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Search for rare Higgs decays and production of the di-Higgs boson at CMS

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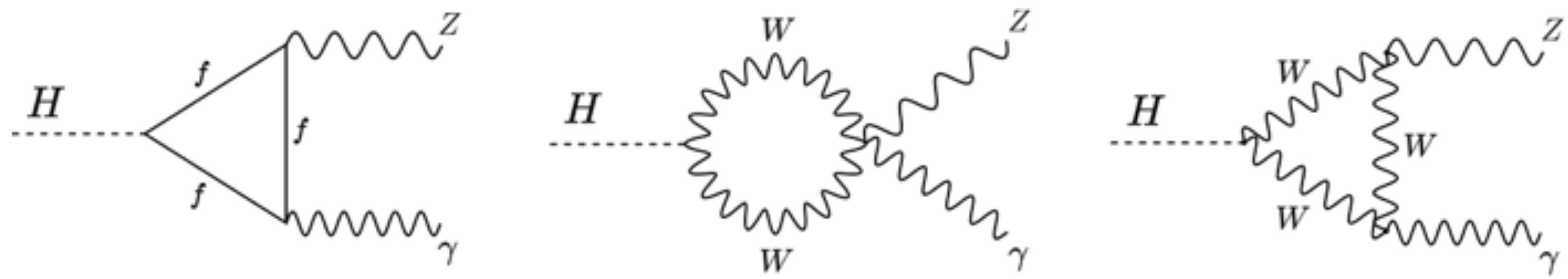
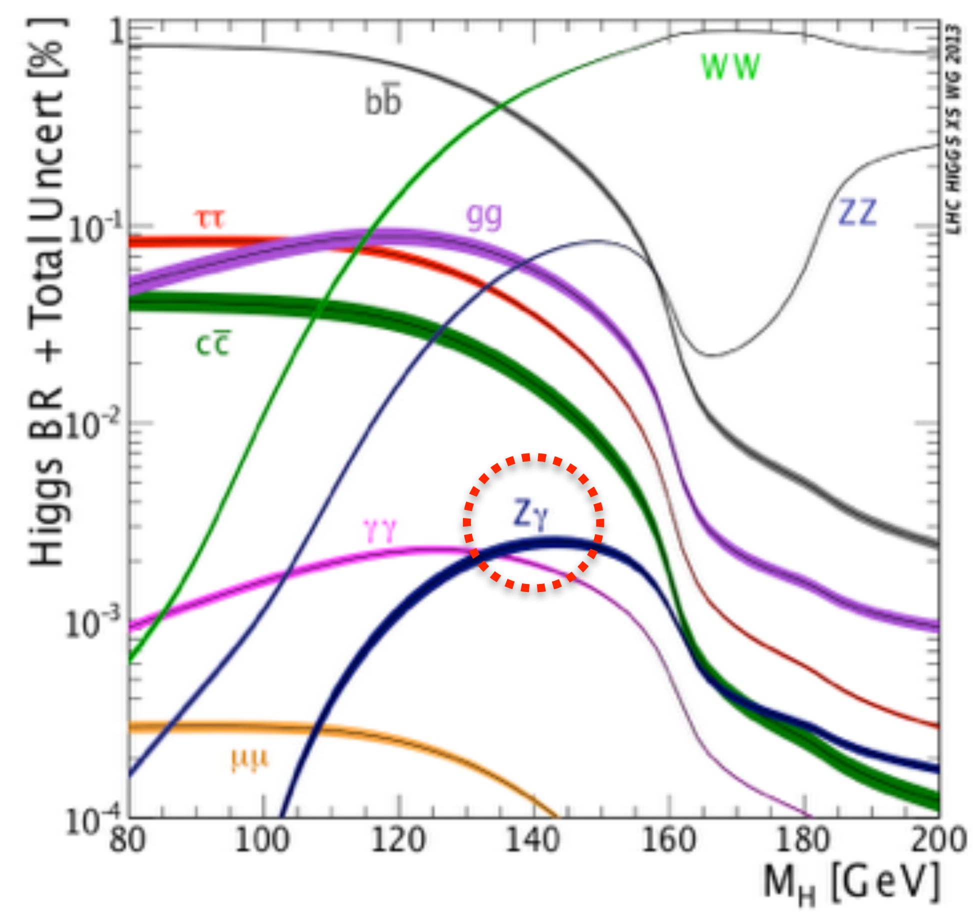
$H \to Z\gamma$

$BR(H \to Z\gamma) = 1.6 \times 10^{-3}$



- Within the SM, the partial width ($\Gamma_{Z\gamma}$) for the $H \to Z\gamma$ decay channel is rather small, resulting in a BR between 0.11% and 0.25% in 120-160 GeV
- The measurement of $\Gamma_{Z\gamma}$ provides important information on the underlying dynamics of the Higgs sector because it is induced by loops of heavy charged particles, just as $H \to \gamma\gamma$



$H \rightarrow Z\gamma$

- $\Gamma_{Z\gamma}$ is sensitive to physics beyond SM, and could be substantially modified by new charged particles without affecting the gluon-gluon fusion Higgs boson production cross section [1], such as derived from an extended Higgs sector [2], or by the presence of new scalars [3,4]

[1] M. Carena, I. Low, and C.E.M. Wagner, JHEP 8 (2012) 60
[2] C.-W. Chiang and K. Yagyu, PRD 87 (2013) 33003
[3] I. Low, J. Lykken, and G. Shaughnessay PRD 84 (2011) 35027
[4] C.-S.Chen, C.-Q. Geng, D. Huang, and L.-H.Tsai, PRD 87 (2013) 75019

$H \to Z\gamma$

- We look for $H \to Z\gamma$ with the Z boson decaying into an electron or a muon pair
- A clean final-state with good mass resolution (~1-3%)
- leading/trailing lepton $p_T > 20/10$ GeV, $p_T^{\gamma} > 15$ GeV
- $|\eta^{\gamma}| < 2.5$, but excluding the ECAL barrel-endcap transition region, $|\eta^{e}| < 2.5$ and $|\eta^{\mu}| < 2.4$
- $m_{ll} > 50$ GeV, $\Delta R(l, \gamma) > 0.4$
- $p_T^{\gamma}/m_{ll\gamma} > 15/110$ to suppress Z+jets
- $m_{ll} + m_{ll\gamma} > 185$ GeV
- $p_T^{jet} > 30$ GeV and $|\eta^{jet}| < 4.7$
- Zeppenfeld $\eta_{Z\gamma} - (\eta_{j1} + \eta_{j2})/2$
- $\Delta\eta jj > 3.5$, $\Delta\Phi(Z\gamma, jj) > 2.4$

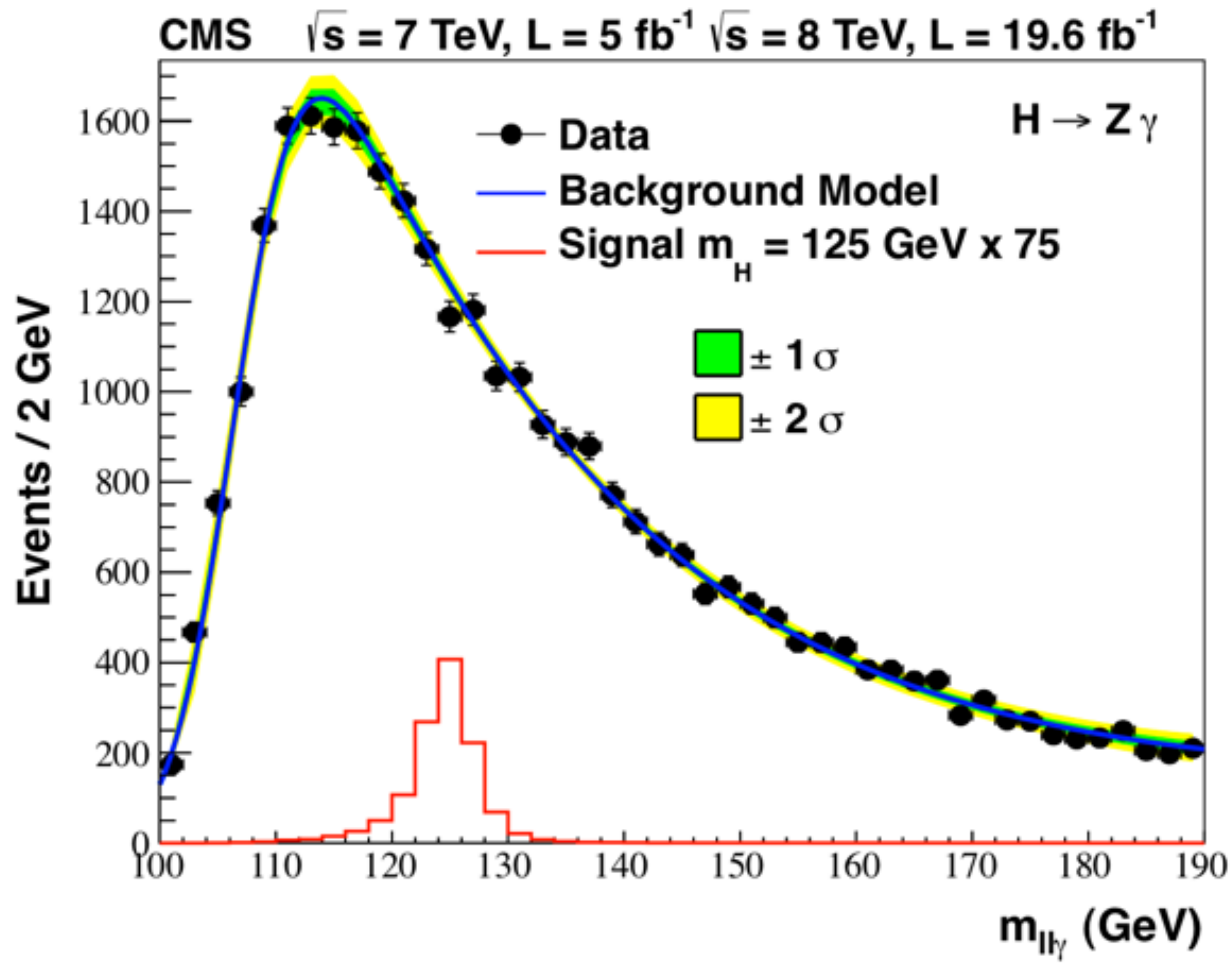
VBF dijet tag

Table 1: Observed and expected event yields for a 125 GeV SM Higgs boson.

