An experimental overview of effective field theory exploration at the LHC

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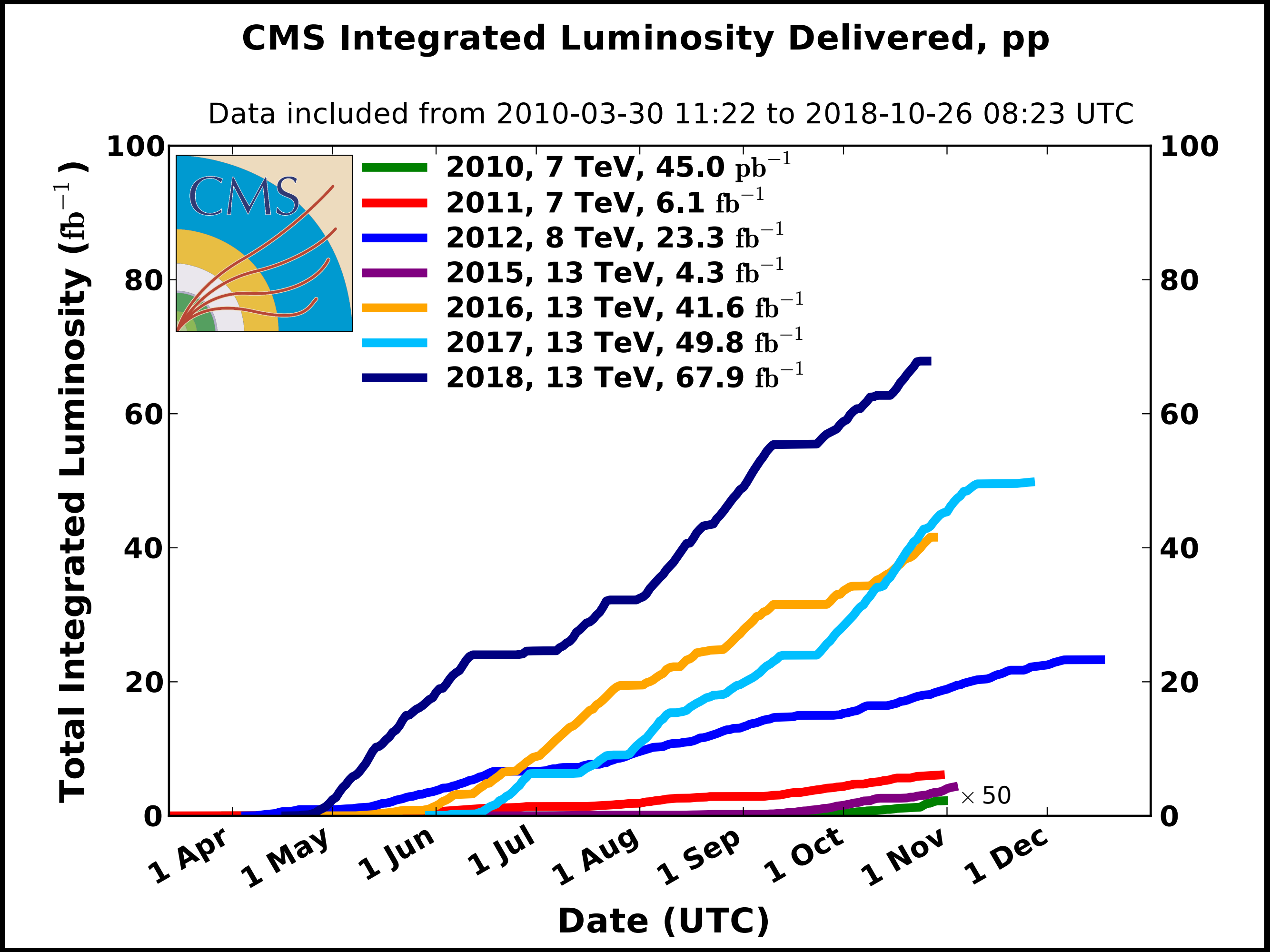
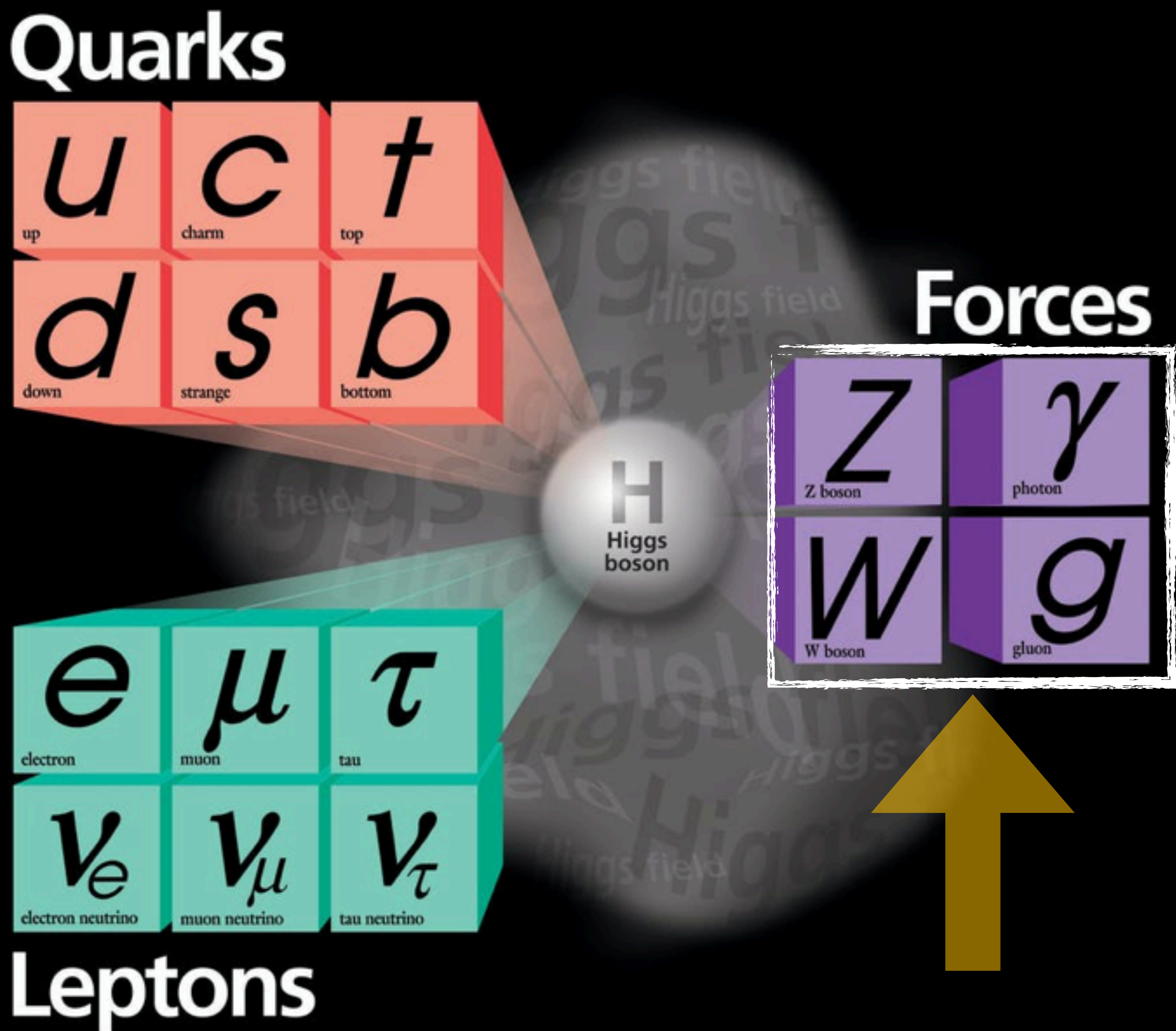
A few other caveats…

- This talk will cover several analyses
- I will be focusing more on the interpretation of the analyses as opposed to specific selection criteria used in an analysis
- I have focussed on recent results that use the full LHC Run II dataset
- Mostly focused on CMS results



The Standard Model of Particle Physics

But is it complete?

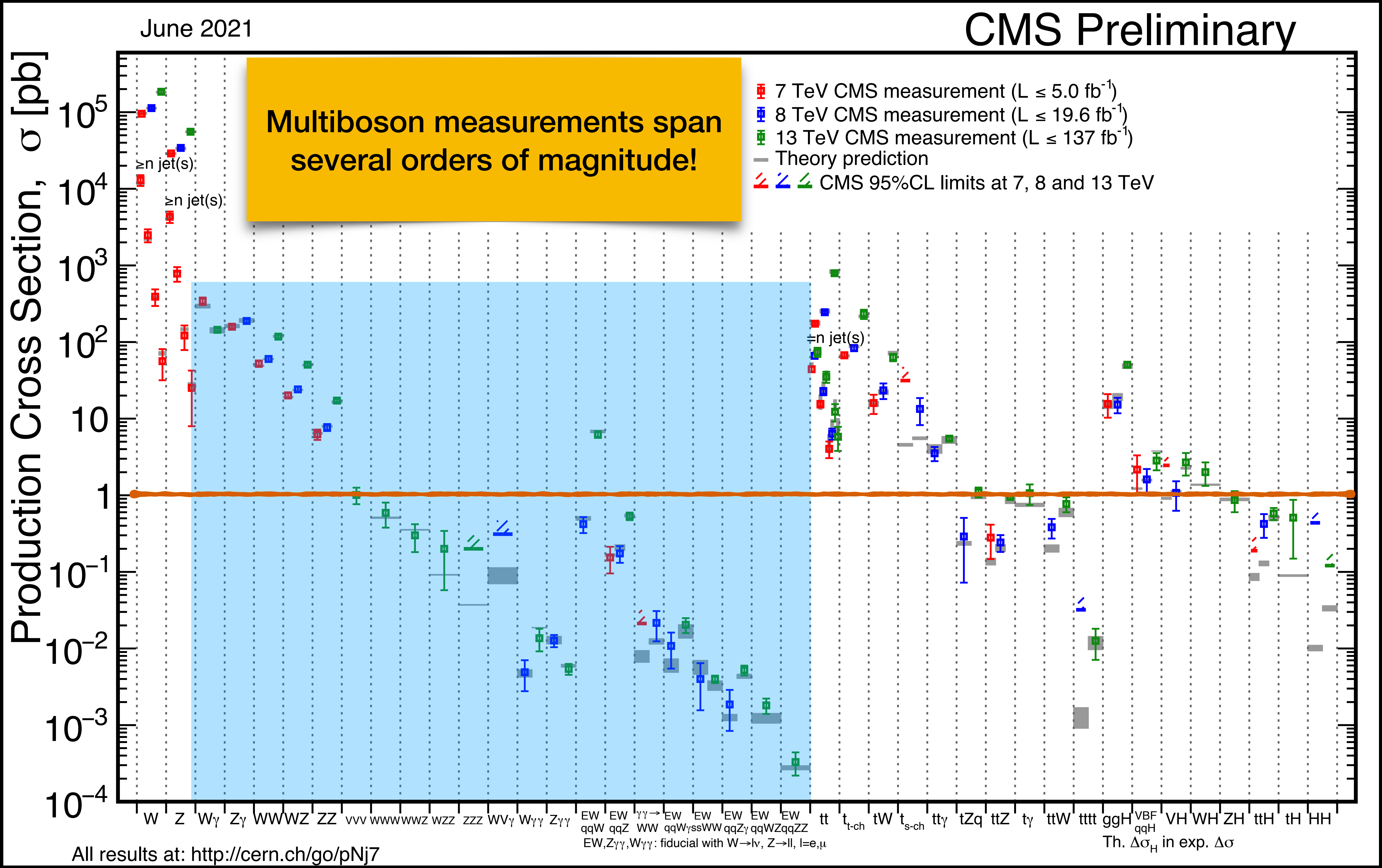


Open questions:

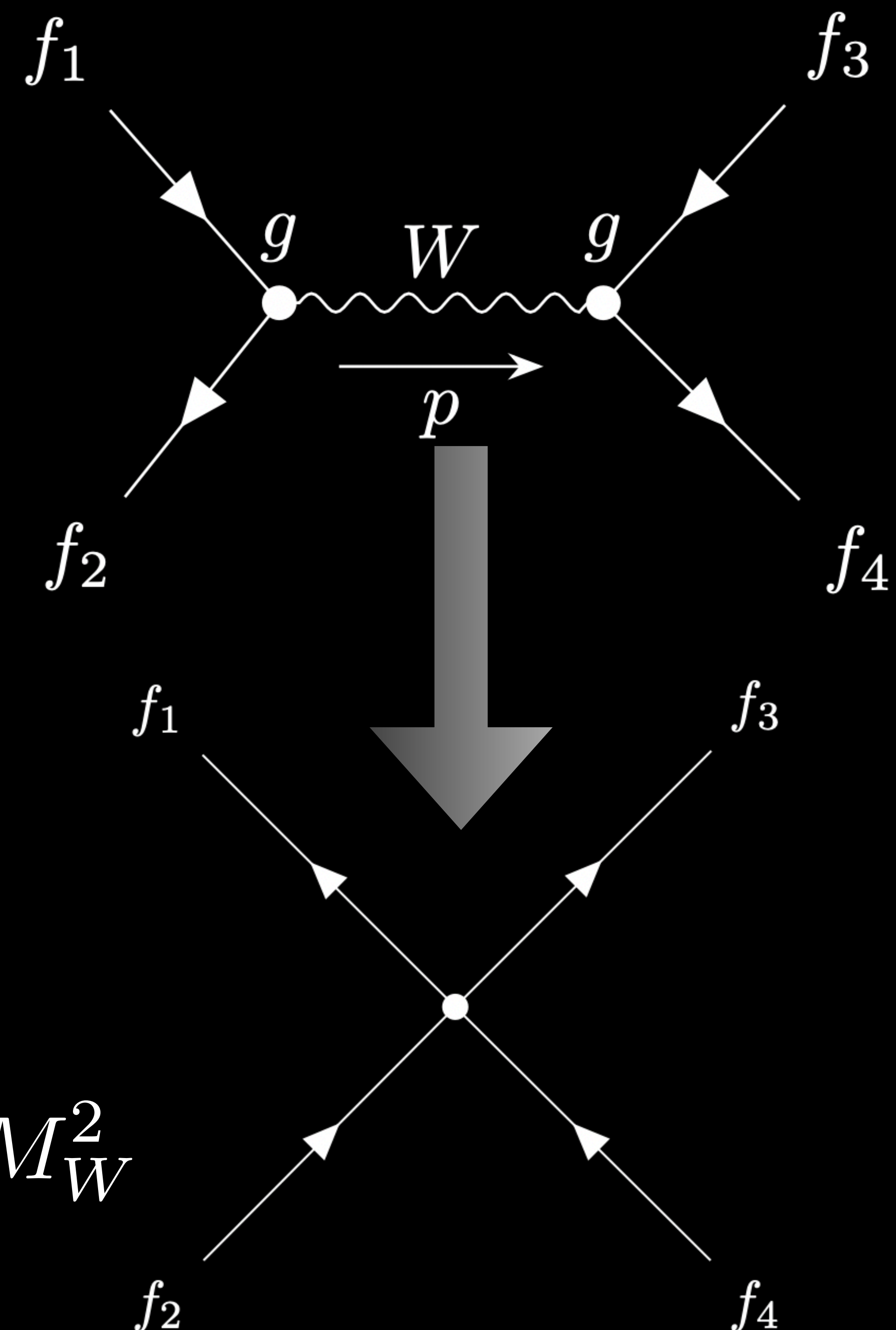
- Origin of neutrino mass?
- What is Dark matter?
- Not a complete theory that includes gravitational interactions

Focus of today's talk: bosons γ, W, Z

Standard Model Measurements



Text book example of effective field theories



Valid when: $p^2 \ll M_W^2$

Error increases as a function of momentum transfer, √s

Higher Dimensional Operators

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \sum_i \frac{c_i}{\lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\lambda^4}\mathcal{O}_j + \cdots$$

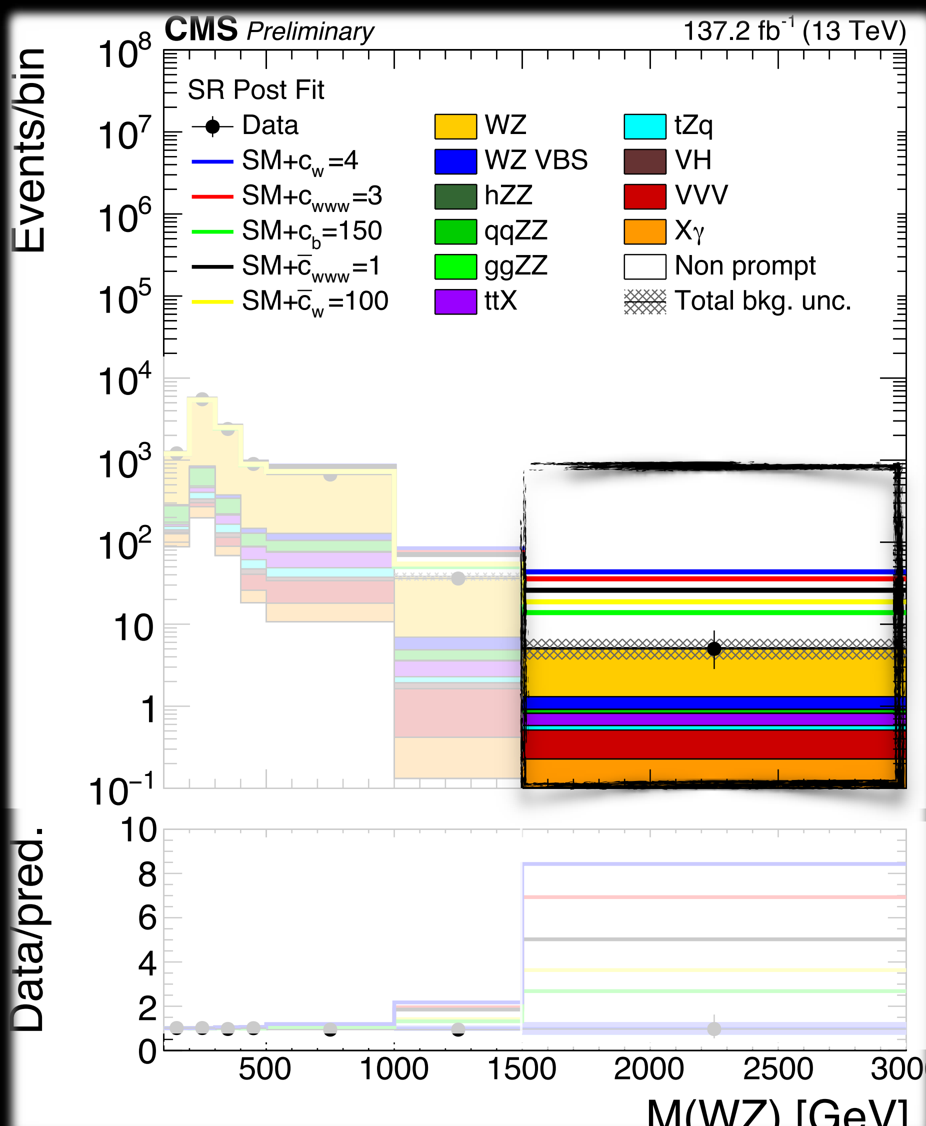
Multiplicative terms associated with each of these operators are called **Wilson Coefficients**

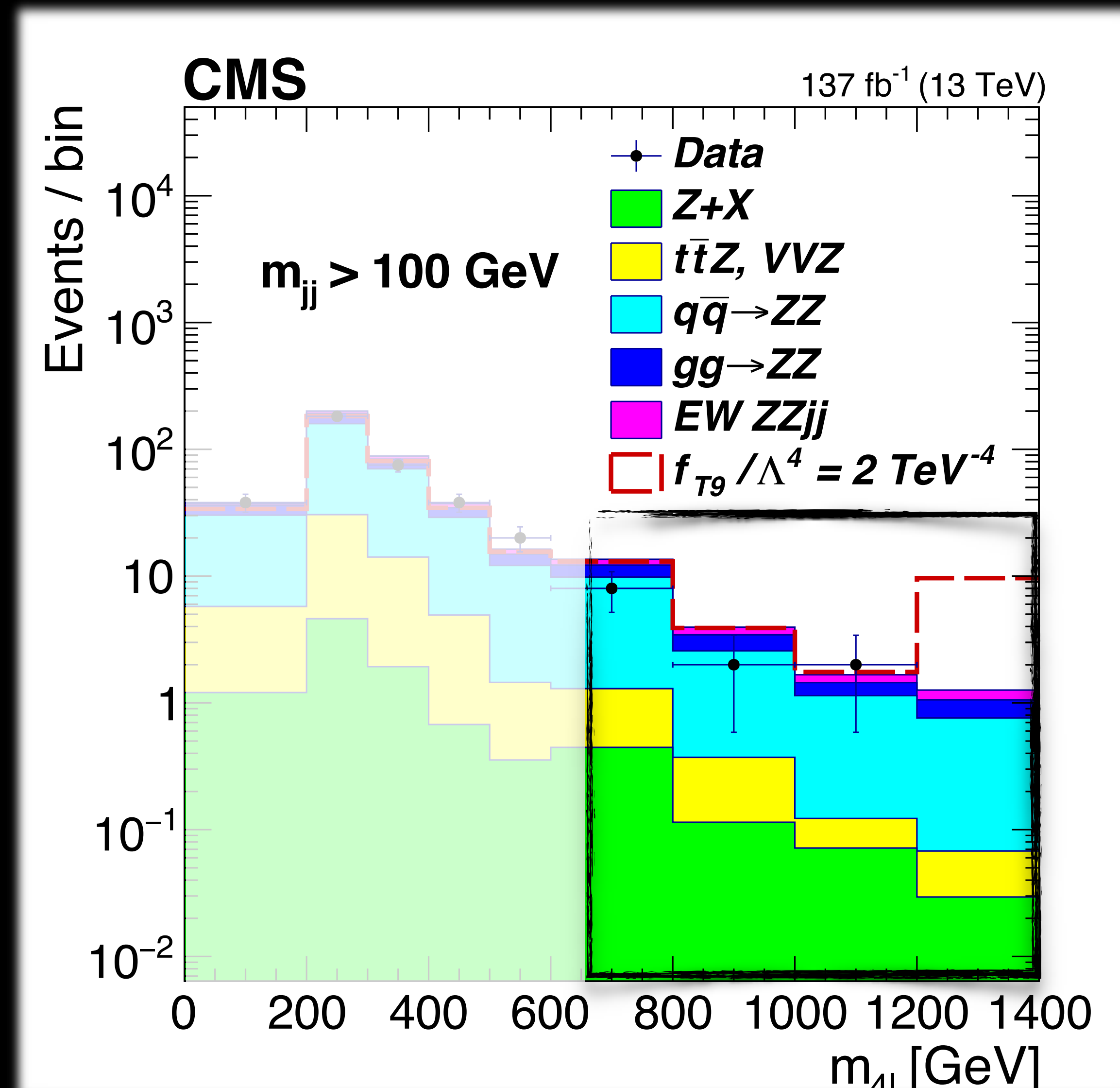
Operators of dimension-6 in Warsaw basis

Operators of dimension-8

Effective field theories

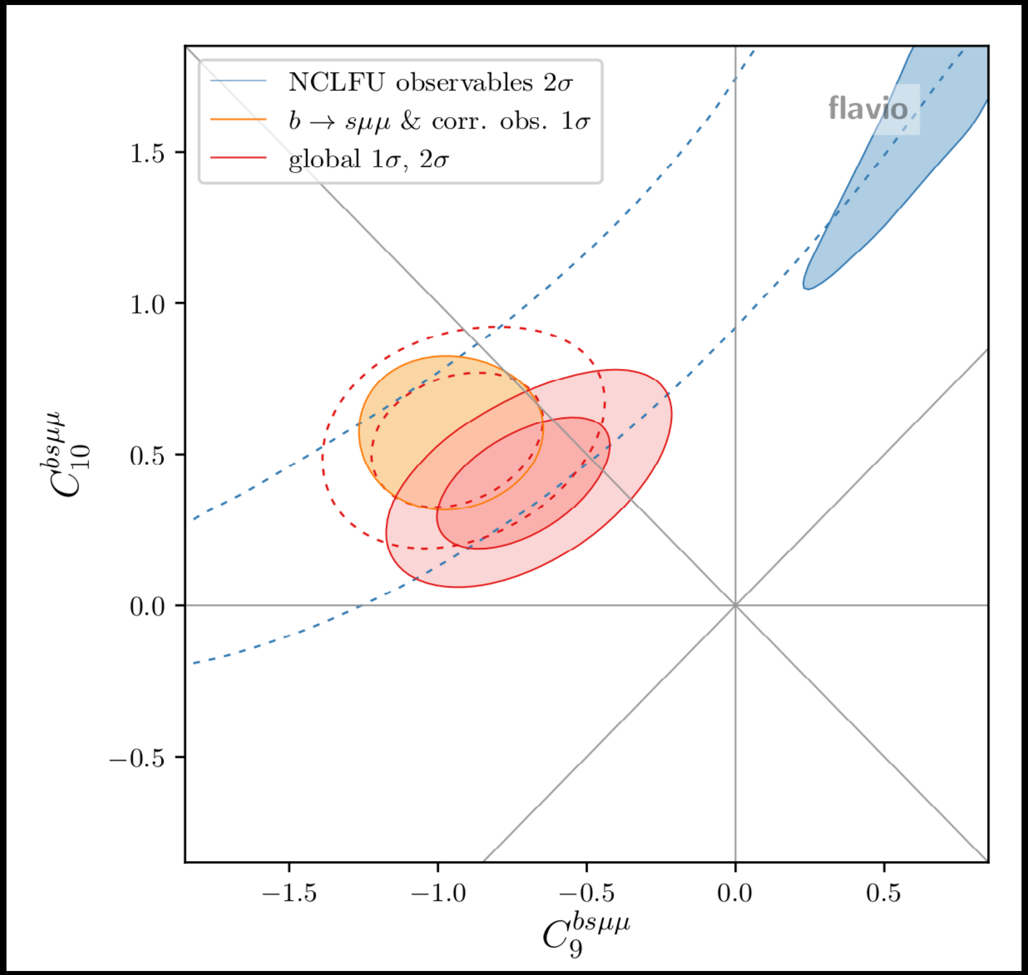
Complementary to BSM searches



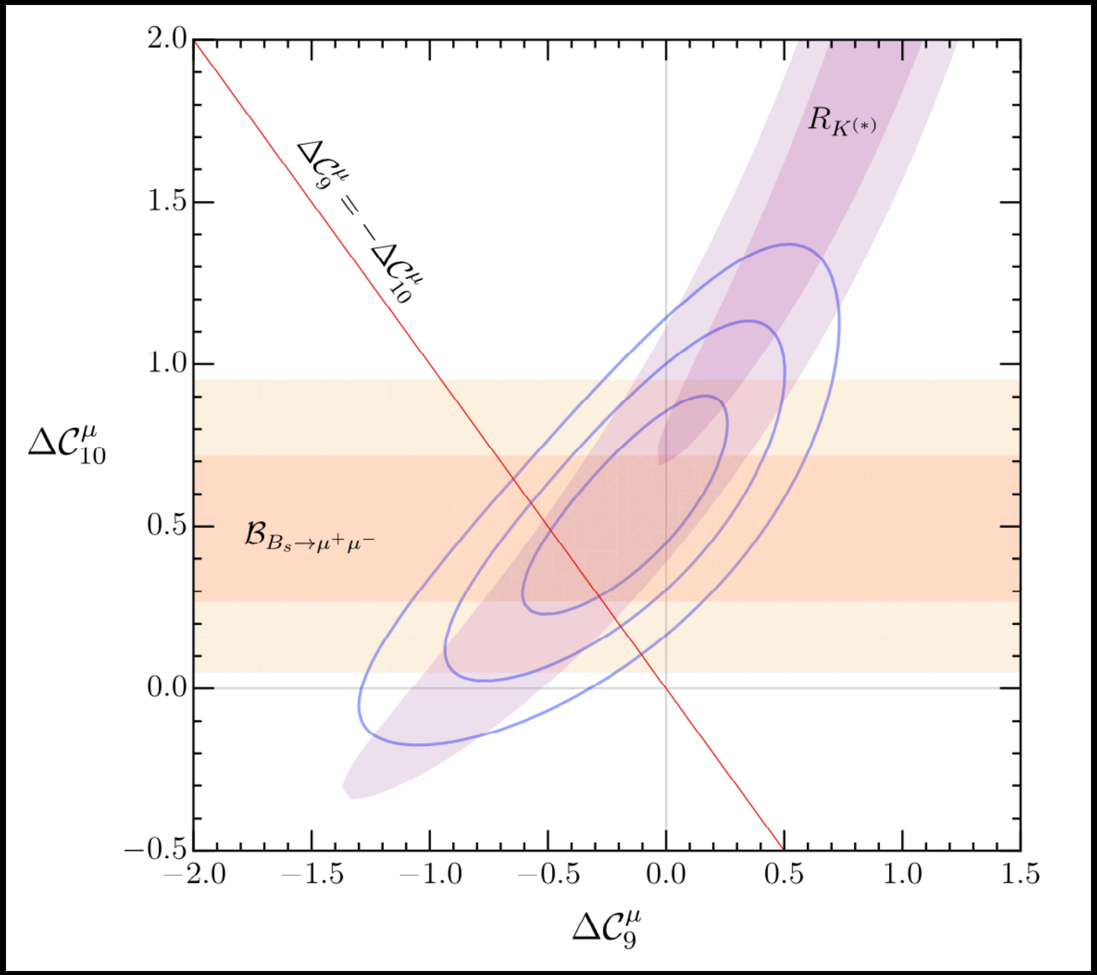


Instead of bump hunting, looking for new physics in the tails of distributions

The EFT framework is useful — an example from the leptonic sector



https://arxiv.org/pdf/1903.10434.pdf

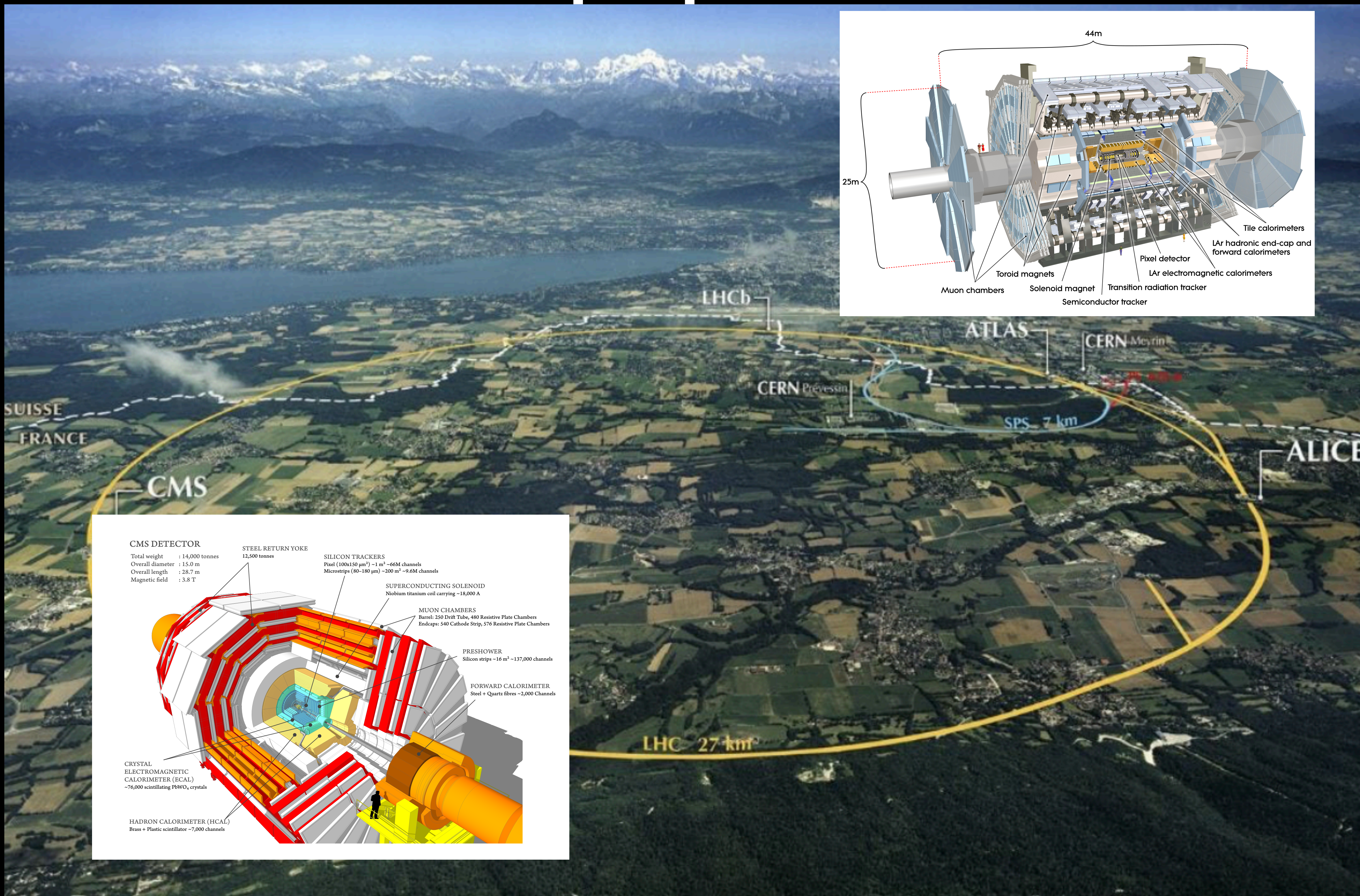


https://arxiv.org/pdf/2103.16558.pdf

- Tension in the leptonic sector with the SM at 3.6 σ observed in $b \to s l^+ l^-$
- EFT fits performed that factor 3.1 σ deviation from SM in measurement of R_k
- *Combination of these measurements leads to a* ***4.6 σ significance*** *of the hypothesis of a purely left-handed lepton flavor universality-violating contact interaction*

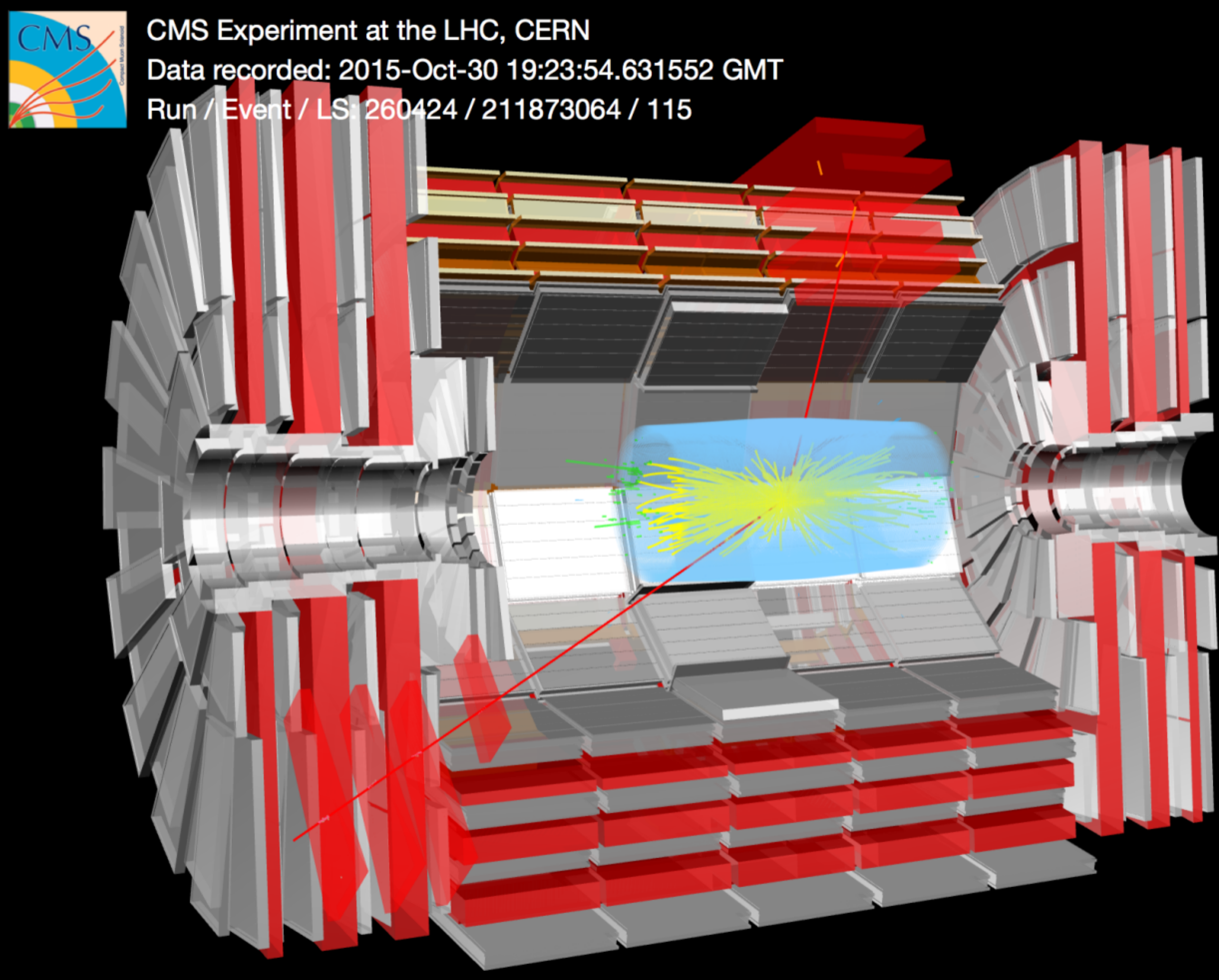
$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)}$$

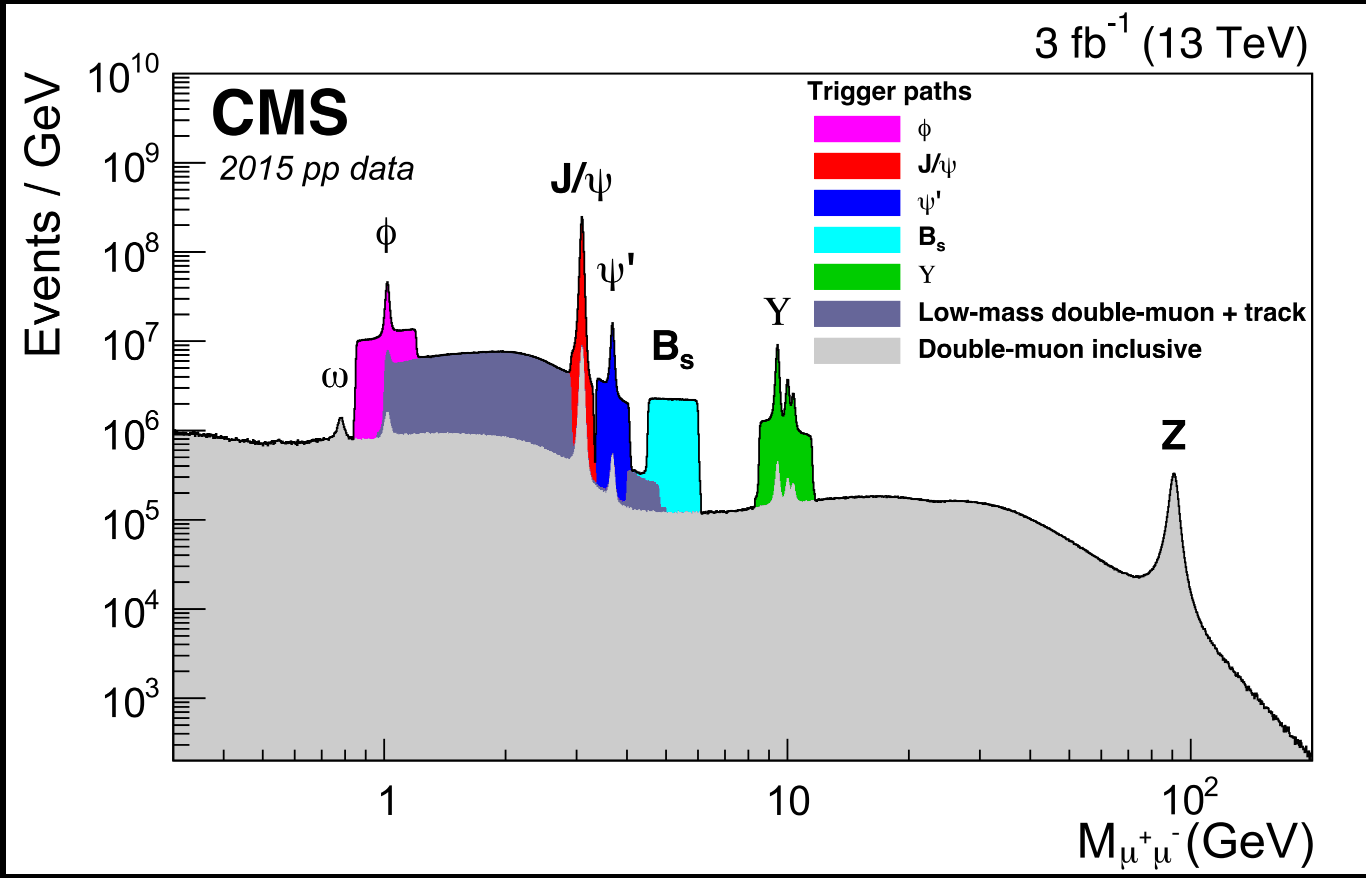
Search for new physics with multibosons at the multipurpose detectors



