En Route to the Electro Weak Symmetry Breaking

"Search for the Higgs in WW/ZZ Decays"

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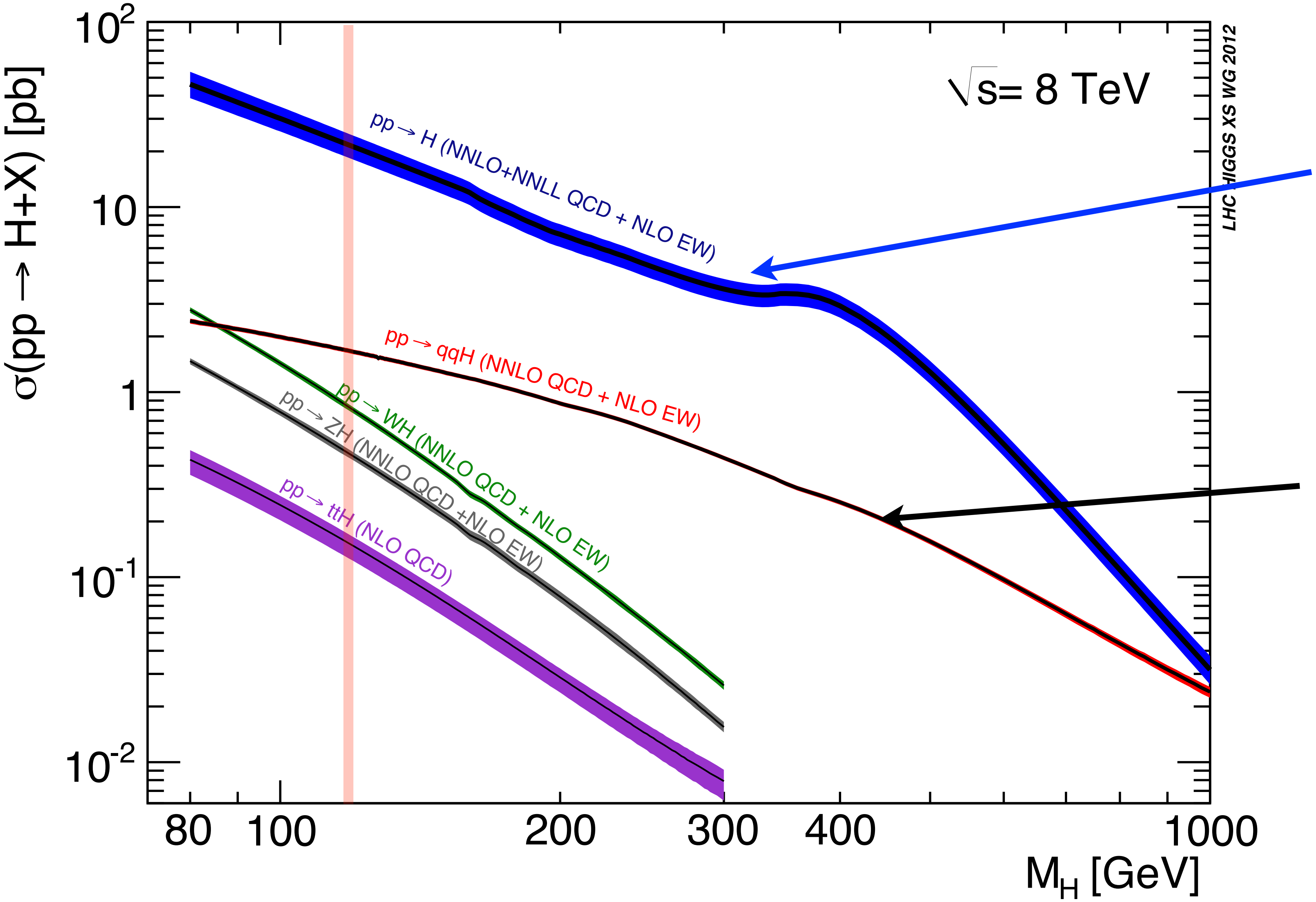
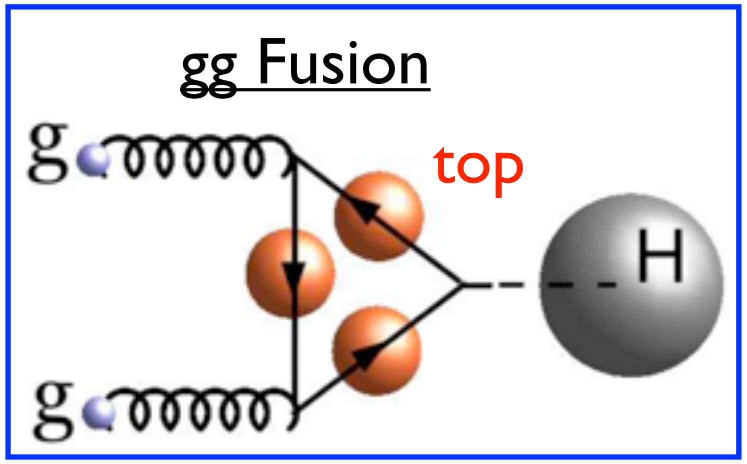
46th Annual Fermilab Users Meeting

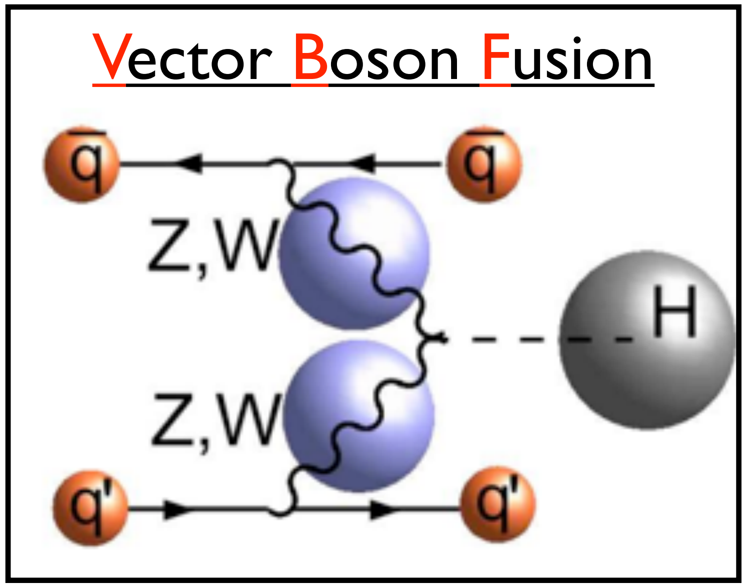
Tollestrup Award Presentation, 13/06/2013

The SM Higgs Production at the LHC

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



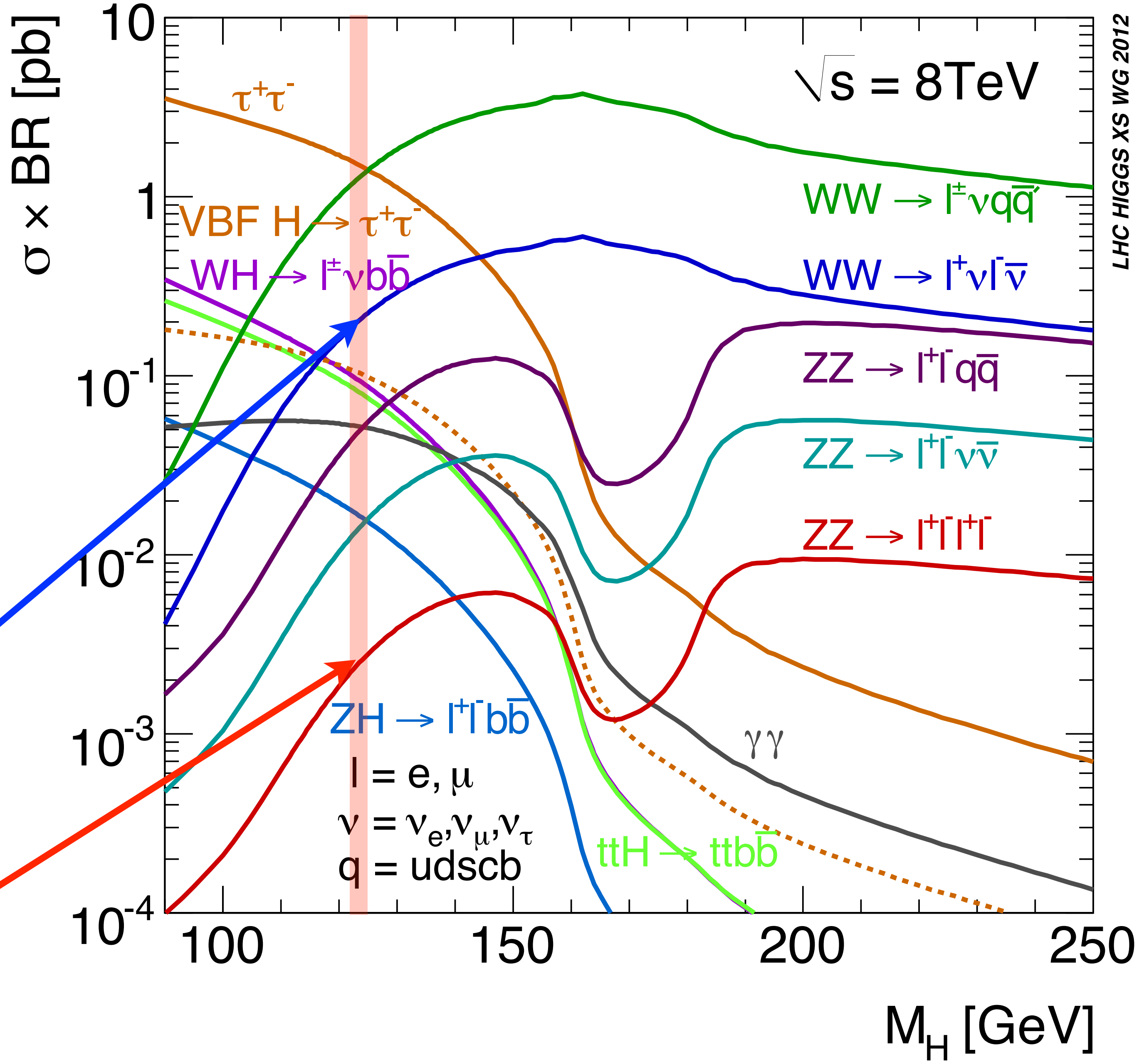




Detecting the SM Higgs Boson

- 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 ($\rightarrow 2l2\nu$)	**Large signal rate early discovery channel**
ZZ ($\rightarrow 4l$)	**Excellent mass resolution, Complex topology for property measurements**



Roadmap to the Discovery

First 7 TeV Collision March 30, 2010 CMS center

CMS PAS EWK-10-009

DRAFT
CMS Physics Analysis Summary

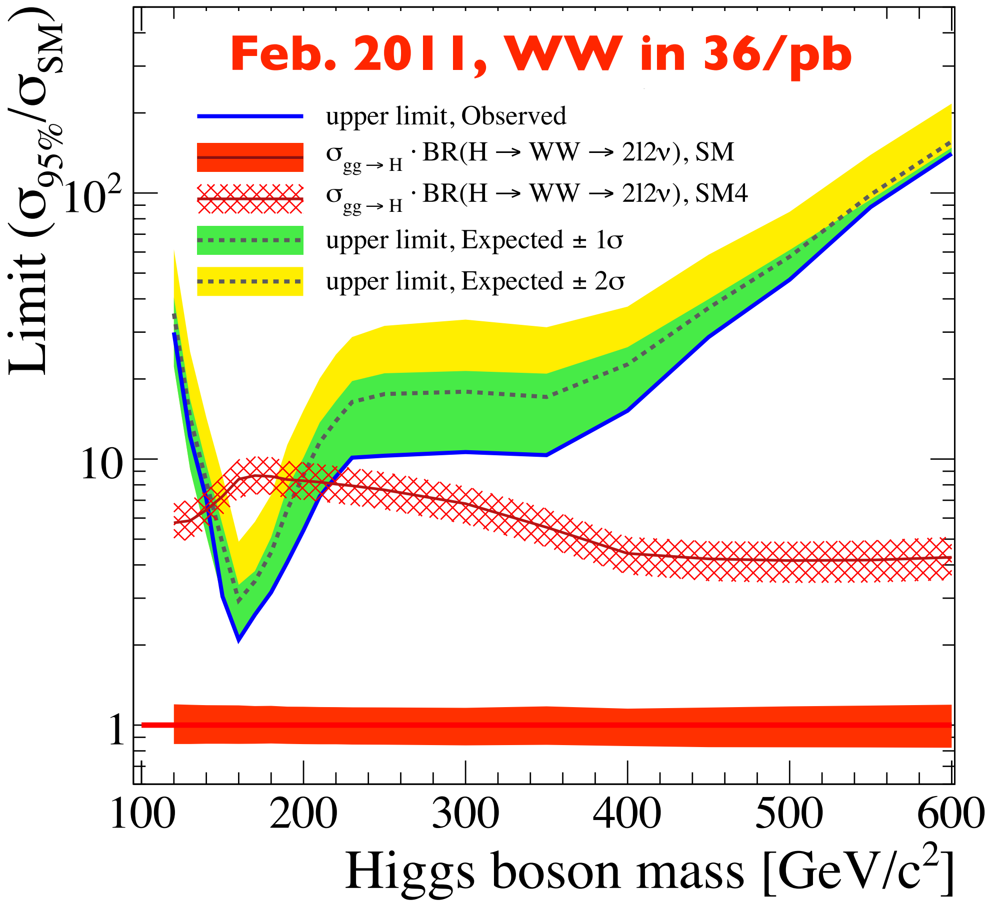
The content of this note is intended for CMS internal use and distribution only

2011/02/04
Head Id: 37001
Archive Id: 37003
Archive Date: 2011/02/04
Archive Tag: trunk

First Measurement of W^+W^- Production and Search for Higgs Boson in pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration

