LHCP 2021

9th edition of the Large Hadron Collider Physics conference

The search for rare decays

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On behalf of the ATLAS and CMS Collaborations

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Outline

Focusing on rare decay searches in the electroweak sector

$W^{\pm} \to \pi^{\pm}\gamma$

arXiv:2011.06028

Accepted by PLB

$W^{\pm} \to \pi^{\pm}\pi^{\pm}\pi^{\mp}$

PRL **122** (2019) 151802

$Z \to 4\ell$

arXiv:2103.01918

Submitted to JHEP

$Z \to e\tau/\mu\tau$

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

The physics case of W rare decays

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

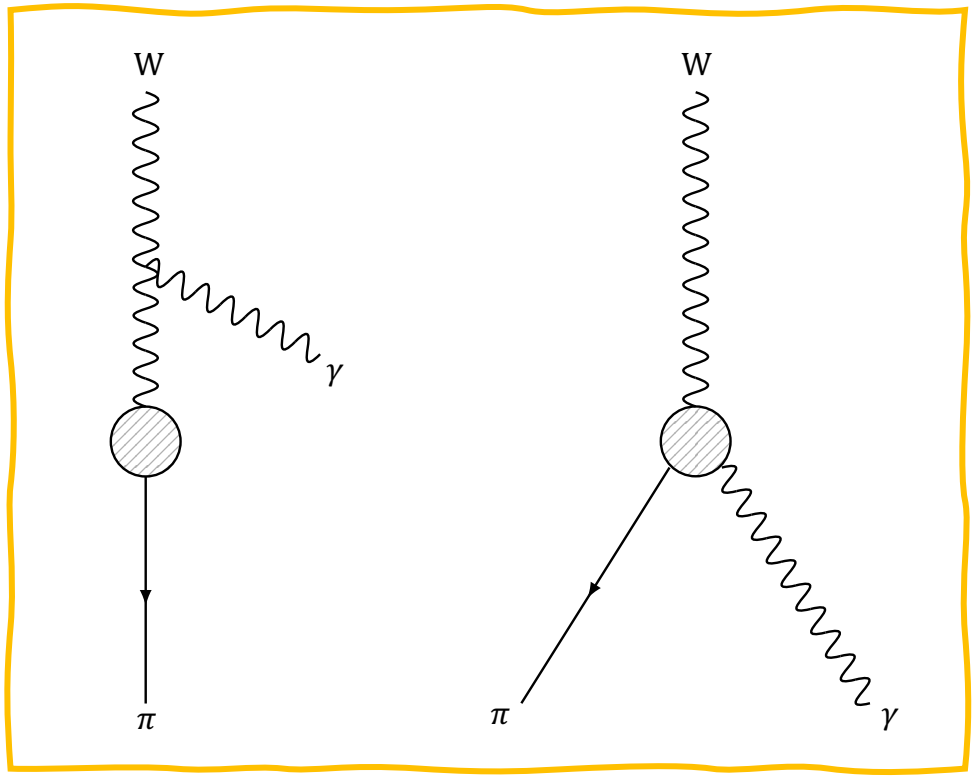
At the same time, a nice test of the standard model…

- …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)

$W \to \pi\gamma$



Theoretical predictions have rather large uncertainties:

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

95% CL upper limit measured before*:

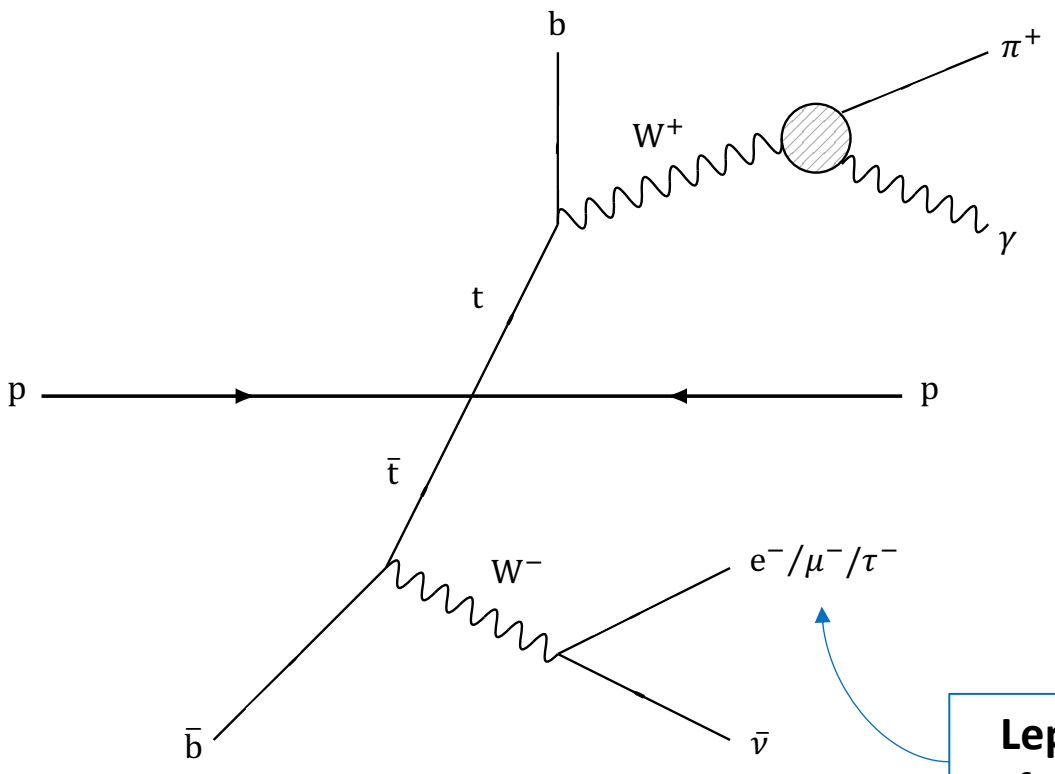
$$\mathfrak{B}(W^{\pm} \to \pi^{\pm}\gamma) < 7.0 \times 10^{-6}$$ [CDF]

* using inclusive photon trigger

Analysis strategy*

Isolate $t\bar{t}$ events

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



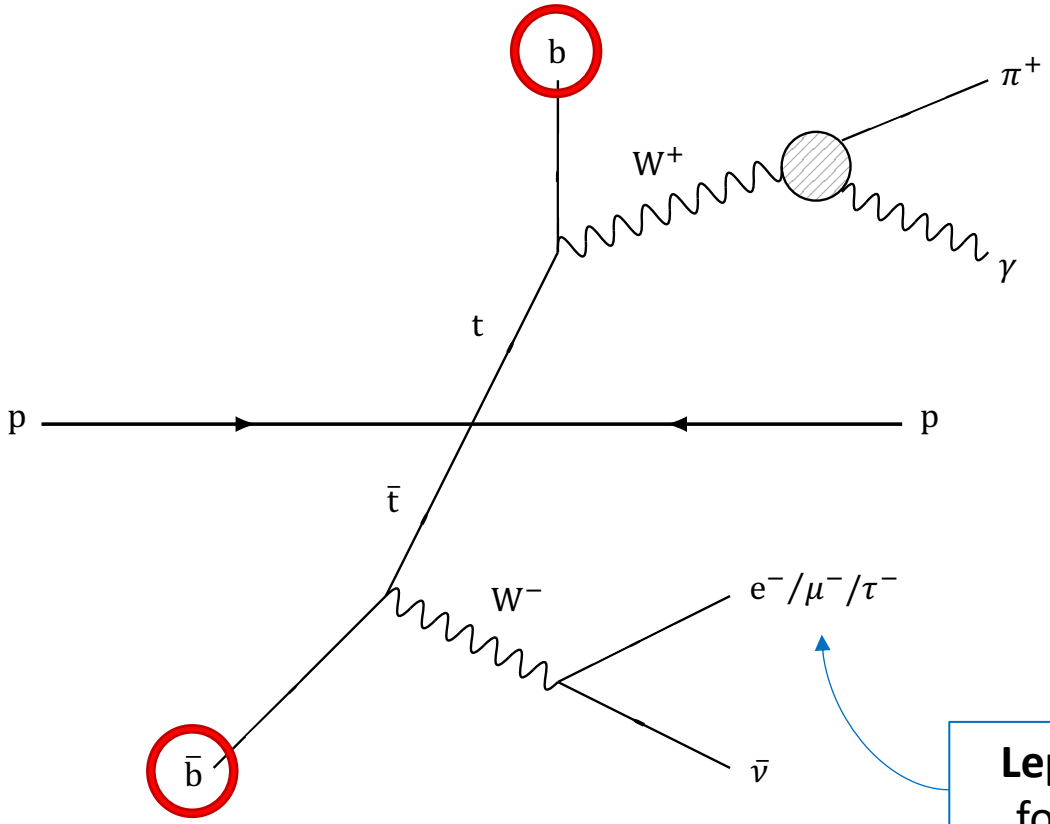
Leptonic decay of one W for trigger and event ID

