Search for associated production of a Higgs boson with a single top quark

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for the CMS Collaboration
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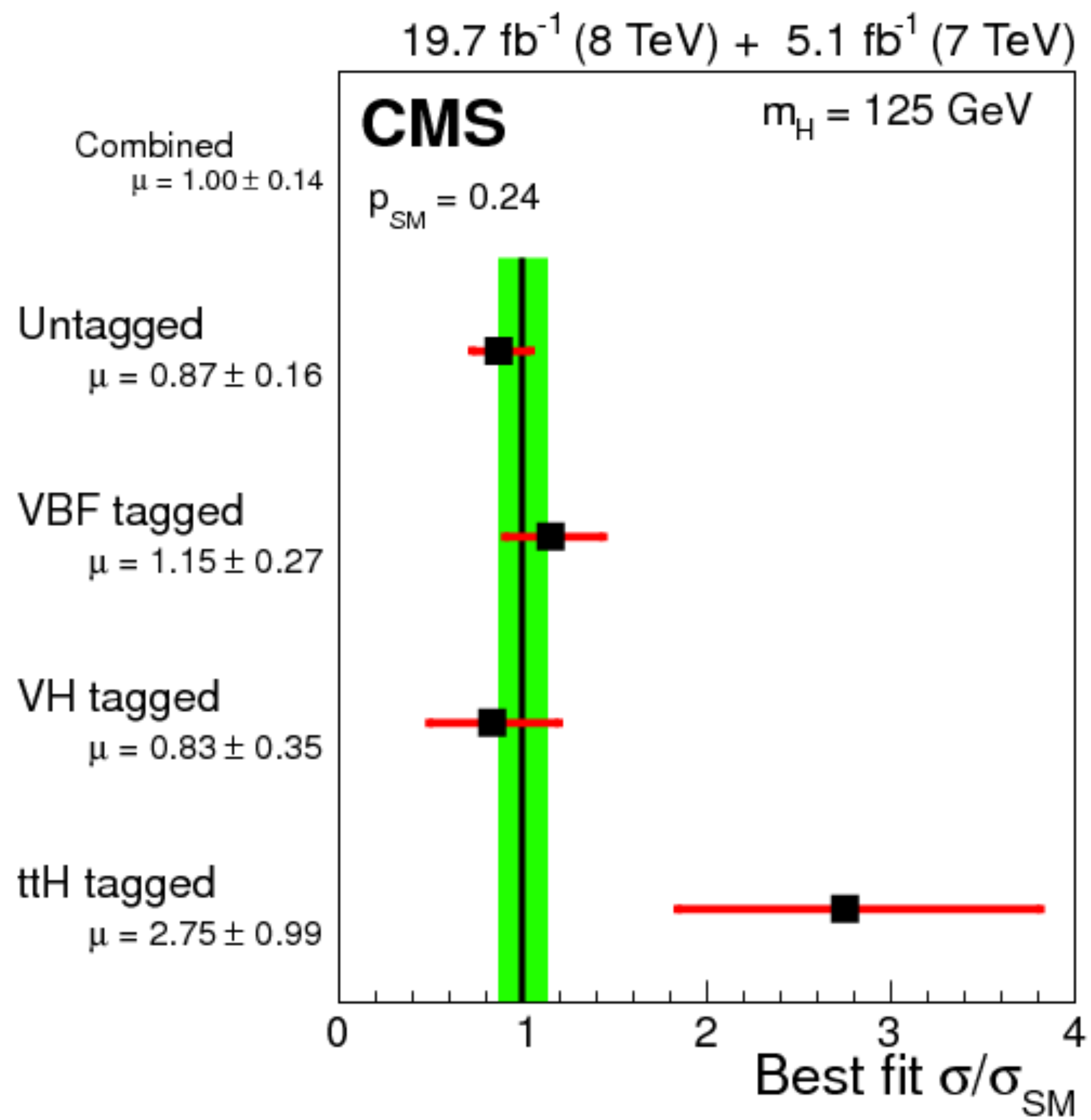
At the bottom

- We all know the four favorite Higgs production mechanisms and tend to forget about another
- The SM cross section for single top plus Higgs production is ~1000x smaller than that for gluon fusion
  - $\sigma(tHq) = 18.3$ fb
- Why even bother looking?



