Recent Results on Properties of the Higgs boson in the $H \rightarrow ZZ \rightarrow 4l$ decay channel at CMS

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Outline

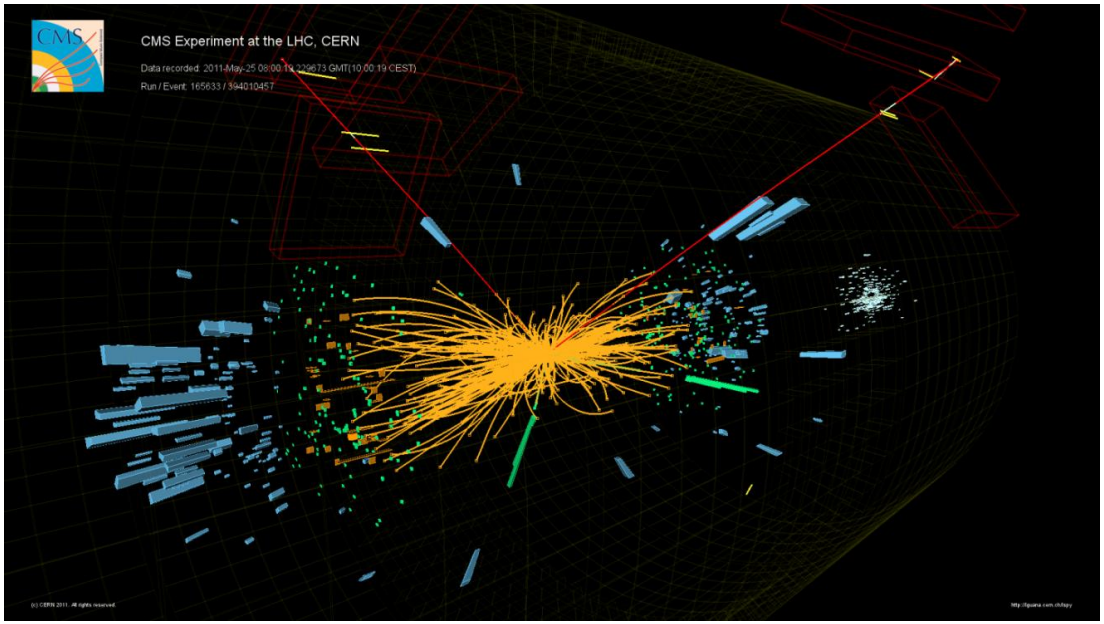
- $H \rightarrow ZZ \rightarrow 4l$ decay channel
- Significance and Signal strength
- Mass measurement
- Spin-parity measurements
- Width measurement
- Conclusions

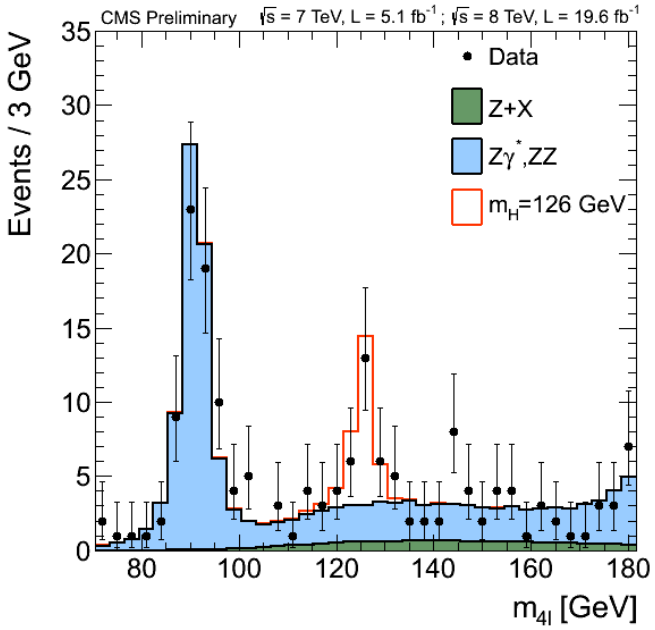
The $H \rightarrow ZZ \rightarrow 4l$ Channel

Very small branching fraction, but:

- Very clean signature
  - 2 pairs of **high p_T** and **isolated μ** or **e**
  - full reconstructed event topology
  - small background contribution
- Excellent resolution

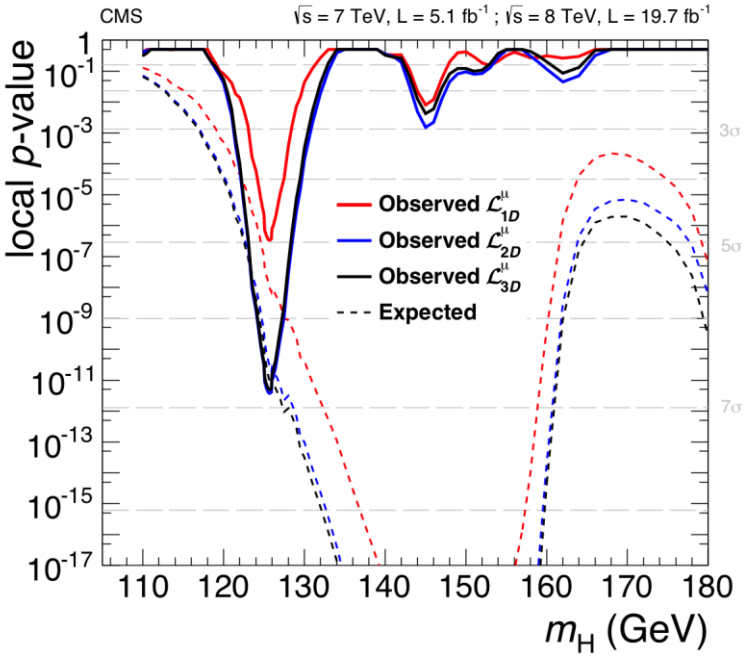
High precision **mass** measurement and **spin-parity** quantum numbers

