Dibosons in CMS
Candles of SM and a path to New Physics

Rafael Coelho Lopes de Sá (Fermilab)
For the CMS collaboration

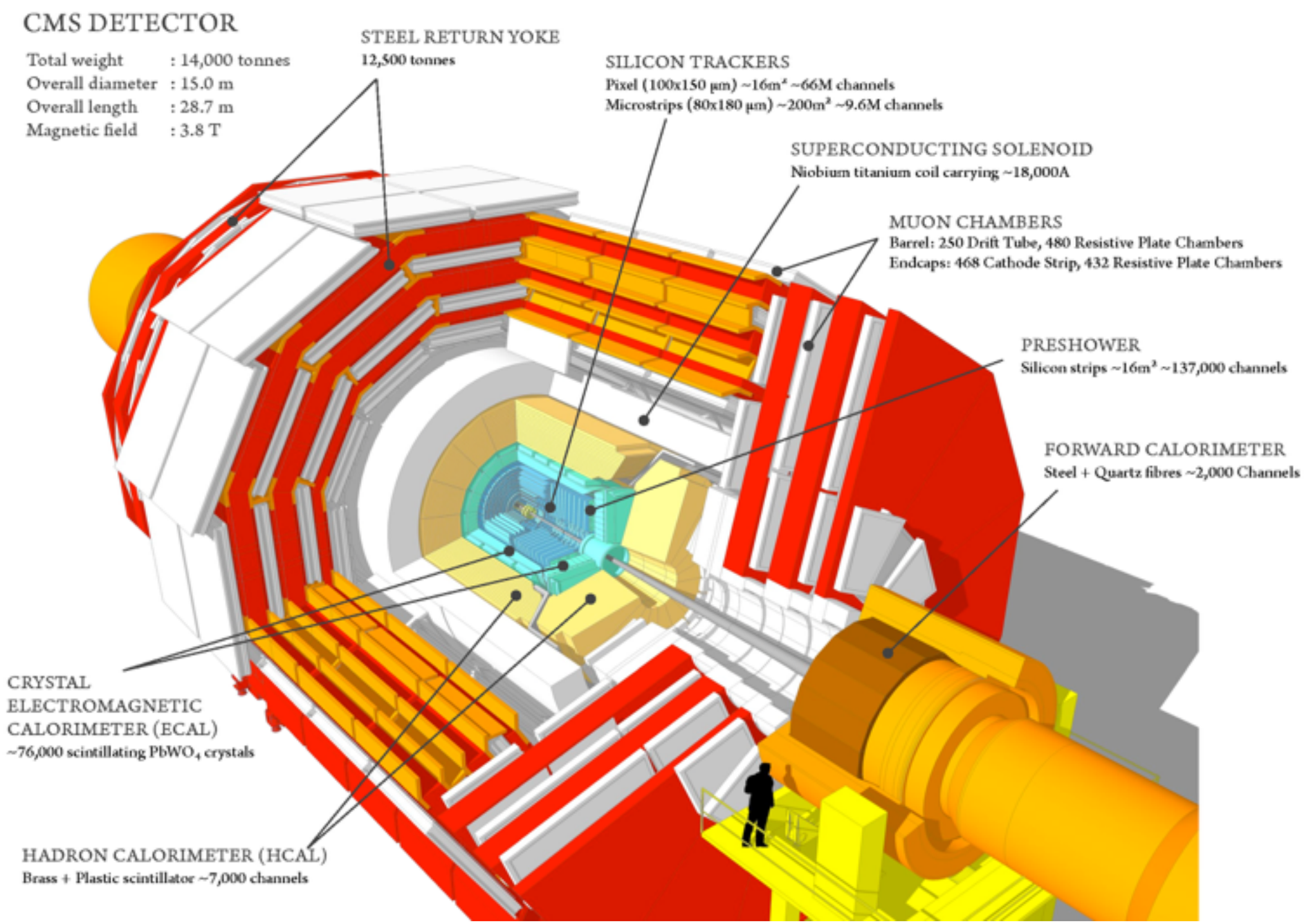
Joint theoretical-experimental seminar
Fermilab

Contents of the talk

- Introduction:
  - The CMS detector and the LHC data.
  - Why study dibosons?
- New Standard Model diboson measurements:
  - WW, WZ, and ZZ cross sections at 13 TeV
- New Beyond the Standard Model diboson searches:
  - Searches for new resonances decaying to WW, WZ and ZZ.
- Turning precision measurements into New Physics searches: SMEFT
- Review of 7 and 8 TeV diboson cross sections:
  - WW and WZ inclusive and differential cross sections.
  - EFT analysis.
- Phenomenology analysis of the WW EFT analysis.
- Conclusions and perspectives.

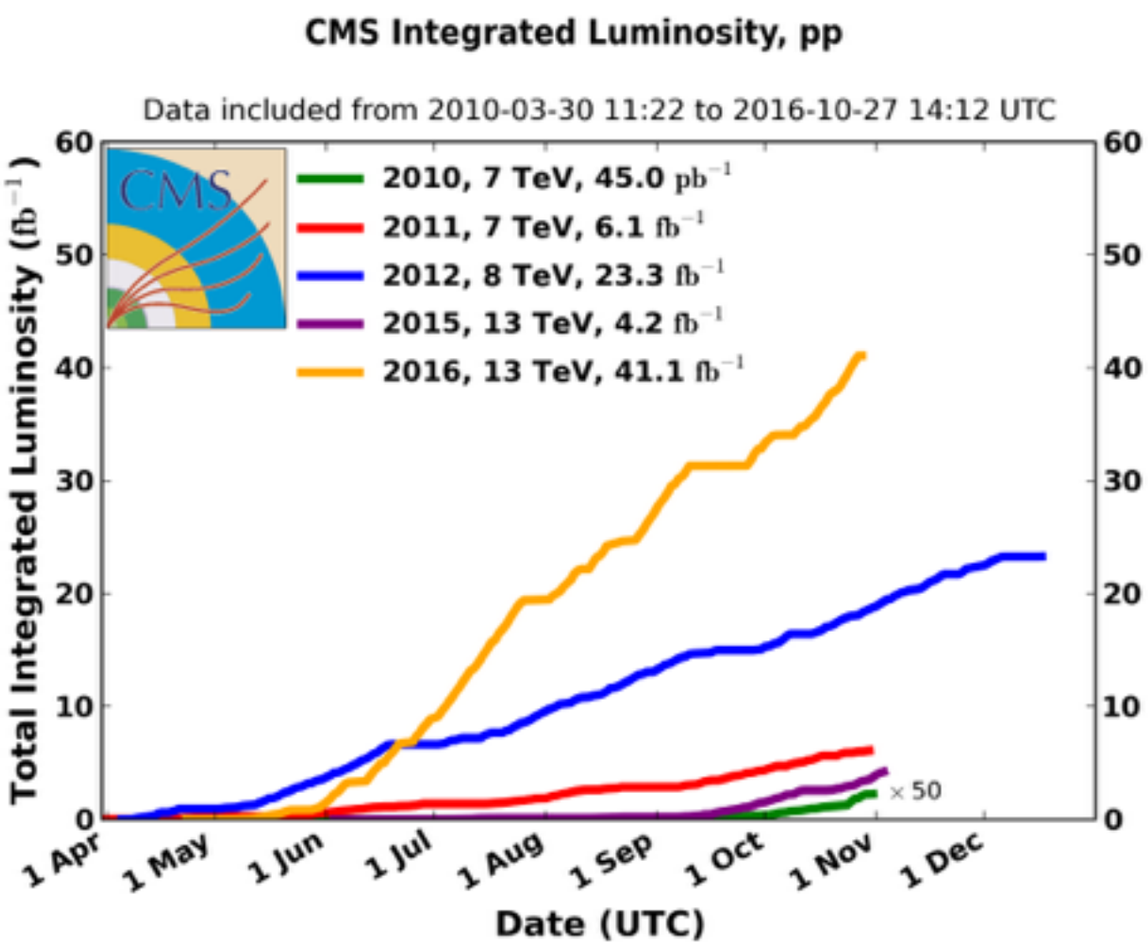
The CMS experiment

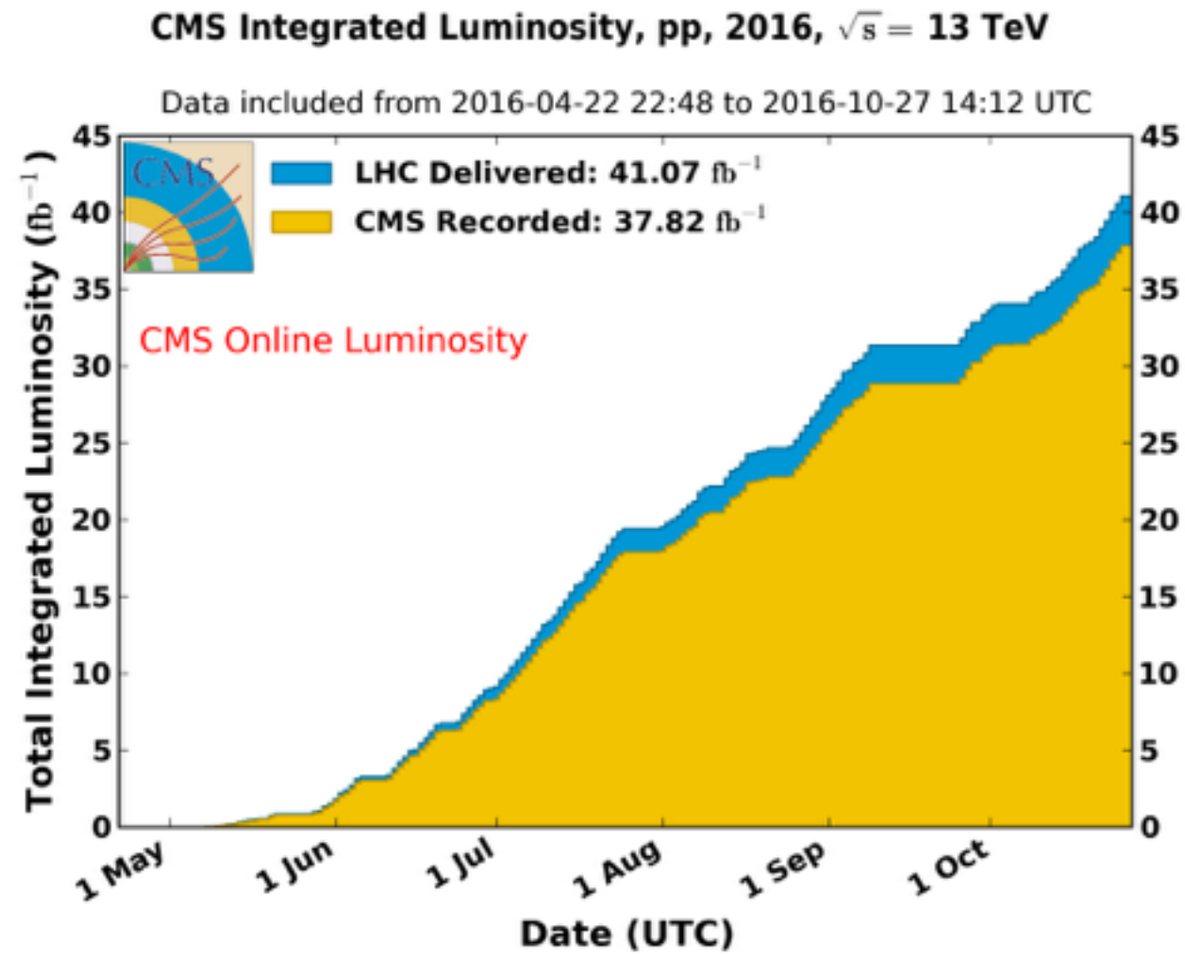
- The CMS experiment is one of the two general purpose experiments collecting data at the CERN LHC.



2016: a wonderful year (for the LHC)

- The LHC just ended the 2016 proton-proton collisions with record integrated luminosity delivered to CMS and ATLAS (over 41fb^{-1})
- CMS recording efficiency is ~92% (over 37fb^{-1})
- The results presented here use the data since 2011 up to the first 12.9fb^{-1} from 2016.



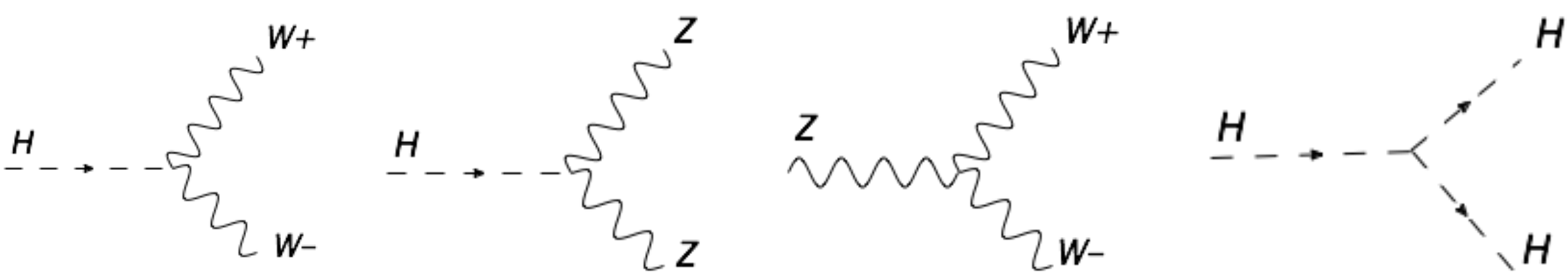


Why study massive boson interactions?

- One of the main goals of the LHC is to study the mechanism of Electroweak Spontaneous Symmetry Breaking.
- This process determines particle content of the Standard Model:

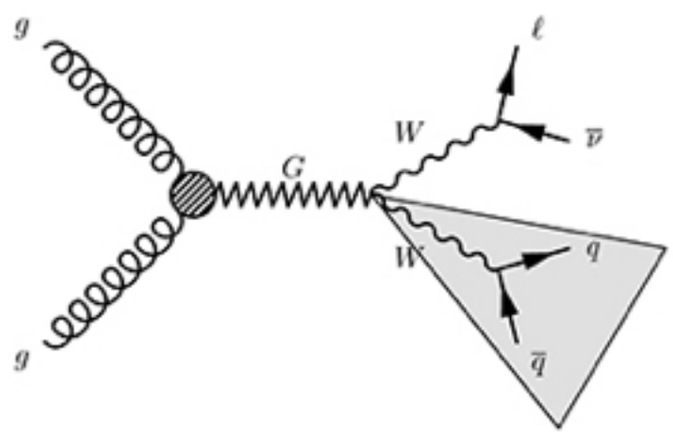
(massless vector) W^a_μ, B_μ	$\Rightarrow$	(massive vector) W^+_μ, W^-_μ, Z_μ
(Higgs doublet) σ, χ^a		(Higgs field) H

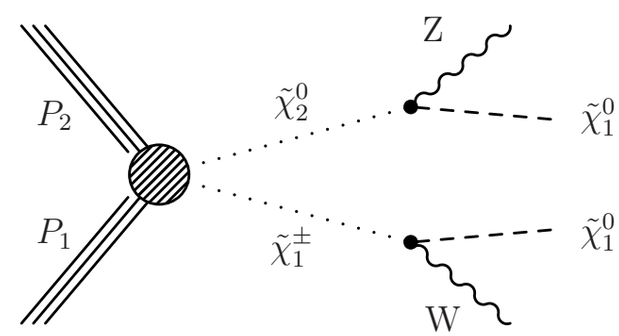
- The dynamics of massive bosons is a window into the physics of spontaneous symmetry breaking.
- New Physics associated to Electroweak Symmetry Breaking could alter the dynamics of the Higgs, W and Z bosons.



The two roads

- Traditionally, there have been two ways to study the physics of massive bosons:
  - Searches for new particles decaying to massive bosons:
    - New resonances decaying to dibosons.
    - New particles decaying to vector bosons in association with other particles