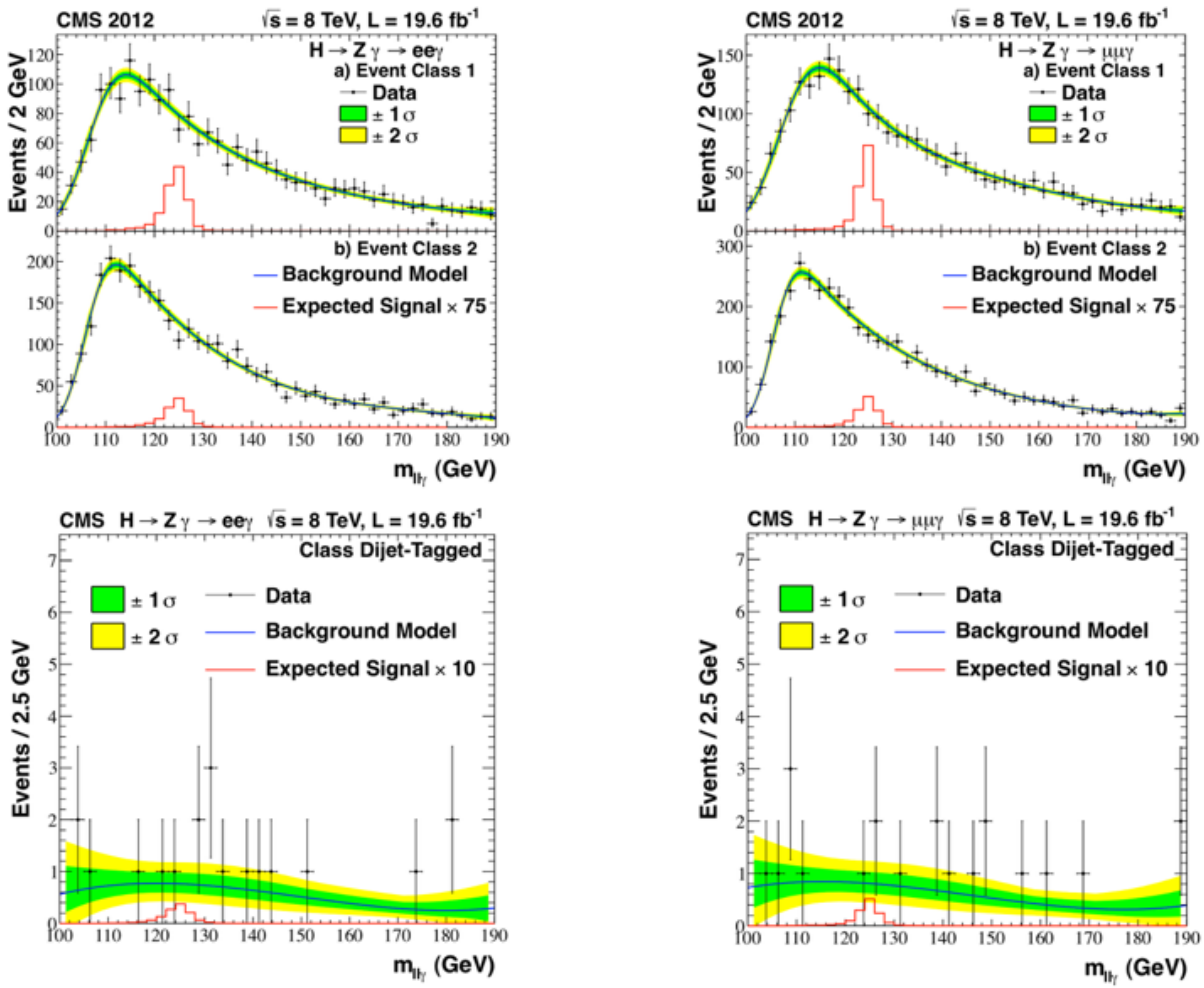
Sample	Integrated luminosity (fb^{-1})	Observed event yield for $100 < m_{\ell\ell\gamma} < 190$ GeV	Expected number of signal events for $m_H = 125$ GeV
2011 ee	5.0	2353	1.2
2011 $\mu\mu$	5.1	2848	1.4
2012 ee	19.6	12899	6.3
2012 $\mu\mu$	19.6	13860	7.0

- Signal yield is similar to $H \to ZZ \to 4l$ at 125 GeV
- Background processes :
  - SM Z+γ associated production
  - SM Z+jets where jet fakes photon

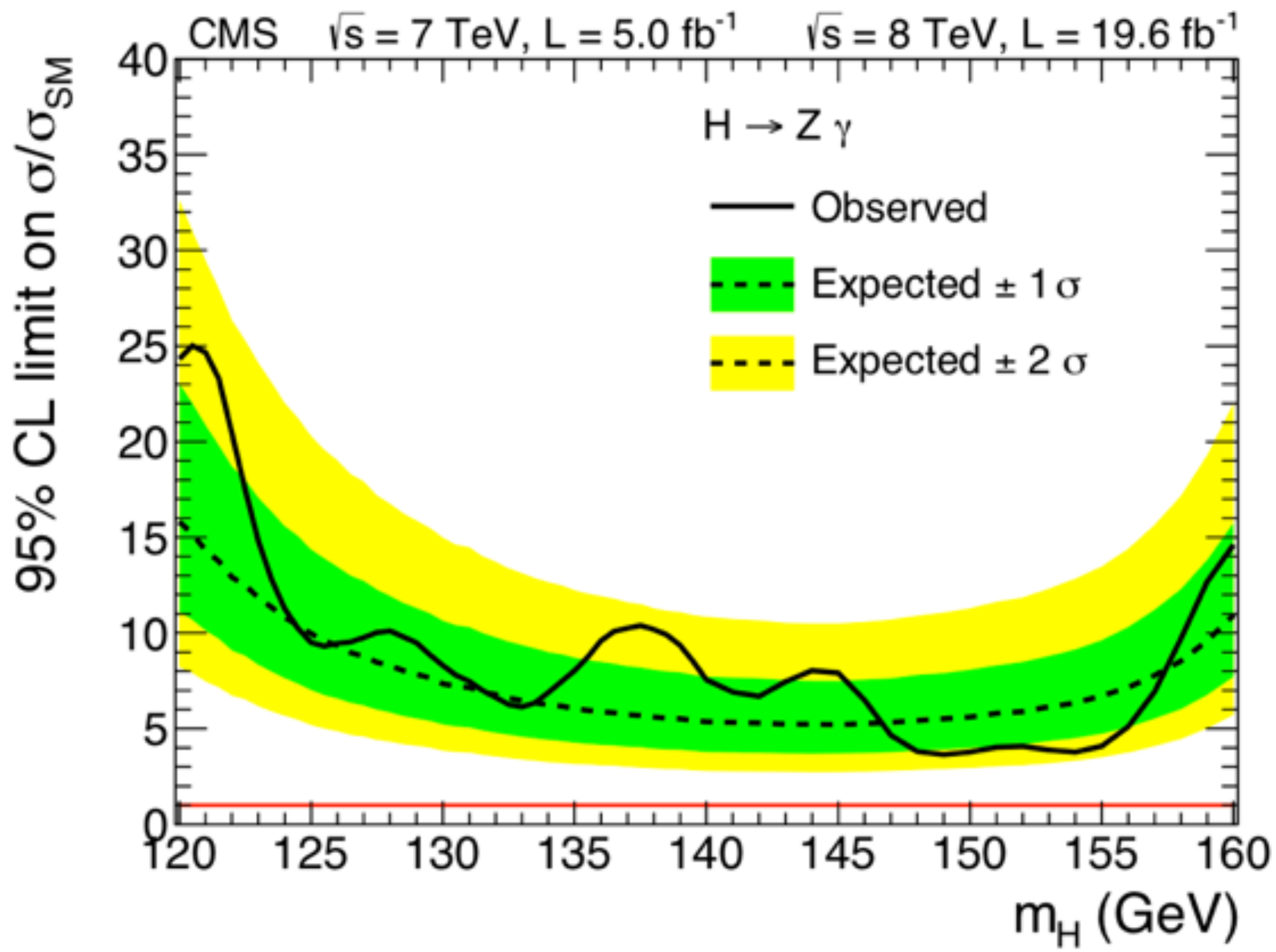
H→Zγ mass spectrum



H→Zγ Background and signal modeling

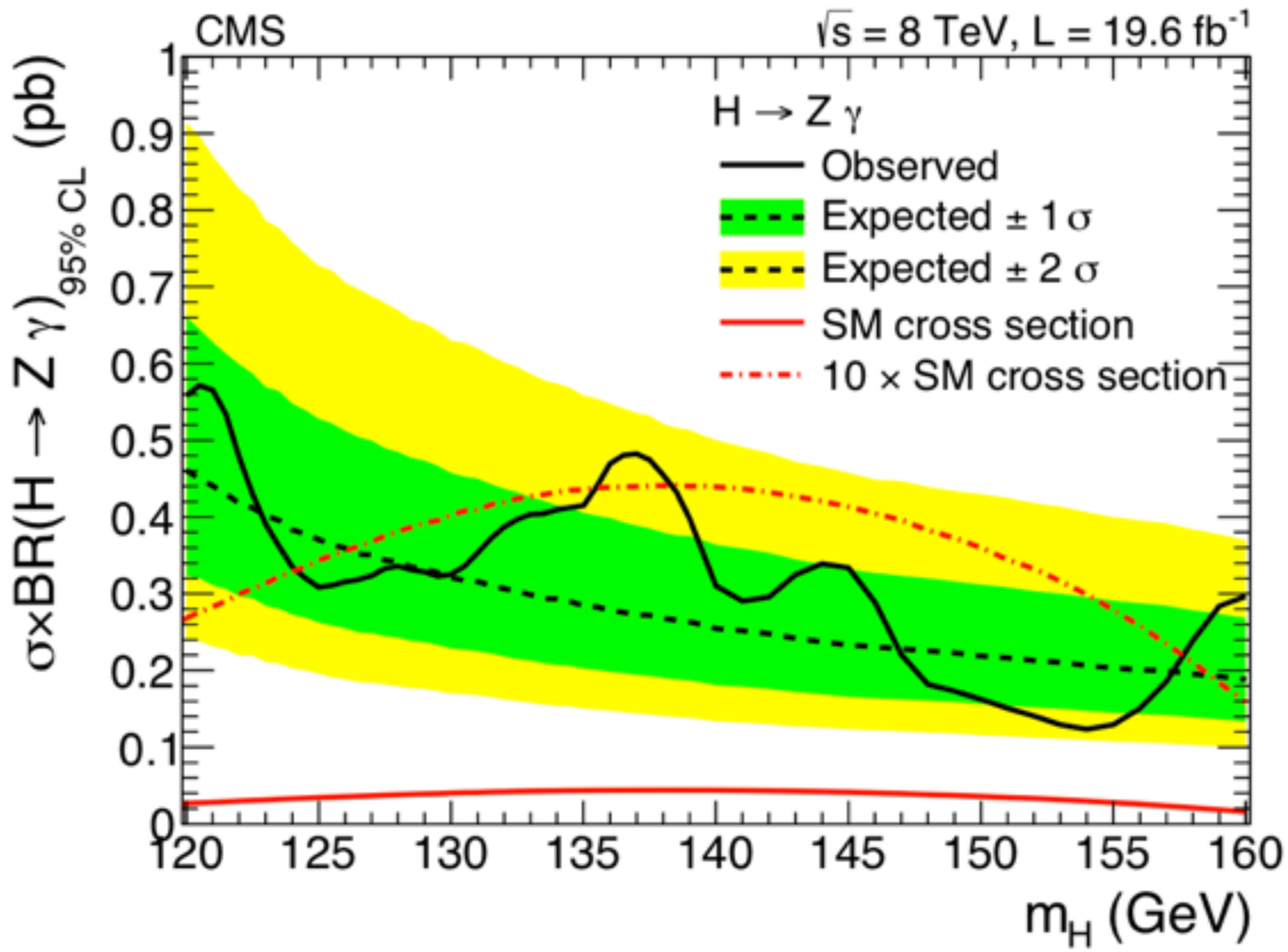


$H \rightarrow Z\gamma$ limits



- the observed and expected limits for $m_{ll\gamma}$ at 125 GeV are within one order of magnitude of the SM prediction
- Future sensitivity of ATLAS : 2.3σ (300/fb), 3.9σ (3000/fb) [ATL-PHYS-PUB-2014-006]

