Scalar: CMS Run 1 final results, prospectives for Run 2 (and HL-LHC)

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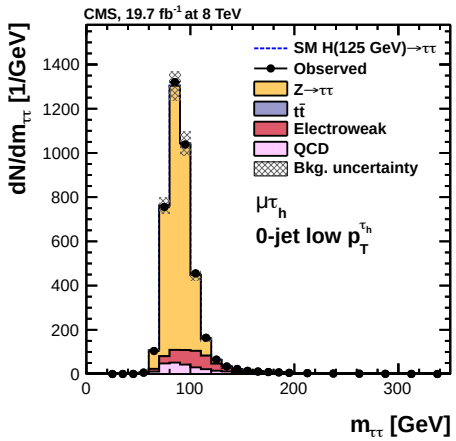
Introduction

- A new scalar particle discovered in 2012 with $\sim 5 + 5\text{fb}^{-1}$ at $7 + 8$ TeV
- Published results for main channels available with full Run 1 dataset ($\sim 5 + 20\text{fb}^{-1}$)

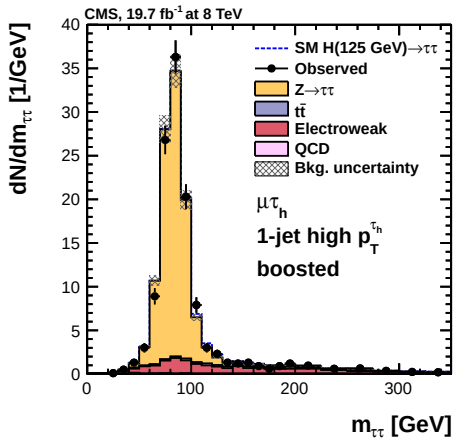
Channel	Paper
$H \to \tau\tau$	arXiv:1401.5041
$W/Z + H \to bb$	arXiv:1310.3687
$H \to WW \to 2\ell 2\nu$	arXiv:1312.1129
$H \to ZZ \to ZZ \to 4\ell$	arXiv:1312.5353
$H \to \gamma\gamma$	arXiv:1407.0558
$tt + H$ Combination	arXiv:1408.1682
Spin/CP and Anomalous Couplings	arXiv:1411.3441
Width from off-shell production	arXiv:1405.3455
Combination	arXiv:1412.8662

$H \to \tau\tau$

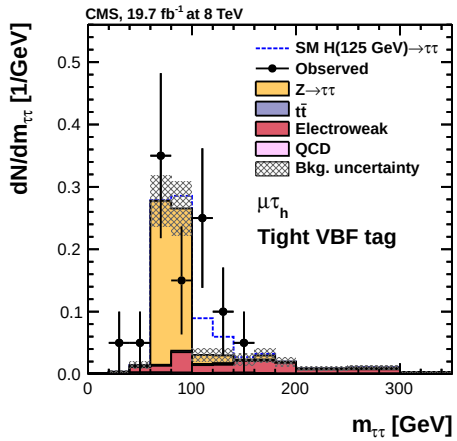
- Events selected in $e\mu$, $e\tau_h$, $\mu\tau_h$ and $\tau_h\tau_h$ final states
- $\tau\tau$ mass reconstructed using kinematic fit of visible products and $\not{E}_T$ with likelihood constraints on decay kinematics
- $Z \to \tau\tau$ background estimated from $Z \to \mu\mu$ events in data with μ replaced by simulated τ
- $W + jets$ and multijet background estimated from high transverse mass and same-sign control regions
- Events further categorized according to production: additional leptons, di-jet VBF tagged, boosted (high lepton or $\tau\tau$ p_T), 0/1 jets



(a) 0 Jet low p_T

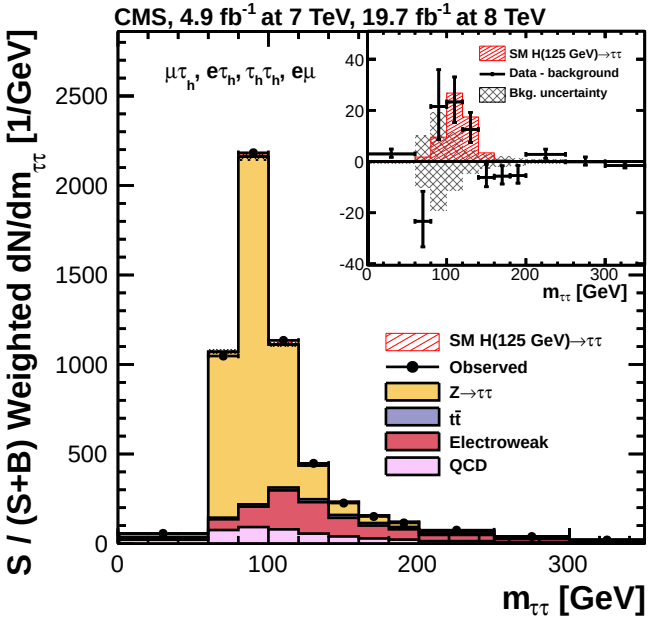


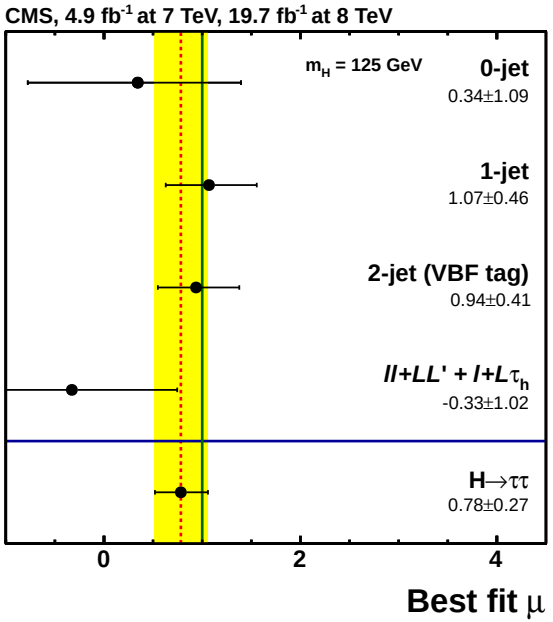
(b) 1 jet boosted



(c) VBF tight

SM $H \to \tau\tau$ Results

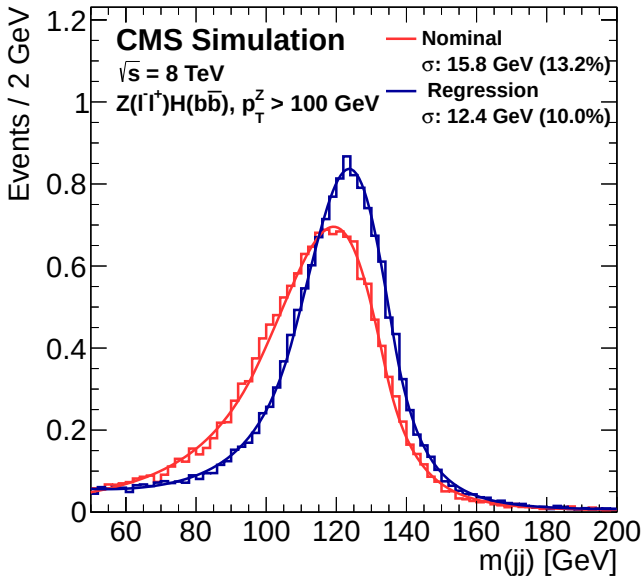


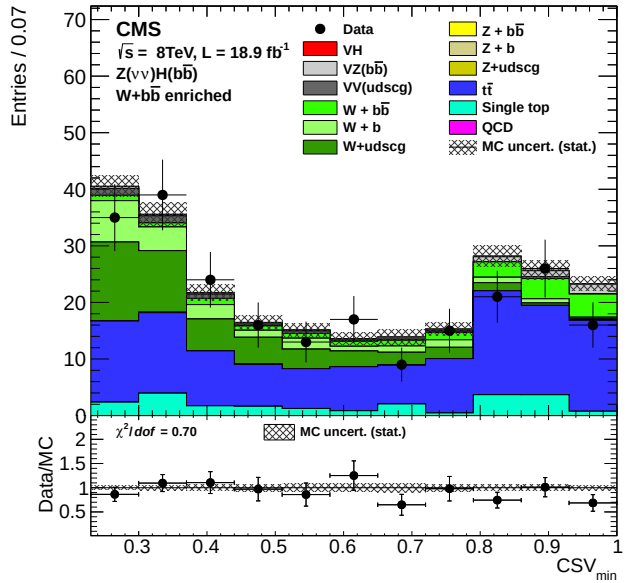


- Final results extracted from binned likelihood fit to $m_{\tau\tau}$ distribution
- $\sigma/\sigma_{SM} = 0.78 \pm 0.27$, Observed Significance 3.2σ (Expected 3.7σ)
- $m_H = 122 \pm 7$ GeV (6%)

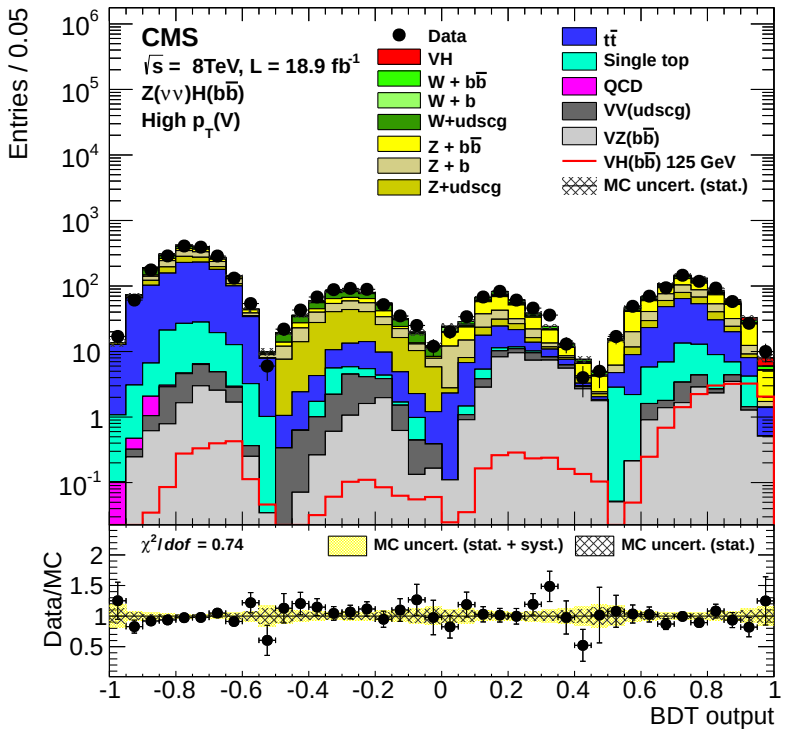
$W/Z + H \to bb$

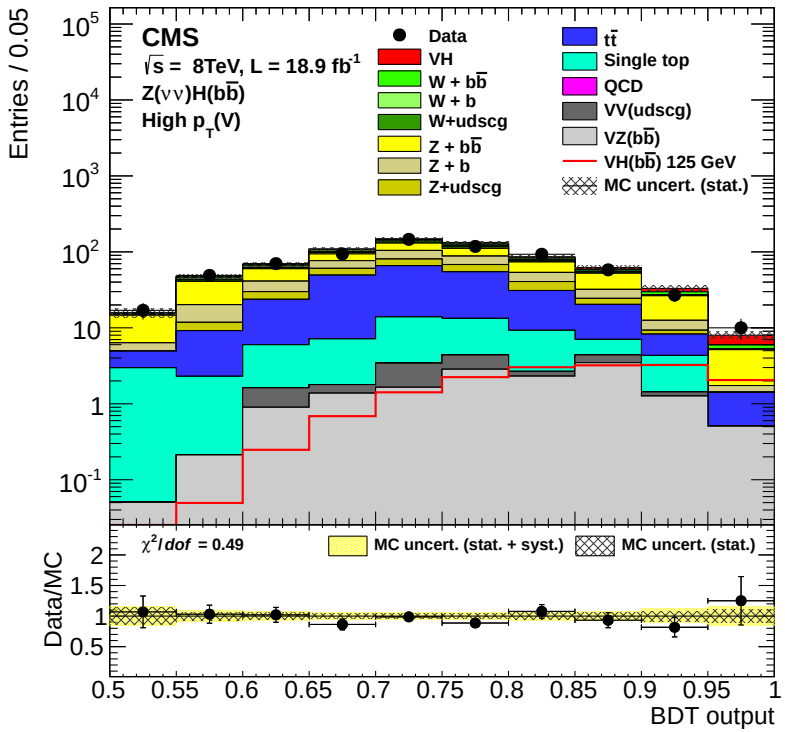
- $H \to bb$ has high branching ratios but huge QCD backgrounds
- To achieve reasonable S/B, select $W/Z + H \to \ell\nu\ \ell\ell\ \nu\nu + bb$ events with significant W/Z boost
- Require two central b-tagged jets: $\sim 10\%$ mass resolution after b-jet energy regression
- MVA (mass-dependent) trained on dijet, W/Z kinematics, and additional jet kinematics, plus b-tagging discriminants.
- Background yields scaled from inverted b-tagging (W/Z+light flavour), tighter b-tagging plus extra jets ($t\bar{t}$), M_{jj} sidebands (W/Z+$b\bar{b}$)