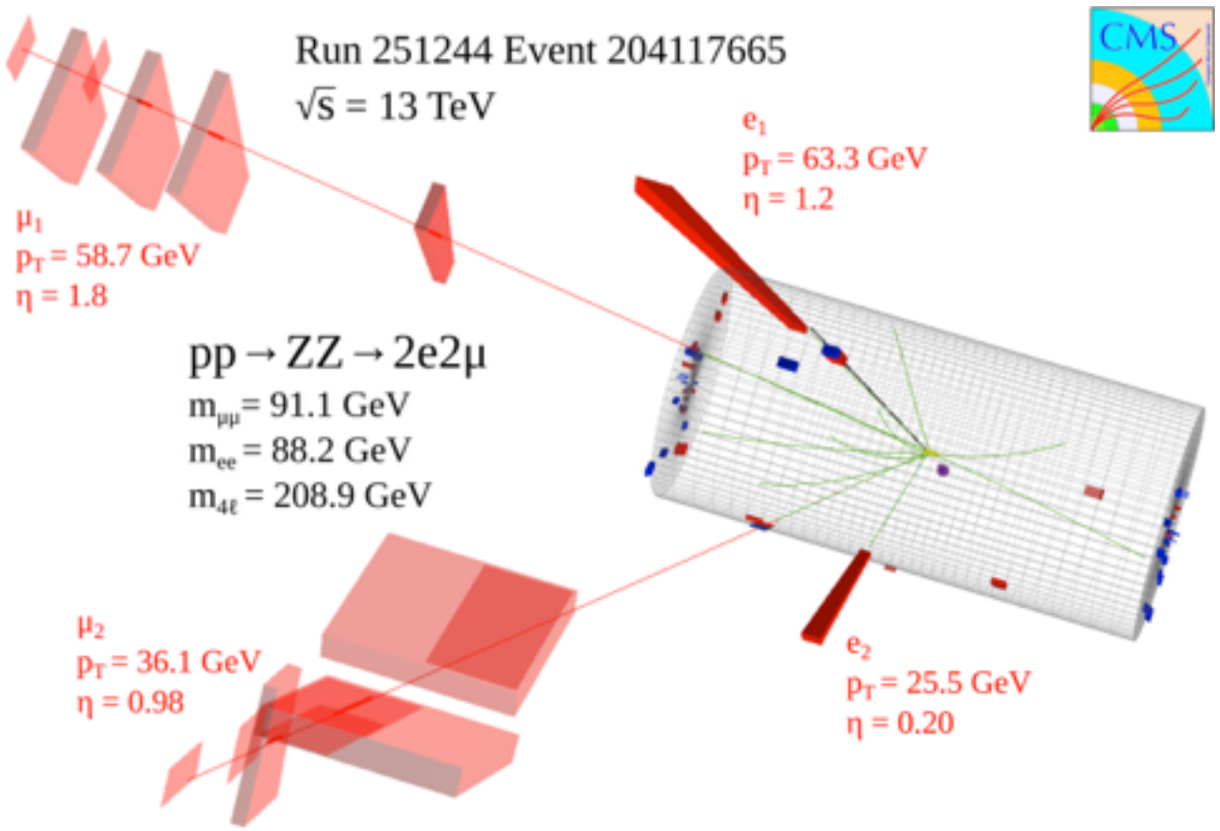


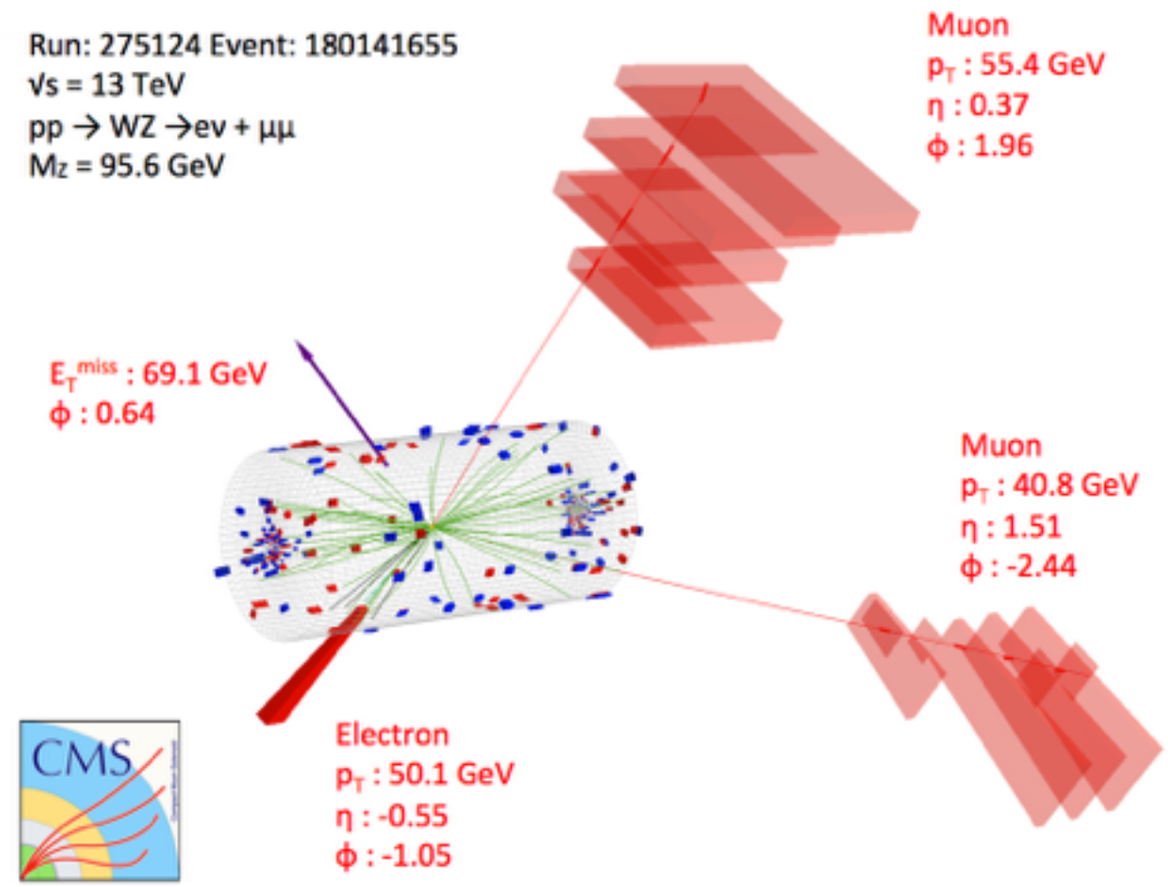


  - Searches for anomalous diboson production:
    - Fiducial and differential measurements
    - Pseudo-observables measurements
- First we need to establish that we can measure these final states with very high precision.

13 TeV diboson cross section measurements

- Diboson cross sections have been measured at the LHC at 7, 8, and 13 TeV
- Today we show recent results of WW, WZ, and ZZ cross sections at 13 TeV
- These measurements are limited by the small integrated luminosity collected in 2015. The measurements with 2016 data will be dominated by systematic uncertainties.



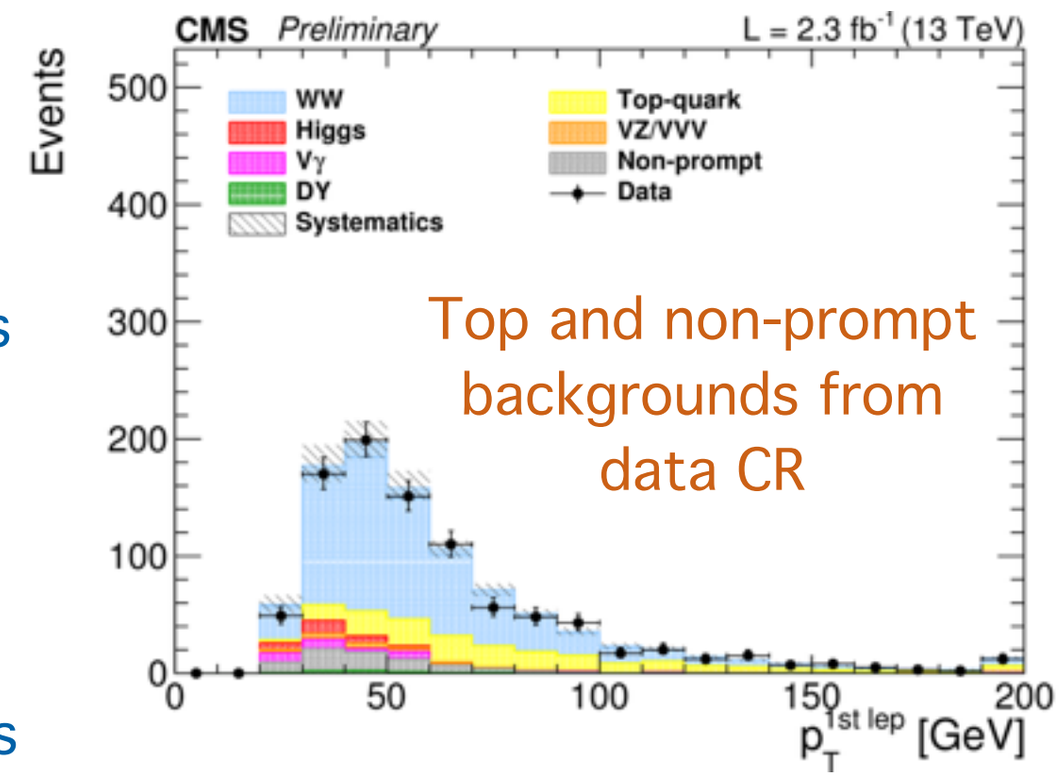


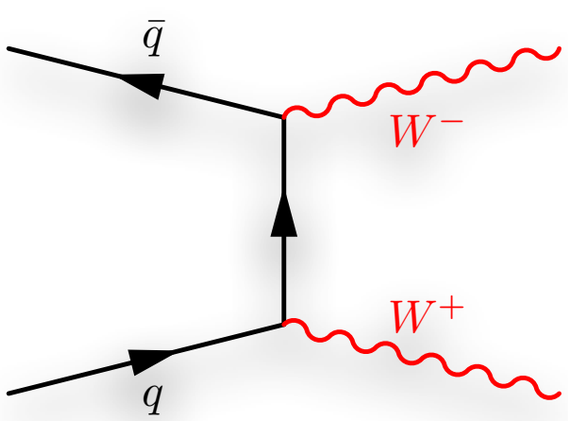
WW cross section measurement at 13 TeV

- Measurement performed in the fully leptonic WW→eνμν channel selecting events with a low number of jets.

$p_T(e,\mu) > 20$ GeV
$|\eta(e/\mu)| < 2.5/2.4$
$m(e\mu) > 12$ GeV
$p_T(e\mu) > 30$ GeV ← Rejects event with non-prompt leptons
$E_T^{miss} > 20$ GeV
min(proj E_T^{miss}, proj track E_T^{miss}) > 20 GeV
0 b-quark jets with $p_T > 20$ GeV, $|\eta| < 2.4$
0 or 1 jet with $p_T > 30$ GeV, $|\eta| < 4.7$

Rejects top events





Category	Value ± stat. ± exp. syst. ± theo. syst. ± lumi. [pb]
0-jet	113.6 ± 6.3 ± 5.1 ± 6.5 ± 3.3
1-jet	135.3 ± 15.4 ± 34.0 ± 14.4 ± 6.0
Combination	115.3 ± 5.8 ± 5.7 ± 6.4 ± 3.6

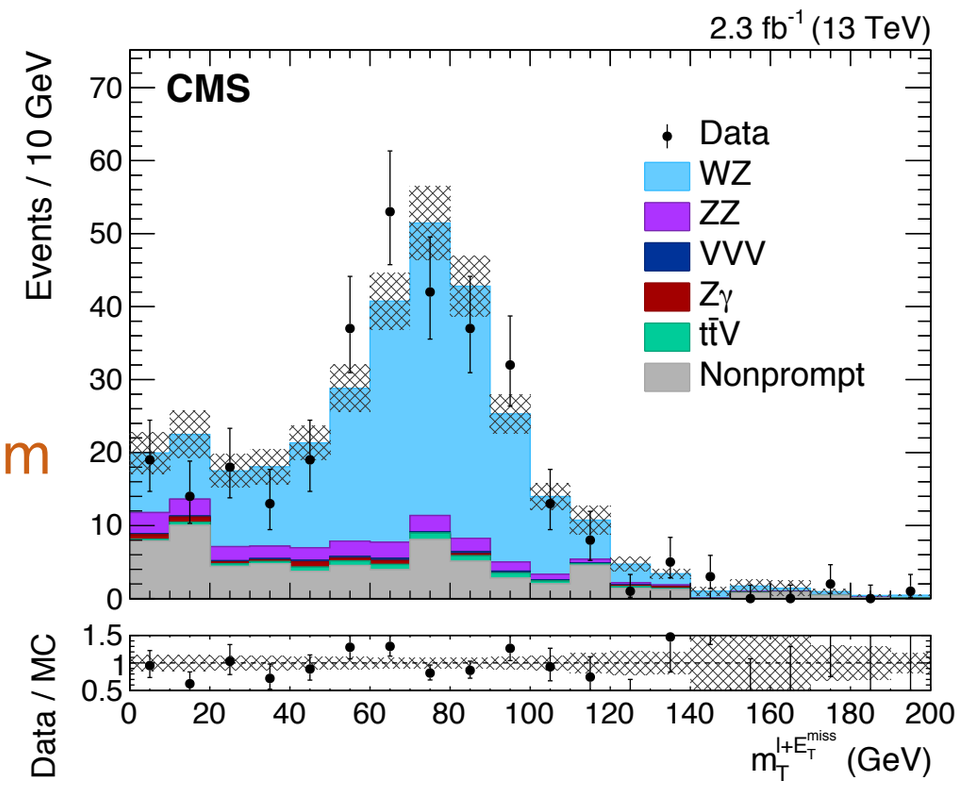
SM NNLO prediction: 120.3±3.0 pb
[Phys. Rev. Lett. 113 (2014) 21201 and Phys. Lett. B754 (2016) 275-280]

WZ cross section measurement at 13 TeV

- Also performed in the fully leptonic channel WZ → 3ℓν
- Requires m(3ℓ) > 100 GeV to increase purity of the signal

p_T(ℓ from W) > 20 GeV
p_T(leading ℓ from Z) > 20 GeV
p_T(subleading ℓ from Z) > 10 GeV
|η(e/μ)| < 2.5/2.4
76 < m_Z < 106 GeV
MET > 30 GeV
m(ℓℓ') > 4 GeV
m(ℓℓℓ') > 100 GeV
0 b-quark jets with p_T > 20 GeV, |η| < 2.4

Non-prompt backgrounds from data CR



Inclusive cross section

60 < m_Z < 120 GeV
W→ℓν and Z→ℓℓ BRs from PDG

$$\sigma(\mathrm{pp} \to \mathrm{WZ}) = 39.9 \pm 3.2\,(\mathrm{stat})^{+2.9}_{-3.1}\,(\mathrm{syst}) \pm 0.4\,(\mathrm{theo}) \pm 1.3\,(\mathrm{lumi})\,\mathrm{pb}.$$

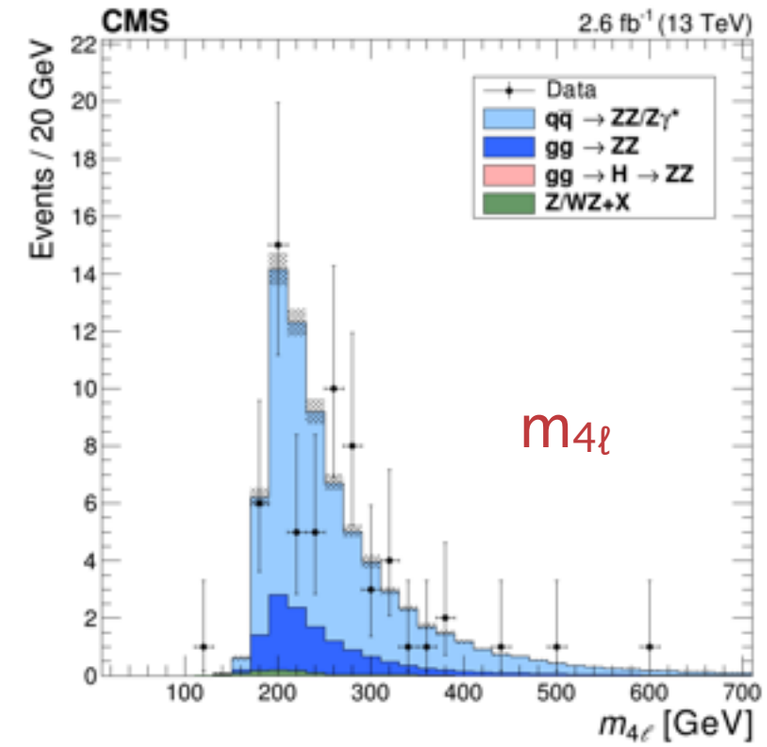
SM NNLO prediction: $50.0^{+1.1}_{-1.0}$ pb [MATRIX code]

ZZ cross section measurement at 13 TeV

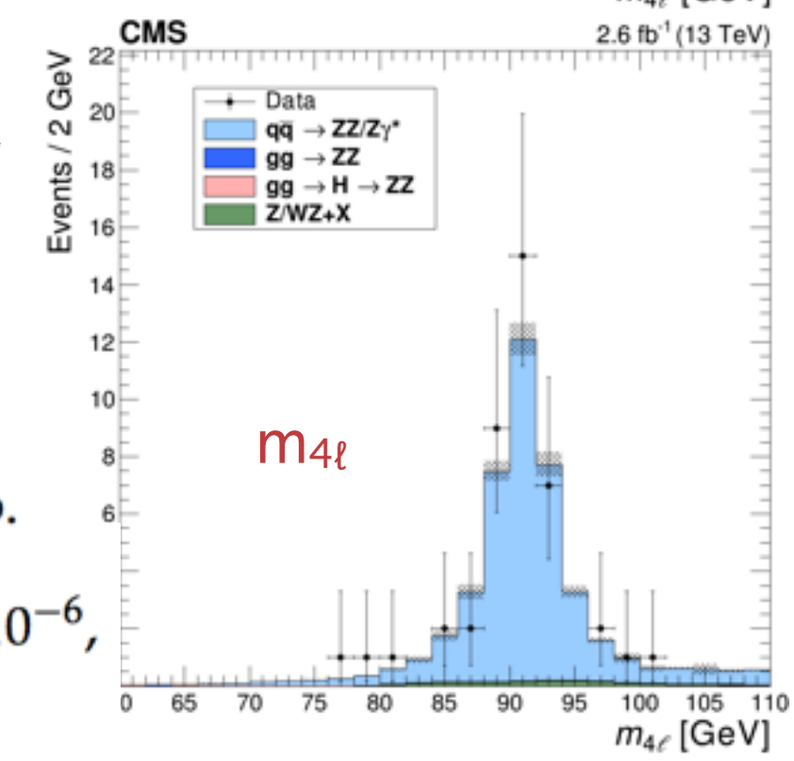
- Fully reconstructed final state ZZ→2ℓ2ℓ'
- The measurement is basically background-free.

p_T(leading) > 20 GeV
p_T(subleading) > 10 GeV
p_T(e/μ) > 7/5 GeV
|η(e/μ)| < 2.5/2.4
ΔR(ℓ,ℓ)>0.02, ΔR(e,μ)>0.05
40 < m_{Z1}(ℓ,ℓ) < 120 GeV
m_{Z2}(ℓ',ℓ') < 120 GeV

Non-resonant ZZ->2ℓ2ℓ':
60 < m_{Z1} < 120 GeV
60 < m_{Z2} < 120 GeV



Resonant Z->2ℓ2ℓ':
80 < m(2ℓ2ℓ') < 100 GeV



Inclusive cross section

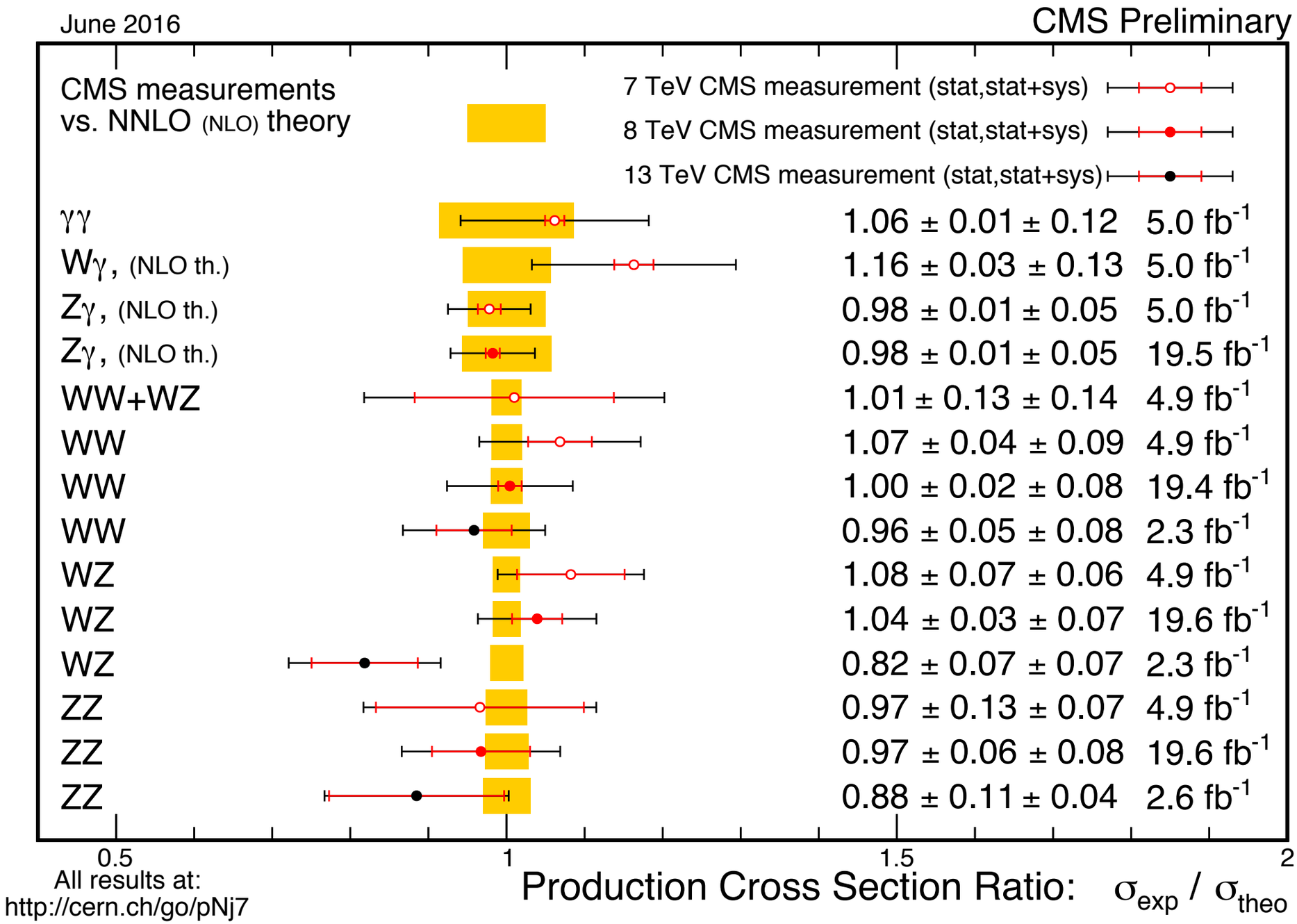
60 < m_Z < 120 GeV
Z→ℓℓ BRs from PDG

$$\sigma(\mathrm{pp} \to \mathrm{ZZ}) = 14.6^{+1.9}_{-1.8}\,(\mathrm{stat})^{+0.5}_{-0.3}\,(\mathrm{syst}) \pm 0.2\,(\mathrm{theo}) \pm 0.4\,(\mathrm{lumi})\ \mathrm{pb}.$$

$$\mathcal{B}(\mathrm{Z} \to \ell^+\ell^-\ell'^+\ell'^-) = 4.9^{+0.8}_{-0.7}\,(\mathrm{stat})^{+0.3}_{-0.2}\,(\mathrm{syst})^{+0.2}_{-0.1}\,(\mathrm{theo}) \pm 0.1\,(\mathrm{lumi}) \times 10^{-6},$$

