



Pursuing
Electroweak Symmetry Breaking
at CMS using WW semi-leptonic final state

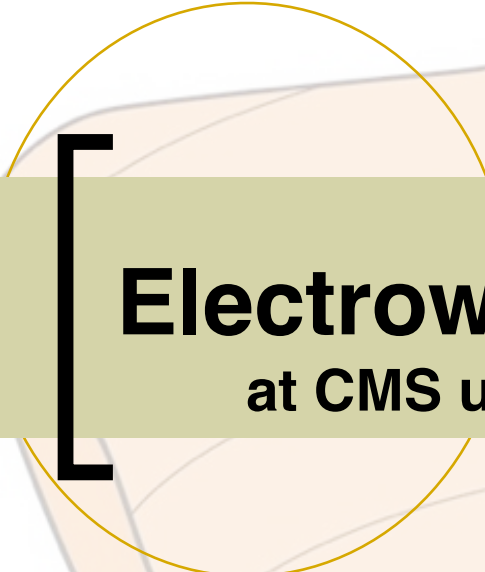
Kalanand Mishra
Fermilab, CMS Collaboration

$\text{Re}(\phi)$

MSU, November 26, 2012

$\text{Im}(\phi)$

$V(\phi)$



Outline



- Introduction to electroweak symmetry breaking
 - Discovery of a new Higgs-like boson
 - Measurement of its properties at the LHC
- WW events with the semi-leptonic final state
 - Measurement of production rate
- Probe of EWKSB in various topologies
 - Anomalous trilinear and quartic gauge couplings
 - Non-SM models: techni-color, Z' , ...
 - Vector boson fusion and WW scattering
- Summary

Reminder

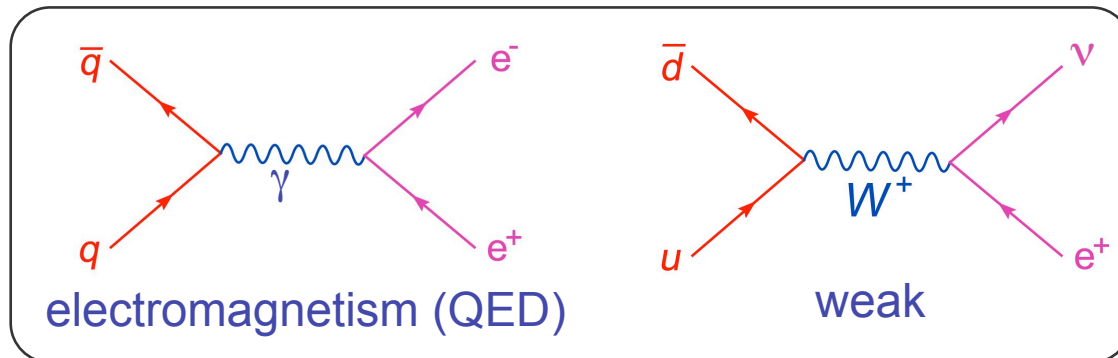
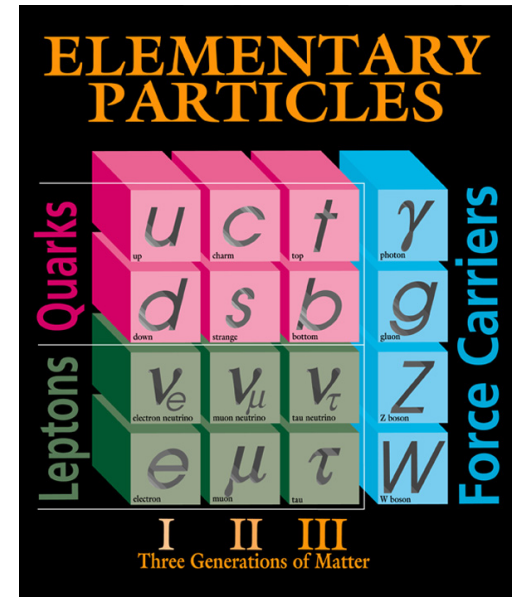
STOP ME if I go too fast or if you have questions!!

Introduction

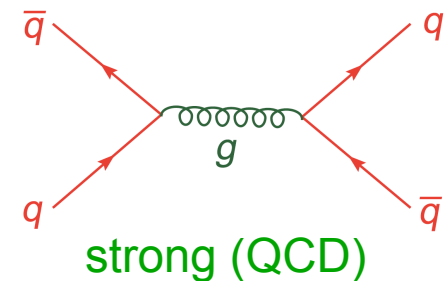
Symmetries of elementary particles



- All **matter** composed of spin $\frac{1}{2}$ **fermions**
- All **forces** carried by spin 1 **vector bosons**
- Fundamental symmetries of nature require that all elementary particles and force carriers be massless, but in real world they have widely differing masses \Rightarrow so some **symmetry must be broken**



Unified electroweak force





Electroweak symmetry breaking

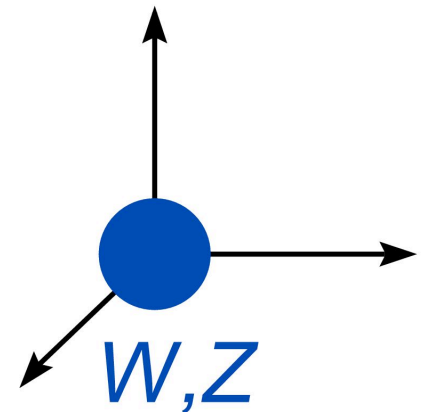
- Photon and gluon are massless, have two helicity states

$$h = \pm 1 \quad \begin{array}{c} \circlearrowleft \\ \rightarrow \\ \circlearrowright \end{array} \quad \begin{array}{c} \circlearrowright \\ \rightarrow \\ \circlearrowleft \end{array}$$

$$m_W, m_Z \neq 0 \Rightarrow h = 0 \text{ also allowed}$$

Electroweak symmetry is broken.

Massless photon, but massive W, Z bosons. Allows longitudinal degrees of freedom for W, Z.



Higgs Mechanism in a nutshell



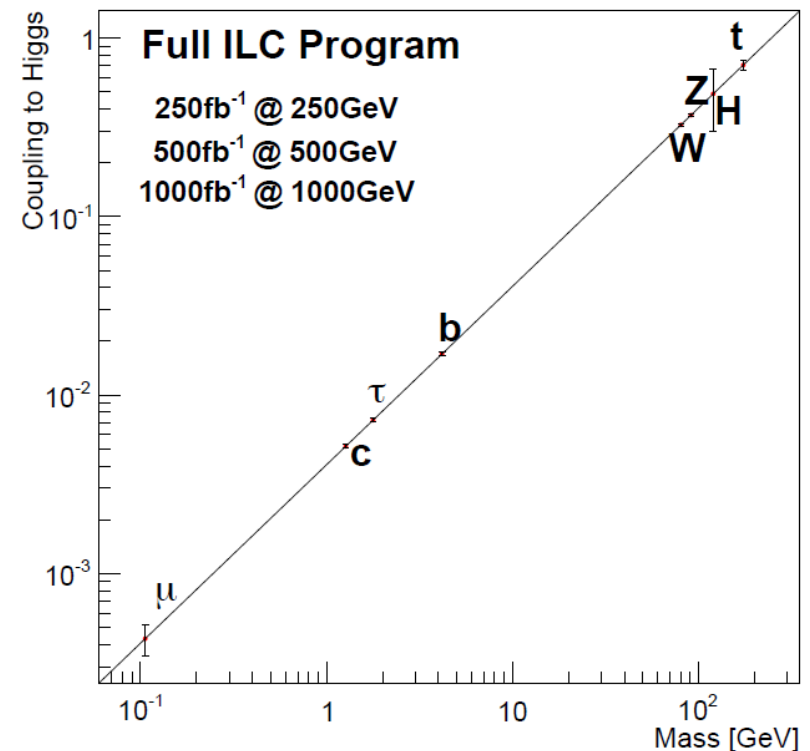
1.) Higgs mechanism gives mass to **W** and **Z bosons**, and to the **matter particles**.

Brout, Englert, Guralnik, Hagen, Higgs, Kibble (1964)

2.) Mass of W and Z predicted.
 Verified with great precision at LEP, SLD, Tevatron.

3.) Also predicts one extra particle: **The Higgs boson**. Its mass is not predicted.

We've now discovered it (or something very similar) at the LHC. The mass is ~ 125 GeV.



How to find Higgs: experimenter's perspective



How to pick out of a crowd?
What are the backgrounds?



Edinburgh Physics Dept

vs.



LHC

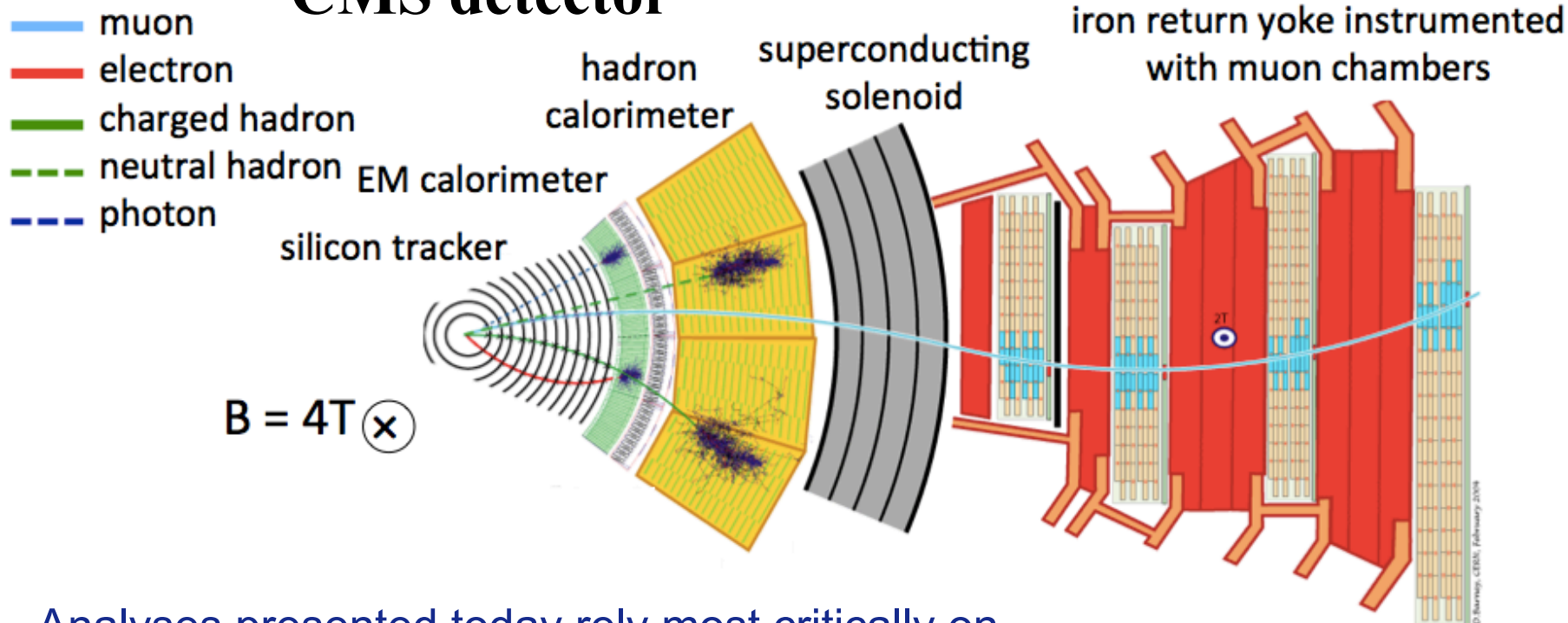
Where to find Higgs: LHC at CERN





Instrument to detect Higgs decay chain

CMS detector

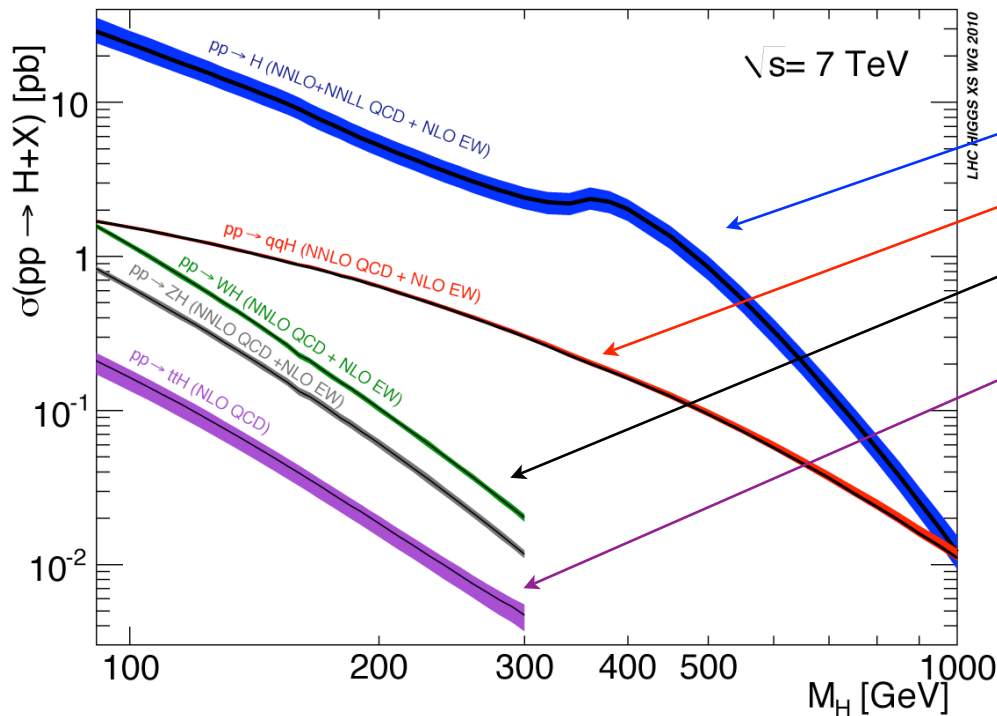
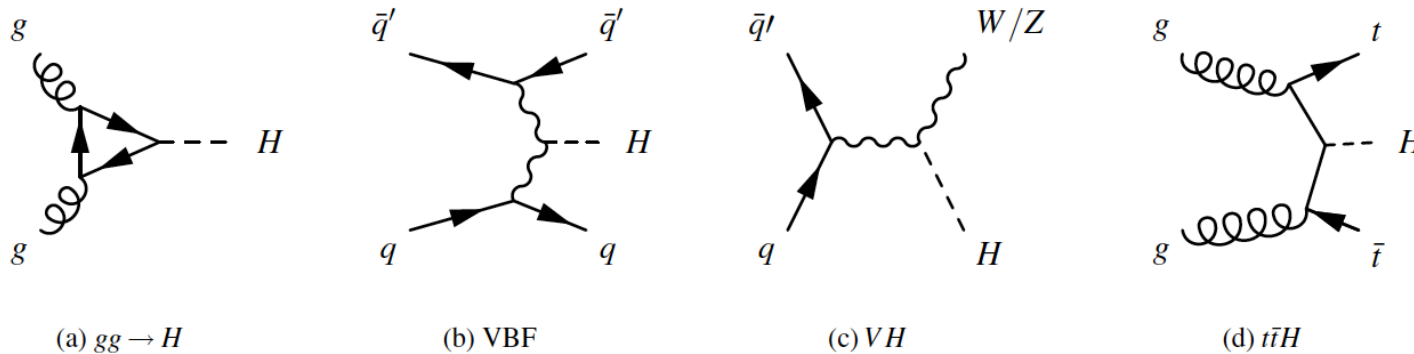


Analyses presented today rely most critically on

- **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



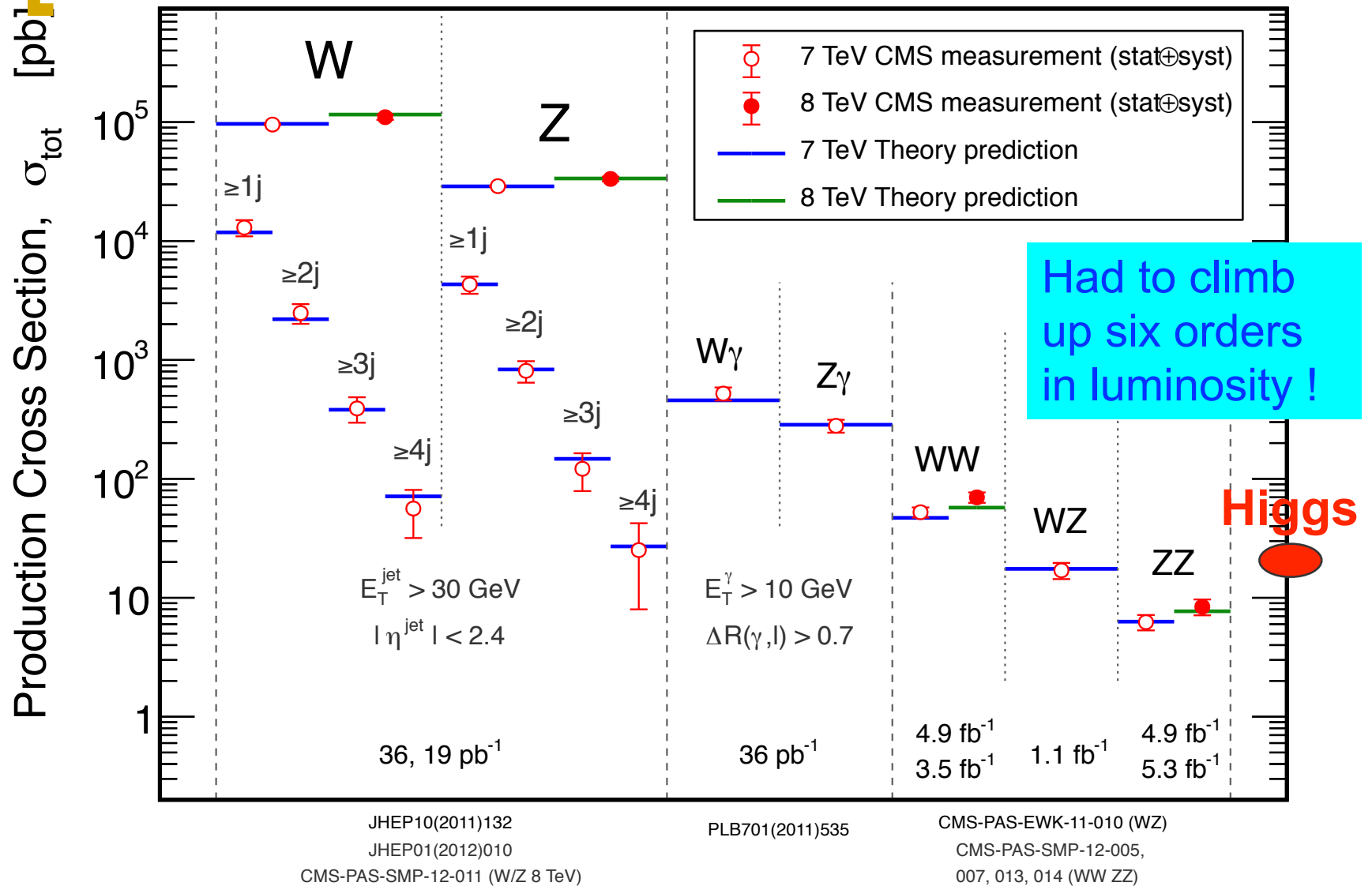
How do we find Higgs at LHC ?



Glue-gluon fusion
Vector boson fusion
in association with W,Z
in association with tt

gg \rightarrow H is the dominant production mechanism

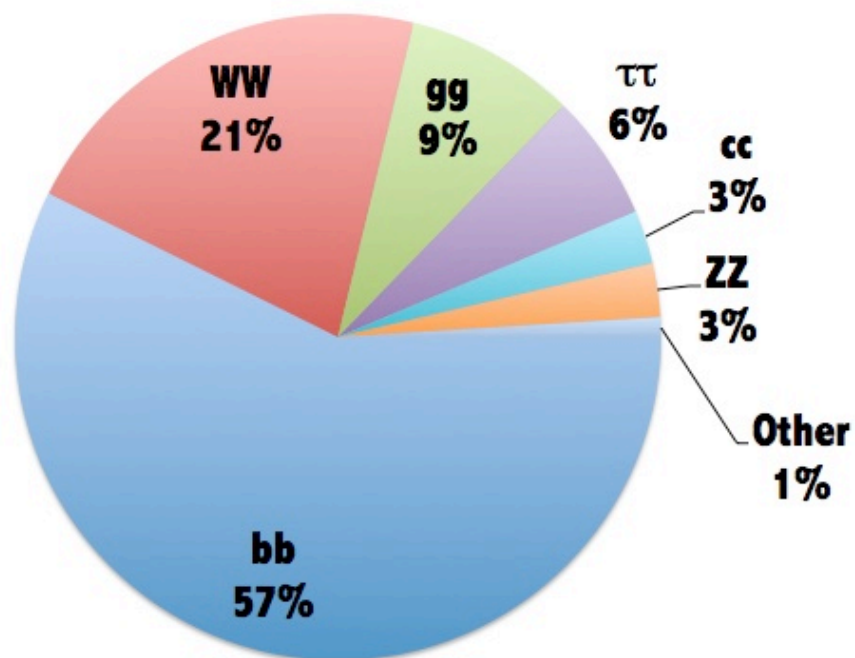
Small production rate: pb/fb processes!



The LHC is still a Higgs Factory!



15 Higgs boson / minute!



- **1M** Higgs already produced
-More to come (3X at 13 TeV)
- Difficulty: several production mechanisms to disentangle.
-Reduce systematics by measuring related processes.

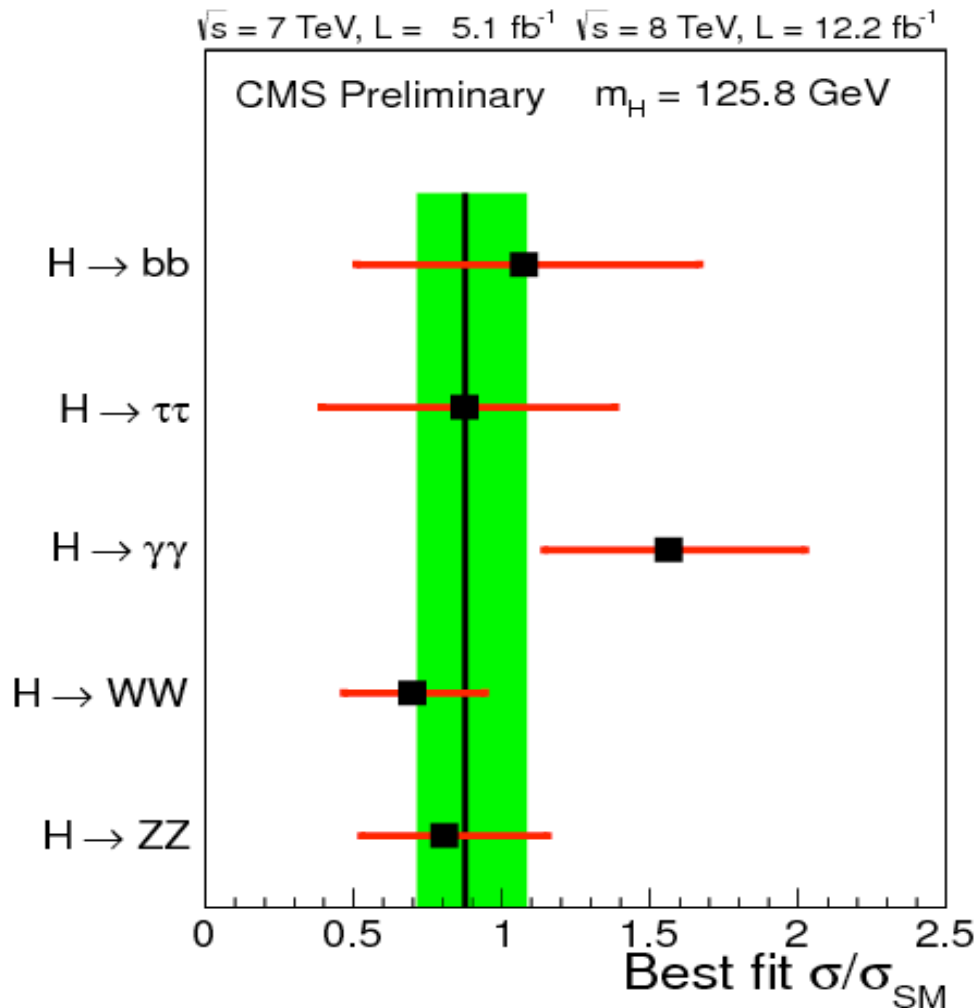
$$\sigma_{i \rightarrow f}^{\text{observed}} \propto \sigma_{\text{prod}} (g_{Hi})^2 (g_{Hf})^2$$

Extract couplings to anything we can see or produce from.

