Higgs-boson spin-parity and width

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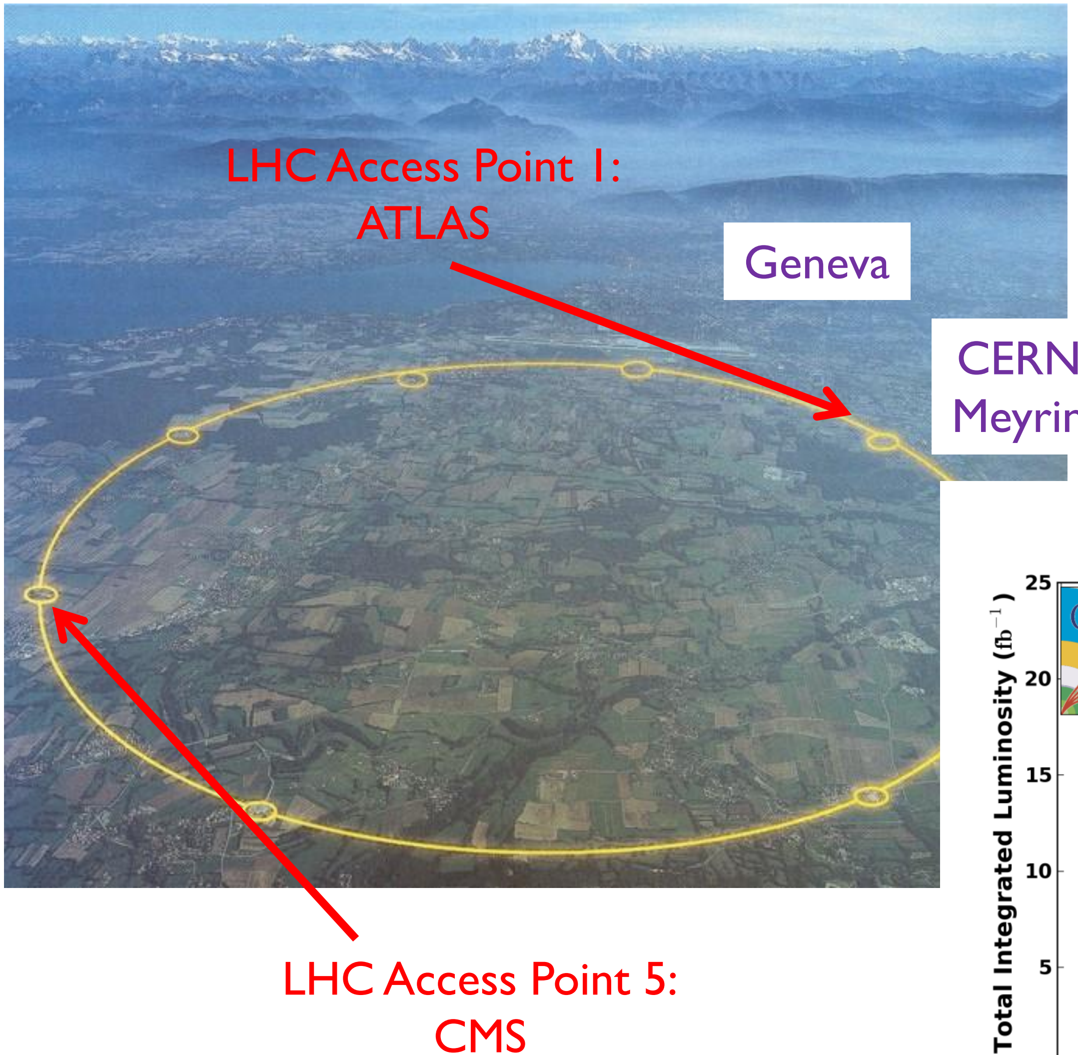
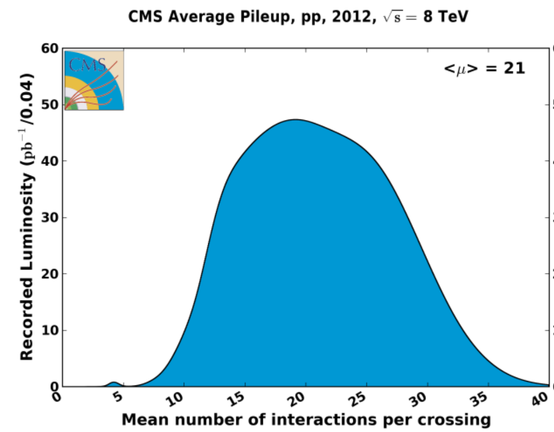
Outline

- The LHC and the CMS detector
- After Higgs discovery
- Spin-parity measurement
  - The «MELA» technique
- Width measurement
  - Theory review of off-shell Higgs production
  - Experimental techniques and combination with on-shell analysis
  - Upper limits on Higgs width and combination

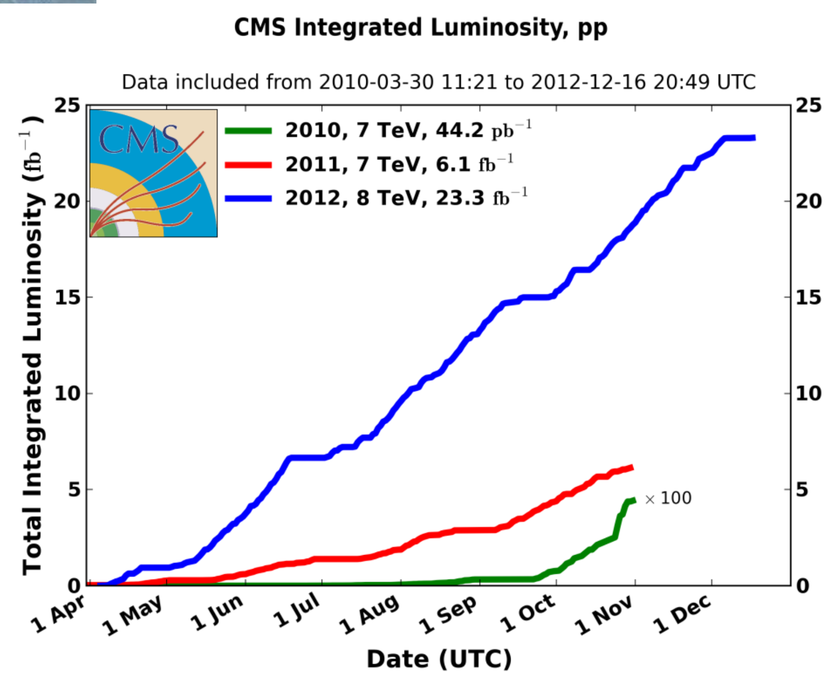
LHC and CMS



LHC Access Point 1:
ATLAS
Geneva
CERN
Meyrin
LHC Access Point 5:
CMS



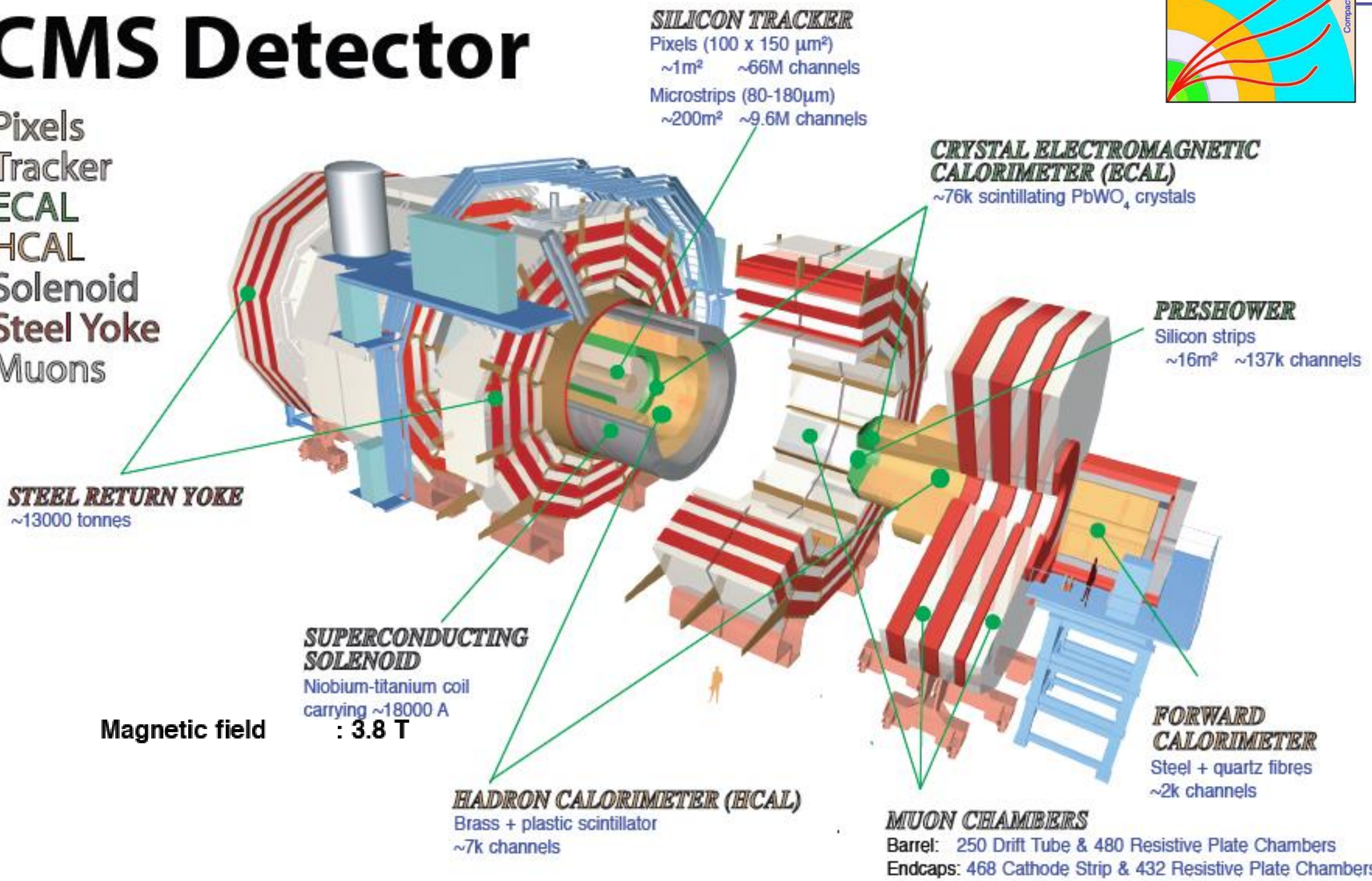
CMS Average Pileup, pp, 2012, $\sqrt{s}$ = 8 TeV
<μ> = 21
Recorded Luminosity (pb^{-1}/0.04)
Mean number of interactions per crossing
0
5
10
15
20
25
30
35
40
50
60



CMS Integrated Luminosity, pp
Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC
2010, 7 TeV, 44.2 pb^{-1}
2011, 7 TeV, 6.1 fb^{-1}
2012, 8 TeV, 23.3 fb^{-1}
× 100
Total Integrated Luminosity (fb^{-1})
0
5
10
15
20
25
1 Apr
1 May
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct
1 Nov
1 Dec
Date (UTC)

