What a W boson produced with another heavy boson can teach us at CMS?

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Wayne State
HEP seminar,
October 25, 2013

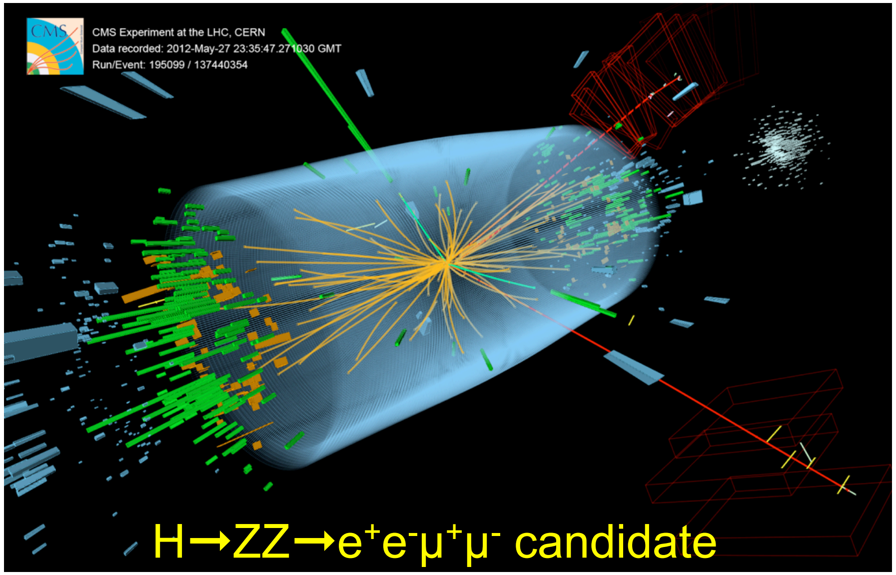
Outline

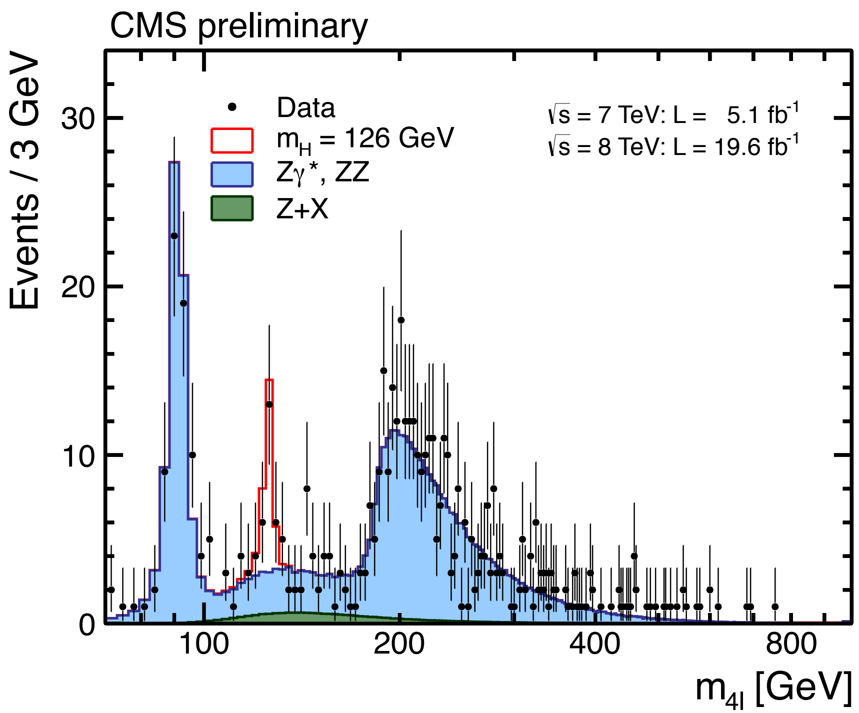
- Starting with the Higgs lamp post
  - What does it tell us experimentally
  - How it influences our physics program going forward
- WV (where V= W or Z) production
  - Production mechanism
  - Connection to Higgs & new physics searches
- Measurements in the post-Higgs-discovery world
  - Anomalous gauge boson couplings
  - Higher mass Higgs states
  - VV scattering
- Summary

References (I will point to CMS public doc #)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

Discovery of a Standard Model like Higgs Boson





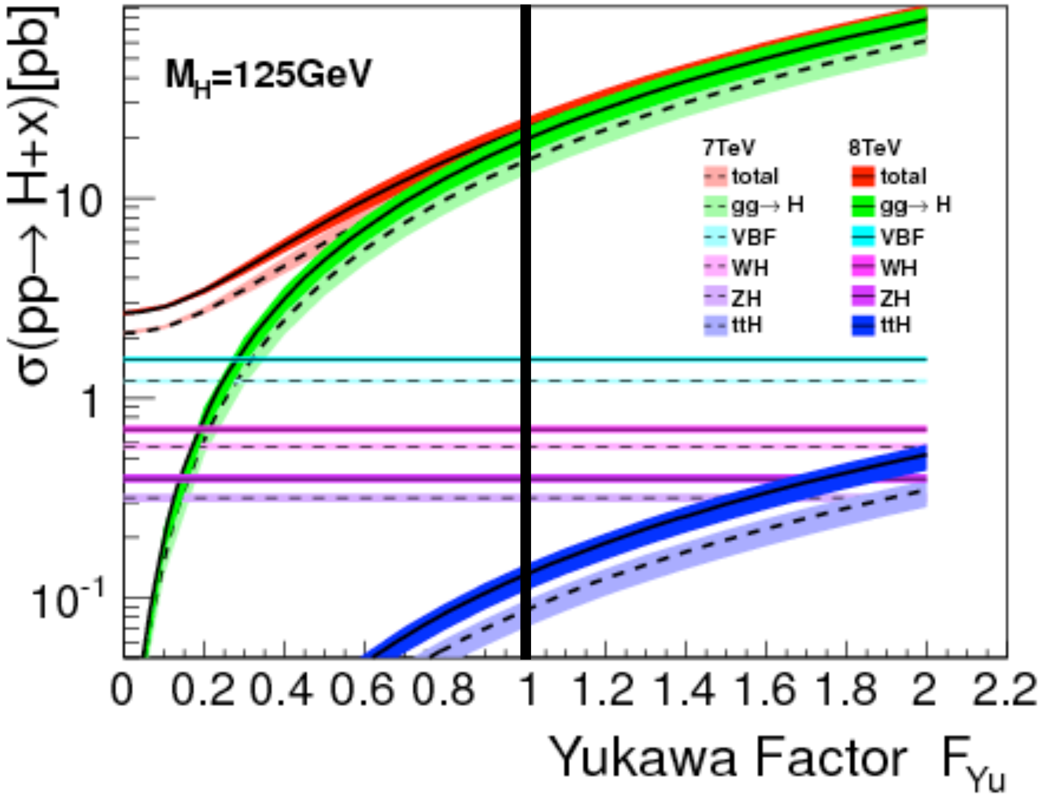
2013 Nobel Prize in Physics awarded jointly to François Englert and Peter Higgs, "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".

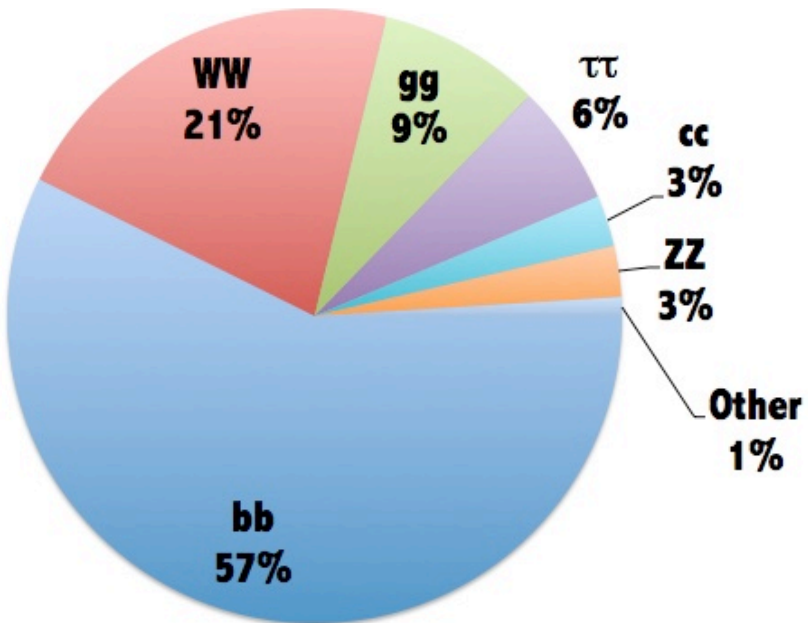
What the Higgs observation tells us immediately

Mass: m_H = 125.7 ± 0.4 GeV

Given H mass, the SM predicts cross section & BR precisely.

And its quantum numbers: **$J^P = 0^+$**

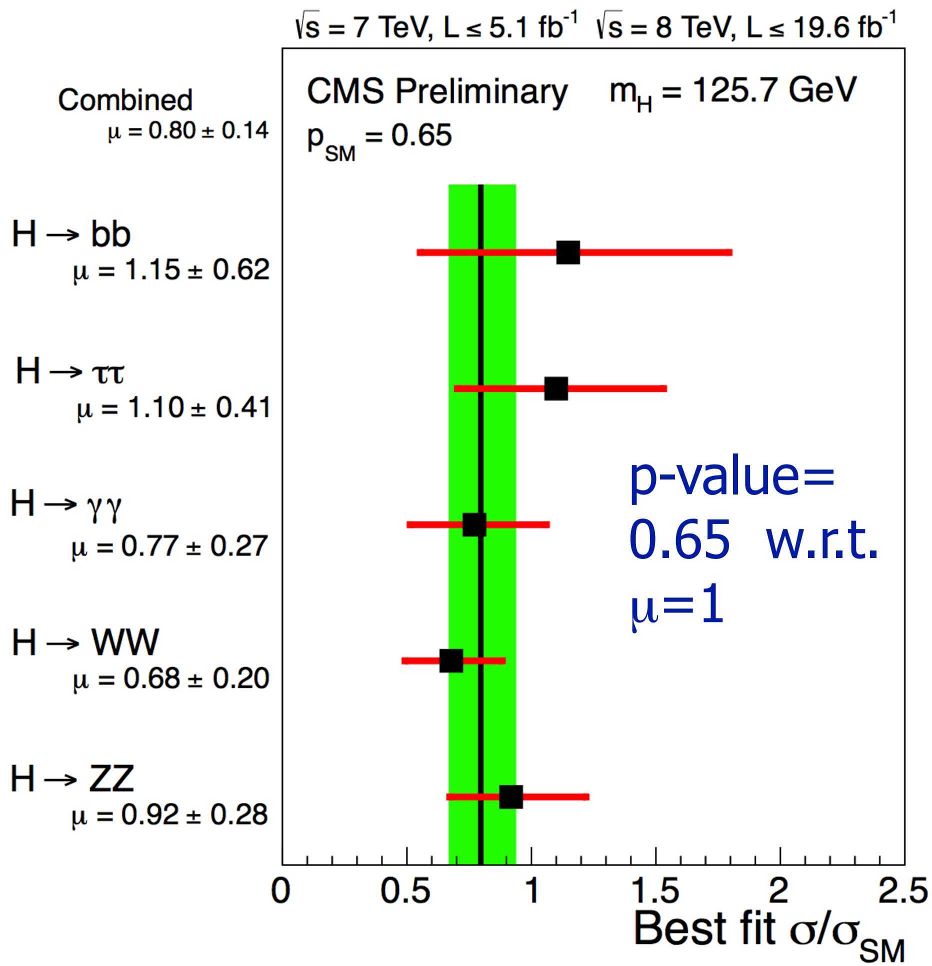


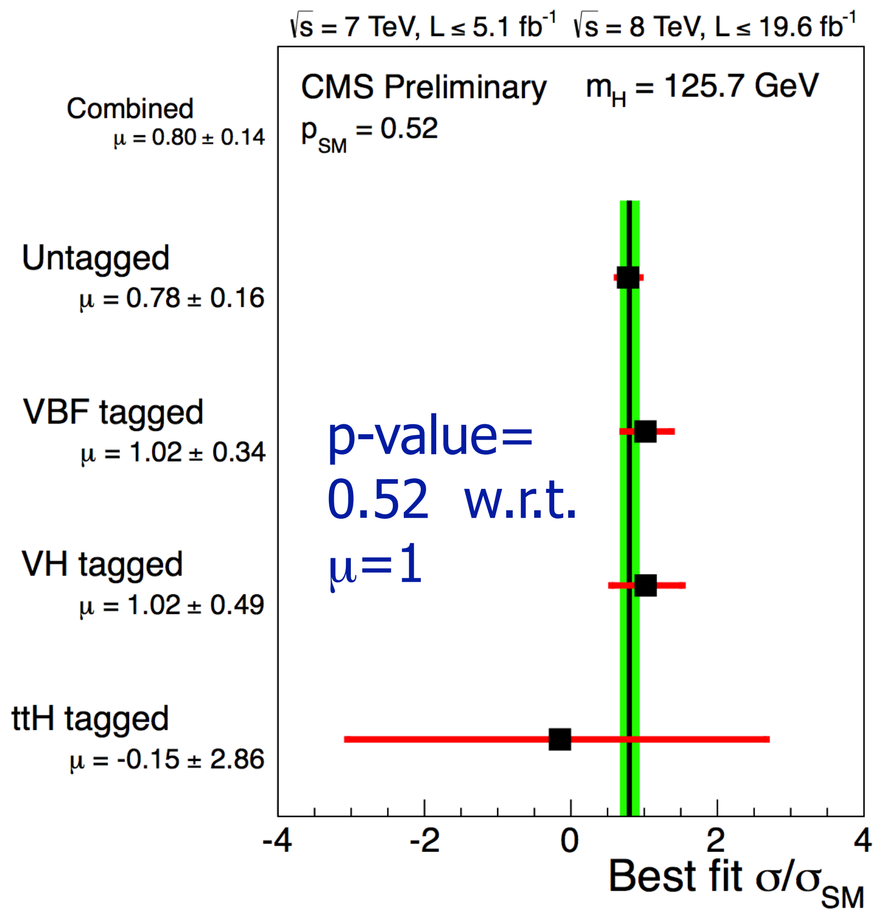


H (125) branching fraction

At LHC can only measure production rate x BR

Consistent with SM Higgs in all production & decay modes





Combined signal strength: μ=0.80±0.14

Spin-parity quantum numbers

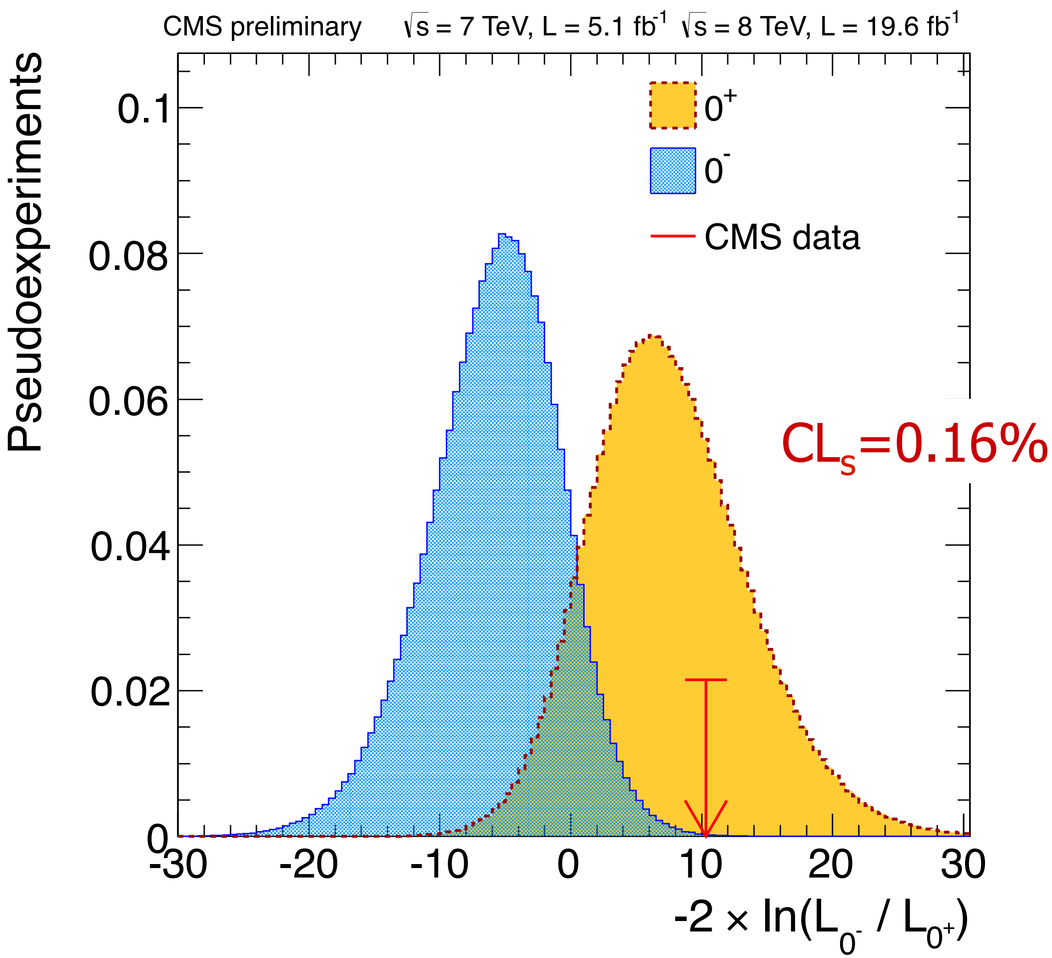
Observation of Higgs signal in various decay modes already tells us something about its spin !

Spin of particle	$\gamma\gamma$	ZZ^*	$\tau\tau$	bb
Spin 0	☺	☺	☺	☺
Spin 1	☹ *	☺	☺	☺
Spin 2	☺	☺	☹	☺
Seen?	Yes	Yes	~Yes	~Yes

*Landau-Yang theorem → still worth testing in decays as there are caveats

Have also measured spin-parity explicitly

CMS HIG-13-002



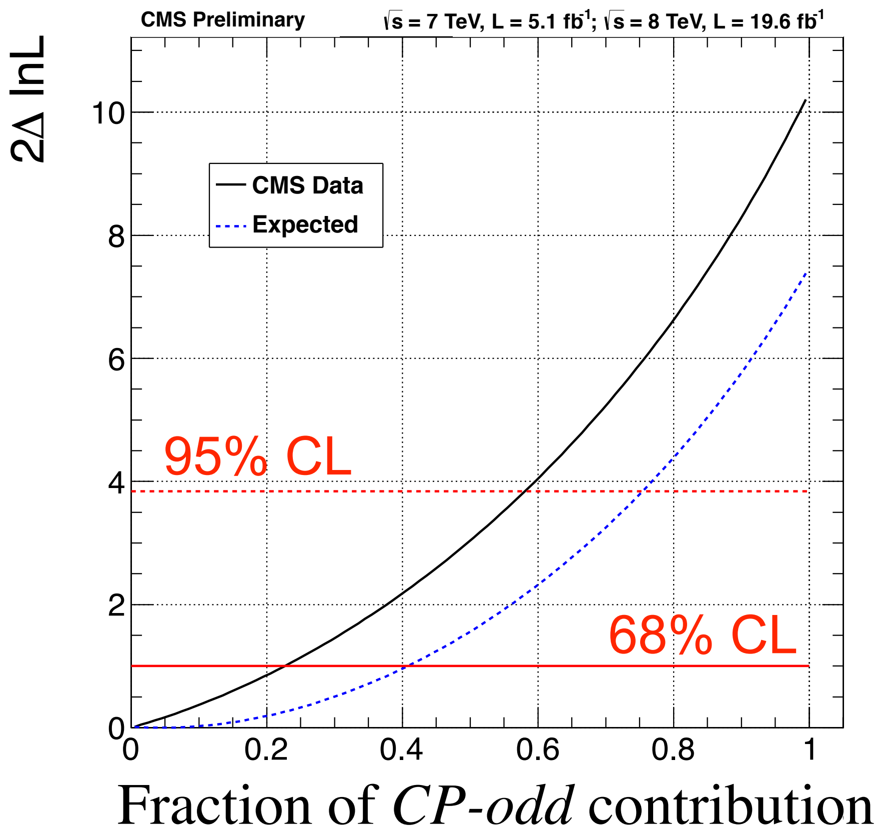
More J^P hypotheses have been tested in a similar way

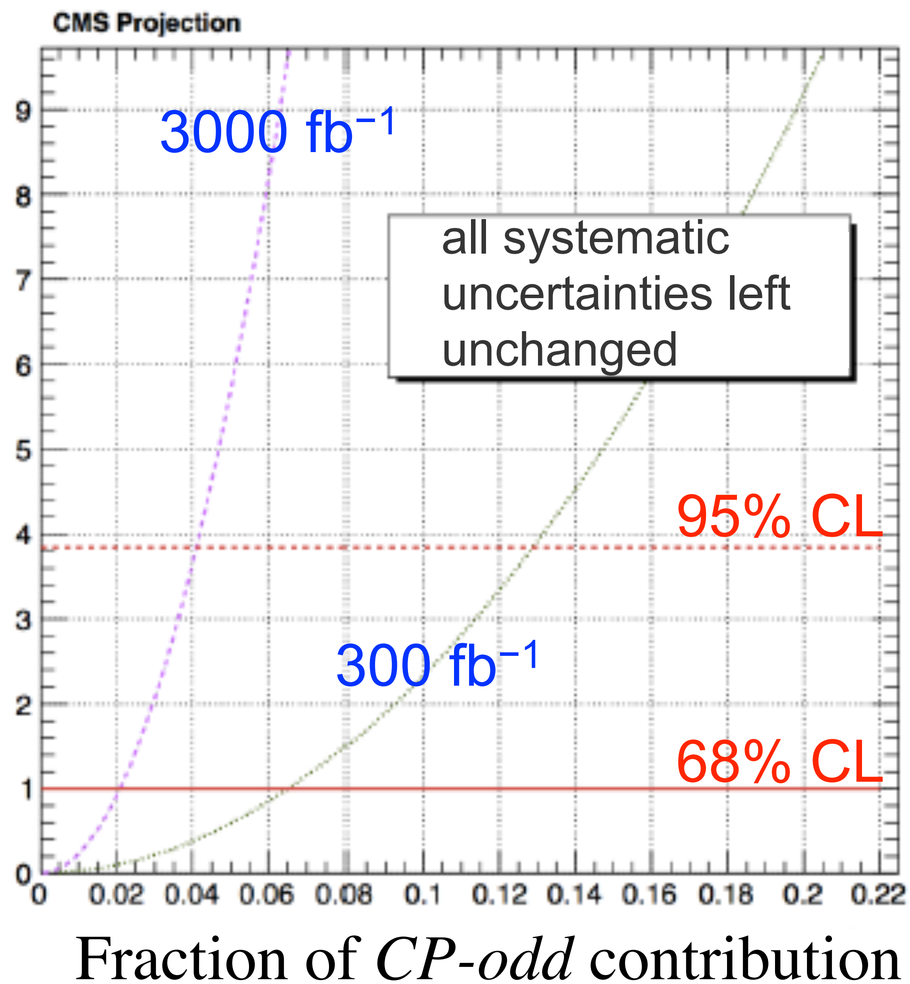
J^P	CL_s
0^-	0.16%
0_h^+	8.1%
2_{mgg}^+	1.5%
$2_{mq\bar{q}}^+$	<0.1%
1^-	<0.1%
1^+	<0.1%

Evidence for scalar nature 0^+ but CP admixture not completely excluded

Any CP violation in Higgs sector?

Significant CP odd contribution allowed by current data





CP violation probe down to 1−10% possible by 2017−20

One more thing ....

Many theories were proposed to imitate QCD
for the electroweak scale

(1) Technicolor
(2) Supersym... ...ic Technico...
(3) Extende... ...ec... ...icolor
(4) Multisc... ...Techn... ...olor
(5) Walking ...xtended ... ...chnicol...
(6) Topcolor ...ssisted Te... ...nicol...
(7) Top Sees...
(8) Supersymm... ...Walki... ...xtended Technicolor
(9) Strong dynamics ... ...xtra-dimensions
(10)....

Natural Weak Scale SUSY e.g. MSSM,was wounded by LHC with new, severe direct limits.
Models with a few % fine-tuning still allowed.

Most of these models were killed on July 4th 2012

Now firmly in the post-Higgs era ...

*"The Higgs boson changes everything. We're obligated to understand it using all tools." - **Chip Brock** (MSU, co-chair Energy Frontier) in the wrap-up talk at Snowmass 2013*

IMO there are two obvious goals for HEP going forward

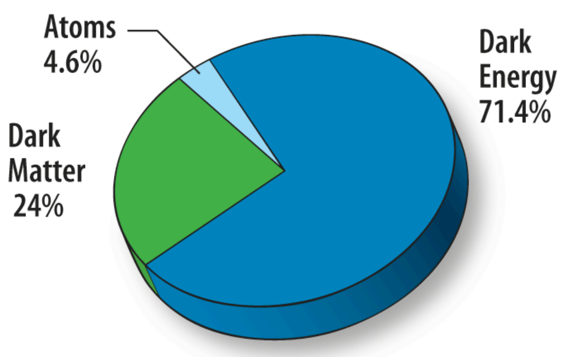
Goal 1: Under the Higgs lamp post

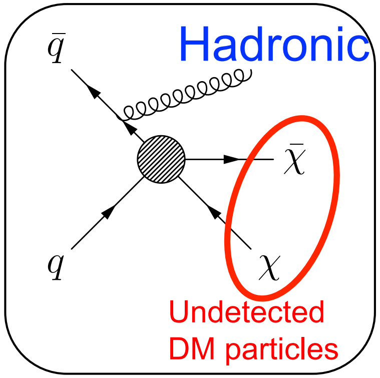
- Couplings to fermions & bosons
  - -Invisible width ⇒ couples to dark matter
- Higgs self coupling
- Anomalous gauge & Higgs couplings
- WW scattering ...

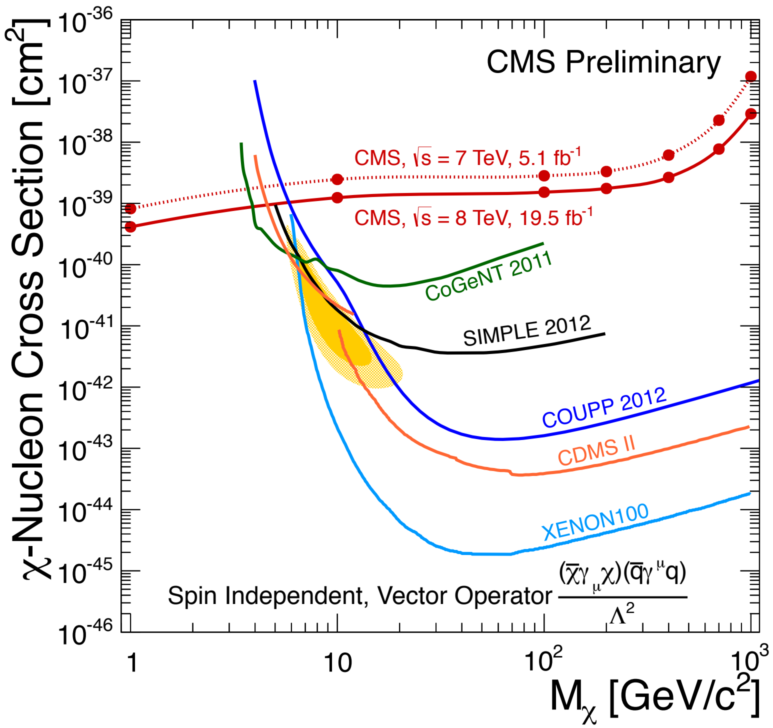
Now firmly in the post-Higgs era ...

