Constraints on the Higgs boson width from off-shell production and decay to ZZ→4l or 2l2ν

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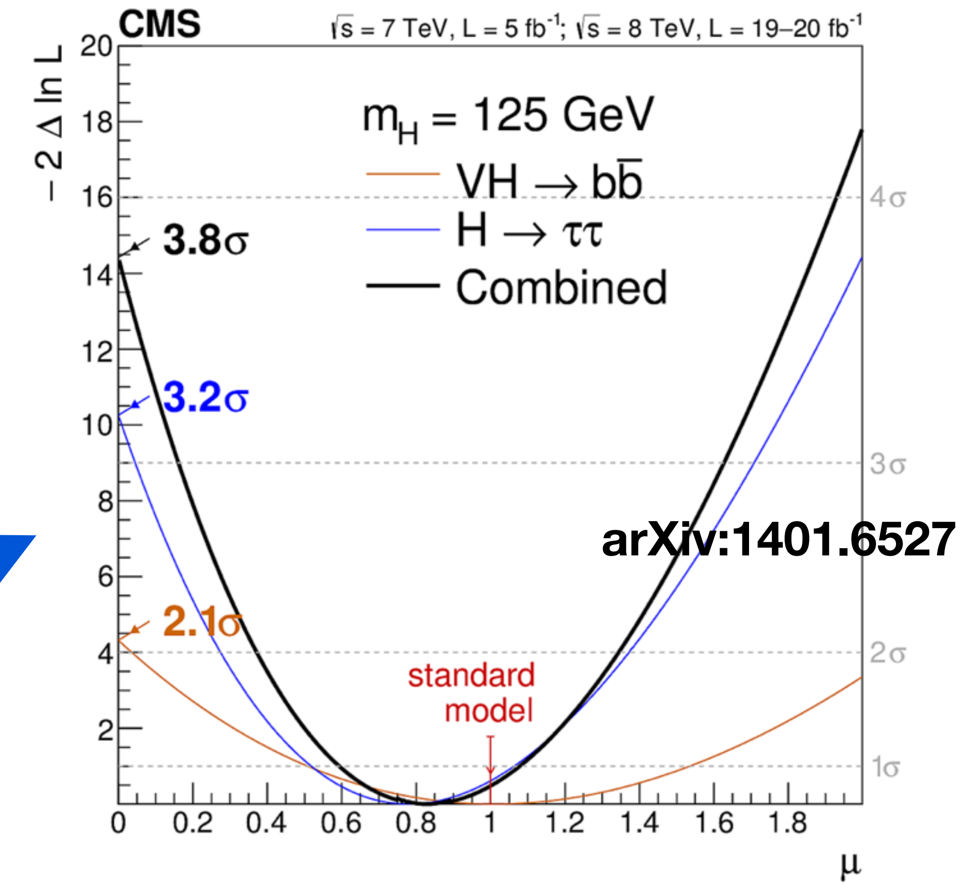
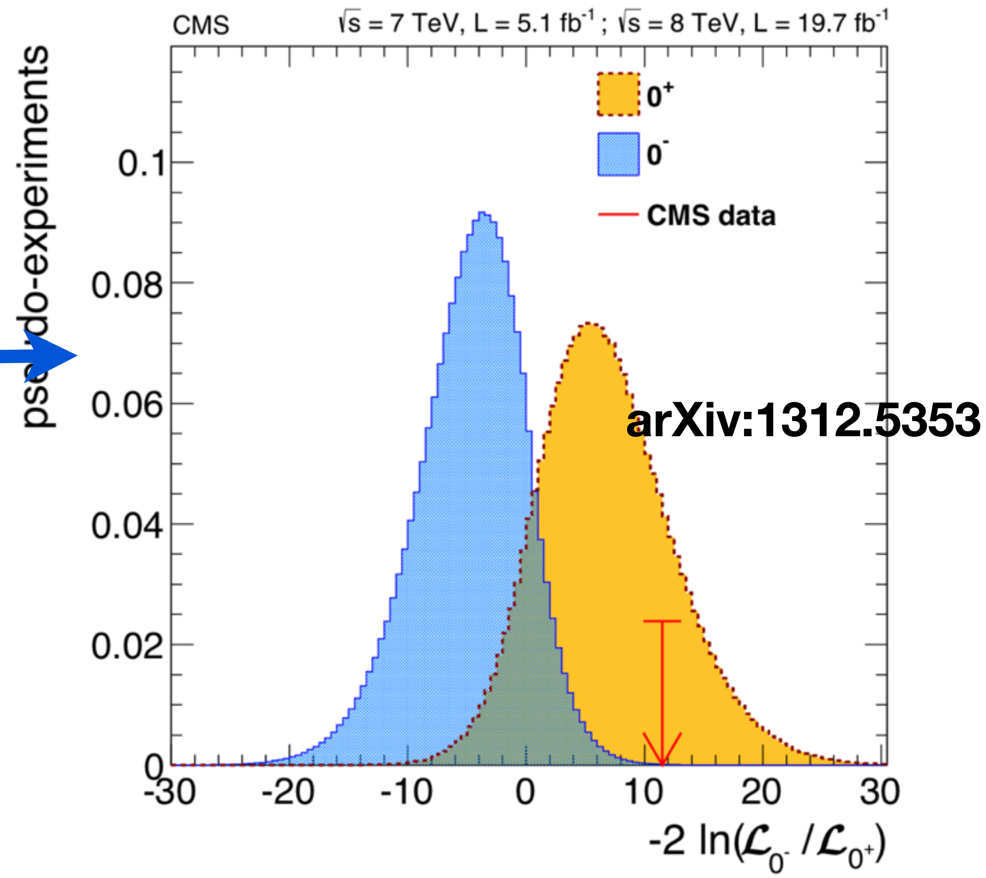
On behalf of the CMS collaboration

CERN LHC seminar
April 15, 2014

After discovery

- Great progress since Higgs boson discovery
  - Observation in boson channels
  - Evidence in fermion channels
  - Mass measurements
    - CMS H→ZZ→4l measurement 125.6±0.4(stat.)±0.2(syst.)GeV
  - Spin/parity studies

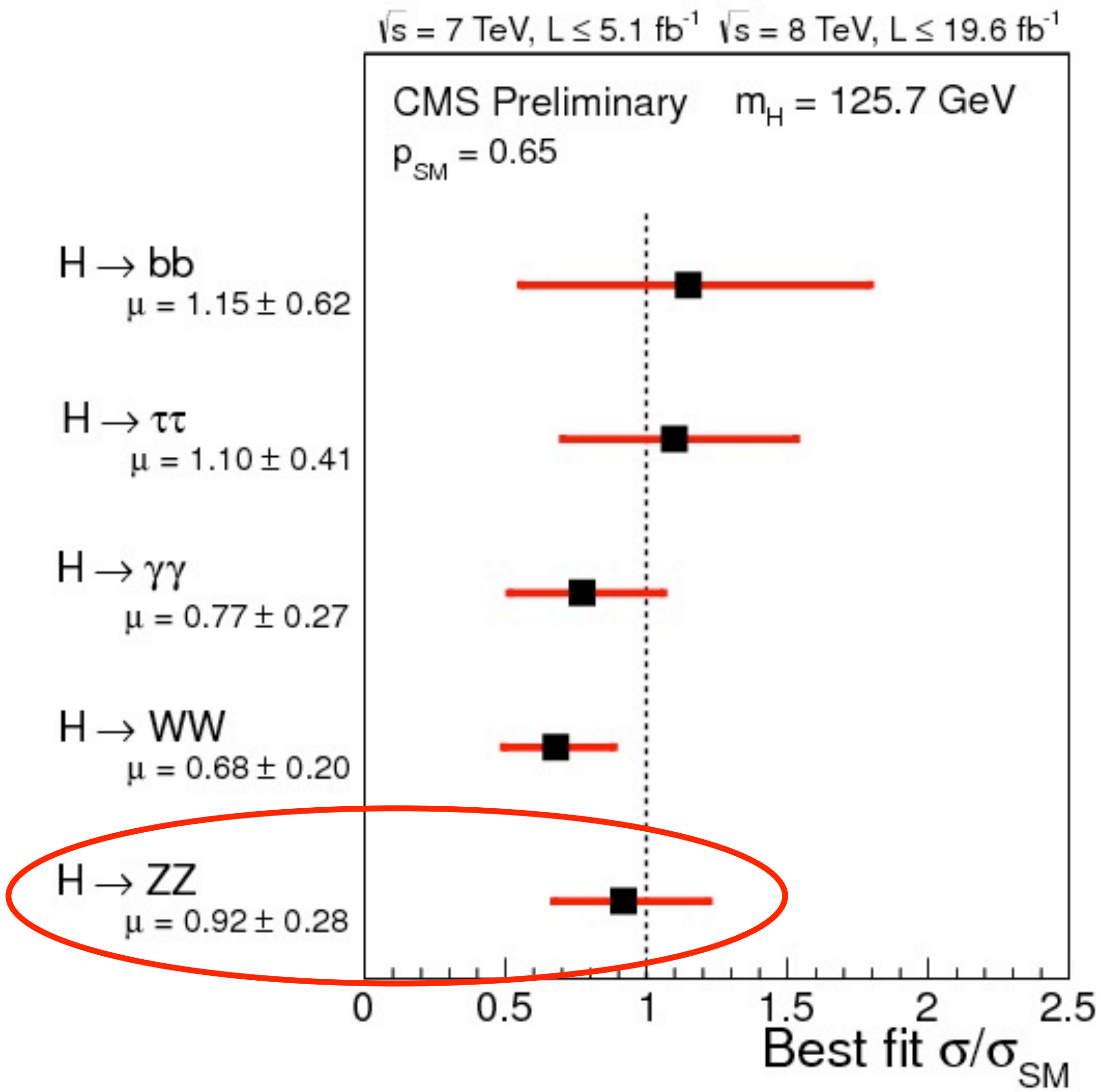




Looks more and more like the SM Higgs boson

Property measurements - signal strength

"Signal strength" $\mu = \sigma/\sigma_{SM}$



Narrow width approximation

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

Define $r = \Gamma_H/\Gamma_H^{SM}$

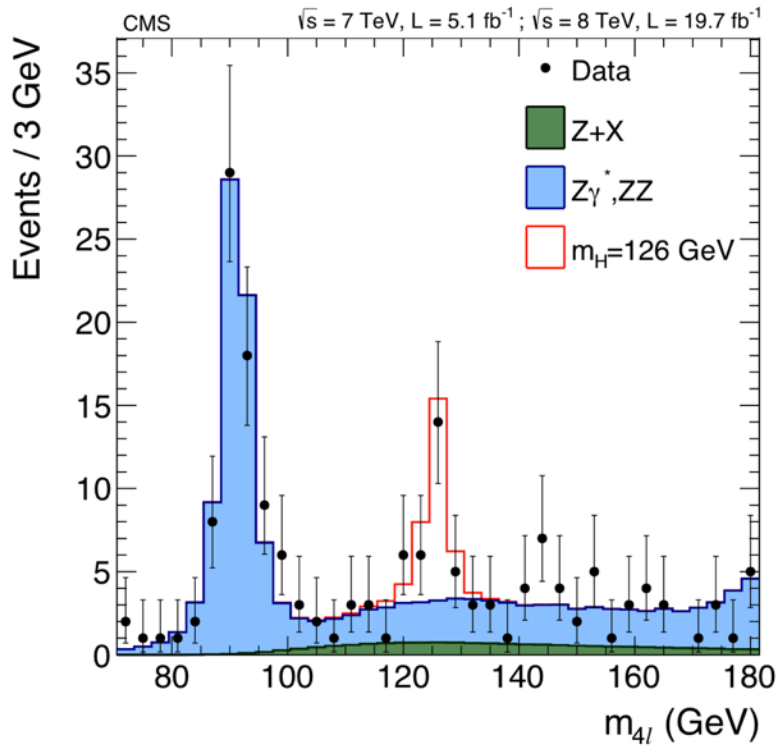
$$\kappa_g = g_{ggH}/g^{SM}_{ggH} \quad \kappa_Z = g_{HZZ}/g^{SM}_{HZZ}$$

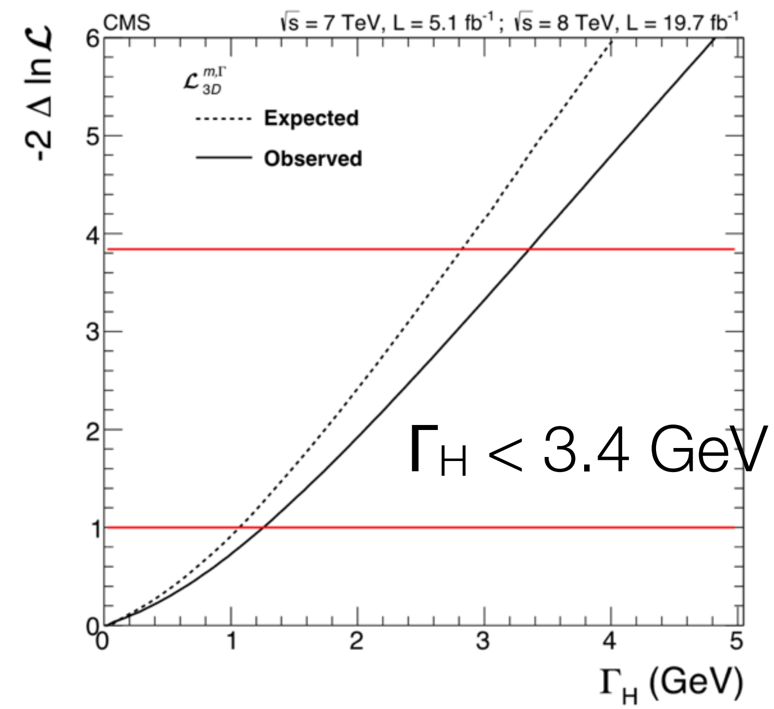
$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} = \frac{\kappa_g^2 \kappa_Z^2}{r}(\sigma\cdot\mathcal{B})_{SM} \equiv \mu(\sigma\cdot\mathcal{B})_{SM}$$

The **μ** unchanged if the numerator and denominator are scaled by a common factor

