# Measurement of the Higgs boson mass, width and spin-CP quantum numbers at LHC and Tevatron

Standard Model at LHC
Madrid (Spain, 8-11 April 2014)

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on behalf of the ATLAS, CMS, CDF and D0 collaborations

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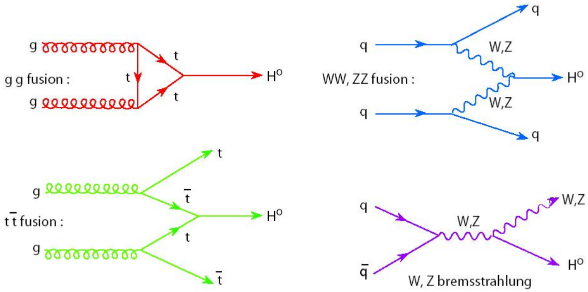
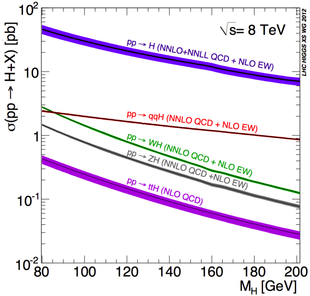
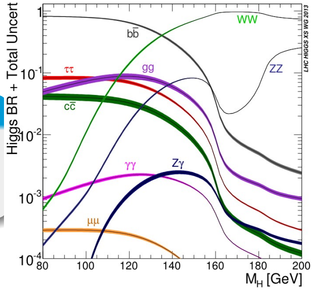
# Foreword

- A new boson compatible with the SM Higgs was discovered at the LHC in 2012
- Tevatron also sees an excess of events in the same mass range
- The measurements of this boson properties probe the SM
  - Mass
  - Spin and CP-numbers
  - Width

# Higgs boson production and decays




## Channels used for Higgs properties measurements

| LHC | Tevatron |
|---|---|
| production: gg fusion and VBF | production: VH |
| decay: bosonic decay channels | decay: $H \to b\bar{b}$ |

# Outline

# Outline

1. Higgs boson mass
2. Spin and CP quantum numbers
3. Higgs boson width

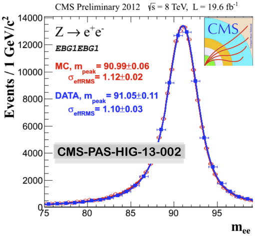
# Higgs boson mass

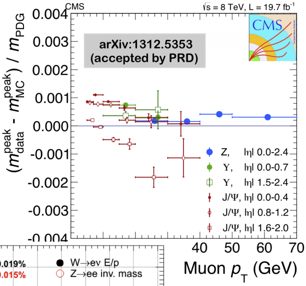
## measurement strategy at the LHC

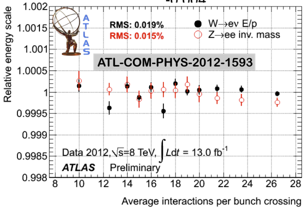
- Higgs boson mass is a fundamental parameter
  - Not predicted by theory
  - Once the Higgs boson mass is measured then SM predictions are fully determined
  - This is the first precision measurement of the new boson properties
- Measurement strategy
  - Use high resolution channels: $\gamma\gamma$ and $4\ell$
  - The mass is obtained from a likelihood fit performed for test mass scanning the interesting mass range

# Mass resolution and scale uncertainties

- CMS: $e/\gamma$ energy estimated using multivariate regression
- ATLAS: weighted sum of energy deposits in the different calorimeter layers
- Scale and resolution is obtained from $W, Z, J/\psi$ and $\Upsilon$ resonances
- Additional smearing is applied to MC to match the resolution in data



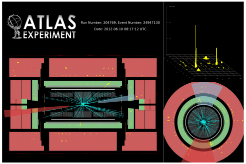



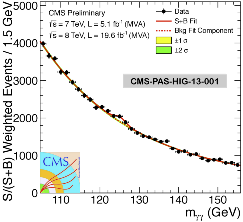



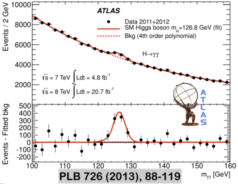

- Resulting systematic uncertainty on mass measurements is $\sim 0.5\%$ per channel ($H \to \gamma\gamma$, $H \to 4\ell$)