"We have now completed the Standard Model. It is high time for us to go on to the dark universe." - ***Rolf Heuer*** *(CERN DG, at ECFA 2013)*

<u>Goal 2:</u> Search for dark matter particle or NP with natural DM candidates at cosmic, energy, and intensity frontiers



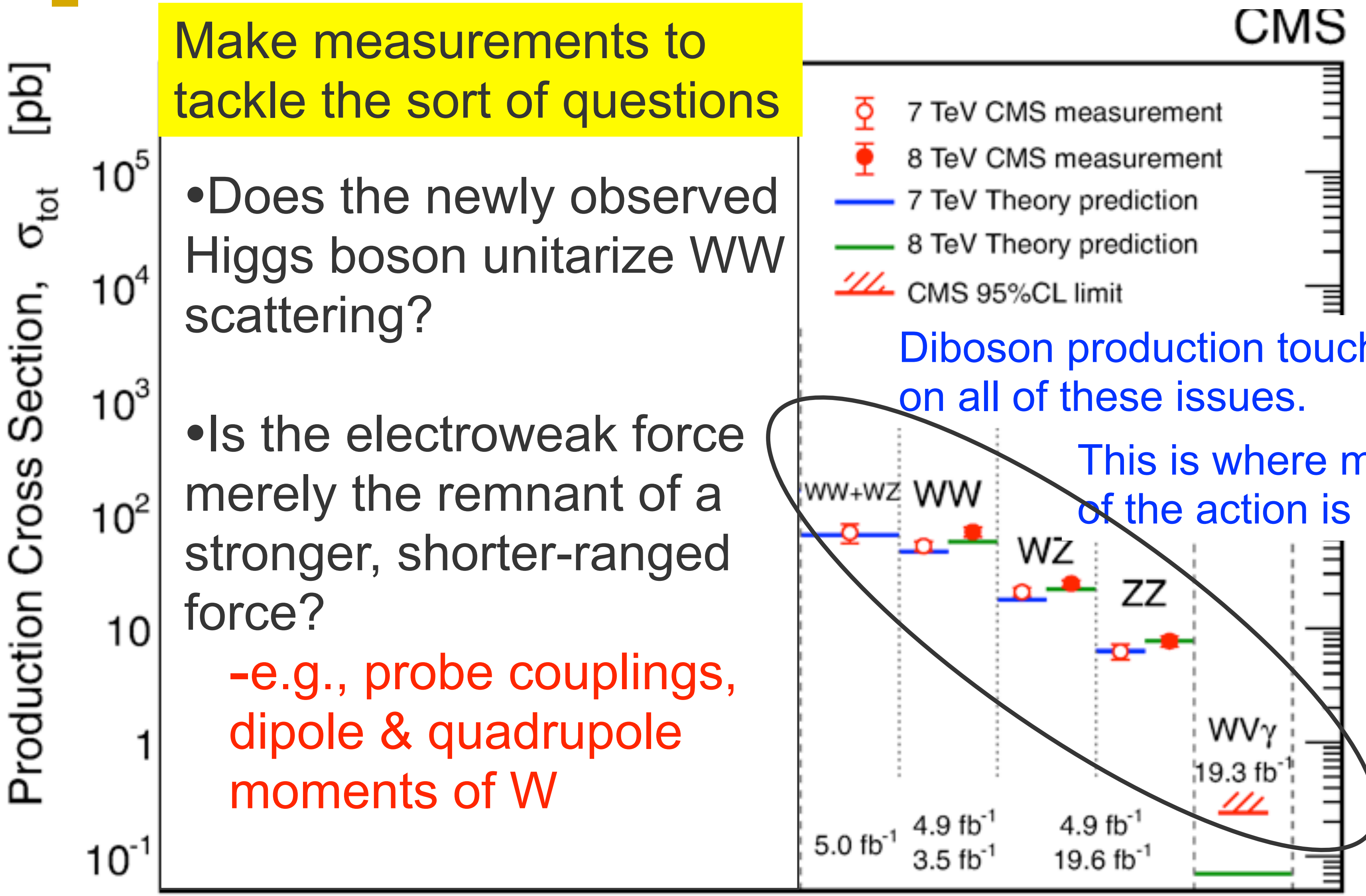




I will describe measurements towards goal #1

Make measurements to tackle the sort of questions

- Does the newly observed Higgs boson unitarize WW scattering?
- Is the electroweak force merely the remnant of a stronger, shorter-ranged force?
  - -e.g., probe couplings, dipole & quadrupole moments of W

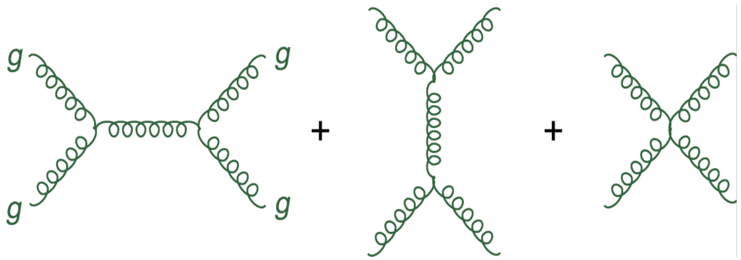


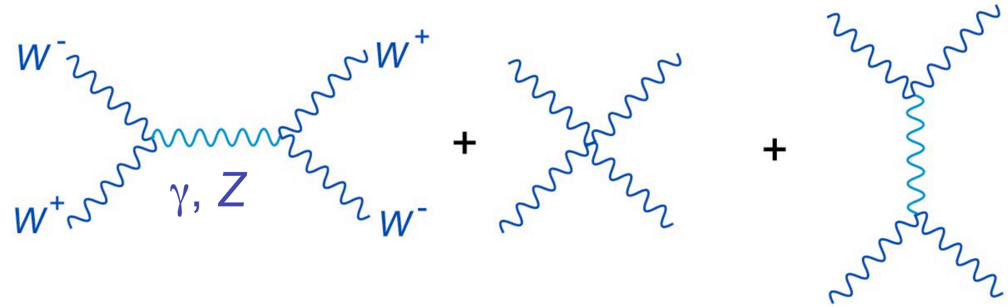
Diboson production touches on all of these issues.

This is where most of the action is !

Gauge boson couplings

A non-Abelian gauge theory will exhibit gauge boson self-interactions. For example





In the case of electroweak theory the self interaction could be

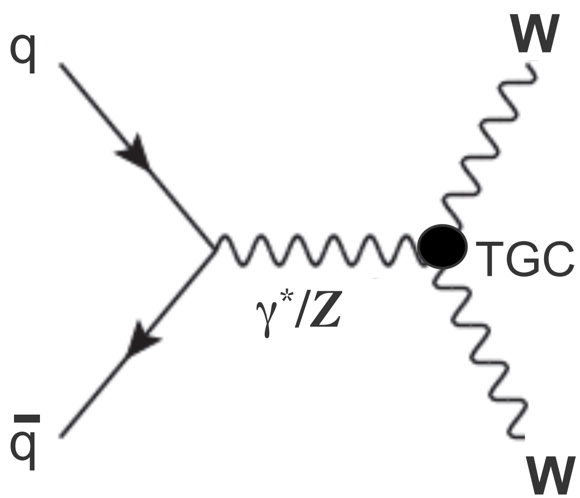
- trilinear (WWγ, WWZ) or
- quartic (WWγγ, WWZγ, WWZZ, WWWW)

At LHC, can test these with <u>unprecedented</u> precision. Observations of anomalous couplings would be an indication of new physics.

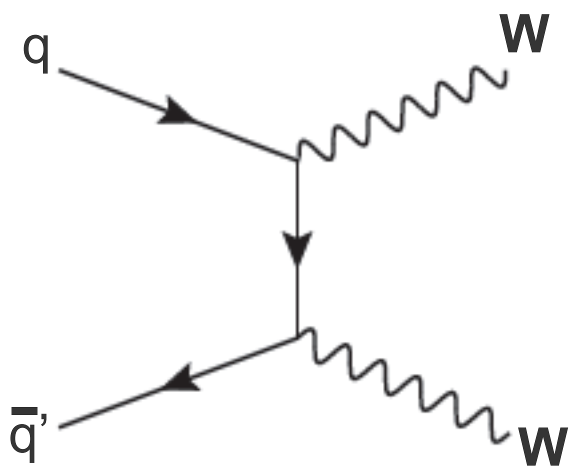
Production of W boson with another heavy boson

i.e., WV, where W decays to $\ell\nu$ and V = W or Z

I will mostly focus on the case where V→qqbar

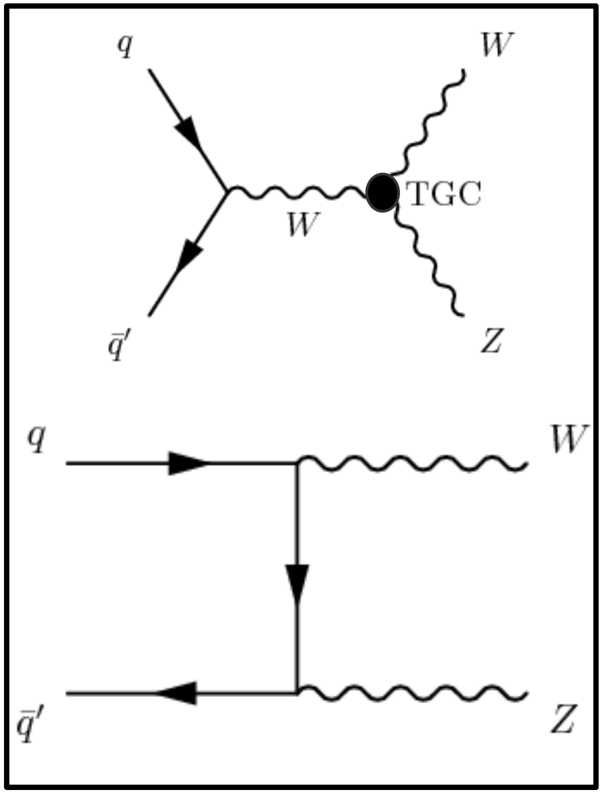


s-channel



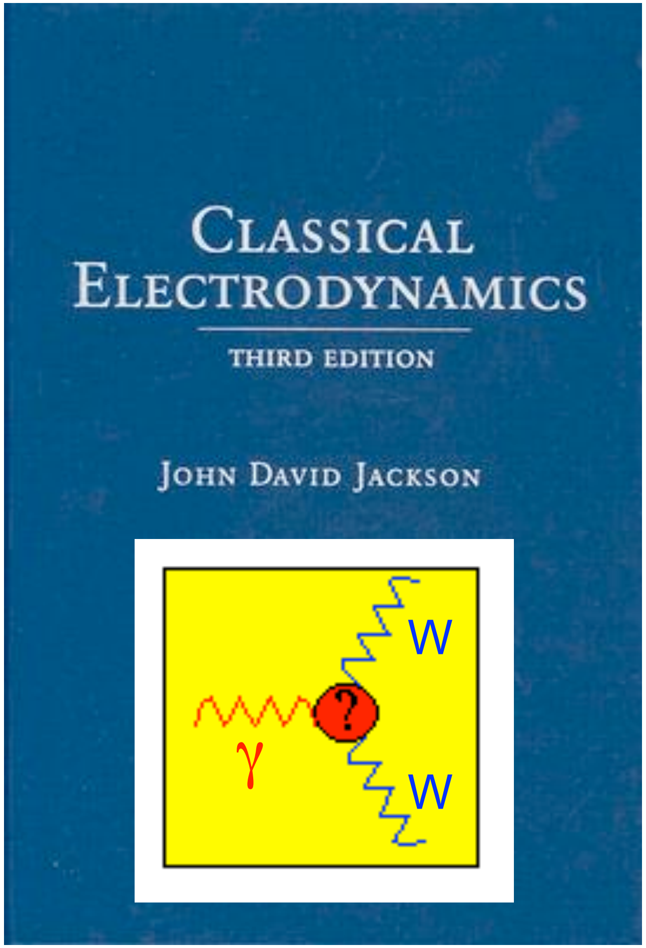
t-channel

Similar diagrams for WZ



•Rate is a mix of TGC process and ISR/FSR

Understanding W interaction in semi-classical theory



✦Interaction between W and e.m. field completely determined by three numbers:

- -W's electric charge
  - •Effect on the E-field goes like $1/r^2$
- -W's magnetic dipole moment
  - •Effect on the H-field goes like $\mathbf{1/r^3}$
- -W's electric quadrupole moment
  - •Effect on the E-field goes like $\mathbf{1/r^4}$

✦Measuring Triple Gauge Couplings ($WW\gamma$)
≡ measuring the 2nd and 3rd numbers

- -Because of $\propto 1/r^n$, largest at small distances
- -Small distance = high energy ($\hat{s}$)

Sensitivity to new physics is at short distances/ high $\hat{s}$

SM as an Effective Field Theory: Wilsonian approach

That which is not forbidden is required:

includes all interactions consistent with **space-time, global, and gauge symmetries**.

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty} \sum_i \frac{c_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n+4)}$$

$E << \Lambda$

For the case WWγ and WWZ couplings

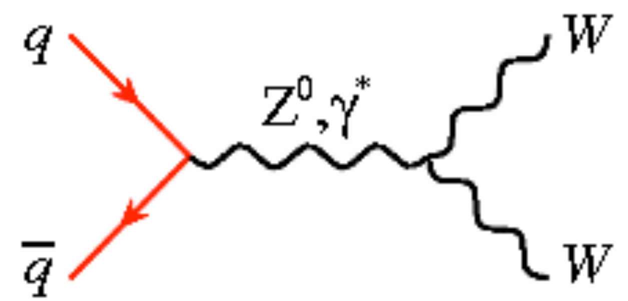
$$L = g\left(W_{\mu\nu}^{\dagger} W^{\mu} A^{\nu} - W_{\mu}^{\dagger} A_{\nu} W^{\mu\nu}\right) + \left(1 + \Delta\kappa_{\gamma}\right)\left(W_{\mu}^{\dagger} W_{\nu} F^{\mu\nu}\right) + \frac{\lambda_{\gamma}}{M_W^2}\left(W_{\rho\mu}^{\dagger} W_{\nu}^{\mu} F^{\nu\rho}\right)$$

(with)

$$W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu - g W_\mu \times W_\nu$$

\+ three similar terms for the Z

\+ nine other terms that do evil things (violate CP and/or EM gauge invariance)



Connecting the two together

Think of these parameters as ≡ muon "g-2"

- The convention is that every parameter you see (e.g. $\Delta g_1^Z, \Delta\kappa_\gamma, \lambda_\gamma$) is zero in the SM.
- **Dimension 4 operators alter $\Delta g_1^Z, \Delta\kappa_\gamma$ and $\Delta\kappa_Z$: effects grow as $\hat{s}^{1/2}$**
- **Dimension 6 operators alter λ_γ and λ_Z : effects grow as $\hat{s}$.**

$$\mu_W = e\frac{2+\Delta\kappa_\gamma+\lambda_\gamma}{2M_W}$$

Jackson Eq. 5.59, 3rd ed.

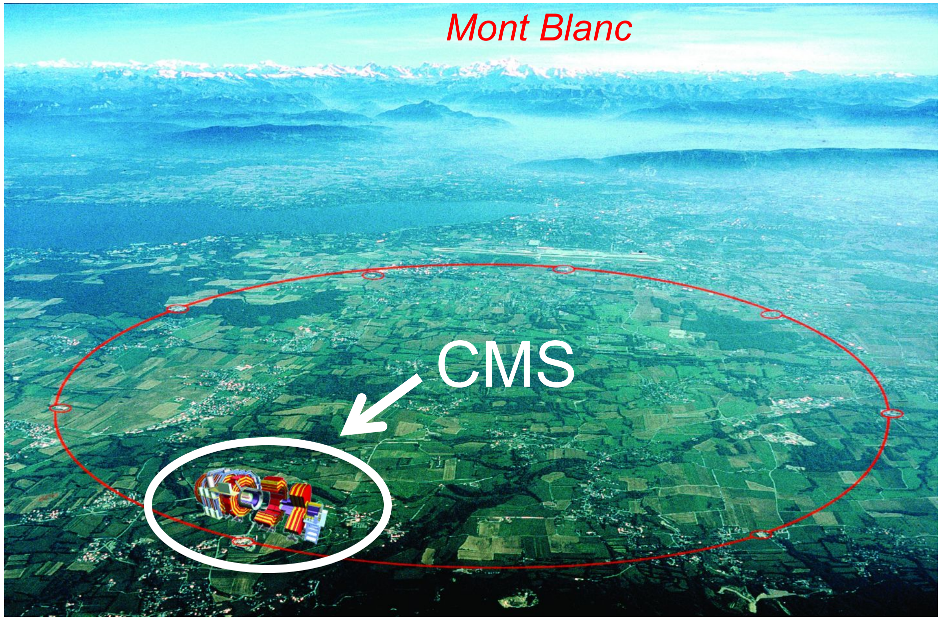
$$Q_W = -e\frac{1+\Delta\kappa_\gamma-\lambda_\gamma}{M_W^2}$$

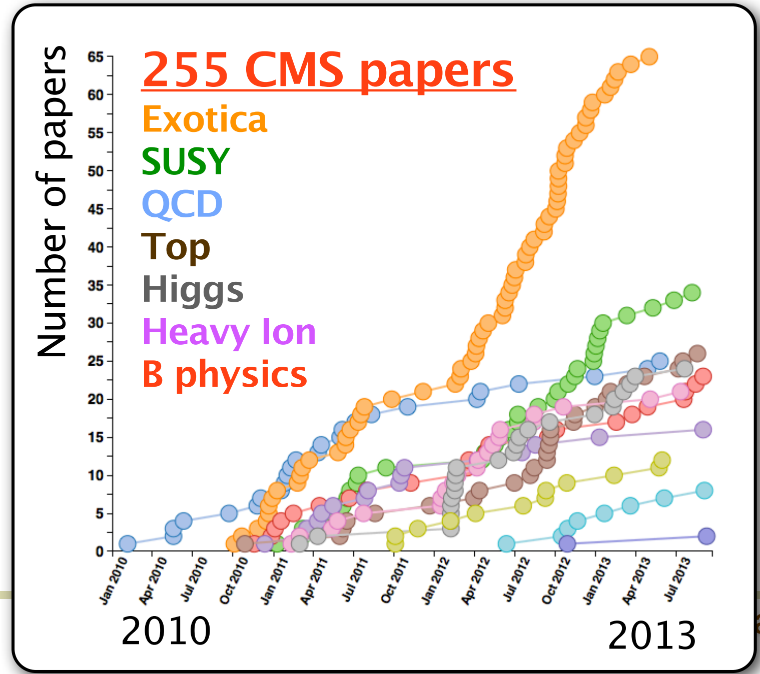
Jackson Eq. 4.9, 3rd ed.

Much more constrained at LHC than at previous colliders

Let's look at the data

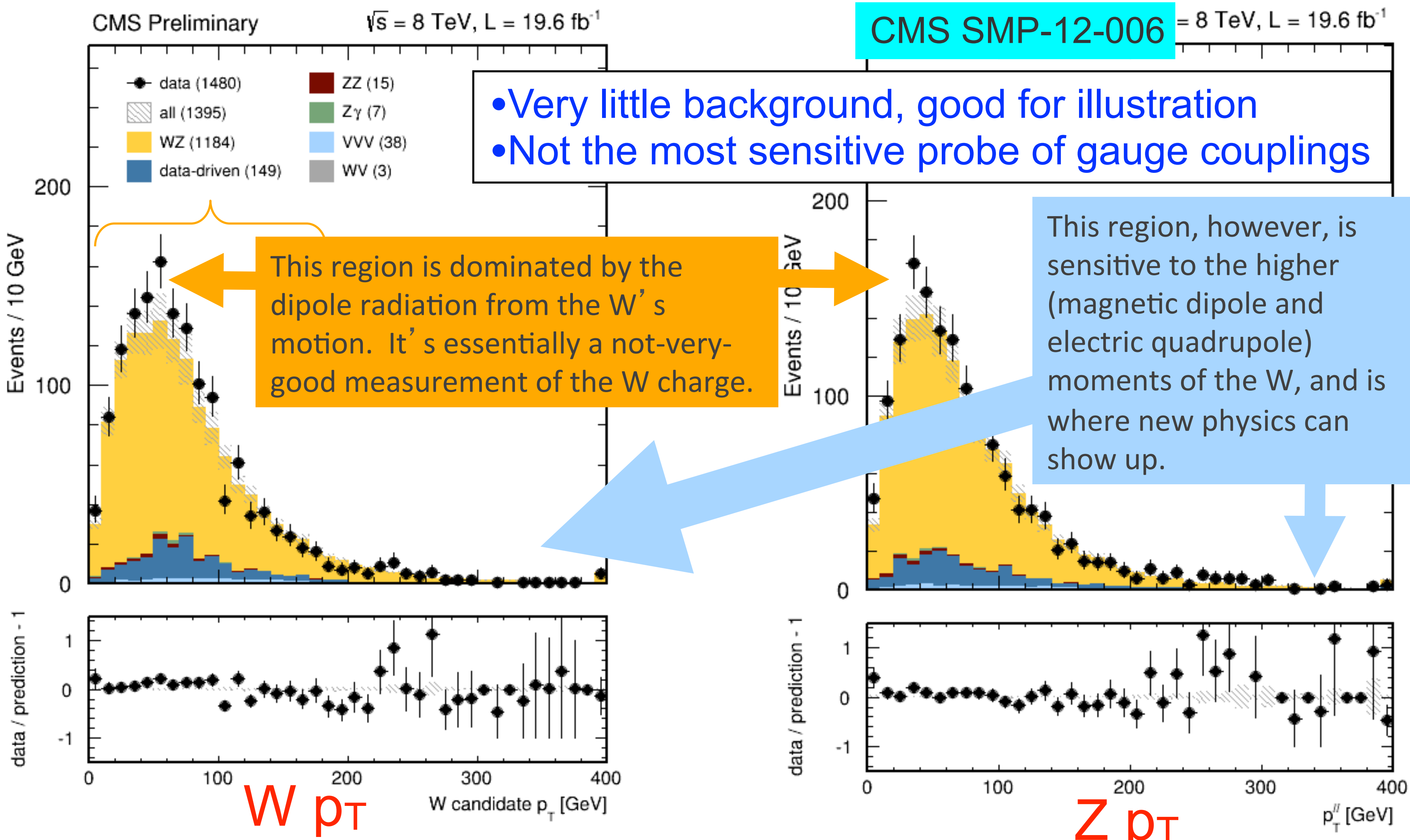
- LHC: proton-proton and lead-lead collider at CERN (near Geneva, Switzerland)
  - -Run I: 2009-13, energy: 7-8 TeV
- CMS: collaboration of over 3000 scientists from 42 countries
  - -Over 30% from US





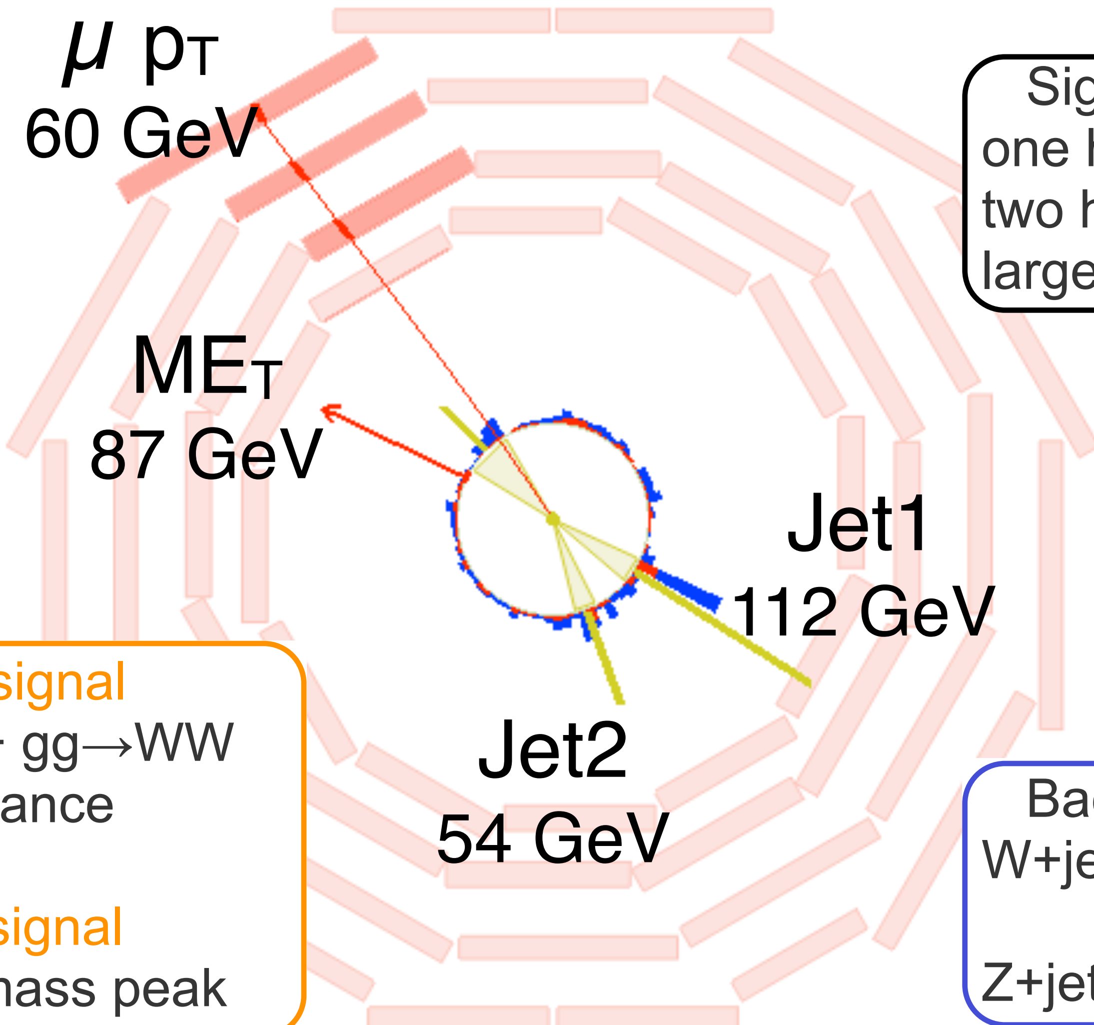
E.g., W charge & dipole moment in WZ events

- Very little background, good for illustration
- Not the most sensitive probe of gauge couplings



$W(\to \ell\nu) + W/Z(\to qq)$

CMS SMP-12-015



Signature:
one high p_T lepton
two high p_T jets
large missing E_T

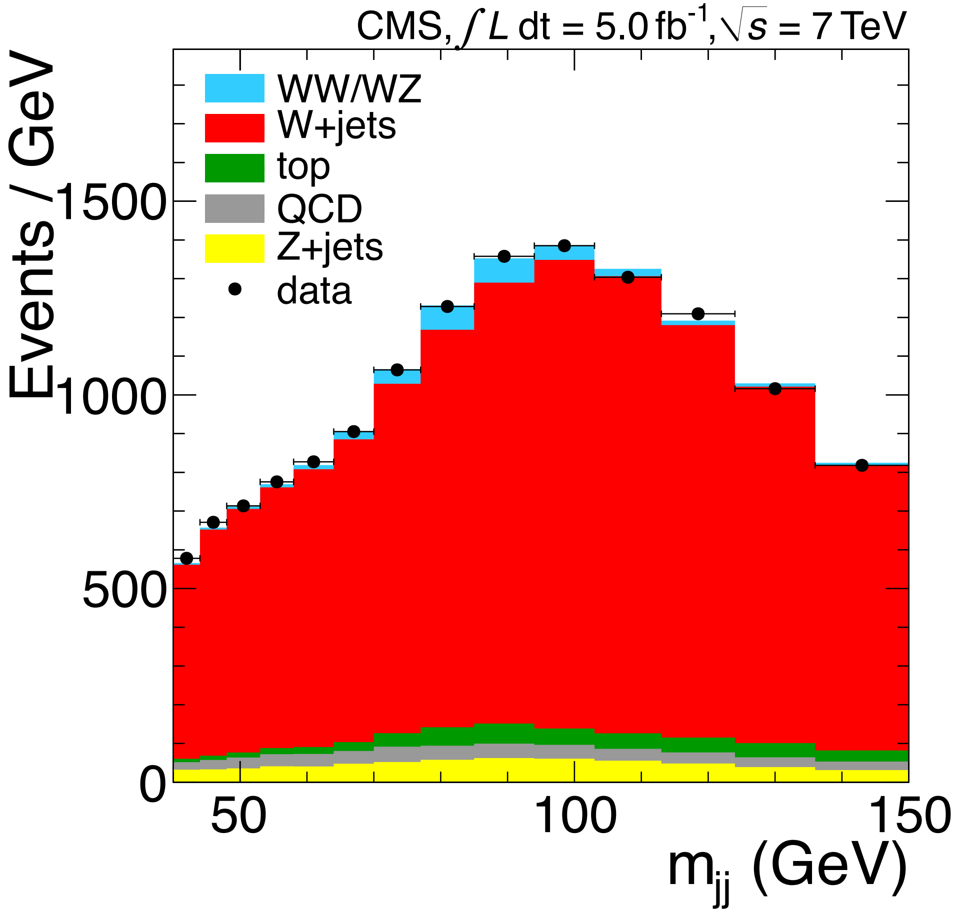
SM WW signal
$qq \to WW + gg \to WW$
no resonance

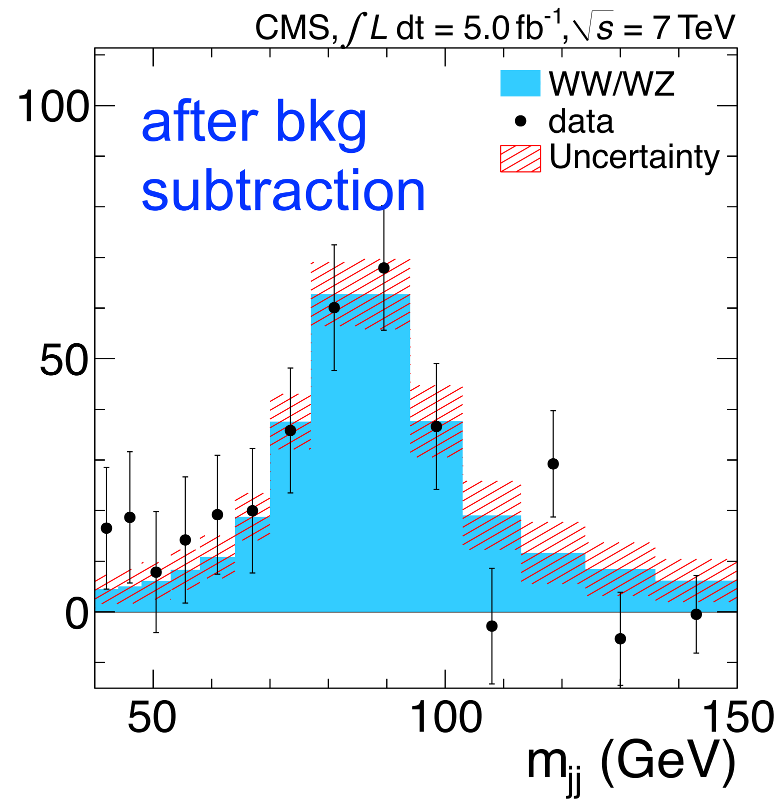
H→WW signal
resonant mass peak

Background:
W+jets (dominant)
top
Z+jets, multijet

Established presence of WW+WZ in such events

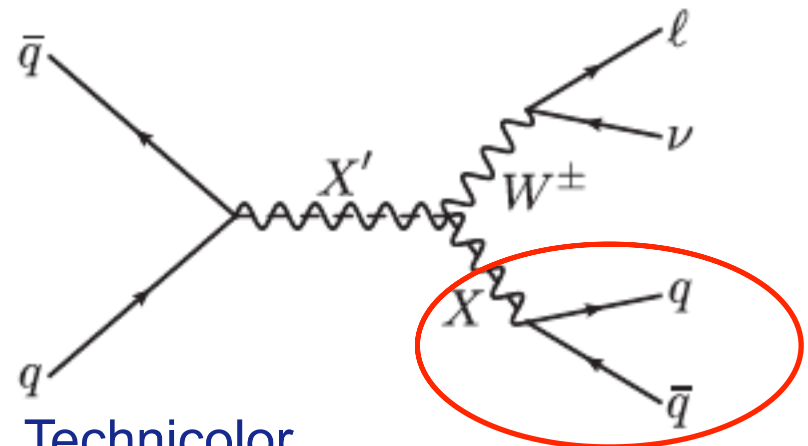
Large background. The main thrust of the analysis is to model this well & control systematics.