CMS Detector

- Pixels
- Tracker
- ECAL
- HCAL
- Solenoid
- Steel Yoke
- Muons

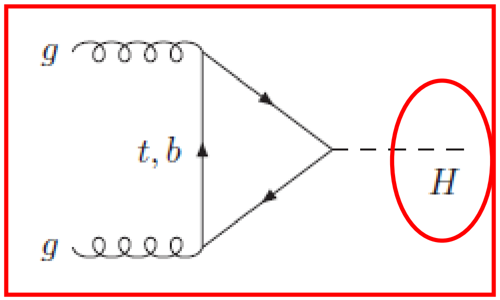


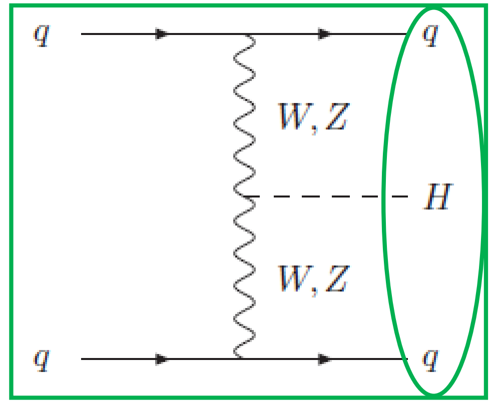
Magnetic field : 3.8 T

Higgs production mechanisms

- Main production mechanisms at pp colliders
  - DIS: p = 3q (+ g + $\bar{q}$)

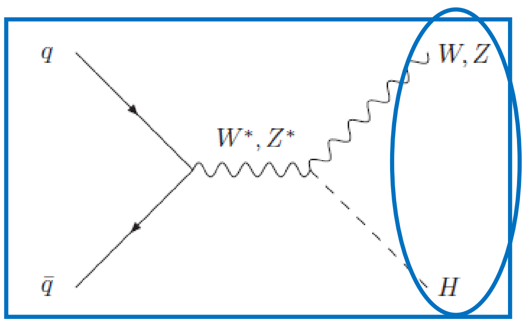
Gluon-gluon Fusion (ggF)

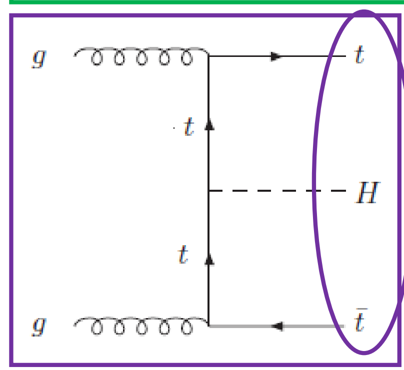




Vector-boson Fusion (VBF)

Associated with a W or Z boson ('Higgstrahlung', VH)

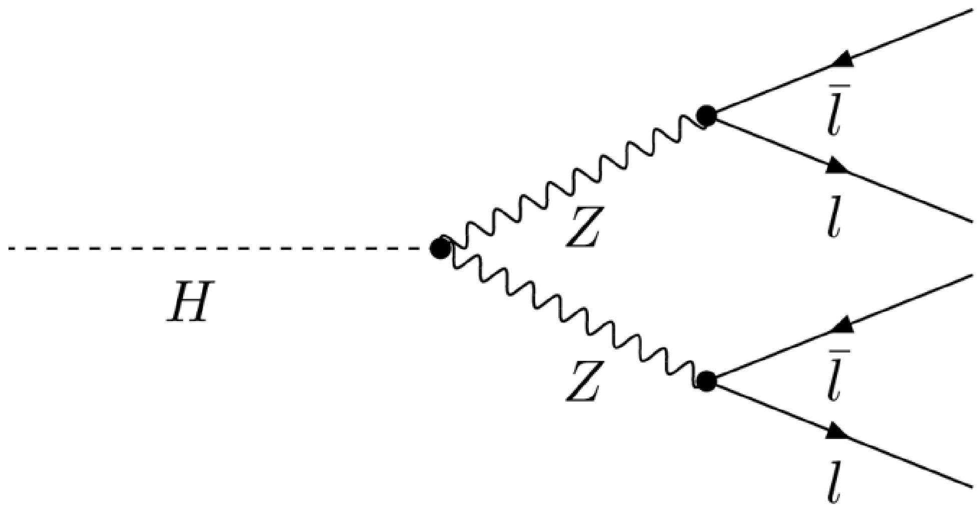


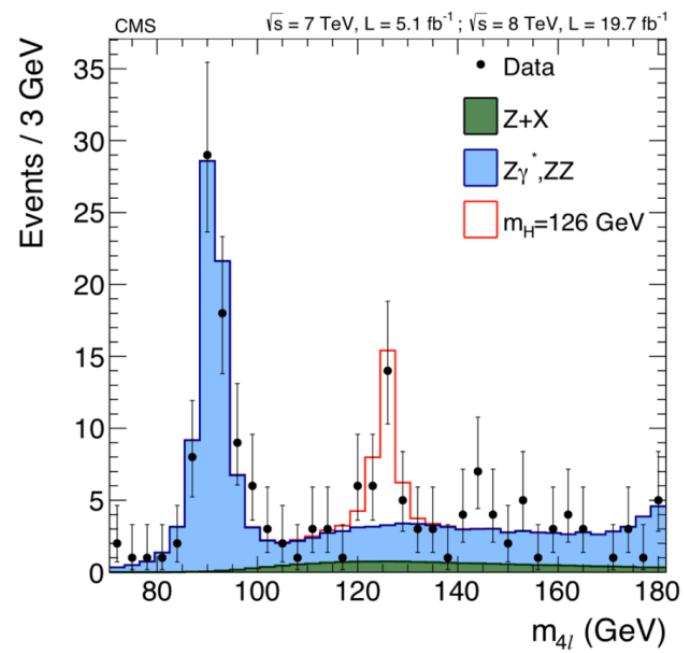


Associated with a $t\bar{t}$ pair (ttH)

Higgs decay modes

- Here we examine the ZZ decay mode
  - There are many more



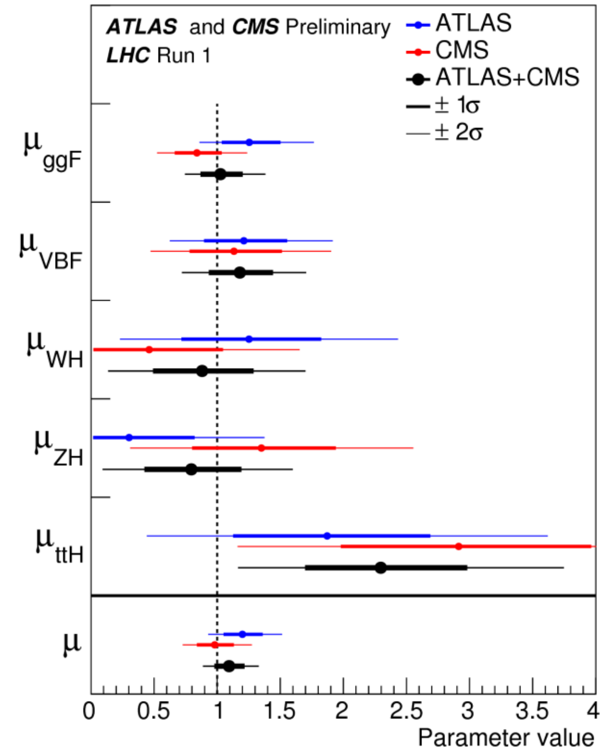


After Higgs discovery

- Great progress since "Higgs boson" discovery in CMS
  - Observation in boson decay channels
  - Evidence in fermion channels
  - Mass determination
    - CMS measurement:
      125.1 ± 0.4(stat.) ± 0.2(syst.) GeV

Looks more and more like the SM Higgs boson

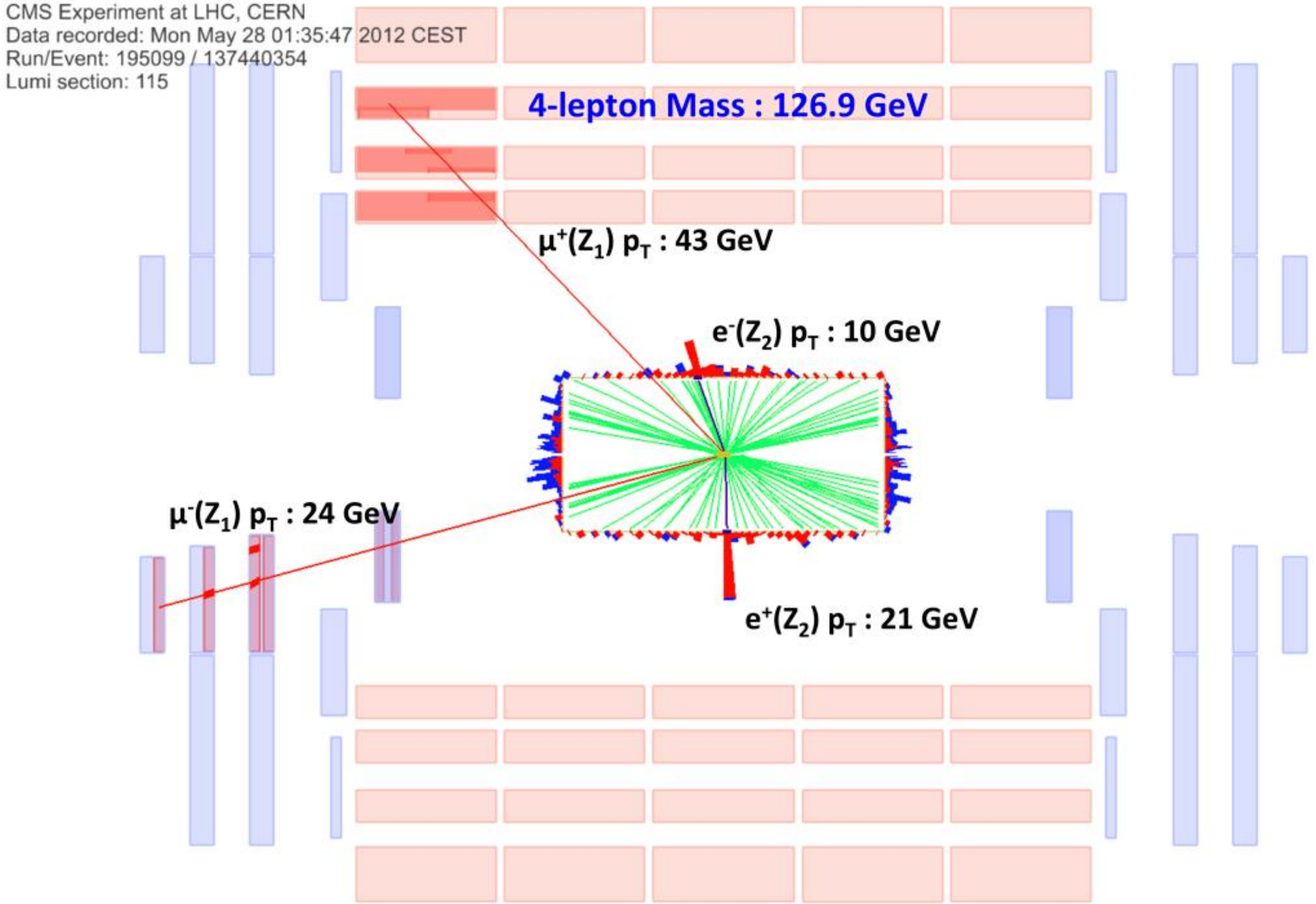
$\mu = \sigma/\sigma_{SM}$



Analysis overview

- Phys. Rev. D 89 (2014) 092007
- Use 7 and 8 TeV data (2011-2012)
- Event selections:
  - Two pairs of leptons (electrons or muons), isolated and prompt, 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
- Background:
  - Irreducible background is $q\bar{q} \rightarrow ZZ$, modeled from MC
  - Reducible background is Z+X (Z and WZ, at least one lepton is non-prompt): much smaller, evaluated using a "fake rate" method, with control regions in data