Roadmap to the Higgs-like Particle Discovery



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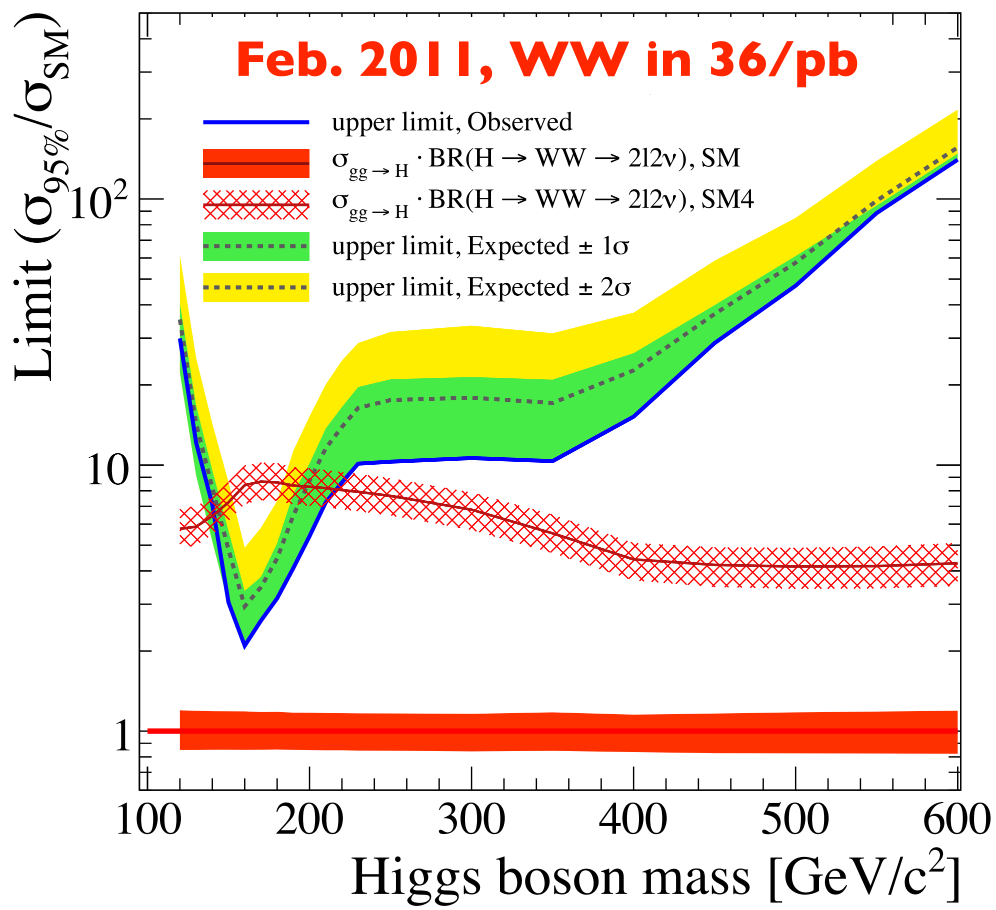
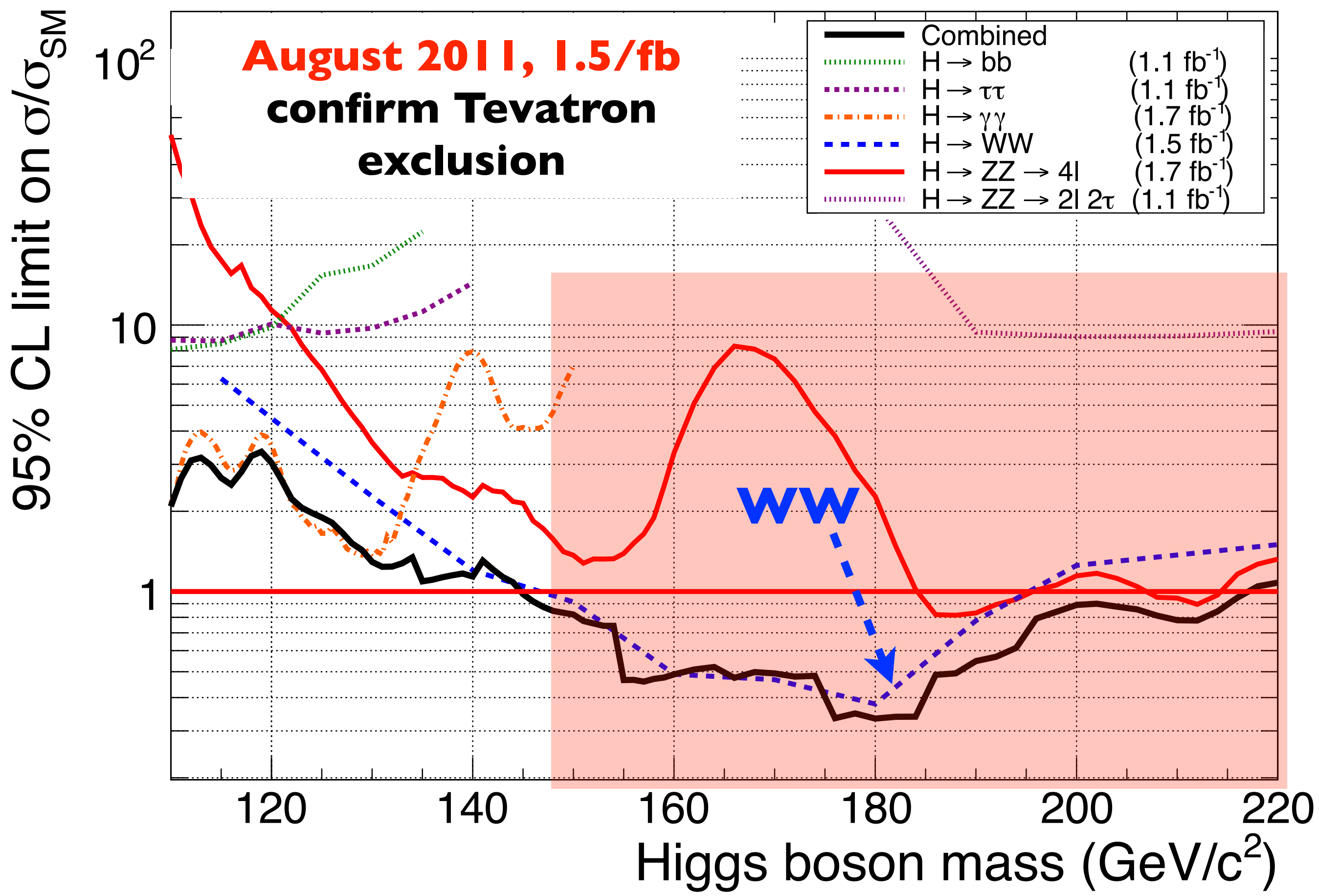
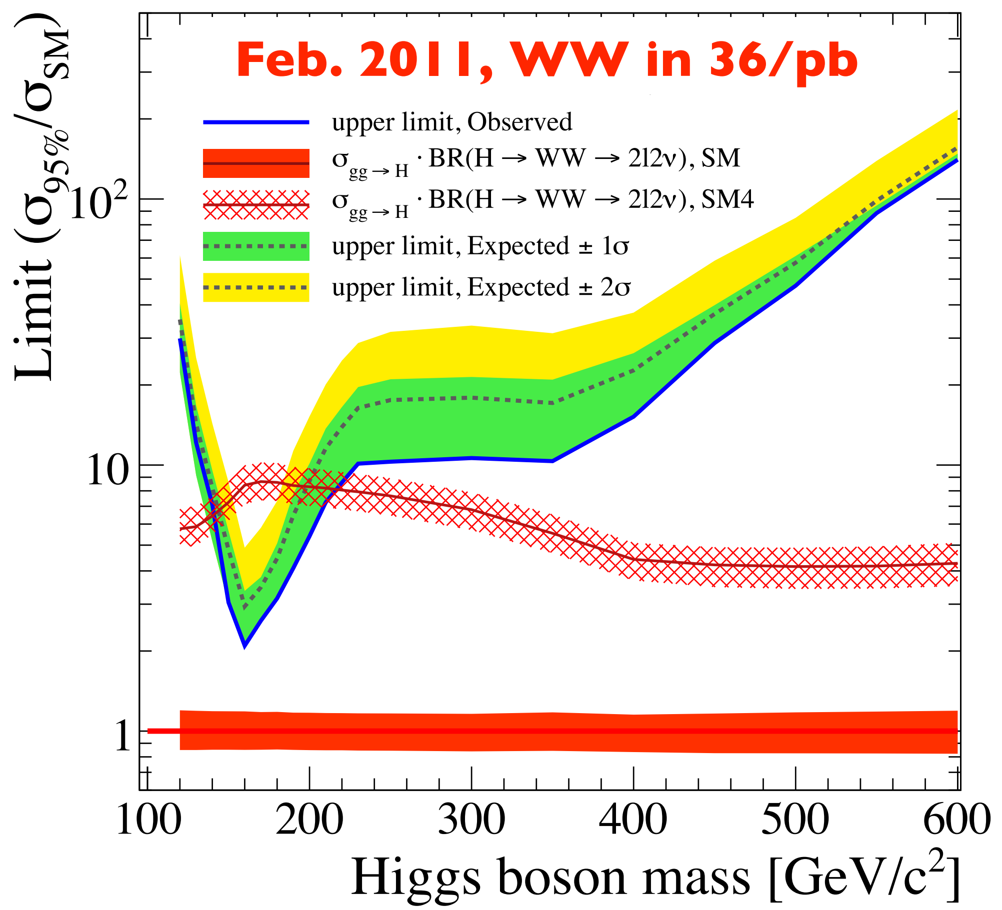
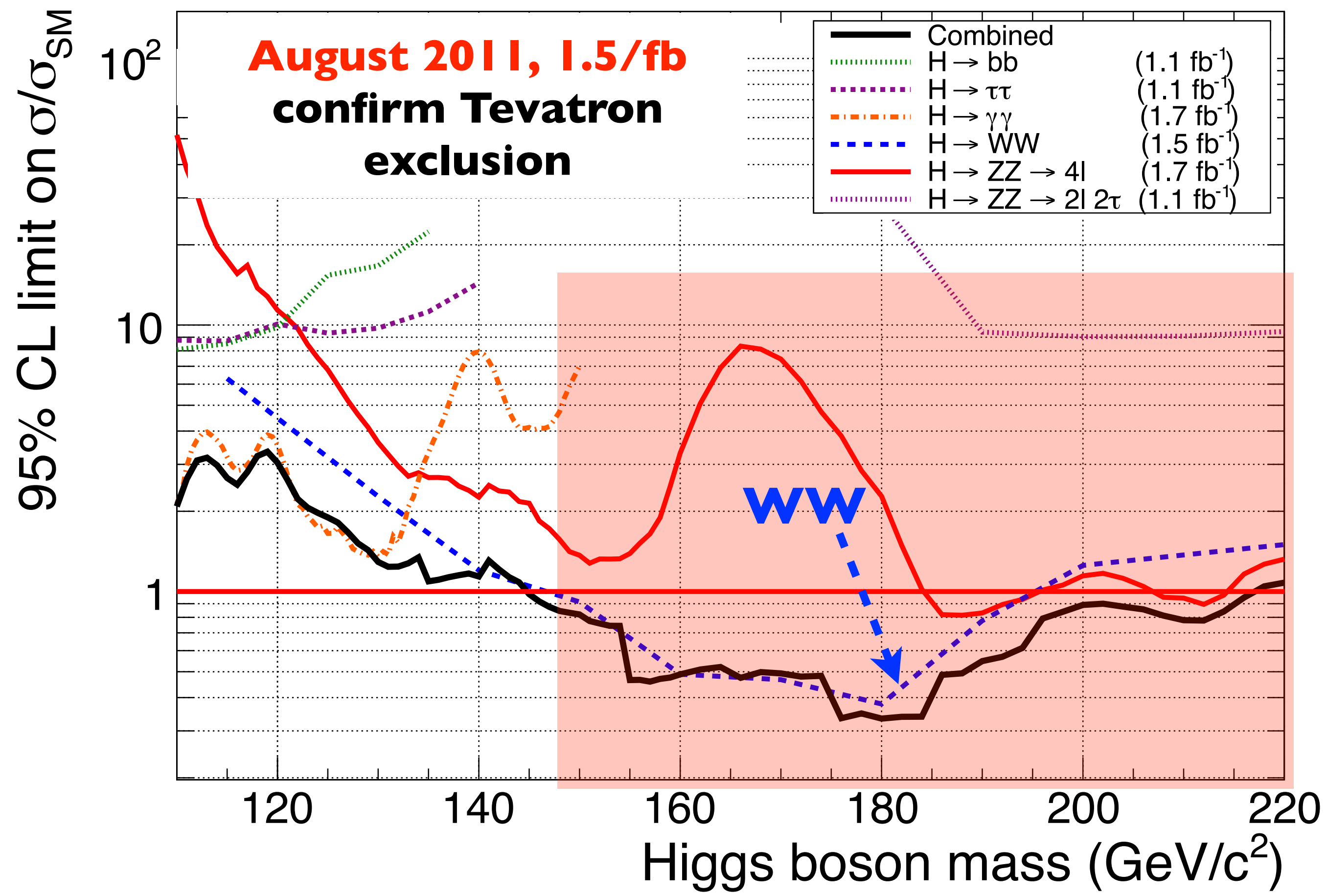
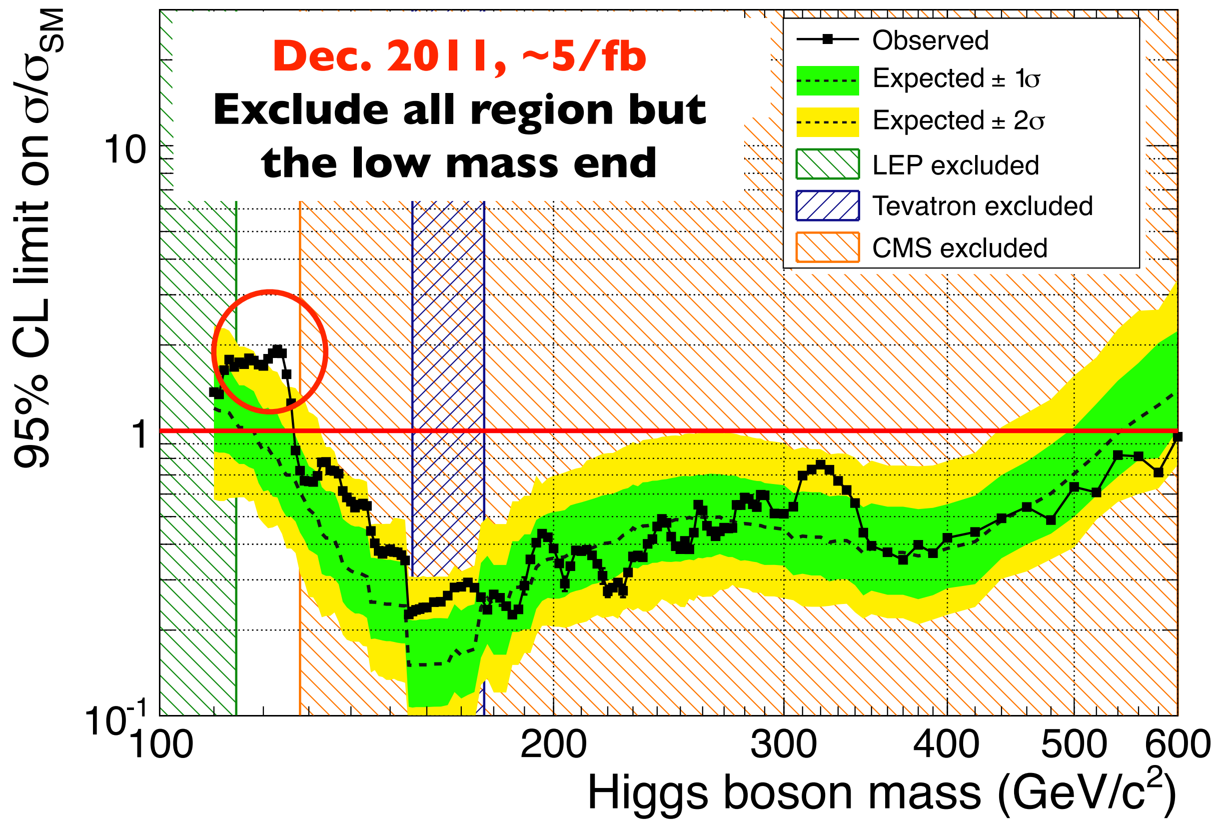




Roadmap to the Higgs-like Particle Discovery







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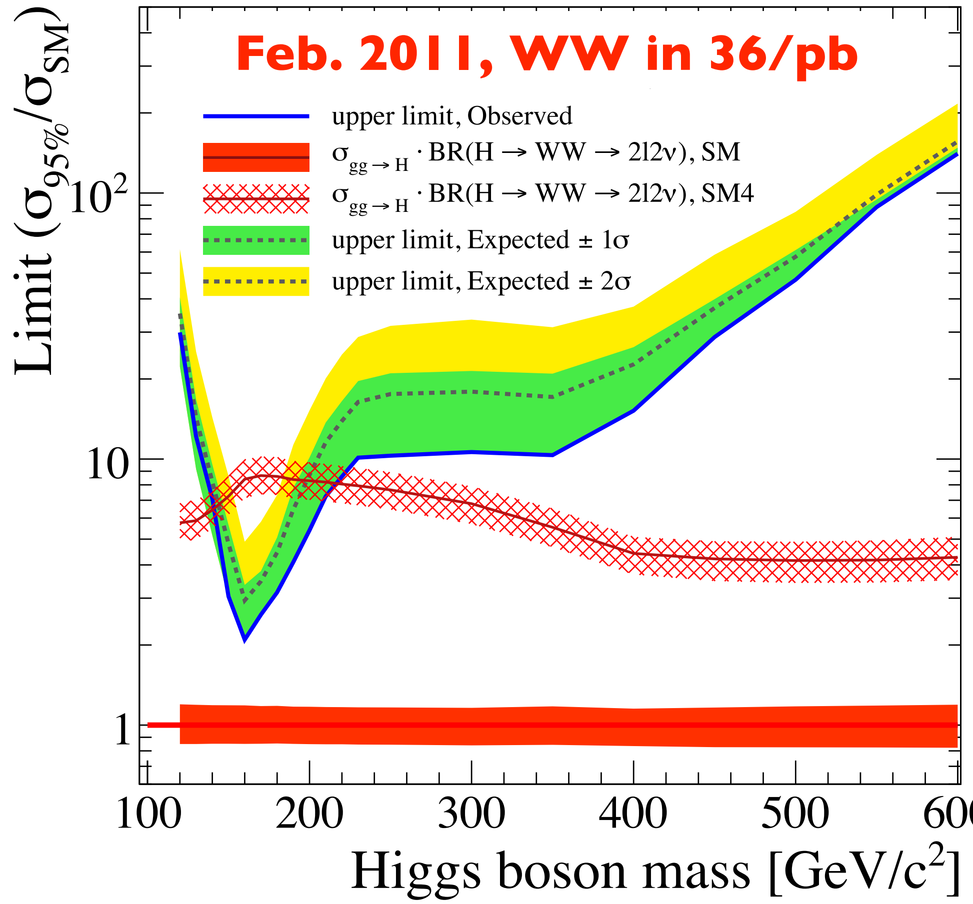
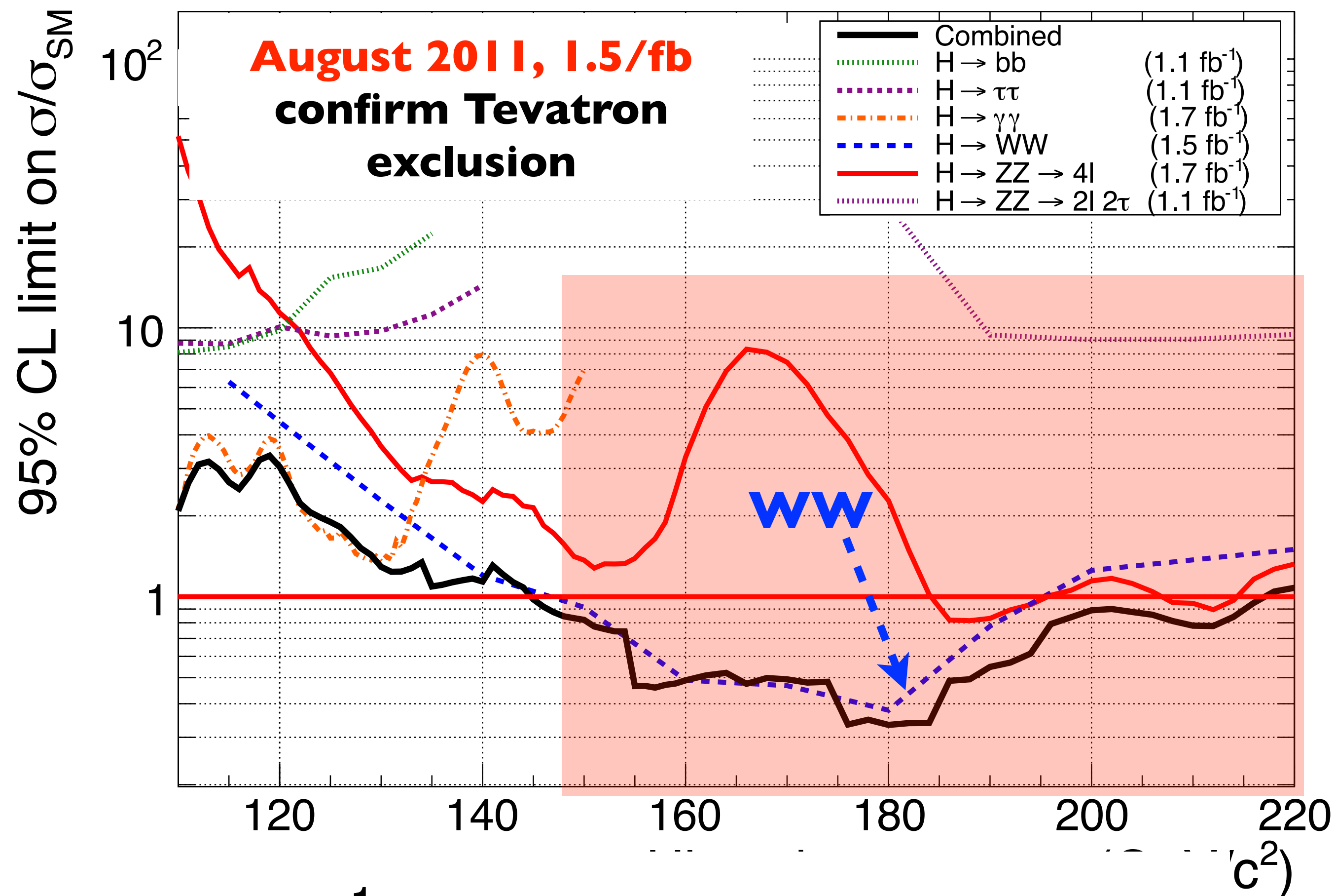
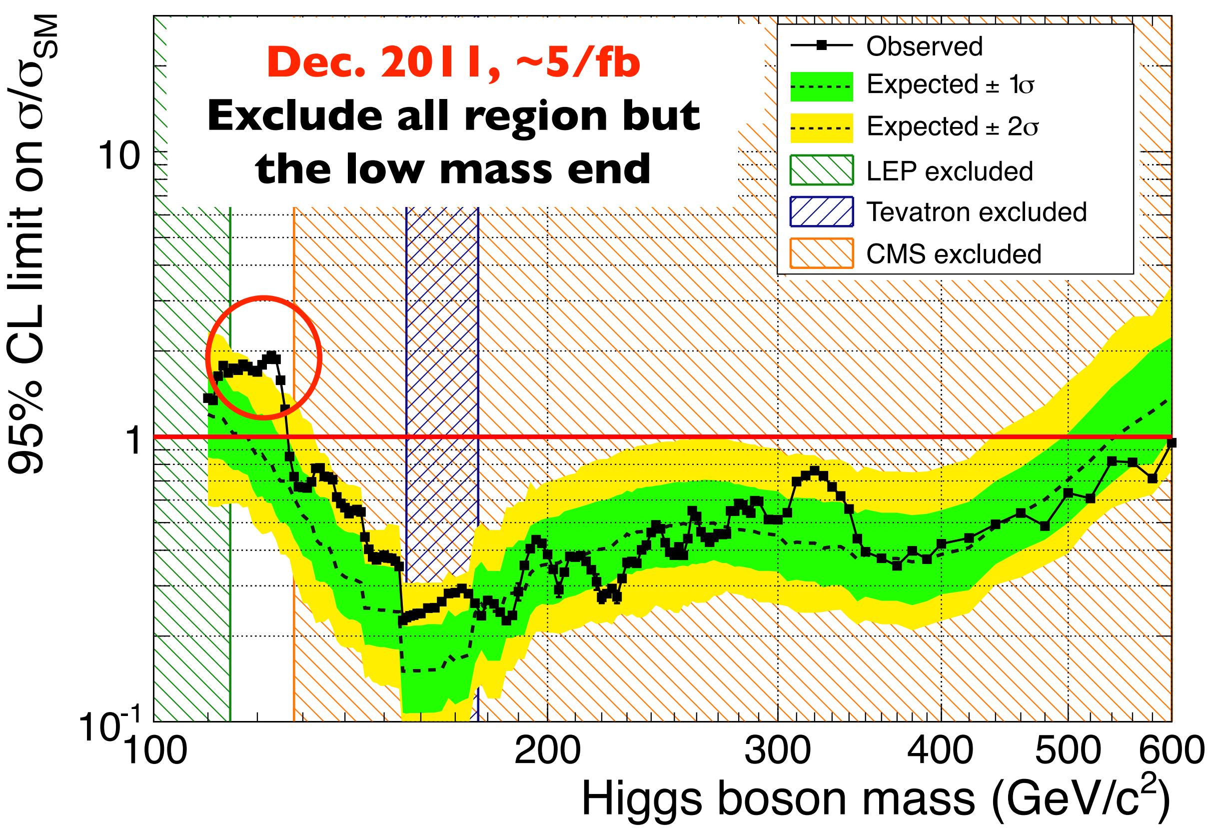
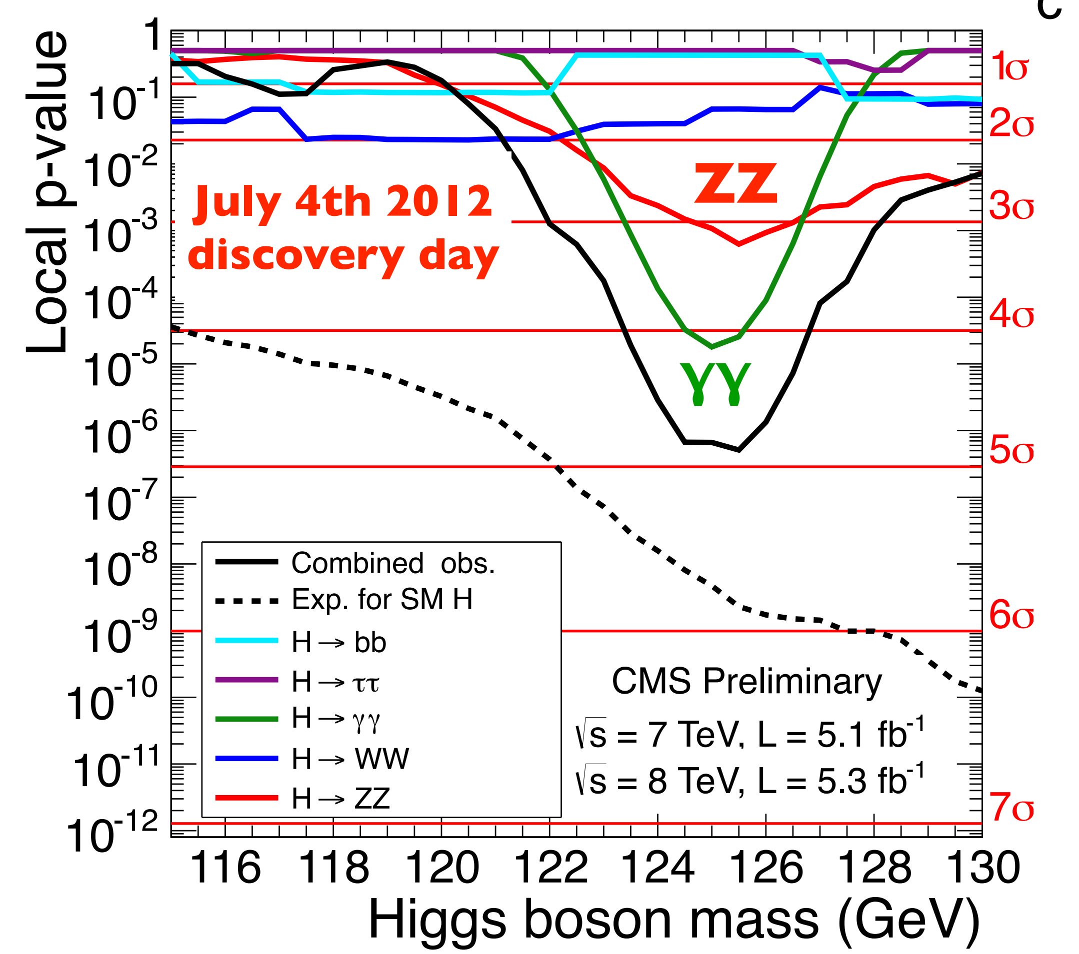
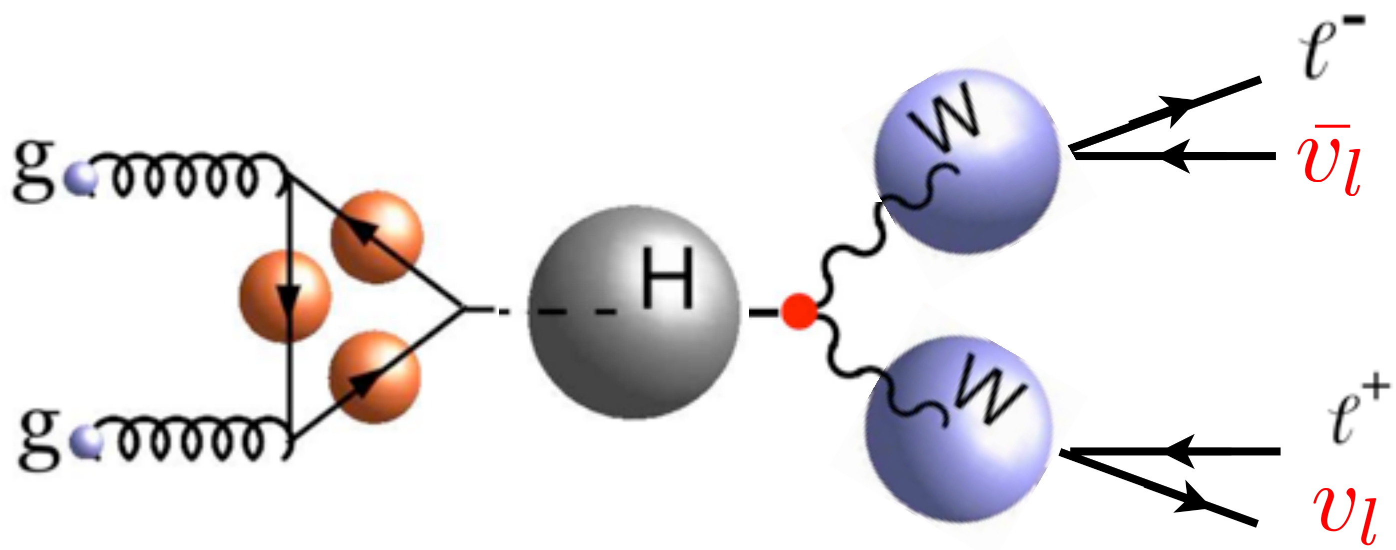








