Positron

P_T = 30 GeV

m_{ee} = 9

Experimental Status of tribosons in CMS (and ATLAS)

Saptaparna Bhattacharya

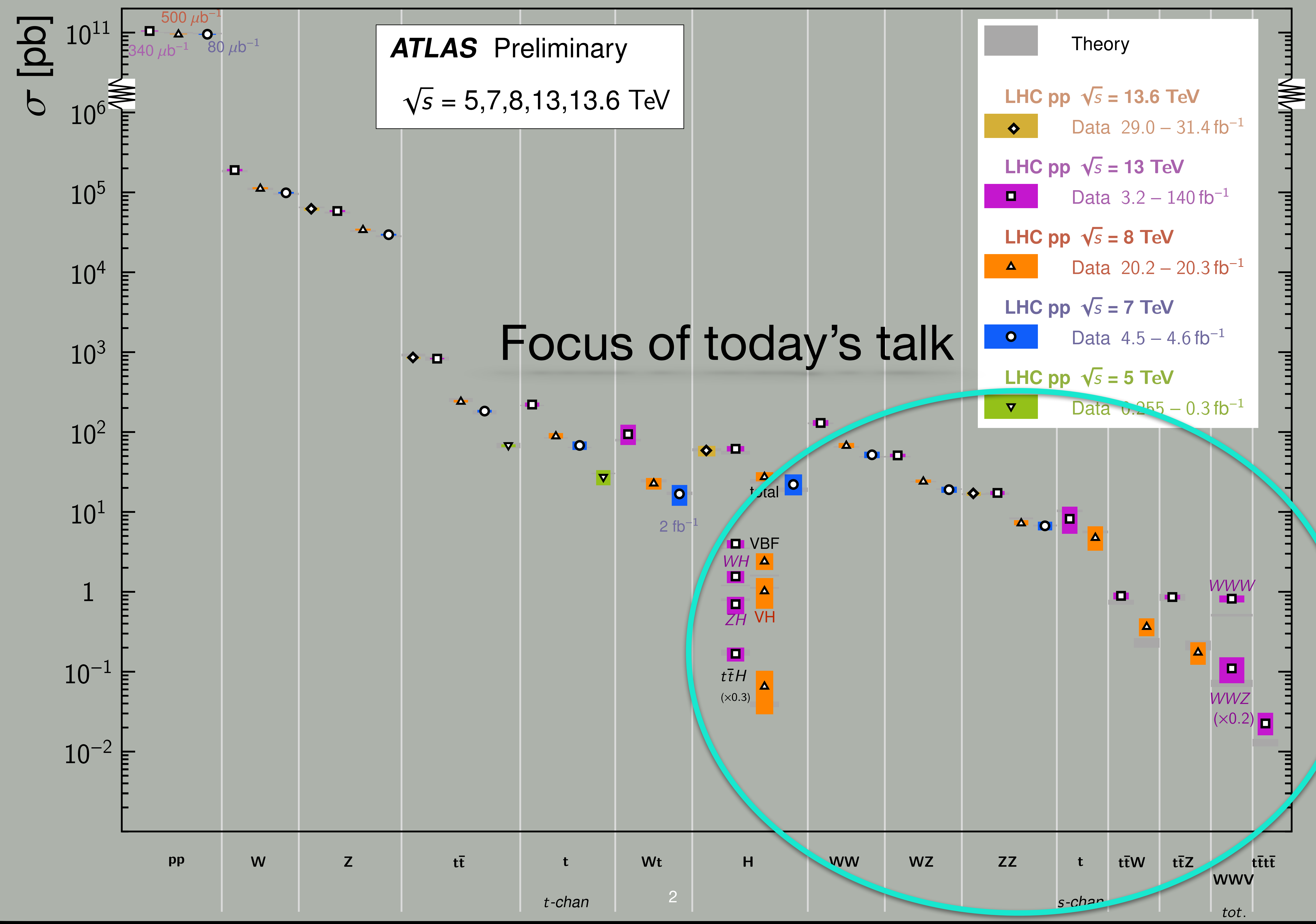
Humboldt Fellow, Wayne State Pathway-to-faculty Fellow

tron

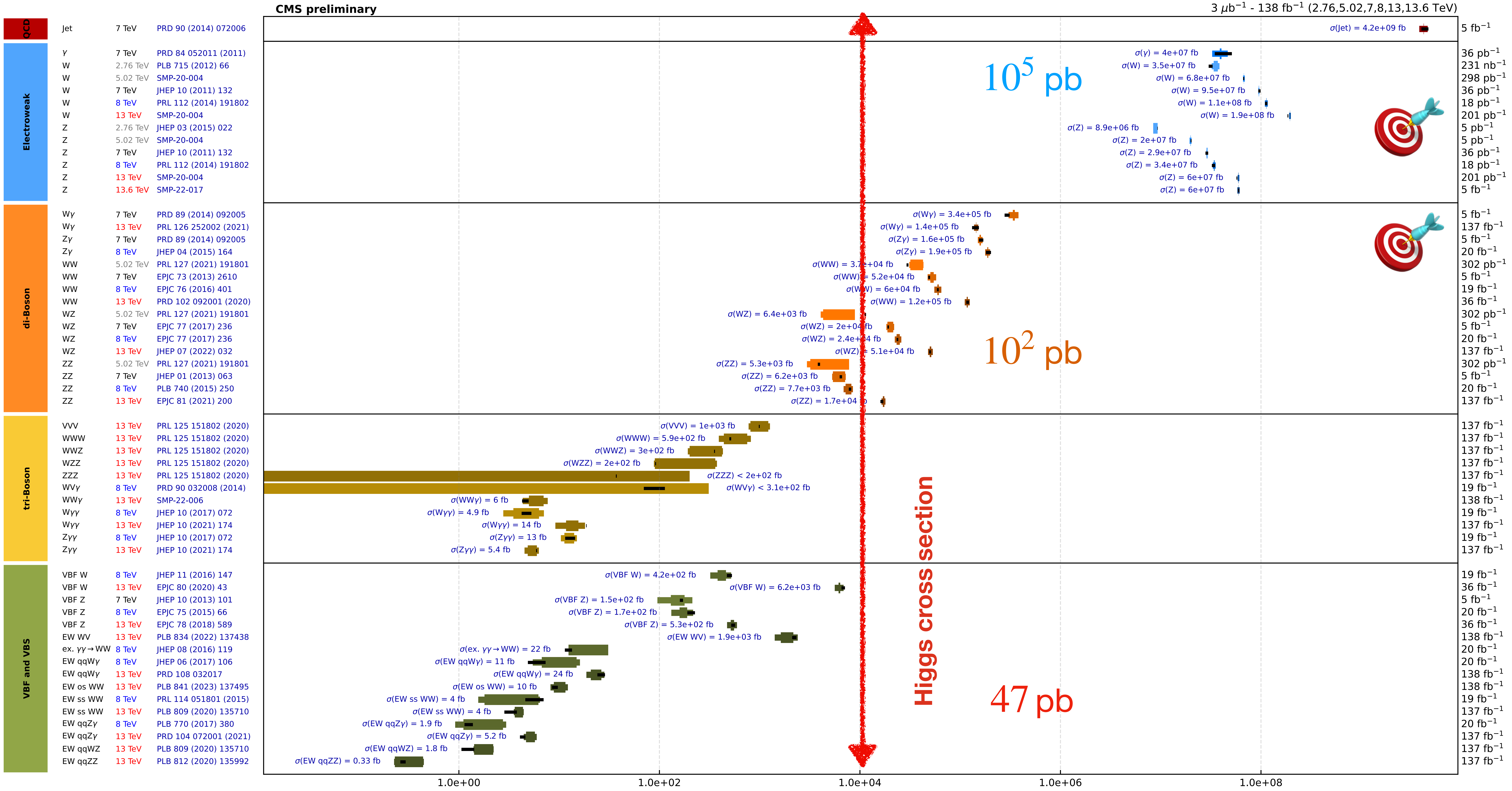
GeV

Standard Model Total Production Cross Section Measurements

Status: October 2023



Overview of CMS cross section results



Span several orders of magnitude!

Broad status of triboson observation in CMS

- CMS-PAS-SMP-22-006: Observation of $WW\gamma$ and search for $H\gamma$ production in proton-proton collisions at $\sqrt{s}$ = 13 TeV

- CMS-PAS-SMP-19-014: Observation of the production of three massive gauge bosons at $\sqrt{s}$ = 13 TeV

- CMS-PAS-SMP-19-014: Measurements of the $W^{\pm}\gamma\gamma$ and $Z\gamma\gamma$ cross sections at $\sqrt{s}$ = 13 TeV and limits on anomalous quartic gauge couplings

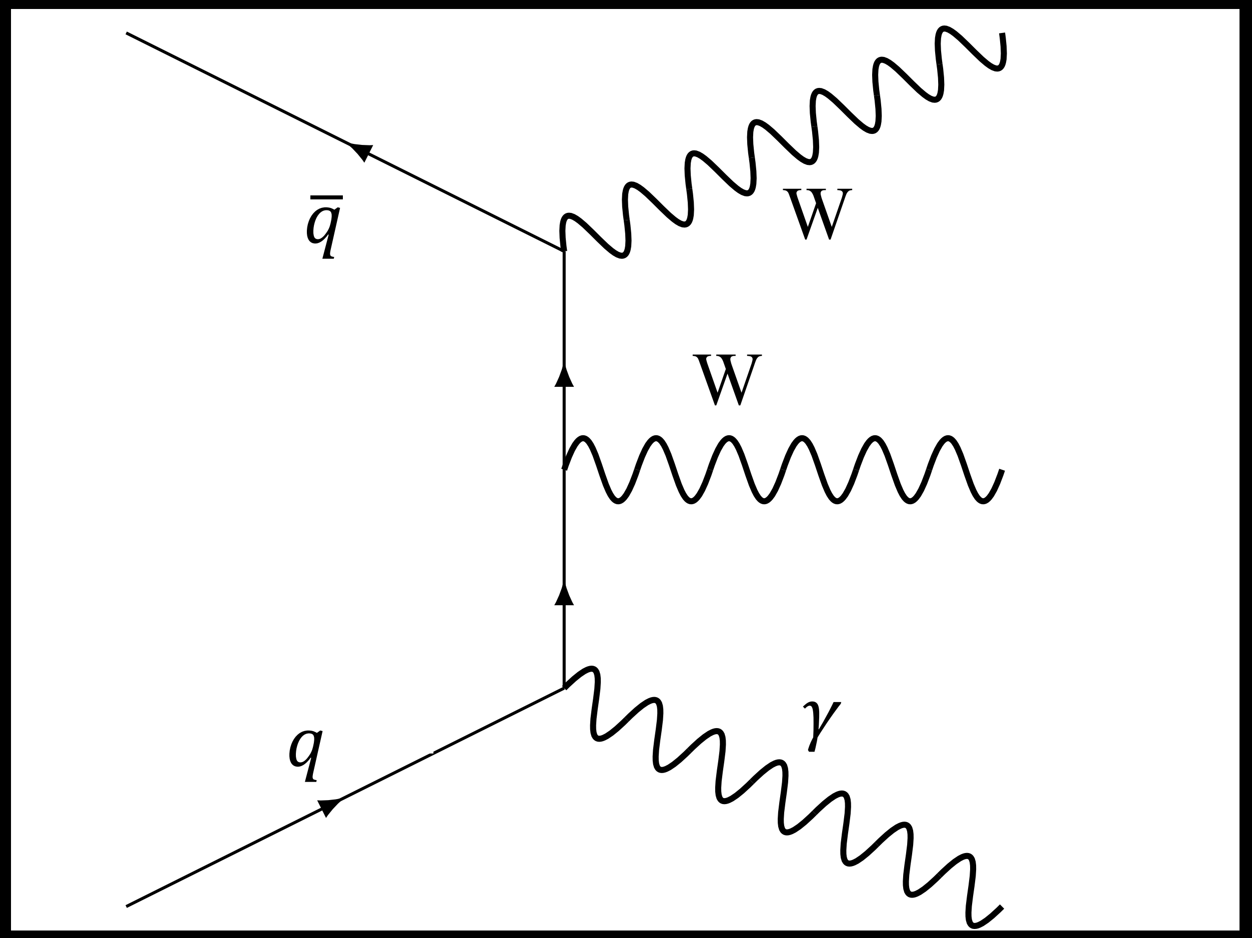
Triboson cross sections

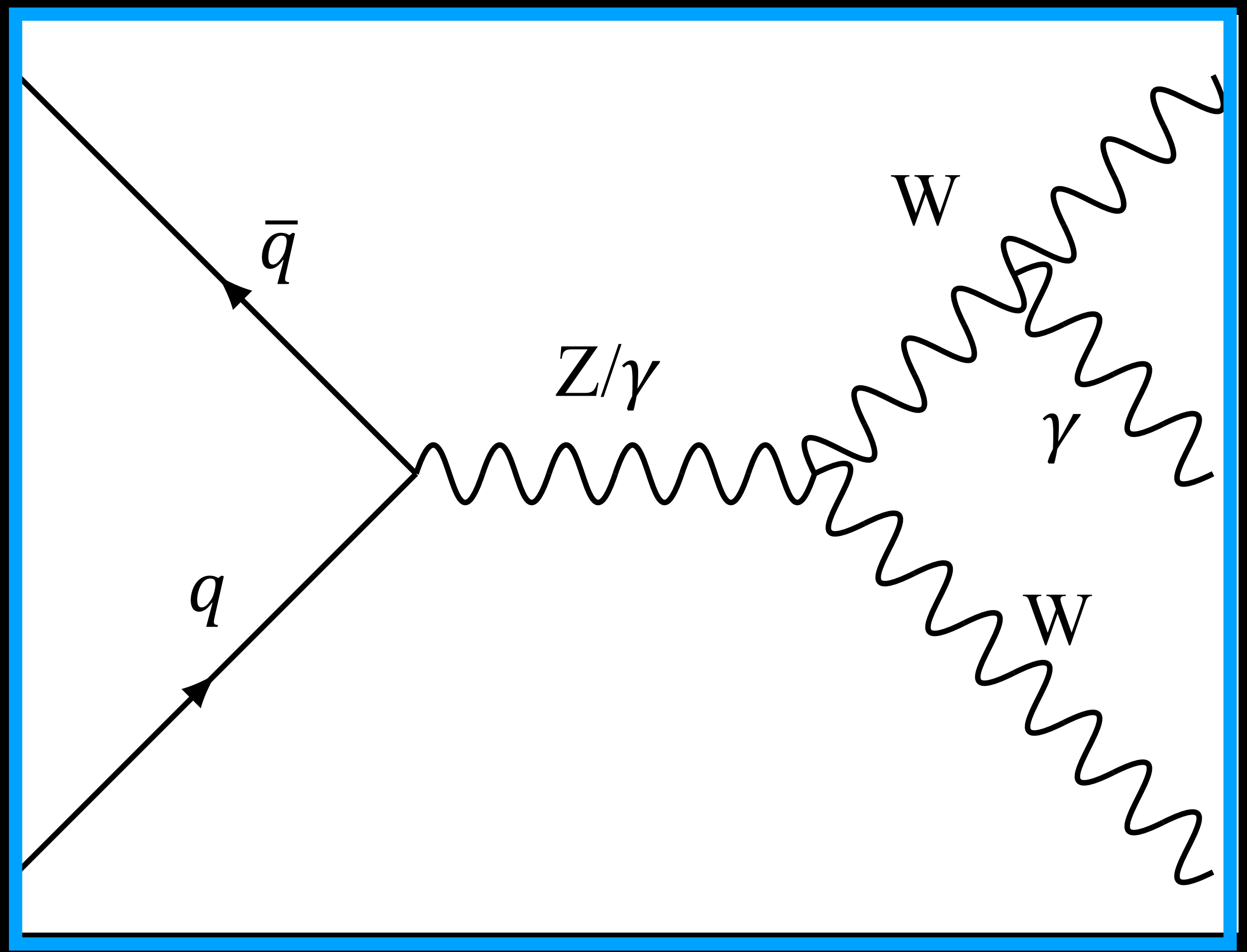

A NEW TRI-BOSON PROCESS
DISCOVERY

Observation of $WW\gamma$ production at $\sqrt{s} = 13$ TeV

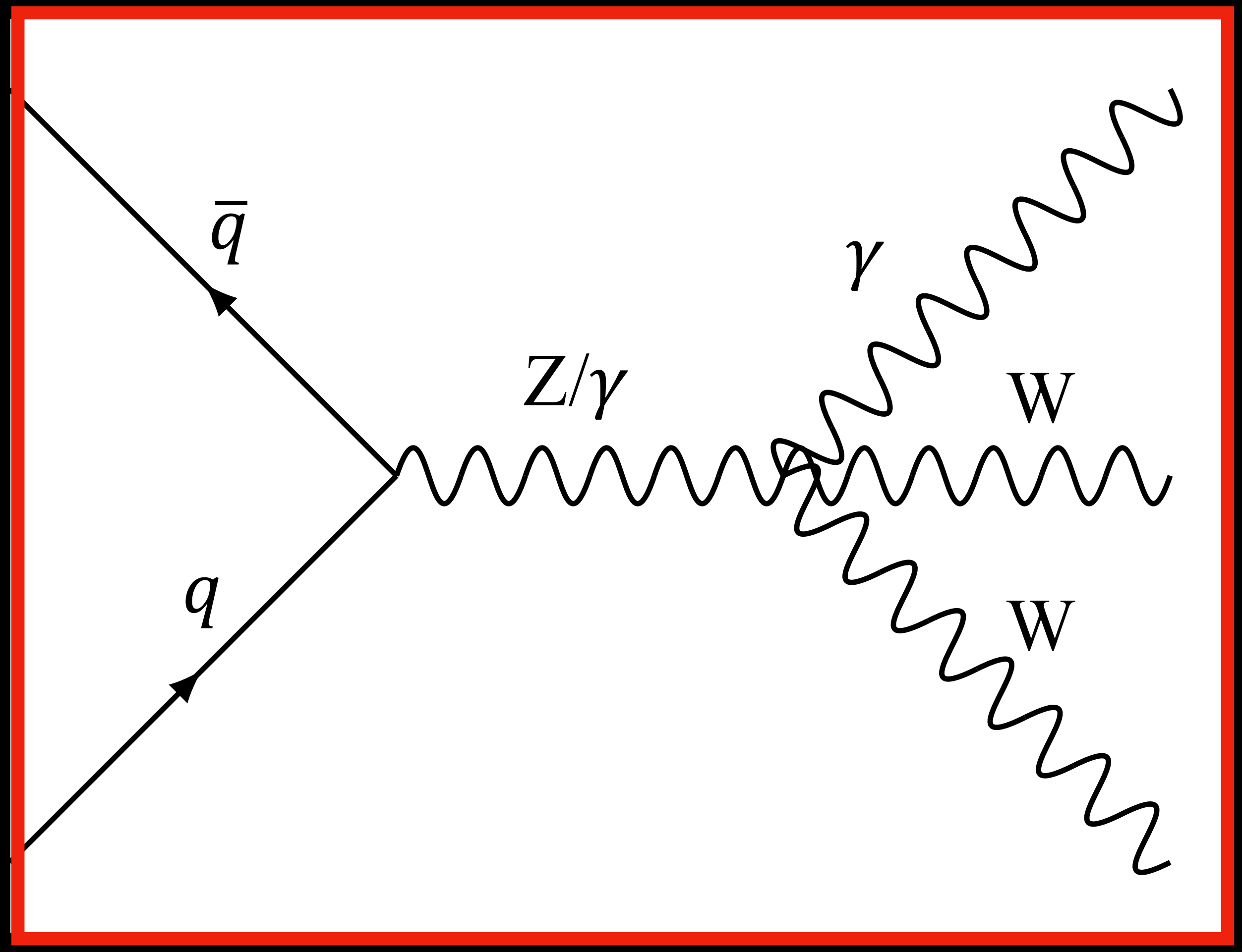
- $WW\gamma$ process observed (expected) with a significance of 5.6 (5.1) σ
- Fiducial cross section measured as: 5.9 ± 0.8 (stat.) ± 0.8 (syst.) ± 0.7 (modeling*) fb
- Associated search for H with a photon explored → generated by coupling of the Higgs boson to light quarks

https://arxiv.org/abs/2310.05164

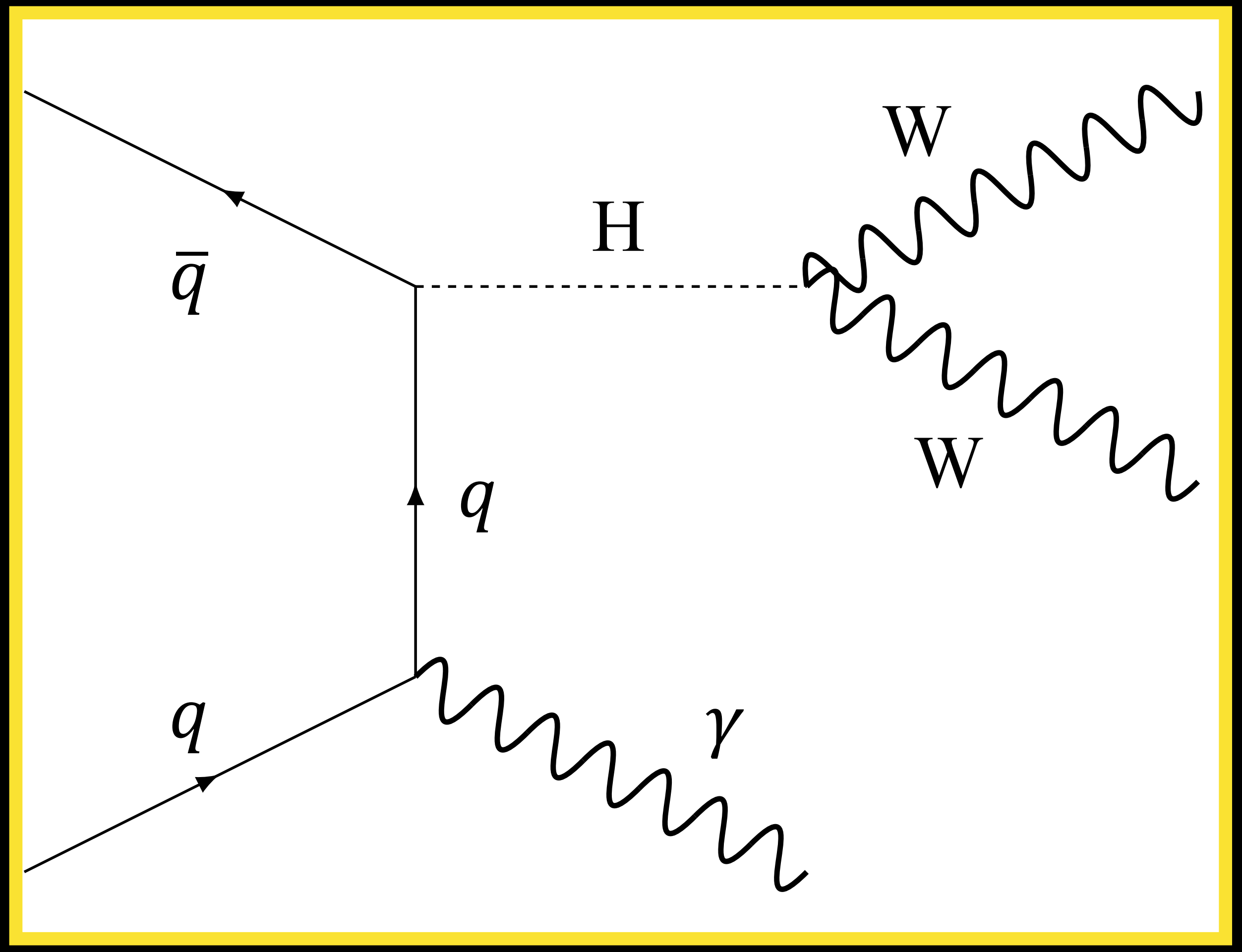




Trilinear coupling



Quartic coupling



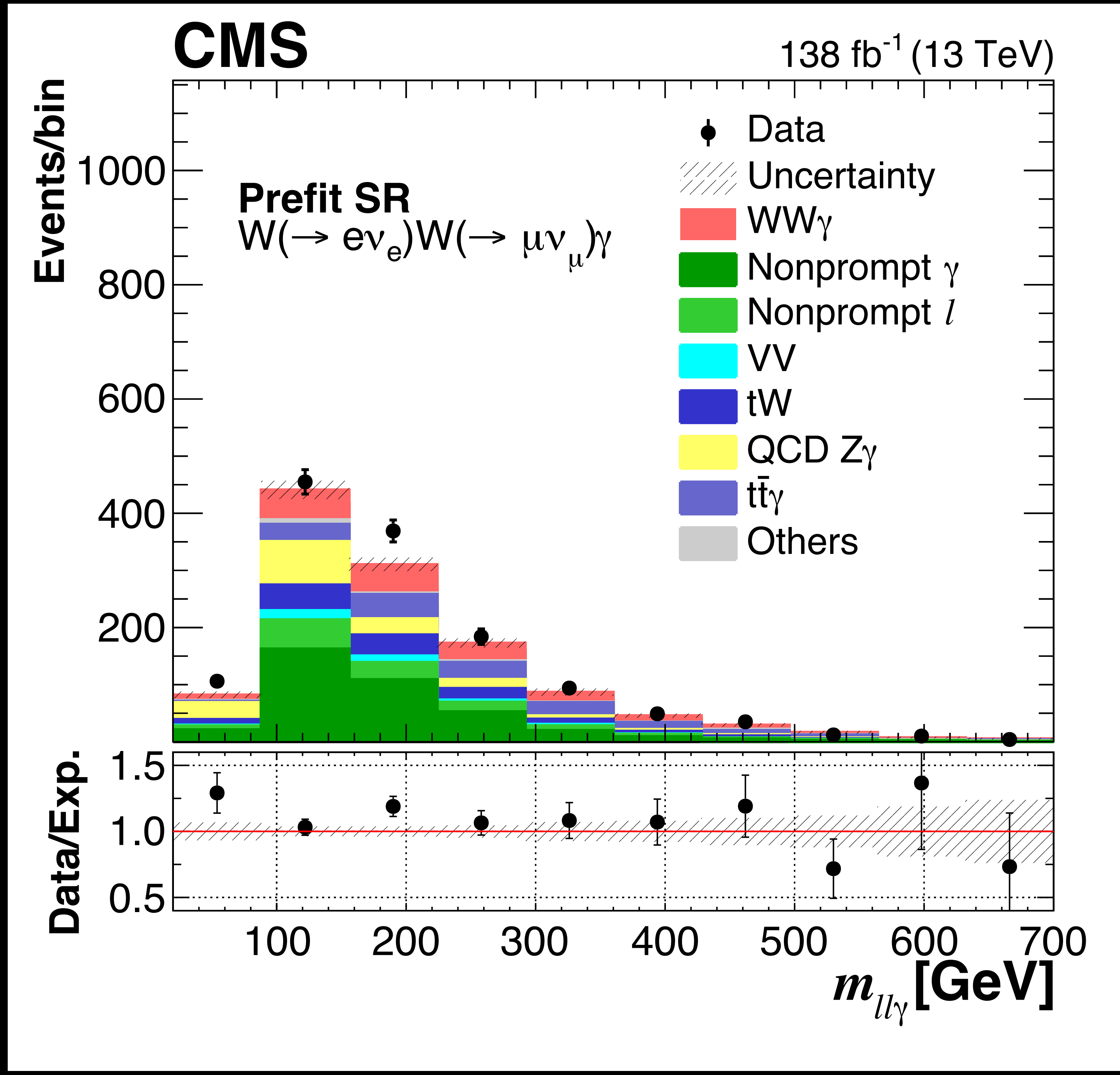
Associated production ($H\gamma$)

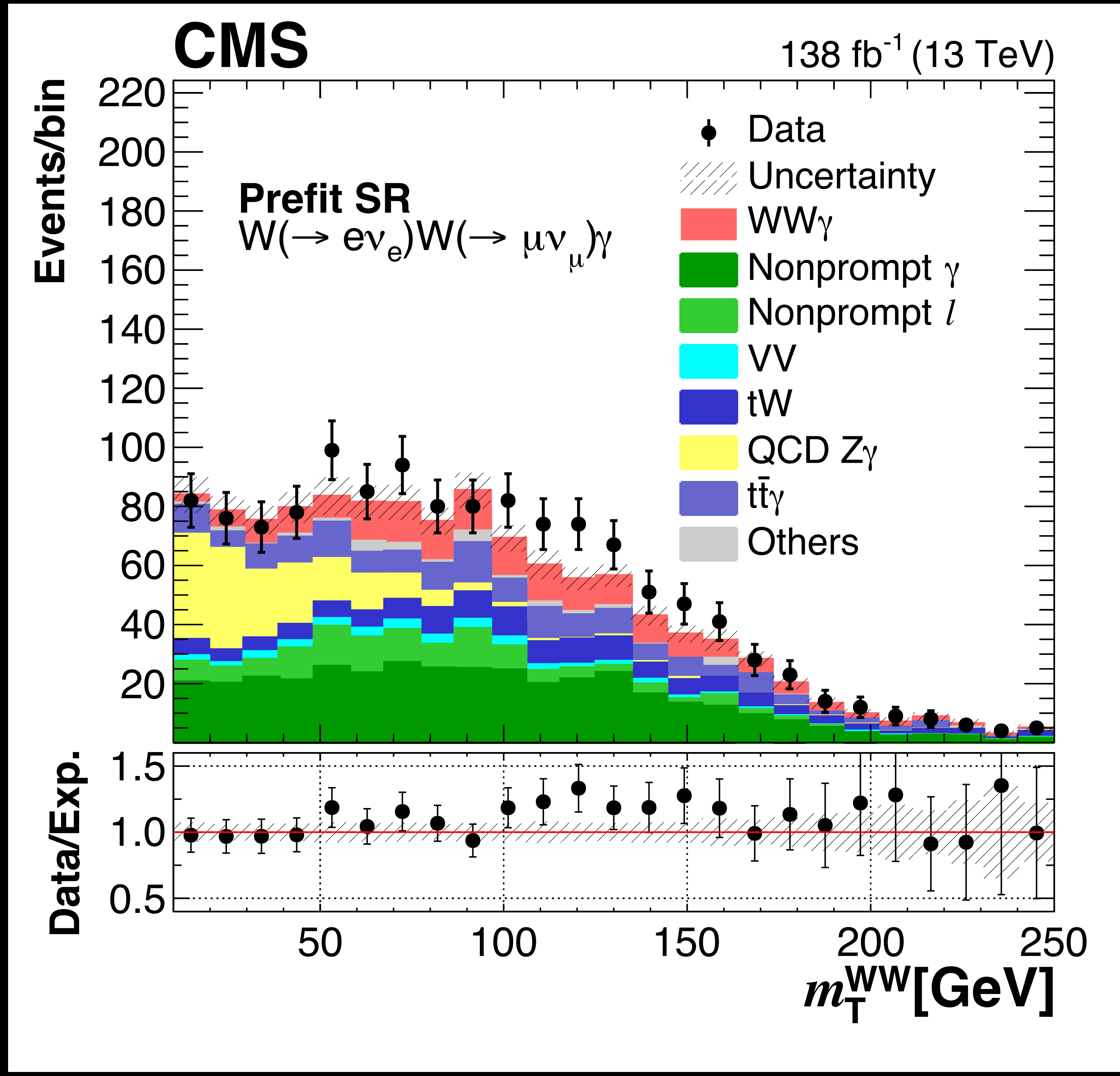
*The theoretical modeling uncertainties include the renormalization and factorization of QCD scales, PDFs, and parton shower modeling

