenging due to charm tagging

- Dedicated searches based on the *lepton multiplicities*
High mass - $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) > m_t$

- 2 inclusive SRs targeting different
  $\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$ with 3 subcategories based on $t$–tagged and $W$–tagged jets (TT, TW, T0)

- Discriminant variables:
  $\vec{m}_{\text{jet}, R=1.2}$, $m_T^b, m_T^{b,\text{min}}, m_T^{b,\text{max}}, E_T^{\text{miss}}$

- Main background contribution comes $Z(\nu\nu) + \text{jets}$, followed by $t\tilde{t}V$ (where $V = W, Z$) and $t\tilde{t}$

$\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \sim m_t$

- Based on Recursive Jigsaw Reconstruction (RJR) by requiring an Initial State Radiation jet

- SRs binned in RISR ($\equiv E_T^{\text{miss}} / p_T^{\text{ISR}} \sim m_{\tilde{\chi}_1^0}/m_{\tilde{t}}$)

- Main background contribution $t\tilde{t}$
ATLAS Stop 0L - Results ATLAS-CONF-2017-020

- Top left: Data and Standard Model (SM) predictions in Signal Regions (SRs)
- 95% CL limits in the mass planes $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ for $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ (top right) and $m_{\tilde{g}} - m_{\tilde{t}_1}$ (bottom right) in fully hadronic final states.
CMS Stop 0-lepton CMS-SUS-16-049

**High $\Delta m(\tilde{t}_1, \tilde{\chi}^0_1)$**

- Search regions are defined from different requirements on $m_T(b_1, b_2, E_T^{\text{miss}})$, $t/W$–tagged jets, $N_{\text{jets}}$, “resolved-top”, $E_T^{\text{miss}}$

- 51 disjoint search regions

**Low $\Delta m(\tilde{t}_1, \tilde{\chi}^0_1)$**

- ISR approach

- 53 disjoint regions

- Development of a novel soft $b$–tagging algorithm based on the presence of a secondary vertex for recovering $b$–tagged below $p_T(b) < 20$ GeV
95% CL exclusion limits on $pp \to \tilde{t}_1 \tilde{t}_1$ in three different topologies;

- High mass region: $m_{\tilde{t}_1}$ up to 1.04 TeV and $m_{\tilde{\chi}_1^0}$ up to 500 GeV are probed;

- Low mass region ($\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m_W$): $m_{\tilde{t}_1}$ up to 580 GeV are probed for $m_{\tilde{\chi}_1^0}$ of 540 GeV;

- Bottom exclusion taken from SUS-16-032. Mass splits up to 10 GeV have been probed.
CMS Stop **two-lepton** CMS-SUS-17-001

- Searches based on different flavors of $m_{T^2}$ calculation ($m_{T^2}(\ell\ell)$, $m_{T^2}(b\ell\bar{b}l)$):
  \[
  M_{T^2}(\ell\ell) = \min_{\vec{p}_T^{\text{miss}} = \vec{p}_T^{\text{miss}} + \vec{E}_T^{\text{miss}}} \left( \max \left[ M_T(\vec{p}_T^{\text{vis1}}, \vec{p}_T^{\text{miss}}), M_T(\vec{p}_T^{\text{vis2}}, \vec{p}_T^{\text{miss}}) \right] \right)
  \]

- Construct 12 disjoint SRs based on $E_T^{\text{miss}}$, $m_{T^2}(\ell\ell)$ and $m_{T^2}(b\ell\bar{b}l)$:
  - Dominant background in low $m_{T^2}$ region comes from single top and $t\bar{t}$
  - In high $m_{T^2}$ regions $t\bar{t} + X$ has significant contributions with $t\bar{t}Z(\nu\nu)$ being the dominant one. CRs defined in

$$pp \rightarrow t\bar{t}Z \rightarrow (t \rightarrow b\ell^\pm\nu)(t \rightarrow bjj)(Z \rightarrow \ell\ell)$$

