Measurement of Higgs Properties with H→ZZ with CMS

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on behalf of the CMS collaboration

ICTP-NCP school on LHC Physics

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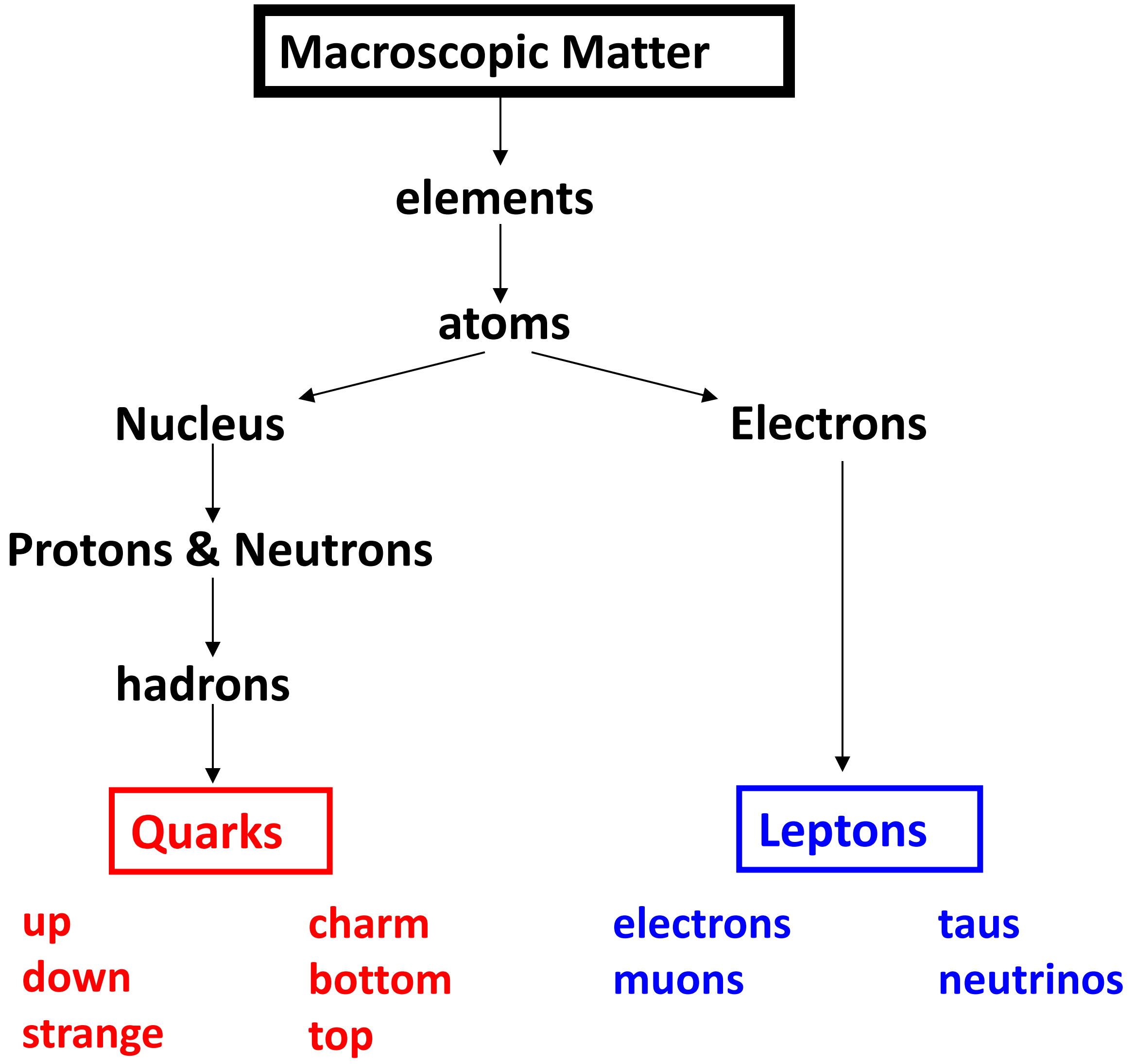
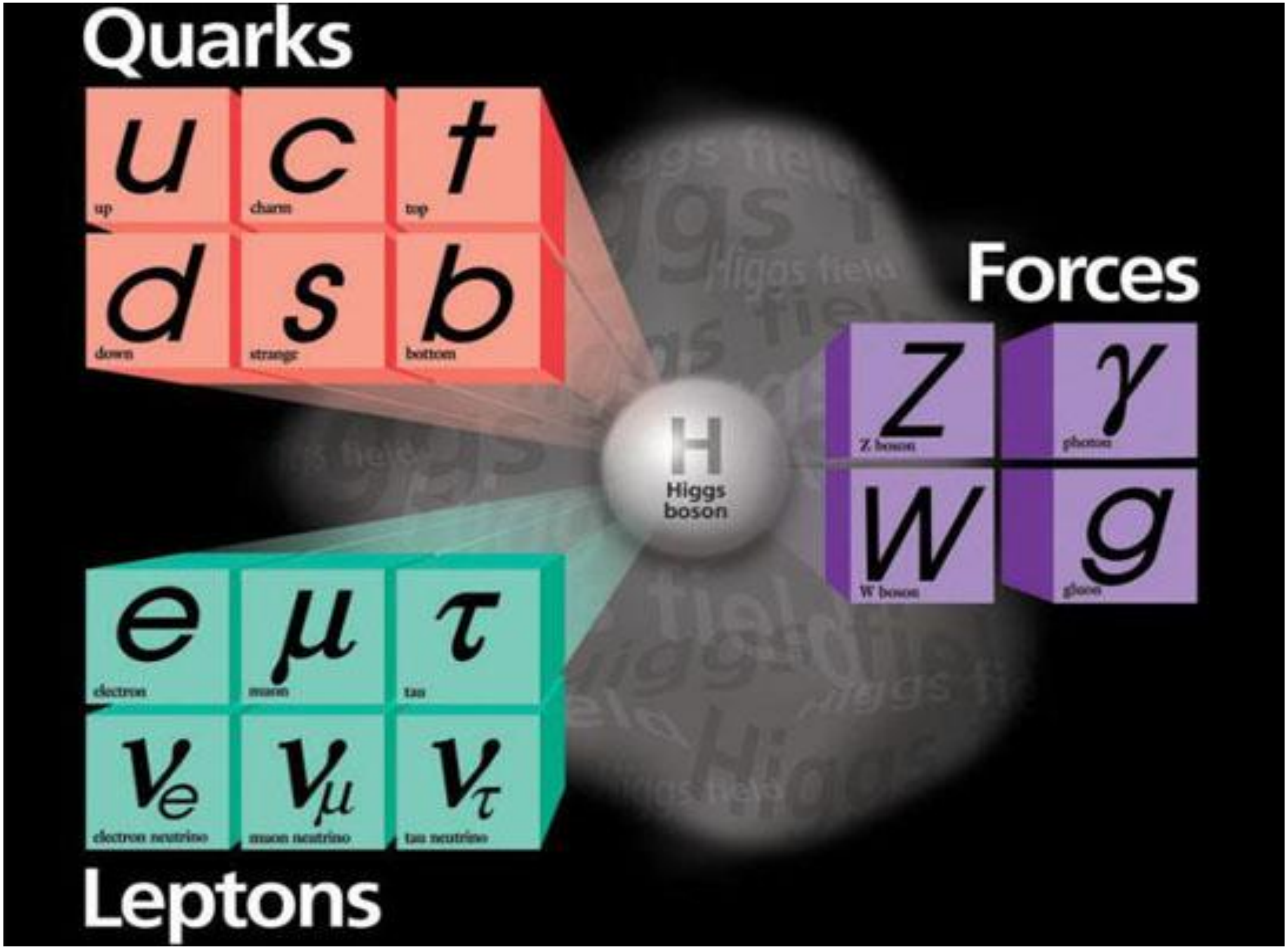


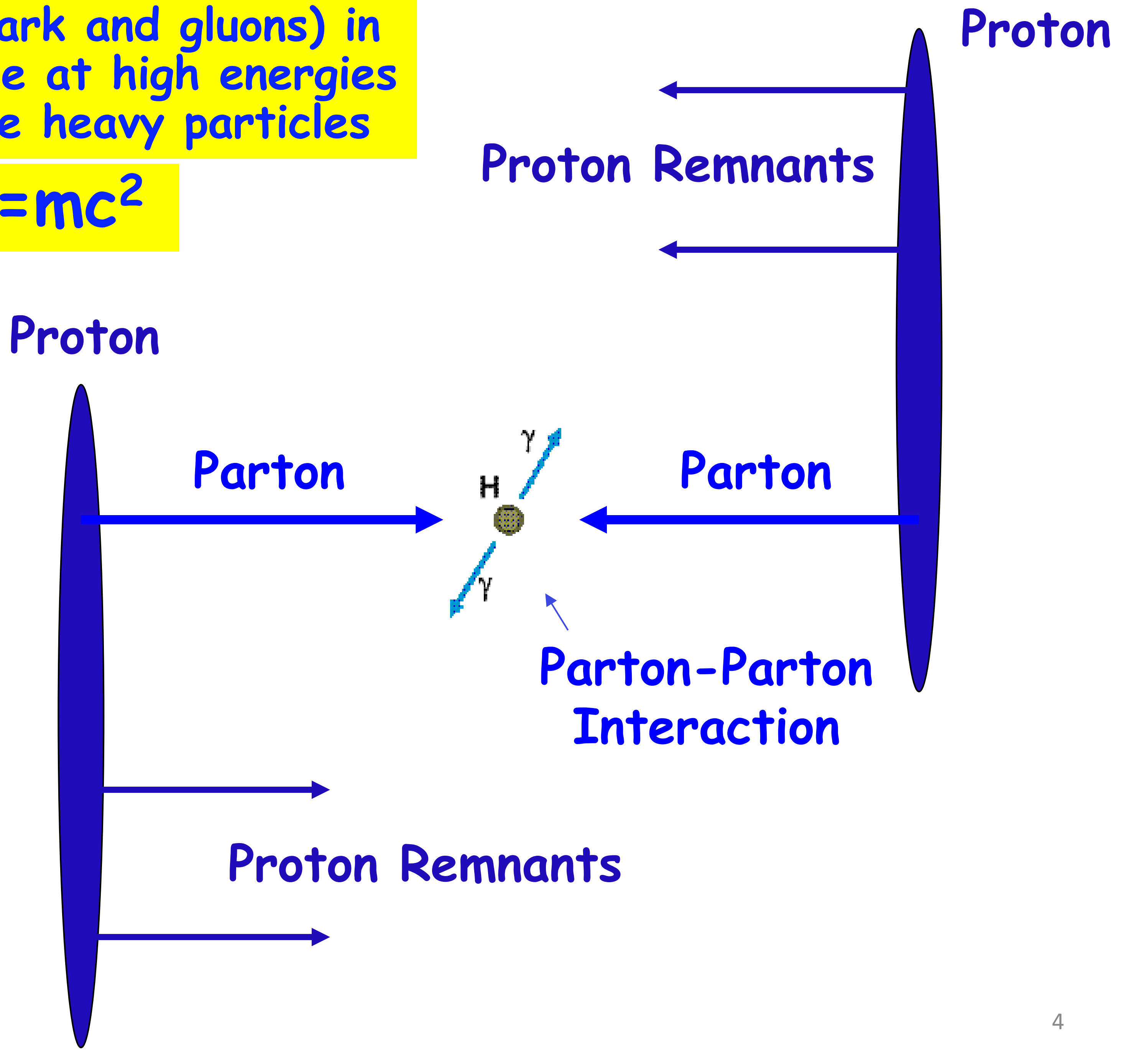
Building blocks for Matter: Quarks and Leptons

The Higgs boson provides for explanation for the mass of quarks, leptons and weak bosons. It is a cornerstone of the theory of fundamental interactions.

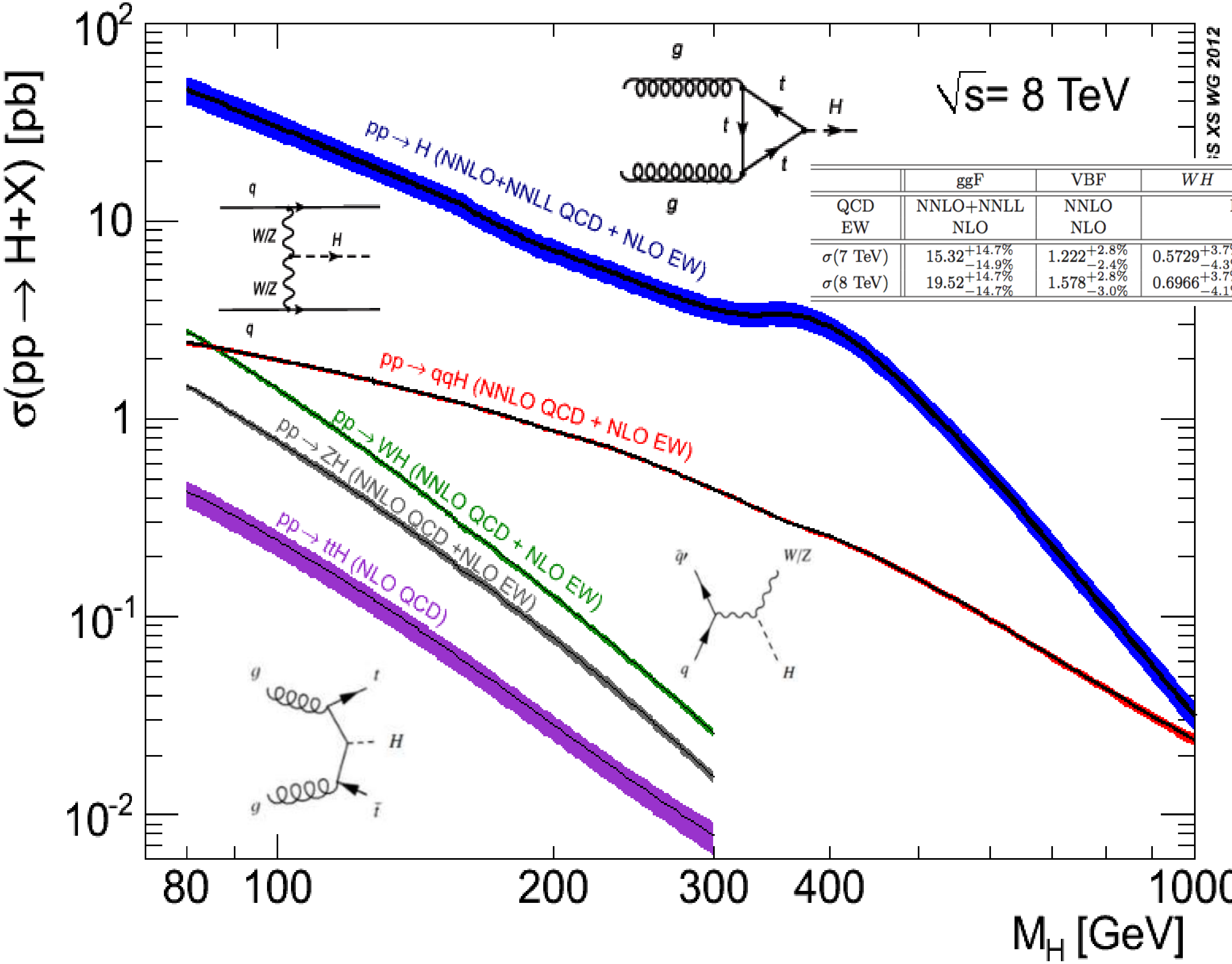


Partons (quark and gluons) in proton collide at high energies and produce heavy particles

