Theory outlook after the CMS Higgs width constraint

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Outline

- Motivating direct Higgs width measurement
- CMS implementation of Higgs width constraint
  - theory background
  - experimental analysis
- Interpreting the measurement, future outlook
  - SM
  - New physics
- Conclusions

Importance of Higgs width

$$N_{\text{events}} = L\sigma \text{Br}\,\epsilon \sim \frac{g_p^2 g_d^2}{\Gamma}$$

- On the Higgs resonance, LHC can only measure (sums of) products of couplings
- Extraction of Higgs couplings requires assumptions about how different final state analyses are related
  - Assume no non-SM production modes

    Higgs exotic production: FY [1404.2924]
  - Restrict parameter space of coupling deviations to get an overconstrained system, perform global likelihood fit

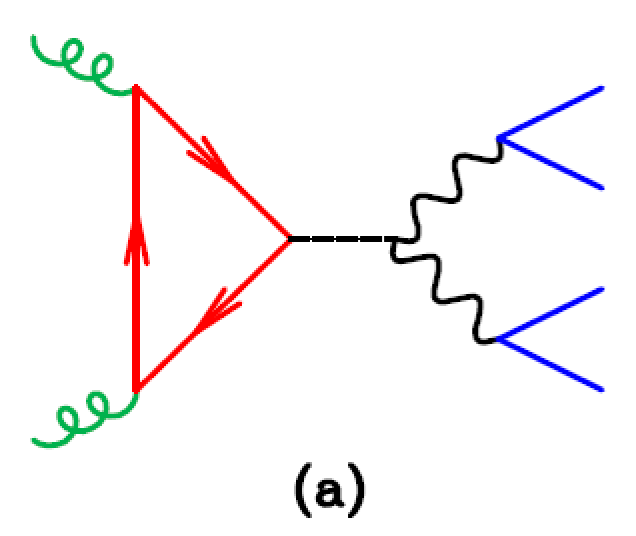
    See J. Anderson's talk
  - An unconstrained width also allows for large rates of exotic decays

    Curtin, Essig, Gori, Jaiswal, Katz, Liu, Liu, McKeen, Shelton, Strassler, Surujon, Tweedie, Zhong [1312.4992]

Importance of Higgs width

$$N_{\text{events}} = L\sigma \text{Br}\ \epsilon \sim \frac{g_p^2 g_d^2}{\Gamma}$$

- Readily motivates direct measurement of the Higgs width – not possible on-resonance
- Moving off-resonance, differential rates are controlled by Higgs couplings (and phase space), not the width



$$\frac{\mathrm{d}\sigma_{pp\to H\to ZZ}}{\mathrm{d}M_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

Caola, Melnikov [1307.4935]

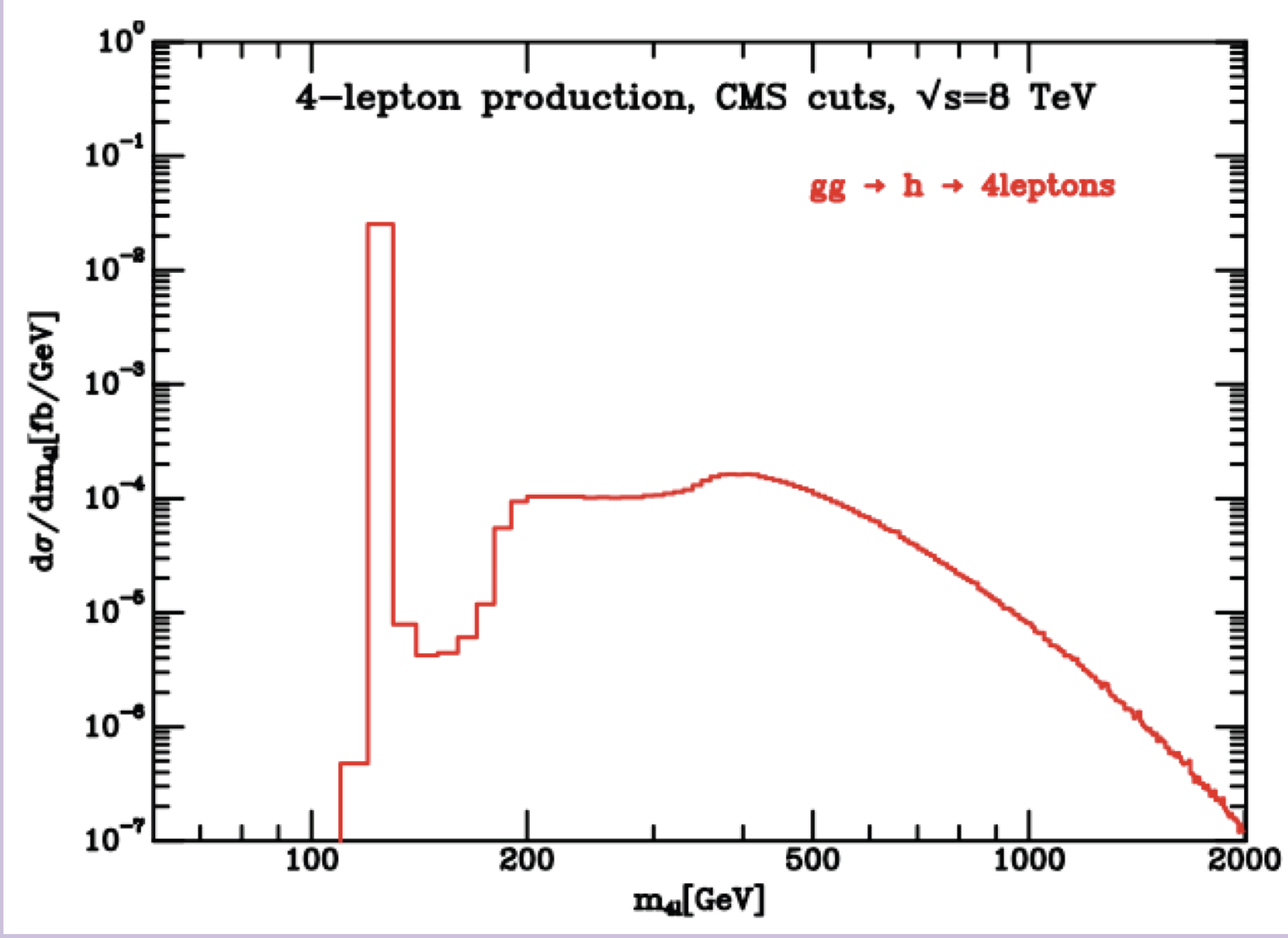
Campbell, Ellis, Williams [1311.3589]

Theory background – off-peak H to ZZ*

The narrow width assumption fails to capture the tail of the Higgs amplitude squared distribution

15% of the total differential rate lies above $m_{4l} > 130$ GeV

Kauer, Passarino [1206.4803]



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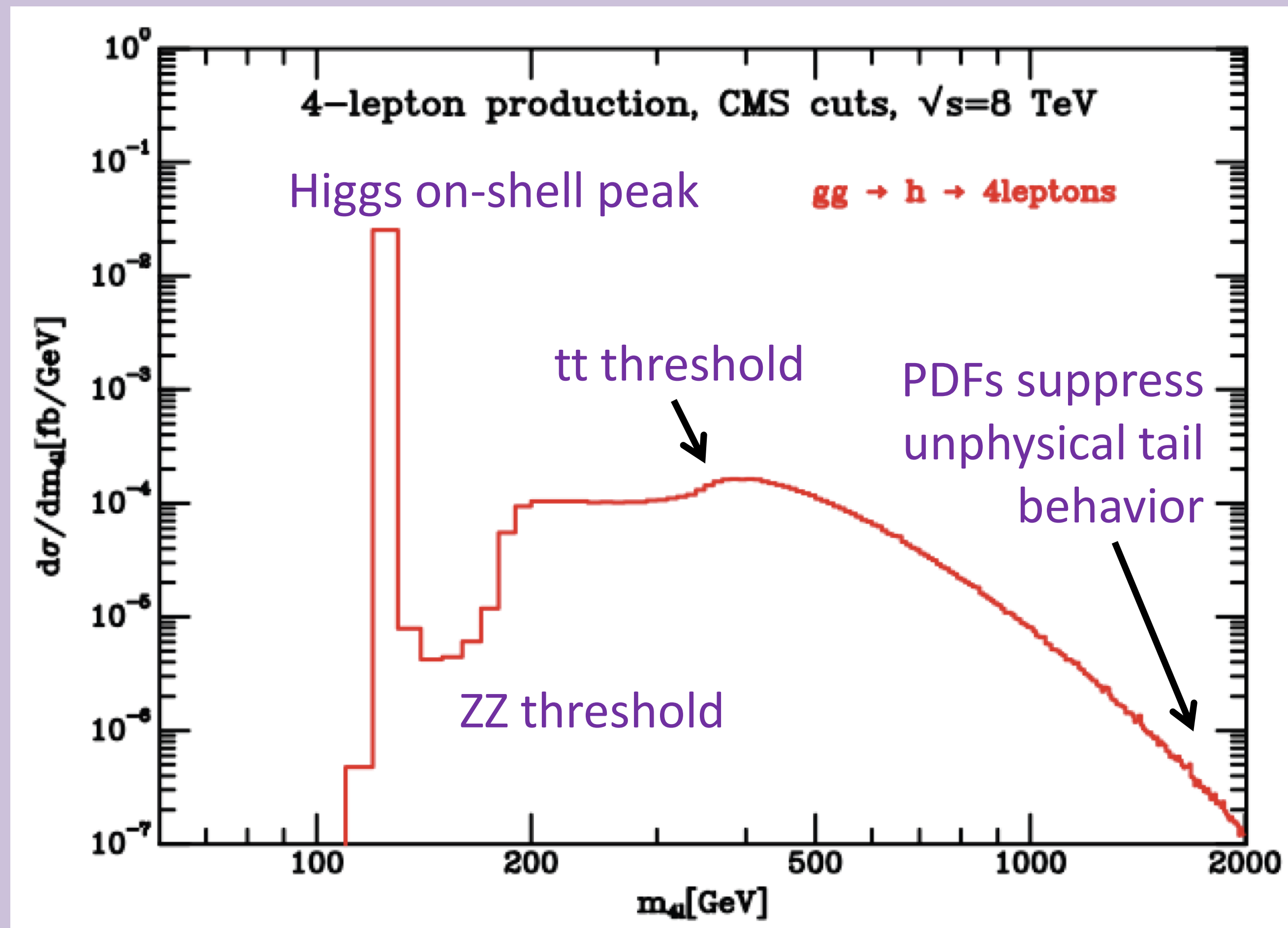
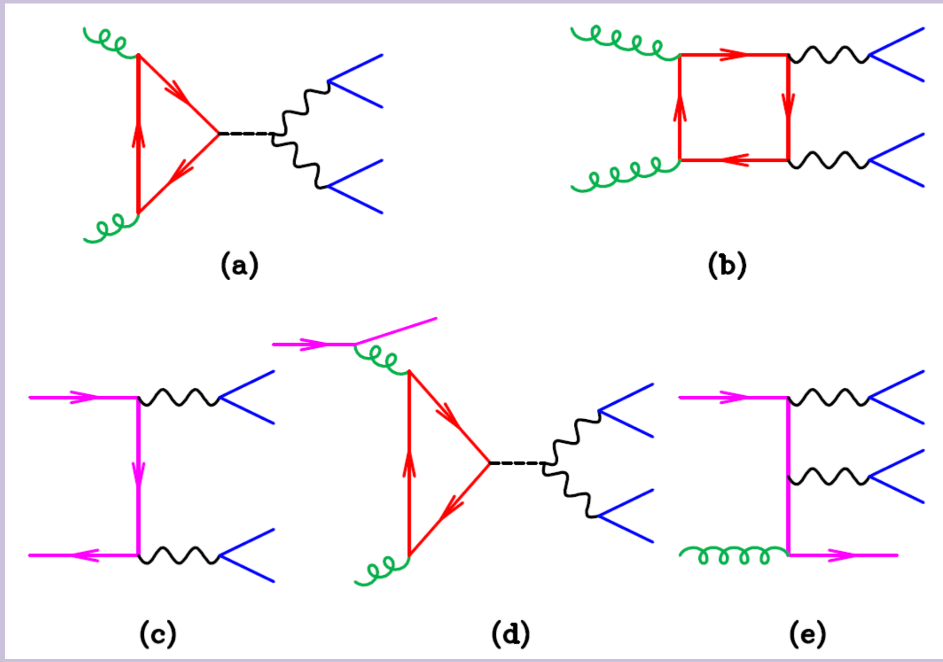


