Constraints on Higgs total width using H*(126) → ZZ events

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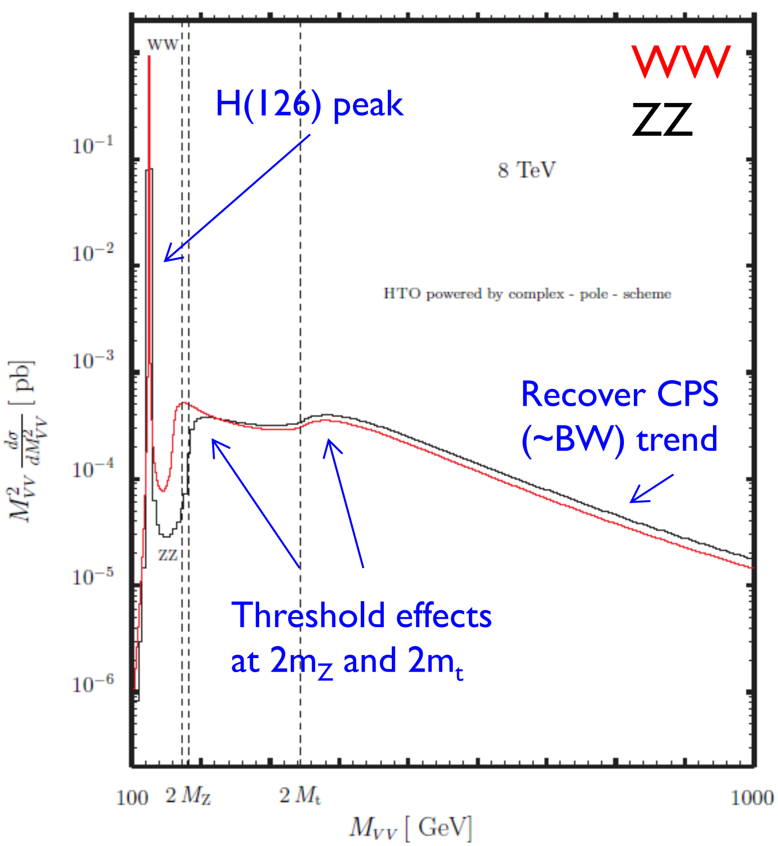
on behalf of the CMS collaboration

20/3/14, XLIX Rencontres de Moriond on Electroweak Interactions and Unified Theories

Principles of the analysis

gluon-gluon fusion production



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

- Off-shell $H^* \to VV$ (V = W, Z)
  - Peculiar cancellation between BW trend and $\Gamma(H \to ZZ)$ as a function of m_{VV} creates an **enhancement of H(126) cross-section at high mass**

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

  - About **7.6% of total cross-section** in the ZZ final state, but can be enhanced by experimental cuts

	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

Constraint on width

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

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

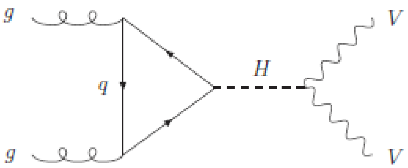
Can be used to set a constraint on the total Higgs width:

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

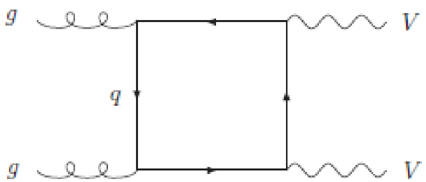
$$\frac{d\sigma^{off-peak}_{gg\to H\to ZZ}}{dm_{ZZ}} = \kappa_g^2\kappa_Z^2\frac{d\sigma^{off-peak,SM}_{gg\to H\to ZZ}}{dm_{ZZ}} = \mu r\frac{d\sigma^{off-peak,SM}_{gg\to H\to ZZ}}{dm_{ZZ}}$$

$$\kappa_g = g_{ggH}/g^{SM}_{ggH}$$
$$\kappa_Z = g_{HZZ}/g^{SM}_{HZZ},$$
$$r = \Gamma_H/\Gamma^{SM}_H$$

- Once the "signal strength" μ is fixed from an independent source a determination of r is obtained
  - N.B. r-scaling while keeping μ fixed is equivalent to coupling scaling



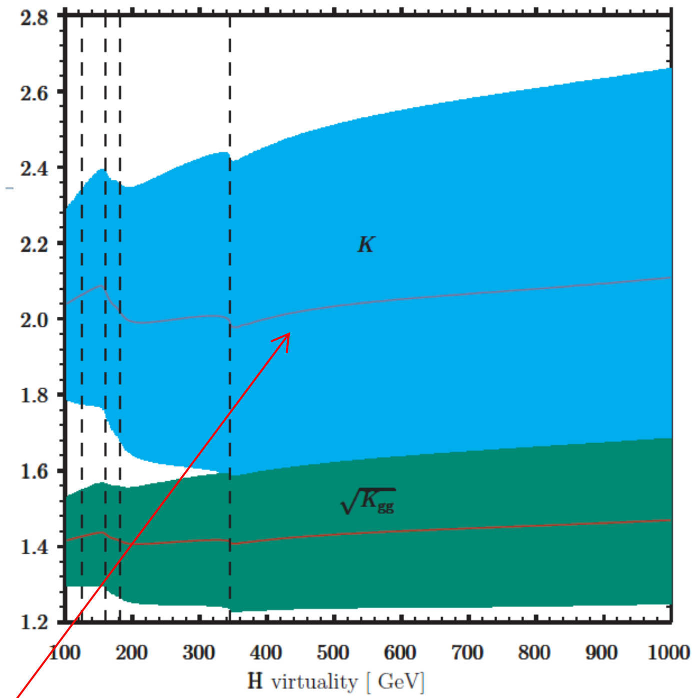
- Caution: the interference with continuum gg → ZZ is not negligible at high m_{ZZ}



Monte Carlo simulation

gluon-gluon fusion

- Using latest versions of gg2VV and MCFM (LO in QCD)
  - Including signal H(125.6), background and interference
  - "Running" QCD scales (= $m_{ZZ}/2$) + scale and PDF variations for systematics
  - Signal m_{ZZ}-dependent k-factors (NNLO/LO) applied G. Passarino (arXiv:1312.2397)
  - Using results from M. Bonvini et al. (Phys. Rev. D88 (2013) 034032), use $k_{continuum} = k_{signal}$, assigning an additional 10% uncertainty on this assumption



other production modes

- VBF production is 7% of the total at H(126) peak
  - Slightly enhanced at high mass by trend of $\sigma_{VBF}(m_{ZZ})$ ~ 10%
  - Using PHANTOM to model it, with same settings
- VH and ttH do not contribute to tail effect

Analysis procedure

- Fit r, using one or more variables:

$$\mathcal{P}_{\rm tot} = \mu r\,\mathcal{P}_{\rm sig} + \sqrt{\mu r}\,\mathcal{P}_{\rm int} + \mathcal{P}_{\rm bkg}$$

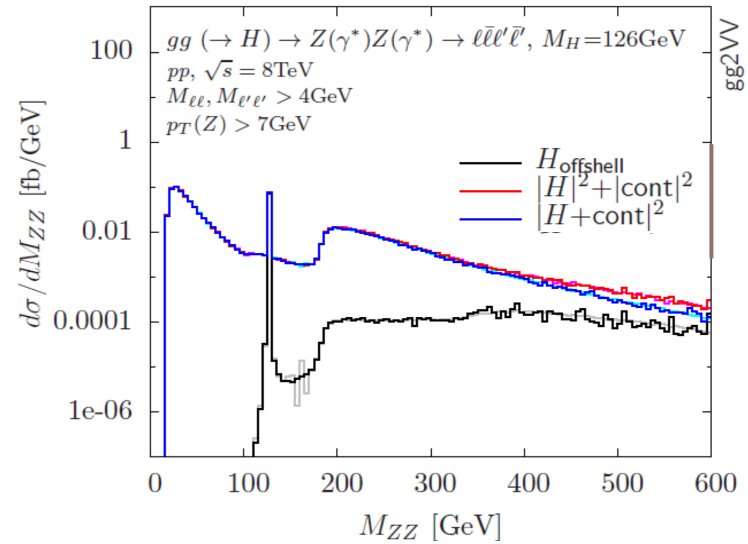
$\mathcal{P}$ are MC- or data-derived templates for variables in each analysis