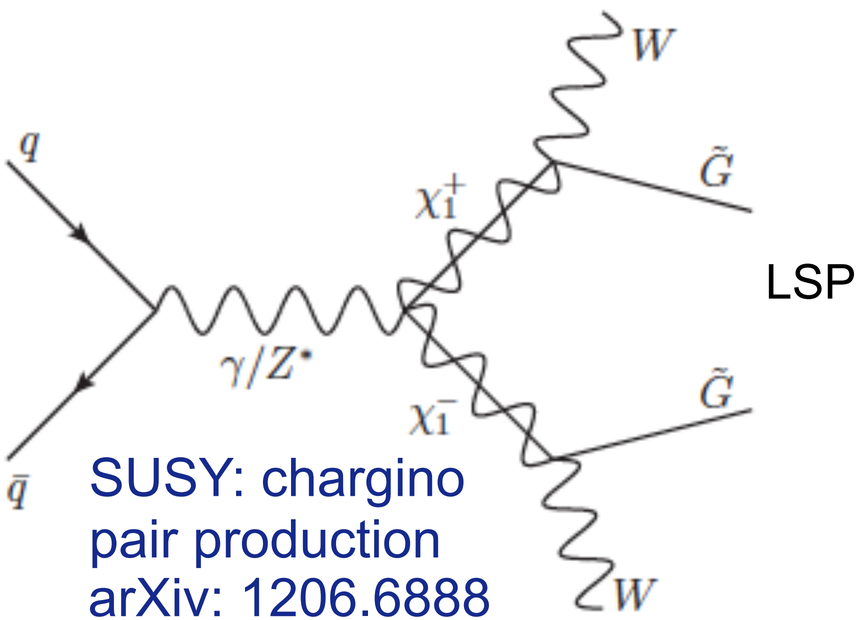


Very sensitive to new physics

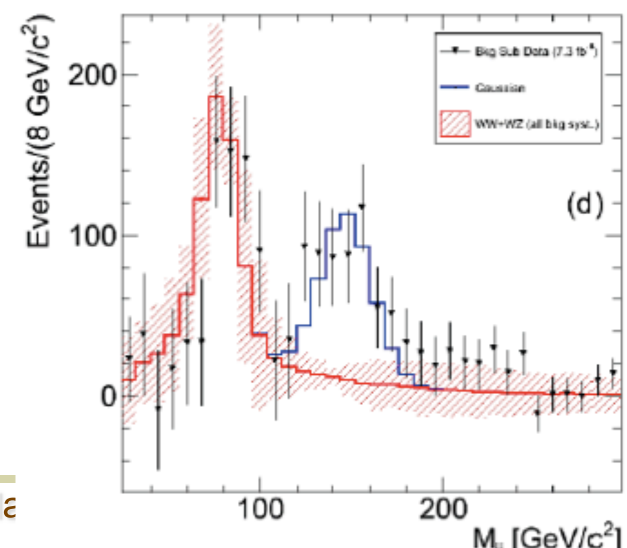
New physics can enhance WW or WZ production rate or produce a new particle.



Technicolor,
Z', W', RS graviton
Buckley, Hooper, Kopp, Martin, Neil; arXiv: 1107.5799



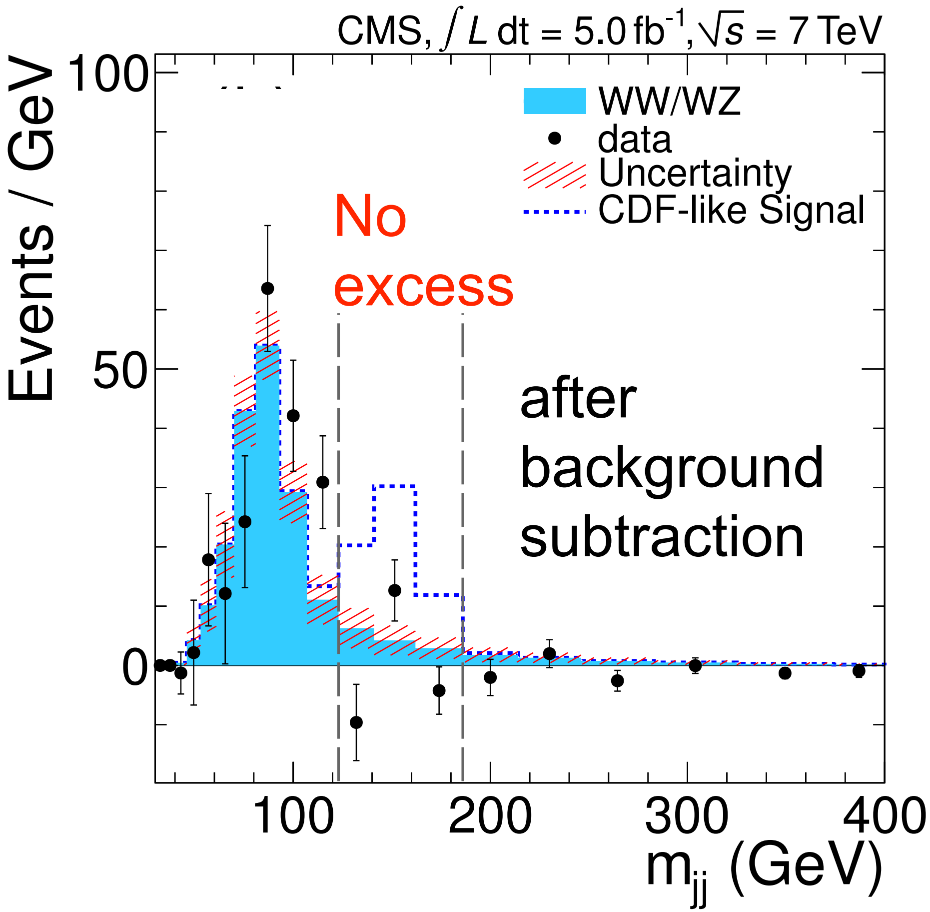
SUSY: chargino pair production
arXiv: 1206.6888

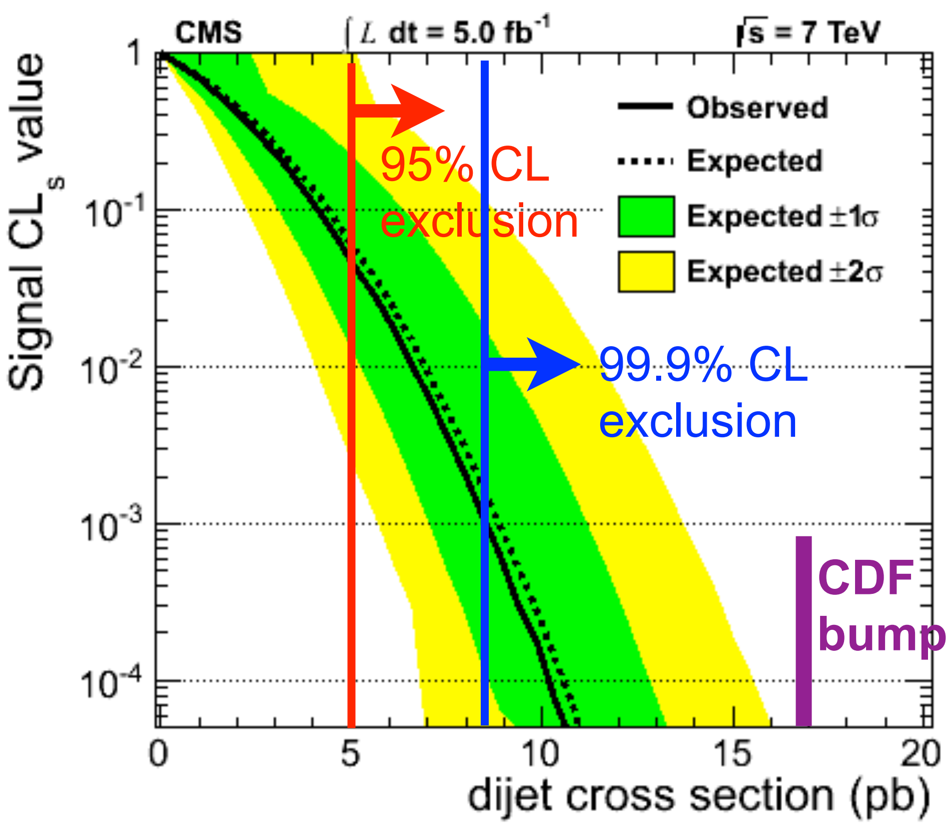


One of the most interesting SUSY searches these days

Following CDF 2011 result increased m_{jj} window

CMS EWK-11-017



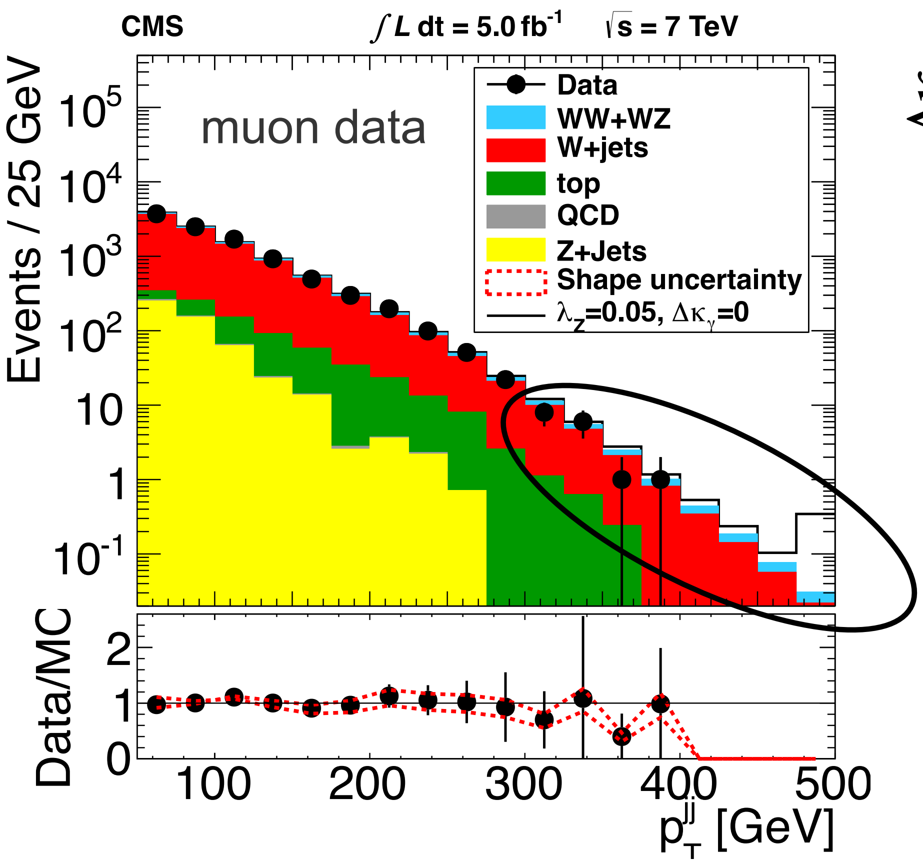


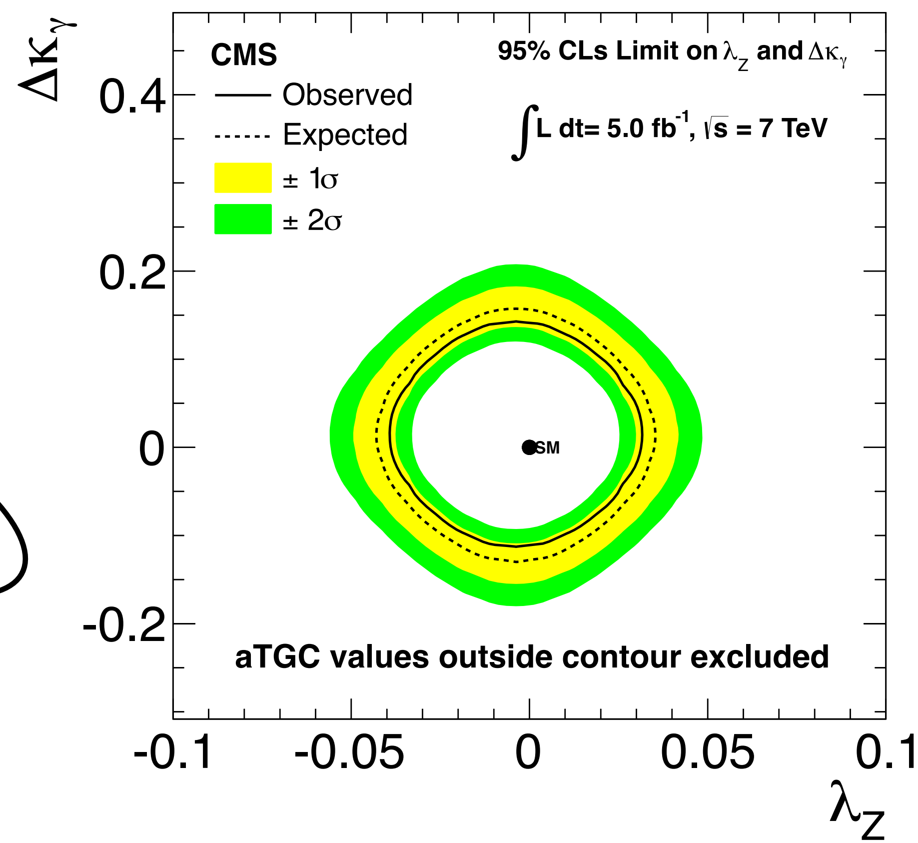
Excluded several classes of BSM models such as low scale technicolor, leptophobic Z', ... etc.

Probe of anomalous couplings

CMS SMP-12-015

Anomalous couplings can show up at large W p_T.

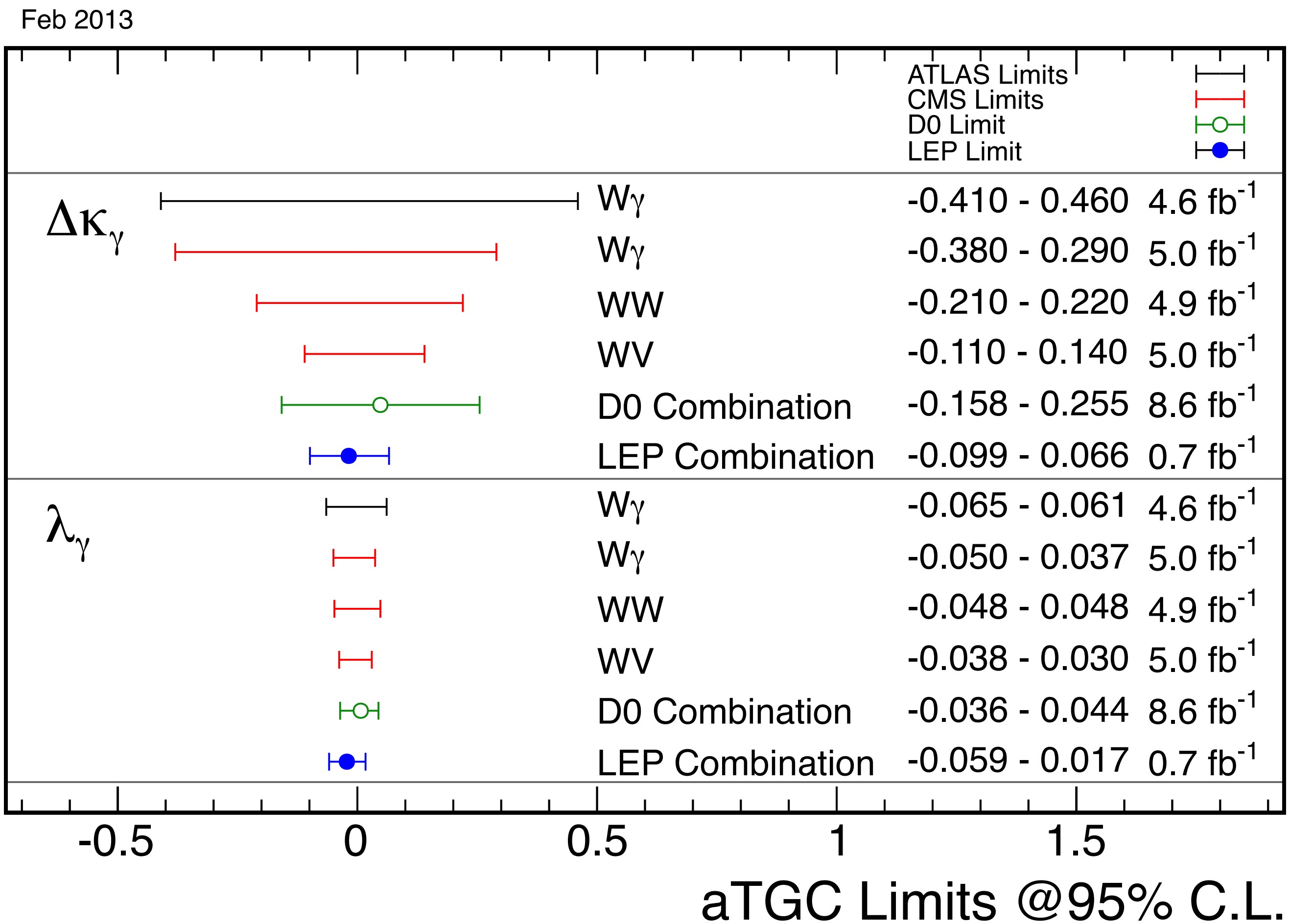




Putting it all together: WWγ couplings

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

Only includes 7 TeV published results. (8 TeV results are in preparation)

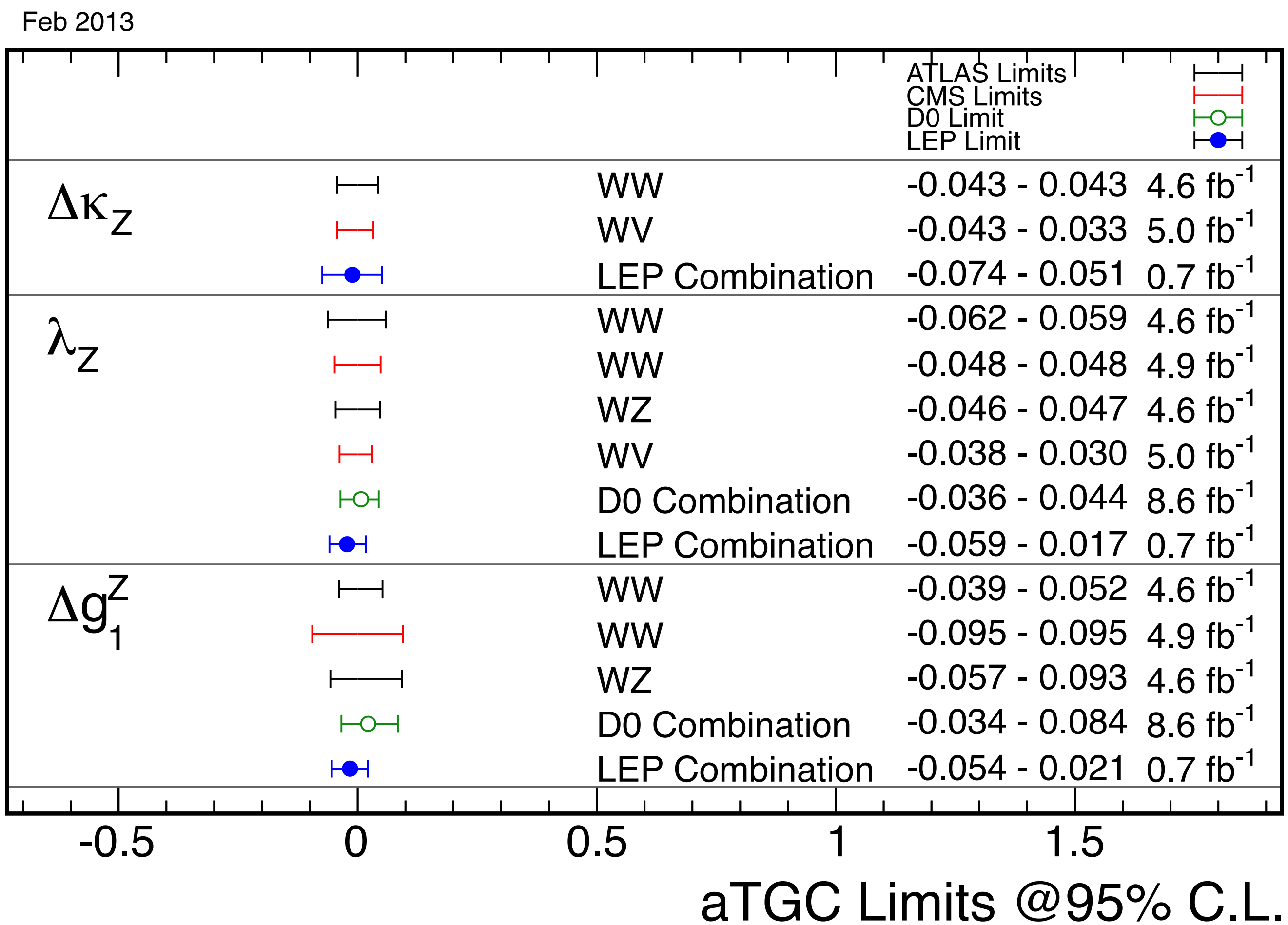


Dipole moment of W constrained at $\mathcal{O}(10^{-2})$, quadrupole moment at $\mathcal{O}(10^{-4})$.

Compare this to muon “g−2” which differs by 0.1% from the SM value (=3.4 sigma effect) !!!

Constraints on WWZ couplings

Only includes 7 TeV published results.



Obtained assuming equal coupling parametrization

$$\lambda_Z = \lambda_\gamma = \lambda$$

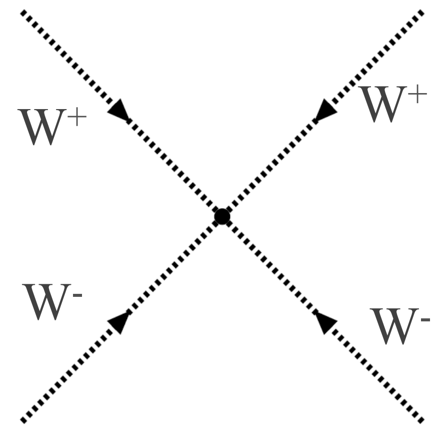
$$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \cdot \tan^2\theta_W$$

The CMS limits shown here and on the previous slide are the most stringent in the world, to date.