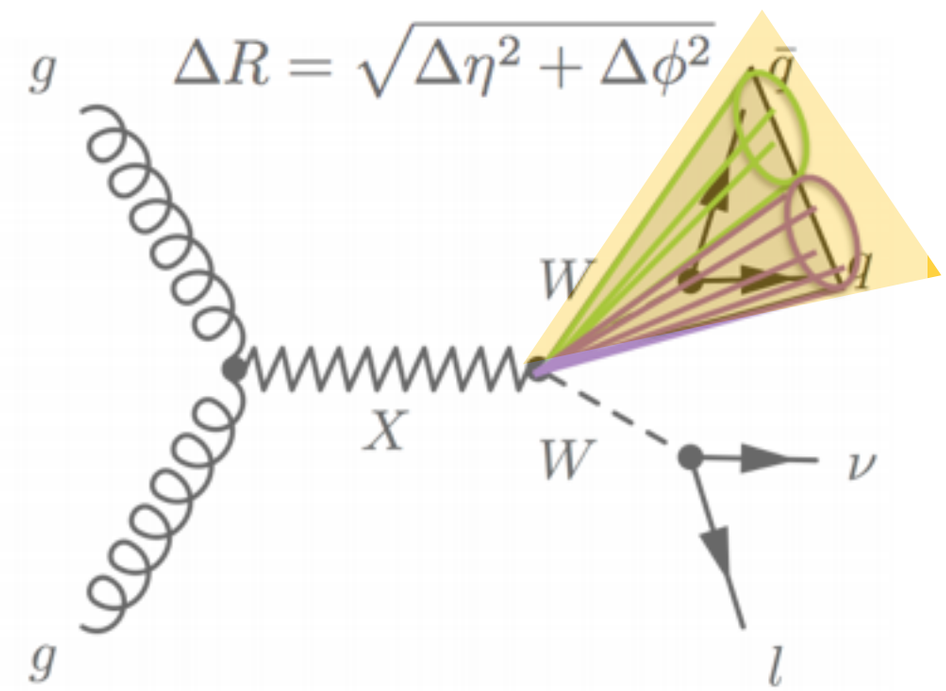
SM NNLO prediction for inclusive cross section:
$16.2^{+0.6}_{-0.4}$ fb [MATRIX code]

Summary of recent cross section measurements



Searches for diboson resonances

- Recent searches have been performed for new resonances decaying to dibosons in the WW, WZ, and ZZ final states.
- Since we are looking for rare new phenomena, these searches benefit from using final states in which at least one W or Z decays hadronically.



$$\Delta R_{qq} \approx 2\frac{M_V}{p_T^V}$$

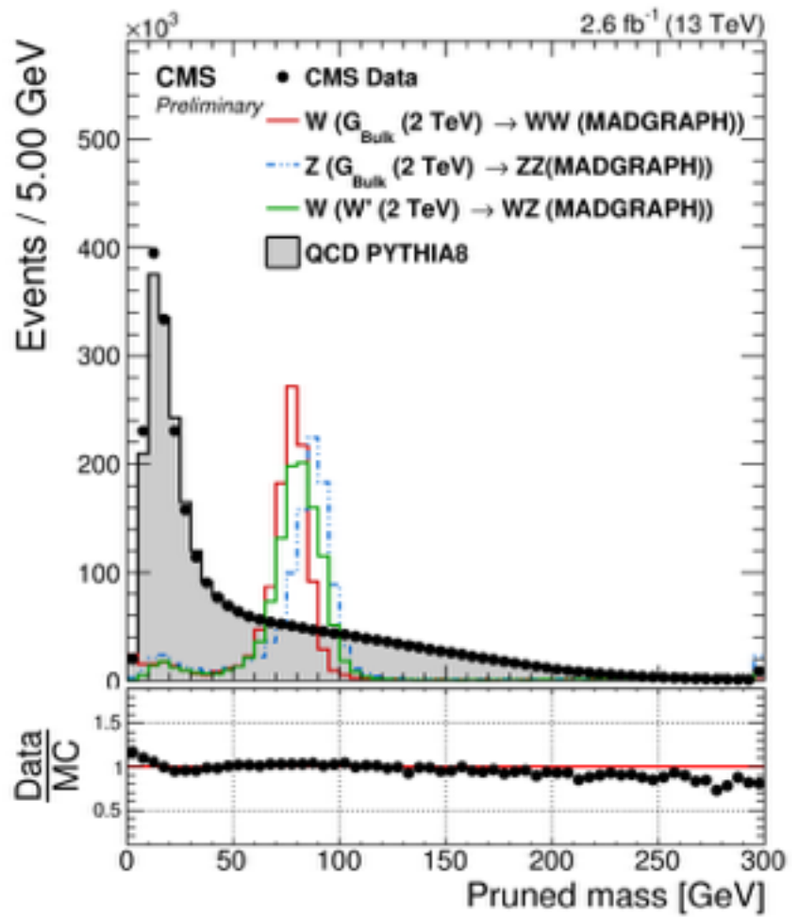
The standard CMS jet reconstruction uses an anti-k_T algorithm with R=0.4

For a new particle with m_X~1TeV → ΔR_{qq}~0.4

Since we wouldn't be able distinguish the two jets, we do the opposite: we reconstruct jets with R=0.8 to contain the full decay (fat jet)

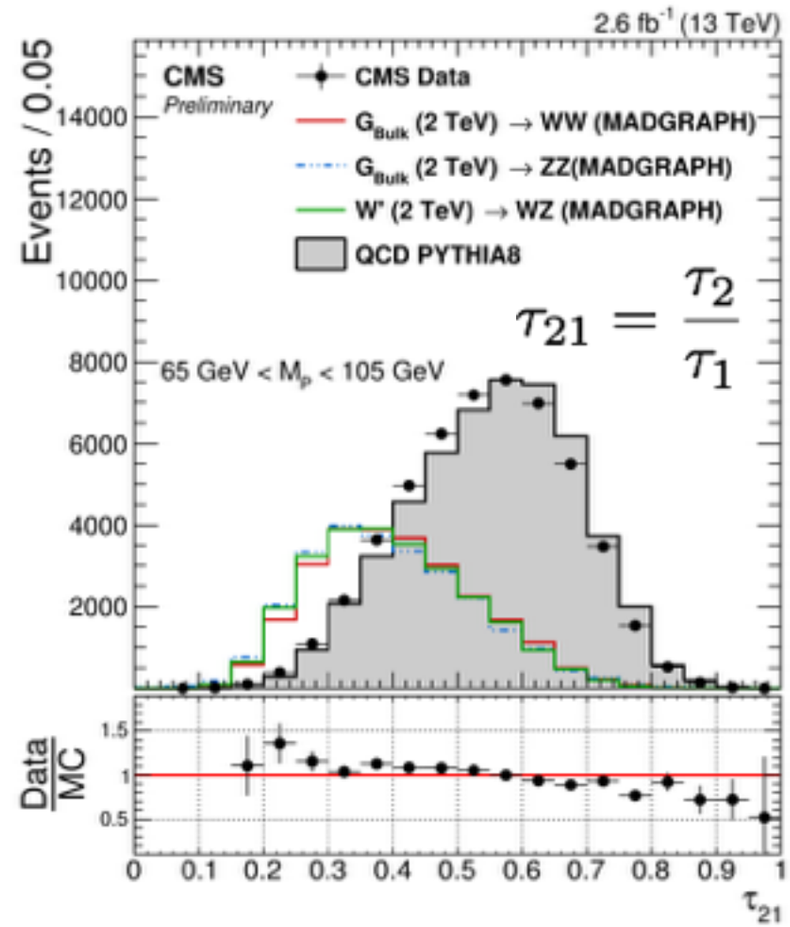
Identifying W and Z bosons in hadronic decays

Jet Mass



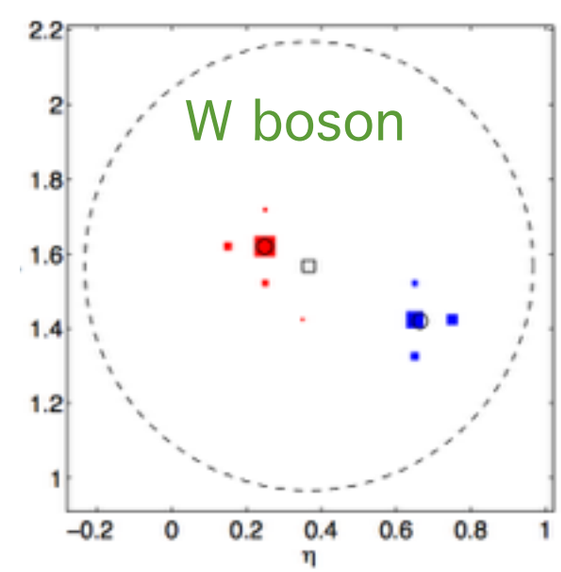
Pruning removes particles consistent with soft and large angle radiation from the jet constituents → improves mass resolution

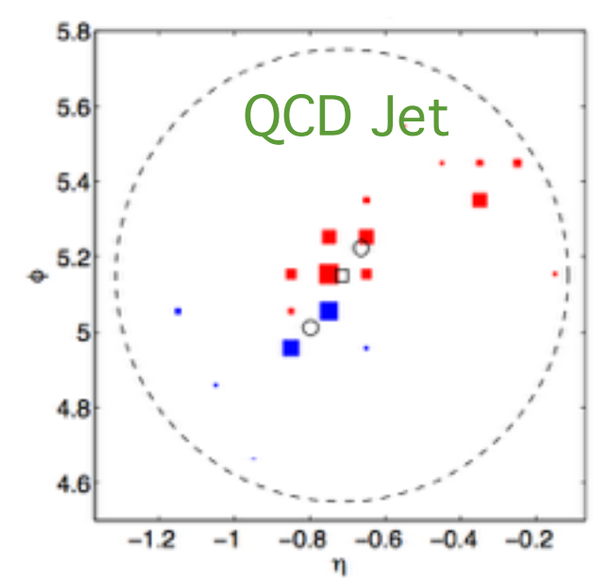
$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \min(\Delta R_{1k}, \ldots, \Delta R_{Nk})$$



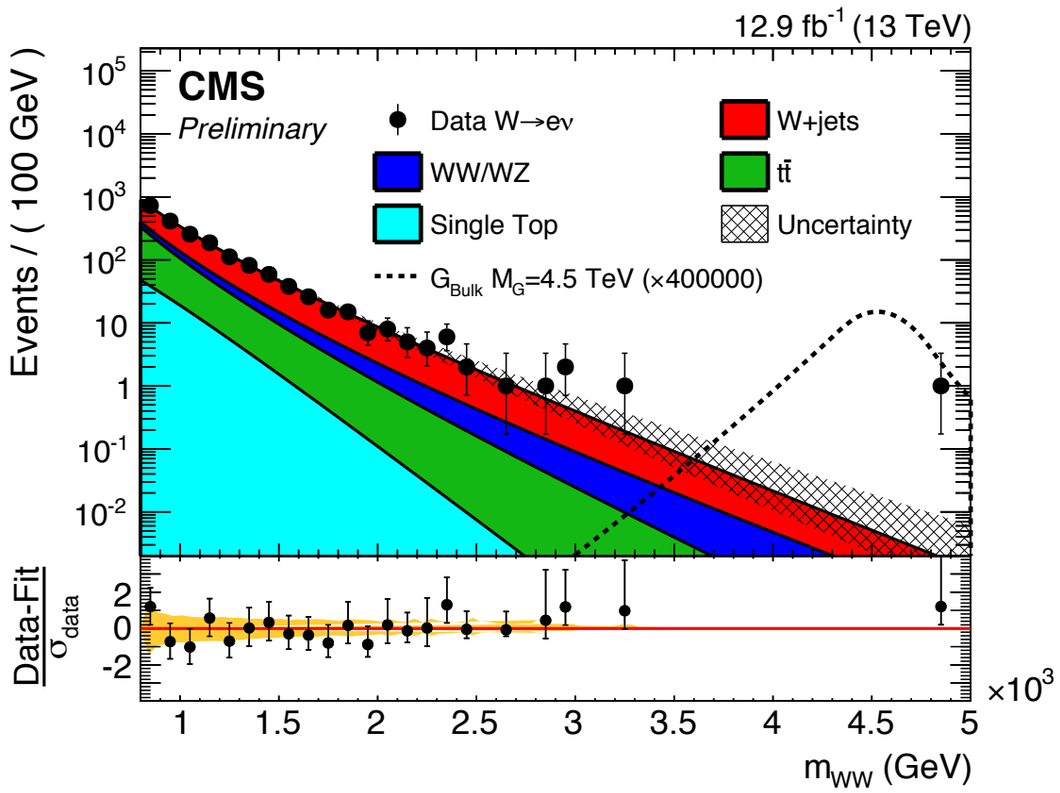
N-Subjetiness

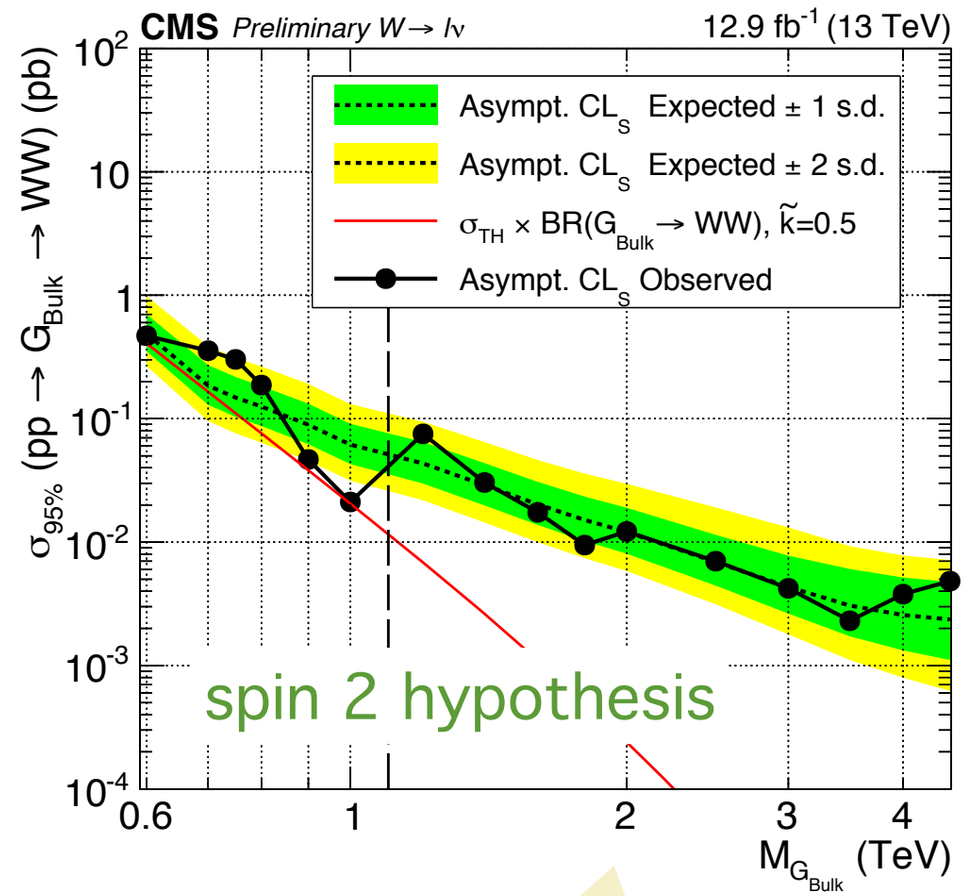
Variable measures how well the constituents are aligned with 2 momentum axes