Property measurements - width

arXiv:1312.5353





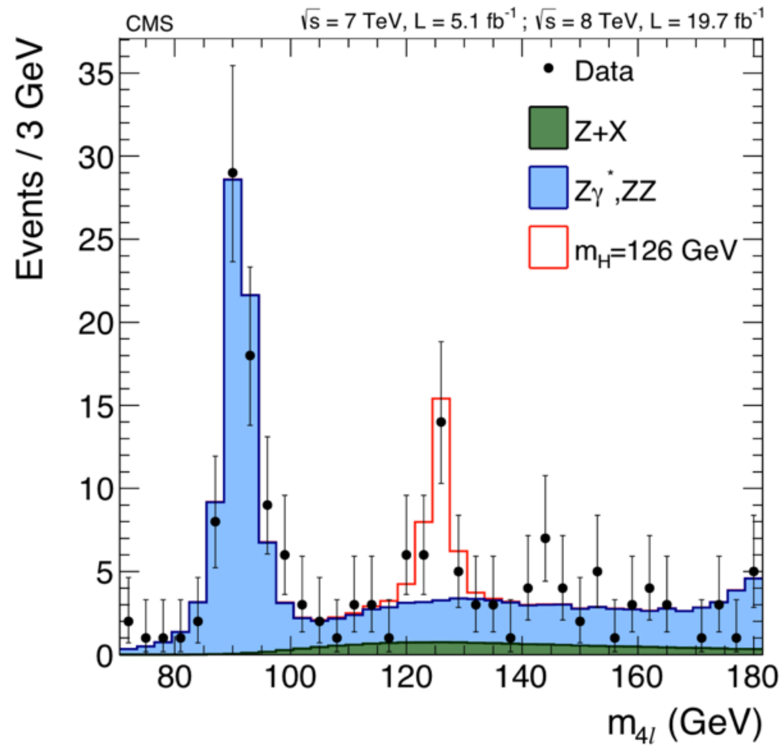
$\Gamma_H < 3.4$ GeV

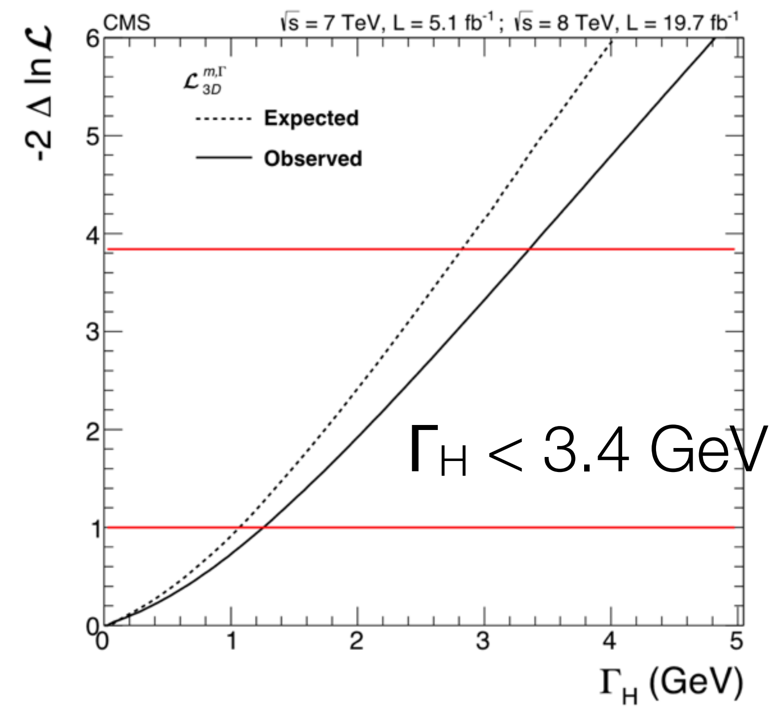
H→γγ results $\Gamma_H < 6.9$ GeV (**CMS-HIG-13-016**)

Direct measurements are limited by experimental resolutions

Property measurements - width

arXiv:1312.5353





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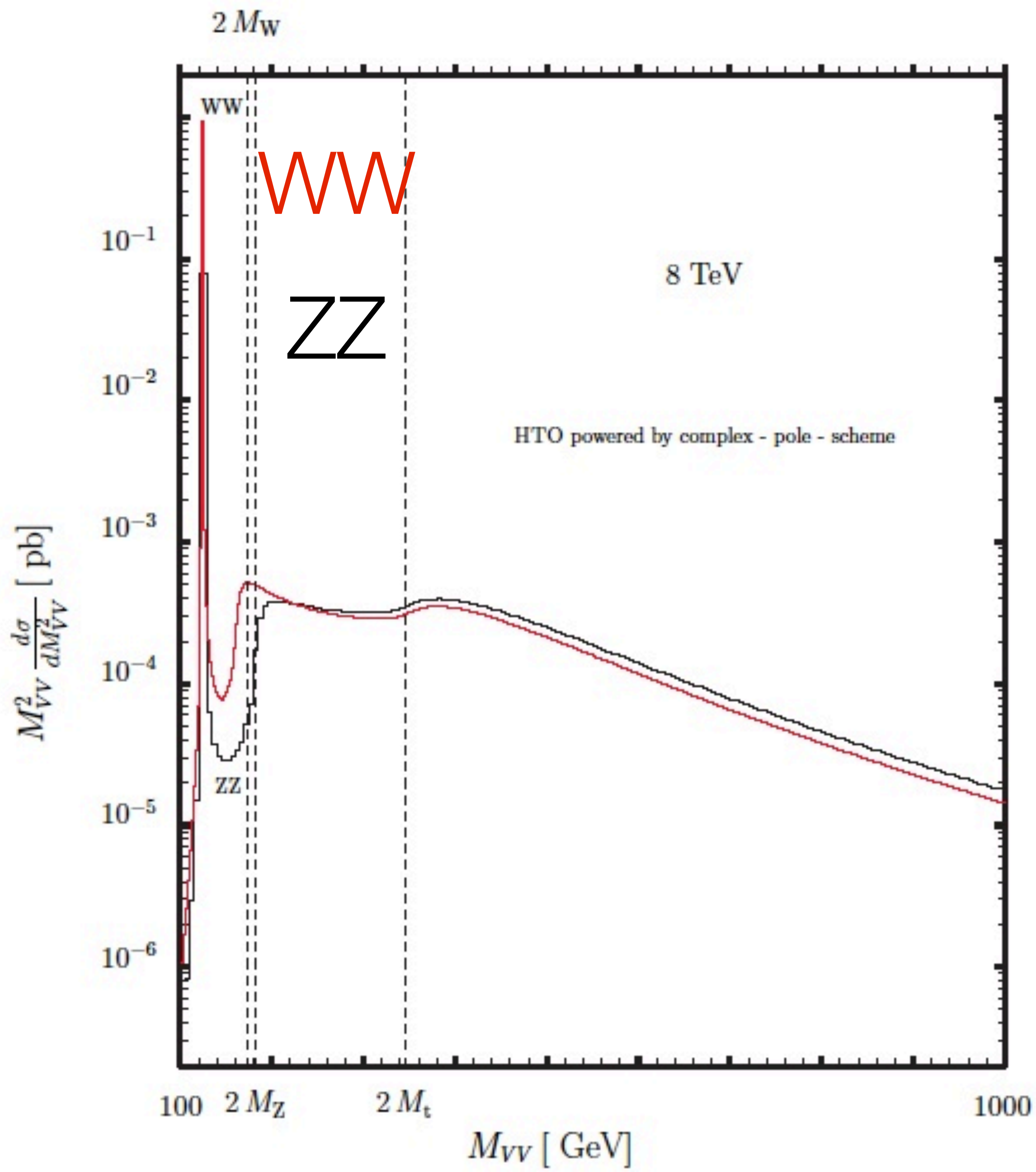
perimental resolutions

Waiting for a lepton collider...

Higgs off-shell production and decay



Off-shell production cross section has been shown to be sizable at high VV invariant mass

A mixed effect of production and decay: enhancement at $2m_V$ and $2m_t$ thresholds

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

With current experimental cuts in $H \to ZZ \to 4l$ analysis, this ratio is further enhanced

N. Kauer and G. Passarino, JHEP 08 (2012) 116

Constraining the Higgs boson width

F. Caola, K. Melnikov (Phys. Rev. D88 (2013) 054024)
J. Campbell et al. (arXiv:1311.3589)

The production cross section as a function of m_{ZZ}

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \propto g^2_{ggH} g^2_{HZZ} \frac{F(m_{ZZ})}{(m^2_{ZZ} - m^2_H)^2 + m^2_H \Gamma^2_H}$$

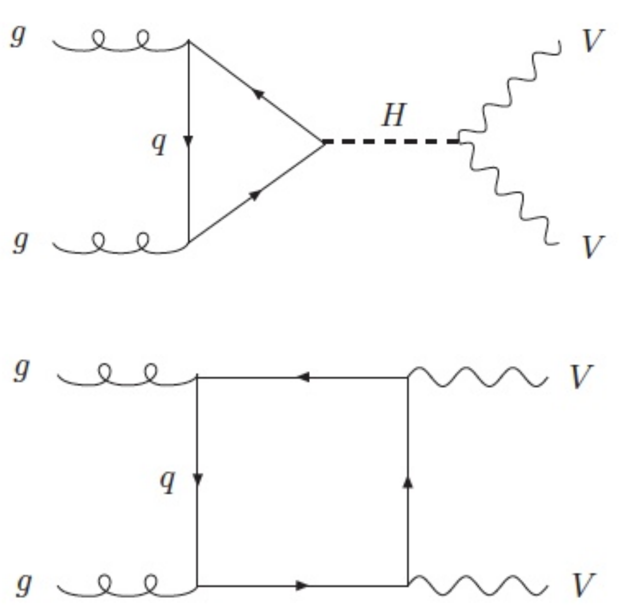
On-shell vs. off-shell

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

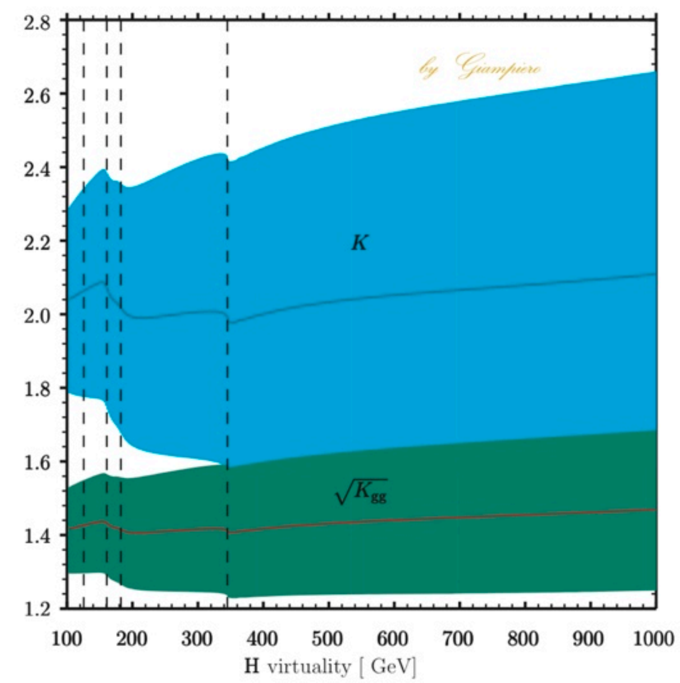
Away from the resonance, the cross section is independent of the width.
The ratio of off-shell and on-shell production leads to a direct constraint of Γ_H
Assuming the coupling constants remain invariant at the low and high mass region.

Data and MC samples

- 2012 data, 8 TeV, corresponding to $L = 19.7\ fb^{-1}$
- $gg \to ZZ \to 4l/2l2\nu$ events are generated at LO using gg2VV3.1.5 and/or MCFM6.7
    - Generations include Higgs boson signal, continuum background and their interference
    - Higgs boson mass set to 125.6 GeV (corresponding SM width 4.15 MeV)
    - The renormalization and factorization scales are set to $m_{ZZ}/2$ (running scales)
    - NNLO K factors applied as a function of mZZ; same K factors applied to continuum backgrounds (**M. Bonvini et al. (Phys. Rev. D88 (2013) 034032)**)



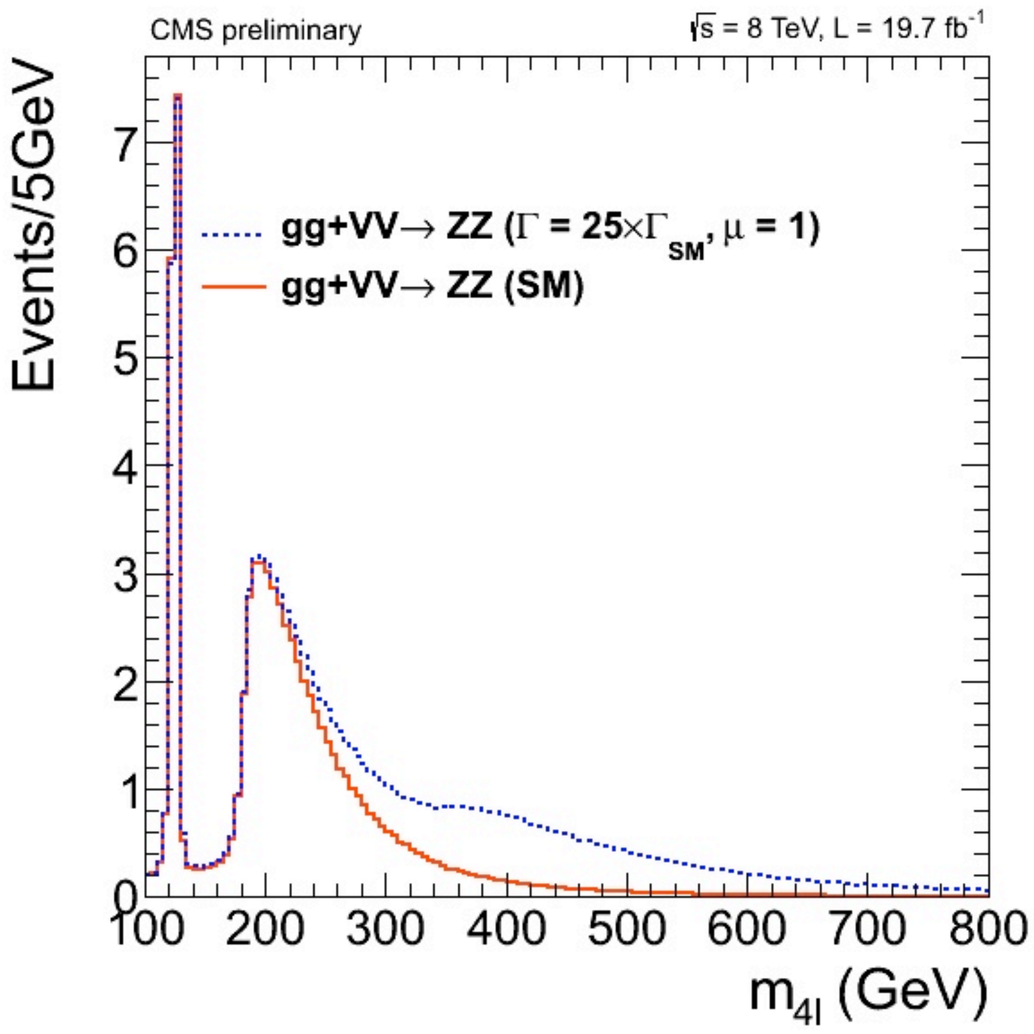
Higgs signal interferes with continuum background



G. Passarino (arXiv:1312.2397)

MC samples

- Vector Boson Fusion(VBF) Higgs production mode is expected to also produce an off-shell tail, and could be as large as 10% in the high mass region, compared to gg fusion mode. qq'→ZZ+qq'→4l/2l2ν+qq' events are generated using PHANTOM, including the signal, background and their interference



- Background samples are generated from POWHEG or MADGRAPH, and normalized to NLO cross sections where available
- GEANT4 based CMS detector simulation

Analysis strategy

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

Once the μ taken from a measurement or calculation, the off-shell cross section gives direct constraint on $r=\Gamma/\Gamma_{SM}$

μ from CMS on-peak 4l measurement is used (with its stat. uncertainty)