Quartic gauge couplings involving W boson

This is a high priority – we need to understand QGCs to tell if the Higgs unitarizes the process WW→WW

- In the SM, the allowed couplings are:
  WWγγ, WWZγ, WWWW, WWZZ



- Observable in two topologies at the LHC
  - Triple gauge boson production (e.g., Wγγ, WWγ, WWW, WWZ: very rare processes)
  - Scattering process (γγ → WW, WW → WW)
- Anomalous couplings
  - Should use the linear realization with light Higgs
  - aQGCs for SM allowed processes introduced at dimension 6
  - However they are the same operators as aTGC (very constrained now)
- Lowest independent aQGC interactions are dimension 8

Linear realization of EWK symmetry breaking

All dimension-8 operators (includes light Higgs)

hep-ph/0606118
Eboli et. al.

$$\mathcal{L}_{S,0} = \left[(D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[(D^\mu \Phi)^\dagger D^\nu \Phi \right]$$
$$\mathcal{L}_{S,1} = \left[(D_\mu \Phi)^\dagger D^\mu \Phi \right] \times \left[(D_\nu \Phi)^\dagger D^\nu \Phi \right]$$

$$\mathcal{L}_{M,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right]$$
$$\mathcal{L}_{M,1} = \mathrm{Tr}\left[\hat{W}_{\mu\nu} \hat{W}^{\nu\beta} \right] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right]$$
$$\mathcal{L}_{M,2} = \left[B_{\mu\nu} B^{\mu\nu} \right] \times \left[(D_\beta \Phi)^\dagger D^\beta \Phi \right]$$
$$\mathcal{L}_{M,3} = \left[B_{\mu\nu} B^{\nu\beta} \right] \times \left[(D_\beta \Phi)^\dagger D^\mu \Phi \right]$$
$$\mathcal{L}_{M,4} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\mu \Phi \right] \times B^{\beta\nu}$$
$$\mathcal{L}_{M,5} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} D^\nu \Phi \right] \times B^{\beta\mu}$$
$$\mathcal{L}_{M,6} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\nu} D^\mu \Phi \right]$$
$$\mathcal{L}_{M,7} = \left[(D_\mu \Phi)^\dagger \hat{W}_{\beta\nu} \hat{W}^{\beta\mu} D^\nu \Phi \right]$$

$$\mathcal{L}_{T,0} = \mathrm{Tr}\left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta} \hat{W}^{\alpha\beta} \right]$$
$$\mathcal{L}_{T,1} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta} \right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu} \right]$$
$$\mathcal{L}_{T,2} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu} \hat{W}^{\nu\alpha} \right]$$
$$\mathcal{L}_{T,5} = \mathrm{Tr}\left[\hat{W}_{\mu\nu} \hat{W}^{\mu\nu} \right] \times B_{\alpha\beta} B^{\alpha\beta}$$
$$\mathcal{L}_{T,6} = \mathrm{Tr}\left[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta} \right] \times B_{\mu\beta} B^{\alpha\nu}$$
$$\mathcal{L}_{T,7} = \mathrm{Tr}\left[\hat{W}_{\alpha\mu} \hat{W}^{\mu\beta} \right] \times B_{\beta\nu} B^{\nu\alpha}$$
$$\mathcal{L}_{T,8} = B_{\mu\nu} B^{\mu\nu} B_{\alpha\beta} B^{\alpha\beta}$$
$$\mathcal{L}_{T,9} = B_{\alpha\mu} B^{\mu\beta} B_{\beta\nu} B^{\nu\alpha}$$

L_M have D6 equivalents (a_0, a_c),
L_T are novel to D8

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{L}_{S,0}, \mathcal{L}_{S,1}$	X	X	X	O	O	O	O	O	O
$\mathcal{L}_{M,0}, \mathcal{L}_{M,1}, \mathcal{L}_{M,6}, \mathcal{L}_{M,7}$	X	X	X	X	X	X	X	O	O
$\mathcal{L}_{M,2}, \mathcal{L}_{M,3}, \mathcal{L}_{M,4}, \mathcal{L}_{M,5}$	O	X	X	X	X	X	X	O	O
$\mathcal{L}_{T,0}, \mathcal{L}_{T,1}, \mathcal{L}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,5}, \mathcal{L}_{T,6}, \mathcal{L}_{T,7}$	O	X	X	X	X	X	X	X	X
$\mathcal{L}_{T,9}, \mathcal{L}_{T,9}$	O	O	X	O	O	X	X	X	X

Non-linear realization (old idea, w/o a light Higgs)

- In the two realizations
  - Linear: all lowest order independent aQGCs are dimension 8
  - Nonlinear: a number of dimensions, QGCs involving γ are dim 6
- Consider $WW\gamma\gamma$, the largest contributing nonlinear terms are
  - Non-linear: limits set on a/Λ^2

$$L_6^0 = -\frac{e^2}{16\Lambda^2} a_0 F^{\mu\nu} F_{\mu\nu} \vec{W}^\alpha \cdot \vec{W}_\alpha$$

$$L_6^c = -\frac{e^2}{16\Lambda^2} a_c F^{\mu\alpha} F_{\mu\beta} \vec{W}^\beta \cdot \vec{W}_\alpha$$

hep-ph/9304240, two-parameter chiral Lagrangian for QGC

  - Equivalent linear terms L_{M0}, ..., L_{M7}, limits set on q/Λ

$$\frac{q_i}{\Lambda^4} = \frac{8a_i}{\Lambda^2 M_W^2}$$

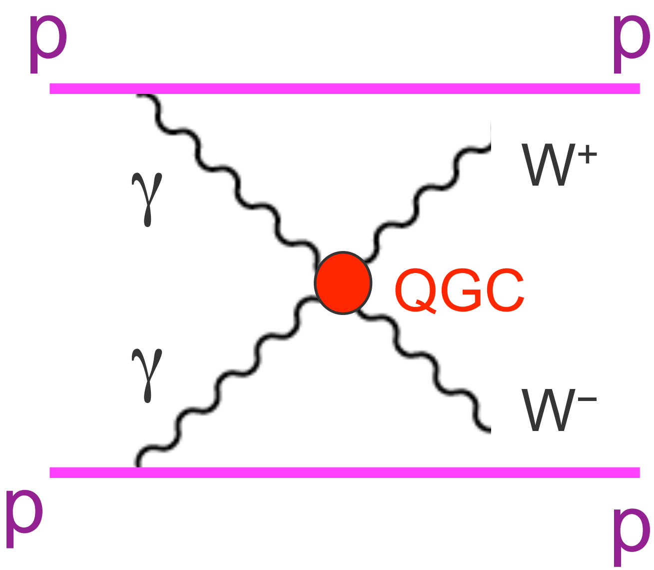
Straightforward conversions

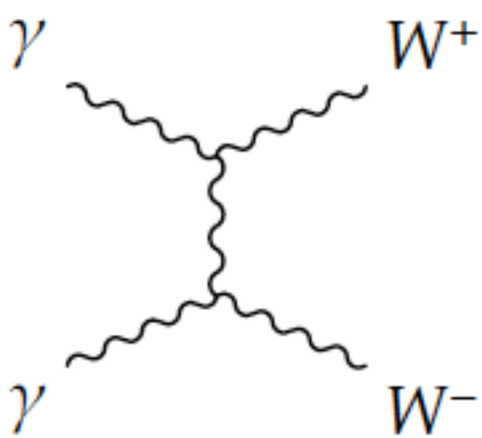
Burden of legacy

- Adopt linear approach for setting aQGC limits
- However, in order to easily compare with the existing results
  - use D6 equivalent for operators that exist in both approaches

Quartic couplings in γγ→WW process

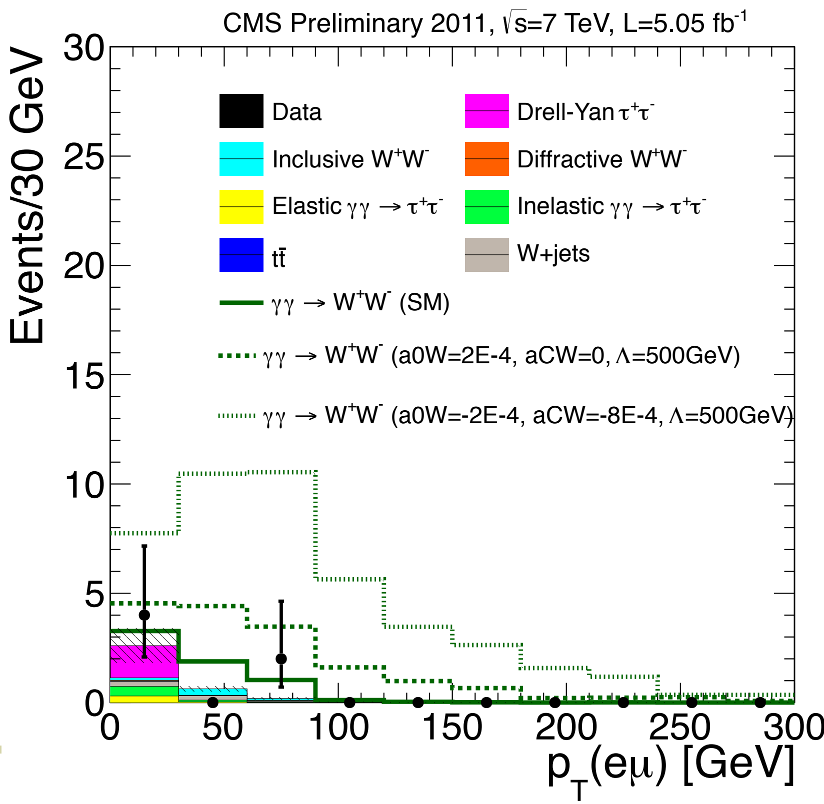
CMS FSQ-12-010





Limits on aQGC without form-factors:

$$-2.80 \times 10^{-6} < a_0^W/\Lambda^2 < 2.80 \times 10^{-6}\ \mathrm{GeV}^{-2}$$
$$-1.02 \times 10^{-5} < a_C^W/\Lambda^2 < 1.02 \times 10^{-5}\ \mathrm{GeV}^{-2}$$



$o(10^2)$ x more constraining than the LEP combined limit

Probing quartic couplings via WVγ production

Leading order diagrams

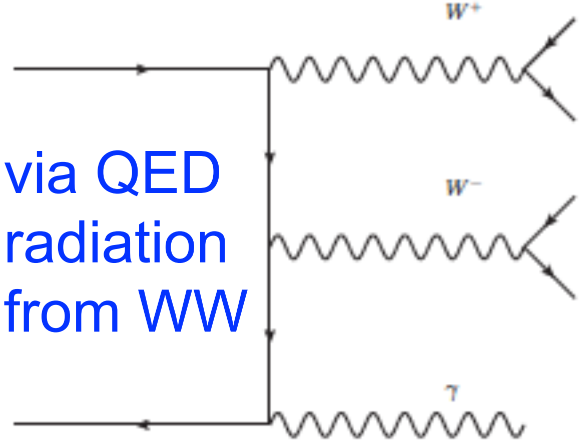
References:

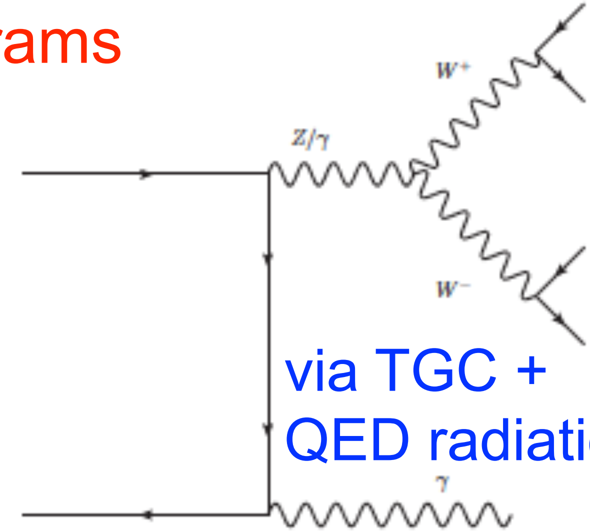
1.) Yang et al, arXiv: 1211.1641

2.) LEP combination, hep-ex/0612034

3.) Bozzi et al, arXiv: 0911.0438

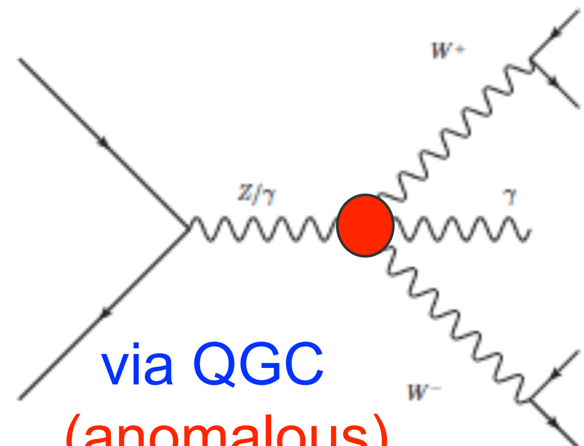
via QED radiation from WW





via TGC + QED radiation

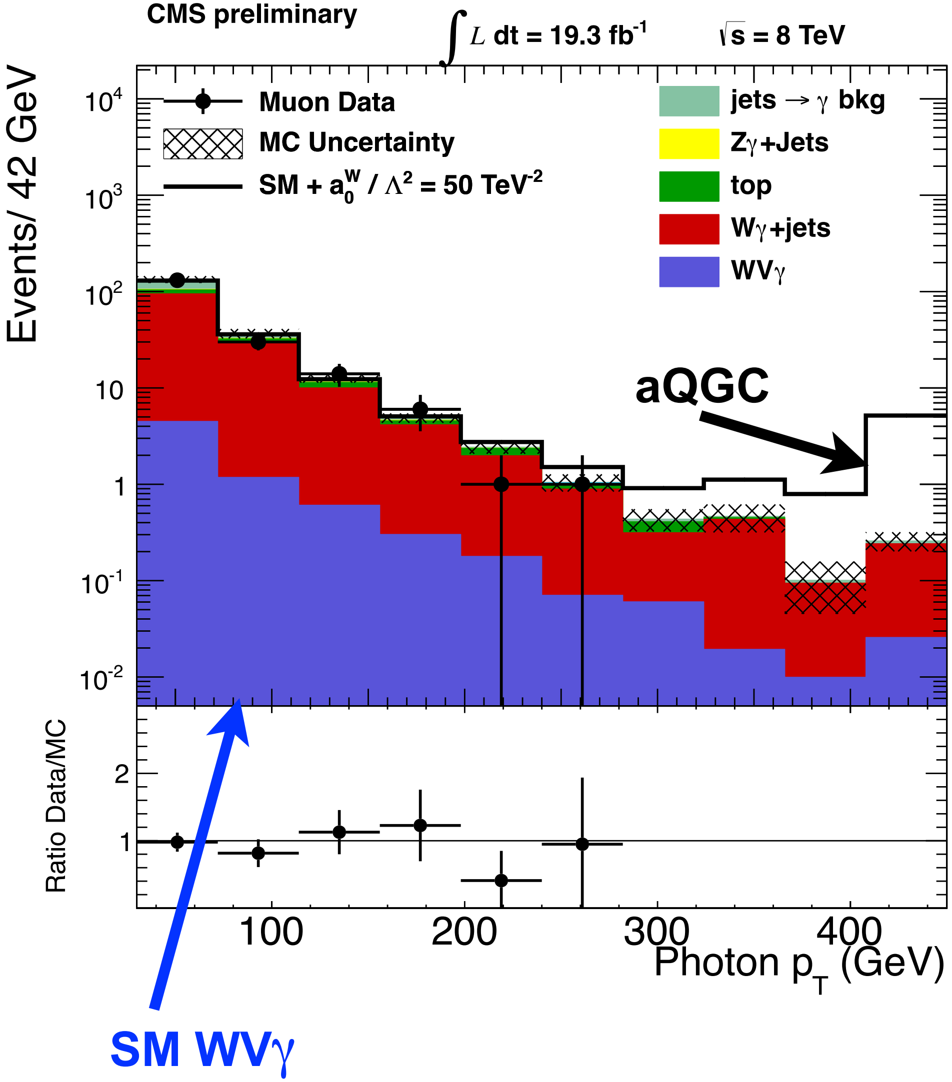
- SM production highly suppressed
  - -By a factor of 10^3 compared to WW
- aQGC at WWγγ and WWγZ vertices <u>can enhance production for high photon p_T events by several factors</u>



via QGC (anomalous)

Cross section for WVγ

CMS SMP-13-007



Not sensitive yet to SM rate.

$\sigma(WV\gamma) < 241$ fb

i.e, $3.4\times\sigma_{SM}$

(for photon E_T threshold 5 GeV)

Set limits on anomalous quartic couplings.

Limits on WWγγ and WWZγ couplings

SMP-13-007

Observed Limits	Expected Limits
$-21\ (\mathrm{TeV}^{-2}) < a_0^W/\Lambda^2 < 20\ (\mathrm{TeV}^{-2})$	$-24\ (\mathrm{TeV}^{-2}) < a_0^W/\Lambda^2 < 23\ (\mathrm{TeV}^{-2})$
$-34\ (\mathrm{TeV}^{-2}) < a_C^W/\Lambda^2 < 32\ (\mathrm{TeV}^{-2})$	$-37\ (\mathrm{TeV}^{-2}) < a_C^W/\Lambda^2 < 34\ (\mathrm{TeV}^{-2})$
$-25\ (\mathrm{TeV}^{-4}) < f_{T,0}/\Lambda^4 < 24\ (\mathrm{TeV}^{-4})$	$-27\ (\mathrm{TeV}^{-4}) < f_{T,0}/\Lambda^4 < 27\ (\mathrm{TeV}^{-4})$
$-12\ (\mathrm{TeV}^{-2}) < \kappa_0^W/\Lambda^2 < 10\ (\mathrm{TeV}^{-2})$	$-12\ (\mathrm{TeV}^{-2}) < \kappa_0^W/\Lambda^2 < 12\ (\mathrm{TeV}^{-2})$
$-18\ (\mathrm{TeV}^{-2}) < \kappa^W/\Lambda^2 < 17\ (\mathrm{TeV}^{-2})$	$-19\ (\mathrm{TeV}^{-2}) < \kappa^W/\Lambda^2 < 18\ (\mathrm{TeV}^{-2})$

Order of magnitude improvement over LEP, but less stringent than $\gamma\gamma \rightarrow WW$. In the dipole units, these limits are probing QGC $\mathcal{O}$(100 %) !!

Observed Limits	Expected Limits
$-77\ (\mathrm{TeV}^{-4}) < f_{M,0}/\Lambda^4 < 81\ (\mathrm{TeV}^{-4})$	$-89\ (\mathrm{TeV}^{-4}) < f_{M,0}/\Lambda^4 < 93\ (\mathrm{TeV}^{-4})$
$-131\ (\mathrm{TeV}^{-4}) < f_{M,1}/\Lambda^4 < 123\ (\mathrm{TeV}^{-4})$	$-143\ (\mathrm{TeV}^{-4}) < f_{M,1}/\Lambda^4 < 131\ (\mathrm{TeV}^{-4})$
$-39\ (\mathrm{TeV}^{-4}) < f_{M,2}/\Lambda^4 < 40\ (\mathrm{TeV}^{-4})$	$-44\ (\mathrm{TeV}^{-4}) < f_{M,2}/\Lambda^4 < 46\ (\mathrm{TeV}^{-4})$
$-66\ (\mathrm{TeV}^{-4}) < f_{M,3}/\Lambda^4 < 62\ (\mathrm{TeV}^{-4})$	$-71\ (\mathrm{TeV}^{-4}) < f_{M,3}/\Lambda^4 < 66\ (\mathrm{TeV}^{-4})$

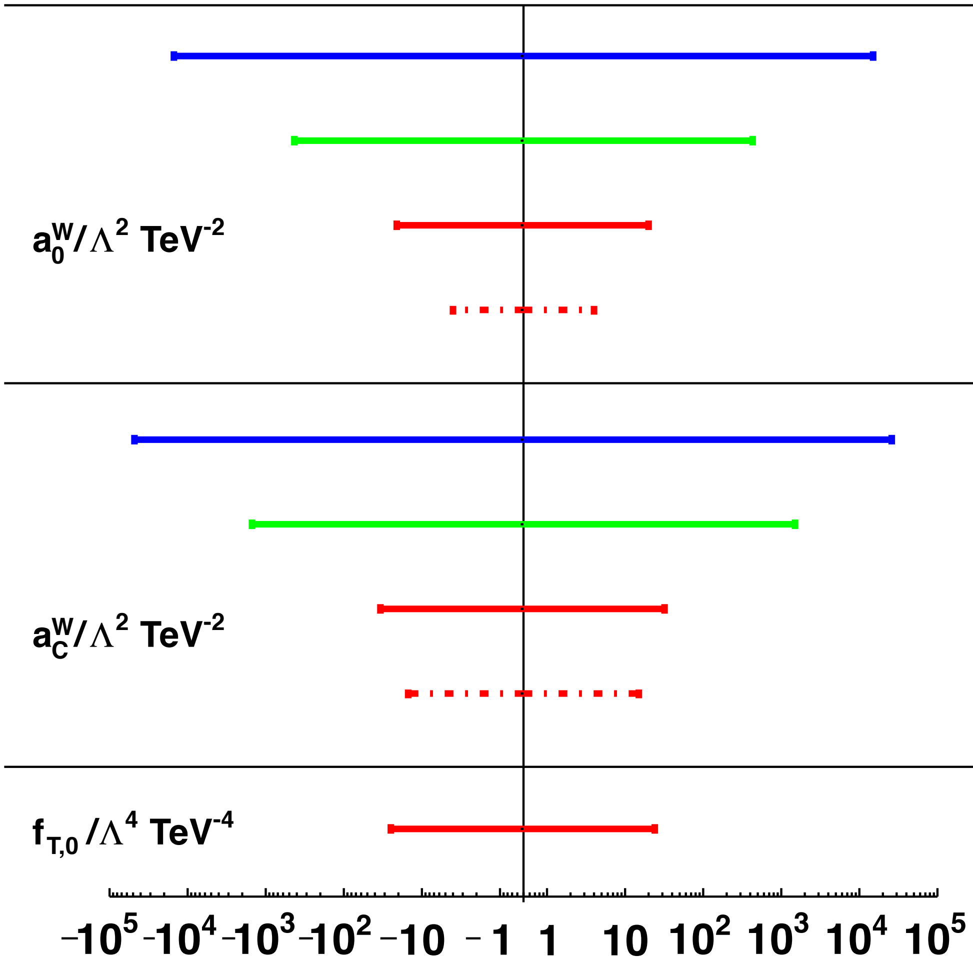
The first ever limit on WWZγ couplings κ_0^W and κ_C^W. The first limit on dim 8 parameters f_M.

Many studies of QGC done: now some complete analysis!

July 2013

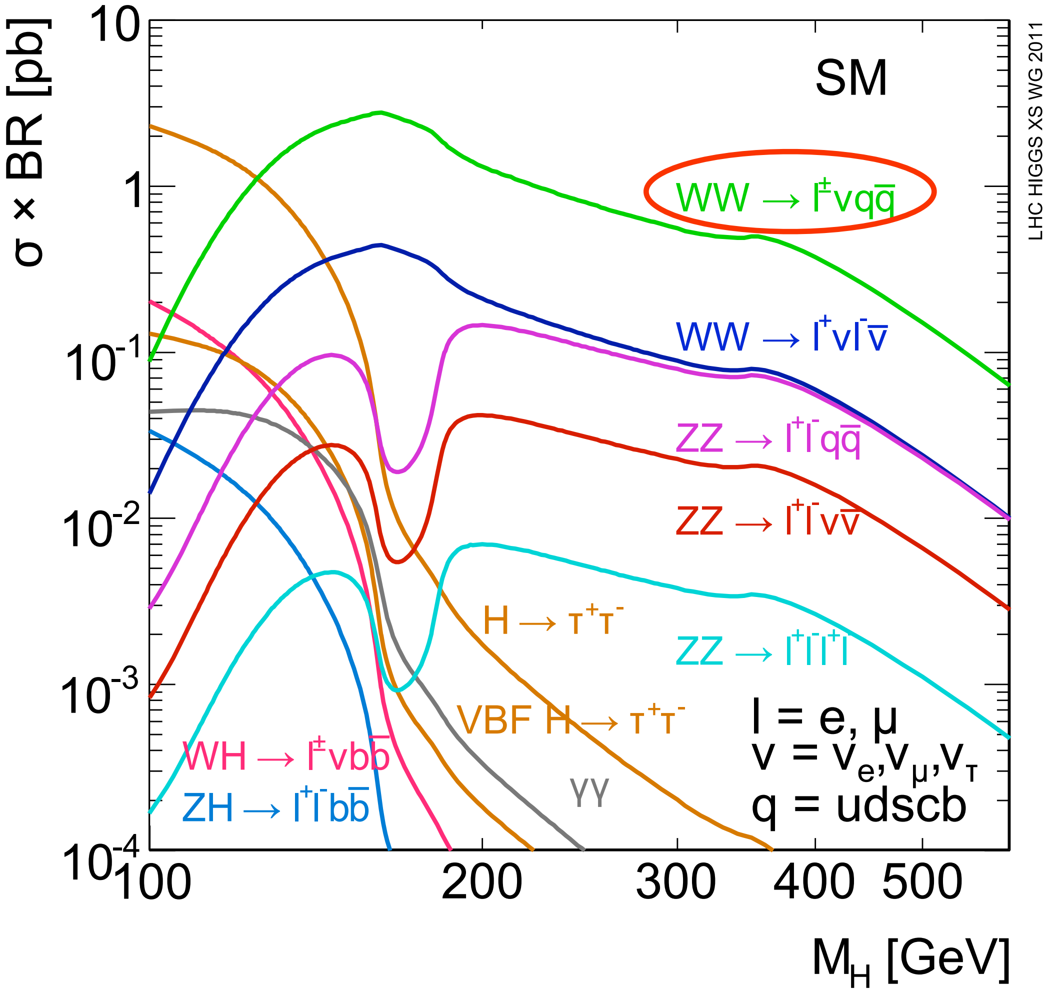
LEP L3 limits (blue) | CMS $WW\gamma$ limits (red solid)

D0 limits (green) | CMS $\gamma\gamma \to WW$ limits (red dash-dot)



Anomalous $WW\gamma\gamma$ Quartic Coupling limits @95% C.L.	Channel	Limits	L	$\sqrt{s}$
a_0^W/Λ^2 TeV^{-2}	$WW\gamma$	[- 15000, 15000]	0.43fb^{-1}	0.20 TeV
	$\gamma\gamma \to WW$	[- 430, 430]	9.70fb^{-1}	1.96 TeV
	$WW\gamma$	[- 21, 20]	19.30fb^{-1}	8.0 TeV
	$\gamma\gamma \to WW$	[- 4, 4]	5.05fb^{-1}	7.0 TeV
a_C^W/Λ^2 TeV^{-2}	$WW\gamma$	[- 48000, 26000]	0.43fb^{-1}	0.20 TeV
	$\gamma\gamma \to WW$	[- 1500, 1500]	9.70fb^{-1}	1.96 TeV
	$WW\gamma$	[- 34, 32]	19.30fb^{-1}	8.0 TeV
	$\gamma\gamma \to WW$	[- 15, 15]	5.05fb^{-1}	7.0 TeV
$f_{T,0}/\Lambda^4$ TeV^{-4}	$WW\gamma$	[- 25, 24]	19.30fb^{-1}	8.0 TeV

Can also search for any high mass Higgs state

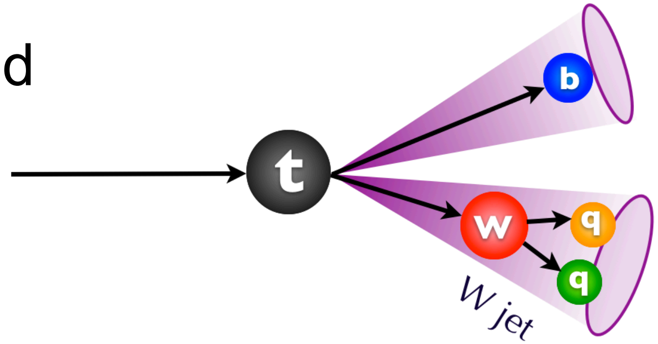


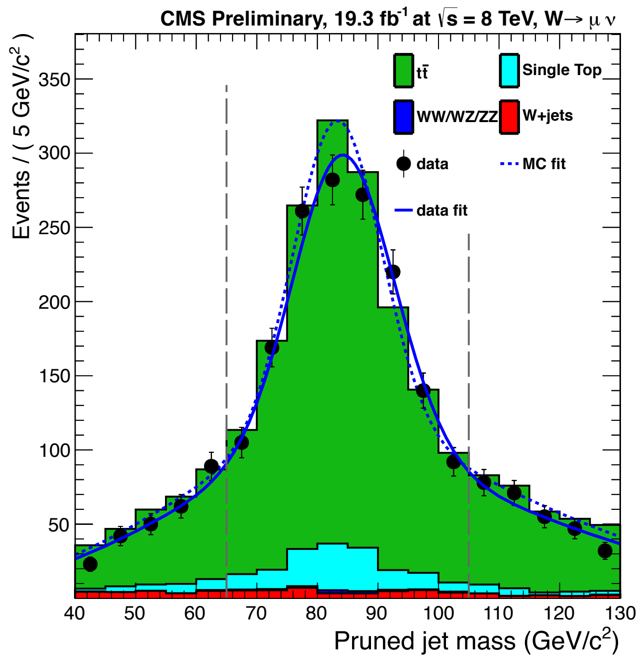
- H→WW→ℓvjj has the largest BR × σ over most of the mass range
  - Using W mass constraint, the decay is sufficiently reconstructed to produce a mass peak
- Principal drawback is the large W+jets background
  - Employ data-driven techniques to understand and control this process.