Signal strength $\mu = \sigma\text{BR}/\sigma\text{BR}_{\text{SM}}$: new HCP results



$ZZ^*, WW^*, \tau\tau, bb$: 12 fb⁻¹ 2012
 $\gamma\gamma$ as PLB 4th July



CMS $\mu = 0.88 \pm 0.21$

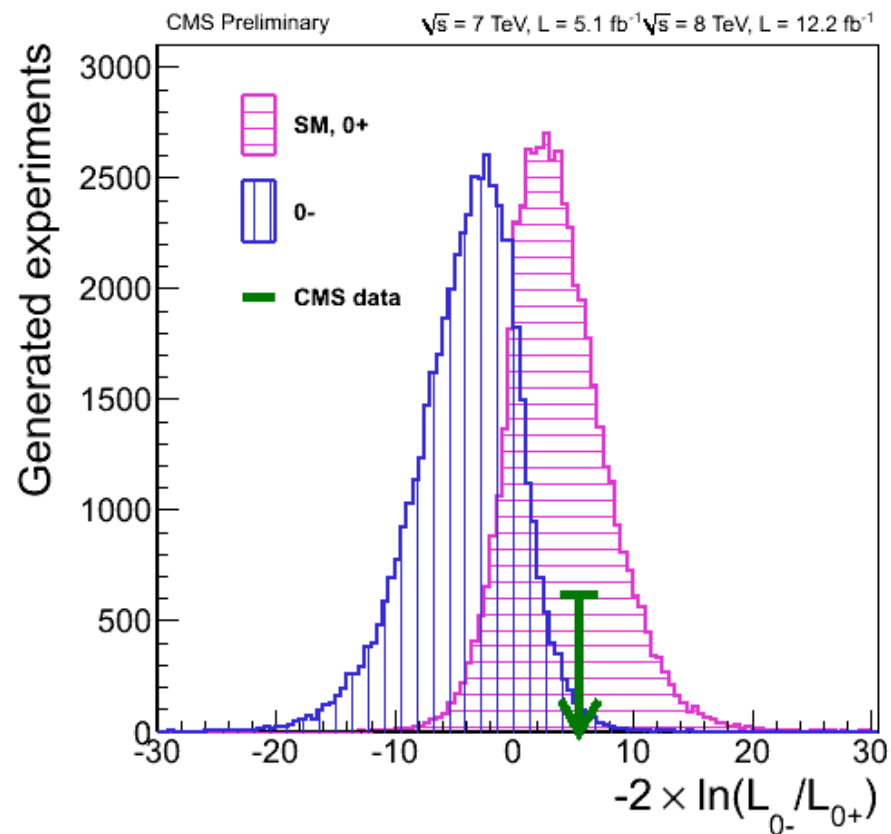
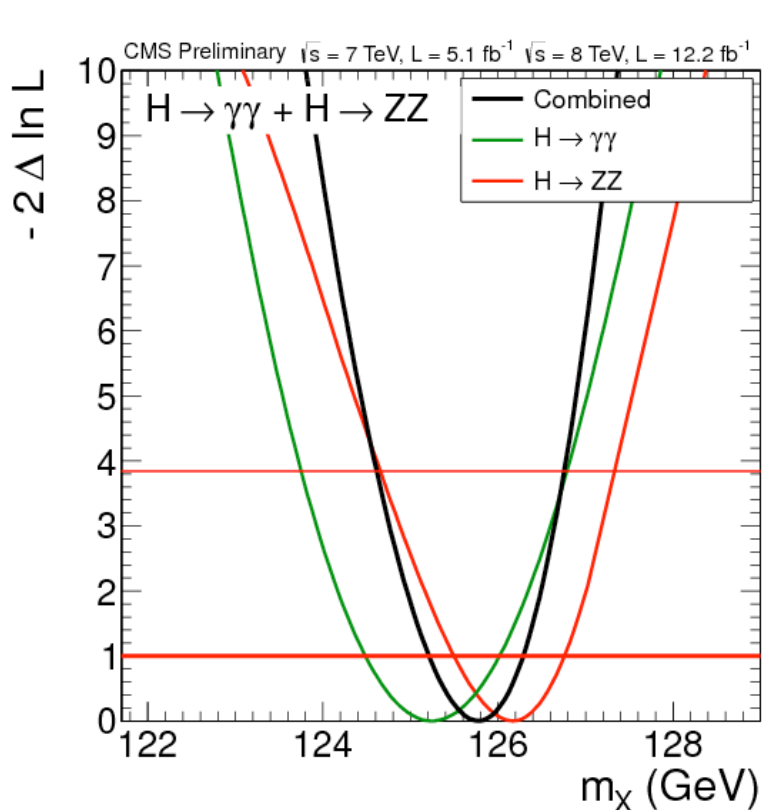
ATLAS $\mu = 1.3 \pm 0.3$

Agreement with SM prediction (and CMS/ATLAS) already at ~20%

Mass and spin/CP measurements



New HCP Update $ZZ^* \rightarrow 4\ell$



ATLAS: $M_H = 126.0 \pm 0.4_{\text{stat}} \pm 0.4_{\text{sys}} \text{ GeV}$

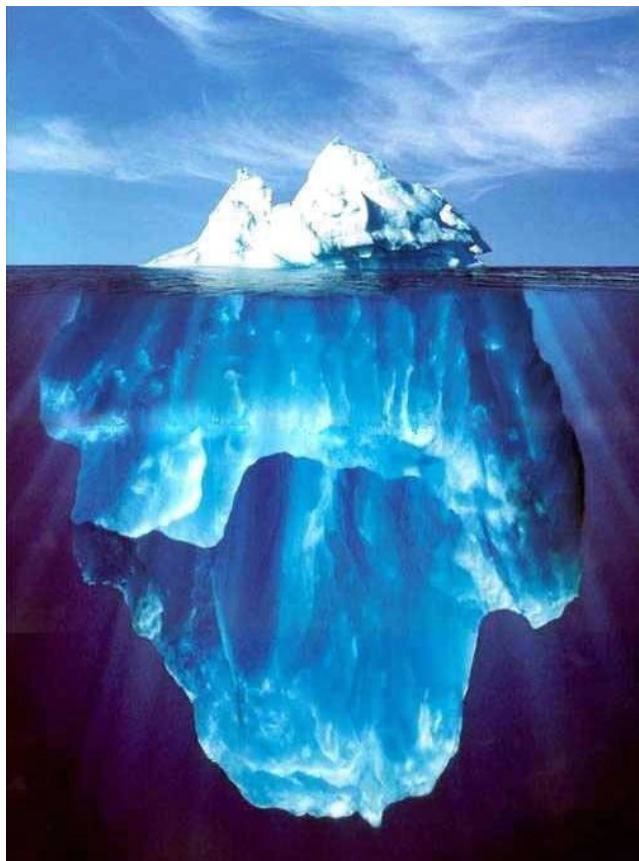
CMS: $M_H = 125.8 \pm 0.4_{\text{stat}} \pm 0.4_{\text{sys}} \text{ GeV}$

Data prefer 0^{++} . 0^{+-} consistency
ONLY at 2.45σ (1.93 exp)

Questions we aim to answer next at the LHC



Whether H(125)

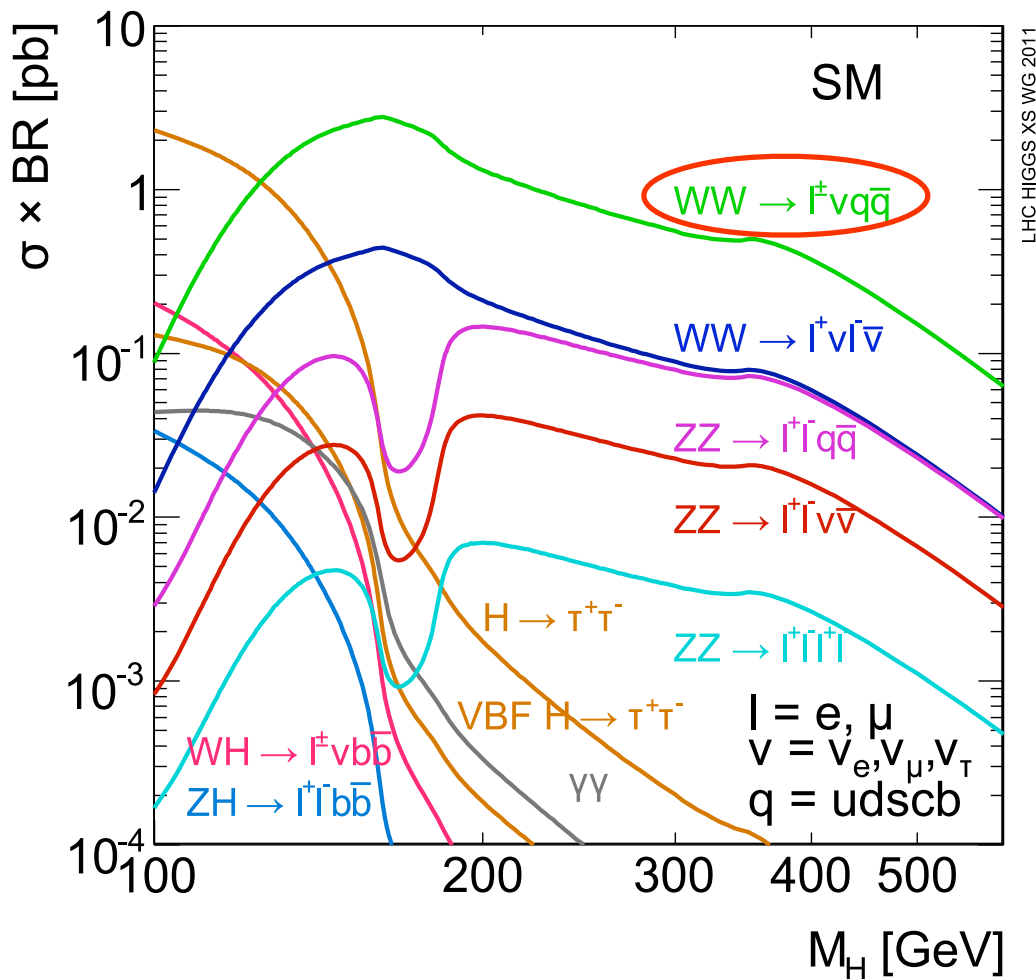


- Couples to fermions?
 - Accounts for fermion masses?
 - Fermion couplings \propto masses?
- Are there others?
- Quantum numbers: $J^{CP} = 0^{++}$?
- Decays to new/ dark matter particles?
- All production modes as expected?
- Implications of $M_H \approx 125$ GeV?
- Fully accounts for EWSB (W, Z couplings)?
 - Any sign of new strong dynamics?

Already have some good hints. More to learn this year....

WW semi-leptonic final state

Why a dedicated WW semi-leptonic analysis

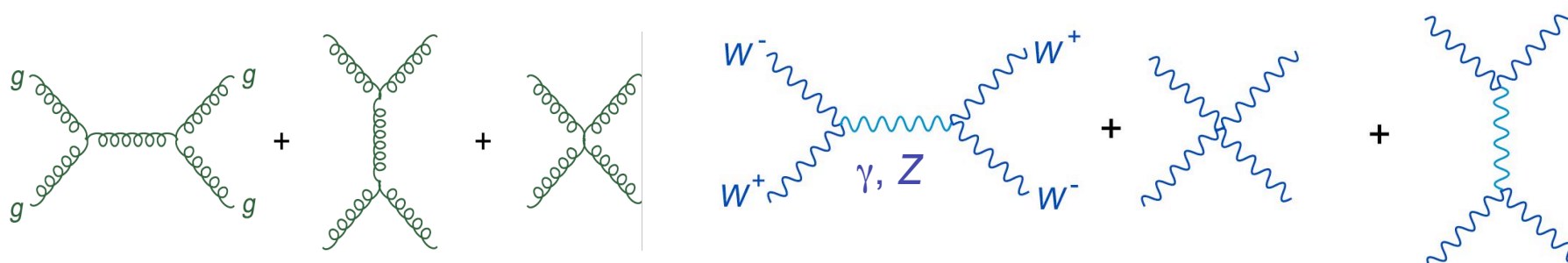


- ◆ $H \rightarrow WW \rightarrow \ell \nu jj$ does a lot of heavy lifting.
 - ☑ Largest $BR \times \sigma$ over most of the mass range
 - ☑ Using W mass constraint, the decay is sufficiently reconstructed to produce a mass peak
- ◆ Principal drawback is the large W+jet background
 - We employ data-driven techniques to understand and control this process.

Second reason: probe gauge boson couplings



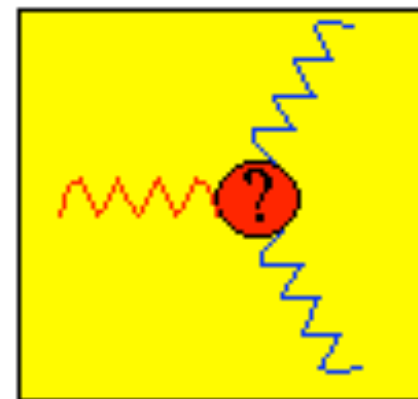
A non-Abelian gauge theory will exhibit gauge boson self-interactions. For example



In the case of EWK theory they could be

- trilinear ($WW\gamma$, WWZ) or
- quartic ($WW\gamma\gamma$, $WZW\gamma$, $WWZZ$, $WWWW$)

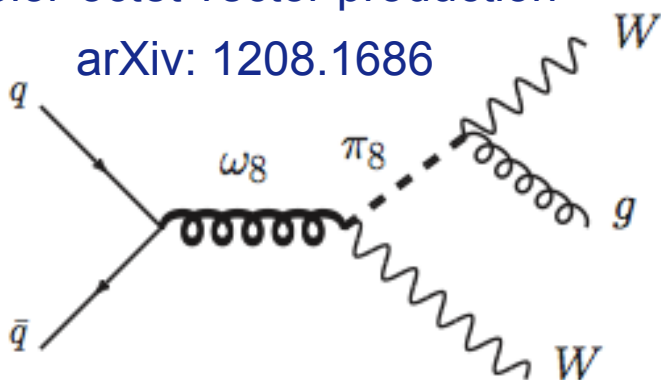
Observations of anomalous couplings would be an indication of new physics. Semi-leptonic channel is the most sensitive !



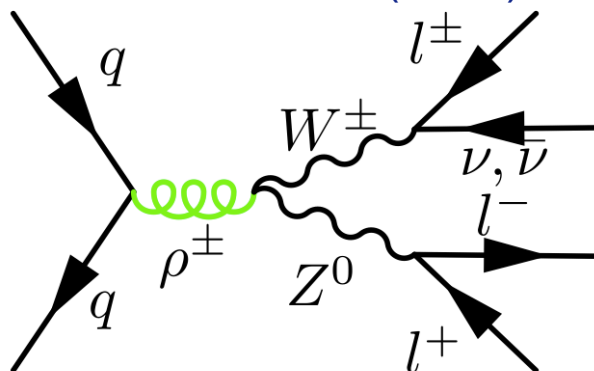
Third reason: probe non-SM models of EWSB

Color-octet vector production

arXiv: 1208.1686

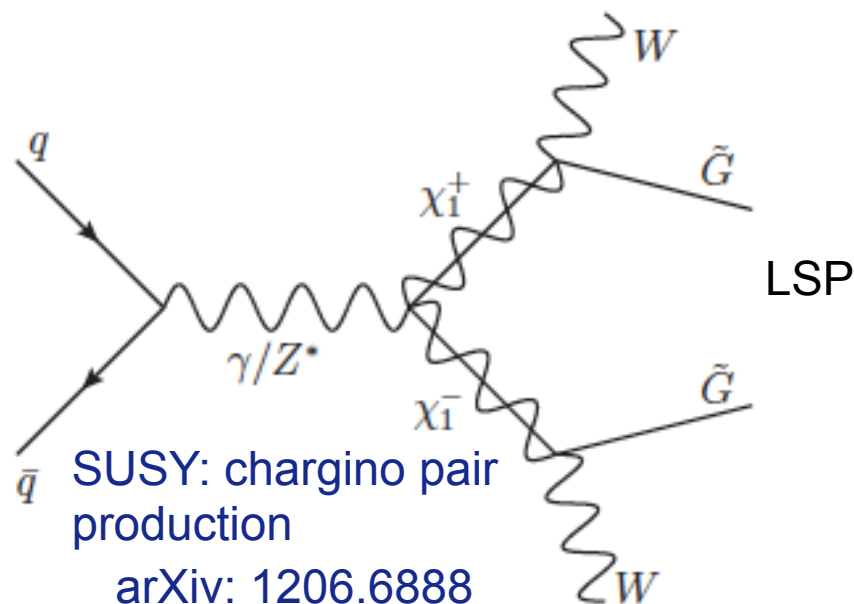


Low scale technicolor
Lane and Eichten, Phys.
Lett. B222, 274 (1989)



New physics can enhance WW or WZ production rate.

Signature: measured cross section > SM prediction. Helps to have the channel with the highest BR.

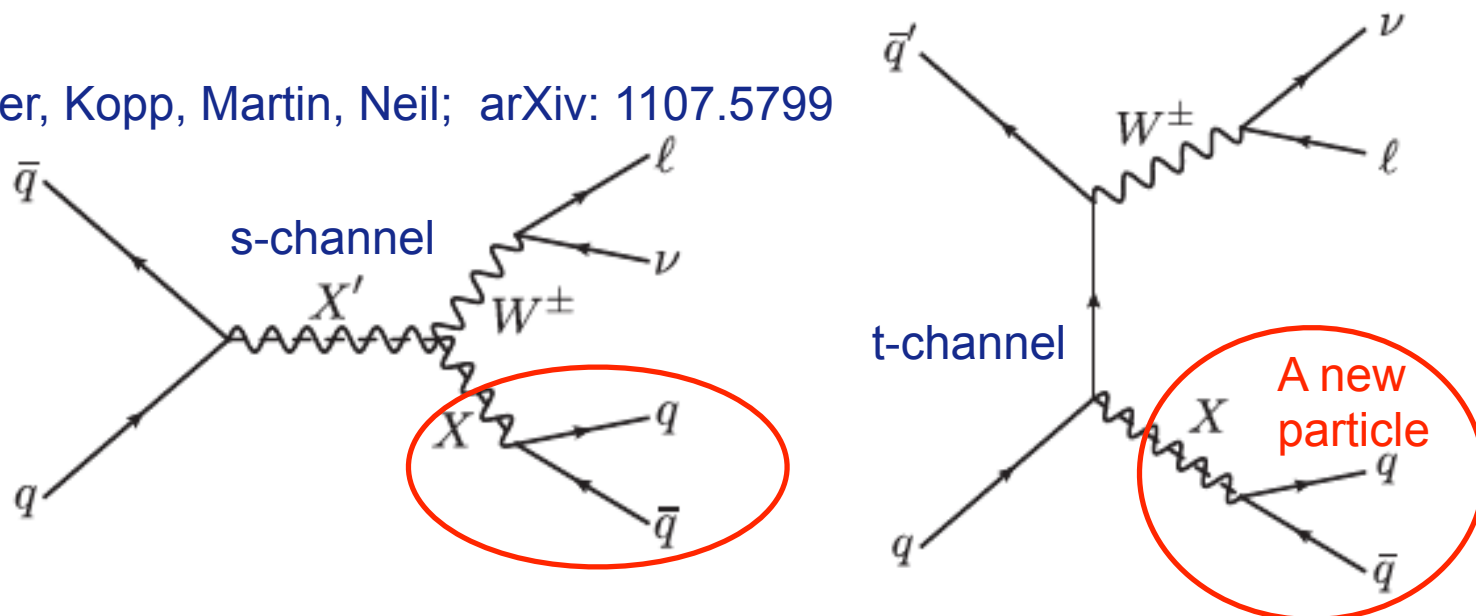


Fourth reason: new physics, dark matter,

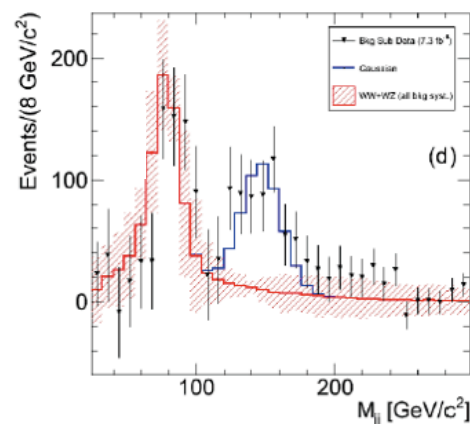
New physics can show up in this topology.

Buckley, Hooper, Kopp, Martin, Neil; arXiv: 1107.5799

Models:
technicolor,
 Z' , W' , RS
graviton



Most accessible in semi-leptonic final state, e.g., dijet mass bump in $W + 2\text{jet}$ events.

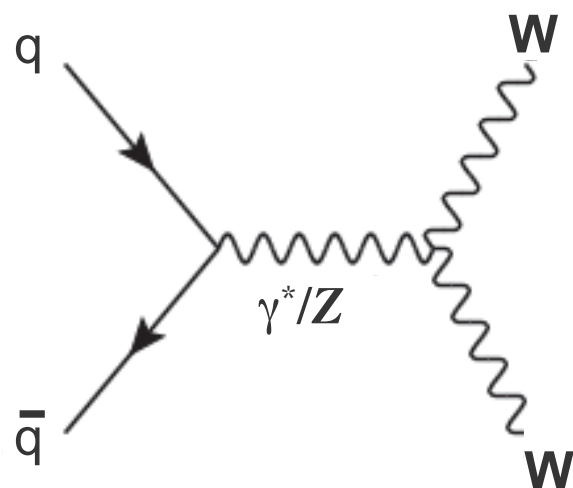




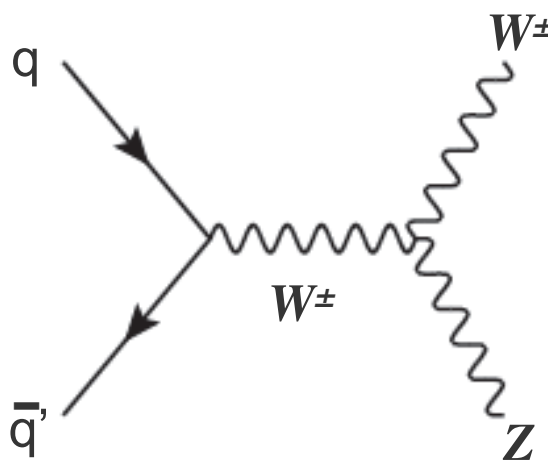
But you have to walk before you can run!

Needed to measure WW production rate first !

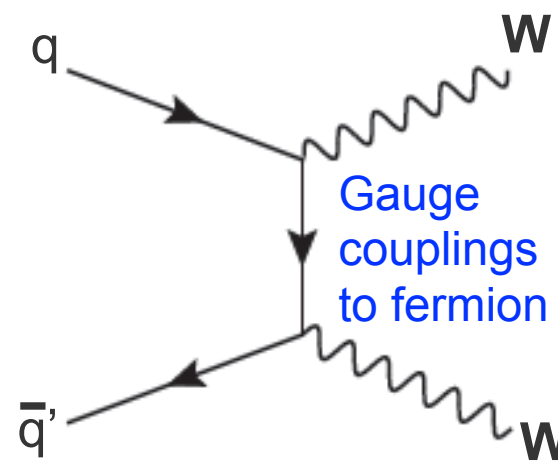
Diboson production at the Leading Order in α_s



s-channel WW



s-channel WZ

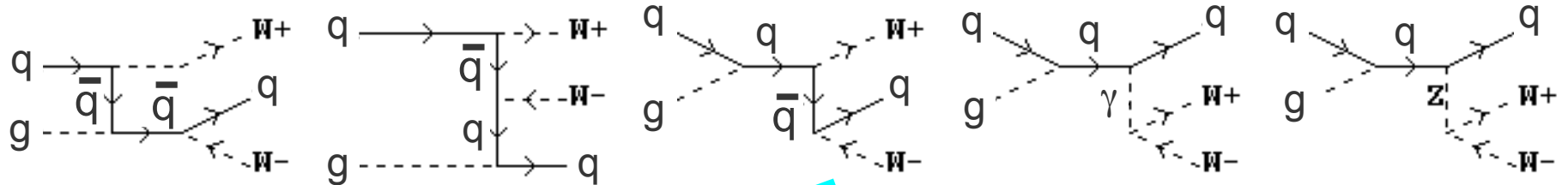


t-channel WW (similar diagrams for WZ, ZZ)

- The s- and t-channel WW diagrams are divergent but their sum is not

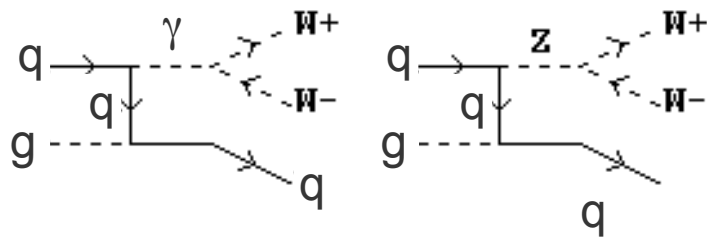


Significant contribution from NLO ($\approx 50\%$ of LO)

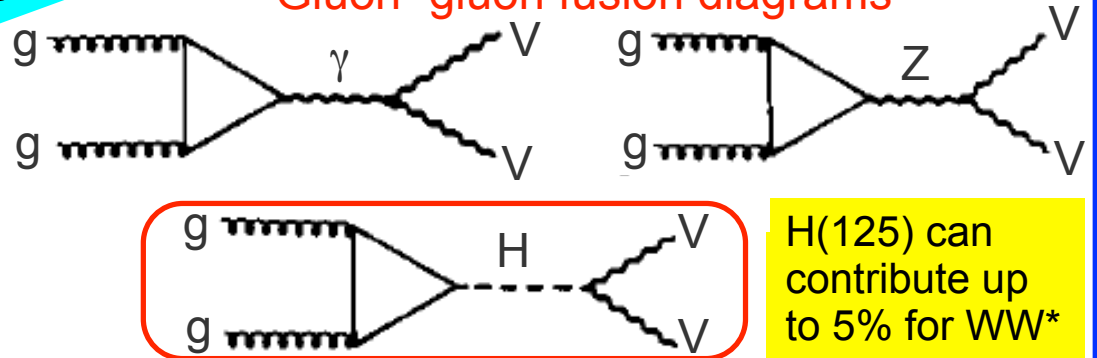


Quark-gluon diagrams

~6% gg contribution

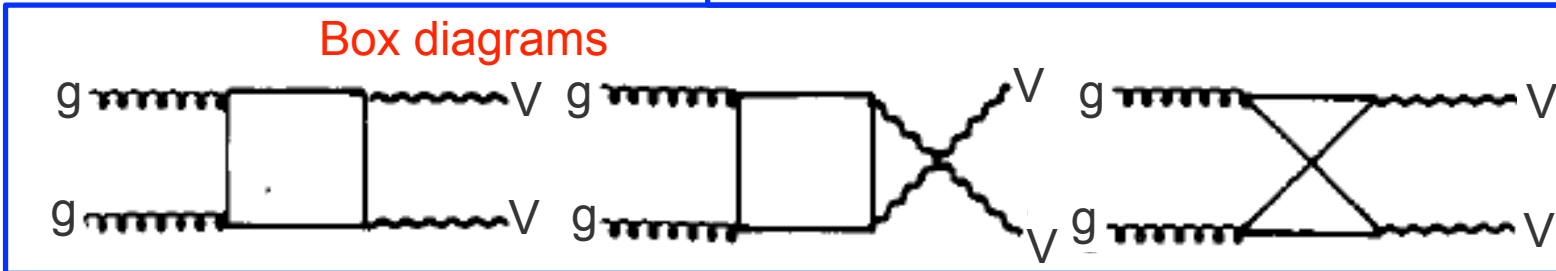


Gluon-gluon fusion diagrams



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

Box diagrams



Plus vector boson fusion diagrams

WW production rate measurement



W^+W^- : What do we see?

