Constraint on Higgs boson total width using off-shell production in the ZZ decay

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on behalf of the CMS Collaboration

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Outline

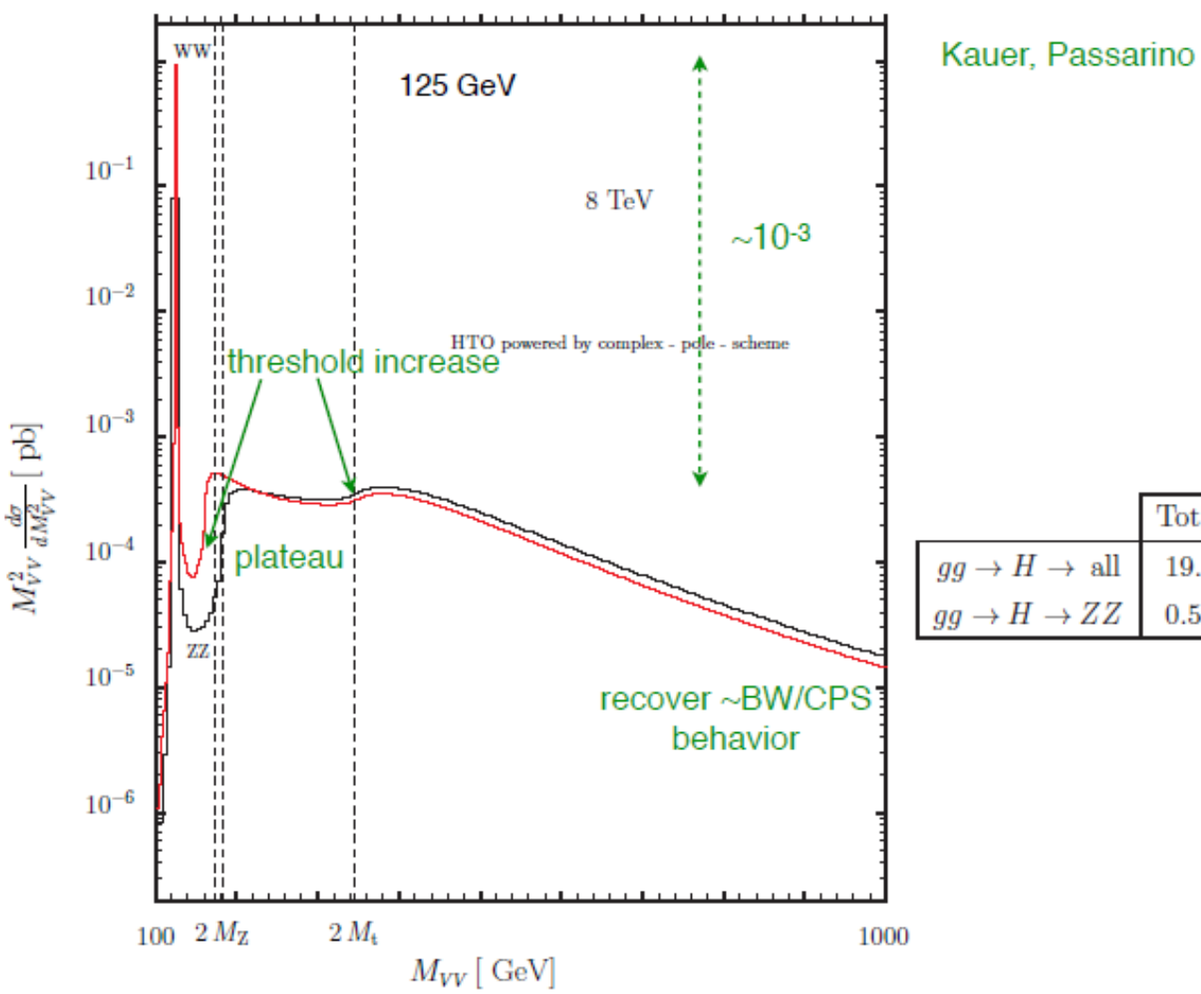
- Prior Status
- Theoretical Background
- Statistical approach
- H→ZZ→4l analysis and results
- H→ZZ→2l2v analysis and results
- Combination results
- Conclusion

Prior Status of Γ_H

- Current limit in 4l on total width of Higgs is $\leq$ 3.4 GeV $\approx$ 800xΓ_{SM} (Γ_{SM} = 4.25 MeV)
- At LHC, resolution limits direct measurement to O(1) GeV
- We can use off-shell production to make a stricter limit on total width of Higgs

Theoretical Background

- Well known that the Zero Width Approximation is poor approximation far from Higgs mass[1]
  - Competing effects from BW in high mass region and $\Gamma_{H\to 4l}$ cause plateau in region above $2m_Z$
  - ~8% of total $H\to ZZ$ cross section found in $m_{ZZ} > 2m_Z$ region



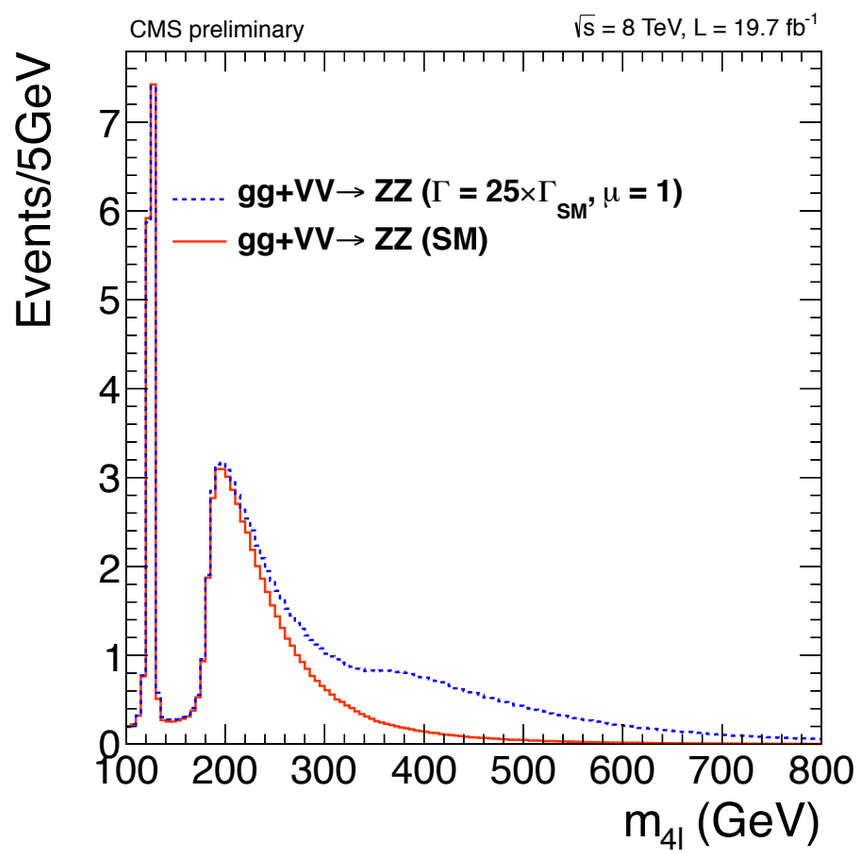
	Tot[pb]	$M_{ZZ} > 2M_Z$[pb]	R[%]
$gg \to H \to$ all	19.146	0.1525	0.8
$gg \to H \to ZZ$	0.5462	0.0416	7.6

[1]Kauer, Passarino (*JHEP* **08** (2012))

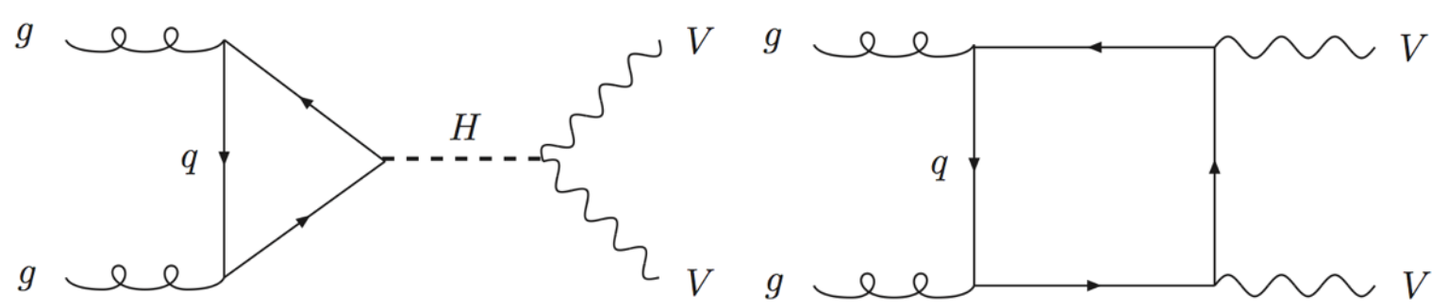
Theoretical Background

- As suggested in a recent paper[2], we can make a *model-independent* measurement of the Higgs width

$$\sigma^{\text{on-peak}}_{gg\to ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma} \qquad \sigma^{\text{off-peak}}_{gg\to ZZ} \propto g^2_{ggH} g^2_{HZZ}$$



- m_{ZZ} distribution can be used alone, but kinematic discriminants can improve sensitivity

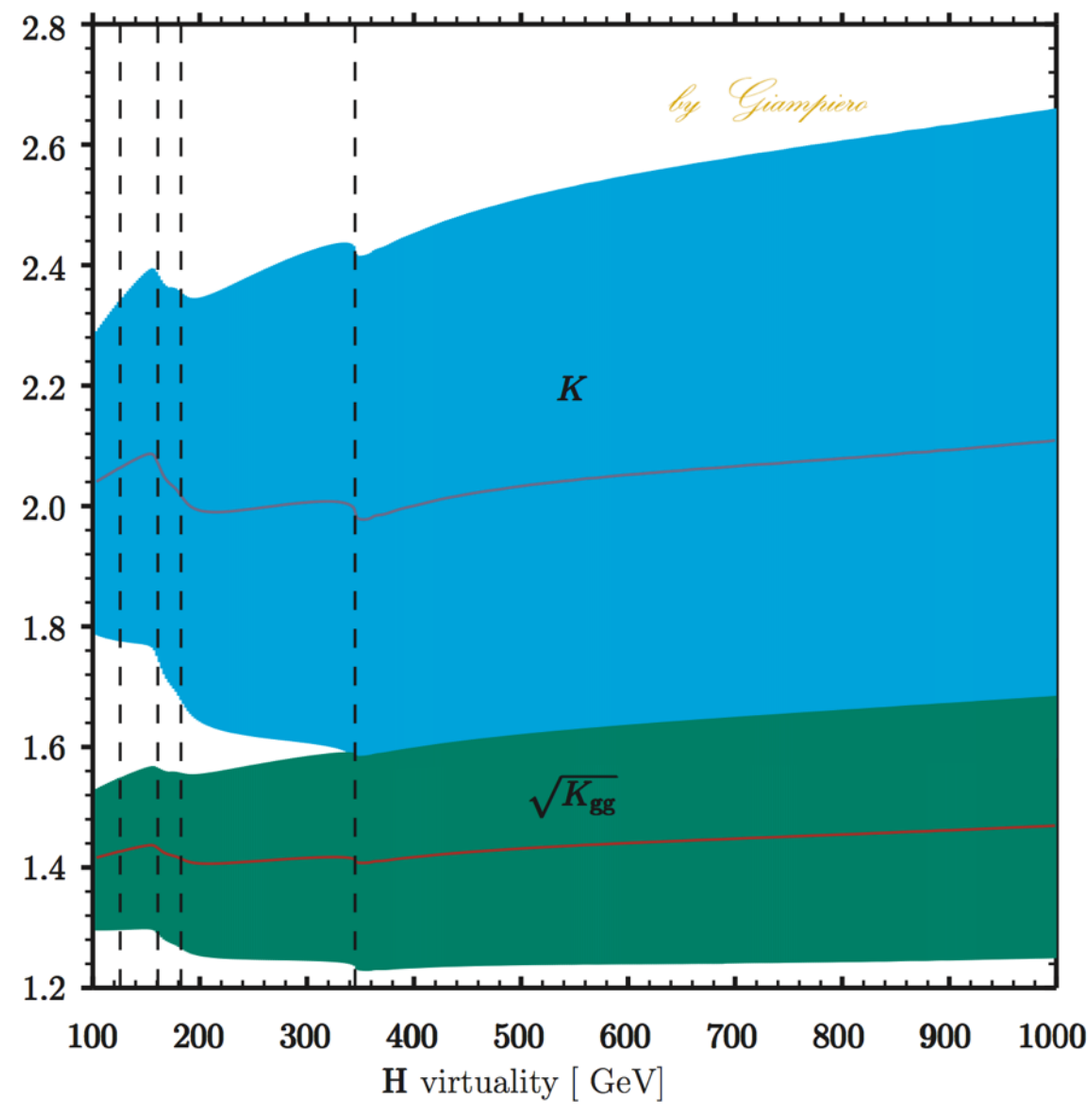


- Interference is significant at high masses, accounted for in analysis of off-shell signal