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

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

Analysis strategy*

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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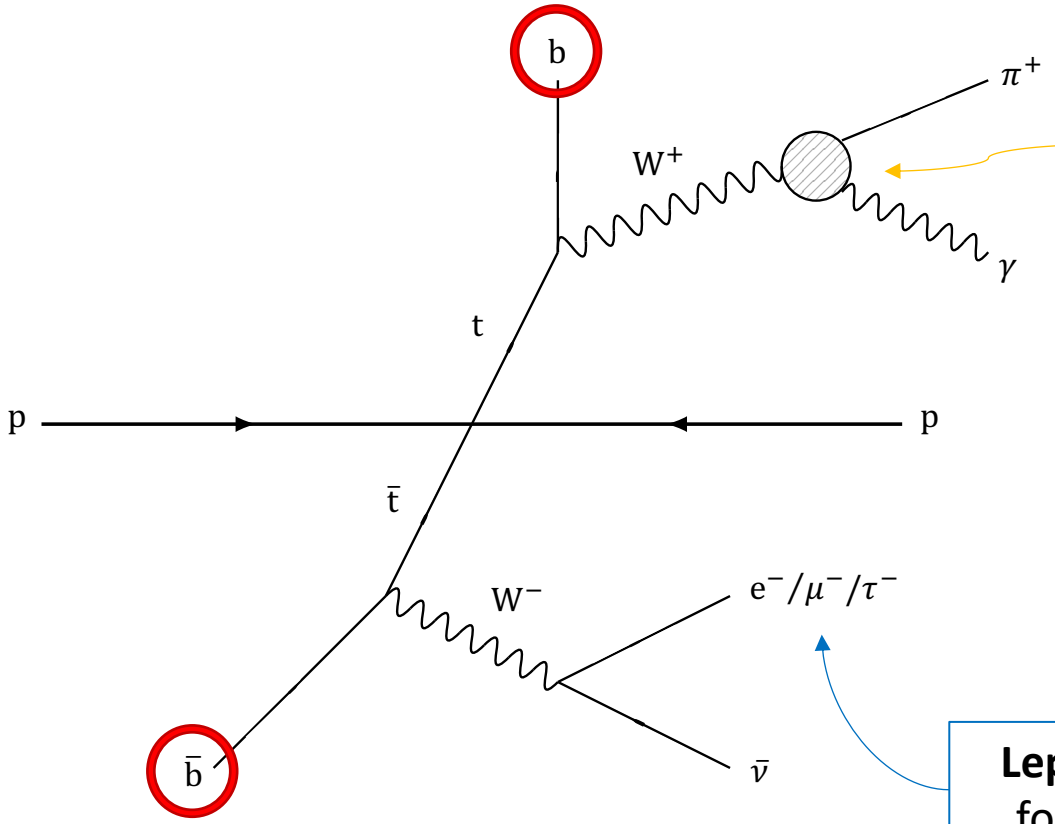

W^+ (W^-) analyzed to find the rare decay

γ Isolated high-p_T photon

π Isolated high-p_T pion

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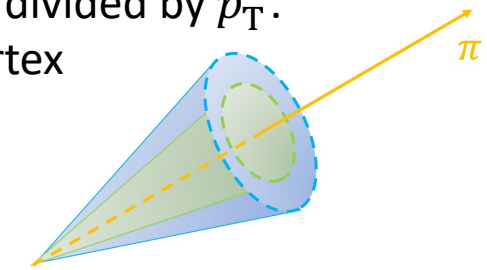
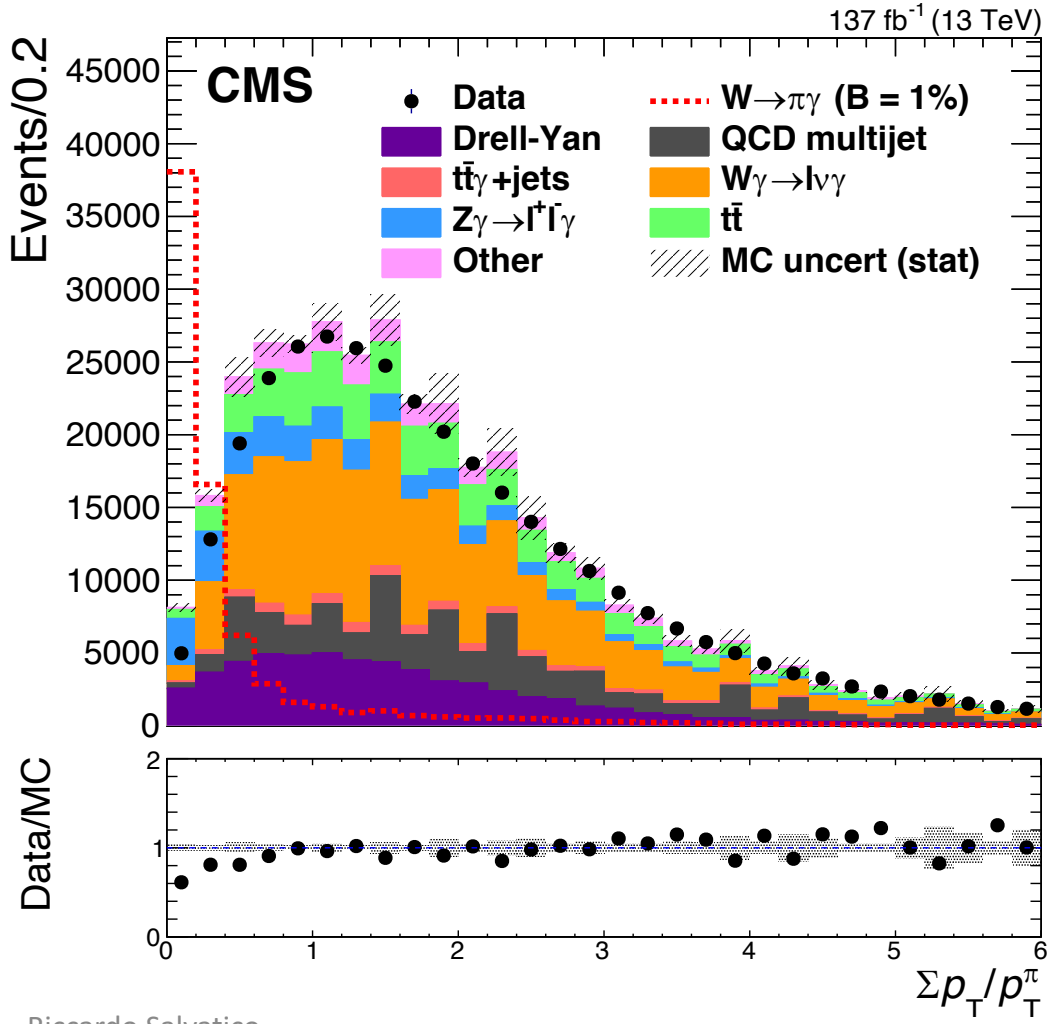
Leptonic decay of one W for trigger and event ID

*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^{π}.
Pileup subtraction: charged particles required to come from primary vertex