$$E=mc^2$$

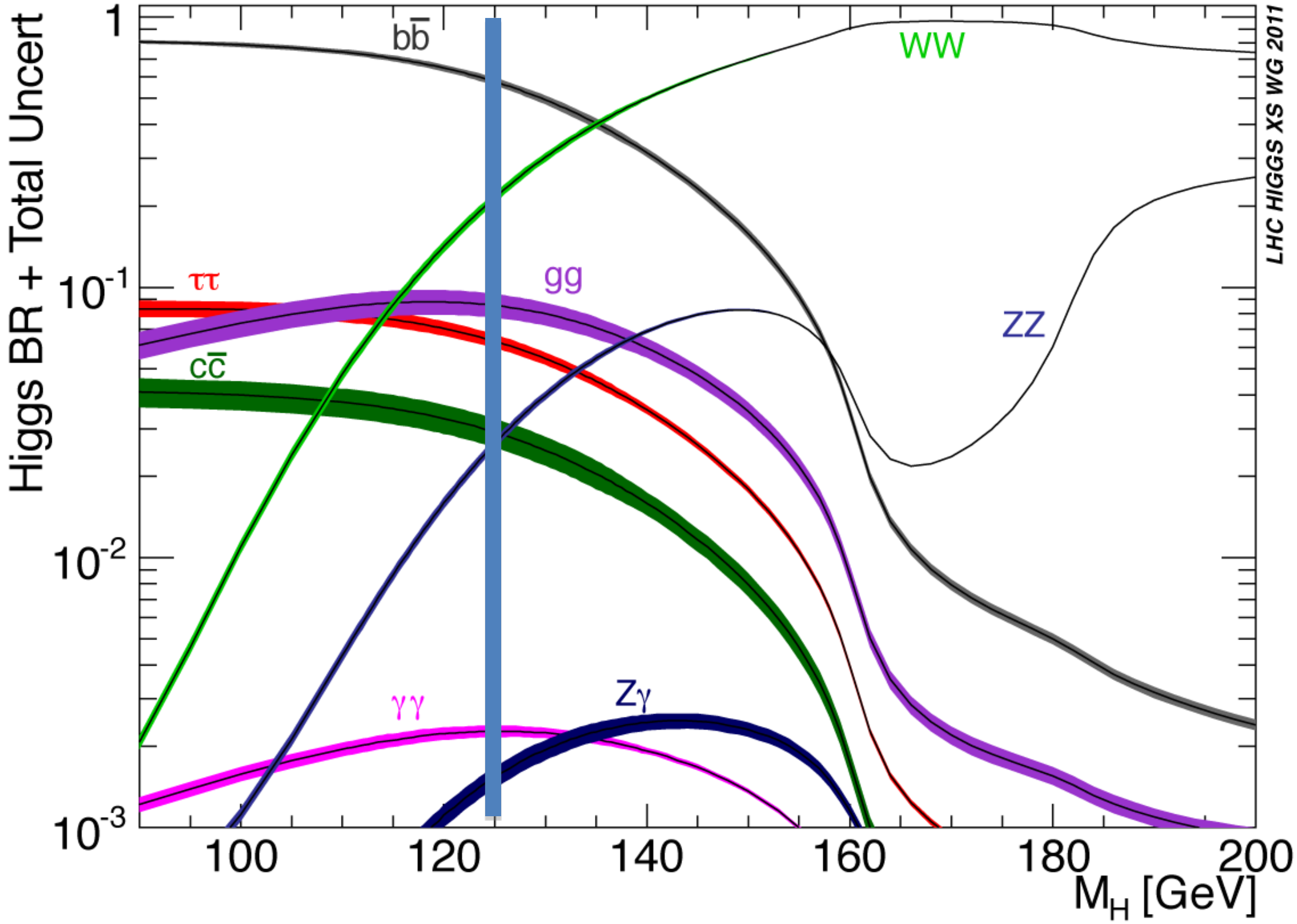


Higgs Cross-Sections at LHC



	ggF	VBF	WH	ZH	$t\bar{t}H$
QCD EW	NNLO+NNLL NLO	NNLO NLO	NNLO NLO		NLO LO
σ(7 TeV)	$15.32^{+14.7\%}_{-14.9\%}$	$1.222^{+2.8\%}_{-2.4\%}$	$0.5729^{+3.7\%}_{-4.3\%}$	$0.3158^{+4.9\%}_{-5.1\%}$	$0.0863^{+11.8\%}_{-17.8\%}$
σ(8 TeV)	$19.52^{+14.7\%}_{-14.7\%}$	$1.578^{+2.8\%}_{-3.0\%}$	$0.6966^{+3.7\%}_{-4.1\%}$	$0.3943^{+5.1\%}_{-5.0\%}$	$0.1302^{+11.6\%}_{-17.1\%}$

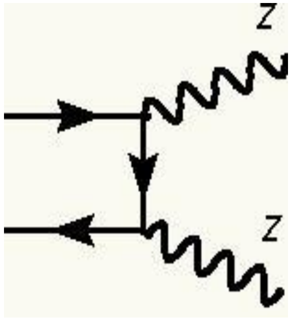
Main Decay Modes

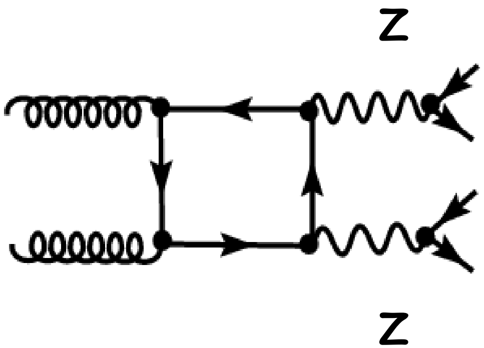


B_b	B_τ	B_μ	B_c	B_g
$0.577^{+3.2\%}_{-3.3\%}$	$0.0632^{+5.7\%}_{-5.7\%}$	$(2.2\times10^{-4})^{+6.0\%}_{-5.9\%}$	$0.0291^{+12.2\%}_{-12.2\%}$	$0.0857^{+10.2\%}_{-10.0\%}$
B_γ	$B_{Z\gamma}$	B_W	B_Z	Γ_H[MeV]
$(2.28\times10^{-3})^{+5.0\%}_{-4.8\%}$	$(2.28\times10^{-3})^{+9.0\%}_{-8.8\%}$	$^{+4.3\%}_{-4.2\%}$	$2.64^{+4.3\%}_{-4.2\%}$	$4.07^{+4.0\%}_{-3.9\%}$

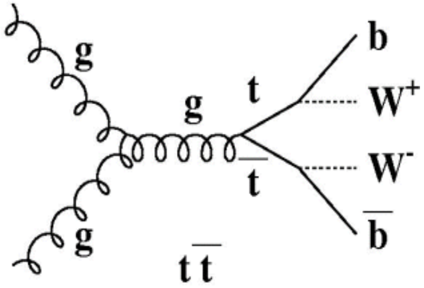
Higgs decay to Z^0Z^0

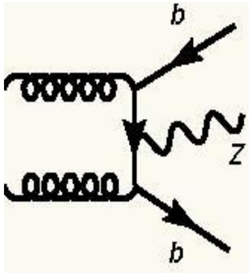
Irreducible Z^0Z^0 backgrounds



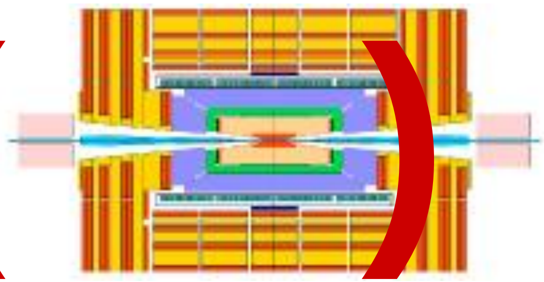


Reducible 4l backgrounds





Principle of Triggering

T()

Event accepted?

YES

NO

Successive steps

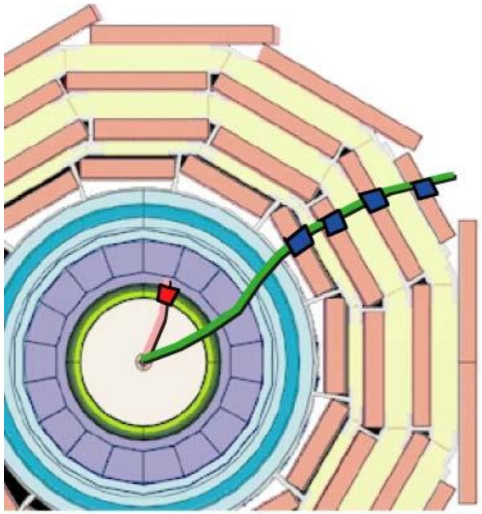
Depends on

Event type
Properties of the measured trigger objects

<u>Trigger objects (candidates):</u> e/γ, μ, hadronic jets,τ-Jets, missing energy, total energy

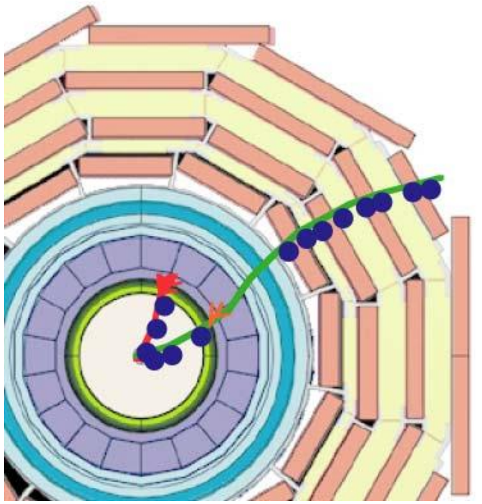
<u>Trigger conditions:</u> according to physics and technical priorities

Trigger Levels in CMS



Level-1 Trigger

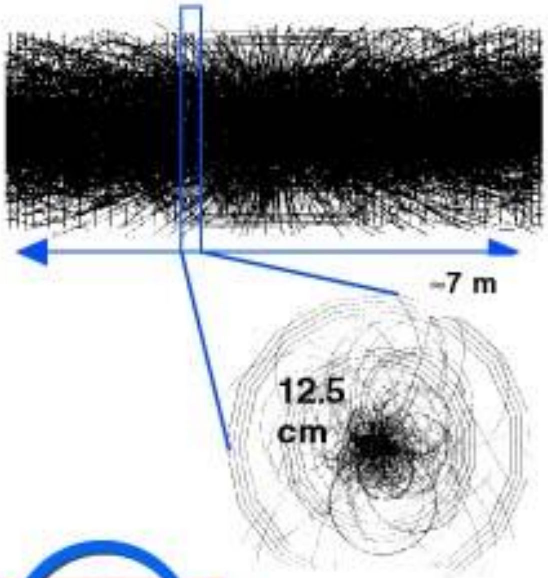
Macrogranular information from calorimters and muon system (e, μ, Jets, $E_T^{missing}$)
Threshold and topology conditions possible
Latency: 3.2 μs
Input rate: 40 MHz
Output rate: up to 100 kHz
Custom designed electronics system



High Level Trigger (several steps)

More precise information from calorimeters, muon system, pixel detector and tracker
Threshold, topology, mass, … criteria possible as well as matching with other detectors
Latency: between 10 ms and 1 s
Input rate: up to 100 kHz
Ouput (data acquisition) rate: approx. 100 Hz
Industrial processors and switching network

Level-1 Trigger



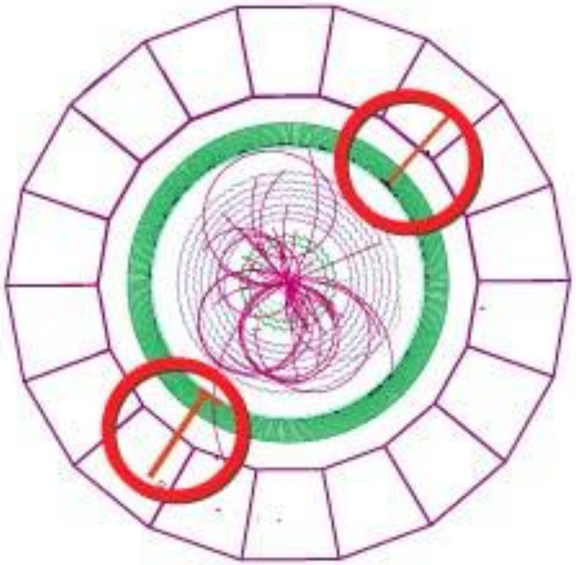
Only calorimeters and muon system involved

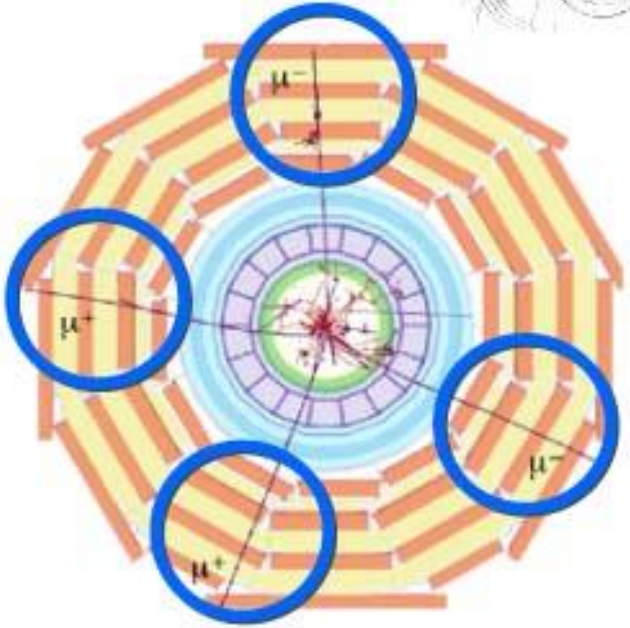
Reason: no complex pattern recognition as in tracker required (appr. 1000 tracks at 10^{34} $cm^{-2}s^{-1}$ luminosity), lower data volume

Trigger is based on:

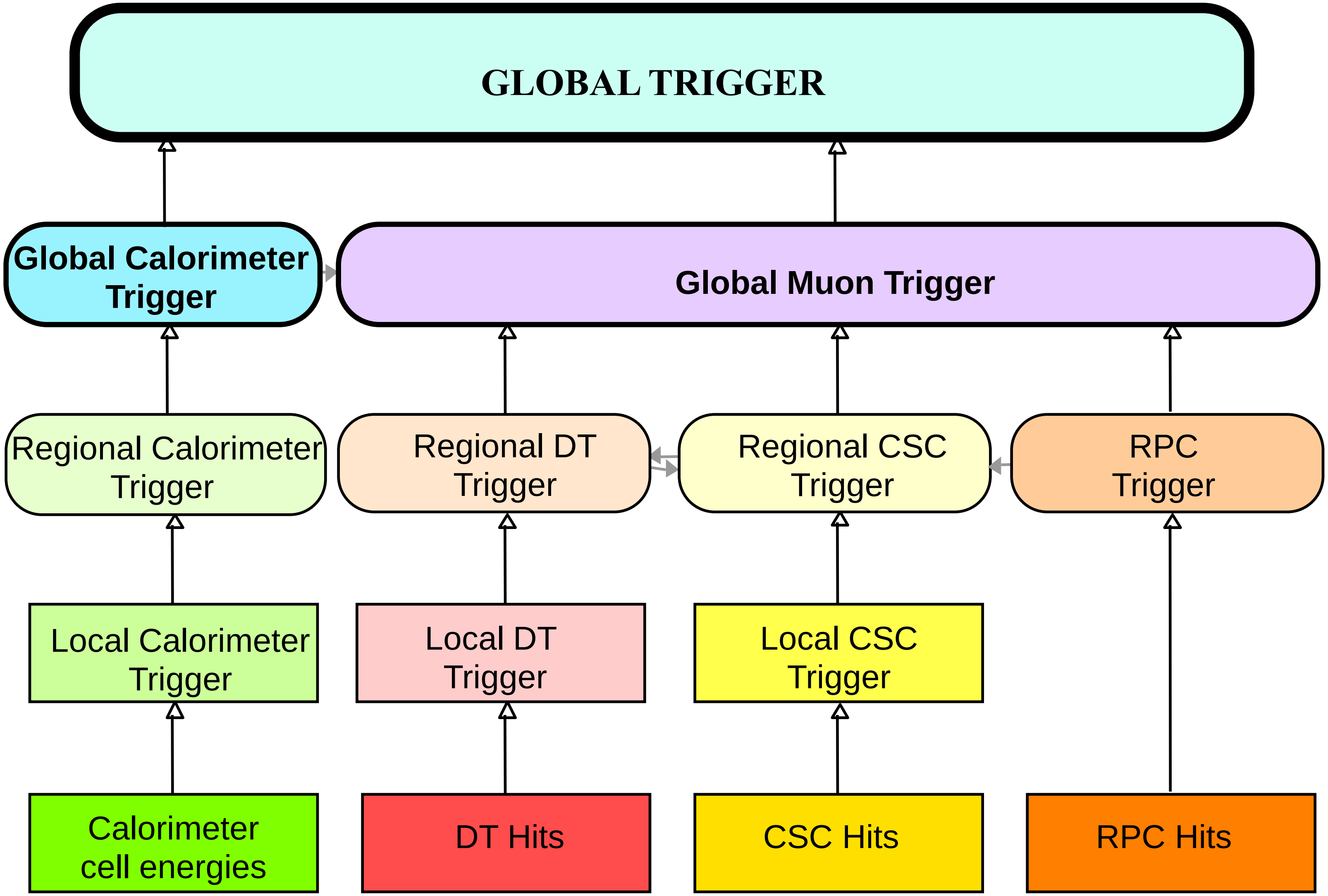
Cluster search in the calorimeters

Track search in muon system





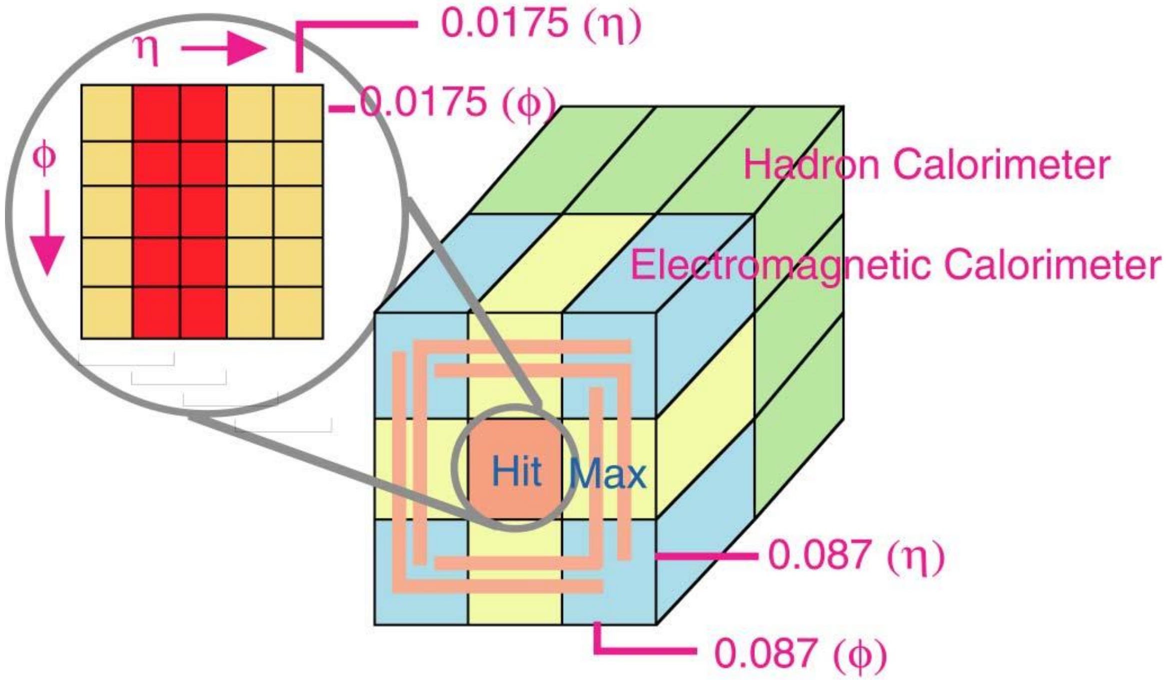
Architecture of the Level-1 Trigger



Level-1 Calorimeter Trigger

<u>Goals</u>

Identify electron / photon candidates
Identify jet / τ-jet candidates
Measure transverse energies (objects, sums, missing E_T)
Measure location
Provide MIP/isolation information to muon trigger



Higgs Properties

- Properties of Higgs Boson candidate (126 GeV) with the $H \to ZZ \to 4\ell$ decay channel (ℓ=e,μ)

  - mass and width (from the on-shell)
  - signal strength
  - spin-parity
  - tensor-structure?

