Searches for new physics in events with leptons at CMS

PHENO 2022

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on behalf of the
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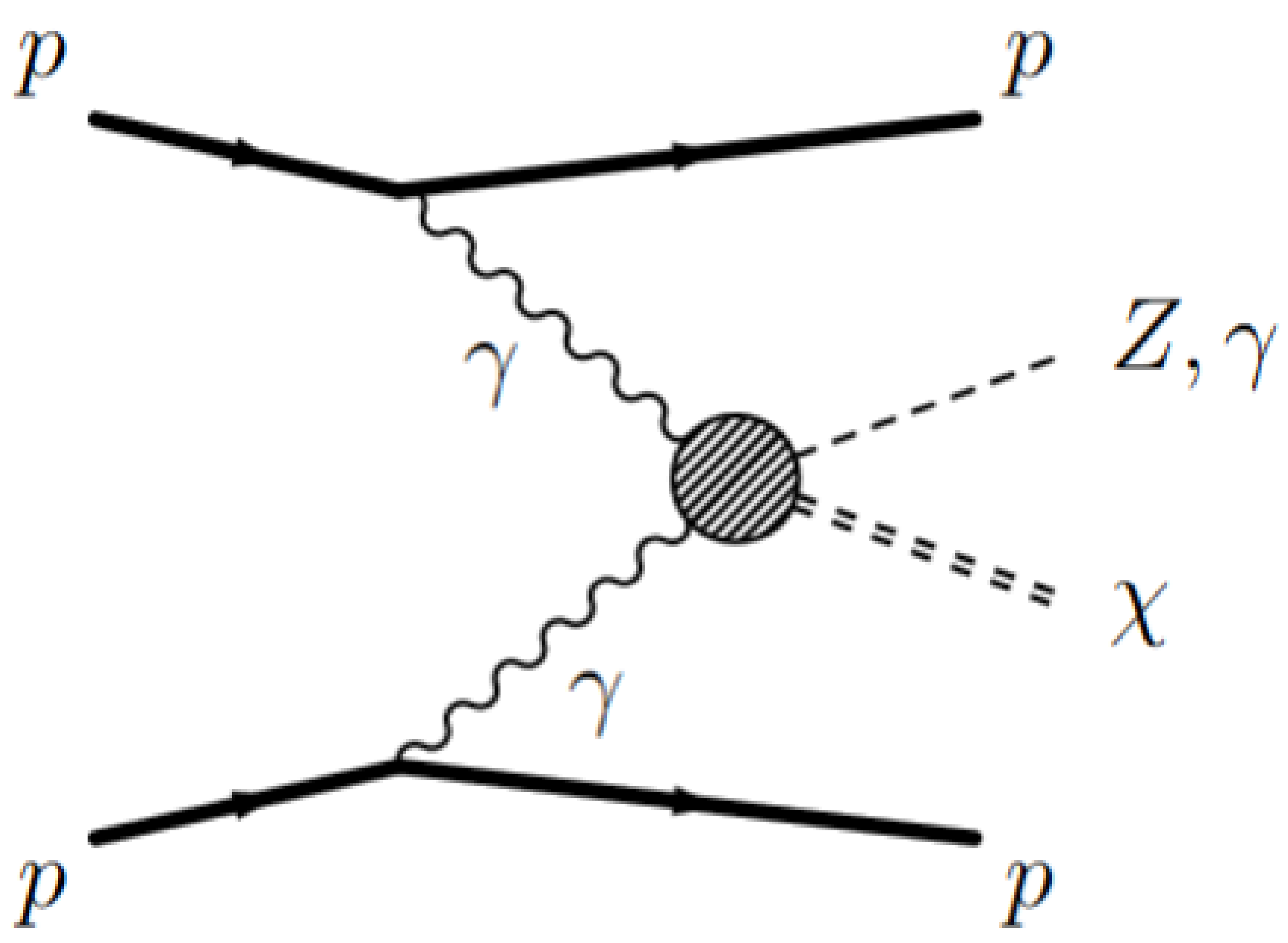
Introduction

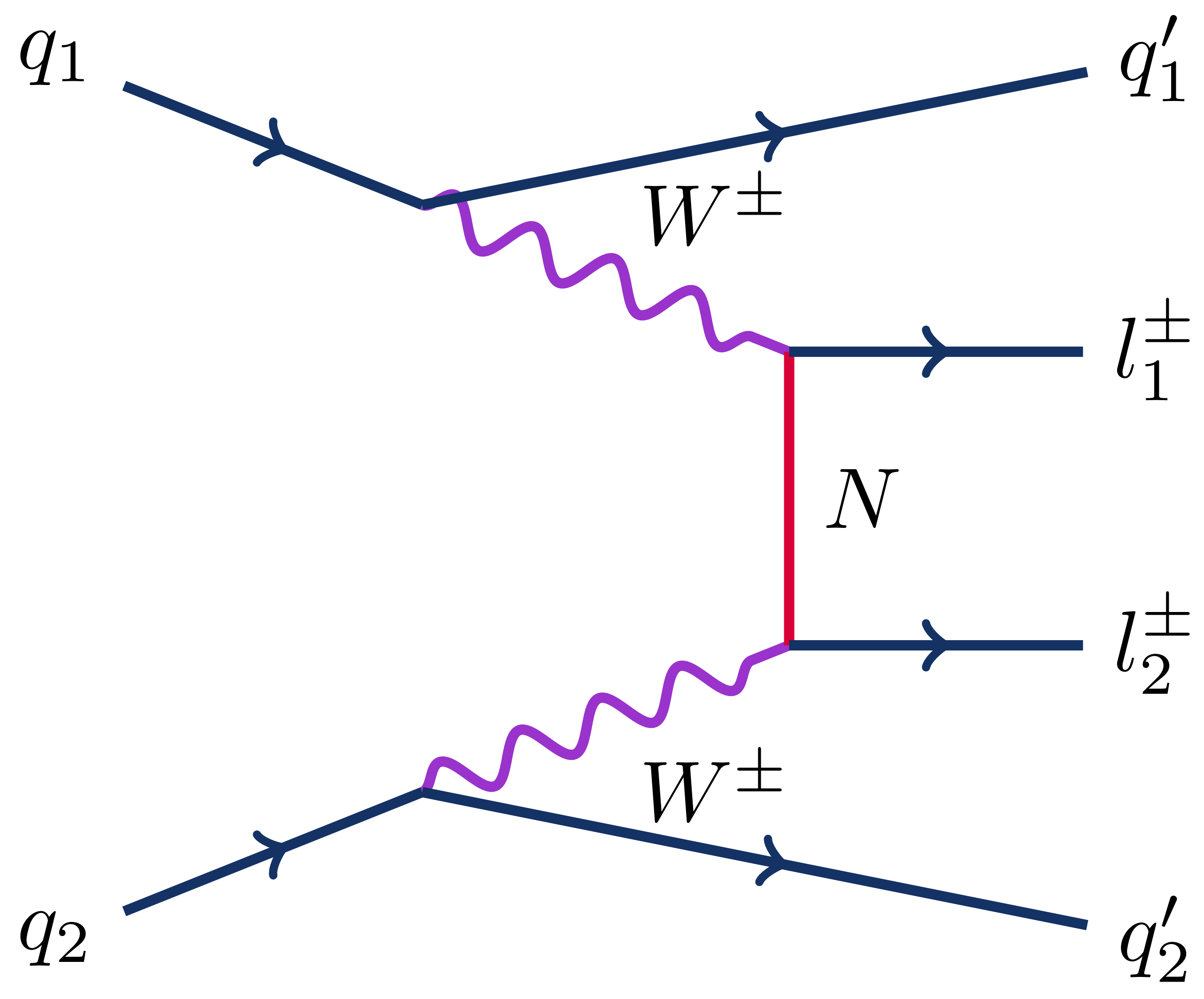
Leptons provide *exceptionally clean* search signatures for new physics at the LHC, and many BSM physics models predict leptonic final states.

Today, we'll discuss two recent, first-of-their-kind searches w/ leptons at CMS:



Z or γ + X missing mass search

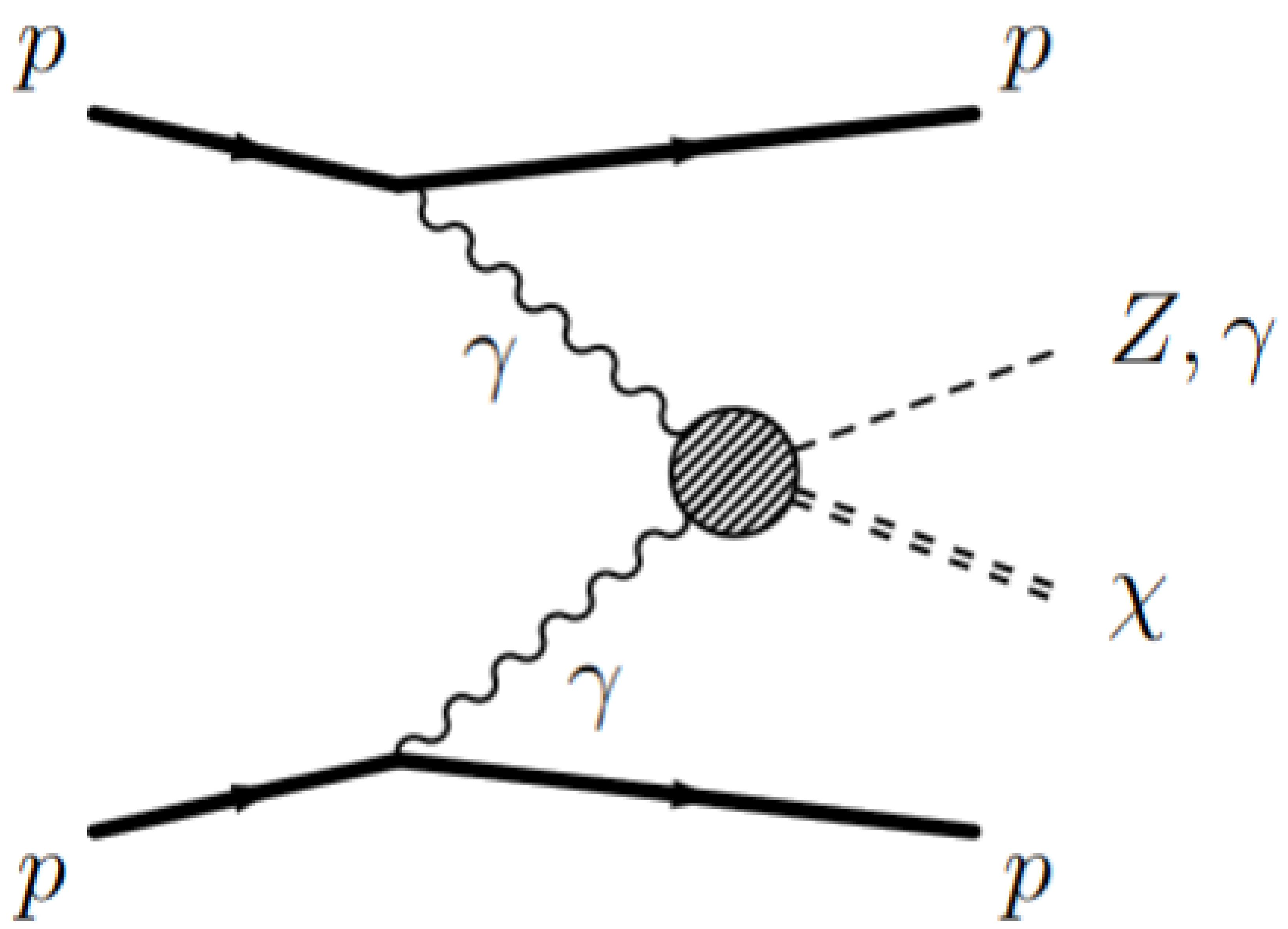
EXO-19-009



Majorana neutrino search in VBF $\mu^{\pm}\mu^{\pm}$ events

EXO-21-003

Missing mass search w/ the CMS-TOTEM Precision Proton Spectrometer (PPS)



Using up to 37 fb^{-1} of 2017 data

EXO-19-009

Public since March 2022

Proton Reconstruction w/ PPS

New for Run 2!