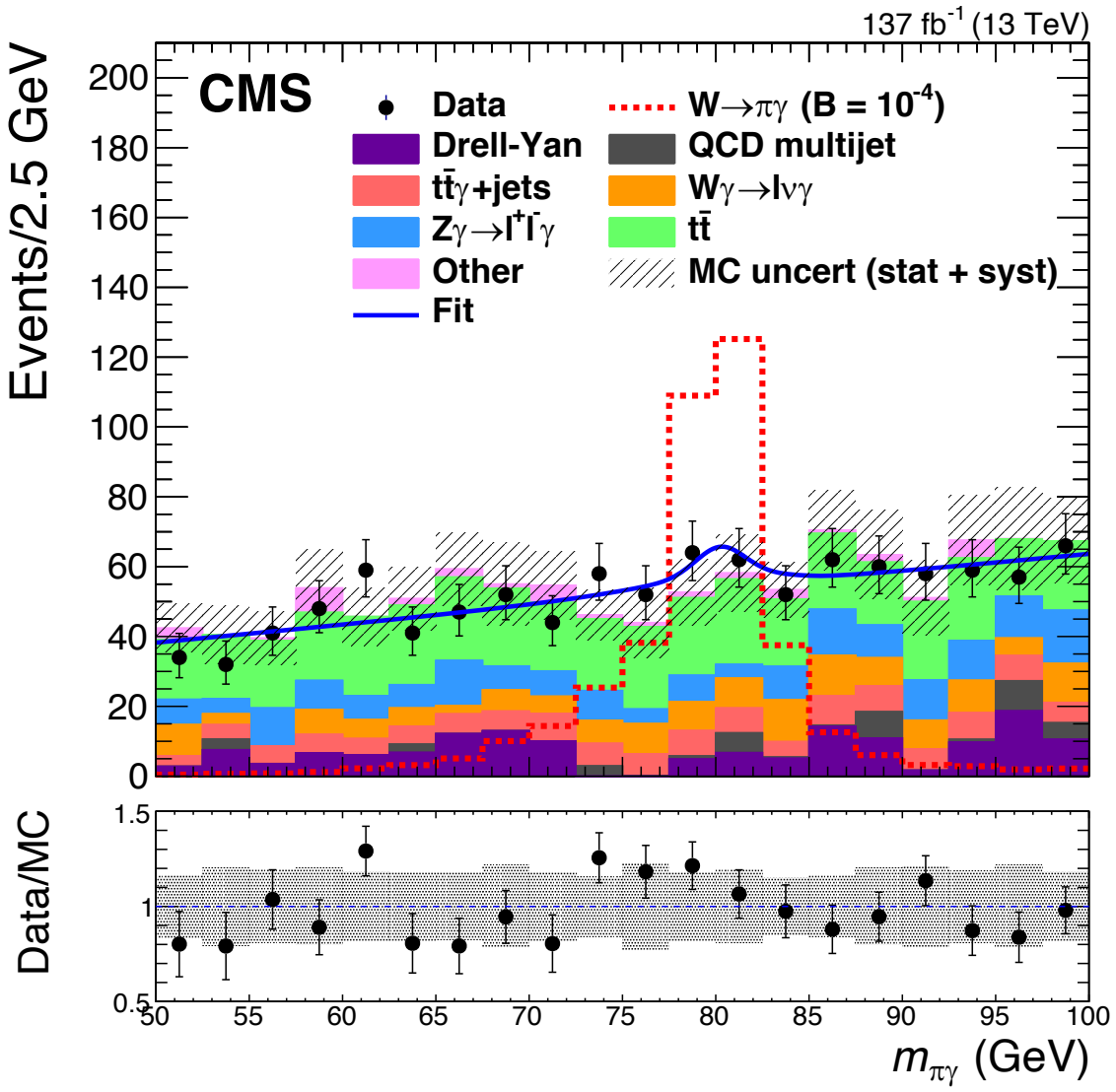




The pion from $W \to \pi\gamma$ decay originates from an EWK process → hadronic activity in its vicinity is expected to be low

This variable is used as input to a BDT, together with kinematic properties of π, γ, ℓ and number of b-tagged jets

Results



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

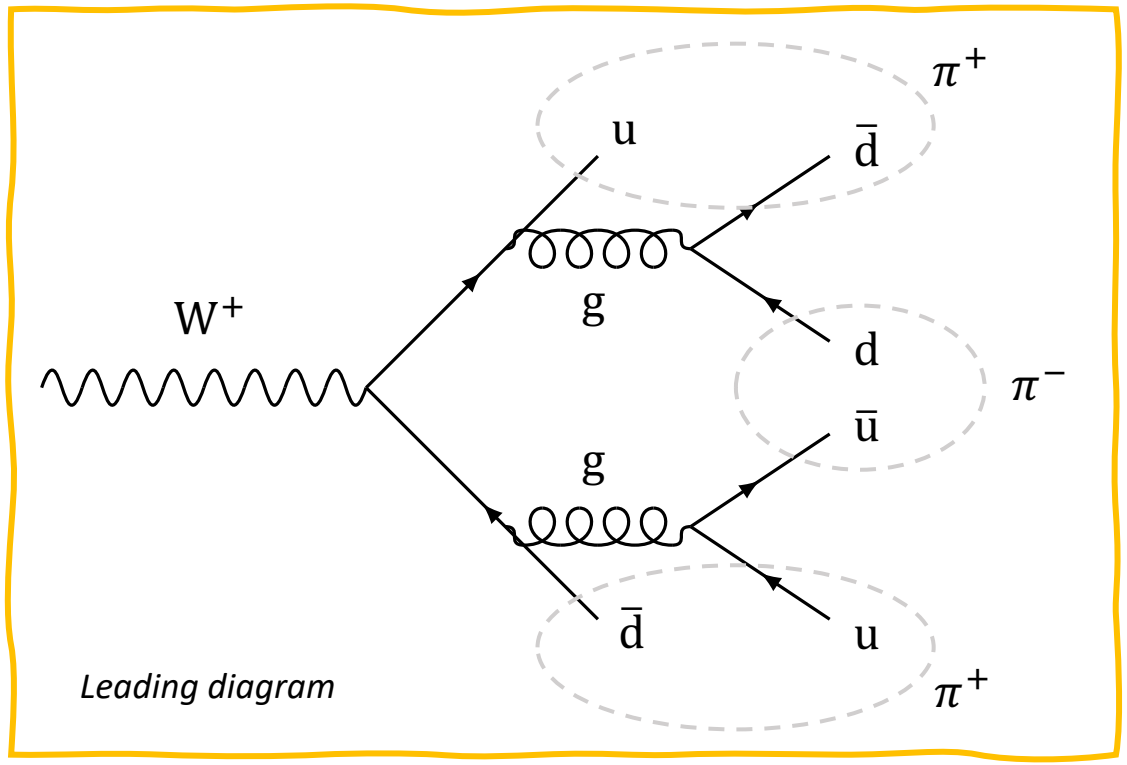
No significant excess above the expected background is observed

$$\mathfrak{B}(W^{\pm} \to \pi^{\pm}\gamma) < 1.50 \times 10^{-5} \quad \text{CL} = 95\%$$

- **Statistical uncertainty is dominant**
  - It represents ~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!

$W \to \pi\pi\pi$



$\mathfrak{B}(W^\pm \to \pi^\pm\pi^\pm\pi^\mp)$ expected to be the same order of magnitude as $Z \to \pi^+\pi^-\pi^0$ – 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 τ decays (τ_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 τ_h candidates

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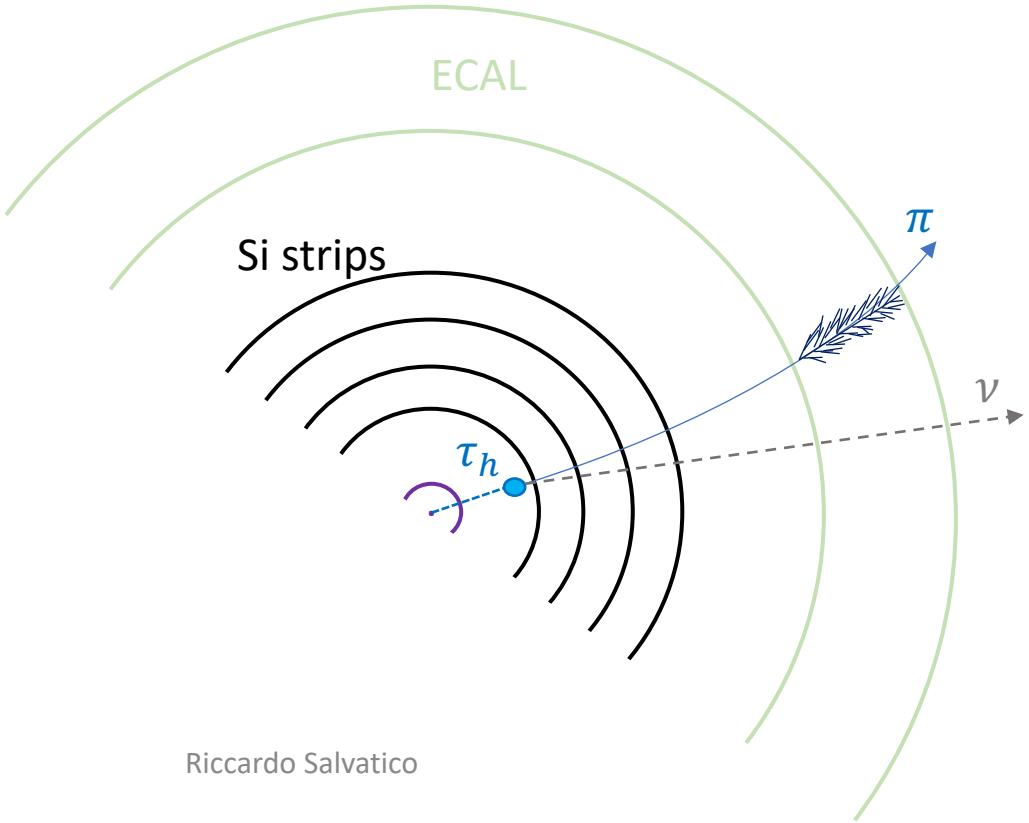