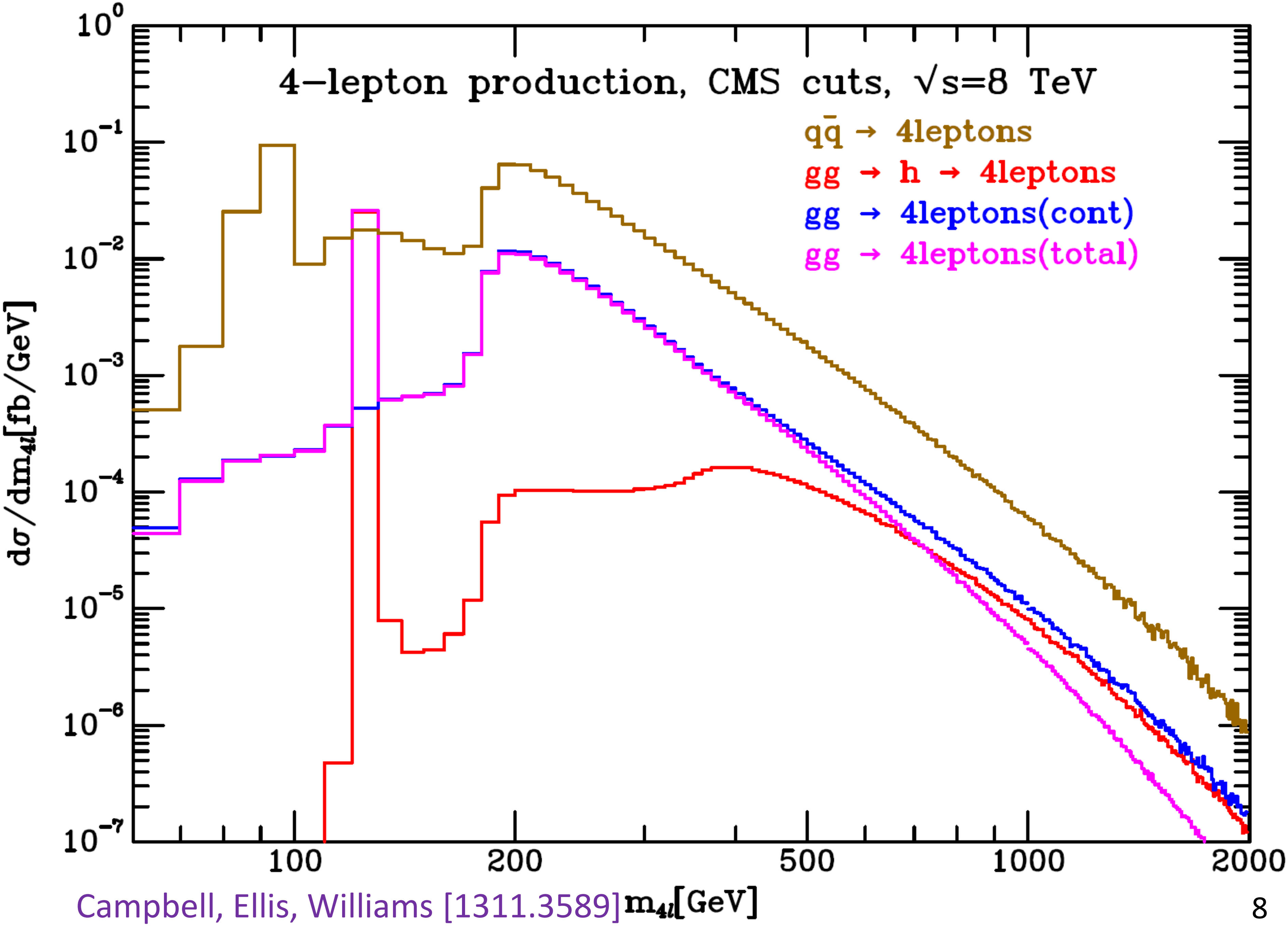
Campbell, Ellis, Williams [1311.3589]

Full SM picture

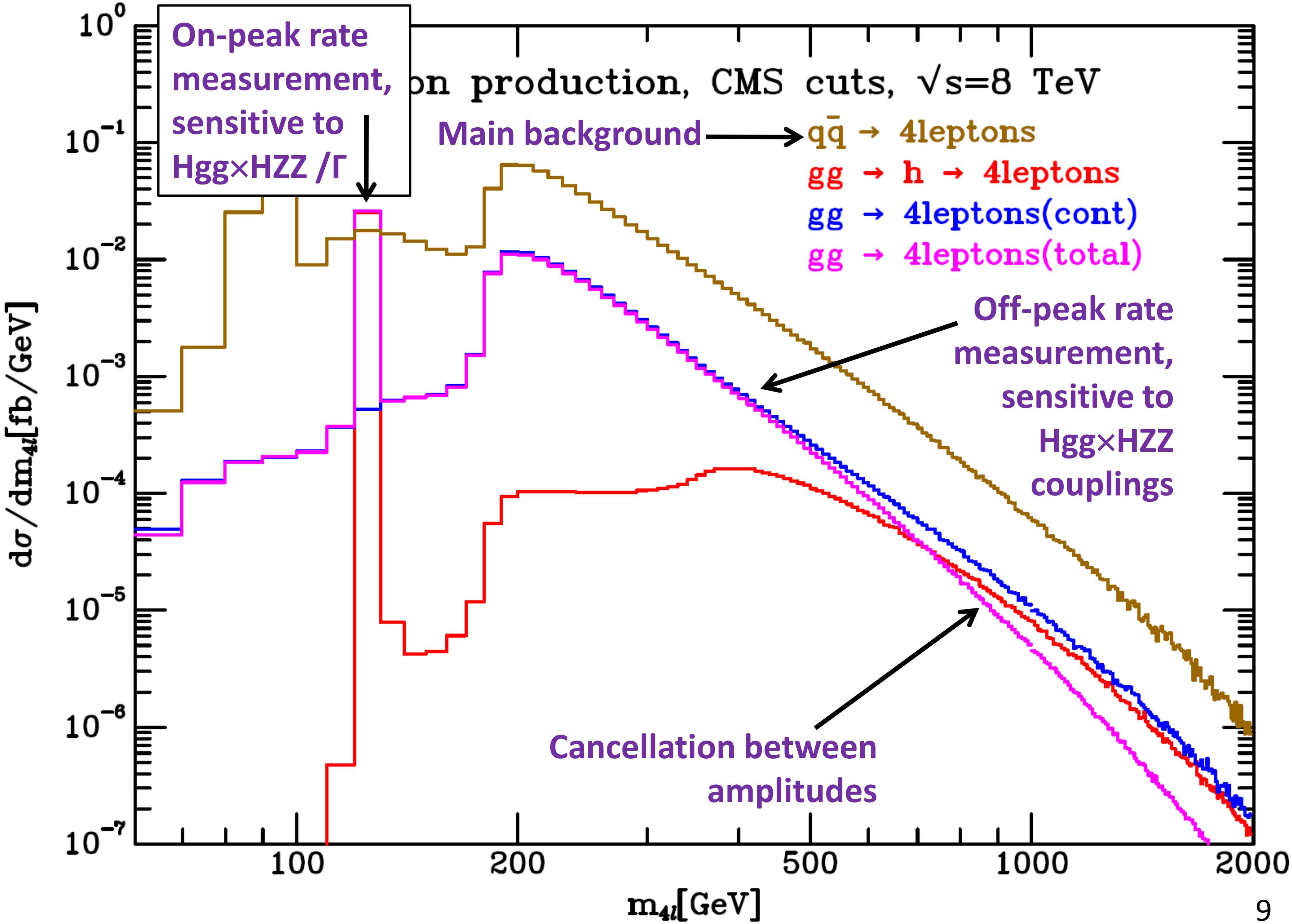
- The Higgs amplitude interferes with gg→ZZ (box diagram only known at LO)
  - Summed amplitude cancels unphysical tail behavior
- The largest contribution to the ZZ*→4l high mass tail comes from qq̄ initial state
  - Also have subleading qg contributions



