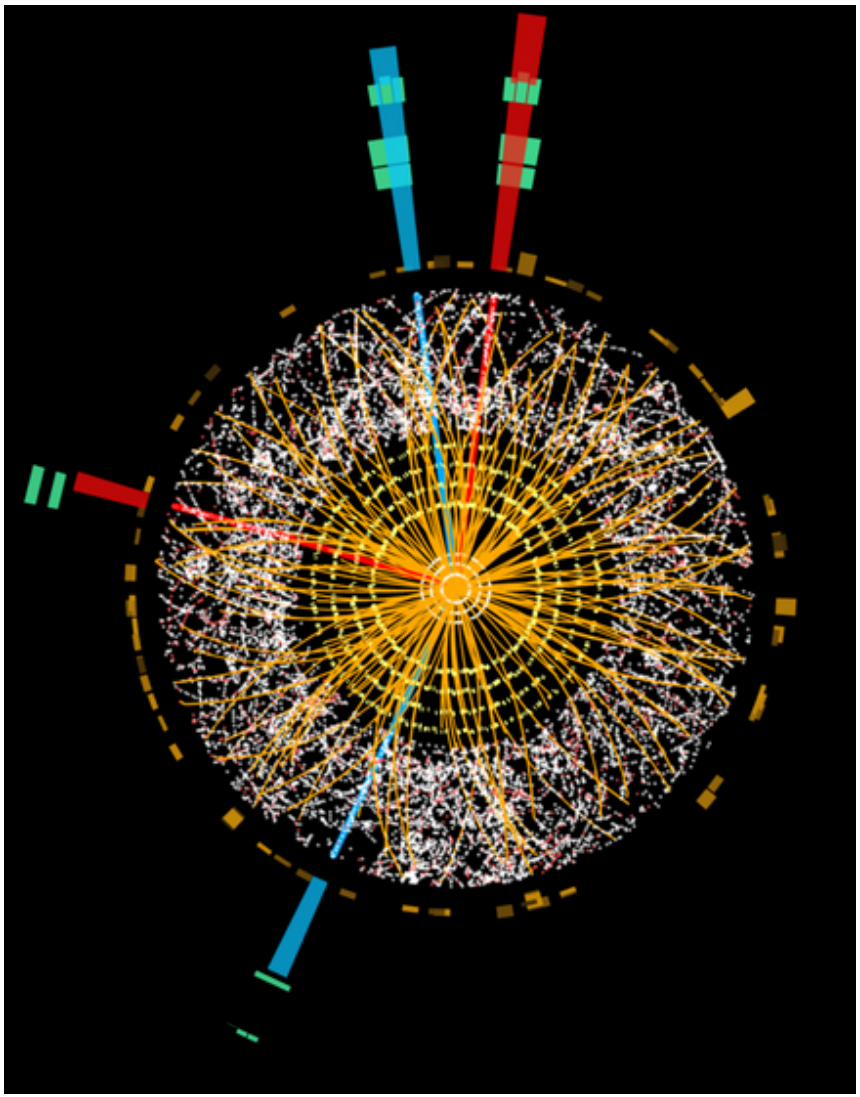
# Higgs differential cross-sections, spin/CP measurements, rare channels at the LHC



LHCP 2015, St. Petersburg

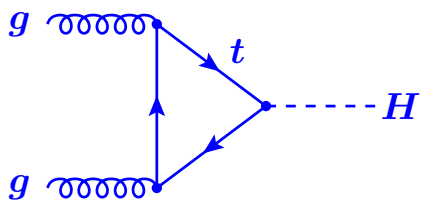
September 1, 2015

Kerstin Tackmann (DESY)

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

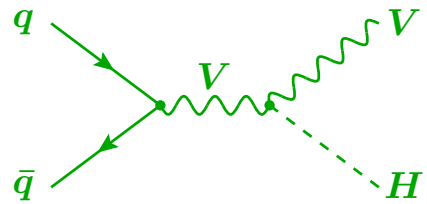
# Main Higgs boson production modes at the LHC.

## Gluon fusion: 19.5 pb



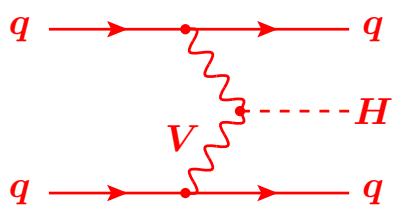

Higgs tends to have low $p_T$

## Associated production: 1.1 pb



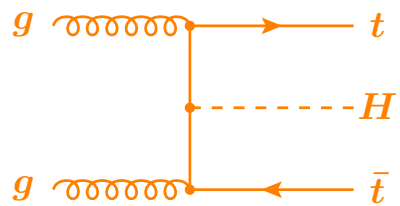

Clear signature: reconstruct $W$ and $Z$ in leptonic and/or hadronic decays

## Vector boson fusion: 1.6 pb




Distinct signature with 2 forward jets and little hadronic activity in between

## Associated production with $t\bar{t}$: 0.1 pb

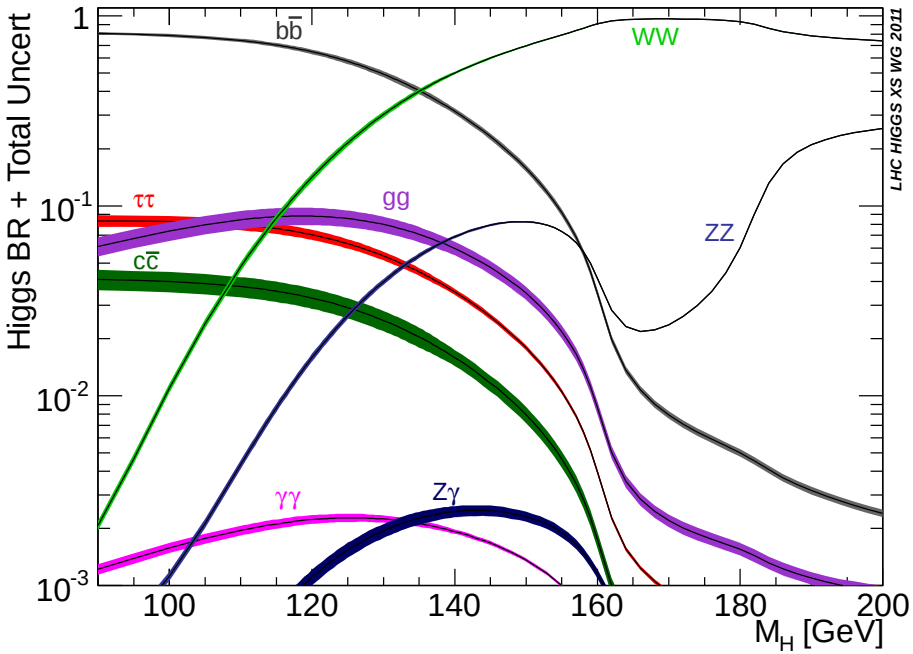



Tag presence of two top quarks

Predicted production cross sections given at $m_H$ =125 GeV and $\sqrt{s}$ =8 TeV

[Summarized by LHC Higgs cross section working group]

# SM Higgs boson decays.




[Summarized by LHC Higgs cross section working group]

Predicted decay branching fractions

$m_H$=125 GeV

| | |
|---|---|
| $H \to b\bar{b}$ | 57.7% |
| $H \to WW^*$ | 21.5% |
| $H \to \tau\tau$ | 6.3% |
| $H \to ZZ^*$ | 2.6% |
| $H \to \gamma\gamma$ | 0.23% |
| $H \to Z\gamma$ | 0.16% |
| $H \to \mu\mu$ | 0.02% |
| $H \to J/\psi\gamma$ | $2.8 \times 10^{-6}$ |

## This talk

- Property measurements from bosonic decays, $H \to WW^*, ZZ^*, \gamma\gamma$
- Search for rare decays, $H \to Z\gamma, \mu\mu, J/\psi\gamma, \gamma^*\gamma$

Next talk by Marco Pieri will present Higgs coupling studies

Results are based on improved detector calibration, reconstruction and analysis techniques and significantly improved over initial Run1 results

# Cross sections.

[JHEP09 (2014) 112, PLB 738 (2014), arXiv:1504.05833 [hep-ex]
CMS-HIG-14-028, CMS-HIG-14-016]

→ talk by Predrag Milenovic

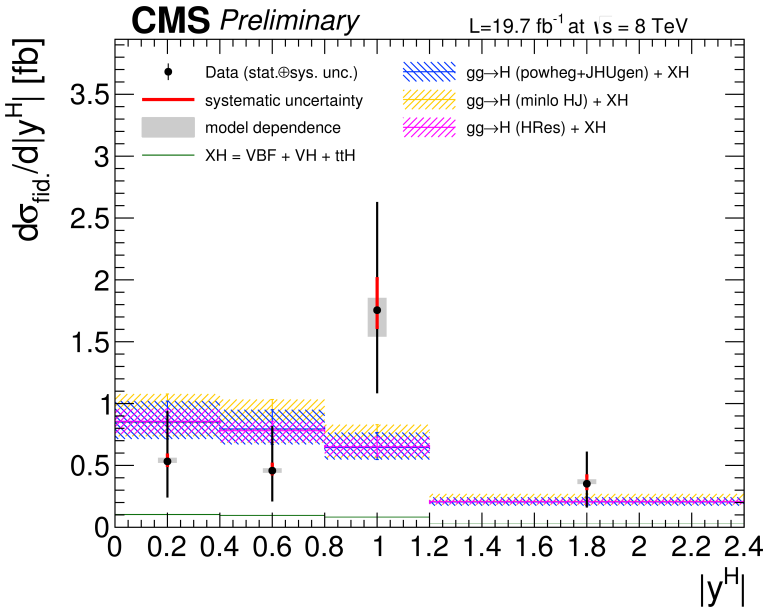
## Almost model-independent measurements

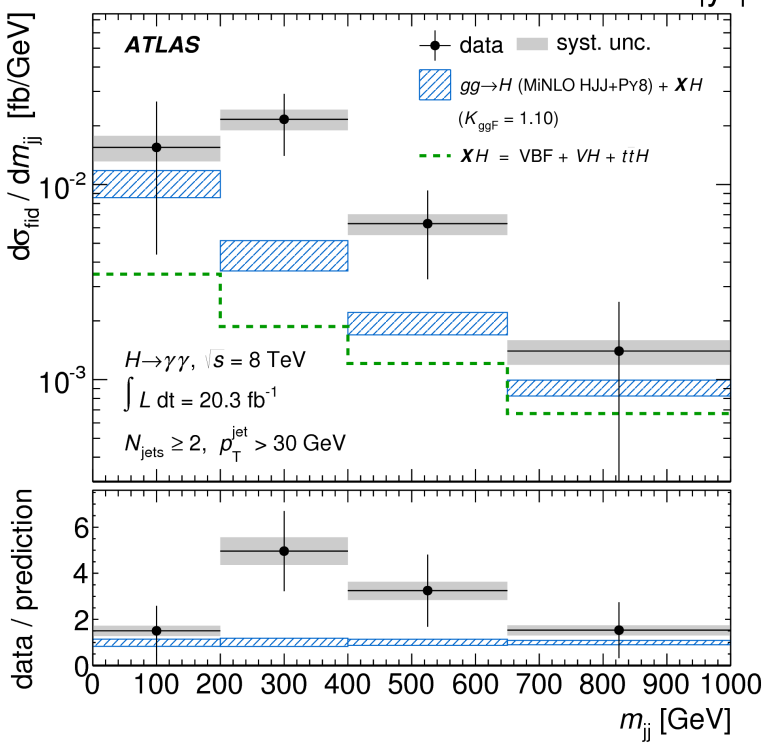
- High-resolution channels $H \to \gamma\gamma/4\ell$
- Fiducial region defined to minimize acceptance corrections
  - ⋆ Including photon, lepton and jet kinematics, and isolation (ATLAS photons and CMS leptons)
- Unfolded to particle level

## Perform measurements of

- Fiducial cross sections (and extrapolate to total)
- Production kinematics sensitive to production modes, QCD effects, PDFs, ...
- Associated jet activity sensitive to production modes, QCD effects, ...
- Spin and CP sensitive quantities
- VBF sensitive quantities