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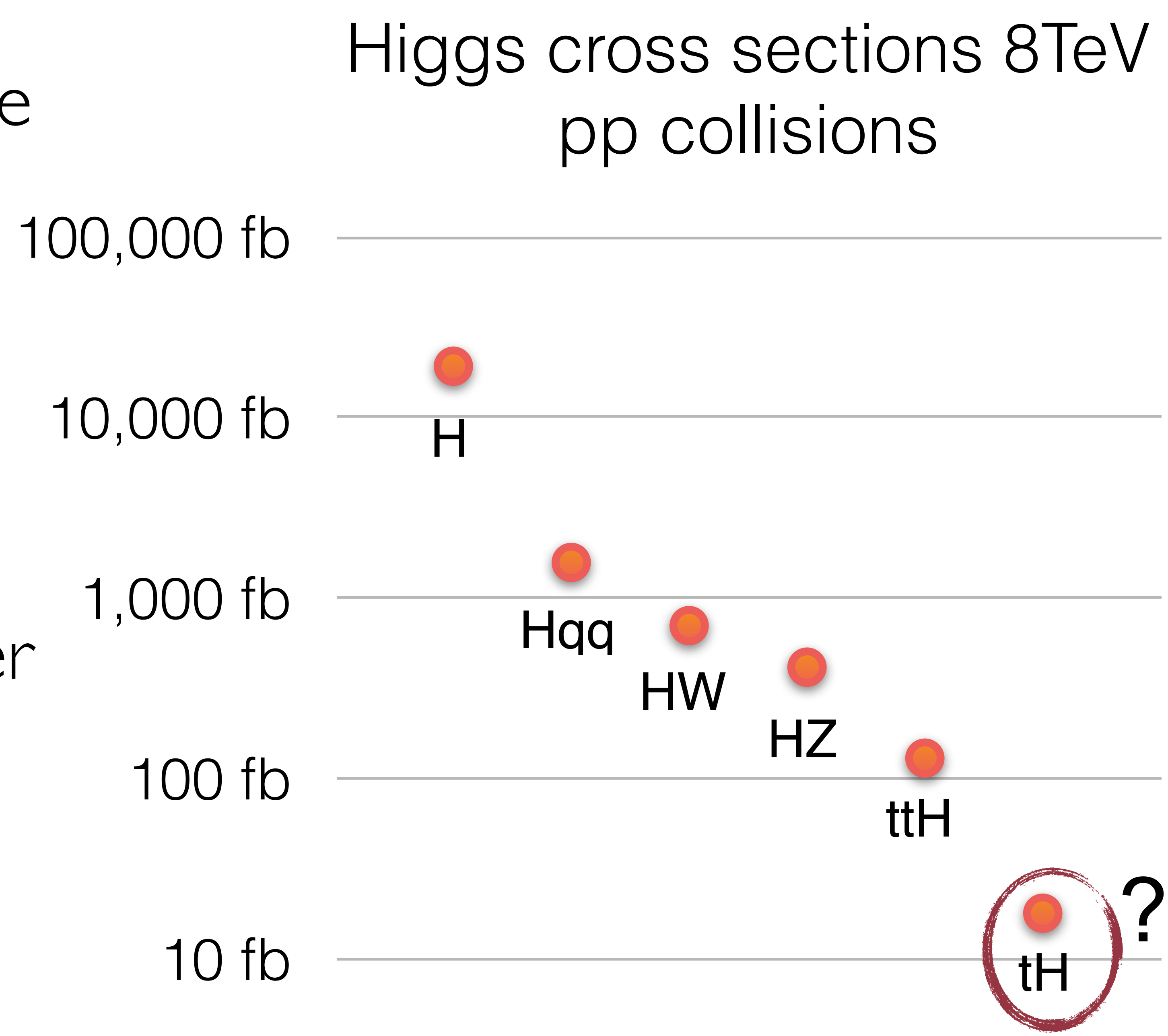
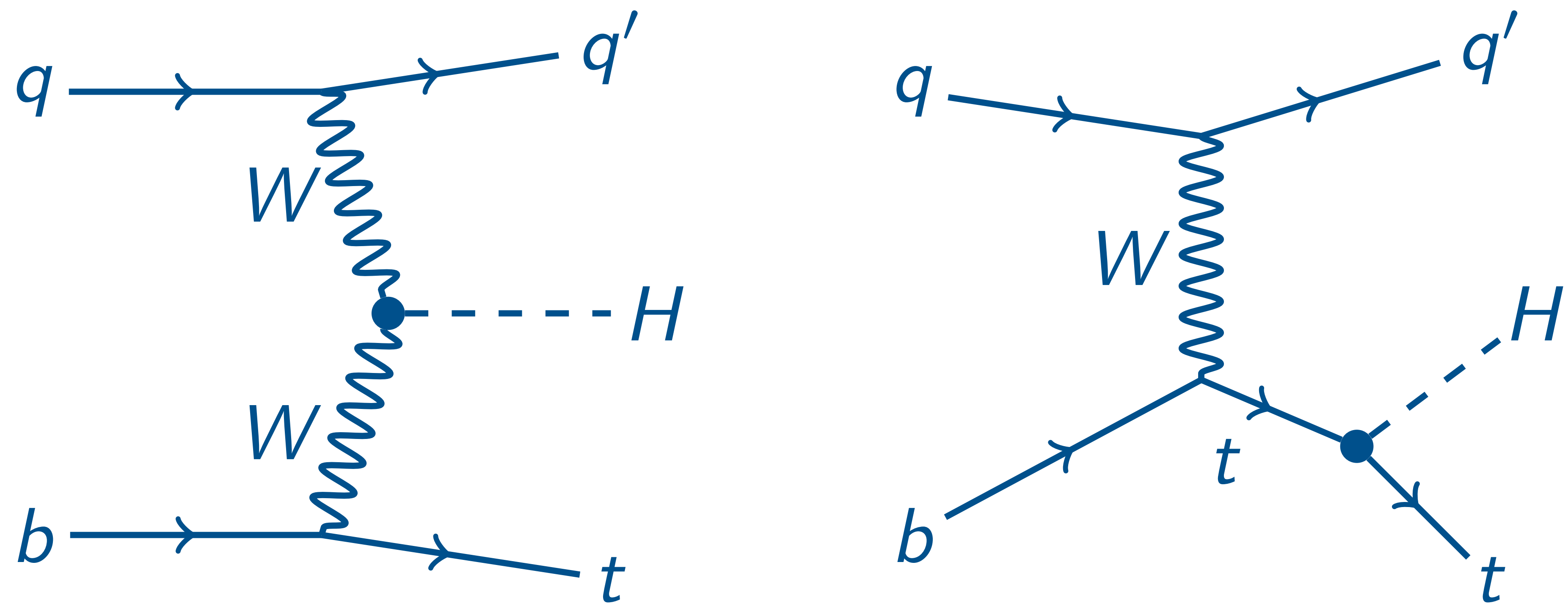
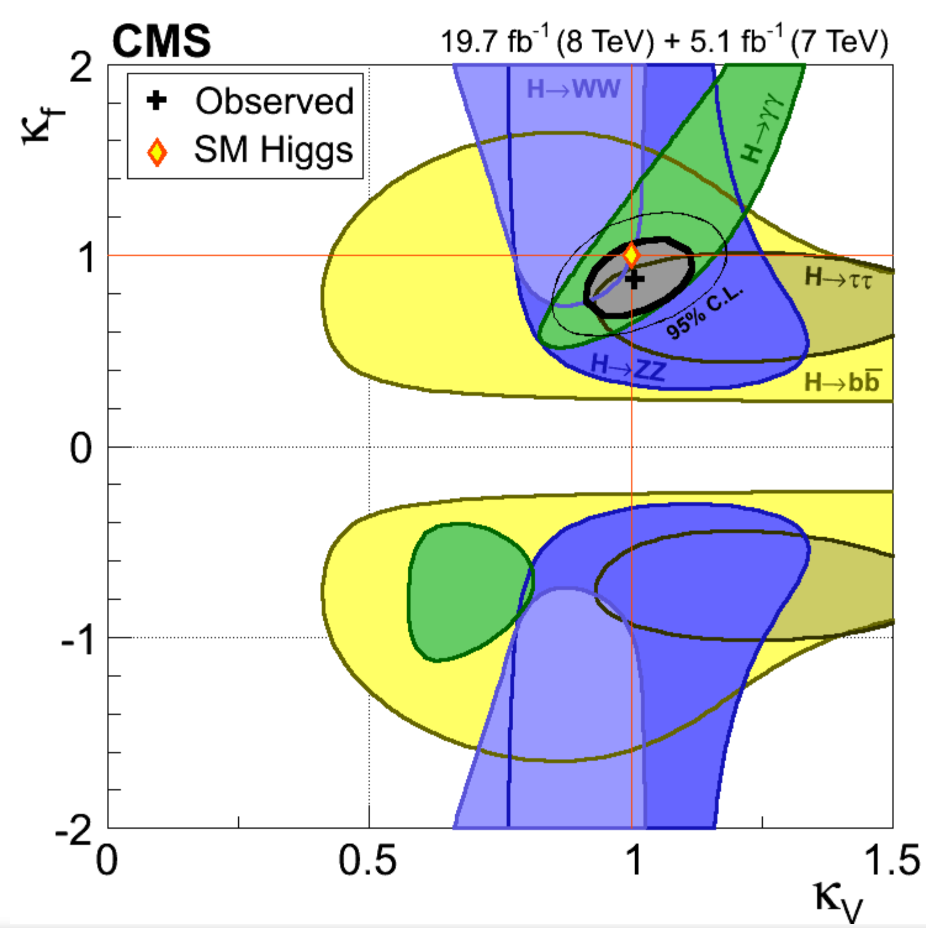