- CMS Detector luminosity 5 fb^{-1} at $\sqrt{s}$ =7 TeV and 19.6 fb^{-1} at $\sqrt{s}$ =8 TeV
- Constraints on Higgs width by off shell production $\sqrt{s}$ = 8 TeV with $H \to ZZ \to 4\ell$ and $H \to ZZ \to 2\ell 2\nu$

Results based on CMS-HIG-13-002
and CMS PAS HIG-14-002

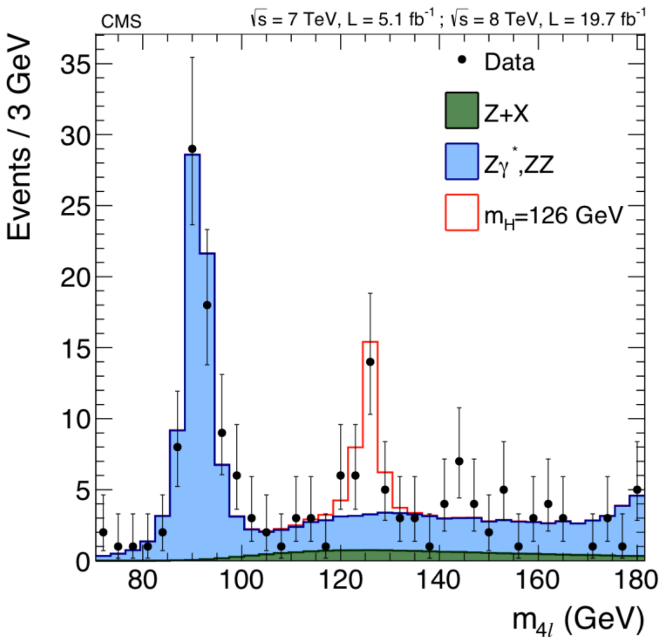
Analysis Strategy

- Each event consists of two pair of same-flavor and opposite-charge leptons in final state compatible with ZZ system
- Background

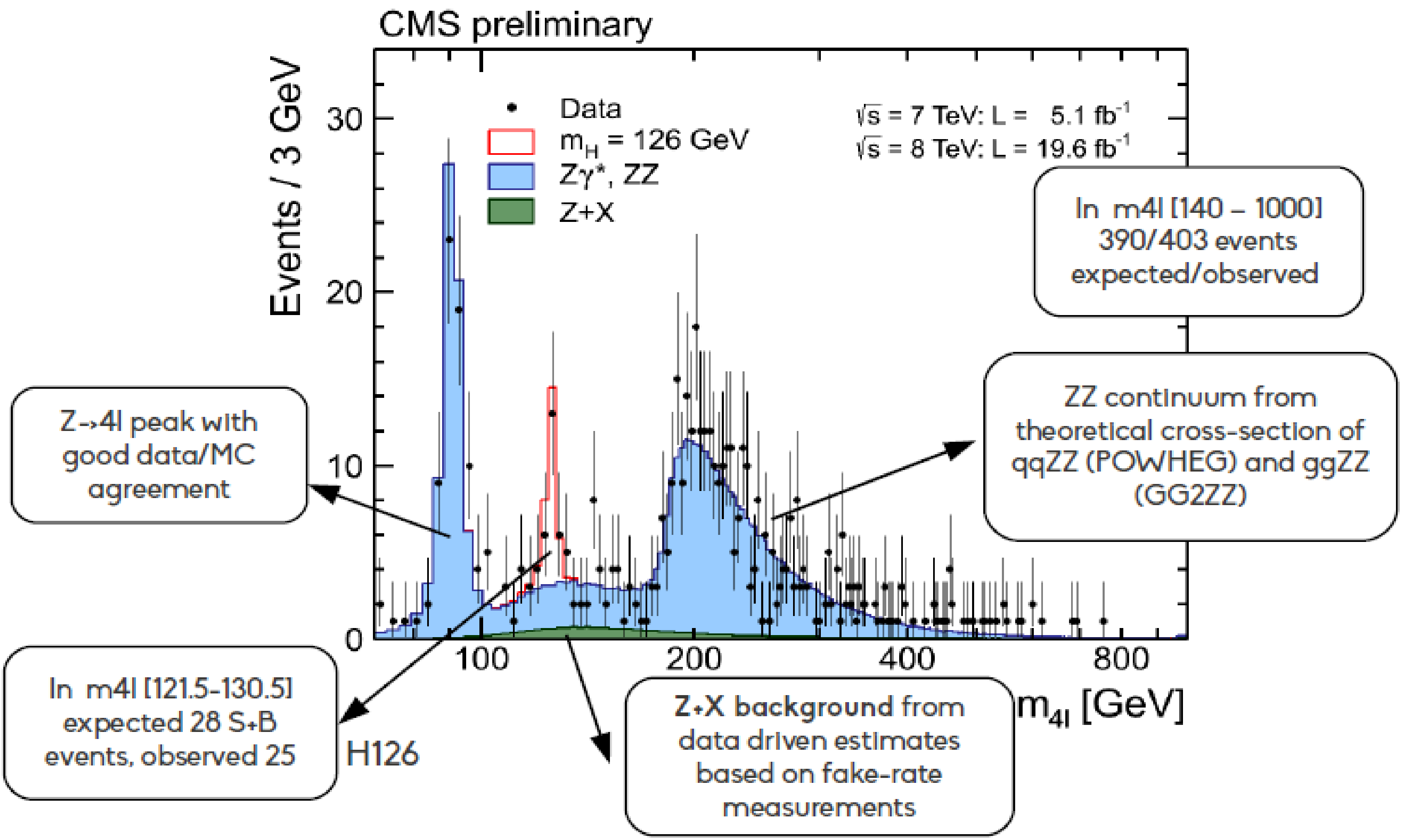
irreducible : direct ZZ ($Z\gamma^*$)

reducible : Z+X

Instrumental due misidentification of leptons



Four Leptons Mass Spectrum



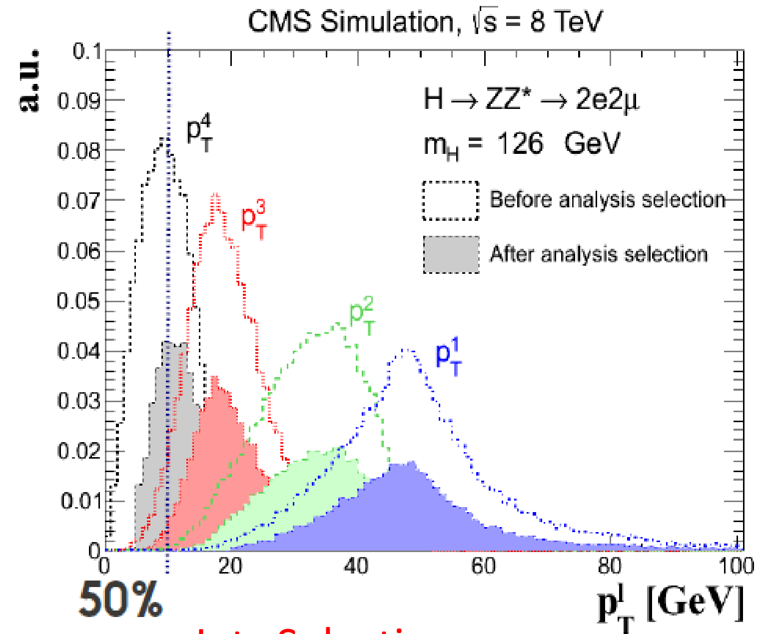
Event Selection

- Electron

  pT>7 GeV ,|η|<2.5
- Muon

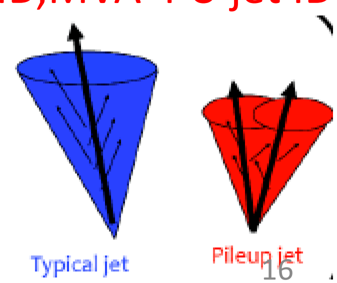
  pT>5 GeV ,|η|<2.4
- $40 < m_{Z1} < 120 \;\; , 12 < m_{Z2} < 120$
- p_T^1 >20 GeV, p_T^2 >10 GeV
- $100 < m_{ZZ} < 1000$
- Impact Parameter cut
- Final state recovery (photon)

pT>2 GeV, |η|<2.4



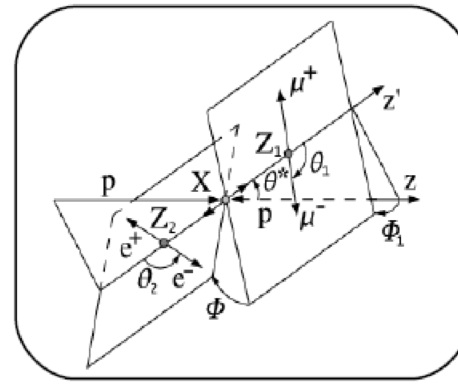
Jets Selection:

- pT > 30 GeV
- |η|<4.7
- Loose Jet ID,MVA PU jet ID



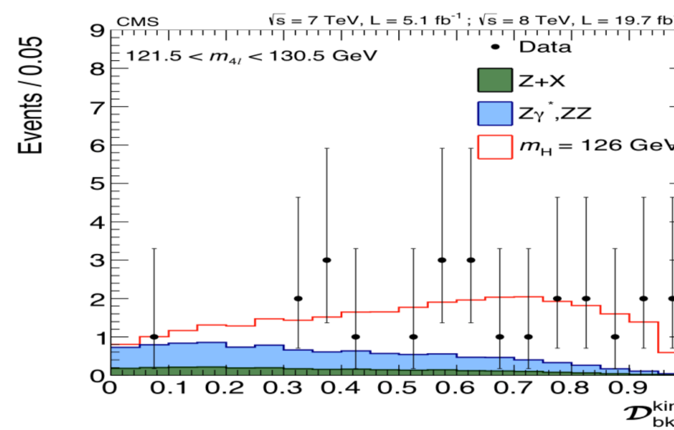
Kinematic discriminant

- An additional dimension to profit from kinematical difference between Higgs Decay and ZZ background



$$K_D = \frac{P_{sig}}{P_{sig} + P_{bkg}} = \left[1 + \frac{P_{bkg}(m_{Z_1}, m_{Z2}, \vec{\Omega} \mid m_{4l})}{P_{sig}(m_{Z_1}, m_{Z2}, \vec{\Omega} \mid m_{4l})} \right]$$

where $P_{sig(bkg)}$ is the probability of an event with given Topology (masses , angles)to come from signal or background

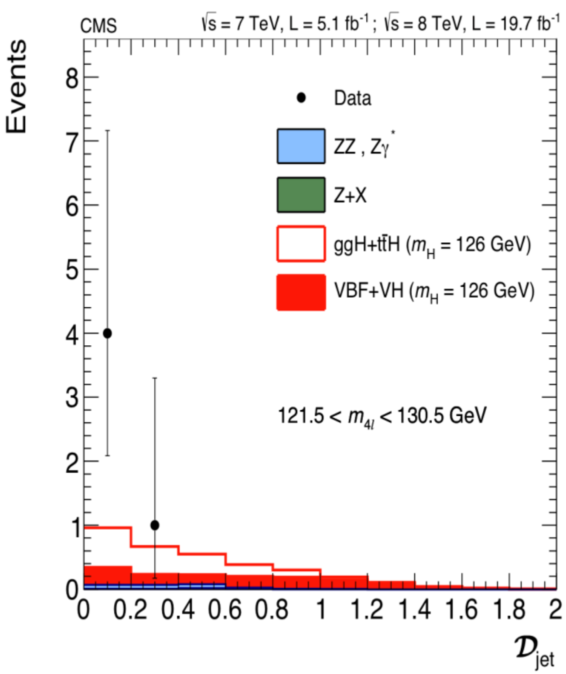


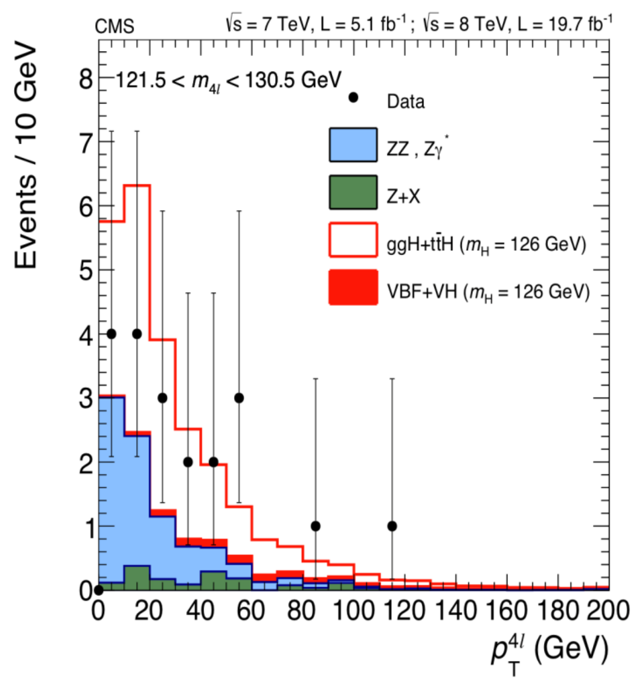
Jets category-coupling

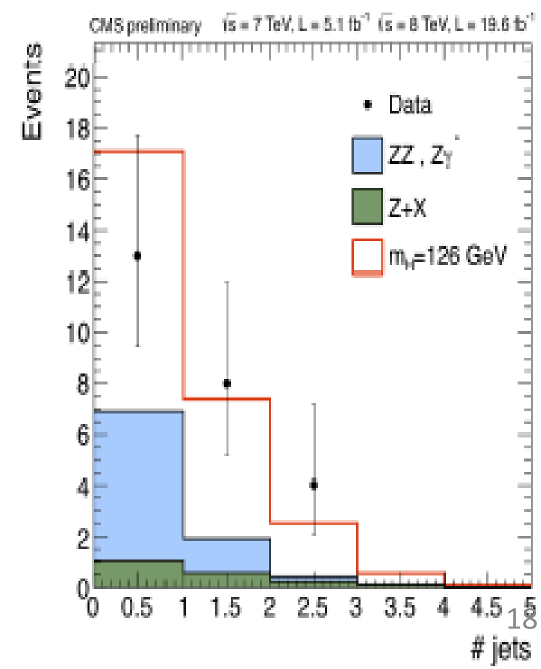
- Adding another dimension to the analysis to separate production mechanism

Category I – "di-jets"
- More than 2 jets (p_T › 30)
- ~20% of signal is VBF

Category II - "untagged"
- Remaining events
- ‹5% of signal is VBF



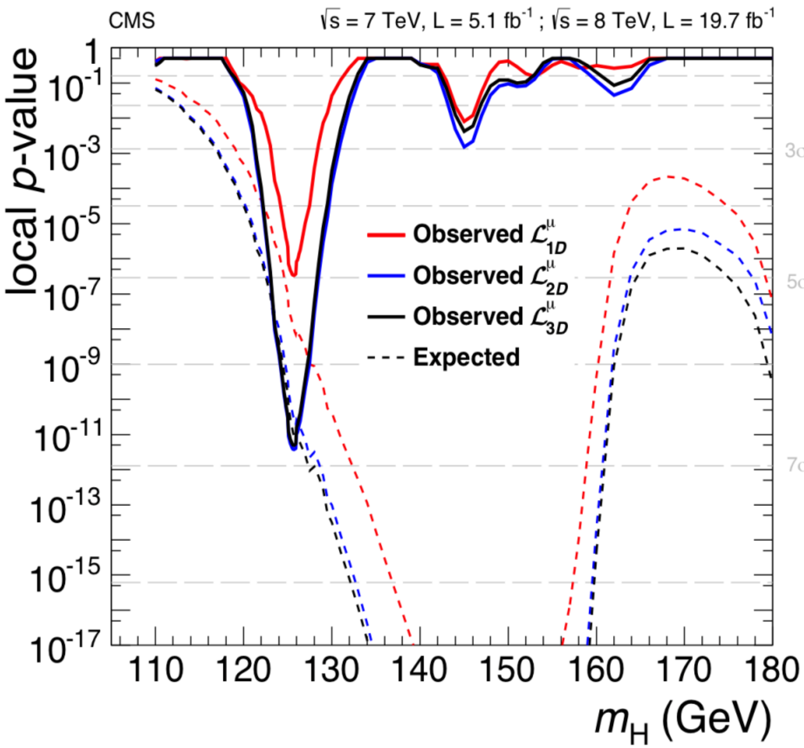




Significance of the Excess

Build a 3D model:

- Category I: $P(m_{4l}, K_D, V_D) = P(V_D|m_{4l}) \times P(K_D|m_{4l}) \times P(m_{4l})$
- Category II: $P(m_{4l}, K_D, p_T/m_{4l}) = P(p_T/m_{4l}|m_{4l}) \times P(K_D|m_{4l}) \times P(m_{4l})$



The **minimum of the local p-value is reached at *m4l =*** 125.7 GeV and it corresponds to a local significance 6.8 (for an expectation of 6.7).