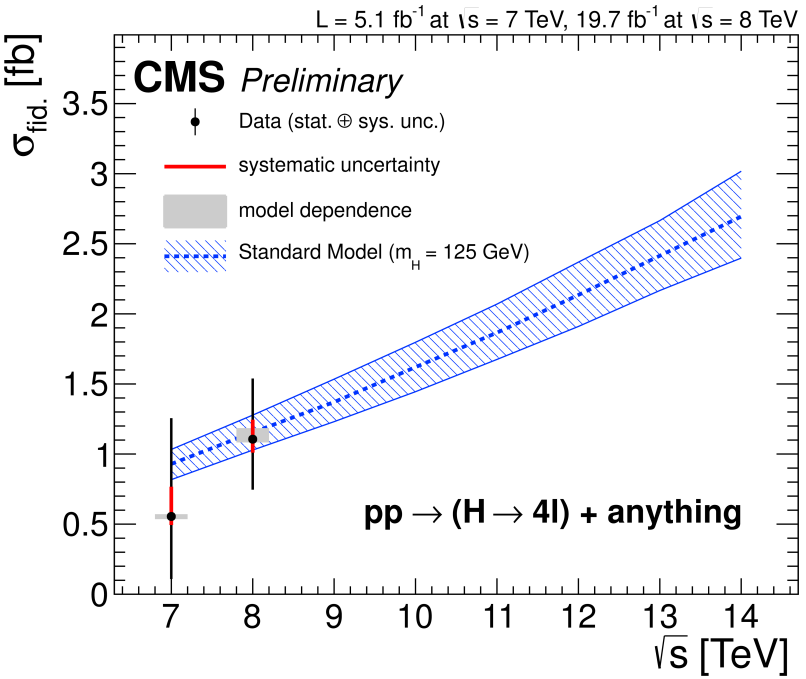
## Measurements still statistically limited



# Cross sections: fiducial measurements.

## Fiducial $\sigma$ at 7 and 8 TeV




## Fiducial $\sigma$ CMS (8 TeV)

$$\sigma_{\mathrm{fid}} = 1.11^{+0.41}_{-0.35}(\mathrm{stat})^{+0.14}_{-0.10}(\mathrm{syst})^{+0.08}_{-0.02}(\mathrm{mod})\ \mathrm{fb}$$

$H \to 4\ell$

$$\sigma^{\mathrm{SM}}_{\mathrm{fid}} = 1.15^{+0.12}_{-0.13}\ \mathrm{fb}$$

$$\sigma_{\mathrm{fid}} = 32 \pm 10(\mathrm{stat}) \pm 3(\mathrm{syst})\ \mathrm{fb}$$

$H \to \gamma\gamma$

$$\sigma^{\mathrm{SM}}_{\mathrm{fid}} = 31^{+4}_{-3}\ \mathrm{fb}$$

## Fiducial $\sigma$ ATLAS (8 TeV)

$$\sigma_{\mathrm{fid}} = 2.11^{+0.53}_{-0.47}(\mathrm{stat})^{+0.08}_{-0.08}(\mathrm{syst})\ \mathrm{fb}$$

$H \to 4\ell$

$$\sigma^{\mathrm{SM}}_{\mathrm{fid}} = 1.30^{+0.13}_{-0.13}\ \mathrm{fb}$$

$$\sigma_{\mathrm{fid}} = 43.2 \pm 9.4(\mathrm{stat})^{+3.2}_{-2.9}(\mathrm{syst}) \pm 1.2(\mathrm{lumi})\ \mathrm{fb}$$

$H \to \gamma\gamma$

$$\sigma^{\mathrm{SM}}_{\mathrm{fid}} = 30.5 \pm 3.3\ \mathrm{fb}$$

## $H \to WW^* \to e\nu\mu\nu$ fiducial ggH cross section ATLAS (8 TeV)

$$\sigma^{ggH}_{\mathrm{fid,0j}} = 27.6^{+5.4}_{-5.3}(\mathrm{stat})^{+4.1}_{-3.9}(\mathrm{syst})\ \mathrm{fb}$$

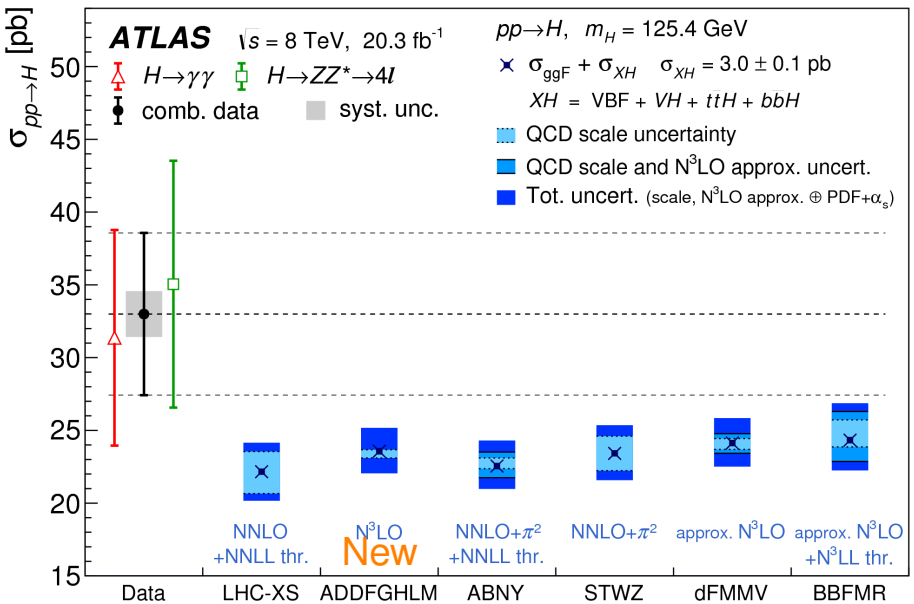
$$\sigma^{ggH,\mathrm{SM}}_{\mathrm{fid,0j}} = 19.9 \pm 3.3\ \mathrm{fb}$$

$$\sigma^{ggH}_{\mathrm{fid,1j}} = 8.3^{+3.1}_{-3.0}(\mathrm{stat})^{+3.7}_{-3.5}(\mathrm{syst})\ \mathrm{fb}$$

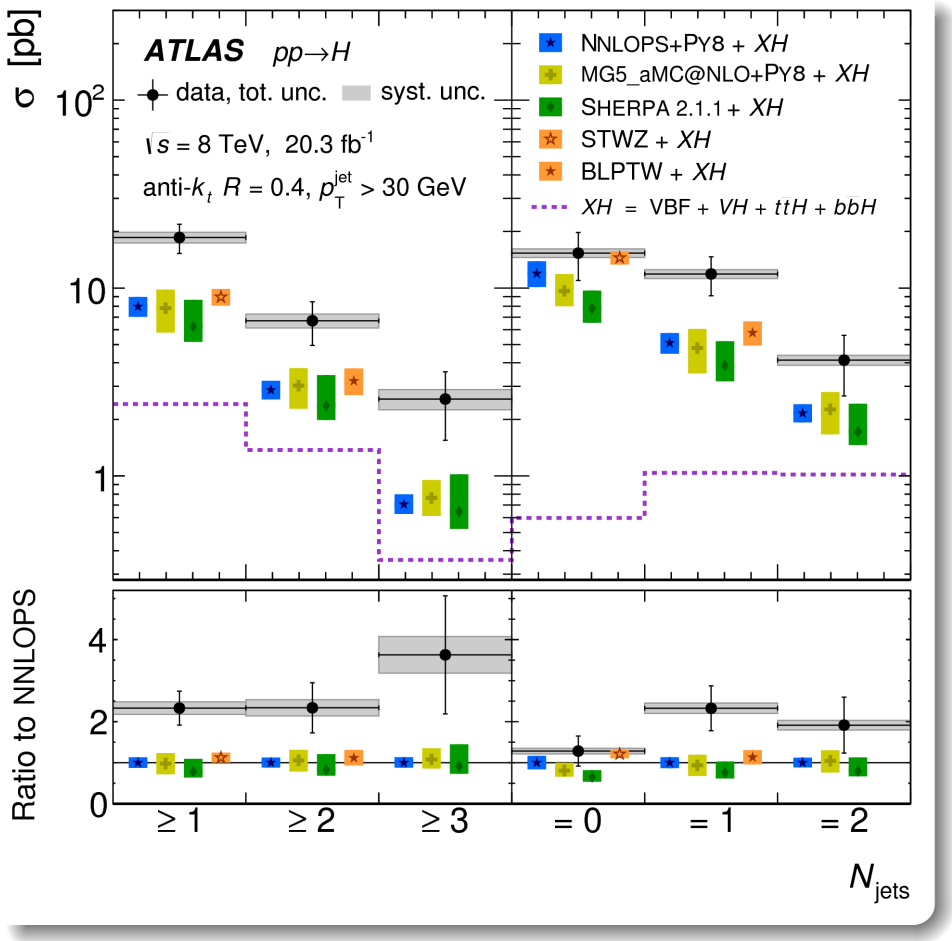
$$\sigma^{ggH,\mathrm{SM}}_{\mathrm{fid,1j}} = 7.3 \pm 1.8\ \mathrm{fb}$$

# Cross sections: combination.

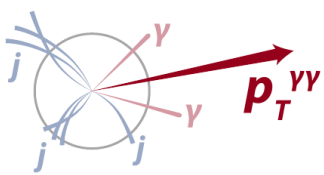
- Sacrifice some model independence for combining $H \to \gamma\gamma$ and $H \to 4\ell$ to gain statistical power
  - ★ Extrapolate to full photon and lepton phase space
    - Fiducial acceptance of 60±1% ($H \to \gamma\gamma$) and 47±1% ($H \to 4\ell$)
  - ★ Assume SM branching fractions

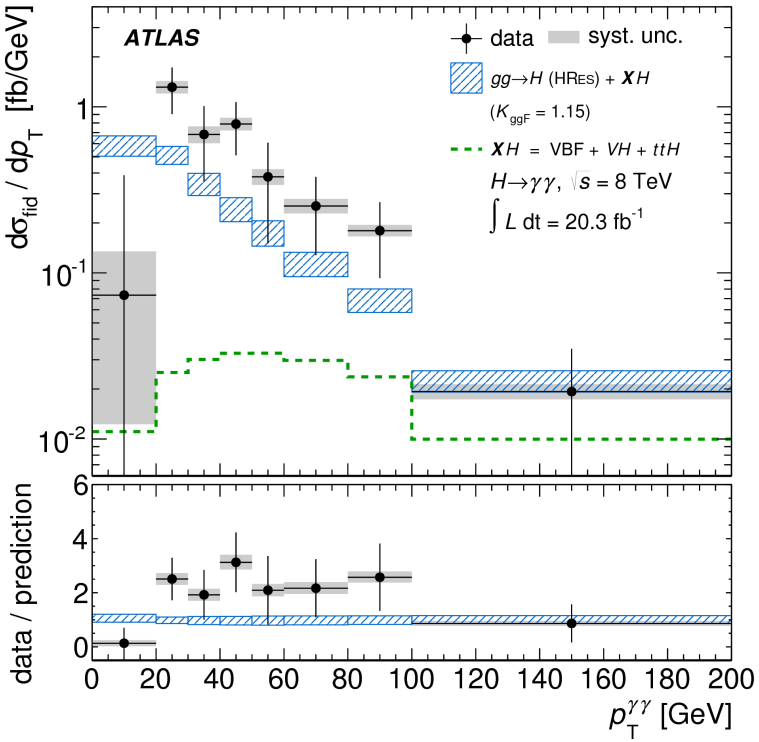


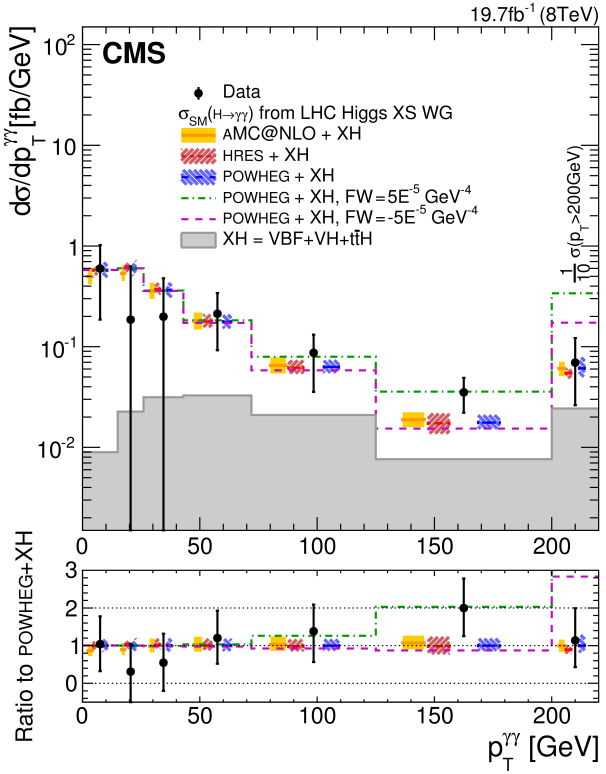

$p$-values 5.5% (LHC-XS) and 9% (ADDFGHLM)