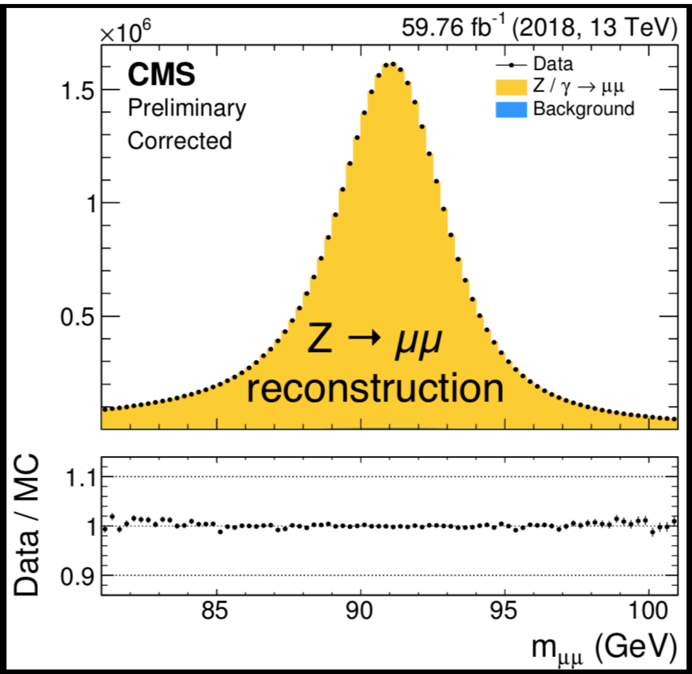
Muon detection in CMS

Excellent lepton detection capabilities in CMS



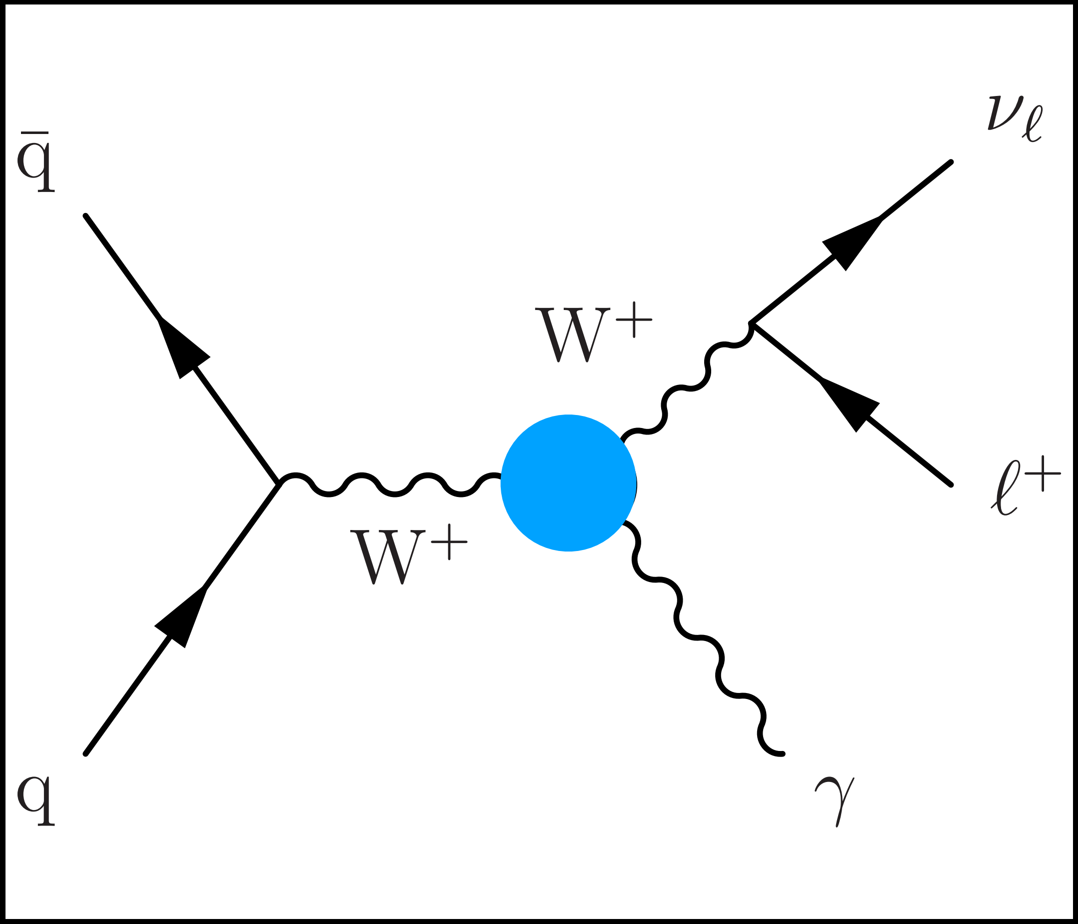


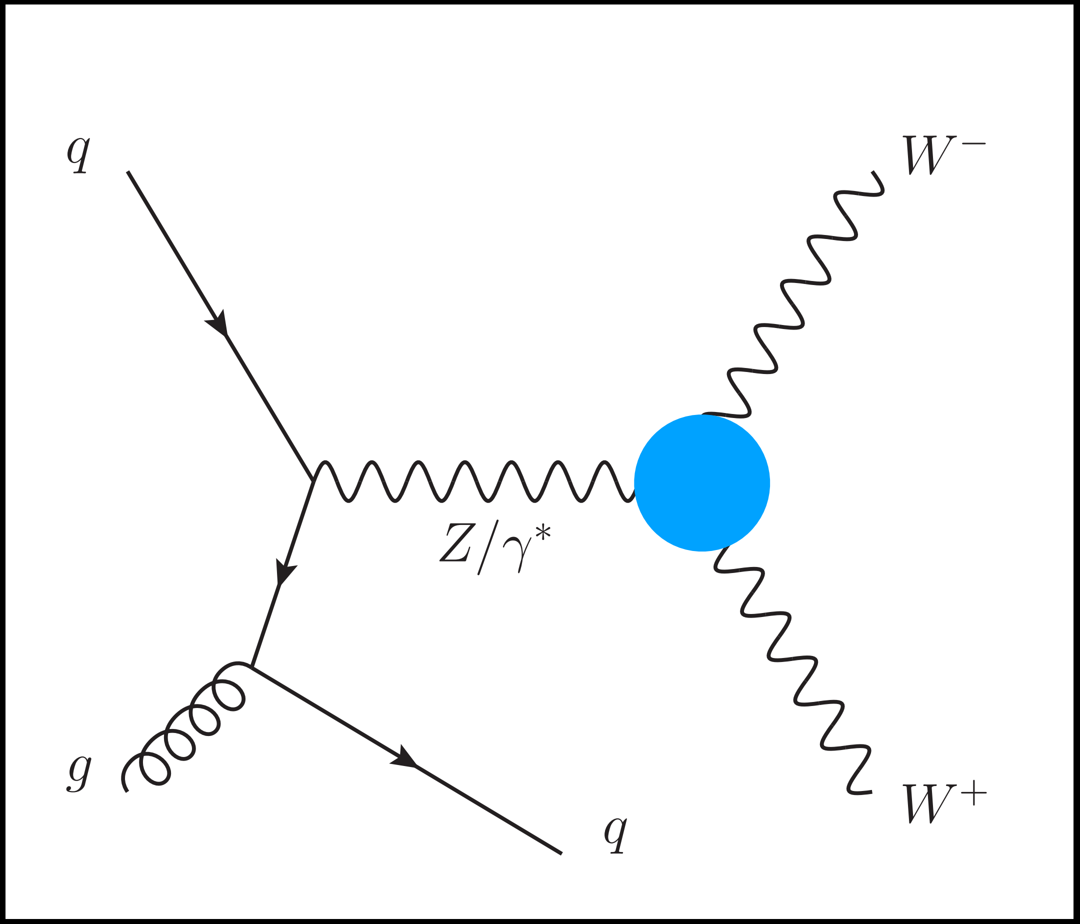
Dilepton mass resolution: 1-2%



Processes of interest

Diboson production at the LHC





W± γ production

W+ W- /WZ production

In all cases, decay at least one gauge boson leptonically

Exploration of dimension-6 operators

$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \sum_i \frac{c_i}{\lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\lambda^4}\mathcal{O}_j + \cdots$$

Use Standard Model Effective Field Theory or SMEFT framework to characterize impact of dim-6 operators

$$\sigma(C_{3\mathrm{W}}) = \sigma_{\mathrm{SM}} + C_{3\mathrm{W}}\sigma_{\mathrm{interference}} + C_{3\mathrm{W}}^2\sigma_{\mathrm{BSM}}$$

Linear

Quadratic

Slew of dimension-6 operators

1 : X^3

Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

2 : H^6

Q_H	$(H^\dagger H)^3$

3 : $H^4 D^2$

$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

5 : $\psi^2 H^3 + \text{h.c.}$

Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

4 : $X^2 H^2$

Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

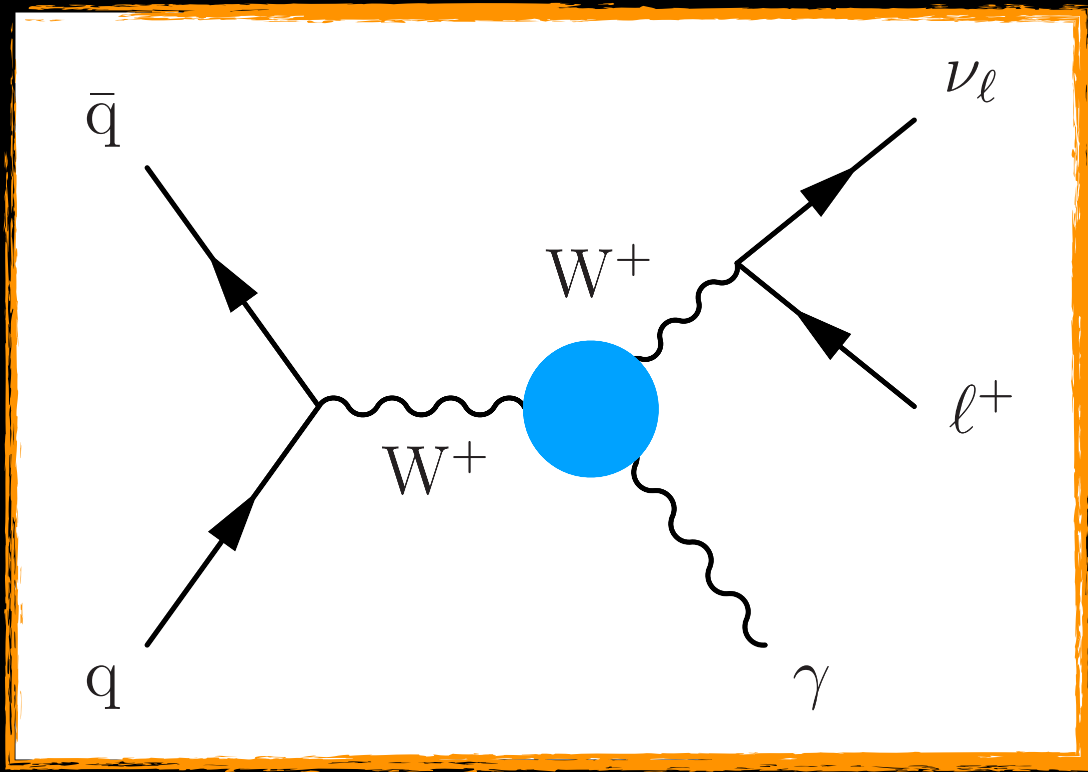
6 : $\psi^2 XH + \text{h.c.}$

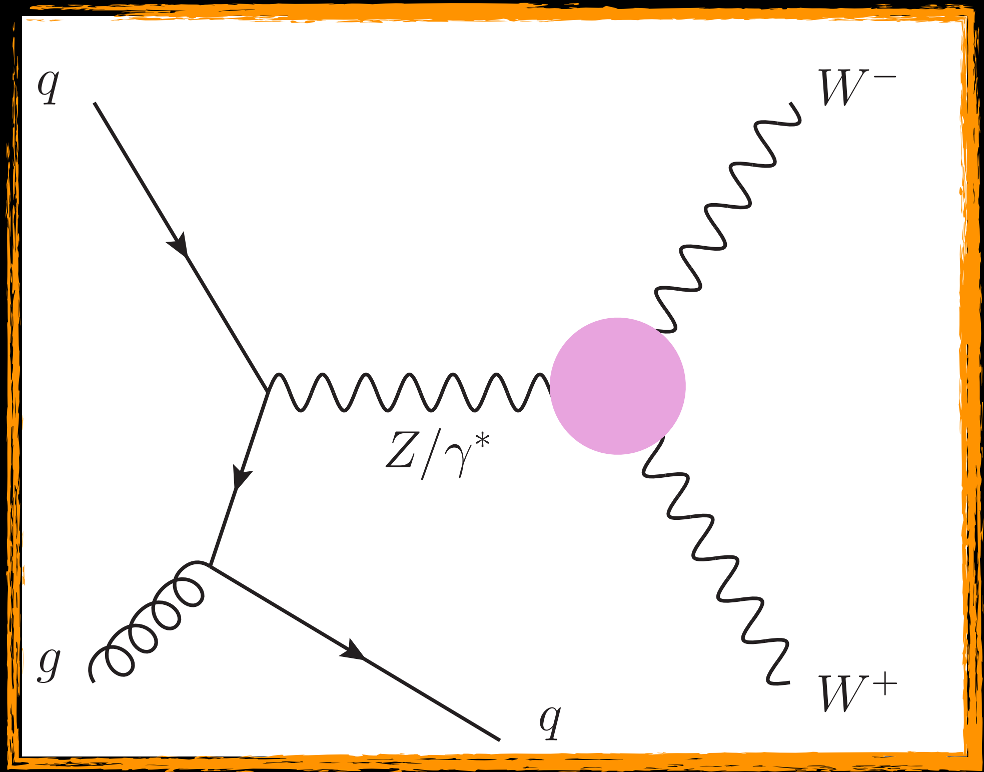
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

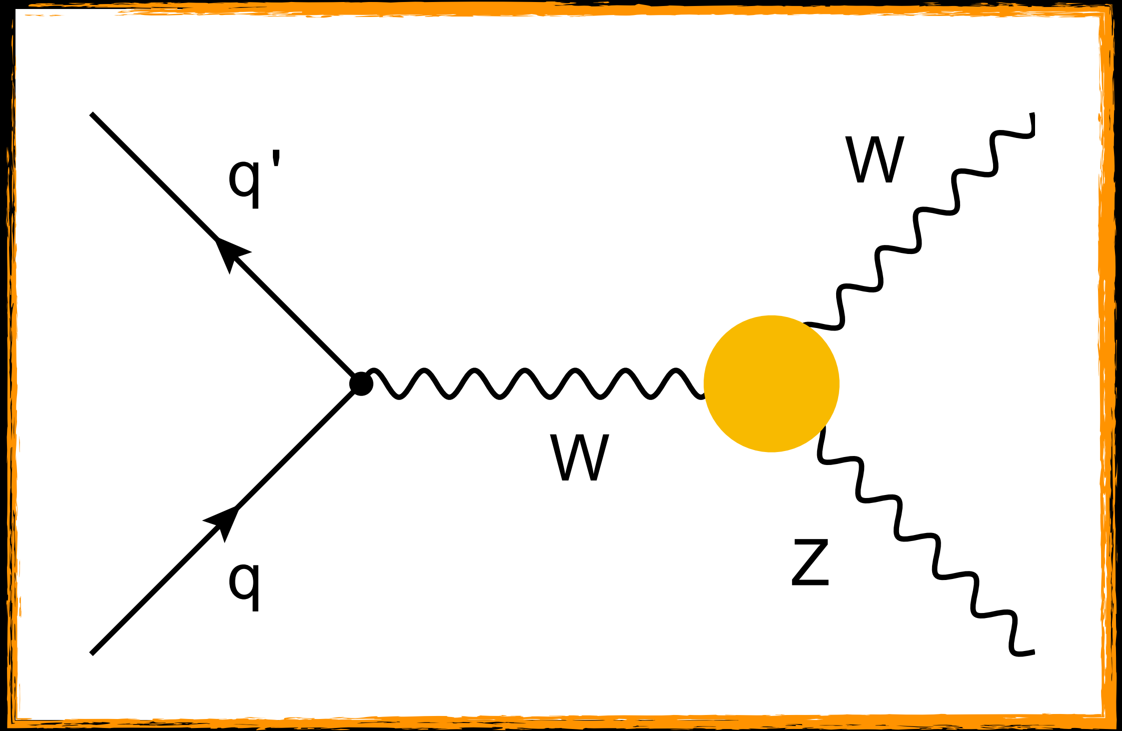
7 : $\psi^2 H^2 D$

$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

Description of analyses - dim6 exploration



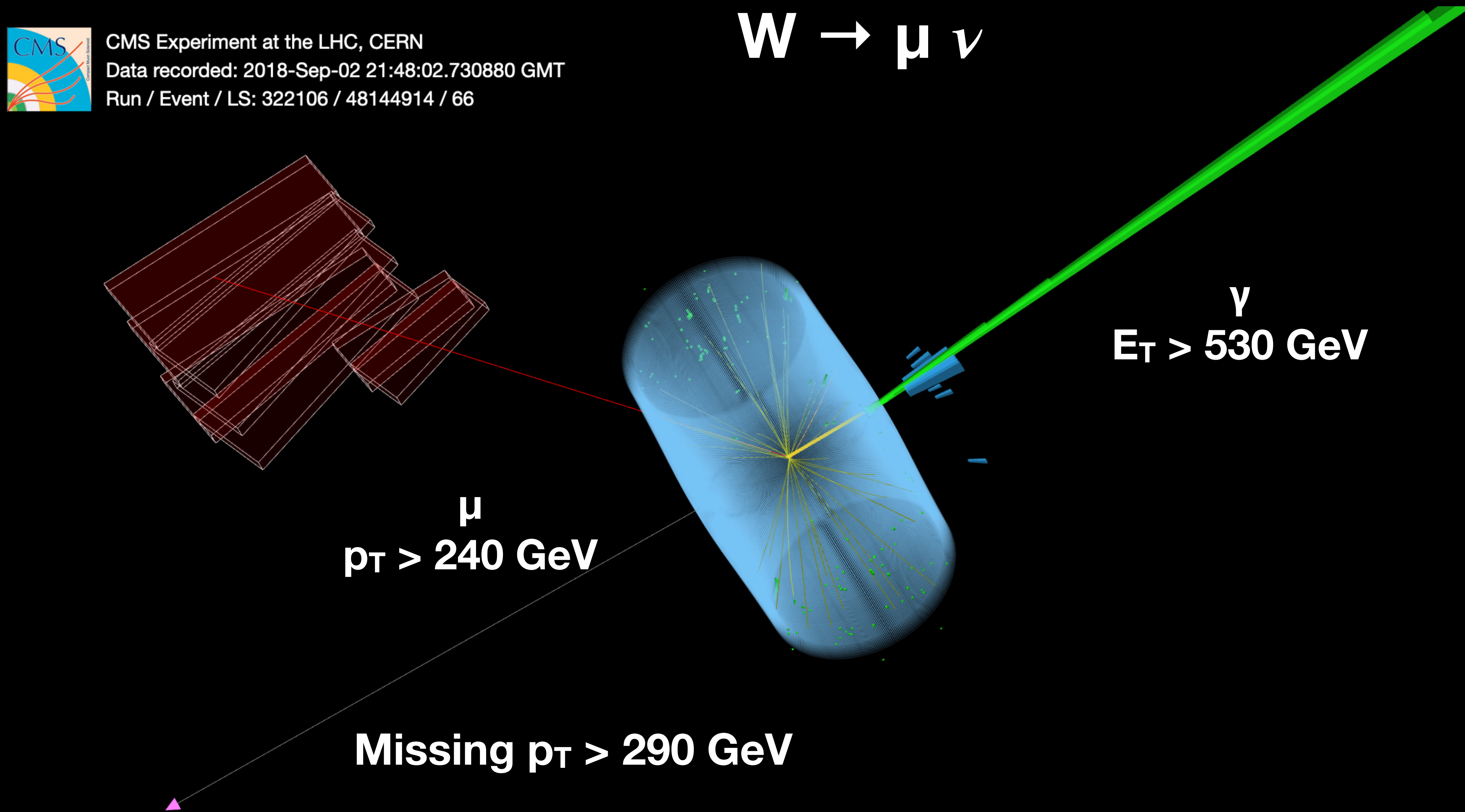




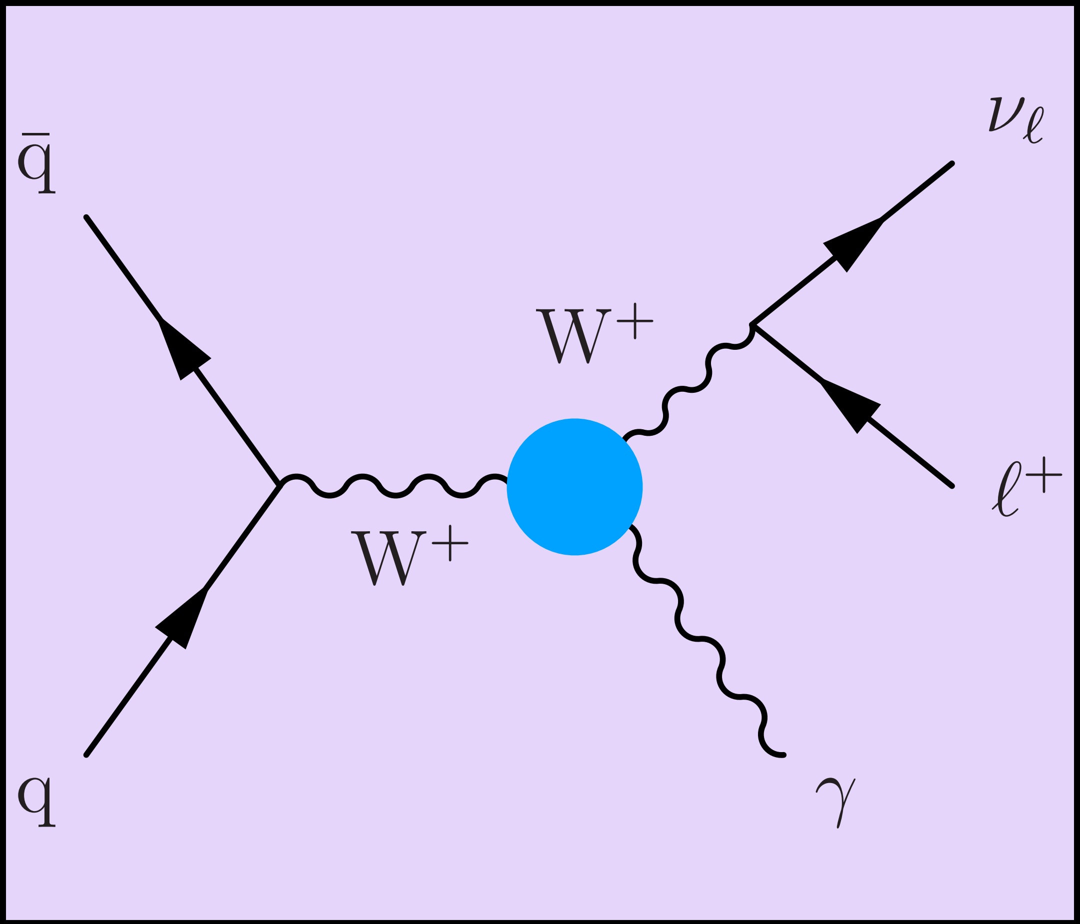
- EFT exploration performed with combination of four final states:
  - WW and WZ in leptonic final states
  - Final state consisting of four charged leptons
  - Leptonically decaying Z-boson in vector-boson-fusion topology

W±γ

CMS: https://arxiv.org/abs/2111.13948



Effective field theory constraints from the $W^{\pm}\gamma$ process



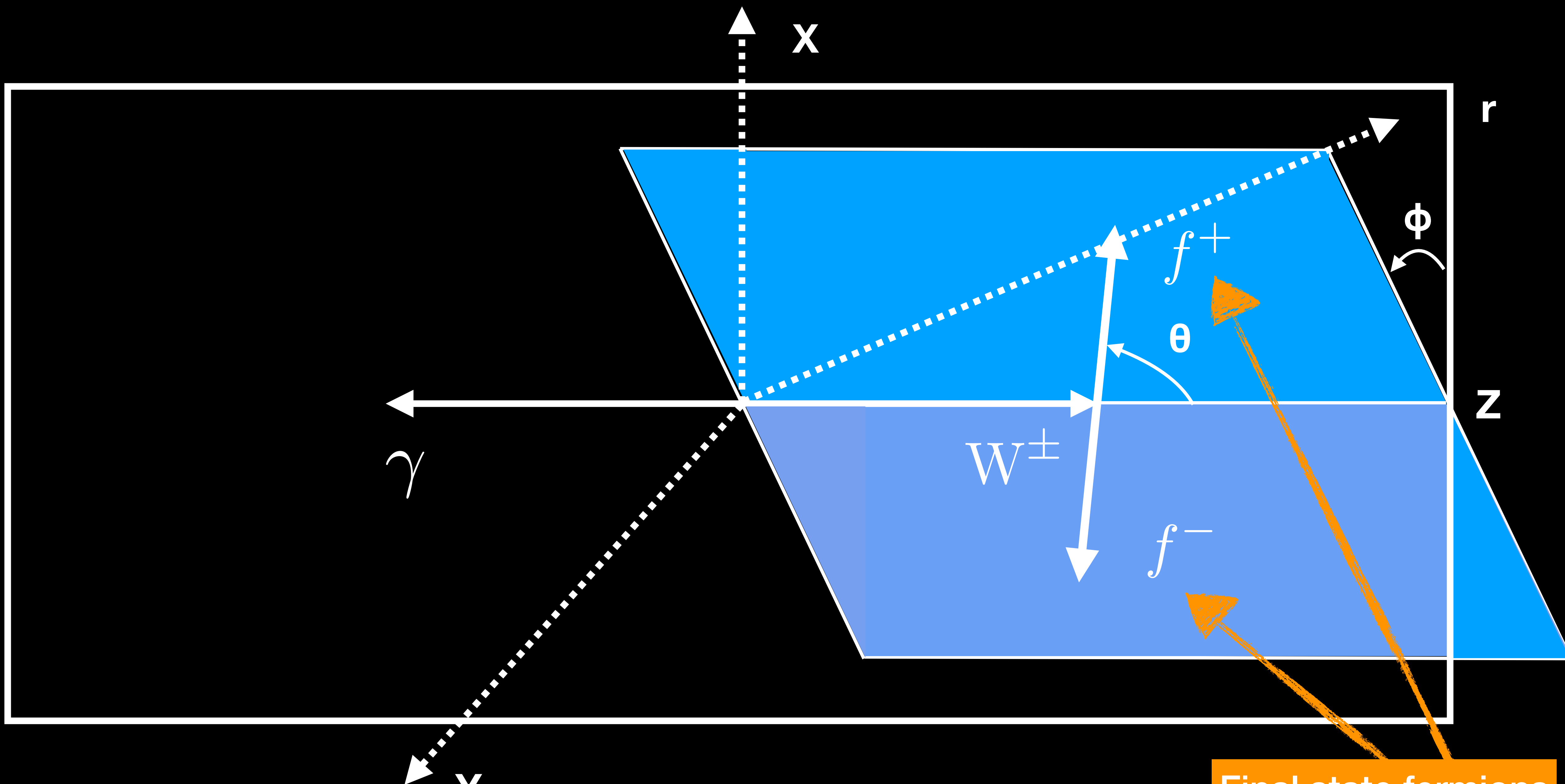
- Focus is on

$$\mathcal{O}_{3W} = \epsilon^{abc} W_{\mu}^{a\nu} W_{\nu}^{b\rho} W_{\rho}^{a\mu}$$

$$\sigma(C_{3\mathrm{W}}) = \sigma_{\mathrm{SM}} + C_{3\mathrm{W}}\sigma_{\mathrm{interference}} + C_{3\mathrm{W}}^2\sigma_{\mathrm{BSM}}$$

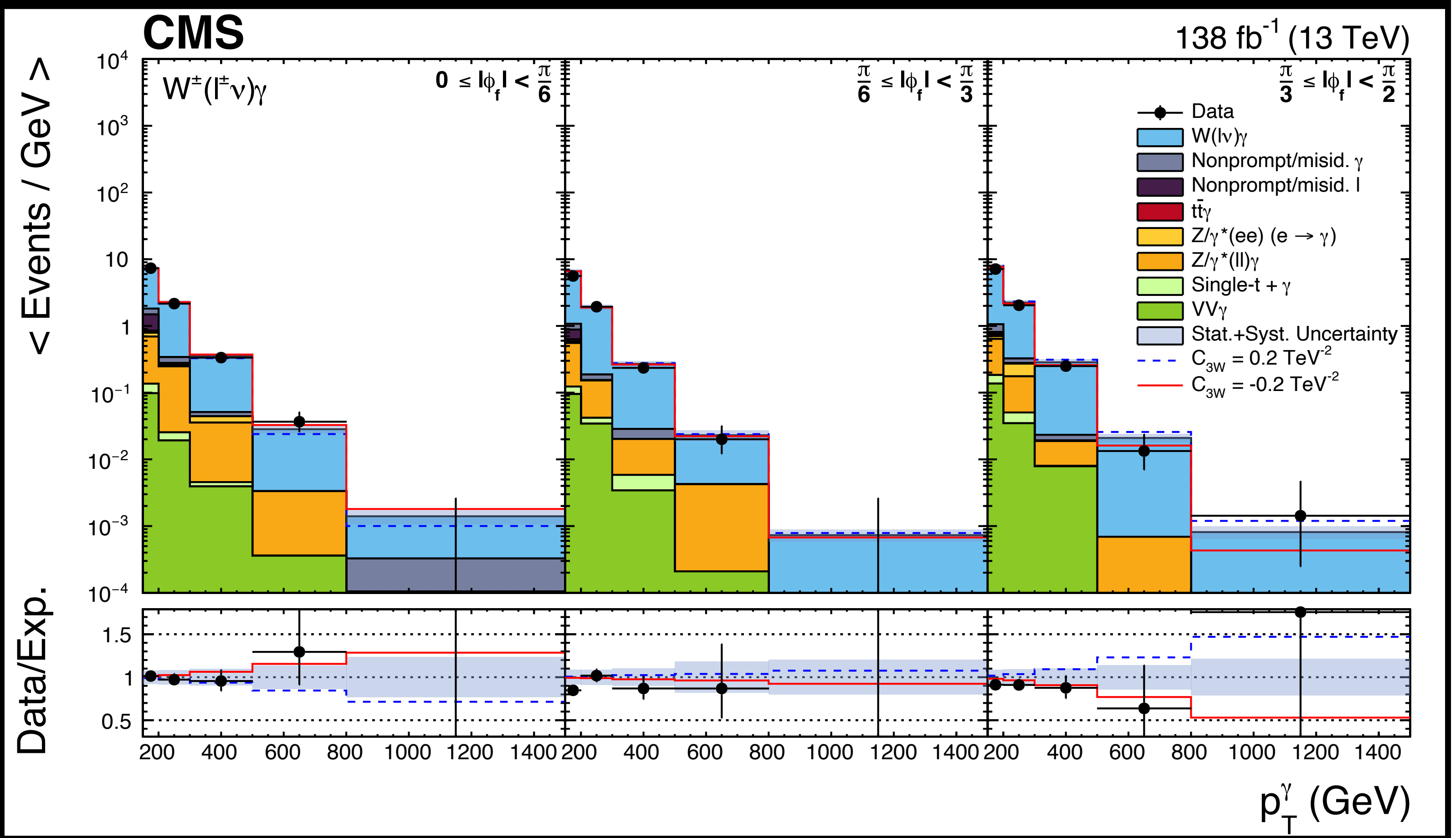
- The interference with the SM cannot be experimentally detected with "inclusive" observables (decay angles) for *ff* → $W_T V_T$
- Different helicity configurations for SM and BSM components
- Leads to suppression of interference effects
- Can probe only pure-BSM contributions
- "Diboson interference resurrection" performed (arXiv:1708.07823, arXiv:1901.04821)
  - Requires definition of specific coordinate system

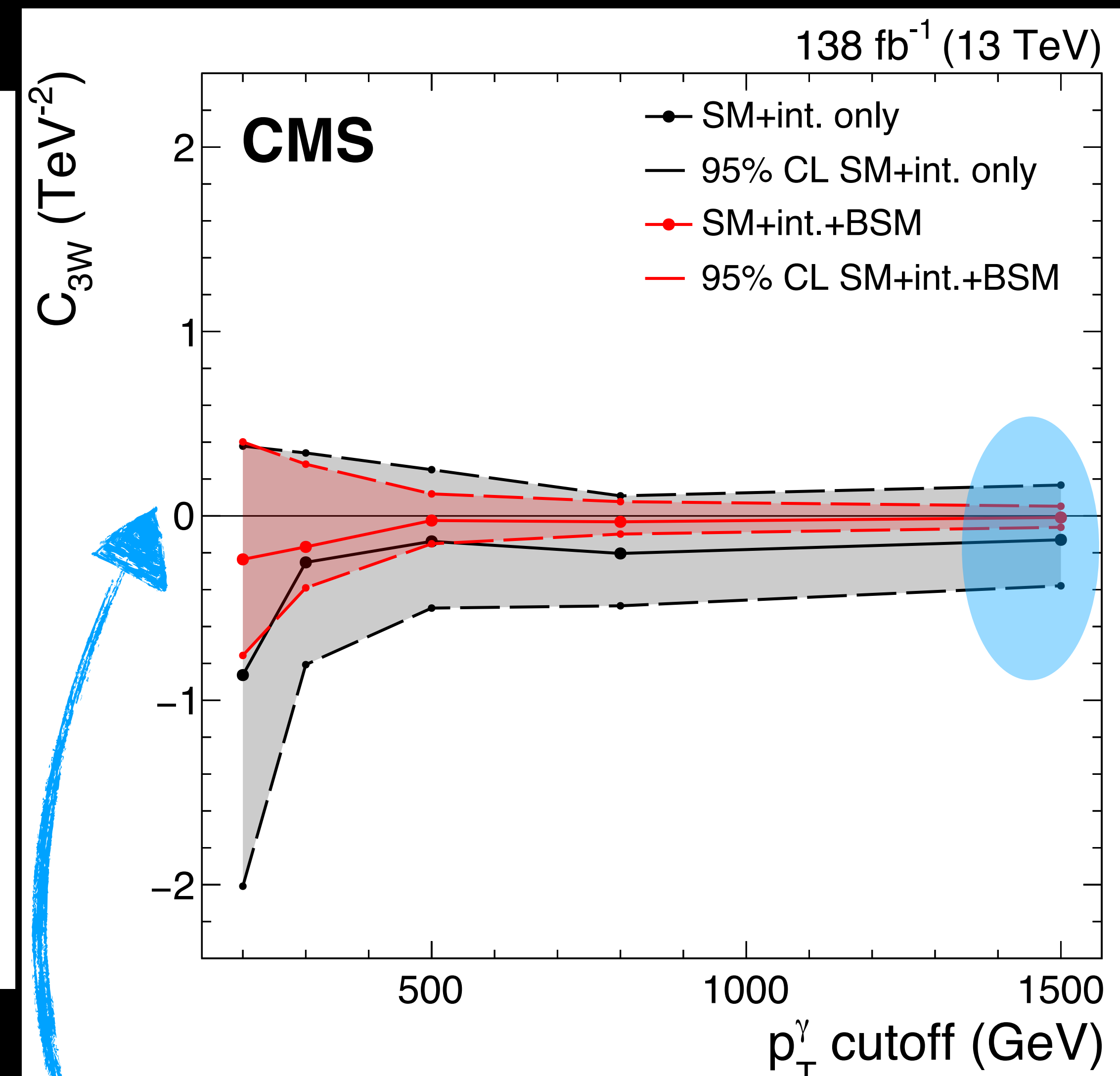
Special coordinate system



- Define frame by a Lorentz boost to the center-of-mass frame of the $W^{\pm}\gamma$ system
  - boson momenta are back-to-back
- Angle Φ now acquires sensitivity to interference with SM

Constraints on Wilson Coefficients from the W±γ process

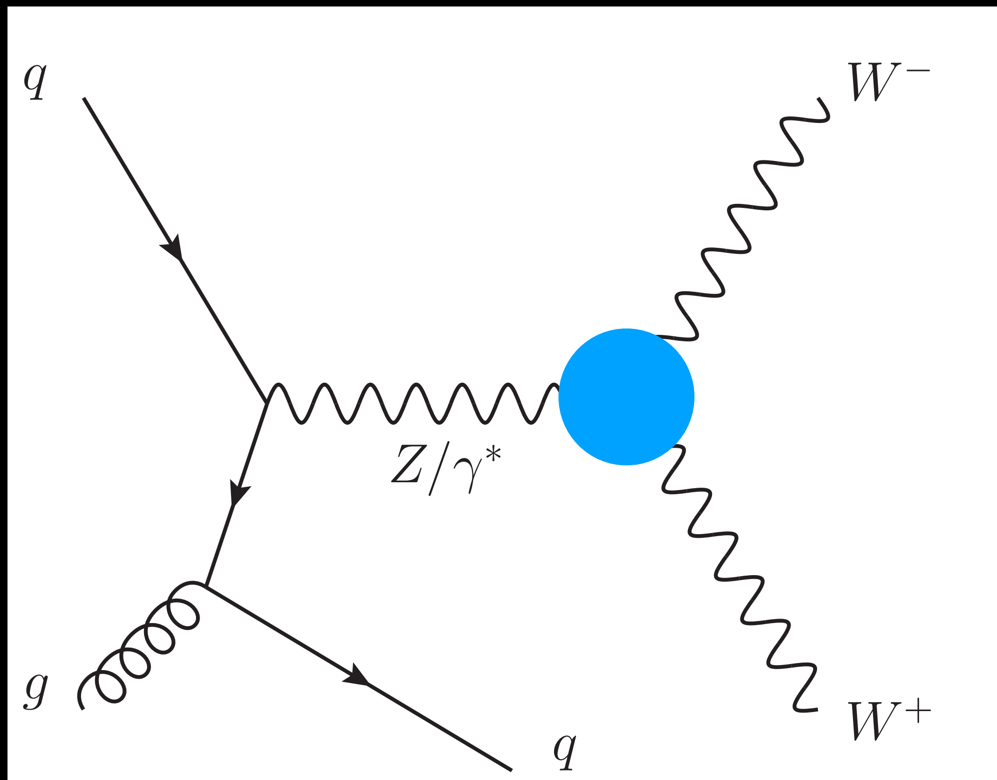




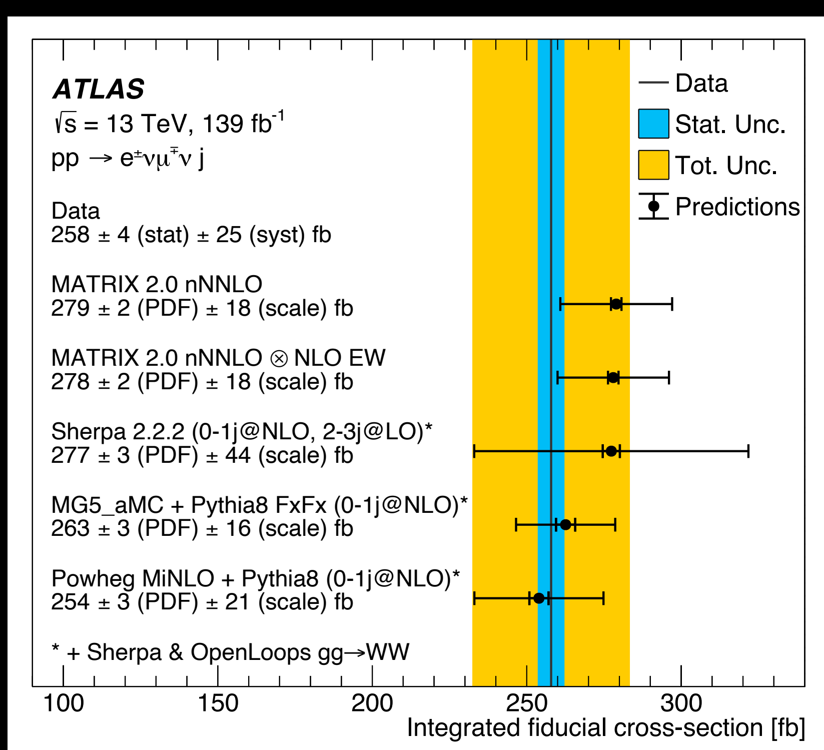
- ✓ Backgrounds very well modeled in MC
- ✓ Both lepton and photon p_T variables show excellent agreement between data and MC

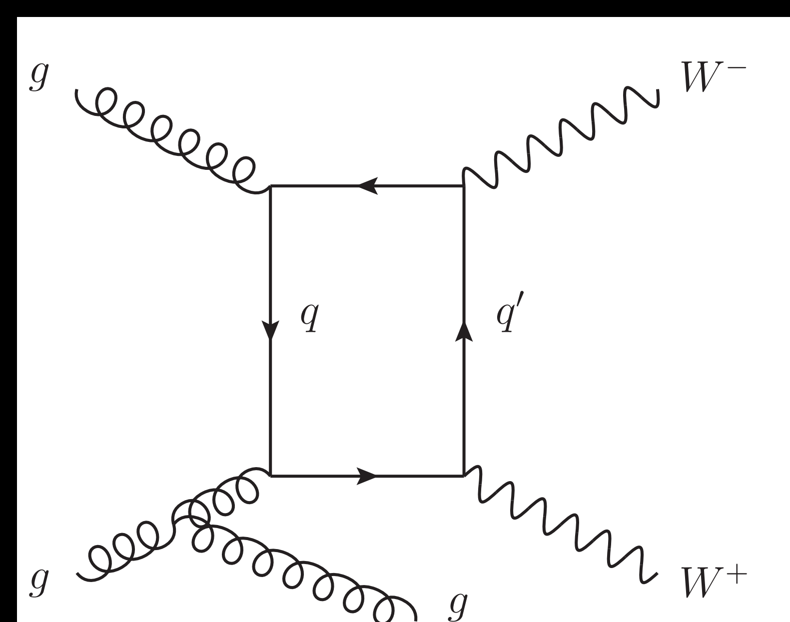
- Stringent limits obtained with Φ binning
- Without Φ binning limits range from:
  - [-7, 4] TeV^{-2} p_T^γ < 500 GeV
  - [-5, 3] TeV^{-2} p_T^γ > 1000 GeV

Measurement of the WW + 1 jet



- Specific focus on production W+W- with an additional jet
- Access to trilinear gauge coupling which could acquire contributions from dim-6 operators
- Just like in the Wγ analysis, interference with SM suppressed due to helicity configurations in SM vs. BSM

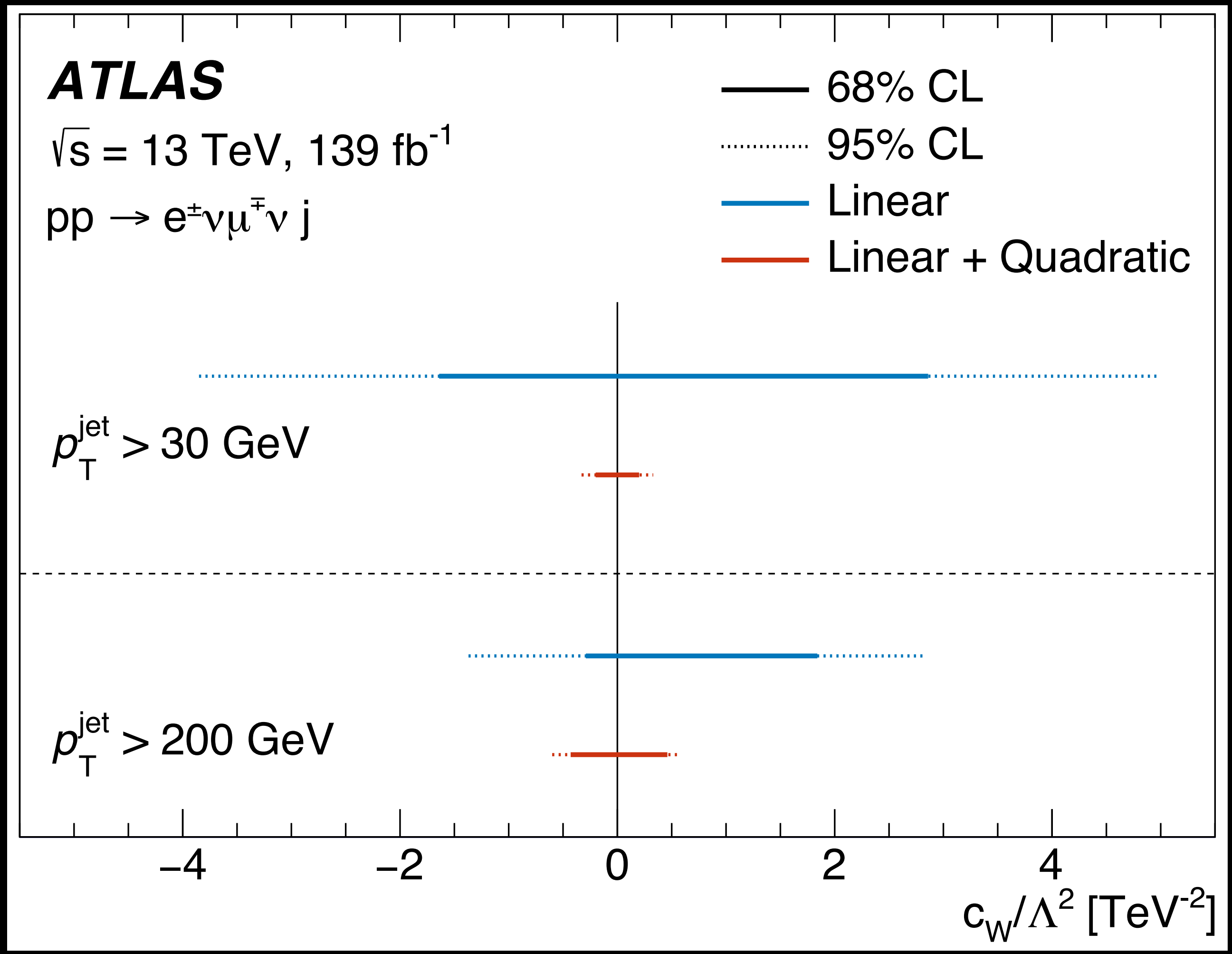




- Production mode also includes loop-induced gluon–gluon fusion process (gg → WW)