[2]Caola, Melnikov (*Phys Rev D* **88** (2013) 054024)

Monte Carlo Simulation

- Gluon-gluon Fusion (gg2VV, MCFM)
  - NNLO/LO K-factors for signal are m_{ZZ} dependent[3]
  - Use same k-factor for signal and background, shown to be true for WW[4] expect to be identical for ZZ
- Vector Boson Fusion (PHANTOM)
  - Contributes only ~7% at peak, grows to ~10% in high mass region
- VH and ttH do not contribute in the high mass region



[3] Passarino (arXiv:1312.2397) [4] Bonvini et al. (*Phys Rev D* **88** (2013) 034032)

Statistical Approach

- Perform a maximum likelihood fit in CMS Higgs combination tool using selected event candidates, split into the final states

- Each event has an associated likelihood describing the probability it belongs to signal, background, or interference:

$$\mathcal{L}_i = N_{\mathrm{gg\to ZZ}}\left[\mu\Gamma \times \mathcal{P}^{gg}_{\mathrm{sig}} + \sqrt{\mu\Gamma} \times \mathcal{P}^{gg}_{\mathrm{int}} + \mathcal{P}^{gg}_{\mathrm{bkg}}\right] + N_{\mathrm{VBF}}\left[\mu\Gamma \times \mathcal{P}^{VBF}_{\mathrm{sig}} + \sqrt{\mu\Gamma} \times \mathcal{P}^{VBF}_{\mathrm{int}} + \mathcal{P}^{VBF}_{\mathrm{bkg}}\right] + N_{\mathrm{q\bar{q}ZZ}}\mathcal{P}^{q\bar{q}}_{\mathrm{bkg}} + N_{\mathrm{ZX}}\mathcal{P}^{ZX}_{\mathrm{bkg}}$$

where P is the normalized probability distribution for each process

- Total gg/VV→ZZ process (above in brackets) normalized together; P_{int} may have both positive and negative values but P_{tot} is positive-definite

- For self-contained analysis, use observed signal strength from 4l Legacy results, $\mu = 0.93^{+0.26}_{-0.24}$.

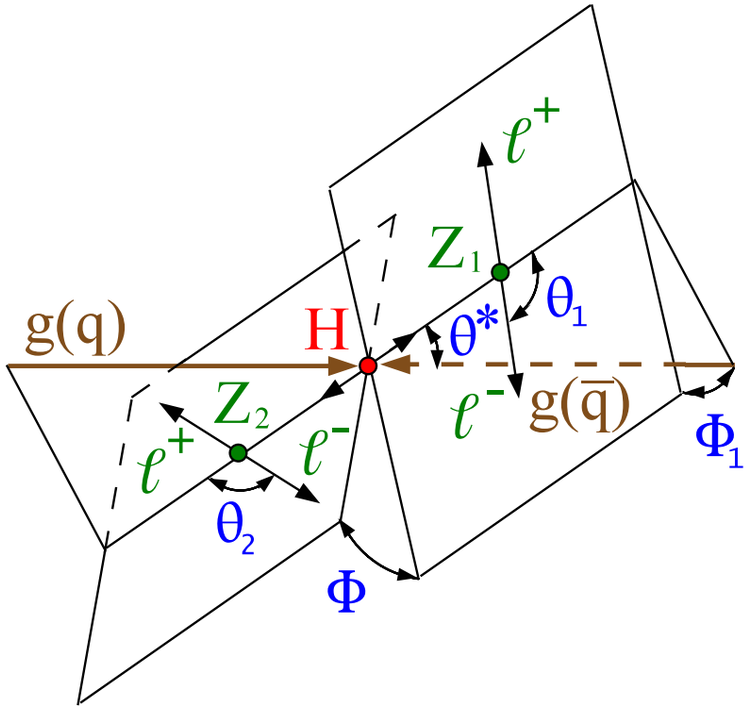
$H \rightarrow ZZ \rightarrow 4l$

4l Analysis

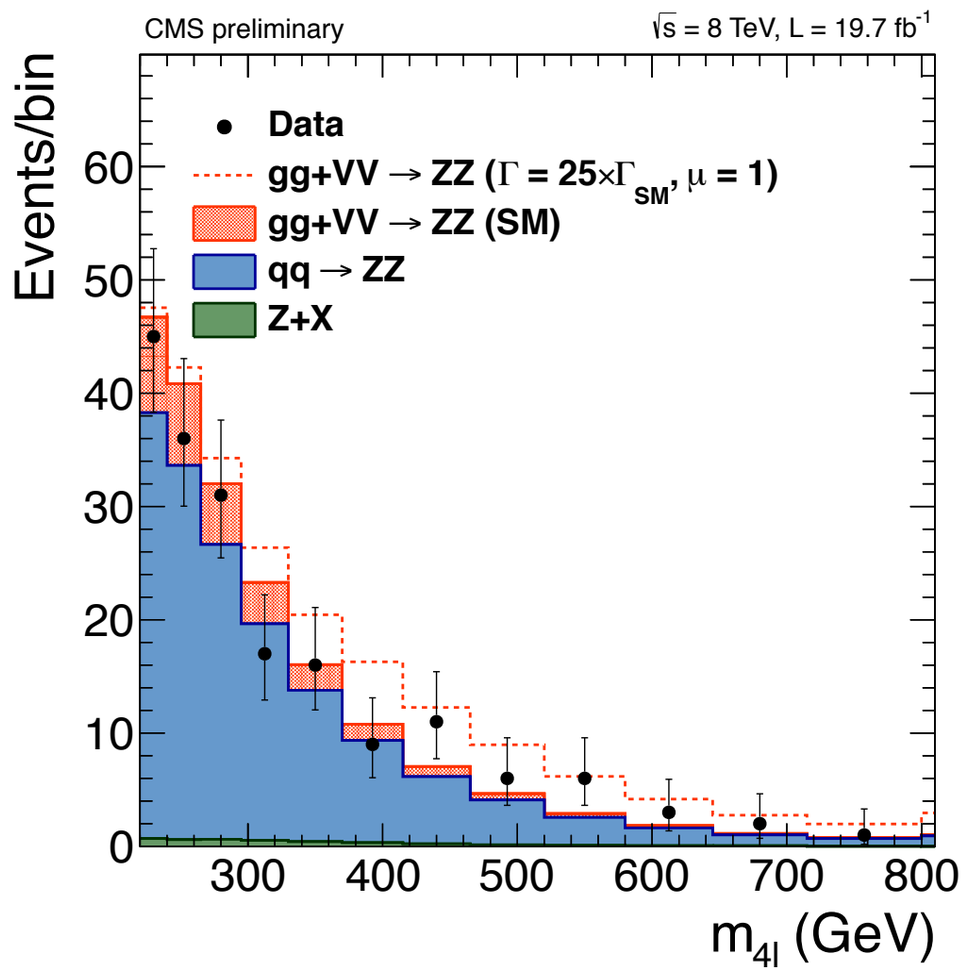
- Selection is consistent with Legacy paper (arXiv:1312.5353)
- Designed discriminant for gg→ZZ production using matrix element likelihood approach (MELA)
  - Optimal for separation of gg→ZZ from qq̄→ZZ, where gg→ZZ includes signal, continuum background, and their interference with any relative signal strength

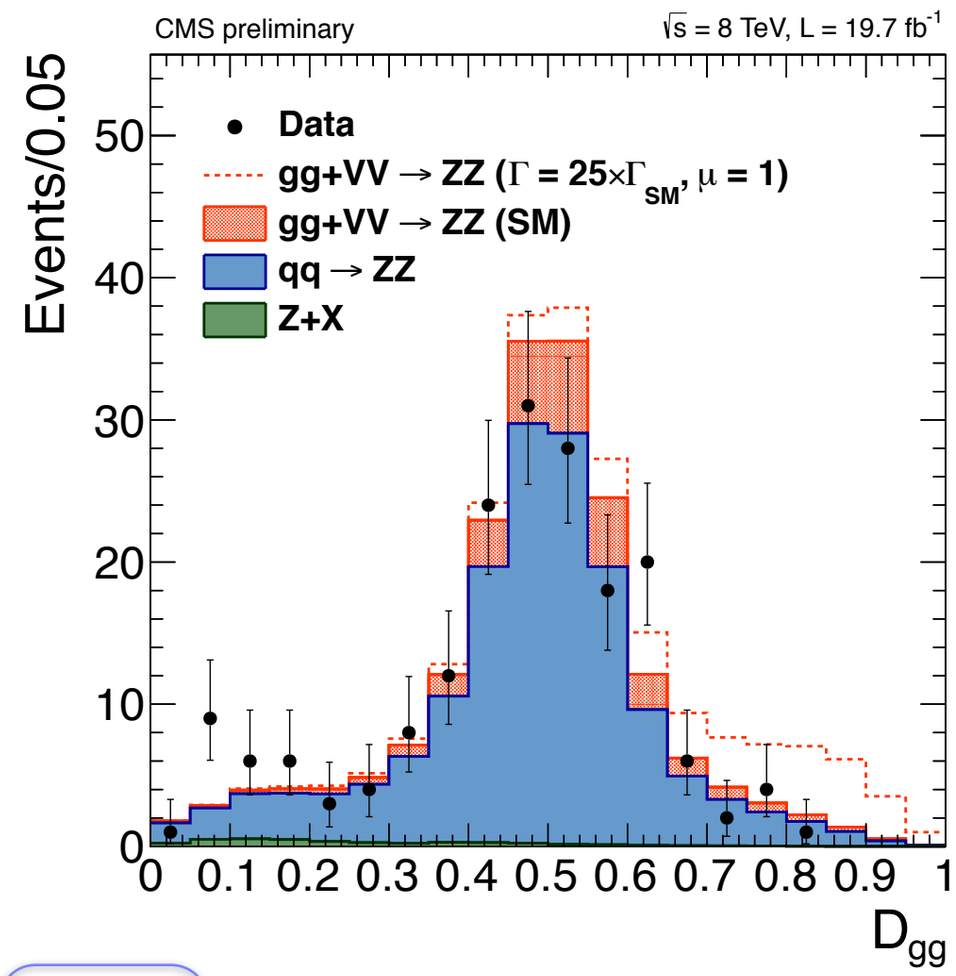
$$\mathcal{D}_{gg,a} = \frac{\mathcal{P}_{gg,a}}{\mathcal{P}_{gg,a} + \mathcal{P}_{q\bar{q}}}$$

- Construct two probabilities to make a discriminant
  - Built with 7 variables that completely describe decay kinematics (m_{Z1}, m_{Z2}, five angles)
  - $P_{gg(q\bar{q})}$ are joint probabilities for gg→ZZ signal + background + interference (qq̄→ZZ background) from MCFM matrix elements