Discovery through interference

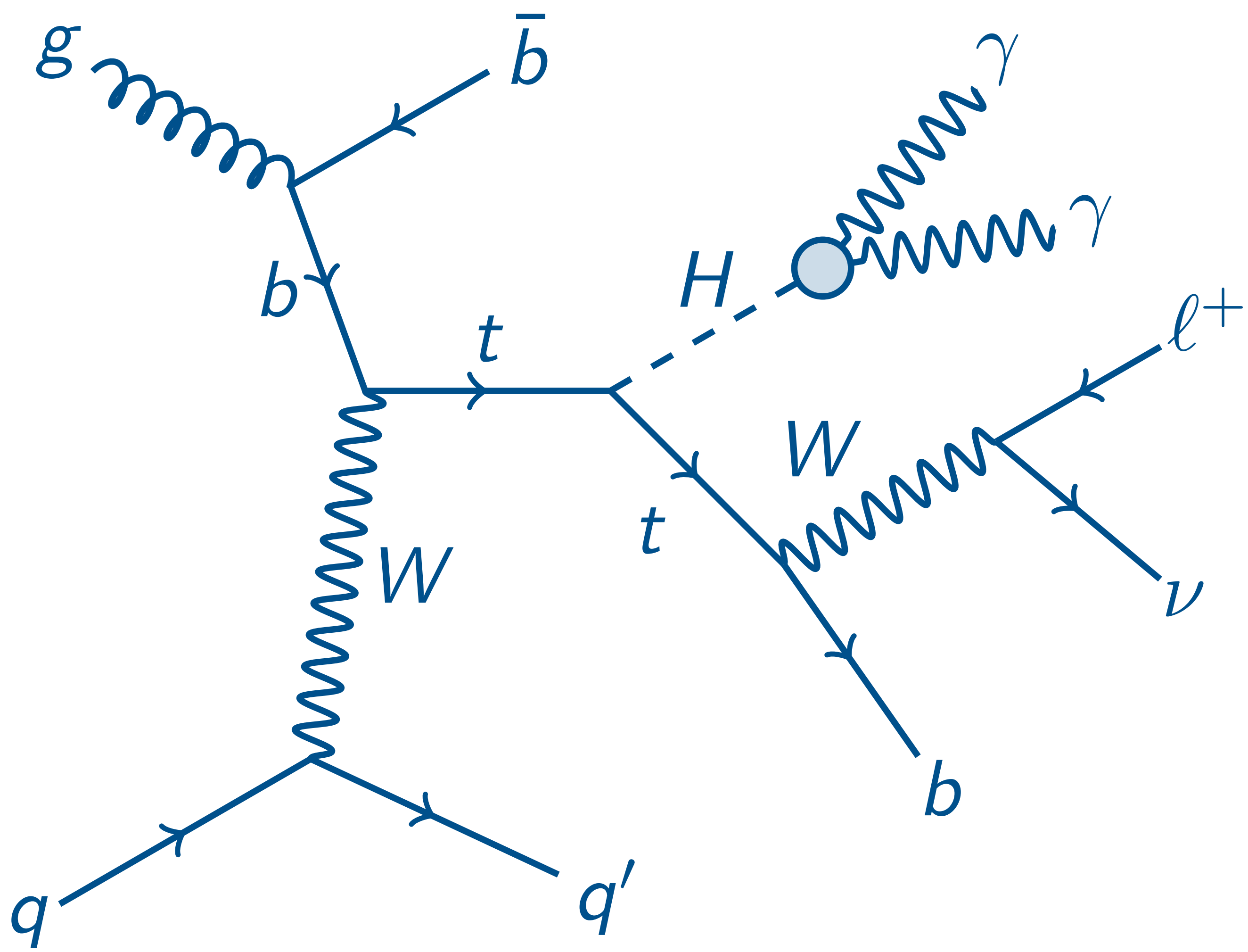


- Small cross section due to destructive interference between two diagrams
- Should the sign of the top Yukawa coupling be inverted (y_t = -1), interference is constructive, and cross section is x13 larger!
- y_t = -1 disfavored, but not eliminated
  - Composite Higgs, FCNC processes could enhance cross section further



Searches for tHq (y_t = -1) at CMS

- CMS has completed four direct searches for the tHq process
  - $H \rightarrow \gamma\gamma$: Smallest branching ratio but very pure; BR enhancement
  - $H \rightarrow WW/\tau\tau$ multileptons: small branching ratio, non-prompt lepton backgrounds
  - $H \rightarrow \tau_{had}\tau_{l}$: similar issues, smaller rate (new result!)
  - $H \rightarrow b\bar{b}$: Largest branching ratio but very large $t\bar{t}$ background
- A number of commonalities among the searches:
  - All searching for the anomalous (y_t = -1) production mode
  - All take advantage of top-quark semi-leptonic decay
  - All have $t\bar{t}$ as their most significant background
- Combined result takes inputs from all four channels (new result!)



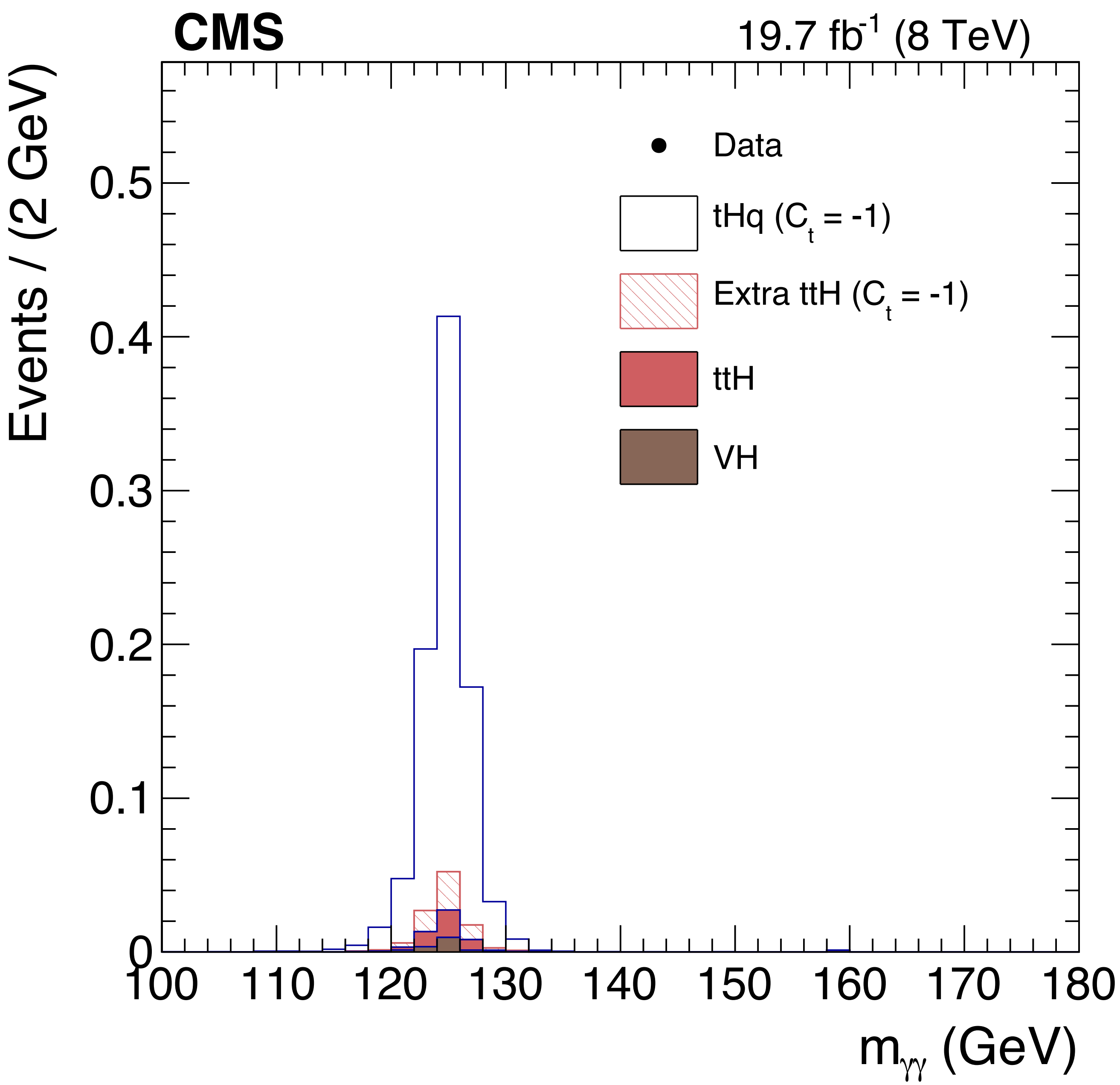
- Two high-pT photons
  - Signal region 122 < $m_{\gamma\gamma}$ < 128 GeV
  - Use sidebands for background estimate
- One isolated **μ** or e
- One b jet
- One forward jet

$H \to \gamma\gamma$: backgrounds

- Resonant backgrounds from other processes with $H \to \gamma\gamma$
  - Reduce with cut on likelihood discriminant formed from kinematic quantities distinguishing $t\bar{t}$ from t, estimate from simulations
- Remaining backgrounds have smooth shape in $m_{\gamma\gamma}$
  - Fit $m_{\gamma\gamma}$ spectrum with an exponential function, use higher-statistics control regions to estimate systematic uncertainties