H → ZZ → 2l2l’

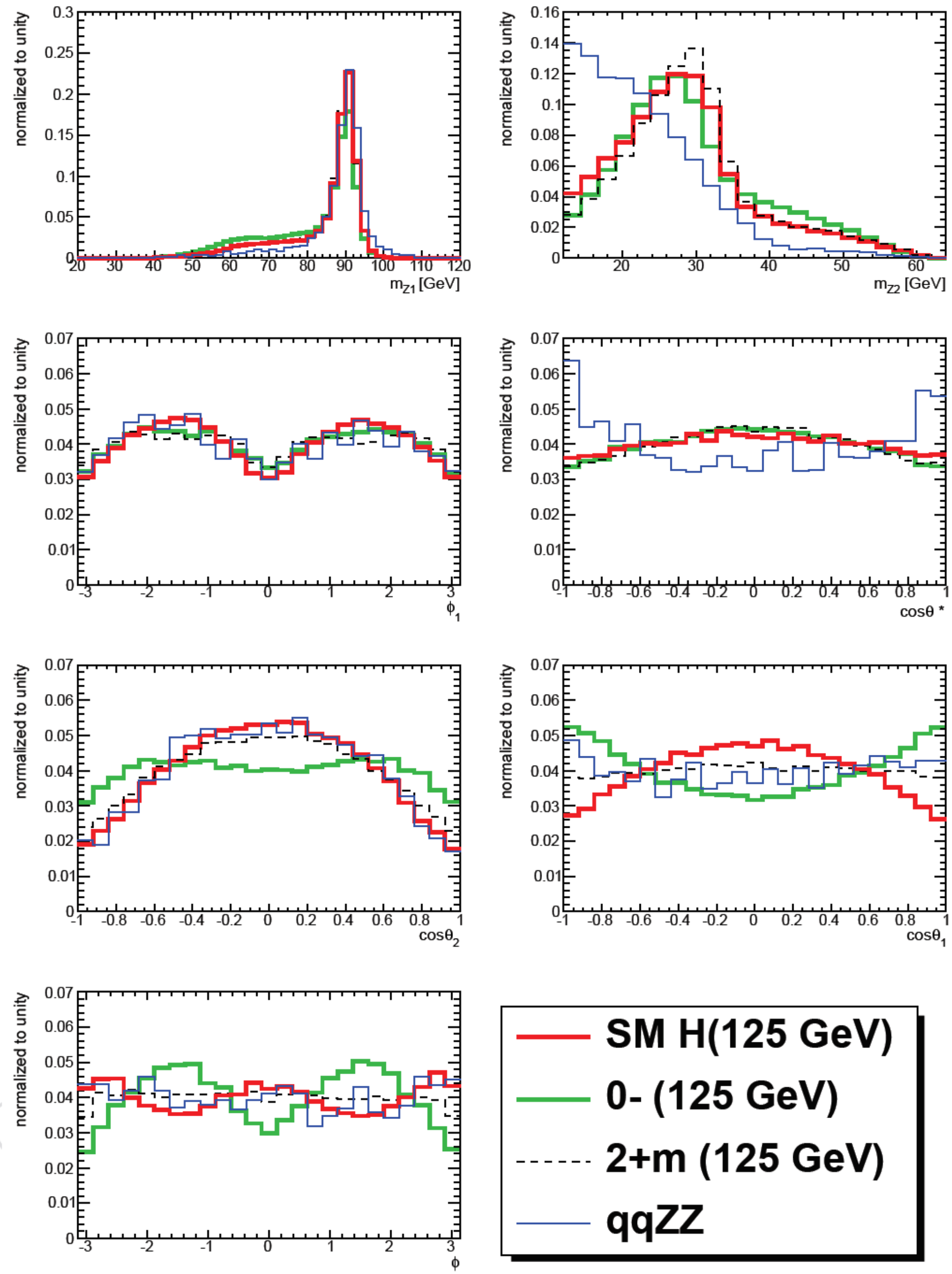

CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:35:47 2012 CEST
Run/Event: 195099 / 137440354
Lumi section: 115
4-lepton Mass : 126.9 GeV
$\mu^+(Z_1)$ p_T : 43 GeV
$e^-(Z_2)$ p_T : 10 GeV
$\mu^-(Z_1)$ p_T : 24 GeV
$e^+(Z_2)$ p_T : 21 GeV

How to measure a particle spin-parity?

- Infer from kinematics of decay products (in particular angles in space)
- Simplest case: pp → S → S_1S_2
  - No spin: spherical-harmonic part of the mother particle's wavefunction is constant → isotropic decay (no preferred direction for decay product emission)
- Other important cases:
  - pp → S → V_1V_2 : $\cos\theta^*$ (angle between pp-axis and V_1 direction) has a peculiar distribution depending on V polarization. For massless V (= only transversely polarized): $dN/d\cos\theta^* \sim \cos^2\theta^*$
  - pp → S → V_1V_2 → 4f : up to 7 independent angles/quantities to be analyzed, some of those independent of production plane («helicity angles»)

Input variables

- $pp \rightarrow H \rightarrow ZZ \rightarrow 4l =$
  $pp \rightarrow S \rightarrow V_1V_2 \rightarrow 4f$

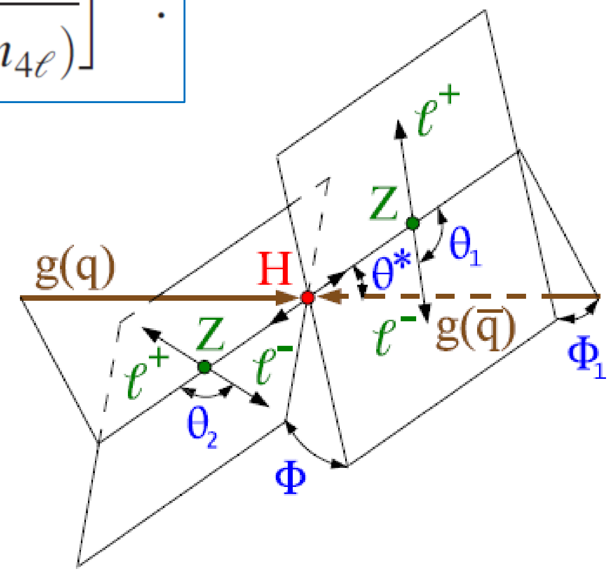


MELA discriminant

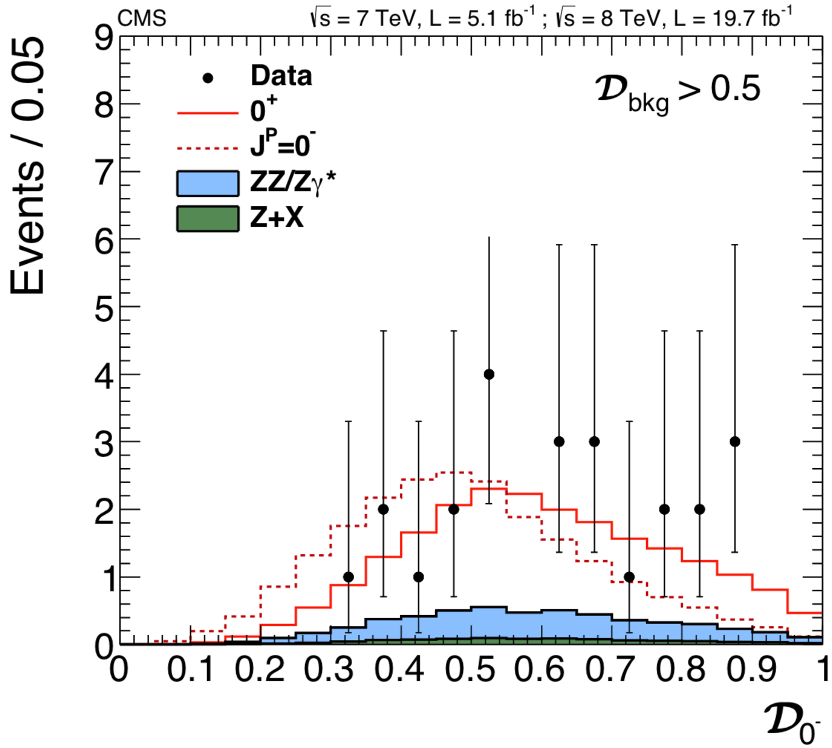
- In the matrix element likelihood approach (MELA), design specific discriminants for $J^P = 0^+$ vs. other hypotheses:

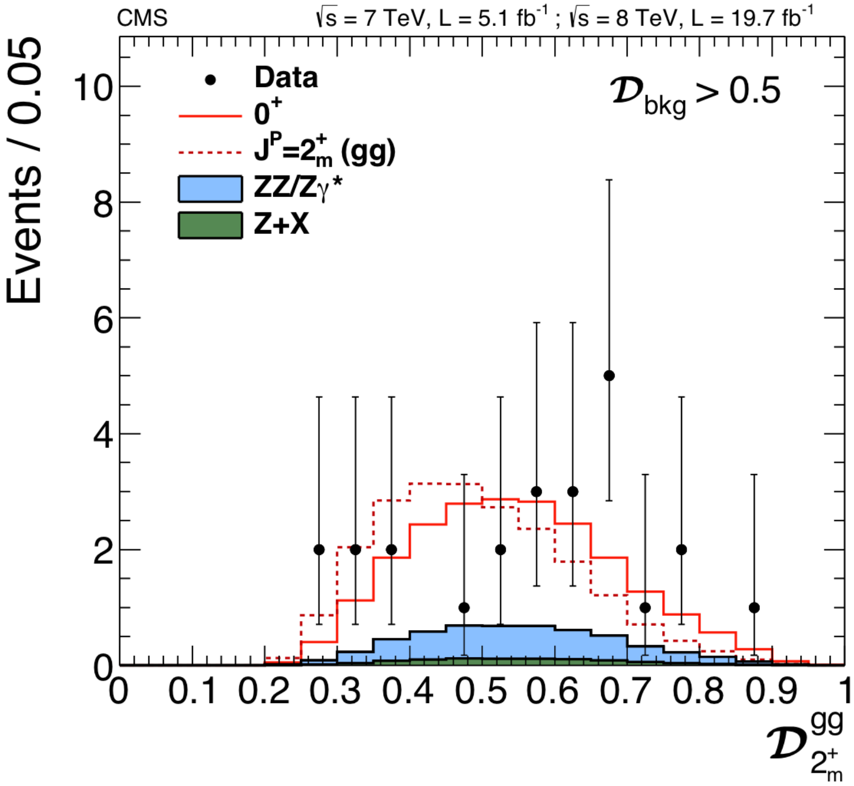
$$\mathcal{D}_{J^P} = \frac{\mathcal{P}^{\text{kin}}_{0^+}}{\mathcal{P}^{\text{kin}}_{0^+} + \mathcal{P}^{\text{kin}}_{\text{bkg}}} = \left[1 + \frac{\mathcal{P}^{\text{kin}}_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}^{\text{kin}}_{0^+}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}.$$