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<td>$</td>
<td>M_Z - m(\ell\ell)</td>
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<td>$N_{\text{bjets}}$</td>
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<td>$&gt; 5\text{ GeV}^{1/2}$</td>
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<td>$\cos \Delta\phi(E_T^{\text{miss}}, j_1)$</td>
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</tr>
<tr>
<td>$\cos \Delta\phi(E_T^{\text{miss}}, j_2)$</td>
<td>$&lt; 0.96$</td>
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Observation agrees within errors with the Standard Model expectations

95% CL exclusion limits on the mass plane $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$

Interpretations on $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \rightarrow W^{\pm} \tilde{\chi}_1^0$ are also available
Summary of $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ searches

- Updated results from CMS are expected in time for Moriond QCD
Complementary models studied from ATLAS and CMS
• Searches for $\tilde{t}$ production with Higgs ($h$) or $Z$ bosons
  $\tilde{t}_1 \rightarrow t\tilde{\chi}_2^0$, $\tilde{\chi}_2^0 \rightarrow h/Z\tilde{\chi}_1^0$
  $\tilde{t}_2 \rightarrow h/Z\tilde{t}_1$, $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$. Provide additional sensitivity in the region $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \sim m_t$
• Final states considered:
  • three-leptons plus a $b$–tag jet ($3\ell 1b$), aiming at top squark decays involving $Z$ boson
    • Dominant backgrounds: $t\bar{t}Z$, $WZ$.
  • one-lepton plus four $b$ – tag jet ($1\ell 4b$), targeting top squark decays involving Higgs boson
    • Dominant background: $t\bar{t}$;
  • Three overlapped SRs targeting different mass splits ($m_{\tilde{t}_2} - m_{\tilde{\chi}_1^0}$) have been designed for each final-state
• **Top:** 95% CL exclusion limits on $m_{\tilde{t}_2} - m_{\tilde{\chi}_1^0}$ for a fixed $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} = 180$ GeV, assuming $\text{BR}(\tilde{t}_2 \rightarrow Z\tilde{t}_1)=1$ (left) $\text{BR}(\tilde{t}_2 \rightarrow h\tilde{t}_1)=1$ (right)

• **Bottom right:** 95% CL exclusion limits on $m_{\tilde{t}_1} - m_{\tilde{\chi}_2^0}$ for $m_{\tilde{\chi}_1^0} = 0$ GeV, assuming a $\text{BR}(\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0)=0.5$ and $\text{BR}(\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0)=0.5$
Stop Searches performed in R-Parity Violation models

- Final-state examined: $1\ell + jets$ final state
- SRs are binned in jet multiplicity with the lower one being at five-jets
- Dominant backgrounds in $N_{b-tag} = 0$ are $t\bar{t} + jets$ and $W + jets$ while for $N_{b-tag} > 0$ the dominant source is $t\bar{t} + jets$
Stop Searches performed in R-Parity Violation models

Final-state examined: $1\ell + \text{jets}$ final state

SRs are binned in jet multiplicity with the lower one being at five-jets

Dominant backgrounds in $N_{b\text{-tag}} = 0$ are $t\bar{t} + \text{jets}$ and $W + \text{jets}$ while for $N_{b\text{-tag}} > 0$ the dominant source is $t\bar{t} + \text{jets}$
... from stops ...

... to sbottoms ...
CMS Sbottom searches  

**CMS-SUSY-16-032**

- **Non-compressed** ($\Delta m(\tilde{b}_1, \tilde{\chi}_1^0) > 150$ GeV):
  - Main discriminants:
    \[ \text{Min}[M_T(j_1, E_{\text{miss}}^T), M_T(j_2, E_{\text{miss}}^T)], \text{cotransverse mass } (m_{CT}) \text{ and } H_T \text{ (scalar sum of the two leading jets)} \]
  - SRs binned in $m_{CT}$ and $H_T$