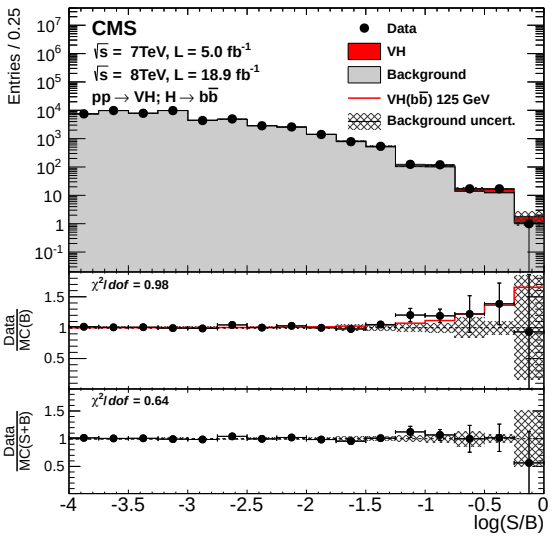
$W/Z + H \to b\bar{b}$ Results

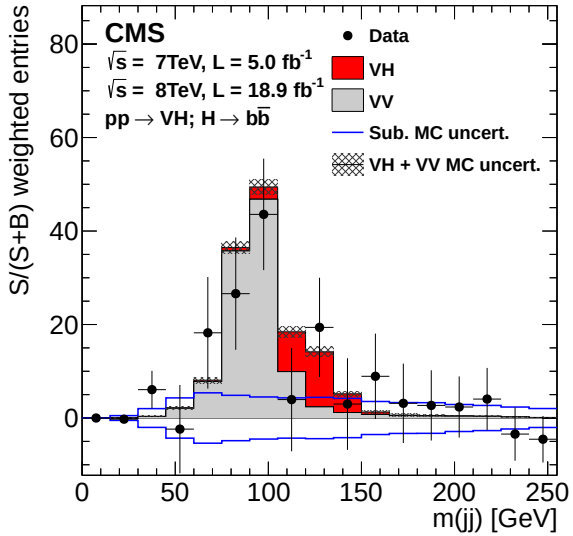


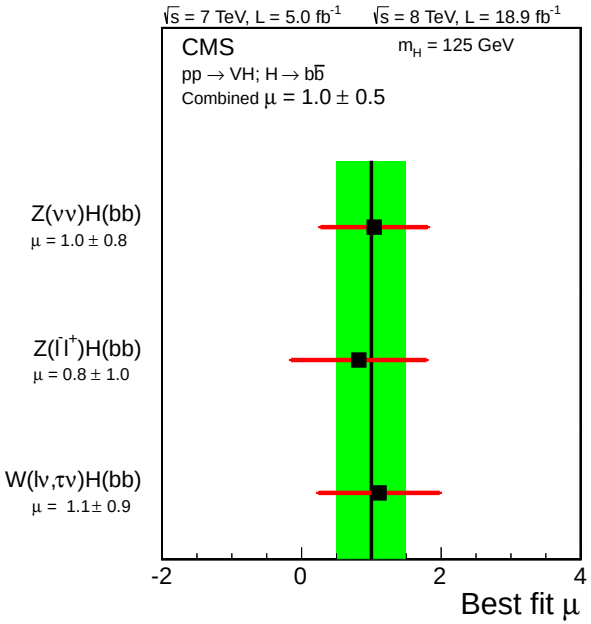


- Results extracted from fit to final BDT distribution, partitioned using dedicated BDT's into individual background and signal-enriched regions

$W/Z + H \to b\bar{b}$ Results



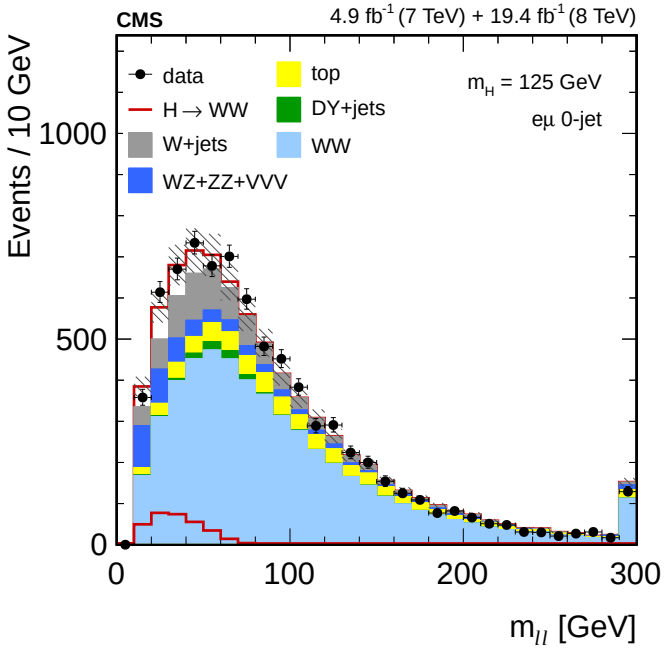


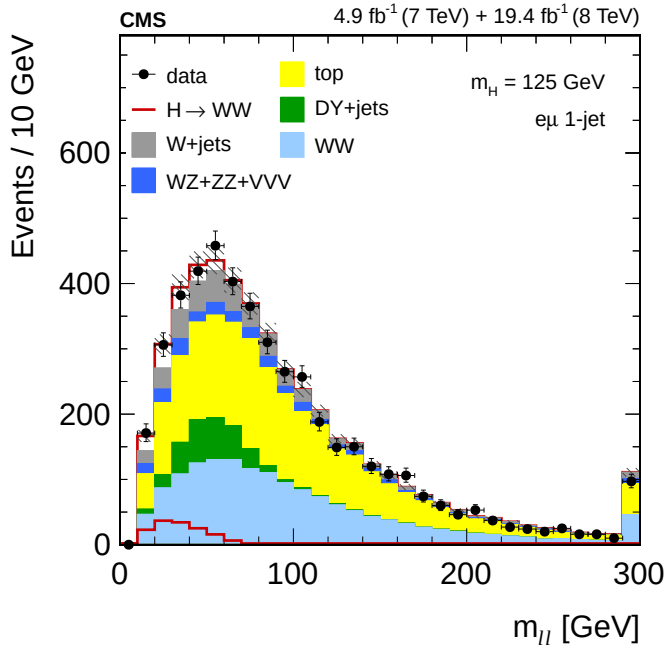


- $\sigma/\sigma_{SM} = 0.84 \pm 0.44$ (including also contribution from $tt + H \to b\bar{b}$ and taking into account gluon-induced $Z + H$ production)
- Observed Significance 2.0σ (Expected 2.6σ)

WW-level Event Selection:

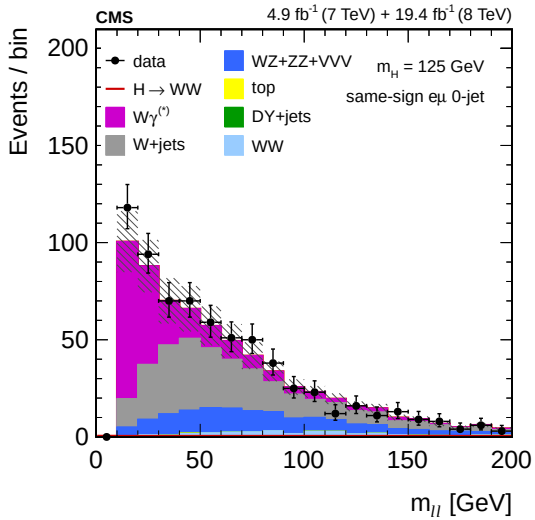
- Two opposite charge leptons with 20/10 (15) GeV p_T threshold for opposite-flavour (same flavour) events
- Events further divided into 0-jet, 1-jet, di-jet tagged, additional lepton categories
- Cut on projected $\not\!\!E_T$ variable wrt nearest lepton
- Soft-muon and b-tag veto (also on soft jets in 0-jet bin), Z-mass veto for same-flavour pairs

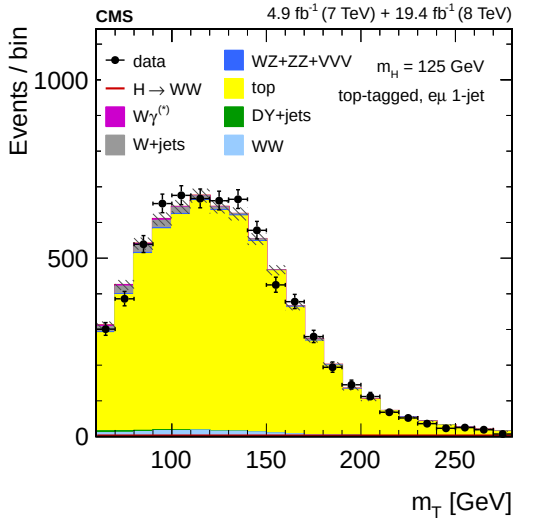




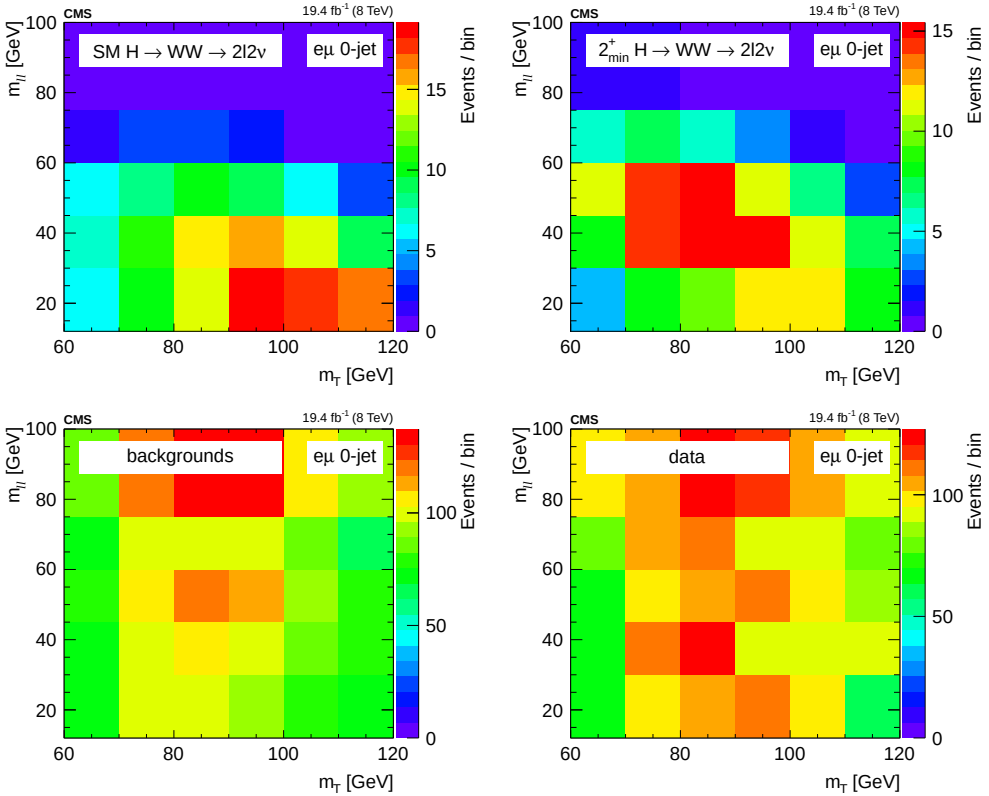
Background Estimation:

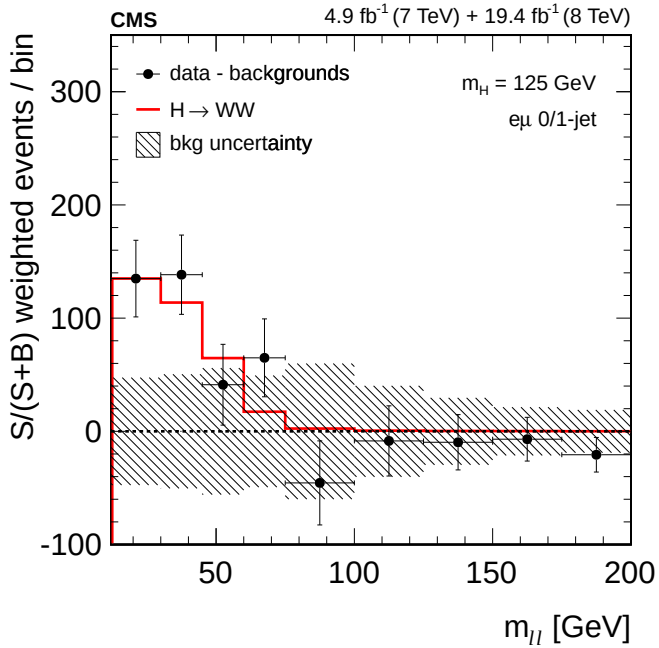
- W+jets background estimated from $\ell+$ loose ℓ sample, fake rates estimated from dijet sample
- $t\bar{t}$ background estimated from b-tagged events, tagging efficiency from double-b-tag sample
- $W\gamma^*$ estimated from three-lepton control sample
- $Z \to \ell\ell$ estimated from yield in Z-peak
- $Z \to \tau\tau$ estimated from embedded sample
- Small $W\gamma$ contribution estimated from simulation + control region, cross-checked in same-sign events
- WW background normalized in situ