  - Built with 7 variables completely describing kinematics (m_{Z1}, m_{Z2}, five angles)
  - $P_{0+,(JP)}$ are joint probabilities for scalar particle or alternative hypotheses



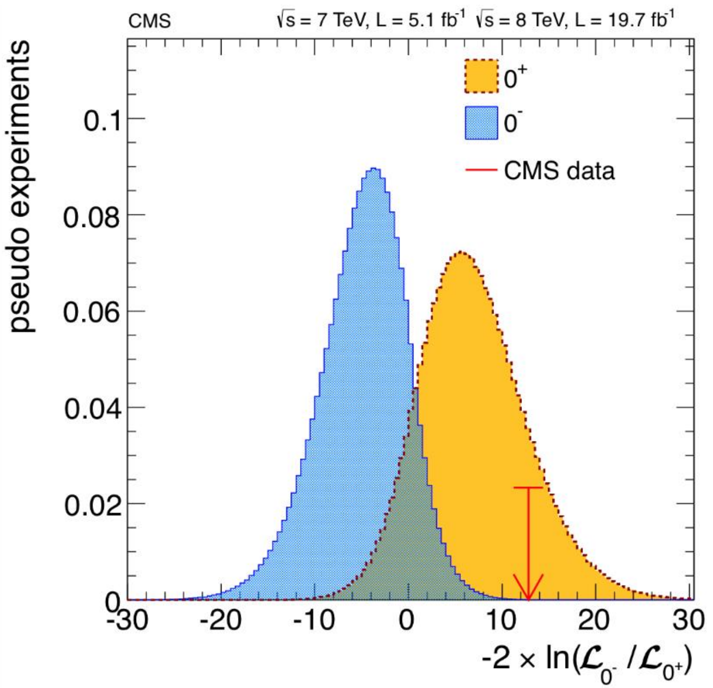
Example: Higgs vs. pseudoscalar or spin-2

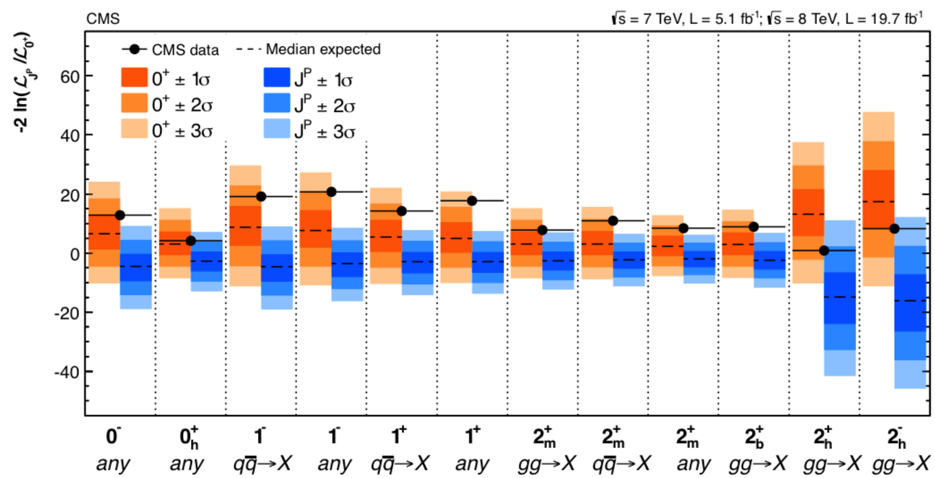




Spin-parity results

- «Toy-MonteCarlo» method:
  - Generate many fake datasets (same size as the observed data) corresponding to 0^+ or alternative spin-parity hypotheses
  - Compute likelihood ratio for each dataset
  - Compare to observation

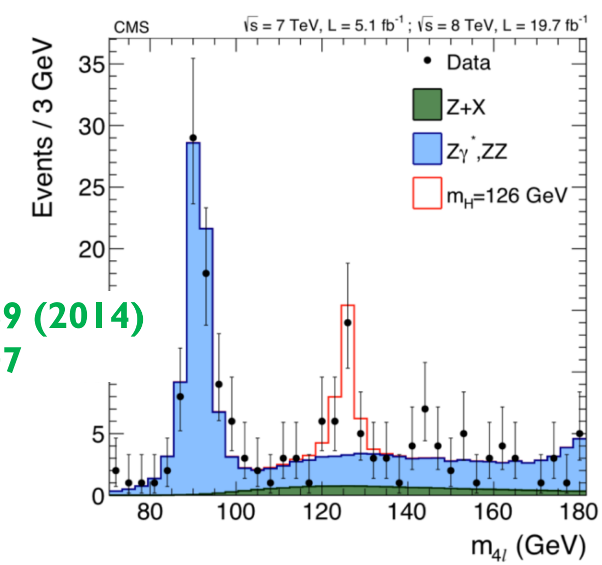


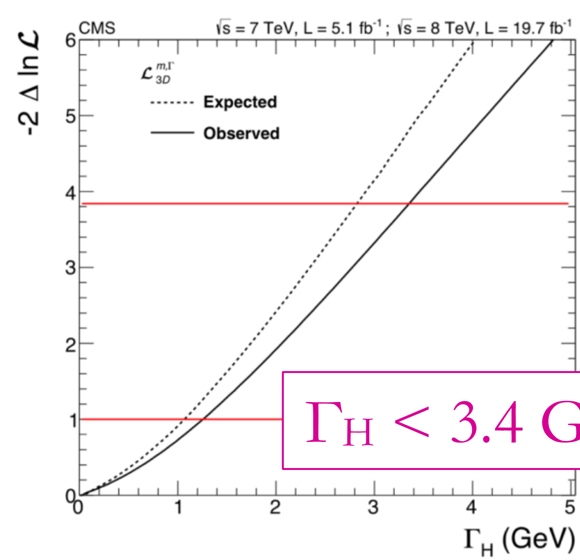


Property measurements - width

- Direct decay width measurements at the peak limited by experimental resolution:
  - $f(m) \sim BW(m, \Gamma) \otimes R(m, \sigma)$
  - If $\Gamma << \sigma$, not possible to disentangle natural width
    - SM Higgs width at m_H = 125.0 GeV is Γ_H = 4.15 MeV
    - Experimental resolution is $\sigma \sim$ 1-3 GeV for $H \to ZZ \to 4l$

Phys. Rev. D 89 (2014) 092007





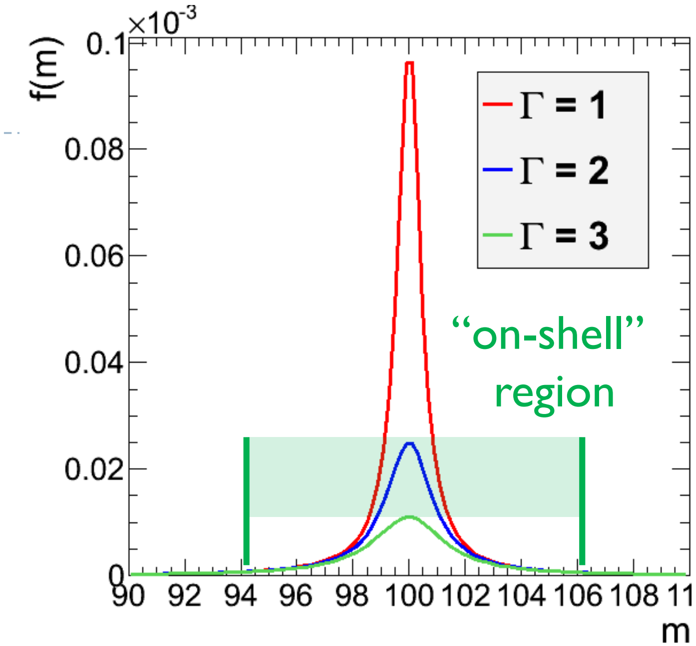
$\Gamma_H < 3.4$ GeV @ 95% CL

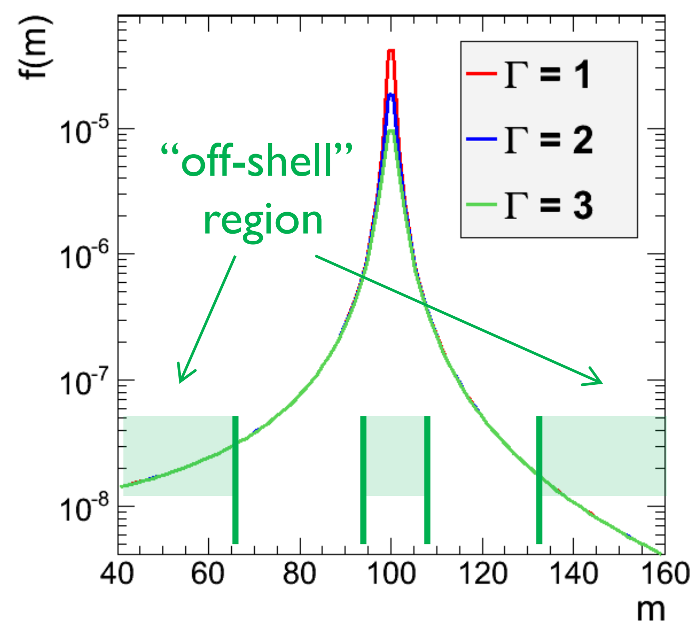
A different idea…

- Assume a dummy (relativistic BW) resonance "R" with m = 100 and variable width

$$f(m) \sim \frac{1}{(m^2 - m_R^2)^2 + m_R^2 \Gamma_R^2}$$

  - On-shell: $\int_{m_R - n\Gamma_R}^{m_R + n\Gamma_R} f(m)dm \sim \frac{1}{m_R \Gamma_R}$
  - Off-shell: $\int_{m_0}^{+\infty} f(m)dm \sim \frac{1}{m_0^2}$
- Ratio of the two gives Γ !
- Experimentally, this never worked before because of tiny off-shell yields and backgrounds