PPS allows CMS to measure forward protons using silicon tracking detectors

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- Main measurement: proton momentum loss ($\xi = \Delta p/p$) of outgoing protons from pp collisions w/ small scattering angles; sensitive to $\xi \in [2\%, 20\%]$
- Calibration relies on precise understanding of LHC's $\vec{B}$ field and beam optics

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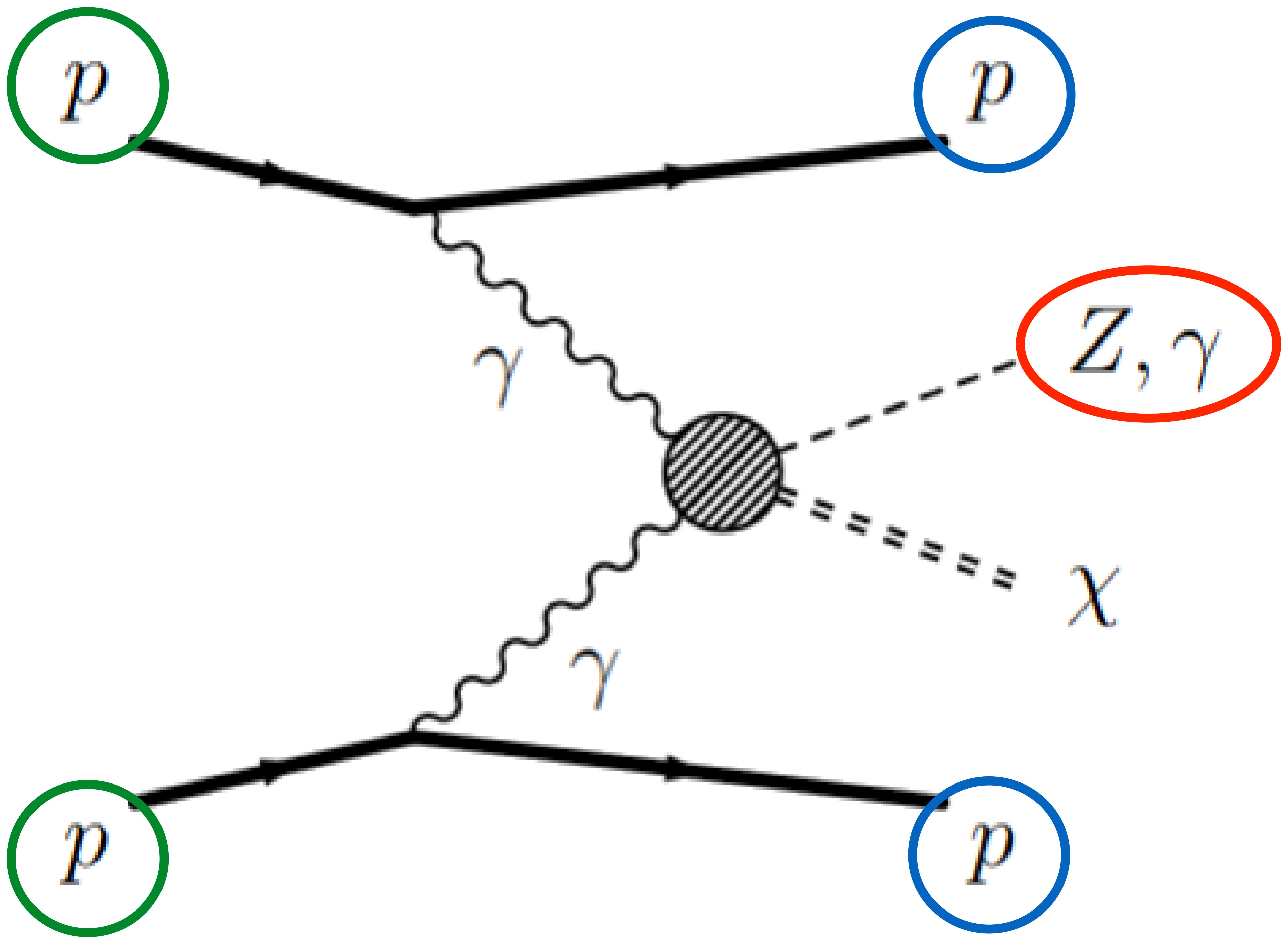
Search Strategy



Select events with Z→ℓℓ or a photon; use outgoing proton momenta to reconstruct the missing mass:

$$m^2_{\text{miss}} = \left[\underbrace{(P^{\text{in}}_{p_1} + P^{\text{in}}_{p_2})}_{\text{LHC}} - (\underbrace{P_V}_{\text{CMS}} + \underbrace{P^{\text{out}}_{p_1} + P^{\text{out}}_{p_2}}_{\text{PPS}}) \right]^2$$

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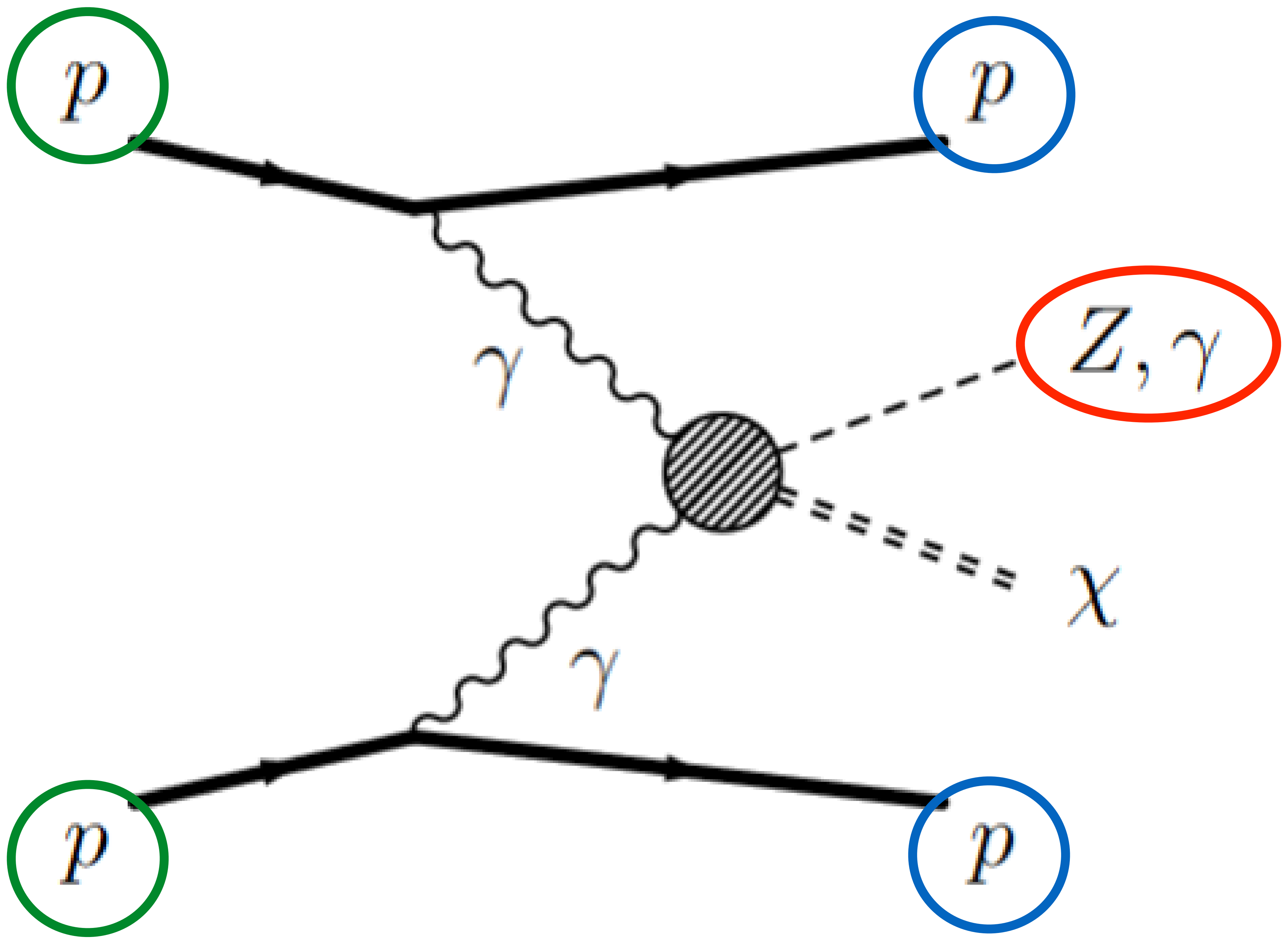

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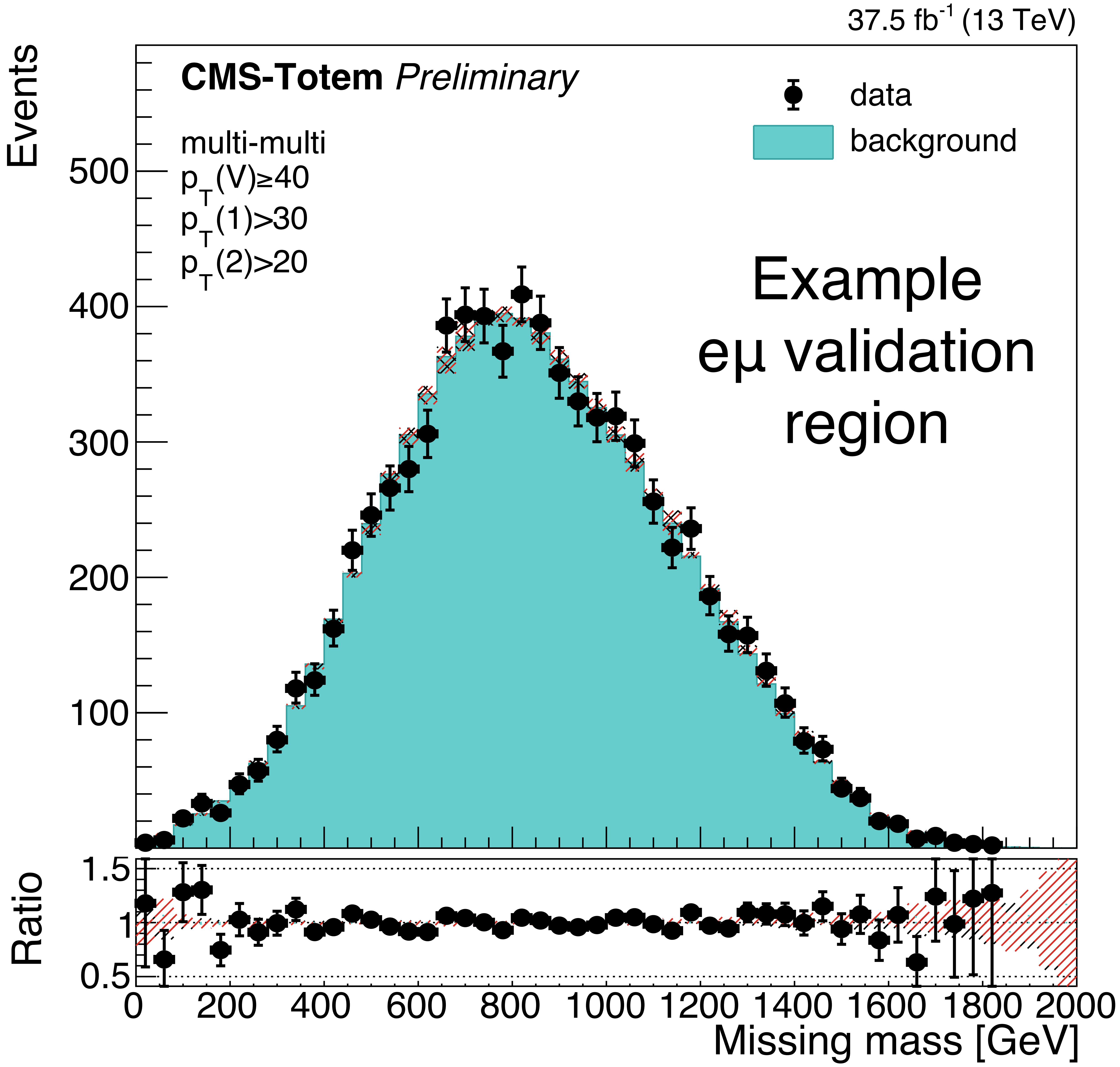
- Search performed at high mass (600-1600 GeV), where PPS provides mass resolution of ~2%
- **First missing mass-based search at the LHC!**

Background Estimation

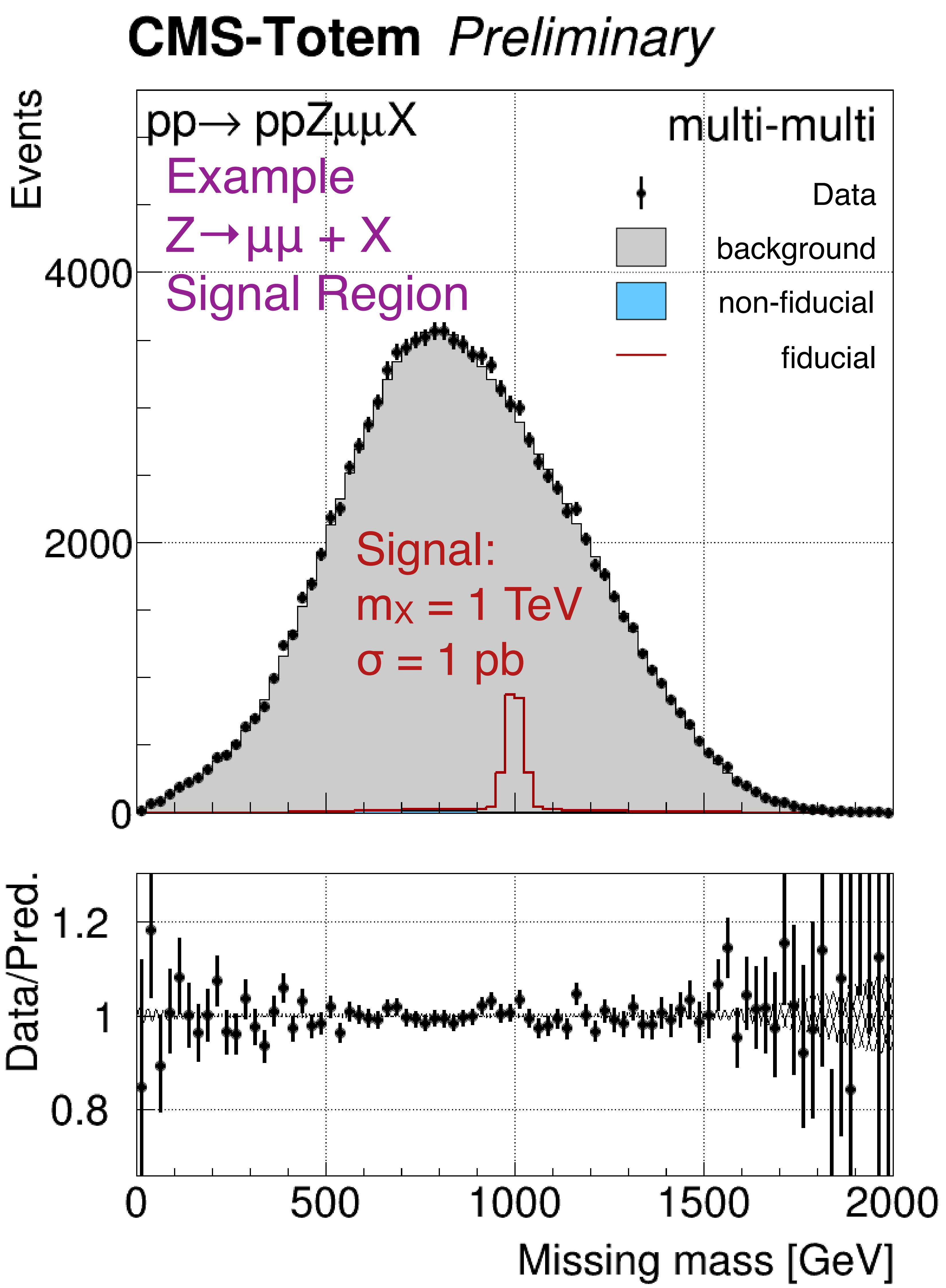


Primary background is combinatorial (coincidence of pileup protons)