Observation of $WW\gamma$ production at $\sqrt{s} = 13$ TeV

- $WW\gamma \rightarrow e^{+}\nu_{e}\mu^{-}\bar{\nu}_{\mu}\gamma$ or $\mu^{+}\nu_{\mu}e^{-}\bar{\nu}_{e}\gamma$ final state
- Events with b-jets vetoed
- Additional loose leptons vetoed
- Backgrounds suppressed by
  - $M_{\ell\ell} > 10$ GeV
  - $p_T^{\ell\ell} > 15$ GeV
  - $m_T^{WW} > 10$GeV

$$m_T^{WW} = \sqrt{2p_T^{\ell\ell}\, p_T^{\text{miss}}[1 - \cos\Delta\phi(\overrightarrow{p_T}^{\ell\ell}, \overrightarrow{p_T}^{\text{miss}})]}$$





Observation of $WW\gamma$ production at $\sqrt{s} = 13$ TeV

Control region	Same sign $WW\gamma$ control region	Topγ control region
Definition	Require charged leptons of identical charge	Flip b-veto and remove cut on transverse mass of the WW-system
Target processes	Validate non-prompt lepton background modeling	Validate top-quark and non-prompt photon background modeling

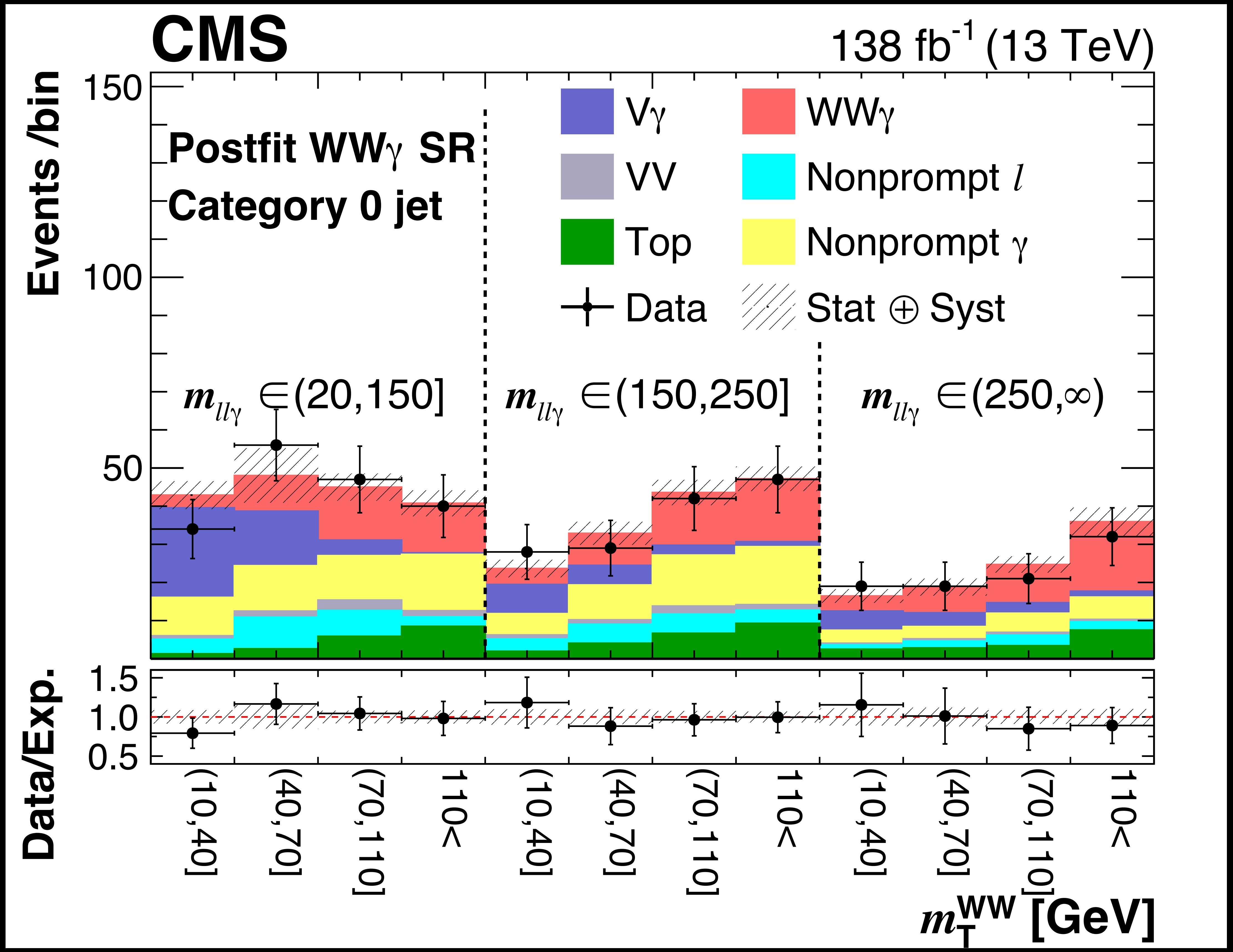
Observation of $WW\gamma$ production at $\sqrt{s} = 13$ TeV

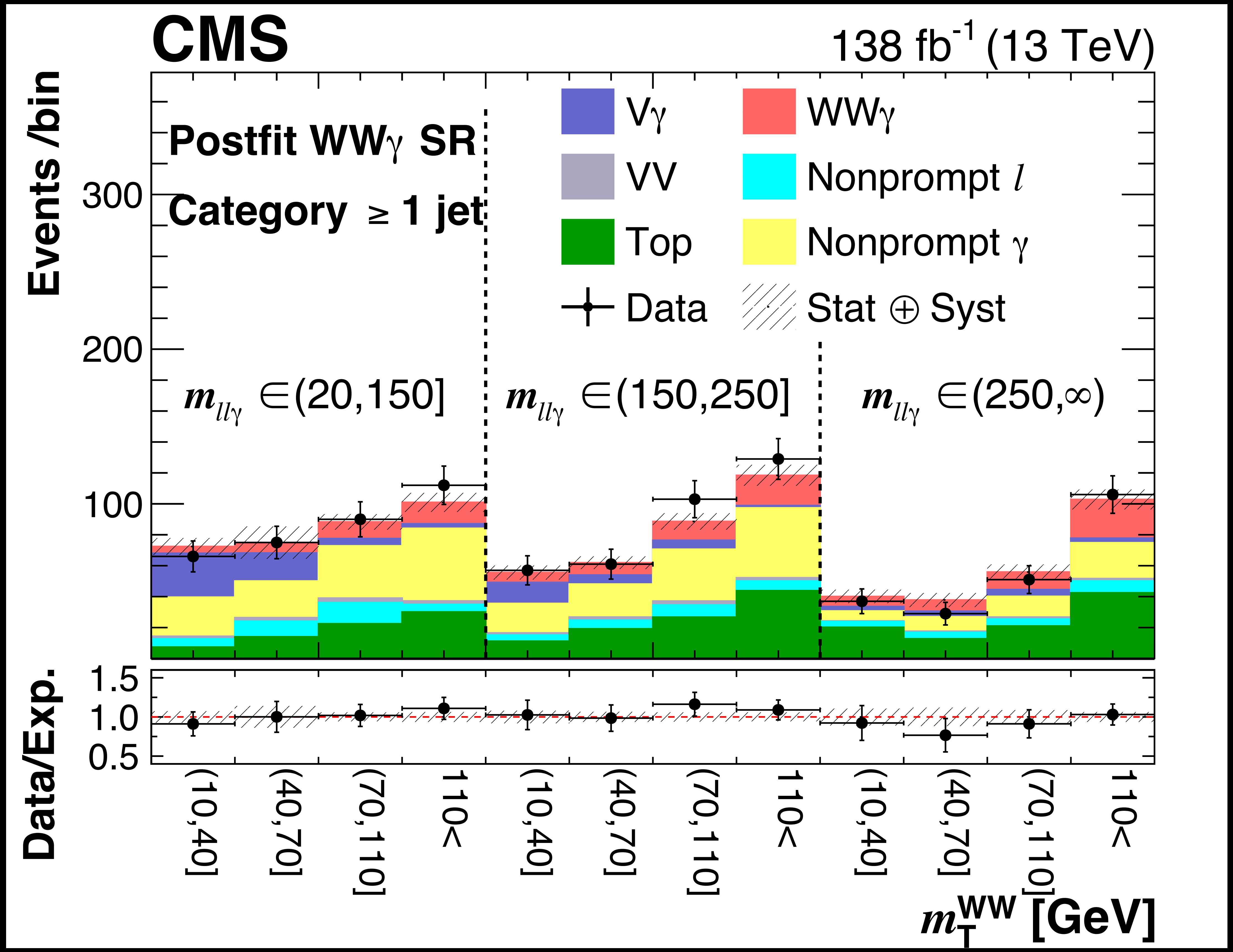
Process	SR (0 jet)	SR (≥1 jet)	SR (total)	SSWWγ CR	Topγ CR
WWγ	122 ± 23	132 ± 27	254 ± 47	1.0 ± 0.2	12.8 ± 2.7
QCD Vγ	72.0 ± 6.4	94.7 ± 9.3	167 ± 14	12.2 ± 2.2	12.6 ± 1.2
VV	15.1 ± 1.4	21.6 ± 2.4	36.7 ± 3.5	24.9 ± 1.7	2.0 ± 0.3
Top	56.6 ± 6.5	271 ± 26	328 ± 32	2.4 ± 0.6	2434 ± 85
Nonprompt ℓ	45.7 ± 4.0	77.2 ± 6.5	122.9 ± 9.7	197 ± 14	40 ± 11
Nonprompt γ	109.1 ± 9.0	301 ± 24	410 ± 32	19.9 ± 1.6	793 ± 62
Total	420 ± 20	898 ± 29	1318 ± 43	257 ± 14	3294 ± 57
Data	414	916	1330	259	3287

Background dominated

- Simultaneous extraction of signal and control regions

Observation of $WW\gamma$ production at $\sqrt{s} = 13$ TeV

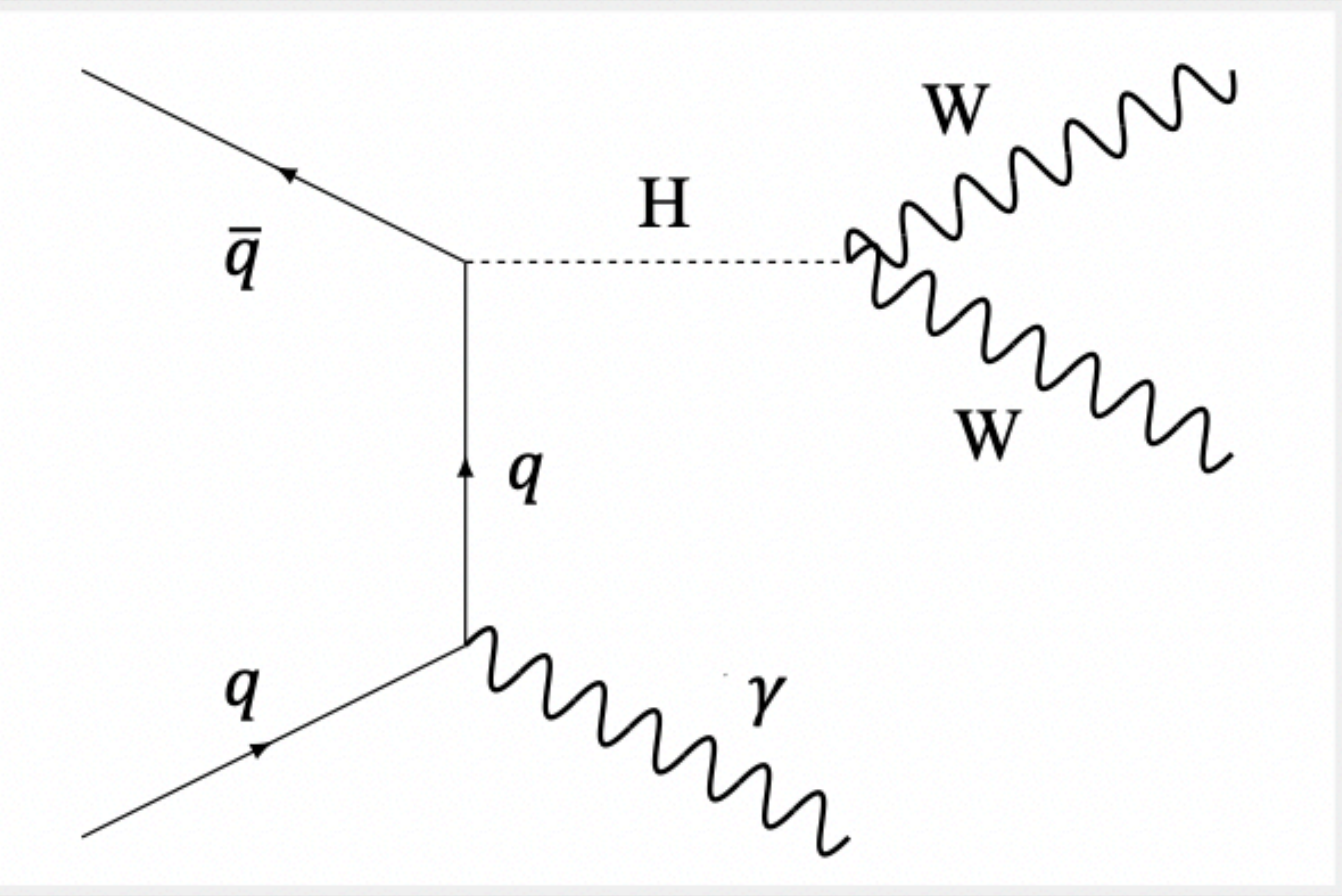




- Signal extracted from a binned maximum likelihood fit using two dimensional distributions in m_T^{WW} and $m_{\ell\ell\gamma}$ (product of the Poisson probability mass functions for each bin forms the likelihood function)

Search for $H\gamma$

- Selection modified to target $H\gamma$ by requiring
  - $\Delta\phi_{\ell\ell} < 2.5$
  - $\Delta R_{\ell\ell} < 2.3$
- Design requirements: oppositely charged W-bosons from the Higgs decay → opposite spin orientation



Process	σ upper limits obs. (exp.) [fb]	κ_q limits obs. (exp.) at 95% CL	$\bar{\kappa}_q$ limits obs. (exp.) at 95% CL
$u\bar{u} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	85 (67)	$\lvert\kappa_u\rvert \leq 16000\ (13000)$	$\lvert\bar{\kappa}_u\rvert \leq 7.5\ (6.1)$
$d\bar{d} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	72 (58)	$\lvert\kappa_d\rvert \leq 17000\ (14000)$	$\lvert\bar{\kappa}_d\rvert \leq 16.6\ (14.7)$
$s\bar{s} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	68 (49)	$\lvert\kappa_s\rvert \leq 1700\ (1300)$	$\lvert\bar{\kappa}_s\rvert \leq 32.8\ (25.2)$
$c\bar{c} \to H + \gamma \to e\mu\nu_e\nu_\mu\gamma$	87 (67)	$\lvert\kappa_c\rvert \leq 200\ (110)$	$\lvert\bar{\kappa}_c\rvert \leq 45.4\ (25.0)$

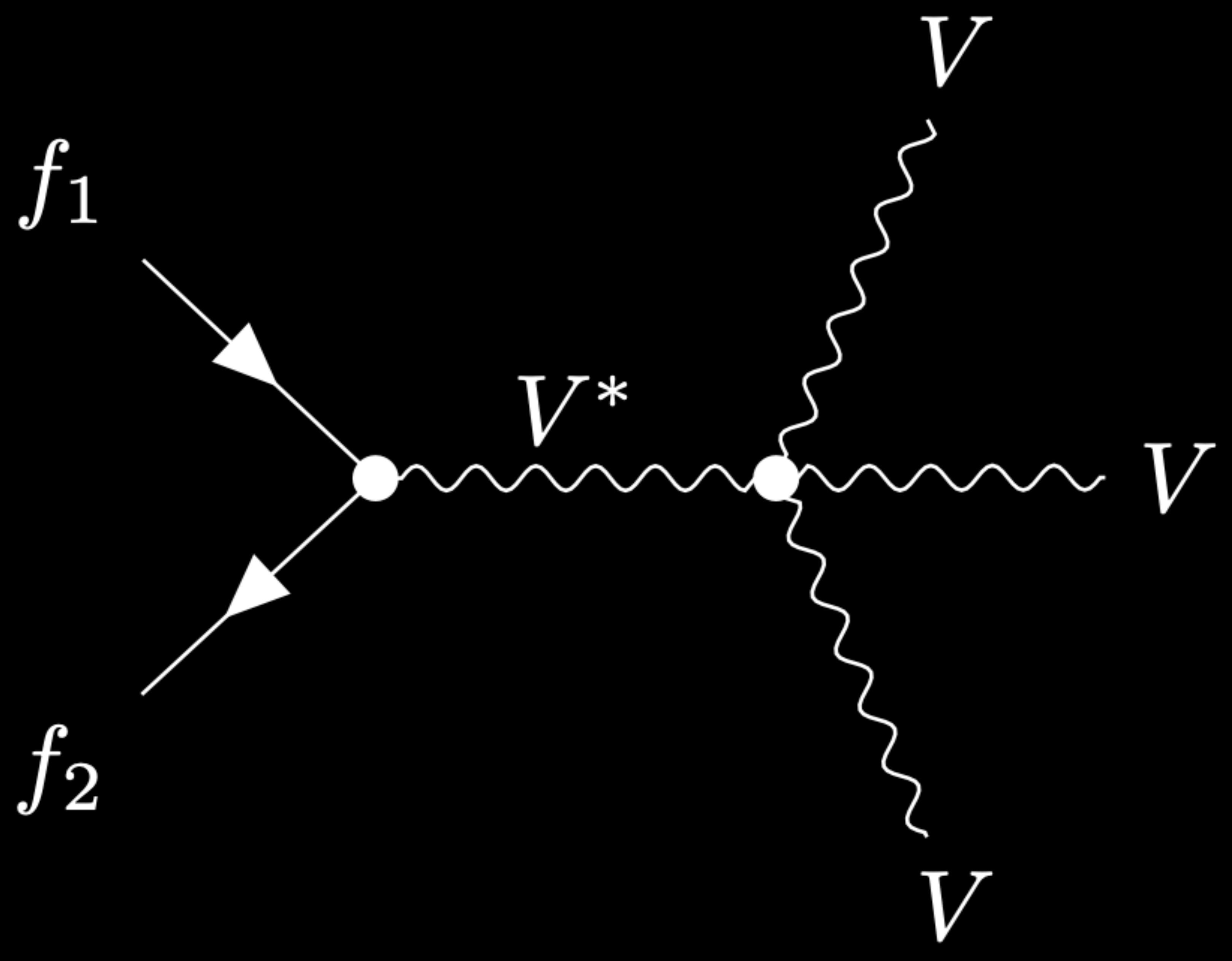
First observation of triboson production

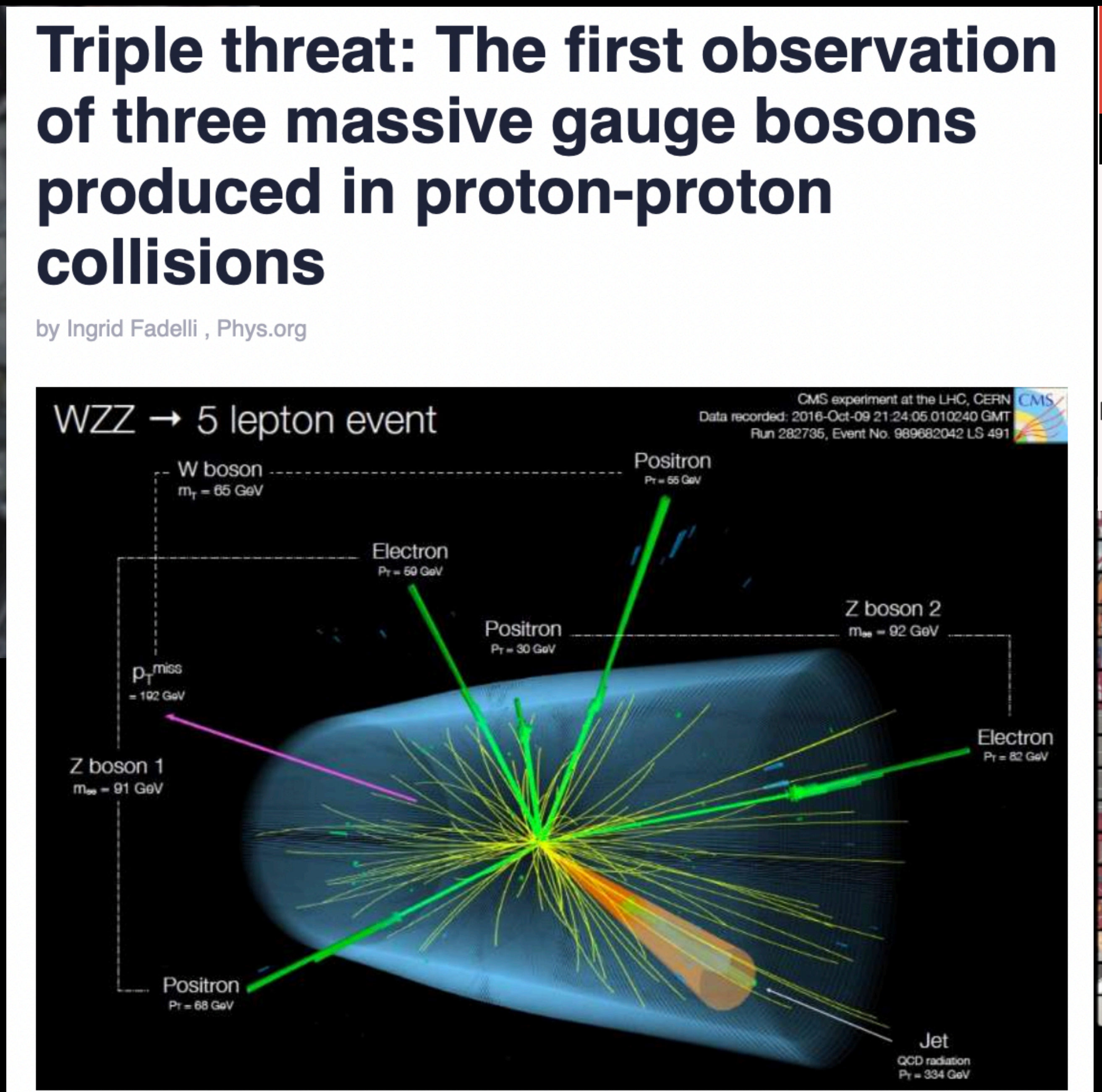
https://arxiv.org/abs/2006.11191

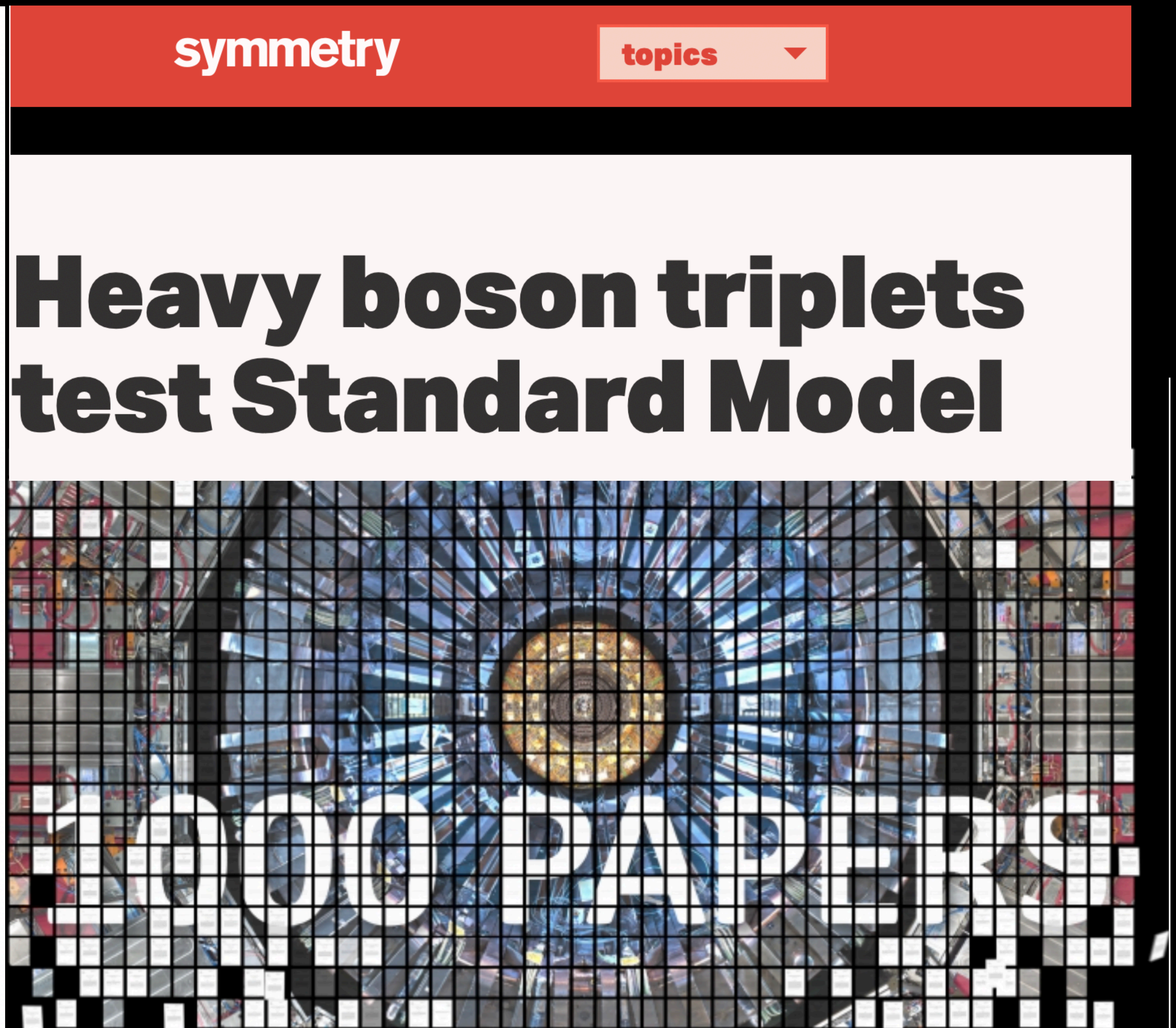
Announced on April, 2020

Note: V (V=$W^{\pm}$, Z^0)

- W: 1983 ✓
- WW: 1997 ✓✓
- VVV: 2020 ✓✓✓



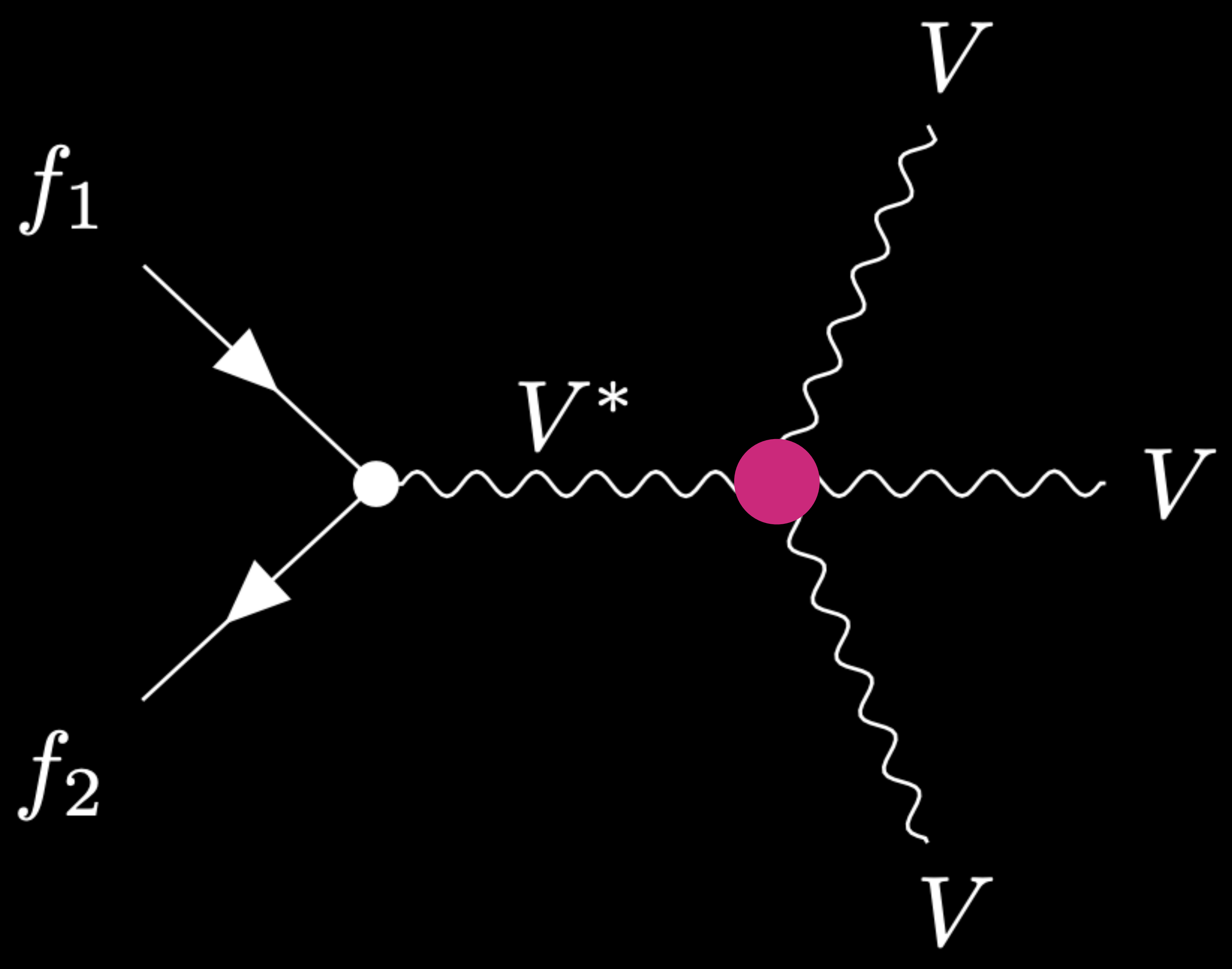


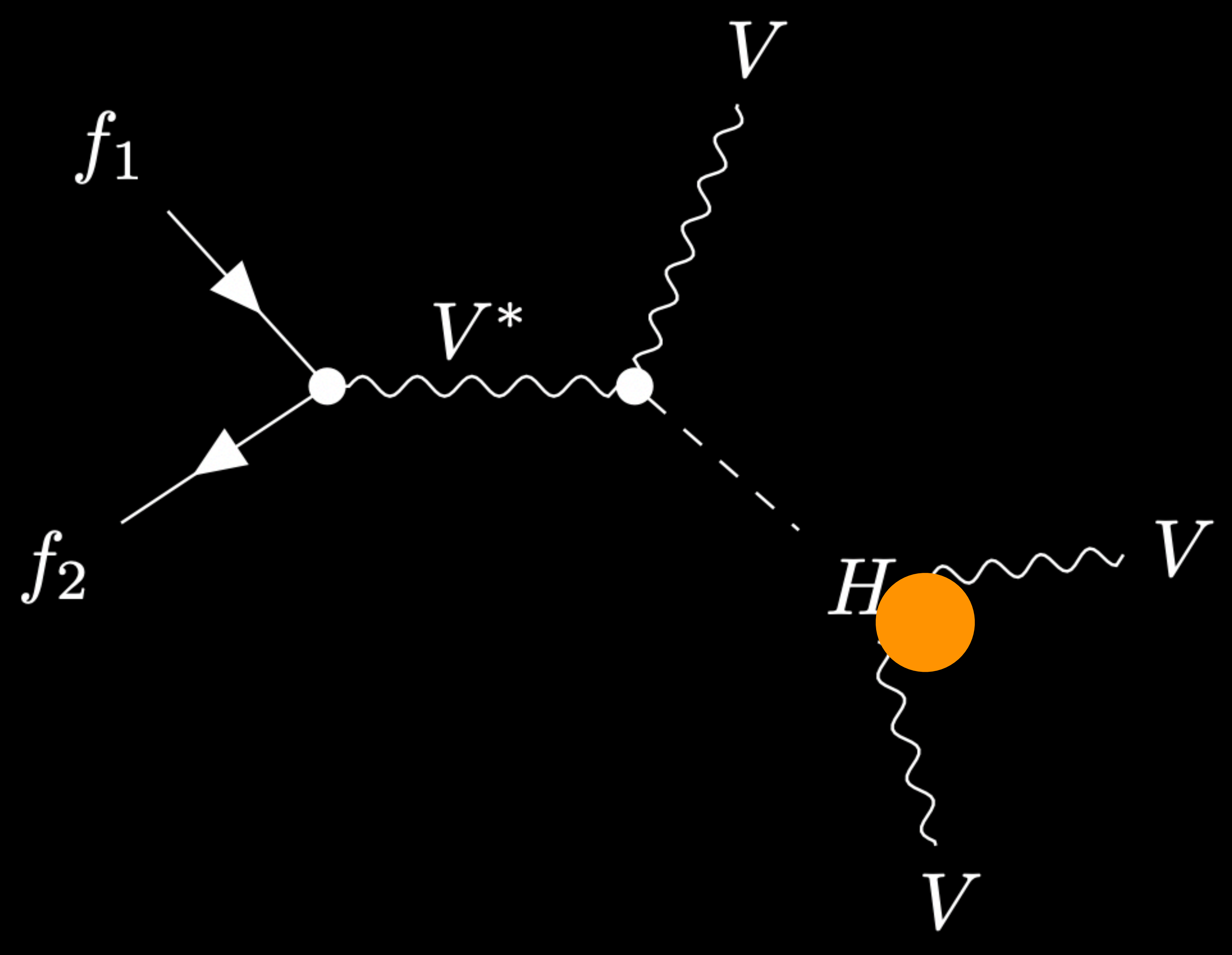


- Culmination of persistent endeavor by both ATLAS and CMS Collaborations
- Recent result from ATLAS on observation of the WWW process