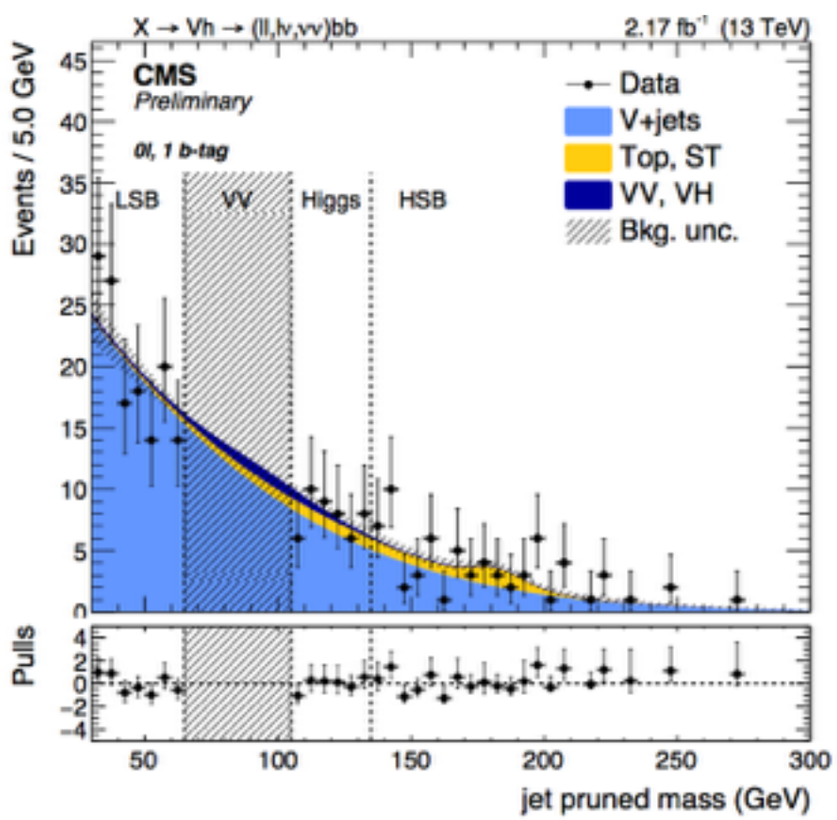


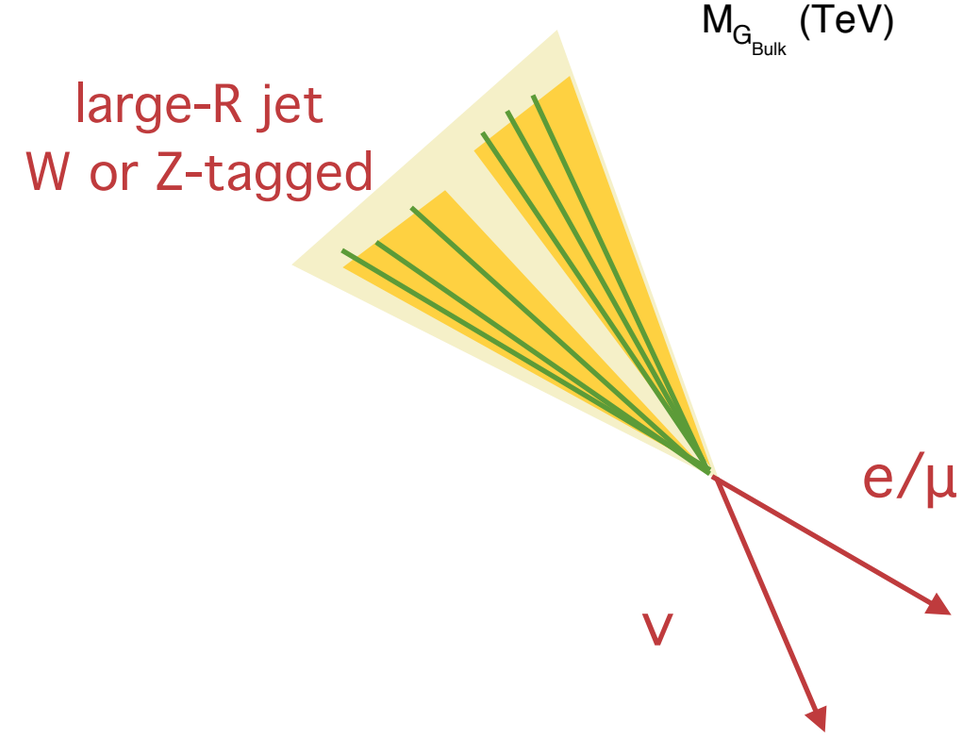


Search for X → W(→ℓν)V(→qq)





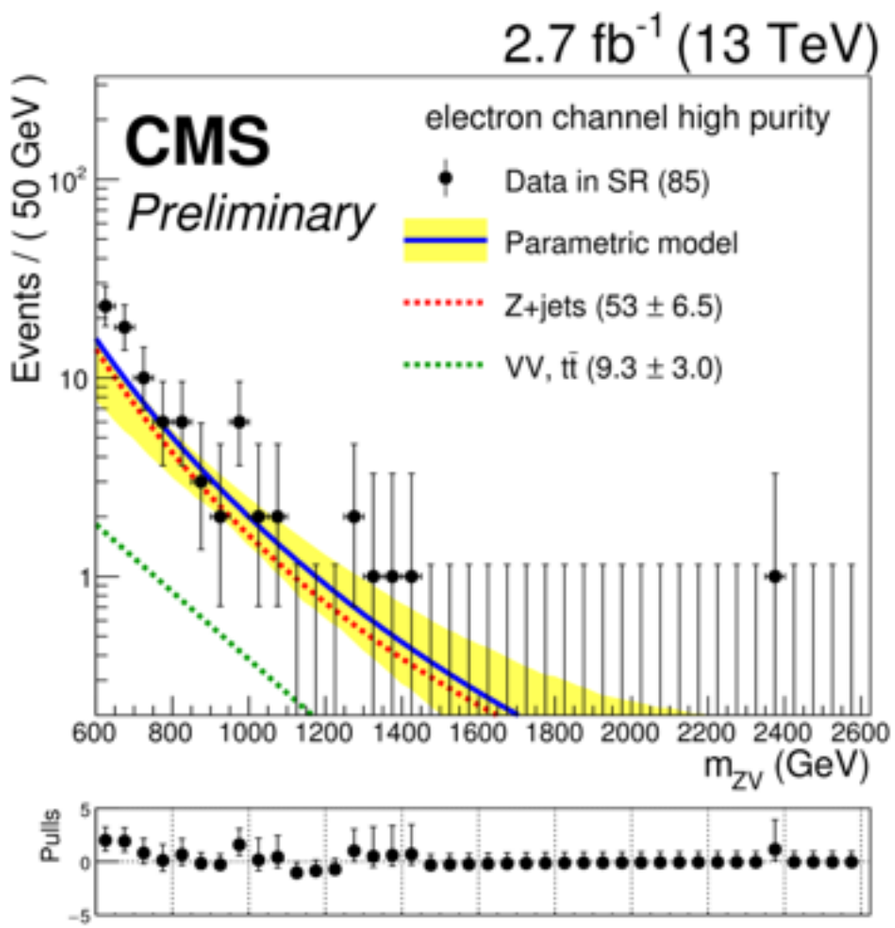


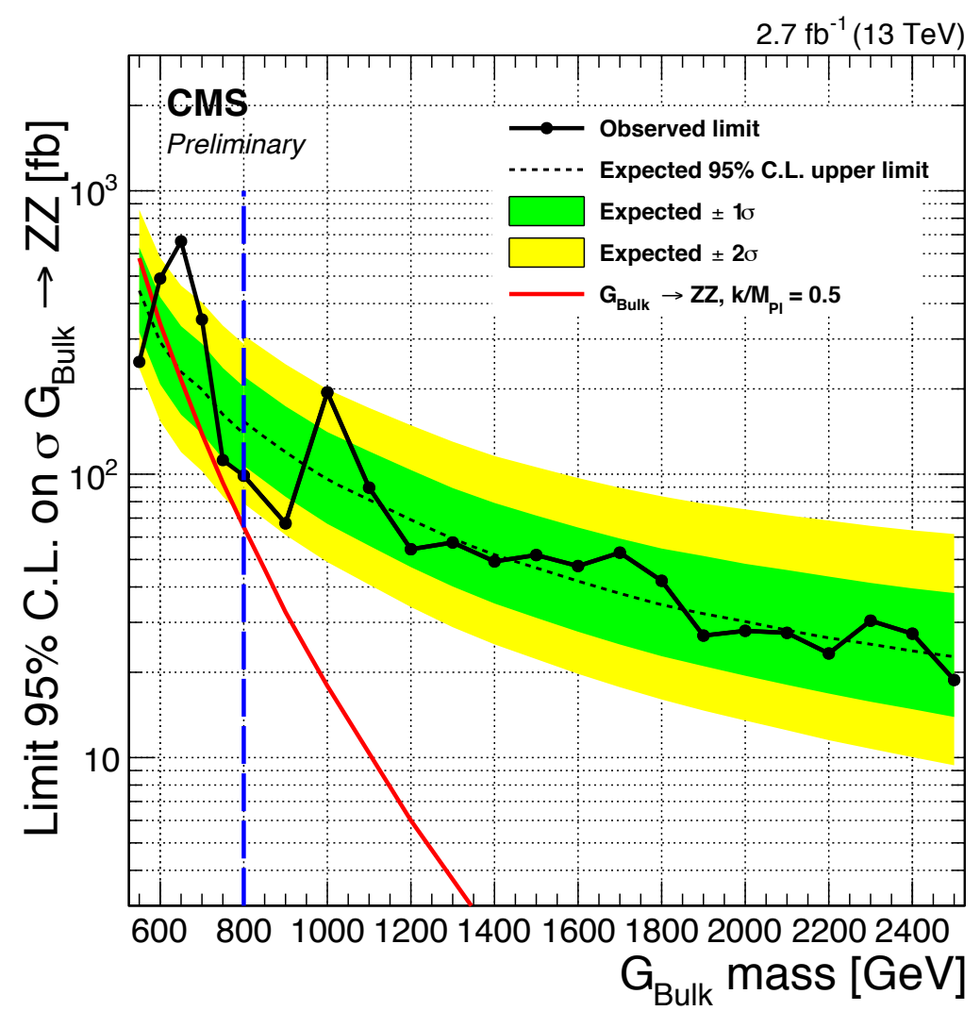


Search for X → Z(→ℓℓ)V(→qq)

Two strategies to increase sensitivity

1. At low mass, reconstruct merged and resolved hadronic V. In each category separate b-tagged (high purity) and non b-tagged (low purity) jets.
2. At high mass, separate low (high purity) and high (low purity) n-subjetiness (τ_{21})

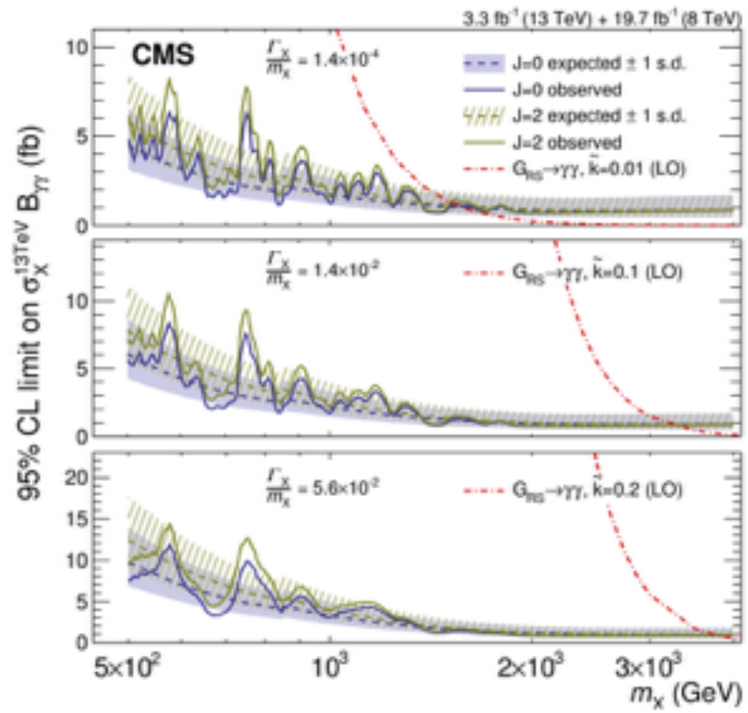




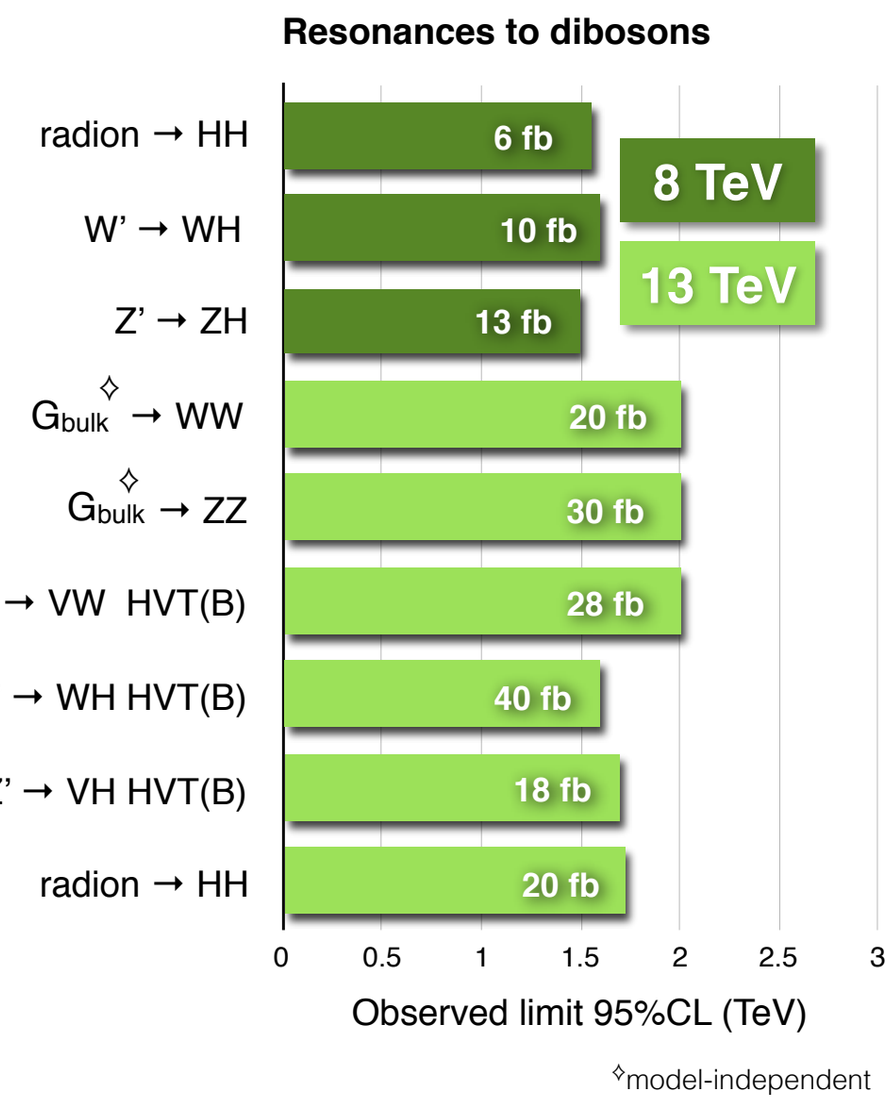
An overview of the current situation

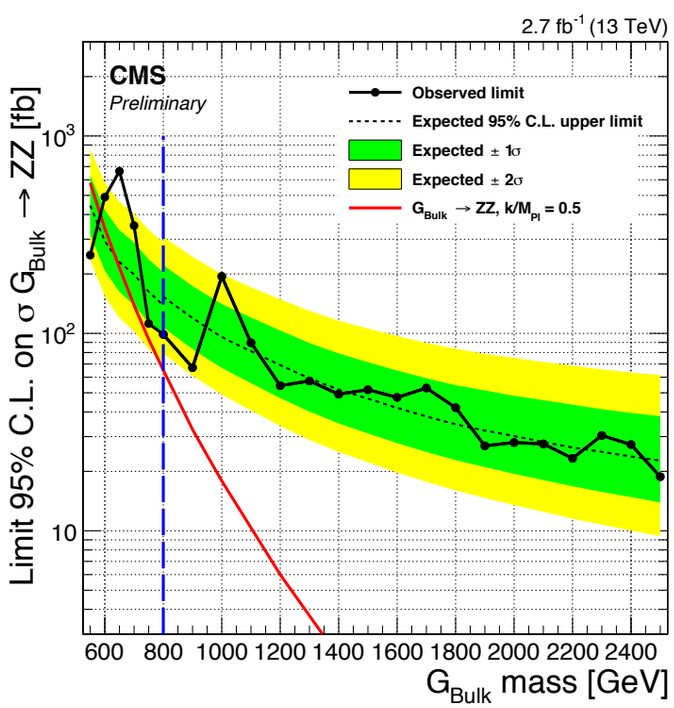
CMS has performed a very large number of searches in diboson final states (VV, VH, HH, Vγ, γγ, ...)

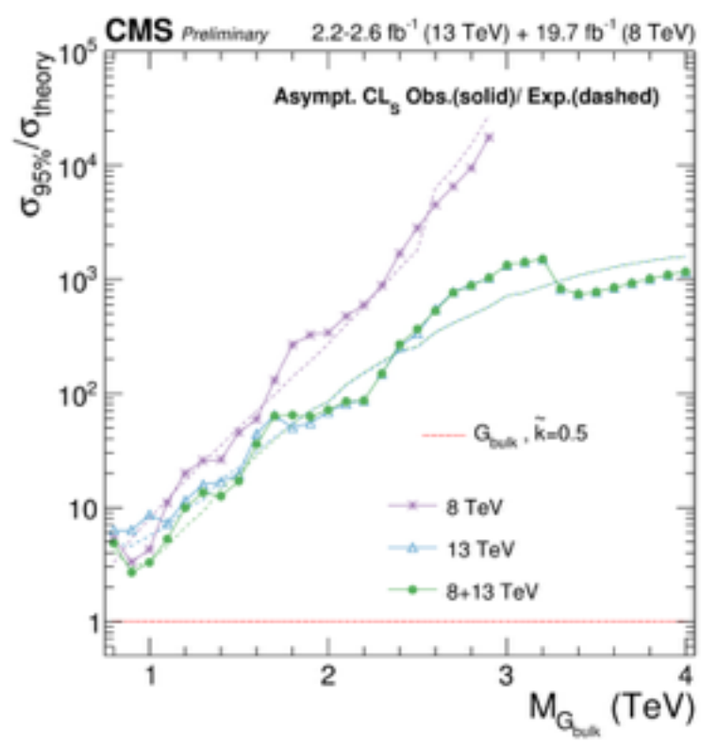
Some fluctuations drew a lot of attention!