Campbell, Ellis, Williams [1311.3589]



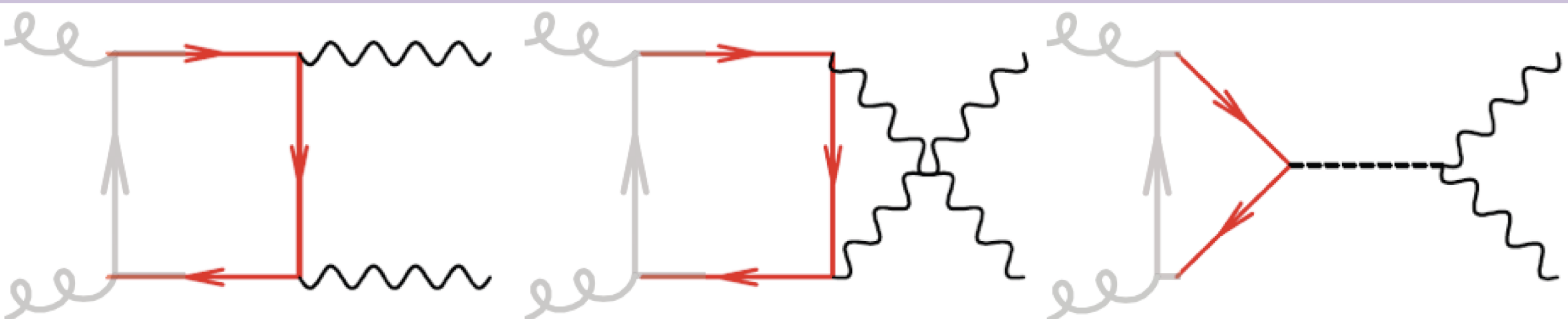
Campbell, Ellis, Williams [1311.3589]


On-peak rate measurement, sensitive to Hgg×HZZ /Γ
on production, CMS cuts, √s=8 TeV
Main background
q q̄ → 4leptons
gg → h → 4leptons
gg → 4leptons(cont)
gg → 4leptons(total)
Off-peak rate measurement, sensitive to Hgg×HZZ couplings
Cancellation between amplitudes
dσ/dm4l[fb/GeV]
m4l[GeV]
100
200
500
1000
2000
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7

Full SM picture

- High energy behavior requires cancellation between Higgs and non-Higgs amplitudes
- Consider $t\bar{t} \rightarrow ZZ$ scattering

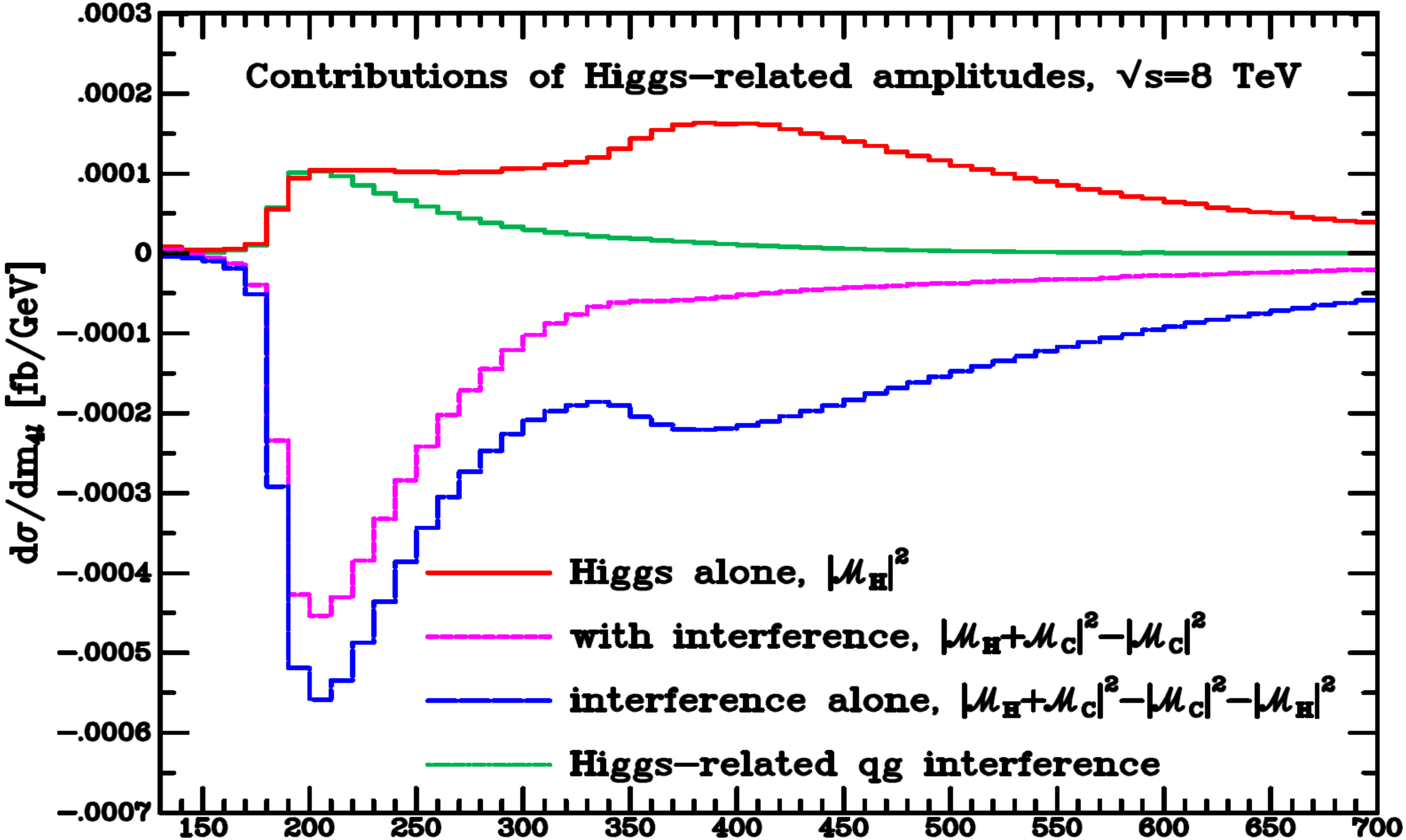
Figure from J. Campbell



$aE^2 + (b + c)m_t E$ $\qquad$ $-aE^2 + (d - c)m_t E$ $\qquad$ $-(b + d)m_t E$

- Measuring this cancellation would demonstrate the Higgs unitarization of ZZ production
  - Not the focus of the CMS measurement, but implications for NP interpretation of the measurement

Higgs–Continuum Interference



Campbell, Ellis, Williams [1311.3589] m_{4l} [GeV]

Higgs–Continuum Interference

- **In the SM**, the net Higgs contribution is expected to decrease the number of events in the tail
    - But have different scaling behavior between interference and Higgs alone
    - Off-peak, interference $\sim g_p g_d$; Higgs alone squared $\sim (g_p g_d)^2$
  - – Implies the net effect from non-SM Higgs coupling can be an overall increase or decrease in differential rate
- Higgs cross section known at NNLO+NNLL
- Off-peak $gg \rightarrow ZZ$ continuum known only at LO
  - – CMS uses the NNLO Higgs signal K factor to rescale the $gg \rightarrow ZZ$ continuum and interference
    - Refer to Bonvini, et al. [1304.3053] where signal-background interference in $gg \rightarrow H \rightarrow WW$ was studied (more later)
  - – CMS assigns a 10% systematic to this K factor rescaling – likely underestimated

