En Route to the Electro Weak Symmetry Breaking

"Recent Studies of Higgs Boson at CMS"

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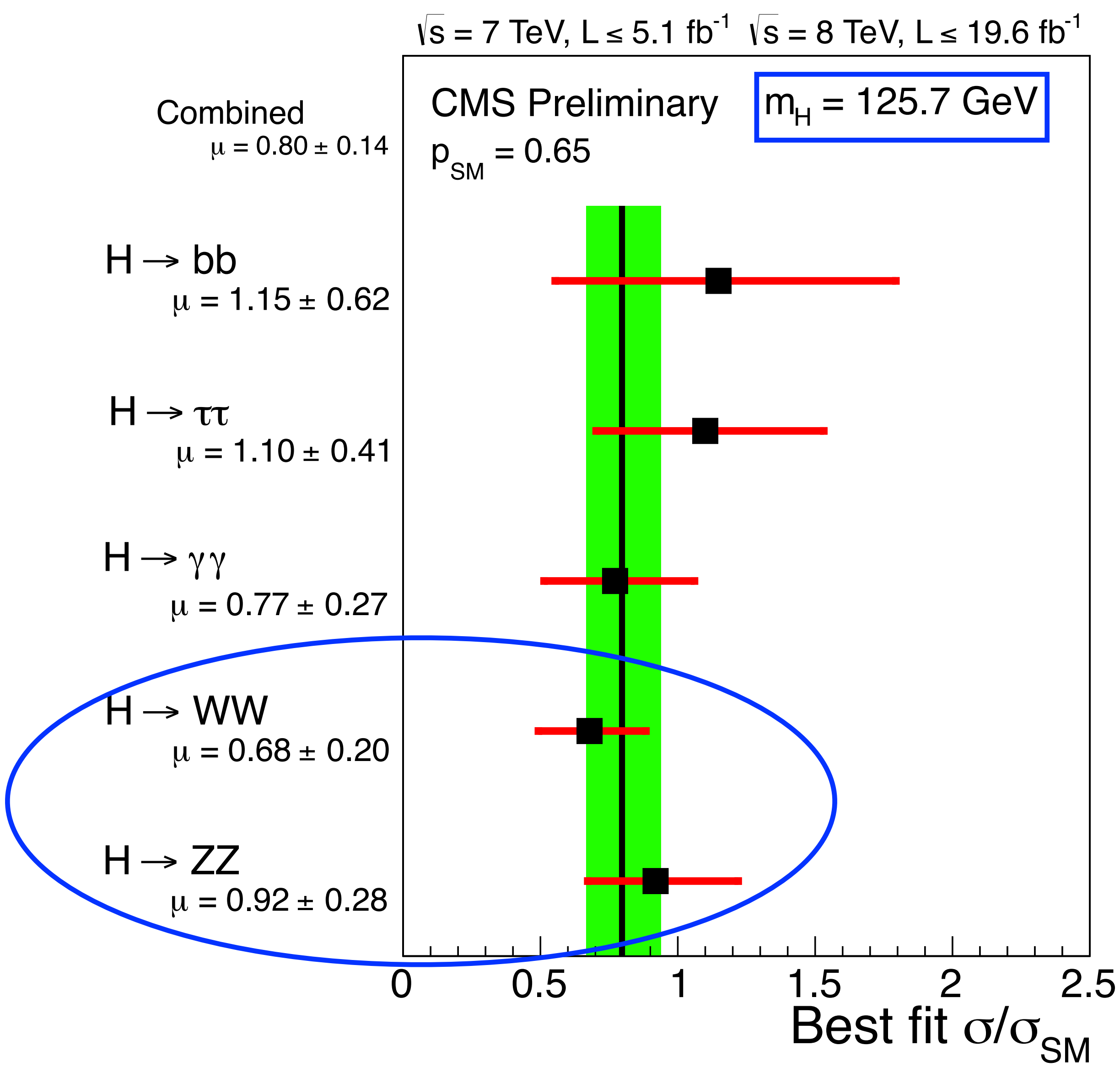
Fermilab Joint Experimental-Theoretical Physics Seminar

June 28, 2013

Outline

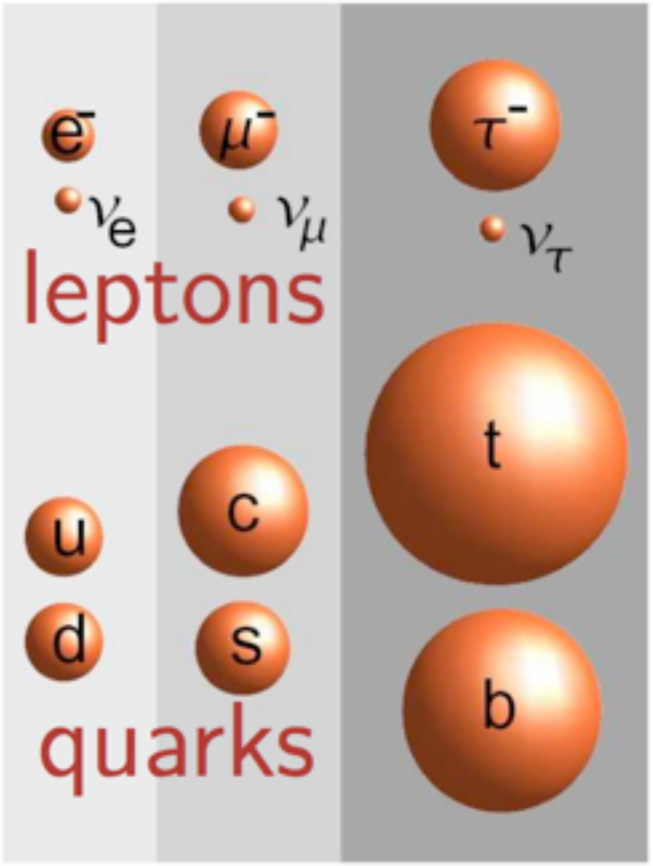
- Reminder of the SM Higgs Mechanism
- Higgs search overview at the CMS
  - A brief history of "Higgs" discovery
- Highlights of the latest CMS Higgs studies
- Methods to probe the XVV interactions
  - The spin and parity measurements of the new particle
- Higgs studies in WW/ZZ decays at CMS
- Prospects of the future LHC Higgs measurements



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

The Successful SM

- The SM describes fundamental constituents of matter and interactions elegantly through gauge invariance
- The fundamental matter is made of spin 1/2 fermions



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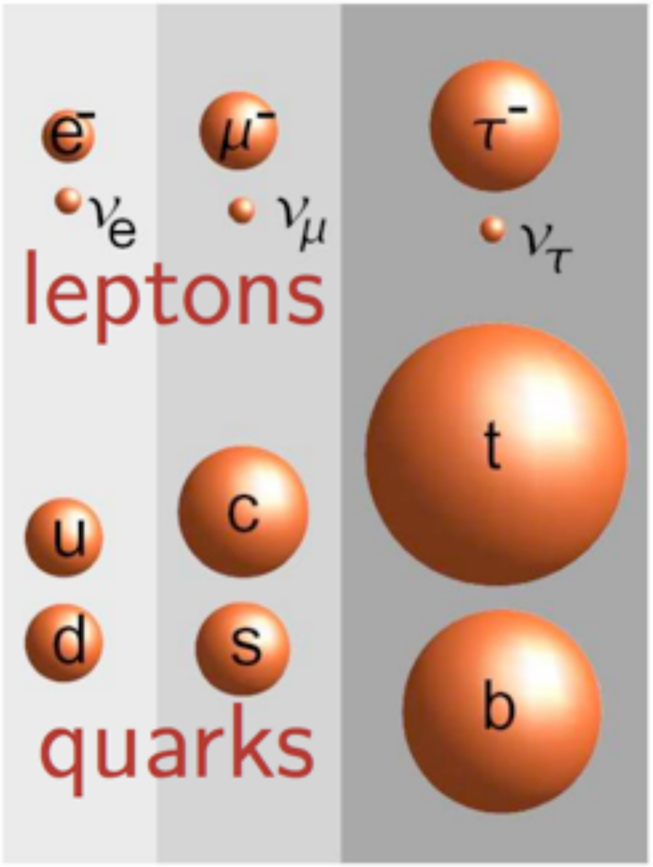
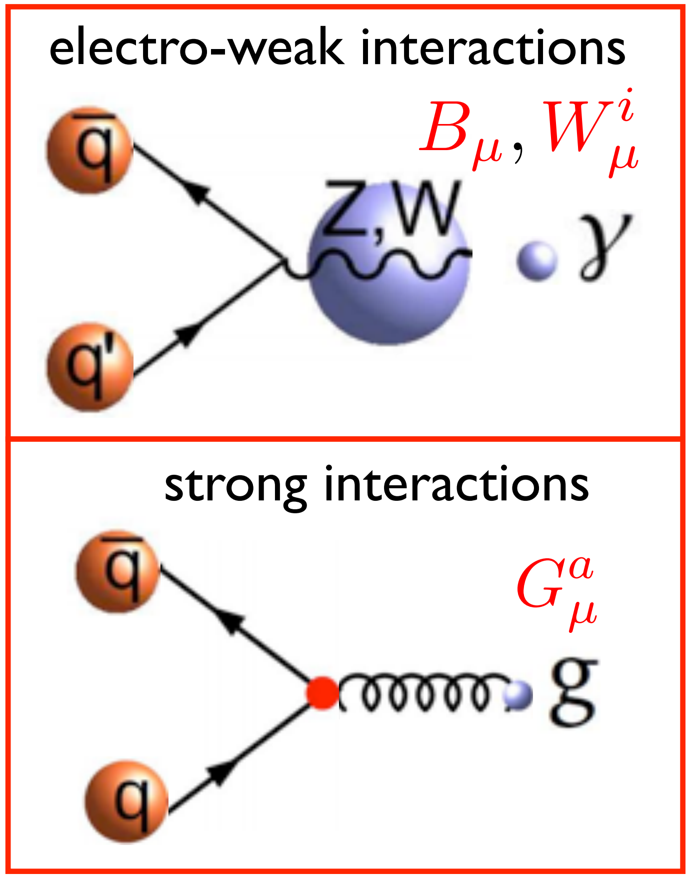
- The SM describes fundamental constituents of matter and interactions elegantly through gauge invariance
- The fundamental matter is made of spin 1/2 fermions
- Interactions are mediated by spin 1 gauge bosons
  - Requiring theory invariant under gauge transformations
    - Electro-weak(EWK) interactions: SU(2)⊗U(1)
    - Strong interactions: SU(3)





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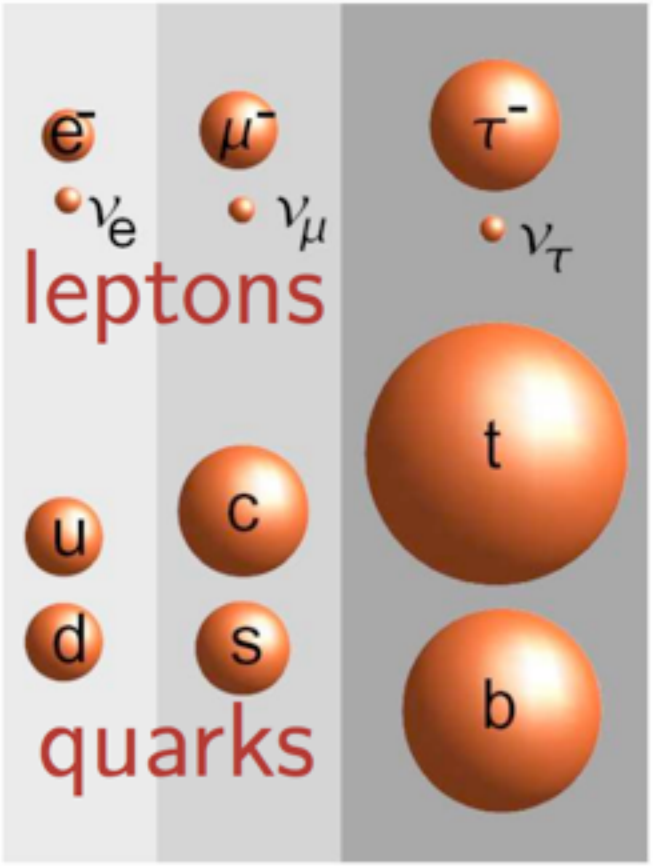

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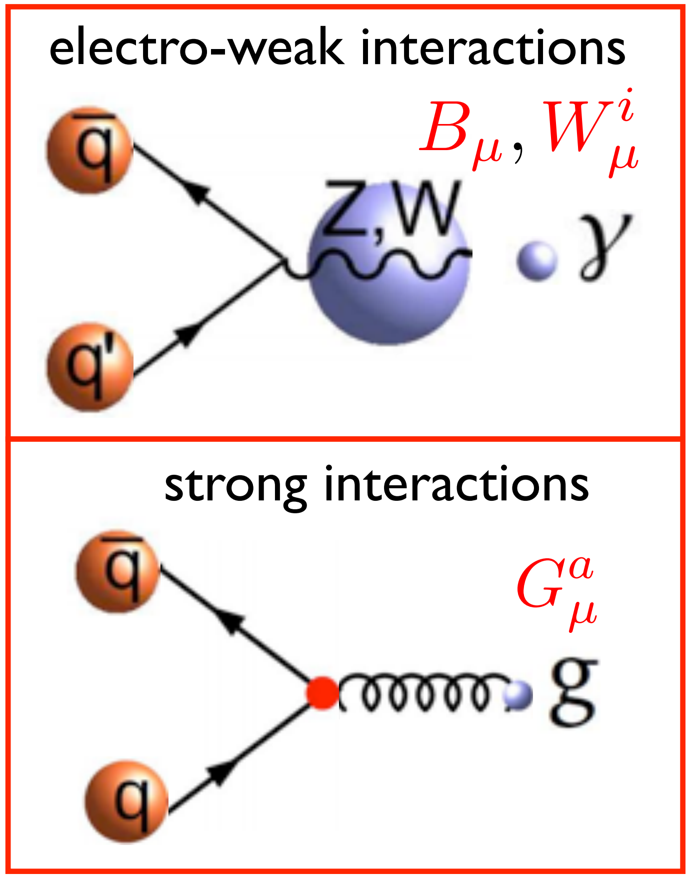
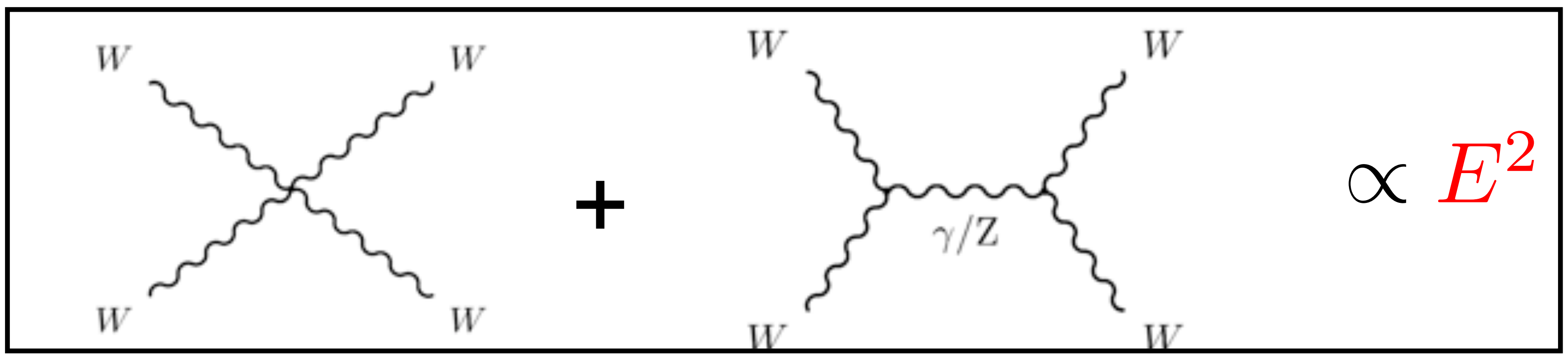


- **The SM has been highly predictive**
  - The discovery of the W/Z bosons and the rigorous precision measurements at the EWK scale

The Incomplete SM

1. The fermions and bosons are massless as a consequence of the gauge invariance
   - The electro weak symmetry must be broken when particles acquire mass
2. The SM has unphysical predictions of some physical observables
   - Such as the WW longitudinal scattering amplitude violates unitarity



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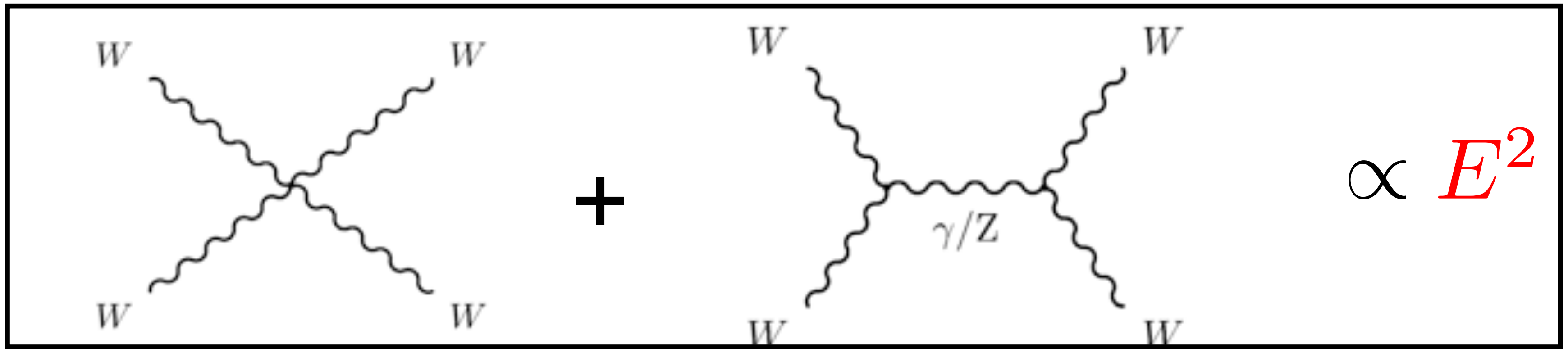


- Higgs mechanism (1960s): "spontaneous symmetry breaking in the EWK sector"
   - Generate particle masses without perturbing the gauge invariance, ensures good high energy behavior
   - **This is by no means "the only way", but by far the most "economical way"**

The Higgs Mechanism (I)

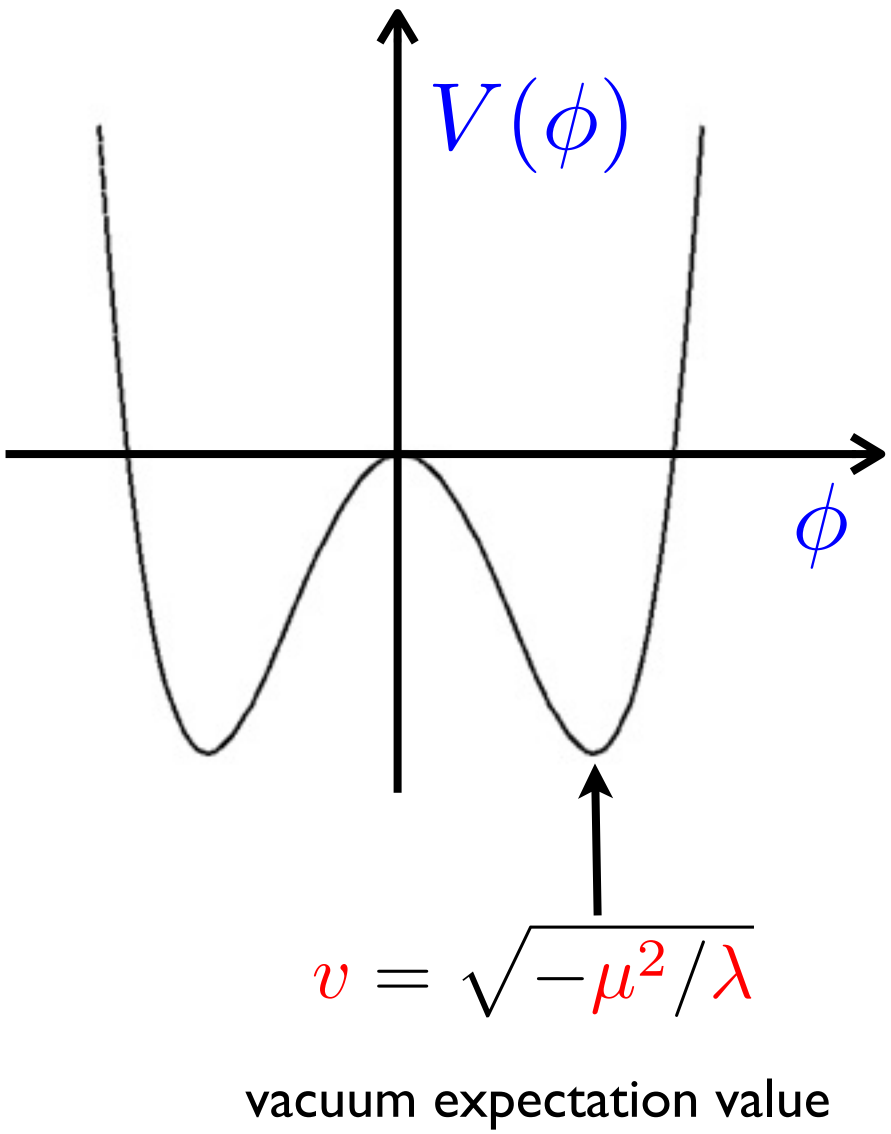
- Spontaneous symmetry breaking mechanism: a simple example with scalar field

$$\mathcal{L} = T - V = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - (\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4)$$

  - Impose $\mu^2 < 0$ and $\lambda > 0$ → There is no mass term!
  - The potential is invariant under parity

$$V(\phi) = V(-\phi)$$

  - The ground state (vacuum) v breaks the parity symmetry



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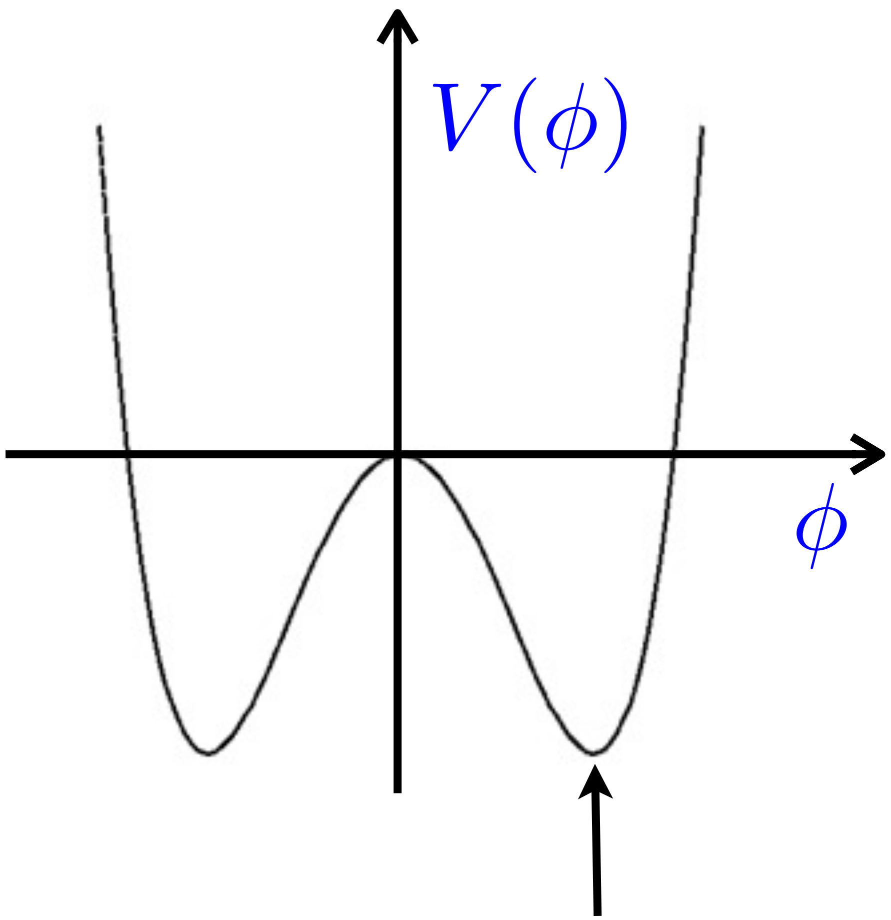
- The ground state (vacuum) v breaks the parity symmetry
- Expand the field near the vacuum to study the particle spectrum

$$\phi = v + \eta$$

$$\mathcal{L} = \frac{1}{2}\partial_\mu \eta \partial^\mu \eta - (\lambda v^2 \eta^2 + ...)$$

  - **We now have a mass term!**

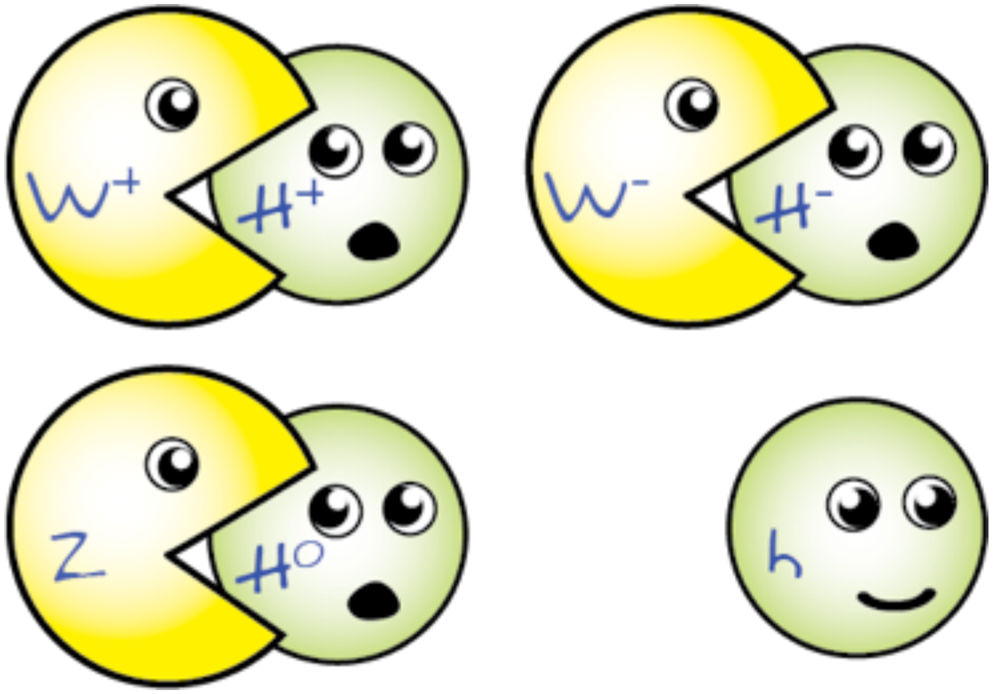


$v = \sqrt{-\mu^2/\lambda}$

vacuum expectation value

The Higgs Mechanism (II)

- The Higgs mechanism, "electroweak symmetry breaking mechanism in the SM"
  - SU(2) complex scalar doublet with 4 real components
  - Construct a potential that is invariant under electroweak symmetry, but not its ground state
  - Expanding the fields near the vacuum leads to
    - one real Higgs field "Higgs boson"
    - the other 3 get "eaten" by W/Z to generate the mass and longitudinal polarizations of W/Z



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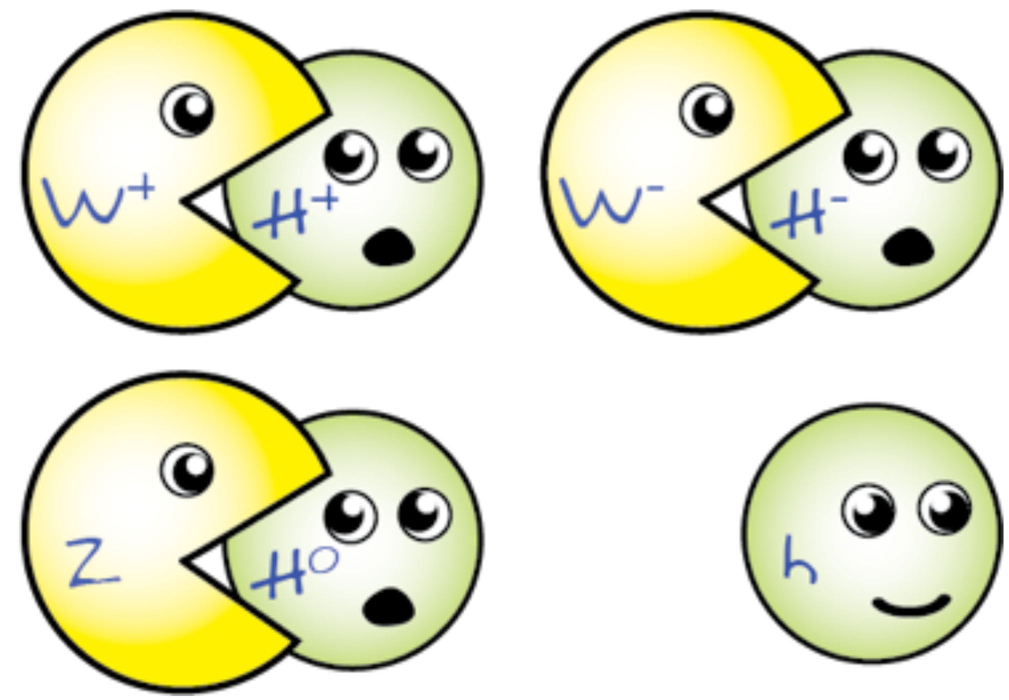
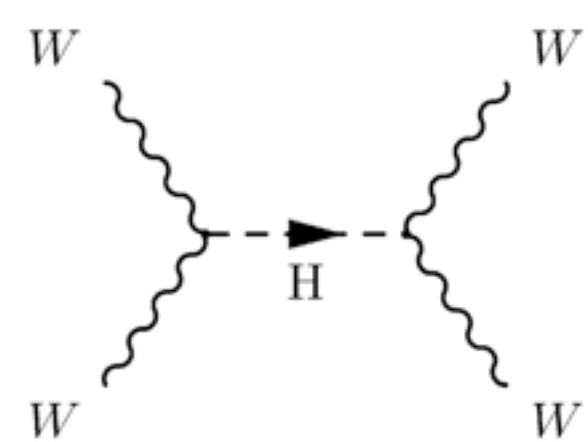
- WW longitudinal scattering amplitude unitarized by HWW interaction



$$\zeta_e \left[(\overline{e_L}\Phi) e_R + \overline{e_R}(\Phi^\dagger e_L) \right]$$

$$\rightsquigarrow m_e = \zeta_e v / \sqrt{2}$$



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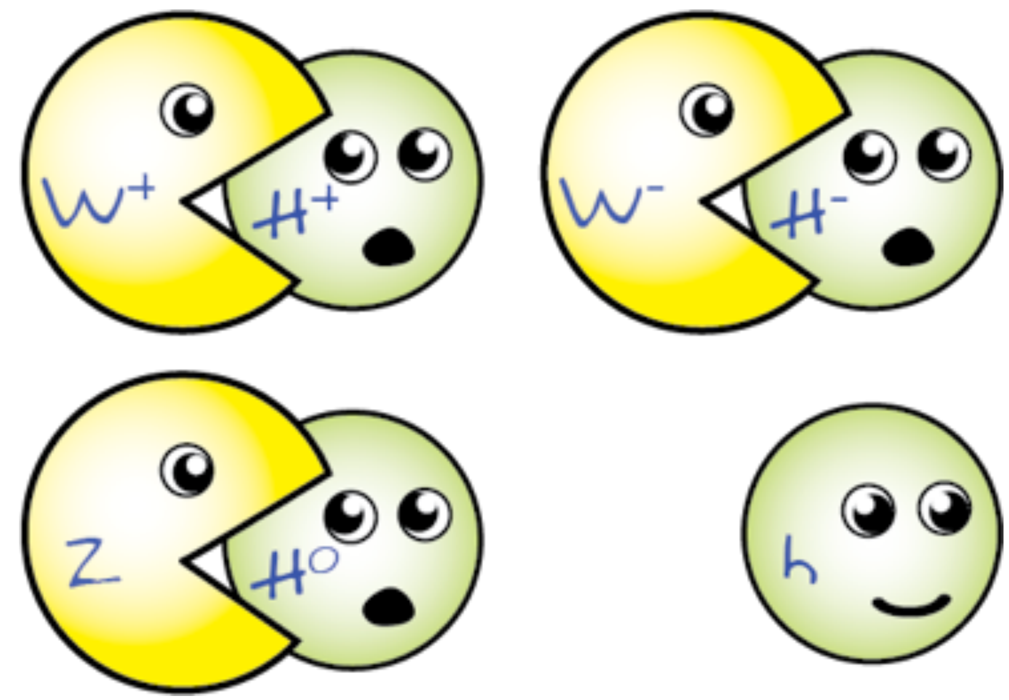
- WW longitudinal scattering amplitude unitarized by HWW interaction
- **EWSB → one physical scalar Higgs boson**
  - **Its mass is the only unknown parameter**



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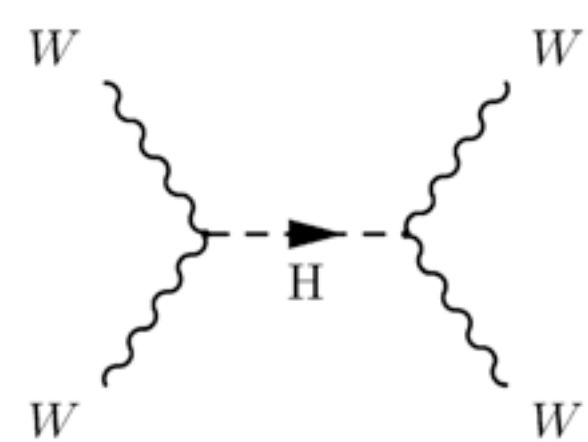


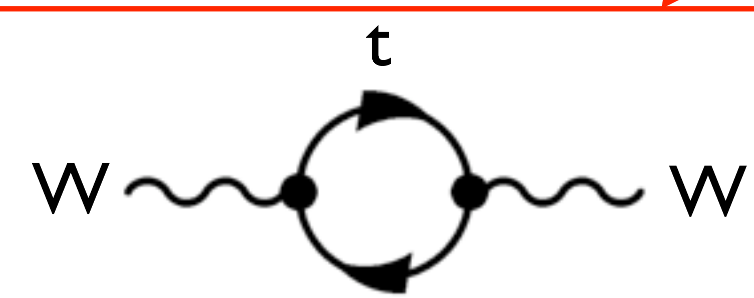
Direct Higgs Searches Prior to the LHC

- Large Electron Positron (LEP)
  - The electron-positron collider that ran until ~2000 at a center-of-mass energy up to ~ 209 GeV
  - **It excludes the SM Higgs with mass < 114.4 GeV at 95% C.L.**
- Tevatron
  - The proton--anti-proton collider that ran till 2011 at a center-of-mass energy ~ 2 TeV
  - **It excludes SM Higgs with mass in the range [156-177] GeV**

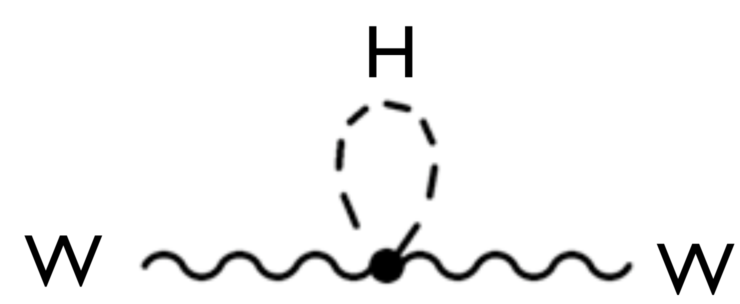
Constraints from EWK Precision Measurements

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}} \frac{1}{G_F s_W^2}(1 + \Delta r)$$

- EWK precision measurements can be used to constrain the Higgs mass if it contains high order corrections from Higgs loop
  - e.g. the W mass measurement
- All relevant EWK precision measurements are combined in a global fit for the Higgs mass
  - LEP EWK working group fit
    - **mH < 161 GeV at 95% C.L.**

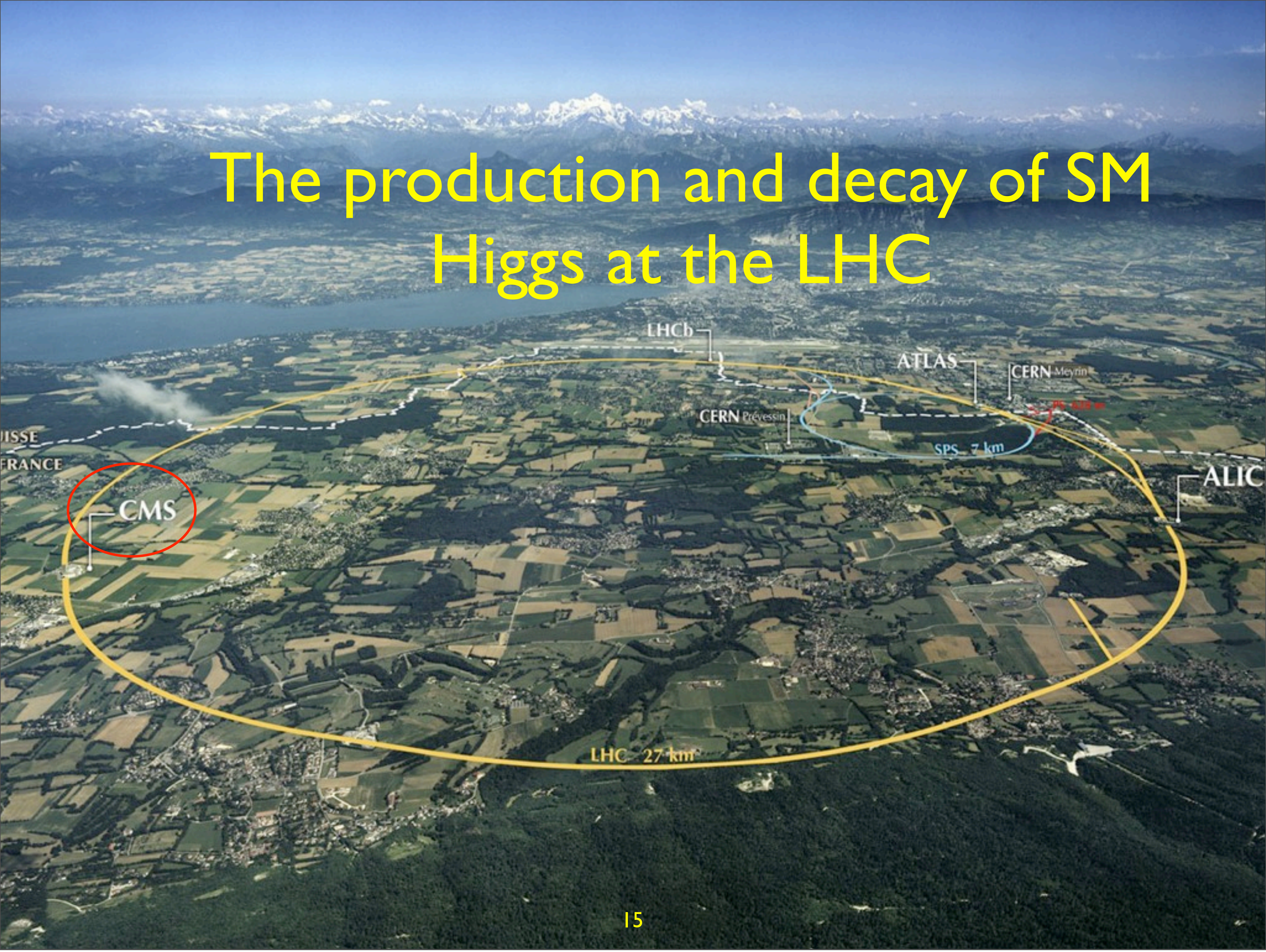


$$\Delta r_{top} \approx 0.03 \cdot (\frac{m_{top}}{175GeV})^2$$



$$\Delta r_H \approx 0.003 \cdot (\log\frac{m_H^2}{c_W^2 m_Z^2} - \frac{5}{6})$$

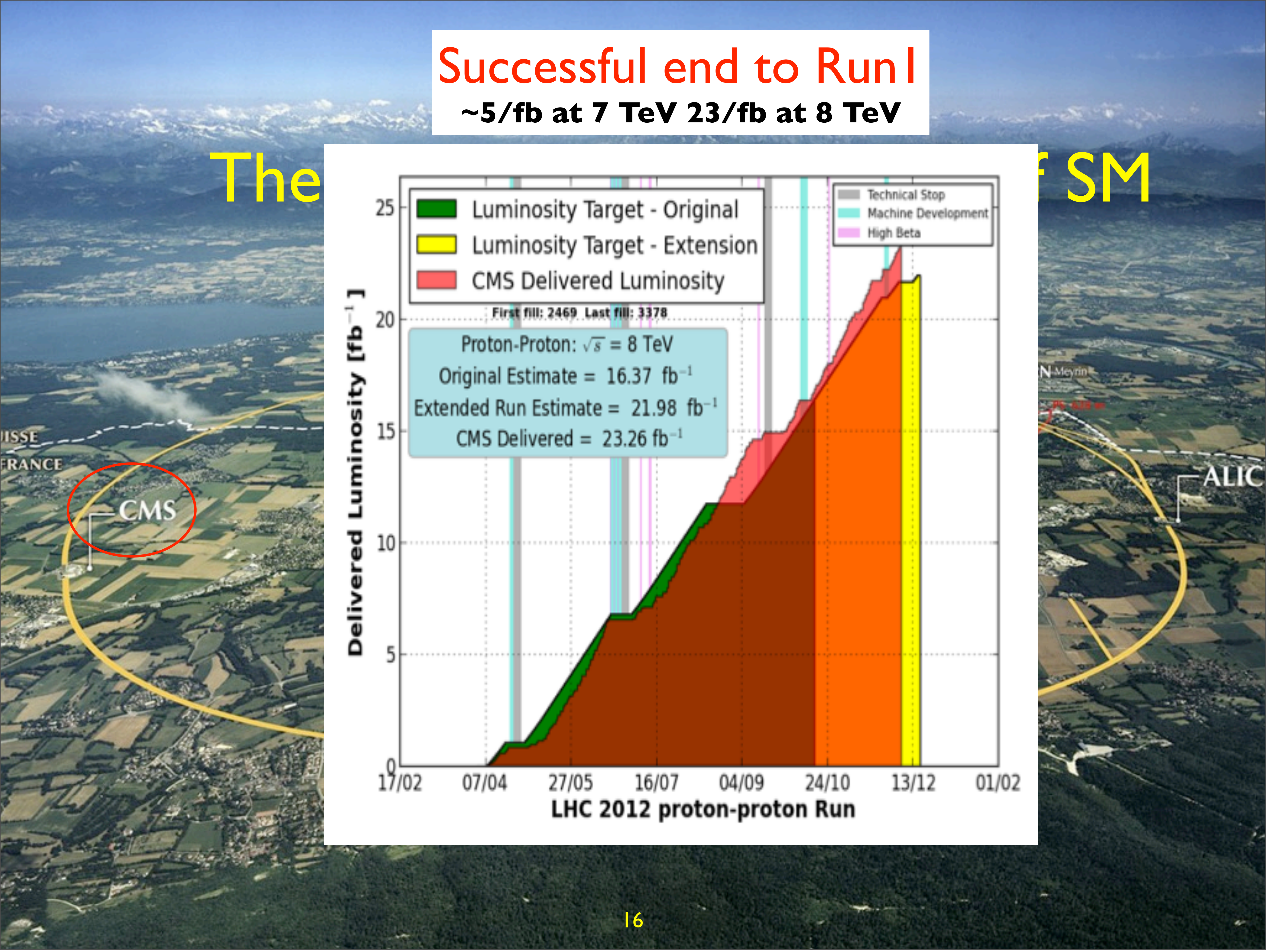
The production and decay of SM Higgs at the LHC



Successful end to Run1

~5/fb at 7 TeV 23/fb at 8 TeV

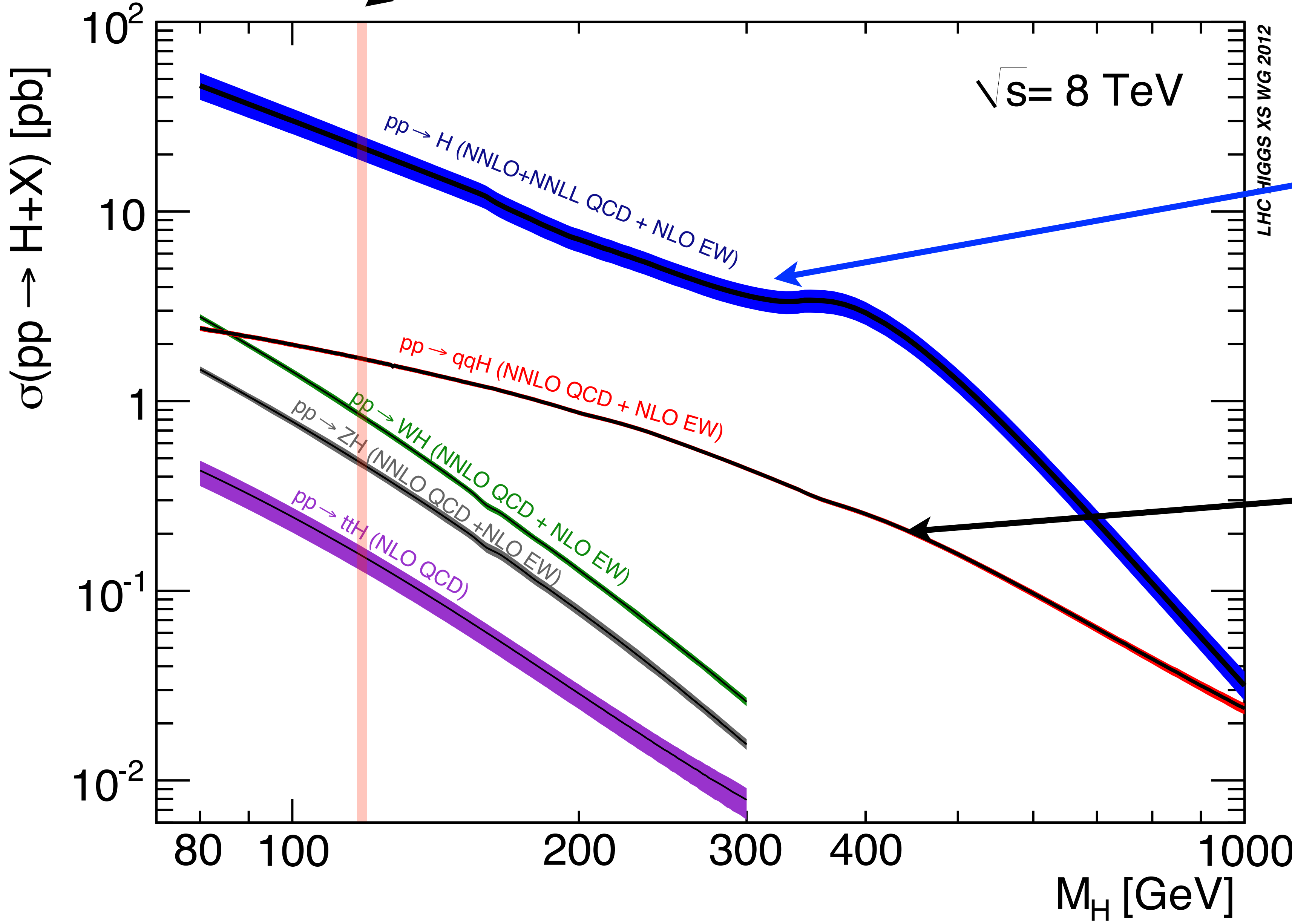
The ... f SM

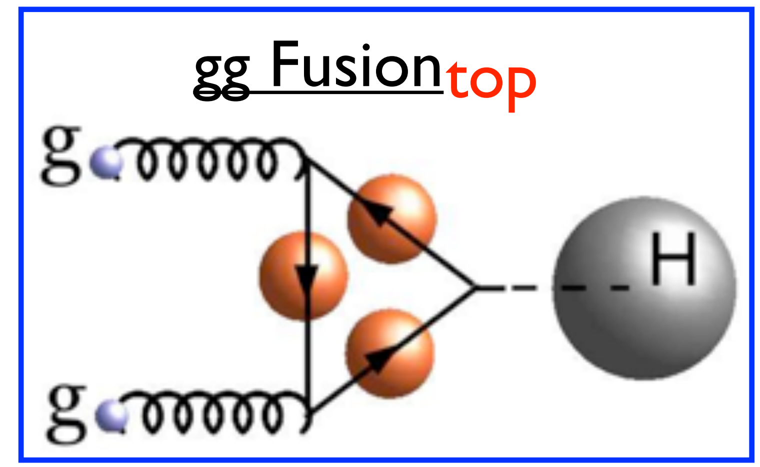


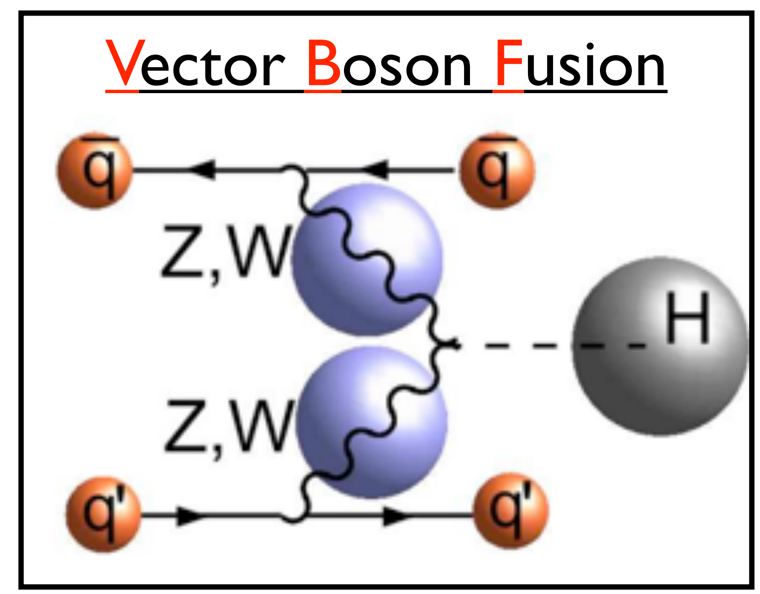
The SM Higgs Production at the LHC

- The SM Higgs is mainly produced in gluon fusion at the LHC

mH=125 GeV
σ(ggH) ~ 20 pb
σ(qqH) ~ 1.6 pb





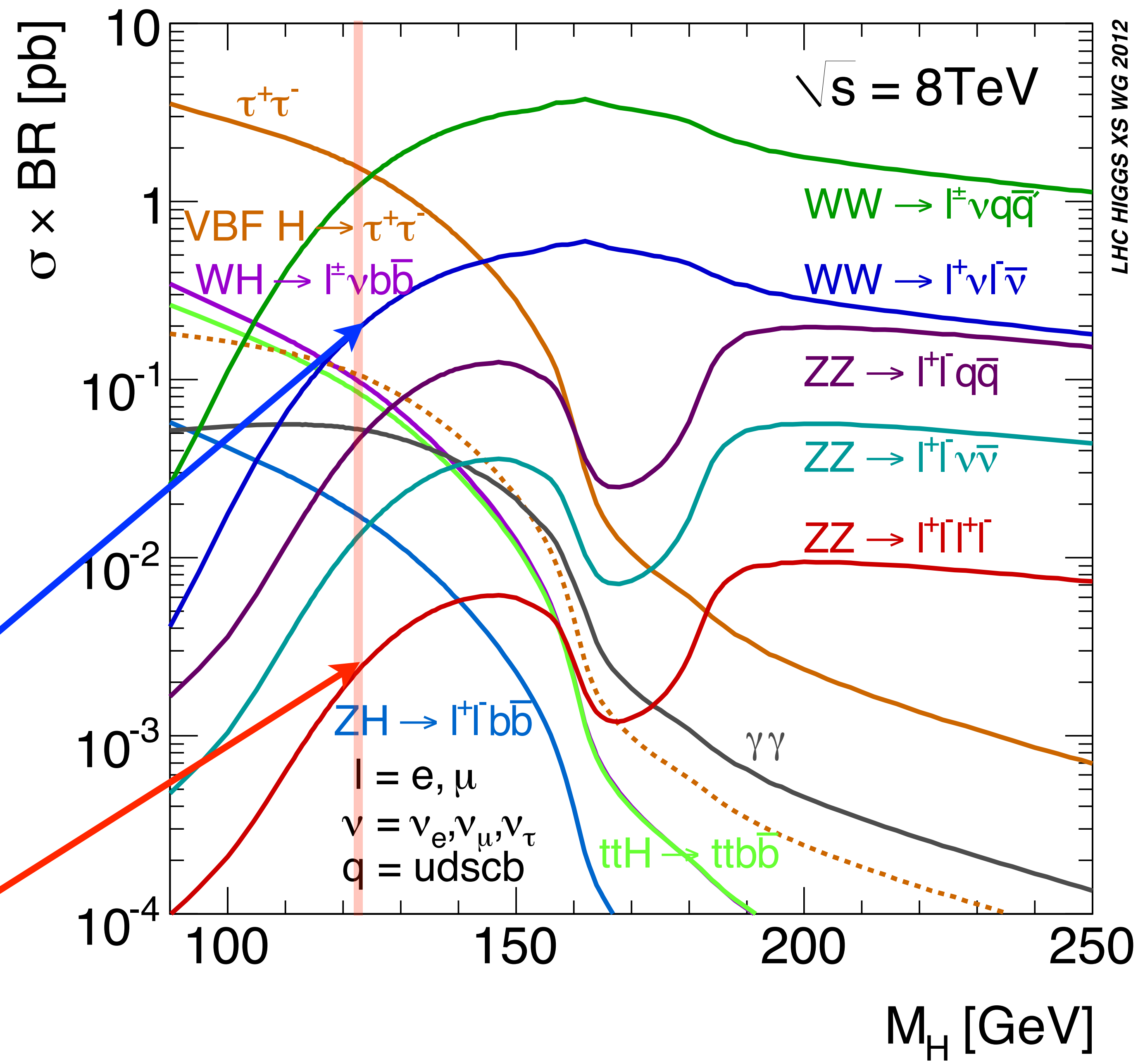


Friday, June 28, 2013

Detecting the SM Higgs Boson

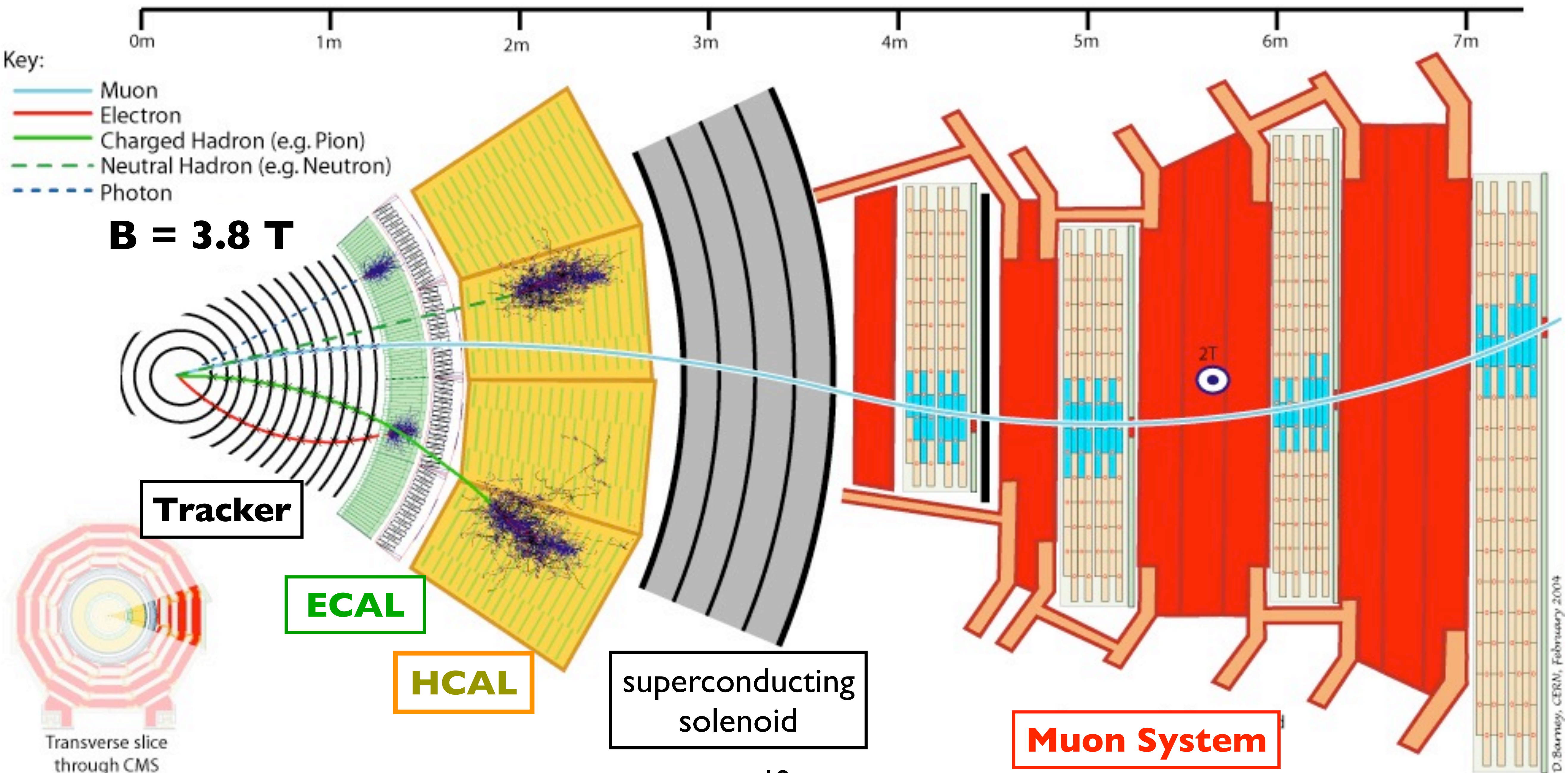
- Higgs can be detected in multiple channels
- The relative sensitivity of each channel depends on experimental constraints
    - Final states with multi-leptons and well measured objects are key channels
    - Two of the most important channels for the Higgs search in the full mass range