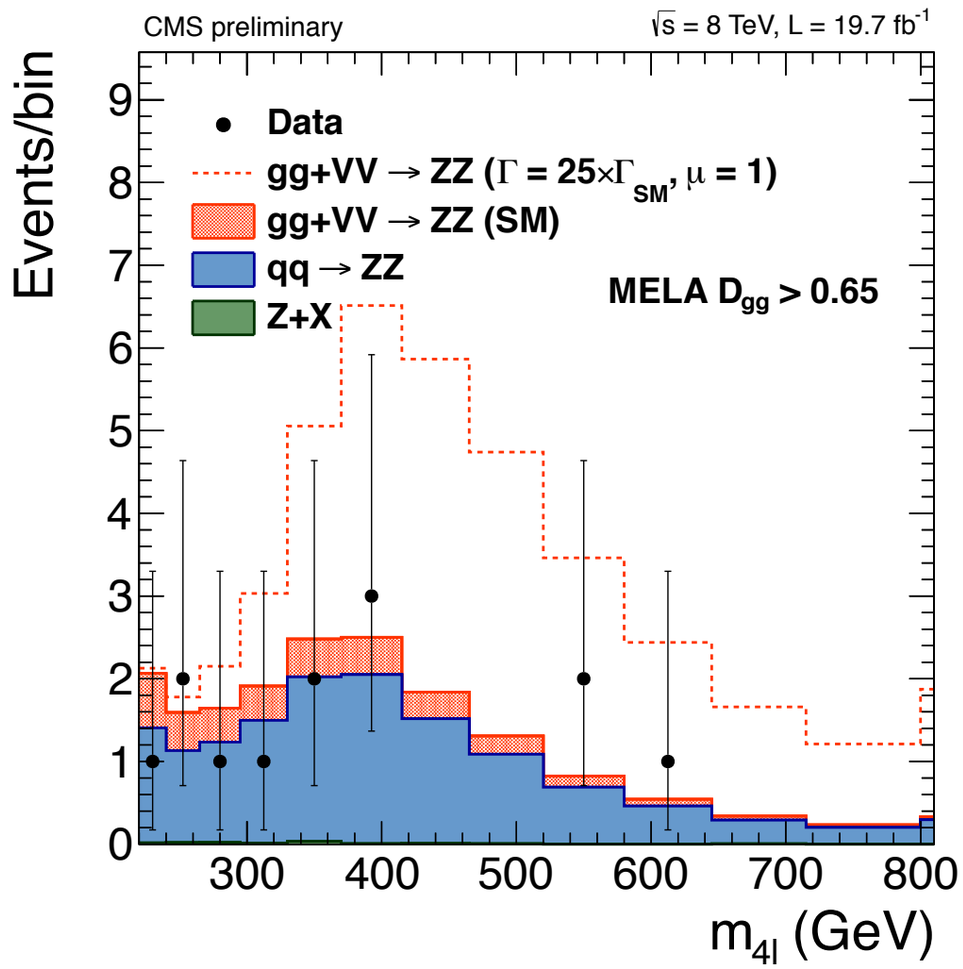
m_{4l} & D_{gg} Distributions/Yields

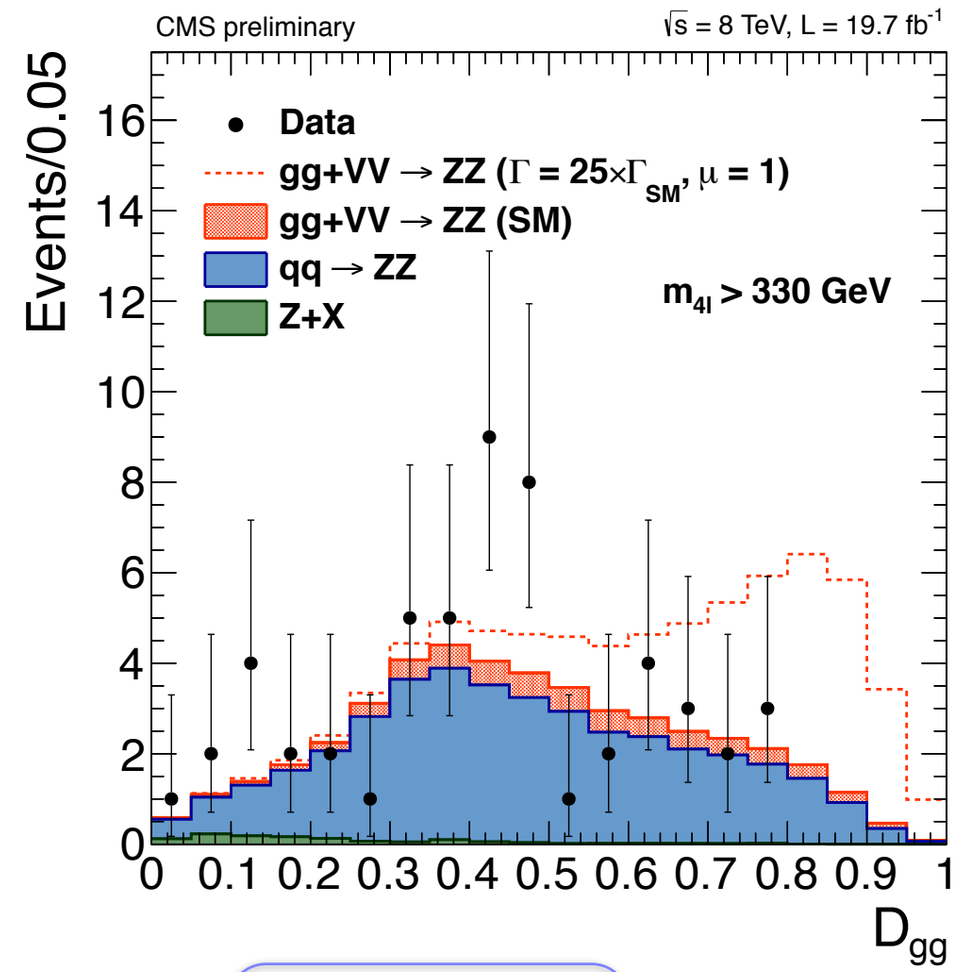




		Full region	Signal-enriched region
	gg + VBF $\to 4\ell$ (signal, $\Gamma_H/\Gamma_H^{SM} = 1$)	$2.22^{+0.15}_{-0.17}$	$1.20^{+0.08}_{-0.09}$
	gg + VBF $\to 4\ell$ (background)	$31.1^{+3.0}_{-3.1}$	2.12 ± 0.21
(a)	gg + VBF $\to 4\ell$ (total, $\Gamma_H/\Gamma_H^{SM} = 1$)	$29.6^{+2.8}_{-2.9}$	$1.73^{+0.16}_{-0.17}$
	gg + VBF $\to 4\ell$ (total, $\Gamma_H/\Gamma_H^{SM} = 15$)	$51.8^{+4.9}_{-5.0}$	13.1 ± 1.1
(b)	$q\bar{q} \to 4\ell$	154.7 ± 7.4	8.6 ± 0.4
(c)	Reducible background	3.7 ± 0.6	0.44 ± 0.08
(a+b+c)	Total expected ($\Gamma_H/\Gamma_H^{SM} = 1$)	188.0 ± 7.9	10.8 ± 0.4
	Observed	183	8

m_{4l} & D_{gg} Distributions/Yields





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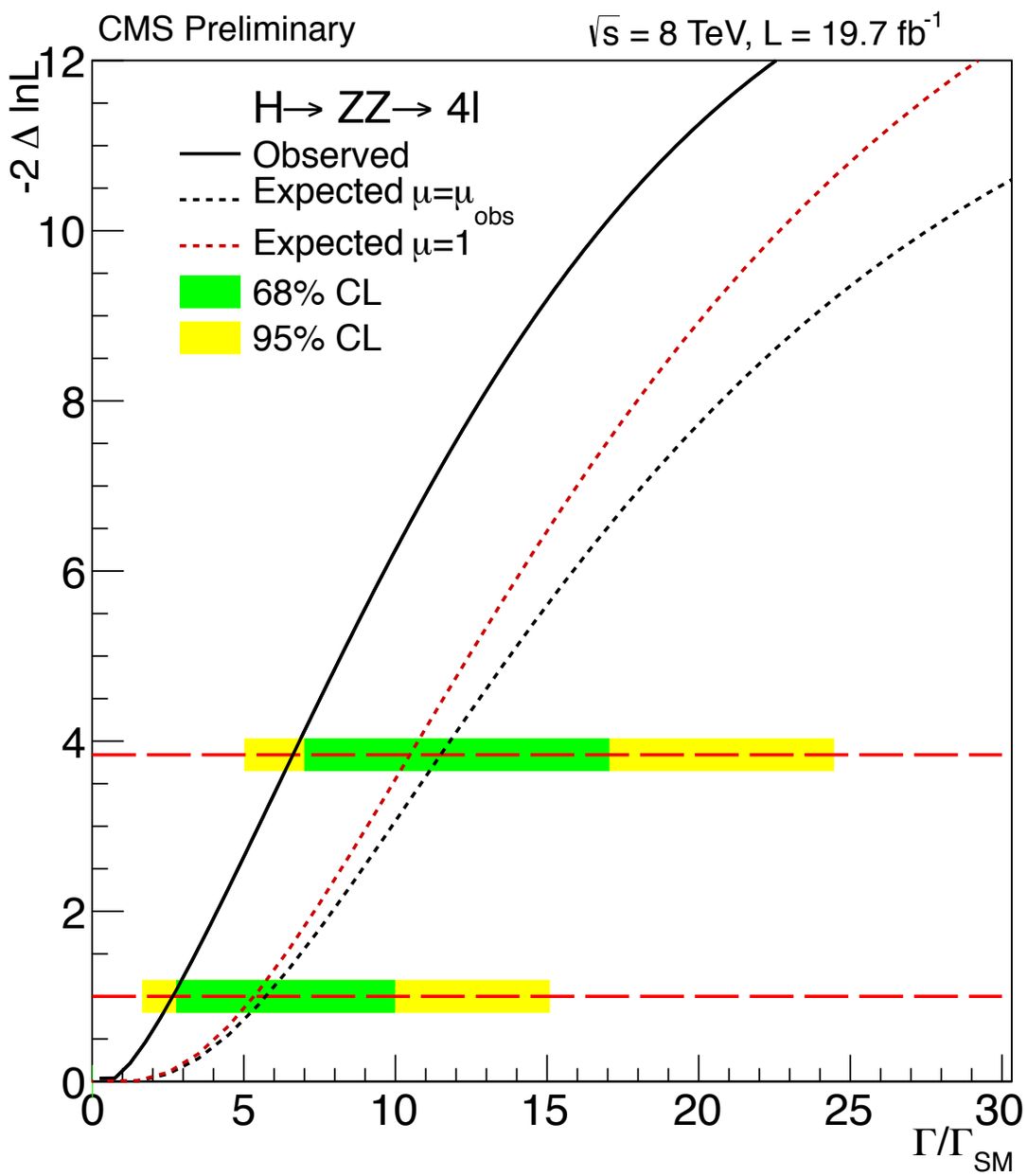
4l Limits



- Small deficit of signal events in high mass region
- Observed (Expected) $\Gamma \leq 27.4$ (47.7) MeV at 95% CL
- Best fit at $\Gamma = 2.0^{+9.6}_{-2.0}$ MeV