$H \to WW \to 2\ell 2\nu$: Fit Strategy

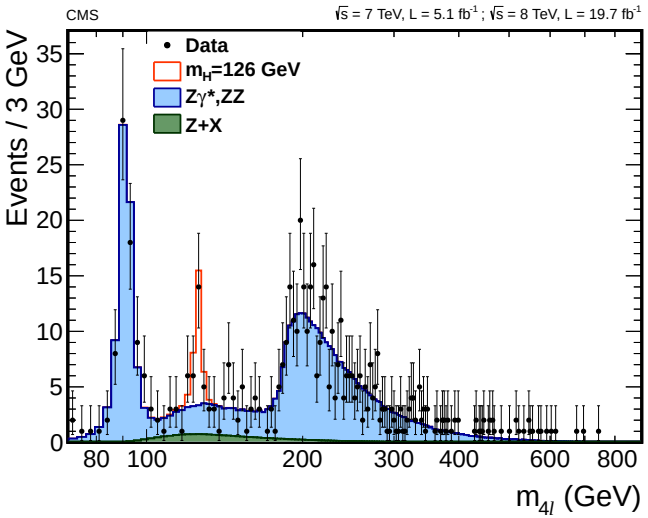


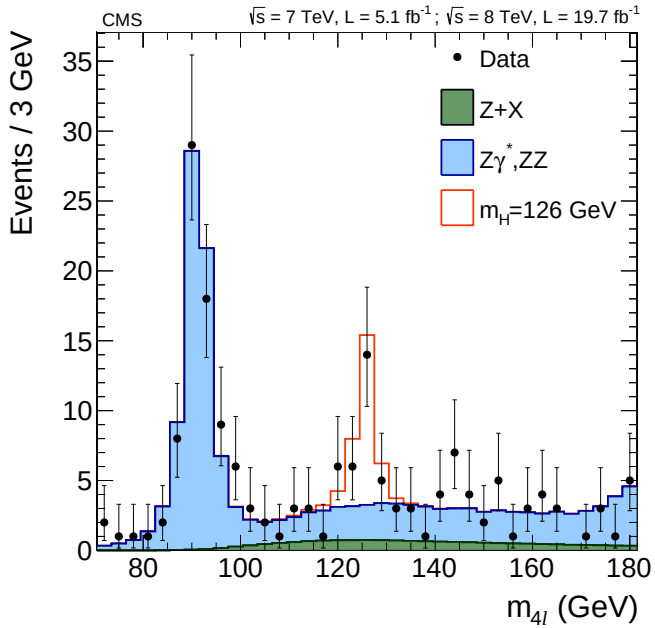


- Results in 0/1 jet opposite flavour categories extracted from binned 2D likelihood fit to $m_{\ell\ell}$-m_T distribution
- $\sigma/\sigma_{SM} = 0.72^{+0.20}_{-0.18}$
- Observed Significance 4.3σ (Expected 5.8σ)

$H \to ZZ \to 4\ell$

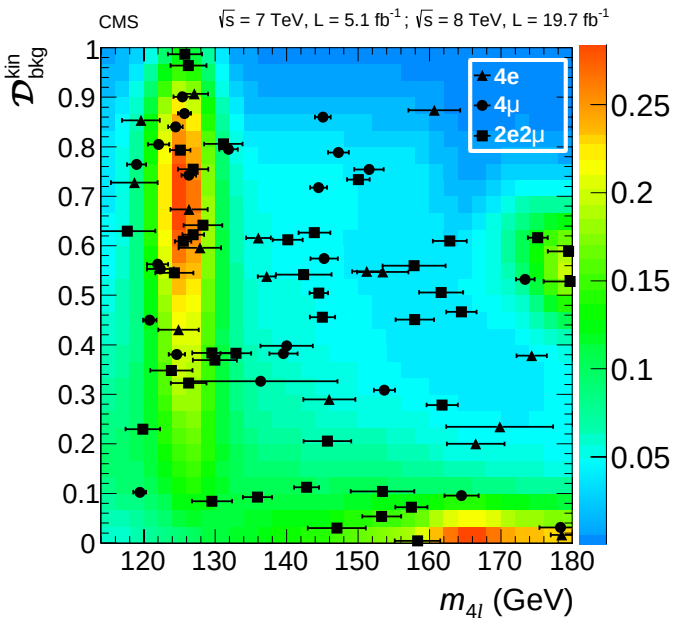
- "Golden channel" - Narrow mass peak on small background
- Select 4 leptons of appropriate charge and flavour combinations (+FSR recovery) with $40 < m_{Z1} < 120$ GeV, $12 < m_{Z2} < 120$ GeV
- Electron acceptance: $|\eta| < 2.5$, $p_T > 7$ GeV, Muon acceptance: $|\eta| < 2.4$, $p_T > 5$ GeV
- Irreducible $ZZ \to 4\ell$ continuum background estimated from MC
- Reducible $Z + b\bar{b}$ and $t\bar{t}$ backgrounds estimated from Z + same-sign dilepton/Z + loose dilepton samples, with fake rates from Z + loose ℓ sample

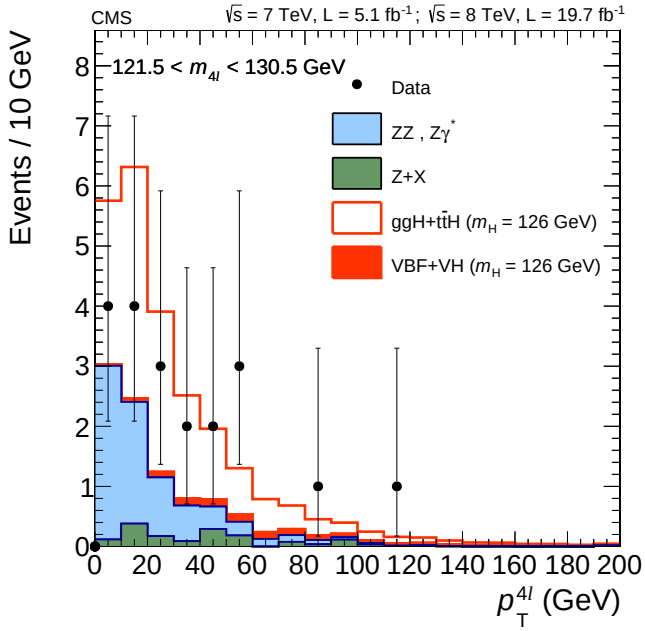




$H \to ZZ \to 4\ell$ Results

- Results extracted from 3d unbinned maximum likelihood fit to $m_{4\ell}$ distribution with matrix element likelihood discriminant and $p_T^{4\ell}$

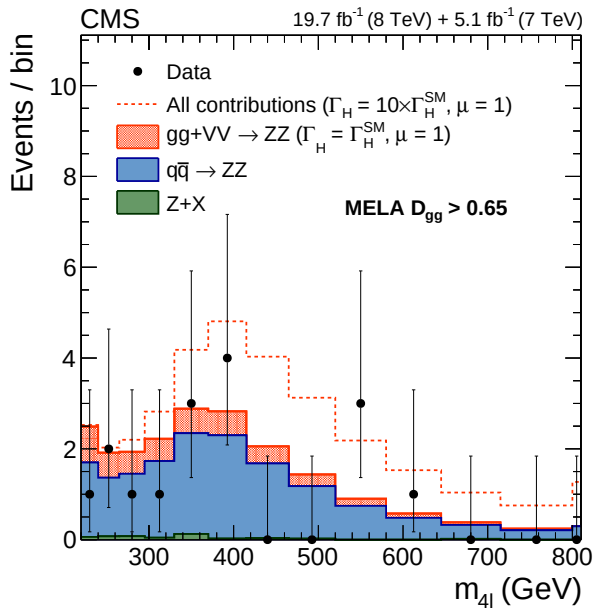


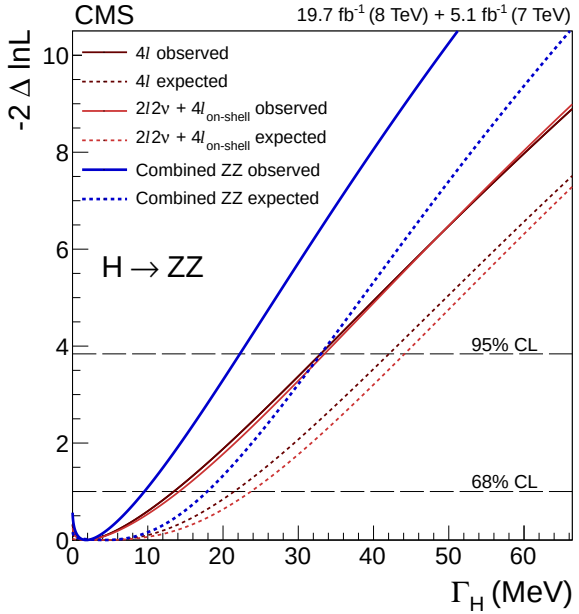


- $\sigma/\sigma_{SM} = 0.93^{+0.26}_{-0.23}(\text{stat.})^{+0.13}_{-0.09}(\text{syst.})$, 6.8σ observed significance (6.7σ expected)
- $m_H = 125.6 \pm 0.4(\text{stat.}) \pm 0.2(\text{syst.})$ GeV

$H \to ZZ \to 4\ell$: Indirect Width Constraint

- High mass tail sensitive to Higgs width through $gg \to H^* \to ZZ + gg \to ZZ$+interference
- Indirect constraint on width with simultaneous fit to high mass region (assuming no new particles in the gluon fusion production loop)

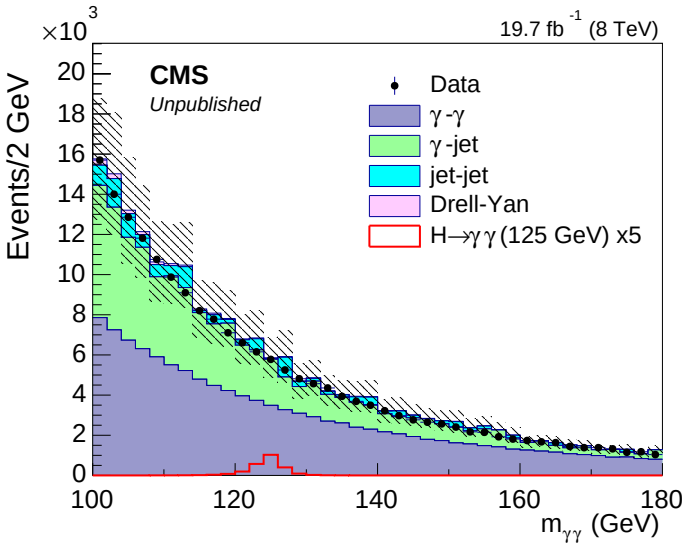


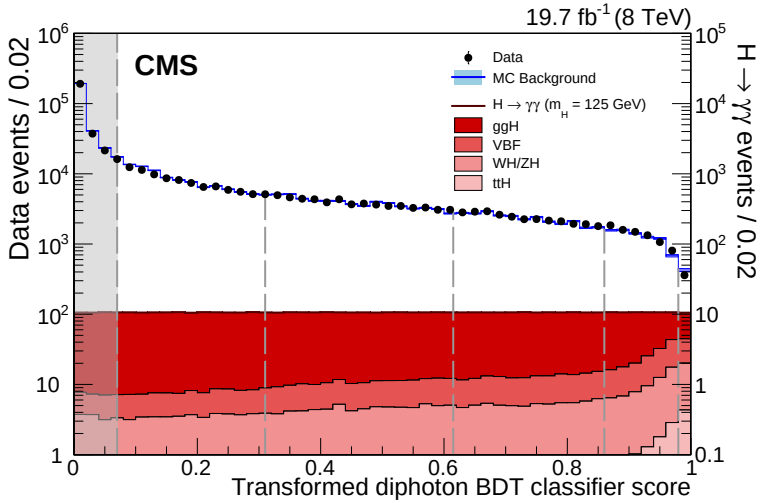


- $\Gamma_H < 22$ MeV (95% C.L.) ($\Gamma_{SM} \sim= 4$ MeV)