Channel	Feature
WW (→2l2ν)	**Large signal rate early discovery channel**
ZZ (→4l)	**Excellent mass resolution, Complex topology for property measurements**



Measuring Major Objects in CMS

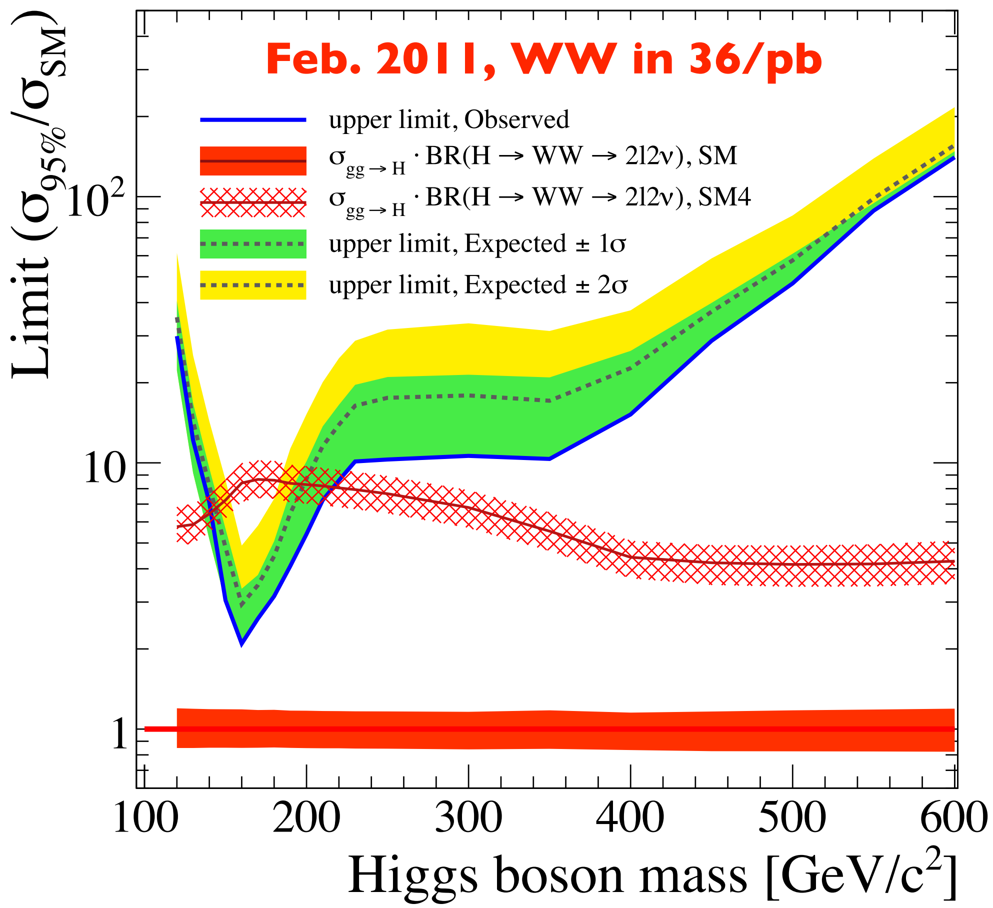
- Particle-Flow (PF) event reconstruction in CMS
  - Combine full information from all subsystems to give a coherent description of all stable particles
  - **Tracker performance and reconstruction of the tracks are cornerstones of PF**
    - precise reconstruction of charged particles and determination of the primary vertex position



Roadmap to the Discovery

First 7 TeV Collision March 30, 2010 CMS center

Roadmap to the Higgs-like Particle Discovery (I)



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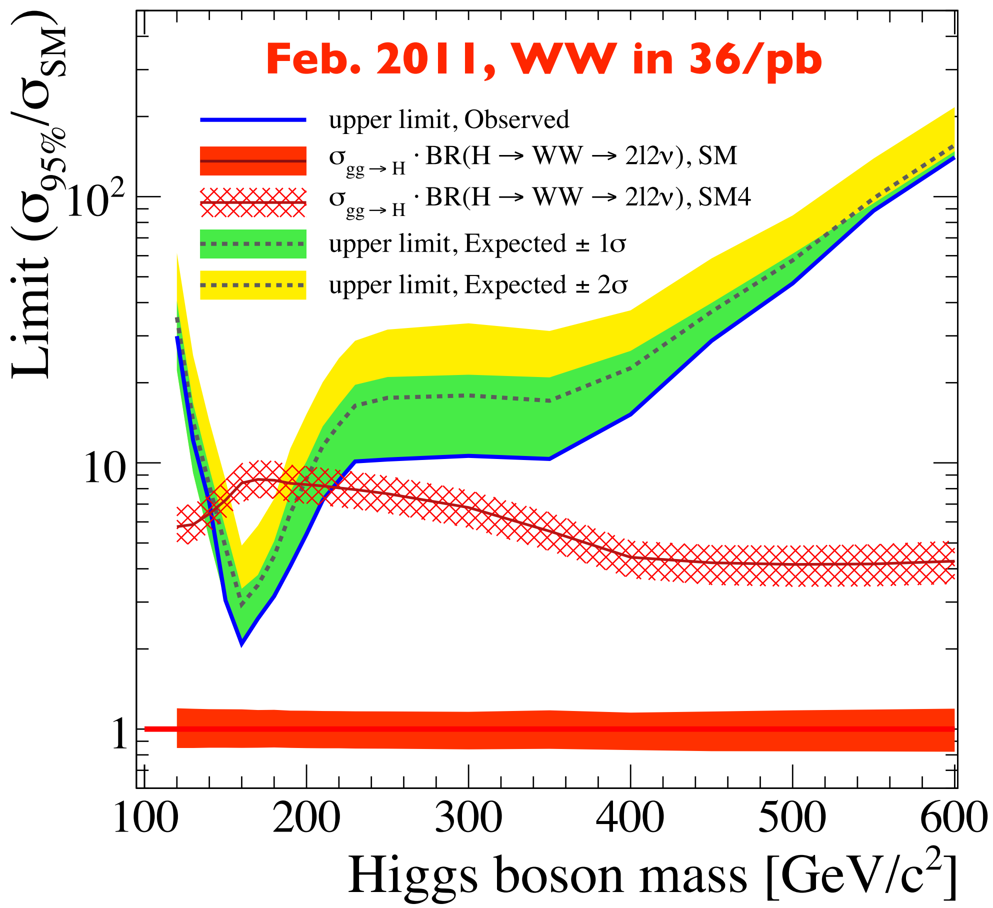

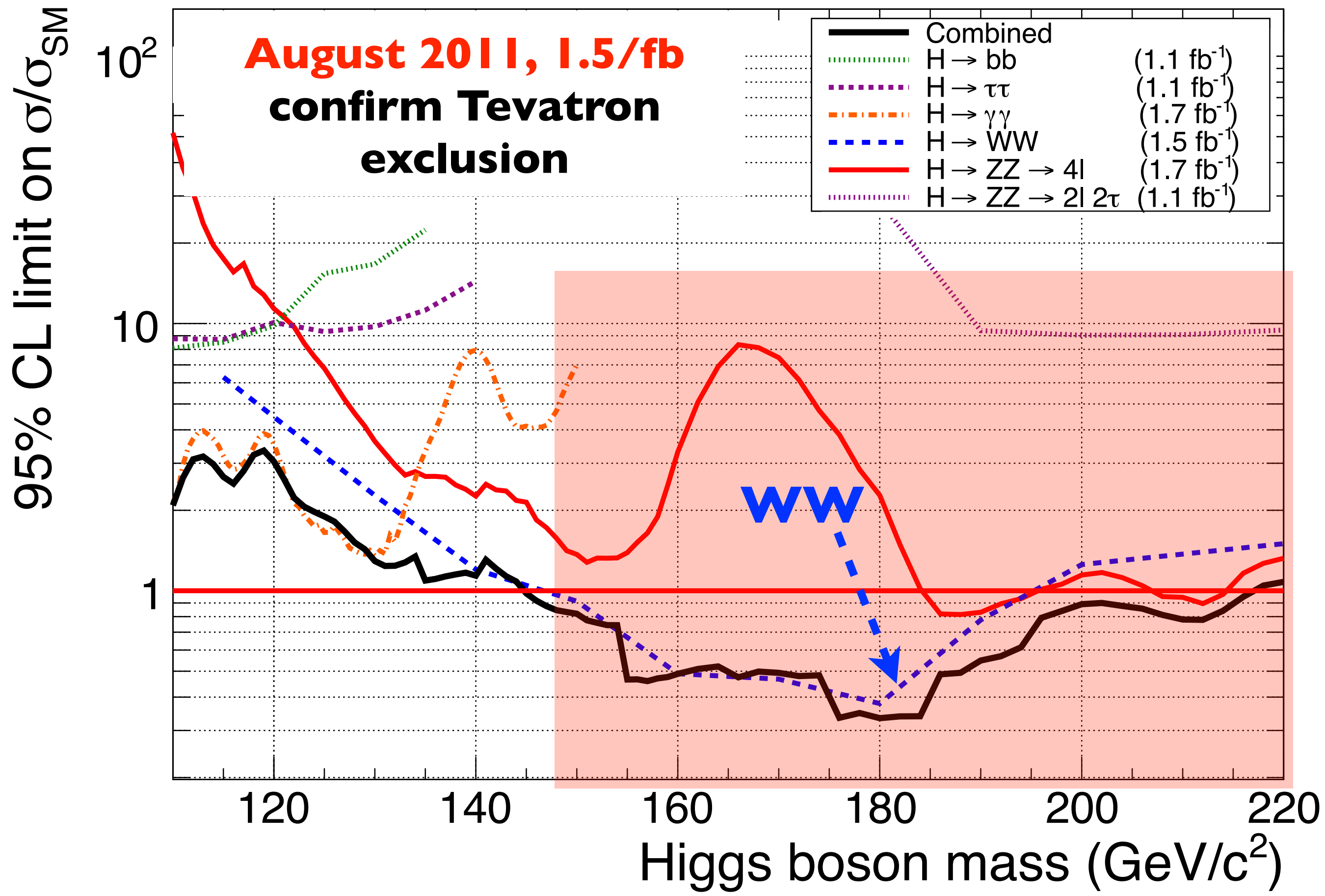

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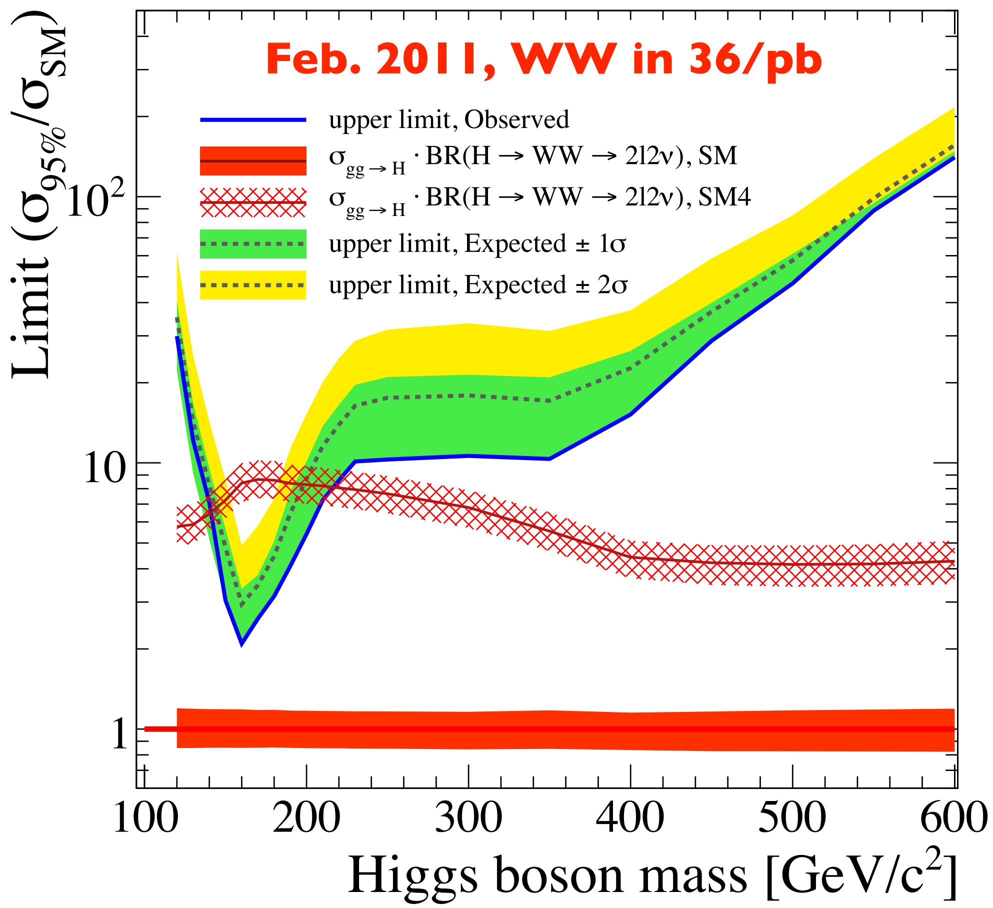

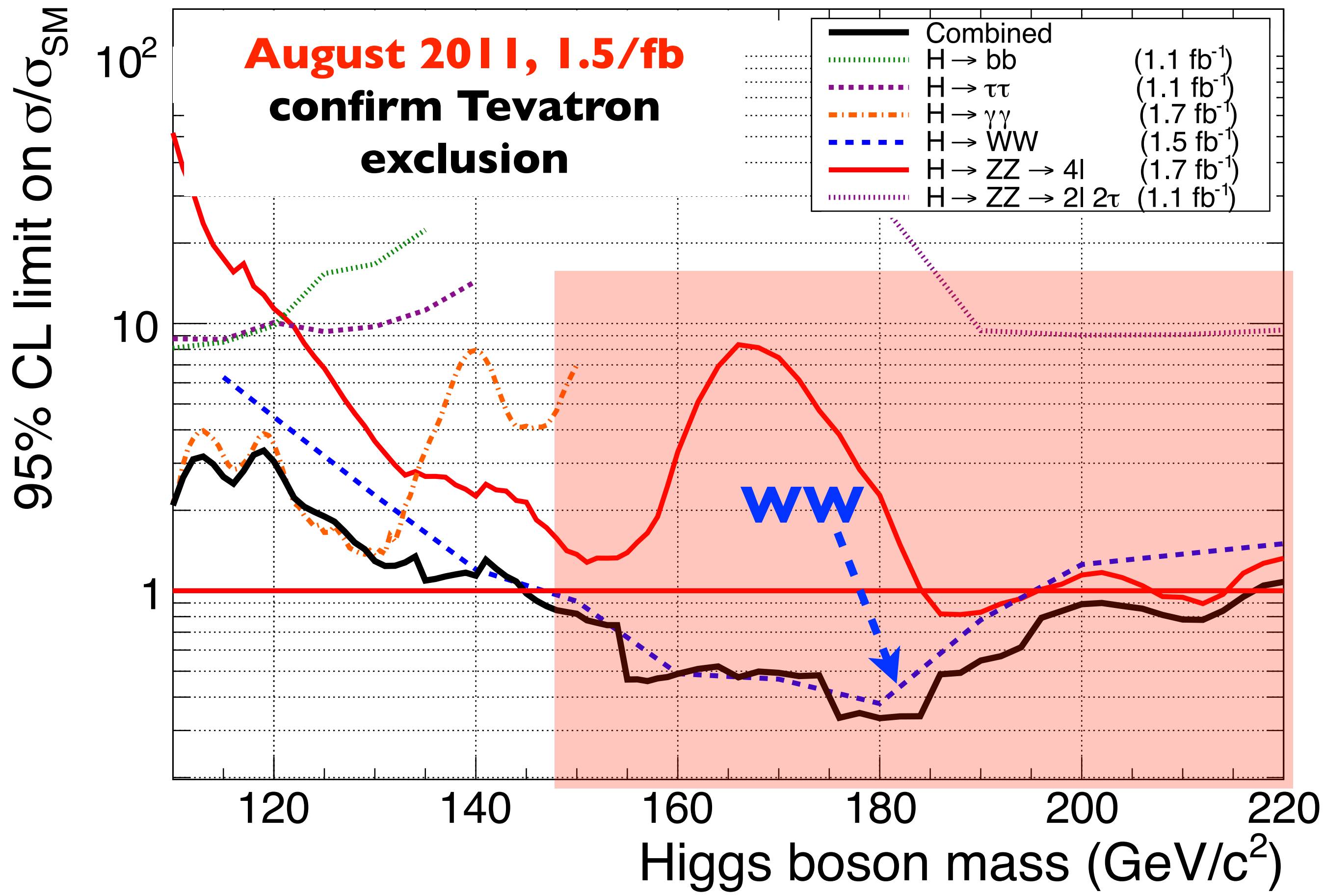

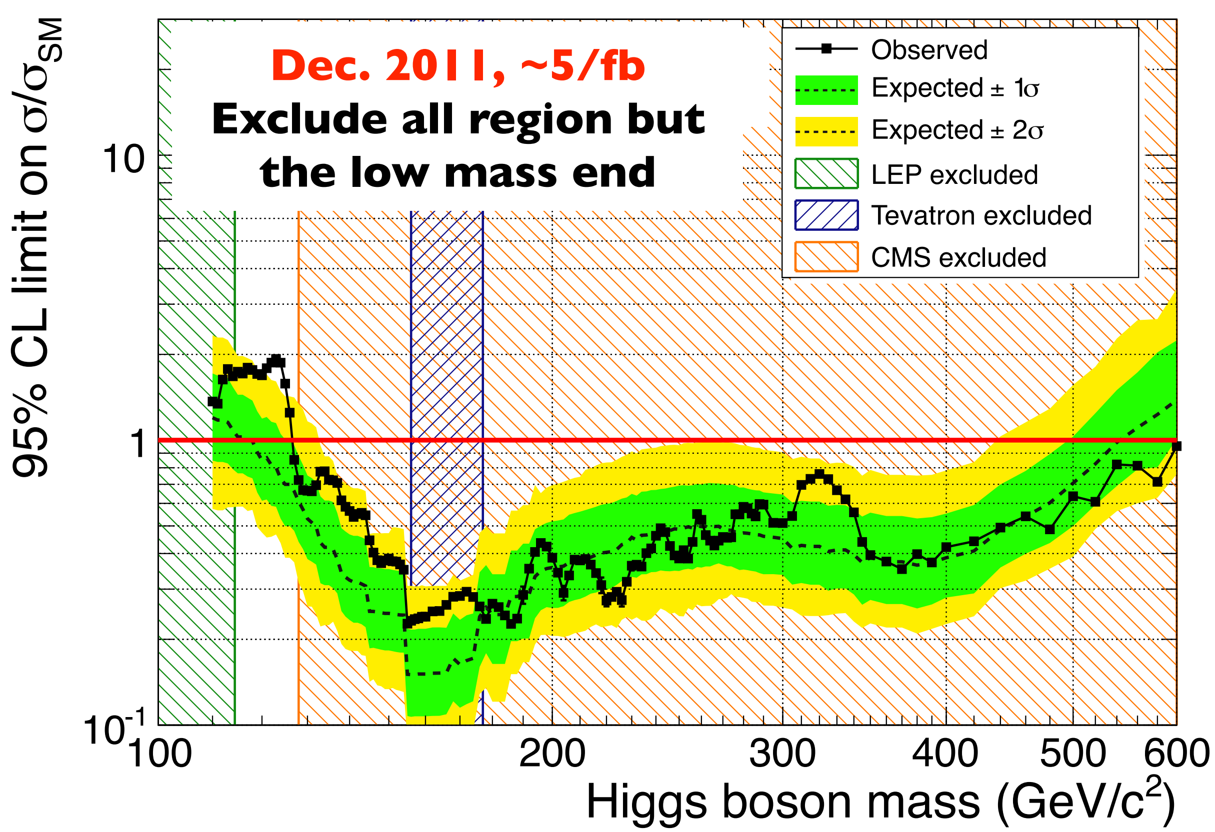

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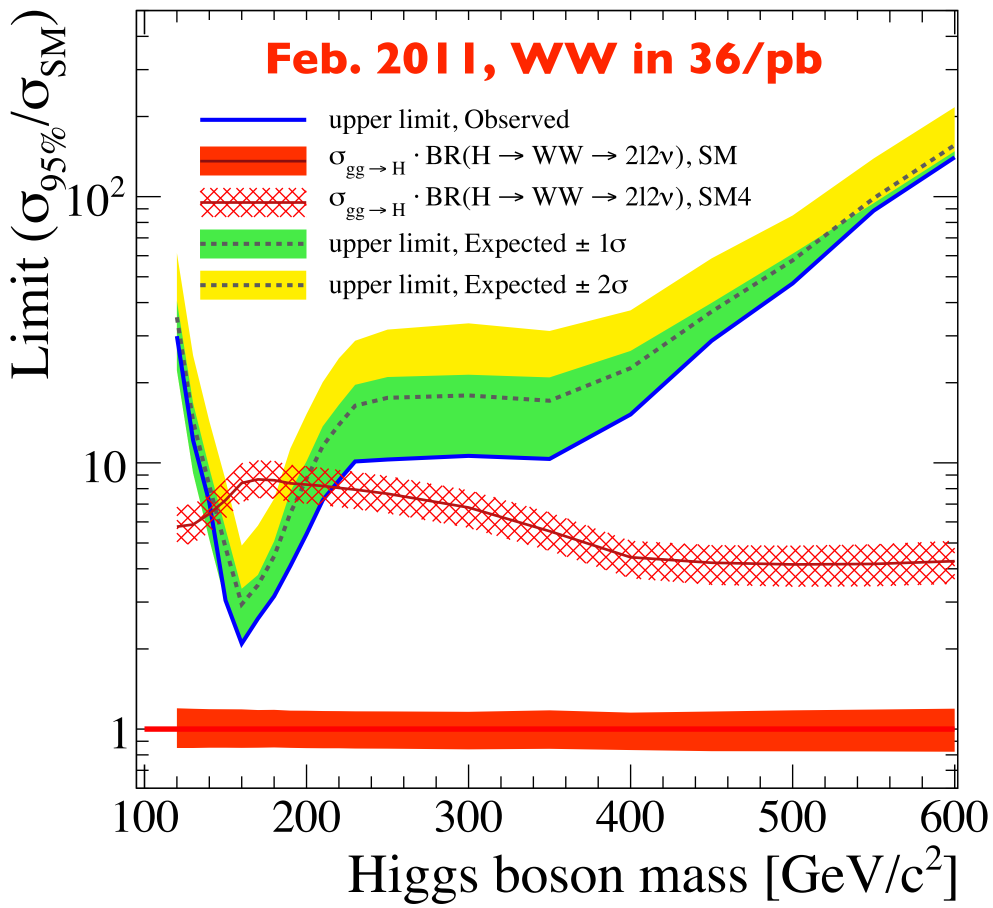
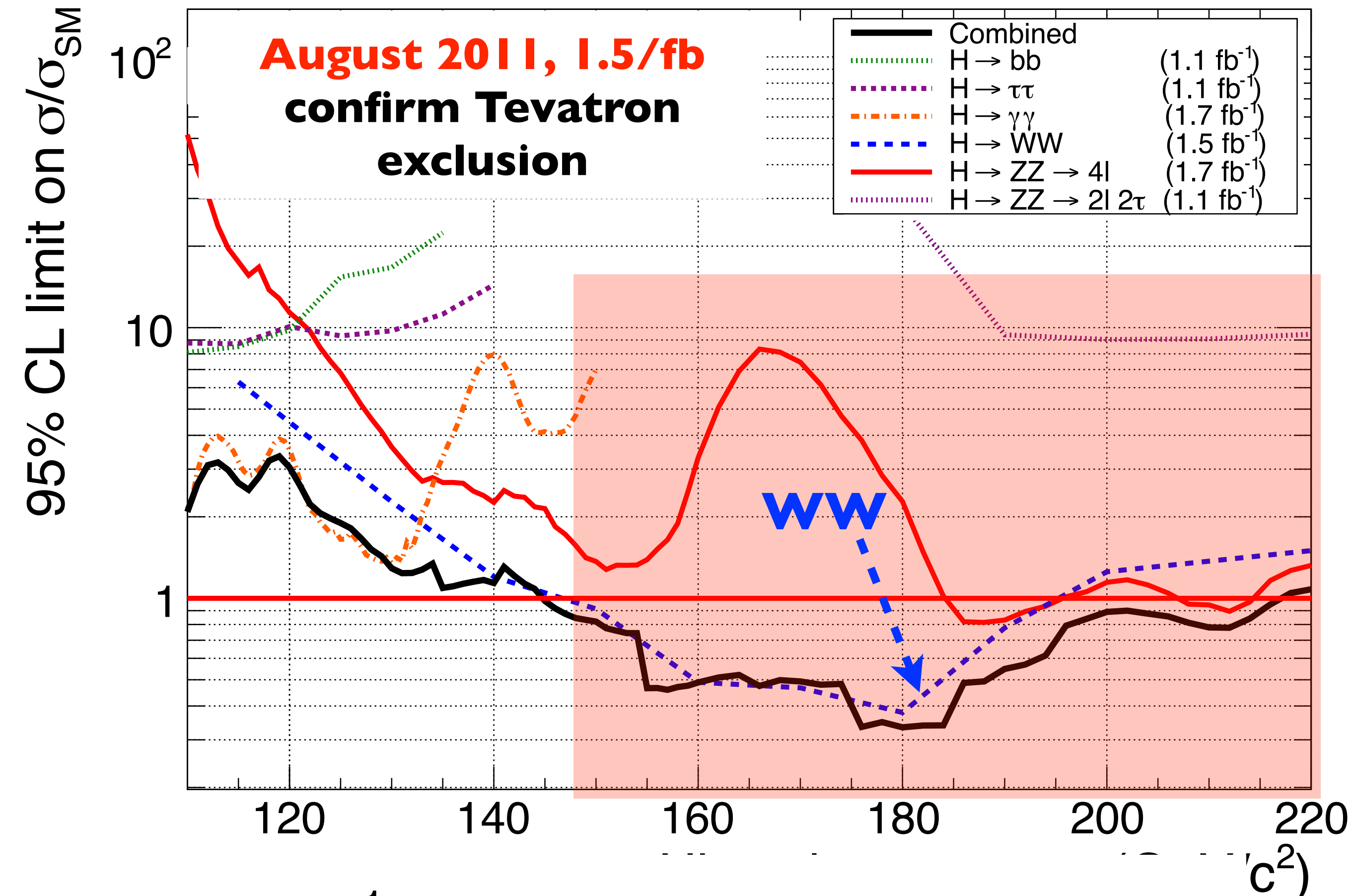
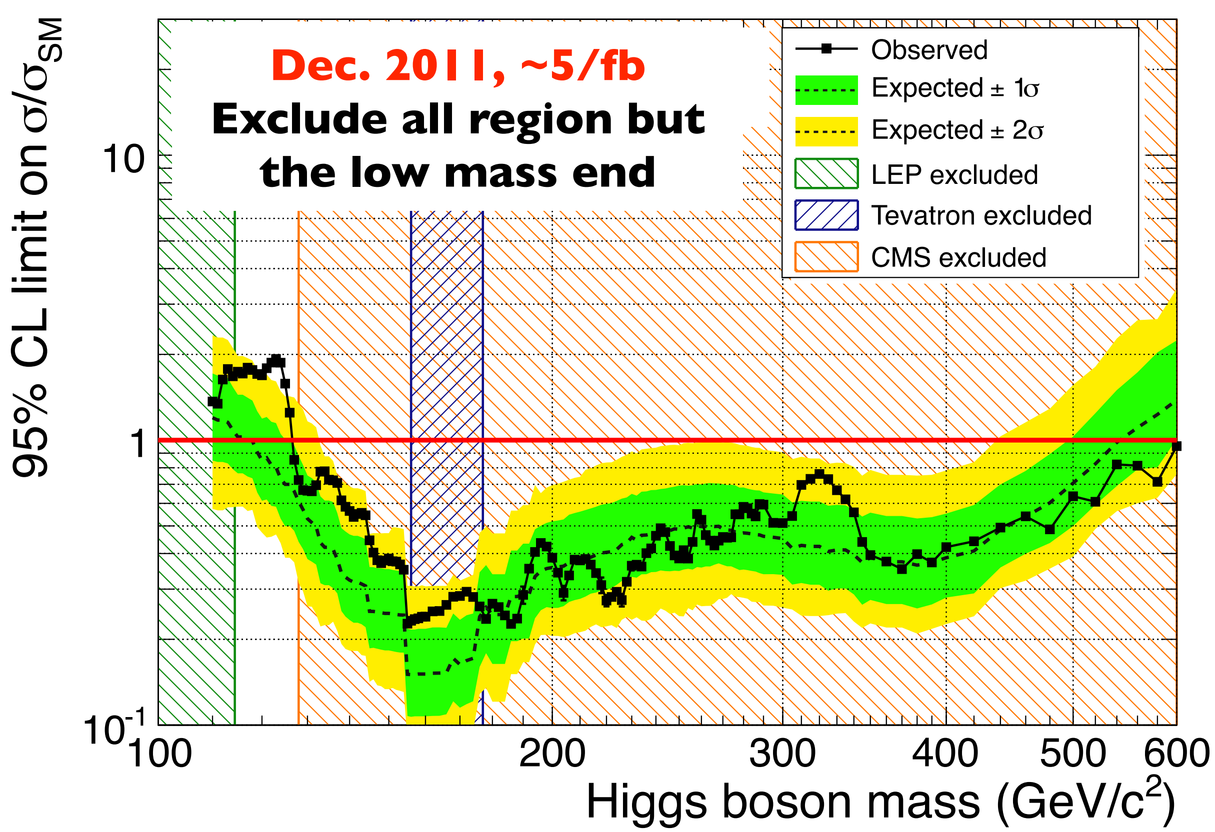
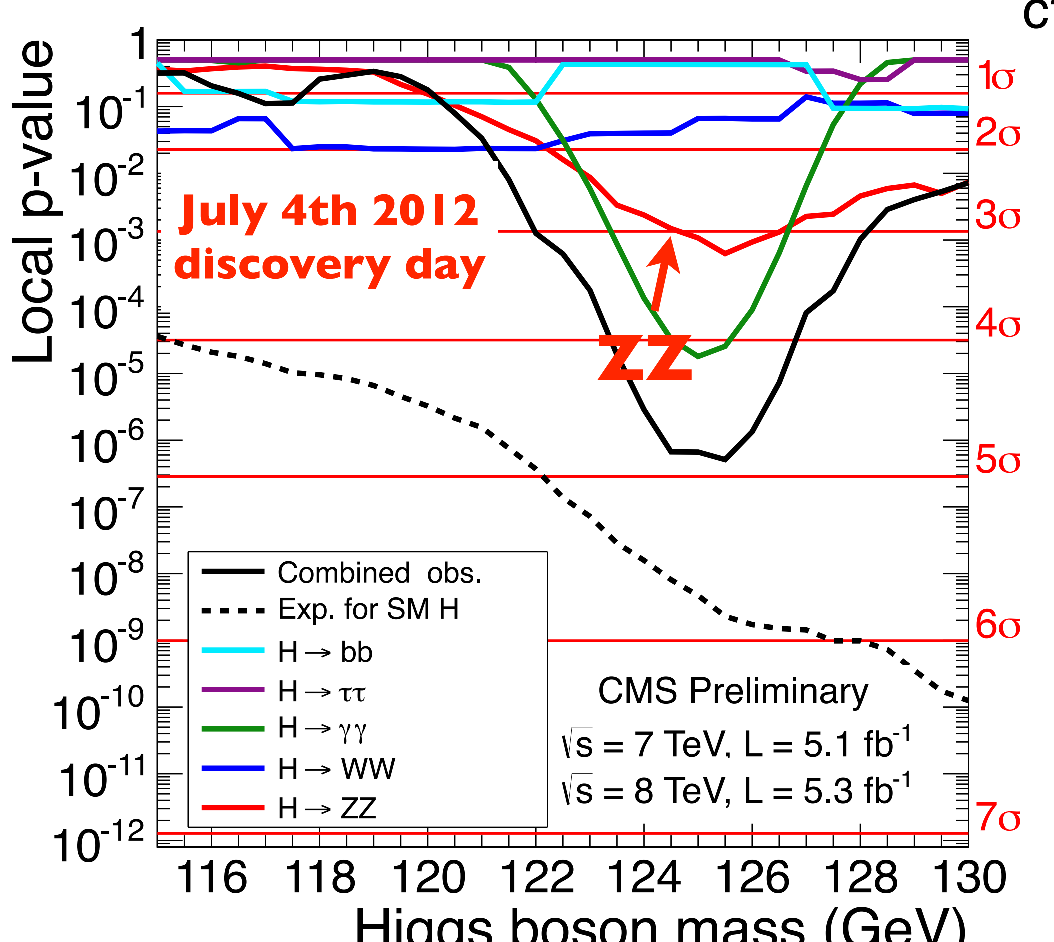








What do we know of this new particle?

(As of May 2013)

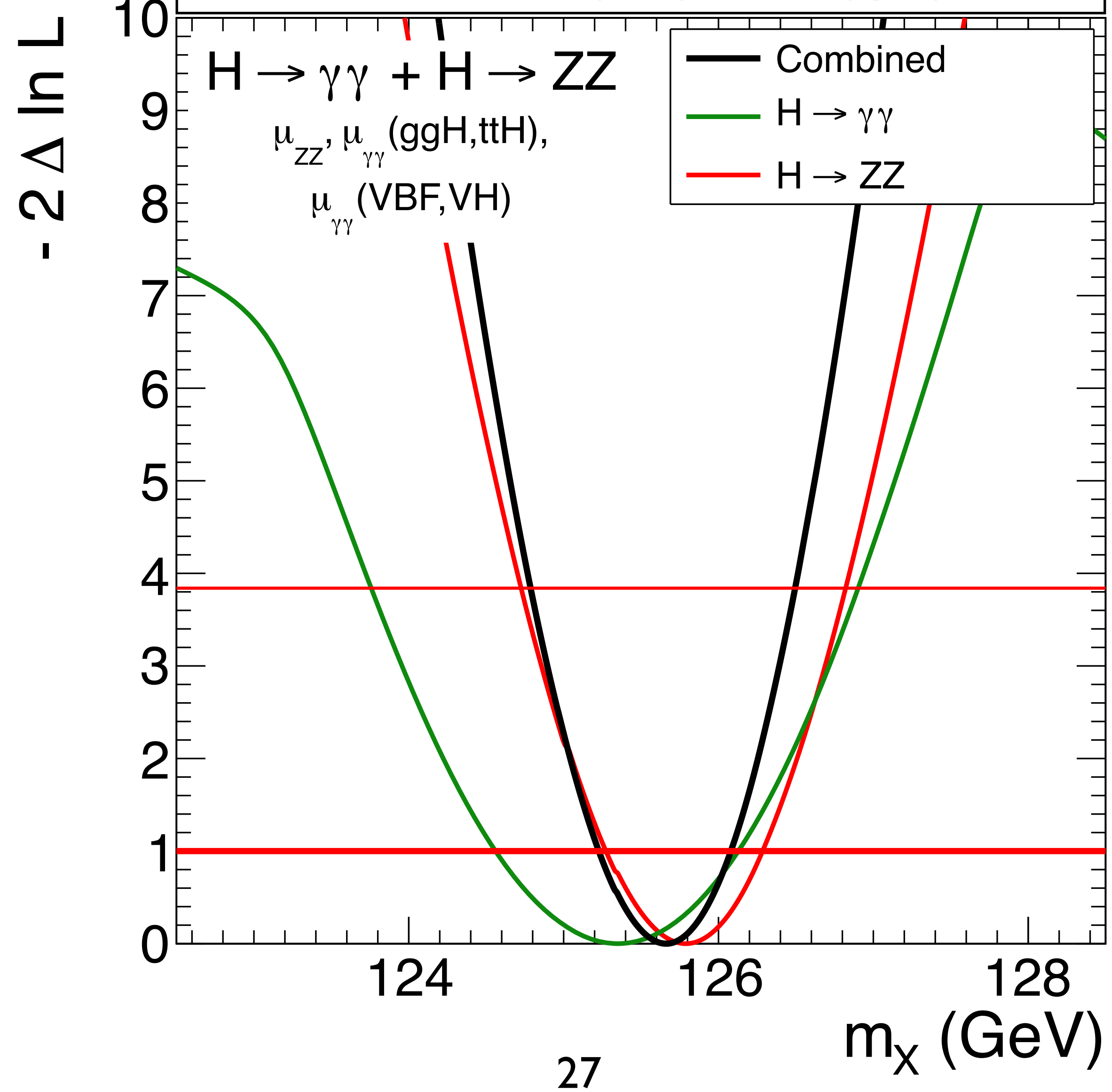
Test the compatibility of data with the SM Prediction, starting from SM tensor structure assumption

What have we learned about the new particle?