$H \to Z\gamma$ limits

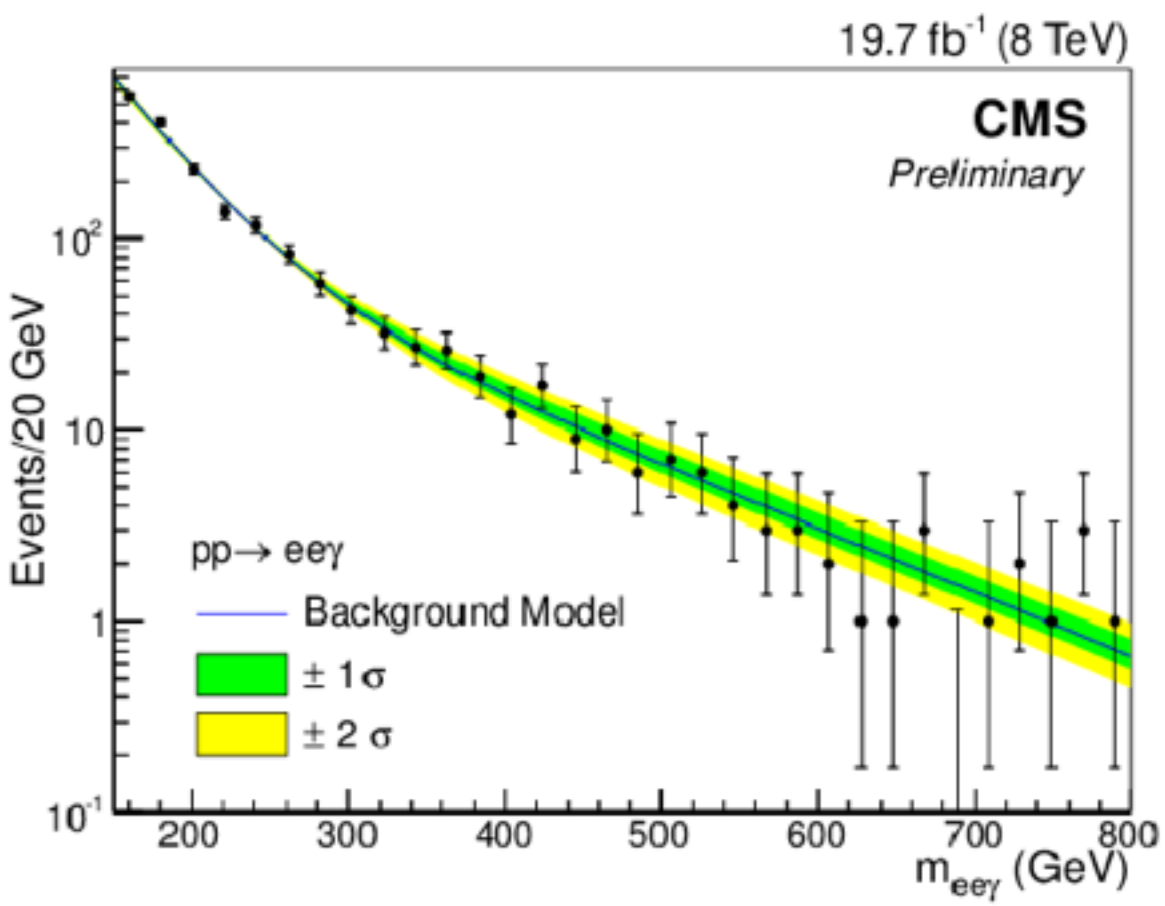


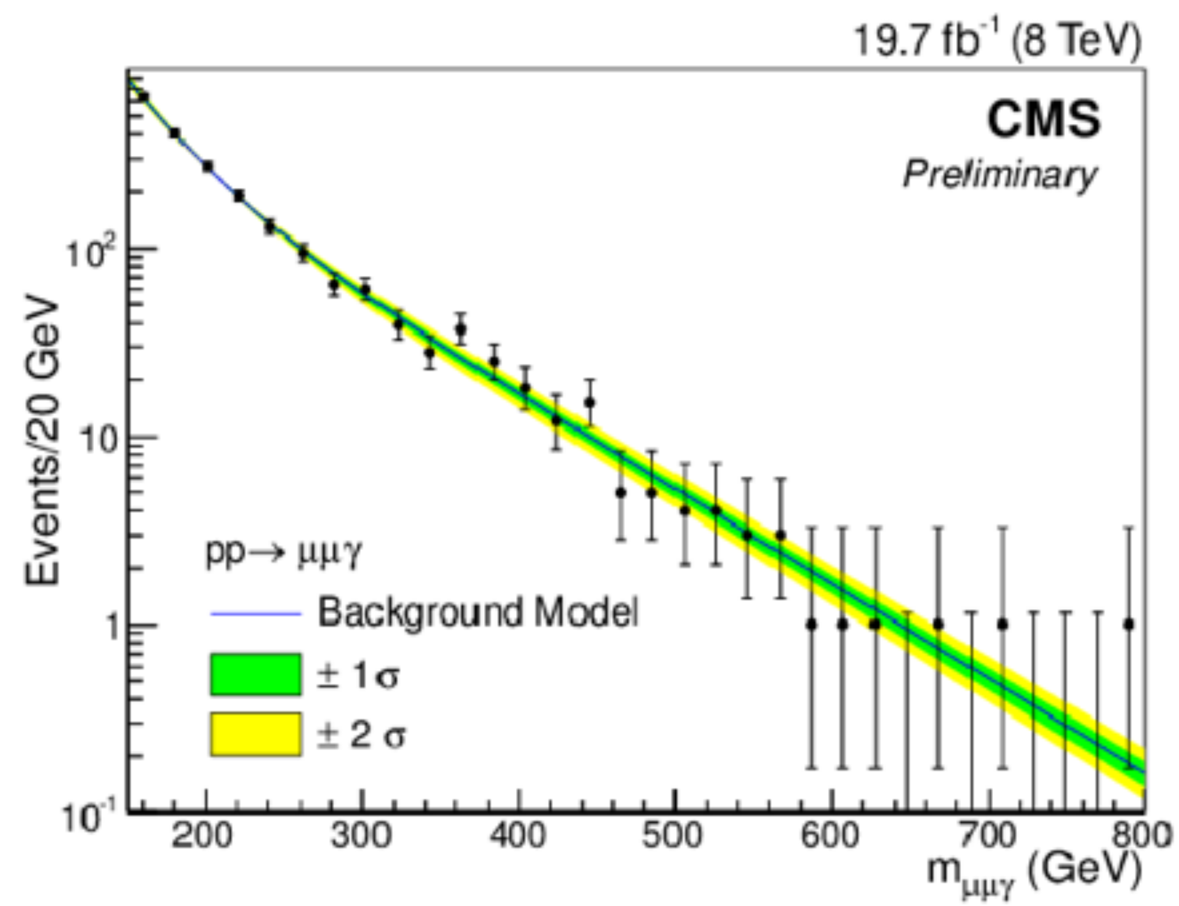
- Excludes models predicting σ x BR to be larger than one order of magnitude of the SM prediction for 125-157 GeV mass range
- Models predicting significant enhancements for $\Gamma_{Z\gamma}$ with respect to the SM expectations due to a pseudoscalar admixture are now excluded

$A \to Z\gamma$

CMS PAS HIG-14-031

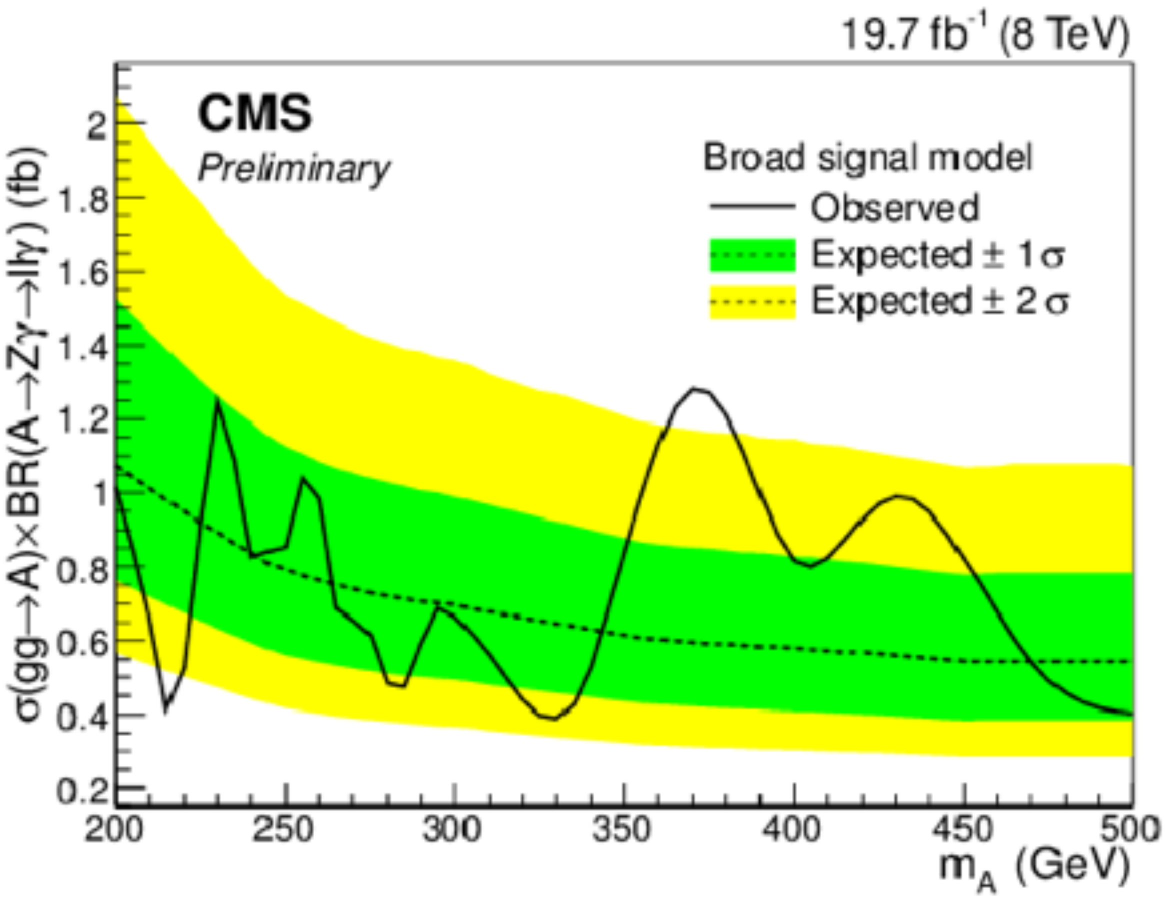
- Search for a high mass scalar particle



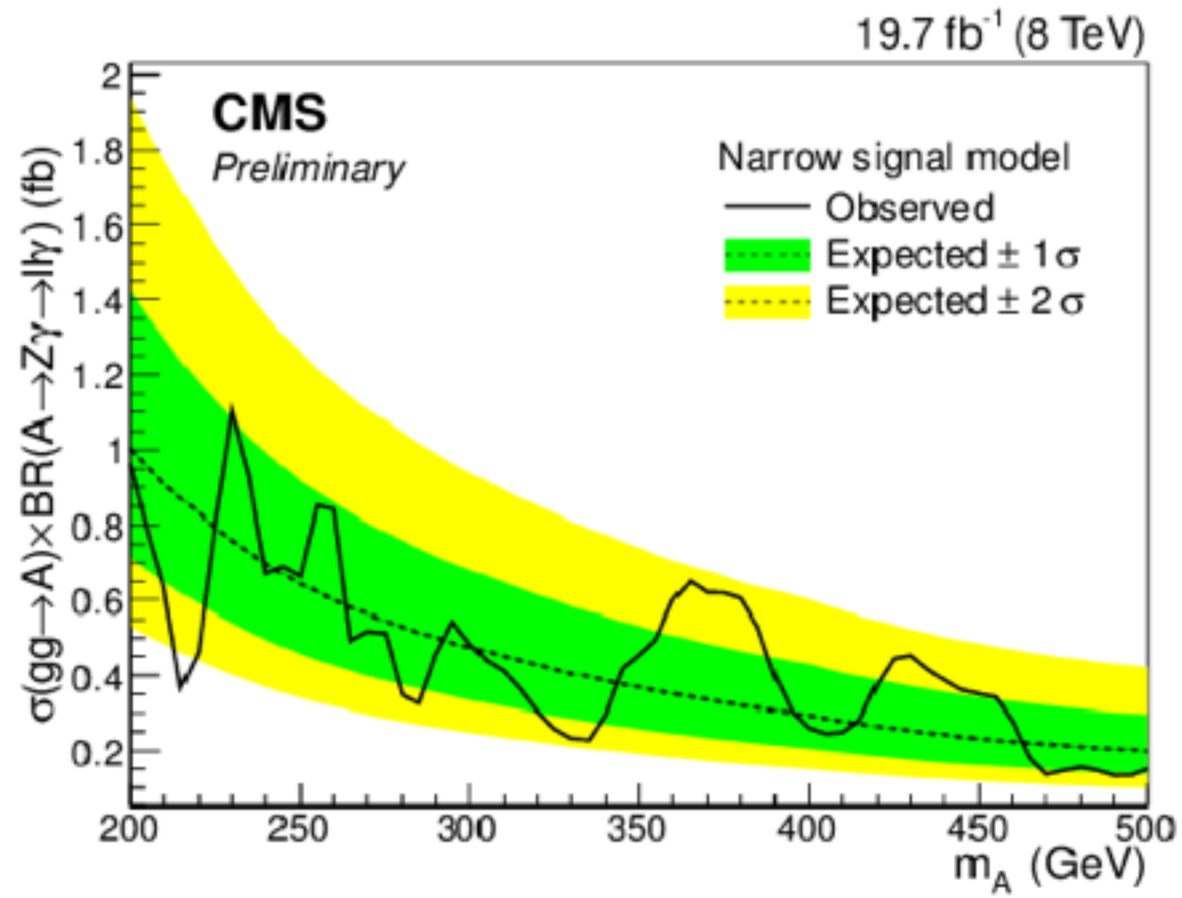


A→Zγ limits

CMS PAS HIG-14-031



Broad resonance signal (Γ_h^{SM})

