Probing Broken Symmetries: The Higgs Boson and Beyond

Kalanand Mishra, *Fermilab*

University of Cincinnati
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Outline

- **Higgs boson: connection to a broken symmetry**
  - What does it tell us experimentally?
- **Probes of the broken symmetry**
  - Weak boson pair production
  - Measurement of production rates
  - Connection to new physics
- **Focus on electroweak interaction at high energies**
  - New physics searches in weak boson couplings
- **Summary**

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As you know ....

ATLAS and CMS collaborations observed a particle consistent with the Standard Model Higgs boson

- Reported on July 4th 2012
- Cited in 2013 Nobel Prize

ELSEVIER

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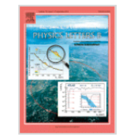


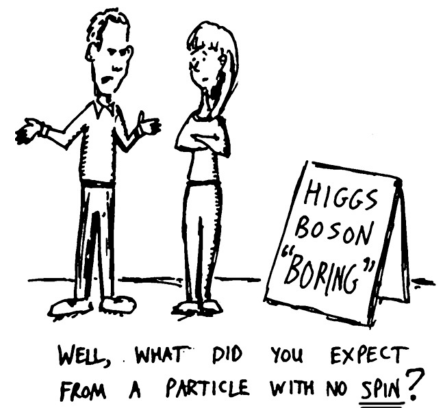
Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

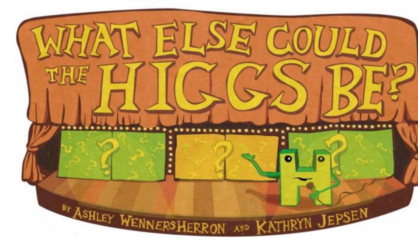
This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

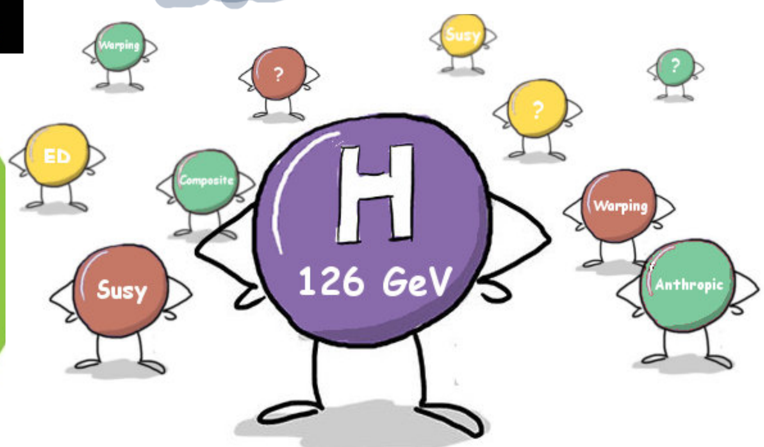
2013 Nobel Prize in Physics to François Englert & Peter Higgs, *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS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

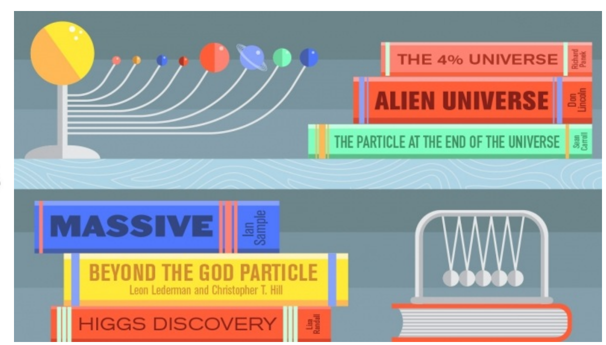
What's next ?

Lot of buzz and excitement since then ….









But let's take a step back

What the Higgs boson was meant to do?

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What the Higgs boson was meant to do?

➜ To give mass to the fundamental particles

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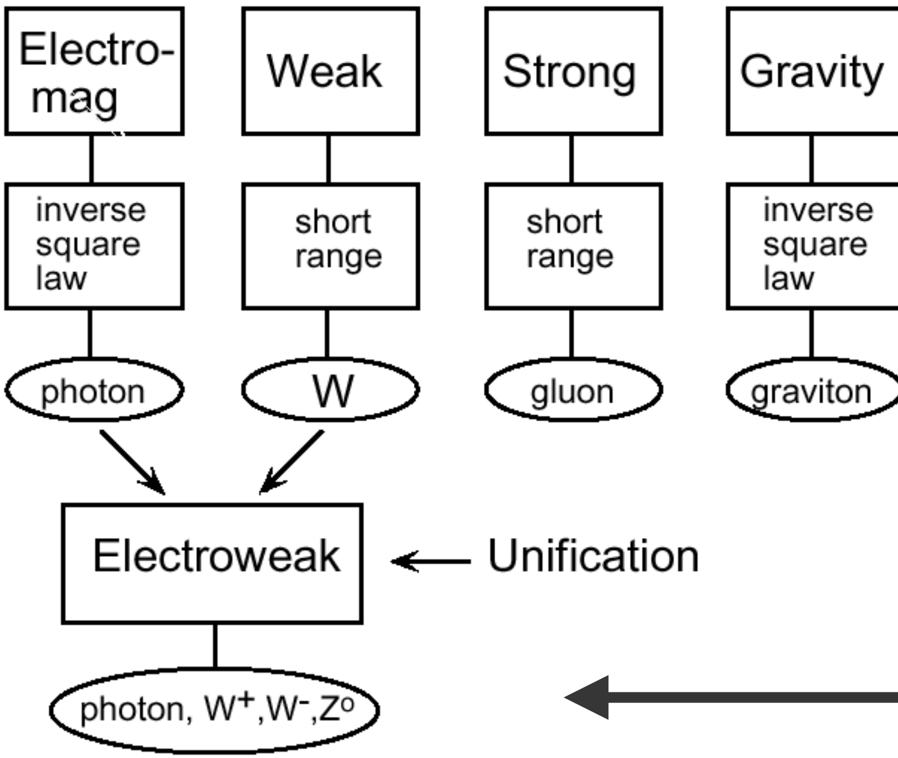
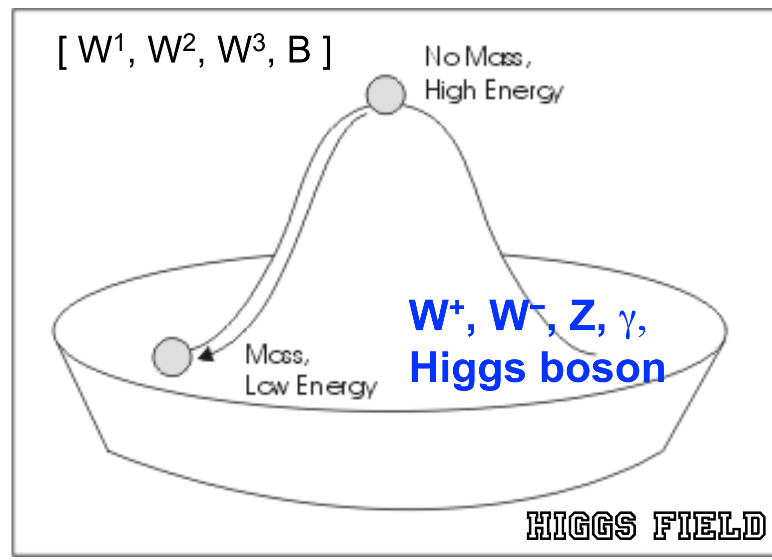
➜ To give mass to the fundamental particles

- Massless photon, massive W, Z bosons ⟹ symmetry of the electroweak force is broken



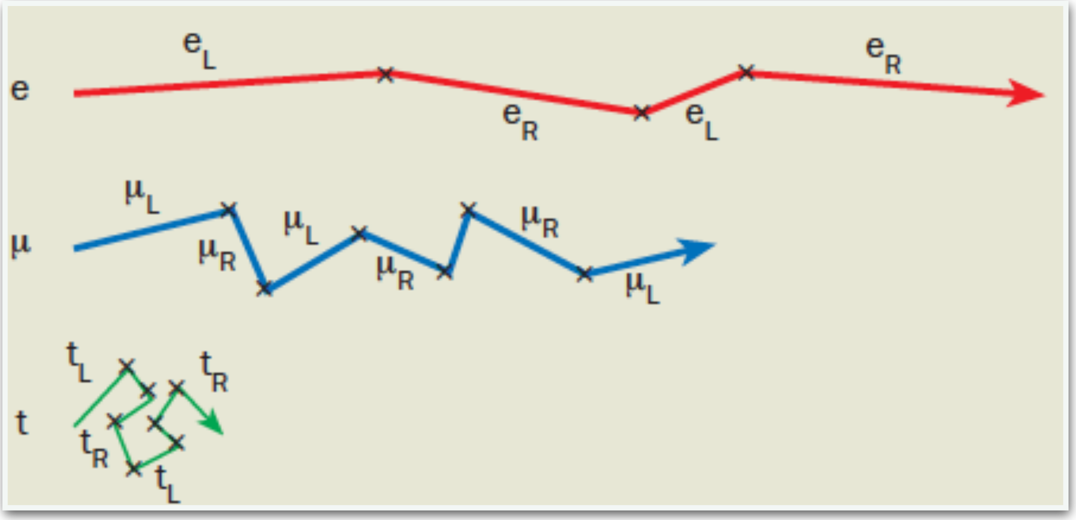


But let's take a step back

What the Higgs boson was meant to do?

➜ To give mass to the fundamental particles

Matter particles in the "vacuum" acquire mass as they collide with Higgs



Also change handedness when they collide with the Higgs boson:

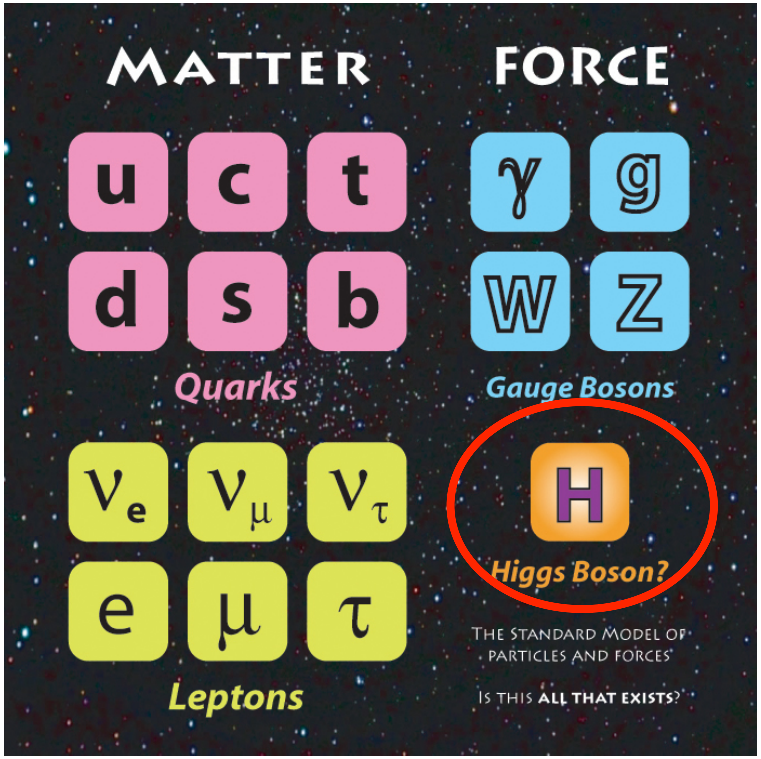
left-handed ↔ right-handed

But let's take a step back

What the Higgs boson was meant to do?

➜ And to complete the Standard Model

all masses due to Higgs



- A quantum field theory
  - symmetries of space & time ⇒ conservation laws (momentum, energy, …)
- Based on symmetry of forces
  - mass generation via Higgs
  - no unknown particles left

But let's take a step back

What the Higgs boson was meant to do?

➜ And to complete the Standard Model

In a world without Higgs boson …

- Quarks and leptons would remain massless
  ➜ Nucleon mass little changed, but proton outweighs neutron

- W, Z boson masses → (1/2500 × observed)
  ➜ Rapid β-decay ⇒ lightest nucleus is one neutron

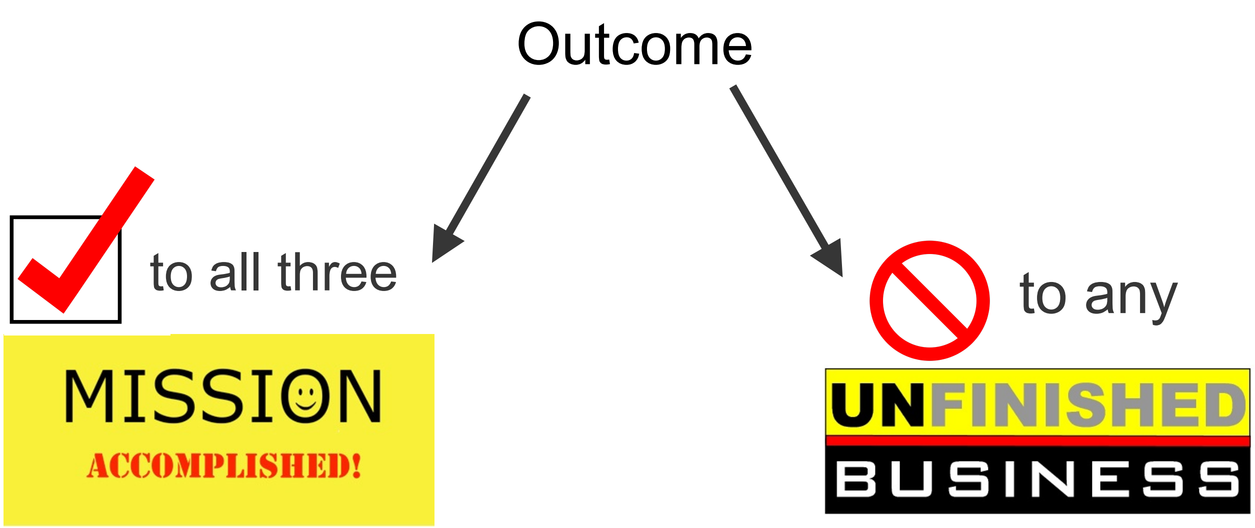
⇒ no hydrogen atom, no chemistry, no stable structures like the solids and liquids we know

. . . the character of the physical world would be <u>profoundly changed</u>

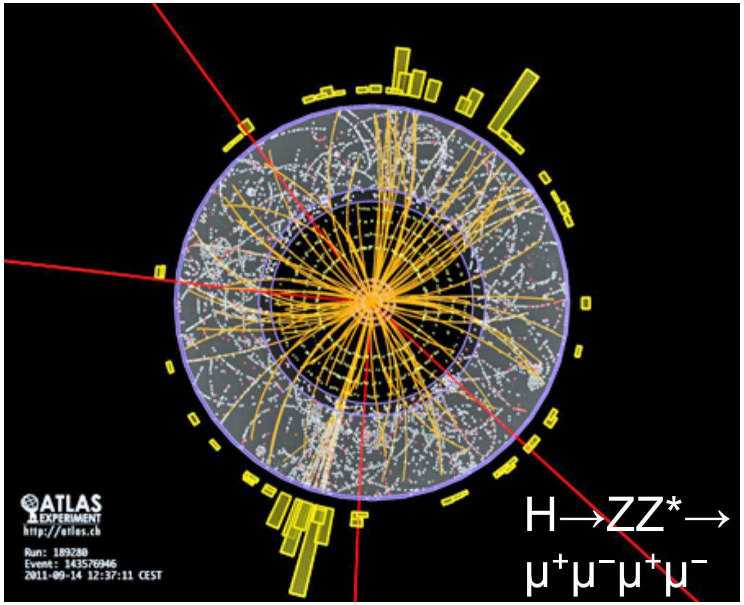
But let's take a step back

What do the data tell us:

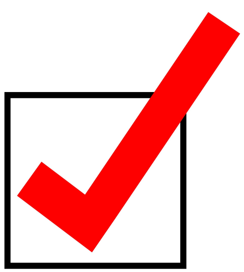
- Is the observation consistent with hypothesis?
- Has the Higgs boson delivered everything expected from it?
- Are all conceptual issues related to the Standard Model resolved after this discovery?

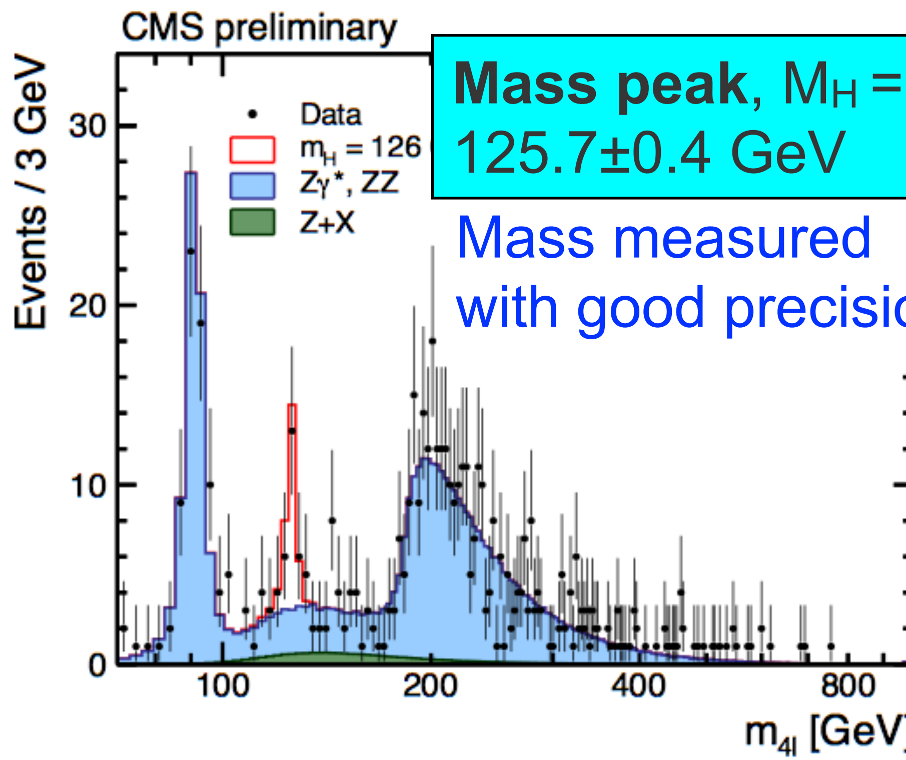


Is the observation consistent with hypothesis?



It exists!



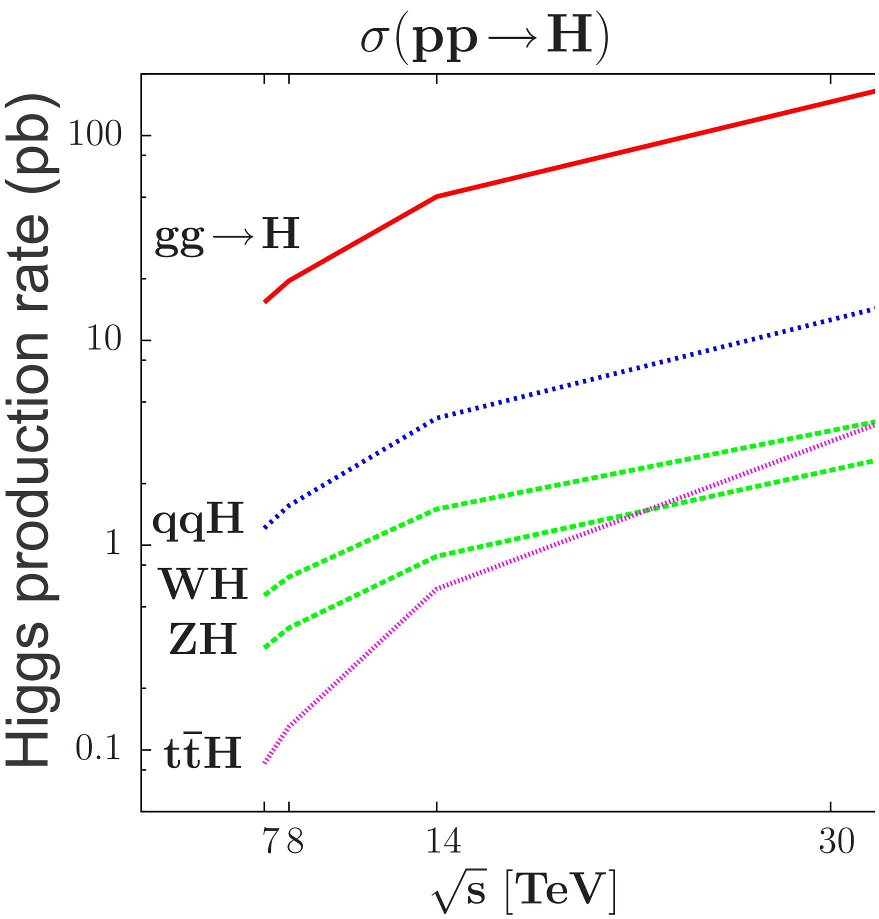


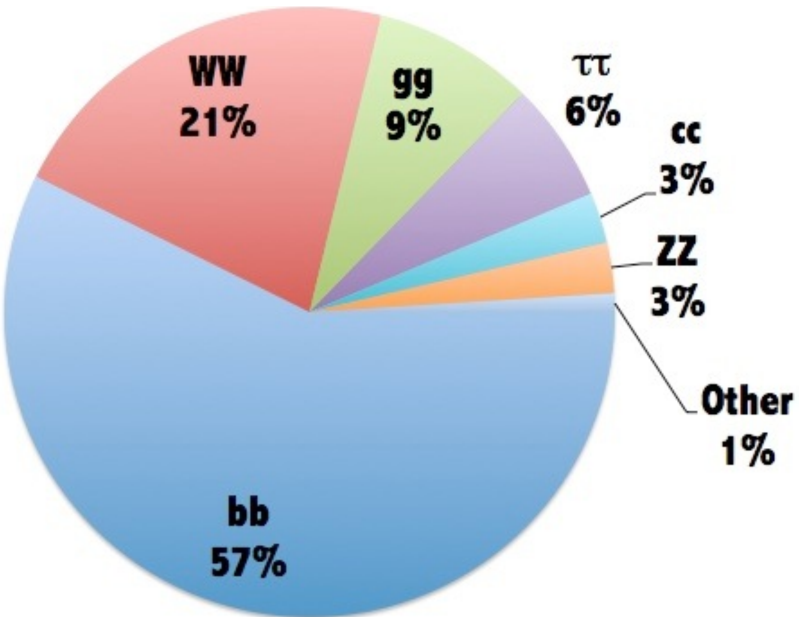
Mass peak, M_H = 125.7±0.4 GeV

Mass measured with good precision

If you know the mass you know …

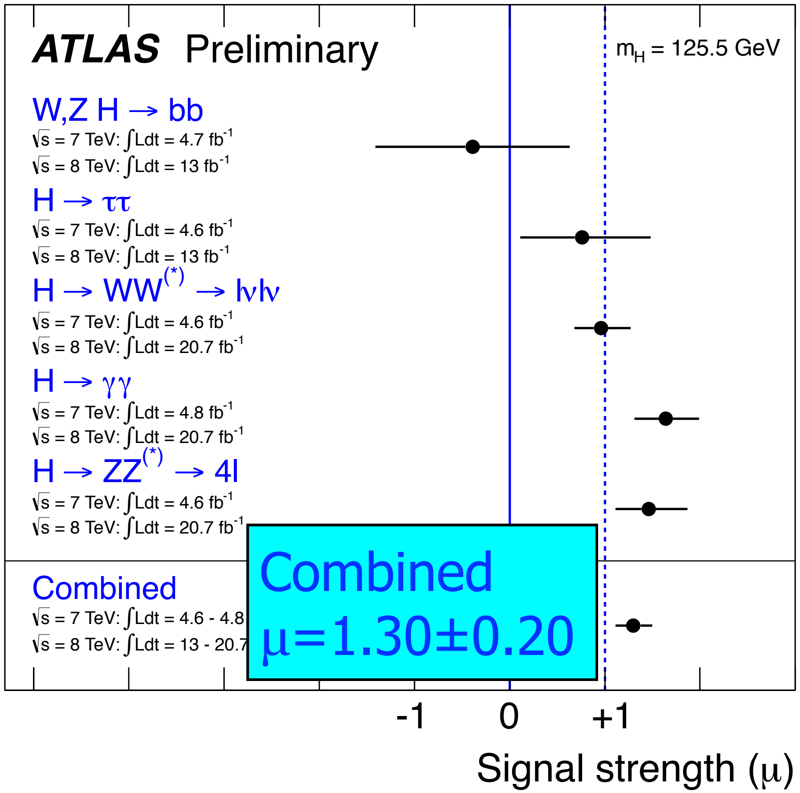
Production and decay rates

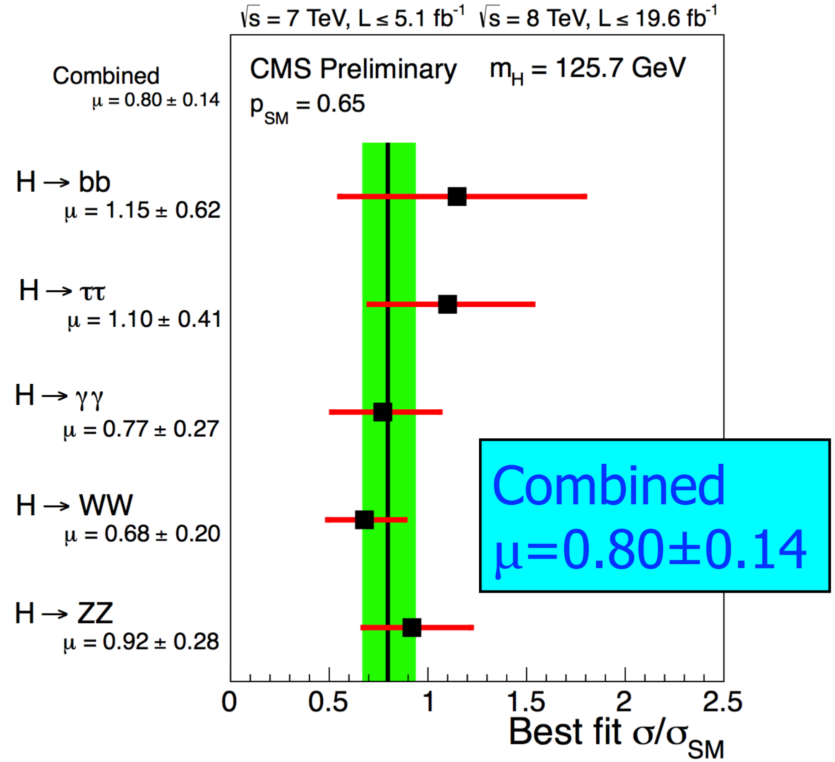




Decay rate

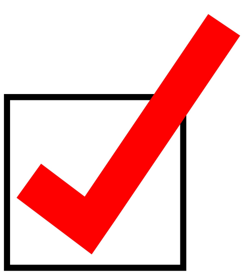
At LHC can only measure the product of the two





It clearly helps to have two experiments

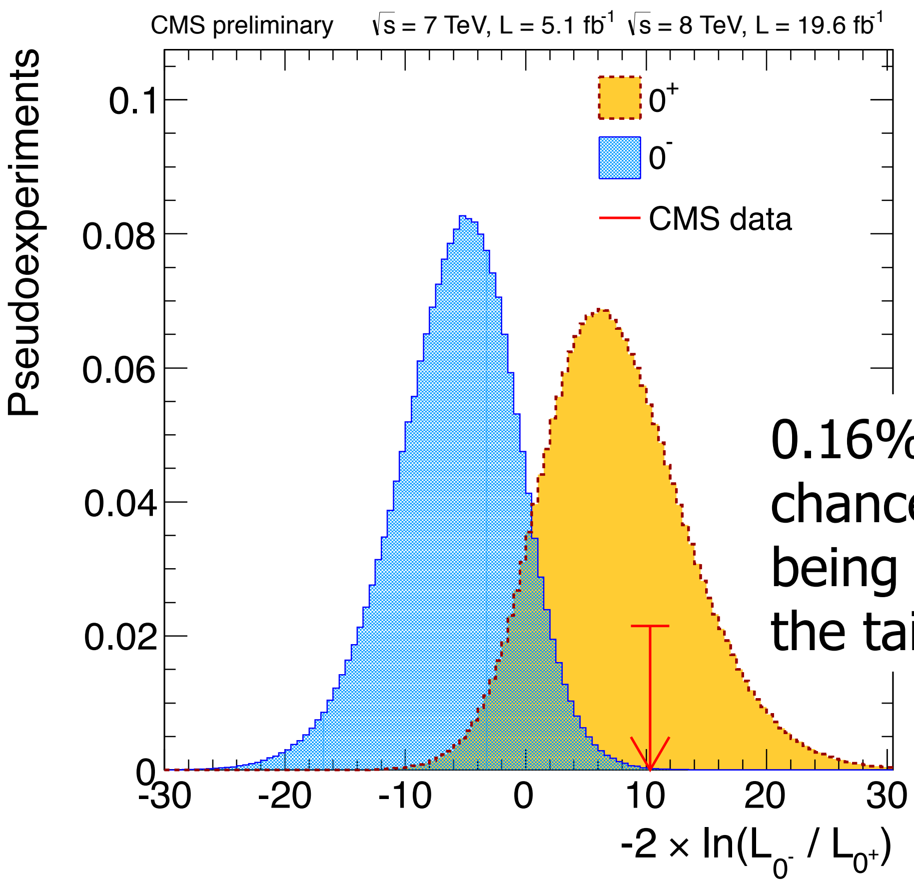
Significant deviation from 1 would be very important



In addition expect the SM Higgs boson to have

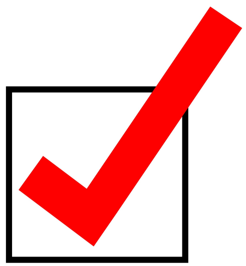
spin = 0, even parity

The only fundamental scalar particle in the Standard Model



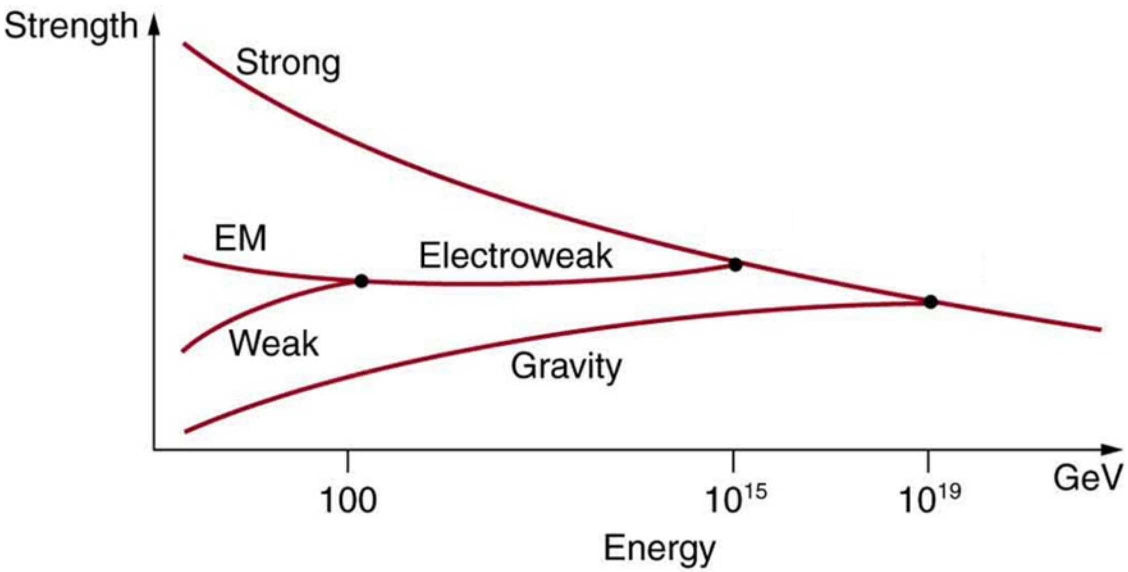
0.16% chance of being in the tail

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



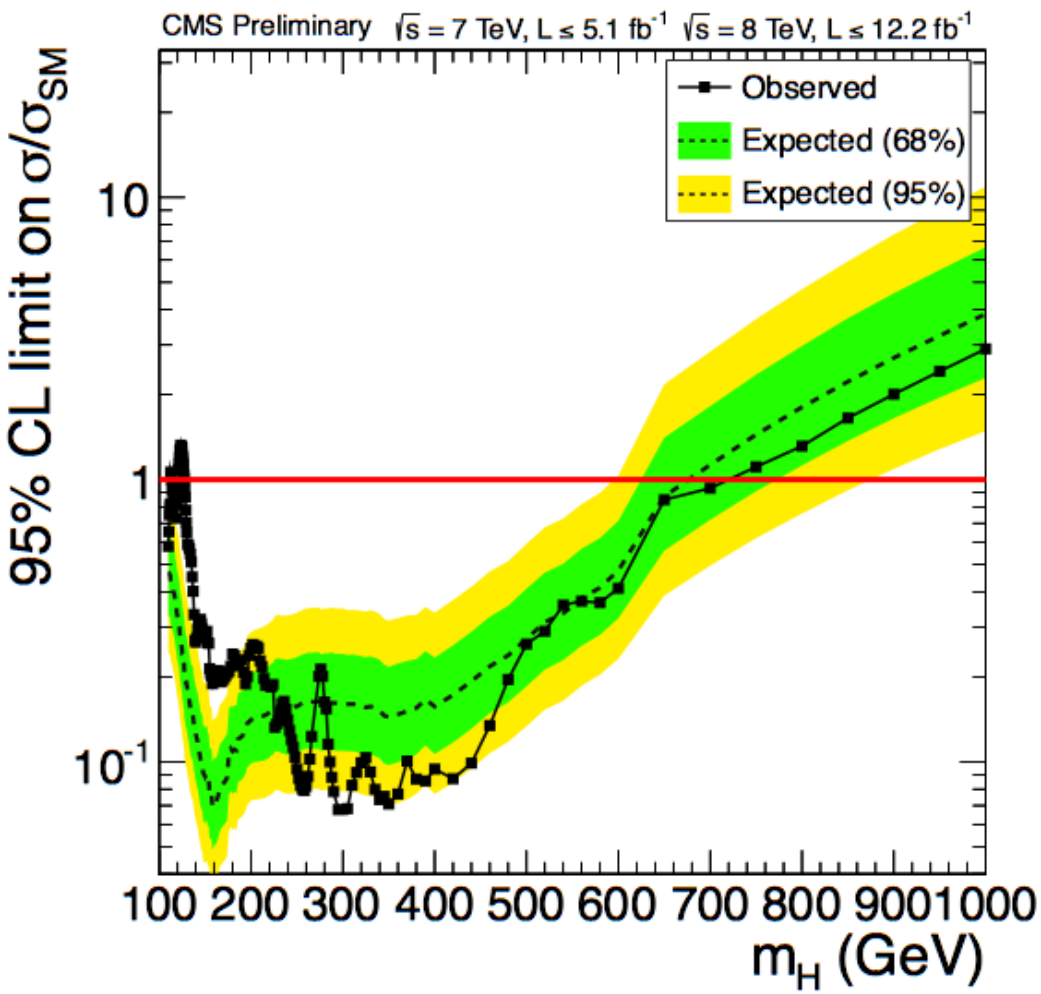
Is Higgs alone or has a family?