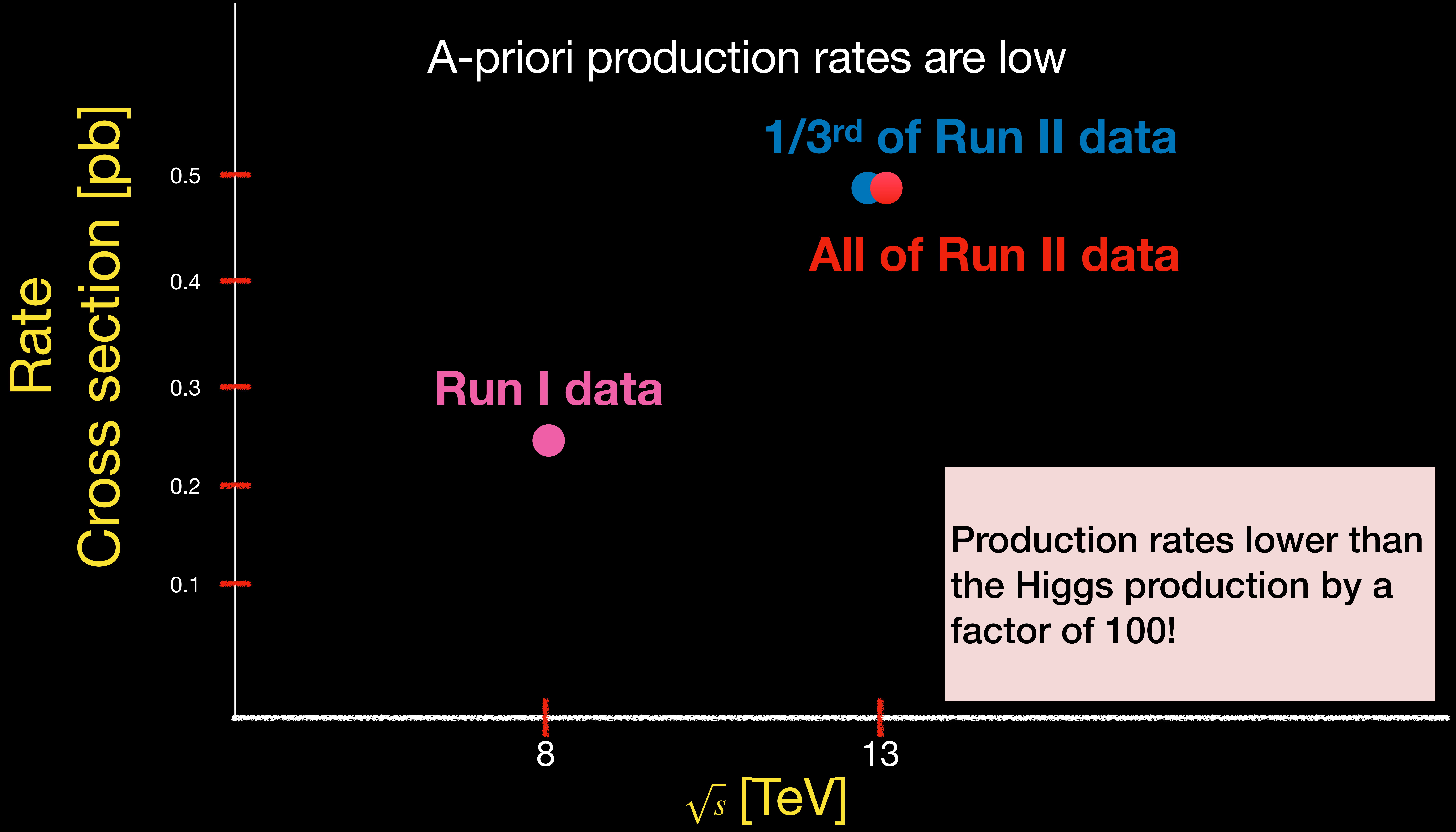
What is so special about VVV?

- Unique access to the quartic coupling
- Mediation by the Higgs boson



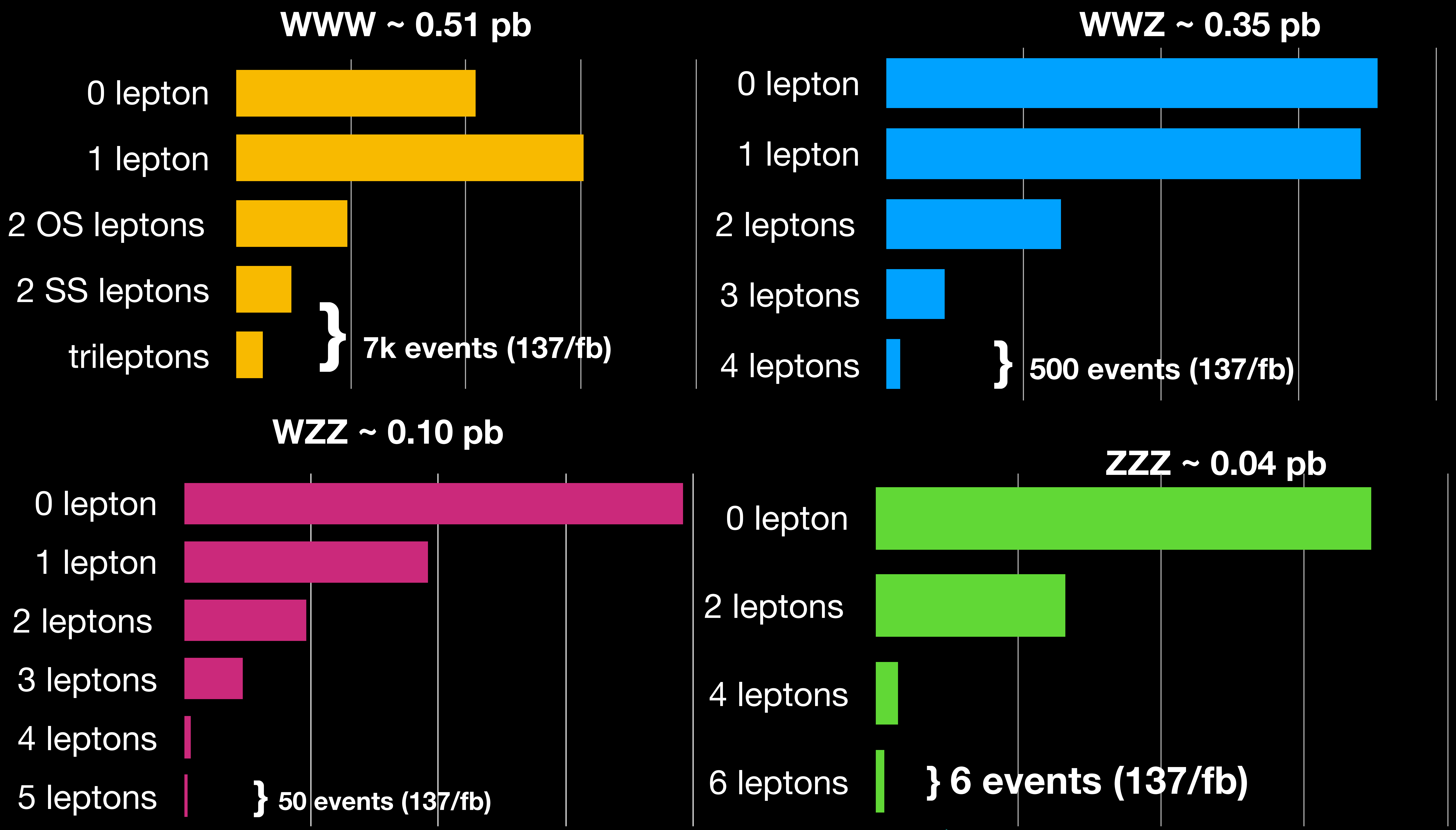


Culmination of several searches over several years



Production rates lower than the Higgs production by a factor of 100!

Cross sections X branching fractions



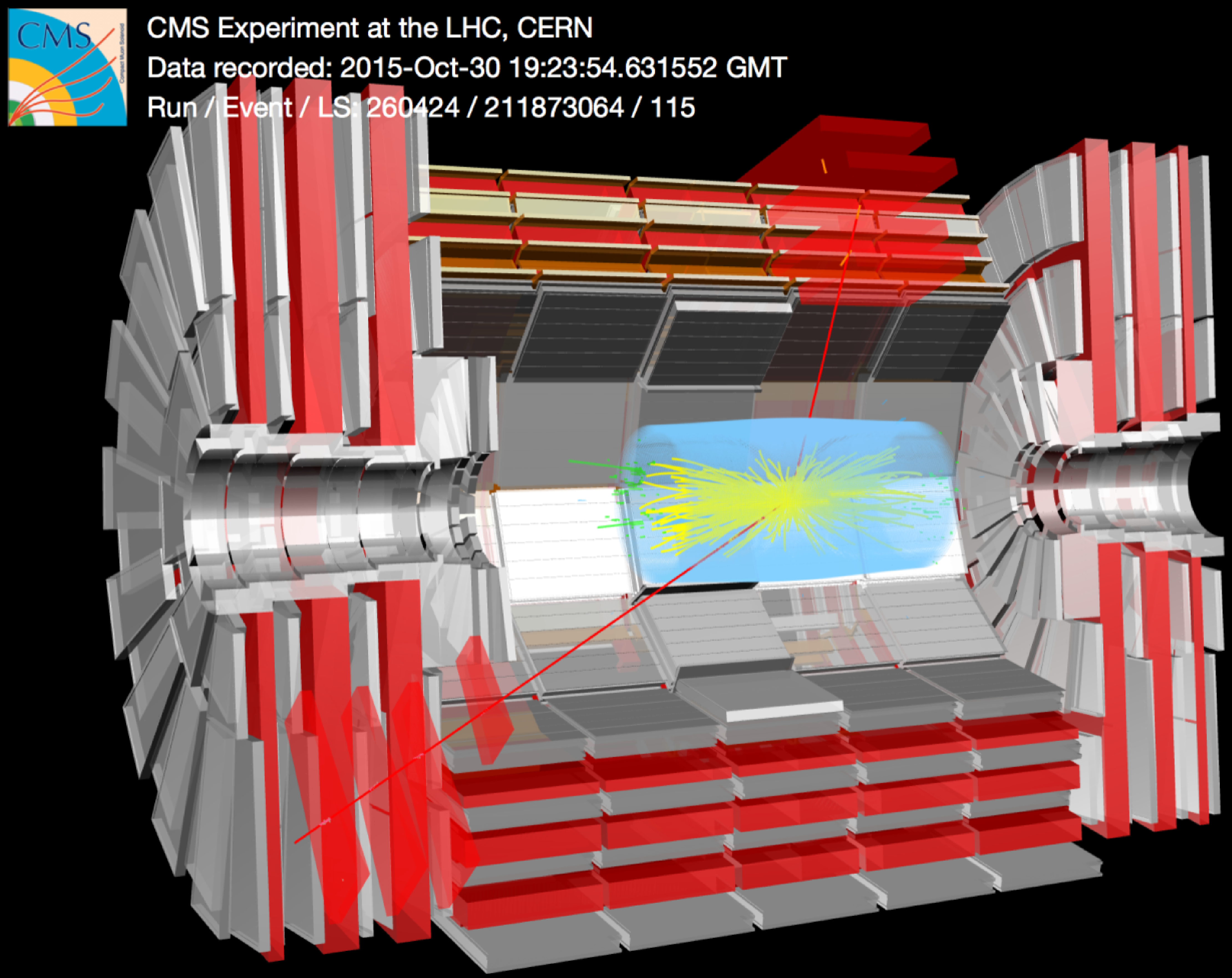
Explore leptonic final states; backgrounds reduced with a BDT based approach and complementary cut based analysis

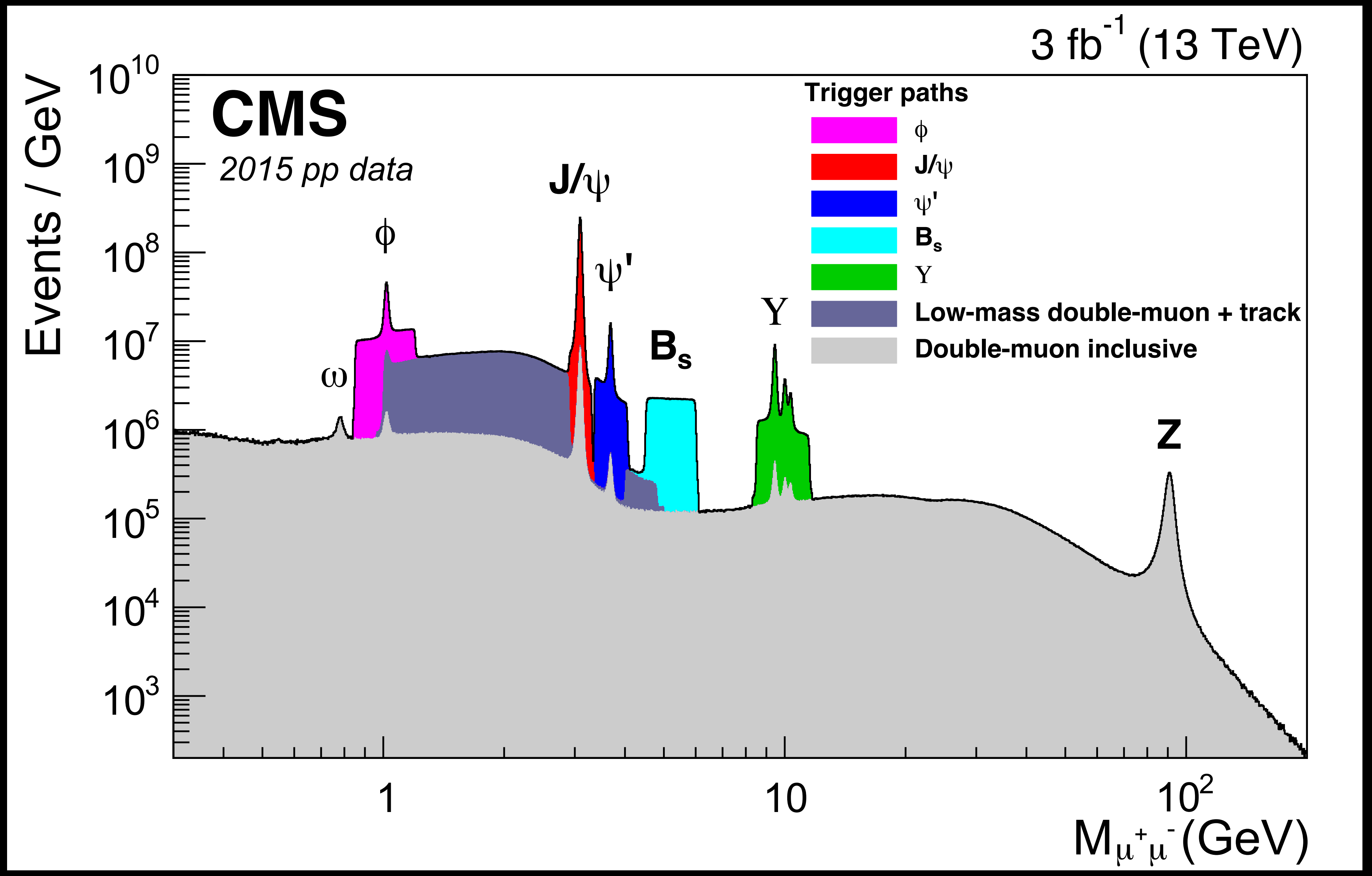
Background reduction →

$\sigma_{background} \sim \sigma_{signal}$

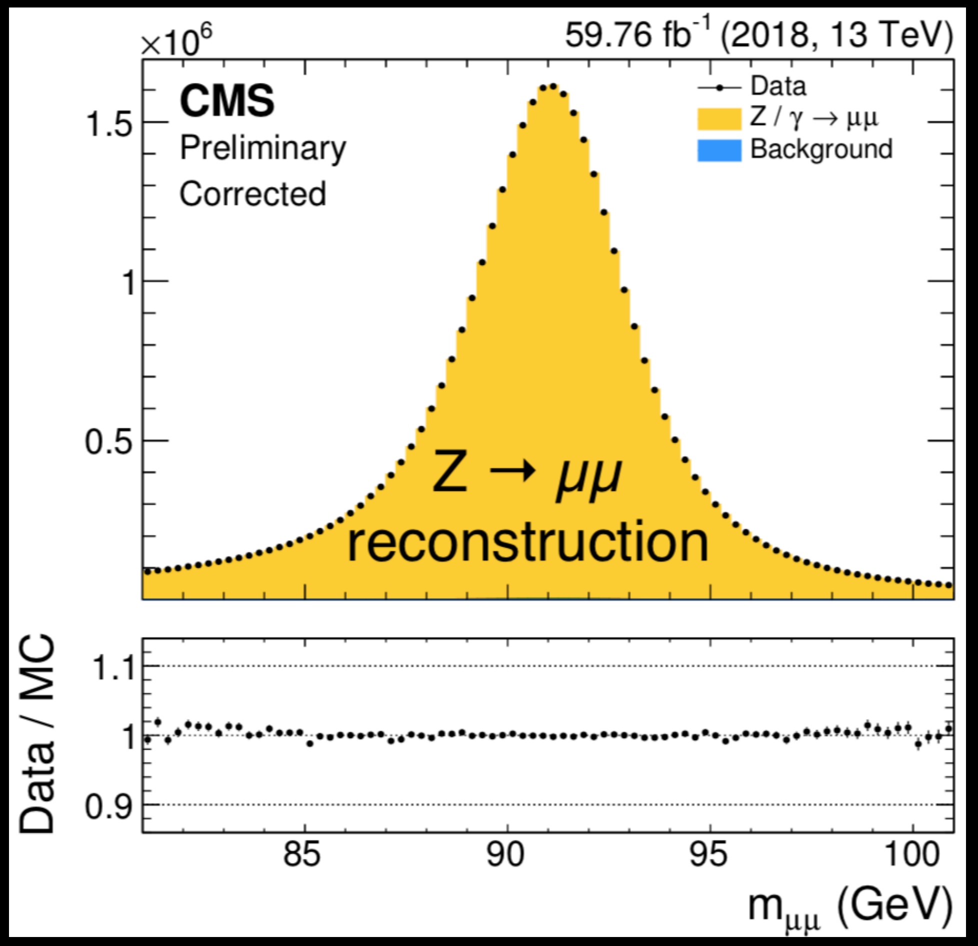
Lepton detection in CMS

Excellent lepton detection capabilities in CMS → can be replied on for SM-like analysis





Dilepton mass resolution: 1-2%



Background processes

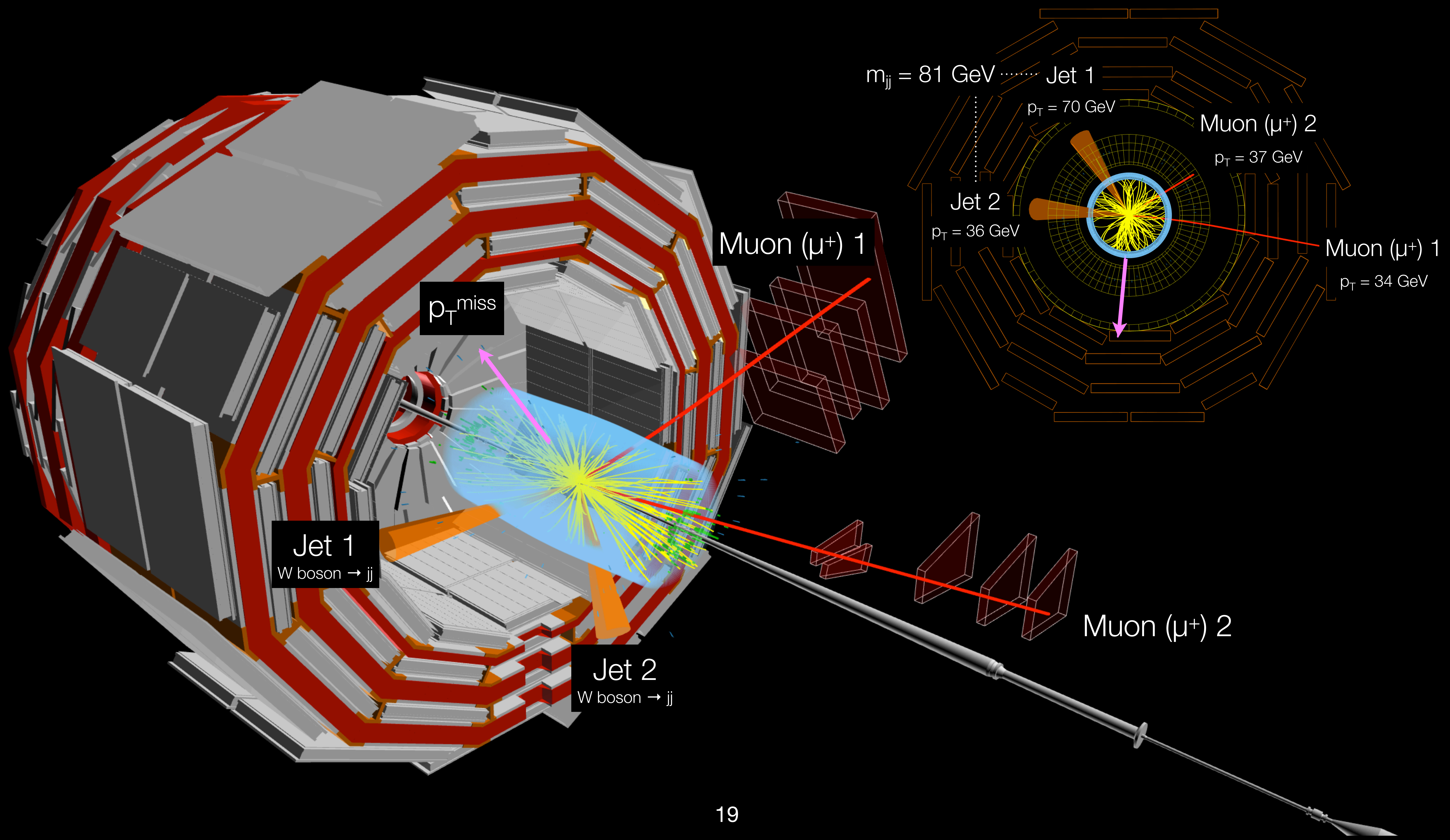
Process	Final state	Background
WWW	Same signed leptons ✅	top-quark pair production, diboson process (WZ)
WWW	Three leptons	top-quark pair production, diboson process (WZ)
WWZ	Four leptons	top-quark pair produced with a Z-boson, diboson process (ZZ)
WZZ	Five leptons ✅	diboson process (ZZ)
ZZZ	Six leptons ✅	top-quark pair produced with a Higgs boson, diboson process (ZZ)

Prompt lepton: lepton that originates from the primary interaction vertex

Type of background contribution: Misidentified leptons, prompt leptons

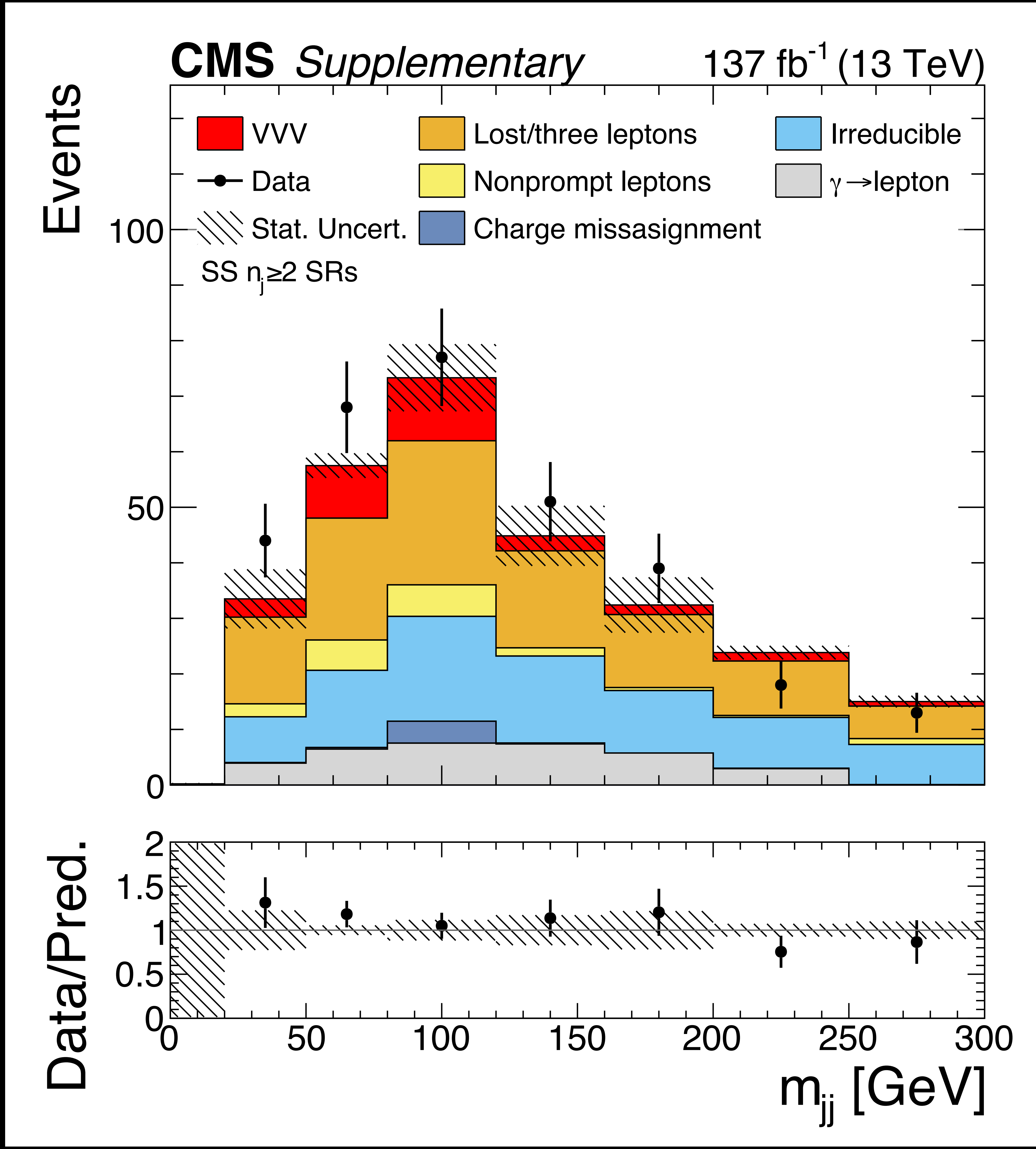
WWW → 2 lepton + 2 jet event

CMS experiment at the LHC, CERN
Data recorded: 2016-Jul-02 14:25:40.606976 GMT
Run 276242, Event No. 96020969 LS 52



Search for WWW in dilepton final state

- Categorization:
  - 2 same-signed leptons + 2 jets
    - further categorized based on $|M_{jj} - M_W| \leqslant 15$ GeV
  - 2 same-signed leptons + 1 jet
- Major backgrounds are WZ and nonprompt contribution, some prompt ($W^\pm W^\pm jj$ / ttW)
- Boosted Decision Trees trained against nonprompt and prompt backgrounds