Phenomena of merged jet from boosted W

Example: boosted $t\bar{t}$ events

- W jets can be identified using jet and subjet properties:
  - Jet mass = W mass
  - Two subjets
  - Subjet mass << jet mass
  - Both subjets should have similar momentum



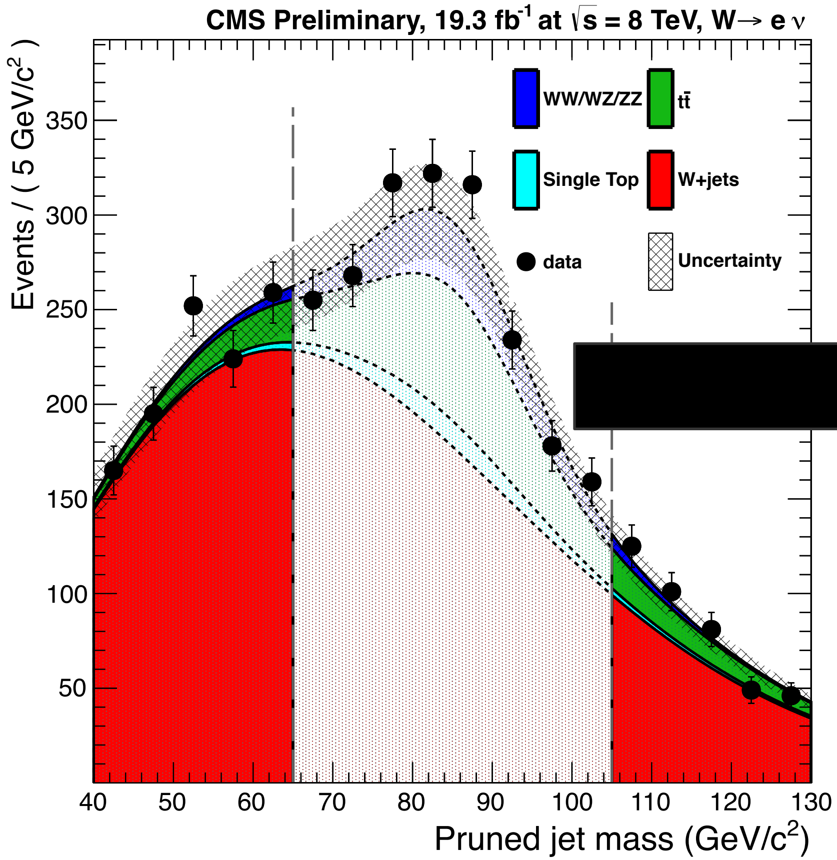


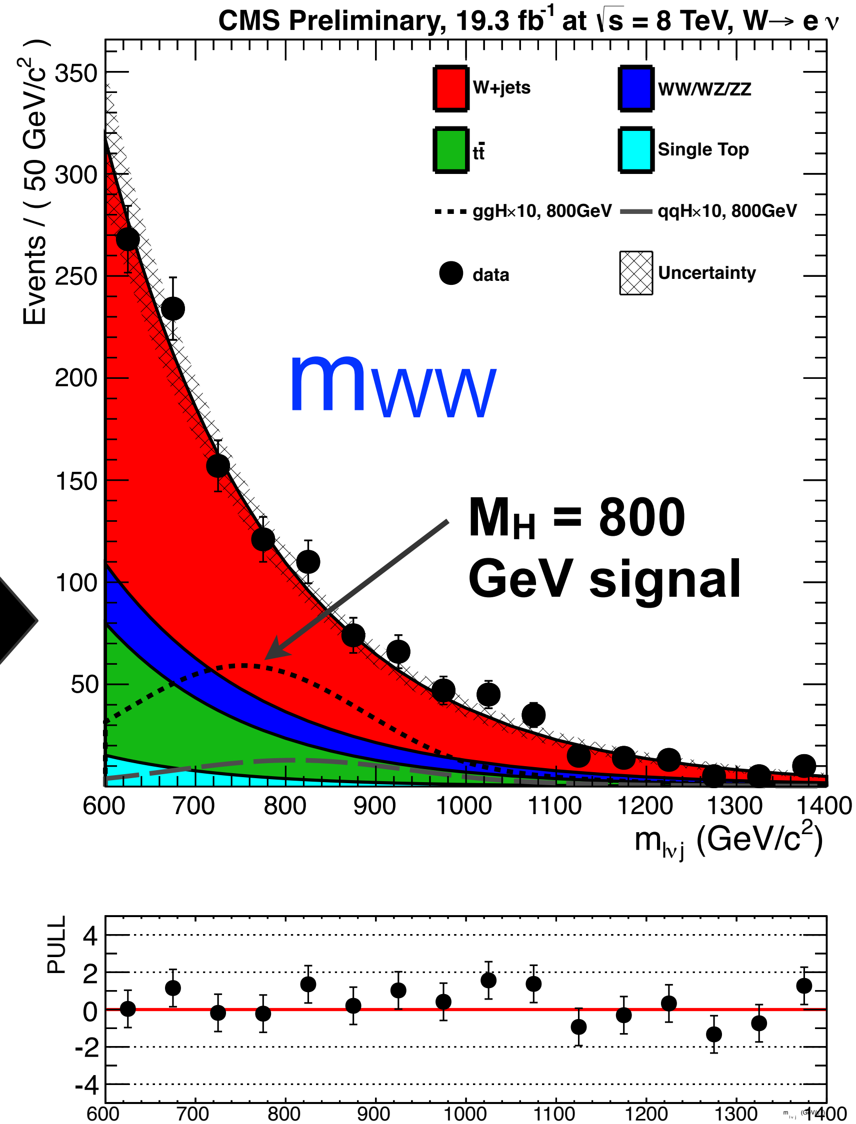
Pure sample of hadronic W decaying to a single jet (Cambridge-Aachen, R=0.8) in $t\bar{t}$ (→ ℓ+MET + fat-jet + 2b-jets) events

Now probe WW mass spectrum

CMS HIG-13-008

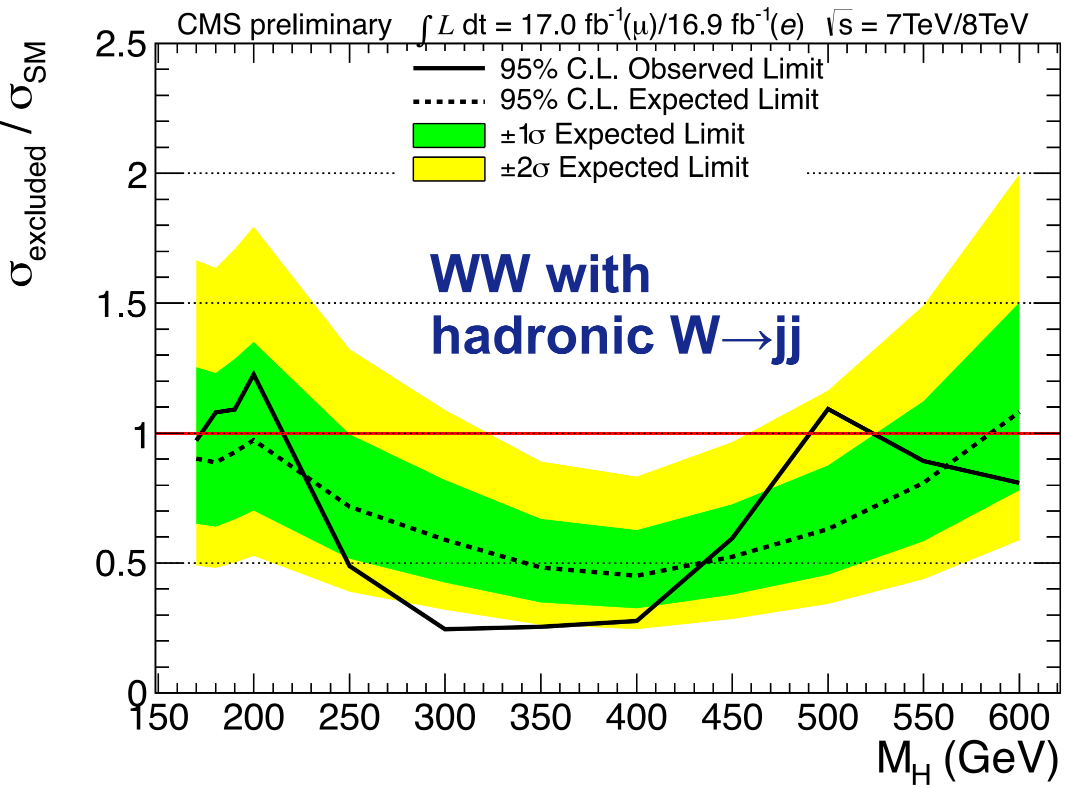
m_W



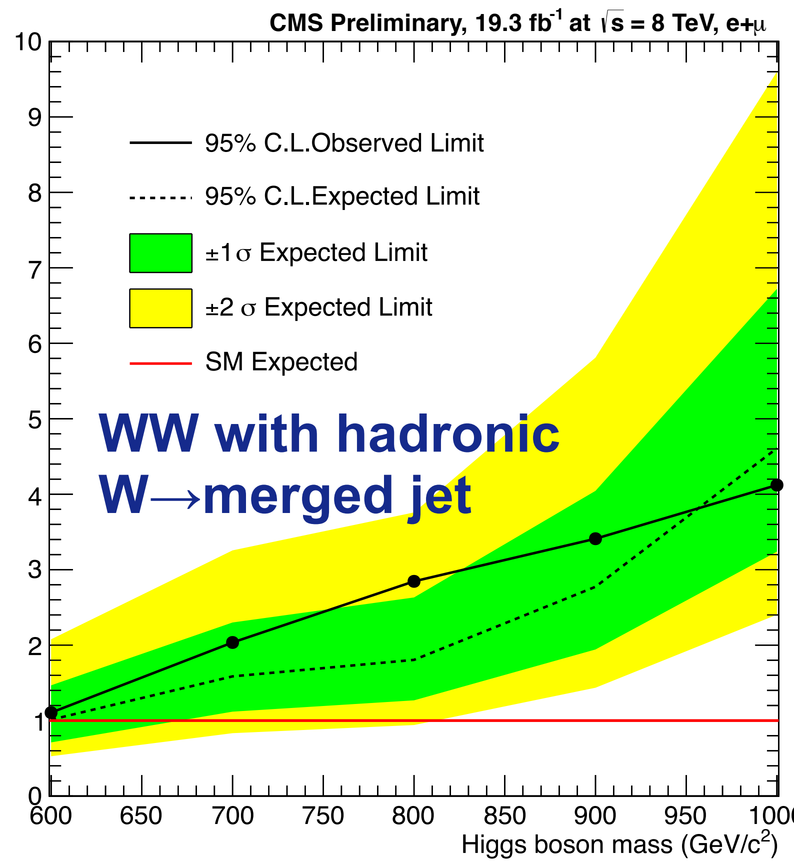


Limits on higher mass Higgs states

CMS HIG-12-046



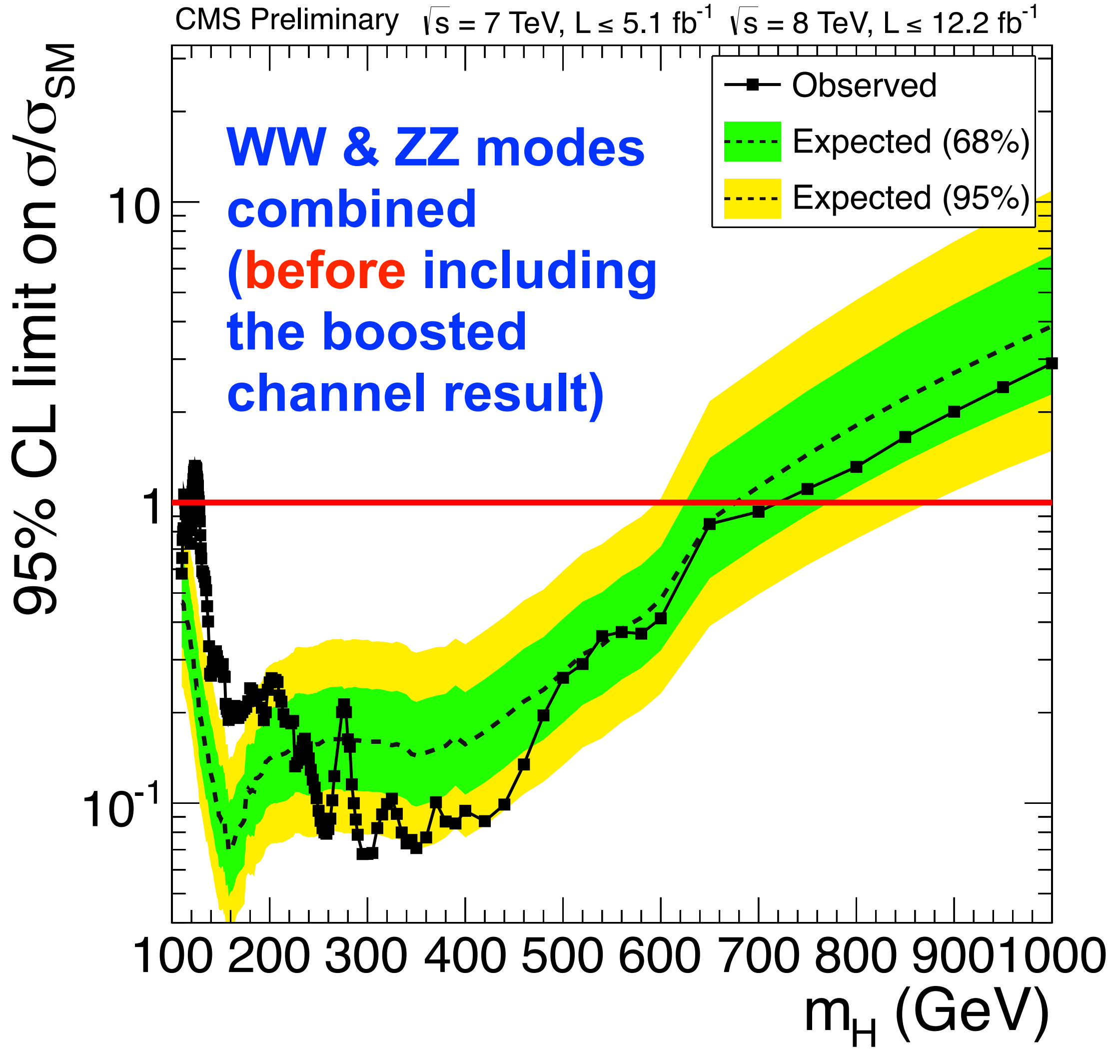
Reconstruct hadronic W from two resolved jets for m_H < 600 GeV, as a merged jet for m_H > 600 GeV



Find no new states up to 600 GeV.
Interesting territory above 600 GeV.

Combining with other channels

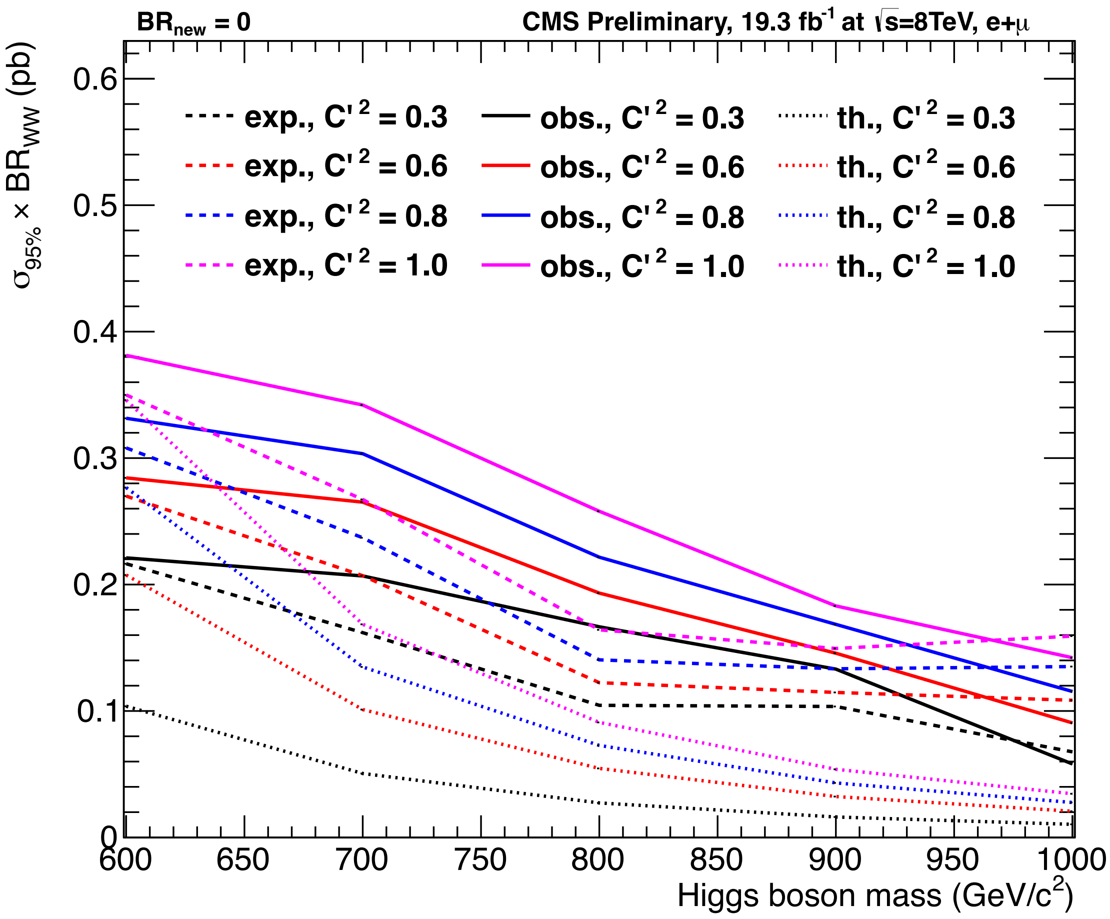
CMS HIG-12-045



- No heavy Higgs (or VV resonance) up to 800 GeV
- The idea of an SM-like Higgs gets fuzzy at high mass b/c the width ~ m_H
  - -So, also present the result in terms of a narrow particle with modified couplings

BSM interpretation

CMS HIG-13-008



In the BSM interpretation, search for an electroweak singlet scalar, where a heavy Higgs boson mixes with H(126)

$$C^2 + C'^2 = 1$$

The heavy Higgs cross cross-section and width are modified as

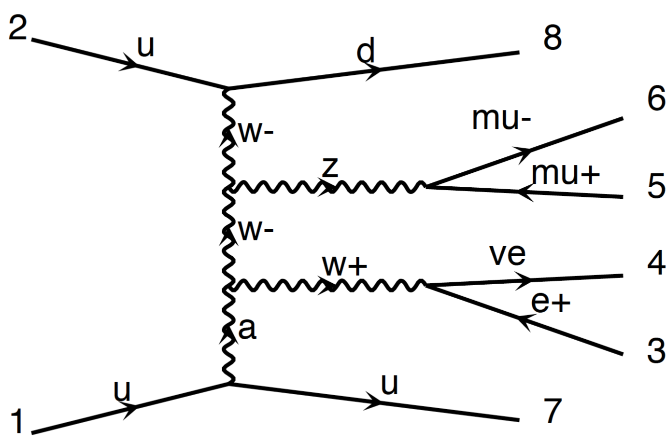
$$\mu' = C'^2(1 - \mathcal{BR}_{\text{new}})$$

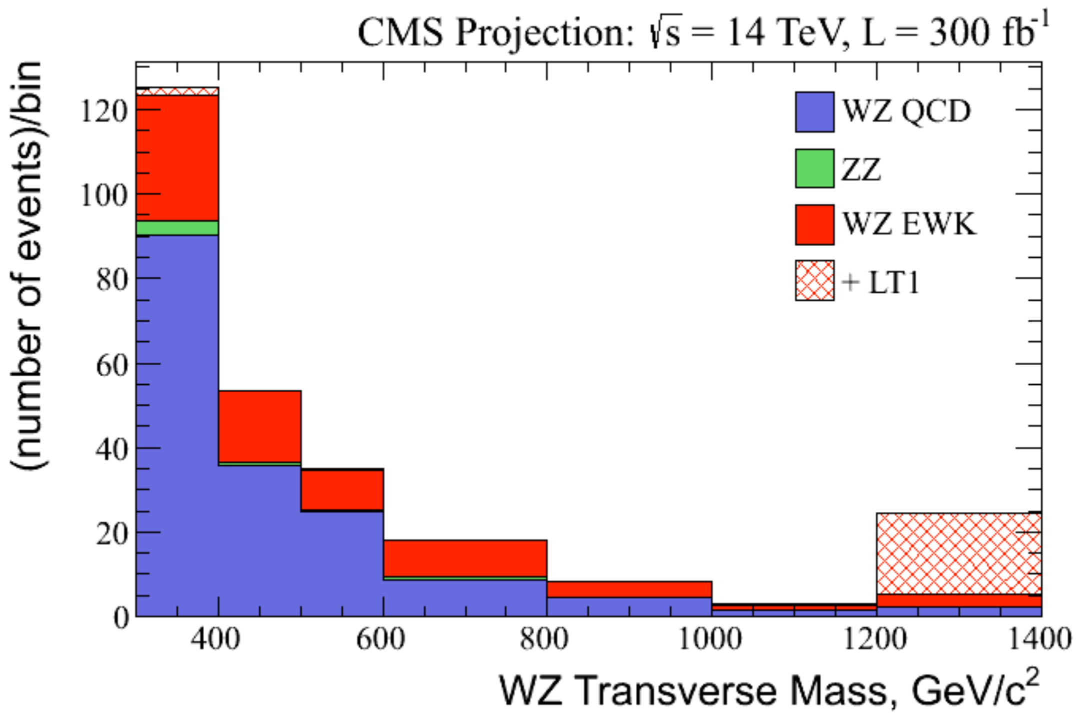
$$\Gamma' = \Gamma_{\text{SM}} \times \frac{C'^2}{(1 - \mathcal{BR}_{\text{new}})}$$

Some projections for VV scattering

CMS FTR-13-006

Projections done for WZ (all leptonic) scattering at 14 TeV





Significance	3σ	5σ
SM EWK scattering discovery	75 fb^{-1}	185 fb^{-1}
f_{T1}/Λ^4 at 300 fb^{-1} f_{T1}/Λ^4 at 3000 fb^{-1}	0.8 TeV^{-4} 0.45 TeV^{-4}	1.0 TeV^{-4} 0.55 TeV^{-4}

Summary

It has been just a year since a new boson was discovered. Thanks to the outstanding performance of the LHC, we now know a great deal more about the nature of this Higgs boson.

☑ WV events continue to play important roles in the study of electroweak symmetry breaking

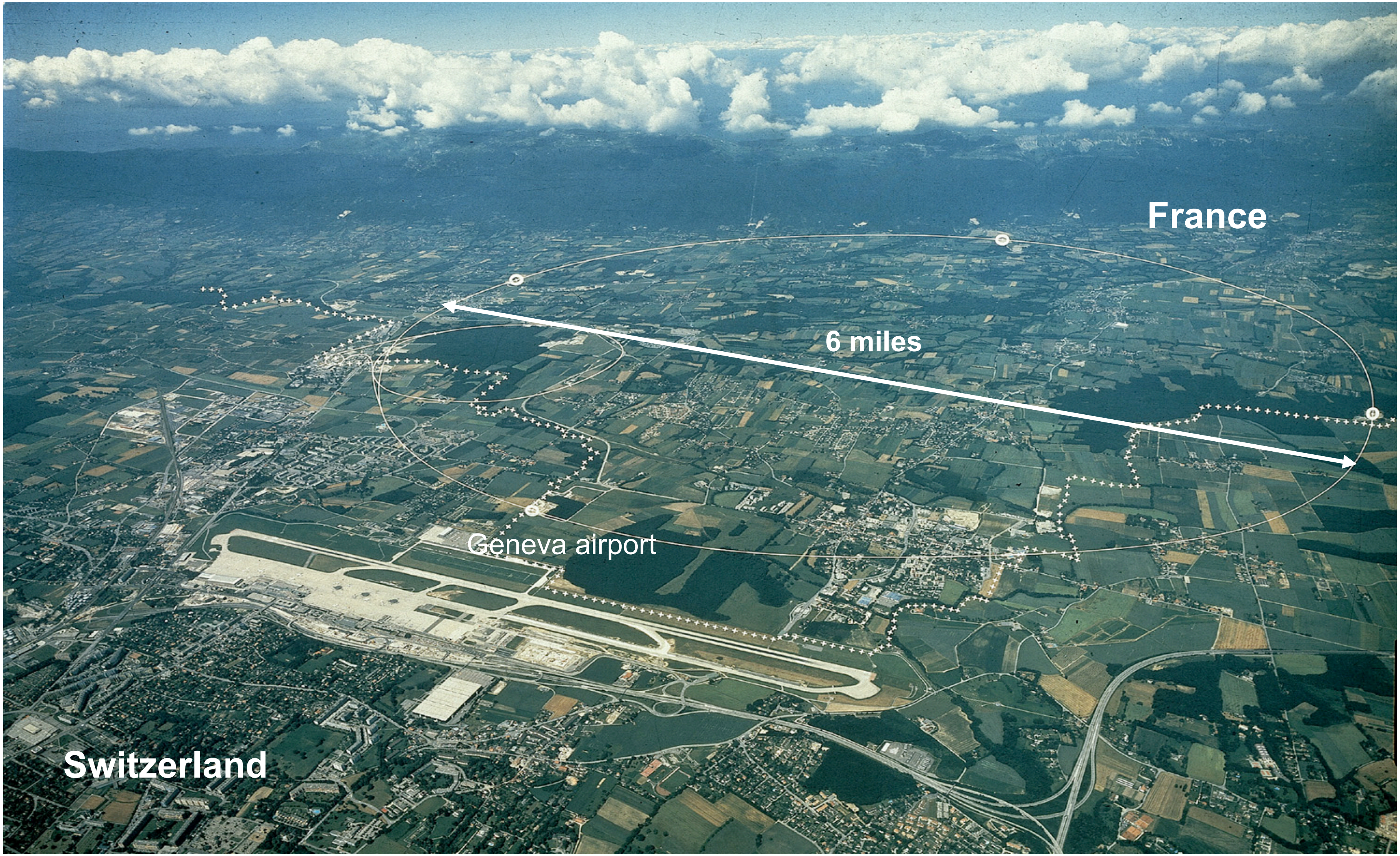
- Probe high mass Higgs states,VV resonances
- Sensitive to New Physics @TeV scale

☑ Constrain gauge and Higgs boson couplings

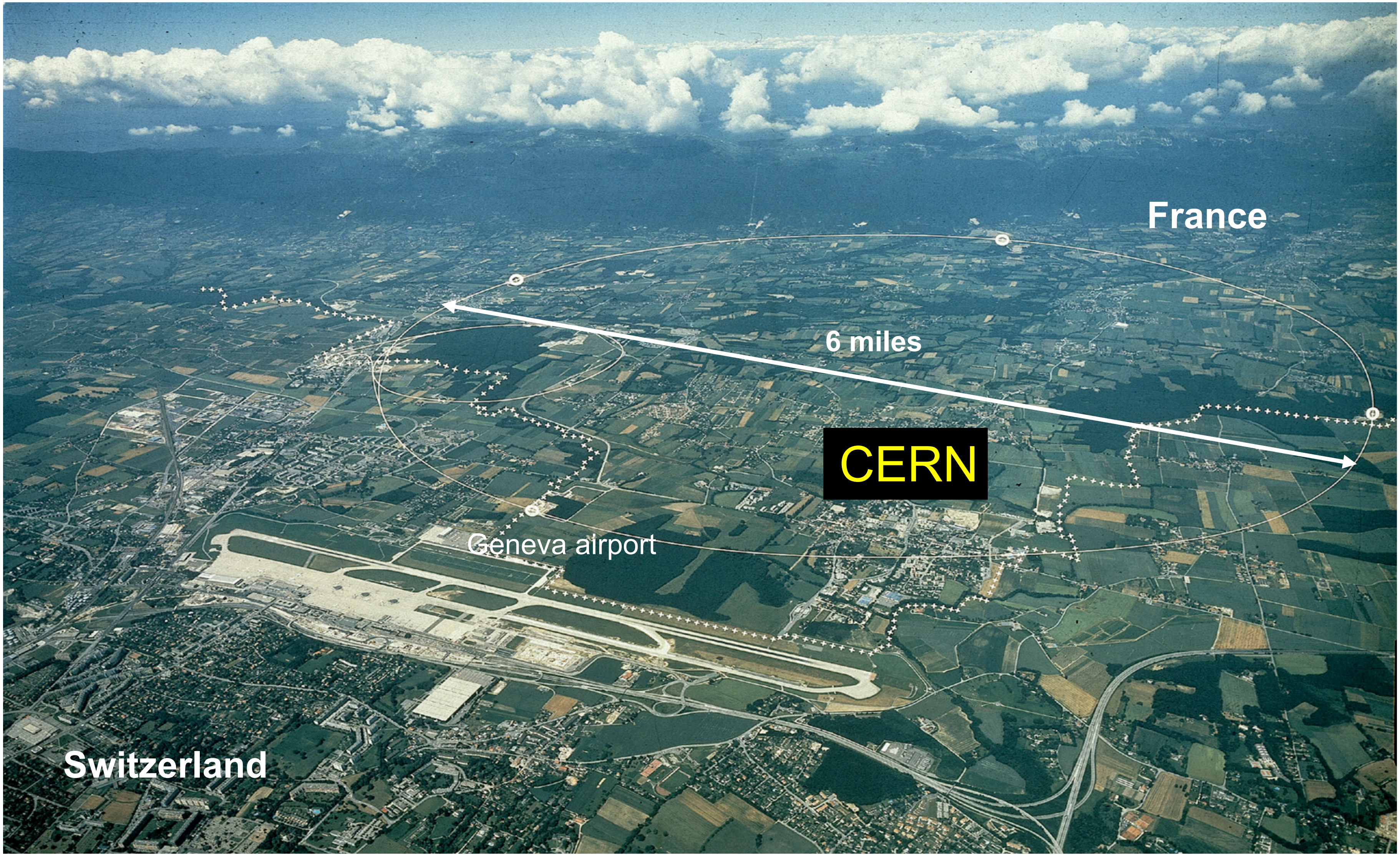
- Trilinear gauge couplings @ few % level
- The first $\gamma\gamma \rightarrow WW$ and VVV results on quartic couplings

