The search for rare decays

Riccardo Salvatico

On behalf of the ATLAS and CMS Collaborations

1 University of Kansas
Focusing on rare decay searches in the electroweak sector

$W^\pm \rightarrow \pi^\pm \pi^\pm \pi^\mp$

$Z \rightarrow 4\ell$

$Z \rightarrow e\tau/\mu\tau$

$W^\pm \rightarrow \pi^\pm \gamma$

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arXiv:2011.06028
Accepted by PLB

arXiv:2103.01918
Submitted to JHEP

arXiv:2105.12491
Submitted to PRL

A choice made out of personal taste and time constraints. There are many more exciting results out there! Check them out
No exclusive hadronic decay of the W (Z, H) boson has ever been observed

Foreseen by the standard model but with low branching fractions
(strong suppression mechanisms: “Sudakov effects” → obvious interest to determine their branching fractions)

At the same time, a nice test of the standard model...

...even though theoretical calculations for these branching fractions may have (very) large uncertainties
– or may not exist at all!

Observation could help validate the QCD factorization method, commonly used to perform these calculations

Possibly another viable option to measure some fundamental properties of the W boson (e.g., the mass)
Theoretical predictions have rather large uncertainties:

$$10^{-9} \lesssim \mathcal{B}(W^\pm \to \pi^\pm \gamma) \lesssim 10^{-7}$$

95% CL upper limit measured before*:

$$\mathcal{B}(W^\pm \to \pi^\pm \gamma) < 7.0 \times 10^{-6}$$  [CDF]

* using inclusive photon trigger
Isolate $t\bar{t}$ events

Analysis strategy*

Hard to perform this search at CMS by triggering on the photon

Leptonic decay of one $W$ for trigger and event ID

$W \rightarrow \tau \nu$ considered part of signal events only if $\tau \rightarrow \mu (e) \nu_{\mu(e)} \nu_{\tau}$

* M. Mangano, T. Melia, Rare exclusive hadronic $W$ decays in a $t\bar{t}$ environment
Isolate $t\bar{t}$ events

The presence of two $b$ jets is a specific trait of the $t\bar{t}$ topology → reduce contribution from non-$t\bar{t}$ backgrounds

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Analysis strategy*

Isolate $t\bar{t}$ events

$W^+ (W^-)$ analyzed to find the rare decay

Isolated high-$p_T$ photon

Isolated high-$p_T$ pion

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Leptonic decay of one $W$ for trigger and event ID

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*M. Mangano, T. Melia, *Rare exclusive hadronic W decays in a $t\bar{t}$ environment*
Pion isolation

$\sum p_T$ of all the particles contained in a cone of $0.02 \leq \Delta R \leq 0.5$ around the pion, divided by $p_T^\pi$.

Pileup subtraction: charged particles required to come from primary vertex

The pion from $W \rightarrow \pi\gamma$ decay originates from an EWK process → hadronic activity in its vicinity is expected to be low

This variable is used as input to a BDT, together with kinematic properties of $\pi, \gamma, \ell$ and number of $b$-tagged jets

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Results

Unbinned maximum likelihood fit to $m_{\pi\gamma}$

No significant excess above the expected background is observed

$\mathcal{B}(W^\pm \rightarrow \pi^\pm \gamma) < 1.50 \times 10^{-5}$  CL = 95%

- Statistical uncertainty is dominant
  - It represents $\sim$80% of the total uncertainty

- Main systematic uncertainties
  - Integrated luminosity
  - $t\bar{t}$ production cross section, measured by CMS
  - Signal and background parametrization

First search for this decay at the LHC!
Leading diagram

**$W \rightarrow \pi\pi\pi$**

$\mathcal{B}(W^\pm \rightarrow \pi^\pm\pi^\pm\pi^\mp)$ expected to be the same order of magnitude as $Z \rightarrow \pi^+\pi^-\pi^0$ – in the range $10^{-8} - 10^{-6}$

...but there exists no theoretical calculation, nor any previous measurement!