Mass	125.7 ± 0.3 (stat) ± 0.3 (syst) GeV

ZZ 125.8 ± 0.5 (stat) ± 0.2 (syst) GeV

γγ 125.4 ± 0.5 (stat) ± 0.6 (syst) GeV



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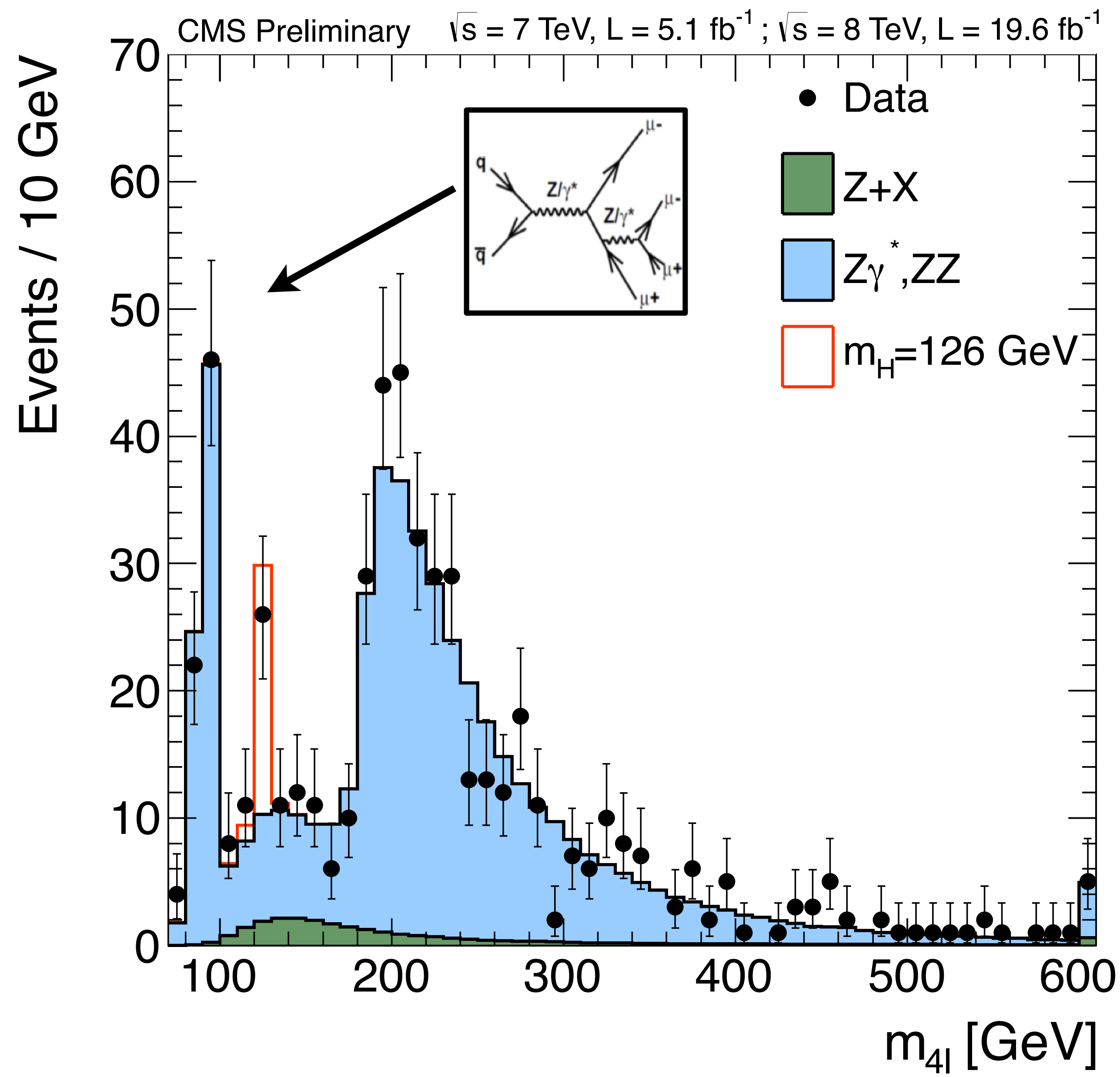
Significance	> 10 σ

Decay	Expected Significance	Observed Significance
ZZ	**7.1 σ**	**6.7 σ**
WW	**5.3 σ**	**3.9 σ**
γγ	3.9 σ	3.2 σ
ττ	2.6 σ	2.8 σ
bb	2.2 σ	2.0 σ

→ **3.4 σ**



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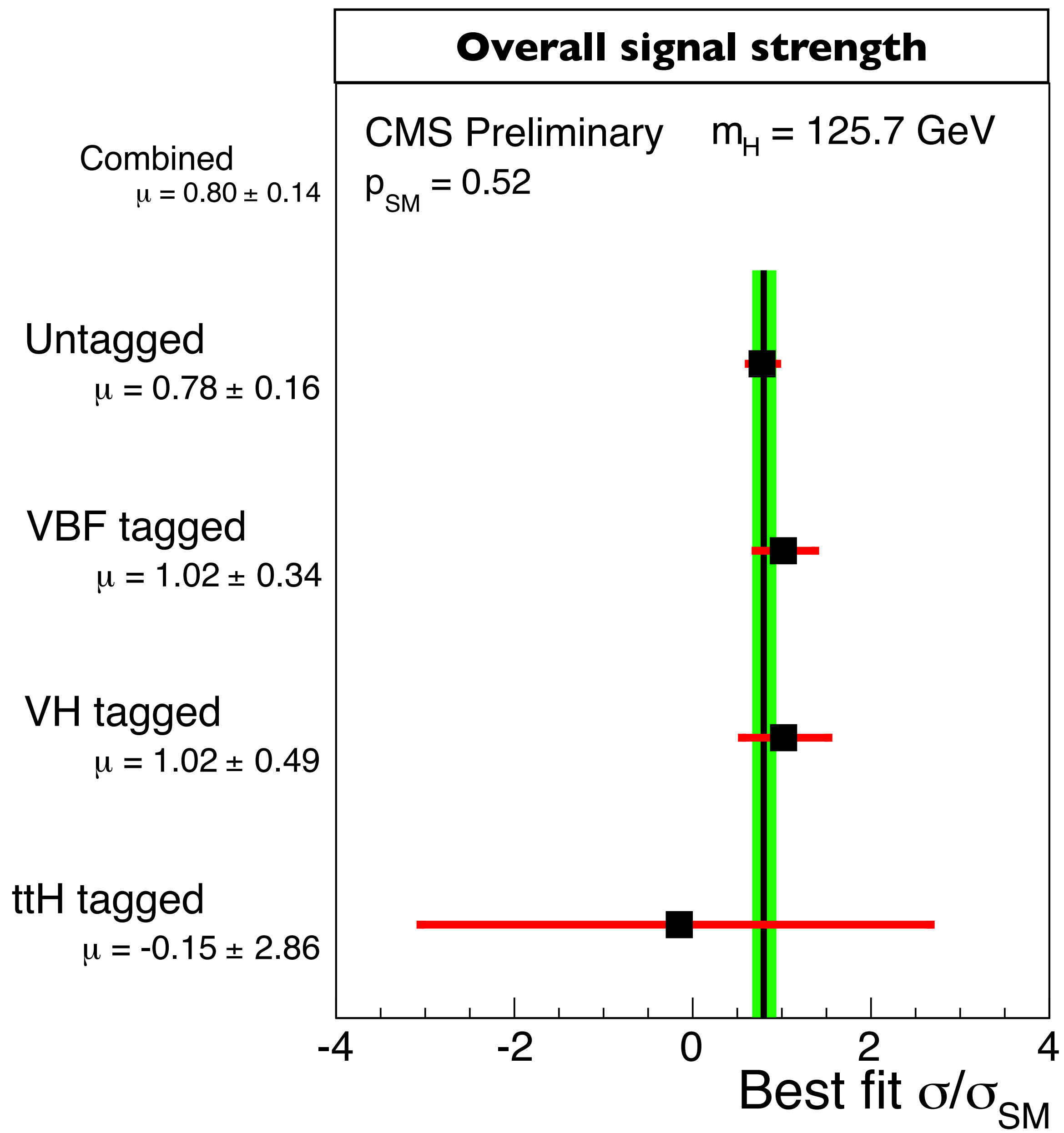
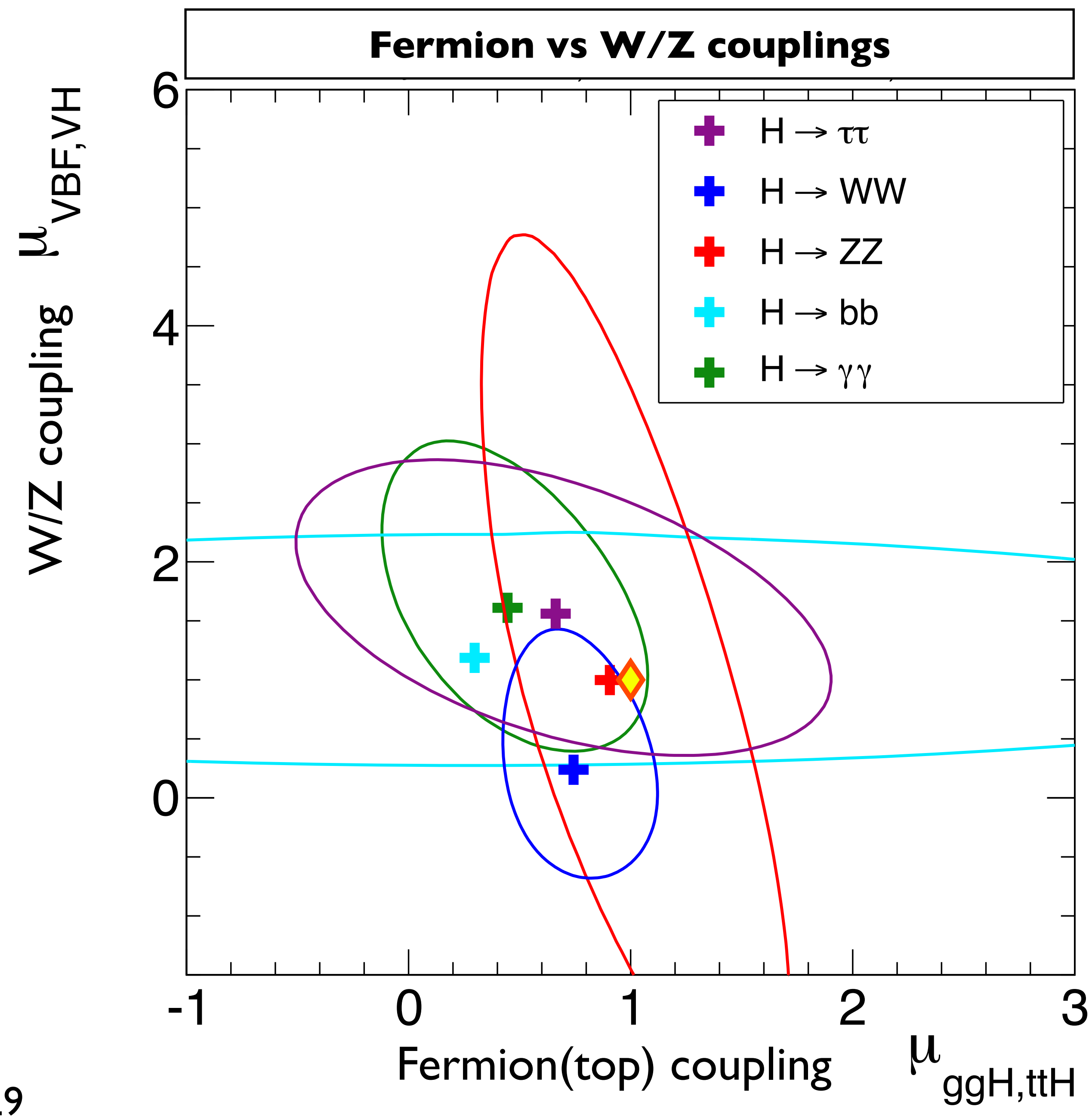
Productions	Mainly from gg Fusion





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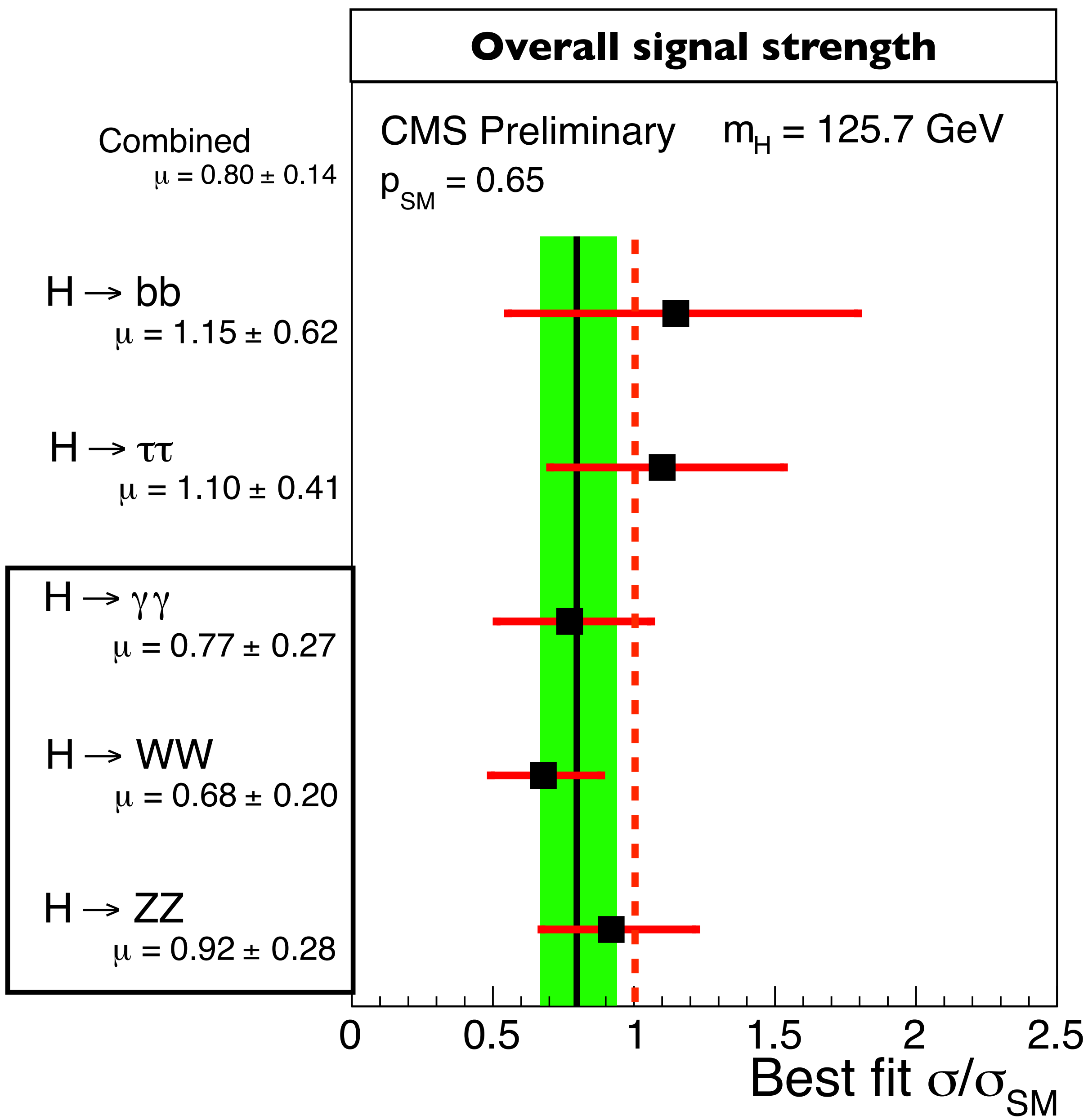

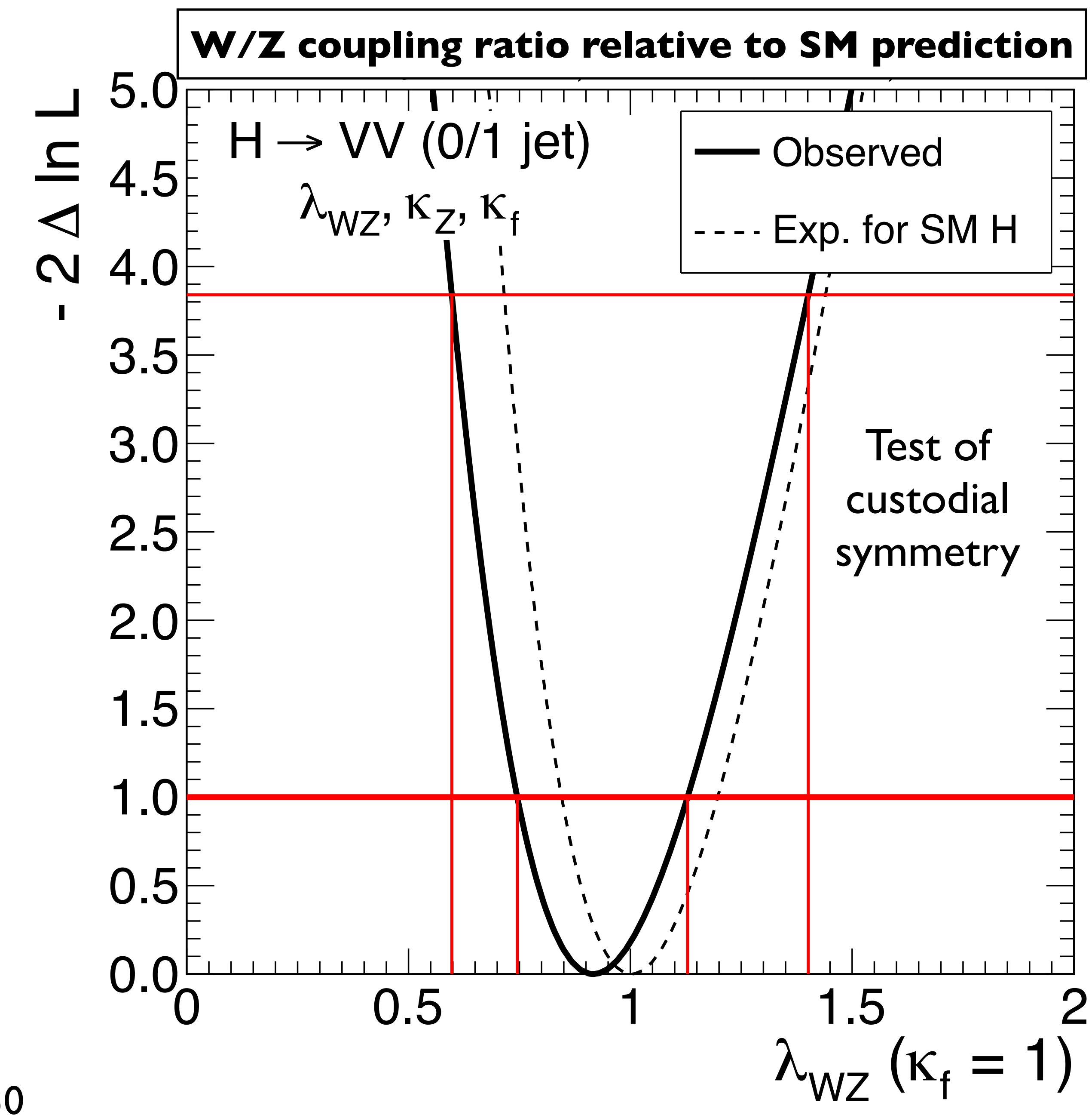

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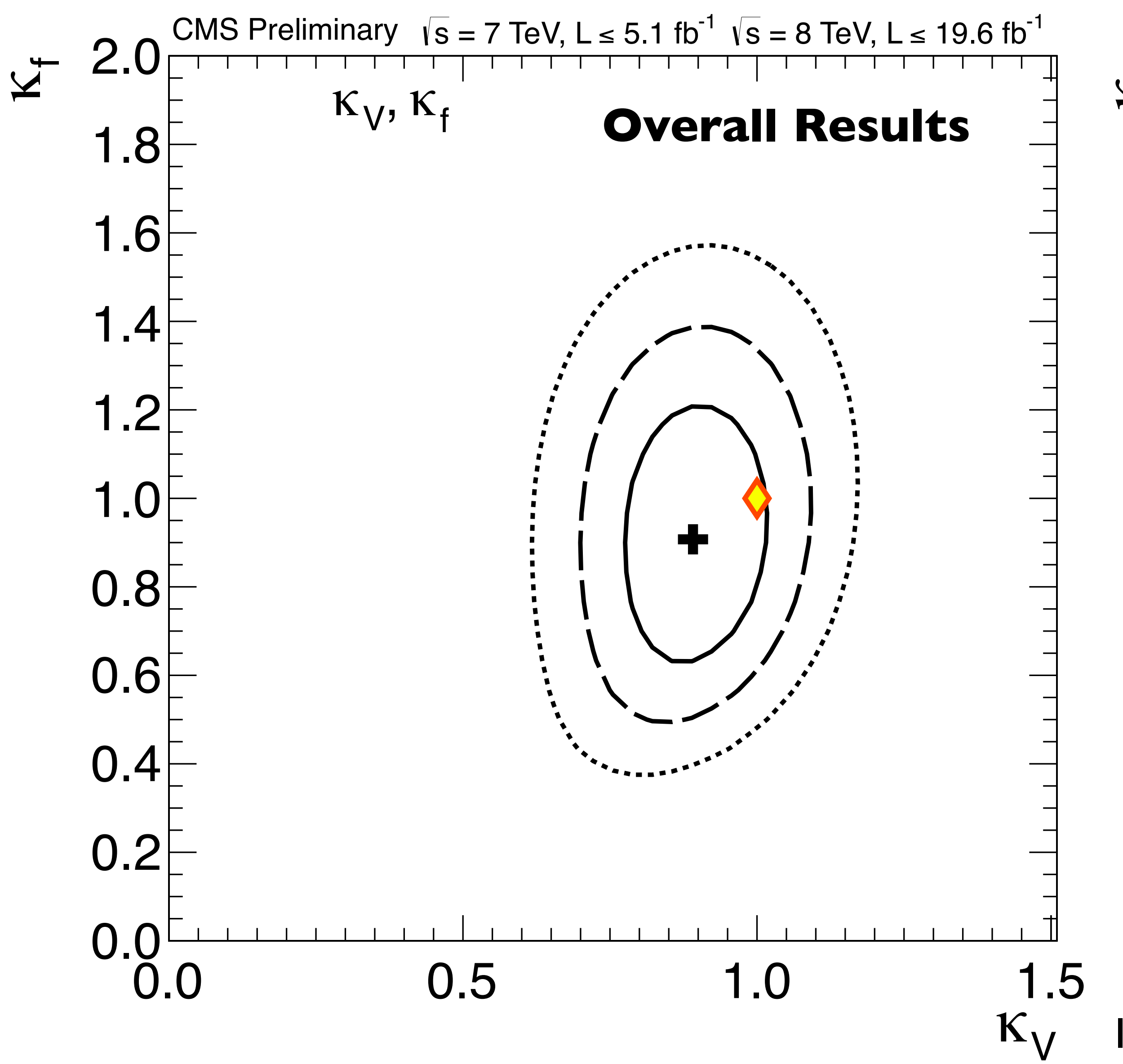
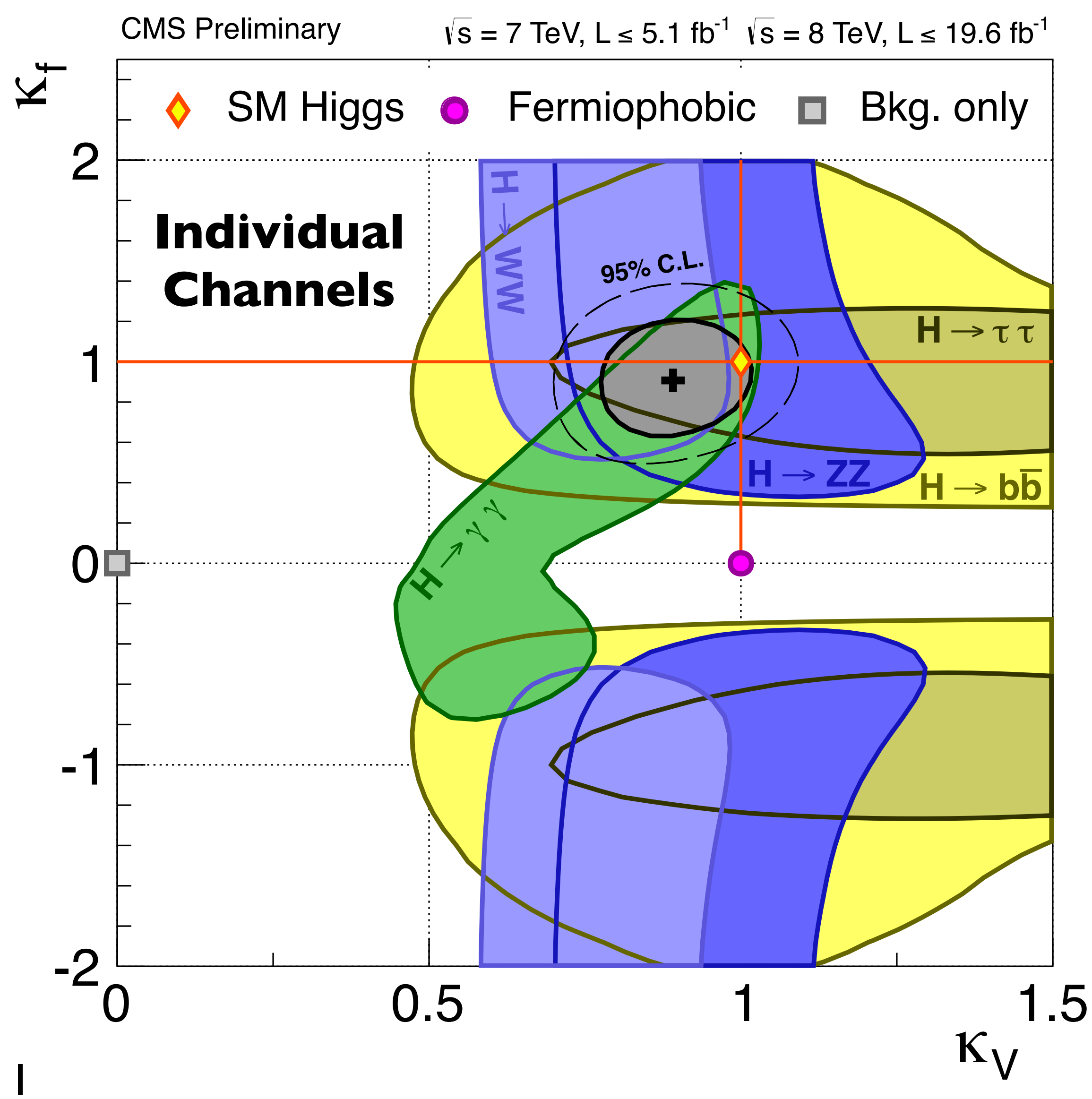
Couplings	No significant deviations from SM Prediction

Test the deviations of couplings relative to the SM prediction $\kappa_i = \frac{g_i}{g_{i,\mathrm{SM}}}$





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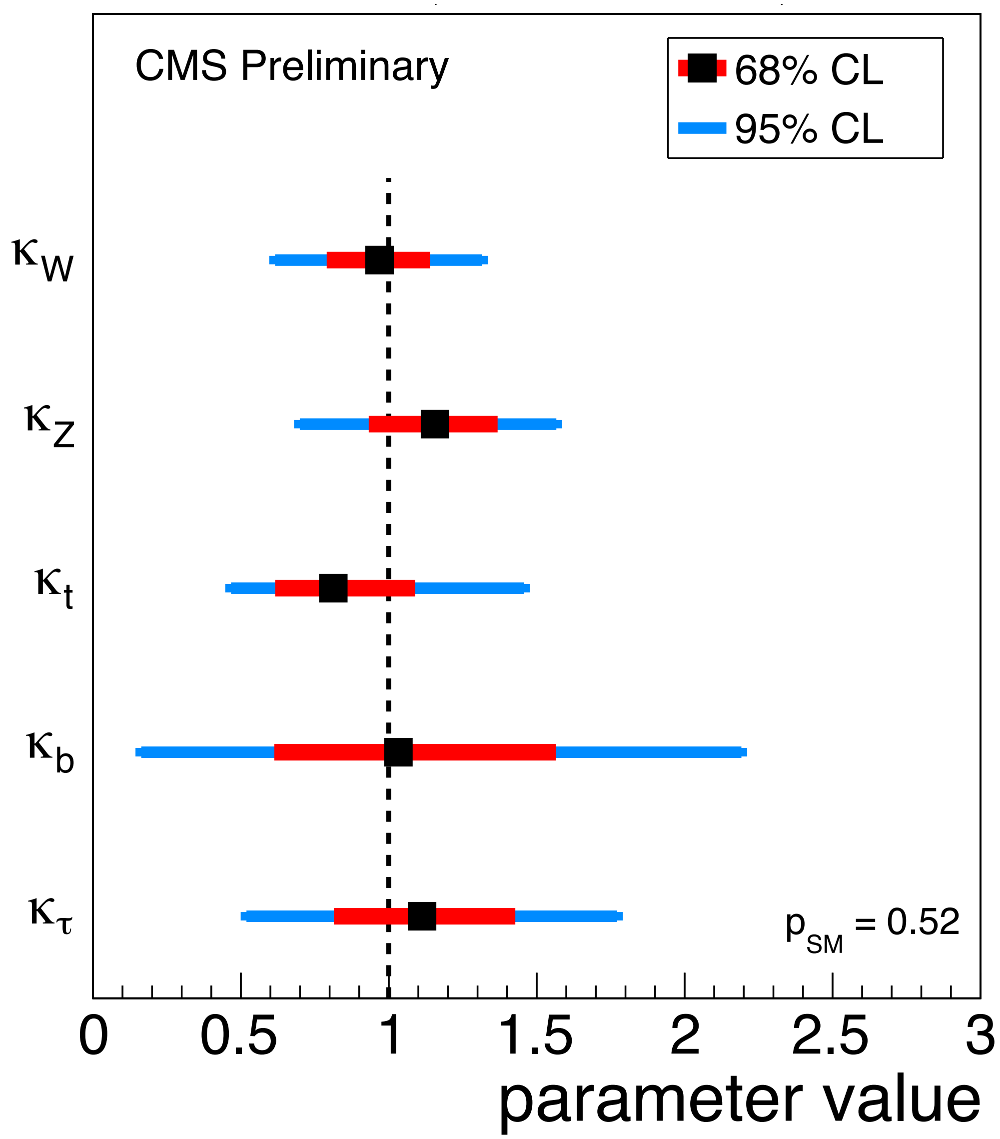
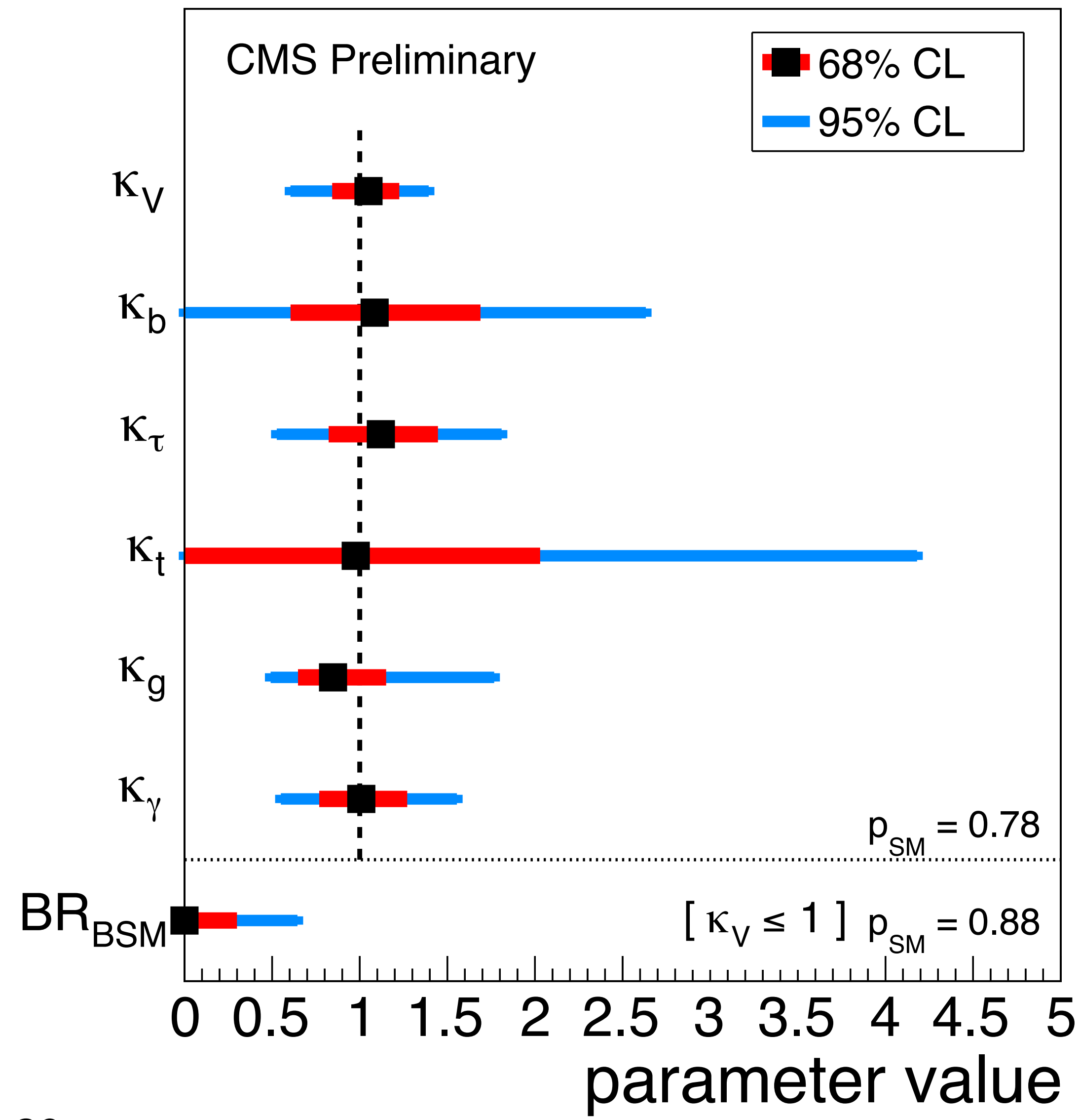
SM couplings in the loop, no BSM



No assumption of SM couplings in the loop, with an overall BSM width



Going beyond the SM Tensor Structure

What is the *underlying physics* that describes the interaction between the new particle and known SM particles?

X→VV Scattering Amplitudes

- A general description of the scattering amplitudes based on effective couplings

SM 0+

$$A_{J=0}(X \to V_1 V_2) = v^{-1} \left(g_1^{(0)} m_V^2 \epsilon_1^* \epsilon_2^* \right)$$

scenario	X production	$X \to VV$ decay	comments
0_m^+	$gg \to X$	$g_1^{(0)} \neq 0$	SM Higgs boson scalar

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SM 0+   0-

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0_m^+	$gg \to X$	$g_1^{(0)} \neq 0$	SM Higgs boson scalar
0^-	$gg \to X$	$g_4^{(0)} \neq 0$	pseudo-scalar

X→VV Scattering Amplitudes

- A general description of the scattering amplitudes based on effective couplings

SM 0+ | 0+ High order | 0-

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scenario	X production	$X \to VV$ decay	comments
0_m^+	$gg \to X$	$g_1^{(0)} \neq 0$	SM Higgs boson scalar
0^-	$gg \to X$	$g_4^{(0)} \neq 0$	pseudo-scalar
0_h^+	$gg \to X$	$g_2^{(0)} \neq 0$	scalar with higher-dimension operators

X→VV Scattering Amplitudes

- A general description of the scattering amplitudes based on effective couplings

SM 0+ | 0+ High order | 0-

$$A_{J=0}(X \to V_1 V_2) = v^{-1}\left(g_1^{(0)} m_V^2 \epsilon_1^* \epsilon_2^* + g_2^{(0)} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3^{(0)} f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4^{(0)} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu} \right)$$

Experimental measurements of those tensor structures are crucial to confirm the SM Higgs mechanism or other new physics

scenario	X production	$X \to VV$ decay	comments
0_m^+	$gg \to X$	$g_1^{(0)} \neq 0$	SM Higgs boson scalar
0^-	$gg \to X$	$g_4^{(0)} \neq 0$	pseudo-scalar
0_h^+	$gg \to X$	$g_2^{(0)} \neq 0$	scalar with higher-dimension operators

X→VV Scattering Amplitudes

- A general description of the scattering amplitudes based on effective couplings

SM 0+ | 0+ High order | 0-

$$A_{J=0}(X \to V_1V_2) = v^{-1}\left(g_1^{(0)} m_V^2 \epsilon_1^* \epsilon_2^* + g_2^{(0)} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3^{(0)} f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4^{(0)} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

$$A_{J=1}(X \to V_1V_2) = b_1 \left[(\epsilon_1^* q)(\epsilon_2^* \epsilon_X) + (\epsilon_2^* q)(\epsilon_1^* \epsilon_X)\right] + b_2\ \epsilon_{\alpha\mu\nu\beta} \epsilon_X^\alpha \epsilon_1^{*,\mu} \epsilon_2^{*,\nu} \tilde{q}^\beta$$

$$\begin{aligned} A_{J=2}(X \to V_1V_2) = \Lambda^{-1} \Big[& 2g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} \\ & + g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*(1)\mu\nu} f_{\mu\alpha}^{*(2)} + f^{*(2)\mu\nu} f_{\mu\alpha}^{*(1)}\right) + g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f_{\alpha\beta}^{*(2)} \\ & + m_V^2 \left(2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu}\right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^*\right) \\ & + g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}_{\alpha\beta}^{*(2)} + g_9^{(2)} m_V^2 \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma \\ & + g_{10}^{(2)} m_V^2 \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu}(q\epsilon_2^*) + \epsilon_2^{*\nu}(q\epsilon_1^*)\right) \Big] \end{aligned}$$

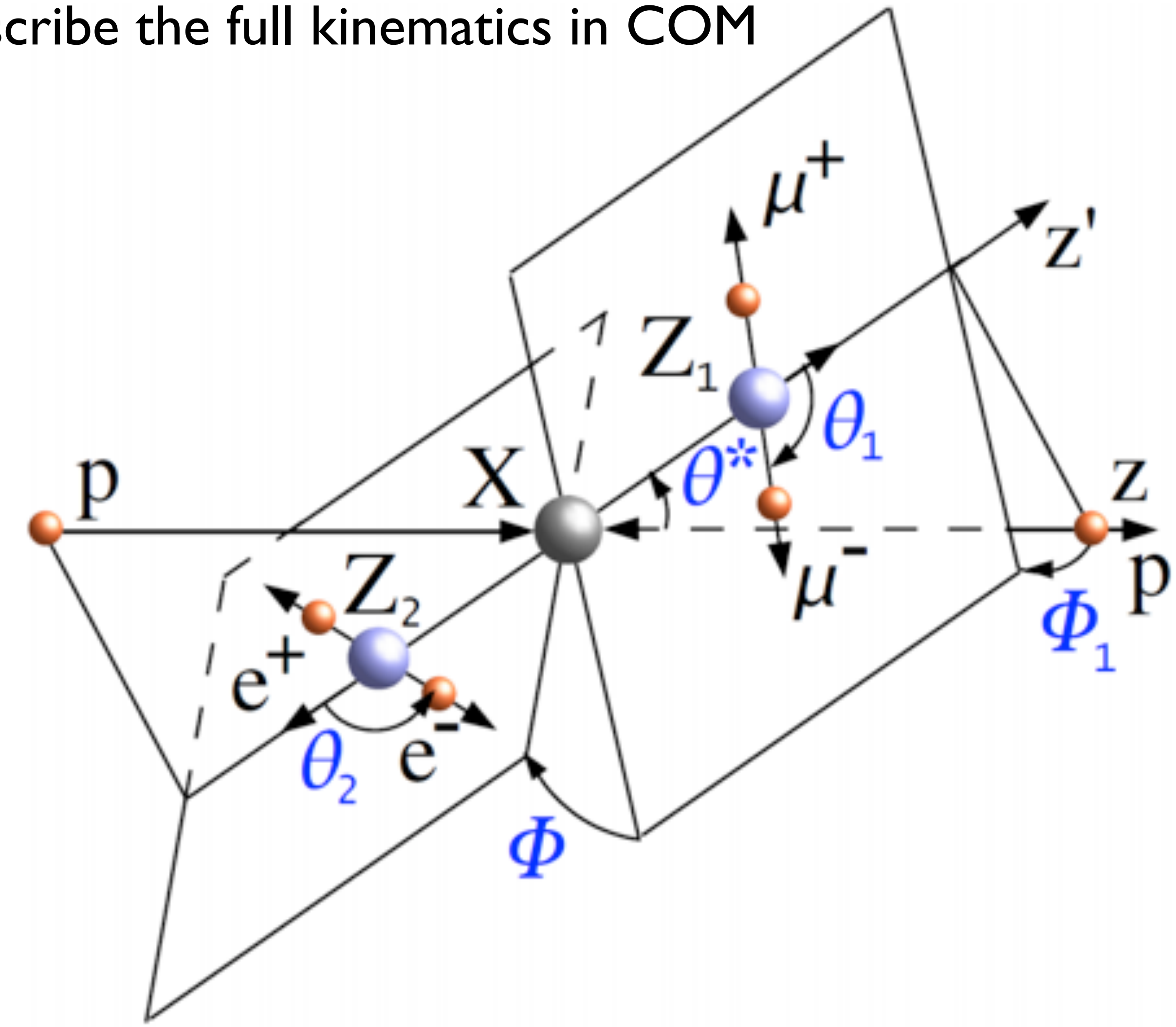
scenario	X production	$X \to VV$ decay	comments
0_m^+	$gg \to X$	$g_1^{(0)} \neq 0$	SM Higgs boson scalar
0^-	$gg \to X$	$g_4^{(0)} \neq 0$	pseudo-scalar
0_h^+	$gg \to X$	$g_2^{(0)} \neq 0$	scalar with higher-dimension operators
1^+	$q\bar{q} \to X$	$b_2 \neq 0$	exotic pseudo-vector
1^-	$q\bar{q} \to X$	$b_1 \neq 0$	exotic vector
2_m^+	$g_1^{(2)} \neq 0$ in	$g_1^{(2)} = g_5^{(2)} \neq 0$	graviton-like tensor with minimal couplings
2_h^+	$g_4^{(2)} \neq 0$	$g_4^{(2)} \neq 0$	tensor with higher-dimension operators
2_h^-	$g_8^{(2)} \neq 0$	$g_8^{(2)} \neq 0$	“pseudo-tensor”

Experimental Methods to Probe the Tensor Structure

including the spin and parity of the new particle

Full Kinematics Description in X→ZZ→4l

- Full kinematics: total 12 degrees of freedom
  - For a given m(4l), 7 mass-angular variables describe the full kinematics in COM
    - invariant masses: m_{Z1}, m_{Z2}
    - production angles: θ^*, Φ_1
    - decay angles: θ_1, θ_2, ϕ



- The kinematic distributions of the variables depend on the X→VV scattering amplitudes
  - Predictions can be made both from *generators* and *analytical calculations*

Yanyan Gao, Andrei Gritsan et al, *Phys. Rev. D 81, 075002 (2010)*,
Sarah Bolognese, Yanyan Gao, Andrei Gritsan et al, *Phys. Rev. D 86, 095031(2012)*

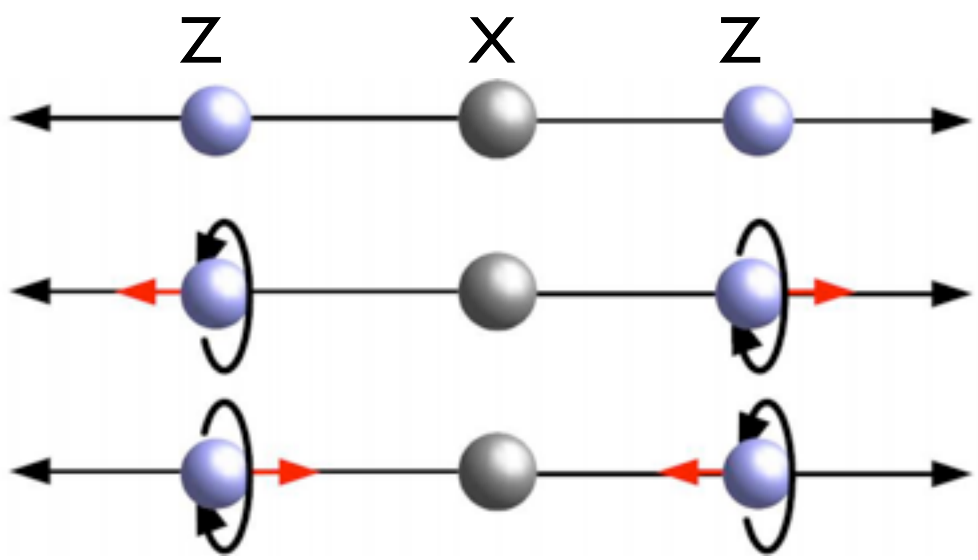
X→VV Helicity Amplitudes

- The scattering amplitude can also be written as the sum of all helicity amplitudes
  - E.G. a Higgs like spin 0 resonance has 3 helicity amplitudes which are uniquely predicted by theory

$$A_{00}(\vec{g}, m_{Z1}, m_{Z2})$$

$$A_{++}(\vec{g}, m_{Z1}, m_{Z2})$$

$$A_{--}(\vec{g}, m_{Z1}, m_{Z2})$$



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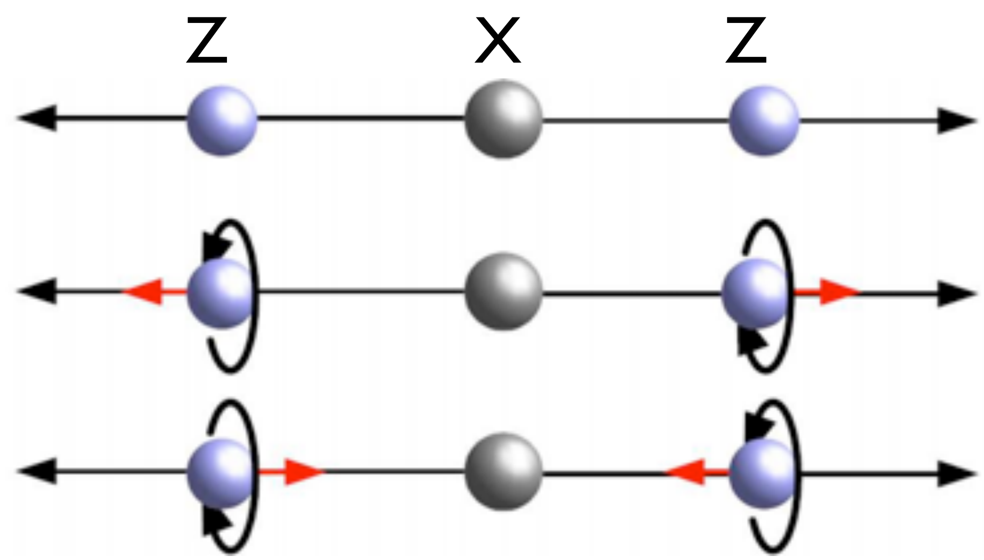


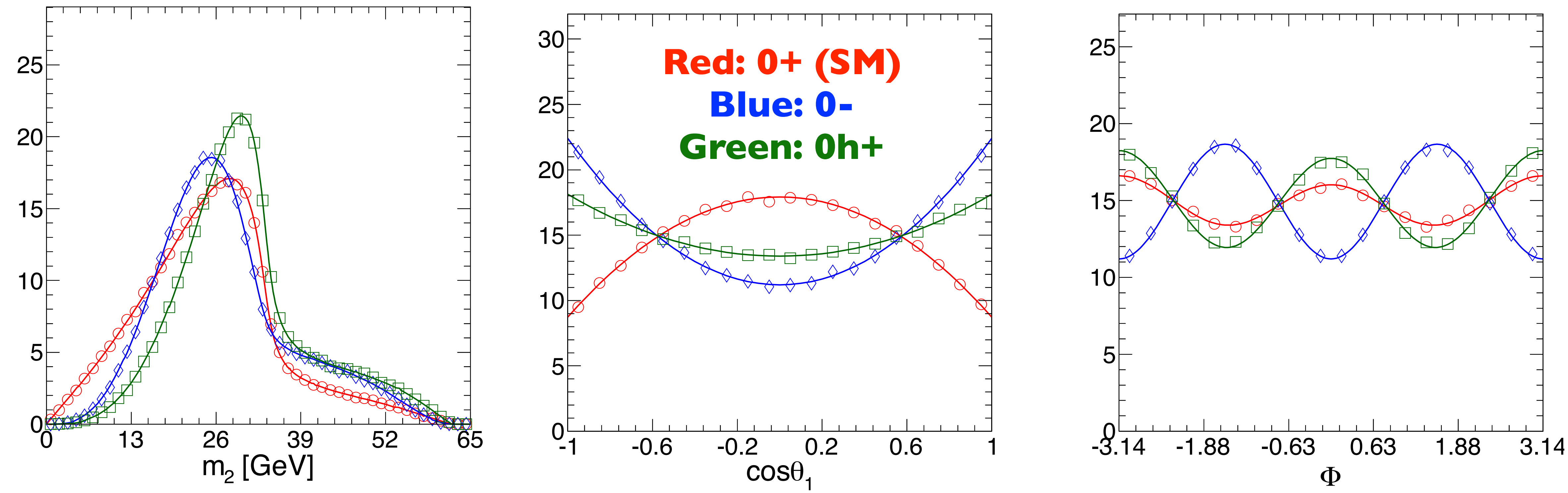
- The helicity amplitudes can be directly probed in experimental angular distributions

$$d\sigma \sim |\sum_{a,b} A_{ab} P_{ab}(\Omega)|^2 dm_{Z1} dm_{Z2} d\Omega$$

  - The full 7D differential cross-sections $\mathcal{P}(m_{Z1}, m_{Z2}, \vec{\Omega} | m_{4\ell})$ can be analytically calculated and used to study the underlying X→VV interactions

Kinematics of Signal Models with Different Spin/Parity

X→ZZ→4l Perfect match between generator (data points) and analytical calculations (lines)



Kinematics of Signal Models with Different Spin/Parity

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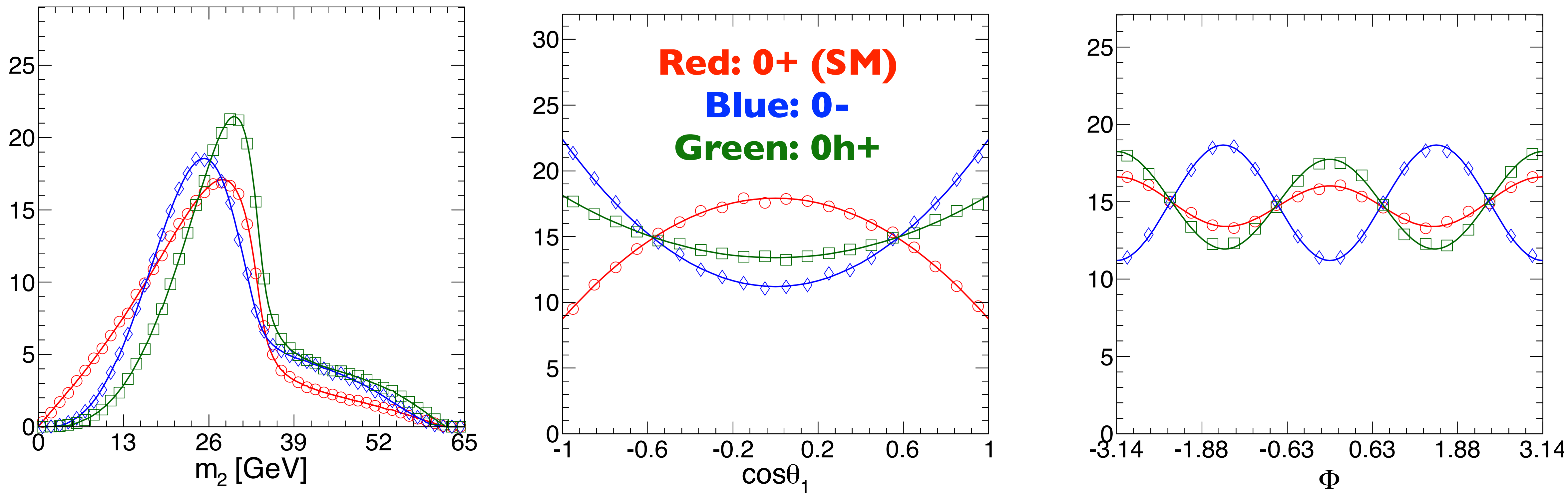
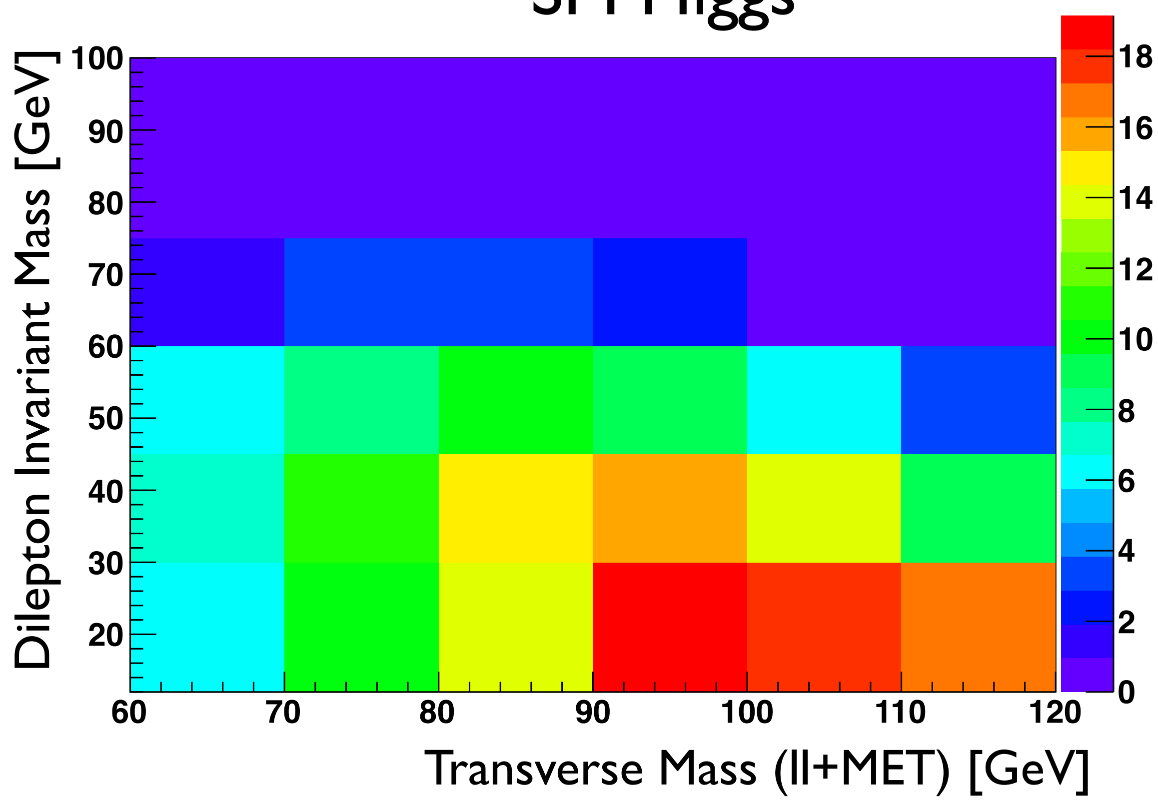
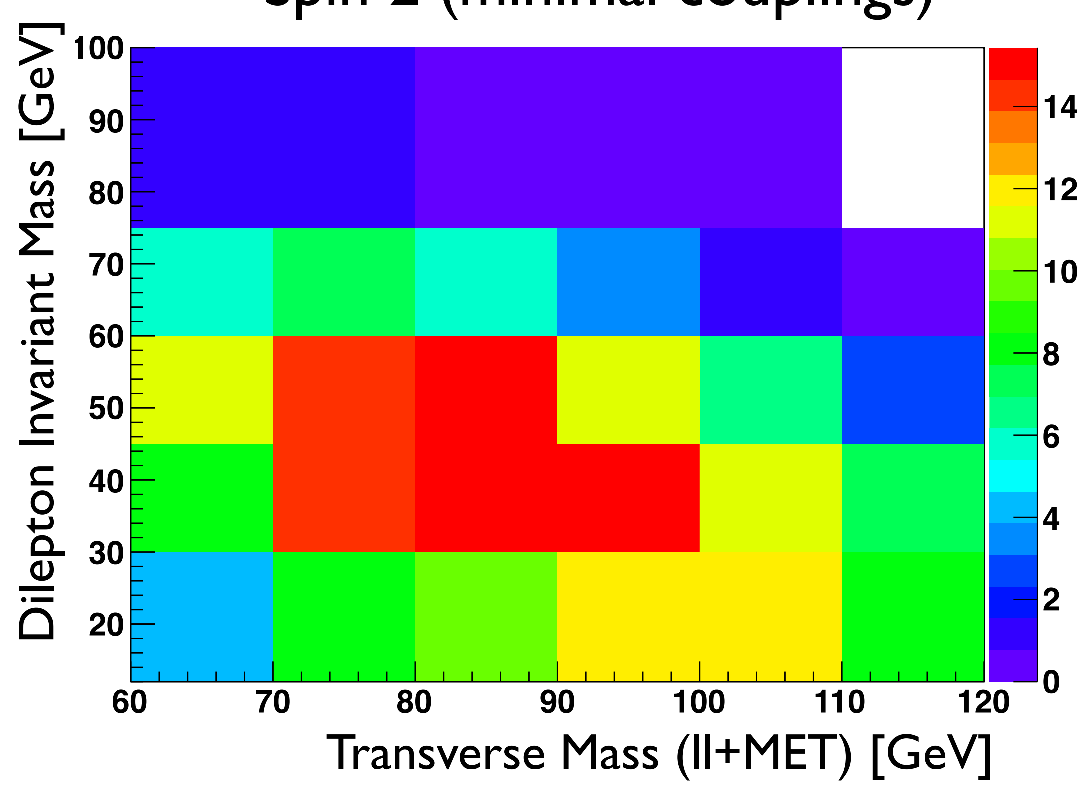