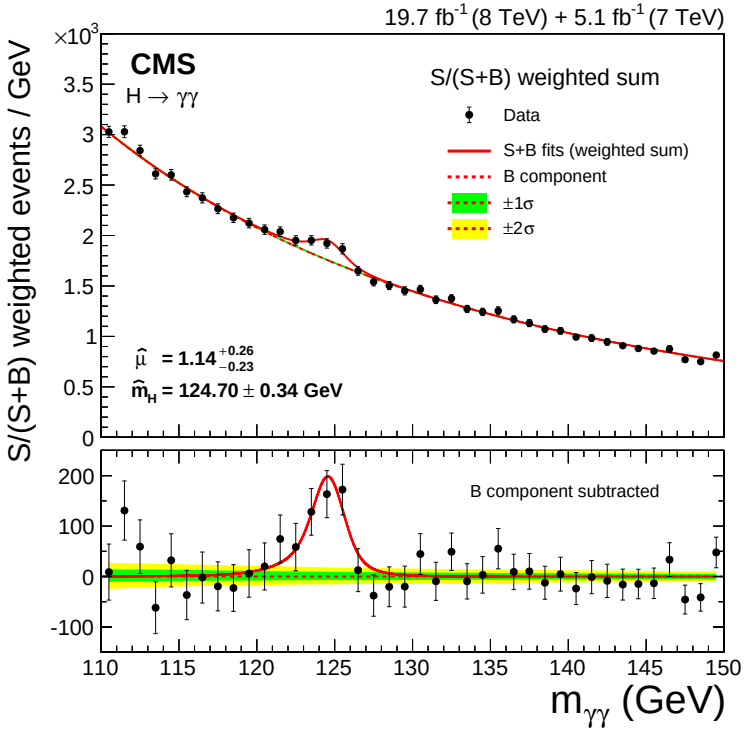
$H \to \gamma\gamma$

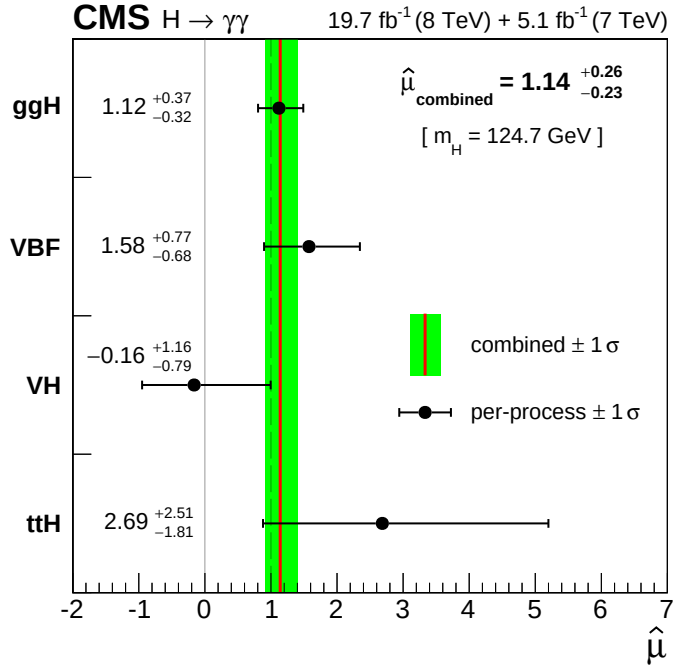
- Select two isolated high p_T photons
- Multivariate energy corrections for local and global electromagnetic cluster containment (Resolution and energy scale corrections from $Z \to ee$)
- Primary vertex selection ambiguous in high pileup: combine information on track recoil against di-photon system with conversion pointing where available (correct vertex in $\sim 80\%$ of events)
- Multivariate discriminant used to categorize events based on kinematics, photon identification quality, per event mass resolution





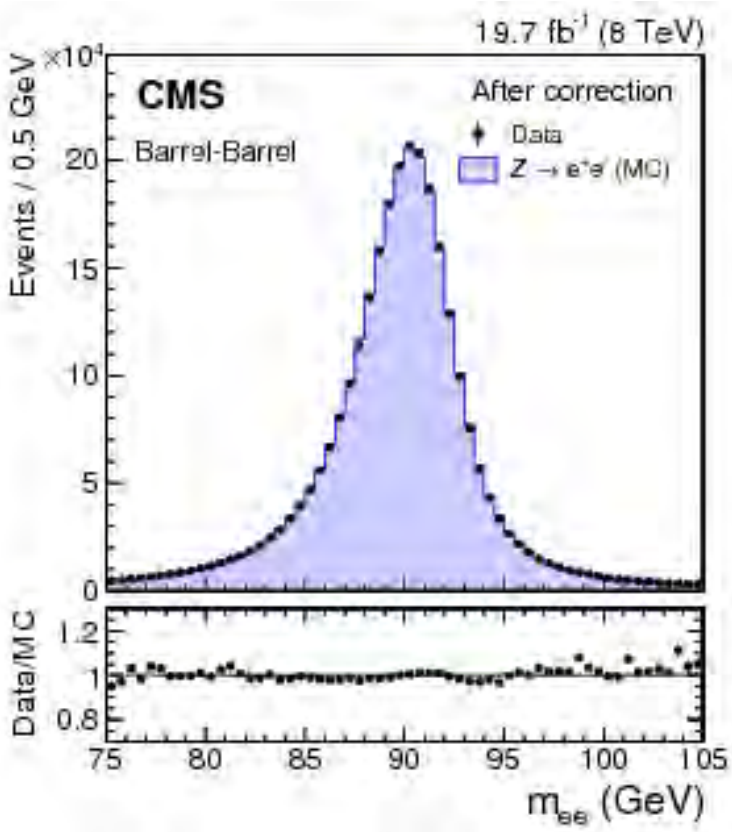
$H \to \gamma\gamma$

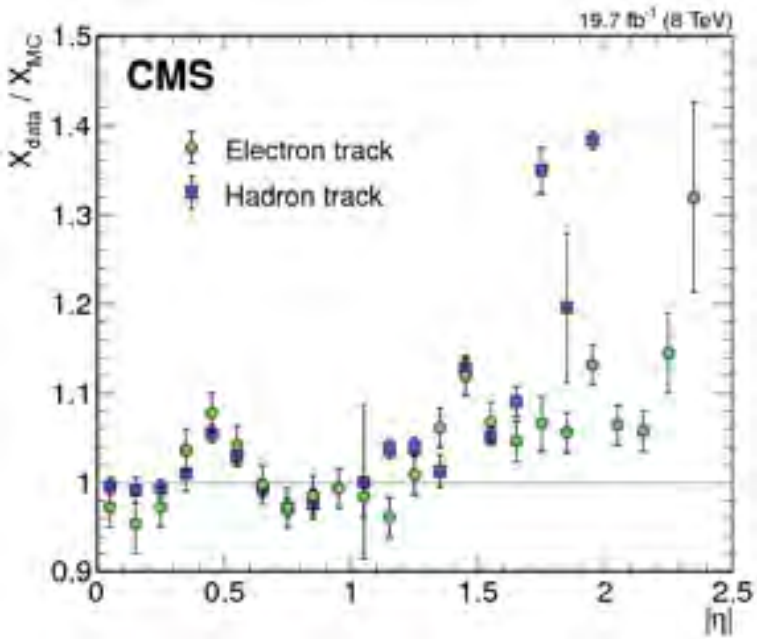




- Events further categorized to tag production modes
- Overall $\sigma/\sigma_{SM} = 1.14 \pm 0.21(\text{stat.})^{+0.09}_{-0.05}(\text{syst.})^{+0.13}_{-0.09}(\text{th.})$
  5.7σ observed significance (5.2σ expected)

$H \to \gamma\gamma$

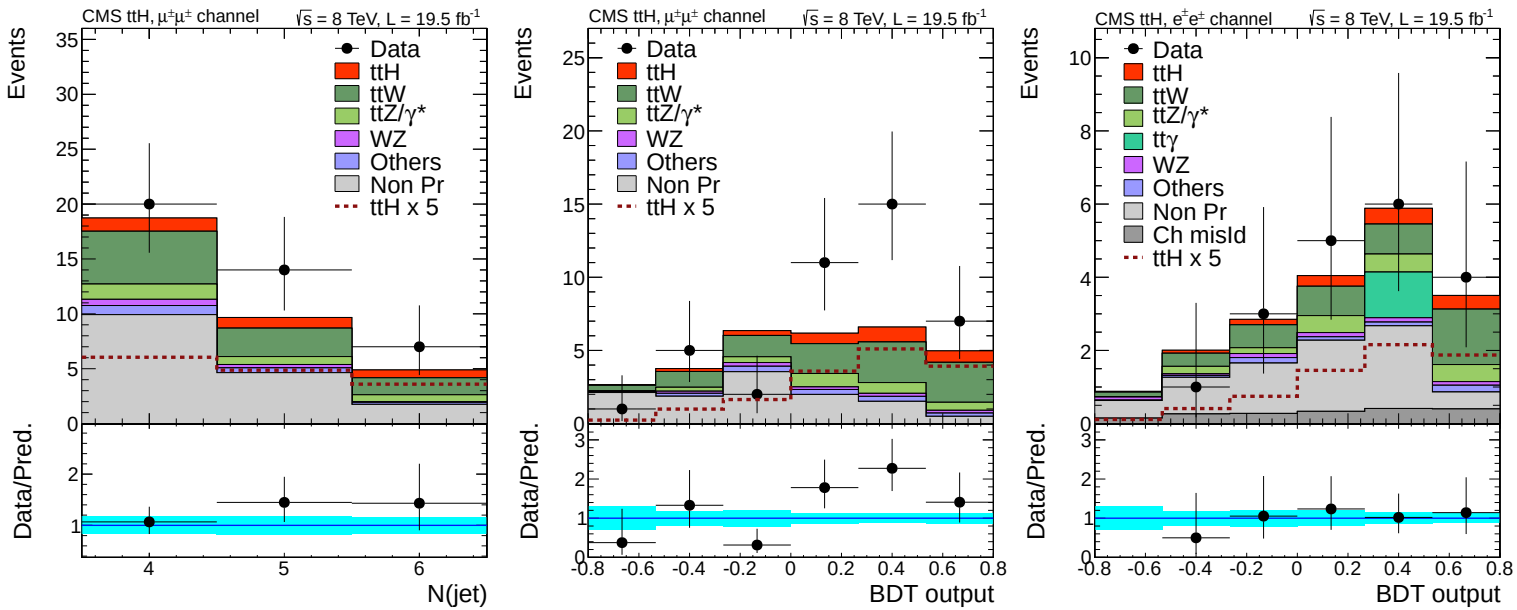




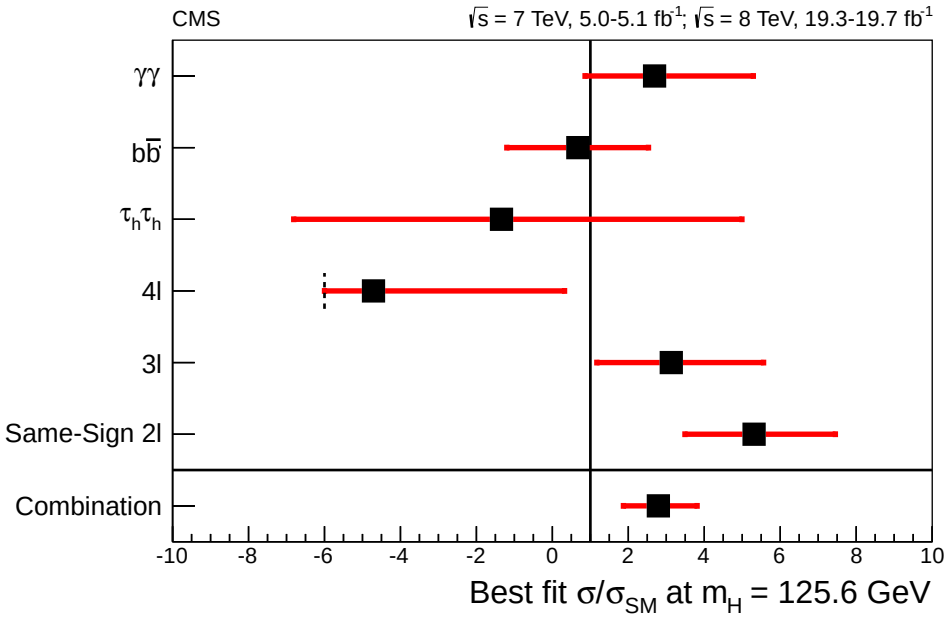
- Energy scale and resolution exhaustively calibrated and checked with $Z \to ee$ with detailed simulation studies for electron$\to$ photon extrapolation
- $m_H = 124.70 \pm 0.31(\text{stat.}) \pm 0.15(\text{syst.})$ GeV

$tt + H$

- Dedicated $tt + H$ selections have been constructed for scalar decays to bb, hadronic taus, photons
- Additional $tt + H$ multilepton selections collect events from scalar decays to leptonic τ, WW, ZZ
- Dedicated lepton identification to suppress especially leptons from B decays in $t\bar{t}$+jets
- Select same sign leptons, or 3/4 leptons + 2 b-tagged jets, final selection with kinematic BDT