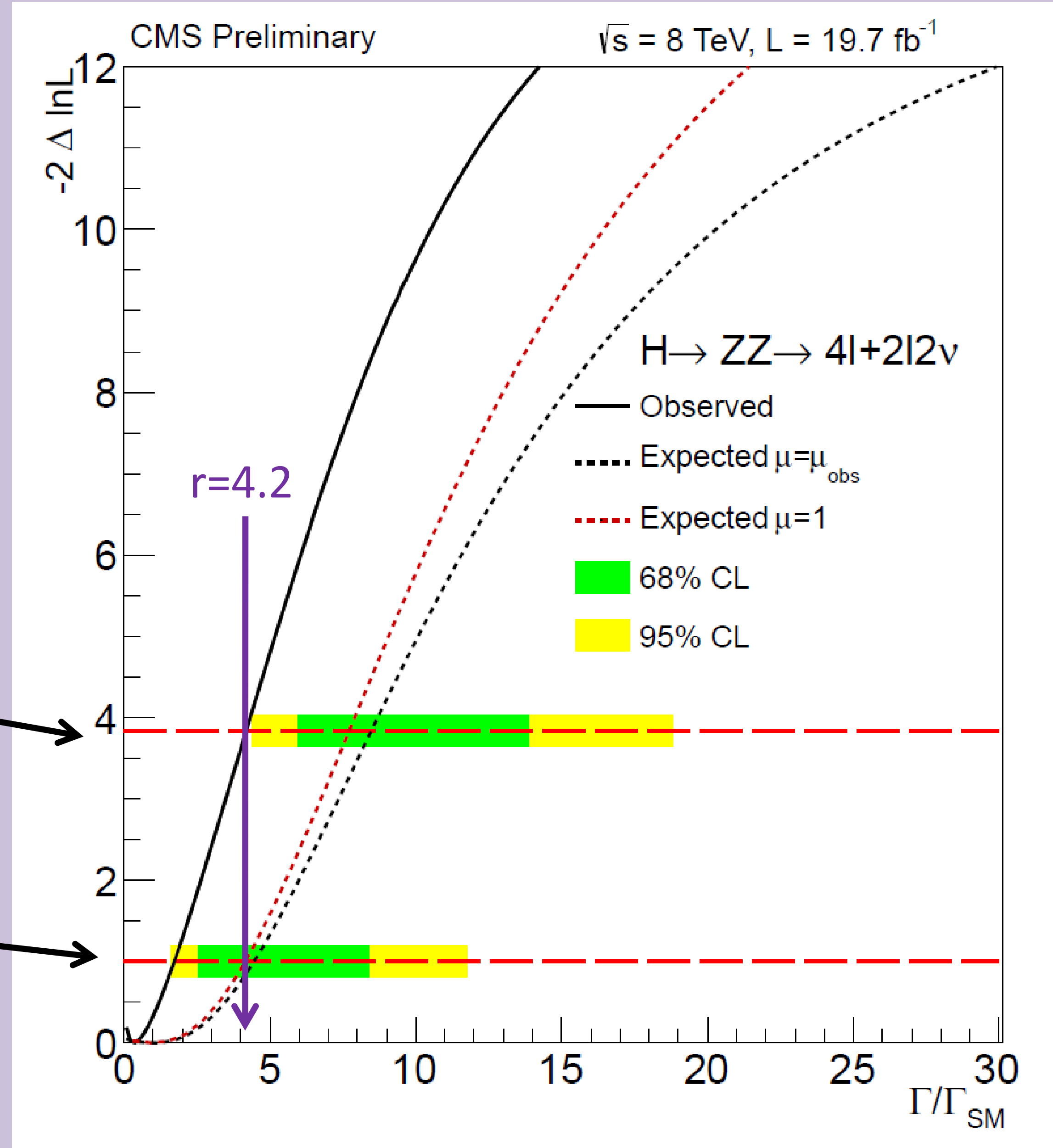
CMS HIG-14-002

CMS combined 4l+2l2ν result

- CMS observes fewer events than expected in both 4l and 2l2ν
  - Stronger than expected Higgs width constraint

95% CL

68% CL



See A. Whitbeck's talk

SM: Critiquing the result

- Using Higgs NNLO K factor for LO gg→ZZ continuum with 10% systematic uncertainty is suspect
    - Especially as the width constraint gets closer to 1, the interference term is more dominant
    - For example

$$N_{off}^{4\ell}(m_{4\ell} > 130 \text{ GeV}) = 2.78\left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 5.95\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

$$N_{off}^{4\ell}(m_{4\ell} > 300 \text{ GeV}) = 2.02\left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 2.91\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

Campbell, Ellis, Williams [1311.3589]

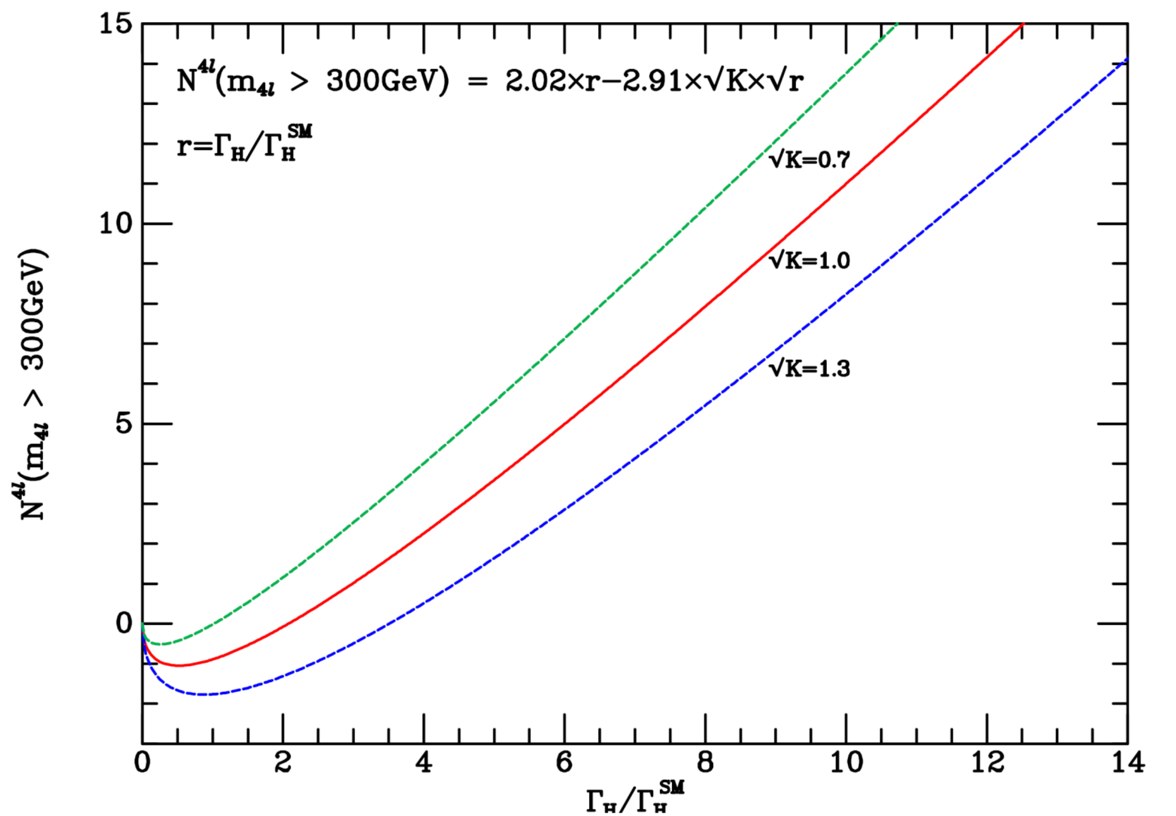
– 10% systematic driven by arbitrary rescaling of the K-factor in gg→WW with m_H=600 GeV: does not readily map to present case

$$K \simeq 1 + \frac{\alpha_s}{2\pi}(2\pi^2 + c_1)$$

Bonvini, et al. [1304.3053]

SM: Critiquing the result

- Applying a relative K-factor between Higgs NNLO and LO gg→ZZ continuum (i.e. if K-factors are not equal)



$$\frac{\Gamma_H}{\Gamma_H^{SM}} < \{3.0, 4.2, 5.75\} \text{ for } \sqrt{K} = \{0.7, 1.0, 1.3\}.$$

Figure from R.K. Ellis

SM: Critiquing the result

- Expect full NLO gg→ZZ continuum and interference to be calculated in time for 300 fb^{-1} and 3 ab^{-1} LHC
- This measurement is rapidly becoming systematics limited
  - Experimental systematics mentioned earlier
  - Theory uncertainties expected to stay relevant
  - For example, gluon fusion cross section at LHC14 is currently 48.80 pb $^{+7.5\%,\ +7.2\%}_{-8.0\%,\ -6.0\%}$ [QCD scale, PDF+α_s uncertainties]

LHC Higgs Xsec Working Group

NP: Critiquing the result

- Since gg to ZZ* is a loop process for Higgs and continuum, new physics models can modify expectation in every step of interpretation
  - Exotic production modes in on-peak and/or off-peak region
  - Threshold effects in off-peak region
  - New resonances in off-peak region
  - New contributions to gluon fusion Higgs and/or continuum loop

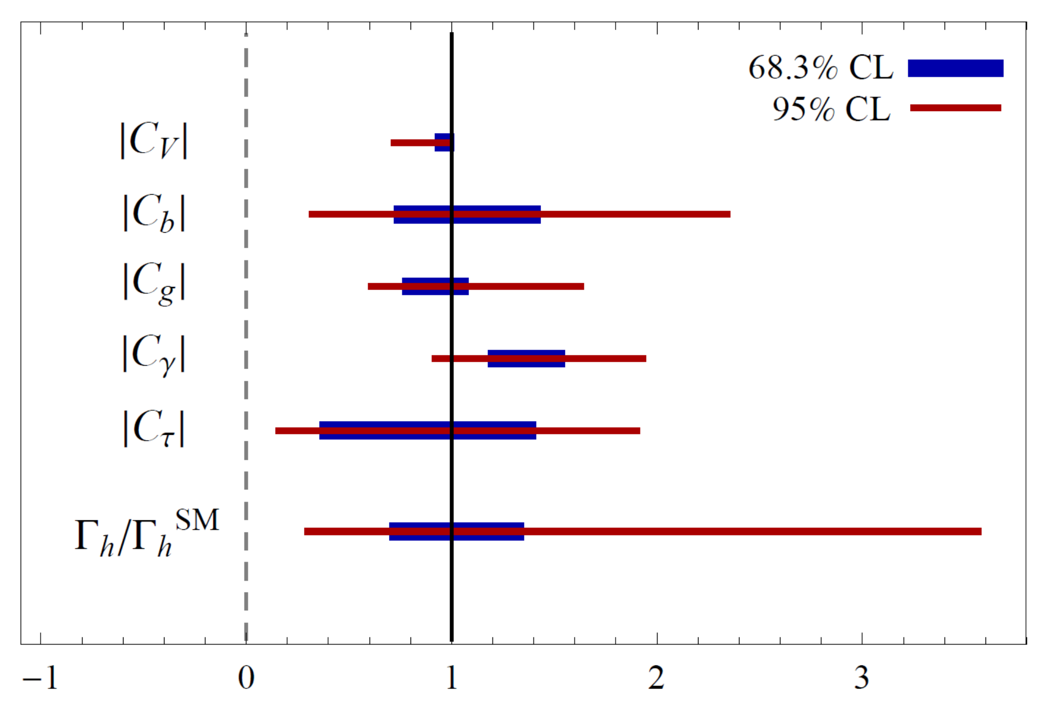
See, e.g. K. Kumar, R. Vega-Morales, FY [1205.4244]

- Free variation of Higgs couplings to vectors reintroduces unitarity problems, making the rescaling of the differential rate curves nonsensical

See also Englert, Spannowsky [1405.0285]

NP: Critiquing the result

- Unclear how many viable models are ruled out by Higgs width constraint
  - Keeping all signal strengths $\mu \approx \mu_{SM}$ and allowing width to be 4x larger requires new sources of EWSB beyond scalar doublets



Can get better limits from coupling fits

Also have lower limit on Higgs width from observed modes

But not a direct measurement!