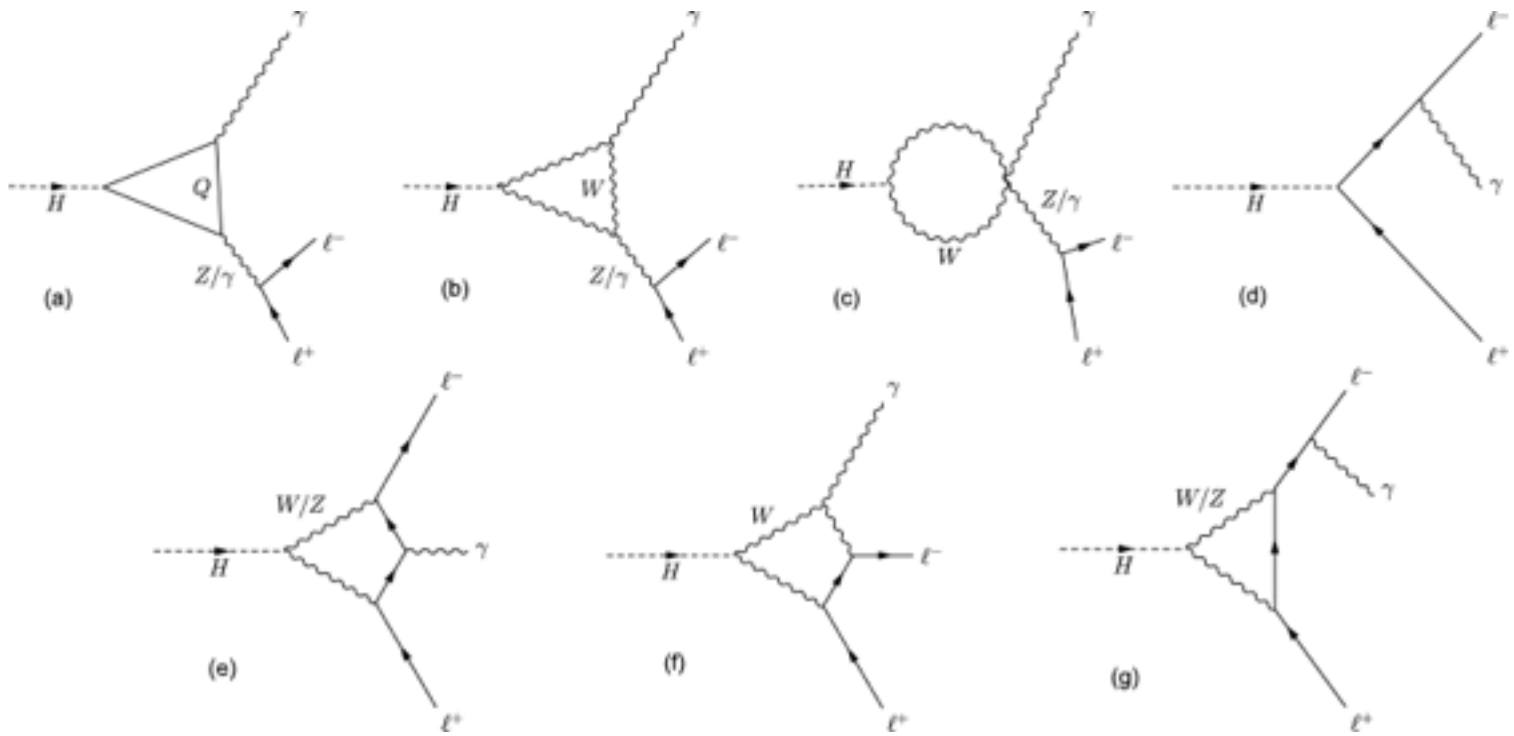


Narrow resonance signal (1% Mx)

$H\rightarrow\gamma^*\gamma\rightarrow ll\gamma$ (Higgs Dalitz decay)

$BR(H\rightarrow\gamma^*\gamma\rightarrow\mu\mu\gamma) = 3.3 \times 10^{-5}$

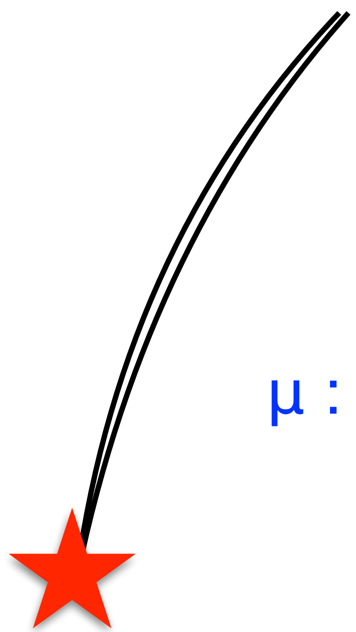
PLB 753, 341 (2016)



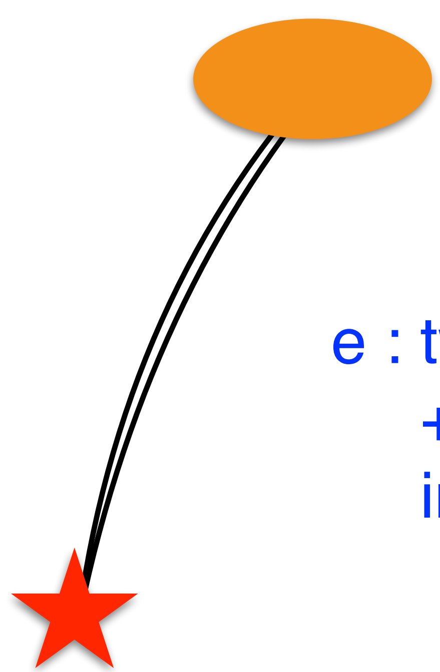
In analogy to $\pi^\circ\rightarrow ee\gamma$ decays via an internal conversion of one of the photons, discovered by R. H. Dalitz, we call the $H\rightarrow\gamma^*\gamma$ process Higgs Dalitz decay

- an extra handle on the measurement of the Higgs's couplings
- consists of non-trivial angular correlations that could result in a forward-backward asymmetry
- sensitive to new physics via loops