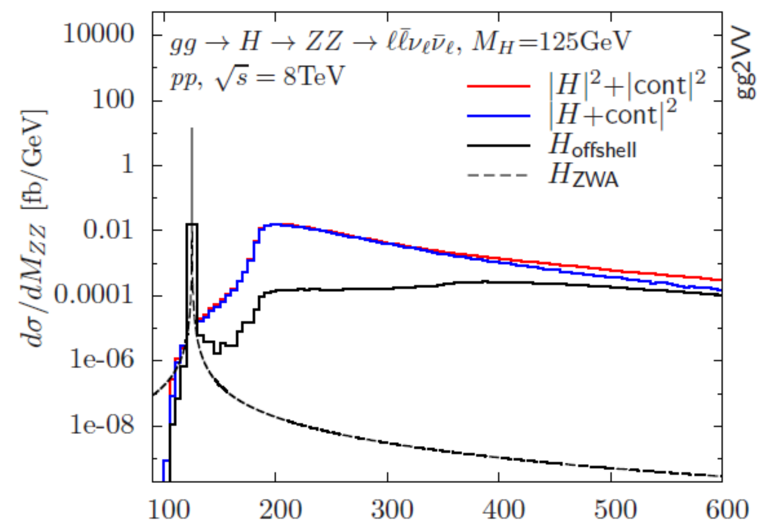
- For a self-contained ZZ analysis use μ from CMS on-peak 4-lepton analysis CMS collab., arXiv:1312.5353:
  - SM width/couplings evaluated at m_H = 125.6 GeV
  - Use observed signal strength (“μ observed”, $0.93^{+0.26}_{-0.24}$)
    - N.B. An additional assumption we must make is that $\mu_{ggF} = \mu_{VBF} = \mu$ (necessary because couplings are in principle different in the two processes, but μ_{VBF} not enough constrained by present ZZ data)
  - Expected results are provided also for μ = $1.00^{+0.27}_{-0.24}$ (“μ expected”, expected uncertainty from low-mass analysis)

The 4l and 2l2ν final states

Generator-level distributions with approximated CMS experimental cuts

- 4l final state (l = e, μ)
  - At high mass, basically only background is $q\bar{q} \rightarrow ZZ$ (known at NLO, QCD uncertainties at the level of %)
  - Fully reconstructed state → can use matrix element probabilities of lepton 4-vectors to distinguish between gg and $q\bar{q}$ production
- 2l2ν final state (l = e, μ)
  - Much larger BR (x6) but smaller acceptance (tight p_T selection)
  - Rely on transverse mass distributions





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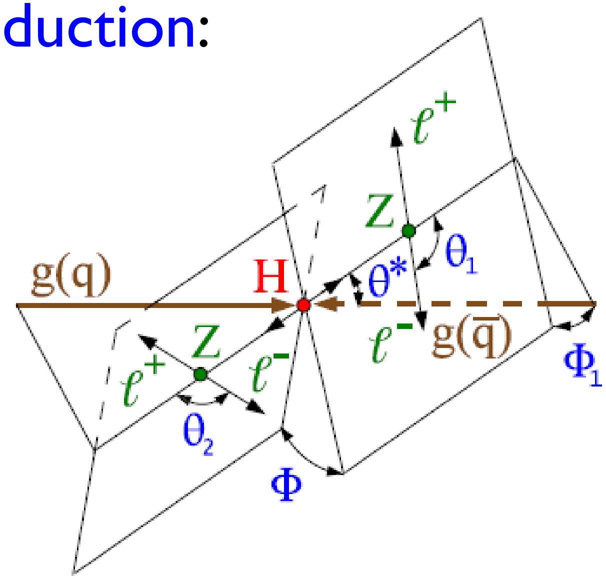
4l analysis

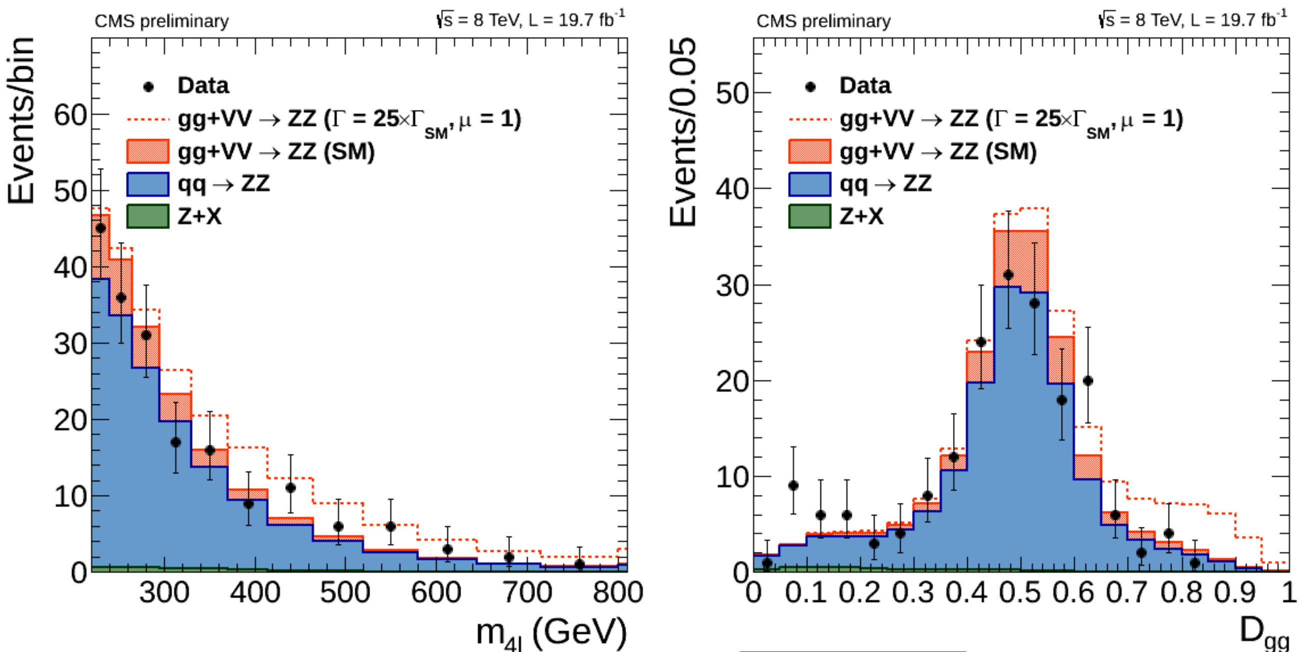
- No changes in selection w.r.t. CMS collab., arXiv:1312.5353
  - Lepton p_T cuts, Z invariant masses, impact parameter significance, loose isolation
- In the matrix element likelihood approach (MELA), design a specific discriminant for $gg \to ZZ$ production:

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



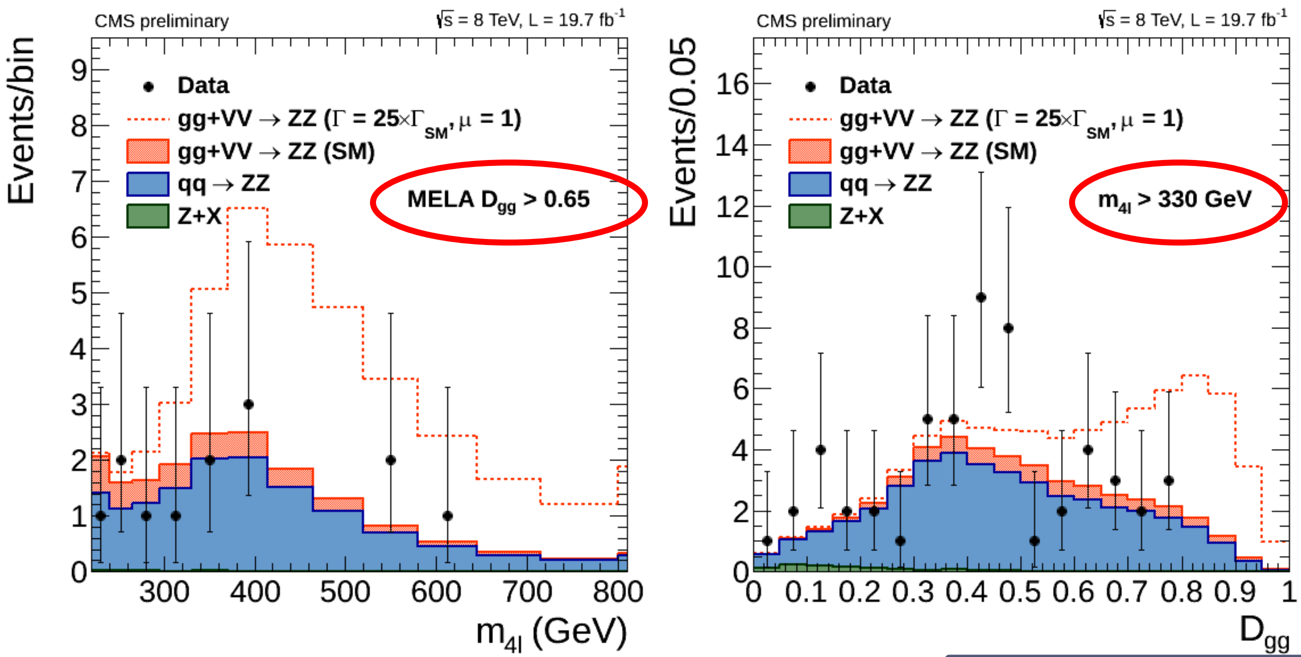
  - Built with 7 variables completely describing kinematics (m_{Z1}, m_{Z2}, five angles)
  - $P_{gg,(q\bar{q})}$ are joint probabilities for $gg \to ZZ$, signal + background + interference ($q\bar{q} \to ZZ$) from MCFM matrix elements

m_{4l} and D_{gg} distributions / yields



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



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	Observed	183	8

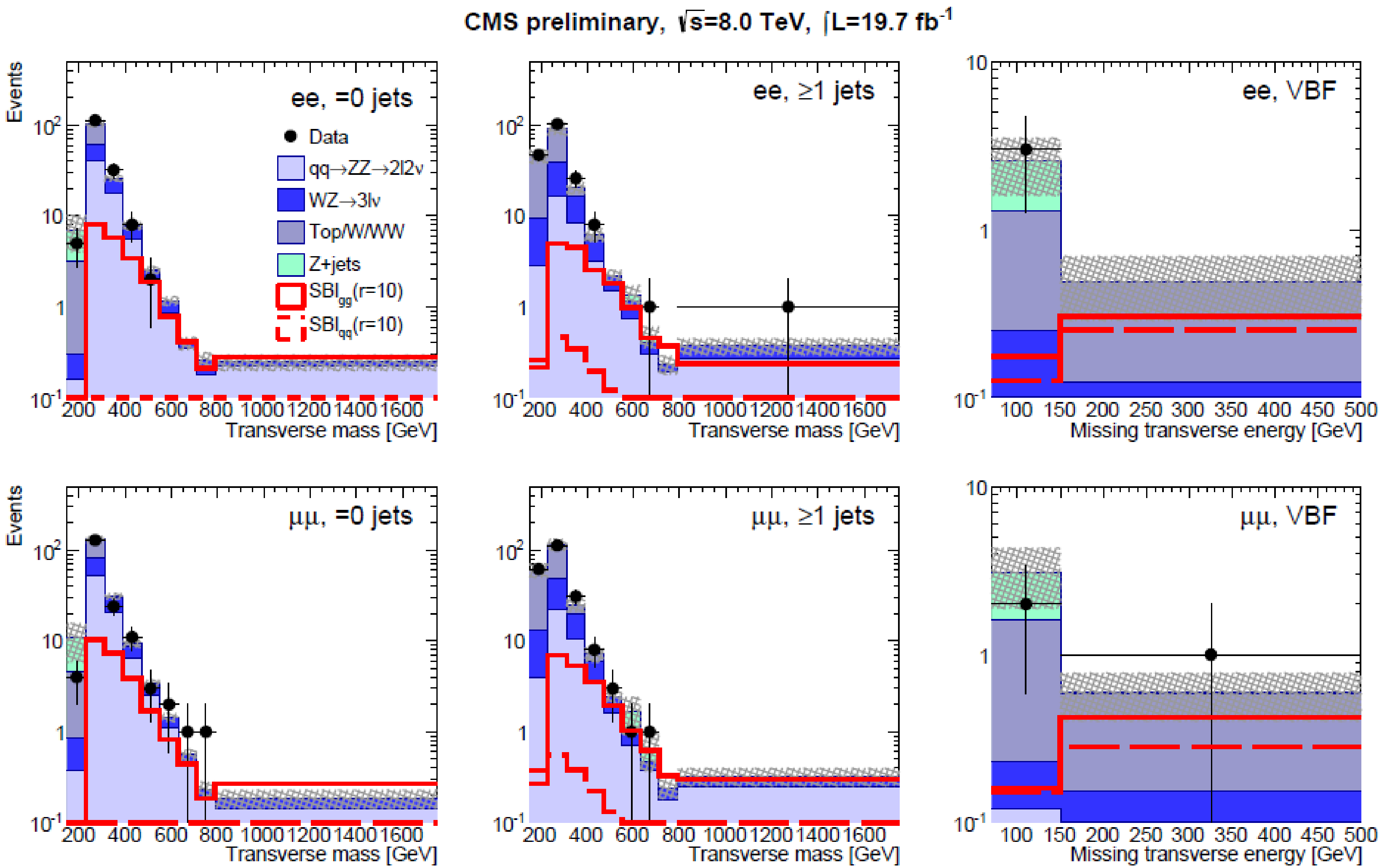
2l2ν analysis

- No changes in selection w.r.t. CMS collab. , PAS-HIG-13-014
  - Large $p_T(Z)$ and $E_{T,miss}$
  - Vetoing 3rd lepton and b-tagged jets (removing Z+heavy-flavor jets)
- Events split in three purity categories according to 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-derived estimation of reducible backgrounds (double and single top, WW, W+jets, Z+jets), $q\bar{q} \rightarrow$ ZZ and WZ from MC
- Fit the distribution of the transverse mass for 0 and 1-jet category