WZ (lost leptons)

$t\bar{t}$ (non prompt)

$W^\pm W^\pm jj$

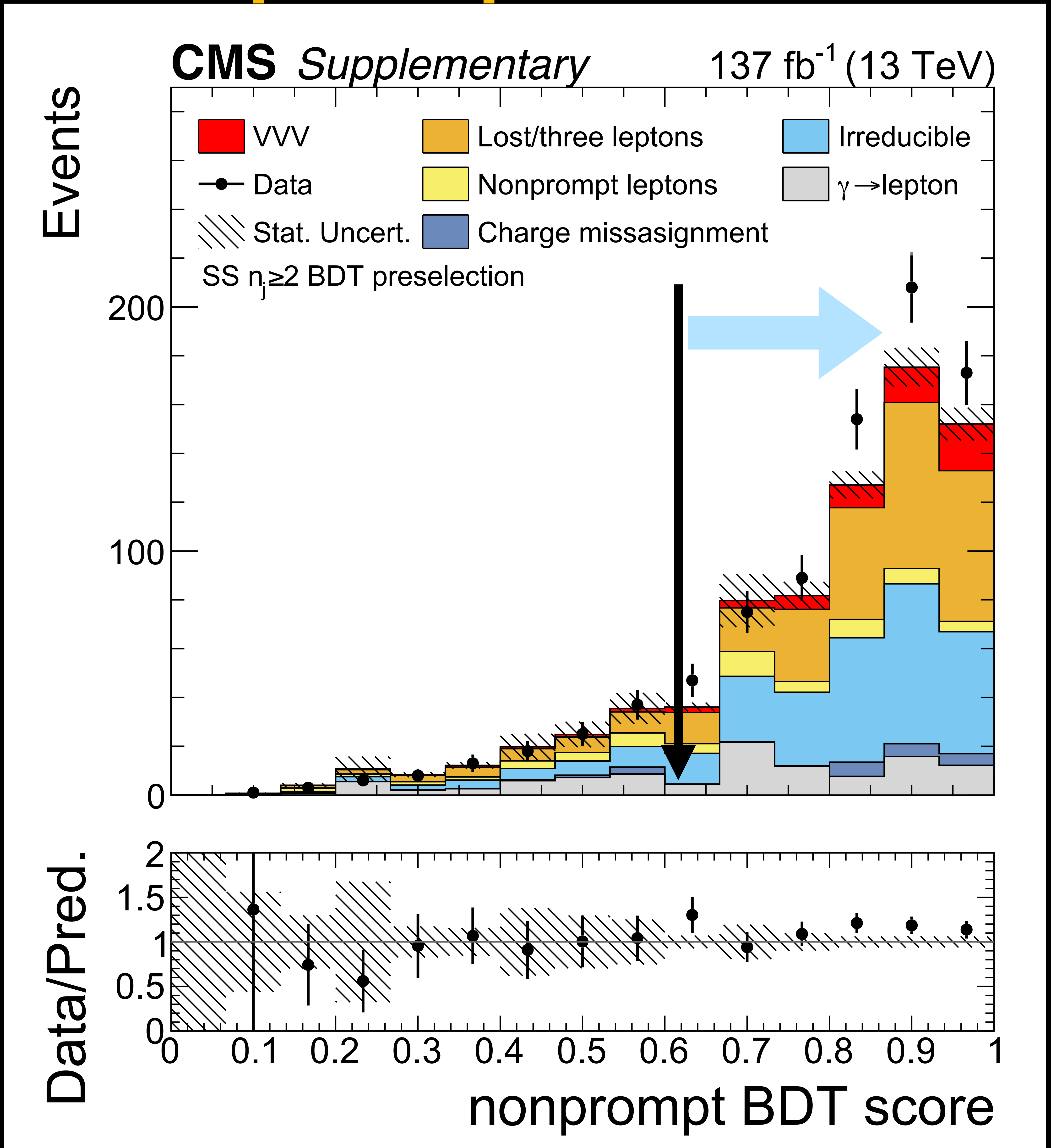
$W^\pm \gamma$

Z+jets

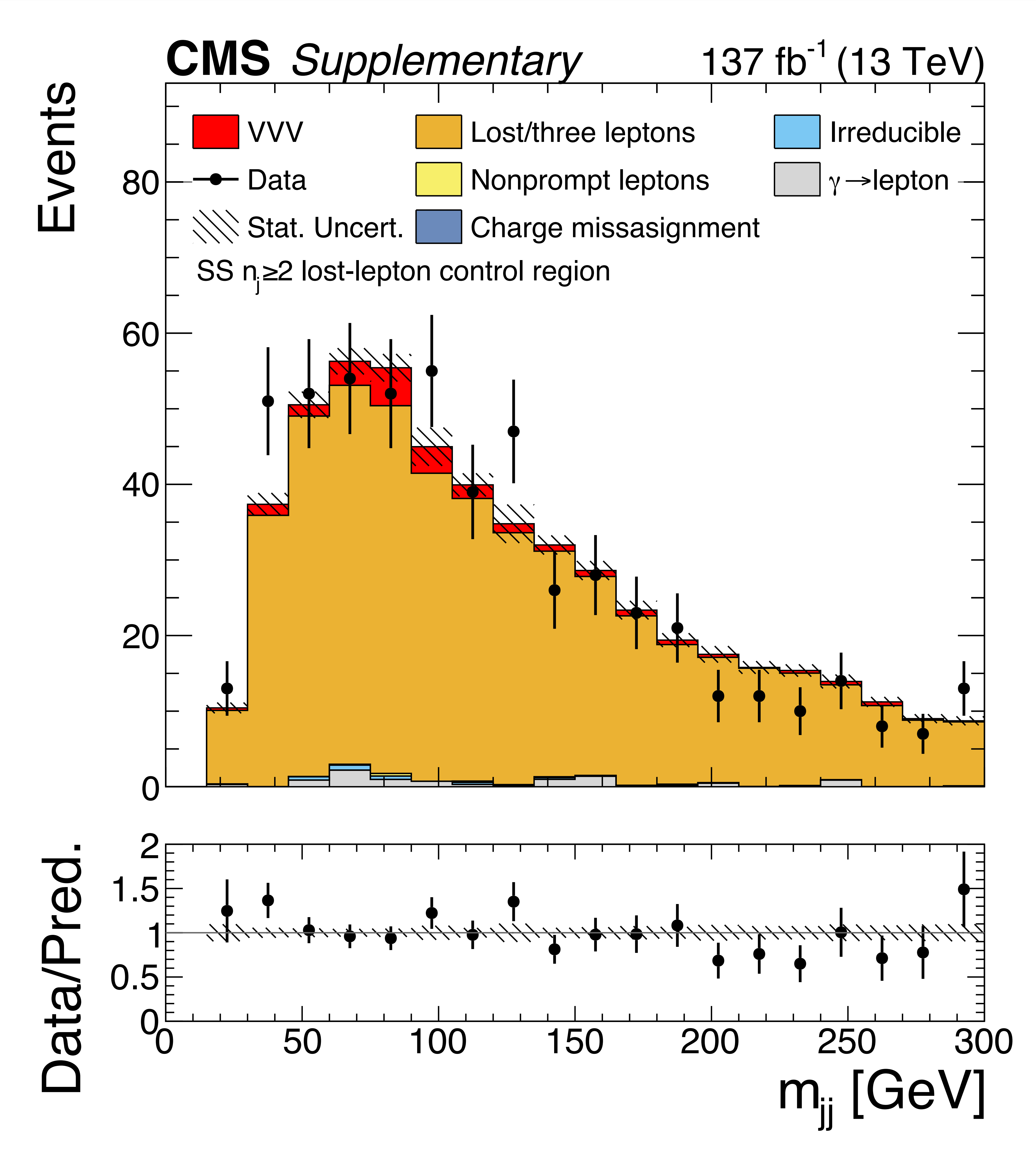
Using boosted decision trees to tackle backgrounds from nonprompt sources

Input variables (indicative, not exhaustive):

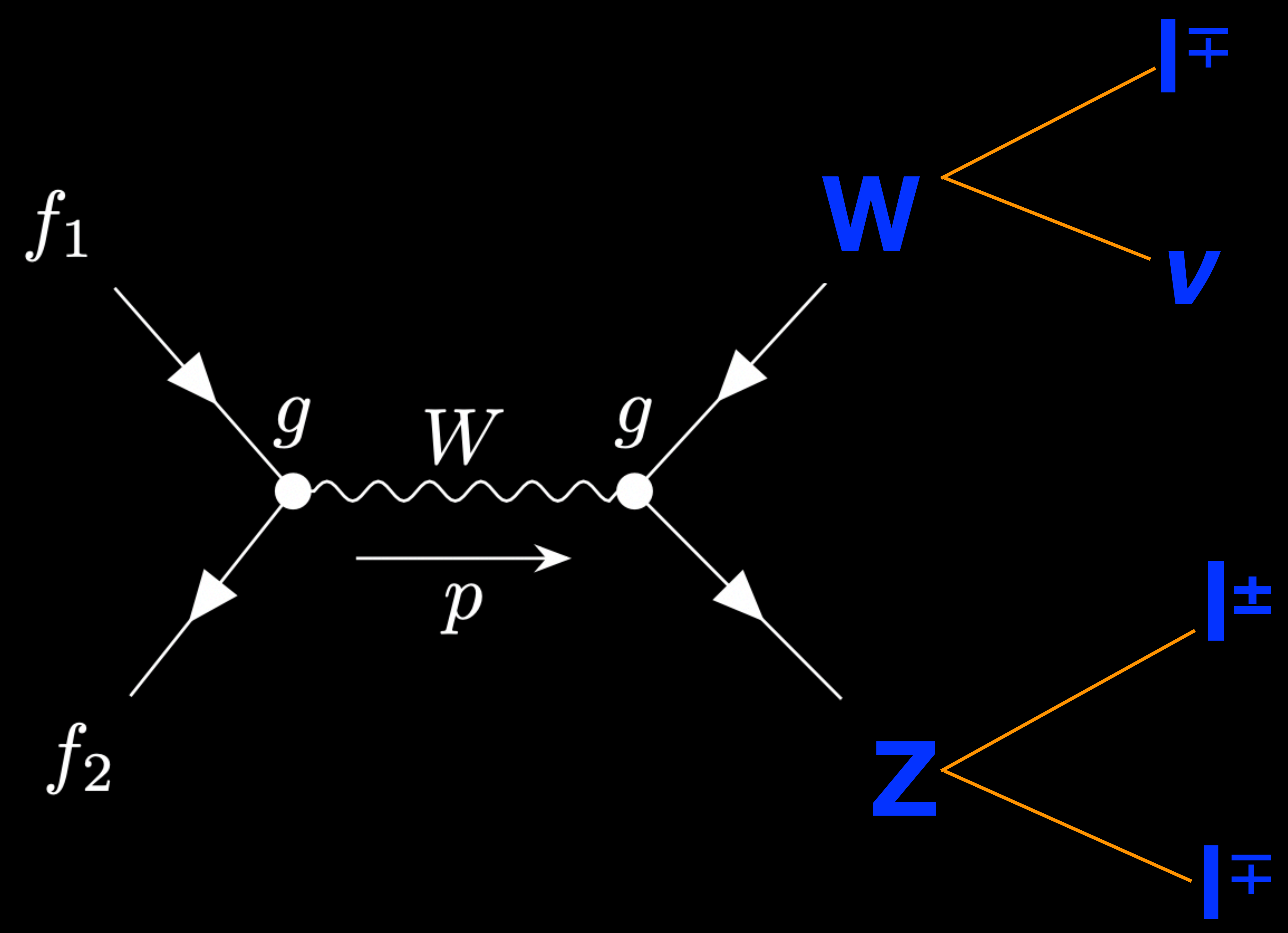
- p_T^{miss} (typically indicative of neutrinos in the event)
- Lepton p_T
- Jet p_T
- Transverse mass (m_T)
- Mass of the two jets (M_{jj})



Understanding prompt backgrounds

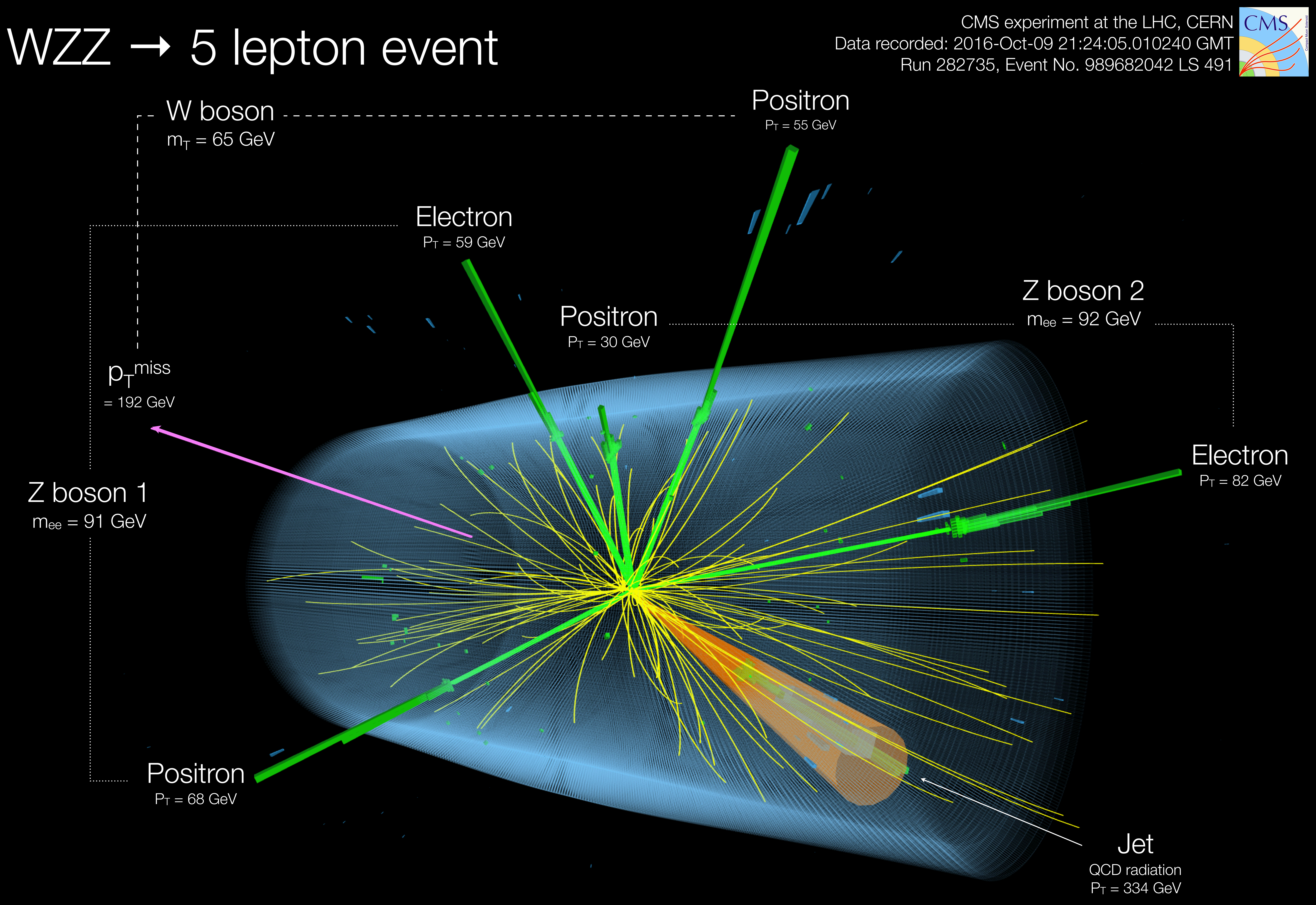


- Dijet invariant mass in a control region with 3 leptons



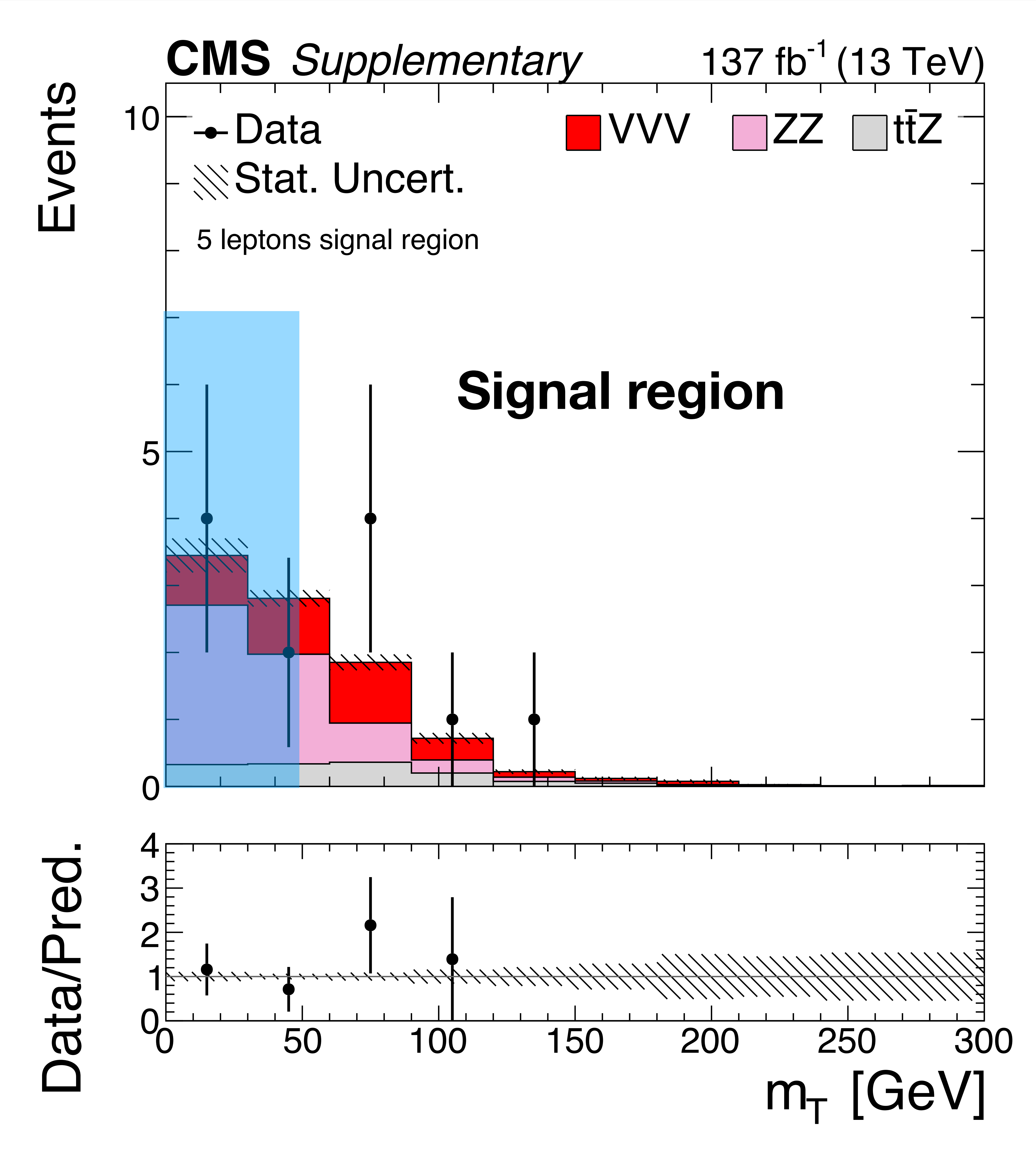
- Contributes when one of the leptons fails to pass the minimum pT threshold in the analysis
- Referred to as a lost lepton background

WZZ in five lepton final state

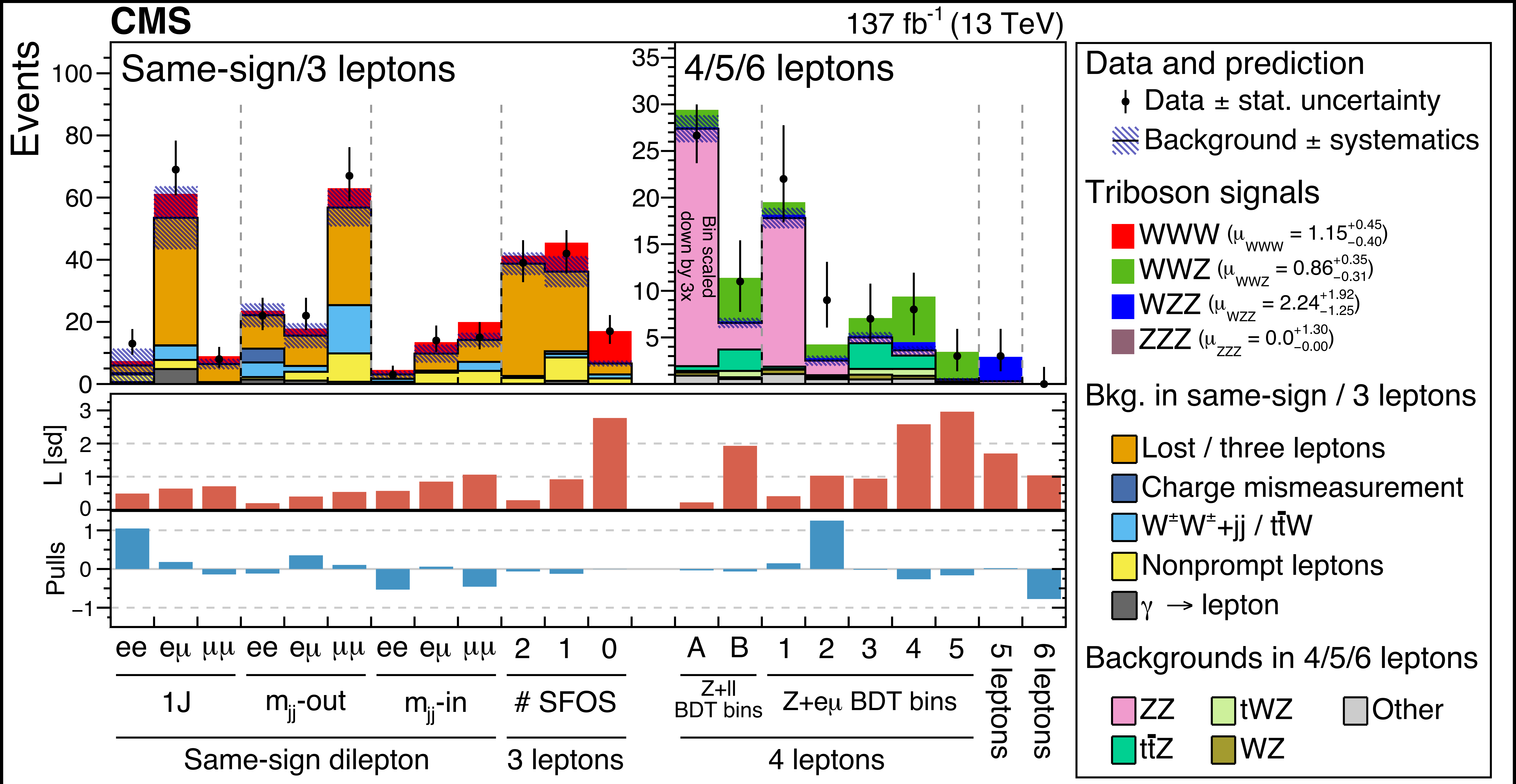


WZZ in five lepton final state

- In 5 lepton channel:
  - Require 2 Z boson candidates and associate remaining lepton with a W
  - Separate by flavor of the W candidate lepton and require M_T > 50 GeV if electron



Combination of all final states

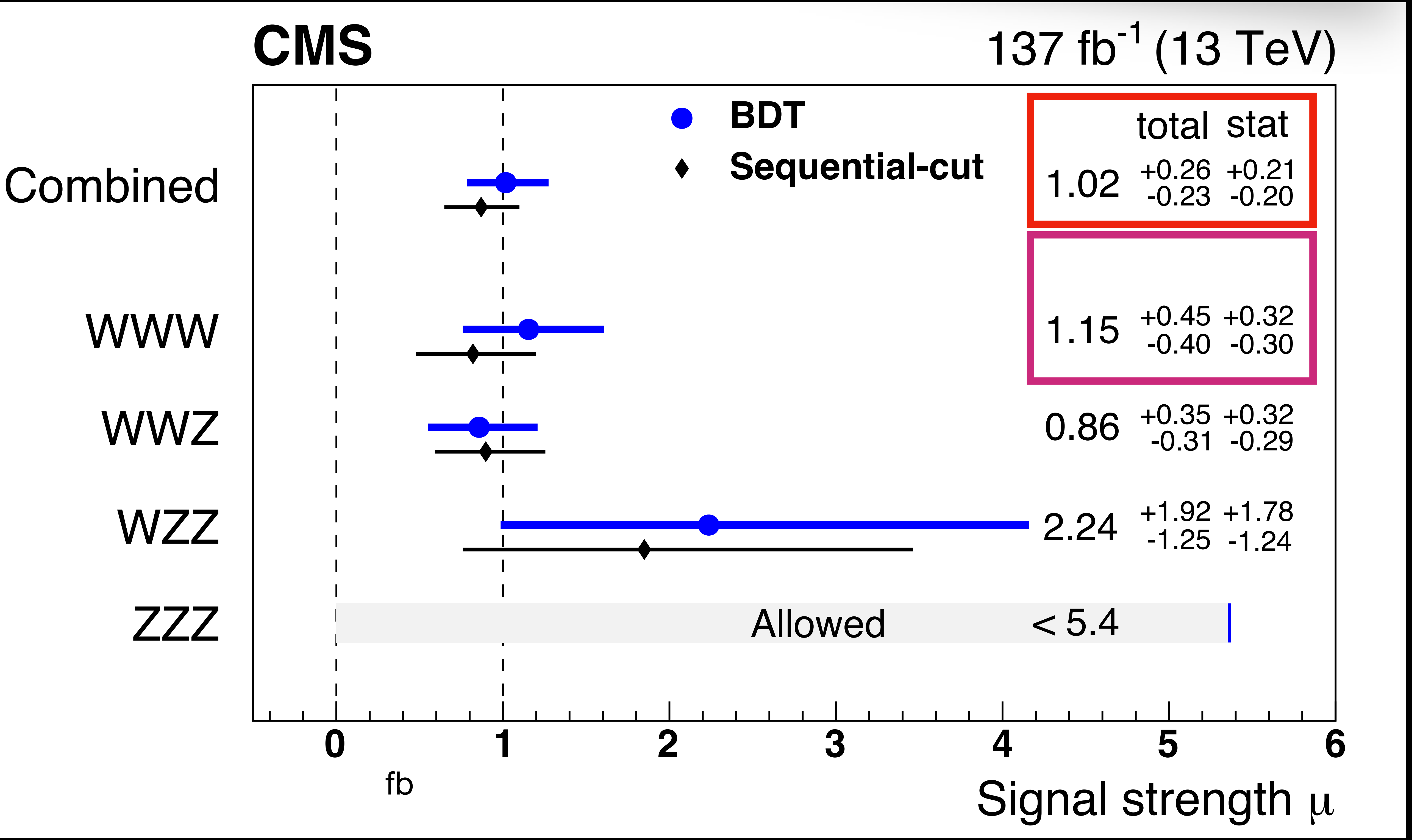


Contribution from Higgs-mediated mode ~1/3 in the sensitive channels

Observation of the VVV process

Combined observed significance at 5.7 s.d.
Observed significance for WWW and WWZ at 3.3 s.d. and 3.4 s.d.