X→WW→2l2ν

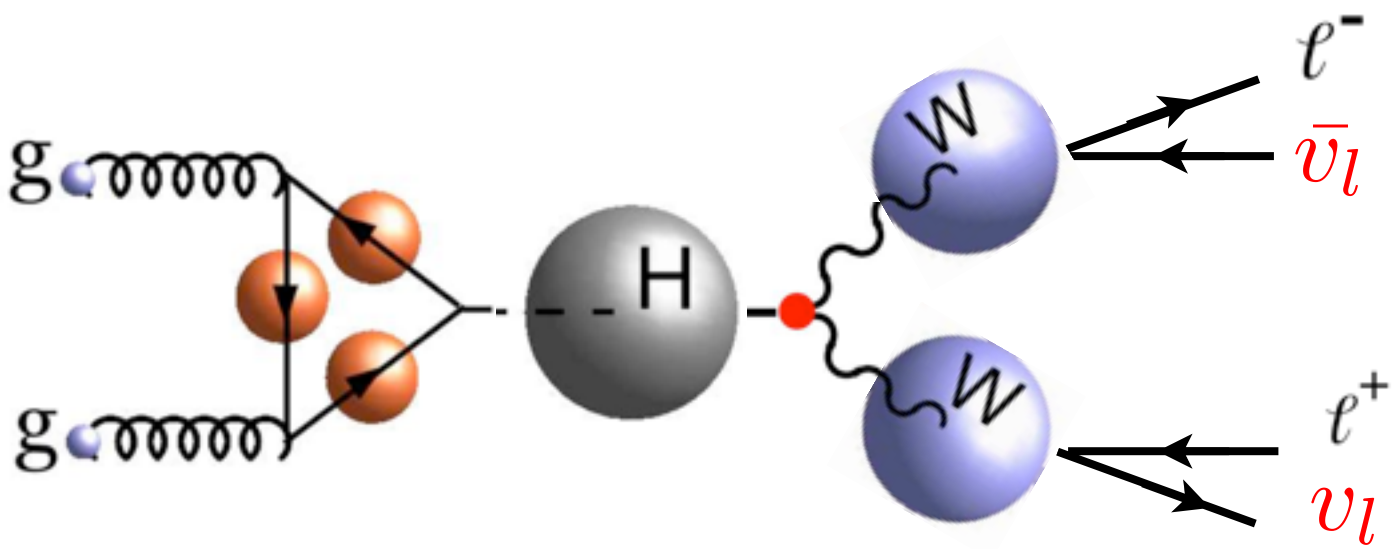
SM Higgs



Spin 2 (minimal couplings)



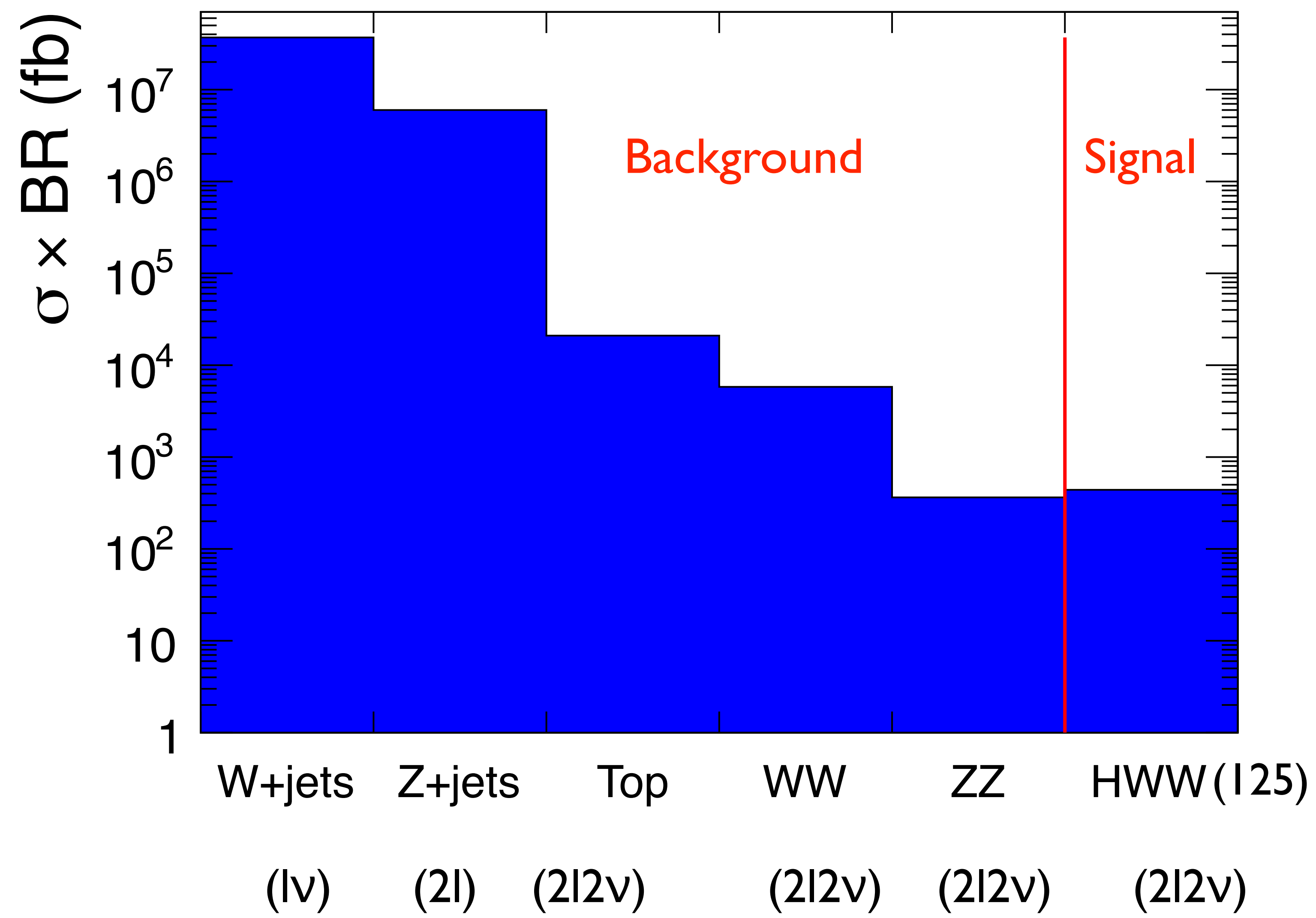
$H \rightarrow WW \rightarrow 2l2\nu$



Dilepton, large MET, low Jet activity, no mass peak

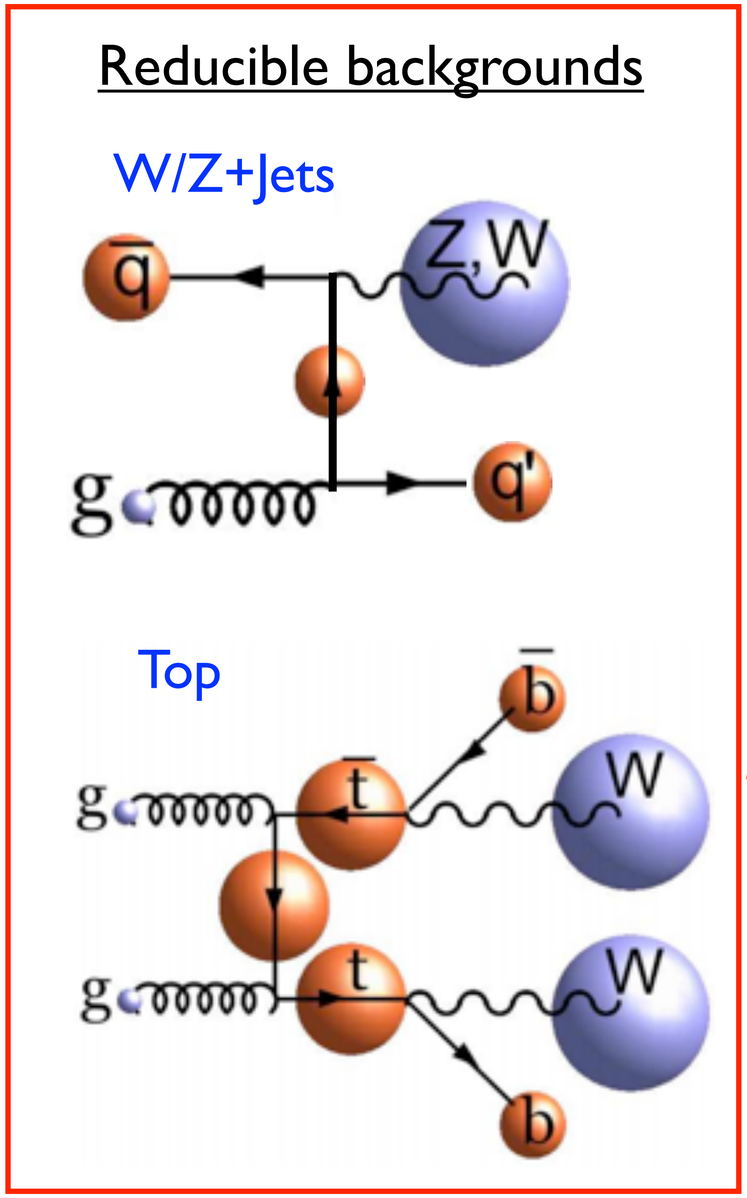
Analysis Challenges

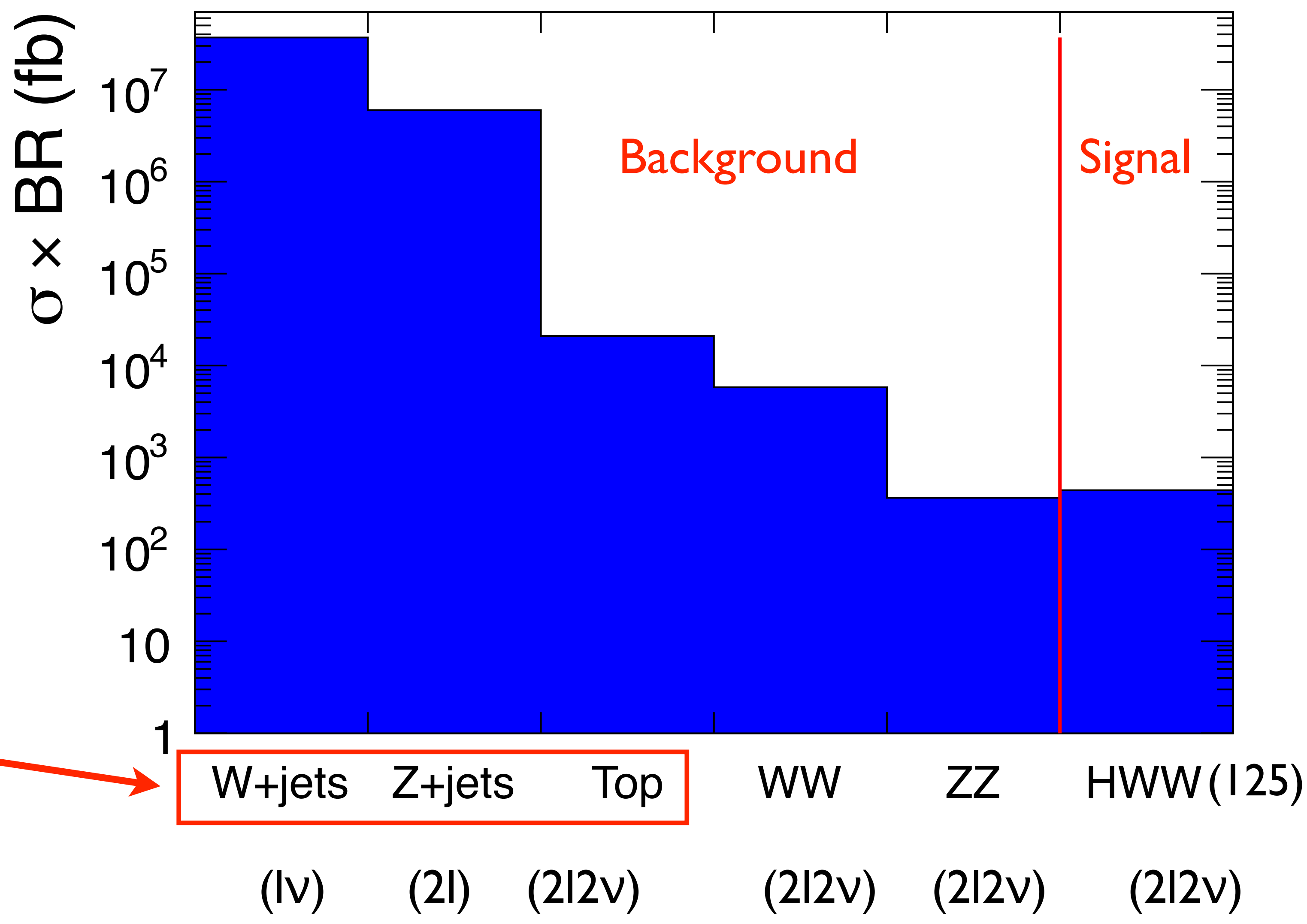
- Large backgrounds and no mass peak



Analysis Challenges

- Large backgrounds and no mass peak



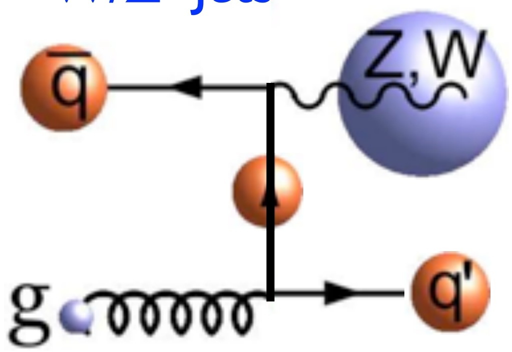


Analysis Challenges

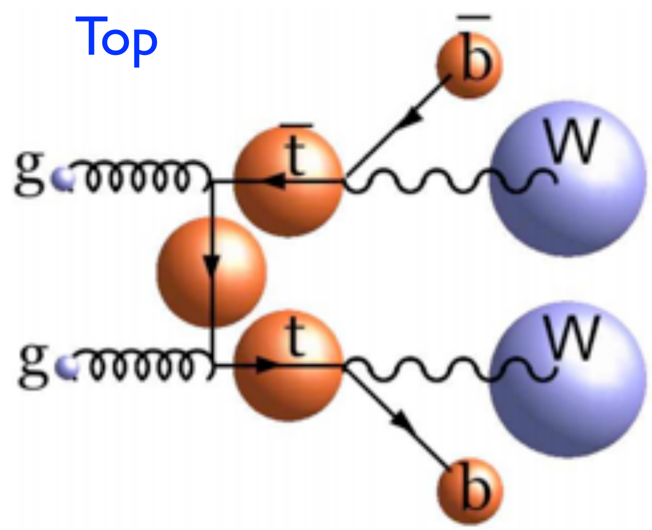
- Large backgrounds and no mass peak

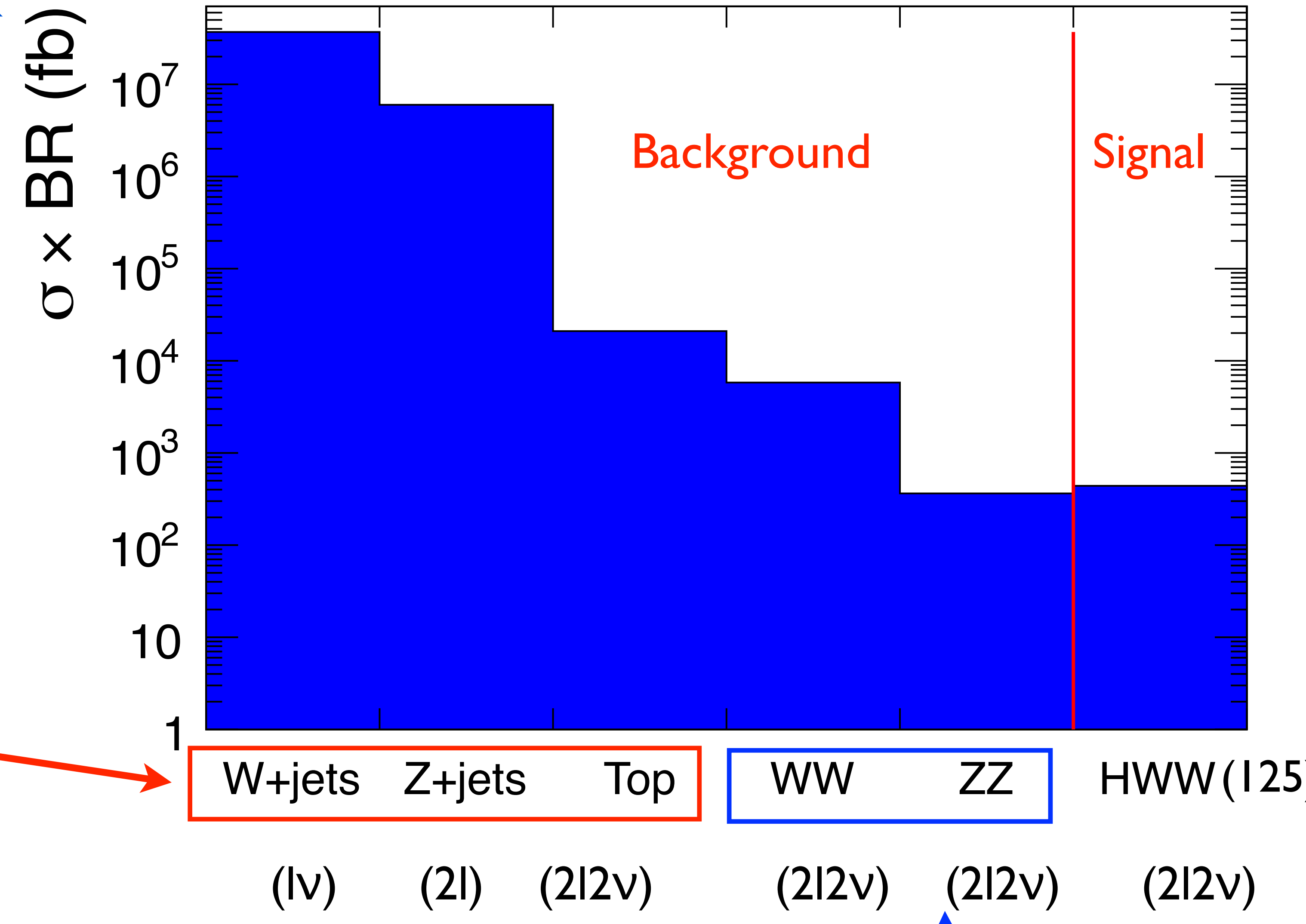
<u>Reducible backgrounds</u>

W/Z+Jets

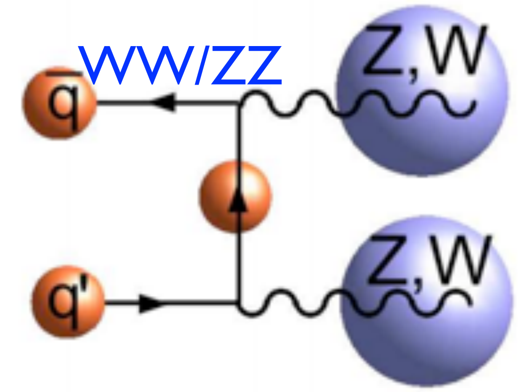


Top





<u>Irreducible backgrounds</u>



Analysis Challenges

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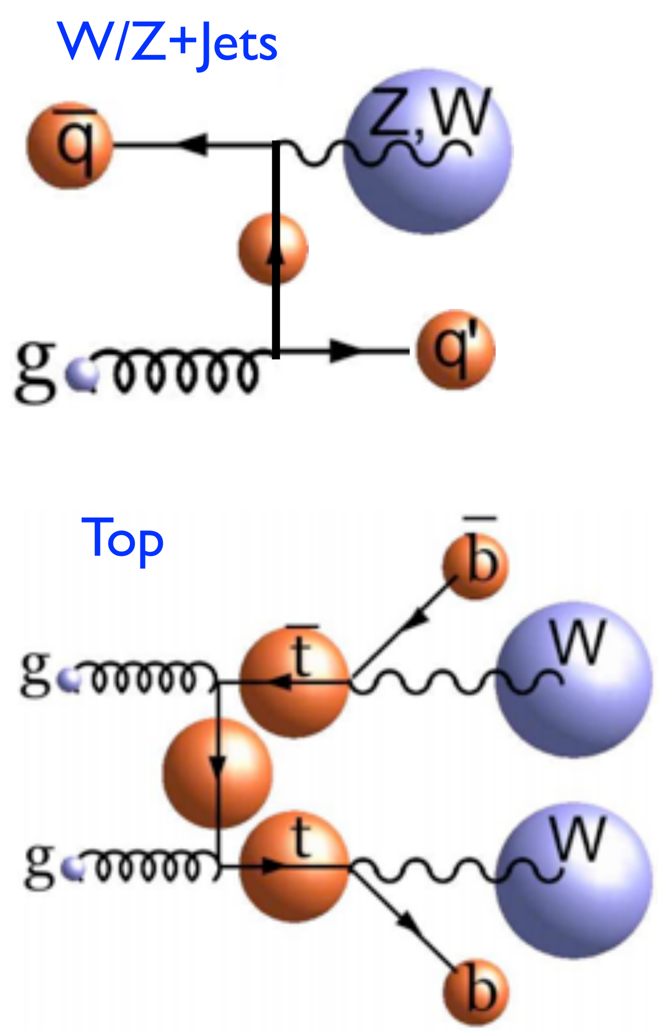
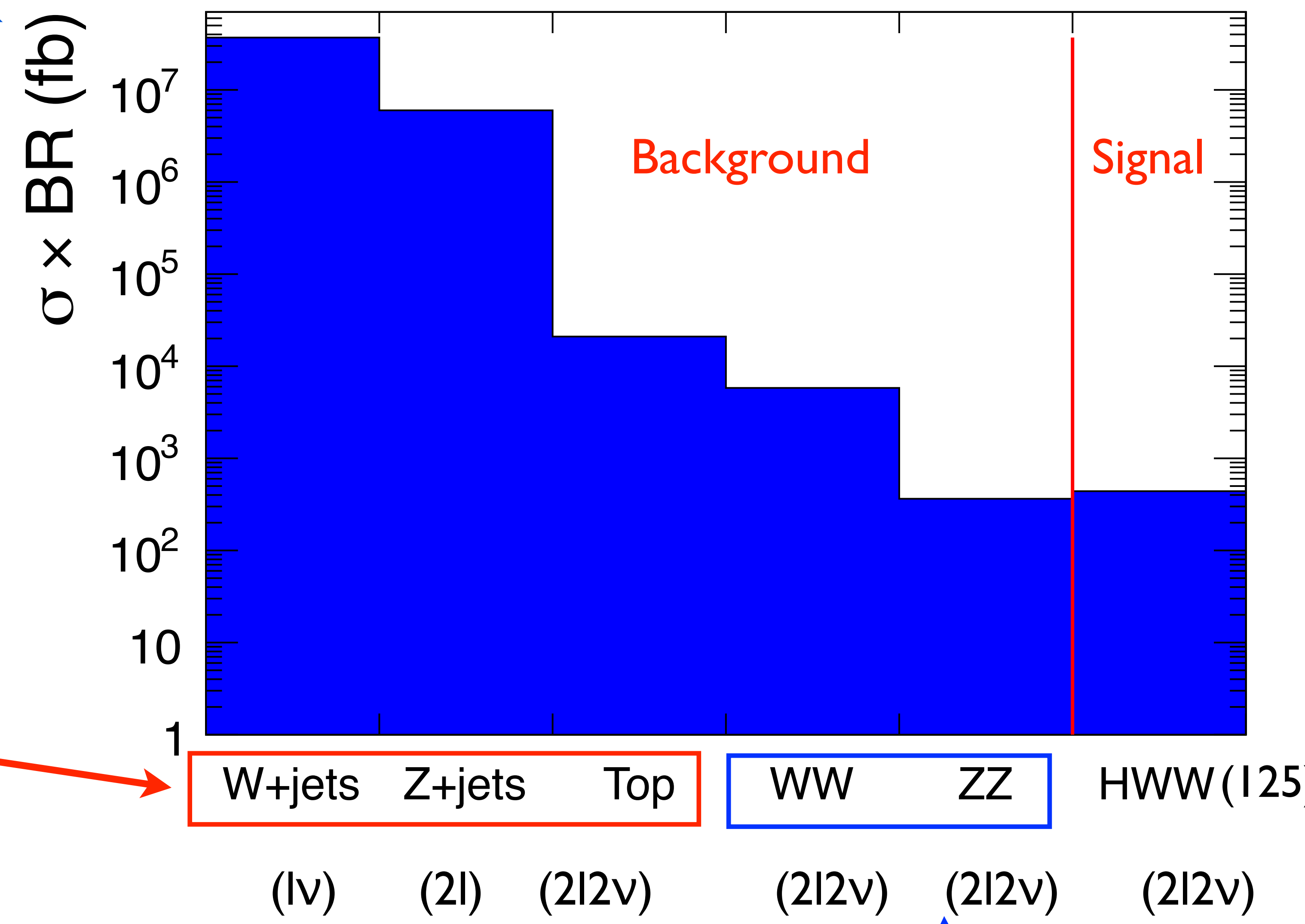
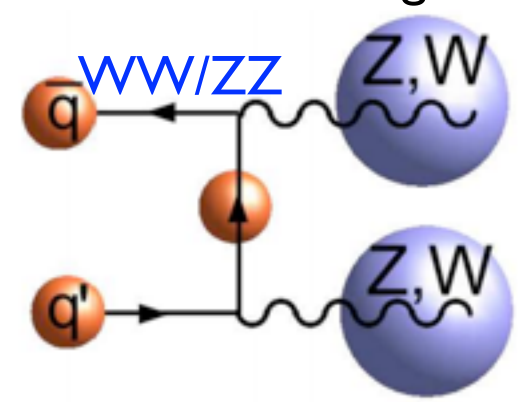




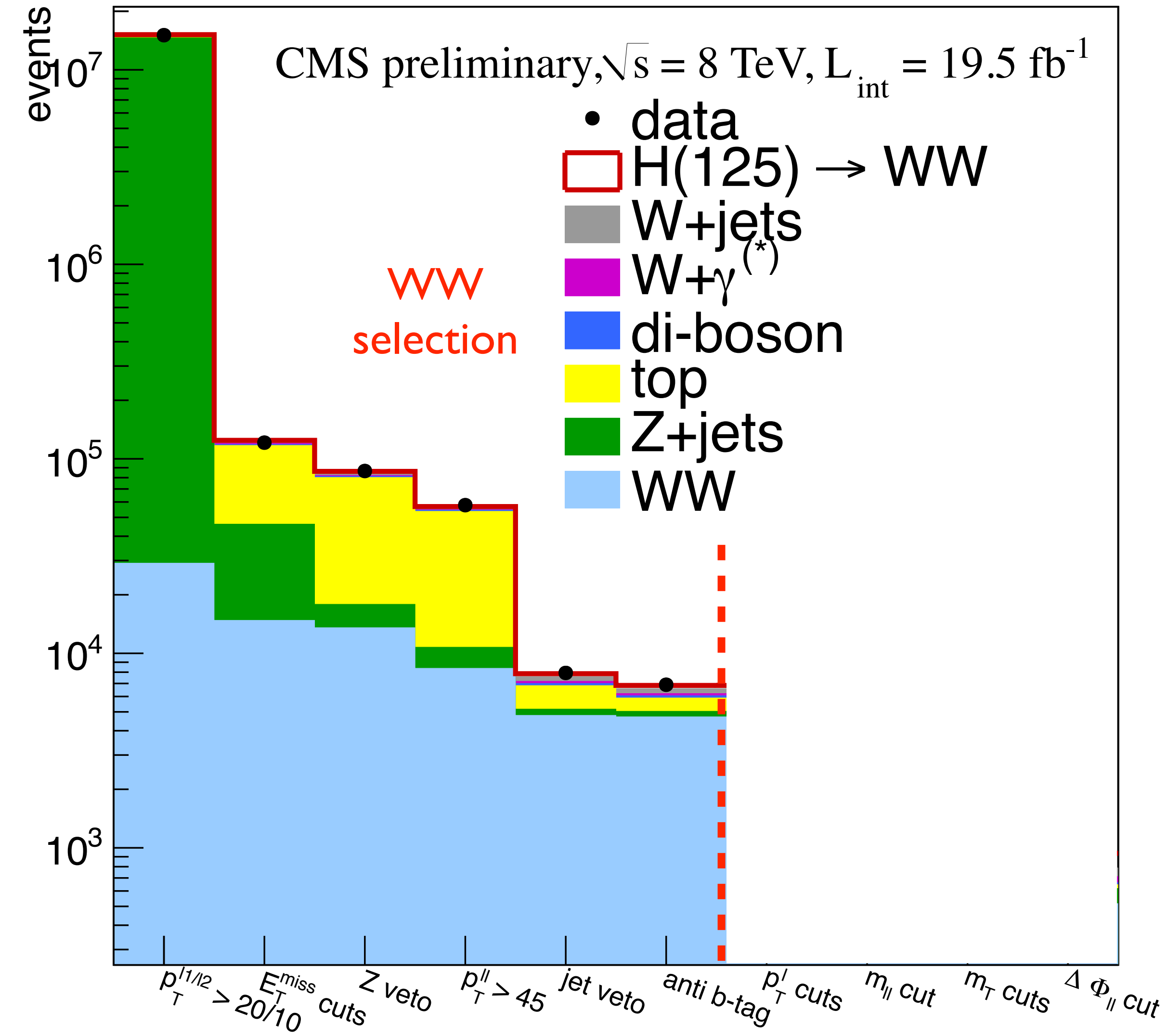
Irreducible backgrounds



- **Key in the analysis**
  - Optimize selections to reduce reducible background
  - Exploit full kinematics to separate HWW and WW

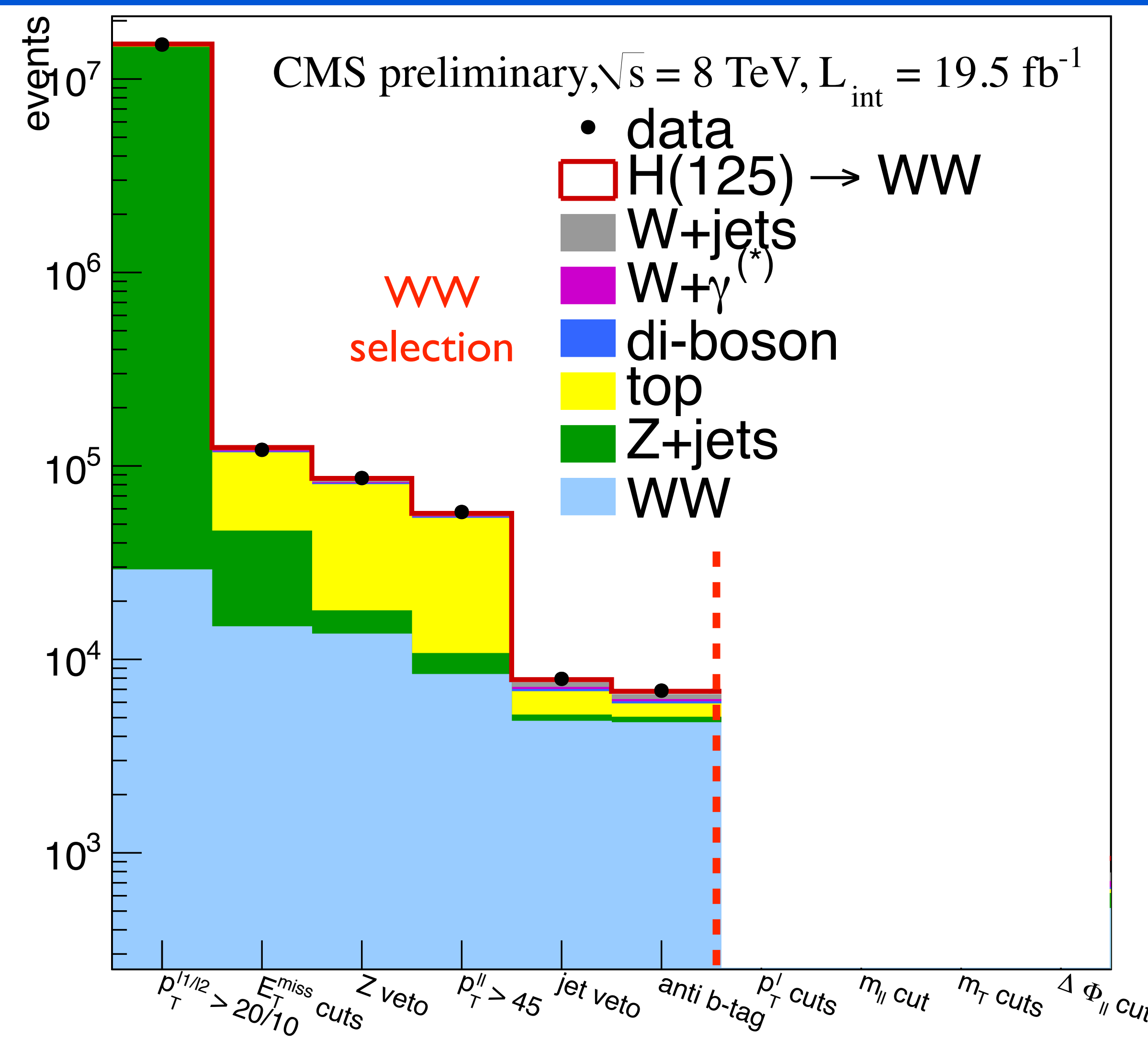
Analysis Overview

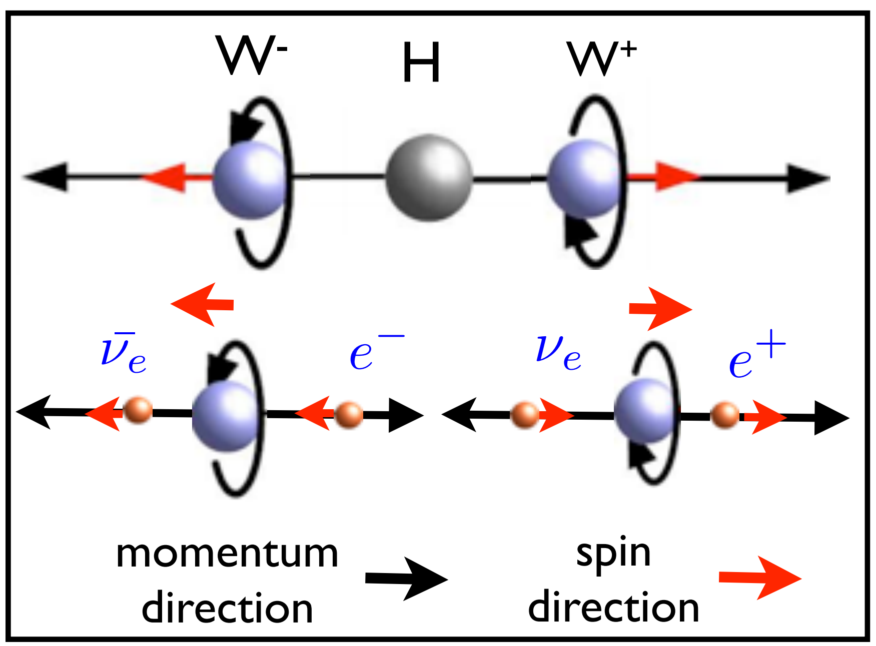
- WW selection
  - Reject reducible backgrounds

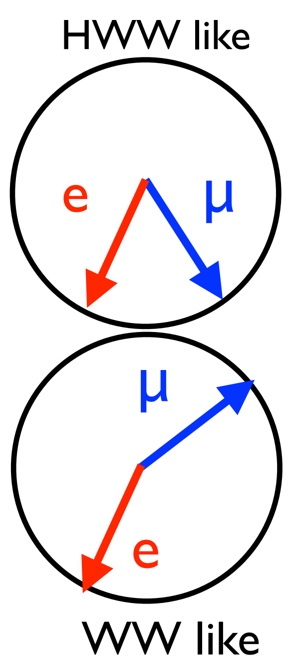


Analysis Overview

- WW selection
  - Reject reducible backgrounds
- Distinguish the WW background using the spin and mass of the Higgs
  - Low dilepton opening angles ($\Delta\Phi_{ll}$)
  - Transverse mass (dilepton and MET)

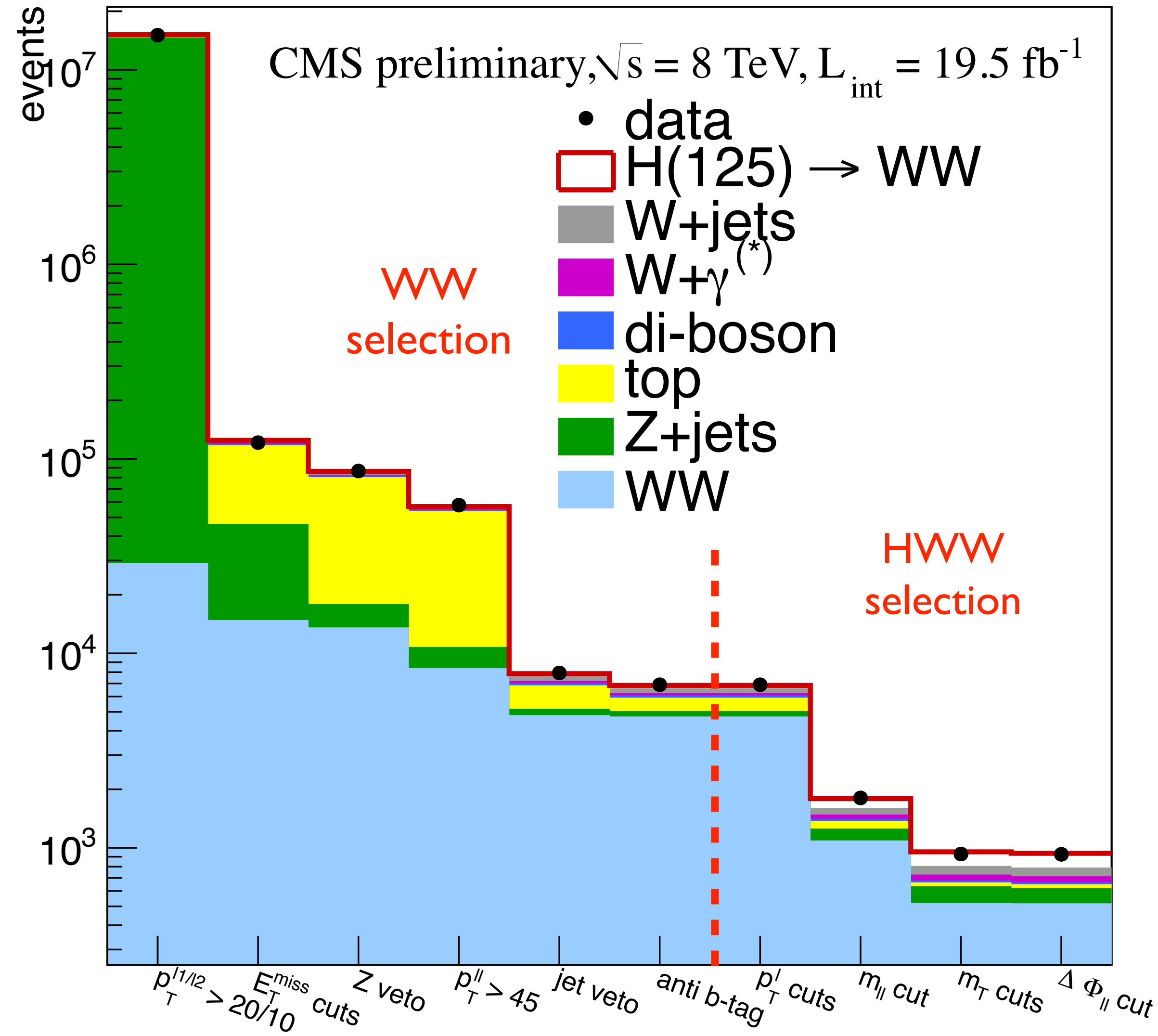


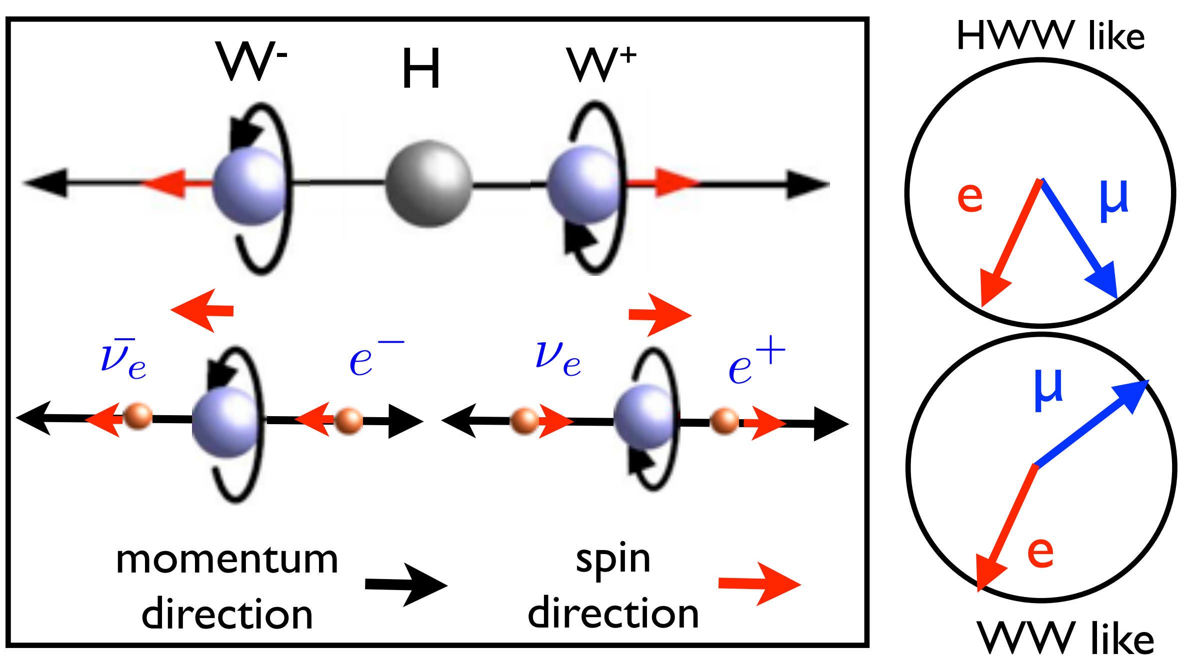




Analysis Overview

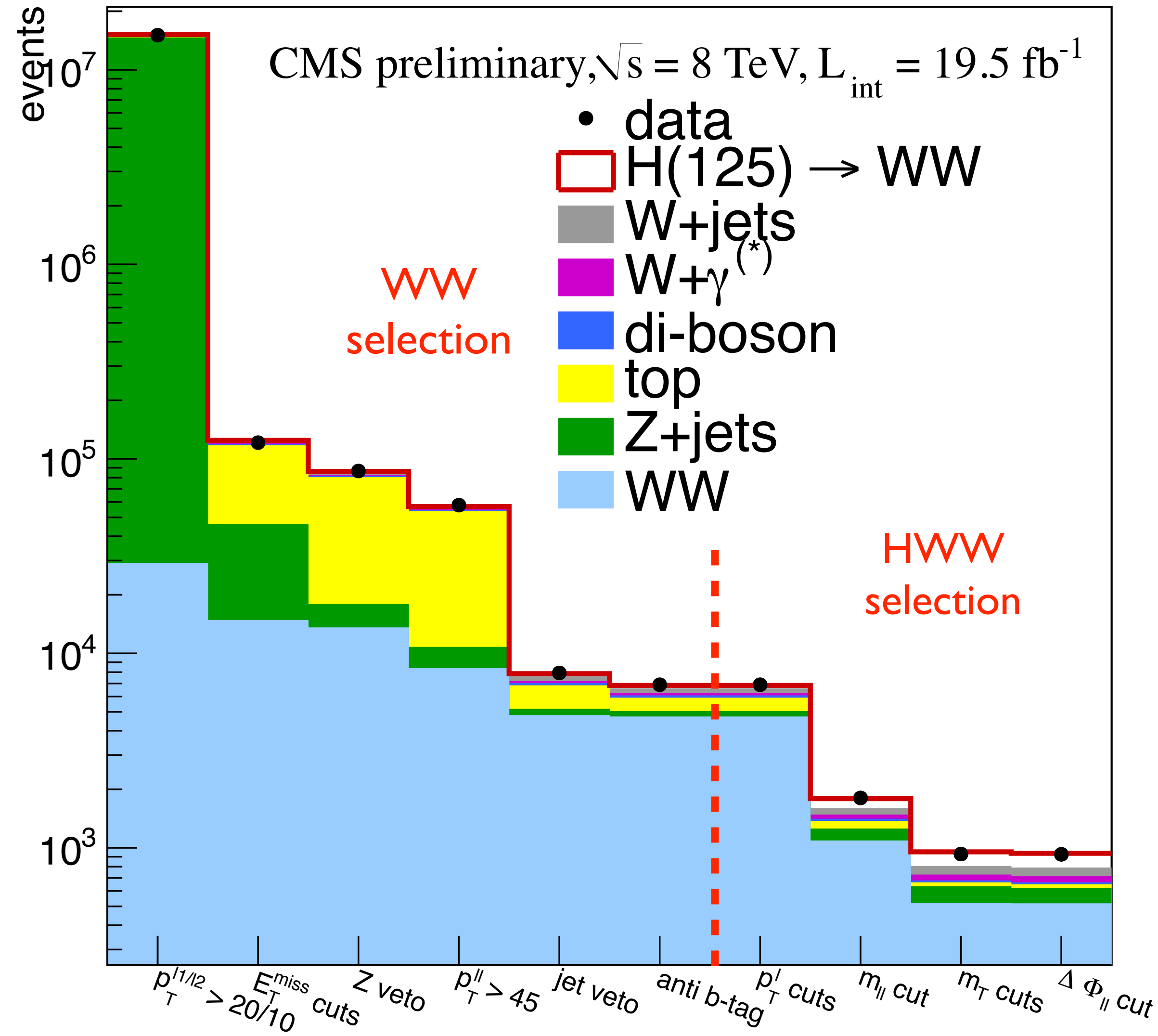
- WW selection
  - Reject reducible backgrounds
- Distinguish the WW background using the spin and mass of the Higgs
  - Low dilepton opening angles ($\Delta\Phi_{ll}$)
  - Transverse mass (dilepton and MET)
- Two complementary approaches to extract the Higgs production cross-section
  - Cut and count
  - Use full shape of kinematic distributions