Mass and Width measurement

3D based Model measurement

$$(m_{4l}, \delta m_{4l}, K_D)$$

- Per-event mass errors brings ~8% improvement
- Scale and resolution are main sys. Uncertainties

calibrated with Z(J/y)->ll and Z->4l

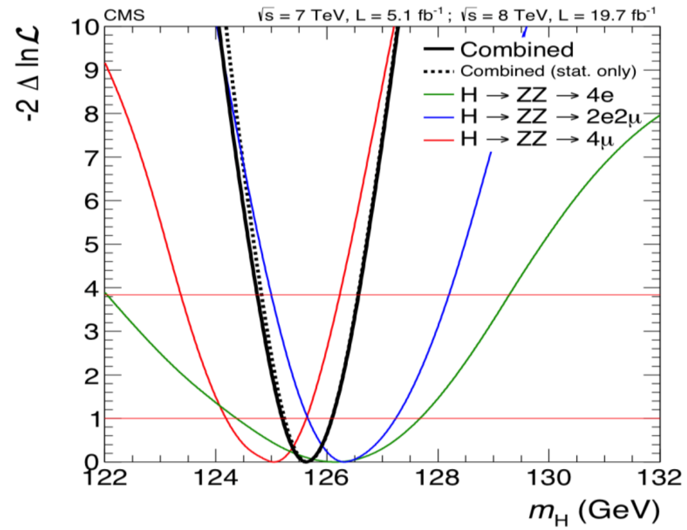
m = 125.6 ± 0.4 (stat.) ± 0.2 (syst.) GeV.

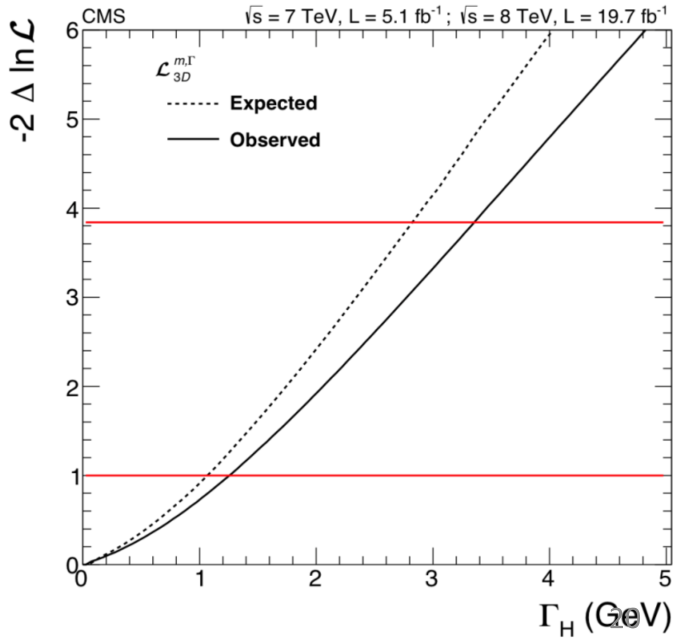
Data is compatible with the narrow width resonance

$$\Gamma_H = 0.0^{+1.3}_{-0.0} \text{ GeV}$$

upper bound 3.4GeV(95% CL)

expected 2.8 GeV





Signal Strength

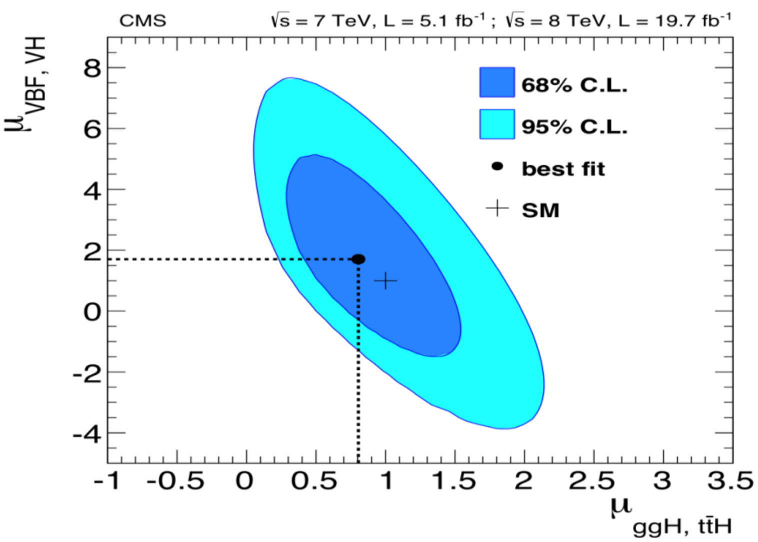
Results around best fit mass m=125.6 GeV

$$\frac{\sigma_{obs}}{\sigma_{SM}} = 0.93^{+0.26}_{-0.23}(stat.)^{+0.13}_{-0.09}(syst.)$$

$$\frac{\sigma_{obs}}{\sigma_{SM\ 0/1\,jet}} = 0.83^{+0.31}_{-0.25} \qquad \frac{\sigma_{obs}}{\sigma_{SM\ dijet}} = 1.45^{+0.89}_{-0.62}$$

$$\frac{\sigma_{obs}}{\sigma_{SM\ ggH,ttH}} = 0.80^{+0.46}_{-0.36} \qquad \frac{\sigma_{obs}}{\sigma_{SM\ VBF,VH}} = 1.7^{+2.2}_{-2.1}$$

- Jet categories help to test couplings to bosons and fermions separately
- Signal strength shows good compatibility of scalar couplings with SM

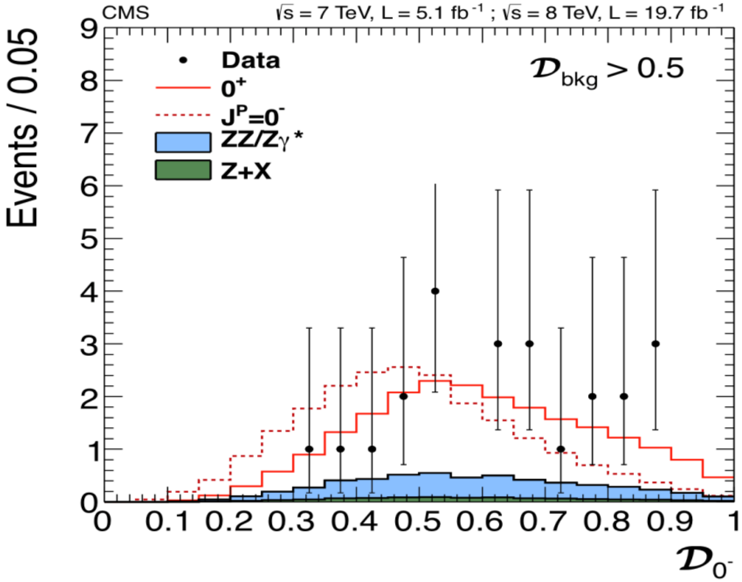


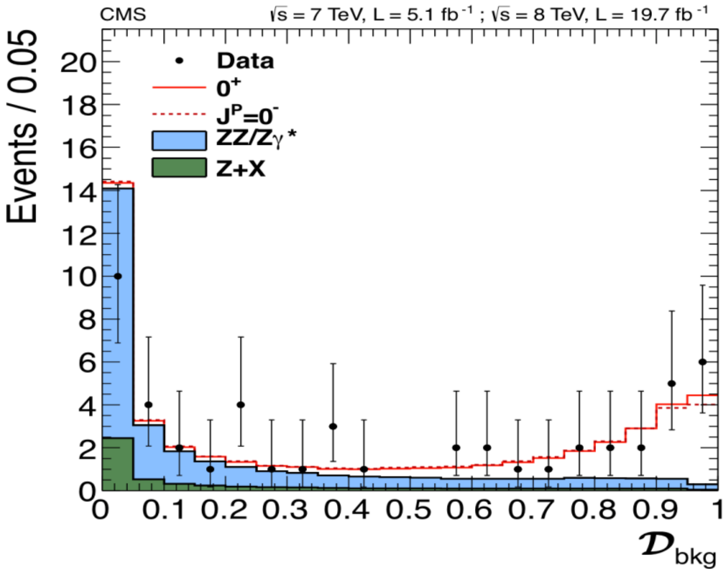
Spin-Parity Measurements

- In order to determine the spin and the parity of the Higgs boson, a **methodology with Matrix element base kinematic *discriminants is used***

$$D_{j^P} = \frac{P_{0^+}}{P_{0^+} + P_{j^P}} \qquad D_{bkg} = \frac{P_{0^+}}{P_{0^+} + P_{bkg}}$$

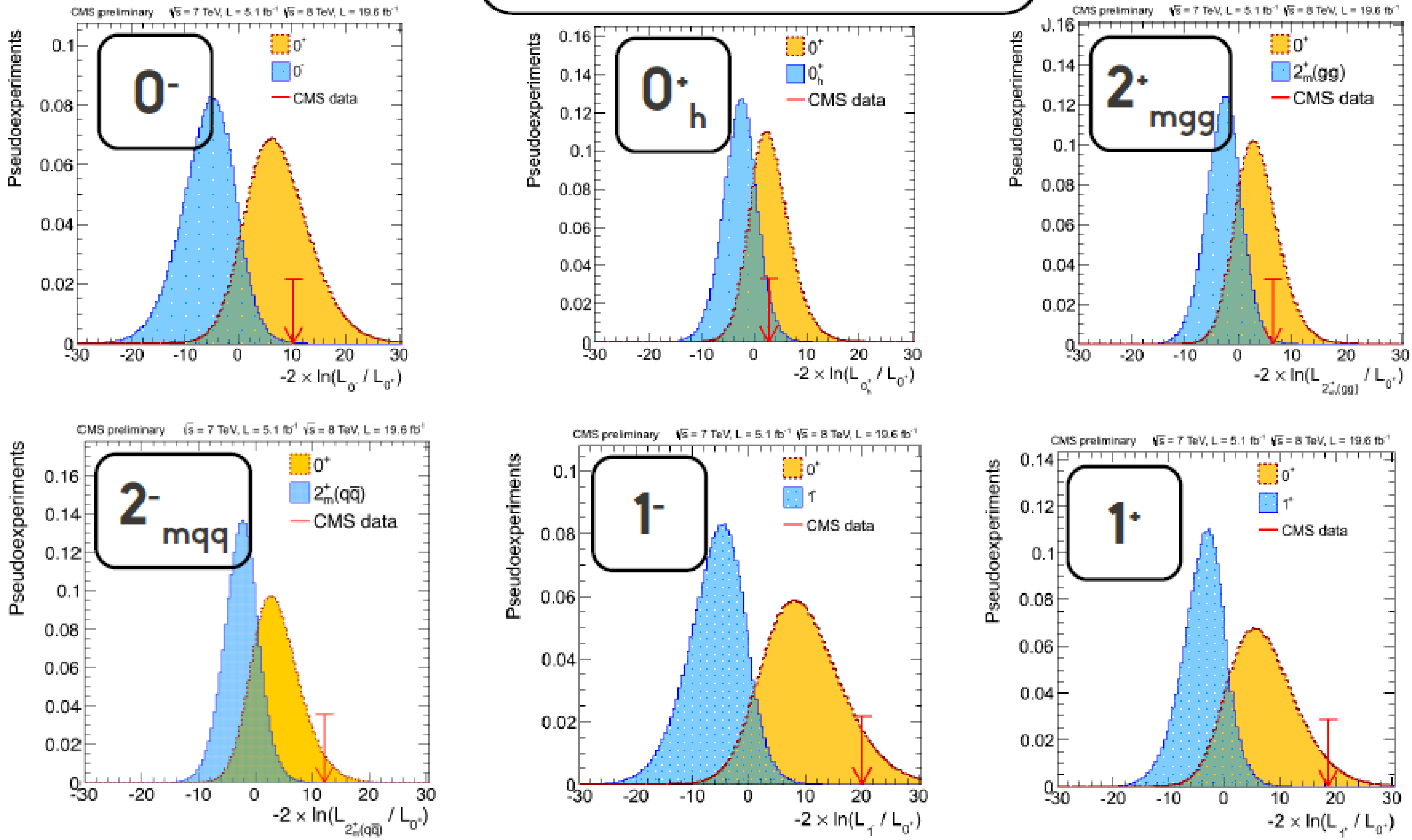
- The different spin-parity hypotheses are thus tested using the **two-dimensional likelihood** $\ell_{2D} = \ell_{2D}(D_{j^P}, D_{bkg})$





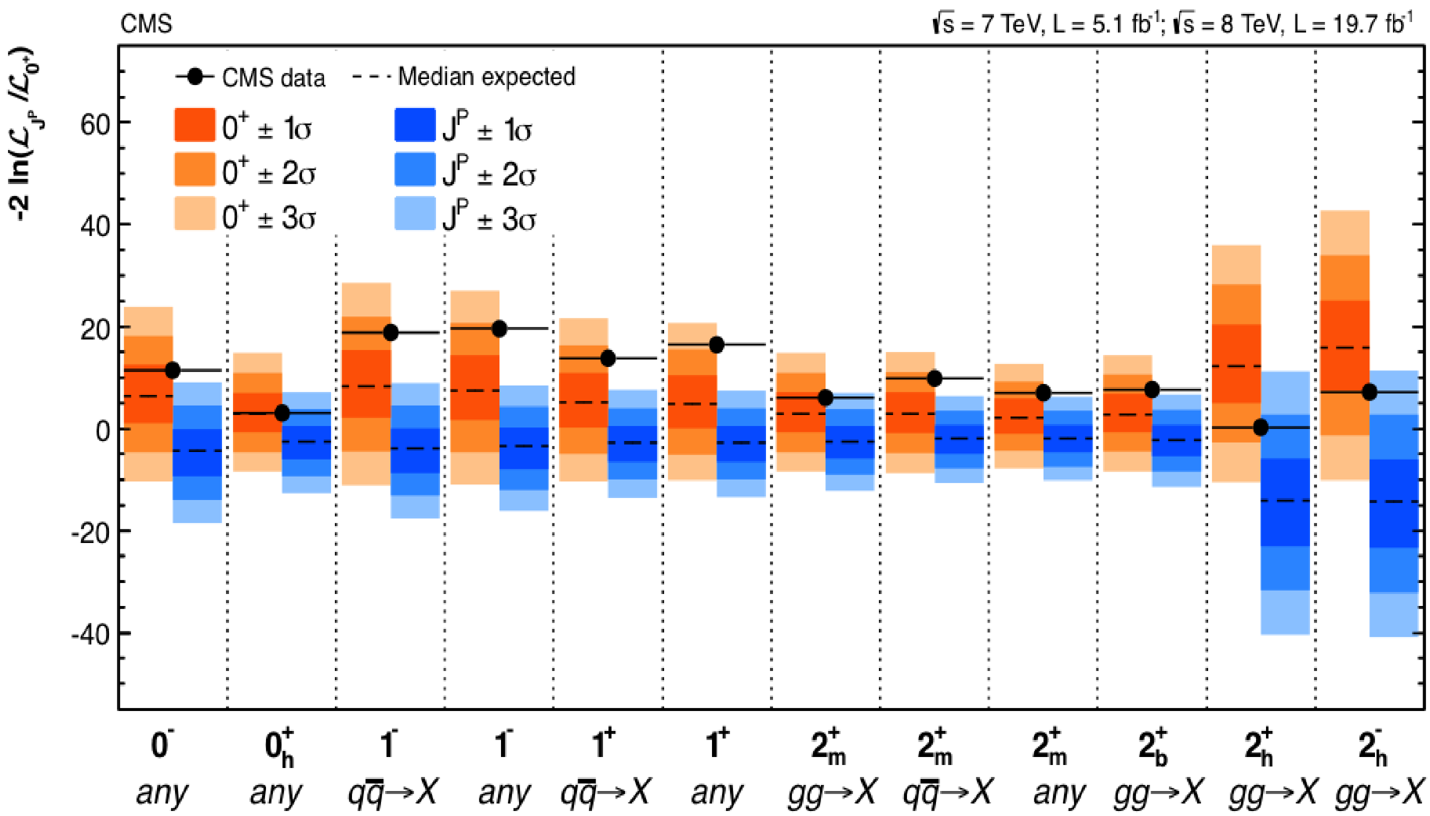
Spin-Parity Measurements

All but 0^+_h hypothesis excluded at 95% CL



Spin-Parity Measurements

Summary of the expected and observed values for the test-statistic q distributions for the twelve alternative hypotheses tested with respect to the SM Higgs boson