First search ever for this decay!
Search strategy

Exploit **algorithm** designed for reconstruction of hadronic $\tau$ decays ($\tau_h$)

1. Seeded by energy deposits in the ECAL
2. Combines tracks in silicon strip detector with charged particles in the jet

Use advanced discriminators developed for this algorithm to reject quark and gluon jets, electrons, and muons

**Trigger**

Require two $\tau_h$ candidates
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Isolation requirement without using displacement information (pions from W decay are prompt)
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Require $p_T^W > 40$ GeV: 90% efficient for signal, rejects 2/3 of background

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• QCD multijet background is the dominant
  → estimated using data-driven methods

• $Z/\gamma^{(*)} \rightarrow \ell\ell$ and $t\bar{t}$
  → normalization from MC, $m_{3\pi}$ distribution from data control regions specifically designed for those
Results

Statistical uncertainty dominates (~ 90%)

Systematic contributions include:
• Pion ID efficiency
• Background estimation
• Theoretical uncertainties in the yield of W bosons

$\mathcal{B}(W \to \pi\pi\pi) < 1.01 \times 10^{-6}$
Not a dedicated measurement of $Z \rightarrow 4\ell$; instead, a **generic measurement of cross sections in $4\ell$ events**

$4\ell = 4\mu, 4e, 2\mu2e$

2 same-flavor, opposite-charge muons or electrons
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Several SM processes can contribute to these final states

- **t-channel $q\bar{q} \to 4\ell$**
- **Gluon-induced $gg \to 4\ell$**
- **Internal conversion in $Z$ boson decays**
- **$H$ boson-mediated $s$-channel production**
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A number of BSM models could contribute too

- Modifications to SM coupling of H and gauge bosons
- Possible four-fermion interactions
- Four-lepton production via decay of new particles:
  - e.g., cascade decays of MSSM particles (possibly insensitive to searches based on missing $p_T$)
- Generic models with additional gauge ($Z'$) or H bosons
The analysis

Very rich analysis, with (multi-) differential and integrated measurements of production cross sections

Event selection

• One, two or three leptons at trigger level
• Offline: $p_T^\ell > 20 \text{ GeV}$ (leading), $p_T^\ell > 10 \text{ GeV}$ (sub-leading)
• $m_{\ell\ell} > 5 \text{ GeV}$ (suppress $J/\psi$)
• $\Delta R(\ell, \ell) > 0.05$ (suppress conversion electrons)

Background estimation and subtraction

• **Main bkg**: lepton quadruplet formed by combination of prompt leptons ($Z/\gamma^*, t\bar{t}$) and leptons from hadron decay → data-driven estimation
• Minor contribution (~ 0.8% in the $Z \to 4\ell$ region) from $Z + \Upsilon$ events → estimated using simulated events

Detector corrections

Unfolding using combination of per-lepton efficiency correction and iterative Bayesian unfolding technique
Extraction of the rare branching fraction

$$\mathcal{B}(Z \rightarrow 4\ell) = \frac{(\sigma_{\text{meas}} - \sigma_{\text{non}-q\bar{q} \rightarrow 4\ell}^{\text{pred}}) \times f_Z \times f_{\text{non}-\tau}}{\sigma_Z \times A} = (4.41 \pm 0.13 \text{ (stat)} \pm 0.23 \text{ (syst)} \pm 0.09 \text{ (theo)} \pm 0.12 \text{ (lumi)}) \times 10^{-6} = (4.41 \pm 0.30) \times 10^{-6}$$

$\sigma_{\text{meas}} = 22.1 \pm 1.3 \text{ fb in the } Z \rightarrow 4\ell \text{ region}$

$\sigma_{\text{non}-q\bar{q} \rightarrow 4\ell}^{\text{pred}}$ predicted fiducial xsec from sources other than $q\bar{q} \rightarrow 4\ell$

$f_Z$ fraction of $q\bar{q} \rightarrow 4\ell$ coming from single $Z$ production

$f_{\text{non}-\tau}$ fraction of events where no leptons originate from $\tau$ decays

$\sigma_Z$ total cross section for single-$Z$ production

$A$ acceptance factor

The most precise $\mathcal{B}(Z \rightarrow 4\ell)$ measurement to date!
Part of the vast program of lepton flavor violation studies at the LHC

\[ Z \rightarrow e\tau/\mu\tau \] at the LHC – two particularly interesting channels

- A sample of \( \sim 8 \text{ billion} \) \( Z \) boson decays only in Run2
- No stringent indirect constraints as for \( Z \rightarrow e\mu \)

Our current theoretical knowledge: one \( Z \) decay in \( \sim 10^{54} \) can be \( Z \rightarrow \mu\tau \) (via neutrino mixing)
An observation of LFV in these charged-lepton interactions would be an unambiguous sign of new physics.