Two trigger-matched π candidates reconstructed in **1-prong** τ_h decay mode

Offline selection

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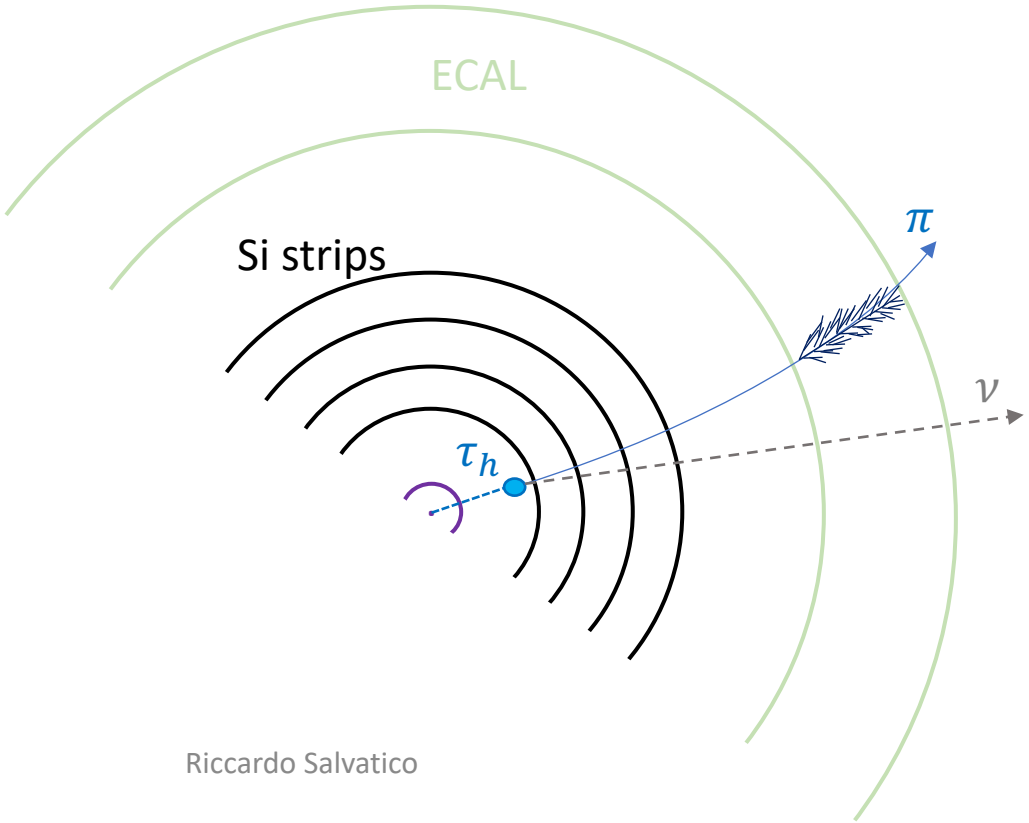

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A third π candidate reconstructed as **1-prong** τ_h and with lower p_T. 3 candidates well separated from each other

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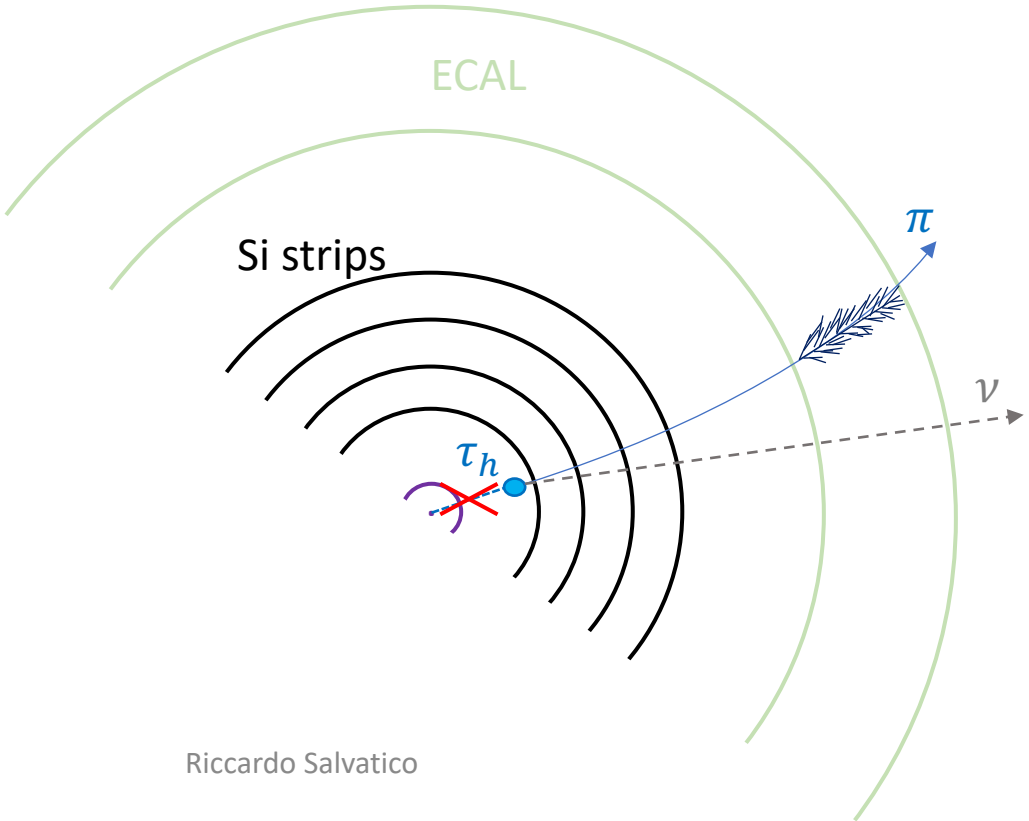

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Isolation requirement without using displacement information (pions from W decay are prompt)

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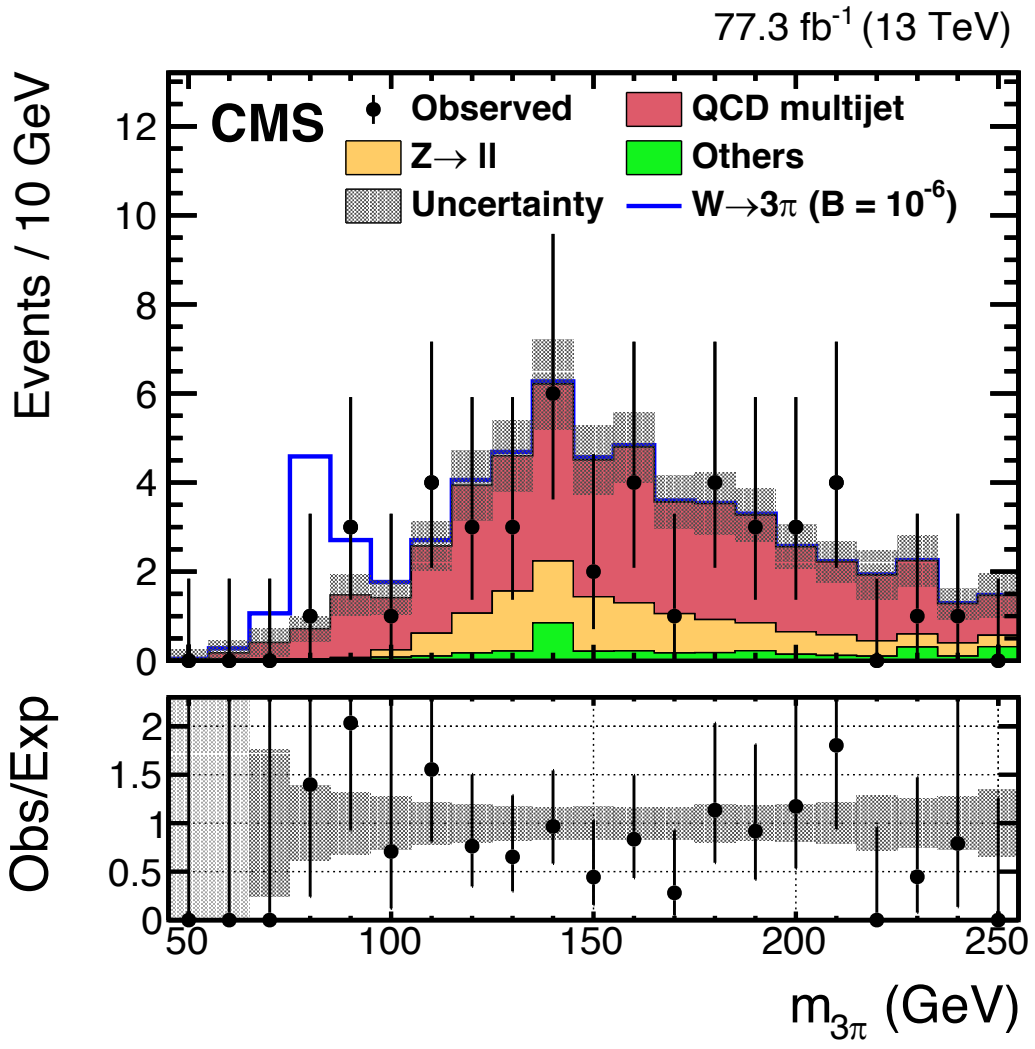
Isolation requirement without using displacement information (pions from W decay are prompt)

Require $p_{\mathrm{T}}^{\mathrm{W}} > 40$ GeV: 90% efficient for signal, rejects 2/3 of background