$\mu(\mathrm{obs}) = 0.93^{+0.26}_{-0.24}$

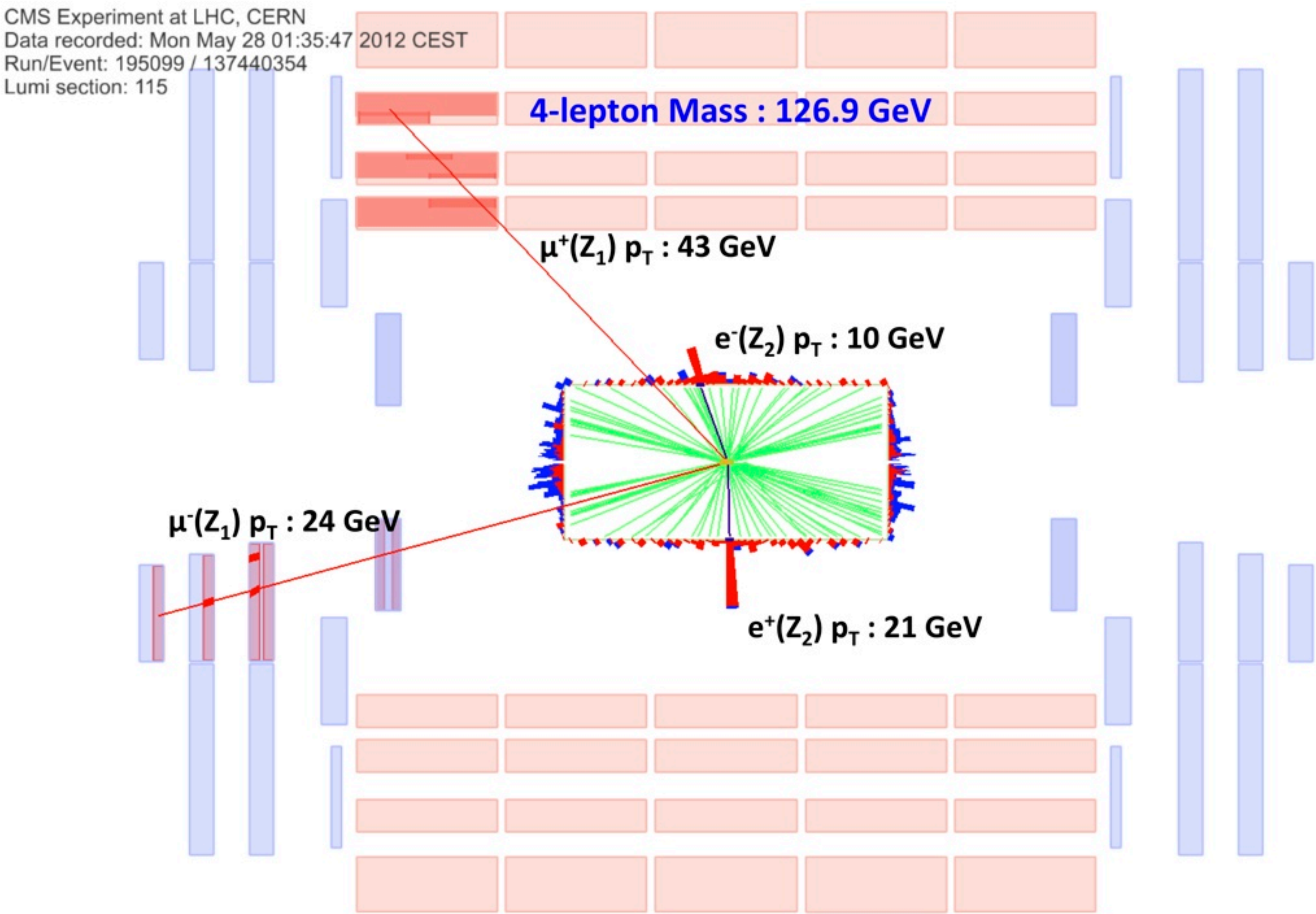
$\mu(\mathrm{exp}) = 1.00^{+0.27}_{-0.24}$

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

The parameterization of gg→ZZ and VBF processes includes three correlated distributions for signal, background and their interference;

Assuming $\mu_{ggF} = \mu_{VBF}$

H→ZZ→2l2l'


CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115
4-lepton Mass : 126.9 GeV
μ+(Z1) pT : 43 GeV
e-(Z2) pT : 10 GeV
μ-(Z1) pT : 24 GeV
e+(Z2) pT : 21 GeV

4l analysis - overview

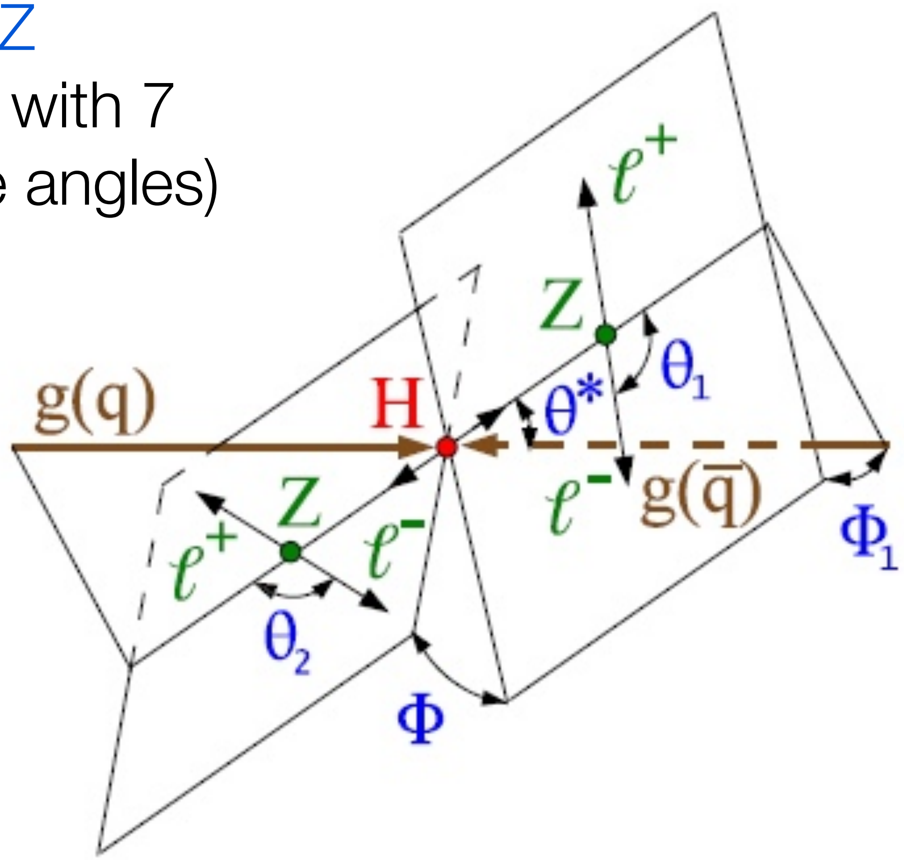
- Same event reconstruction and selection as those used in the previous measurement of Higgs boson properties (**arXiv: 1312.5353**)
- Event selections:
    - Two pairs of leptons (electrons or muons), isolated, of opposite sign and same flavor; Z_1: closest to the Z boson mass; Z_2: the remaining with highest scalar sum of p_T
    - At least one lepton has $p_T > 20$ GeV, and another has $p_T > 10$ GeV
    - $40 < m_{Z1} < 120$ GeV; $12 < m_{Z2} < 120$ GeV
    - Off-shell analysis region: $220 < m_{4l} < 1600$ GeV
- Background:
    - Irreducible background is qq→ZZ, modeled from MC
    - Reducible background (much smaller) is Z+X (Z and WZ, at least one lepton is non-prompt), evaluated using a “fake rate” method, with control regions in data

4l analysis - MELA D_{gg}

Matrix element likelihood approach (MELA)

A kinematic discriminant to separate gg→ZZ from qq→ZZ

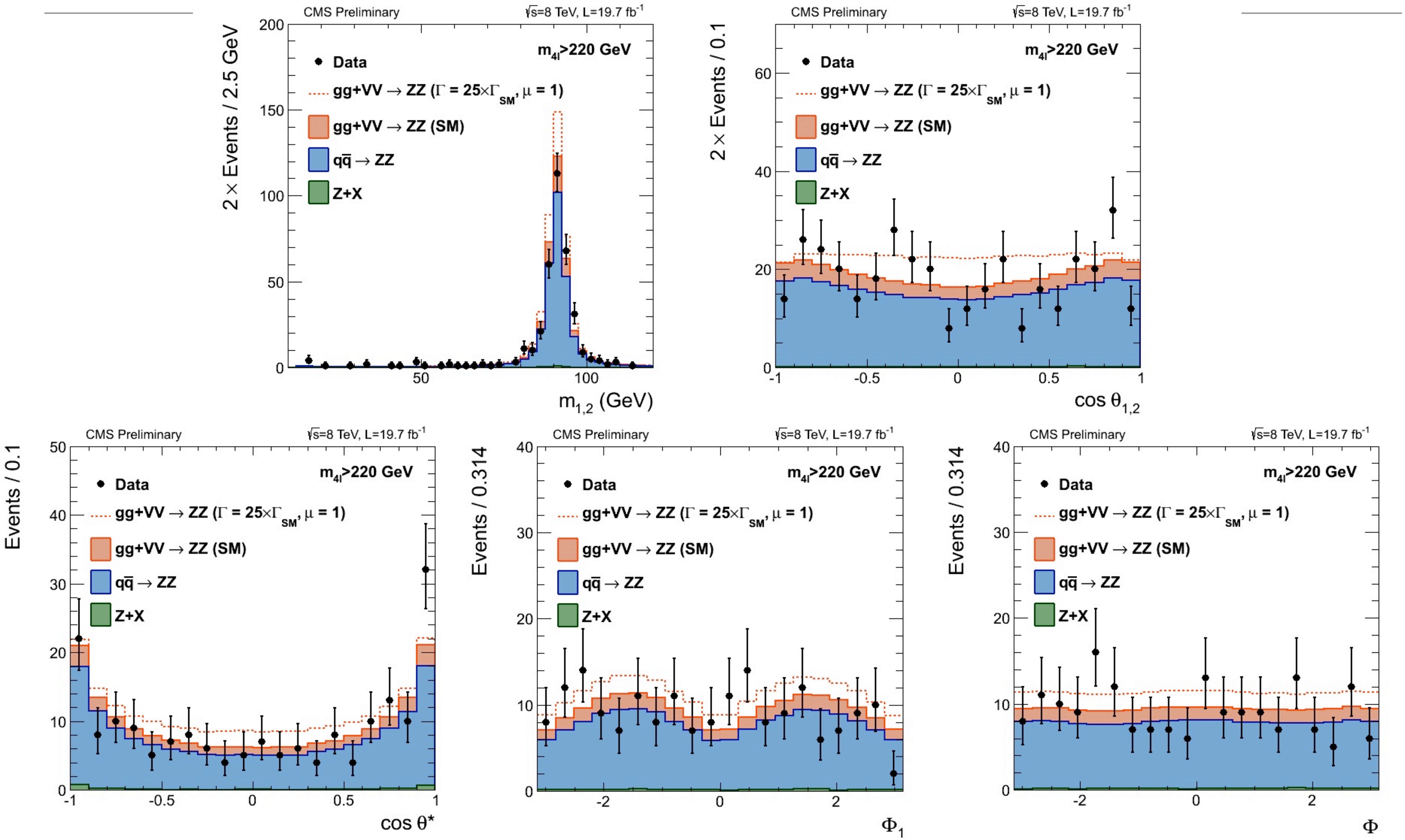
Characterize event topology in ZZ center-of-mass frame, with 7 variables completely describing kinematics (m_{Z1}, m_{Z2}, five angles)



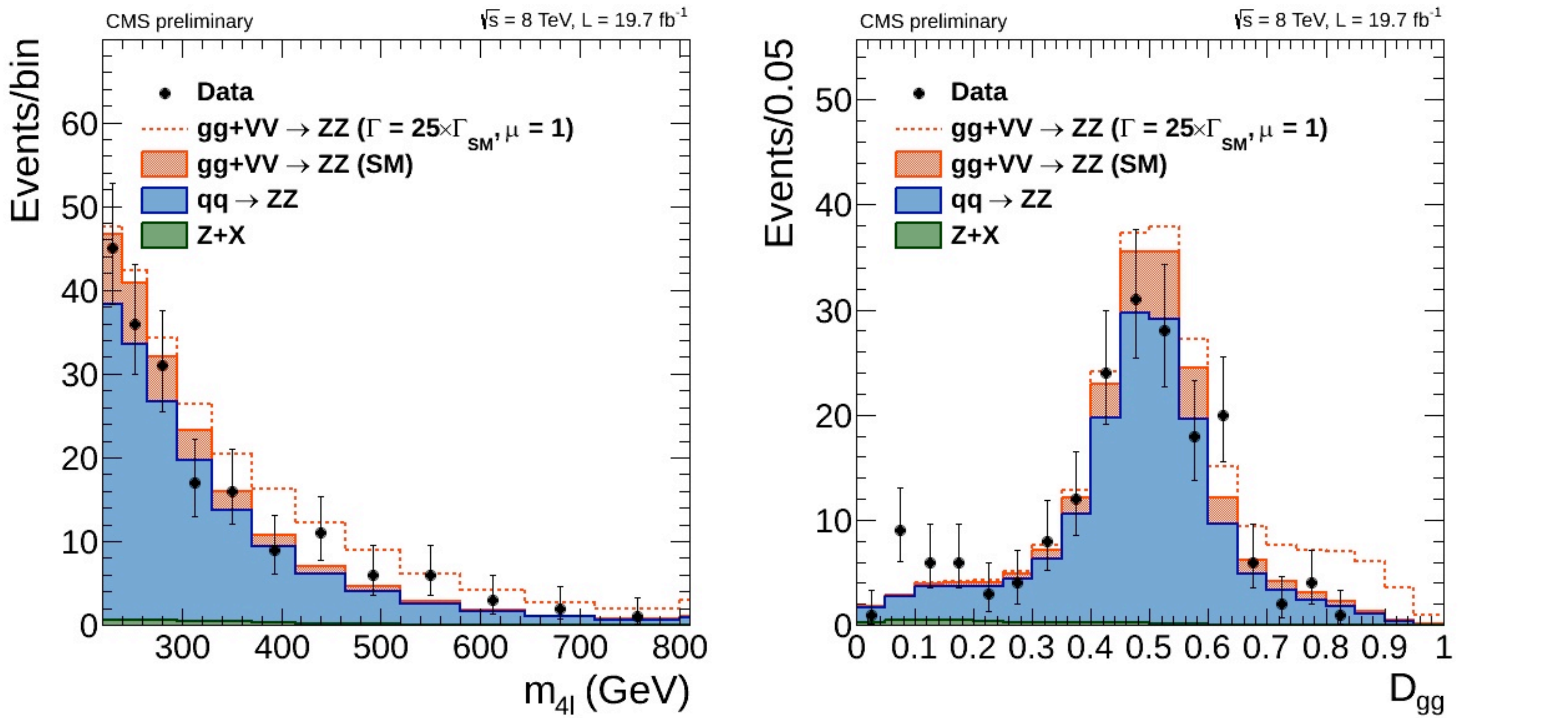
$$\mathcal{D}_{gg} \equiv \frac{\mathcal{P}_{gg}}{\mathcal{P}_{gg} + \mathcal{P}_{q\bar{q}}} = \left[1 + \frac{\mathcal{P}^{q\bar{q}}_{bkg}}{a \times \mathcal{P}^{gg}_{sig} + \sqrt{a} \times \mathcal{P}^{gg}_{int} + \mathcal{P}^{gg}_{bkg}}\right]^{-1}$$

(Depends on parameter a (relative weight of signal in the likelihood ratio). Since the expected exclusion is r ~ 10, use a = 10)

