How Wide is the Higgs Boson: off-shell constraints from CMS

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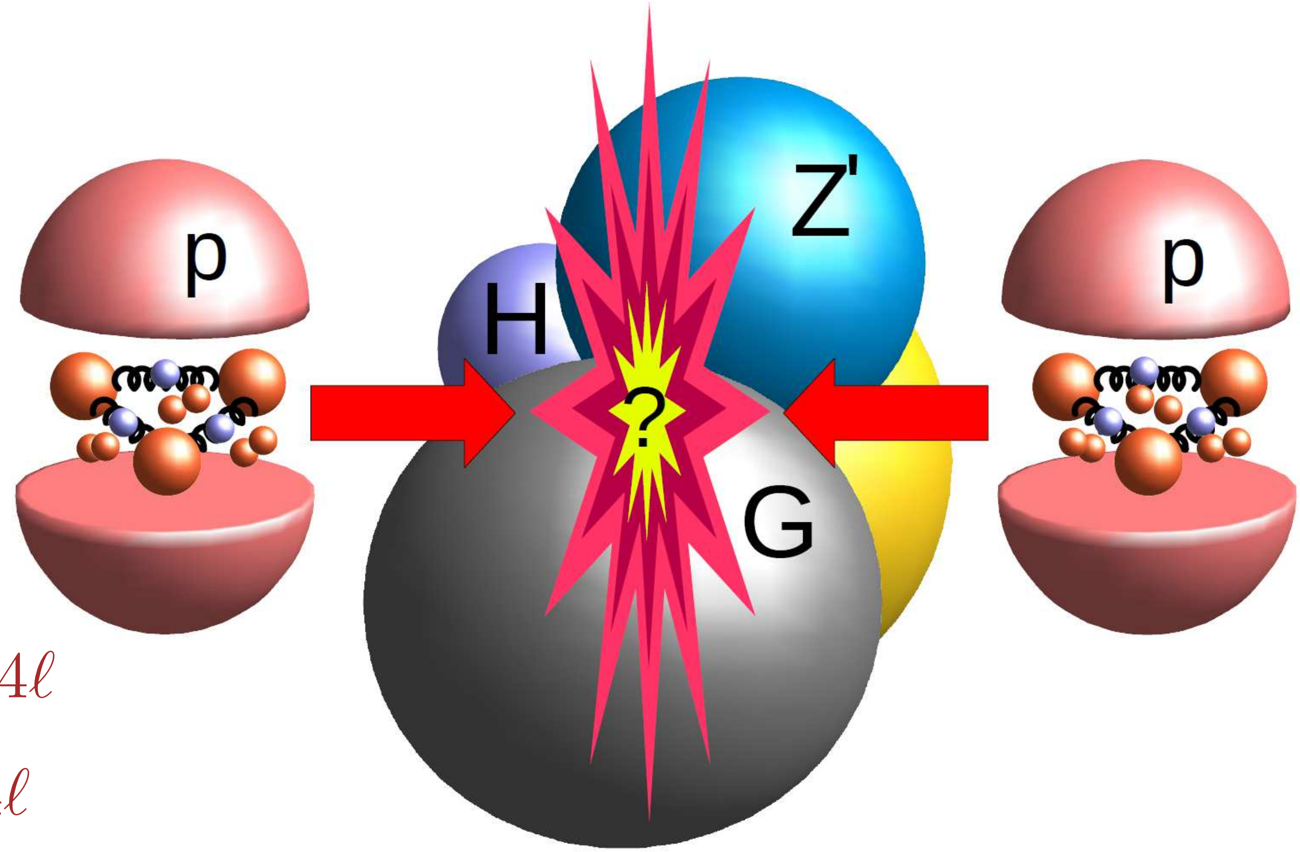
SLAC Experimental Seminar

Overview

- Introduction
- The Higgs boson
- How we see it
- Off-shell production
- Data analysis
  - $H \to Z^*Z^* \to 4\ell$
  - $H^* \to ZZ \to 4\ell$
  - $H^* \to ZZ \to 2\ell 2\nu$
- Theoretical considerations
- Summary and outlook

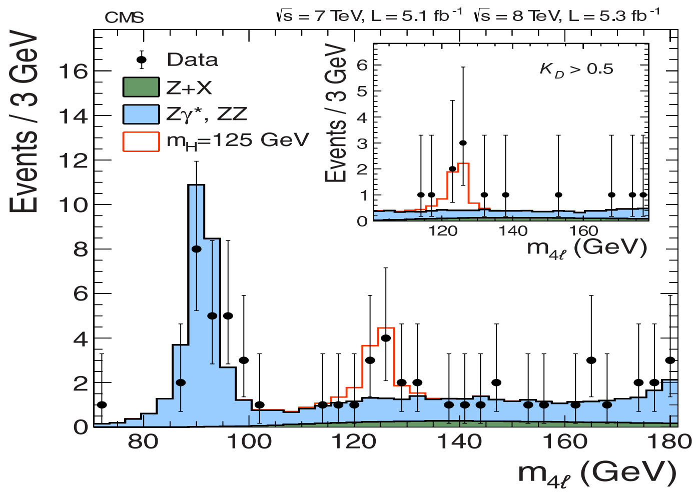


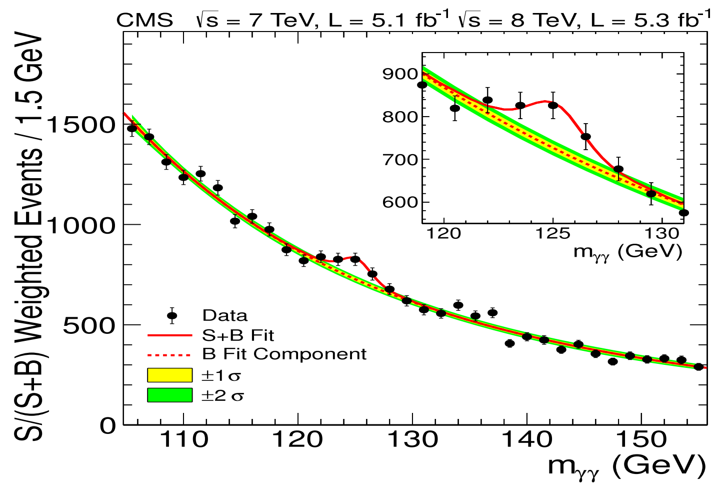
A FEW SLIDES OF HISTORY

July 2012: Observation of a New Boson

- Observation of a New Boson on CMS: 5σ excess

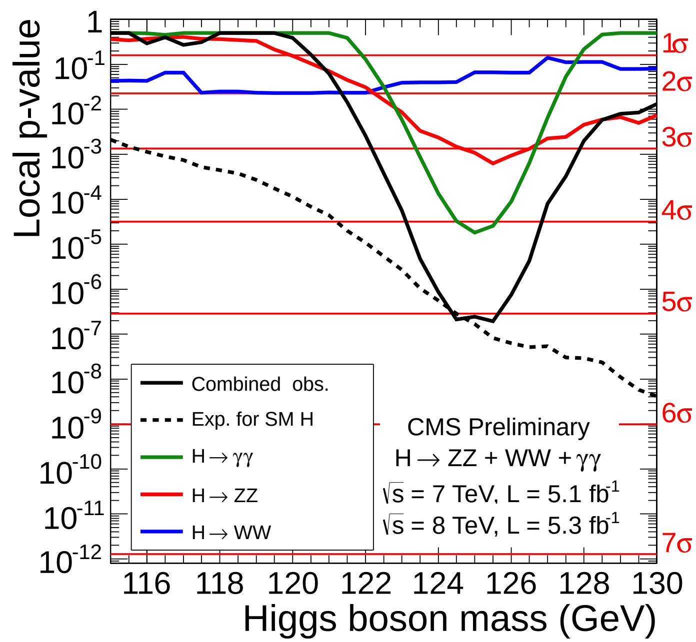
$X \to Z^{(*)}Z^{(*)}$ $\qquad\qquad$ $X \to \gamma\gamma$





- Probability of background

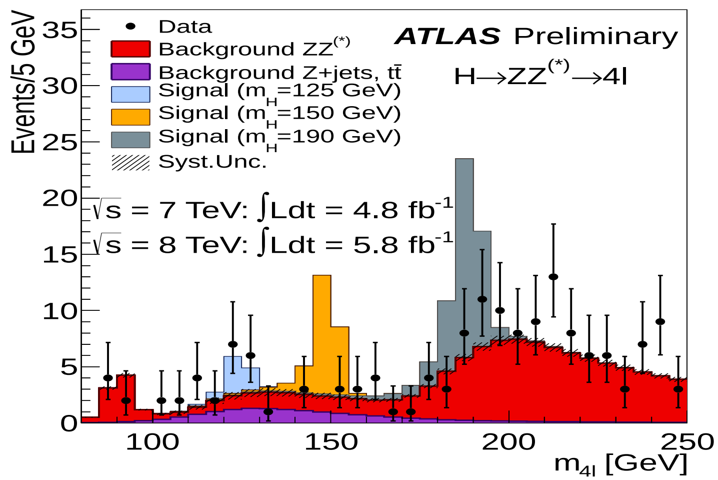
$$\sim 0.2 \times 10^{-6}$$

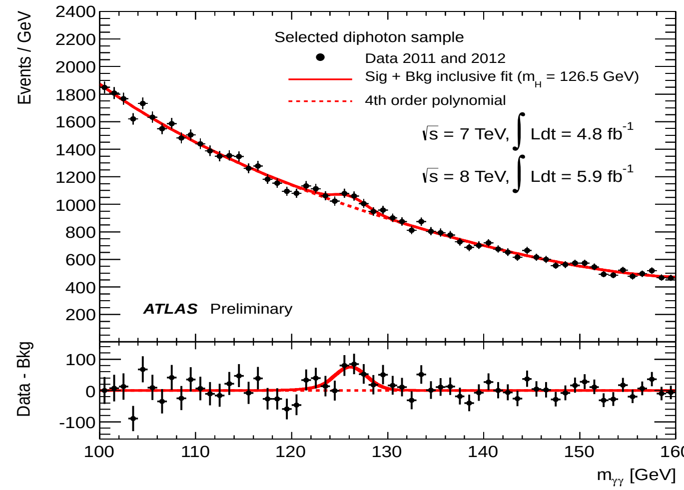


July 2012: Observation of a New Boson

- Observation of a New Boson on ATLAS: 5σ excess

$X \to Z^{(*)}Z^{(*)}$ $\qquad$ $X \to \gamma\gamma$





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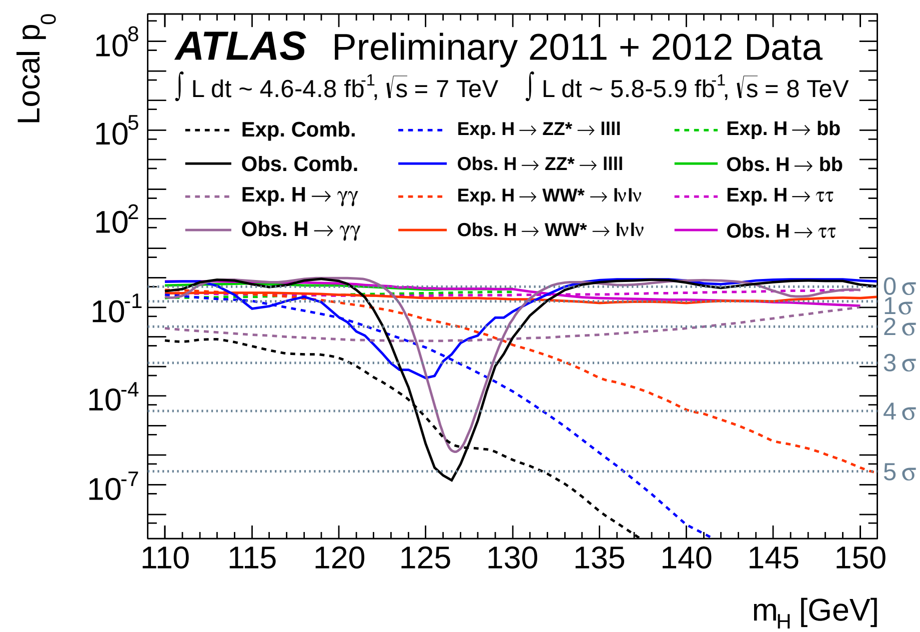
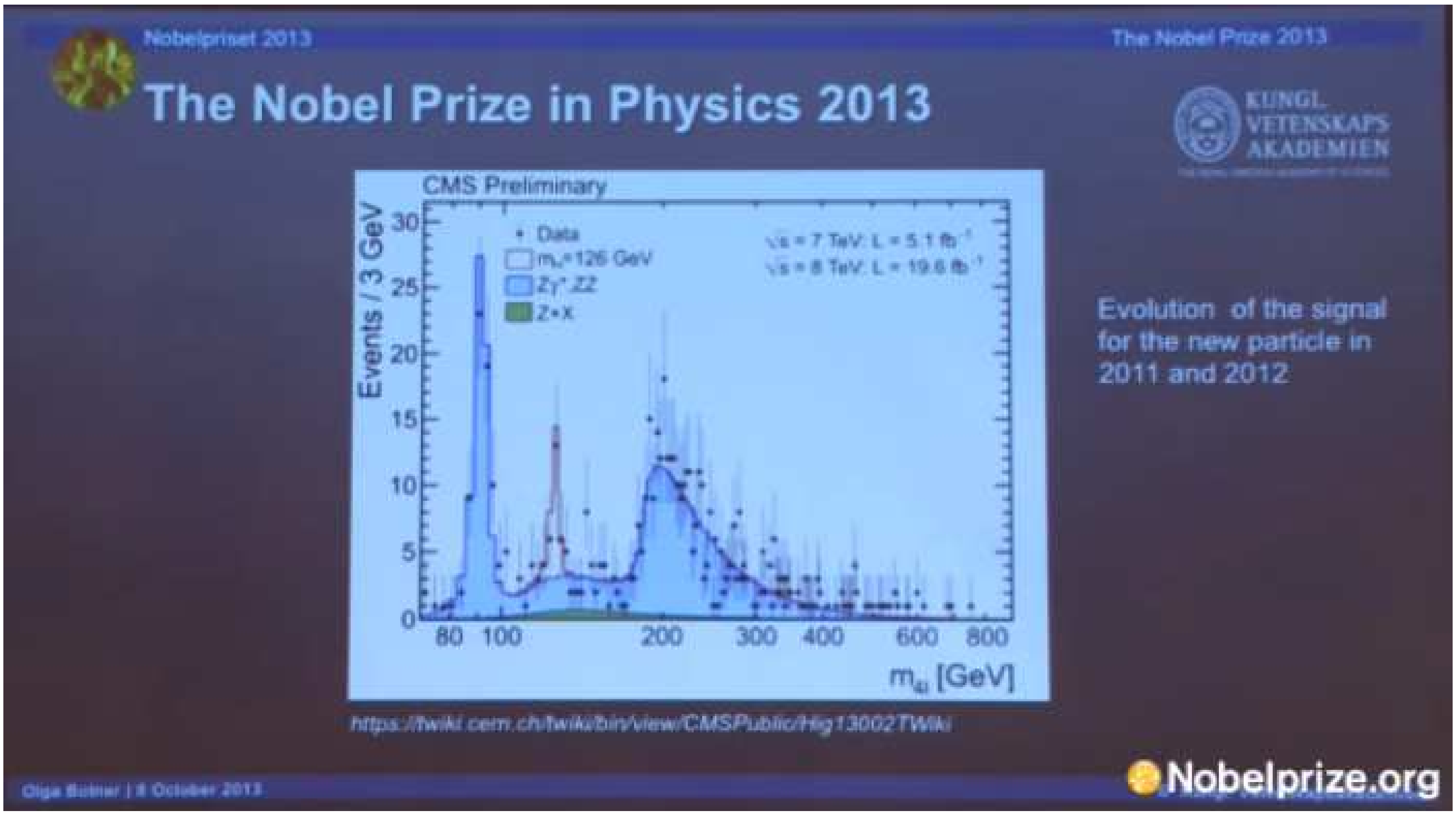


The Higgs Boson Signal on CMS

- Excellent signal $H \to ZZ, WW, \gamma\gamma, \tau^+\tau^-, b\bar{b}$

  6.8, 4.3, 3.2, 3.2, 2.1σ

  (6.7, 5.8, 3.9, 3.7, 2.1σ expected)



Discovery of a Higgs Boson

- Discovery of a Higgs Boson

– absolutely new form of matter-energy
– consistent with fundamental $J^P = 0^+$
  scalar excitation of a vacuum field

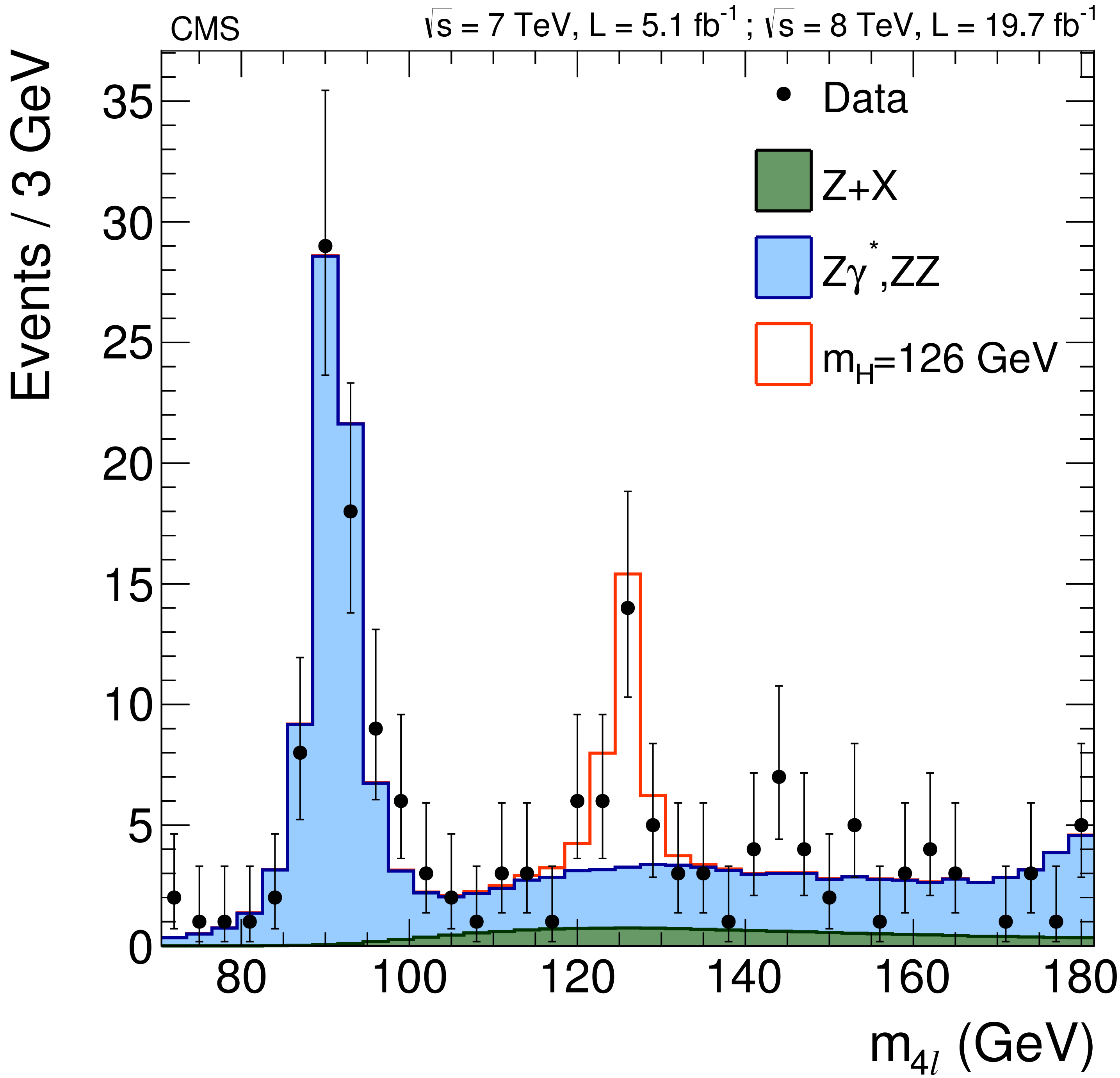
- It would be foolish to stop here

– mass (is Universe stable, are EW data consistent?..)
– width / lifetime (are there missing final states?)
– quantum numbers (is there CP violation?..)
– coupling strength in production and decay (is it the right Higgs?..)

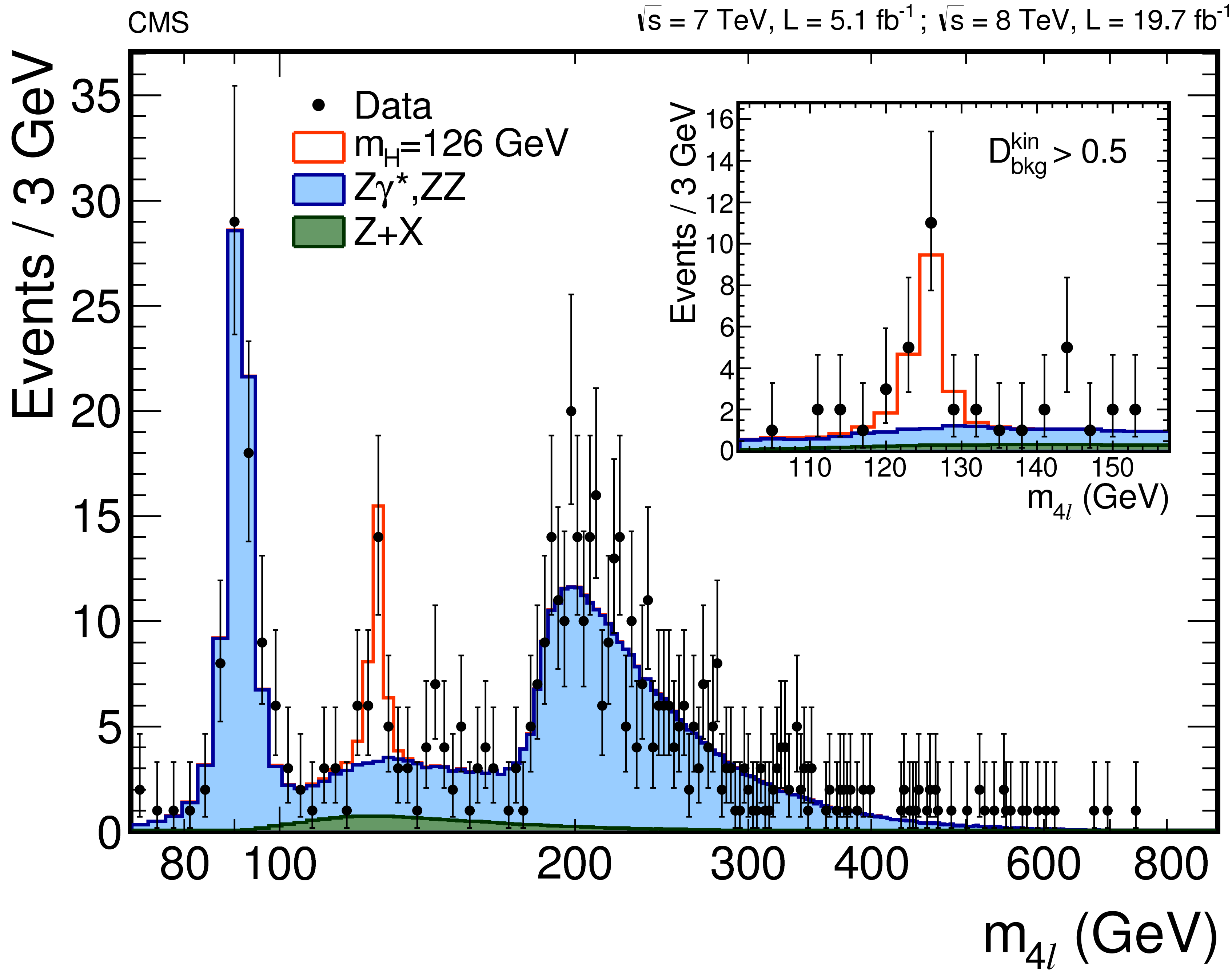
- It is also a triumph of predictive power of scientific knowledge

– we knew where to look
– but a discovery was not guaranteed, also true for the next steps