# Di-photon mass measurements

- Channel features
  - Clean signature: two isolated, high-$p_T$ photons
  - Excellent mass resolution: 1-2%
  - Large QCD background
- Analysis roadmap
  - Events categorized according to photon resolution and kinematics
  - Additional categorization on production mode
  - Signal extracted from simultaneous S+B fit in all categories



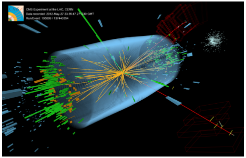

**Measured mass**

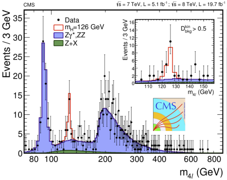
**ATLAS:** $126.8 \pm 0.2(stat) \pm 0.7(syst)$

**CMS:** $125.4 \pm 0.5(stat) \pm 0.6(syst)$

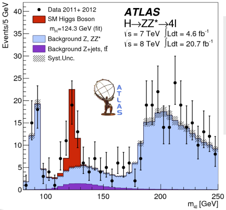
# $ZZ \to 4\ell$ mass measurements

- Channel features
  - Golden channel: four isolated leptons
  - Extremely pure: $S/B \sim 2$
  - Very small branching fraction ($\sim 10^{-4}$)
- Analysis roadmap
  - Maximize acceptance for low-$p_T$ leptons
  - CMS: use $m_{4l}$ and kin. discriminant(KD) use event-by-event errors
  - ATLAS: use $m_{4l}$ for S/B separation Categorization: VBF, VH and untagged





arXiv:1312.5353 (accepted by PRD)



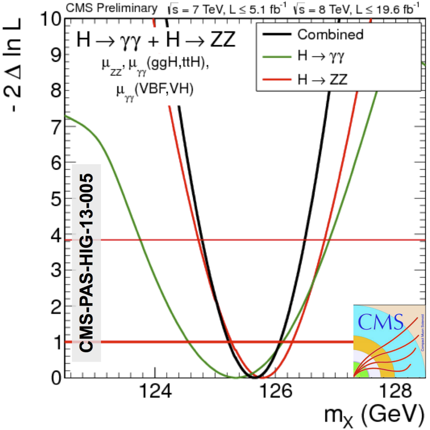
PLB 726 (2013), 88-119

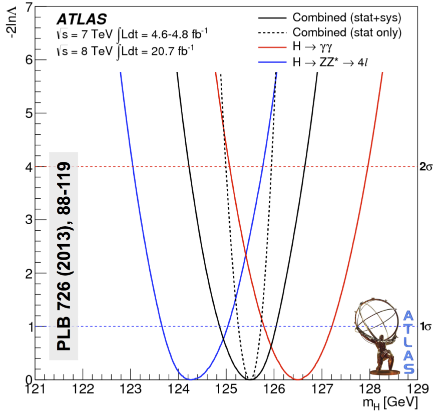
**Measured mass**

**ATLAS:** $124.3^{+0.6}_{-0.5}(stat)^{+0.5}_{-0.3}(syst)$
**CMS:** $125.6 \pm 0.4(stat) \pm 0.2(syst)$

# Mass measurements combination

Measurements from di-photon and four lepton final states are combined under assumption that the same state decays in both modes




**CMS**:

$m_H = 125.7 \pm 0.3(syst) \pm 0.3(stat)$

**ATLAS**:

$m_H = 125.5^{+0.5}_{-0.6}(syst) \pm 0.2(stat)$

# Outline

# Spin/parity of the new boson

- Standard Model prediction: Higgs boson is a $0^+$ state
  - very good test of SM compatibility
- General form of non-zero spin state scattering amplitude has large amount of free parameters
  - we can exclude alternative hypotheses via test statistics:

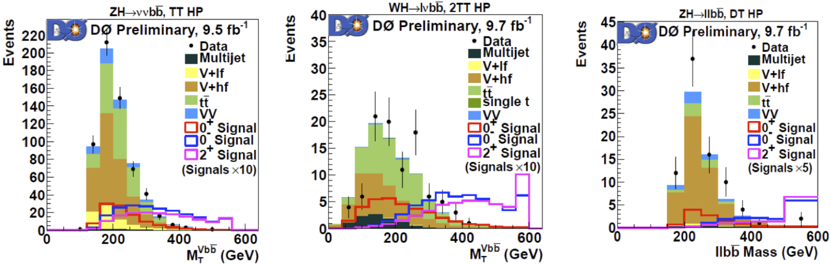
$$q = -2ln\frac{\mathcal{L}(B+\hat{\mu}_{SM}S_{SM};\hat{\hat{\theta}}_{SM})}{\mathcal{L}(B+\hat{\mu}_{ALT}S_{ALT};\hat{\hat{\theta}}_{ALT})}$$

- Most sensitive channels:
  - $H \to ZZ \to 4\ell$
  - $H \to \gamma\gamma$
  - $H \to WW \to 2\ell 2\nu$
  - $VH$ production following $H \to b\bar{b}$ for Tevatron

# $VH,\ H \to b\bar{b}$ channel

## Tevatron results

- VH production kinematics depend on $J^P$: let $\beta = 2p/\sqrt{s}$
  - $0^+$: S-wave production, $\sigma \propto \beta$ near threshold
  - $0^-$: P-wave production, $\sigma \propto \beta^3$ near threshold
  - $2^+$: D-wave dominates for graviton-like production, $\sigma \propto \beta^5$



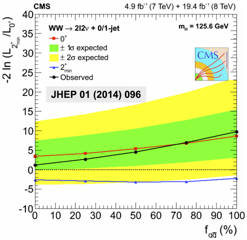

D0 Note 6387, D0 Note 6406

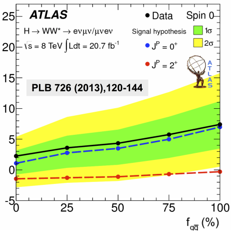
### Exclusion results

- $0^-$ model excluded at 97.9%CL ($2.3\sigma$ obs, $3.1\sigma$ exp)
- $2^+$ model excluded at 99.9%CL ($2.4\sigma$ obs, $3.2\sigma$ exp)

# $H \to WW \to 2\ell 2\nu$ decay channel

- Channel features
  - Two high-$p_T$ leptons and MET
  - Large branching fraction
  - Large backgrounds
- Analysis roadmap
  - Select two high-$p_T$ different flavor leptons plus MET
  - Event categorization:
  - $\to$ **CMS**: 0,1 jet bins
  - $\to$ **ATLAS**: 0-jet only
  - Hypothesis test with 2D templates:
  - $\to$ **CMS**: $(m_{\ell\ell}, m_T)$
  - $\to$ **ATLAS**: two BDT discriminants $(\delta\phi_{\ell\ell}, m_{\ell\ell}, m_T)$:
  - separate SM from background
  - separate alternative hypothesis from background

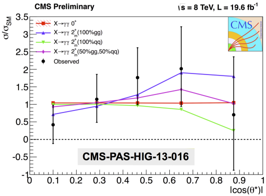


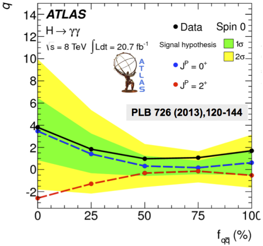




- **Observed results favour SM hypothesis**
- **Expected exclusion for $2^+_m$ model $1 - CL_S > 0.94$**

# $H \to \gamma\gamma$ decay channel

- Analysis roadmap
  - Distribution of production angle is sensitive to spin/parity
    $$cos\theta^* = 2\frac{E_2 p_{Z1} - E_1 p_{Z2}}{m_{\gamma\gamma}\sqrt{m^2_{\gamma\gamma} + p^2_{T\gamma\gamma}}}$$
  - Events categorization:
    **CMS**: cut-based, 4 categories
    **ATLAS**: no categorization
  - Hypothesis testing:
    **CMS**: simultaneous fit to $m_{\gamma\gamma}$ in 5 $cos\theta^*$ bins
    **ATLAS**: 2D fit of $(cos\theta^*, m_{\gamma\gamma})$