Results



- QCD multijet background is the dominant

  → estimated using data-driven methods

- $Z/\gamma^{(*)} \to \ell\ell$ and $t\bar{t}$

  → normalization from MC, $m_{3\pi}$ distribution from data control regions specifically designed for those

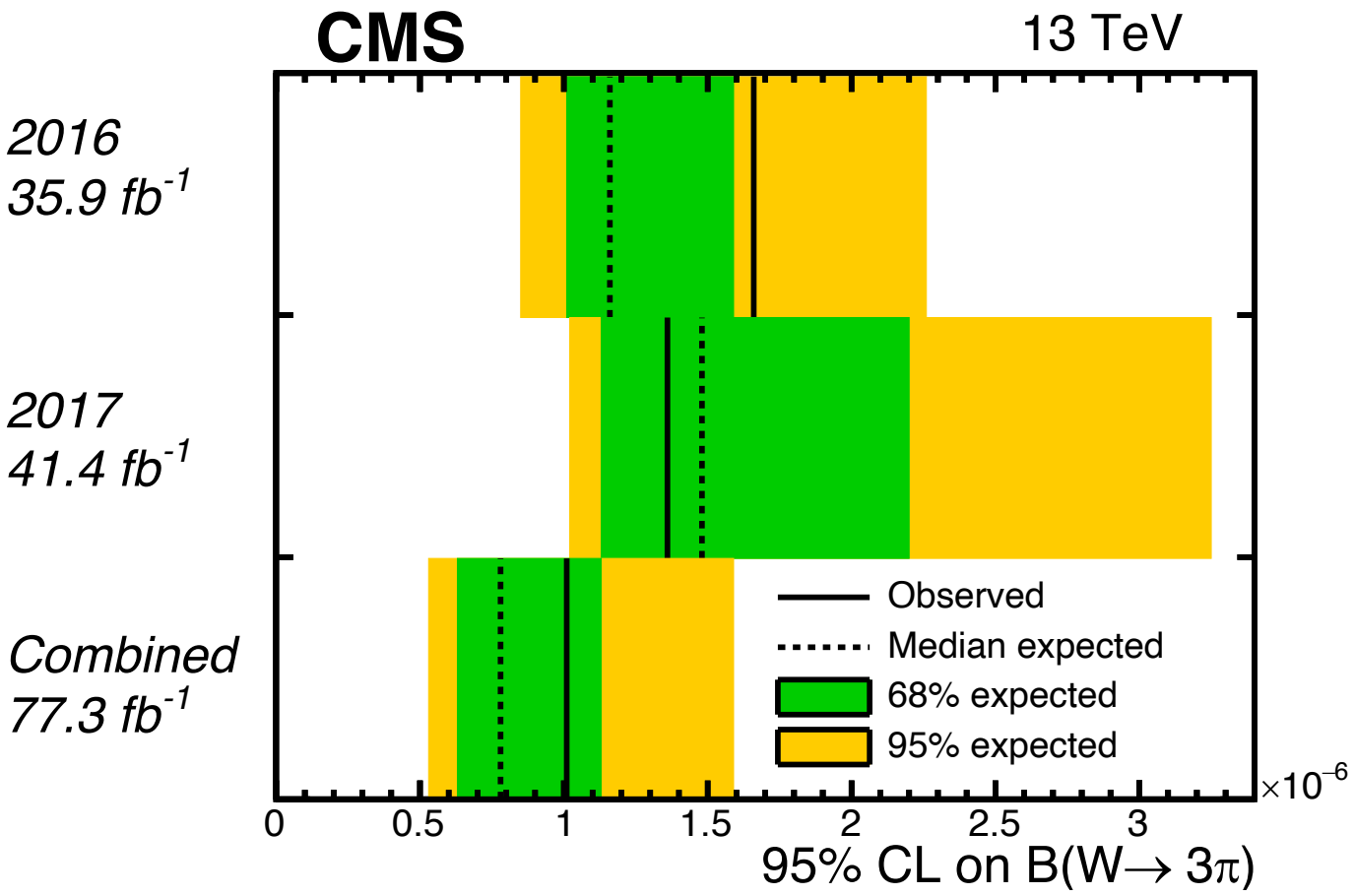
Results

Statistical uncertainty dominates (~ 90%)

Systematic contributions include:

- Pion ID efficiency
- Background estimation
- Theoretical uncertainties in the yield of W bosons

$$\mathfrak{B}(W \to \pi\pi\pi) < 1.01 \times 10^{-6}$$



$\mathbf{Z \to 4\ell}$

See also Sabine's talk

Not a dedicated measurement of $Z \to 4\ell$; instead, a **generic measurement of cross sections in 4ℓ events**

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

2 same-flavor, opposite-charge muons or electrons

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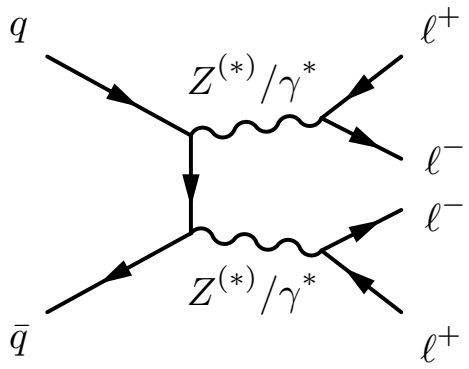
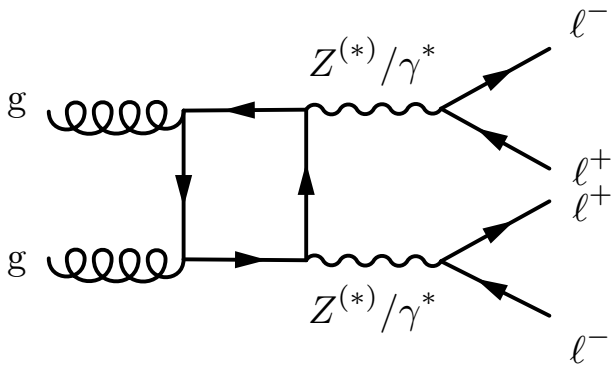
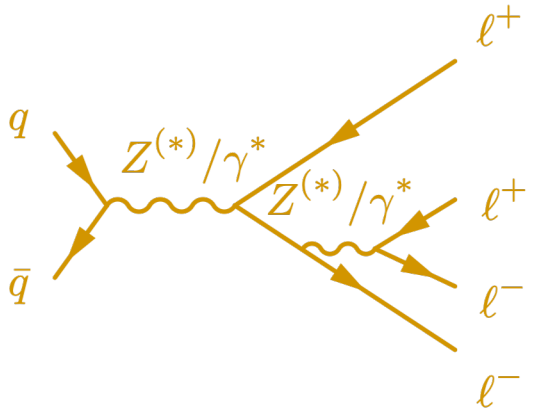
Several SM processes can contribute to these final states