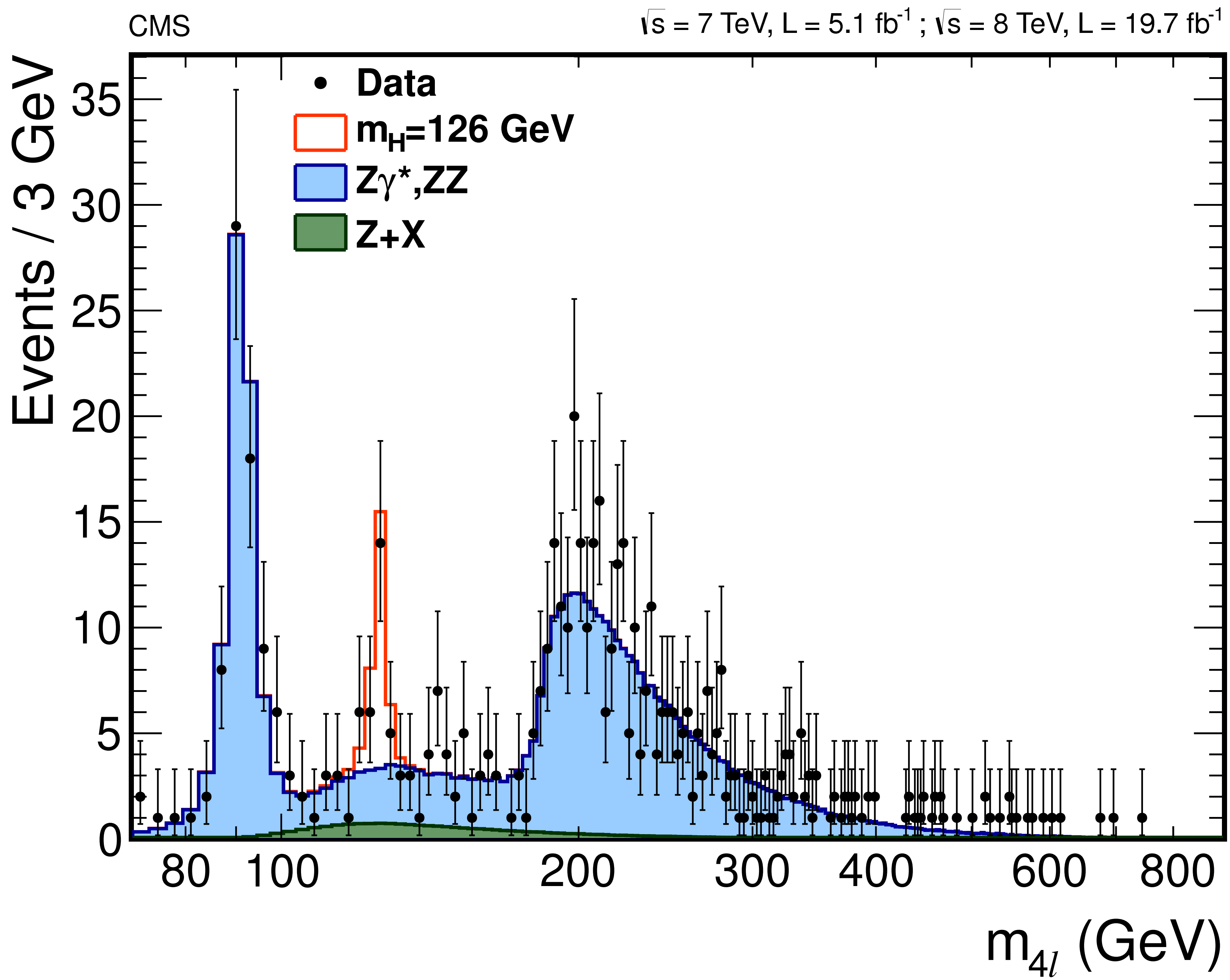
The Higgs$\rightarrow ZZ \rightarrow 4\ell$ Signal on CMS



The Higgs→ $ZZ \to 4\ell$ Signal on CMS



The Higgs$\rightarrow ZZ \rightarrow 4\ell$ Signal on CMS



TOPIC FOR TODAY

References for Today Presentation

- "Constraints on the Higgs boson width
  from off-shell production and decay to Z-boson pairs"

  CMS-HIG-14-002 (Moriond - 2014), arXiv:1405.3455 [hep-ex]

  submitted to PLB on May 14, 2014

- "Measurement of the properties of a Higgs boson
  in the four-lepton final state" (CMS $H \to ZZ$ Run1 "legacy")

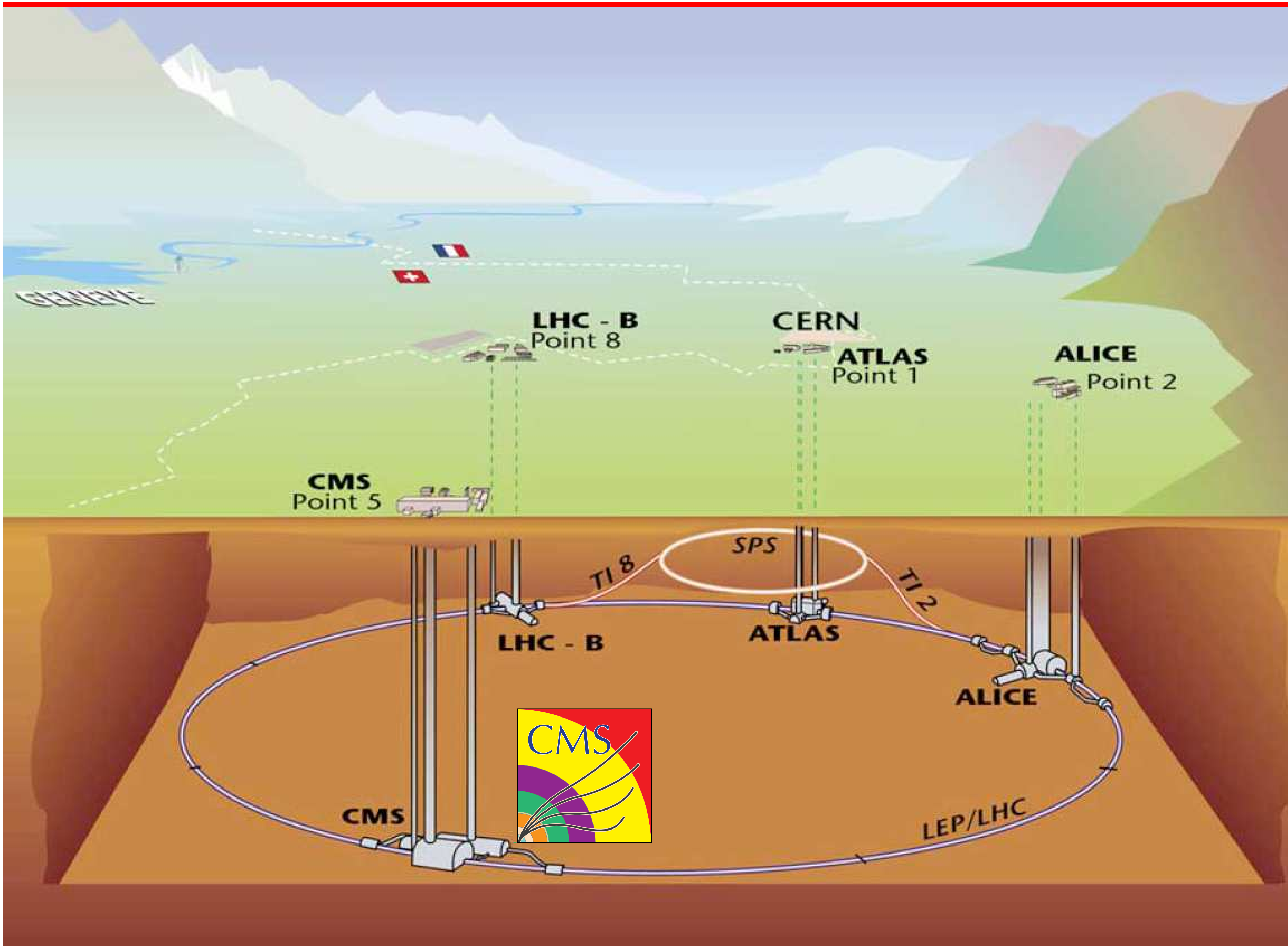
  CMS-HIG-13-002 (Moriond - 2013), arXiv:1312.5353 [hep-ex]

  published in PRD,89,092007 on May 14, 2014

- "Higgs Working Group Report
  of the Snowmass 2013 Community Planning Study"

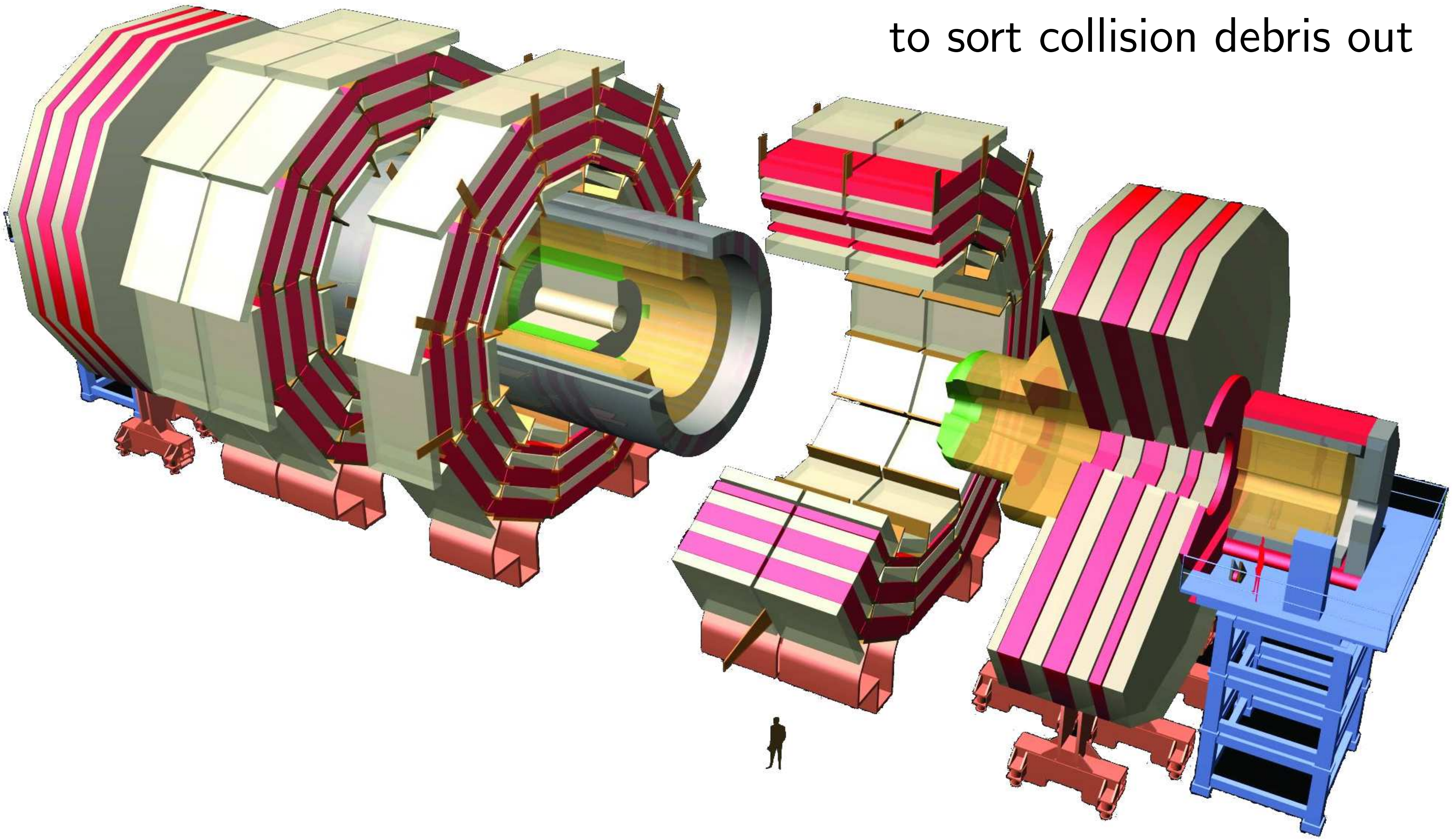
  arXiv:1310.8361 [hep-ex]

The Large Hadron Collider



The CMS Detector

- Complex detector
  to sort collision debris out



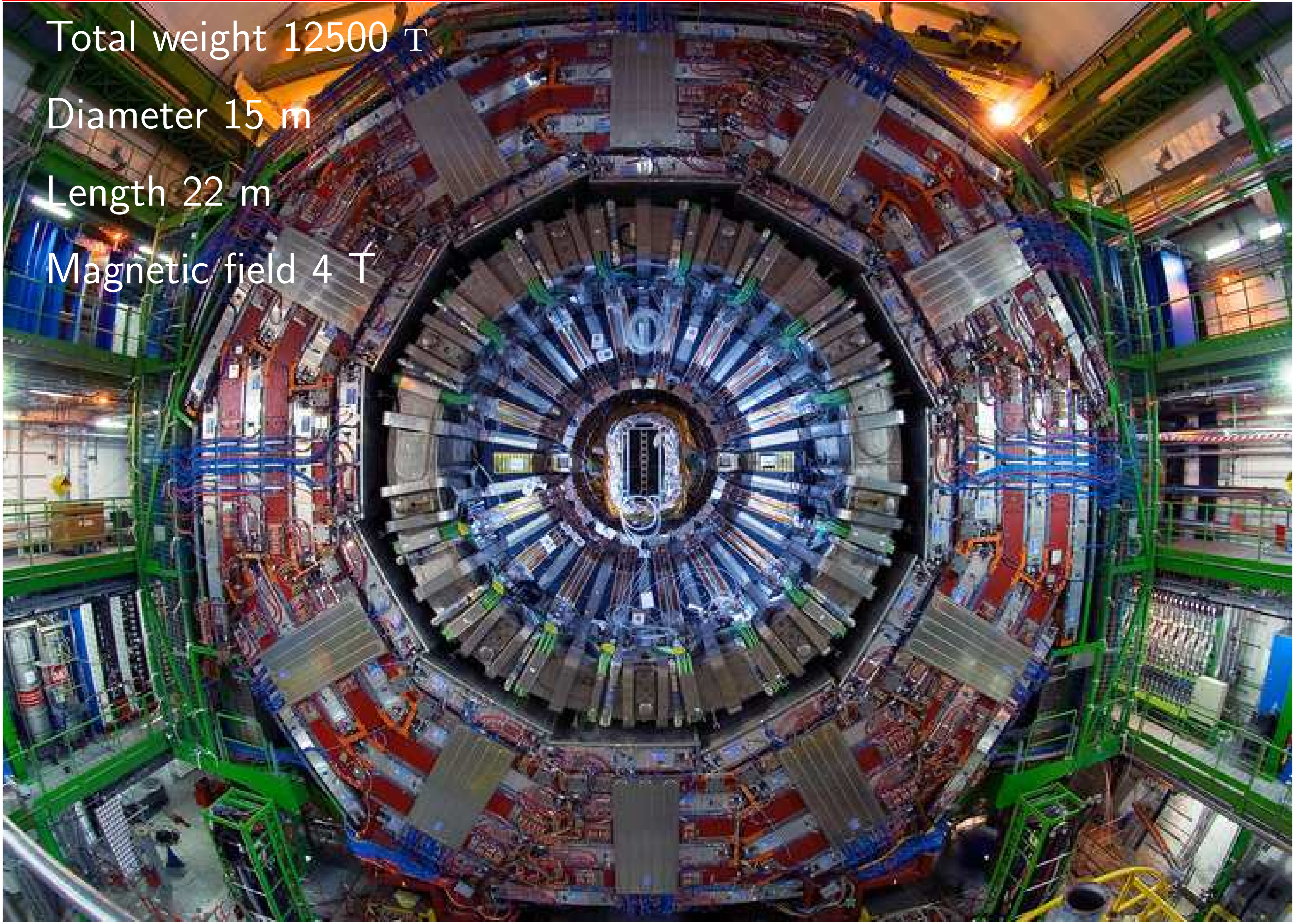
The CMS Detector

Total weight 12500 T

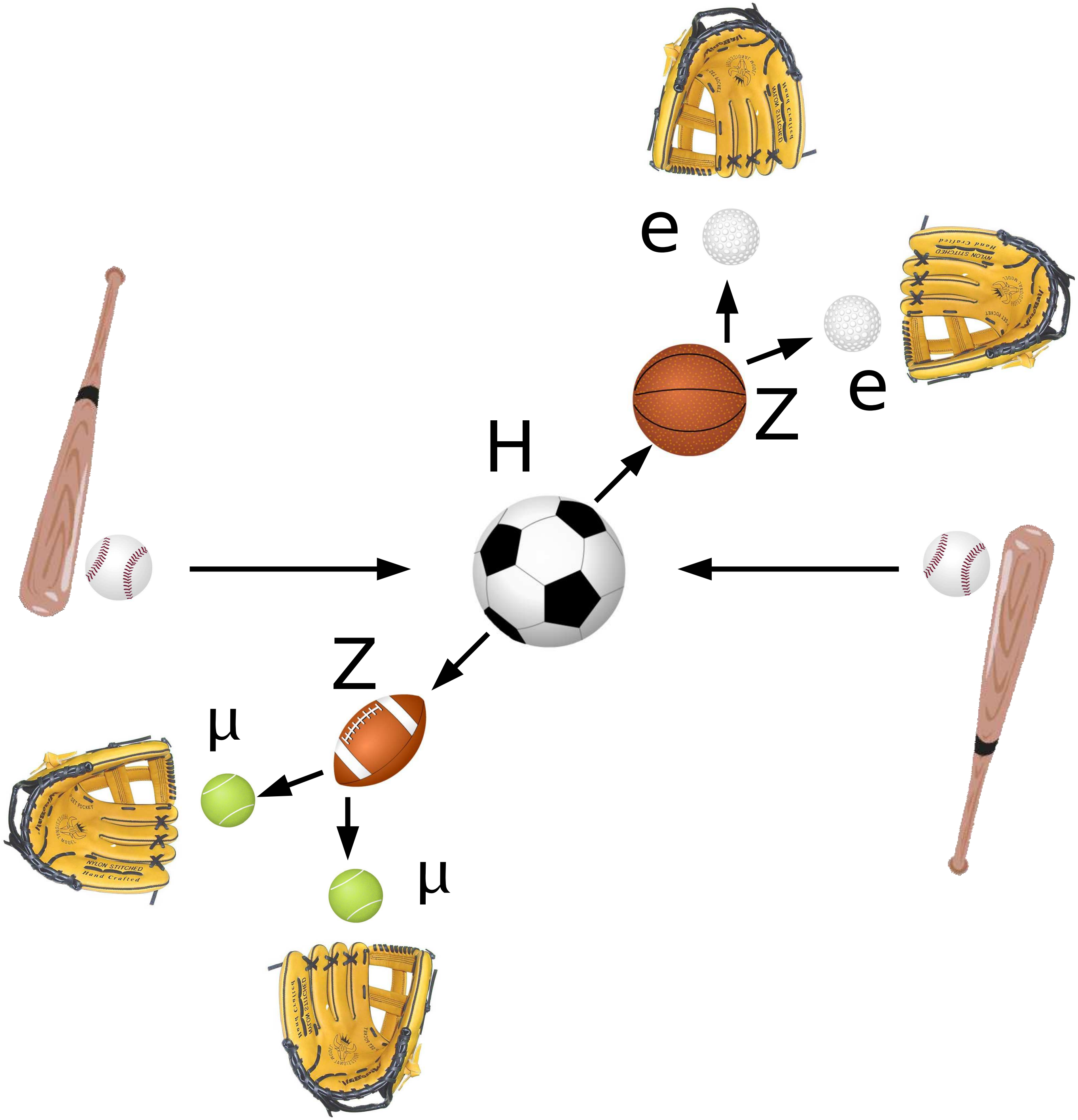
Diameter 15 m

Length 22 m

Magnetic field 4 T

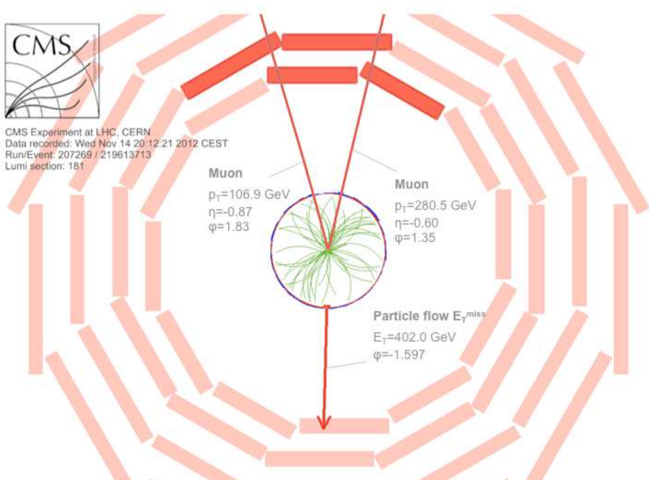


The Experiment

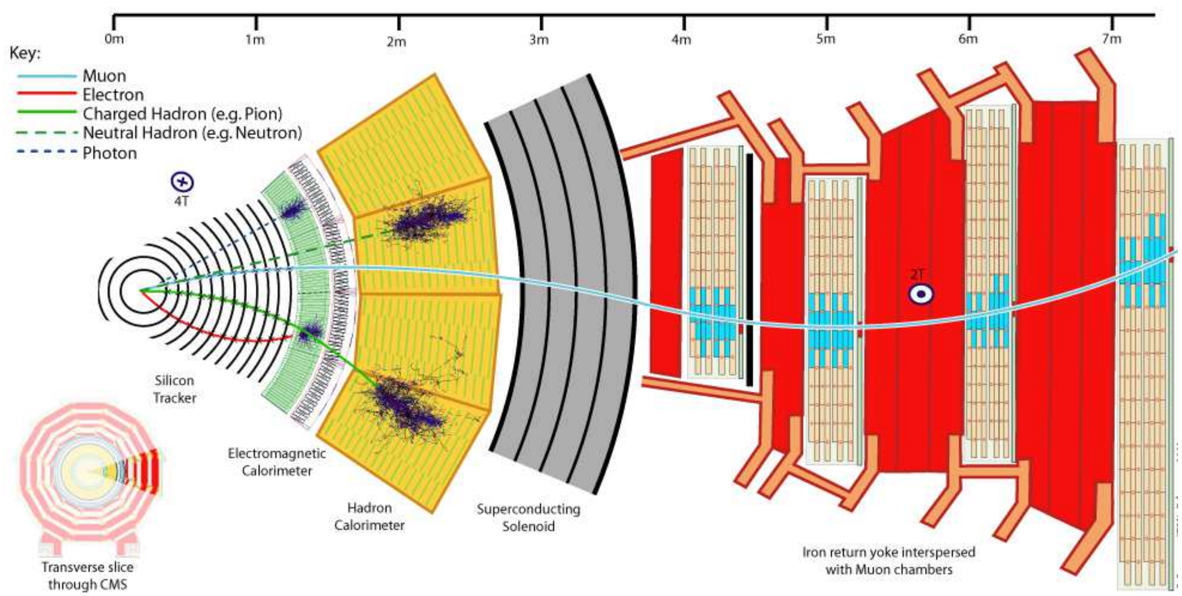


Detection of Major Objects

- Leptons: $\ell^\pm$ in Si Tracker: $e^\pm$ (EM Calorimeter), $\mu^\pm$ (Muon System)
- Photons: γ (EM Calorimeter)
- Quark q & gluon g jets → "Particle Flow" thru Hadronic Calorimer
- Neutrinos $\nu \Rightarrow$ missing energy ("MET")