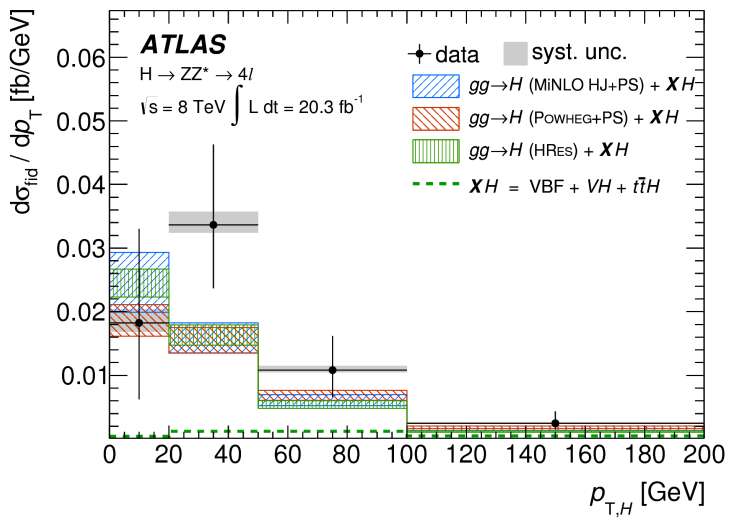


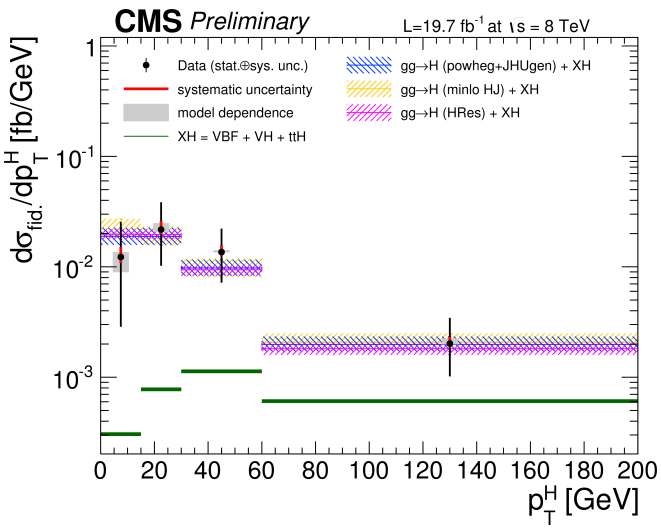
# Cross sections: Higgs boson $p_T$.



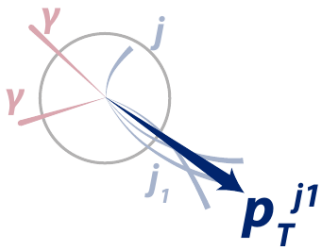



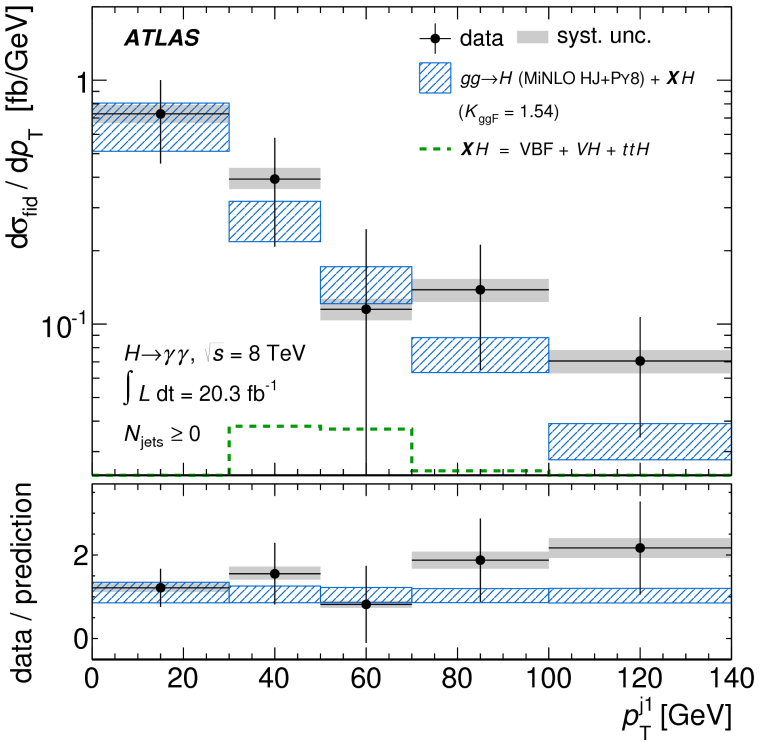



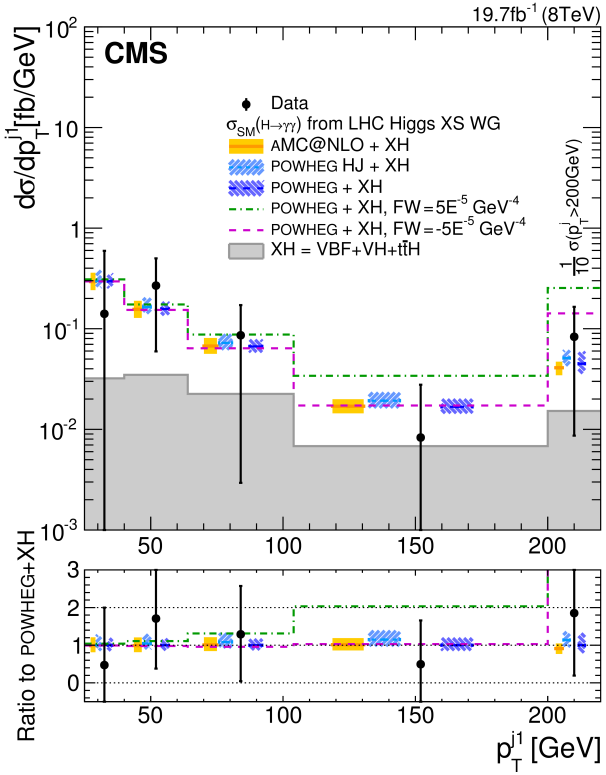



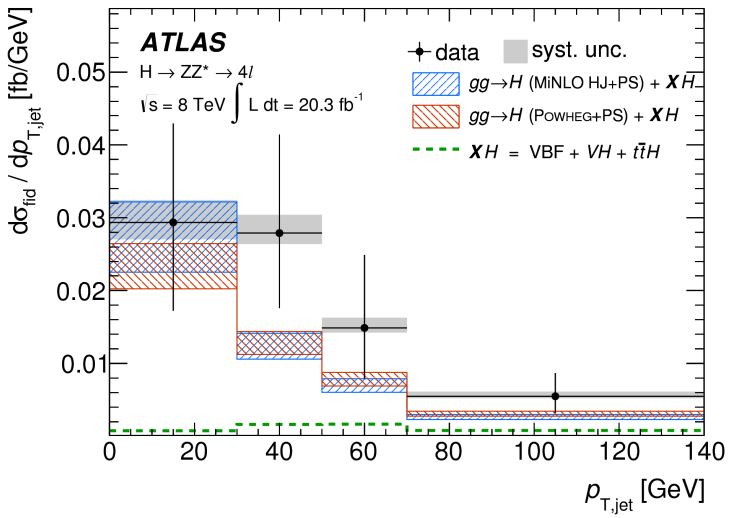



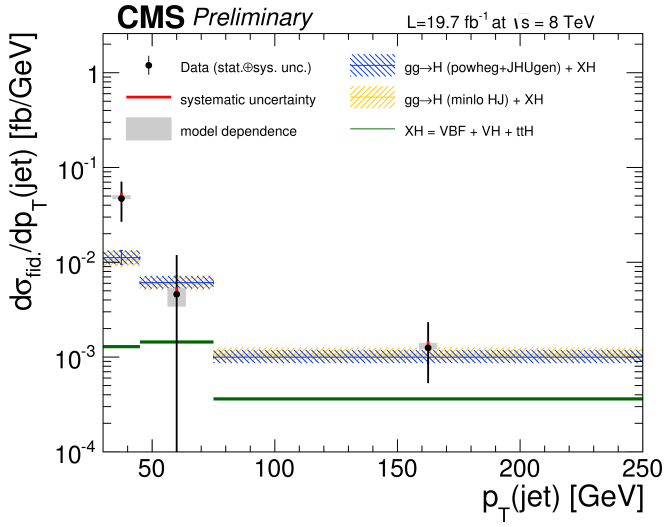
# Cross sections: Leading jet $p_T$.



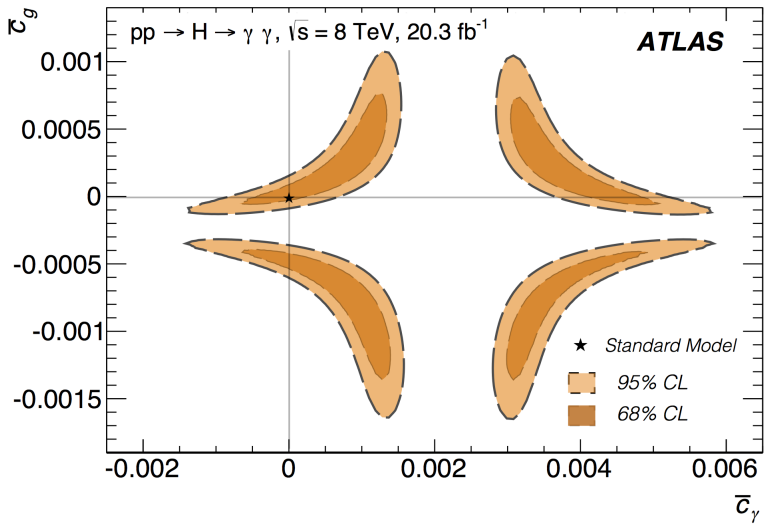



# Cross sections: ATLAS $H \to \gamma\gamma$ interpretation.

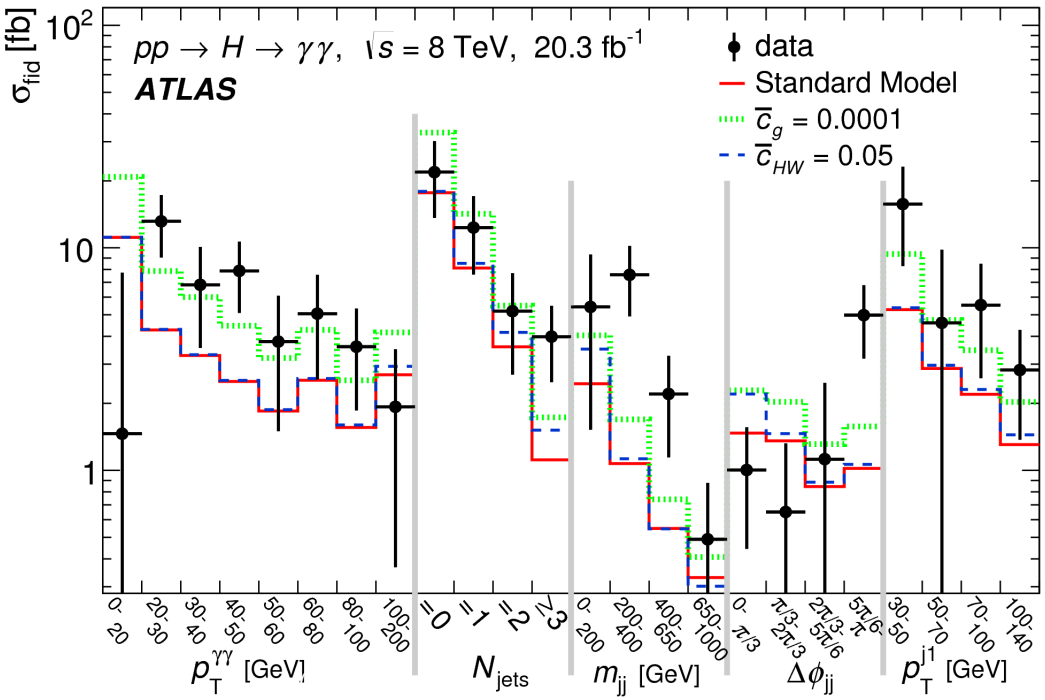
- Probe tensor structure and Higgs interactions
- Non-SM terms in effective Lagrangian describing Higgs–gauge boson interactions