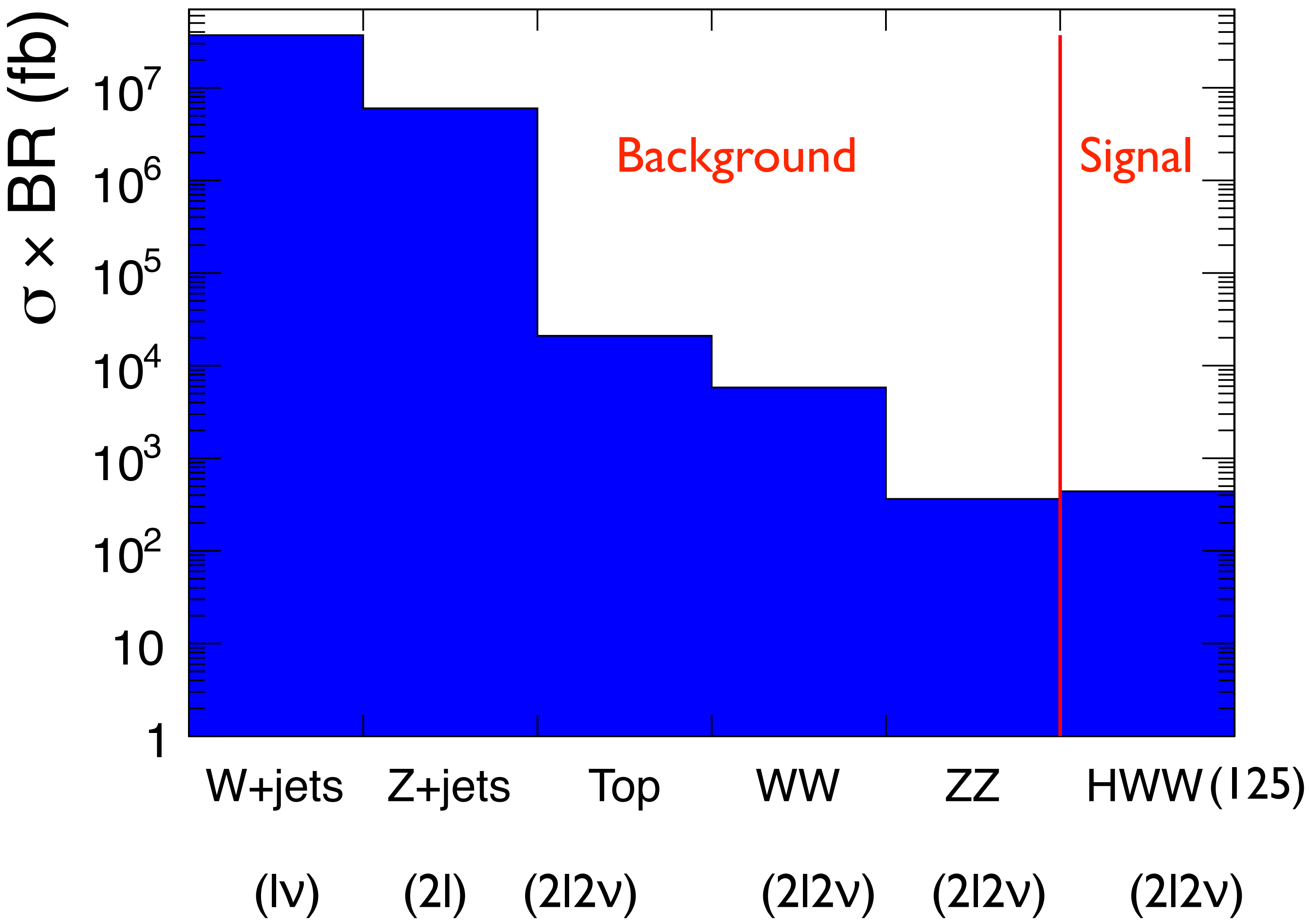
H→WW→2l2ν



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

Analysis Challenges

- Large backgrounds and no mass peak



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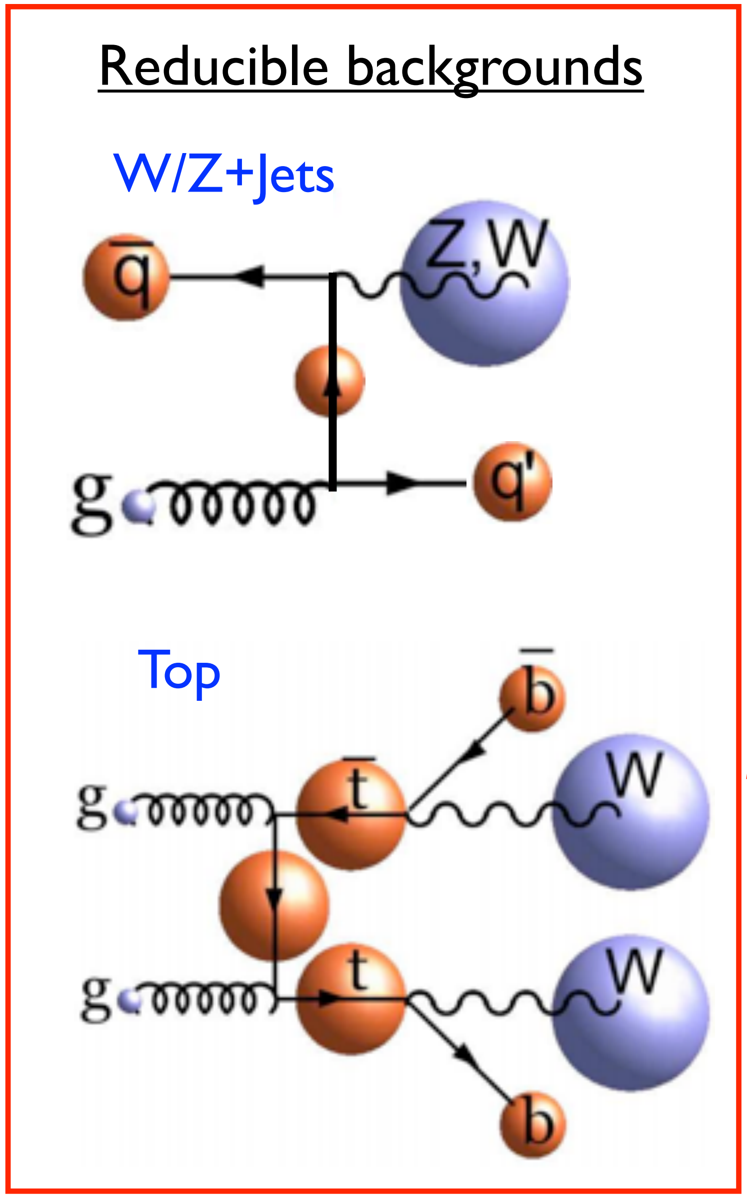
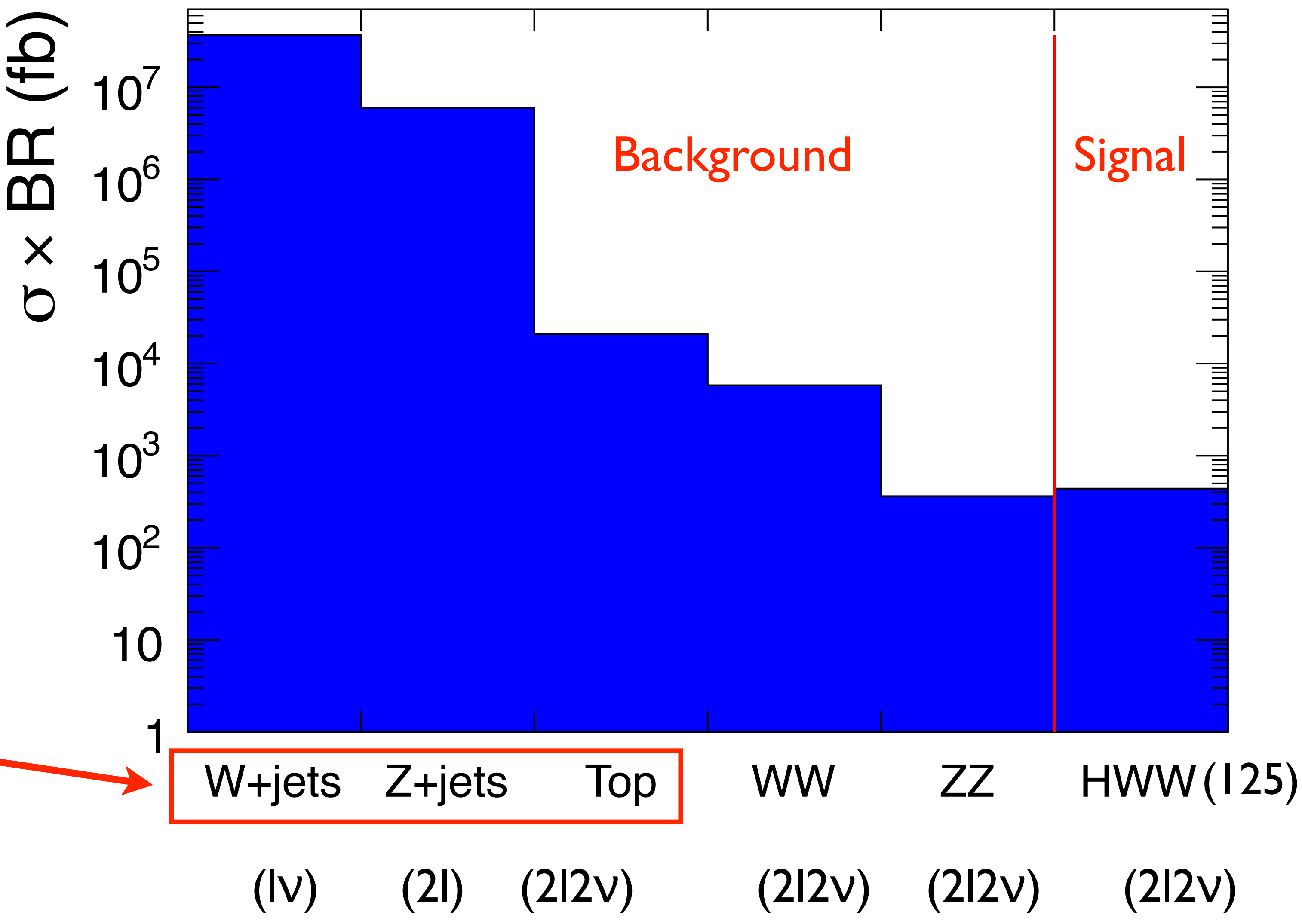


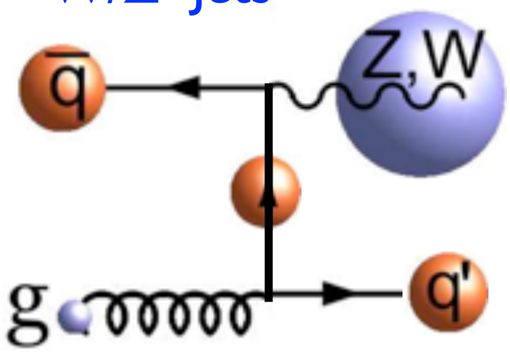


Analysis Challenges

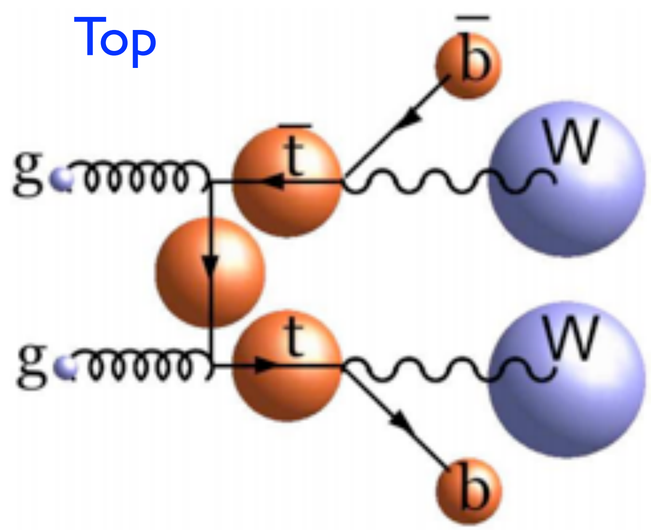
- Large backgrounds and no mass peak

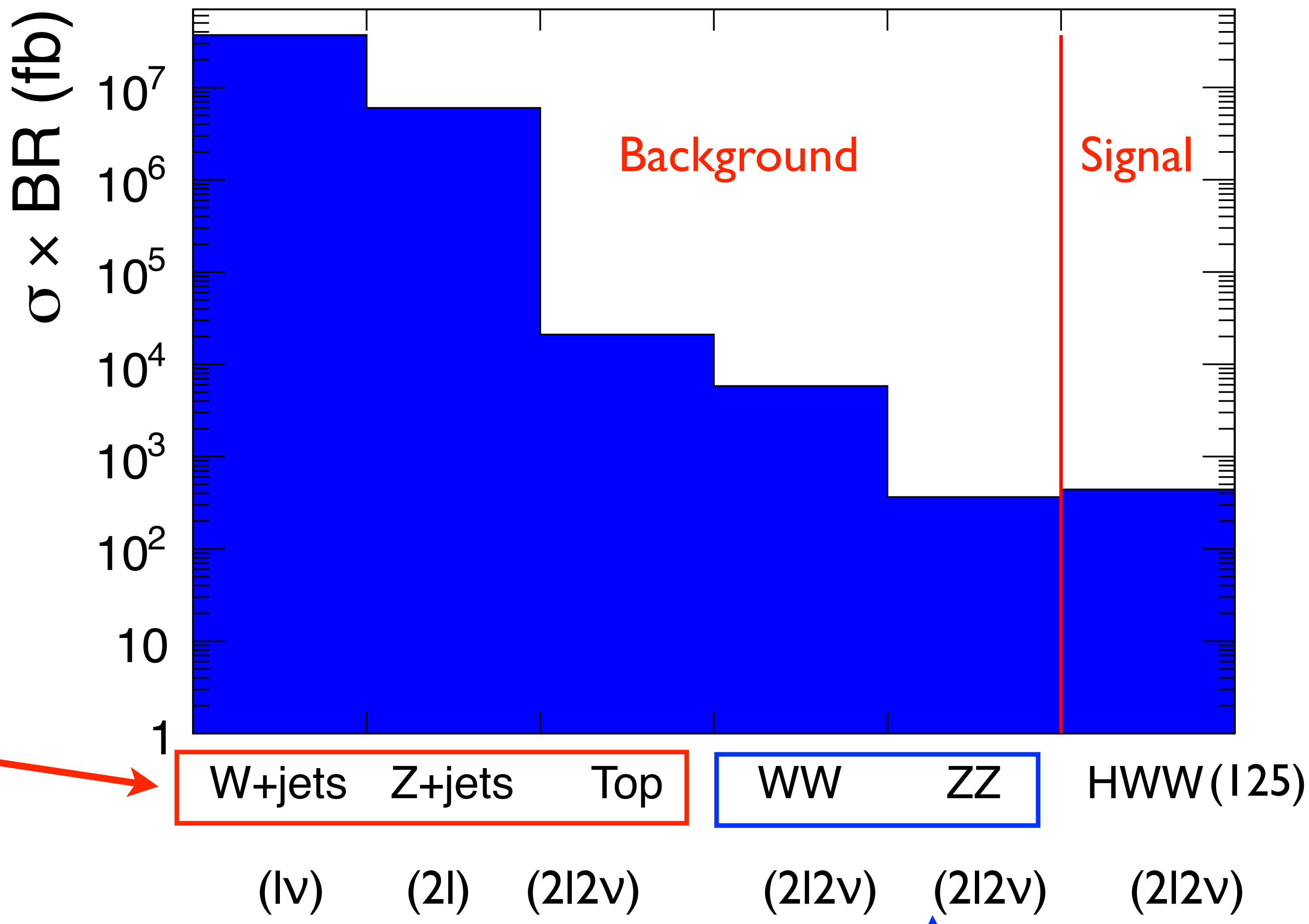
Reducible backgrounds

W/Z+Jets

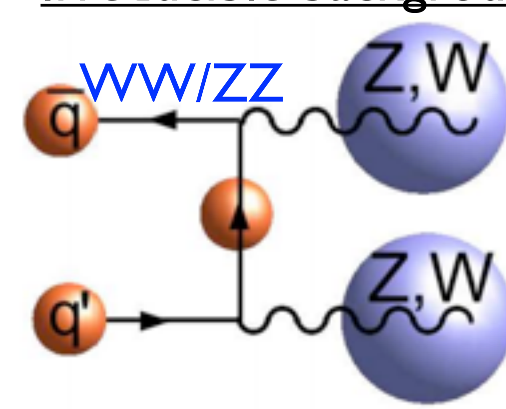


Top





Irreducible backgrounds



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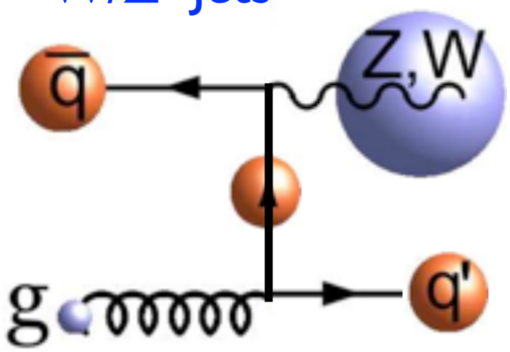

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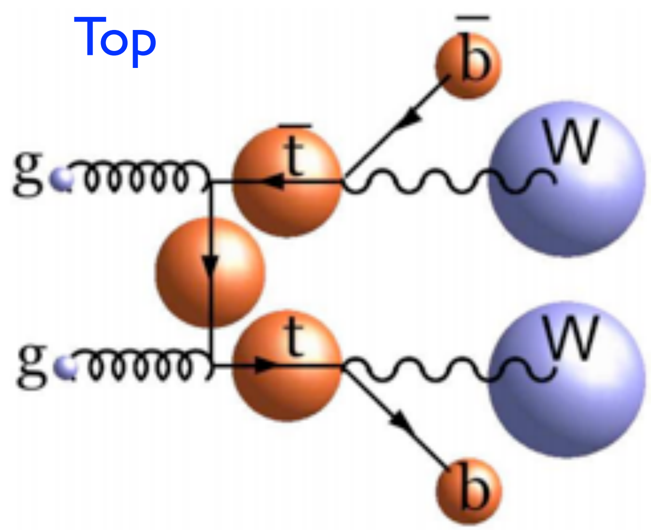

