Search for production of a Higgs boson and a single top quark

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for the CMS Collaboration

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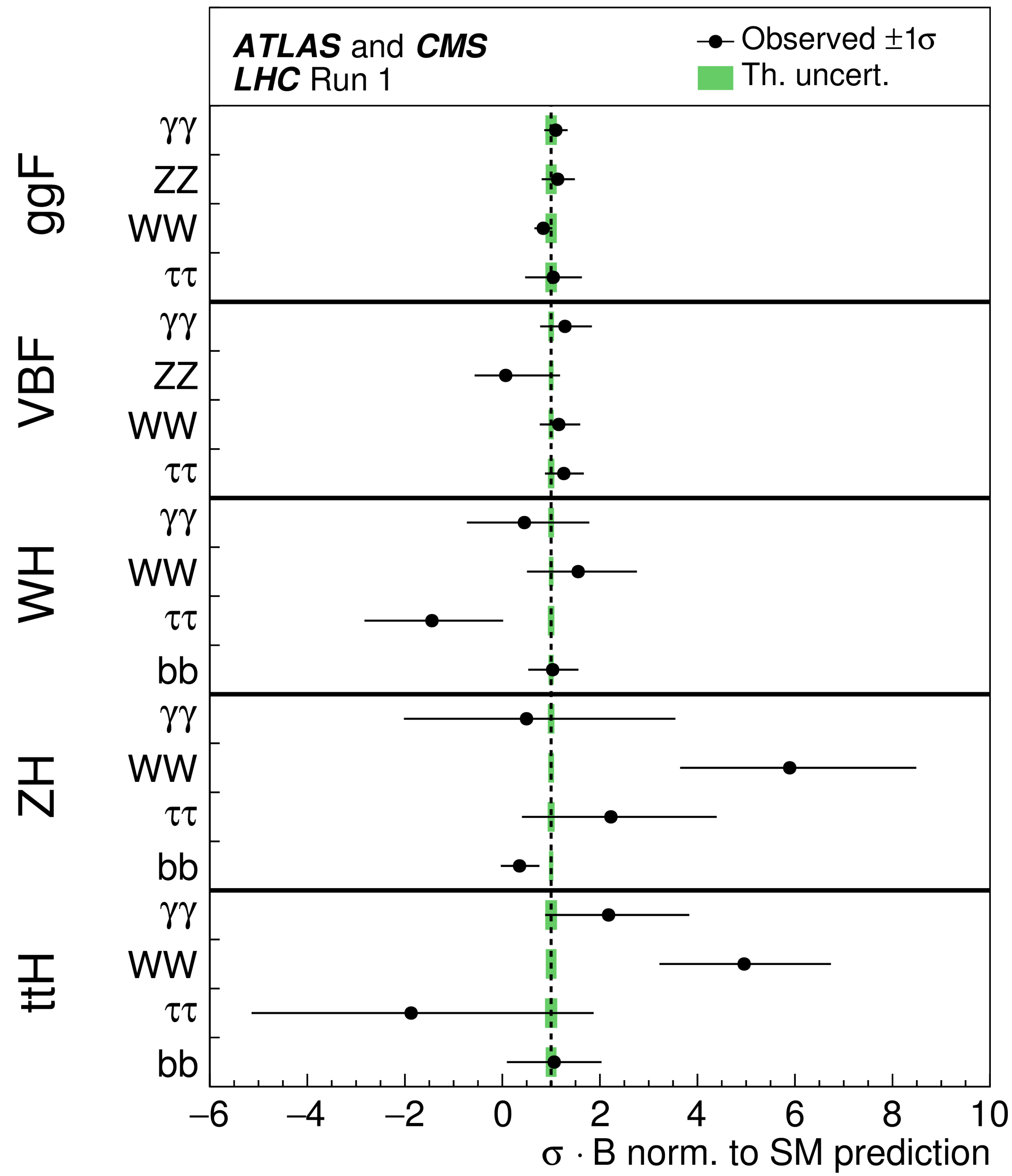
CMS

- We all know the five favorite Higgs production mechanisms and tend to forget about another
- The SM cross section for single top plus Higgs production is ~500x smaller than that for gluon fusion
  - $\sigma(tHq)$ = 71 fb
  - $\sigma(tHW)$ = 16 fb
- Why even bother looking?