Estimated via event mixing:

- Replace protons in data events with those from an orthogonal dataset of randomly chosen events w/ same beam conditions
- Validate in eμ data events, and in simulated Z or γ events

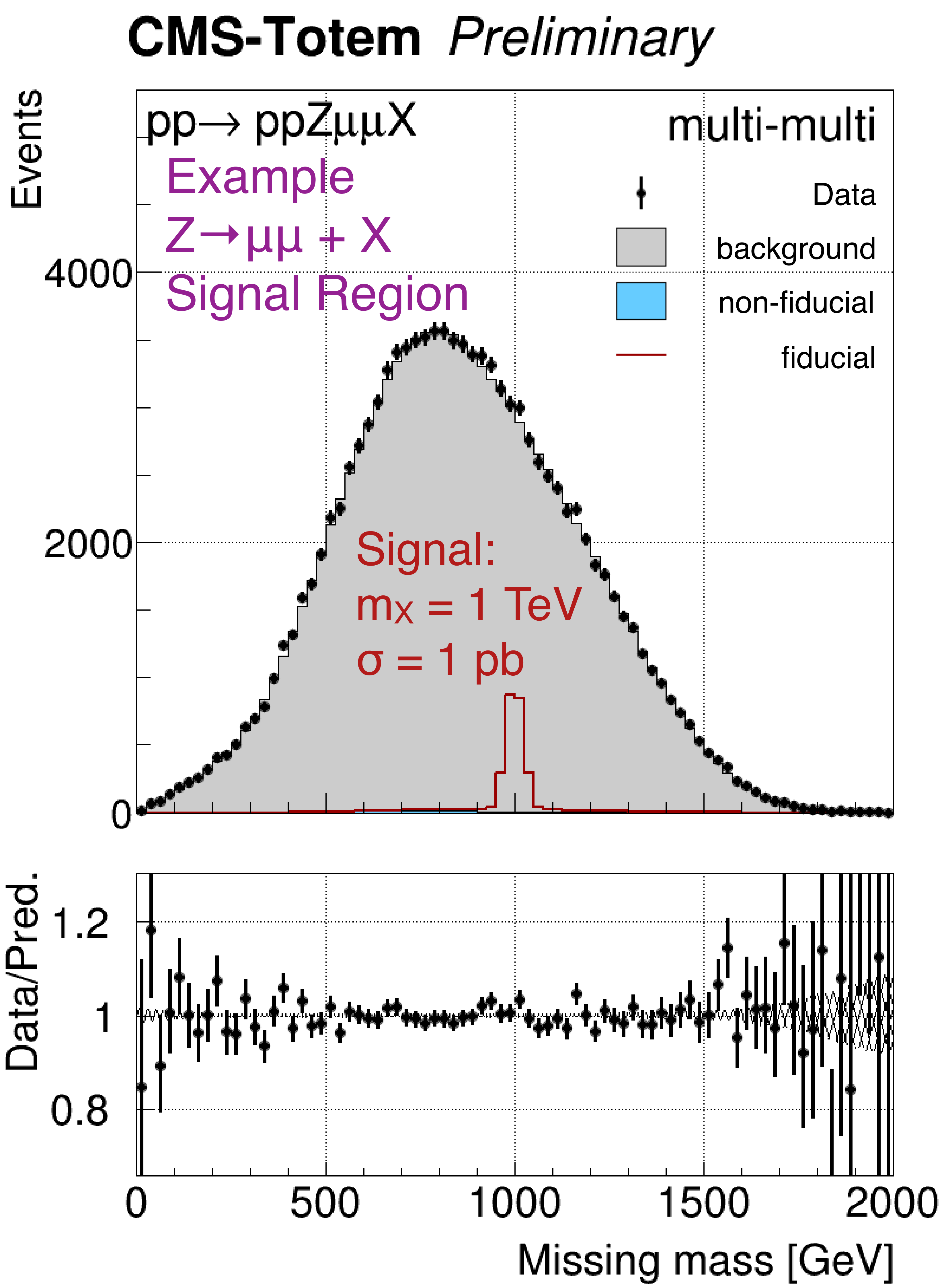
Results

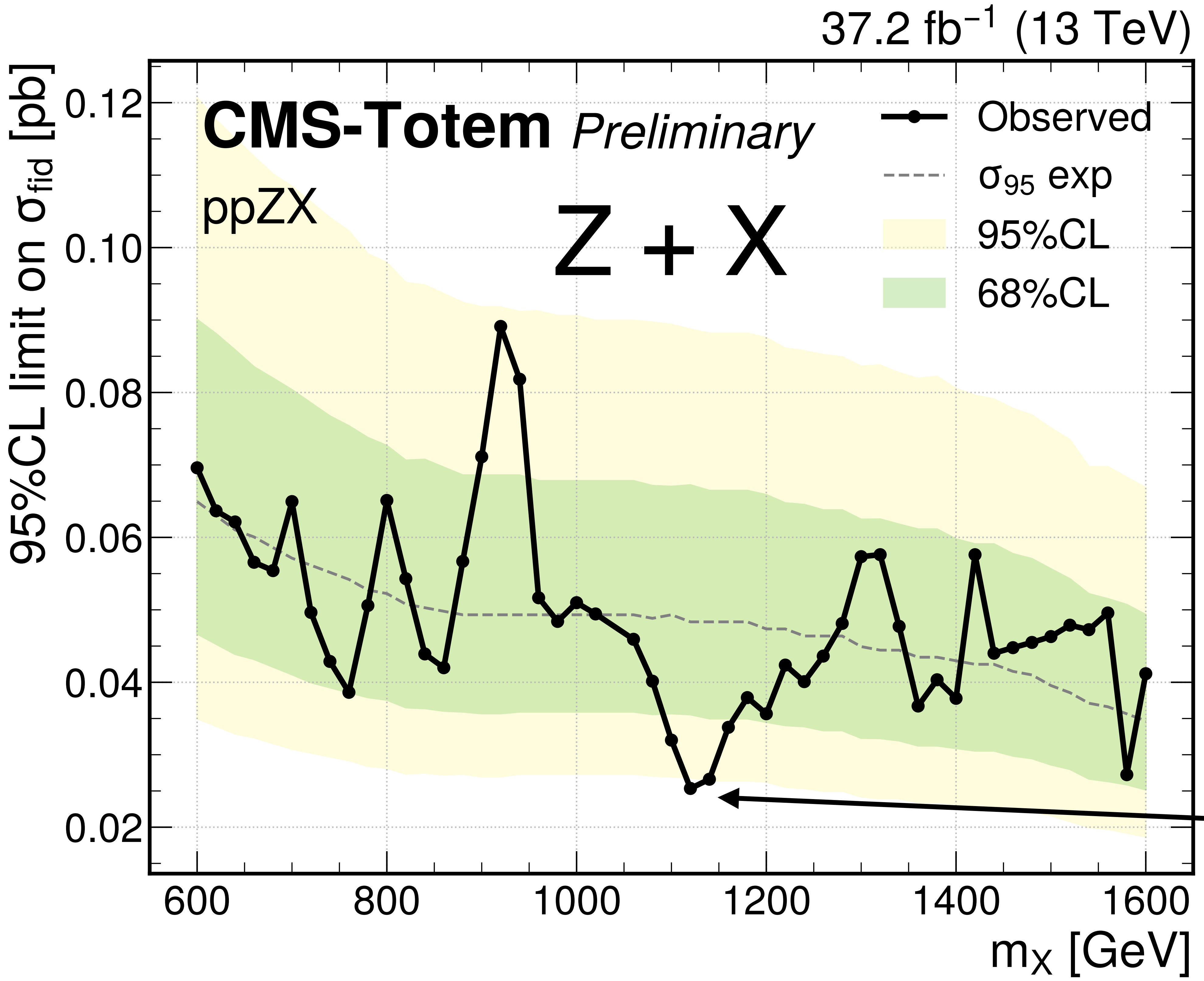


Fiducial selection: good quality, high p_T $Z\to\ell\ell$ or γ; protons within PPS (details in backup).

No significant excess in the missing mass distributions!

Results



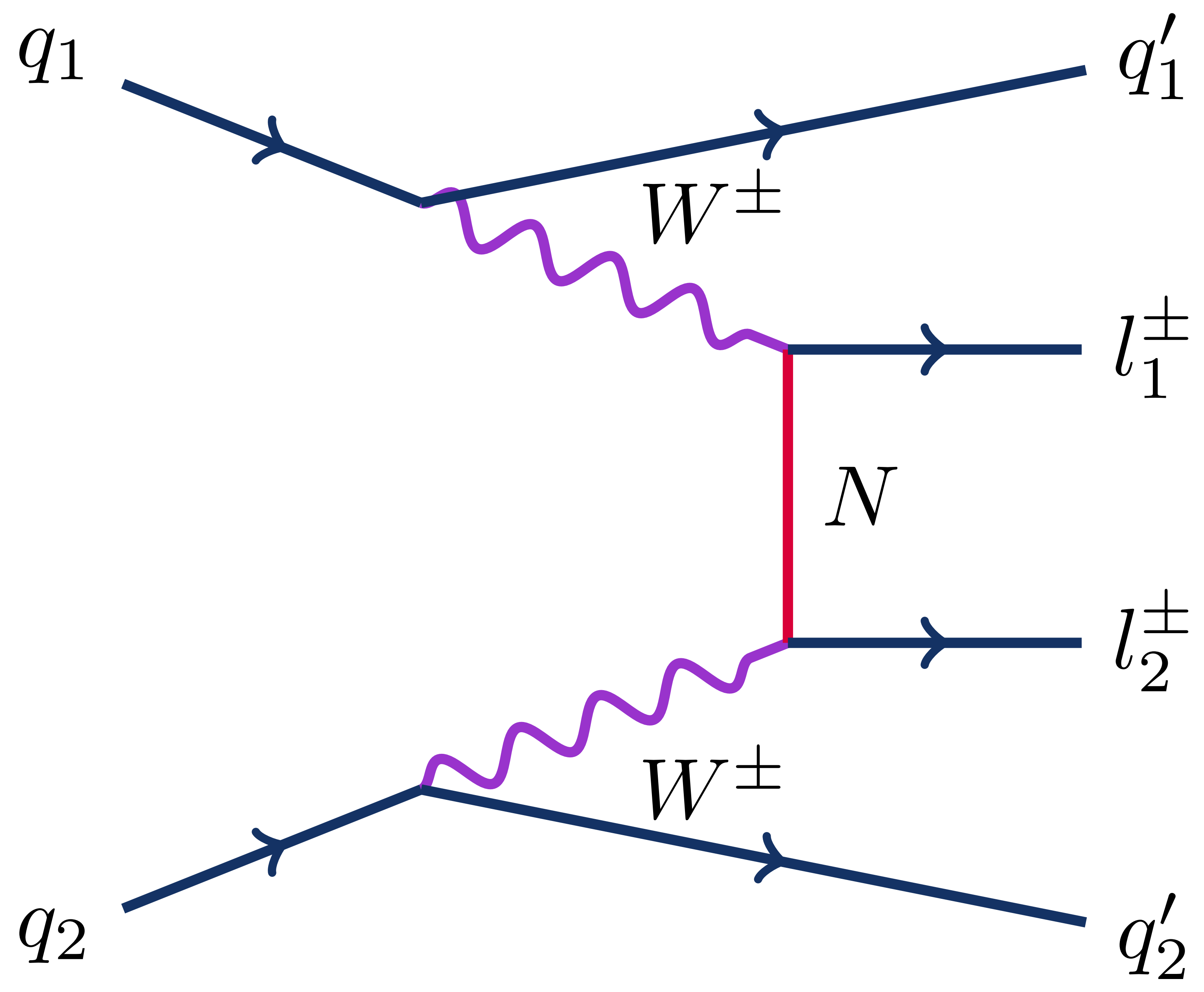


Set limits on σ_{fid} as low as 25 fb

Fiducial selection: good quality, high p_T $Z \rightarrow \ell\ell$ or γ; protons within PPS (details in backup).

No significant excess in the missing mass distributions!