Process	Yield
tHq, y_t = -1	0.67
ttH	0.03 + 0.05
VH	0.01 + 0.01
other H	0

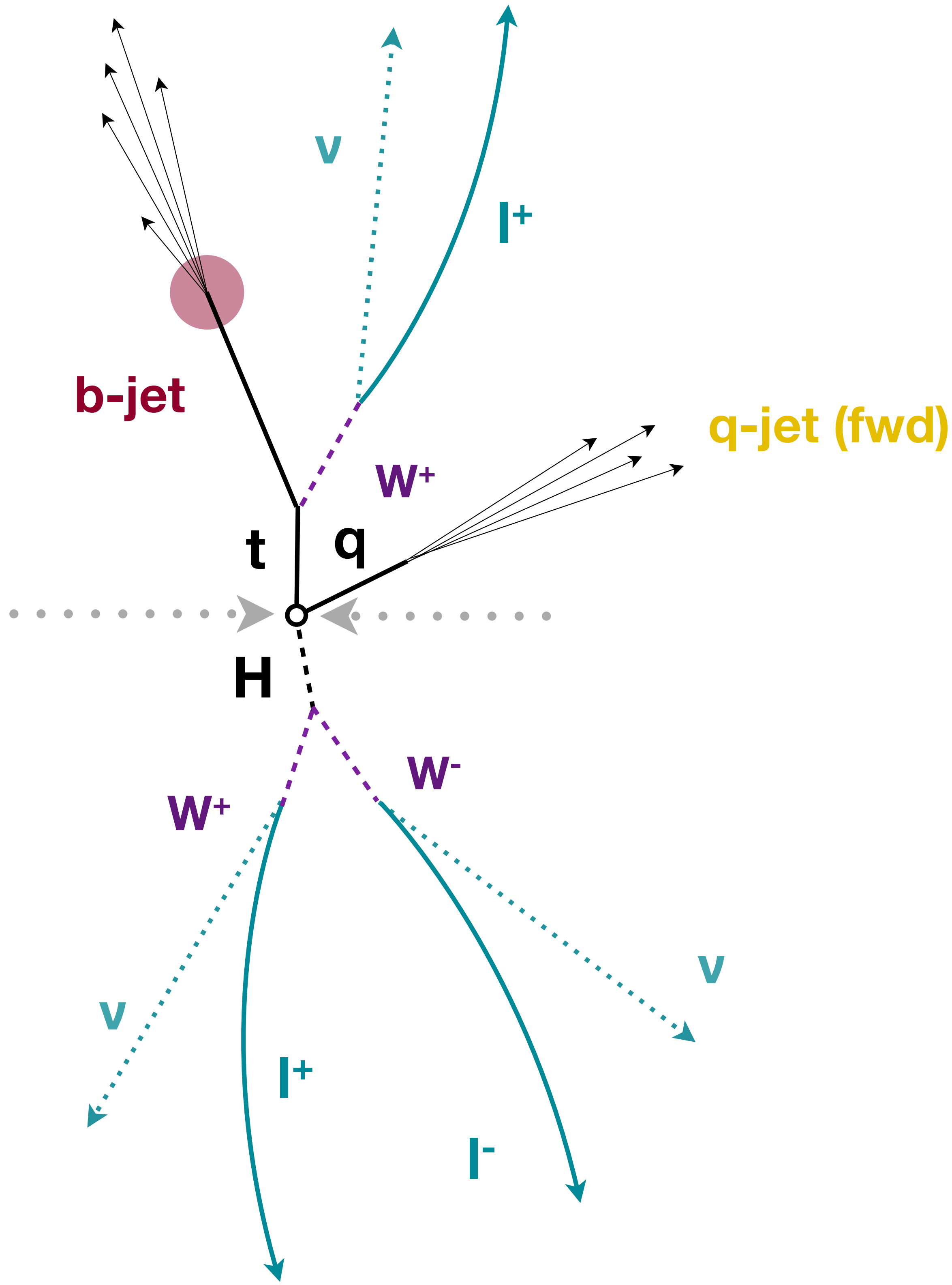
Note: yields include increases in $B(H \to \gamma\gamma)$ due to y_t = -1



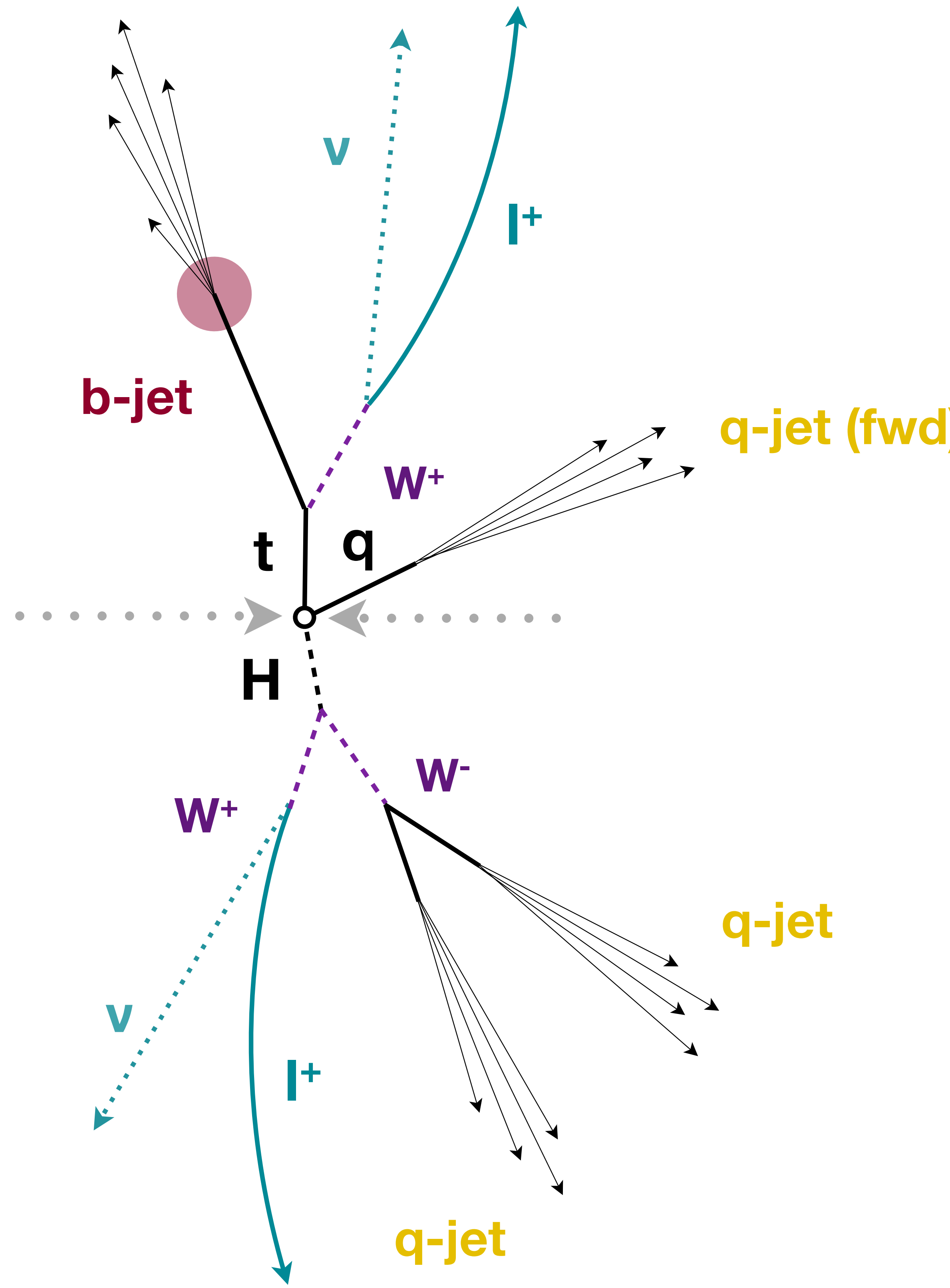
- Zero events in sidebands
- Zero events in signal region
- Set 95% CL upper limit of $4.1 \times \sigma_{tHq}(y_t = -1)$
- Observed limit coincides with expected limit

CMS HIG-14-001

- Trilepton final state
  - μμμ, μμe, μee, eee
  - Exactly one b-tagged jet
  - At least one forward non b-tagged jet
  - Missing energy
  - Z veto