- In the simplest scenario, the Higgs is a single particle
- But it doesn't make a simpler story ➜ can't explain how the different forces of nature might be components of a single force



Extensions of the SM aimed at unification (e.g., supersymmetry) typically have >1 Higgs

What do the data say

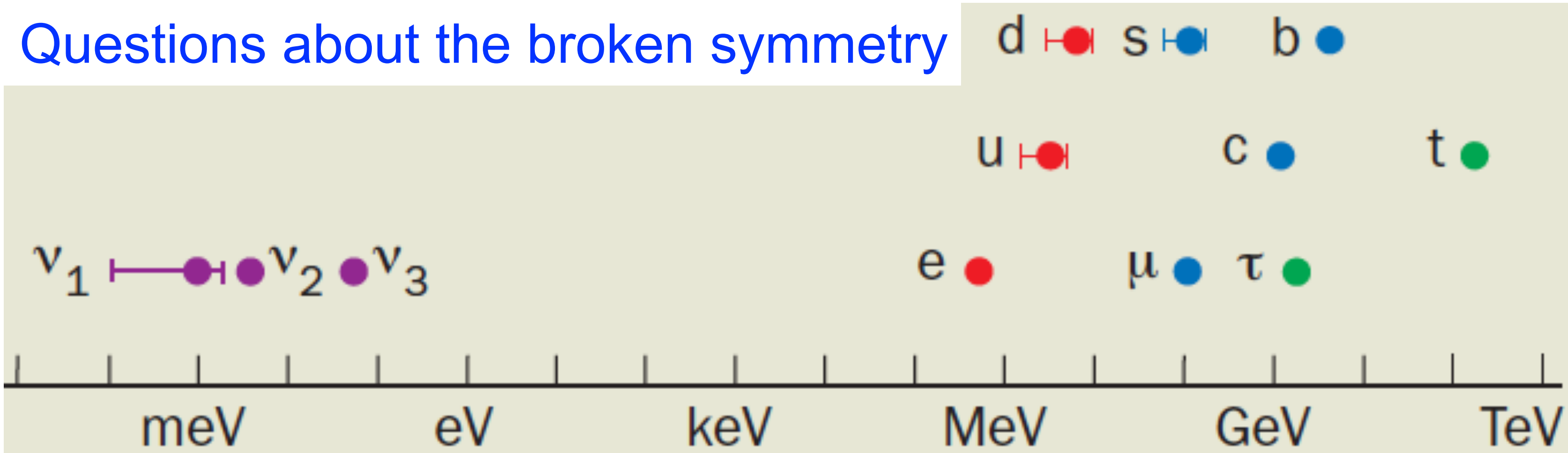


No additional Higgs states up to 700 GeV.

But interesting territory > 700 GeV to probe

So, what questions remain unanswered now

Questions about the broken symmetry

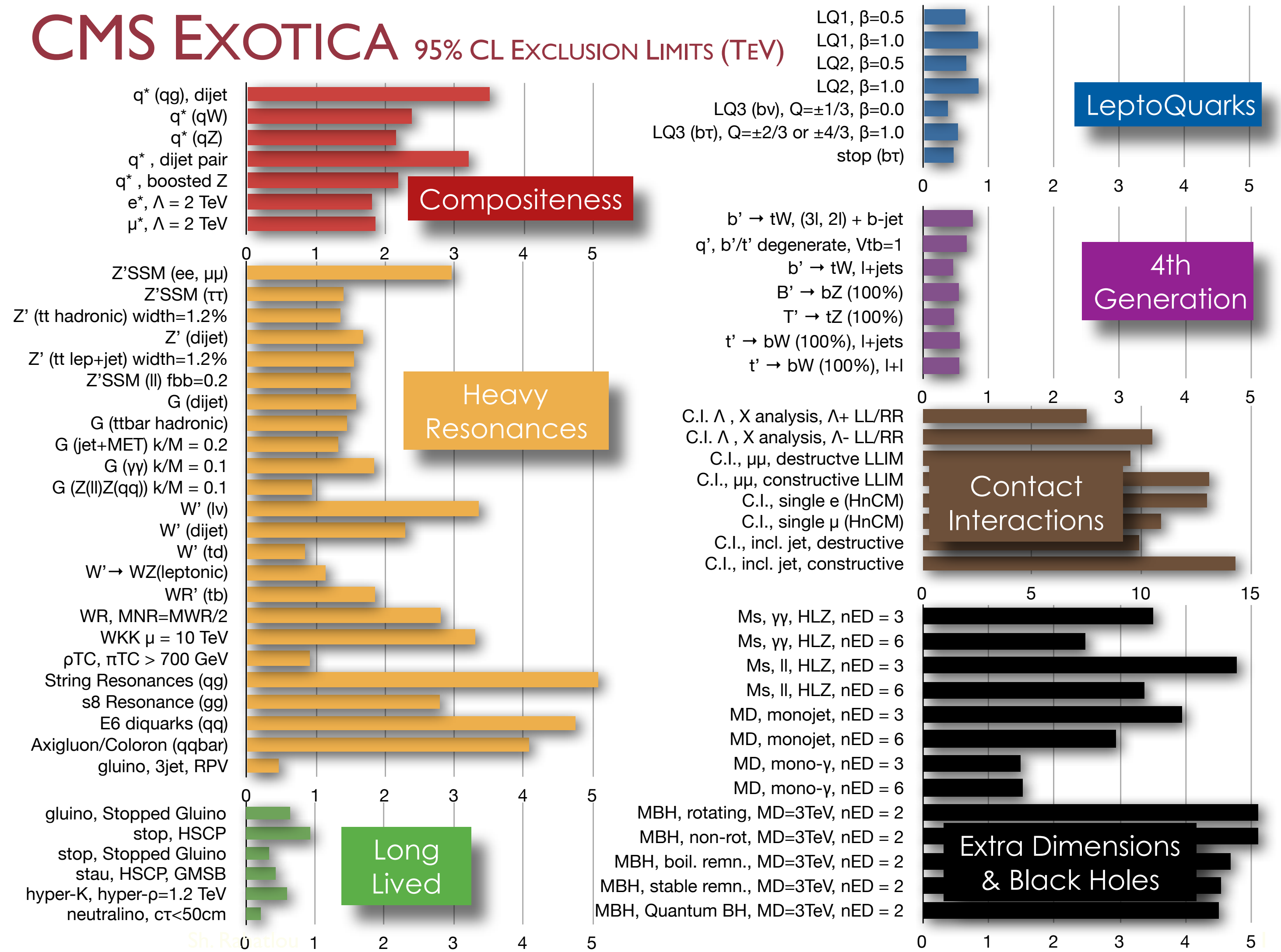


The fermion masses: note the log scale !

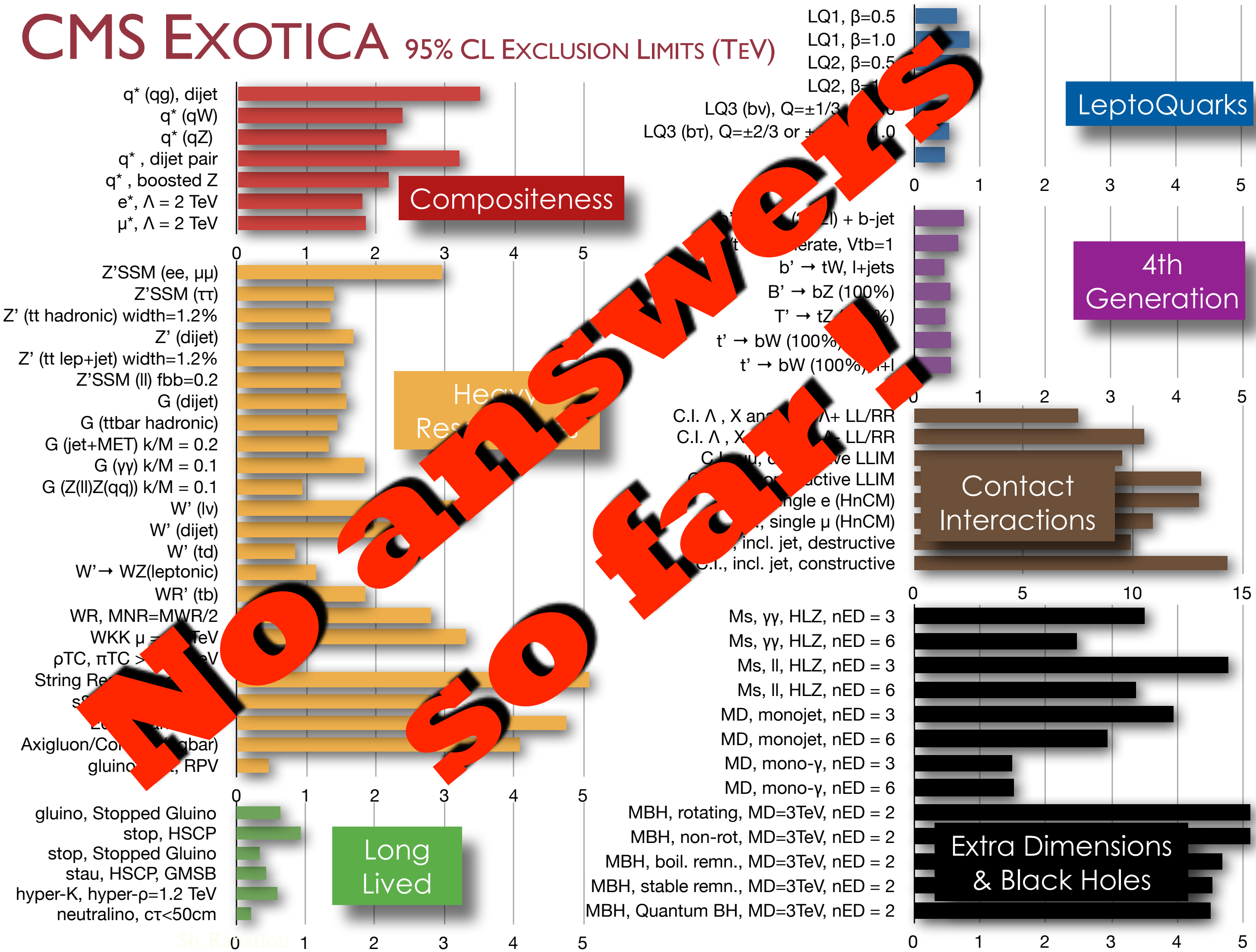
- Why 10 orders of magnitude difference in these masses?
- Why do fermions with the same charge have different masses?
- Why many fundamental forces, or unification at high energy?

SM Higgs doesn't explain any of these ➜ need new physics

But what kind of new physics?



But what kind of new physics?

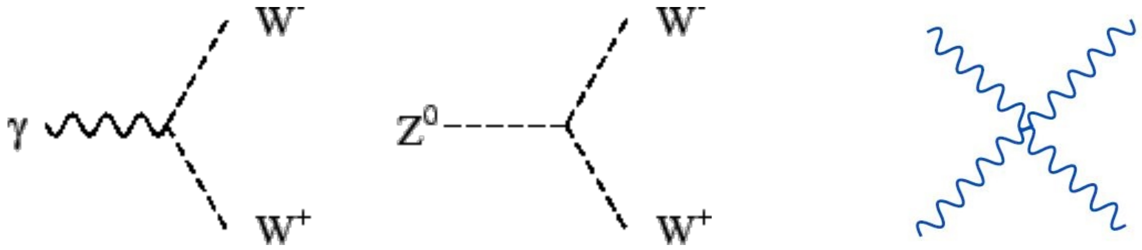


So what's next ?

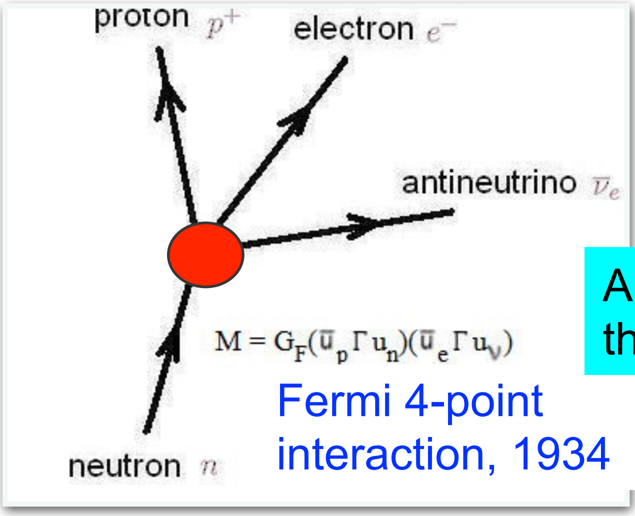
An alternative approach to search for new physics

- The Standard Model with a Higgs boson is a low-energy effective theory
  - valid below an energy scale Λ of the underlying physics

- A good bet is that the underlying physics has something to do with weak boson interactions at high energies
  - not probed with sufficient precision until now
  - kinematically wasn't fully accessible at previous colliders

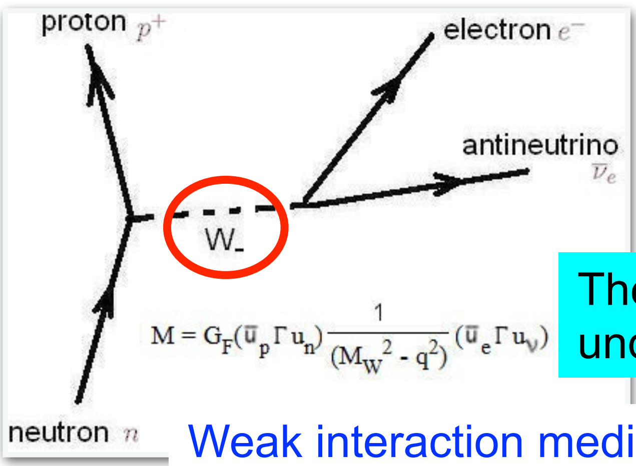


How does this alternative approach work?



An effective theory

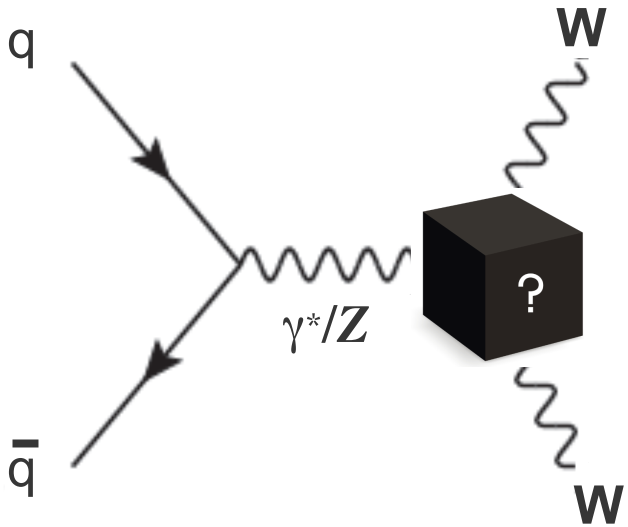
Fermi 4-point interaction, 1934



The actual underlying physics

Weak interaction mediated by W boson, 1960's

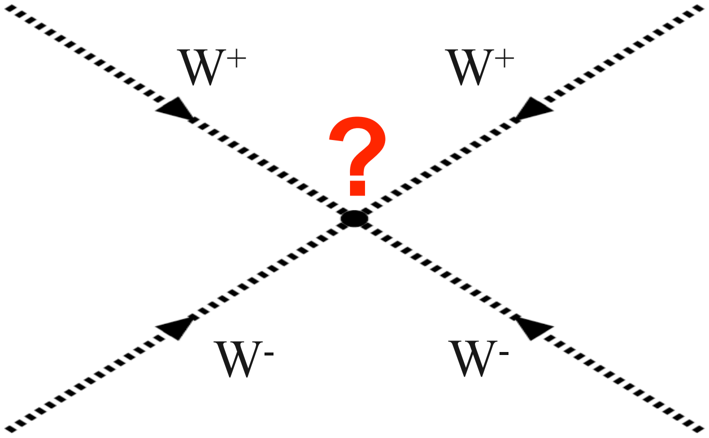
Same way as the explanation for the β decay.



The Standard Model's breaking point

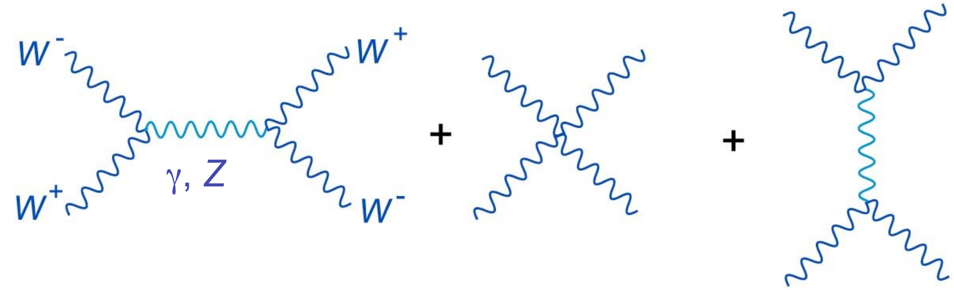
- While the Standard Model perfectly describes things at low energies, without something Higgs-like, its predictions at high-energy make no sense.
- For instance, at very high energies it predicts that things happen more than 100 percent of the time !!!!

Let's consider one such process ➜



Something weird is going on here

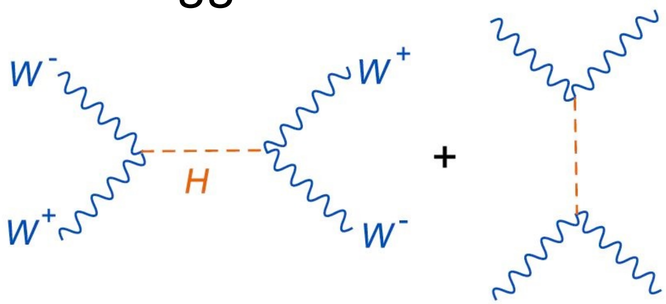
Without *a* Higgs boson



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

divergent: SM blows up as E^2

With Higgs boson



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

no problem now!

- Rationality is restored when something like the Higgs steps in
  - Or some kind of New Physics
  - Is one Higgs enough, does it stop the divergence?

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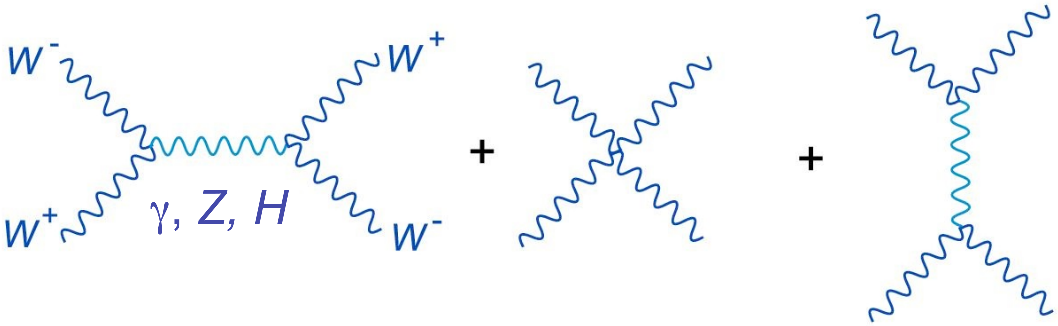
Production of heavy boson pairs

☑ Probe Higgs boson directly

I'll focus on the case when one W decays to a lepton (electron or muon) and neutrino, while the other W decays to quark-antiquark pair.

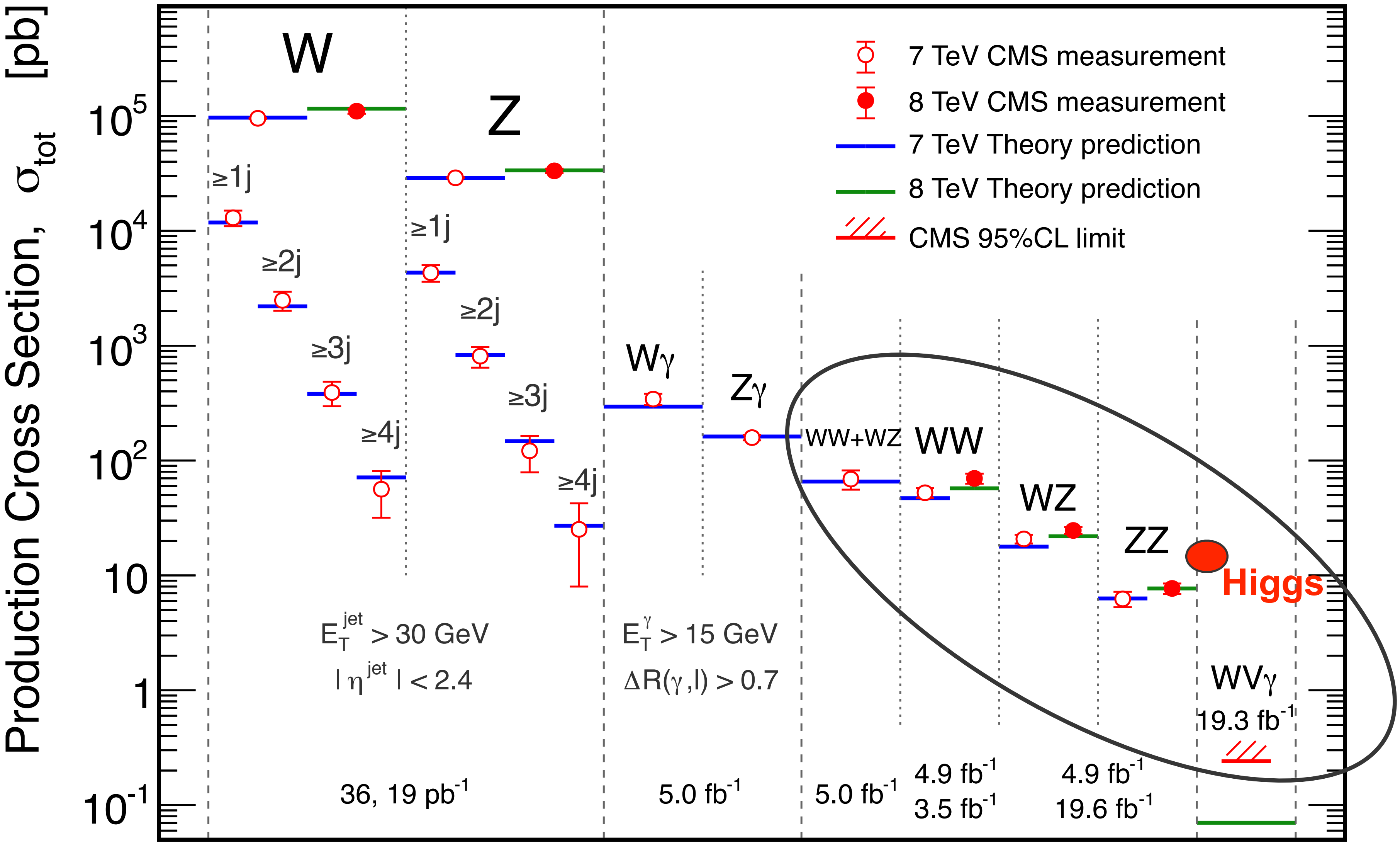
☑ Probe both Higgs & New Physics



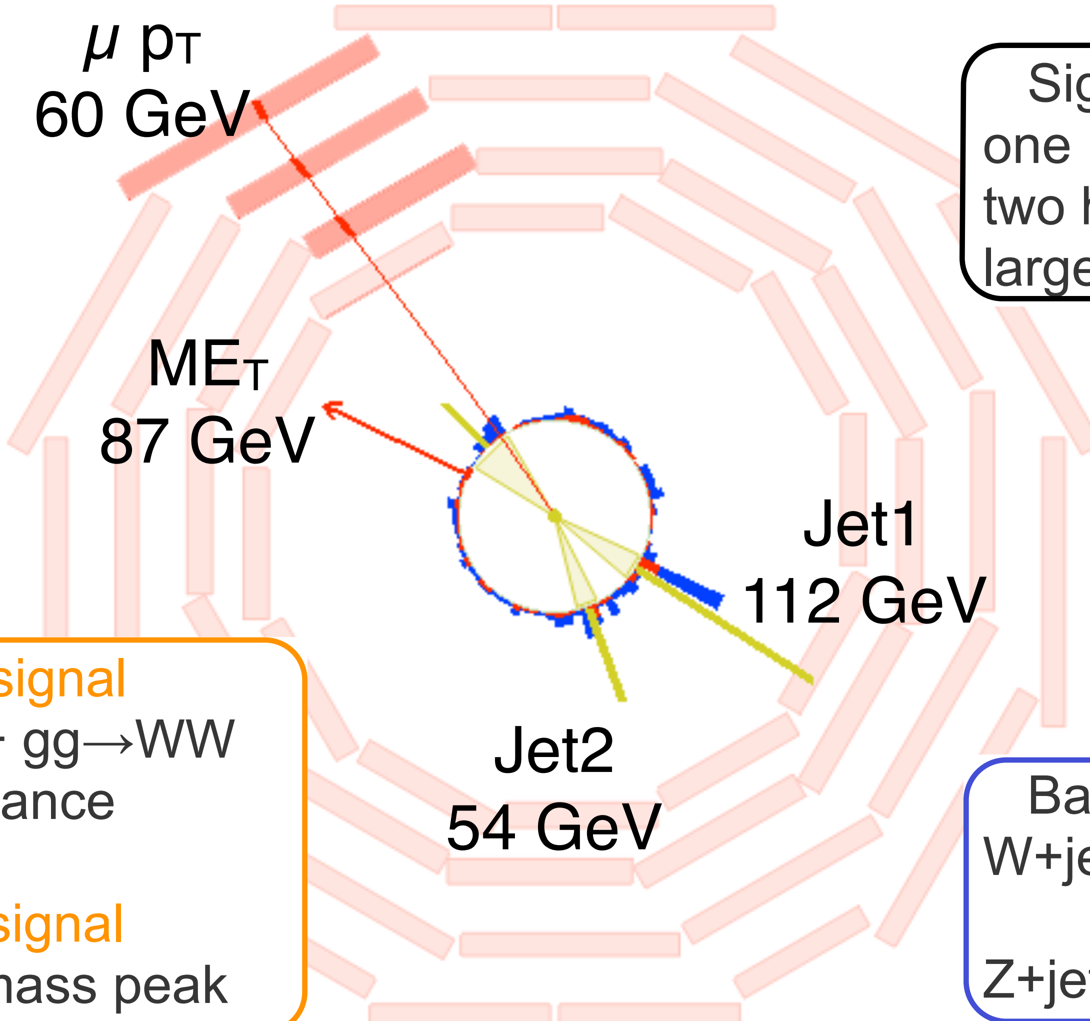
Standard Model
= expected

new type of couplings
= new physics

But have very small production rate



Experimental signature



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

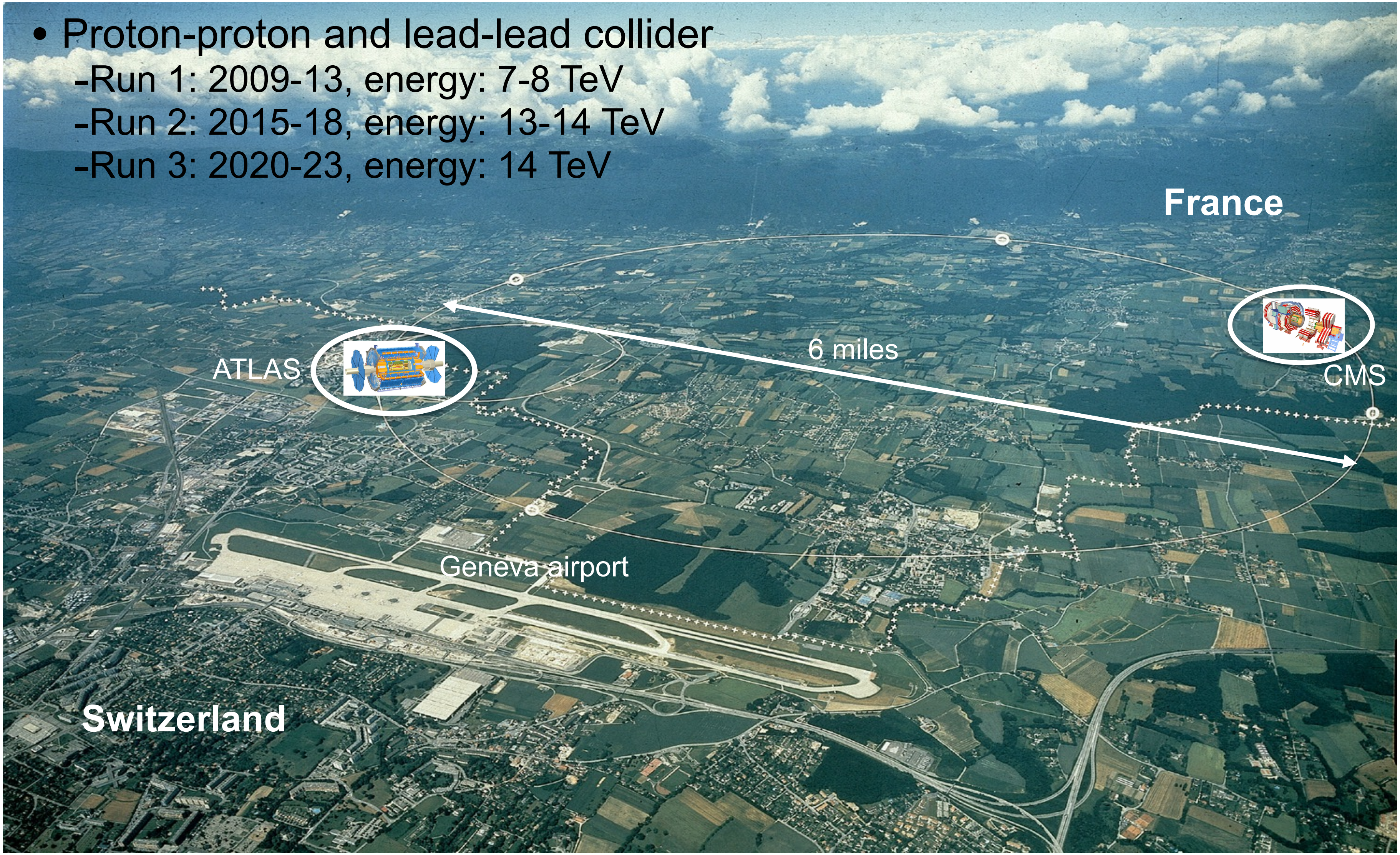
SM WW signal
$qq \rightarrow WW + gg \rightarrow WW$
no resonance