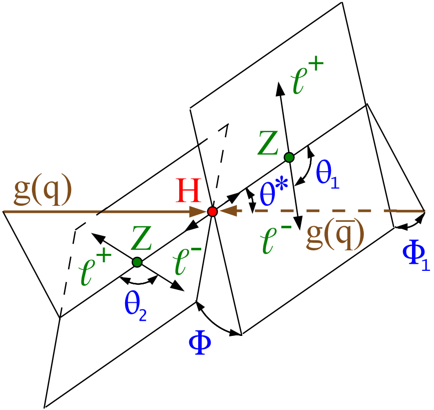




- **Observed results favour SM hypothesis**
- **Expected separation:** $1 - CL_S > 17(55) - 60(99)\%$ **for CMS (ATLAS)**

# $ZZ \to 4\ell$ decay channel

Allows to test many different spin-parity hypotheses

- Event selection identical to the mass analysis
- Spin/parity hypotheses separated using angular correlation between leptons
  - **CMS**: use Matrix Element kinematic discriminant
  - **ATLAS**: use BDT-based discriminant
- Hypothesis testing:
  - **CMS**: 2D fit of *superKD*$(m_{4l} \times KD)$ vs $KD(J^P)$
  - **ATLAS**: template fit of BDT score distribution



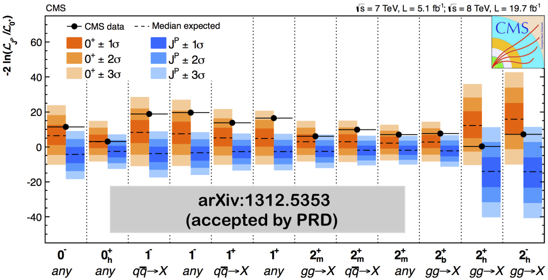

$$\mathcal{D}_{J^P} = \left[1 + \frac{\mathcal{P}^{kin}_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega})|m_{4l}}{\mathcal{P}^{kin}_{0^+}(m_{Z_1}, m_{Z_2}, \vec{\Omega})|m_{4l}}\right]^{-1}$$

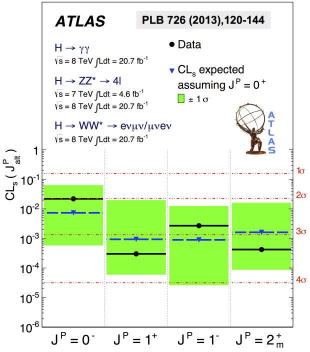
# $ZZ \to 4\ell$ decay channel

## Results

- Observed results favour SM hypothesis
- Tested spin-1 and $0^-$ hypothesis excluded at $CL_S > 99\%$
- Tested spin-2 hypothesis excluded at $CL_S > 95\%$

(combination)



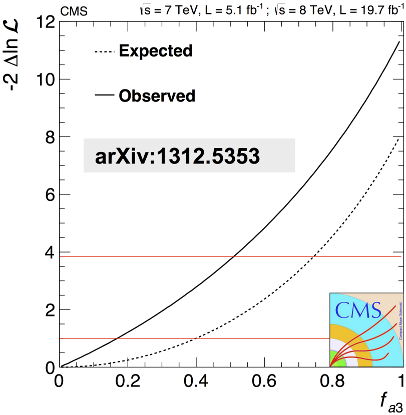



# Beyond hypothesis testing

- Spin and parity are strictly correlated with anomalous couplings of the Higgs boson
- CMS $H \to ZZ \to 4l$ analysis started to exploit this:

$$A(\mathrm{H} \to \mathrm{ZZ}) = v^{-1}\left(\underbrace{a_1 m_Z^2 \epsilon_1^* \epsilon_2^*}_{\text{SM}} + \underbrace{a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}}_{\text{aCP even}} + \underbrace{a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}}_{\text{aCP odd}}\right)$$

- Re-parametrize the likelihood fit for $0^+$ vs $0^-$ as a function of $f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1+|a_2|^2\sigma_2} + |a_3|^2\sigma_3$
- Observed (expected) exclusion: $f_{a3} < 0.5(0.7)$ @95%CL