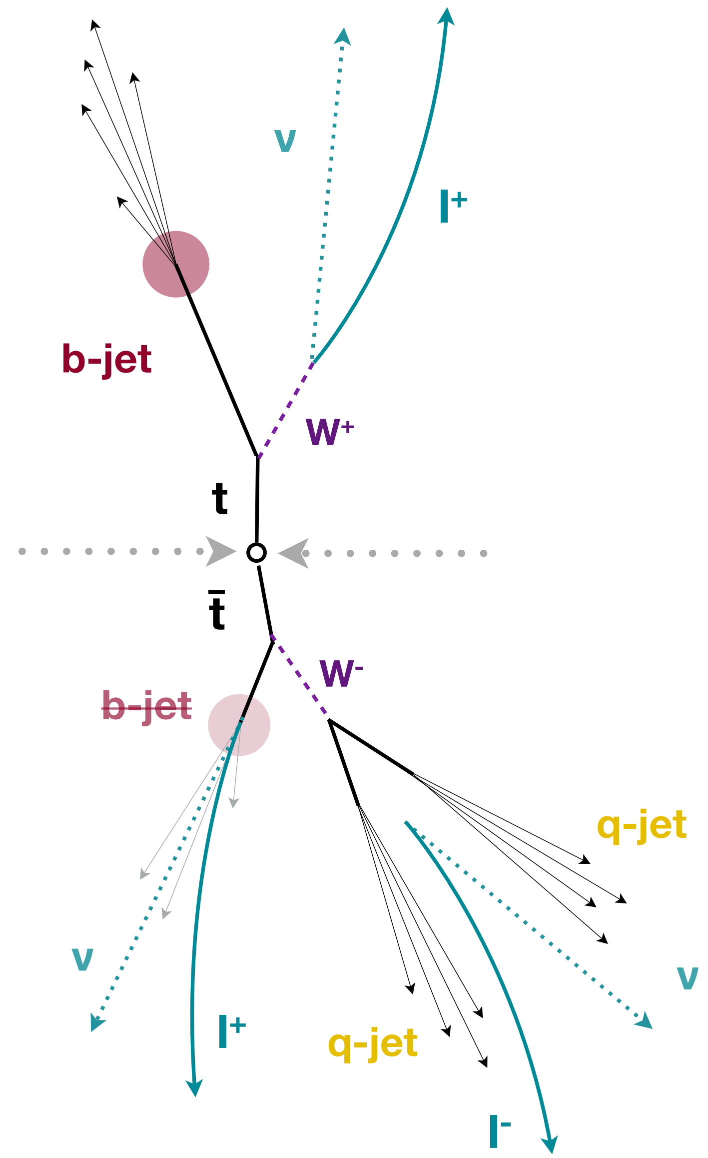


- Same-sign dilepton final state
  - $\mu\mu$ and $e\mu$
  - At least one b-tagged jet
  - At least one central jet
  - At least one forward non b-tagged jet
  - Reject τ_{had}



H→WW/ττ→leptons: backgrounds

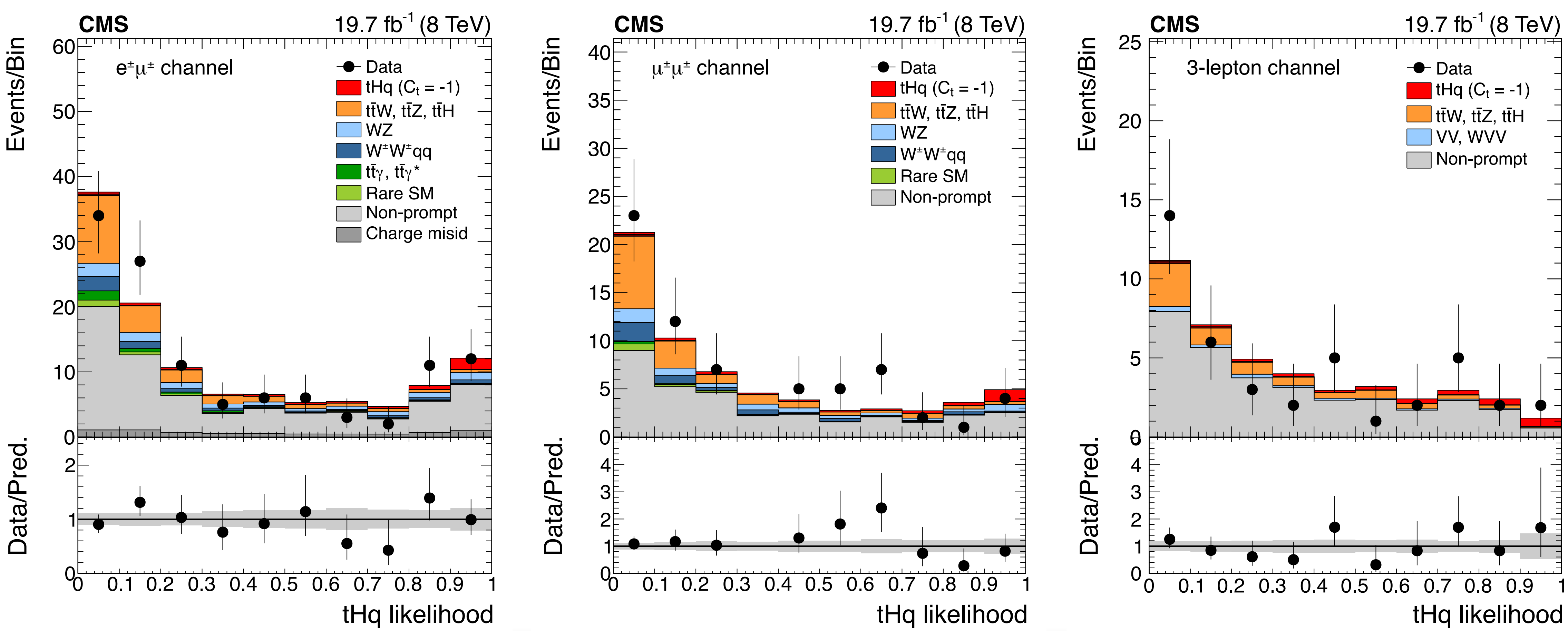
- ~1/2 background is from non-prompt leptons, mostly from $t\bar{t}$
  - Estimate rate with "tight-loose method," fake rate taken from control samples and then applied to ID/isolation sideband regions
- Also account for charge mis-ID, get rate from Z events
- Discriminating likelihood formed from information on forward activity, jet and b-jet multiplicity, lepton kinematics/charge