W^+W^-
CMS:
Phys. Rev. D 102 092001 (2020)
ATLAS:
Eur. Phys. J. C 79 (2019) 884
JHEP 06 (2021) 003

Measurement of the WW + 1 jet



- Requirement of hard jet alters the relative contributions of different helicity configurations
  - Reduces the suppression of the interference of SM and anomalous amplitudes

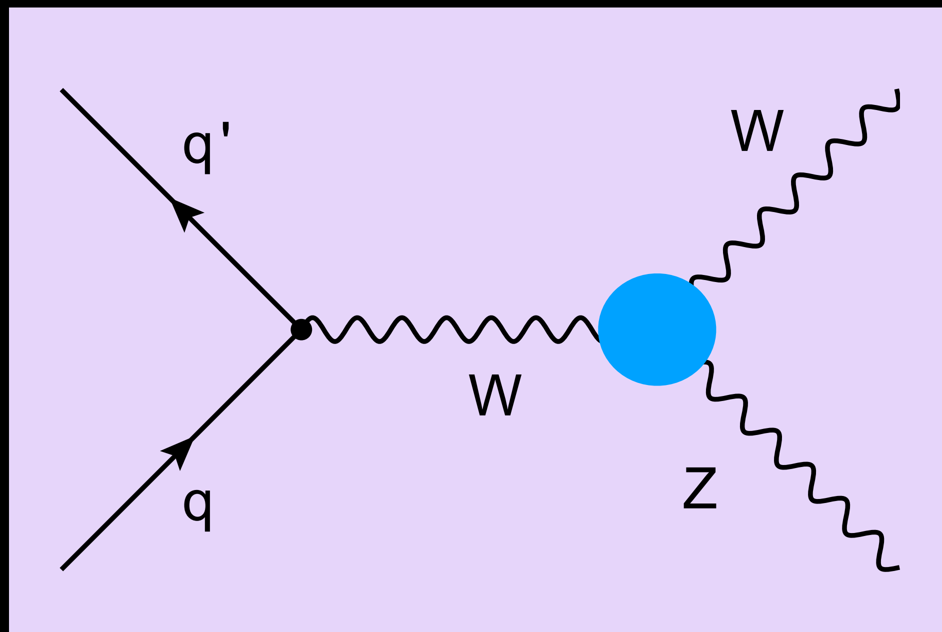
- Limits are weaker than those obtained by the ATLAS measurement of *WW* events with no associated jets

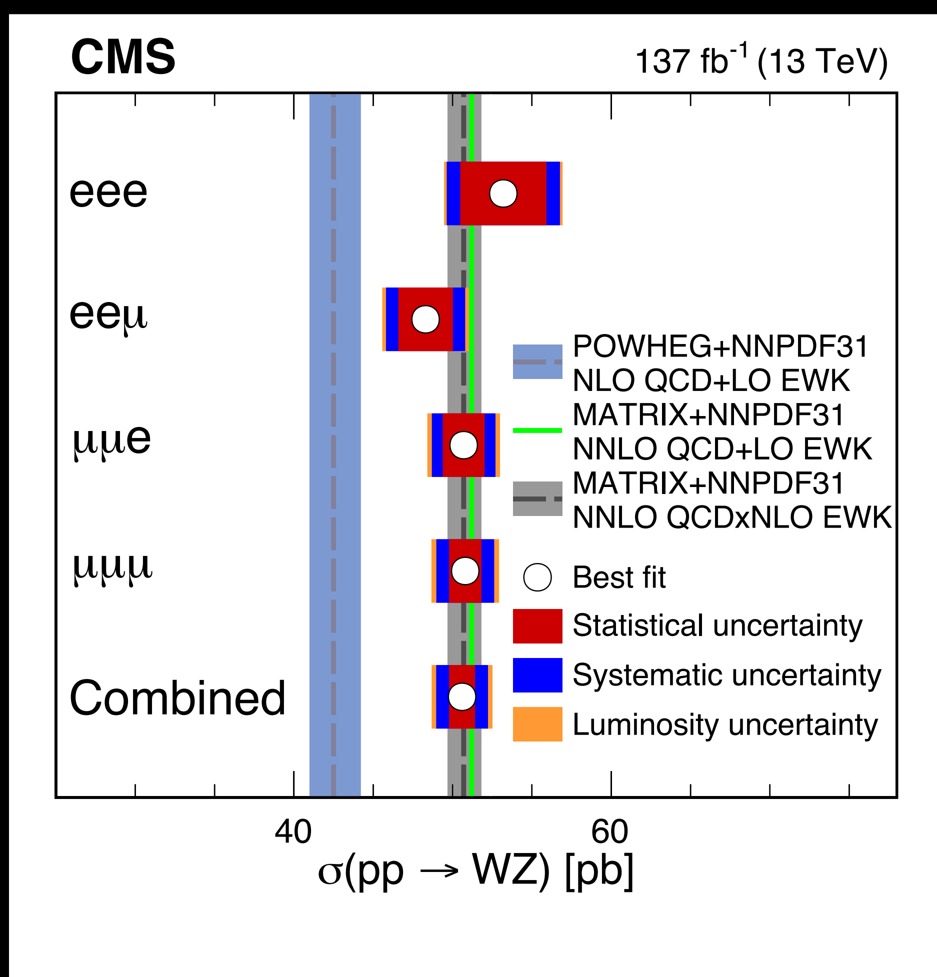
- Limits obtained from this measurement when only including linear terms have improved relative to the previous measurement

Jet p_T	Linear only	68% CI obs.	95% CI obs.	68% CI exp.	95% CI exp.
> 30 GeV	yes	[–1.64, 2.86]	[–3.85, 4.97]	[–2.30, 2.27]	[–4.53, 4.41]
> 30 GeV	no	[–0.20, 0.20]	[–0.33, 0.33]	[–0.28, 0.27]	[–0.39, 0.38]
> 200 GeV	yes	[–0.29, 1.84]	[–1.37, 2.81]	[–1.12, 1.09]	[–2.24, 2.10]
> 200 GeV	no	[–0.43, 0.46]	[–0.60, 0.58]	[–0.38, 0.33]	[–0.53, 0.48]

https://arxiv.org/pdf/1707.08060.pdf

Measurement of the WZ process



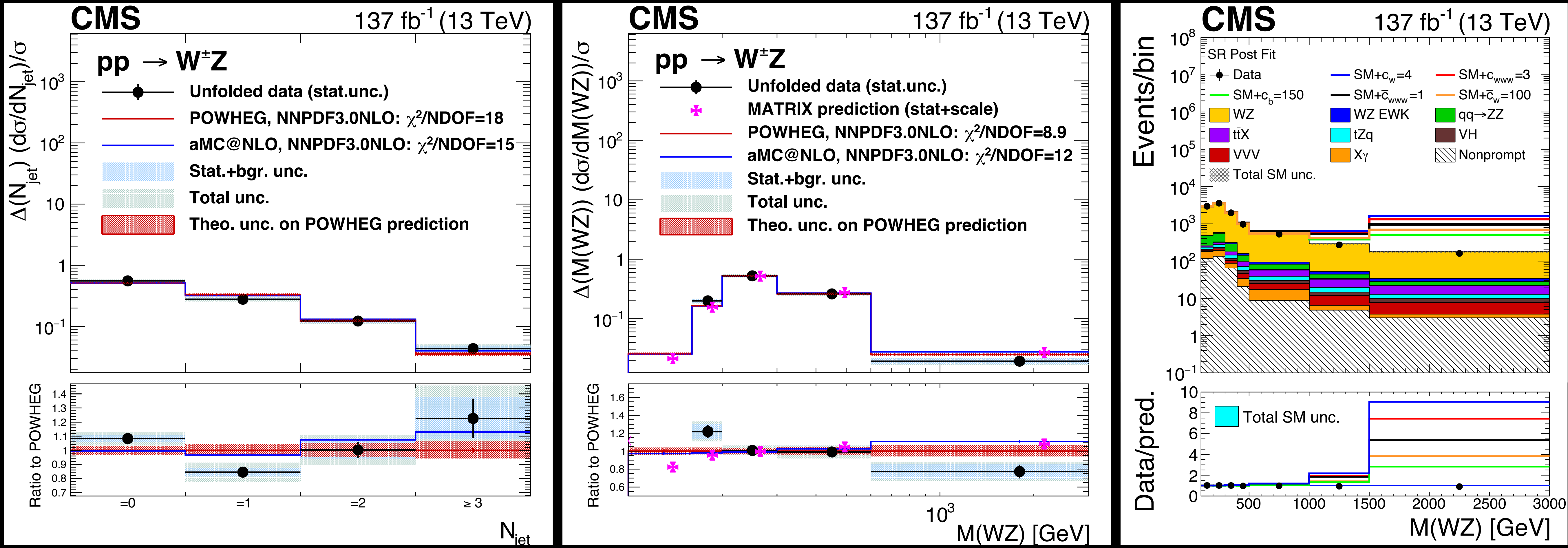


- Electroweak process: sensitive to the PDFs of u and d quarks; relatively unaffected by the gluon
- High WZ cross section makes it the dominant process that can be studied in the trilepton final state
- Ratio of W^+Z/W^-Z cross section is one of the most precisely measurable quantities
- Constitutes first measurement of longitudinally polarized W-bosons

θ^W: angular distance between the momenta of the W boson and the charged lepton from its primary decay

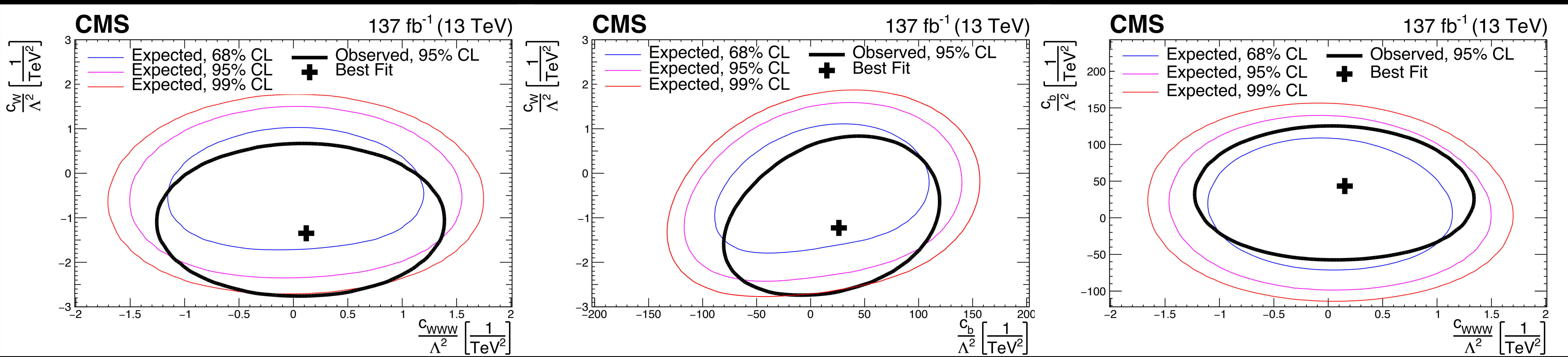
CMS: https://arxiv.org/abs/2110.11231

Measurement of the WZ process



- ☑ Unfolded distributions of sensitive variables well modeled
- ☑ Simulated signal samples normalized to NNLO cross sections

Measurement of the WZ process



Parameter	95% CI, Exp. (TeV^{-2})	95% CI, Obs. (TeV^{-2})	Best fit, Obs. (TeV^{-2})
c_w/Λ^2	$[-2.05, 1.27]$	$[-2.52, 0.33]$	-1.34
c_{www}/Λ^2	$[-1.27, 1.33]$	$[-1.04, 1.19]$	0.15
c_b/Λ^2	$[-86.0, 125.0]$	$[-42.7, 113.0]$	43.6
$\tilde{c}_{www}/\Lambda^2$	$[-0.76, 0.65]$	$[-0.62, 0.53]$	-0.03
$\tilde{c}_w/\Lambda^2$	$[-46.1, 46.1]$	$[-45.9, 45.9]$	0.0

CP conserving (first three rows)

CP non-conserving (last two rows)

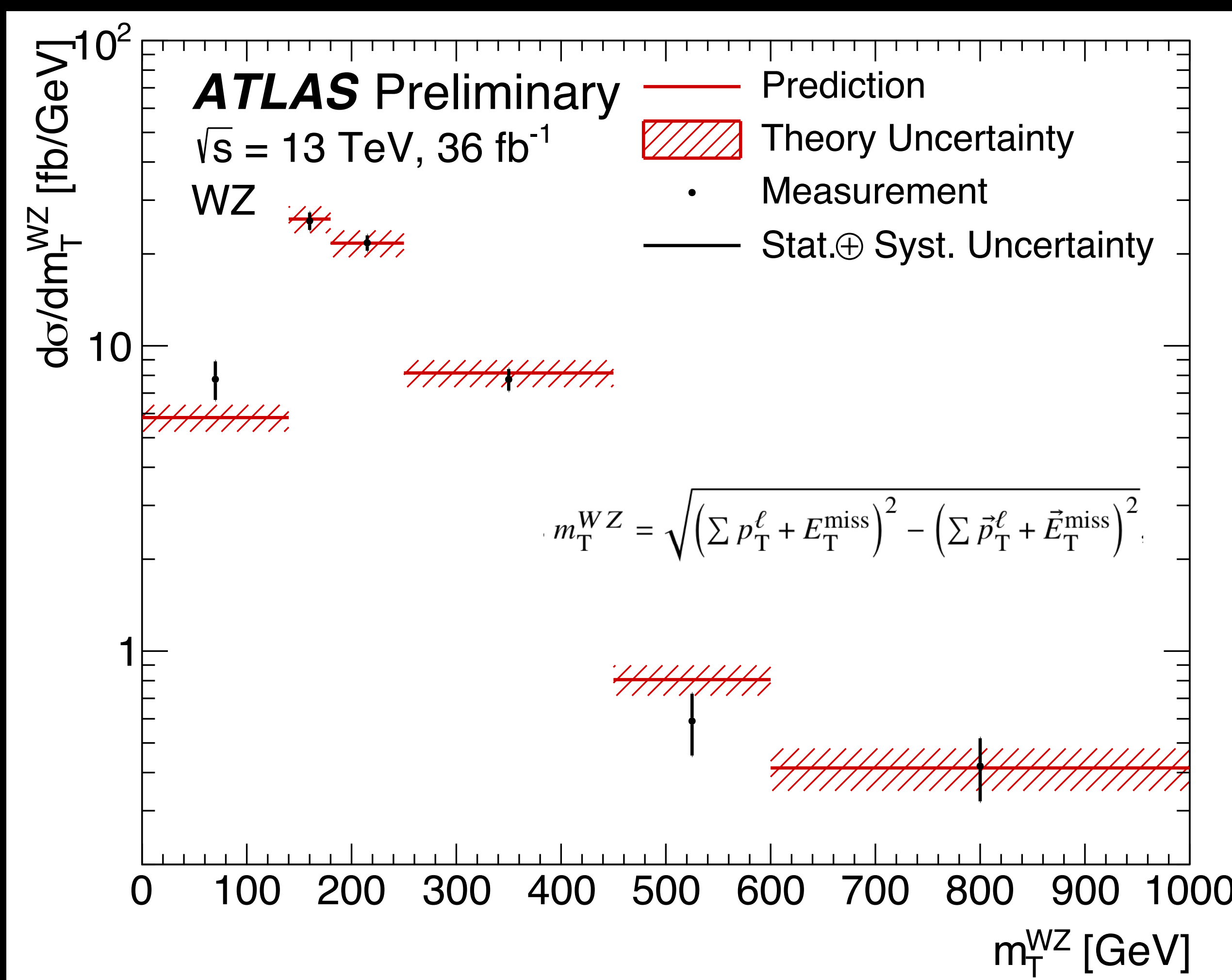
Limits computed taking interference with SM (Λ^{-2}) + pure BSM (Λ^{-4}) into account

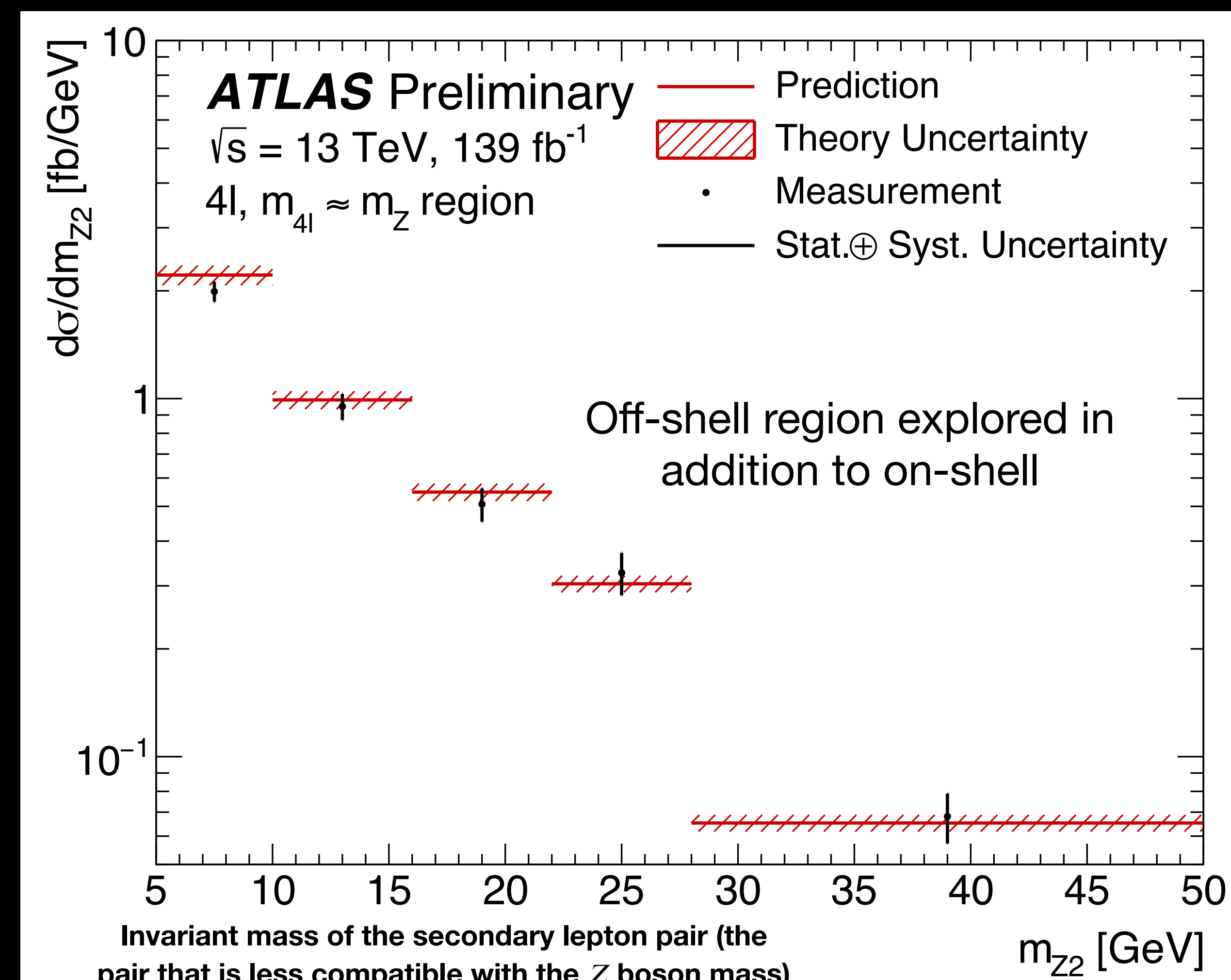
- ✓ Improvement over limits from W^+W^- analysis (taking luminosity scaling into account) for C_w and C_{www}

Combined effective field theory interpretation of differential cross-sections measurements of WW, WZ, 4l, and Z-plus-two-jets production using ATLAS data

- EFT exploration performed with combination of four final states:
  - WW and WZ in leptonic final states
  - Final state consisting of four charged leptons
  - Leptonically decaying Z-boson in vector-boson-fusion topology
- Effect of 33 SMEFT operators explored

ATLAS:
http://cdsweb.cern.ch/record/2776648



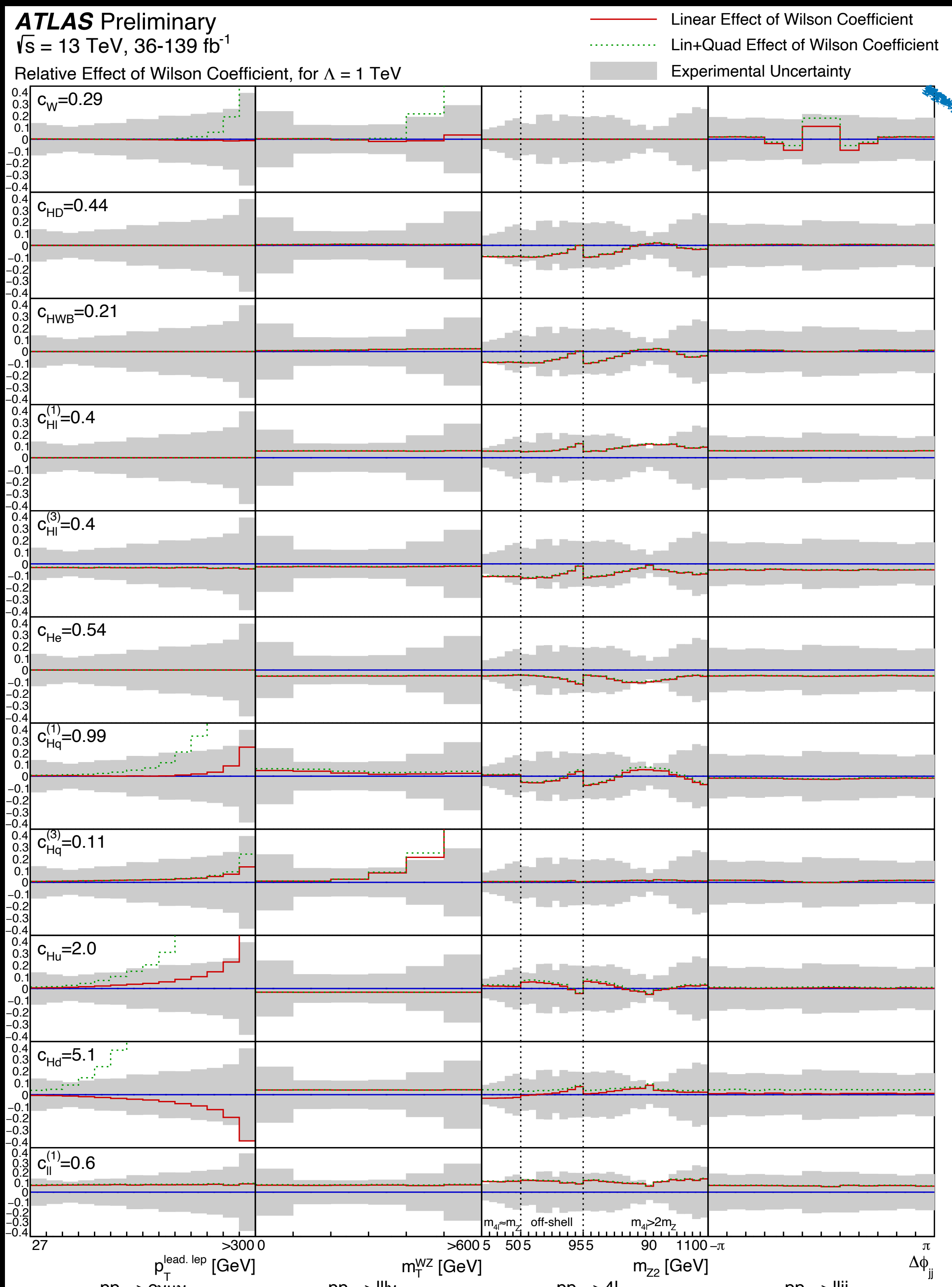


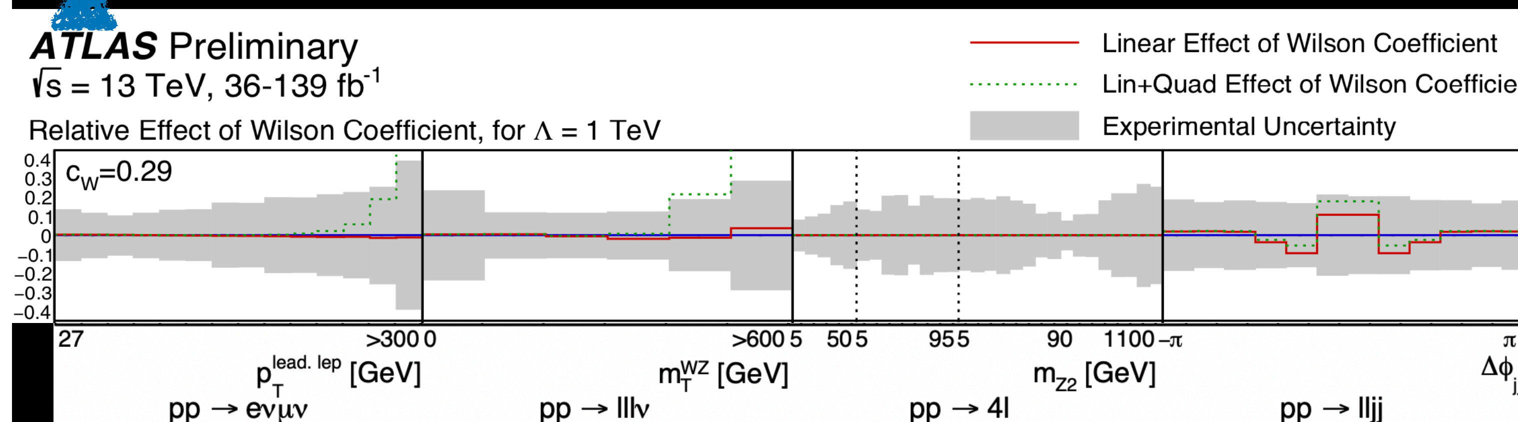
Combined effective field theory interpretation of differential cross-sections measurements of WW, WZ, 4l, and Z-plus-two-jets production using ATLAS data

☑ Form of the gauge boson operators under exploration (leptonic operators also explored the analysis, focusing only on a subset)

Wilson coefficient and operator		Final state affected at leading order			
		$e^{\pm}\nu\mu^{\mp}\nu$	$\ell^+\ell^-\ell^{\pm}\nu$	4ℓ	$\ell^+\ell^- jj$
c_G	$f^{abc}G_{\mu}^{a\nu}G_{\nu}^{b\rho}G_{\rho}^{c\mu}$				✓
c_W	$\epsilon^{IJK}W_{\mu}^{I\nu}W_{\nu}^{J\rho}W_{\rho}^{K\mu}$	✓	✓		✓
c_{HD}	$(H^{\dagger}D_{\mu}H)^{*}(H^{\dagger}D_{\mu}H)$		✓	✓	✓
c_{HWB}	$H^{\dagger}\tau^{I}HW_{\mu\nu}^{I}B^{\mu\nu}$	✓	✓	✓	✓
$c_{Hl}^{(1)}$	$(H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{l}\gamma^{\mu}l)$	✓	✓	✓	✓
$c_{Hl}^{(3)}$	$(H^{\dagger}i\overleftrightarrow{D}_{\mu}^{I}H)(\bar{l}\tau^{I}\gamma^{\mu}l)$	✓	✓	✓	✓
c_{He}	$(H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{e}\gamma^{\mu}e)$		✓	✓	✓
$c_{Hq}^{(1)}$	$(H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{q}\gamma^{\mu}q)$	✓	✓	✓	✓
$c_{Hq}^{(3)}$	$(H^{\dagger}i\overleftrightarrow{D}_{\mu}^{I}H)(\bar{q}\tau^{I}\gamma^{\mu}q)$	✓	✓	✓	✓
c_{Hu}	$(H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{u}\gamma^{\mu}u)$	✓	✓	✓	✓
c_{Hd}	$(H^{\dagger}i\overleftrightarrow{D}_{\mu}H)(\bar{d}\gamma^{\mu}d)$	✓	✓	✓	✓

Combined effective field theory interpretation of differential cross-sections measurements of WW, WZ, 4l, and Z-plus-two-jets production using ATLAS data

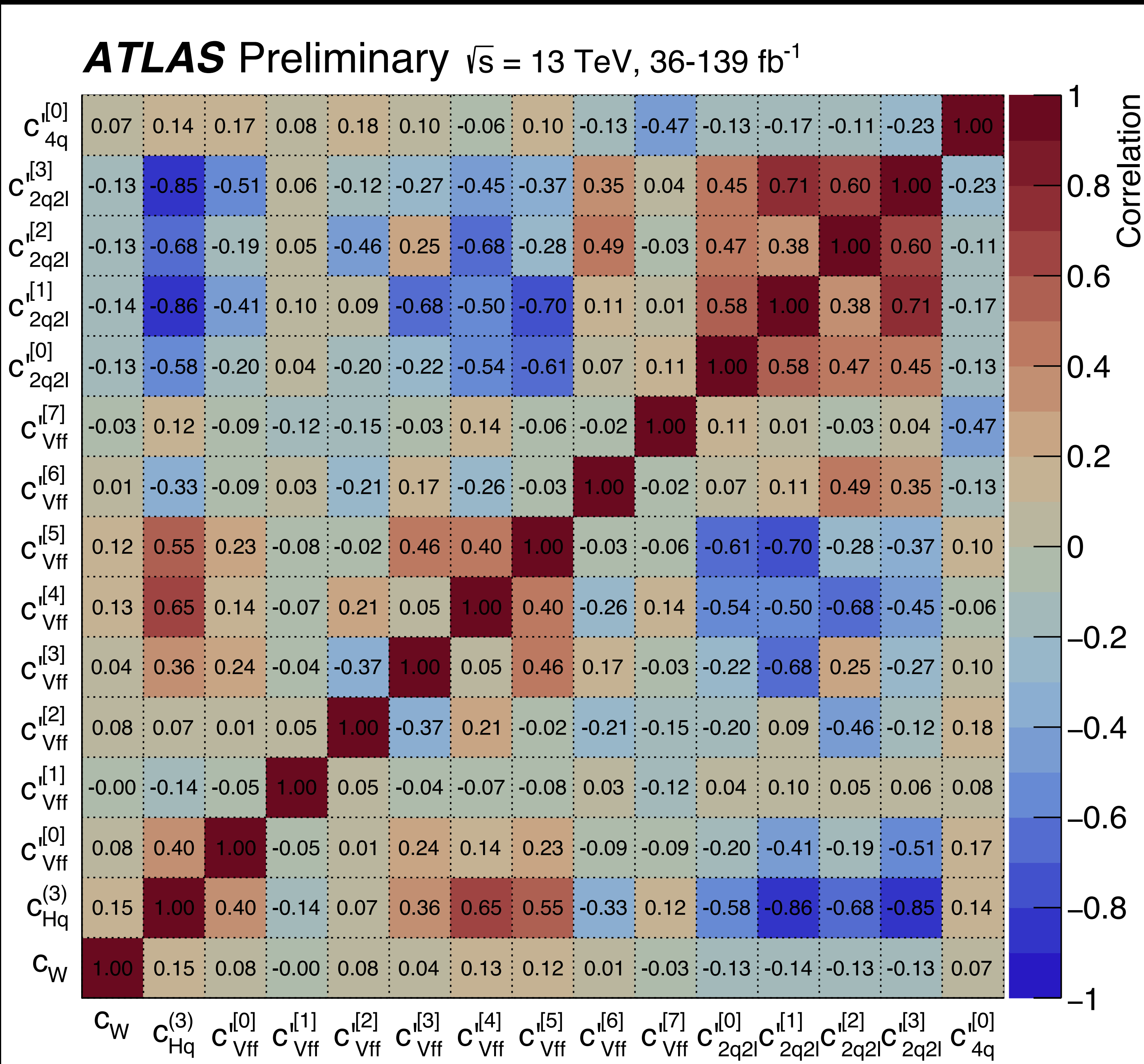




- ☑ Impact of the Wilson coefficients on the differential cross sections, relative to the SM cross section
- ☑ Value of the Wilson coefficient obtained from 2σ sensitivity of the SMEFT model including only linear terms

Combined effective field theory interpretation of differential cross-sections measurements of WW, WZ, 4l, and Z-plus-two-jets production using ATLAS data

ATLAS EXPERIMENT

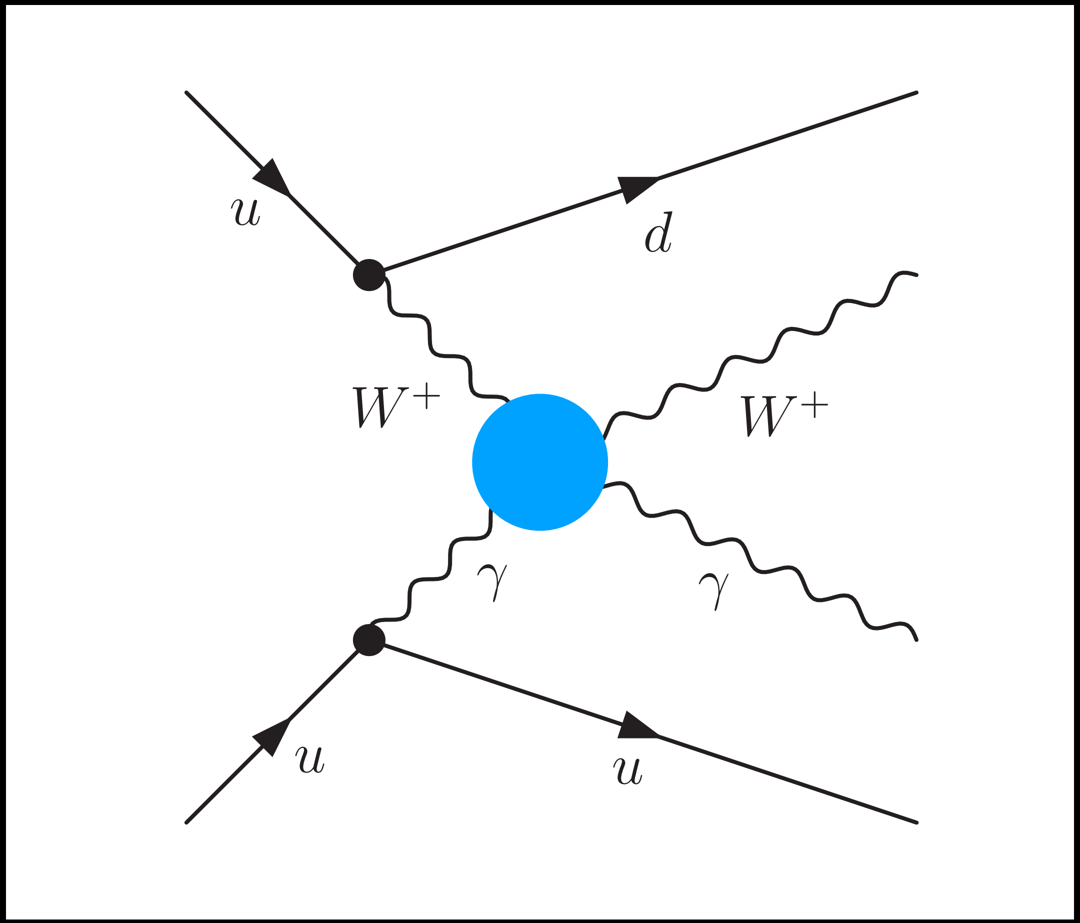


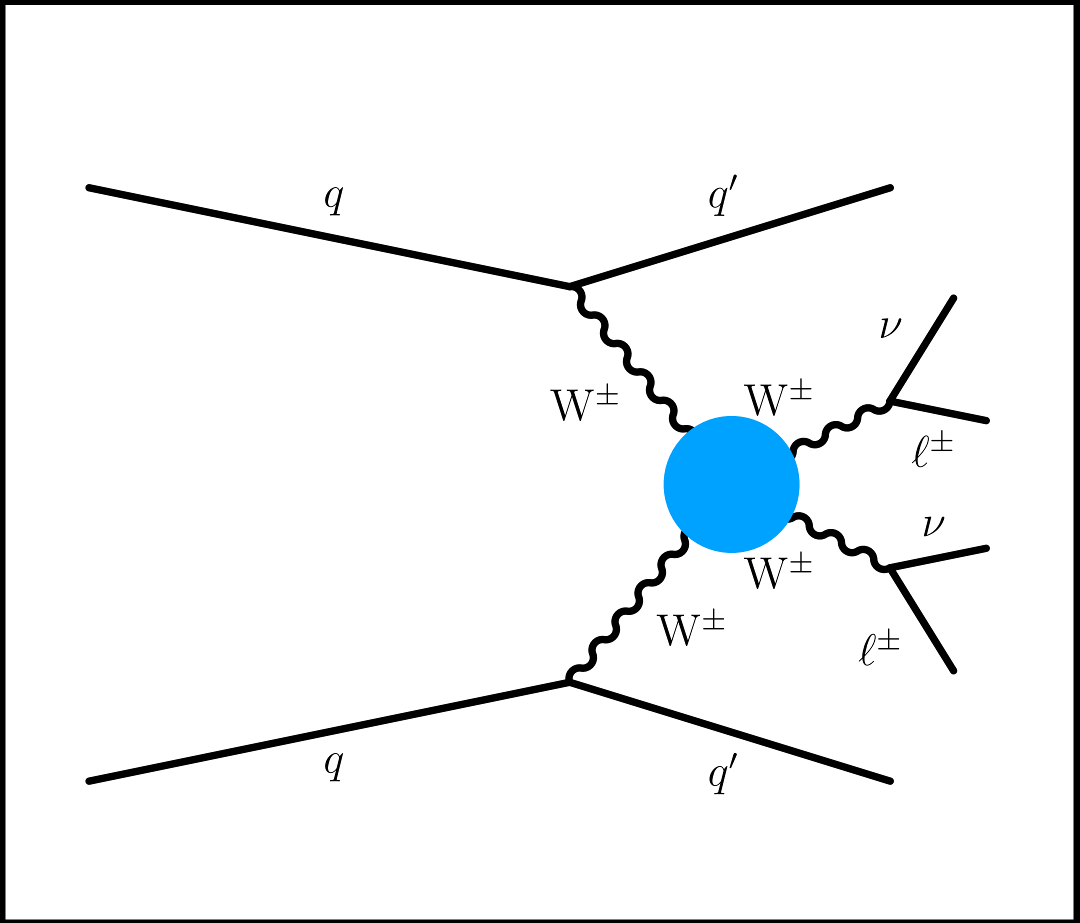
Correlation between the 15 parameters of interest

- Focus of this analysis is the simultaneous measurement of all Wilson coefficients
- Construct a modified basis (linear combination of Warsaw basis vectors https://cds.cern.ch/record/2694284, https://cds.cern.ch/record/2743067) to reduce flat directions and identify sensitive directions
- Hessian matrix constructed in the space of Wilson coefficients and eigenvectors are identified
- This analysis sets the stage for global combination efforts

Processes of interest

- ☑ Vector-boson scattering production at the LHC
- ☑ Triboson production*





*more on that later

Exploration of dimension-8 operators

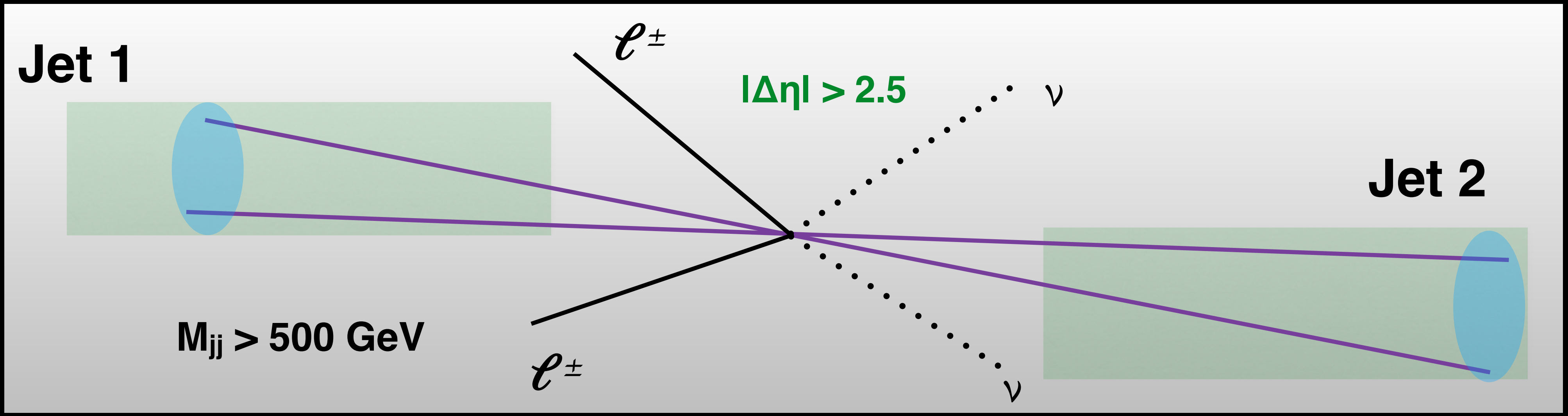
$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \sum_i \frac{c_i}{\lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\lambda^4}\mathcal{O}_j + \cdots$$