BACKUP SLIDES

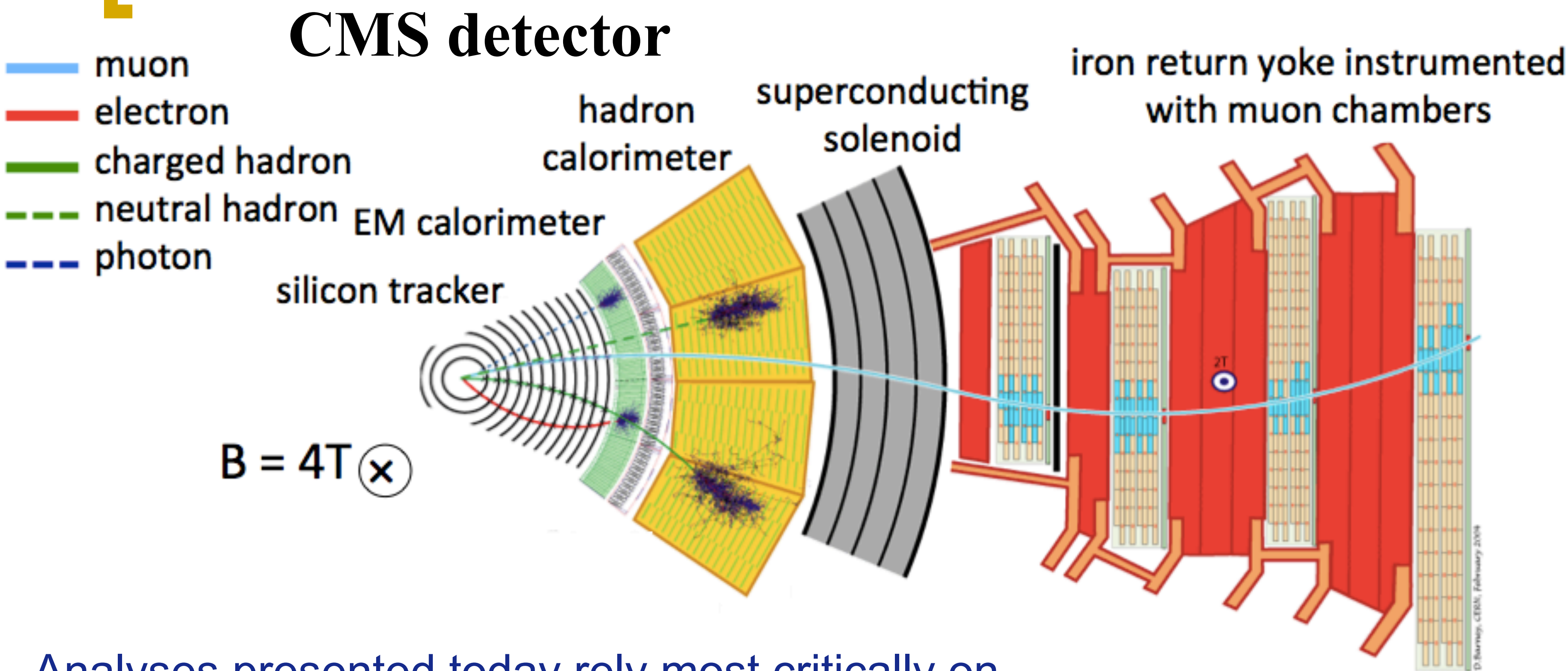
Where to find Higgs: LHC at CERN



Where to find Higgs: LHC at CERN



Instrument to detect Higgs decay chain



Analyses presented today rely most critically on

- **electrons**: tracks matched to clusters in EM calorimeter
- **muons**: minimum ionizing tracks, penetrate deep into muon system
- **jets / H_T**: constructed with combined tracking + calo info
- **MET**: constructed with combined tracking + calo info, hermetic detector

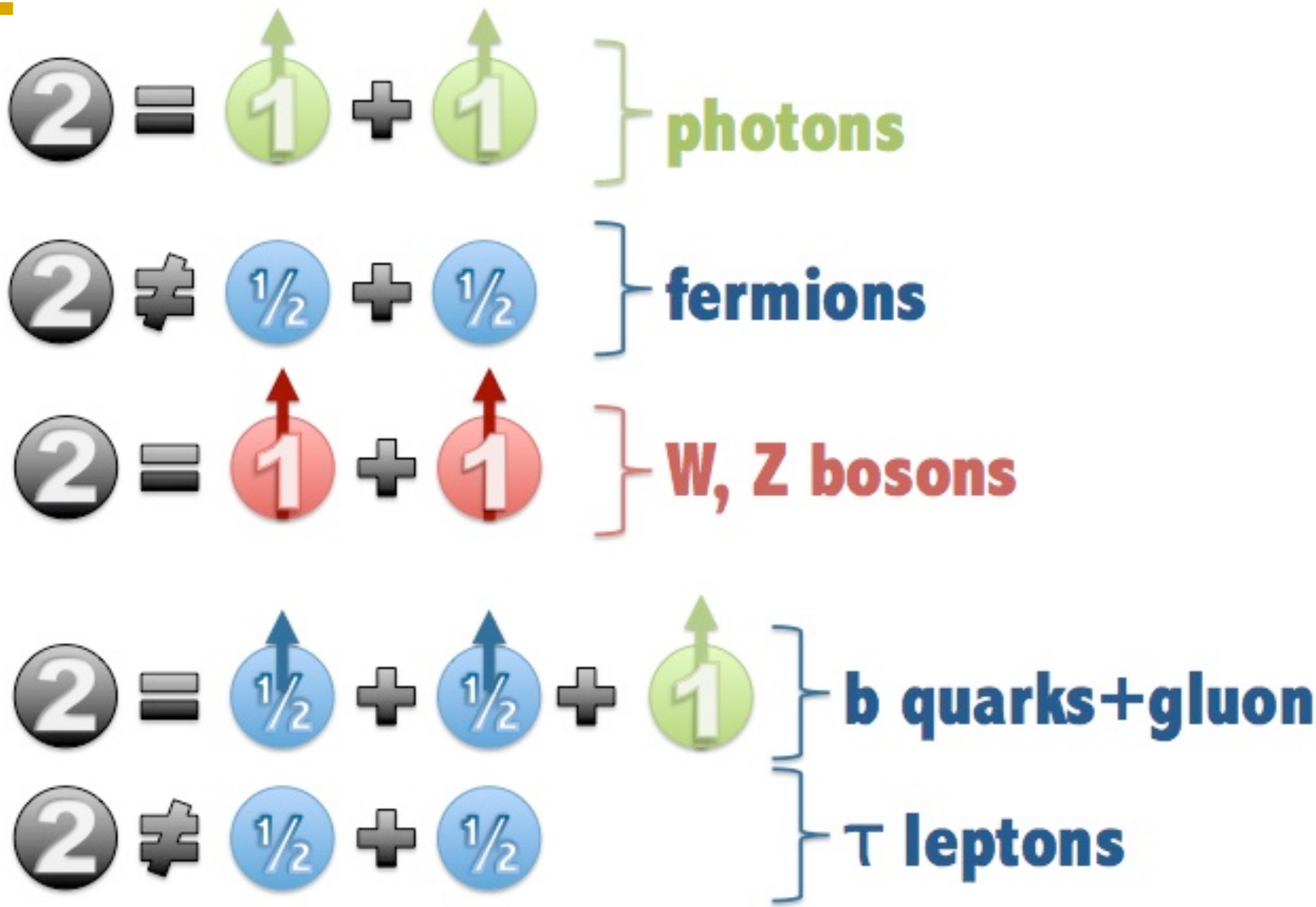
Higgs boson observation in a nutshell

For a mass of $m_H = 125.7 \pm 0.4$ GeV

Decay	Expected	Observed	
ZZ	7.1 σ	6.7 σ	
γγ	3.9 σ	3.2 σ	bosons
WW	5.3 σ	3.9 σ	
bb	2.2 σ	2.1 σ	3.4 σ combined!
ττ	2.6 σ	2.8 σ	fermions

bb: includes VH and VBF, WW: includes ggF, VH, VBF

Side note: why spin-2 can decay to bb but not $\tau\tau$

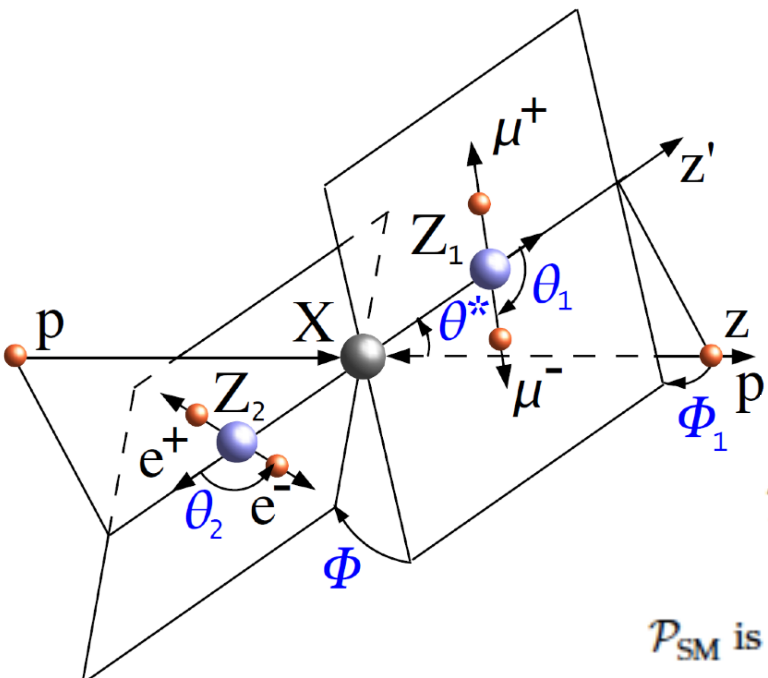


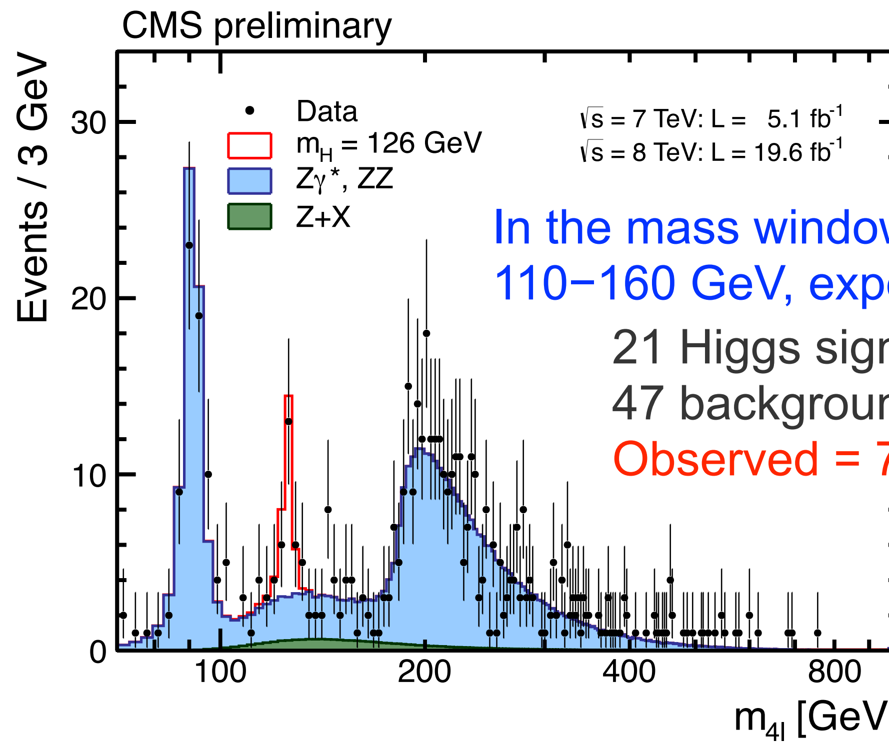
Enough events to measure spin-parity

CMS HIG-13-002

In H→ZZ* full final state reconstruction sensitive to J^P

- 2 masses (M_{Z1}, M_{Z2}), 5 angles
- Form a matrix-element based discriminant





In the mass window 110−160 GeV, expect

21 Higgs signal

47 background

Observed = 71

$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}_{\rm SM}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

$\mathcal{P}_{\rm SM}$ is the probability distribution for the SM Higgs boson hypothesis,

$\mathcal{P}_{J^P}$ is the probability distribution for an alternative model.

Interesting Q: how much CP odd allowed by data?

Measure fraction of CP-violating contribution

Most general spin-0 H → VV amplitude

$$A = v^{-1}\left(a_1 m_Z^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

$$= A_1 + A_2 + A_3$$

At LO, SM $a1 = 1$, $a2 = a3 = 0$

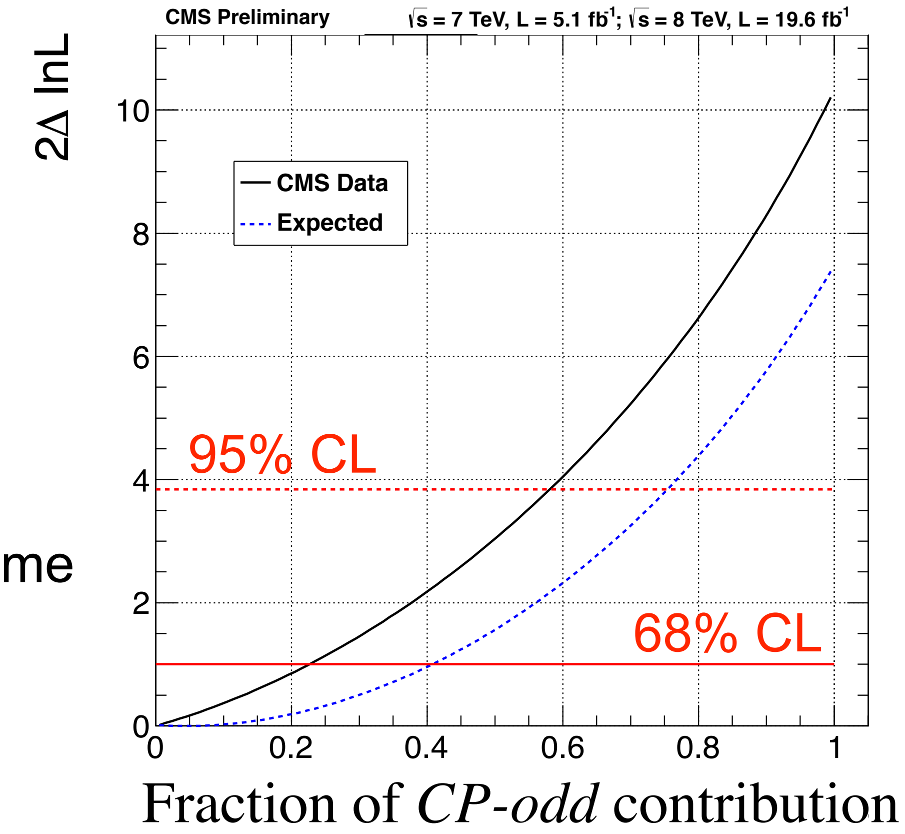
A3 : CP odd amplitude

Fit for $f_{a3} = |A_3|^2 / |A_1|^2 + |A_3|^2$

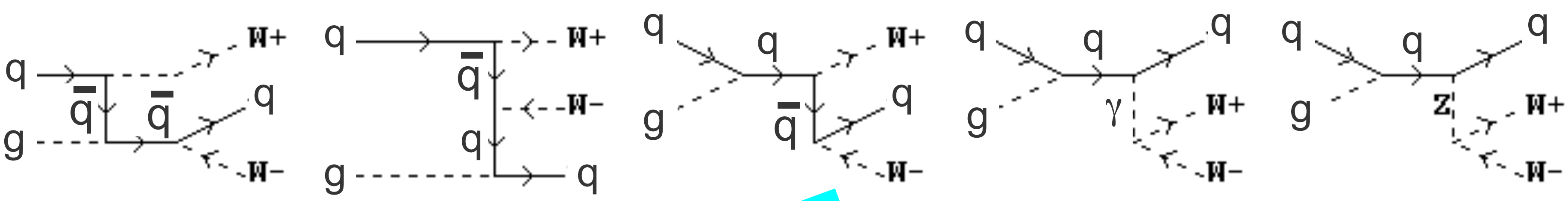
- check presence of CP violation (assume a_2=0, interference term negligible)

$f_{a3} = 0.00^{+0.23}_{-0.00}$

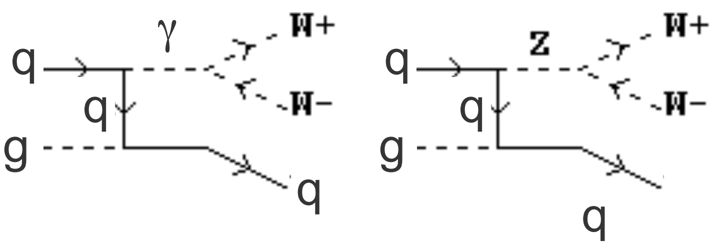
f_{a3} <0.58 @95%CL



Large NLO & radiative corrections (≳50% of LO)

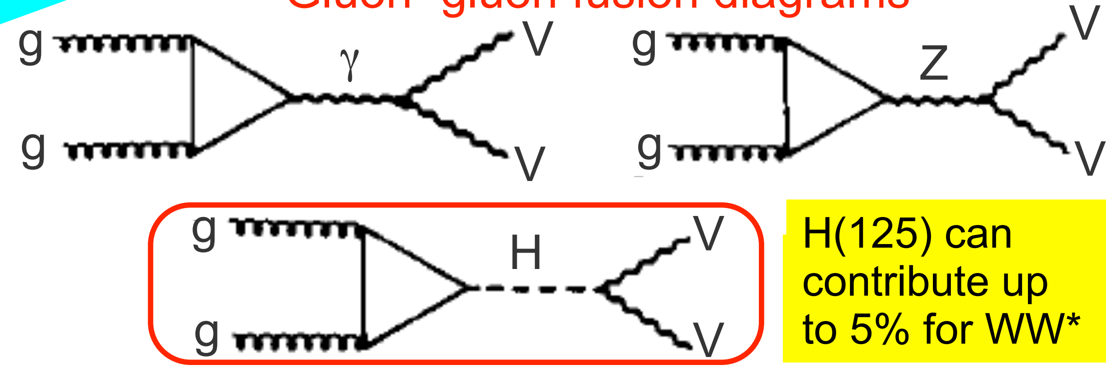


Quark−gluon diagrams



~6% gg contribution

Gluon−gluon fusion diagrams



H(125) can contribute up to 5% for WW*

Box diagrams

Plus VBF, MPI, ... diagrams

Some representative diagrams @NLO

Born

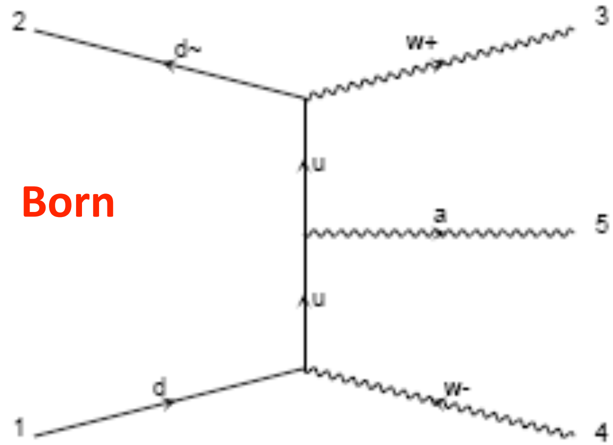
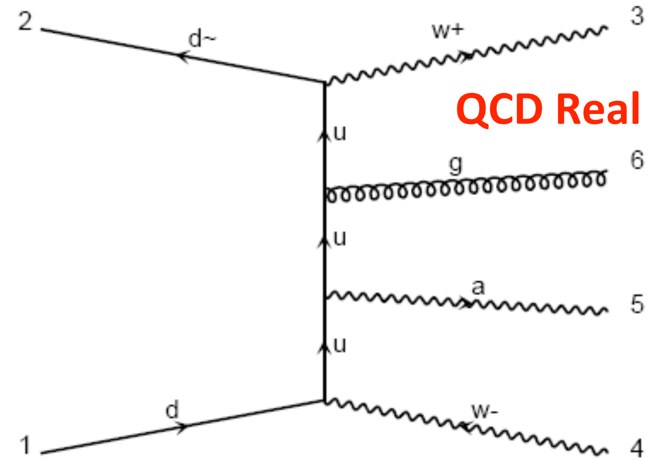


diagram 7 QCD=0, QED=3

QCD Real emission



real diagram 1 QCD=1, QED=3

One-loop QCD

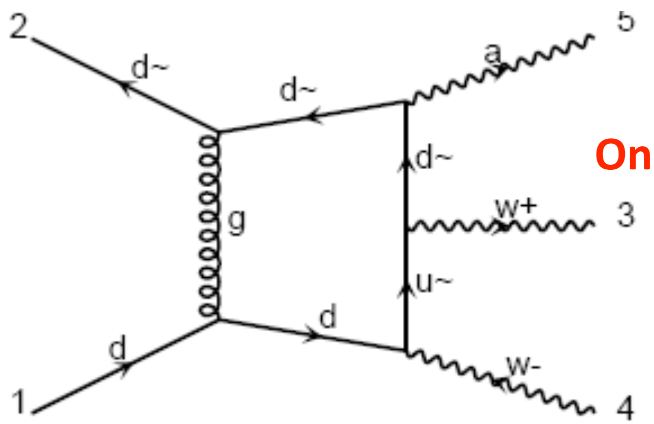


diagram 38 QCD=2, QED=3

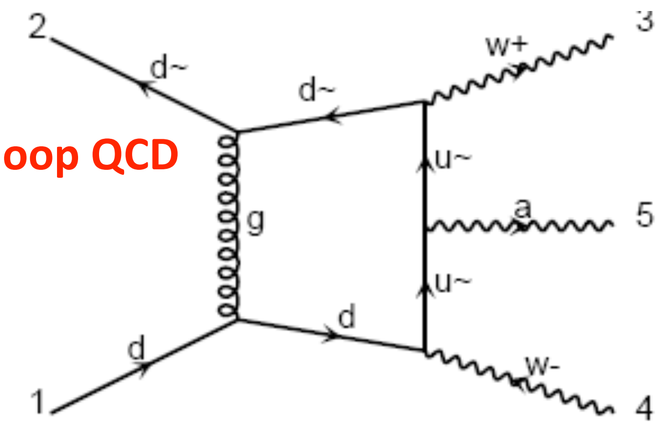
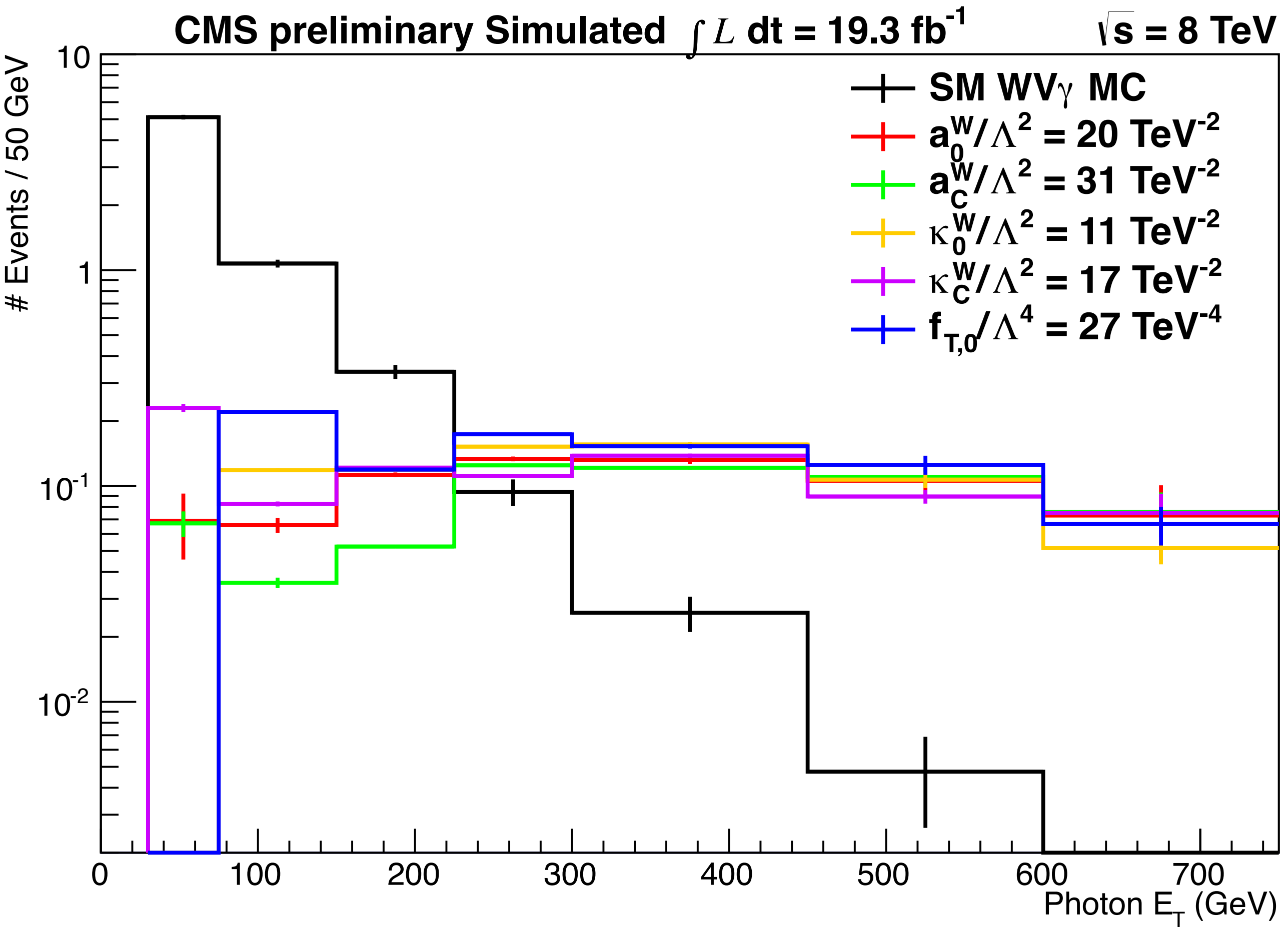


diagram 39 QCD=2, QED=3

Cross section for WVγ

CMS SMP-13-007



$\sigma(WV\gamma)$ < 241 fb, 3.4x σ_{SM}

Not sensitive yet to SM rate. Set limits on anomalous quartic couplings.