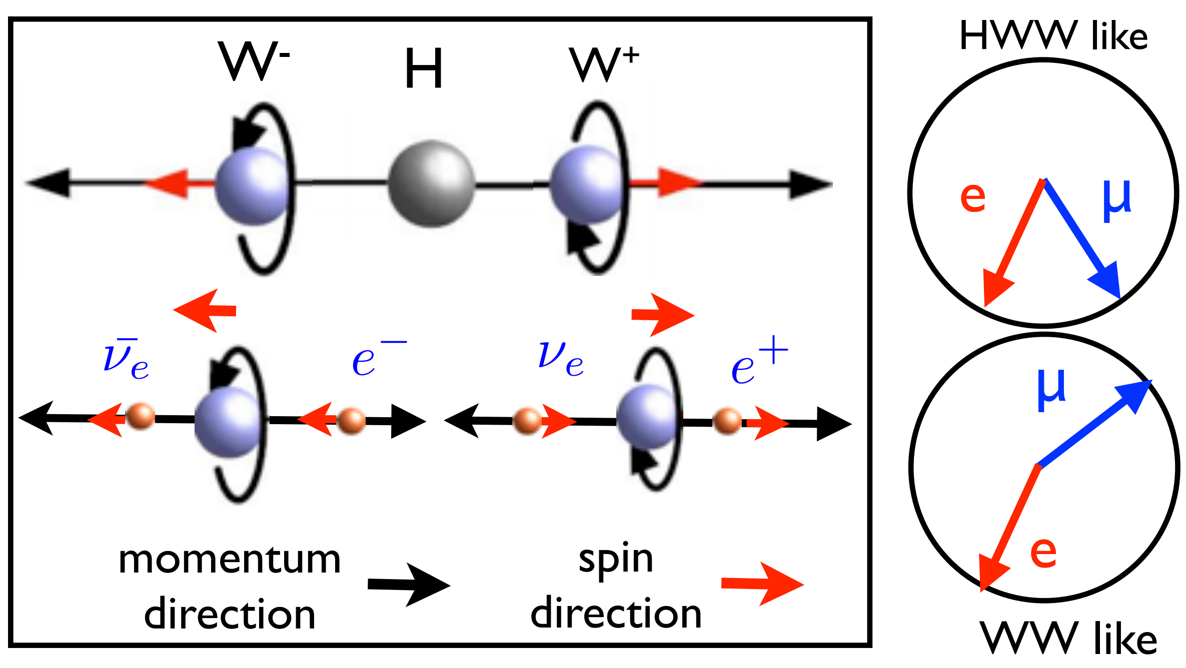




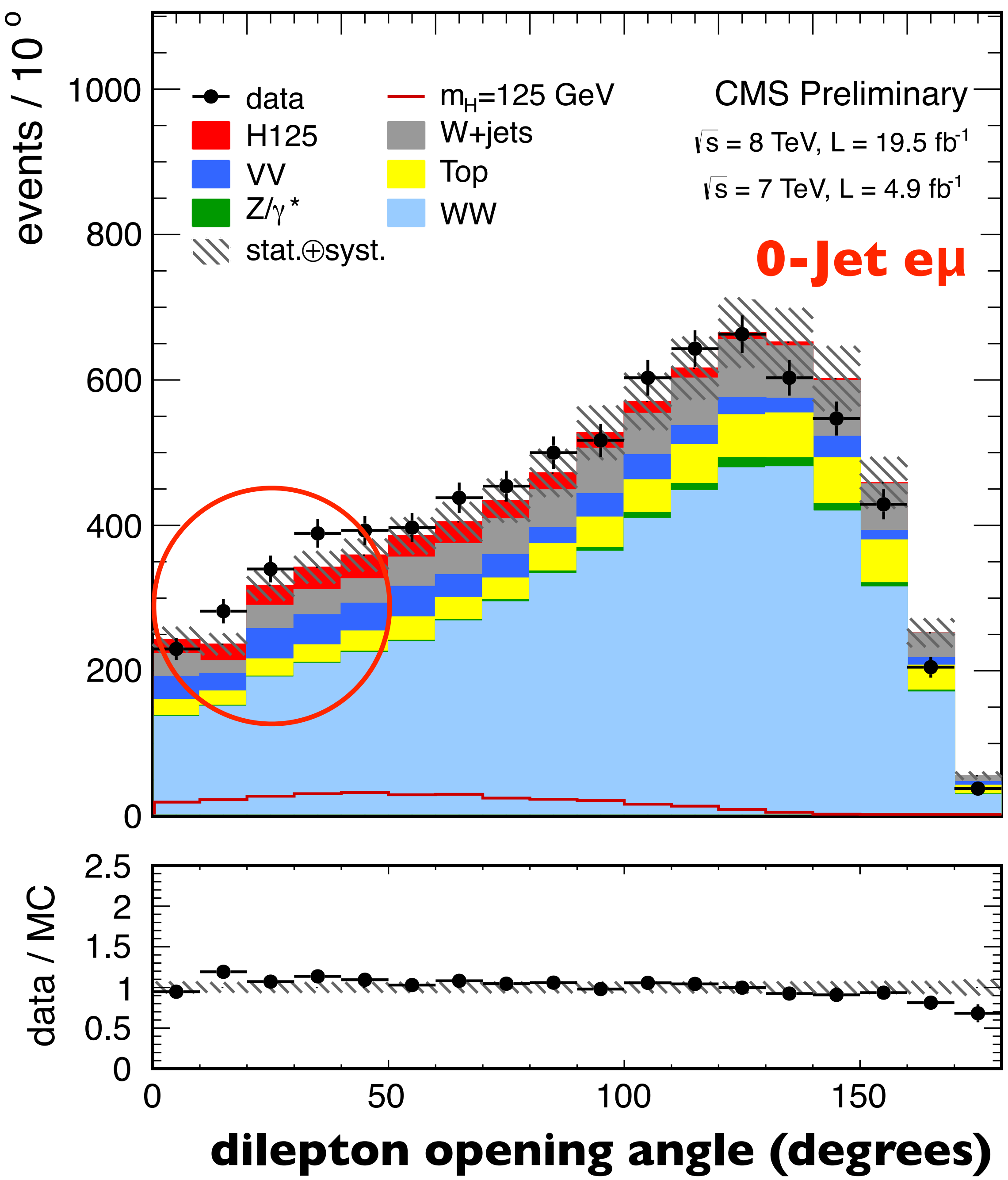
Analysis Overview

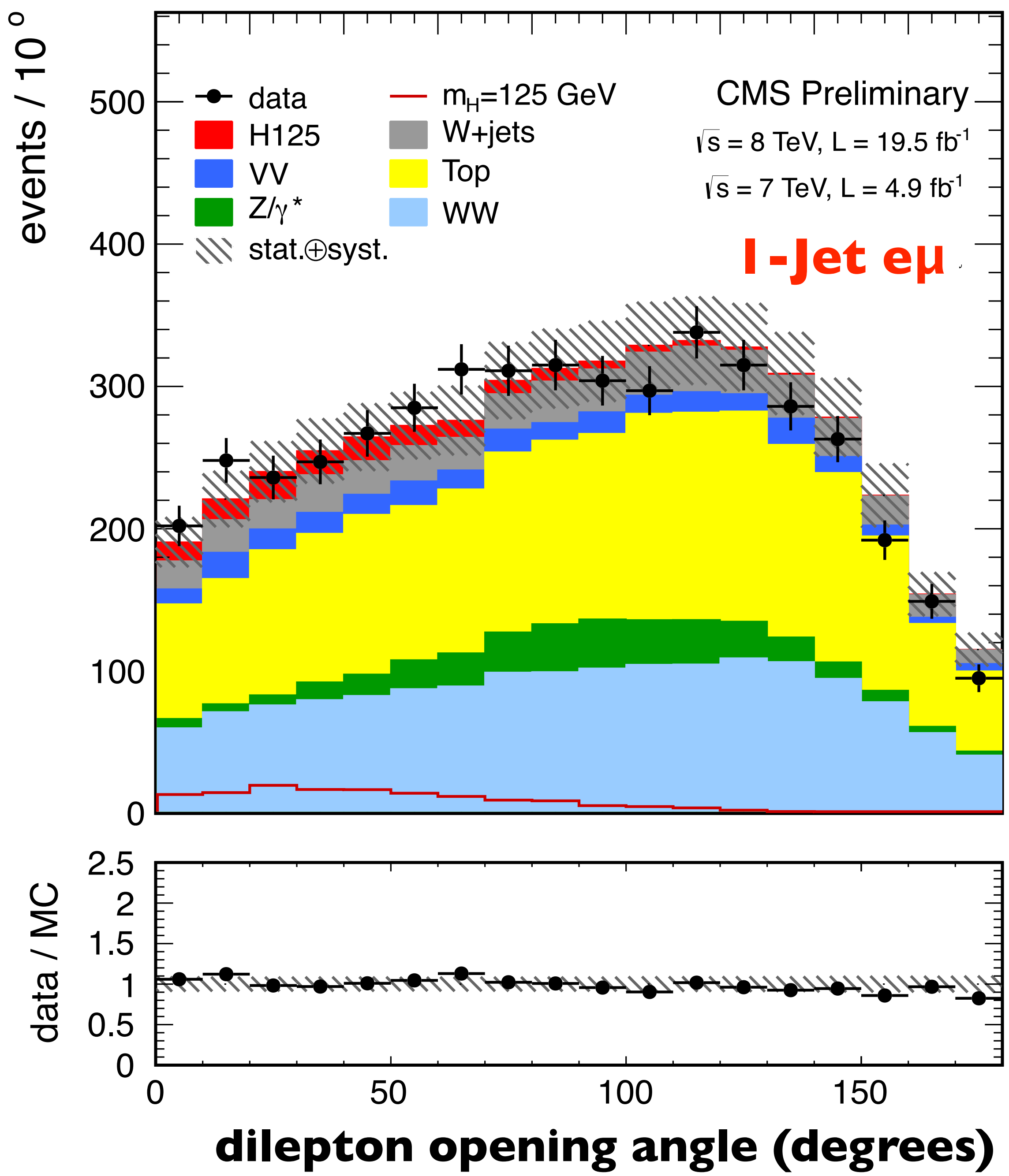
- WW selection
  - Reject reducible backgrounds
- Distinguish the WW background using the spin and mass of the Higgs
  - Low dilepton opening angles ($\Delta\Phi_{ll}$)
  - Transverse mass (dilepton and MET)
- Two complementary approaches to extract the Higgs production cross-section
  - Cut and count
  - Use full shape of kinematic distributions
- Optimize search in categories
  - number of jets: 0/1/2
  - lepton flavor: ee/eμ/μμ
  - 0-Jet eμ is the most sensitive channel

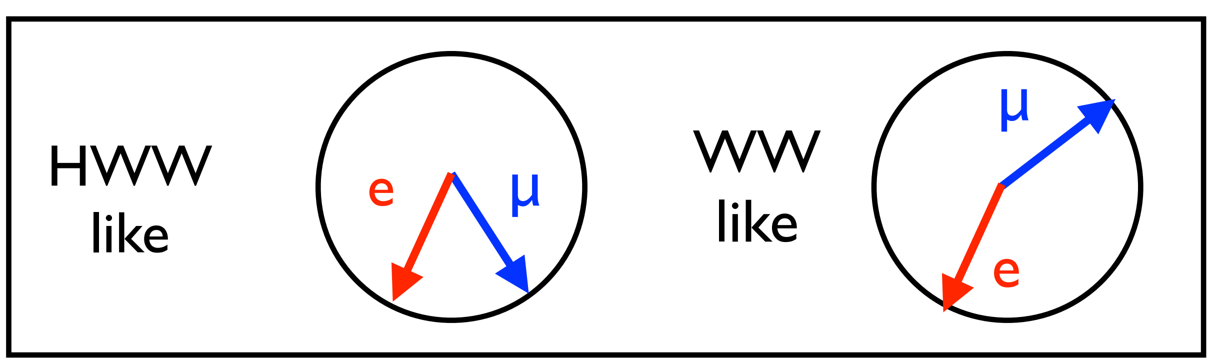




Events After the WW Selection

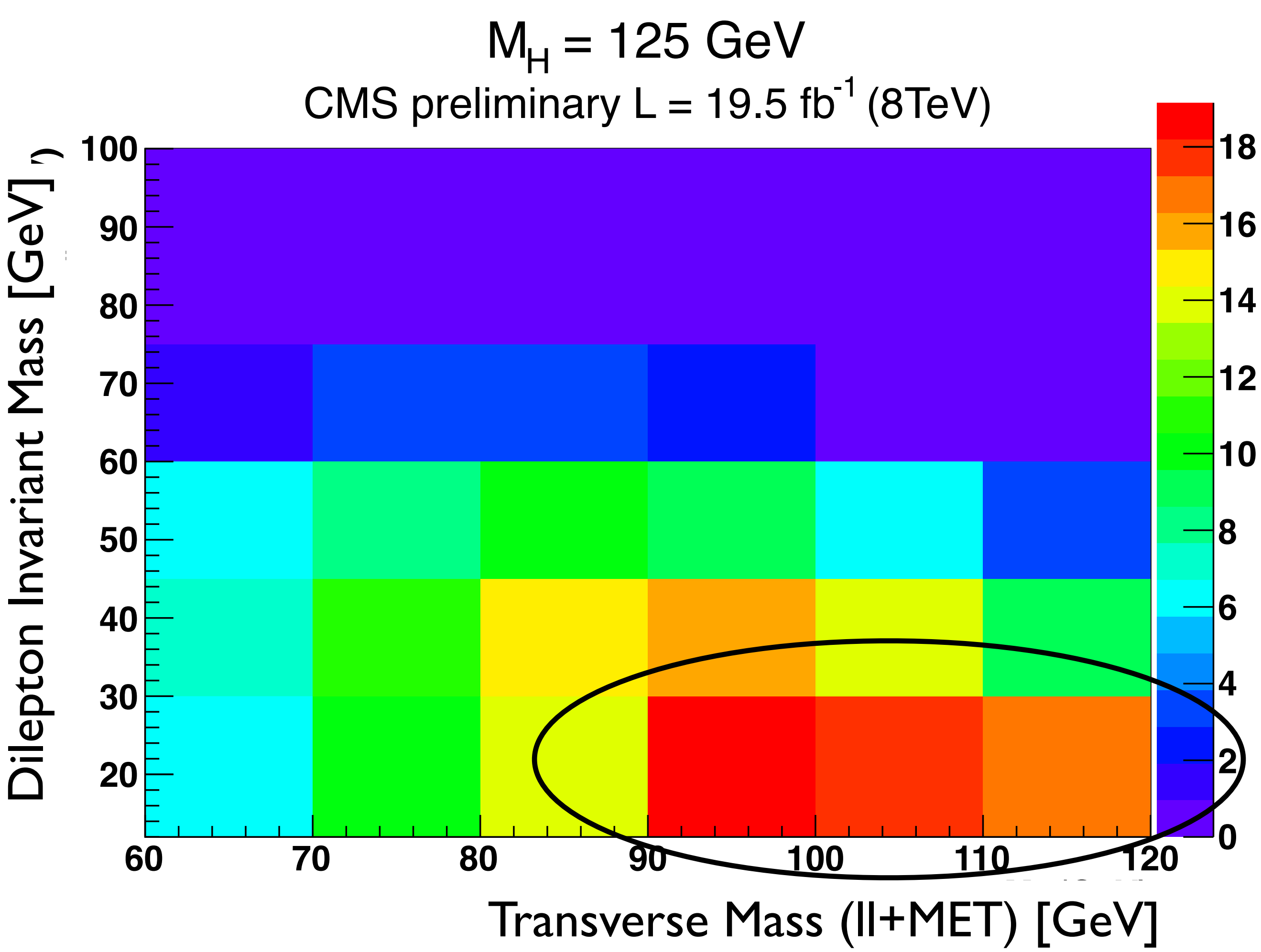


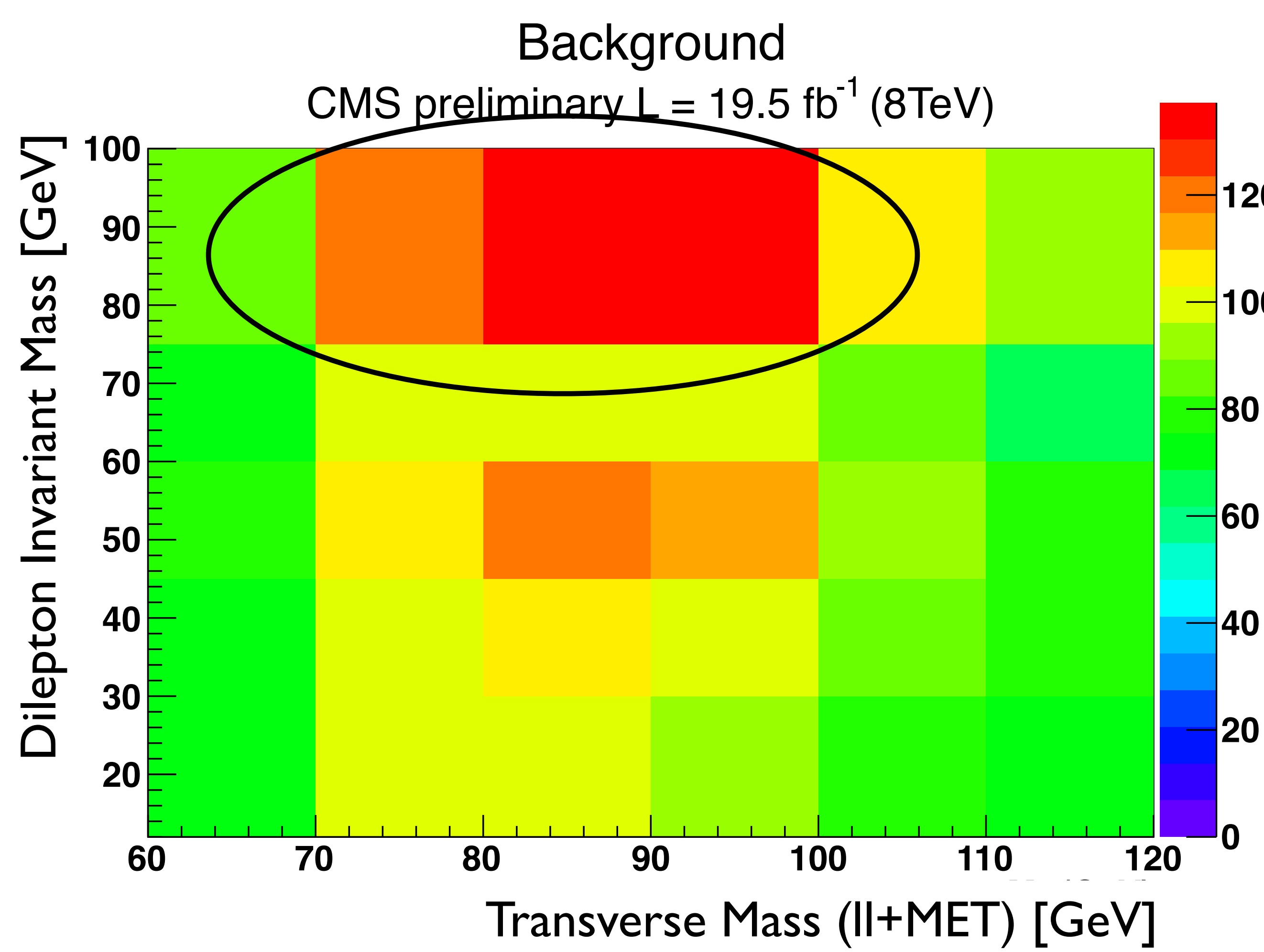




H→WW Cross-section Extraction

- Exploit full kinematic phase space in eμ channel with less backgrounds (~~Drell-Yan~~)
  - Dilepton invariant mass and transverse mass (ll+MET)
  - Data in the background region can be used to constrain both background normalization and shape



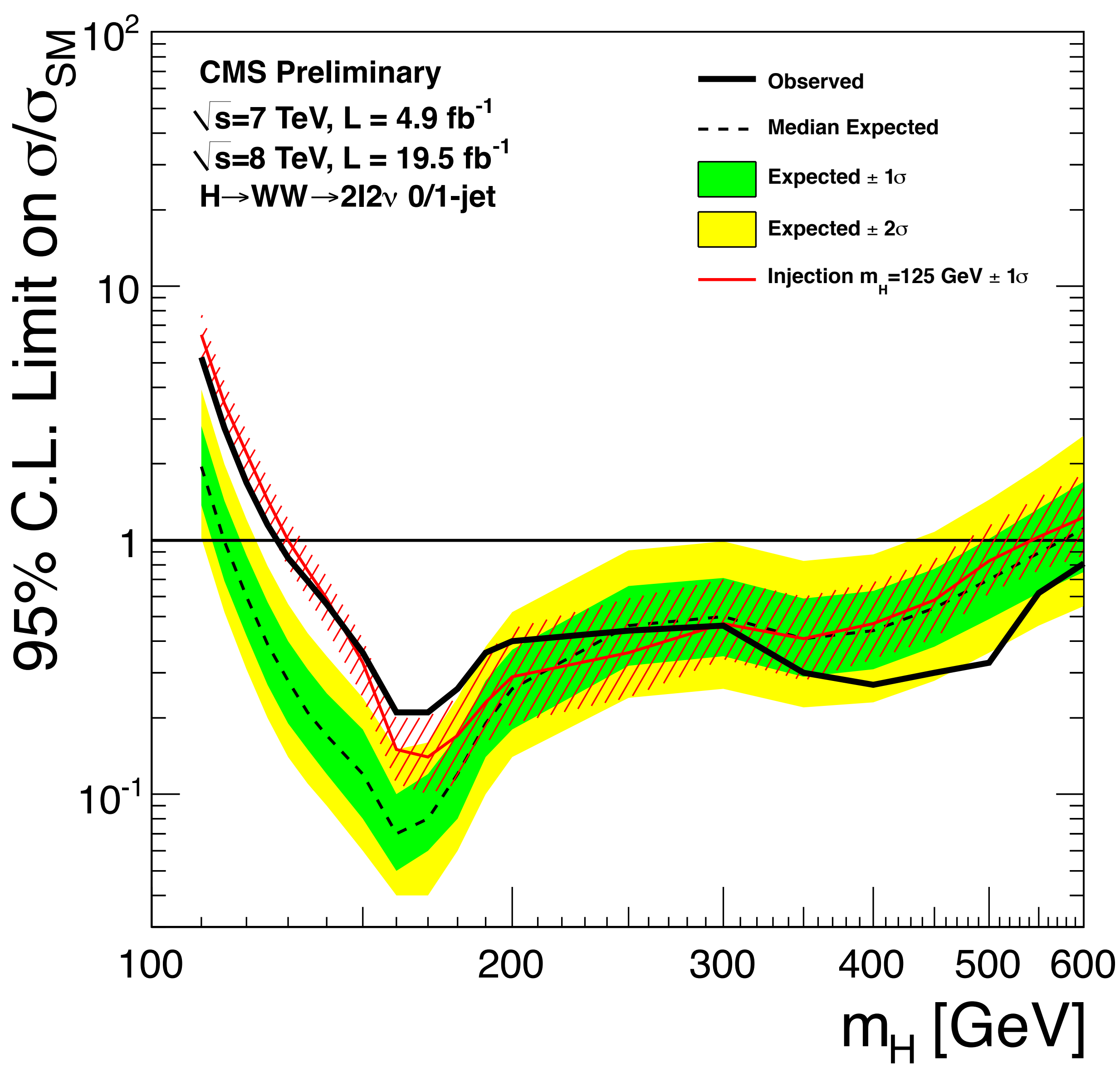


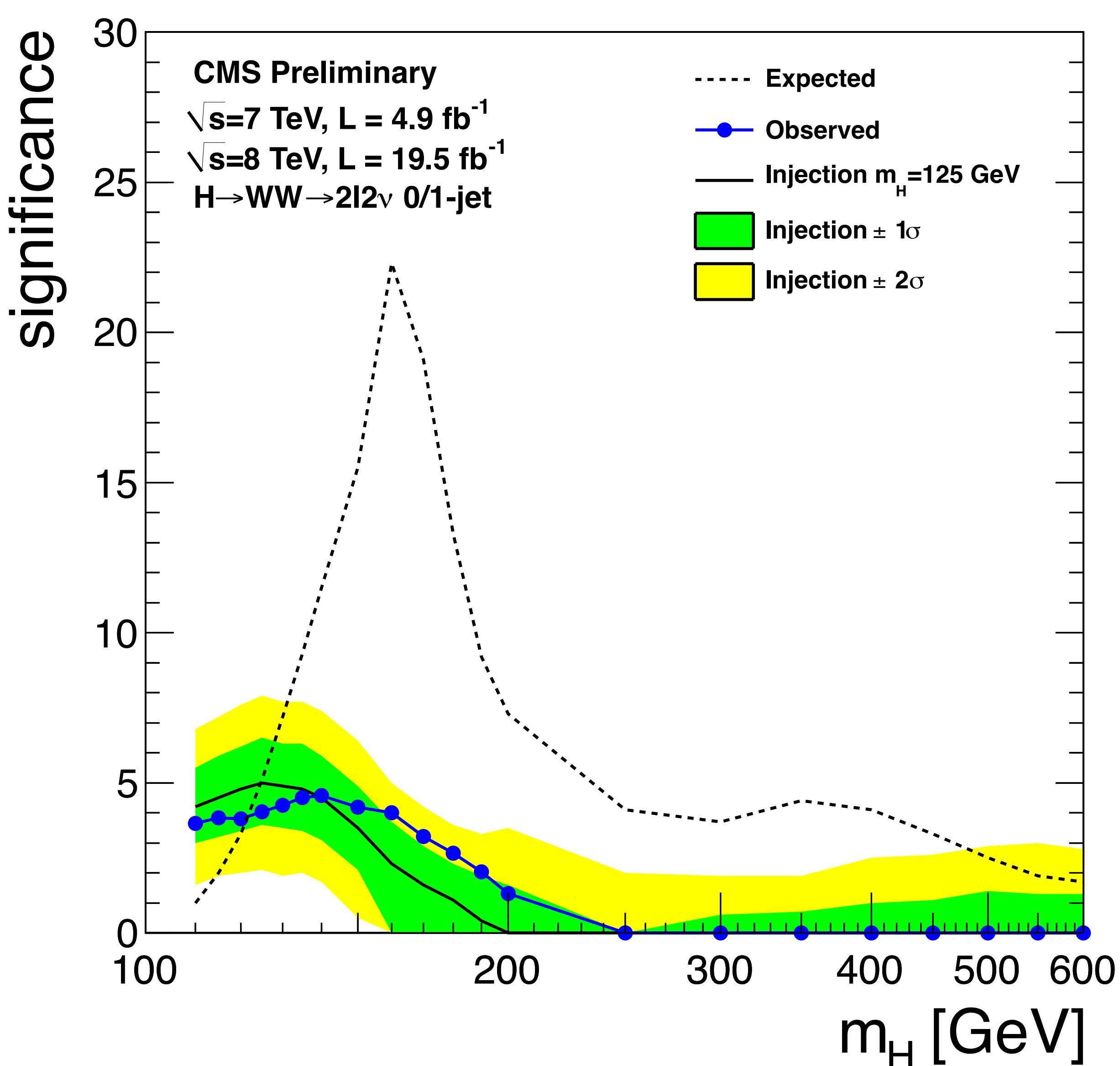
Summary of the Results

- The SM Higgs boson is excluded up to 600 GeV in the high mass range
- We observe an excess in the low mass region

mH = 125	Expected	Observed
Significance	5.1	4.0
$\mu=\sigma/\sigma_{SM}$	1	0.76 ± 0.13(stat) ± 0.16(syst)

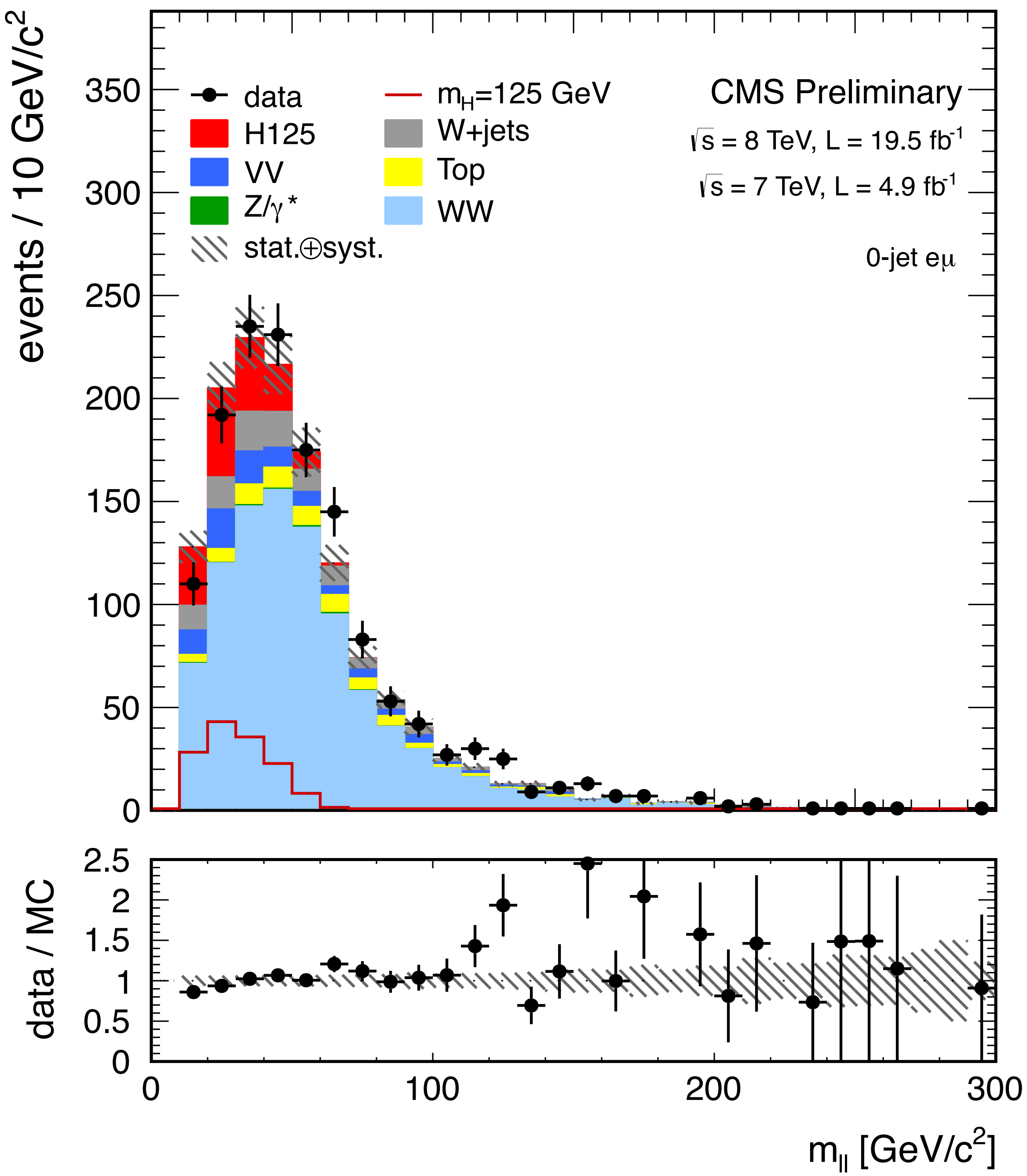
currently the most precise signal measurement of all decay channels

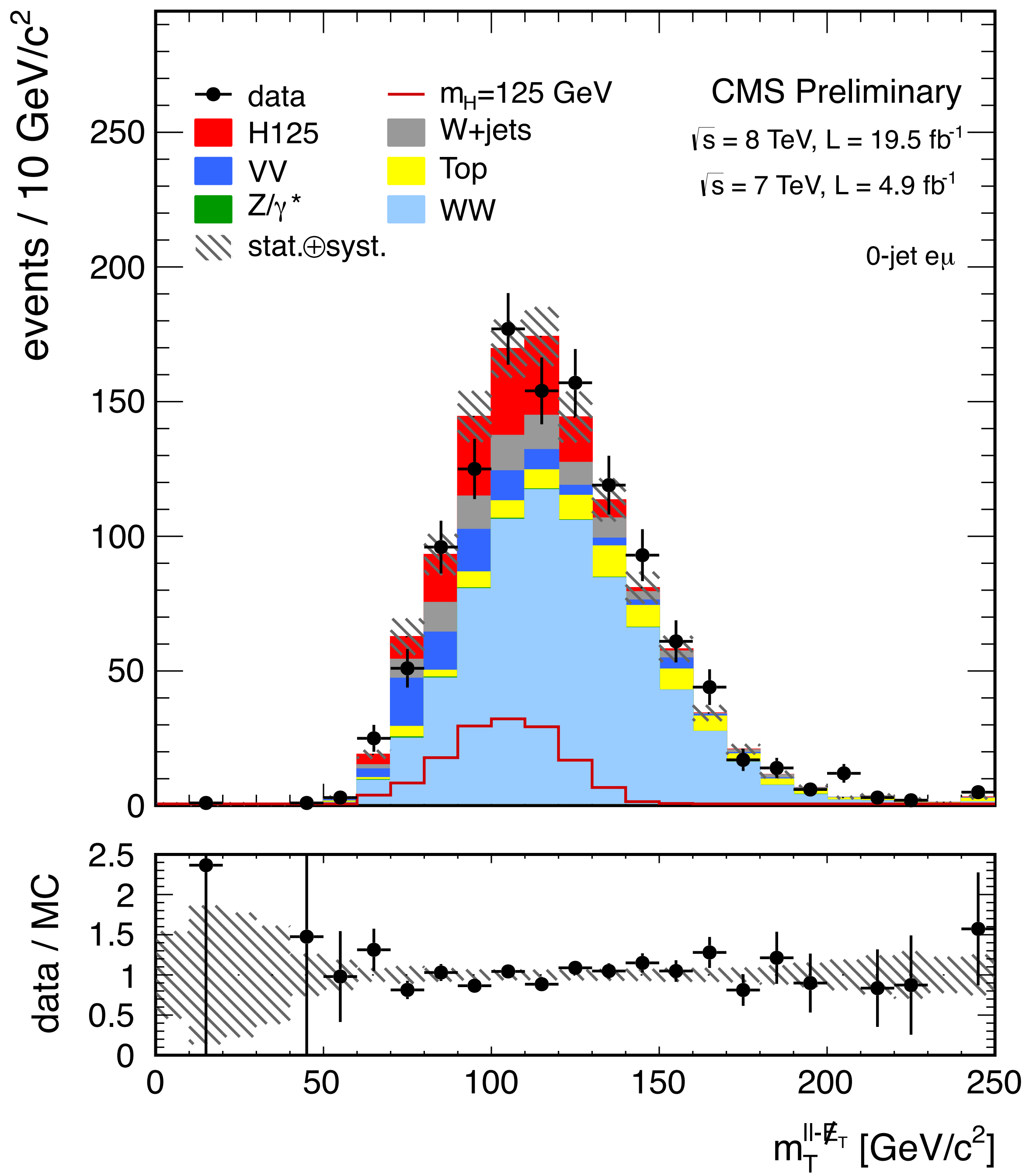




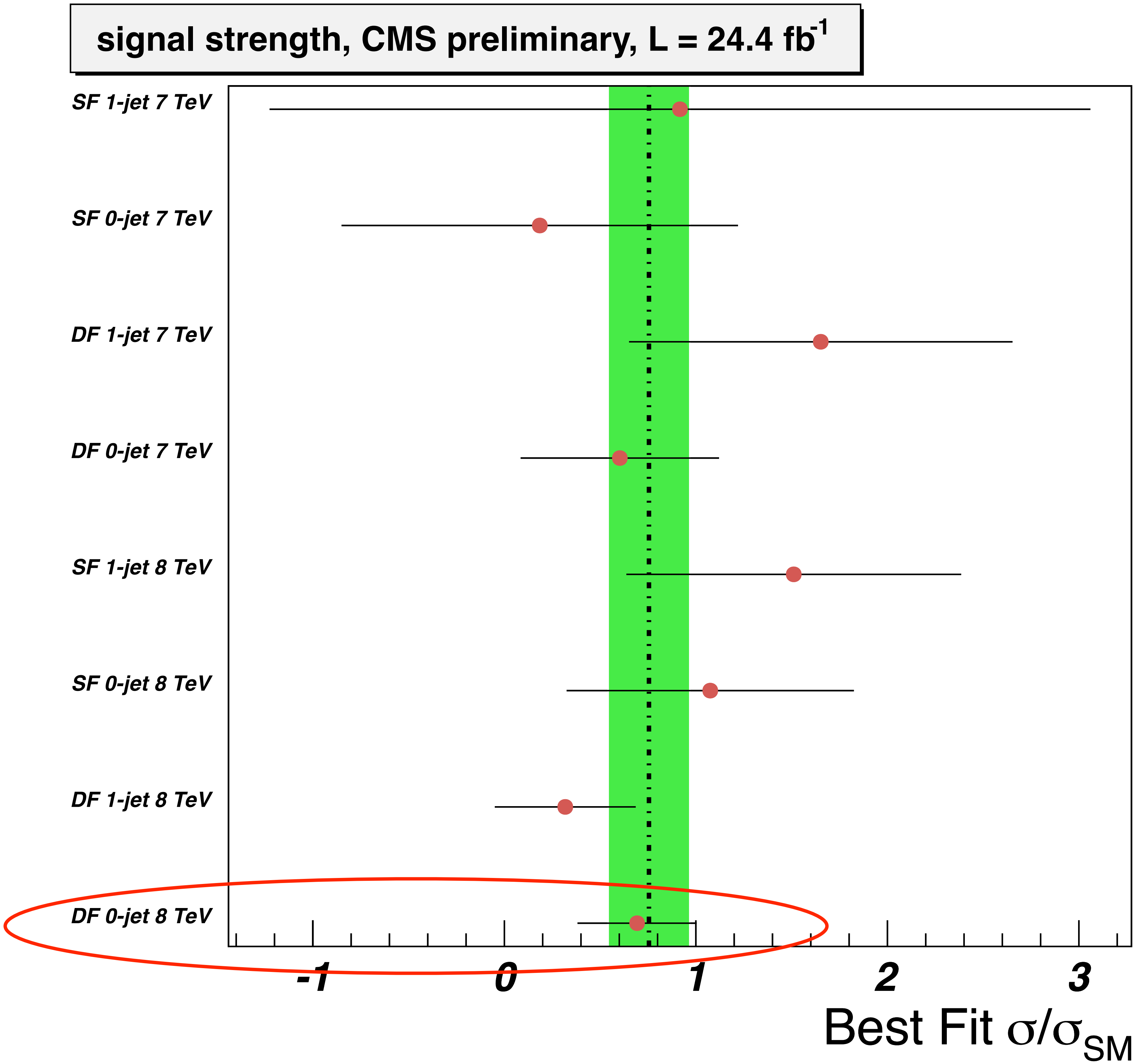
Kinematic Distributions in Signal Regions

- Closer look at the signal region, apply all cut-based selections except the variable plotted
  - Kinematic distributions agree well with the SM Higgs + background hypothesis

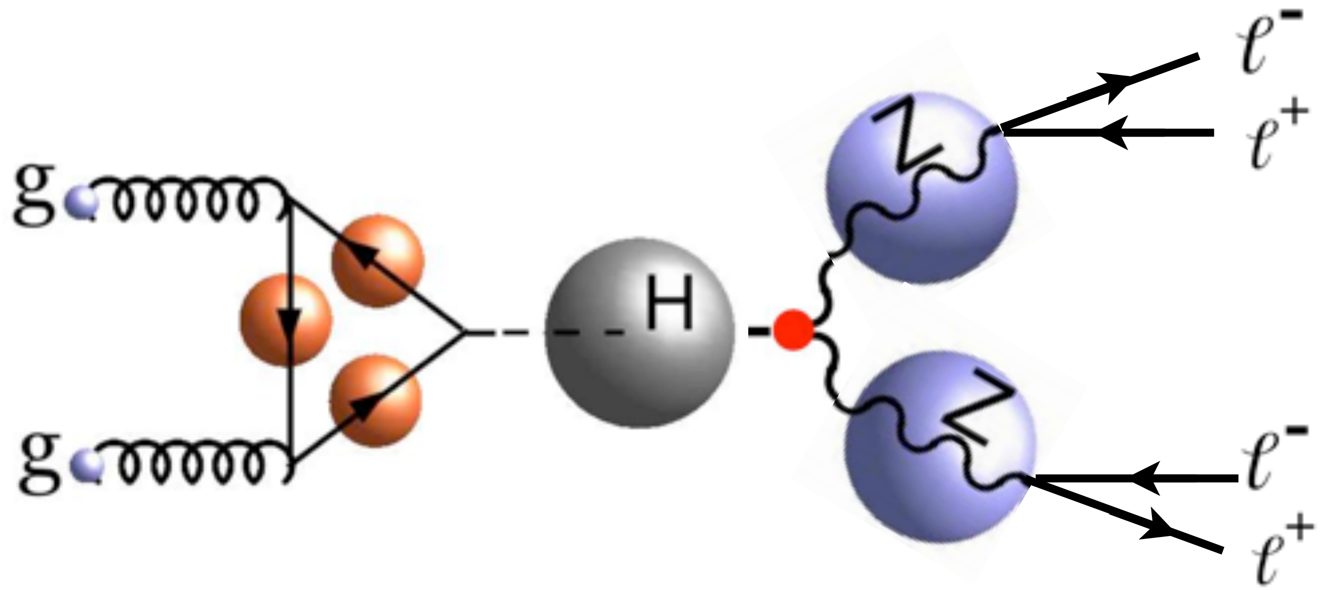




Results in Different Final States

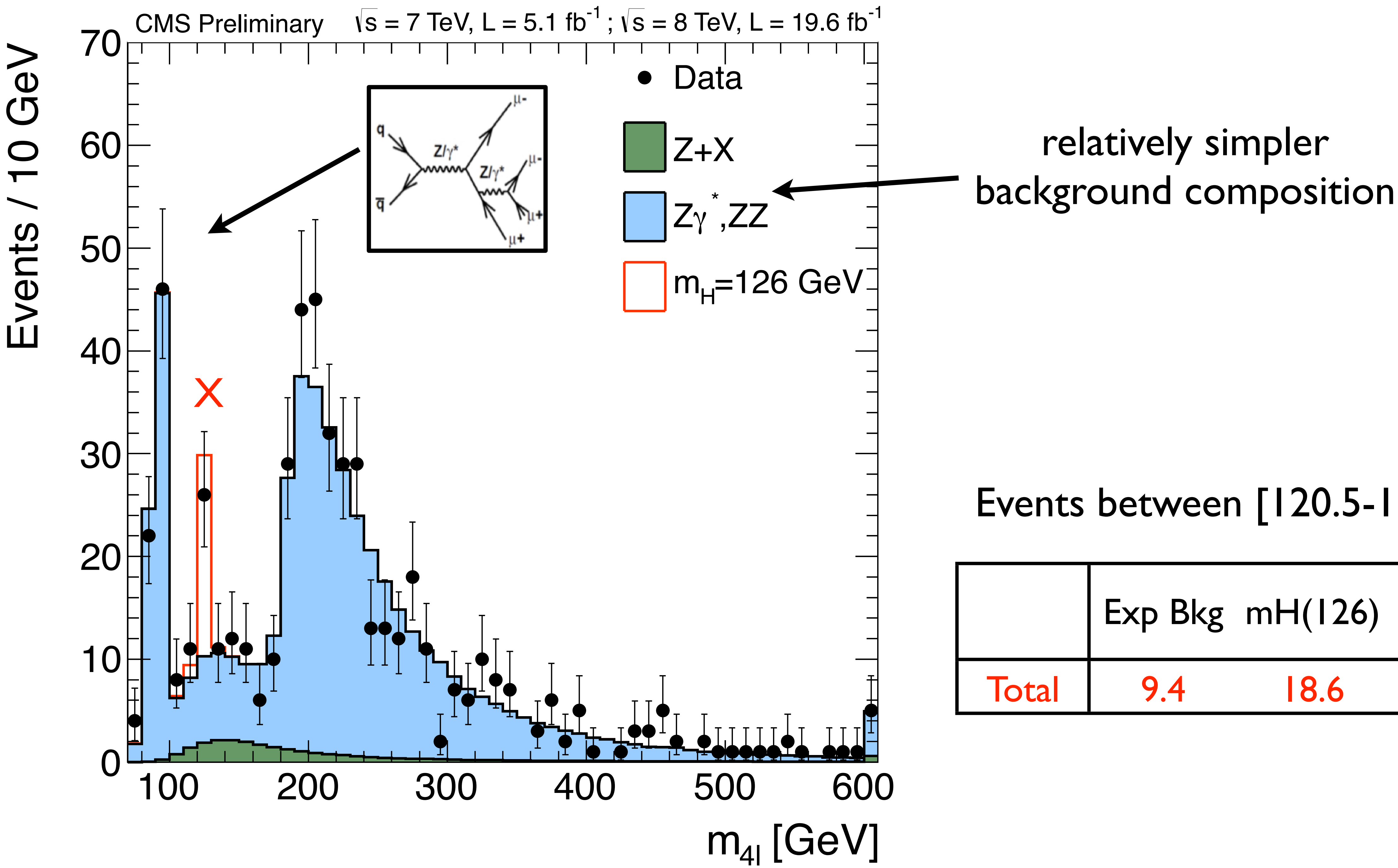


$H \to ZZ \to 4l$



The "golden channel" for both SM Higgs search and Higgs property measurements

- The m(4l) is the most important variable



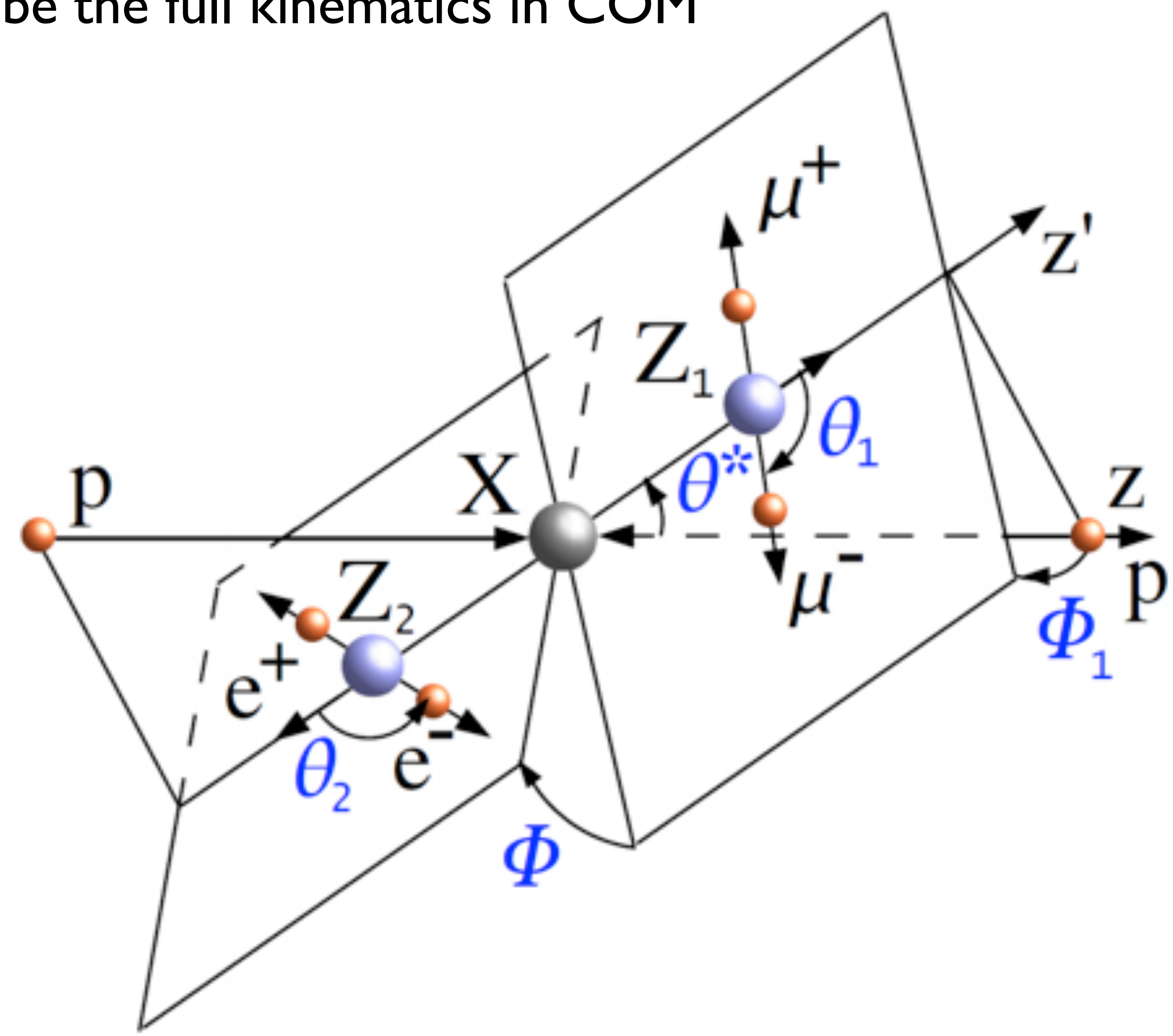
Events between [120.5-131.5]

	Exp Bkg	mH(126)	Data
Total	9.4	18.6	25

- Analysis is statistically limited (~0.8 signal events/fb)
  - **Need to exploit full kinematics to improve the search sensitivity**

Full Kinematics Description

- Full kinematics: total 12 degrees of freedom
  - For a given m(4l), 7 mass-angular variables describe the full kinematics in COM
    - invariant masses: m_{Z1}, m_{Z2}
    - production angles: θ^*, Φ_1
    - decay angles: θ_1, θ_2, ϕ

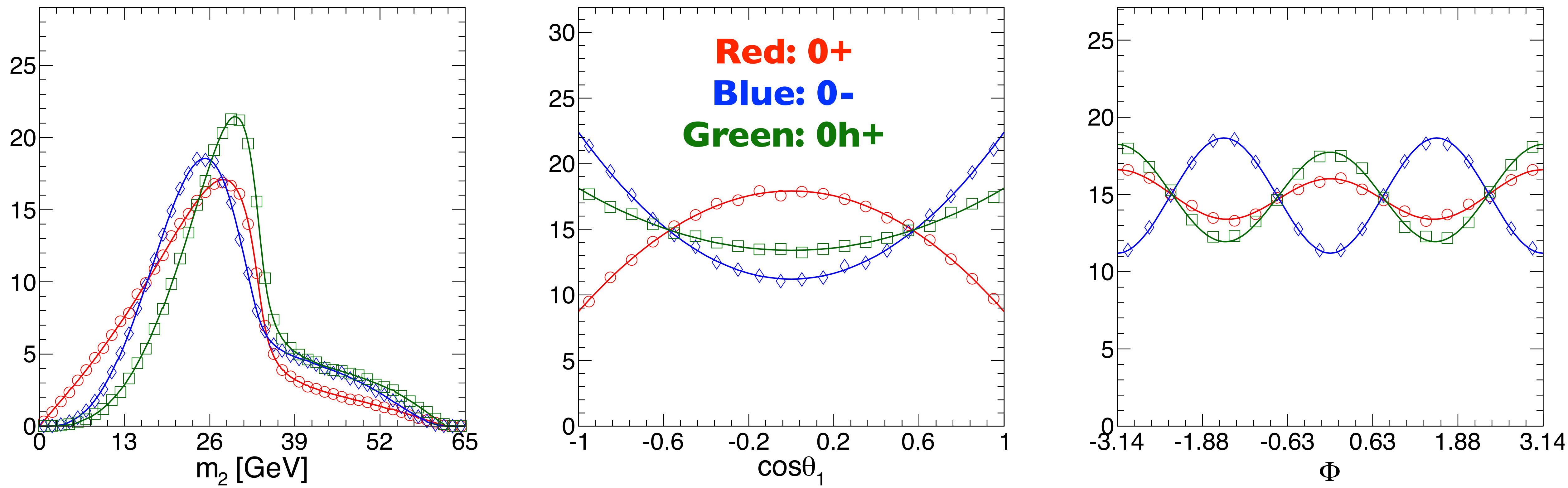


- These variables directly probe underlying physics (scattering amplitudes) of X→VV interaction
  - Ideally they can be used to fit data to measure the underlying XVV couplings

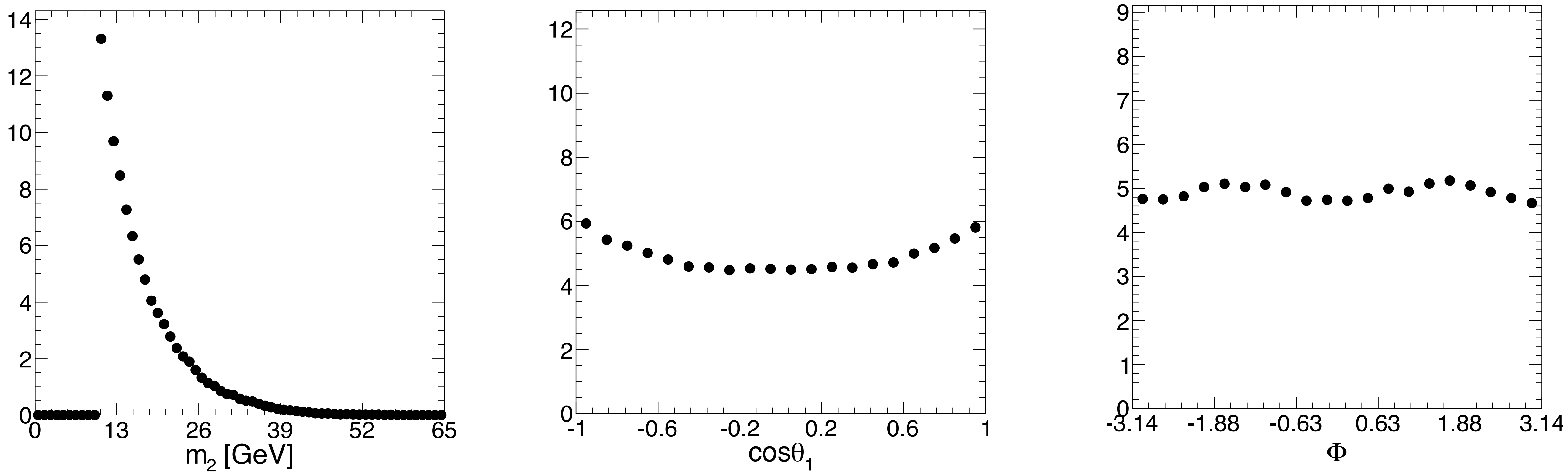
Selected Mass-Angular Distributions

- Selected signal models

Data points: Ideal MC events   Lines: Analytical Calculations



- Main ZZ background



Single Kinematic Discriminant for SM Higgs Search

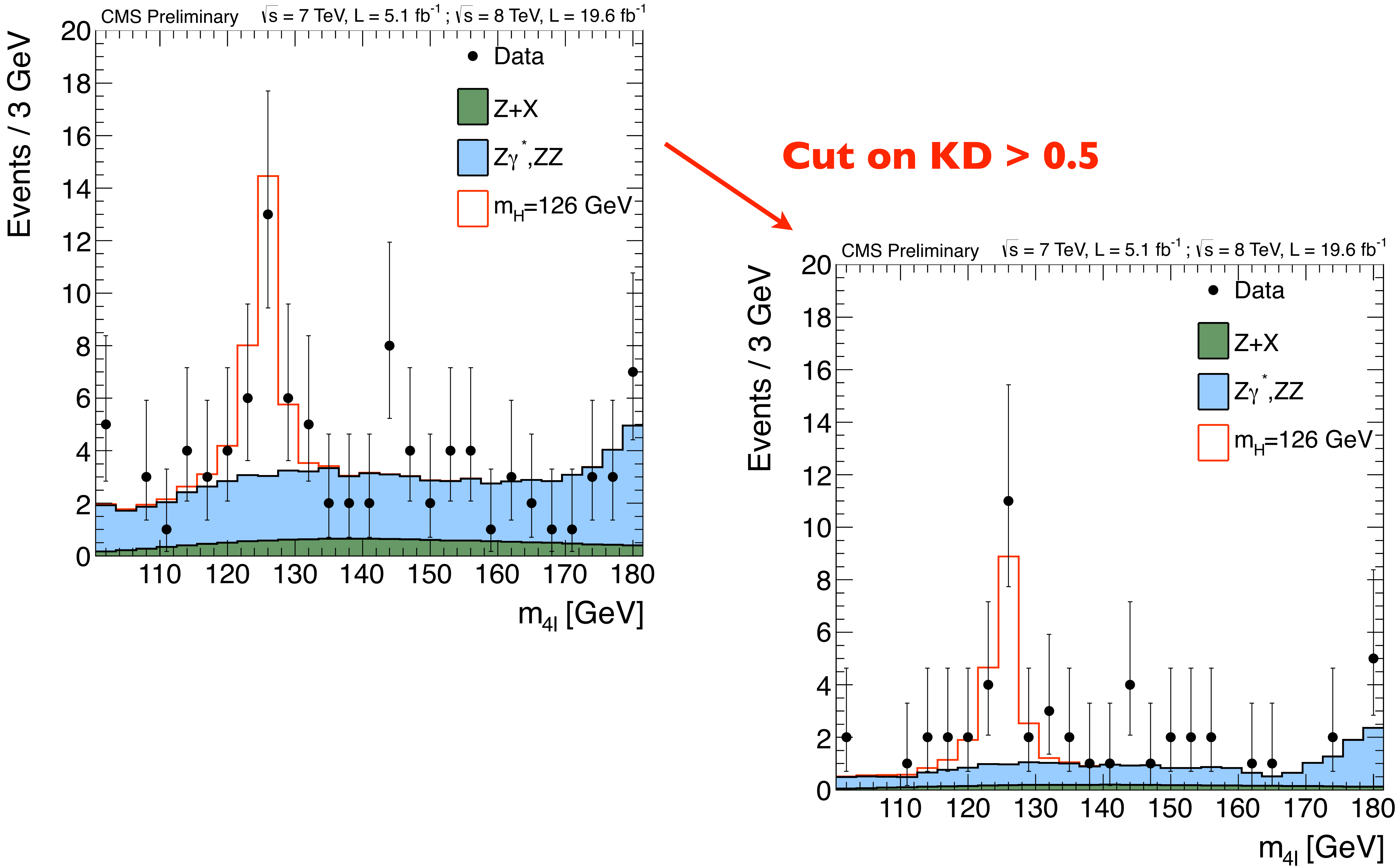
- With current statistics, it is not feasible to compare directly the full 7D mass-angular variables
- We construct single kinematic discriminant for each m(4l)
  - Matrix Element Likelihood Analysis