☑ **CP conserving quartic operators are of the form:**

$$\mathcal{L}_{\mathrm{S},0} = \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \times \left[(D_\mu\Phi)^\dagger D_\nu\Phi\right] \qquad \mathcal{L}_{\mathrm{M},0} = Tr\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \left[(D_\beta\Phi)^\dagger D^\beta\Phi\right]$$

$$\mathcal{L}_{\mathrm{T},0} = Tr\left[W_{\mu\nu}W^{\mu\nu}\right] \times Tr\left[W_{\alpha\beta}W^{\alpha\beta}\right]$$

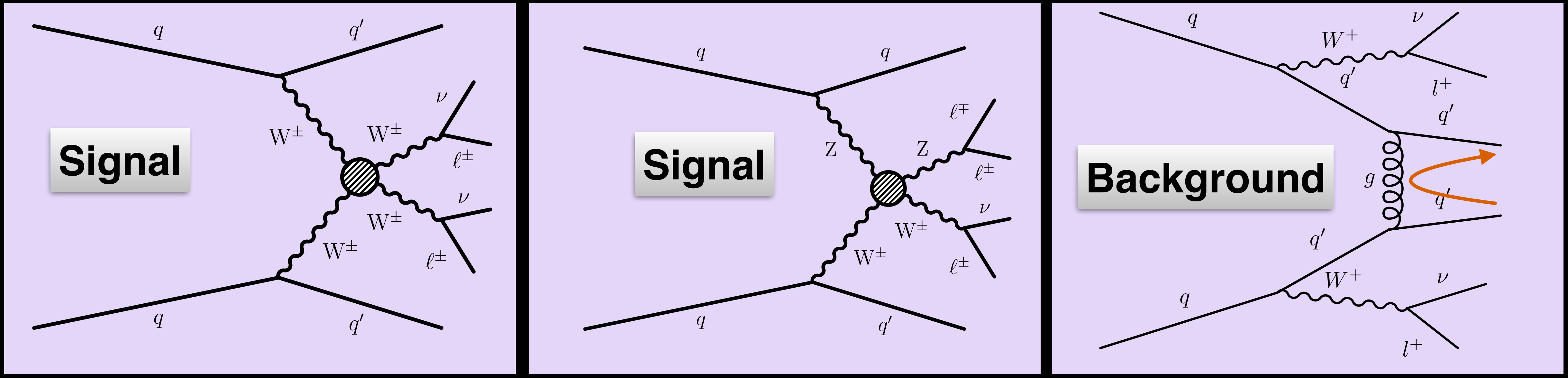
Vector boson scattering processes



- Final state consists of **same-signed leptons** and **2 high p_T jets**
- **Rapidity gap between jets (no color flow)**
- Large invariant mass of the two jets
- **Use of Zeppenfeld variable**

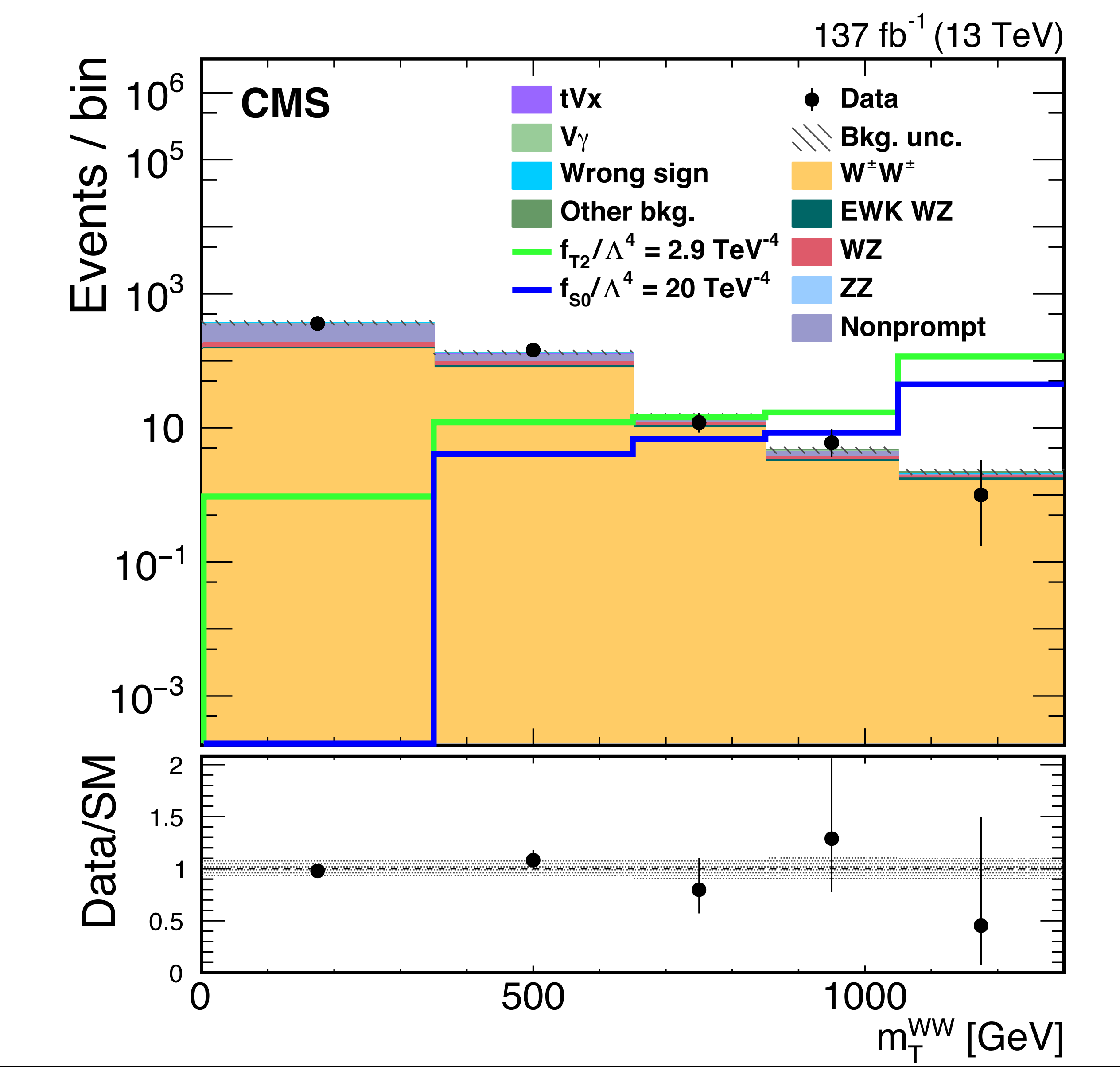
Provides unique access to quartic couplings

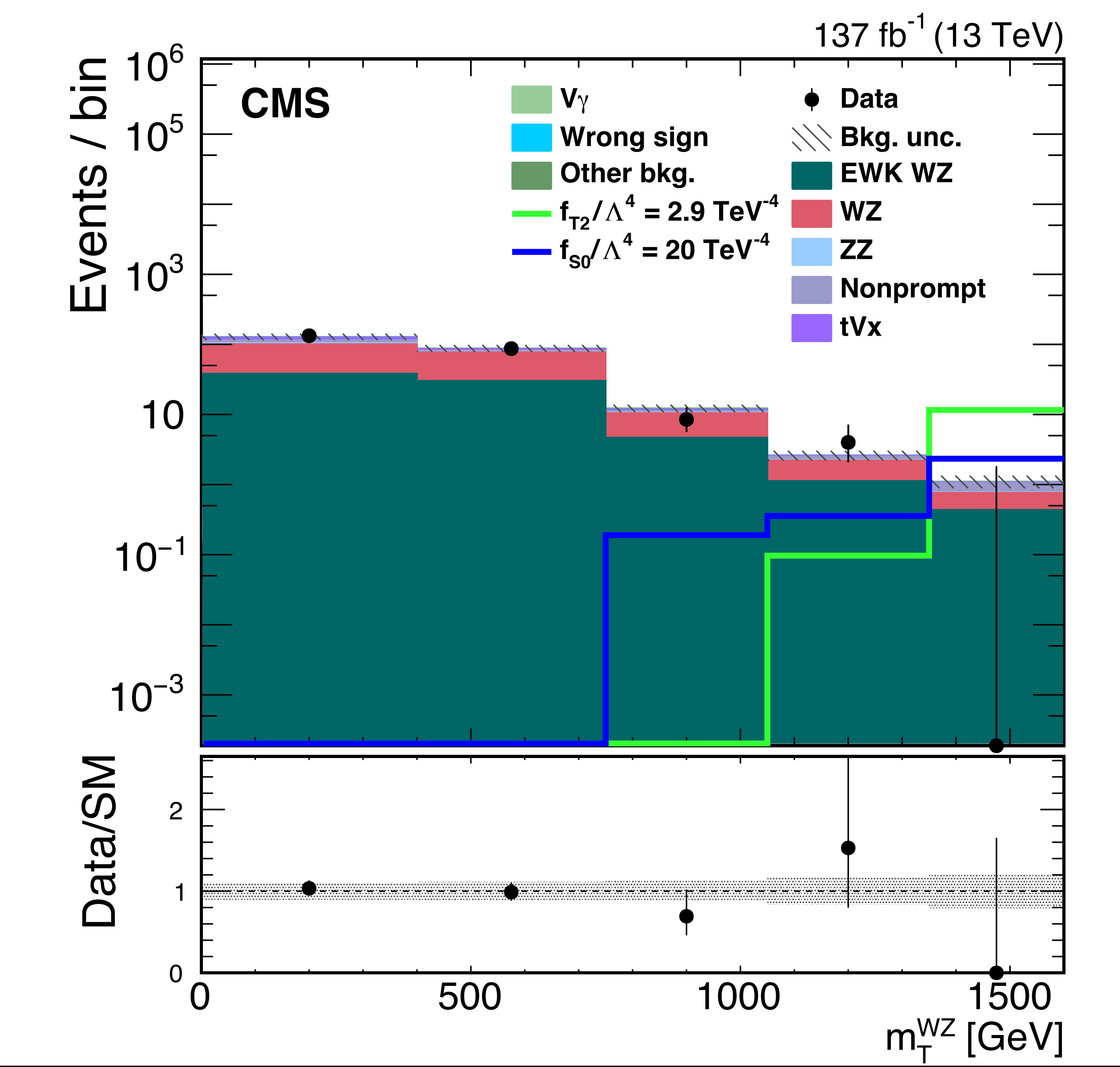
$$z_l^* = |\eta_l - \frac{1}{2}(\eta_{j1} + \eta_{j2})|/|\Delta\eta_{jj}|$$



Exploration of WW and WZ processes with two additional jets

CMS: Phys. Lett. B 809 (2020) 135710



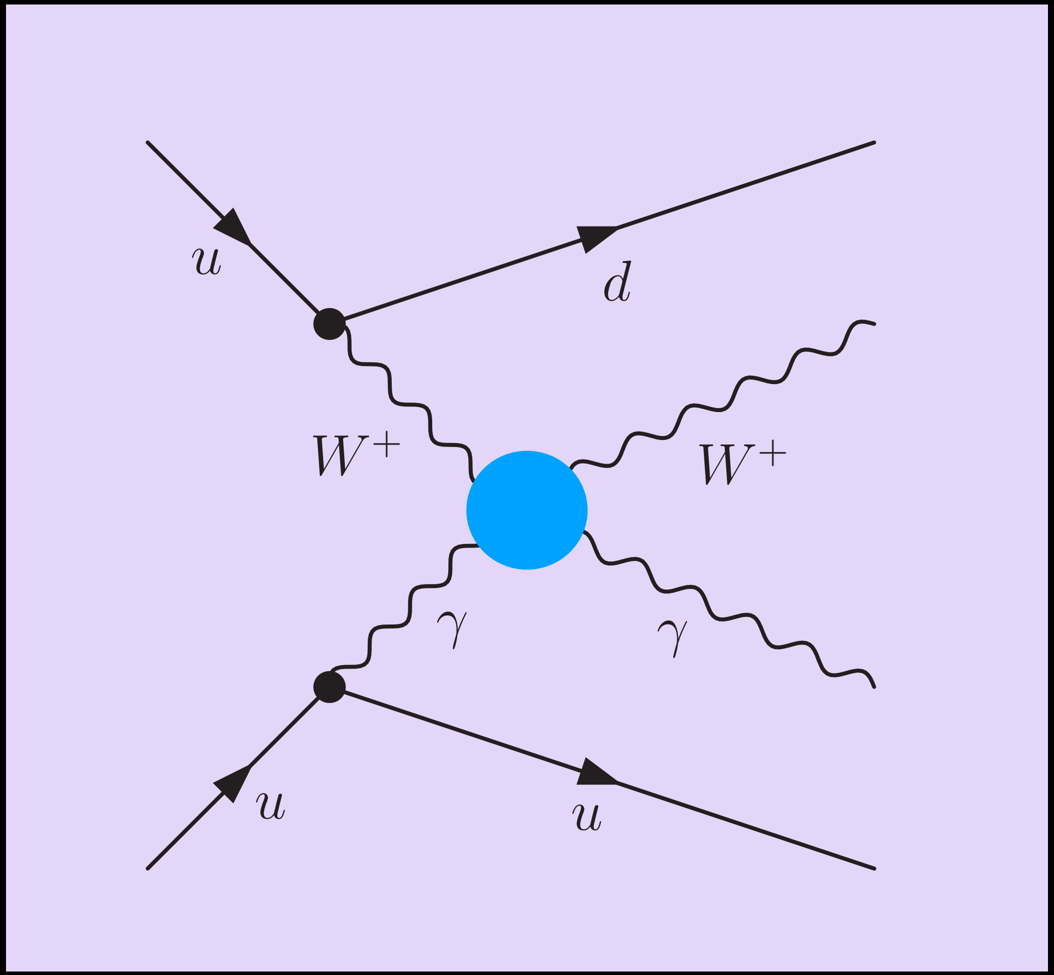


☑ mT(VV) sensitive to presence of dim-8 operators

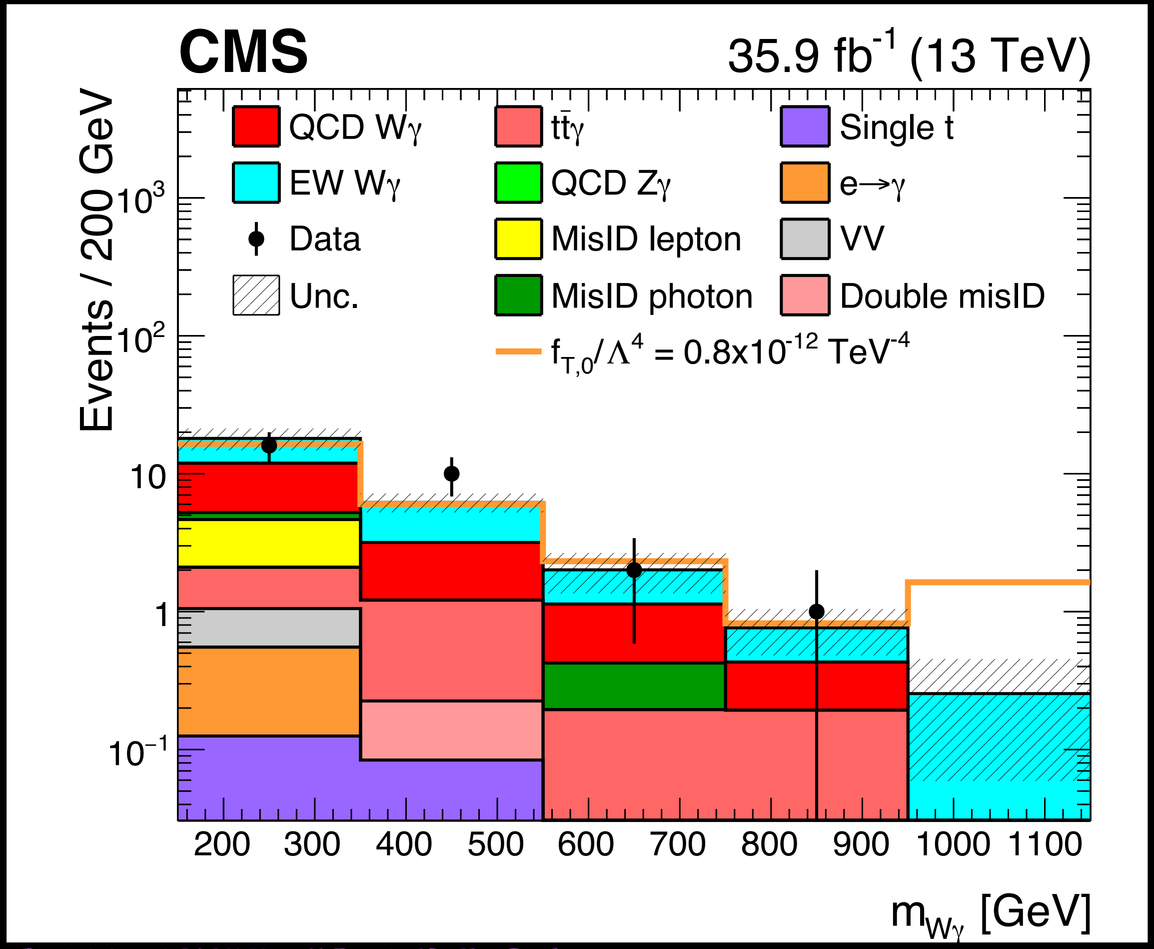
$$m_{\mathrm{T}}(VV) = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i p_{z,i}\right)^2}$$

CMS: Phys. Lett. B 811 (2020) 135988

Wγ + 2 jets



- First observation of the Wγ + 2 jets process with observed (expected) significance of 5.3 (4.8) σ
- Exploration of dim-8 operators possible due to presence of SM quartic coupling
- Invariant mass of the Wγ system is sensitive to presence of dim-8 operators



- Exploration of full set of "mixed" operators performed
- For the parameters $f_{M2\text{-}5}$, $f_{M6\text{-}7}$ most stringent limits

Factoring in EFT validity

- EFT validity taken into account by restricting EFT integration at the unitarity limit
- Unitarity limit is at ~1.5 TeV

Philosophy 1. **Disregard unitarity limits (CMS mainstream)**
- technically simplest,
- fair to quantify the relative precision of different measurements and the degree of agreement/disagreement with the SM,
- obtained numbers do not have direct EFT interpretation and unitarity violation usually occurs well within the measured range.

Philosophy 2. **Unitarization techniques:**
Amplitude saturation, e.g., K-matrix (ATLAS mainstream),
Form factor approach (e.g. VBFNLO)
- describe the maximum possible signal related to a given operator,
- no unique prescription,
- part of a model,
- obtained numbers not easy to interpret within the EFT.

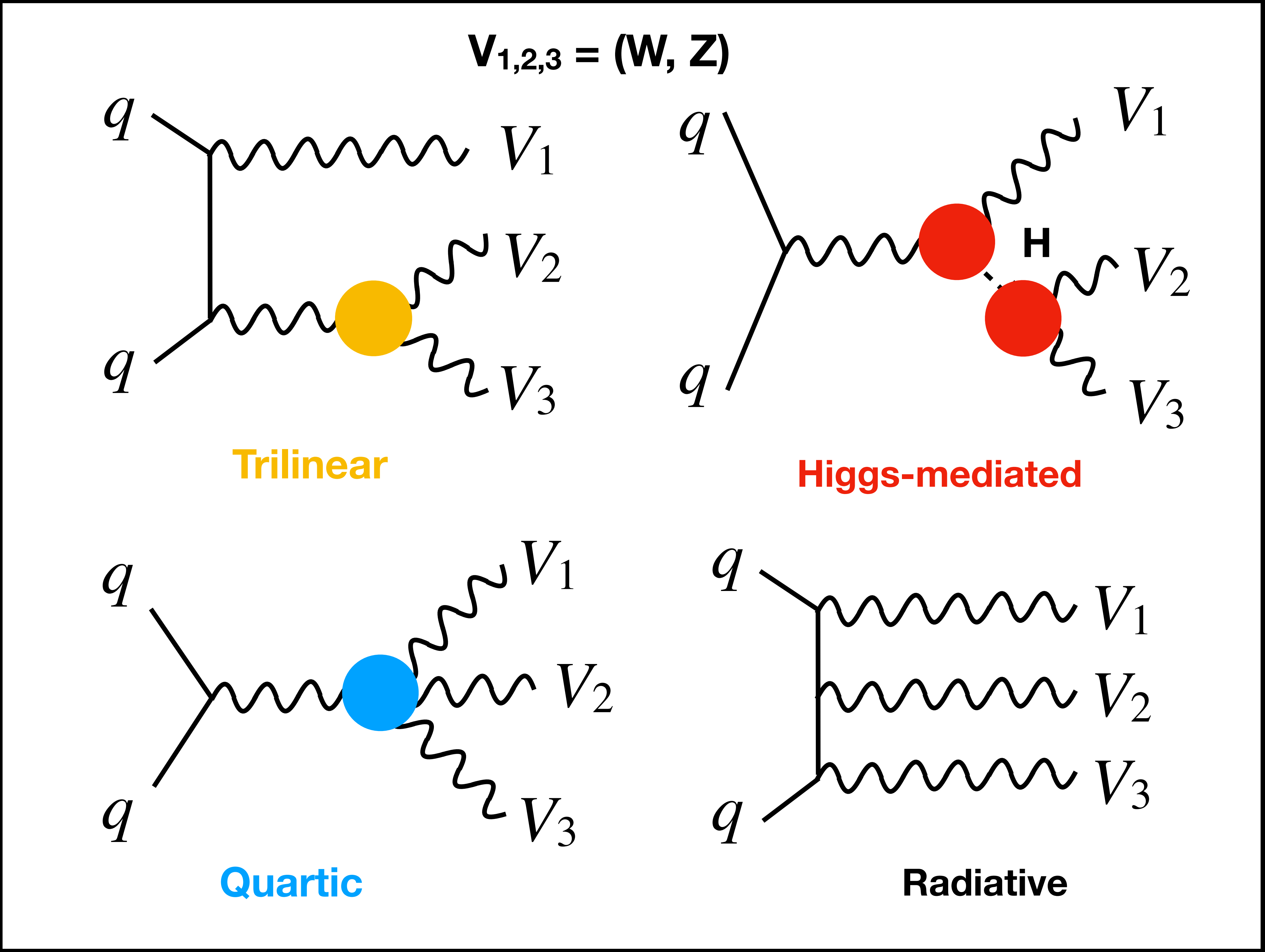
From Michal Szleper's talk

Truncation, validity, uncertainties

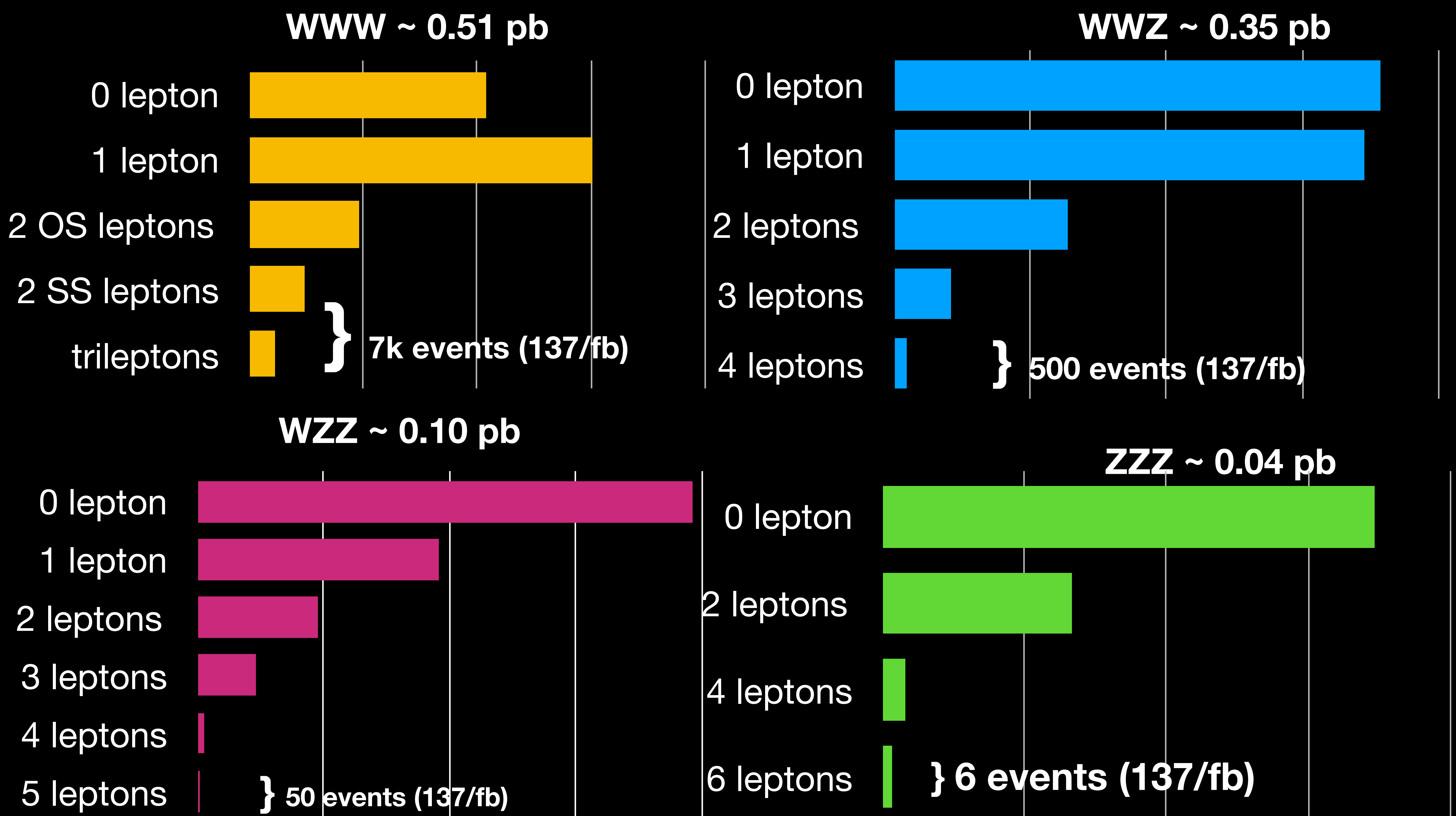
Ilaria Brivio, Sally Dawson, Jorge de Blas, Gauthier Durieux, Pierre Savard (editors), Roberto Contino, Céline Degrande, Adam Falkowski, Florian Goertz, Christophe Grojean, Fabio Maltoni, Ken Mimasu, Giuliano Panico, Francesco Riva, William Shepherd, Eleni Vryonidou, Andrea Wulzer, Cen Zhang **https://arxiv.org/abs/2201.04974v1**

- Limits worse by a factor of 5 in comparison with limits without unitarity constraints but more physical

Triboson processes



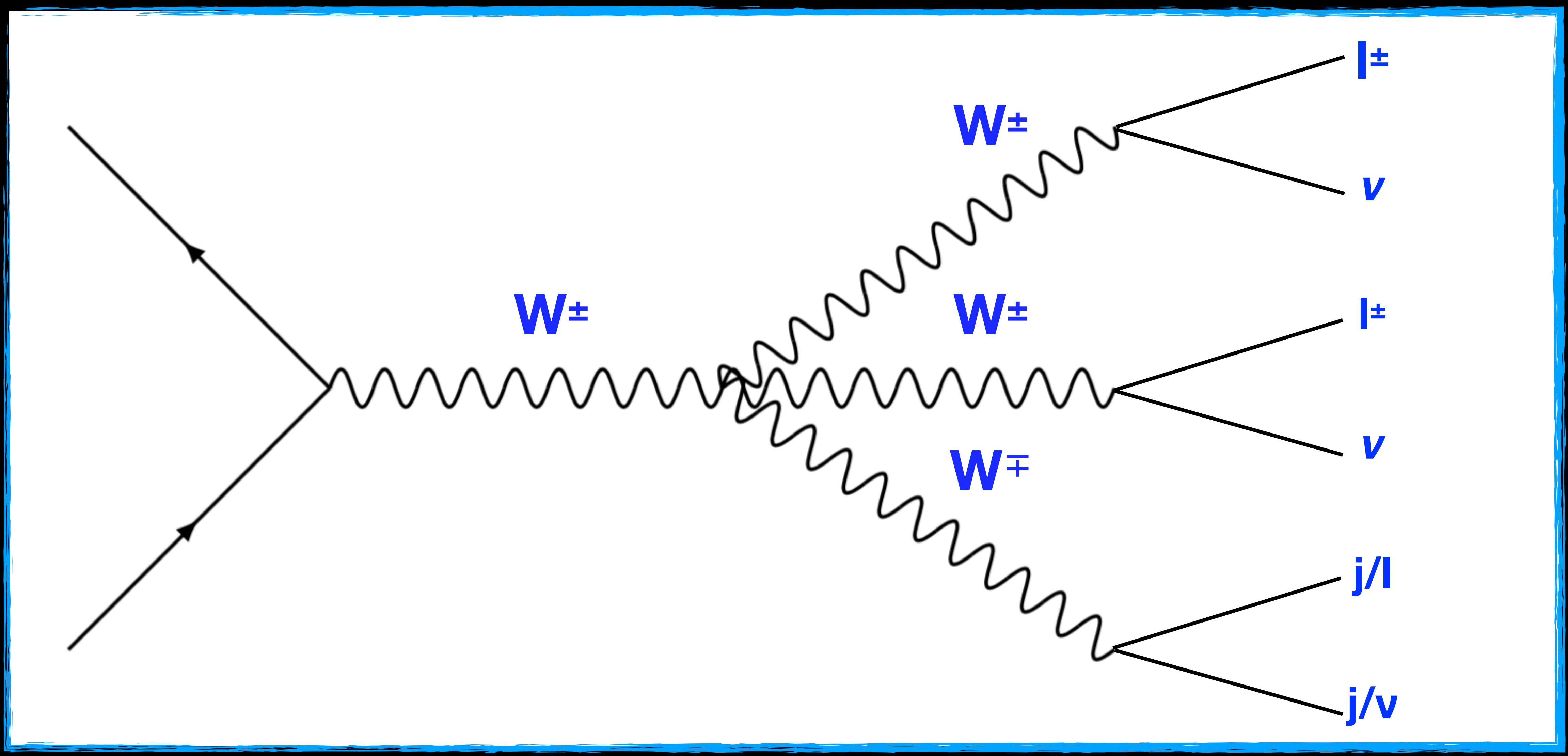
Cross sections X branching fractions



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

Background reduction → $\sigma_{background} \sim \sigma_{signal}$

WWW production in the Standard Model

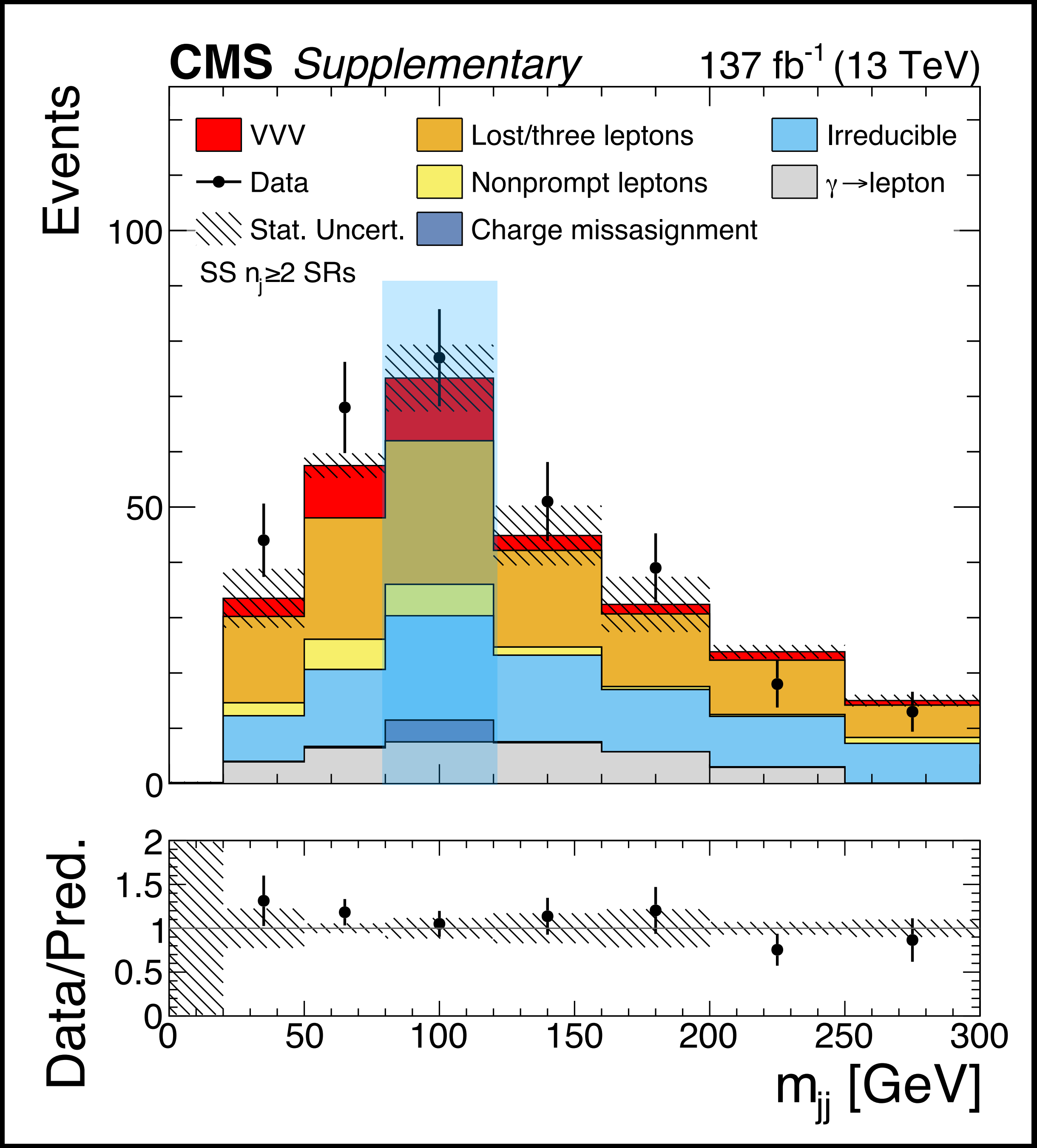


Require:

- ✔ Two leptons of <u>identical charge</u> arising out of the decay of two W-bosons
- ✔ Three leptons

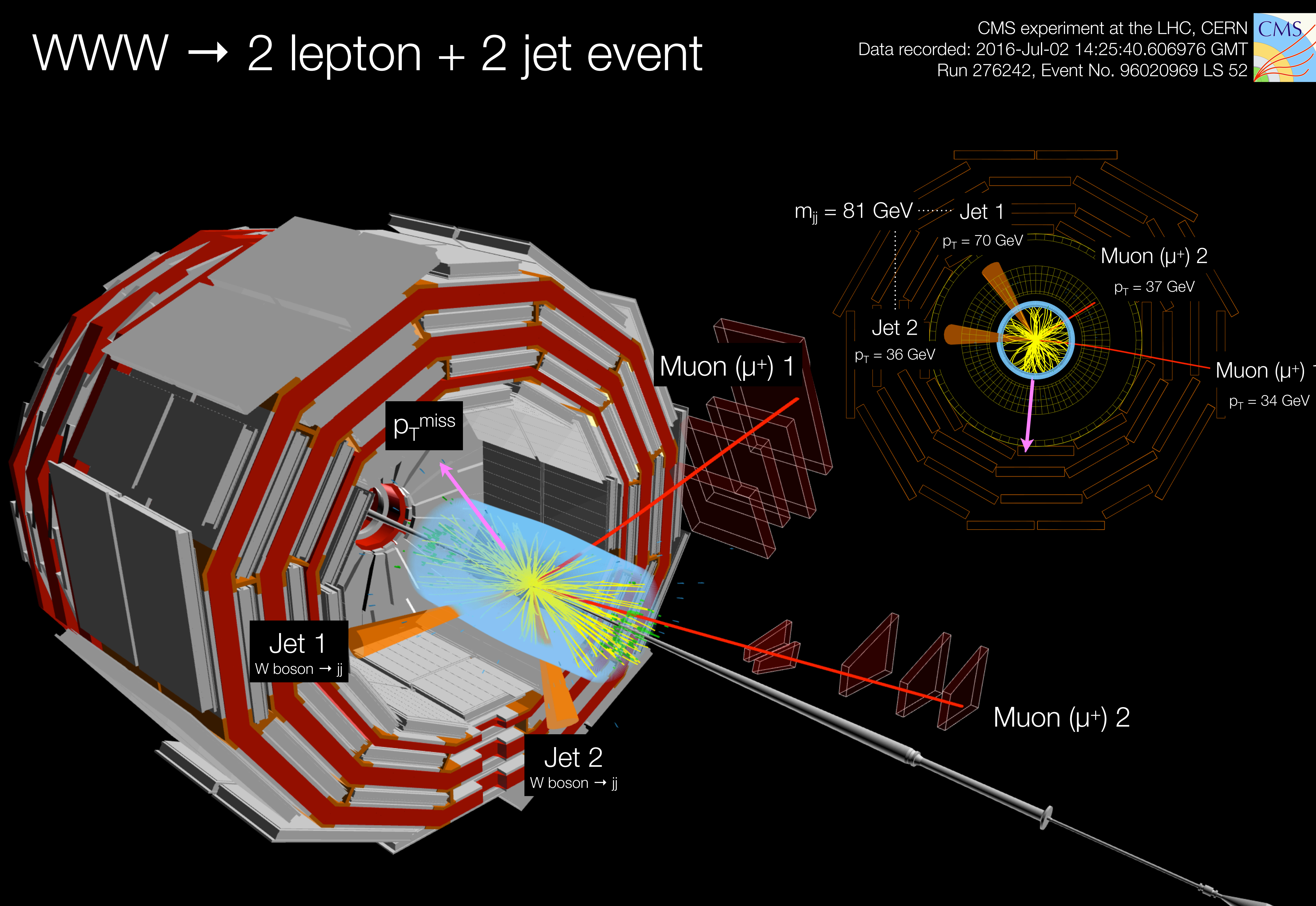
Search for WWW in dilepton final state

- Search for WWW in:
  - 2 same-signed leptons + 2 jets
    - further categorized based on $|M_{jj} - M_W| \lesssim 15$ GeV
  - 2 same-signed leptons + 1 jet
- Major backgrounds are WZ and nonprompt contribution, some prompt ($W^{\pm}W^{\pm}jj$ / ttW)
- BDTs trained against nonprompt and prompt backgrounds