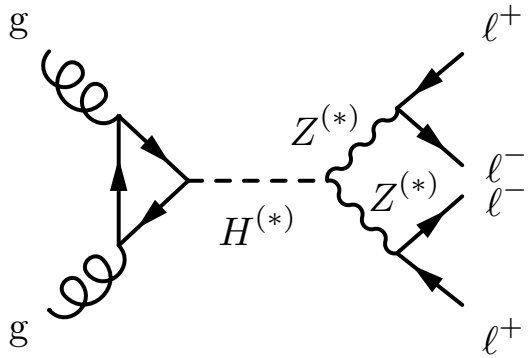
t-channel $q\bar{q} \to 4\ell$



Gluon-induced $gg \to 4\ell$



Internal conversion in Z boson decays



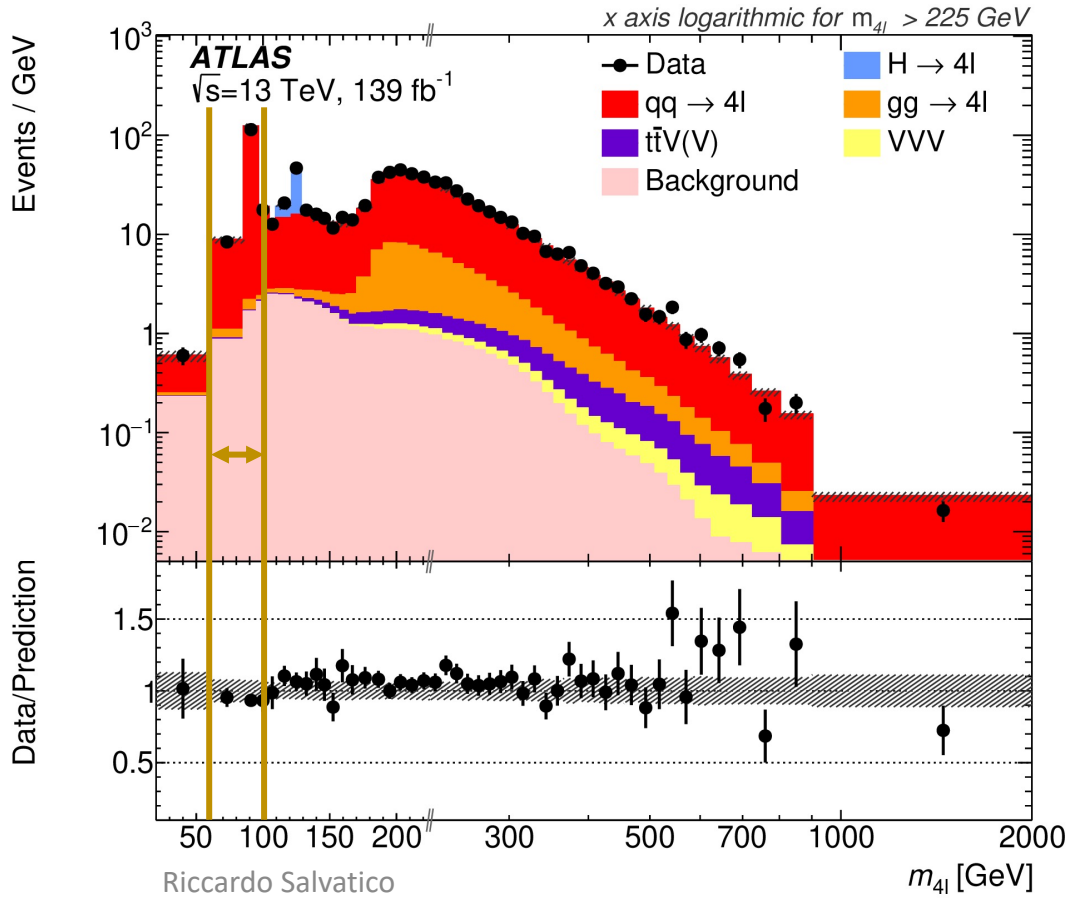
H boson-mediated s-channel production

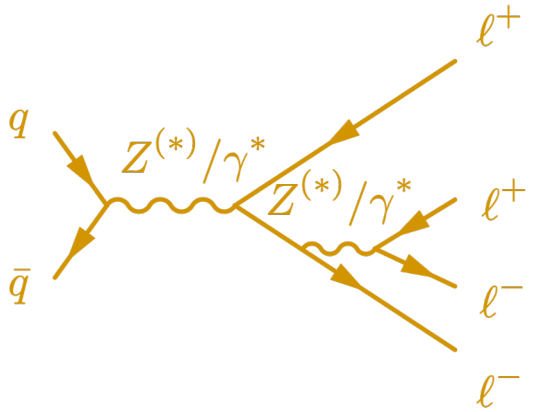
$Z \to 4\ell$

Not a dedicated measurement of $Z \to 4\ell$; instead, a **generic measurement of cross sections in 4ℓ events**

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

2 <u>same-flavor</u>, <u>opposite-charge</u> muons or electrons





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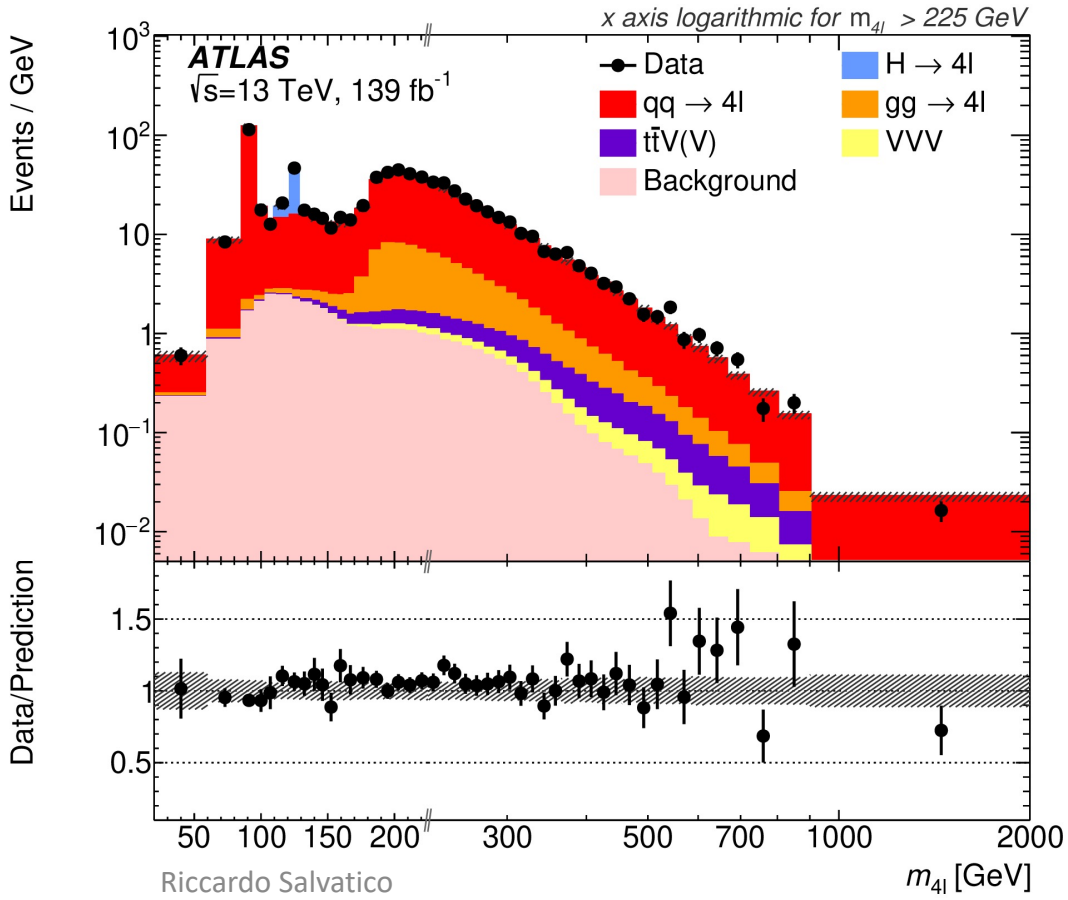


A number of BSM models could contribute too

- ❑ 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: $p_{\mathrm{T}}^{\ell} > 20$ GeV (leading), $p_{\mathrm{T}}^{\ell} > 10$ GeV (sub-leading)
- $m_{\ell\ell} > 5$ GeV (suppress J/ψ)
- $\Delta R(\ell, \ell) > 0.05$ (suppress conversion electrons)

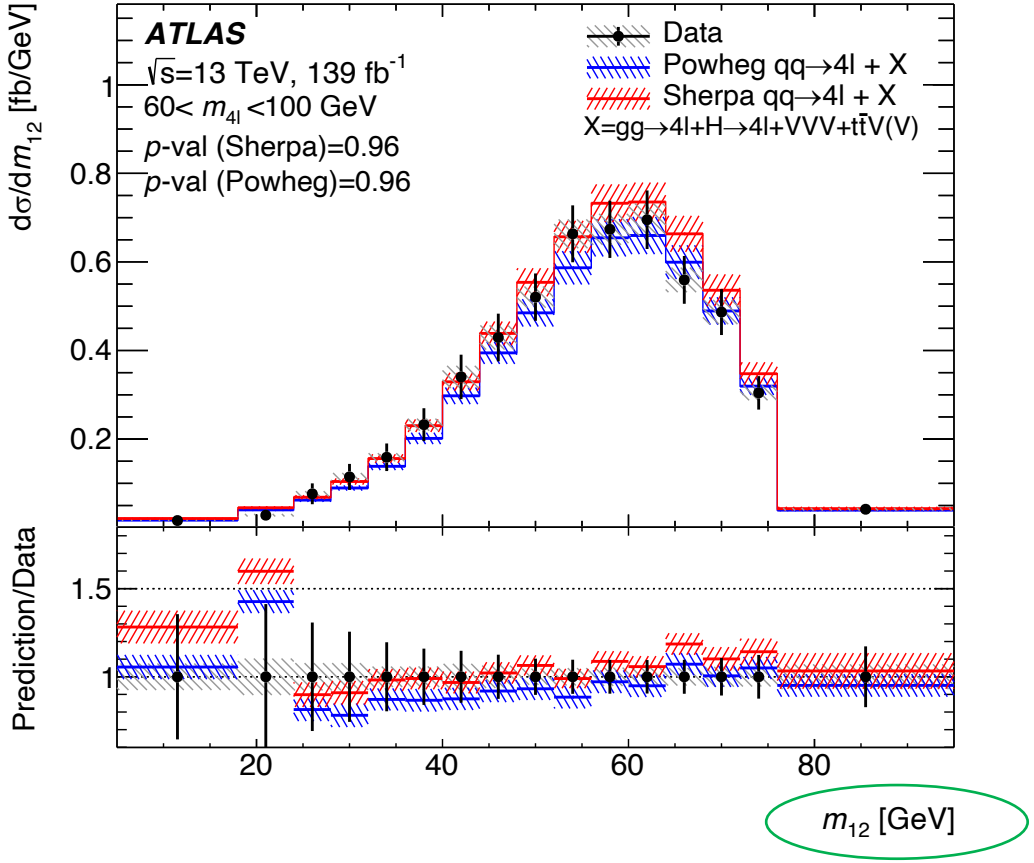
Background estimation and subtraction

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



Mass of the lepton pair closest to m_Z

$$\mathfrak{B}(Z \to 4\ell) = \frac{\left(\sigma^{\text{meas}} - \sigma^{\text{pred}}_{\text{non}-q\bar{q}\to 4\ell}\right) \times f_Z \times f_{\text{non}-\tau}}{\sigma_Z \times A} =$$

$$= (4.41 \pm 0.13\ (\text{stat}) \pm 0.23\ (\text{syst}) \pm 0.09\ (\text{theo}) \pm 0.12\ (\text{lumi})) \times 10^{-6} =$$

$$= (4.41 \pm 0.30) \times 10^{-6}$$

$\sigma^{\text{meas}} = 22.1 \pm 1.3$ fb in the $Z \to 4\ell$ region

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

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

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

σ_Z total cross section for single-Z production

A acceptance factor

The most precise $\mathfrak{B}(Z \to 4\ell)$ measurement to date!