Higgs decays

Summary by D. De Florian
@ Higgs Couplings 2013

Decay amplitude can produce a significant deformation of the Higgs lineshape

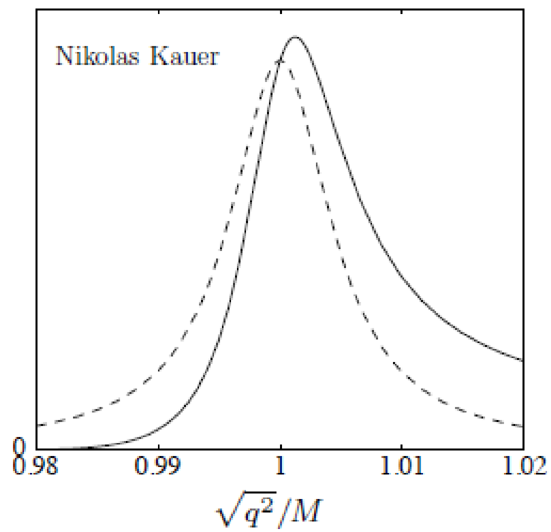
Threshold effects

$$|\mathcal{M}_d(H \to f\bar{f})|^2 \sim M_f^2 q^2 \quad \text{for } \sqrt{q^2} \gtrsim 2\, M_f$$

$$|\mathcal{M}_d(H \to VV)|^2 \sim (q^2)^2 \quad \text{for } \sqrt{q^2} \gtrsim 2\, M_V$$

can compensate the $\frac{1}{q^4}$ in

$$D_H(q^2) = \frac{1}{\left(q^2 - M_H^2\right)^2 + \Gamma_H^2\, M_H^2}$$

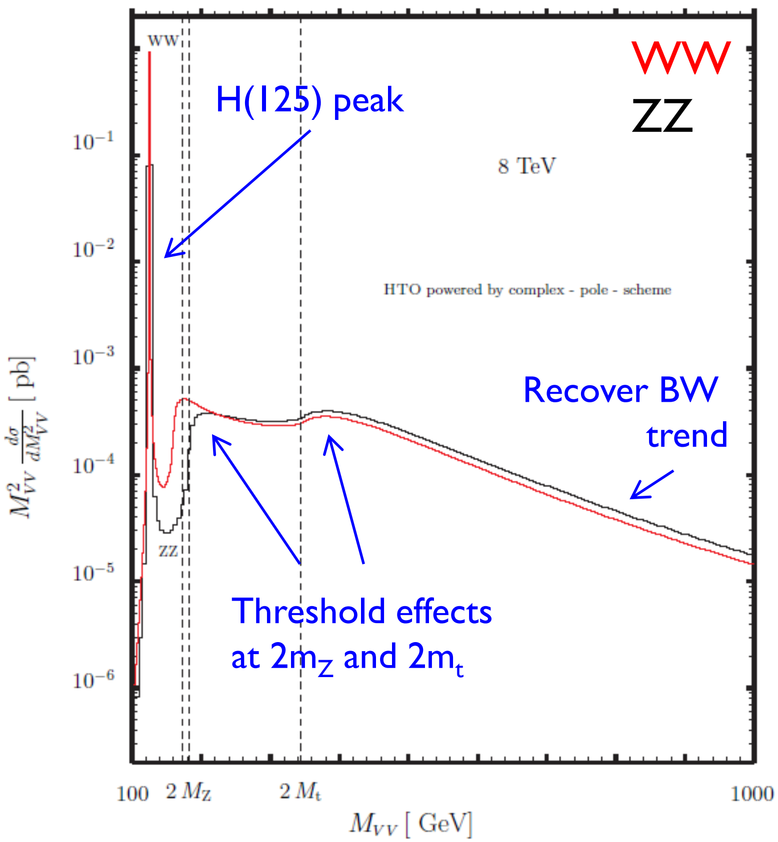


resulting in a lineshape strongly enhanced at large virtualities

The idea in detail

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

gluon-gluon fusion production



- Off-shell $H^* \rightarrow VV$ (V = W, Z)
  - Peculiar cancellation between BW trend and decay amplitude creates an **enhancement of H(125) cross-section at high m_{VV}**

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

  - 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:

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

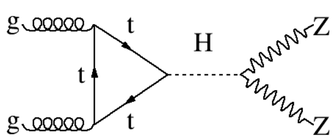
$$\frac{d\sigma^{\mathrm{off-peak}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \kappa^2_g \kappa^2_Z \frac{d\sigma^{\mathrm{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \mu r \frac{d\sigma^{\mathrm{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}}$$

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

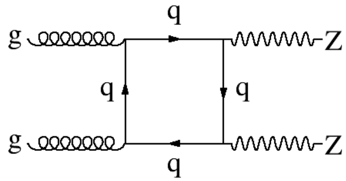
$$\kappa_Z = g_{HZZ} / g^{SM}_{HZZ}$$

$$r = \Gamma_H / \Gamma^{SM}_H$$

- Once the "signal strength" μ is fixed from an independent source a determination of r is obtained



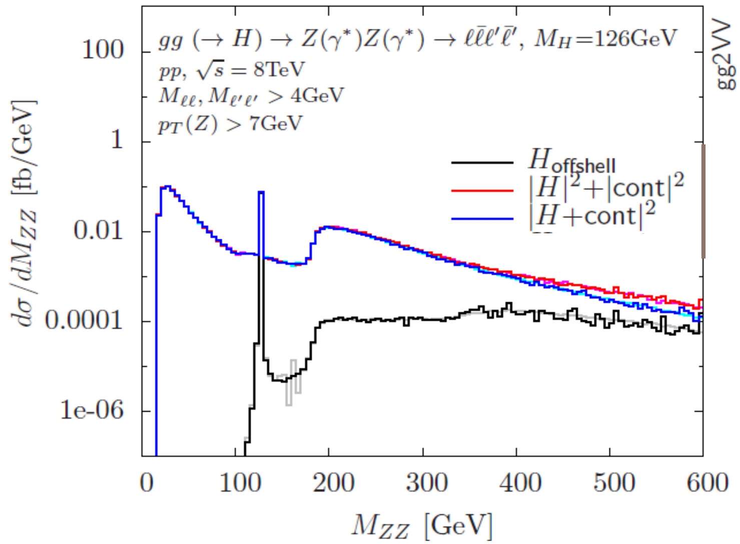
- Caution: the interference with continuum $gg \to ZZ$ is not negligible at high m_{ZZ}

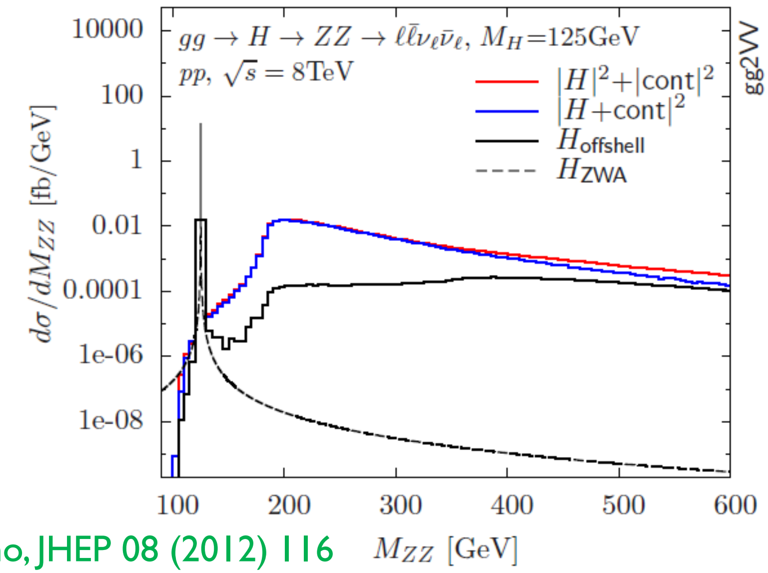


The 4l and 2l2ν final states

Generator-level distributions with approximated CMS experimental cuts

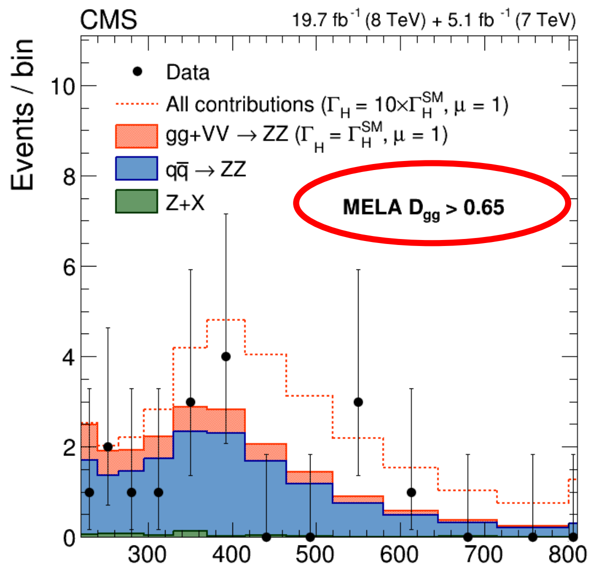
- 4l final state (l = e, μ)
  - At high mass, basically only background is $q\bar{q} \rightarrow ZZ$
  - Fully reconstructed state → can use matrix element probabilities of lepton 4-vectors to distinguish between gg and $q\bar{q}$ production
- 2l2ν final state (l = e, μ)
  - Much larger BR (x6) but smaller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