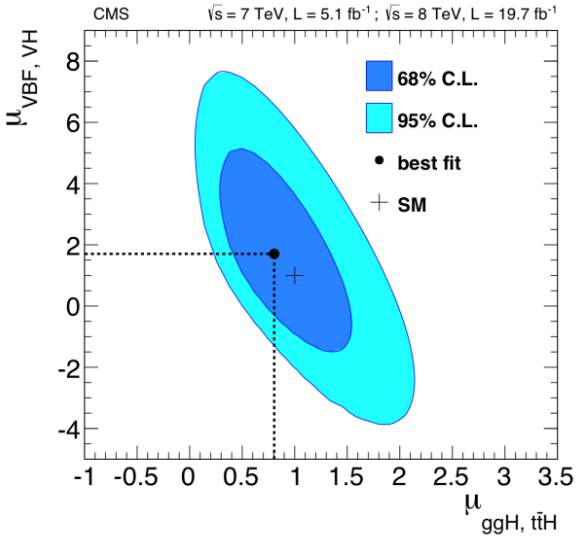




Significance and Signal Strength

- Minimum of the **local p-value** at m_H = **125.7 GeV (6.8σ)**
- Discovery of the new boson in the four-lepton channel alone
- The only significant excess in the range m_H < 1 TeV





- **Signal strength** ($\mu = \sigma/\sigma_{SM}$)

$$\mu = 0.93^{+0.26}_{-0.23}\,(stat.)^{+0.13}_{-0.09}\,(syst.)$$

- Partial signal strength for gluon fusion and VBF

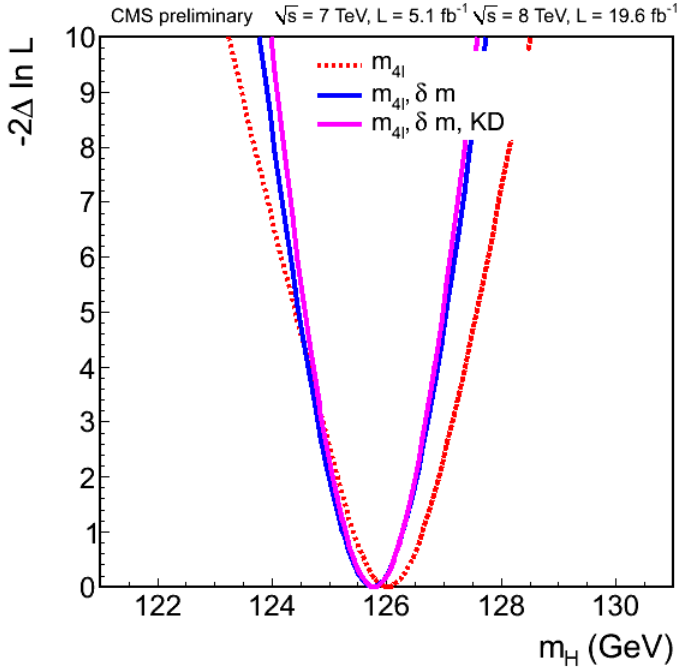
$$\mu_{ggH,ttH} = 0.80^{+0.46}_{-0.36}$$

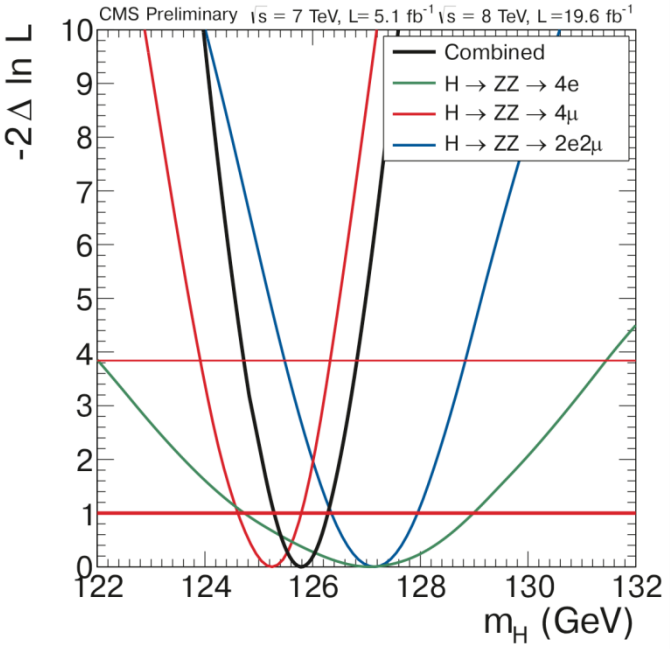
$$\mu_{VBF,VH} = 1.7^{+2.2}_{-2.1}$$

Mass Measurement

- Mass measurement performed using 3D fit with (m_{4l}, δm_{4l}, $\mathcal{D}_{kin}$)
- Using per-event mass errors 8% improvement
- Main systematic uncertainties due to lepton scale and resolution

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





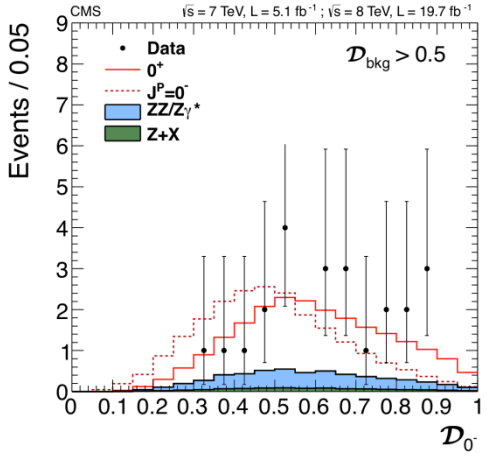
Spin-Parity Measurements

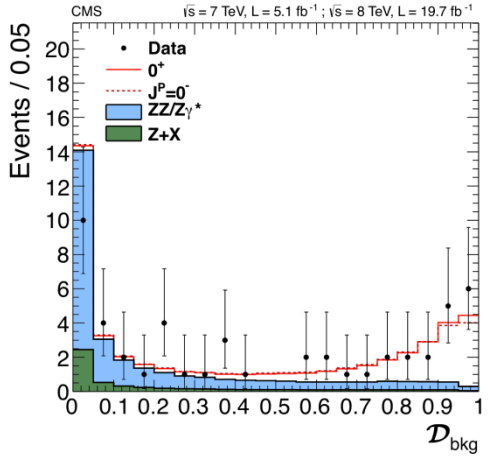
- 2D fit based on $\mathcal{D}_{bkg}$ and $\mathcal{D}_{JP}$ **kinematic discriminants**