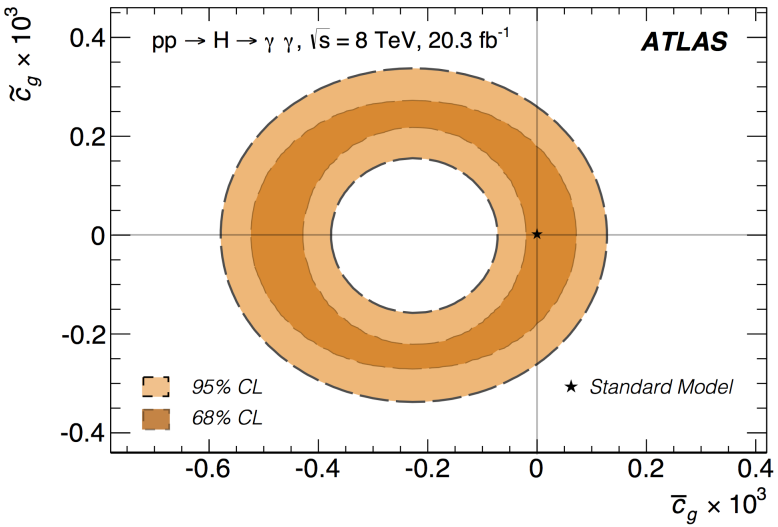
$$\mathcal{L} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O$$
$$+ \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}$$

[arXiv:1508.02507 [hep-ex]]




Based on 5 differential distributions:



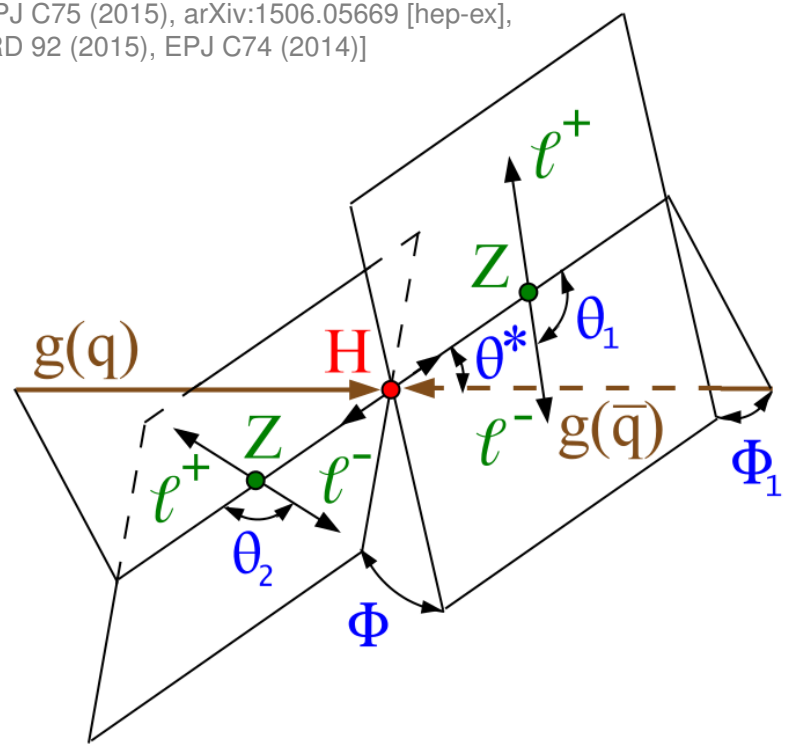



→ talk by Manuela Venturi

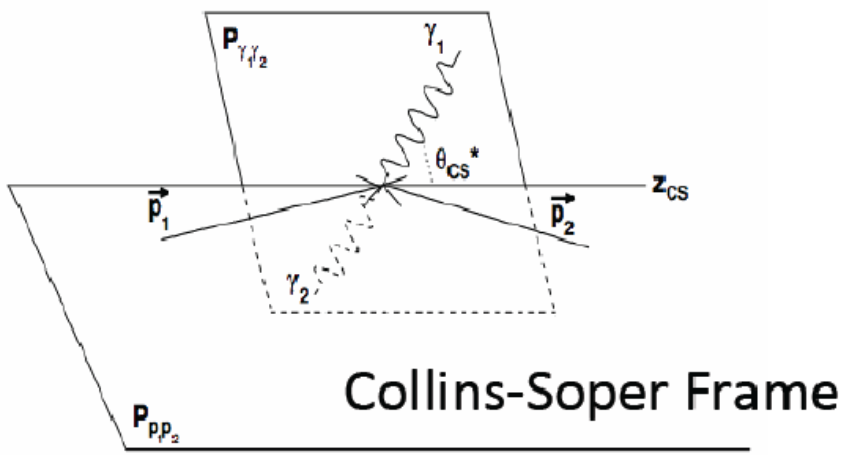
# Spin and CP tests at LHC.

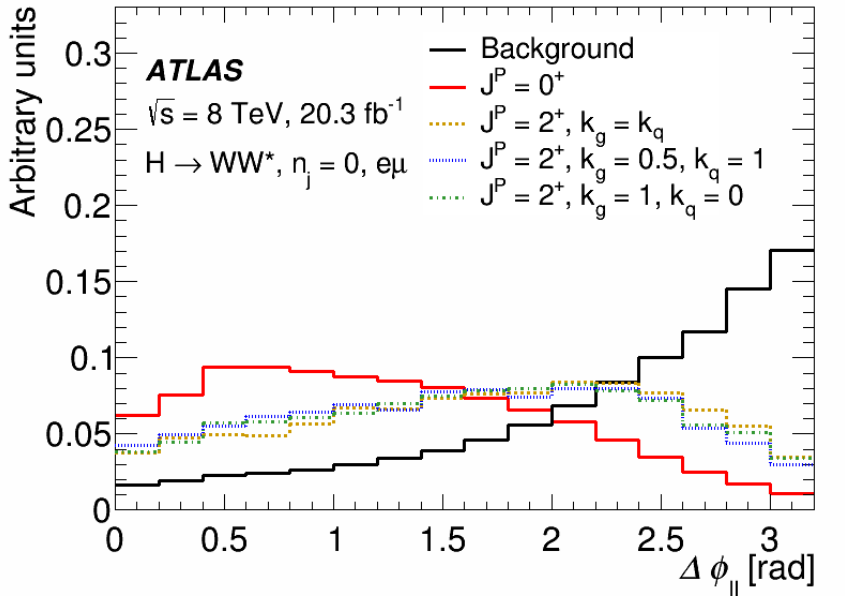
[EPJ C75 (2015), arXiv:1506.05669 [hep-ex], PRD 92 (2015), EPJ C74 (2014)]

- Observation of $H \to \gamma\gamma \Rightarrow J \neq 1$ (Landau-Yang theorem)
- Observation of $H \to WW^*/ZZ^*$ disfavors the $CP$-odd hypothesis (can occur through loops)




Spin and CP tests use angular and kinematic distributions in bosonic decays



# Spin and CP tests: Analyses.

## $H \to ZZ^*$

- Matrix-element based likelihood ratio (MELA) and BDT approaches to distinguish between different spin and parity hypotheses
- Separation of $H \to ZZ^*$ signal and $ZZ^*$ background through MELA or BDT discriminant

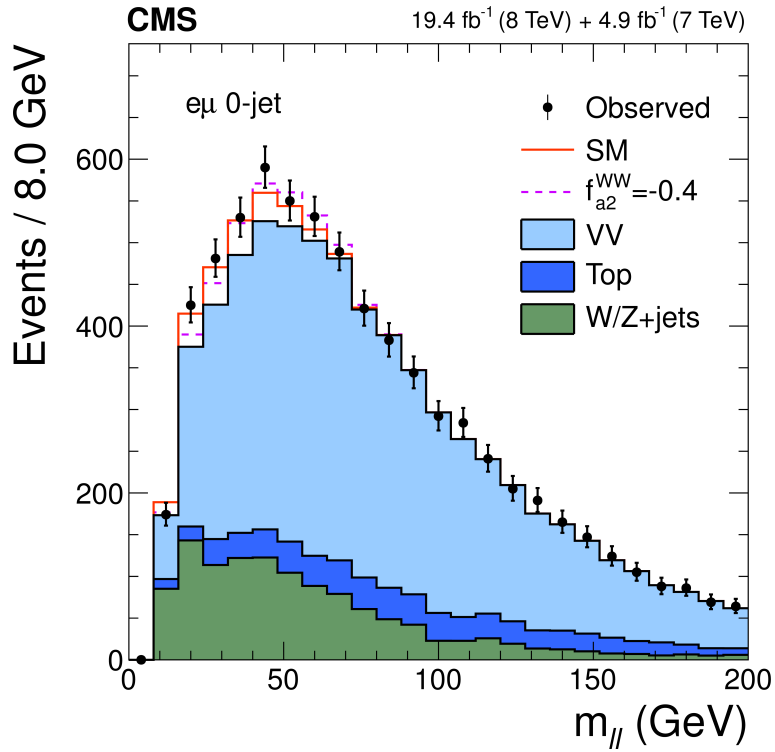
## $H \to WW^*$

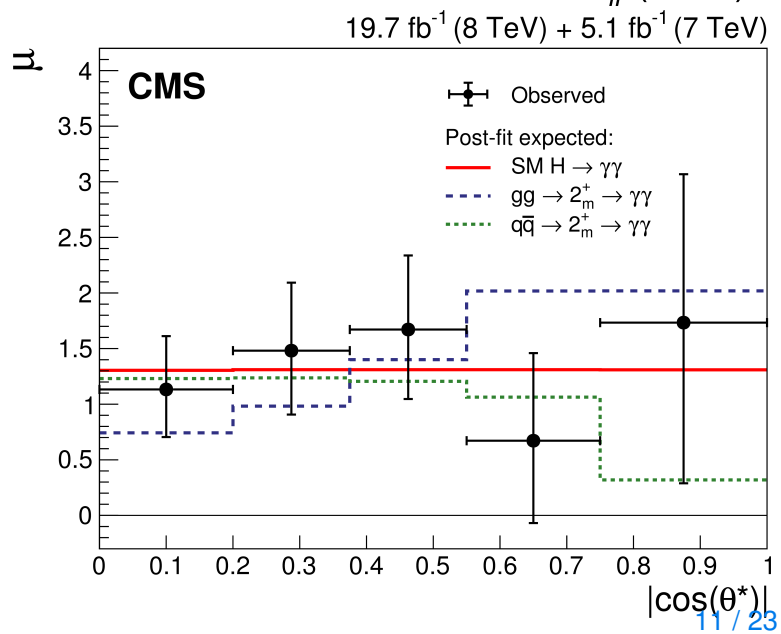
- Based on $m_{\ell\ell}$, $m_T$ (and $p_{T,\ell\ell}$, $\Delta\phi_{\ell\ell}$ in ATLAS, combined in a BDT)

## $H \to \gamma\gamma$

- Based on cos($\theta^*$) (and $p_T^{\gamma\gamma}$ in ATLAS)