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12015>

μ p_T
60 GeV

ME_T
87 GeV

Jet1
112 GeV

Jet2
54 GeV

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

Lepton $p_T > 25$ GeV
(35 GeV for ele)
 $ME_T > 25$ (30) GeV
Jet $p_T > 35$ GeV
 $\Delta\eta(\text{Jet1}, \text{Jet2}) < 1.5$

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

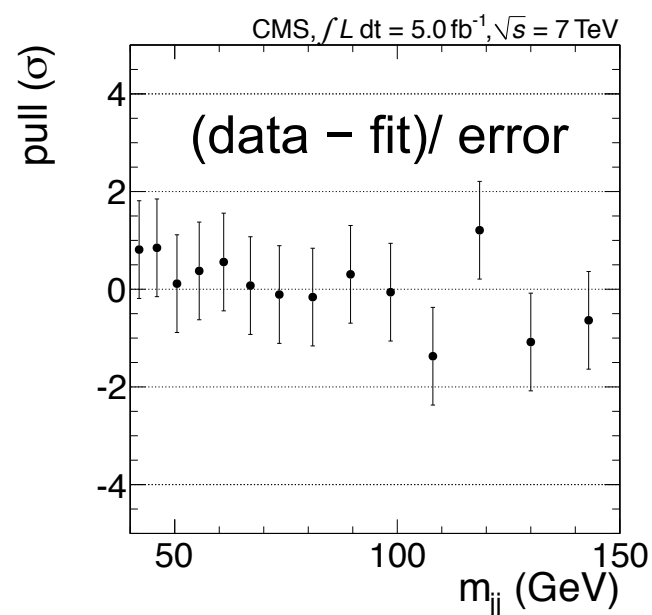
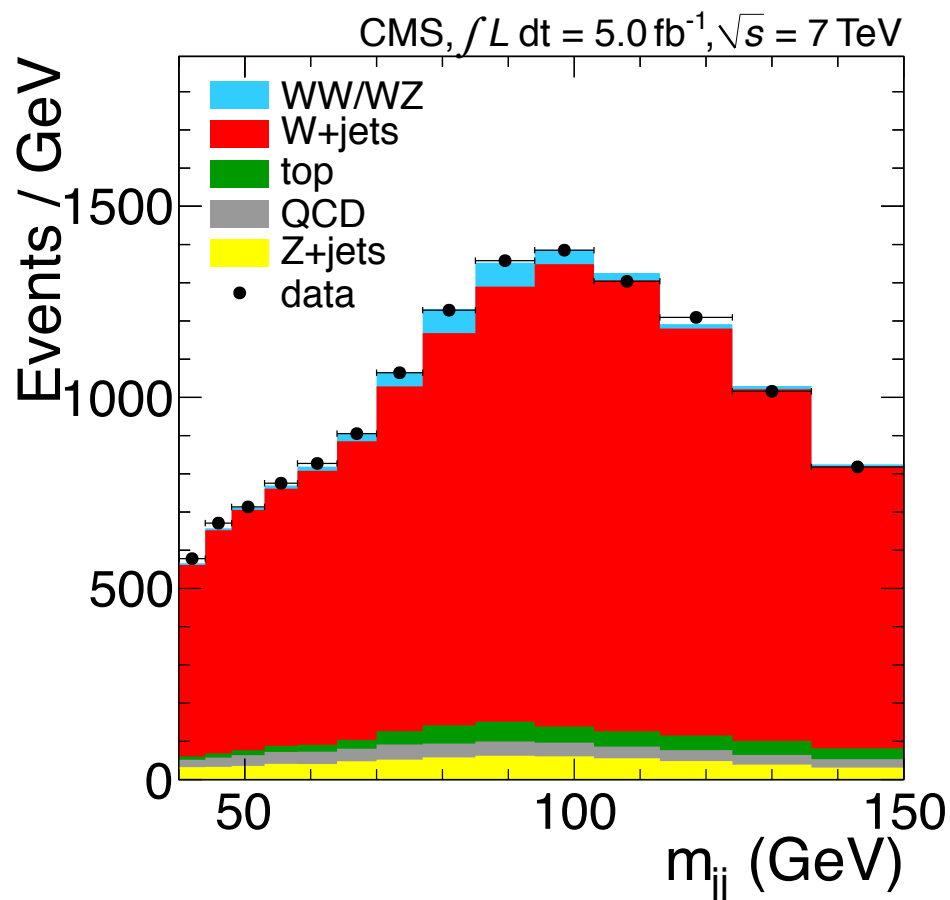
$H \rightarrow WW$ signal
resonant mass peak

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



First need to establish diboson bump !

Jet resolution doesn't allow to cleanly separate WW from WZ, so get admixture of the two. Fit the dijet mass spectrum.



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



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:

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

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)

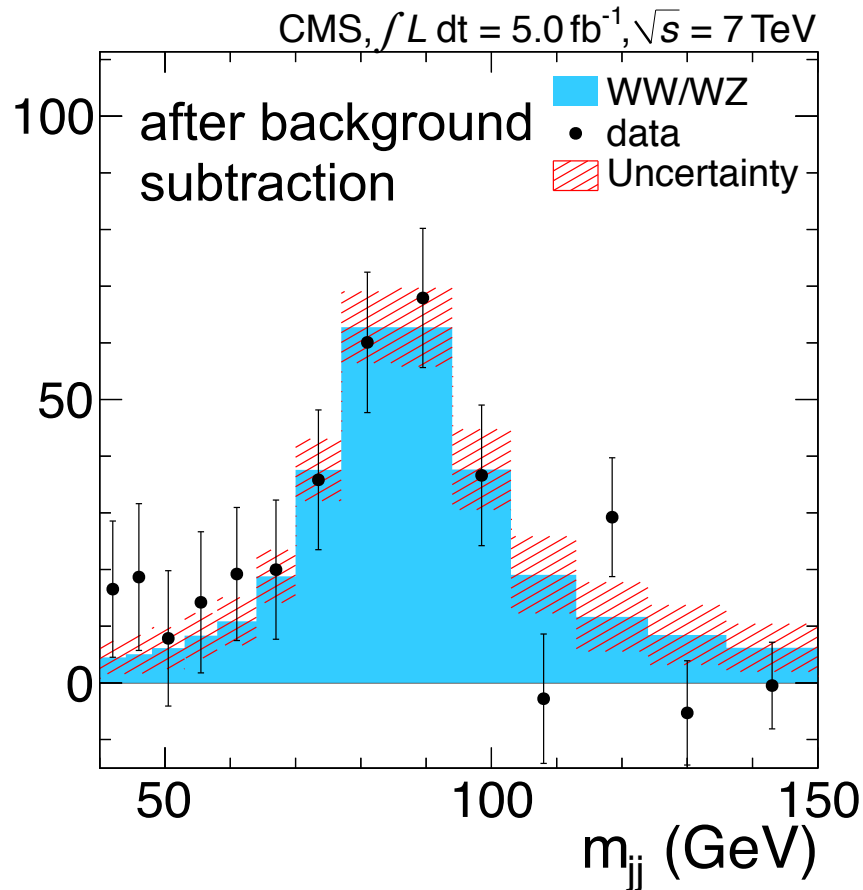
Fit results

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 × efficiency ($\mathcal{A}\epsilon$)	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

WW+WZ $\rightarrow \ell\nu qq$ cross section at 7 TeV



arXiv:1210.7544 (*Eur. J. Phys. C*)

- #diboson = $2682 \pm 339(\text{stat}) \pm 357(\text{syst})$, NLO prediction = 2564
- The first observation of diboson in semi-leptonic channel at LHC.

$\sigma = 68.9 \pm 8.7 \text{ (stat)} \pm 9.7 \text{ (sys)} \pm 1.5 \text{ (lum)} \text{ pb}$
NLO prediction (MCFM): $65.6 \pm 2.2 \text{ pb}$

Consistent with NLO



Anomalous couplings in WW/WZ production

5 independent couplings remain after assuming basic symmetry

$$\mathcal{L}_{anom} = ig_{WWZ} \left[\Delta g_1^Z (W_{\mu\nu}^* W^\mu Z^\nu - W_{\mu\nu} W^{*\mu} Z^\nu) + \Delta \kappa^Z W_\mu^* W_\nu Z^{\mu\nu} + \frac{\lambda^Z}{M_W^2} W_{\rho\mu}^* W_\nu^\mu Z^{\nu\rho} \right] + ig_{WW\gamma} \left[\Delta \kappa^\gamma W_\mu^* W_\nu \gamma^{\mu\nu} + \frac{\lambda^\gamma}{M_W^2} W_{\rho\mu}^* W_\nu^\mu \gamma^{\nu\rho} \right],$$

Equal coupling parametrization

$$\Delta \kappa_Z = \Delta g_1^Z - \Delta \kappa_\gamma \cdot \tan^2 \theta_W \quad \lambda_Z = \lambda_\gamma = \lambda$$

Further assume that $\Delta g_1^Z = 0$ (SM), leaves two parameters: λ_Z , $\Delta \kappa_\gamma$

Coupling	Particle Data Group Fit
Λ_γ	$0.028^{+0.020}_{-0.021}$
Λ_Z	$0.088^{+0.060}_{-0.057}$
Δg_1^Z	$0.016^{+0.022}_{-0.019}$
$\Delta \kappa_\gamma$	$0.027^{+0.044}_{-0.045}$
$\Delta \kappa_Z$	$0.026^{+0.059}_{-0.056}$

LEP combination
@ 95% CL

$[-0.026, 0.208]$

$[-0.063, 0.115]$

Tevatron (DØ)
arXiv:1208.5458

λ_Z : $[-0.039, 0.042]$

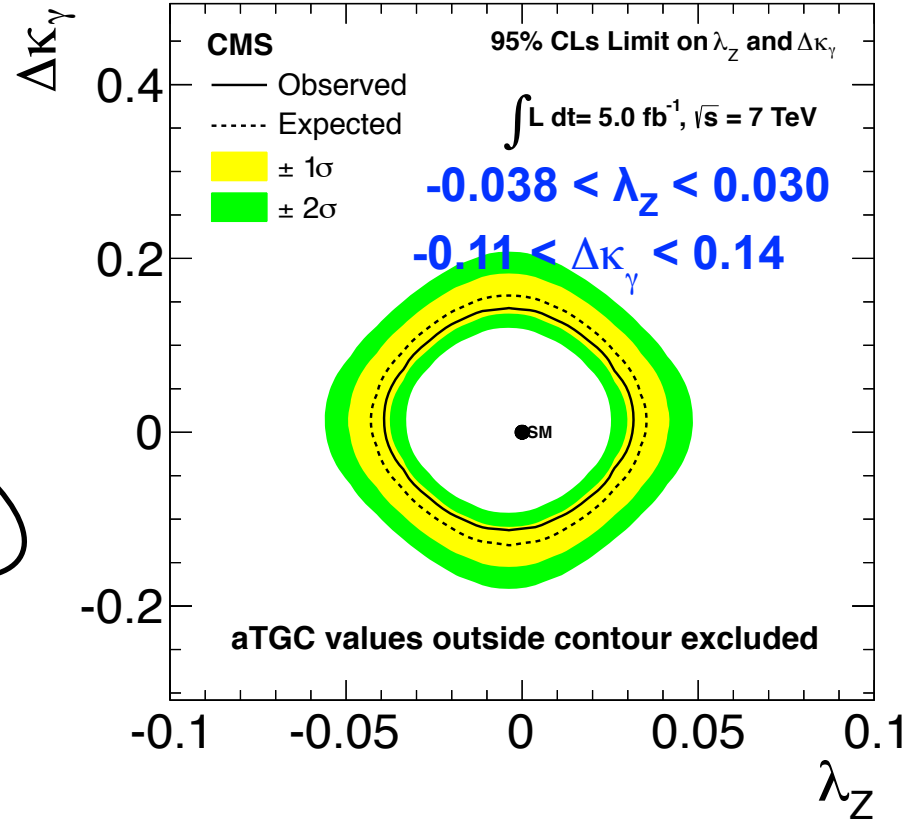
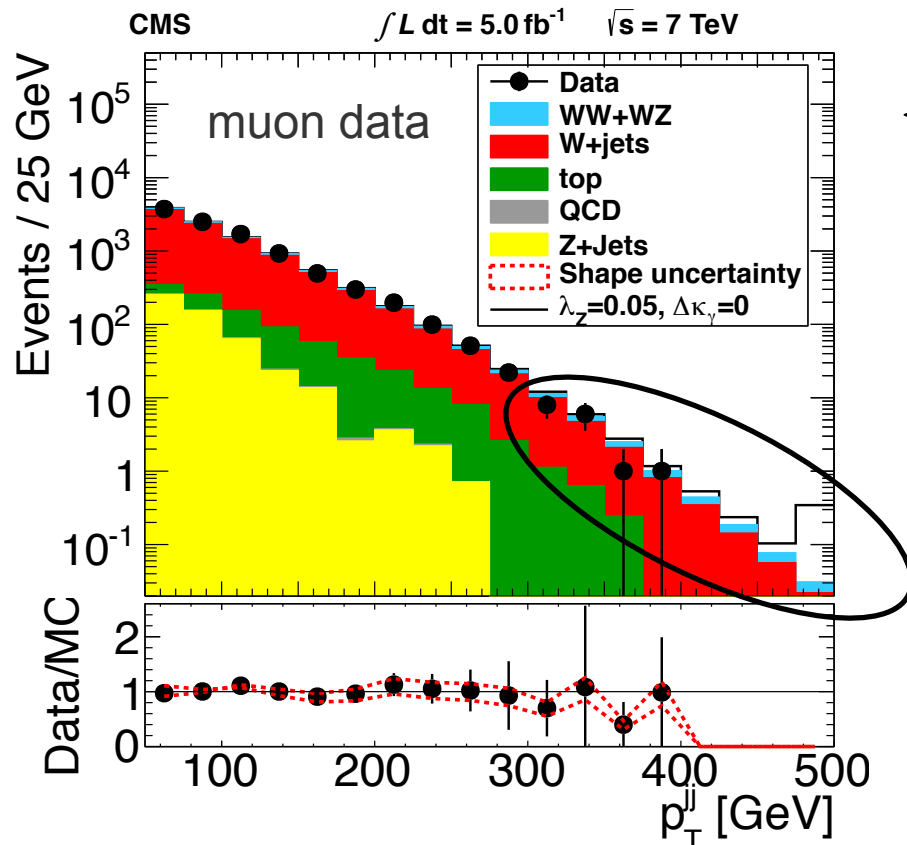
$\Delta \kappa_\gamma$: $[-0.049, 0.124]$

Note: assumes form factor of 2 TeV



Limits from $WW/WZ \rightarrow \ell\nu qq$ measurement

Use dijet (hadronic W) p_T as the observable



Anomalous couplings show up in high p_T tails. Model using MCFM.

Improve upon the LEP limit in some cases.

Search for the SM Higgs boson



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

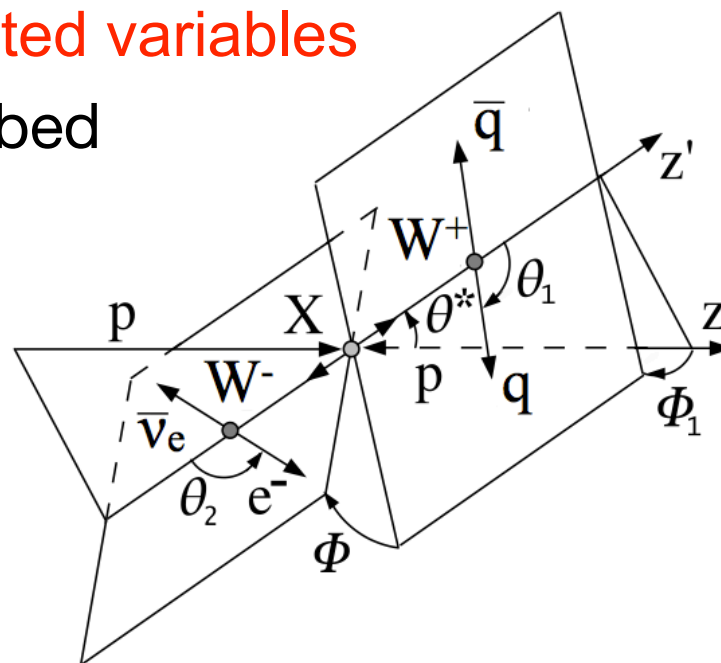
- Higgs boson kinematics is fully described by $\rightarrow \{m_{WW}, m_{jj}, \theta_1, \theta_2, \theta^*, \phi, \phi_1\}$

- 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

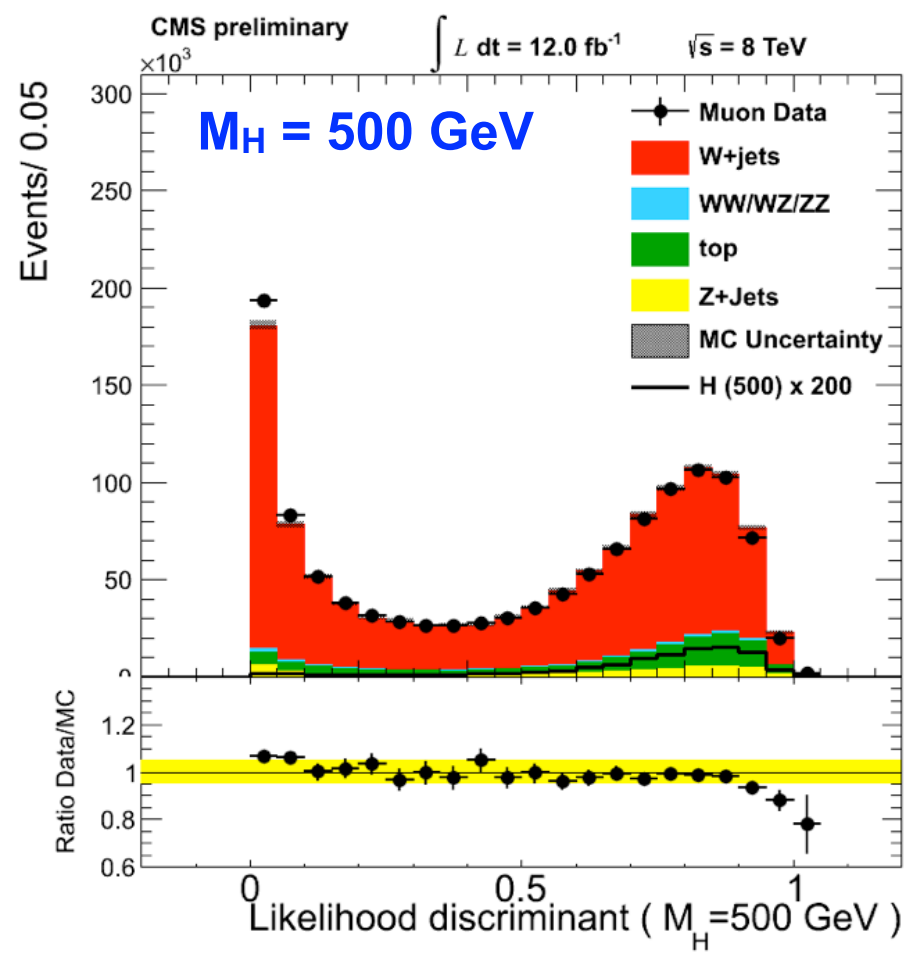
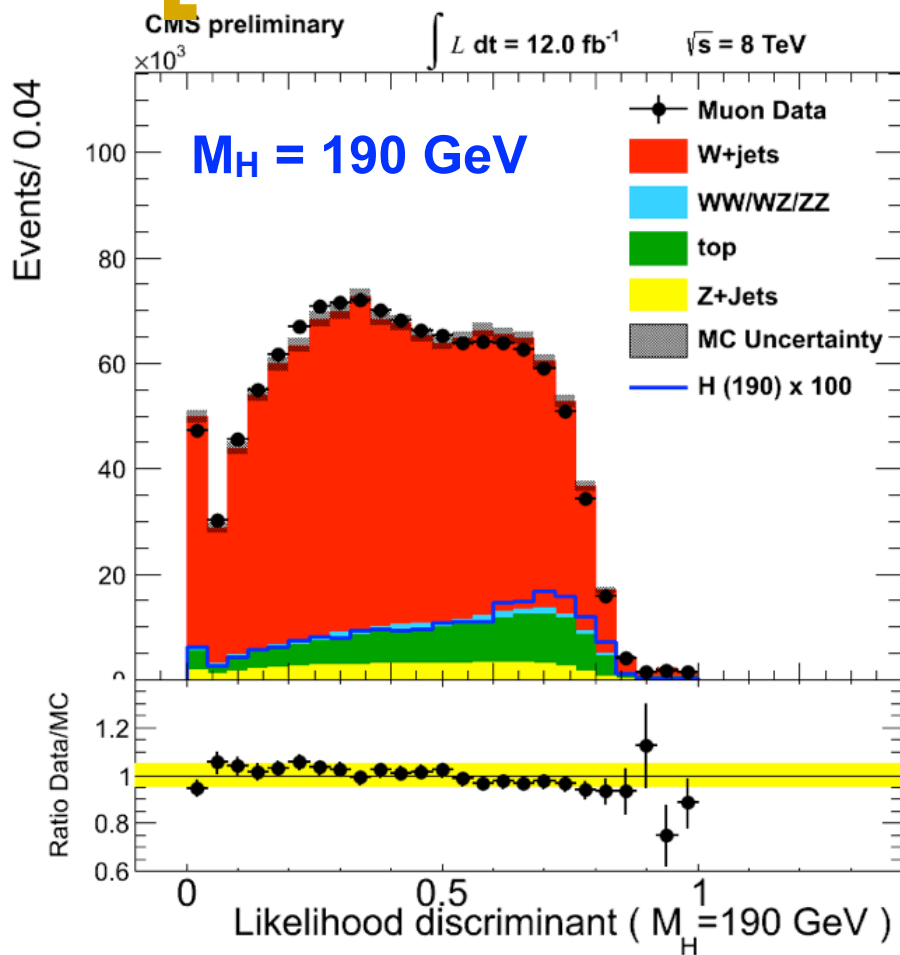
- **Lepton charge** is a good variable since signal is charge-symmetric, W^+ jets is not



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

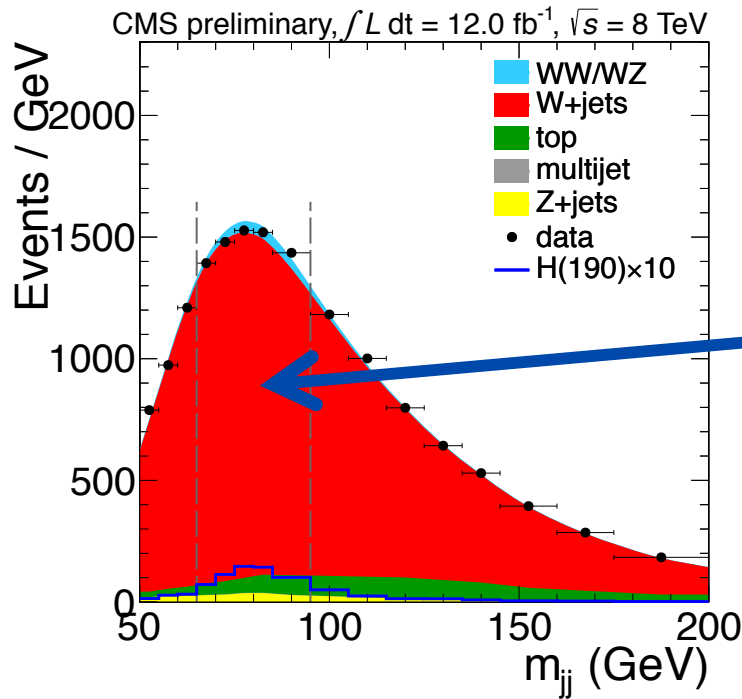


Examples of likelihood output

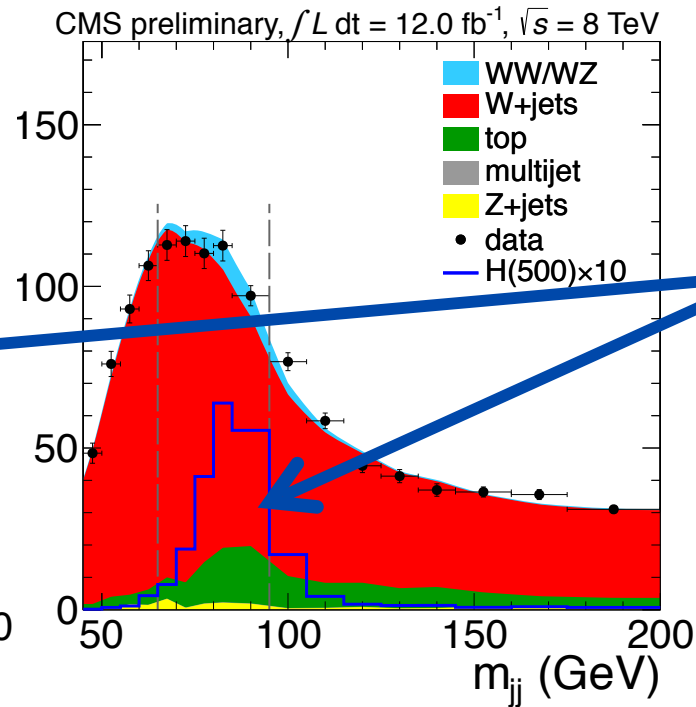


Optimize 48 likelihoods: 12 mass points (M_H :170, 180, 190, 200, 250,..., 600 GeV) x 2 lepton flavors x 2 N_{jets} (i.e., =2 or 3)