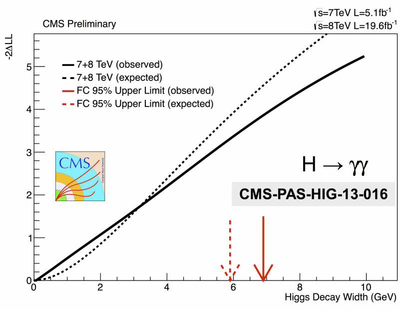


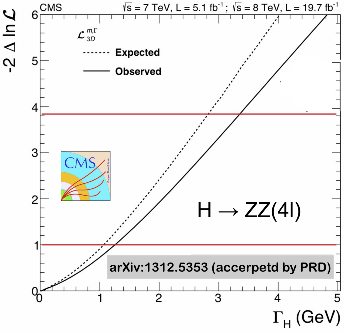
# Outline

# Direct constraints

SM prediction: $\Gamma_H \sim 4\ MeV$

- Direct measurements heavily limited by experimental resolution, $\mathcal{O}(1\%)$
- Current upper limits:
  - $\Gamma_H \leq 3.7\ GeV$ from $H \to \gamma\gamma$
  - $\Gamma_H \leq 3.4\ GeV$ from $H \to ZZ \to 4\ell$



# Width constraints from off-shell Higgs

## $H^* \to ZZ(\to 4\ell, 2\ell 2\nu)$ decay channels

NEW ANALYSIS

- off-shell Higgs boson production is small but the $BR$ to 2 real $Z$ is large above $2m_Z$
- *peak yield* depends on couplings and width

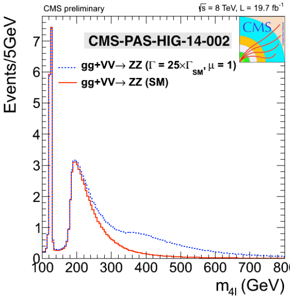
$$\sigma_{pp\to H\to ZZ} \sim \frac{g^2_{Hgg} g^2_{HZZ}}{\Gamma}$$

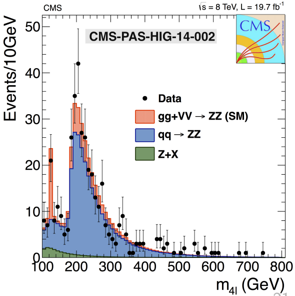
- *off-shell* Higgs yield is independent of width

$$\sigma_{pp\to H\to ZZ} \sim g^2_{Hgg} g^2_{HZZ}$$

$\Rightarrow$ simultaneous measurement of on-peak and off-peak production allows to constrain the Higgs boson width

- interference and VBF production are taken into account
- build probability templates for signal, background and interference:
  - using $m_{4\ell}$ and a kinematic discriminant $D_{gg}$ in case of **ZZ** $\to$ **4**$\ell$
  - using $m^T_{ll}$ in case of **ZZ** $\to$ **2**$\ell$**2**$\nu$



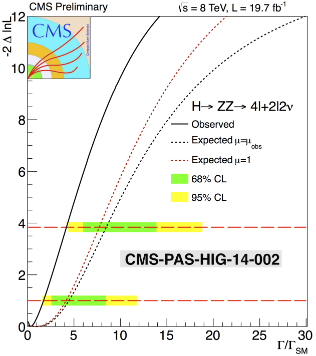



# Width constraints from off-shell Higgs

## Results

NEW ANALYSIS

- Unbinned likelihood fit constraining the peak yield to the observed value
- $m_H = 125.6\ GeV$, $\Gamma_H^{SM} = 4.15\ MeV$
- We expect to exclude $\Gamma_H < 35.3\ MeV$ @ 95% CL
- We observed exclusion $\Gamma_H < 17.4\ MeV$ @ 95% CL




| | $4\ell$ | $2\ell2\nu$ | Combined |
|---|---|---|---|
| Expected 95% CL limit, $r$ | 11.5 | 10.7 | 8.5 |
| Observed 95% CL limit, $r$ | 6.6 | 6.4 | 4.2 |
| Observed 95% CL limit, $\Gamma_H$(MeV) | 27.4 | 26.6 | 17.4 |
| Observed best fit, $r$ | $0.5^{+2.3}_{-0.5}$ | $0.2^{+2.2}_{-0.2}$ | $0.3^{+1.5}_{-0.3}$ |
| Observed best fit, $\Gamma_H$(MeV) | $2.0^{+9.6}_{-2.0}$ | $0.8^{+9.1}_{-0.8}$ | $1.4^{+6.1}_{-1.4}$ |