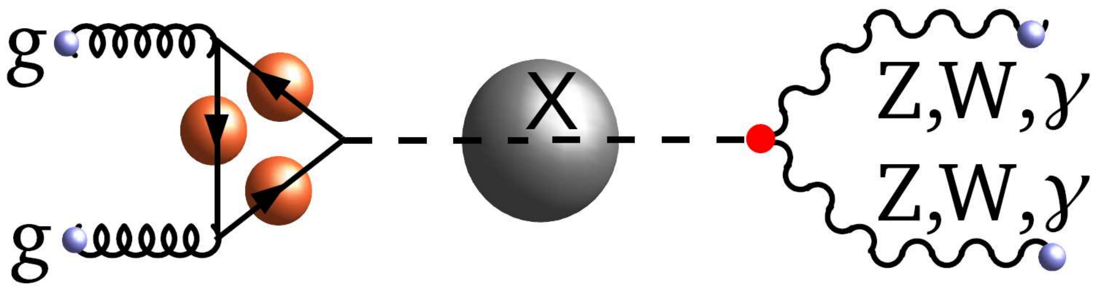


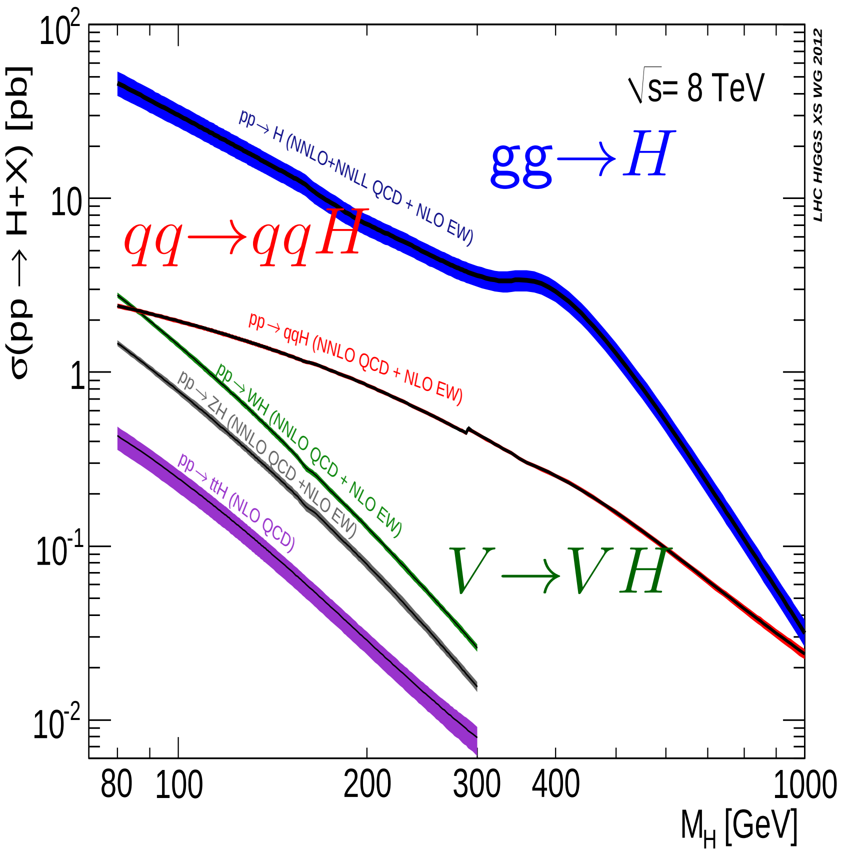
$ZZ \to (\mu^+\mu^-)(\nu\bar{\nu})$

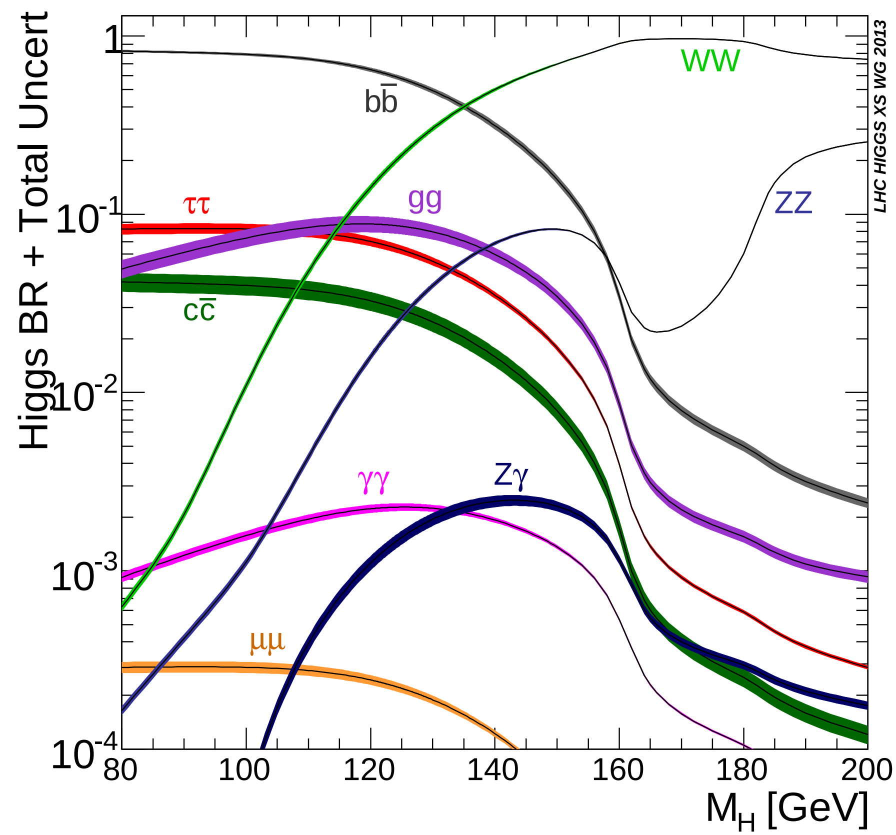


Production and Decay of a Higgs Boson

- Excite vacuum: gg, VBF,.. $\rightarrow H \rightarrow ZZ^{(*)}, WW^{(*)}, \gamma\gamma, \tau^+\tau^-, b\bar{b}$,..



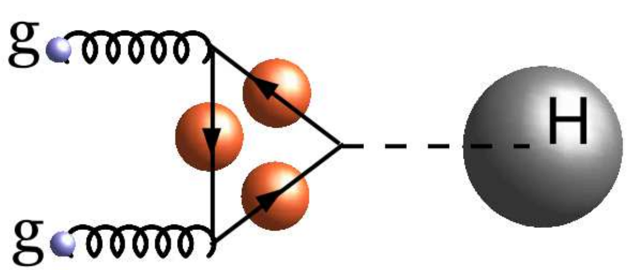




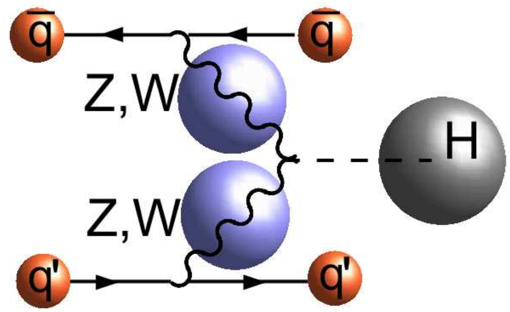
Signal and Background

- At LHC might have produced > 200000 Higgs bosons / experiment

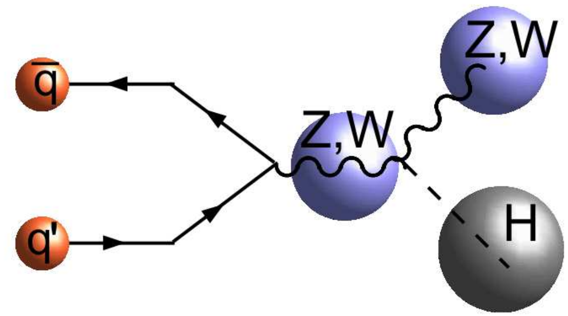
gluon fusion



weak boson fusion

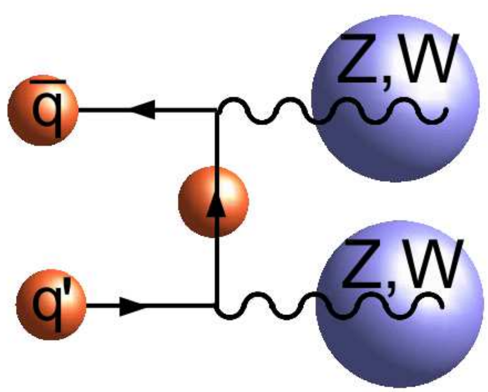


associated production

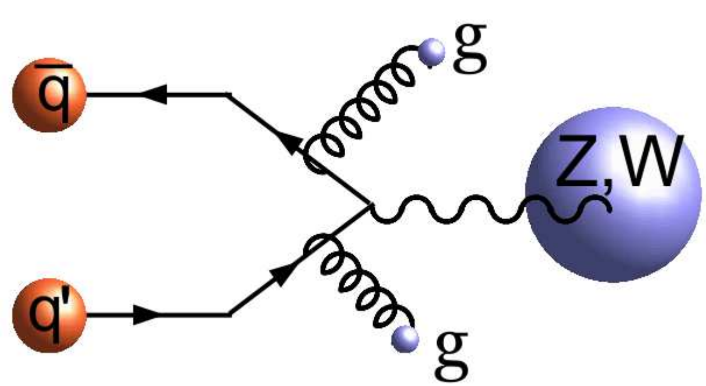


- The challenge is to distinguish signal from backgrounds, examples:

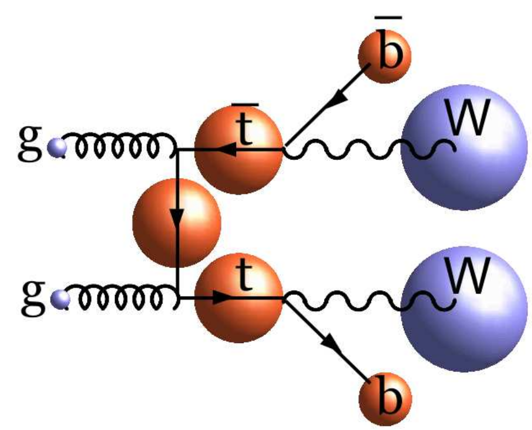
$q\bar{q} \to ZZ^{(*)}(\gamma^{(*)})$



$q\bar{q} \to Z(\gamma)+$jets

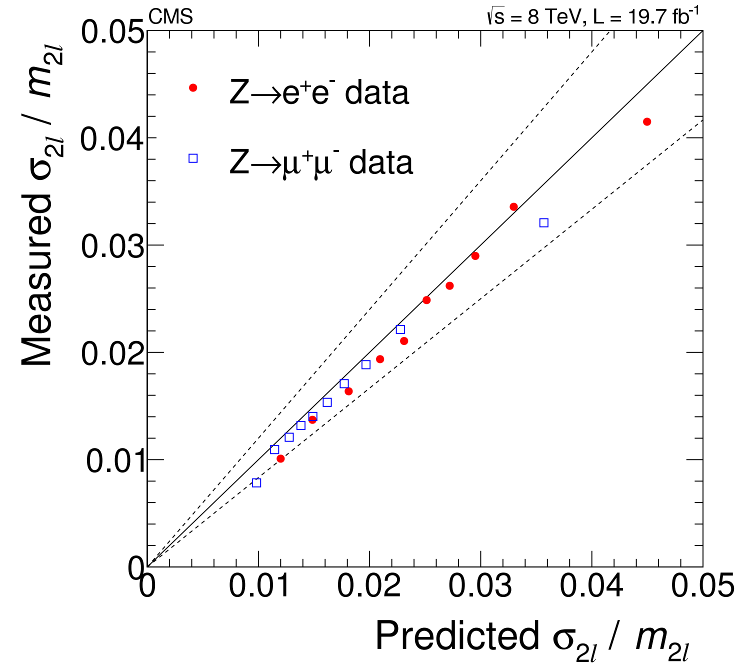


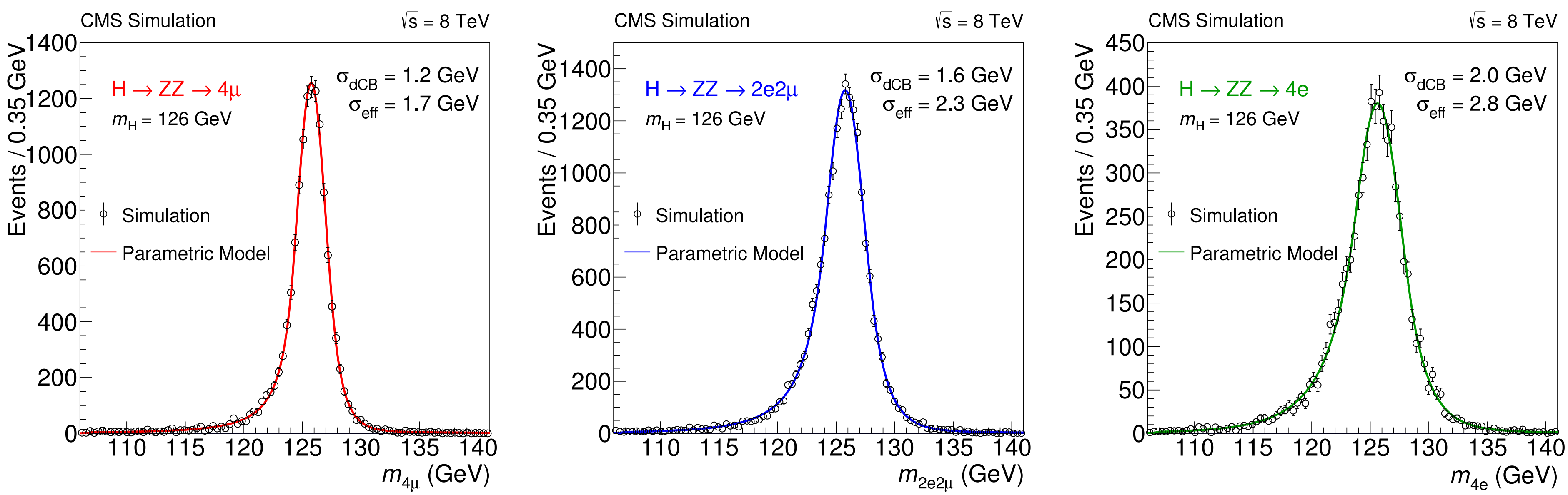
gg$\to t\bar{t}$



Track / Mass Resolution

- $H \to ZZ \to (\ell^+\ell^-)(\ell^+\ell^-)$
  - excellent mass resolution $\sim 1\%$
  - good control with $Z, J/\psi \to \ell^+\ell^-$
  - measure mass m_H and width Γ_H





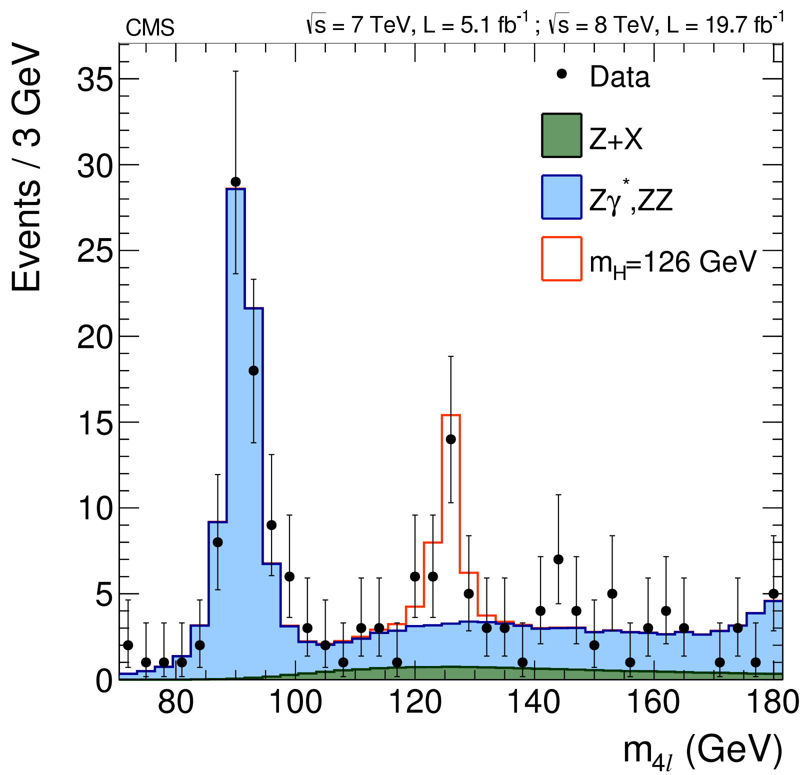
Fit mass and width of Higgs$\to ZZ \to 4\ell$

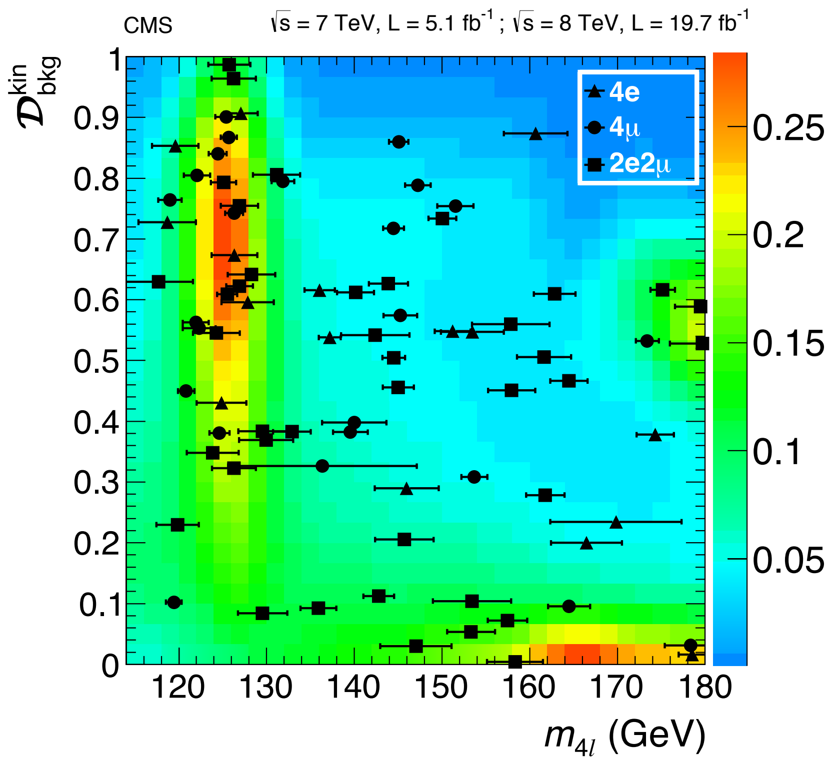
- Employ a 3D fit

  $m_{4\ell}$ – invariant mass

  $\mathcal{D}^{\rm kin}_{\rm bkg}$ – MELA (matrix element likelihood) to suppress background

  $\delta m_{4\ell}$ – per-event error estimate on invariant mass



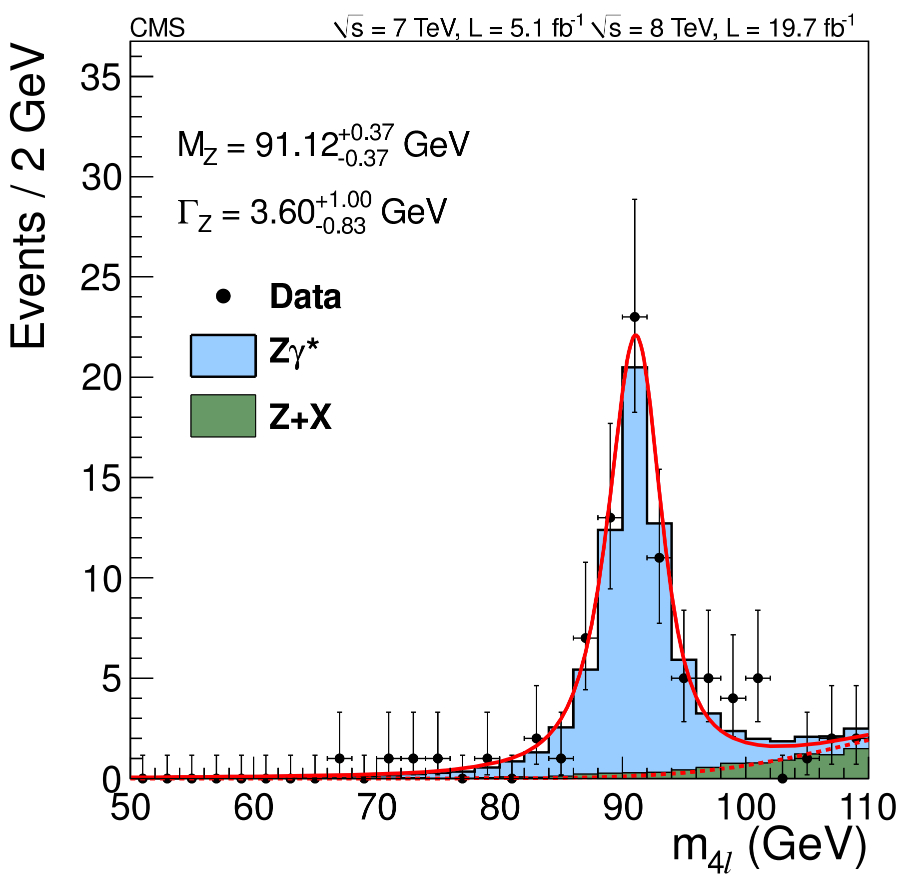


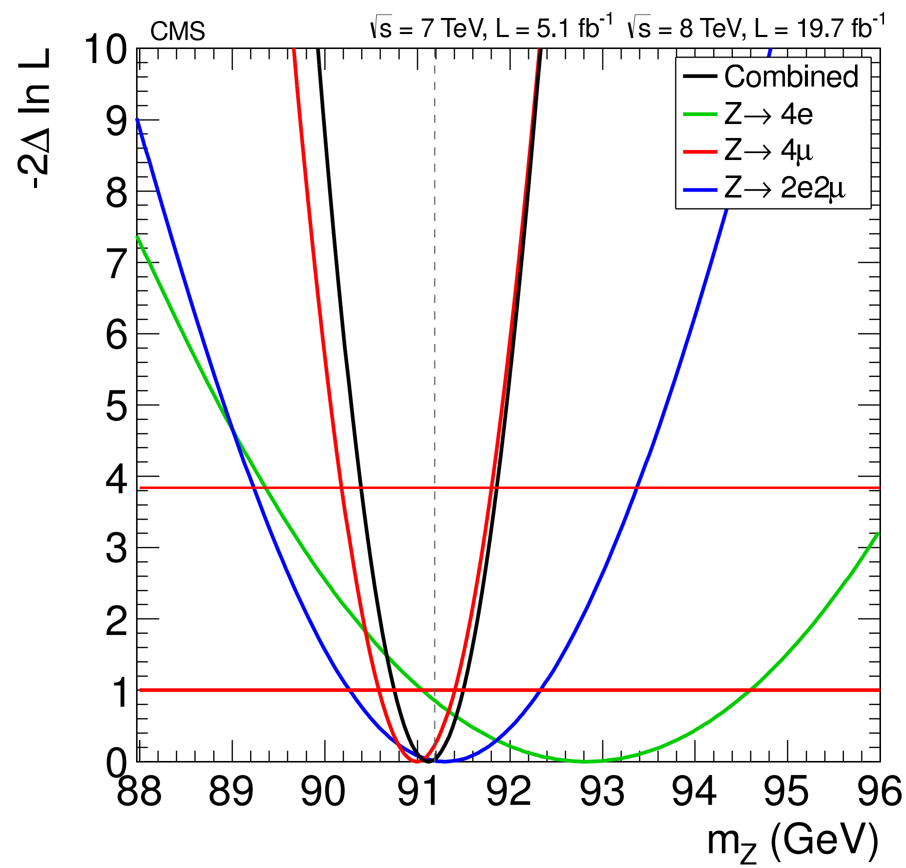
Test with $Z \to 4\ell$

- Excellent candle $Z \to \ell^+\ell^-\gamma^* \to \ell^+\ell^-\ell^+\ell^-$

$$m_Z = 91.12 \pm 0.37 \text{ GeV} \qquad \text{(compare PDG 91.19 GeV)}$$

$$\Gamma_Z = 3.6^{+1.0}_{-0.8} \text{ GeV} \qquad \text{(compare PDG 2.50 GeV)}$$

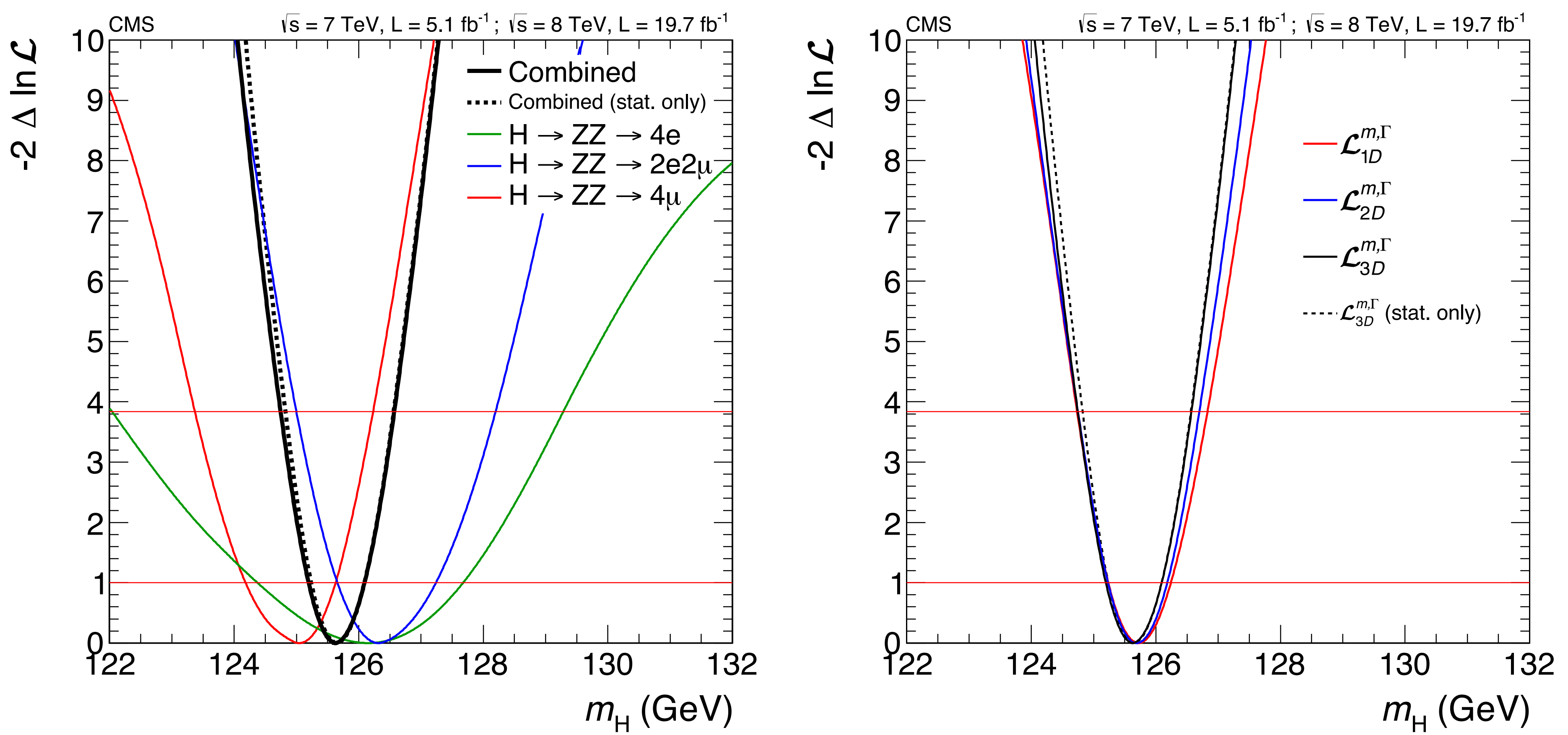




Mass H(126)