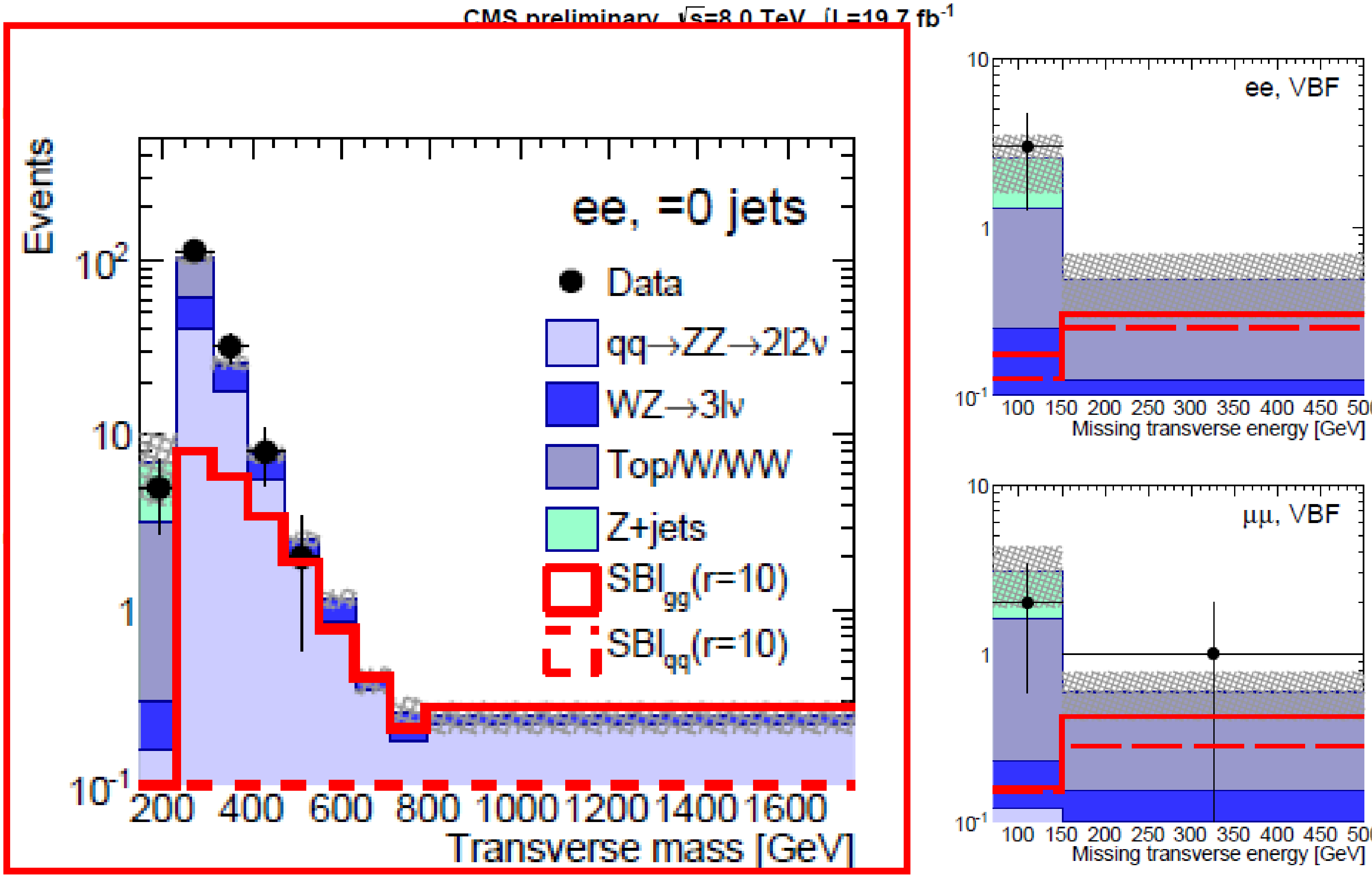
$$m_{\mathrm{T}}^2 = \left[\sqrt{p_{\mathrm{T},\ell\ell}{}^2 + m_{\ell\ell}{}^2} + \sqrt{E_{\mathrm{T}}^{\mathrm{miss}\,2} + m_{\ell\ell}{}^2}\right]^2 - \left[\vec{p}_{T,\ell\ell} + \vec{E}_T^{\mathrm{miss}}\right]^2$$

and $E_{T,miss}$ for VBF-like

m_T / $E_{T,miss}$ distributions



m_T / $E_{T,miss}$ distributions



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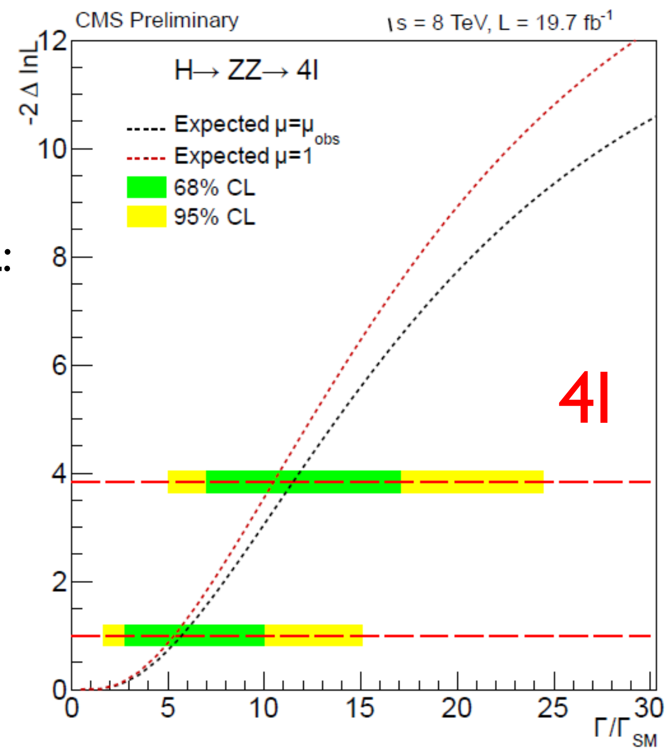
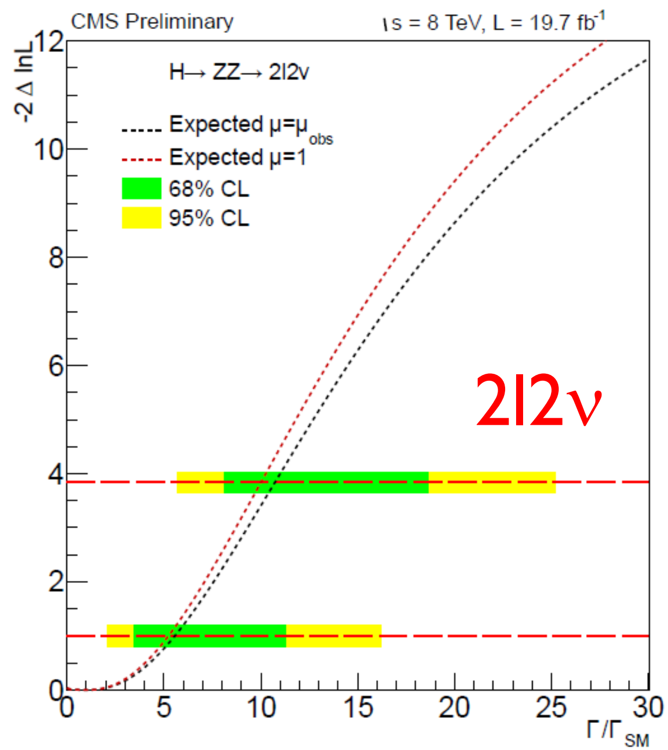
Expected / observed limits

At 95% CL:

Expected
r < 11.5





At 95% CL:

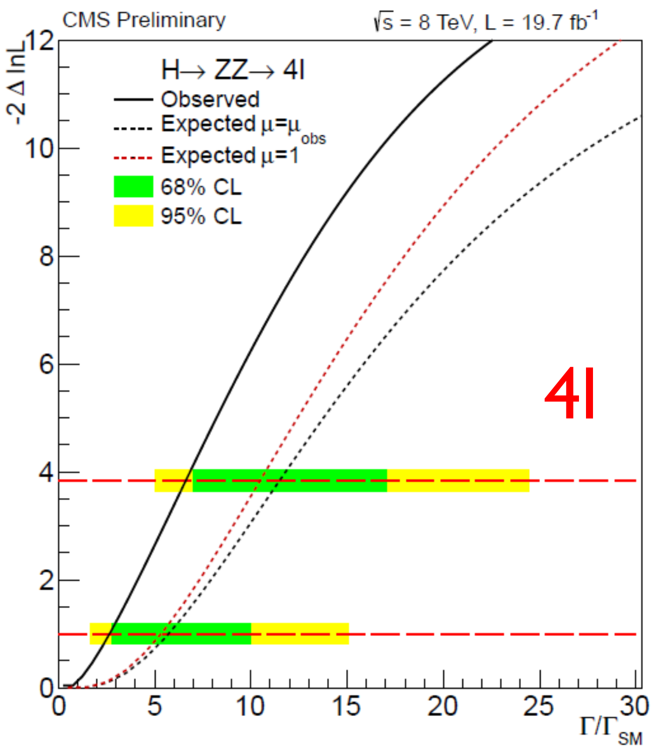
Expected
r < 10.7

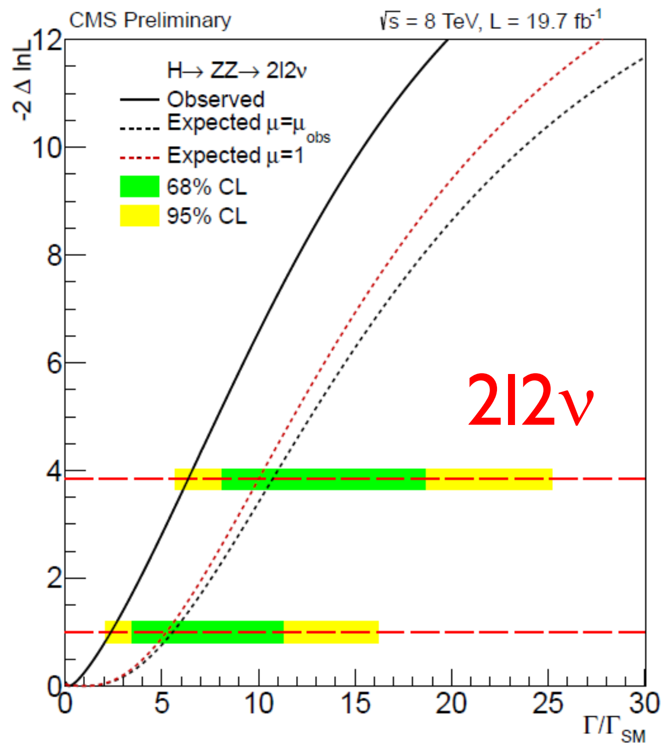
- Main systematic uncertainties:
  - QCD scale and PDFs for $q\bar{q} \to ZZ$ and $gg \to ZZ$
  - μ uncertainties from CMS 4l low-mass paper
  - Uncertainty on k-factor approximation for $gg \to ZZ$ continuum
  - Experimental uncertainties (lepton trigger/reconstruction efficiencies etc.)

Expected / observed limits

At 95% CL:

Expected
r < 11.5
Observed
r < 6.6



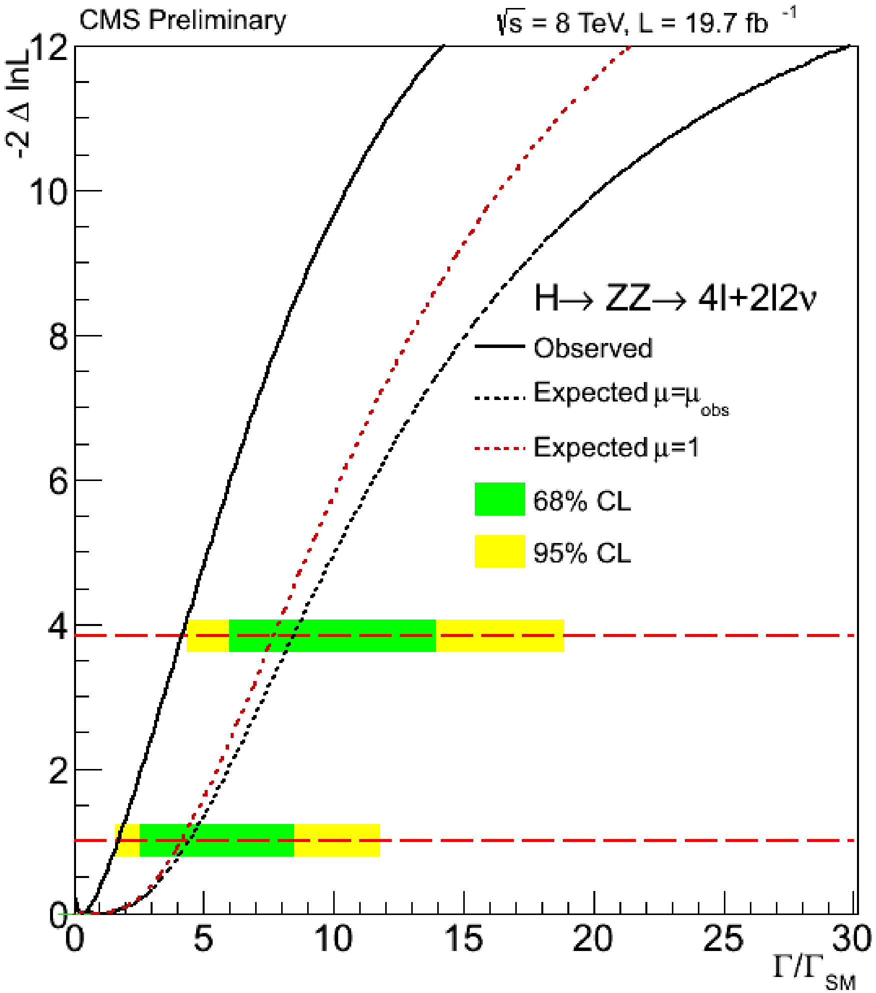


At 95% CL:

Expected
r < 10.7
Observed
r < 6.4

- Main systematic uncertainties:
  - QCD scale and PDFs for $q\bar{q} \to ZZ$ and $gg \to ZZ$
  - μ uncertainties from CMS 4l low-mass paper
  - Uncertainty on k-factor approximation for $gg \to ZZ$ continuum
  - Experimental uncertainties (lepton trigger/reconstruction efficiencies etc.)

Combined limit



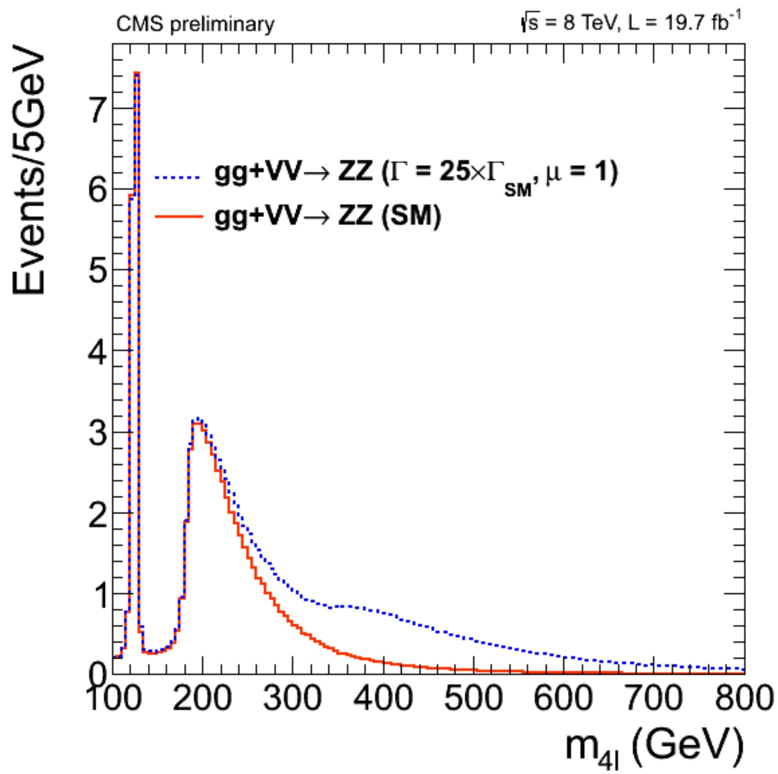
- Combined observed (expected) values
  - $r = \Gamma/\Gamma_{SM} < 4.2$ (8.5) @ 95% CL
    (p-value = 0.02)
  - $r = \Gamma/\Gamma_{SM} = 0.3^{+1.5}_{-0.3}$
- equivalent to:
  - $\Gamma < 17.4$ (35.3) MeV @ 95% CL
  - $\Gamma = (1.4^{+6.1}_{-1.4})$ MeV