4l analysis - inputs to D_{gg}

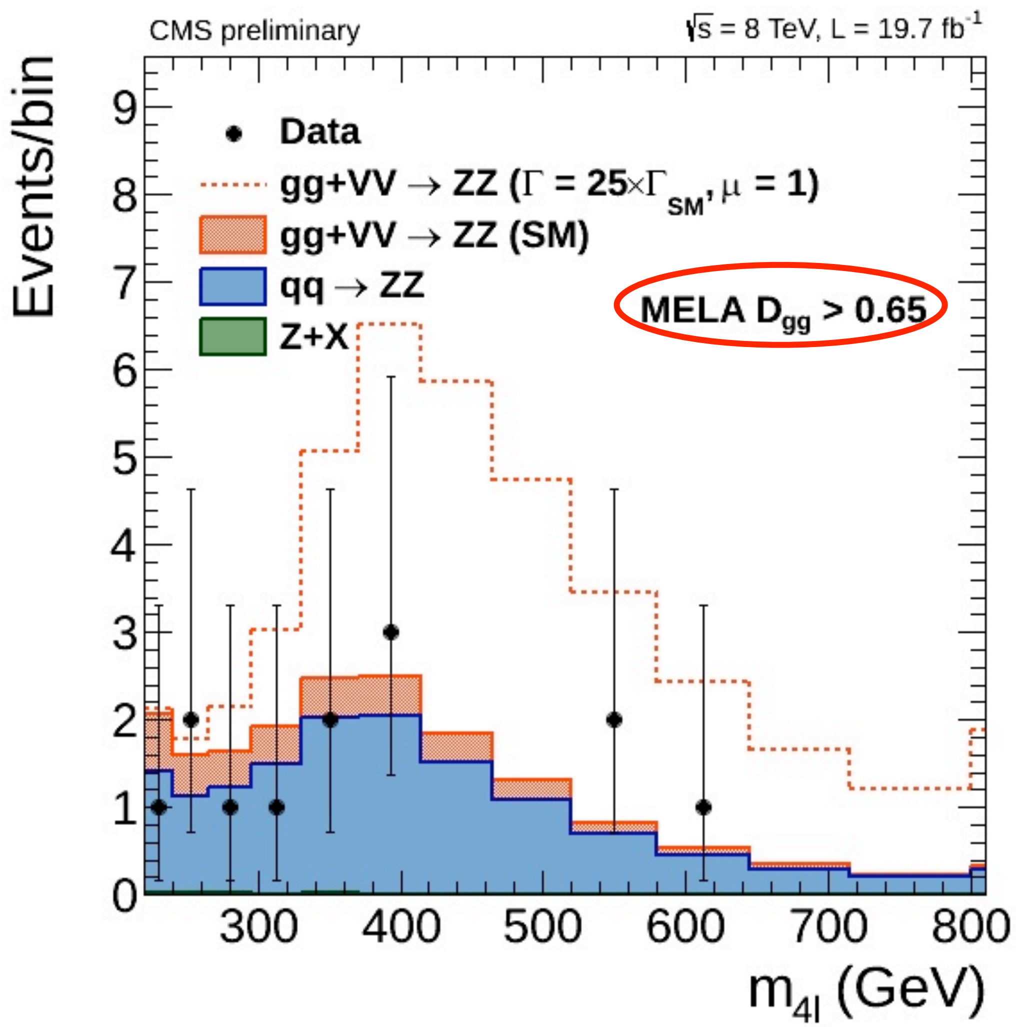


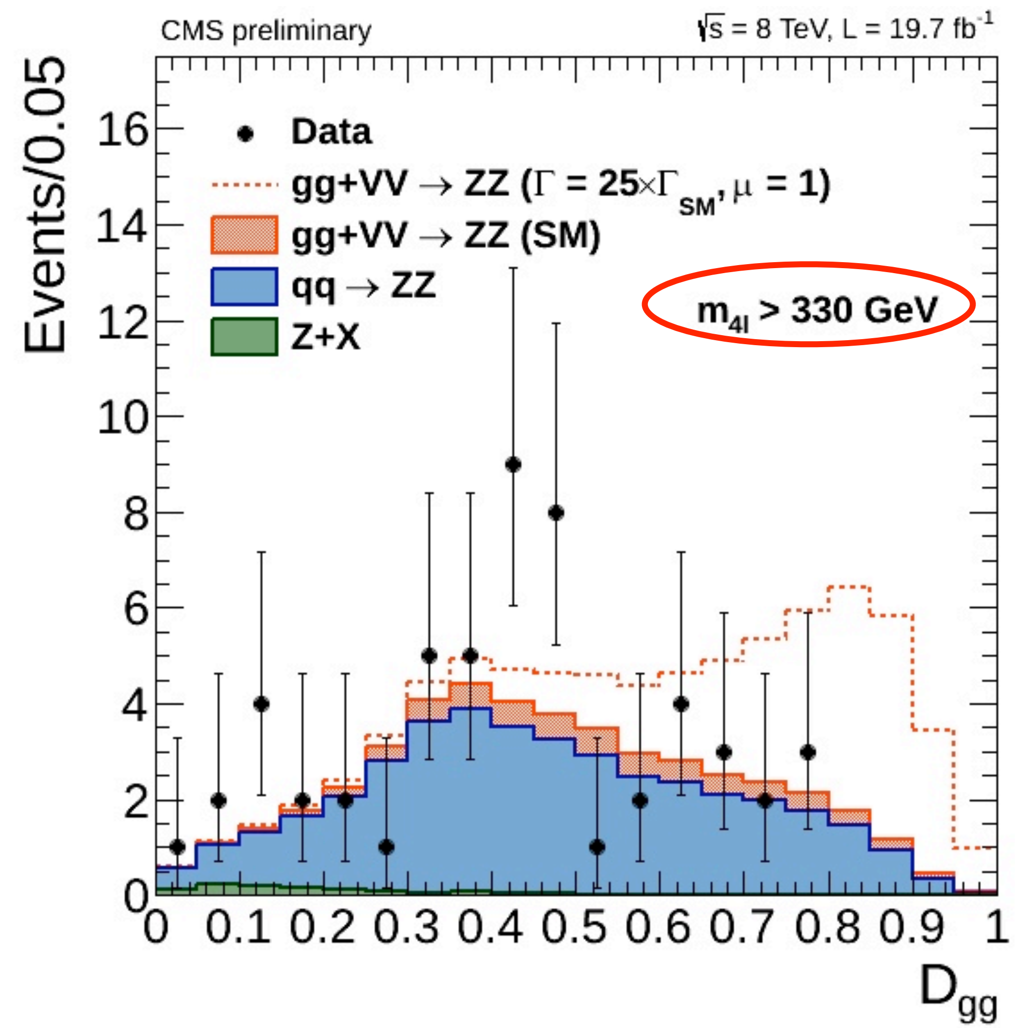
4l analysis - m_{4l} and D_{gg} distributions



		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

4l analysis - m_{4l} and D_{gg} distributions





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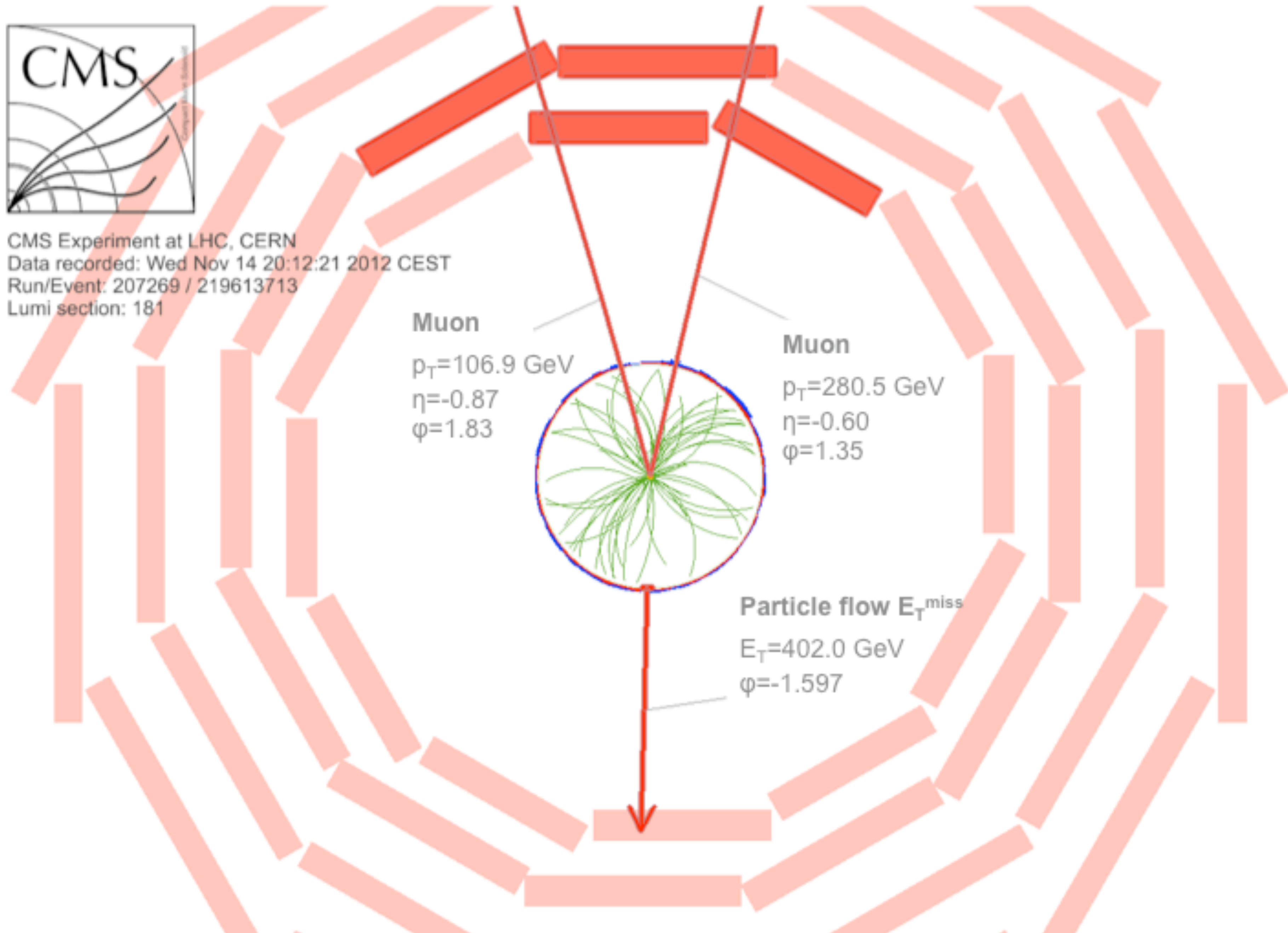
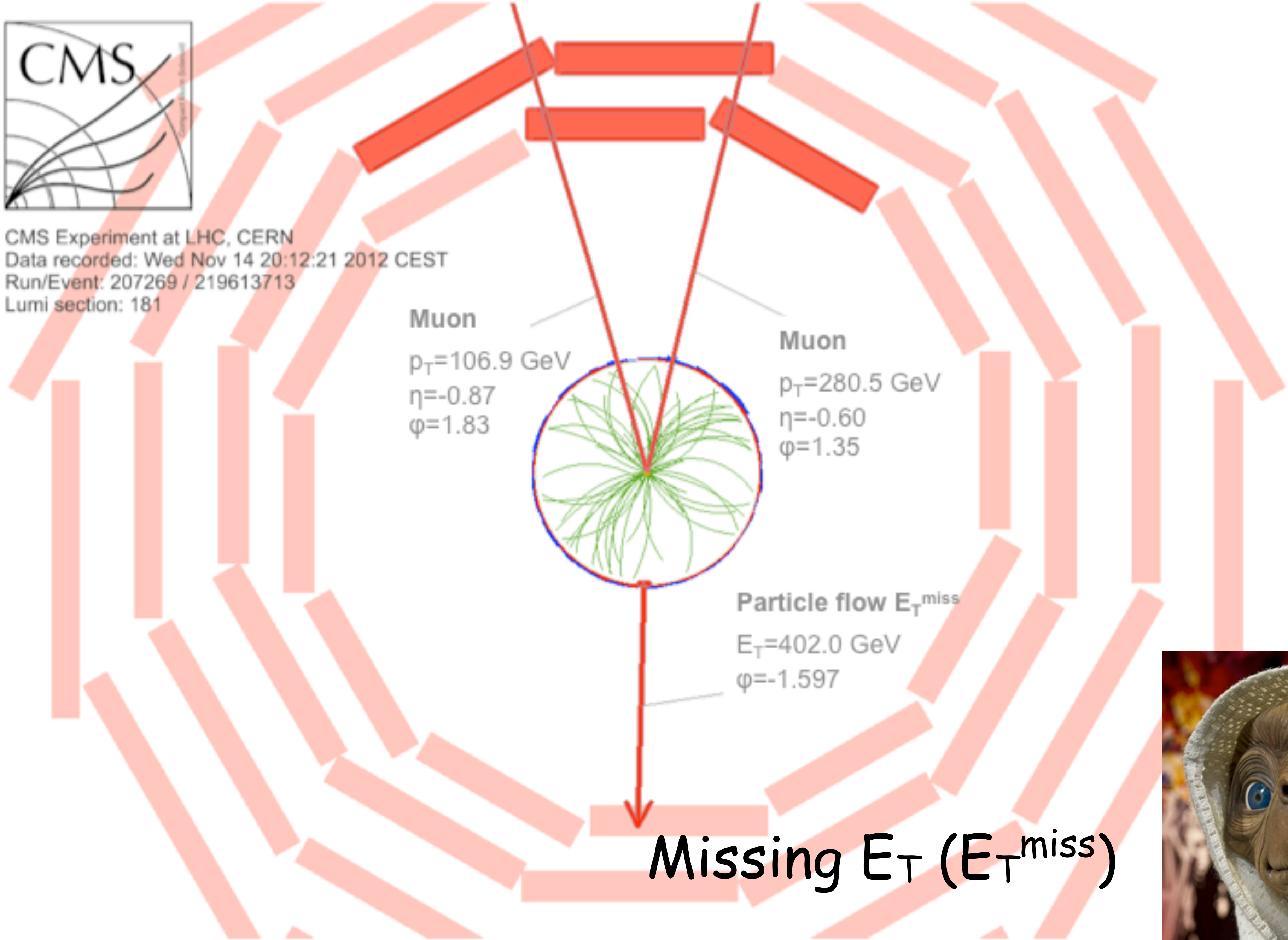
$H \rightarrow ZZ \rightarrow 2l2\nu$



$H \to ZZ \to 2l2\nu$



2l2ν analysis - overview

- 6 times higher branching ratio compared to 4l final state
  - Branching ratio matters in high mass region where cross section is low
- No access to Higgs on-shell production
  - Z+jets background is several orders of magnitude higher (fake E_T^{miss} due to hadronic energy mis-measurement)
- Other backgrounds
  - Irreducible: ZZ, WZ
  - Non-resonant (not involving a Z boson): top, WW

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

2l2ν analysis - event selection

- Z+large E_T^{miss} signature
  - To select a Z→ll: a pair of electrons or muons, isolated, $p_T > 20$ GeV, $|m(ll) - 91| < 15$ GeV
  - To reject WZ: veto 3rd lepton ($p_T > 10$ GeV)
  - To reject top processes: veto b-tagged jet; veto soft-muon ($p_T > 3$ GeV)
  - To reject Z+jets: $E_T^{miss} > 80$ GeV; Azimuthal angle of E_T^{miss} and the closest jet: $\Delta\phi > 0.5$
- To improve sensitivity, selected events are categorized according to number and topology of jet ($p_T > 30$ GeV)
  - VBF, 0 jet, ≥1 jet(non-VBF)
  - VBF is defined as $m(jj) > 500$ GeV and $\Delta\eta(jj) > 4$