- Employ a 3D fit

$$m_H = 125.6 \pm 0.4\ (\text{stat.}) \pm 0.2\ (\text{syst.})\ \text{GeV}$$

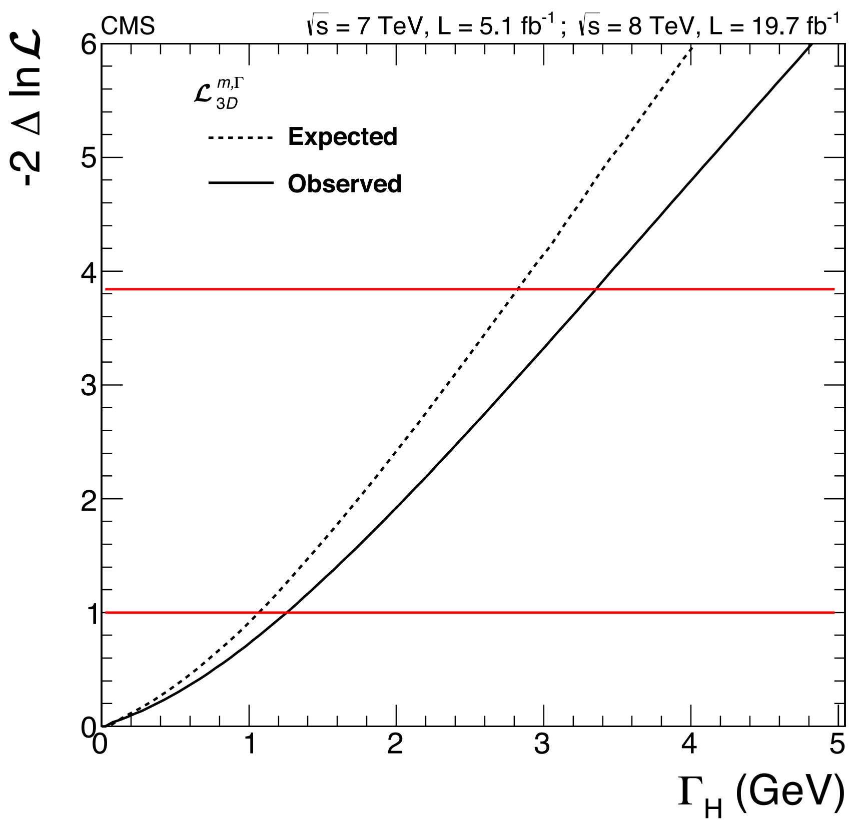


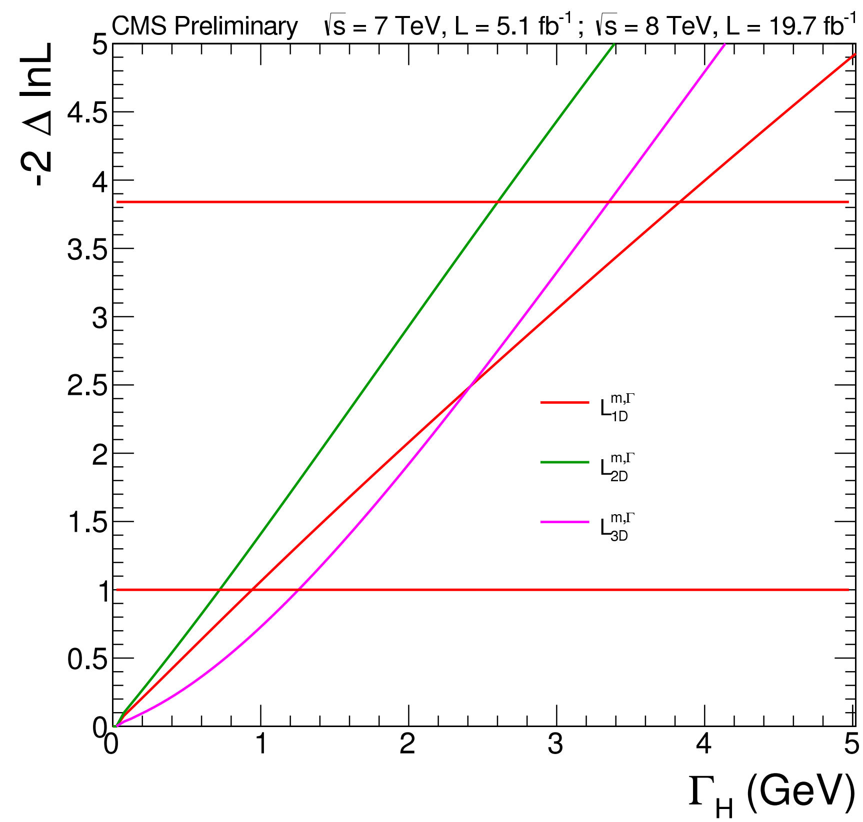
Width H(126)

- Employ a 3D fit

$$\Gamma_H = 0.0^{+1.3}_{-0.0}\ \text{GeV} \quad < 3.4\ \text{GeV at } 95\%\ \text{CL}$$

$$\text{expect } \Gamma_H^{\text{SM}} = 0.00415\ \text{GeV at } m_H = 125.6\ \text{GeV}$$





CAN WE DO BETTER?

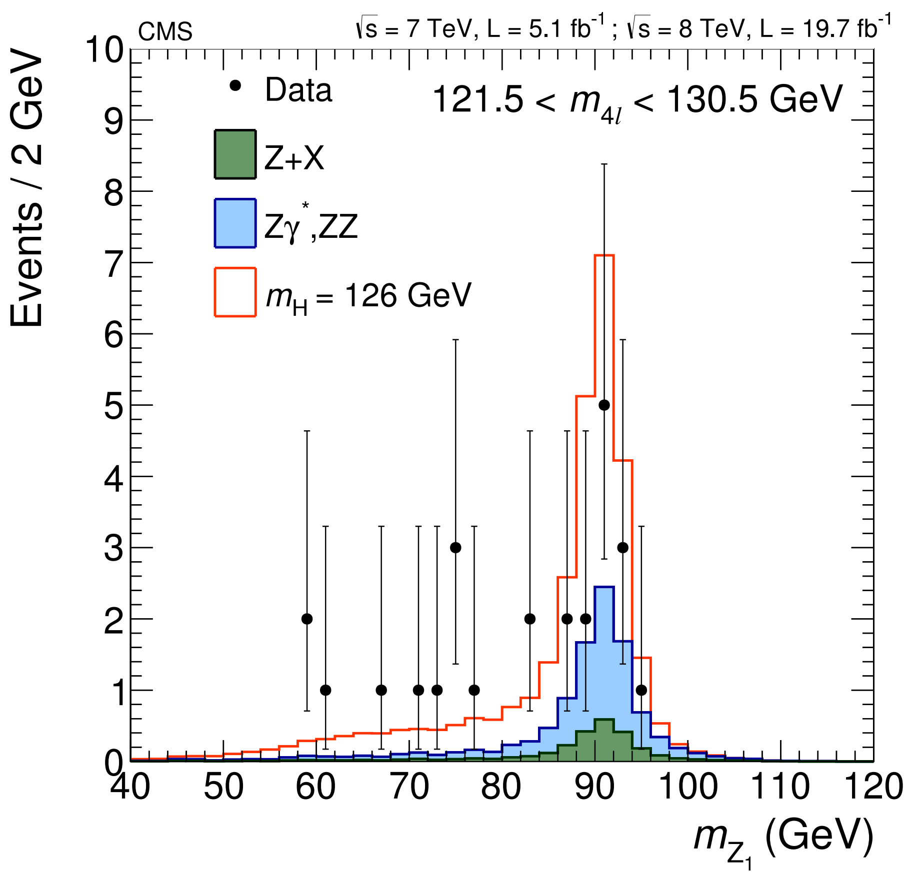
Off-shell effects

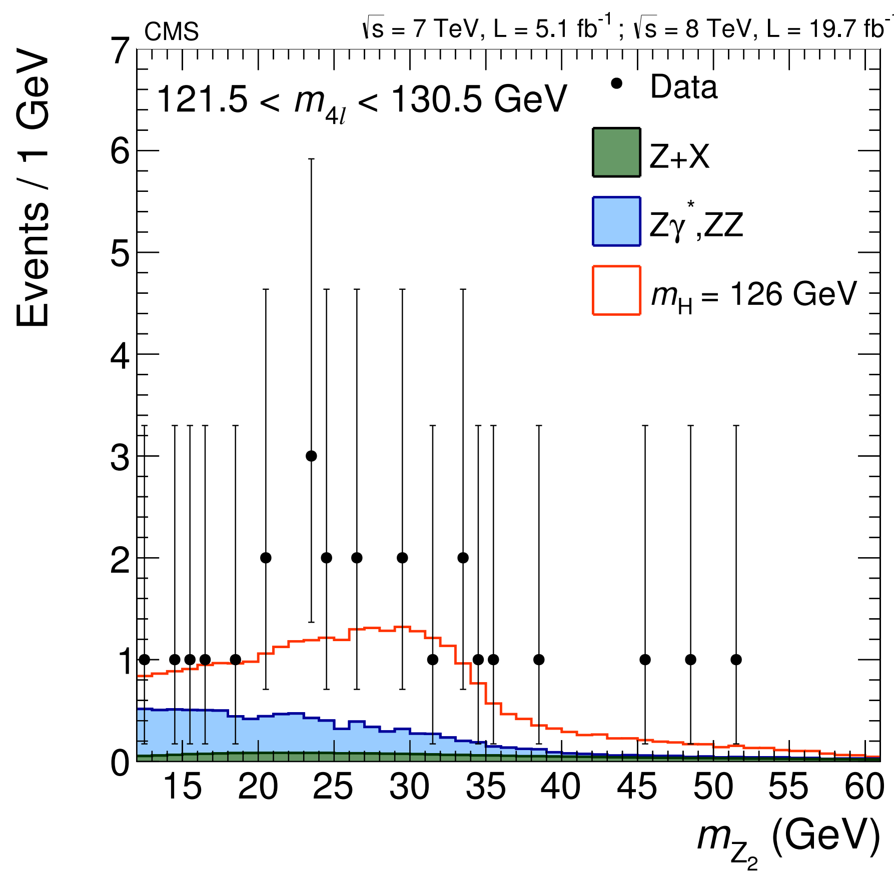
- $m_H = 125.6$ GeV $< 2\,m_Z = 182.4$ GeV

  $\Rightarrow H \to Z^{(*)}Z^*$ with off-shell Z^* $\Rightarrow$ suppression

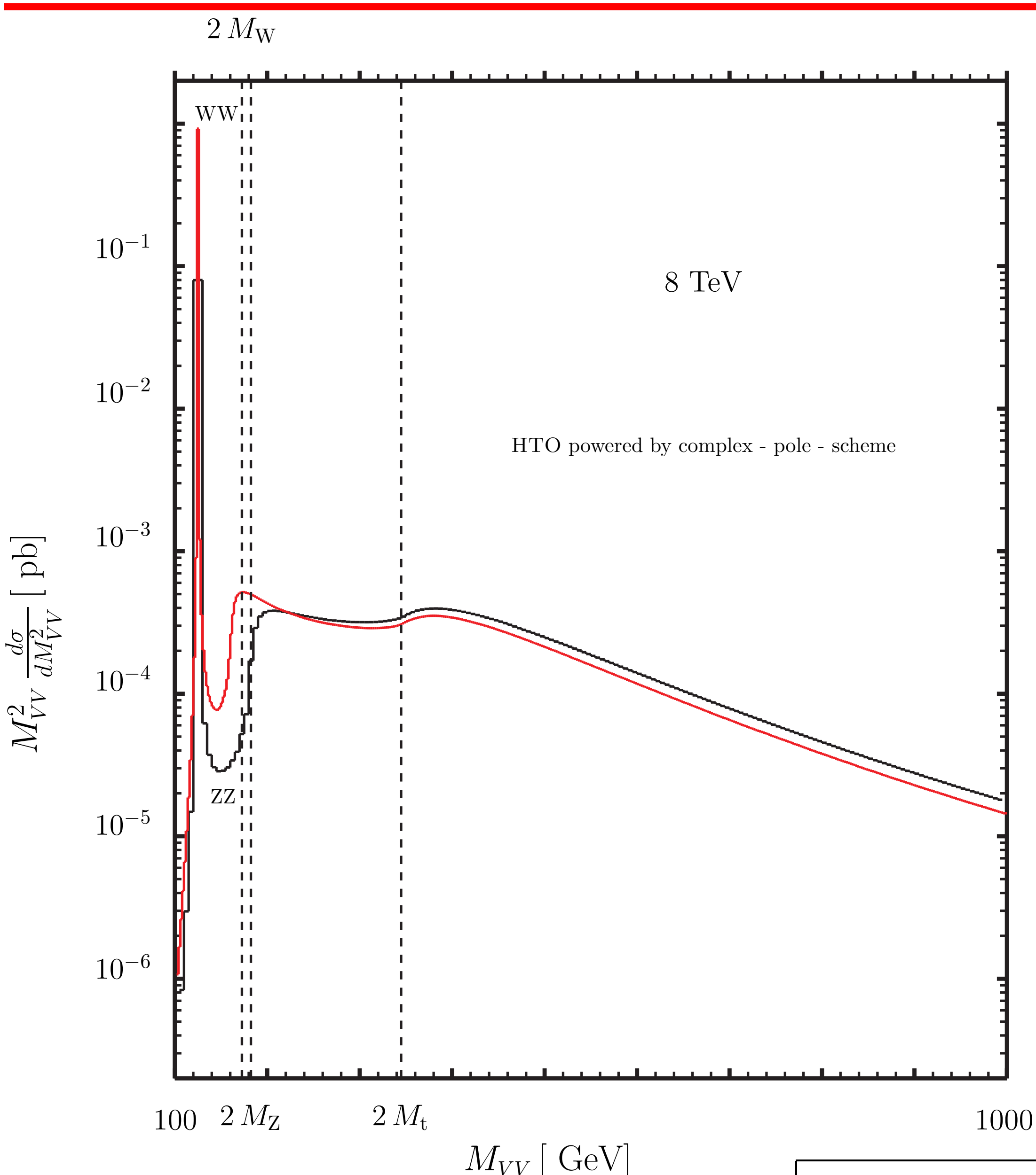
- Higgs boson remains on shell

$$\frac{d\,\sigma_{gg\to H\to ZZ}}{d\,m_{ZZ}^2} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$





Higgs off-shell effects



- Sizeable off shell H

$gg \to H \to Z^{(*)}Z^*$

on shell H, suppressed Z^*

$gg \to H^* \to ZZ$

suppressed H^*, on shell Z

N. Kauer, G. Passarino
arXiv:1206.4803 [hep-ph]
MC: gg2VV, LO in QCD

	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

Higgs boson width from off-shell production

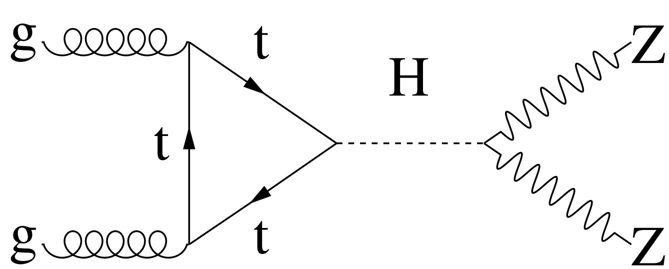
$$\frac{\mathrm{d}\,\sigma_{gg\to H\to ZZ}}{\mathrm{d}\,m_{ZZ}^2} \sim \frac{g_{\mathrm{ggH}}^2 g_{\mathrm{HZZ}}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H{}^2}$$

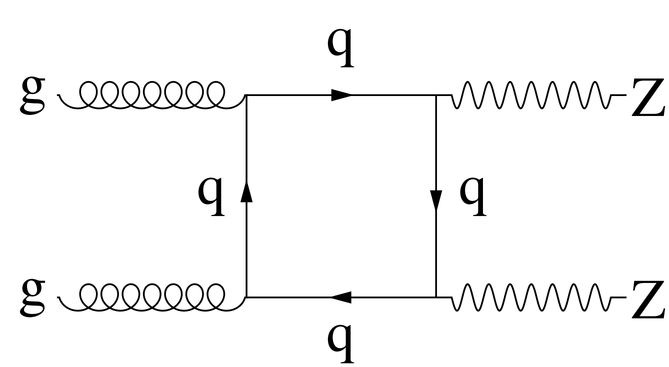
- On peak ($m_{ZZ} \sim m_H$) and off peak ($m_{ZZ} - m_H \gg \Gamma_H$)
  F. Caola, K. Melnikov: arXiv:1307.4935 [hep-ph]

$$\sigma_{\mathrm{gg\to H\to ZZ}}^{\mathrm{onpeak}} = \mathrm{const}\ \frac{g_{\mathrm{ggH}}^2 g_{\mathrm{HZZ}}^2}{\Gamma_H} \qquad \sigma_{\mathrm{gg\to H\to ZZ}}^{\mathrm{offpeak}} = \mathrm{const}'\ g_{\mathrm{ggH}}^2 g_{\mathrm{HZZ}}^2$$

$\Rightarrow$ measurement of Γ_H

- Complication: signal - background destructive interference



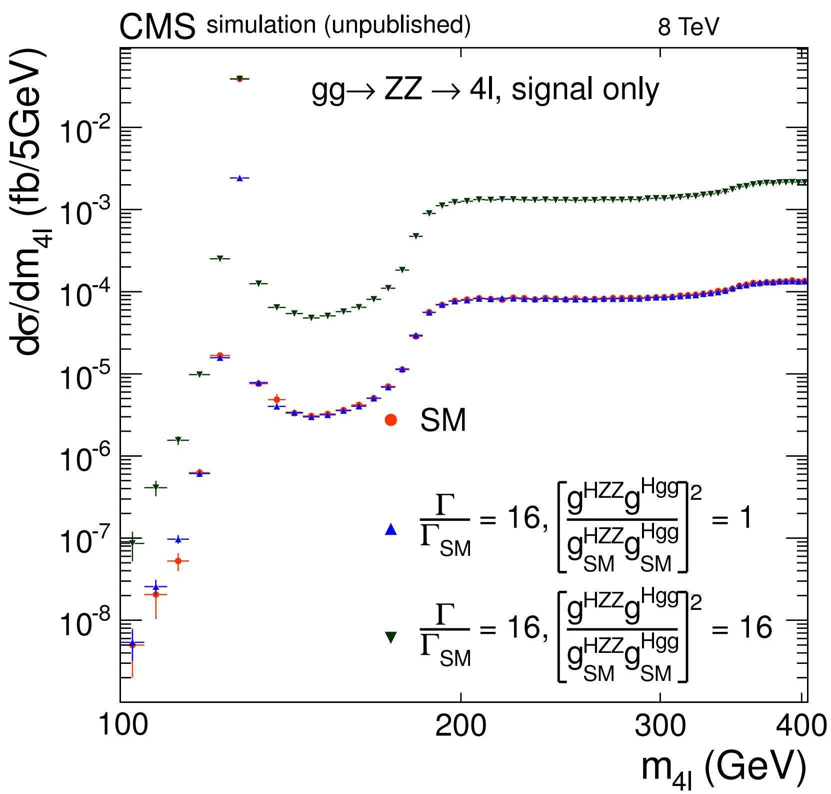


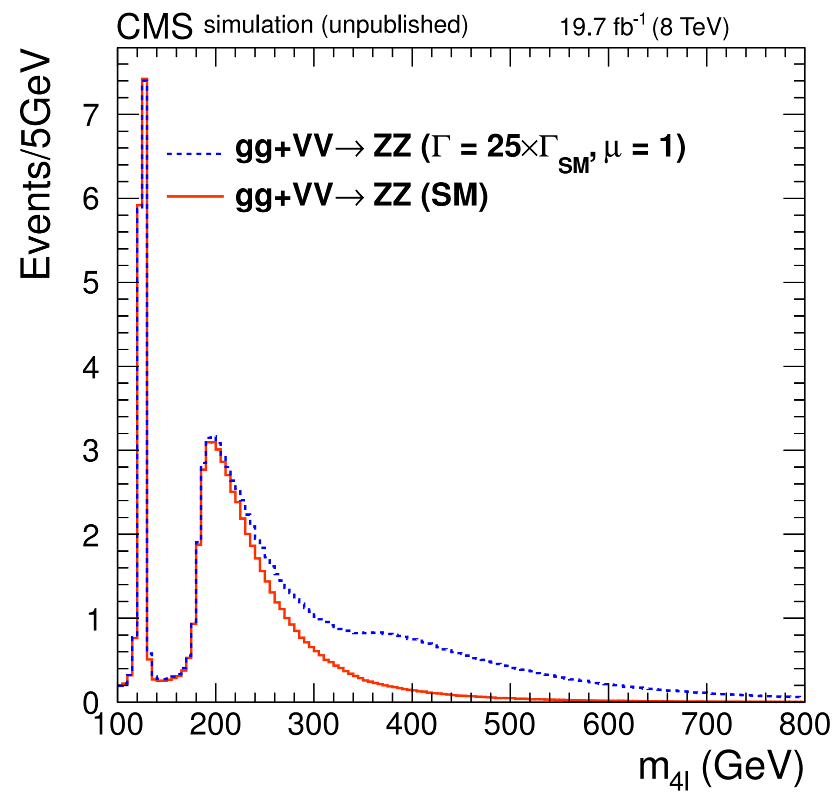
Higgs boson width from off-shell production

$$\sigma^{\text{onpeak}}_{gg\to H\to ZZ} = \text{const}\ \frac{g^2_{\text{ggH}}g^2_{\text{HZZ}}}{\Gamma_H} \qquad \sigma^{\text{offpeak}}_{gg\to H\to ZZ} = \text{const}'\ g^2_{\text{ggH}}g^2_{\text{HZZ}}$$

- Given the signal strength at the peak $\mu = \sigma/\sigma_{\text{SM}}$

  $\Rightarrow$ off-shell signal $\propto \Gamma_H$, interference $\propto \sqrt{\Gamma_H}$

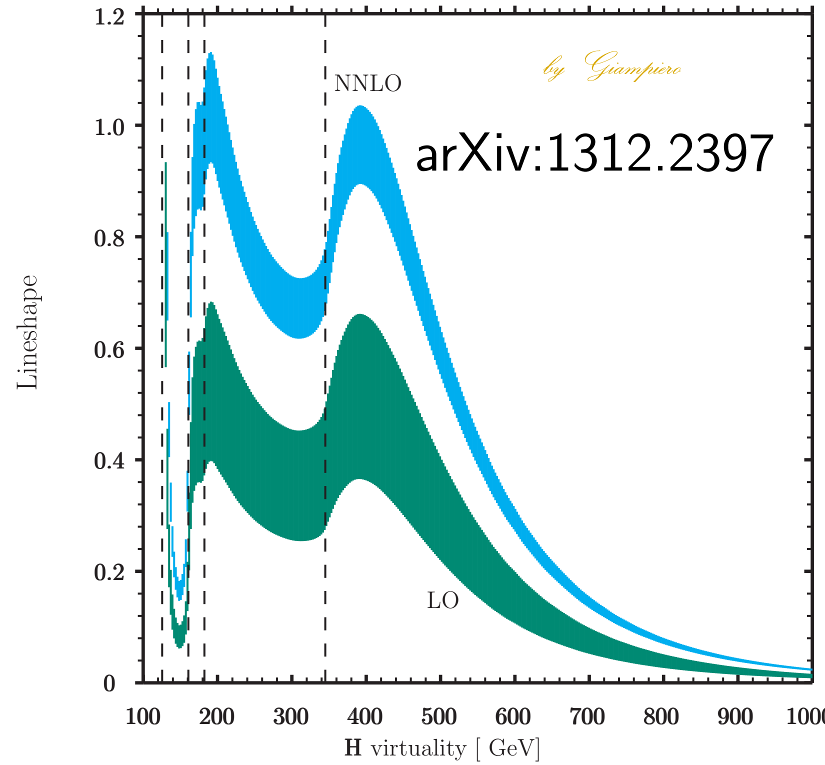




Monte Carlo Simulation (off shell)