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

  - **Peak towards 1 for SM Higgs and toward 0 for the other processes**
- P_{sig} and P_{bkg} are calculated with two complementary approaches based on
  - Analytical angular distribution
  - Vector algebra matrix elements based on the 4-momenta of the final state particles

Effect of Kinematic Discriminants

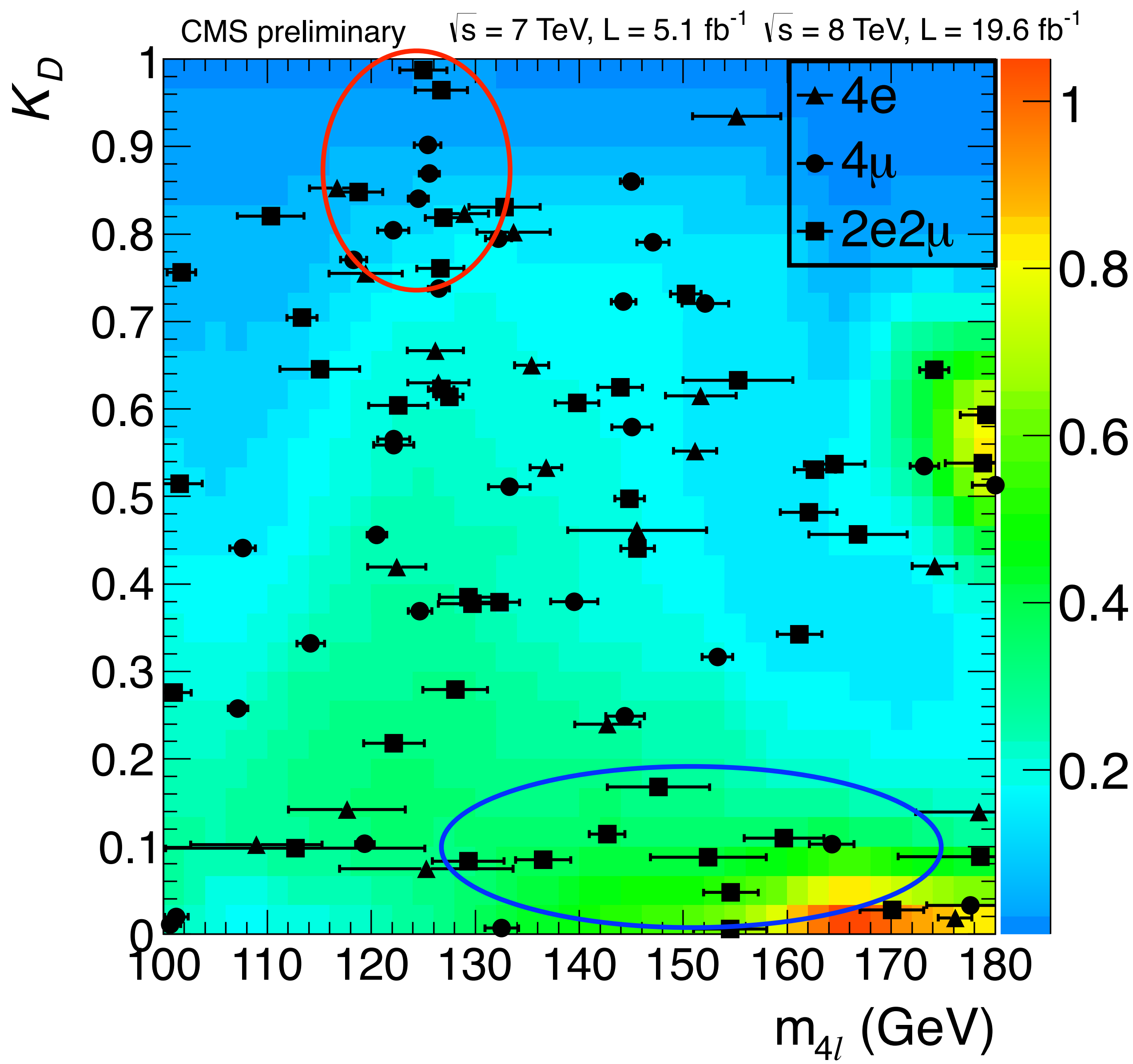
- Including the kinematic discriminant improves the search sensitivity by ~ 15%



H→ZZ Cross-section Extraction

- The kinematic discriminant is combined with m(4l) for the Higgs search

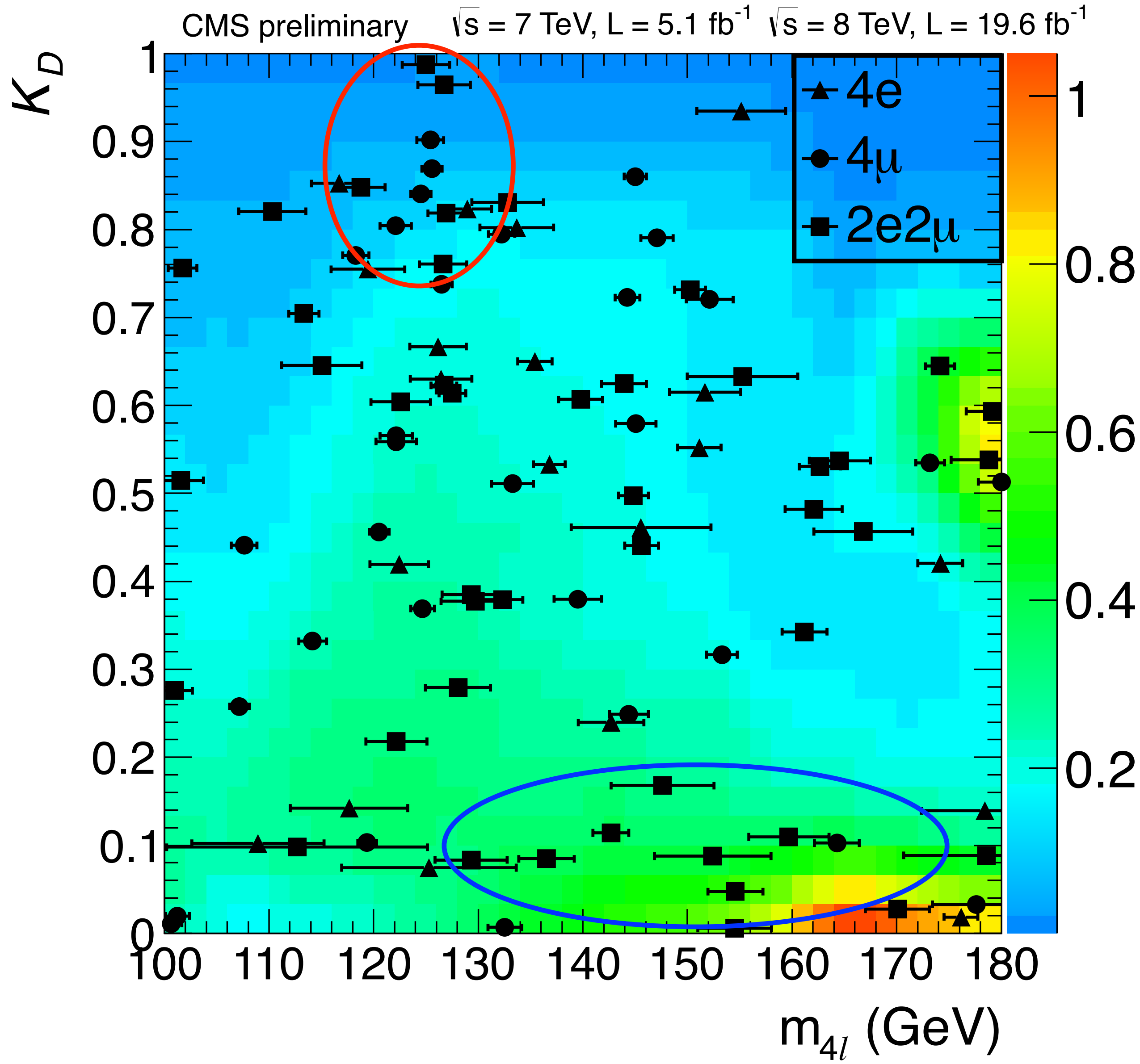
Data overlaid with Background



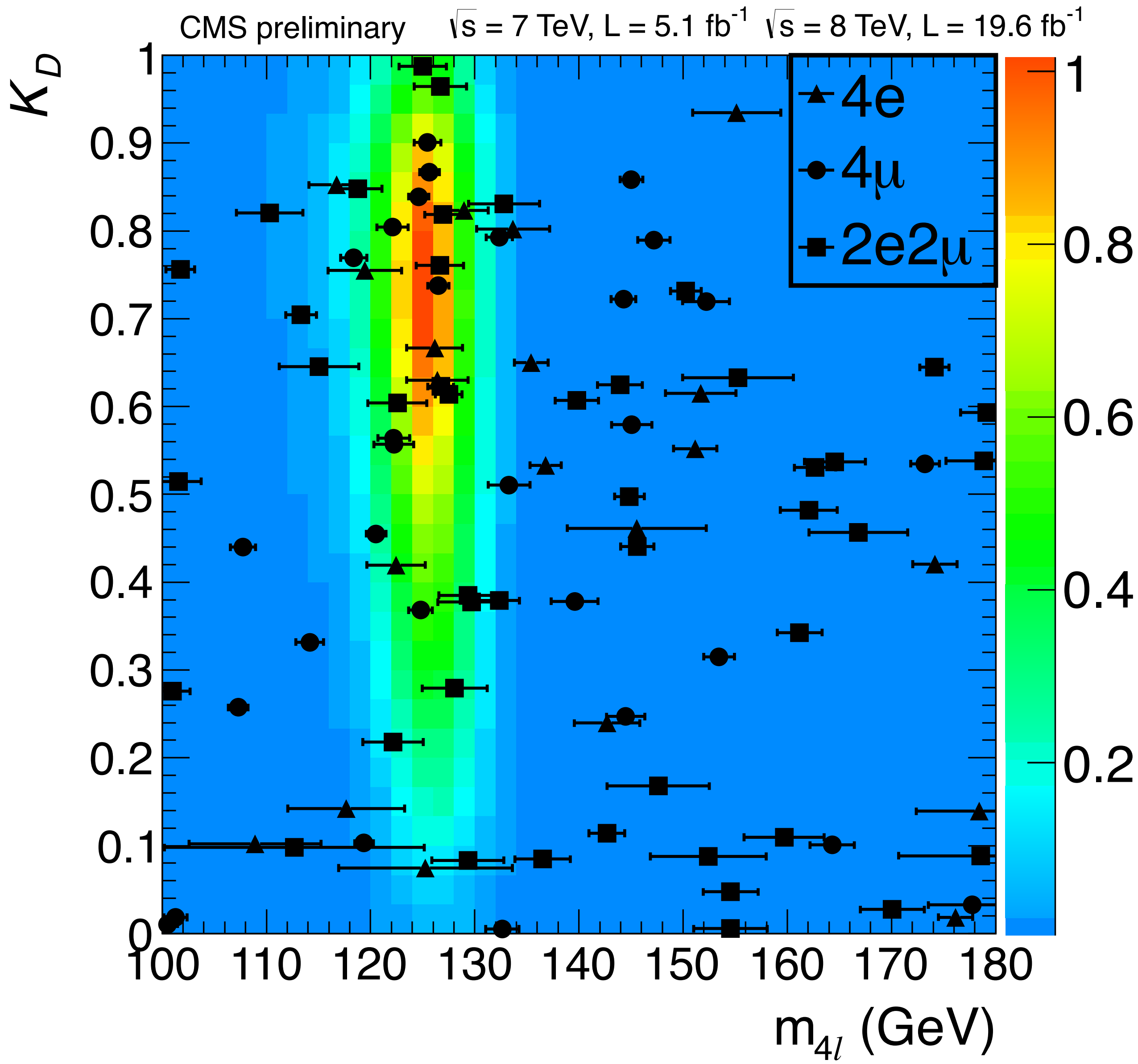
H→ZZ Cross-section Extraction

- The kinematic discriminant is combined with m(4l) for the Higgs search

Data overlaid with Background



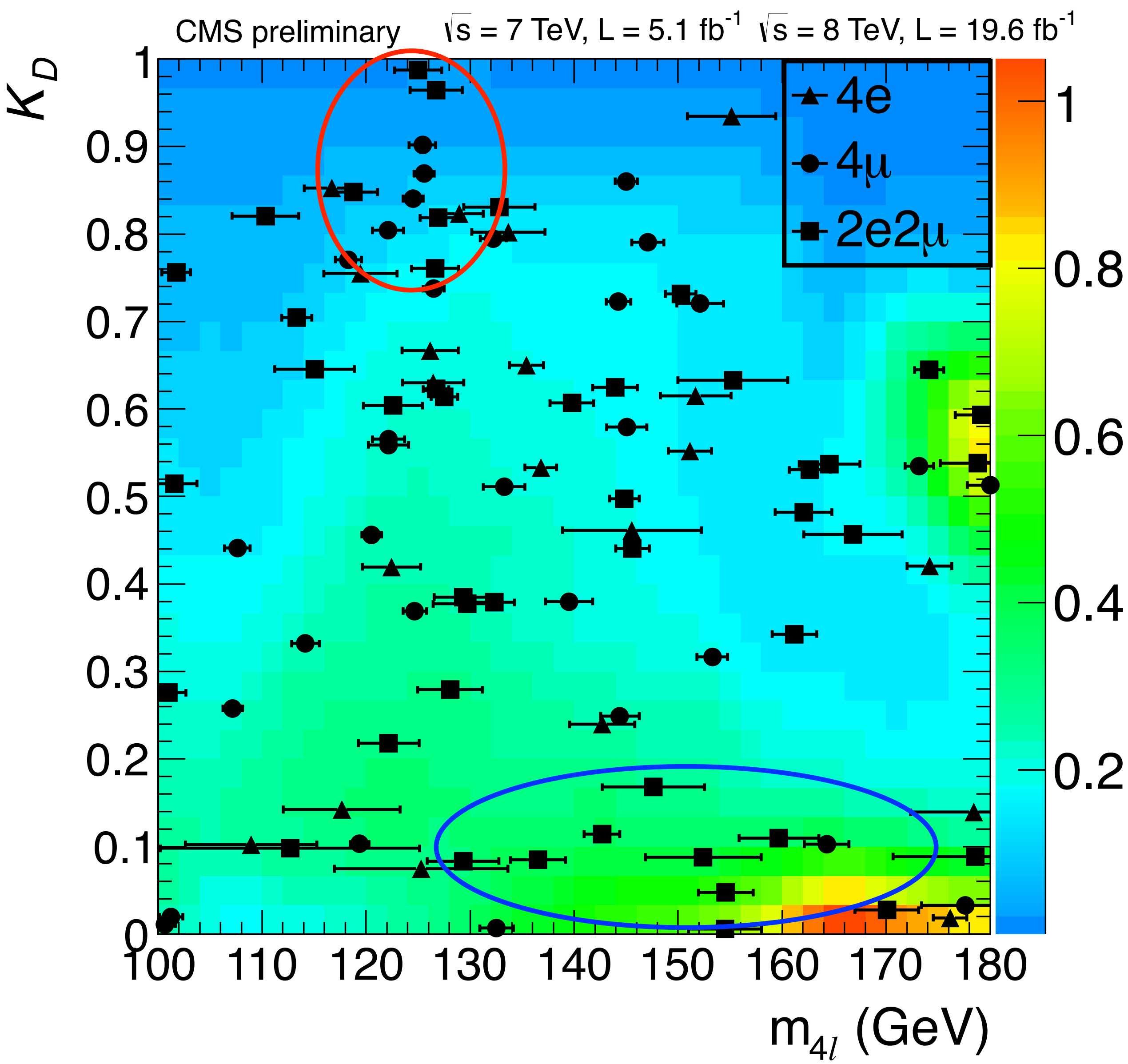
Data overlaid with Signal



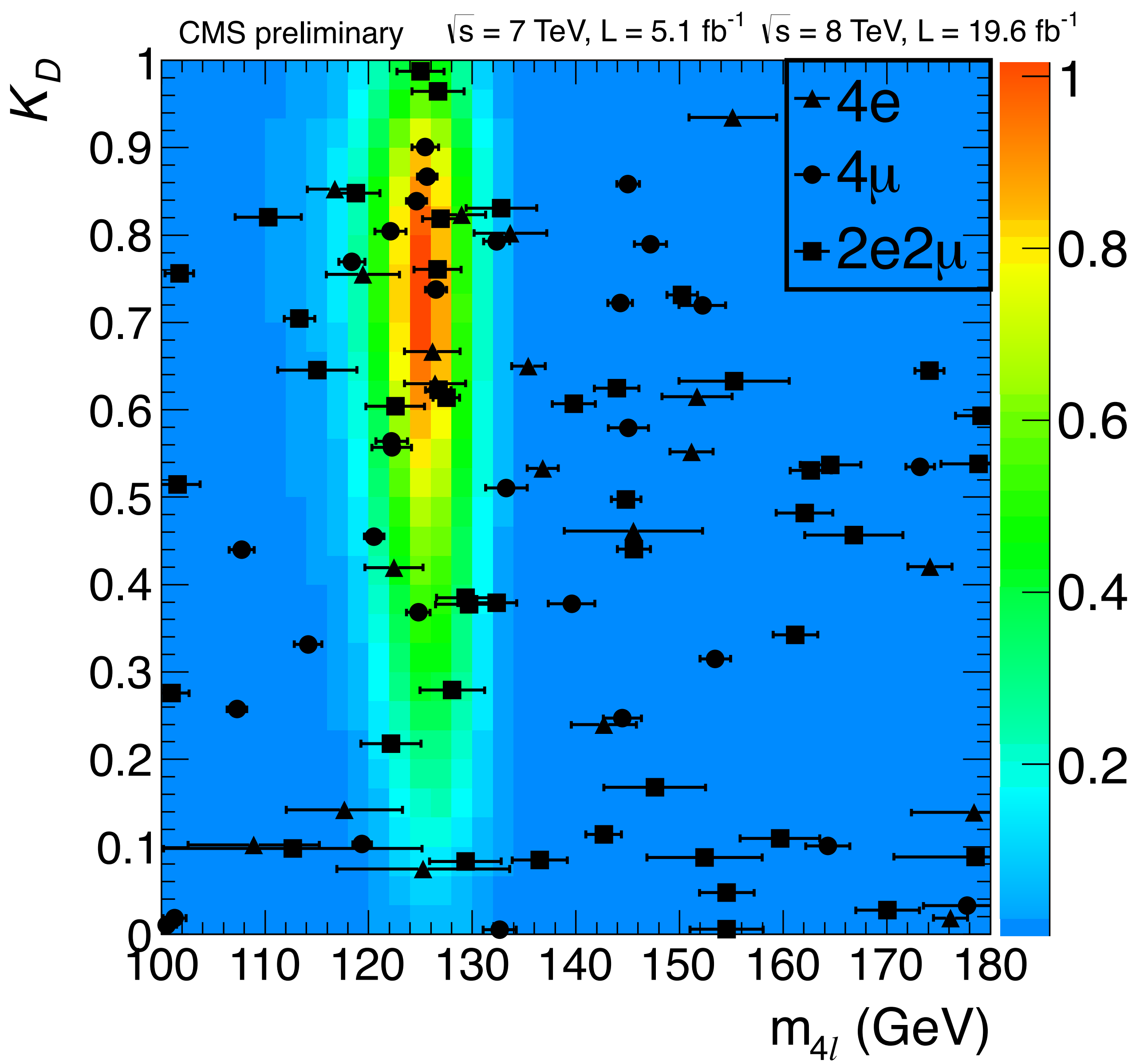
H→ZZ Cross-section Extraction

- The kinematic discriminant is combined with m(4l) for the Higgs search

Data overlaid with Background



Data overlaid with Signal



- We observed an excess with a local p-value corresponding to 6.7σ (7.0σ expected)

$$\mu \equiv \sigma/\sigma_{SM} = 0.91^{+0.30}_{-0.24}$$

$$m_H = 125.8 \pm 0.5(\mathtt{stat}) \pm 0.2(\mathtt{syst})\ \mathrm{GeV}$$

Explore the XVV Tensor Structures

- The current statistics does not allow a full measurements of the underlying tensor structure
- As a first step we can compare data with a few bench mark models
  - Parity Odd 0-
  - (simple) spin 1 and 2 scenarios

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

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

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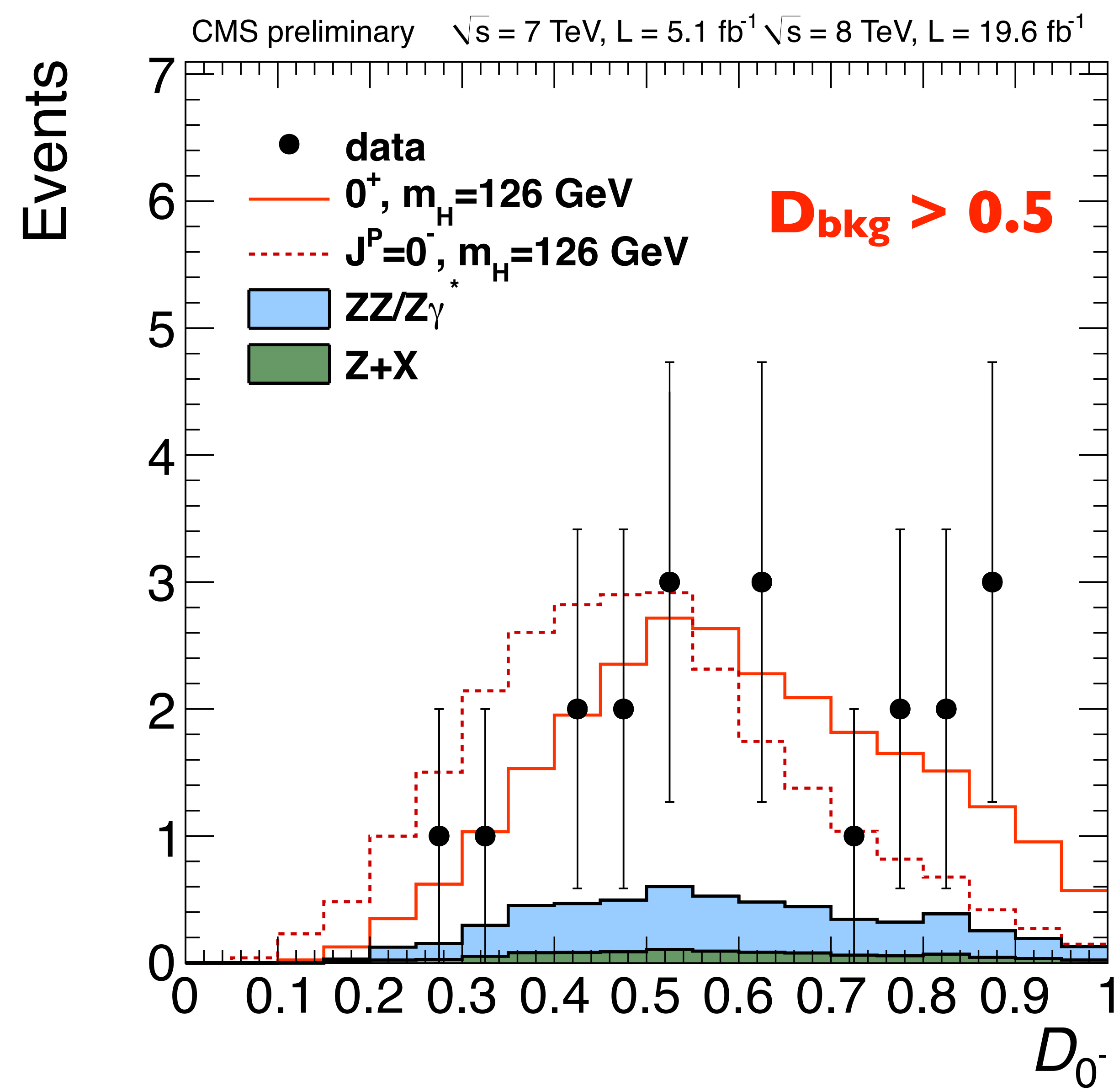

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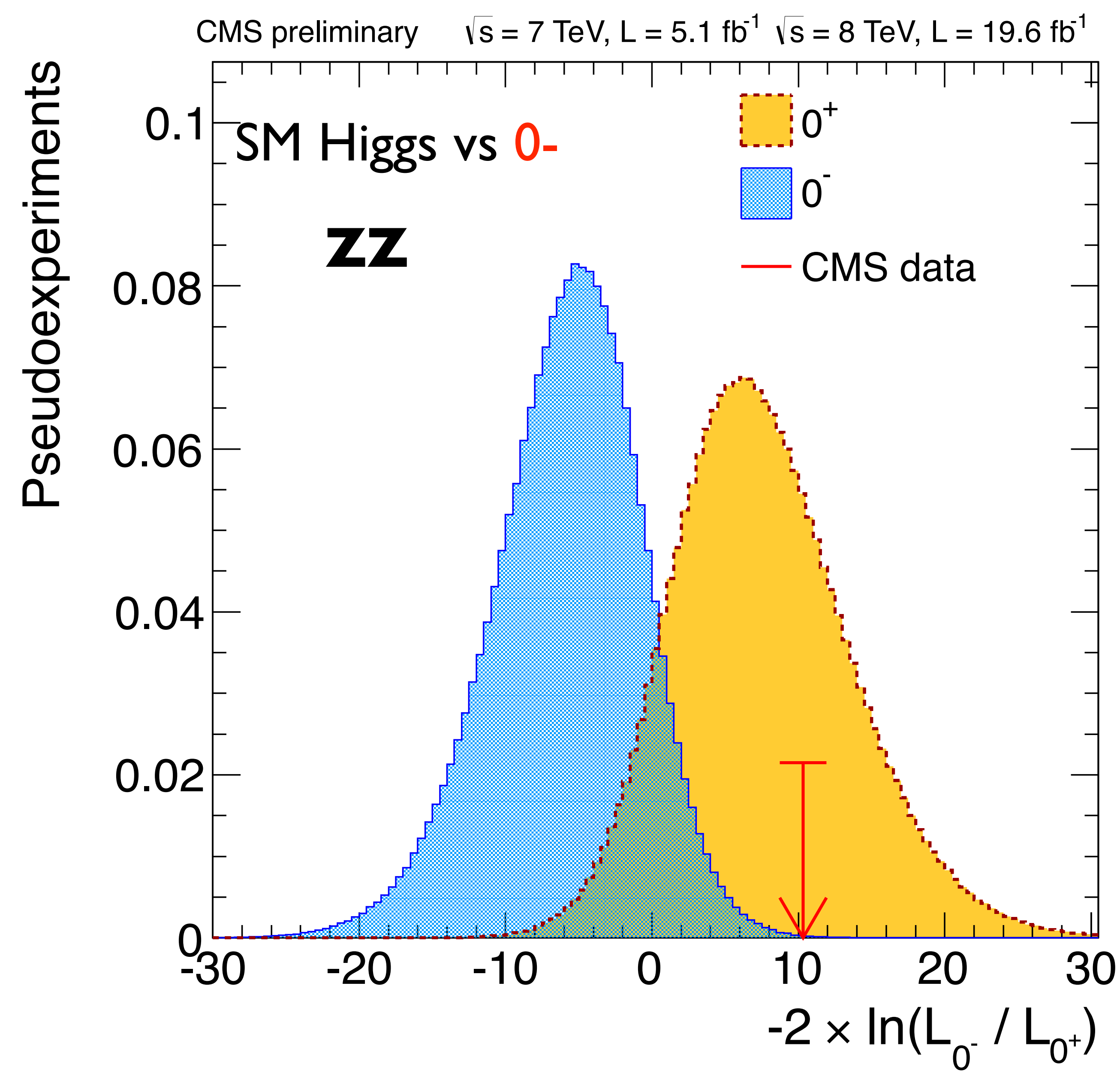
Parity Results

- Parity (assuming spin 0)
  - Data is more consistent with 0+
  - disfavors a pure CP-odd state



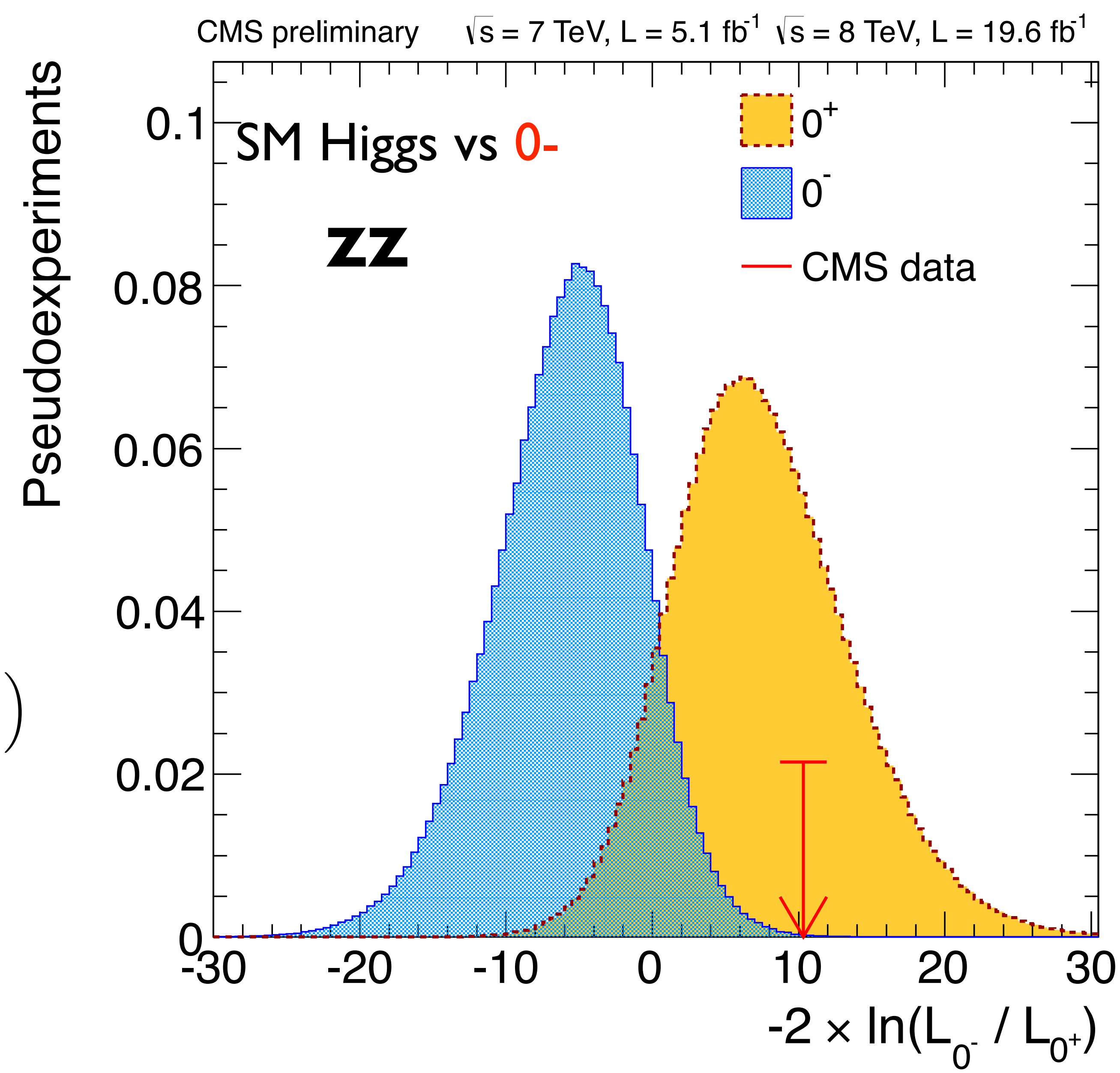
Parity Results

- Parity (assuming spin 0)
  - Data is more consistent with 0+
  - disfavors a pure CP-odd state
- Fit the fraction of 0^-
  - CP violating component (g1, g4)

$$A_{J=0}(X \to V_1 V_2) = v^{-1} \left(g_1^{(0)} m_V^2 \epsilon_1^* \epsilon_2^* + g_4^{(0)} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu} \right)$$

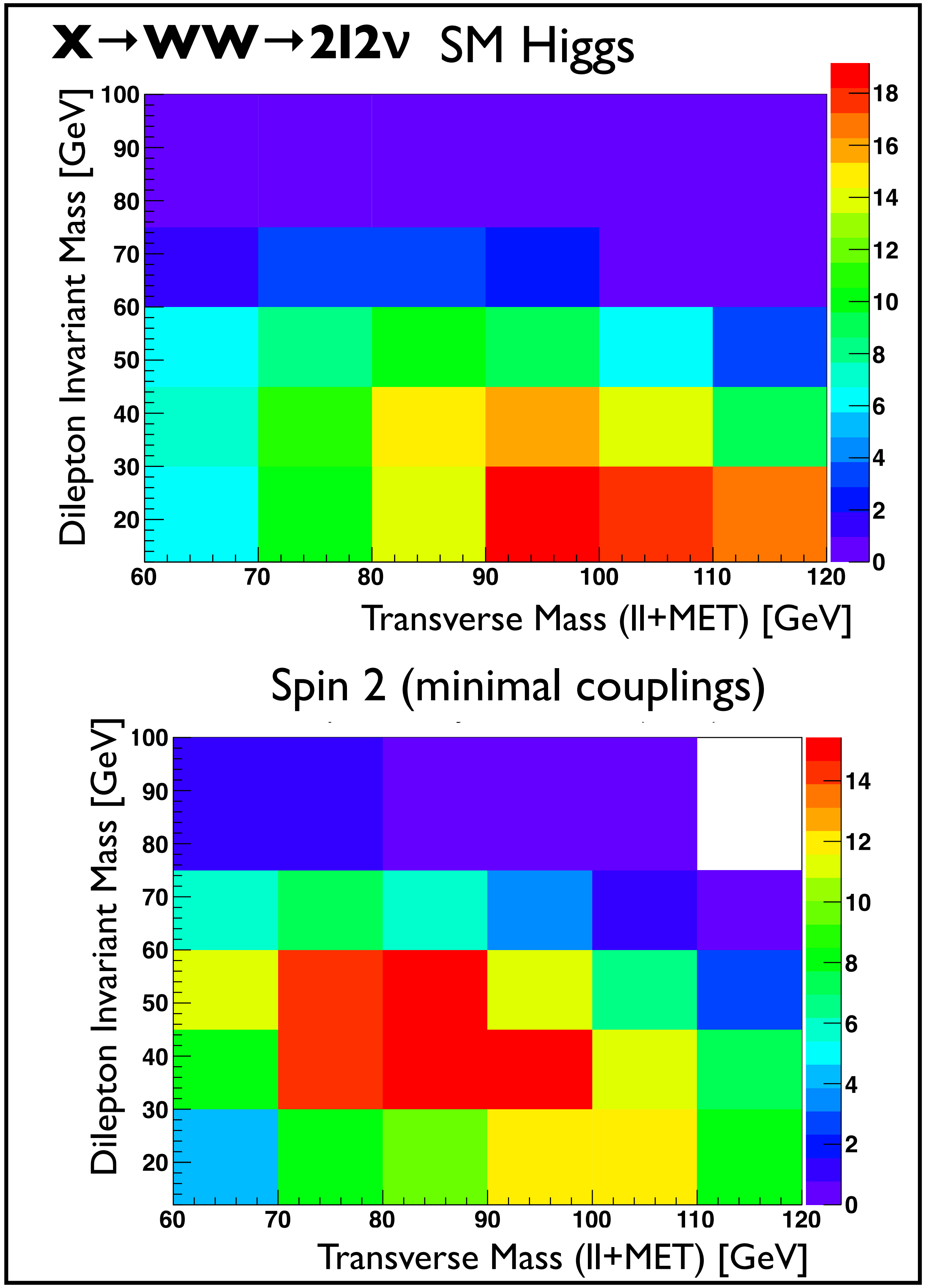
$$\texttt{frac}(0^-) = 0.00^{+0.23}_{-0.00}$$

  - Increasing important as luminosity goes up



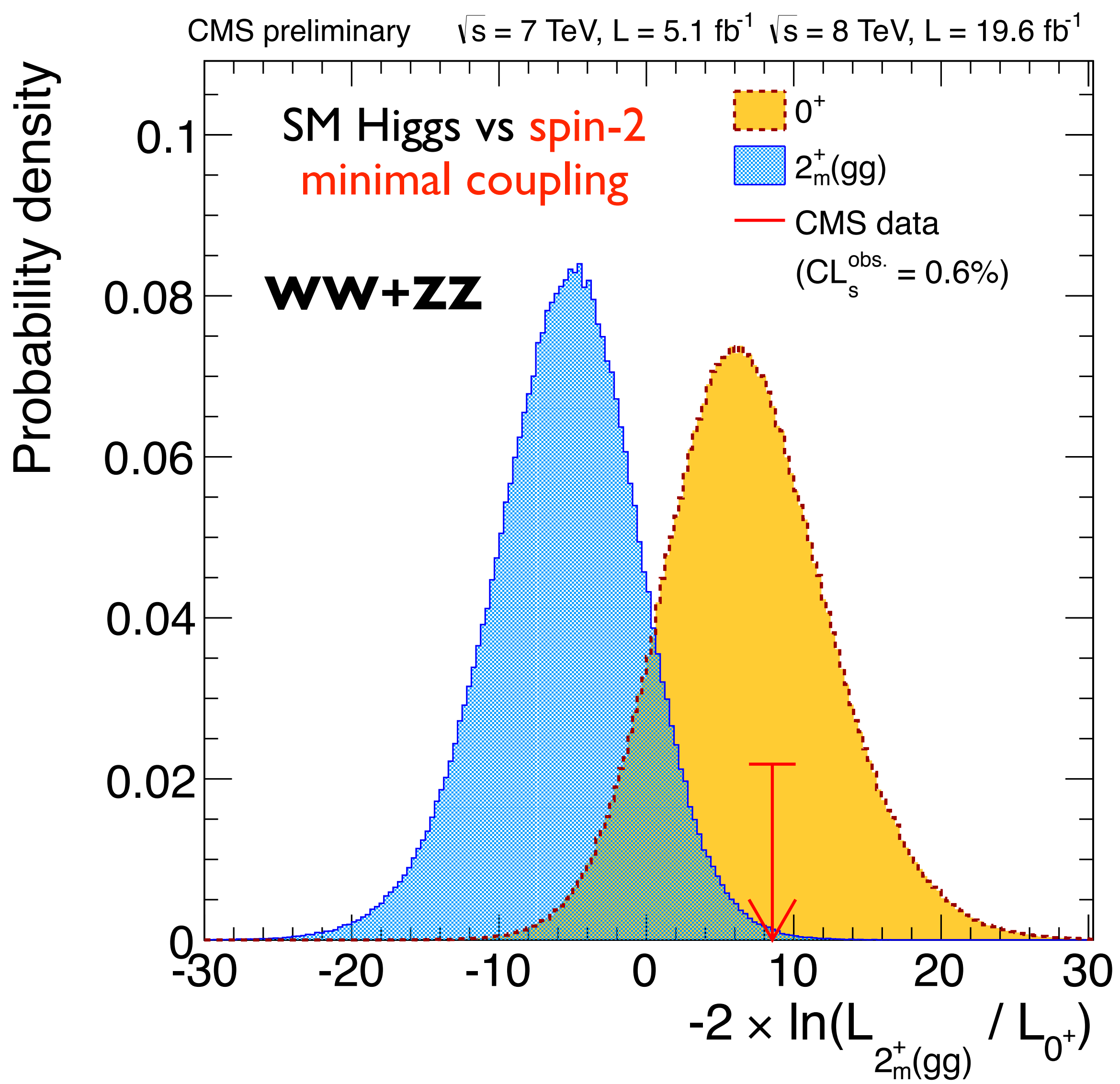
Explore Higher Spin Hypotheses

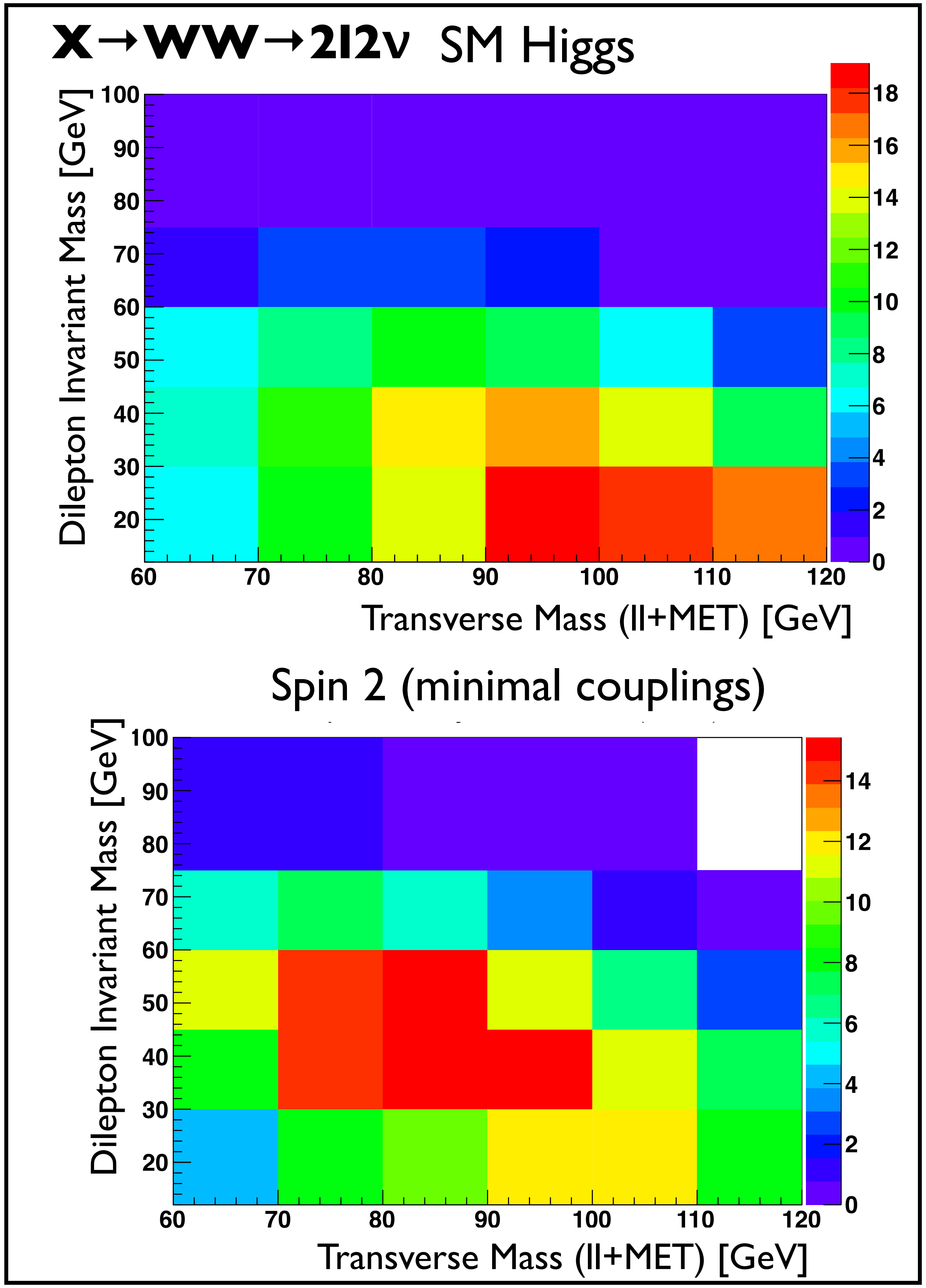
- Explore both ZZ and WW final states



Explore Higher Spin Hypotheses

- Explore both ZZ and WW final states
- **Data is more consistent with spin 0**
  - disfavors several spin-1 and 2 bench marks
    - with < 5% CLs value





Summary and Outlook

Is the particle the SM Higgs boson?

Mass	125.7 ± 0.3 (stat) ± 0.3 (syst) GeV
Overall signal strength	0.80 ± 0.14
Couplings with SM particles	Consistent with SM prediction within large errors
Spin and parity	Data favors the SM prediction 0+

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- **Still early to tell ← many impostors!**
- The spin and parity studies are currently model dependent and not conclusive
- The coupling measurements are not precise enough to test many other BSM scenarios

Predicted deviations in couplings compared to the SM Higgs mechanism

R. Gupta et al, ariXiv:1206.3560

	ΔhVV	Δhtt	Δhbb
mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
MSSM	<1%	3%	10%-100%

- Need more data to reveal its true nature and establish its connection with the EWSB

How well can we measure the Higgs couplings at (HL)LHC?

nominal LHC

2013 → LS1 → 2015-2017 → LS2 (phase 1 upgrade) → 2019-2021

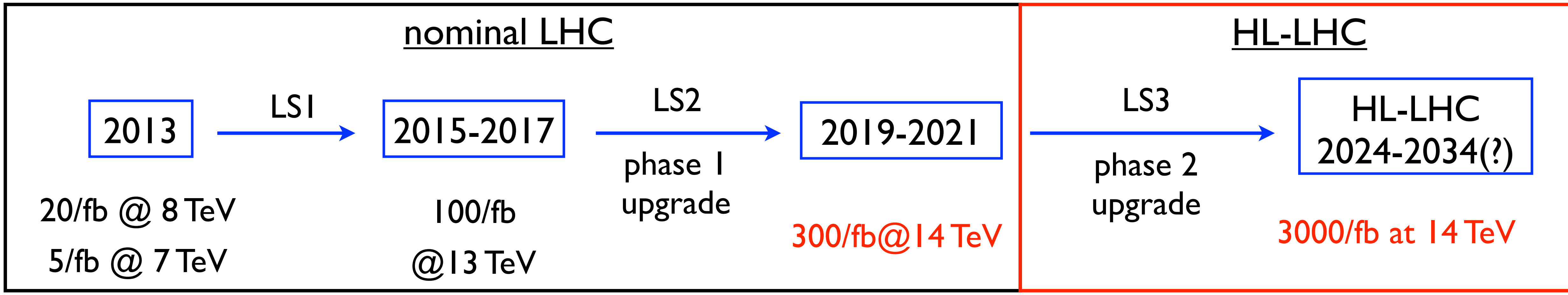
- 2013: 20/fb @ 8 TeV, 5/fb @ 7 TeV
- 2015-2017: 100/fb @13 TeV
- 2019-2021: 300/fb@14 TeV

HL-LHC

LS3 (phase 2 upgrade) → HL-LHC 2024-2034(?)

- HL-LHC 2024-2034(?): 3000/fb at 14 TeV

How well can we measure the Higgs couplings at (HL)LHC?