$H \rightarrow ZZ \rightarrow 2l2\nu$

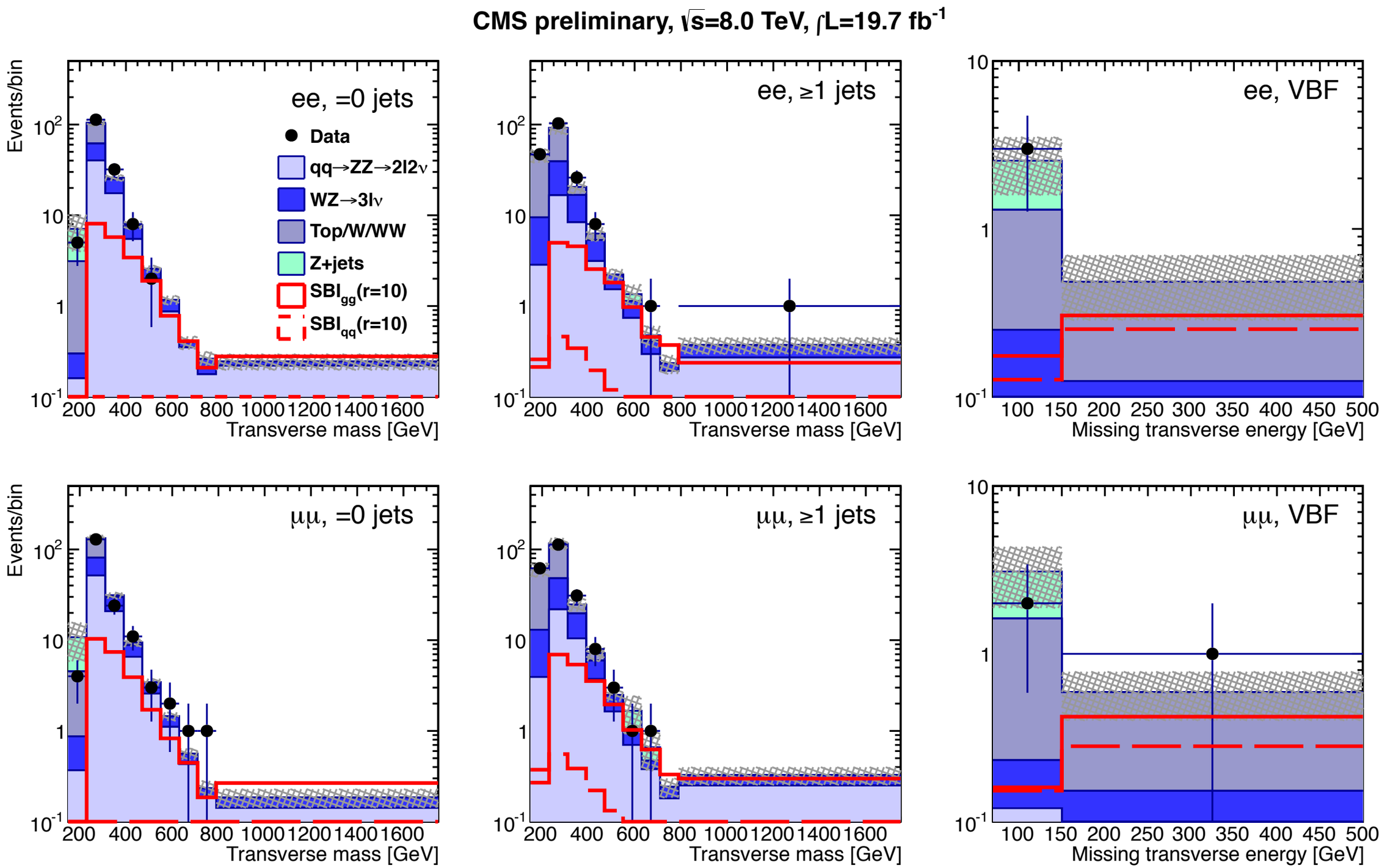
2l2ν Analysis

- Selection identical to PAS-HIG-13-014
  - See backup for explicit details
- Split events into three categories by number of selected jets (p_T > 30 GeV and $|\eta|$ < 4.7)
  - VBF-like: two jets with m_{JJ} > 500 GeV and $|\Delta\eta_{JJ}|$ > 4
  - >=1 jets: excluding events in VBF-like category
  - 0 jets
- Data-driven estimate of reducible backgrounds (double and single top, WW, W+jets, Z +jets), $q\bar{q}\rightarrow ZZ/WZ$ from MC
- Fit the distribution of transverse mass for 0 and 1-jet categories:

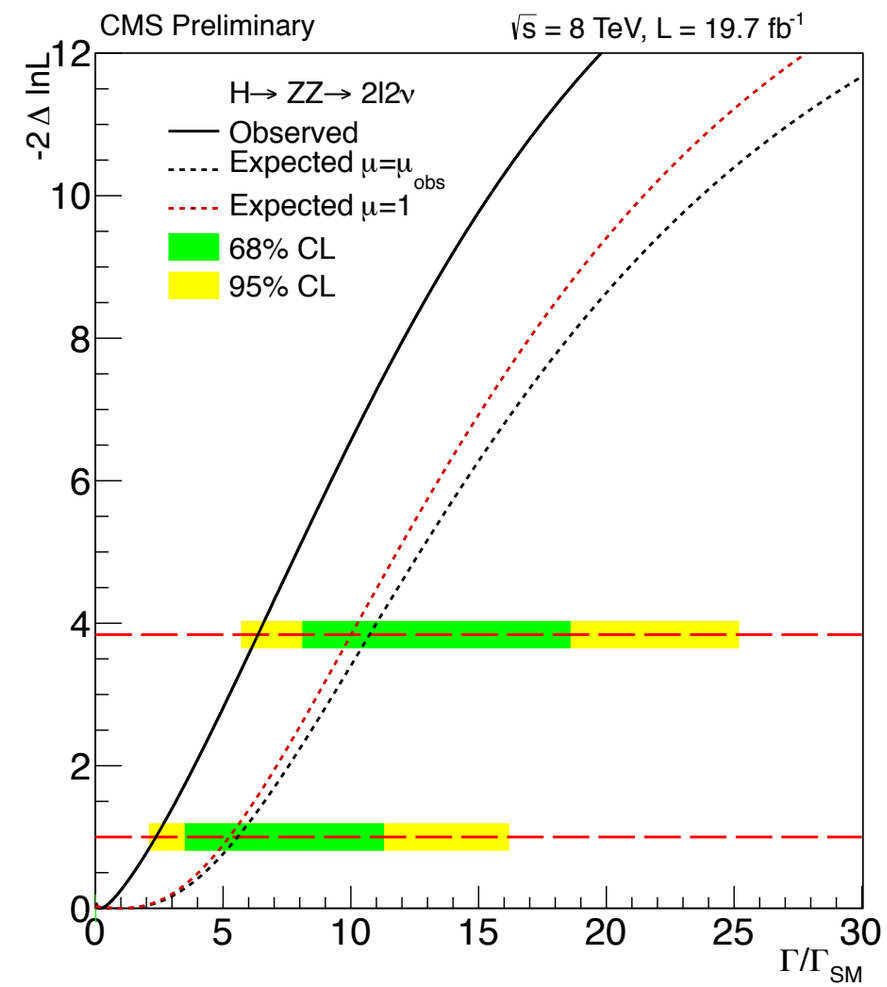
$$m_T^2 = \left[\sqrt{p_{T,2l}^2 + m_{2l}^2} + \sqrt{E_T^{miss\,2} + m_{2l}^2}\right]^2 - \left[\vec{p}_{T,2l} - \vec{E}_T^{miss}\right]^2$$

- Fit MET for VBF category

m_T/MET Distributions



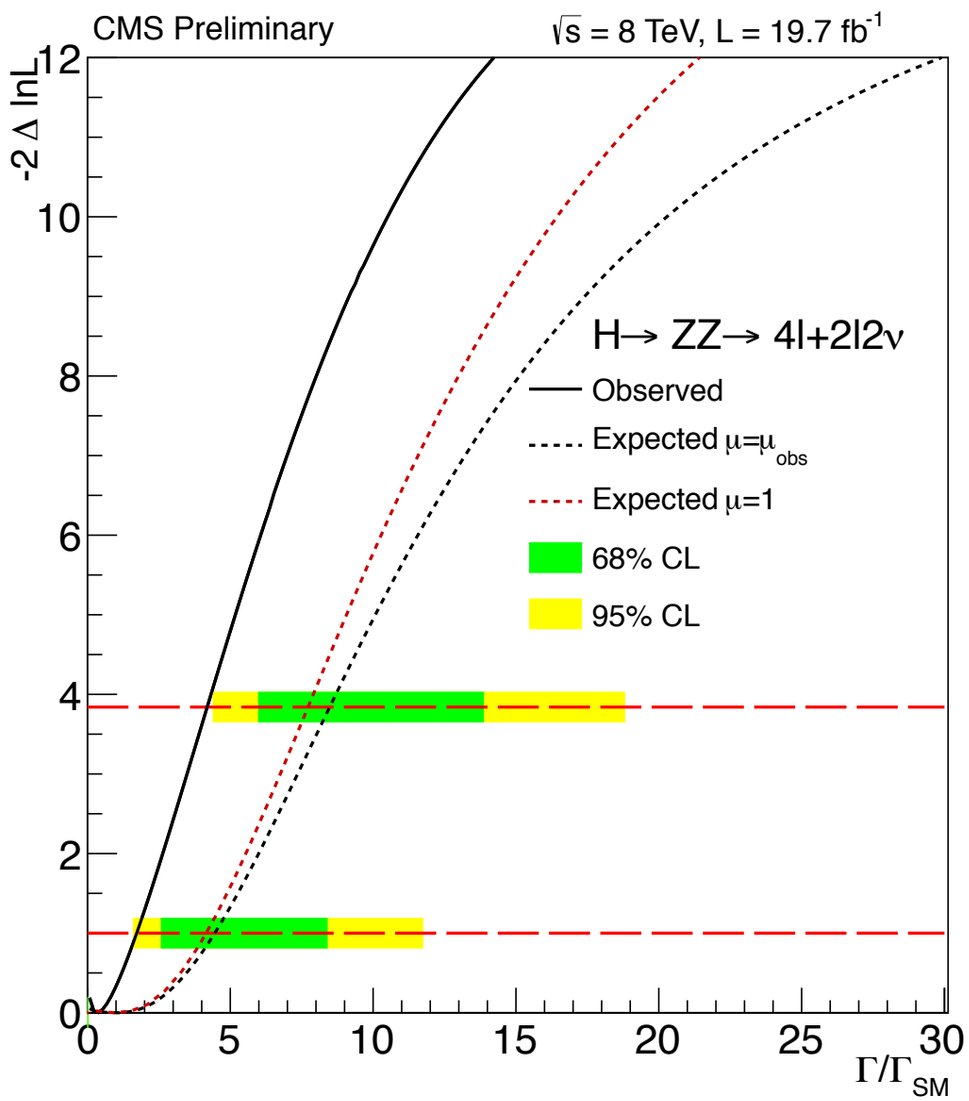
2l2ν Limits



- As with 4l, small deficit of signal events in high mass region
- Observed (Expected) Γ ≤ 26.6 (44.4) MeV at 95% CL
- Best fit at Γ = $0.8^{+9.1}_{-0.8}$ MeV

		ee	$\mu\mu$
(a)	gg + VBF (signal, $\Gamma_H/\Gamma_H^{SM} = 1$)	2.30±0.03	2.72±0.03
	gg + VBF (background)	5.4±0.2	6.5±0.2
	gg + VBF (total, $\Gamma_H/\Gamma_H^{SM} = 1$)	4.8±0.1	5.7±0.3
	gg + VBF (total, $\Gamma_H/\Gamma_H^{SM} = 10$)	19.2±0.6	22.6±1.2
(b)	$qq \to ZZ$	25.0±0.5	29.4±0.5
	WZ	11.6±0.4	13.5±0.4
	$t\bar{t}$/tW/WW	3.3±1.1	4.2±1.4
	Z + jets	1.5±0.9	2.4±1.4
(a+b)	Total expected ($\Gamma_H/\Gamma_H^{SM} = 1$)	46.2±1.6	55.3±2.1
	Observed	39	52

Combination Results



	4ℓ	$2\ell 2\nu$	Combined
Expected 95% CL limit, r	11.5	10.7	8.5
Observed 95% CL limit, r	6.6	6.4	4.2
Observed 95% CL limit, Γ_H(MeV)	27.4	26.6	17.4
Observed best fit, r	$0.5^{+2.3}_{-0.5}$	$0.2^{+2.2}_{-0.2}$	$0.3^{+1.5}_{-0.3}$
Observed best fit, Γ_H(MeV)	$2.0^{+9.6}_{-2.0}$	$0.8^{+9.1}_{-0.8}$	$1.4^{+6.1}_{-1.4}$

- Observed (Expected) $\Gamma \leq 17.4$ (35.3) MeV at 95% CL
- Best fit at $\Gamma = 1.4^{+6.1}_{-1.4}$ MeV
- Primary Systematic Uncertainties:
  - QCD scale and PDF for both qqZZ and ggZZ
  - μ uncertainties from 4l Legacy results
  - k-factor for ggZZ background
  - Experimental uncertainties (trigger/ reconstruction efficiencies, etc)