Search for Majorana neutrinos and the Weinberg operator in VBF $\mu^{\pm}\mu^{\pm}$ events



Using 138 fb^{-1} of Run 2 data

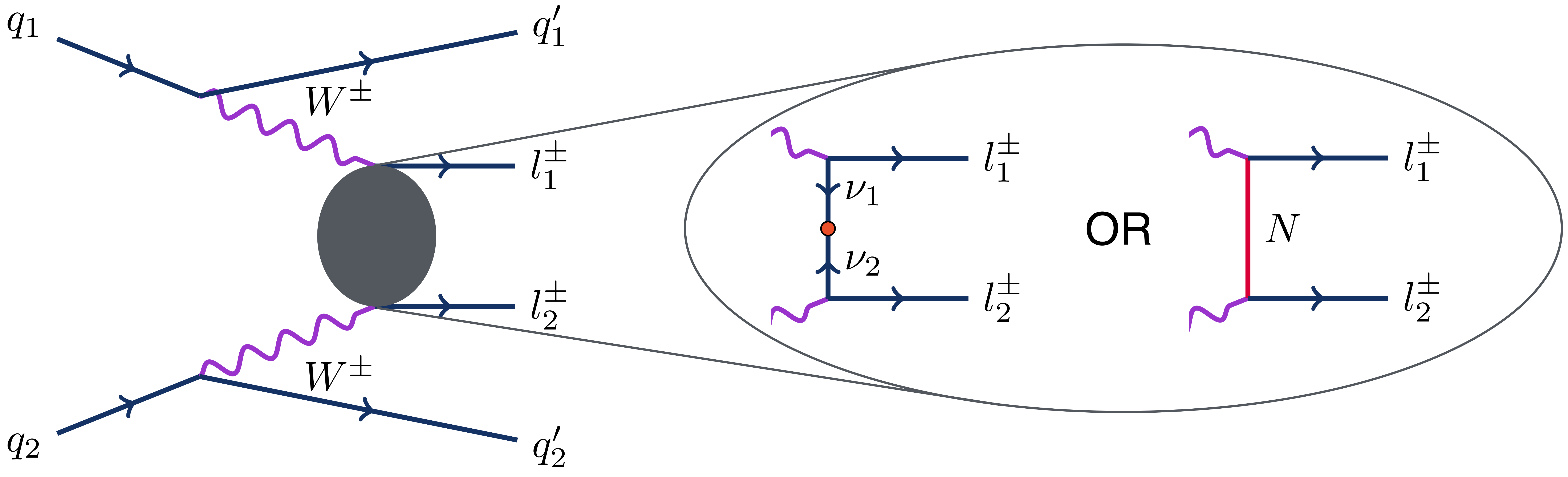
EXO-21-003

Public since March 2022

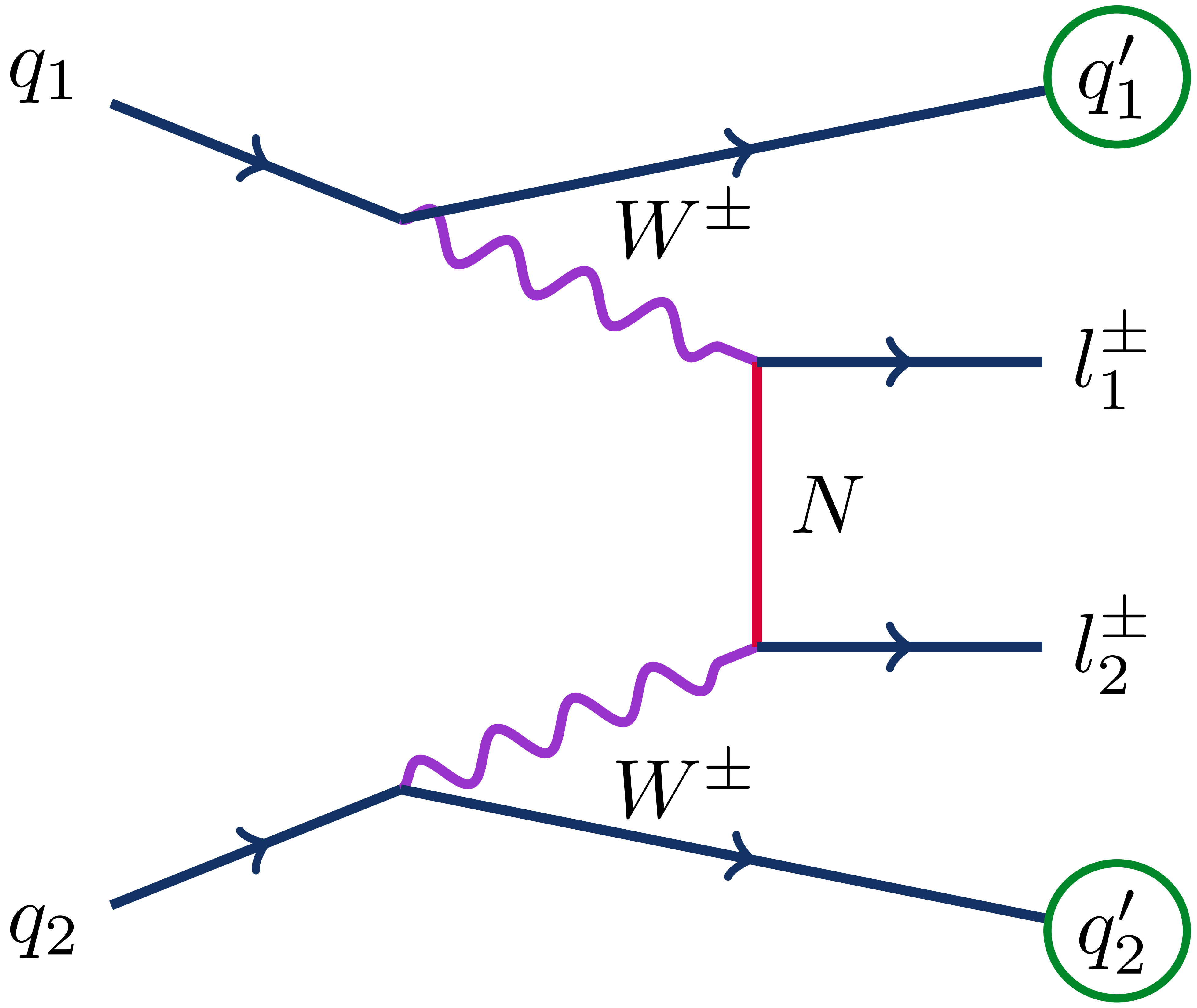
Motivation

Aims to explain nonzero mass of neutrinos (ν) via either:

- EFT w/ dim-5 Weinberg operator; generates m_ν *and* leads to lepton-number violating 0νββ decay
- Heavy Majorana neutrino (N) in type-I seesaw model



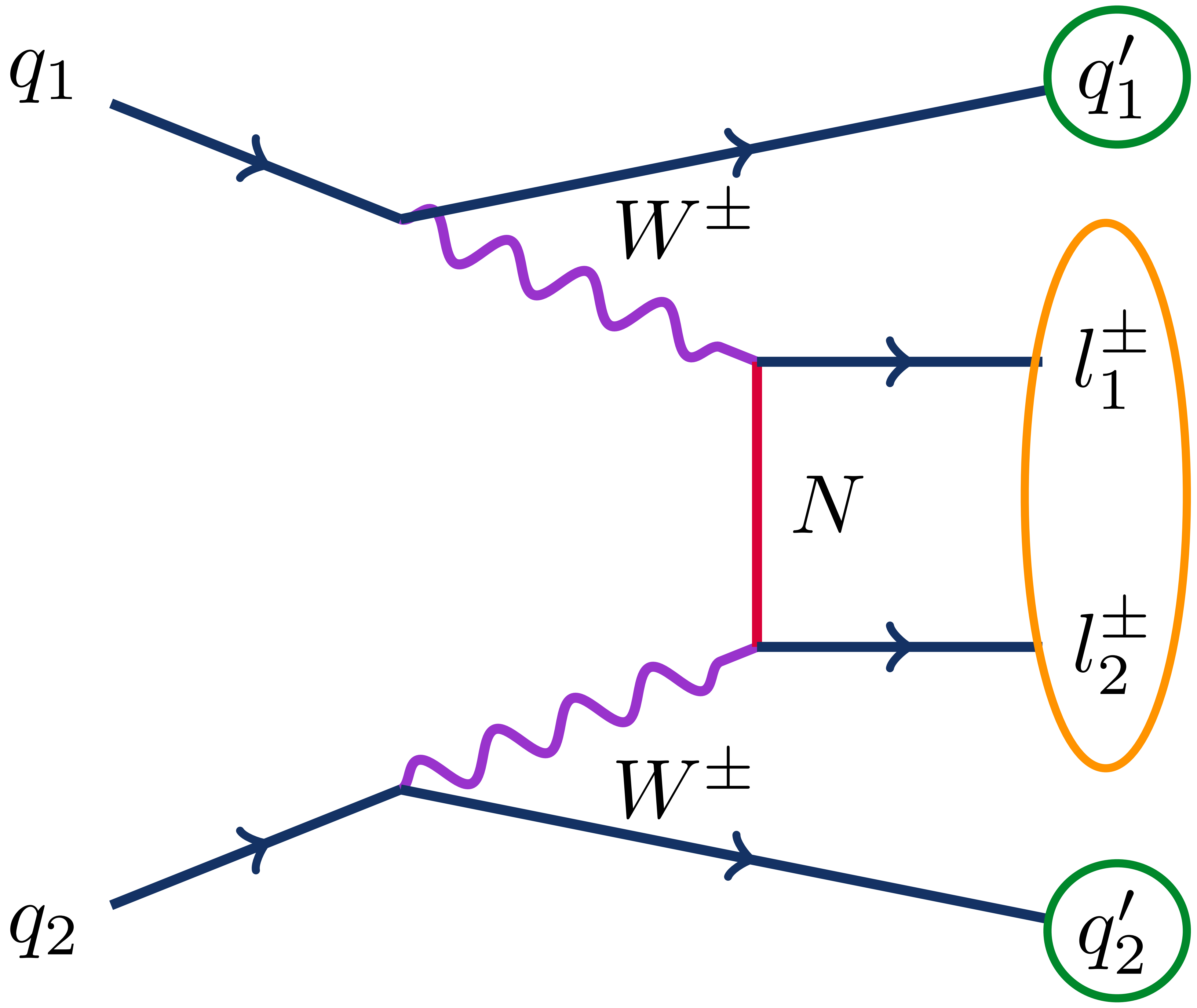
Signal vs. Background Discrimination



Suppress background by requiring:

- Forward VBF jet kinematics (large m_{jj}, $\Delta\eta_{jj}$, etc.)

Signal vs. Background Discrimination



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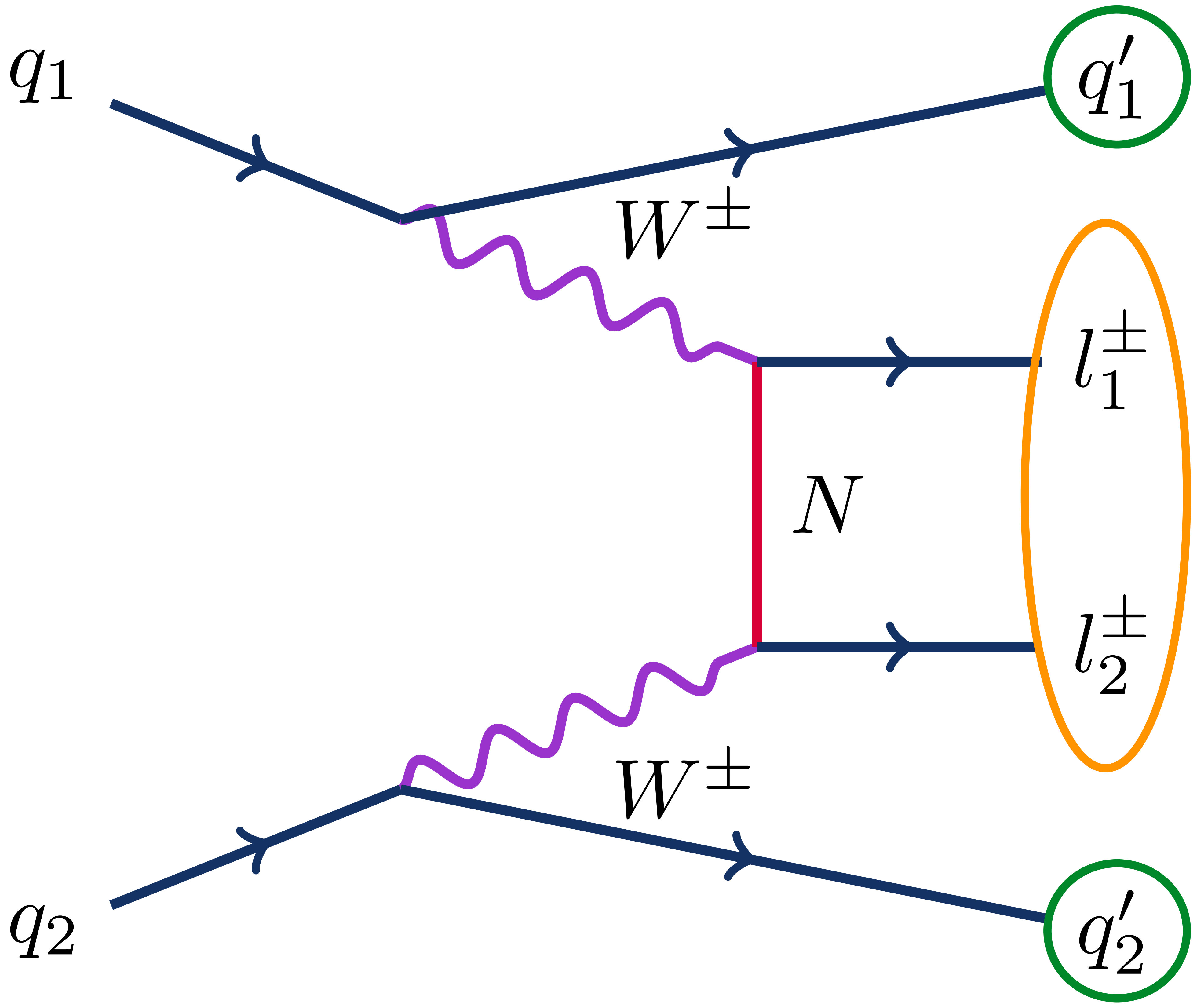

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- Small jet activity ($H_T = \Sigma$ jet p_T) relative to leptonic activity: search is binned in H_T / $p_T(\mu_1)$