CMS HIG-15-002, JHEP 08 (2016) 045

At the bottom

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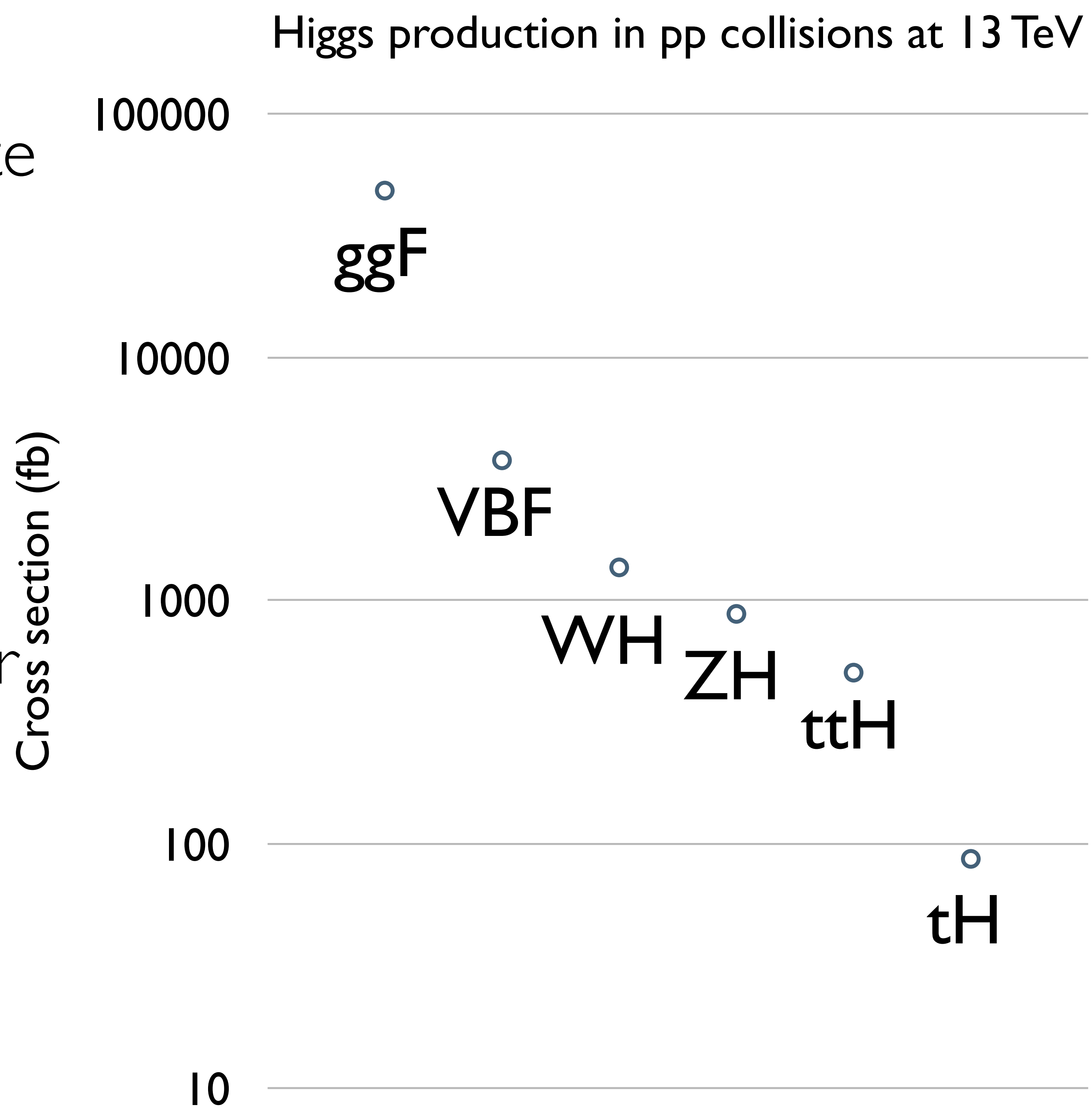
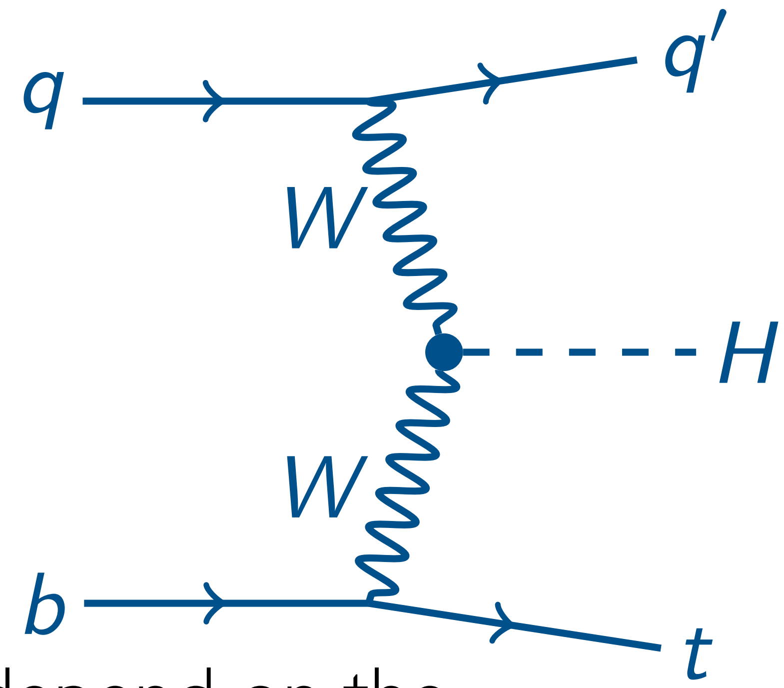
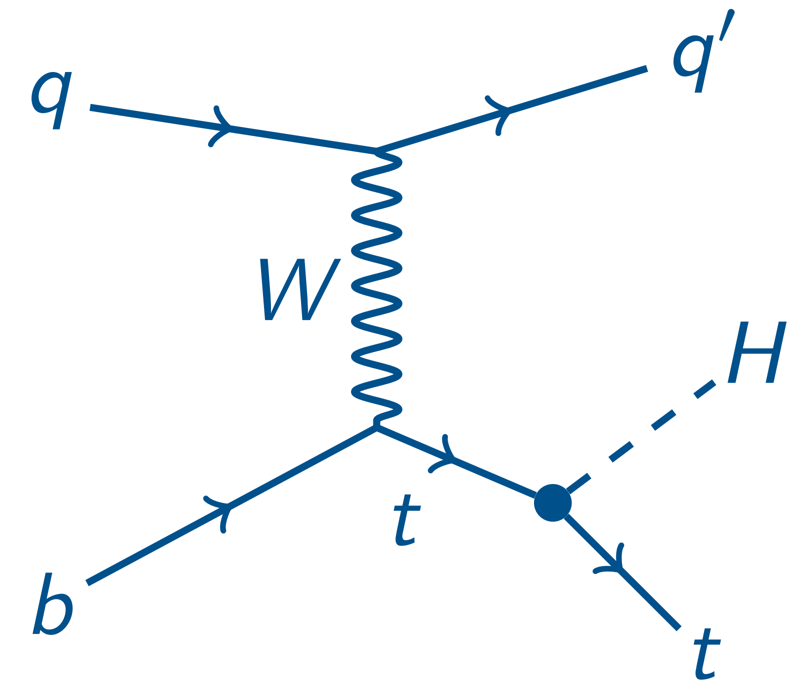