- **Compressed** ($\Delta m(\tilde{b}_1, \tilde{\chi}_1^0) < 150$ GeV):
  - Based on an ISR jet recoiling against $E_{T}^{\text{miss}}$.
  - Compressed SRs are binned in $E_{T}^{\text{miss}}$ and $b/c-\text{tag}$ jet multiplicity

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**Plots**

- **Left plot**: Plot of $m_{CT}$ vs.Events, with different signal categories.
- **Middle plot**: Two-panel plot showing $N_{b\text{-tags}} + N_{c\text{-tags}} + N_{SV}$ vs $m_{SP}$ and $m_{b}$ vs 95% CL upper limit on cross section (pb).
- **Right plot**: 3D scatter plot with CMS Preliminary, 35.9 fb$^{-1}$, $\sqrt{s} = 13$ TeV.
CMS search in razor + $H \rightarrow \gamma \gamma$ (sbottom) CMS-SUY-16-045

- In the MSSM Higgs bosons may be produced through the cascade decays of heavier sparticles;
- Search performed in $H \rightarrow \gamma \gamma$ decay-mode and in association with at least one jet
- Approach based on razor variables and the momentum and mass resolution of the diphoton system
- Two main classes of background:
  - SM Higgs (taken from MC)
  - non-resonant QCD estimated from a data-driven technique by fitting the $\gamma \gamma$ mass distribution (dominant systematic uncertainty arises from normalization and shape of that function)
CMS search in razor+ $H \rightarrow \gamma\gamma$ (sbottom)  

**Left:** Observed significance in units of standard deviations per search region; The yellow and green bands represent the 1σ and 2σ regions, respectively.

**Right:** 95% CL exclusion limits on the mass plane $m_{\tilde{b}} - m_{\chi_1^0}$

- $pp \rightarrow \tilde{b}\tilde{b}, \tilde{b} \rightarrow b\chi_2^0 \rightarrow bH\chi_1^0$
- Observed ± 1σ_{theory}  $m_{\chi_2^0} - m_{\chi_1^0} = 130$ GeV
- Expected ± 1σ_{experiment}

**CMS Preliminary**  35.9 fb$^{-1}$ (13 TeV)
Compressed Electroweakino searches
Naturalness imposes constraints on the masses of higgsinos.

Light higgsinos would likely have a compressed mass spectrum.

Experimentaly challenging signature: Muons $p_T$ down to 3.5 GeV has been considered.

Results interpreted in the context of direct $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ (cross sections based on Wino scenario).
Summary

• Both experiments have a rich program on the SUSY production of $3^{rd}$ generation squarks;

• Both experiments improved the object reconstruction and identification to obtain sensitivities in very challenging regions in the mass plane $m_{\tilde{t}_1} - m_{\chi_1^0}$

• Advanced techniques have also been employed to gain sensitivity in the different regions;

• Current searches explore a wide range of final states and topologies;

• All searches produced null results so far;

• More data are expected to be collected in the upcoming years, stay tuned and you never know what the data might be hiding!

Thank you
Back-up
Background estimation strategies

*SUSY searches heavily rely on our understanding of the Standard Model processes*

Reducible background
Receives contributions from non-prompt leptons. Estimation based on data-driven techniques (Matrix Method, Fake Factor);

Irreducible backgrounds
Normalize Monte Carlo predictions ($t\bar{t}$, $VV$, ..) to data in dedicated Control Regions (CR);
- Extracted Normalization Factor (NF) is validated in Validation Regions (VR);
- Final background estimation comes from a simultaneous likelihood fit of Signal Regions and CR;

Backgrounds producing “fake” $E_T^{miss}$ due to jet mismeasurement
Contributions from this category are suppressed by requiring the jets and $E_T^{miss}$ to not point in the same direction ($\Delta\phi(jets, E_T^{miss})$)

Small backgrounds
Contributions from these sources are taken directly from Monte Carlo predictions.
• Searches performed for right-handed $\tilde{t}$ pair production with the $\tilde{t}$ decaying to a bino or higgsino $\tilde{\chi}_1^0$;