- gg $\to ZZ^{(*)}/Z\gamma^*$ gg2VV and

MCFM: J. Campbell, K. Ellis, C. Williams
arXiv:1311.3589 [hep-ph]



- LO in QCD, Pythia shower
- running QCD scale $\mu_{R,F} = m_{ZZ}/2$
- uncertainties $\mu_{R,F} \in [m_{ZZ}, m_{ZZ}/4]$
- signal K-factor ~ 2
- bkg K-factor = signal K $\pm 10\%$

(soft-collinear approximation arXiv:1304.3053 for gg $\to WW$)

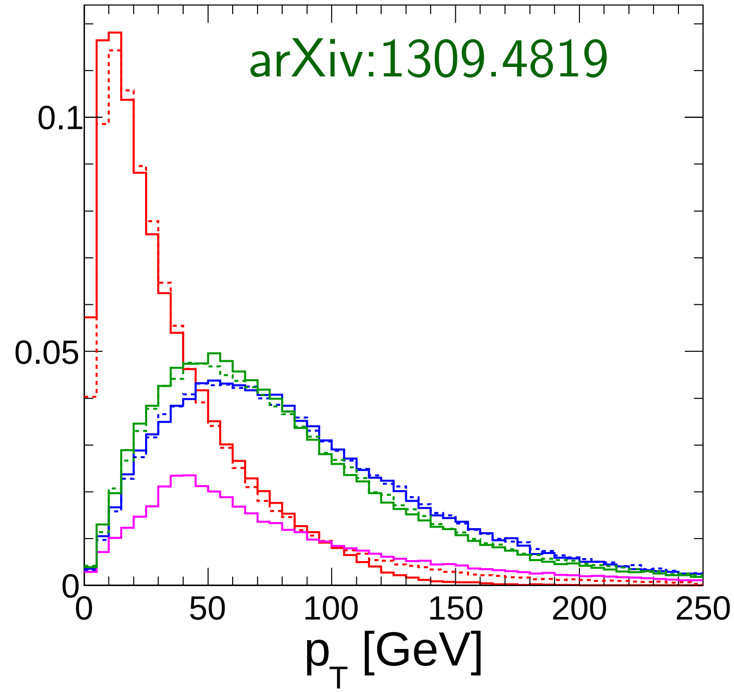
- No references for width studies in VBF: $V^*V^* \to ZZ^{(*)}$

use Phantom: A. Ballestrero *et al.*, arXiv:0801.3359 [hep-ph]

- Generate sig, bkg, sig+bkg+interference ⇒ extract interference
  match signal on-peak cross-section to best known

Monte Carlo Simulation

- On-shell signal MC
  - NLO QCD production `POWHEG`
  - $H \to VV \to 4f$ decay `JHUGen`
  - anomalous couplings with `JHUGen`
    spin-0, 1, 2, $q\bar{q}$, gg, VBF, VH, $H2j$



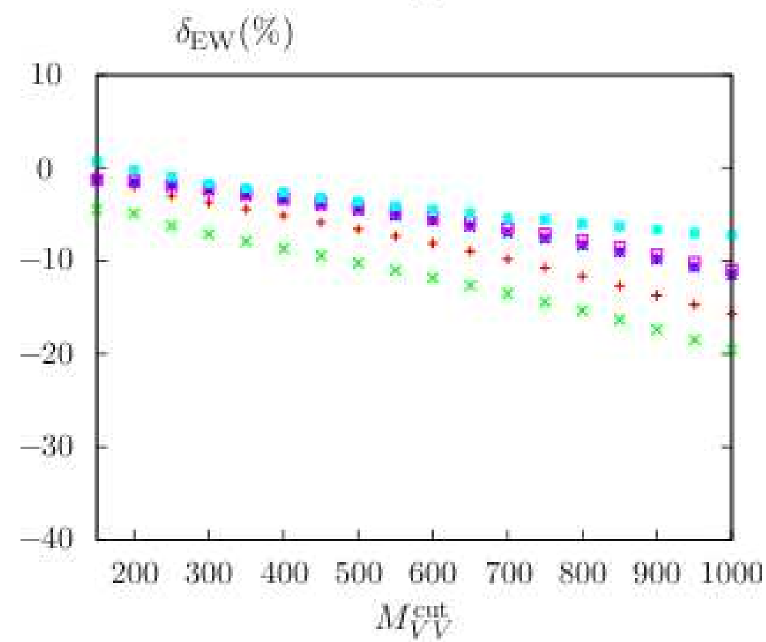
- Dominant $q\bar{q} \to ZZ$ background
  - NLO QCD `POWHEG`

    NLO EW re-weighting

    follow arXiv:1307.4331, arXiv:1305.5402

  $-(5-10)\%$ in $220-500$ GeV range

  $\sim 40\%$ uncertainty on the correction



Use Kinematics to Suppress Background

- One challenge is the dominant $q\bar{q} \to ZZ$ background

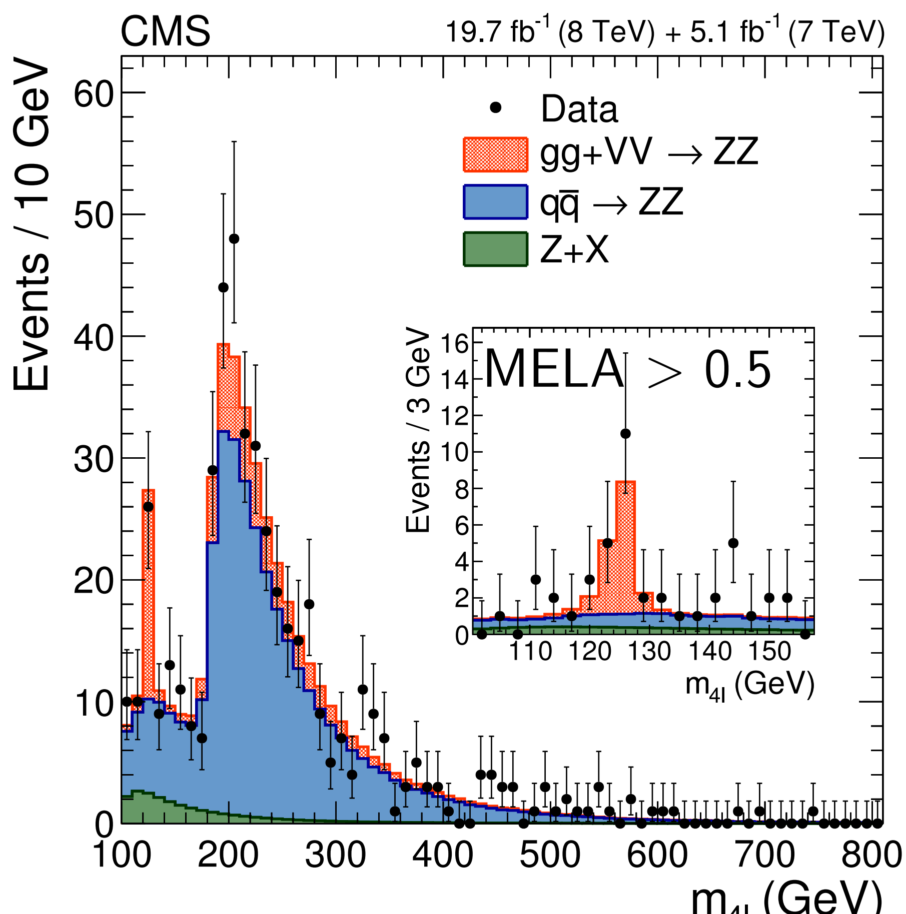
- Follow the same approach as at the Higgs discovery

MELA technique

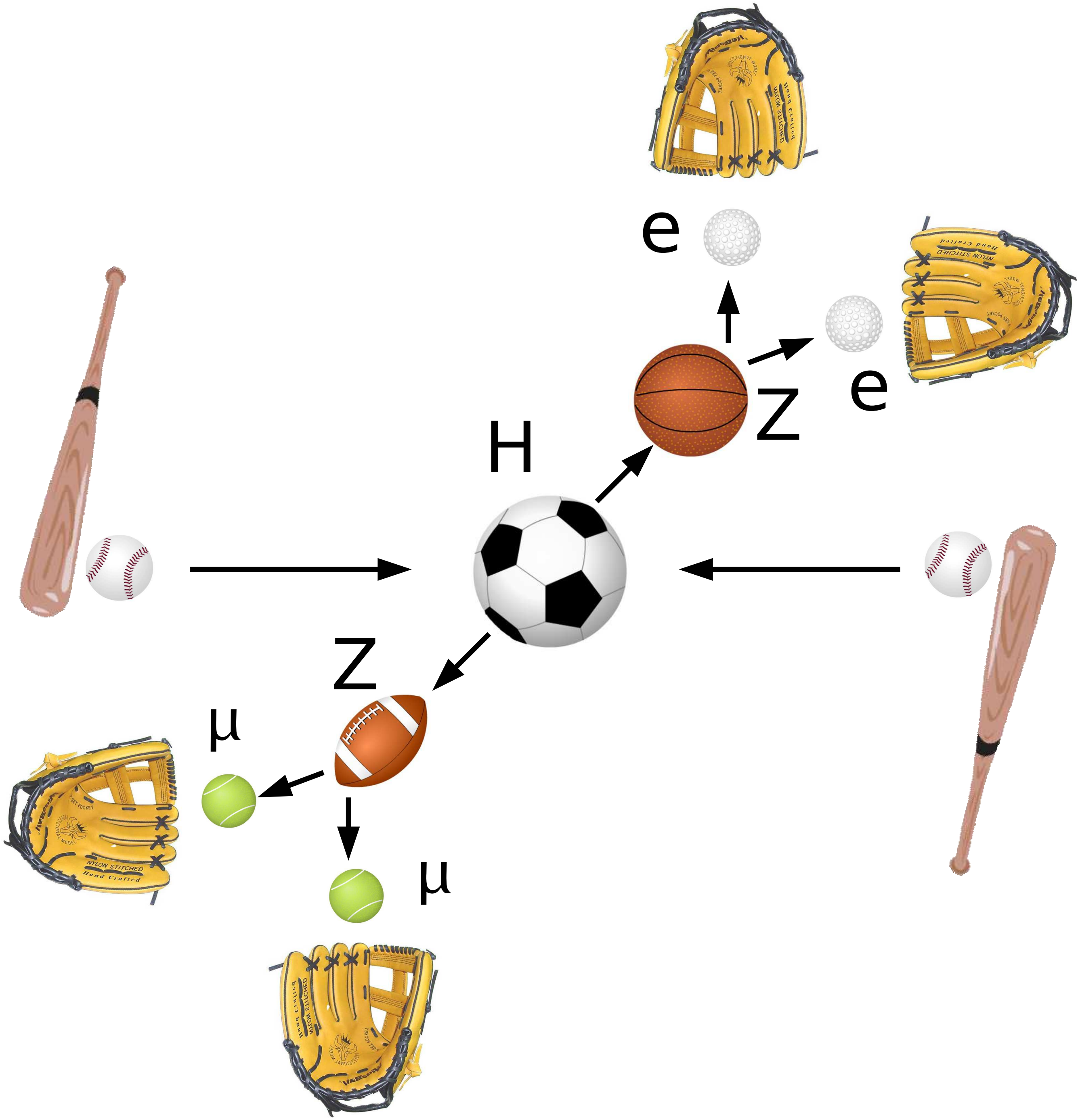
(Matrix Element Likelihood Approach)

to suppress $q\bar{q} \to ZZ$

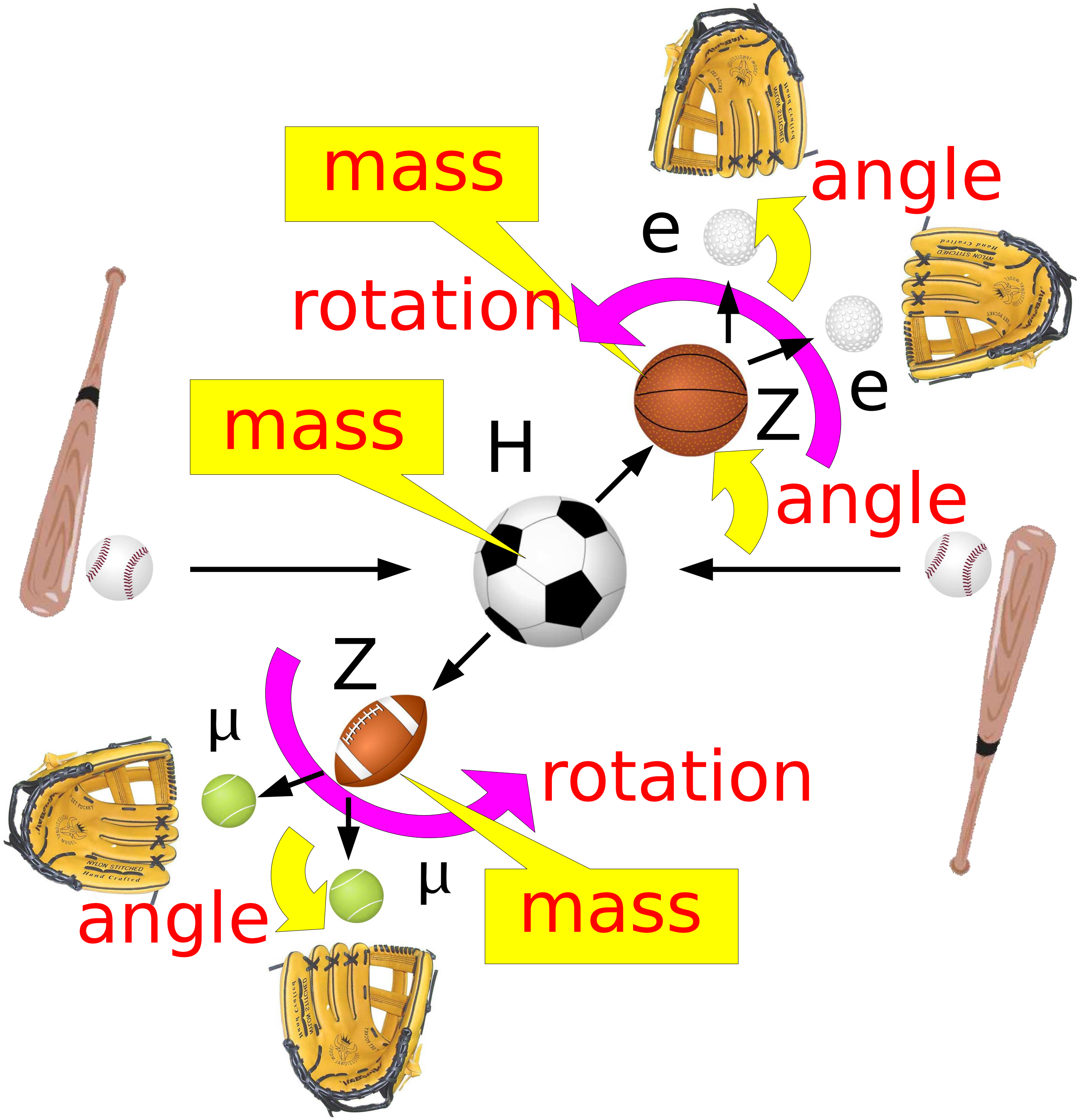
vs $gg \to ... \to ZZ$



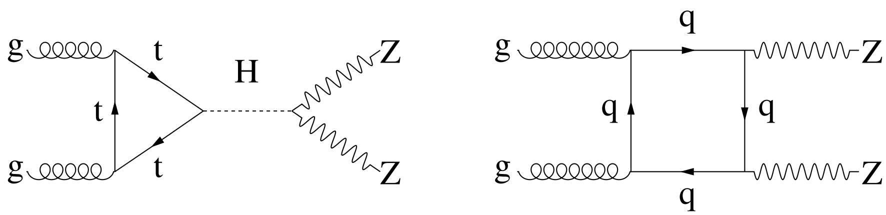
Matrix Element Likelihood Approach



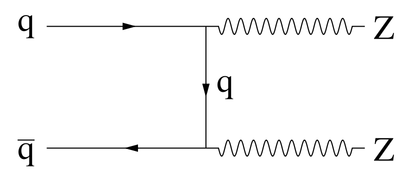
Matrix Element Likelihood Approach



Matrix Element Likelihood Approach



vs.



- Optimal discriminant to separate gg $\to ZZ$ vs $q\bar{q} \to ZZ$

$$\mathcal{D}_{gg} = \frac{\mathcal{P}^{gg}_{\rm tot}}{\mathcal{P}^{gg}_{\rm tot} + \mathcal{P}^{q\bar{q}}_{\rm bkg}} = \left[1 + \frac{\mathcal{P}^{q\bar{q}}_{\rm bkg}}{10 \times \mathcal{P}^{gg}_{\rm sig} + \sqrt{10} \times \mathcal{P}^{gg}_{\rm int} + \mathcal{P}^{gg}_{\rm bkg}}\right]^{-1}$$

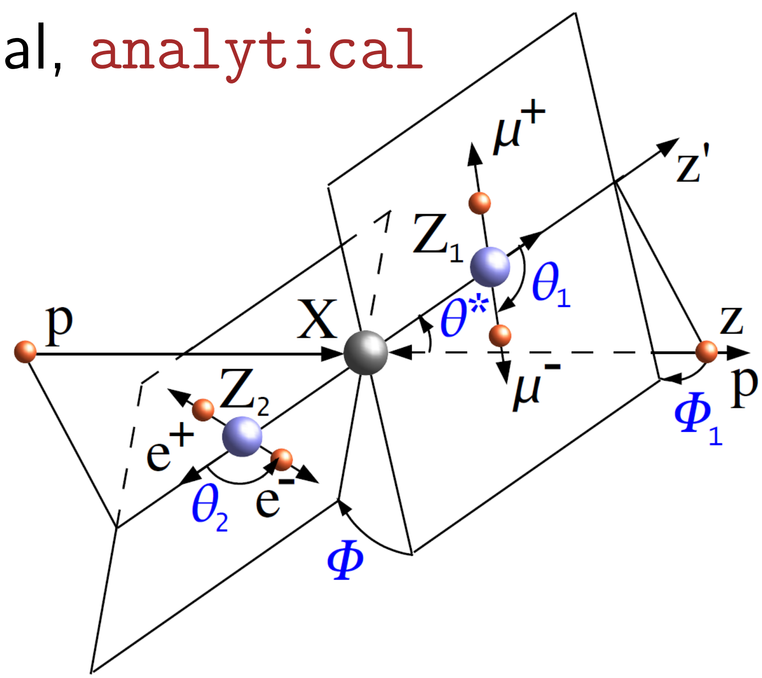
MCFM - continuum, JHUGen - onpeak signal, analytical

- Higgs discovery:

$$\mathcal{D}^{\rm kin}_{\rm bkg} = \frac{\mathcal{P}_{0+}}{\mathcal{P}_{0+} + \mathcal{P}^{q\bar{q}}_{\rm bkg}}$$

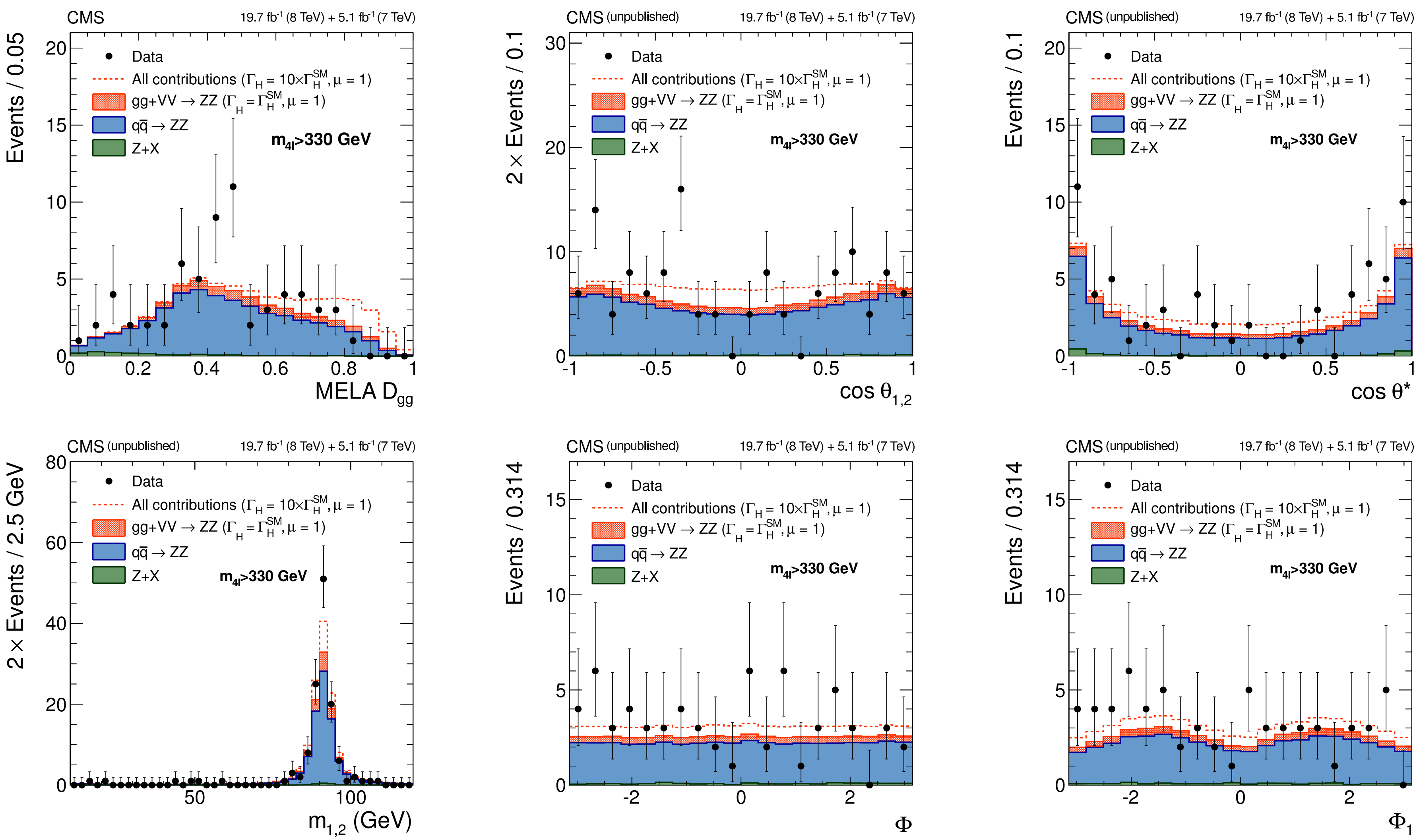
- Higgs spin-parity:

$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{0+}}{\mathcal{P}_{0+} + \mathcal{P}_{J^P}}$$



Kinematics

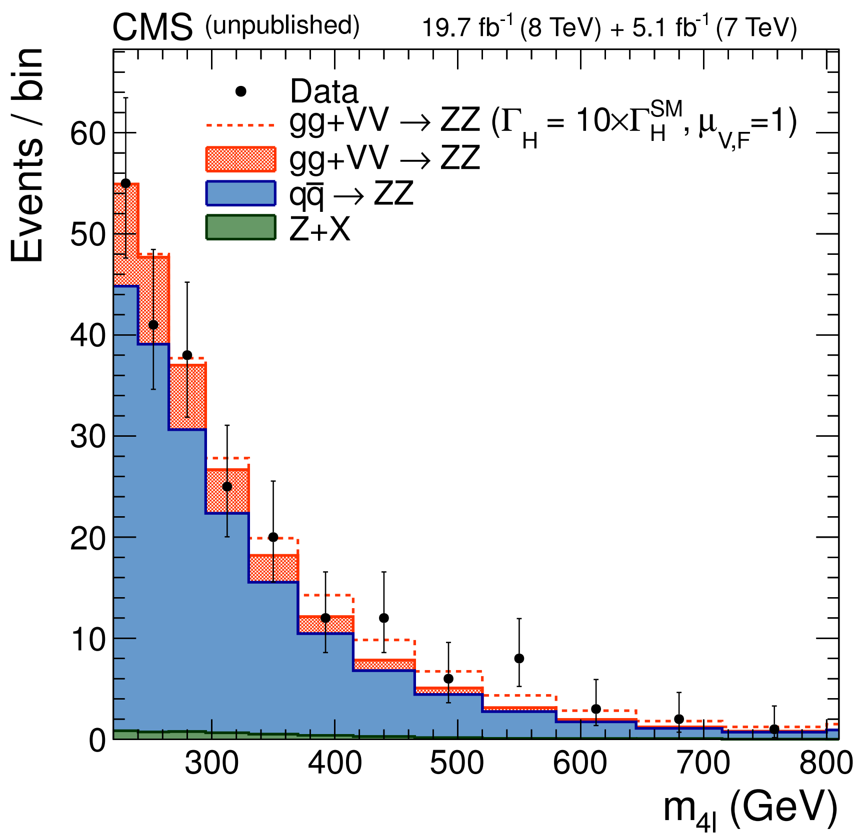
- MELA $\mathcal{D}_{gg}(m_{ZZ}, m_{Z1}, m_{Z2}, \cos\theta_1, \cos\theta_2, \cos\theta^*, \Phi, \Phi_1)$