$H \rightarrow WW$ signal
resonant mass peak

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

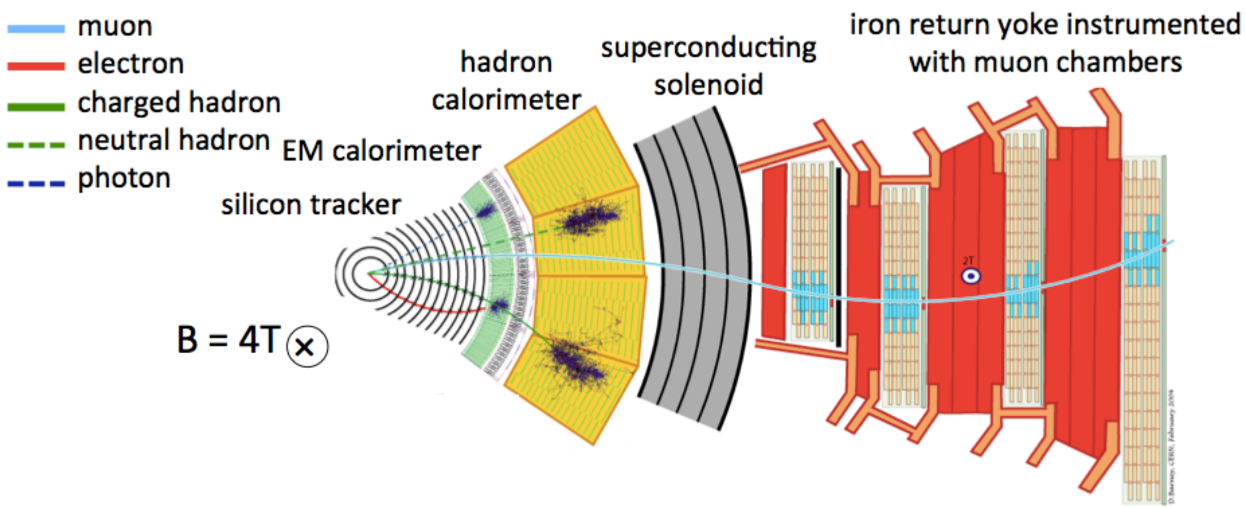
The Large Hadron Collider at CERN

- Proton-proton and lead-lead collider
  - -Run 1: 2009-13, energy: 7-8 TeV
  - -Run 2: 2015-18, energy: 13-14 TeV
  - -Run 3: 2020-23, energy: 14 TeV



And its detectors

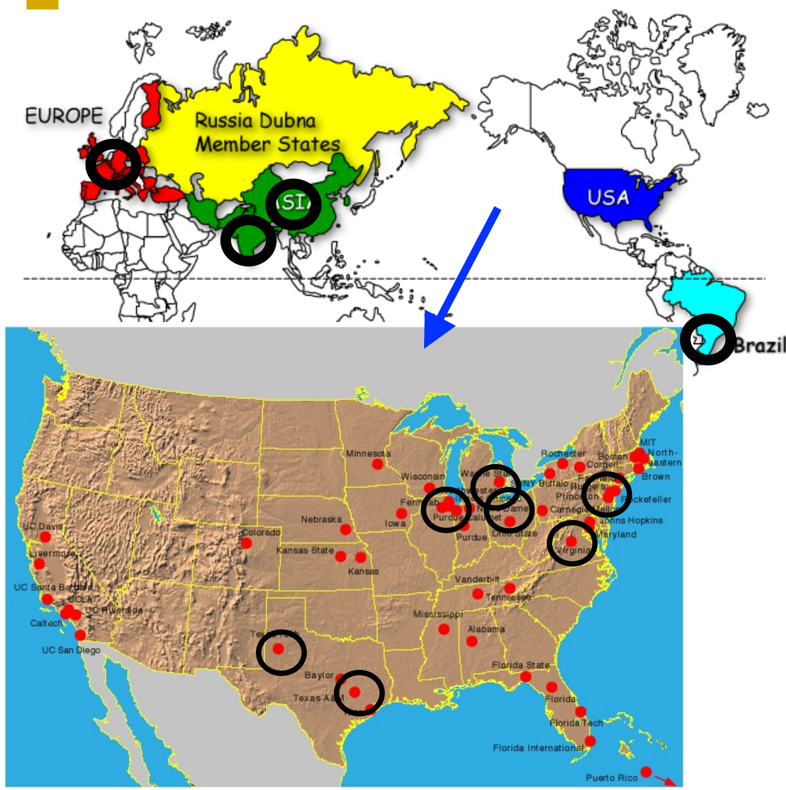
- Two multi-purpose detectors: ATLAS and CMS
  - have similar components, both support a large physics program
- I've been a member of the CMS collaboration for the past 5 years



The results I will present today rely most critically on

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

Strength in collaboration: a personal experience

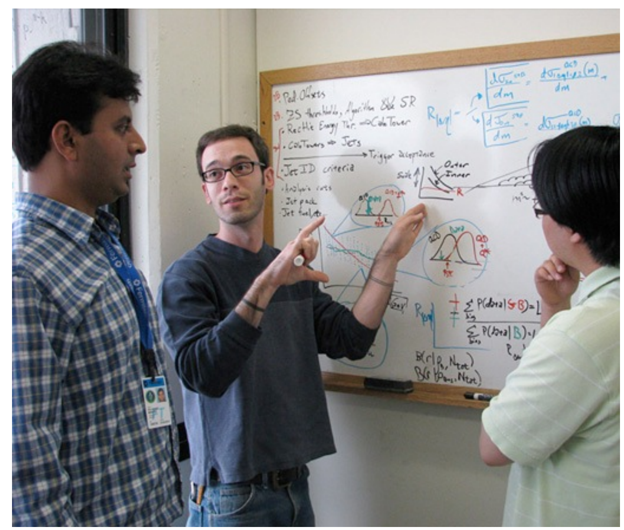


Nural Akchurin[1], Jake Anderson[2], Chayanit Asawatangtrakuldee[11], Andrea Benaglia[3], Andrew Beretvas[2], Jeffrey Berryhill[2], Pushpa Bhat[2], Sarah Boutle[4], Chris Clarke[5], Fabio Colombo[3], Analu Custodio[10], Jordan Damgov[1], Leonardo Di Matteo[3], Phil Dudero[1], Ricardo Eusebi[6], Pietro Govoni[12], Dan Green[2], Joey Goodell[4], Robert Harr[5], Pratima Jindal[13], Ajay Kumar[7], Kristina Krylova[5], Kevin Lannon[9], Sung-Won Lee[1], Qiang Li[11], Shuai Liu[11], Wuming Luo[9], Yajun Mao[11], Kellen McGee[5], Kalanand Mishra[2], Md. Naimuddin[7], Chris Neu[4], Ilya Osipenkov[6], Alexx Perloff[6], Kirti Ranjan[7], Sasha Sakharov[5], Ram K Shivpuri[7], Kevin Siehl[5], Andre Sznajder[10], Nhan V. Tran[2], Zijun Xu[11], Weimin Wu[2], John Wood[4], Fan Yang[2], Francisco Yumiceva[2], and Wei Zou[11]

[1] Texas Tech University, Lubbock, Texas, USA
[2] Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[3] Milano-Bicocca University and INFN, Milan, Italy
[4] University of Virginia, Charlottesville, Virginia, USA
[5] Wayne State University, Detroit, Michigan, USA
[6] Texas A&M University, College Station, Texas, USA
[7] Delhi University, Delhi, India
[8] University of Nebraska at Lincoln, Nebraska, USA
[9] University of Notre Dame, Notre Dame, Indiana, USA
[10] Universidade do Estado do Rio de Janeiro (UERJ), Brazil
[11] Peking University, China
[12] CERN
[13] Princeton Unversity, New Jersey, USA

The people I have worked with (the "$\ell\nu jj$ team"):

- About 30 people on 4 continents
- In the past four years
  - 10 high impact papers
  - detector, calibration, upgrade

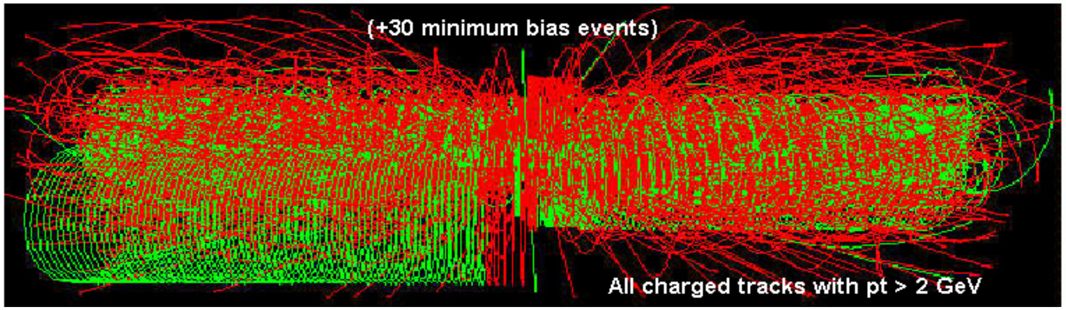


http://lpc.fnal.gov/

Collision environment more challenging than ...

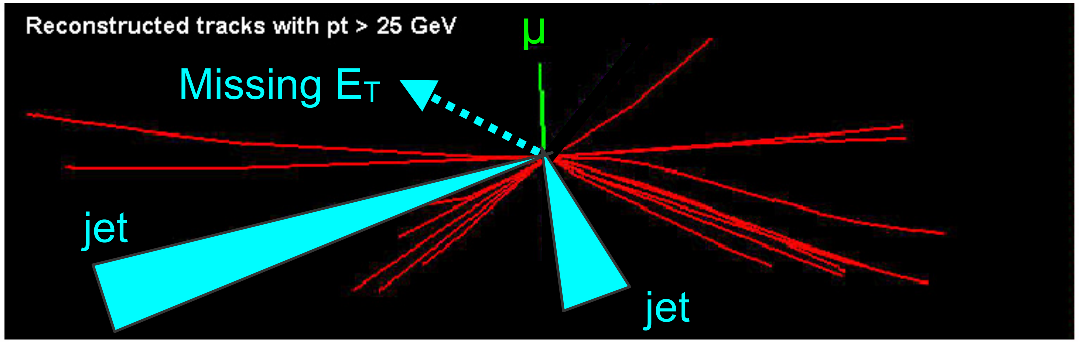
… a needle in a million haystacks!

Starting from this event



- 600,000,000 proton-proton interactions/sec
- 0.0005 Higgs / second

We look for this signature



Selectivity: 1 in 10^{12}

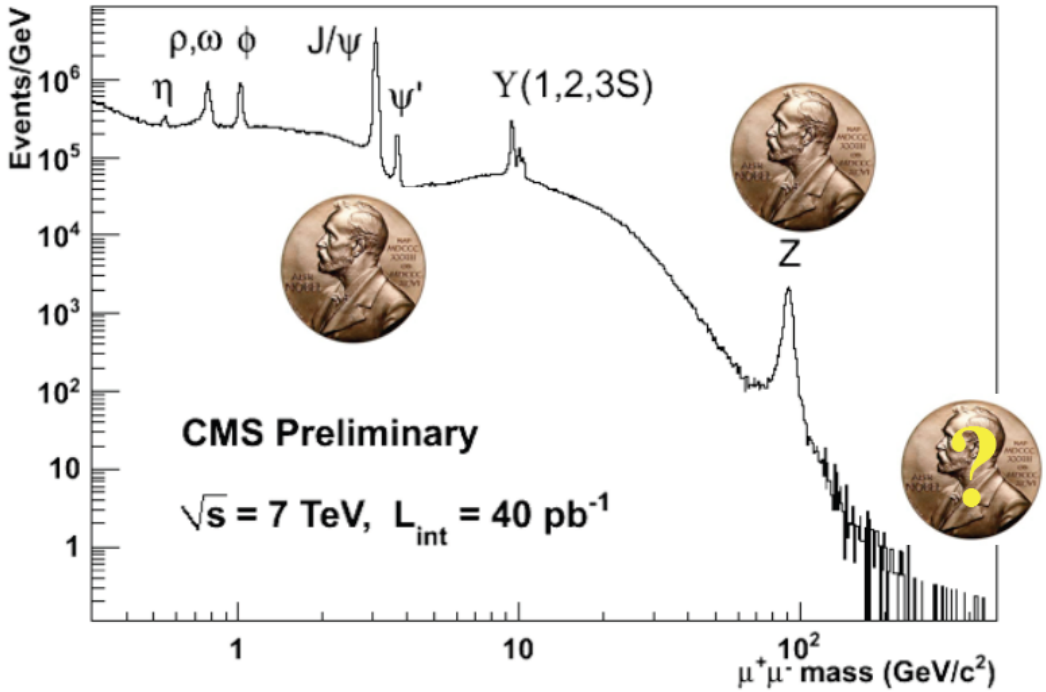
Like looking for 1 person in 200 world populations

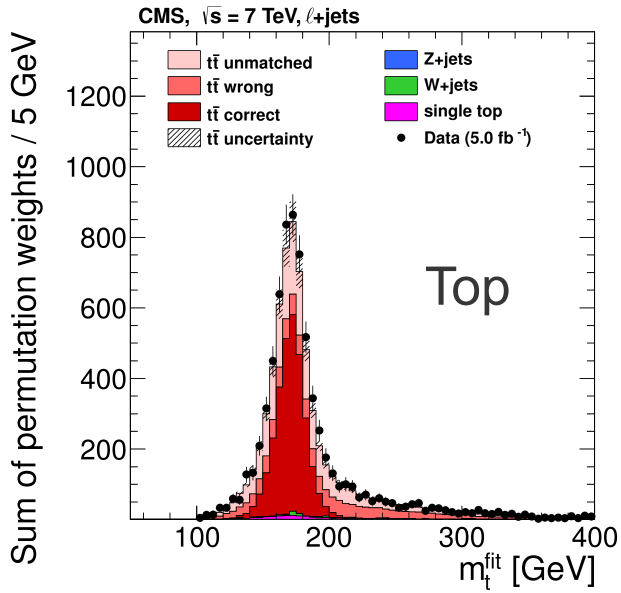
Significant effort invested in calibrating the two detectors ➜

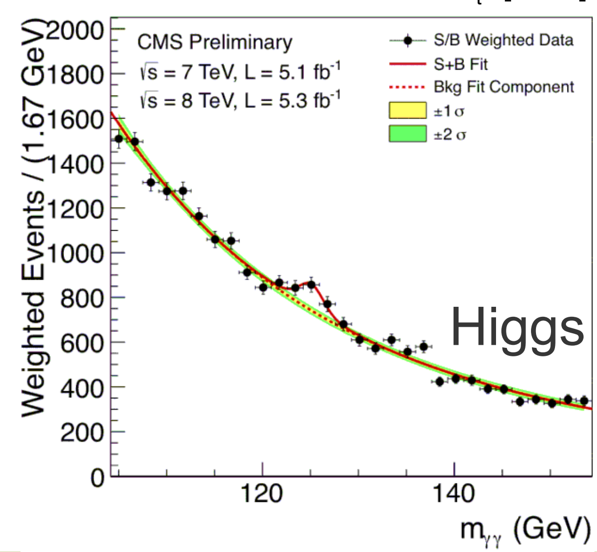
Detector calibration with early data

Re-established the Standard Model

- known peaks → calibrate detector
- new peak → heralds new discovery







Excellent calibrations of electrons, muons, photons, jets, missing E_T, b-tag, …

Pileup from additional proton-proton interactions

Created a huge experimental challenge

So much that the entire community with stake in its resolution got together …

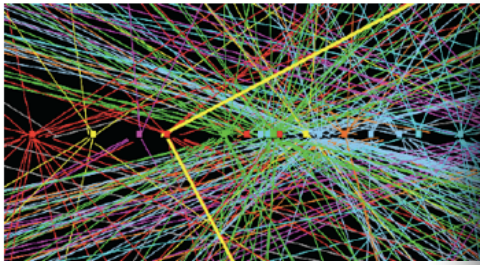
Jet substructure performance at high luminosity
BOOST 2012 working group

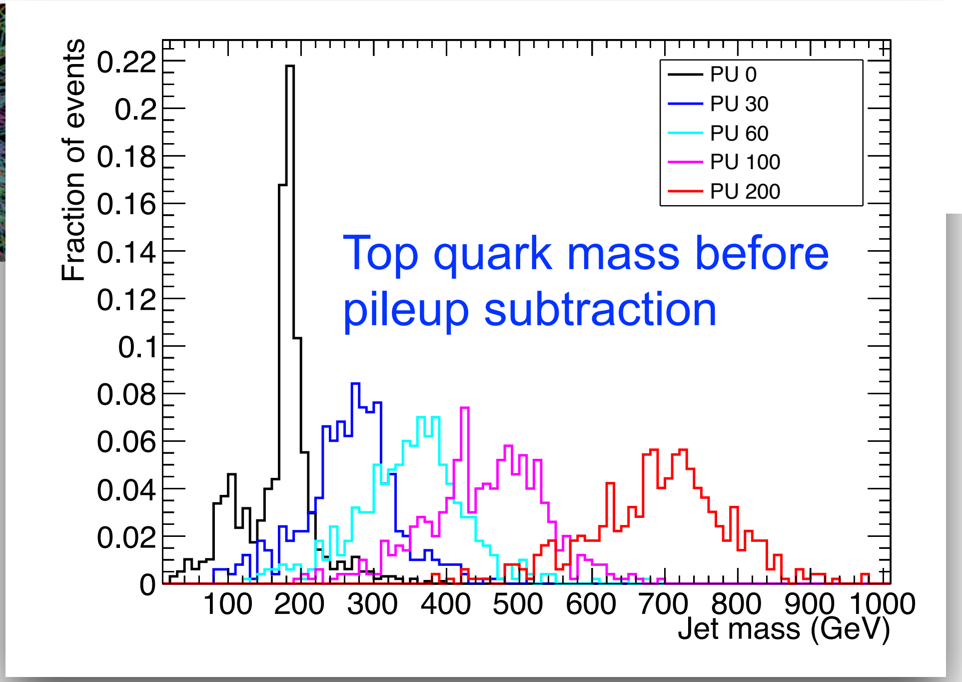
Conveners: Gregory Soyez and Ariel Schwartzman

Pile-up subtraction plus grooming

Coordinator: Mishra Kalanand

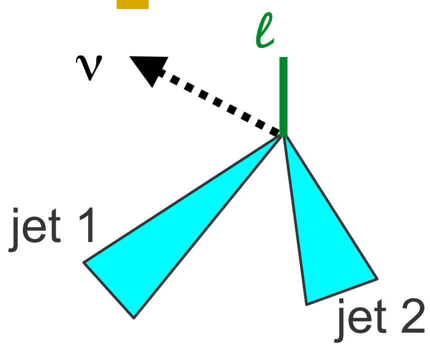
- Study the application of jet-areas pile-up subtraction during grooming



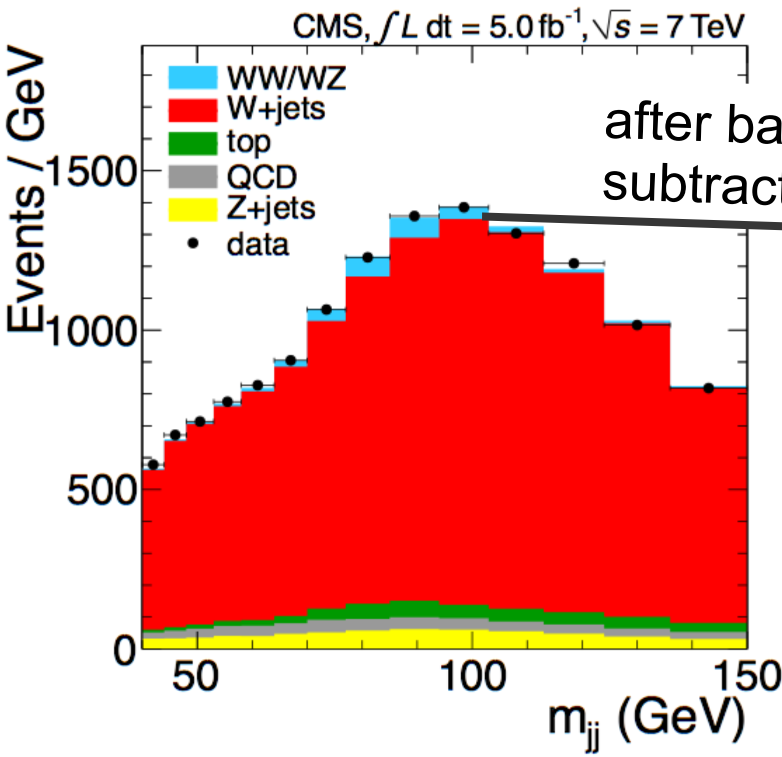


BOOST 2012 report
arXiv:1311.2708
To appear in *Eur J Phys* C

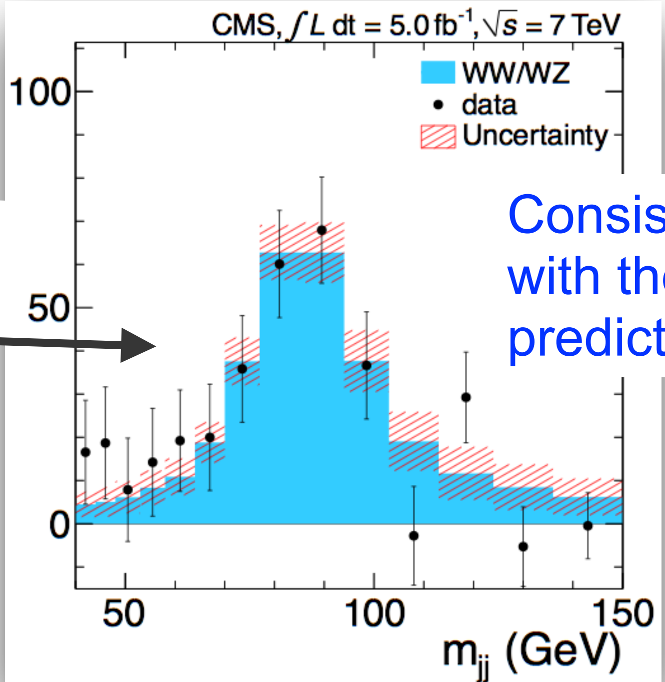
Reconstructing W or Z→$q\bar{q}$



- Establish presence of WW+WZ in such events
- Jet resolution doesn't allow to cleanly separate WW from WZ, so get admixture of the two



after background subtraction

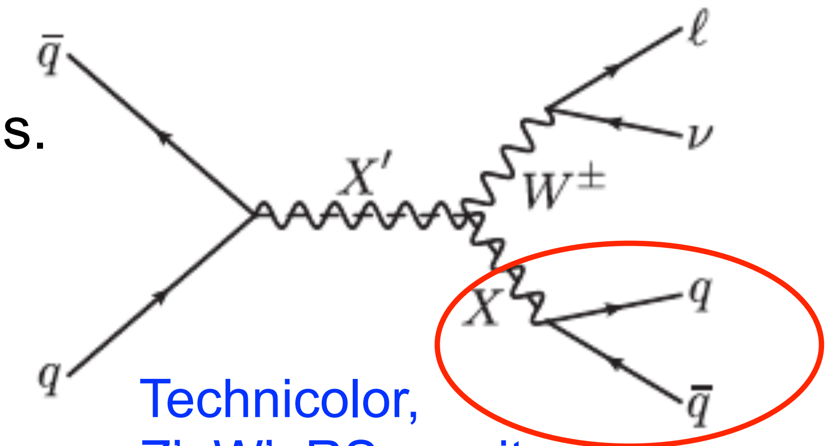


Consistent with the SM prediction

The first observation of diboson in semi-leptonic channel at LHC.

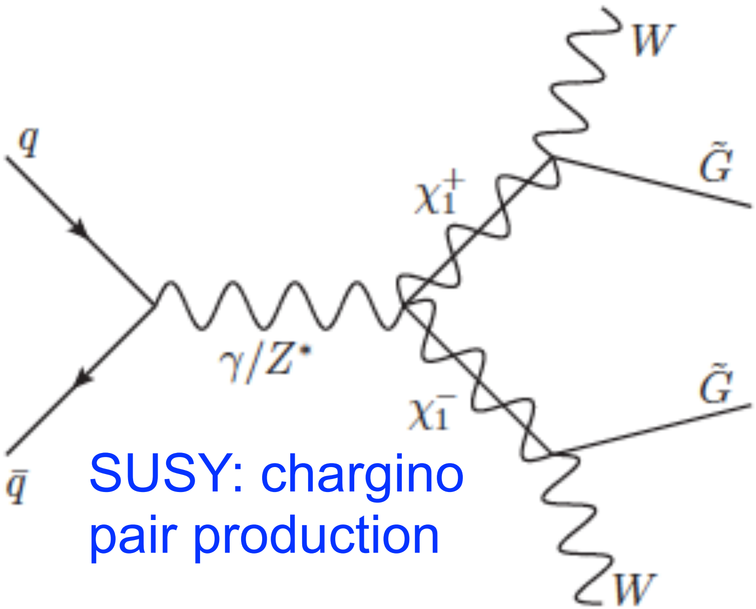
Sensitive to new physics even at "low scale"

New physics can enhance WW/WZ production or can produce new particles.



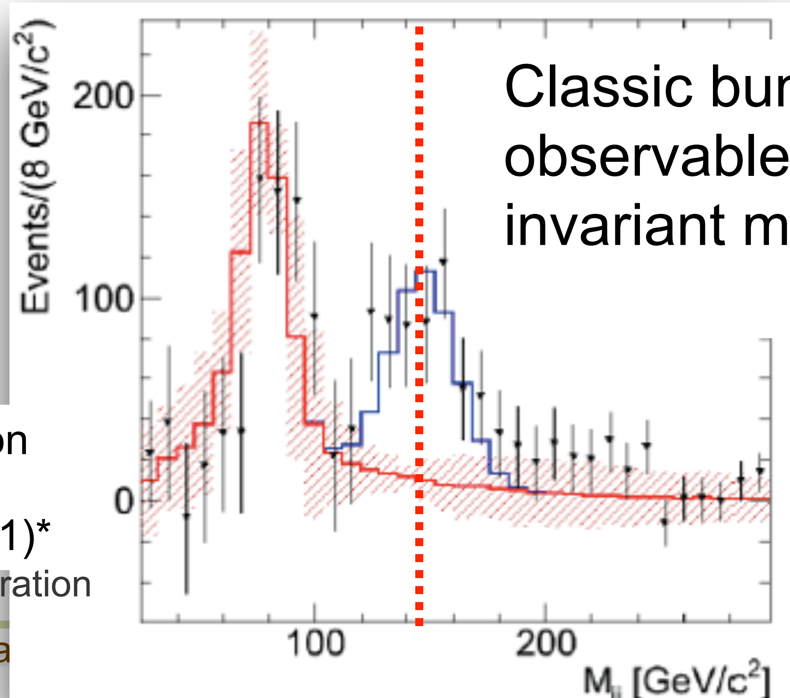
Technicolor, Z', W', RS graviton

A new particle



SUSY: chargino pair production

LSP

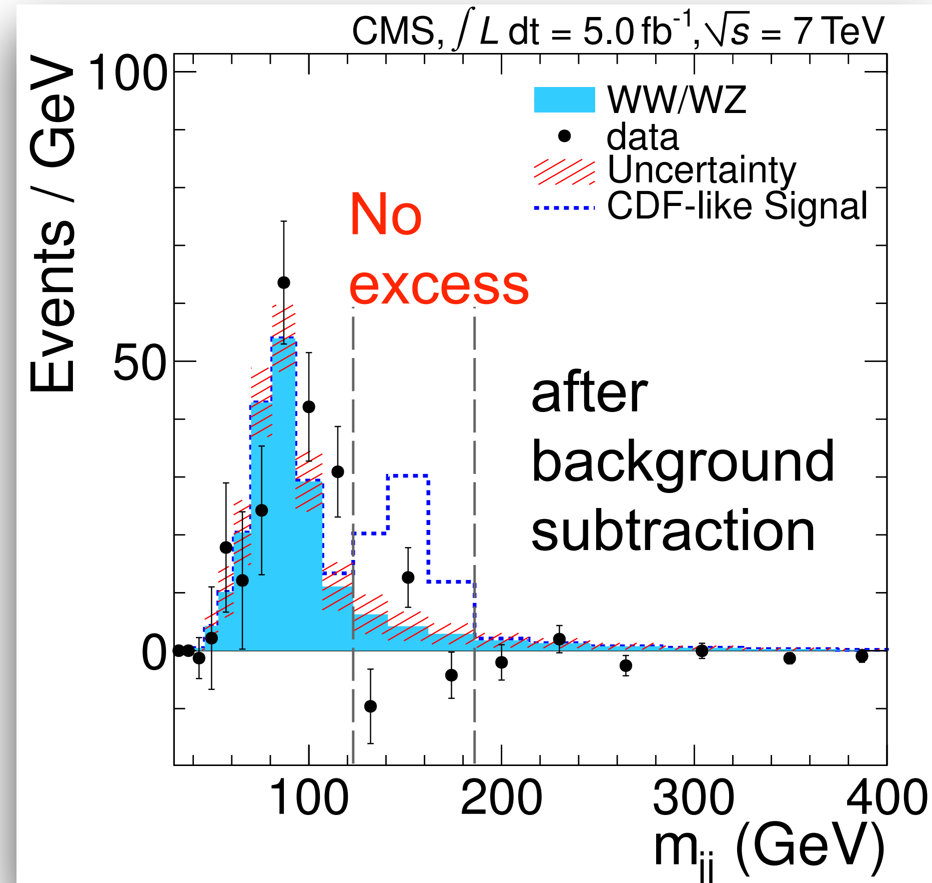


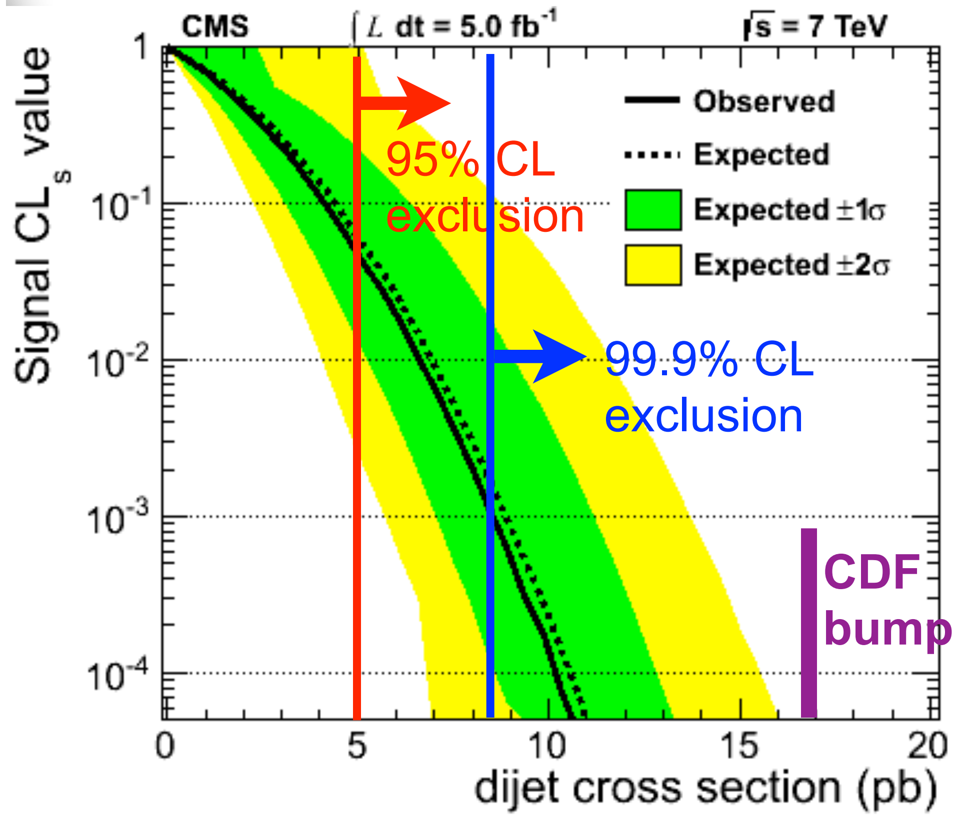
Classic bump hunt: observable is the invariant mass

CDF Collaboration Phys. Rev. Lett. 106,171801 (2011)*

*Now found to be a mis-calibration

Following CDF 2011 result increased m_{jj} window



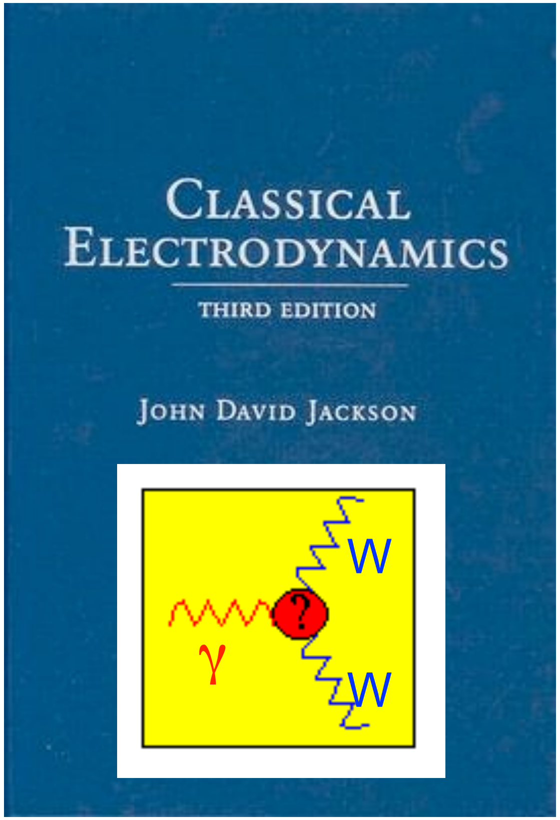


Excluded several classes of new physics models such as low scale technicolor, leptophobic Z', ... etc.