- Higgs coupling measurements projected with two types of scenarios
  - **Scenario 1**: systematic uncertainties stays the same
  - **Scenario 2**: theory uncertainties halved and experimental uncertainties scales with $\sqrt{L}$

%	300 / fb		3000 / fb	
	Scenario 1	**Scenario 2**	**Scenario 1**	**Scenario 2**
$\Delta h\gamma\gamma$	6.5	5.1	5.4	1.5
ΔhVV	5.7	2.7	4.5	1.0
Δhgg	11	5.7	7.5	2.7
Δhbb	15	6.9	11	2.7
Δhtt	14	8.7	8.0	3.9
$\Delta h\tau\tau$	8.5	5.1	5.4	2.0

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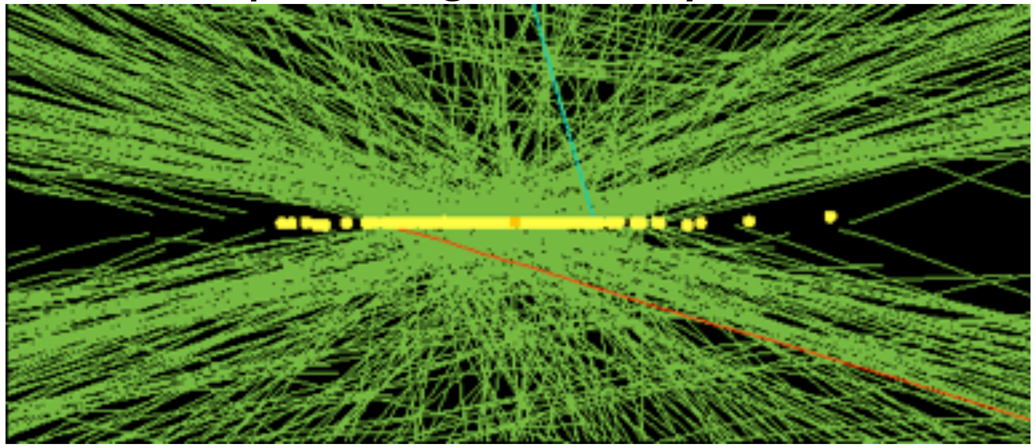
event with **78 vertices** reconstructed from a special high intensity run



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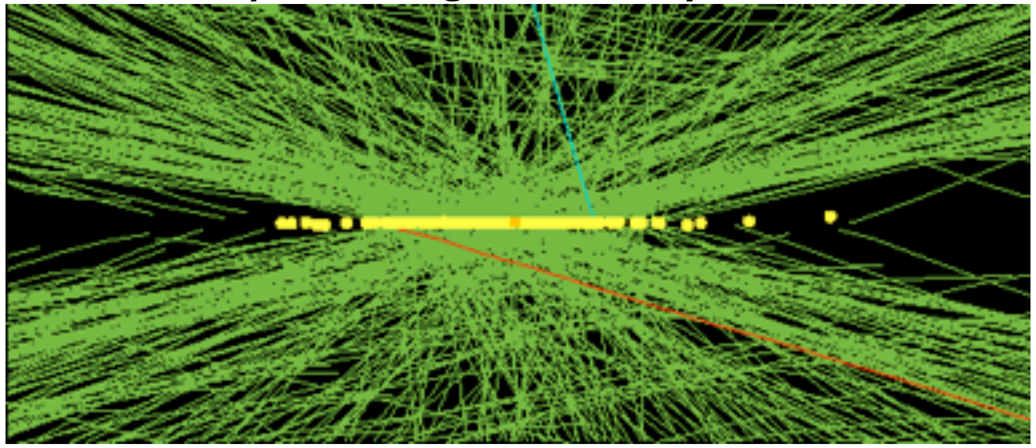

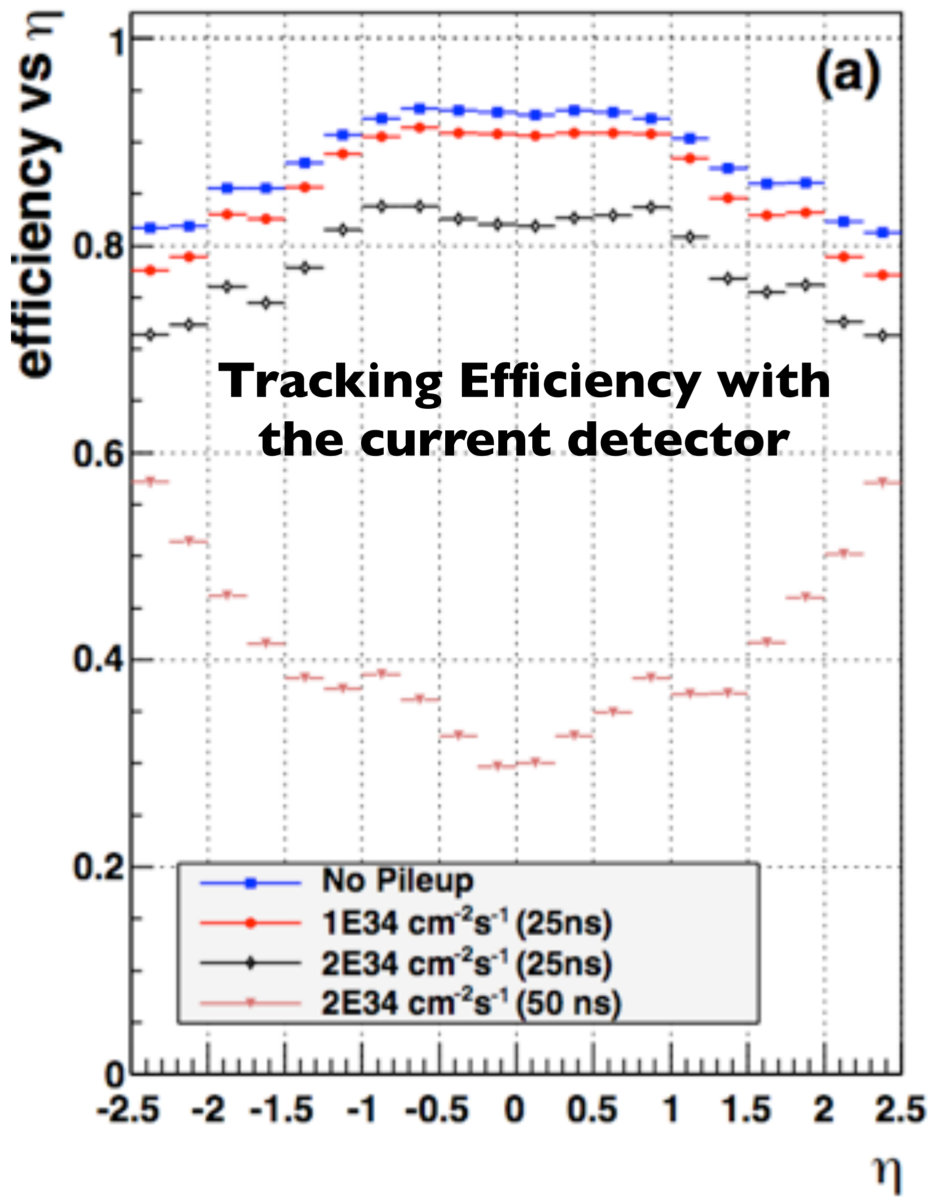

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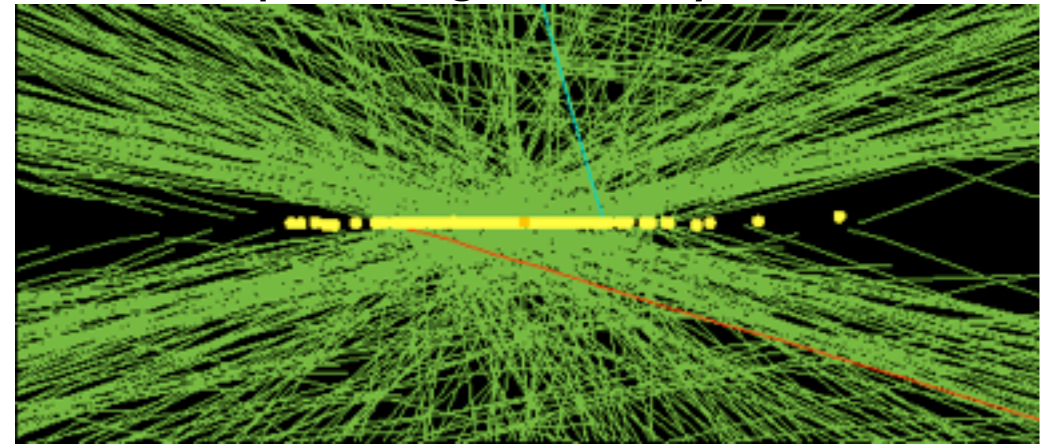
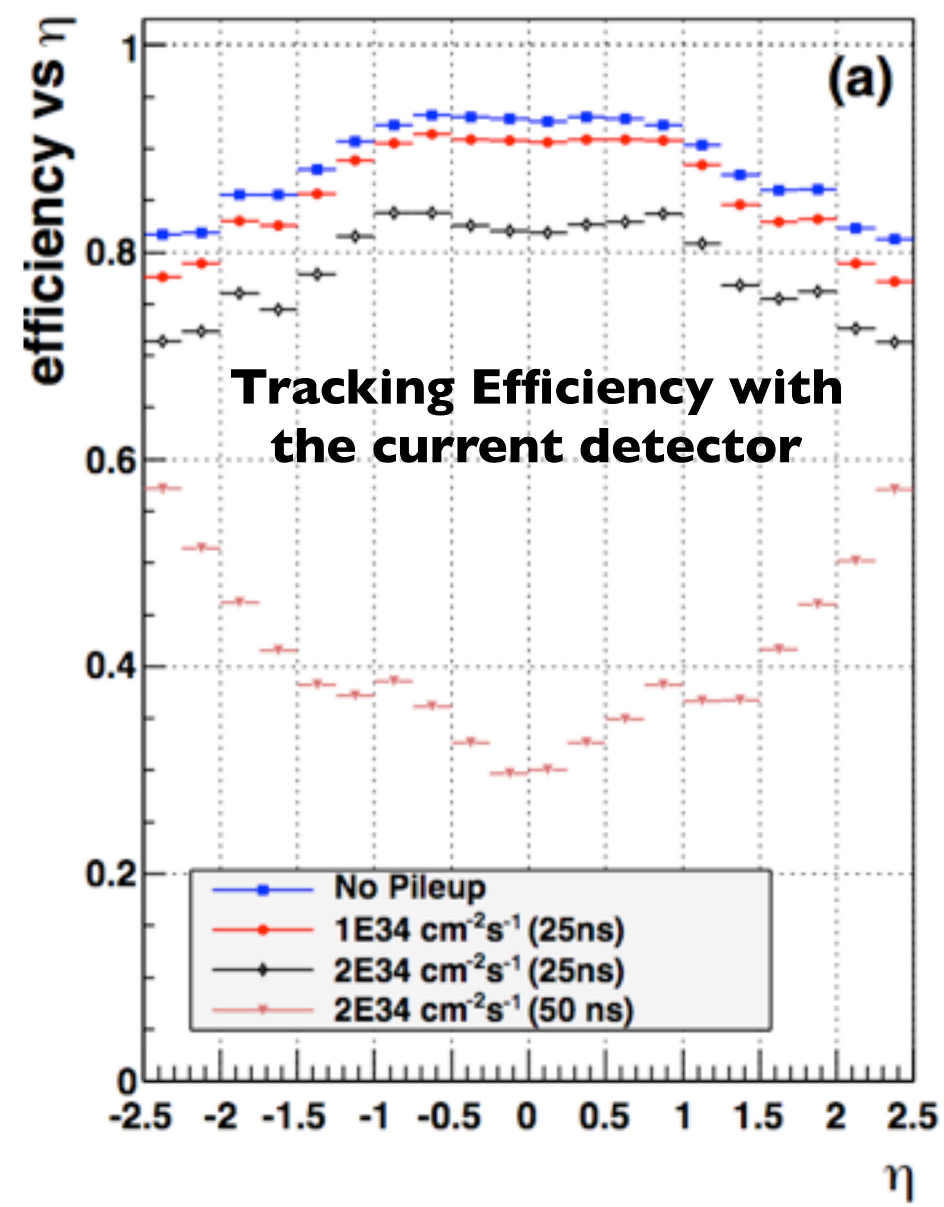
- The high pileup environment poses severe challenges to the physics object performances
    - Expect degradation in lepton efficiency, MET resolution and b-tag efficiencies etc
- Detector upgrades are necessary to maintain or improve current performance in face of high PU
    - Especially the objects with low-medium pT, the typical decay products of the light new particle
    - **These upgrades are underway (pixel/ Tracker/HCAL/ECAL etc)**

event with **78 vertices** reconstructed from a special high intensity run





Conclusion

- **After Run1, LHC discovered a light Higgs candidate with 125 GeV**
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  - Precision measurements on the CP violating component (<~10% for 300/fb)
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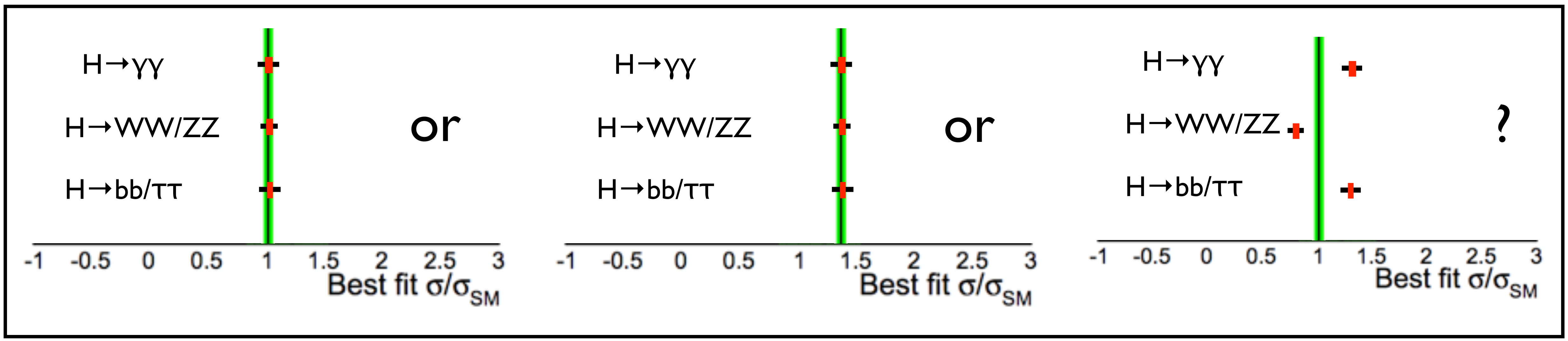
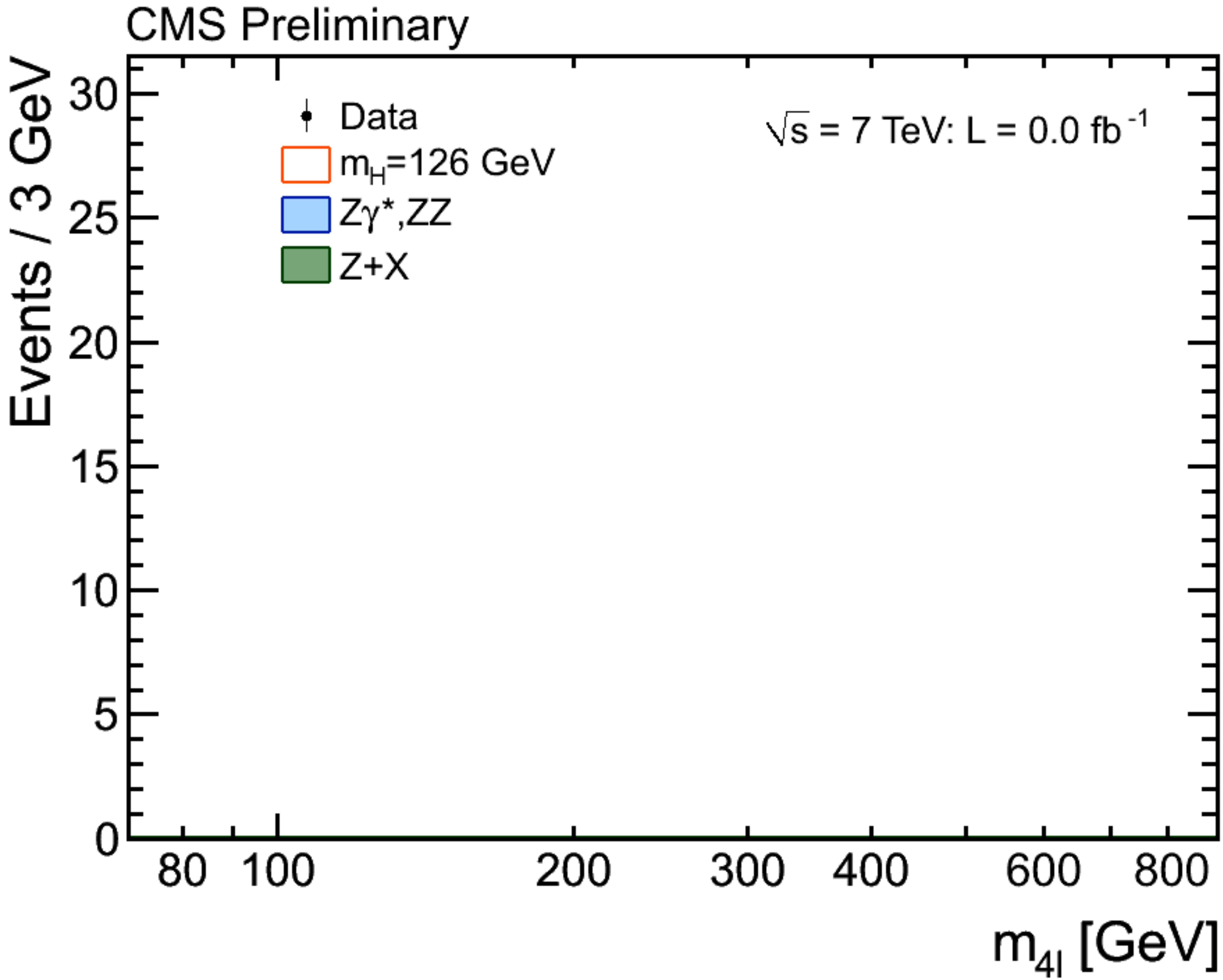


- **Together with some other positive NP signatures (hopefully), Higgs measurements can help shed light on the EWSB**



Friday, June 28, 2013

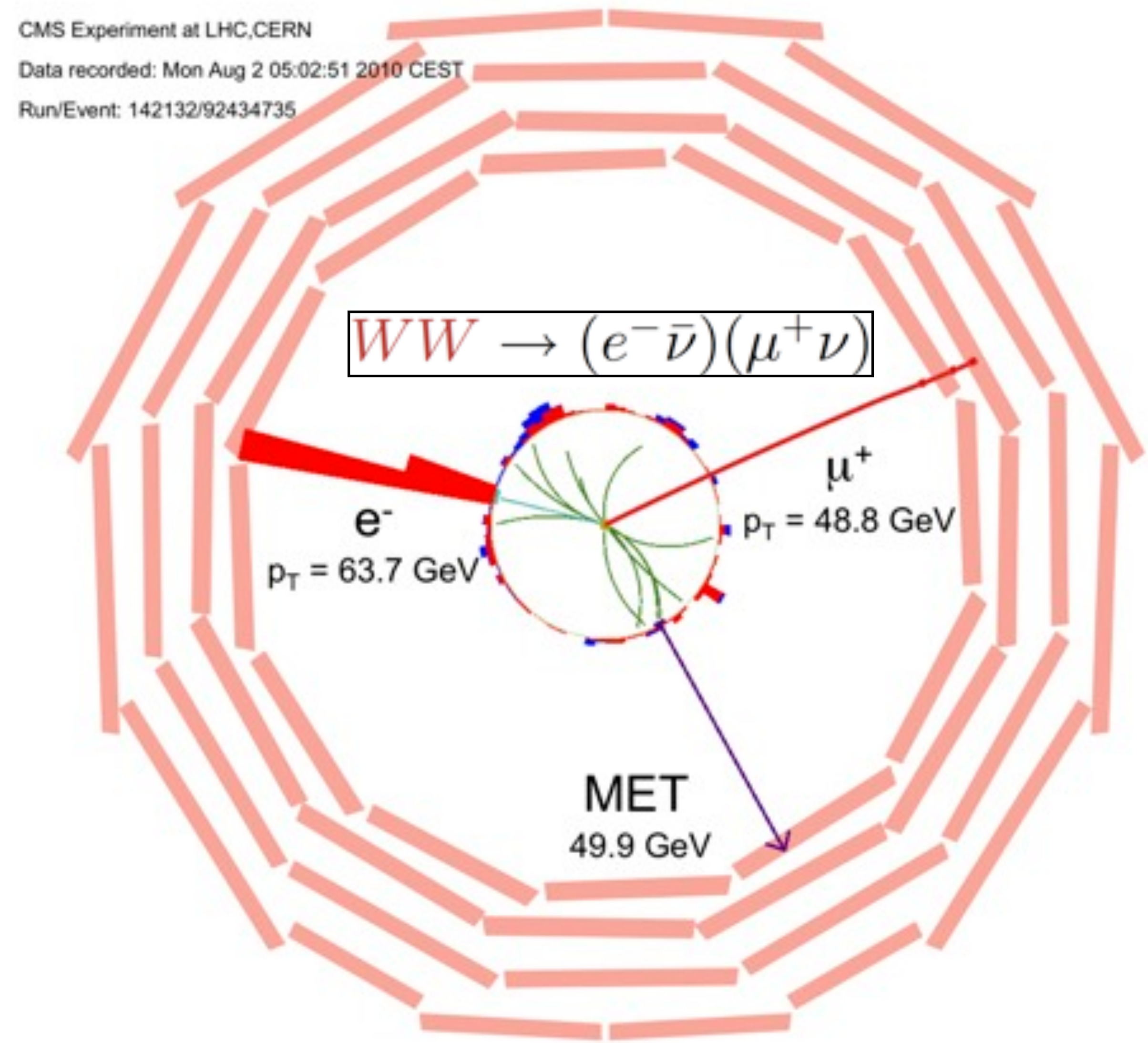
Backup Slides

The WW Selection

- Two oppositely charged isolated leptons

$$p_T^1 > 20\ GeV \qquad p_T^2 > 10\ GeV$$

- Large missing energy
  - Different flavor (eμ) final state:
    - MET > 20 GeV
  - Same flavor (ee/μμ) final state
    - Combine the MET related variables in a MVA to maximize DY reduction
- Top veto
  - Remove events with soft muons or b-jets
- Dilepton pT > 30 GeV
  - Further reduce W/Z+jets and W/Z+γ/γ*

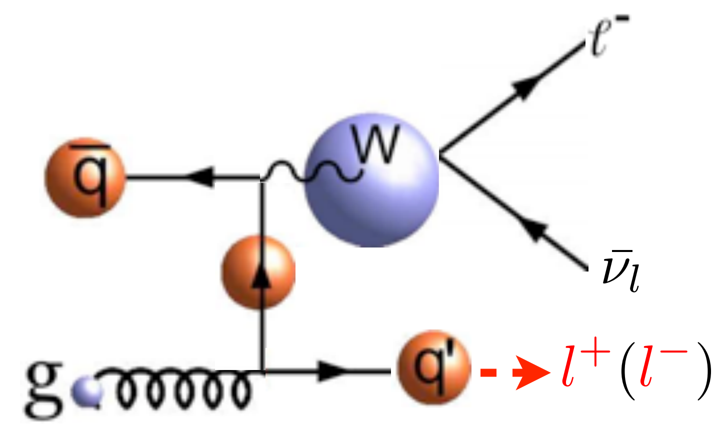


Expected backgrounds 12/fb at 8 TeV

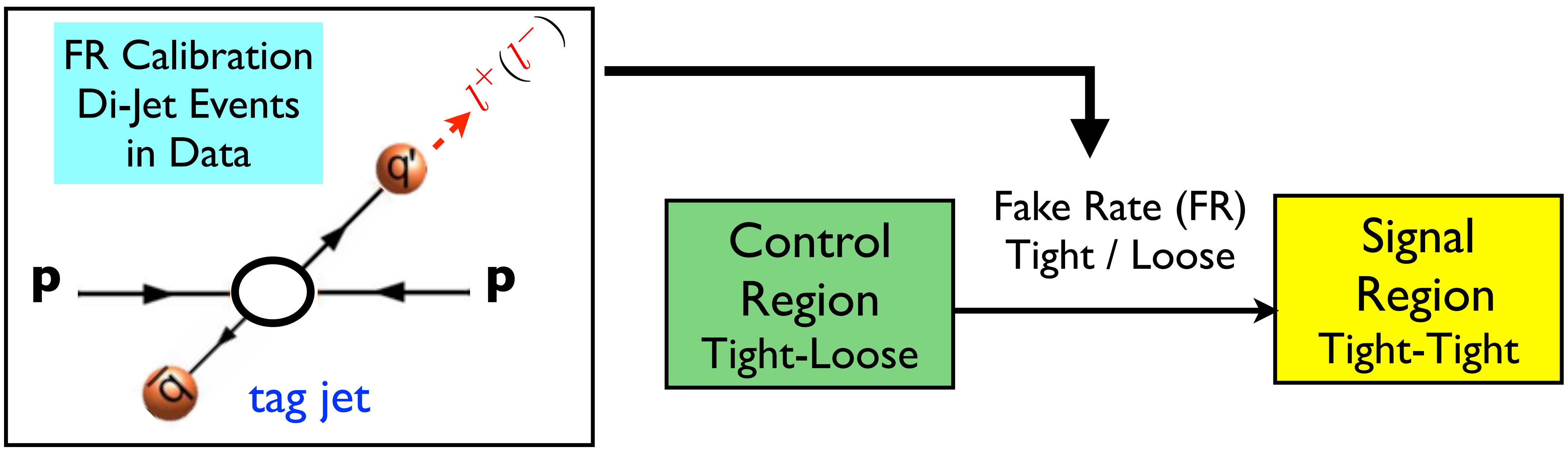
	All bkg	WW	Top	W+jets	Drell-Yan	WZ/ZZ	W/Z+γ(*)
0-Jet	4233 ± 220	3146 ± 192	417 ± 45	334 ± 91	128 ± 22	118.1 ± 7.1	89 ± 22
1-Jet	2899 ± 152	976 ± 111	1369 ± 56	288 ± 83	131 ± 28	88.6 ±5.6	46 ± 12
2-Jet	3229 ± 137	473 ± 21	1865 ± 100	220 ± 58	579 ± 70	51.2 ± 3.5	41.3 ± 3.9

W+Jets Background Estimation

- W+Jets events are reduced by tight lepton identification and isolation criteria
  - The residual background is due to jets faking the leptons



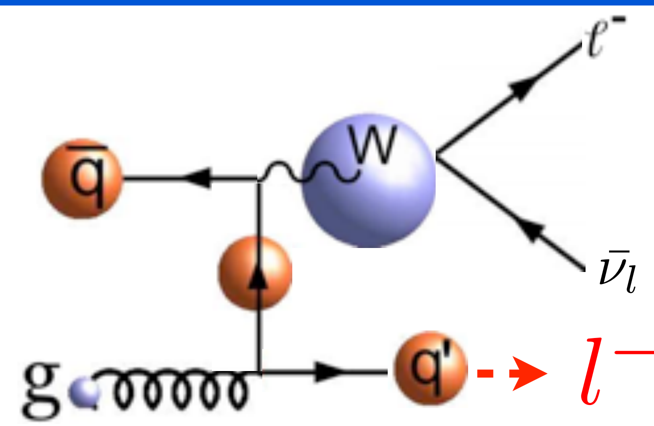
- The residual background is estimated in a data-driven way

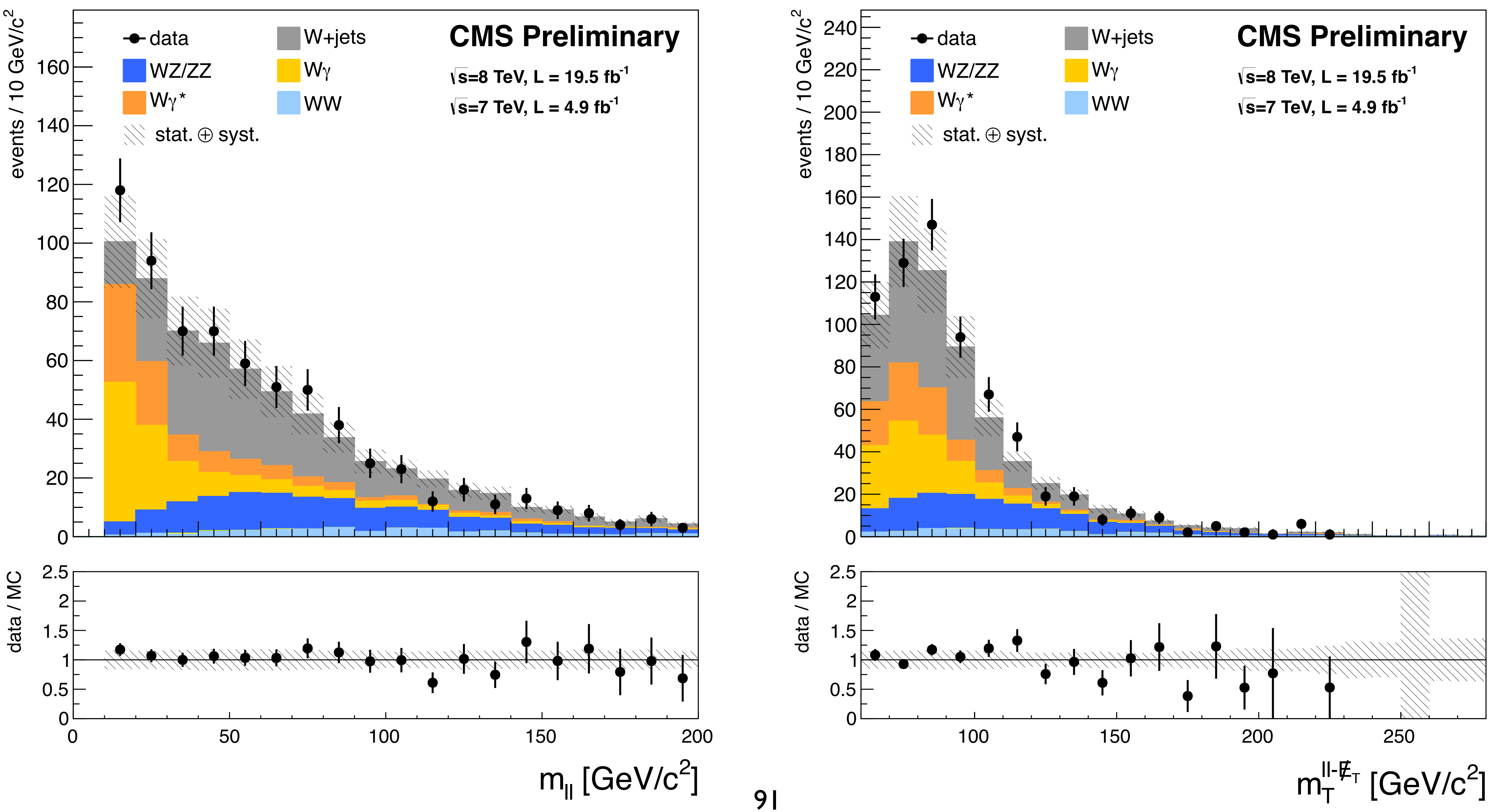


- The systematic uncertainty is ~36%
  - How well does the kinematics of the fake lepton progenitors in di-jet events match the W+Jets events

Same sign W+Jets Control Region

- Cross-check the data-driven method in a second W+jets control region "same sign events"
    - Both normalization and kinematic shapes are well modeled





WW Background Estimations

- For low mass Higgs, there is a signal free WW control region to estimate WW background

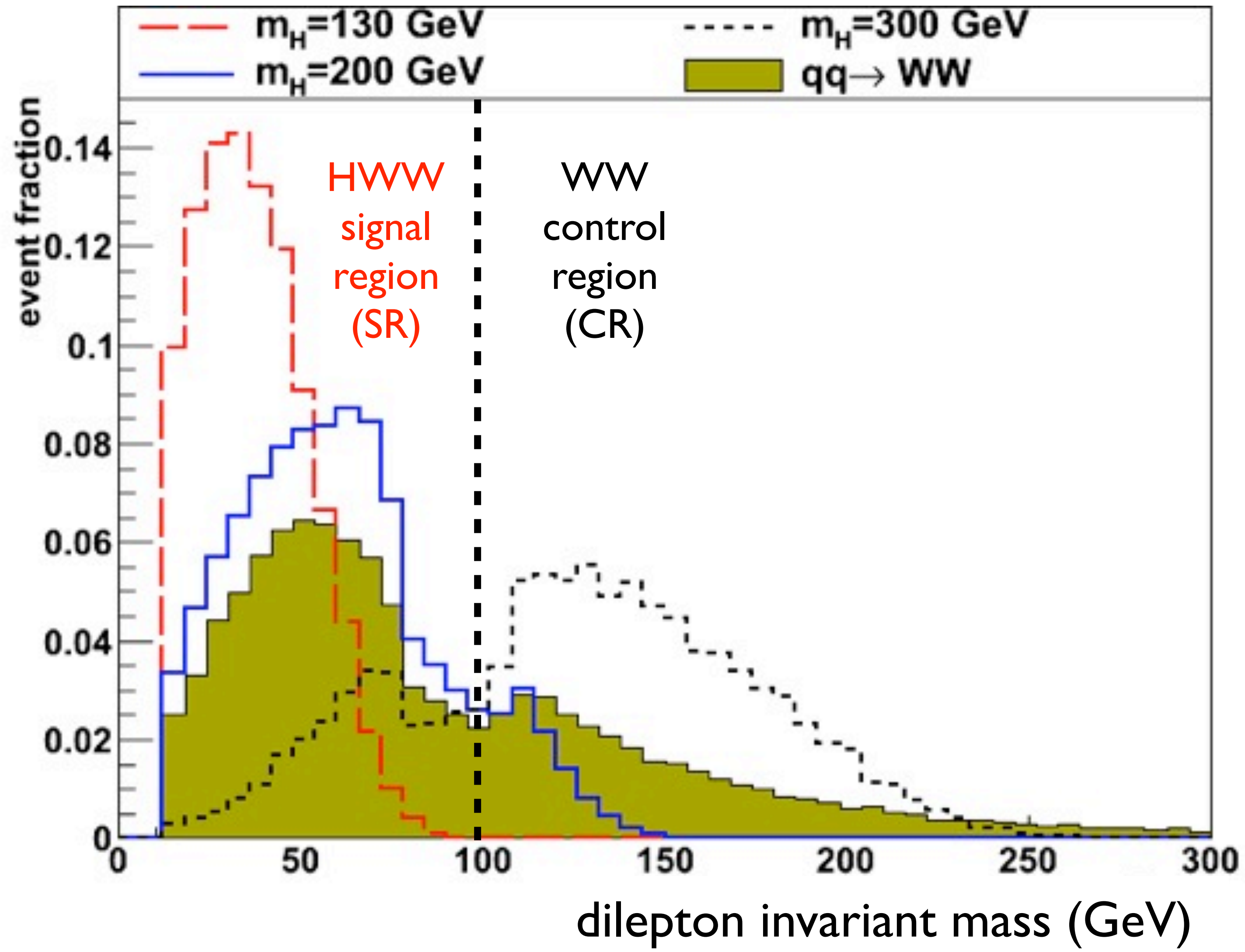
$$N_{\rm S}^{\rm data} = N_{\rm C}^{\rm data} (N_{\rm S}/N_{\rm C})^{\rm MC}$$

Theoretical uncertainties are assigned

1) PDF variations

2) QCD scale variations

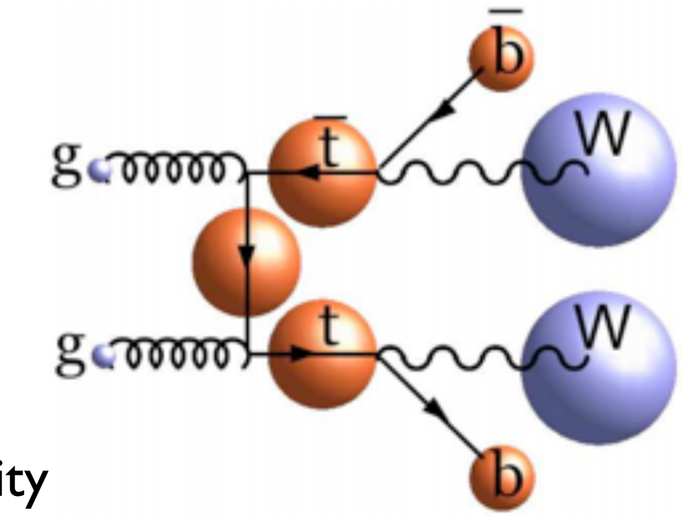
3) Parton showering



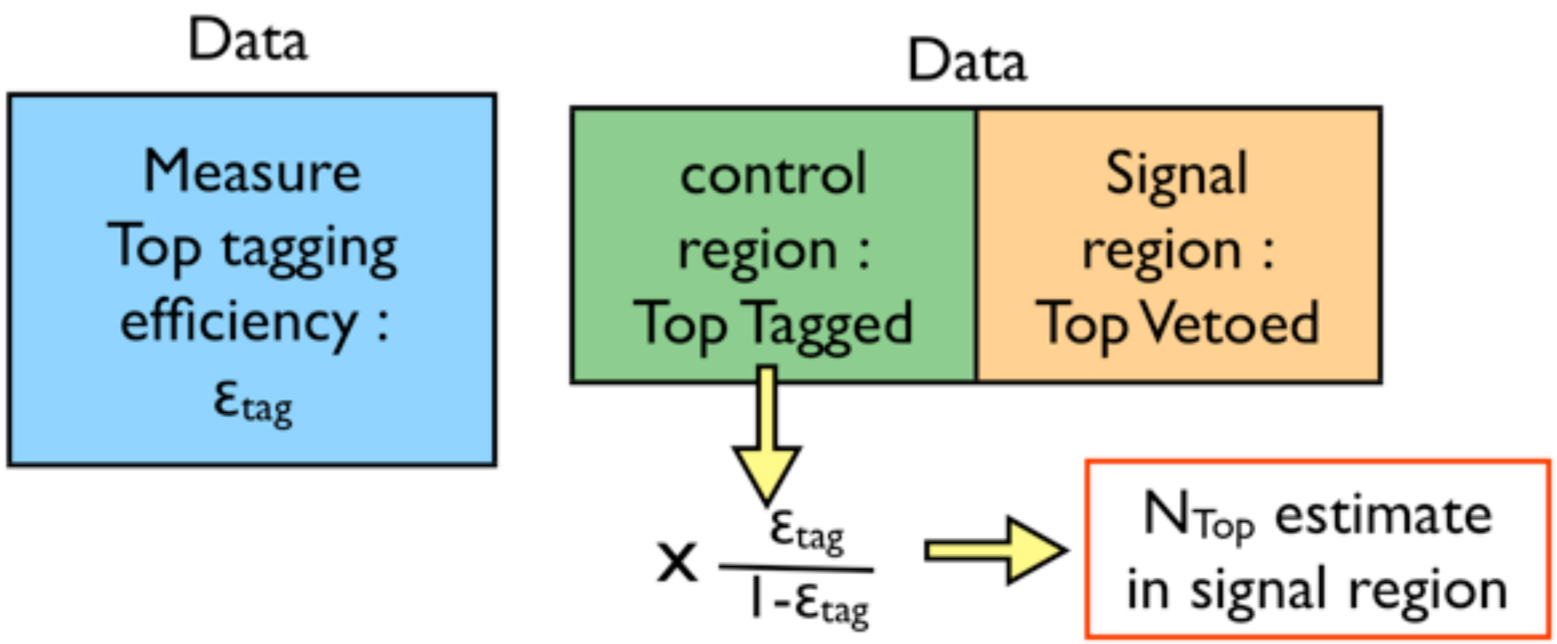
  - The systematic uncertainty is ~10%(20%) for 0(1)-Jet bin

- For high mass Higgs, there is no signal free region
  - We rely on MC to estimate the WW background primarily for the cut-based
  - For the shape based analysis, the WW yield is determined from the fit

Top Background Estimation



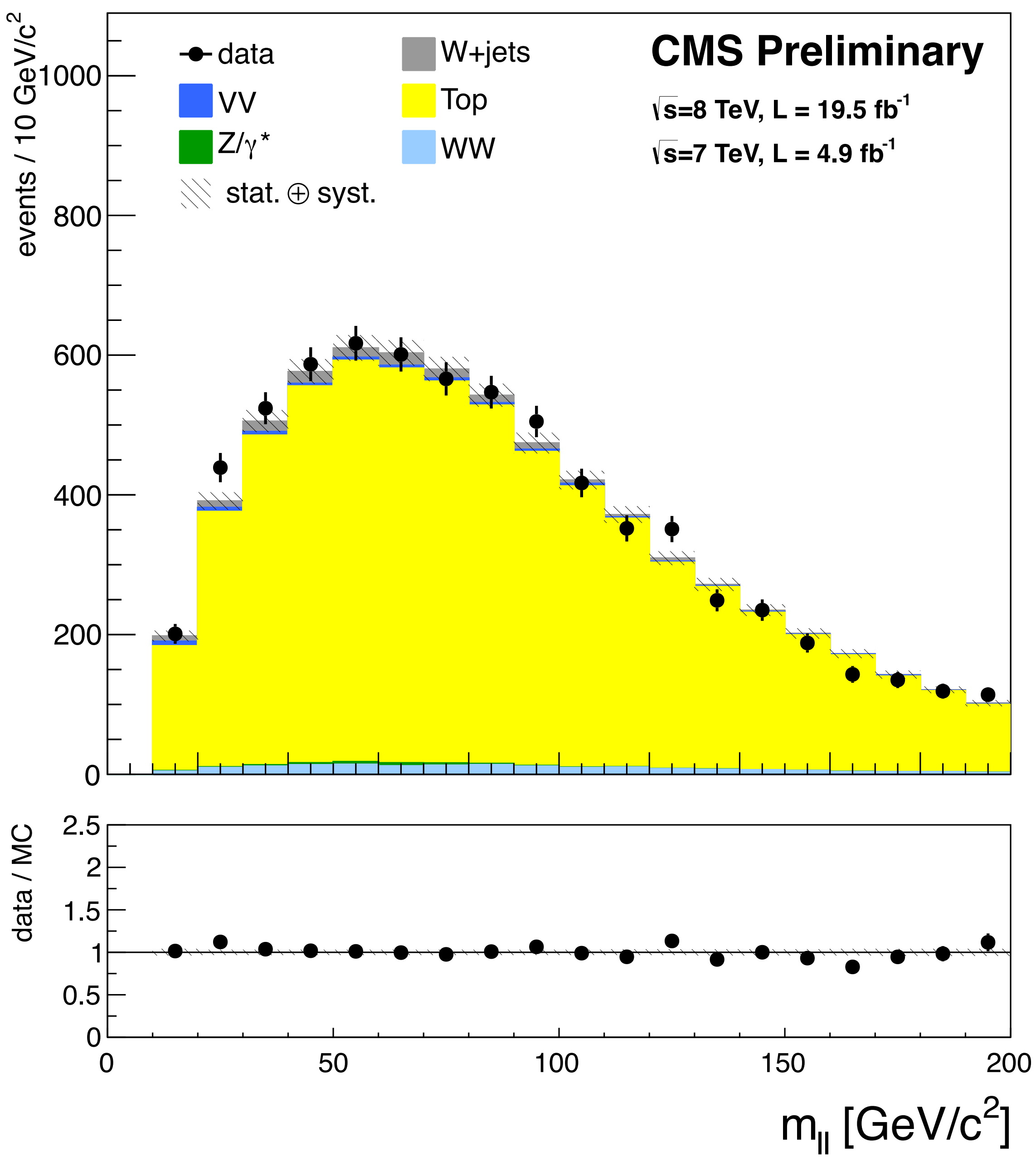
- The top background is reduced by vetoing events with b-quark
  - Top-tagging: look for b-quark signature (soft muons and b-tagged jets)
  - The residual background contributes mostly to events with jets
    - Top background in events with 0-jet is much smaller → better sensitivity
- The residual top background is estimated using data-driven methods

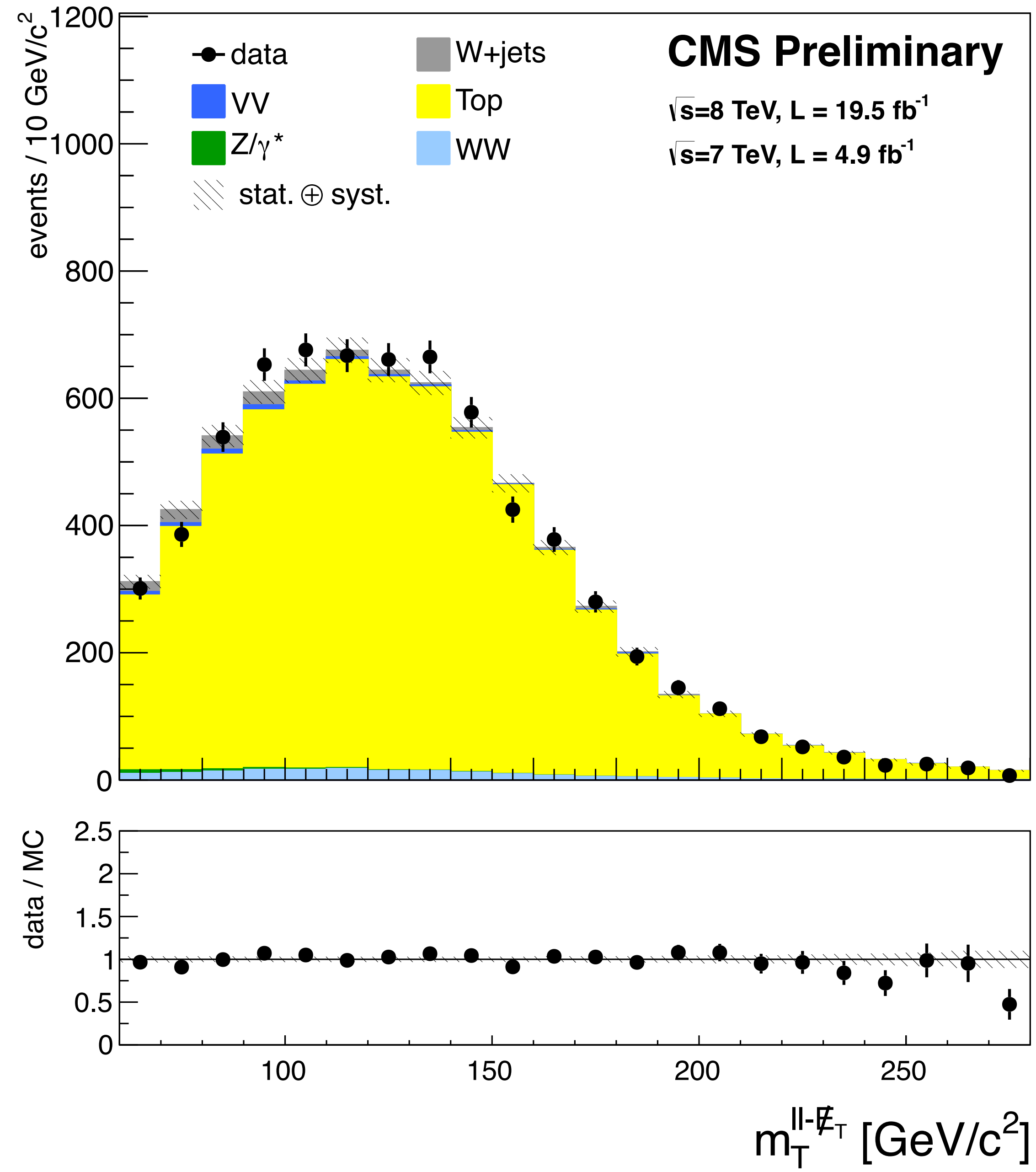


- The systematic uncertainty is ~20% (5%) in the 0-Jet (1-Jet) bin
  - 0-Jet: theory calculations of relative tW and ttbar compositions
  - the statistics in the top-tag control region

Kinematics in Top Enriched Region

- Perform the same signal fit on top enriched region
    - different flavor events with 1-jet (b-tagged)

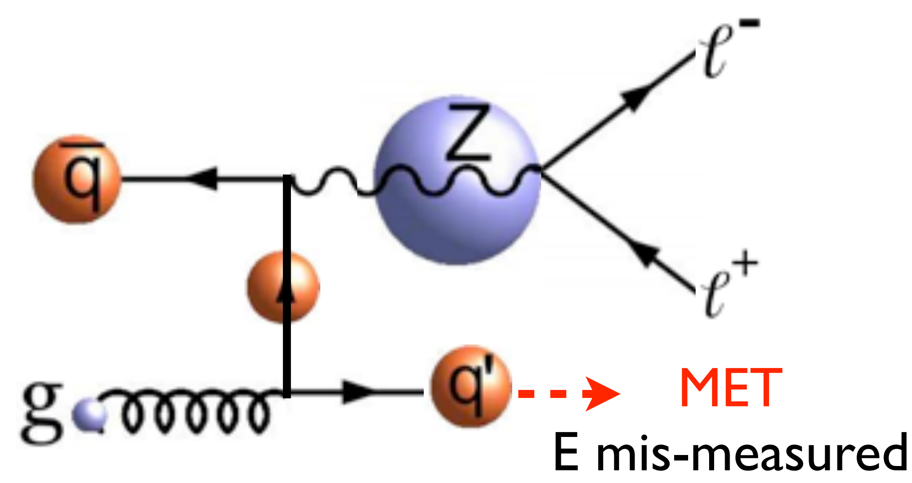




- Top in data is consistent with the data-driven background estimates

Drell-Yan Background Estimation

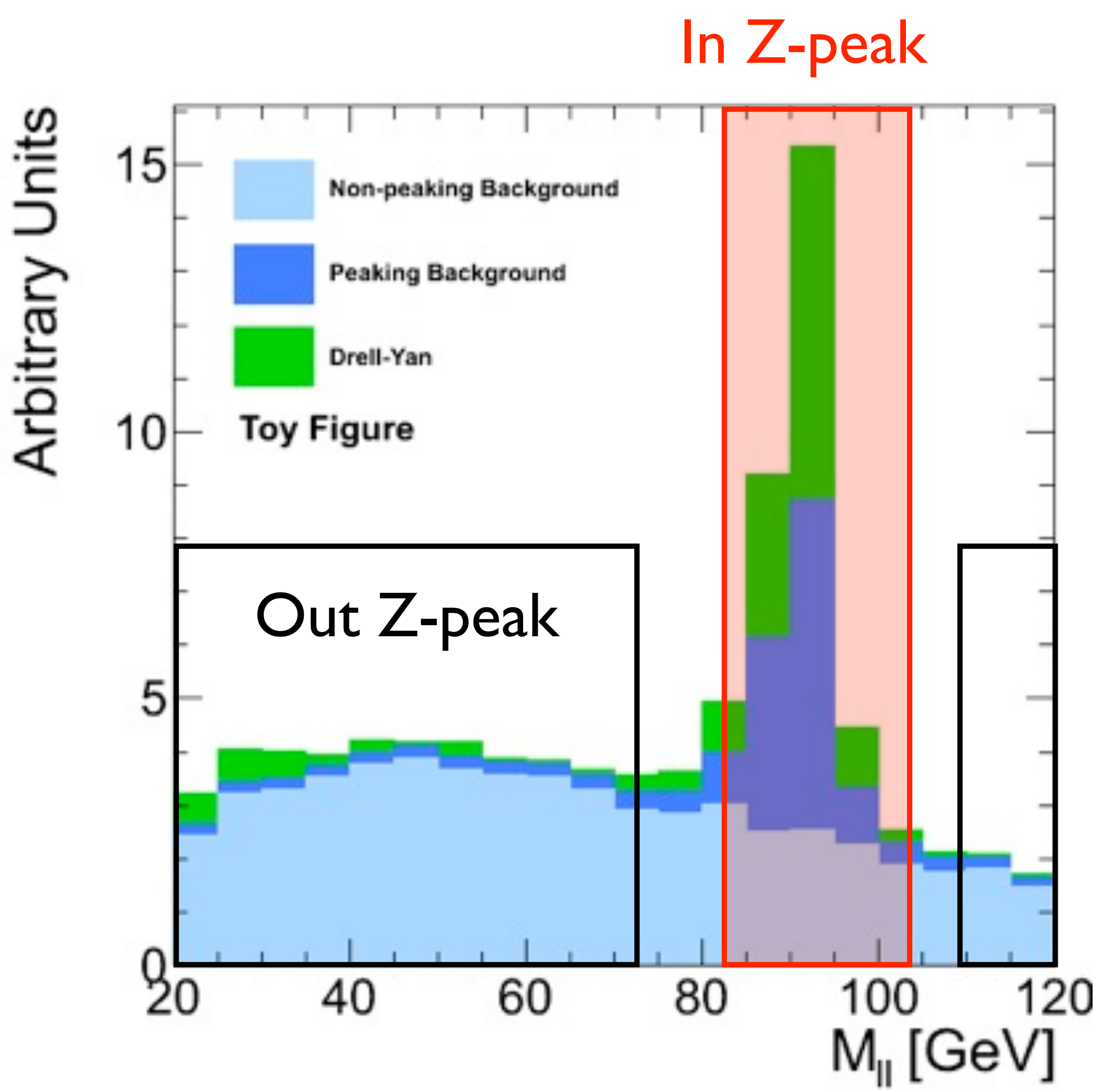
- Understanding the Drell-Yan background is crucial in the ee/μμ channels
  - This background arises due to mis-measured MET, which is difficult to model in MC
  - Veto the events in the Z peak and apply tighter MET cut than eμ channel ⇒ worse sensitivity