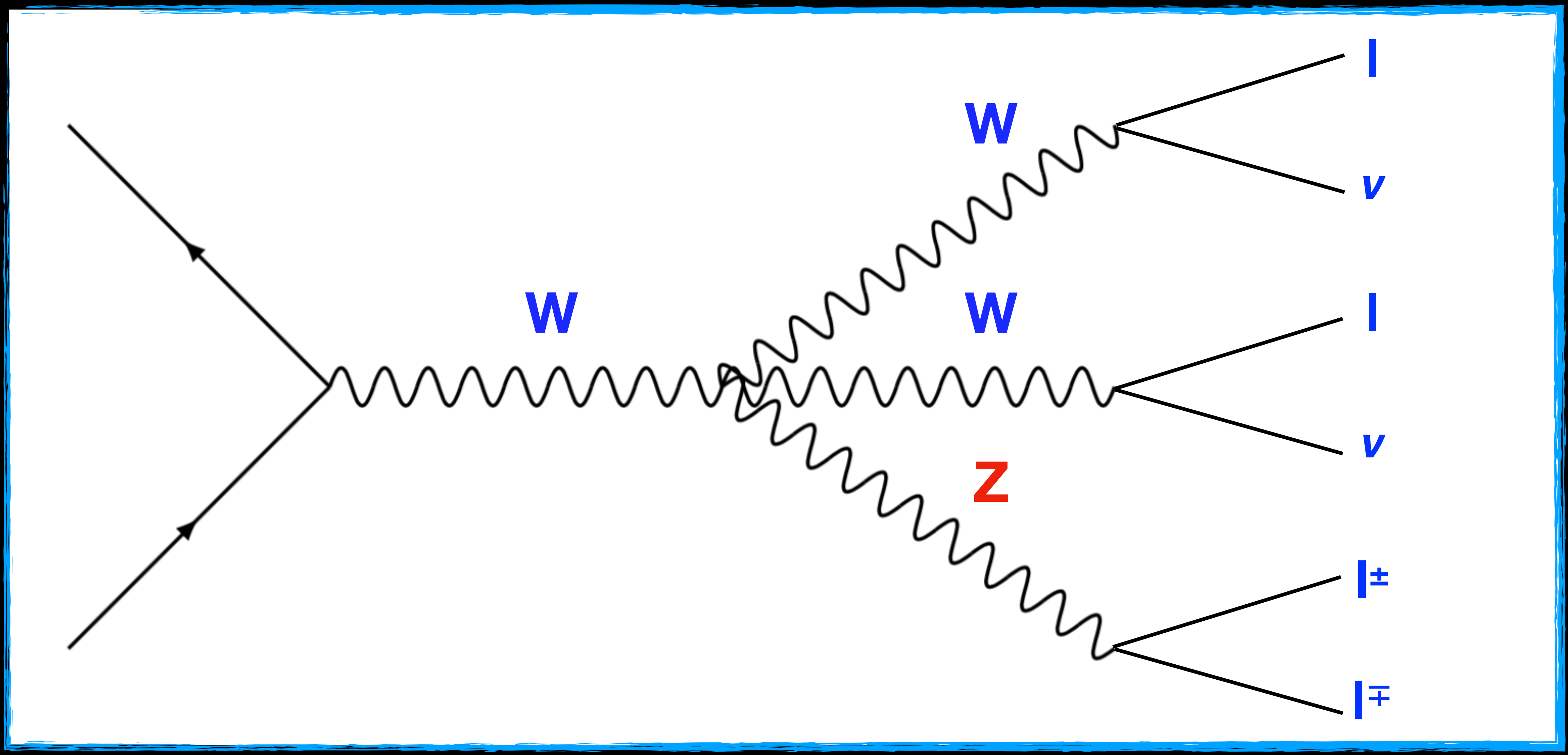


WWW in dilepton final state

WWW → 2 lepton + 2 jet event



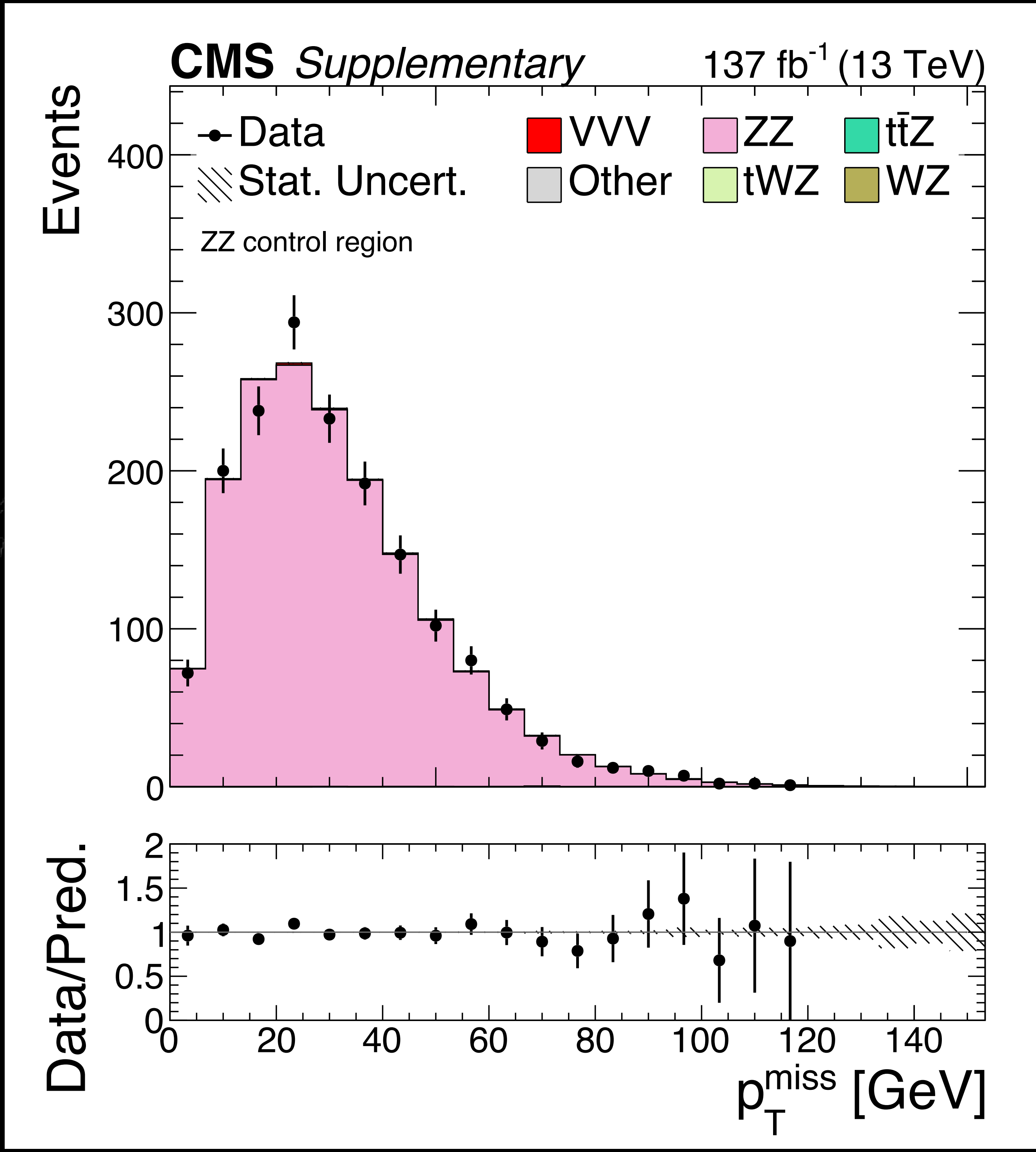
Search for WWZ in four final state



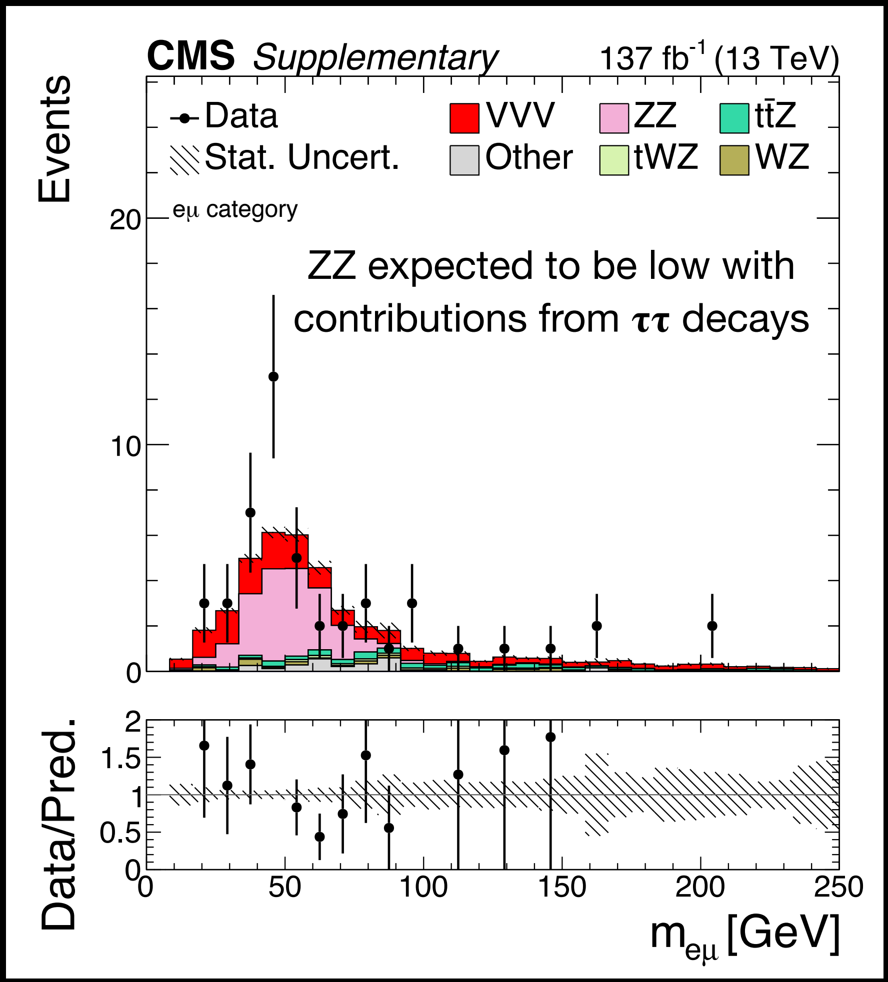
Require four leptons targeting decay products arising out of the W and Z-bosons

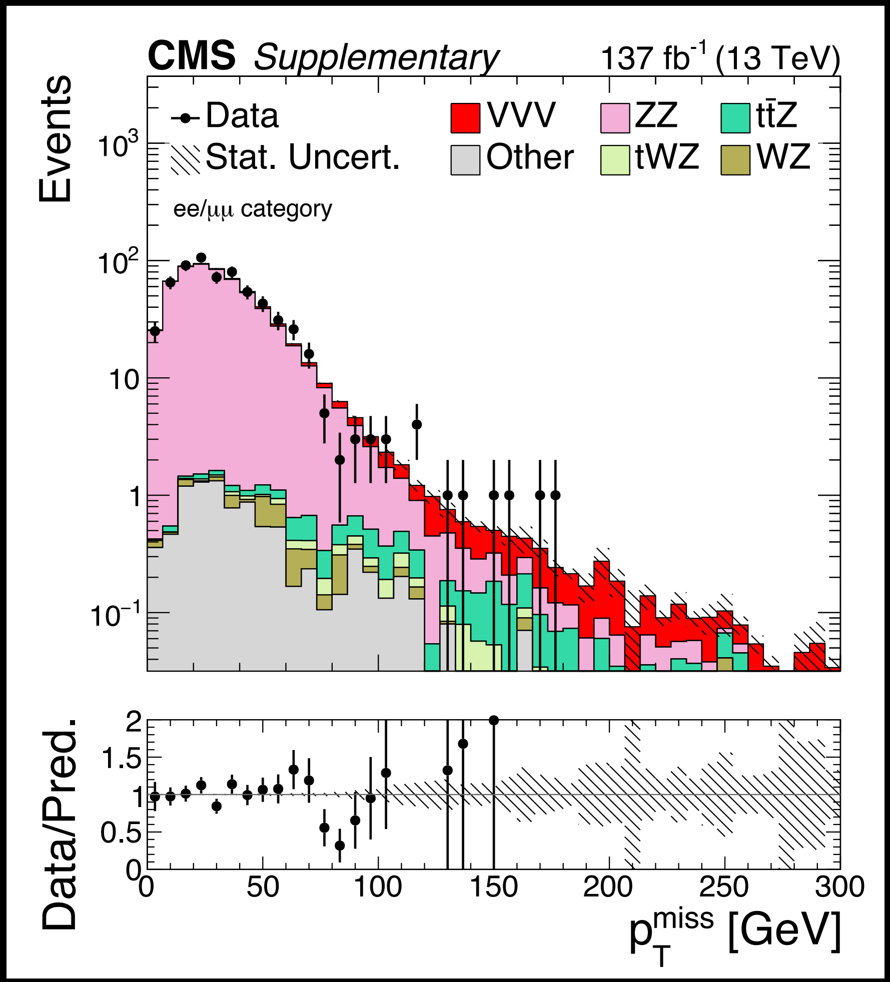
Very clean channel!

- Requiring the presence of four leptons leads to the presence of almost no non-prompt leptons
- Further requiring that there be two Z-boson candidates, as expected in a ZZ process, can lead to a control region that is 98% pure in ZZ
- This control region enables the study of the ZZ process, which is the major background in this channel
- Need to identify variables that can lead to the discrimination of ZZ from WWZ process (target signal)



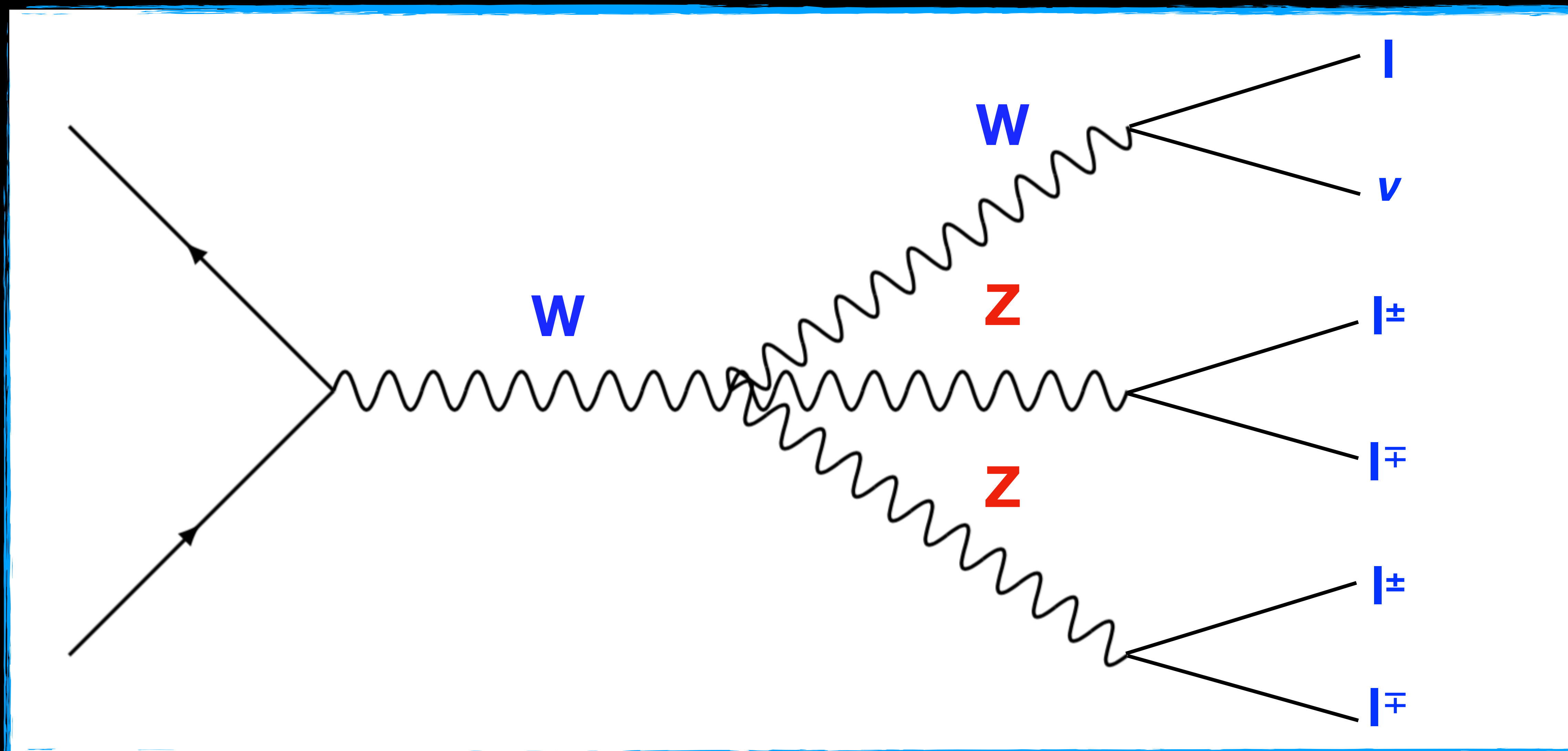
Some interesting variables to separate signal from backgrounds





- Can break down signal region into various components:
  - Require the presence of one Z-boson
    - Further split the signal region based on the presence of e-μ pairs
    - ZZ contributes through $\tau\tau$ decays (of each Z) leading to e-μ pairs but mass of the e-μ pair will be lower than the Z-mass due to presence of neutrinos

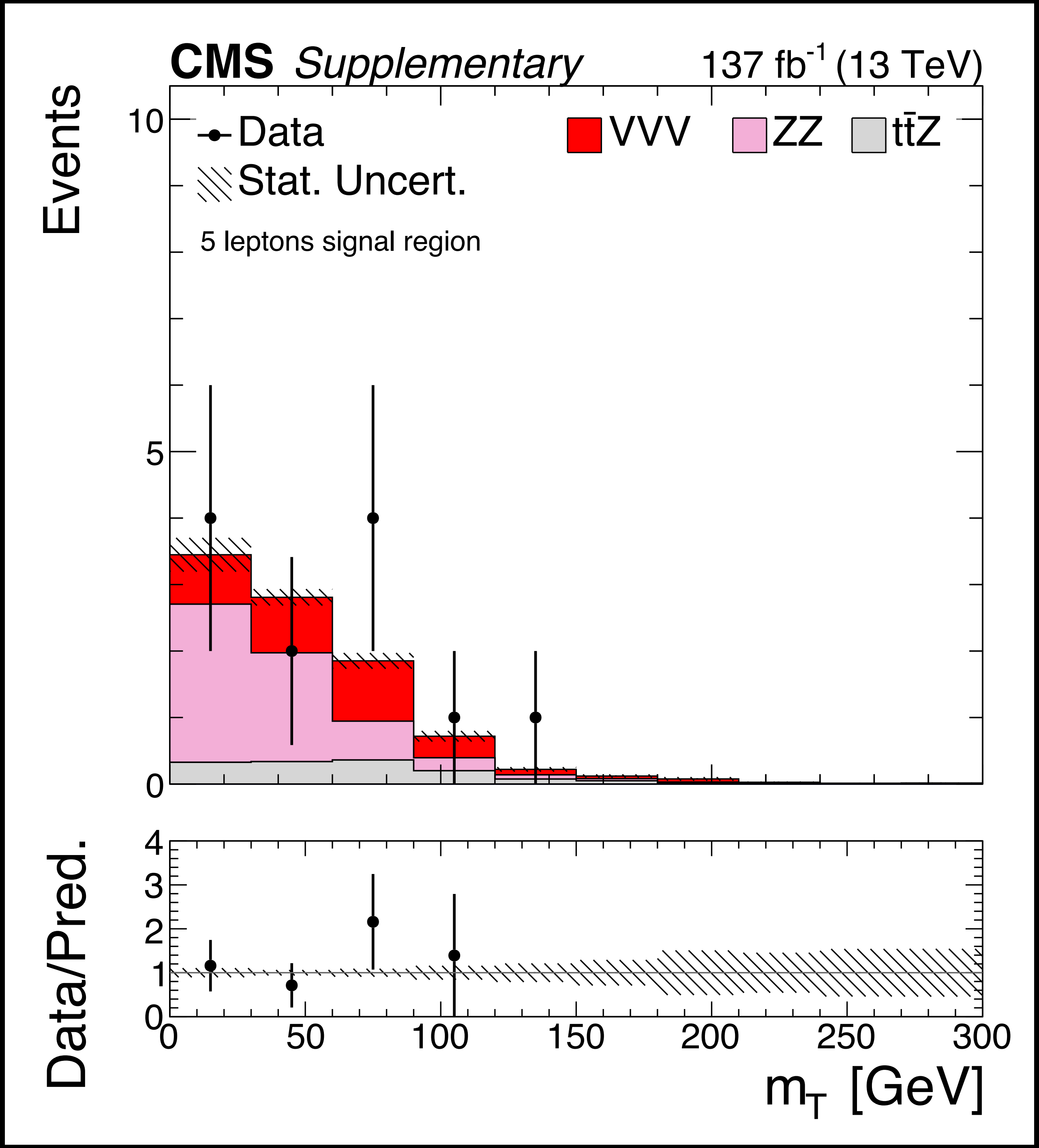
Search for WZZ in five lepton final state



Require five leptons targeting decay products arising out of the W and Z-bosons

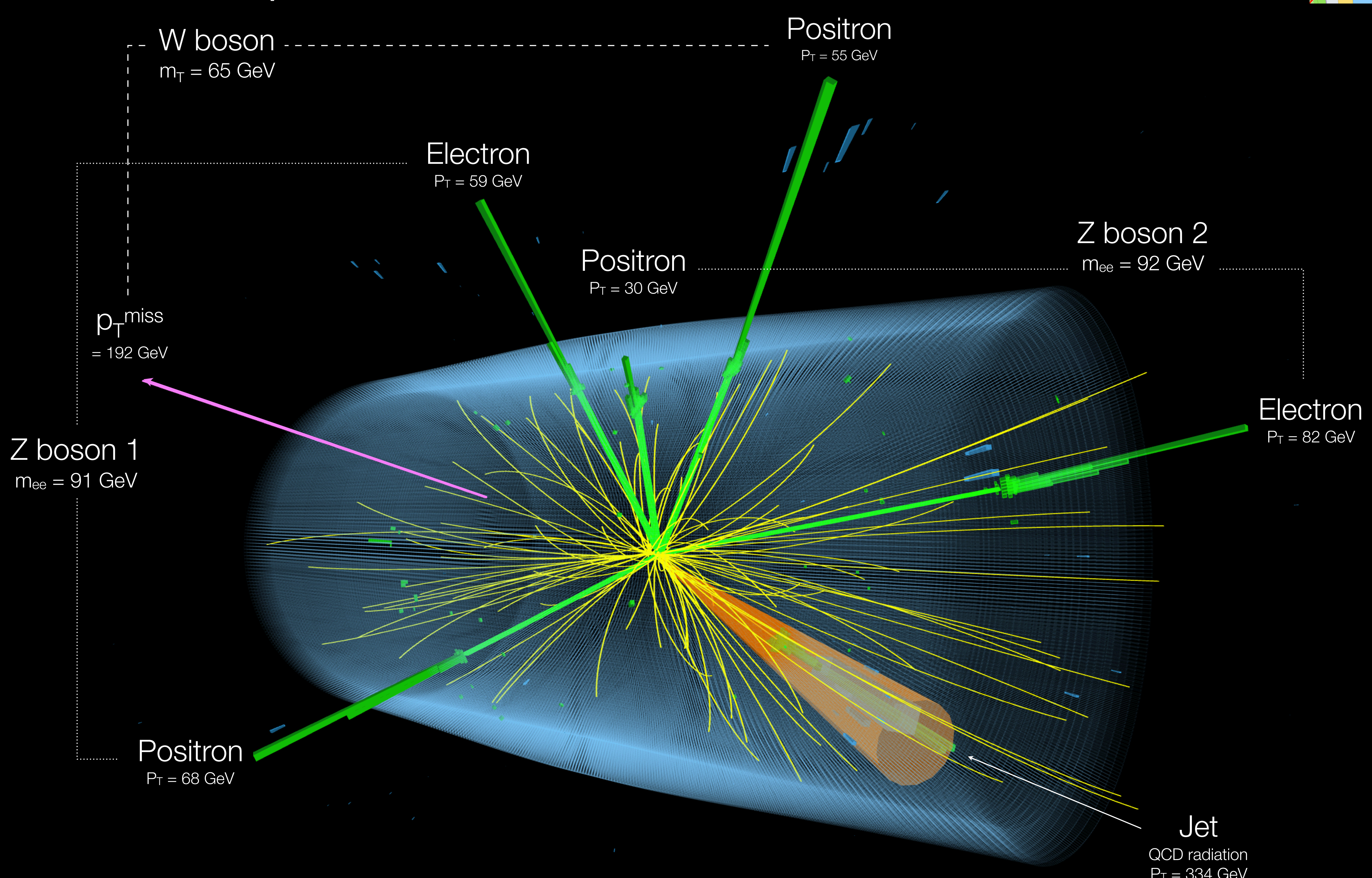
WZZ in five lepton final state

- 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

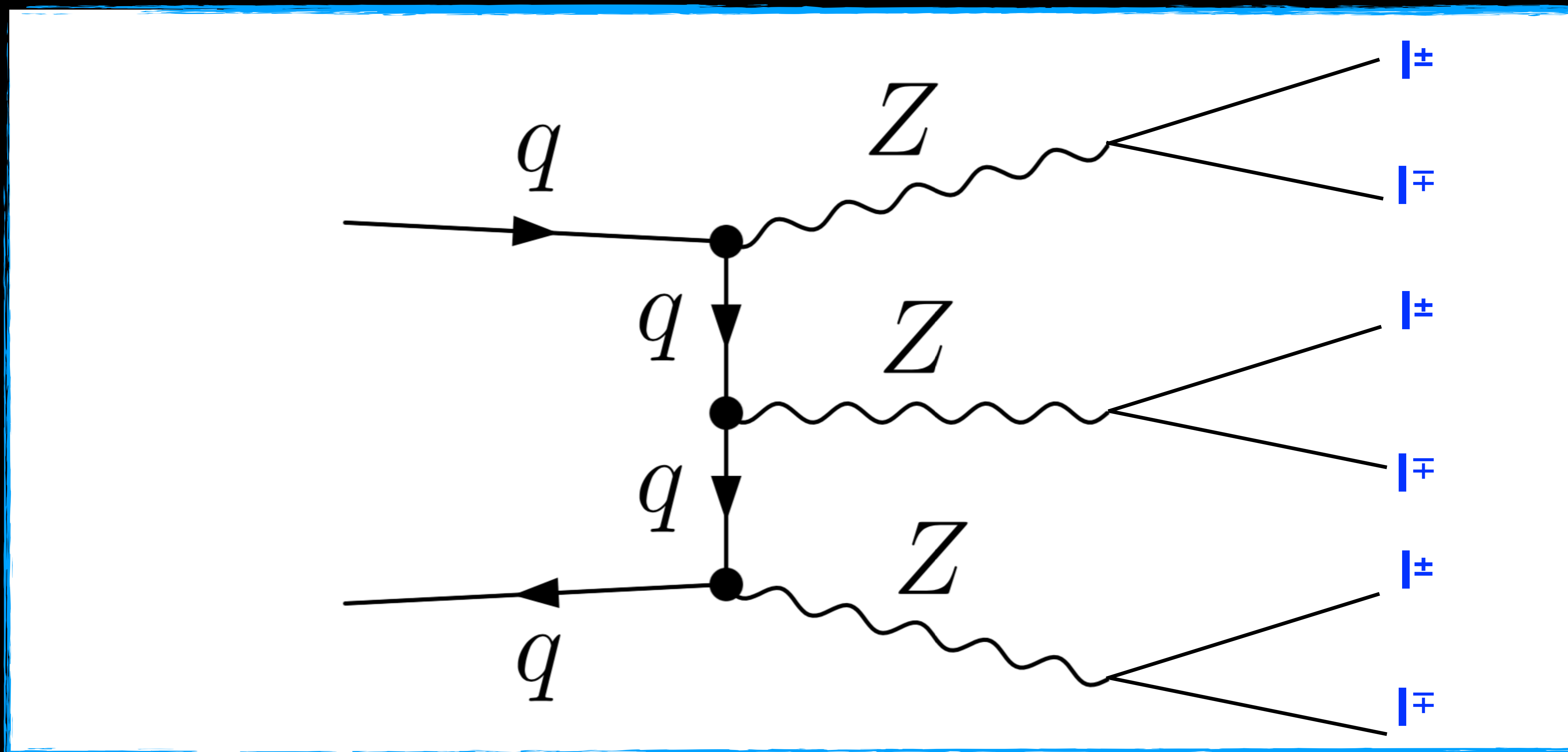


WZZ in five lepton final state

WZZ → 5 lepton event



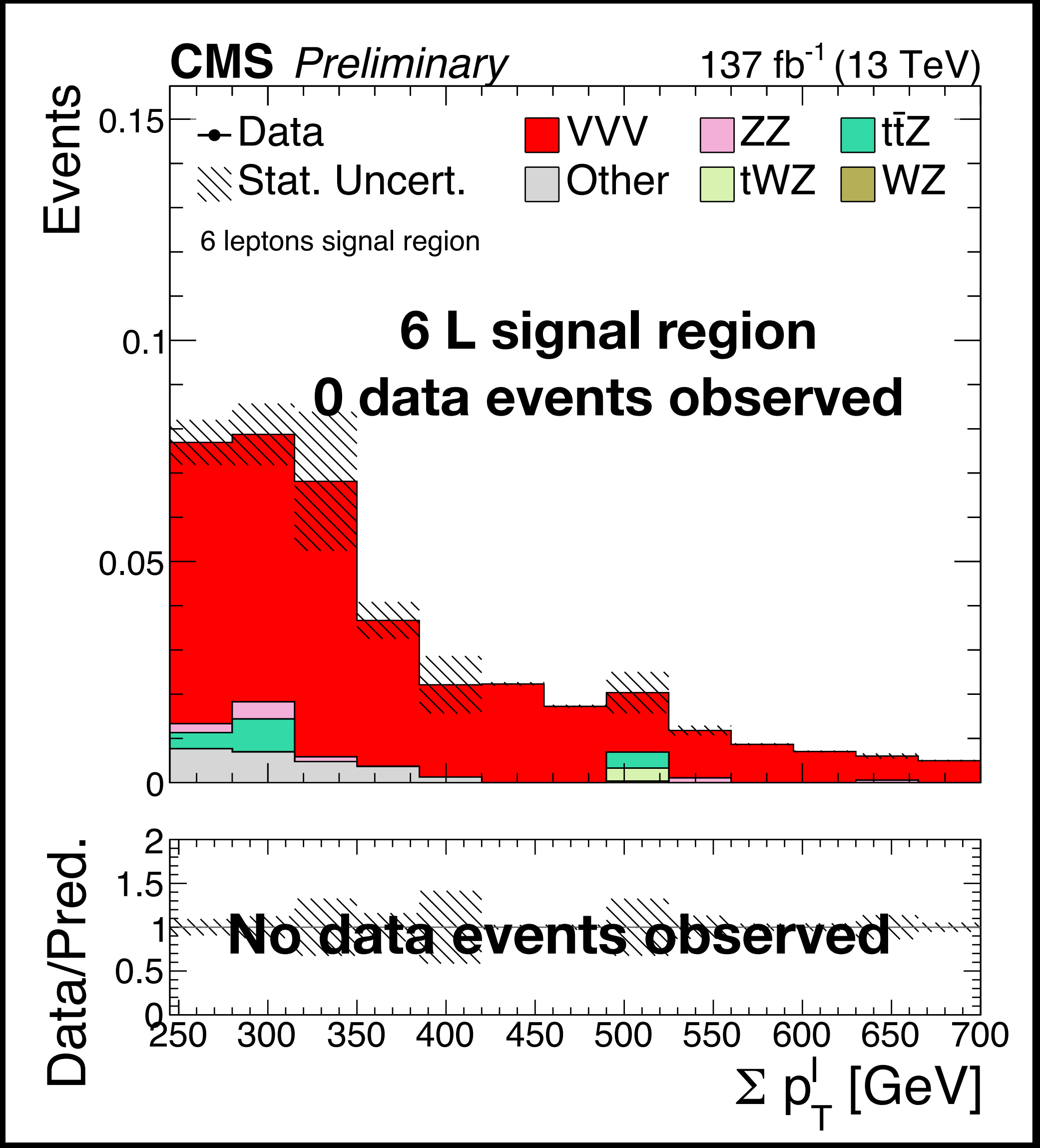
ZZZ in six lepton final state



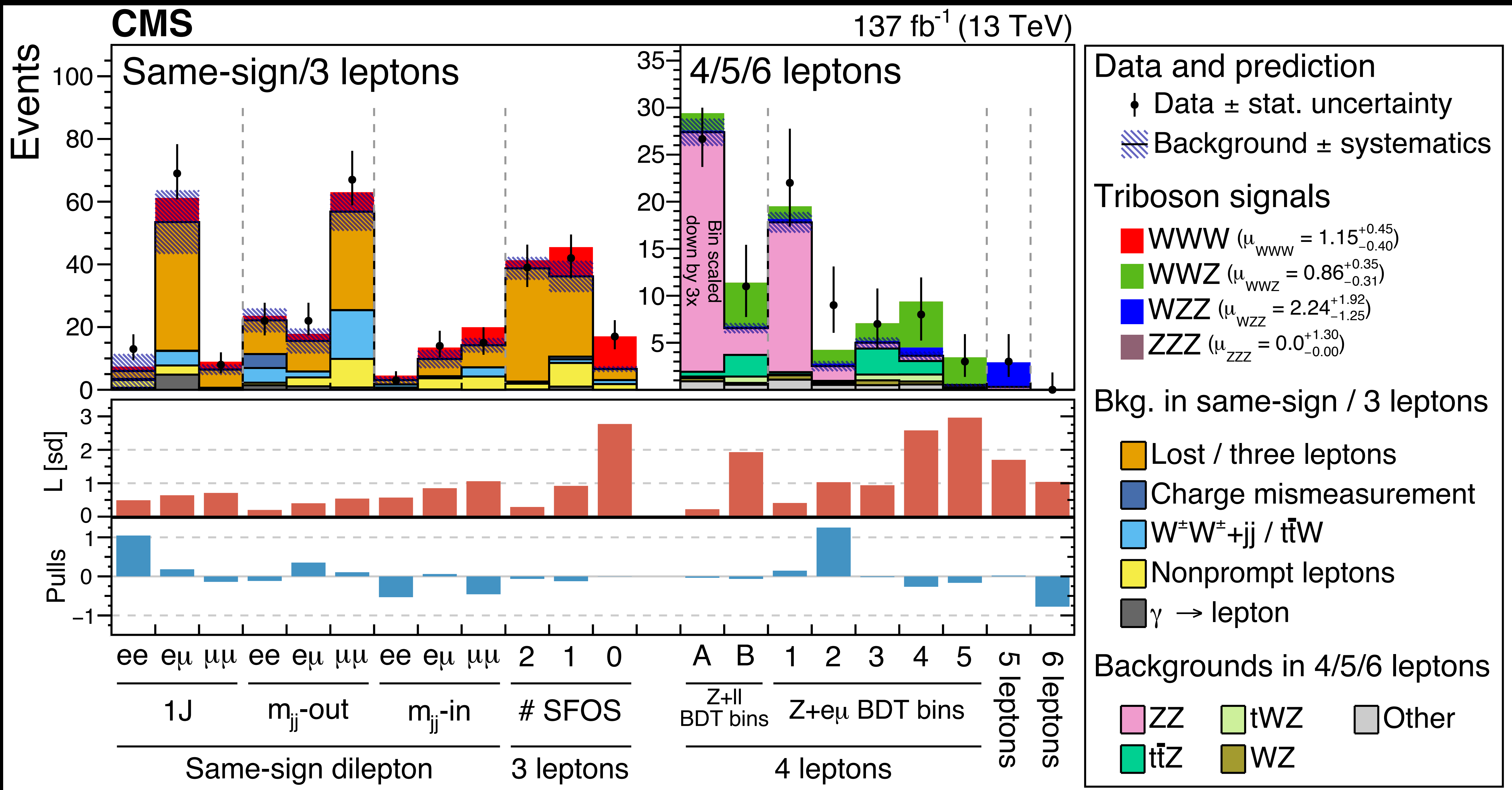
Require six leptons targeting decay products arising out of the Z-bosons

Search for ZZZ in six lepton final state

- In 6 lepton channel:
  - Require ∑ pT of all leptons > 250 GeV, powerful against backgrounds which contribute at percent level



Combination of all final states



Observation of Heavy Tribosons with Run II data

Major milestone in Standard Model physics!

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Observation of the Production of Three Massive Gauge Bosons at $\sqrt{s} = 13\ \mathrm{TeV}$

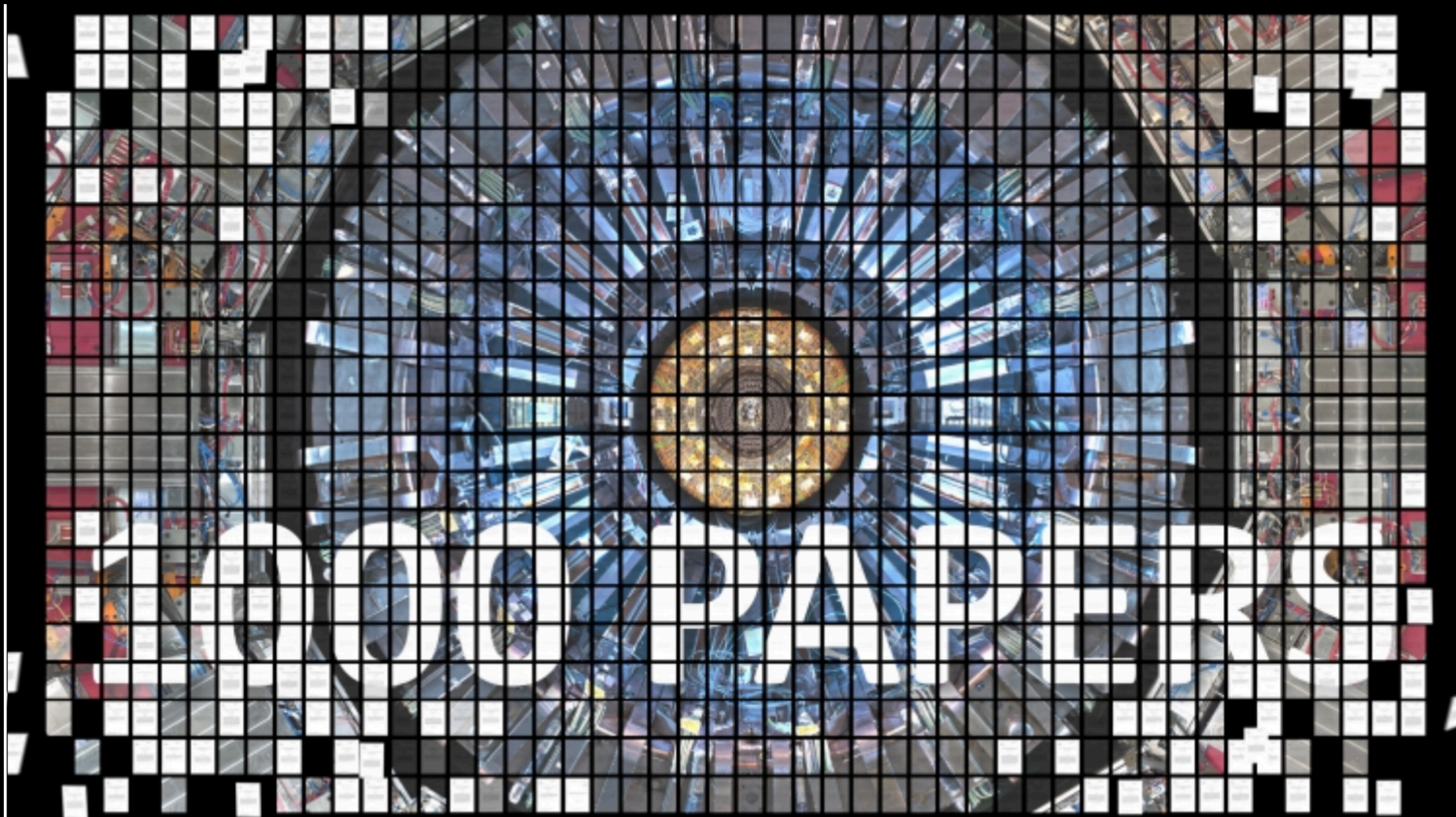
A. M. Sirunyan *et al.* (CMS Collaboration)
Phys. Rev. Lett. **125**, 151802 – Published 5 October 2020

Physics See synopsis: Hat Trick Observation for Bosons

Auxiliary material: http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP-19-014/

Observation of Heavy Tribosons with Run II data

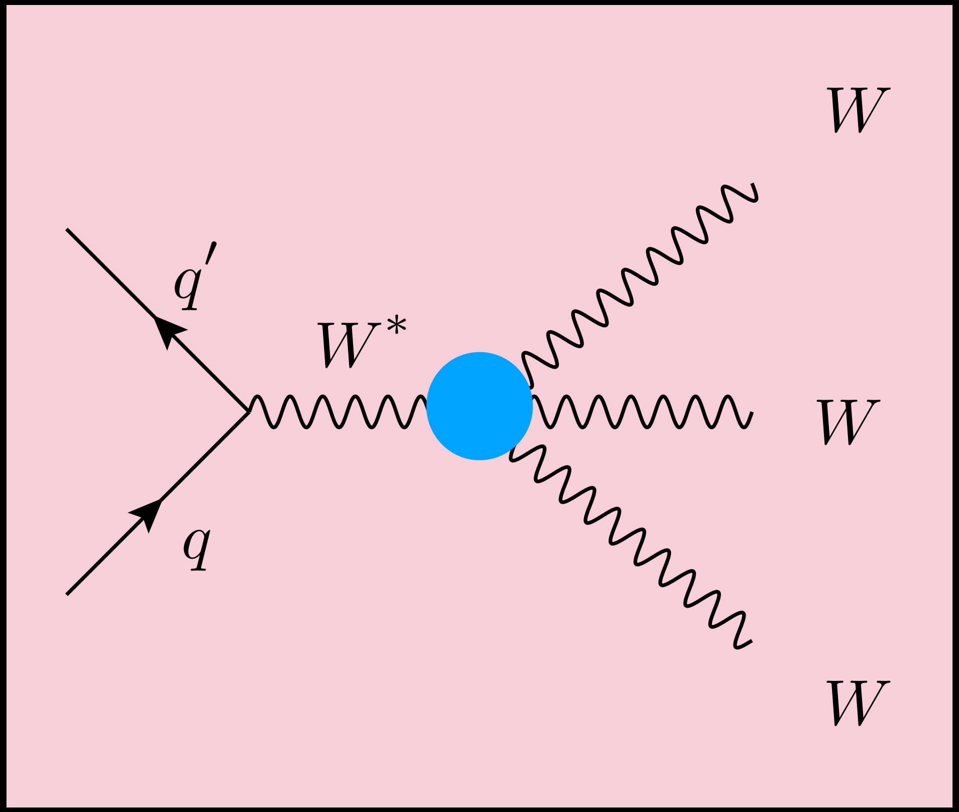
Culmination of persistent endeavor by both ATLAS and CMS Collaborations

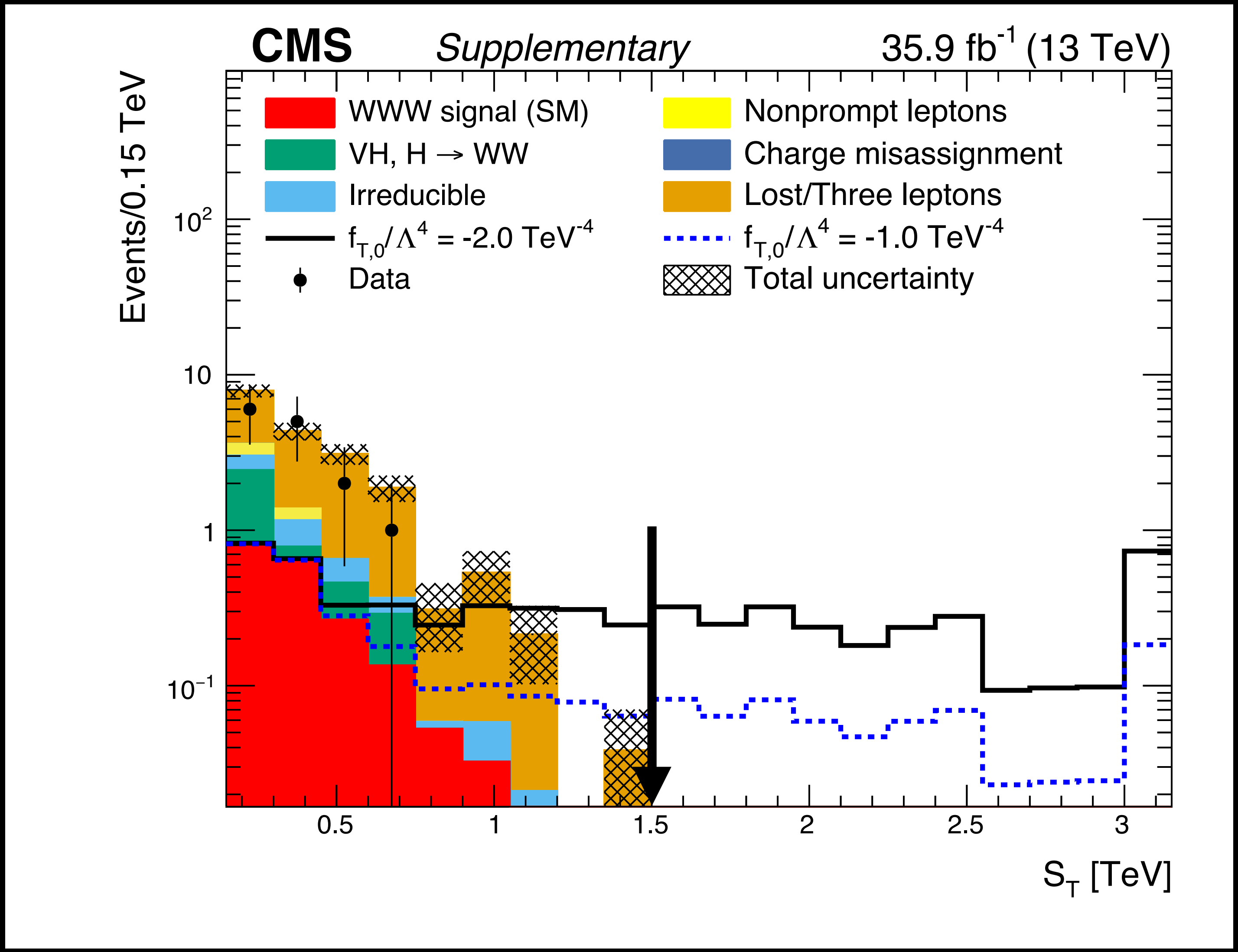


Recent result from ATLAS on observation of the WWW process

Effective field theory exploration in WWW process

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\lambda^4}\mathcal{O}_j$$





$$\mathcal{L}_{\mathrm{T},0} = \mathrm{Tr}\left[W_{\mu\nu}W^{\mu\nu}\right] \times \mathrm{Tr}\left[W_{\alpha\beta}W^{\alpha\beta}\right]$$

Effective field theories in VVV process

- Currently pursuing an Effective Field Theory interpretation with VVV process
- Including as many final states as possible
- Presence of higher order operators expected to lead to **high p_T decay products: 2 resolved jets → 1 fatJet**
- Explore **dim-6** and **dim-8** operators