Outline

- **Higgs boson: connection to a broken symmetry**
  - What does it tell us experimentally?
- **Probes of the broken symmetry**
  - Weak boson pair production
  - Measurement of production rates
  - Connection to new physics
- **Focus on electroweak interaction at high energies**
  - New physics searches in weak boson couplings
- **Summary**

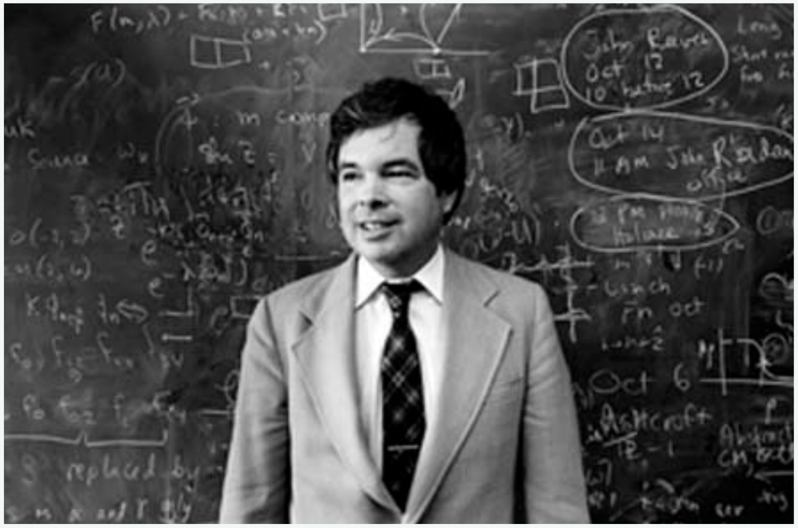
Understanding W interaction in semi-classical theory



- Interaction between W and e.m. field completely determined by 3 numbers:
  - W's electric charge $1/r^2$
  - W's magnetic dipole moment $\mathbf{1/r^3}$
  - W's electric quadrupole moment $\mathbf{1/r^4}$
- Measuring the WWγ couplings ≡ measuring the 2nd and 3rd numbers above

Sensitivity to new physics is at short distances/ high mass

In quantum field theory ...



Ken Wilson (1936–2013)
Nobel prize 1982

Wilsonian approach

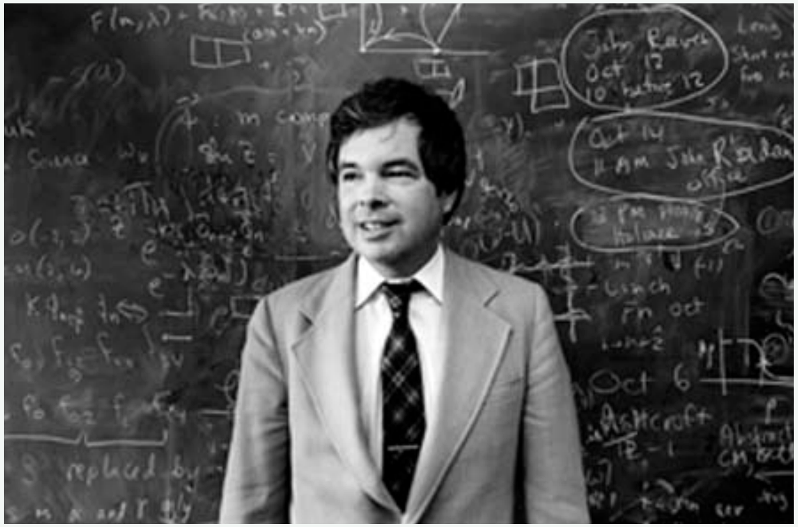
That which is not forbidden is required:

include all interactions consistent with space-time, global, and gauge symmetries

Data = SM + Correction from new physics

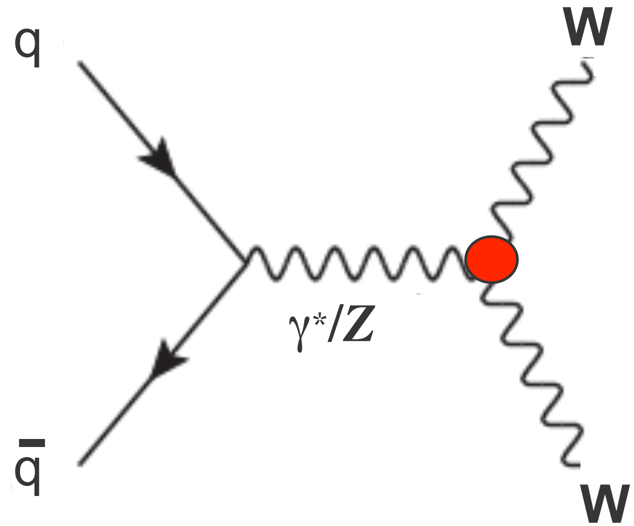
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n=1}^{\infty} \sum_{i} \frac{c_i^{(n)}}{\Lambda^n} \mathcal{O}_i^{(n+4)}$$

In quantum field theory ...



Ken Wilson (1936–2013)
Nobel prize 1982

Wilsonian approach



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

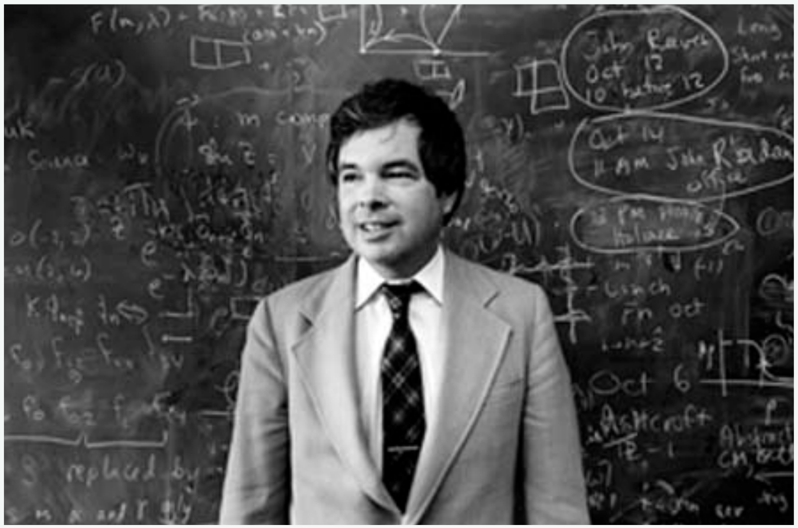
(with)

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

\+ three similar terms for the Z

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

In quantum field theory ...



Ken Wilson (1936−2013)
Nobel prize 1982

Wilsonian approach

The convention is that every parameter you see (e.g. Δg_1^Z, $\Delta\kappa_\gamma$, λ_γ) is zero in the SM.

For Δg and $\Delta\kappa$: effects grow as $\sqrt{\text{energy}}$

For λ : effects grow as energy

Unprecedented reach at LHC

Connecting the two together

Dipole and quadrupole moment of W boson

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

Jackson 3rd ed, Eq. 5.59

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

Eq. 4.9

We probe their deviation from 0.

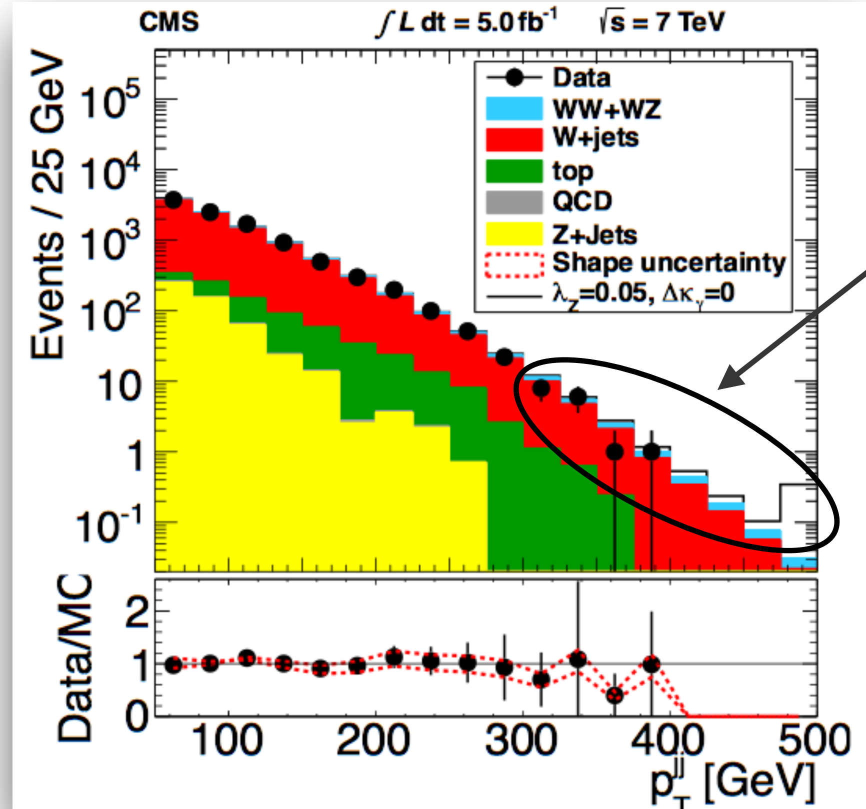
Analogous to muon magnetic dipole moment

Value of "(g−2)/2" = 0.00116591802 (50) in the Standard Model

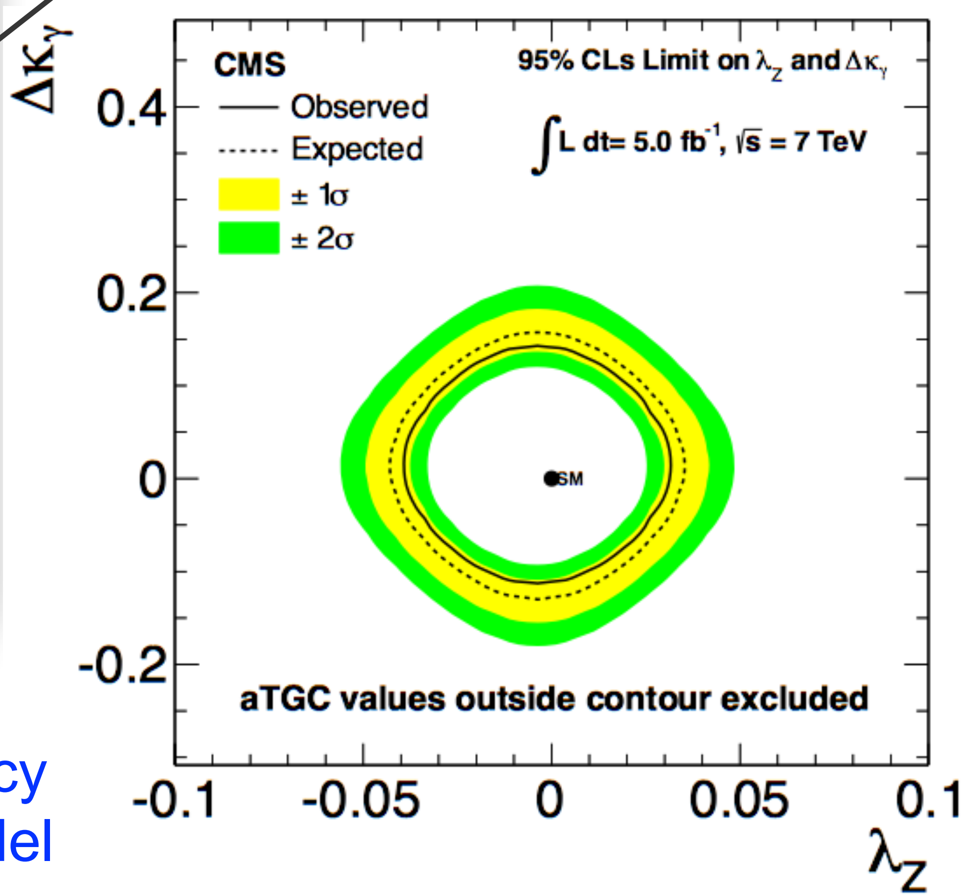
Measurement (BNL) = 0.00116592089 (63)

3.4 sigma effect

Measurement in data

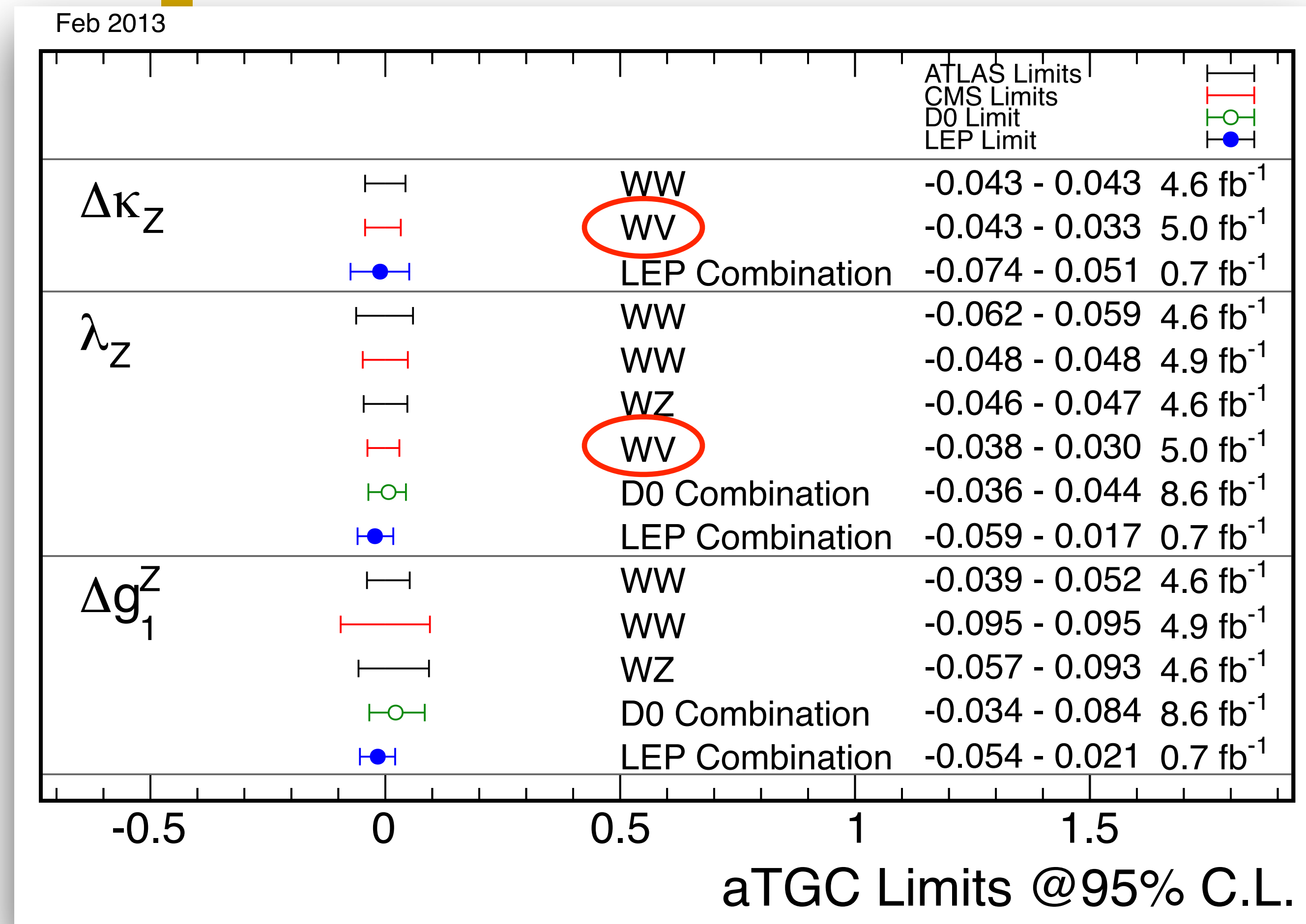


Anomalous events can show up at large W p_T.



So far good consistency with the Standard Model

Constraints on triple vertex couplings



Obtained assuming equal coupling relation

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

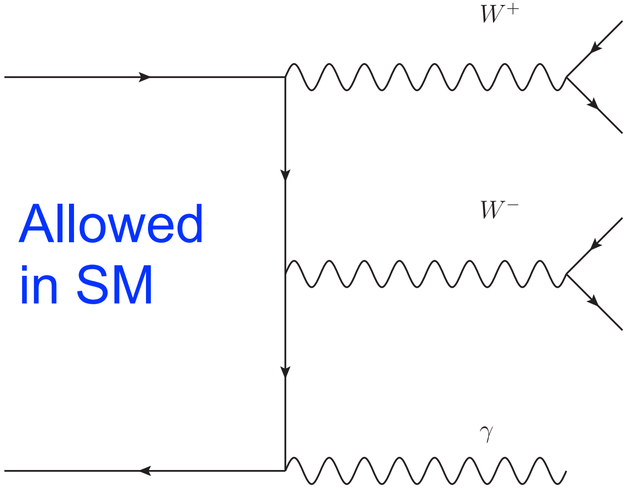
$$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \cdot \tan^2\theta_W$$

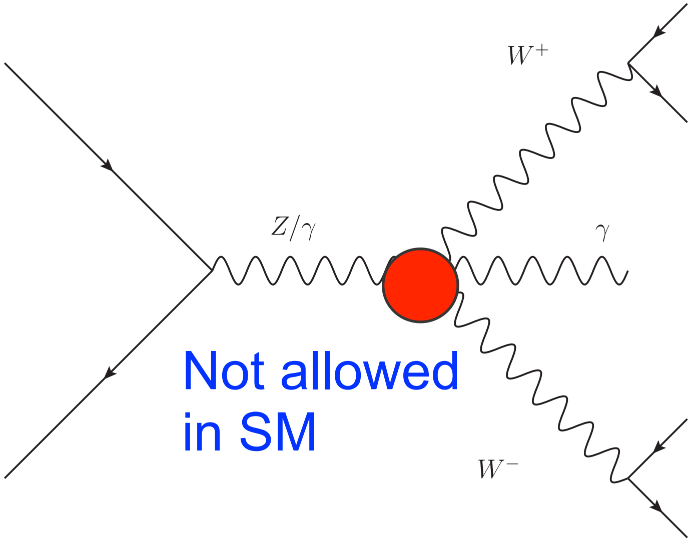
Dipole moment of W constrained at $\mathcal{O}(10^{-2})$, quadrupole moment at $\mathcal{O}(10^{-4})$.

Compare this to muon “g−2” which differs by < 0.001% from the SM value !!!

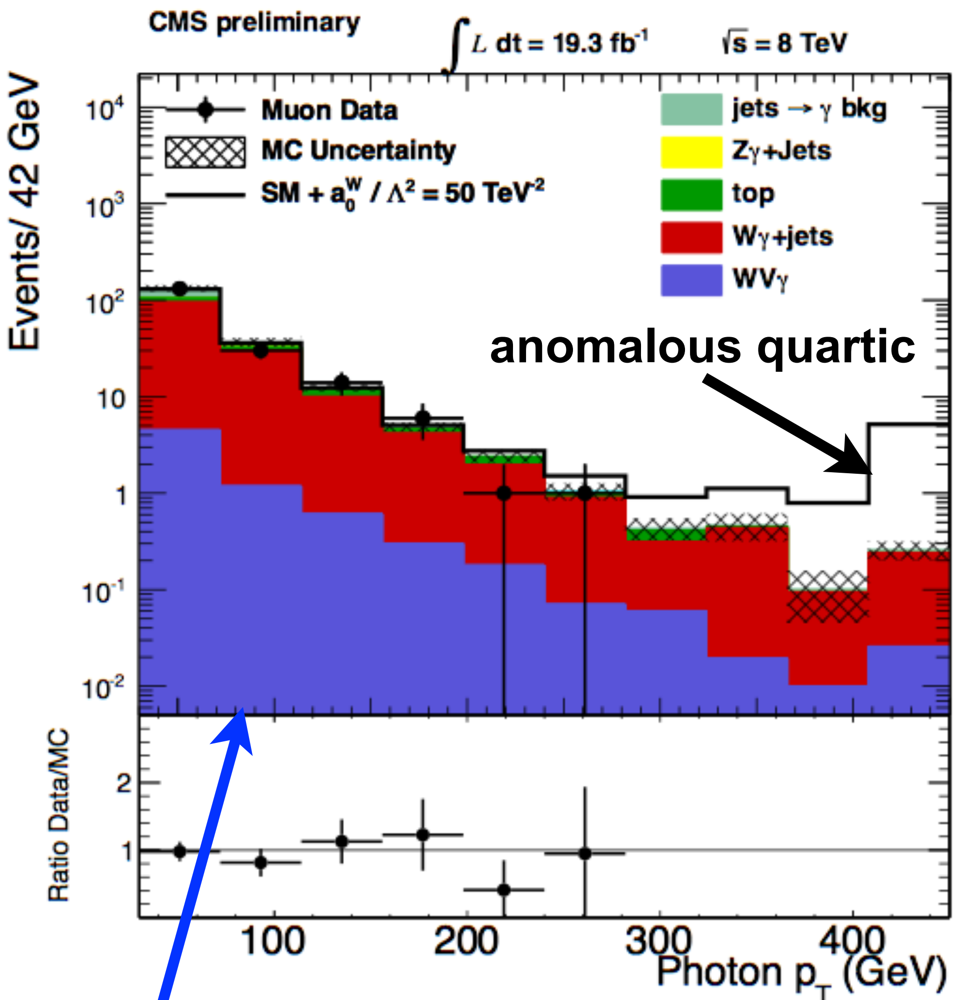
4-vertex couplings involving W boson

- Possible couplings:
  $WW\gamma\gamma$, $WWZ\gamma$, WWWW, WWZZ
- Observable in multi-boson production





What do the data say



Standard Model WVγ

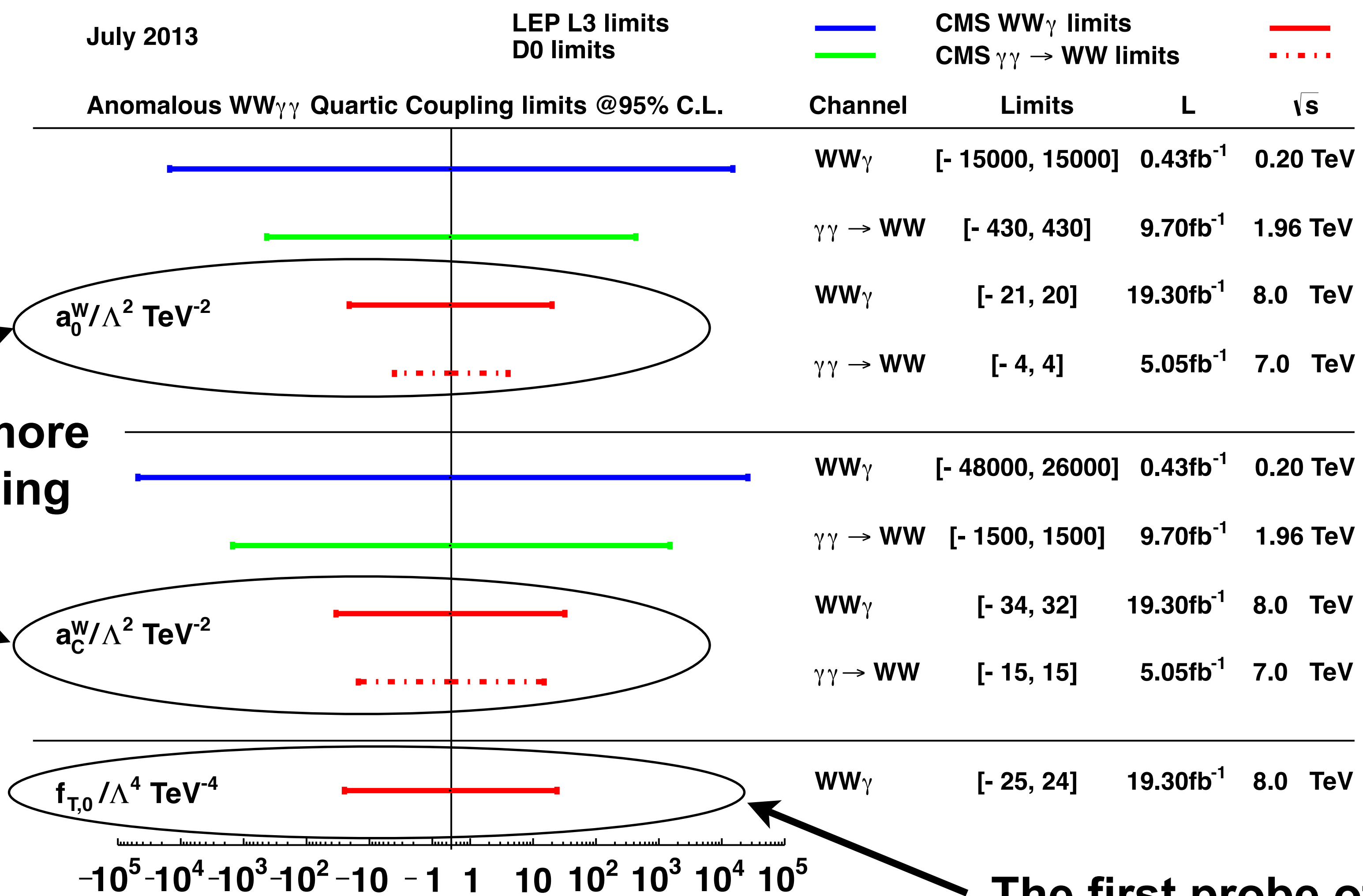
in WVγ production

V = W or Z → $q\bar{q}$

i.e., look for a photon in addition to WW or WZ.

- ☐ Not sensitive yet to the Standard Model WVγ rate
  - Upper limit: 3.4x SM
- ☑ But good sensitivity to anomalous couplings

Constraints on 4-vertex couplings



o(100) x more constraining than LEP

The first probe of this parameter

Outline

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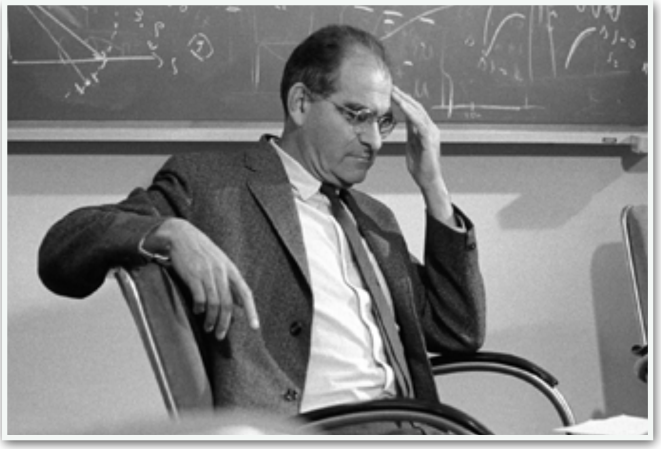
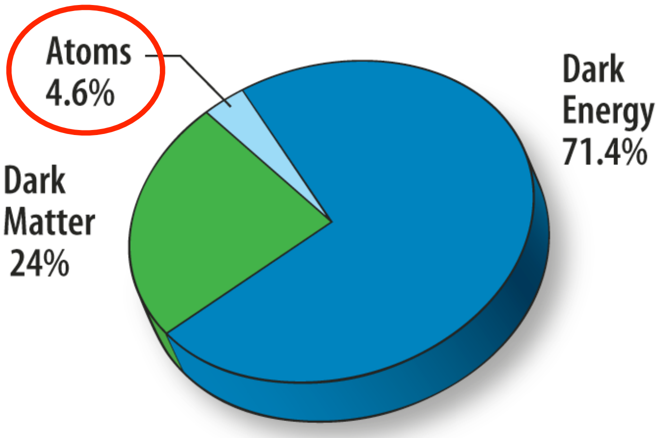
Very relevant for our current situation



“About 500 years ago man’s curiosity took a special turn toward detailed experimentation. It was the beginning of science as we know it today. Instead of reaching directly at the whole truth, at an explanation for the entire universe, science tried to acquire partial truths in small measure …. Instead of asking general questions and receiving limited answers, it asked limited questions and found general answers.”

— Viki Weisskopf, *Physics in the Twentieth Century*



- Visible matter is < 5% of our universe
- But crucial to probe the origin of mass
  - which will hopefully also tell us about the emergence of gravity from it
  - and the nature of dark matter

Goals going forward with the LHC 14 TeV run

SNOWMASS CSS 2013 ON THE MISSISSIPPI
JULY 29 – AUGUST 6, 2013

"The Higgs boson changes everything. We're obligated to understand it using all tools."

− Chip Brock (co-chair Energy Frontier)

Now that we are firmly in the post-Higgs era …

⇒ Obligated to look under the Higgs lamp post and explore

Goals going forward with the LHC 14 TeV run

Now that we are firmly in the post-Higgs era …

- Deeper probes of the origin of mass
  - Higgs couplings to fermions; W, Z bosons; self coupling
  - Invisible width ⇒ Higgs couples to dark matter
  - Anomalous couplings of W, Z, and Higgs bosons
- New physics at high energy
  - WW scattering
  - Feasible to explore with the first year of 13−14 TeV data

Summary

It has been only a year and half since the 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.