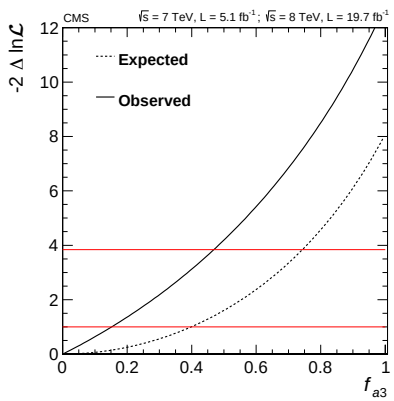
$tt + H$

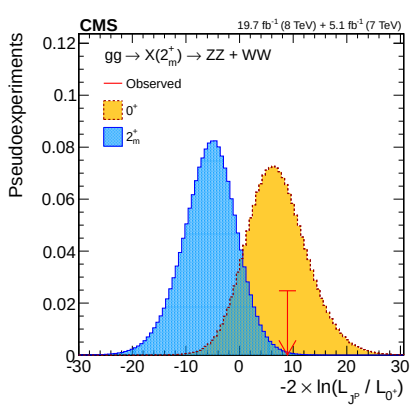


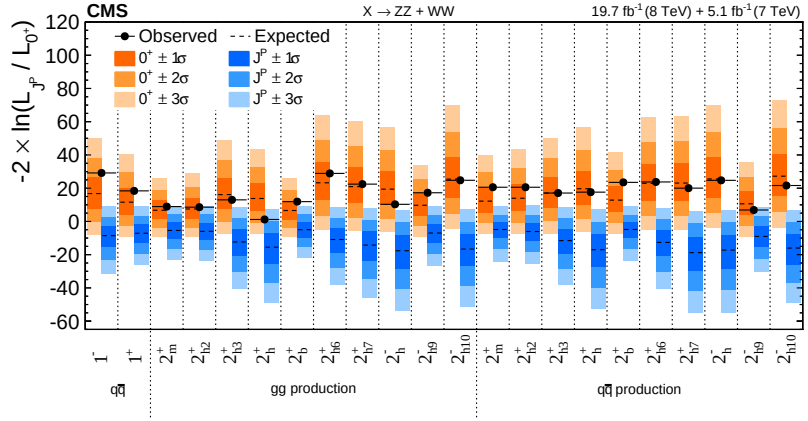
- Combined $tt + H$ $\sigma/\sigma_{SM} = 2.8^{+1.0}_{-0.9}$
- About 2σ high with respect to SM expectation, driven by $\mu^{\pm}\mu^{\pm}$ channel
- significance with respect to no-scalar hypothesis is 3.4σ (1.2σ expected)

Spin/Parity

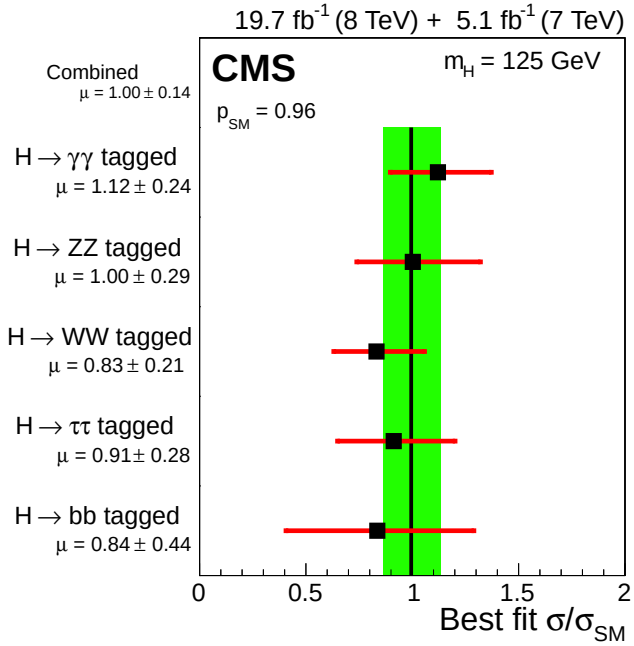
- Angular distributions in $ZZ, WW, \gamma\gamma$ decays used to test alternate spin/parity hypotheses
- Pure pseudoscalar and wide range of spin 1 and 2 variations are strongly excluded (but parameter space of spin 2 is large)

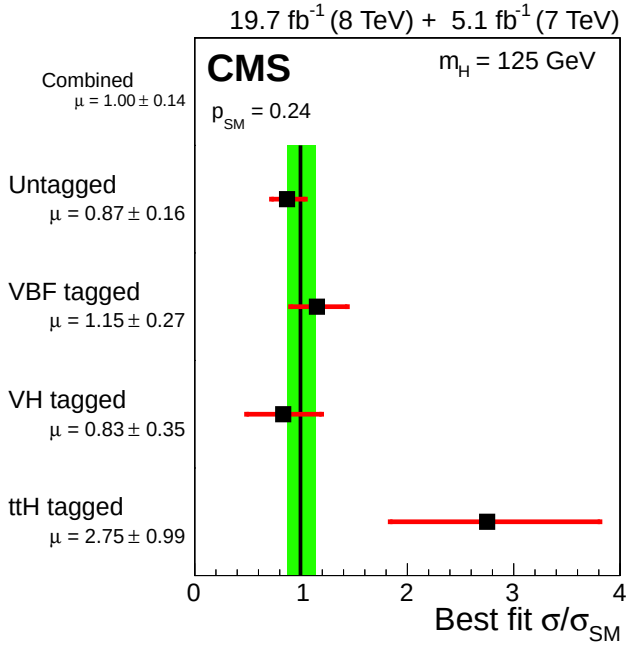






Conclusion: Run 1





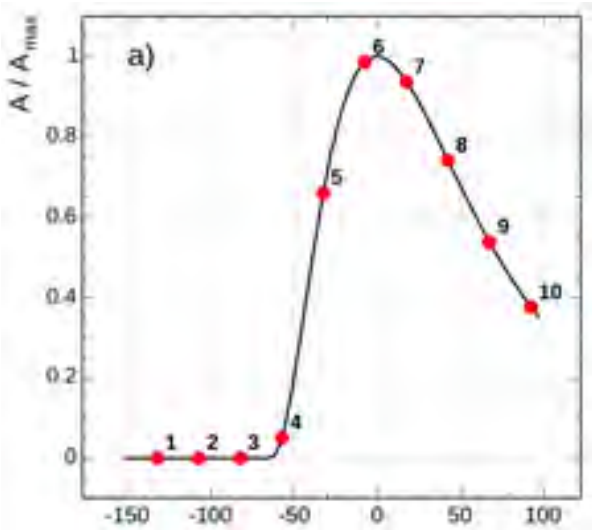
- Overall $\sigma/\sigma_{SM} = 1.00 \pm 0.14$
- Combining $H \to ZZ, \gamma\gamma$: $m_H = 125.02^{+0.26}_{-0.27}(\text{stat.})^{+0.14}_{-0.15}(\text{syst.})$
- Measured signal strengths broadly consistent with SM expectations
- Tests of angular distributions indicate particle is indeed a scalar

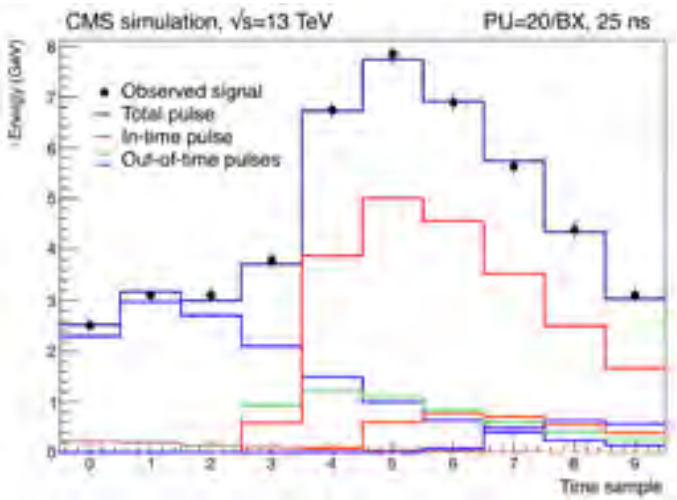
Prospects for Run 2

- Gluon fusion Higgs cross section increases by ~ 2.3 from 8 TeV to 13 TeV
- $tt + H$ cross section increases by ~ 4
- Background cross sections of course also increase
- Up to ~ 100 fb^{-1} expected for Run 2
- "signal strength" measured so far: model-dependent cross section extrapolated to full phase space
- Run 2: **Fiducial Cross Sections, Differential Cross Sections**
- Complete the transition from discovery to precision physics
- Maintain object and analysis performance with 25ns bunch spacing

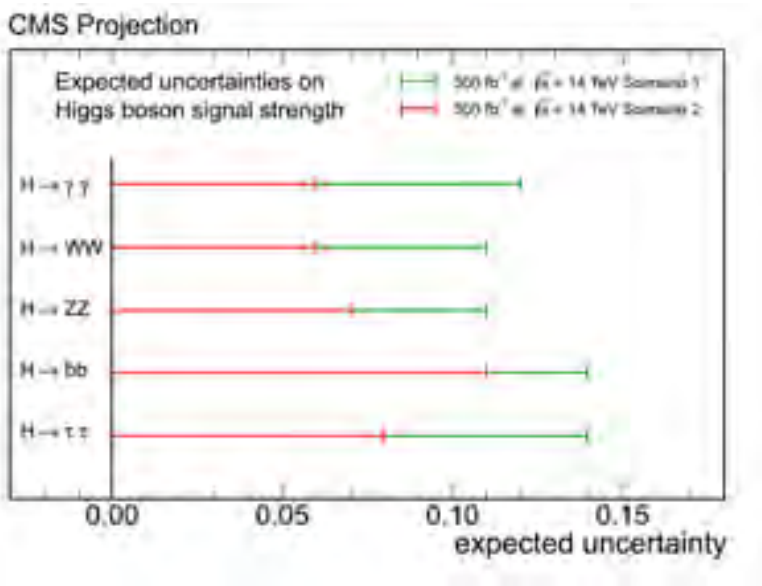
Actions for Run 2

- Incorporating knowledge/experience/developments/optimization from Higgs analyses into default reconstruction (Global Event Description)
- Improved Monte Carlo simulation: NLO+PS QCD description for all Higgs production modes, merged NLO+PS QCD accuracy for additional jets
- New calorimeter local reconstruction to mitigate out of time pileup with 25ns bunch spacing.

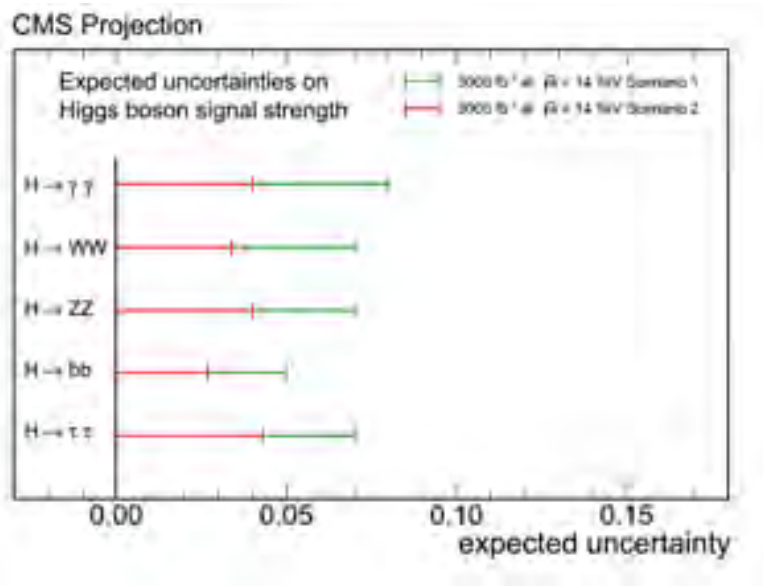




Beyond Run 2: HL-LHC



(f) 300 fb^{-1}

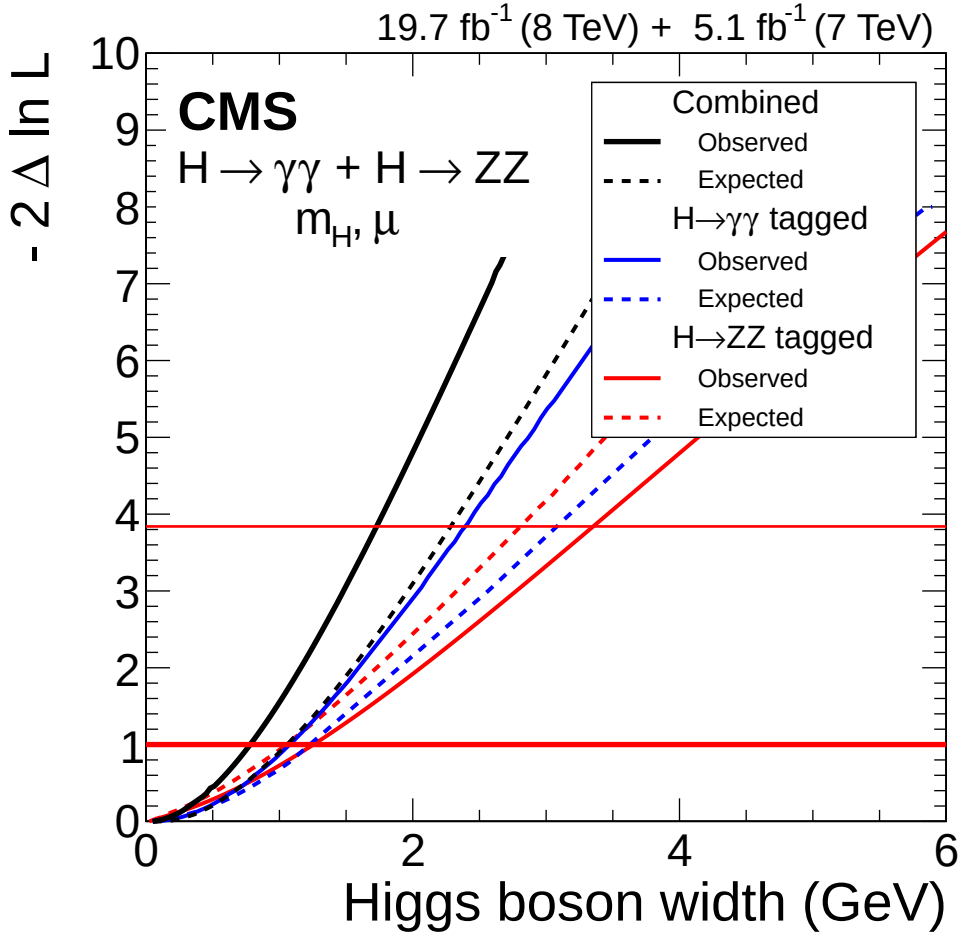


(g) 3000 fb^{-1}

- Naive scaling of signal and background yields by cross section and luminosity, starting from preliminary results
- Neglects analysis improvements, degradation from higher pileup and detector aging, improvements from upgrade detector
- Depends on assumptions about systematic uncertainty evolution optimistic/pessimistic