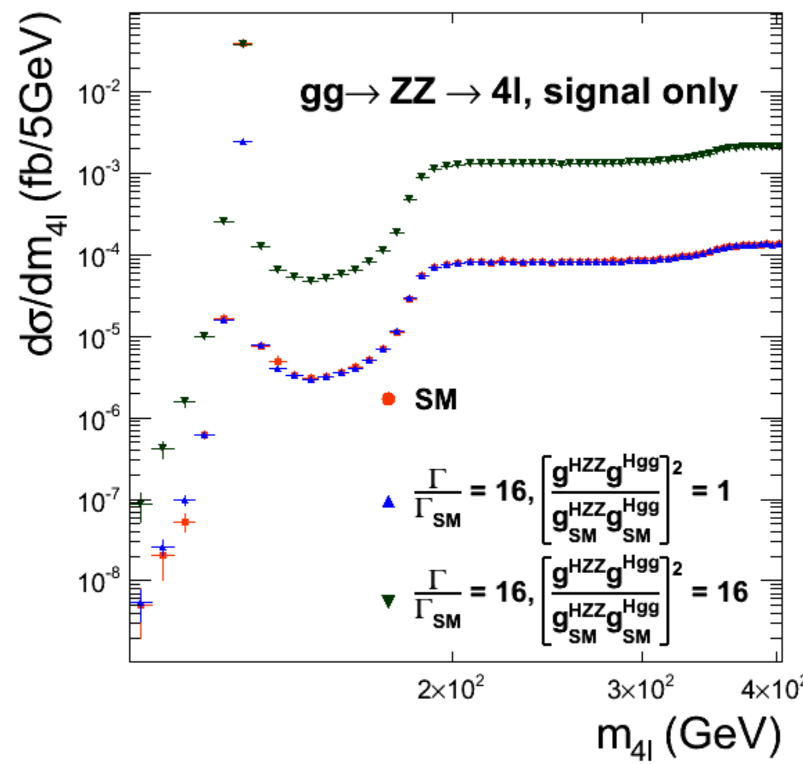
Conclusions

- First experimental constraint on Higgs total width using H*(126) → ZZ events has been presented
- Mild model-dependence
  - Just based on Higgs propagator structure
  - Assumptions on gg → ZZ continuum production beyond LO
  - Assumption of SM production of $q\bar{q}$ → ZZ and, in general, no other BSM sources enhancing high-mass ZZ yields
- Combining 4l and 2l2ν final states
  - Using variables related to ZZ inv. mass and kinematic discriminants
  - Small deficits in signal regions observed in both channels
- Combination results:
  - $\Gamma/\Gamma_{SM} < 4.2$ (8.5 expected) @ 95% CL
    → $\Gamma < 17$ MeV (35 MeV expected) @ 95% CL
  - Direct measurements at the peak set a limit of $\Gamma < 3.4$ GeV

Backup

Effect of Γ / coupling scalings





PHANTOM settings

- LO generation
  - NNLO/LO k-factor is 6% and independent on m_{ZZ} (from CERN Yellow Report 3)
  - 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:

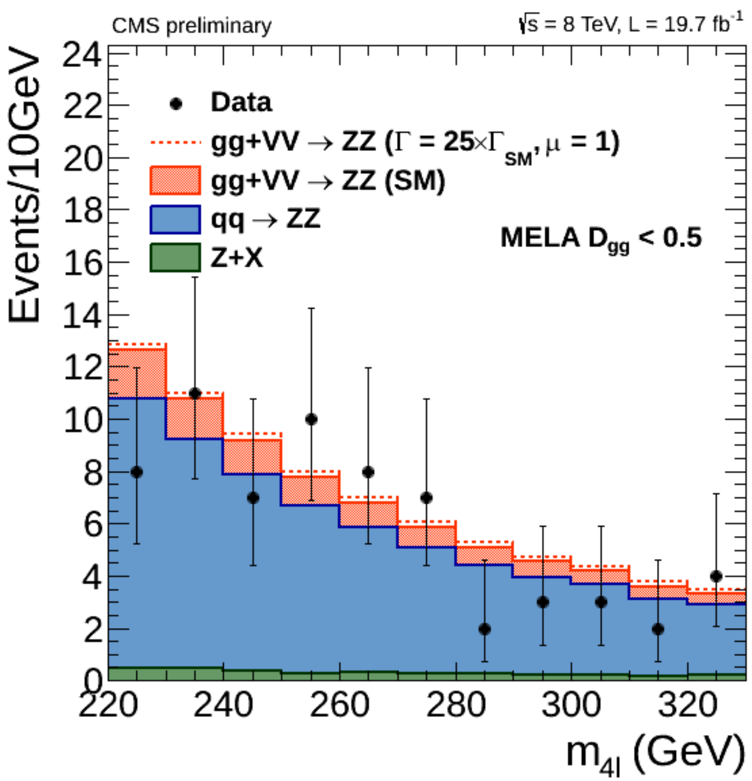
$$\begin{pmatrix} p_1 \\ p_{10} \\ p_{25} \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ 10 & \sqrt{10} & 1 \\ 25 & 5 & 1 \end{pmatrix} \begin{pmatrix} S \\ I \\ B \end{pmatrix}$$

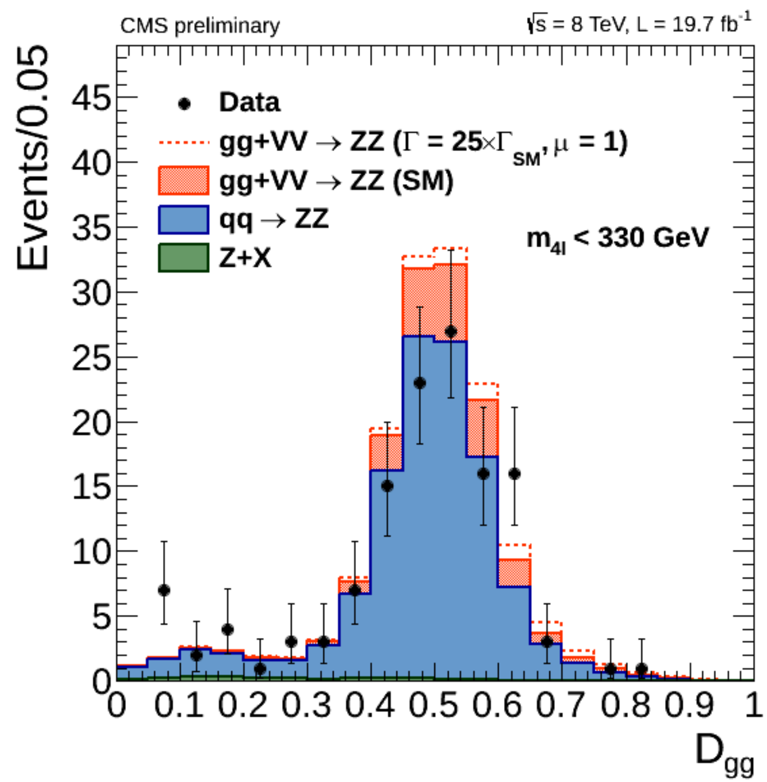
Full formula of MELA D_{gg}

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

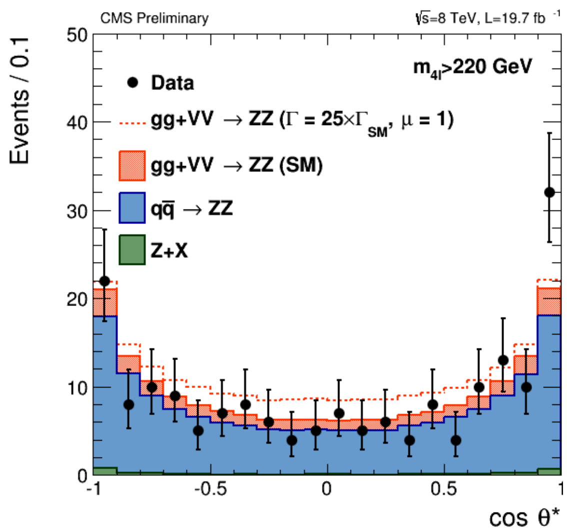
- Depends on parameter *a* (relative weight of signal in the likelihood ratio). Since the expected exclusion is r ~ 10, use *a* = 10