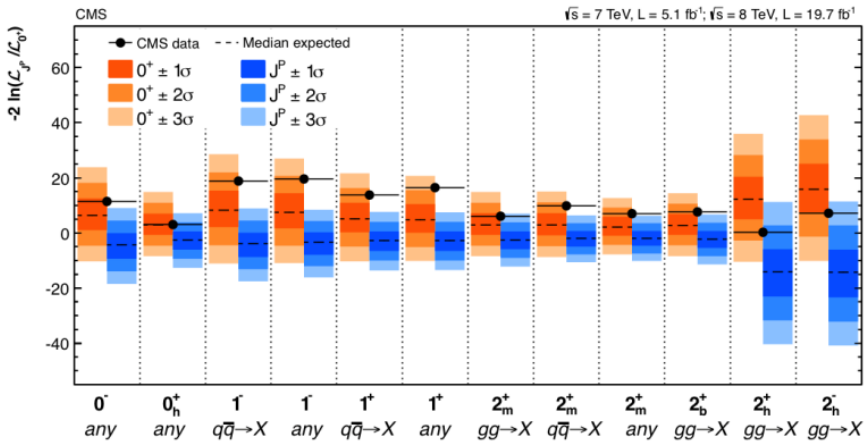
$\mathcal{D}_{bkg}$ separates SM Higgs from background

$\mathcal{D}_{JP}$ discriminates alternative J^P hypothesis from SM Higgs

- twelve models tested

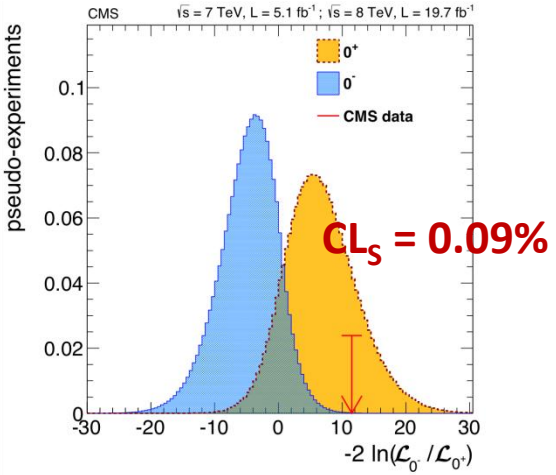






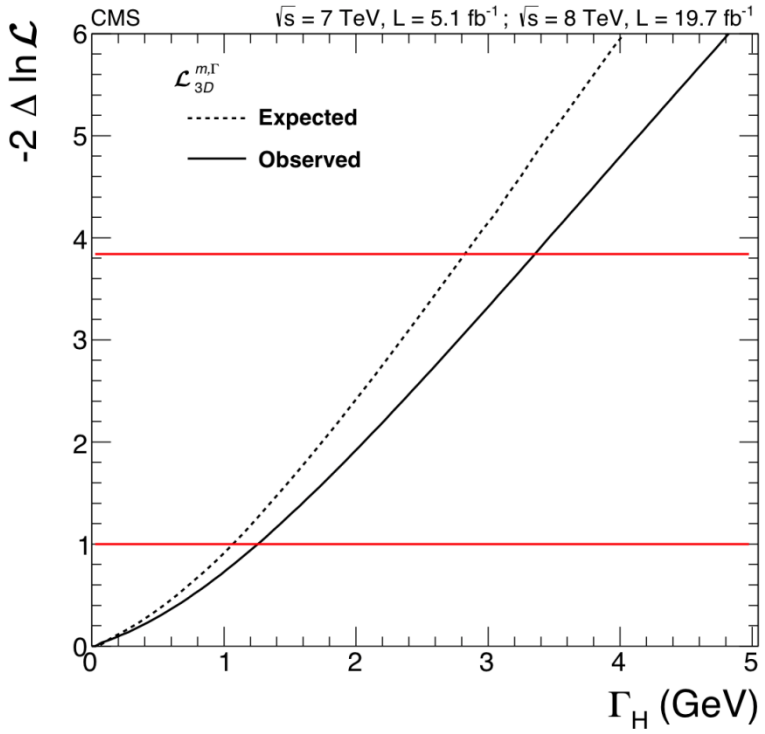
0^+ vs 0^-

0^+ hypothesis highly favoured!



Width Measurement

- Standard Model prediction at m_H = 125.6 GeV is ***Γ*** **~ 4 MeV**
- Direct measurement strongly limited by experimental resolution
- Current upper limit of 3.4 GeV at 95% C.L.



Sensitivity at the resonance peak far beyond the expected width

Width Measurement

Goal: to constrain the Higgs boson width using the Higgs boson production and decay away from the resonance

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

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

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

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

$$\boxed{r = \Gamma_H/\Gamma_H^{SM}}$$

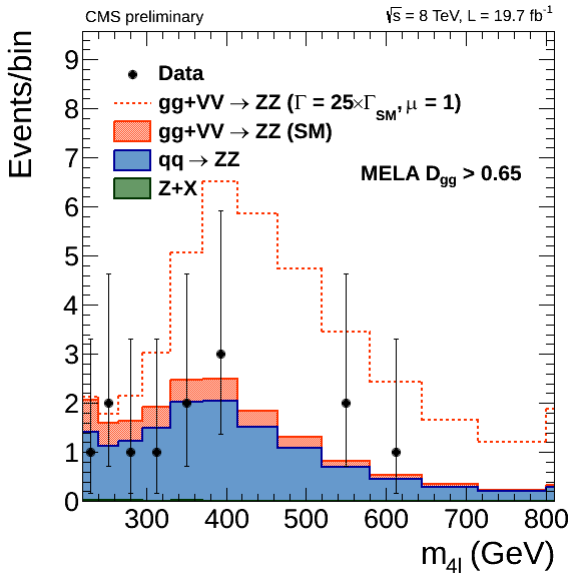
- Signal strength μ provided by the measurement of the on-shell production
- r value (and Γ_H) can be obtained by measuring the ratio of the production in the off-shell and on-shell region