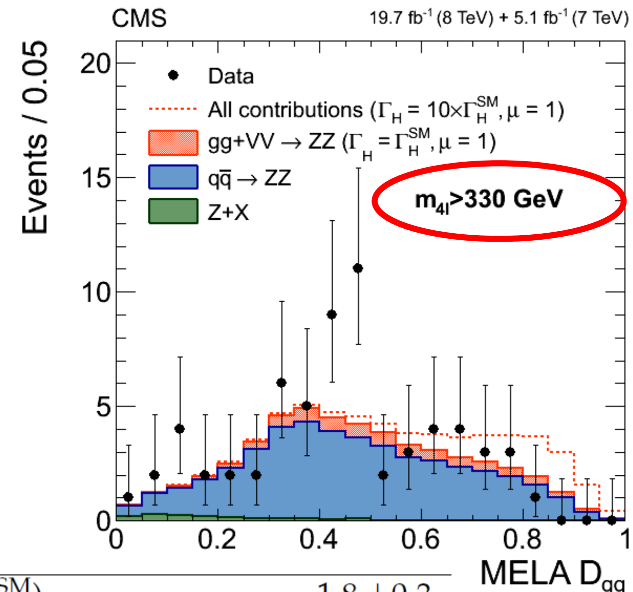




N. Kauer and G. Passarino, JHEP 08 (2012) 116

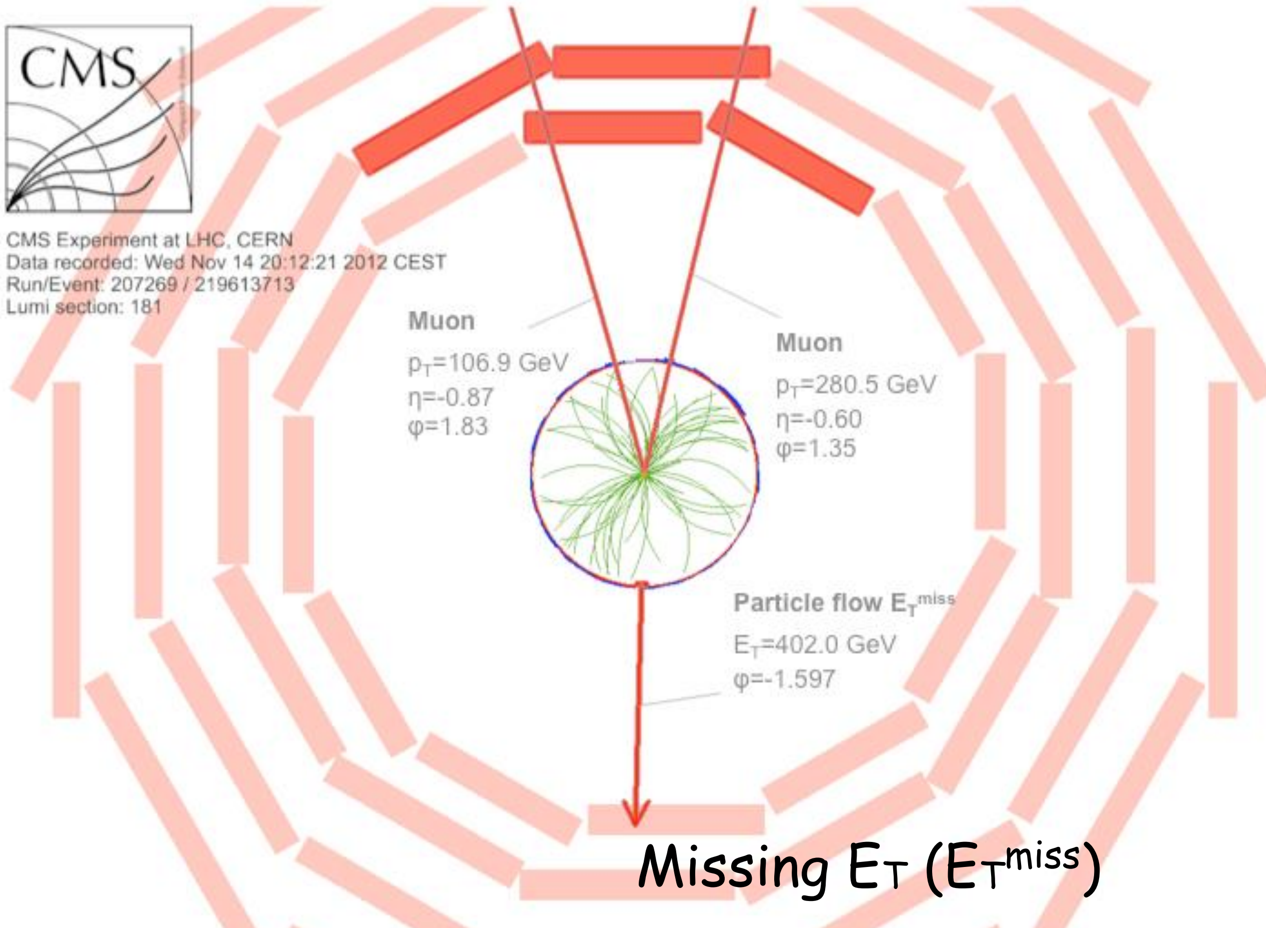
Yields in signal-enriched region





(a)	total gg ($\Gamma_H = \Gamma_H^{SM}$)	1.8 ±0.3
	gg signal component ($\Gamma_H = \Gamma_H^{SM}$)	1.3 ±0.2
	gg background component	2.3 ±0.4
(b)	total gg ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	9.9 ±1.2
(c)	total VBF ($\Gamma_H = \Gamma_H^{SM}$)	0.23 ±0.01
	VBF signal component ($\Gamma_H = \Gamma_H^{SM}$)	0.11 ±0.01
	VBF background component	0.35±0.02
(d)	total VBF ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	0.77 ±0.04
(e)	$q\bar{q}$ background	9.3 ±0.7
(f)	other backgrounds	0.05 ±0.02
(a+c+e+f)	total expected ($\Gamma_H = \Gamma_H^{SM}$)	11.4 ±0.8
(b+d+e+f)	total expected ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	20.1 ±1.4
	observed	11

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

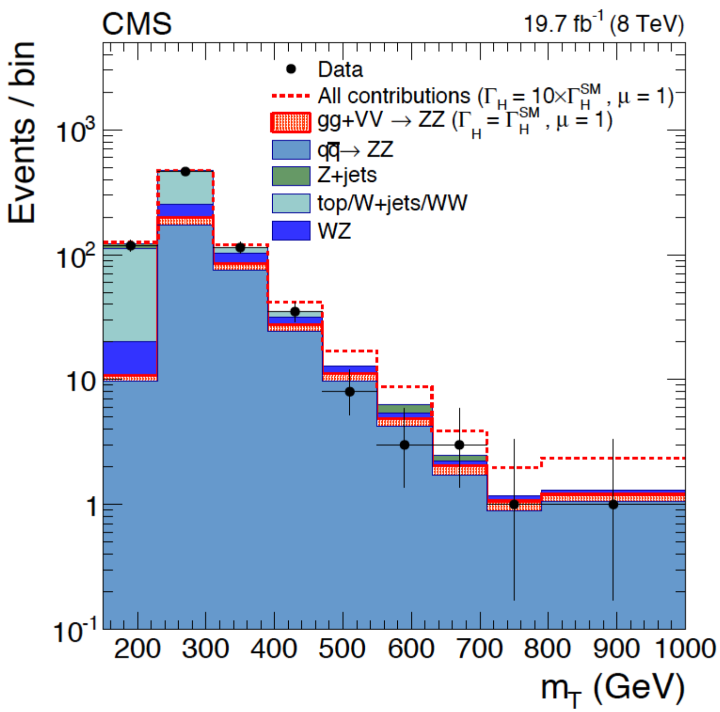


Analysis overview

- 6 times higher branching fraction compared to 4l final state
  - Branching ratio matters in high mass region where cross section is low
- Use only 8 TeV data
- Z+jets background is several orders of magnitude higher (fake E_T^{miss} due to hadronic energy mis-measurement)
- Other backgrounds
  - Irreducible: non-resonant ZZ, WZ
  - Non-resonant (not involving a Z boson): top production, WW
- Analysis variable is transverse mass:

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

m_T distribution and yields



		ee	$\mu\mu$
	gg signal ($\Gamma_H = \Gamma_H^{SM}$)	2.2±0.3	2.6±0.3
	gg background	4.9±0.8	5.9±0.9
(a)	total gg ($\Gamma_H = \Gamma_H^{SM}$)	4.4±0.7	5.3±0.8
(b)	total gg ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	18.3±2.5	21.5±2.7
	VBF signal ($\Gamma_H = \Gamma_H^{SM}$)	0.15±0.01	0.17±0.01
	VBF background	0.56±0.04	0.66±0.04
(c)	total VBF ($\Gamma_H = \Gamma_H^{SM}$)	0.43±0.03	0.48±0.03
(d)	total VBF ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	1.14±0.07	1.27±0.07
(e)	$q\bar{q} \to ZZ$	21.7±2.0	25.9±2.1
	WZ	11.0±1.2	12.7±1.3
	$t\bar{t}$/tW/WW	3.3±1.1	4.2±1.4
	Z + jets	1.5±0.9	2.4±1.4
(a+c+e)	total expected ($\Gamma_H = \Gamma_H^{SM}$)	42.3±2.8	51.0±3.2
(b+d+e)	total expected ($\Gamma_H = 10 \times \Gamma_H^{SM}$)	57.0±3.7	67.9±4.2
	observed	39	52

Systematic uncertainties

- Theoretical uncertainties
  - QCD renormalization and factorization scales
  - Variation of Parton Distribution Functions (PDFs)
- Experimental uncertainties
  - Lepton trigger, identification, isolation efficiencies
  - In the 2l2ν analysis, uncertainties on and jet energy scale are propagated to E_T^{miss}
  - Background estimations from data
  - Uncertainty on integrated luminosity
  - Limited statistics in MC or data control samples

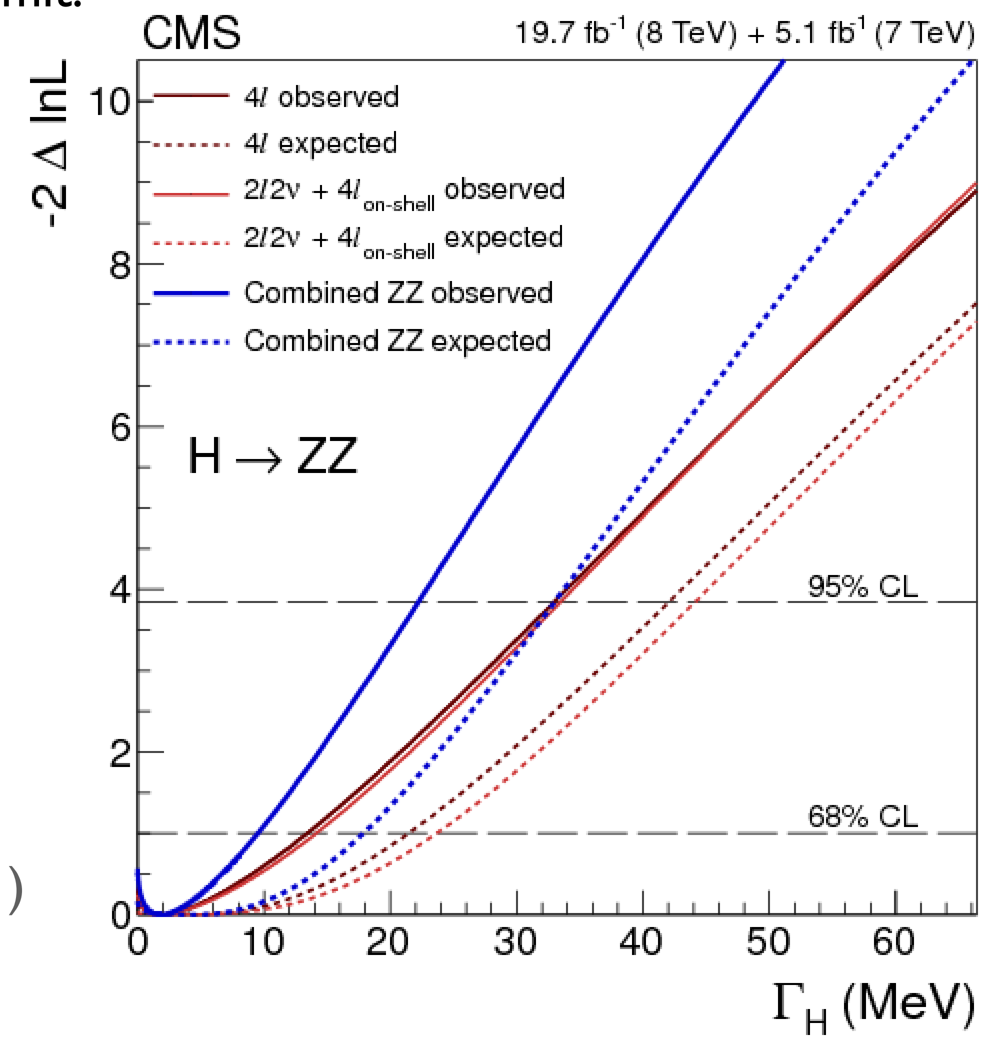
Combined results

Observed (expected) 95% CL limit:
r < 5.4 (8.0)
p-value = 0.25

Best fit value:
$r = 0.4^{+1.8}_{-0.4}$

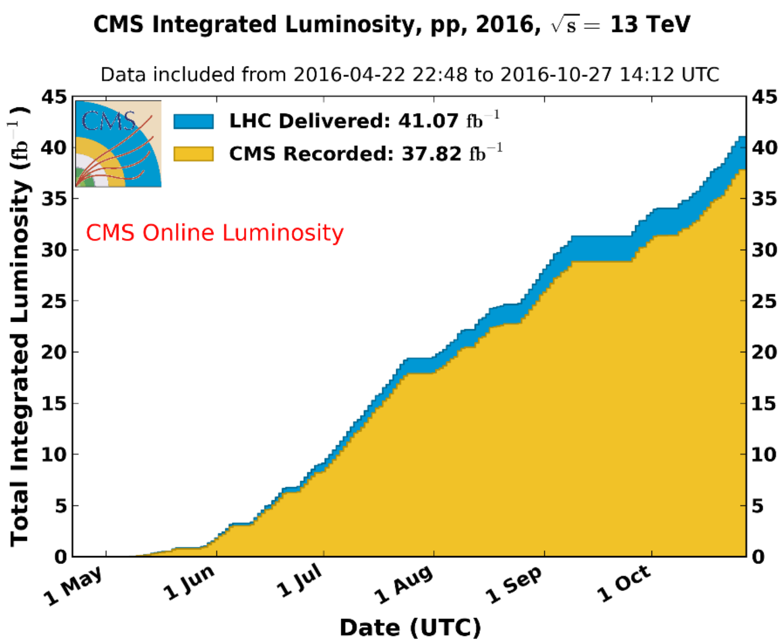
Equivalent to
Γ < 22 (33) MeV
$\Gamma = 1.8^{+7.7}_{-1.8}$ MeV