☑ Now we seek a full understanding of the origin of mass

- related to the broken symmetry of the electroweak force
- door to new underlying physics hidden behind the SM

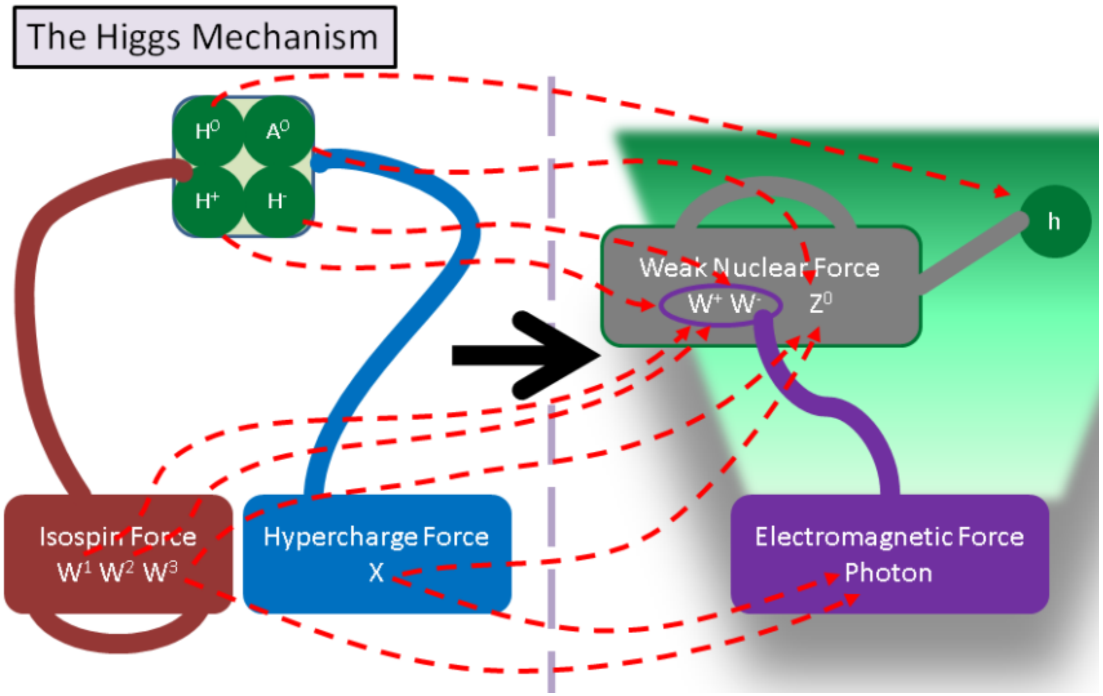
☑ With 7-8 TeV data, started to probe it

- at 3-boson vertex @ few % level
- at 4-boson vertex @ interesting levels for the first time

☑ The 13−14 TeV LHC will take us to the finish line of our goal

BACKUP SLIDES

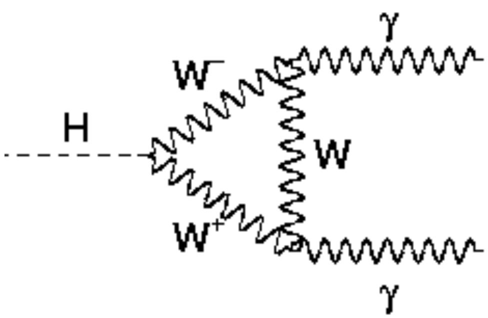
Higgs mechanism

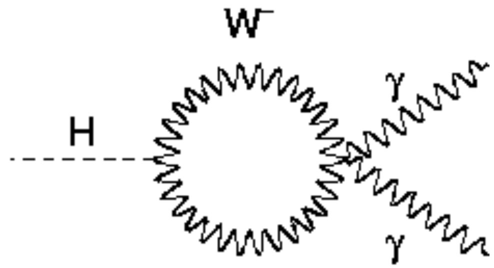


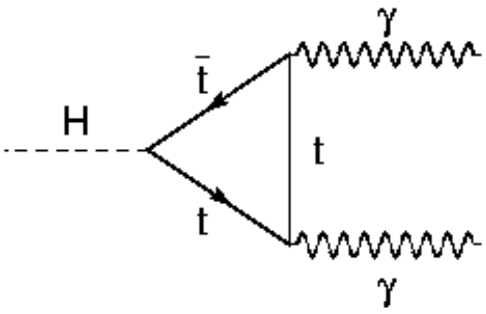
- Higgs field mixes the massless W and X force carriers
- making three of them massive
- retaining one Higgs boson

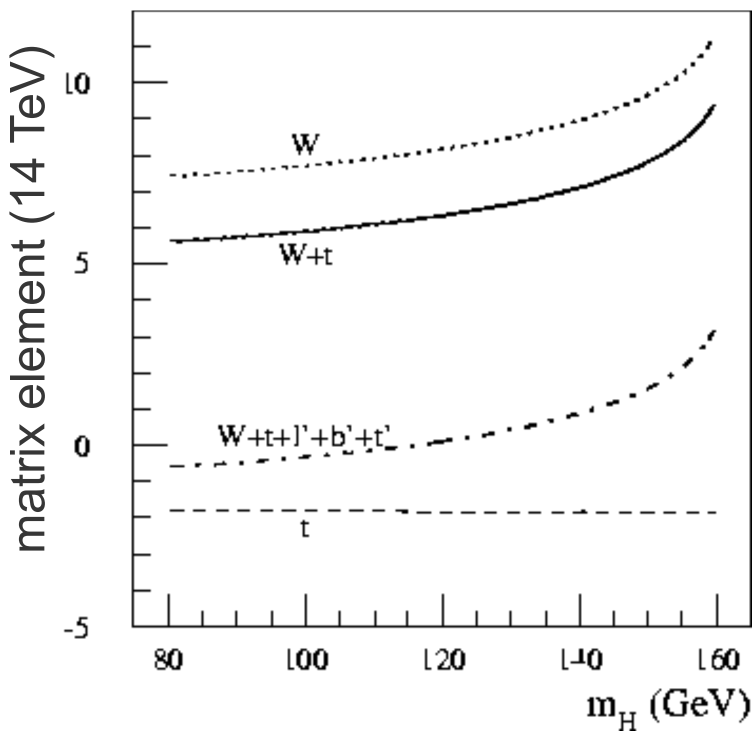
Symmetry of weak force spontaneously broken, Higgs boson the agent.

Higgs decay to two photons







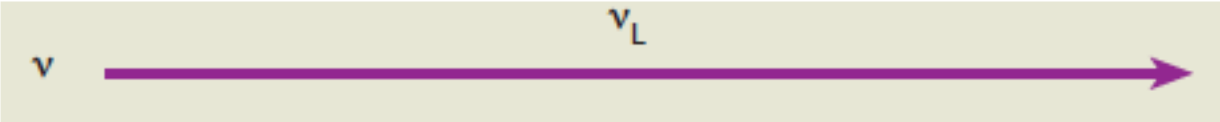


Notice that the W loop diagram dominates, however the top loop diagram has opposite sign. Heavy fermions in the loop can further bring down the rate.

What about neutrino masses?

Experiments have shown that neutrinos are always left-handed.

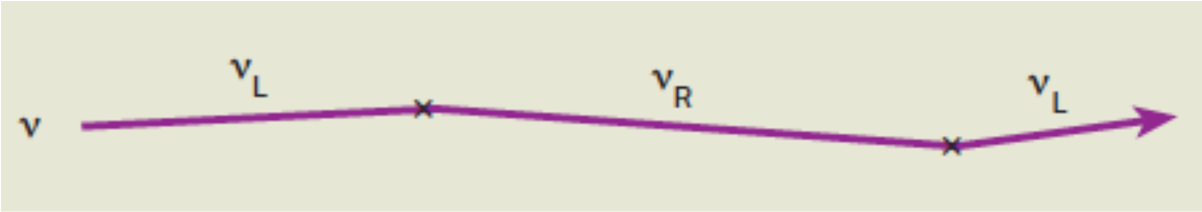
Since right-handed neutrinos do not exist in the Standard Model, the theory predicts that neutrinos can never acquire mass.



Therefore, the discovery of neutrino mass in itself is a clear evidence that, at the very least, the SM is incomplete.

Possible explanations of the neutrino masses

In one extension to the SM, left- and right-handed neutrinos exist. These Dirac neutrinos acquire mass via Higgs mechanism but right-handed neutrinos interact much more weakly than any other particles.



According to another extension of the SM, extremely heavy right-handed neutrinos are created for a brief moment before they collide with the Higgs boson to produce light left-handed Majorana neutrinos.

Other possibilities, e.g., RPV models with two pairs of Higgs doublets

arXiv:1401.1818

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
WW	5.3 σ	3.9 σ
bb	2.2 σ	2.1 σ
ττ	2.6 σ	2.8 σ

bosons (ZZ, γγ, WW)

fermions (bb, ττ): 3.4 σ combined!

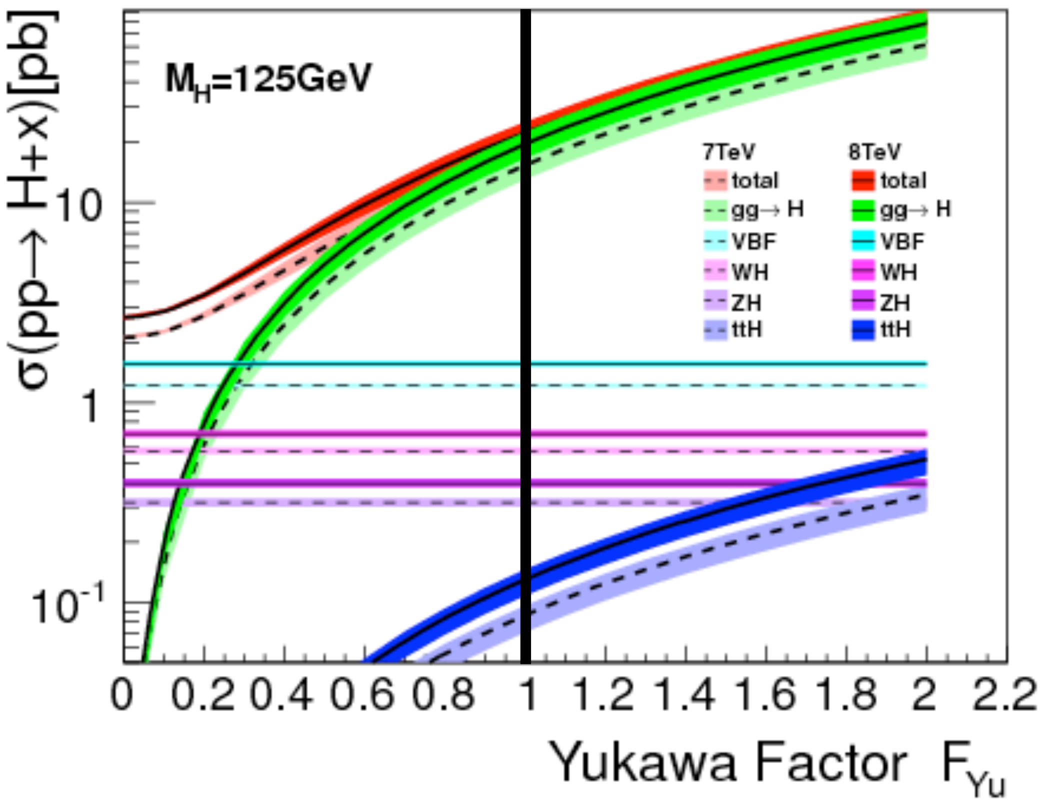
bb: includes VH and VBF, WW: includes ggF, VH, VBF

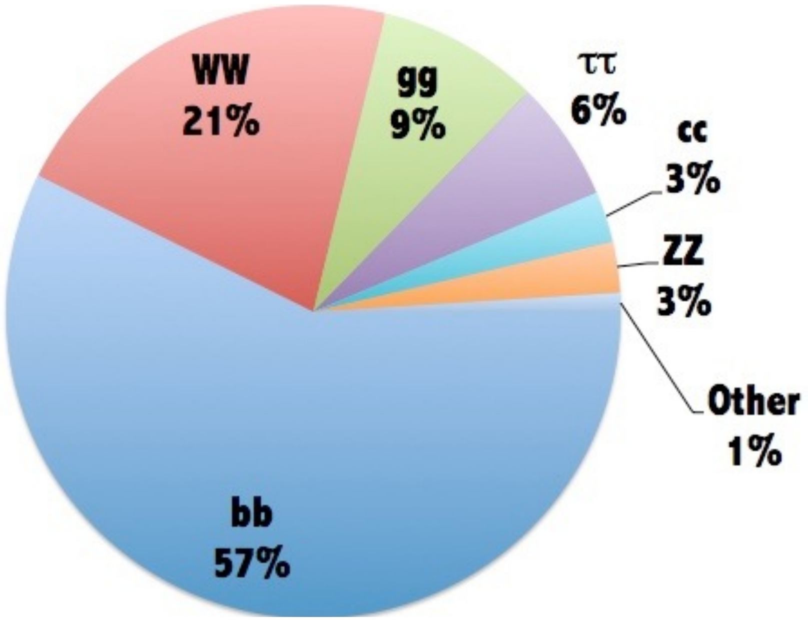
What the Higgs observation tells us immediately

Mass: m_H = 125.7 ± 0.4 GeV

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

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

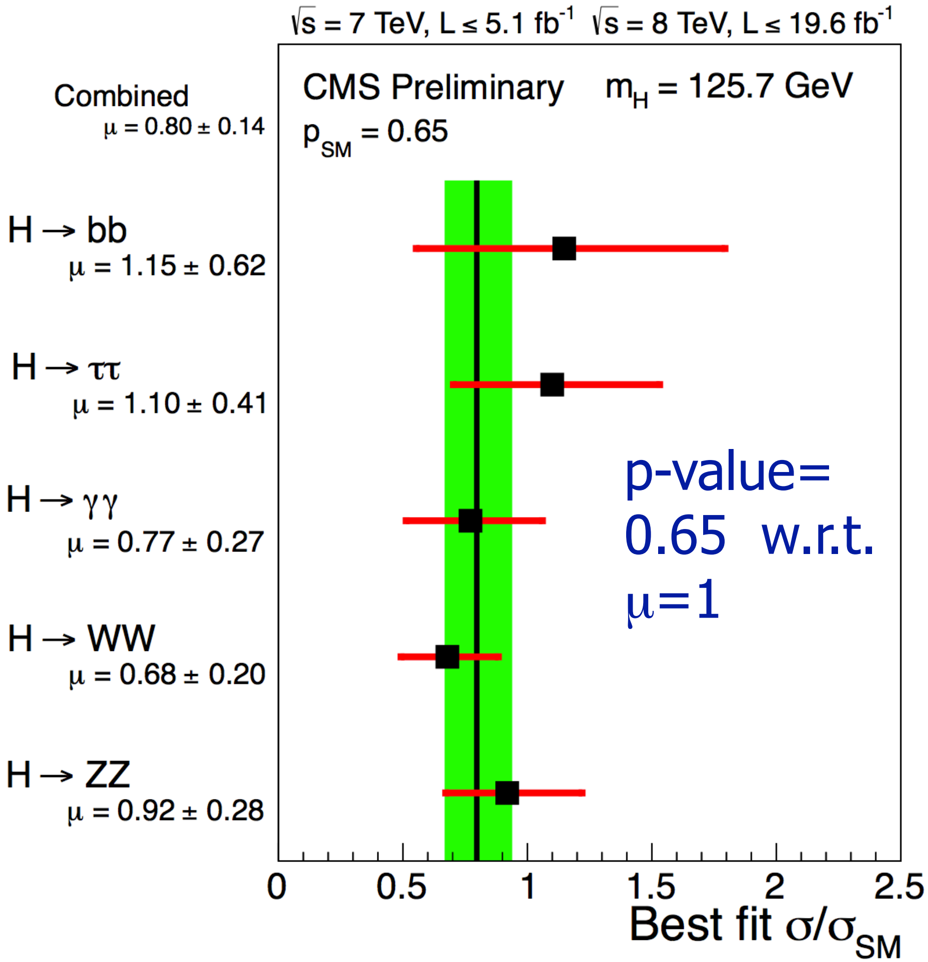


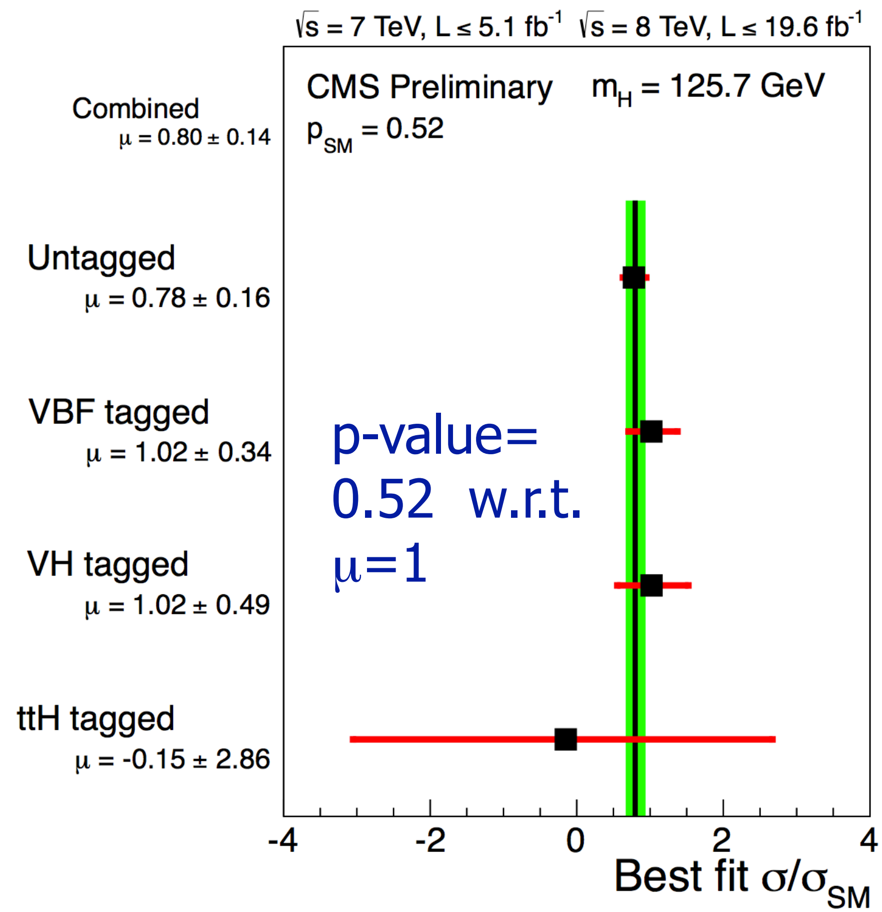


H (125) branching fraction

At LHC can only measure production rate x BR

Consistent with SM Higgs in all production & decay modes





Combined signal strength: $\mu = 0.80 \pm 0.14$

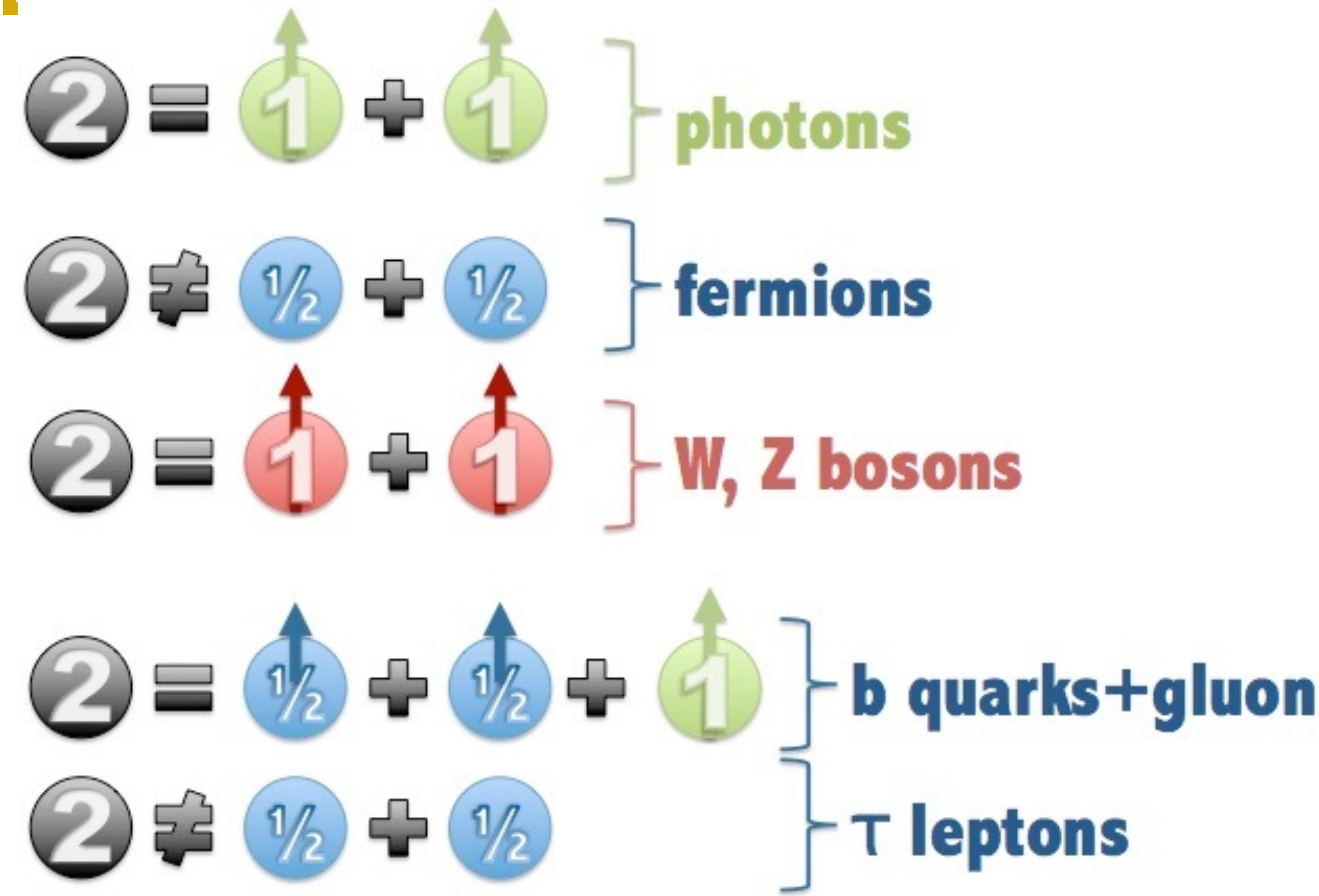
Spin-parity quantum numbers

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

Spin of particle	γγ	ZZ*	ττ	bb
Spin 0	☺	☺	☺	☺
Spin 1	☹ *	☺	☺	☺
Spin 2	☺	☺	☹	☺
Seen?	Yes	Yes	~Yes	~Yes

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

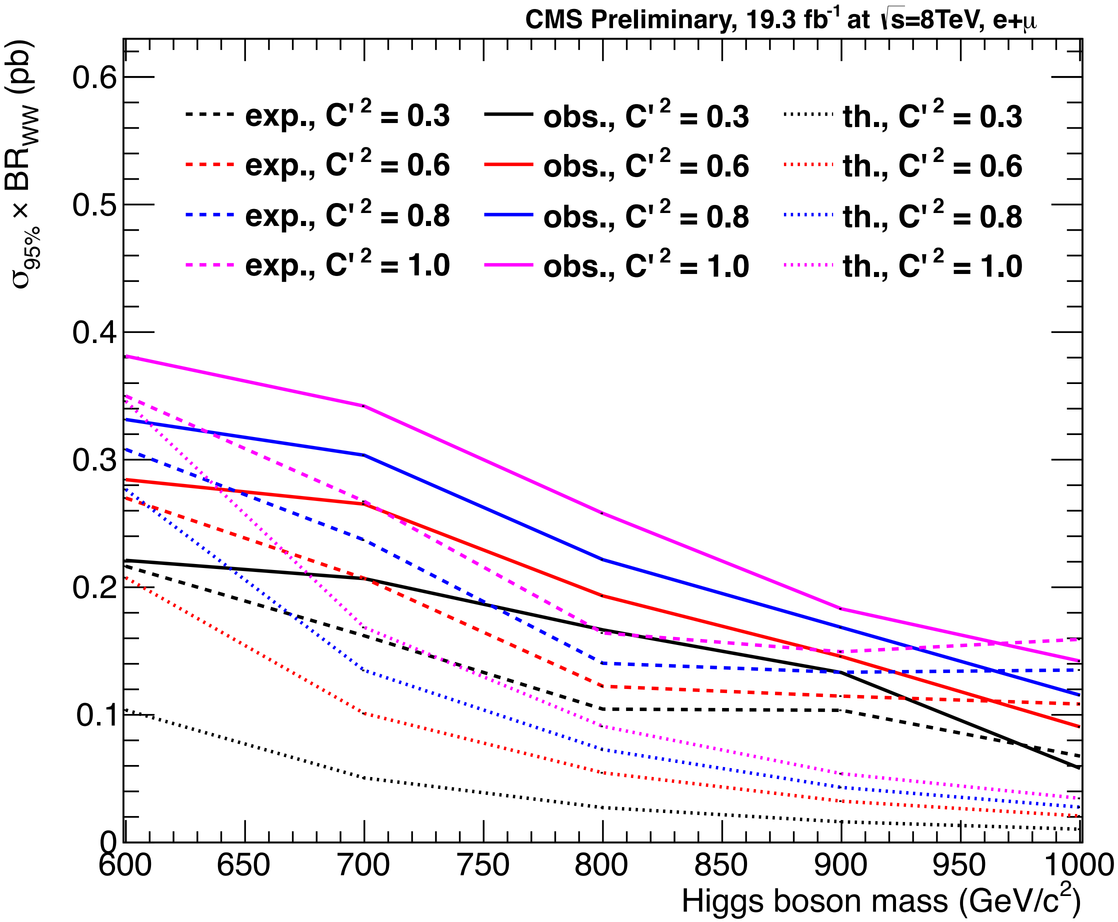
Side note: why spin-2 can decay to bb but not $\tau\tau$



Let's allow heavy Higgs to mix with H(126)

Heavy Higgs mixes with H(126) and modifies its coupling

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



C'=0 ⇒ No heavy Higgs state. We only see H(126) tail.

C'=1 ⇒ Full contribution from heavy Higgs only.

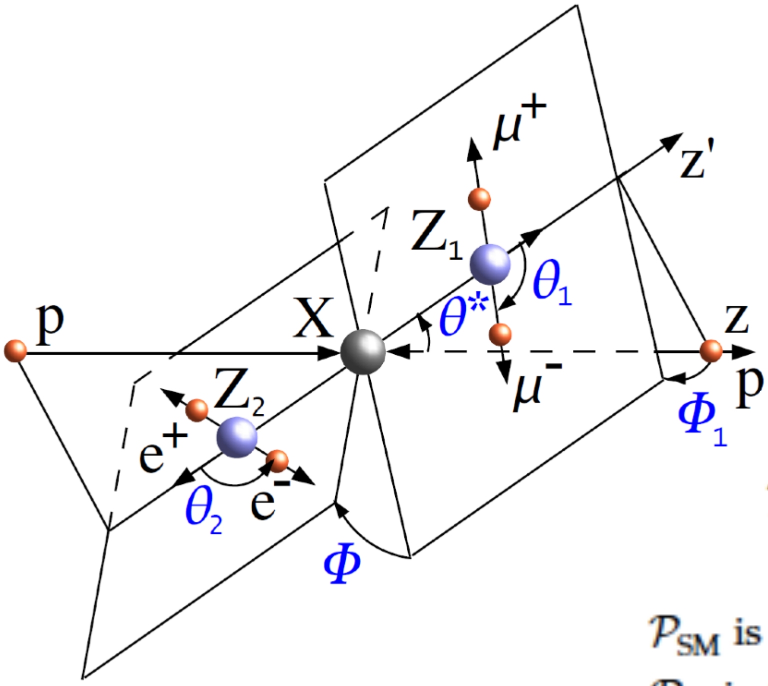
Typically $C'^2 > 0.6$ excluded for heavy Higgs < 600 GeV, closing in on 600-1000 GeV.

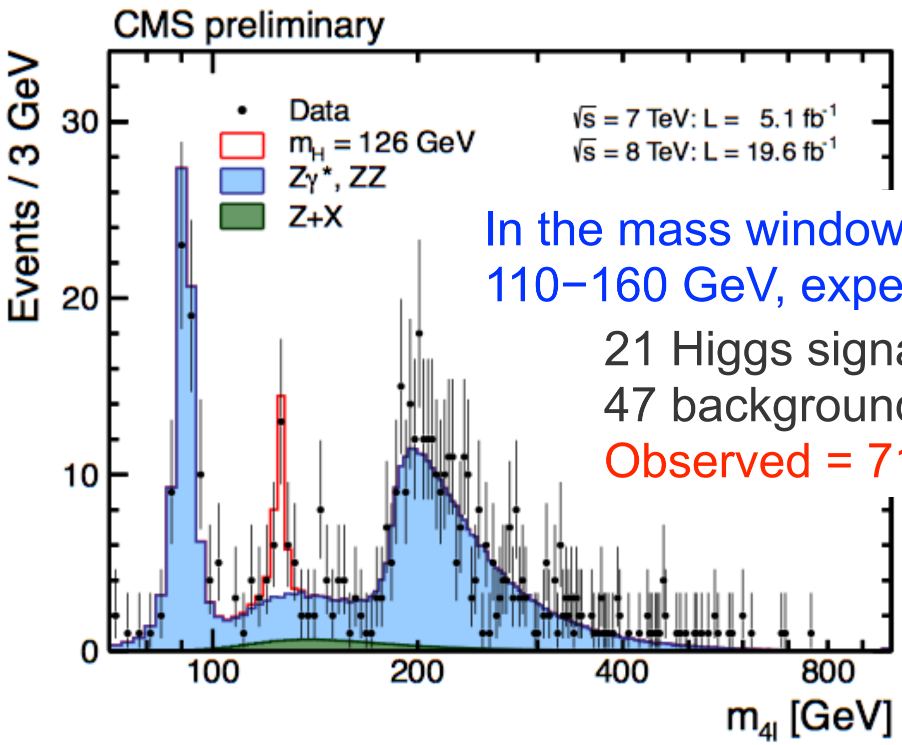
Enough events to measure spin-parity

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

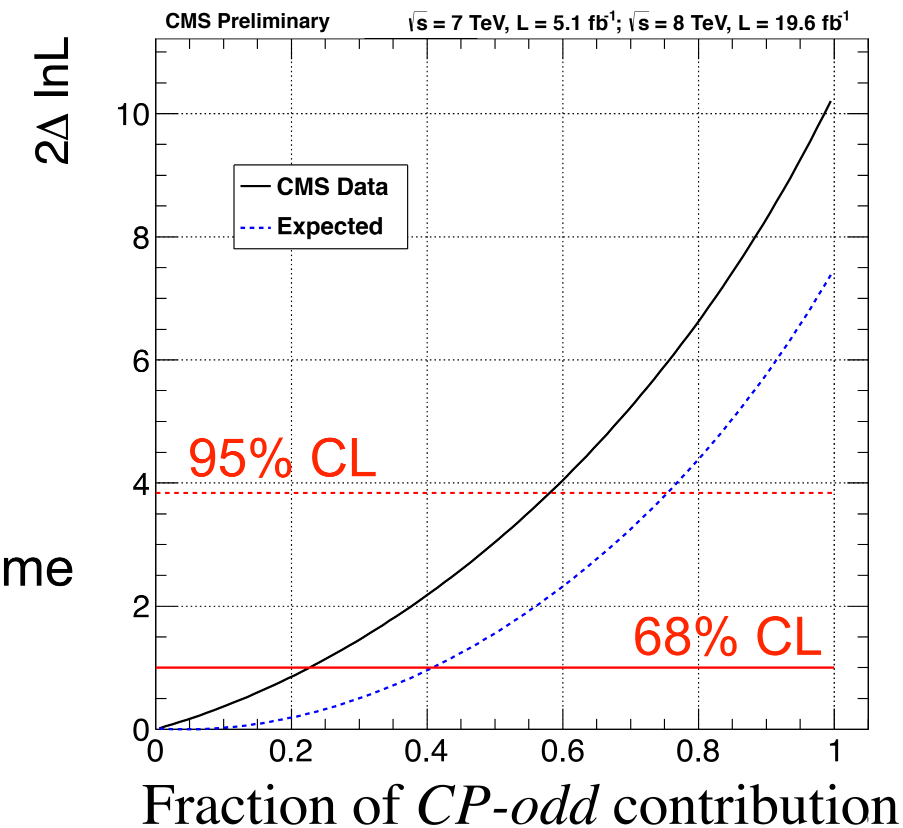
A3 : CP odd amplitude

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)

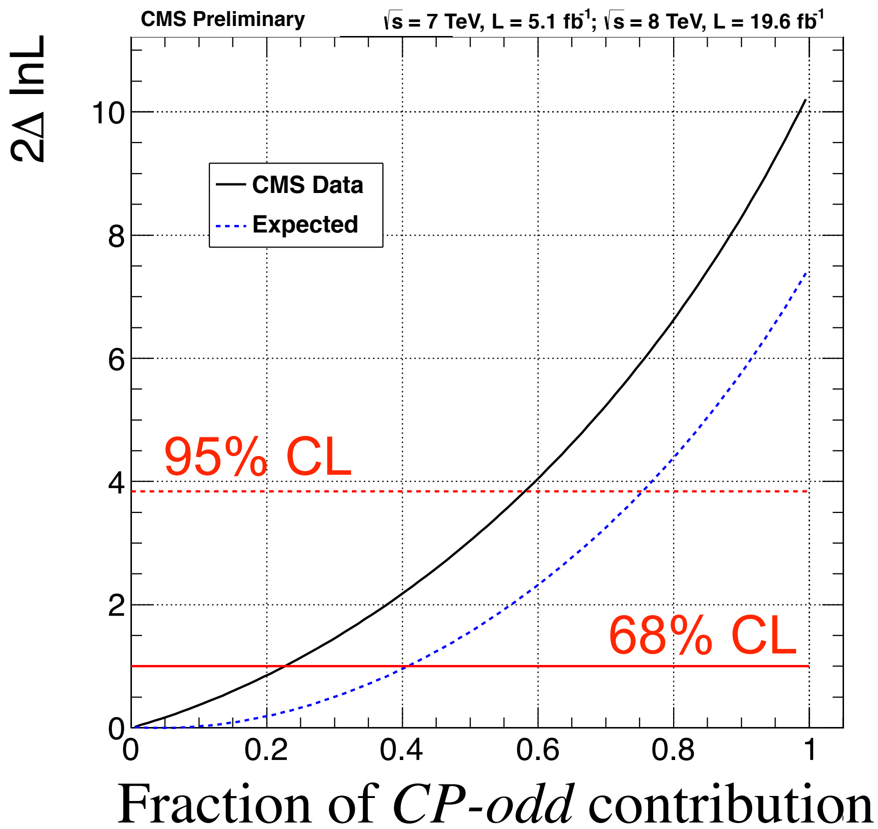
$f_{a3} = 0.00^{+0.23}_{-0.00}$

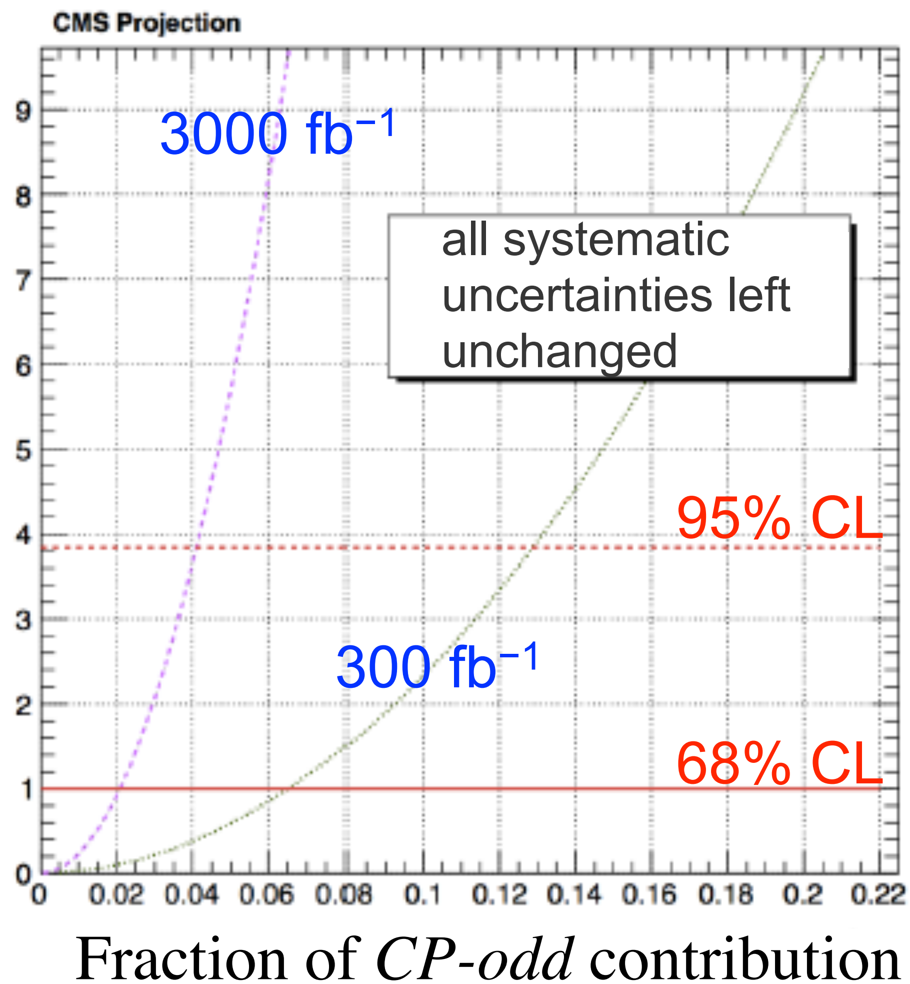
f_{a3} <0.58 @95%CL



Any CP violation in Higgs sector?