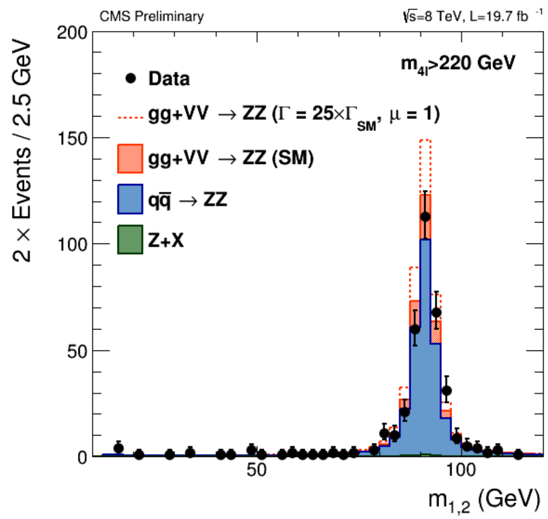
4l: background-enriched region

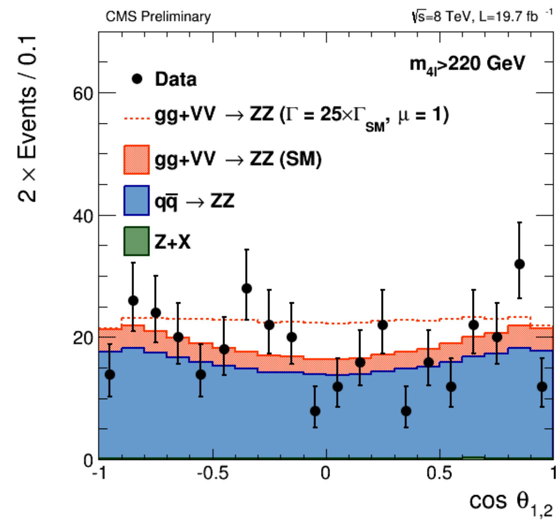


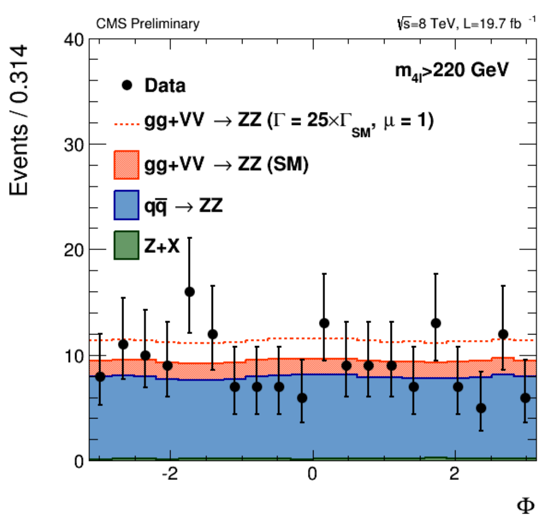


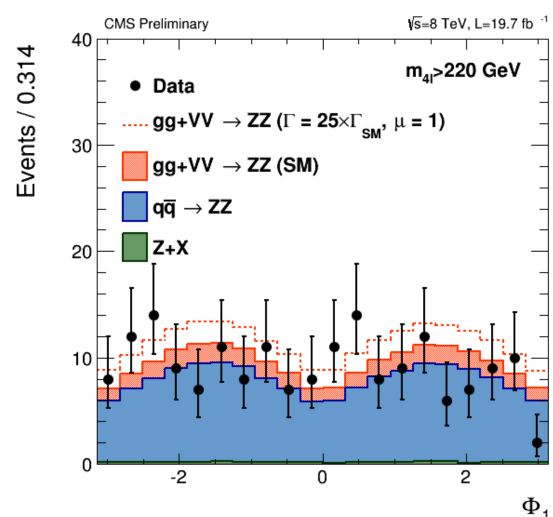
4l: variables entering D_{gg}



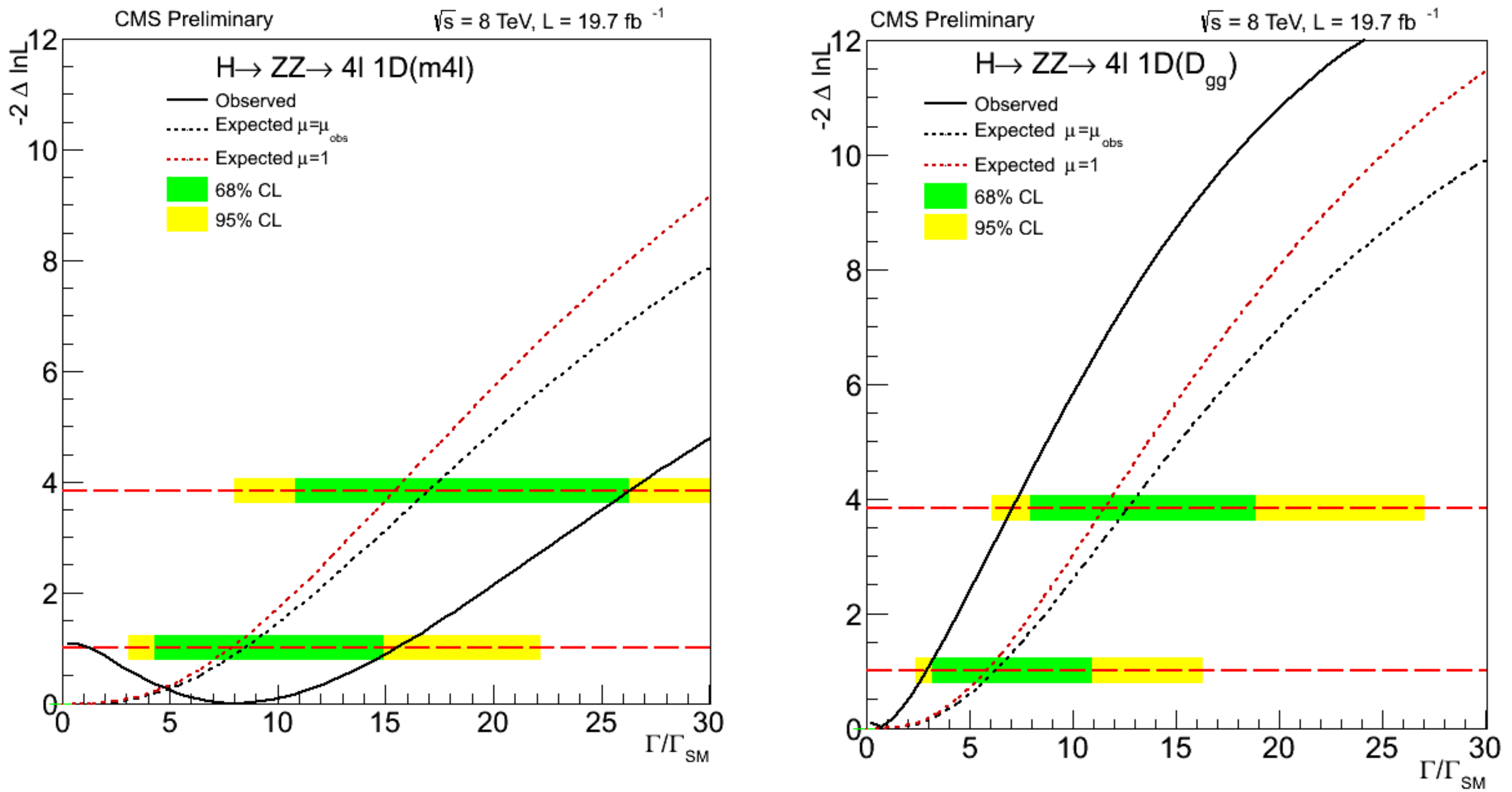








4l: 1D result with D_{gg} and m4l



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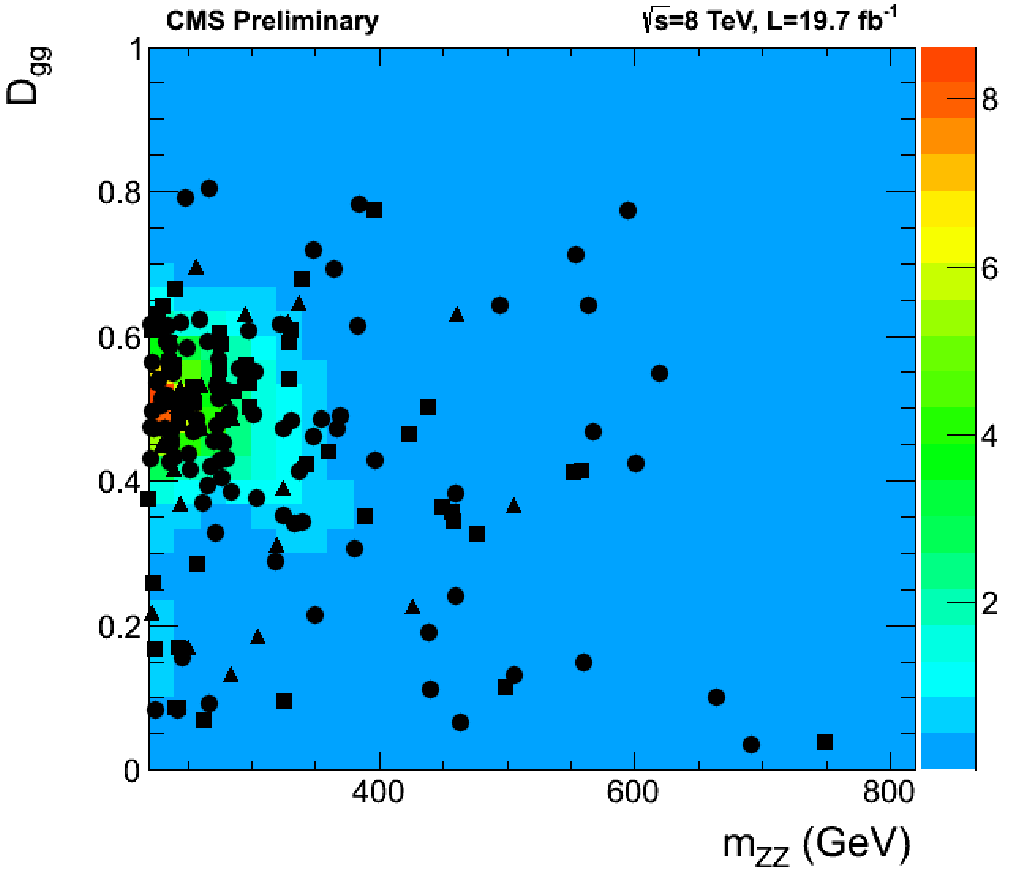
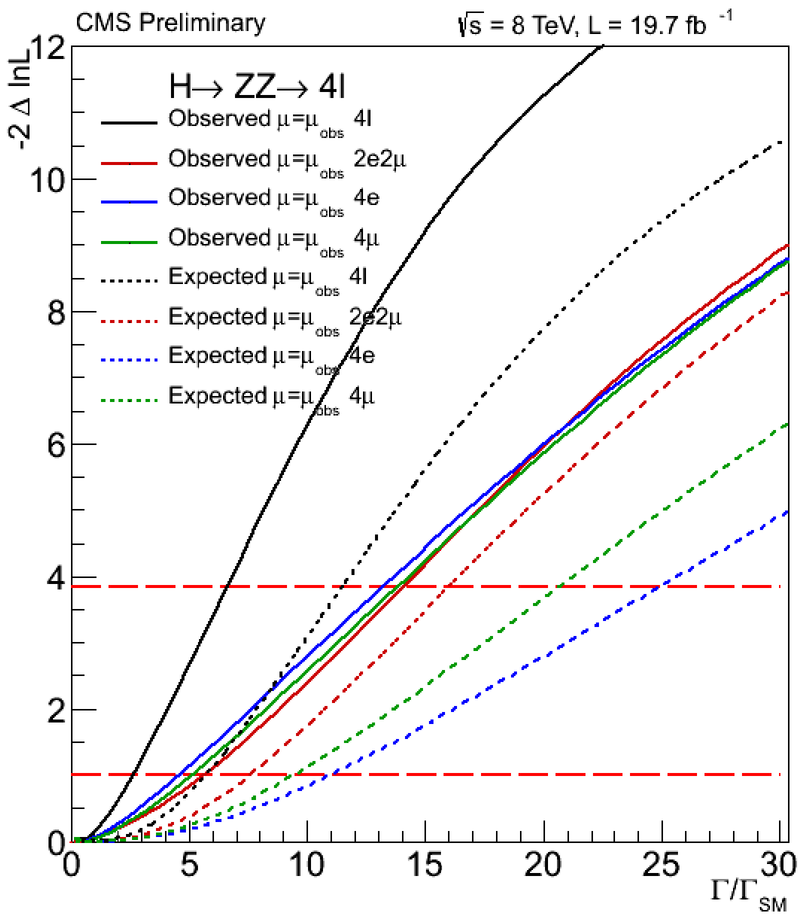
41: 2D templates



4l: breakdown by channel



$2l2\nu$: selection

- We pre-select **boosted Z candidates**
  - dilepton+single lepton triggers
  - two isolated leptons p_T>20 GeV

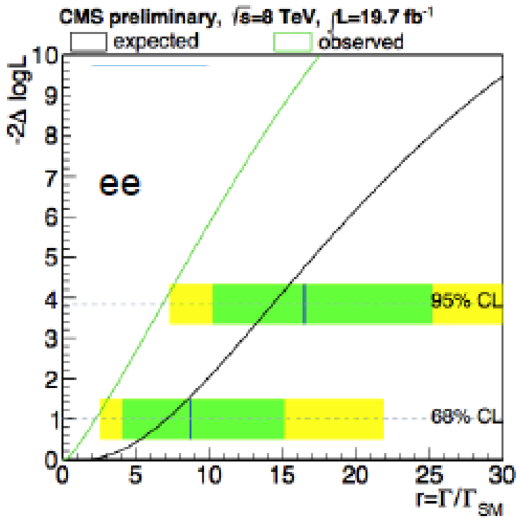