Tensor structure of couplings – test for CP violation

- Spin-0 Bosons general decay amplitude

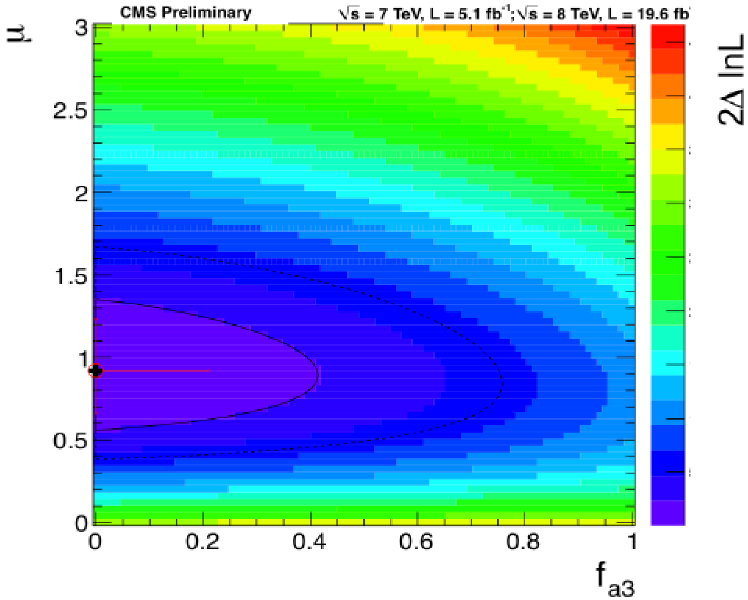
$$A = v^{-1}\varepsilon_1^{*\mu}\varepsilon_2^{*\nu}(a_1 g_{\mu\nu} m^2{}_H + a_2 q_\mu q_\nu + a_3 \varepsilon_{\mu\nu\alpha\beta} q_1^{\alpha} q_2^{\beta}) = A_1 + A_2 + A_3$$

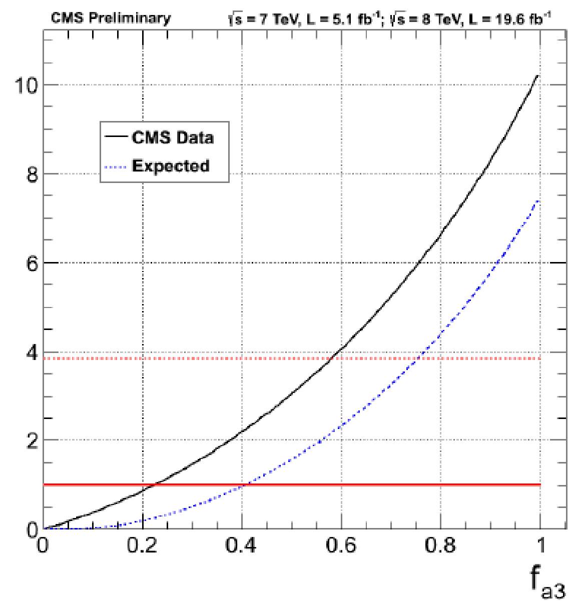
- A_1 dominates for SM Higgs (0^+) and A_3 for (0^-)

- Presence of both amplitudes indicates CP violation

Fraction of CP violating contribution

$$f_{a3} = \frac{|A_3|^2}{|A_1|^2 + |A_3|^2}$$



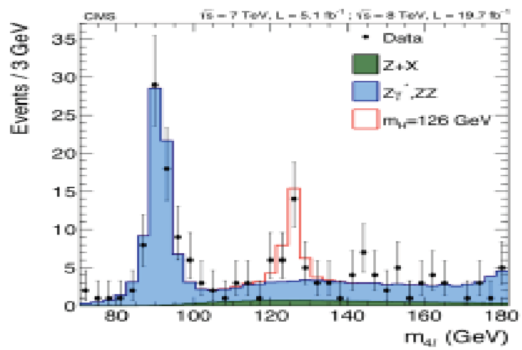


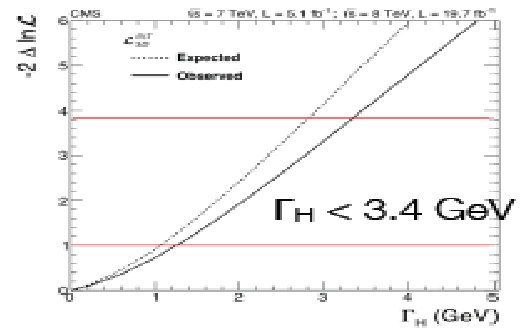
$$f_{a3} = 0.0^{+0.23}_{-0.00}$$

SM Higgs total width ~4 MeV @125GeV

Property measurements - width

arXiv:1312.5353



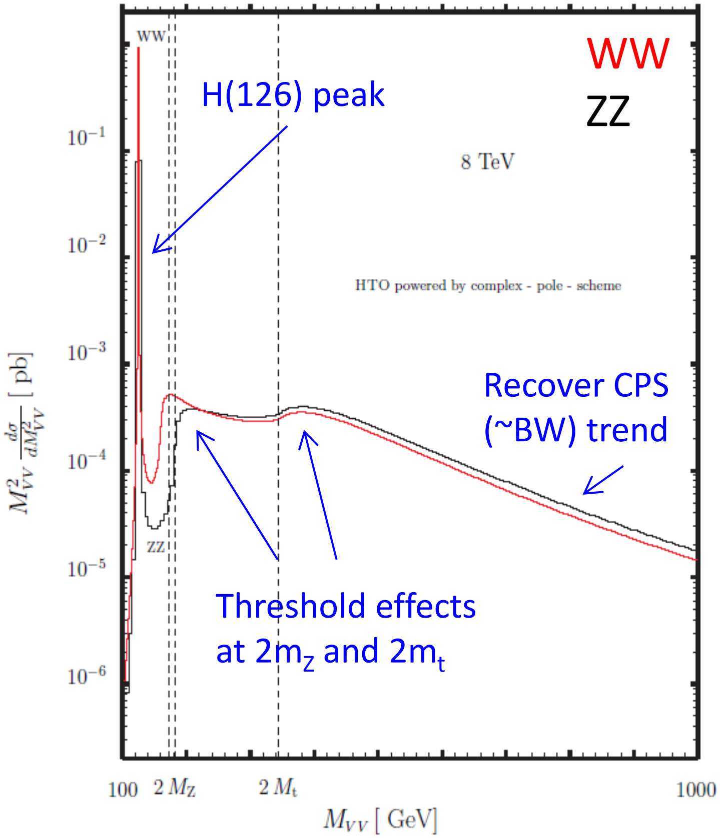


H→γγ results Γ_H < 6.9 GeV (**CMS-HIG-13-016**)
Direct measurements are limited by experimental resolutions

Waiting for a lepton collider...

Principles of the analysis

gluon-gluon fusion production



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

Off-shell $H^* \to ZZ$

– Peculiar cancellation between BW trend and $\Gamma(H \to ZZ)$ as a function of m_{ZZ} 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)

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

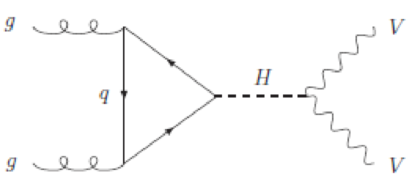
Can be used to set a constraint on the total Higgs width:

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

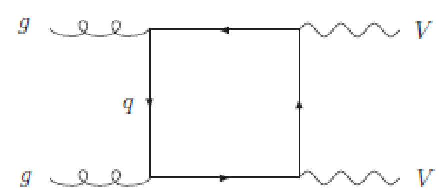
$$\frac{d\sigma^{\mathrm{off-peak}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \kappa^2_g \kappa^2_Z \frac{d\sigma^{\mathrm{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}} = \mu r \frac{d\sigma^{\mathrm{off-peak,SM}}_{gg\to H\to ZZ}}{dm_{ZZ}}$$

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

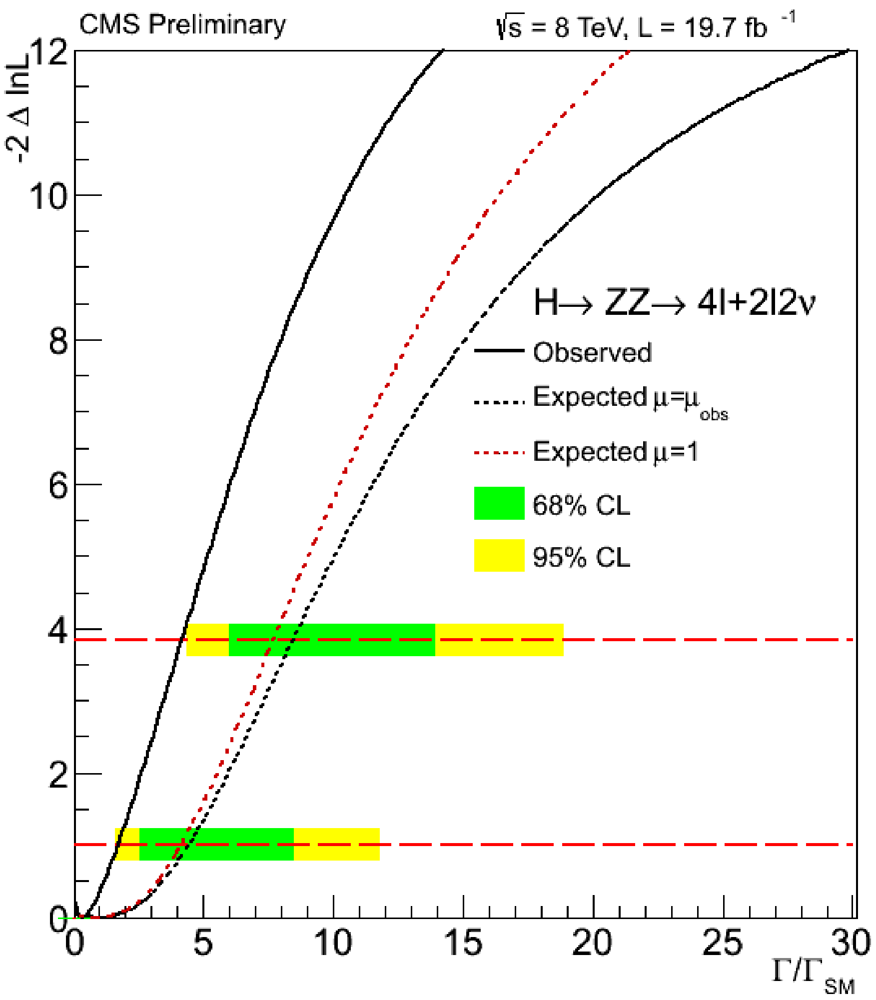
- Once the "signal strength" μ is fixed from an independent source a determination of r is obtained
  - N.B. r-scaling while keeping μ fixed is equivalent to coupling scaling



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



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

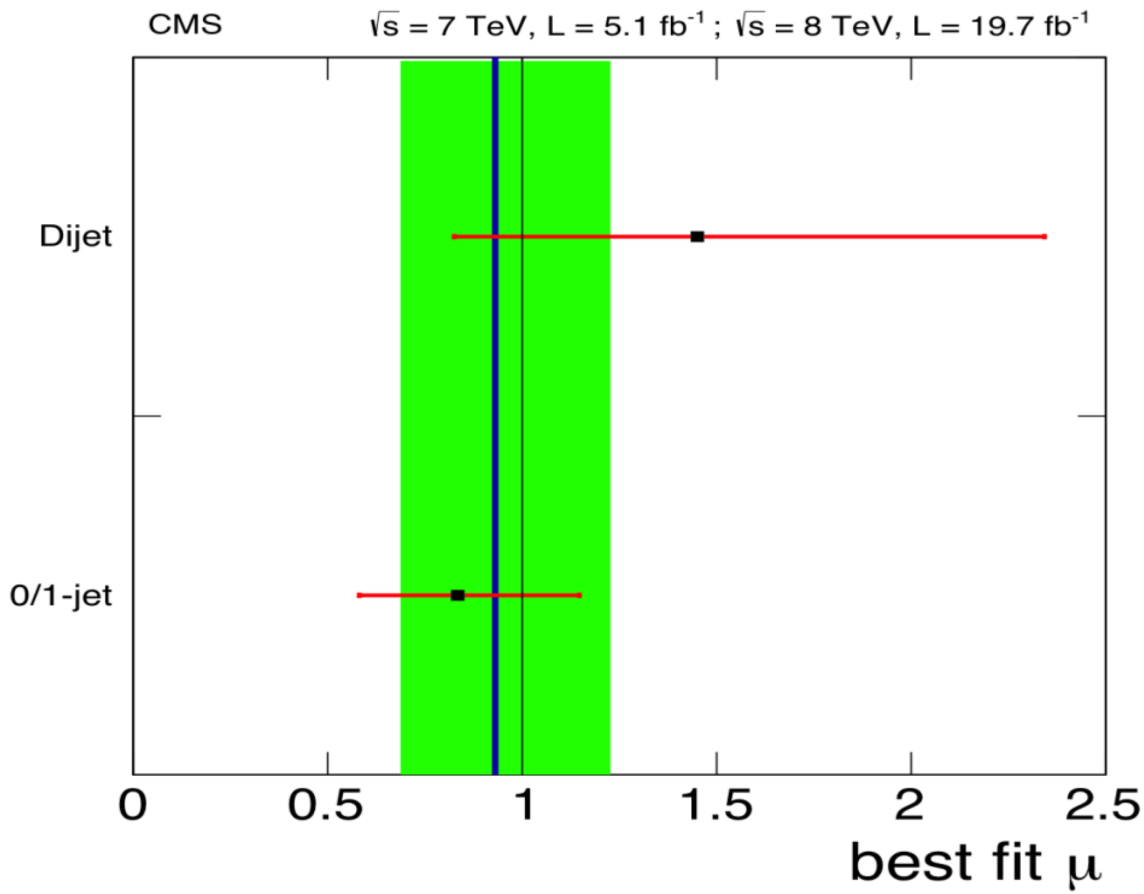
- Higgs properties using H(126) $\rightarrow$ ZZ events has been presented consistent with standard model (Spin , Parity , signal strength ,No cp violation)
  direct width measurement gives an upper bound of 3.4 GeV .
- Combining 4l and 2l2ν final states
  - Using variables related to ZZ inv. mass and kinematic discriminants
  - Small deficits in signal regions observed in both channels
- Combination results:
  - $\Gamma/\Gamma_{SM} < 4.2$ (8.5 expected) @ 95% CL
    $\rightarrow$ $\Gamma < 17$ MeV (35 MeV expected) @ 95% CL