Conclusions

- First experimental limit on total Higgs width using off-shell H→ZZ events
  - Both channels see small deficit of signal in high mass region
  - Combined results: Observed (Expected) $\Gamma \leq 17.4$ (35.3) MeV at 95% CL with best fit at $\Gamma = 1.4^{+6.1}_{-1.4}$ MeV
- Very little model dependence
  - Off-shell enhancement only dependent on Higgs propagator structure
    - No enhancement from heavy fermions; Higgs has scalar spin-parity
  - Assume no BSM enhancements to $q\bar{q}$→ZZ background or overall ZZ yields in high mass region
- Could be further combined with H→WW

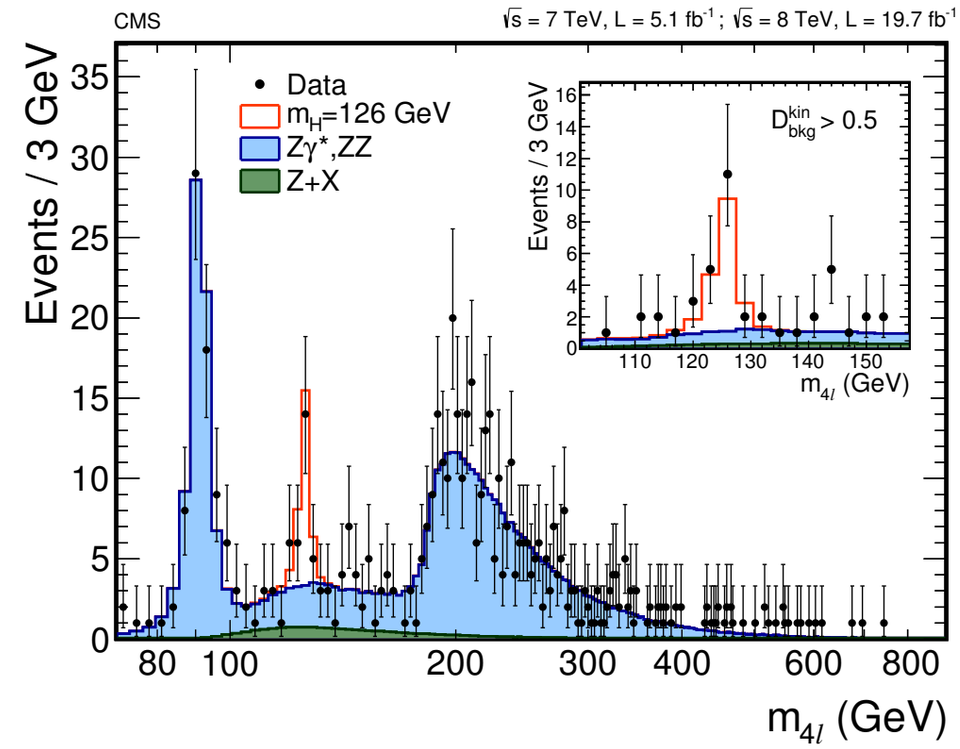
Citations

- Kauer, Passarino, “Inadequacy of zero-width approximation for a light Higgs boson signal” (*JHEP* **08** (2012), arXiv:1206.4803)
- Caola, Melnikov, “Constraining the Higgs boson width with ZZ production at the LHC” (*Phys Rev D* **88** (2013), arXiv: 1307.4935)
- Passarino, “Higgs CAT” (2013, arXiv:1312.2397)
- Bonvini et al., “Signal-background interference effects in ggHWW beyond leading order” (*Phys Rev D* **88** (2013), arXiv:1304.3053)

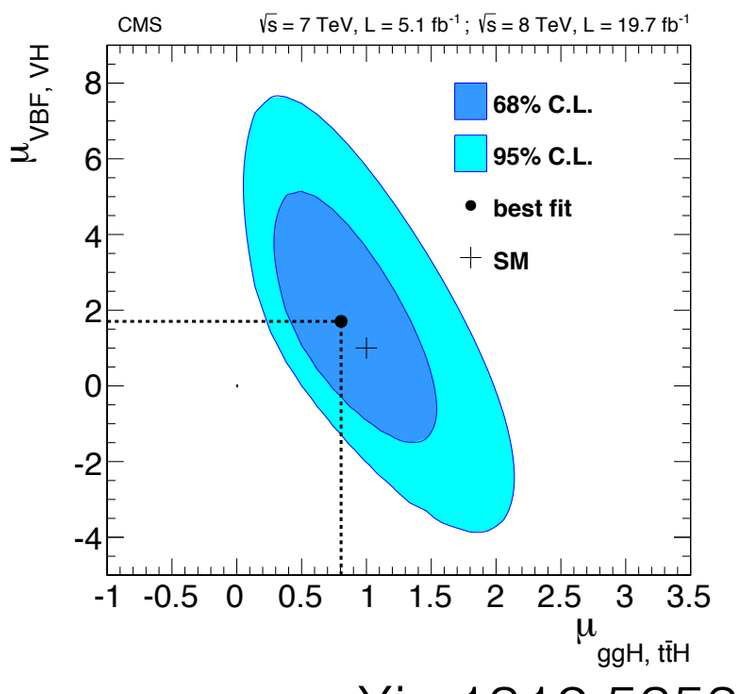
BACKUP

Legacy Results

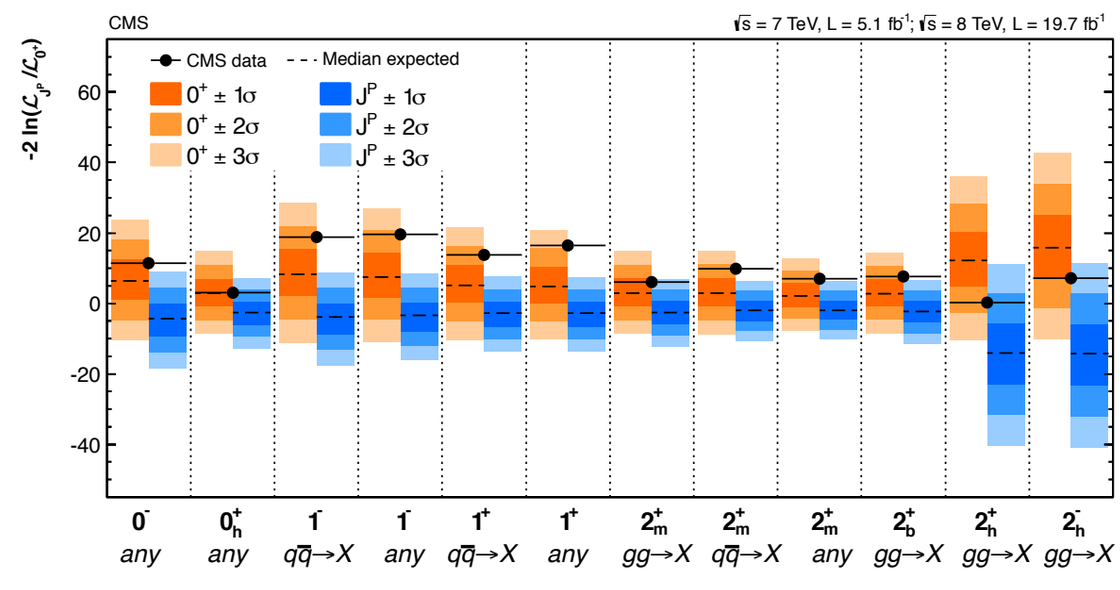
- Observation of a Higgs boson candidate
  - Narrow resonance with local significance of 6.8σ, signal strength in agreement with SM
  - Resonance has mass of 125.6 ± 0.4 (stat.) ± 0.2 (sys.) GeV
  - $\Gamma_{tot} \leq 3.4$ GeV



Primarily ggF production



Higgs in agreement with scalar particle



arXiv:1312.5353, Accepted to *Phys Rev D* (2014)

MC Samples

- Use gg2VV and MCFM to generate ggF samples (includes signal[mH=125.6], background, and interference terms)
  - LO in QCD, running QCD scale used (m4l/2) with scale and PDF
  - Settings and cuts:
    - CTEQ6L LO PDF
    - m_H = 125.6 GeV, Γ_H = 4.15 MeV - matching values from Legacy
    - Running scale for renormalization & factorization of m4l/2 for MCFM (generation and hadronization), fixed scale of $m_H/2$ for GG2VV (reweighting applied)
    - m_{ll} > 4 GeV (OSSF), m_{4l}>95 GeV, p_T(lepton) > 3 GeV, |η(lepton)| < 2.7
    - p_T(lepton pair) > 0.1 GeV for MCFM samples, >1 GeV (>2 GeV) for different (same) flavor lepton pairs in GG2VV
    - All cuts are looser than analysis or have <1% impact

MC Samples

- Use PHANTOM to generate at same settings
  - LO generation
    - NNLO/LO k-factor is 6% and independent on m_{ZZ} (YR3)
    - Do not apply explicitly, normalize cross-section at the peak relatively to ggF
  - Central scale mZZ/√2
    - Same scale and PDF variations as ggF, effect much smaller (1-2%)
    - Signal, background, interference not available separately. Generate total amplitudes with r = 1, 10, 25 (and equal coupling scalings) and extract the 3 components from:

$$\begin{pmatrix} p_1 \\ p_{10} \\ p_{25} \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ 10 & \sqrt{10} & 1 \\ 25 & 5 & 1 \end{pmatrix} \begin{pmatrix} S \\ I \\ B \end{pmatrix}$$

Discriminant

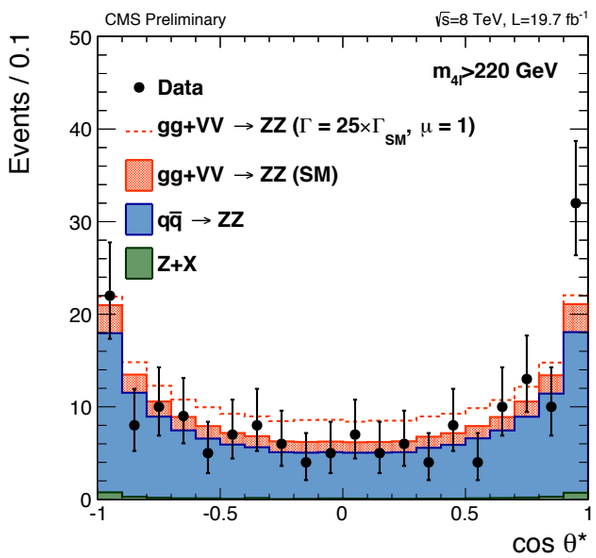
$$\mathcal{P}_{gg,a}(\vec{\Omega}, m_1, m_2 | m_{4\ell}, m_H) = a \times \mathcal{P}^{gg}_{\text{sig}} + \sqrt{a} \times \mathcal{P}^{gg}_{\text{int}} + \mathcal{P}^{gg}_{\text{bkg}}$$

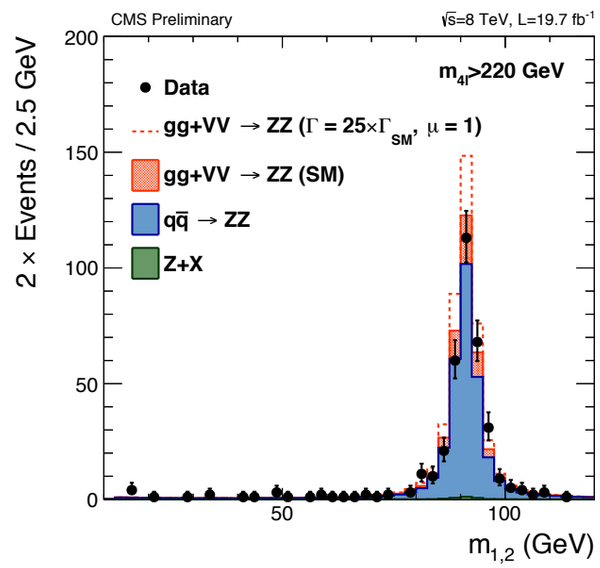
$$\mathcal{P}_{q\bar{q}}(\vec{\Omega}, m_1, m_2 | m_{4\ell}) = \mathcal{P}^{q\bar{q}}_{\text{bkg}}$$