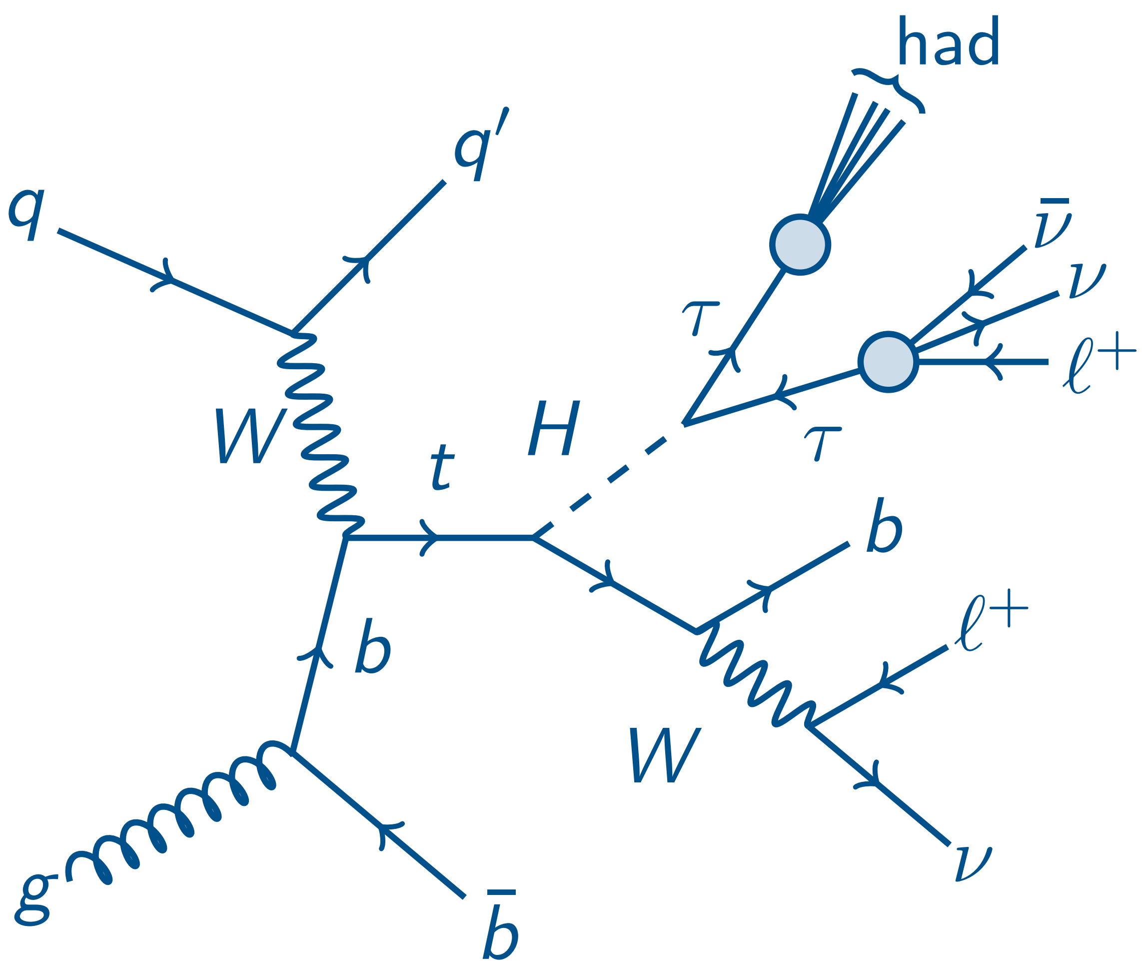
Prediction	eμ	μμ	3l
Signal	3.3	2.2	1.5
Background	106	53	42

CMS HIG-14-026

- Set limit through likelihood fit
- Combine three channels
  - Expected UL: $5.0^{+2.1}_{-1.4} \times \sigma_{tHq}(y_t=-1)$ at 95% CL
  - Observed UL: $6.7 \times \sigma_{tHq}(y_t=-1)$ at 95% CL
- Largest systematic uncertainties from non-prompt lepton rate estimate



H→ττ: selection



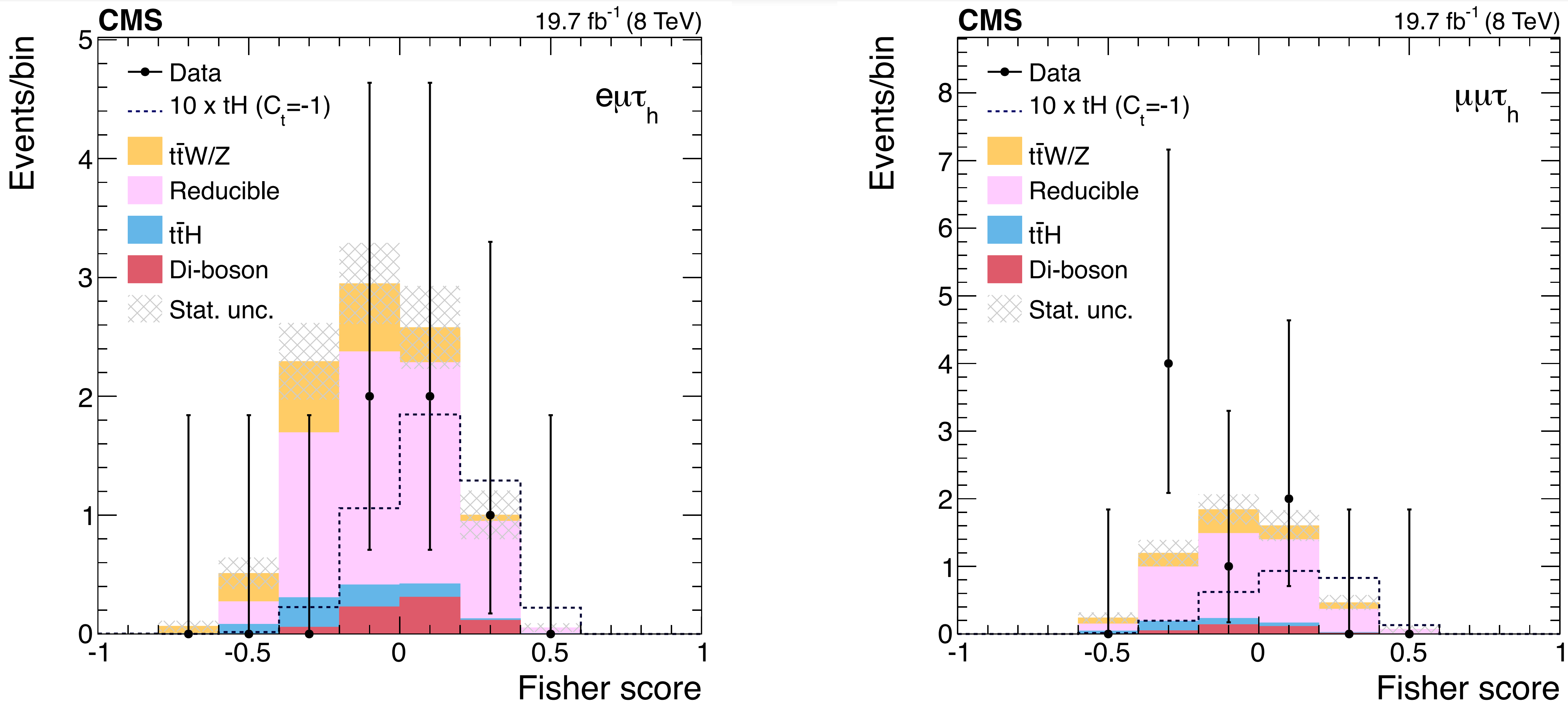
- Very much like the trilepton analysis, but use a hadronic **τ**
  - Same-sign e**μ** or **μμ**
    - Careful attention to lepton isolation, multivariate technique
  - Isolated **τ**$_h$, opposite sign
  - At least one b jet

$H \to \tau\tau$: backgrounds

- Largest background is from $t\bar{t}$ with non-prompt leptons
- As in multilepton analysis, determine a fake rate and apply it in a sideband sample to estimate background level
- Linear discriminant to separate backgrounds, using properties of most-forward jet, b-jet properties, other kinematic variables
  - Sample with inverted τ isolation used for training, validation

Process	$e\mu\tau_h$	$\mu\mu\tau_h$
tHq, $C_t = -1$	0.42 ± 0.05	0.26 ± 0.03
tHW, $C_t = -1$	0.06 ± 0.01	0.04 ± 0.01
$t\bar{t}H$	0.6 ± 0.1	0.3 ± 0.1
$t\bar{t}V$	1.8 ± 0.4	0.9 ± 0.2
VV	0.7 ± 0.1	0.3 ± 0.1
Reducible	6.3 ± 3.1	4.5 ± 1.9
Tot. background	9.5 ± 3.7	5.4 ± 2.4
Data	5	7