2l2ν analysis - background estimations

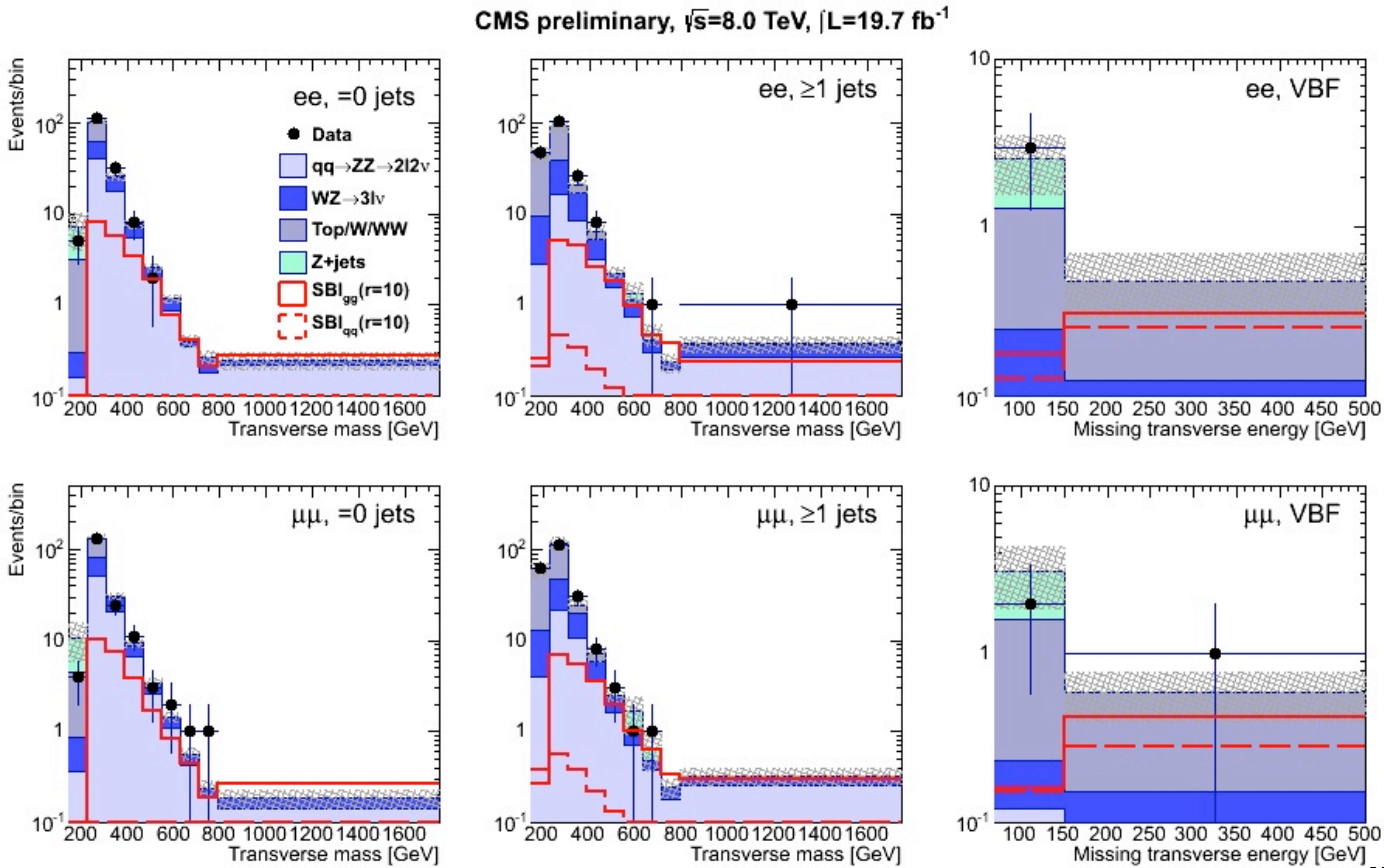
- qq→ZZ, WZ estimated from MC
- Non-resonant background (tt, tW, WW)
  - Estimated from data using lepton flavor symmetry: compute the ee/eμ and μμ/eμ ratios in sideband, and apply the ratios to eμ events in signal region

$$\alpha_{\mu} = \frac{N_{\mu\mu}^{\mathrm{SB}}}{N_{\mathrm{e}\mu}^{\mathrm{SB}}}, \qquad \alpha_{\mathrm{e}} = \frac{N_{\mathrm{ee}}^{\mathrm{SB}}}{N_{\mathrm{e}\mu}^{SB}}$$

$$N_{\mu\mu} = \alpha_{\mu} \times N_{\mathrm{e}\mu}, \qquad N_{\mathrm{ee}} = \alpha_{\mathrm{e}} \times N_{\mathrm{e}\mu}$$

- Z+jets background
  - Modeled by photon+jets events in data: reweight photon p_T spectrum to match that of dilepton in data, and model E_T^{miss} with photon sample

2l2ν analysis - m_T and E_T^{miss} distributions



2l2ν analysis - event yields

Signal enriched region: E_T^{miss} > 100 GeV and m_T > 350 GeV

		ee	$\mu\mu$
	gg + VBF (signal, $\Gamma_H/\Gamma_H^{SM} = 1$)	2.3±0.5	2.7±0.6
	gg + VBF (background)	5.4±1.2	6.5±1.4
(a)	gg + VBF (total, $\Gamma_H/\Gamma_H^{SM} = 1$)	4.8±1.1	5.7±1.3
	gg + VBF (total, $\Gamma_H/\Gamma_H^{SM} = 10$)	19.2±5.5	22.6±6.7
	$q\bar{q} \rightarrow ZZ$	25.0±2.1	29.4±2.5
(b)	WZ	11.6±1.2	13.5±1.4
	$t\bar{t}$/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±3.0	55.3±3.7
	Observed	39	52

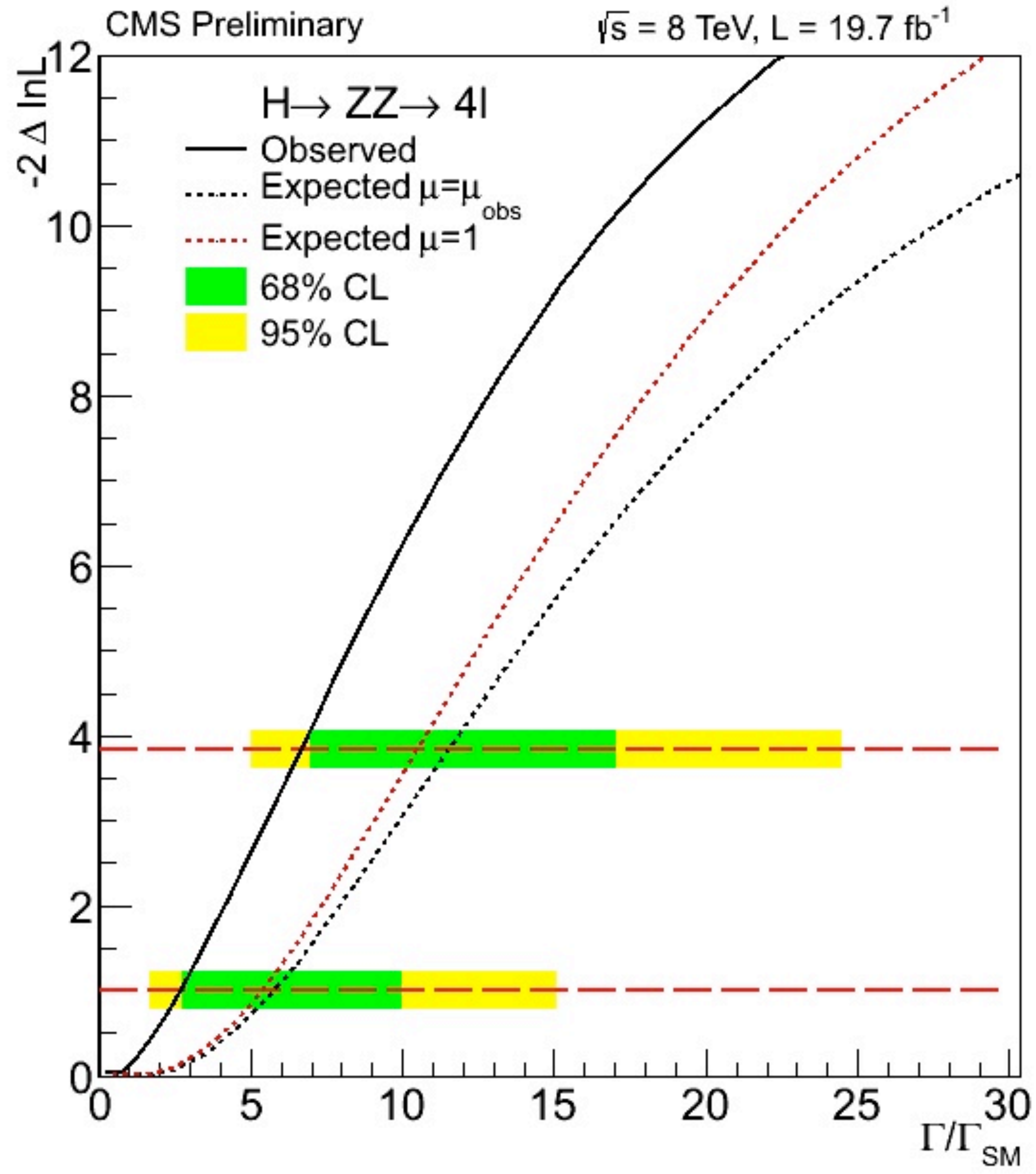
Systematic uncertainties

- Theoretical uncertainties
  - gg→ZZ processes: QCD renormalization and factorization scales varied by a factor of two both up and down, and applied corresponding NNLO K factors; PDF variations by using CT10, MSTW2008 and NNPDF2.1
  - Additional 10% on continuum gg→ZZ background, accounting for limited knowledge on its NNLO cross section
  - QCD scales and PDF uncertainties on qq→ZZ and WZ backgrounds
  - In the 4l analysis, uncertainty of VBF shapes to account for approximate simulation
  - In the 2l2ν analysis, theoretical uncertainties on jet-binning

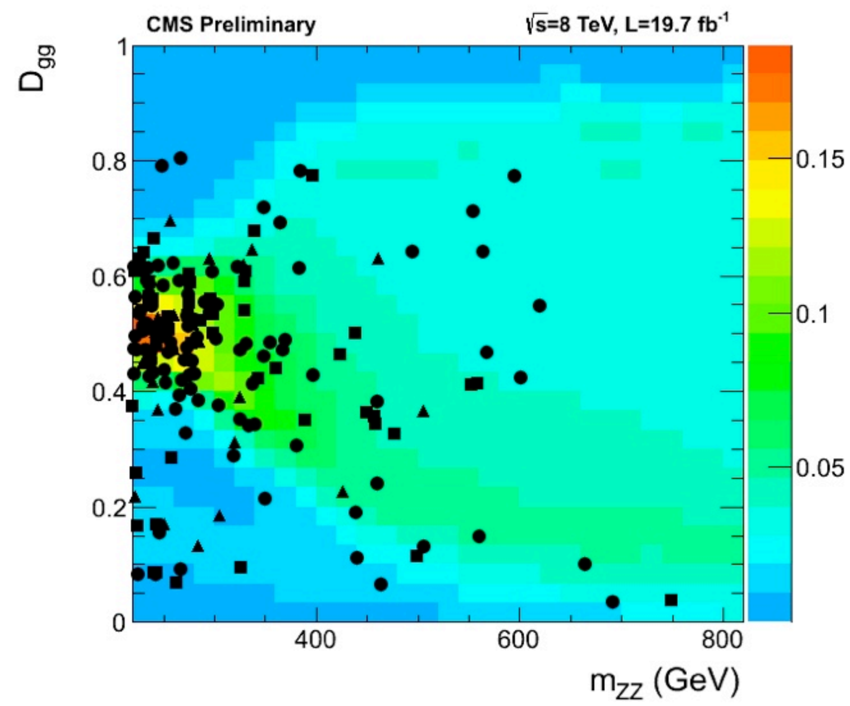
Systematic uncertainties

- Experimental uncertainties
  - Lepton trigger, identification, isolation
  - In the 2l2ν analysis, uncertainties on lepton momentum scale and jet energy scale are propagated to E_T^{miss}; b-tagging efficiency
  - Background estimations from data
  - Integrated luminosity of data
  - Limited statistics in MC or data control samples
- For systematics affect both normalization and shape, variations of shape are taken into account

Results in 4l analysis



2D fit using m_{4l} and D_{gg}



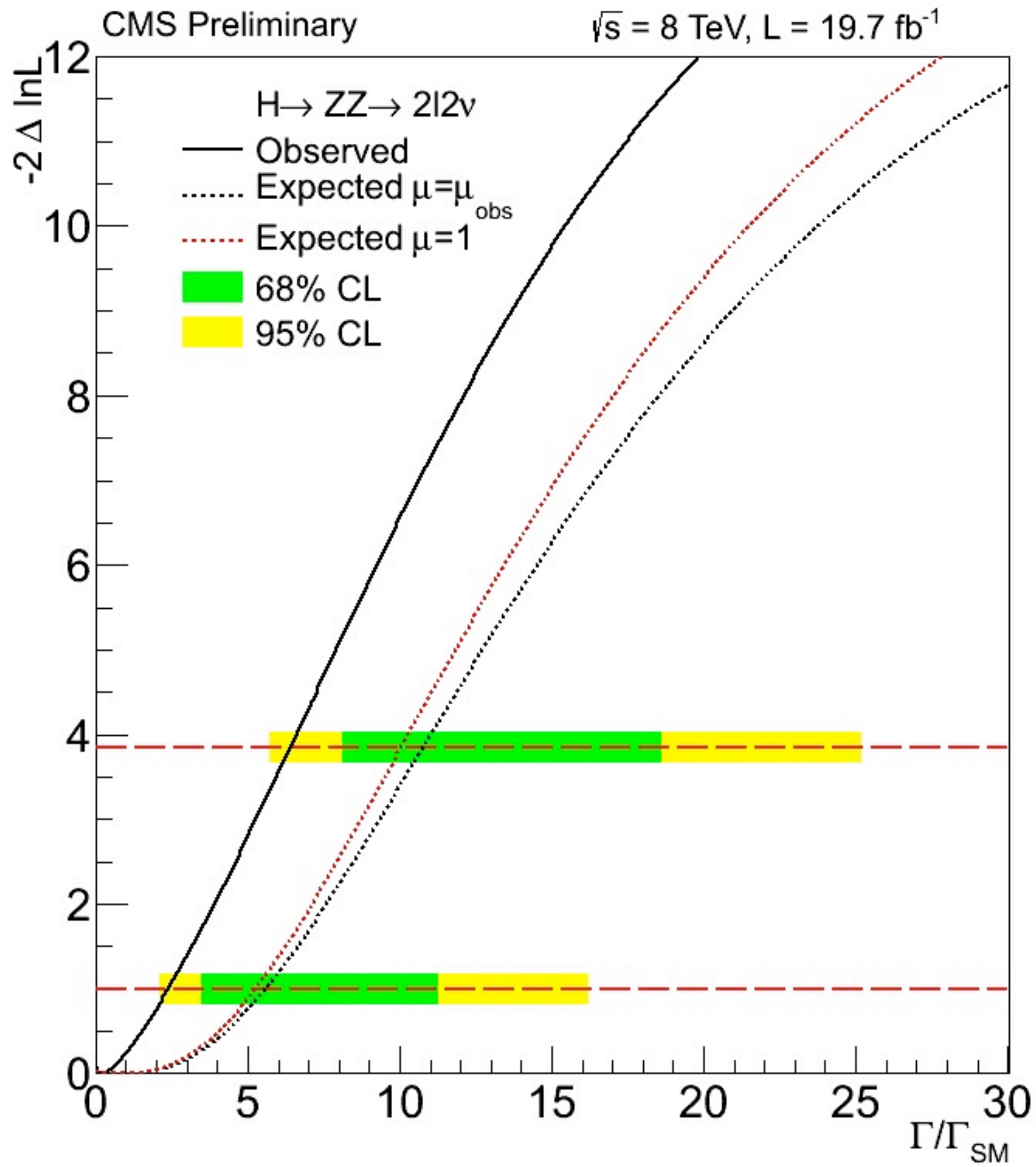
Observed (expected) 95% CL limit:
r < 6.6 (11.5)