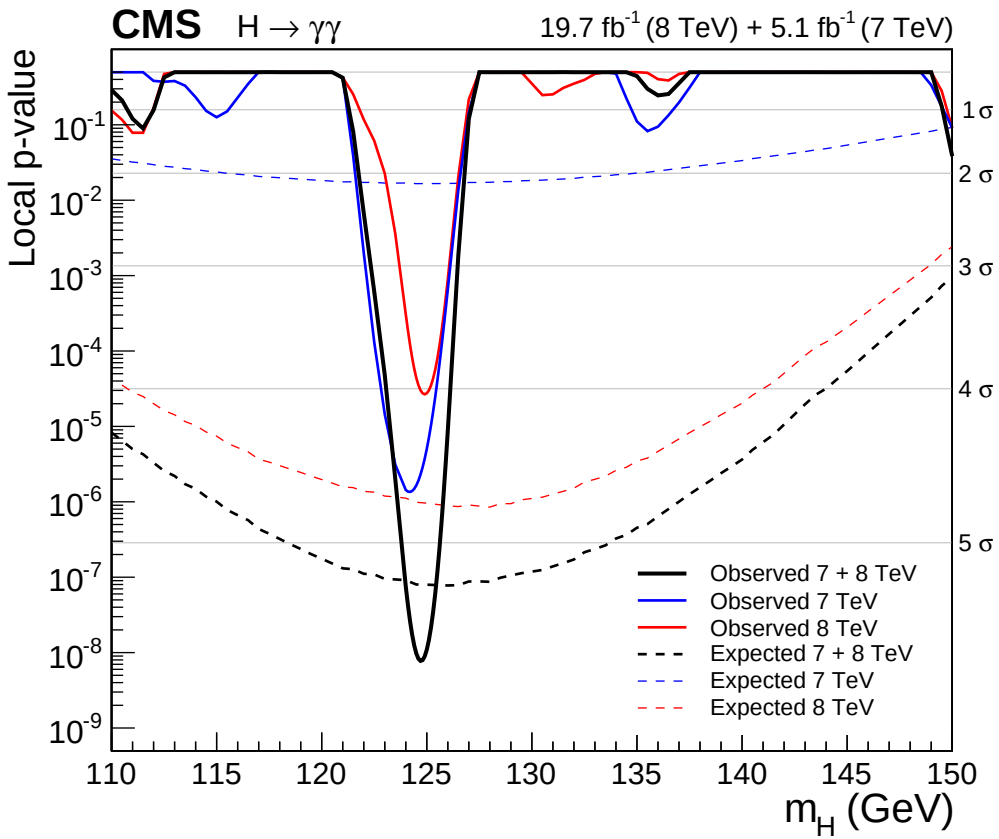
Backup

Direct Width Constraints

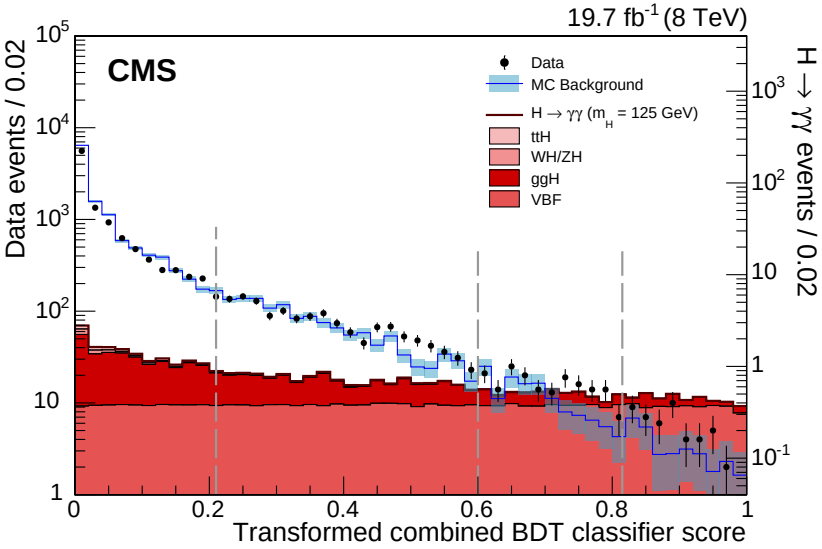


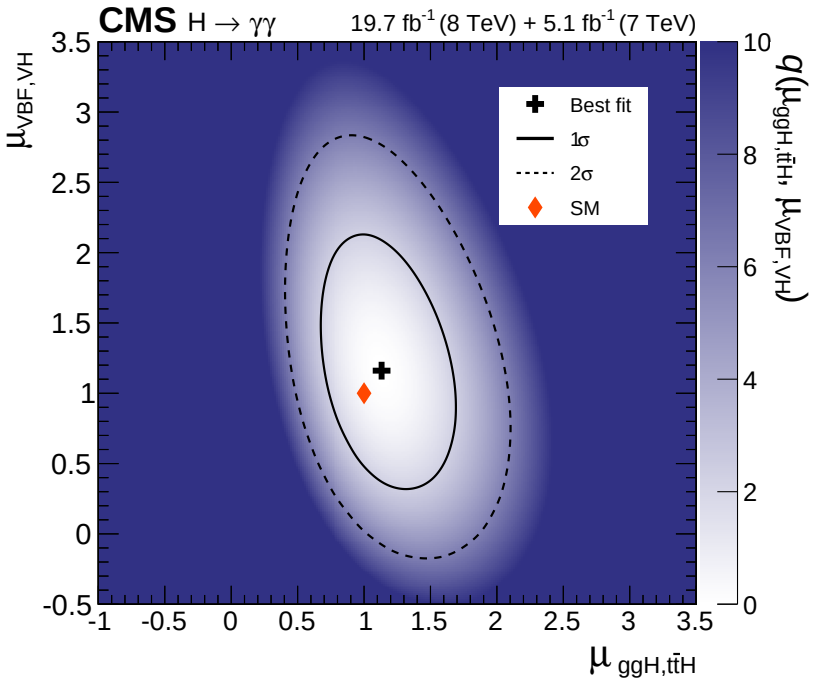
Gamma < 1.7 GeV (95% C.L)