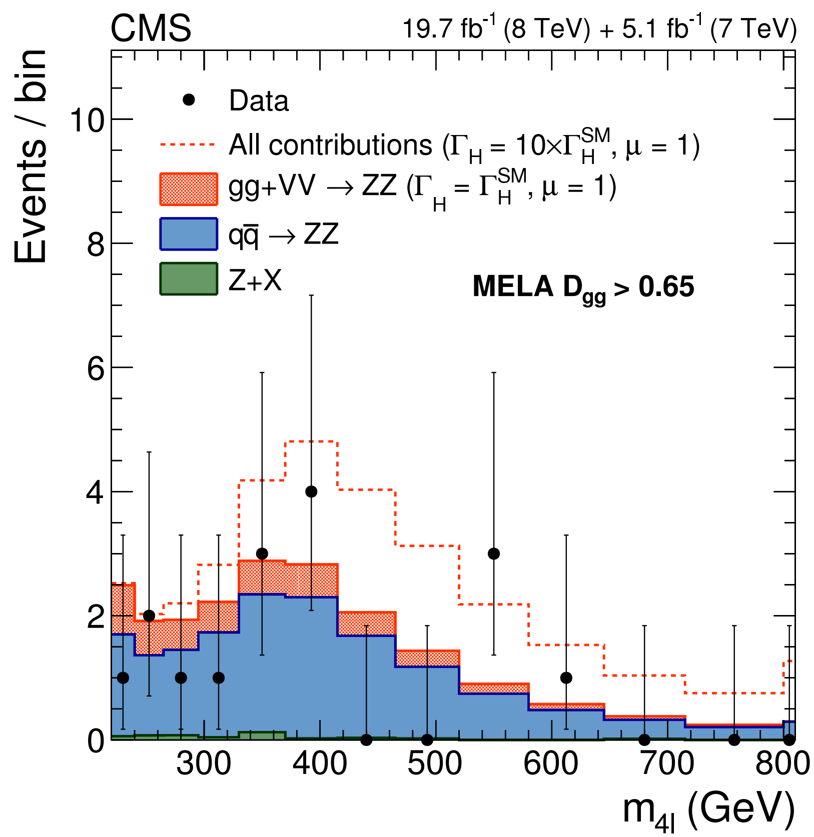
$H^* \to ZZ \to 4\ell$ Mass after Kinematic Selection

- Optimal use of kinematic information

before



after $\mathcal{D}_{gg} > 0.65$

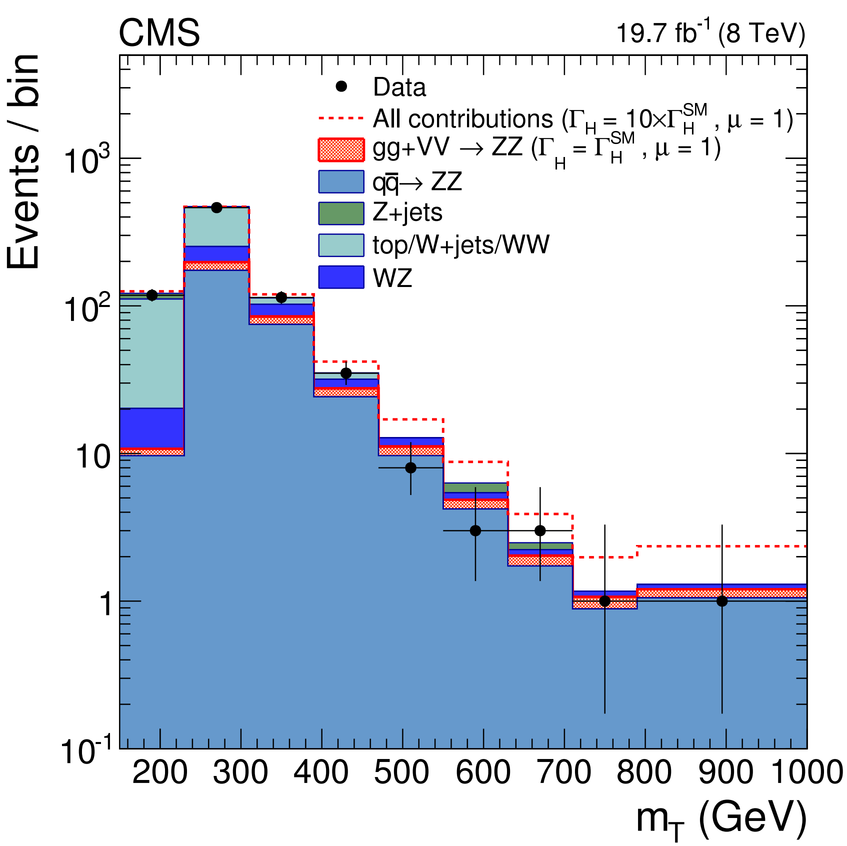


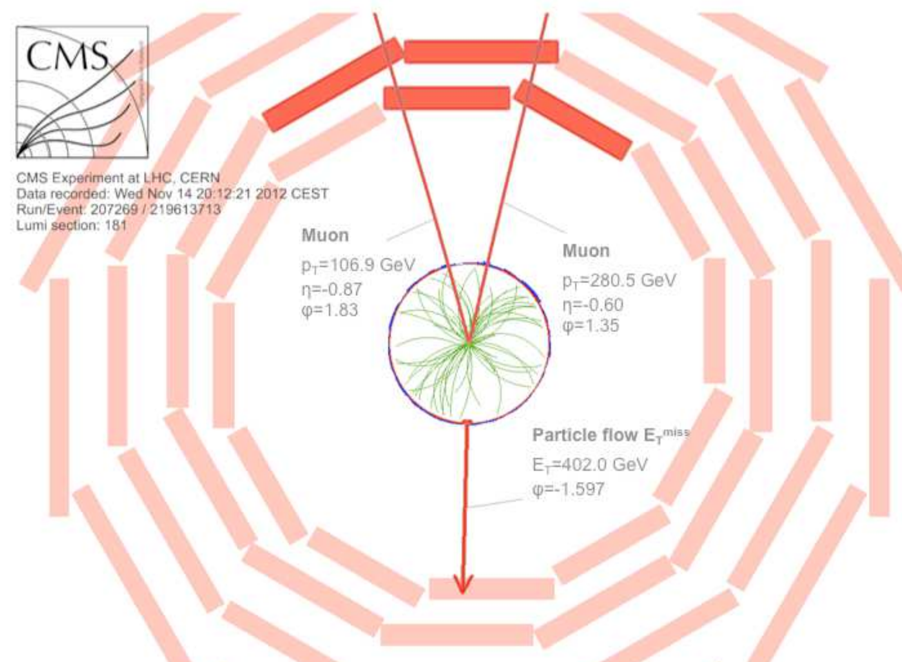
Semileptonic Channel $H \to ZZ \to 2\ell 2\nu$

- Partial reco, but $\times 5.5$ higher branching

$\Rightarrow$ comparable to 4ℓ sensitivity at high mass
but no hope at low mass (overwhelmed with Z+jets background)

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





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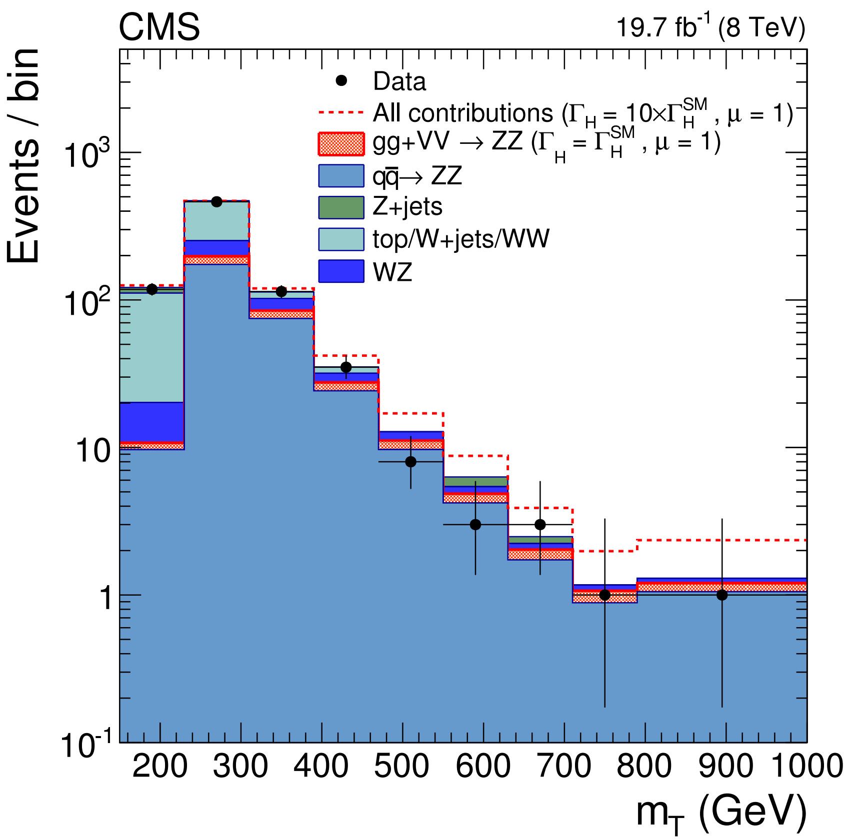
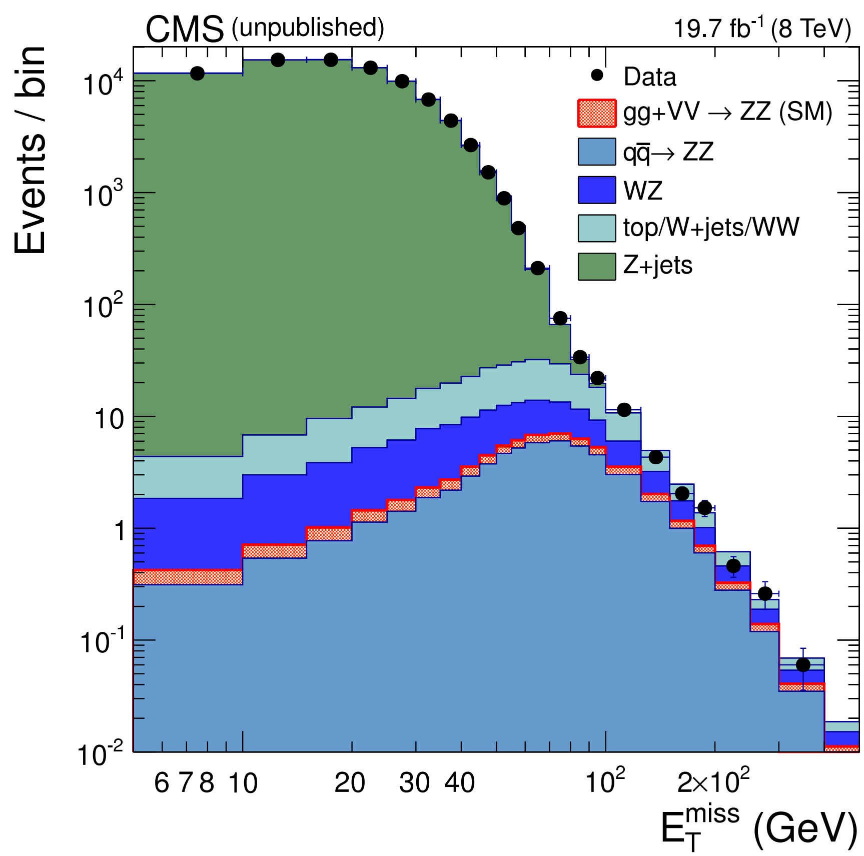


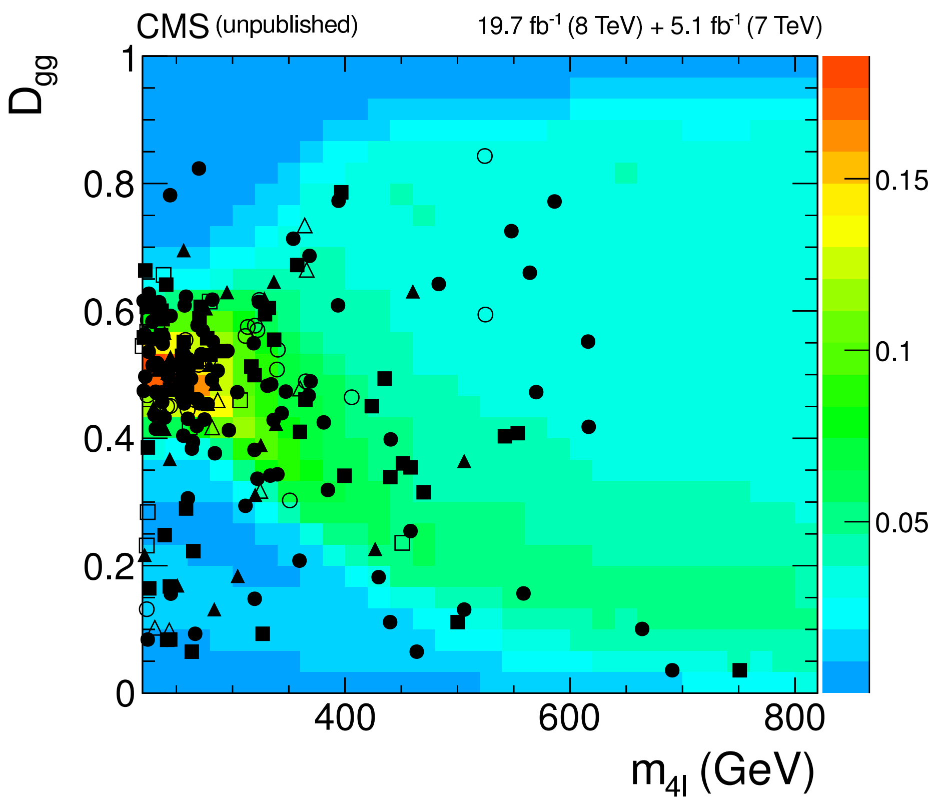


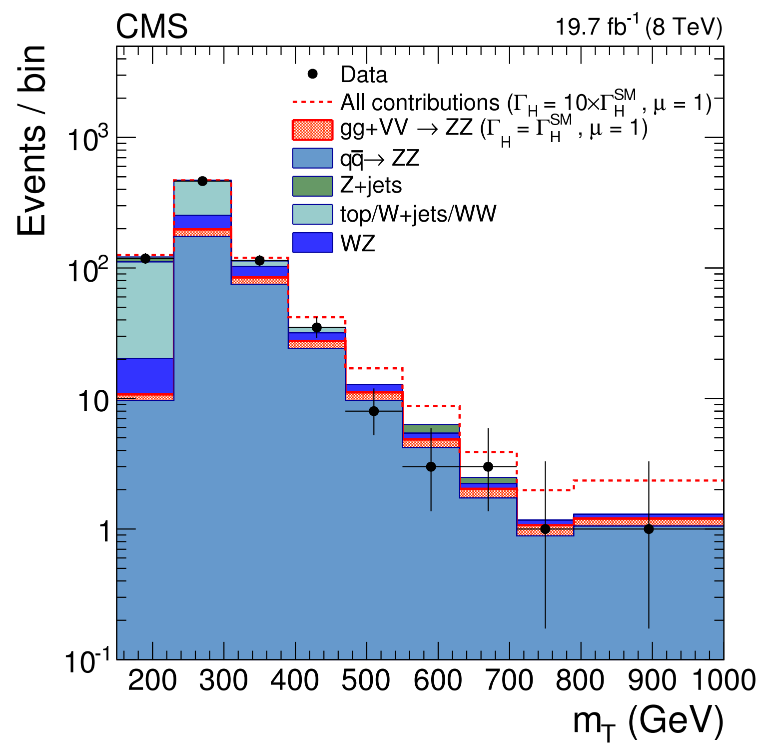
Look at enhanced signal region

- For illustration purpose define the enhanced signal regions

$H \to ZZ \to 4\ell$ $\qquad$ $H \to ZZ \to 2\ell 2\nu$

$m_{4\ell} > 330$ GeV, $\mathcal{D}_{gg} > 0.65$ $\qquad$ $m_T > 350$ GeV, $E_T^{\text{miss}} > 100$ GeV



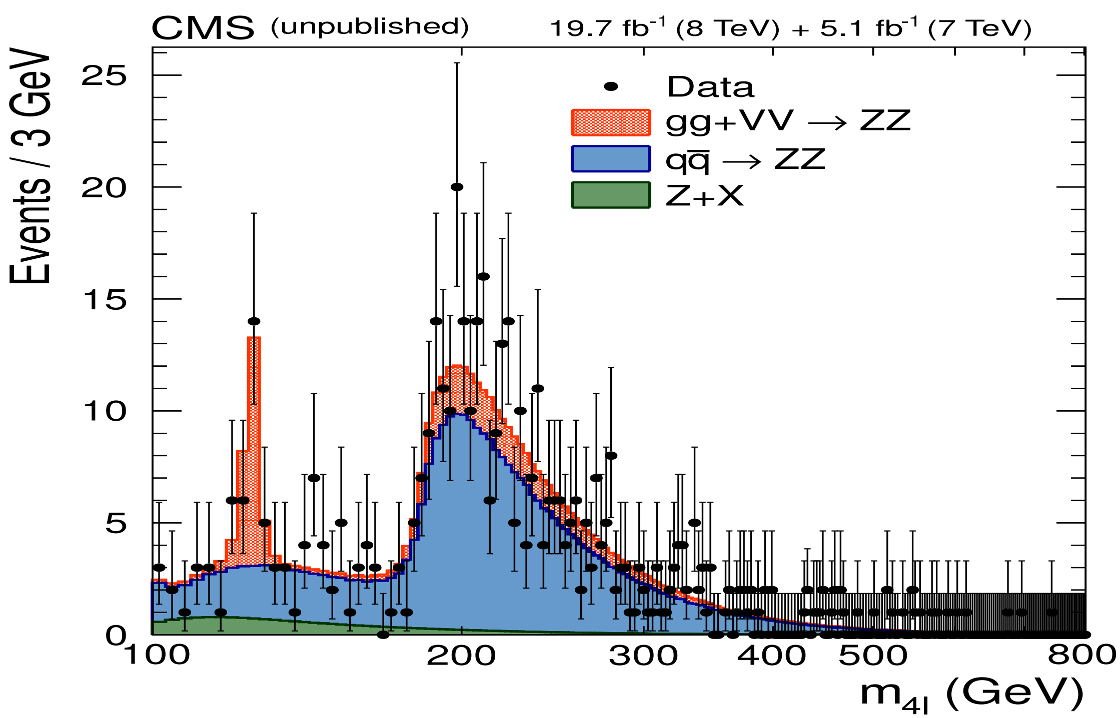


Enhanced signal $H \to ZZ \to 4\ell$ and $2\ell 2\nu$

		4ℓ	$2\ell 2\nu$
(a)	total gg $(\Gamma_H = \Gamma_H^{\rm SM})$	1.8 ± 0.3	9.6 ± 1.5
	gg signal component $(\Gamma_H = \Gamma_H^{\rm SM})$	1.3 ± 0.2	4.7 ± 0.6
	gg background component	2.3 ± 0.4	10.8 ± 1.7
(b)	total gg $(\Gamma_H = 10 \times \Gamma_H^{\rm SM})$	9.9 ± 1.2	39.8 ± 5.2
(c)	total VBF $(\Gamma_H = \Gamma_H^{\rm SM})$	0.23 ± 0.01	0.90 ± 0.05
	VBF signal component $(\Gamma_H = \Gamma_H^{\rm SM})$	0.11 ± 0.01	0.32 ± 0.02
	VBF background component	0.35± 0.02	1.22 ± 0.07
(d)	total VBF $(\Gamma_H = 10 \times \Gamma_H^{\rm SM})$	0.77 ± 0.04	2.40 ± 0.14
(e)	$q\bar{q}$ background	9.3 ± 0.7	47.6 ± 4.0
(f)	other backgrounds	0.05 ± 0.02	35.1 ± 4.2
(a+c+e+f)	total expected $(\Gamma_H = \Gamma_H^{\rm SM})$	11.4 ± 0.8	93.2 ± 6.0
(b+d+e+f)	total expected $(\Gamma_H = 10 \times \Gamma_H^{\rm SM})$	20.1 ± 1.4	124.9 ± 7.8
	observed	11	91

How to Extract the Width

- Relative size of low and high mass Higgs signal
  - analysis at high mass $\Rightarrow$ $g_{\rm ggH}$ $g_{\rm HZZ}$ (gg$\to H$) or $g_{\rm HVV}$ $g_{\rm HZZ}$ (VBF)
  - must relate to on-peak to measure Γ
- Composition of production: gg$\to H$ vs VBF
  - need to know to describe the shape
- Is the coupling $g_{\rm HVV}(m_{ZZ})$ running (anomalous)?



Extracting the Width

- Determine strength and production composition from the peak
  - μ_{ggH} and $\mu_{\rm VBF}$ provide both (ratio to SM $\mu = \sigma/\sigma_{\rm SM}$)

$$\mathcal{P}_{\rm tot}^{\rm onshell}(\vec{x}) = \mu_{ggH} \times [\mathcal{P}_{\rm sig}^{gg}(\vec{x}) + \mathcal{P}_{\rm sig}^{t\bar{t}H}(\vec{x})] + \mu_{\rm VBF} \times [\mathcal{P}_{\rm sig}^{\rm VBF}(\vec{x}) + \mathcal{P}_{\rm sig}^{\rm VH}(\vec{x})] \\ + \; \mathcal{P}_{\rm bkg}^{q\bar{q}}(\vec{x}) + \mathcal{P}_{\rm bkg}^{gg}(\vec{x}) + \ldots$$

- Relate to high mass
  - Γ_H is the only free parameter remaining

$$\mathcal{P}_{\rm tot}^{\rm offshell}(\vec{x}) = \left[\mu_{ggH} \times \frac{\Gamma_H}{\Gamma_0} \times \mathcal{P}_{\rm sig}^{gg}(\vec{x}) + \sqrt{\mu_{ggH} \times \frac{\Gamma_H}{\Gamma_0}} \times \mathcal{P}_{\rm int}^{gg}(\vec{x}) + \mathcal{P}_{\rm bkg}^{gg}(\vec{x})\right] \\ + \left[\mu_{\rm VBF} \times \frac{\Gamma_H}{\Gamma_0} \times \mathcal{P}_{\rm sig}^{\rm VBF}(\vec{x}) + \sqrt{\mu_{\rm VBF} \times \frac{\Gamma_H}{\Gamma_0}} \times \mathcal{P}_{\rm int}^{\rm VBF}(\vec{x}) + \mathcal{P}_{\rm bkg}^{\rm VBF}(\vec{x})\right] \\ + \; \mathcal{P}_{\rm bkg}^{q\bar{q}}(\vec{x}) + \ldots$$

CONSTRAINTS FROM THE LOW MASS

Constraints from the low mass

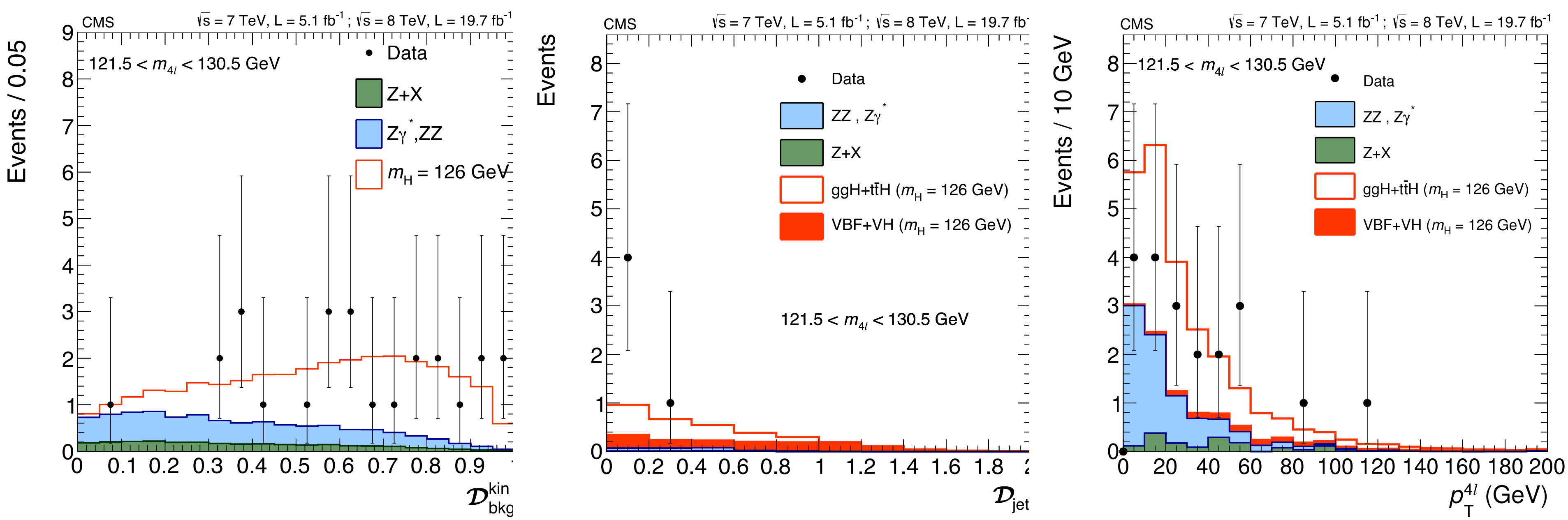
- Employ a 3D fit and 2 jet tagging catetories