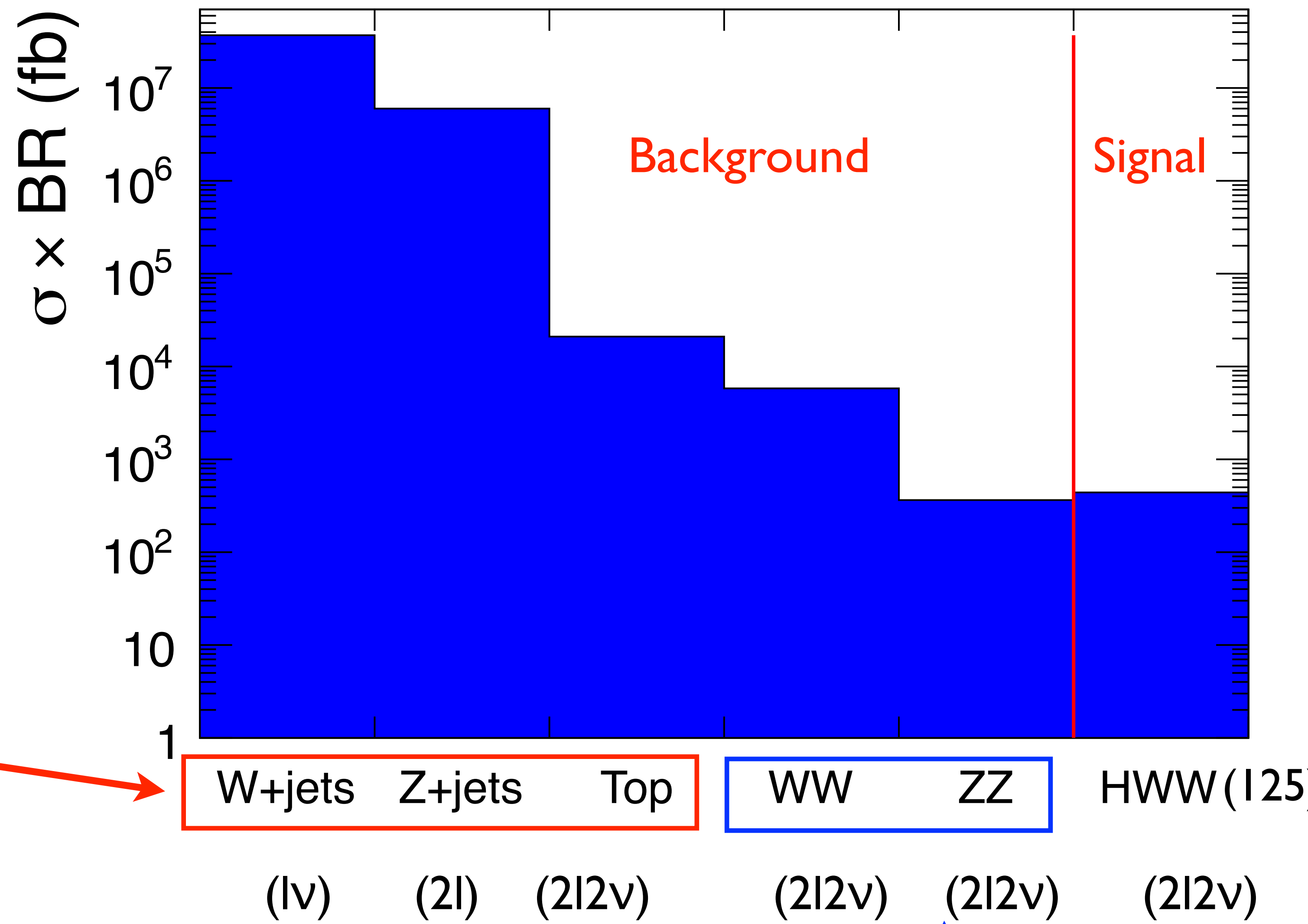

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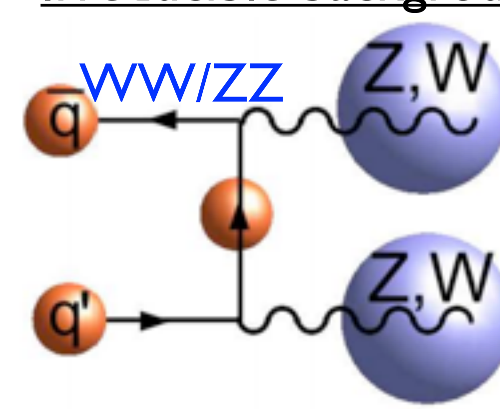
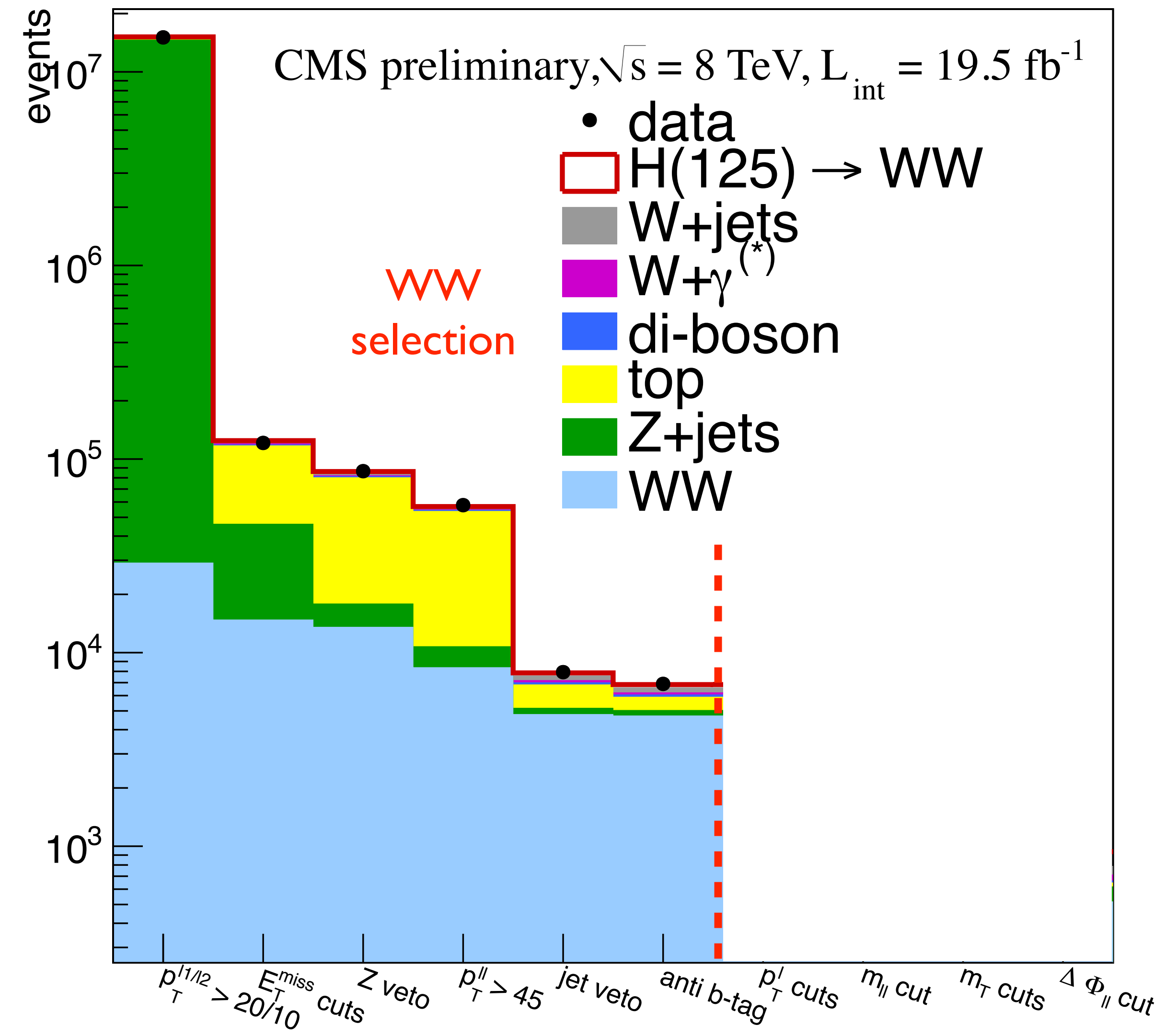


- **Key in the analysis**
  - Optimize selections to reduce reducible background
  - Exploit full kinematics to separate HWW and WW

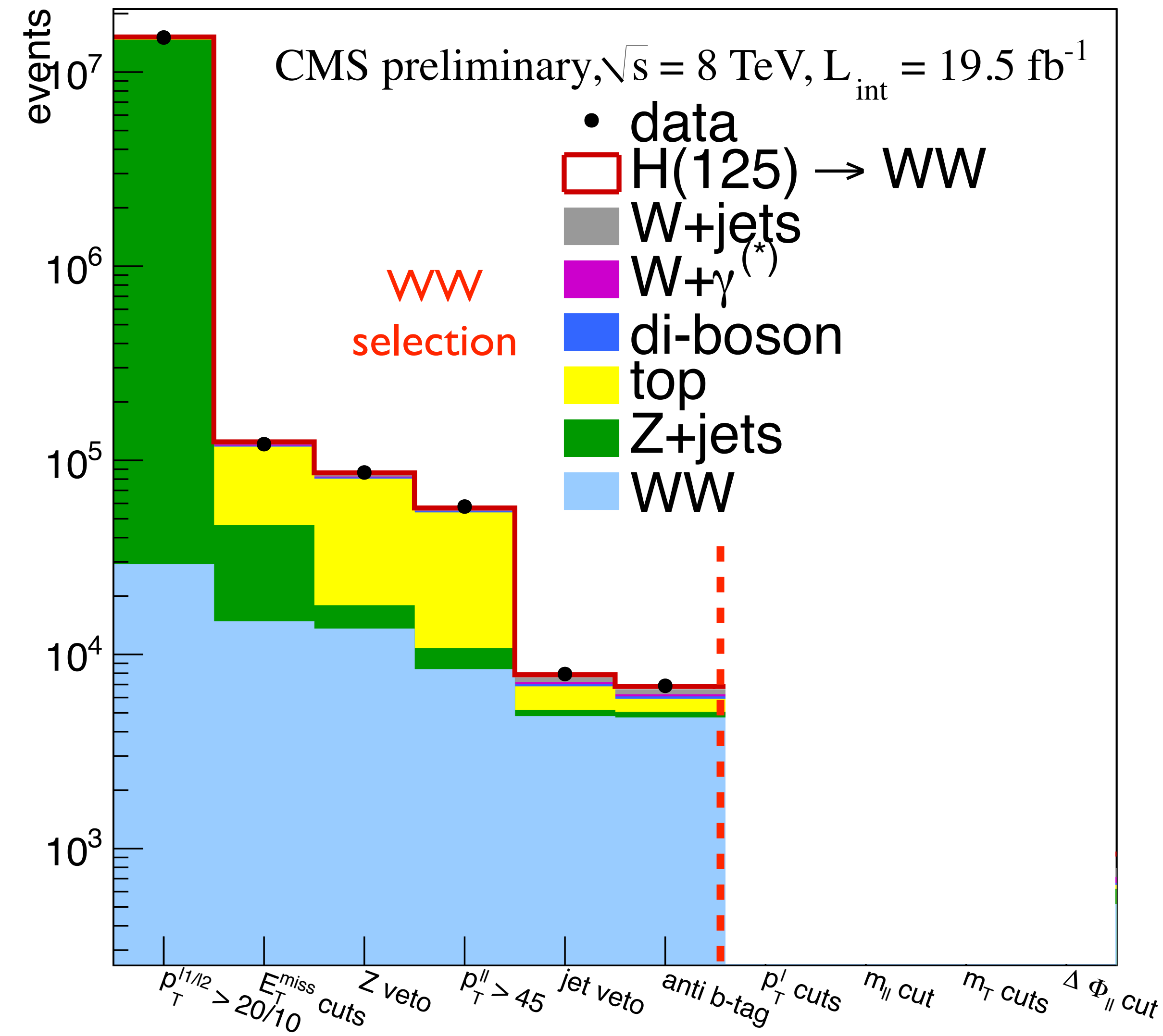
Analysis Overview

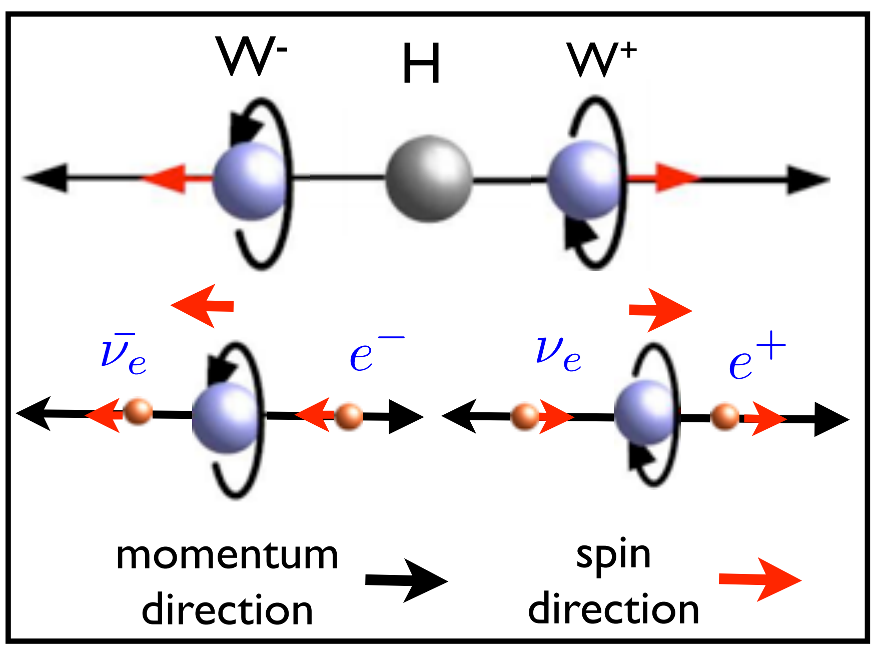
- WW selection
  - Reject reducible backgrounds

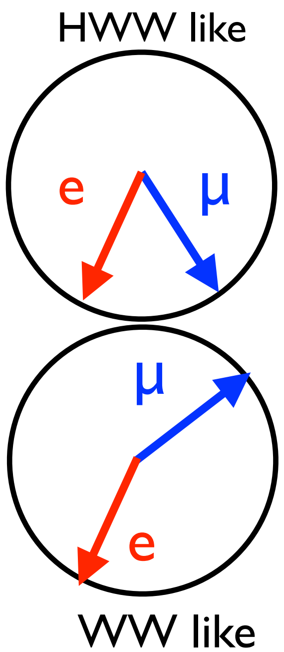


Analysis Overview

- 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

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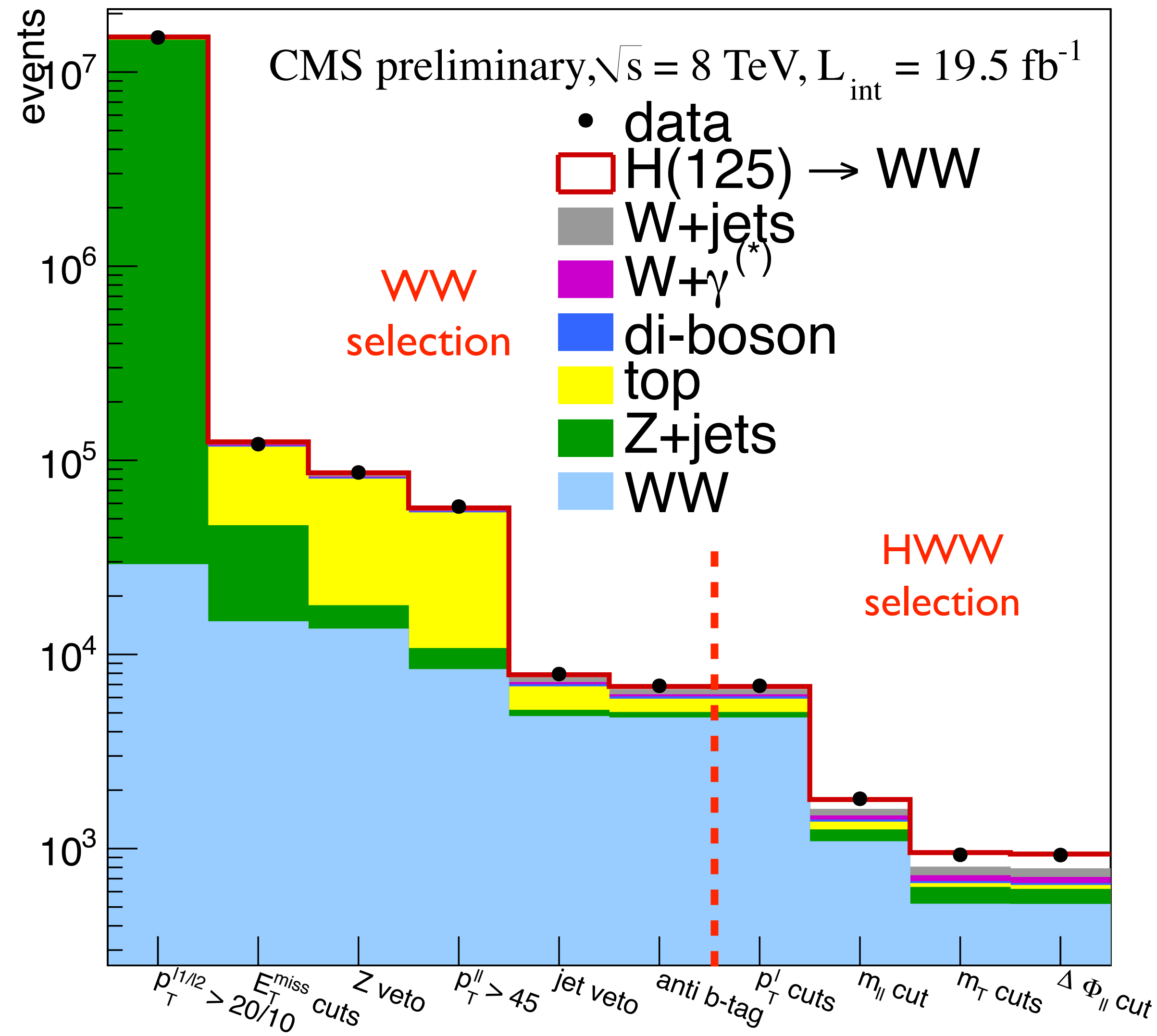
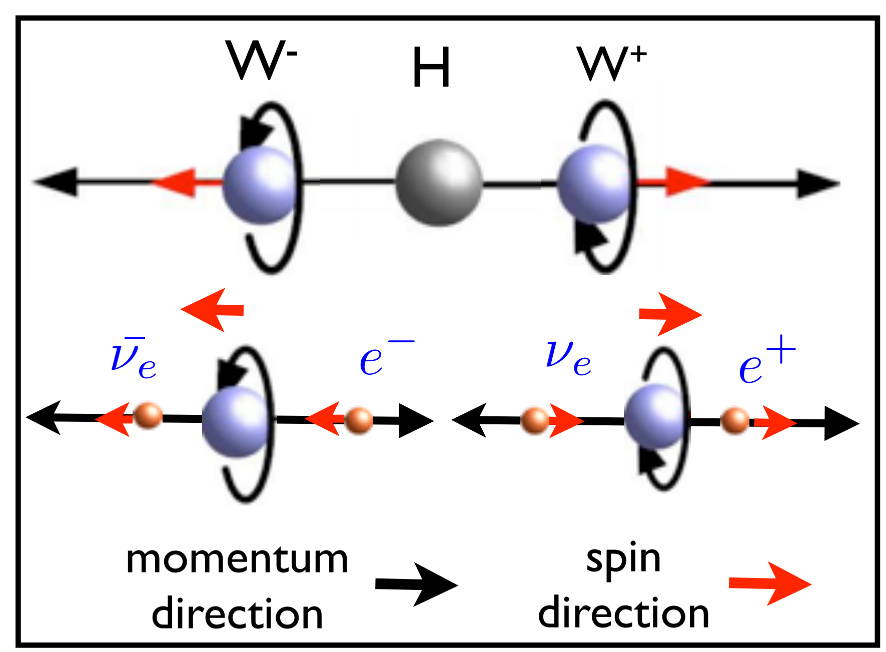
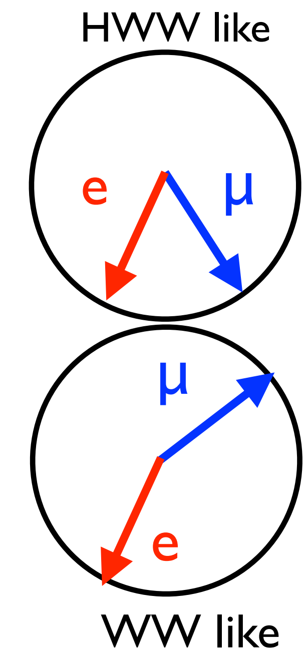
- Two complementary approaches to extract the Higgs production cross-section
  - Cut and count
  - Use full shape of kinematic distributions