But no observation was convincingly consistent with a new particle directly produced at the LHC

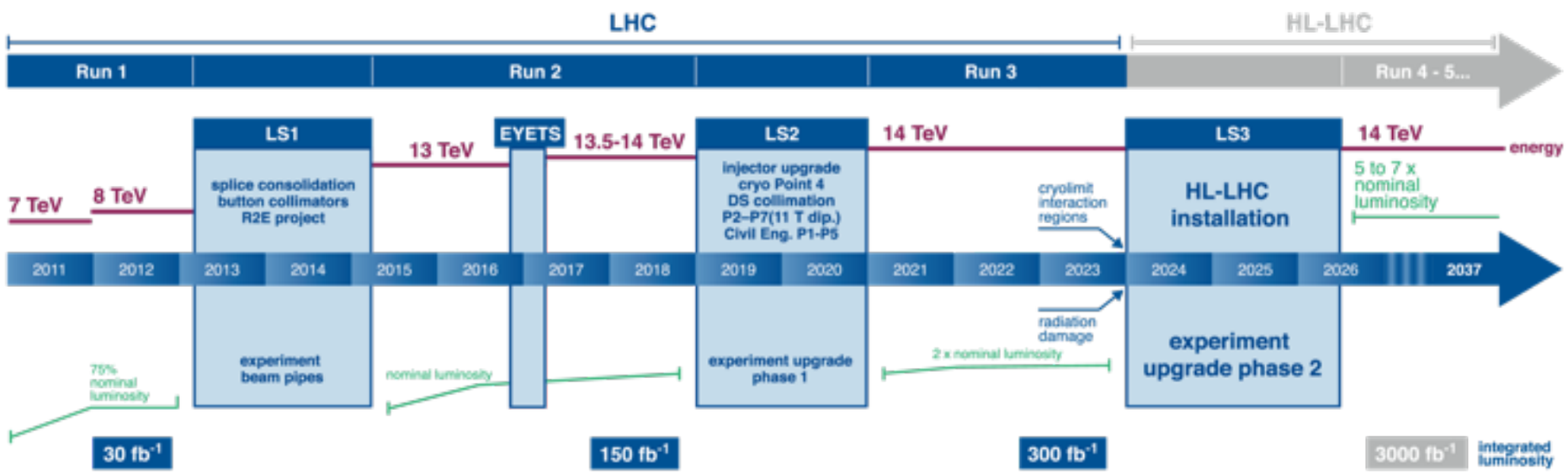




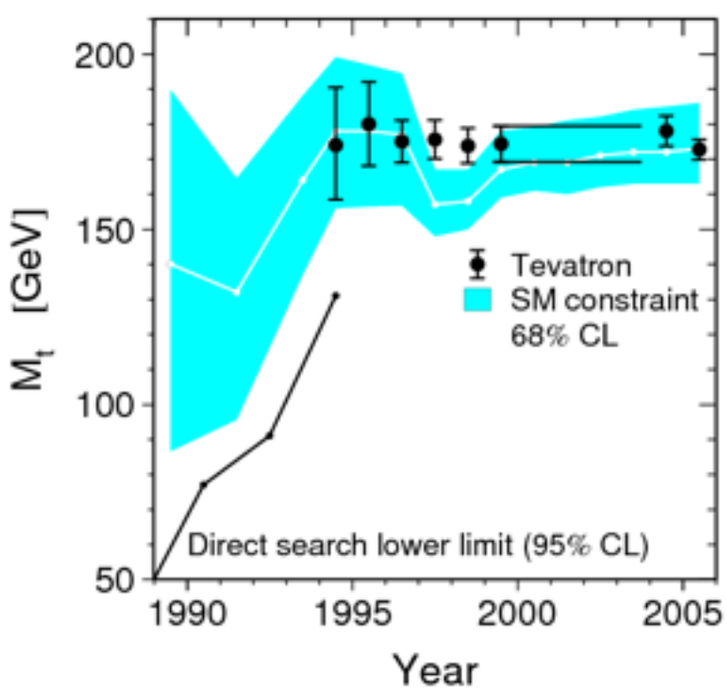


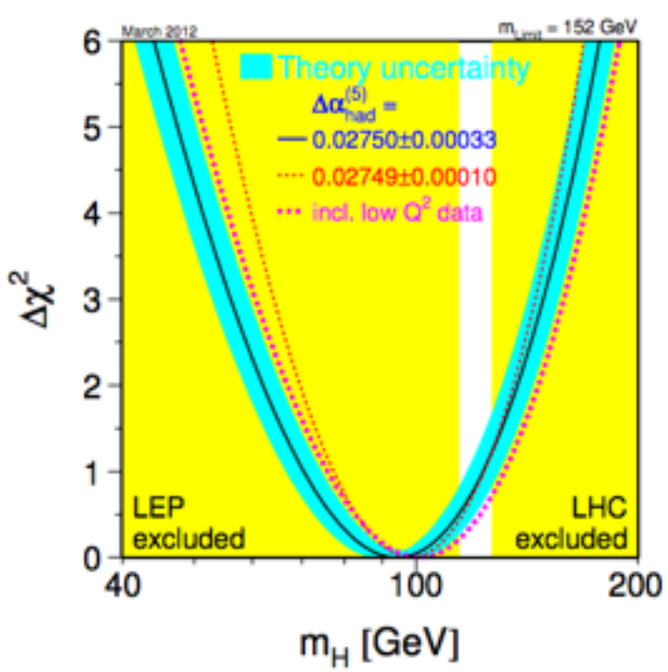
Where do we go from now?

- From now on, the LHC will start collecting much more integrated luminosity but the energy will not surpass 14 TeV



- If no New Physics is discovered directly, how can we best use the LHC data to discover physics at very large scales?

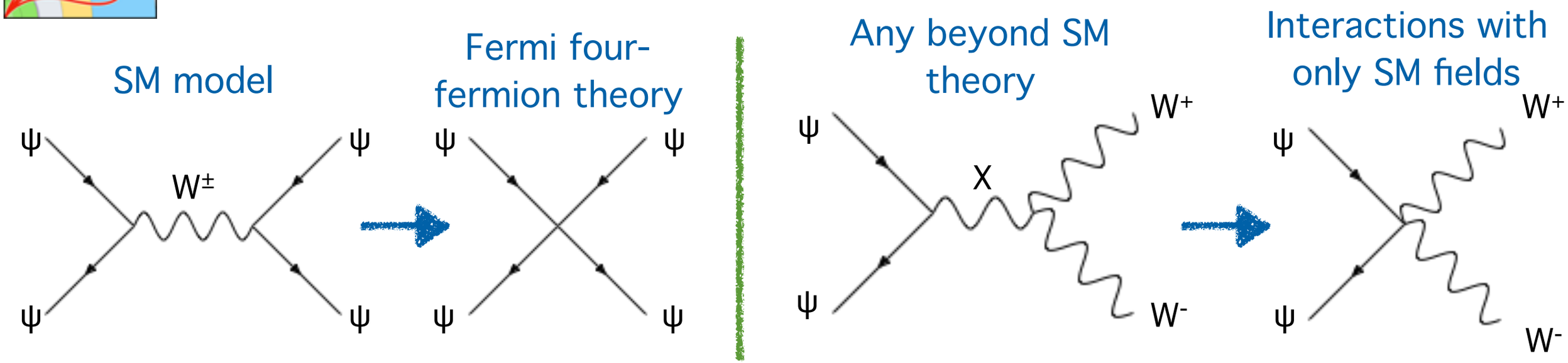




It is possible to learn about particles that are not directly observable.

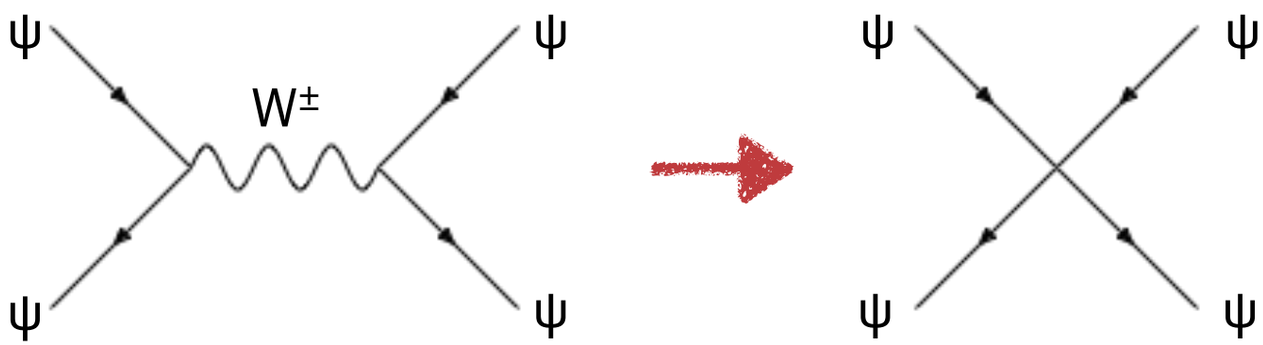
Wine & Cheese

The EFT approach to New Physics



- Any Beyond Standard Model physics can be thought of as modifications of the interactions containing only SM fields
  - How to determine the hierarchy between the modifications and classify all possible modifications?
  - How to enforce the SU(3)xSU(2)xU(1) symmetry at low energies?
  - How to derive a self-consistent check of this approach?
  - How to calculate higher-order (loop) corrections?
- If we can answer yes to all these questions: SM test → New Physics Search

Hierarchy: The SM Effective Field Theory



$$g^2 \langle \underbrace{\bar{\psi}\psi W_\mu}_{D=4} \underbrace{W_\nu \bar{\psi}\psi}_{D=4} \rangle \to \frac{g^2}{k^2 - M_W^2}$$

$$\frac{g^2}{M_W^2} \langle \underbrace{\bar{\psi}\psi\bar{\psi}\psi}_{D=6} \rangle$$

Classify the effect of any beyond SM model using operators with D > 4

$$\mathcal{L} = \mathcal{L}_4^{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \ldots$$

$$\frac{1}{\Lambda^2}\mathcal{L}_6 \to \left(\frac{E}{\Lambda}\right)^2 \qquad \frac{1}{\Lambda^4}\mathcal{L}_8 \to \left(\frac{E}{\Lambda}\right)^4$$

For large scales E/Λ ≪ 1, only operators with lower mass dimension will matter.

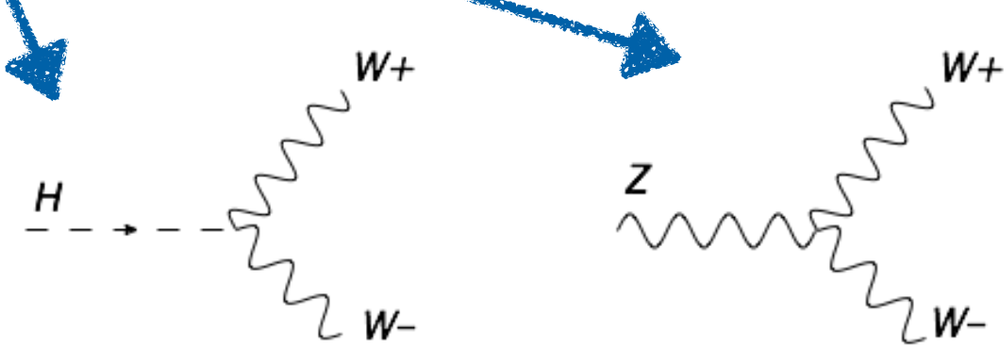
$\mathcal{L}_5 \longrightarrow$ neutrino mass operator

$\mathcal{L}_6 \longrightarrow i(H^\dagger D^\mu H)\partial^\nu B_{\mu\nu},\ i(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu},\ \ldots$

$\mathcal{L}_8 \longrightarrow \mathrm{Tr}[W_{\mu\nu}W^{\mu\nu}] \times \mathrm{Tr}[W_{\alpha\beta}W^{\alpha\beta}],\ \ldots$

All terms written with SU(2)xU(1) covariant fields and derivatives. Preserve symmetry.

The SU(2)xU(1) symmetry at low energy relates the effect of the operators in different channels



Classification : the curse of dimensionality

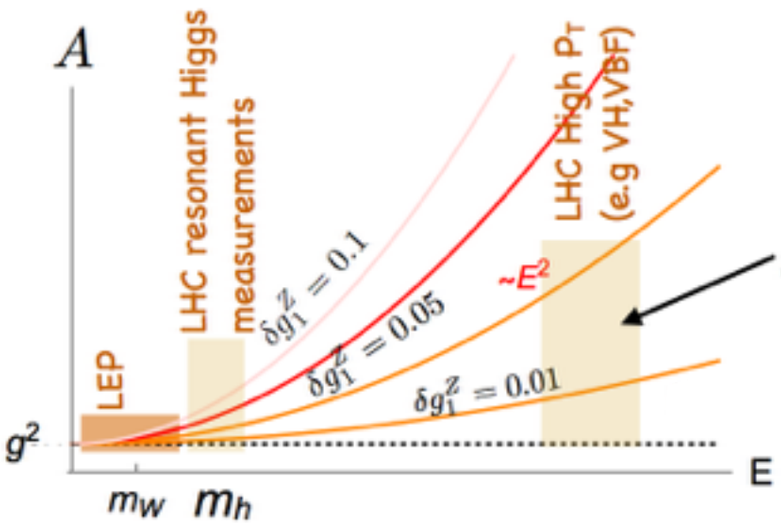
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{\delta L\neq 0}}\mathcal{L}_5 + \frac{1}{\Lambda^2_{\delta B=0}}\mathcal{L}_6 + \frac{1}{\Lambda^2_{\delta B\neq 0}}\mathcal{L}'_6 + \frac{1}{\Lambda^3_{\delta L\neq 0}}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \cdots$$

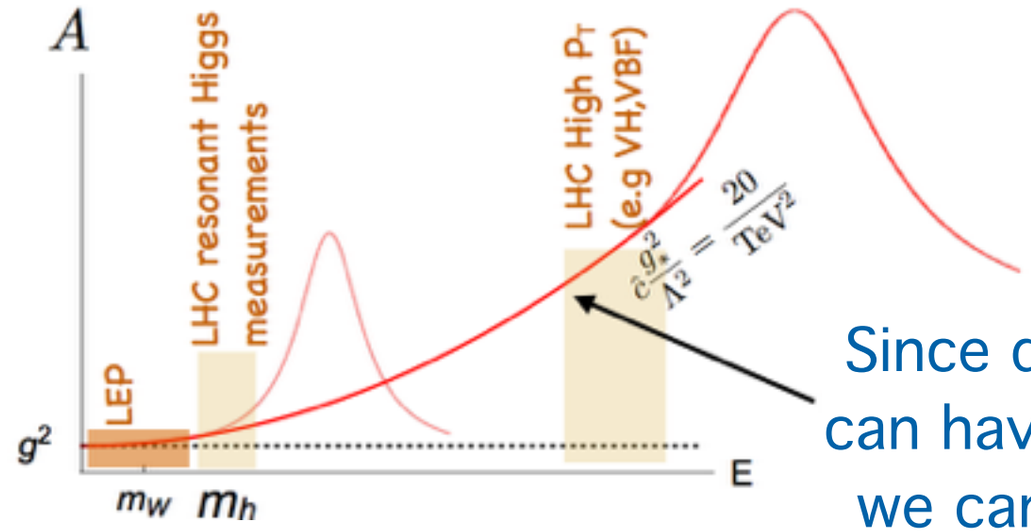
- 14 operators, 18 parameters
- 1 operator, 7 parameters
- 59 operators, 2499 parameters [arXiv:1312.2014]
- 4 operators, 408 parameters (all violate B number) [arXiv:1405.0486]
- 30 operators (all violate L number, 7 violate B number) [arXiv:1410.4193]
- 993 operators [arXiv:1510.00372]

The 2499 parameters in D=6 can be reduced to a bit more than 50 assuming flavor symmetry and CP conservation

Existing measurements are limited to 2 operators. We can do better!

Self-consistency checks

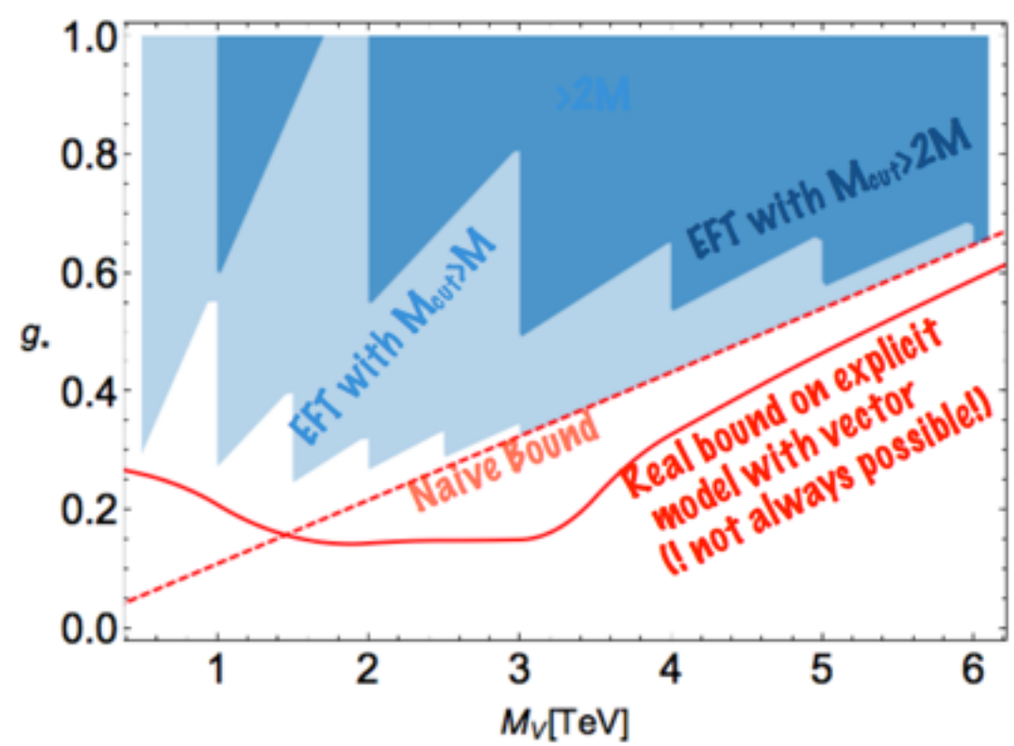




Since dibosons processes can have very high energy, we can easily go outside the validity region of the EFT approach.

One proposal that we are pursuing is to explicitly remove very high energy events from the observable used to measure the EFT operators (similar to unitarization methods used in the past)

Toy example with W^+H events [plots from arXiv:1604.06444]



Self-consistency checks

- With the full SMEFT approach, we (experimentalists) can provide these tests and design measurements that will satisfy them.
  - Provide results as a function of both the scale Λ and the coupling constant g* assuming the naive scaling

$$c_i^{(D)} \simeq \frac{(\text{coupling})^{n_i-2}}{(\text{high mass scale})^{D-4}}$$

n_i: number of SM fields
Allow to interpolate between limits for strongly and weakly coupled theories

  - Provide results removing high energy events (compared to the scale) from the the measurements.
  - Provide results including only the interference between Standard Model and higher dimensional operators

$$\sigma[\text{interference between } \mathcal{M}_{\text{SM}} \text{ and } \frac{\mathcal{M}_6}{\Lambda^2}] \to \sigma_{\text{int}} \approx \frac{g^* g_{\text{SM}}}{\Lambda^2}$$

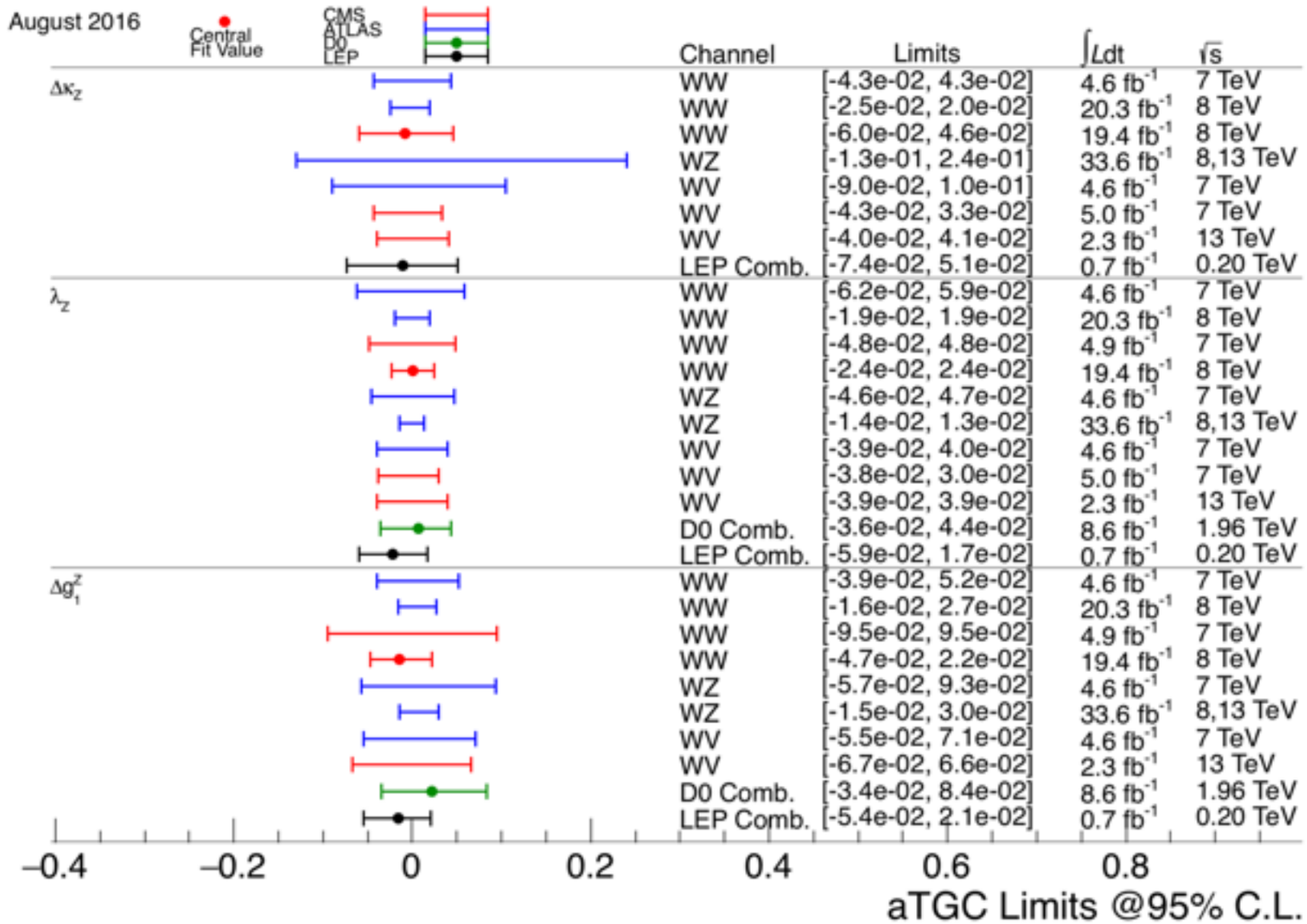
$$\sigma[|\frac{\mathcal{M}_6}{\Lambda^2}|^2] \to \sigma_{\text{square}} \approx \frac{(g^*)^2}{\Lambda^4}$$

More important in weakly coupled theories

More important in strongly coupled theories

Anomalous diboson production at CMS

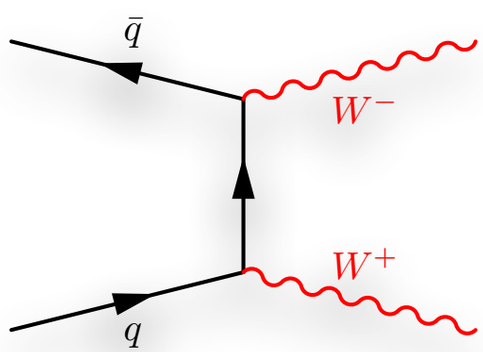
- CMS has a large number of searches for anomalous production of diboson events.
- Almost all of these measurements use the language of Anomalous Couplings, without any comment on the hierarchy or on the classification of the modifications. The SMEFT analysis of the WW cross section is an exception.