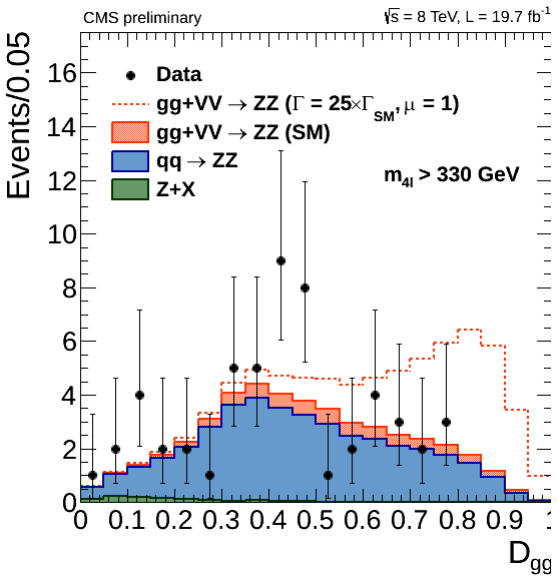
Warning: the destructive interference with continuum $gg \to ZZ$ is not negligible at high m_{ZZ}

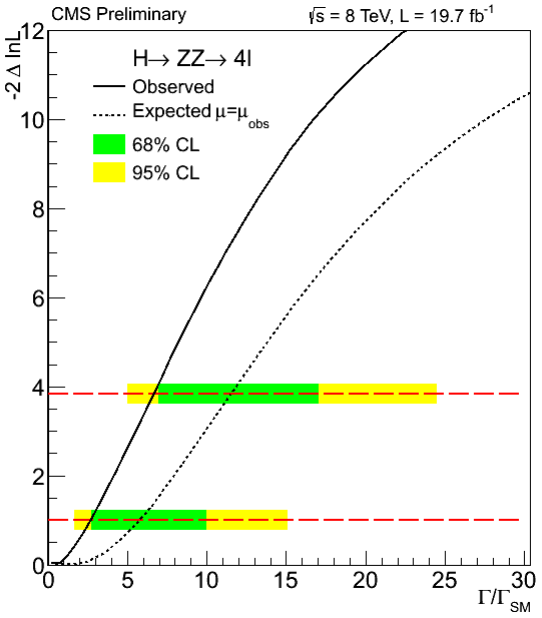
Width Measurement

- Specific kinematic discriminant $\mathcal{D}_{gg}$ defined, to separate $gg \rightarrow ZZ$ and $qq \rightarrow ZZ$ processes (MELA)
- $m_{4l} > 220$ GeV region is examined
- Signal-enriched region defined by $m_{4l} > 330$ GeV and $\mathcal{D}_{gg} > 0.65$

$\Gamma_H < 6.6\ \Gamma_H^{SM}$ (expected $\Gamma_H < 11.5\ \Gamma_H^{SM}$) equivalent to $\Gamma_H < 27.4$ MeV at 95% C.L.





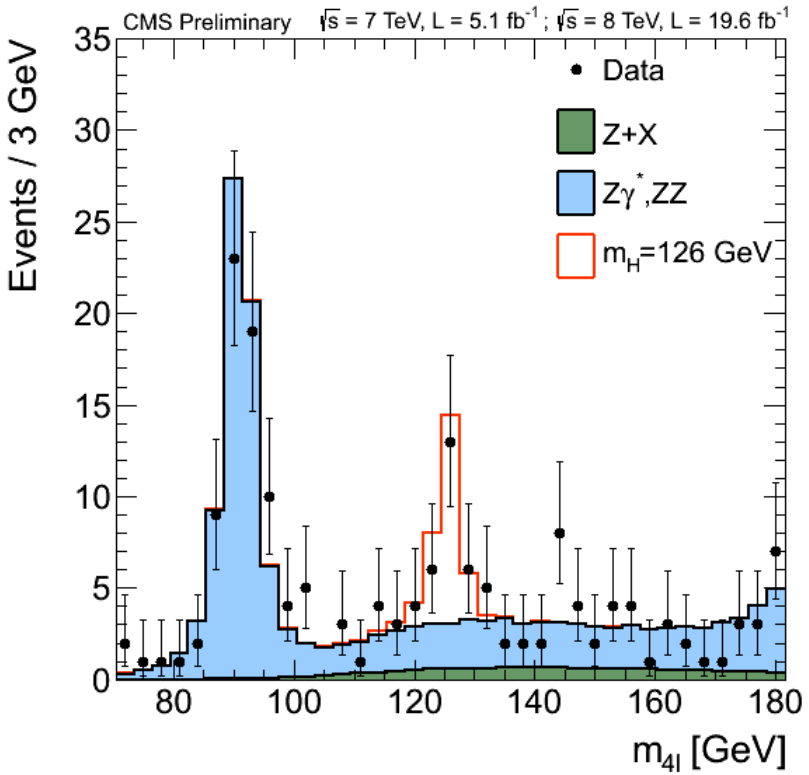


Conclusions

- The analyzed resonance is clearly visible in the $H \rightarrow ZZ \rightarrow 4l$ decay channel, allowing the study of its properties with high precision
- The particle is compatible within uncertainties with a SM Higgs boson and alternative spin-parity hypotheses are disfavored by the data
- The experimental constraint on Higgs total width is determined using off-shell production and decay, improving by more than two orders of magnitude the previous experimental result

Backup

Analysis Strategy



Analysis based on reconstruction, identification and isolation of leptons

Event selection and kinematics

- $p_T^e > 5$ GeV and $p_T^\mu > 7$ GeV
- $p_T^1 > 20$ GeV and $p_T^2 > 10$ GeV
- $40 < m_{Z1} < 120$ GeV
- $12 < m_{Z2} < 120$ GeV
- $110 < m_{4l} < 1000$ GeV
- Isolation cut
- Impact parameter cut