Only based on shape information, no use of signal rates



# Spin and CP tests: Spin models.

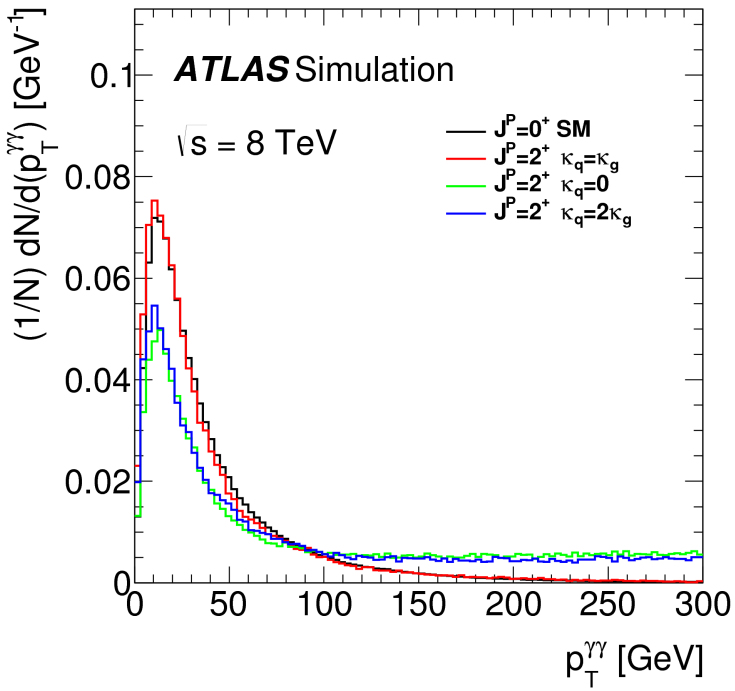
## Spin-2

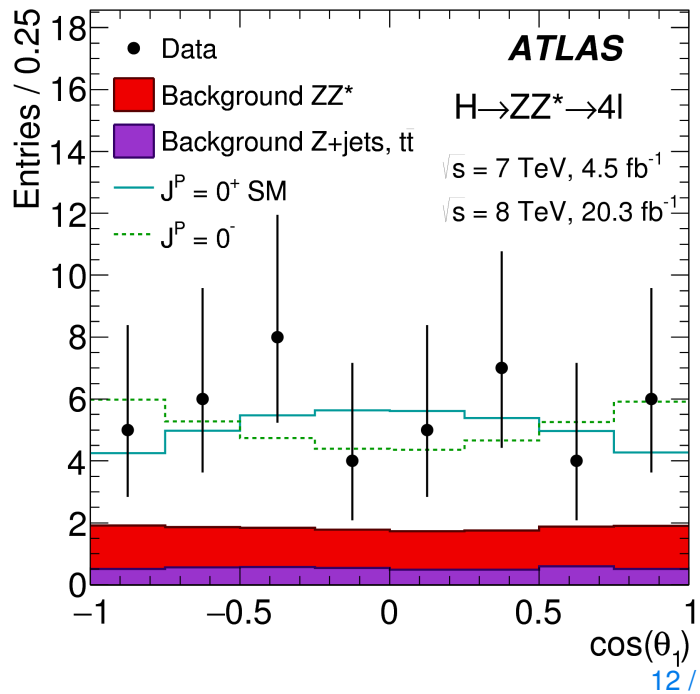
$$\mathcal{L}_2 = \frac{1}{\Lambda}\left(\sum_V \kappa_V X^{\mu\nu} T^V_{\mu\nu} + \sum_f \kappa_f X^{\mu\nu} T^f_{\mu\nu}\right)$$

- With universal couplings $\kappa_V = \kappa_f$
  - ⋆ Disfavored by observed Higgs BFs
- and non-universal couplings $\kappa_V \neq \kappa_f$
  - ⋆ Strong distortion of Higgs $p_T$
- Valid up to scale $\Lambda$
  - ⋆ ATLAS requires $p_T^X < 300$ GeV for non-universal coupling scenarios
- ATLAS considers also processes with emission of additional partons
- CMS considers also models with higher-order operators

## Spin-0

- Testing pure (fixed hypothesis) $0^-$ and non-SM $0^+$



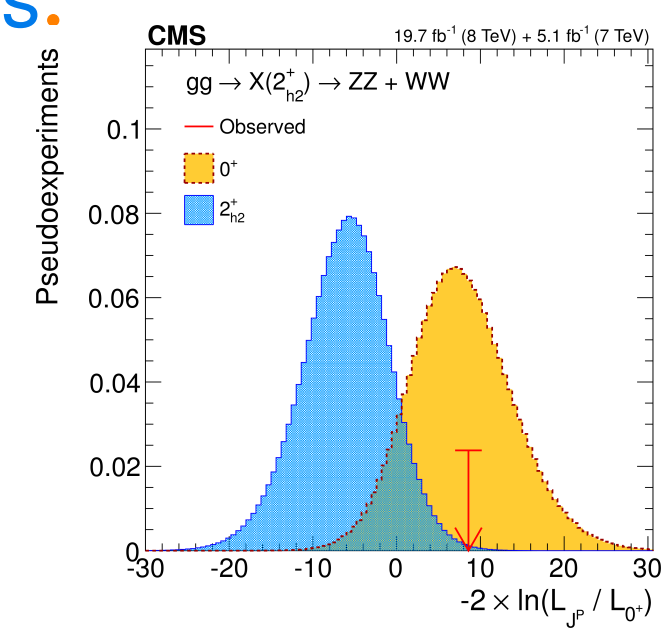



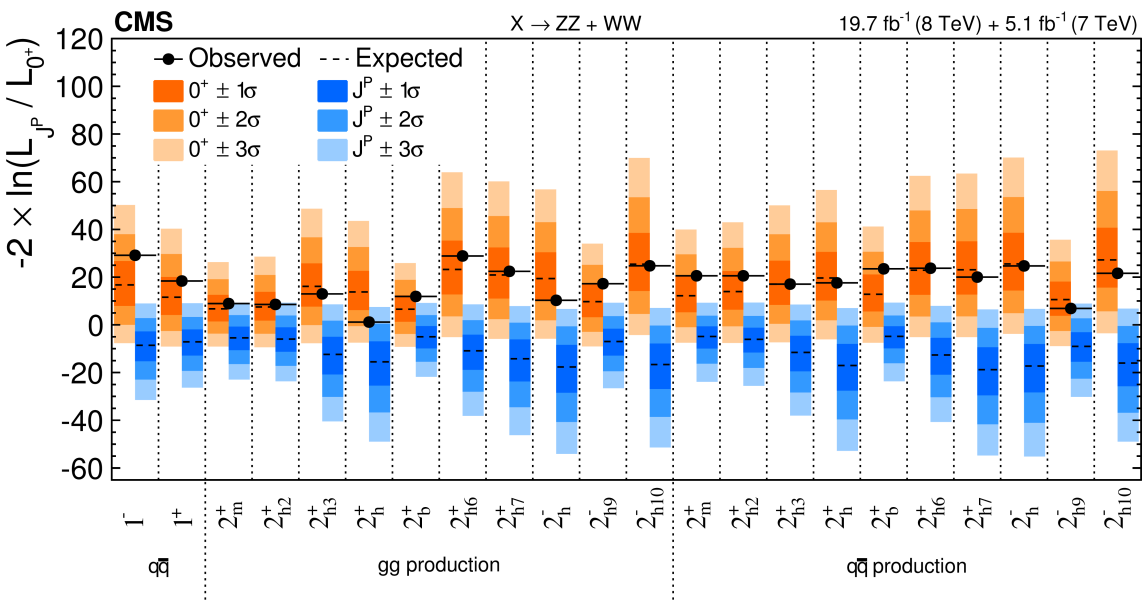
# Spin and CP tests: Fixed hypotheses.

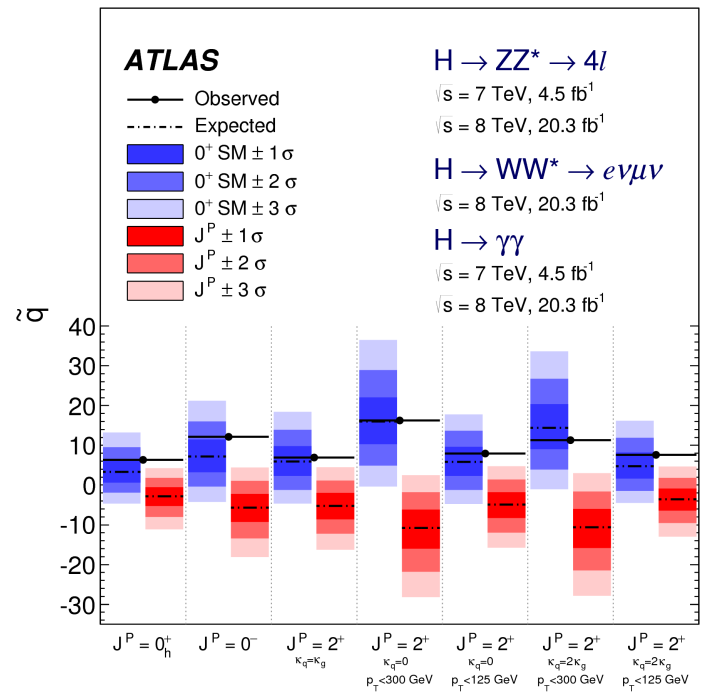
Combining information from $H \to ZZ^*$, $H \to WW^*$ (and $H \to \gamma\gamma$ in ATLAS)

- Testing alternative spin and CP hypotheses against SM $0^+$

Alternative tested $0^\pm$, $1^\pm$ and $2^\pm$ typically excluded at >99% CL



# Spin and CP tests: CP mixing ATLAS.

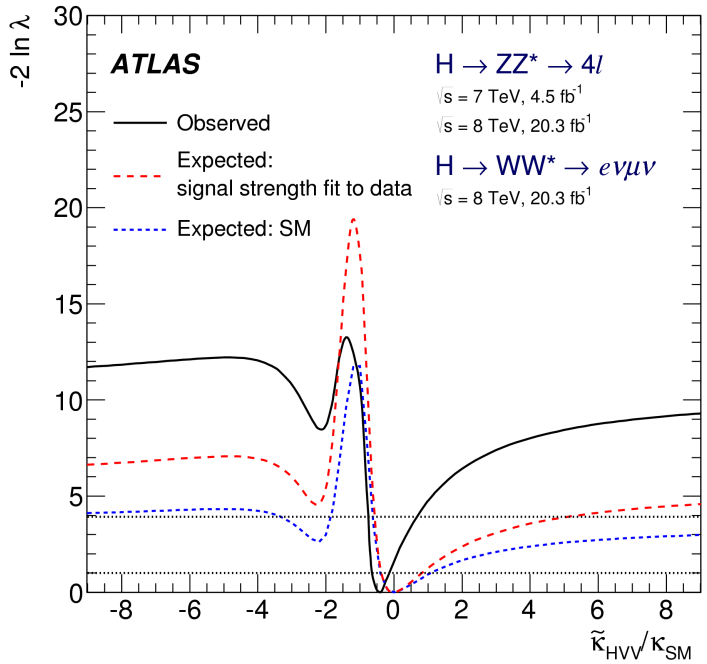
## SM $0^+$ and BSM $0^\pm$ Lagrangrian:

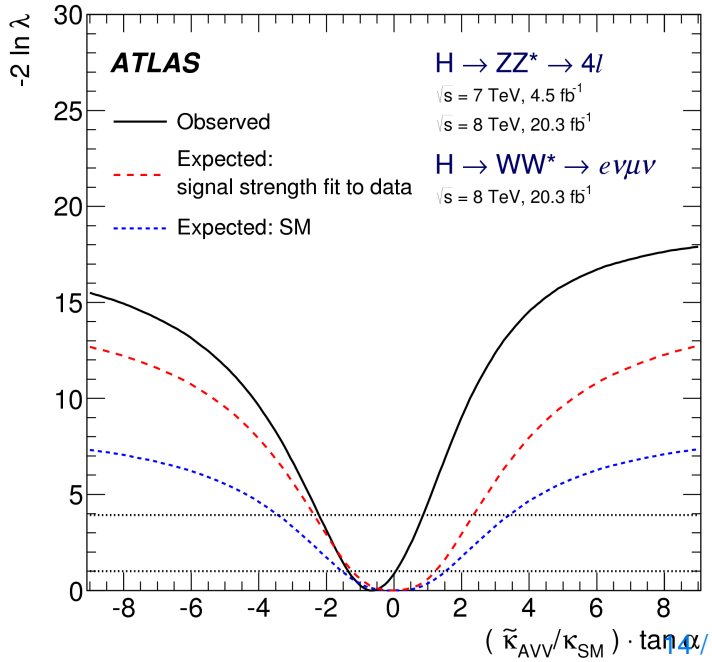
$$\mathcal{L}_0^V = \Big\{\cos(\alpha)\kappa_{\rm SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W_\mu^+ W^{-\mu}\right] - \tfrac{1}{4}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] - \tfrac{1}{2}\tfrac{1}{\Lambda}\left[\cos(\alpha)\kappa_{HWW}W_{\mu\nu}^+ W^{-\mu\nu} + \sin(\alpha)\kappa_{AWW}W_{\mu\nu}^+ \tilde{W}^{-\mu\nu}\right]\Big\} X_0$$