Best fit value:
$r = 0.5^{+2.3}_{-0.5}$

Equivalent to
Γ < 27.4 MeV
$\Gamma = 2.0^{+9.6}_{-2.0}$ MeV

1D fit on m_{4l} : r < 26.3 (17.0 expected)
1D fit on D_{gg} : r < 7.1 (12.7 expected)

Results in 2l2ν analysis



1D fit using m_T or E_T^{miss}

Observed (expected) 95% CL limit:
r < 6.4 (10.7)

Best fit value:
$r = 0.2^{+2.2}_{-0.2}$

Equivalent to
Γ < 26.6 MeV
$\Gamma = 0.8^{+9.1}_{-0.8}$ MeV

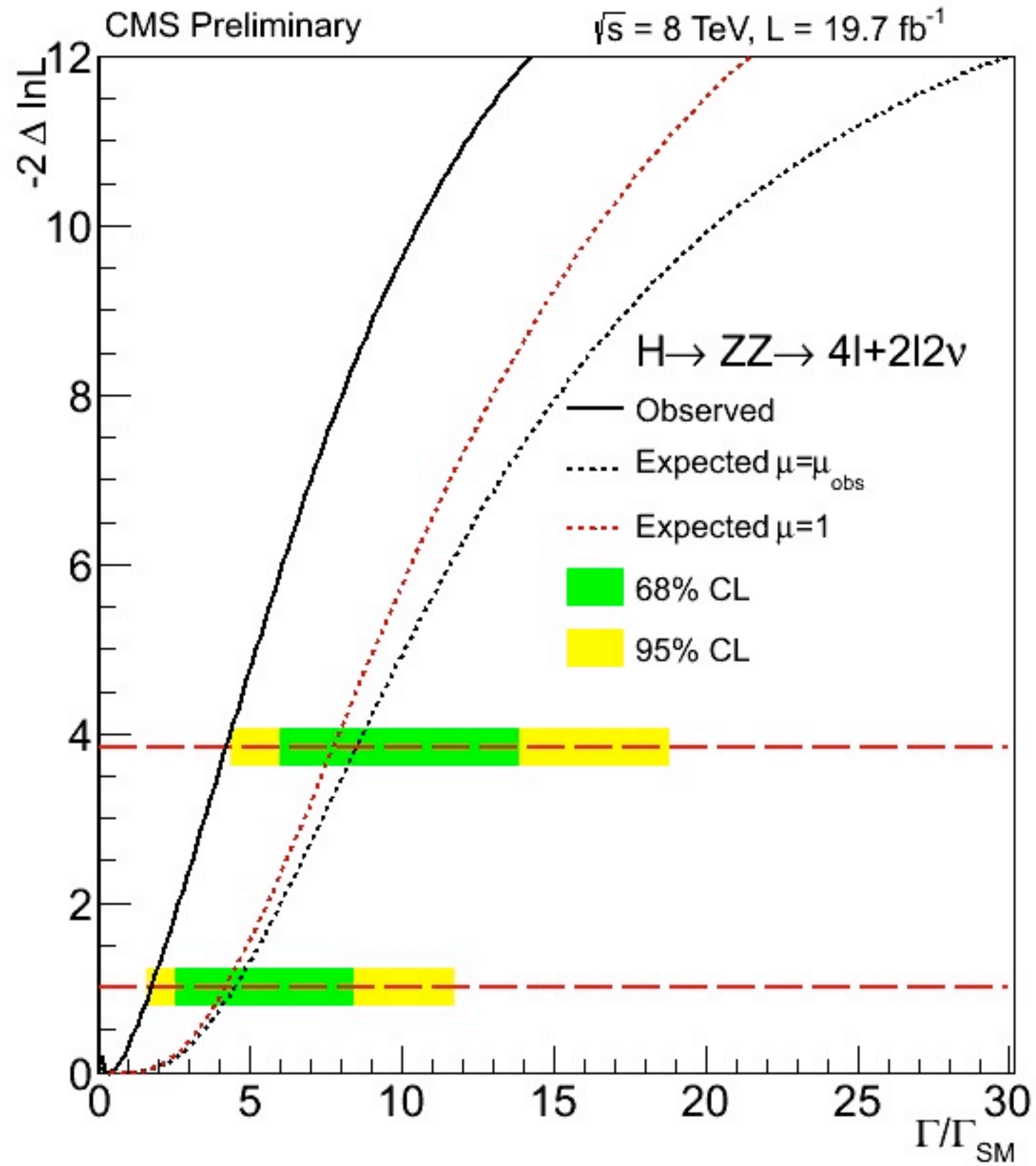
ee-only : r < 6.9 (14.3 expected)
μμ-only : r < 14.0 (13.7 expected)
Counting analysis in "signal enriched region":
r < 12.4 (16.4 expected)

Combined results

Observed (expected)
95% CL limit:
r < 4.2 (8.5)
p-value = 0.02

Best fit value:
$r = 0.3^{+1.5}_{-0.3}$

Equivalent to
$\Gamma < 17.4\ (35.3)$ MeV
$\Gamma = 1.4^{+6.1}_{-1.4}$ MeV



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

Summary

- First experimental constraint on the Higgs boson width from off-shell production has been presented
- Analysis performed in 4l and 2l2ν final states
  - 4l analysis uses invariant mass and kinematic discriminant
  - 2l2ν analysis relies on transverse mass and missing transverse energy
  - Small deficits in signal regions observed in both channels
- Combined results
  - $\Gamma/\Gamma_{SM} < 4.2$ (8.5 expected) @ 95% CL, equivalent to $\Gamma < 17.4$ (35.3 expected) MeV
  - Improve by more than two orders of magnitude over the on-peak measurement
- A good example of interaction between theorists and experimentalists. We welcome new ideas to dig deeper in the data

Summ

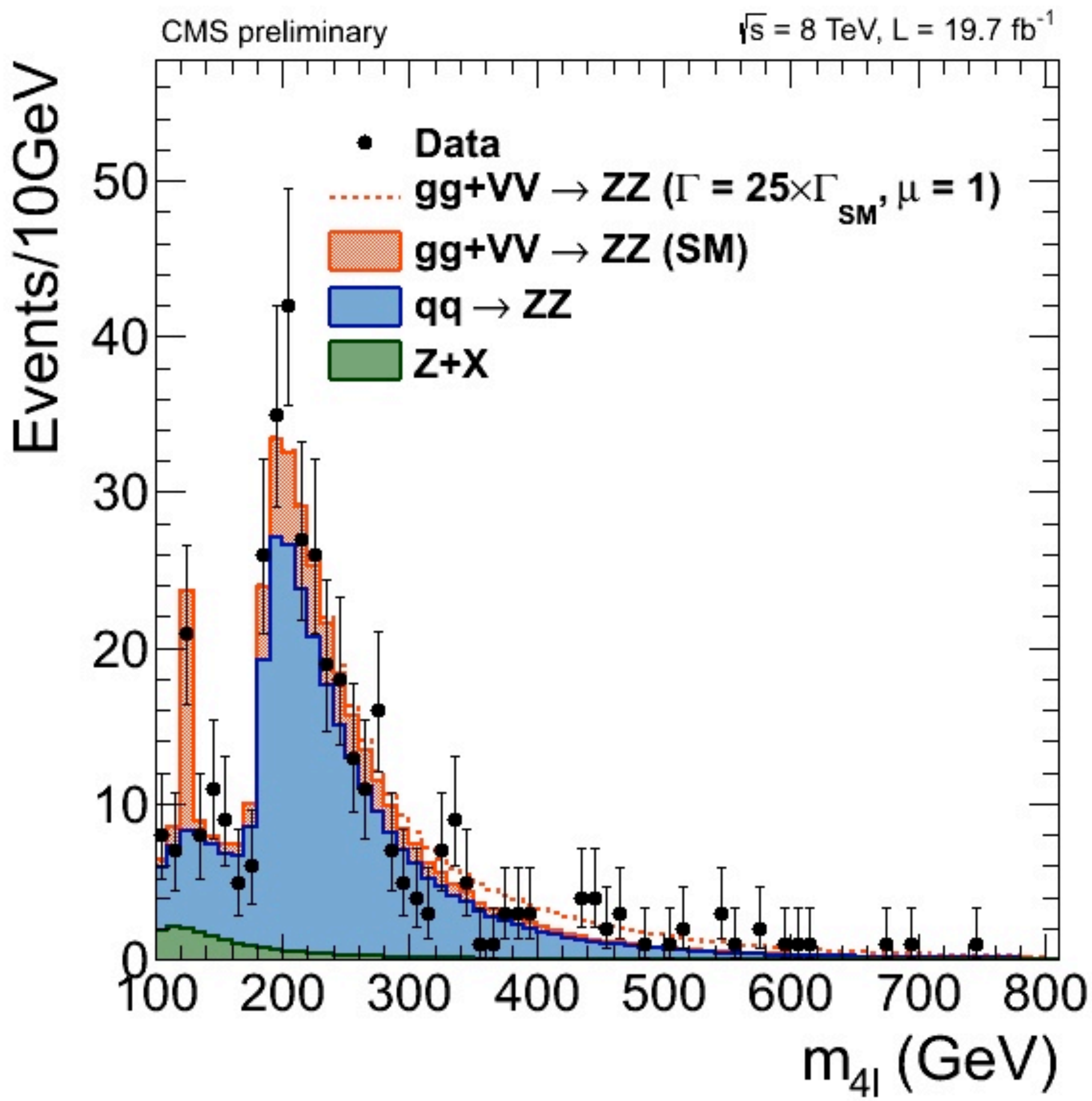
- First ex duction has been p
- Analysi
  - 4l a
  - 2l2v y
  - Sm
- Combi
  - Γ/Γs ected) MeV
  - Imp asurement

- A good example of interaction between theorists and experimentalists. We welcome new ideas to dig deeper in the data

Thank you !