Significant CP odd contribution allowed by current data

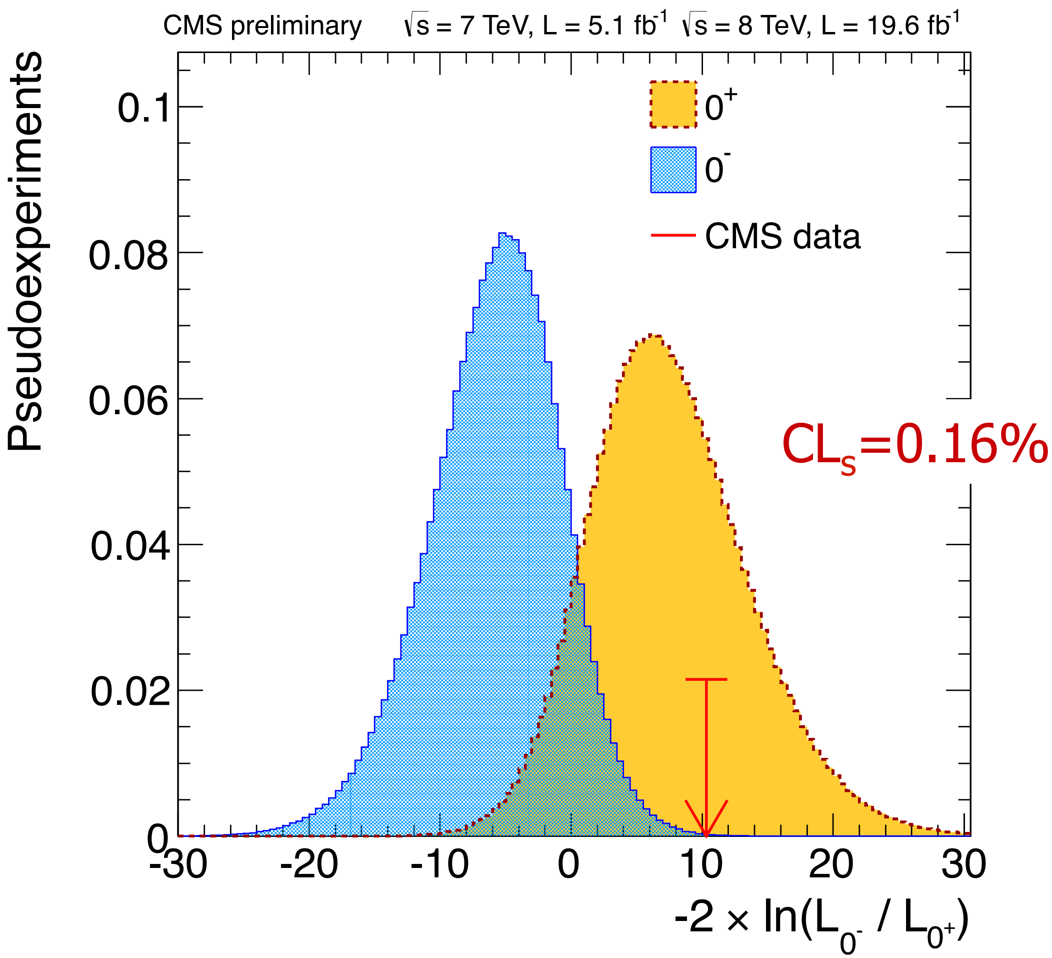




CP violation probe down to 1−10% possible by 2017−20

Have also measured spin-parity explicitly

CMS HIG-13-002



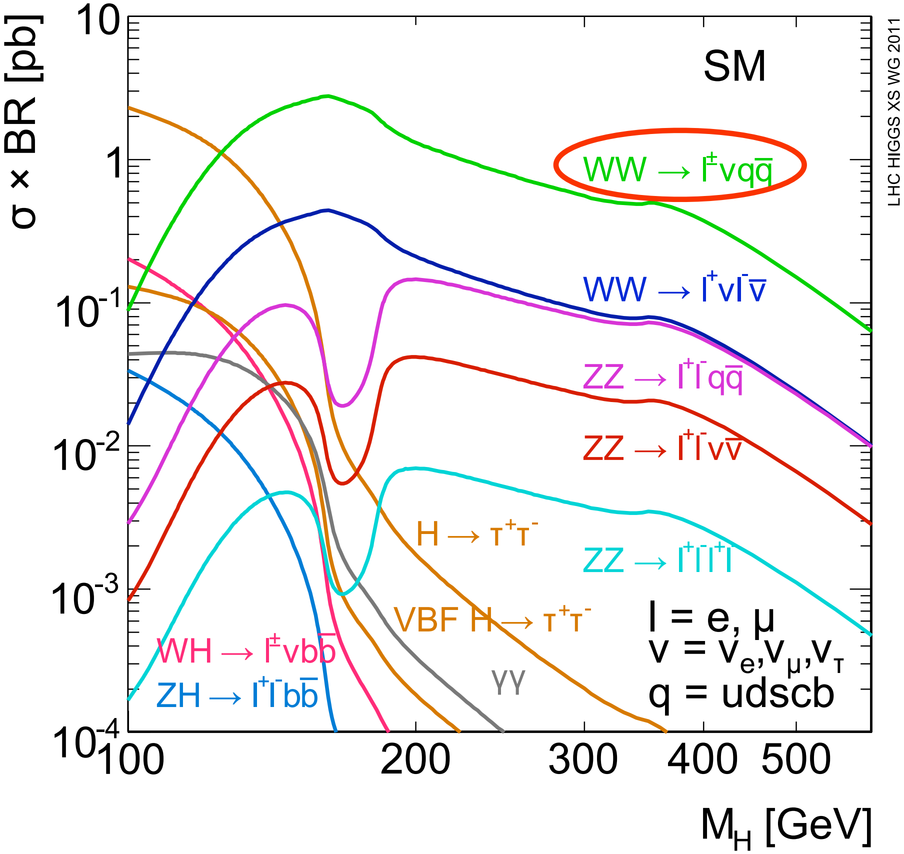
More J^P hypotheses have been tested in a similar way

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

Search for high mass Higgs states

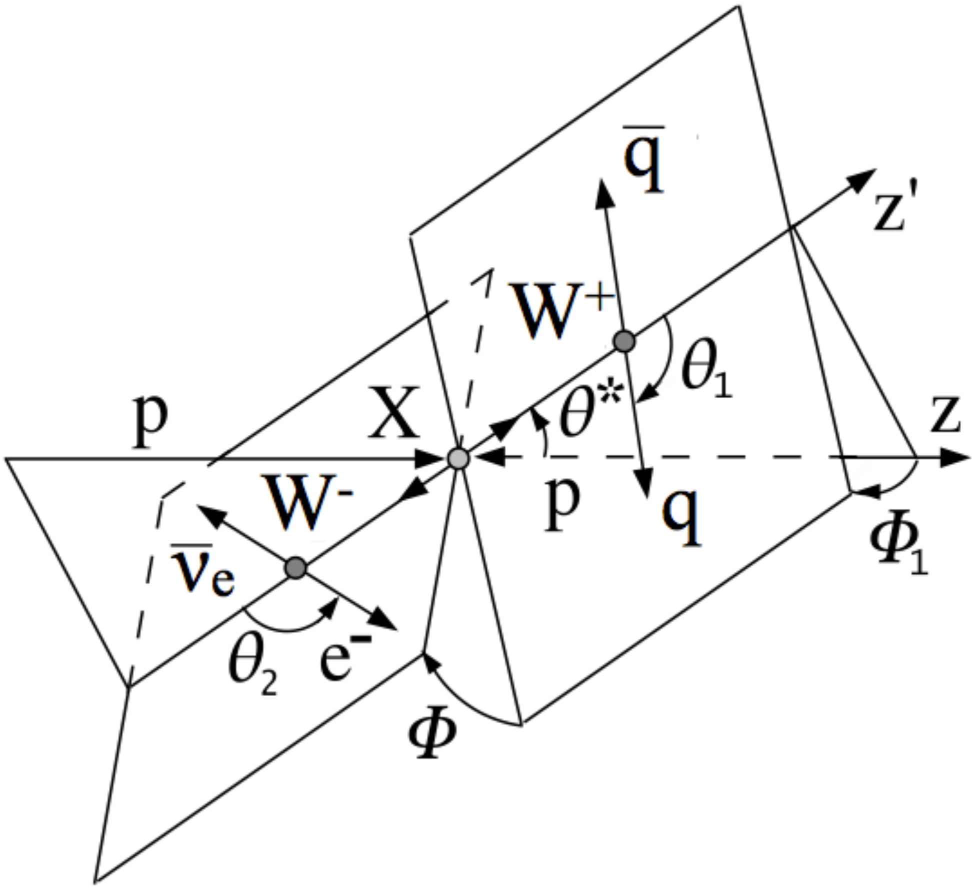
Why in *this* final state? It wasn't planned in the ATLAS/CMS TDR!



- $H \to WW \to \ell\nu q\bar{q}$ has the largest production rate 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.

The main thrust of the analysis is to model this background well.

Strategy: exploit full kinematic information



Higgs boson kinematics is fully described by 5 angles

{θ_1, θ_2, θ^*, ϕ, ϕ_1}

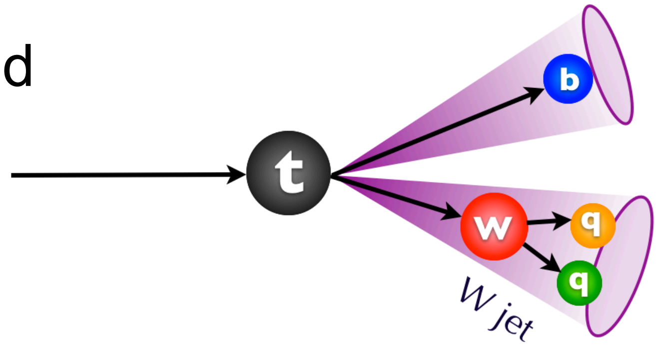
production angles: θ^*, ϕ
decay angles: θ_1, θ_2, ϕ_1

Essentially an uncorrelated complete set. Use likelihood discriminant to separate Higgs signal from the dominant W+jets and top backgrounds.

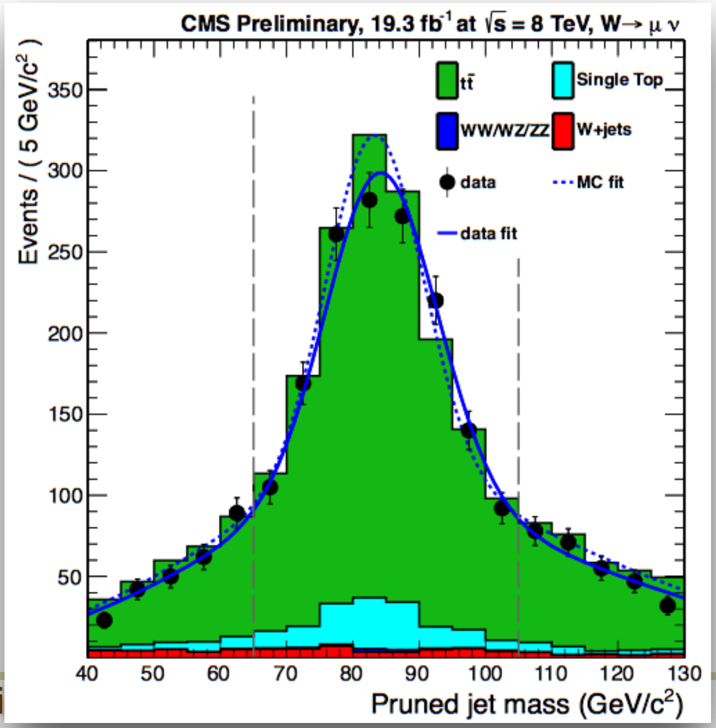
Phenomena of merged jet from boosted W

Example: boosted top events (an excellent calibration sample)

- 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



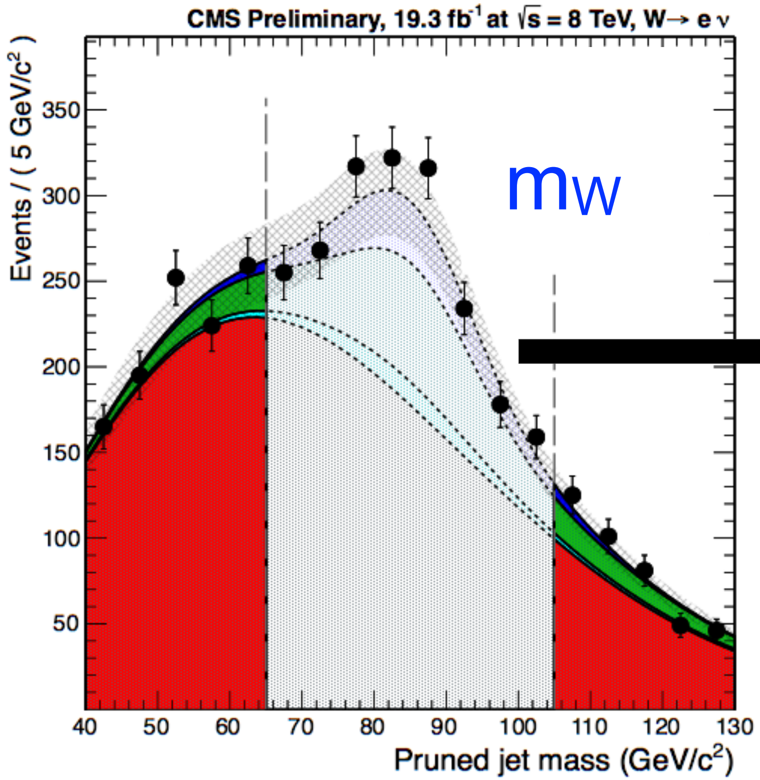
Pure sample of W decaying hadronically to a single jet (Cambridge-Aachen, R=0.8) in $t\bar{t}$ ($\rightarrow \ell$+MET + fat-jet) b-tagged events

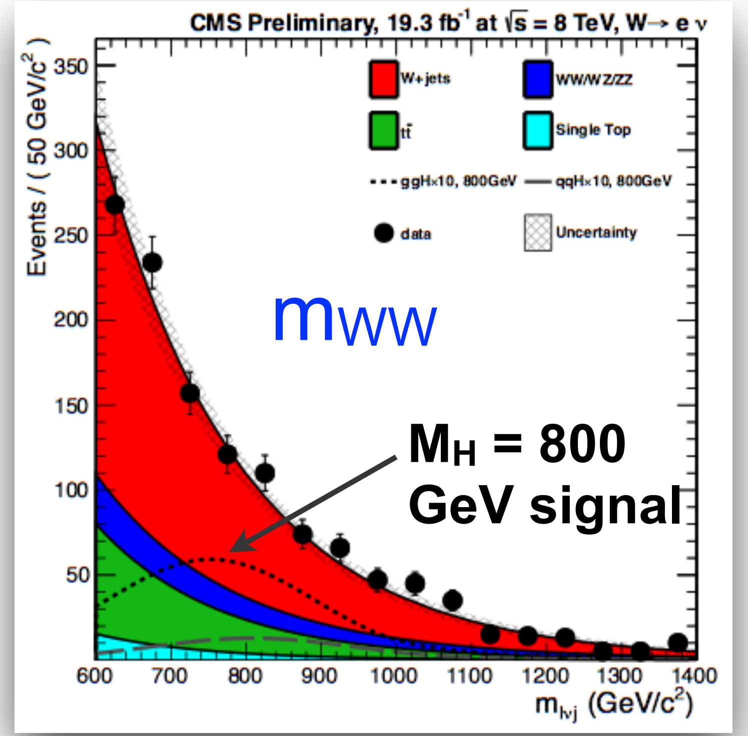


Now probe WW invariant mass spectrum

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

CMS HIG-12-046, HIG-13-008



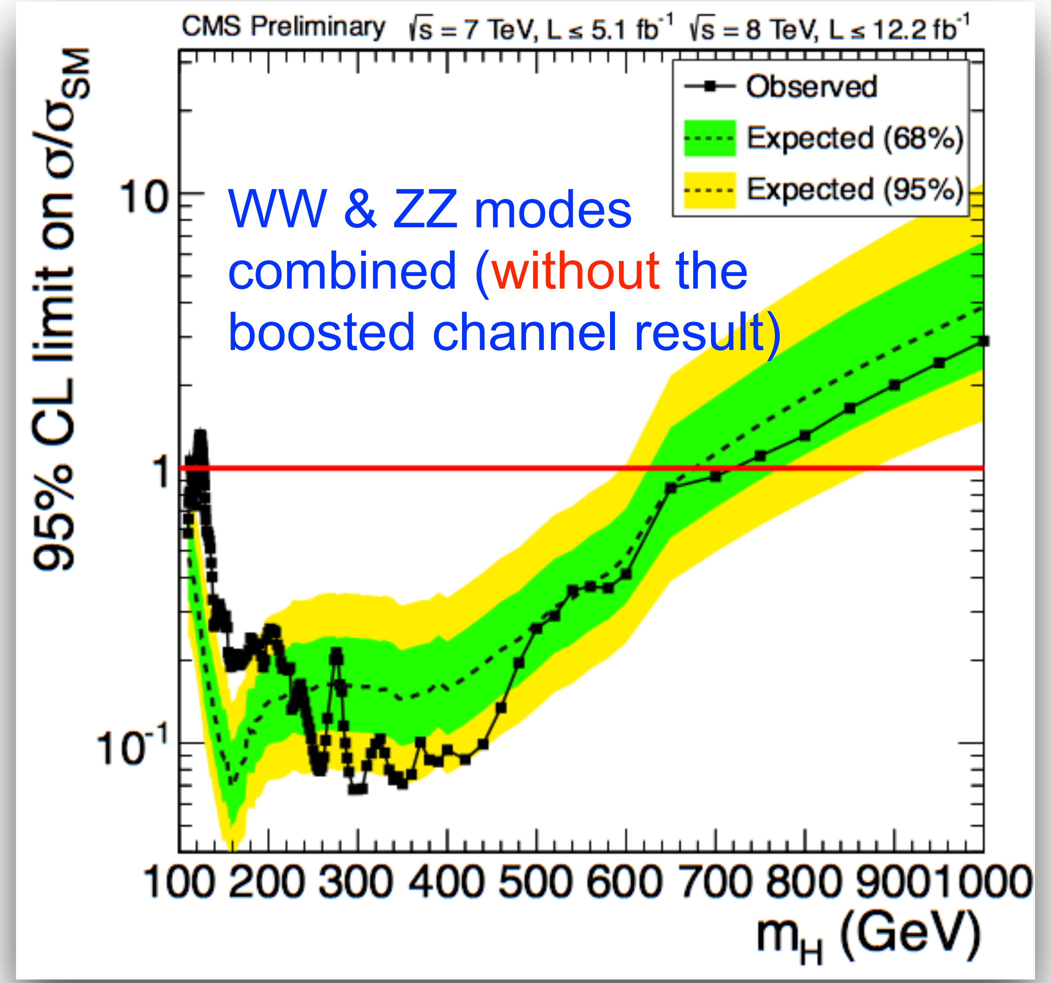


Optimize separately for each mass point (M_H:170, 180, 190, 200, 250,.., 600, 700, …, 1000 GeV) and for the two lepton flavors (e, μ). Merged jet analysis for $M_H > 600$ GeV.

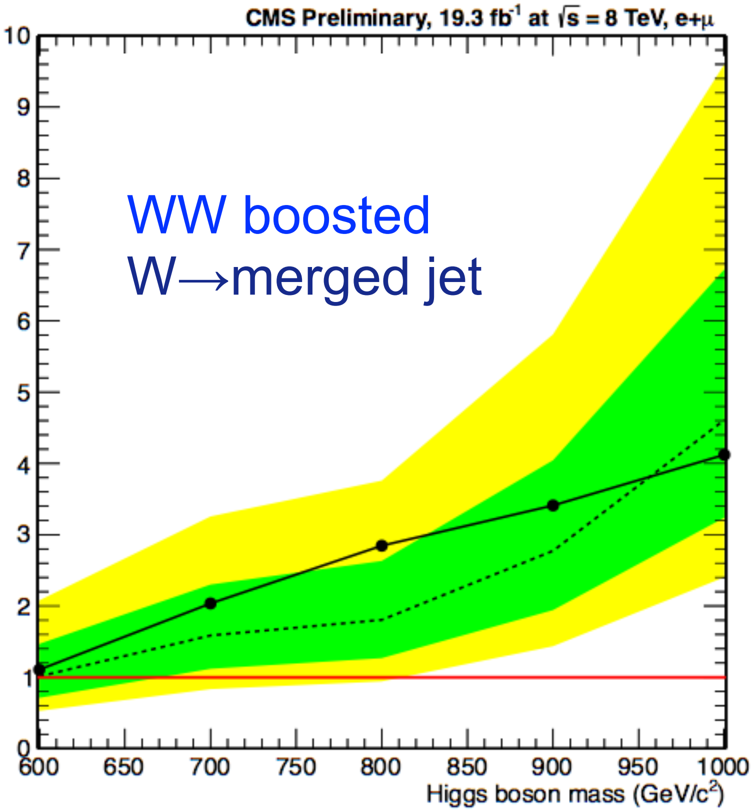
Constraints on higher mass Higgs states

No new states up to 600 GeV.

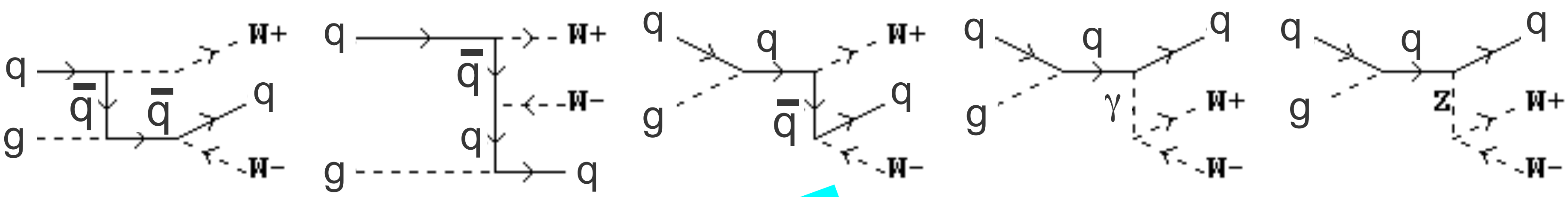
Eur. Phys. J. C 73, 2469 (2013)



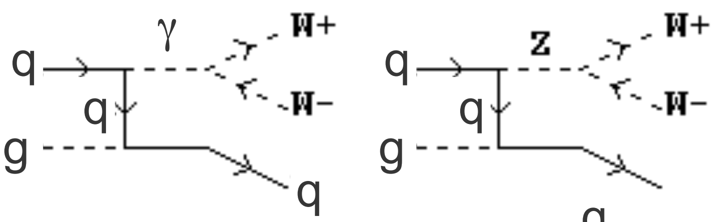
But interesting territory > 600 GeV to probe at Run-2



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

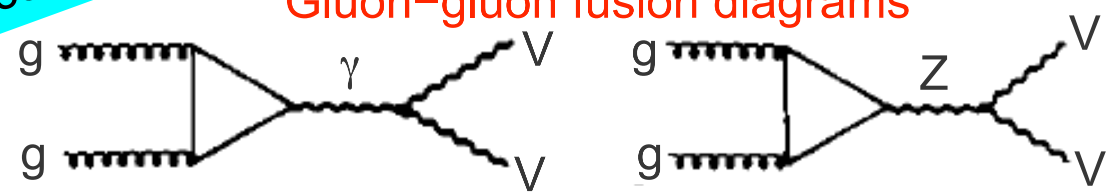


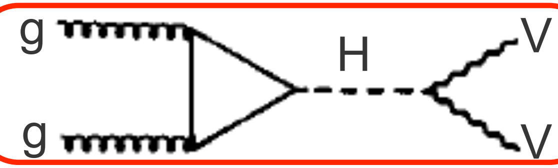
Quark−gluon diagrams



~6% gg contribution

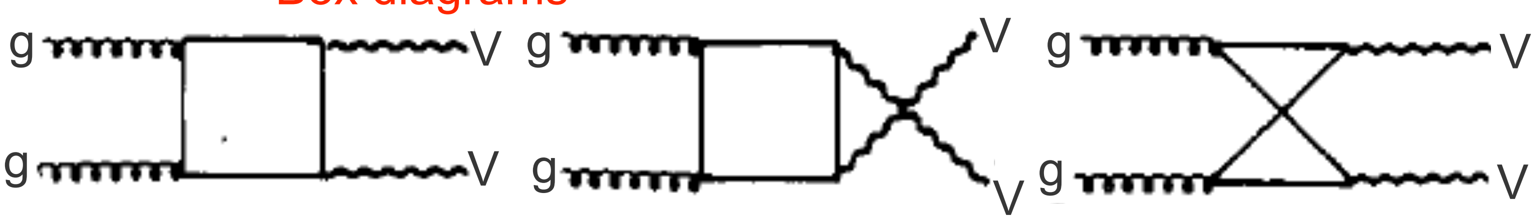
Gluon−gluon fusion diagrams





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

Box diagrams



Plus VBF, MPI, ... diagrams

Some representative diagrams @NLO

Born

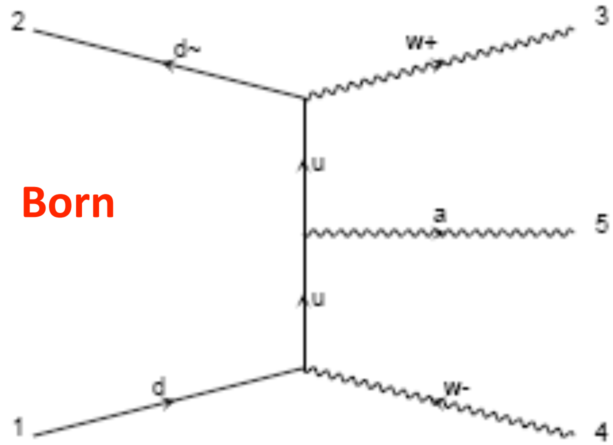
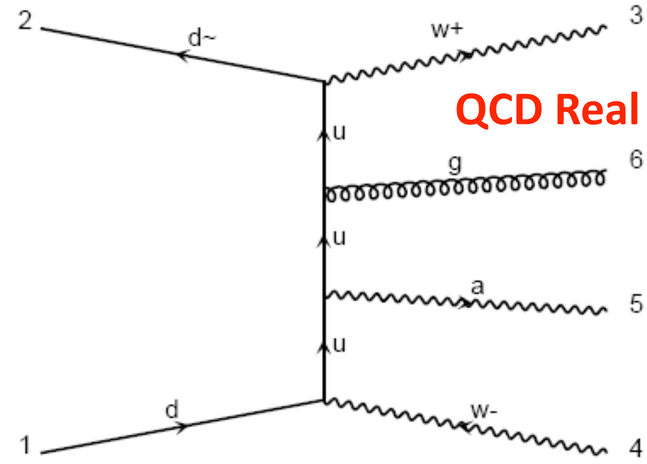


diagram 7 QCD=0, QED=3

QCD Real emission



real diagram 1 QCD=1, QED=3

One-loop QCD

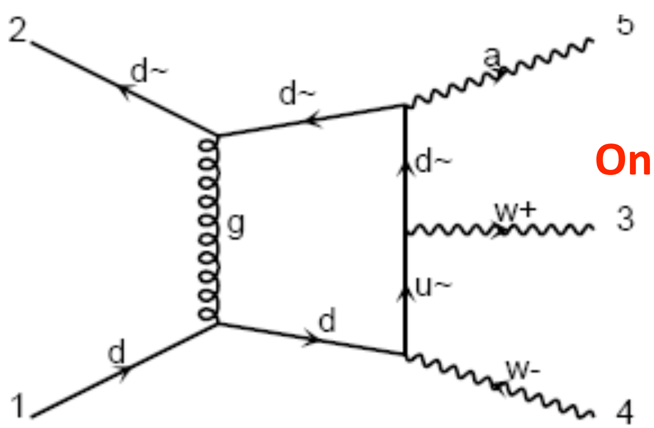


diagram 38 QCD=2, QED=3

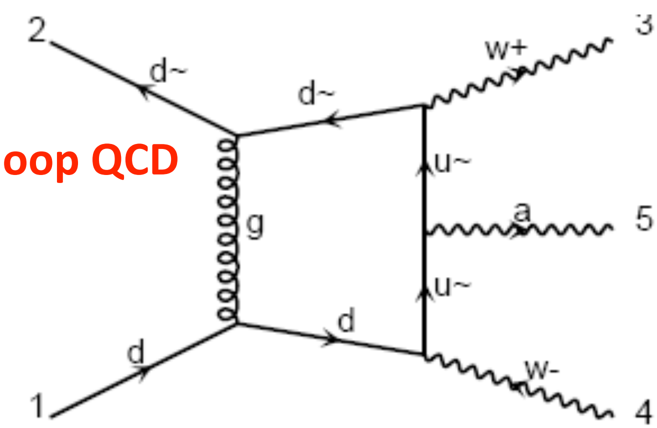


diagram 39 QCD=2, QED=3

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.