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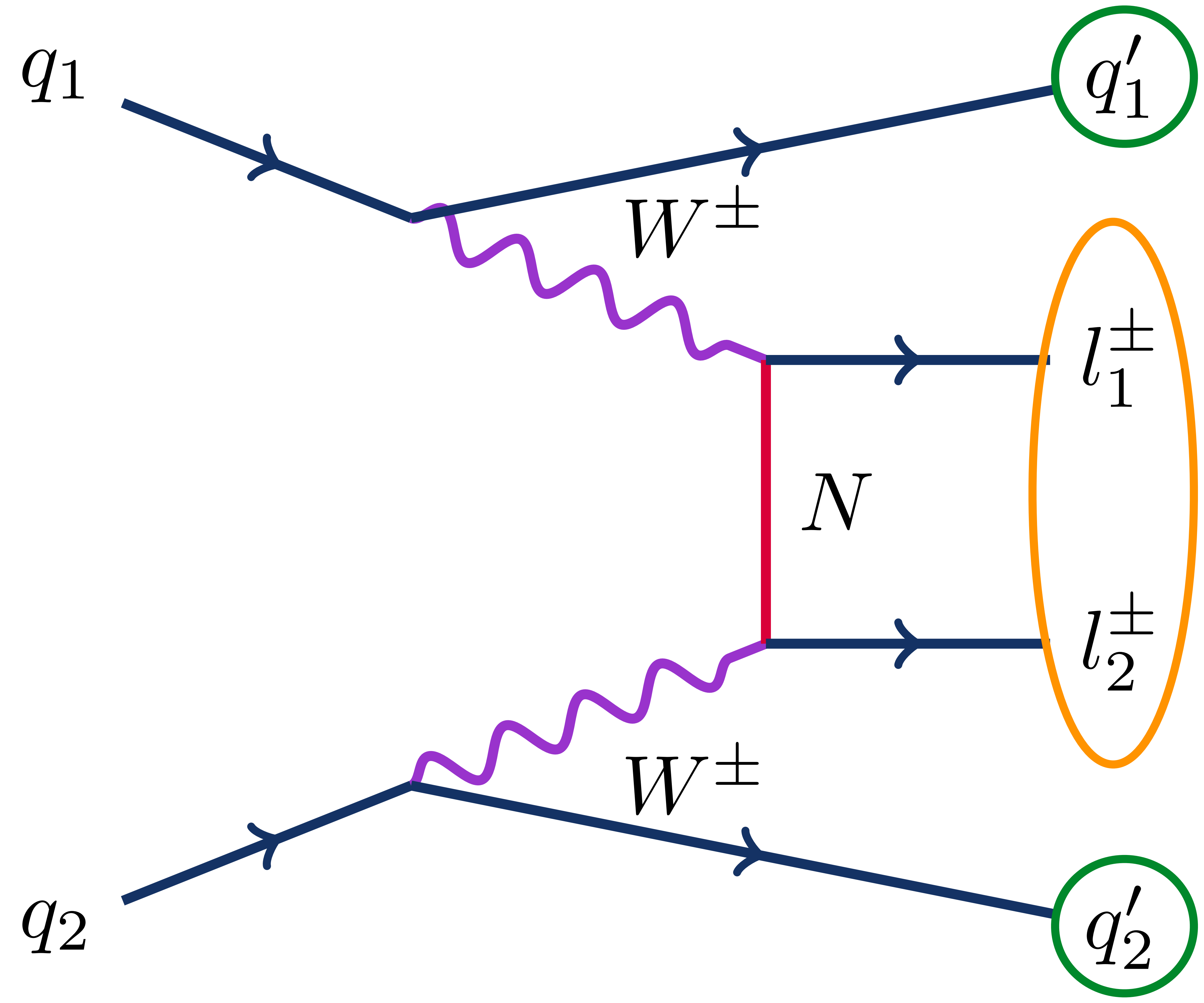

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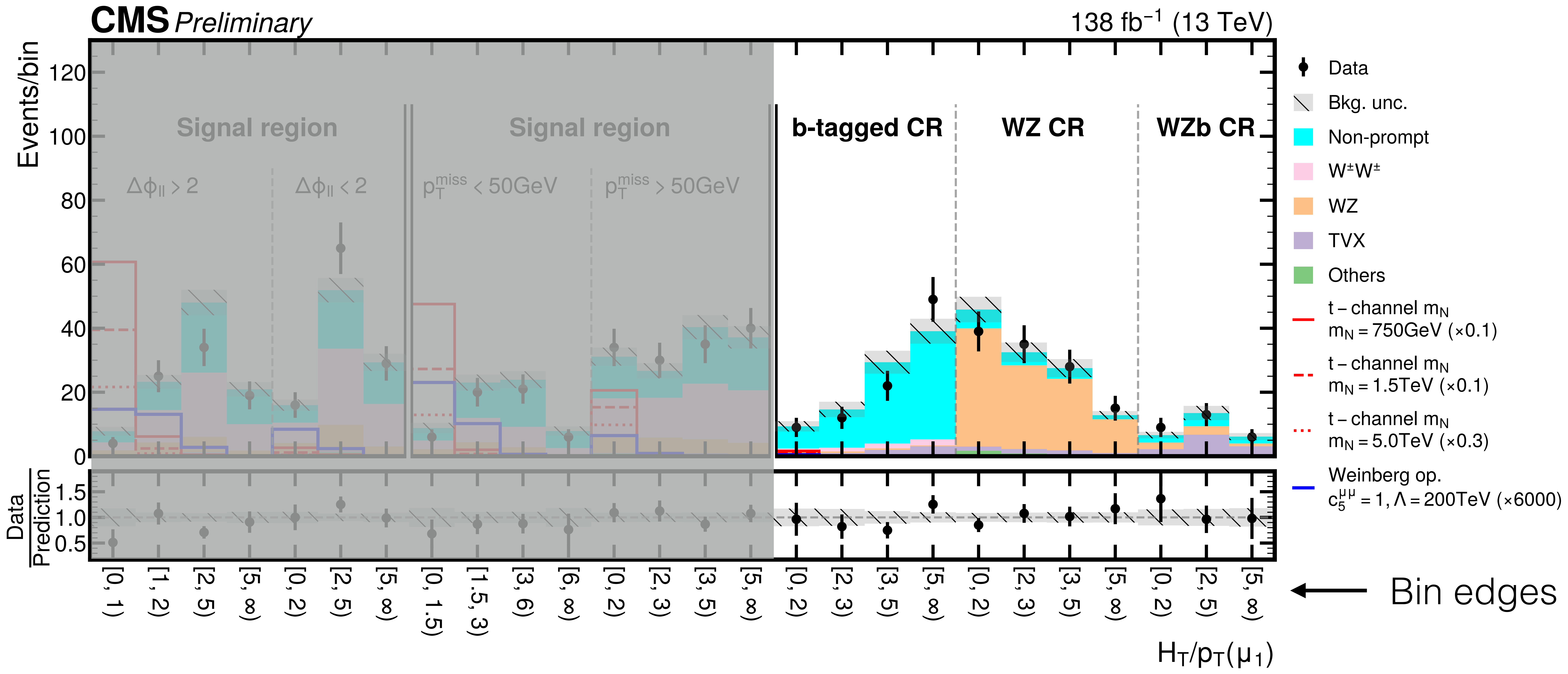
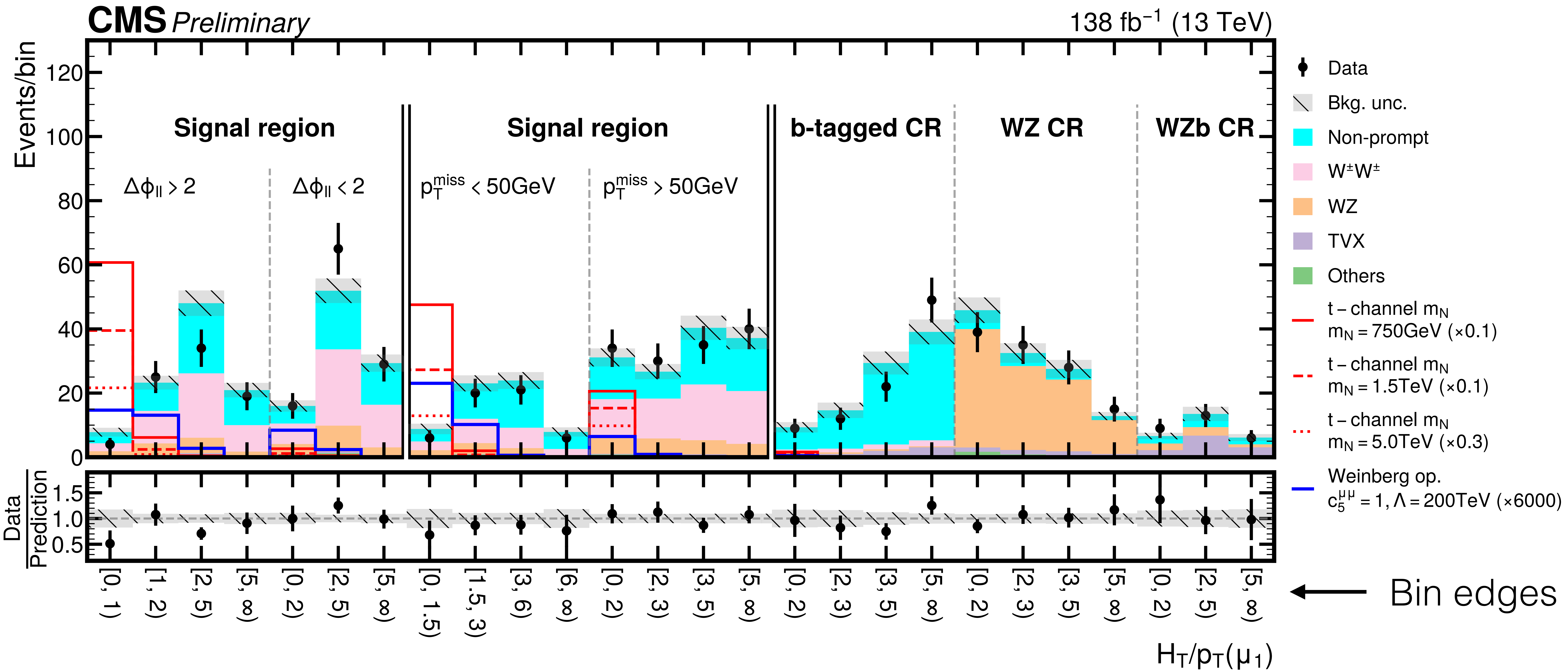
- Same-sign dimuons (rare in SM)
- Small jet activity ($H_T = \Sigma$ jet p_T) relative to leptonic activity: search is binned in $H_T / p_T(\mu_1)$
- Large $\Delta\phi_{\mu\mu}$
- Small p_T^{miss} (no final state neutrinos!)

Background Estimation



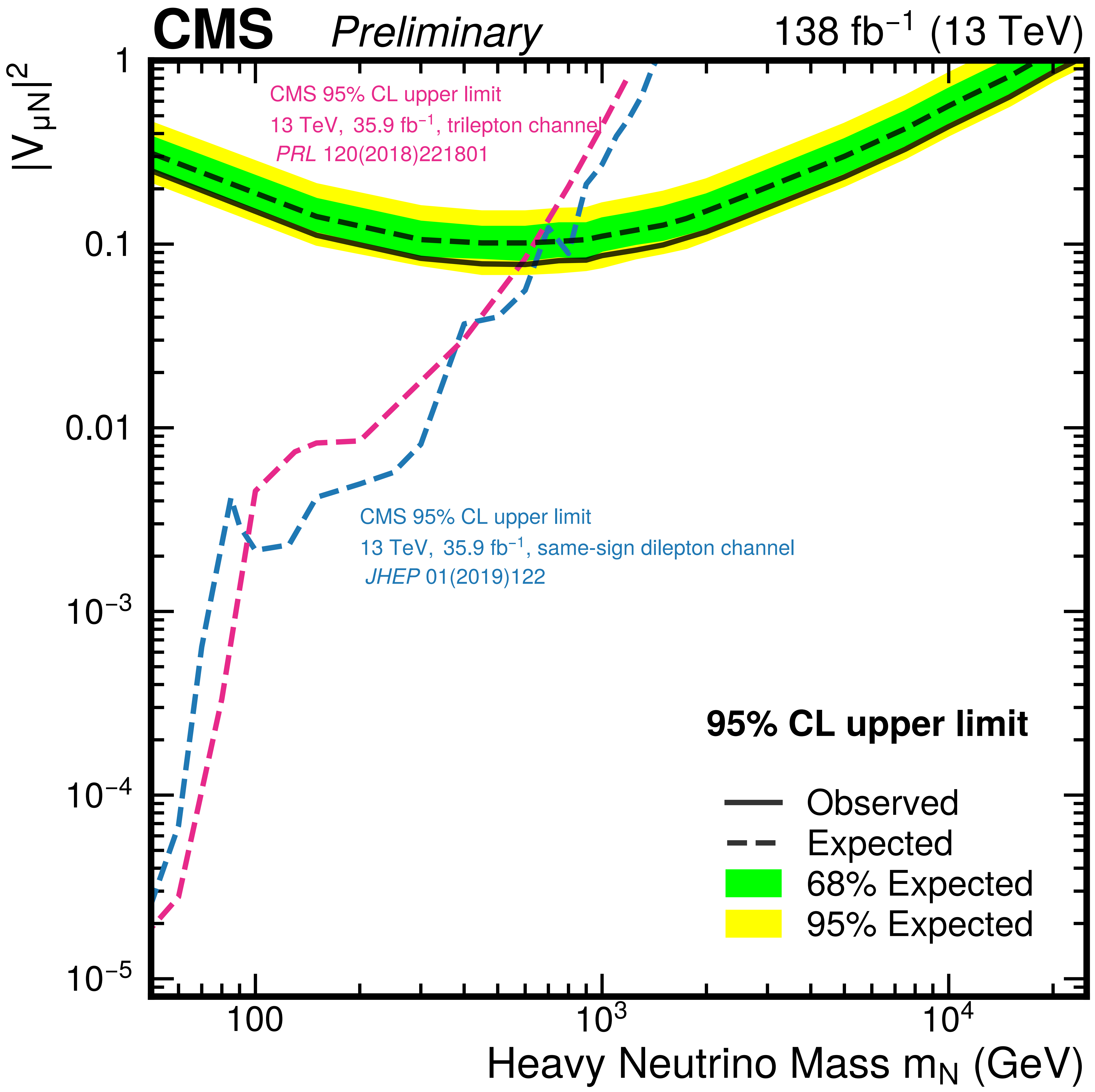
Use data control regions to estimate backgrounds in VBF-enriched regions, primarily due to fake/non-prompt leptons and dibosons.