• $\tilde{\chi}_1^0$ undergoes RPV decays with a non-zero $\lambda''_{323}$ ($\approx \mathcal{O}(10^{-1} - 10^{-2})$)

• Final-state examined: $1\ell + jets$ final state

• Three sets of jet $p_T$ thresholds (40, 60, 80) have been considered to provide sensitivity to a broad range of possible signals

• SRs are binned in jet multiplicity with the lower one being at five-jets

• Dominant backgrounds in $N_{b-tag} = 0$ are $t\bar{t} + jets$ and $W + jets$ while for $N_{b-tag} > 0$ the dominant source is $t\bar{t} + jets$
• \(t\bar{t} + \text{jets}\) estimation based on a data-driven technique. Extraction of an initial template of the \(b\)–tag multiplicity spectrum in events with five jets and the parameterization of the evolution of this template to higher jet multiplicities.

\[
N_{j,b}^{t\bar{t}+\text{jets}} = N_{j}^{t\bar{t}+\text{jets}} \cdot f_{j,b}
\]

\[
f_{(j+1),b} = f_{j,b} \cdot x_0 + f_{j,(b-1)} \cdot x_1 + f_{j,(b-2)} \cdot x_2
\]

where \(x_i\) describe the probability of one additional jet to be either not \(b\)–tagged \((x_0)\), \(b\)–tagged \((x_1)\) or \(b\)–tagged and leading to a second \(b\)–tagged jet to move into the fiducial acceptance \((x_2)\)

• Validation of the jet-scaling parameterization in dileptonic \(t\bar{t}\) events
ATAS Stop RPV  

ATLAS-CONF-2017-013

- Right: Expected SM background and observation in different $b$–tag multiplicities in $\ell + 9$jets final state

- Left: 95% CL limits on the mass plane $m_{\tilde{t}_1} - m_{\tilde{\chi}^0_1}$ for pure bino or pure higgsino $\tilde{\chi}^0_1$
ATLAS Stop two-leptons \textit{ATLAS-CONF-2016-076}

..highlights from 2016 summer conferences

- Examining $\tilde{t}_1$ pair production in three-body-decays;
- Searches based on super-razor variables;
- Particularly sensitive in $m_W + m_b < \Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m_t$
- Two dedicated SRs, one for $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \sim m_W$ and the other $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \sim m_t$
$\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm \rightarrow W\tilde{\chi}_1^0$

...motivated by gaugino universality

Searches based on fully hadronic final states

*ATLAS-CONF-2016-077 CMS-SUS-16-049*

Searches based on *one-lepton* final states

*ATLAS-CONF-2016-050 CMS-PAS-SUS-16-028*

To be updated from both experiments

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ATLAS

Stop pair production, $t \rightarrow b\tilde{\chi}_1^\pm$, $m_{\tilde{t}} = 2 \times m_{\tilde{\chi}_1}$

ATLAS Preliminary SSB+SRC $F_s = 13$ TeV, 13.3 fb$^{-1}$

All limits at 95% CL

CMS

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

$pp \rightarrow t\bar{t}\rightarrow b\tilde{\chi}_1^\pm$, $W^* \tilde{\chi}_1^\pm$

NLO+NLL exclusion

Observed $\pm 1 \sigma_{\text{theory}}$, $m_{\tilde{t}} = (m_{\tilde{t}} + m_{\tilde{\chi}_1})/2$

Expected $\pm 1 \sigma_{\text{experiment}}$

CMS assumption:

$m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0}$

ATLAS assumption:

$m_{\tilde{\chi}_1^\pm} = (m_{\tilde{t}} + m_{\tilde{\chi}_1^0})/2$

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ATLAS

Stop pair production, $t \rightarrow b\tilde{\chi}_1^\pm$, $m_{\tilde{t}} = 2 \times m_{\tilde{\chi}_1}$