$^* r = \Gamma/\Gamma_{SM}$

# Summary

- First precision measurement in the Higgs sector is $m_H$
  - Allows to complete SM electroweak predictions
  - Expected precision is better than 0.2% for final LHC Run 1 combination
    **CMS**: $m_H = 125.7 \pm 0.3(syst) \pm 0.3(stat)$,
    **ATLAS**: $m_H = 125.5^{+0.5}_{-0.6}(syst) \pm 0.2(stat)$
- Spin/parity of the new boson consistent with $0^+$
  - A lot of alternative hypotheses were tested
  - Move towards anomalous couplings fits
- **NEW ANALYSIS** from CMS: put extremely tight constraint on the Higgs boson width from the off-shell production, $\Gamma_H < 17.4\ MeV$ @95%CL.

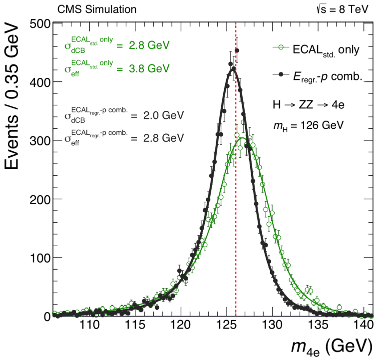
**Overall, very good compatibility with SM is found**

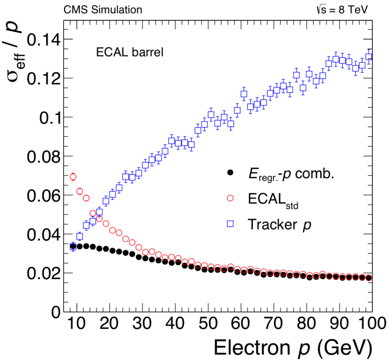
# References

| Experiment | Channel | Ref |
|---|---|---|
| ATLAS | Mass | PLB 726 (2013), pp.88-119 |
| | Spin-CP | PLB 726 (2013), pp.120-144 |
| | $H \to \gamma\gamma$ | ATL-PHYS-PUB-2013-014 |
| CMS | $H \to WW \to \ell\nu\ell\nu$ | JHEP 01 (2014) 096 |
| | $H \to ZZ \to 4\ell$ | arXiv:1312.5353 (accepted by PRD) |
| | $H \to \gamma\gamma$ spin and width | CMS-PAS-HIG-13-016 |
| | Mass | CMS-PAS-HIG-13-005 |
| | $H \to ZZ$ width from off-shell production | CMS-PAS-HIG-14-002 |
| Tevatron | Spin-CP | PRD 88 (2013) 052014 |

# BACKUP

# Resolution of electrons



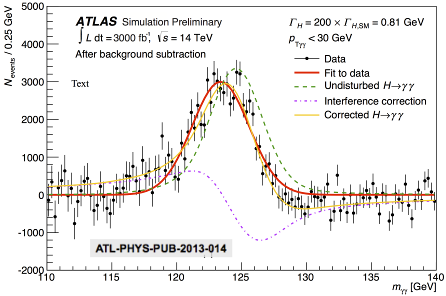

- Electron energy estimation is significantly improved by combining ECAL and tracker measurements
- Electron energy resolution is close to the designed one