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),
<u>L_T are novel to D8</u>

	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

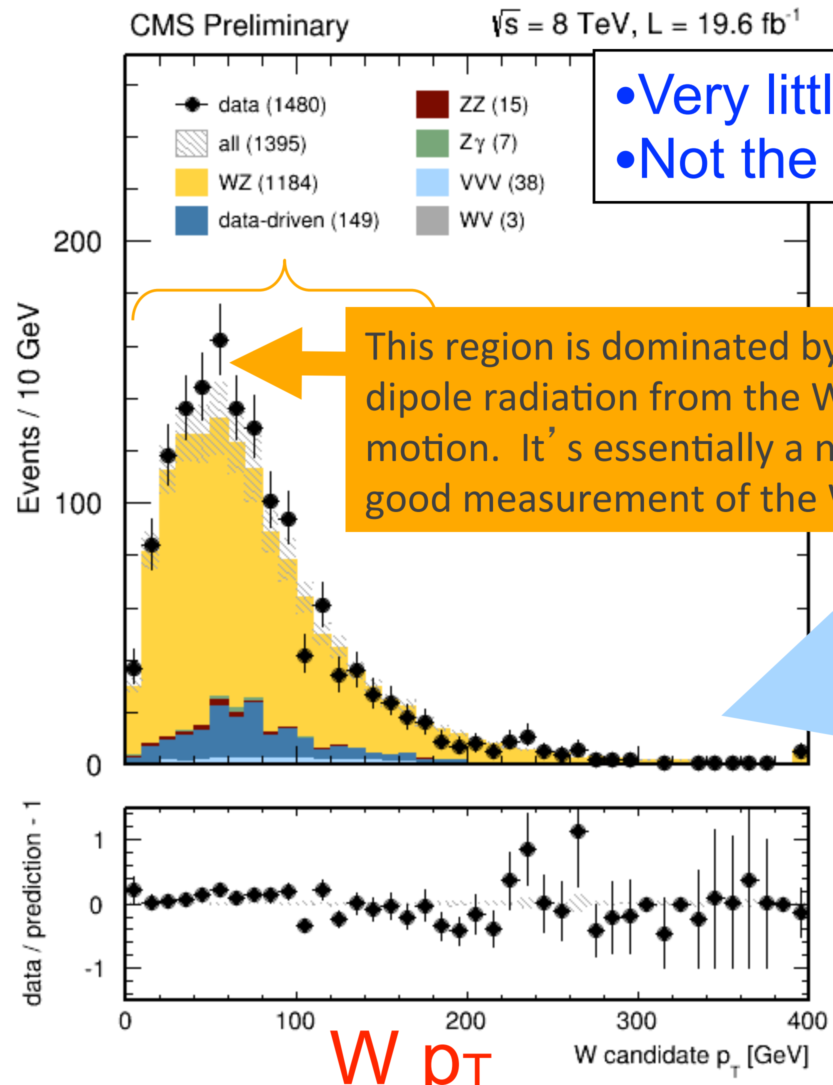
Burden of legacy

- 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

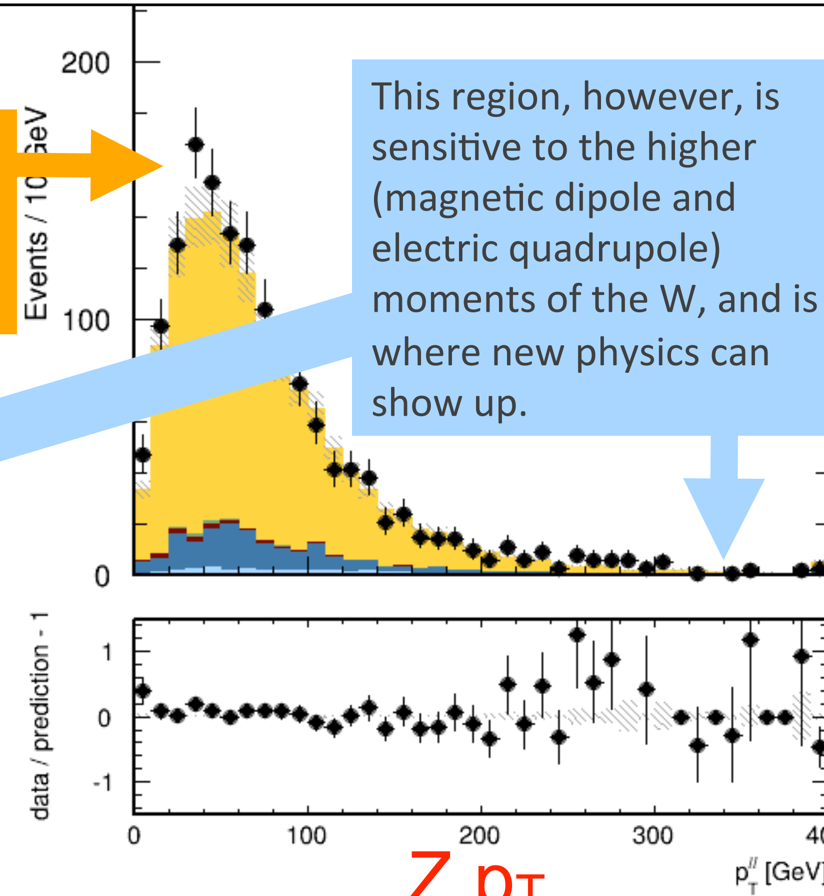
E.g., W charge & dipole moment in WZ events

CMS SMP-12-006

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



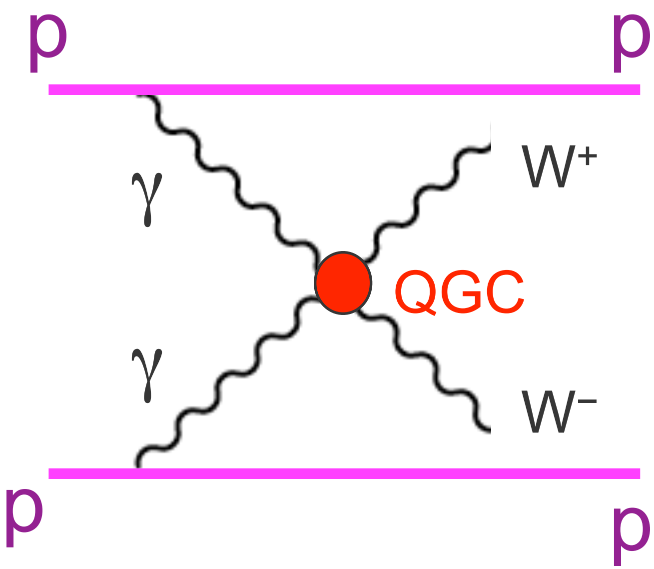
This region is dominated by the dipole radiation from the W's motion. It's essentially a not-very-good measurement of the W charge.



This region, however, is sensitive to the higher (magnetic dipole and electric quadrupole) moments of the W, and is where new physics can show up.

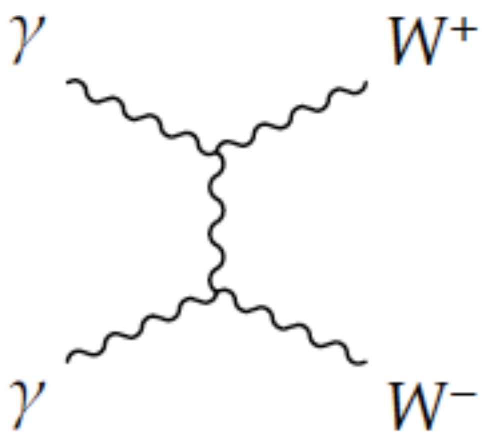
Quartic couplings in γγ→WW process

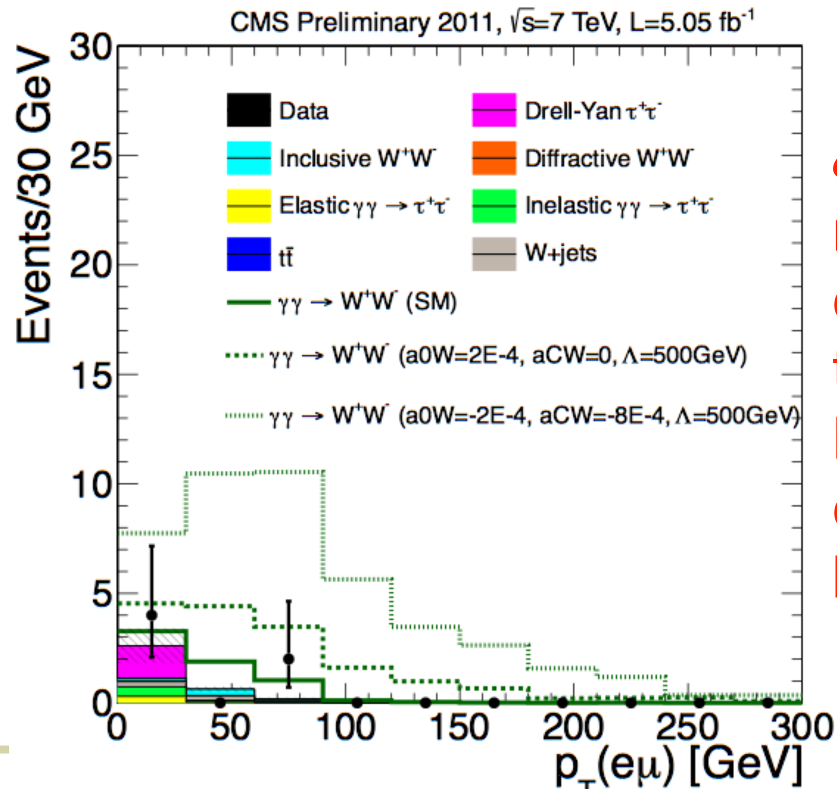
CMS FSQ-12-010



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

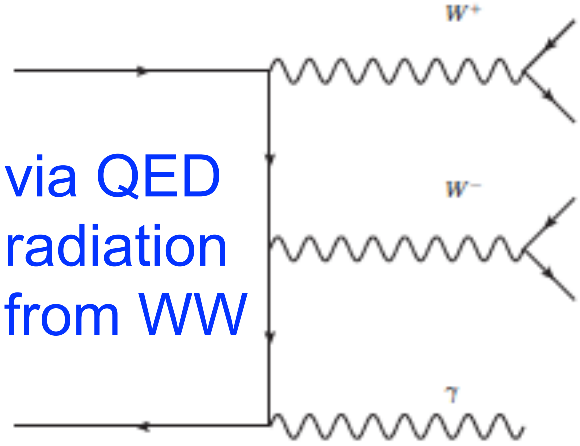
Leading order diagrams

References:

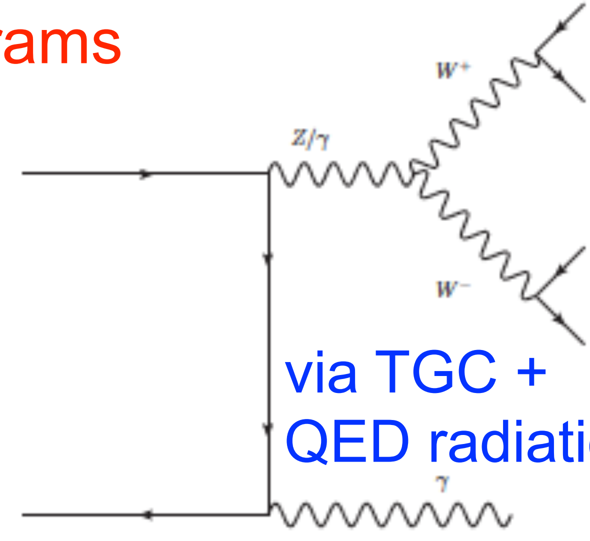
1.) Yang et al, arXiv: 1211.1641

2.) LEP combination, hep-ex/0612034

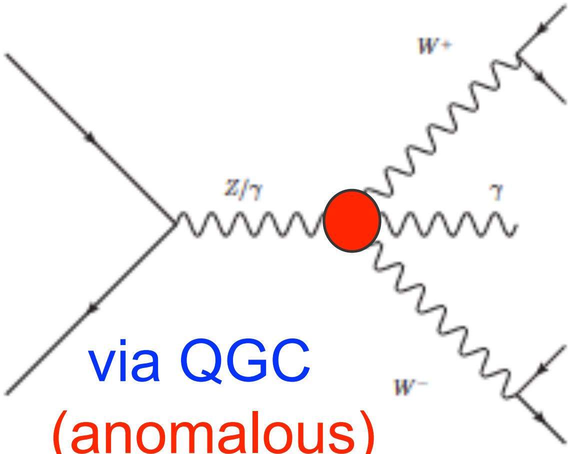
3.) Bozzi et al, arXiv: 0911.0438



via QED radiation from WW



via TGC + QED radiation



via QGC (anomalous)

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

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 γγ→WW. In the dipole units, these limits are probing QGC *O*(100% SM) !!

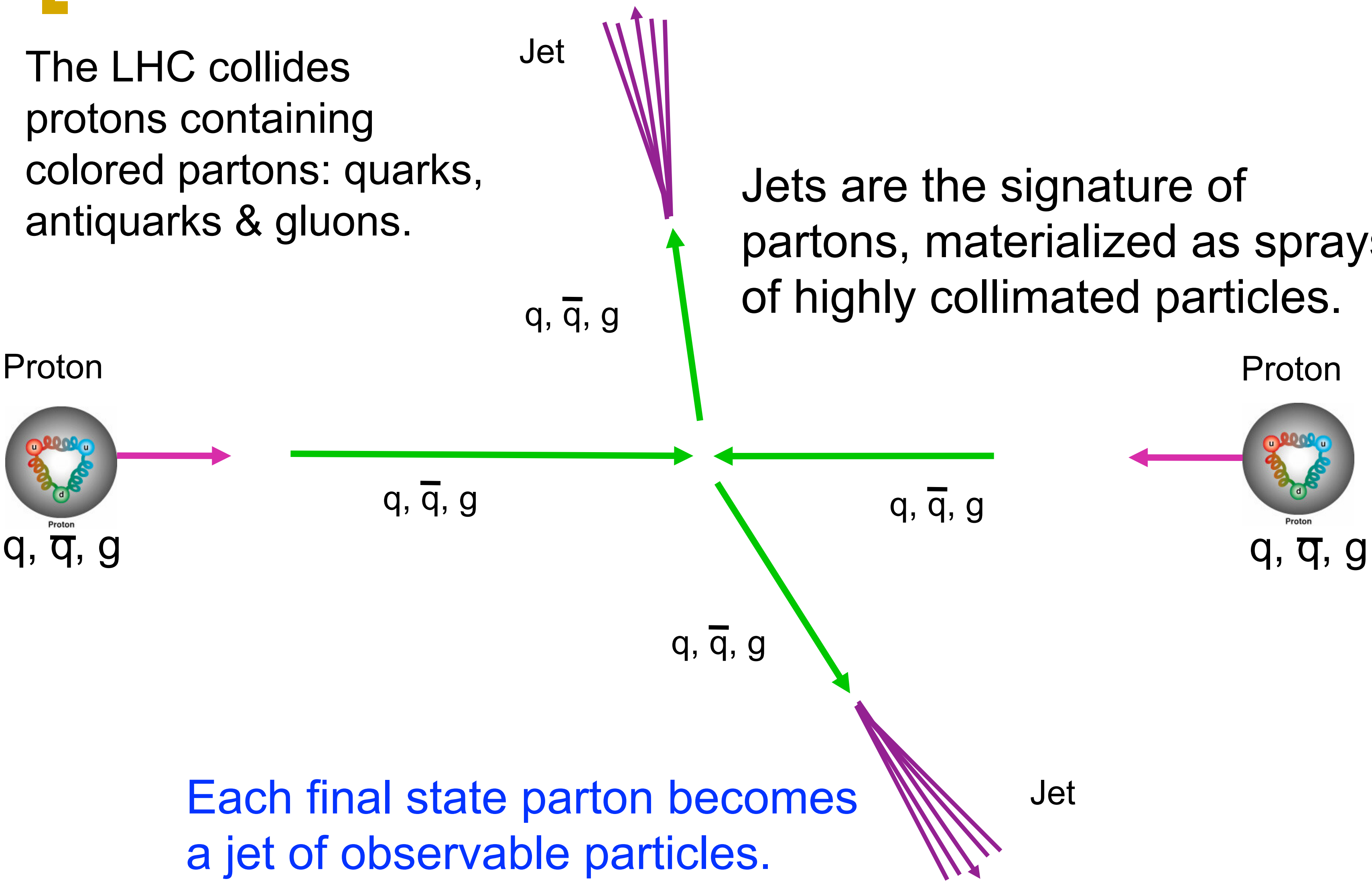
Observed Limits	Expected Limits
$-77\ (\mathrm{TeV}^{-4}) < f_{M,0}/\Lambda^4 < 81\ (\mathrm{TeV}^{-4})$	$-89\ (\mathrm{TeV}^{-4}) < f_{M,0}/\Lambda^4 < 93\ (\mathrm{TeV}^{-4})$
$-131\ (\mathrm{TeV}^{-4}) < f_{M,1}/\Lambda^4 < 123\ (\mathrm{TeV}^{-4})$	$-143\ (\mathrm{TeV}^{-4}) < f_{M,1}/\Lambda^4 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

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

Particle jets

The LHC collides protons containing colored partons: quarks, antiquarks & gluons.

Jets are the signature of partons, materialized as sprays of highly collimated particles.

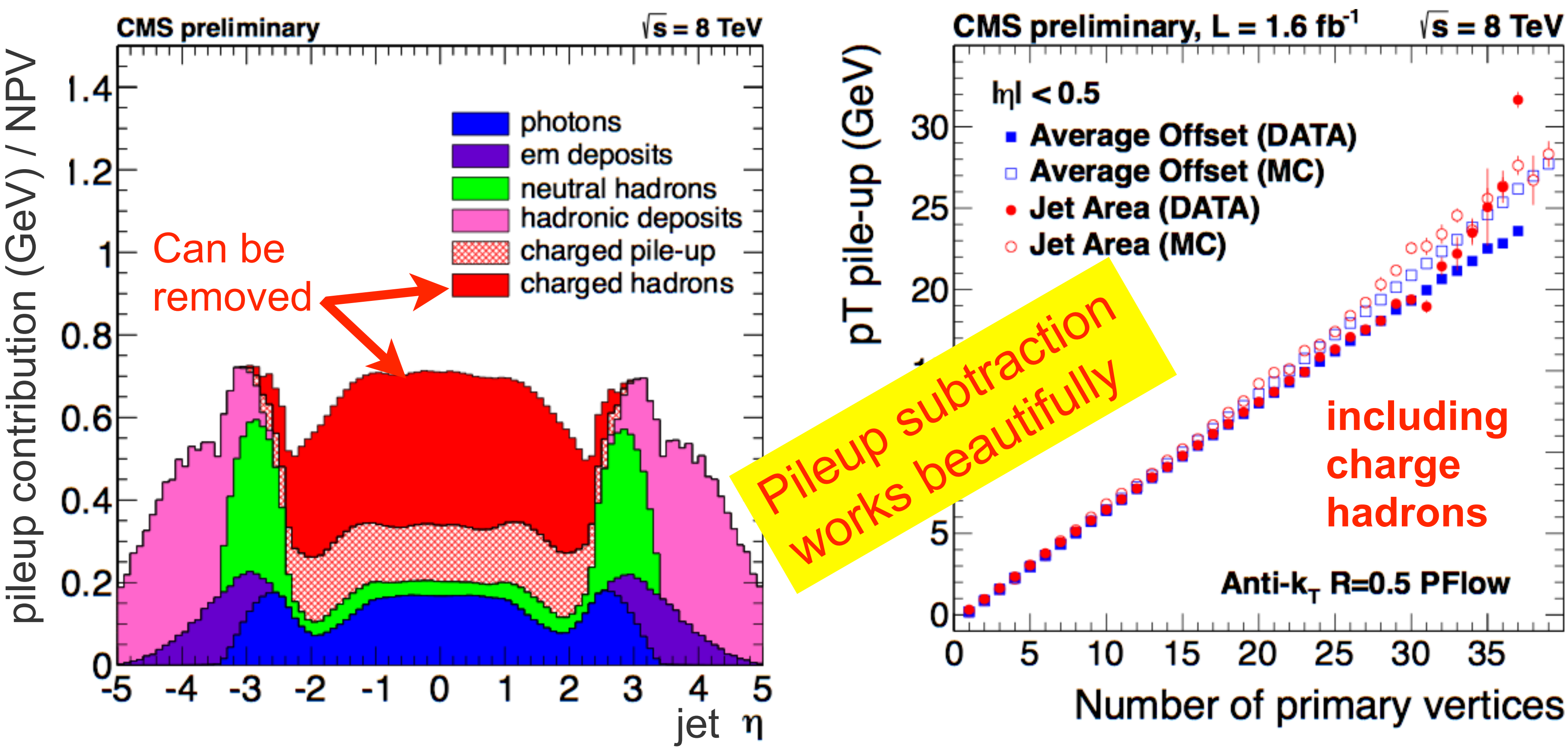


Each final state parton becomes a jet of observable particles.

Dealing with pileup: subtract its contribution

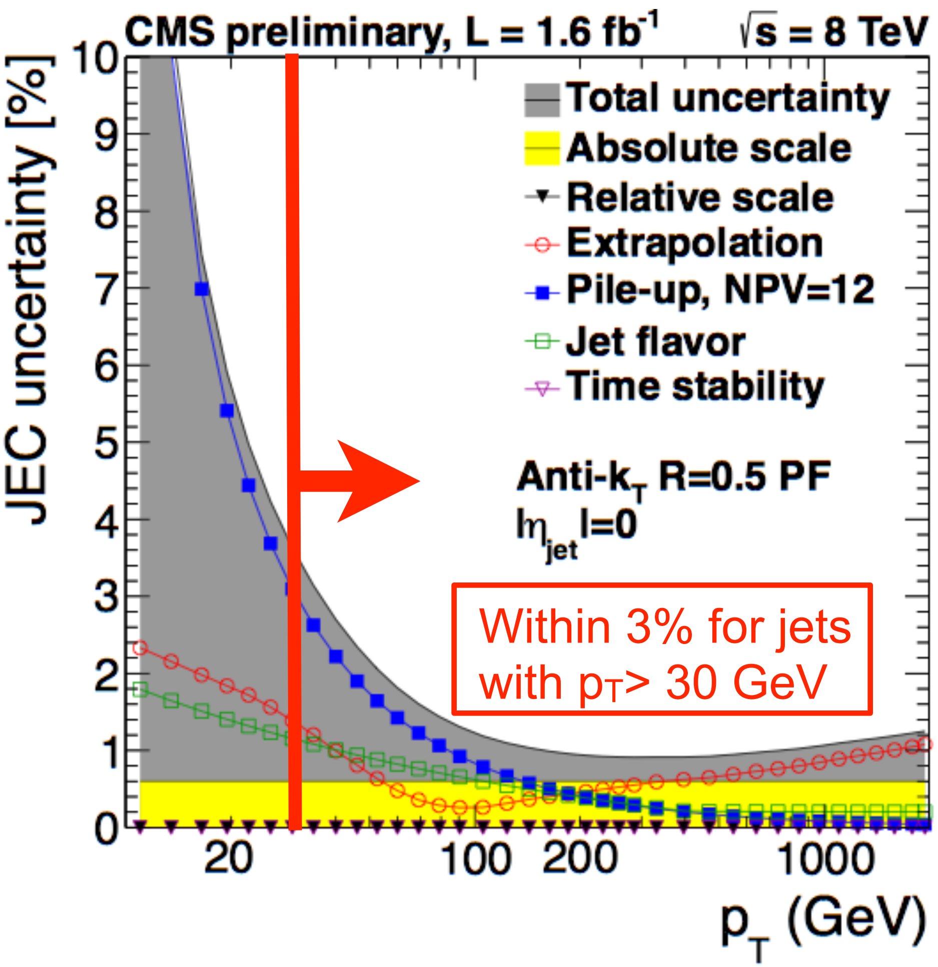
✦Pileup affects jet energy, MET, and lepton isolation

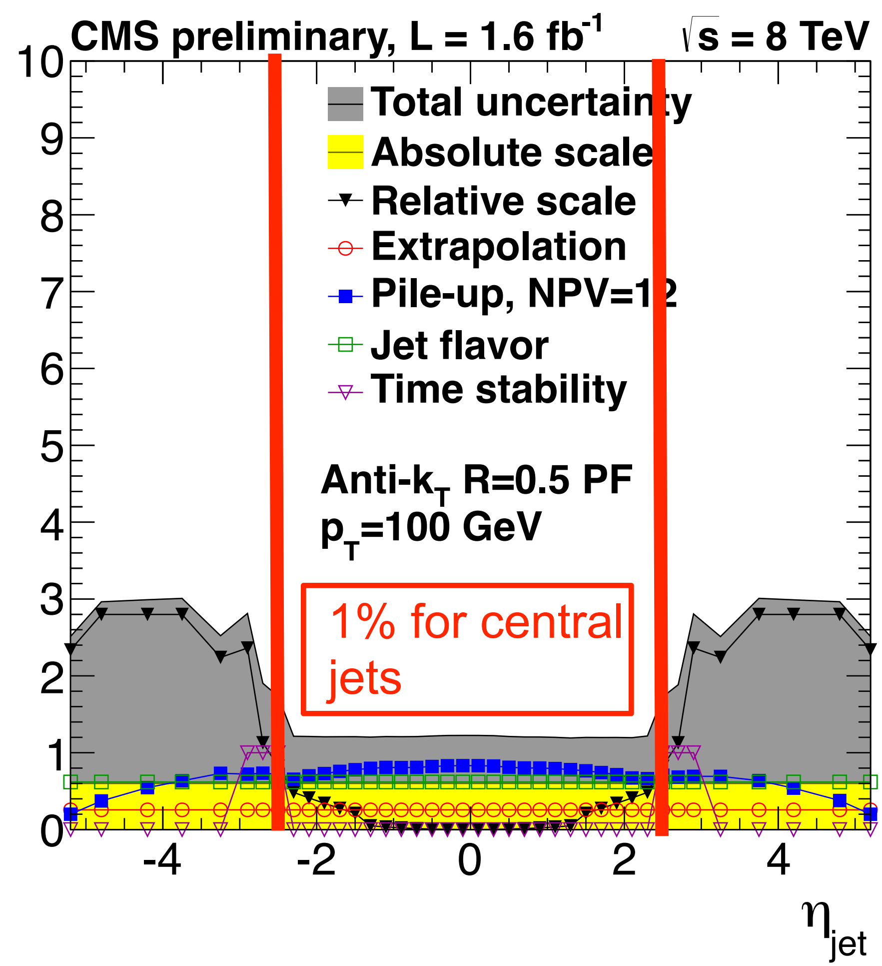
- Example: pileup contribution to jet p_T per primary vertex.
- Measure in data using several methods. Get consistent results.



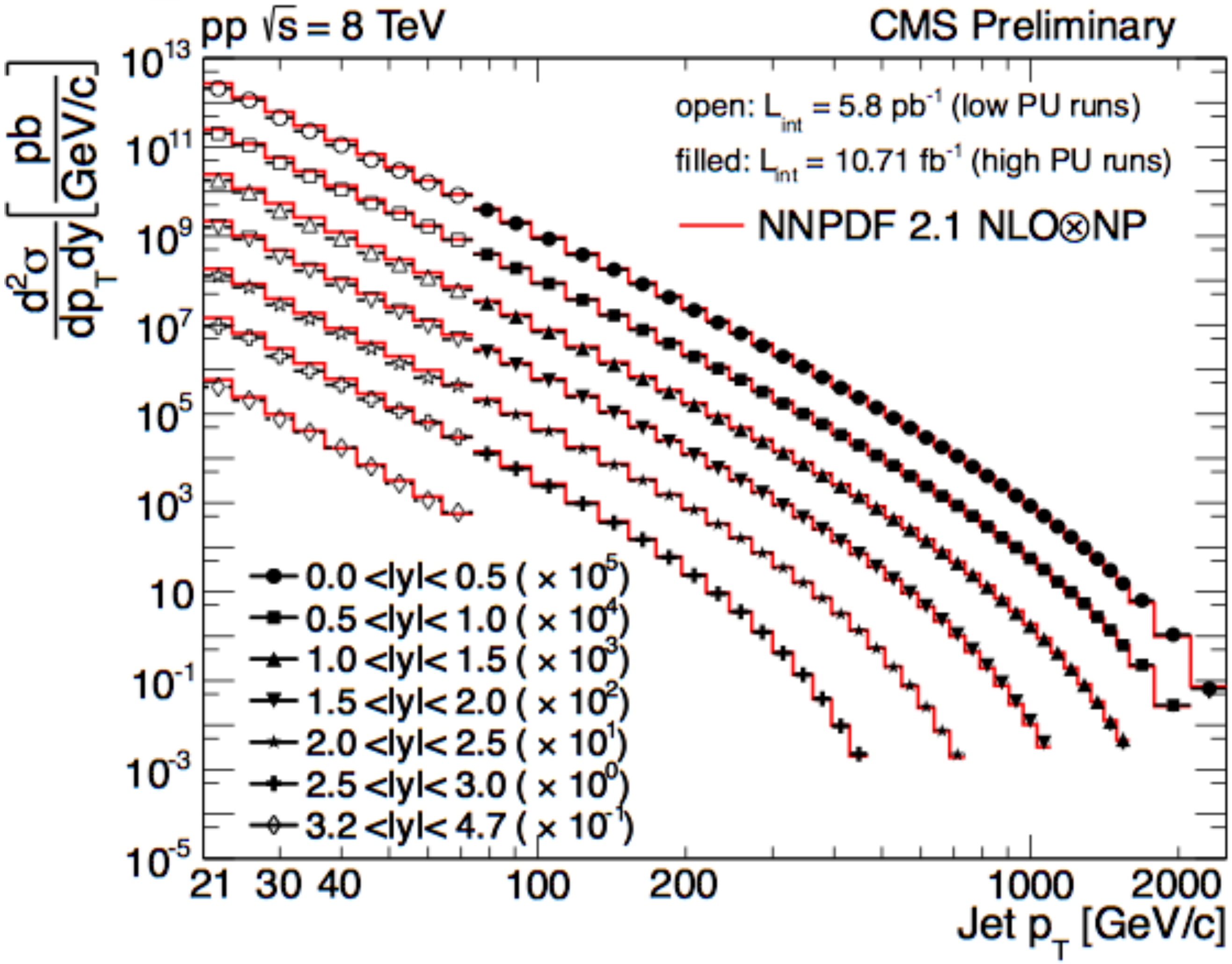
Good understanding of detector performance

- ✦An example: jet energy scale
  - Well calibrated





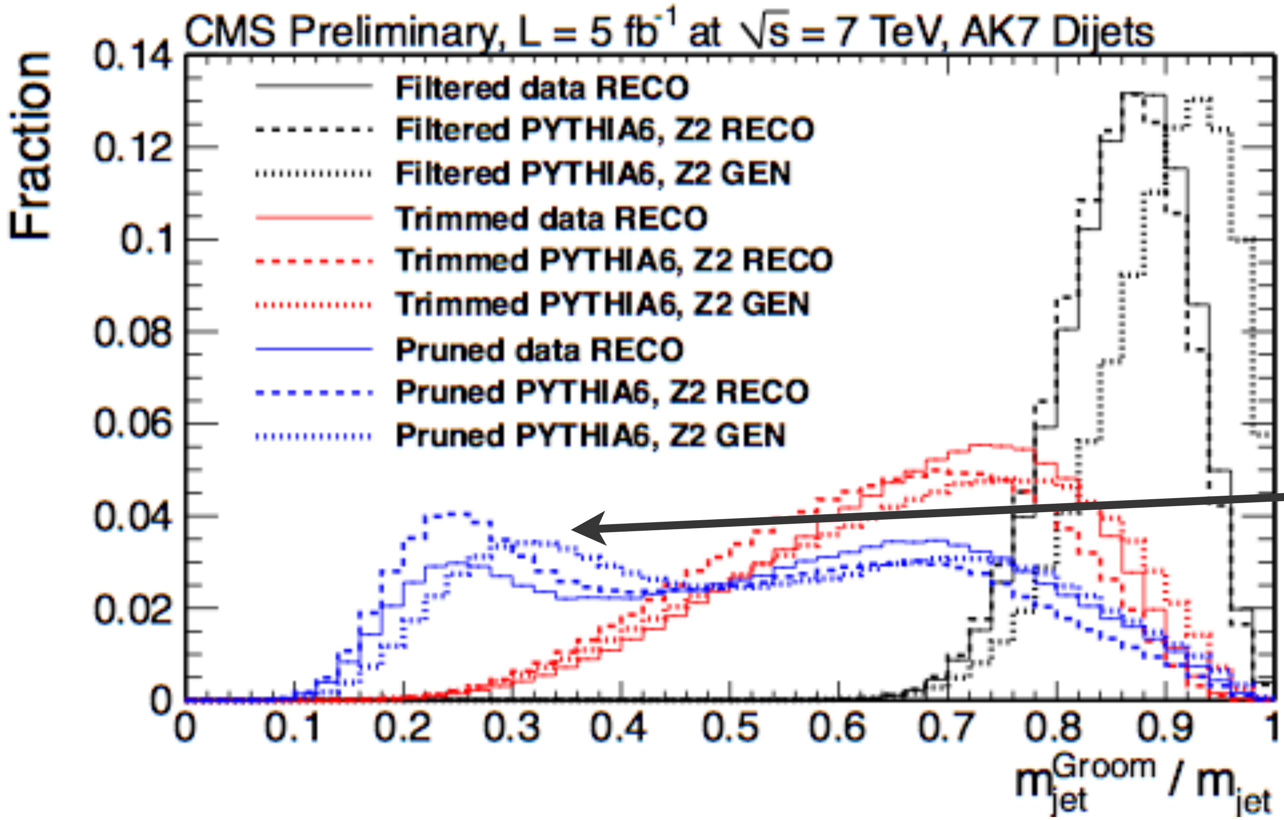
Excellent understanding of jet production at LHC



Probe jet production rate (i.e., the effect of the strong force) over 15 orders of magnitude !!!

No surprises up to 2 TeV transverse momentum.