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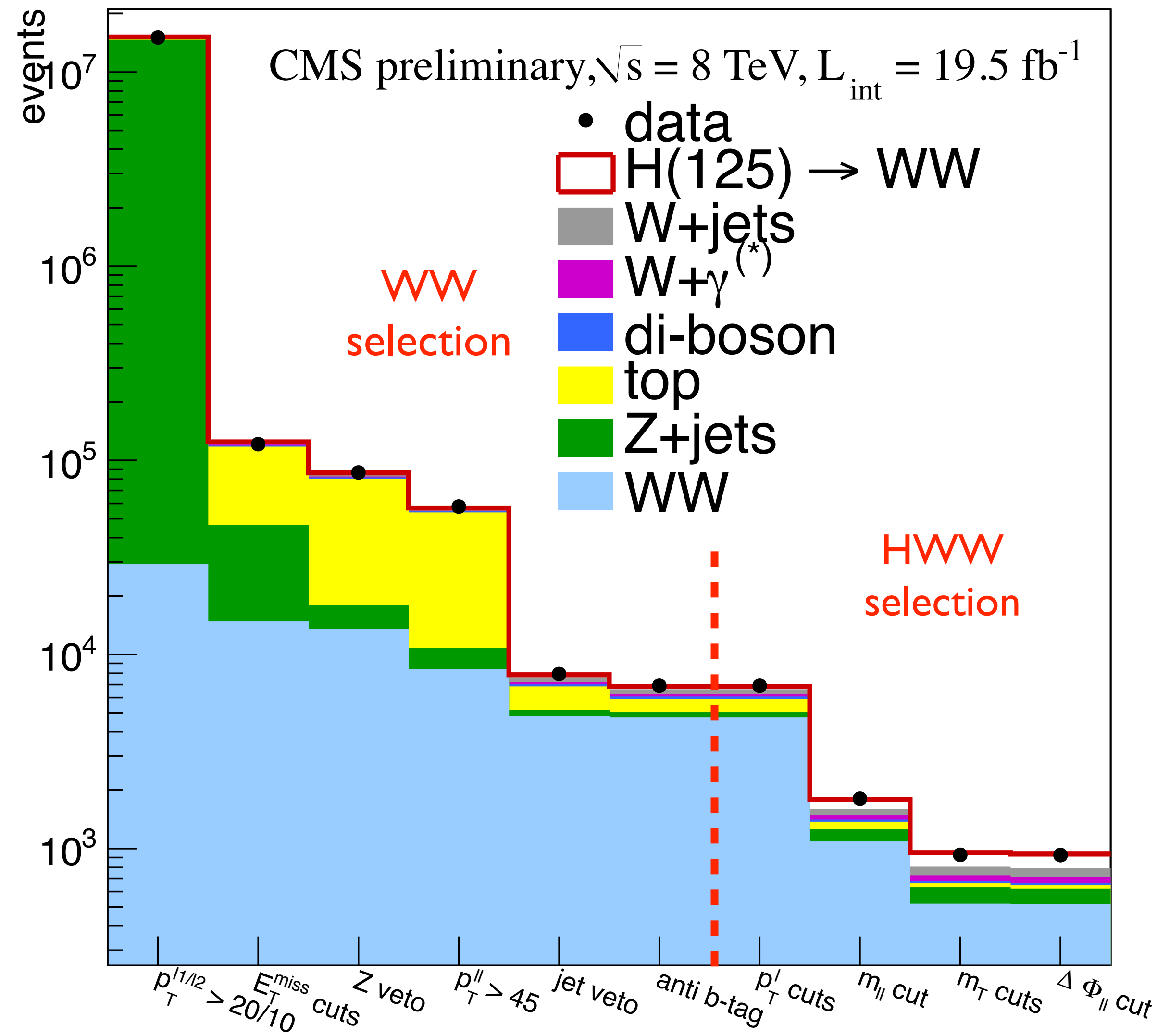
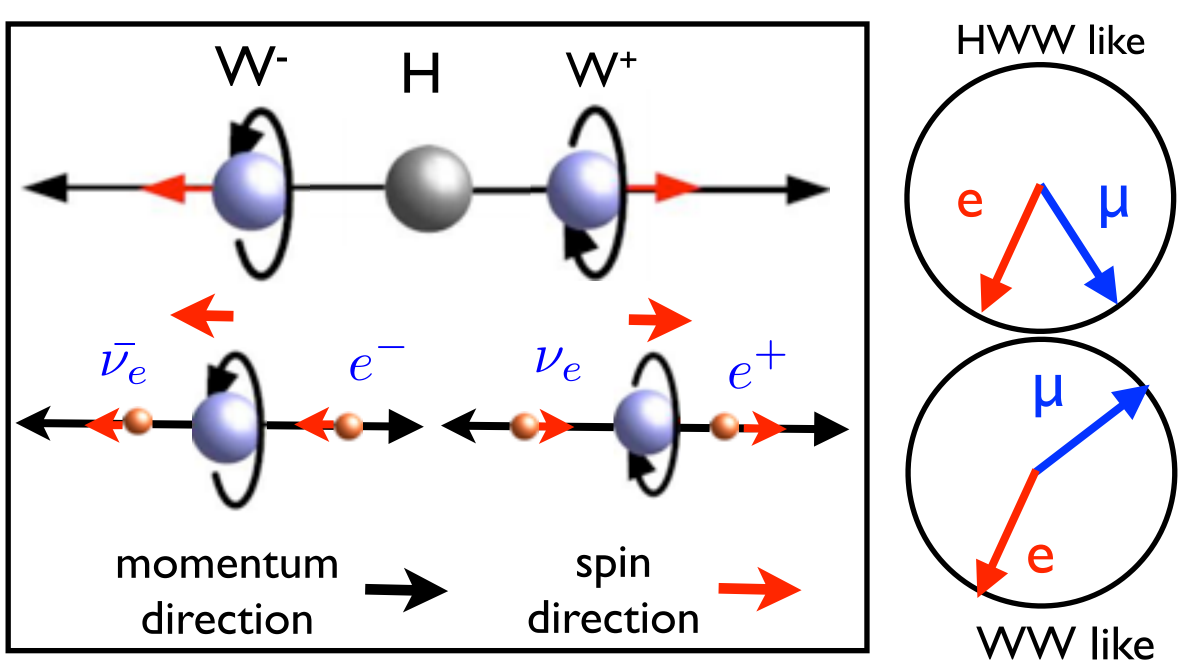
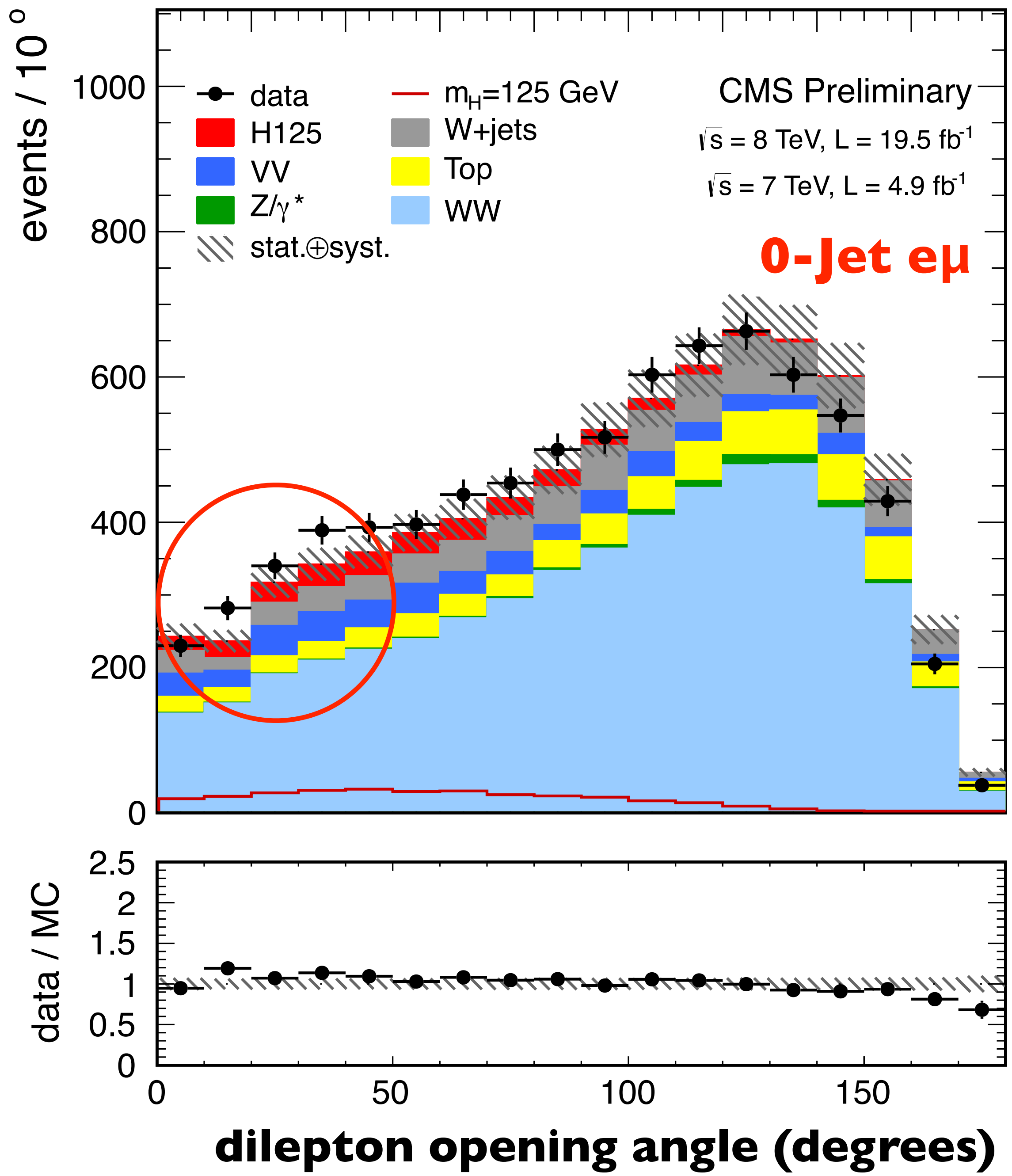
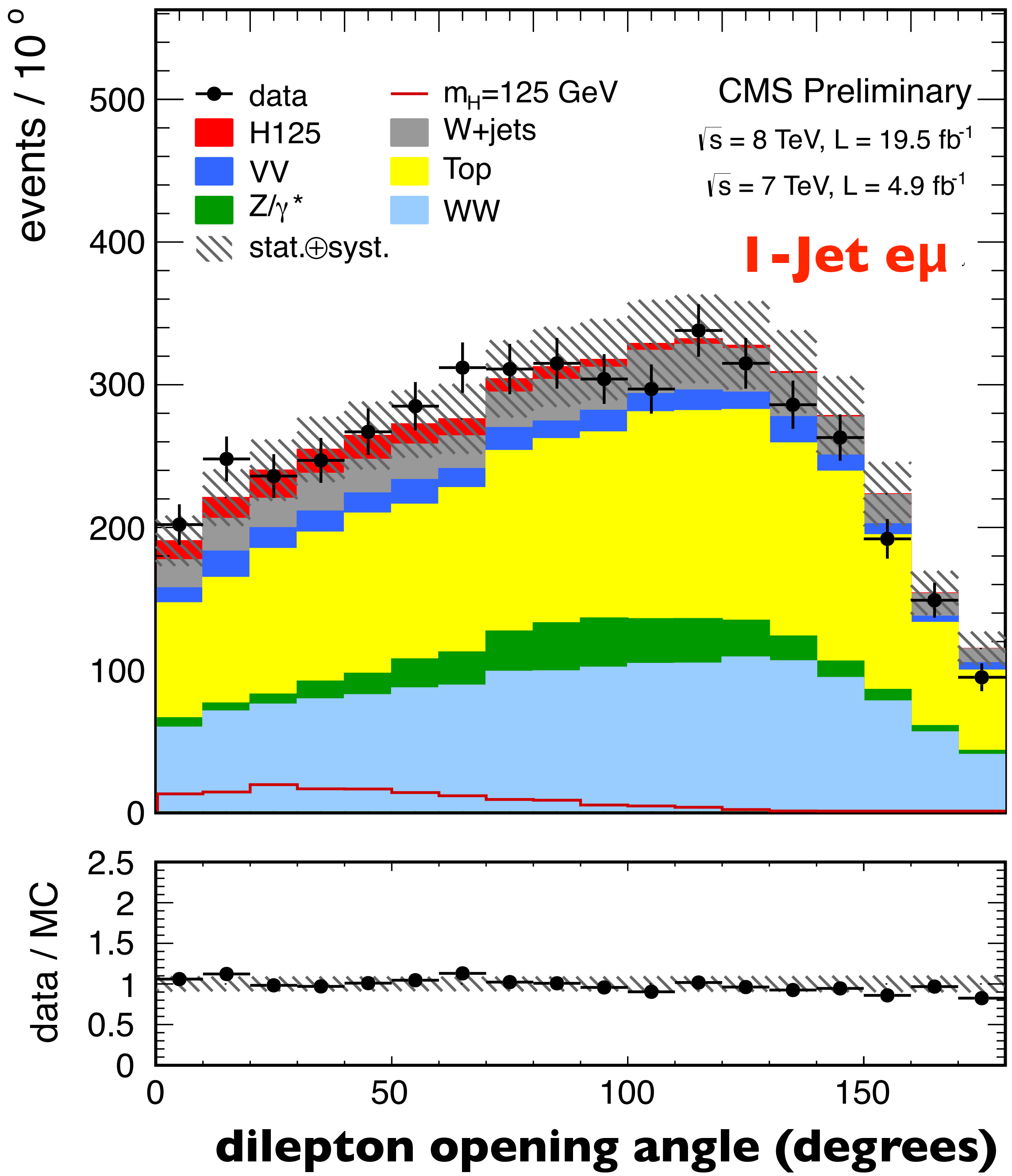
- Two complementary approaches to extract the Higgs production cross-section
  - Cut and count
  - Use full shape of kinematic distributions
- Optimize search in categories
  - number of jets: 0/1/2
  - lepton flavor: ee/eμ/μμ
  - 0-Jet eμ is the most sensitive channel