Use m_{jj} fit to obtain background normalization

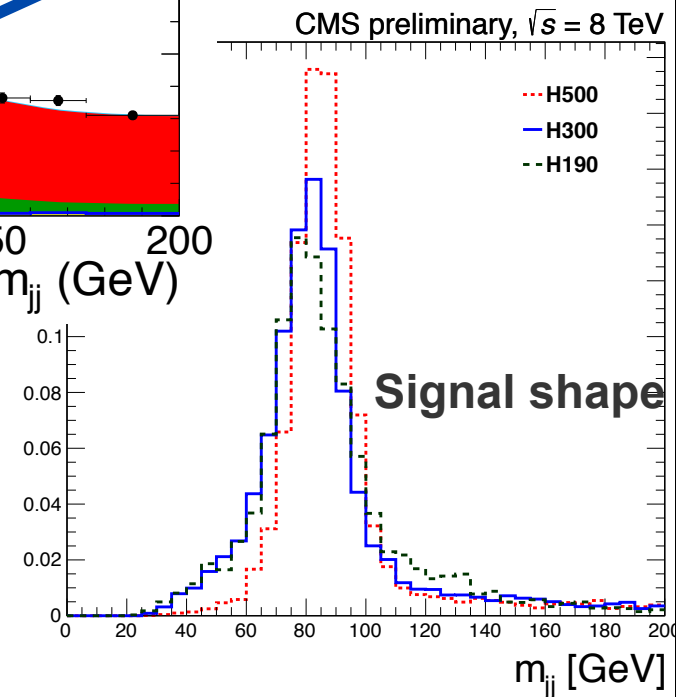


Muon W+2j data, selection optimized for $M_H = 190 \text{ GeV}$



Muon W+2j data, selection optimized for $M_H = 500 \text{ GeV}$

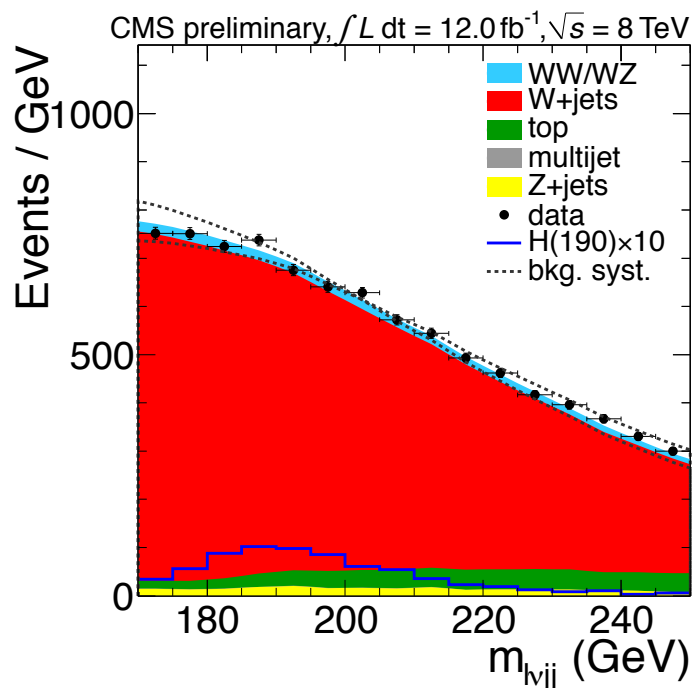
Signal region is excluded from fit



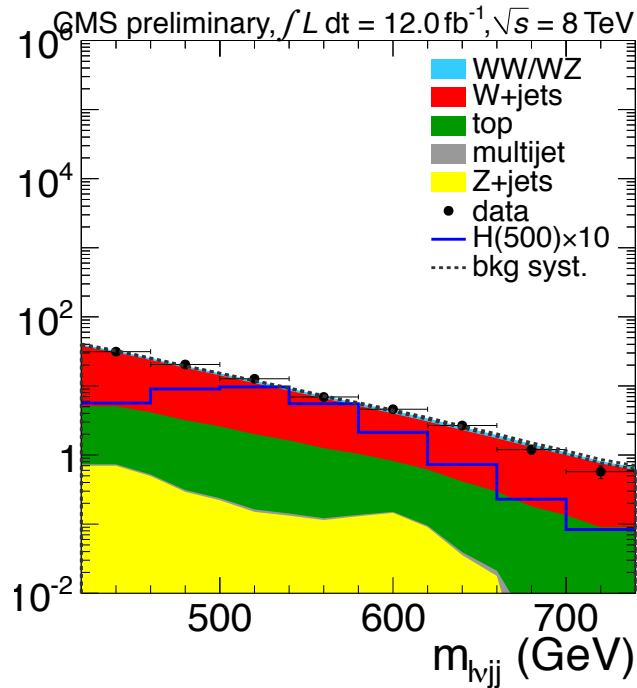


Now plot m_{WW} spectrum in signal region

Use data sidebands to model W +jets background shape

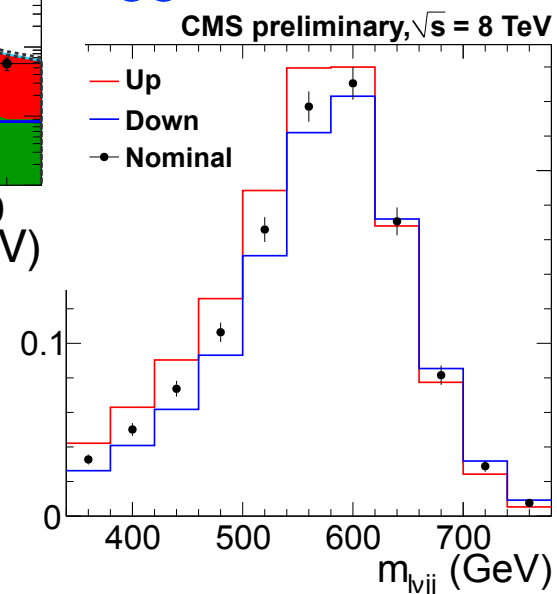


Muon $W+2j$ data with m_{jj} in range [65, 95] GeV, selection optimized for $M_H = 190$ GeV



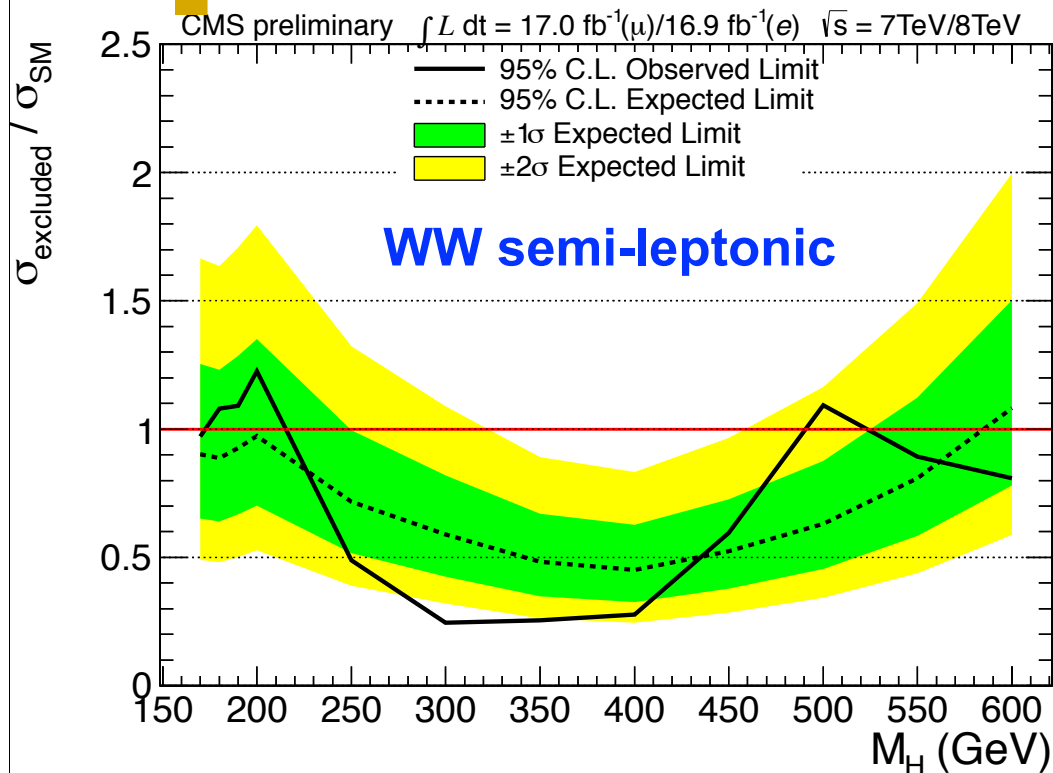
Muon $W+2j$ data with m_{jj} in range [65, 95] GeV, selection optimized for $M_H = 500$ GeV

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



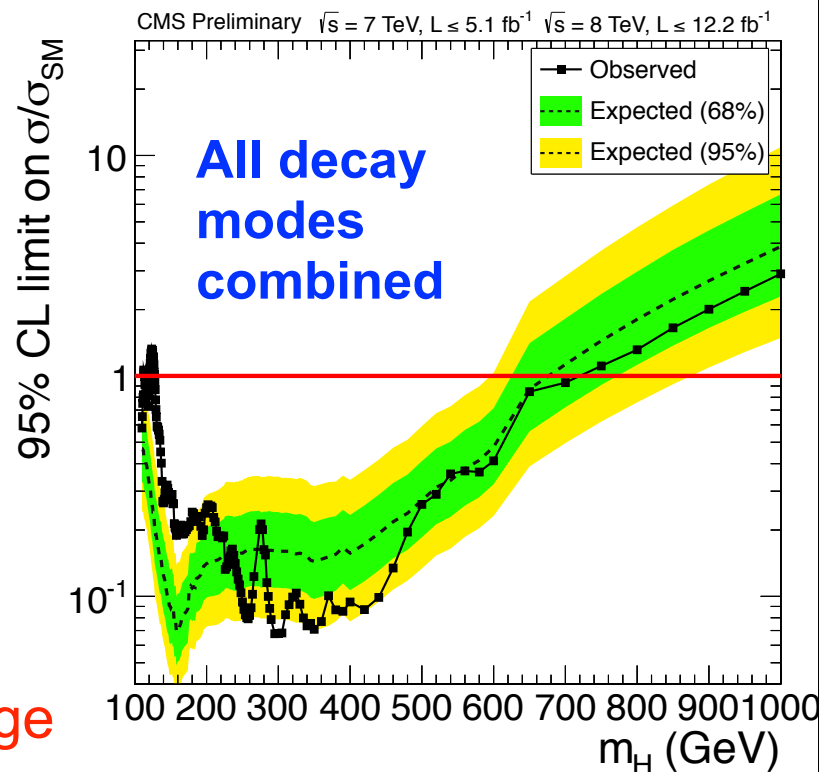


Limits on the Higgs cross section



Expect to reach full sensitivity up to 1 TeV using this year's data

- Most sensitive at high masses
- In Spring, excluded M_H in WW decays ($2l2\nu$ & $lvqq$) in [130,600] GeV, thus **greatly narrowing the allowed mass range**

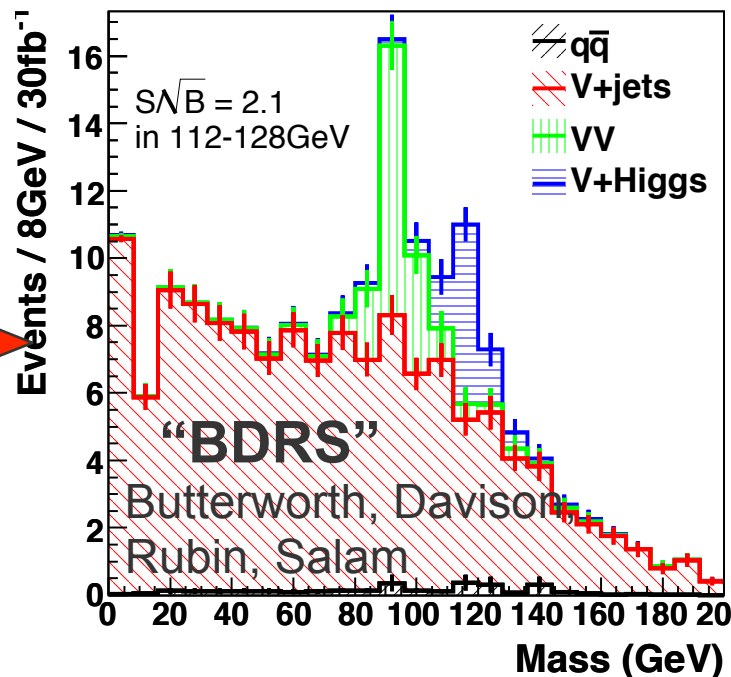
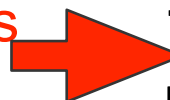




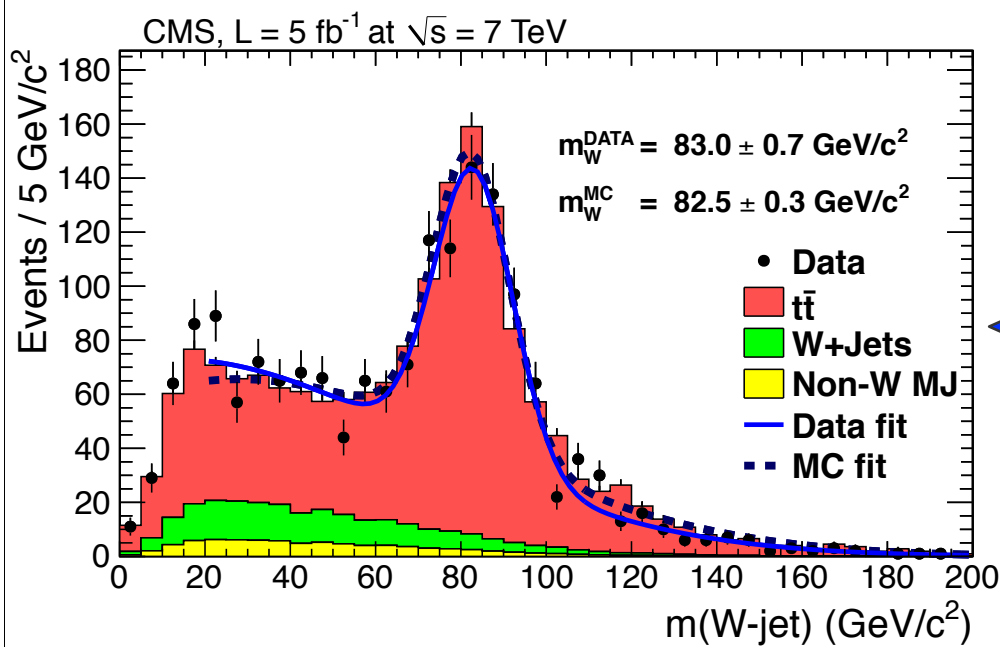
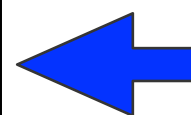
Next: reconstruct $H \rightarrow bb$ peak

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



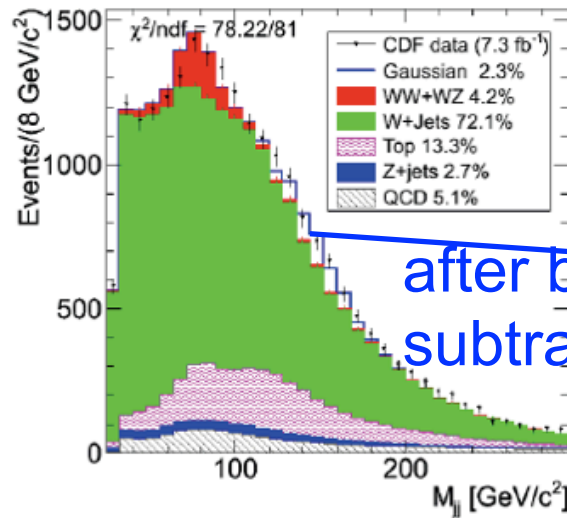
Started with hadronic W in boosted top events

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

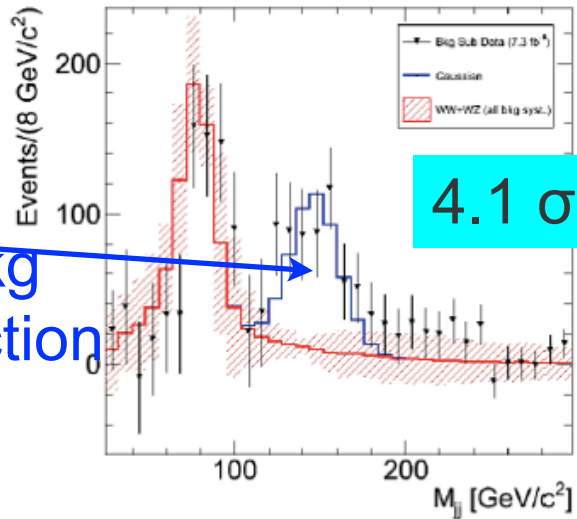
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12019>

Search for non-SM models of EWSB

Search for new physics with W+jj events

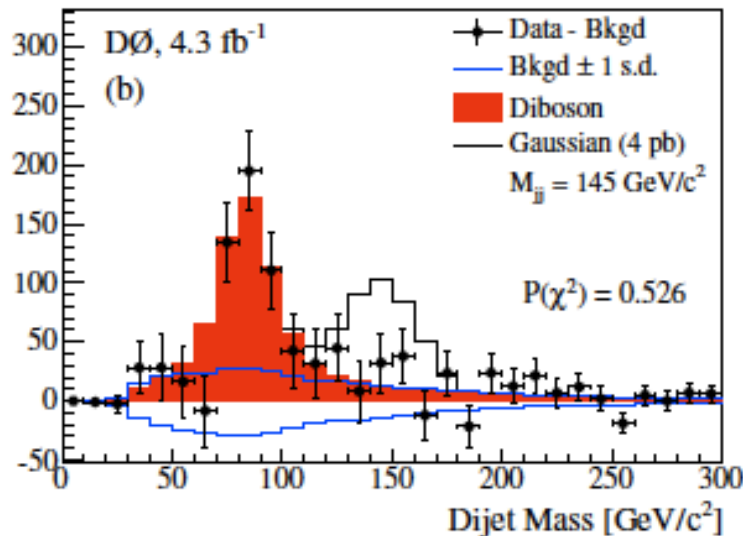


after bkg subtraction



PRL 106:171801 (2011)

- CDF W+jj data show excess in m_{jj} spectrum near 150 GeV, width = 15 GeV
- Production rate 4 pb



PRL 107:011804 (2011)

- $D\emptyset$ excludes such excess @ >99% CL

Need for similar analysis at LHC

- If new physics, should appear at LHC
- If not, need to understand bkg modeling in this important topology

CMS analysis: what are the improvements?



arXiv:1208.3477 (to appear in PRL)

$W \rightarrow \ell\nu$ selection

$$p_T^{\mu(e)} > 25 \text{ (35) GeV}$$

$$\cancel{E}_T^{\mu(e)} > 25 \text{ (30) GeV}$$

$$M_T > 50 \text{ GeV}$$

Unimportant differences

Jet selection

$$p_T^{j1} > 40 \text{ GeV vs 30 GeV at CDF}$$

$$\|\vec{p}_T^{j1} + \vec{p}_T^{j2}\| > 45 \text{ GeV vs 40 GeV}$$

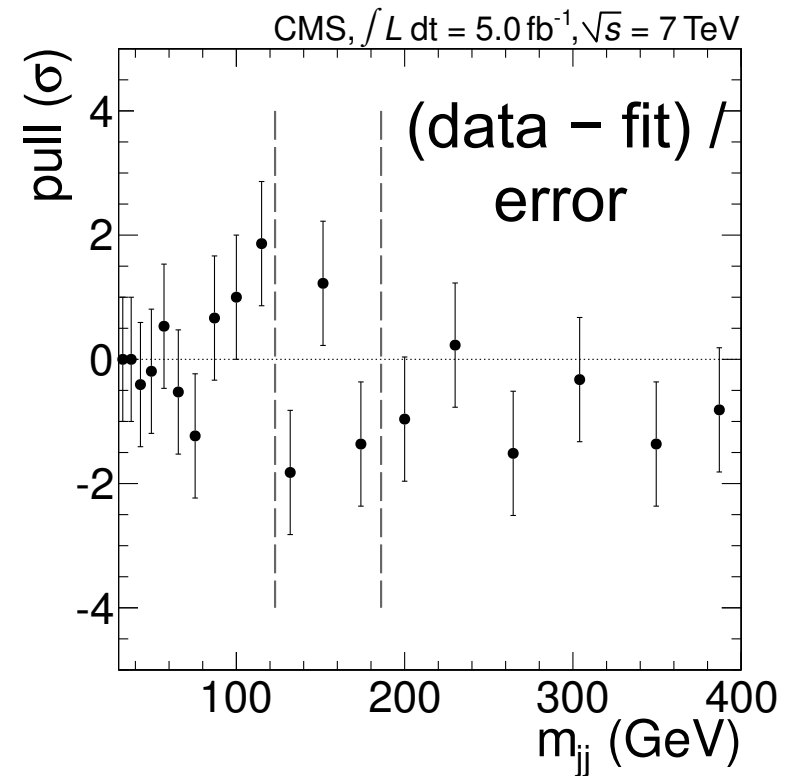
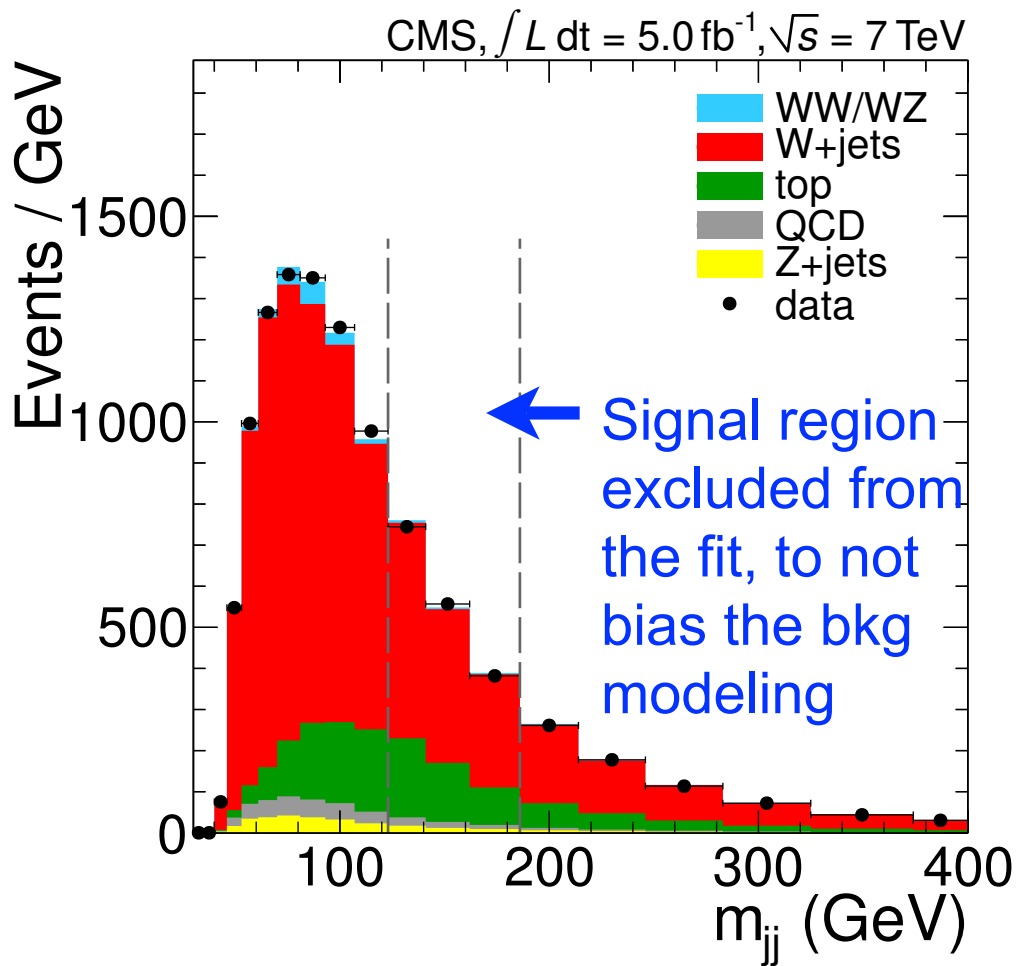
$$|\Delta\eta(j1, j2)| < 1.2 \text{ vs no cut}$$

$$0.3 < p_T^{j2} / m_{jj} < 0.7 \text{ vs no cut}$$

Also analyze 3-jet events

- Higher leading jet p_T helps in beating down the background
- Higher boost, smaller $\Delta\eta$, and Jacobian cut for dijet system
- Improve S/B for all resonant signals (diboson, TC, Z', WH)

Modeling of dijet mass spectrum



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

Fit using Standard Model contribution only



Process	muons		electrons	
	2-jet	3-jet	2-jet	3-jet
W plus jets	58919 ± 530	13069 ± 366	29787 ± 1153	8397 ± 292
Dibosons	1236 ± 114	333 ± 32	685 ± 65	184 ± 18
t \bar{t}	4570 ± 307	9049 ± 382	2556 ± 174	4265 ± 253
Single-top	1765 ± 87	1001 ± 50	916 ± 46	521 ± 26
Drell–Yan plus jets	1837 ± 79	561 ± 24	1061 ± 46	364 ± 16
Multijet (QCD)	29 ± 284	0 ± 90	3944 ± 1133	324 ± 160
Fit χ^2 probability	0.454	0.729	0.969	0.991
Total from fit	68294 ± 307	24013 ± 193	38949 ± 228	14055 ± 143
Data	67900	24046	38973	14145

No significant excess in data in any of the four channels

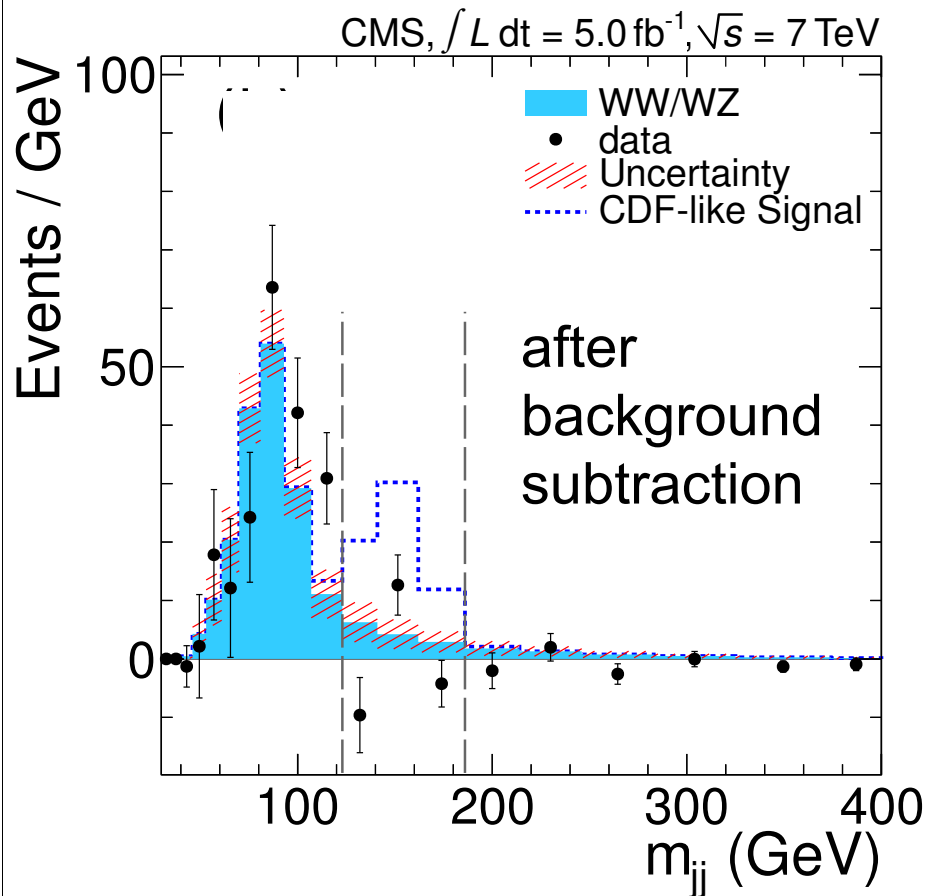
- Good modeling of data by the Standard Model processes



What about the signal region?