$Z \to e\tau/\mu\tau$

See also Ann-Kathrin's poster

Part of the vast program of lepton flavor violation studies at the LHC

$Z \to e\tau/\mu\tau$ at the LHC – two particularly interesting channels

A sample of ~ 8 billion Z boson decays only in Run2

No stringent indirect constraints as for $Z \to e\mu$

Our current theoretical knowledge: one Z decay in $\sim 10^{54}$ can be $Z \to \mu\tau$ (via neutrino mixing)

!

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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 $\mathfrak{B}(Z \to \ell\tau)$ up to 10^{-5}

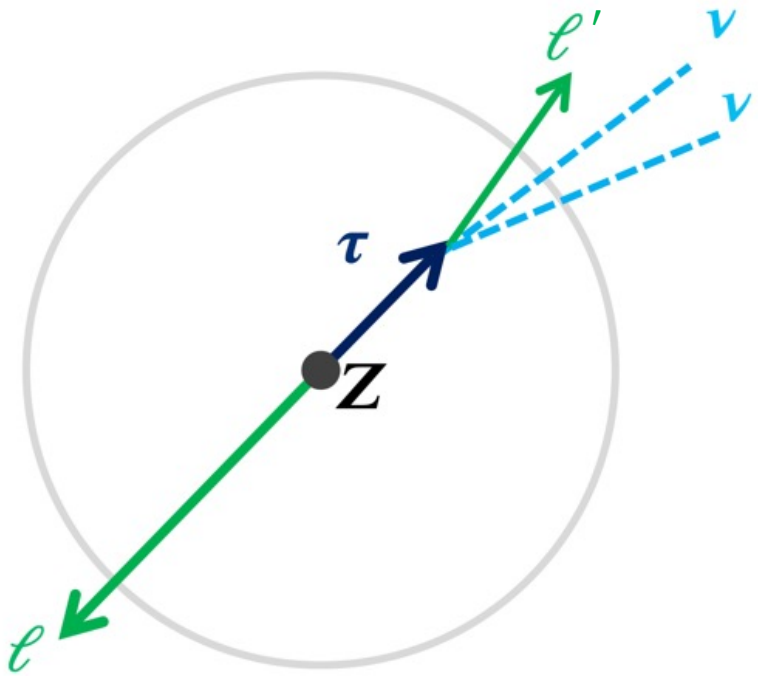
Search strategy

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

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

Signal

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



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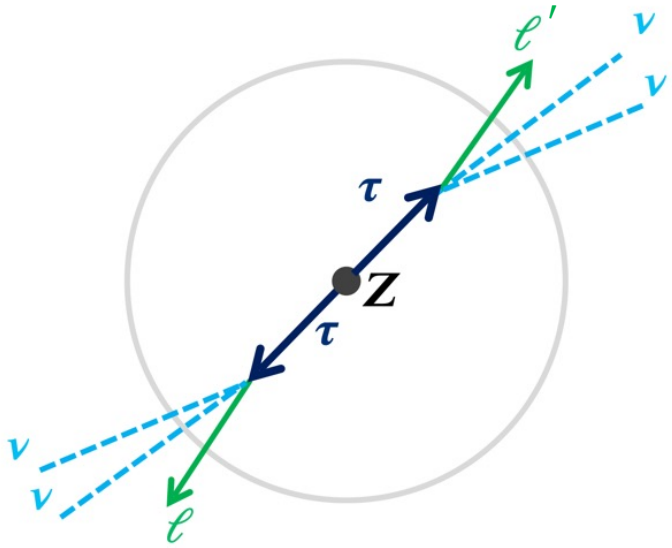

Main background sources

- $Z \to \tau\tau \to \ell\ell' + 4\nu$

Search strategy

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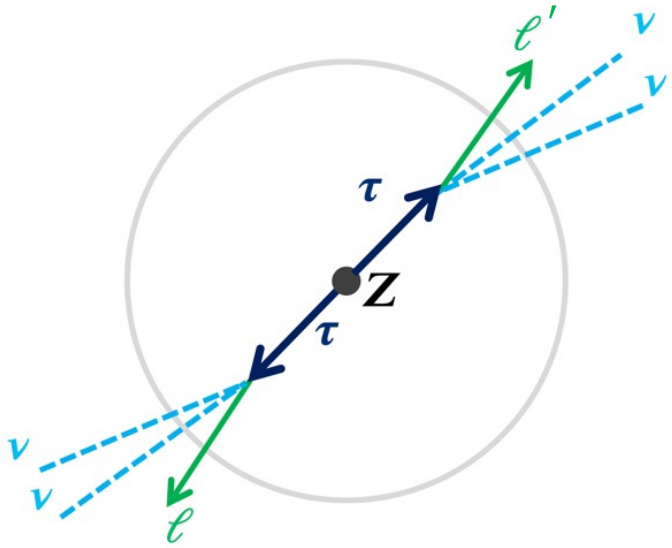

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- $Z \to \tau\tau \to \ell\ell' + 4\nu$
- $t\bar{t}, VV, H$ production with 2ℓ final states

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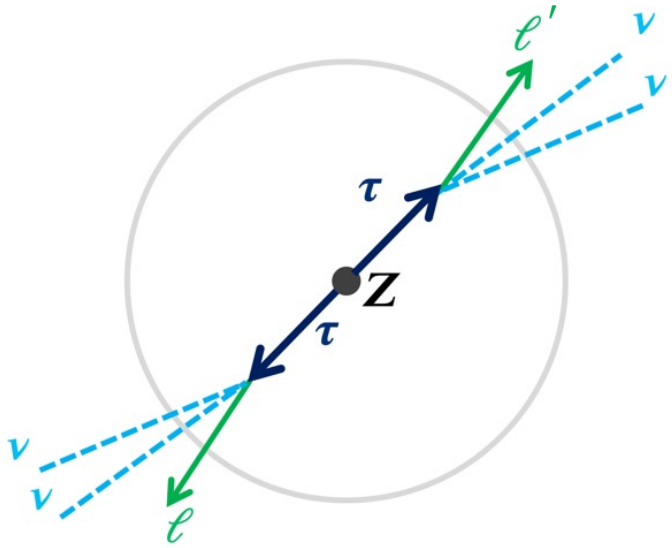

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- *Fakes* – mostly $W(\to \ell\nu) + \text{jets}$

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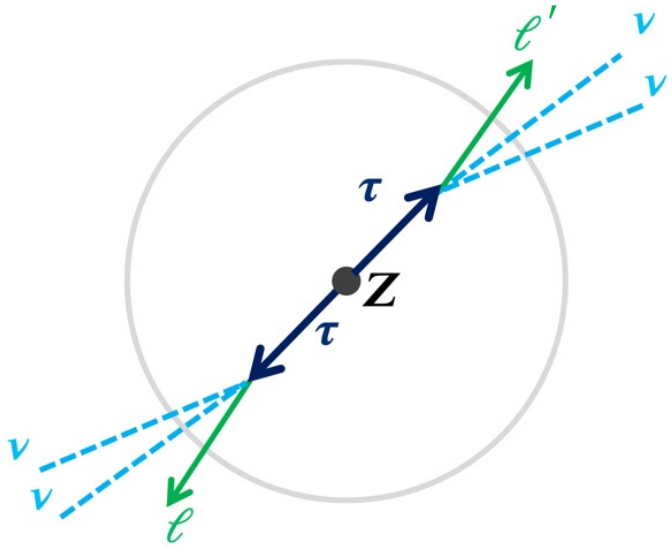
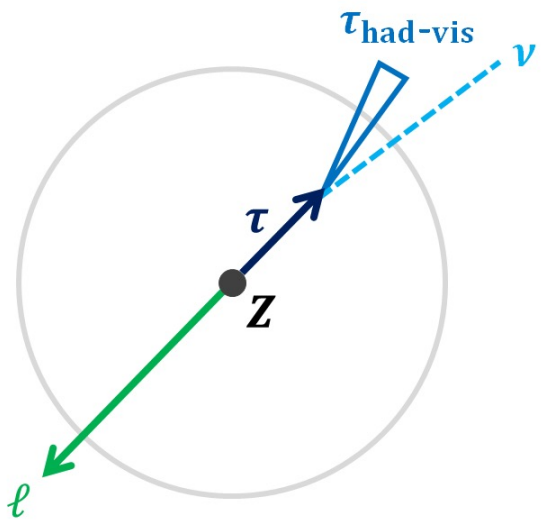




$\tau_{\text{had-vis}}$ visible products of hadronic τ decays

Main background sources

- $Z \to \tau\tau \to \ell\ell' + 4\nu$
- $t\bar{t}$, VV, H production with 2ℓ final states
- *Fakes* – mostly $W(\to \ell\nu) + \text{jets}$

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

Channel exploited in previous ATLAS search.
Used for combination!