Process	Final State	Significance s.d. observed (expected)	Cross sections (fb)
WWW	same-signed dilepton and trilepton	**3.3** (3.1)	$590^{+160\ +160}_{-150\ -130}$
WWZ	four leptons	**3.4** (4.1)	$300^{+120\ +50}_{-100\ -40}$
WZZ	five leptons	**1.7** (0.7)	$200^{+160\ +40}_{-110\ -20}$
ZZZ	six or more leptons	**0.0** (0.9)	< 200



The strength of the signal with respect to SM expectation

Significance of the VVV process at the High-Luminosity LHC*

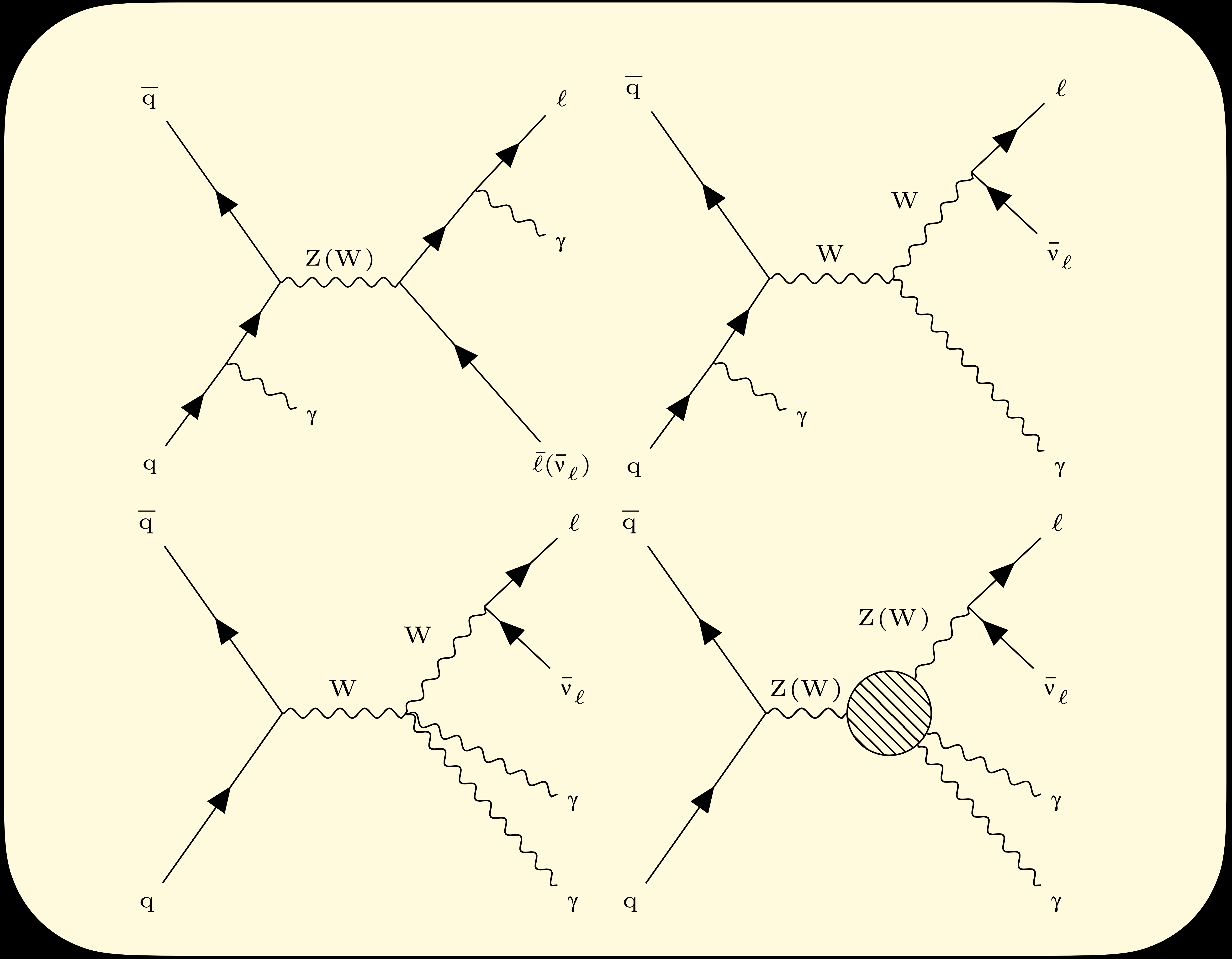
Process	Final State	Significance observed (expected) σ at Run II	Significance expected (3000 fb^{-1}) σ Projected assuming uncertainties are the same as Run II
WWW	same-signed dilepton and trilepton	**3.3** (3.1)	Can be pursued in the realm of precision measurements
WWZ	four leptons	**3.4** (4.1)	Can be pursued in the realm of precision measurements
WZZ	five leptons	**1.7** (0.7)	**> 5.0**
ZZZ	six or more leptons	**0.0** (0.9)	**> 5.0**

*Unofficial projections

Measurements of the $W^{\pm}\gamma\gamma$ and $Z\gamma\gamma$

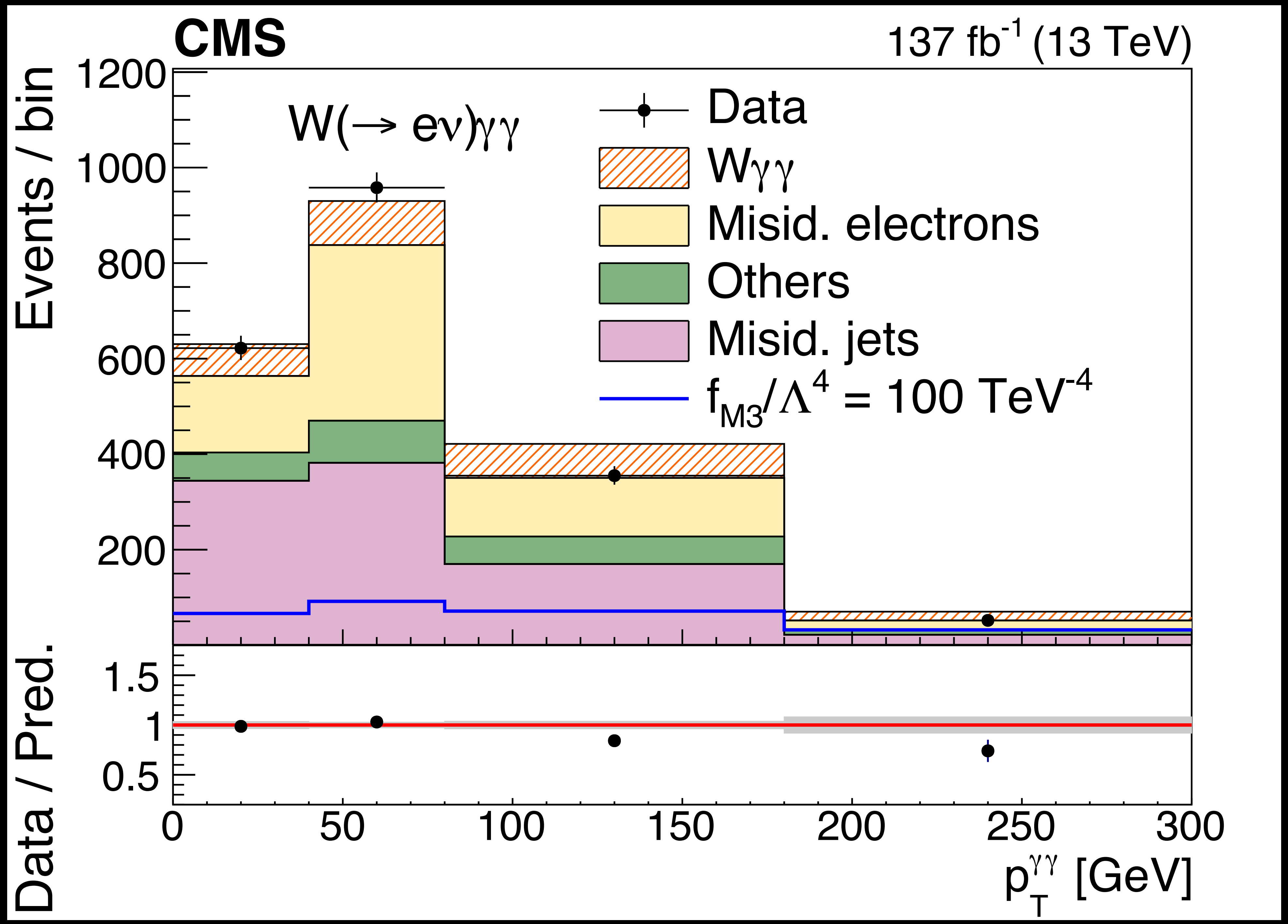
https://arxiv.org/pdf/2105.12780.pdf

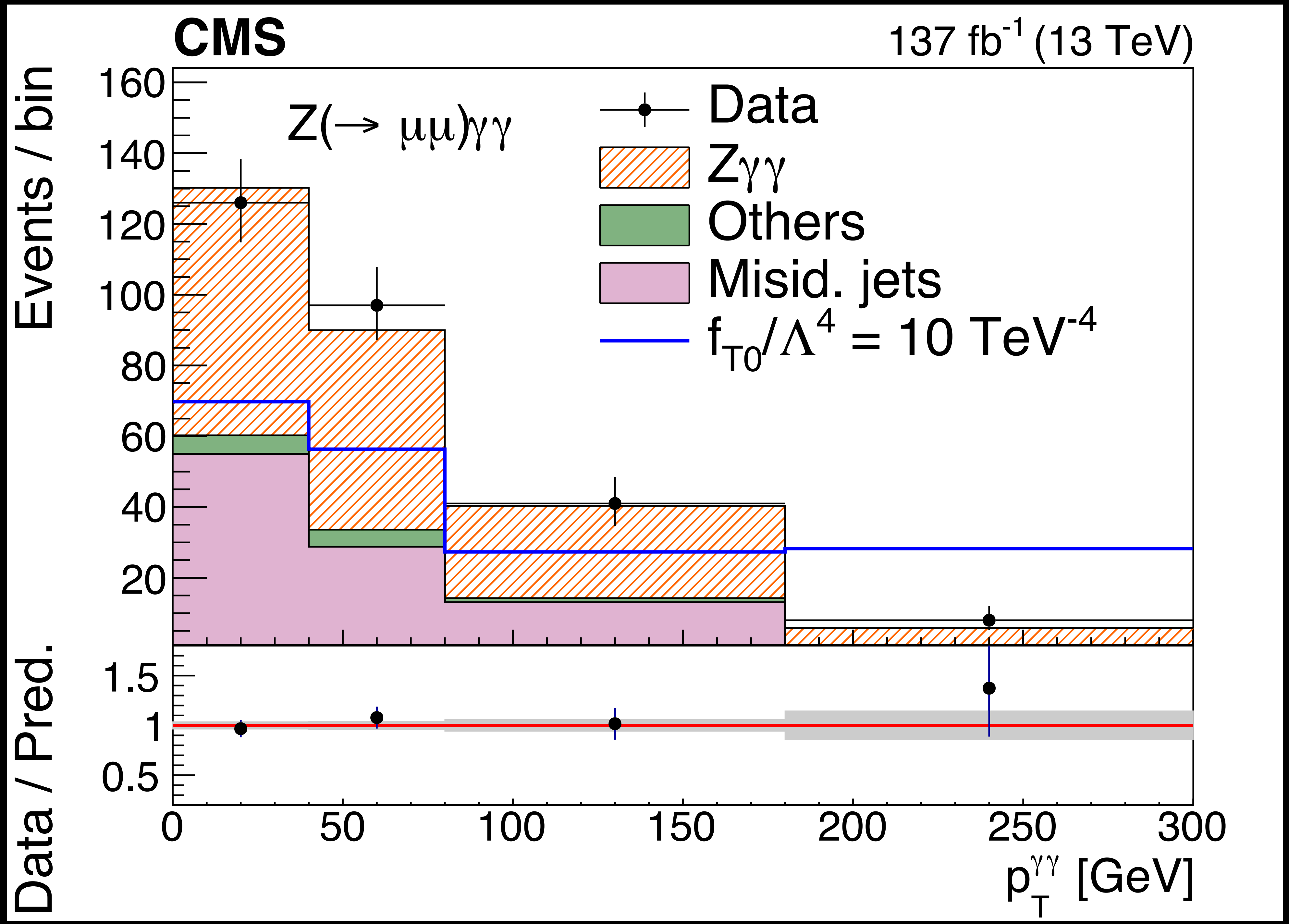
- Final state: $W \to \ell\nu$ and $Z \to \ell^+\ell^-$ ($\ell = e, \mu$)
- Explore potential effect of new physics and characterize in terms of the effective field theory approach
- $W^{\pm}\gamma\gamma$: 3.1 σ and $Z\gamma\gamma$: 4.8 σ
- Electron and muon candidates $p_T >$ 15 GeV
- Photon candidates $p_T >$ 20 GeV
- For $W^{\pm}\gamma\gamma$ require exactly one lepton
- For $Z\gamma\gamma$ require two leptons
  - $M_{\ell\ell} >$ 55 GeV



Measurements of the $W^{\pm}\gamma\gamma$ and $Z\gamma\gamma$

- Background contributions
  - jets misidentified as photons
  - electrons reconstructed as photons
- Jet → photon misidentification background in the diphoton phase space estimated by solving system of equations (so-called "tight-loose" method based on passing/failing isolation requirements)





Measurements of the $W^{\pm}\gamma\gamma$ and $Z\gamma\gamma$

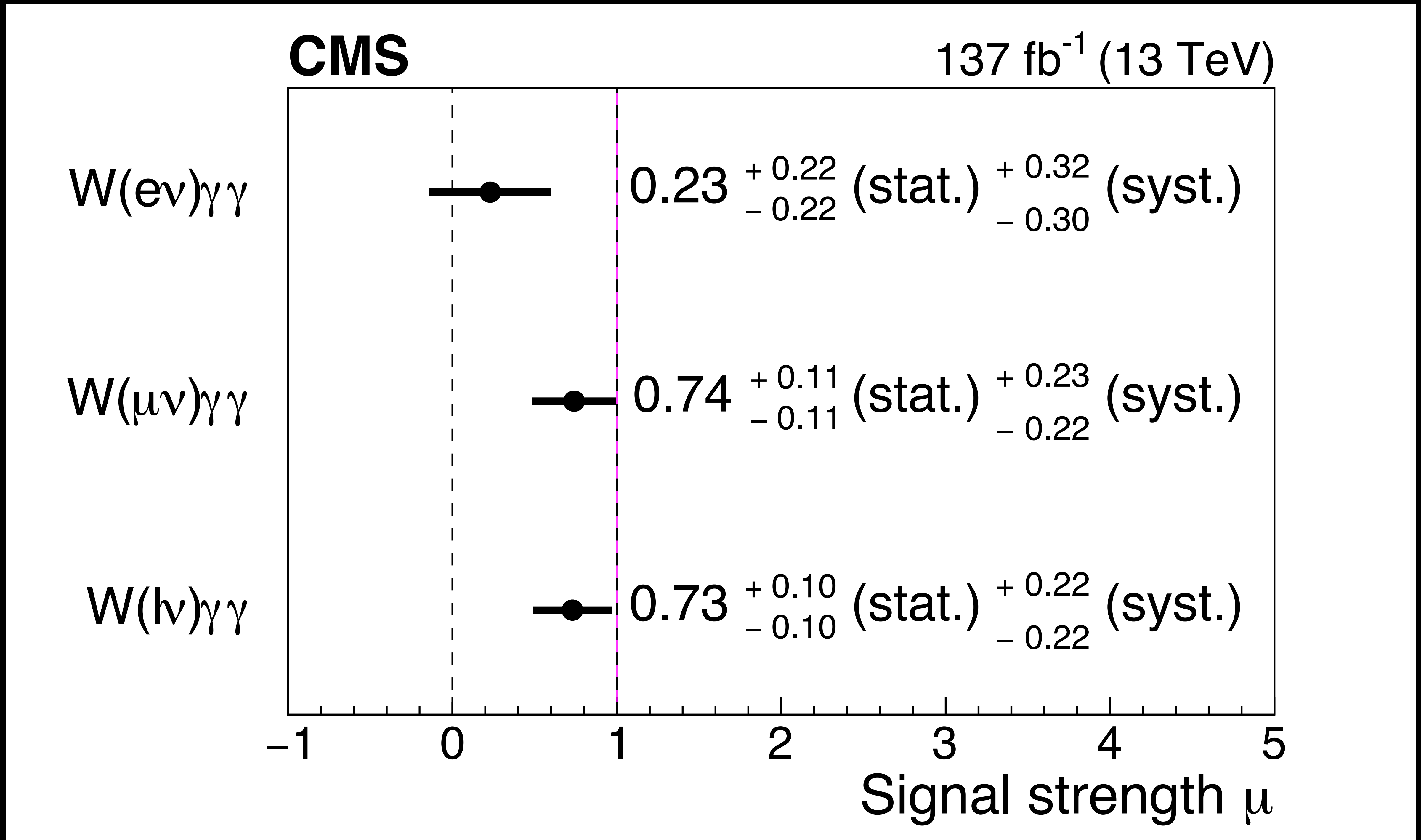
- Binned maximum likelihood fits to the diphoton p_T distribution performed to extract signal strength

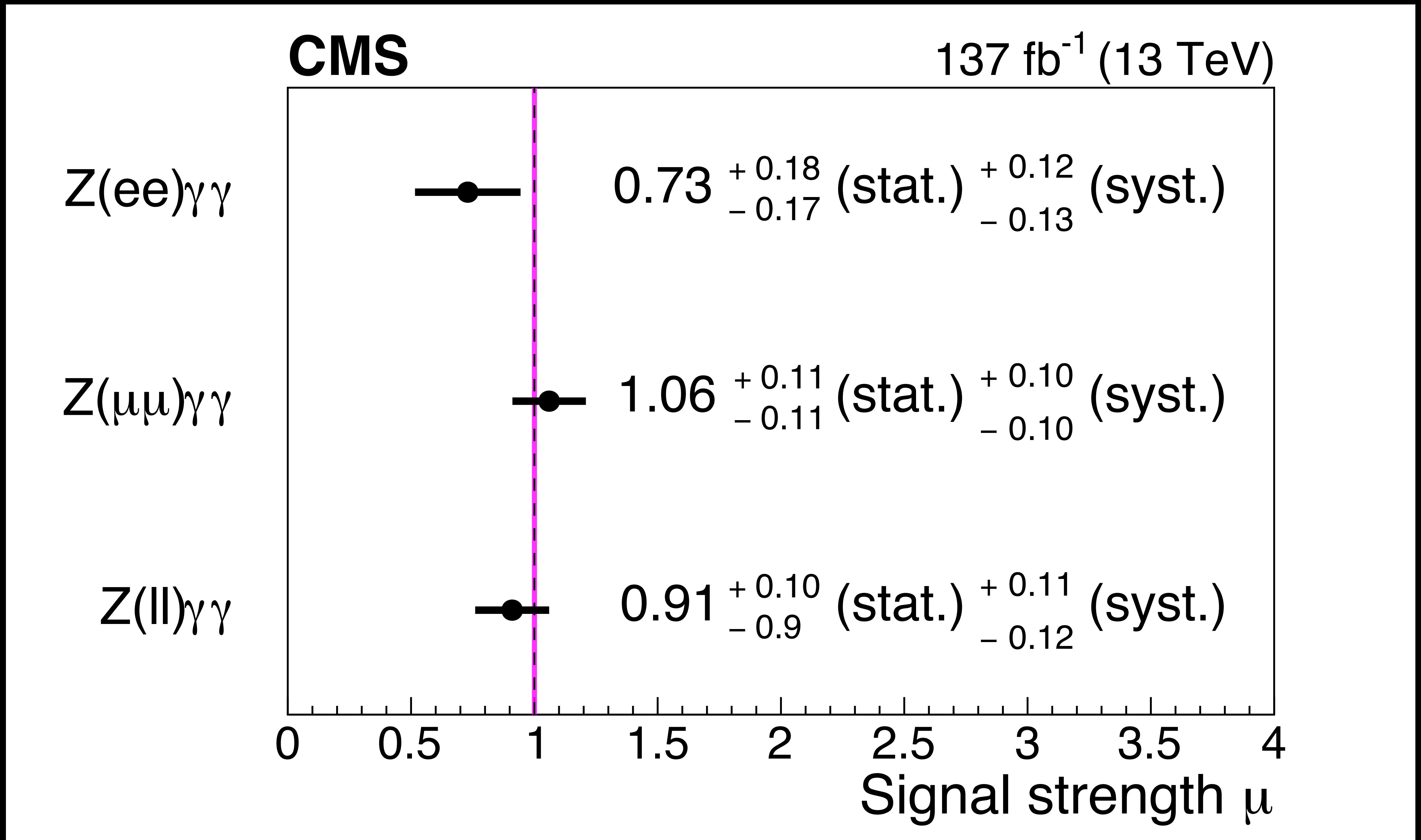
Process	$e\nu_e\gamma\gamma$	$\mu\nu_\mu\gamma\gamma$
Misid. jets	918 ± 23 (stat) ± 180 (syst)	1441 ± 27 (stat) ± 280 (syst)
Misid. electrons	669 ± 28 (stat) ± 34 (syst)	107 ± 9 (stat) ± 7 (syst)
Others	217 ± 11 (stat) ± 20 (syst)	286 ± 11 (stat) ± 25 (syst)
Total backgrounds	1804 ± 38 (stat) ± 180 (syst)	1834 ± 30 (stat) ± 280 (syst)
Expected signal	248 ± 6 (stat) ± 17 (syst)	500 ± 8 (stat) ± 33 (syst)
Total prediction	2052 ± 38 (stat) ± 180 (syst)	2334 ± 31 (stat) ± 280 (syst)
Data	1987	2384

Process	$ee\gamma\gamma$	$\mu\mu\gamma\gamma$
Misid. jets	42 ± 4 (stat) ± 9 (syst)	98 ± 5 (stat) ± 27 (syst)
Others	6 ± 1 (stat) ± 1 (syst)	11 ± 2 (stat) ± 1 (syst)
Total backgrounds	48 ± 4 (stat) ± 9 (syst)	109 ± 6 (stat) ± 27 (syst)
Expected signal	68 ± 2 (stat) ± 5 (syst)	157 ± 3 (stat) ± 11 (syst)
Total prediction	116 ± 4 (stat) ± 8 (syst)	266 ± 6 (stat) ± 23 (syst)
Data	110	272

Measurements of the $W^{\pm}\gamma\gamma$ and $Z\gamma\gamma$

- $\sigma(W\gamma\gamma)^{\text{meas}} = 13.6^{+1.9}_{-1.9}(\text{stat.})^{+4.0}_{-4.0}(\text{syst.}) \pm 0.08\ (\text{PDF} + \text{scale})\ \text{fb}$ Theoretical value: 18.70 ± 0.12 fb
- $\sigma(Z\gamma\gamma)^{\text{meas}} = 5.41^{+0.58}_{-0.55}(\text{stat.})^{+0.64}_{-0.70}(\text{syst.}) \pm 0.06\ (\text{PDF} + \text{scale})\ \text{fb}$ Theoretical value: 5.96 ± 0.06 fb





Measurements of the $W^{\pm}\gamma\gamma$ and $Z\gamma\gamma$

$$\mathscr{L}_{EFT} = \mathscr{L}_{SM} + \sum_i \frac{f_i^8}{\Lambda^4}\mathcal{O}^8$$

Cross section modified as:

$$|\mathscr{M}|^2 = |\mathscr{M}_{SM}|^2 + 2Re(\mathscr{M}^*_{SM}\mathscr{M}_{D-8}) + |\mathscr{M}_{D-8}|^2$$

Pure SM

Interference between SM and BSM

Pure BSM

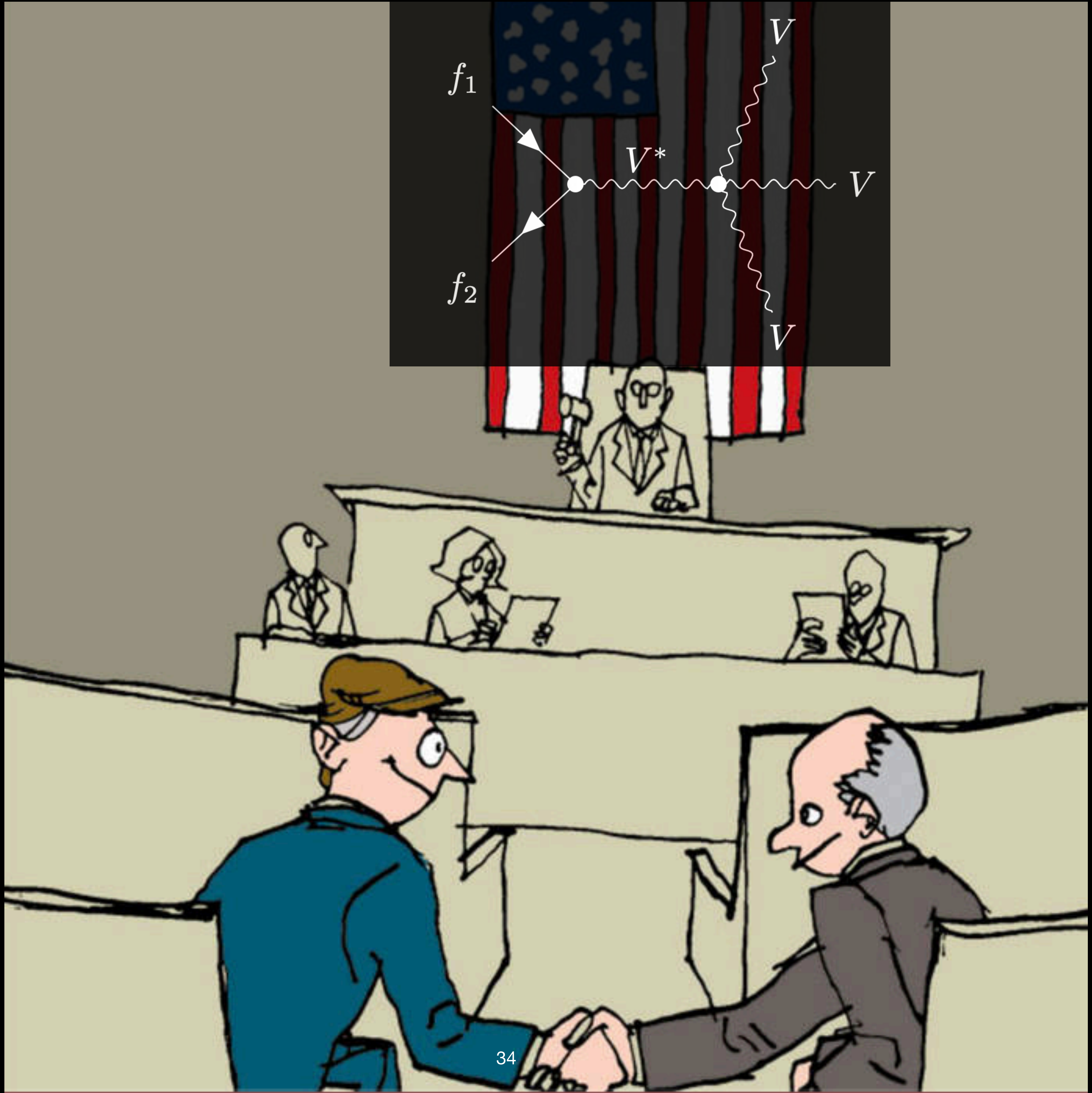
Transverse operators:

- $\mathcal{O}_{T,5} = Tr[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times B_{\alpha\beta}B^{\alpha\beta}$
- $\mathcal{O}_{T,6} = Tr[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times B_{\mu\beta}B^{\alpha\nu}$
- $\mathcal{O}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$
- $\mathcal{O}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$

EFT interpretation in $W^{\pm}\gamma\gamma$ and $Z\gamma\gamma$

Parameter	$W\gamma\gamma$ (TeV^{-4}) Expected	$W\gamma\gamma$ (TeV^{-4}) Observed	$Z\gamma\gamma$ (TeV^{-4}) Expected	$Z\gamma\gamma$ (TeV^{-4}) Observed
f_{M2}/Λ^4	$[-57.3, 57.1]$	$[-39.9, 39.5]$	—	—
f_{M3}/Λ^4	$[-91.8, 92.6]$	$[-63.8, 65.0]$	—	—
f_{T0}/Λ^4	$[-1.86, 1.86]$	$[-1.30, 1.30]$	$[-4.86, 4.66]$	$[-5.70, 5.46]$
f_{T1}/Λ^4	$[-2.38, 2.38]$	$[-1.70, 1.66]$	$[-4.86, 4.66]$	$[-5.70, 5.46]$
f_{T2}/Λ^4	$[-5.16, 5.16]$	$[-3.64, 3.64]$	$[-9.72, 9.32]$	$[-11.4, 10.9]$
f_{T5}/Λ^4	$[-0.76, 0.84]$	$[-0.52, 0.60]$	$[-2.44, 2.52]$	$[-2.92, 2.92]$
f_{T6}/Λ^4	$[-0.92, 1.00]$	$[-0.60, 0.68]$	$[-3.24, 3.24]$	$[-3.80, 3.88]$
f_{T7}/Λ^4	$[-1.64, 1.72]$	$[-1.16, 1.16]$	$[-6.68, 6.60]$	$[-7.88, 7.72]$
f_{T8}/Λ^4	—	—	$[-0.90, 0.94]$	$[-1.06, 1.10]$
f_{T9}/Λ^4	—	—	$[-1.54, 1.54]$	$[-1.82, 1.82]$

Across the aisle

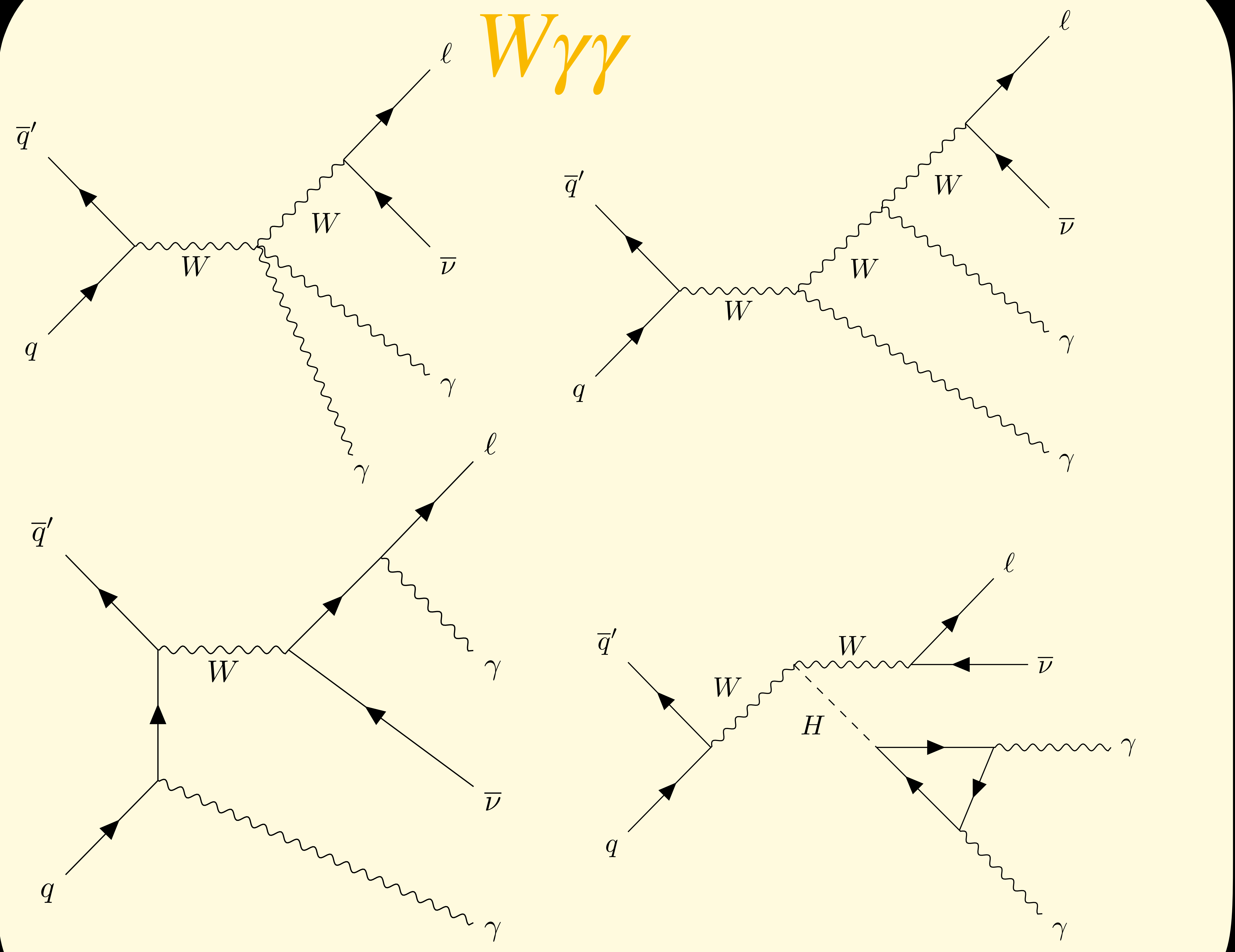


Observation of $W\gamma\gamma$ production at $\sqrt{s} = 13$ TeV

https://arxiv.org/abs/2308.03041

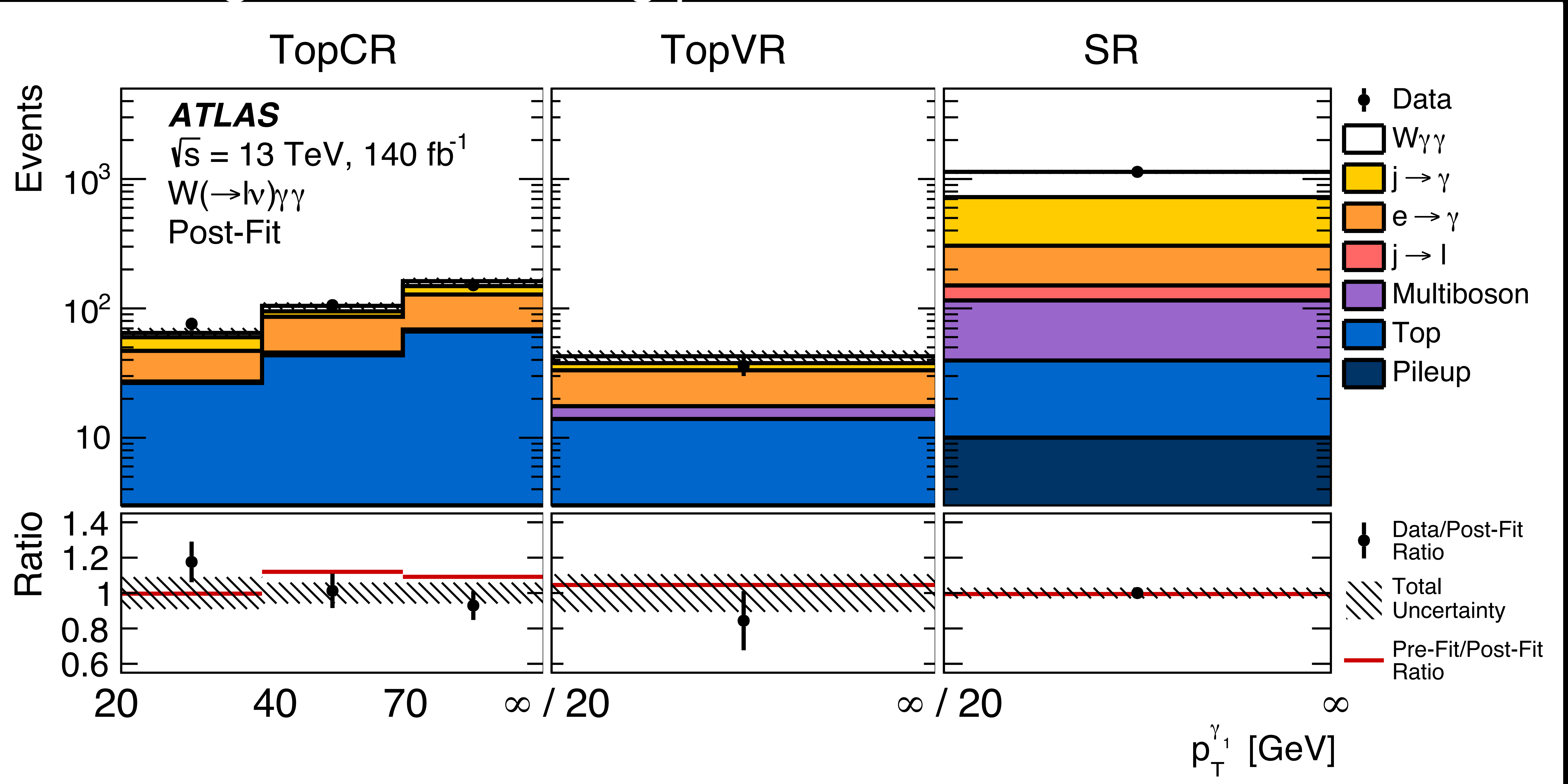
- $W\gamma\gamma$ observed with a significance of 5.6 σ
- Final state: $W \to \ell\nu$ ($\ell = e, \mu$)
- Fiducial cross section:
  - $\sigma_{\text{fid}} = 13.8 \pm 1.1\ (\text{stat.})^{+2.1}_{-2.0}\ (\text{syst.}) \pm 0.1\ (\text{lumi})$ fb
- Largest background from jets that fake a photon ($j \to \gamma$)