E.g., theories predicting the existence of heavy neutrinos to explain tiny masses and large mixing of SM neutrinos expect enhanced $\mathcal{B}(Z \to \ell\tau)$ up to $10^{-5}$.
Search strategy

Consider events $Z \rightarrow \ell\tau_{\ell}, \rightarrow \ell\ell' + 2\nu$

Exclude events with same-flavor lepton pairs to suppress $Z \rightarrow \ell\ell$

**Signal**

- Exactly two light (charged) leptons
- Charge $\ell \neq$ Charge $\ell'$
- $\ell$ and $\ell'$ approximately back-to-back
- Neutrinos tend to be collinear with $\ell'$ due to boosted $\tau$
- $m_{\ell\ell'2\nu} \sim m_Z$
Search strategy

Consider events $Z \rightarrow \ell \tau_{\ell}, \ell \ell' + 2\nu$

Main background sources

- $Z \rightarrow \tau \tau \rightarrow \ell \ell' + 4\nu$
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- $Z \rightarrow \tau \tau \rightarrow \ell \ell' + 4\nu$
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- $Z \rightarrow \tau \tau \rightarrow \ell \ell' + 4\nu$
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- *Fakes* – mostly $W(\rightarrow \ell \nu) +$ jets
Search strategy

Consider events $Z \rightarrow \ell \tau_{\ell}, \rightarrow \ell \ell' + 2\nu$

Main background sources

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- Fakes – mostly $W(\rightarrow \ell \nu) + \text{jets}$

- Veto $Z \rightarrow \ell \tau_{\text{had}} \rightarrow \ell \tau_{\text{had-vis}} + \nu$ events

Channel exploited in previous ATLAS search. Used for combination!

$\tau_{\text{had-vis}}$ visible products of hadronic $\tau$ decays
Search strategy

Consider events $Z \rightarrow \ell\tau_{\ell}, \rightarrow \ell\ell' + 2\nu$

**Signal**

Several selection criteria used to separate signal and background events and to create signal and control regions

- **Neural networks** are a fundamental component

**Main background sources**

- **Low-level variables**
  - Momentum components of $\ell, \ell'$ and $E_T^{\text{miss}}$

- **High-level variables**
  - Kinematic properties of the $e - \mu - E_T^{\text{miss}}$ system (e.g., $e - \mu - 2\nu$ invariant mass)
Results

Simultaneous fit to:

- combined NN output in the SR (subdivided into $\tau\tau$ and $\mu\tau$ channels, and high/low $p_T$ of the subleading lepton)
- $e - \mu - 2\nu$ invariant mass in the CR $Z \rightarrow \tau\tau$
- event yield in top quark-dominated CR

No significant excess observed

Unpolarized $\tau$ scenario:

- $\mathcal{B}(Z \rightarrow e\tau) < 7.0 \times 10^{-6}$
- $\mathcal{B}(Z \rightarrow \mu\tau) < 7.2 \times 10^{-6}$

Combination with $\tau_{\text{had}}$ results:

- $\mathcal{B}(Z \rightarrow e\tau) < 5.0 \times 10^{-6}$
- $\mathcal{B}(Z \rightarrow \mu\tau) < 6.5 \times 10^{-6}$

95% CL

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Results on rare decays of the electroweak bosons were presented:

- $W \rightarrow \pi \gamma$
  - A new and effective search strategy for this kind of decays

- $W \rightarrow \pi\pi\pi$
  - First ever attempt to observe this process

- $Z \rightarrow 4\ell$
  - The most precise measurement to date

- $Z \rightarrow e\tau/\mu\tau$
  - The most stringent limits to date

The landscape of rare $W/Z$ decays and searches is much vaster! Some more results in the next slide

- ATLAS public webpage
- CMS public webpage
Some more rare decay searches

ATLAS Collaboration, “Searches for exclusive Higgs and Z boson decays into $J/\psi \gamma$, $\psi(2S)\gamma$ and $\Upsilon(nS)\gamma$ at $\sqrt{s} = 13$ TeV with the ATLAS detector”, PLB 786 (2018) 134

ATLAS Collaboration, “Searches for exclusive Higgs and Z boson decays to $\phi \gamma$ and $\rho \gamma$ with the ATLAS detector”, JHEP 07 (2018) 127