In the signal region $123 < m_{jj} < 186 \text{ GeV}$ (excluded from the fit)				
Total predicted	14511 ± 125	7739 ± 95	7944 ± 92	4347 ± 70
Data	14050	7751	8023	4438

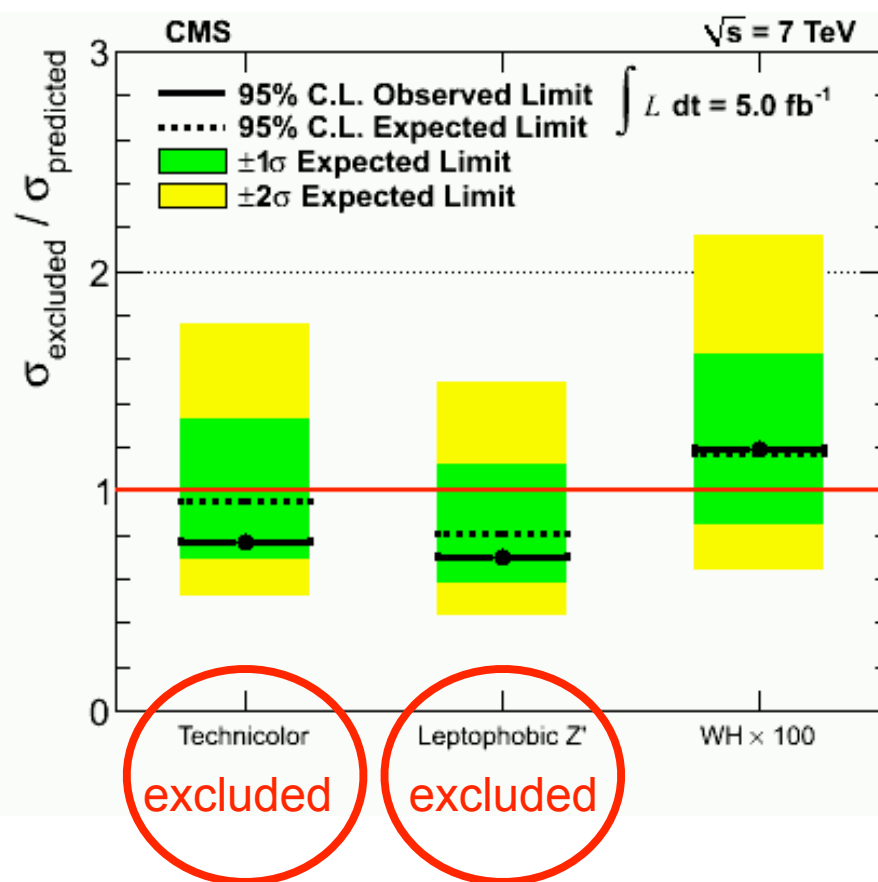
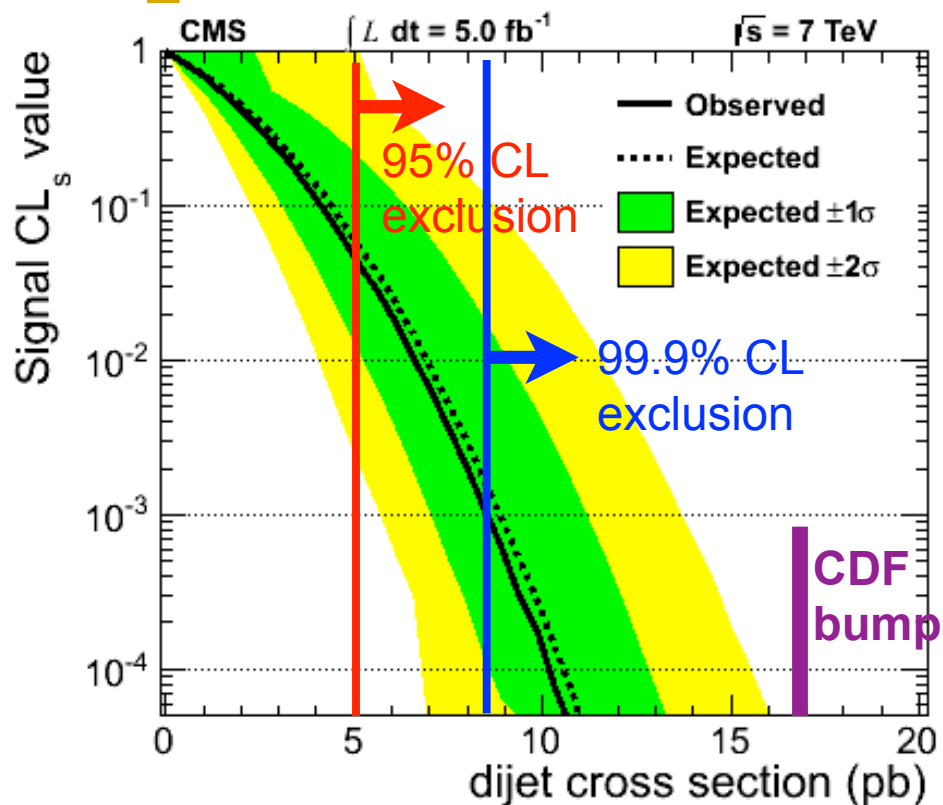
No excess in the signal region



- Set upper limit on the magnitude of the bump
- Assume a Gaussian peak at 150 GeV, width 15 GeV



Upper limits on generic and specific NP signals

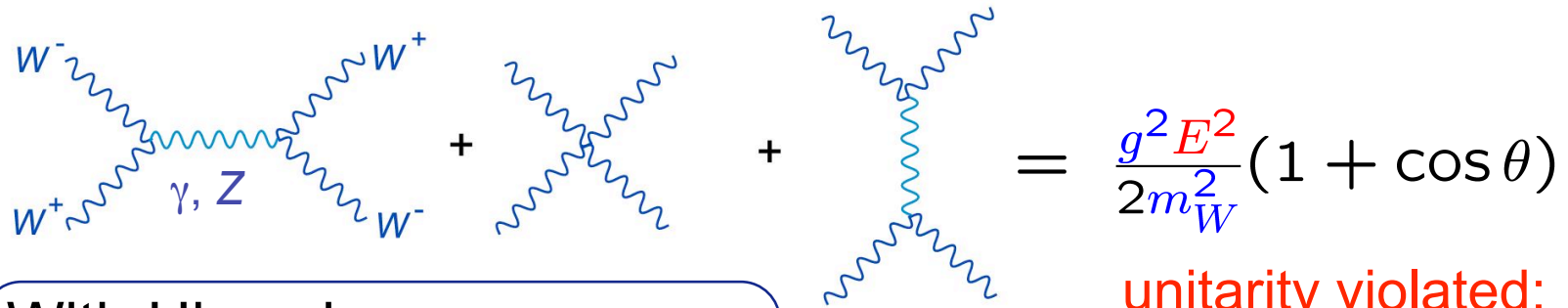


- Exclude CDF anomaly with very high confidence level
- Exclude low scale technicolor and Z' models

WW scattering, gauge boson quartic couplings

Weak interactions at high energy

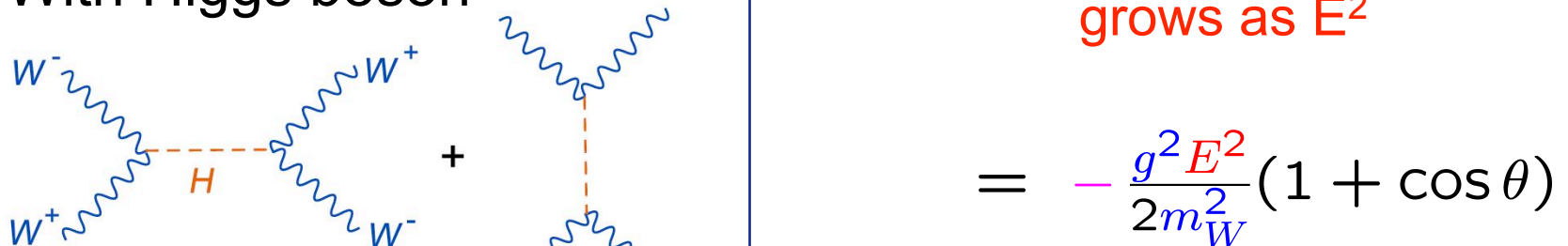
Without Higgs boson, WW scattering becomes divergent



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

unitarity violated:
grows as E^2

With Higgs boson



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

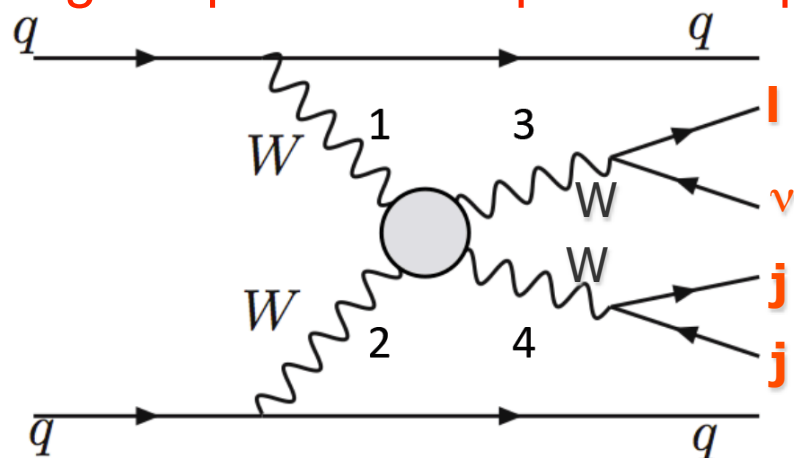
no problem now!

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



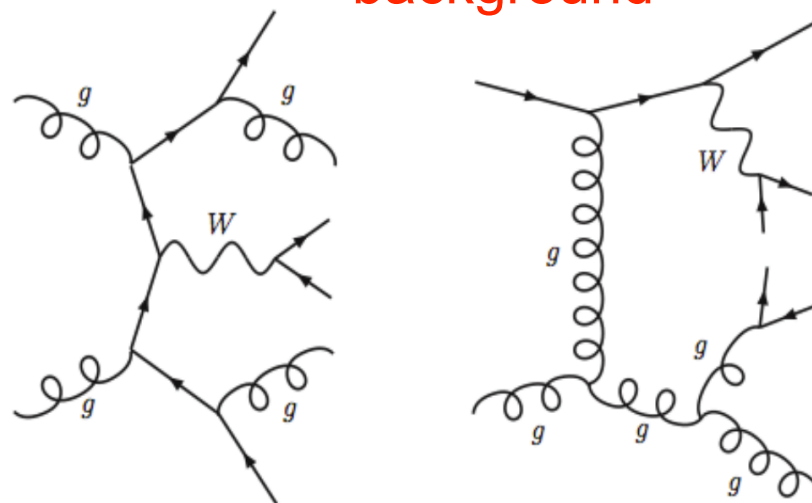
WW+2tag jets: ~ 1 pb

- $\Delta\eta$ between tag jets > 4
- Invariant mass > 600 GeV
- Standard WW selection

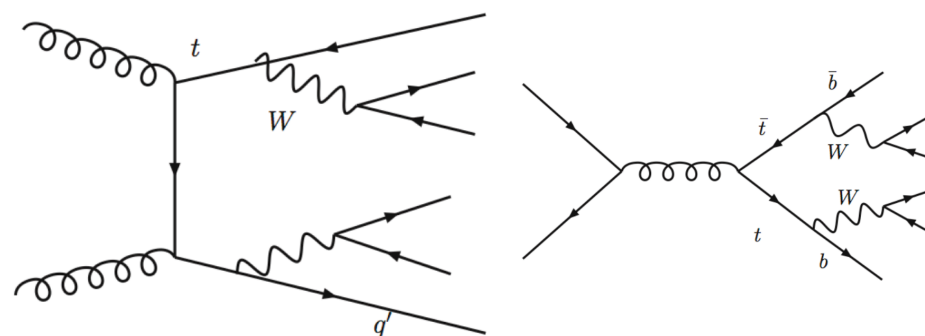
Already have a few hundred interesting events to analyze.

Aim for a result by Moriond.

background



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



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

Probing quartic couplings via VV production

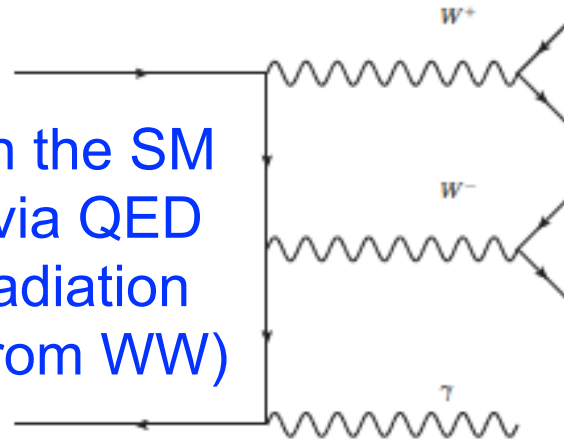


Yang et al,
arXiv:1211.1641

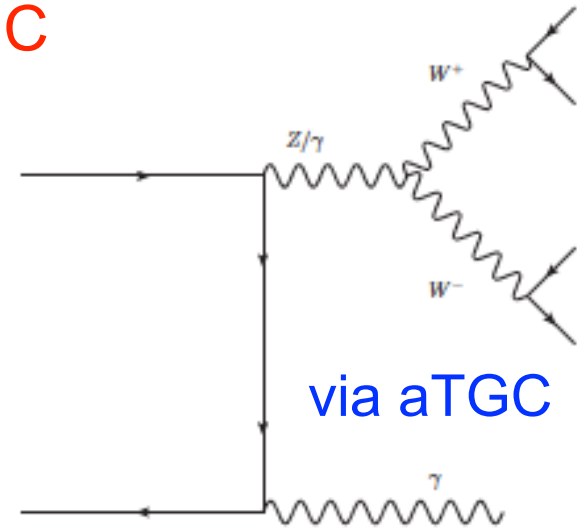
LEP combination,
arXiv:hep-ex/
0612034

WW γ production at LHC

In the SM
(via QED
radiation
from WW)

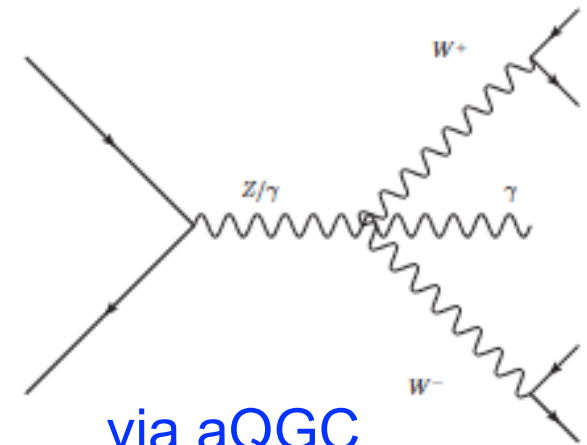


via aTGC



- Anomalous QGC at $WW\gamma\gamma$ and $WW\gamma Z$ vertices can enhance the production for high photon p_T events by several factors.
- Current LEP limits on $aQGC/\Lambda^2$ (where $\Lambda =$ NP scale) is at 1–5%.
- $W\gamma\gamma$ and VBF $\gamma\gamma$ can provide similar constraints

via aQGC



WW γ is within reach



Processes	Cross section [fb]
$W^+W^-\gamma$	18.286
I(F)SR WW	3114.1
$Z\gamma$	4107.2
$ZZ\gamma$	45.818
$W^\pm Z\gamma$	1.3698
$t\bar{t}\gamma$	170.22
$tW^\pm\gamma$	26.858

- Within detector fiducial, expect **40–50 reconstructed WW γ + WZ γ events** combining all channels from full 2012 data.
- Immediate goal is to measure the signal production rate.
 - **S/B more favorable compared to the WW analysis**
- Expect more constraining limits on aQGC than LEP.

BTW: WWW and WWZ not feasible with 8 TeV data. S/B hopeless in both leptonic and semi-leptonic channels.

Summary I



- ☑ Higgs boson was the last missing piece in the Standard Model
 - By excluding M_H range $2M_W-600$ GeV, the semi-leptonic WW channel provided important inputs to the Higgs boson discovery
 - Likely to exclude (or find) any other WW resonance up to 1 TeV using full 2012 dataset

- ☑ First measurement of diboson production ($WW+WZ$) at LHC in the semi-leptonic final state
 - Set stringent limits on anomalous gauge boson couplings
 - In some cases improve over the combined LEP limit

- ☑ Analyzed $W+jj$ data
 - No evidence for any bump near 150 GeV
 - Exclude CDF bump, and technicolor and Z' interpretations

Summary II



- Focus now on a deeper probe of EWSB using WW+ 2-tag jet events in VBF topology
 - Need to first establish VBF production of WW
 - Check if data consistent with H(125) unitarized WW→WW scattering, probe quartic gauge couplings
 - Probe existence of weakly produced WW resonances

- WW semi-leptonic final state will continue to play an important role in the study of electroweak symmetry breaking
 - Measurement of $WW\gamma$ within reach with full 2012 data
 - Will provide constraints on anomalous gauge boson quartic couplings, well beyond the LEP limits

BACKUP SLIDES

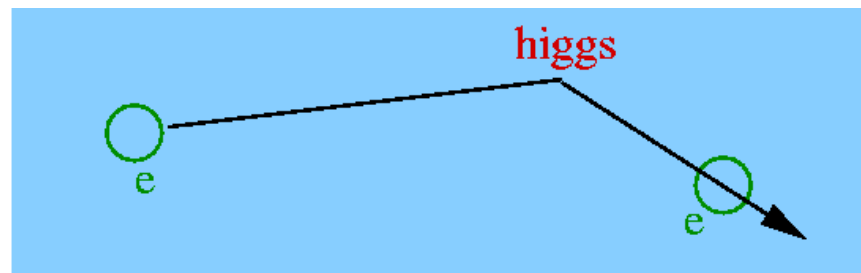


The origin of mass

Fundamental symmetries of nature require that all elementary particles and force carriers be **massless**, but in the **real world** the elementary particles have widely differing masses → so some symmetry must be **broken**

The Higgs Boson

We suspect the vacuum is permeated by a “Higgs field” that is responsible – the quantum of this field is a fundamental scalar.



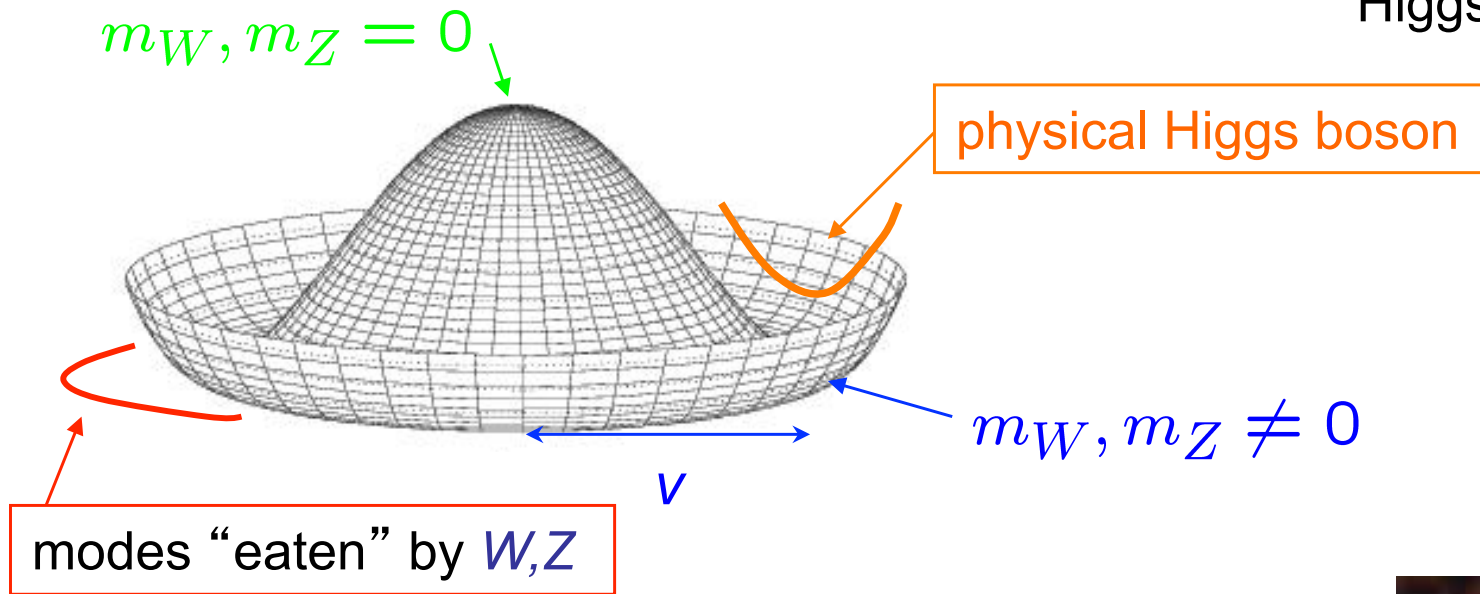
To explain the W mass the Higgs vacuum must be 100 times denser than nuclear matter!!

Higgs Mechanism



Explains how W, Z become massive !