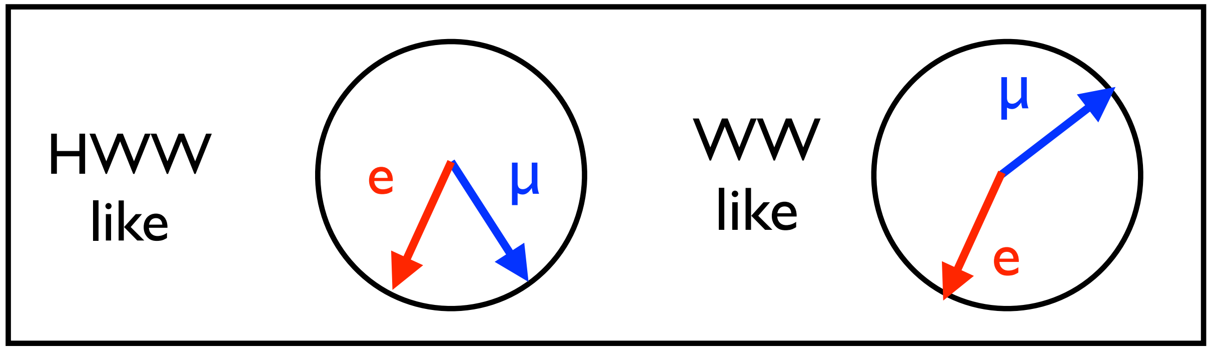




Events After the WW Selection

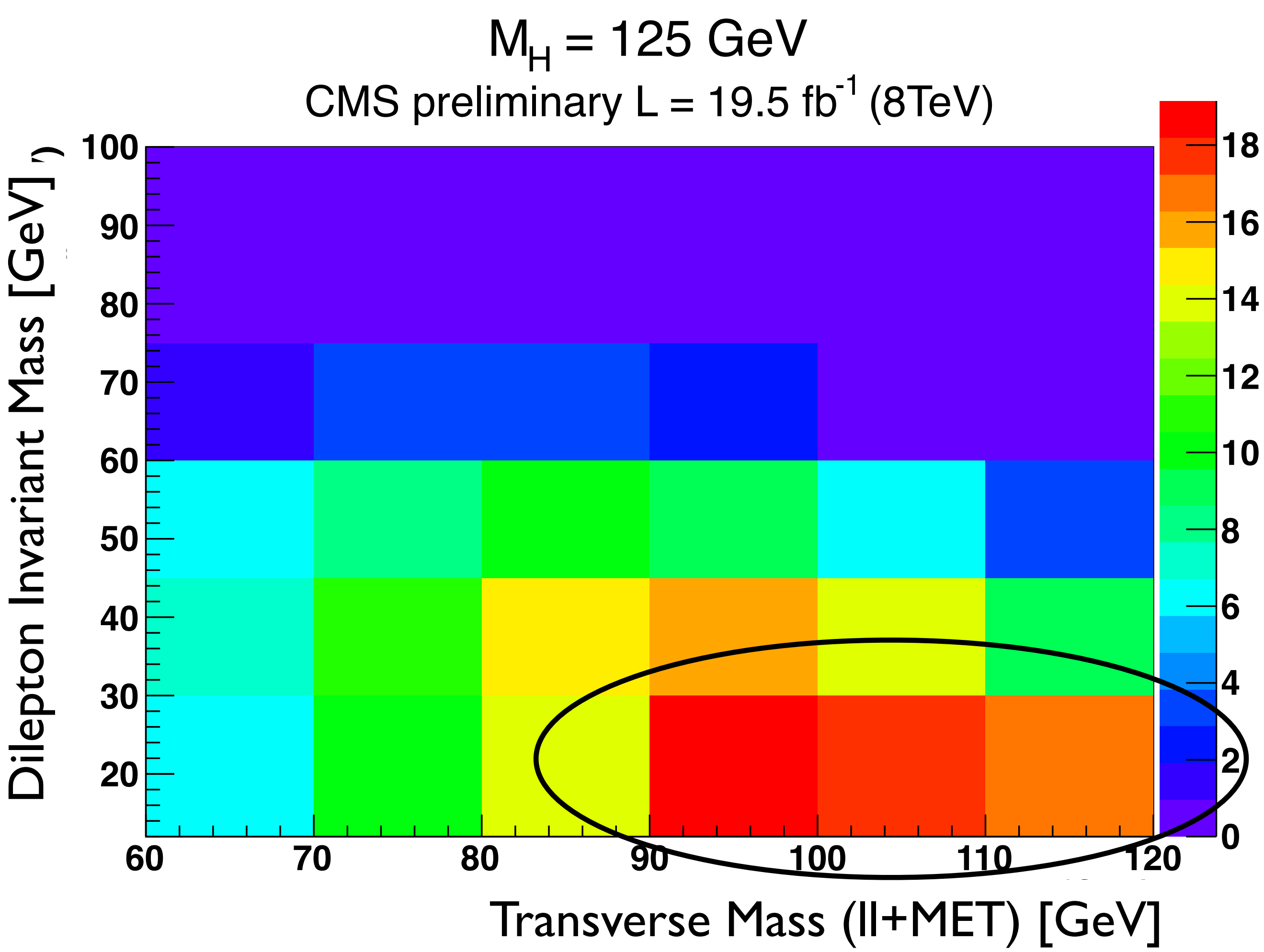


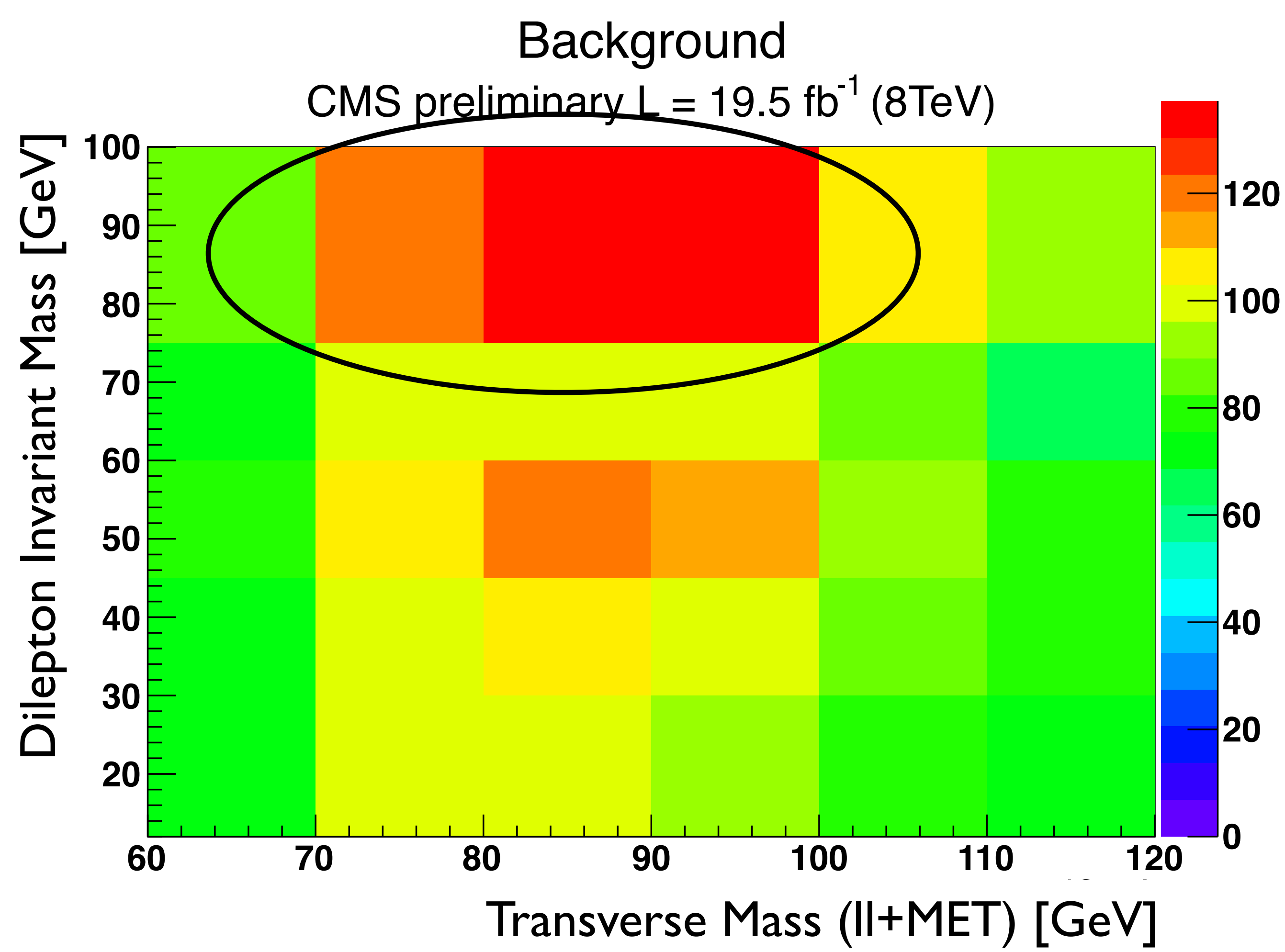




H→WW Cross-section Extraction

- 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



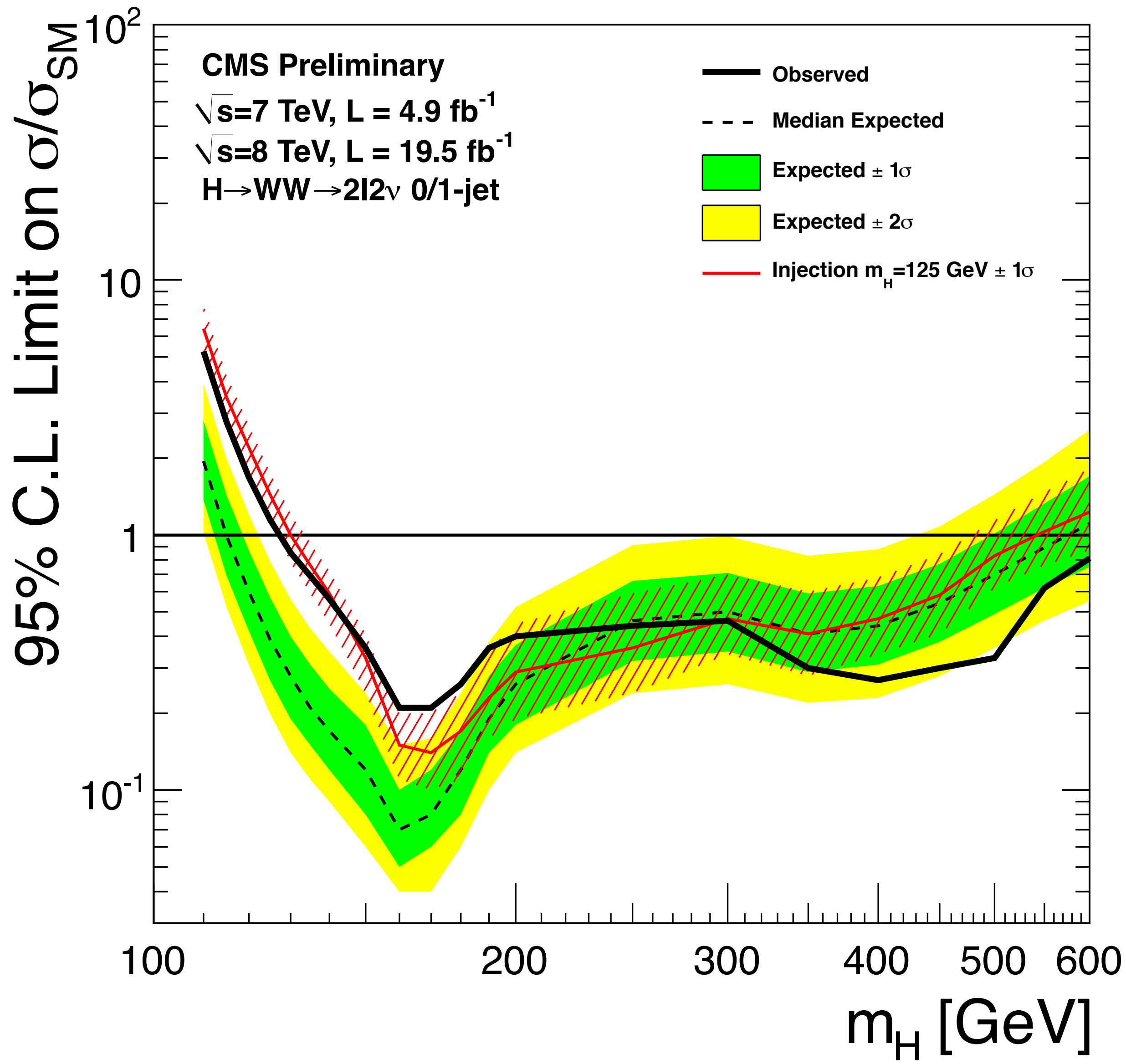


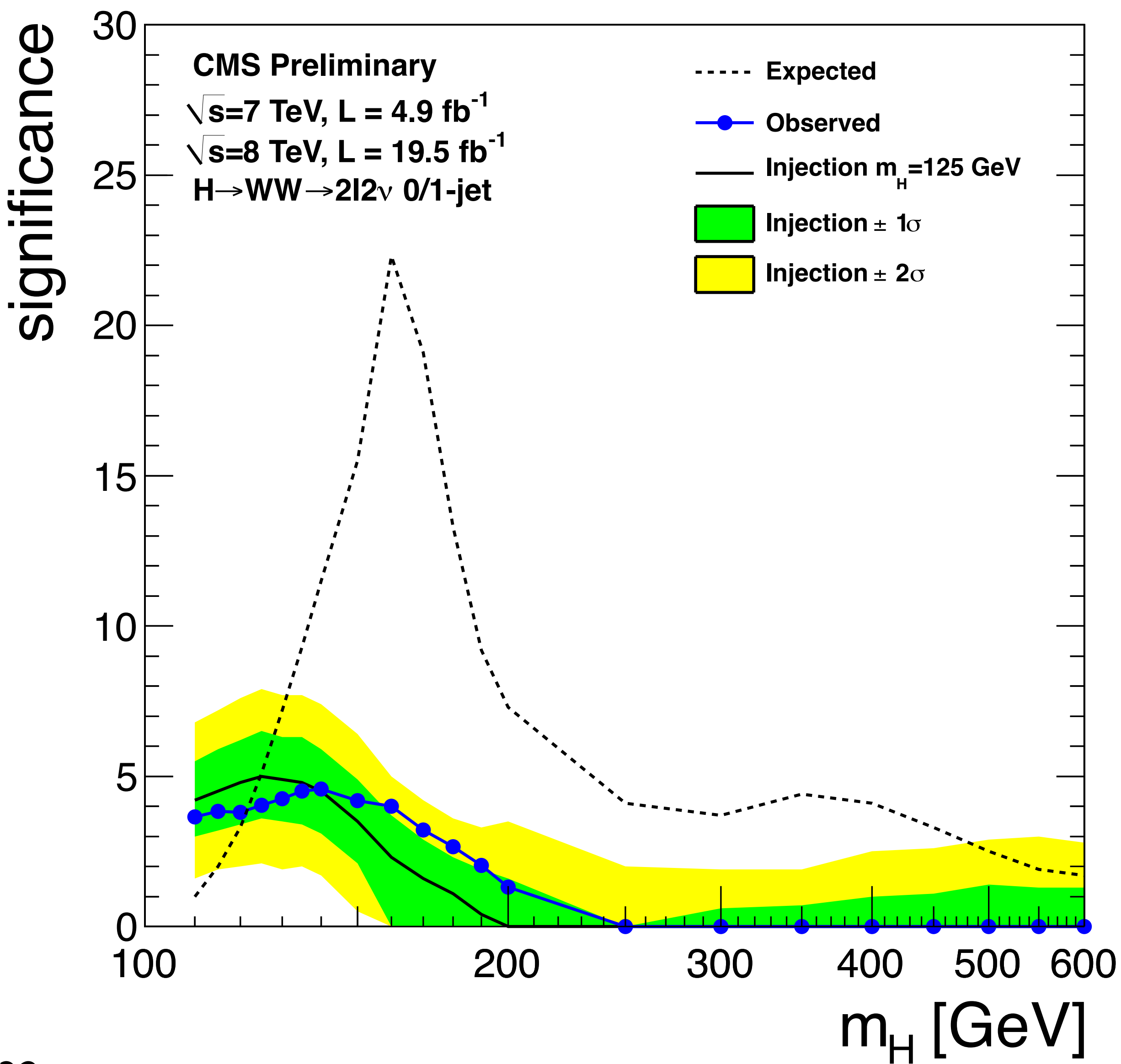
Summary of the Results

- 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

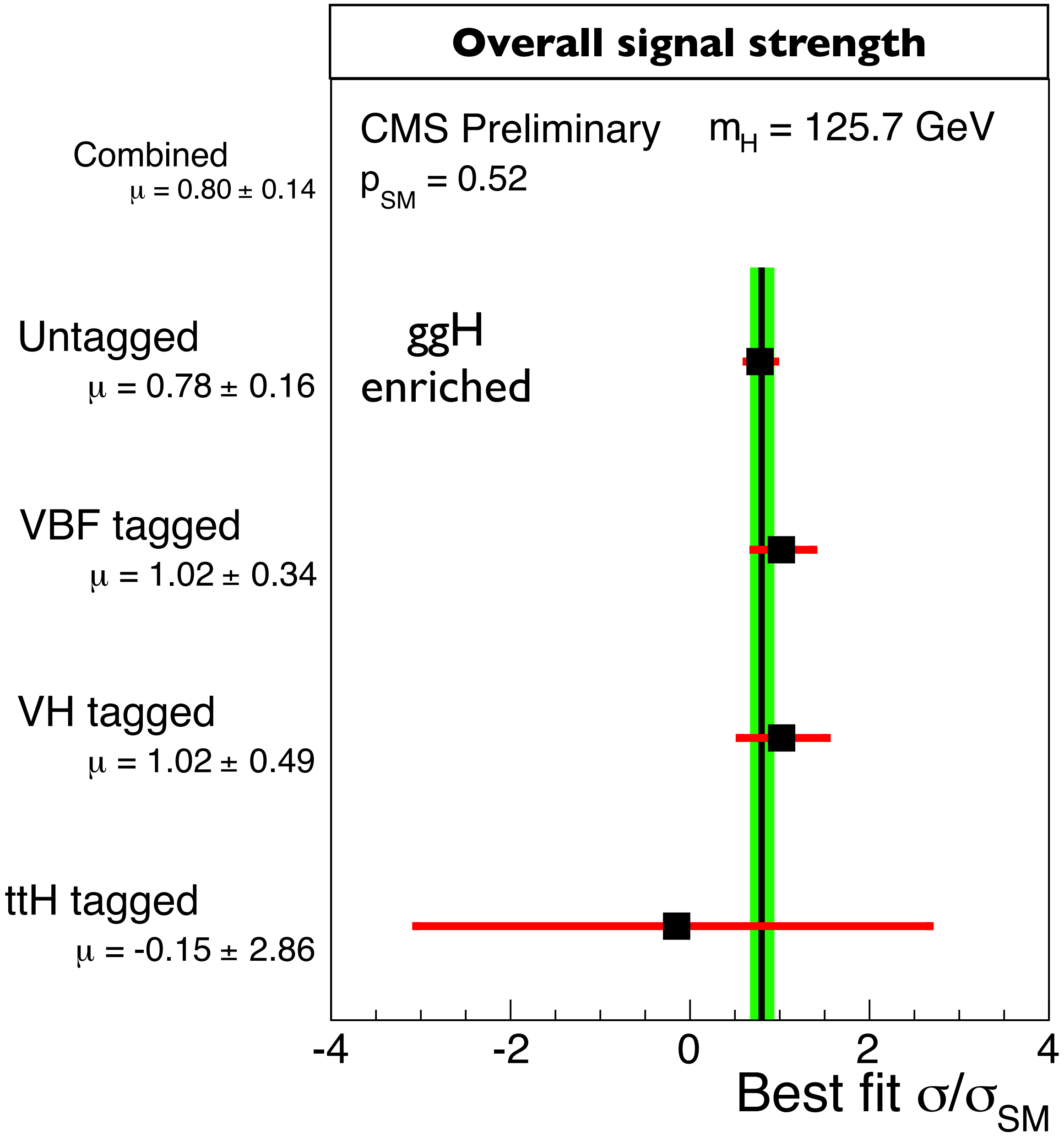


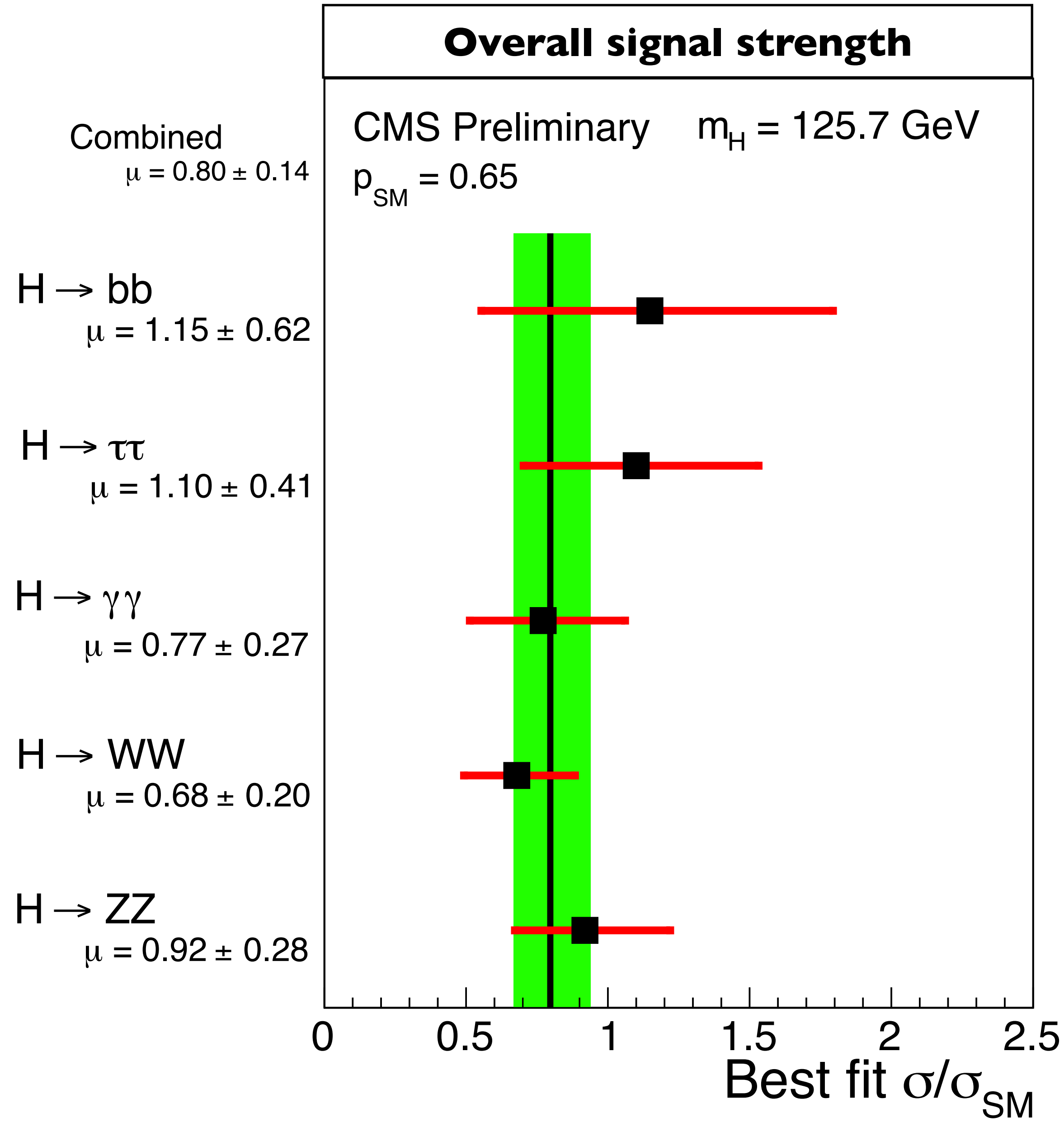


What do we know about this new particle?

Assuming the SM Tensor Structure

Mass	125.7 ± 0.3 (stat) ± 0.3 (syst) GeV
Significance	> 10 σ
Productions	Mainly from gg Fusion
Decays	Mainly ZZ/WW/γγ, evidence from bb/ττ
Couplings	No significant deviations from SM Prediction





Going beyond the SM Tensor Structure

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

- What are the *spin and parity* of this particle?

X→VV Scattering Amplitudes

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

SM 0+

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

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

X→VV Scattering Amplitudes

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

SM 0+ 0-

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

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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

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SM 0+ | 0+ High order | 0-

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0_h^+	$gg \to X$	$g_2^{(0)} \neq 0$	scalar with higher-dimension operators

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

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$$A_{J=1}(X \to V_1 V_2) = b_1 \left[(\epsilon_1^* q)(\epsilon_2^* \epsilon_X) + (\epsilon_2^* q)(\epsilon_1^* \epsilon_X) \right] + b_2\, \epsilon_{\alpha\mu\nu\beta} \epsilon_X^\alpha \epsilon_1^{*,\mu} \epsilon_2^{*,\nu} \tilde{q}^\beta$$

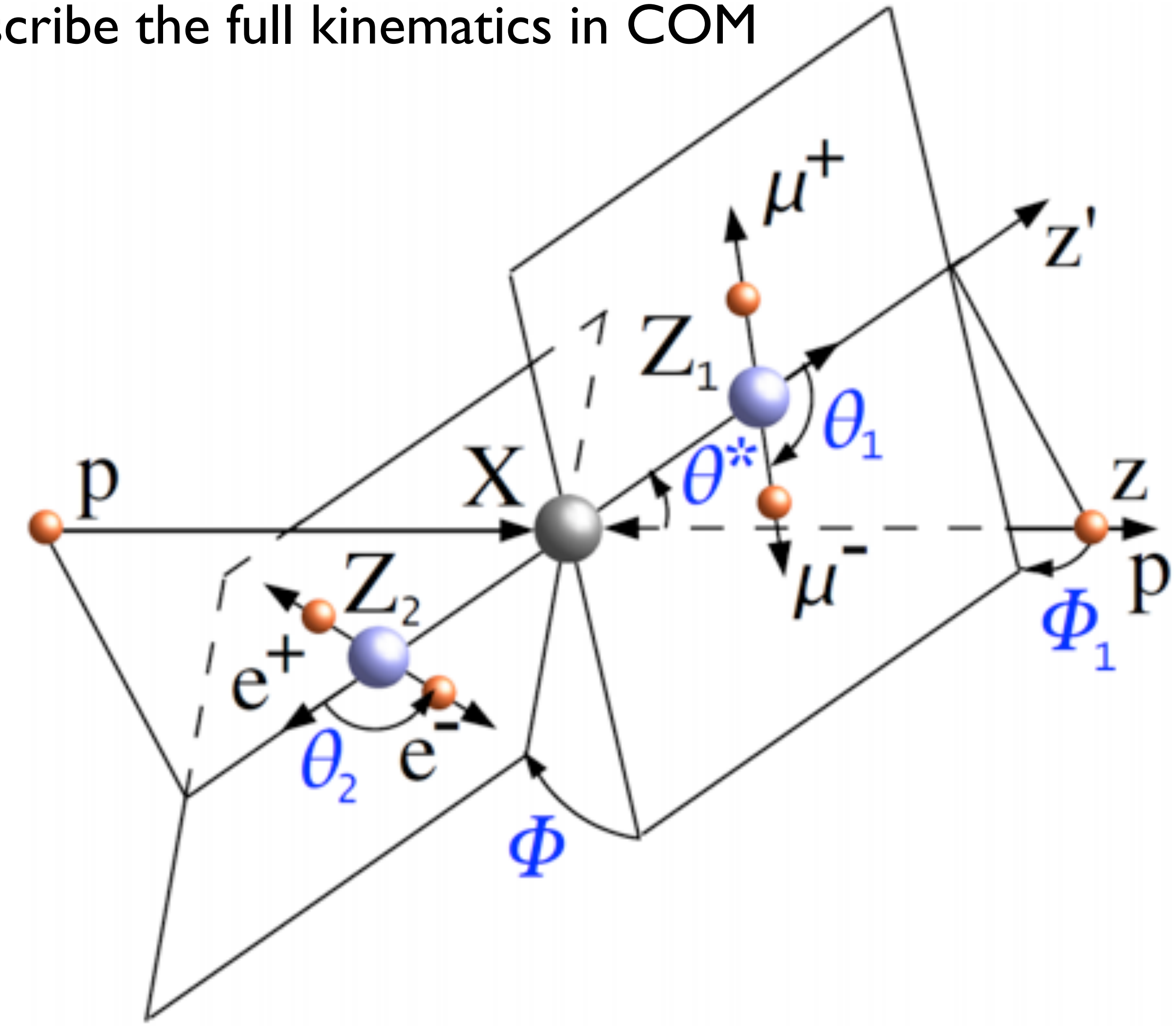
$$\begin{aligned} A_{J=2}(X \to V_1 V_2) = \Lambda^{-1} \Big[& 2 g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2 g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} \\ & + g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*(1)\mu\nu} f_{\mu\alpha}^{*(2)} + f^{*(2)\mu\nu} f_{\mu\alpha}^{*(1)} \right) + g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f_{\alpha\beta}^{*(2)} \\ & + m_V^2 \left(2 g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2 g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu} \right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right) \\ & + g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}_{\alpha\beta}^{*(2)} + g_9^{(2)} m_V^2 \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma \\ & + g_{10}^{(2)} m_V^2 \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q \epsilon_2^*) + \epsilon_2^{*\nu} (q \epsilon_1^*) \right) \Big] \end{aligned}$$

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 Spin and Parity Measurements

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



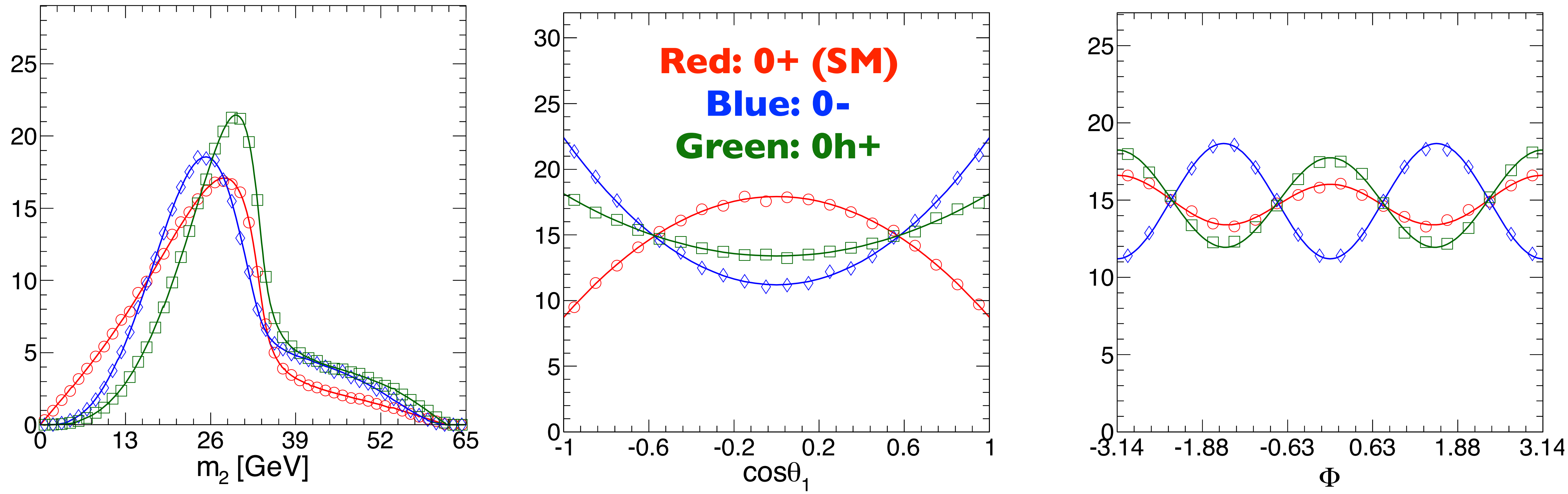
- The kinematic distributions of the variables depend on the X→VV scattering amplitudes
  - Predictions can be made both from *generators* and *analytical calculations*