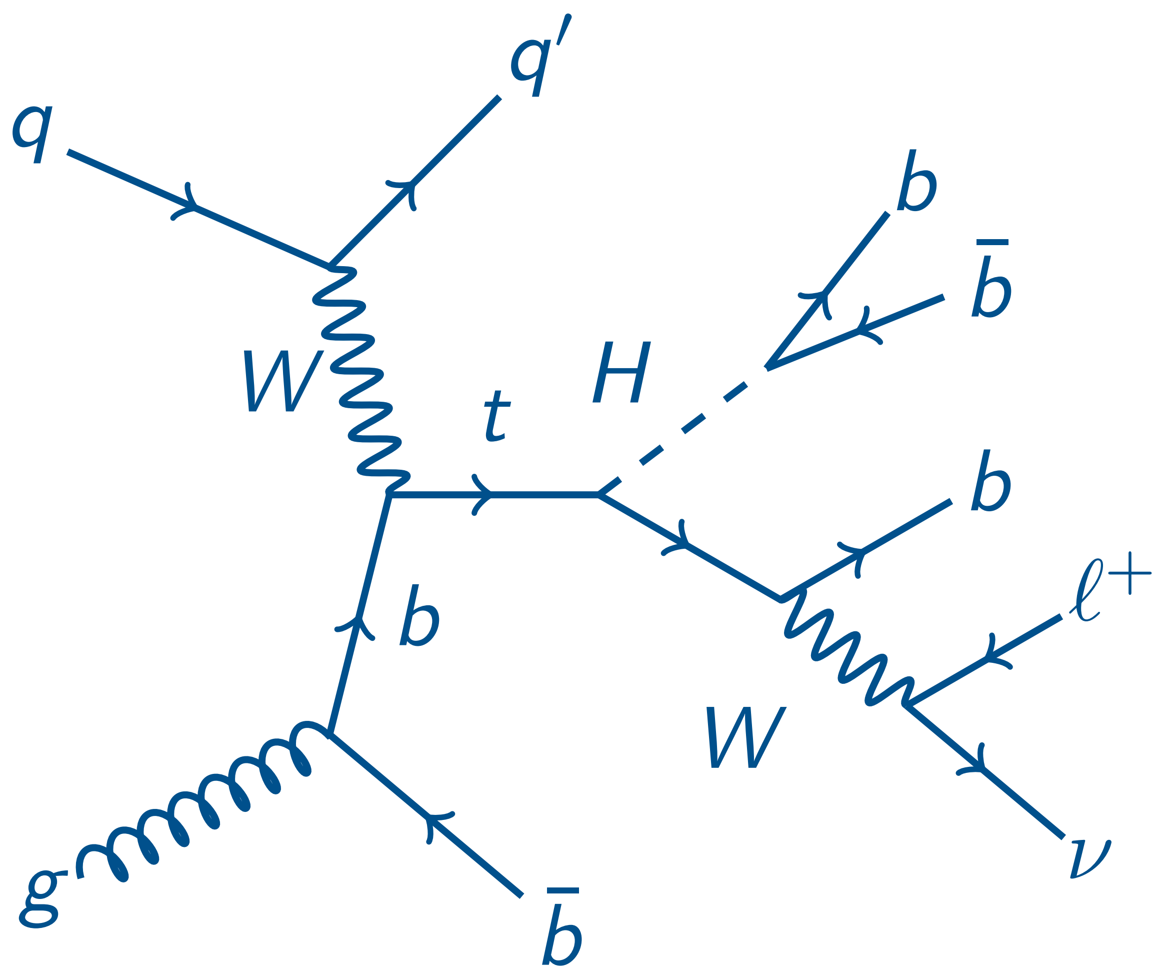
H→ττ: results



- Maximum likelihood fit to set limits
- Expect: $< 11^{+6}_{-4} \times \boldsymbol{\sigma}_{tHq}(y_t = -1)$ at 95% CL
- Observe: $< 9 \times \boldsymbol{\sigma}_{tHq}(y_t = -1)$ at 95% CL
- Largest systematic uncertainties from non-prompt lepton estimate, but statistical uncertainties dominate

CMS HIG-14-027

$H \to b\bar{b}$: selection



- One isolated high-pT lepton
- Missing energy from ν
- Three or four b jets
- Extra non-b jet (either forward or higher in pT)
- Lots of $t\bar{t}$ background!

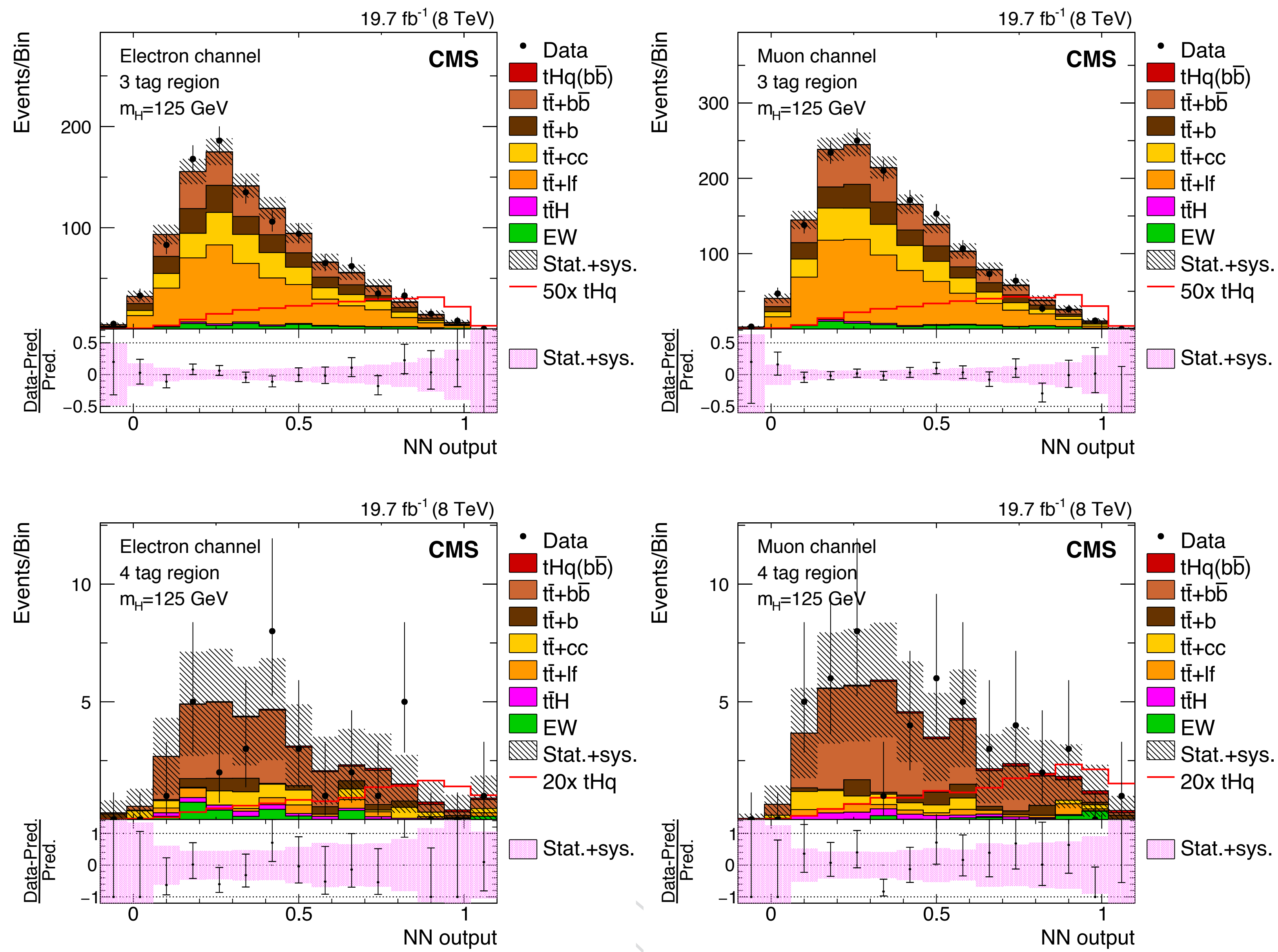
Sample	S/B
3 b jets	13/1900
4 b jets	1.4/66

$H \rightarrow b\bar{b}$: multivariate approaches everywhere

- Need to assign each of the jets to parent quarks of final state
  - Develop multivariate discriminator based event quantities such as invariant masses, ΔR's, jet η and pT values, jet charges
  - Choose single best assignment of jets to quarks as reconstruction hypothesis
  - *Do this separately under two different assumptions of initial state: tHq signal and $t\bar{t}$ background*
- With tHq and $t\bar{t}$ reconstructions done, form kinematic quantities specific to each of the reconstructions and develop another discriminator based on them that distinguishes the two processes
- Use templates in this variable to extract the tHq signal fraction
  - $t\bar{t}$ template from simulation, allowing $t\bar{t}$+HF fraction to vary
  - Verified with data-driven method that makes use of two-tag events, results are consistent