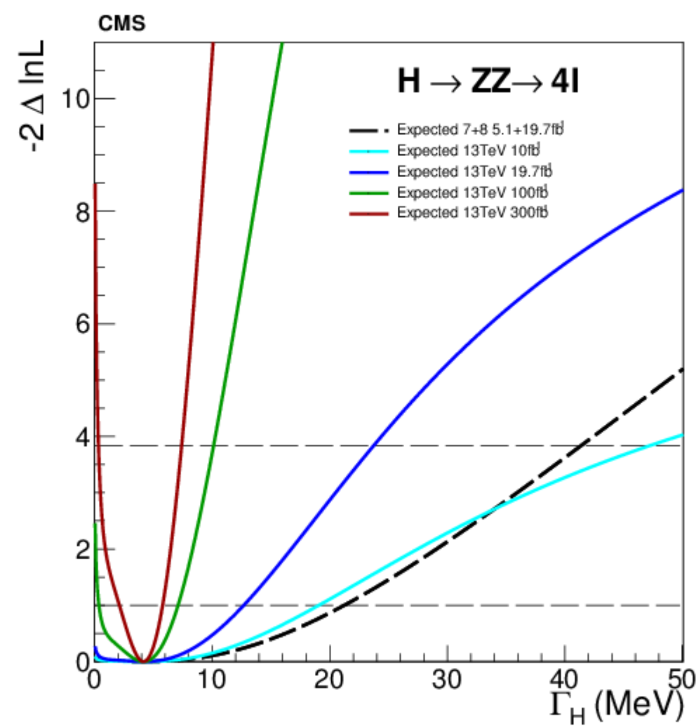
$\mu_{ggF} = 0.81^{+0.47}_{-0.37}$
$\mu_{VBF} = 1.7^{+2.2}_{-1.7}$
both compatible with SM (μ = 1)



The 13 TeV run

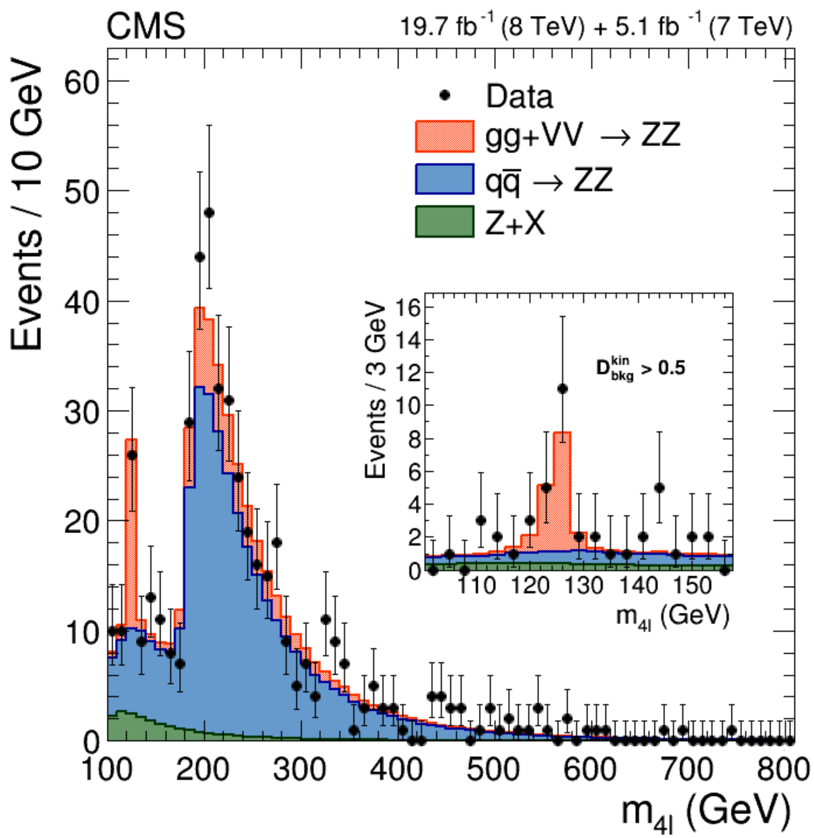
- A 13-TeV run is ongoing (2016-2018) – expect > 100 fb^{-1}
- Next steps:
  - Measure fraction of pseudoscalar component (if Higgs is not a P eigenstate)
  - **[Measure Higgs width!!!]**





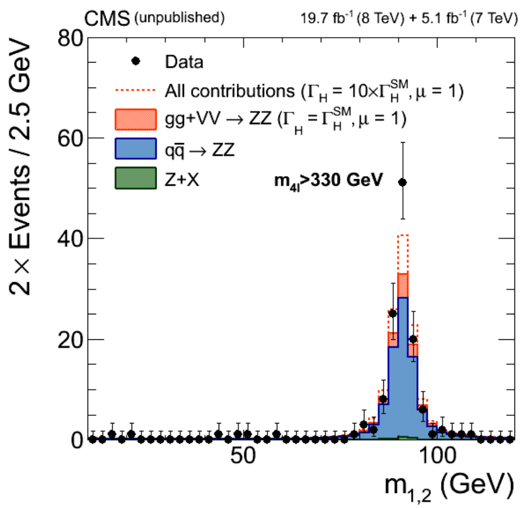
Back up

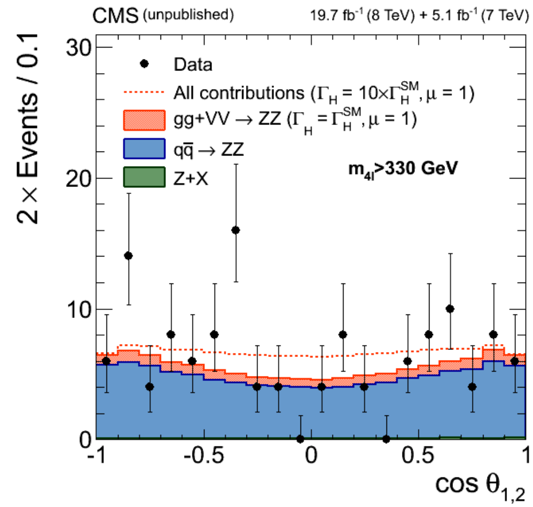
4l mass

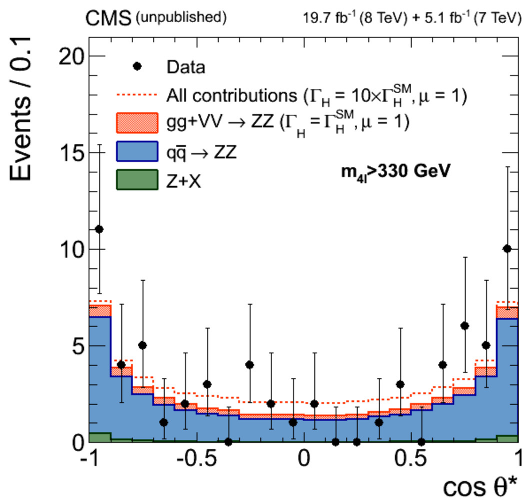


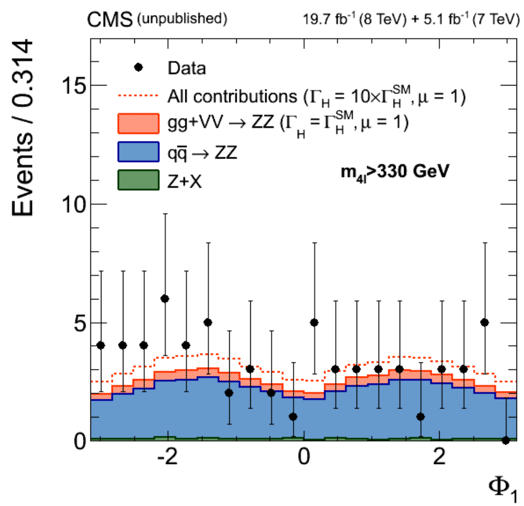
CMS
19.7 fb^{-1} (8 TeV) + 5.1 fb^{-1} (7 TeV)
Data
gg+VV → ZZ
q$\bar{q}$ → ZZ
Z+X
Events / 10 GeV
m_{4l} (GeV)
Events / 3 GeV
D^{kin}_{bkg} > 0.5
m_{4l} (GeV)