$m_{4\ell}$ – invariant mass

$\mathcal{D}_{\rm bkg}^{\rm kin}$ – MELA (matrix element likelihood) to suppress background

if at least 2 jets: $\mathcal{D}_{\rm jet}$ – to identify VBF or VH $(m_{jj},\, \eta_{jj})$

if <2 jets: $p_T(4\ell)$ – to identify VBF or VH



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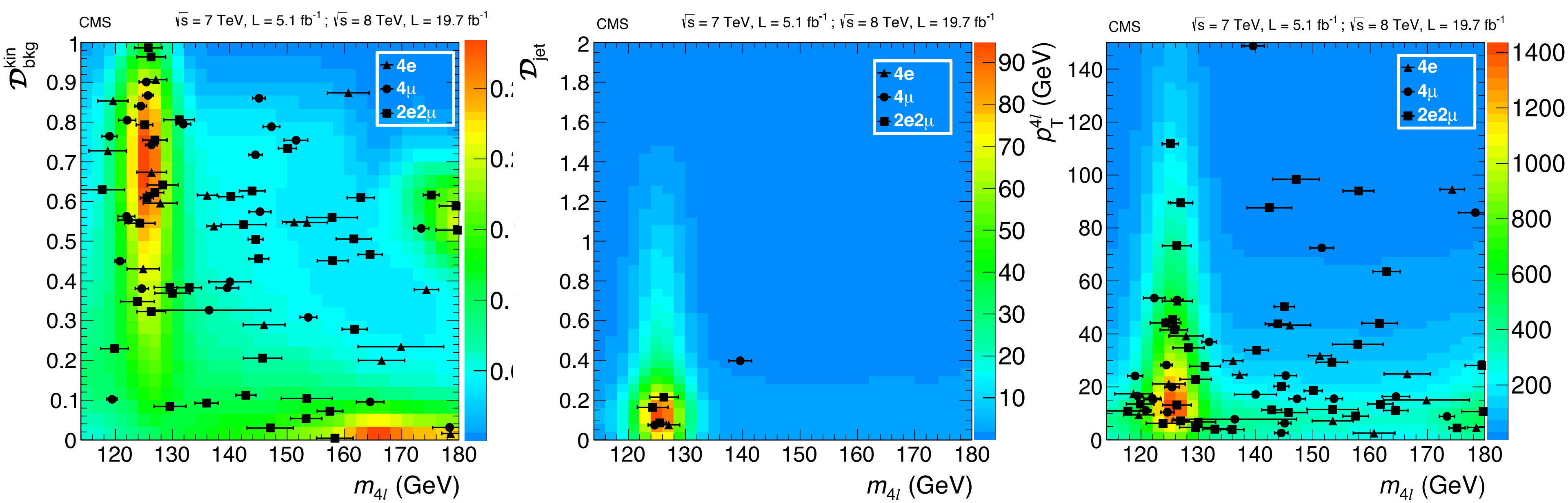


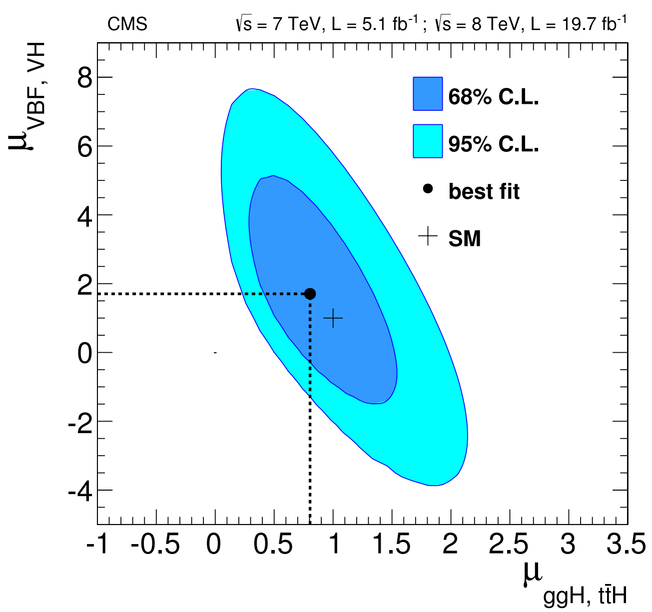
Production Mechanism Results

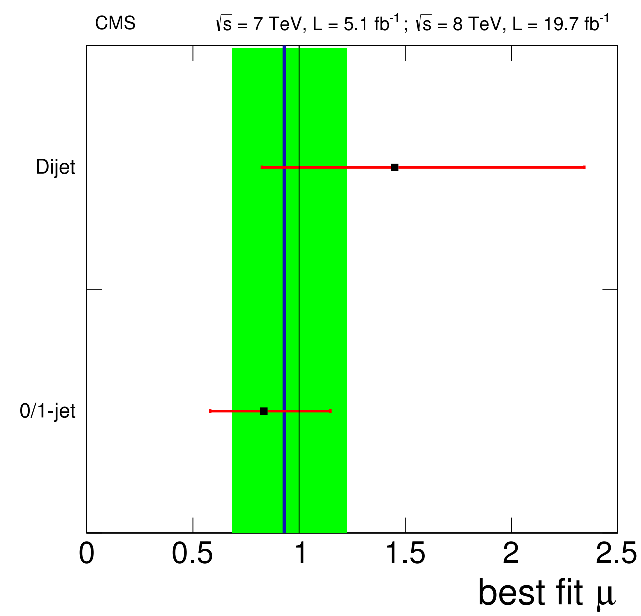
$$\mathcal{P}_{\rm tot}^{\rm onshell}(\vec{x}) = \mu_{ggH} \times [\mathcal{P}_{\rm sig}^{gg}(\vec{x}) + \mathcal{P}_{\rm sig}^{t\bar{t}H}(\vec{x})] + \mu_{\rm VBF} \times [\mathcal{P}_{\rm sig}^{\rm VBF}(\vec{x}) + \mathcal{P}_{\rm sig}^{\rm VH}(\vec{x})]$$
$$+ \ \mathcal{P}_{\rm bkg}^{q\bar{q}}(\vec{x}) + \mathcal{P}_{\rm bkg}^{gg}(\vec{x}) + \ldots$$

$\mu_{ggH} = 0.80^{+0.46}_{-0.36}$ $\qquad \sigma_{\rm SM}(ggH + t\bar{t}H) = 14.99$ pb $+ 0.085$ pb

$\mu_{\rm VBF} = 1.7^{+2.2}_{-2.1}$ $\qquad \sigma_{\rm SM}(\rm VBF + VH) = 1.214$ pb $+ 0.896$ pb

$\mu = \sigma/\sigma_{\rm SM} = 0.93^{+0.26+0.13}_{-0.23-0.09}$





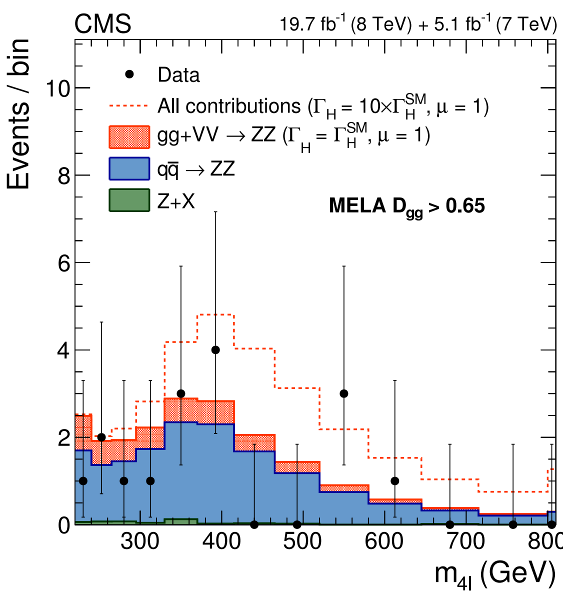
CONSTRAINTS FROM THE HIGH MASS

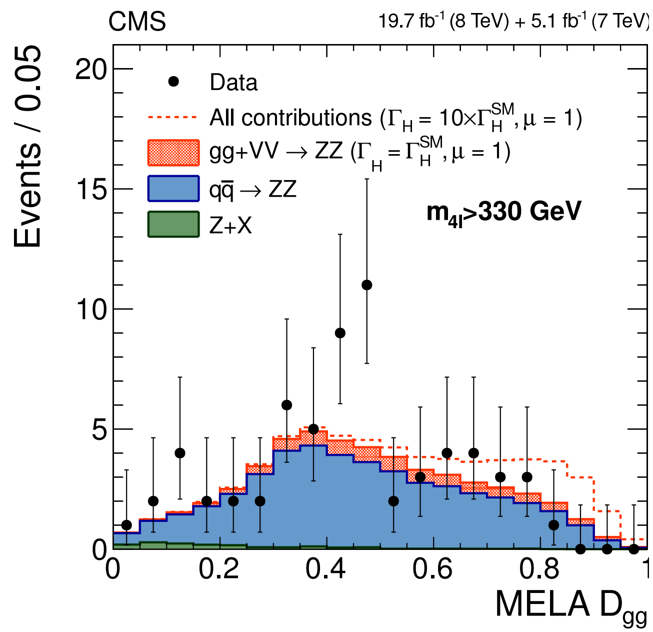
High Mass: $H \to ZZ \to 4\ell$

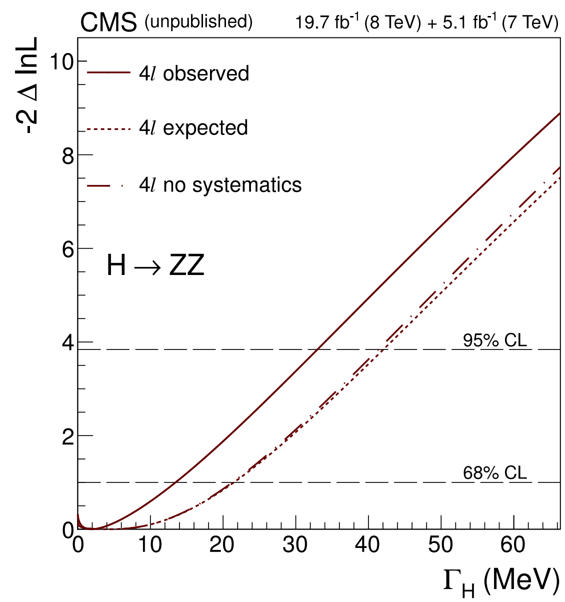
$$\mathcal{P}_{\rm tot}^{\rm offshell}(\vec{x}) = \left[\mu_{ggH} \times \frac{\Gamma_H}{\Gamma_0} \times \mathcal{P}_{\rm sig}^{gg}(\vec{x}) + \sqrt{\mu_{ggH} \times \frac{\Gamma_H}{\Gamma_0}} \times \mathcal{P}_{\rm int}^{gg}(\vec{x}) + \mathcal{P}_{\rm bkg}^{gg}(\vec{x})\right]$$
$$+ \left[\mu_{\rm VBF} \times \frac{\Gamma_H}{\Gamma_0} \times \mathcal{P}_{\rm sig}^{\rm VBF}(\vec{x}) + \sqrt{\mu_{\rm VBF} \times \frac{\Gamma_H}{\Gamma_0}} \times \mathcal{P}_{\rm int}^{\rm VBF}(\vec{x}) + \mathcal{P}_{\rm bkg}^{\rm VBF}(\vec{x})\right]$$

$\Gamma_H = 1.9^{+11.7}_{-1.9}$ MeV < 33 MeV at 95% CL

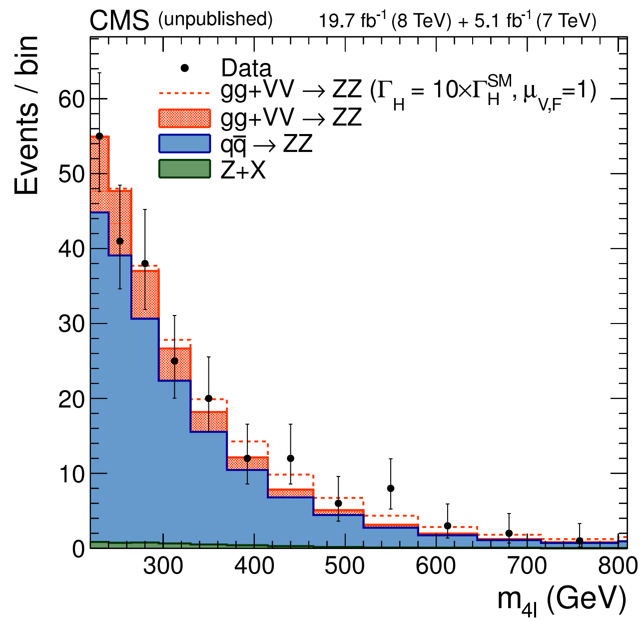
expected: $4.2^{+17.3}_{-4.2}$ MeV < 42 MeV at 95% CL

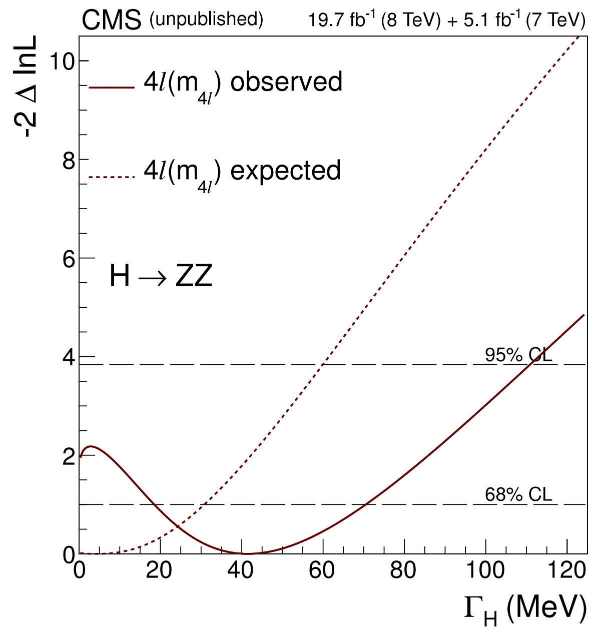


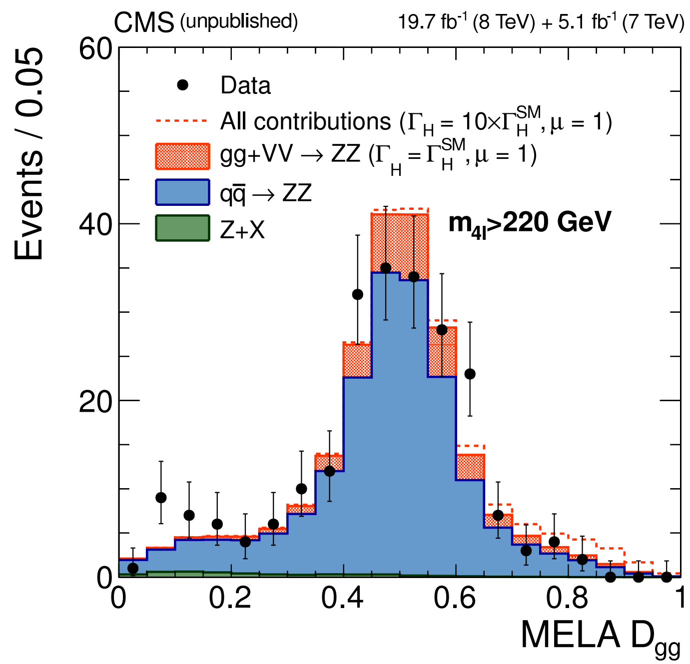


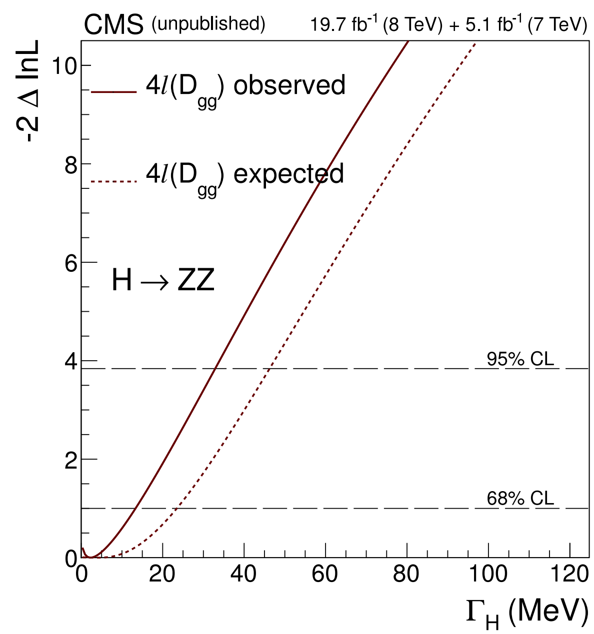


1D Fit in $H \to ZZ \to 4\ell$







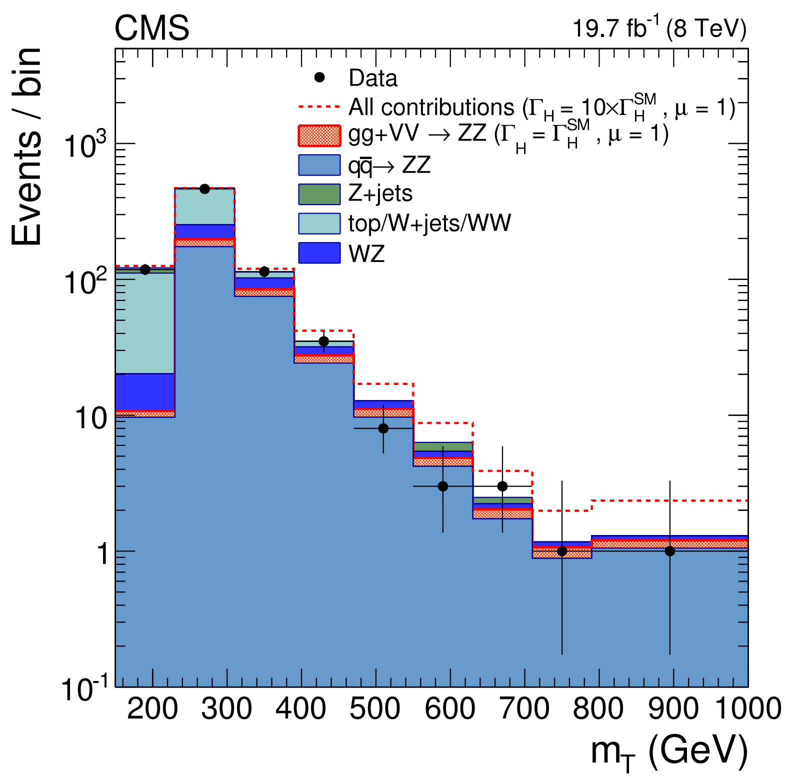


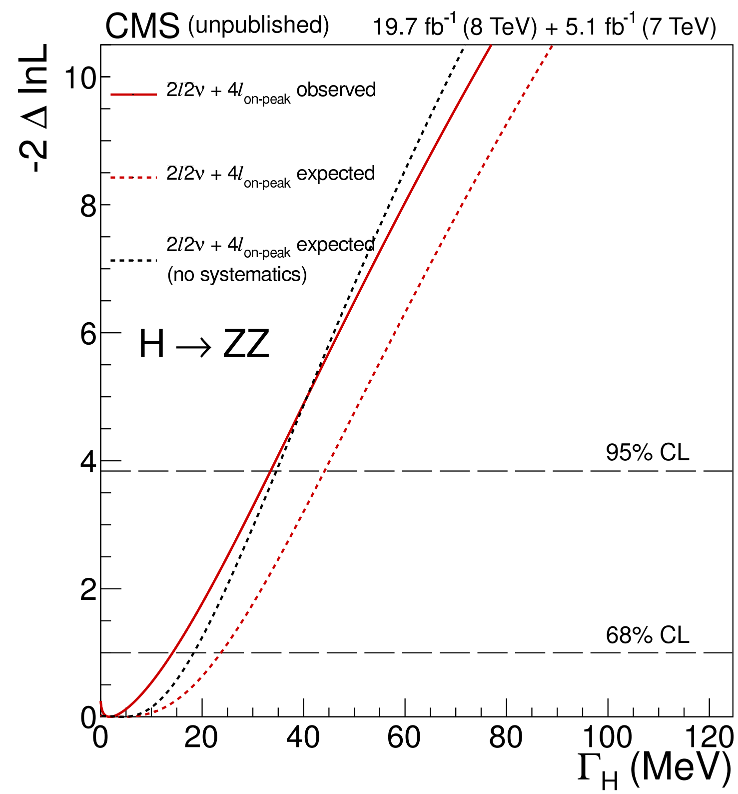
High Mass: $H \to ZZ \to 2\ell 2\nu$

- Combine $H \to ZZ \to 2\ell 2\nu$ at high mass and 4ℓ at low mass

$$\Gamma_H = 1.8^{+12.4}_{-1.8}\ \text{MeV} \quad < 33\ \text{MeV at 95\% CL}$$

$$\text{expected: } 4.2^{+19.3}_{-4.2}\ \text{MeV} < 44\ \text{MeV at 95\% CL}$$

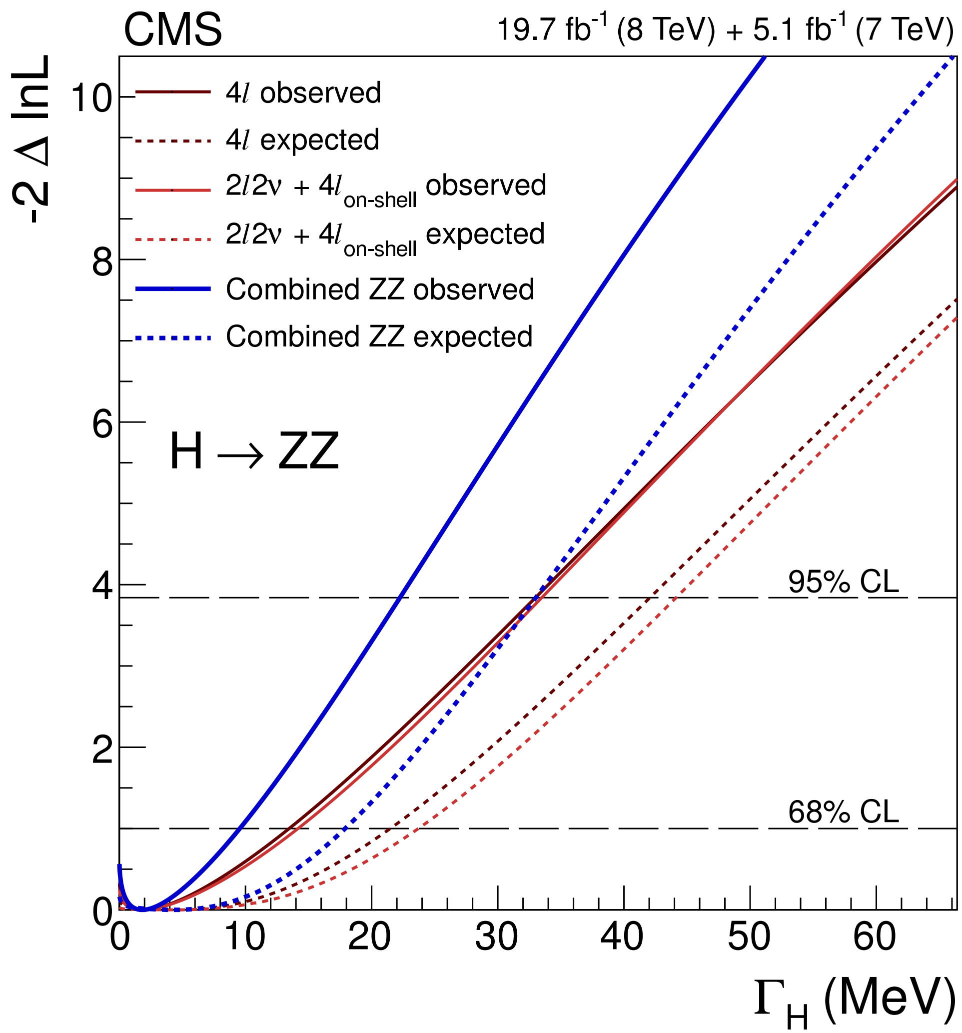




Combined Result

$\Gamma_H = 1.8^{+7.7}_{-1.8}$ MeV < 22 MeV $= 5.4 \times \Gamma_H^{SM}$ at 95% CL

expected: $4.2^{+13.5}_{-4.2}$ MeV < 33 MeV $= 8 \times \Gamma_H^{SM}$ at 95% CL



Model (in)dependence

$$\sigma^{\mathrm{onpeak}}_{\mathrm{gg\to H\to ZZ}} = \mathrm{const}\ \frac{g^2_{\mathrm{ggH}} g^2_{\mathrm{HZZ}}}{\Gamma} \qquad \sigma^{\mathrm{offpeak}}_{\mathrm{gg\to H\to ZZ}} = \mathrm{const}'\ g^2_{\mathrm{ggH}} g^2_{\mathrm{HZZ}}$$