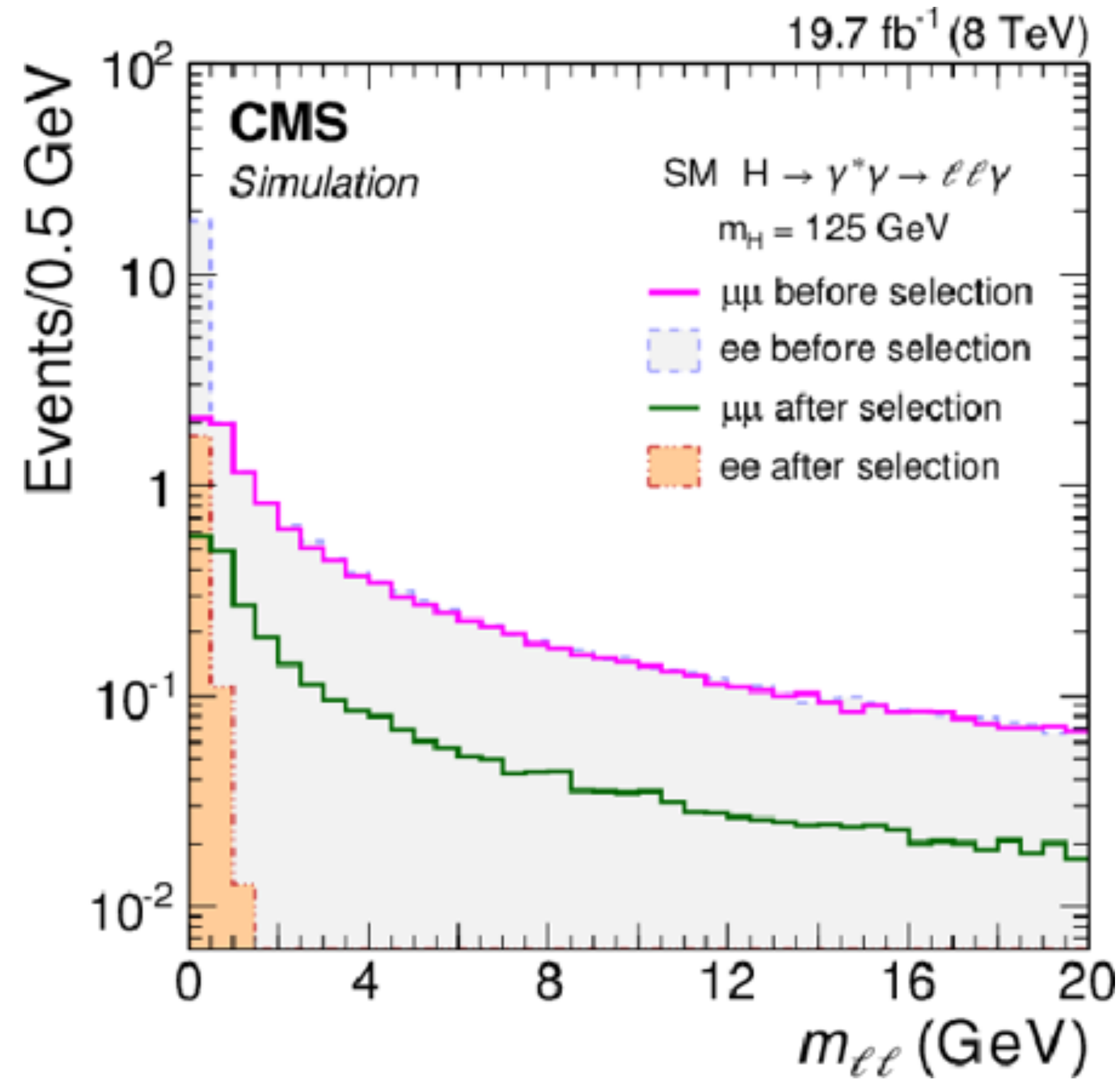
H→γ*γ→llγ : experimental challenges



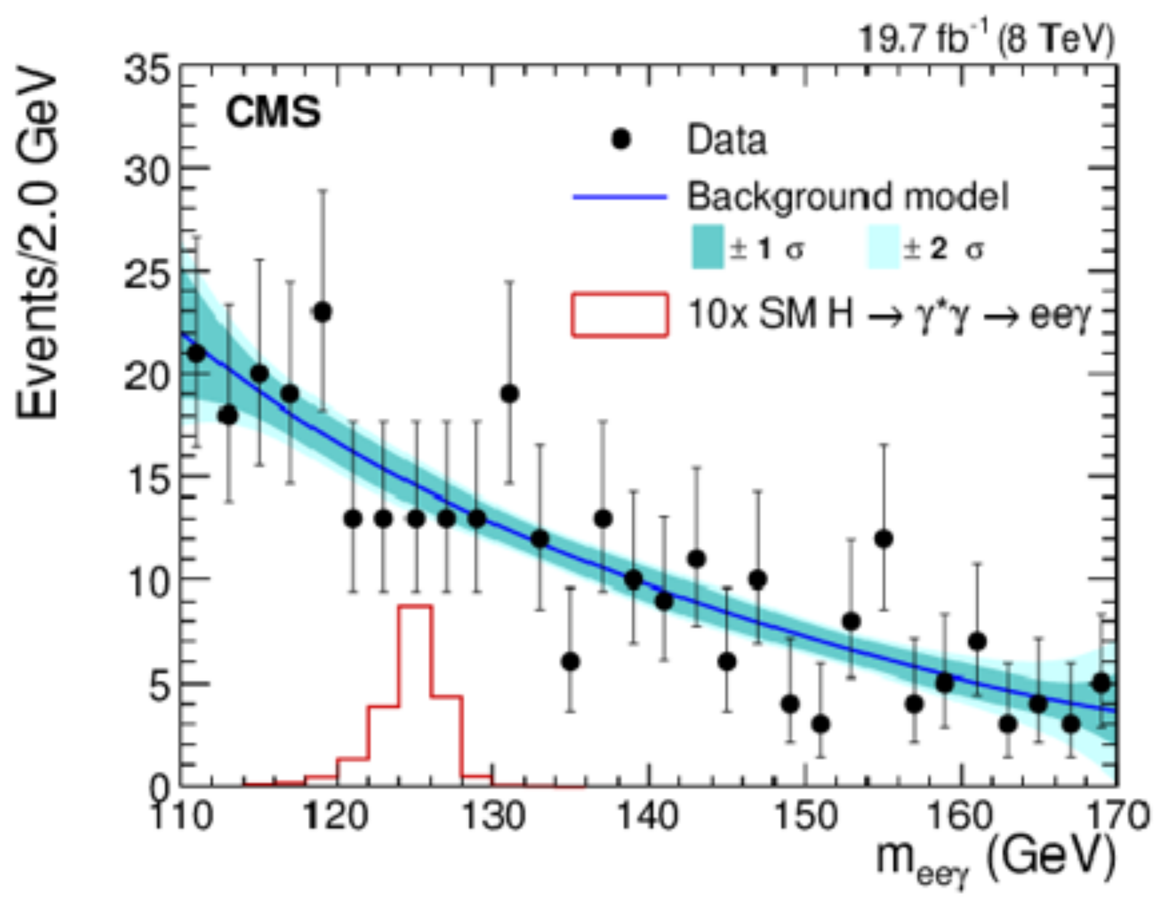
μ : two close-by charged tracks

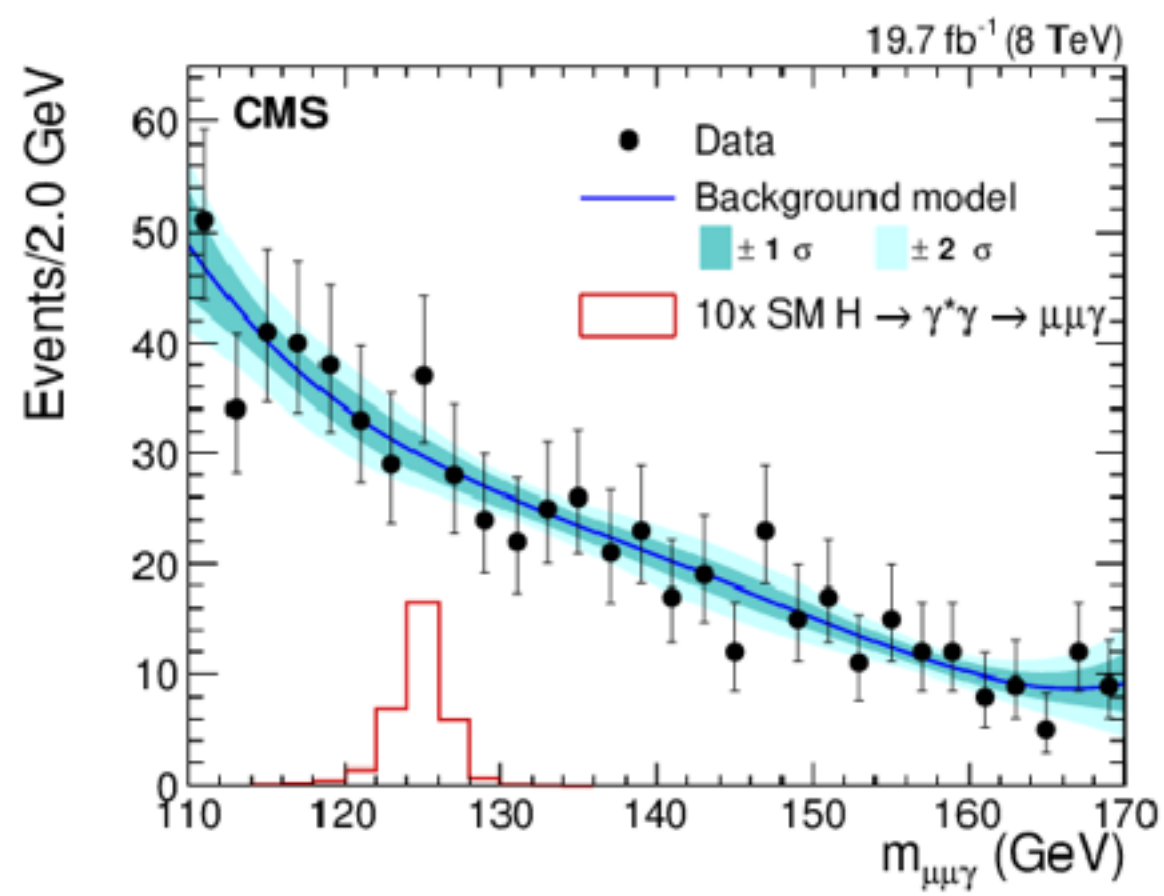


e : two close-by charged tracks
+ one merged energy cluster
in electromagnetic calorimeter

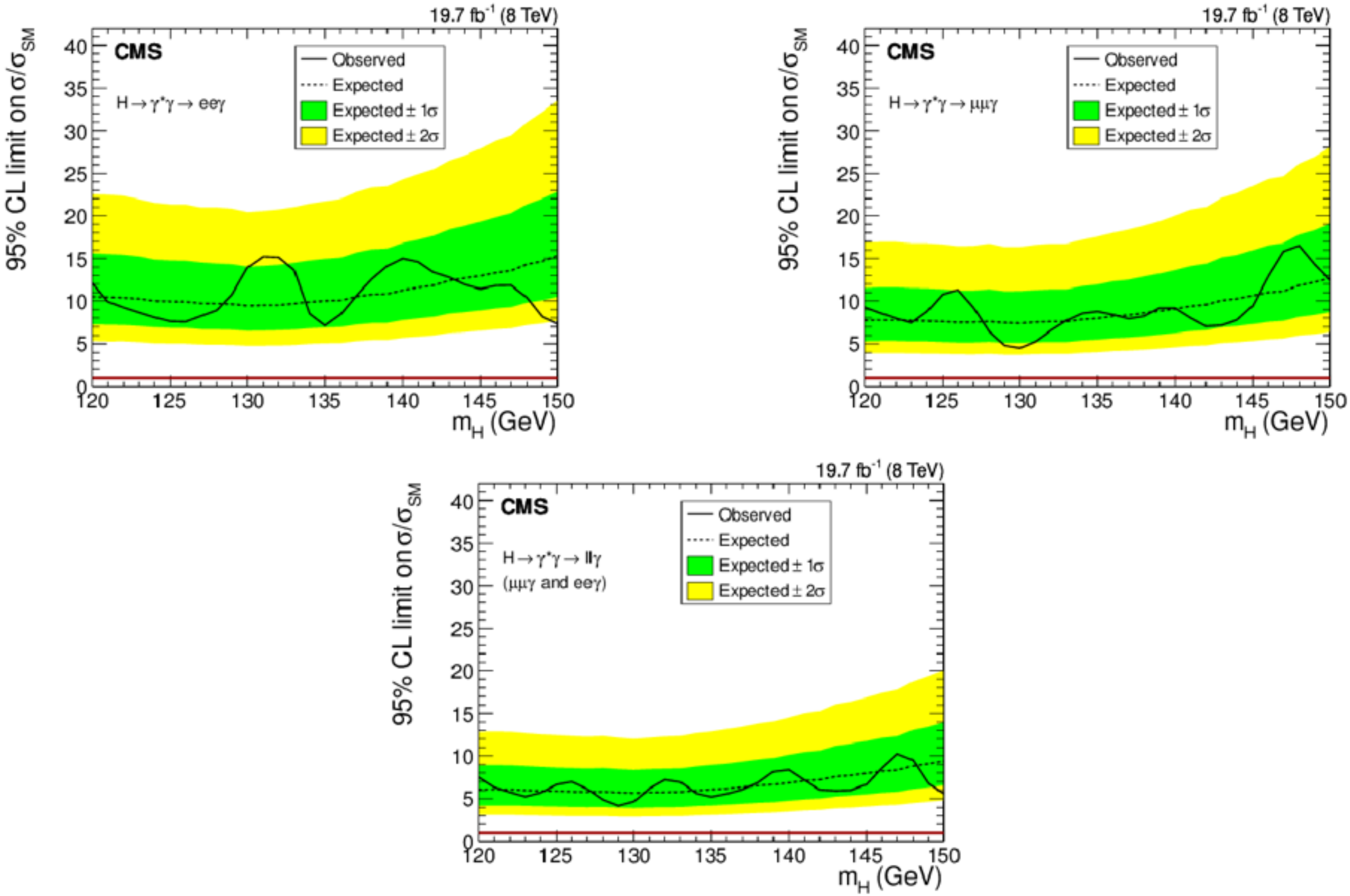


$H \to \gamma^*\gamma \to ll\gamma$: mass spectra



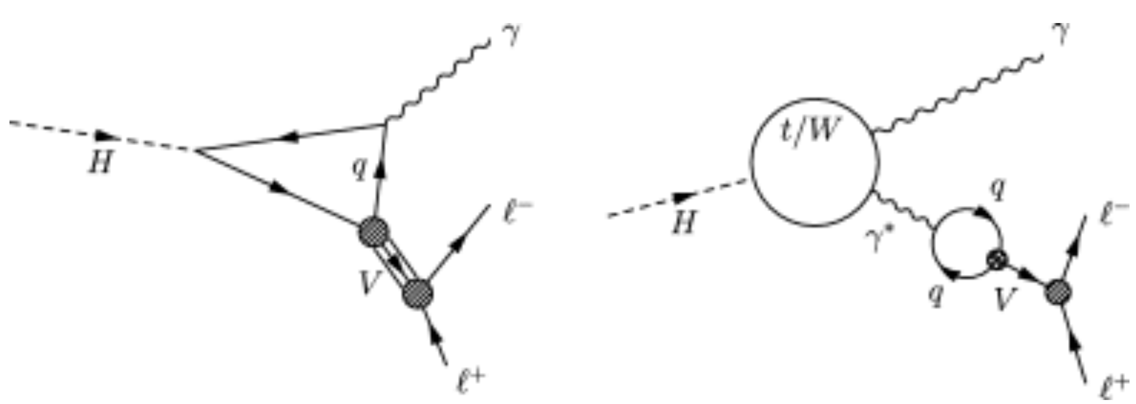


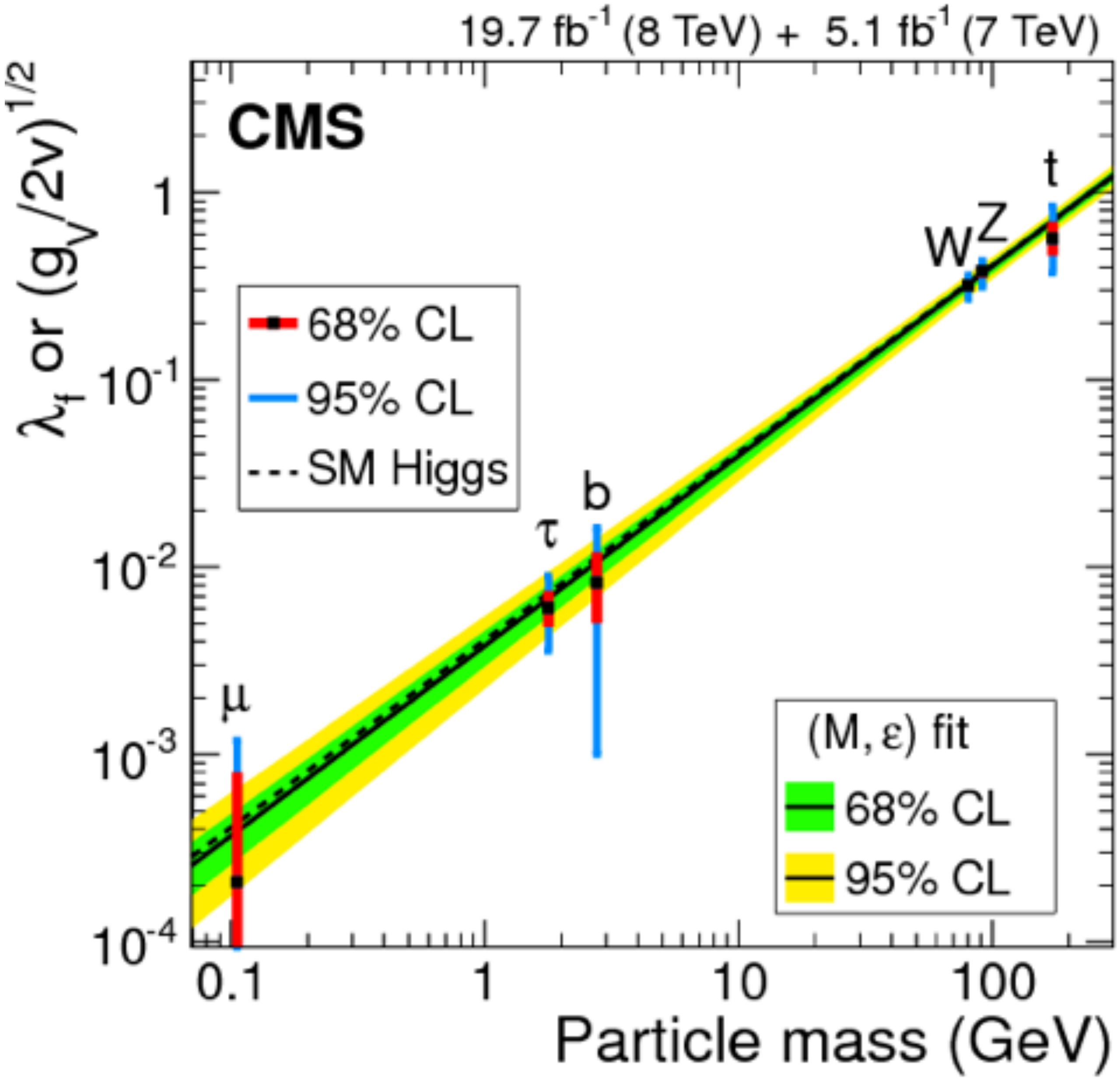
$H \rightarrow \gamma^*\gamma \rightarrow ll\gamma$: limits