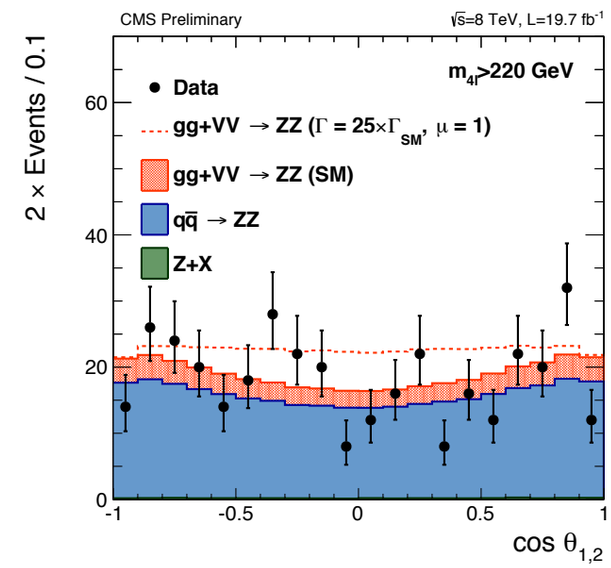
$$\mathcal{D}_{gg,a} = \frac{\mathcal{P}_{gg,a}}{\mathcal{P}_{gg,a} + \mathcal{P}_{q\bar{q}}} = \left[1 + \frac{\mathcal{P}^{q\bar{q}}_{\text{bkg}}}{a \times \mathcal{P}^{gg}_{\text{sig}} + \sqrt{a} \times \mathcal{P}^{gg}_{\text{int}} + \mathcal{P}^{gg}_{\text{bkg}}}\right]^{-1}$$

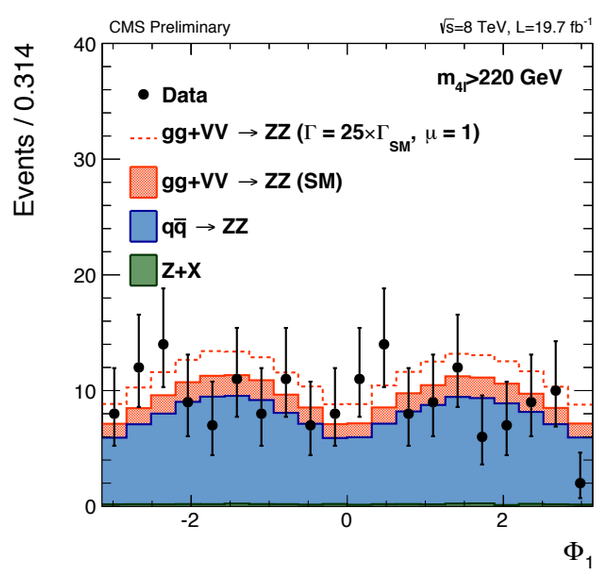
- Note that $D_{gg,a}$ requires choice of signal strength, studies show $\Gamma/\Gamma_{SM} \approx 10$ in analysis of Run1 data, use a=10