- Higgs boson coupling HVV (g_{HVV})
  - experimental limits prefer tree-level SM HVV coupling
  - anomalous HVV couplings enhance off-shell production

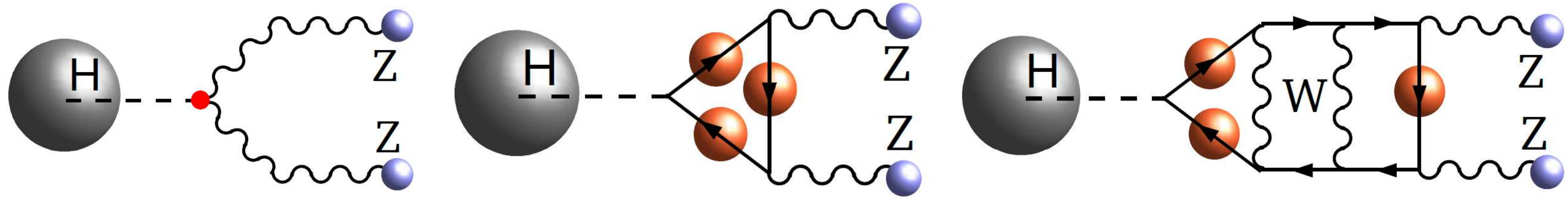
    $\Rightarrow$ conservative limit
- Higgs boson production in gluon fusion (g_{ggH})
  - top quark dominance, no new particles in the loop
- Higgs boson production mechanism
  - very mild dependence (e.g. VH vs VBF), fit directly in the data
- Background model
  - no BSM in background; benefit from improved SM calculations

CP Results in $H \to ZZ \to 4\ell$

- Assumed tree-level HVV coupling either in decay or VBF production

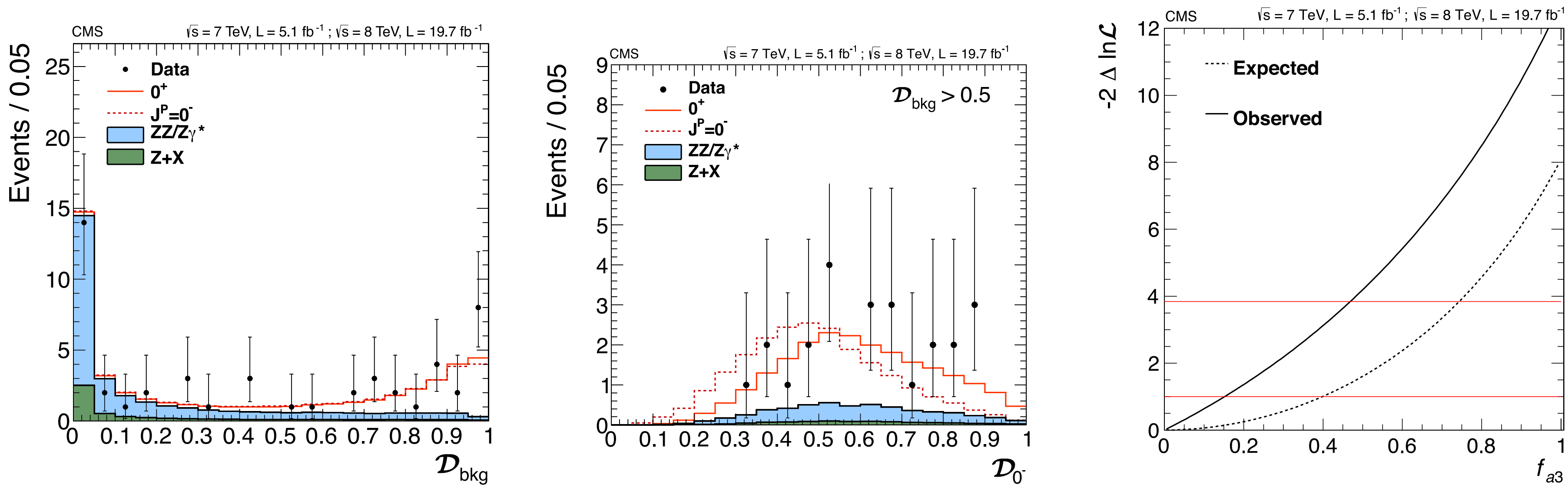
$$A(HVV) = \frac{1}{v}\left(a_1 m_V^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

SM Higgs 0^+: (a_1) CP $\sim$few% (a_2) CP $\sim 10^{-10}$? (a_3) $\not{CP}$



(or beyond SM) (or beyond SM)

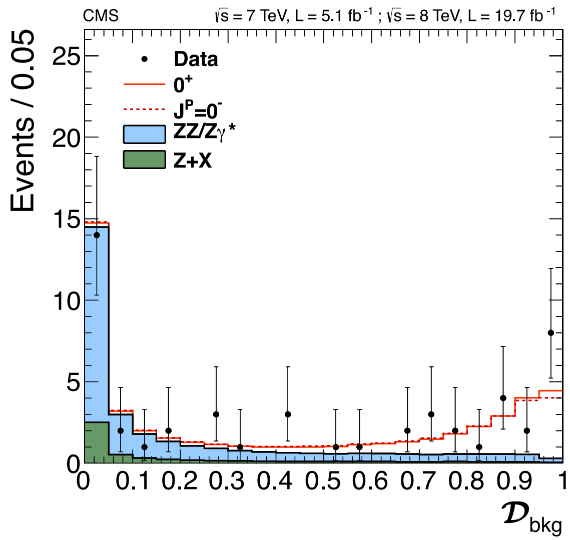
- Test with optimal MELA observables for many J^P models, e.g. 0^-

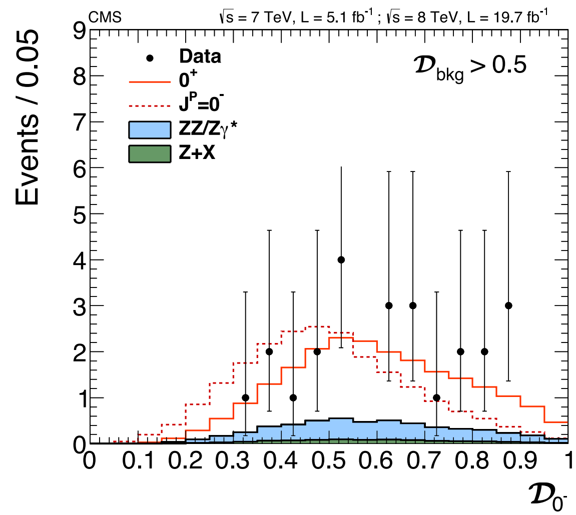


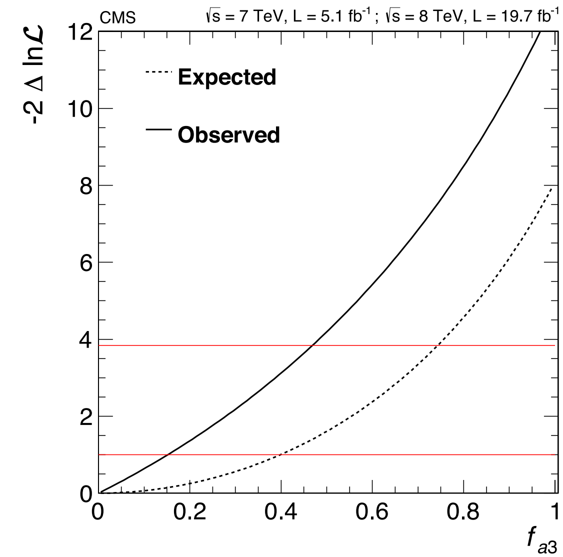
CP Results in $H \to ZZ \to 4\ell$

- Exclude pure pseudo-scalar 0^- at 99.95% CL

$$f_{a3} = \frac{\sigma(a_3)}{\sigma(a_1) + \sigma(a_3)} = 0.00^{+0.17}_{-0.00} \quad < 0.51 \text{ at } 95\%\text{CL}$$



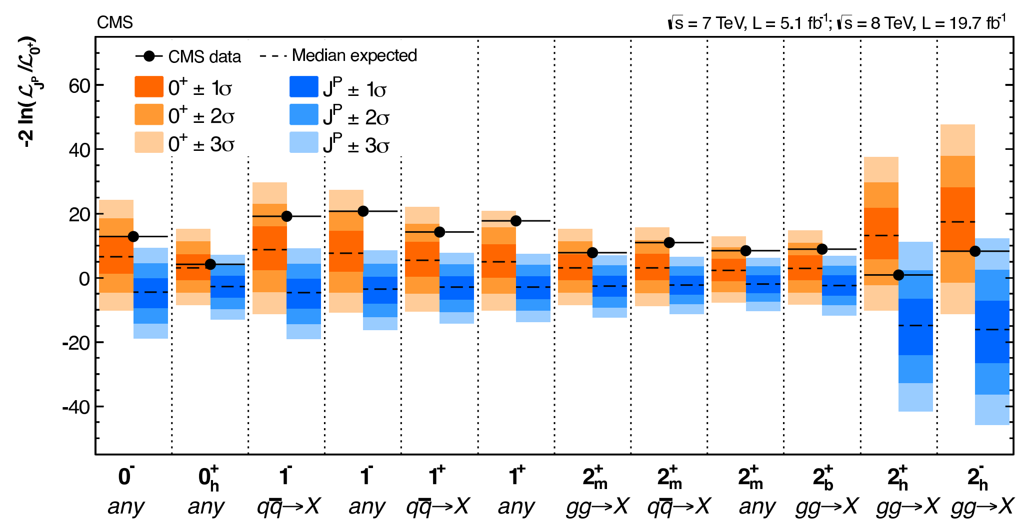




- and many other models:

  spin-0, 1, 2

  consistent with $J^P = 0^+$



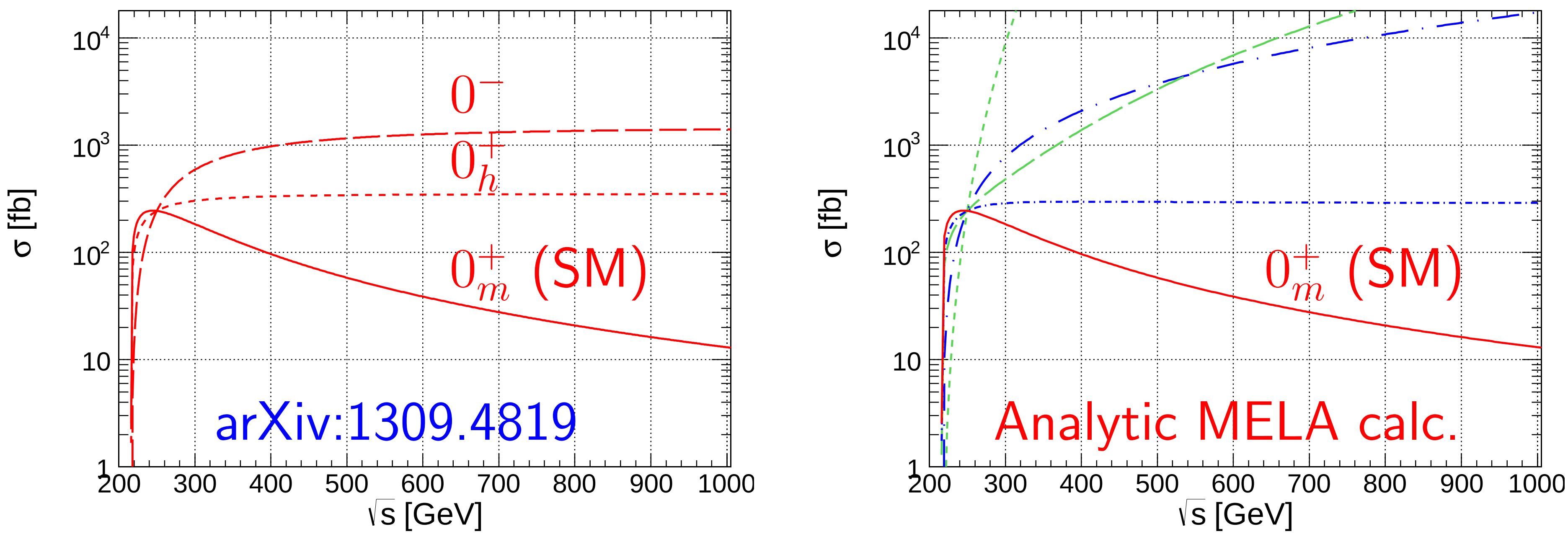
Anomalous HVV Couplings and Off-shell Effects

$$A(HVV) = \frac{1}{v}\left(g_1 m_V^2 \epsilon_1^* \epsilon_2^* + g_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_4 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

- Higher-dimensional non-renormalizable operators lead to

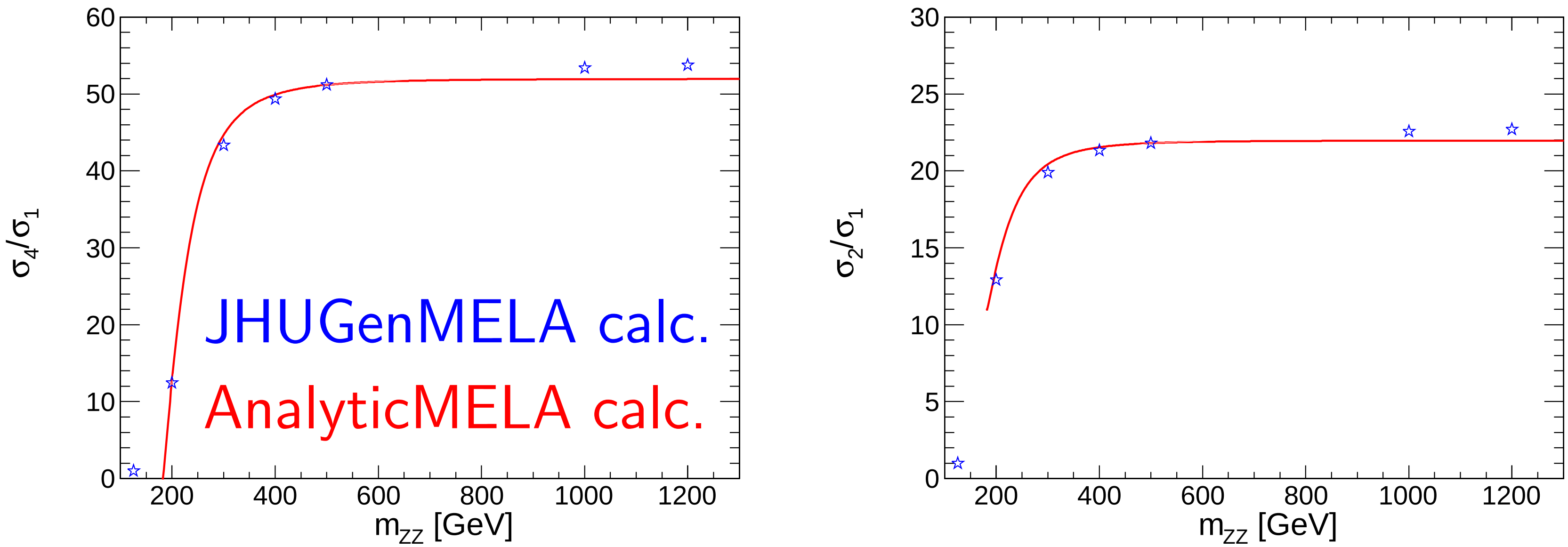
  σ_4/σ_1 blowing up at higher q^2 (for pseudoscalar 0^-)

  same effect for 0_h^+, spin-2, spin-1; example of $f\bar{f} \to V^*(q^2) \to VH$



Anomalous HVV Couplings and Off-shell Effects

- Same enhancement σ_i/σ_1 with higher-dim. operators $H^*(q^2 = m_{ZZ}^2)$

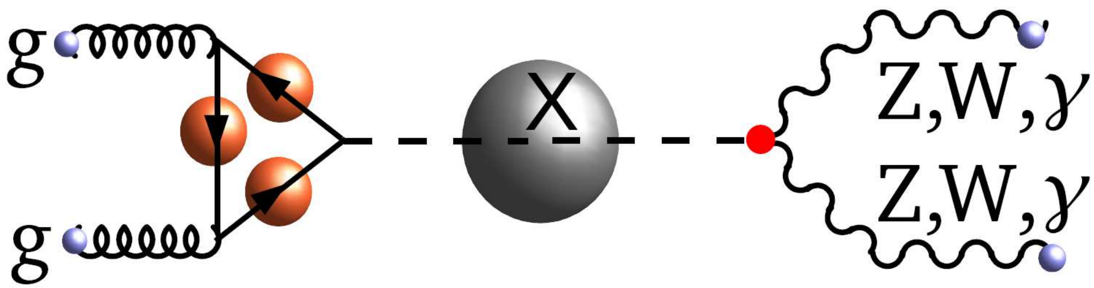


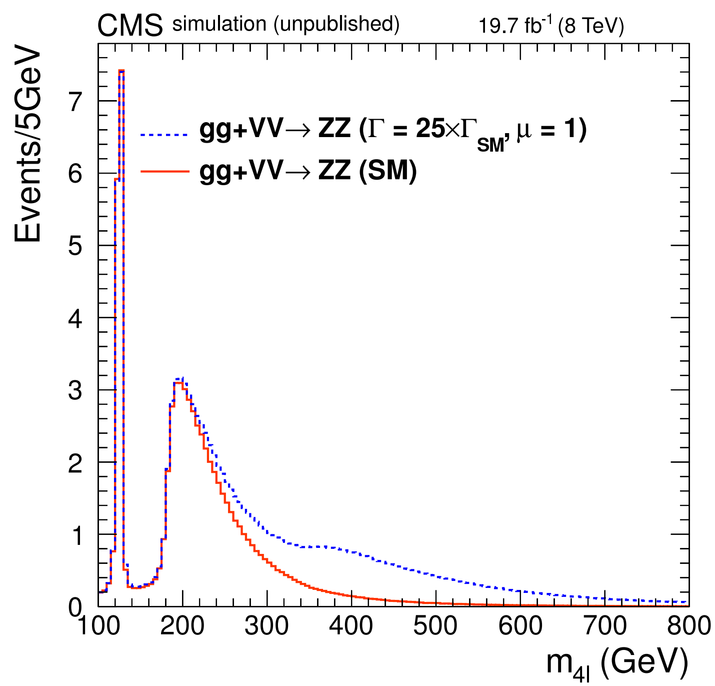
similar study also in arXiv:1403.4951 [hep-ph]

- Conclusion on anomalous HVV couplings:
  - experimental data consistent with SM coupling a_1
  - there is still room for small anomalous contributions
  - width constraint would be only tighter if those are present

Anomalous gg$H$ Couplings

- In gg $\to H$ rely on the dominance of t-quark in the loop
  - assume no new particles in the loop
  - otherwise some modification to offshell / onshell ratio





WHAT IS THE HIGGS BOSON LIFETIME

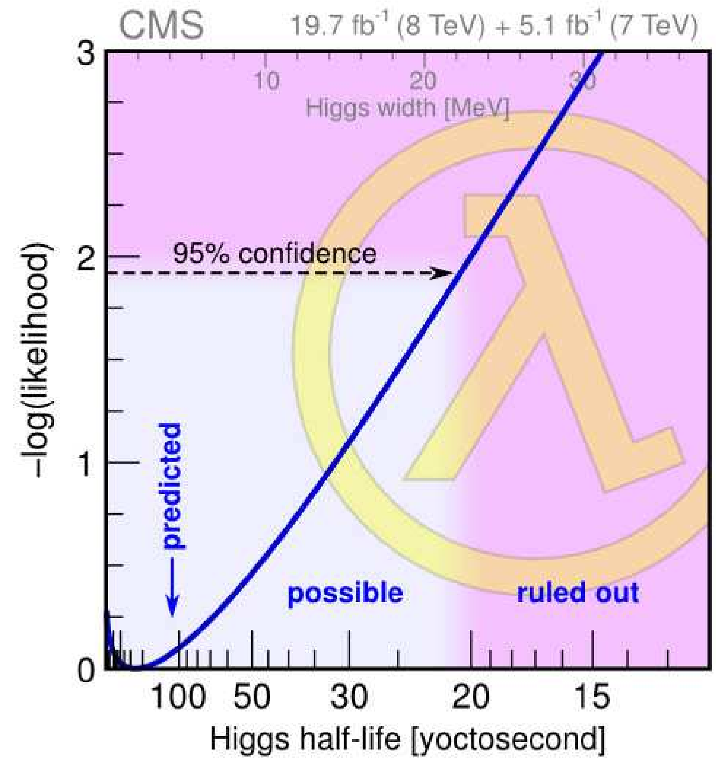
Higgs Boson Lifetime

- How long does the Higgs boson live?

$$\tau_H = \frac{\hbar}{\Gamma_H}, \qquad \text{expect } 1.6 \times 10^{-22} \text{ s}$$

we know it is not stable ($H \to ZZ$, ...)

observe 0.3×10^{-22} s $< \tau_H < \infty$



- Can we set a better upper bound?

  – expect $\sigma_v \sim 50\mu$m vertex resolution, $p \sim 50$ GeV

  – flight distance $\sim \frac{p}{mc} c\tau_H \sim 2 \cdot 10^{-14}$ m $= 20$ fm $\sim 4 \times 10^{-10} \times \sigma_v$

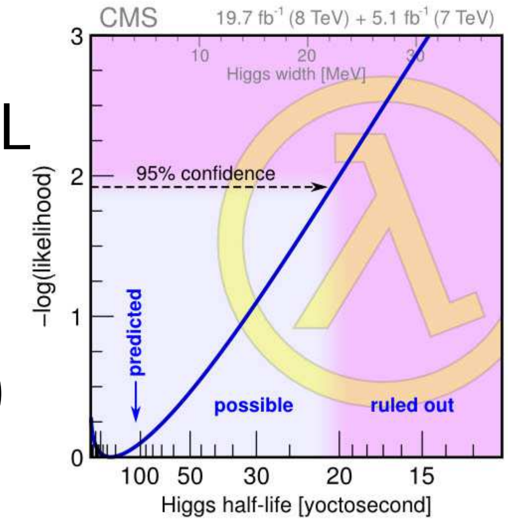
could reach 0.3×10^{-22} s $< \tau_H <$ (?) 0.4×10^{-12} s $< \infty$

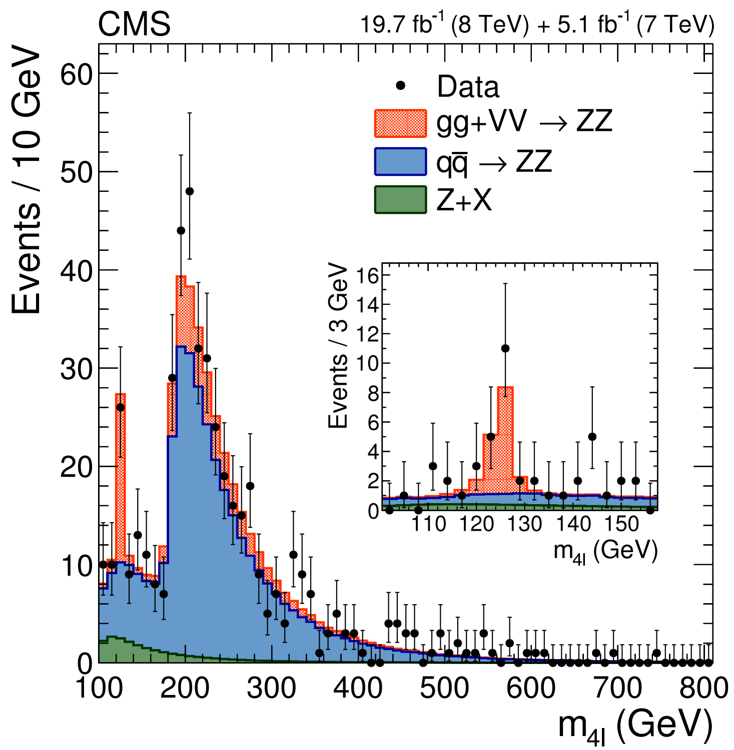
Summary: How Wide is the Higgs Boson?

$0 < \Gamma_H < 22$ MeV $= 5.4 \times \Gamma_H^{SM}$ at 95% CL

$(0.3 \times 10^{-22}$ s $< \tau_H < \infty)$

mild assumptions (no new particles in ggH loop)





- Rich physics with the Higgs boson
  - mass
  - width and lifetime
  - quantum numbers / CP
  - production and decay couplings
- So far consistent picture

reduced room to decay to new states...