$H \to \gamma\gamma$ p-value

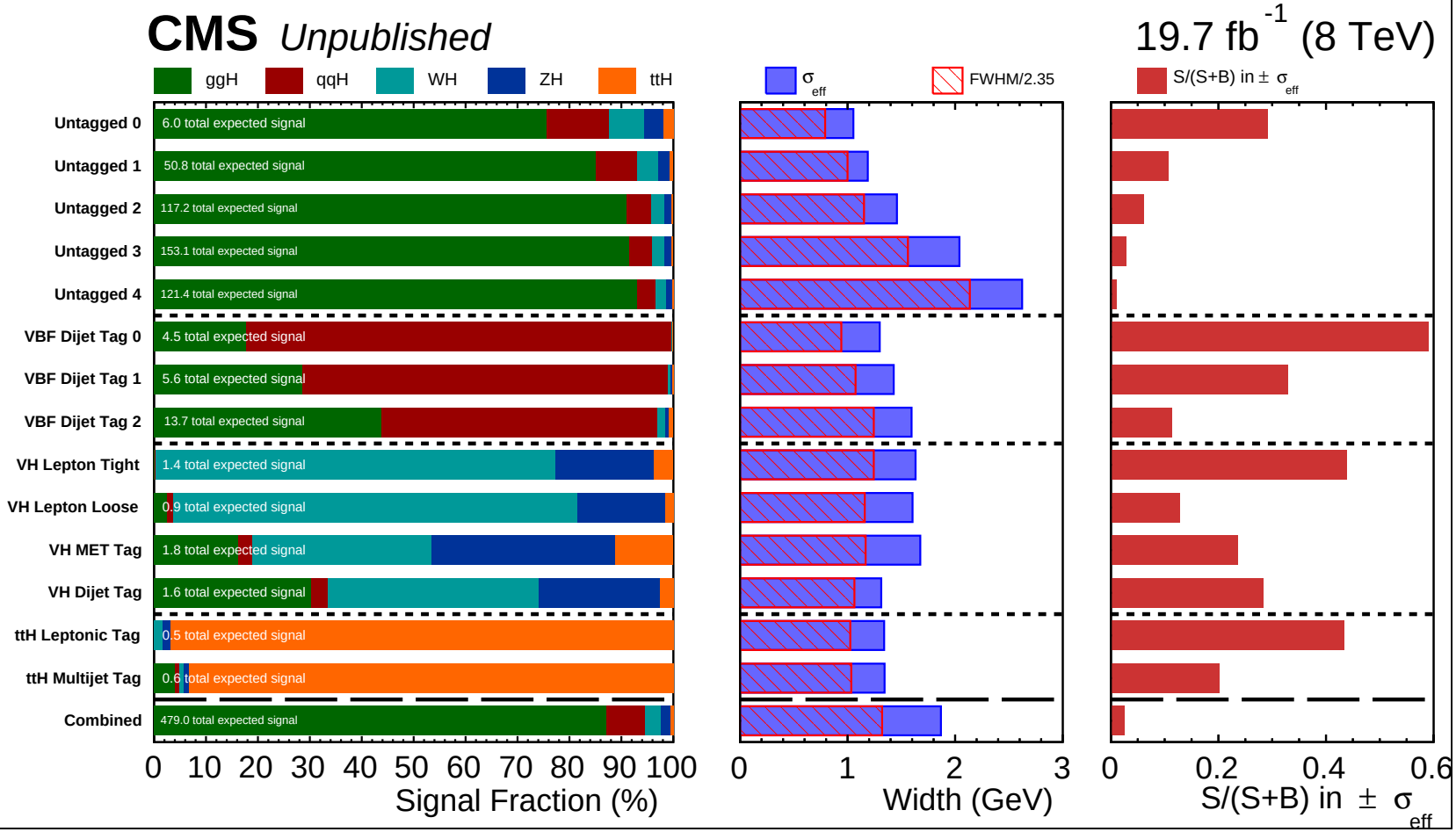


$H \to \gamma\gamma$ VBF Categorization MVA

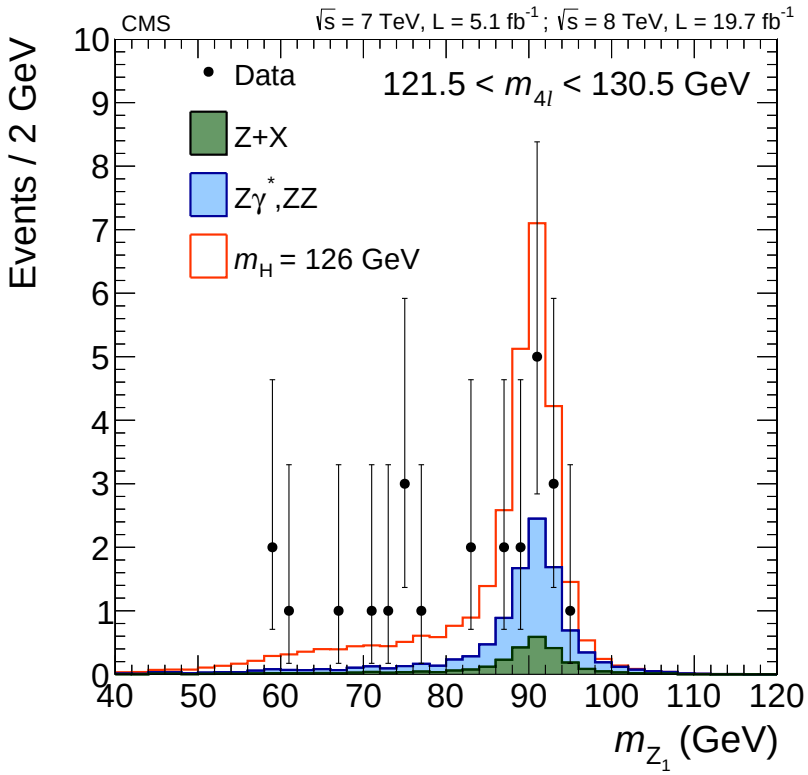




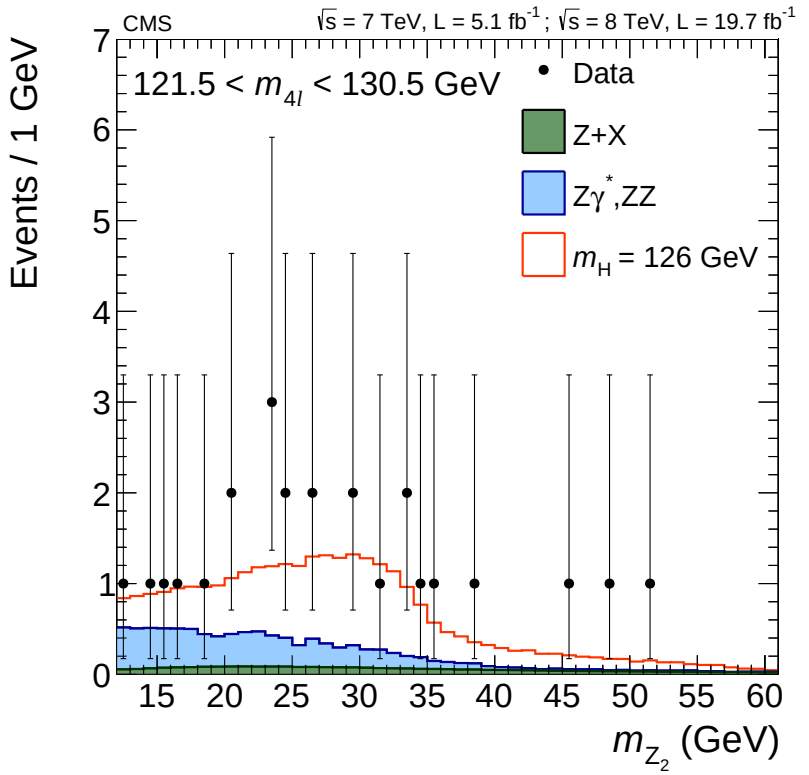
$H \to \gamma\gamma$ Category Composition



$H \to ZZ \to 4\ell$: $Z_{1,2}$ masses

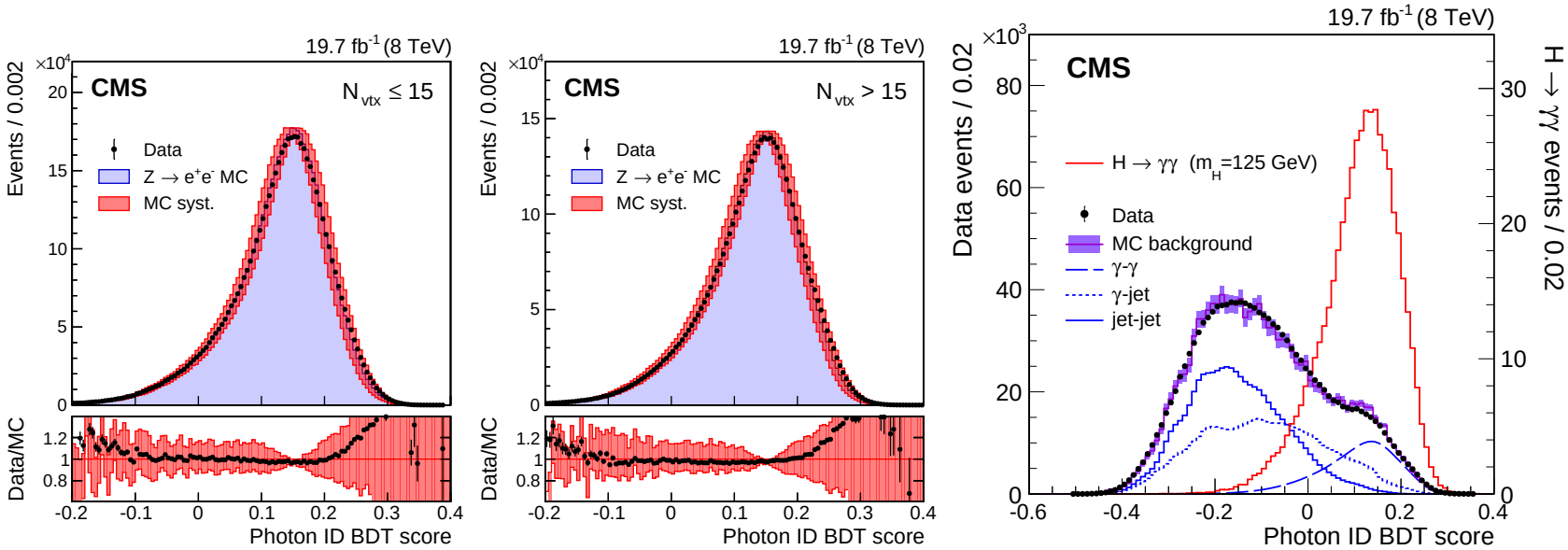


(h) M_{Z1}

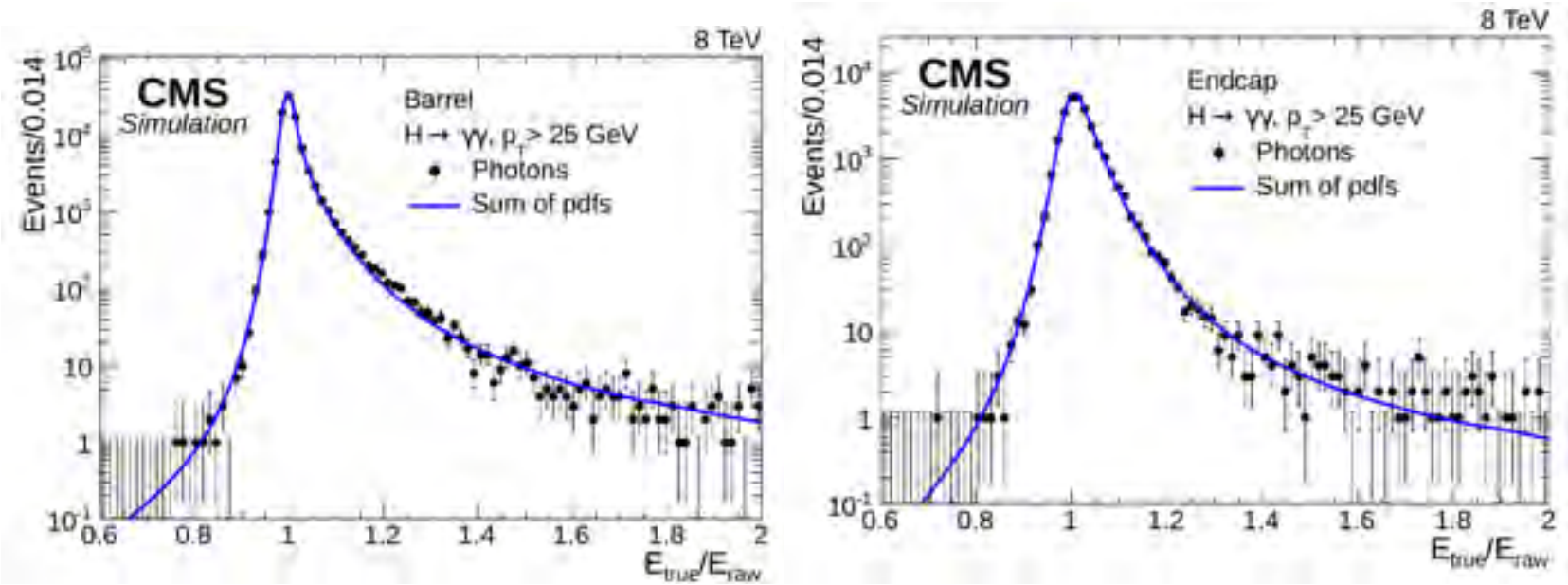


(i) M_{Z2}

$H \to \gamma\gamma$: Photon Identification

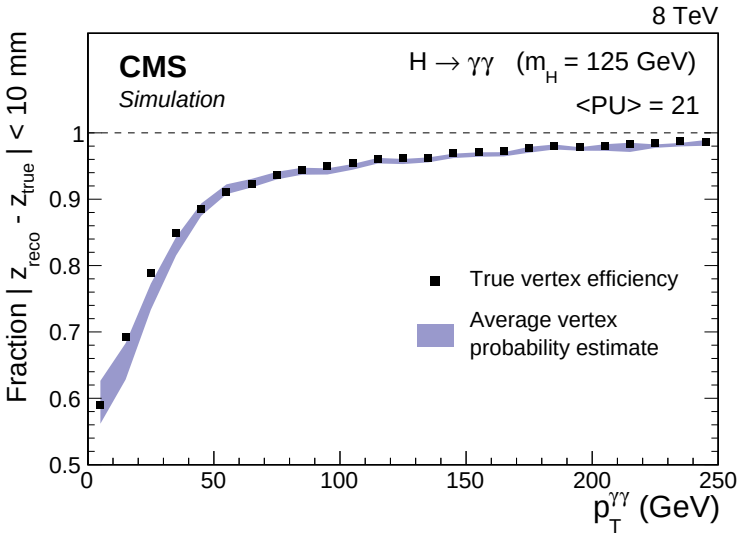


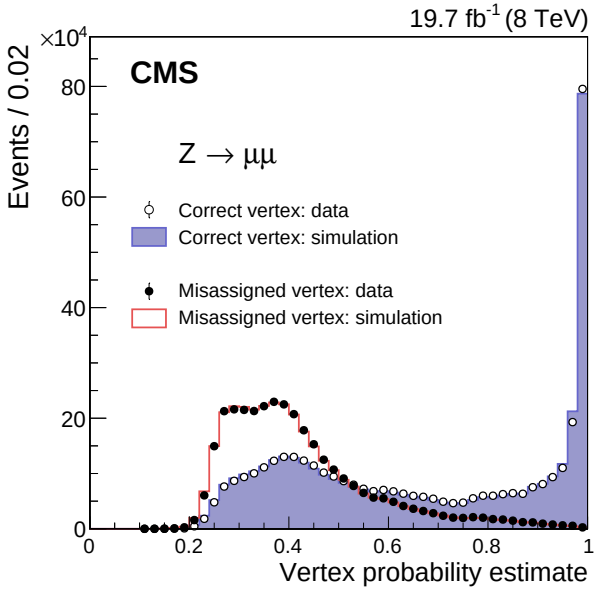
$H \to \gamma\gamma$: Photon Energy Regression

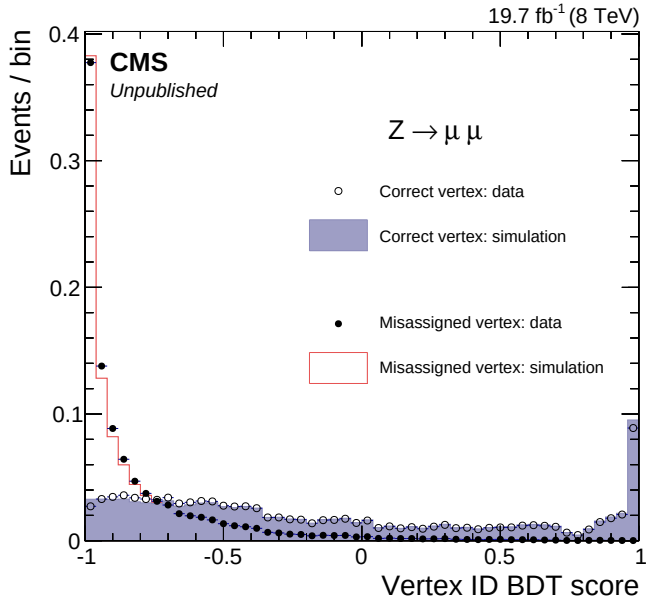


- Multivariate likelihood fit to E_{True}/E_{Raw} distribution in training sample as a semi-parametric function of input variables
- Response distribution fit with double-sided crystal ball in infinitesimal slices of input variables (shower shapes, cluster positions, N_{vtx}) constructed with BDT's
- Corrects energy scale (and estimates per-photon resolution) for local (gaps and cracks) and global (conversion/Bremsstrahlung) shower containment, pileup contamination