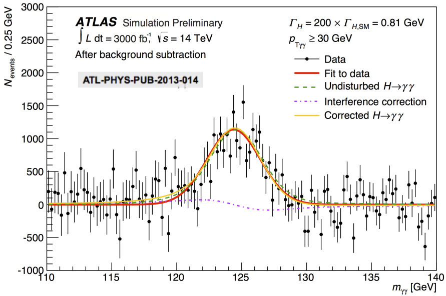
# Spin-parity models and observables (CMS)

| Discriminant | Note |
| --- | --- |
| | Observables used for the signal strength measurement |
| $m_{4\ell}$ | Four-lepton invariant mass, main background discrimination |
| $\mathcal{D}_{\text{bkg}}^{\text{kin}}$ | Discriminate SM Higgs boson against $ZZ$ background |
| $\mathcal{D}_{\text{jet}}$ | Linear discriminant, uses jet information to identify VBF topology |
| $p_{\text{T}}^{4\ell}$ | $p_{\text{T}}$ of the $4\ell$ system, discriminates between production mechanisms |
| | Observables used in the spin-parity hypothesis testing |
| $\mathcal{D}_{\text{bkg}}$ | Discriminates SM Higgs boson against ZZ background, includes $m_{4\ell}$ |
| $\mathcal{D}_{1^-}$ | Exotic vector ($1^-$), VBF |
| $\mathcal{D}_{1^+}$ | Exotic pseudovector ($1^+$), VBF |
| $\mathcal{D}_{2_{\text{m}}^+}^{\text{gg}}$ | Graviton-like with minimal couplings ($2_{\text{m}}^+$), gluon fusion |
| $\mathcal{D}_{2_{\text{m}}^+}^{\text{q}\bar{\text{q}}}$ | Graviton-like with minimal couplings ($2_{\text{m}}^+$), VBF |
| $\mathcal{D}_{2_{\text{b}}^+}^{\text{gg}}$ | Graviton-like with SM in the bulk ($2_{\text{b}}^+$), gluon fusion |
| $\mathcal{D}_{2_{\text{h}}^+}^{\text{gg}}$ | Tensor with higher dimension operators ($2_{\text{h}}^+$), gluon fusion |
| $\mathcal{D}_{2_{\text{h}}^-}^{\text{gg}}$ | Pseudotensor with higher dimension operators ($2_{\text{h}}^-$), gluon fusion |
| | Production-independent observables used in the spin-parity hypothesis testing |
| $\mathcal{D}_{0^-}$ | Pseudoscalar ($0^-$), discriminates against SM Higgs boson |
| $\mathcal{D}_{0_{\text{h}}^+}$ | Non-SM scalar with higher dimension operators ($0_{\text{h}}^+$) |
| $\mathcal{D}_{\text{bkg}}^{\text{dec}}$ | Discriminates against ZZ background, includes $m_{4\ell}$, excludes $\cos\theta^*$, $\Phi_1$ |
| $\mathcal{D}_{1^-}^{\text{dec}}$ | Exotic vector ($1^-$), decay-only information |
| $\mathcal{D}_{1^+}^{\text{dec}}$ | Exotic pseudovector ($1^+$), decay-only information |
| $\mathcal{D}_{2_{\text{m}}^+}^{\text{dec}}$ | Graviton-like with minimal couplings ($2_{\text{m}}^+$), decay-only information |

# Di-photon interferometry

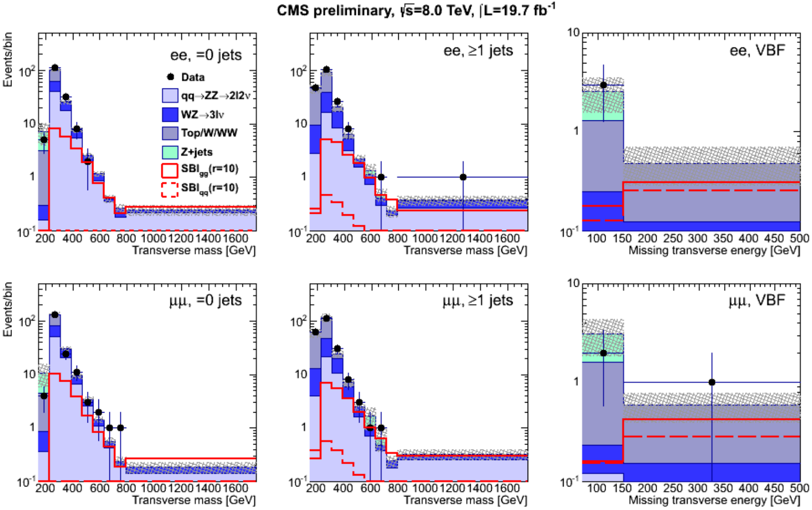
- Exploit destructive interference between $gg \to \gamma\gamma$ and $gg \to H \to \gamma\gamma$ (see for details arXiv:1305.3854)
  - Generate effective mass shift as a function of Higgs boson $p_T$
  - Constrain width from measurement of $m_H$ vs $p_T(H)$
  - Projected sensitivity for 3 $ab^{-1}$: $\Gamma_H < 30 \times \Gamma_H^{SM}$@95%$CL$