- Admixture of BSM $0^+$ and BSM $0^-$ tested separately
- Combination under the assumption of same admixture in $H \to ZZ^*$ and $H \to WW^*$

| Coupling ratio | Best-fit value | 95% CL Exclusion Regions | |
|---|---|---|---|
| Combined | Observed | Expected | Observed |
| $\tilde{\kappa}_{HVV}/\kappa_{\rm SM}$ | $-0.48$ | $(-\infty, -0.55] \bigcup [4.80, \infty)$ | $(-\infty, -0.73] \bigcup [0.63, \infty)$ |
| $(\tilde{\kappa}_{AVV}/\kappa_{\rm SM}) \cdot \tan\alpha$ | $-0.68$ | $(-\infty, -2.33] \bigcup [2.30, \infty)$ | $(-\infty, -2.18] \bigcup [0.83, \infty)$ |

No significant admixture of non-SM CP states



# Spin and CP tests: CP mixing CMS.

## Anomalous couplings (compatible with Lorentz and gauge invariance)

$$A(\mathrm{HVV}) \sim \left[ a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f^{*(1)}_{\mu\nu} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f^{*(1)}_{\mu\nu} \tilde{f}^{*(2),\mu\nu}$$

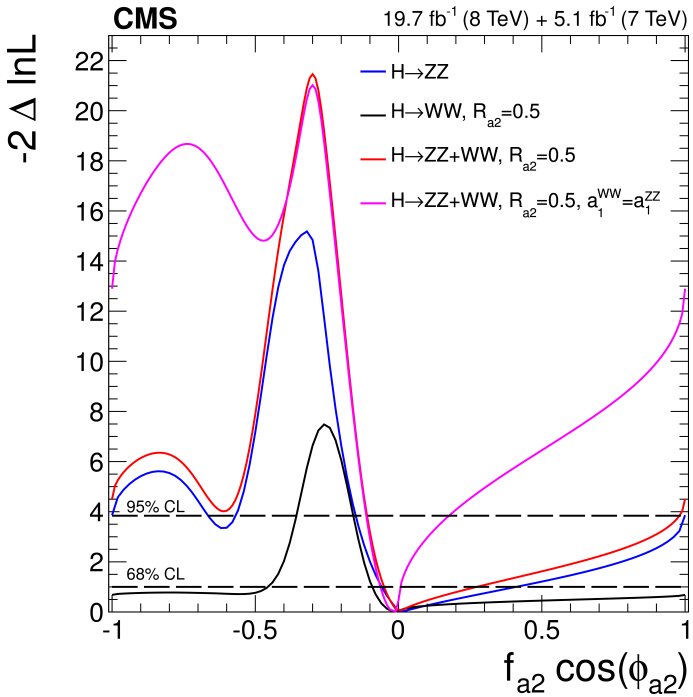
## Tested parameters

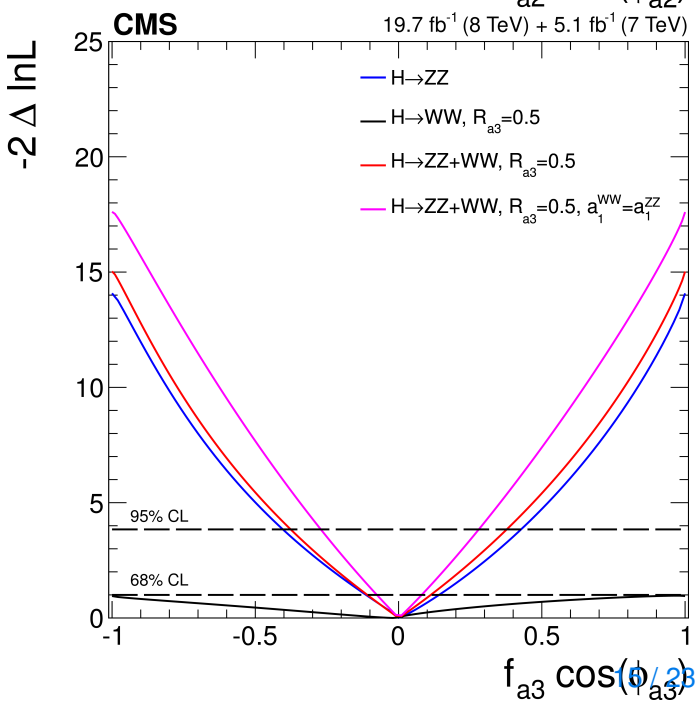
$$f_{a2} = \frac{|a_2|^2 \sigma_2}{|a_1|^2 \sigma_1 + |a_2|^2 \sigma_2 + |a_3|^2 \sigma_3 + \tilde{\sigma}_{\Lambda 1} / \left(\Lambda_1\right)^4 + \ldots}$$

$$\phi_{a2} = \arg\left(\frac{a_2}{a_1}\right)$$

## Combination of $H \to ZZ^*$ and $H \to WW^*$

$$r_{ai} = \frac{a_i^{\mathrm{WW}} / a_1^{\mathrm{WW}}}{a_i / a_1}, \text{ or } R_{ai} = \frac{r_{ai} |r_{ai}|}{1 + r_{ai}^2}$$



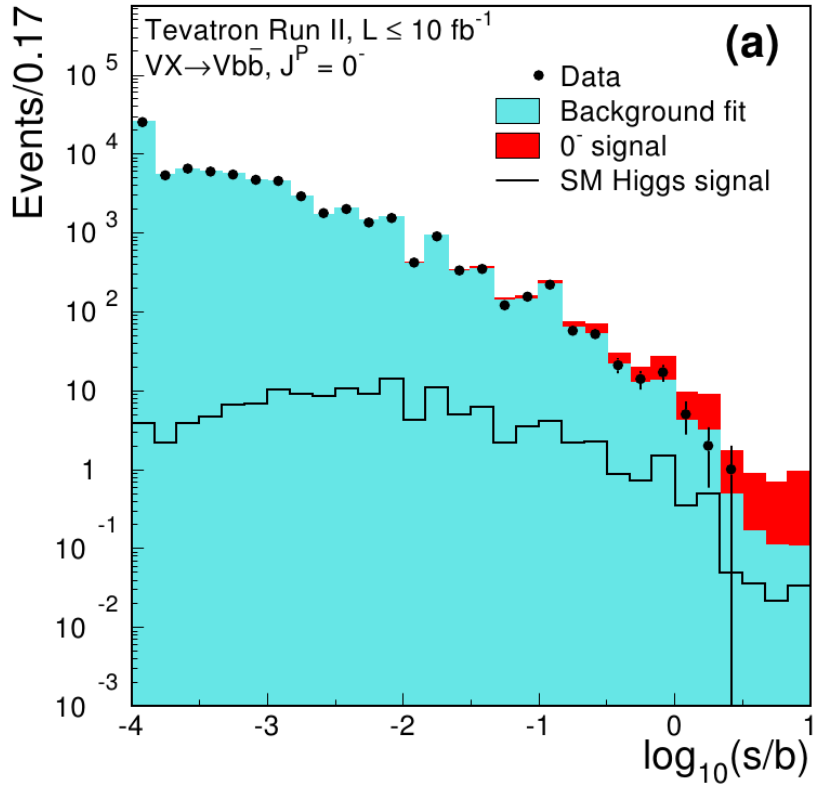
→ talk by Federico Sforza

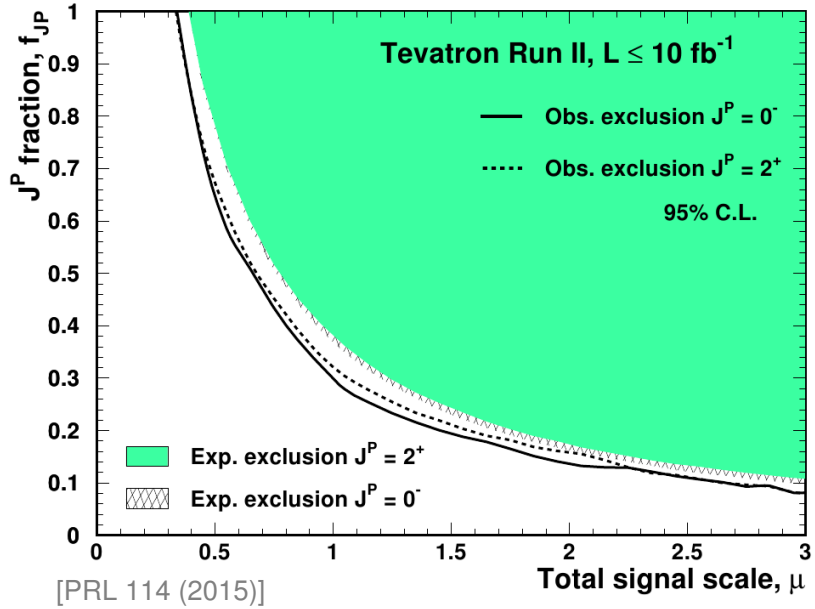
# Spin and CP tests at Tevatron.

## $VH(\to b\bar{b})$

- Kinematic distributions (such as $p_T^V$ and $m_{VH}$) distorted for the tested $J^P = 0^-$ and $2^+$ models
  - ⋆ Differential production rate at threshold $\propto \beta$ / $\beta^3$ / $\beta^5$ for SM / $0^-$ / $2^+$ ($\beta = 2p^V/\sqrt{\hat{s}}$, $\sqrt{\hat{s}} = VH$ energy, all in $VH$ rest frame)
- Analysis based on MVA discriminant (CDF) and $m_{VH}$ (D0)
- Best fit: SM with no exotic admixture

$J^P = 0^-$ ($2^+$) excluded with $5\,\sigma$ ($4.9\,\sigma$) assuming SM production cross section × BF



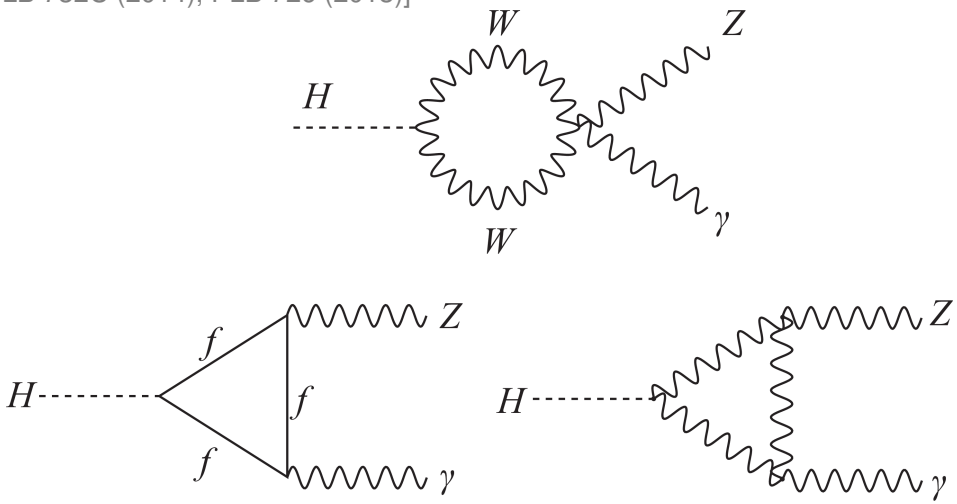

[PRL 114 (2015)]

→ talk by Yuta Takahashi

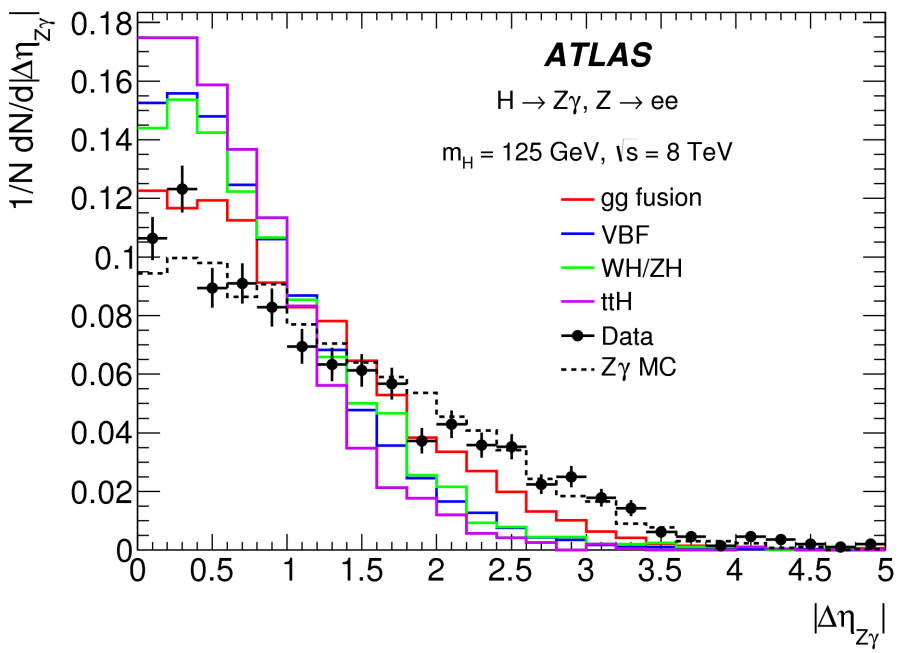
# Rare decays: $H \to Z\gamma$.