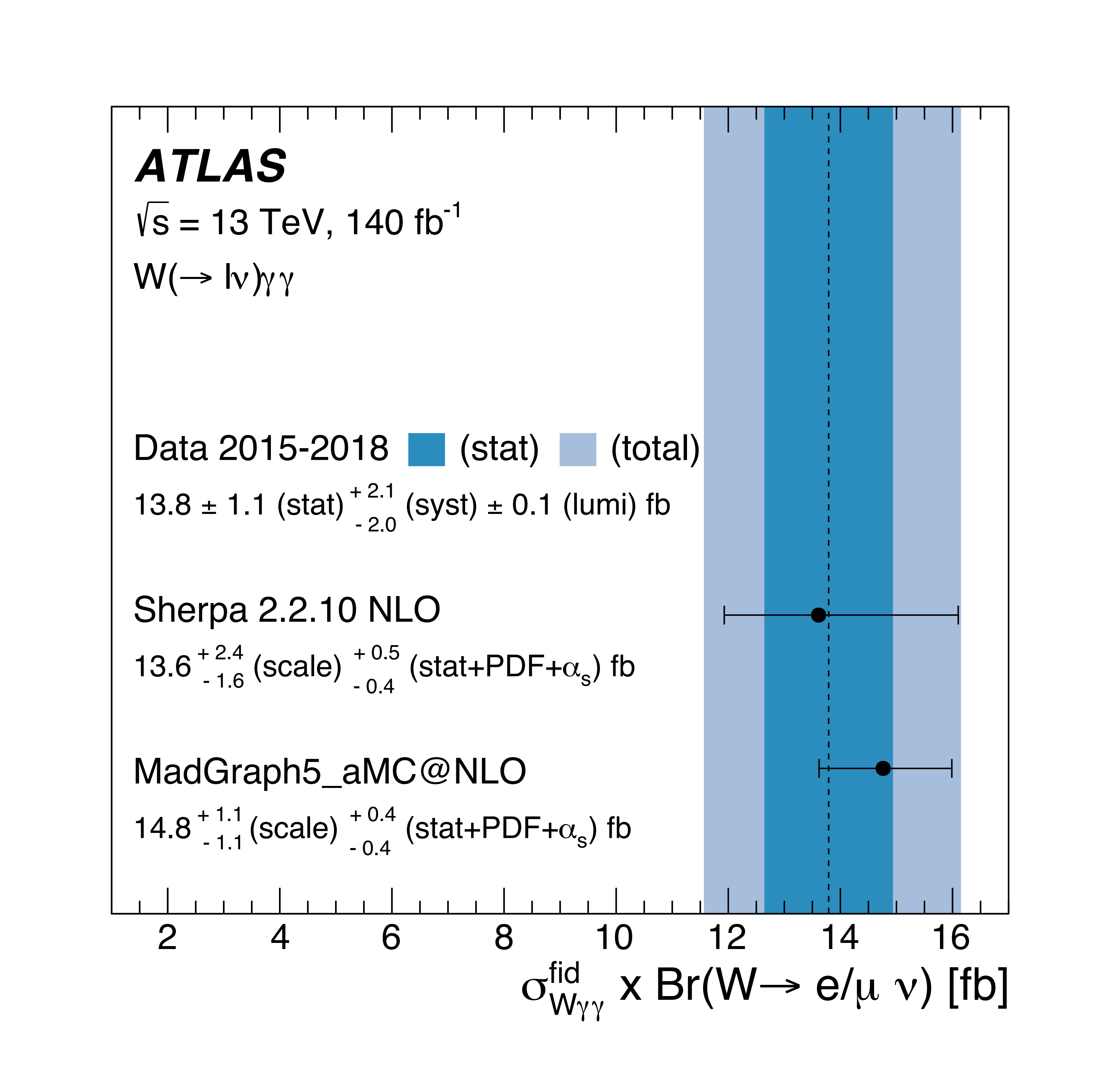
Source	SR	TopCR
$W\gamma\gamma$	410 ± 60	28 ± 5
Non-prompt $j \to \gamma$	420 ± 50	42 ± 20
Misidentified $e \to \gamma$	155 ± 11	120 ± 9
Multiboson ($WH(\gamma\gamma)$, $WW\gamma$, $Z\gamma\gamma$)	76 ± 13	5.2 ± 1.7
Non-prompt $j \to \ell$	35 ± 10	–
Top ($tt\gamma$, $tW\gamma$, $tq\gamma$)	30 ± 7	136 ± 32
Pileup	10 ± 5	–
Total	$1\,136 \pm 34$	332 ± 18
Data	$1\,136$	333



Observation of $W\gamma\gamma$ production at $\sqrt{s} = 13$ TeV

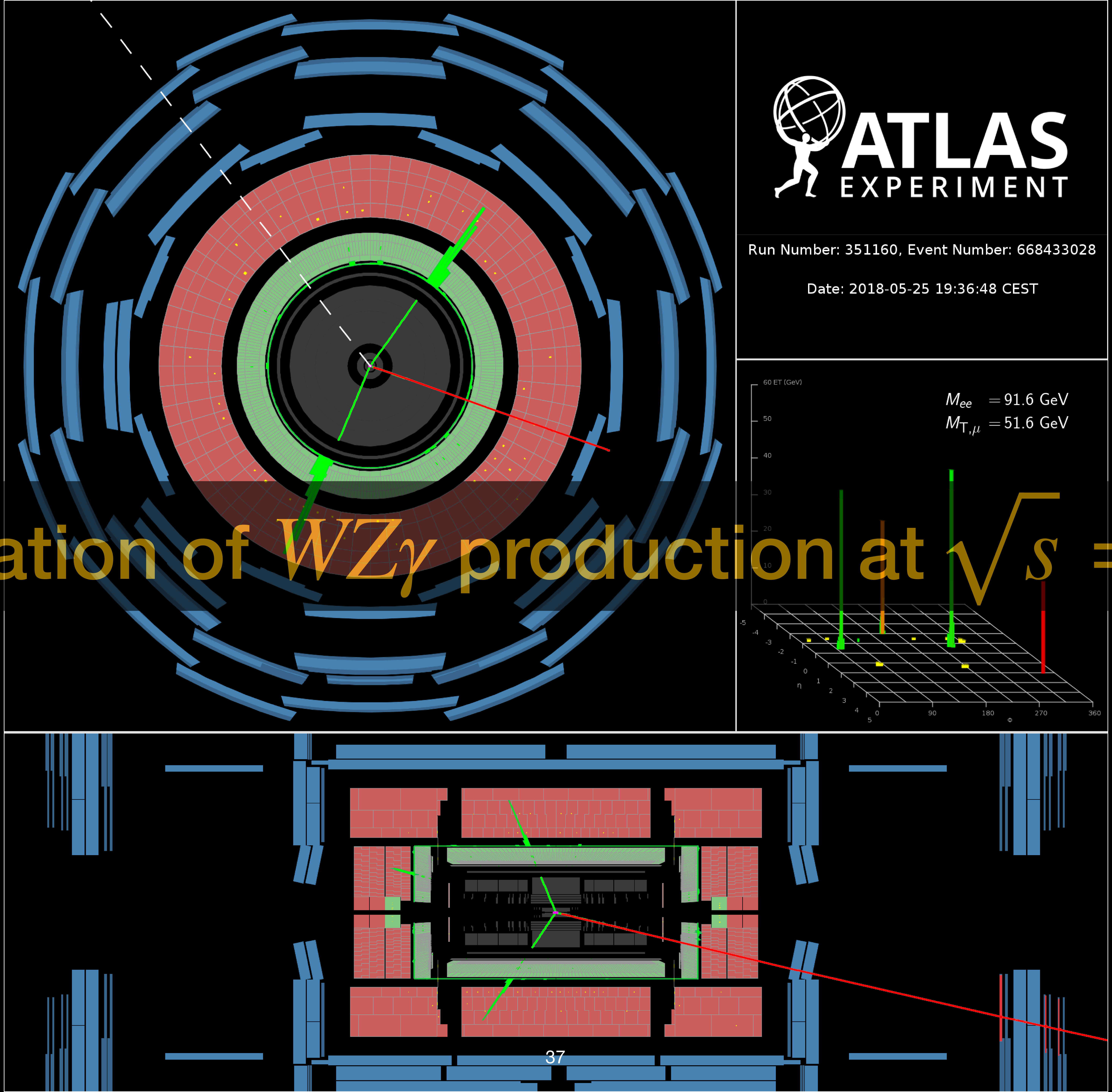
- Final state: $W \to \ell\nu$ ($\ell = e, \mu$)
- Largest background from jets that fake a photon ($j \to \gamma$)
- Estimated using data-driven method by performing a two-dimensional template fit to the leading and sub-leading photon isolation distributions





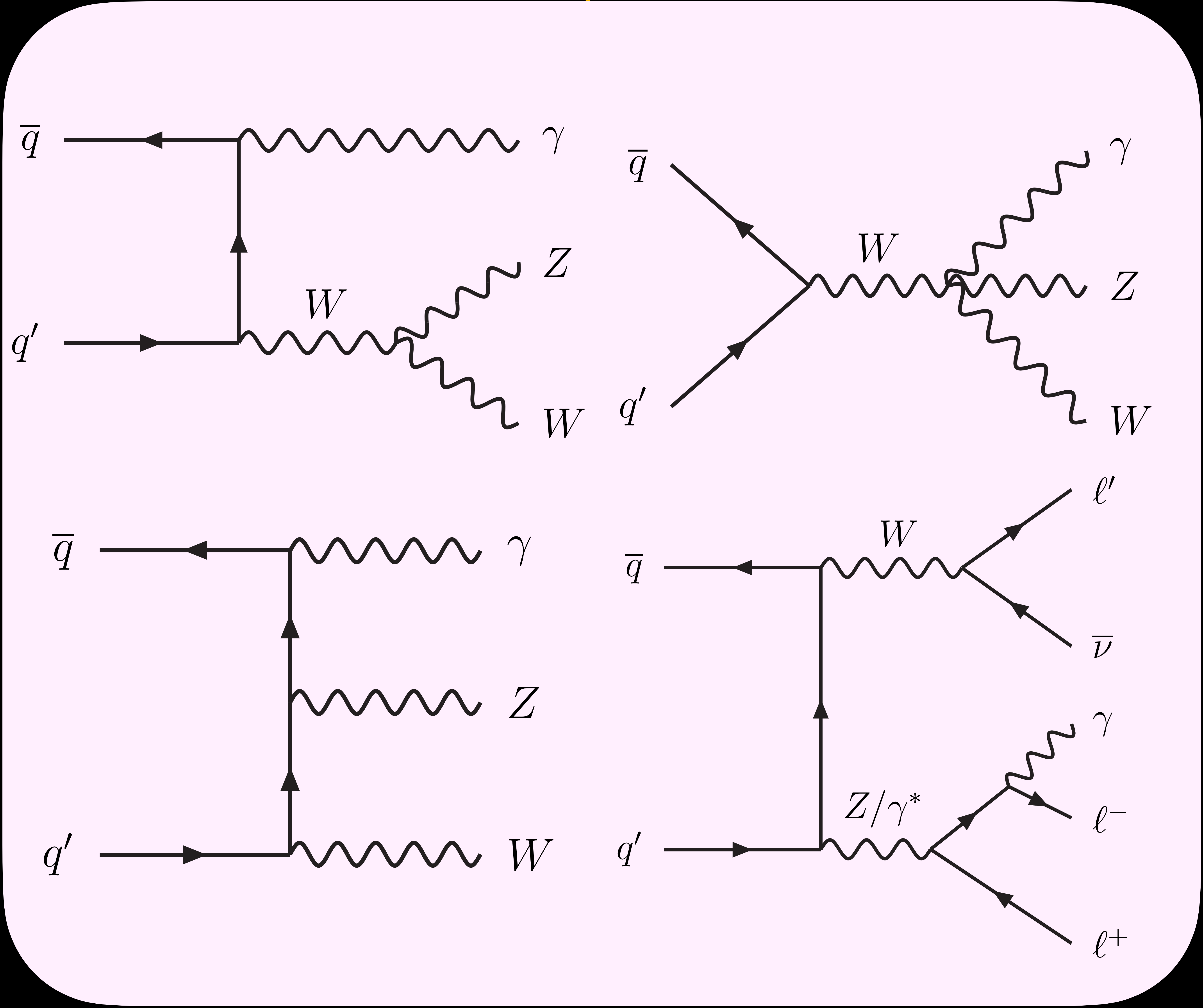
NLO electroweak corrections included

Observation of $WZ\gamma$ production at $\sqrt{s} = 13$ TeV



Observation of $WZ\gamma$ production at $\sqrt{s} = 13$ TeV

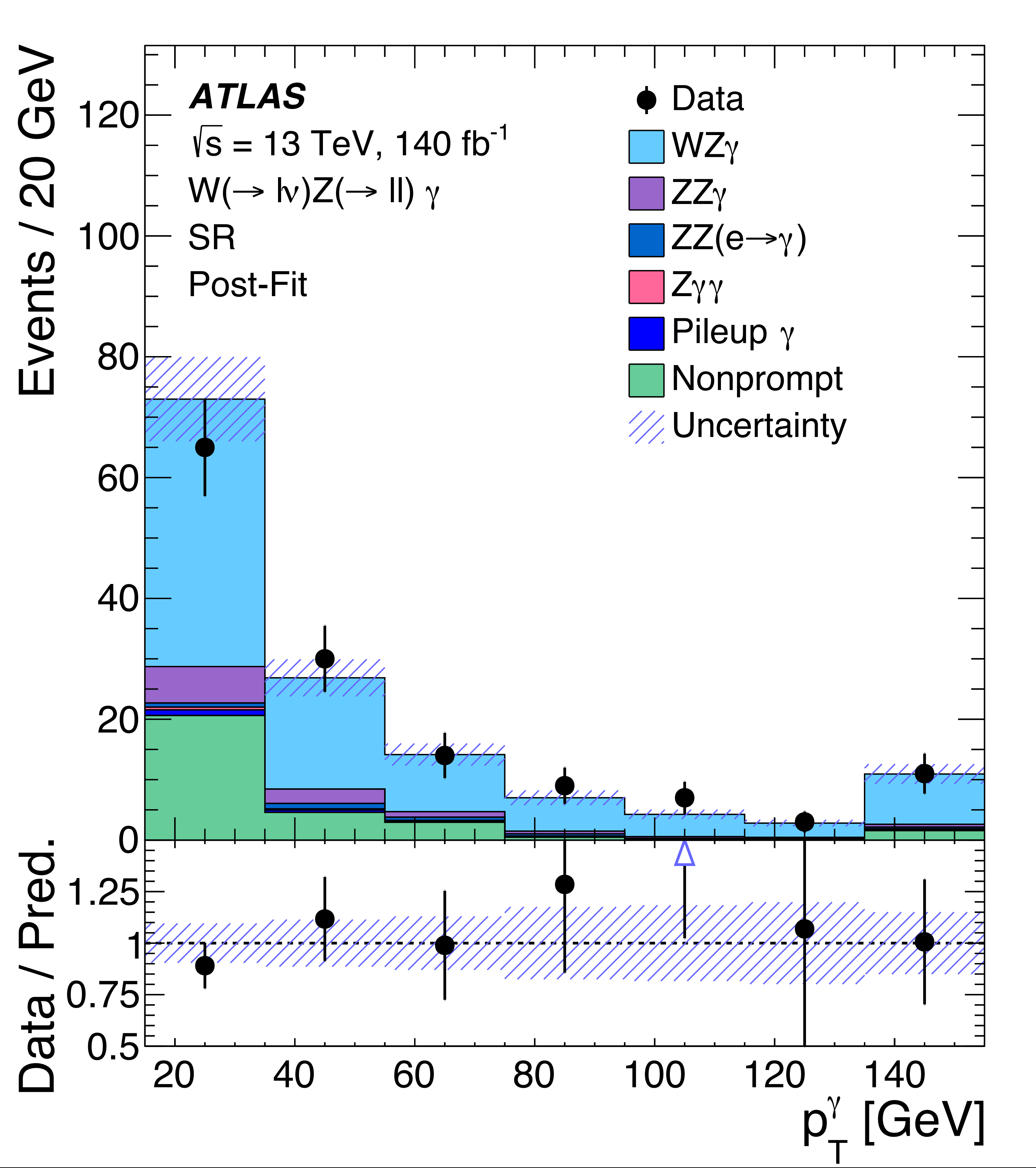
- Final state: $W \to \ell\nu,\ Z \to \ell^+\ell^-$ ($\ell = e, \mu$)
- $WZ\gamma$ observed with a significance of 6.3 σ
- Cross section (fiducial):
    - 2.01 ± 0.30 (stat.) ± 0.16 (syst.) fb
- $K_{\mathrm{EW}} = \sigma_{\mathrm{fid.}}^{\mathrm{NLO\ EW}}/\sigma_{\mathrm{fid.}}^{\mathrm{LO}} = 1.05$
- Fiducial region defined by isolated leptons ($p_T^{\ell} > 30$ GeV) and photons at high p_T ($p_T^{\gamma} > 15$ GeV)
- Backgrounds arise from non-prompt photons and leptons

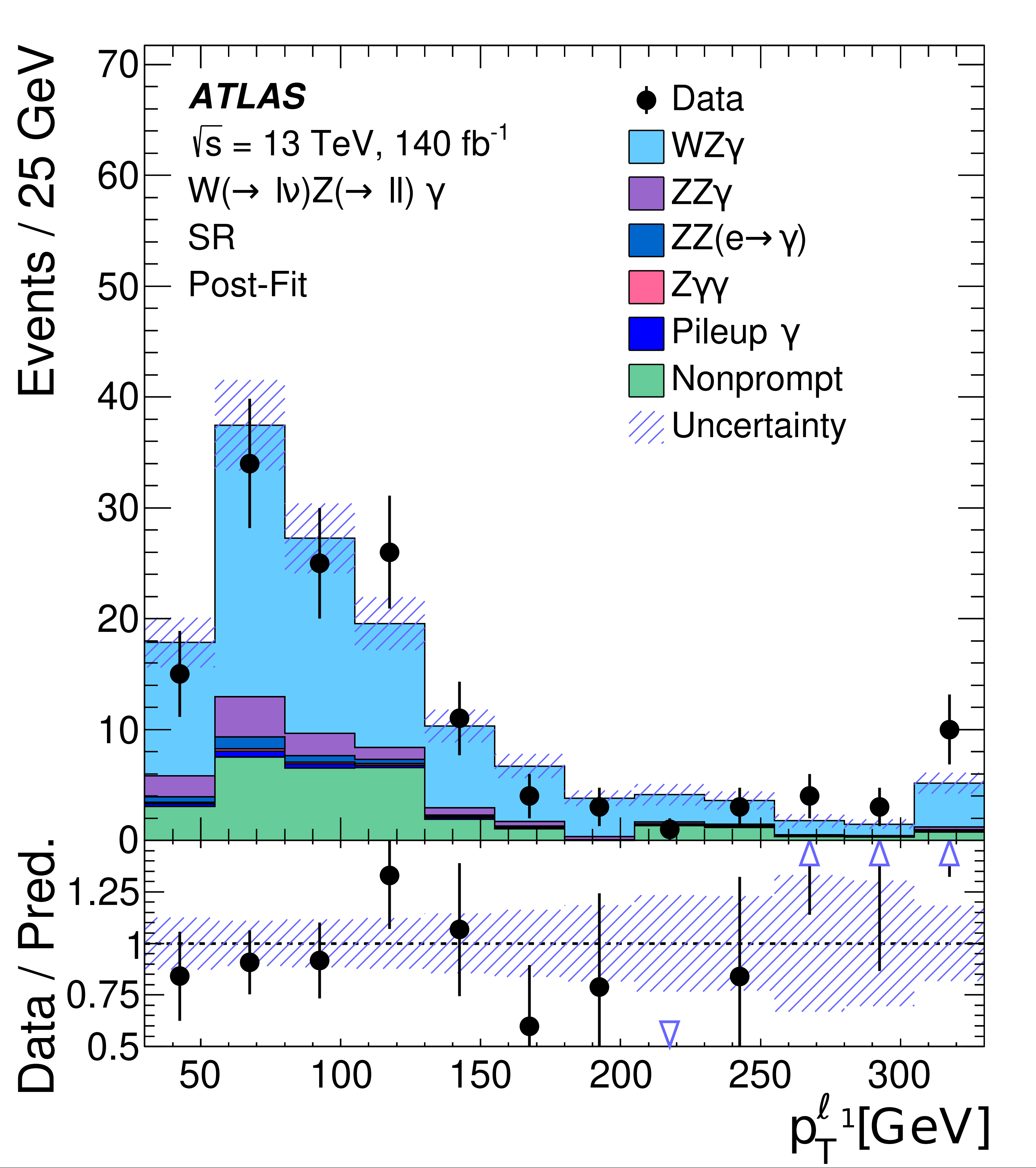


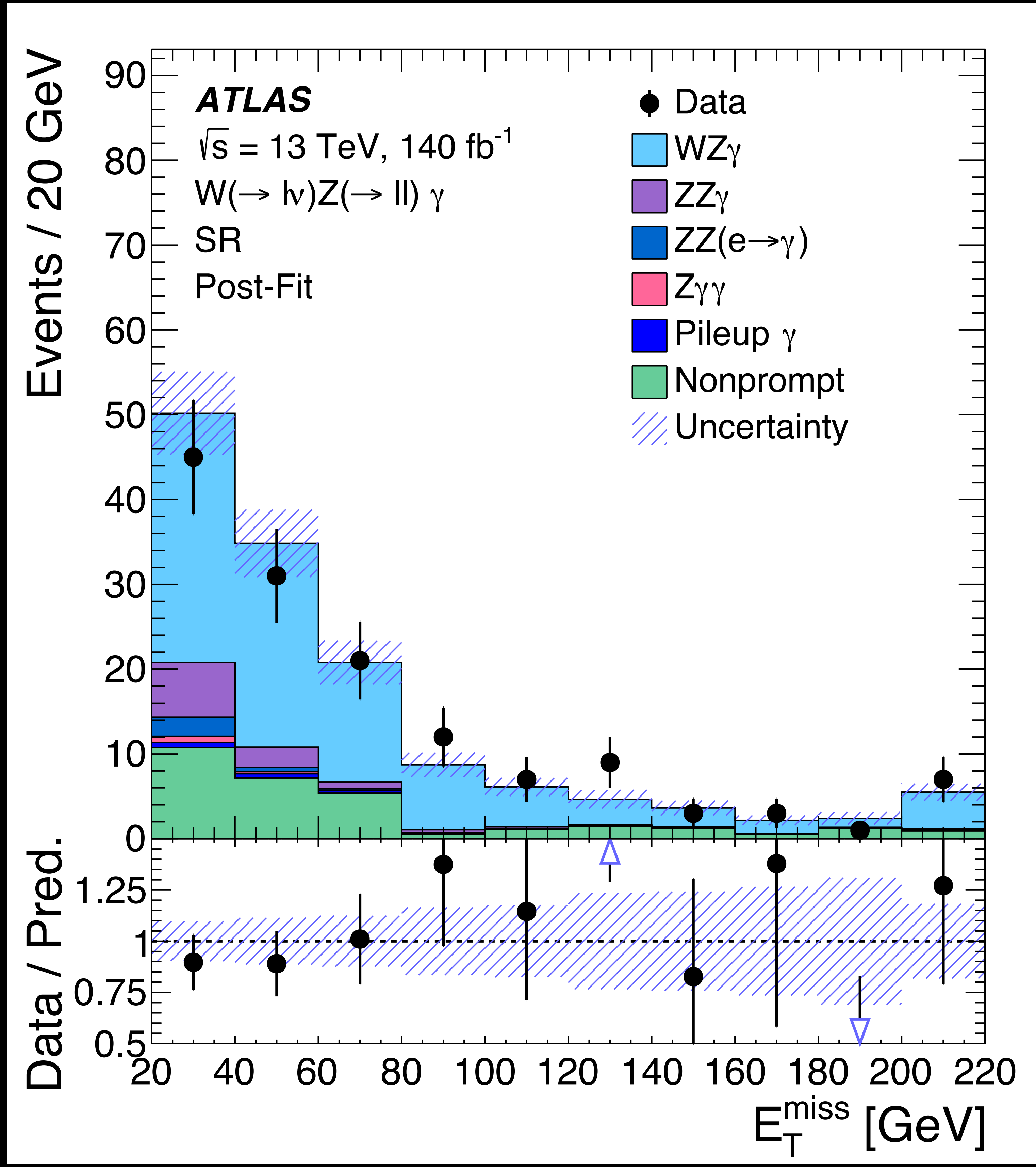
https://arxiv.org/abs/2305.16994

Observation of $WZ\gamma$ production at $\sqrt{s} = 13$ TeV

- Clean final state with large number of signal events with respect to the background contributions







Conclusion

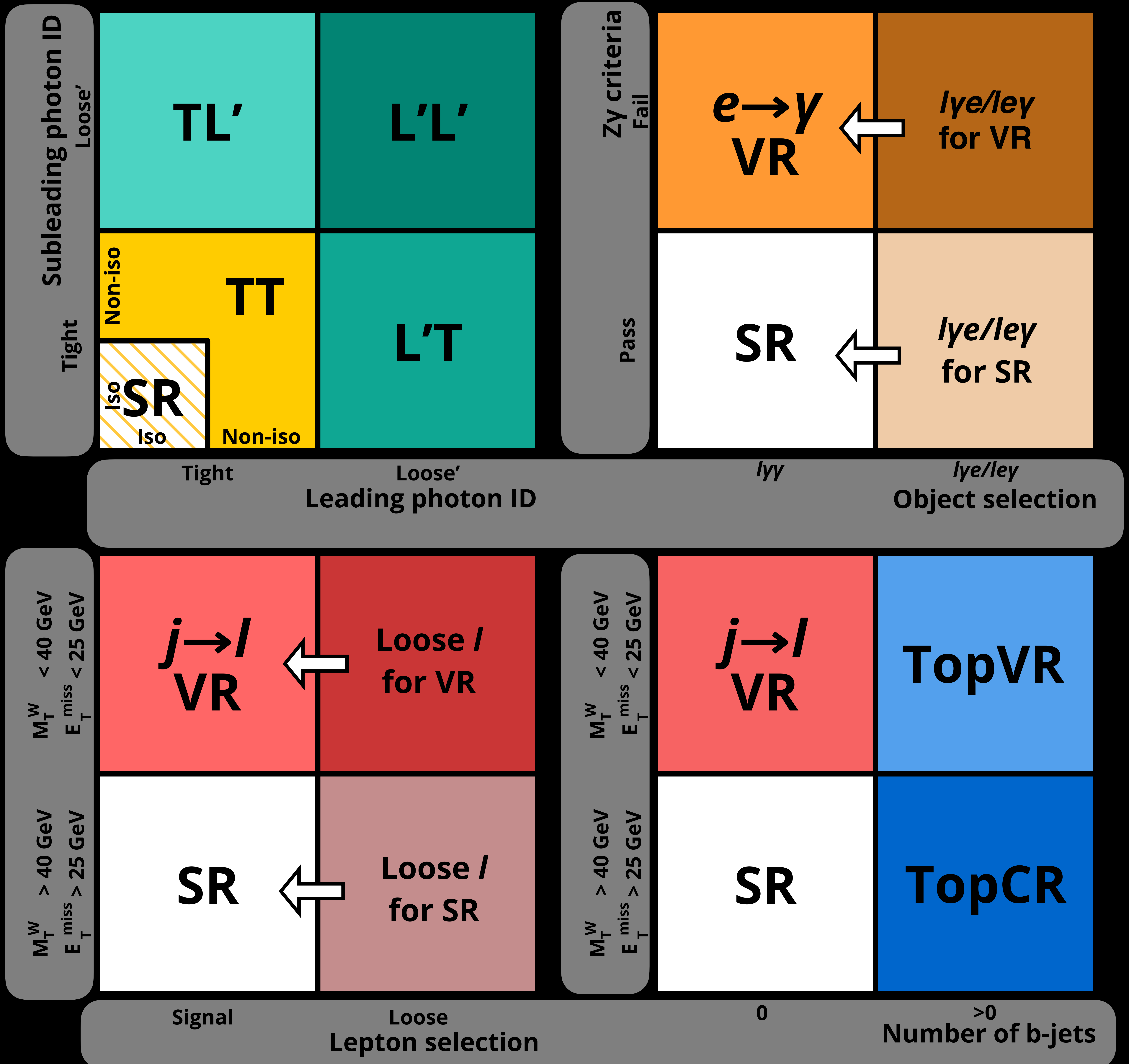
- Both ATLAS and CMS have a comprehensive multiboson program, spanning several processes, across orders of magnitude in cross section, allowing us to probe exotic couplings in the Standard Model
- Only covered most recent results from ATLAS ($Z\gamma\gamma$ and WWW are impressive)
- Discussions on
  - electroweak corrections
  - interference with the Higgs-mediated mode and the quartic and trilinear modes are important