Dobrescu, Lykken [1210.3342]

At an e^+e^- collider

- Use Z decay to muons or electrons and recoil mass consistent with Higgs mass, extract σ(Zh) rate, then measure Br(h→ZZ)

$$\Gamma_H = \Gamma(H \to ZZ)/\mathrm{BR}(H \to ZZ) \propto \sigma(ZH)/\mathrm{BR}(H \to ZZ),$$

- Expect Higgs width precision of about (few–10)%

Table 1-16. *Uncertainties on coupling scaling factors as determined in a completely model-independent fit for different e^+e^- facilities. Precisions reported in a given column include in the fit all measurements at lower energies at the same facility, and note that the model independence requires the measurement of the recoil HZ process at lower energies. ‡ILC luminosity upgrade assumes an extended running period on top of the low luminosity program and cannot be directly compared to TLEP and CLIC numbers without accounting for the additional running period. ILC numbers include a 0.5% theory uncertainty. For invisible decays of the Higgs, the number quoted is the 95% confidence upper limit on the branching ratio.*

Facility		ILC		ILC(LumiUp)	TLEP (4 IP)			CLIC	
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%

Snowmass Higgs report 1310.8361

Summary

- Impressive improvement in direct constraint on Higgs width from LHC
  - SM interpretation and projection relies on NLO calculation of gg→ZZ
  - Interpretation in NP context subject to significant model dependence
- Higgs interferometry has been and will continue to be explored
- Direct measurement of Higgs width is necessary underpinning of understanding Higgs couplings

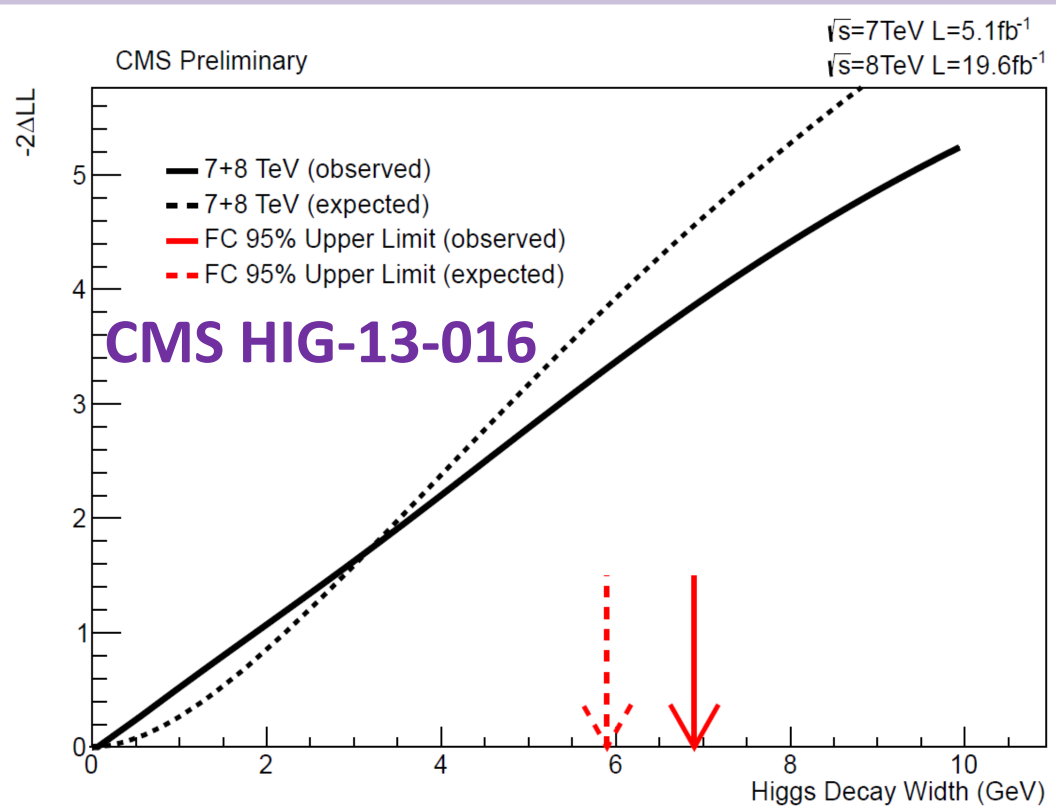
Pre-Moriond Higgs width constraints

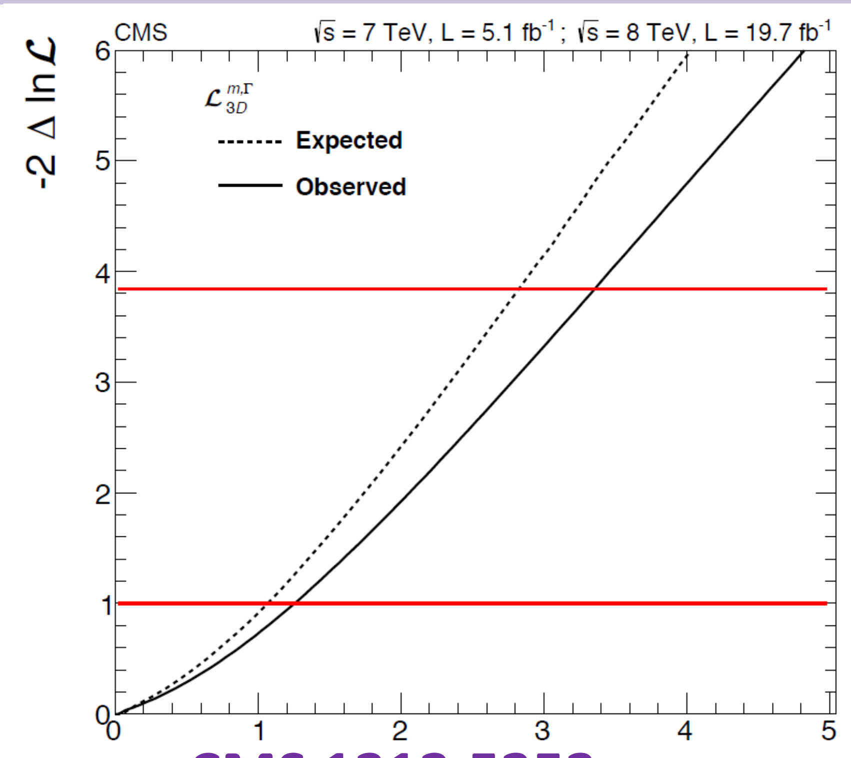
- For m_H = 126 GeV, $\Gamma_{SM} = 4.21$ MeV $^{+3.9\%}_{-3.8\%}$

LHC Higgs Xsec WG [1307.1347]

Left: Observed (expected) 6.9 (5.9) GeV @ 95% C.L. in $\gamma\gamma$ analysis

Right: Observed (expected) 3.4 (2.8) GeV @ 95% C.L. in 4l analysis





CMS 1312.5353

Theory expectation

- In order to have no effect for on-peak rates, couplings scale universally by ξ and the width scales as ξ^4
  - Then signal strength is constant and the off-peak rate is scaled by ξ^4 and ξ^2, equivalent to Γ/Γ_{SM} and $\sqrt{(\Gamma/\Gamma_{SM})}$
- Can then calculate the expected rates (after CMS cuts, which we detail later) as a function of Γ/Γ_{SM}

$$N^{4\ell}_{off}(m_{4\ell} > 130\ \text{GeV}) = 2.78\left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 5.95\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

$$N^{4\ell}_{off}(m_{4\ell} > 300\ \text{GeV}) = 2.02\left(\frac{\Gamma_H}{\Gamma_H^{SM}}\right) - 2.91\sqrt{\frac{\Gamma_H}{\Gamma_H^{SM}}}$$