$H \to J/\Psi + \gamma$

BR($H \to J/\Psi + \gamma$) = 2.8 x 10^{-6}



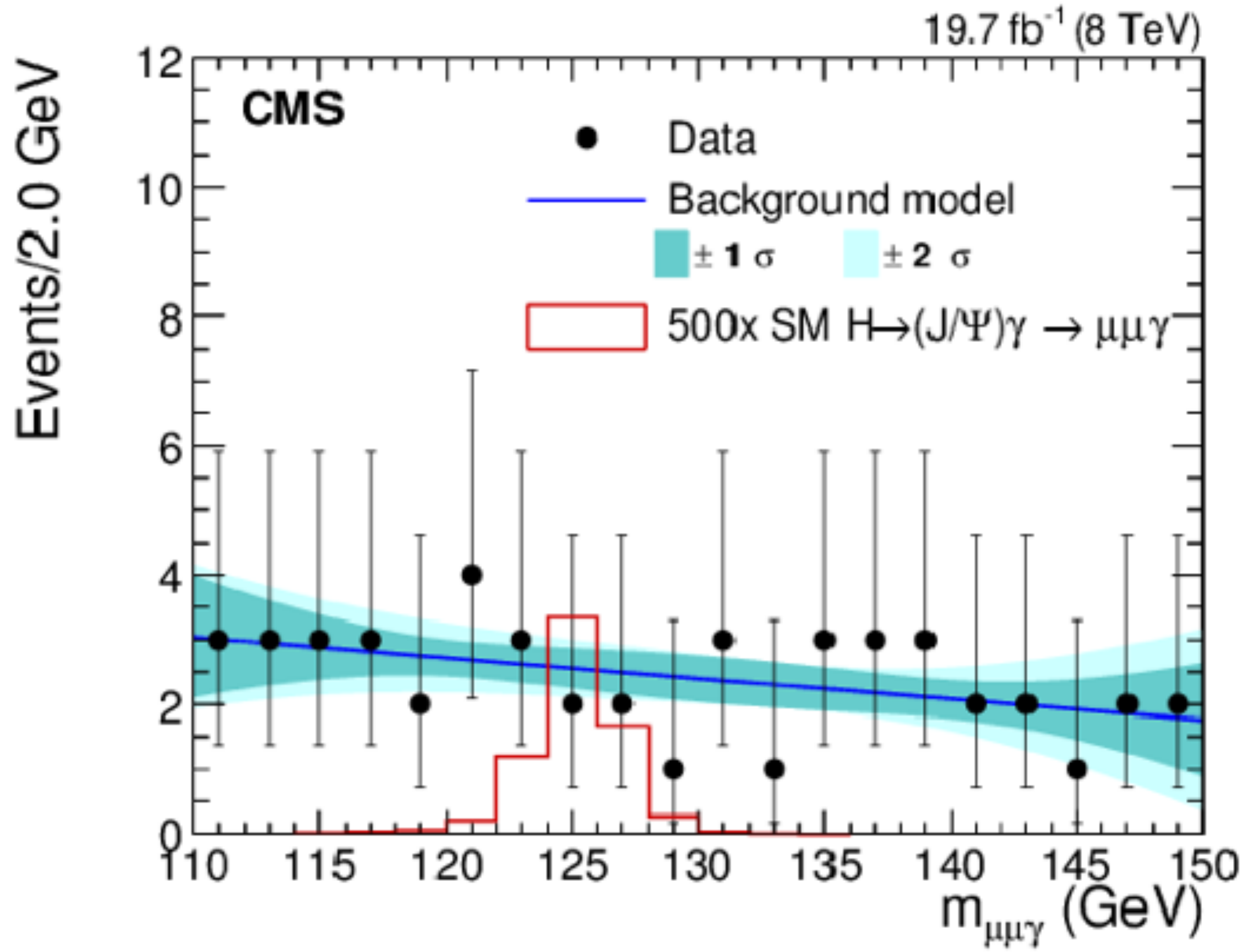


- sensitive to the Higgs-charm coupling

$H \rightarrow J/\Psi + \gamma$

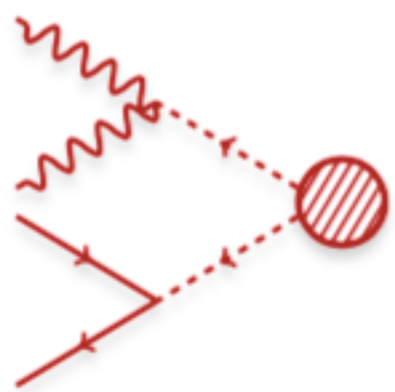
$BR(H \rightarrow J/\Psi + \gamma) = 2.8 \times 10^{-6}$

PLB 753, 341 (2016)

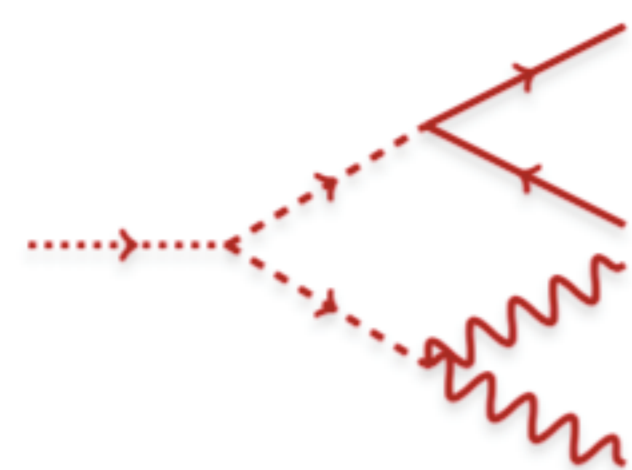


- 95% CL limit on $BR(H \rightarrow J/\Psi\gamma) < 1.5 \times 10^{-3}$
- could be possible at 3000/fb of data at LHC

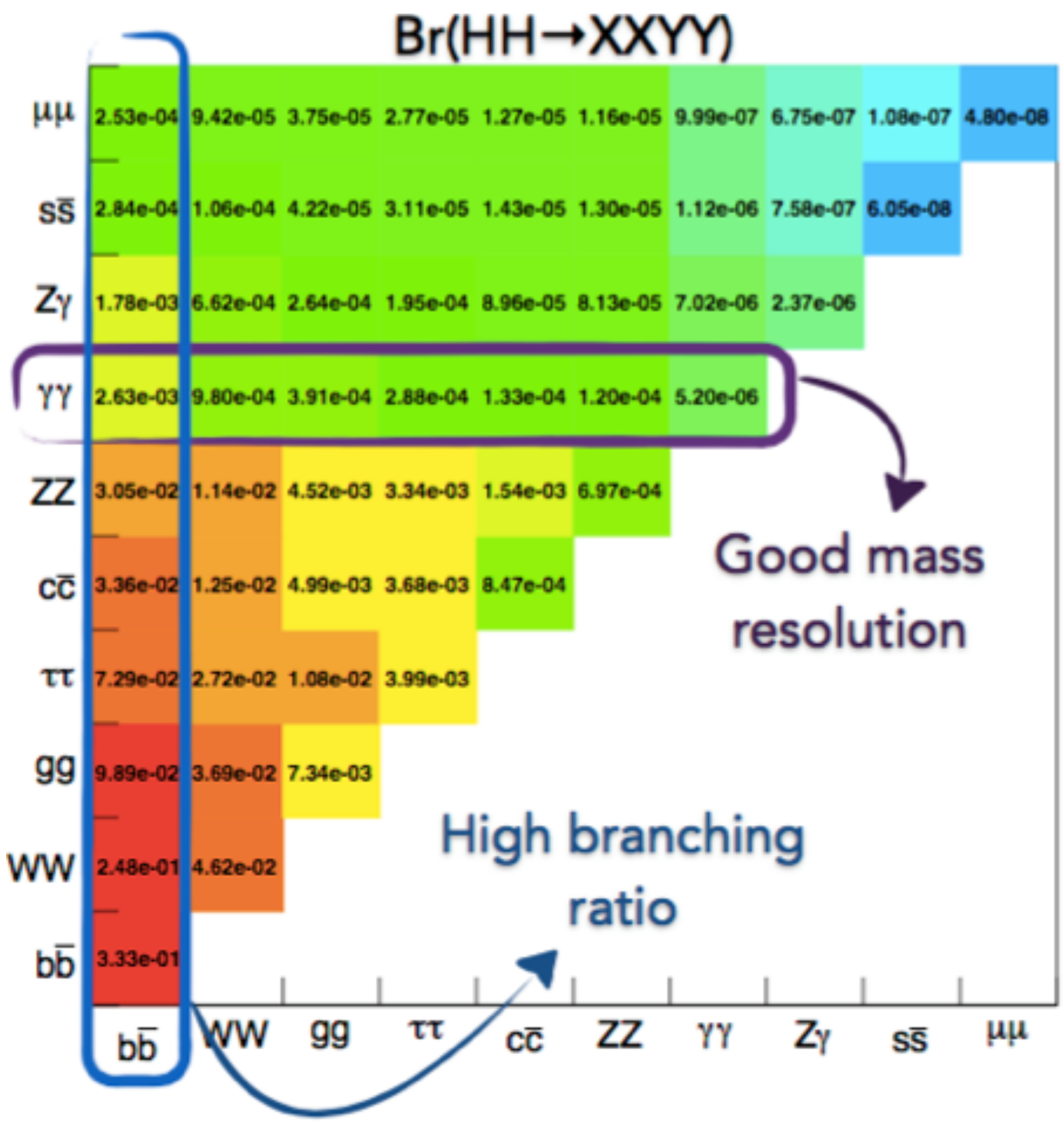
HH production



- Non-resonant
  - need to determine the Higgs self-interaction potential responsible for EWSB → requiring a measurement of trilinear and quadrilinear self-coupling of the Higgs particle, as predicted by the SM
  - Quartic coupling out of each of LHC and HL-LHC
  - SM predicts $\sigma(gg \to HH)$ = 34 fb at 13 TeV → not sensitive, but BSM can induce kinematic differences and cross section enhancement
- Resonant
  - Many BSM models predict resonances decaying into two Higgs bosons : WED, MSSM, 2HDM, etc.
  - Model independent search for spin-0 and spin-2 resonances decaying to HH with Mx = [260, 1100] GeV→ non-boosted regime
  - Benchmark model : Warped Extra Dimensions predicts spin-0 (radion) and spin-2 (KK graviton) new particles that couple to the Higgs bosons