Peep inside the merged jet, use grooming

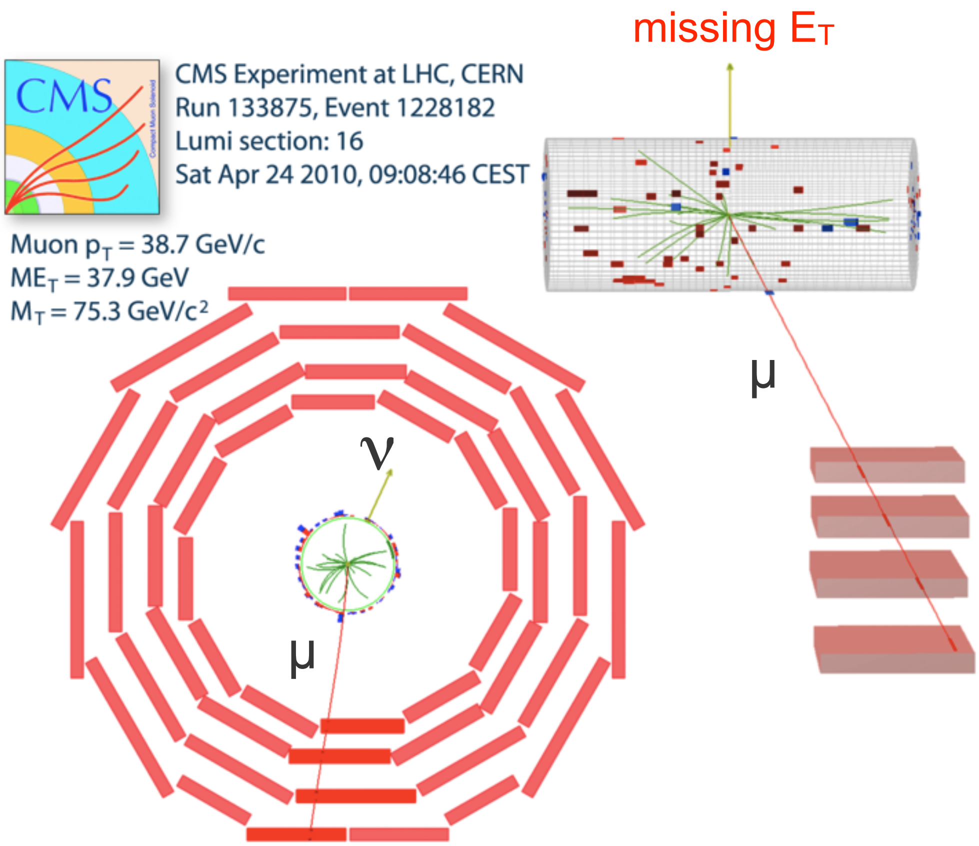


Pruning is the most aggressive, filtering is the least aggressive

bimodal structure provides good separation for qq signal

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

Missing energy due to undetected particles



- When the W boson decays to an electron or muon and a neutrino, the neutrino escapes the detector without being detected.
- This causes an energy imbalance and we "measure" missing transverse energy (MET).
- Undetected particles from new physics can also give rise to MET.

CMS analysis

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

$W \to \ell\nu$ selection	Jet selection
Single-lepton trigger	$p_T^{j1} > 40\,\text{GeV}$
Lepton identification and isolation	$p_T^{j2}, p_T^{j3} > 30\,\text{GeV}$
$p_T^{\mu(e)} > 25\ (35)\,\text{GeV}$	$\|\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2}\| > 45\,\text{GeV}$
$\not{E}_T^{\mu(e)} > 25\ (30)\,\text{GeV}$	$\|\Delta\eta(j1, j2)\| < 1.2$
$M_T > 50\,\text{GeV}$	$\Delta\phi(\not{E}_T, j1) > 0.4$
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:

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

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)

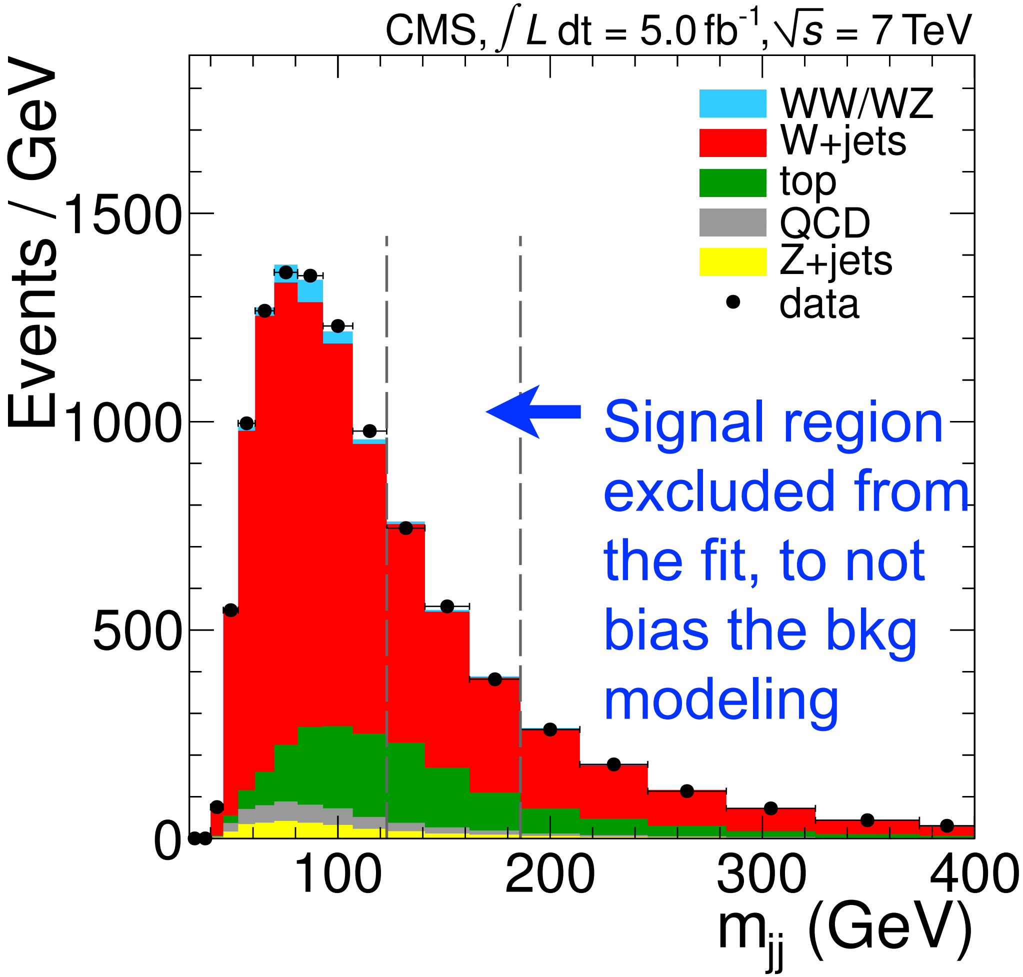
Fit results

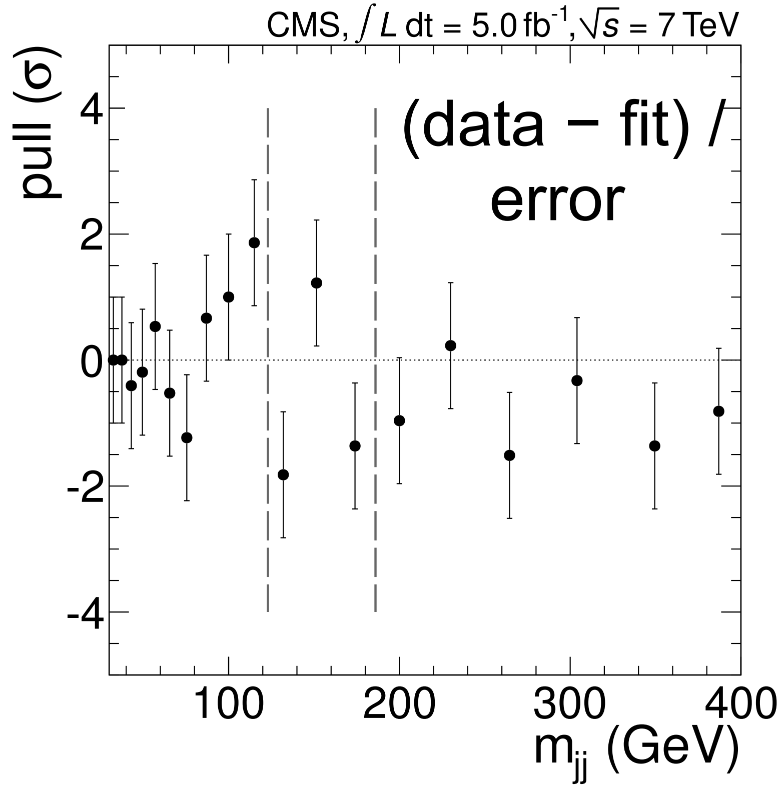
Process	Muon channel	Electron channel
Diboson (WW+WZ)	1899 ± 389	783 ± 302
W plus jets	67384 ± 586	31644 ± 850
$t\bar{t}$	1662 ± 117	946 ± 67
Single top	650 ± 33	308 ± 17
Drell-Yan plus jets (Z+jets)	3609 ± 155	1408 ± 64
Multijet (QCD)	296 ± 317	4195 ± 867
Fit χ^2/dof (probability)	9.73/12 (0.64)	5.30/12 (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

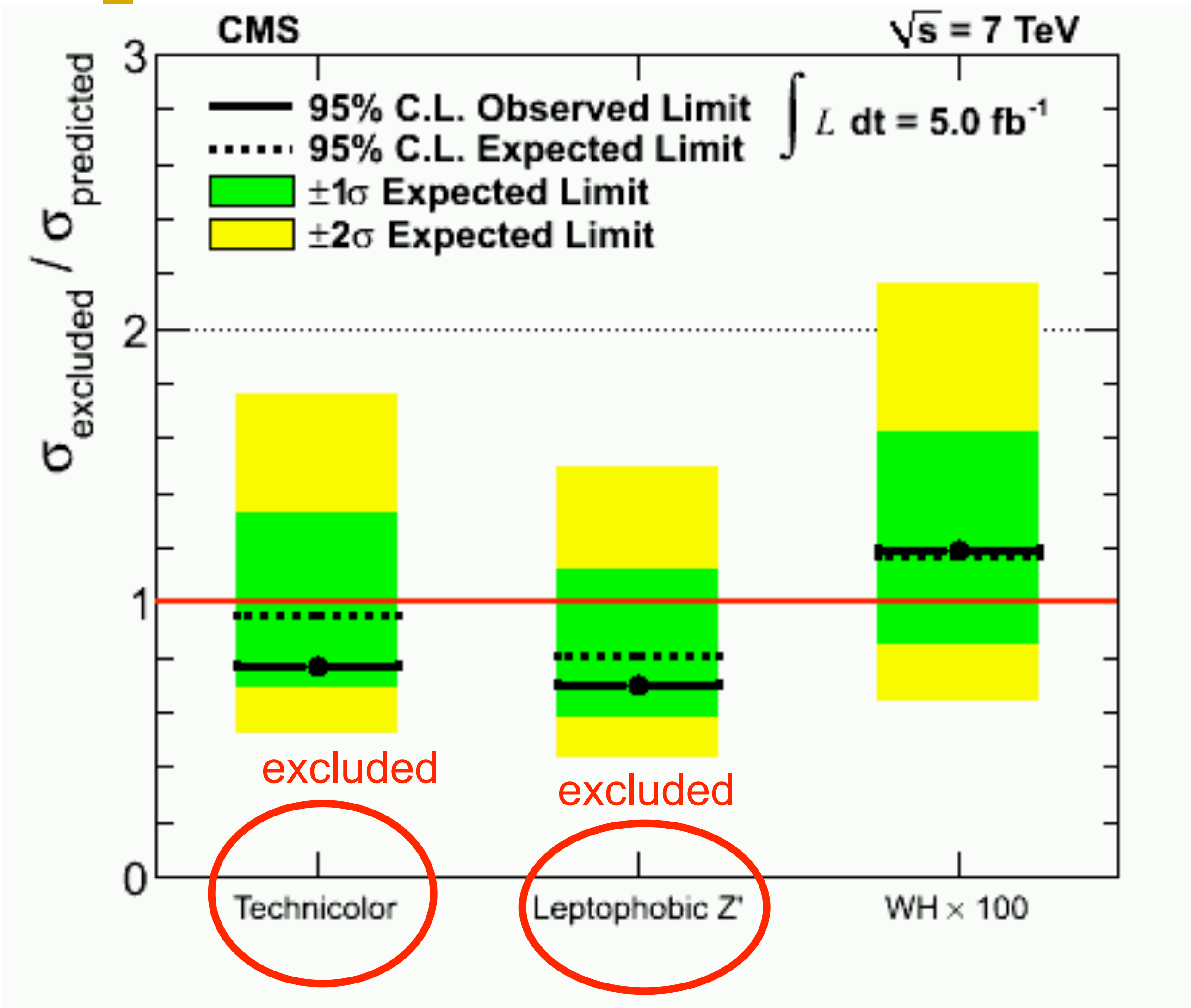
Modeling of dijet mass spectrum





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

Also excluded several new physics models



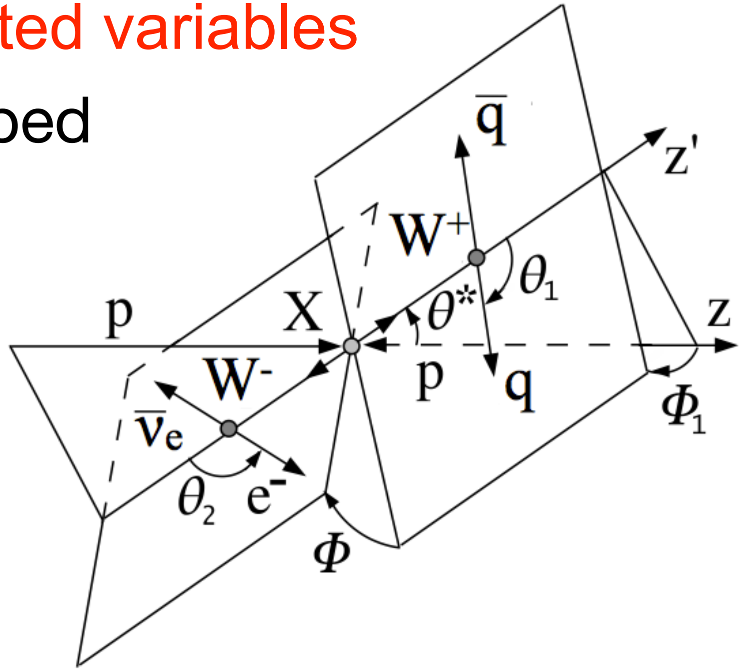
Exclude several classes of BSM models

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

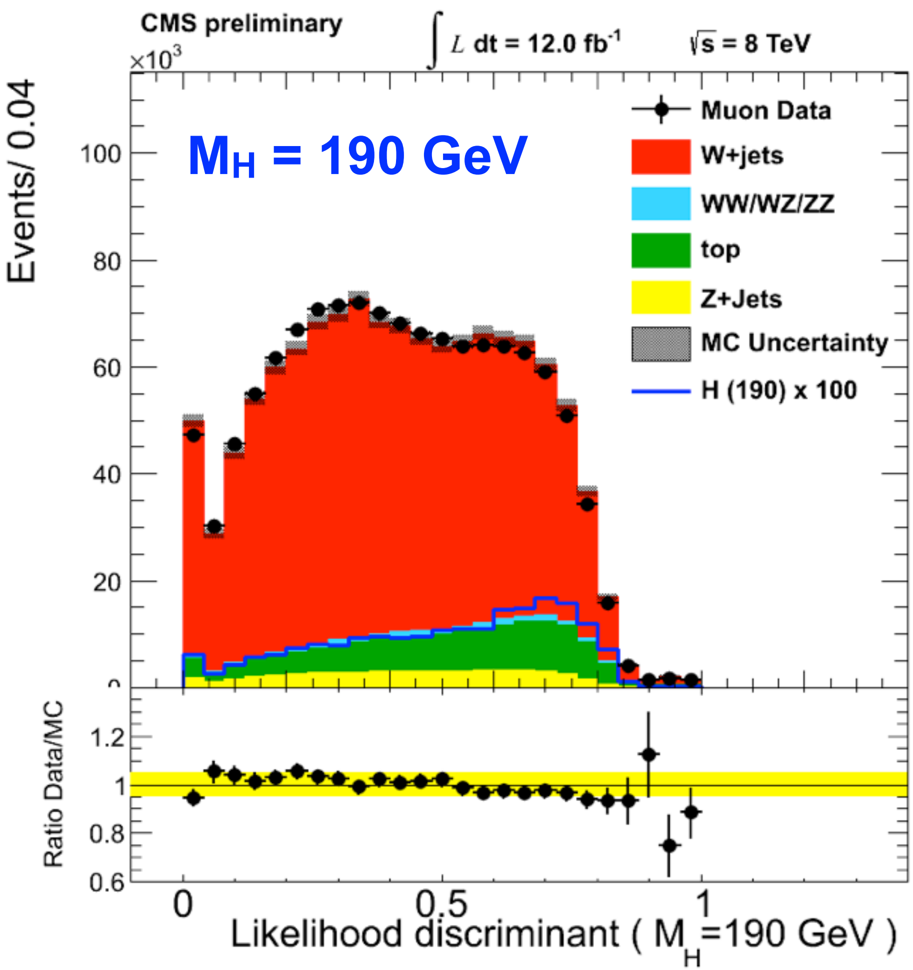
- Higgs boson kinematics is fully described by → $\{m_{WW}, m_{jj}, \boldsymbol{\theta_1}, \boldsymbol{\theta_2}, \boldsymbol{\theta^*}, \boldsymbol{\phi}, \boldsymbol{\phi_1}\}$
  - **m_{WW}** is the variable we use to extract limit, so it is not included
  - **m_{jj}** used to estimate background normalization, so it is not included

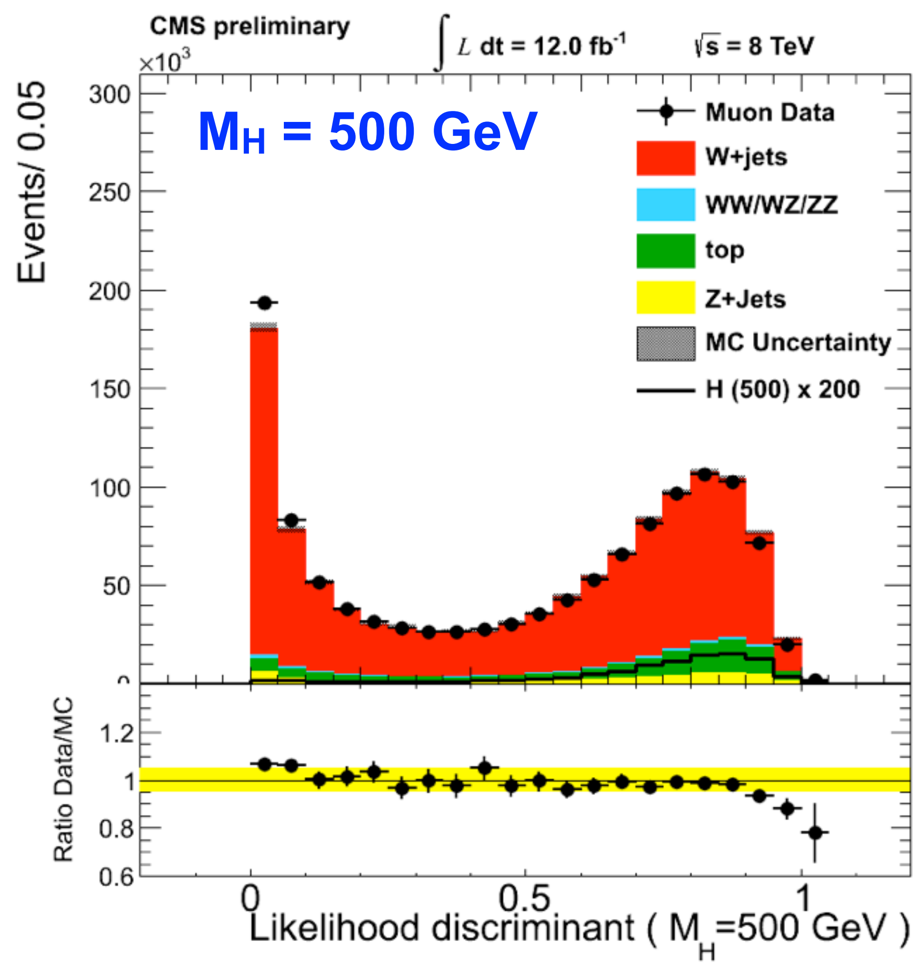


- the **5 angular variables are included**
- **Lepton charge** is a good variable since signal is charge-symmetric, W+jets is not

$\{\theta_1, \theta_2, \theta^*, \phi, \phi_1, (p_T)_{WW}, y_{WW}$, lepton charge$\}$

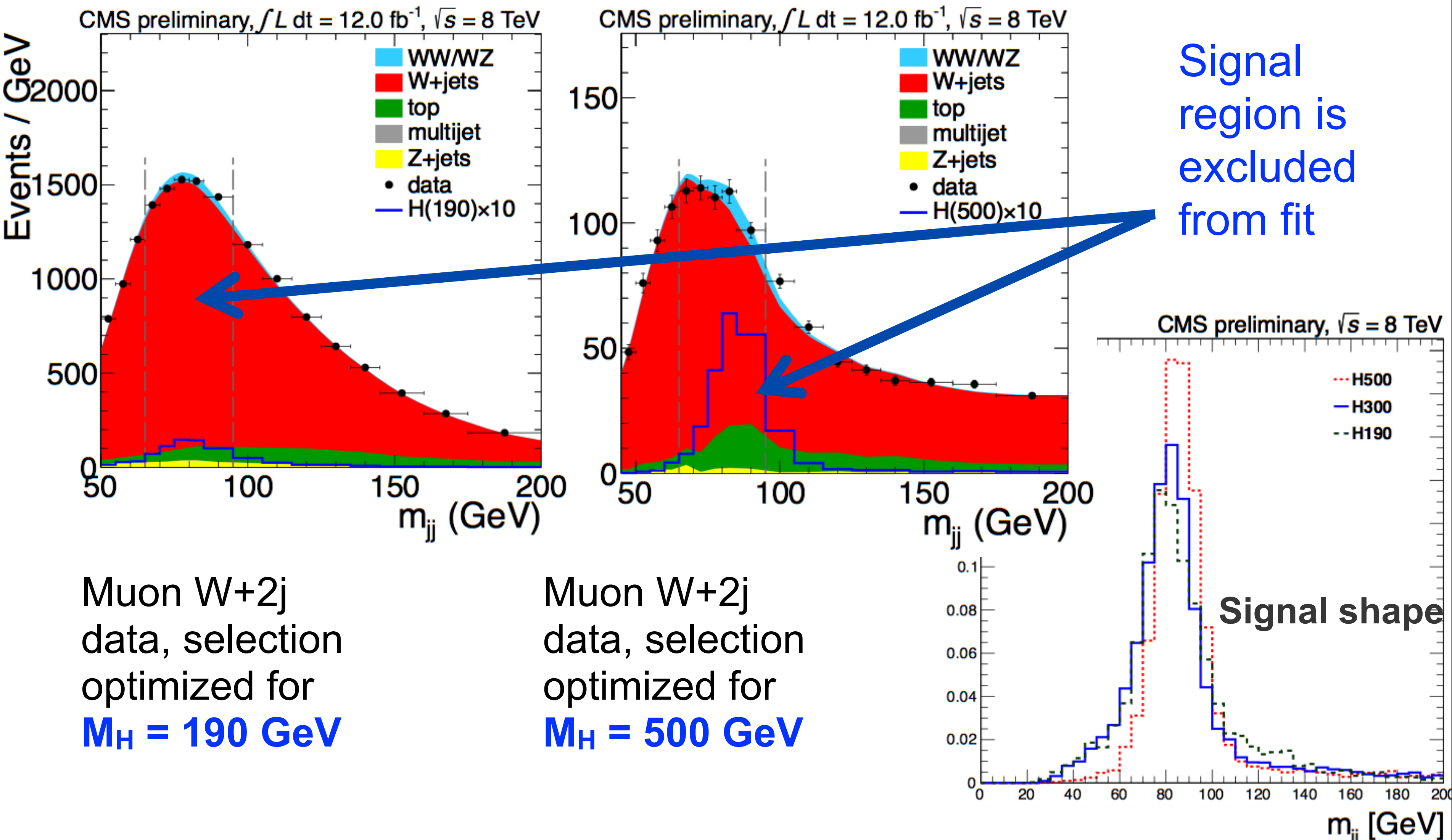
Examples of likelihood output





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

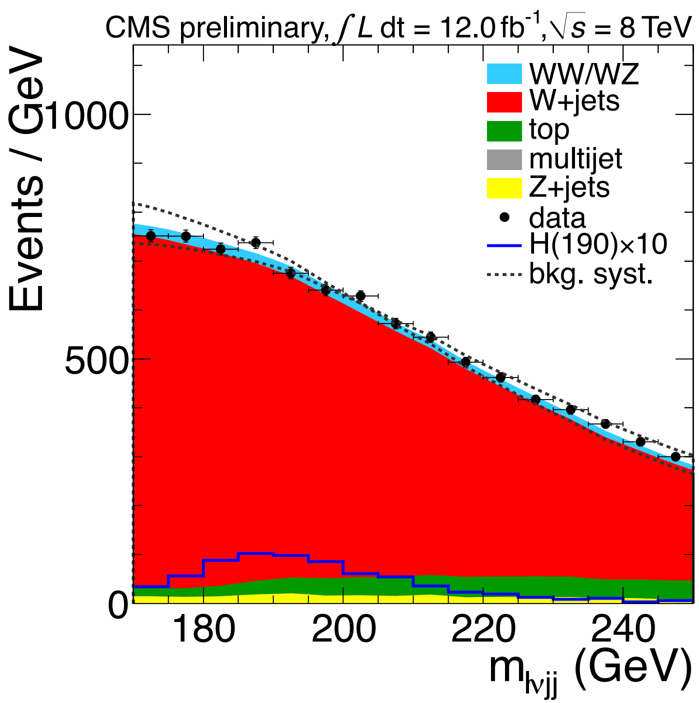


Muon W+2j data, selection optimized for **M_H = 190 GeV**

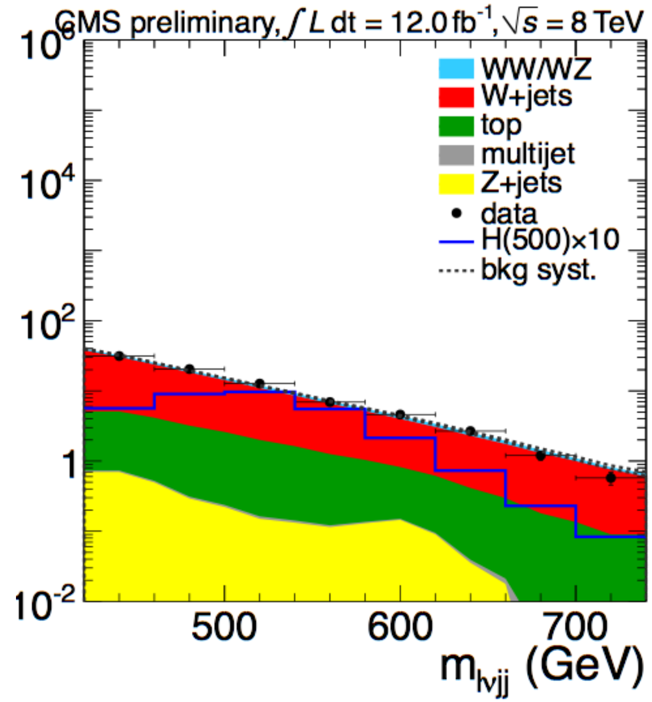
Muon W+2j data, selection optimized for **M_H = 500 GeV**

Now plot m_{WW} spectrum in signal region

Use data sidebands to model W+jets background shape

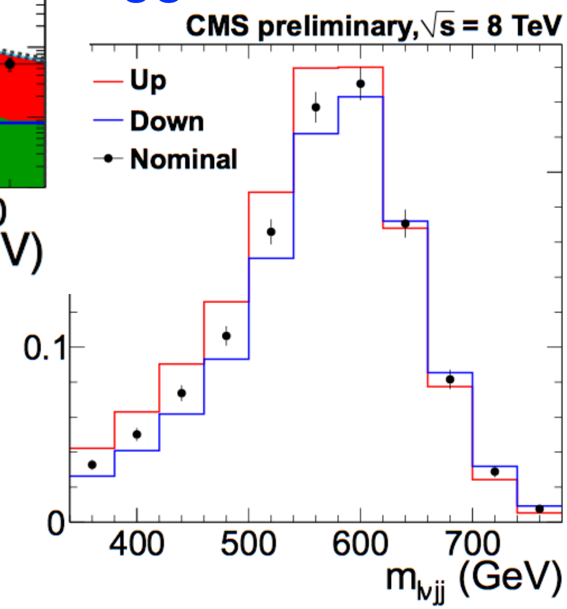


Muon W+2j data with m_{jj} in range [65, 95] GeV, selection optimized for **M_H = 190 GeV**



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

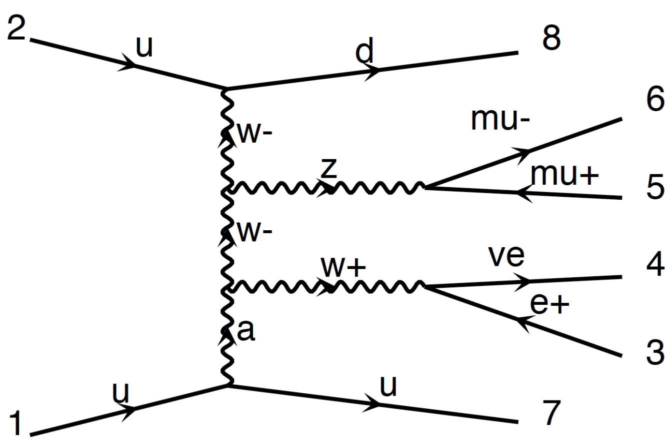
Signal syst for M_H = 600 GeV: dominated by interference btw gg→WW and gg→H→WW

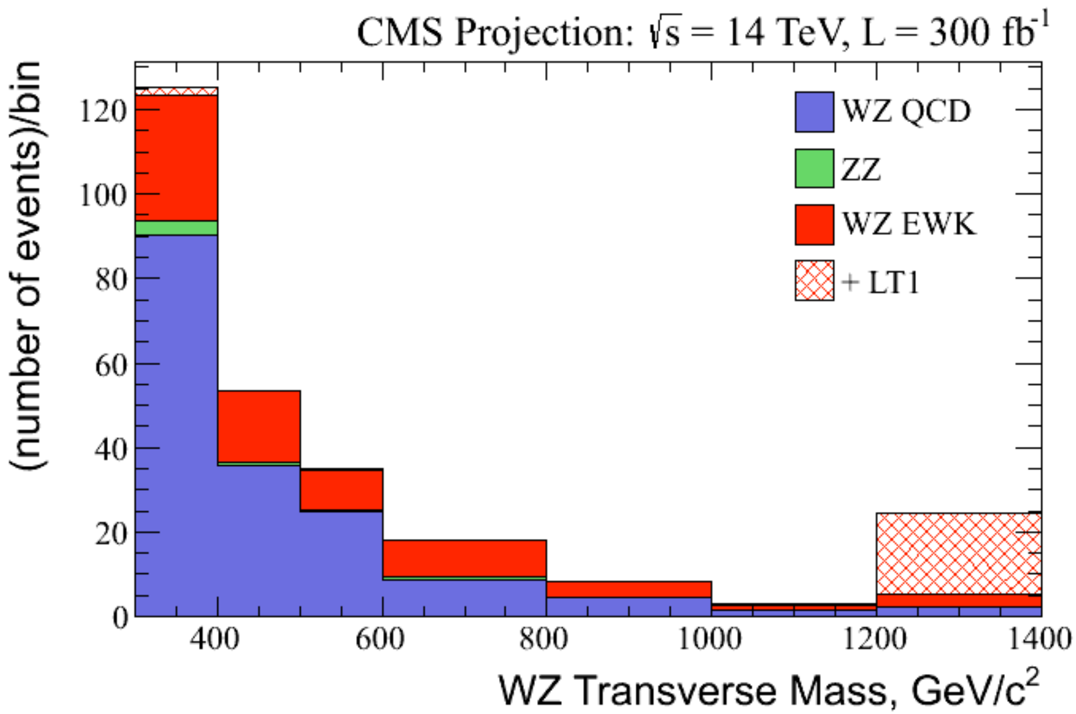


Some projections for VV scattering

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}

In numbers …

Higgs Of all the collisions over three years of LHC operation, only one in 5 billion produced the elusive particle.	**1.2 million**
Collisions The LHC produced roughly 90 billion particle collisions a day over the period of operation.	**5.8 quadrillion**
Physicists Collaborators from more than 40 countries worked on two of LHC's detectors, ATLAS and CMS.	**6,600**
$$$ Dollars The cost of running the LHC for three years came to about $62 per Higgs.	**74 million**
Power (MW) The electric power required to run the LHC and its experiments was enough to power about 50,000 homes.	**50**
Laps per second Traveling near the speed of light, protons in the LHC travel nearly 300,000 kilometers per second.	**11,245**

Source: sciencenews.org

After all, Higgs per $ is not as expensive as you would guess !

Even better- will get 10x cheaper in the next two years !!!