at 8 TeV LHC

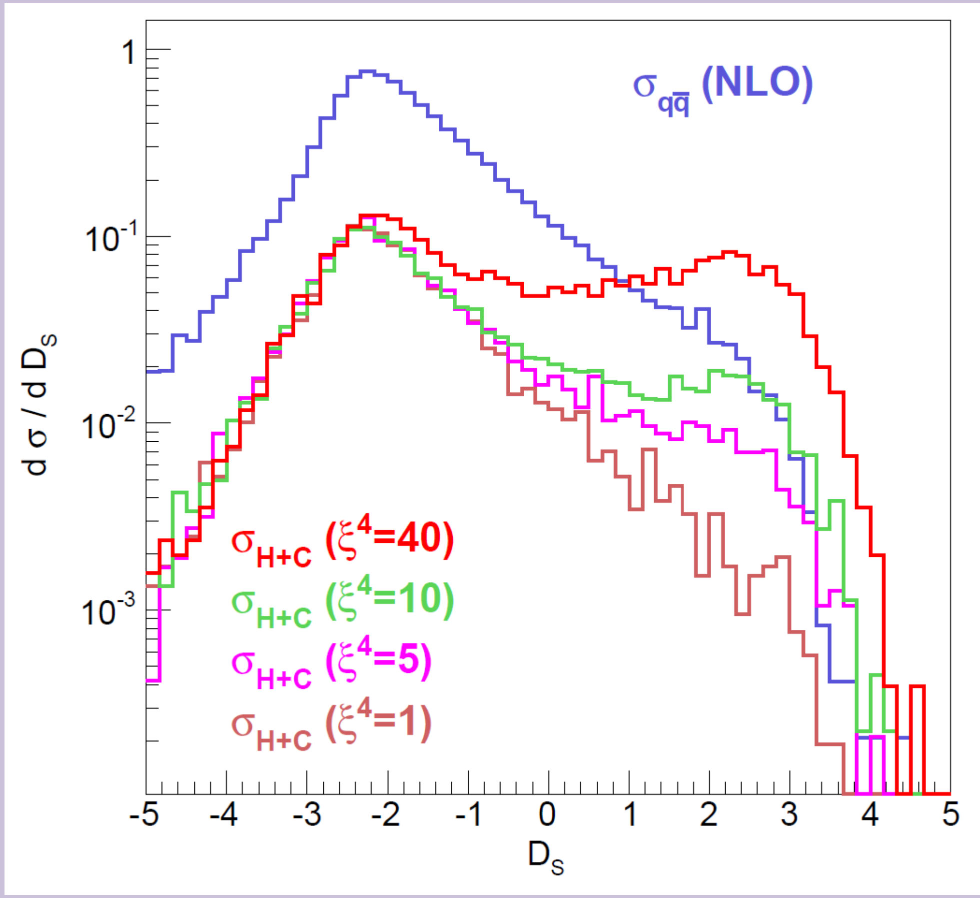
$$\Gamma_H < 43.2\,\Gamma_H^{SM} \text{ at 95\% c.l.,} \quad (m_{4\ell} > 130 \text{ GeV analysis})$$

$$\Gamma_H < 25.2\,\Gamma_H^{SM} \text{ at 95\% c.l.,} \quad (m_{4\ell} > 300 \text{ GeV analysis})$$

Campbell, Ellis, Williams [1311.3589]

Theory expectation

- With a MEM, get improved sensitivity (statistical errors only)



Expected limit $\Gamma_H < \left(15.7 \begin{smallmatrix}-2.9 \\ +3.9\end{smallmatrix}\right) \Gamma_H^{SM}$ at 95% c.l.

Campbell, Ellis, Williams [1311.3589]

CMS implementation

- In CMS language, the on-peak rate scales as

$$\sigma^{\mathrm{on-peak}}_{\mathrm{gg}\to\mathrm{H}\to\mathrm{ZZ}} = \frac{\kappa_{\mathrm{g}}^2\kappa_{\mathrm{Z}}^2}{r}(\sigma\cdot\mathcal{B})_{\mathrm{SM}} \equiv \mu(\sigma\cdot\mathcal{B})_{\mathrm{SM}},$$

- Off-peak, the Higgs only differential rate scales as

$$\frac{d\sigma^{\mathrm{off-peak}}_{\mathrm{gg}\to\mathrm{H}\to\mathrm{ZZ}}}{dm_{\mathrm{ZZ}}} = \kappa_{\mathrm{g}}^2\kappa_{\mathrm{Z}}^2\cdot\frac{d\sigma^{\mathrm{off-peak,SM}}_{\mathrm{gg}\to\mathrm{H}\to\mathrm{ZZ}}}{dm_{\mathrm{ZZ}}} = \mu r\frac{d\sigma^{\mathrm{off-peak,SM}}_{\mathrm{gg}\to\mathrm{H}\to\mathrm{ZZ}}}{dm_{\mathrm{ZZ}}}$$

- Can also include VBF production, but need to assume $\mu_{ggF} = \mu_{VBF}$

$$r = \Gamma_{\mathrm{H}}/\Gamma_{\mathrm{H}}^{\mathrm{SM}}$$

$$\kappa_g = g_{\mathrm{ggH}}/g_{\mathrm{ggH}}^{\mathrm{SM}}$$

$$\kappa_{\mathrm{Z}} = g_{\mathrm{HZZ}}/g_{\mathrm{HZZ}}^{\mathrm{SM}},$$

CMS HIG-14-002

CMS implementation

- CMS constructs probability functions for each possible differential rate contribution

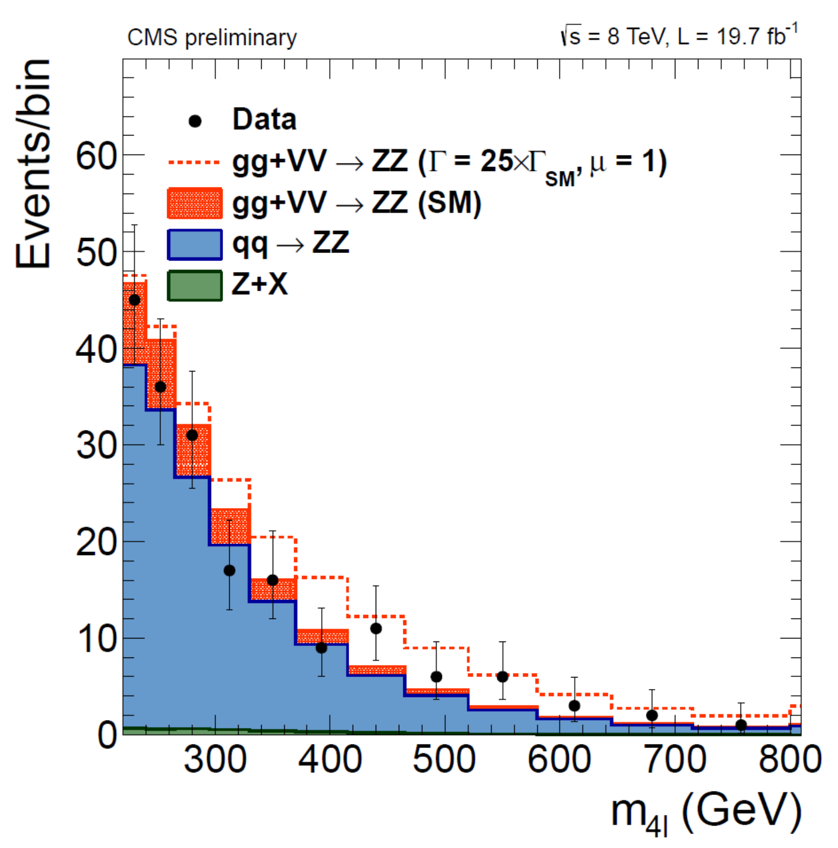
$$\mathcal{L}_i = N_{\mathrm{gg}\to\mathrm{ZZ}}\left[\mu r \times \mathcal{P}^{gg}_{\mathrm{sig}} + \sqrt{\mu r} \times \mathcal{P}^{gg}_{\mathrm{int}} + \mathcal{P}^{gg}_{\mathrm{bkg}}\right] + N_{\mathrm{VBF}}\left[\mu r \times \mathcal{P}^{VBF}_{\mathrm{sig}} + \sqrt{\mu r} \times \mathcal{P}^{VBF}_{\mathrm{int}}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

- Three avenues
  - constrain r, using measured on-peak μ (chosen method)
  - fix μ = 1 and then constrain r
  - global fit to κ_g, κ_Z, κ_W

CMS 4l analysis

- Unchanged selection criteria from earlier 4l analysis
- Start analysis at m_{4l} > 220 GeV, use kinematic discriminant for gg initiated events

Signal enriched region has m_{4l} > 330 GeV

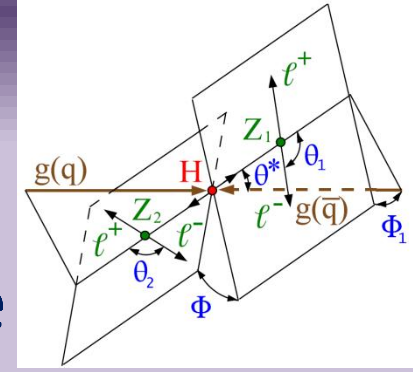


CMS HIG-14-002

CMS 4l analysis

- Unchanged selection criteria from before
  - At least 4 leptons
  - Need OS, SF pair with $40 < m_{Z1} < 120$ GeV
  - Need second OS, SF pair with $12 < m_{Z2} < 120$ GeV
  - Require $p_{T,\,1} > 20$ GeV, $p_{T,\,2} > 10$ GeV, others pass triggers

CMS 4l analysis



- Unchanged selection criteria from before
- Start analysis at $m_{4l} > 220$ GeV
- Use kinematic discriminant based on (m_{Z1}, m_{Z2}, 5 angles) for given m_{4l} to extract gg production