Additional Material

Basis of Dimension-8 operators

- Proposed by Eboli et al. (hep-ph/0606118)
- Three classes of operators
  - Scalar
    - $\mathcal{O}_{S,0} = [(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\mu\Phi)^\dagger D^\nu\Phi]$
    - $\mathcal{O}_{S,1} = [(D_\mu\Phi)^\dagger D^\mu\Phi] \times [(D_\nu\Phi)^\dagger D^\nu\Phi]$
    - $\mathcal{O}_{S,2} = [(D_\mu\Phi)^\dagger D_\nu\Phi] \times [(D^\nu\Phi)^\dagger D^\mu\Phi]$
- Mixed
  - $\mathcal{O}_{M,0} = Tr[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi]$
  - $\mathcal{O}_{M,1} = Tr[\hat{W}_{\mu\nu}\hat{W}^{\nu\beta}] \times [(D_\beta\Phi)^\dagger D^\mu\Phi]$
  - $\mathcal{O}_{M,2} = [B_{\mu\nu}B^{\mu\nu}] \times [(D_\beta\Phi)^\dagger D^\beta\Phi]$
  - $\mathcal{O}_{M,3} = [B_{\mu\nu}B^{\nu\beta}] \times [(D_\beta\Phi)^\dagger D^\mu\Phi]$
  - $\mathcal{O}_{M,4} = [(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\mu\Phi] \times B^{\beta\nu}$
  - $\mathcal{O}_{M,5} = [(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu} D^\nu\Phi] \times B^{\beta\mu} + H.c.$
  - $\mathcal{O}_{M,7} = [(D_\mu\Phi)^\dagger \hat{W}_{\beta\nu}\hat{W}^{\beta\mu} D^\nu\Phi]$
- Transverse
  - $\mathcal{O}_{T,0} = Tr[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times Tr[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}]$
  - $\mathcal{O}_{T,1} = Tr[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times Tr[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}]$
  - $\mathcal{O}_{T,2} = Tr[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}] \times Tr[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}]$
  - $\mathcal{O}_{T,3} = Tr[\hat{W}_{\mu\nu}\hat{W}_{\alpha\beta}] \times Tr[\hat{W}^{\alpha\nu}\hat{W}^{\mu\beta}]$
  - $\mathcal{O}_{T,4} = Tr[\hat{W}_{\mu\nu}\hat{W}_{\alpha\beta}] \times B^{\alpha\nu}B^{\mu\beta}$
  - $\mathcal{O}_{T,5} = Tr[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] \times B_{\alpha\beta}B^{\alpha\beta}$
  - $\mathcal{O}_{T,6} = Tr[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}] \times B_{\mu\beta}B^{\alpha\nu}$
  - $\mathcal{O}_{T,7} = Tr[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}] \times B_{\beta\nu}B^{\nu\alpha}$
  - $\mathcal{O}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$
  - $\mathcal{O}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$

Definition of control regions



Pernicious backgrounds

- The WZ background:
  - Contributes when one of the leptons fails to pass the minimum pT threshold in the analysis
  - Referred to as a “lost lepton” background

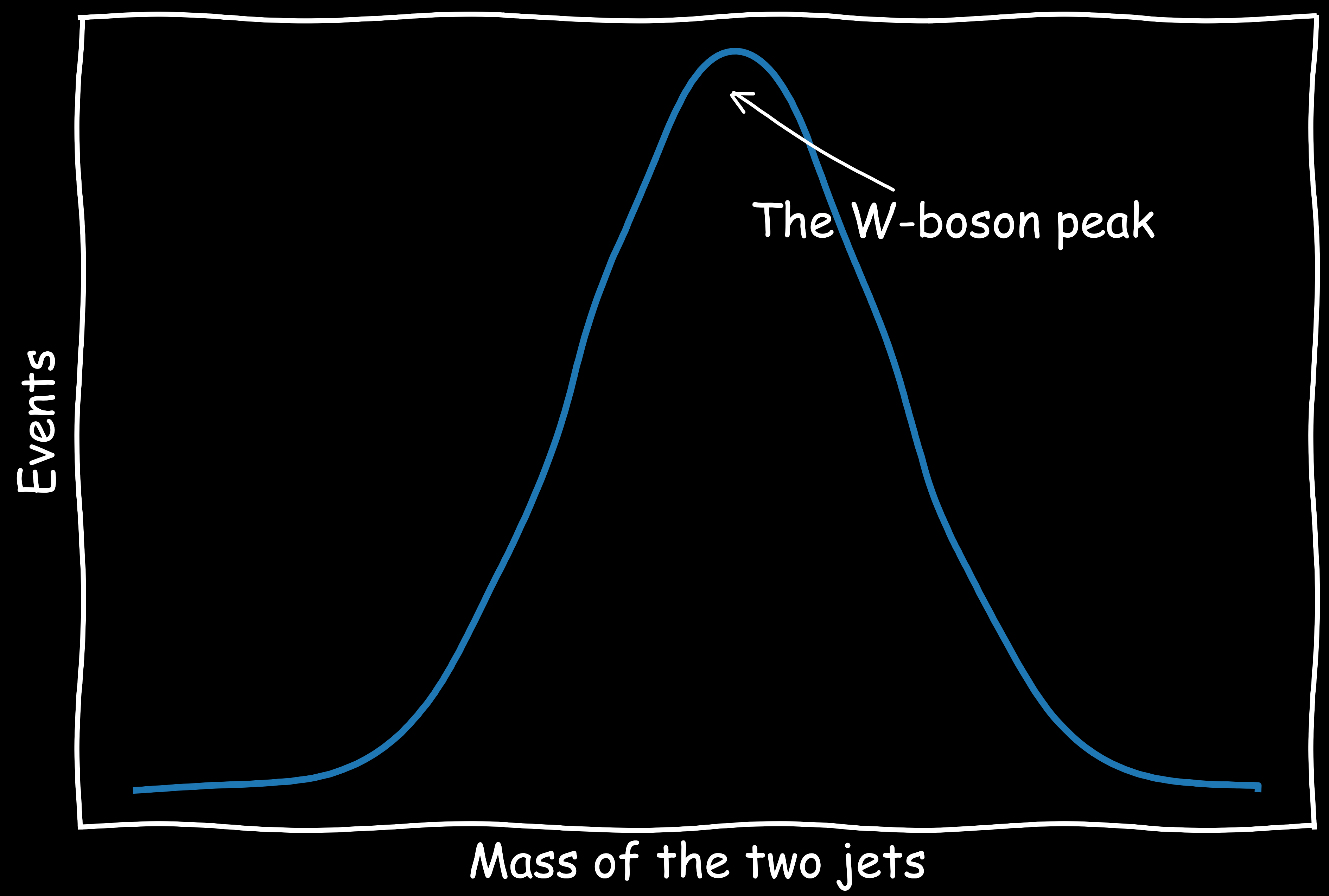
$$W^{\pm}Z \longrightarrow \ell^{\pm}\nu\,\ell^{\pm}\ell^{\mp}$$

$$W^{\mp}\,W^{\pm}\,W^{\pm} \longrightarrow q\;\bar{q}\;l^{\pm}\;\nu\;l^{\pm}\;\nu$$

Interesting variables?

$$W^{\mp}\, W^{\pm}\, W^{\pm} \longrightarrow q\, \bar{q}' \ell^{\pm}\, \nu\, \ell^{\pm}\, \nu$$

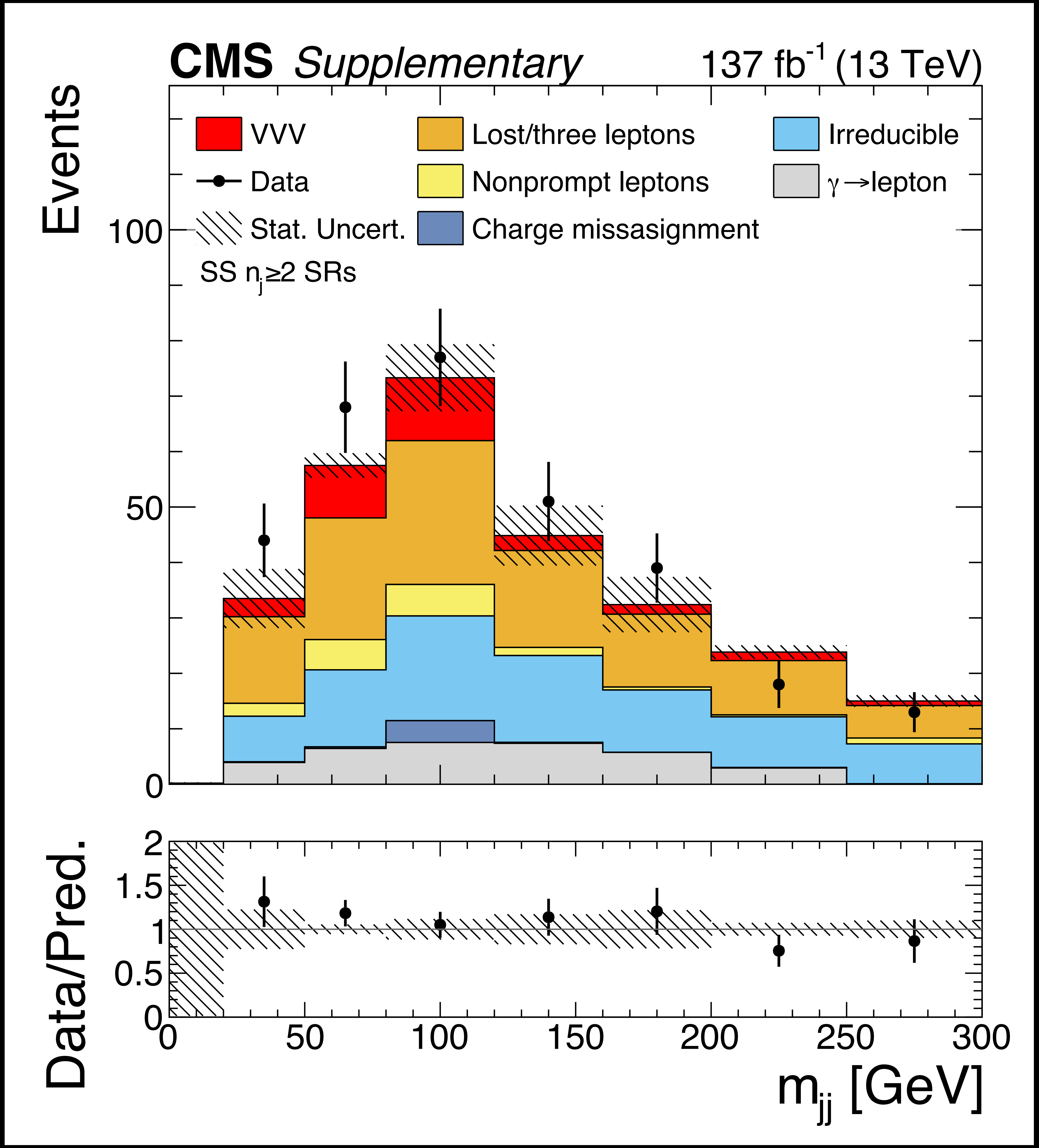
- An event category can be constructed by requiring that 2 identically charged leptons be present
- Require that mass of the jets (emerging from $q\ \bar{q}'$) is consistent with arising from a W-boson



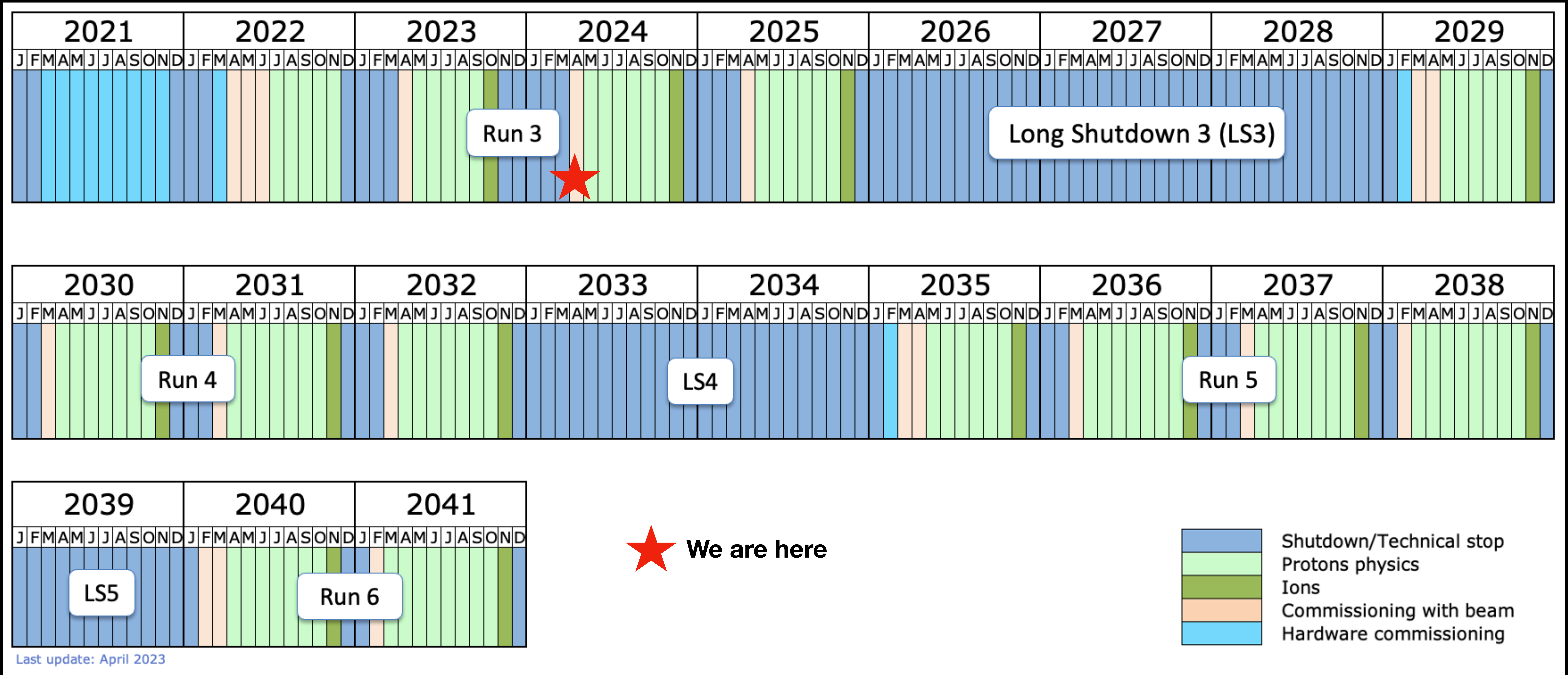
The most interesting distribution

Backgrounds (processes)

- WZ (lost leptons)
- $t\bar{t}$ (non prompt)
- $W^{\pm}W^{\pm}jj$
- $W^{\pm}\gamma$
- Z+jets



The LHC will dominate the collider spectrum till 2040!

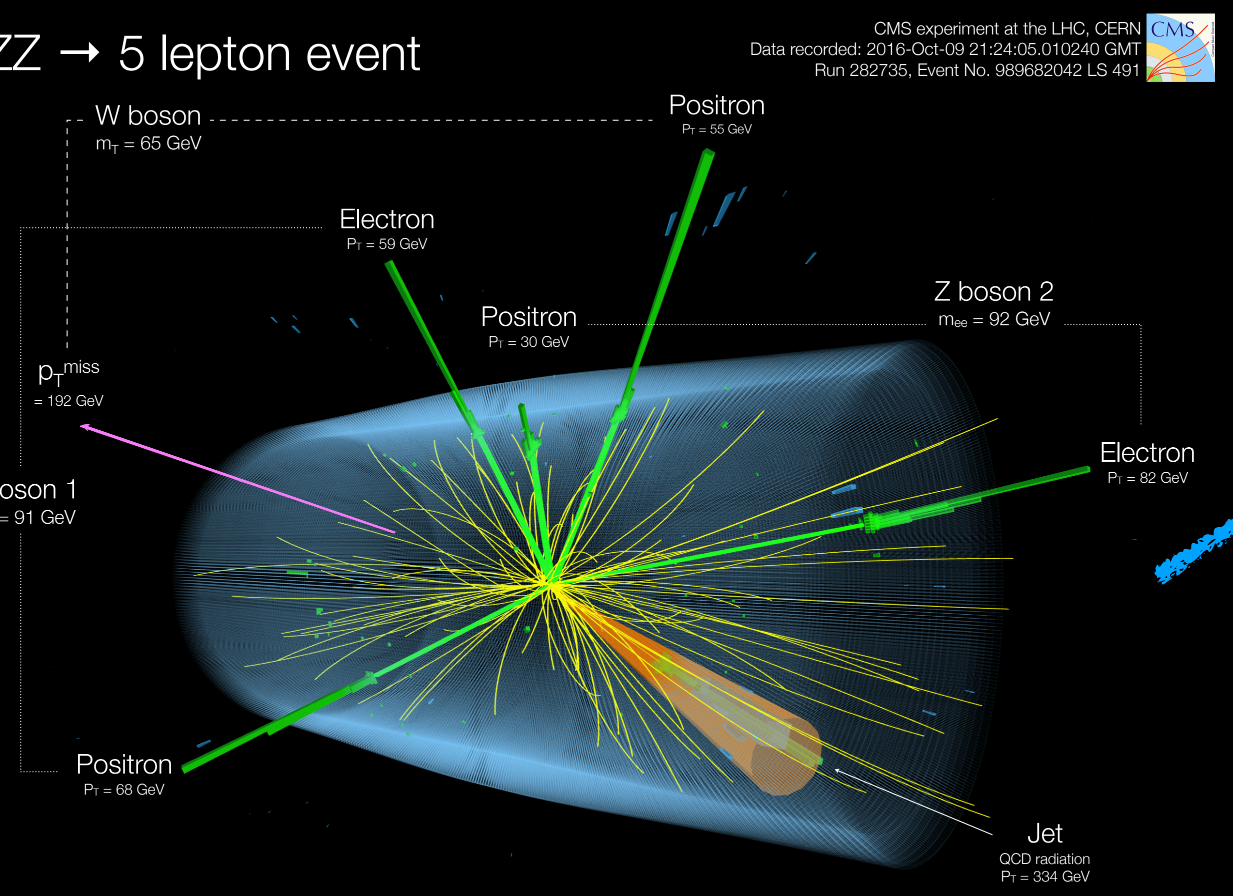


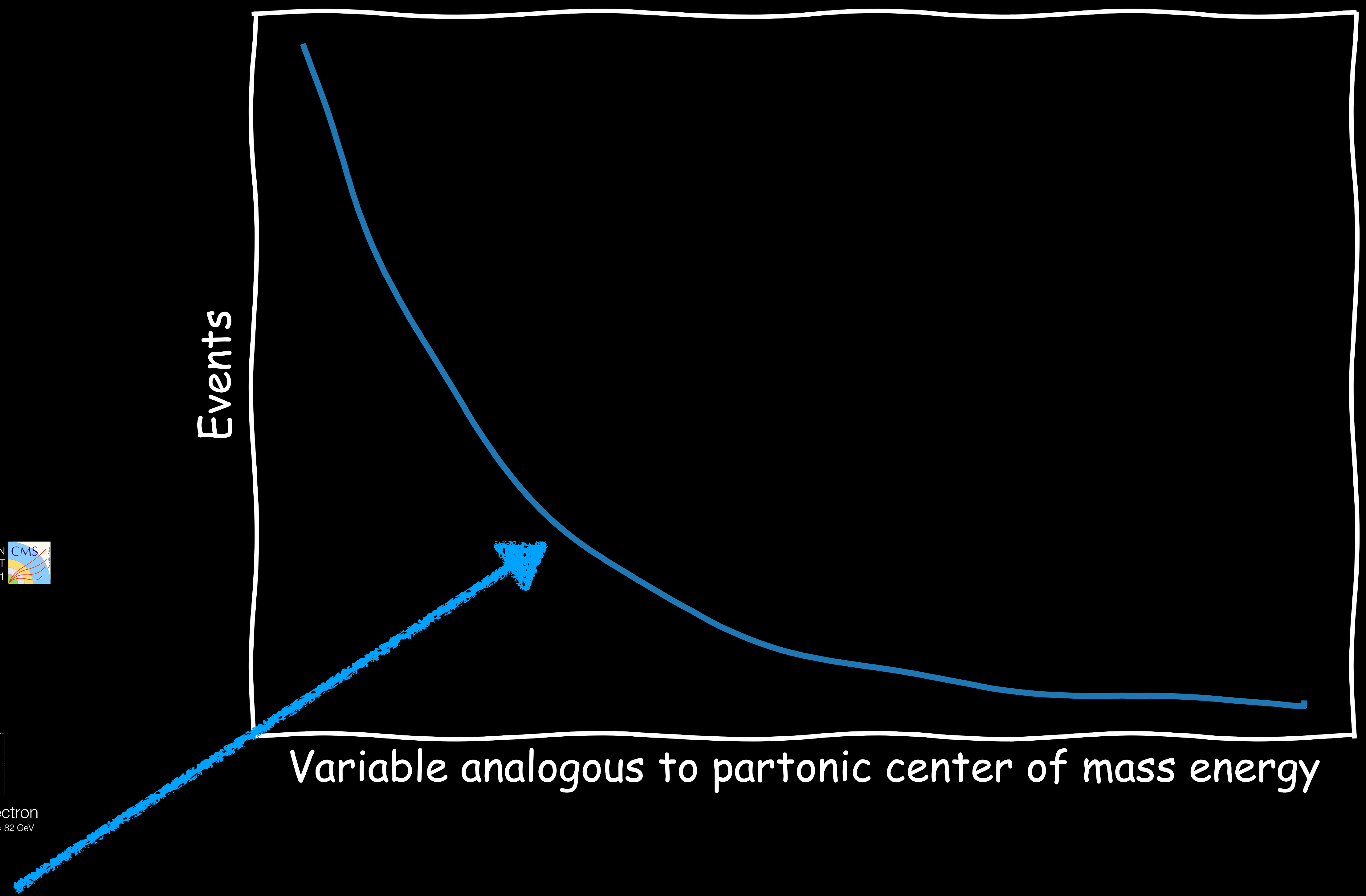
- Run 3 commenced in mid-2022
- Collect 2x data, by 2042: more than 20x data

Radiation damage foreseen that will necessitate the replacement of the endcap detectors CMS-TDR-019