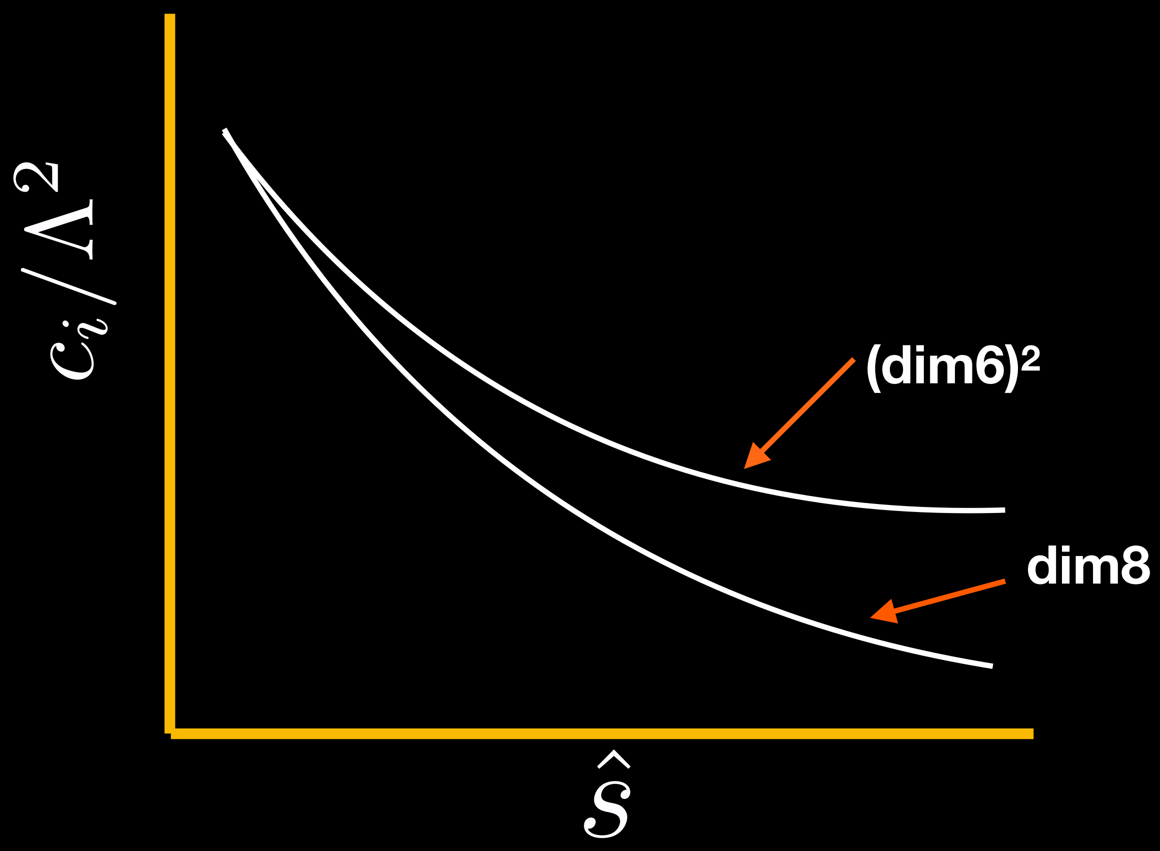
Process	Final states			
	Fully leptonic	Hadronic decay of one gauge boson	Leptonic decay of one gauge boson	Fully hadronic
WWW	$3\ \ell$ + missing energy	$2\ \ell$ + jets ($W^\pm \to \ell^\pm\nu$, $W^\pm \to \ell^\pm\nu$, $W \to q\bar{p}$)	$1\ \ell$ + jets ($W^\pm \to \ell^\pm\nu$, $W^\pm \to q\bar{p}$, $W \to q\bar{p}$)	6 jets
WWZ	$4\ \ell$ + missing energy	$2\ \ell$ + jets ($W \to \ell\nu$, $W \to \ell\nu$, $Z \to q\bar{q}$)	$1\ \ell$ + jets ($W \to \ell\nu$, $W \to q\bar{p}$, $Z \to q\bar{q}$)	6 jets
		$3\ \ell$ + jets ($W \to q\bar{p}$, $W \to \ell\nu$, $Z \to \ell^+\ell^-$)	$2\ \ell$ + jets ($W \to q\bar{p}$, $W \to q\bar{p}$, $Z \to \ell^+\ell^-$)	
WZZ	$5\ \ell$ + missing energy	$3\ \ell$ + jets ($W \to \ell\nu$, $Z \to \ell^-\ell^+$, $Z \to q\bar{q}$)	$1\ \ell$ + jets ($W \to \ell\nu$, $Z \to q\bar{q}$, $Z \to q\bar{q}$)	6 jets
		$4\ \ell$ + jets ($W \to q\bar{p}$, $Z \to \ell^-\ell^+$, $Z \to \ell^-\ell^+$)	$2\ \ell$ + jets ($W \to q\bar{p}$, $Z \to \ell^-\ell^+$, $Z \to q\bar{q}$)	
ZZZ	$6\ \ell$	$4\ \ell$ + jets ($Z \to \ell^-\ell^+$, $Z \to \ell^-\ell^+$, $Z \to q\bar{q}$)	$2\ \ell$ + jets ($Z \to q\bar{q}$, $Z \to q\bar{q}$, $Z \to \ell^-\ell^+$)	6 jets

Final states explored in observation paper

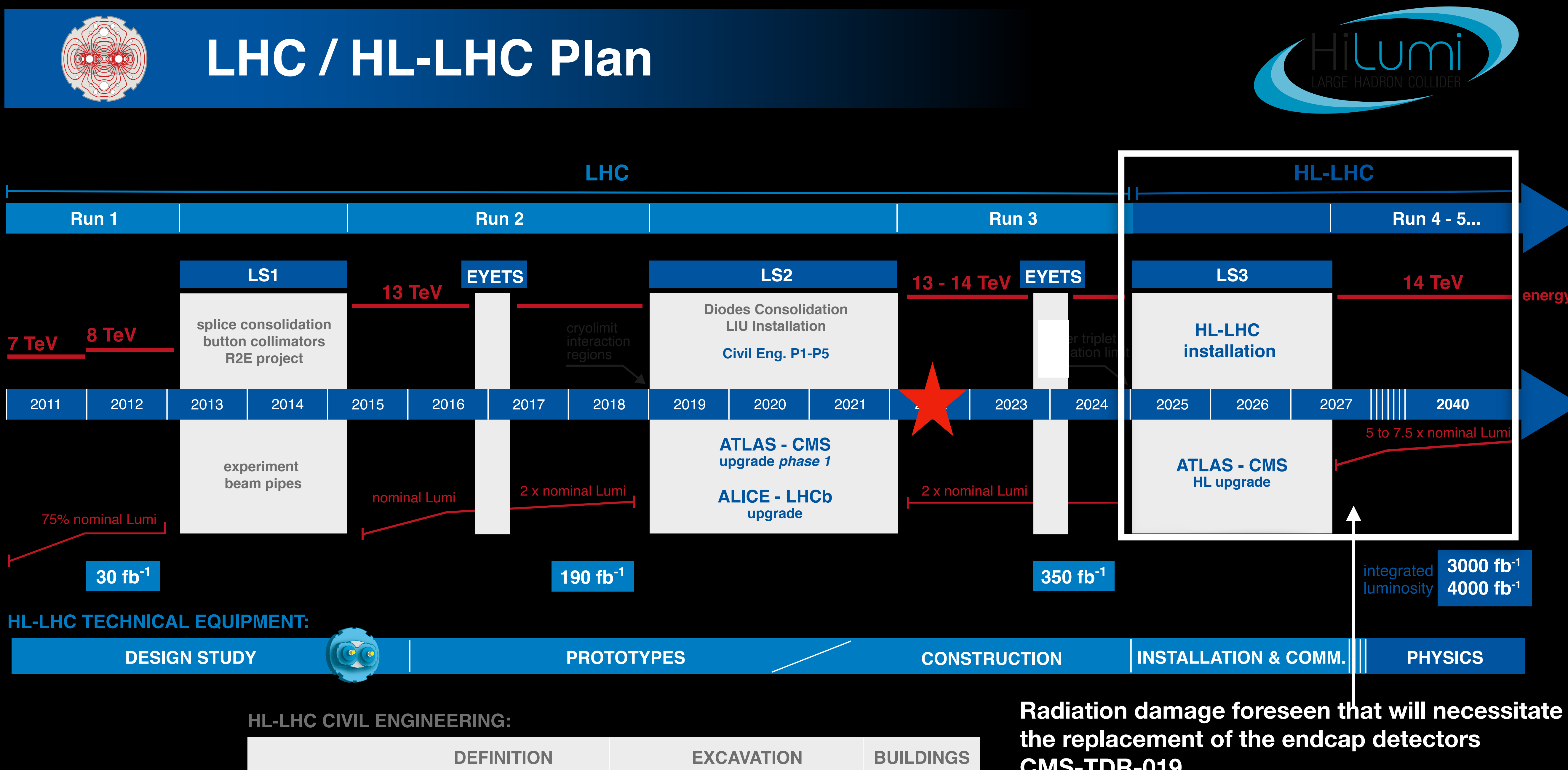
$Z \to \nu\bar{\nu}$ not included for brevity

Salient features associated with VVV

- Study of the Higgs sector possible
  - Best way to include Higgs mediated mode?
  - Can we quantify the interference between the Higgs-mediated modes and other modes of production?
- Critical questions such as $(\text{dim6})^2$ vs. dim8 contributions possible to address
  - Pertinent in the context of global EFT fits
- Explore sensitive variables: proxy for $\hat{s}$ and angular variables ($\Delta\phi$)
  - Absence of "golden" variables as in the case of vector boson scattering topologies



The LHC upgrade schedule



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

★ **We are here**

- Run 3 will commence in mid-2022
- Collect 2x data, by 2027 20x data

VVV significance at HL-LHC

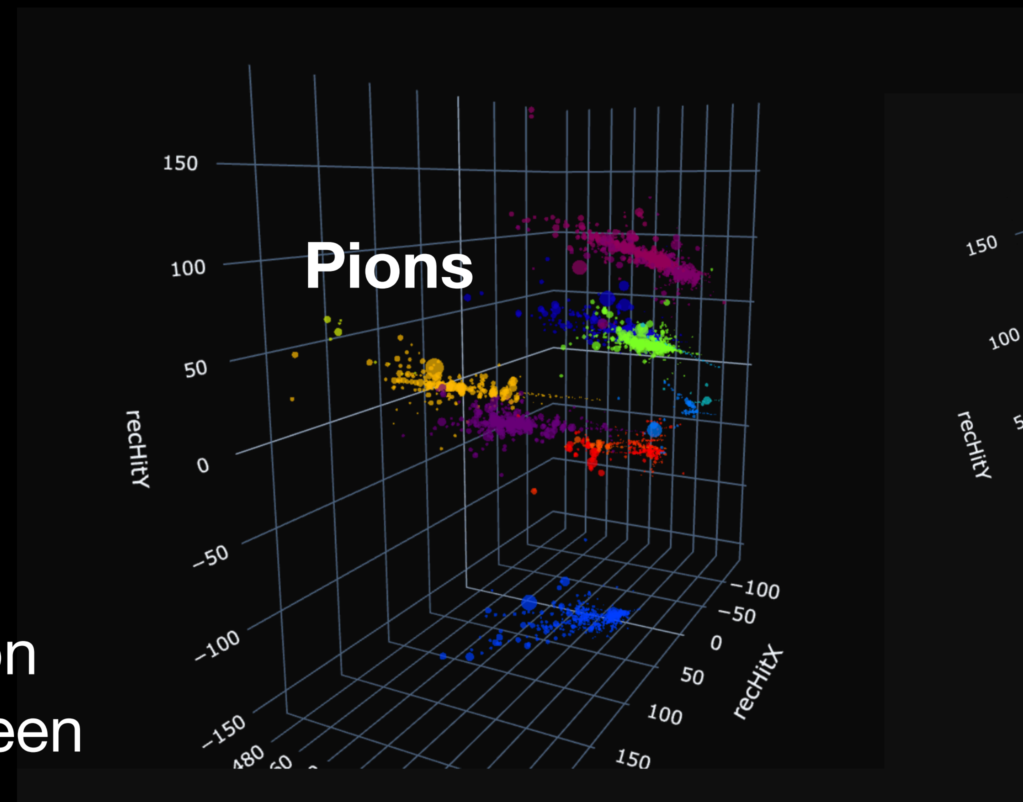
Process	Final State	Significance expected σ
WWW	same-signed dilepton and trilepton	**Can be studied in the realm of precision physics**
WWZ	four leptons	**Can be studied in the realm of precision physics**
WZZ	five leptons	> **5.0**
ZZZ	six or more leptons	> **5.0**

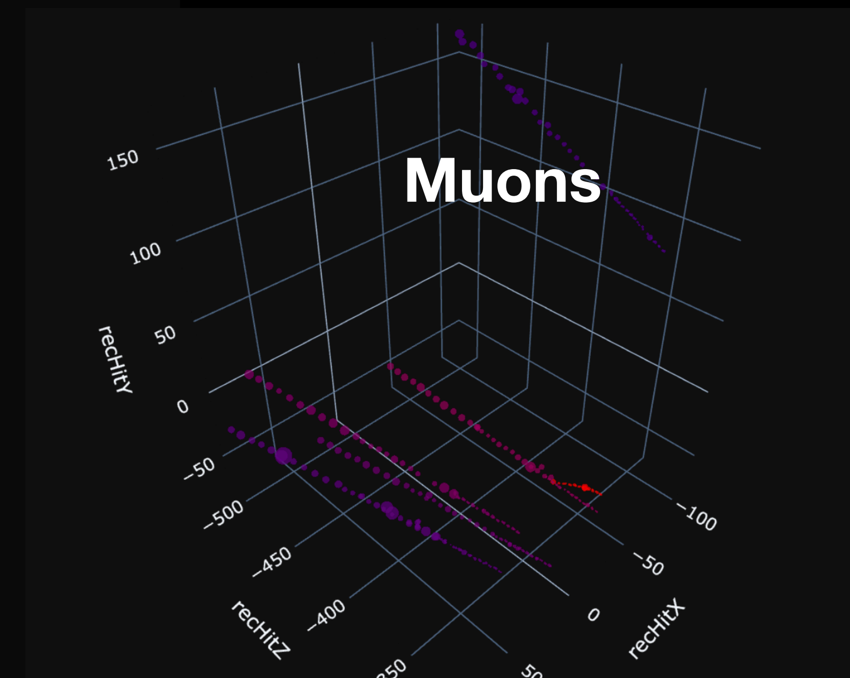
This is a simple projection assuming uncertainties remain the same

Power of new detectors

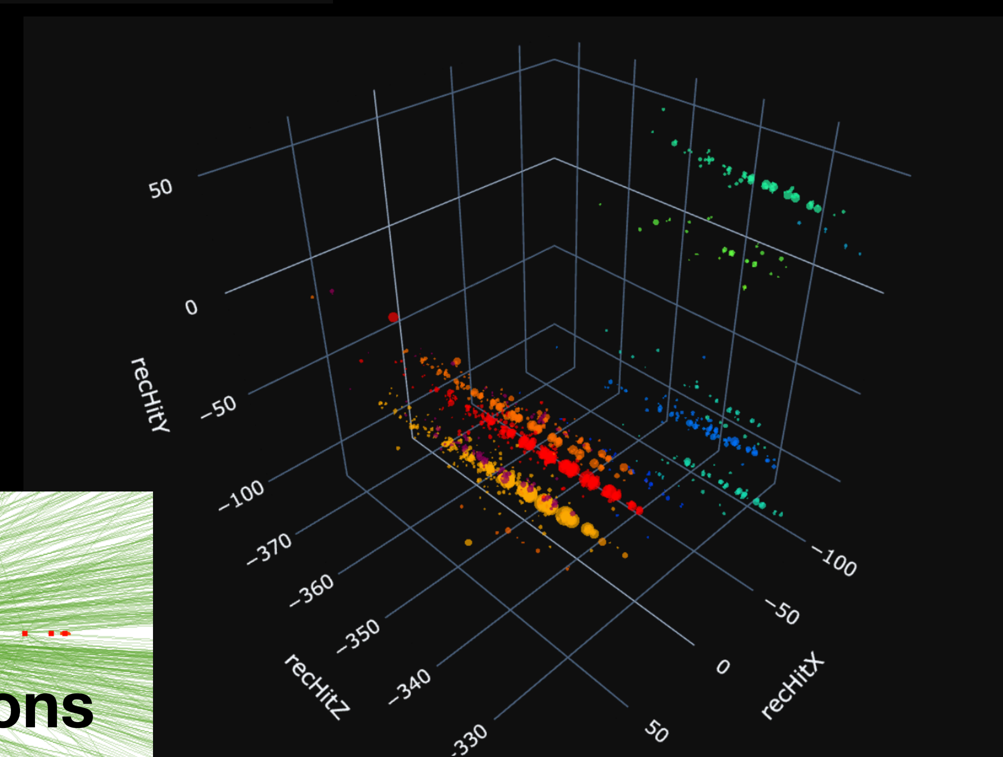
High Granularity Calorimeter

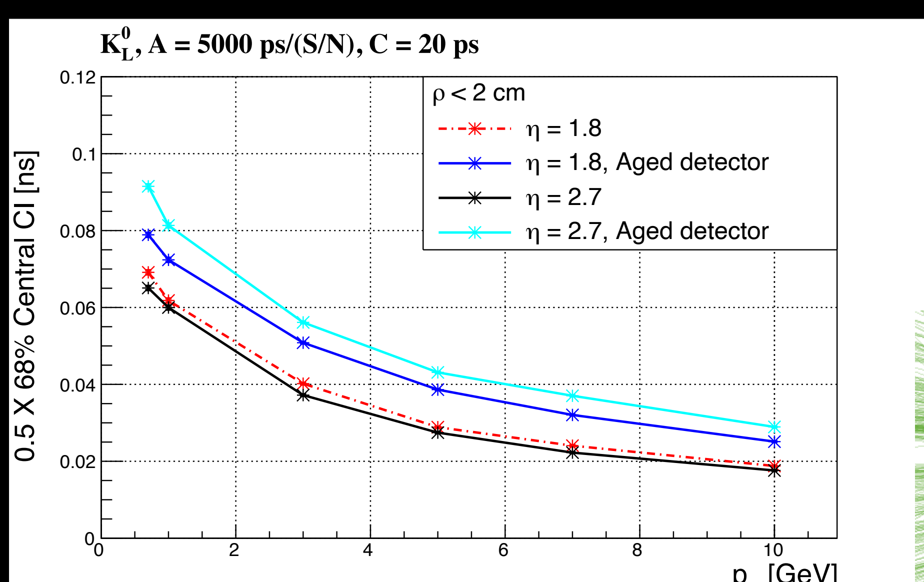
- Unprecedented spatial granularity
- 3D visualization of showers
- Timing capabilities
- Use low shower time resolution (~ few *ps*) to distinguish between spatially overlapping showers
- Use *ps* timing to mitigate pileup

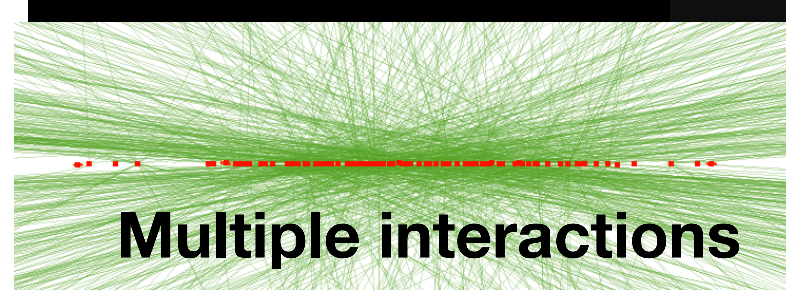




Photons







Path forward…

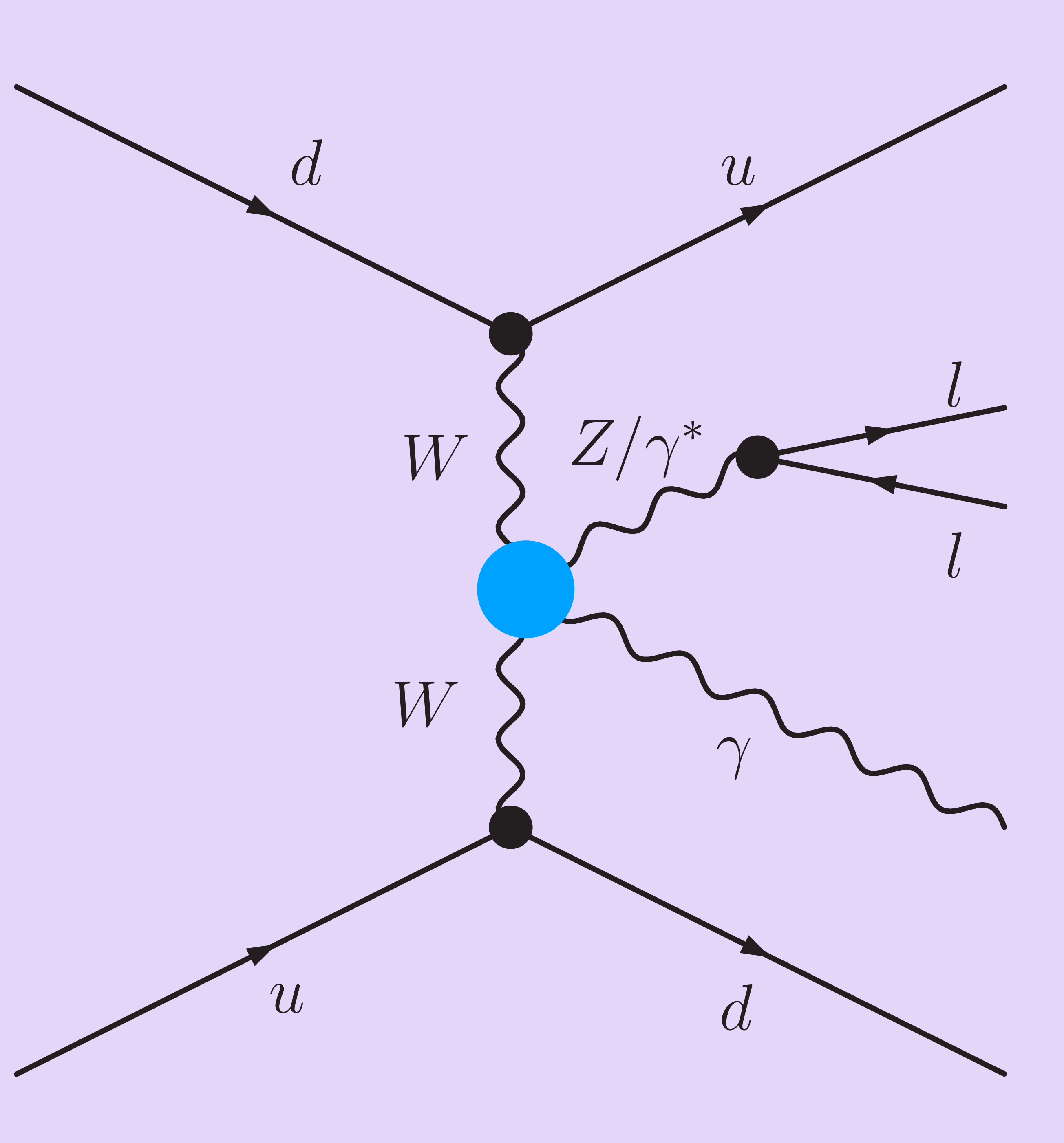
- Presented an exploration of new physics in diboson, vector boson scattering (VBS), triboson topologies using the effective field theory framework presented
- Elucidated unique ways of exploration of dim-6 operators with specific focus on interference with the SM
- Gained access to unexplored VBS processes and observed them with full Run II dataset and improved data analysis methods
- The exploration of dim-8 operators carried out in myriad VBS and triboson topologies providing unique access to the full spate of possible new physics contributions
    - EFT validity constraints are taken into account in all cases
- Detailed exploration possible as we move towards Run III and beyond and improvements foreseen with machine learning based approaches (a la CMS ttZ EFT exploration)

Additional Material

WW and WZ with two additional jets

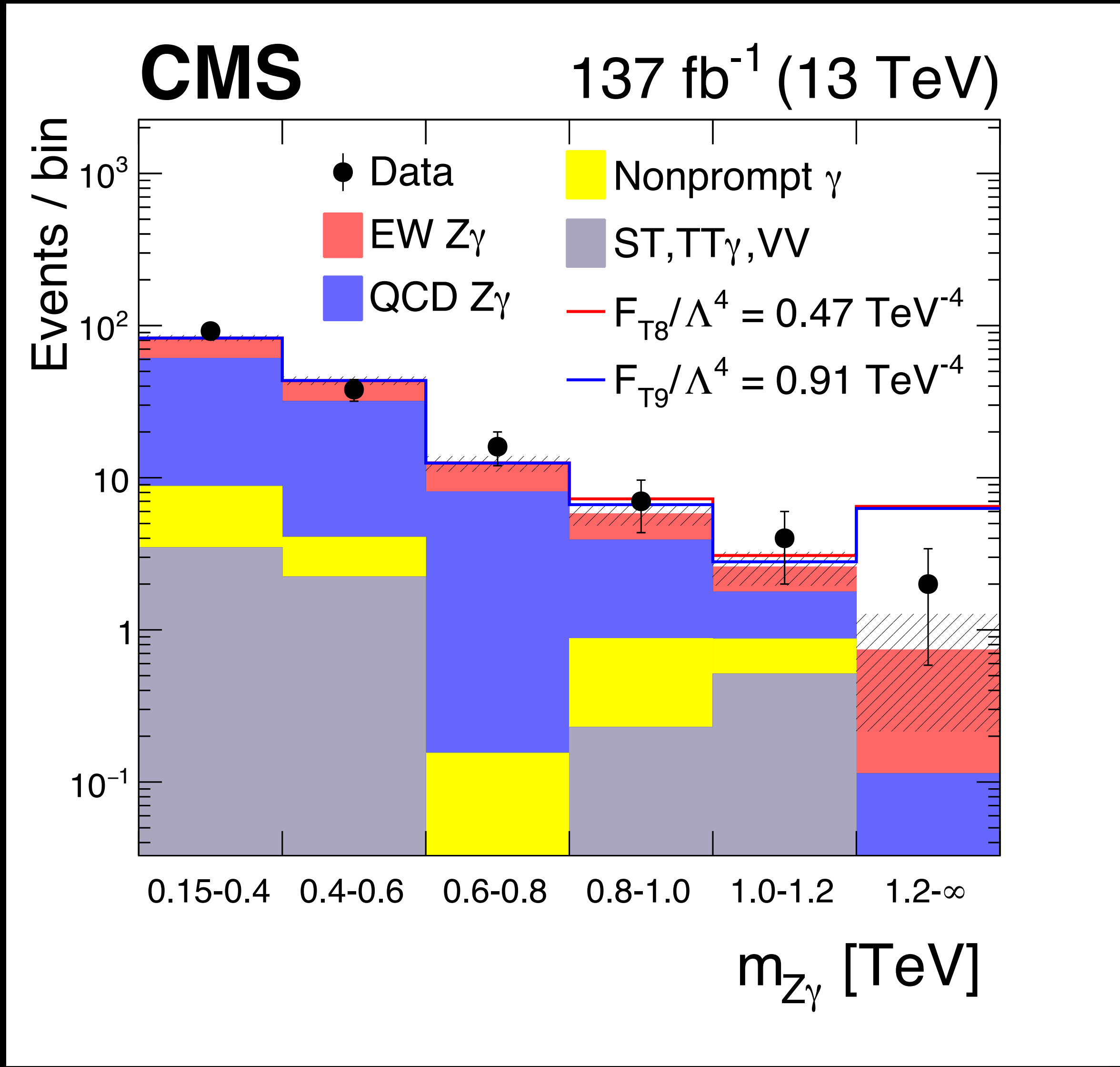
CMS: Phys. Lett. B 809 (2020) 135710

Zγ + 2 jets

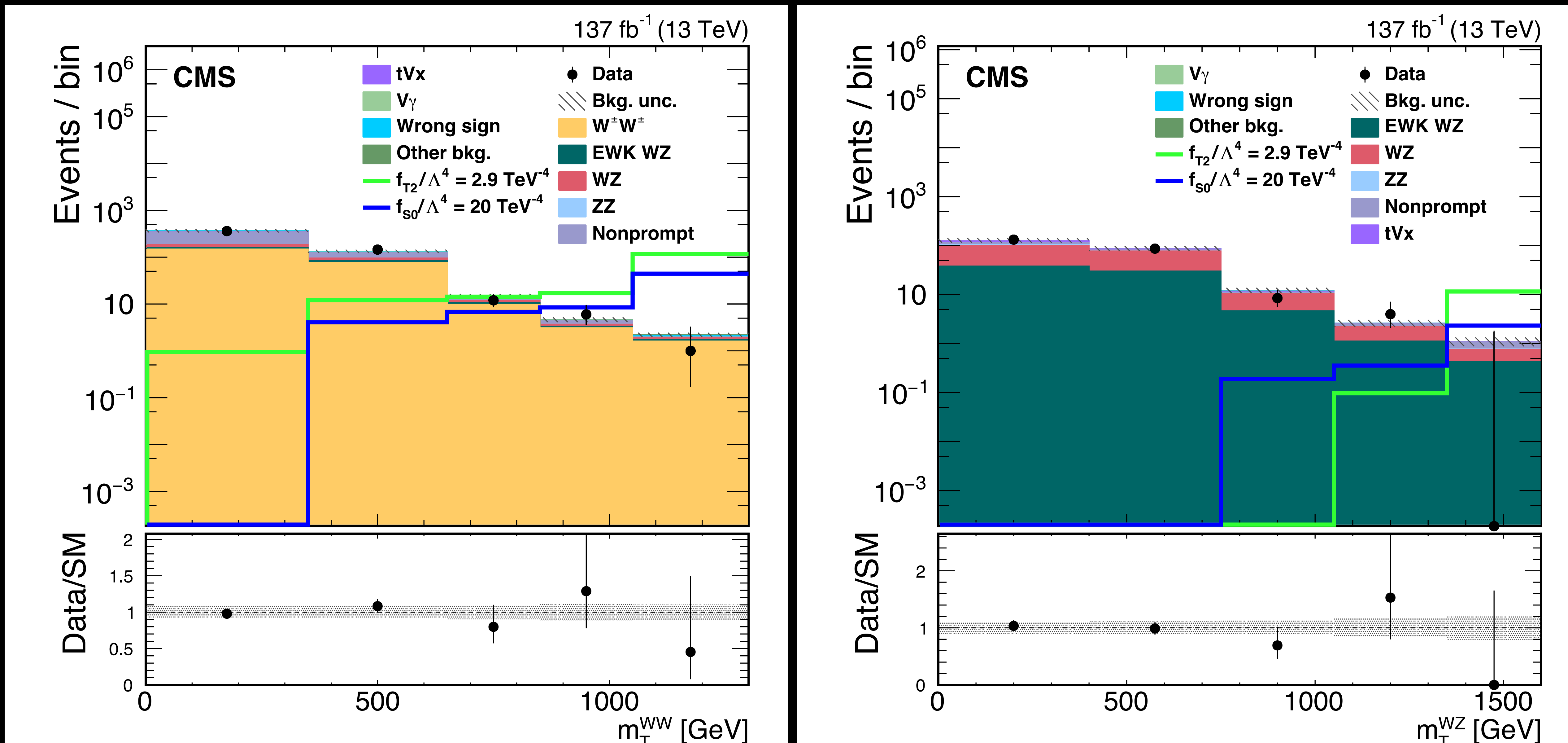


aQGC search region	Common selection, $m_{jj} > 500\,\text{GeV}$, $|\Delta\eta_{jj}| > 2.5$, $p_T^{\gamma} > 120\,\text{GeV}$

- Access to neutral quartic vertex (like previous analysis)
- Limits on T8 and T9 operators improve by a factor of two in comparison to ZZ + 2 jets process



Exploration of WW and WZ processes with two additional jets



- ☑ mT(VV) sensitive to presence of dim-8 operators

$$m_T(VV) = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i p_{z,i}\right)^2}$$

Factoring in EFT validity

- EFT validity taken into account by restricting EFT integration at the unitarity limit
- Unitarity limit is at ~1.5 TeV
- Calculated with VBF NLO (VBFNLO 1.4.0)

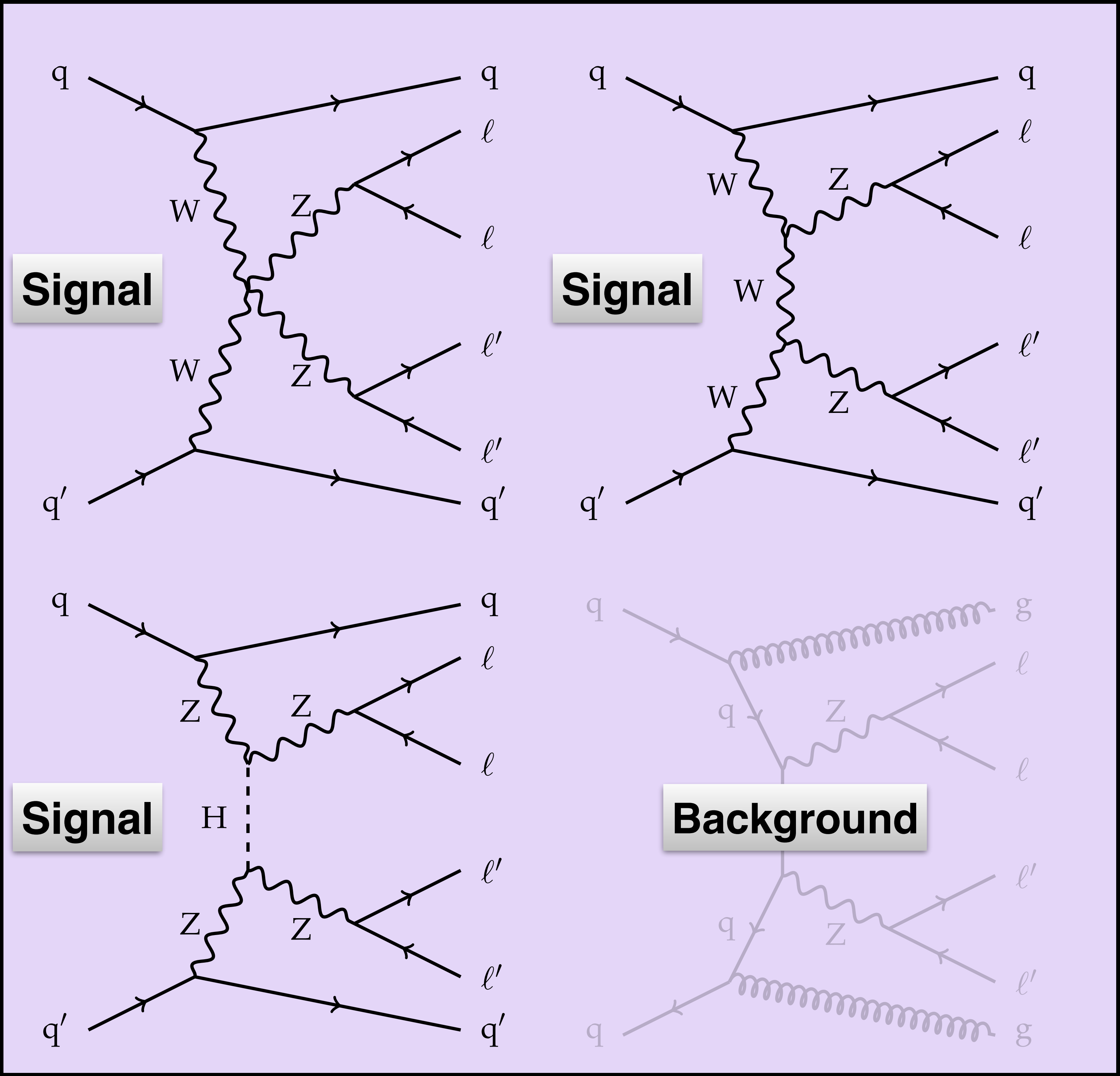
	Observed ($W^{\pm}W^{\pm}$) (TeV^{-4})	Expected ($W^{\pm}W^{\pm}$) (TeV^{-4})	Observed (WZ) (TeV^{-4})	Expected (WZ) (TeV^{-4})	Observed (TeV^{-4})	Expected (TeV^{-4})
f_{T0}/Λ^4	[-1.5, 2.3]	[-2.1, 2.7]	[-1.6, 1.9]	[-2.0, 2.2]	[-1.1, 1.6]	[-1.6, 2.0]
f_{T1}/Λ^4	[-0.81, 1.2]	[-0.98, 1.4]	[-1.3, 1.5]	[-1.6, 1.8]	[-0.69, 0.97]	[-0.94, 1.3]
f_{T2}/Λ^4	[-2.1, 4.4]	[-2.7, 5.3]	[-2.7, 3.4]	[-4.4, 5.5]	[-1.6, 3.1]	[-2.3, 3.8]
f_{M0}/Λ^4	[-13, 16]	[-19, 18]	[-16, 16]	[-19, 19]	[-11, 12]	[-15, 15]
f_{M1}/Λ^4	[-20, 19]	[-22, 25]	[-19, 20]	[-23, 24]	[-15, 14]	[-18, 20]
f_{M6}/Λ^4	[-27, 32]	[-37, 37]	[-34, 33]	[-39, 39]	[-22, 25]	[-31, 30]
f_{M7}/Λ^4	[-22, 24]	[-27, 25]	[-22, 22]	[-28, 28]	[-16, 18]	[-22, 21]
f_{S0}/Λ^4	[-35, 36]	[-31, 31]	[-83, 85]	[-88, 91]	[-34, 35]	[-31, 31]
f_{S1}/Λ^4	[-100, 120]	[-100, 110]	[-110, 110]	[-120, 130]	[-86, 99]	[-91, 97]

- Limits worse by a factor of 5 in comparison with limits without unitarity constraints but more physical

ZZ with two additional jets

CMS: Phys. Lett. B 812 (2020) 135992

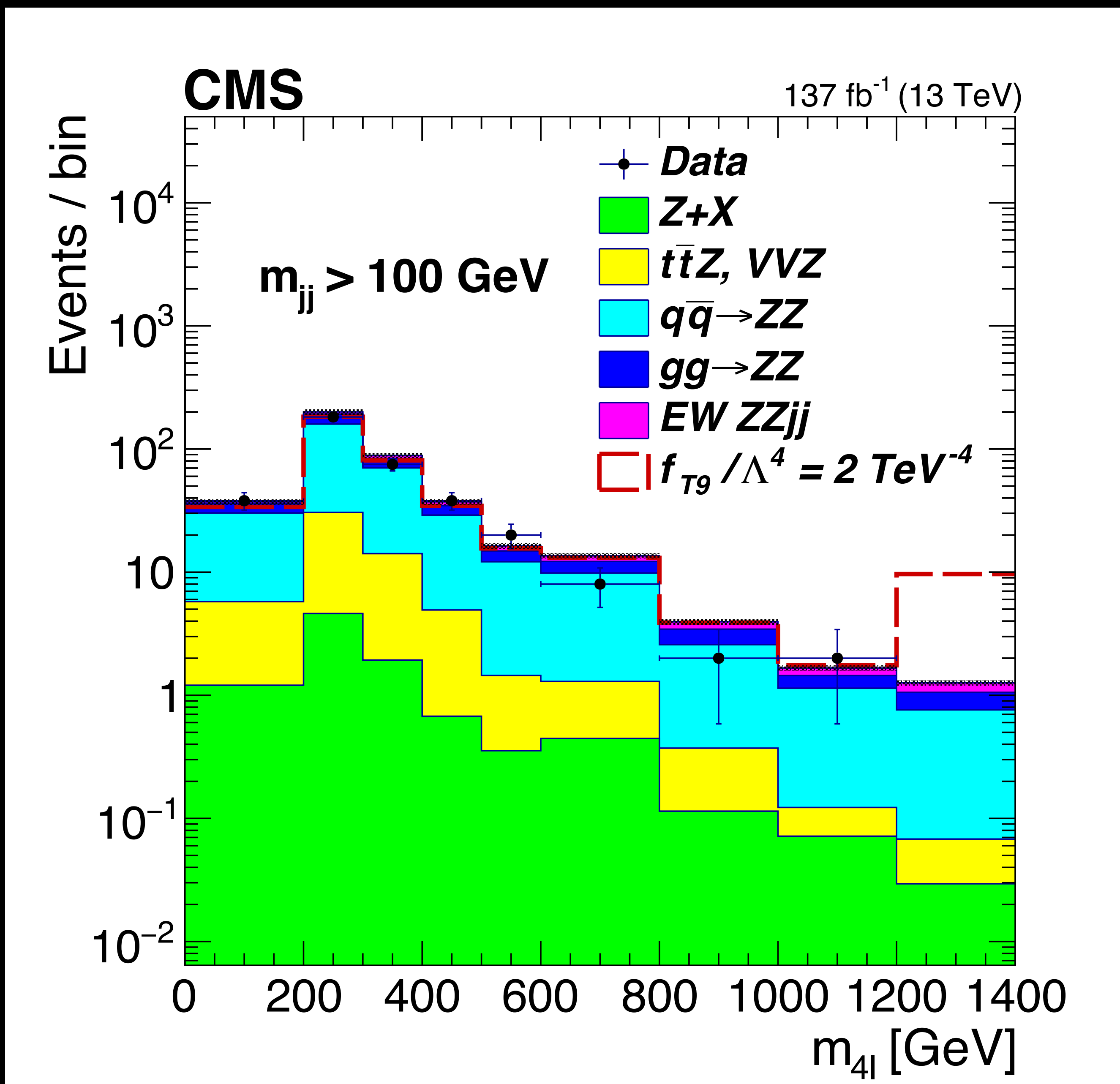
ZZ production with 2 jets



- ☑ Electroweak production of ZZ observed with 4.0 (3.5) σ observed (expected) significance
- ☑ Provides access to the quartic coupling
- ☑ Exploration of dim-8 operators performed
- ☑ Provides access to T8 and T9 operators not possible in other final states

$$\mathcal{L}_{T,8} = B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha}$$