Results



Signal tends to have small $H_T/p_T(\mu_1)$, small MET, and large $\Delta\phi_{\mu\mu}$ relative to backgrounds.
Data agrees well with SM prediction $\implies$ set limits on these models.

Results



Outperforms previous heavy neutrino searches for $m_N > 650$ GeV, and excludes masses up to 23 TeV for $|V_{\mu N}|^2 = 1$.

For the Weinberg operator EFT, the search sets limits on the effective Majorana mass up to $|m_{\mu\mu}| = 10.84$ GeV.

$\Longrightarrow$ first constraints on this process!

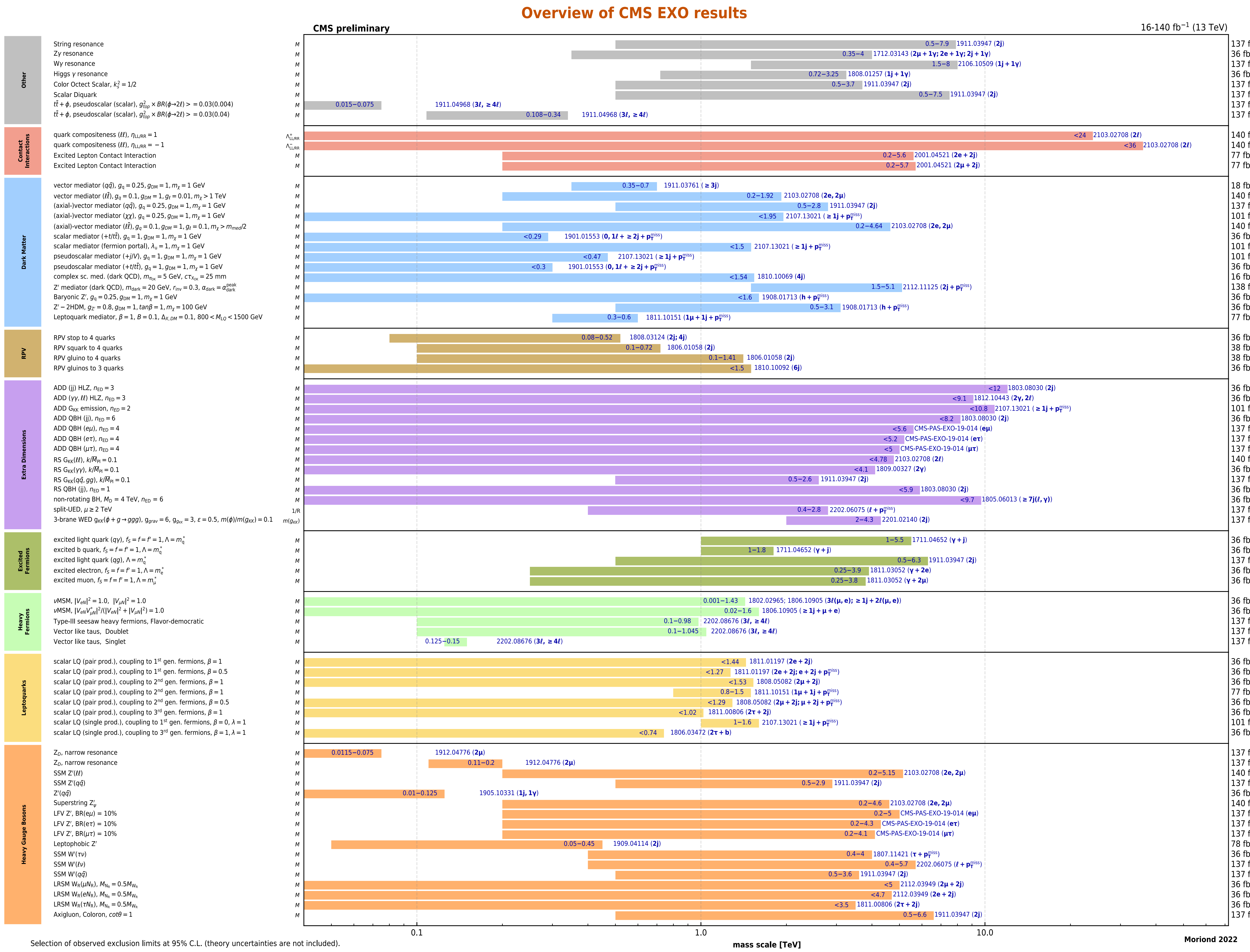
Summary

No evidence for new physics in these leptonic / photonic searches yet, but CMS has set strong constraints across many final states.

However, many new ideas are still being explored!

- Maybe new physics is hiding in some exotic area of phase space that has not yet been probed
- Or perhaps we haven't collected enough data yet! Run 3 and the HL-LHC data will change that
  - Run 2 was *less than 5%* of the total expected LHC dataset!

CMS EXO Summary Plot (link)

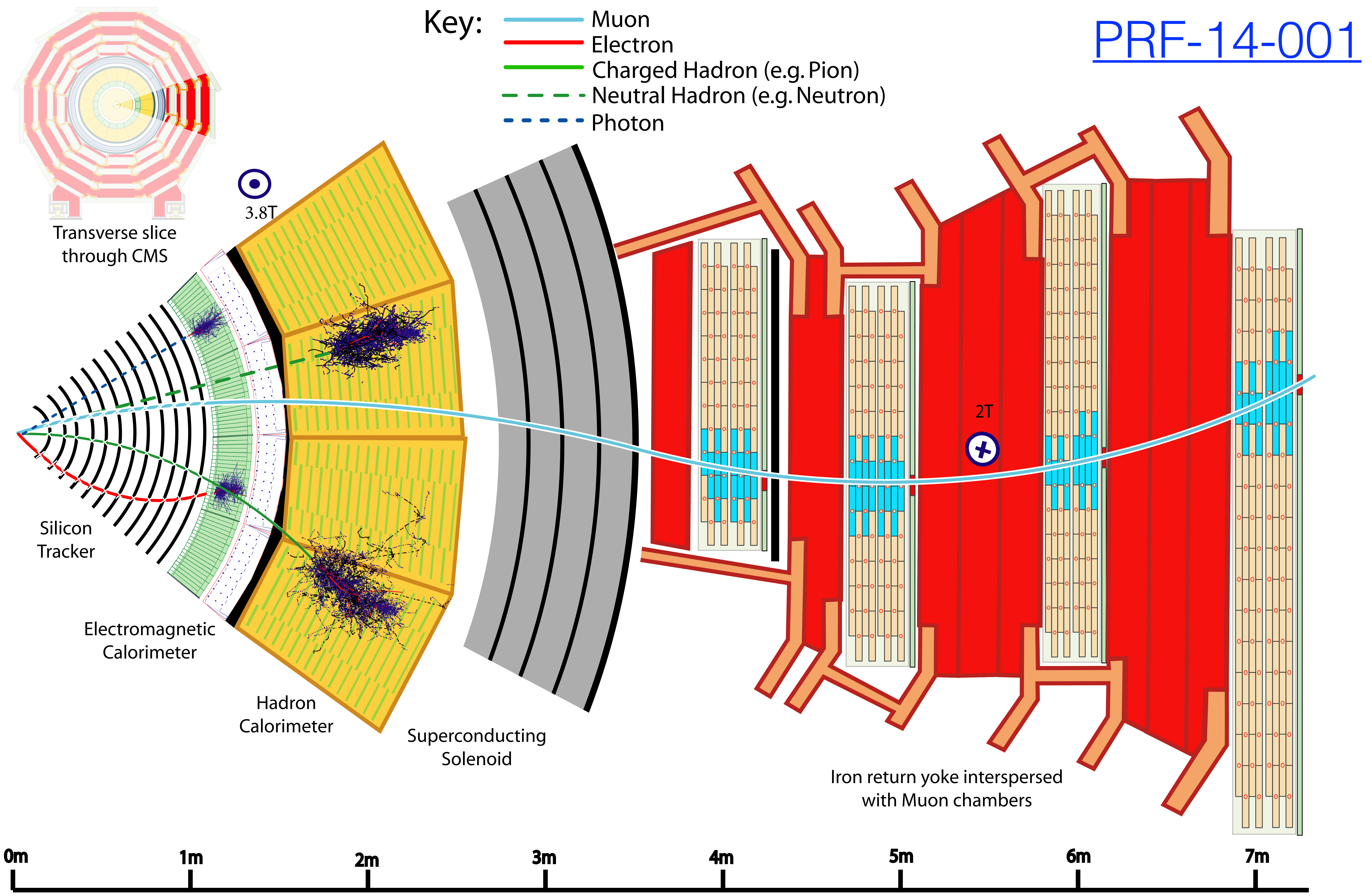


Other new lepton- or photon-based CMS searches since Pheno 2021:

- LFV resonance search in eμ, eτ, and μτ events (EXO-19-014)
- Inclusive nonresonant multilepton search (EXO-21-002)