Brout, Englert,
Guralnik, Hagen,
Higgs, Kibble (1964)



A cosmic superconductor:
Weak fields screened within 0.003 fm

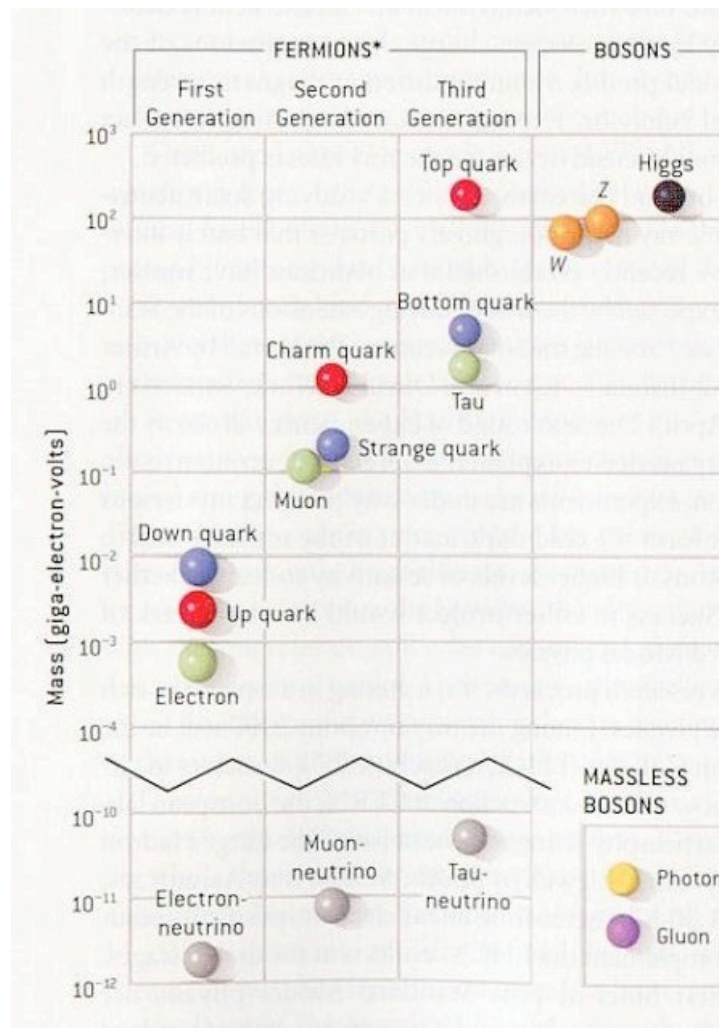
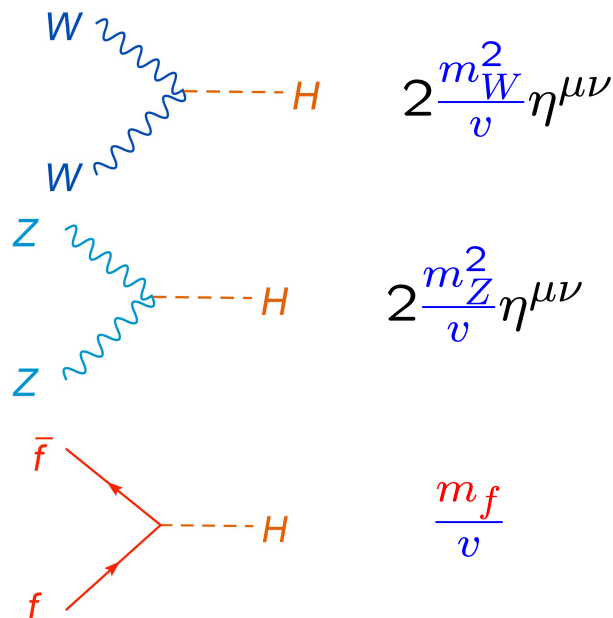


Basic Higgs properties



An elementary spin-0 particle.
Fundamental scalar (0^{++})

Higgs boson couples to mass:

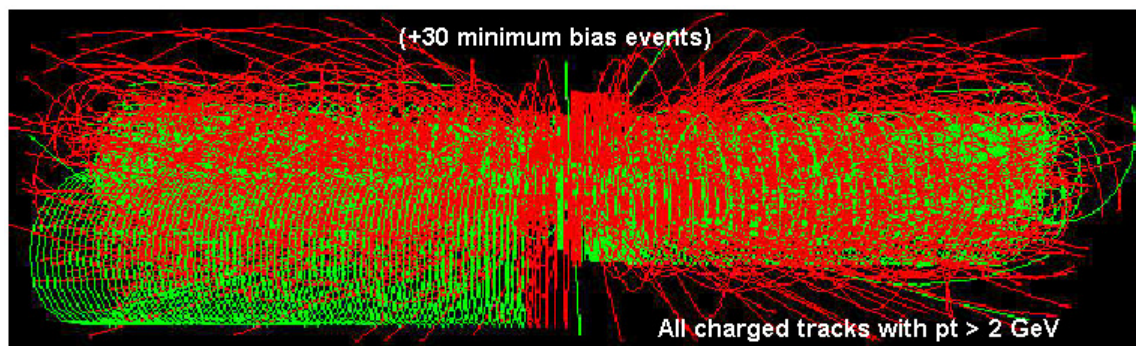


all masses due to Higgs

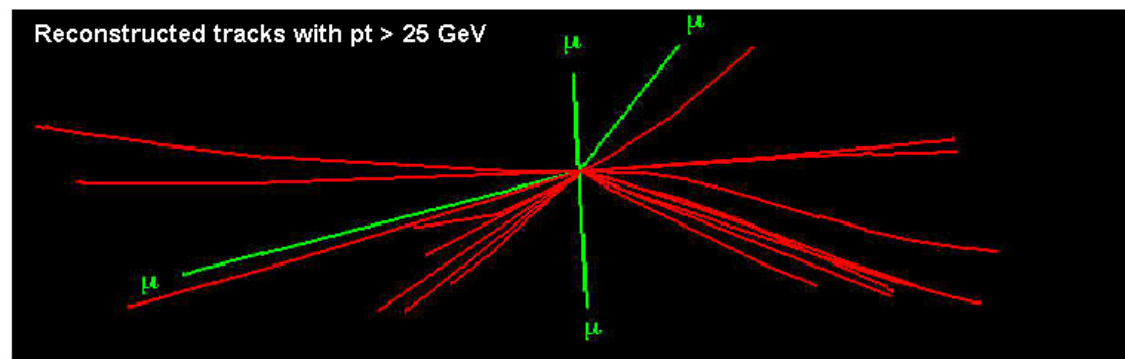
More challenging than a needle in a haystack ...



Starting from this event...



We look for this “signature”



- 800,000,000 proton-proton interactions per second
- ~100,000,000 electronic channels
- 0.0002 Higgs / second

Selectivity: 1 in 10^{13}

Like looking for 1 person in a thousand world populations

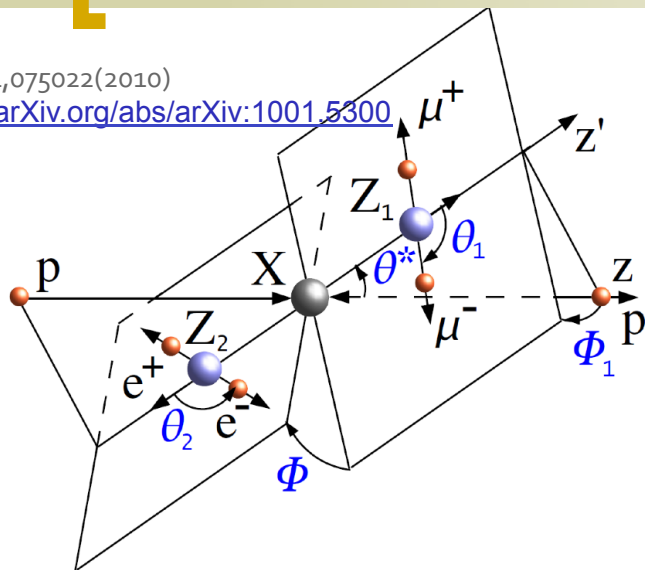
Or for a needle in 20 million haystacks!

Spin-parity determination: angular analysis



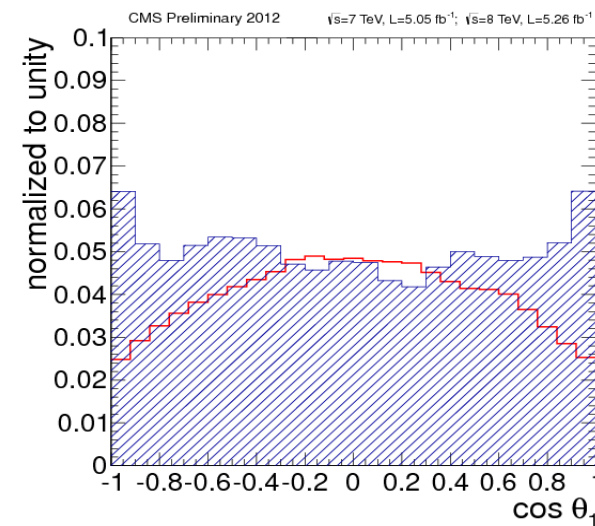
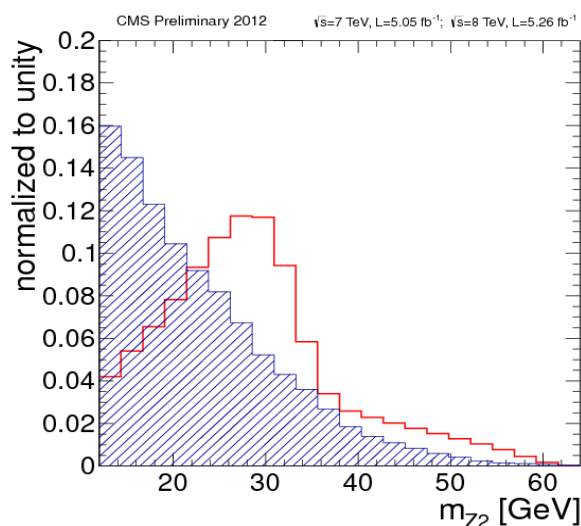
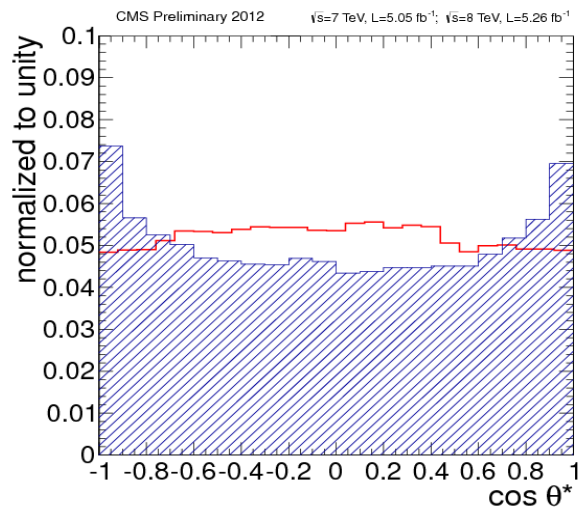
PRD81,075022(2010)

<http://arXiv.org/abs/arXiv:1001.5300>



Matrix Element Likelihood Analysis:
uses kinematic inputs for
signal to background discrimination
 $\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

$$\text{MELA} = \left[1 + \frac{\mathcal{P}_{\text{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})} \right]^{-1}$$



Triggers

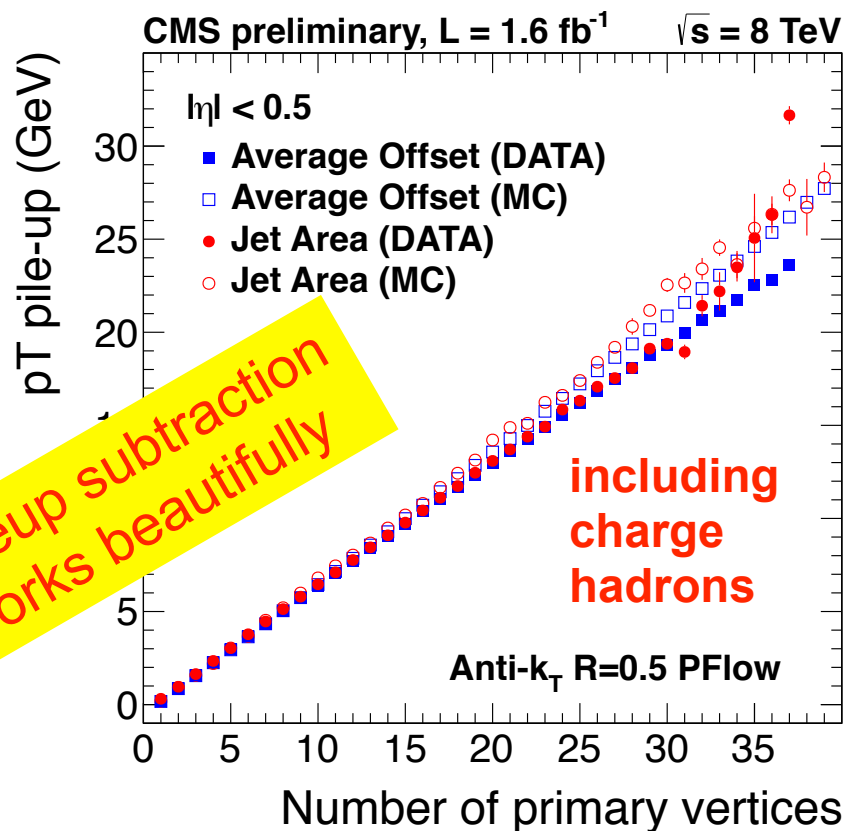
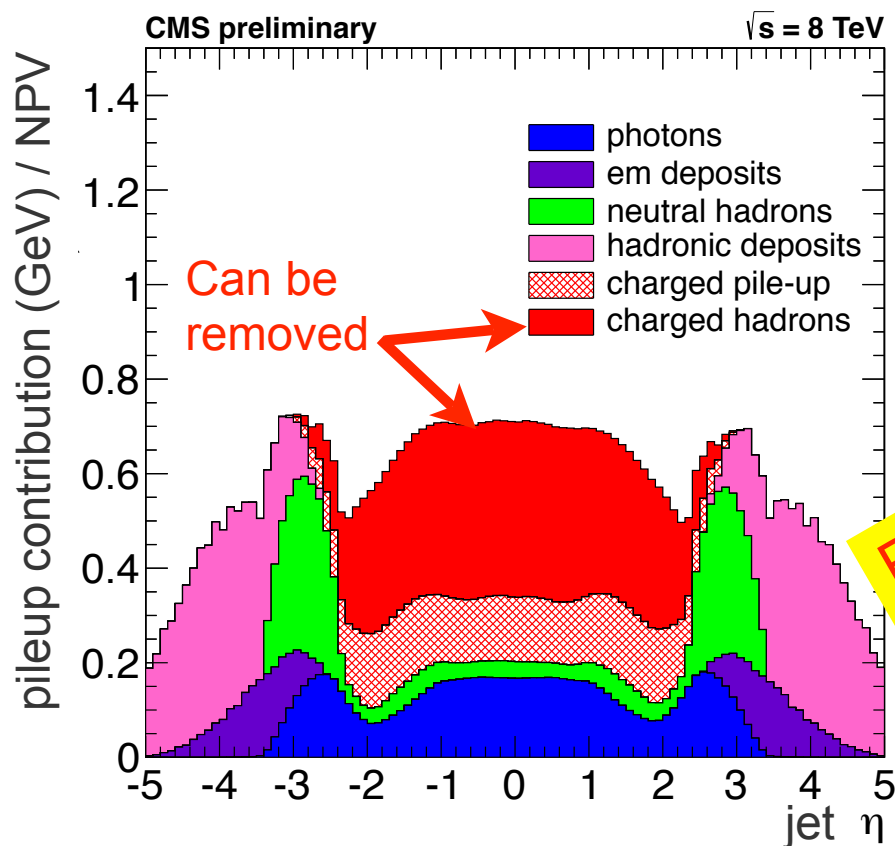


- ◆ All analyses shown here use single or di-lepton triggers
- ◆ Typical single lepton triggers require
 - one isolated lepton
 - threshold: 24 GeV for muon, 27 GeV for electron
 - MET > 20 GeV in case of electron
- ◆ Typical dilepton triggers require
 - two leptons, at least one isolated
 - each with 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

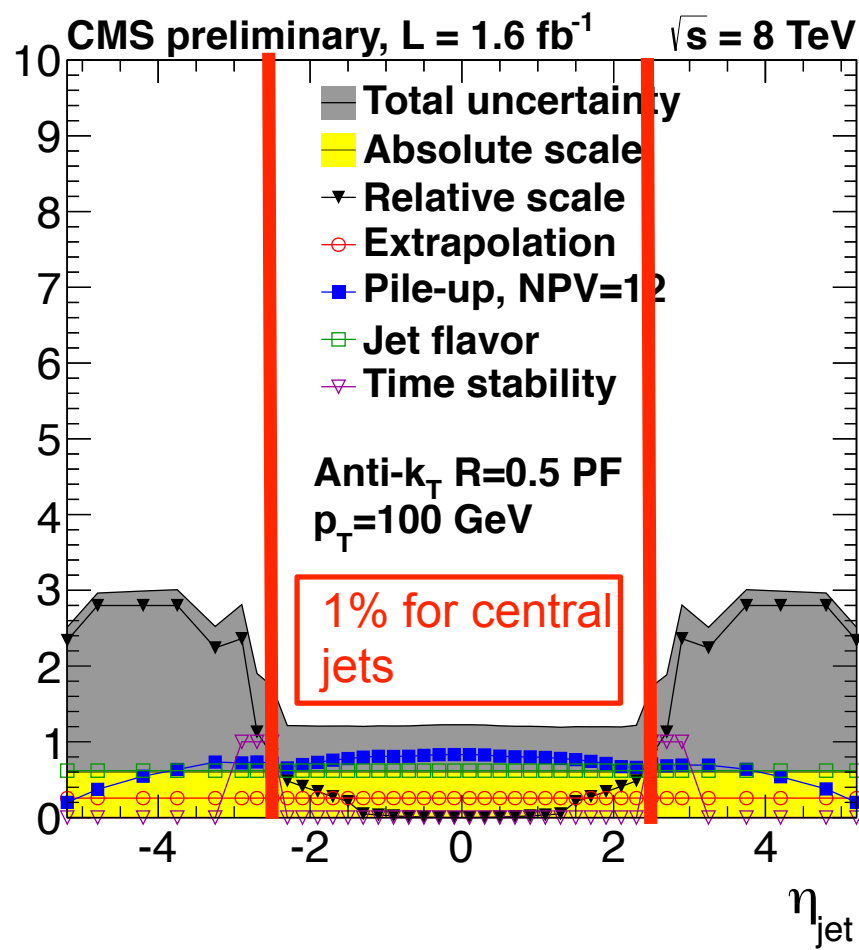
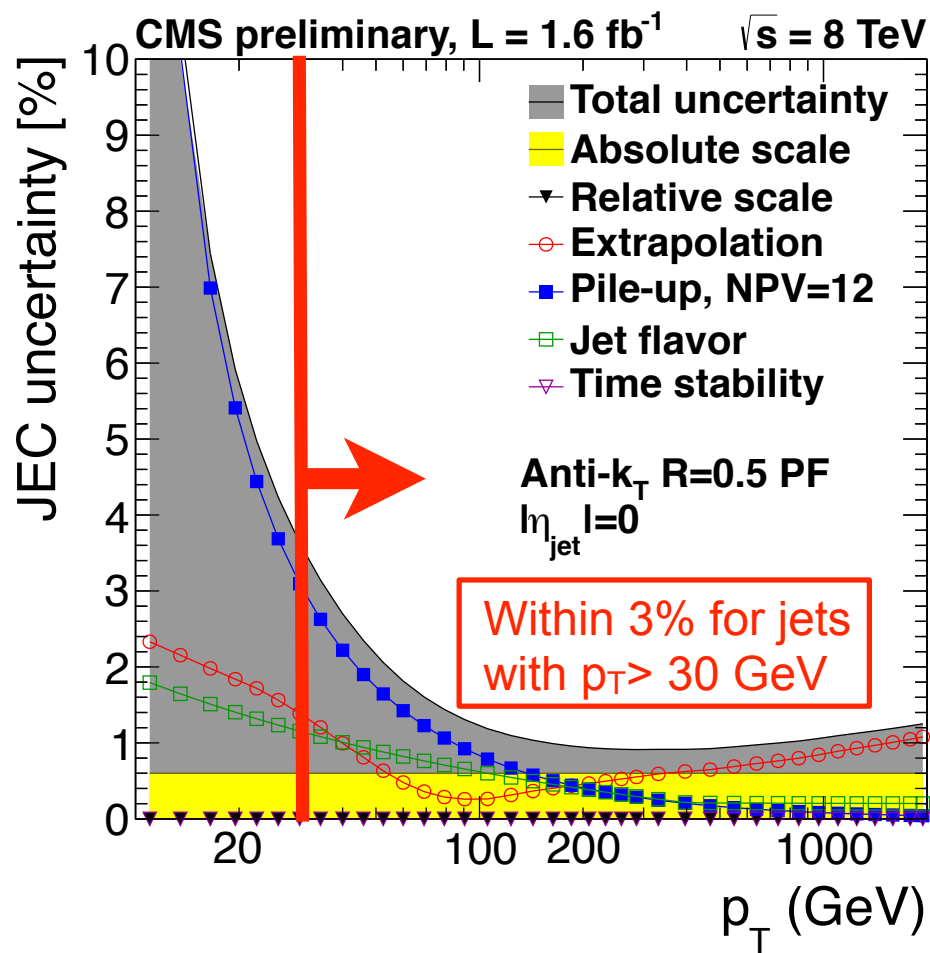
- ◆ Pileup affects jet energy, MET, and lepton isolation
 - Example: pileup contribution to jet p_T per primary vertex.
 - Measure in data using several methods. Get consistent results.



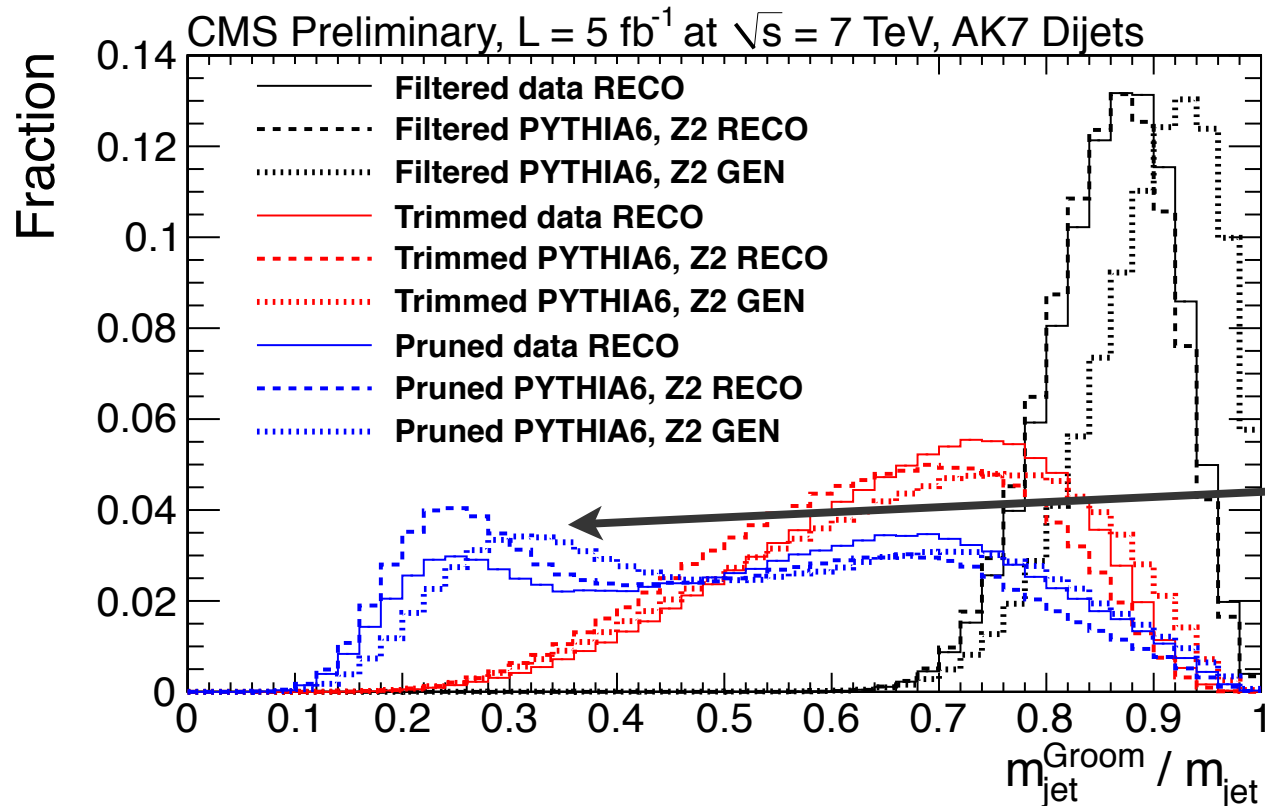
Good understanding of detector performance



- ◆ An example: jet energy scale
 - Well calibrated



Peep inside the merged jet, use grooming



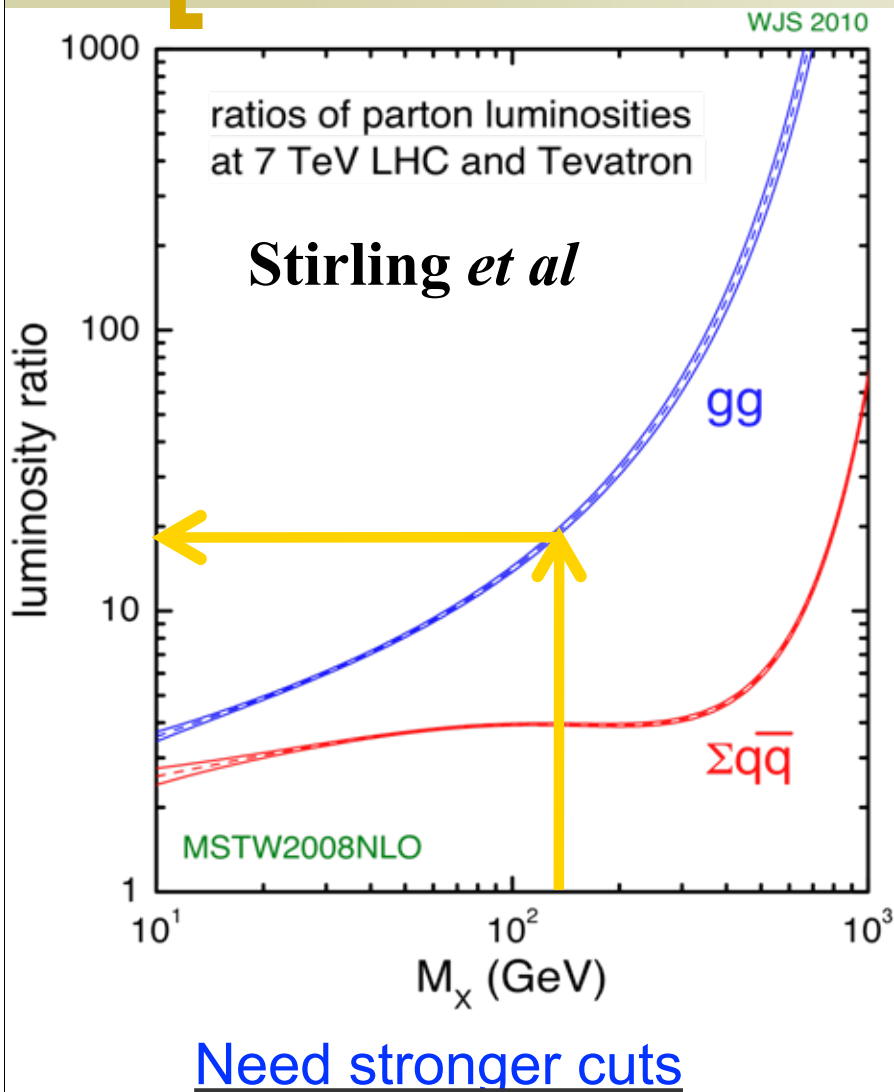
Pruning is the most aggressive, filtering is the least aggressive

bimodal structure provides good separation for qq signal

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



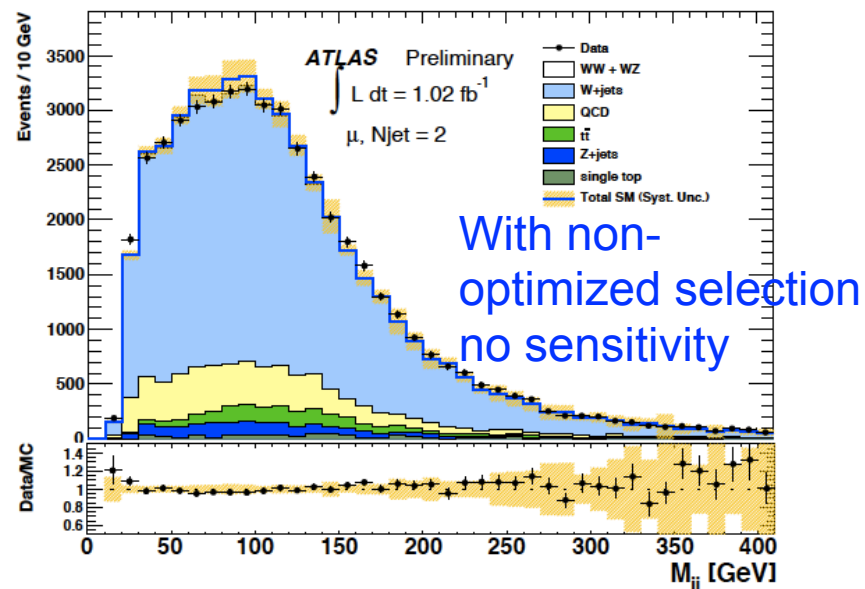
Difficulty to reconstruct qq signal at LHC