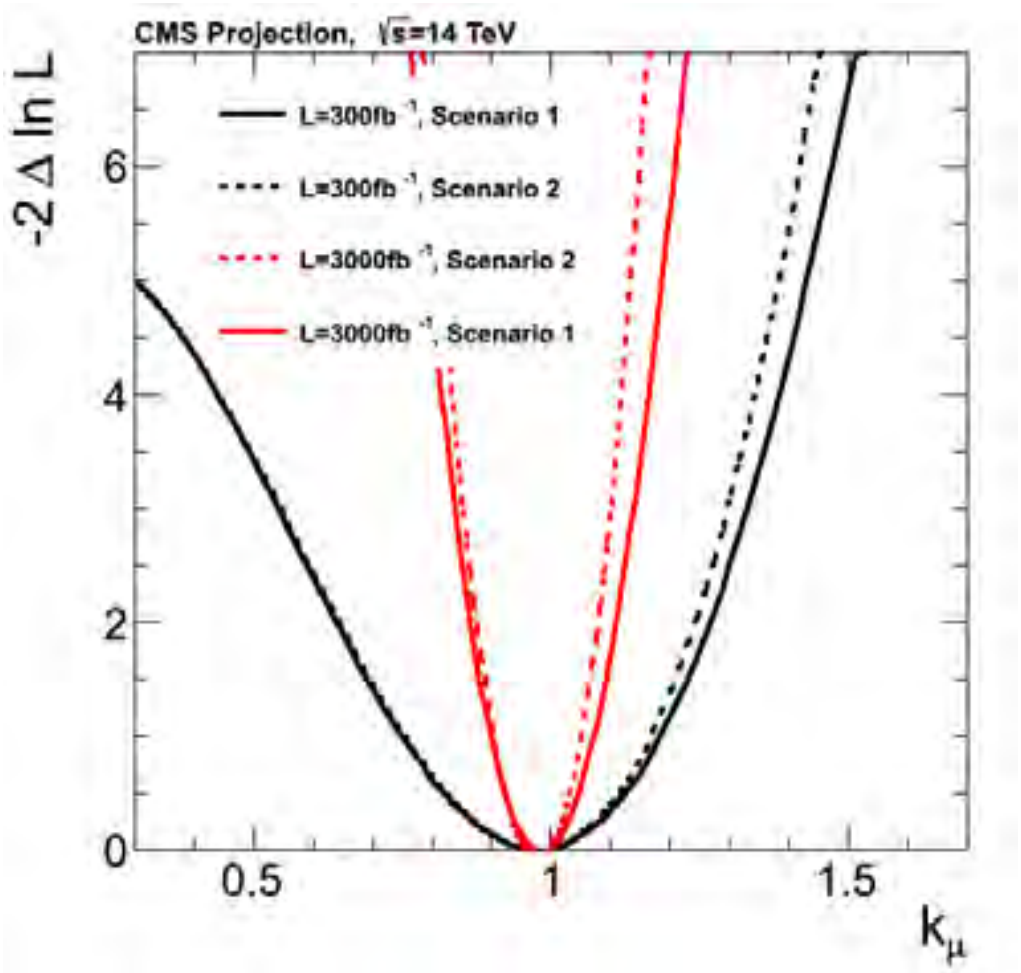
$H \to \gamma\gamma$: Vertex Identification



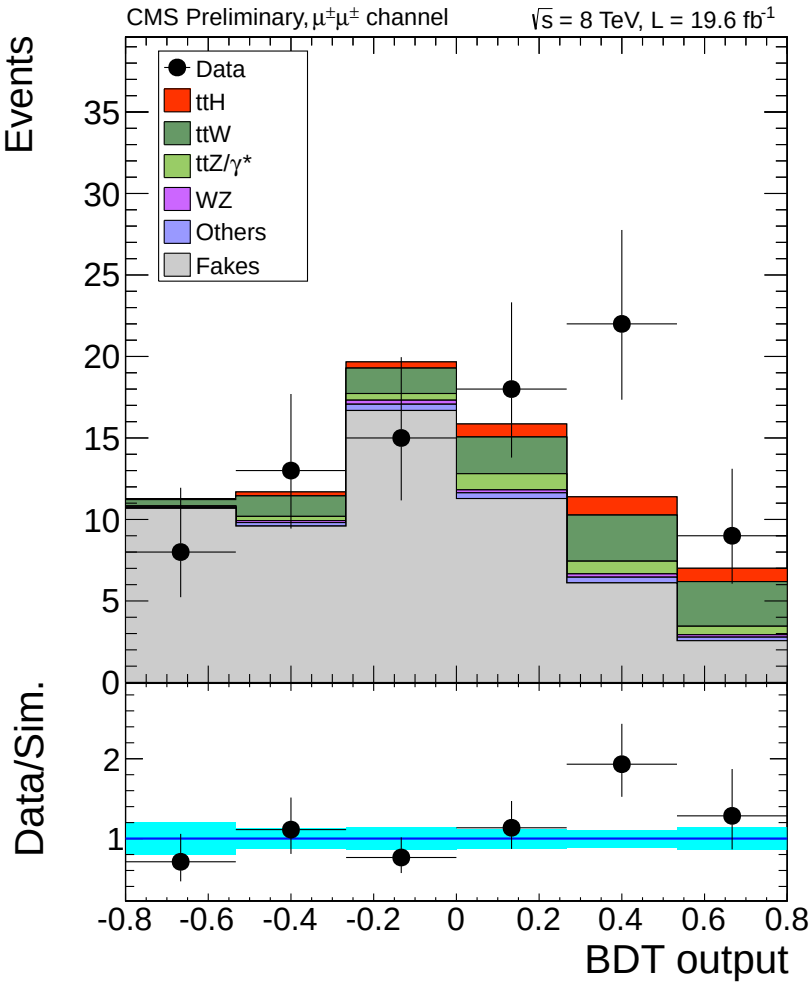




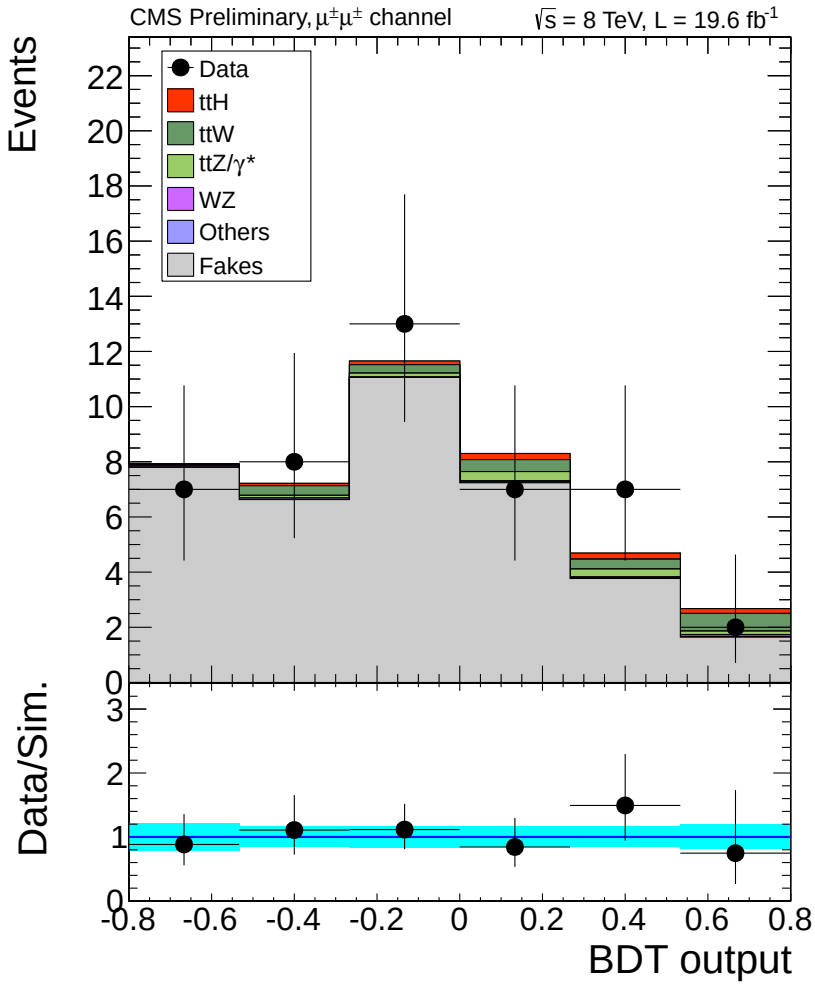
HL-LHC $H \to \mu\mu$



$tt + H \rightarrow$ leptons ($\mu^{\pm}\mu^{\pm}$): Loose/Inverted Muon ID

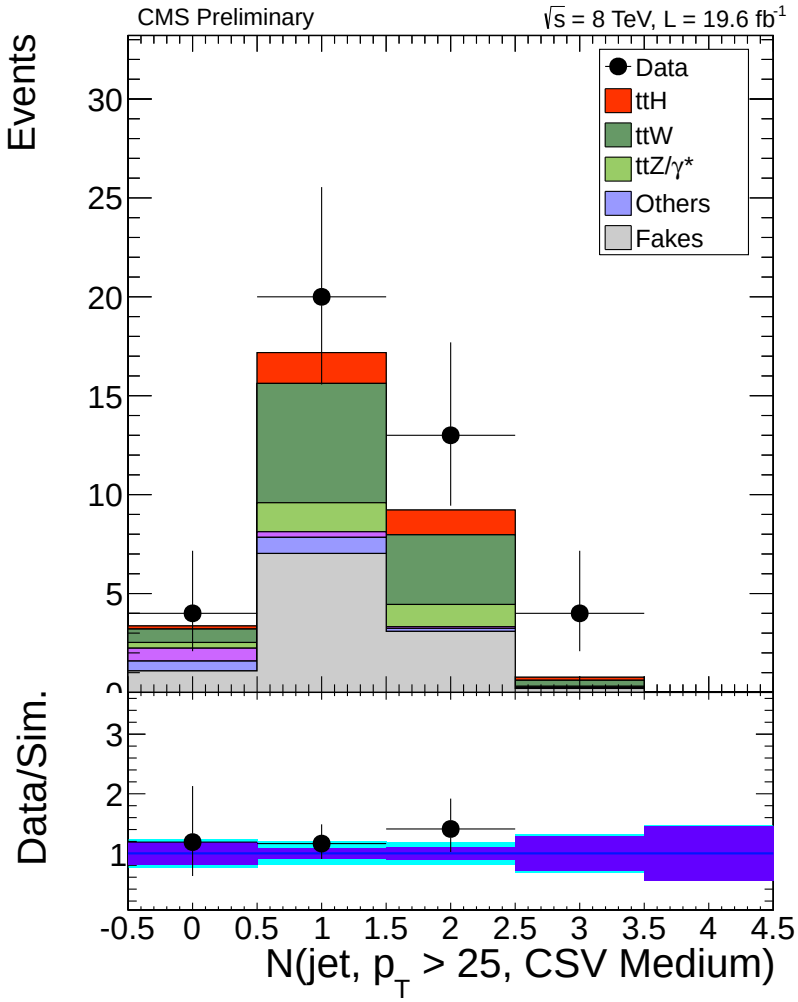


(j) Loose ID

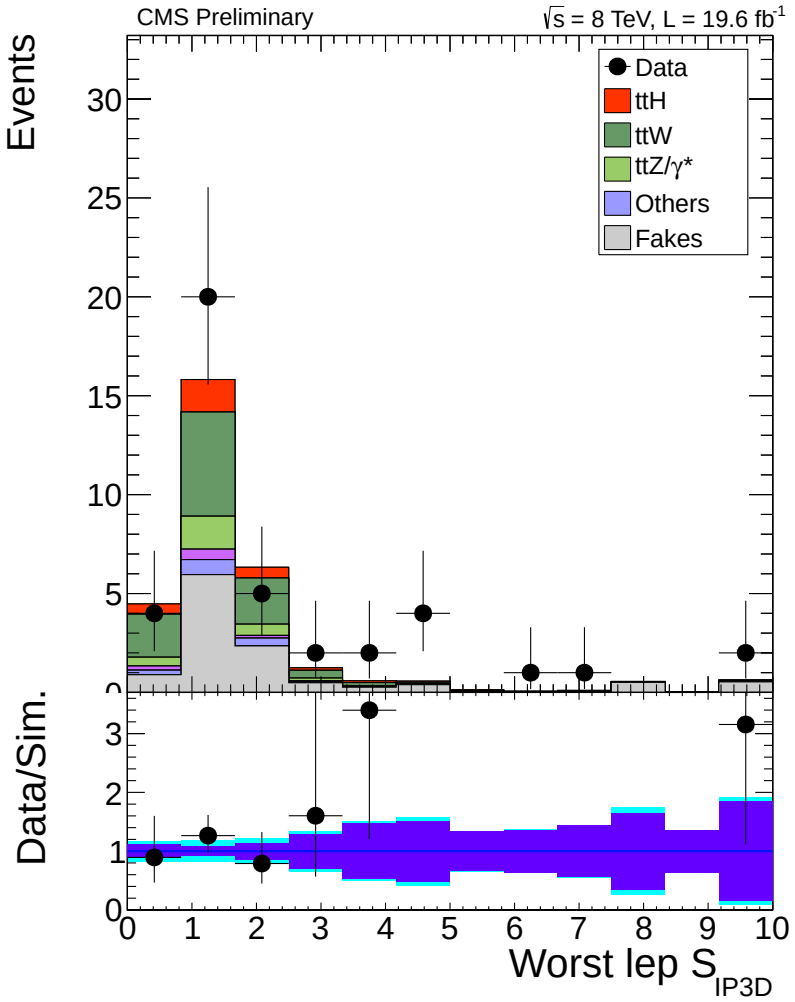


(k) Inverted ID

$tt + H \rightarrow$ leptons $(\mu^{\pm}\mu^{\pm})$



(l) N_{bjets}



(m) Max 3d impact parameter