Backup

The CMS Detector

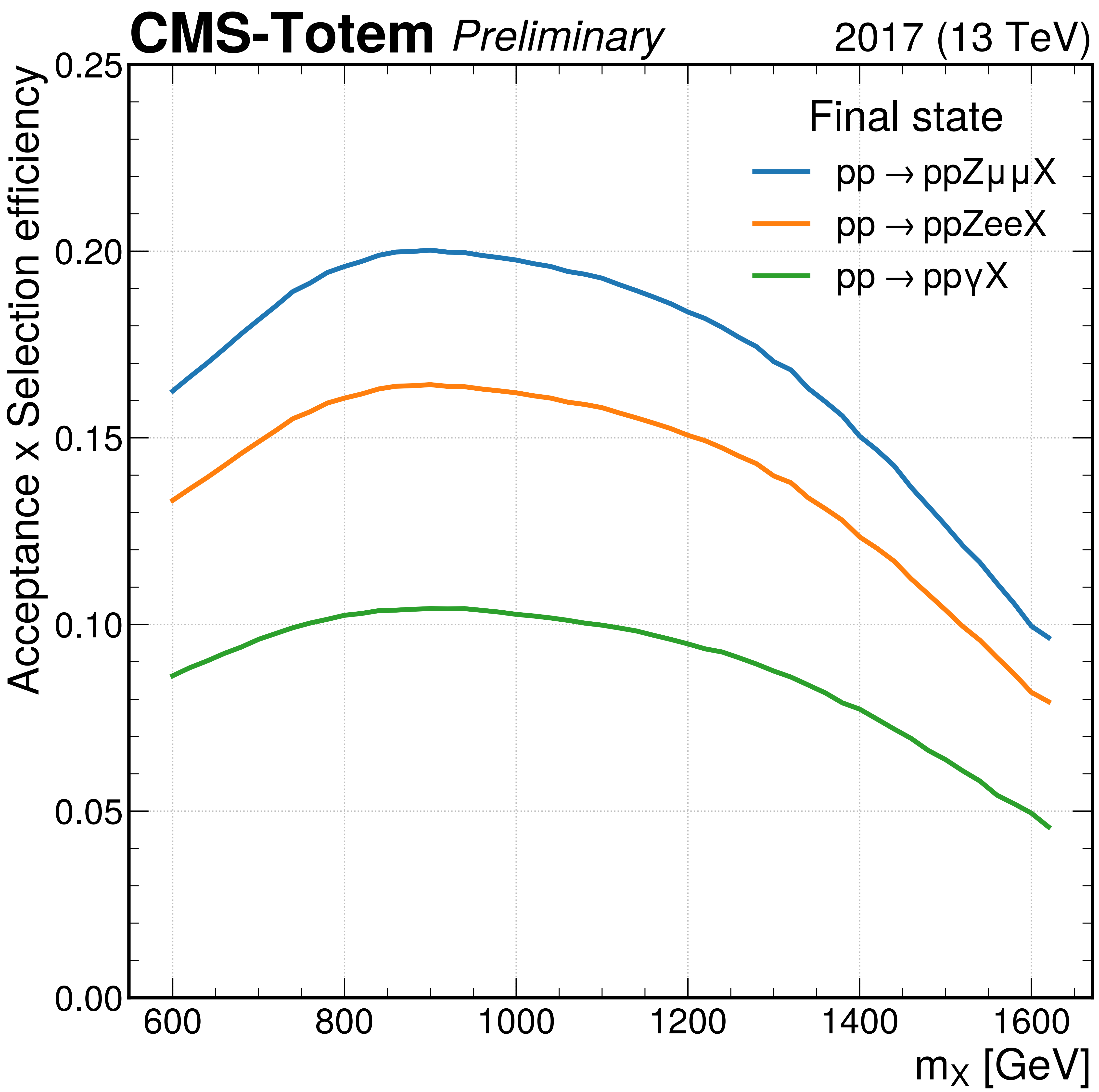


EXO-19-009

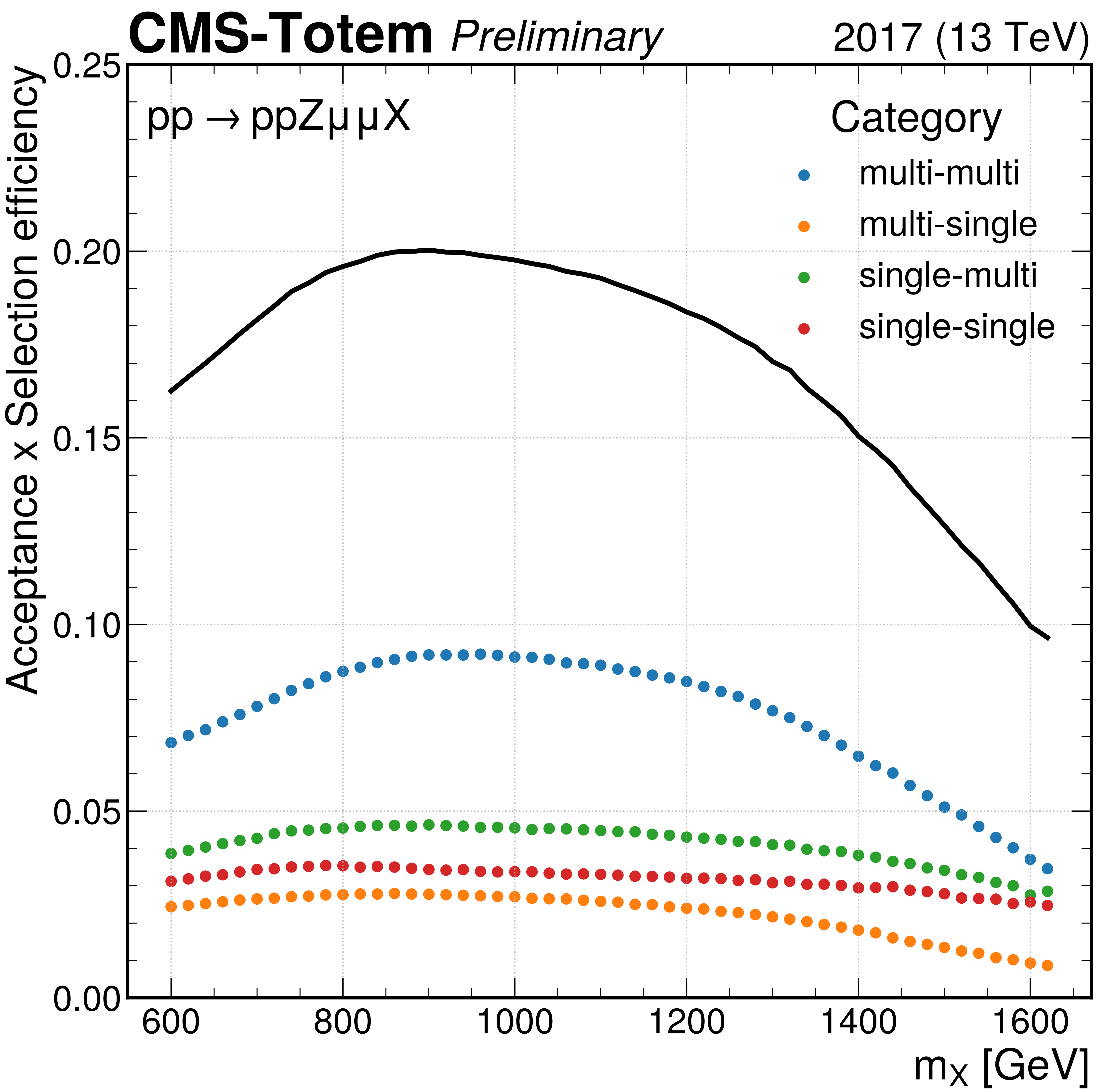
Fiducial requirements:

Selection / Analysis	$Z \to e^+e^- / Z \to \mu^+\mu^-$	γ
Leptons/Photons	$\geq$ 2 same flavour leptons (e or μ) opposite electric charge $p_T(\ell_1, \ell_2) > 30, 20$ GeV $\lvert\eta(\ell)\rvert < 2.4$ $\lvert m(\ell_1\ell_2) - m_Z\rvert < 10$ GeV	=1γ within $\lvert\eta(\gamma)\rvert < 1.4442$
Boson p_T	$p_T(Z) > 40$ GeV	$p_T(\gamma) > 95$ GeV
Protons	$0.02 < \xi_+^{gen} < 0.16 \quad \wedge \quad 0.03 < \xi_-^{gen} < 0.18$	

EXO-19-009



CMS-Totem Preliminary
2017 (13 TeV)
Acceptance x Selection efficiency
0.25
0.20
0.15
0.10
0.05
0.00
600
800
1000
1200
1400
1600
m_X [GeV]
Final state
pp → ppZμμX
pp → ppZeeX
pp → ppγX



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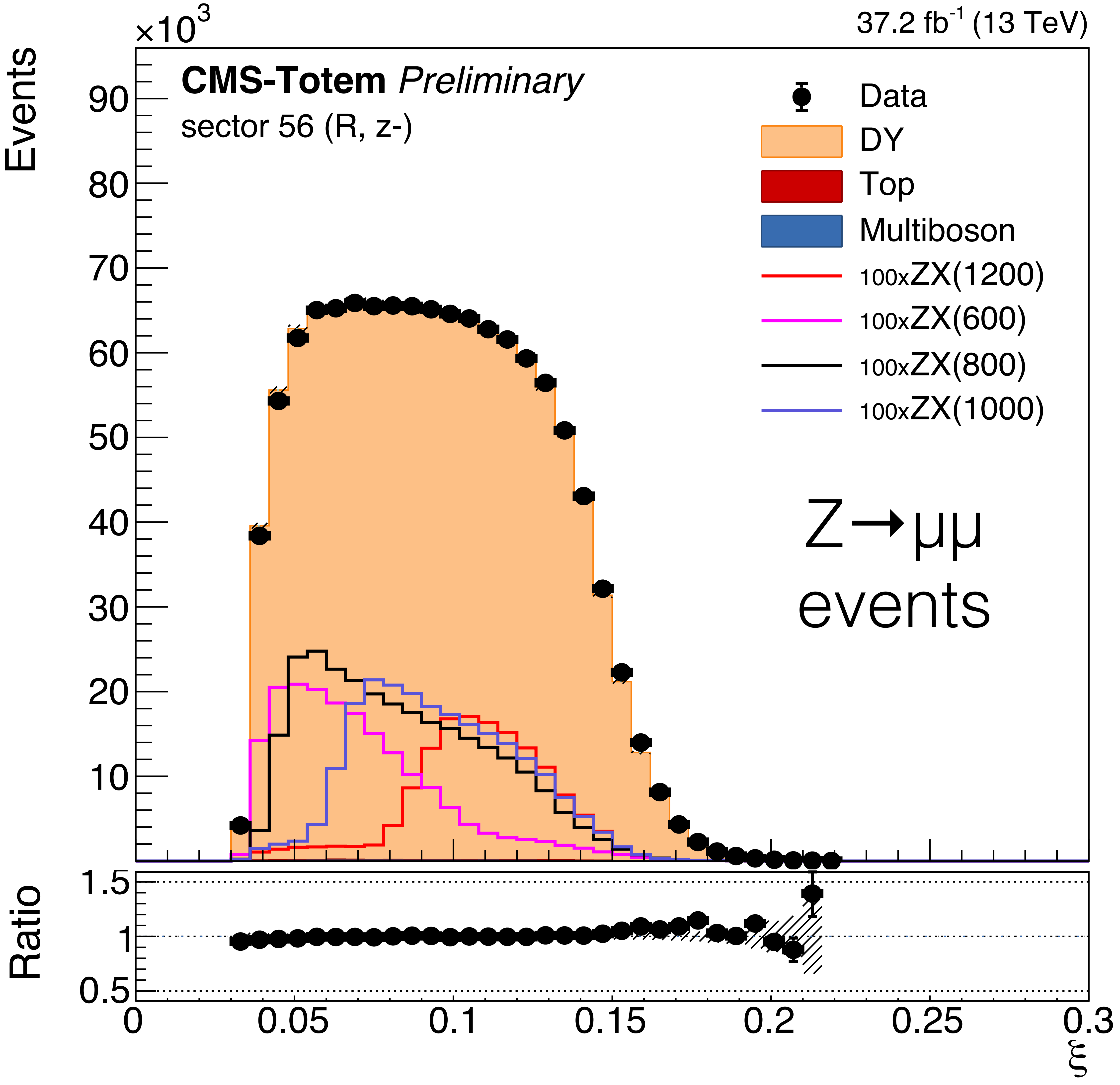
2017 (13 TeV)
Acceptance x Selection efficiency
0.25
0.20
0.15
0.10
0.05
0.00
600
800
1000
1200
1400
1600
m_X [GeV]
pp → ppZμμX
Category
multi-multi
multi-single
single-multi
single-single

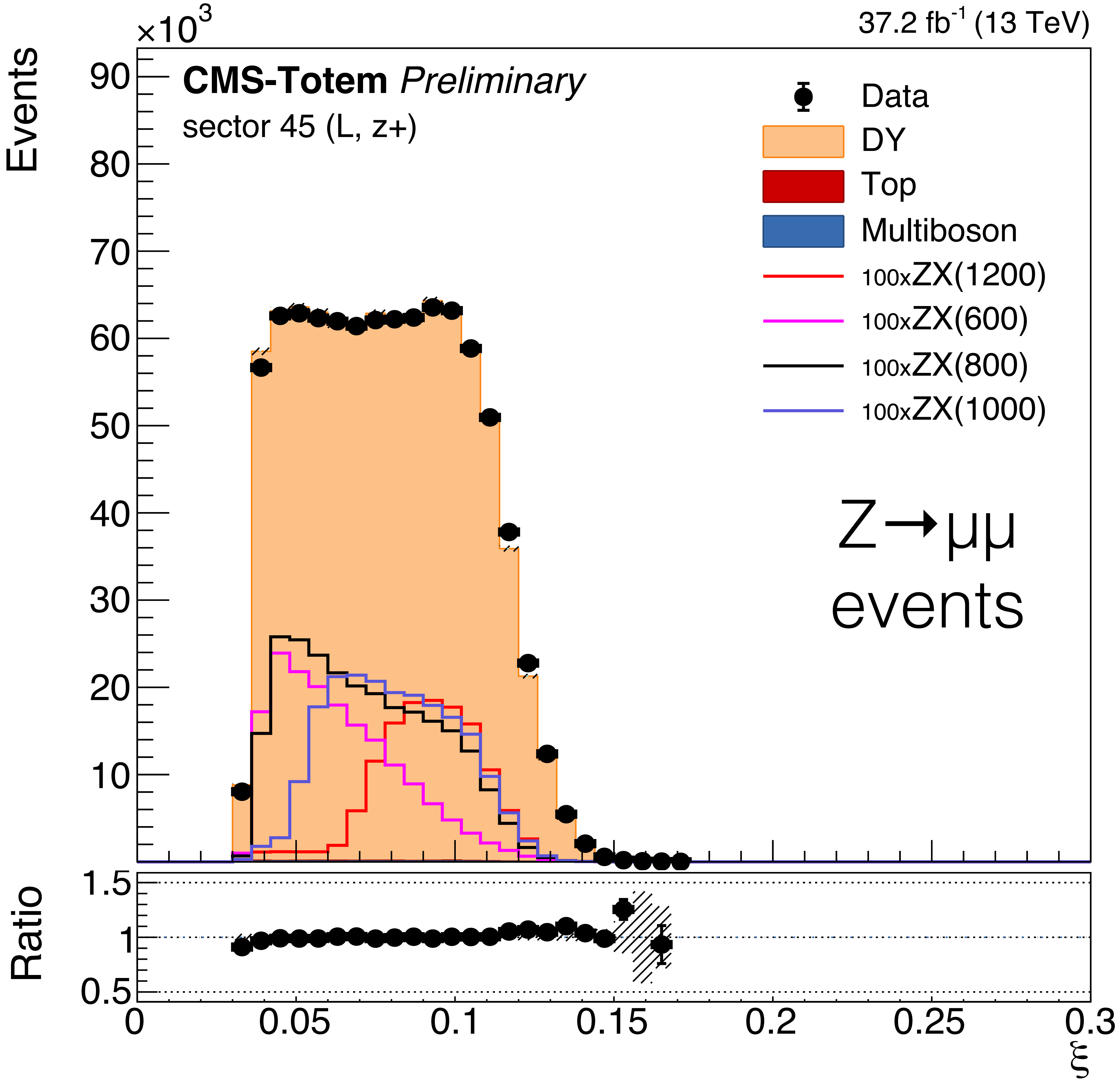
EXO-19-009

The tracking stations provide a measurement of the proton trajectories with respect to the beam position. Knowledge of the magnetic fields traversed by the proton from the IP to the RPs allows for the reconstruction of its fractional momentum loss $\xi = \Delta p/p \sim D_x^{-1} \cdot x$ (with respect to the momentum of incident proton), where x represents the horizontal displacement of the scattered proton at the RP location, and D_x the horizontal dispersion, a property of the accelerator optics. The techniques used for the alignment and calibration of the apparatus and proton reconstruction are detailed in Refs. [13–16].