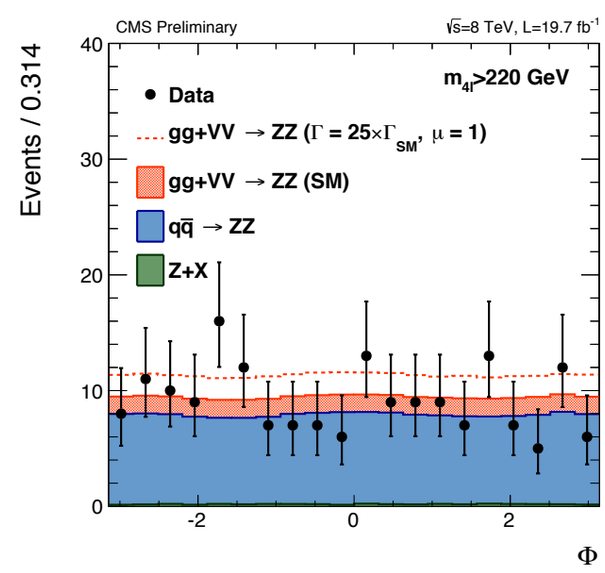
Discriminant Inputs



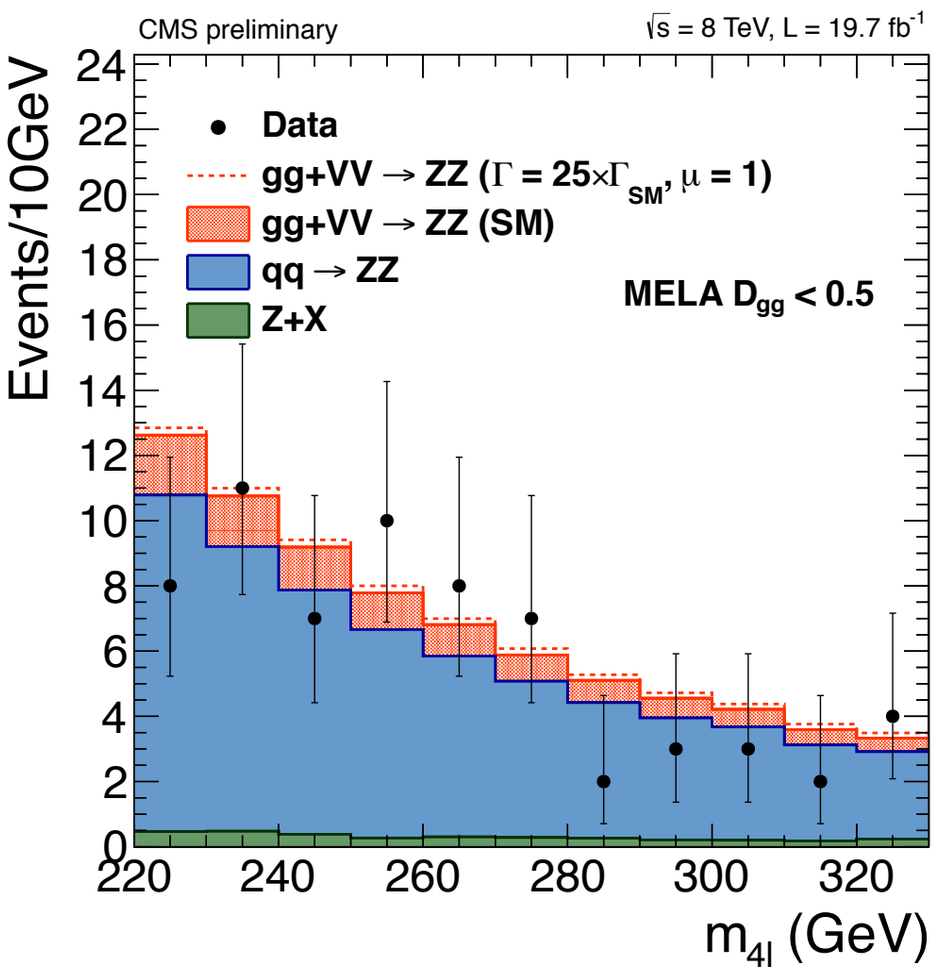


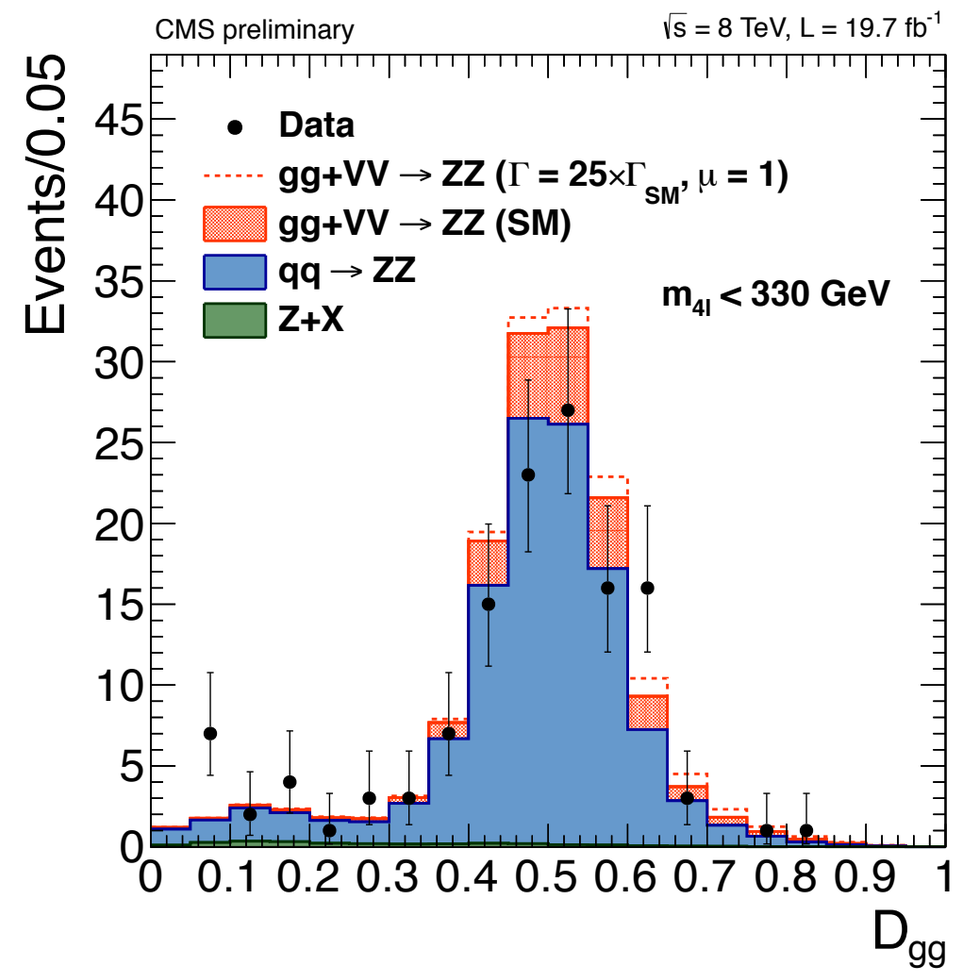




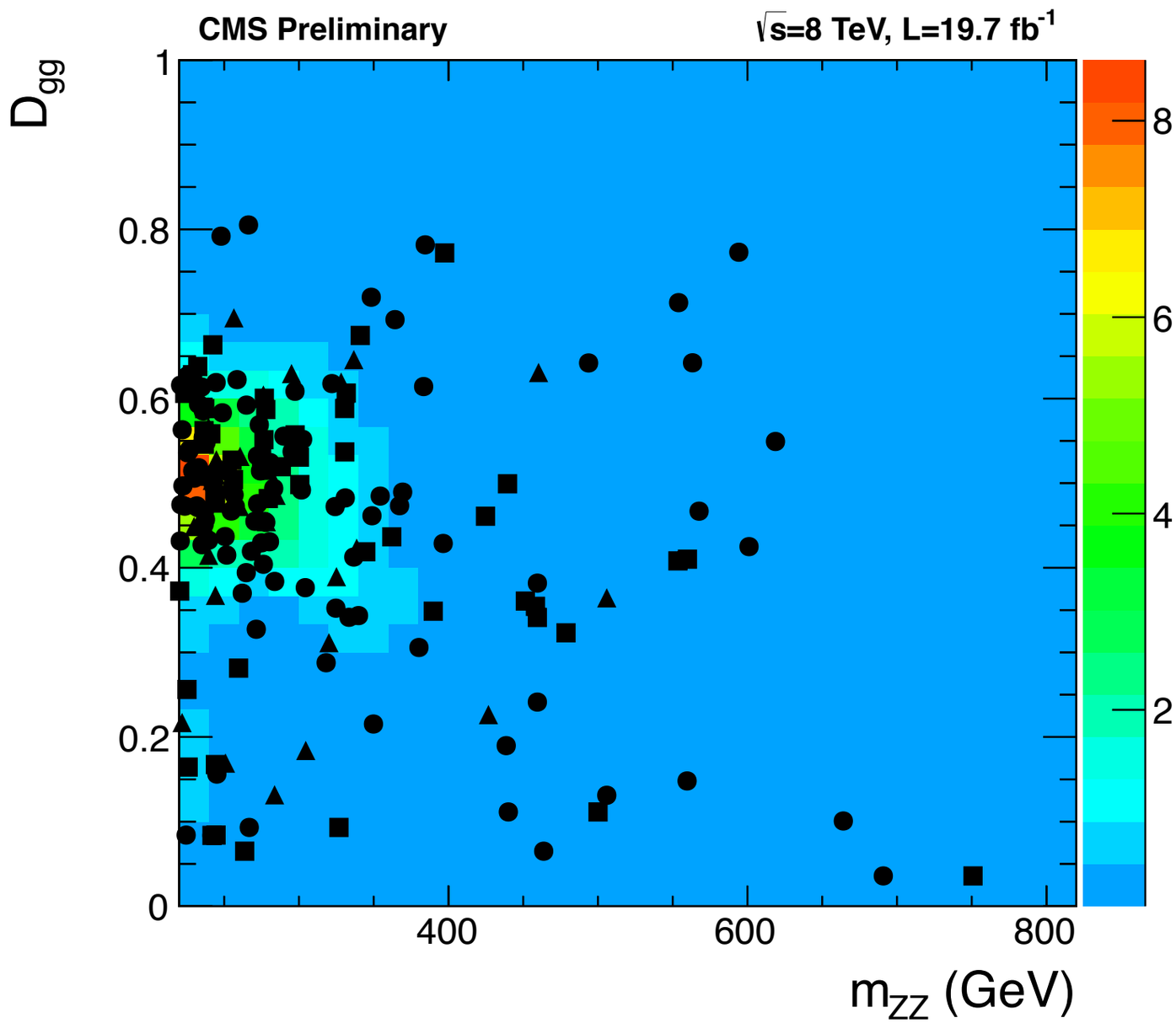


m_{4l} & D_{gg} Distributions/Yields

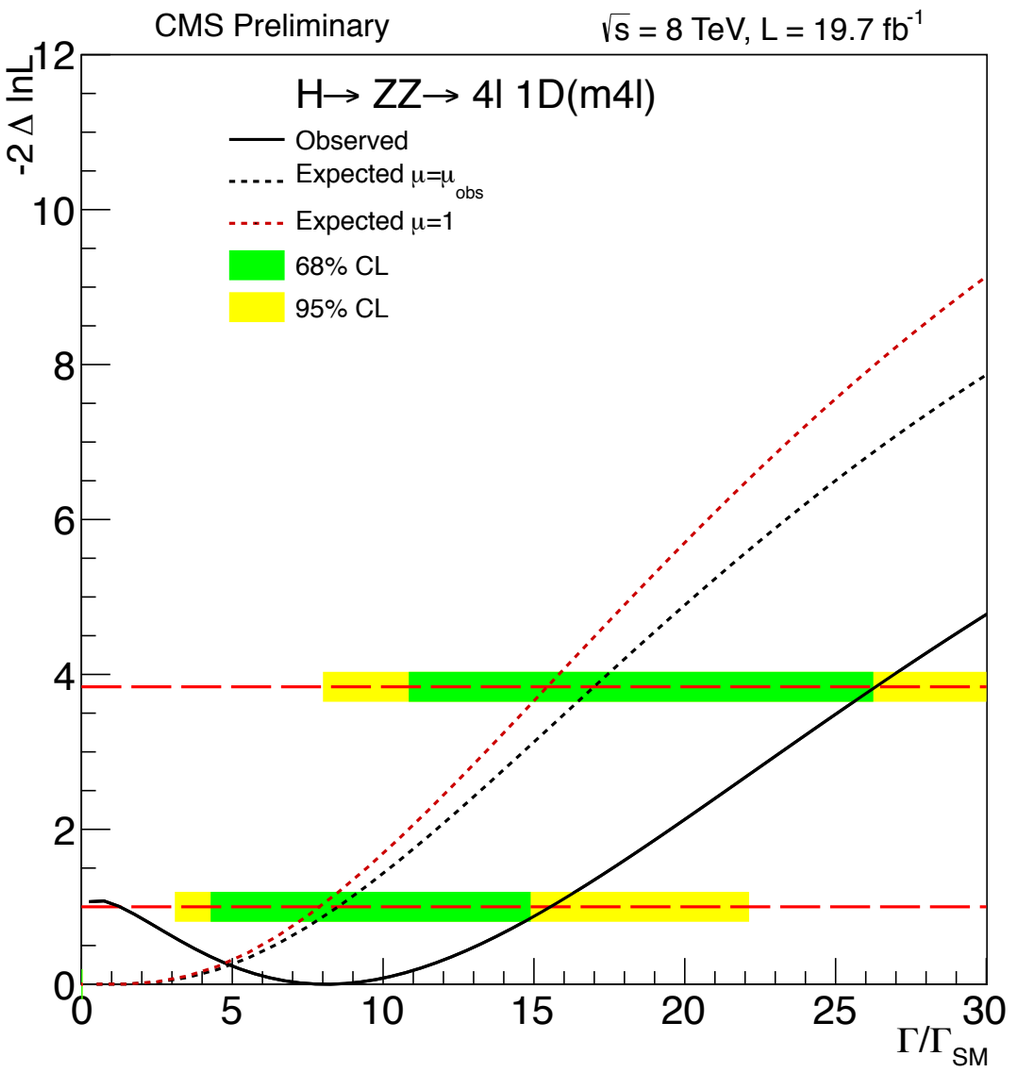


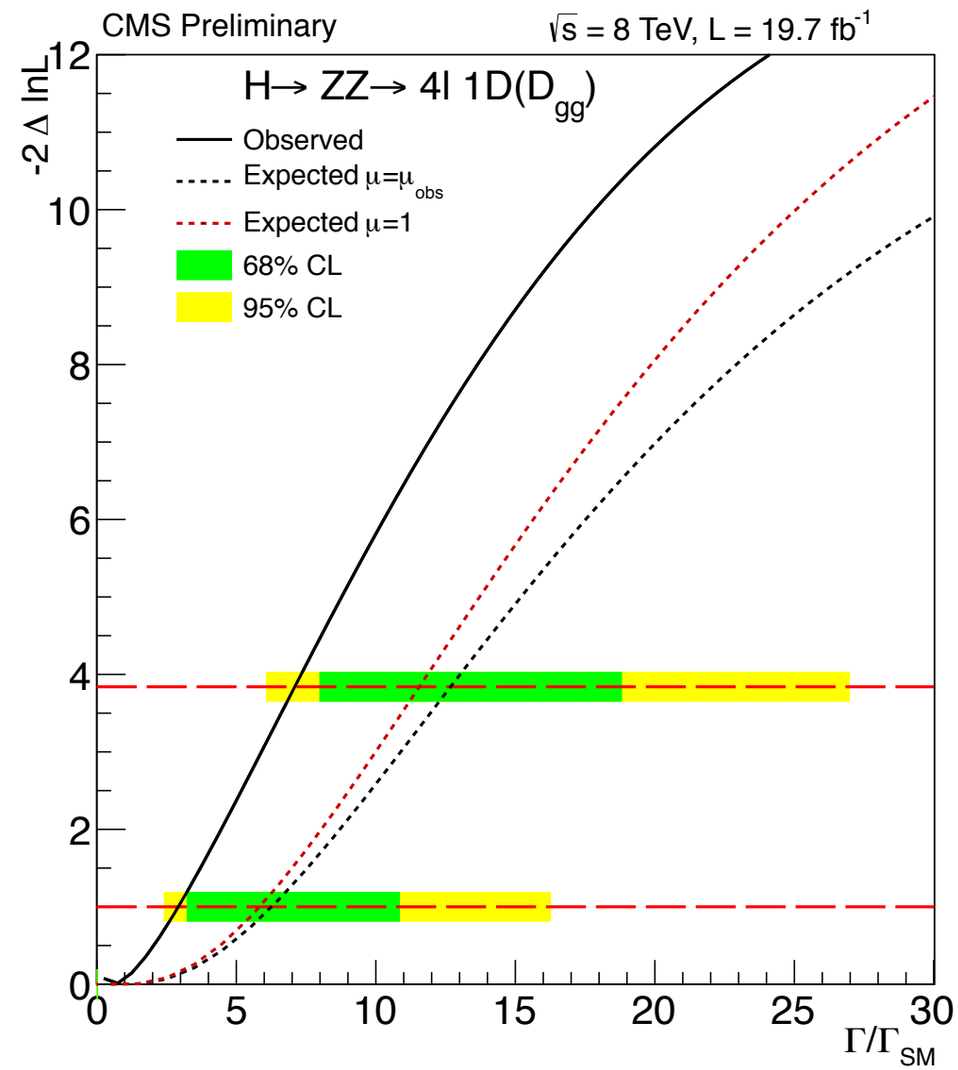


2D Templates



1D Limits


CMS Preliminary
√s = 8 TeV, L = 19.7 fb-1
H→ ZZ→ 4l 1D(m4l)
Observed
Expected μ=μobs
Expected μ=1
68% CL
95% CL
-2 Δ lnL
Γ/ΓSM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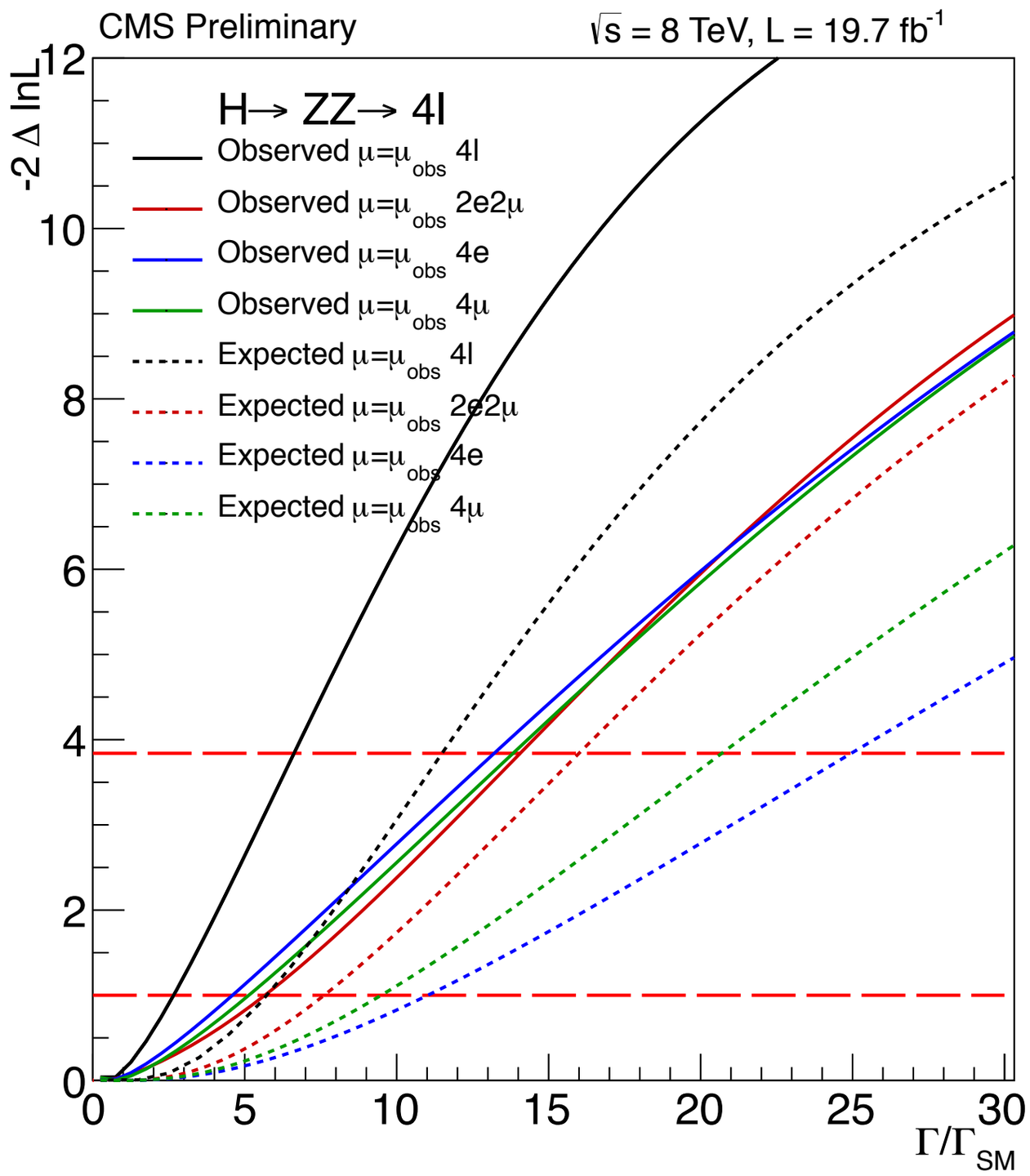
Limits by Channel