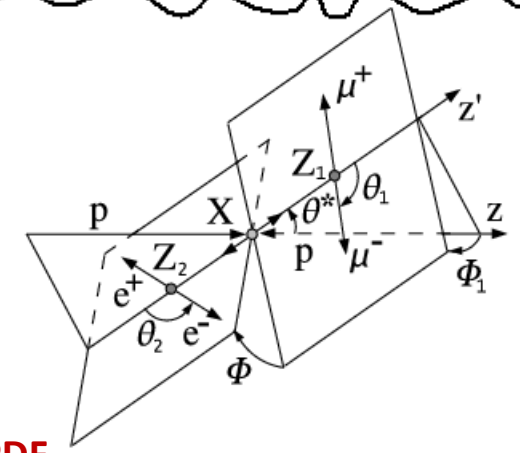
Background sources

- Irreducible four-lepton contribution (direct ZZ /Zγ*→4l production)
- Reducible contribution from Zbb→4l and tt→4l
- Instrumental contribution (misidentification of leptons)

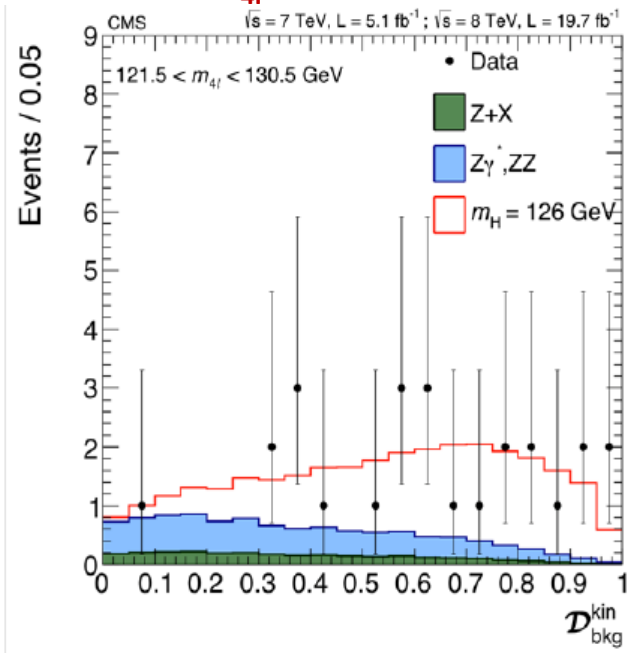
Kinematic Discriminant

Signal/background kinematic discriminant defined using matrix element techniques

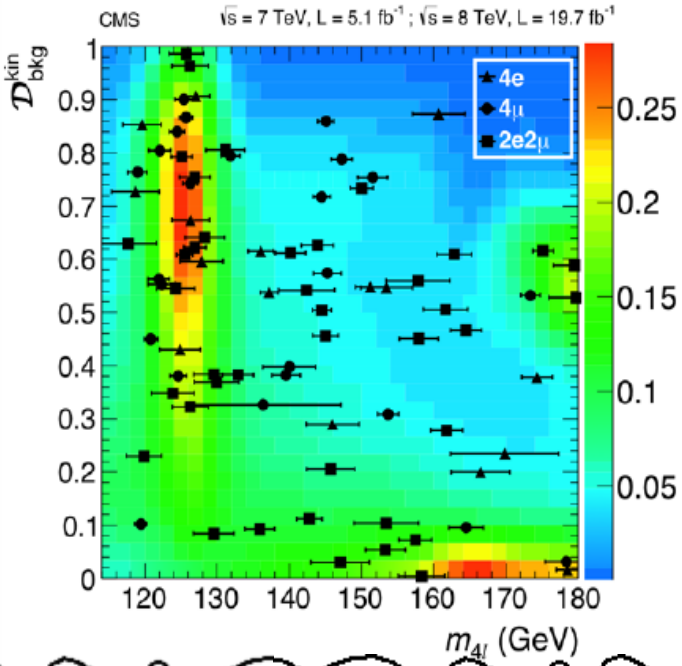
$$\mathcal{D}^{\text{kin}}_{\text{bkg}} = \frac{\mathcal{P}^{\text{kin}}_{\text{sig}}}{\mathcal{P}^{\text{kin}}_{\text{sig}} + \mathcal{P}^{\text{kin}}_{\text{bkg}}}$$



121.5 < m_{4l} < 130.5 GeV



H(126) 2D PDF



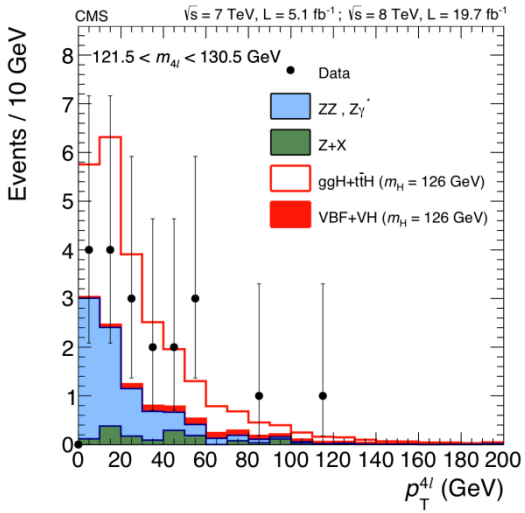
Jet Categories - Couplings

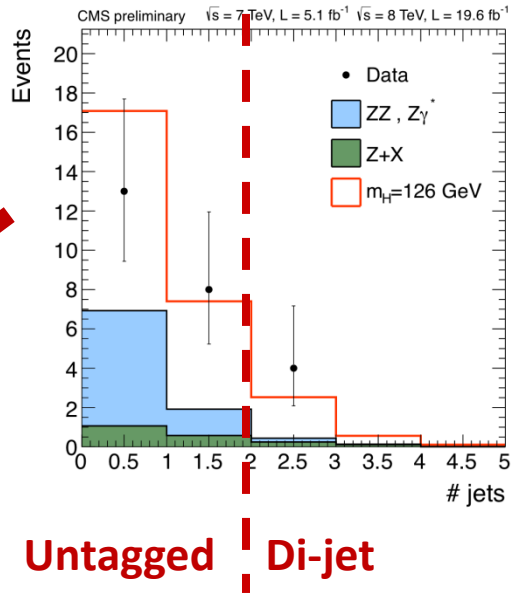
- To increase sensitivity to the coupling to bosons and fermions (μ_V and μ_F) events are splitted in two exclusive categories:

  Untagged: less than two jets (VBF < 5%)
  Di-jet: at least 2 jets with p_T>30 GeV (VBF ~20%)

- One extra dimension added to discriminate production mechanisms:

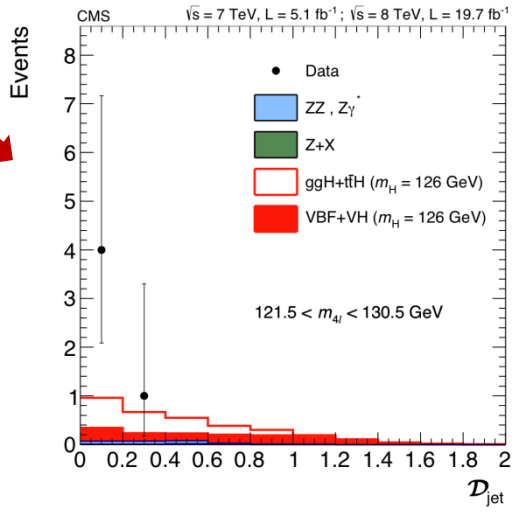
pT_{4l}





Untagged **Di-jet**

$\mathcal{D}_{jet}$ (VBF discriminant)



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

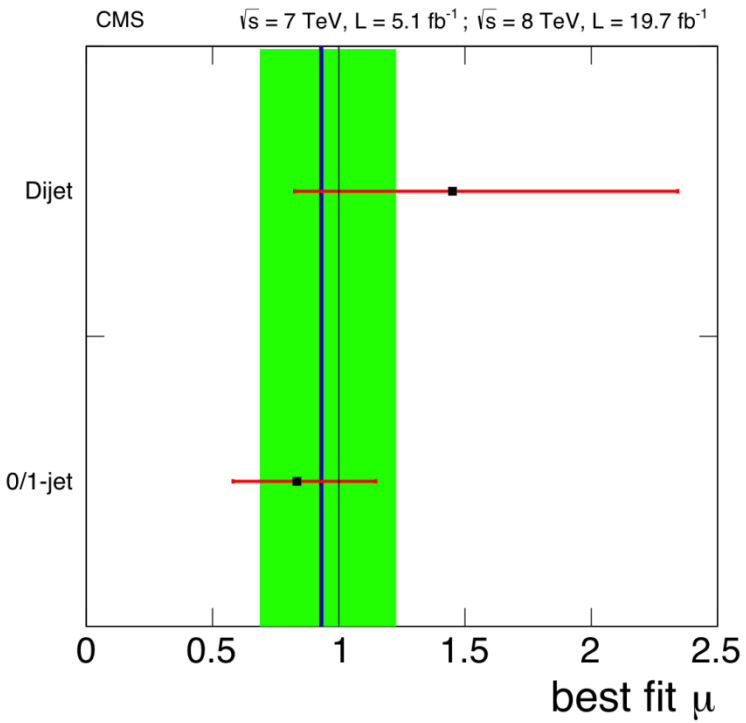
Signal strength at 125.8 GeV $\mu = \mathbf{0.91}^{+0.30}_{-0.24}$