Exploring new physics with tribosons

WZZ → 5 lepton event

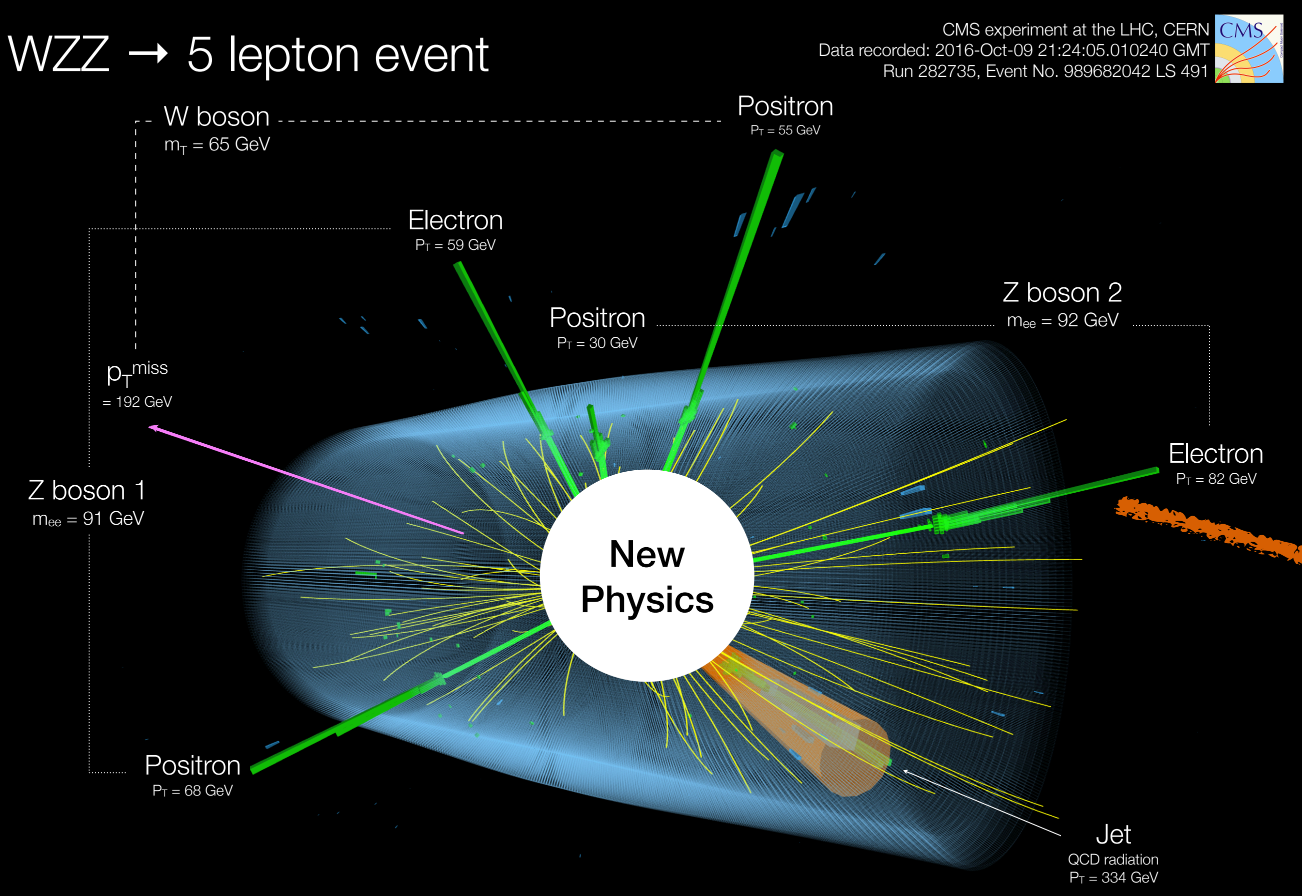




Sum of energy = 0.9 TeV

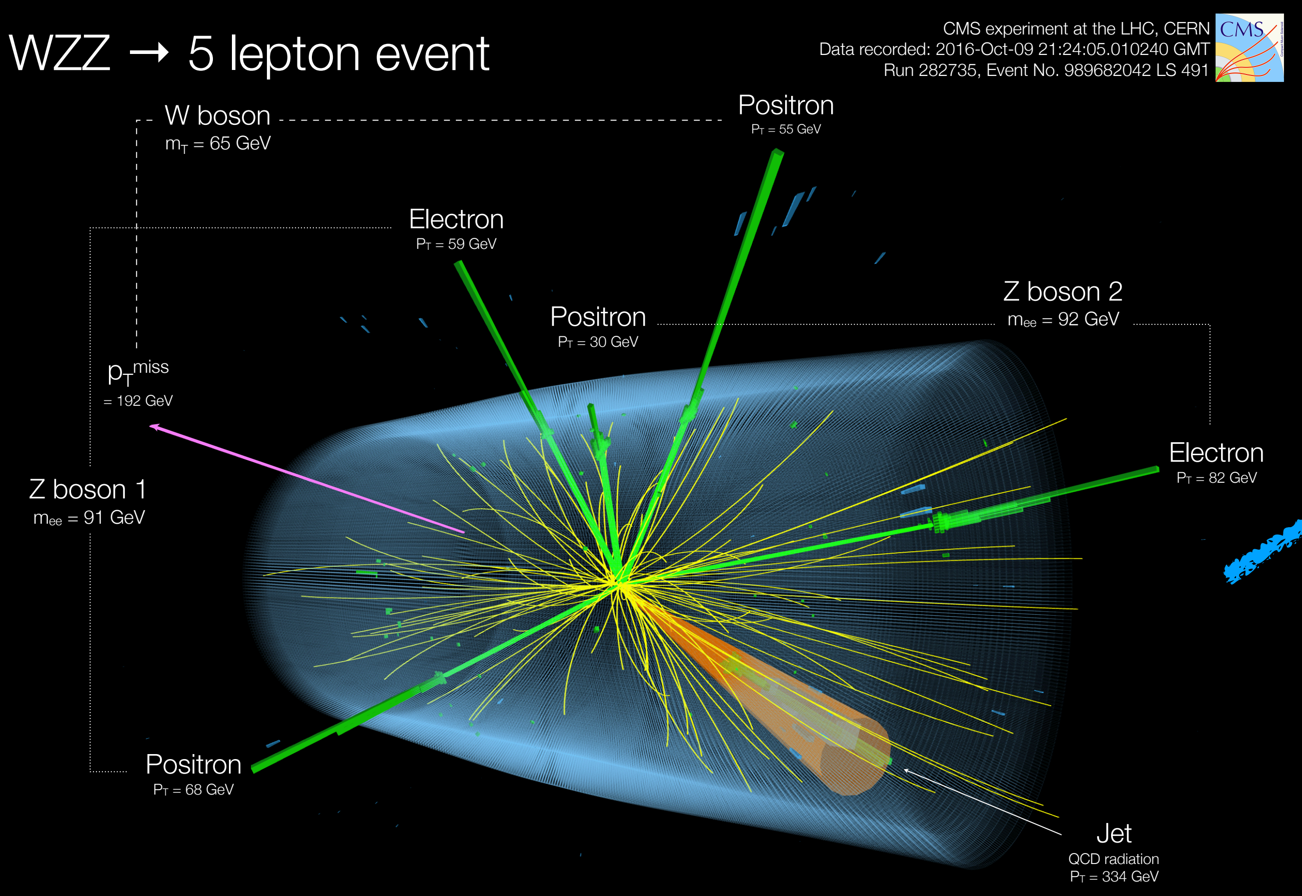
Exploring new physics with tribosons

WZZ → 5 lepton event

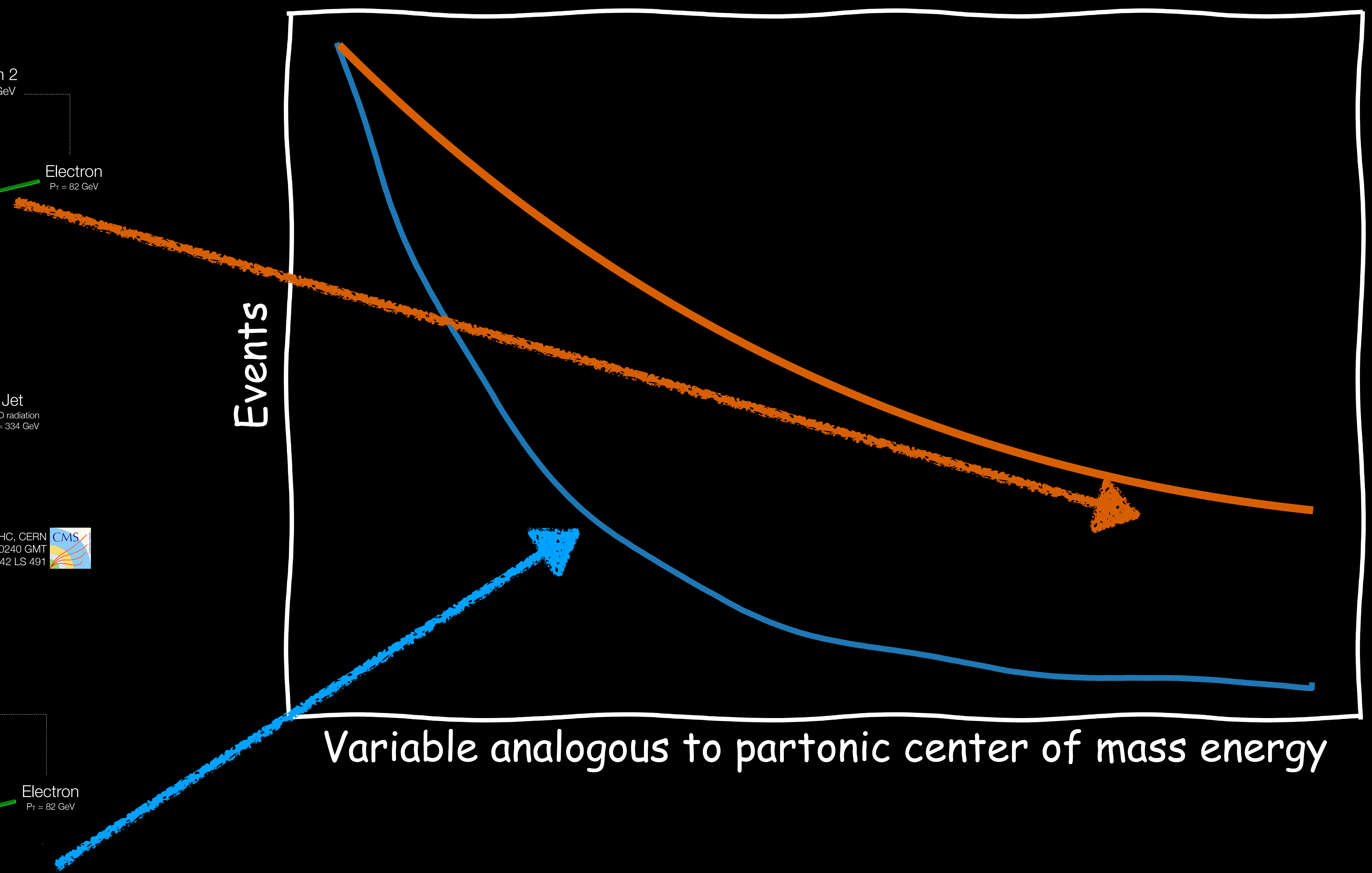


Sum of energy ≫ 0.9 TeV

WZZ → 5 lepton event



Sum of energy = 0.9 TeV

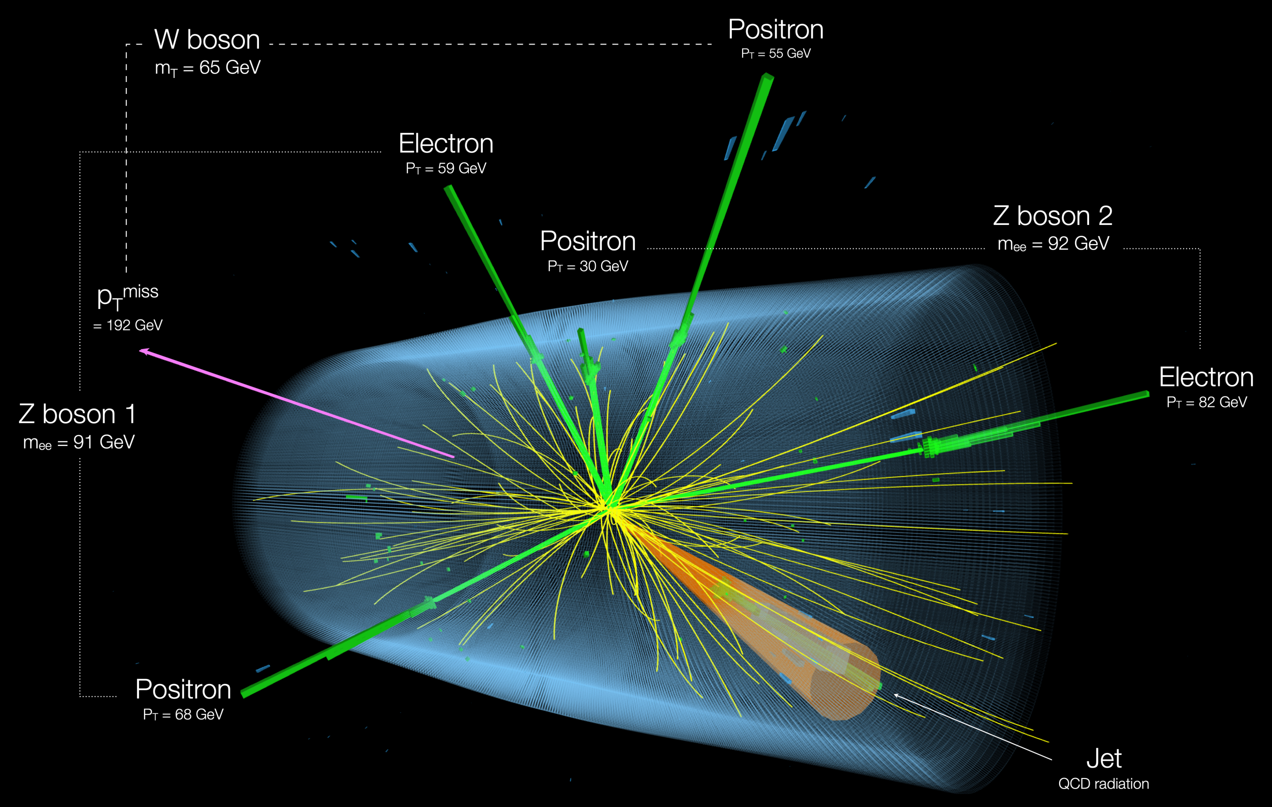


Expect to see an excess in tails of distributions

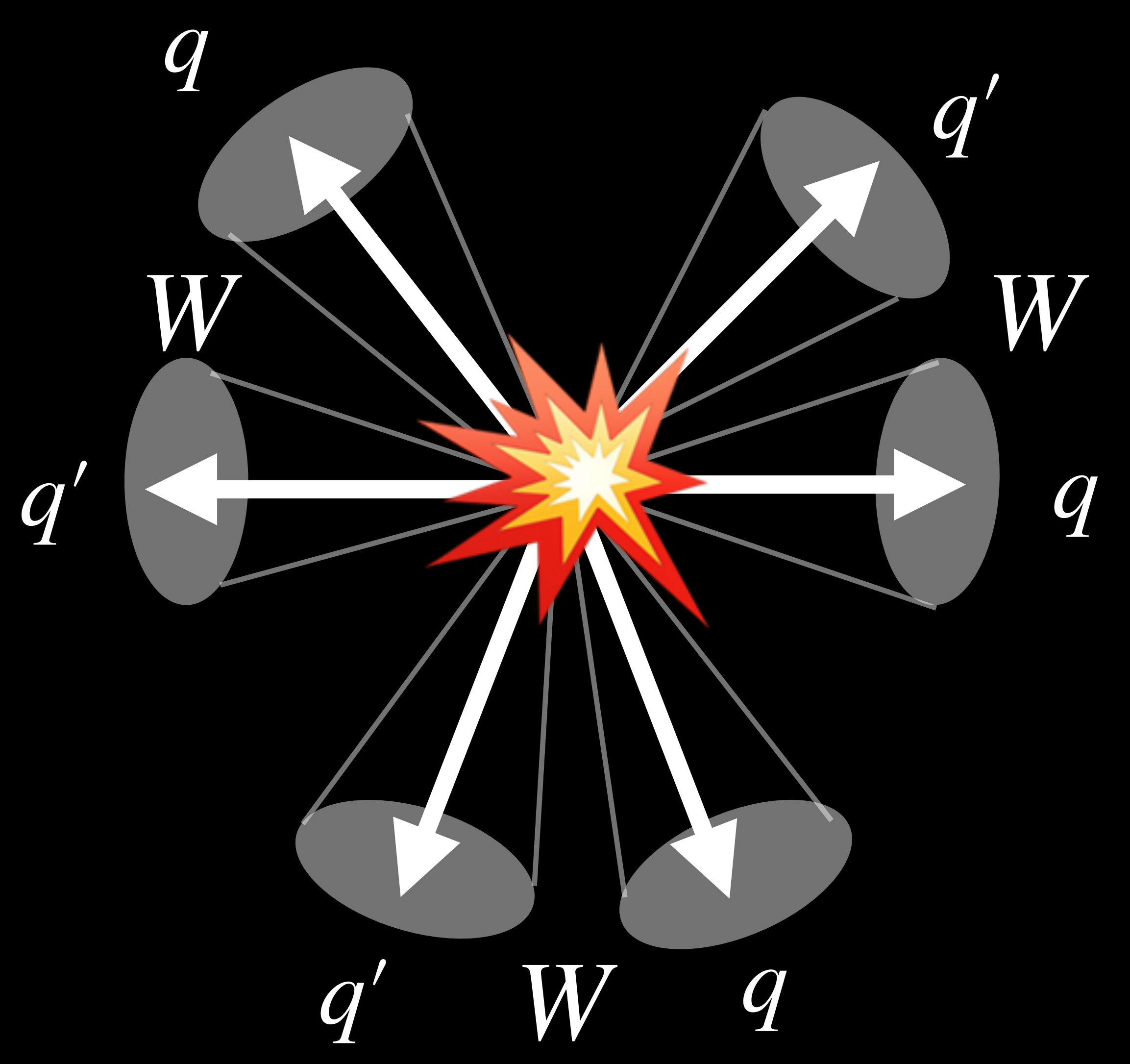
Exploring new physics with tribosons

- **Look for appearance of new physics indirectly in the interactions of the gauge bosons**

Standard Model:



Sum of energy = 0.9 TeV



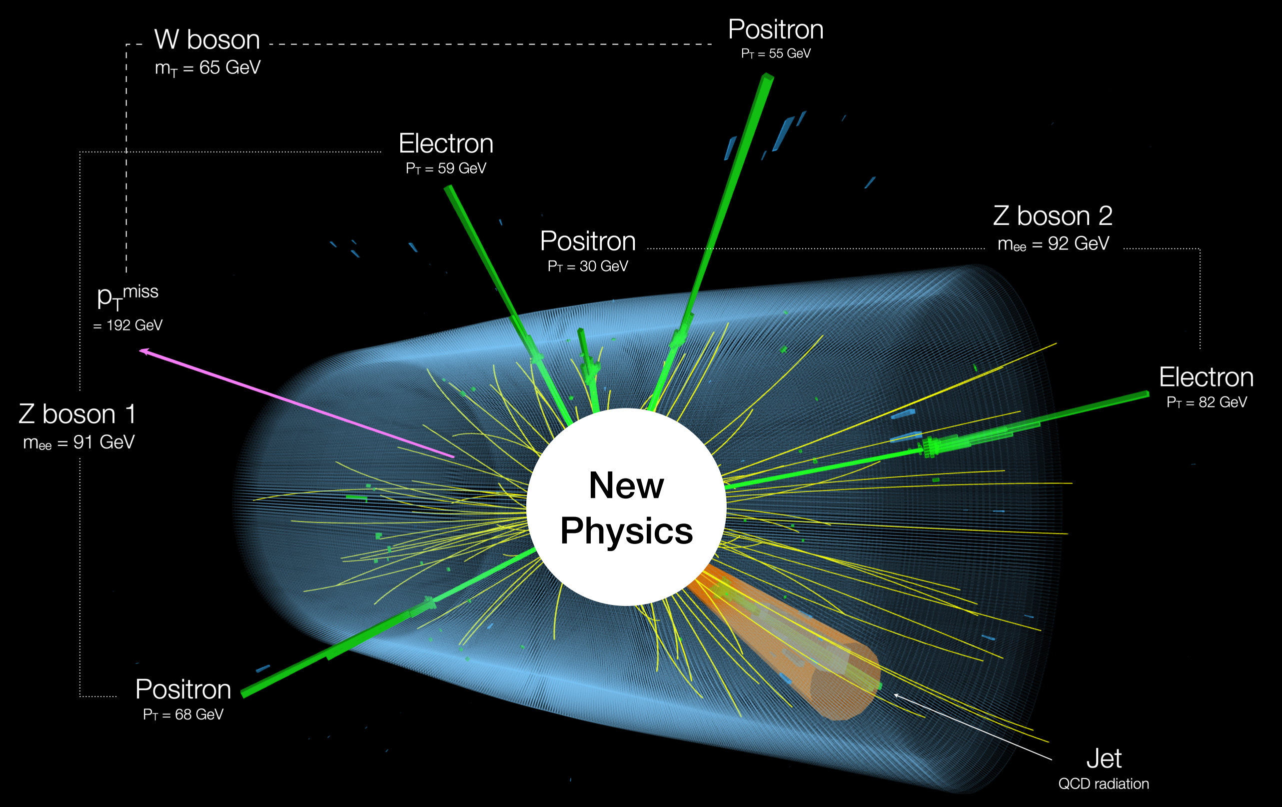
Standard model production

W-decay products are resolved

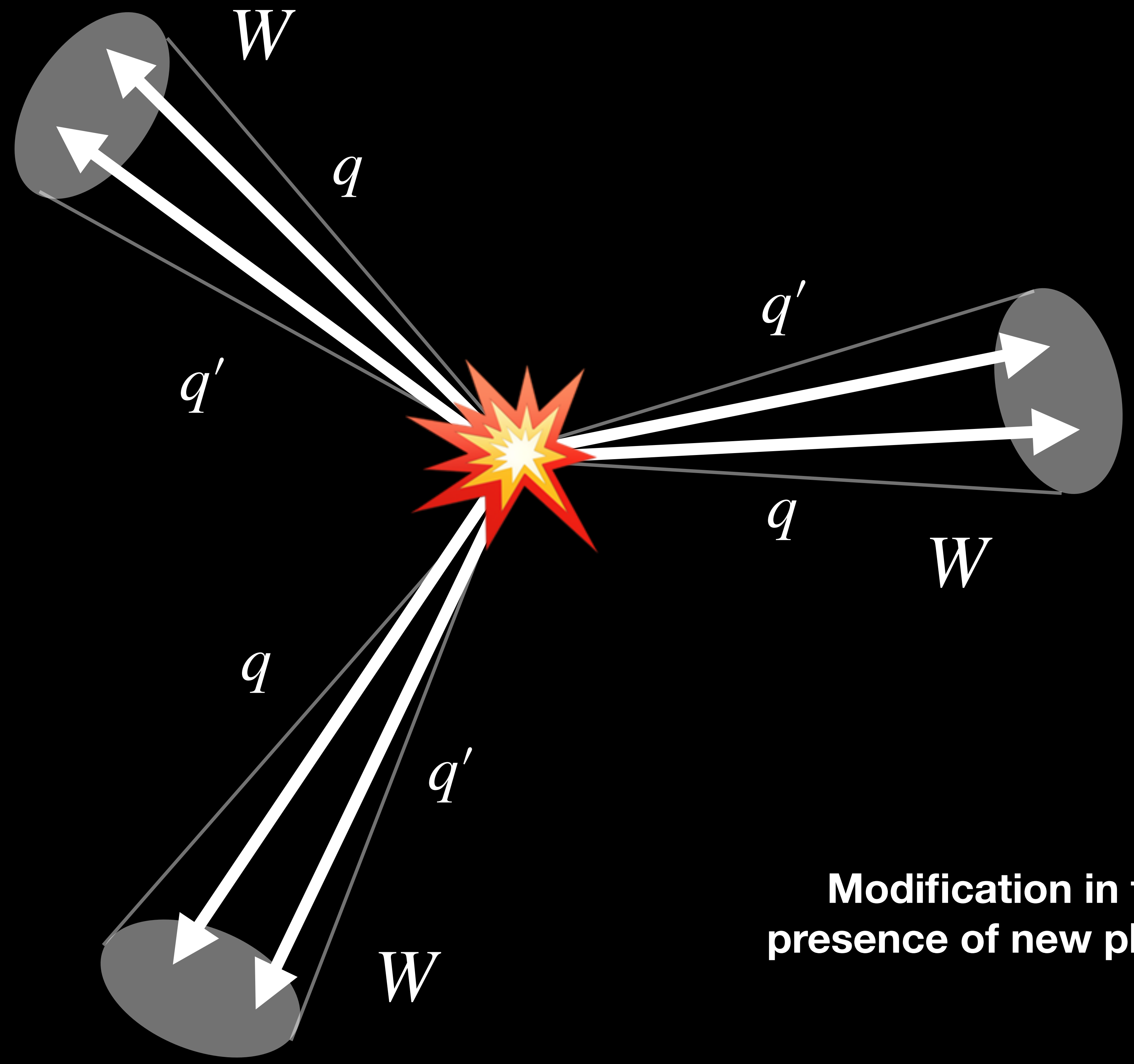
Exploring new physics with tribosons

- **Look for appearance of new physics indirectly in the interactions of the gauge bosons**

New Physics:



Sum of energy ≫ 0.9 TeV



Modification in the presence of new physics

W-decay products are boosted → merged

In how many ways can tribosons decay — let's tabulate

Explored for the first observation of VVV production

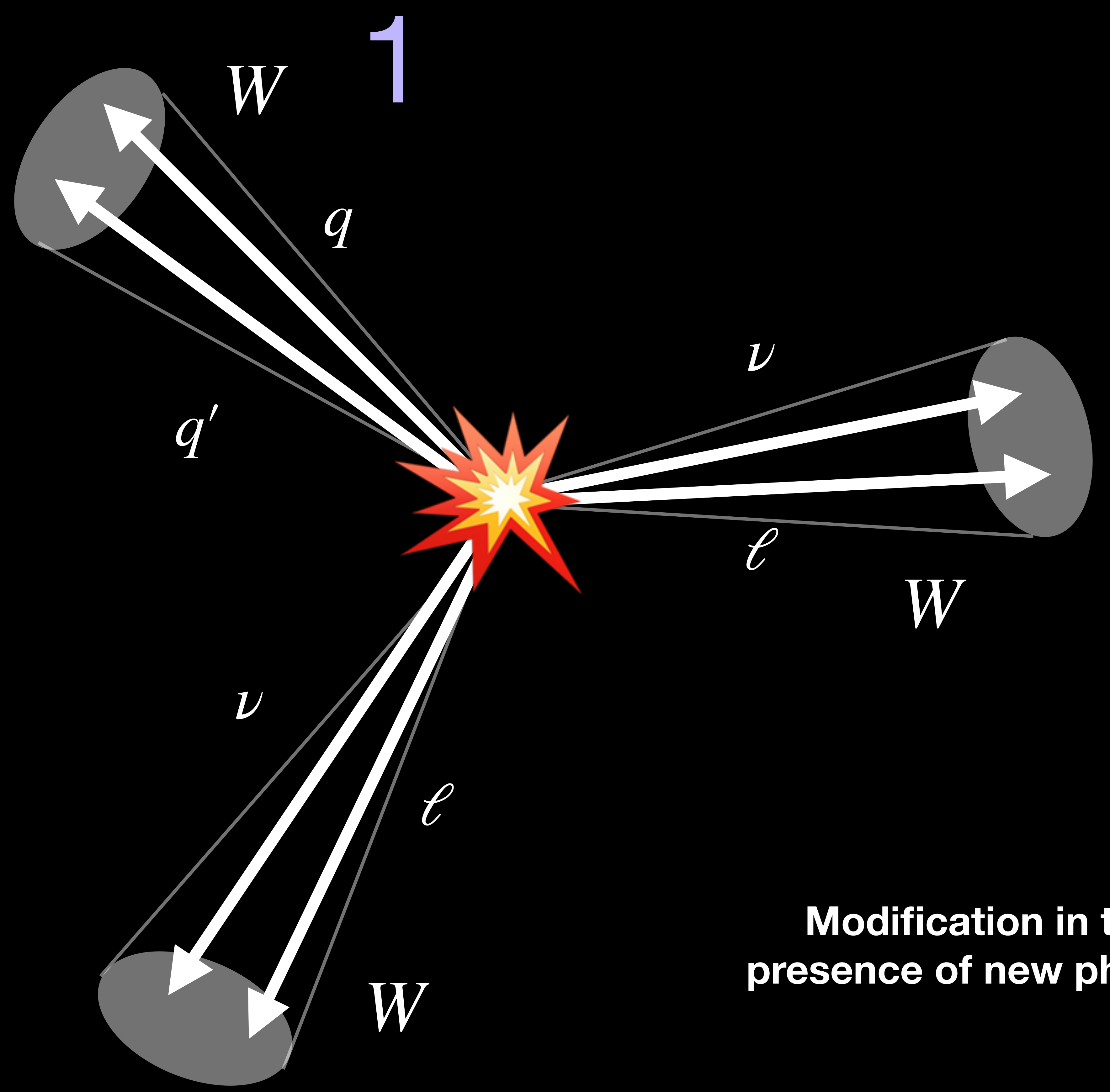
Process	Fully leptonic	At least one gauge boson decays hadronically	At least one gauge boson decays leptonically	Fully hadronic
WWW	3 lepton+missing energy	2 leptons+jets	1 lepton+jets	6 jets/3 boosted jets
WWZ	4 lepton+missing energy	2 lepton+jets 3 lepton+jets	1 lepton+jets 2 lepton+jets	6 jets/3 boosted jets
WZZ	5 lepton+missing energy	3 lepton+jets 4 lepton+jets	1 lepton+jets 2 lepton+jets	6 jets/3 boosted jets
ZZZ	6 leptons	4 lepton+jets	2 lepton+jets	6 jets/3 boosted jets

This table does not include the decays of the Z-bosons to $\nu\bar{\nu}$ for brevity

New final states open up!

$W^{\pm} W^{\pm} W^{\mp} \longrightarrow qq'\ell\nu\ell\nu$

Boosted-jet counter: 1



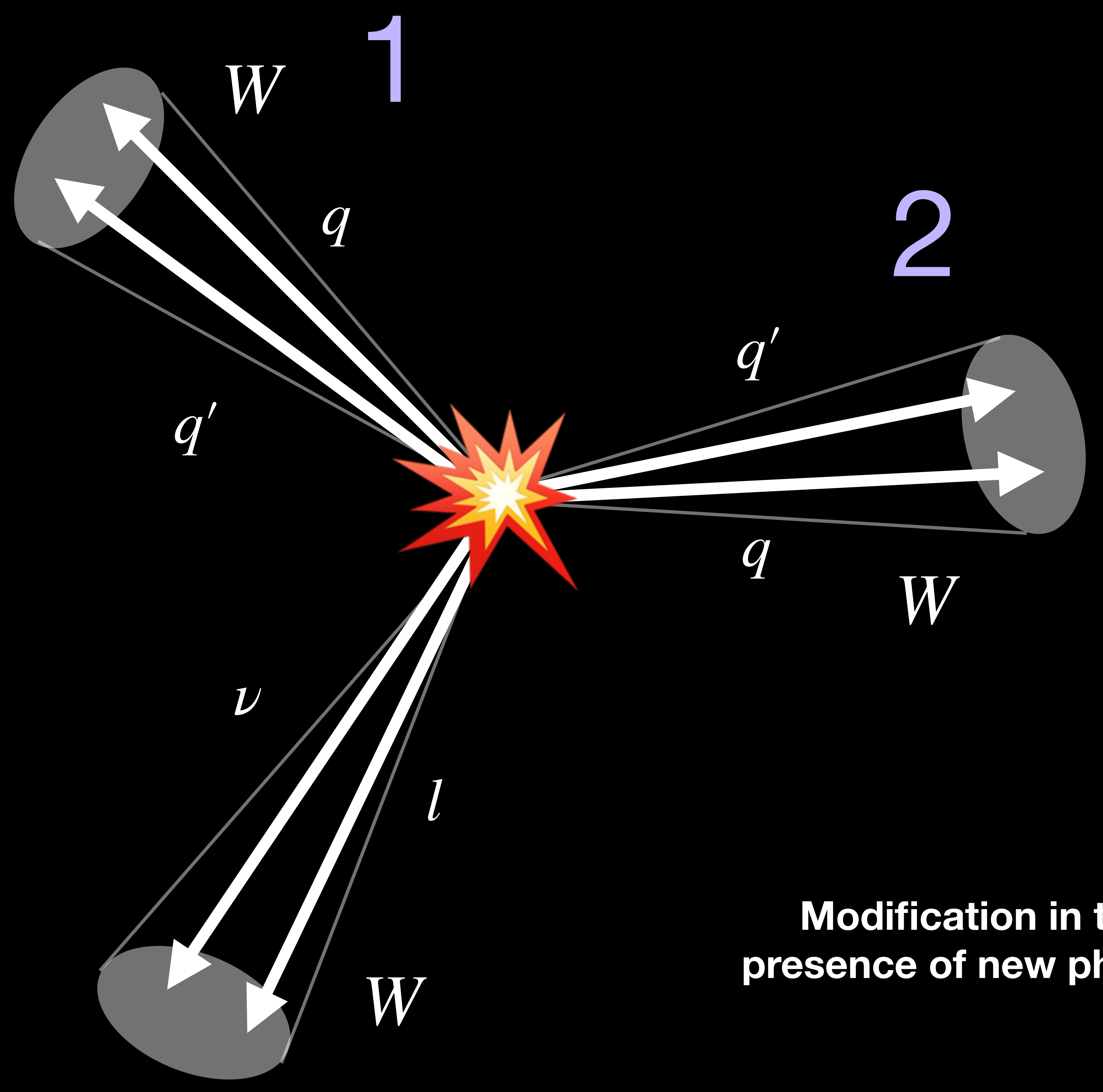
Modification in the presence of new physics

W-decay products are boosted → merged

New final states open up!

$$W^{\pm}\, W^{\pm}\, W^{\mp} \longrightarrow qq'qq'\ell\nu$$

Boosted-jet counter: 2



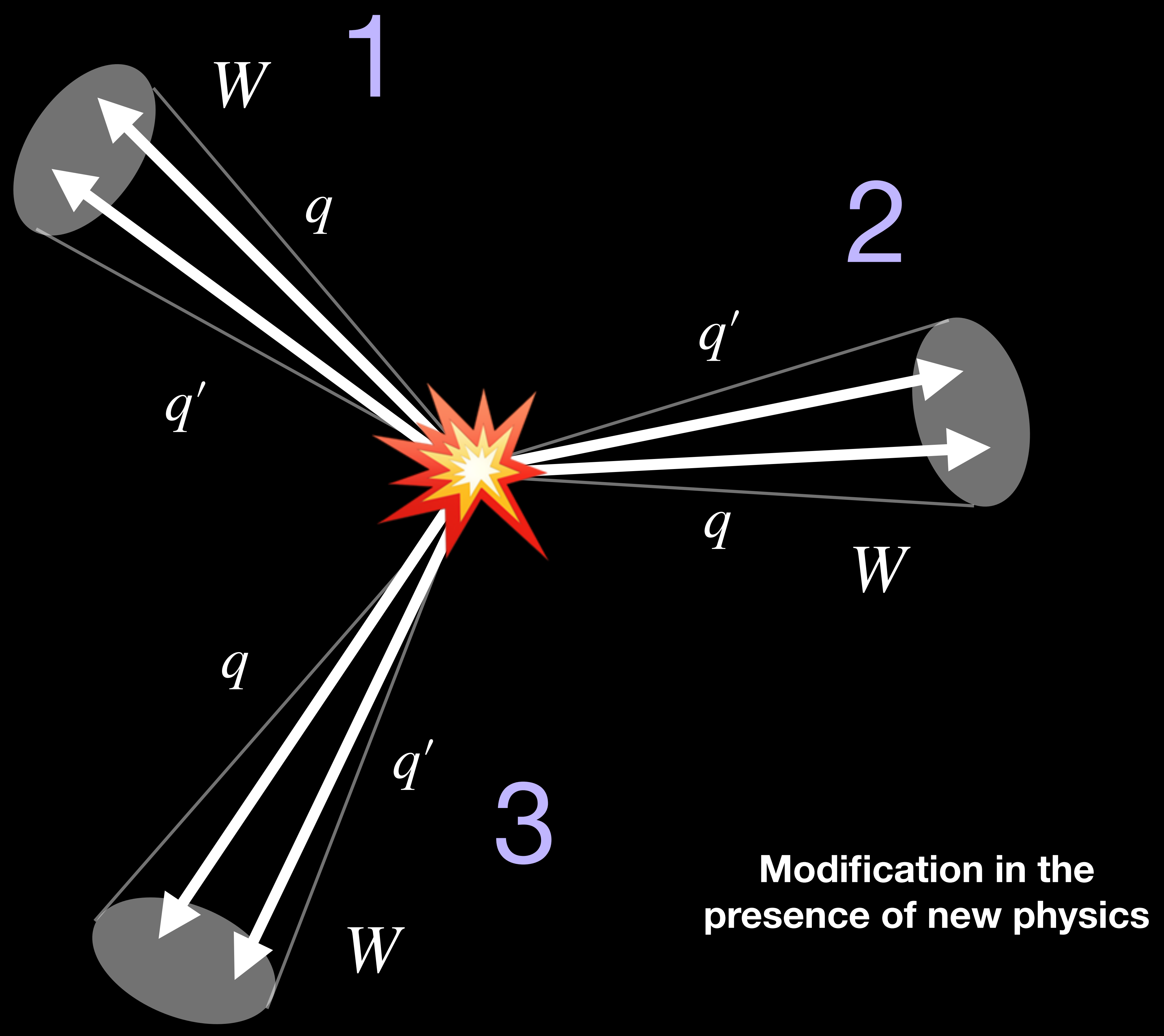
Modification in the presence of new physics

W-decay products are boosted → merged

New final states open up!

$$W^{\pm} W^{\pm} W^{\mp} \longrightarrow qq'qq'qq'$$

Boosted-jet counter: 3



W-decay products are boosted → merged