$H \to b\bar{b}$: results

- Expected upper limit: $5.2^{+2.1}_{-1.7} \times \boldsymbol{\sigma}_{tHq}(y_t=-1)$ at 95% CL
- Observed upper limit: $7.6 \times \boldsymbol{\sigma}_{tHq}(y_t=-1)$ at 95% CL
- Largest systematic uncertainties from $t\bar{t}$ modeling and b-tag efficiencies/mistag rates

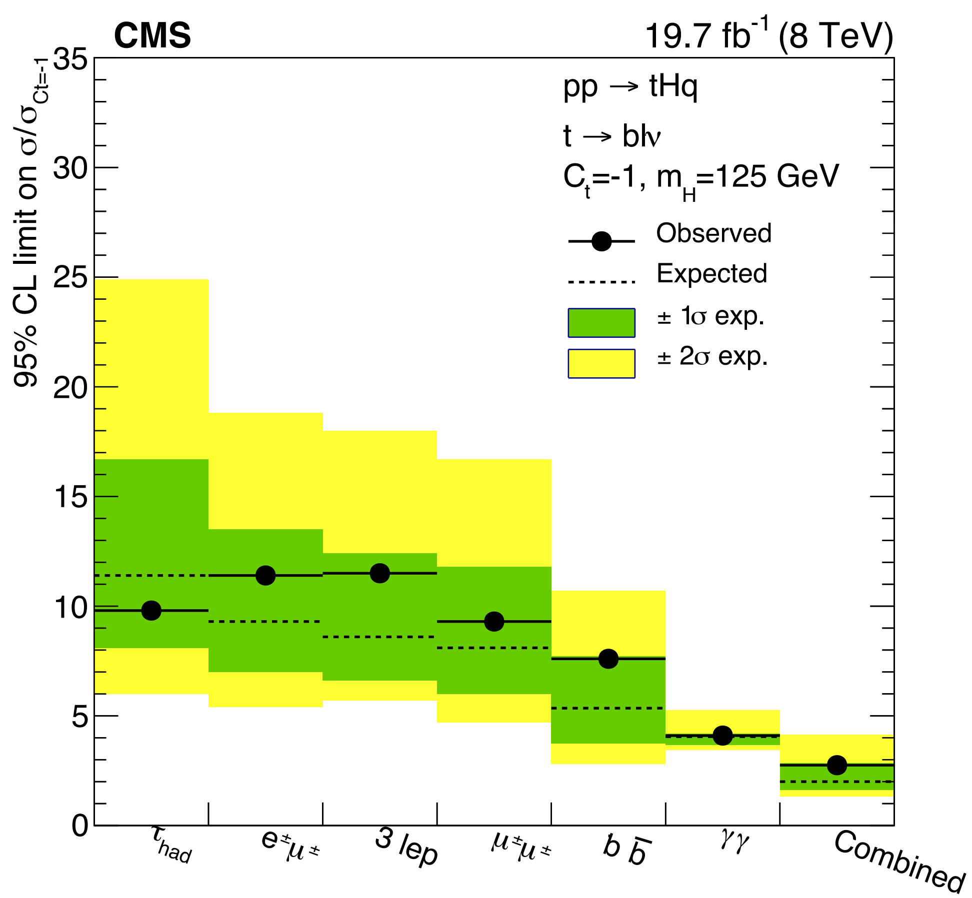


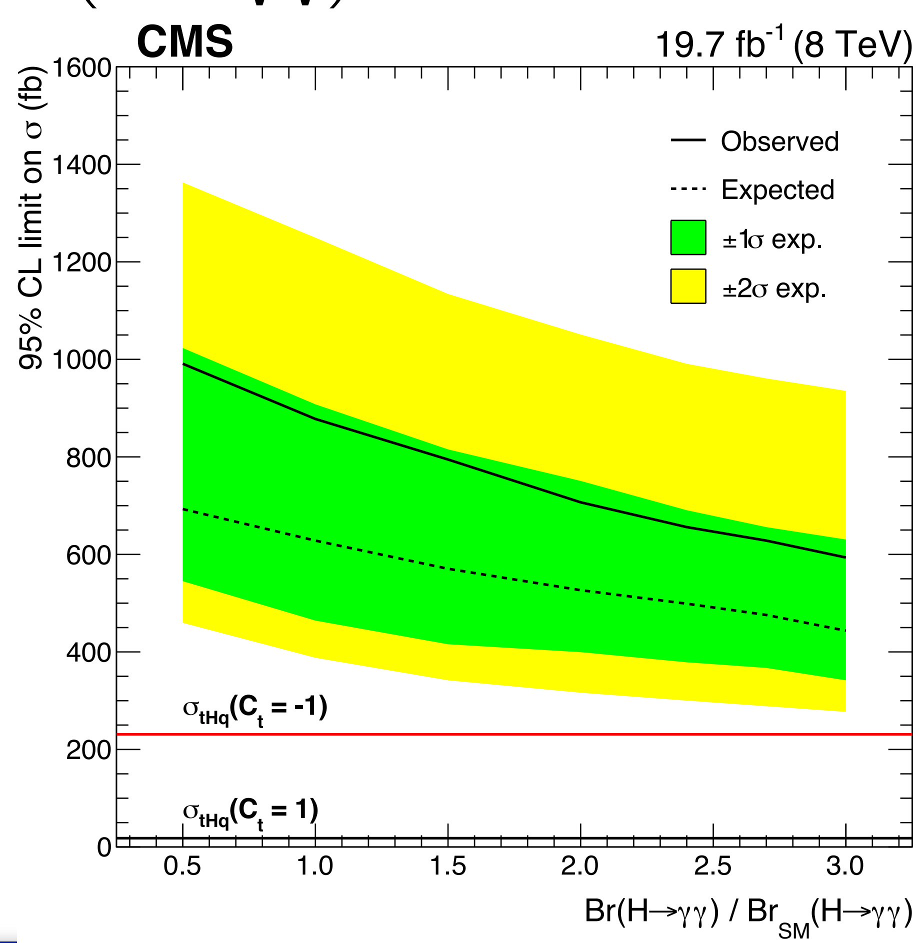
CMS HIG-14-015

$\sigma_{95\%}/\sigma_{yt=-1}$	$H\to\gamma\gamma$	$H\to WW/\tau_l\tau_l$	$H\to\tau_l\tau_h$	$H\to b\bar{b}$
Expected	4.1	5.0	11.4	5.4
Observed	4.1	6.7	9.8	7.6

- Put it all together in likelihood fit — many bins, parameters….
- Check sensitivity to y_t = -1, count any enhancement to tHq and $H\to\gamma\gamma$ as signal
  - Expect < 2.0 × $\sigma_{tHq}(y_t=-1)$, observe 2.8 × $\sigma_{tHq}(y_t=-1)$ at 95% CL
- Also, quote limit on σ_{tHq} as a function of $B(H\to\gamma\gamma)$

CMS HIG-14-027





Conclusions/Outlook

- tHq production rate is sensitive to the sign of the top Yukawa couplings and other new physics
- CMS has completed searches for tHq in four different final states
  - New result in the $H\rightarrow\tau_{had}\tau_{l}$ channel
- Set cross section limit < 2.8 × $\sigma_{tHq}(y_t=-1)$ @ 95% CL with 20 fb^{-1}
  - Combination is a new result
- Not yet sensitive to the anomalous production, but
  - σ_{tHq} is x4 larger at 13 TeV, should have enough LHC data in 2016 to exclude (or discover?) the $y_t=-1$ hypothesis
  - Beyond that, can set limits in the (κ_f, κ_V) plane, have sensitivity to Higgs-mediated FCNC processes tHq with q = u, c, and more
- Interesting opportunities ahead for Run 2 in these searches!