ATLAS Preliminary $F_s = 13$ TeV, 20 fb$^{-1}$

All limits at 95% CL

CMS

CMS Preliminary 12.9 fb$^{-1}$ (13 TeV)

$pp \rightarrow t\bar{t}\rightarrow b\tilde{\chi}_1^\pm$, $W^* \tilde{\chi}_1^\pm$

NLO+NLL exclusion

Observed $\pm 1 \sigma_{\text{theory}}$, $m_{\tilde{t}} = (m_{\tilde{t}} + m_{\tilde{\chi}_1})/2$

Expected $\pm 1 \sigma_{\text{experiment}}$

CMS assumption:

$m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0}$

ATLAS assumption:

$m_{\tilde{\chi}_1^\pm} = (m_{\tilde{t}} + m_{\tilde{\chi}_1^0})/2$
Searches for $\tilde{b}_1 \rightarrow b \tilde{\chi}_1^0$;

Examining final states with exactly two $b$-tag jets and $E_T^{\text{miss}}$.

Main discriminant variable:

$$m_{CT}^2(v_1, v_2) = [E_T(v_1) + E_T(v_2)]^2 - [p_T(v_1) - p_T(v_2)]^2$$

Bound for $\tilde{b}$ is given by:

$$m_{CT}^{\text{max}} = \left( \frac{m_{\tilde{b}_1}^2 - m_{\chi_1^0}^2}{m_{\tilde{b}_1}} \right)$$
New results will be available on Moriond QCD

- Four main SRs with different $N_{jets}$ and $M_{T2}^W$ requirements which are then binned in $E_T^{miss}$

- Main discriminants:
  $M_{T2}^W$: the information from on-shell $W -$ boson is included in the $m_{T2}$ calculator
  Modified topness variable $t_{mod}$ for further background rejection

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<th>$N_{jets}$</th>
<th>$M_{12}^W$ [GeV]</th>
<th>$t_{mod}$</th>
<th>$E_T^{miss}$ [GeV]</th>
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<tr>
<td>= 2</td>
<td>&gt; 200</td>
<td>&gt; 6.4</td>
<td>250–350 350–450 &gt; 450</td>
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<td>= 3</td>
<td>&gt; 200</td>
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<tr>
<td>≥ 4</td>
<td>≤ 200</td>
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<td>250–350 350–450 &gt; 450</td>
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</table>

A. Petridis 33 / 24
CMS Stop **one-soft-lepton** CMS-PAS-SUS-16-031

- Direct $\tilde{t}_1 \tilde{t}_1$ production with subsequent four-body-decays;
- Exploring the very-low $p_T$ region of leptons
ATLAS Stop $1$-lepton ATLAS-CONF-2016-050

Highlights from 2016 summer conferences

- **SR1** targets low mass splittings (decay products are fully resolved)
- **tN_high** targets the high mass region
- $m_T = \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos(\Delta \phi))}$
- asymmetric-$m_{T2}$ is used to reject $t\bar{t}$ events where one lepton is not reconstructed;
- **topness**: a minimising $\chi^2$–type function quantifying the compatibility with a dileptonic $t\bar{t}$ event
Table 1: A summary of the search region bins in each category is presented. The functional form used to model the non-resonant background is also listed. An exponential function of the form $e^{-\alpha x}$ is denoted as "single-exp"; a linear combination of two independent exponential functions of the form $e^{-\alpha x}$ and $e^{-\beta y}$ is denoted as "double-exp"; a modified exponential function of the form $e^{-\alpha x^2}$ is denoted as "mod-exp"; and a Bernstein polynomial of degree $n$ is denoted by "poly-$n$".

<table>
<thead>
<tr>
<th>Bin Number</th>
<th>Category</th>
<th>$M_R$ (GeV) Bin</th>
<th>$R^2$ Bin</th>
<th>Non-Resonant Bkg Model</th>
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<td>0.025 - $\infty$</td>
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