ZZ production with 2 jets



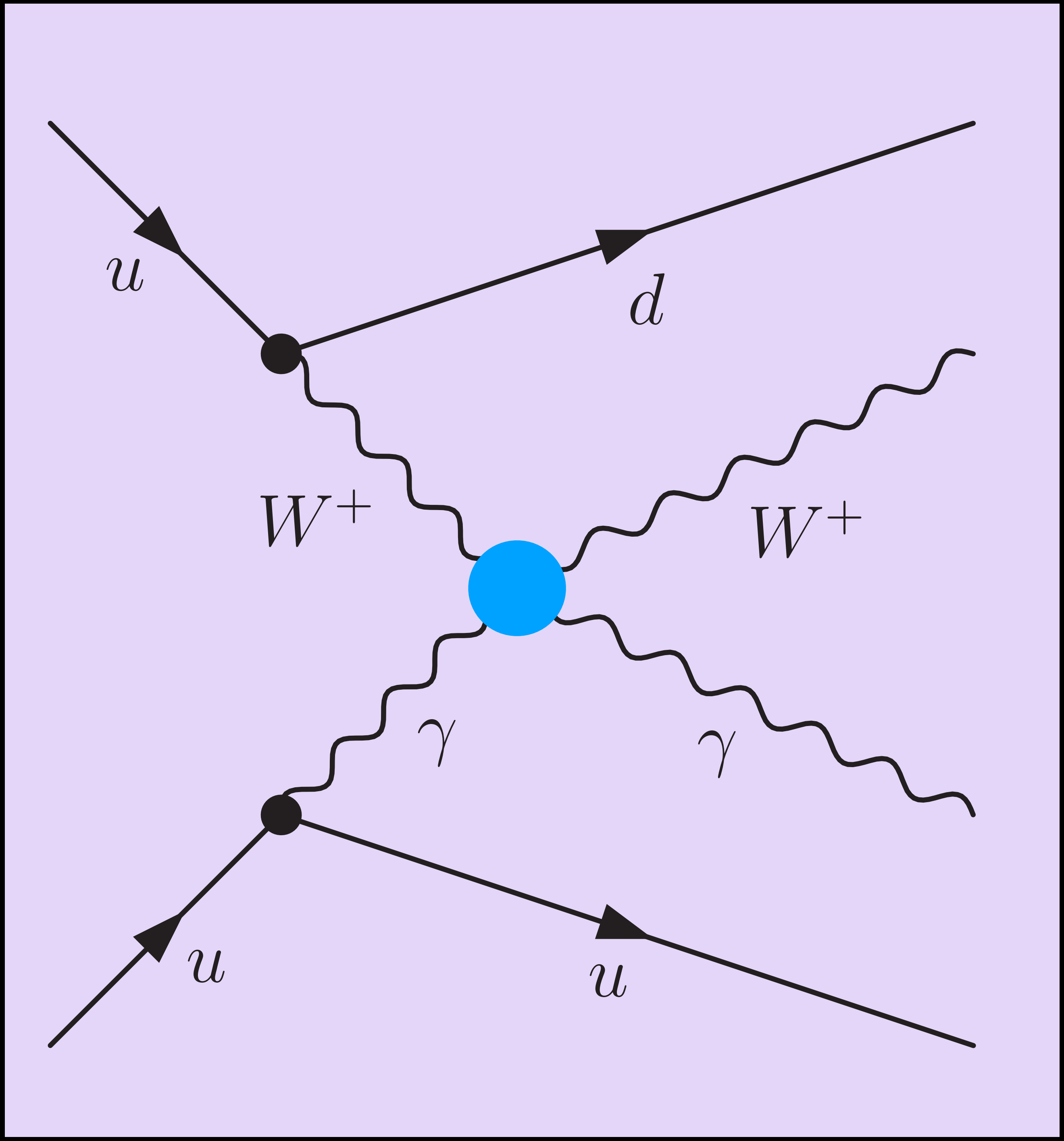
Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
f_{T0}/Λ^4	−0.37	0.35	−0.24	0.22	2.4
f_{T1}/Λ^4	−0.49	0.49	−0.31	0.31	2.6
f_{T2}/Λ^4	−0.98	0.95	−0.63	0.59	2.5
f_{T8}/Λ^4	−0.68	0.68	−0.43	0.43	1.8
f_{T9}/Λ^4	−1.5	1.5	−0.92	0.92	1.8

- ☑ Access to neutral operators
- ☑ Set strict bounds on these sets of operators, inaccessible in charged gauge boson final states
- ☑ Results presented factor in unitarity bounds

Wγ with two additional jets

CMS: Phys. Lett. B 811 (2020) 135988

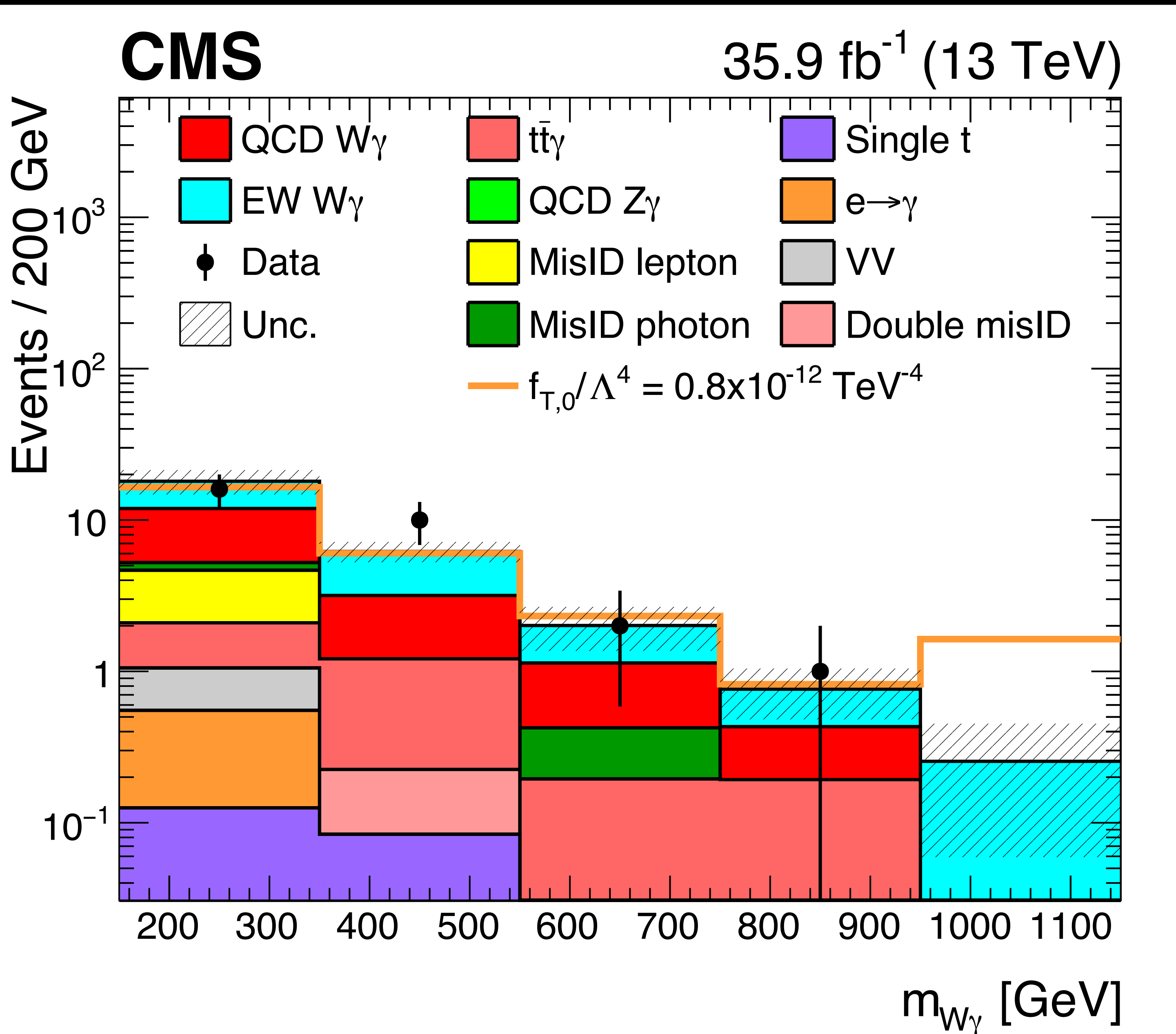
Wγ + 2 jets



- ✔ First observation of the Wγ + 2 jets process with observed (expected) significance of 5.3 (4.8) σ
- ✔ Exploration of dim-8 operators possible due to presence of SM quartic coupling
- ✔ Invariant mass of the Wγ system is sensitive to presence of dim-8 operators

Wγ + 2 jets

- Exploration of full set of "mixed" operators performed
- For the parameters f_{M2-5}, f_{M6-7} most stringent limits

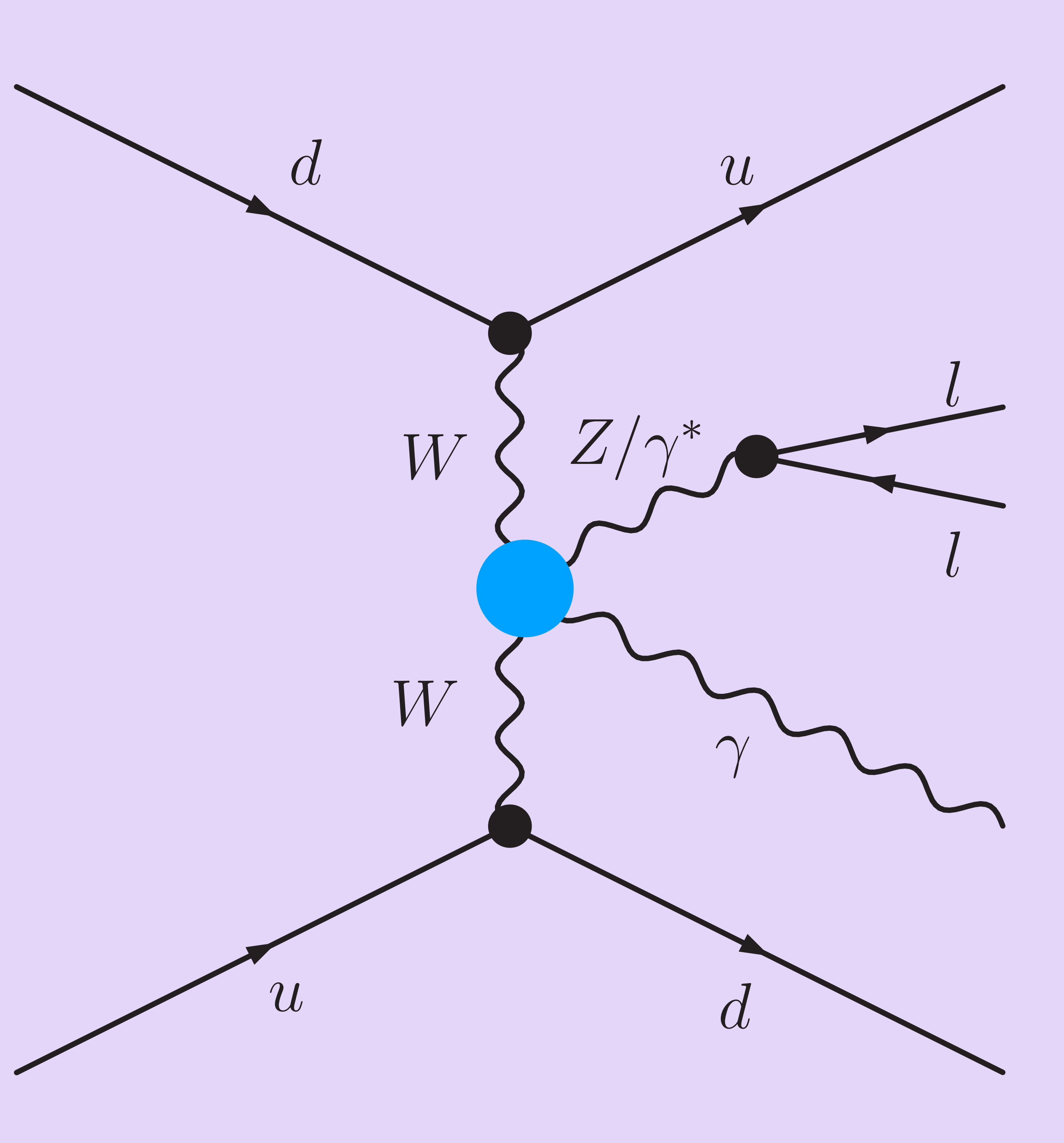


Parameters	Exp. limit	Obs. limit	U_{bound}
$f_{M,0}/\Lambda^4$	$[-8.1, 8.0]$	$[-7.7, 7.6]$	1.0
$f_{M,1}/\Lambda^4$	$[-12, 12]$	$[-11, 11]$	1.2
$f_{M,2}/\Lambda^4$	$[-2.8, 2.8]$	$[-2.7, 2.7]$	1.3
$f_{M,3}/\Lambda^4$	$[-4.4, 4.4]$	$[-4.0, 4.1]$	1.5
$f_{M,4}/\Lambda^4$	$[-5.0, 5.0]$	$[-4.7, 4.7]$	1.5
$f_{M,5}/\Lambda^4$	$[-8.3, 8.3]$	$[-7.9, 7.7]$	1.8
$f_{M,6}/\Lambda^4$	$[-16, 16]$	$[-15, 15]$	1.0
$f_{M,7}/\Lambda^4$	$[-21, 20]$	$[-19, 19]$	1.3
$f_{M,0}/\Lambda^4$	$[-0.6, 0.6]$	$[-0.6, 0.6]$	1.4
$f_{M,1}/\Lambda^4$	$[-0.4, 0.4]$	$[-0.3, 0.4]$	1.5
$f_{M,2}/\Lambda^4$	$[-1.0, 1.2]$	$[-1.0, 1.2]$	1.5
$f_{M,5}/\Lambda^4$	$[-0.5, 0.5]$	$[-0.4, 0.4]$	1.8
$f_{M,6}/\Lambda^4$	$[-0.4, 0.4]$	$[-0.3, 0.4]$	1.7
$f_{M,7}/\Lambda^4$	$[-0.9, 0.9]$	$[-0.8, 0.9]$	1.8

Zγ with two additional jets

CMS: https://arxiv.org/abs/2106.11082

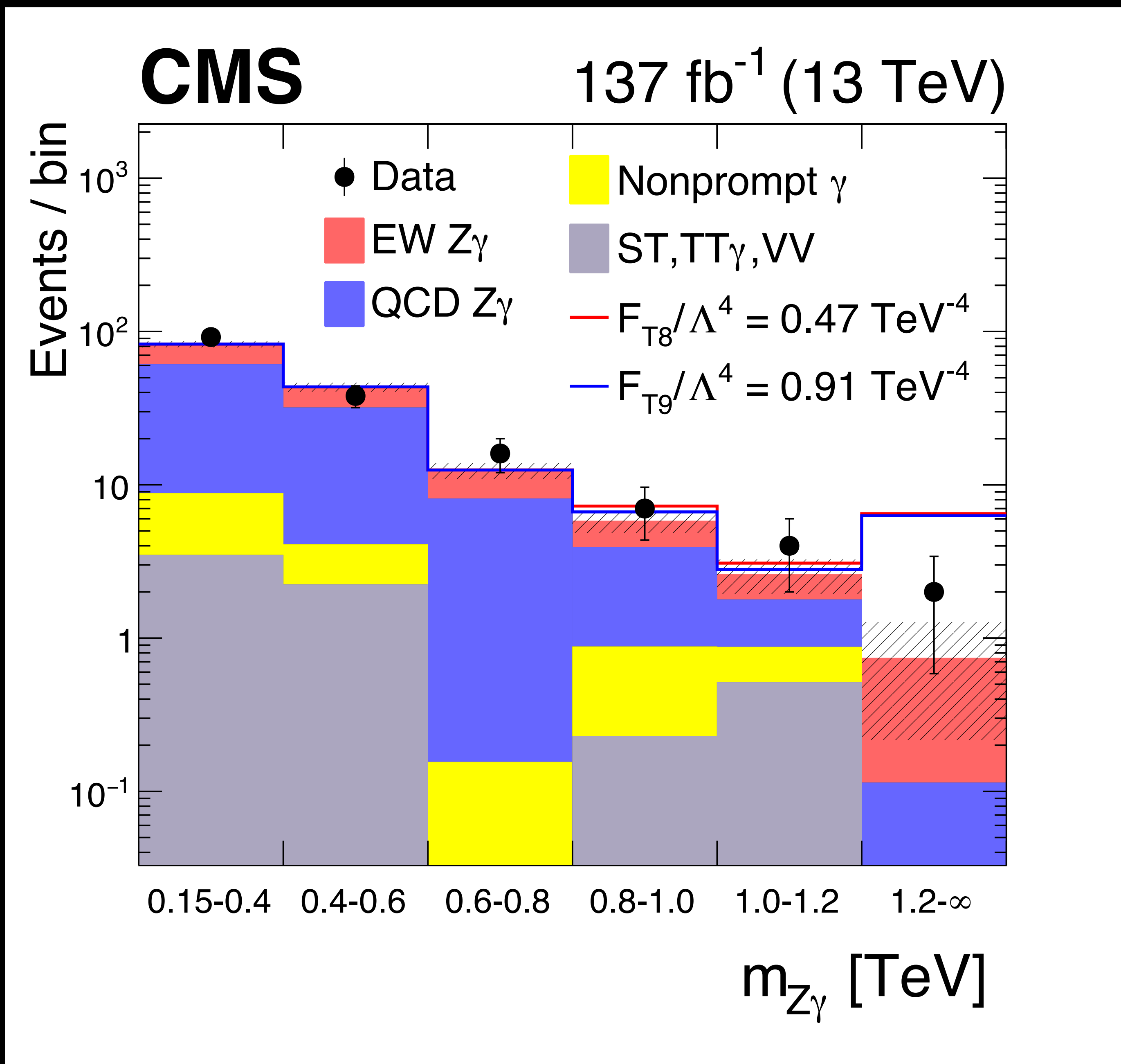
Zγ + 2 jets



aQGC search region	Common selection, $m_{jj} > 500\,\mathrm{GeV}$, $\|\Delta\eta_{jj}\| > 2.5$, $p_T^{\gamma} > 120\,\mathrm{GeV}$

- ☑ Access to neutral quartic vertex (like previous analysis)
- ☑ Allows exploration of T8 and T9 operators
- ☑ Invariant mass of the Zγ system is sensitive to presence of dim-8 operators

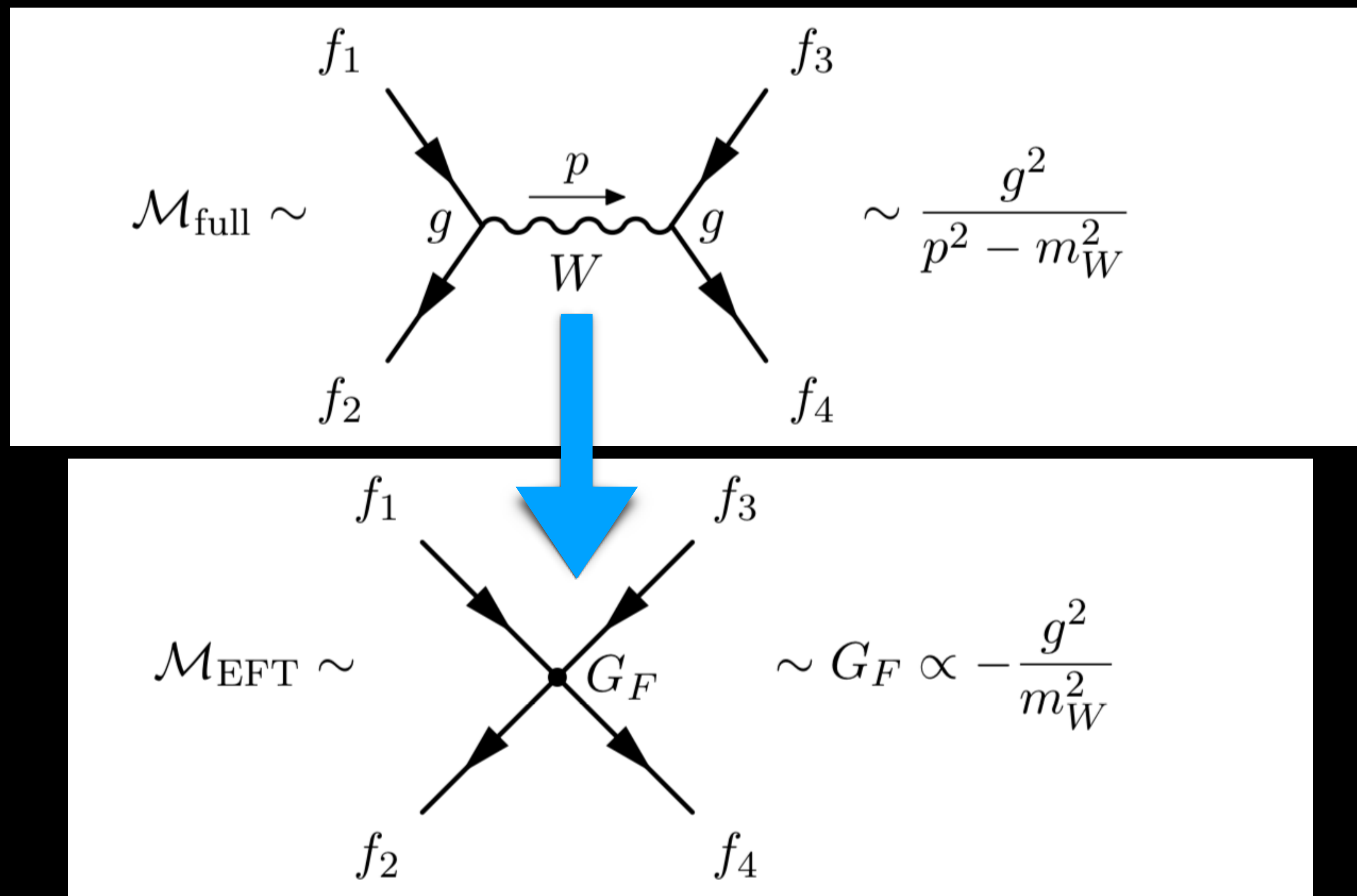
Zγ + 2 jets



Coupling	Exp. lower	Exp. upper	Obs. lower	Obs. upper	Unitarity bound
F_{M0}/Λ^4	−12.5	12.8	−15.8	16.0	1.3
F_{M1}/Λ^4	−28.1	27.0	−35.0	34.7	1.5
F_{M2}/Λ^4	−5.21	5.12	−6.55	6.49	1.5
F_{M3}/Λ^4	−10.2	10.3	−13.0	13.0	1.8
F_{M4}/Λ^4	−10.2	10.2	−13.0	12.7	1.7
F_{M5}/Λ^4	−17.6	16.8	−22.2	21.3	1.7
F_{M7}/Λ^4	−44.7	45.0	−56.6	55.9	1.6
F_{T0}/Λ^4	−0.52	0.44	−0.64	0.57	1.9
F_{T1}/Λ^4	−0.65	0.63	−0.81	0.90	2.0
F_{T2}/Λ^4	−1.36	1.21	−1.68	1.54	1.9
F_{T5}/Λ^4	−0.45	0.52	−0.58	0.64	2.2
F_{T6}/Λ^4	−1.02	1.07	−1.30	1.33	2.0
F_{T7}/Λ^4	−1.67	1.97	−2.15	2.43	2.2
F_{T8}/Λ^4	−0.36	0.36	−0.47	0.47	1.8
F_{T9}/Λ^4	−0.72	0.72	−0.91	0.91	1.9

- ✔ Stringent limits on dim-8 operators
- ✔ Limits on T8 and T9 operators improve by a factor of two in comparison to ZZ + 2 jets process

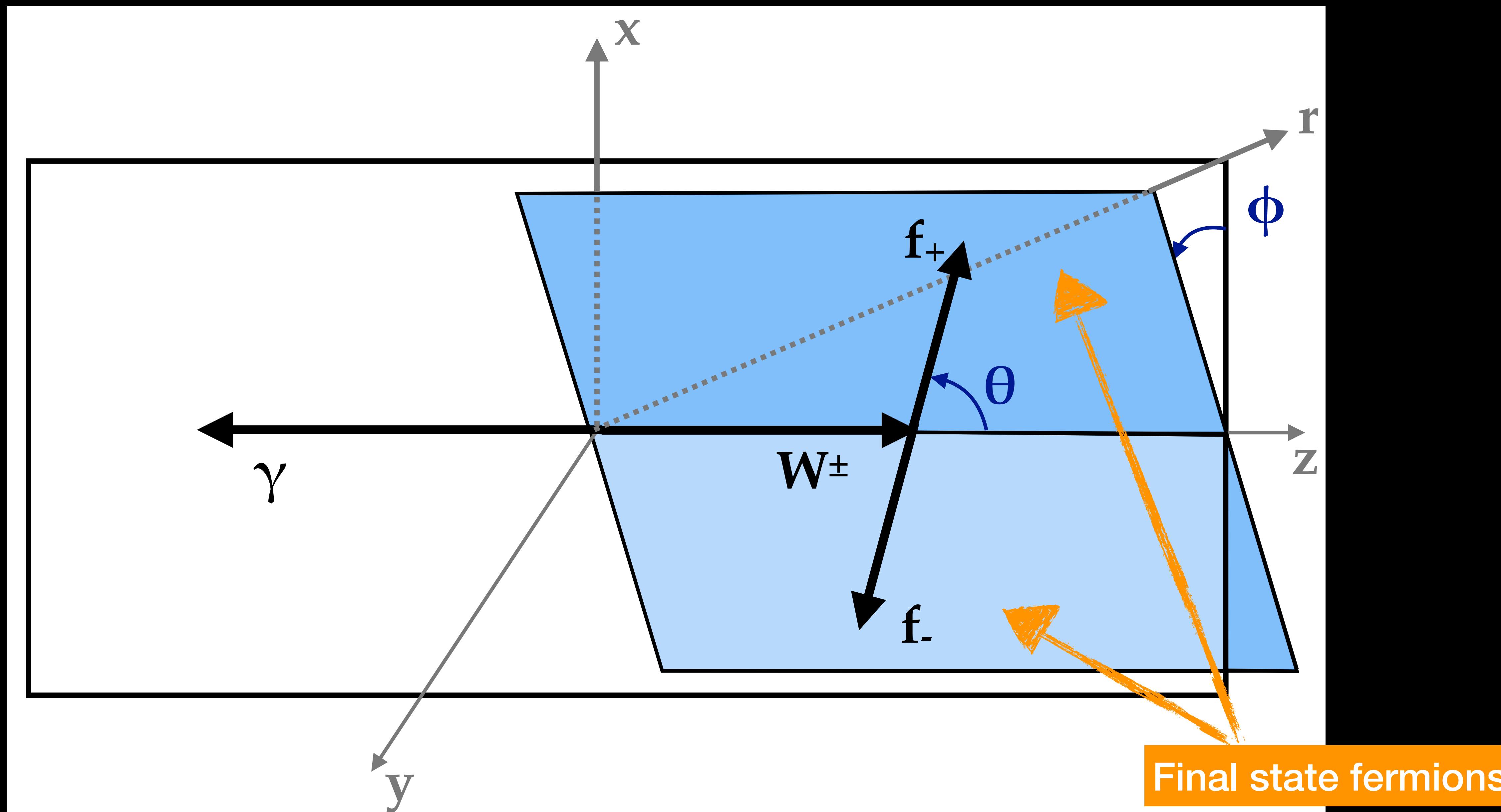
Text book example of effective field theories



Valid when: $p^2 \ll M_W^2$

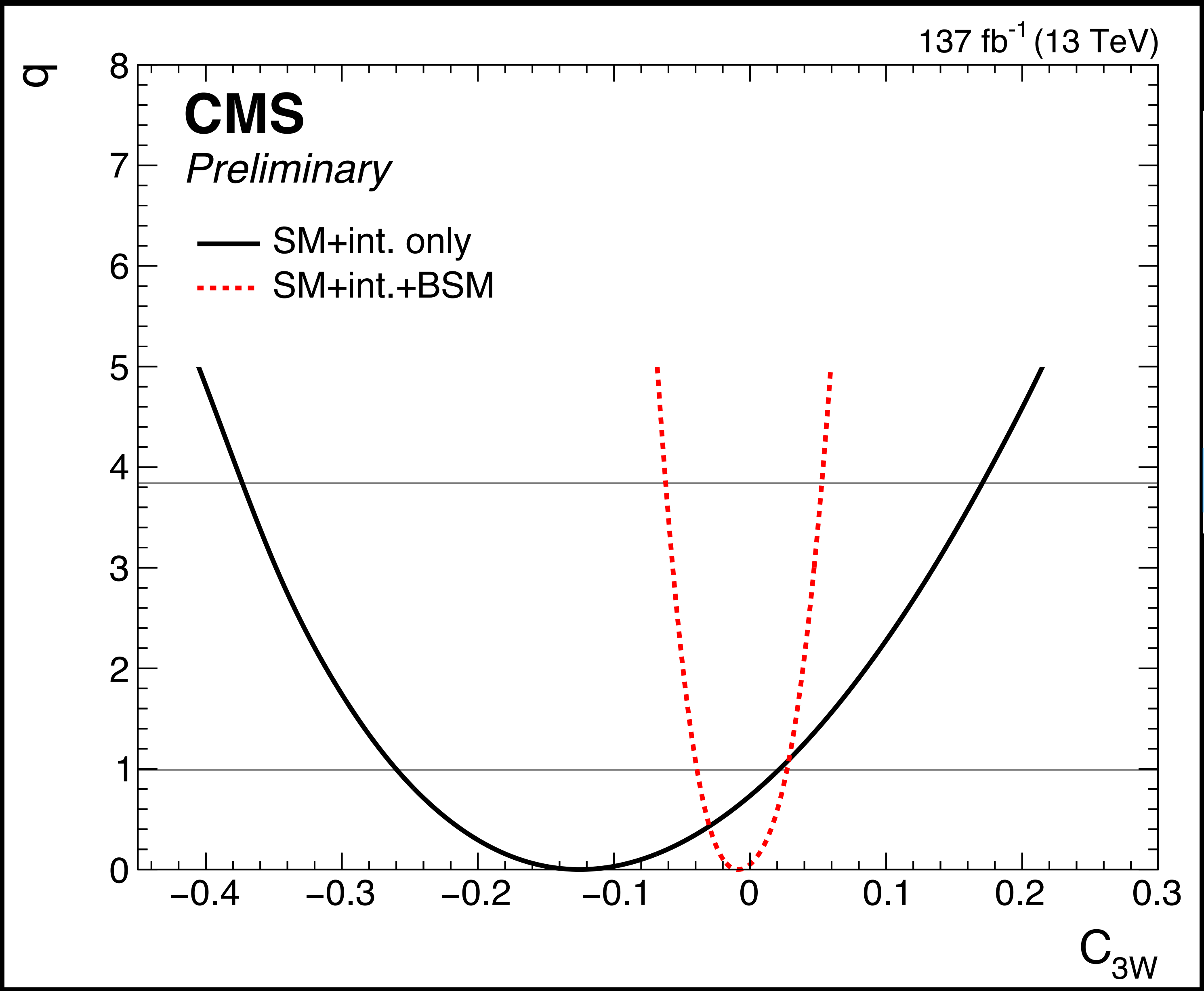
Error increases as a function of momentum transfer, √s

Special coordinate system



- ☑ Define frame by a Lorentz boost to the center-of-mass frame of the $W^{\pm}\gamma$ system
    - ☑ boson momenta are back-to-back
- ☑ Angle Φ now acquires sensitivity to interference with SM

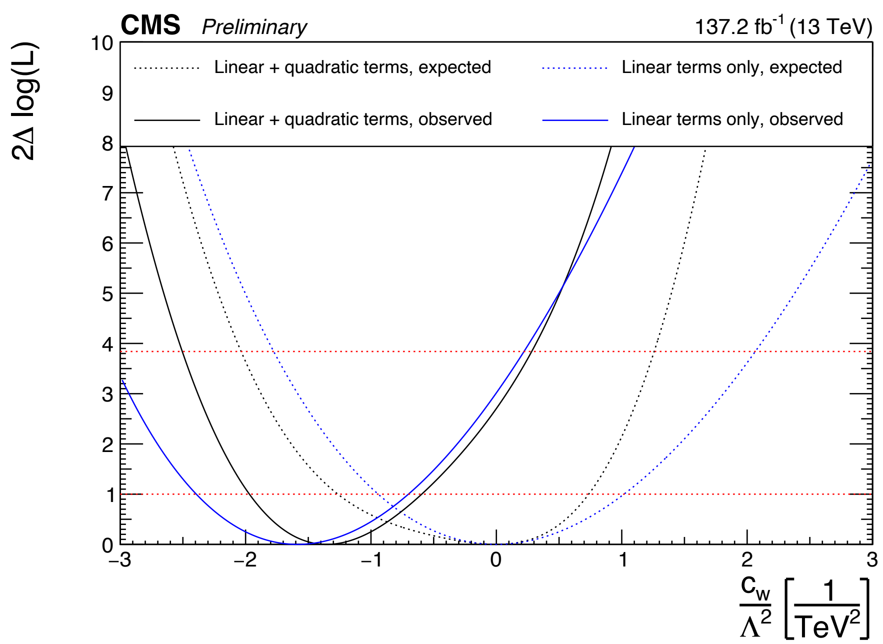
SMP-20-005: W±γ
Results

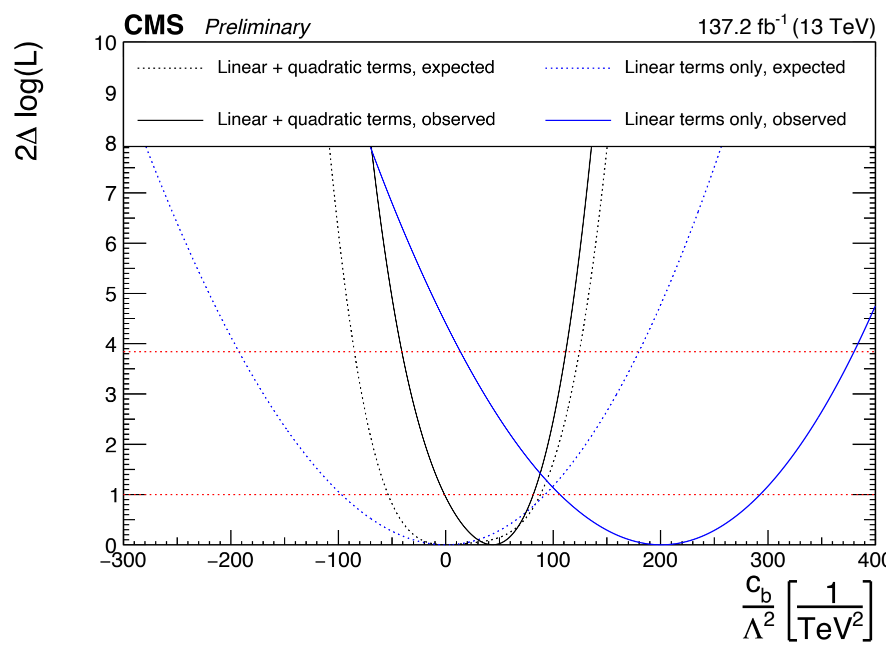


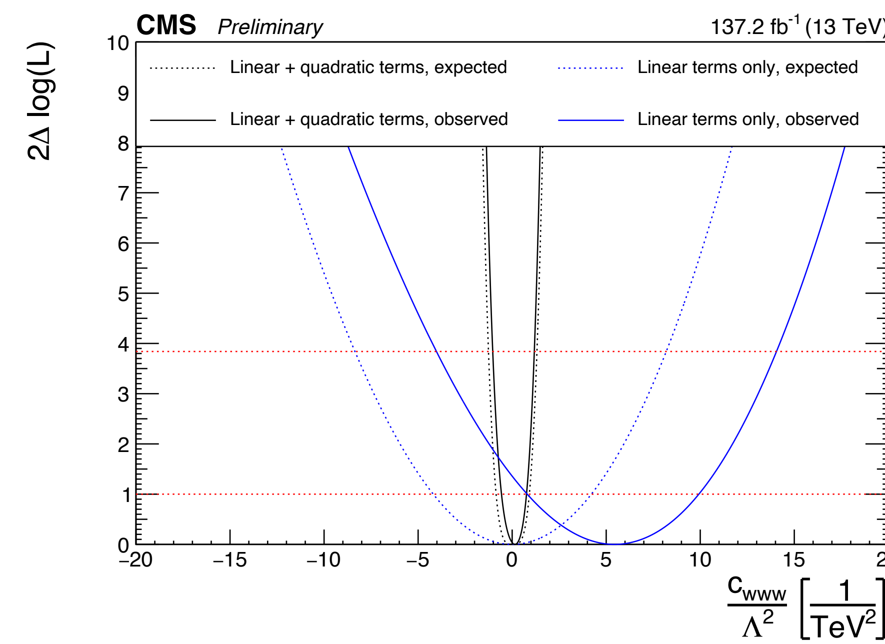
p_T^γ cutoff (GeV)	Best-fit C_{3W} (TeV^{-2})	
	SM+int. only	SM+int.+BSM
200	−0.85	−0.22
300	−0.26	−0.17
500	−0.13	−0.026
800	−0.20	−0.034
1500	−0.13	−0.009

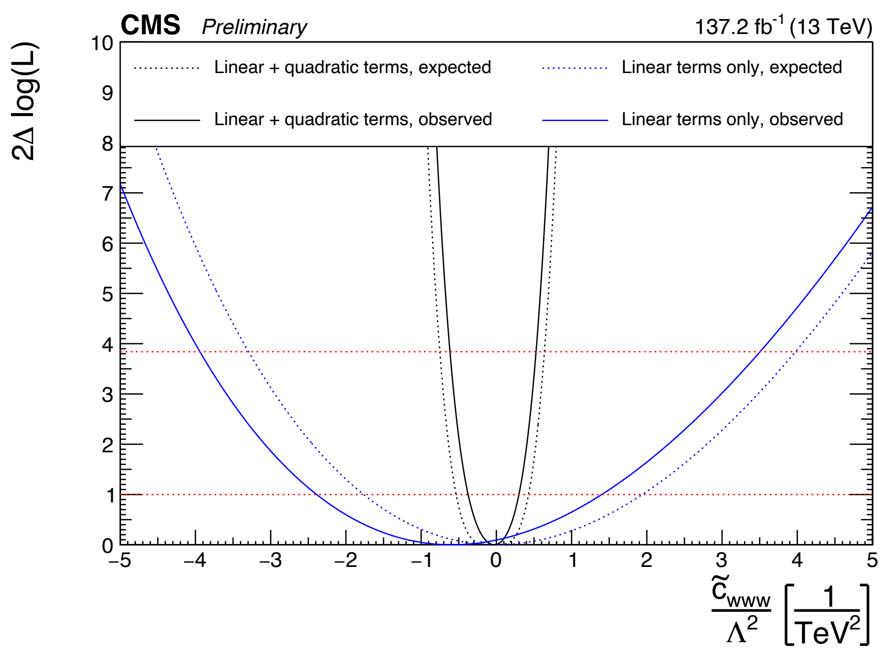
$$\sigma(C_{3\mathrm{W}}) = \sigma_{\mathrm{SM}} + C_{3\mathrm{W}}\sigma_{\mathrm{interference}} + C_{3\mathrm{W}}^2\sigma_{\mathrm{BSM}}$$

SMP-20-014: Measurement of the WZ process







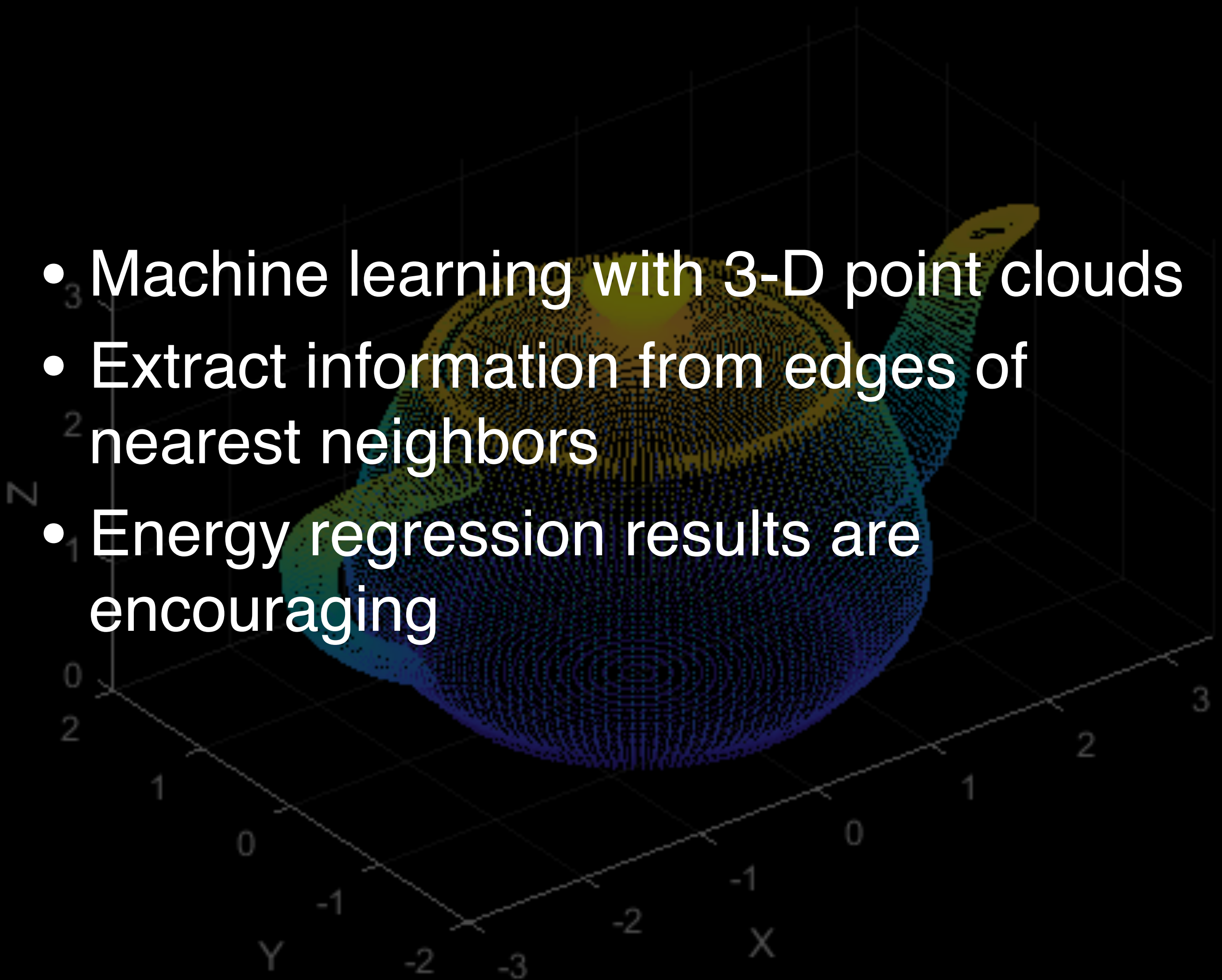


Parameter	95% CI, Exp. (TeV^{-2})	95% CI, Obs. (TeV^{-2})
c_W/Λ^2	$[-1.82, 2.12]$	$[-3.11, 0.26]$
c_{WWW}/Λ^2	$[-8.55, 8.46]$	$[-4.20, 14.25]$
c_b/Λ^2	$[-197.1, 183.3]$	$[9.3, 383.7]$
$\tilde{c}_{WWW}/\Lambda^2$	$[-3.35, 4.07]$	$[-4.01, 3.61]$
$\tilde{c}_W/\Lambda^2$	$[-, -]$	$[-, -]$