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)*

Kinematics of Signal Models with Different Spin/Parity

X→ZZ→4l

Perfect match between generator (data points) and analytical calculations (lines)



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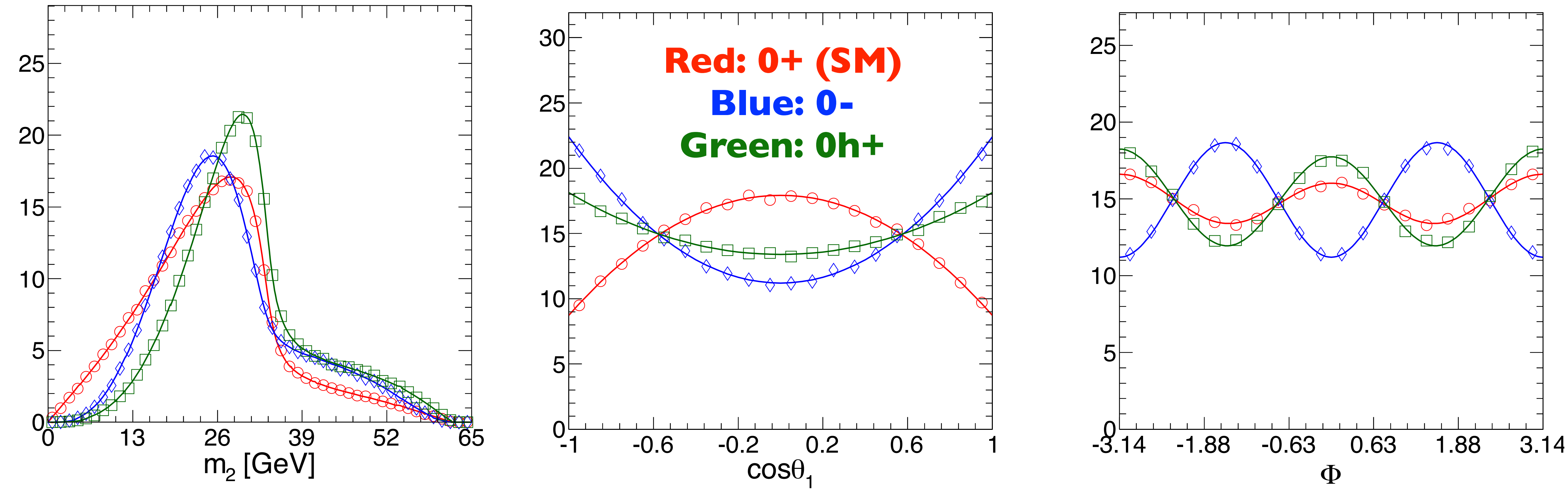
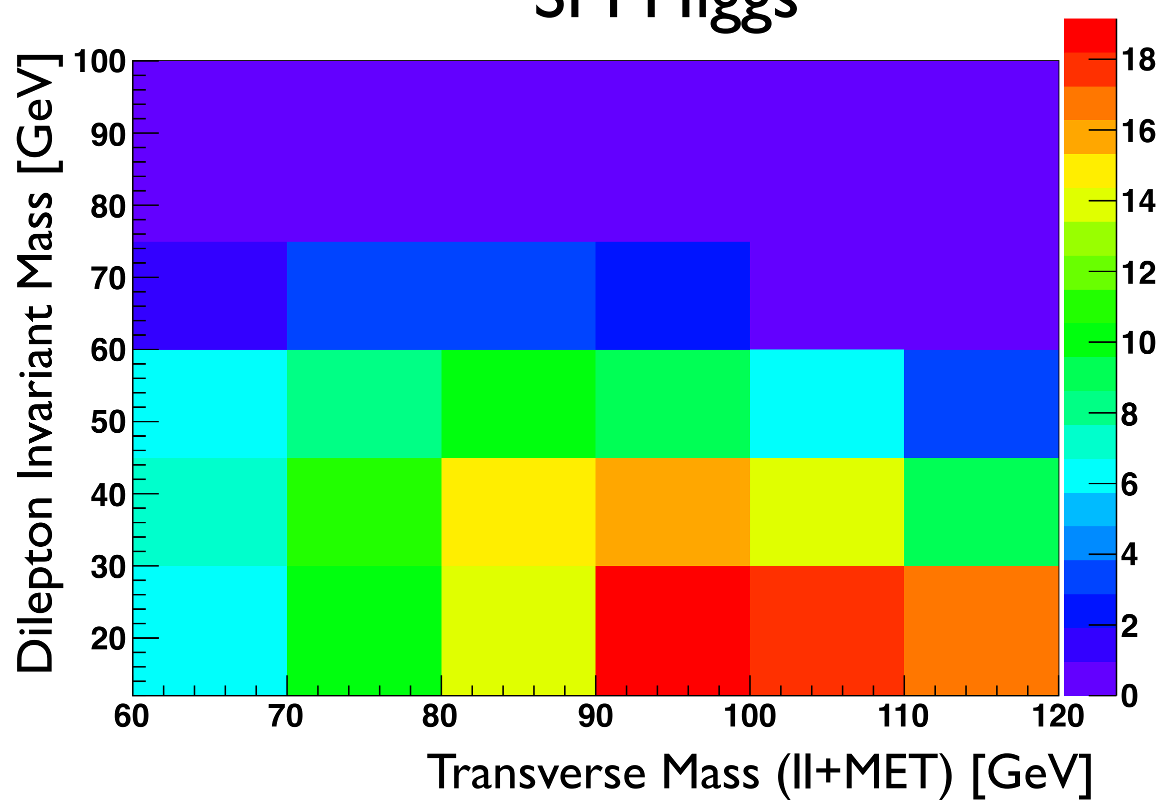
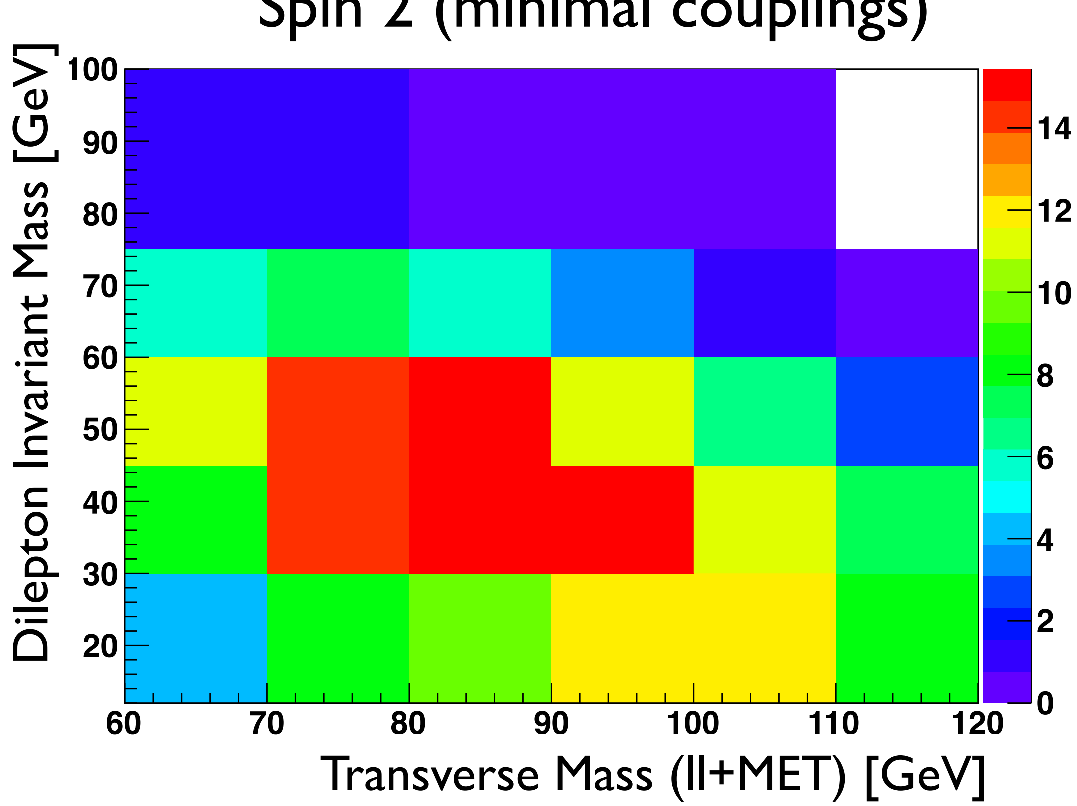


X→WW→2l2ν

SM Higgs

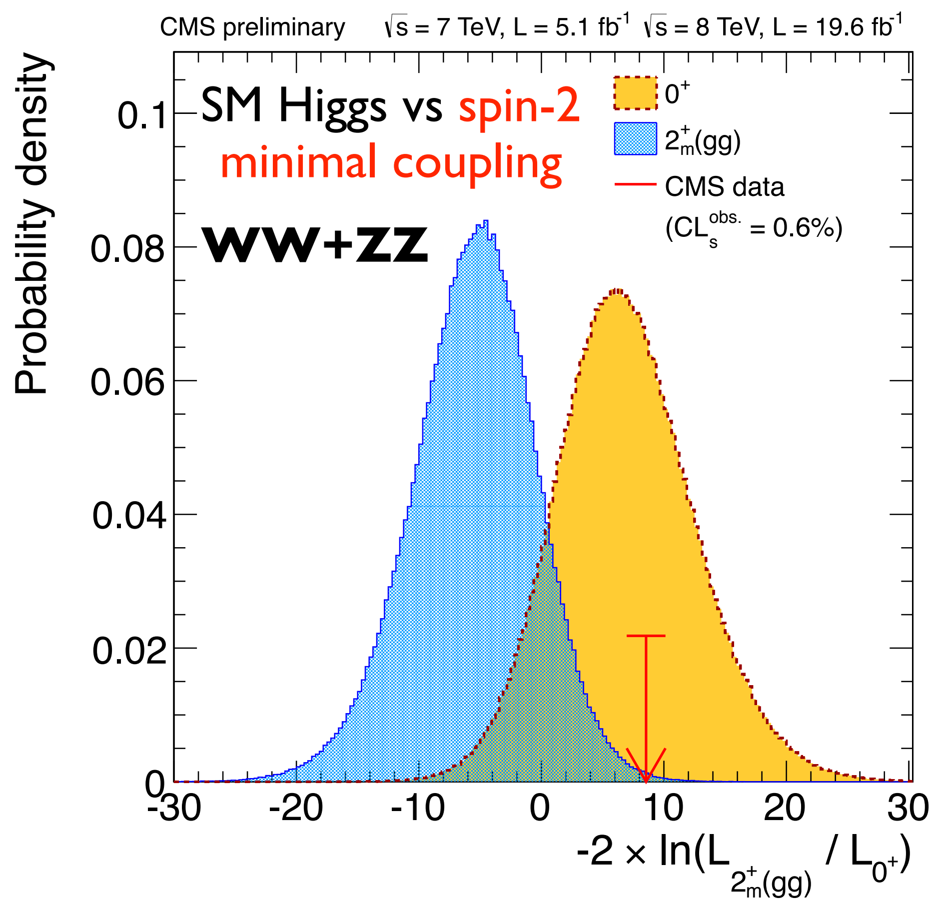


Spin 2 (minimal couplings)



The Spin and Parity Results

- Spin
    - Data is more consistent with spin 0
        - disfavors several spin-1 and 2 bench marks with < 5% CLs value



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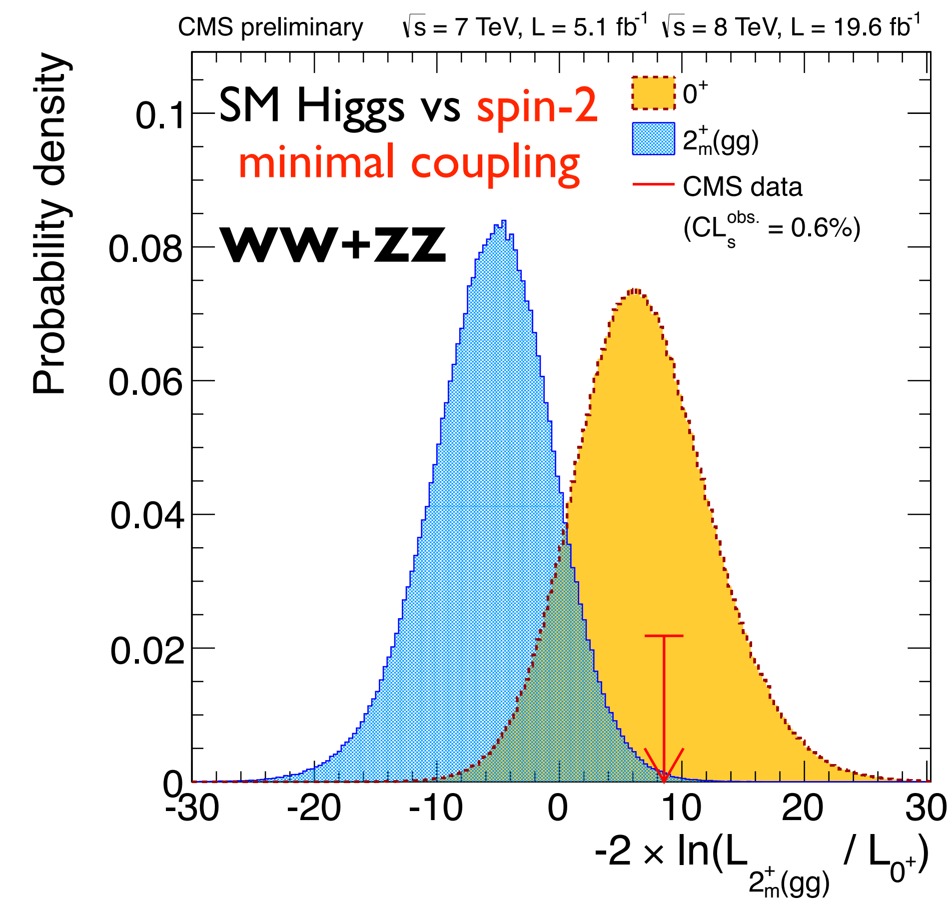
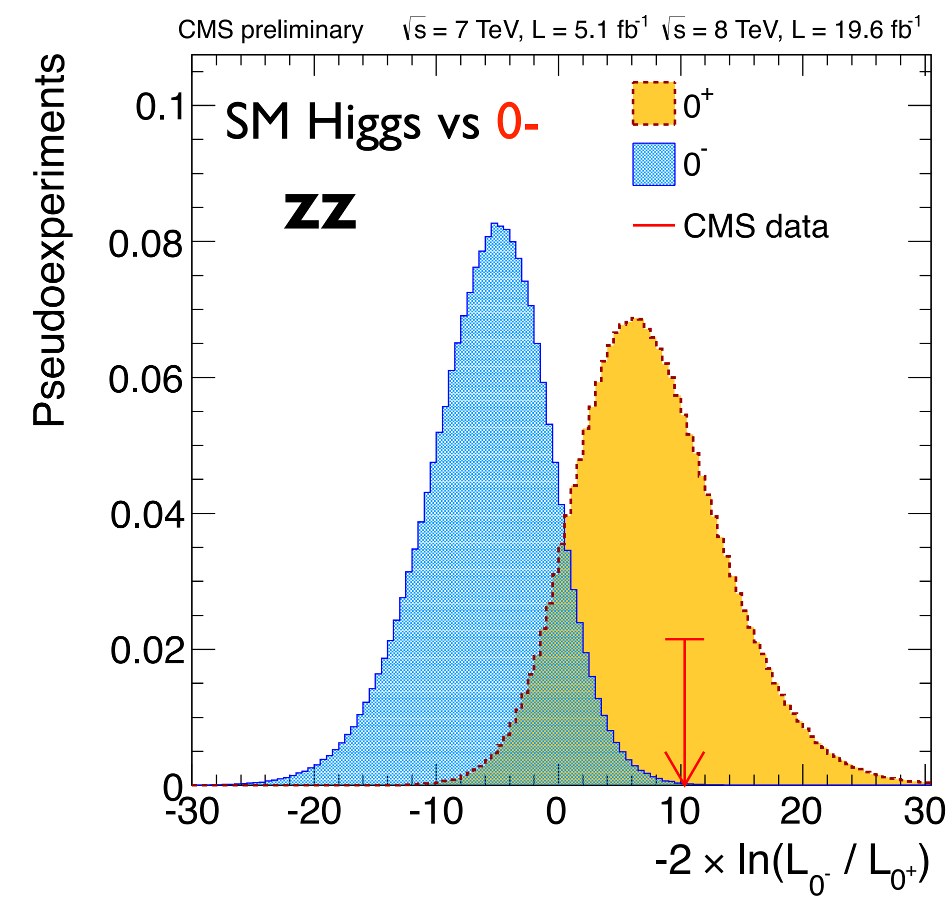


- Parity (assuming spin 0)
  - Data is more consistent with 0+
    - disfavors a pure CP-odd state
    - Fit the fraction of CP-odd state, i.e. CP violating component (g1, g4)

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

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

$$\mathtt{frac}(0^+) < 0.58 \text{ at } 95\% \text{ C.L.}$$



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)
  - Model independent spin measurements
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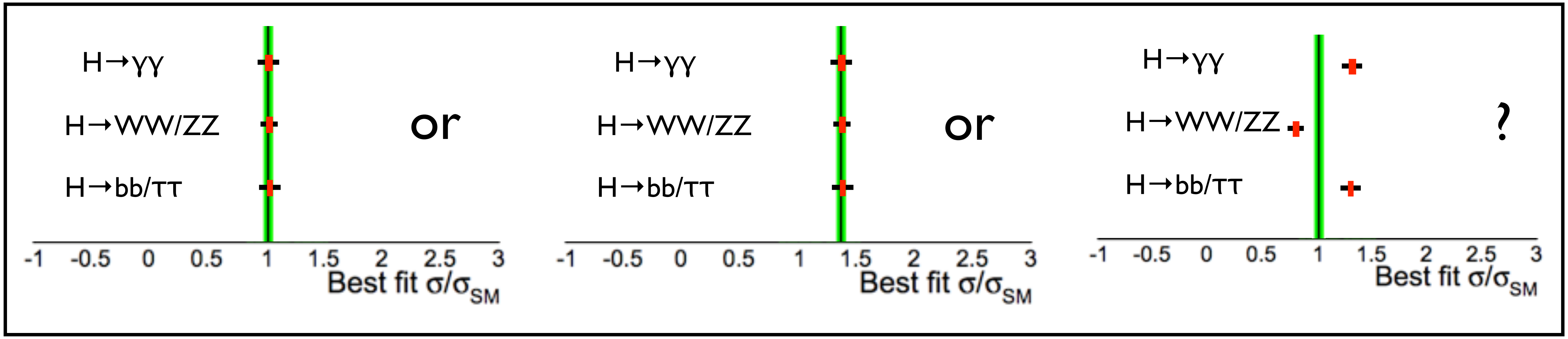


- **Together with some other positive NP signatures (hopefully), Higgs measurements can help shed light on the EWSB and the future of HEP**

Acknowledgment

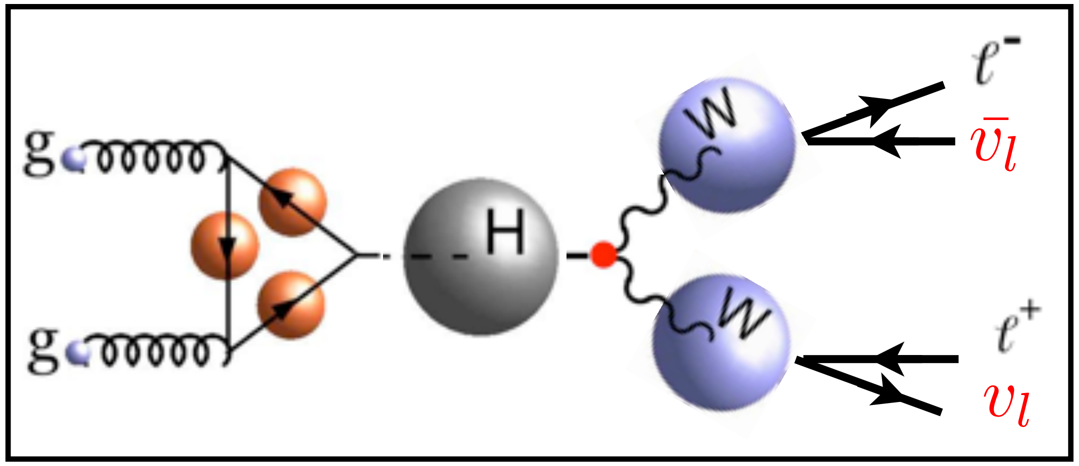
- Thanks to URA and Tollestrup award committee for this award
    - The Higgs discovery is truly a team effort
- Thanks to the LHC for the excellent performance in delivering the data
- Thanks to the CMS collaborations for the support, especially
    - Review committee members
        - Michel Della Negra, Ivan Furic, Ulrich Heintz Peter Kruezer, Pierre Marage, Norbert Neumeister, Michael Schmitt, Paris Sphicas
    - HWW analysis colleagues
        - Kevin Burkett, Claudio Campagnari, Guillelmo Ceballos, Giuseppe Cerati, Dave Evans, Sergo Jindariani, Benjamin Hooberman, Dmytro Kovalskyi, Markus Klute, Christoph Paus, Kevin Sung, Frank Würthwein, Si Xie, Avi Yagil, Jaehyeok Yoo, Marco Zanetti
    - HZZ angular analysis colleagues
        - Sara Bolognesi, Andrei Gritsan, Nhan Tran, Andrew Whitbeck
- Thanks to my theory colleagues Kirill Melnikov and Markus Schulze
- Thanks to Fermilab CMS Center/LPC for the support, especially
    - Lothar Bauerdick, Kevin Burkett and Patty Mcbride