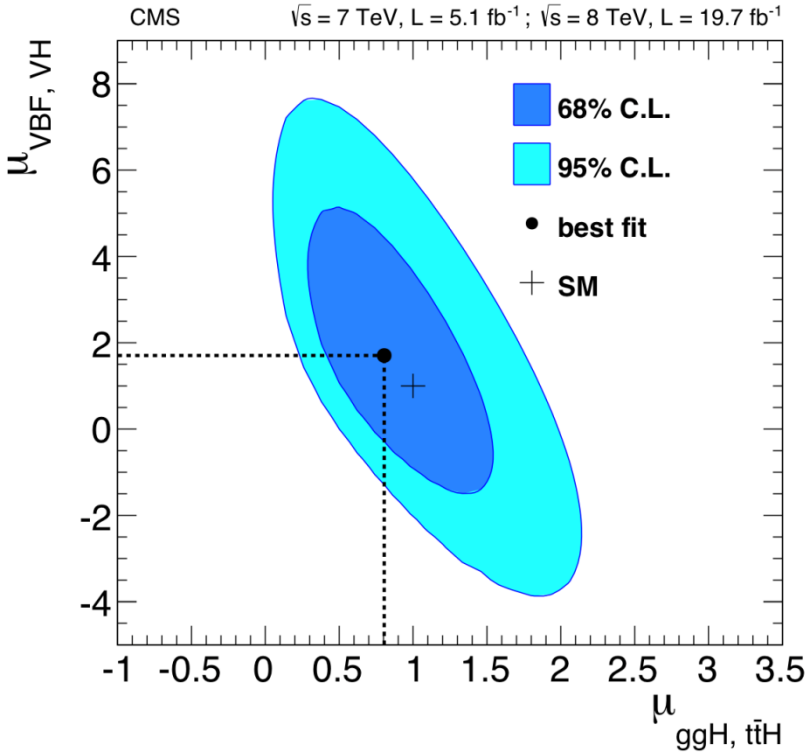
$\mu_{untag} = 0.83^{+0.31}_{-0.25}$

$\mu_{di\text{-}jet} = 1.45^{+0.89}_{-0.62}$

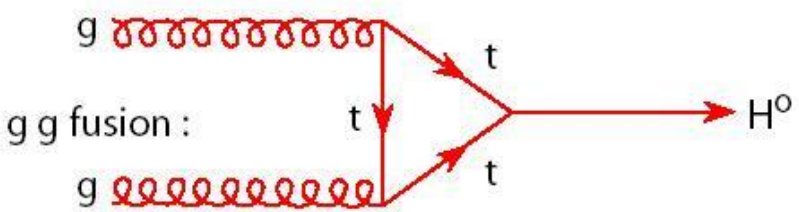
$\mu_{ggH,ttH} = 0.80^{+0.46}_{-0.36}$

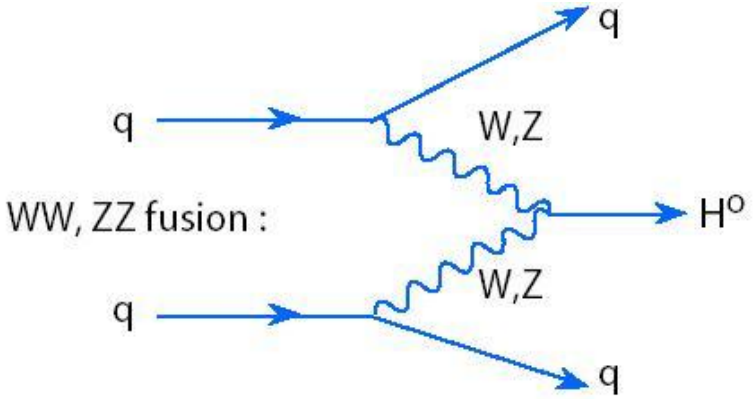
$\mu_{VBF,VH} = 1.7^{+2.2}_{-2.1}$

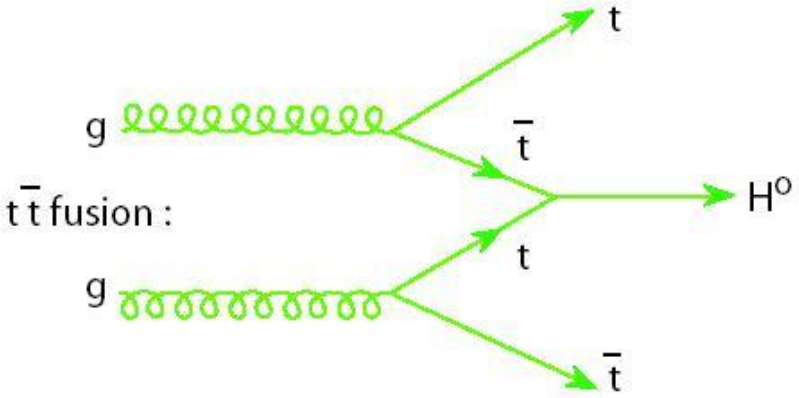


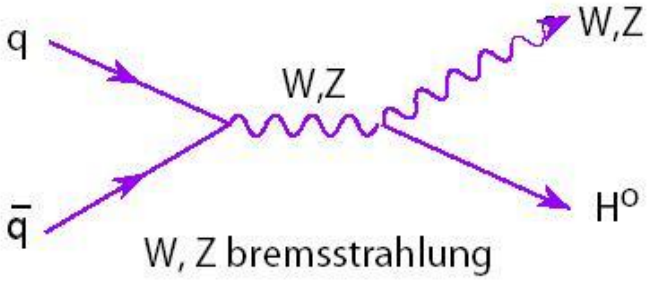


Production Mechanisms

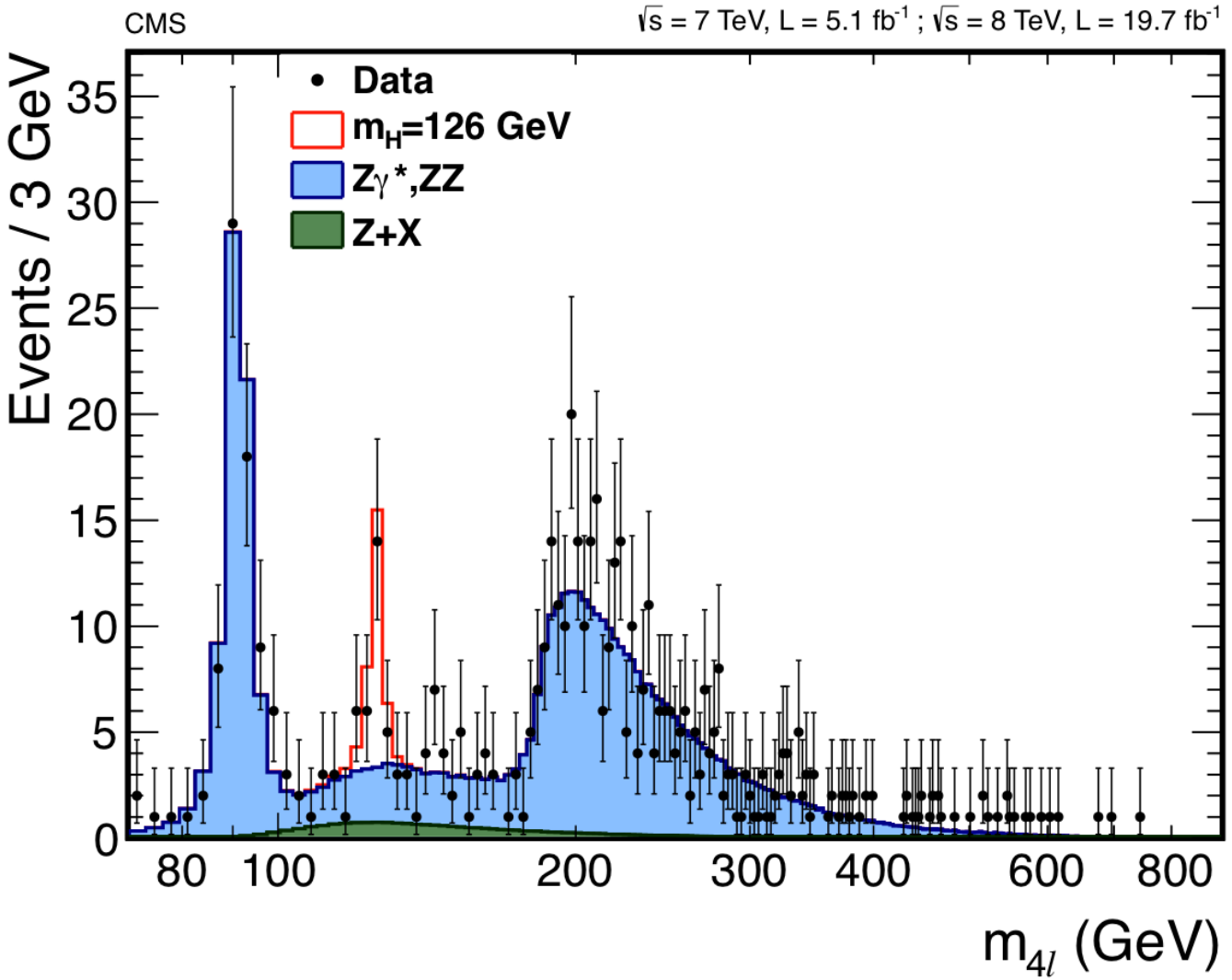




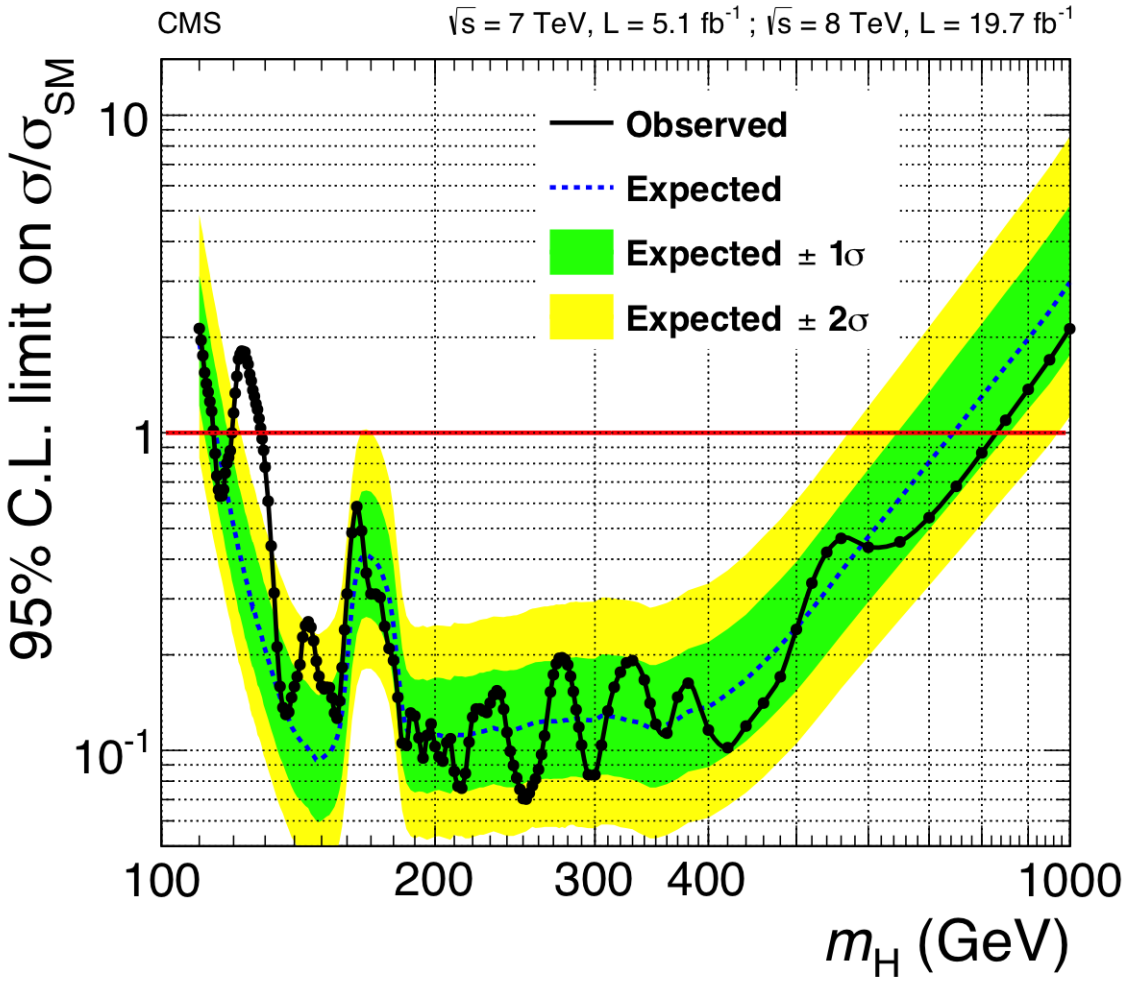




Invariant Mass Distribution



Upper Limit (4l + 2l2τ)