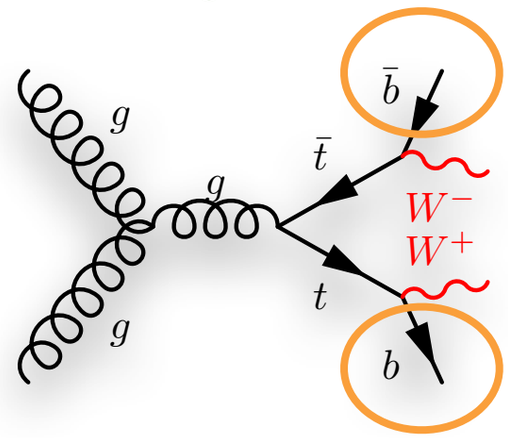
- No measurement available performed self-consistency checks, but some independent papers have considered our WW result.
- Today we will review the the EFT analysis of the WW and WZ cross section measurements at 8 TeV and some self-consistency checks performed by other authors.

WW cross section at 8 TeV

Signal

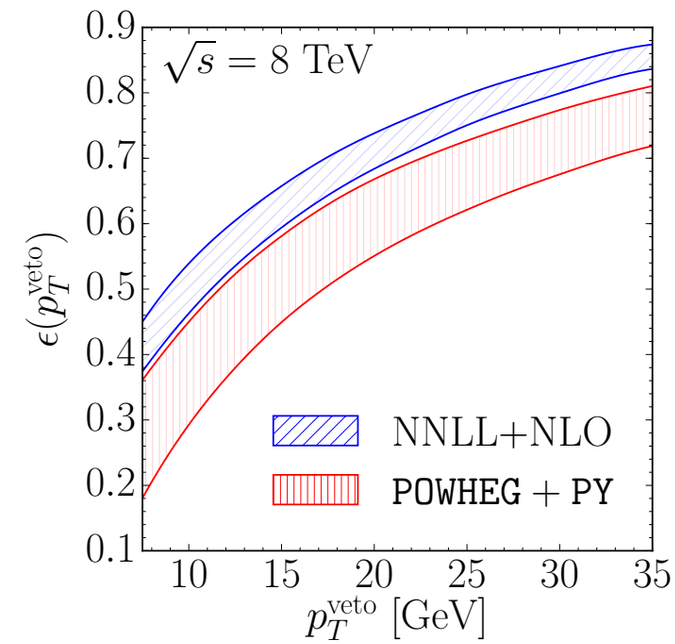


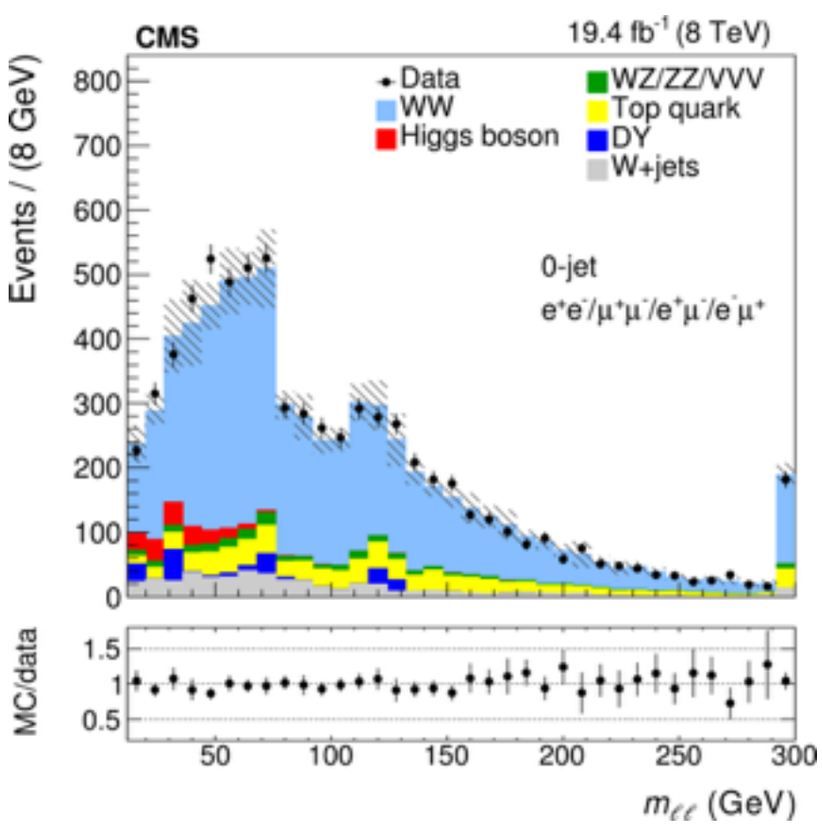
Top quark background
~4x the signal cross section!



Removed in the event selection
Only accept events without jets (jet veto)

From arXiv:1407.4537





Top quark, Drell Yan and non-prompt backgrounds measured in data CR.

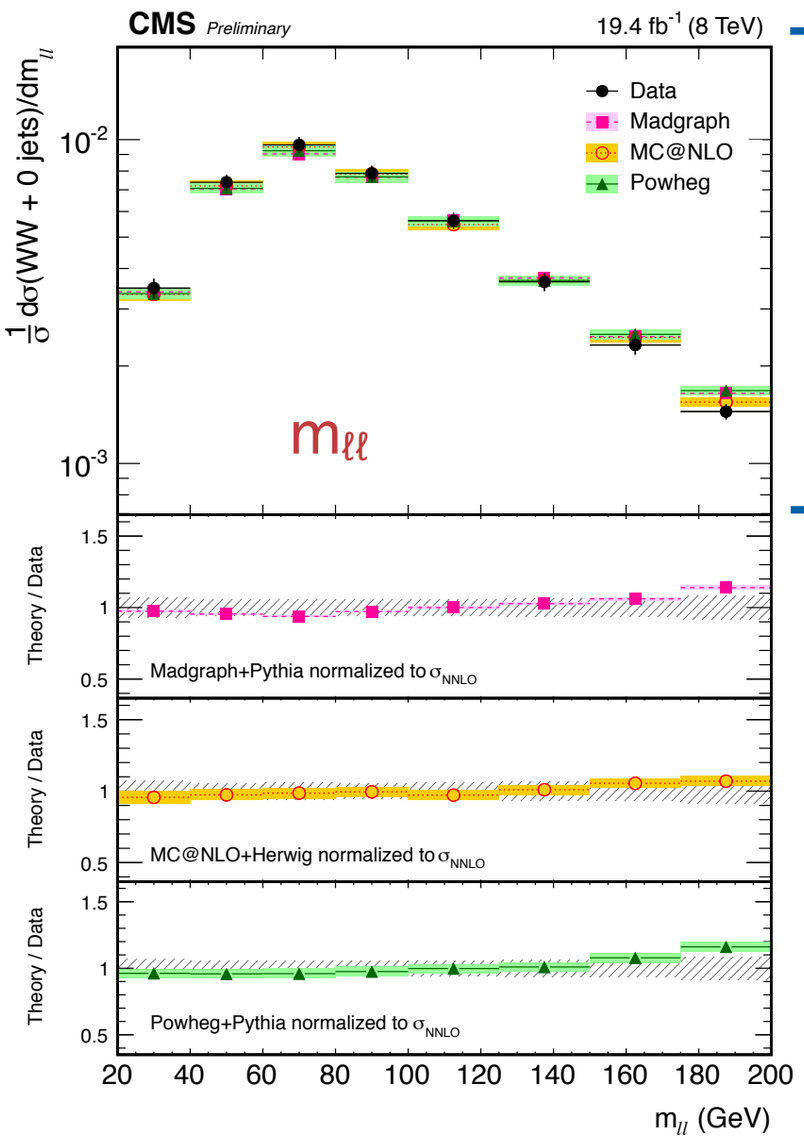
$p_T(\ell) > 20$ GeV
$|\eta(e/\mu)| < 2.5/2.4$
MET > 20 GeV
$p_T(\ell\ell) > 30/45$ GeV (different/same flavor)
$m(\ell\ell) > 12$ GeV
$|m(\ell\ell) - m_Z| > 15$ (same flavor only)
DY MVA veto (same flavor only)
min(projMET, projTkMET) > 20 GeV
Top-quark veto (b-quark jets + soft muons)
0 or 1 jet ($p_T > 30$, $|\eta| < 4.7$)

WW cross section at 8 TeV

Event category		WW production cross section (pb.)
0-jet category	Different-flavor	$59.7 \pm 1.1\,(\text{stat.}) \pm 3.3\,(\text{exp.}) \pm 3.5\,(\text{th.}) \pm 1.6\,(\text{lum.})$
	Same-flavor	$64.3 \pm 2.1\,(\text{stat.}) \pm 4.6\,(\text{exp.}) \pm 4.3\,(\text{th.}) \pm 1.7\,(\text{lum.})$
1-jet category	Different-flavor	$59.1 \pm 2.8\,(\text{stat.}) \pm 6.0\,(\text{exp.}) \pm 6.2\,(\text{th.}) \pm 1.6\,(\text{lum.})$
	Same-flavor	$65.1 \pm 5.5\,(\text{stat.}) \pm 8.3\,(\text{exp.}) \pm 8.0\,(\text{th.}) \pm 1.7\,(\text{lum.})$

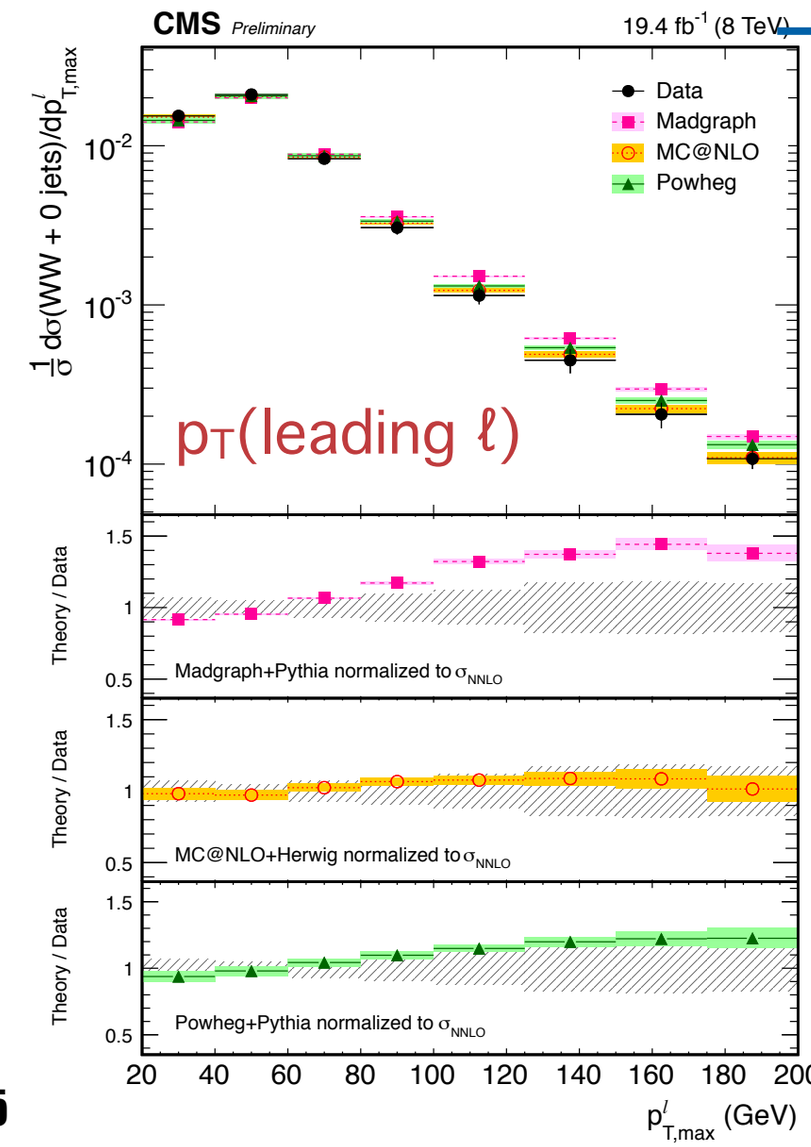
$$\sigma_{W^+W^-} = 60.1 \pm 0.9\,(\text{stat}) \pm 3.2\,(\text{exp}) \pm 3.1\,(\text{theo}) \pm 1.6\,(\text{lumi})\ \text{pb}$$

SM NNLO prediction: $59.8^{+1.3}_{-1.1}$ pb [Phys. Rev. Lett. 113 (2014) 212001]



Variable not very sensitive to QCD corrections

Better choice to look for new physics in precision measurements



Variable very sensitive to QCD corrections

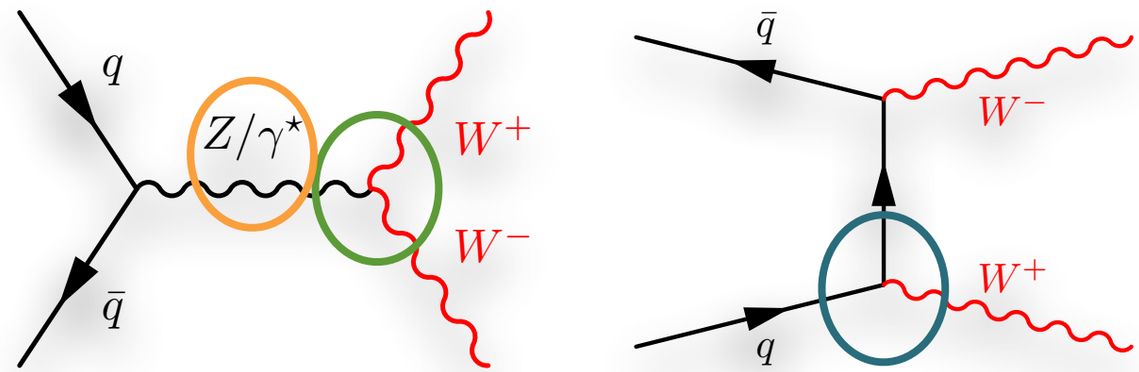
SMEFT analysis of the WW measurement

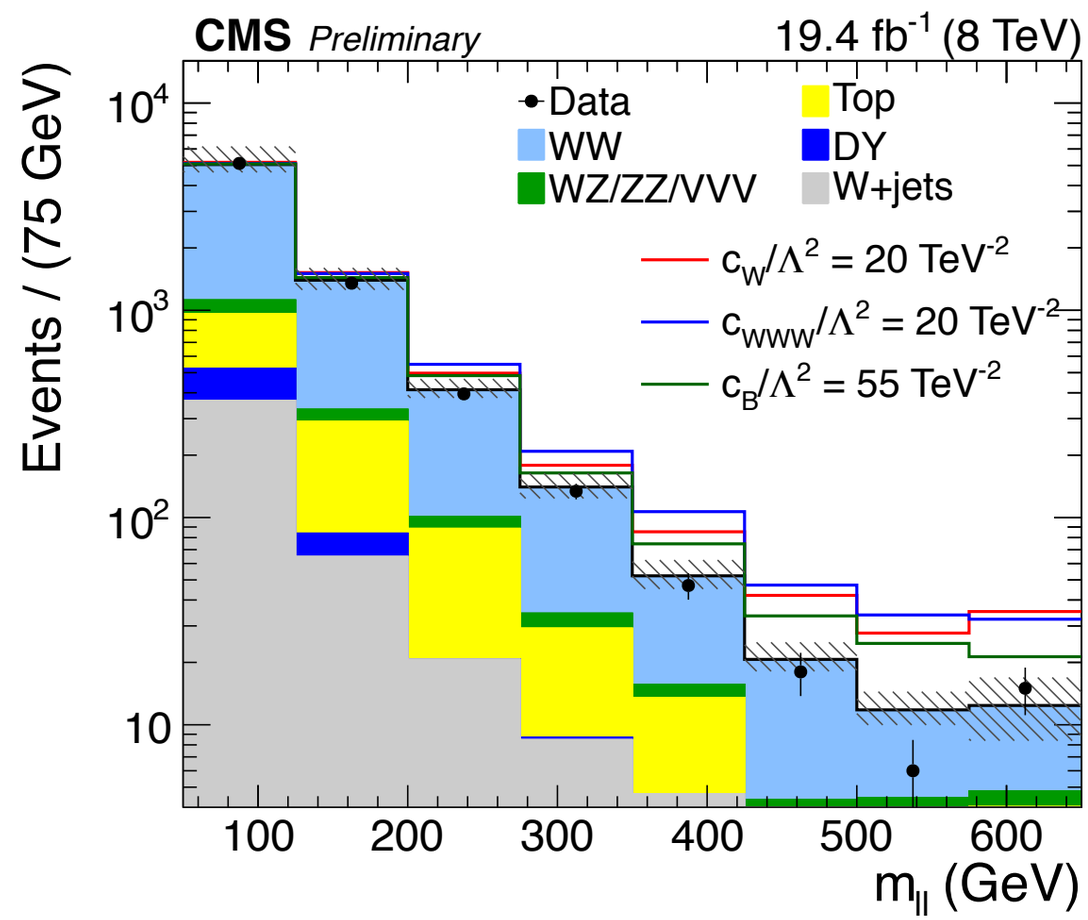
$$\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2}\mathrm{Tr}[W_{\mu\nu}W^{\nu\rho}W^{\mu}_{\rho}],$$

$$\mathcal{O}_{W} = \frac{c_{W}}{\Lambda^2}(D^{\mu}\Phi)^{\dagger}W_{\mu\nu}(D^{\nu}\Phi),$$

$$\mathcal{O}_{B} = \frac{c_{B}}{\Lambda^2}(D^{\mu}\Phi)^{\dagger}B_{\mu\nu}(D^{\nu}\Phi)$$