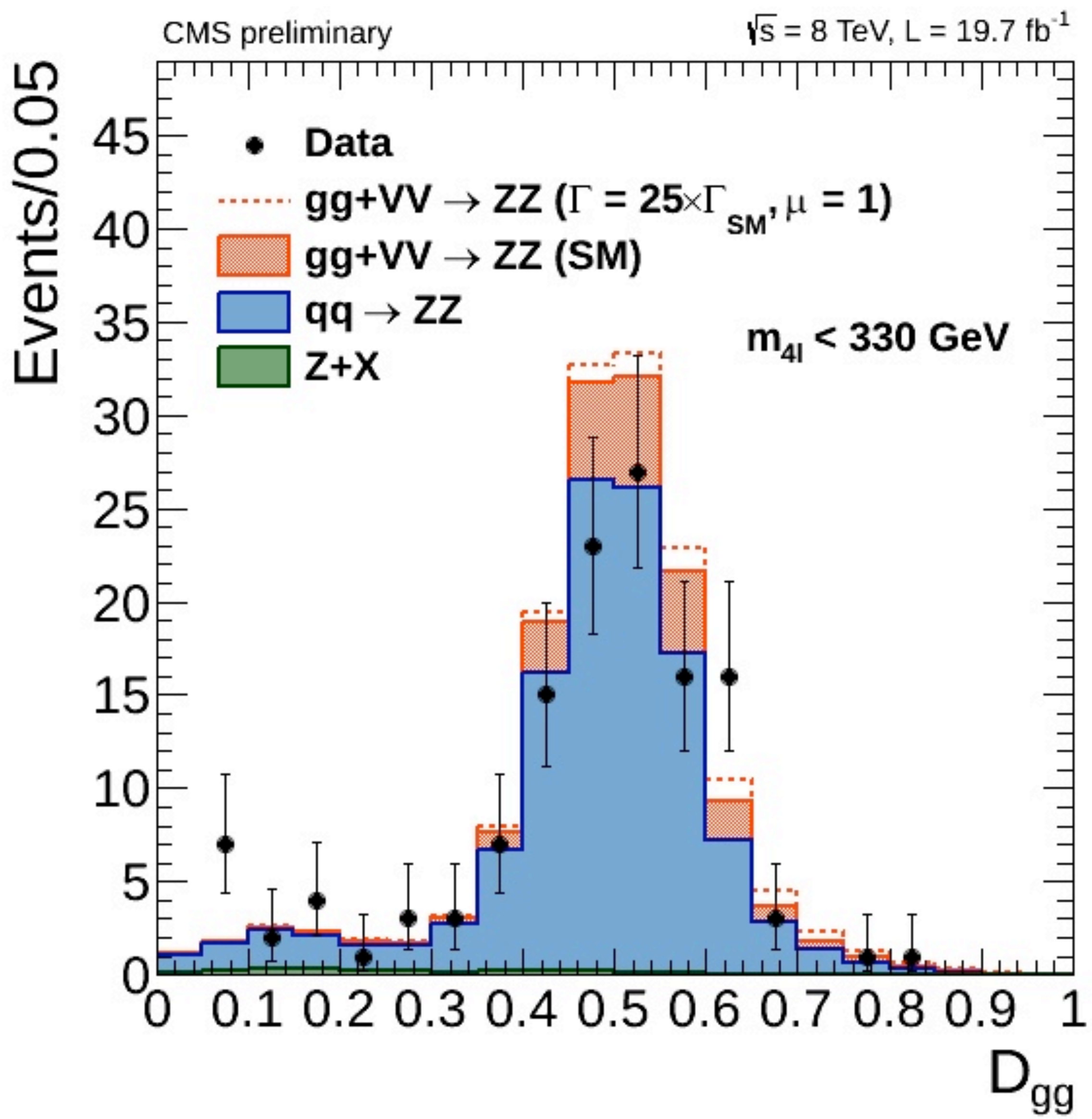
Back up

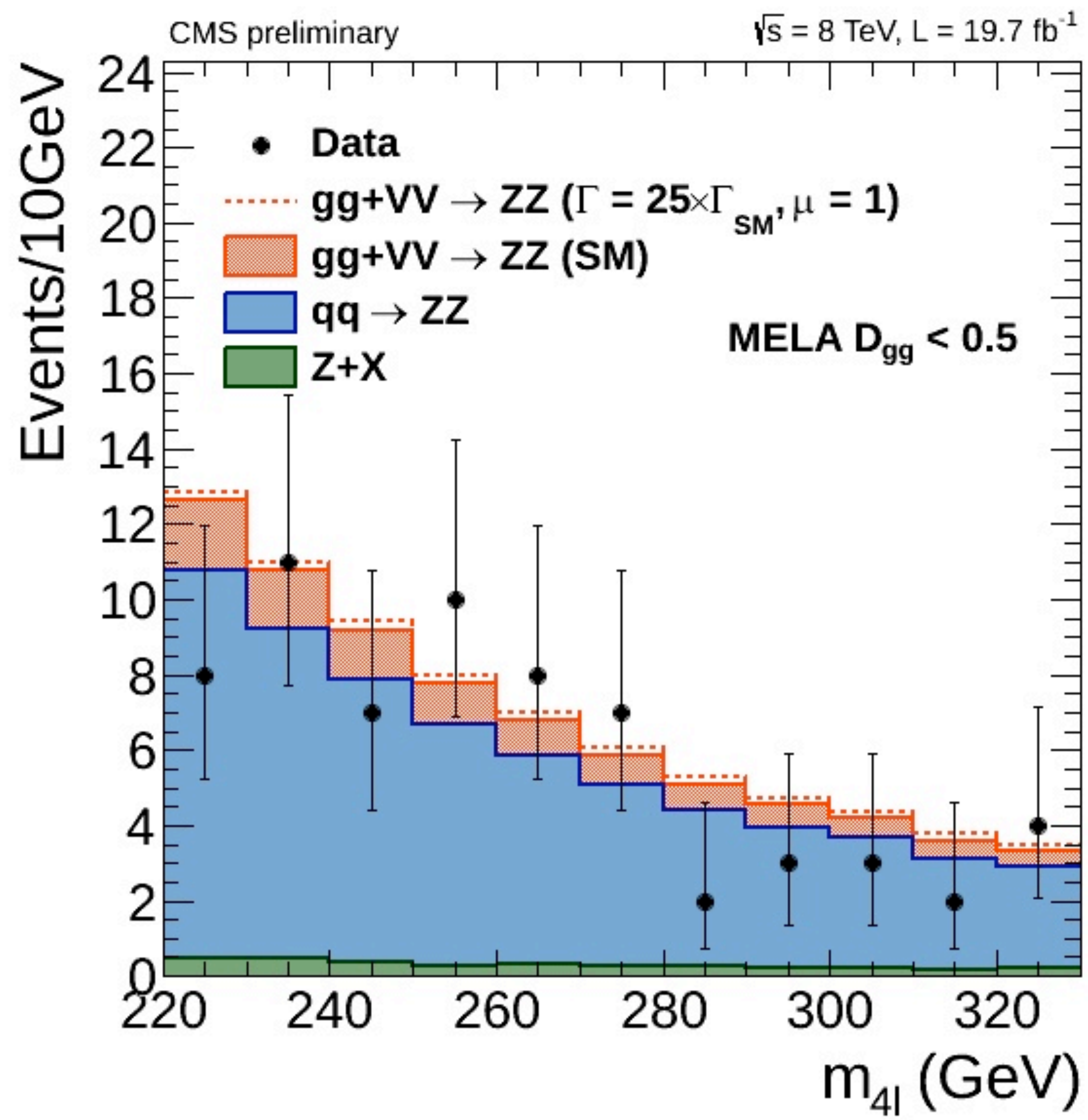
4l mass



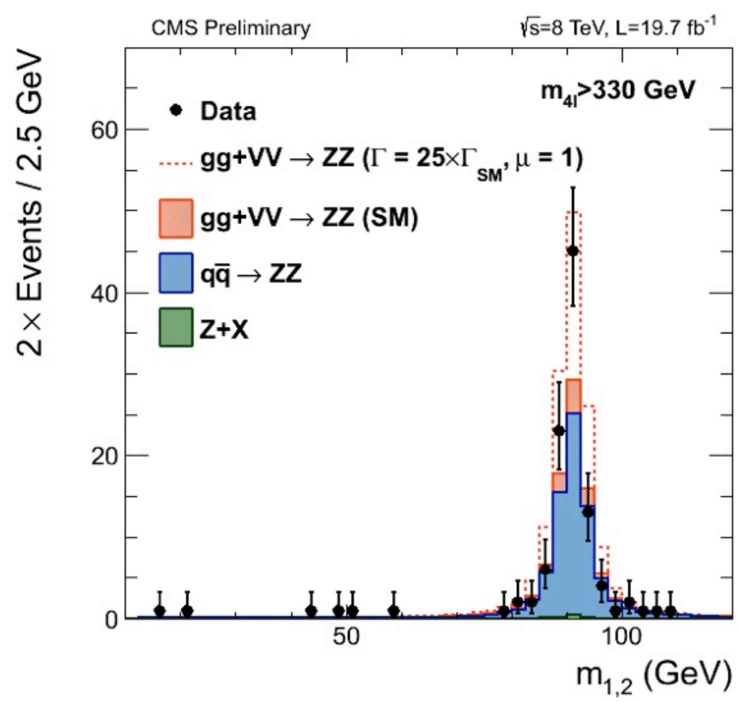
CMS preliminary
√s = 8 TeV, L = 19.7 fb⁻¹
Events/10GeV
Data
gg+VV → ZZ (Γ = 25×Γ_SM, μ = 1)
gg+VV → ZZ (SM)
qq → ZZ
Z+X
0
10
20
30
40
50
100
200
300
400
500
600
700
800
m_4l (GeV)