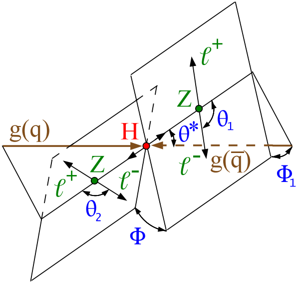



# Width discriminant distributions

$ZZ \to 2\ell 2\nu$



# $D_{gg}$ (ggMELA) kinematic discriminant




- ggMELA discriminant was developed in the context of the Legacy analysis
- High performances for separating gg→ZZ from qq→ZZ where gg→ZZ includes signal, continuum and their interference for any relative signal strength *a*.

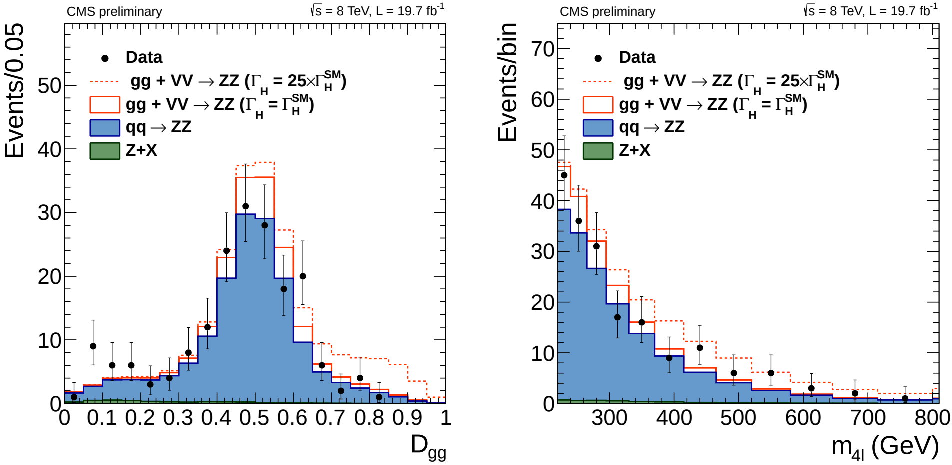
Built from signal and background probabilities: $D_{gg,a} = \frac{P_{gg,a}}{P_{gg,a}+P_{q\bar{q},a}}$, where $P_{gg,a} = a \times P^{gg}_{\text{sig}} + \sqrt{a} \times P^{gg}_{\text{int}} + P^{gg}_{\text{bkg}}$ and $P_{q\bar{q},a} = P^{q\bar{q}}_{\text{bkg}}$

- Signal strength *a* must be chosen when building the discriminant.
- From preliminary studies we expected sensitivity for run 1 data to be around 10×SM, so we chose $D_{gg,10}$.

About 30% improvement when including it in the fit procedure

# Width discriminant distributions

## $ZZ \to 4\ell$



# Systematic uncertainties in width analysis

- $gg \to ZZ$
  - Part of cross section uncertainties cancel in the ratio between off-shell and on-shell
  - Shape uncertainties obtained varying PDFs: CT10, MSTW and NNPDF
  - Correlated shape-yield uncertainties produced varying the scales and applying corresponding K-factor (arXiv:1312.2397)
  - $K_{bkg} = K_{sig} \times (1.0 \pm 0.1)$ (arXiv:13043053+private com.)
- $q\bar{q} \to ZZ$
  - QCD scale: correlate shape and yield uncertainties
  - PDFs: constant 4%
- $\mu$ uncertainty
  - $\mu_{exp} = 1.00^{-0.24}_{+0.27}$
  - $\mu_{obs} = 0.93^{-0.24}_{+0.26}$