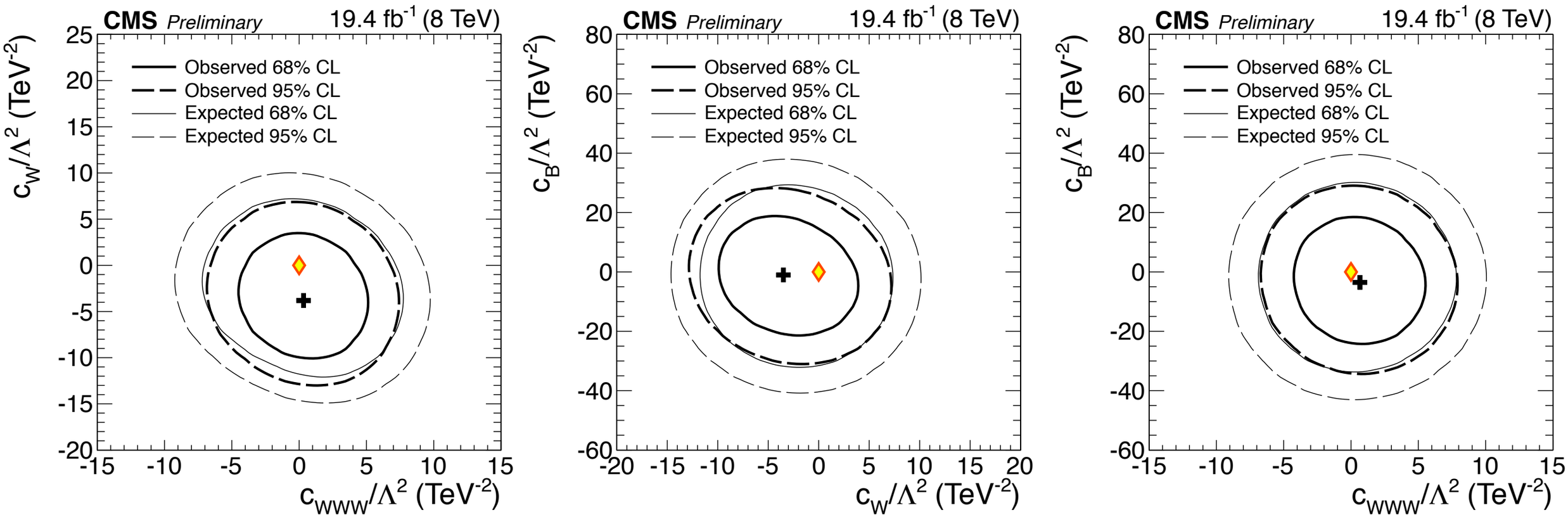
SMEFT CP-conserving D=6 operators containing only vector boson fields (up to EOM)





Very well understood distribution (small QCD corrections)

SMEFT analysis of the WW measurement



Coupling constant	This result (TeV^{-2})	This result 95% interval (TeV^{-2})	World average (TeV^{-2})	
c_{WWW}/Λ^2	$0.1^{+3.2}_{-3.2}$	$[-5.7, 5.9]$	-5.5 ± 4.8	(from λ_γ)
c_W/Λ^2	$-3.6^{+5.0}_{-4.5}$	$[-11.4, 5.4]$	$-3.9^{+3.9}_{-4.8}$	(from g_1^Z)
c_B/Λ^2	$-3.2^{+15.0}_{-14.5}$	$[-29.2, 23.9]$	$-1.7^{+13.6}_{-13.9}$	(from κ_γ and g_1^Z)

For strongly coupled theories ($g^* \sim 4\pi$) that produce c_{WWW}, the limit is $\Lambda \sim 1.5$ TeV (@95%CL)

For strongly coupled theories ($g^* \sim 4\pi$) that produce c_B, the limit is $\Lambda \sim 700$ GeV (@95%CL)

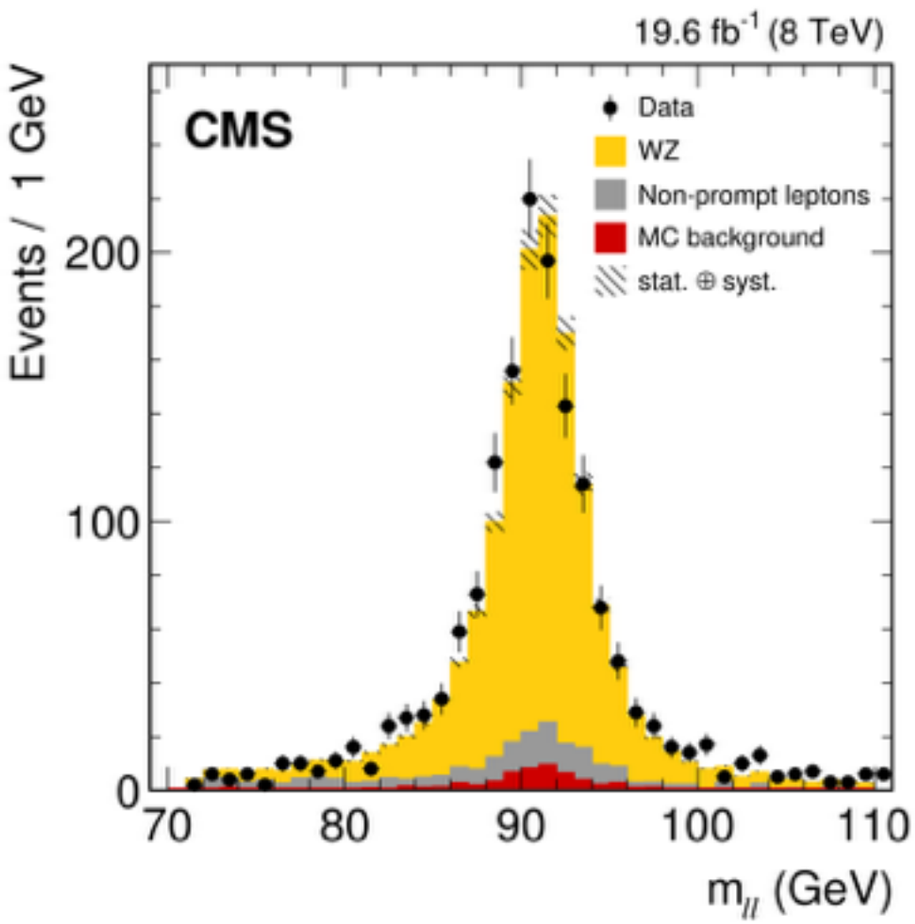
Inclusive WZ cross section at 7 and 8 TeV

Event selection

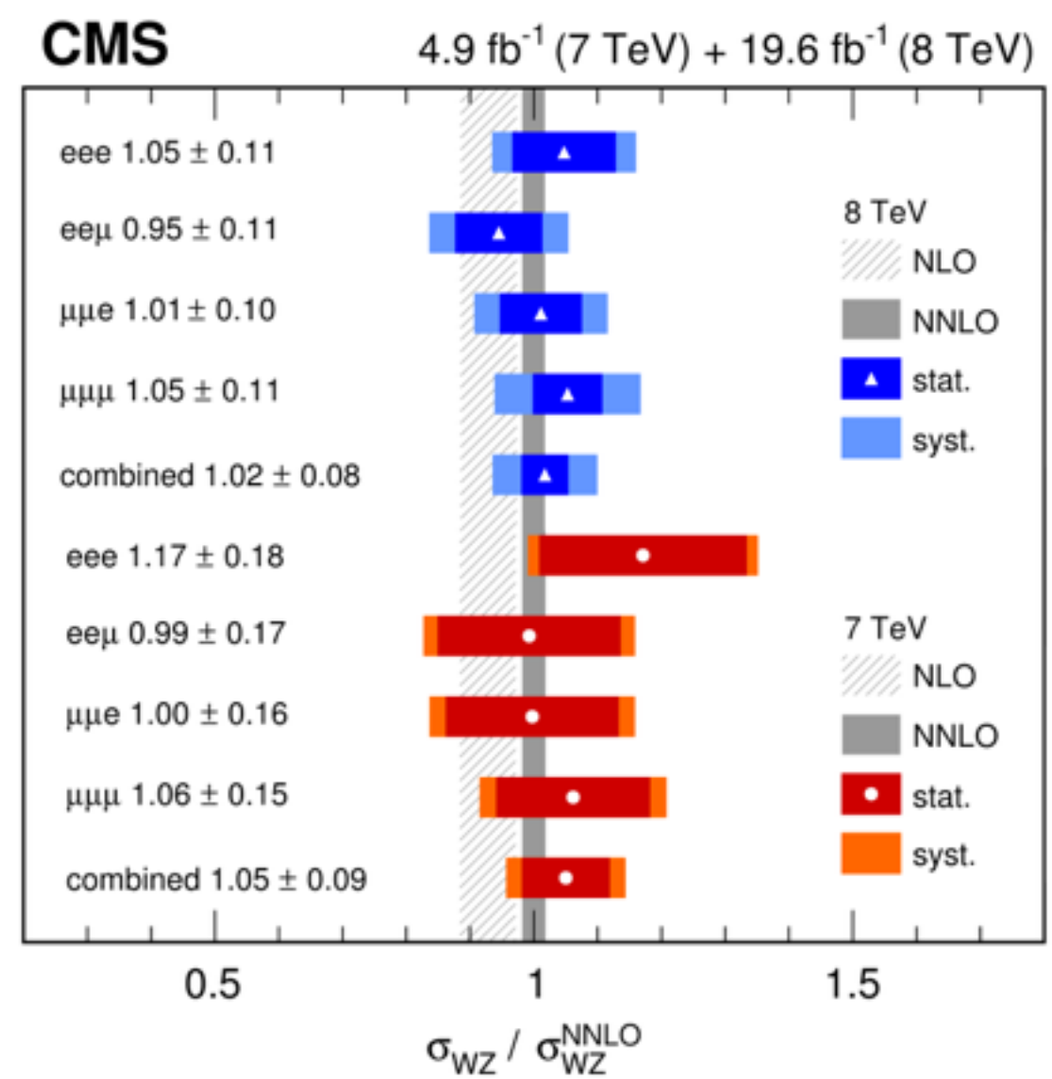
$p_T(\ell$ from W) > 20 GeV
p_T(leading ℓ from Z) > 20 GeV
p_T(subleading ℓ from Z) > 10 GeV
$|\eta(e/\mu)| < 2.5/2.4$
$71 < m_Z < 111$ GeV
MET > 30 GeV
$m(\ell\ell\ell') > 100$ GeV (@ 8 TeV only)

Inclusive cross section

$71 < m_Z < 111$ GeV
W and Z BR from PDG

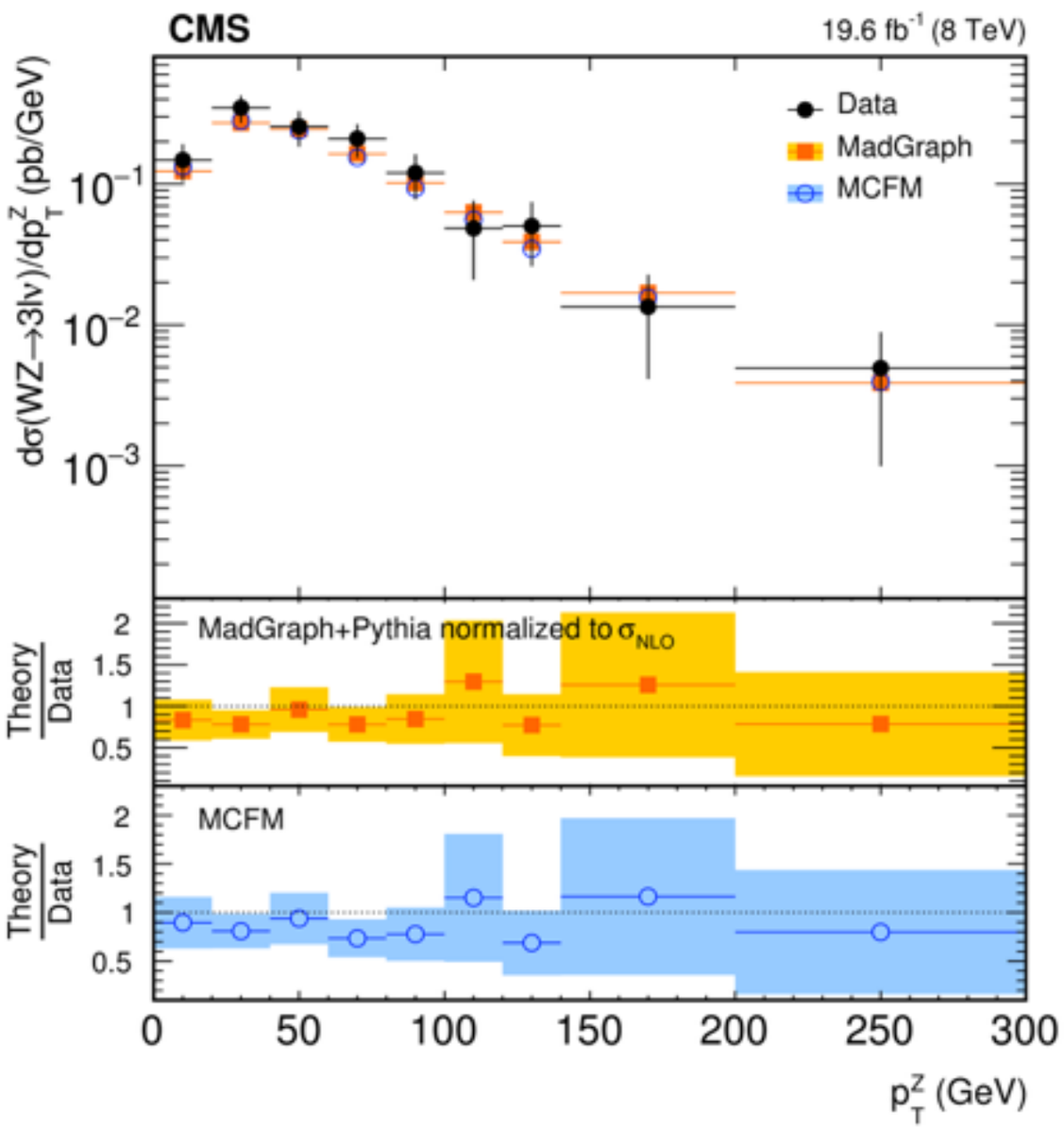


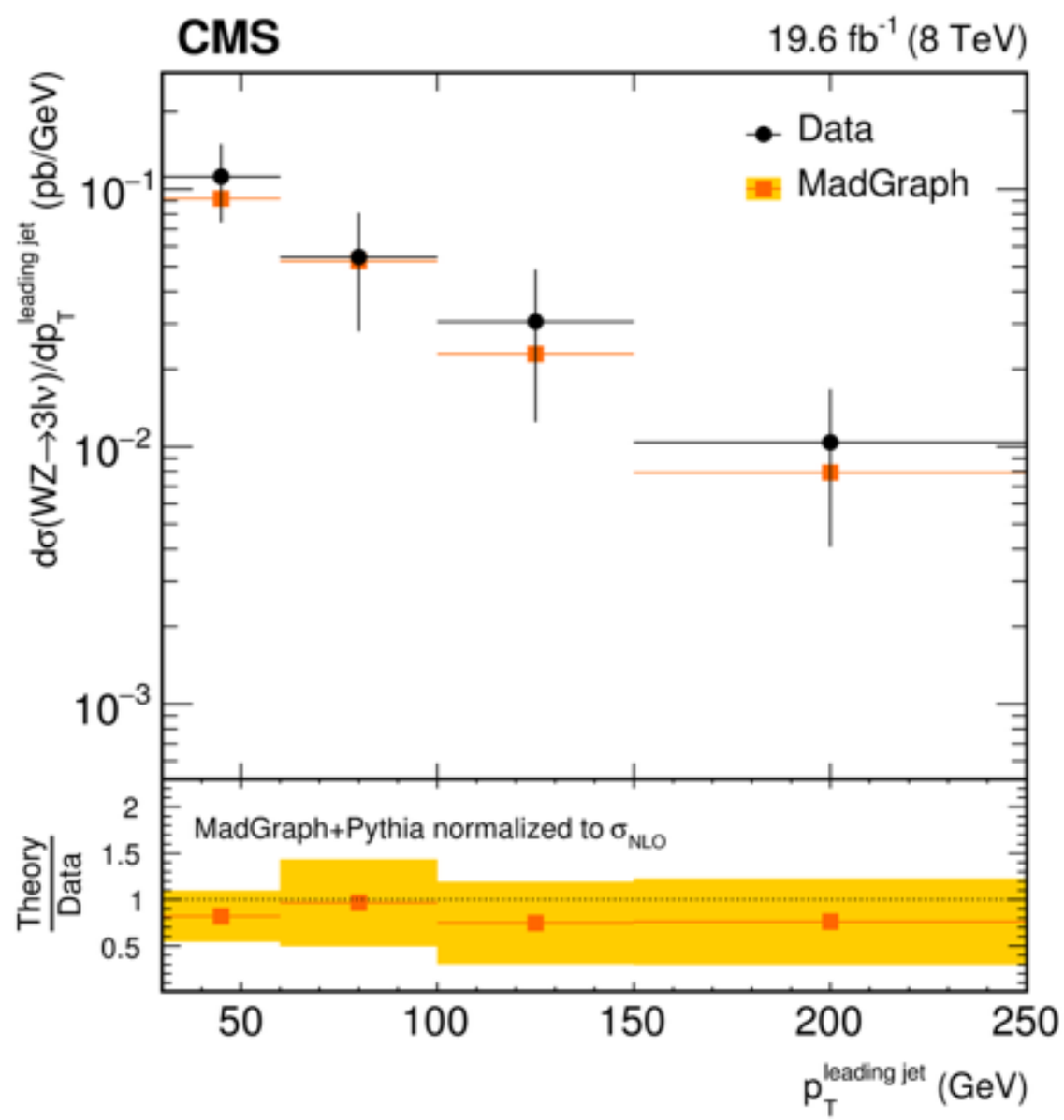
Non-prompt backgrounds measured in data CR.