EXO-19-009

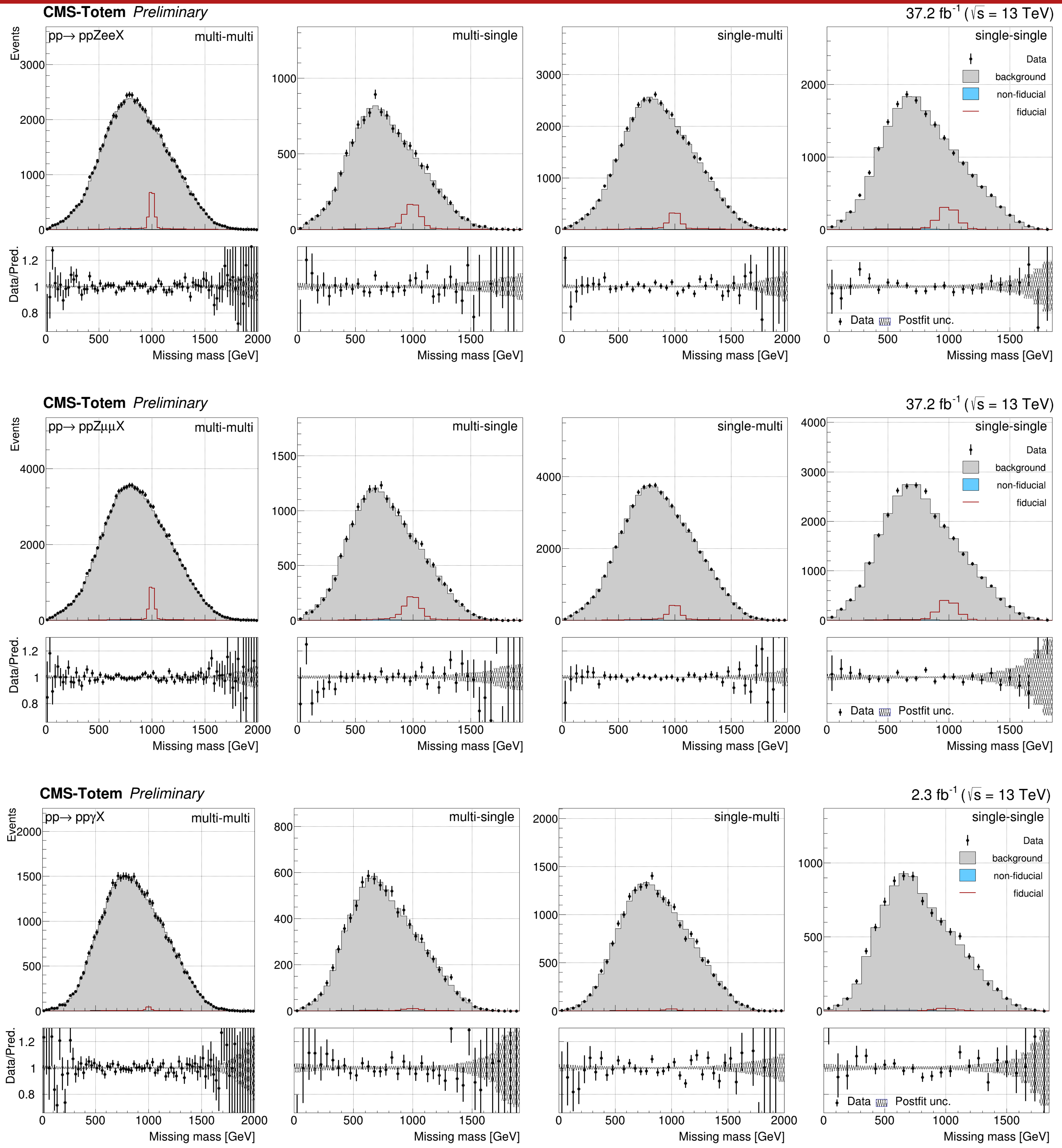


×10^3
37.2 fb^-1 (13 TeV)
Events
CMS-Totem Preliminary
sector 56 (R, z-)
Data
DY
Top
Multiboson
100xZX(1200)
100xZX(600)
100xZX(800)
100xZX(1000)
Z→μμ
events
Ratio
ξ



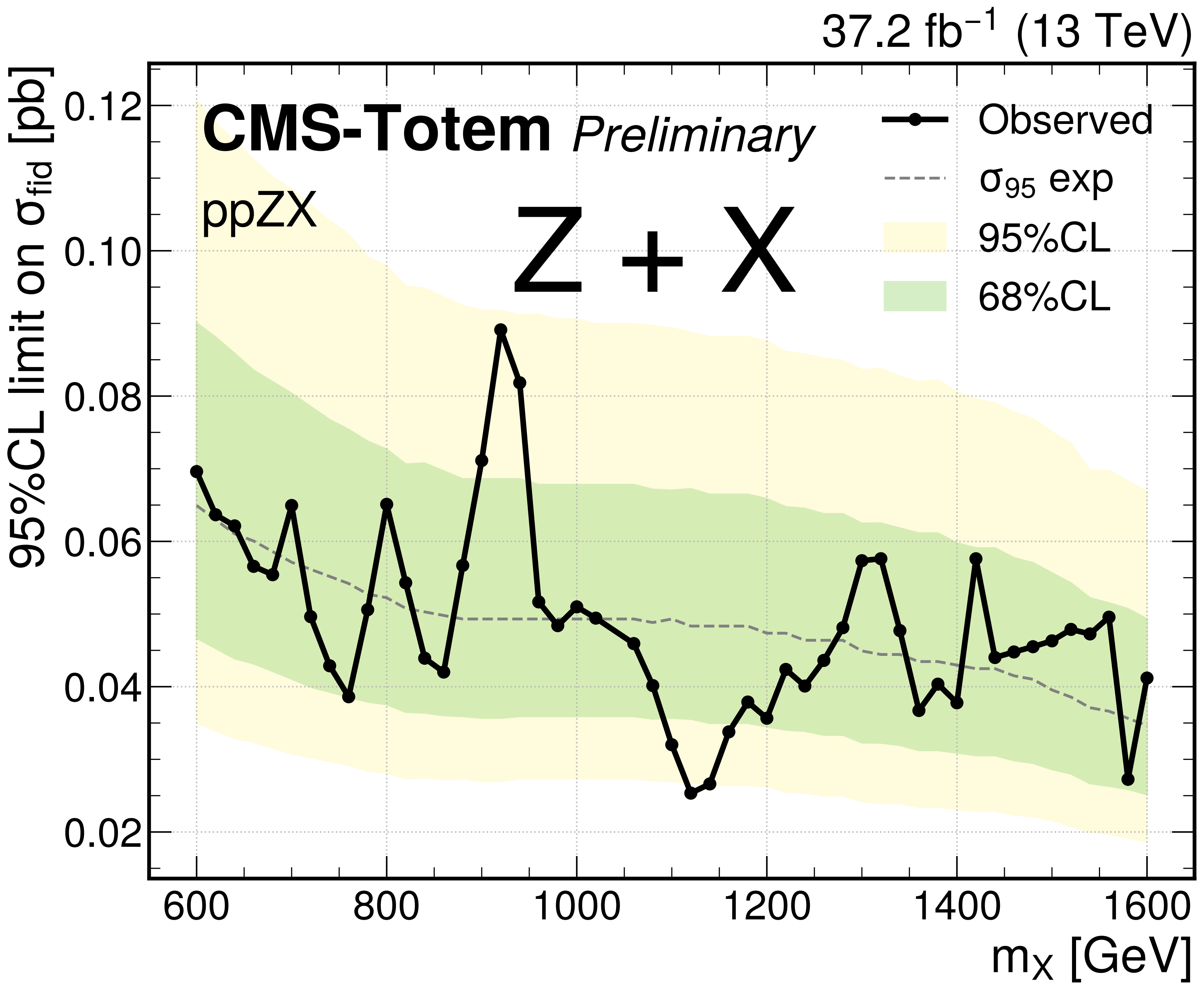
×10^3
37.2 fb^-1 (13 TeV)
Events
CMS-Totem Preliminary
sector 45 (L, z+)
Data
DY
Top
Multiboson
100xZX(1200)
100xZX(600)
100xZX(800)
100xZX(1000)
Z→μμ
events
Ratio
ξ

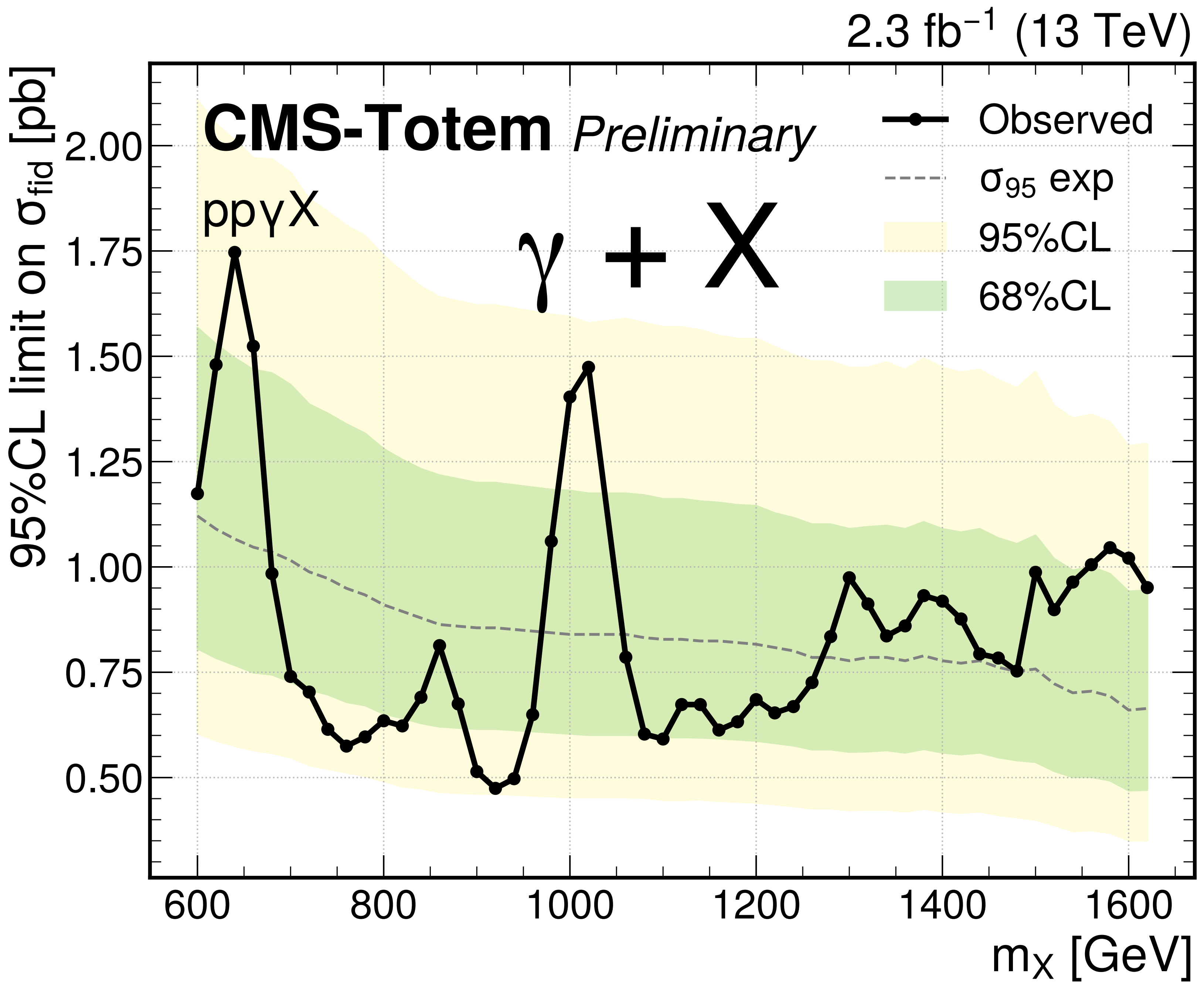
EXO-19-009



CMS-Totem Preliminary
37.2 fb^{-1} ($\sqrt{s}$ = 13 TeV)
pp→ ppZeeX
multi-multi
multi-single
single-multi
single-single
Data
background
non-fiducial
fiducial
Events
Data/Pred.
Data Postfit unc.
Missing mass [GeV]
CMS-Totem Preliminary
37.2 fb^{-1} ($\sqrt{s}$ = 13 TeV)
pp→ ppZμμX
multi-multi
multi-single
single-multi
single-single
Data
background
non-fiducial
fiducial
Events
Data/Pred.
Data Postfit unc.
Missing mass [GeV]
CMS-Totem Preliminary
2.3 fb^{-1} ($\sqrt{s}$ = 13 TeV)
pp→ ppγX
multi-multi
multi-single
single-multi
single-single
Data
background
non-fiducial
fiducial
Events
Data/Pred.
Data Postfit unc.
Missing mass [GeV]

EXO-19-009


37.2 fb^{-1} (13 TeV)
CMS-Totem Preliminary
ppZX
Z + X
Observed
σ_{95} exp
95%CL
68%CL
95%CL limit on σ_{fid} [pb]
0.12
0.10
0.08
0.06
0.04
0.02
600
800
1000
1200
1400
1600
m_X [GeV]


2.3 fb^{-1} (13 TeV)
CMS-Totem Preliminary
ppγX
γ + X
Observed
σ_{95} exp
95%CL
68%CL
95%CL limit on σ_{fid} [pb]
2.00
1.75
1.50
1.25
1.00
0.75
0.50
600
800
1000
1200
1400
1600
m_X [GeV]

EXO-21-003

SR and CR require two jets w/ p_T > 30 GeV, $|\Delta\eta_{jj}|$ > 2.5, m_{jj} > 750 GeV

Variable	SR	WZ CR
lepton p_T	$> 30/30$ GeV	$> 10/25/25$ GeV
dilepton mass $m_{\ell\ell}$	> 20 GeV	—
$\lvert m_{\ell\ell} - m_Z \rvert$	—	< 15 GeV (for one $\mu^+\mu^-$ pair)
trilepton mass $m_{\ell\ell\ell}$	—	> 100 GeV
max $\mathcal{Z}(\ell)$	< 0.75	< 1.0
p_T^{miss}	—	> 30 GeV

with Zeppenfeld variable: $$\mathcal{Z}(\ell) = \left| \eta_\ell - \frac{\eta_{j1} + \eta_{j2}}{2} \right| / \left| \Delta\eta_{jj} \right|$$

Events w/ additional e, μ, or τ leptons, or b-tagged jets, are vetoed.

EXO-21-003

The simplest formalism in which neutrino masses can arise is through a dimension-5 operator as shown by Weinberg [2]: $\mathcal{L}_5 = C_5^{\ell\ell'}/\Lambda\left[\Phi\cdot\overline{L_\ell^c}\right]\left[L_{\ell'}\cdot\Phi\right]$, where Λ is the scale at which the particles responsible for neutrino masses become relevant degrees of freedom; $C_5^{\ell\ell'}$ is a flavor-dependent Wilson coefficient; $L_\ell^T = (\nu_\ell, \ell)$ is the left-handed lepton doublet; and Φ is the SM Higgs doublet with a vacuum expectation value $v = \sqrt{2}\langle\Phi\rangle \approx 246\,\text{GeV}$. The Weinberg operator generates the Majorana neutrino masses as $m_{\ell\ell'} = C_5^{\ell\ell'} v^2/\Lambda$. It leads to an experimental signature involving lepton number violation (LNV), as the Majorana neutrino is its own antiparticle. The LNV process has been tested extensively in searches for neutrinoless double beta decay in the decays of heavy nuclei. These experiments search for a signature consisting of two same-charge electrons and the absence of neutrinos in the final state. These searches set stringent upper limits, in the range 79–180 meV, on $|m_{ee}|$ at the 90% confidence level (CL) [3]. Since muons and tau leptons are much heavier than electrons, same-charge lepton final states involving muons and tau leptons are kinematically forbidden in low-energy nuclear experiments and have to be studied at colliders [4].