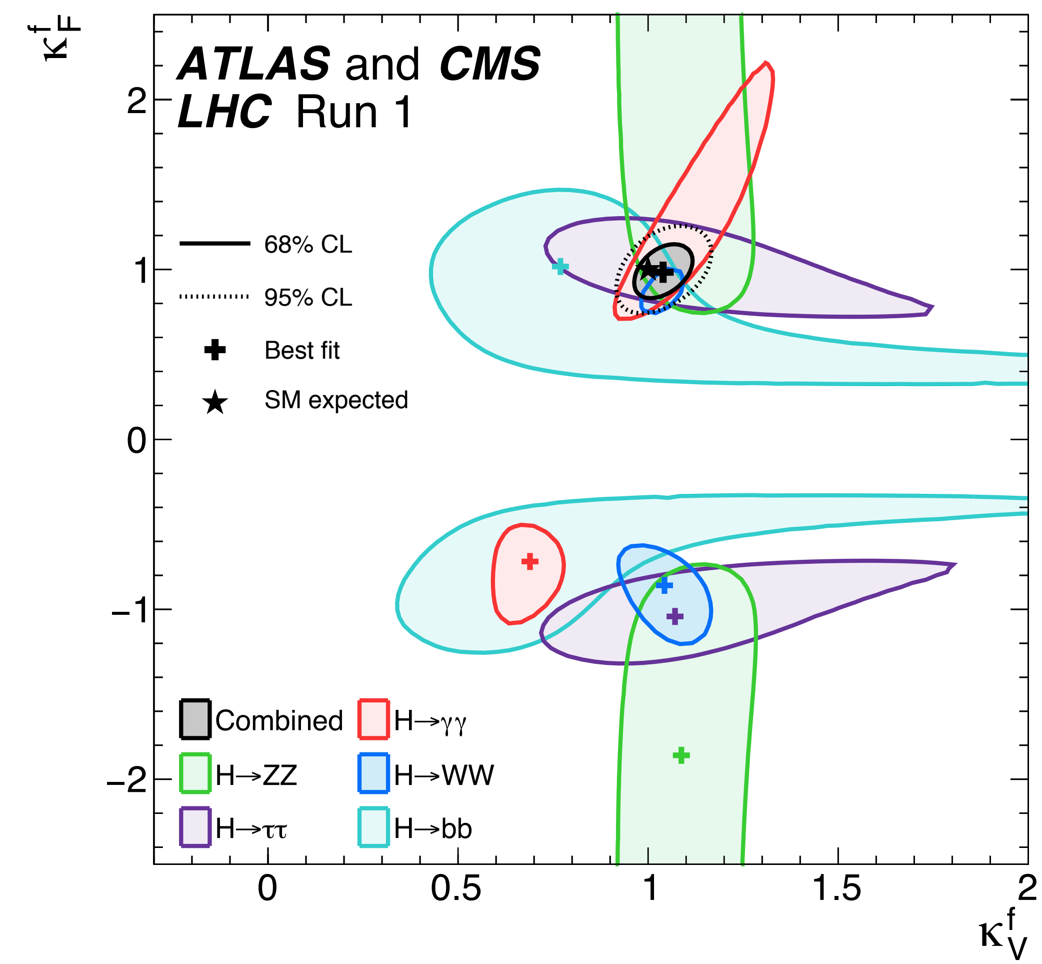
arXiv:1610.07922

- Small cross section due to destructive interference between two diagrams
  - Similar for tHW production