[PLB 732C (2014), PLB 726 (2013)]

SM: BF($H \to Z\gamma$)= 0.16%



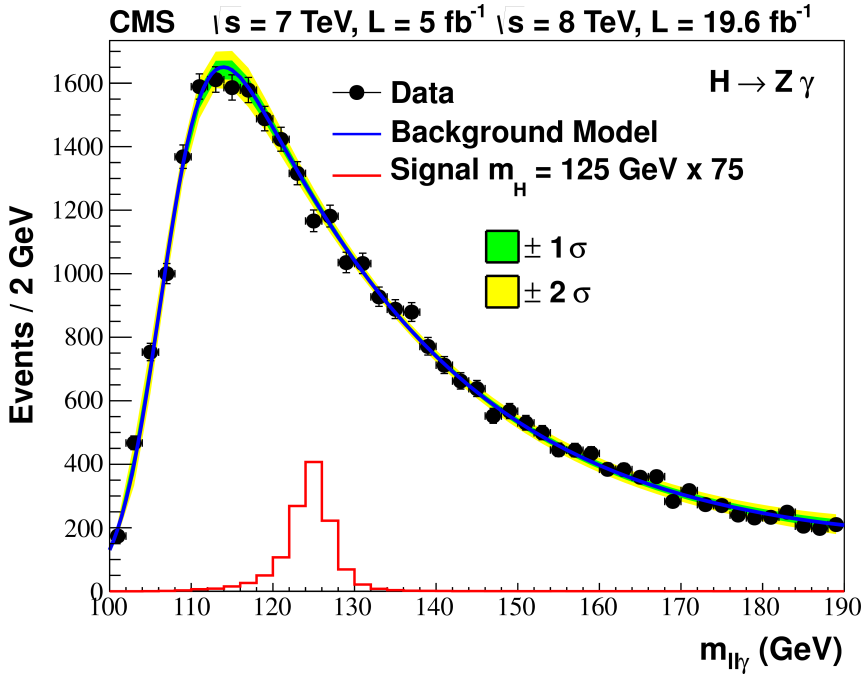

- $H \to Z\gamma$ could be enhanced e.g. from new particles in the loop
  - ⋆ ...although careful parameter tuning often needed to enhance expected signal beyond $\sim 2\times$SM
- Low event yield due to $BR(Z \to \ell\ell) \sim 6.7\%$, $Z \to \ell\ell$ used to enhance S/B
- Signature: 2 same-flavor, opposite-sign isolated leptons ($p_T^\ell >$10-20 GeV, $m_{\ell\ell} \sim m_Z$), 1 isolated photon ($p_T^\gamma >\sim$15 GeV)
- Categorized analysis assuming SM-like Higgs
  - ⋆ $Z$ and $\gamma$ kinematics (and dijet events in CMS)

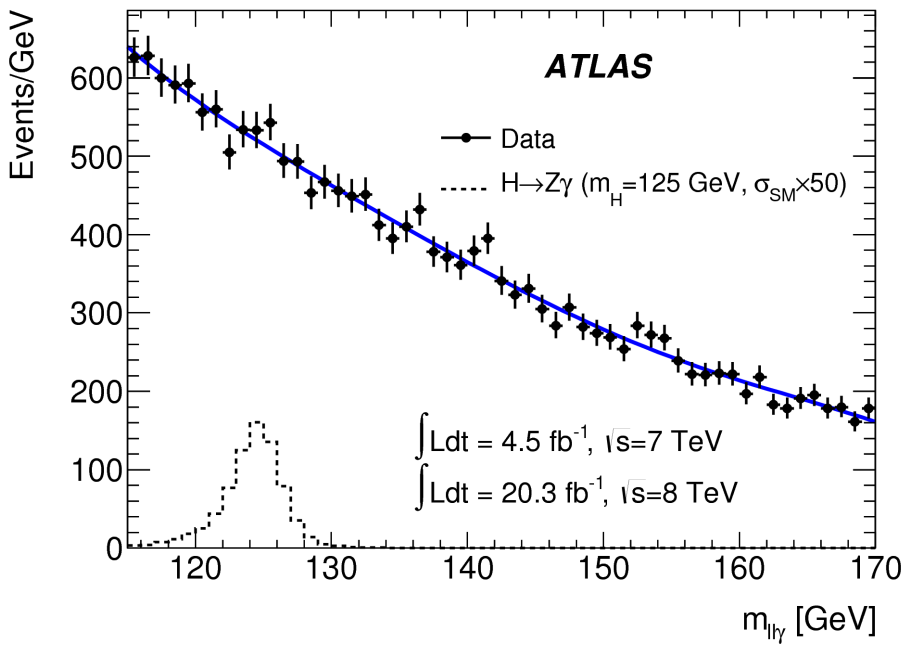



20-40% sensitivity gain from event categorization

# Rare decays: $H \to Z\gamma$.

- Large backgrounds from SM $Z\gamma$ and $Z$+jets (S/B$\sim$0.3%)
- Good $m_{\ell\ell\gamma}$ resolution, $\sigma(m_{\ell\ell\gamma})/m_{\ell\ell\gamma}$ $\sim$1.5%
- Signal+background fit to $m_{\ell\ell\gamma}$ spectrum




$<$9.5$\times$SM @ 95% CL
at $m_H$ =125 GeV
(expected $<$ 10$\times$SM)

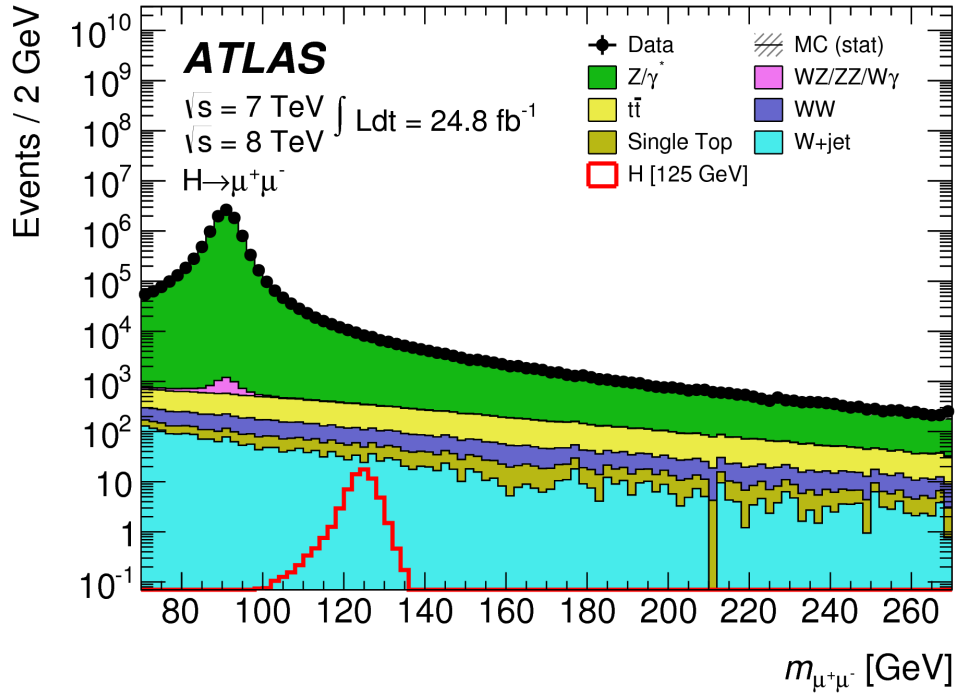
$<$11$\times$SM @ 95% CL
at $m_H$ =125.5 GeV
(expected $<$ 9$\times$SM)

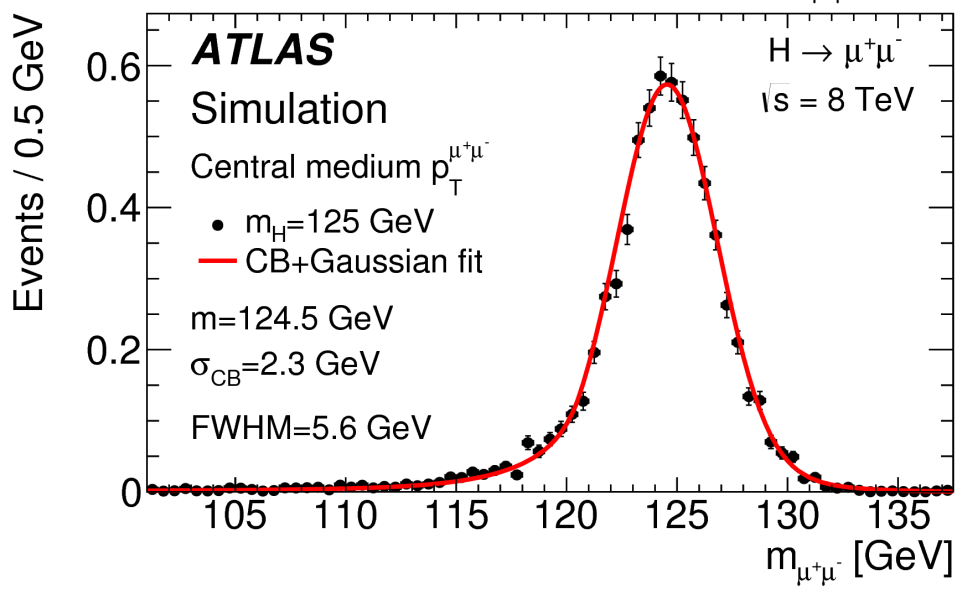
# Rare decays: $H \to \mu\mu$.