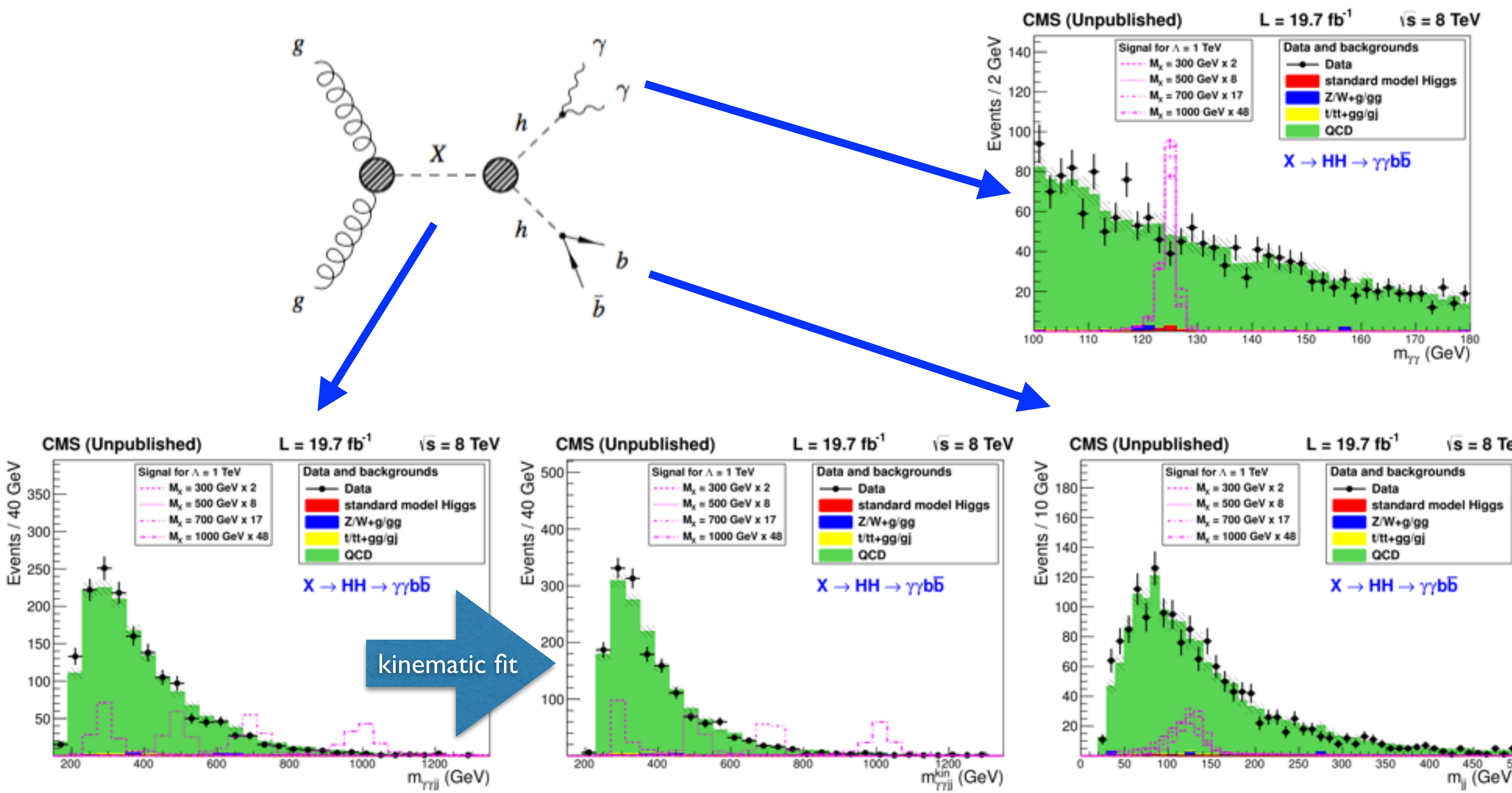
HH→γγbb



- H→bb
  - high branching ratio
  - tag b-jet to obtain good S/√B
- H→γγ
  - high trigger efficiency and selection
  - good mass resolution
- HH→bbγγ
  - low background

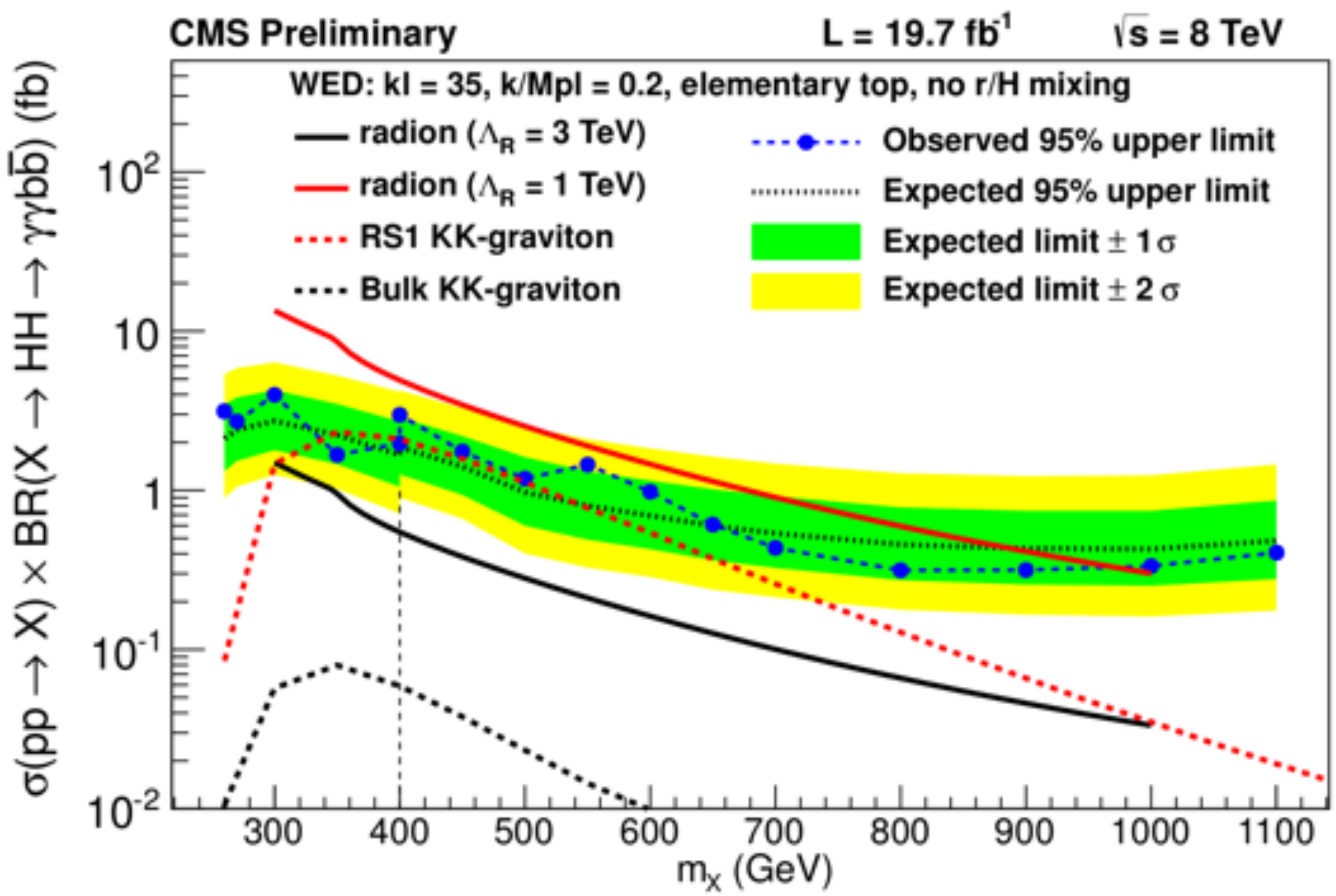
$X \rightarrow HH \rightarrow bb\gamma\gamma$

CMS PAS HIG-13-032



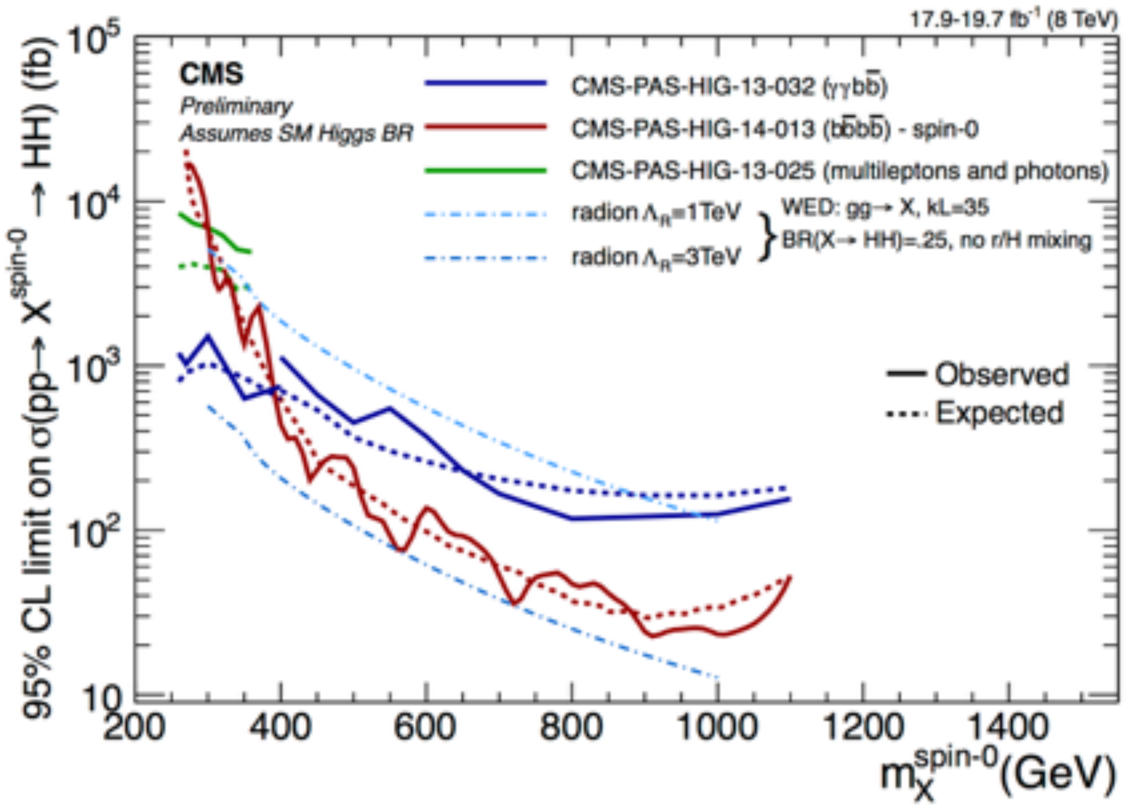
- Low mass regime (260 - 400 GeV) : Fit $m_{\gamma\gamma}$
- High mass regime (400 - 1100 GeV) : Fit $m_{\gamma\gamma jj}$ after kinematically constrain $m_{\gamma\gamma}$ and m_{jj} to 125 GeV within energy resolutions

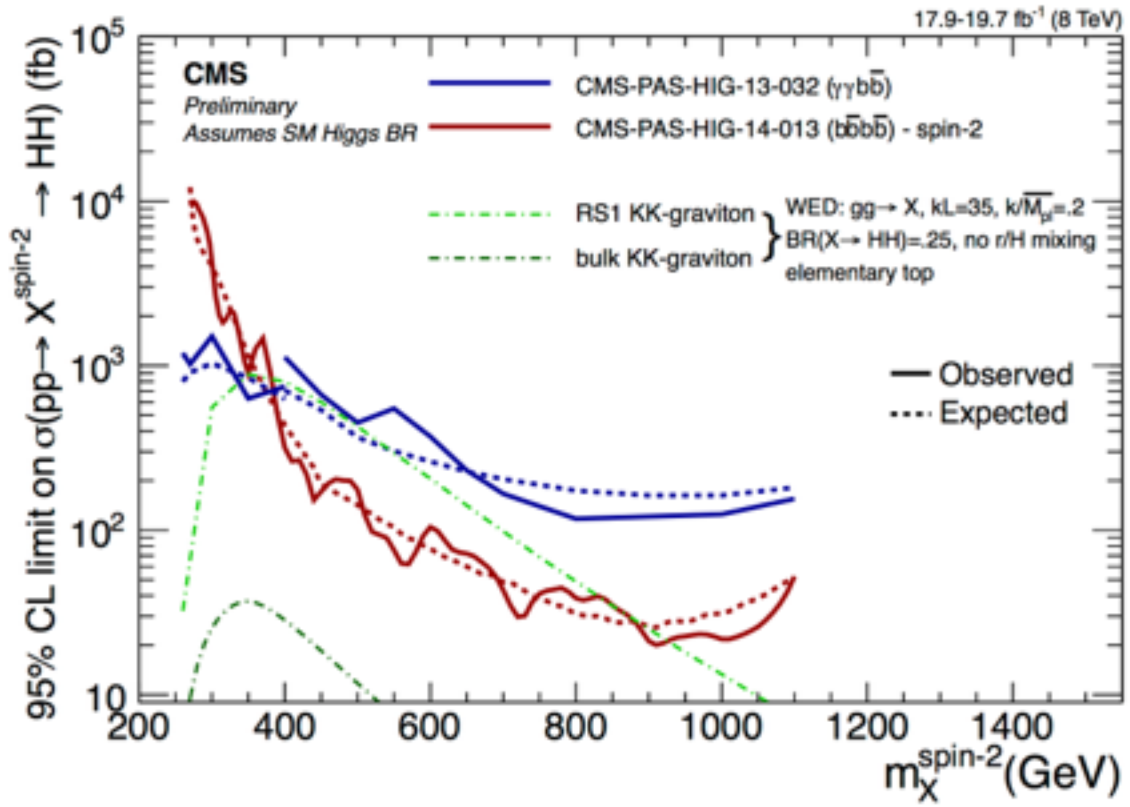
X→HH→bbγγ results



- No significant deviation from expectations
- The **radion** with Λ_R = 1 TeV is excluded below 970 GeV. The **RS1 KK-graviton** is excluded from 340 to 400 GeV at a 95% CL