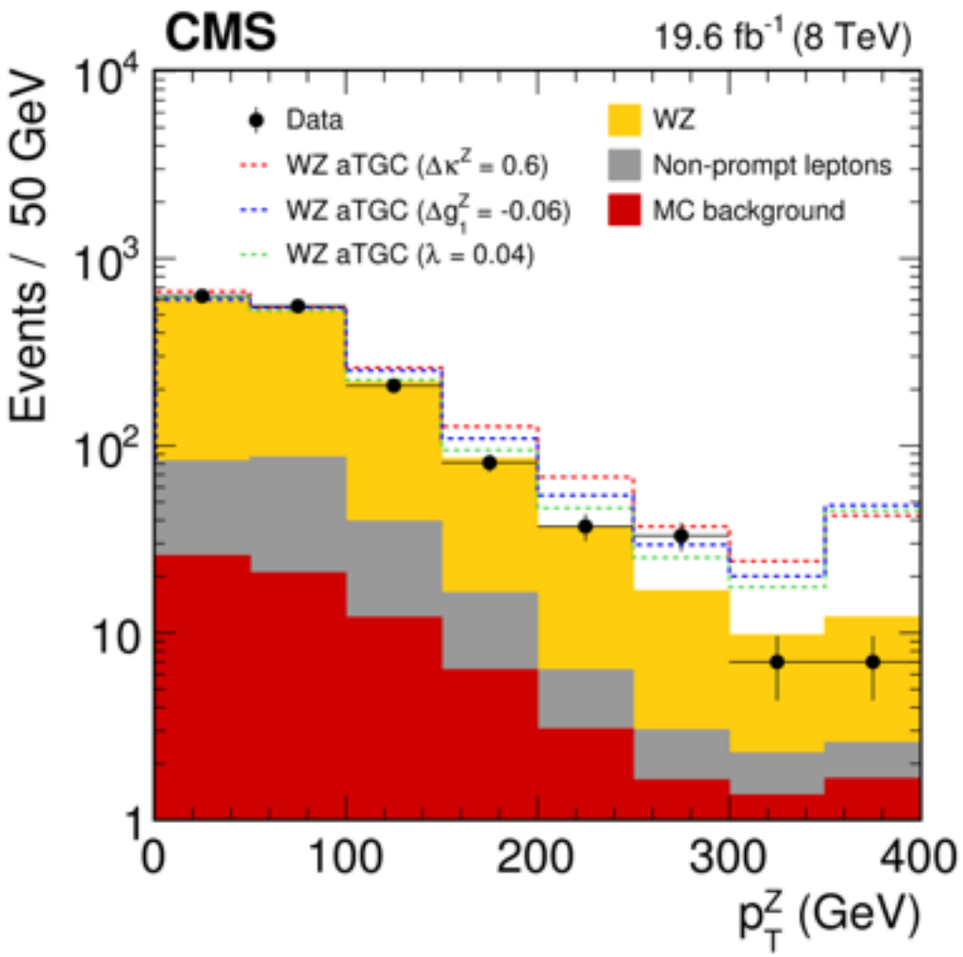
Differential WZ cross section at 7 and 8 TeV

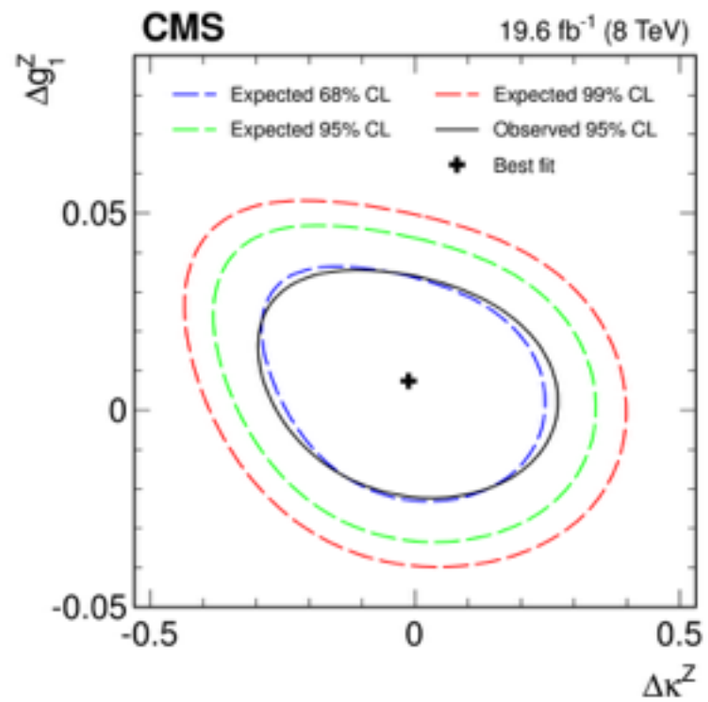
- Fiducial region with $p_T(\ell$ from W) > 20 GeV, p_T(leading ℓ from Z) > 20 GeV, p_T(subleading ℓ from Z) > 10 GeV, $|\eta(\ell)|<2.5$, and $71 < m_Z < 111$ GeV is used to measure differential cross sections.

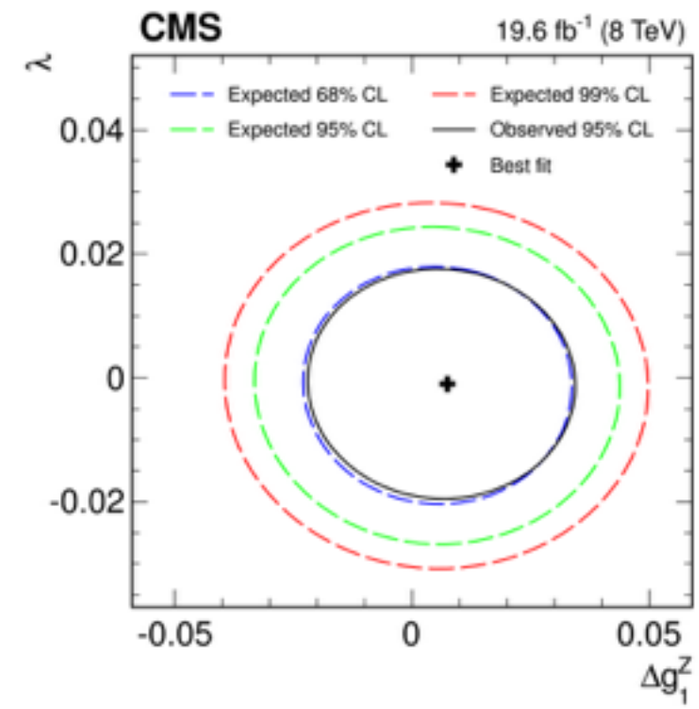




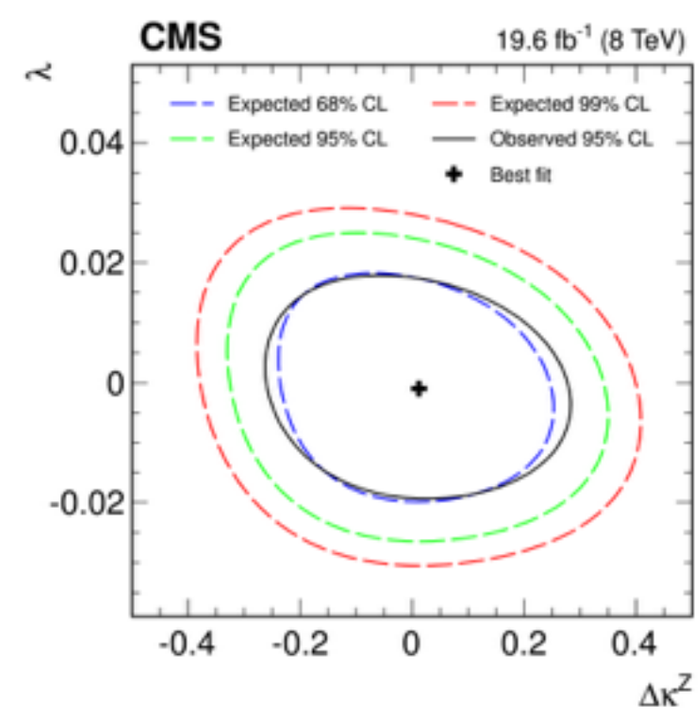
SMEFT analysis of the WZ measurement





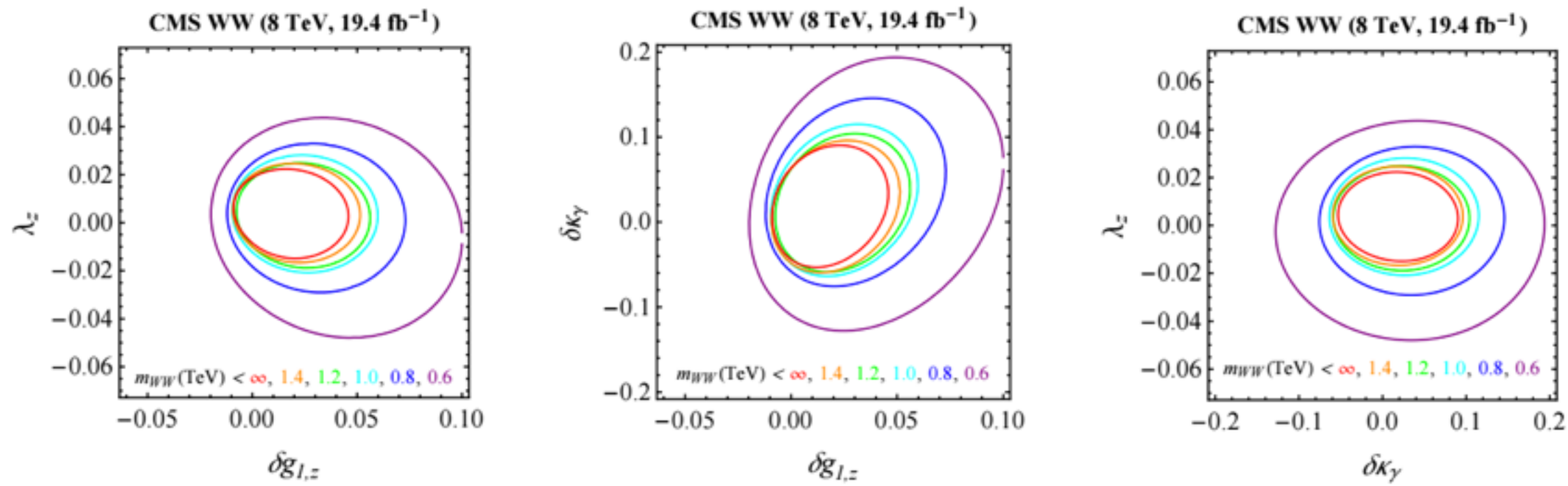


	Observed [TeV^{-2}]	Expected [TeV^{-2}]
c_B/Λ^2	$[-260, 210]$	$[-310, 300]$
c_W/Λ^2	$[-4.2, 8.0]$	$[-6.8, 9.2]$
c_{WWW}/Λ^2	$[-4.6, 4.2]$	$[-6.1, 5.6]$

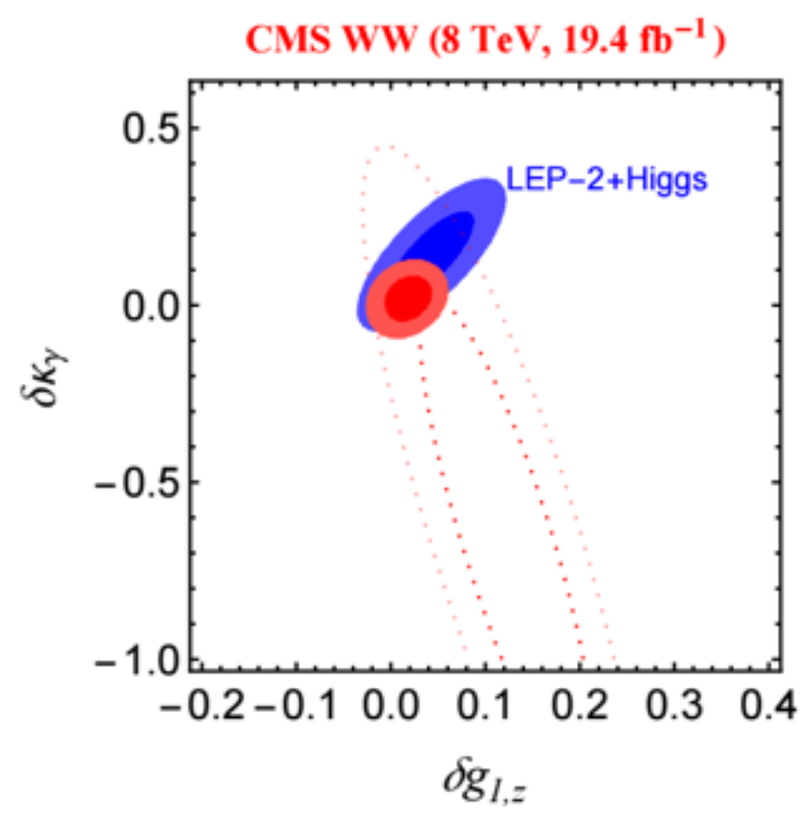


Reinterpretation of the CMS WW analysis

- The 2D limits can be recast imposing different limits on m_{WW}



- Limits are acceptable for cuts down to m_{WW} ~ 1 TeV. Below that, the EFT interpretation is no longer valid.
- This is ok for strongly coupled theories producing c_{WWW} (Λ~1.5TeV), but not c_B (Λ~700GeV).
- The analysis was also recast using only the interference (weak couplings). The limits are much weaker, as expected.



[plots from arXiv:1609.06312]

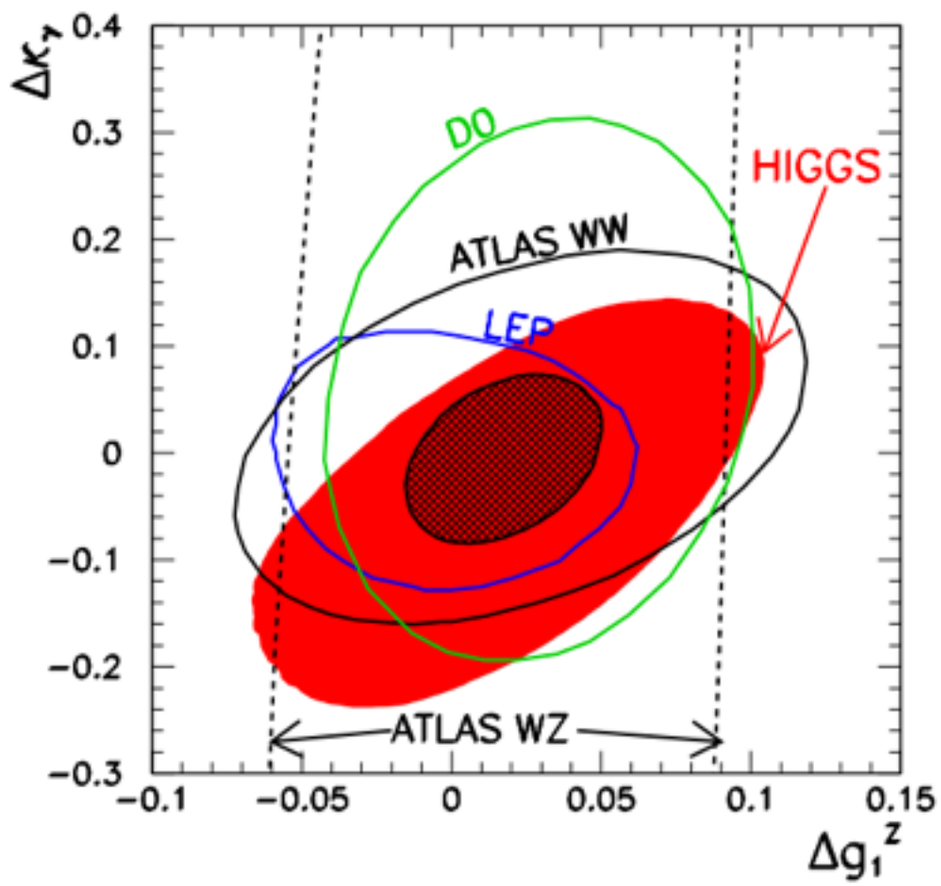
Ideas for the future

- The idea for the future is to perform a global analysis of Higgs and diboson measurements at the LHC.
- Even though the choice of basis for the D=6 operators should be equivalent (up to EOM), it is relevant for how these combinations will be performed in practice.

	Warsaw	SILH	BSM primaries
EWPO	$\mathcal{O}_T = (H^\dagger \overleftrightarrow{D}_\mu H)^2$ $\mathcal{O}_{He} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$ $\mathcal{O}_{HL} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$ $\mathcal{O}'_{HL} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \sigma^a \gamma^\mu L_L)$ +quarks(4)	$\mathcal{O}_T = (H^\dagger \overleftrightarrow{D}_\mu H)^2$ $\mathcal{O}_{He} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$ $\mathcal{O}_W = ig(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H) D^\nu W^a_{\mu\nu}$	$\Delta\mathcal{L}^V_{ee}$
diboson	$\mathcal{O}_{WB} = igg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_B = ig'(H^\dagger \overleftrightarrow{D}^\mu H)\partial^\nu B_{\mu\nu}$ $\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$	$\Delta\mathcal{L}_{g_1^Z}$ $\Delta\mathcal{L}_{\kappa_\gamma}$
Higgs	$\mathcal{O}_{WW} = g^2 \lvert H\rvert^2 W^a_{\mu\nu} W^{a\mu\nu}$ $\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$ $\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$ $\mathcal{O}_{y_f} = y_f \lvert H\rvert^2 \bar{f}_L \widetilde{H} f_R \quad f = u, d, e$ $\mathcal{O}_H = (\partial^\mu \lvert H\rvert^2)^2$	$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$ $\mathcal{O}_{BB} = g'^2 \lvert H\rvert^2 B_{\mu\nu} B^{\mu\nu}$ $\mathcal{O}_{GG} = g_s^2 \lvert H\rvert^2 G^A_{\mu\nu} G^{A\mu\nu}$ $\mathcal{O}_{y_f} = y_f \lvert H\rvert^2 \bar{f}_L \widetilde{H} f_R \quad f = u, d, e$ $\mathcal{O}_H = (\partial^\mu \lvert H\rvert^2)^2$	$\Delta\mathcal{L}^h_{\gamma\gamma}$ $\Delta\mathcal{L}^h_{Z\gamma}$ $\Delta\mathcal{L}^h_{GG}$ $\Delta\mathcal{L}^h_{ff}$ $\Delta\mathcal{L}^h_{V_\mu V^\mu}$
	Partially available at NLO	Easy UV matching (SUSY, Comp Higgs, ...)	Traditional param. Not easy UV matching

Interplay between diboson and Higgs

- The combined analysis will substantially increase the sensitivity to the coefficients of the D=6 operators in SMEFT.
- The idea is to provide combined limits in the (g*, Λ) plane with different energy cuts. We are also working towards a robust determination of the uncertainties associated to D=8 operators and SMEFT NLO corrections.



[plots from arXiv:1304.1151]

Conclusions

- Reviewed the importance of diboson measurements to understand the Standard Model.
- Presented the most recent CMS diboson cross section measurements at 13 TeV using the 2015 dataset.
- Presented some of the most recent CMS searches for diboson resonances at 13 TeV using the 2015 and 2016 dataset.
- Discussed how precision measurements can be used to search for new physics at scales that cannot be probed directly at the LHC.
- Described the SMEFT analysis performed on the 8 TeV WW and WZ cross section measurements and the phenomenology analysis of these measurements.
- Listed some future plans for measurements, including strategies to combine multiple channels, and self-consistency checks of the SMEFT approach in these measurements.