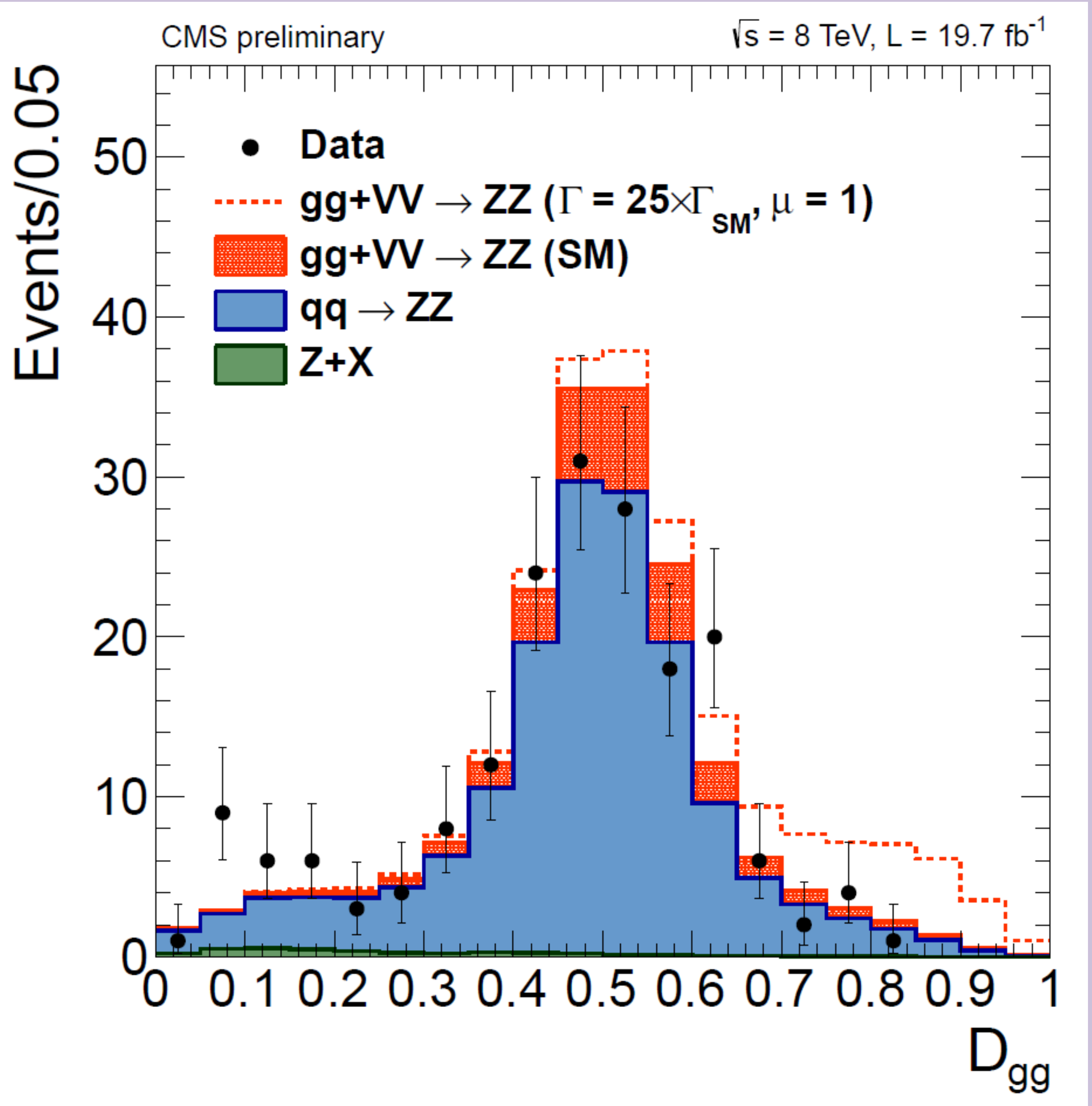
$$\mathcal{D}_{\mathrm{gg}} \equiv \frac{\mathcal{P}_{\mathrm{gg}}}{\mathcal{P}_{\mathrm{gg}} + \mathcal{P}_{\mathrm{q\bar{q}}}} = \left[1 + \frac{\mathcal{P}^{\mathrm{q\bar{q}}}_{\mathrm{bkg}}}{a \times \mathcal{P}^{\mathrm{gg}}_{\mathrm{sig}} + \sqrt{a} \times \mathcal{P}^{\mathrm{gg}}_{\mathrm{int}}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

  – Probabilities from MCFM gg→ZZ and $q\bar{q}$→ZZ
  – a=10, signal-weight parameter determines target exclusion of r=10, is used to construct the discriminant

CMS HIG-14-002

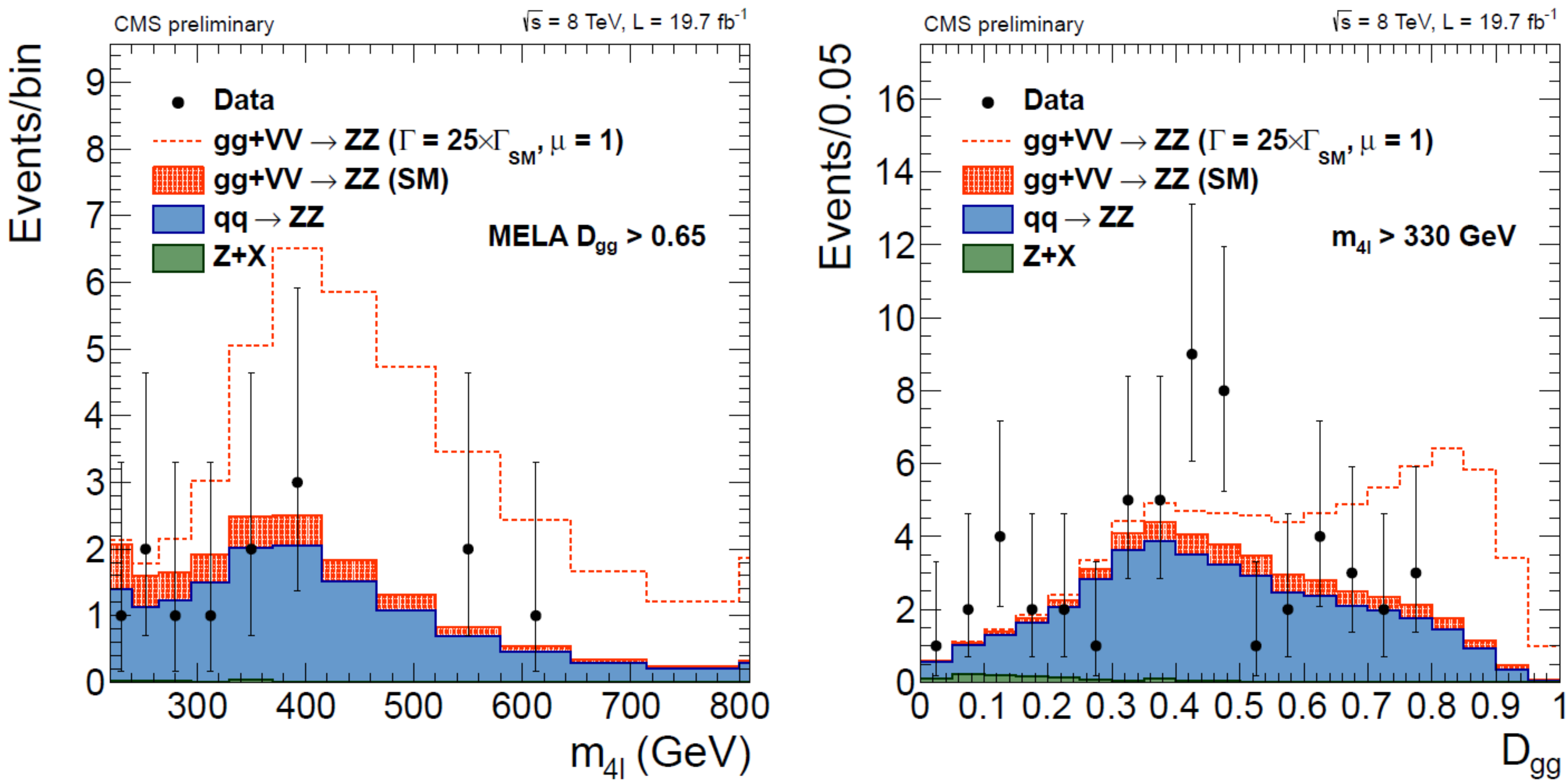
CMS 4l analysis – discriminant

Signal enriched region has $D_{gg} > 0.65$



CMS HIG-14-002

CMS 4l analysis – signal-enriched



CMS 4l analysis – event counts

- Observe fewer events than expected
  - Width constraint better than expectation in this channel

		Full region	Signal-enriched region
	$gg + \mathrm{VBF} \to 4\ell$ (signal, $\Gamma_H/\Gamma_H^{SM} = 1$)	$2.22\,^{+0.15}_{-0.17}$	$1.20\,^{+0.08}_{-0.09}$
	$gg + \mathrm{VBF} \to 4\ell$ (background)	$31.1\,^{+3.0}_{-3.1}$	2.12 ± 0.21
(a)	$gg + \mathrm{VBF} \to 4\ell$ (total, $\Gamma_H/\Gamma_H^{SM} = 1$)	$29.6\,^{+2.8}_{-2.9}$	$1.73\,^{+0.16}_{-0.17}$
	$gg + \mathrm{VBF} \to 4\ell$ (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

Table 1: Expected and observed number of 4ℓ events (sum of the 4e, 4μ and $2e2\mu$) for the off-shell analysis region defined by $m_{4\ell} \geq 220\,\mathrm{GeV}$, and for the signal-enriched region defined by $m_{4\ell} \geq 330\,\mathrm{GeV}$ and $\mathcal{D}_{gg} > 0.65$. The abbreviation gg is used to denote the $gg \to \mathrm{ZZ} \to 4\ell$ process, and the abbreviation VBF to denote the $\mathrm{qq}' \to \mathrm{ZZqq}' \to 4\ell\mathrm{qq}'$ process.