Triggers

✦All analyses shown here use single or di-lepton triggers

✦ Typical single lepton triggers require
- one isolated lepton
- threshold: 24 GeV for muon, 27 GeV for electron
- MET > 20 GeV in case of electron

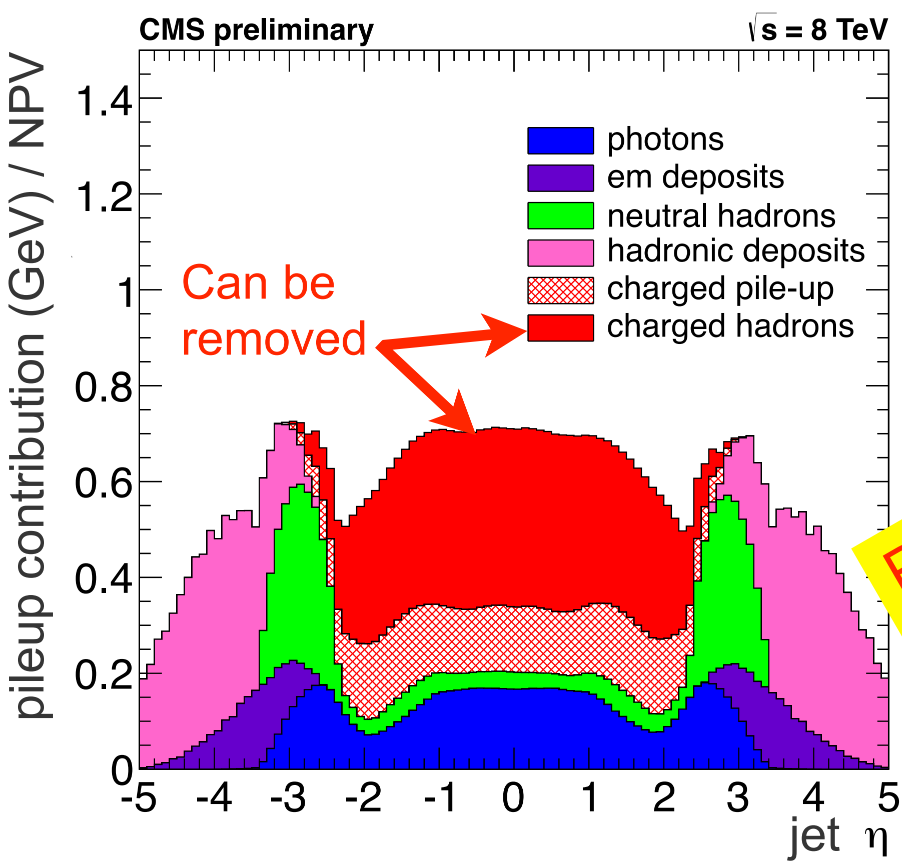
✦Typical dilepton triggers require
- two leptons, at least one isolated
- each with threshold that varies between 5−20 GeV

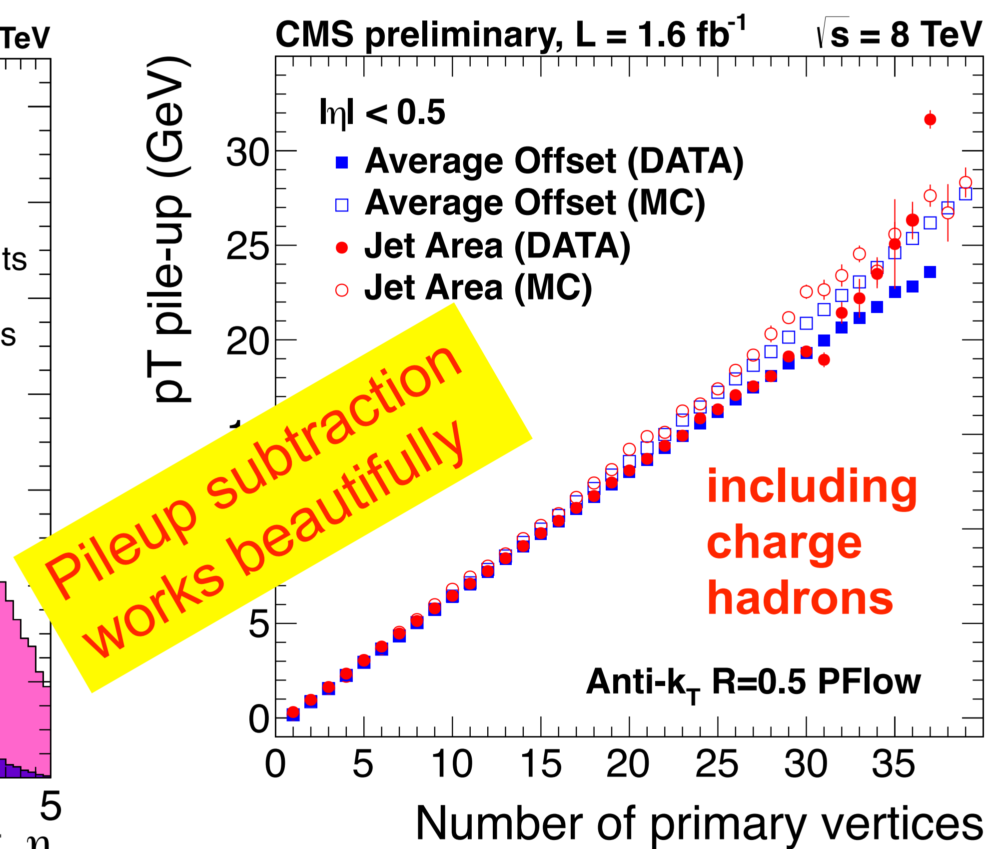
✦Offline analysis-level thresholds are higher than that in trigger. Simulation is corrected for trigger & selection efficiency.

Dealing with pileup: subtract its contribution

✦Pileup affects jet energy, MET, and lepton isolation

- Example: pileup contribution to jet p_T per primary vertex.
- Measure in data using several methods. Get consistent results.

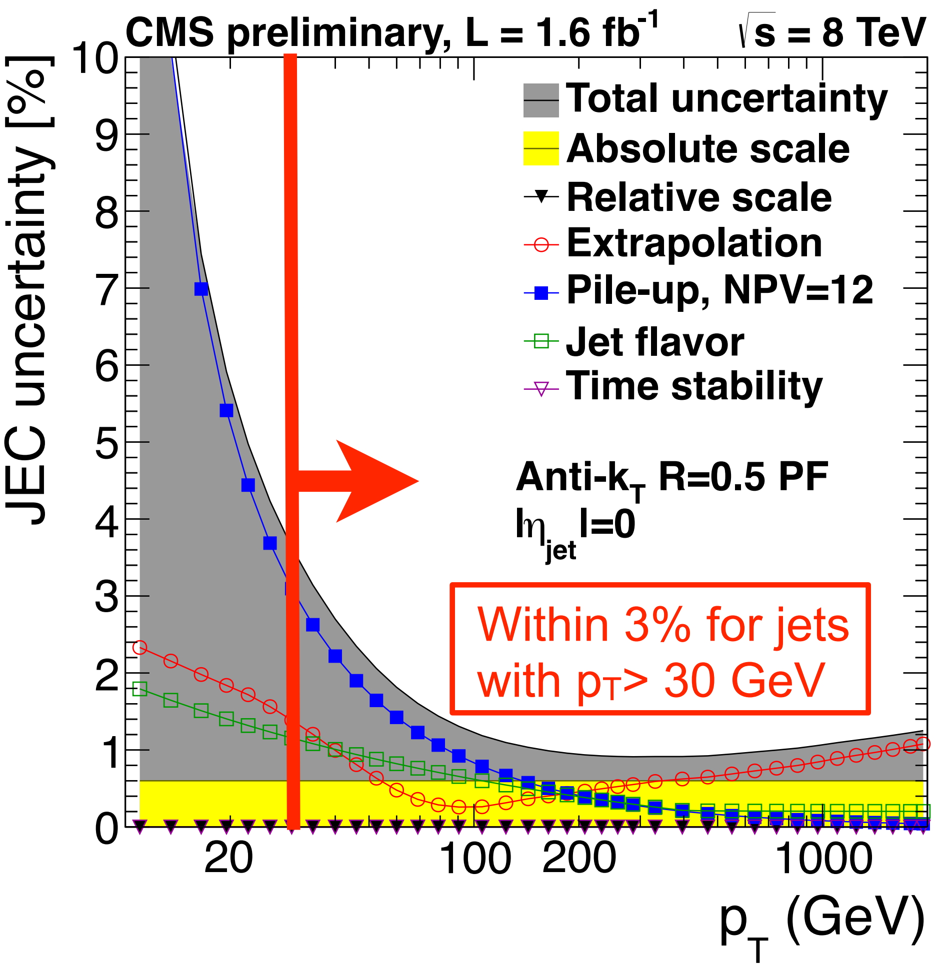


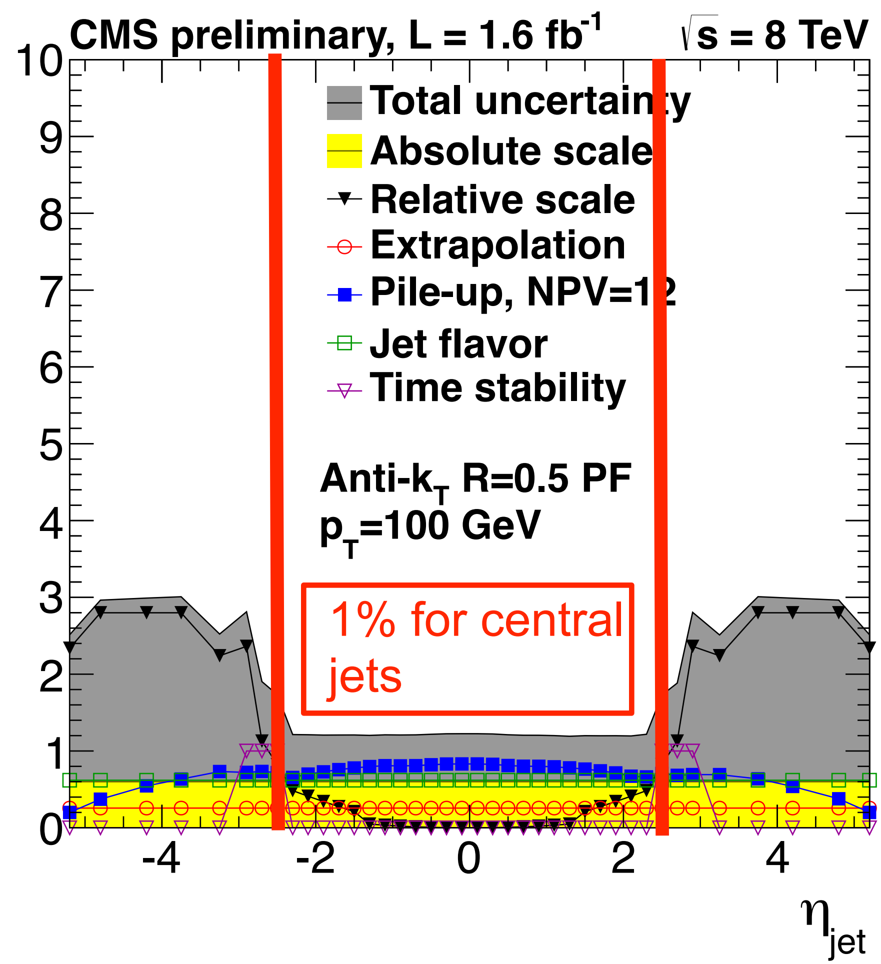


Good understanding of detector performance

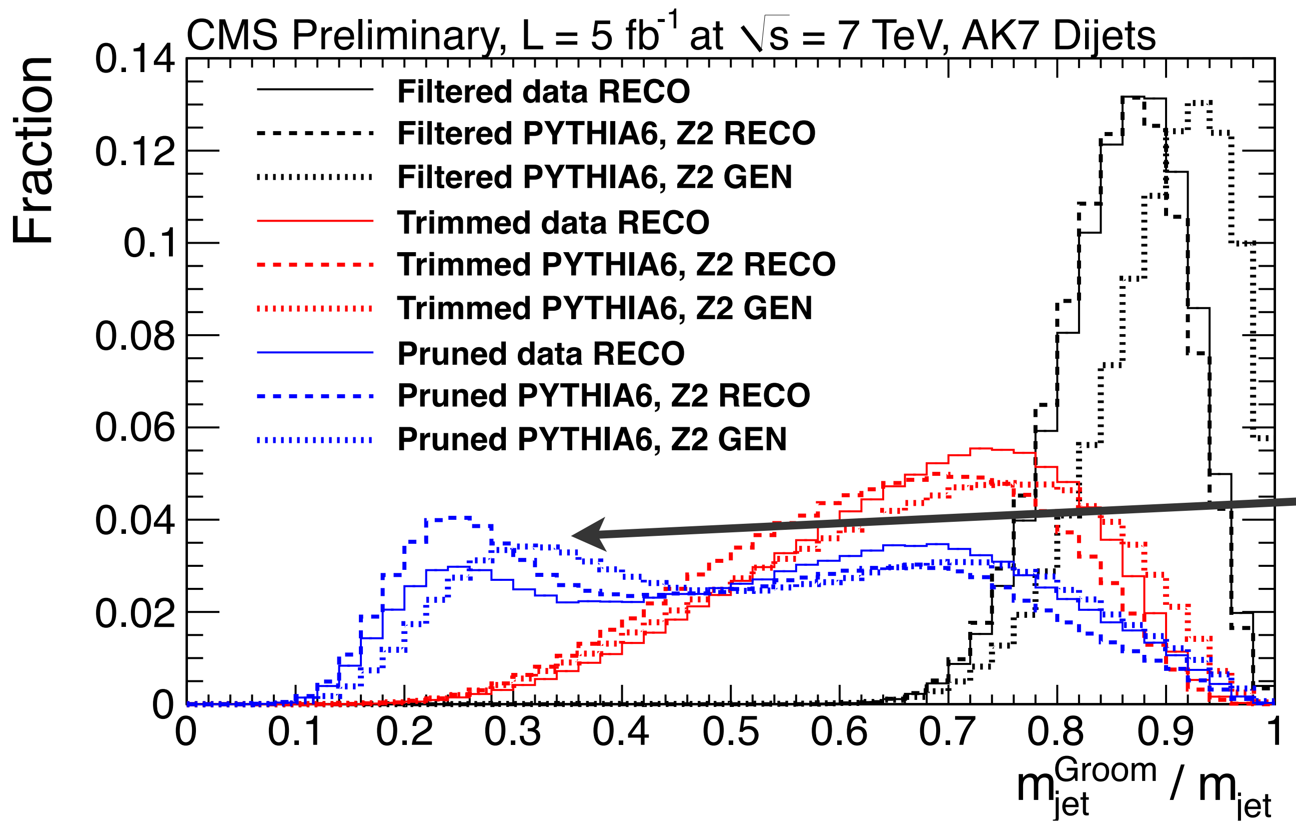
✦ An example: jet energy scale

- Well calibrated





Peep inside the merged jet, use grooming



Pruning is the most aggressive, filtering is the least aggressive

bimodal structure provides good separation for qq signal

Comparison of grooming algorithms at particle level (GEN), reconstructed simulation (RECO) and data

CMS analysis

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11017

$W \to \ell\nu$ selection	Jet selection
Single-lepton trigger	$p_T^{j1} > 40\,\mathrm{GeV}$
Lepton identification and isolation	$p_T^{j2}, p_T^{j3} > 30\,\mathrm{GeV}$
$p_T^{\mu(e)} > 25\ (35)\,\mathrm{GeV}$	$\lVert\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2}\rVert > 45\,\mathrm{GeV}$
$\not{E}_T^{\mu(e)} > 25\ (30)\,\mathrm{GeV}$	$\lvert\Delta\eta(j1, j2)\rvert < 1.2$
$M_T > 50\,\mathrm{GeV}$	$\Delta\phi(\not{E}_T, \mathrm{j1}) > 0.4$
Exclude events with > 1 lepton	$0.3 < p_T^{j2}/m_{jj} < 0.7$

Efficiency x Acceptance for a few typical models

		$\varepsilon\mathcal{A}$			
		muons		electrons	
Signal model	$\sigma \times \mathcal{B}$ (pb)	2-jet	3-jet	2-jet	3-jet
Technicolor	7.4	0.065	0.020	0.039	0.011
Z'	8.1	0.070	0.023	0.042	0.014
WH	0.059	0.060	0.019	0.038	0.013

W+jets shape uncertainty

Two relatively unknown parameters in W+jets shape

- Factorization/renormalization scale (μ)
- Matrix Element – Parton Shower matching threshold (q)

Need to vary them in the fit to get a good modeling of data:

$$\mathcal{F}_{\mathrm{W+jets}} = \alpha \cdot \mathcal{F}_{\mathrm{W+jets}}(\mu_0^2, q'^2) + \beta \cdot \mathcal{F}_{\mathrm{W+jets}}(\mu'^2, q_0^2) + (1 - \alpha - \beta) \cdot \mathcal{F}_{\mathrm{W+jets}}(\mu_0^2, q_0^2),$$

where $0 < \alpha < 1$, $0 < \beta < 1$

- α and β are consistent between muon and electron data
- Data prefer smaller value for ME-PS threshold than 20 GeV

Fit to extract diboson signal

- Diboson contribution floated completely
- QCD constrained using data (i.e., fit to MET distribution)
- Other backgrounds constrained using the most state of the art theory predictions (NLO or NNLO)

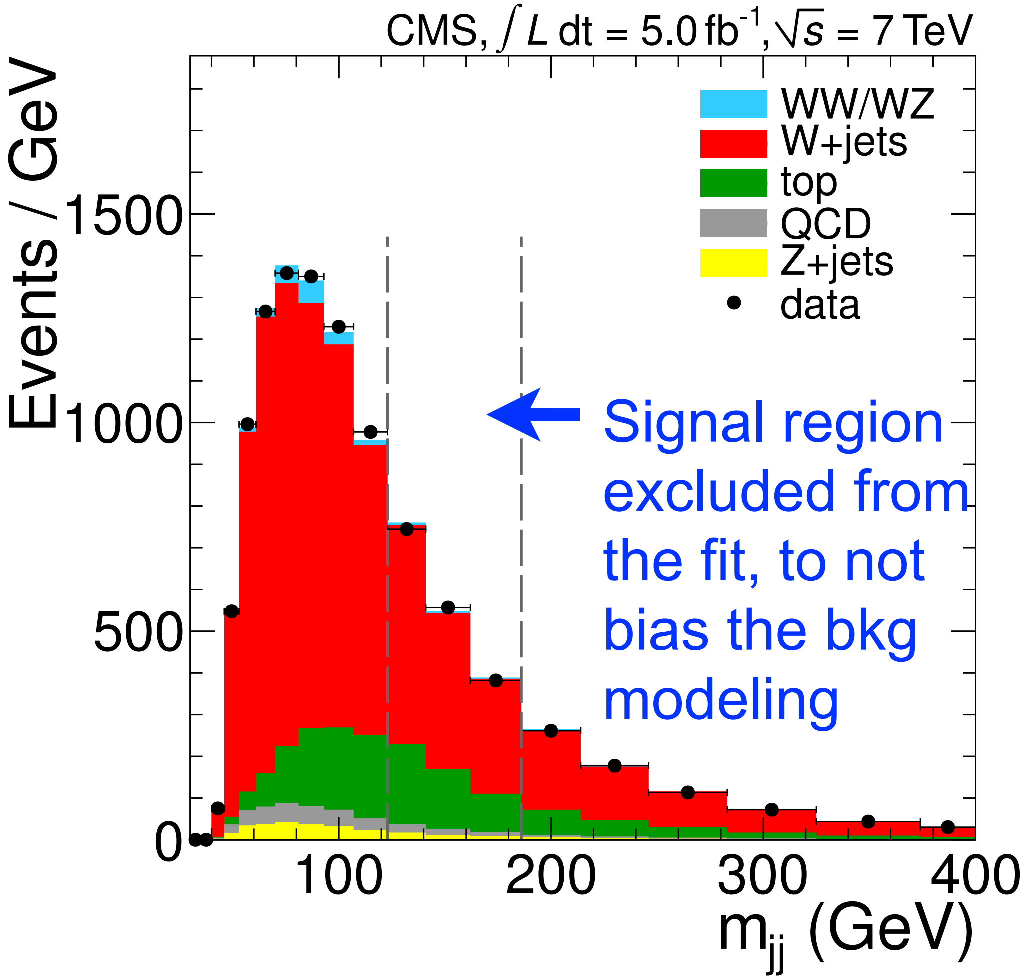
Fit results

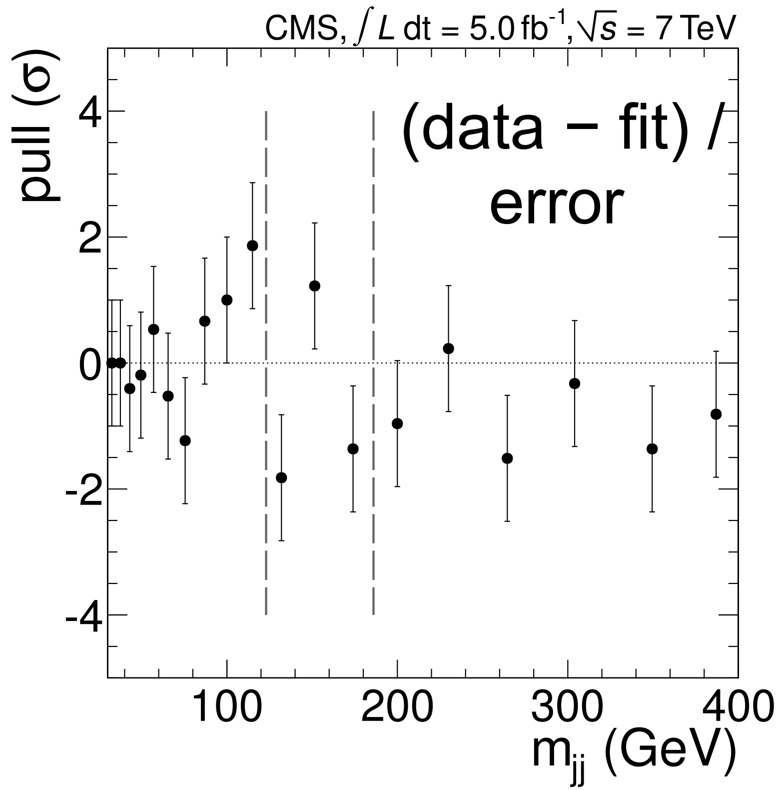
Process	Muon channel	Electron channel
Diboson (WW+WZ)	1899 ± 389	783 ± 302
W plus jets	67384 ± 586	31644 ± 850
$t\bar{t}$	1662 ± 117	946 ± 67
Single top	650 ± 33	308 ± 17
Drell-Yan plus jets (Z+jets)	3609 ± 155	1408 ± 64
Multijet (QCD)	296 ± 317	4195 ± 867
Fit χ^2/dof (probability)	9.73/12 (0.64)	5.30/12 (0.95)
Total from fit	75420	39371
Data	75419	39365
Acceptance $\times$ efficiency ($\mathcal{A}\varepsilon$)	5.153×10^{-3}	2.633×10^{-3}

Channel	Observed	Expected (NLO)
Muon	1900 ± 400	1700
Electron	800 ± 300	870

Theory has about 5% uncertainty

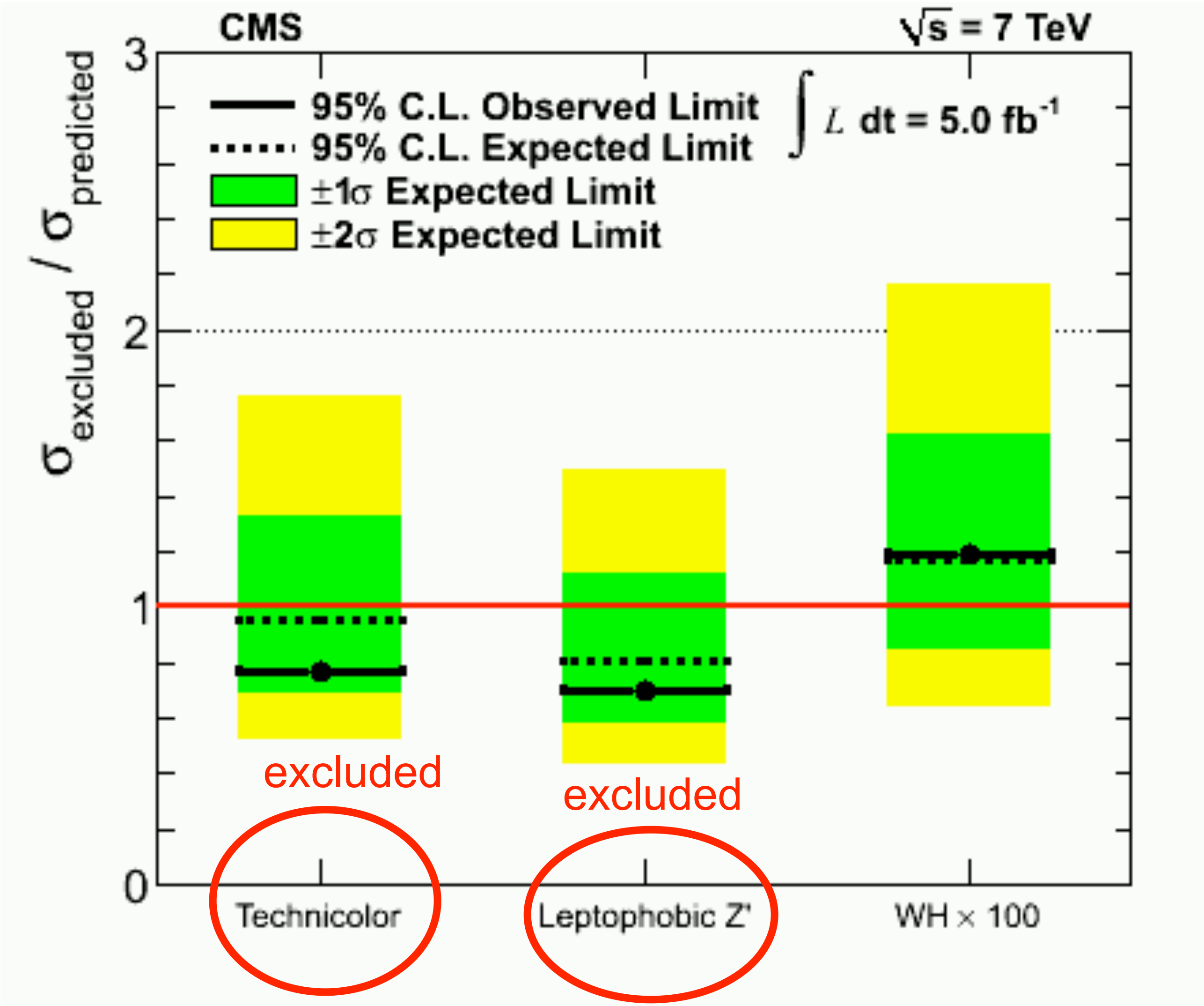
Modeling of dijet mass spectrum





Good modeling of data. Same procedure as in semi-leptonic WW+WZ analysis.

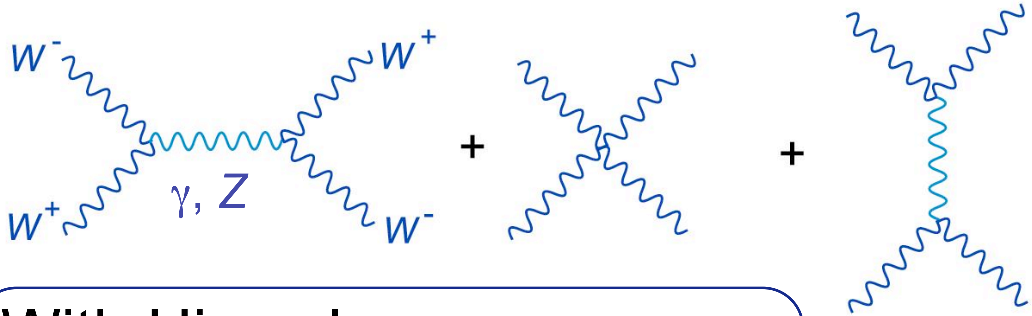
Also excluded several new physics models



Exclude several classes of BSM models

Weak interactions at high energy

Without Higgs boson, WW scattering becomes divergent



$$= \frac{g^2 E^2}{2 m_W^2}(1 + \cos\theta)$$

unitarity violated: grows as E^2

With Higgs boson

Higgs exchange needed to prevent unitarity violation in WW scattering at high energies or New Phenomena possible. With 20/fb, lvjj sensitive to weakly produced NP at 1 TeV.