ATLAS Collaboration, “Searches for the lepton flavor violating decay $Z \rightarrow e \mu$ in pp collisions at at $\sqrt{s} = 8$ TeV with the ATLAS detector”, PRD 90 (2014) 072010


CMS Collaboration, “Search for Higgs and Z boson decays to $J/\psi$ or $\Upsilon$ pairs in the four-muon final state in proton-proton collisions at $\sqrt{s} = 13$ TeV”, PLB 797 (2019) 134811

CMS Collaboration, “Measurements of the pp $\rightarrow ZZ$ production cross section and the $Z \rightarrow 4\ell$ branching fraction, and constraints on anomalous triple gauge couplings at $\sqrt{s} = 13$ TeV”, EPJC 78 (2018) 165

CMS Collaboration, “Observation of the $Z \rightarrow \psi \ell^+ \ell^-$ in pp collisions at $\sqrt{s} = 13$ TeV”, PRL 121 (2018) 141801
BACKUP
# Z → eτ/μτ SR selection

Table 1: Selection criteria for events in the signal region.

<table>
<thead>
<tr>
<th>Selection criterion</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exactly two isolated light leptons (ℓ₀, ℓ₁) with opposite electric charge and different flavor (e or μ); (p_T(ℓ₀) &gt; p_T(ℓ₁))</td>
<td>Select events consistent with signal decays.</td>
</tr>
<tr>
<td>No (τ_{\text{had-vis}}) candidate</td>
<td>Orthogonality with (ℓτ_{\text{had}}) channel.</td>
</tr>
<tr>
<td>Transverse mass (m_T(ℓ₁, E_T^{\text{miss}}) &lt; 35\text{ GeV})</td>
<td>Reject top-quark and diboson events.</td>
</tr>
<tr>
<td>(</td>
<td>Δφ(ℓ₀, E_T^{\text{miss}})</td>
</tr>
<tr>
<td>No (b)-tagged jets (using the 77% efficiency working point [28])</td>
<td></td>
</tr>
<tr>
<td>Invariant mass of the ℓ₀–ℓ₁ pair (m(ℓ₀, ℓ₁) &gt; 40\text{ GeV})</td>
<td>Reject events incompatible with Z-boson decays.</td>
</tr>
<tr>
<td>Neural network (optimized for signal vs. (Z → ττ)) output &gt; 0.2</td>
<td>Ensure selection is orthogonal to the CRZττ region.</td>
</tr>
<tr>
<td>In (μτ_e) channel: (p_T^{\text{track}}(e)/p_T^{\text{cluster}}(e) &lt; 1.1)</td>
<td>Reject (Z → μμ) events.</td>
</tr>
</tbody>
</table>
### $Z \to e\tau/\mu\tau$ – other $\tau$ polarizations

<table>
<thead>
<tr>
<th>Final state, polarization assumption</th>
<th>Observed (expected) upper limit on $\mathcal{B}(Z \to \ell \tau)$ [$\times 10^{-6}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$e\tau$</td>
</tr>
<tr>
<td>$\ell \tau_{\text{had}}$ Run 1 + Run 2, unpolarized $\tau$ [9]</td>
<td>8.1 (8.1)</td>
</tr>
<tr>
<td>$\ell \tau_{\text{had}}$ Run 2, left-handed $\tau$ [9]</td>
<td>8.2 (8.6)</td>
</tr>
<tr>
<td>$\ell \tau_{\text{had}}$ Run 2, right-handed $\tau$ [9]</td>
<td>7.8 (7.6)</td>
</tr>
<tr>
<td>$\ell \tau_{\ell'}$ Run 2, unpolarized $\tau$</td>
<td>7.0 (8.9)</td>
</tr>
<tr>
<td>$\ell \tau_{\ell'}$ Run 2, left-handed $\tau$</td>
<td>5.9 (7.5)</td>
</tr>
<tr>
<td>$\ell \tau_{\ell'}$ Run 2, right-handed $\tau$</td>
<td>8.4 (11)</td>
</tr>
<tr>
<td>Combined $\ell \tau$ Run 1 + Run 2, unpolarized $\tau$</td>
<td>5.0 (6.0)</td>
</tr>
<tr>
<td>Combined $\ell \tau$ Run 2, left-handed $\tau$</td>
<td>4.5 (5.7)</td>
</tr>
<tr>
<td>Combined $\ell \tau$ Run 2, right-handed $\tau$</td>
<td>5.4 (6.2)</td>
</tr>
</tbody>
</table>