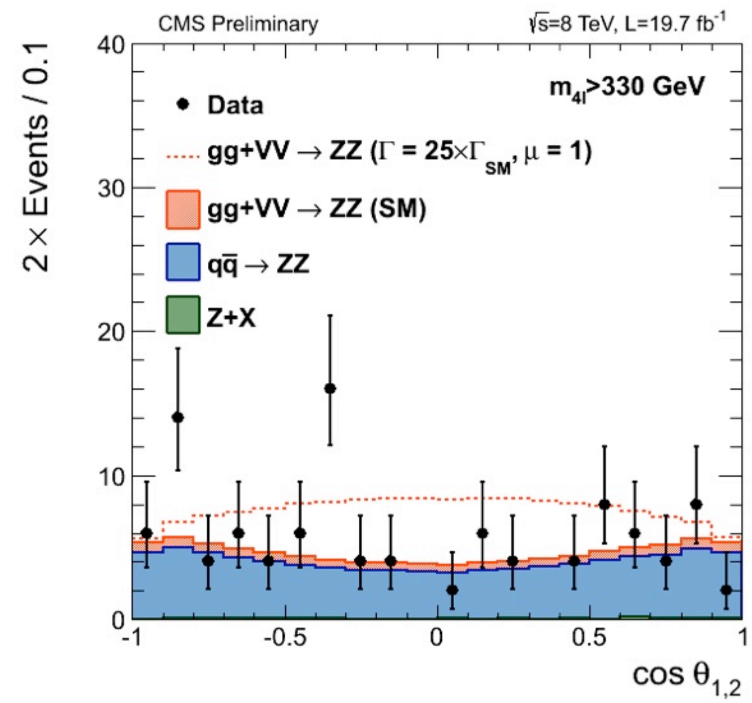
Control regions

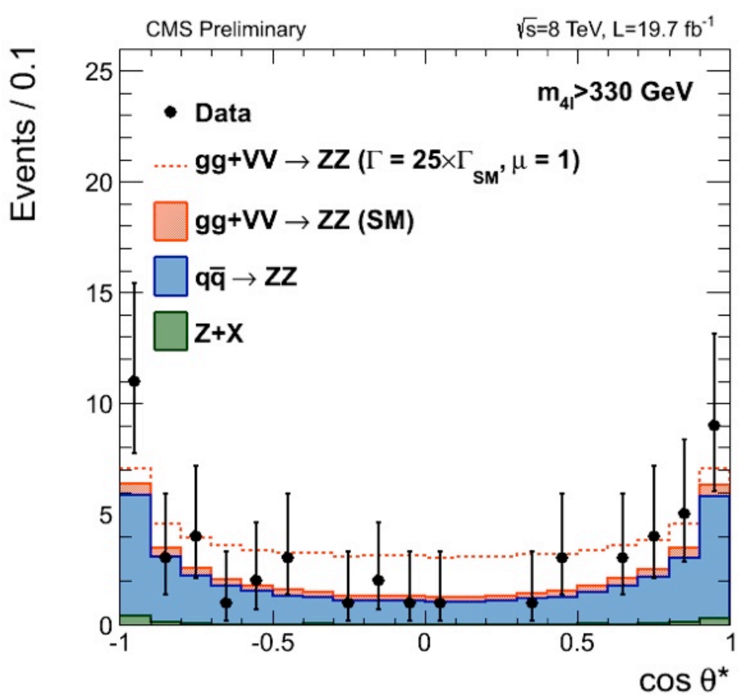


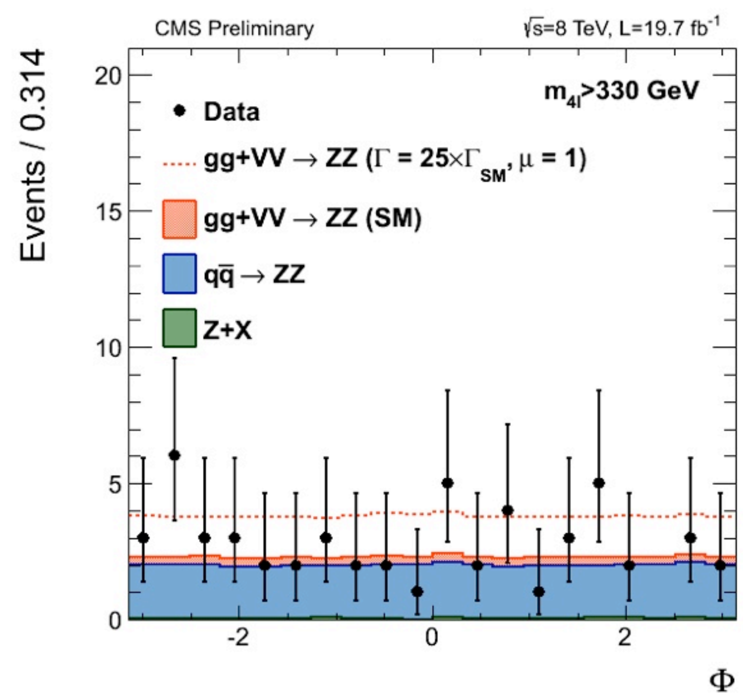


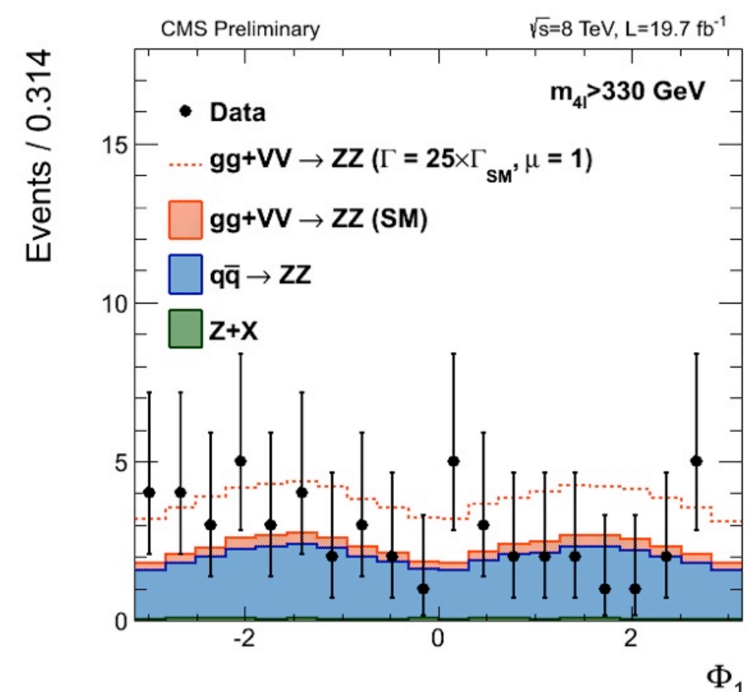
Input to MELA



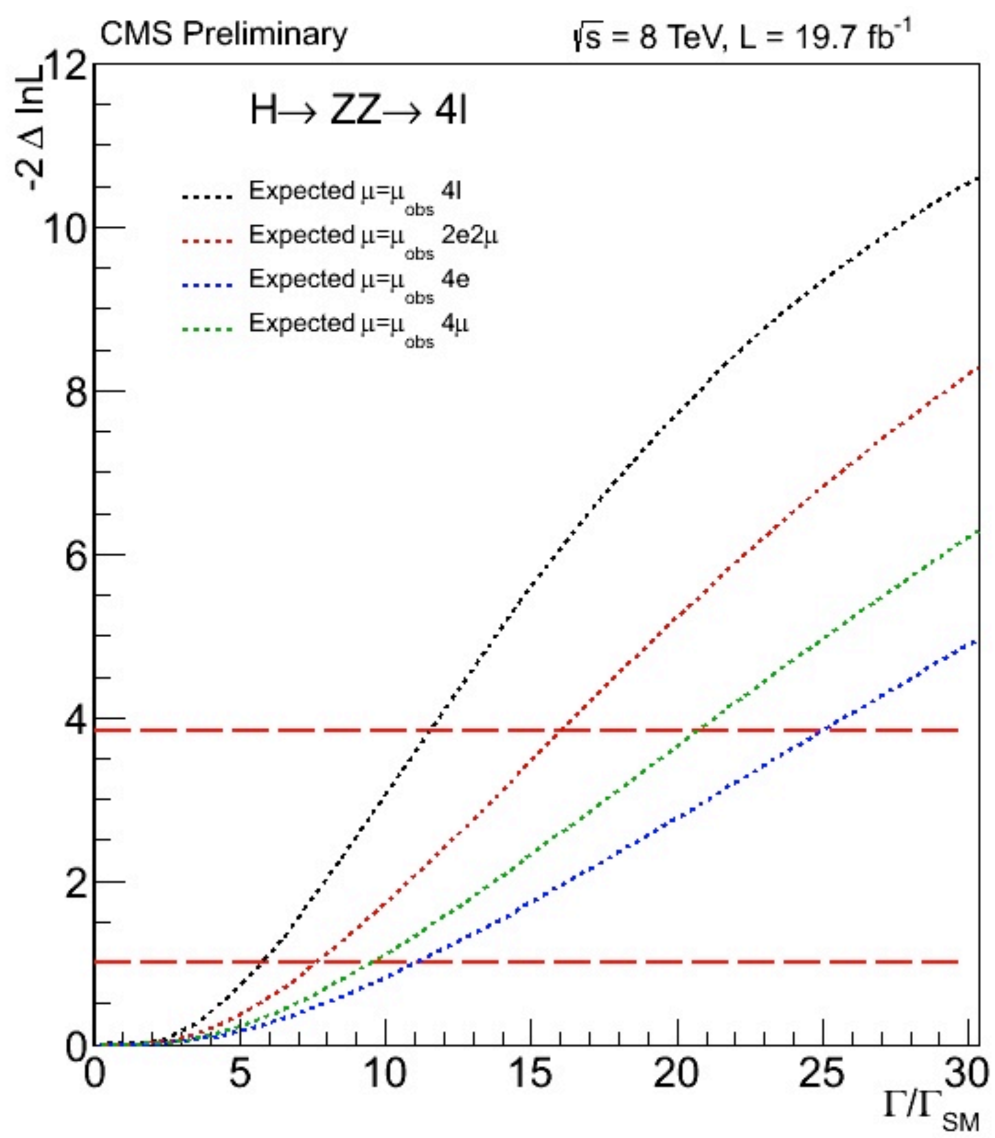




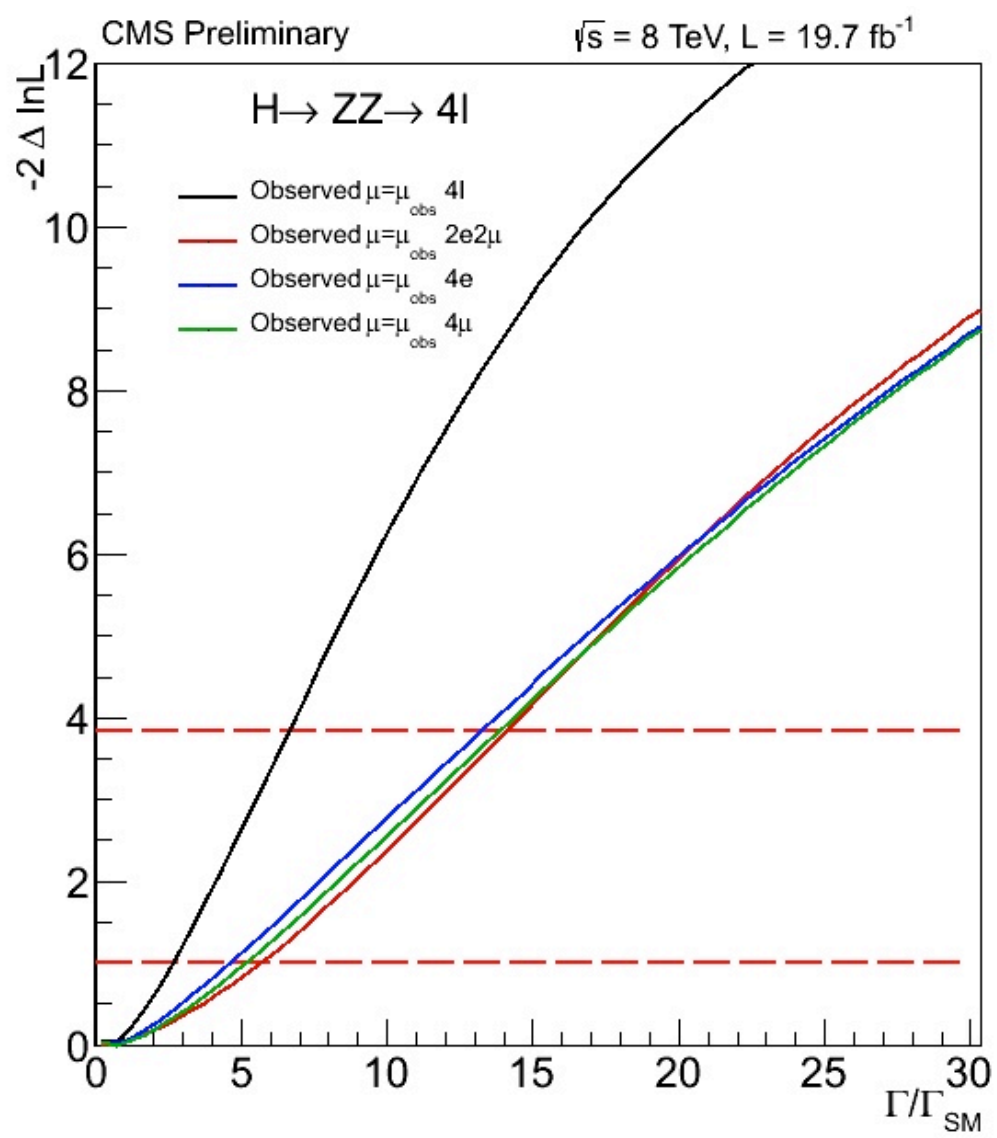




Limits

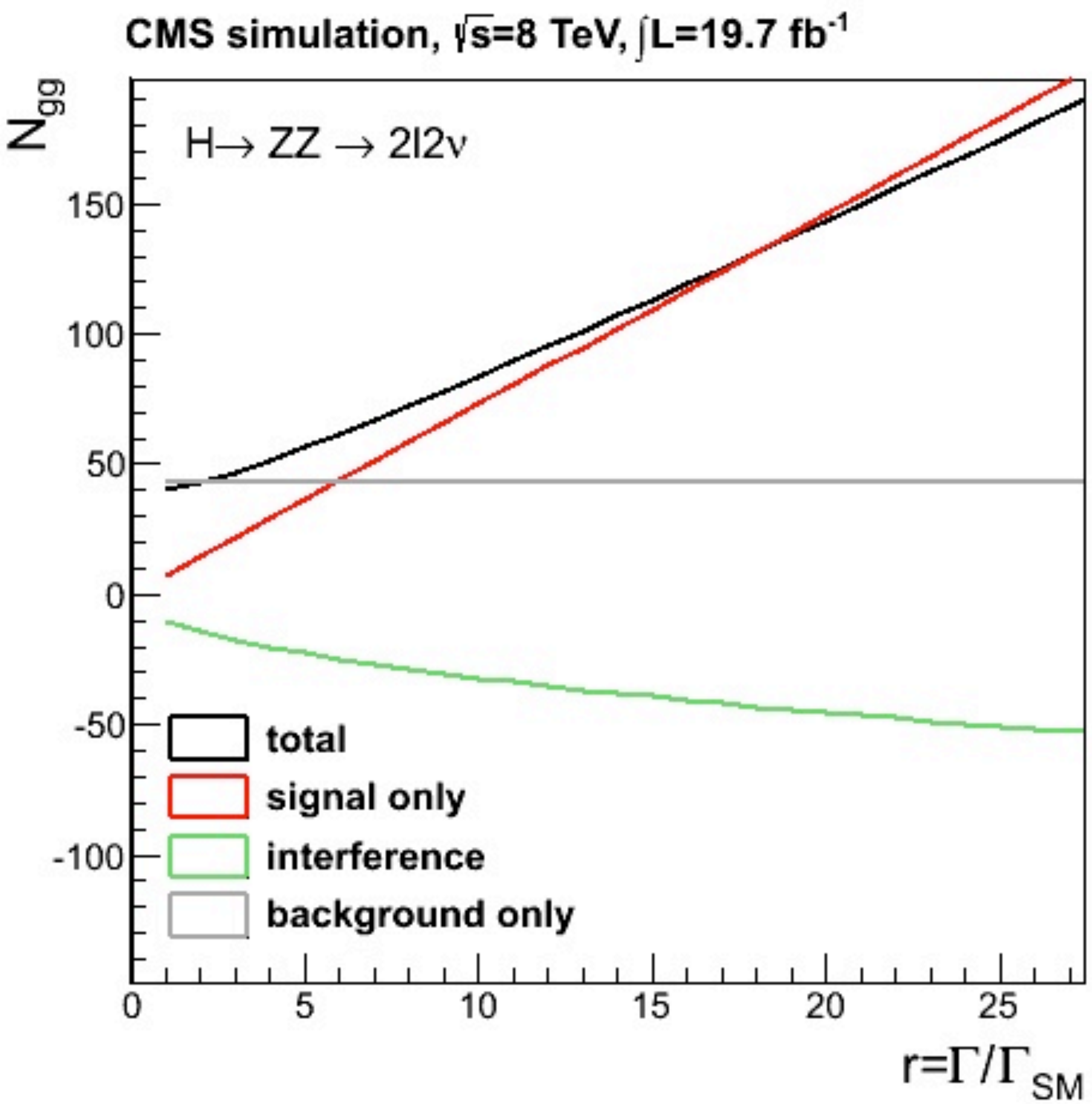


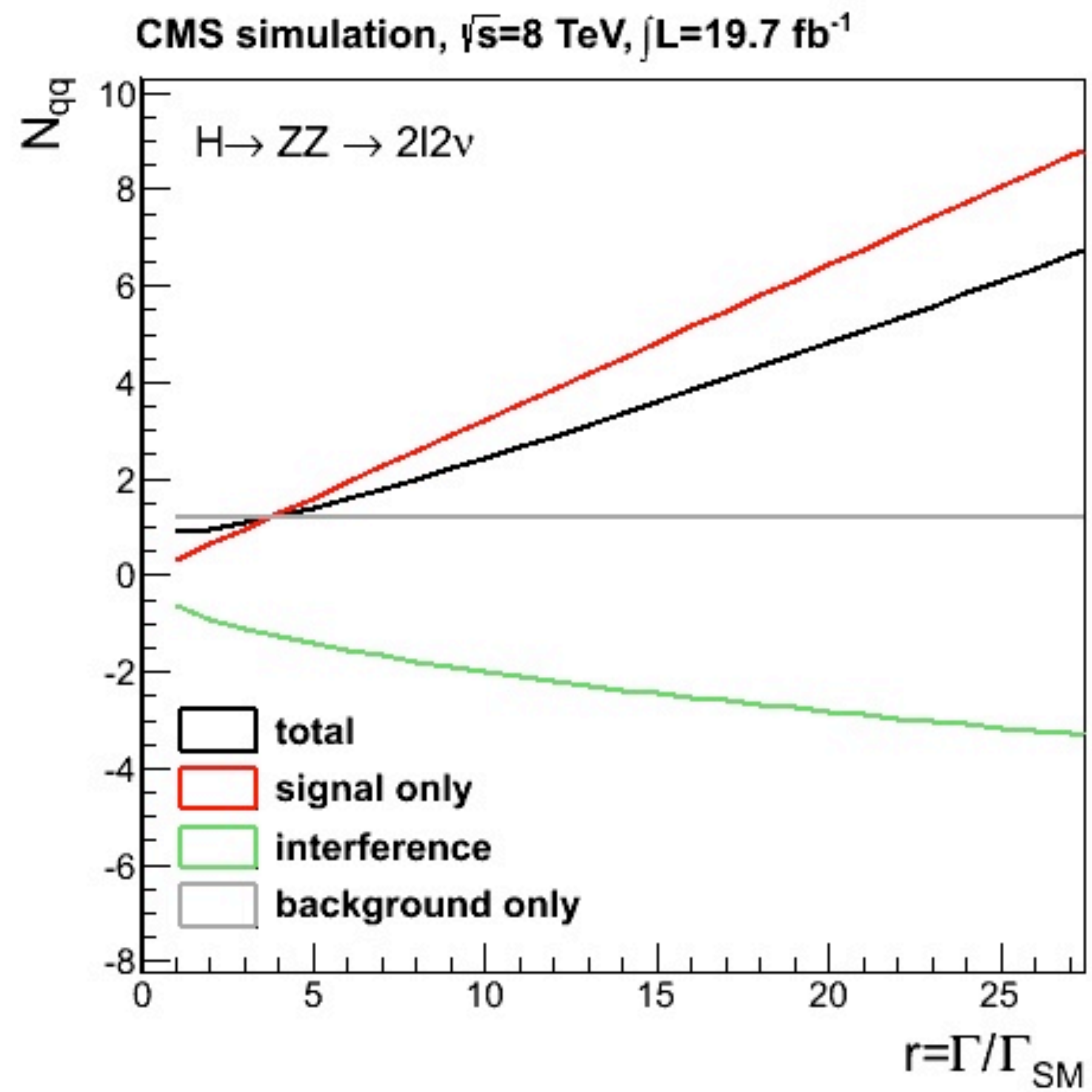
CMS Preliminary
√s = 8 TeV, L = 19.7 fb-1
H→ ZZ→ 4l
-2 Δ lnL
Expected μ=μobs 4l
Expected μ=μobs 2e2μ
Expected μ=μobs 4e
Expected μ=μobs 4μ
Γ/ΓSM



CMS Preliminary
√s = 8 TeV, L = 19.7 fb-1
H→ ZZ→ 4l
-2 Δ lnL
Observed μ=μobs 4l
Observed μ=μobs 2e2μ
Observed μ=μobs 4e
Observed μ=μobs 4μ
Γ/ΓSM

Yields vs width (loose Missing ET cut)





Event yields

channel		$qq \to ZZ \to 2\ell 2\nu$	$WZ \to 3\ell\nu$	Top/WW/W	$Z \to \ell\ell$	total expected	data
ee	=0 jets	66.9 ± 0.8	32.0 ± 0.6	$44 \pm 5 \pm 11$	$8 \pm 3 \pm 2$	$150 \pm 6 \pm 11$	160
	≥ 1 jets	33.9 ± 0.5	41.2 ± 0.7	$93 \pm 8 \pm 23$	$0.3 \pm 0.3 \pm 0.1$	$169 \pm 8 \pm 23$	186
	VBF	0.15 ± 0.04	0.23 ± 0.05	$1.4 \pm 0.4 \pm 0.4$	$1.2 \pm 0.7 \pm 0.3$	$3.0 \pm 0.9 \pm 0.5$	3
$\mu\mu$	=0 jets	83.8 ± 0.8	42.8 ± 0.7	$57 \pm 7 \pm 14$	$7.0 \pm 4.6 \pm 2$	$190 \pm 8 \pm 14$	175
	≥ 1 jets	43.1 ± 0.6	48.2 ± 0.7	$121 \pm 10 \pm 30$	$0.9 \pm 0.8 \pm 0.2$	$213 \pm 10 \pm 30$	219
	VBF	0.22 ± 0.04	0.17 ± 0.04	$1.8 \pm 0.3 \pm 0.5$	$1.5 \pm 1.1 \pm 0.4$	$3.7 \pm 1.1 \pm 0.6$	3

Channel		$gg \to 2\ell 2\nu$			$qq \to qq2\ell 2\nu$		
		B	S	SBI	B	S	SBI
ee	=0 jets	10.7 ± 0.2	1.69 ± 0.02	10.2 ± 0.2	0.034 ± 0.006	0.013 ± 0.001	0.027 ± 0.002
	≥ 1 jets	7.8 ± 0.2	1.58 ± 0.02	7.1 ± 0.2	0.99 ± 0.03	0.138 ± 0.005	0.88 ± 0.01
	VBF	0.18 ± 0.03	0.041 ± 0.003	0.19 ± 0.03	0.18 ± 0.01	0.050 ± 0.003	0.135 ± 0.004
$\mu\mu$	=0 jets	13.6 ± 0.3	2.07 ± 0.02	12.8 ± 0.3	0.048 ± 0.007	0.017 ± 0.002	0.033 ± 0.002
	≥ 1 jets	10.2 ± 0.2	1.87 ± 0.02	9.4 ± 0.2	1.14 ± 0.03	0.159 ± 0.006	1.01 ± 0.01
	VBF	0.27 ± 0.04	0.058 ± 0.004	0.24 ± 0.04	0.21 ± 0.01	0.058 ± 0.003	0.159 ± 0.004

Systematics

Source	Uncertainty [%]
Experimental uncertainties	
Luminosity	2.6
Anti b-tagging	1-3
Lepton ID+Isolation	2
Lepton momentum scale	1-2
Jet energy scale	1
PU effects, uE_T^{miss}	1-3
Trigger	2
non-resonant background estimation from data	15+shape
Z+jets estimation from data	25+shape
Theory uncertainties	
pdf, gluon-gluon initial state	6-11
pdf, quark-quark initial state	3.3-7.6
QCD scale, quark-quark initial state (qqVV)	5.8-8.5+shape
$gg \to ZZ$ k-factor uncertainty	10
Exclusive jet binning for $gg \to ZZ$	0.3-57
Underlying event and parton shower	6-30

Limits per jet bin