Search strategy

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

Signal | **Main background sources**

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

→ **Neural networks** are a fundamental component

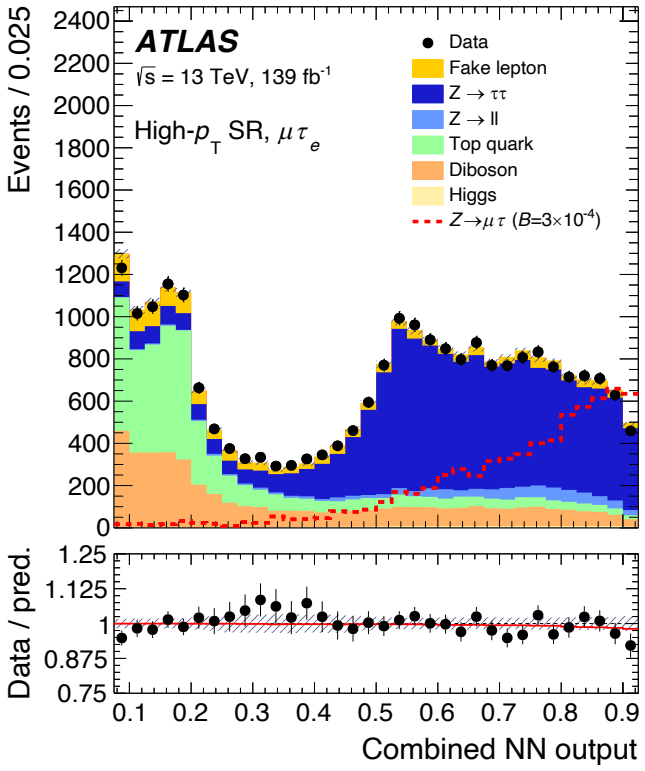
Low-level variables

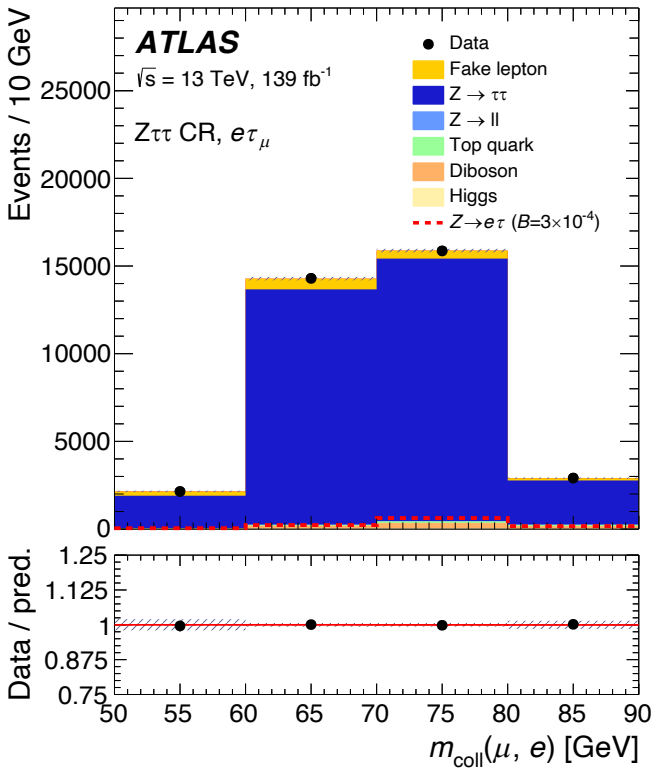
Momentum components of ℓ, ℓ' and $E_{\mathrm{T}}^{\mathrm{miss}}$

High-level variables

Kinematic properties of the $\mathrm{e} - \mu - E_{\mathrm{T}}^{\mathrm{miss}}$ system (e.g., $\mathrm{e} - \mu - 2\nu$ invariant mass)

Results





Simultaneous fit to:

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

<u>No significant excess observed</u>

Unpolarized τ scenario

$\mathfrak{B}(Z \to e\tau) < 7.0 \times 10^{-6}$

$\mathfrak{B}(Z \to \mu\tau) < 7.2 \times 10^{-6}$

Combination with τ_{had} results

$\mathfrak{B}(Z \to e\tau) < 5.0 \times 10^{-6}$

$\mathfrak{B}(Z \to \mu\tau) < 6.5 \times 10^{-6}$

95% CL

Summary

Results on rare decays of the electroweak bosons were presented:

- $W \to \pi\gamma$
  - A new and effective search strategy for this kind of decays
- $W \to \pi\pi\pi$
  - First ever attempt to observe this process
- $Z \to 4\ell$
  - The most precise measurement to date
- $Z \to e\tau/\mu\tau$
  - 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 $Z \to e\mu$ in pp collisions at at $\sqrt{s} = 8$ TeV with the ATLAS detector", PRD **90** (2014) 072010

CMS Collaboration, "Search for decays of Z and Higgs bosons to J/ψ and a photon in proton-proton collisions at $\sqrt{s} = 13$ TeV", EPJC 79 (2019) 94

CMS Collaboration, "Search for Higgs and Z boson decays to J/ψ or Υ 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 $pp \to ZZ$ production cross section and the $Z \to 4\ell$ branching fraction, and constraints on anomalous triple gauge couplings at $\sqrt{s} = 13$ TeV", EPJC 78 (2018) 165

CMS Collaboration, "Observation of the $Z \to \psi\ell^+\ell^-$ in pp collisions at $\sqrt{s} = 13$ TeV", PRL 121 (2018) 141801

BACKUP

$Z \to e\tau/\mu\tau$ SR selection

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

Selection criterion	Purpose
Exactly two isolated light leptons (ℓ_0, ℓ_1) with opposite electric charge and different flavor (e or μ); $p_T(\ell_0) > p_T(\ell_1)$	Select events consistent with signal decays.
No $\tau_{\text{had-vis}}$ candidate	Orthogonality with $\ell\tau_{\text{had}}$ channel.
Transverse mass[2] $m_T(\ell_1, E_T^{\text{miss}}) < 35$ GeV $\lvert\Delta\phi(\ell_0, E_T^{\text{miss}})\rvert > 1$ rad No b-tagged jets (using the 77% efficiency working point [28])	Reject top-quark and diboson events.
Invariant mass of the ℓ_0–ℓ_1 pair $m(\ell_0, \ell_1) > 40$ GeV	Reject events incompatible with Z-boson decays.
Neural network (optimized for signal vs. $Z \to \tau\tau$) output > 0.2	Ensure selection is orthogonal to the CRZ$\tau\tau$ region.
In $\mu\tau_e$ channel: $p_T^{\text{track}}(e)/p_T^{\text{cluster}}(e) < 1.1$	Reject $Z \to \mu\mu$ events.

$Z \to e\tau/\mu\tau$ – other τ polarizations

Final state, polarization assumption	Observed (expected) upper limit on $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
$\ell\tau_{\text{had}}$ Run 1 + Run 2, unpolarized τ [9]	8.1 (8.1)	9.5 (6.1)
$\ell\tau_{\text{had}}$ Run 2, left-handed τ [9]	8.2 (8.6)	9.5 (6.7)
$\ell\tau_{\text{had}}$ Run 2, right-handed τ [9]	7.8 (7.6)	10 (5.8)
$\ell\tau_{\ell'}$ Run 2, unpolarized τ	7.0 (8.9)	7.2 (10)
$\ell\tau_{\ell'}$ Run 2, left-handed τ	5.9 (7.5)	5.7 (8.5)
$\ell\tau_{\ell'}$ Run 2, right-handed τ	8.4 (11)	9.2 (13)
Combined $\ell\tau$ Run 1 + Run 2, unpolarized τ	5.0 (6.0)	6.5 (5.3)
Combined $\ell\tau$ Run 2, left-handed τ	4.5 (5.7)	5.6 (5.3)
Combined $\ell\tau$ Run 2, right-handed τ	5.4 (6.2)	7.7 (5.3)