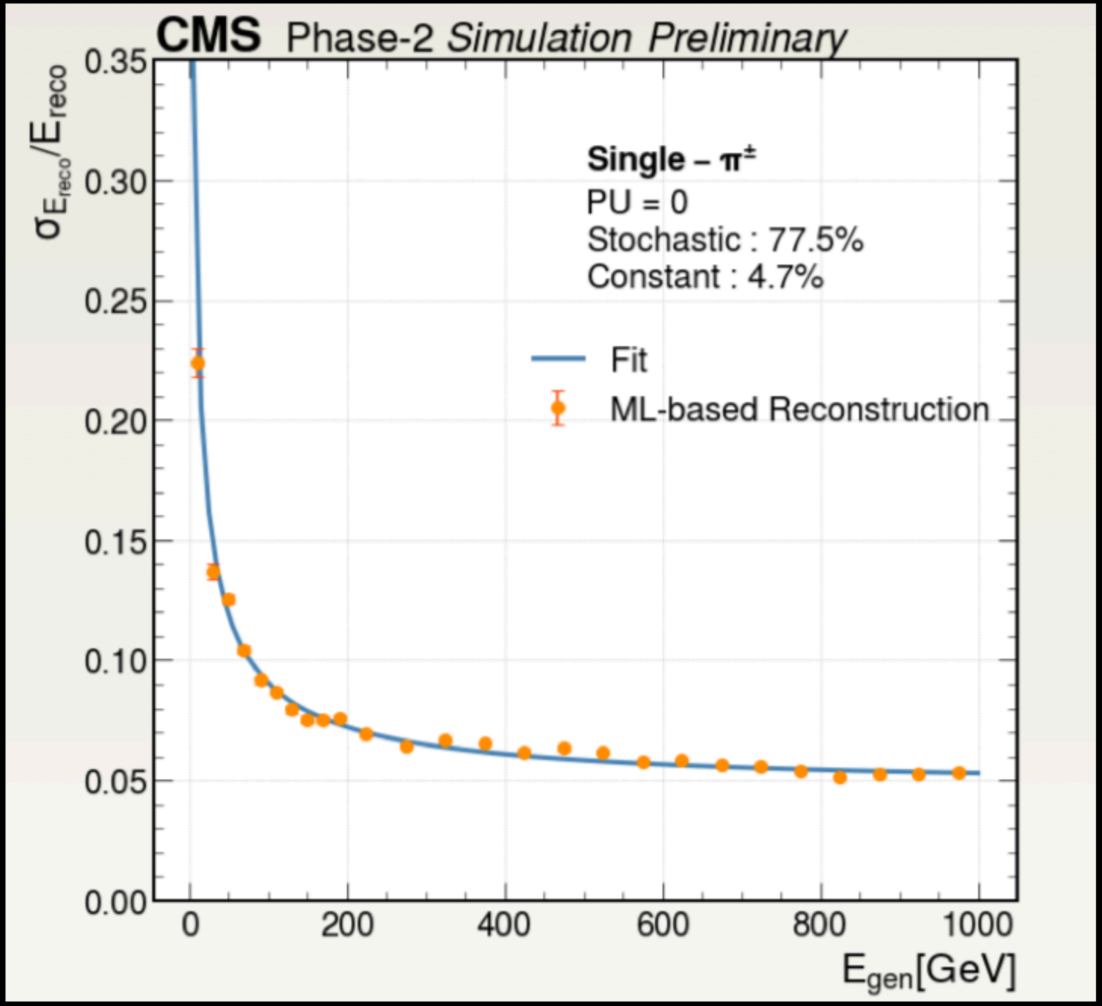
Limits computed taking only interference with SM (Λ^{-2}) into account

CP conserving **CP non-conserving**

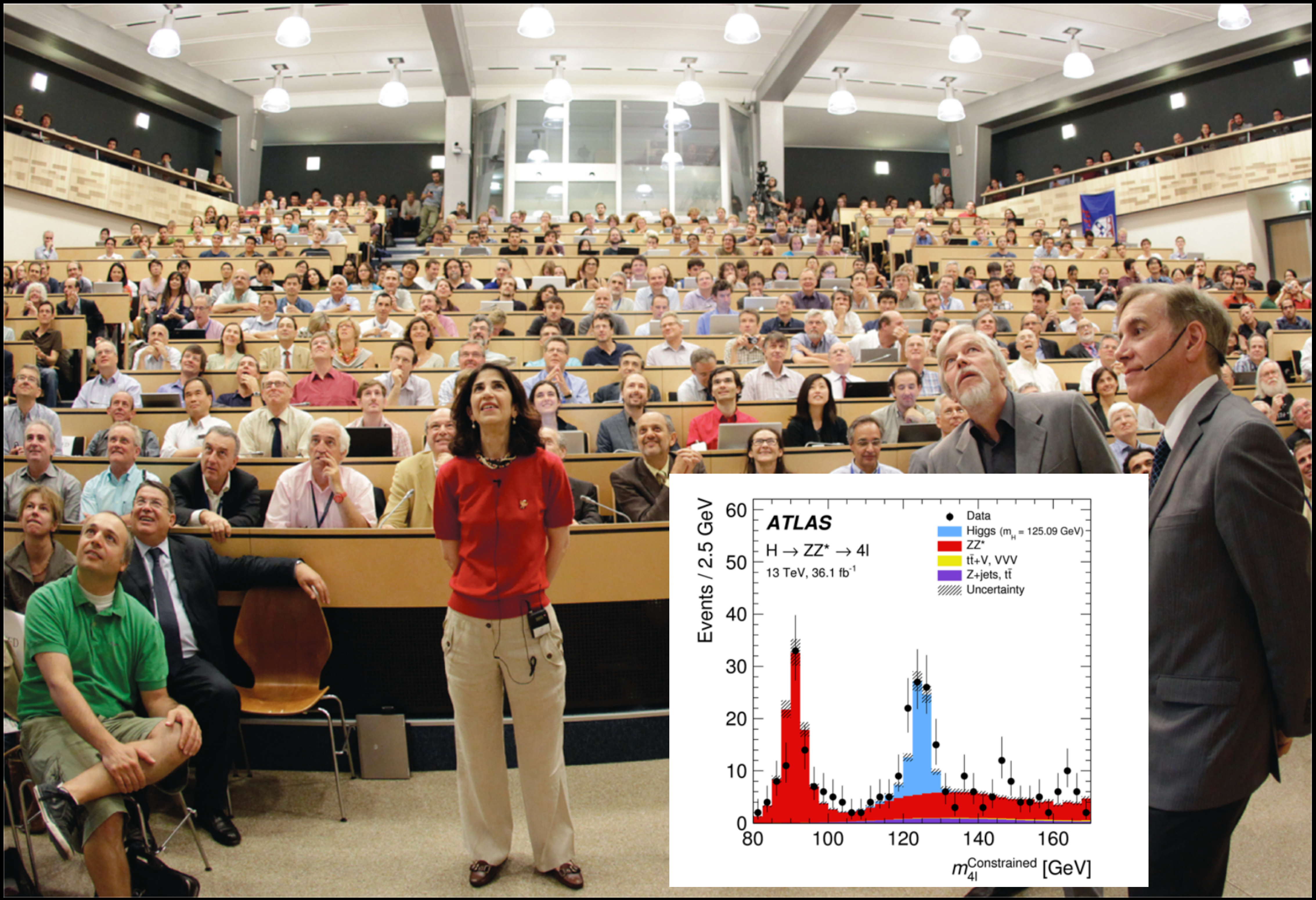
Power of new detectors



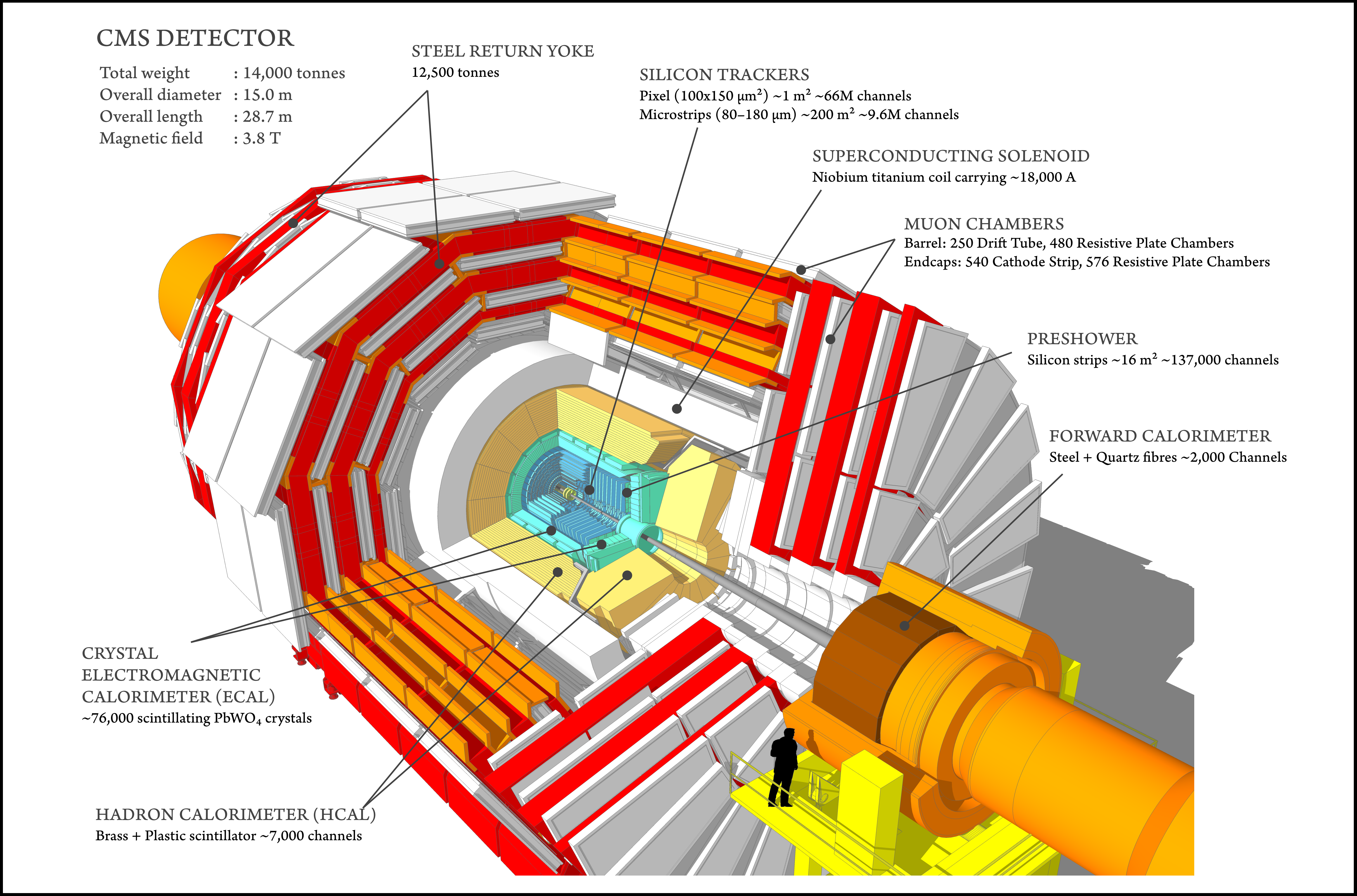
- Machine learning with 3-D point clouds
- Extract information from edges of nearest neighbors
- Energy regression results are encouraging

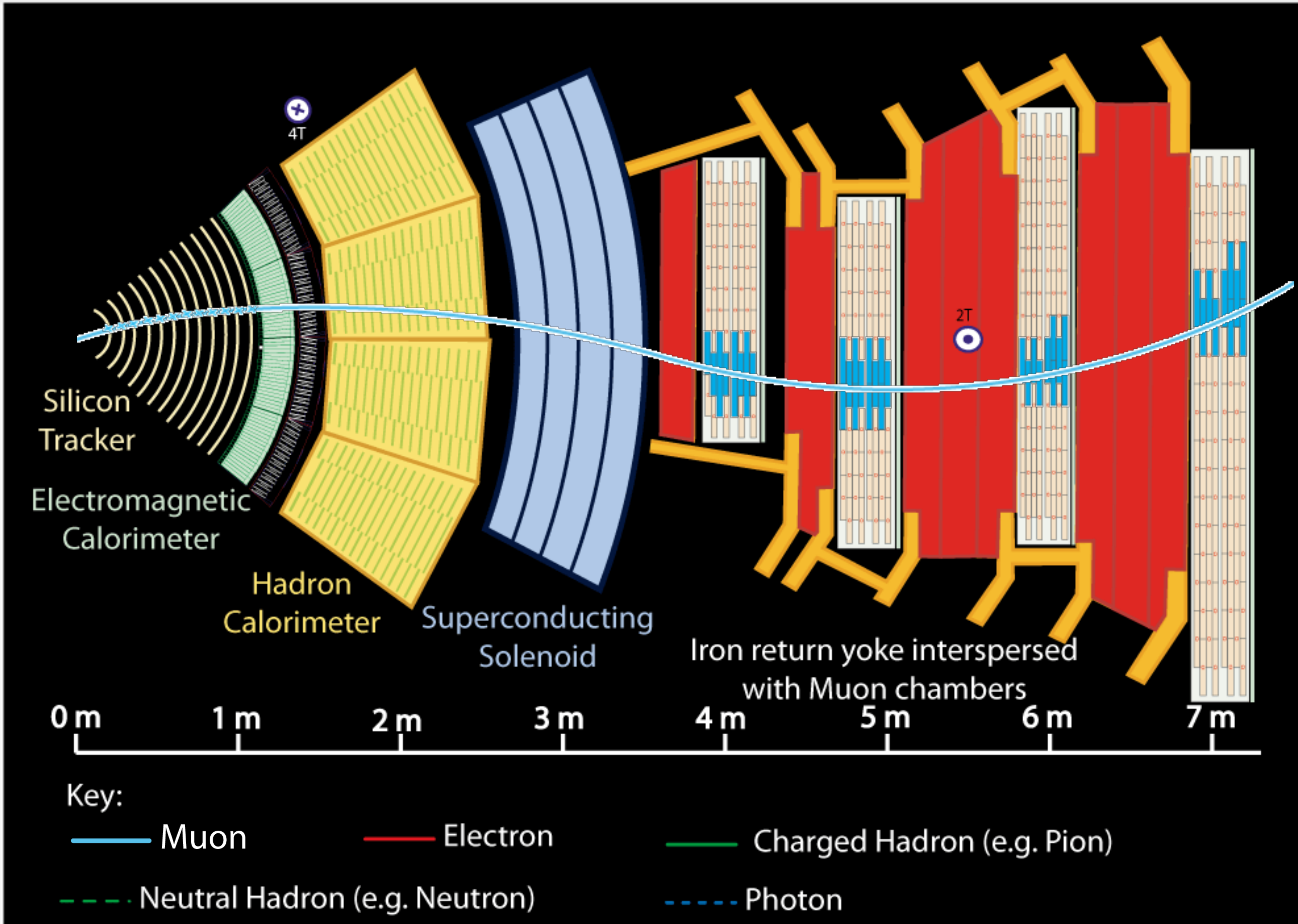


The Higgs Boson found at CERN!

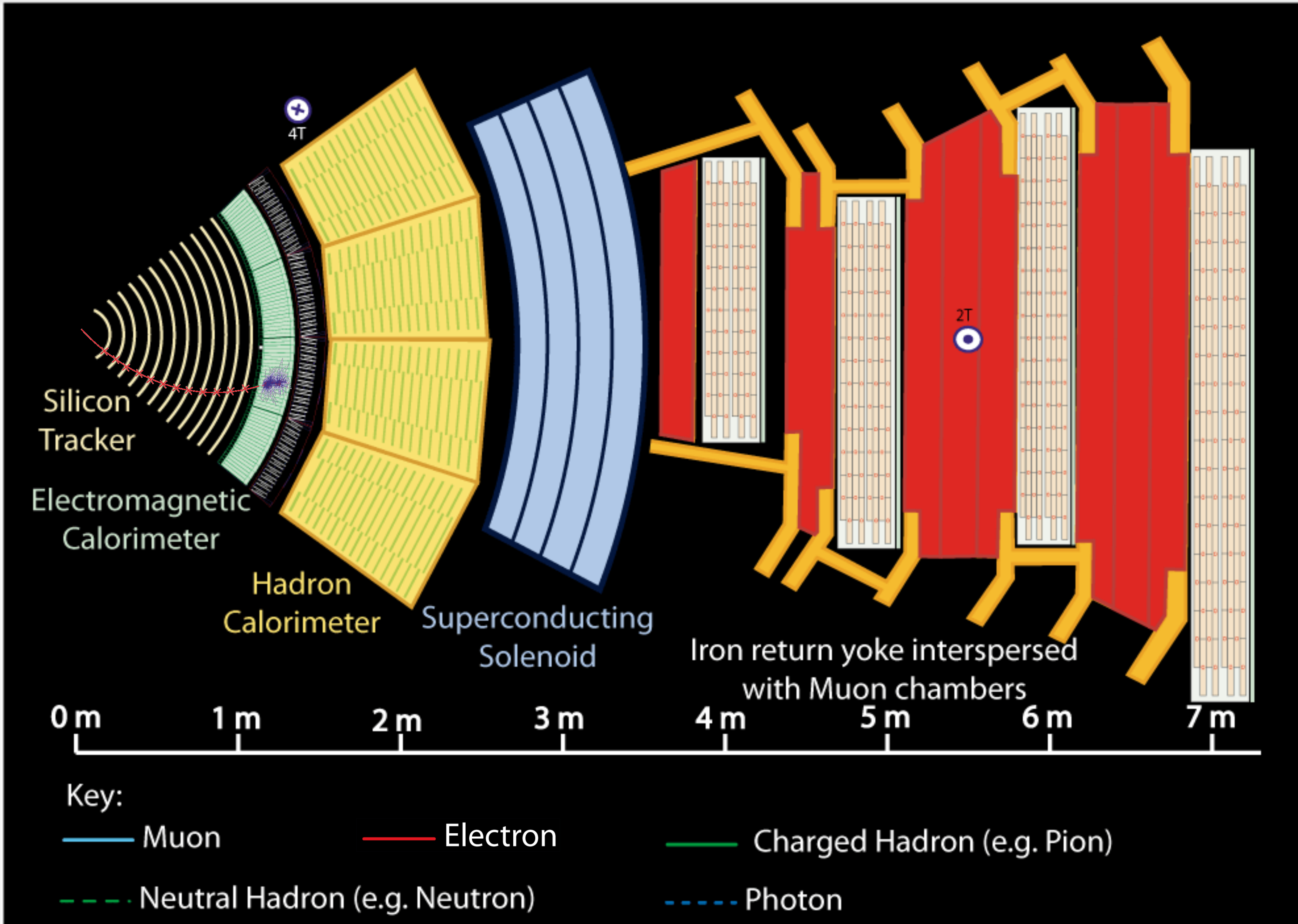


The CMS Experiment





4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon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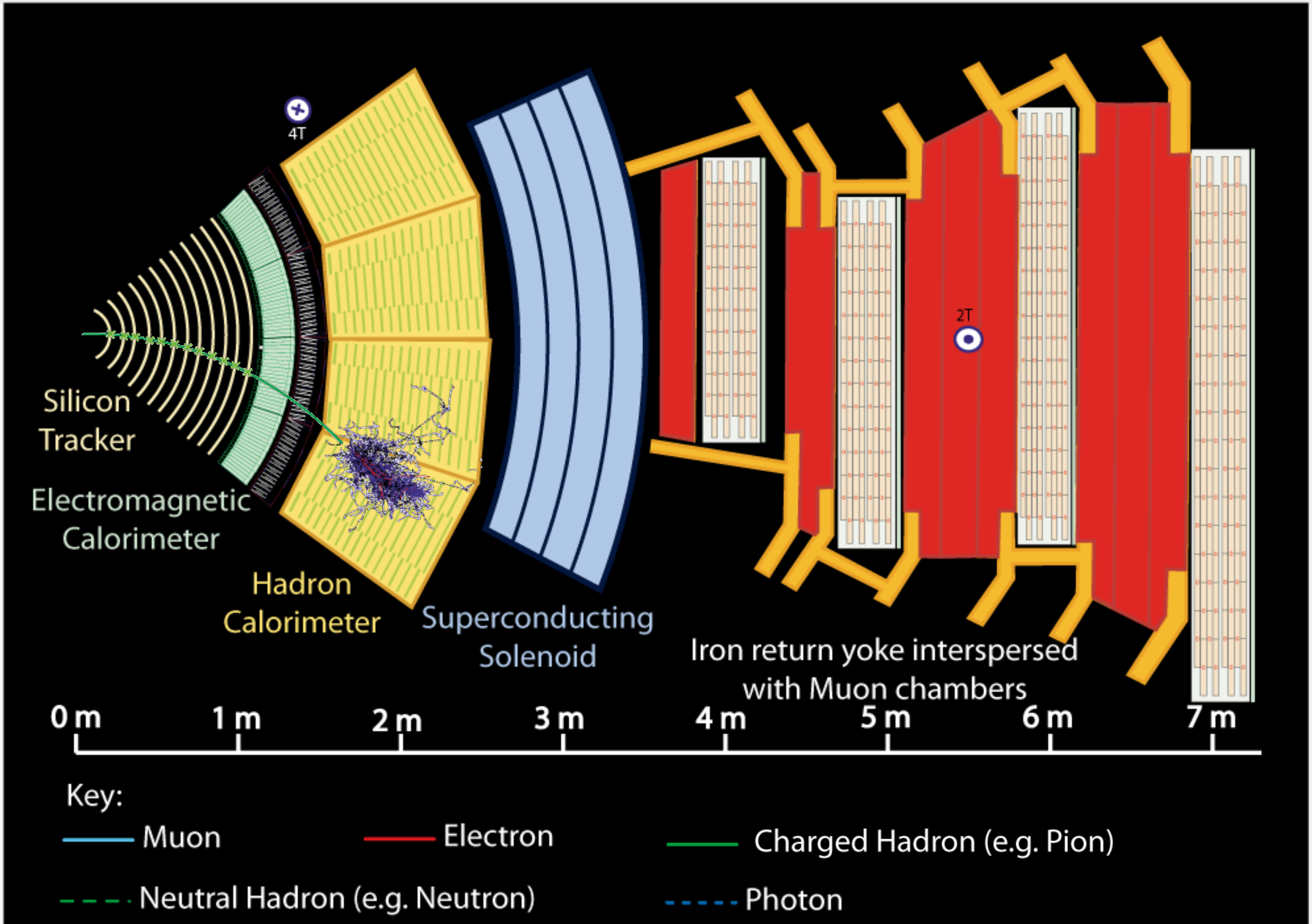
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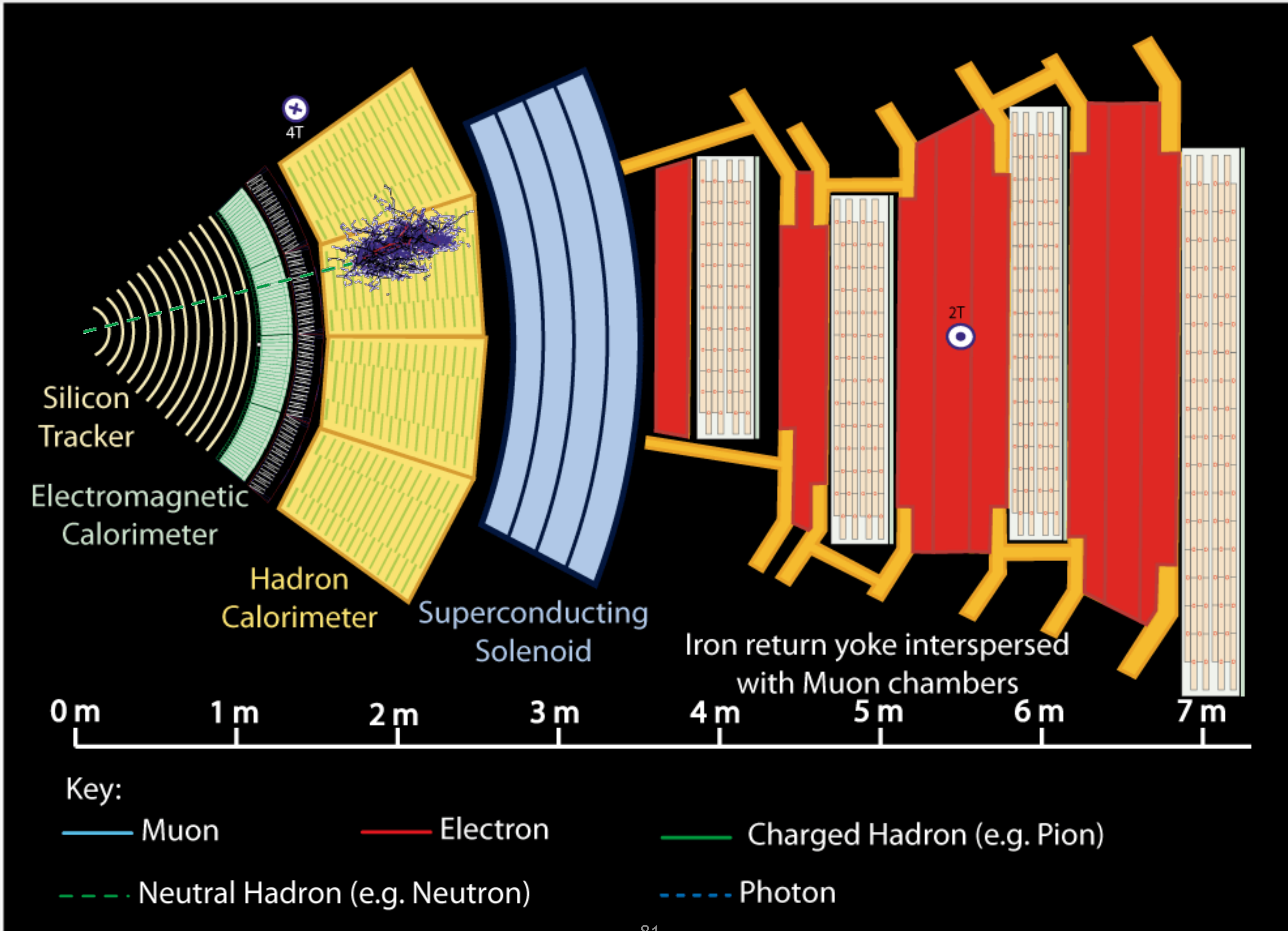
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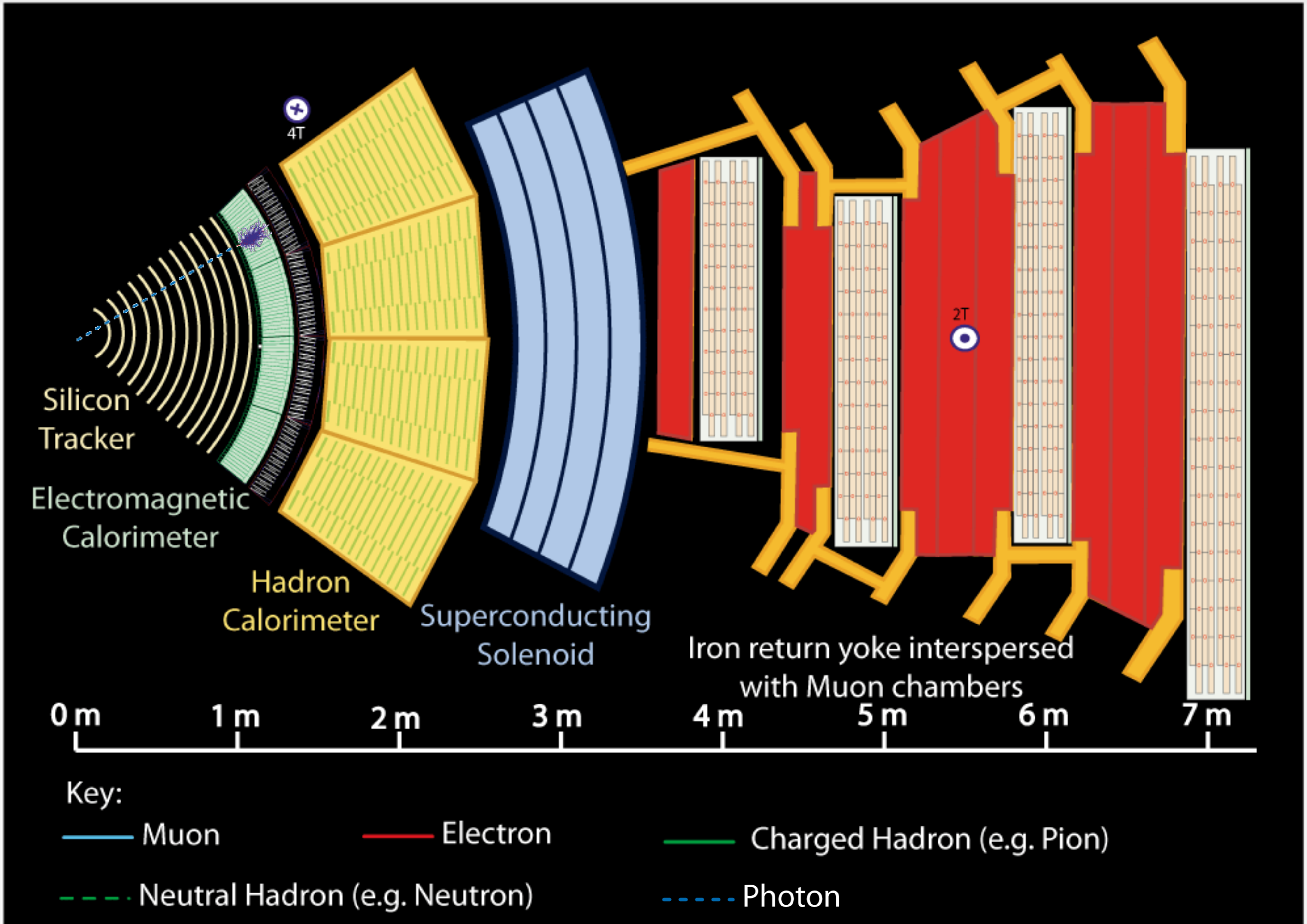
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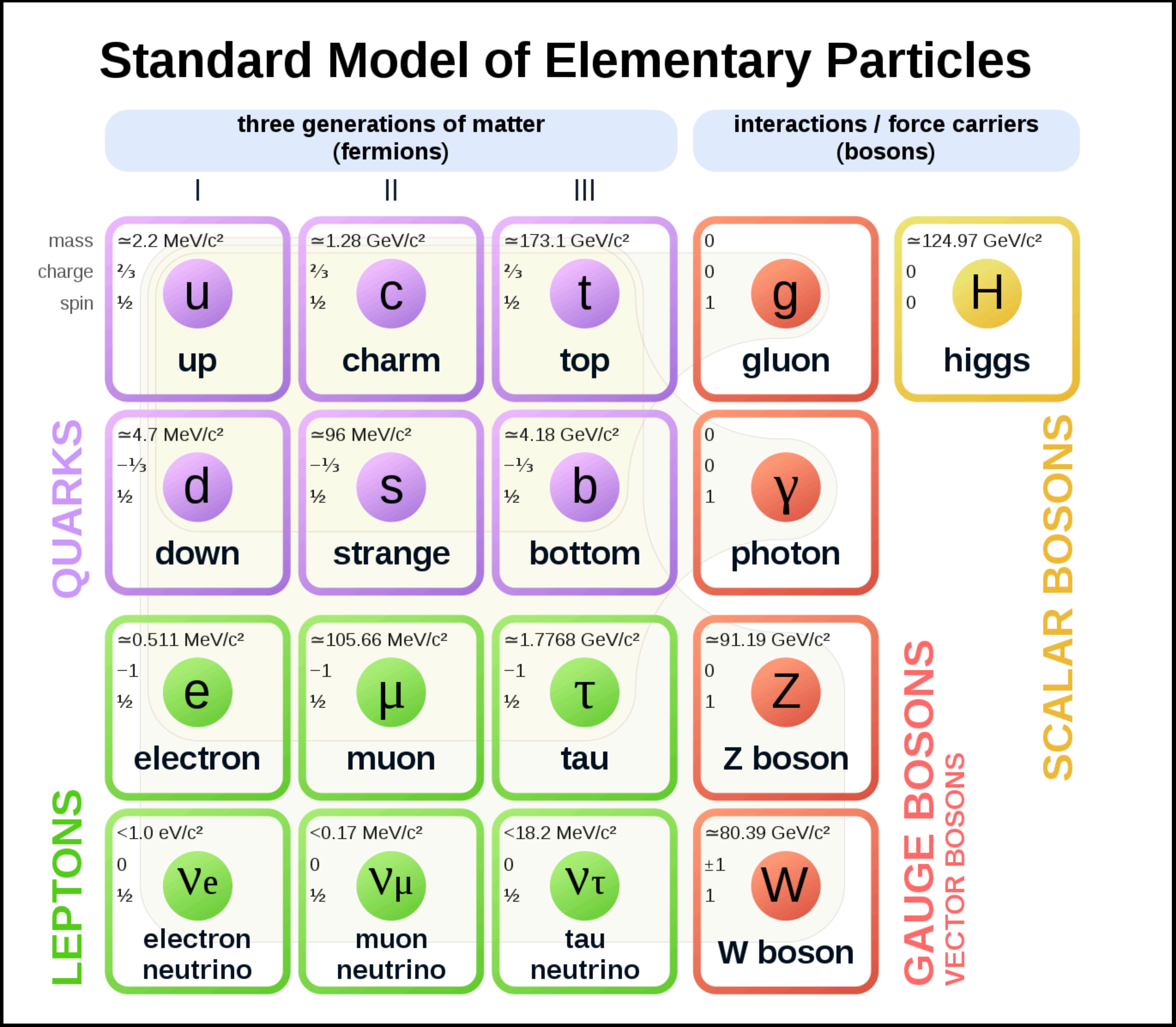
Photon

The Standard Model of Particle Physics

Observations:

- electron: 1897 (JJ Thomson)
- muon: 1936 (Anderson & Neddermeyer)
- electron neutrino: 1956 (Cowan & Reines)
- muon neutrino: 1962 (BNL)
- up, down, strange quark: 1968 (SLAC)
- charm quark: 1974 (SLAC/ BNL)
- tau lepton: 1975 (SLAC)
- bottom quark: 1977 (FNAL)
- gluon: 1979 (DESY)
- W and Z bosons: 1983 (CERN)
- top quark: 1995 (FNAL)
- tau neutrino: 2000 (FNAL)
- Higgs boson: 2012 (CERN)



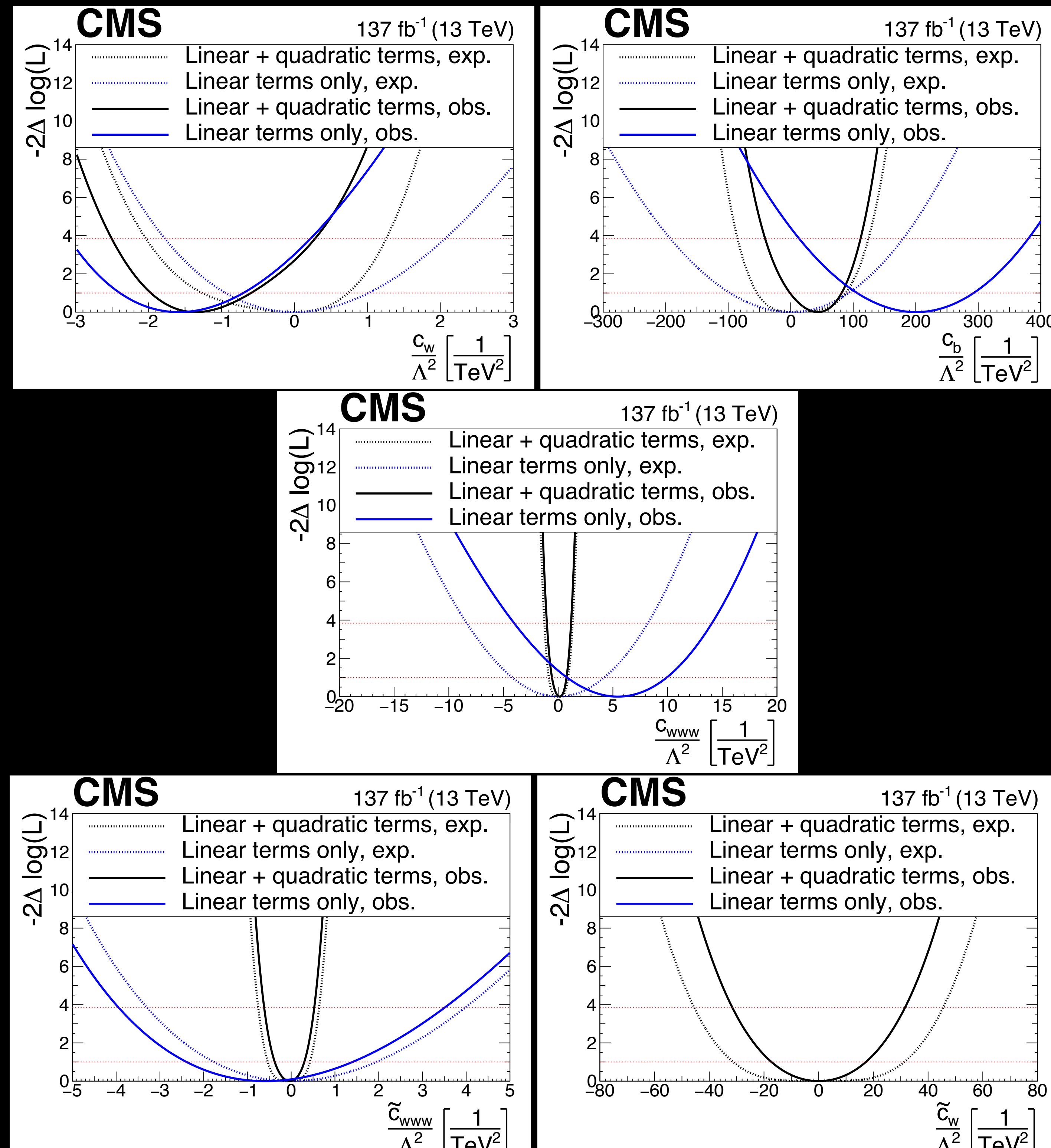
The Snowmass Process

"The Particle Physics Community Planning Exercise ("Snowmass") is a process that takes place approximately every 6-8 years. Organized by the American Physical Society (APS) Division of Particles and Fields (DPF), Snowmass is an opportunity for the entire HEP community to plan and document a long-term vision for particle physics in the US along with its international partners."

https://arxiv.org/abs/2110.11231

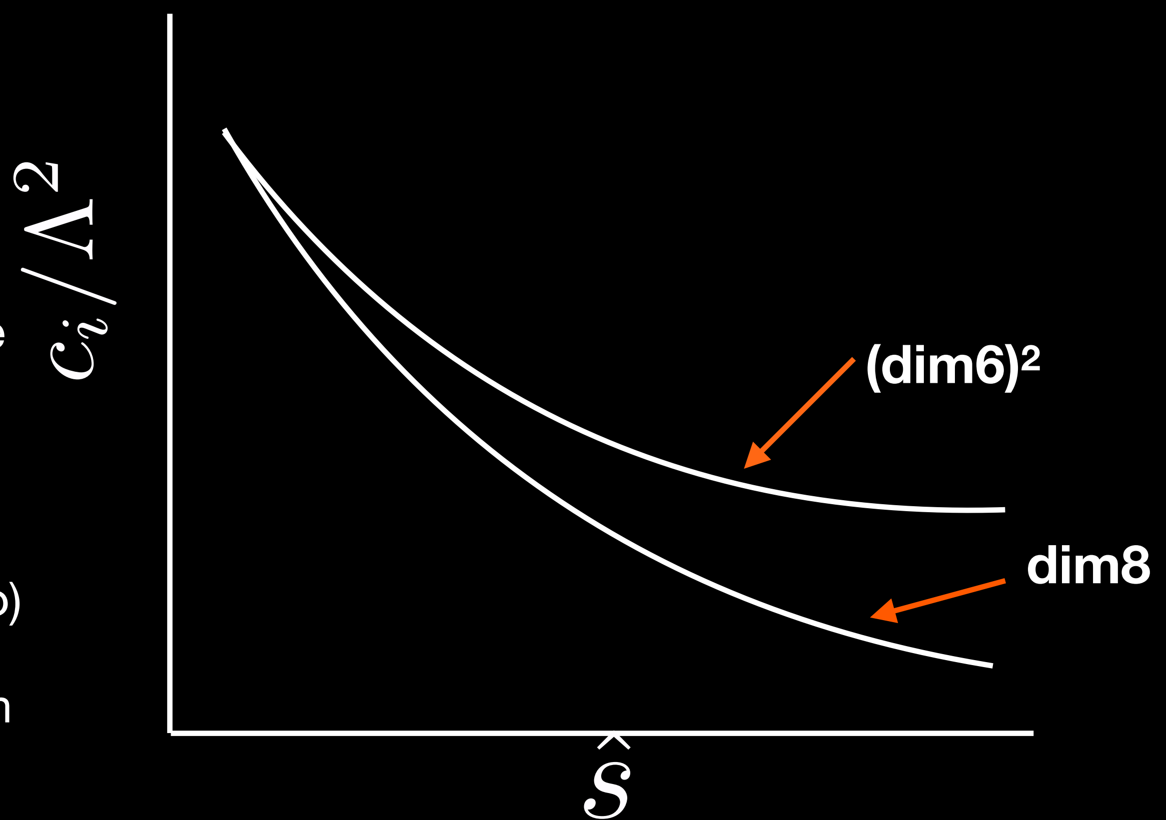
Thanks to the Community Planning Meeting committee!

WZ limits - interference and BSM separated



Salient features associated with VVV

- Study of the Higgs sector possible
  - Best way to include Higgs mediated mode?
  - Can we quantify the interference between the Higgs-mediated modes and other modes of production?
- Critical questions such as (dim6)² vs. dim8 contributions possible to address
  - Pertinent in the context of global EFT fits
- Explore sensitive variables: proxy for $\hat{S}$ and angular variables (Δϕ)
  - Absence of “golden” variables as in the case of vector boson scattering topologies



Operators	WWW	WWZ	WZZ	ZZZ
$\mathcal{O}_{3W} = \epsilon^{abc} W_\mu^{a\nu} W_\nu^{b\rho} W_\rho^{c\mu}$	✓	✓	✓	
$\mathcal{O}_{HD} = (D^\mu H^\dagger H)(H^\dagger D_\mu H)$	✓	✓	✓	✓
$\mathcal{O}_{HWB} = H^\dagger \sigma^i H W_{\mu\nu}^i B^{\mu\nu}$	✓	✓	✓	✓
$\mathcal{O}_{HW} = H^\dagger H W_{\mu\nu} W^{\mu\nu}$	✓	✓	✓	✓

Relevant Operators for specific processes

Operators	WWWW	WWZZ	ZZZZ	ZZZγ
$\mathscr{L}_{S,1}$ $\mathscr{L}_{S,2}$	✅	✅	✅	0
$\mathscr{L}_{M,0}$ $\mathscr{L}_{M,1}$ $\mathscr{L}_{M,6}$ $\mathscr{L}_{M,7}$	✅	✅	✅	✅
$\mathscr{L}_{M,2}$ $\mathscr{L}_{M,3}$ $\mathscr{L}_{M,4}$ $\mathscr{L}_{M,5}$	0	✅	✅	✅
$\mathscr{L}_{T,0}$ $\mathscr{L}_{T,1}$ $\mathscr{L}_{T,2}$	✅	✅	✅	✅
$\mathscr{L}_{T,5}$ $\mathscr{L}_{T,6}$ $\mathscr{L}_{T,7}$	0	✅	✅	✅
$\mathscr{L}_{T,8}$ $\mathscr{L}_{T,9}$	0	0	✅	✅