Combined Run I CMS HH results



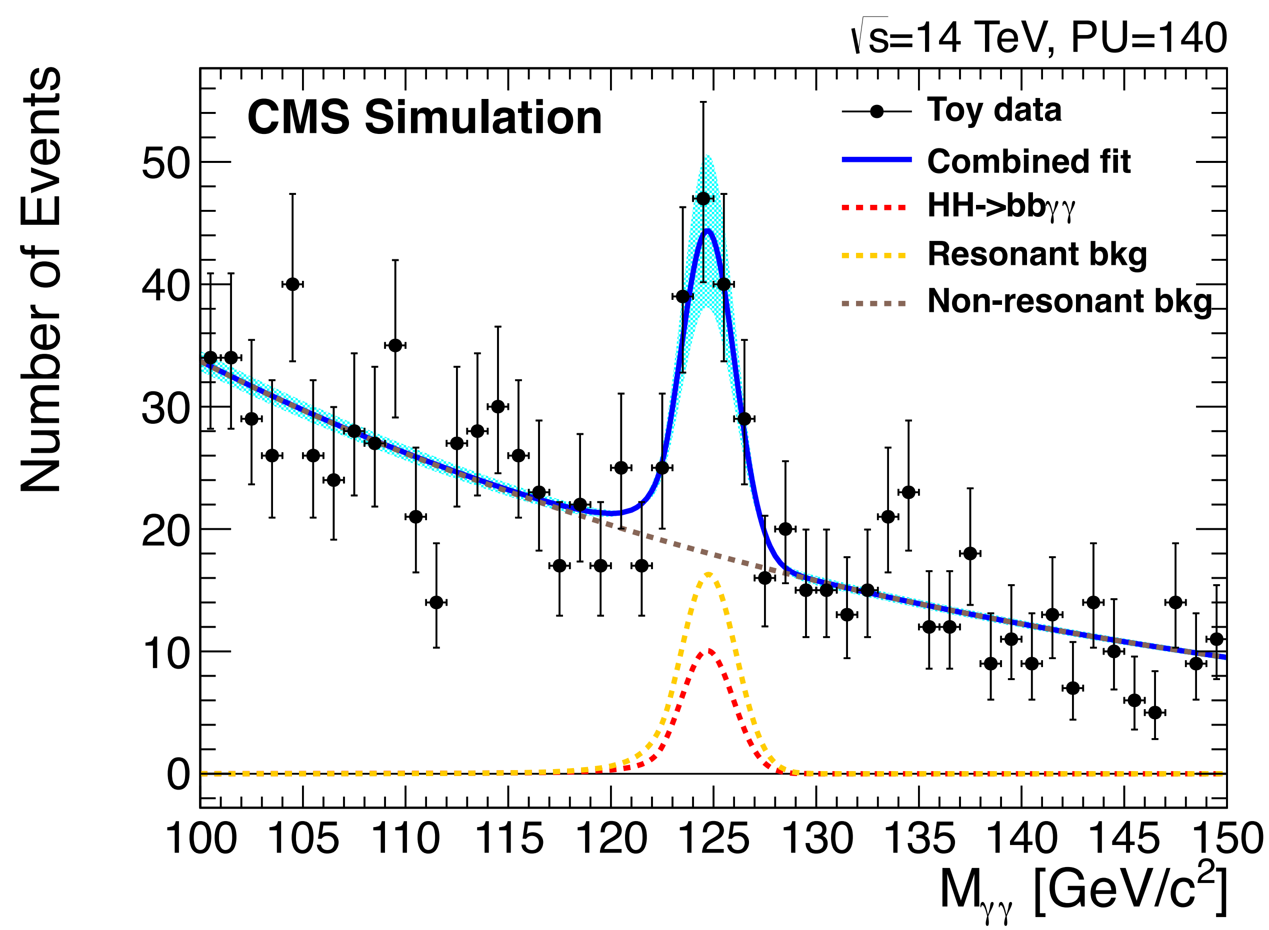


- No significant deviation from expectations
- X→HH→bbγγ and X→HH→bbbbb sensitivities cross. Complementary searches
- Resonant searches constrain BSM physics

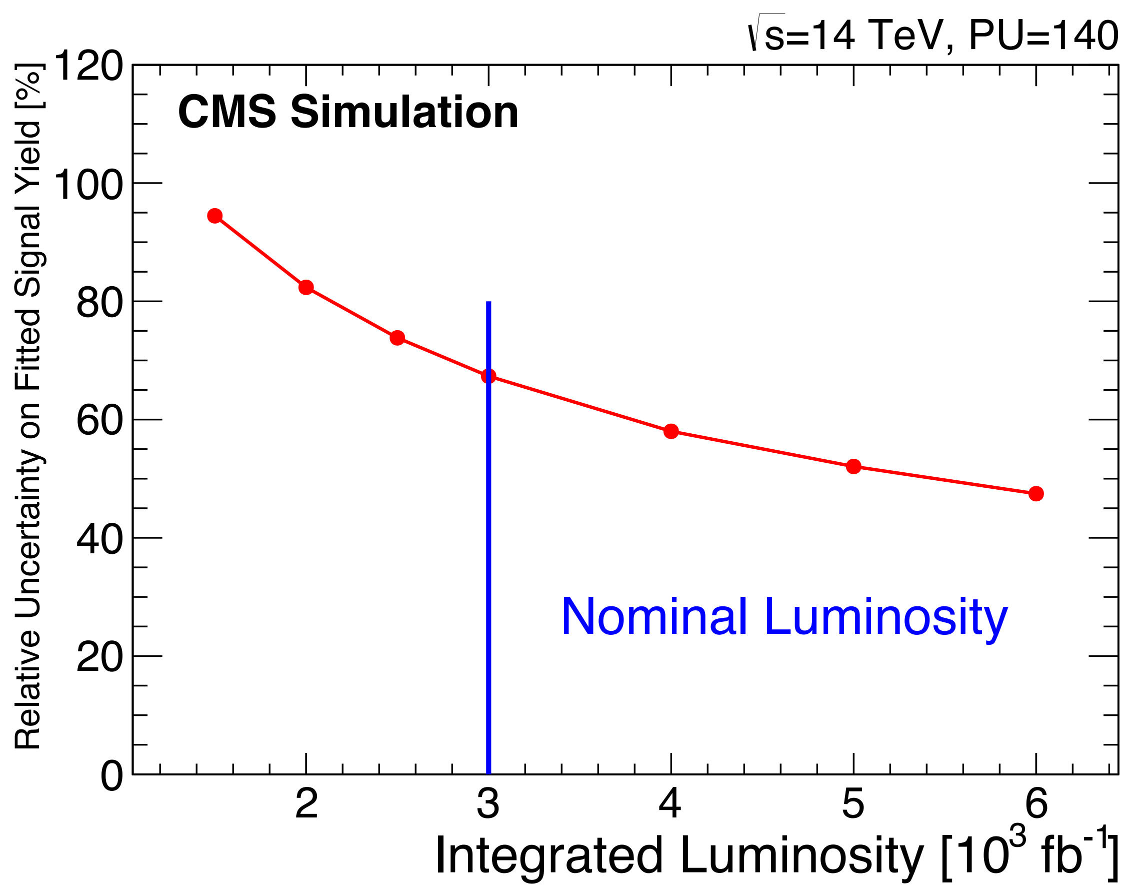
Non-resonant HH→γγbb future study

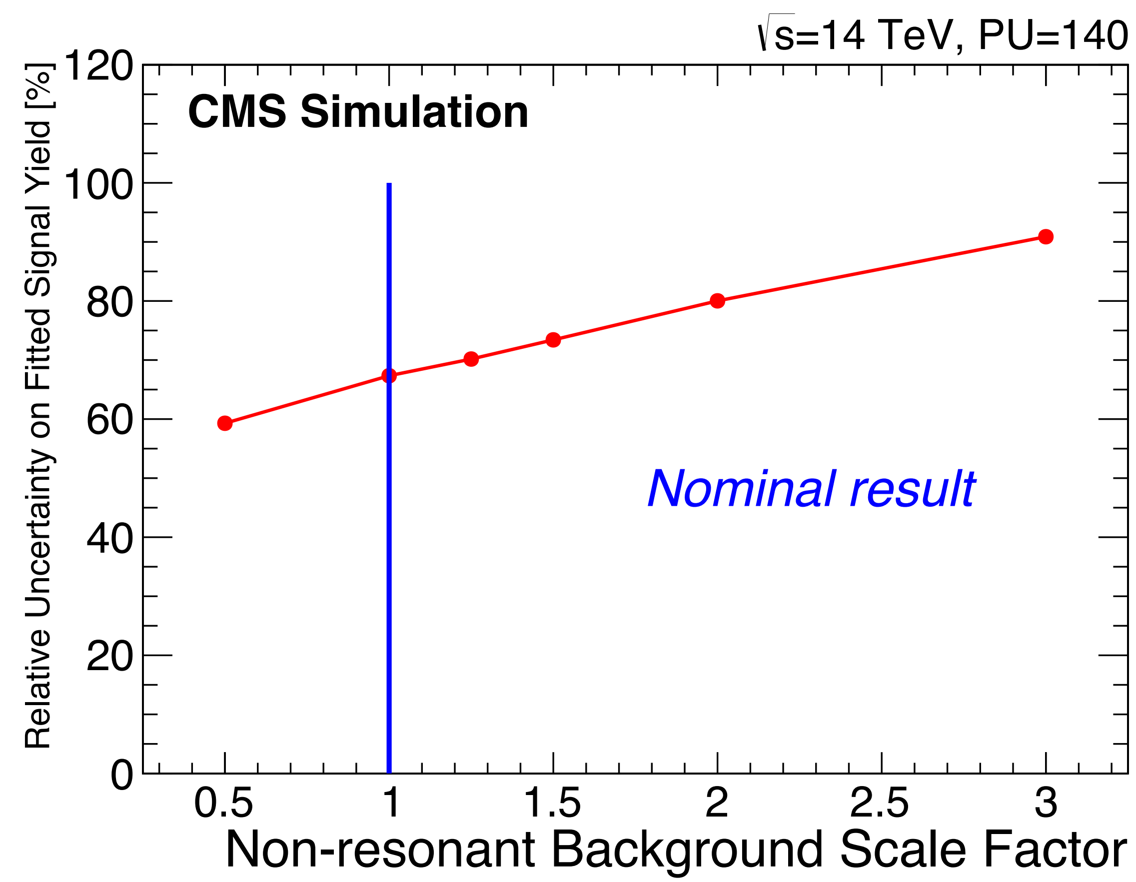
CMS PAS FTR-15-002

- At √s = 14 TeV, expected 390 produced events in 3000/fb
- Parametrize object performance tuned to CMS Phase II detector at <PU> = 140



Non-resonant HH→γγbb future study





Summary

- $H \to Z\gamma$: the observed limit at 125 GeV is within one order of magnitude of the SM prediction. No significant deviation from expectations is seen between 200 and 500 GeV
- $H \to \gamma^{*}\gamma$: the observed limit at 125 GeV is about six times of the SM prediction
- $H \to J/\Psi\gamma$: the observed limit on BR is 540 times higher than SM expectation
- $HH \to bb\gamma\gamma$: No appreciable excess has yet to be seen. However, upper limits place constraints on BSM models
- Stay tuned with more data to come in 2016