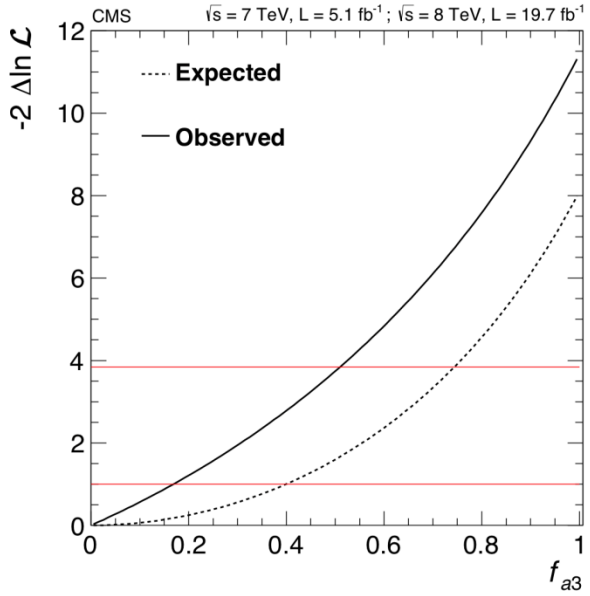


CP-Violation f_{a3}

- Decay amplitude for a spin-0 boson

$$A(X \to V_1V_2) = v^{-1}\varepsilon_1^{*\mu}\varepsilon_2^{*\nu}\left(a_1 g_{\mu\nu} m_X^2 + a_2 q_\mu q_\nu + a_3 \varepsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta\right) \quad \Rightarrow \quad f_{a3} = \frac{|A_3|^2}{|A_1|^2 + |A_3|^2}$$

- SM Higgs boson (0^+) decay is dominated by A_1, while 0^- decay by A_3
- Presence of both amplitudes indicates CP-violation



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

$f_{a3} < 0.58$ at 95% CL