CMS HIG-14-002

CMS 2l2ν analysis

- Designed for heavy Higgs searches
  - ZZ to 2l2ν about 6 times more events than ZZ to 4l
  - Can still probe high mass tail with transverse mass
- Unchanged selection criteria from earlier 2l2ν
  - Categorize 0-jet, ≥1-jet, VBF ($|\Delta\eta| > 4$, $m_{jj} > 500$ GeV, veto central jets, leptons are central) according to number of jets, jet $p_T > 30$ GeV
  - Discriminant is m_T of dilepton system for 0-jet, ≥1-jet, and MET for VBF category

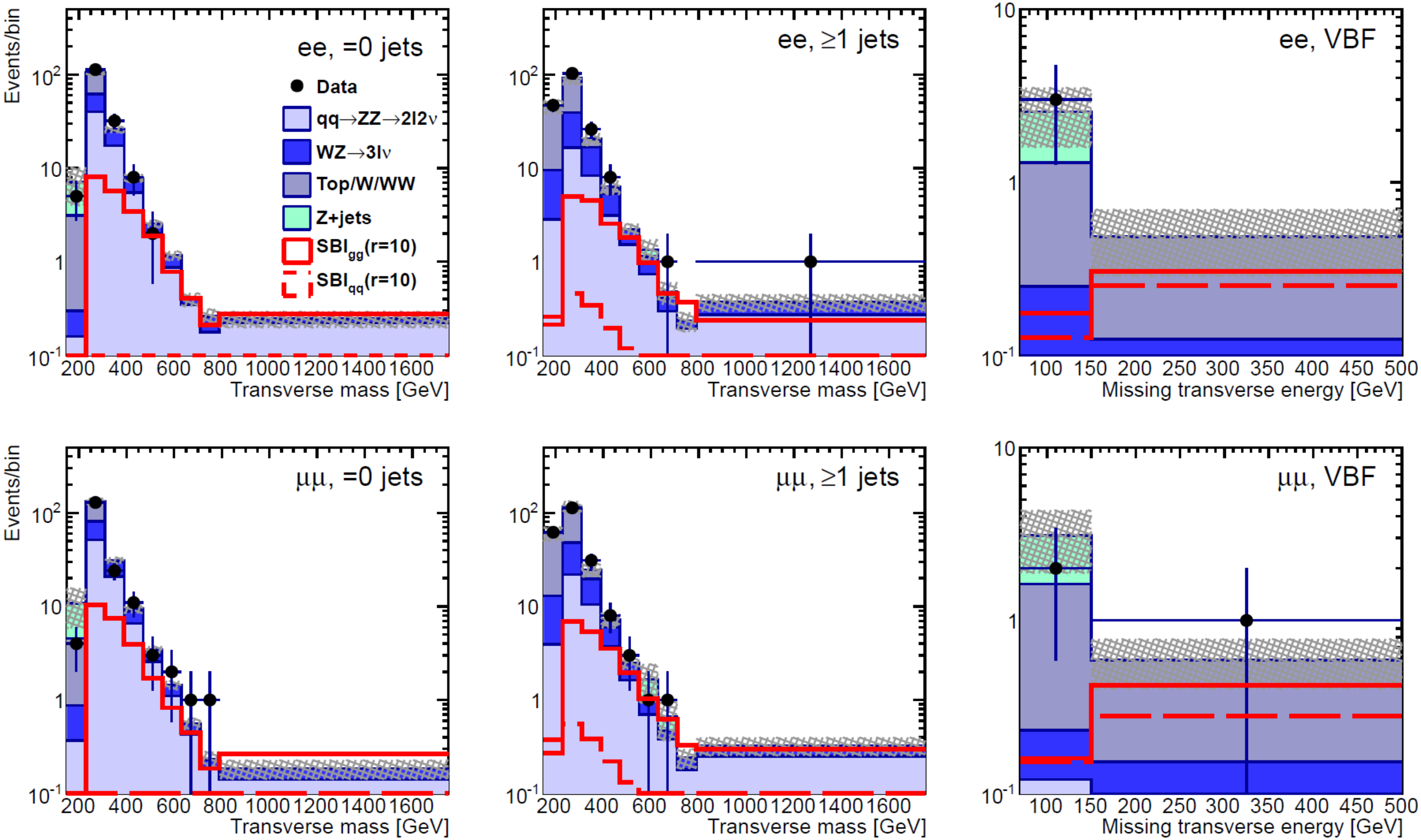
$$m_{\mathrm{T}}^2 = \left[\sqrt{p_{\mathrm{T},\ell\ell}{}^2 + m_{\ell\ell}{}^2} + \sqrt{E_{\mathrm{T}}^{\mathrm{miss}\,2} + m_{\ell\ell}{}^2}\right]^2 - \left[\vec{p}_{T,\ell\ell} + \vec{E}_T^{\mathrm{miss}}\right]^2$$

CMS HIG-13-014

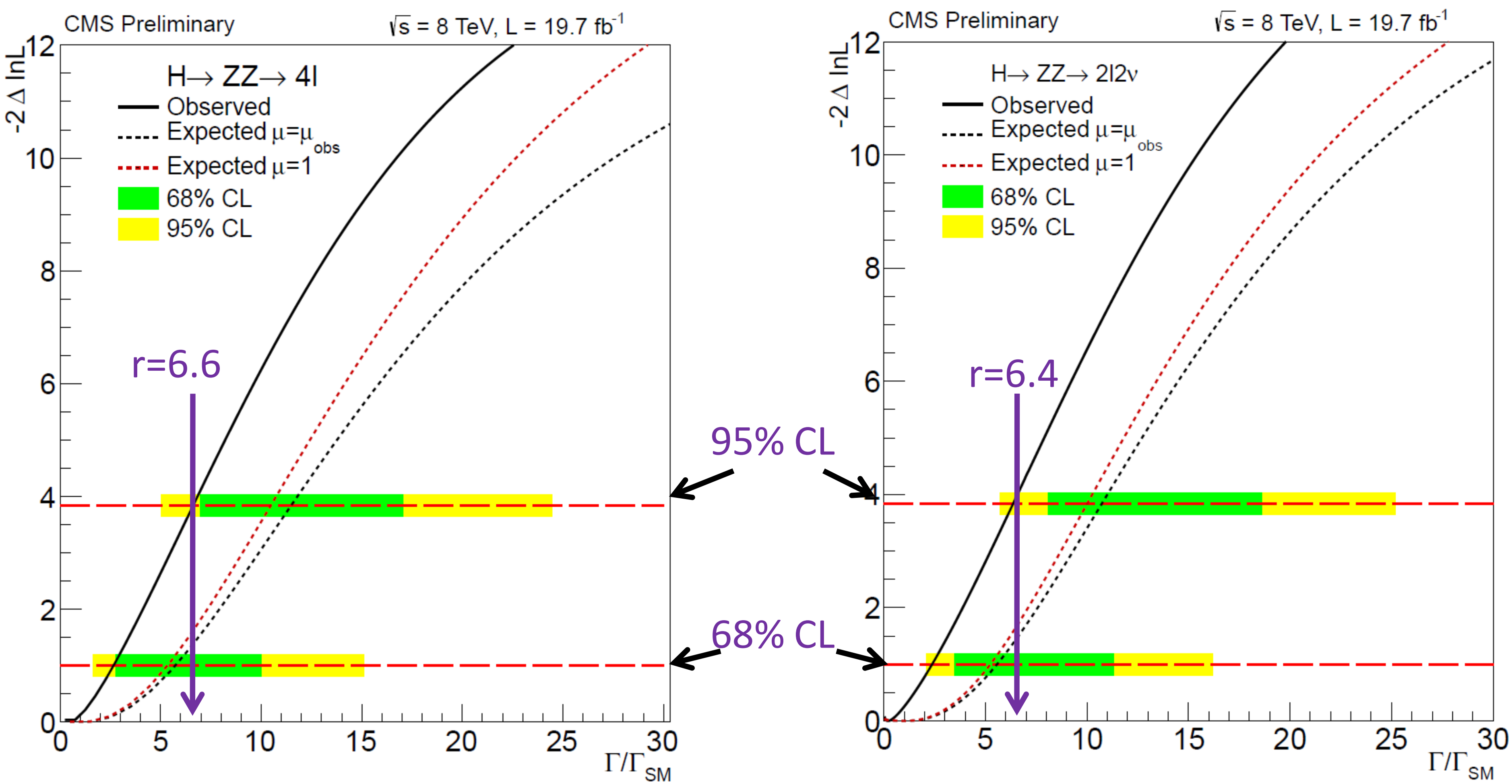
CMS 2l2v analysis

- Designed for heavy Higgs searches
  - ZZ to 2l2v about 6 times more events than ZZ to 4l
  - Can still probe high mass tail with transverse mass
- Unchanged selection criteria from before
    - Only 2 leptons
    - Must be OS, SF pair, each with $p_T > 20$ GeV, $|m_{ll} - m_Z| < 15$ GeV
    - MET > 80 GeV

CMS 2l2ν analysis



CMS result



CMS Preliminary
$\sqrt{s}$ = 8 TeV, L = 19.7 fb^{-1}
$-2\,\Delta\,\ln L$
$H \to ZZ \to 4l$
Observed
Expected $\mu=\mu_{obs}$
Expected $\mu=1$
68% CL
95% CL
r=6.6
Γ/Γ_{SM}
CMS Preliminary
$\sqrt{s}$ = 8 TeV, L = 19.7 fb^{-1}
$-2\,\Delta\,\ln L$
$H \to ZZ \to 2l2\nu$
Observed
Expected $\mu=\mu_{obs}$
Expected $\mu=1$
68% CL
95% CL
r=6.4
Γ/Γ_{SM}
95% CL
68% CL

CMS 2l2v analysis

- Again, observe fewer events than expected

		ee	$\mu\mu$
	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
(a)	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
	$q\bar{q} \to$ ZZ	25.0±0.5	29.4±0.5
	WZ	11.6±0.4	13.5±0.4
(b)	$\mathrm{t\bar{t}}$/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

Table 2: Event yields in a signal-enriched region expected for the signal and background processes and observed in the data for the ee and $\mu\mu$ channels. The abbreviation gg is used to denote the process $gg \to ZZ \to 2\ell 2\nu$. The abbreviation VBF is used to denote the process $\mathrm{qq'} \to \mathrm{ZZqq'} \to 2\ell 2\nu\mathrm{qq'}$. The signal-enriched region is defined by $E_T^{miss} > 100$ GeV and $m_T > 350$ GeV.

CMS result

- Comparable expected limits for 4l and 2l2ν analyses
- Both observe fewer events than expected
  - Stronger constraint on r than expected

	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)	$2.0\,^{+9.6}_{-2.0}$	$0.8\,^{+9.1}_{-0.8}$	$1.4\,^{+6.1}_{-1.4}$

Table 3: Expected and observed 95% CL limits for the 4ℓ and $2\ell 2\nu$ analyses and for the combination. For the observed results, the central fitted values and the 68% CL total uncertainties are also quoted. All quoted values are obtained using the observed value of μ.

Observed $\mu = 0.93\,^{+0.26}_{-0.24}$

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Critiquing the result

Figure from R.K. Ellis