$q\bar{q} \rightarrow WW, WZ$ rate at LHC =
 $\sim 3.5 \times$ Tevatron

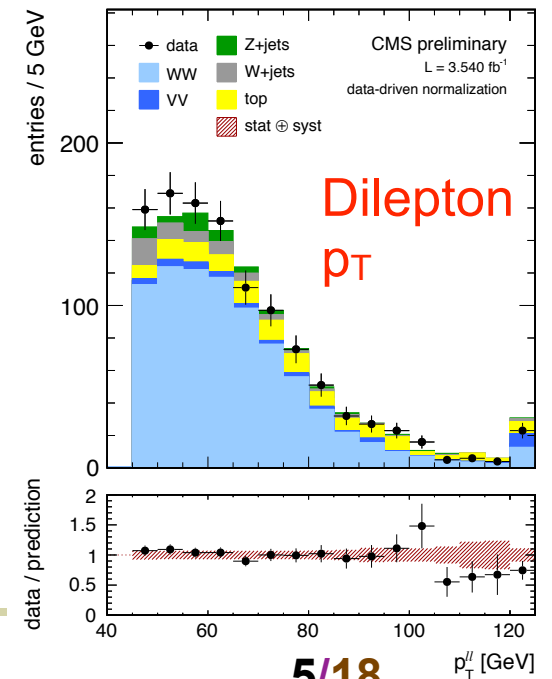
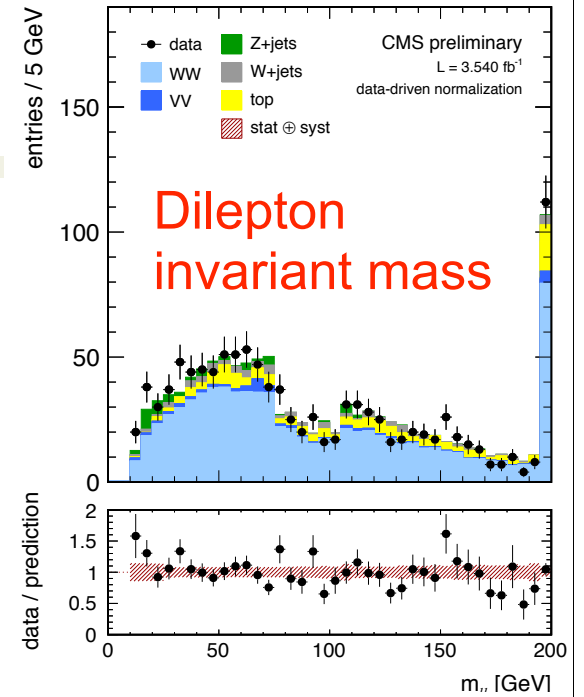
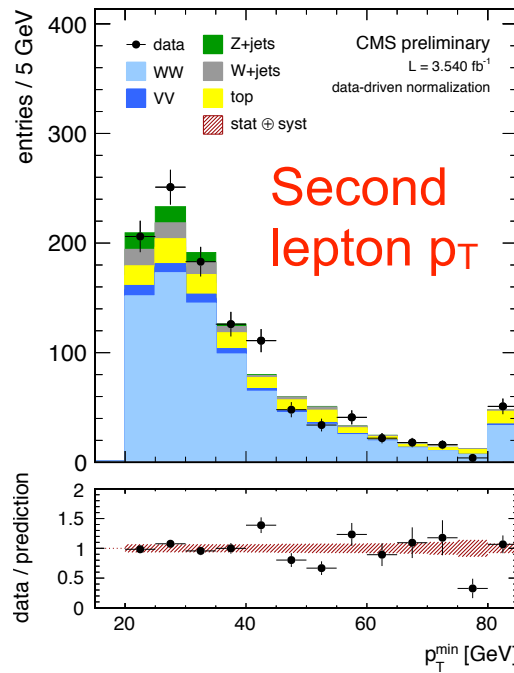
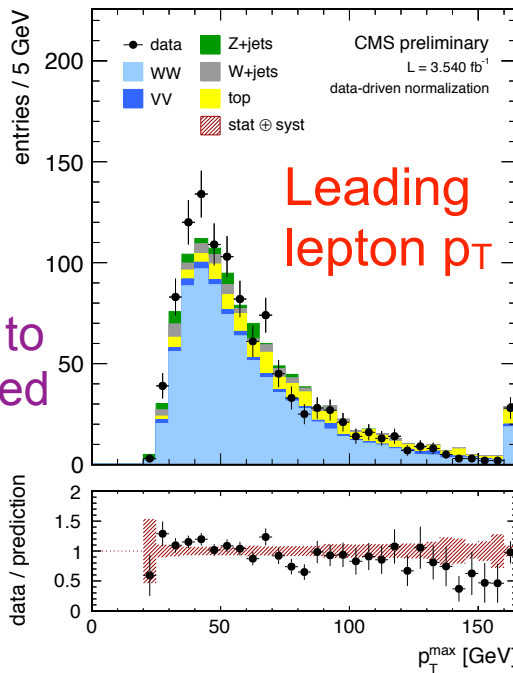
Backgrounds like W/Z+jets, top, multi-jet etc rise **by $\sim 10x$** due to rise in qq and gg cross sections

\Rightarrow Small signal, worse S/N



WW → 2ℓ2ν: kinematics

WW cross section is normalized to the measured value



- ◆ Drell-Yan reduced by MET requirement, and
 - $m_{\ell\ell} > 20$ GeV, and veto $76 < m_{\ell\ell} < 106$ GeV
 - $\Delta\phi(\ell\ell, \text{jet}) < 165^\circ$ to reduce Z+jets
- ◆ W+jets, ttbar reduced by: central jet veto, b-veto
- ◆ Z → ττ reduced using projected MET cut
- ◆ Veto third lepton to reduce WW/WZ

Kalanand Mishra, Fermilab

WW → 2ℓ2ν cross section at 7 TeV (5.0 fb⁻¹)



<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP12005>

S/B = 3.2

Signal efficiency averaged over all lepton flavors: 3.28 ± 0.02 (stat) ± 0.26 (sys) %

Cross section

$$\sigma \cdot \text{BR} = \frac{N_{\text{signal}}}{\text{Acceptance} \cdot \text{Efficiency} \cdot L}$$

BR(W → ℓν) from PDG:
0.1080 ± 0.0009

Campbell, Ellis, Williams. JHEP 07 (2011), 018. arXiv:1105.0020.

Sample	Yield ± stat. ± syst.
gg → W ⁺ W ⁻	46.0 ± 0.6 ± 14.2
q \bar{q} → W ⁺ W ⁻	750.9 ± 4.1 ± 53.1
t \bar{t} + tW	128.5 ± 12.8 ± 19.6
W+jets	59.5 ± 3.9 ± 21.4
WZ+ZZ	29.4 ± 0.4 ± 2.0
Z/γ*	11.0 ± 5.1 ± 2.6
W+γ	18.8 ± 2.8 ± 4.7
Z/γ* → ττ	0.0 ± 1.0 ± 0.1
Total Background	247.1 ± 14.6 ± 29.5
Signal + Background	1044.0 ± 15.2 ± 62.4
Data	1134

σ = 52.4 ± 2.0 (stat) ± 4.5 (sys) ± 1.2 (lum) pb
NLO prediction (MCFM): 47.0 ± 2.0 pb

Consistent with the NLO prediction

WW → 2ℓ2ν at 8 TeV: systematics & results



Theoretical uncertainties

- ▶ PDF and QCD scale: 5%

includes jet veto uncertainty

Experimental measurements

- ▶ Luminosity: 4.4%
- ▶ Lepton efficiency, energy scale and resolution: 1-3%
- ▶ Jet energy scale: 2-3%
- ▶ Missing ET resolution: 2-3%

Need to improve

Background normalisation

- ▶ W+jets: ~35% + statistical
- ▶ Z/γ*: ~20%-100%
- ▶ Top: ~20% + statistical
- ▶ Z/γ* → ττ: up to 50%

Background components:

- Major Backgrounds
 - QCD / W+jet
 - Top
 - Drell Yan

] Data Driven
- Smaller backgrounds
 - Wγ
 - Z → ττ
 - non resonant WZ/ZZ

] MC Simulation

$$\sigma = 69.9 \pm 2.8 \text{ (stat)} \pm 5.6 \text{ (sys)} \pm 3.1 \text{ (lum)} \text{ pb}$$
$$\text{NLO prediction (MCFM): } 57.25 \text{ } \left(\begin{array}{c} +2.35 \\ -1.60 \end{array} \right) \text{ pb}$$

- **Already 4% statistical precision**
- **About 1.8σ higher than the NLO prediction**

WW+WZ → ℓνqq: understanding W+jets bkg

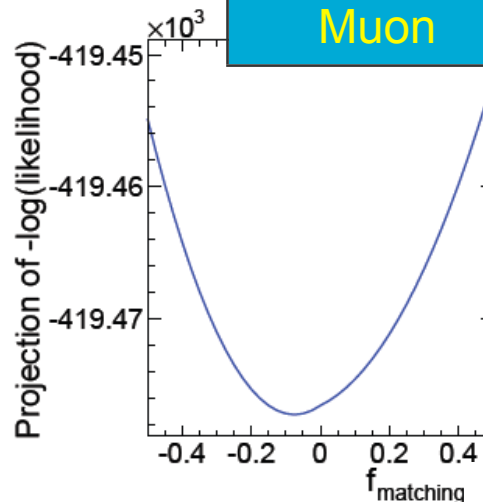
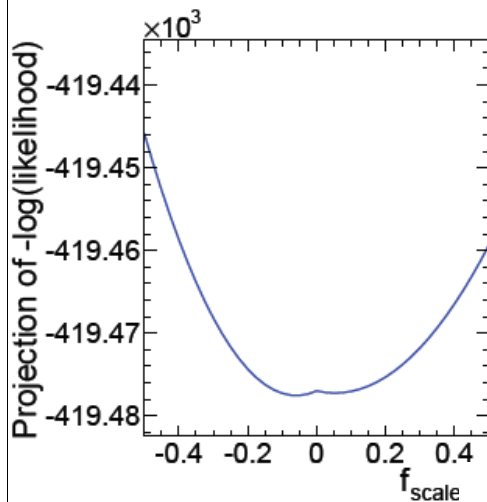


Process	Muon channel	Electron channel
Diboson (WW+WZ)	1899 ± 389	783 ± 302
W plus jets	67384 ± 586	31644 ± 850
t \bar{t}	1662 ± 117	946 ± 67
Single top	650 ± 33	308 ± 17
Drell-Yan plus jets (Z+jets)	3609 ± 155	1408 ± 64
Multijet (QCD)	296 ± 317	4195 ± 867
Fit χ^2/dof (probability)	9.73/12 (0.64)	5.30/12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

W+jets shape uncertainty

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

	α (fSU)	β (fMU)
Electron	-0.003 ± 0.074	-0.136 ± 0.081
Muon	0.053 ± 0.078	-0.075 ± 0.065



Factorization/renormalization scale and ME-PS matching scale vary in the fit.

- α (scale ↑ or ↓ fraction) and β (matching ↑ or ↓ fraction) are consistent b/w electron and muon data
- NLL versus α and β is well-behaved

CMS analysis



<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEWK11017>
(submitted to PRL)

$W \rightarrow l\nu$ selection

Jet selection

Single-lepton trigger

$$p_T^{j1} > 40 \text{ GeV}$$

Lepton identification and isolation

$$p_T^{j2}, p_T^{j3} > 30 \text{ GeV}$$

$$p_T^{\mu(e)} > 25 \text{ (35) GeV}$$

$$\|\vec{p}_T^{j1} + \vec{p}_T^{j2}\| > 45 \text{ GeV}$$

$$\cancel{E}_T^{\mu(e)} > 25 \text{ (30) GeV}$$

$$|\Delta\eta(j1, j2)| < 1.2$$

$$M_T > 50 \text{ GeV}$$

$$\Delta\phi(\cancel{E}_T, j1) > 0.4$$

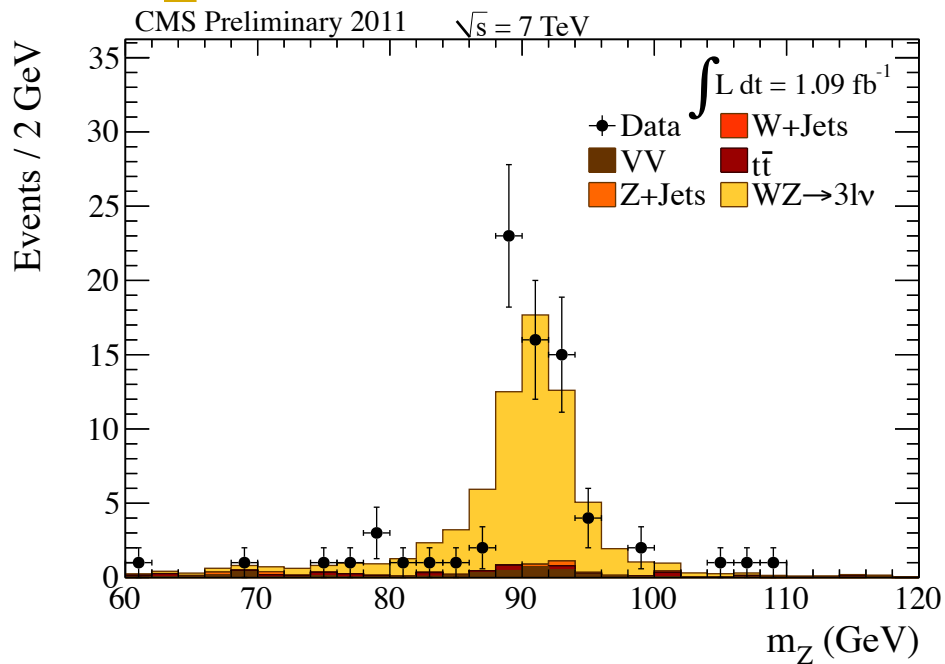
Exclude events with > 1 lepton

$$0.3 < p_T^{j2} / m_{jj} < 0.7$$

Efficiency x Acceptance for a few typical models

Signal model	$\sigma \times \mathcal{B}$ (pb)	$\epsilon\mathcal{A}$			
		muons		electrons	
		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

WZ → $lll'\nu$ cross section at 7 TeV



<http://cdsweb.cern.ch/record/1370067>

- Two iso ℓ : $p_T > 20/15 \text{ GeV}$ (e/ μ)
- 3rd lepton $p_T > 20$, $M_{E_T} > 30 \text{ GeV}$
- $60 < m_{\ell\ell} < 120 \text{ GeV}$; veto 2nd Z

Tiny background

Channel	N_{observed}
eee	22
$ee\mu$	20
$\mu\mu e$	13
$\mu\mu\mu$	20

$\sigma = 17.0 \pm 2.4 \text{ (stat)} \pm 1.1 \text{ (sys)} \pm 1.0 \text{ (lum)} \text{ pb}$
 NLO prediction (MCFM): $17.5 \pm 0.6 \text{ pb}$

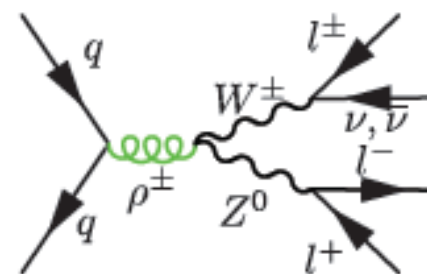
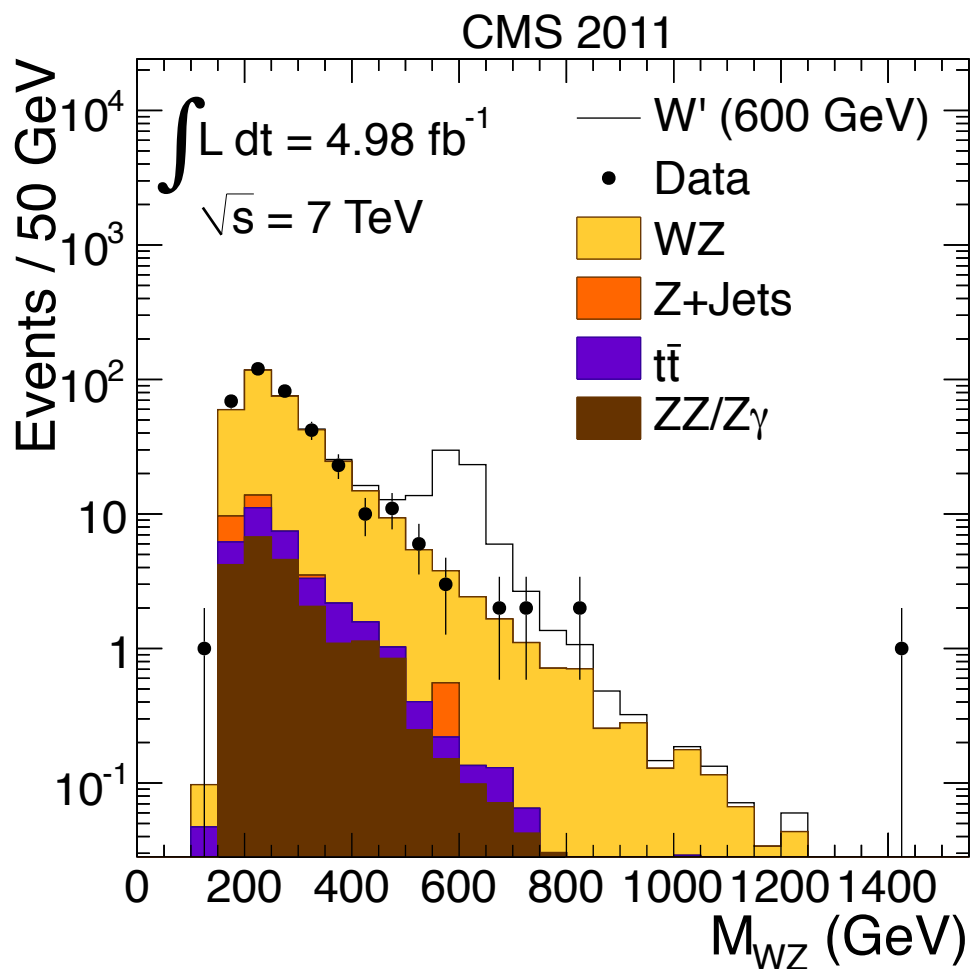
MCFM, real-width bosons,
 CTEQ6L, PDF uncertainty

Consistent
 with NLO

Search for $\rho_{TC} \rightarrow WZ$ and $W' \rightarrow WZ$ ($\rightarrow lll'\nu$)

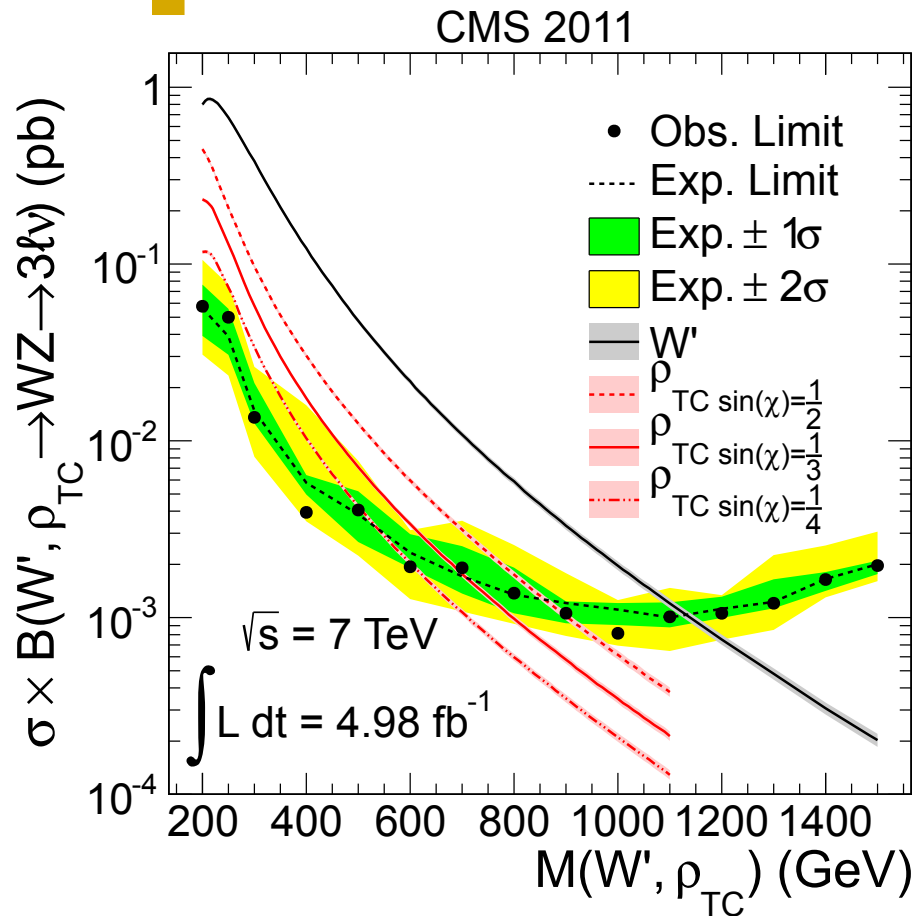


<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11041>

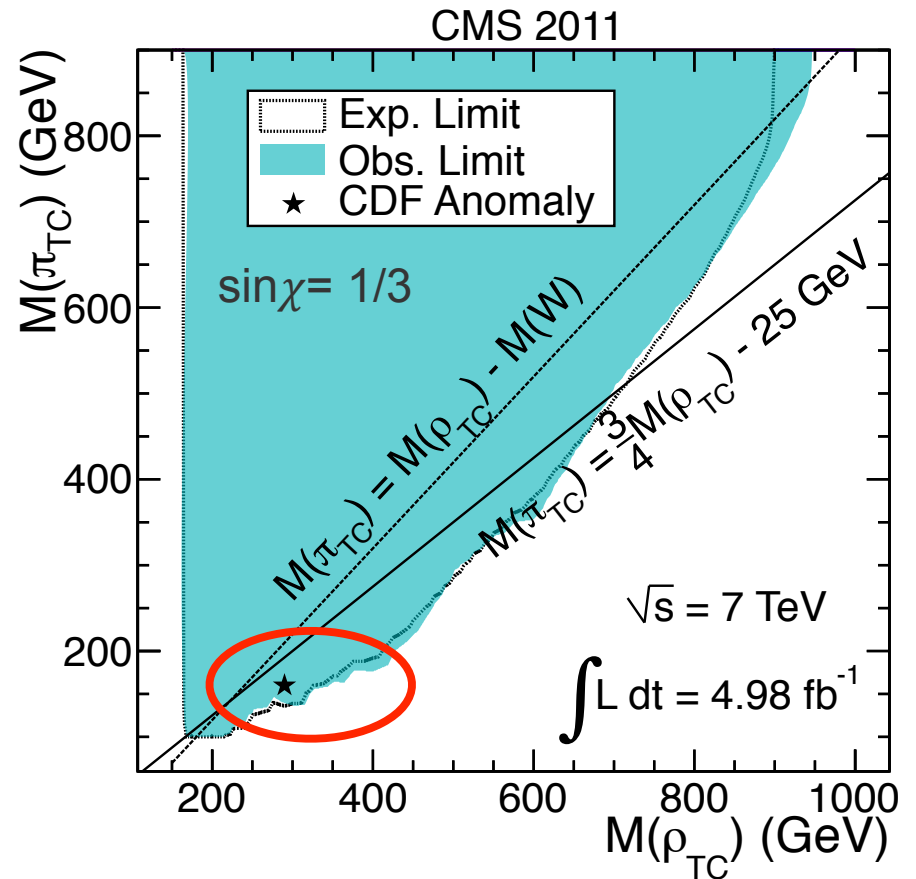


- Event selection same as in WZ cross section analysis
- Smoothly falling spectrum, no interesting structure
- Set limit

Limits on W' , technicolor ρ_{TC}



Exclude W' up to mass
1143 GeV at 95% CL



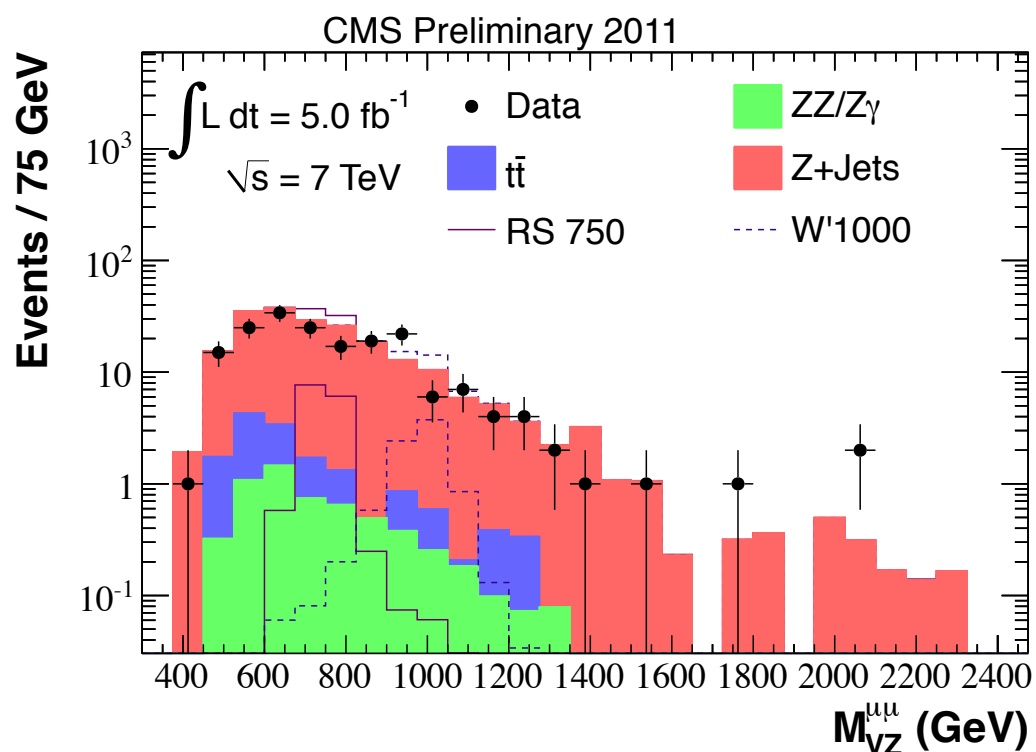
CDF anomaly: $(\rho_{TC} = 290, \pi_{TC} = 160)$