    (medium-id electrons or tight-id muons)
  - |M-91|<15 GeV and p_T(Z)>50 GeV
  - Veto 3[rd] lepton with pT>10 GeV

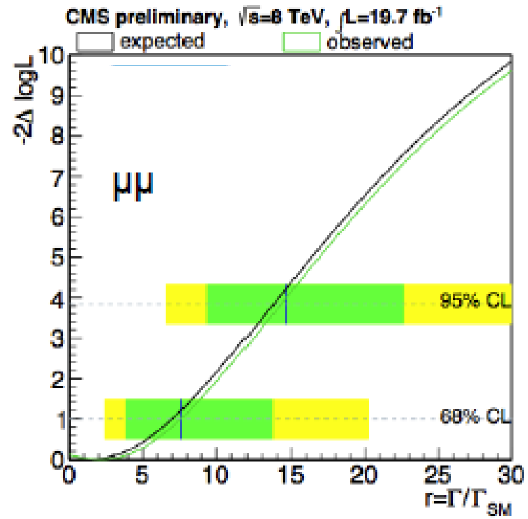
    (veto-id electrons or loose-id muon)
  - No b-tagged jet by CSVL +

    no soft-muon with p_T>3 GeV

- **Search for real E_T^{miss} in Z events**
  - raw particle flow E_T^{miss} is used
  - $\Delta\varphi(jet, E_T^{miss})>0.5$
  - E_T^{miss}>80 GeV

2l2ν: breakdown by channel





- ee channel: deficit in data drives stronger observed limits
- =0 jets drives the sensitivity of the analysis
- Median expected from toys tends to disagree in categories with larger systematic uncertainties