[PLB 738 (2014), PLB 744 (2015)]

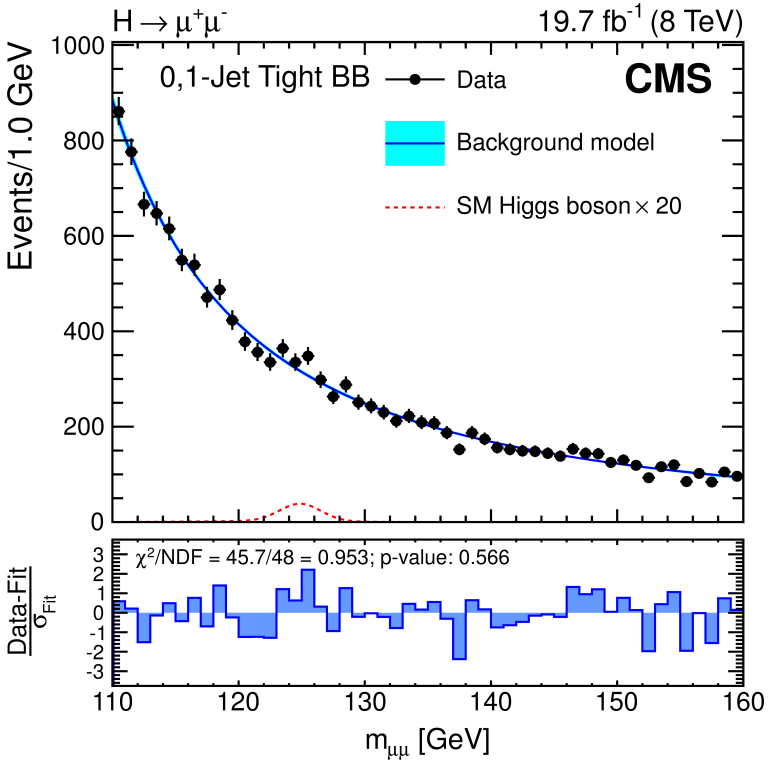
SM: BF($H \to \mu\mu$)= 0.02%

- Clean probe of Higgs couplings to 2nd generation fermions
- Signature: 2 opposite-sign, isolated muons ($p_T^{\mu}$ >25,15 GeV)
- Large background from $Z/\gamma^* \to \mu\mu$, smaller contributions from $t\bar{t}$, $WW$, ... (S/B∼0.4%)
- Good $m_{\mu\mu}$ resolution $\sigma(m_{\mu\mu})/m_{\mu\mu}$ ∼1.5-2.5%
- Categorized analysis assuming SM-like Higgs
  - ⋆ Muon kinematics ($p_T^{\mu\mu}$, $|\eta^{\mu}|$) and dijet categories (VBF)

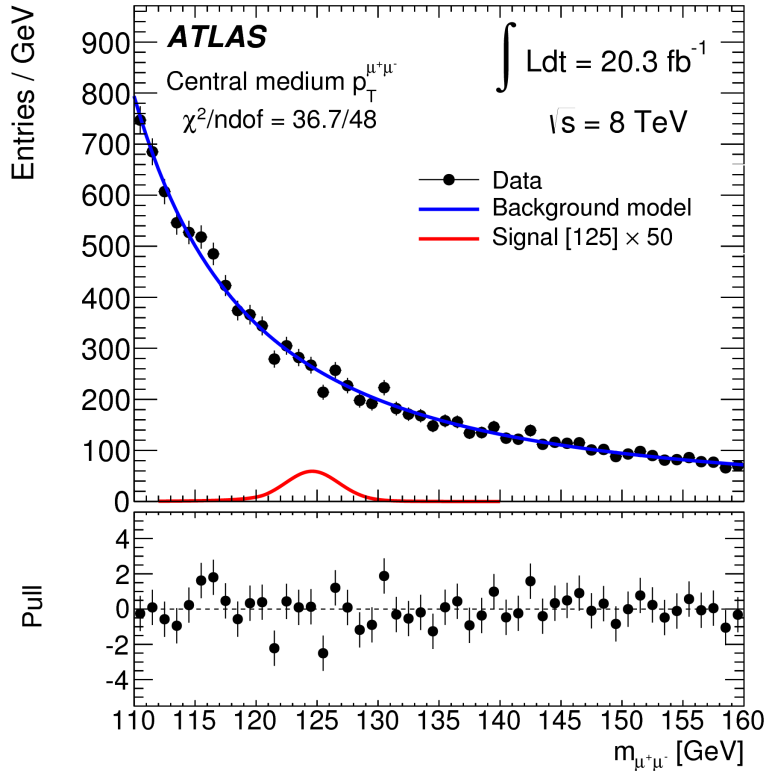


# Rare decays: $H \to \mu\mu$.




$<7.4\times$SM @ 95% CL
(BR($H \to \mu\mu$) $<1.6\times10^{-3}$)
at $m_H$ =125 GeV
(expected $< 6.5\times$SM)




$<7.0\times$SM @ 95% CL
(BR($H \to \mu\mu$) $<1.5\times10^{-3}$)
at $m_H$ =125.5 GeV
(expected $< 7.2\times$SM)

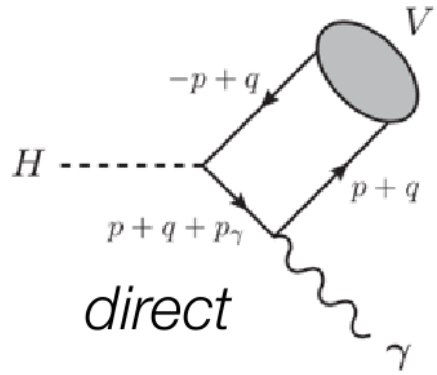
Similar search for $H \to ee$ (CMS 8 TeV data) yields BR($H \to ee$) $<1.9\times10^{-3}$

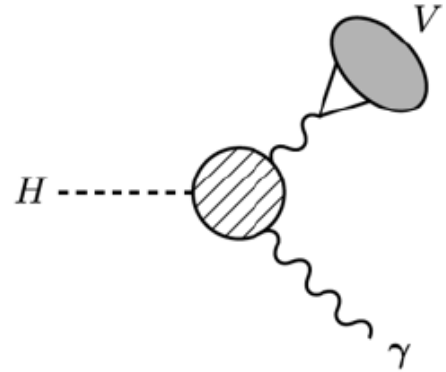
$\to$ Higgs boson couplings are not flavor universal:
$H \to \tau\tau$ decay confirmed by experiments (SM BF($H \to \tau\tau$)= 6.3%)

# Rare decays: $H \to J/\psi\gamma$.

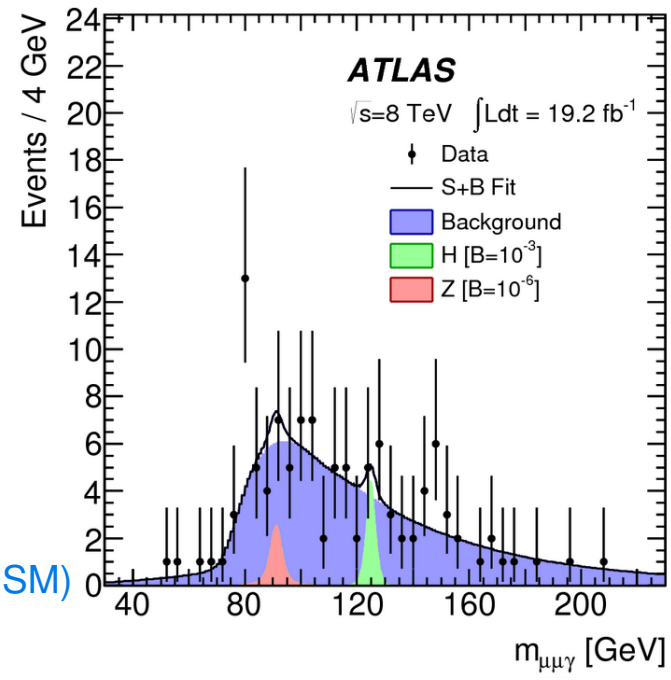
[PRL 114 (2015)]

SM: BF($H \to J/\psi\gamma$) $= 2.8 \times 10^{-6}$




- Interference between large indirect production and small direct production gives access to sign of Higgs–charm coupling
  - ⋆ Theoretically clean (SM BR predicted with few-% uncertainties)
- Signature: 2 opposite-sign same-flavor isolated muons ($p_T^\mu$ >20 GeV) with $|m_{\mu\mu} - m_{J/\psi}|$ <0.15(0.2) GeV, 1 isolated photon ($p_T^\gamma$ >36 GeV)
- Main background from $J/\psi$ + jet→ $\gamma$ misidentification
- Events categorized based on $|\eta^\mu|$ and converted/unconverted $\gamma$
- Simultaneous fit to $m_{\mu\mu\gamma}$ and $p_T^{\mu\mu\gamma}$




BR($H \to J/\psi\gamma$) <1.5×10$^{-3}$ @ 95% CL (540×SM)
(exp. <1.2×10$^{-3}$)

# Rare decays: $H \to \gamma^*\gamma \to \ell\ell\gamma$.

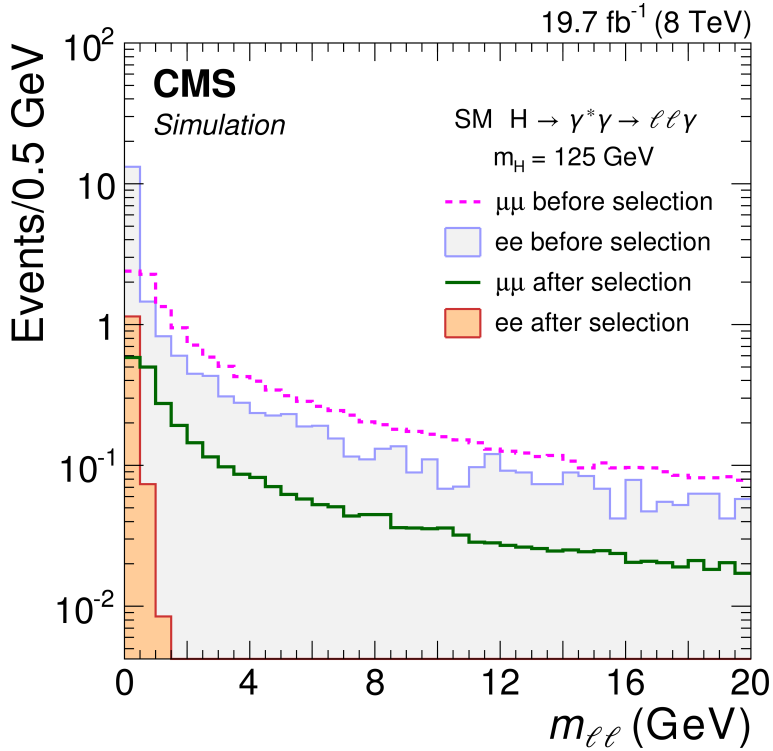
[arXiv:1507.03031 [hep-ex]]

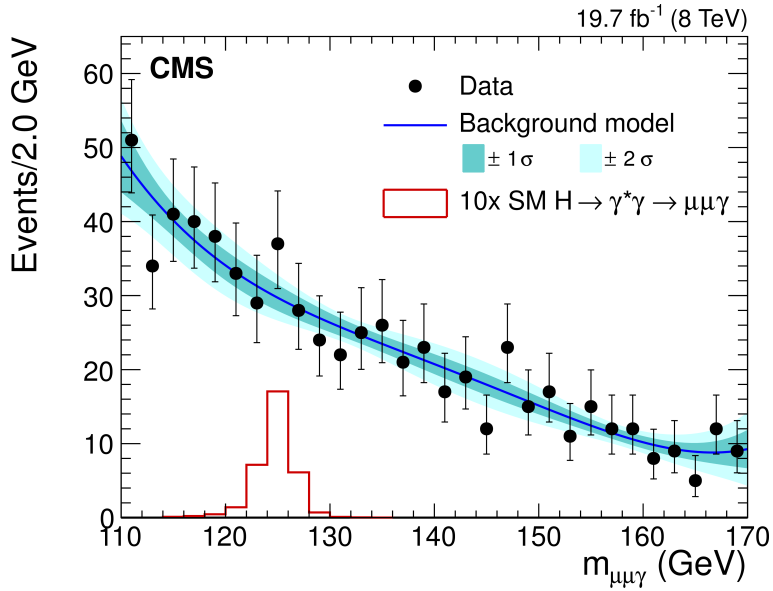
- Non-trivial angular distributions and forward-backward asymmetry in 3-body decay $H \to \ell\ell\gamma$ allow for interesting property measurements

- Signature: 2 opposite-sign same flavor leptons ($m_{\mu\mu(ee)}$ <20 (1.5) GeV, veto $J/\psi$ and $\Upsilon$), 1 isolated photon ($p_T^\gamma > 0.3 m_{\ell\ell\gamma}$)
  - ⋆ $m_{\ell\ell}$ and $p_T^\gamma$ cuts suppress $H \to Z\gamma$
  - ⋆ Select $m_{\mu\mu}$ close to $J/\psi$ mass for $H \to J/\psi\gamma$, $p_T^\gamma$ >40 GeV

BR($H \to \gamma^*\gamma \to \ell\ell\gamma$) <7.7×SM @ 95% CL (exp. 6.4×SM)

BR($H \to J/\psi\gamma$) <1.5×$10^{-3}$ @ 95% CL



# Summary.

- Run1 dataset allowed for already quite detailed property studies of the Higgs boson, 3 years after the discovery
- Measurements of Higgs boson production and decays consistent with SM predictions within the present uncertainties
  - ★ (Almost) model independent measurements of fiducial and differential cross section, limited by statistical uncertainties
  - ★ SM $J^P = 0^+$ preferred, all other tested Spin/CP fixed hypotheses strongly disfavored
  - ★ Still room for CP mixing, limits on BSM $0^-$ and $0^+$ admixtures
  - ★ Set limits on rare decays, no evidence of $H \to \mu\mu$ confirms that coupling to leptons is not flavor universal
- Run2 will allow for more detailed property measurements and ensure an exciting Higgs physics program