Exclude low scale techni-color
interpretation of CDF anomaly

Search for W' & RS graviton in $VZ \rightarrow \ell\ell + j$ (boosted)



<http://cdsweb.cern.ch/record/1444879>



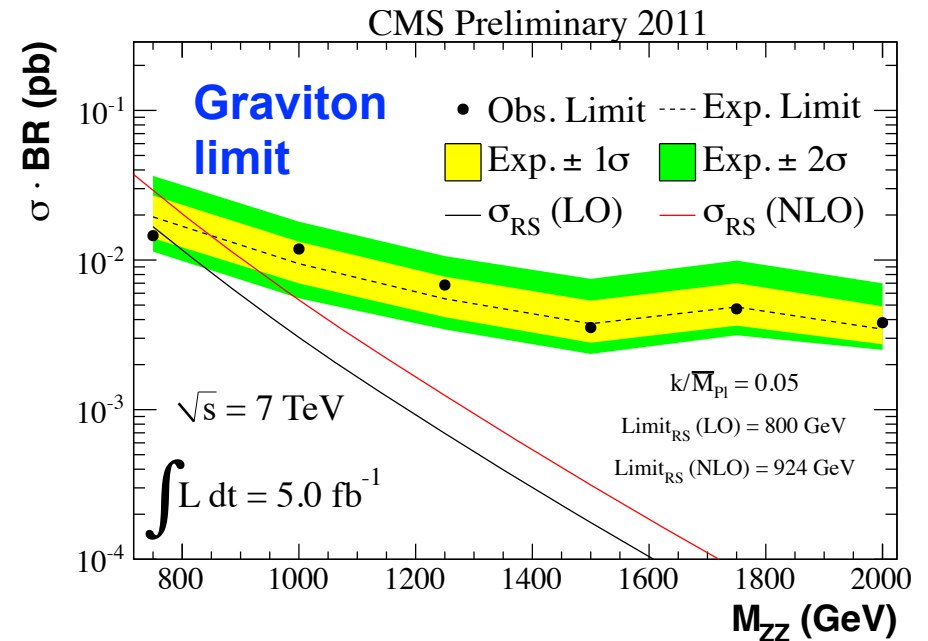
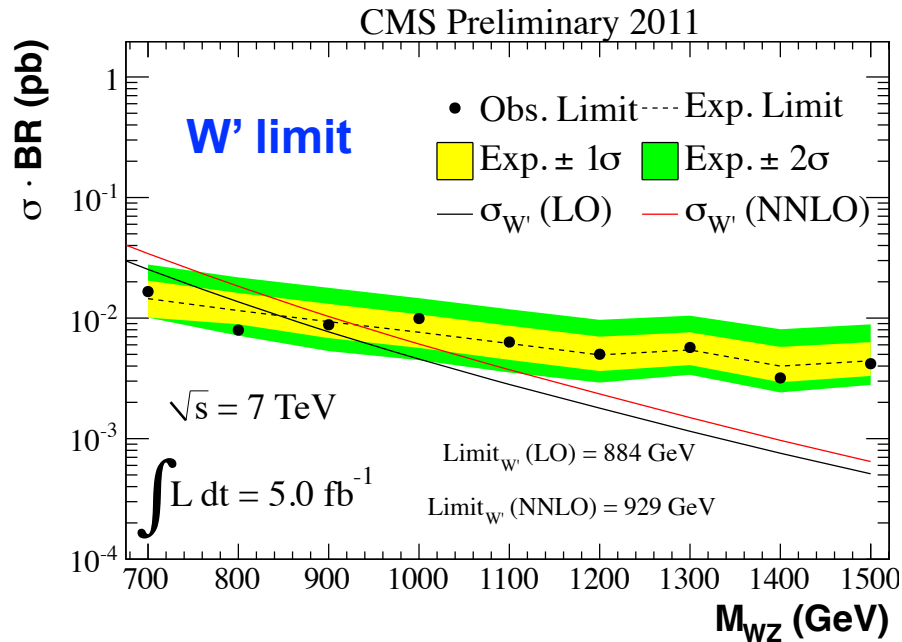
◆ Search for $W' \rightarrow WZ$ and $G \rightarrow WZ$ where one Z decays leptonically

◆ The other boson (W or Z) decays hadronically into a single (merged) jet
 - anti-kT 0.7 jet
 - highly boosted: $p_T > 250 \text{ GeV}$

◆ Plot invariant mass of the VZ system.

Smoothly falling spectrum. Set limit.

Limits on W' & RS graviton



At 95% CL we exclude

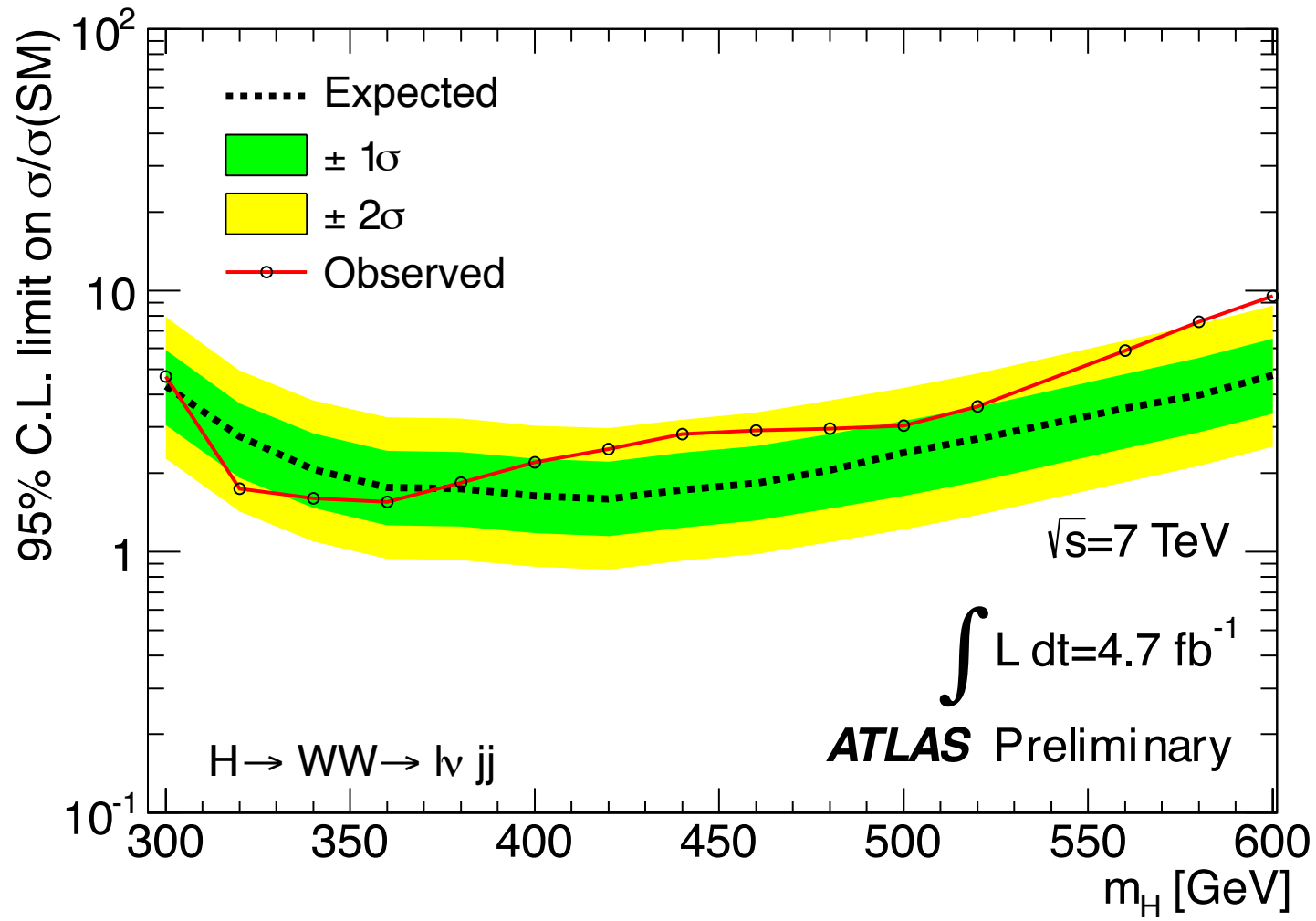
- Sequential W' bosons with masses $< 700\text{--}929 \text{ GeV}$
- RS graviton with $k/M_{\text{Pl}} = 0.05$ and masses $< 700\text{--}924 \text{ GeV}$

The first results from LHC on VZ searches using boosted massive jet.

ATLAS results on $H \rightarrow WW \rightarrow \ell \nu qq$ (March 2012)



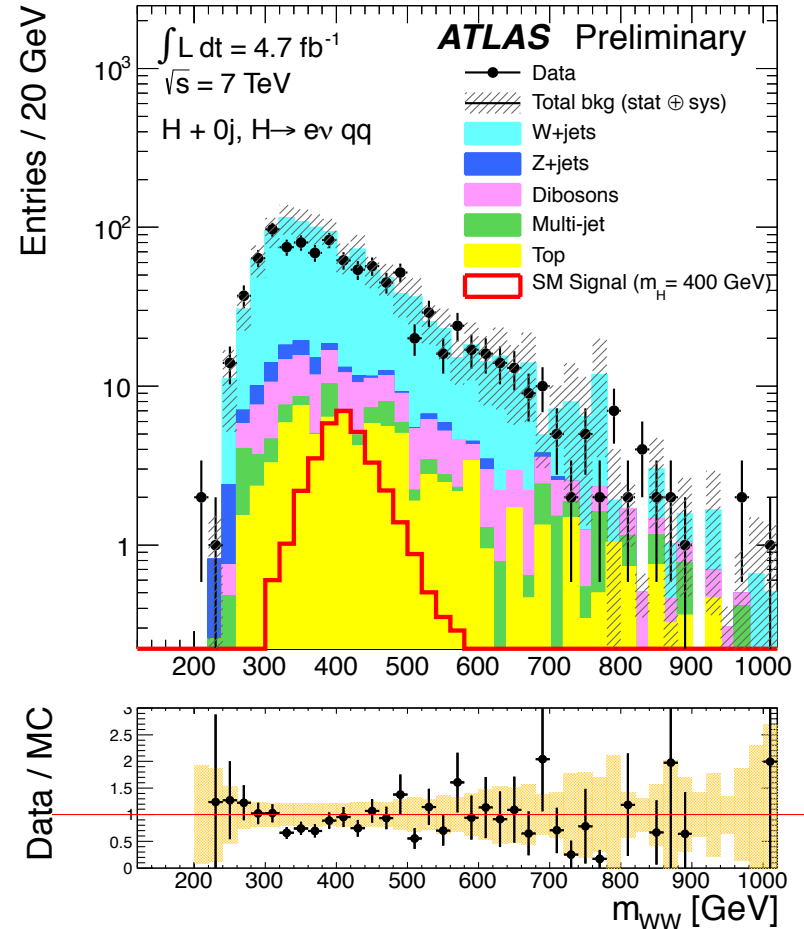
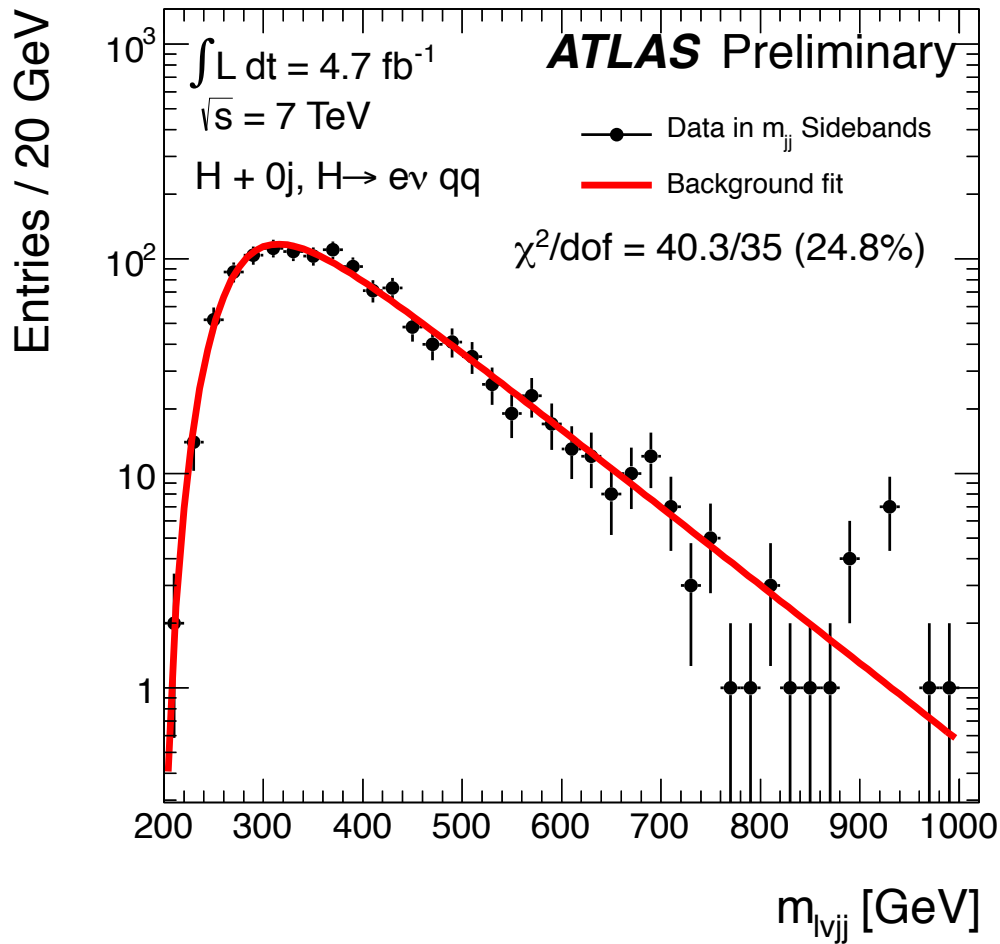
<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-018/>



ATLAS results on $H \rightarrow WW \rightarrow \ell\nu qq$ (March 2012)



<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-018/>

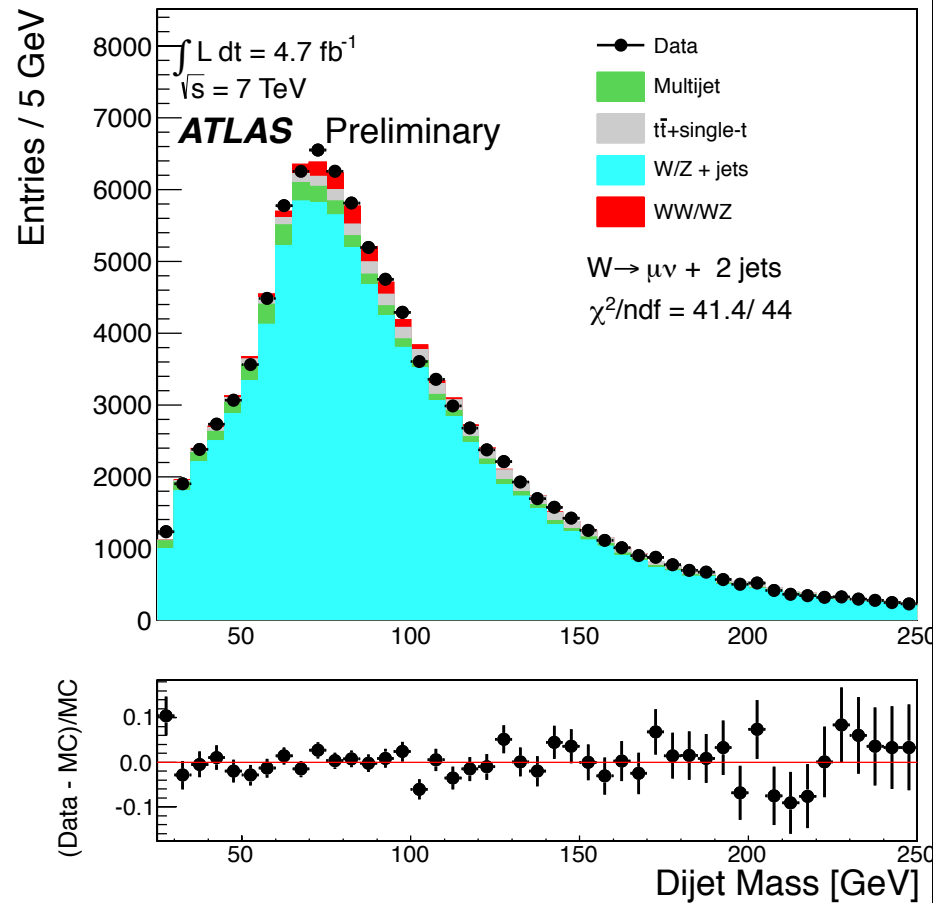
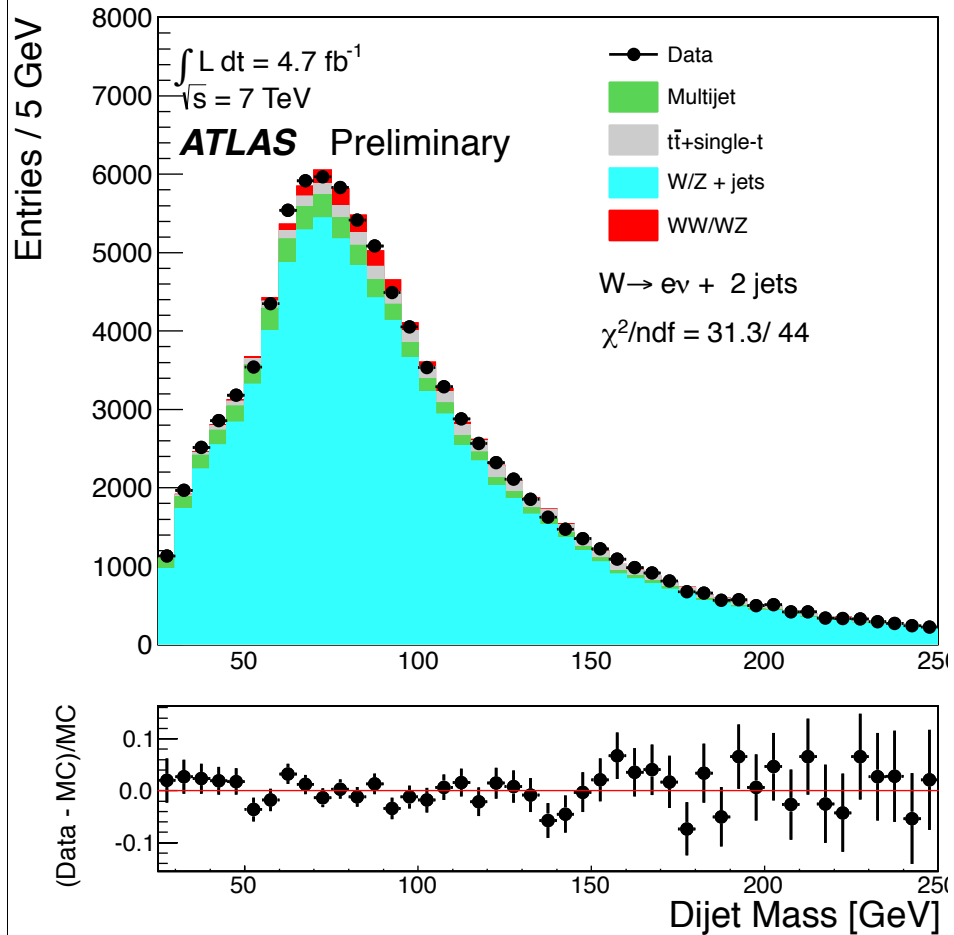


ATLAS results on $WW \rightarrow \ell\nu qq$ (Nov 2012)

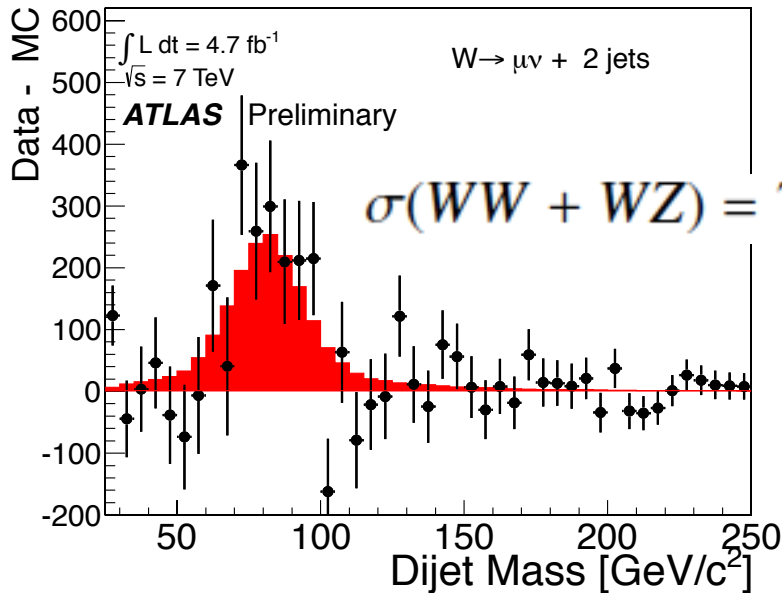
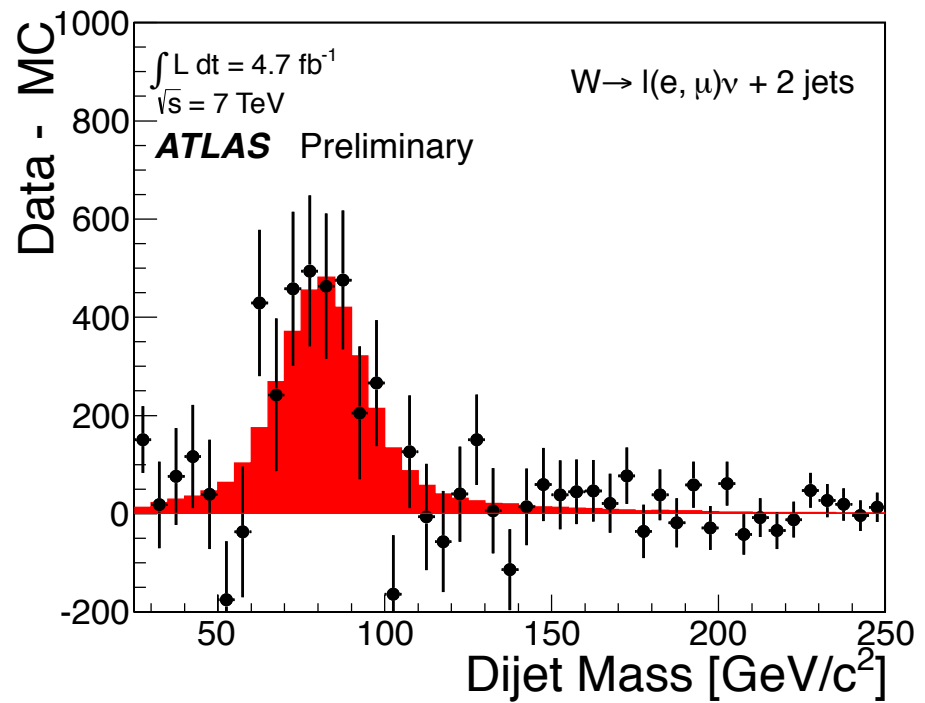
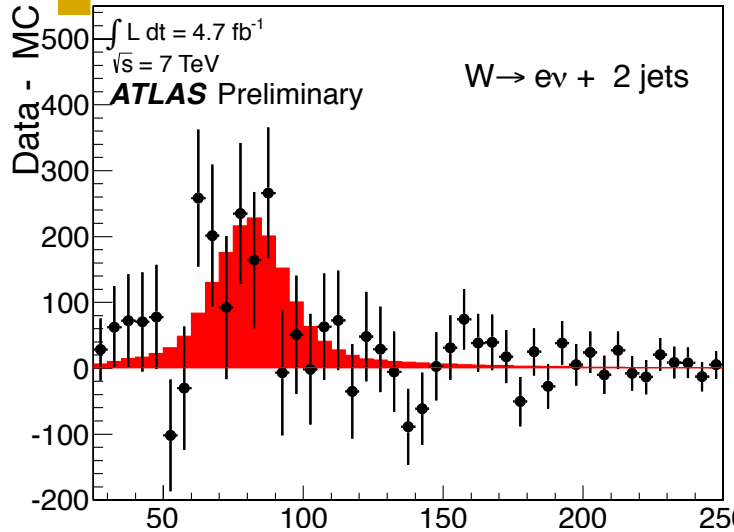


<http://cdsweb.cern.ch/record/1493586>

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-157/>



ATLAS results on $WW \rightarrow \ell\nu qq$ (Nov 2012)



$$\sigma(WW + WZ) = 72 \pm 9 \text{ (stat.)} \pm 15 \text{ (syst.)} \pm 13 \text{ (MC stat.)}$$

	e	μ
WW	1250 ± 60	1360 ± 70
WZ	276 ± 19	306 ± 21