Back up

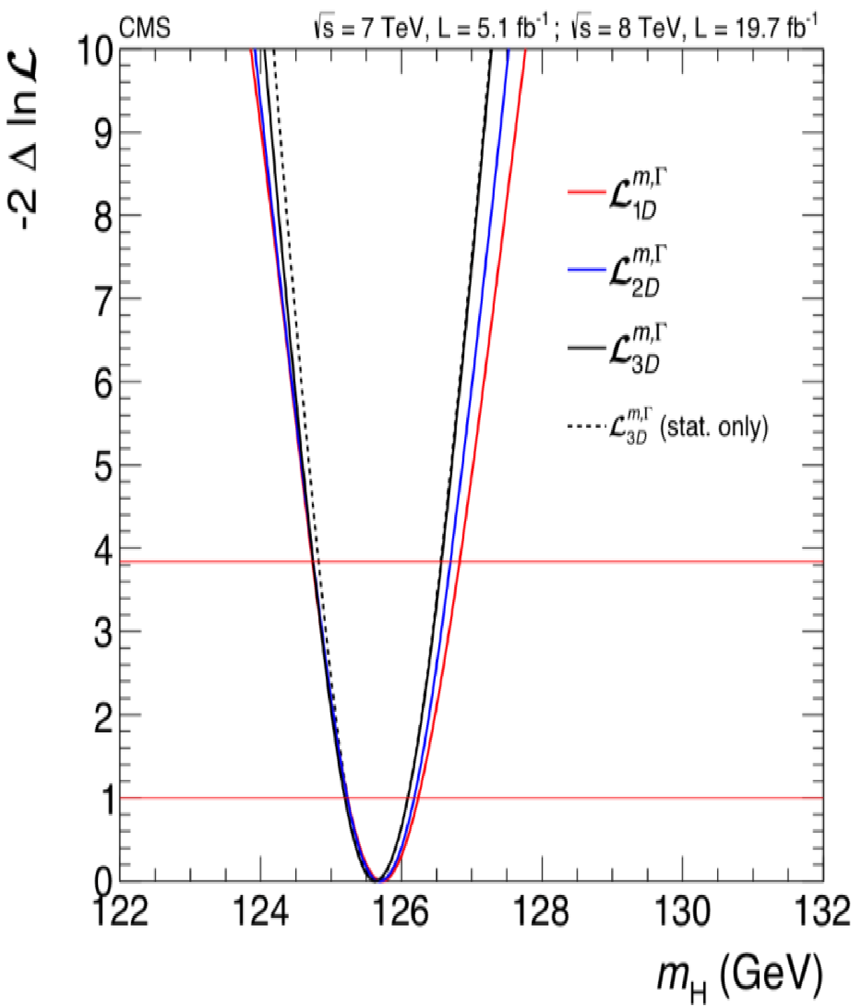
IHEP contributions

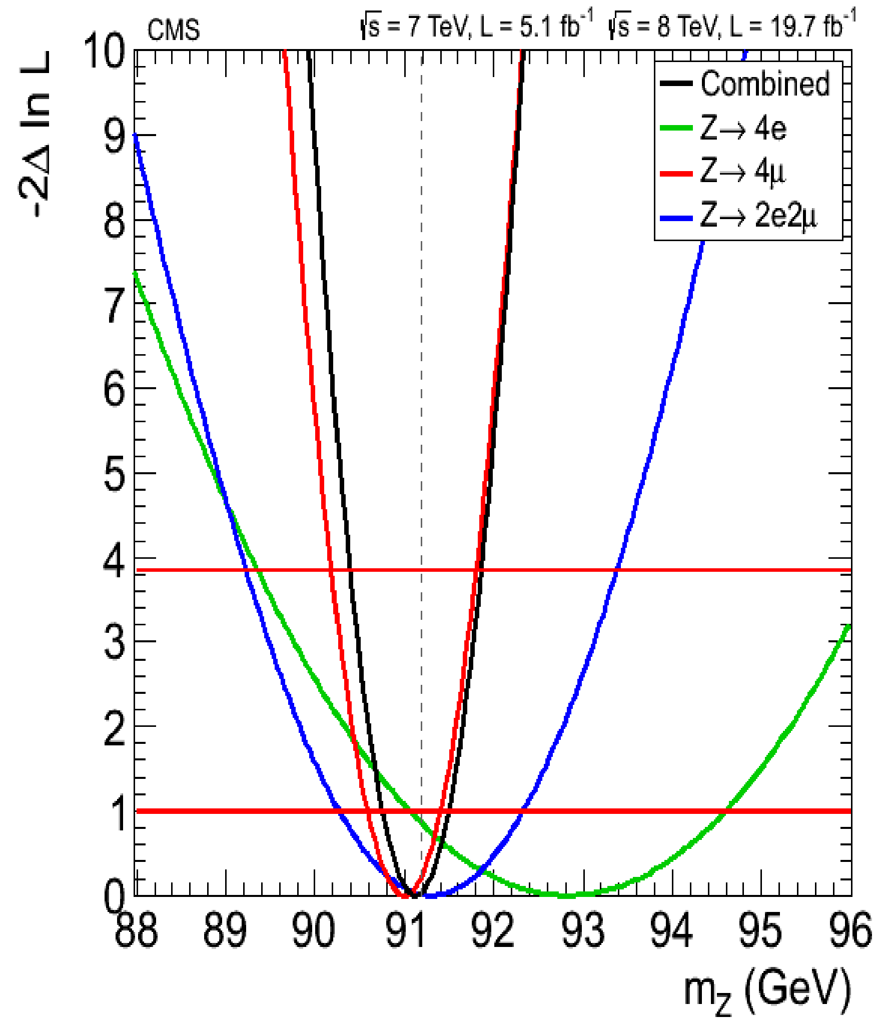
- HZZ4l is one of the most important analyses at LHC
  - There are 26 institutions involved in this analysis in CMS
- IHEP team plays important role in this analysis
  - Leading the mass and width measurement
  - Heavily involved in the determination of quantum numbers
  - Responsible for the statistical analysis
- Also contributed to the width measurement from off-shell production
  - Responsible for the correctness of the statistical analysis

Signal strength



Mass Measurement





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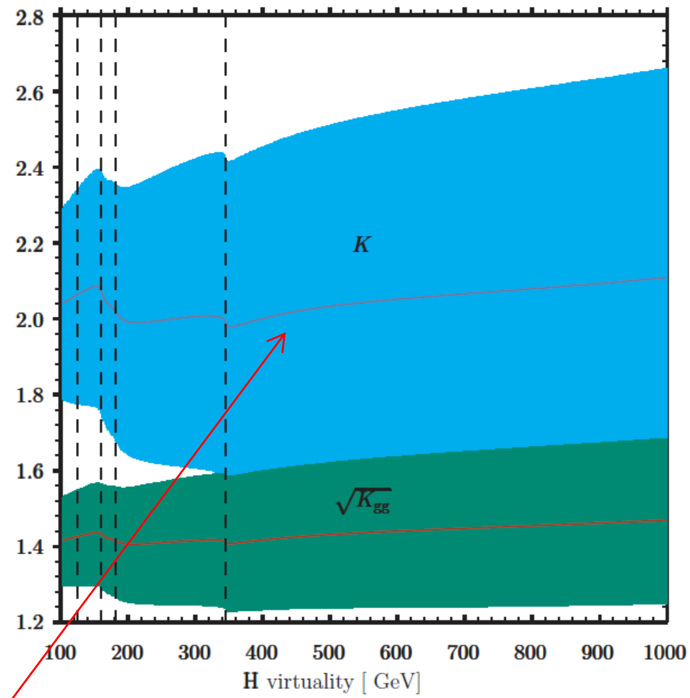
Spin/parity hypotheses

J^P model	J^P production	expected (μ=1)	obs. 0^+	obs. J^P	CL_s
0-	any	2.4σ (2.7σ)	-0.9σ	+3.6σ	0.09%
0_h^+	any	1.7σ (1.9σ)	-0.0σ	+1.8σ	7.1%
1-	qqbar → X	2.6σ (2.7σ)	-1.4σ	+4.8σ	0.001%
1-	any	2.6σ (2.6σ)	-1.7σ	+4.9σ	0.001%
1+	qqbar → X	2.1σ (2.3σ)	-1.5σ	+4.1σ	0.03%
1+	any	2.0σ (2.1σ)	-1.9σ	+4.5σ	0.01%
2_m^+	gg → X	1.7σ (1.8σ)	-0.8σ	+2.6σ	1.9%
2_m^+	qqbar → X	1.6σ (1.7σ)	-1.6σ	+3.6σ	0.03%
2_m^+	any	1.5σ (1.5σ)	-1.3σ	+3.0σ	1.4%
2_b^+	gg → X	1.6σ (1.8σ)	-1.2σ	+3.1σ	0.9%
2_h^+	gg → X	3.7σ (4.0σ)	+1.8σ	+1.9σ	3.1%
2_h^-	gg → X	4.0σ (4.5σ)	+1.0σ	+3.0σ	1.7%

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

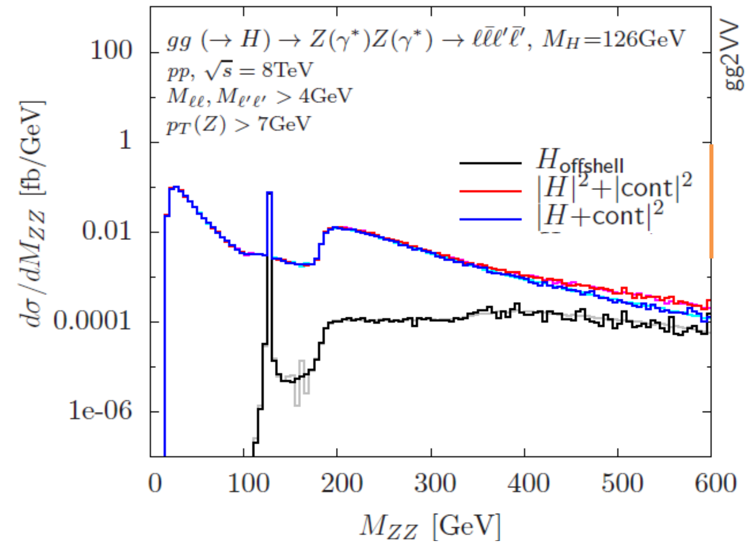
other production modes

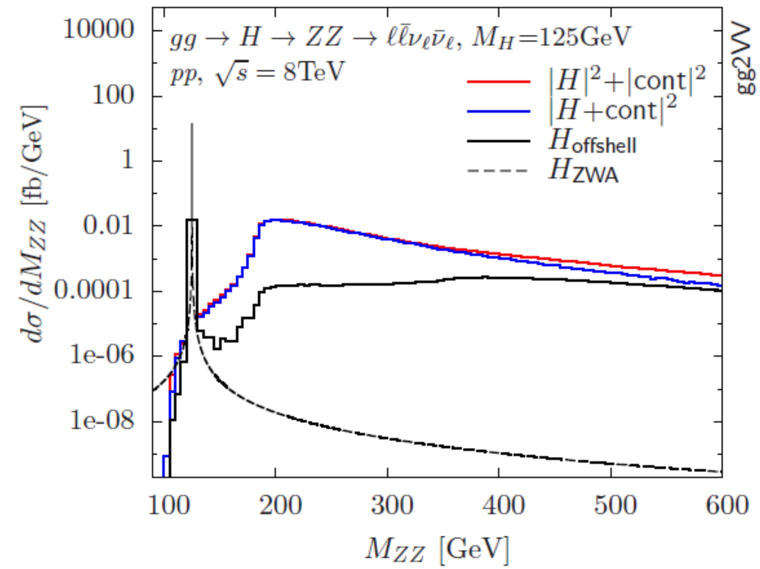
- VBF production is 7% of the total at H(126) peak
  - Slightly enhanced at high mass by trend of $\sigma_{VBF}(m_{ZZ})$ ~ 10%
  - Using PHANTOM to model it, with same settings
- VH and ttH do not contribute to tail effect

The 4l and 2l2ν final states

- 4l final state (l = e, μ)
  - At high mass, basically only background is $\bar{q}q \rightarrow ZZ$ (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 $\bar{q}q$ production
- 2l2ν final state (l = e, μ)
  - Much larger BR (x6) but smaller acceptance (tight p_T selection)
  - Rely on transverse mass distributions

Generator-level distributions with approximated CMS experimental cuts





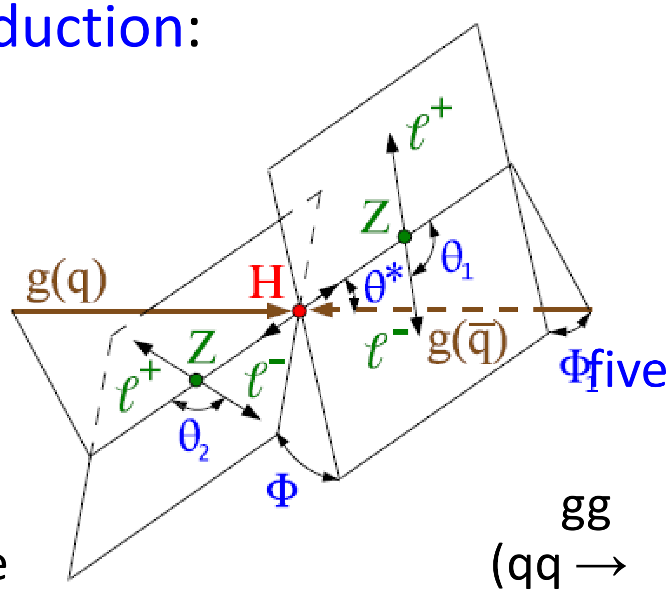
N. Kauer and G. assarino, JHEP 08 (2012) 116

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 → 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}, angles)
  - $P_{gg,(qq)}$ are joint probabilities for → ZZ, signal + background + interference ZZ) from MCFM matrix elements
  -



gg
(qq →

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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

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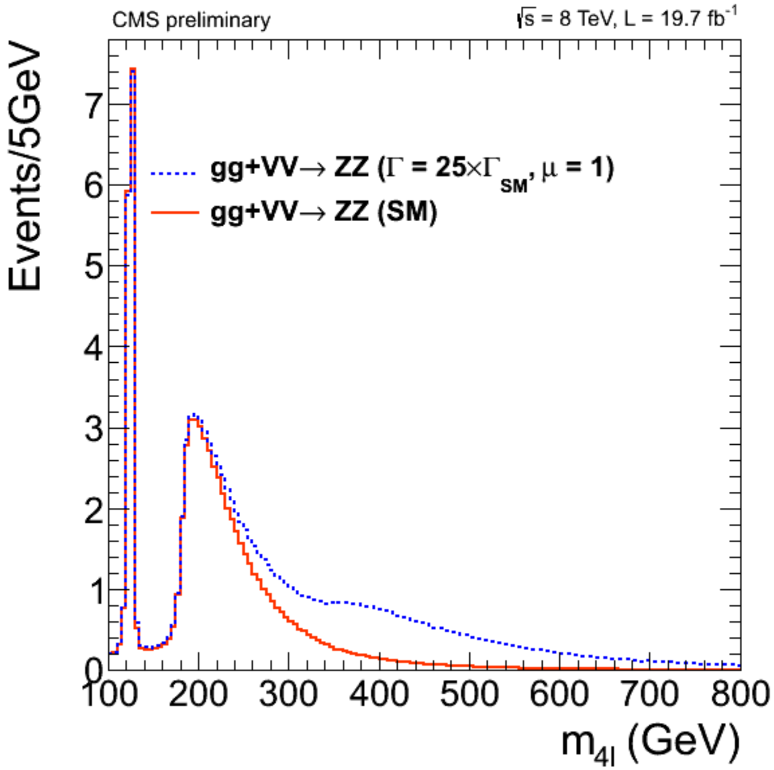
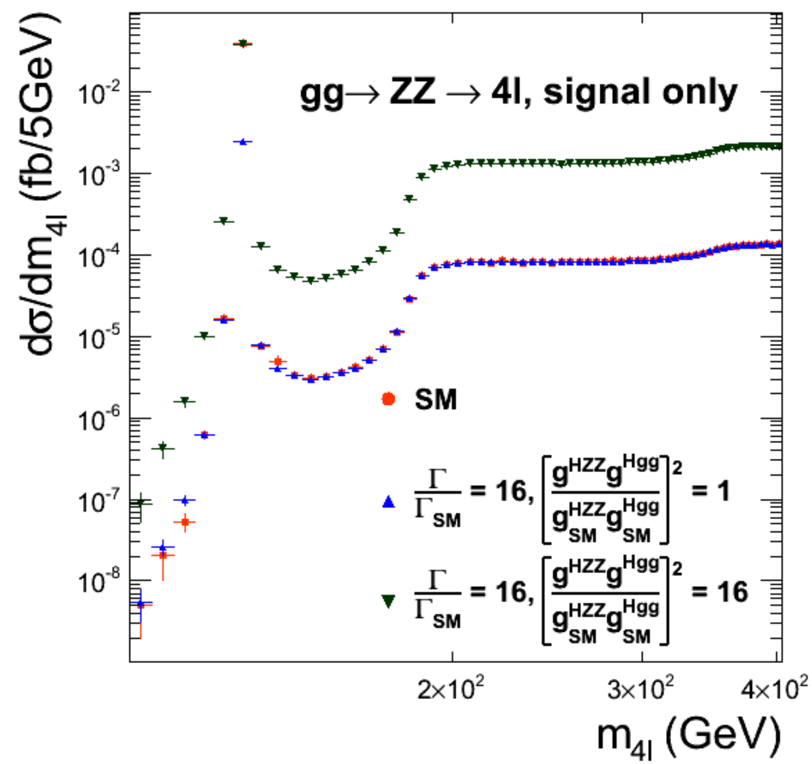
Effect of Γ / coupling scalings





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:

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

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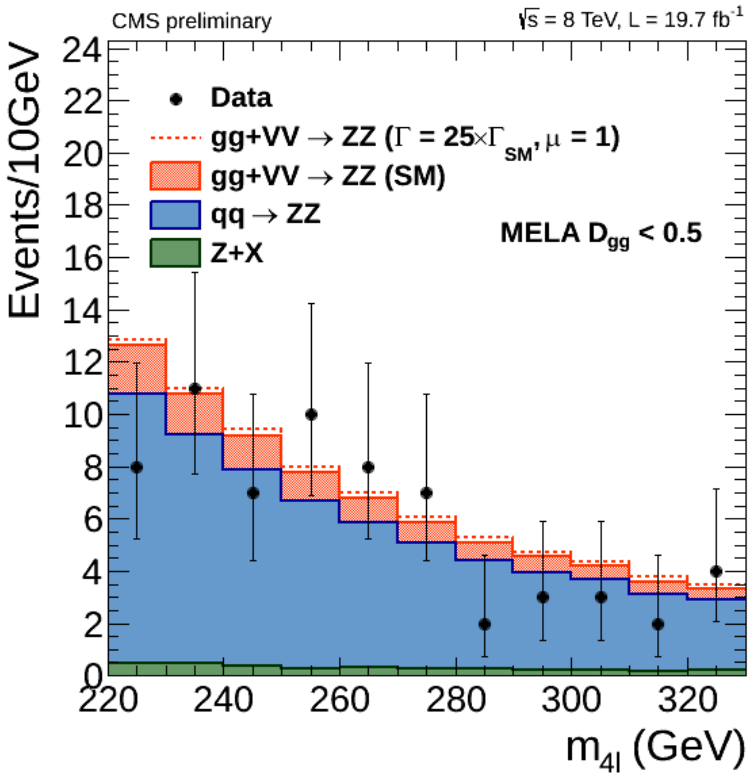
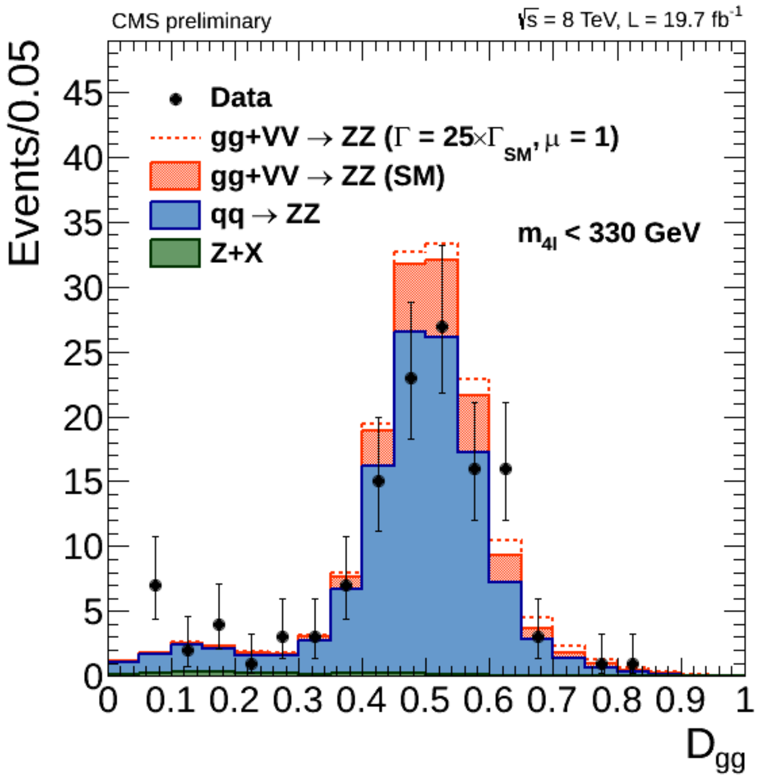
Full formula of MELA D_{gg}

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

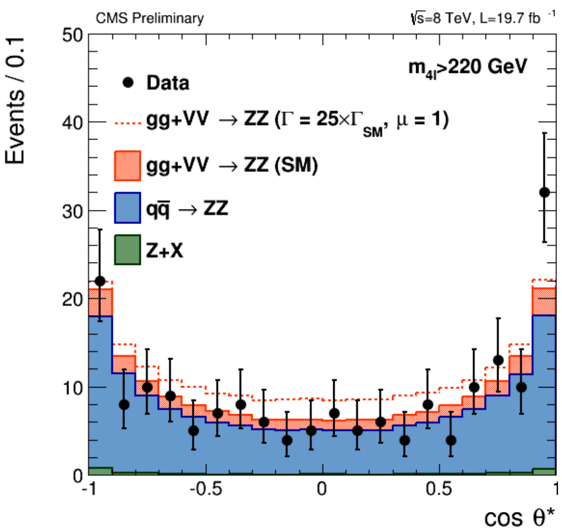
- Depends on parameter *a* (relative weight of signal in the likelihood ratio). Since the expected exclusion is r ~ 10, use *a* = 10

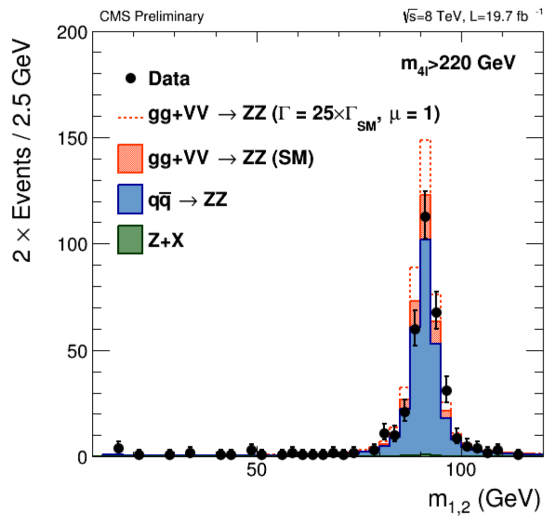
4l: background-enriched region

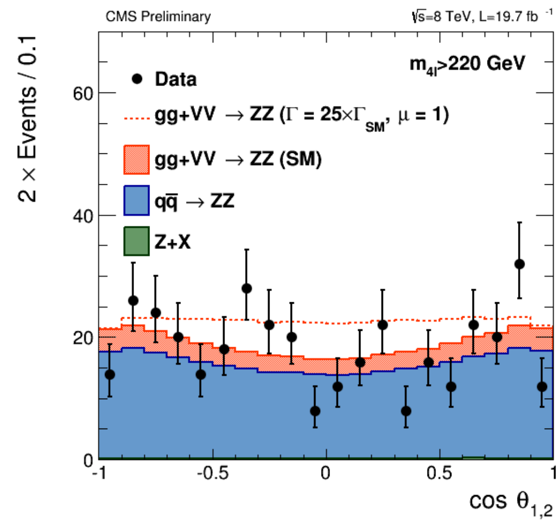


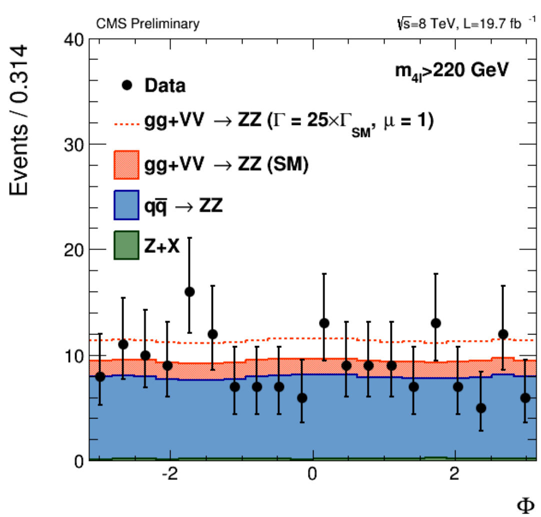


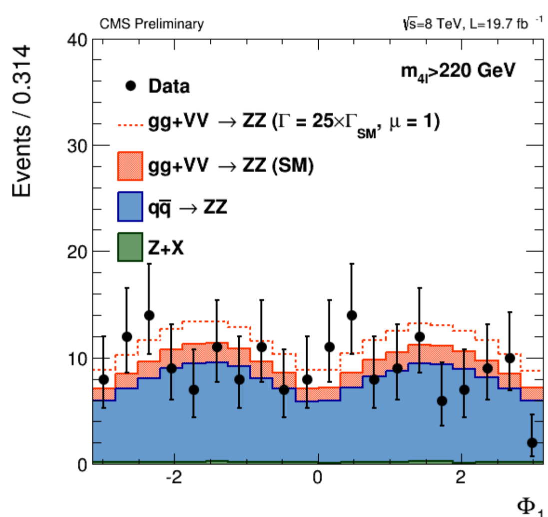
4l: variables entering D_{gg}











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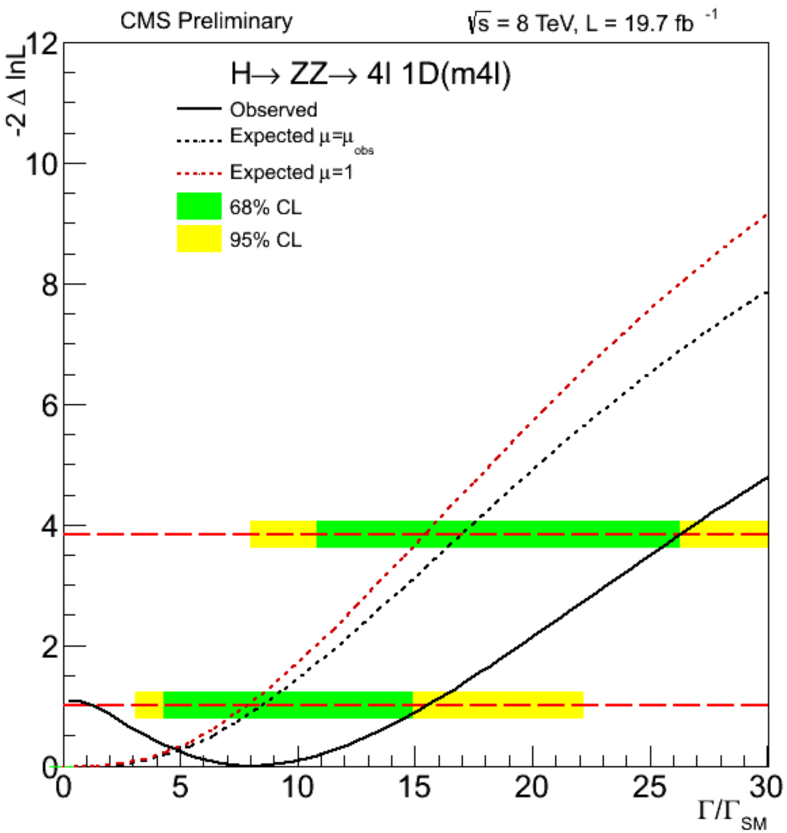
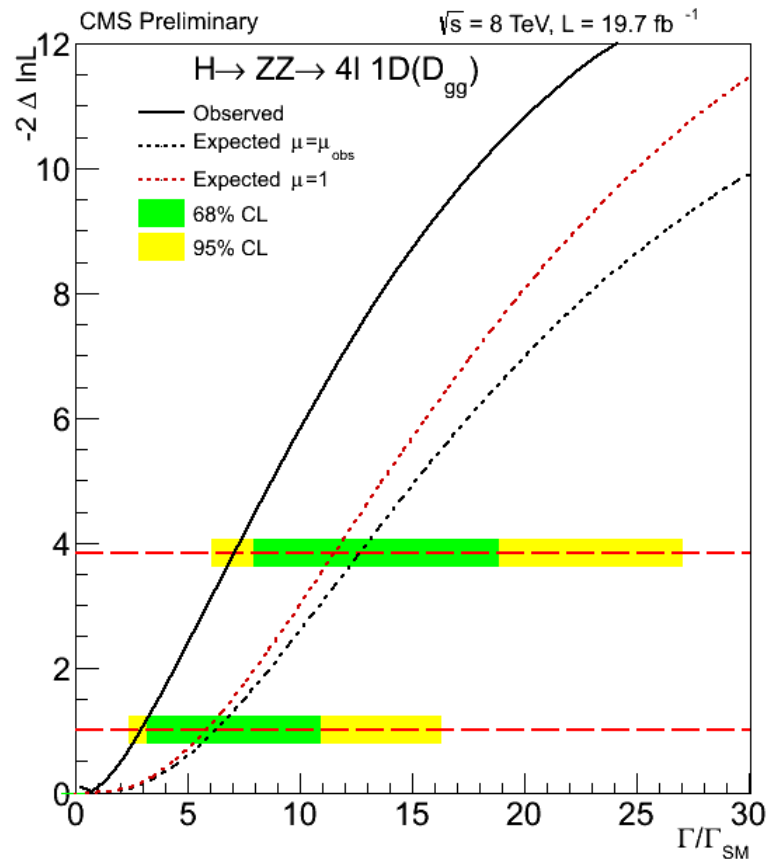
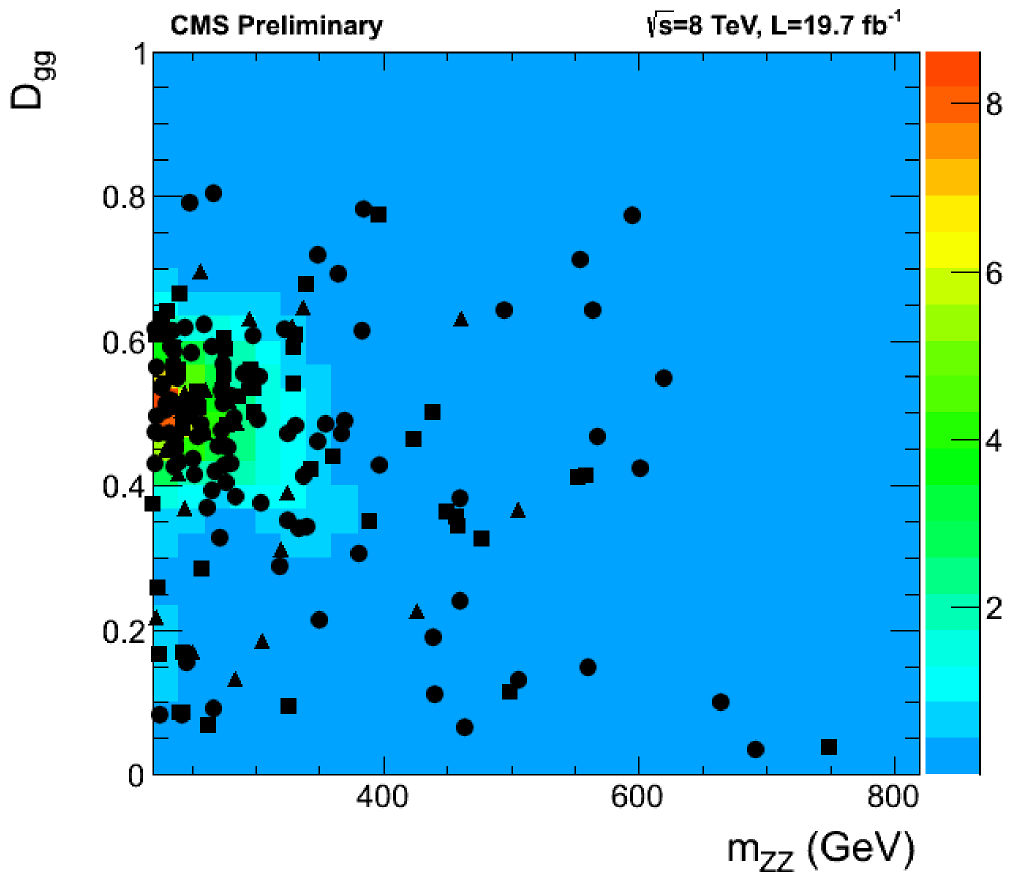
4l: 1D result with D_{gg} and m4l





4l: 2D templates



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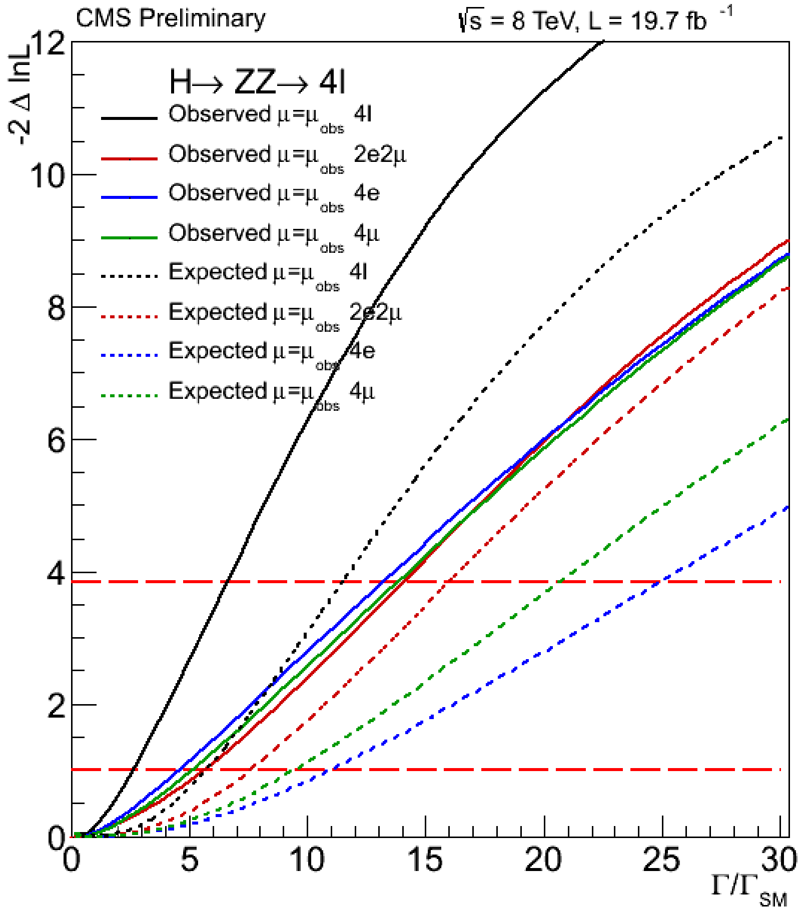
4l: breakdown by channel