Legacy Leptons/Jets

- Trigger specifics: Dilepton (first $p_T \geq 17$ GeV, second ≥ 8 GeV), Trielectron (≥ 15 GeV, ≥ 8 GeV, ≥ 5 GeV)
- Good leptons must pass certain cuts:
- Geometric: $|\eta| < 2.5$ for electrons, < 2.4 for muons
- Momentum: $p_T > 7$ GeV for electrons, > 5 GeV for muons
- Isolation: p_T from charged hadrons, neutral hadrons, and photons (not FSR) from primary vertex must be less than 40% of total p_T in cone about lepton track
- Originate from primary vertex: Significance of impact parameter < 4
- Good Jets must have $|\eta| < 4.7$, $E_T > 30$ GeV, isolated from leptons and FSR photons

HZZ4l Reconstruction

- Once we have at least four good leptons, we attempt to create two Z bosons
- Take pairs of same flavor and opposite charge leptons, assemble invariant mass with any FSR photons (photons $|\eta| < 2.4$, $p_T > 2$ GeV and found within ΔR cone of 0.07 or $p_T > 4$ GeV and found at $0.07 < \Delta R < 0.5$ around lepton)
- Pair with invariant mass closest to m_Z (40 GeV $< m_{ll} <$ 120 GeV) is called Z1
- Remaining leptons must make a second pair that can be off-shell (12 GeV $< m_{ll} <$ 120 GeV) - if more than one, choose pair with highest sum of p_T
- At least one lepton with $p_T > 20$ GeV and a second with $p_T > 10$ GeV
- Any opposite charge pairs must have $m_{ll} > 4$ GeV to eliminate selecting possible jet fragments
- $m_{4l} > 100$ GeV to be considered a possible Higgs candidate

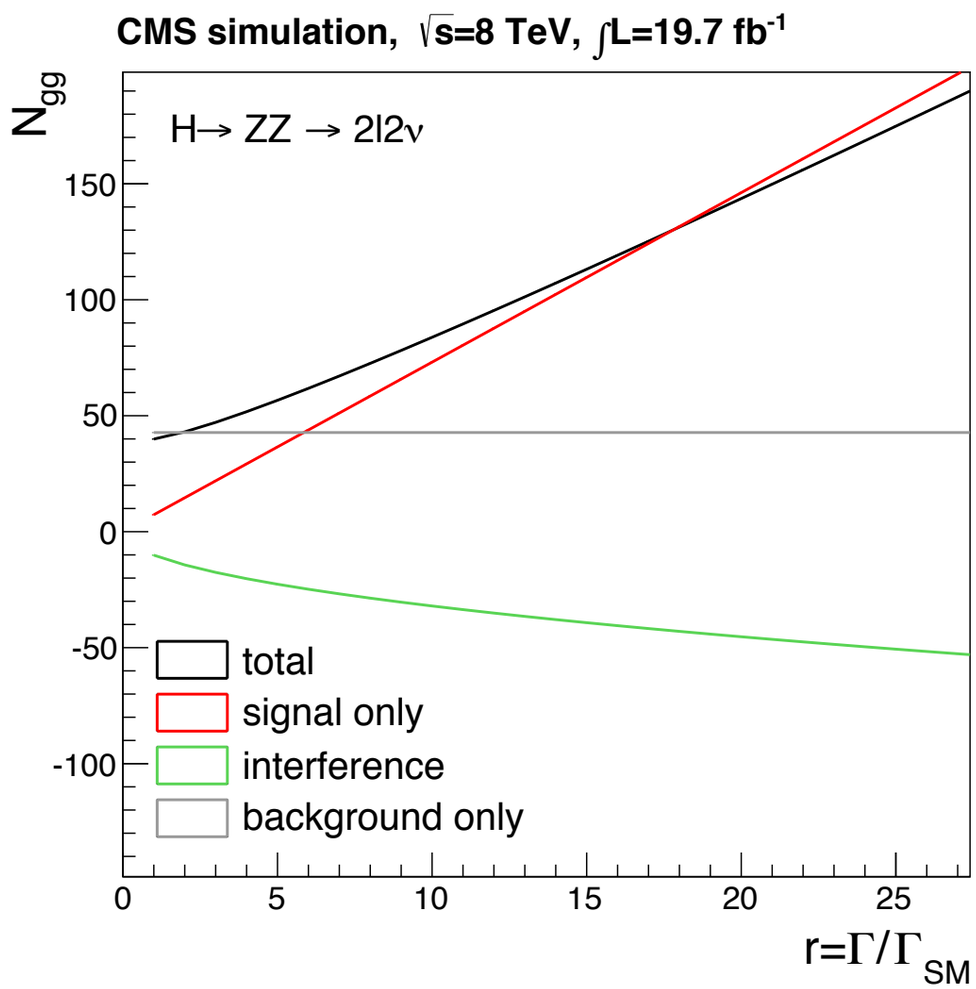
2l2nu Event selection/categorization

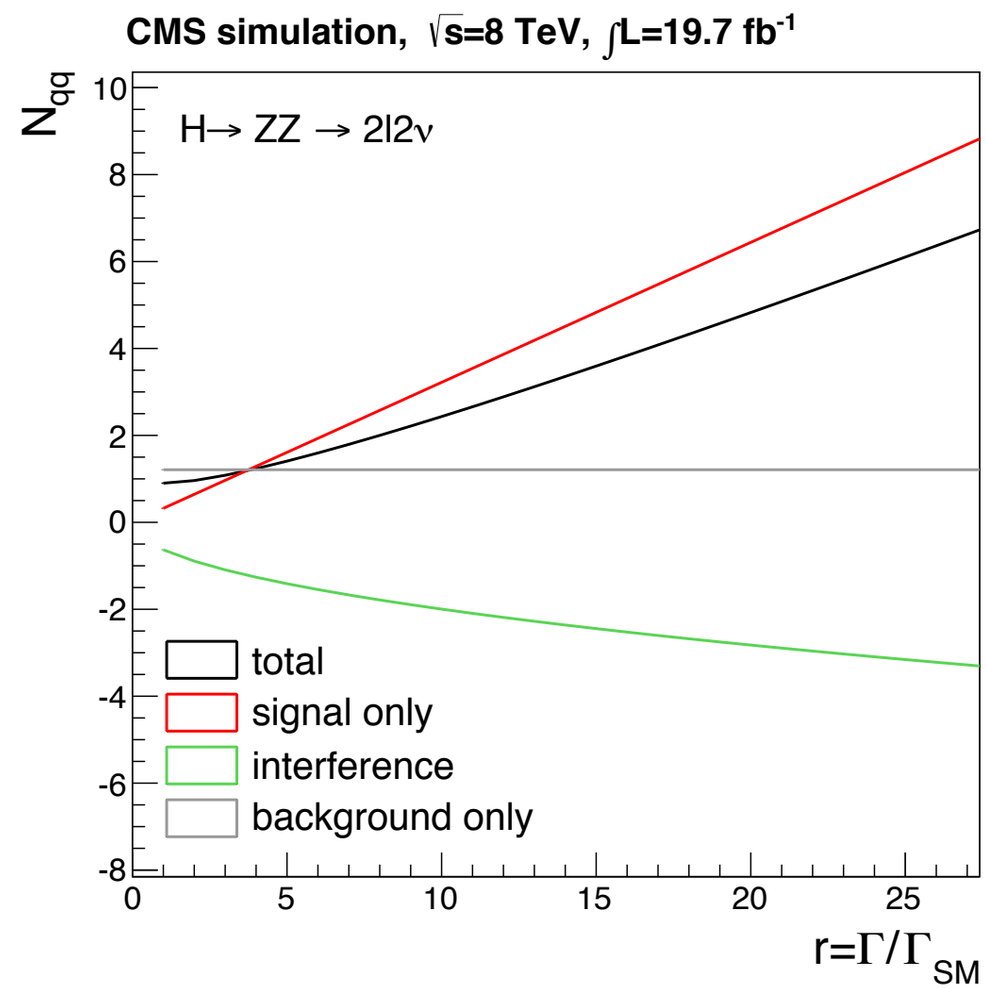
- **Selection :**
  - dilepton+single lepton triggers
  - Two isolated leptons p_T>20 GeV (medium/tight ID for e/μ)
  - |M-91|<15 GeV and p_T(Z)>50 GeV
  - Veto: 3rd lepton (p_T>10 GeV) and Btag (CSVL)
  - Raw PF E_T^{miss}>80 GeV and Δφ(jet,E_T^{miss})>0.5
  - Transverse Mass for shape analysis : $m_T^2 = \left[\sqrt{p_{T,2l}^2 + m_{2l}^2} + \sqrt{E_T^{miss\,2} + m_{2l}^2}\right]^2 - \left[\vec{p}_{T,2l} - \vec{E}_T^{miss}\right]^2$

- **Event categorization based on Jets :**
  - p_T>30 GeV |η|<4.7, loose PF+PU id

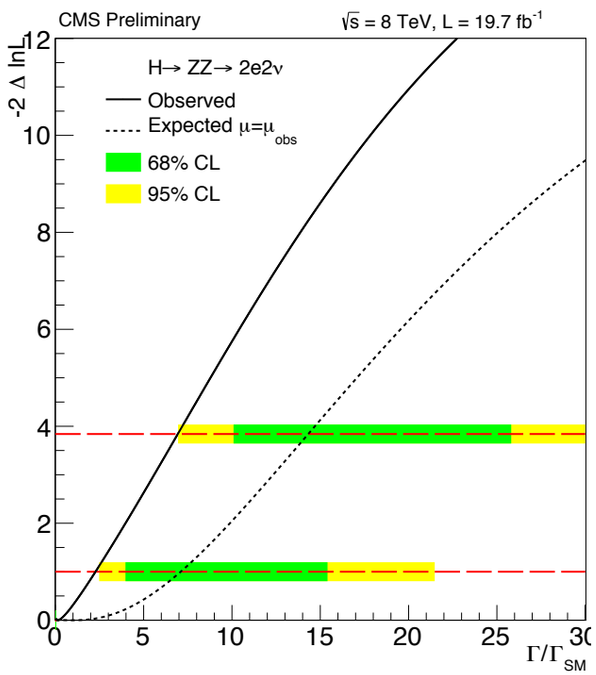
  - **VBF category**
    - M_{jj}>500 GeV, |Δη|>4
    - Central jet veto
  - **=0, ≥1 jets categories**
    - Fall-back for non-VBF tagged events
    - Count number of selected jets

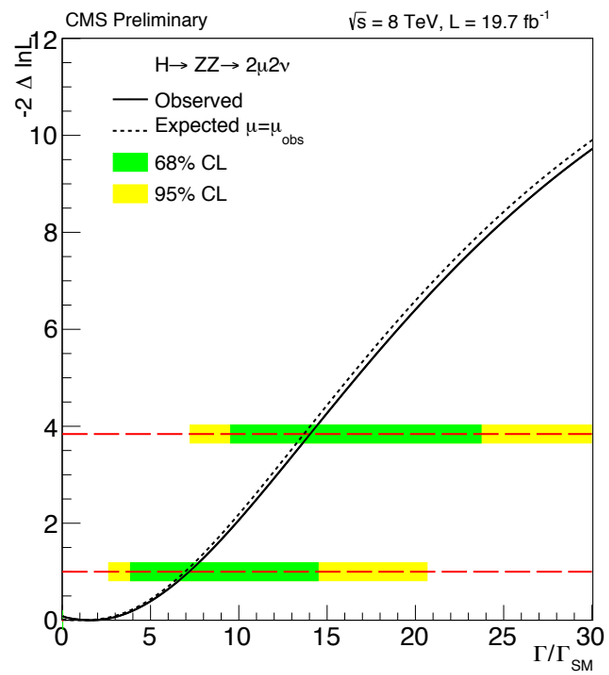
2l2nu Yield Variation





2l2nu breakdown





- ee deficit drives strong limit
- 0 jet category drives sensitivity of the analysis