- The residual Drell-Yan background is estimated

$$N_{\rm in}({\rm data}) \times \frac{N_{\rm out}}{N_{\rm in}}(MC)$$

  - Subtract the non-DY backgrounds such as WZ/ZZ (peaking) and Top and WW (non-peaking) in counting the events in Z-peak



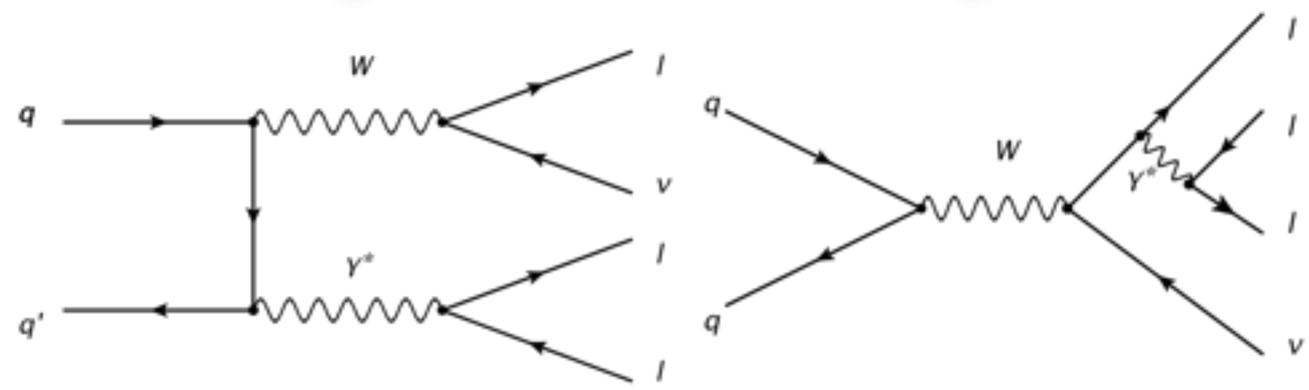
- The systematic uncertainty is ~50%, main limiting factor in these channels
  - mll modeling in MC (N_{out}/N_{in})
  - statistics in the N_{in}(data)

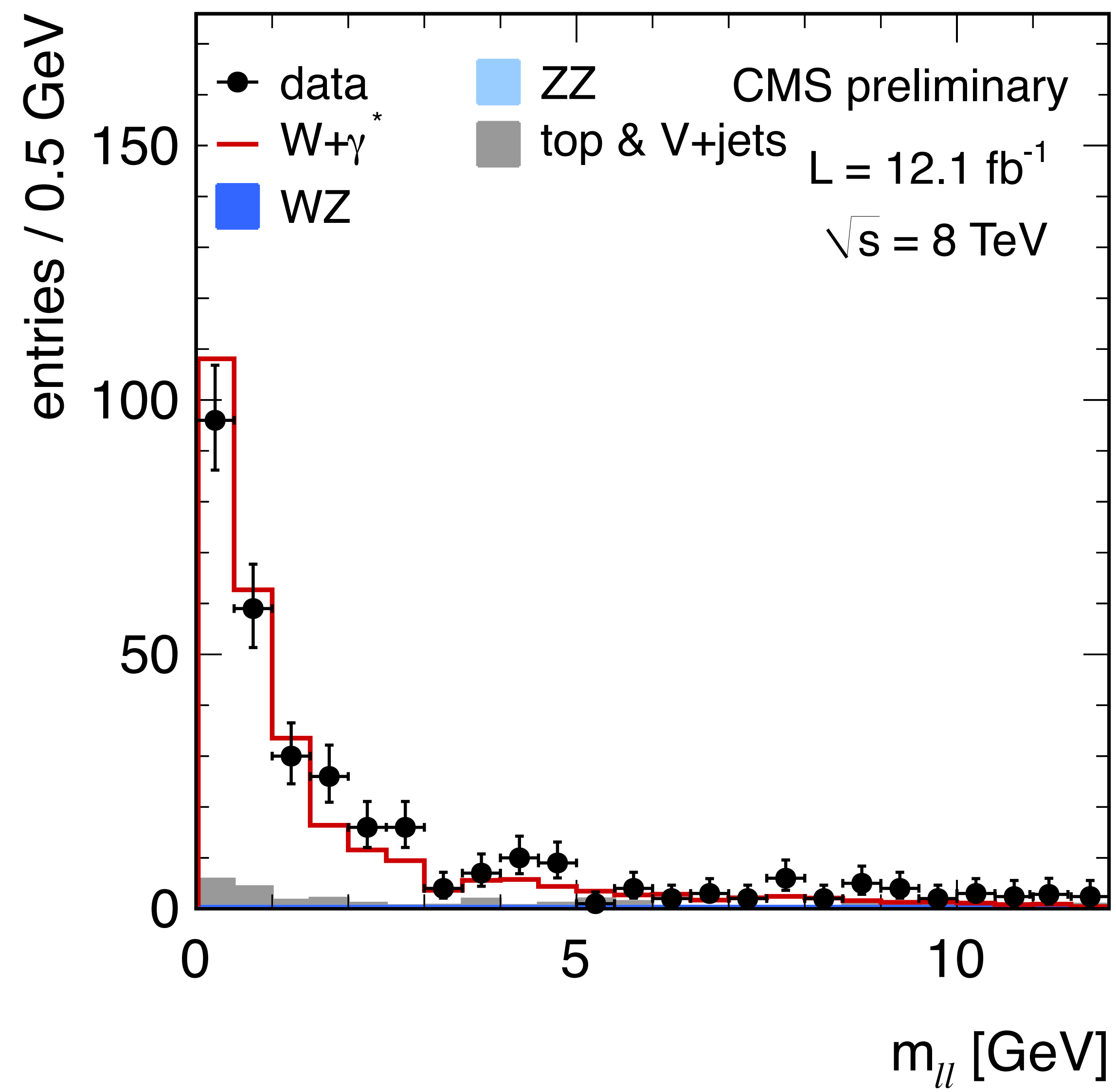
Wγ* Background

- Wγ* comes from ISR and FSR
  - The dileptons from the γ* internal conversions are generally of low pT
    - One of the dilepton is easily mis-reconstructed in the detector
  - Low (mll, mT) signature
    - Reduce by pT(ll) > 45 GeV, mT >80 GeV
- For mγ* > 12 GeV, It is included in WZ/γ*
- For low mγ* < 12 GeV, we use a dedicated MC with the cross-section normalized to data in 3-lepton control region
  - Wγ*→l(μ⁺μ⁻)
- The systematic uncertainty is ~ 30%
  - Compare e(μμ) and μ(μμ) k-factors
  - Compare kfactors in different ranges of mll (test of the mll spectrum)

Wγ* ISR

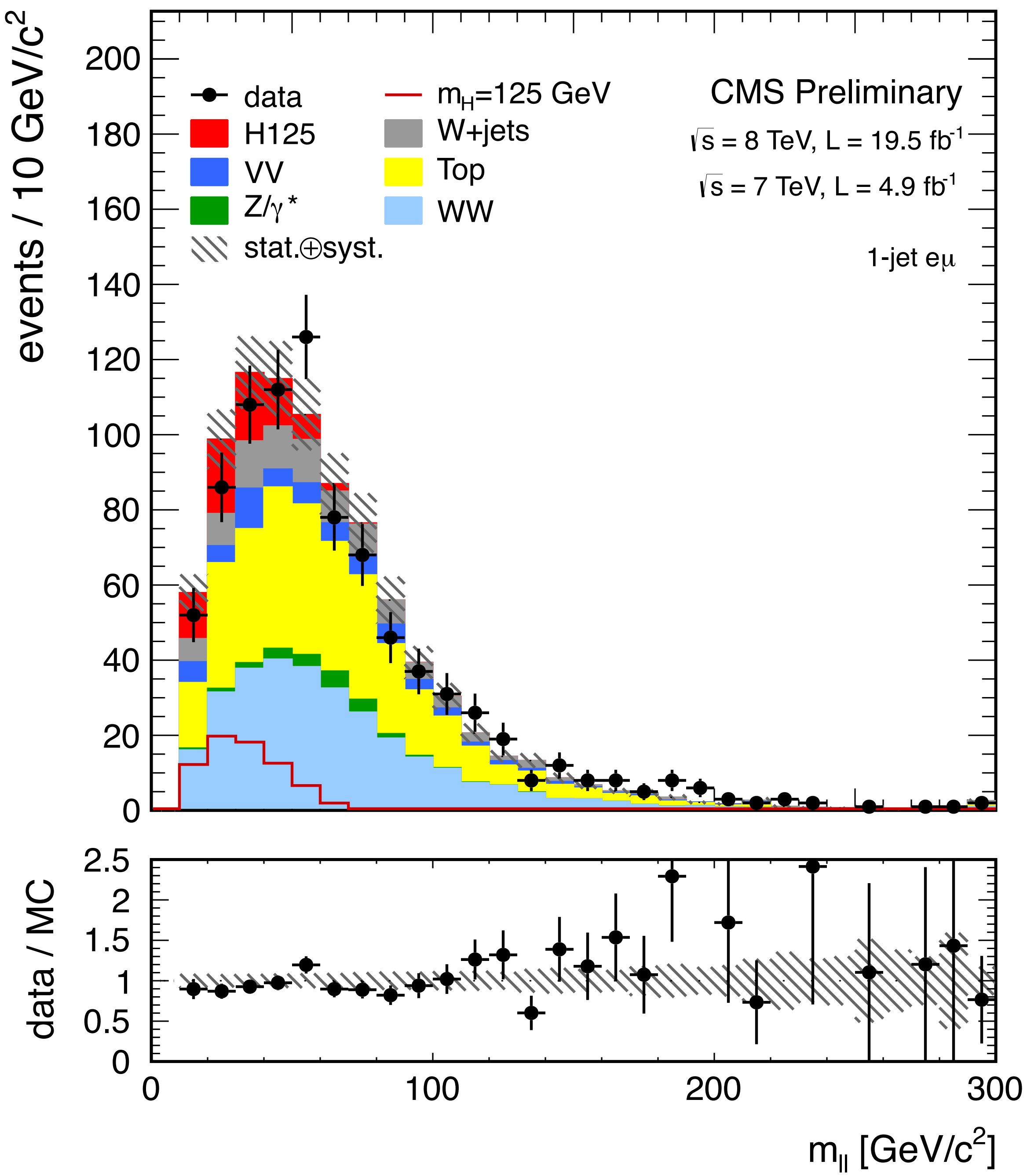
Wγ* FSR

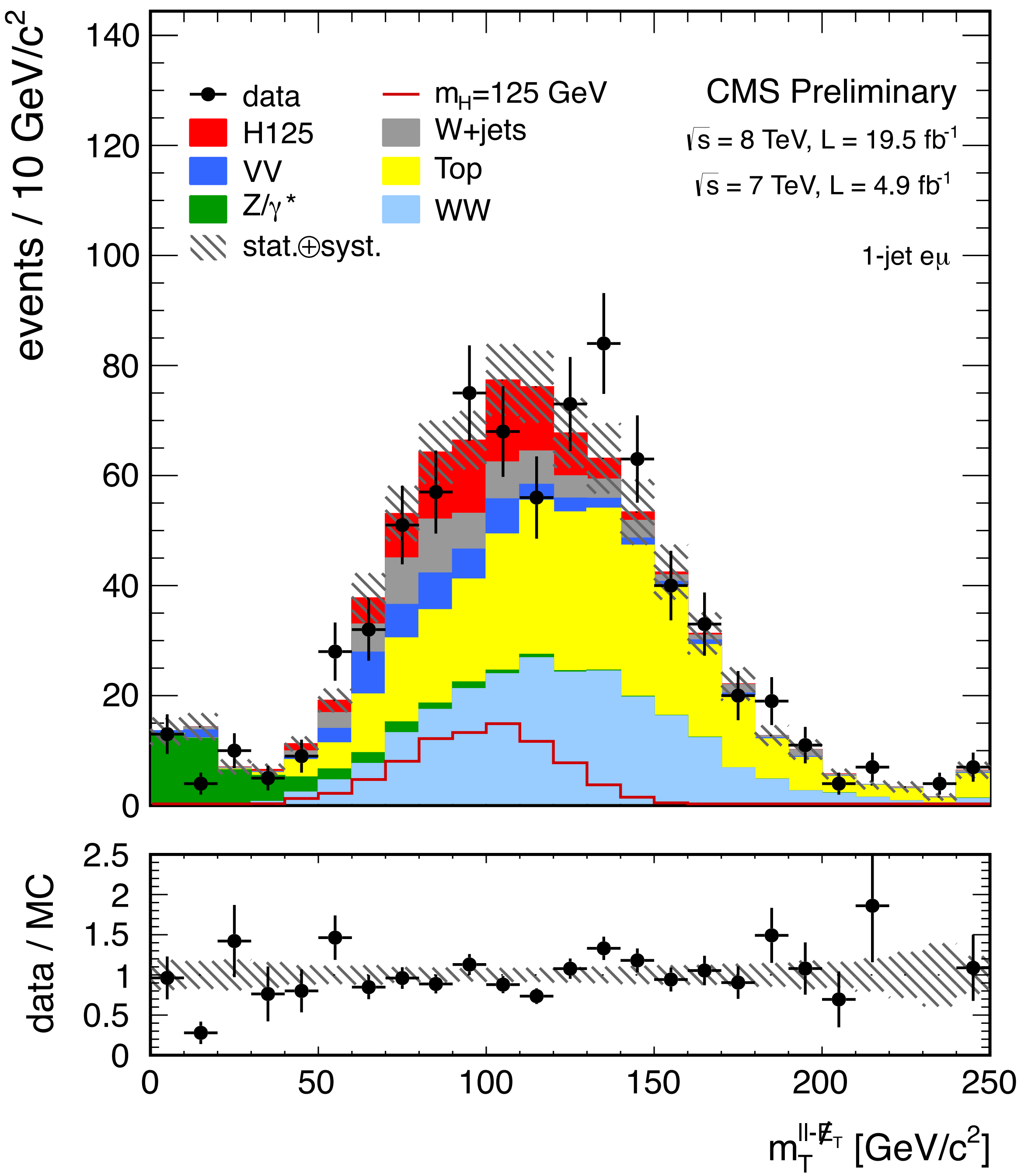




Kinematic Distributions in Signal Regions (1-Jet)

- Closer look at the signal region, apply all cut-based selections except the variable plotted
  - Kinematic distributions agree well with the SM Higgs + background hypothesis





Systematics on Overall Yields

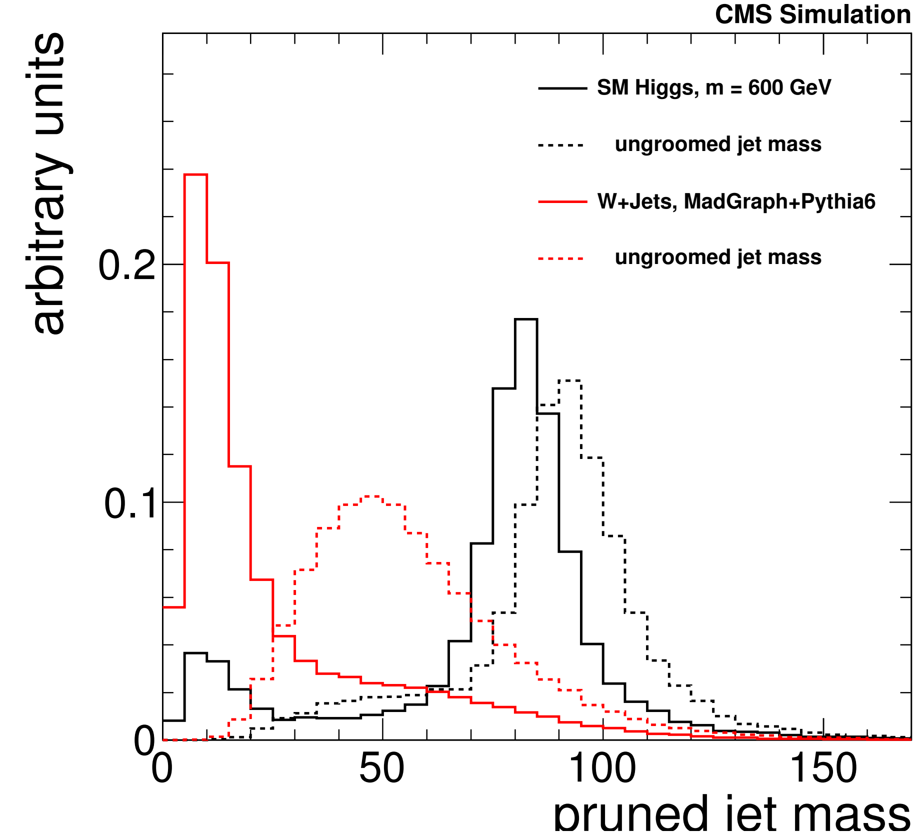
- Overall signal efficiency uncertainty is ~20%
  - dominated by theoretical uncertainties on missing higher order effects and PDF variations
- Overall background uncertainties are ~10% in the HWW signal region
  - W+jets: ~ 36%
  - Top: ~20% (0-Jet) and ~5% (1-Jet)
  - $W\gamma^*$: ~30%
  - Drell-Yan: ~50% (0-Jet), ~20% (1-Jet)
- For all background estimations based on MC prediction, consider
  - Luminosity: 4.4% for 8 TeV and 2% for 7 TeV
  - Lepton selection efficiency (3-4%), momentum resolution (~2%)
  - MET resolution ~2%
  - Jet energy scale resolution ~2%

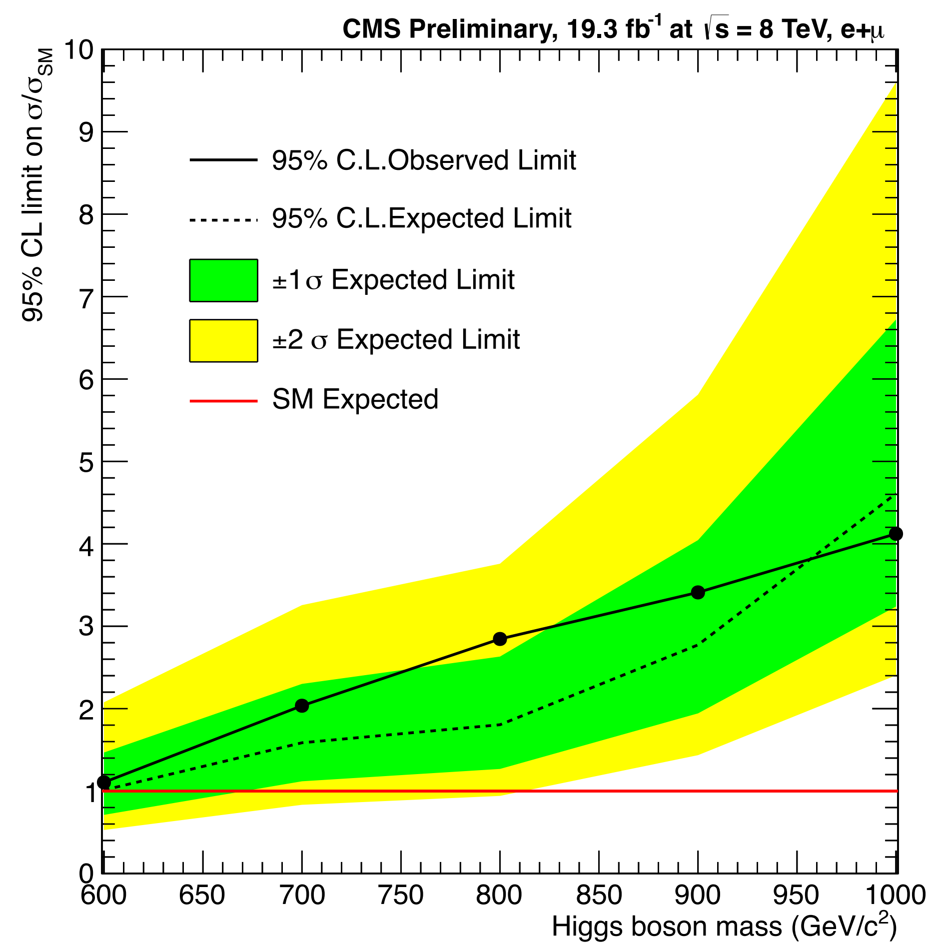
Shape Systematic Uncertainties

- Instrumental Uncertainties
  - Lepton selection efficiency and momentum scale
  - MET and JES resolutions
- WW Background
  - Difference between Madgraph and MC@NLO
  - QCD Scale variations on the renormalization and factorization scales evaluated in MC@NLO
  - PDF uncertainties (not included in HCP analysis, but verified afterwards)
- Wjets Background
  - Fakerate derived with a different away jet pT threshold in the QCD data
- Top Background
  - Difference between Powheg and Madgraph

High Mass Frontier H→WW→(lν)(qq/J)

- It is important to search for high mass resonances, even with the low mass Higgs candidate discovery
  - The EWSB is not yet confirmed
  - The m(WW) spectrum serves as an excellent probe to WW scattering amplitude unification and general doublet-Higgs models
- The hadronic decaying W is highly boosted into a single jet with high resonance
  - For mH=600GeV/1TeV
    - ~65%/82% of the W_{had} decay products are contained in a cone of ΔR< 0.8
    - Jet substructure technique is used to reconstruct the W_{had} in a single jet, reconstructed with Cambridge-Aachen algorithm with a cone of ΔR < 0.8



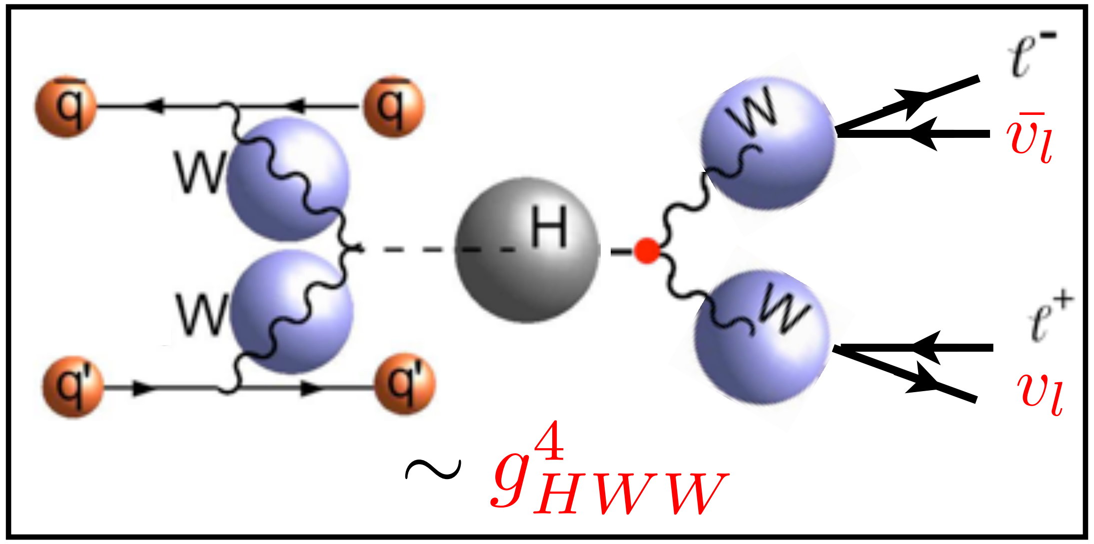


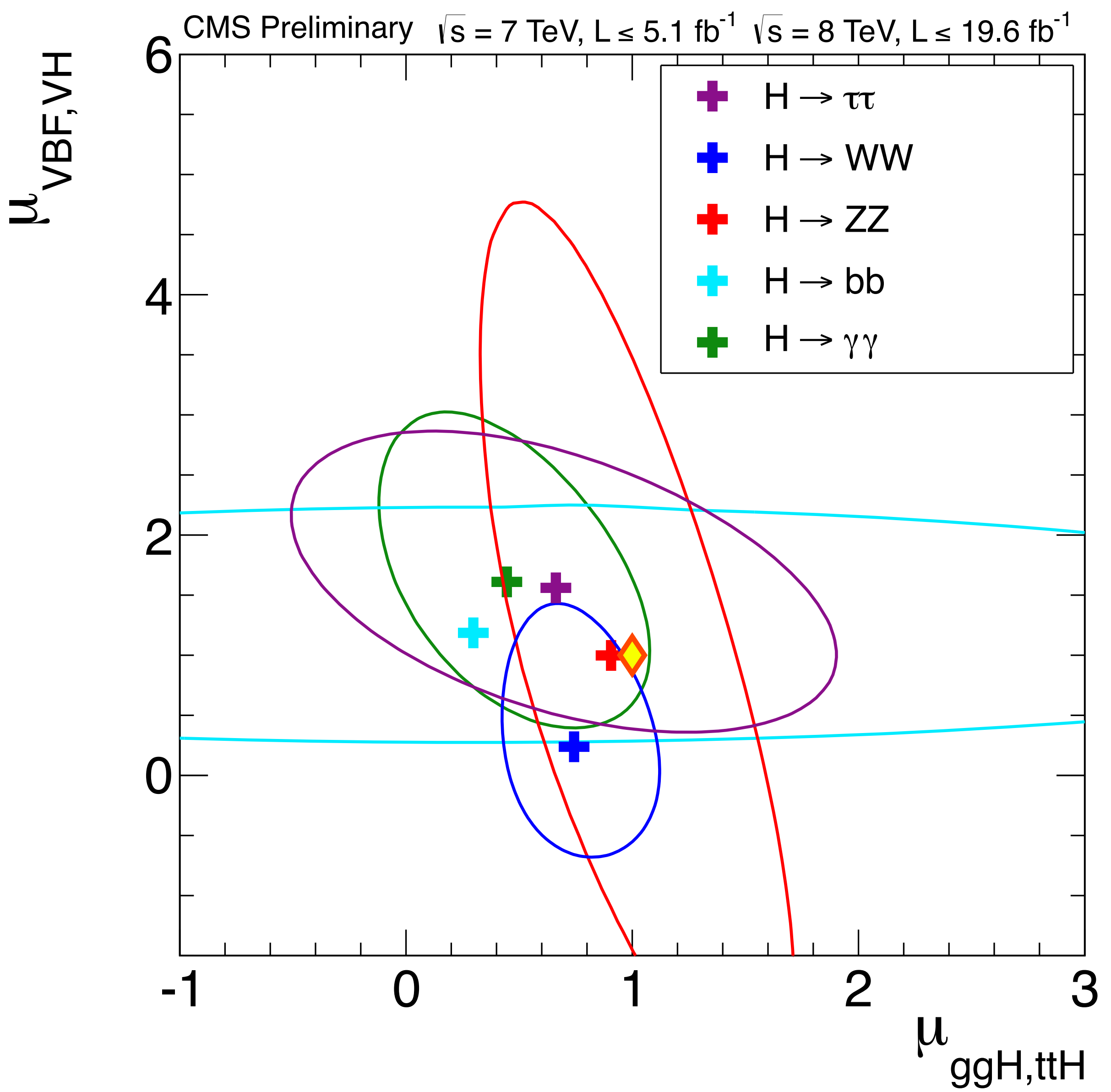
Vector Boson Fusion Production

- The qq→H→WW channel provides a unique measurement on g(H→WW)
- VBF has a clean experimental signature
  - The presence of two forward energetic jets
  - After dedicated selections exploiting both forward jets signatures and Higgs decay kinematics, S/B is ~ 1 for the low mass Higgs
- Current measurement is statistically limited

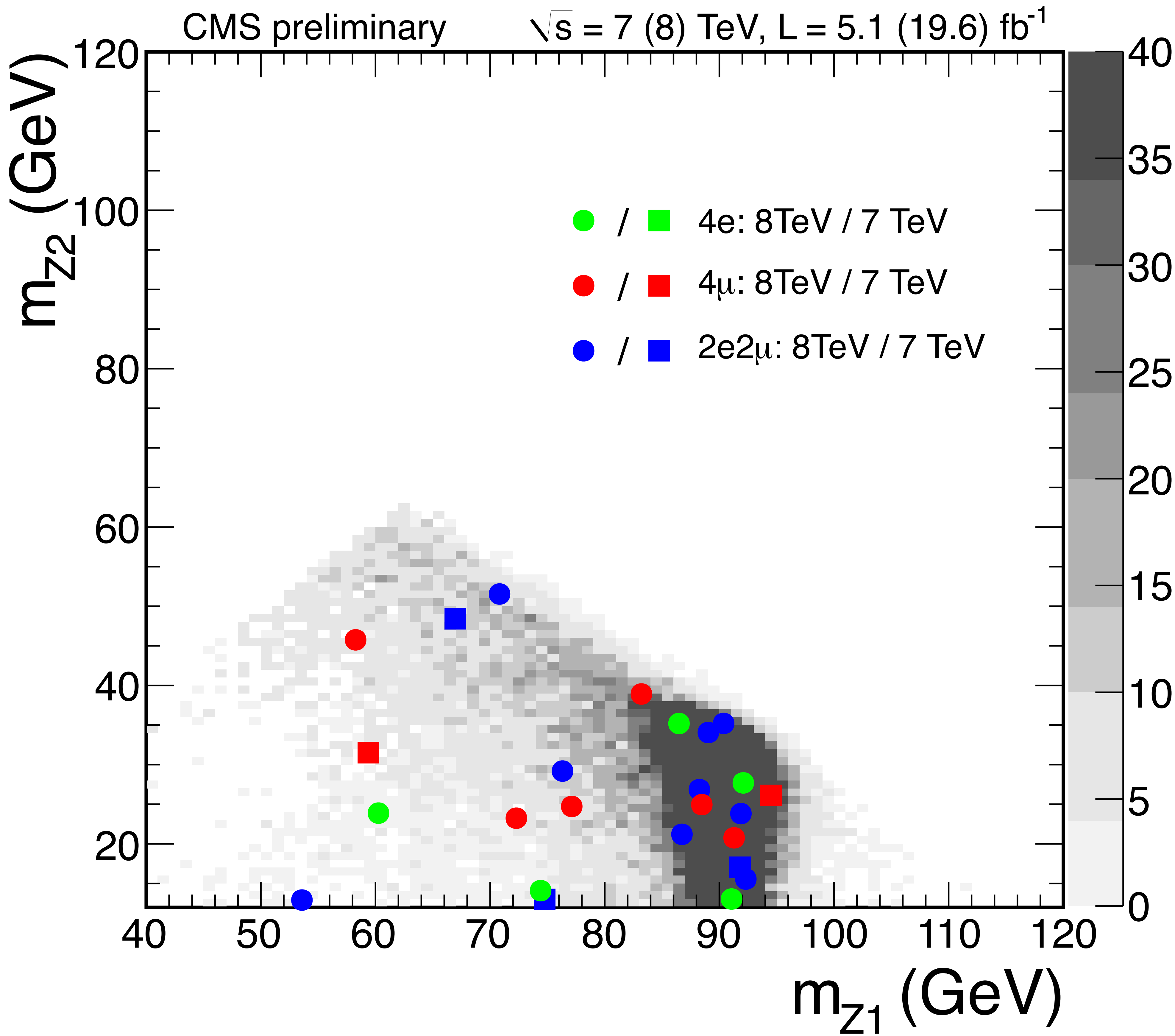
eμ Events at 12.1/fb for mH(125GeV)				
H→WW	All bkg.	Top	WW	Data
1.7 ± 0.2	**2.2 ± 0.6**	0.9 ± 0.3	0.8 ± 0.5	2

- Contribute significantly to the signal strength measurements in different productions
- **increasingly important with more data**



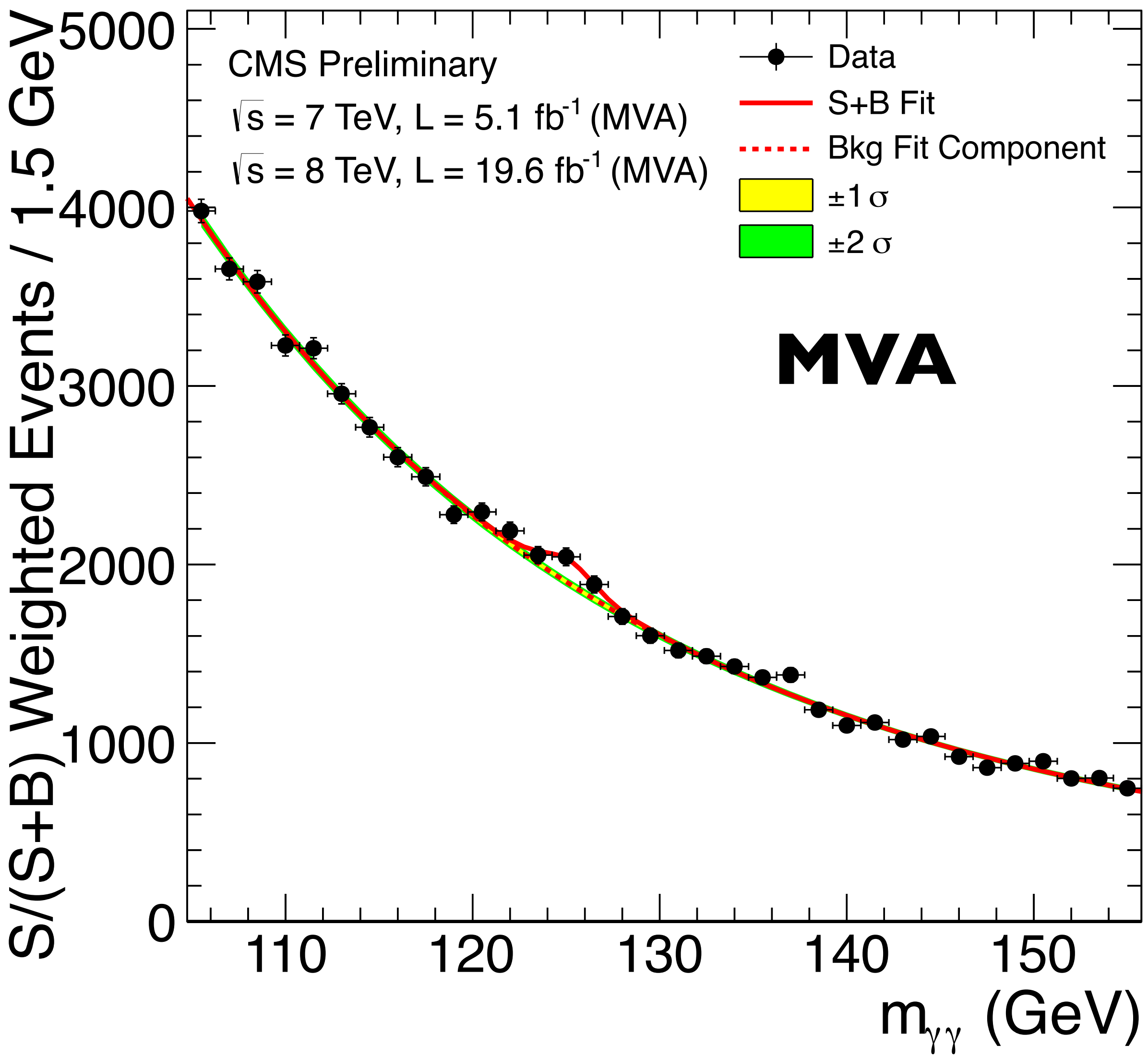


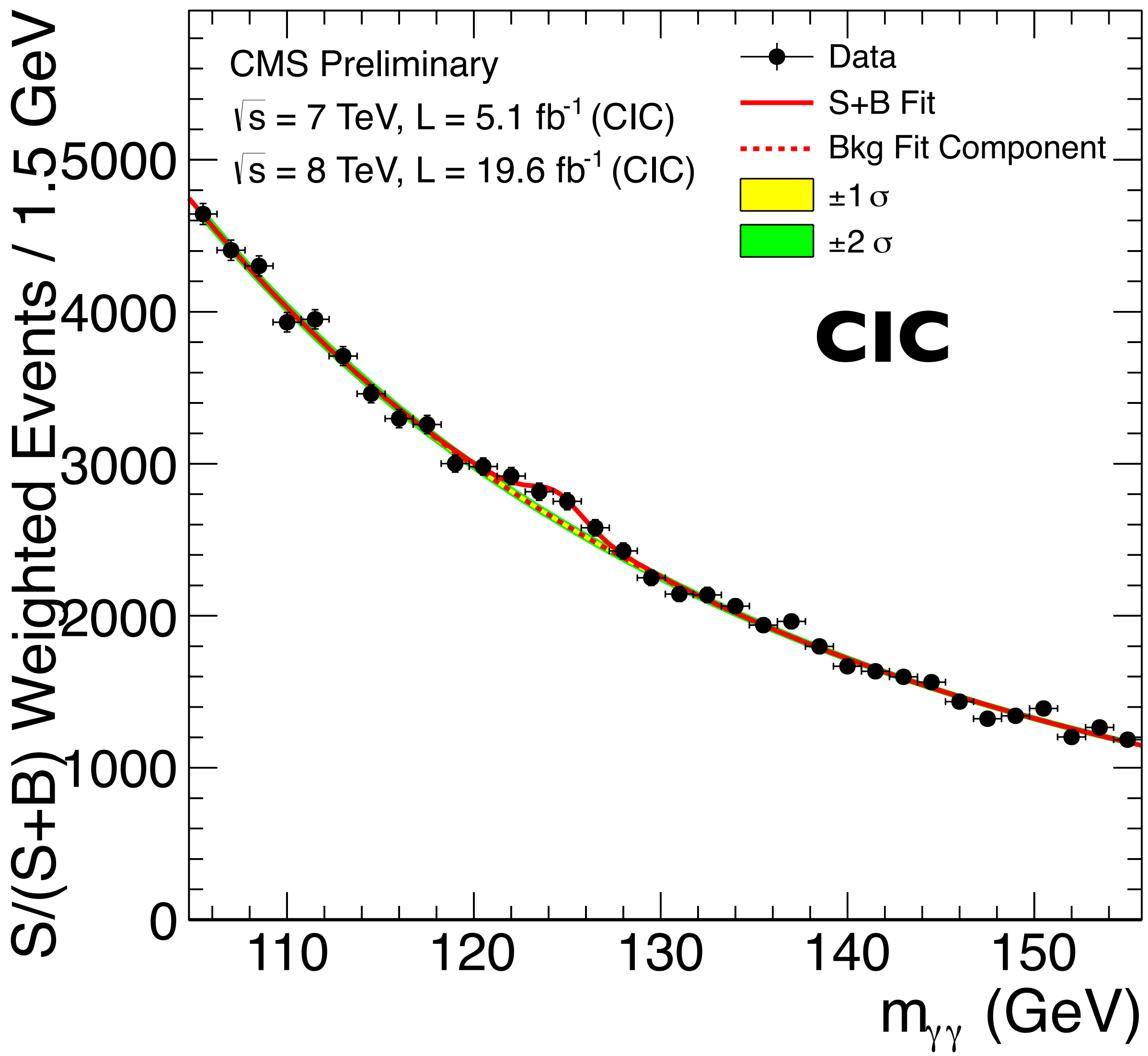
$H \rightarrow ZZ \rightarrow 4l$



Highlights of H→γγ Results (I)

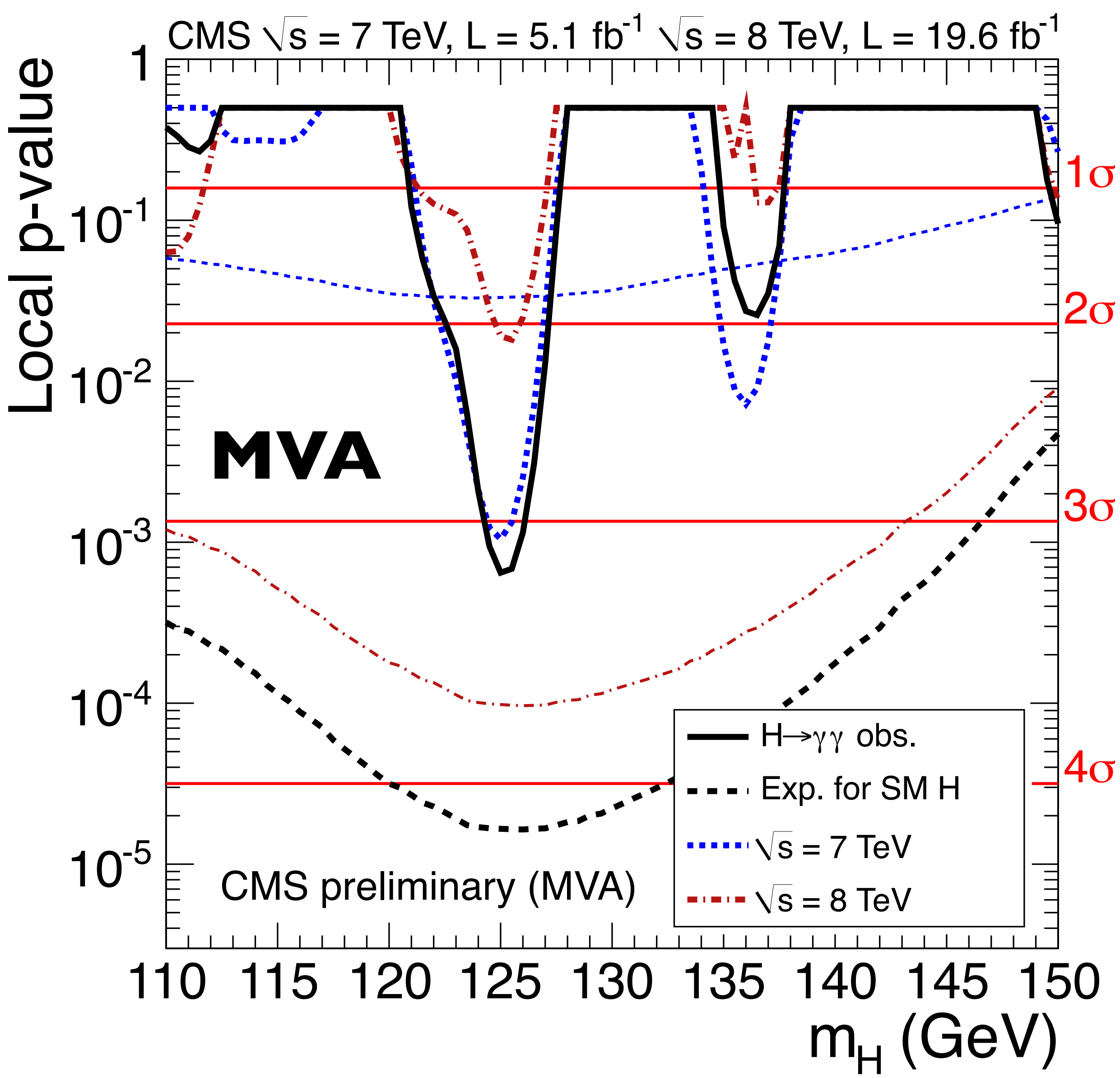
- The m(γγ) with each event weighted by the S/(S+B) value of its category

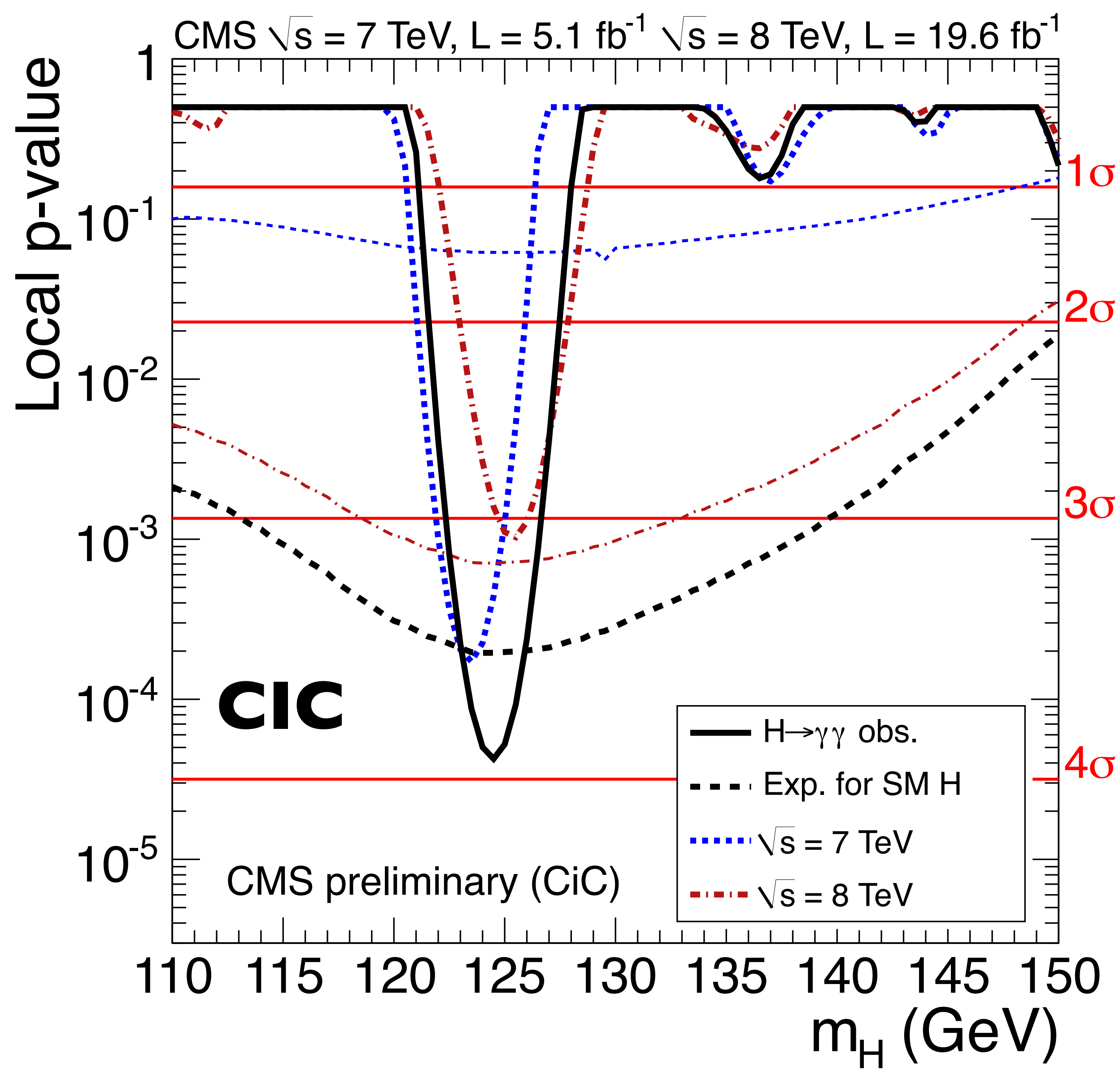




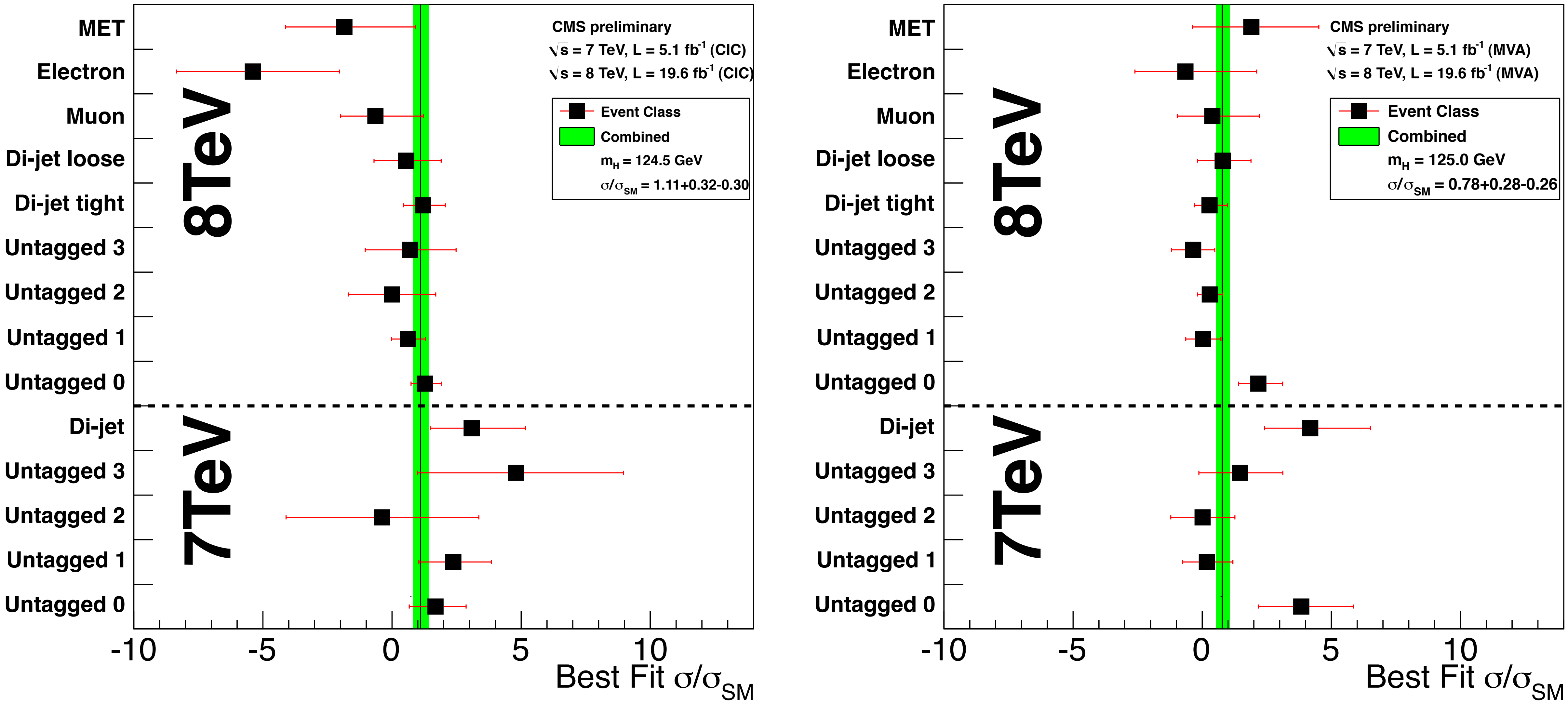
Highlights of H→γγ Results (II)

- Observed local p-values





Highlights of H→γγ Results (III)



	MVA analysis (at m_{H}=125 GeV)	cut-based analysis (at m_{H}=124.5 GeV)
7 TeV	$1.69^{+0.65}_{-0.59}$	$2.27^{+0.80}_{-0.74}$
8 TeV	$0.55^{+0.29}_{-0.27}$	$0.93^{+0.34}_{-0.32}$
7 + 8 TeV	$0.78^{+0.28}_{-0.26}$	$1.11^{+0.32}_{-0.30}$

- Taking account of the correlation between the cut/MVA analysis (0.76), the compatibility between the MVA and cut-based analysis measurements of the signal strength is found to be within 1.5σ for the combined 7 and 8 TeV measurement, and within 1.8σ for the 8 TeV measurement alone.