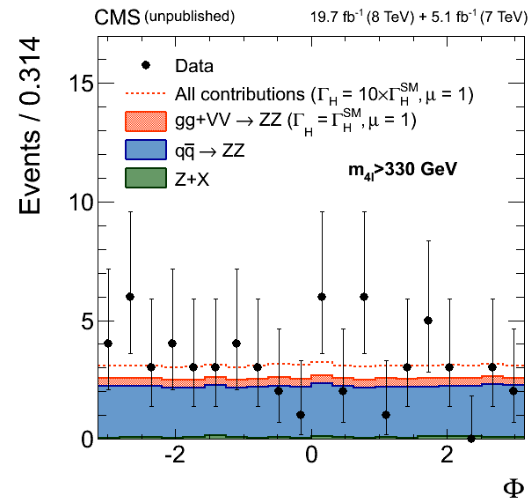
Input to Dgg in signal-enriched region



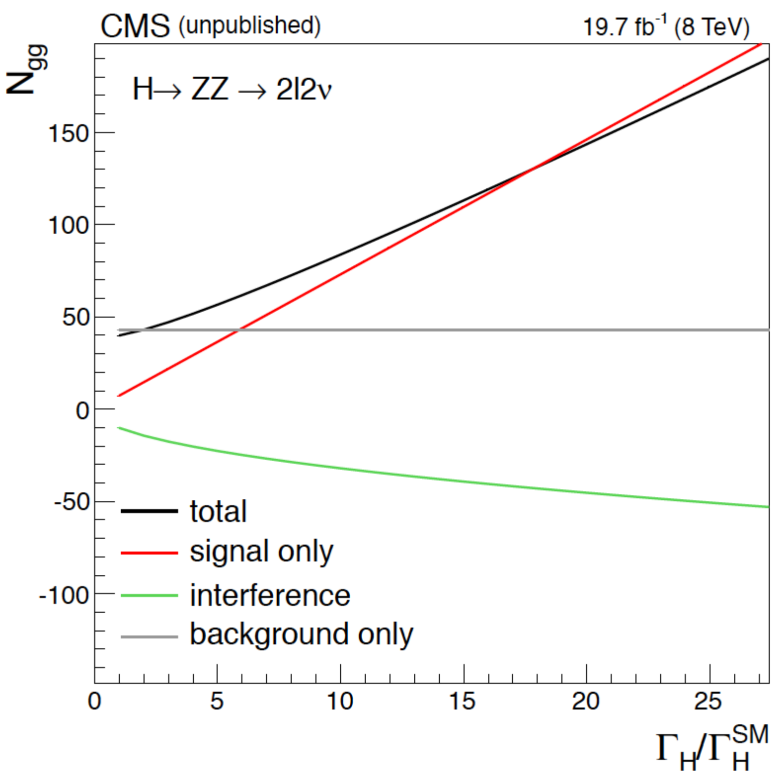


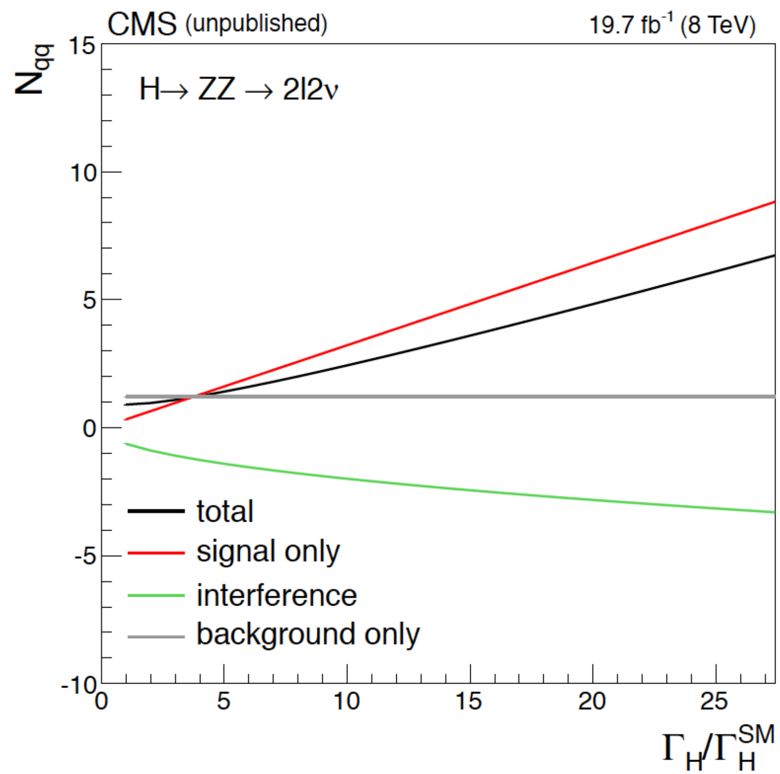






Yields vs width (loose Missing ET cut)

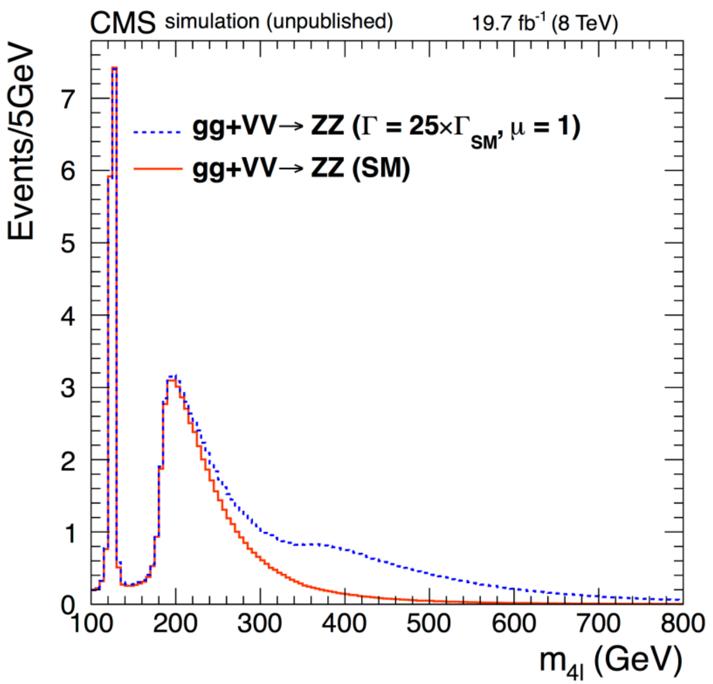


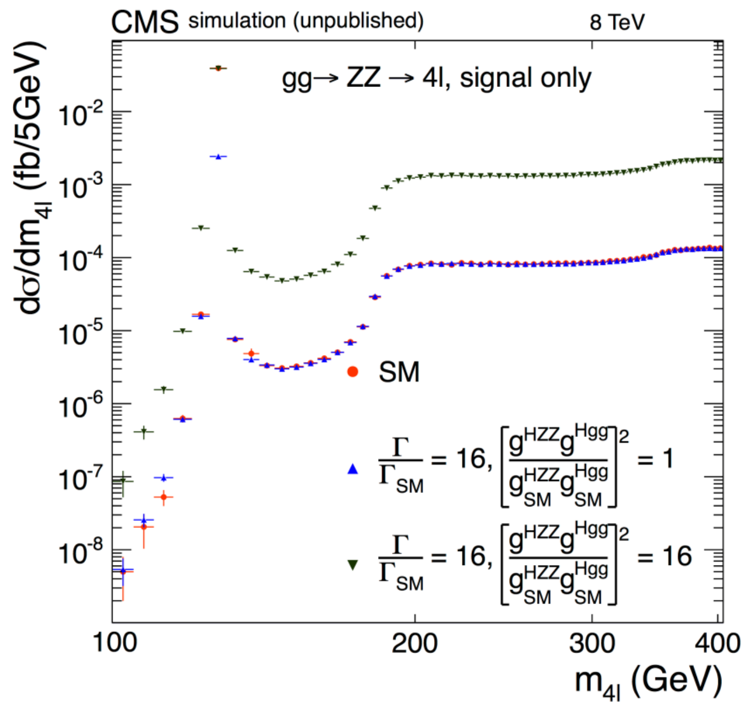


Systematics

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, gluon-gluon initial state (ggZZ)	7+shape
QCD scale, quark-quark initial state (qqVV)	5.8-8.5+shape
$gg \to$ ZZ k-factor uncertainty	10
Underlying event and parton shower	6

Effect of Γ / coupling scalings





R. Covarelli

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:

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

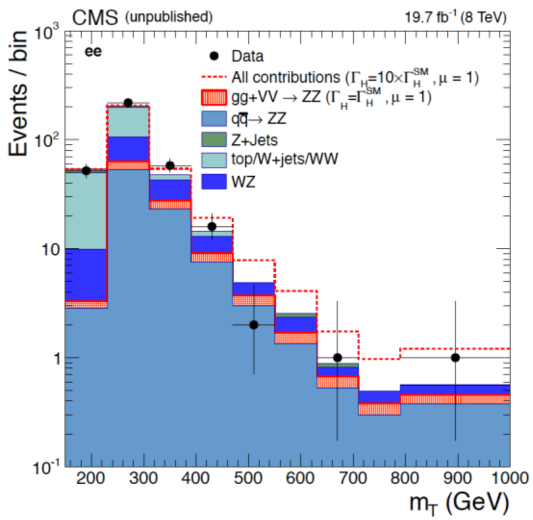
Full formula of MELA D_{gg}

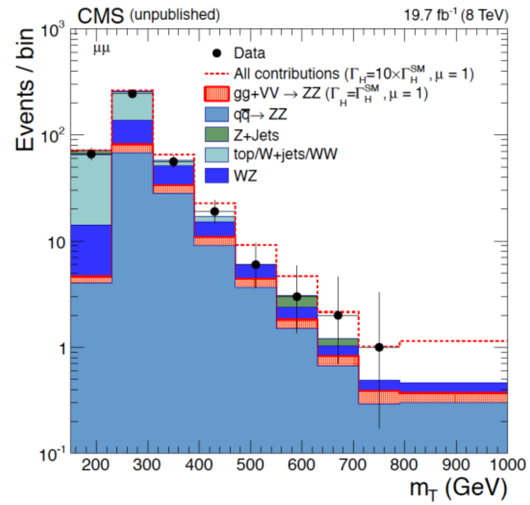
$$\mathcal{D}_{gg,a} = \frac{\mathcal{P}_{gg,a}}{\mathcal{P}_{gg,a} + \mathcal{P}_{q\bar{q}}} = \left[1 + \frac{\mathcal{P}^{q\bar{q}}_{bkg}}{a \times \mathcal{P}^{gg}_{sig} + \sqrt{a} \times \mathcal{P}^{gg}_{int} + \mathcal{P}^{gg}_{bkg}}\right]^{-1}$$

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

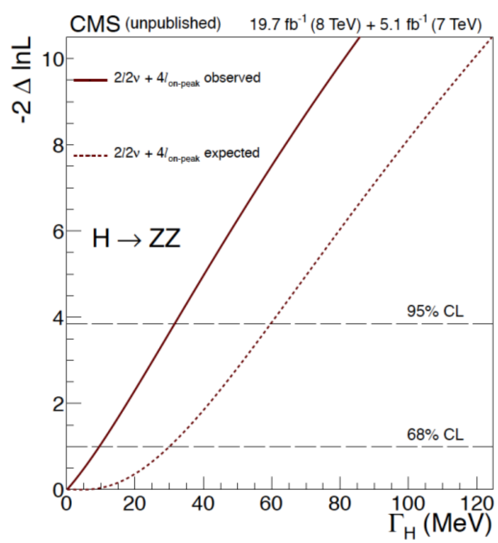
2l2ν: breakdown by channel

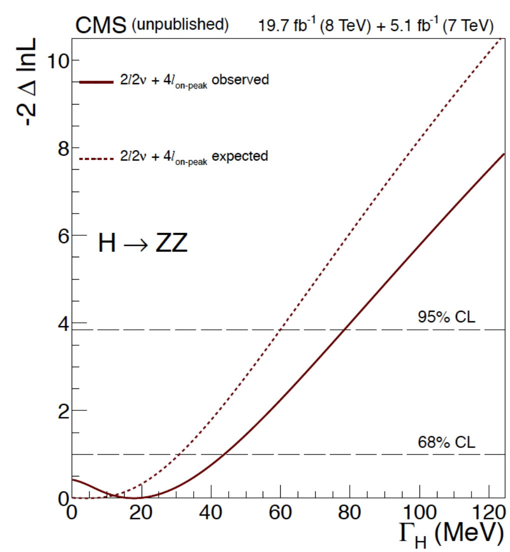
ee





μμ





Results with no systematics