Ballestrero et al, JHEP 1205, 083 (2012) [arXiv:1203.2771]

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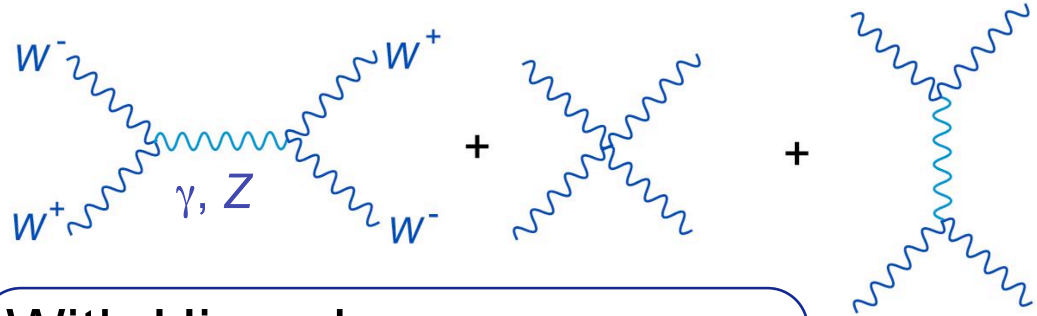
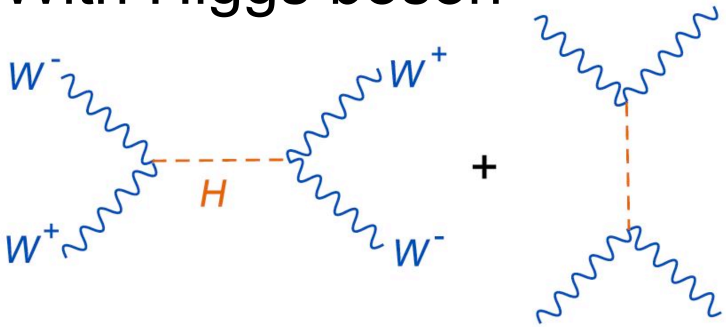


$$= \frac{g^2 E^2}{2 m_W^2}(1 + \cos\theta)$$

unitarity violated: grows as E^2

With Higgs boson



$$= -\frac{g^2 E^2}{2 m_W^2}(1 + \cos\theta)$$

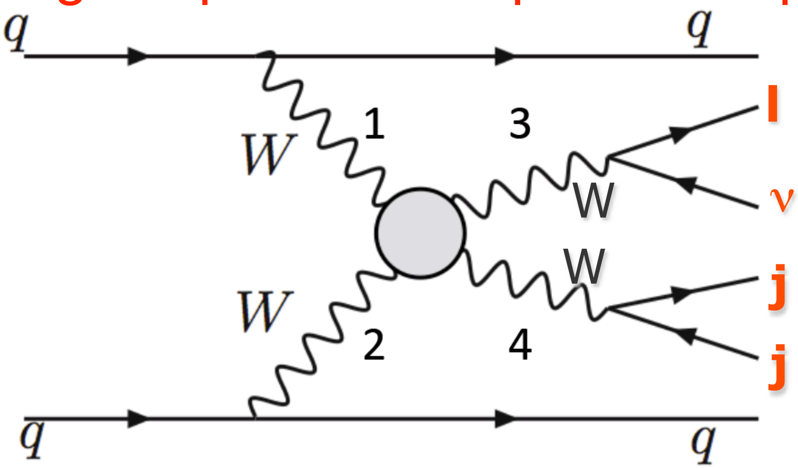
no problem now!

Higgs exchange needed to prevent unitarity violation in WW scattering at high energies or New Phenomena possible. With 20/fb, lvjj sensitive to weakly produced NP at 1 TeV.

Ballestrero et al, JHEP 1205, 083 (2012) [arXiv:1203.2771]

Signal over noise ….

Signal: probes the quartic coupling

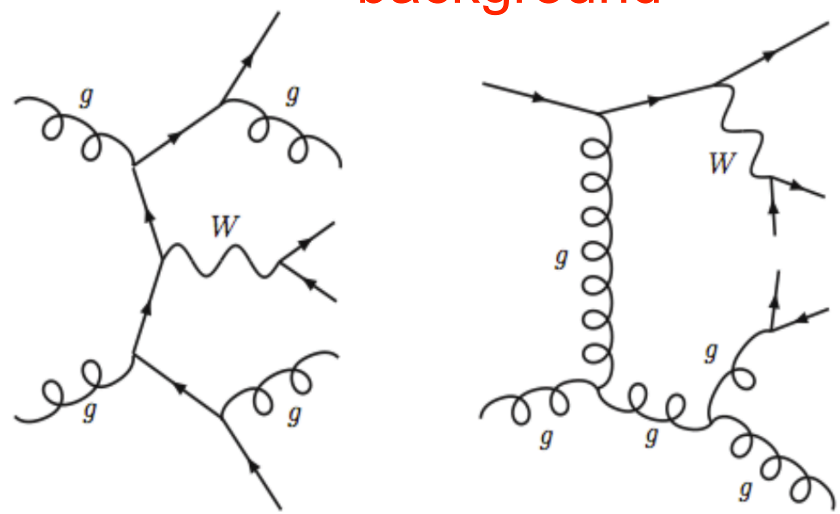


WW+2tag jets: ~1 pb

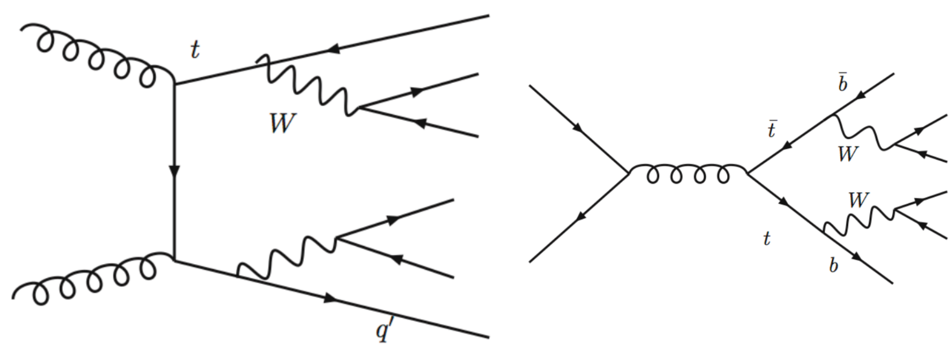
- Δη between tag jets > 4
- Invariant mass > 600 GeV
- Standard WW selection

Already have a few hundred interesting events to analyze. Aim for a result by Moriond.

background



W+2jets+2tag jets: ~10 pb

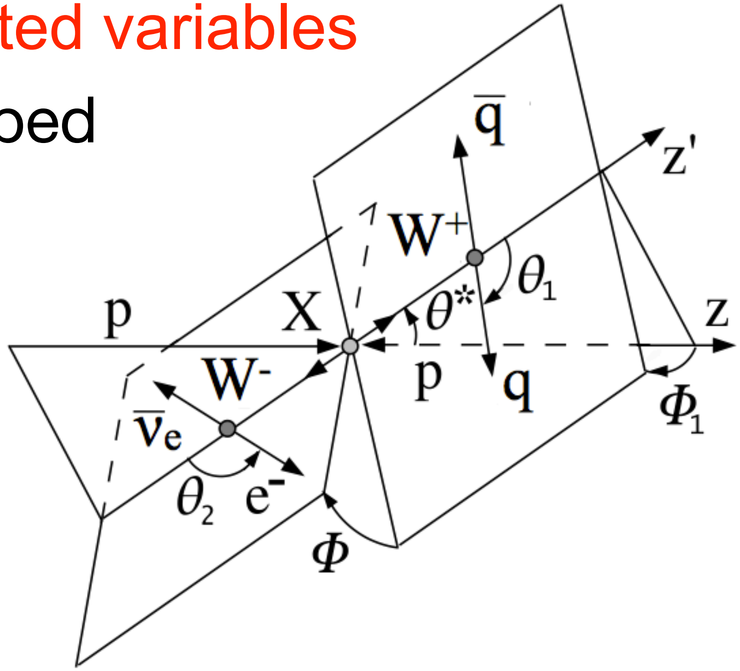


$t\bar{t}$+2 tag jets: ~10 pb

Analysis strategy: improve S/B, systematics !!!

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Hig12046TWiki
http://cdsweb.cern.ch/record/1494573

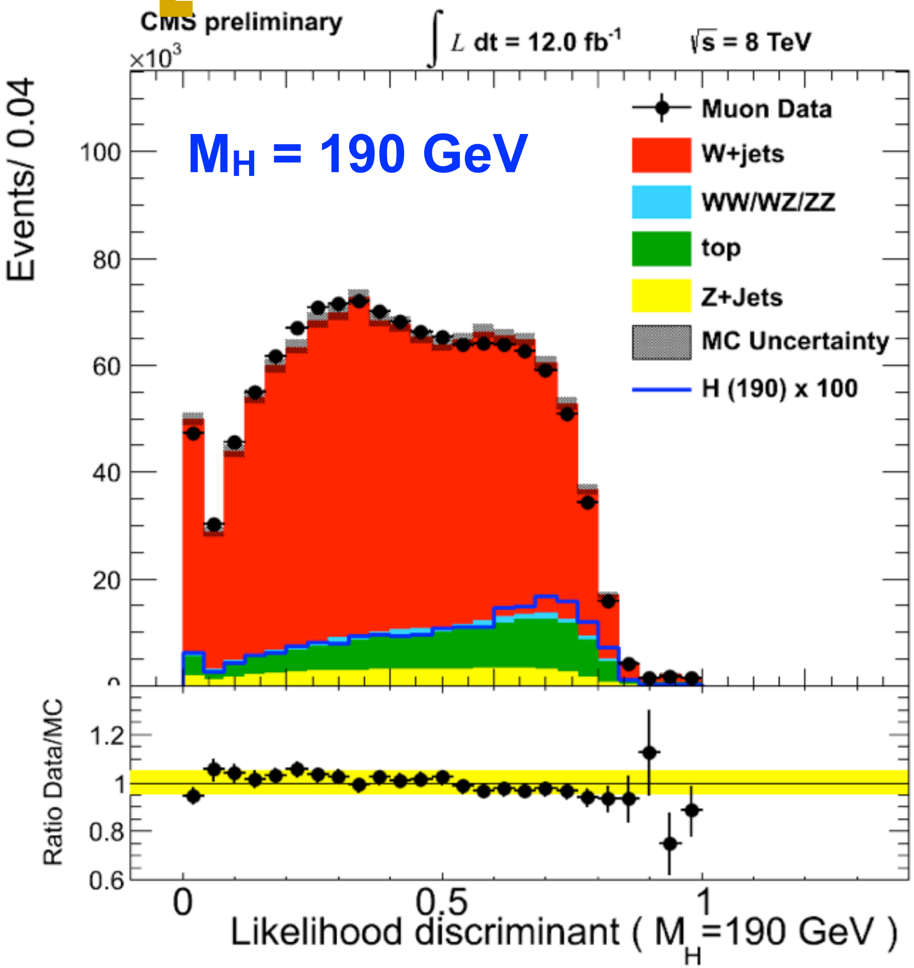
Likelihood discriminant using uncorrelated variables

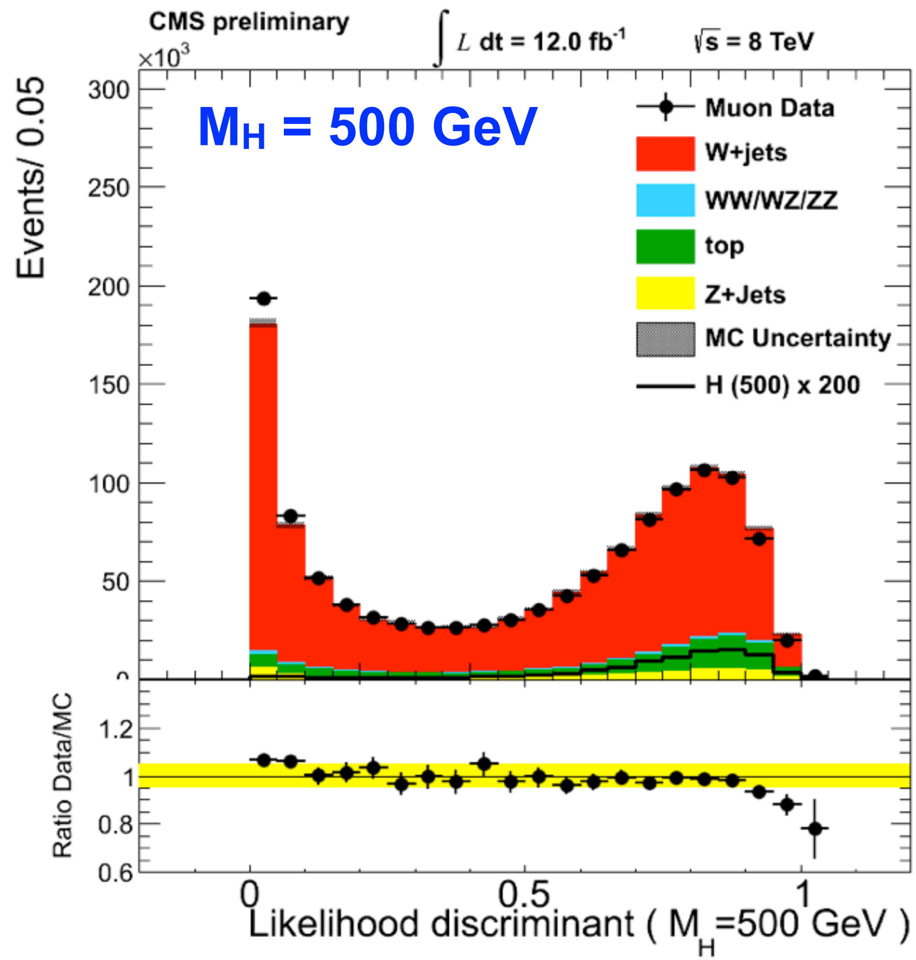


- Higgs boson kinematics is fully described by → {m_{WW}, m_{jj}, $\boldsymbol{\theta_1}$, $\boldsymbol{\theta_2}$, $\boldsymbol{\theta^*}$, $\boldsymbol{\phi}$, $\boldsymbol{\phi_1}$}
  - **m_{WW}** is the variable we use to extract limit, so it is not included
  - **m_{jj}** used to estimate background normalization, so it is not included
- the **5 angular variables are included**
- **Lepton charge** is a good variable since signal is charge-symmetric, W+jets is not

{θ_1, θ_2, θ^*, ϕ, ϕ_1, $(p_T)_{WW}$, y_{WW}, lepton charge}

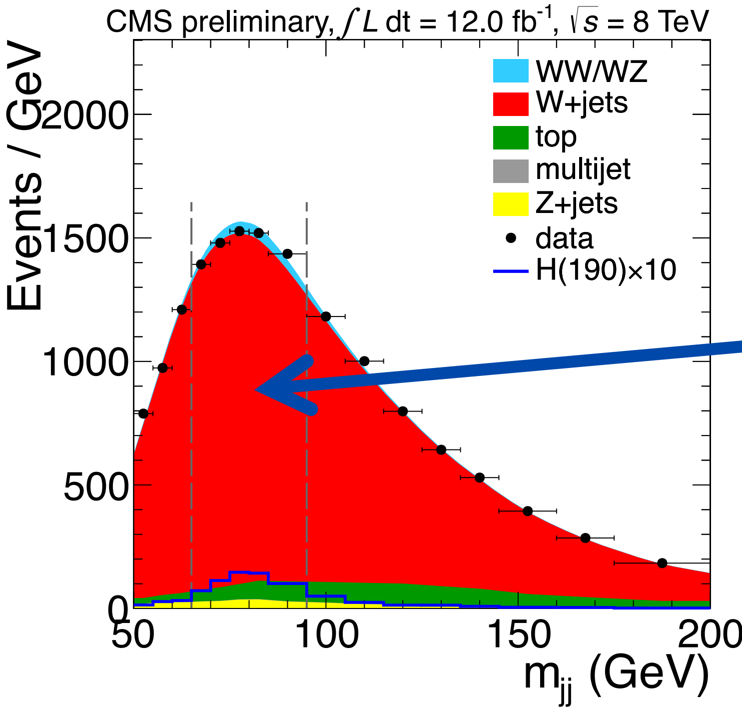
Examples of likelihood output

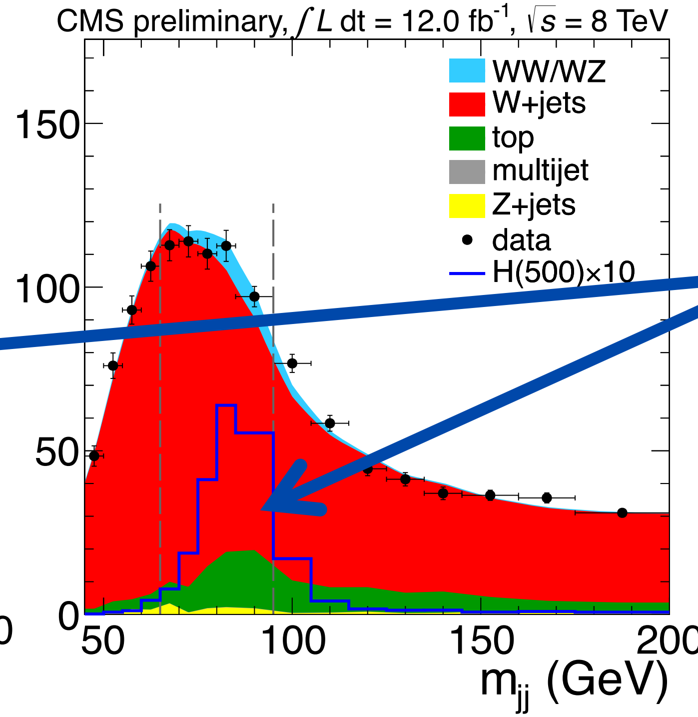




Optimize 48 likelihoods: 12 mass points (M_H:170, 180, 190, 200, 250,.., 600 GeV) x 2 lepton flavors x 2 Njets (i.e., =2 or 3)

Use m_{jj} fit to obtain background normalization

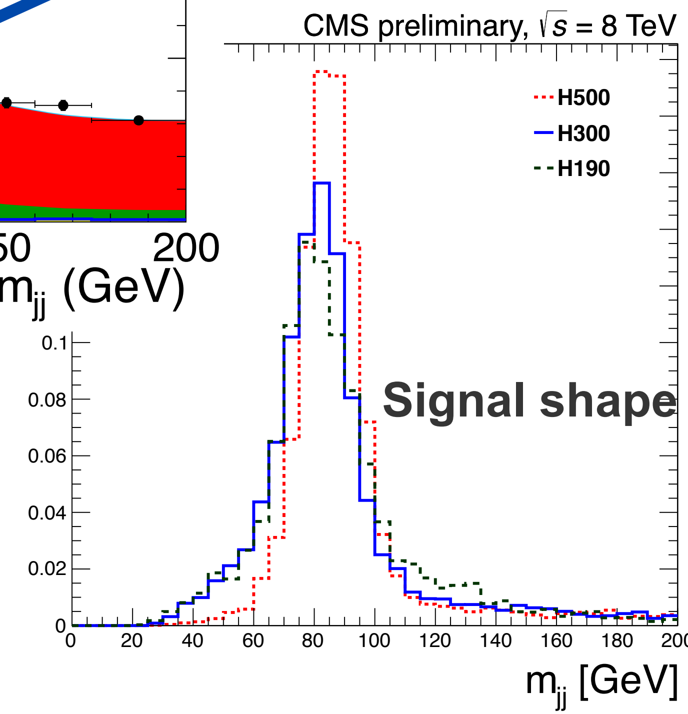




Signal region is excluded from fit

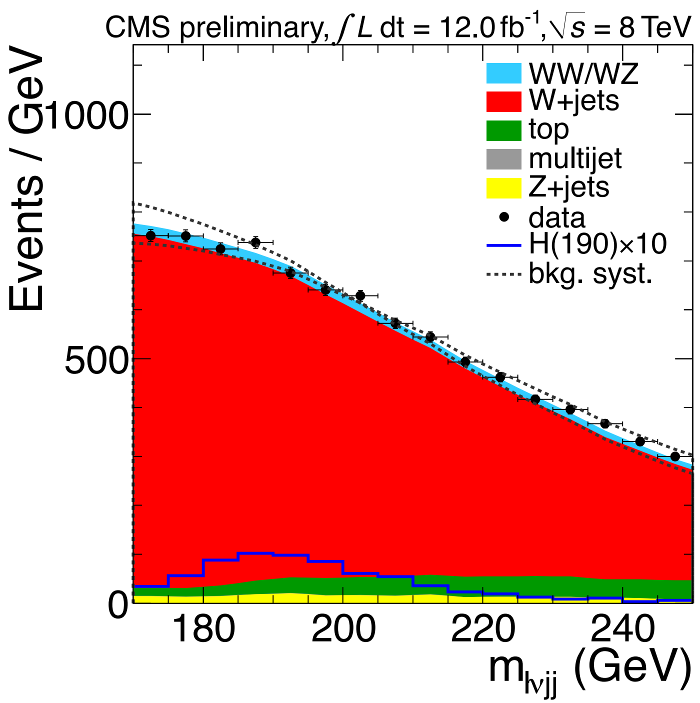
Muon W+2j data, selection optimized for **M_H = 190 GeV**

Muon W+2j data, selection optimized for **M_H = 500 GeV**

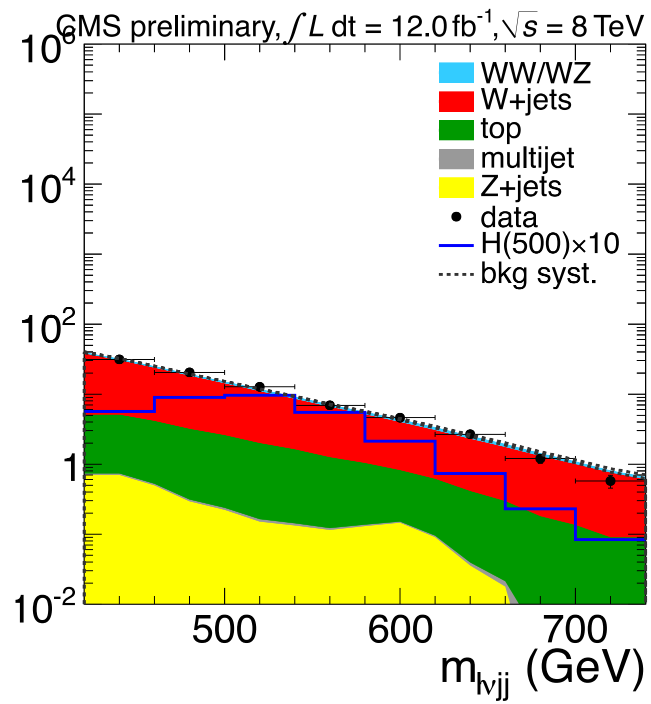


Now plot m_{WW} spectrum in signal region

Use data sidebands to model W+jets background shape

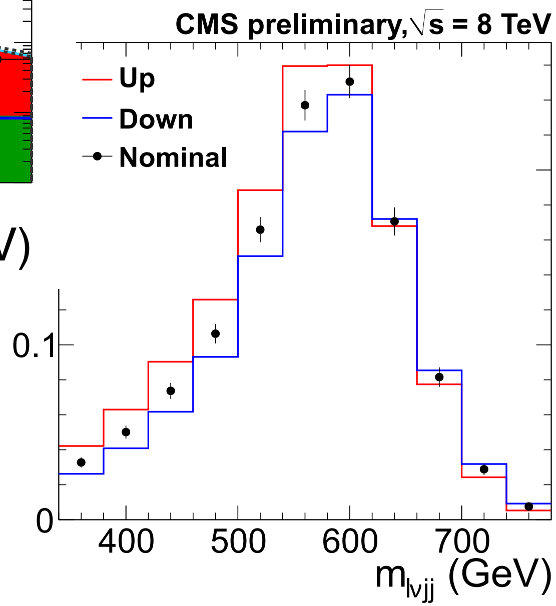


Muon W+2j data with m_{jj} in range [65, 95] GeV, selection optimized for **M_H = 190 GeV**



Muon W+2j data with m_{jj} in range [65, 95] GeV, selection optimized for **M_H = 500 GeV**

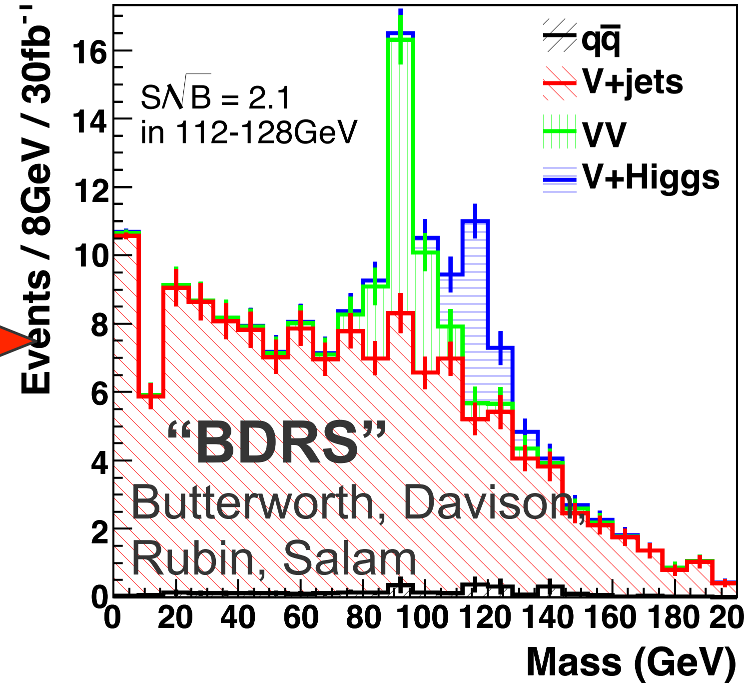
Signal syst for M_H = 600 GeV: dominated by interference btw $gg \rightarrow WW$ and $gg \rightarrow H \rightarrow WW$



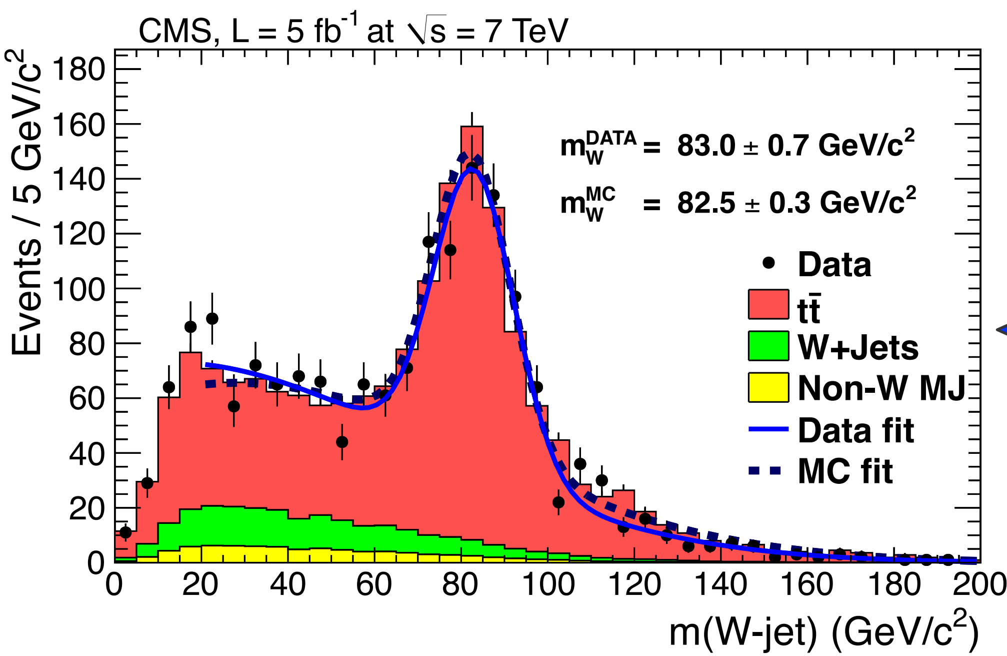
Next: reconstruct H→bb peak

In the boosted regime the two jets from W/Z/Higgs merge.

This is what we aim to do with 2012 data. Reconstruct hadronic decays of boosted Higgs along with W/Z



arXiv: 0802.2470



Started with hadronic W in boosted top events

http://cdsweb.cern.ch/record/1370237

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12019