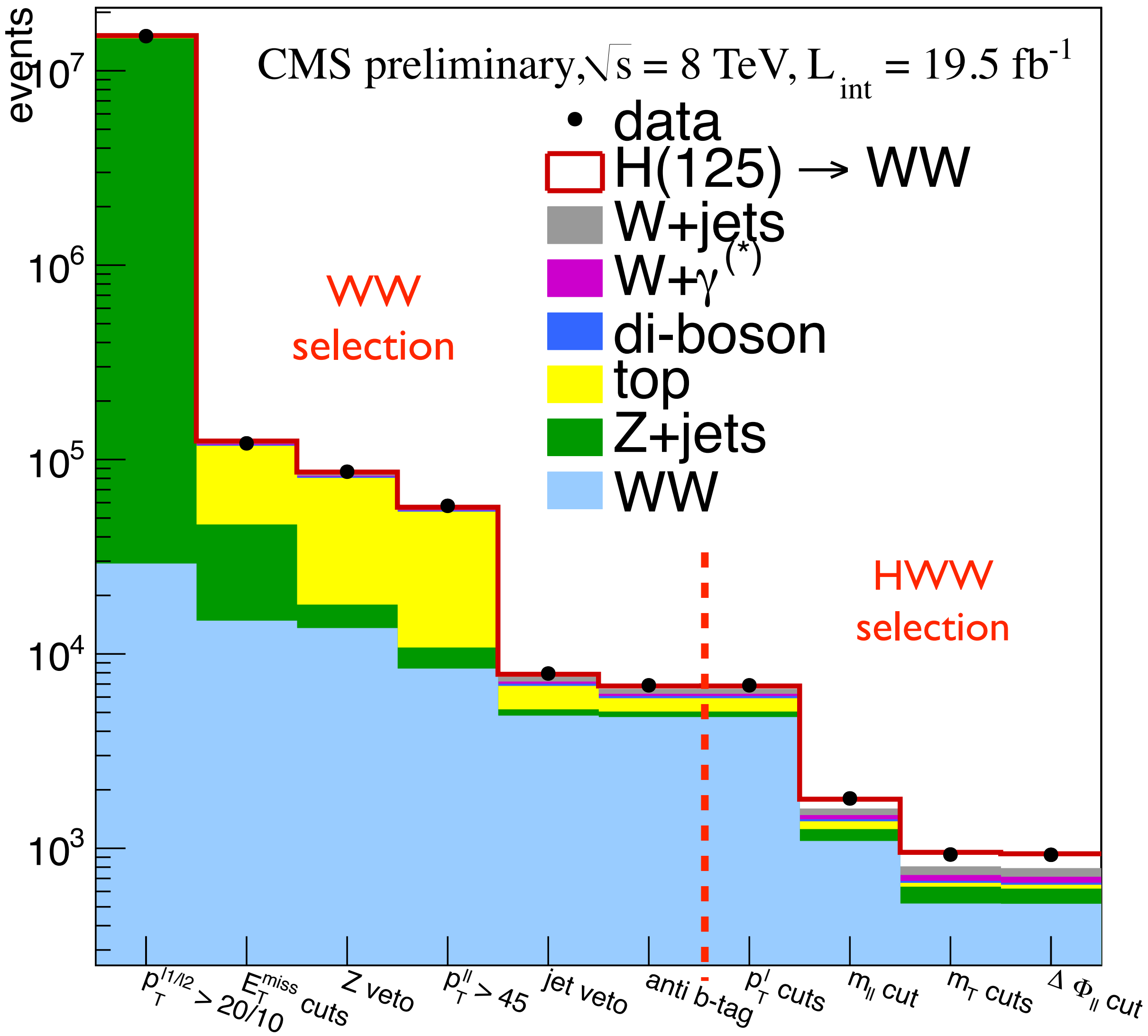
Supporting Slides

Key Analysis Ingredients in H→WW

- Main advantage
  - High signal rate ~ 15 events/fb
- Main challenge
  - Large/complex backgrounds
    - Reducible: W/Z+jets, Top, WZ
    - Irreducible: WW/ZZ
  - Absence of Higgs mass peak
- Key in the analysis
  - Optimize selections
  - Develop reliable background estimations
    - Data driven methods
  - Use full kinematic shapes

Dilepton, large MET, low Jet activity



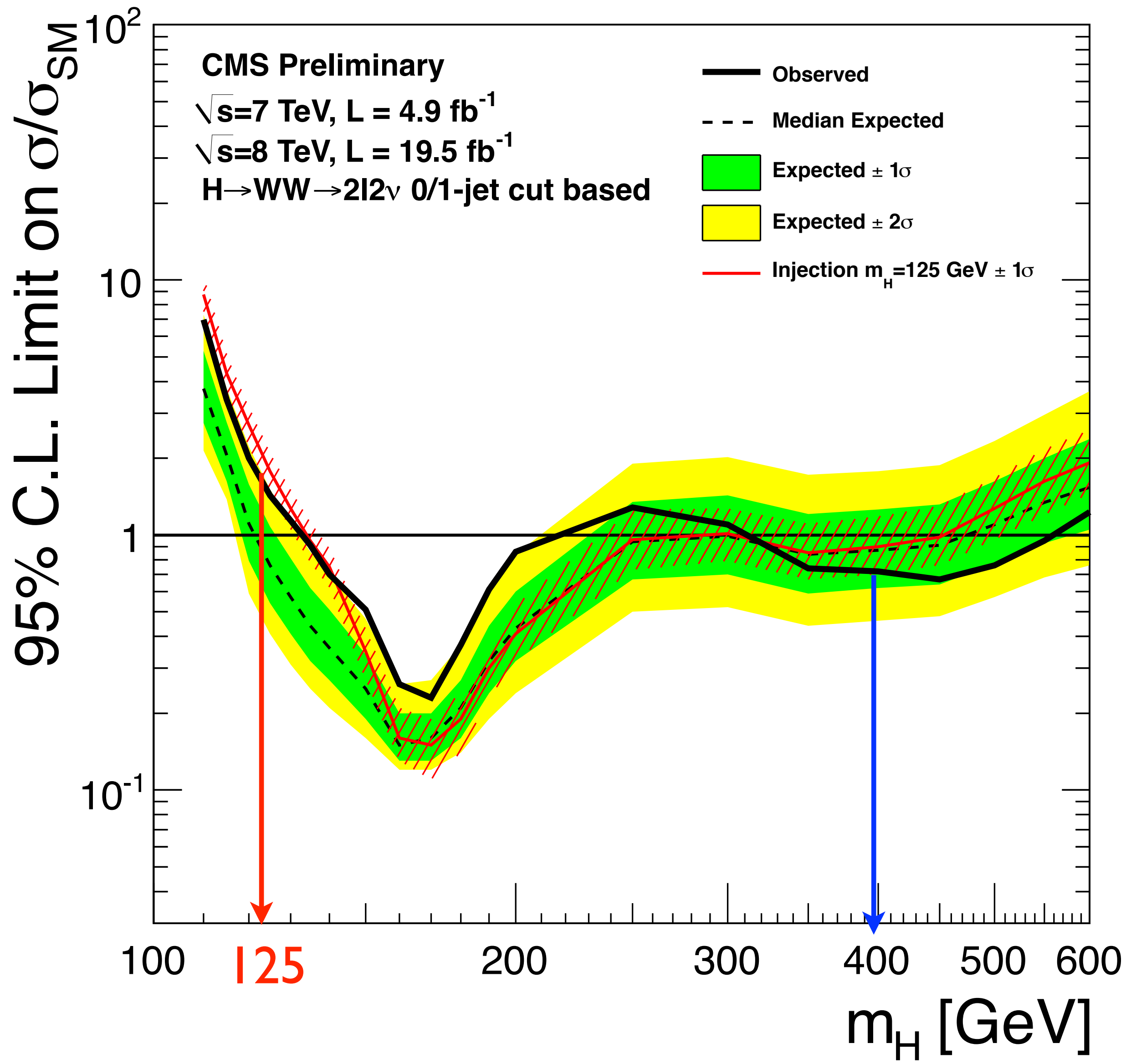


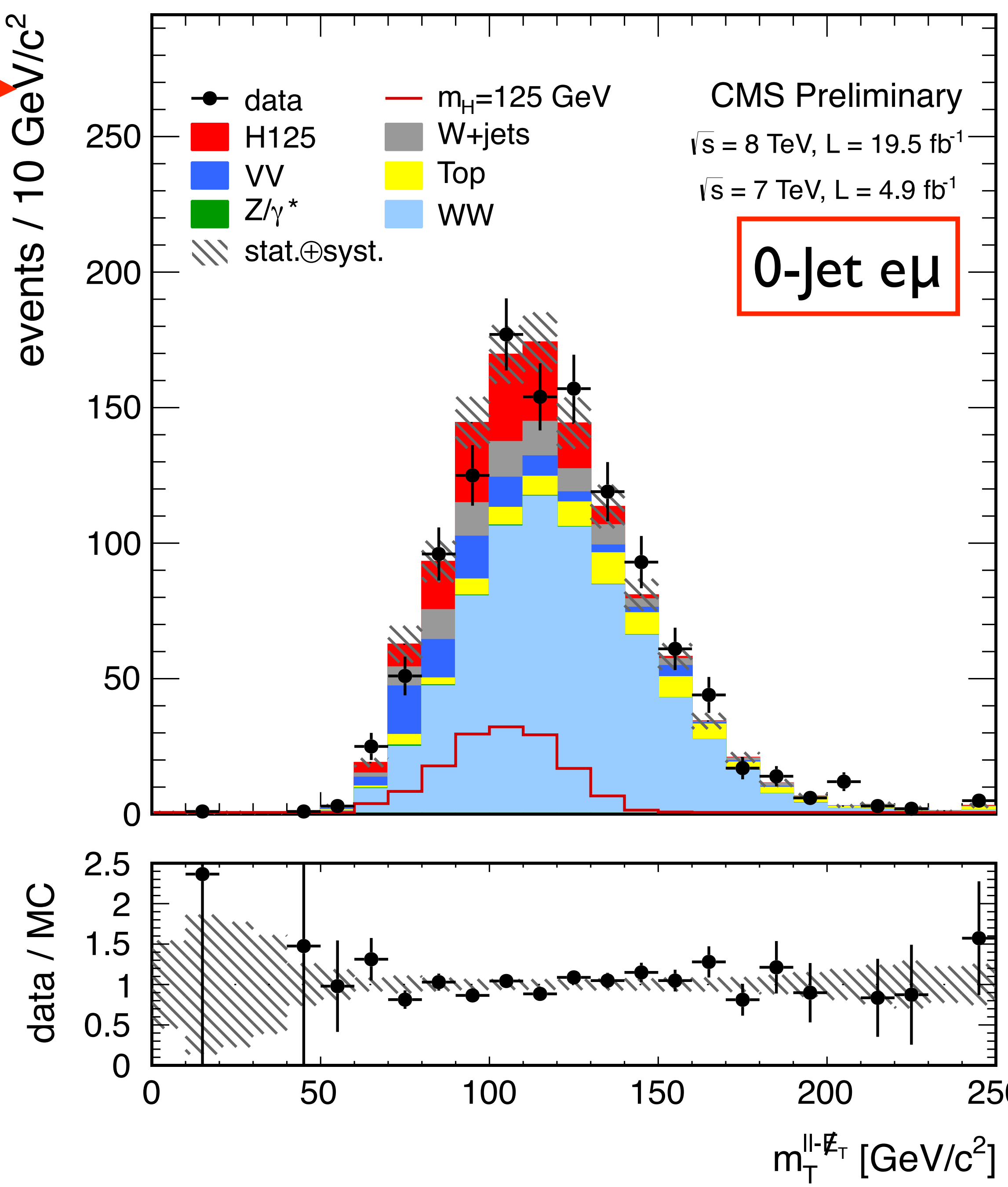
Cut-based Analysis Results

- Number of events in the most sensitive 0-Jet eμ final state for 19.5/fb data at 8 TeV

mH	Data	H→WW	All bkg.	WW	W+jets	W/Z+γ(*)	Top
125	505	90 ± 19	429 ± 34	310 ± 29	48 ± 13	11.4 ± 1.1	20.0 ± 4.3
400	306	64 ± 17	326 ± 30	210 ± 23	8.9 ± 3.8	10.0 ± 1.1	92 ± 18

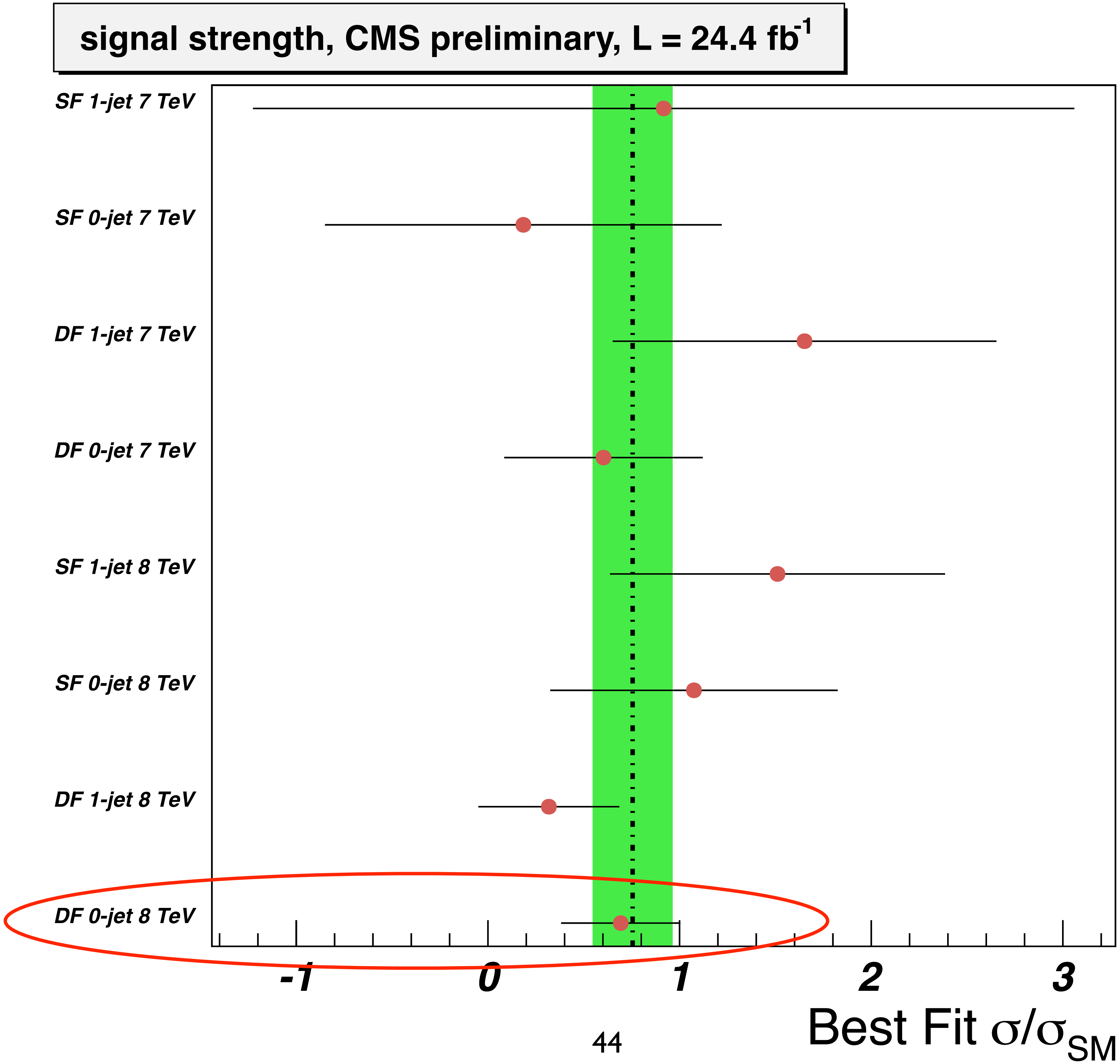
mH 125 GeV signal strength
σ/σ_{SM} = 0.80 ± 0.45





Signal Rates in Different Final States

We observed an excess at ~125 GeV at ~4σ, corresponding to μ= 0.76 ± 0.21

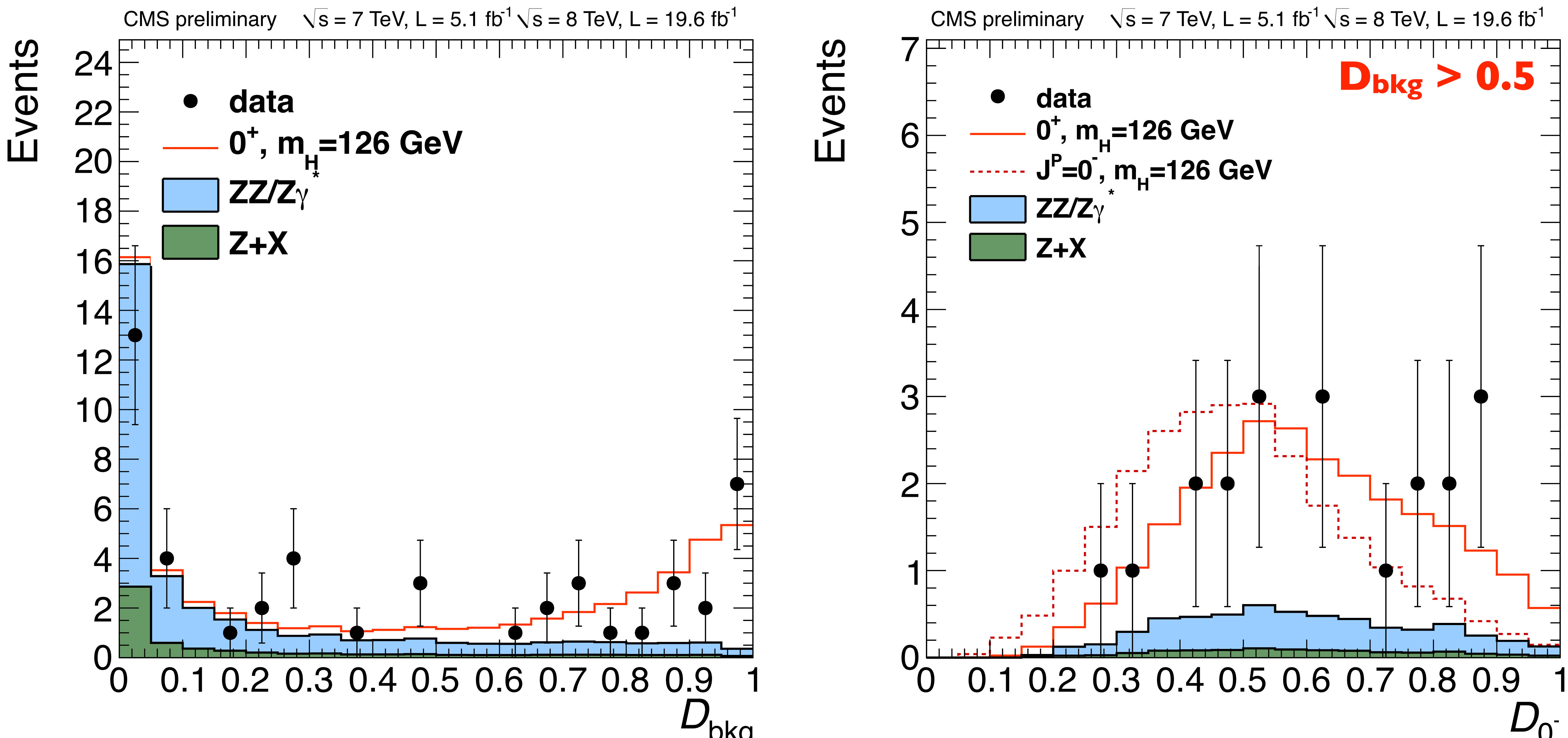


Hypothesis Separations in ZZ Channel

- Background rejection and signal model separations

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

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



Is the particle the SM Higgs boson?

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

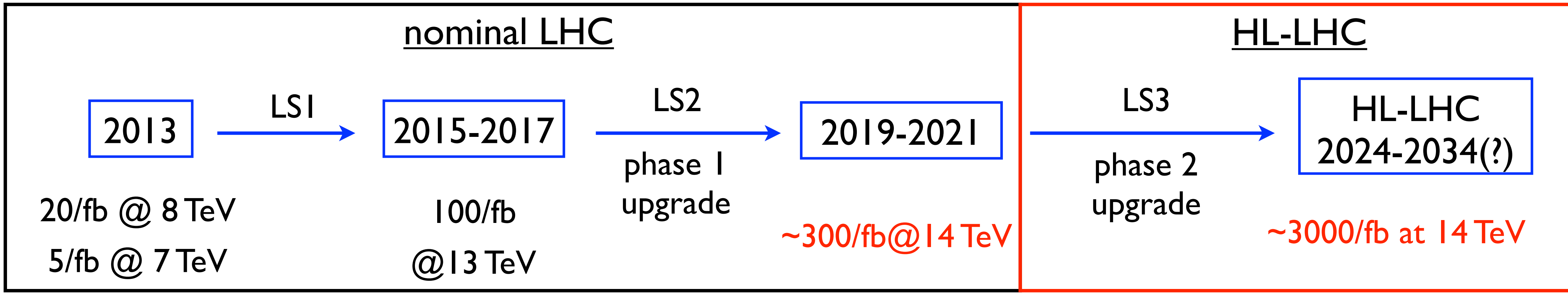
Predicted deviations in couplings compared to the SM Higgs mechanism

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?



- 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**