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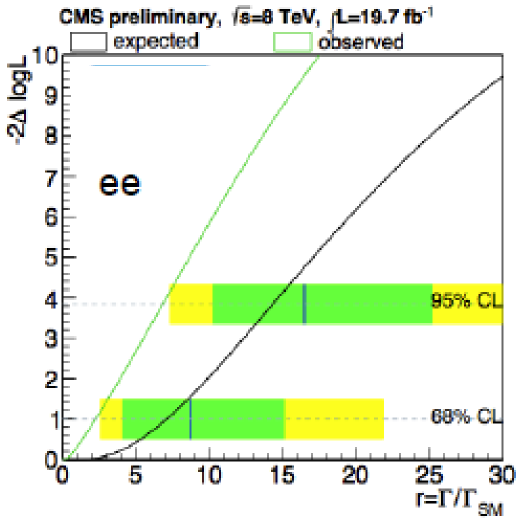
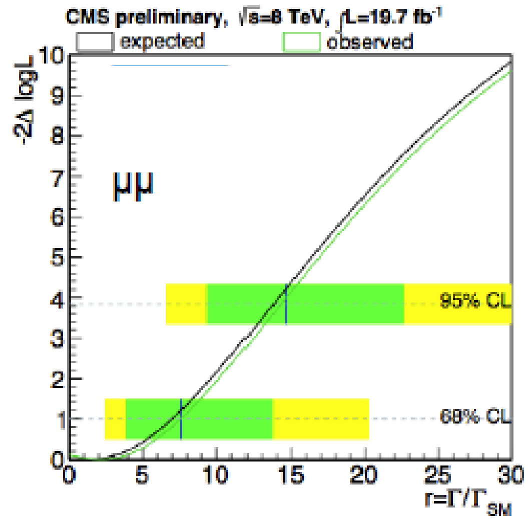
2l2ν: selection

- 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 3rd 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

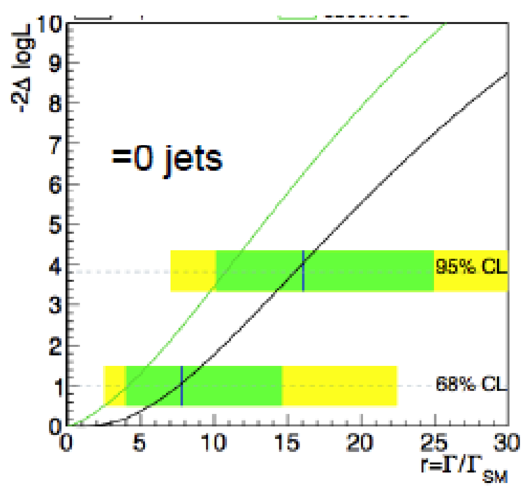
- **Search for real E_T^{miss} in Z events**
  - raw particle flow E_T^{miss} is used
  - $\Delta\varphi(jet, E_T^{miss})>0.5$
  - E_T^{miss}>80 GeV

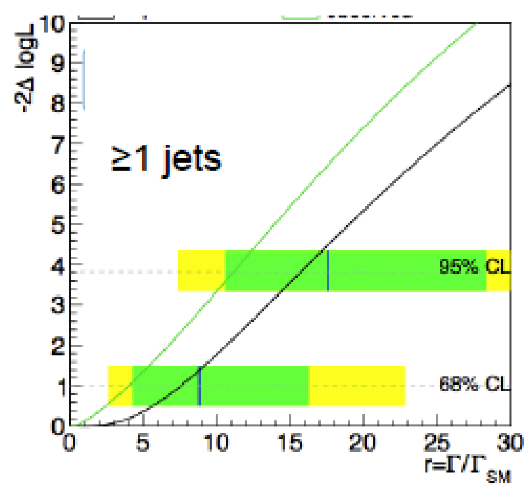
2l2ν: breakdown by channel

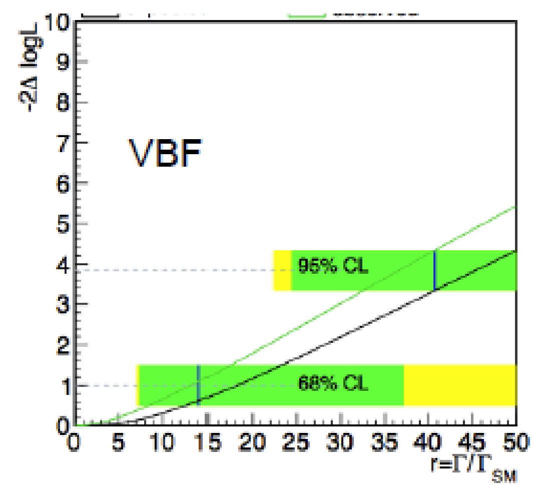




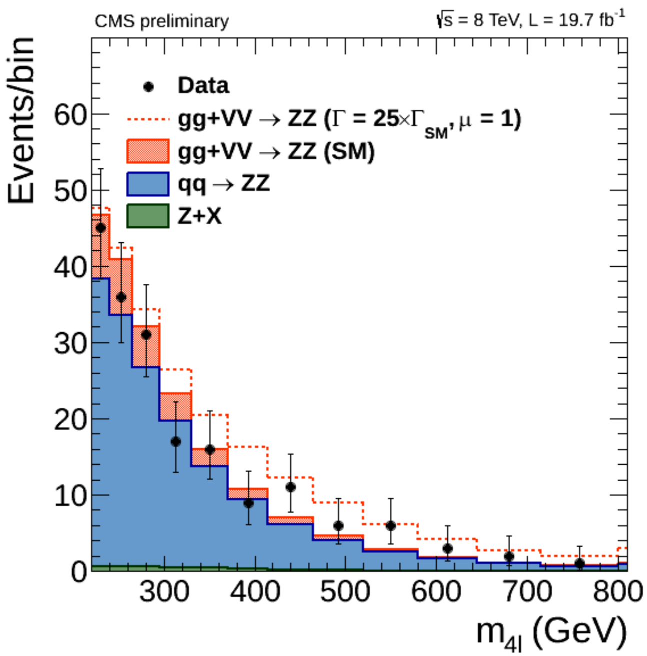
- ee channel: deficit in data drives stronger observed limits
- =0 jets drives the sensitivity of the analysis
- Median expected from toys tends to disagree in categories with larger systematic uncertainties

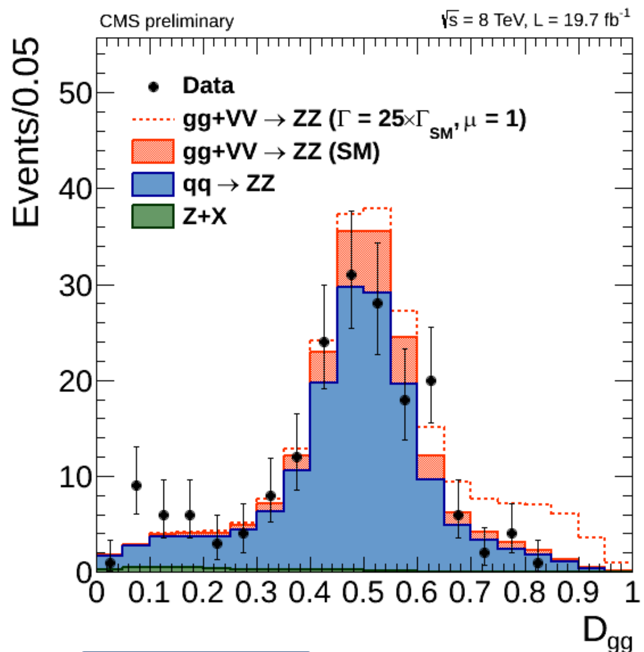






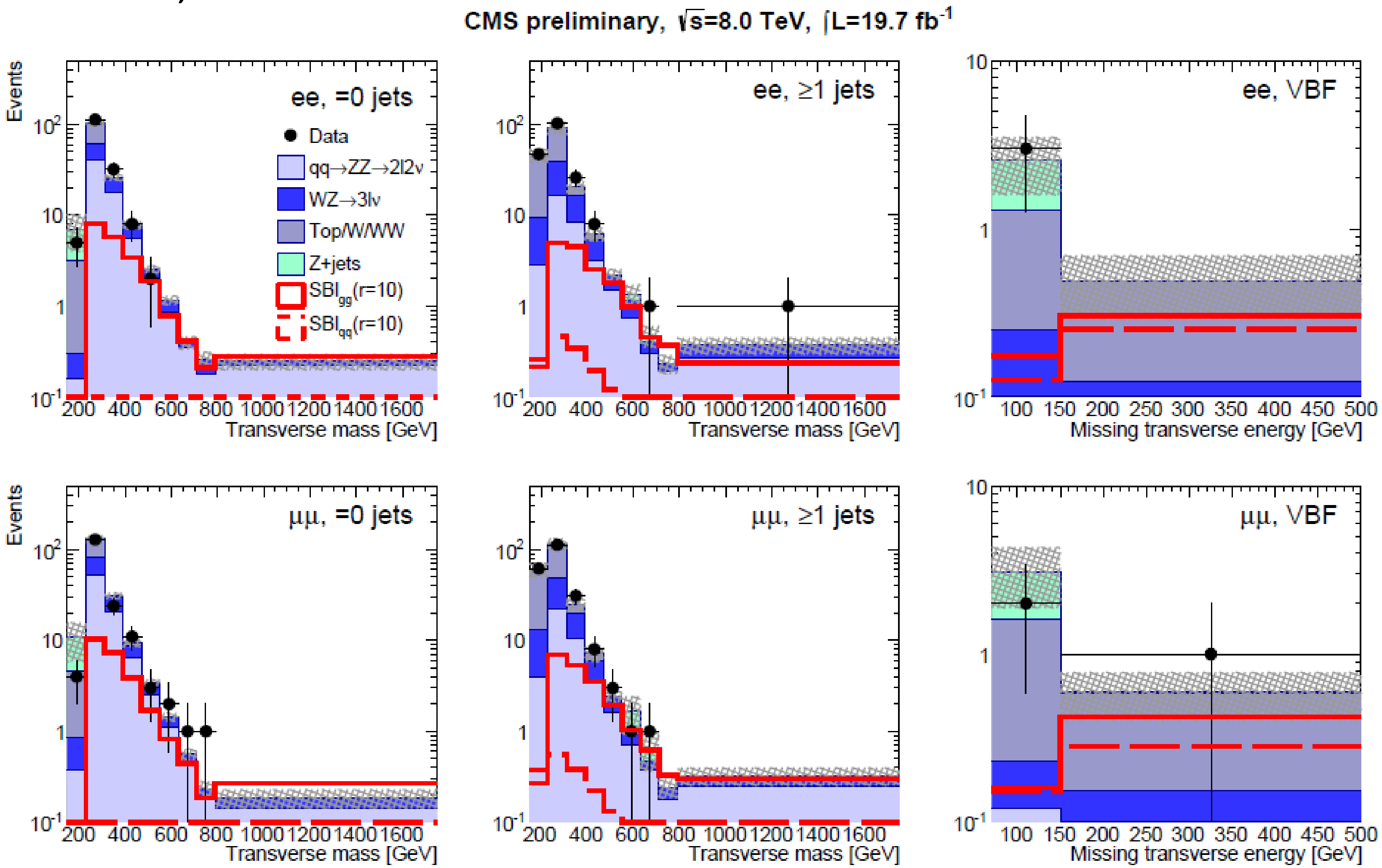
m_{4l} and D_{gg} distributions / yields





		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_T / $E_{T,miss}$ distributions



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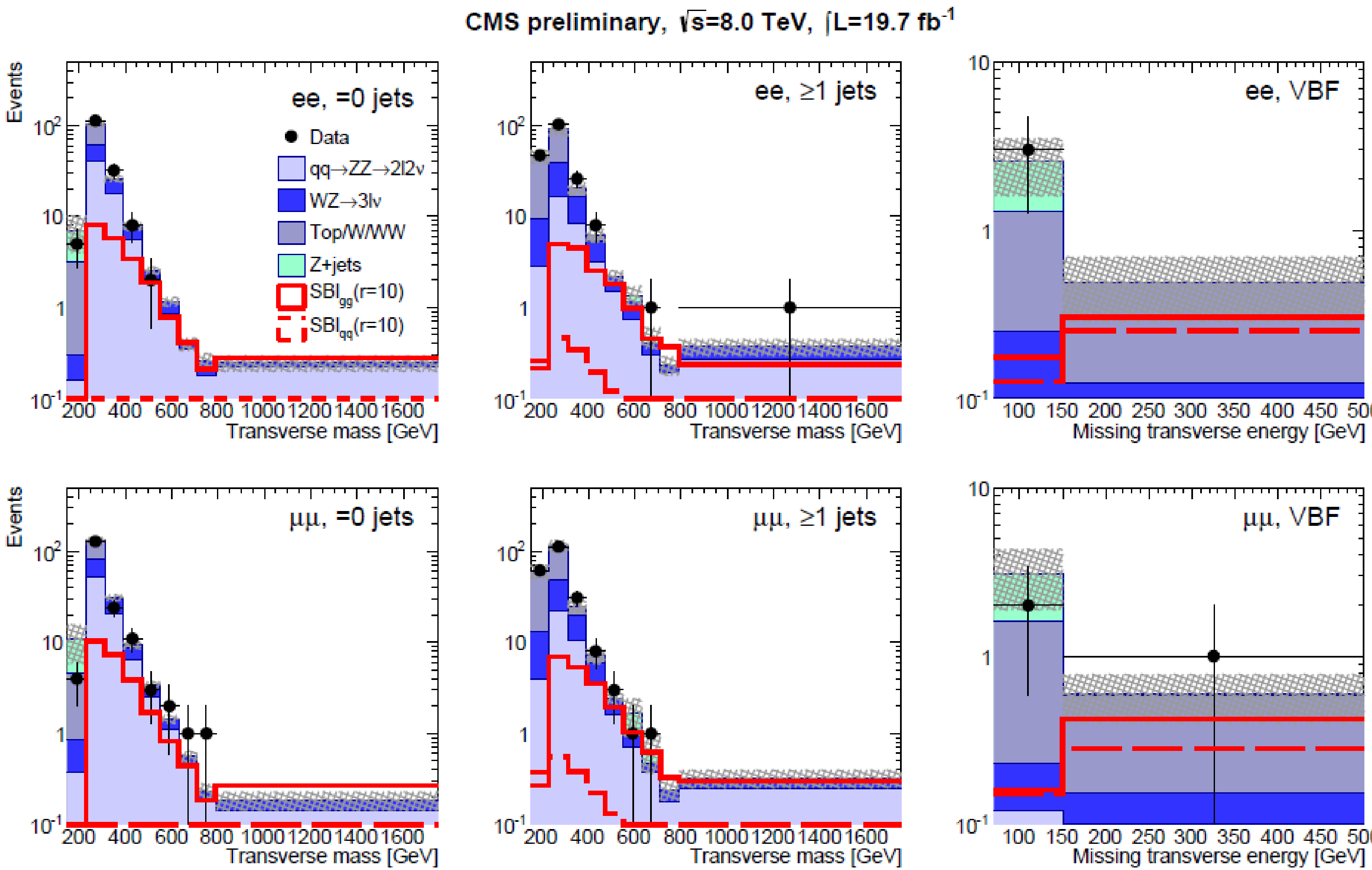
m_T / $E_{T,miss}$ distributions



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Conclusion

- Mild model-dependence
  - Just based on Higgs propagator structure
  - Assumptions on $gg \longrightarrow ZZ$ continuum production beyond LO
  - Assumption of SM production of $qq \longrightarrow ZZ$ and, in general, no other BSM sources enhancing high-mass ZZ yields

Muon

- Discovered by Anderson and Nedermeir in 1936 in cosmic rays.
- Since that time muon parameters are well Defined
  - Charge +/- 1
  - Mass 105.658389 MeV
  - Lifetime 2.19703 μsec
  - Decay (100%) eνν
  - No strong interaction