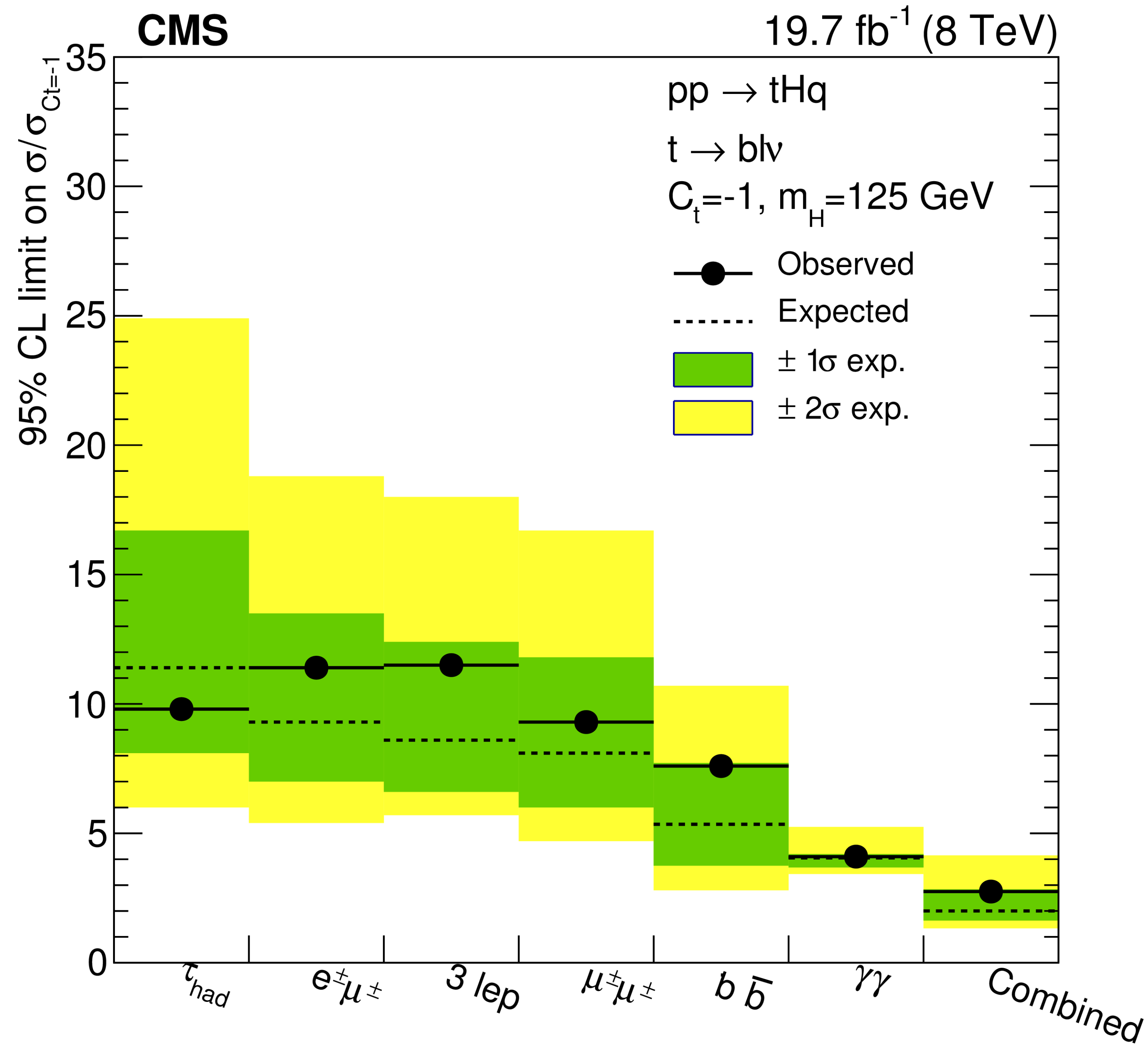




- Most production modes depend on the square of the coupling, insensitive to sign
- If the sign of the top Yukawa coupling is inverted (κ_t = -1), interference is constructive, and cross section is x10 larger!
- Bounds on κ_t largely derived from decays
  - Constraints assume no new particles in loops
  - Composite Higgs, FCNC processes could enhance cross section further



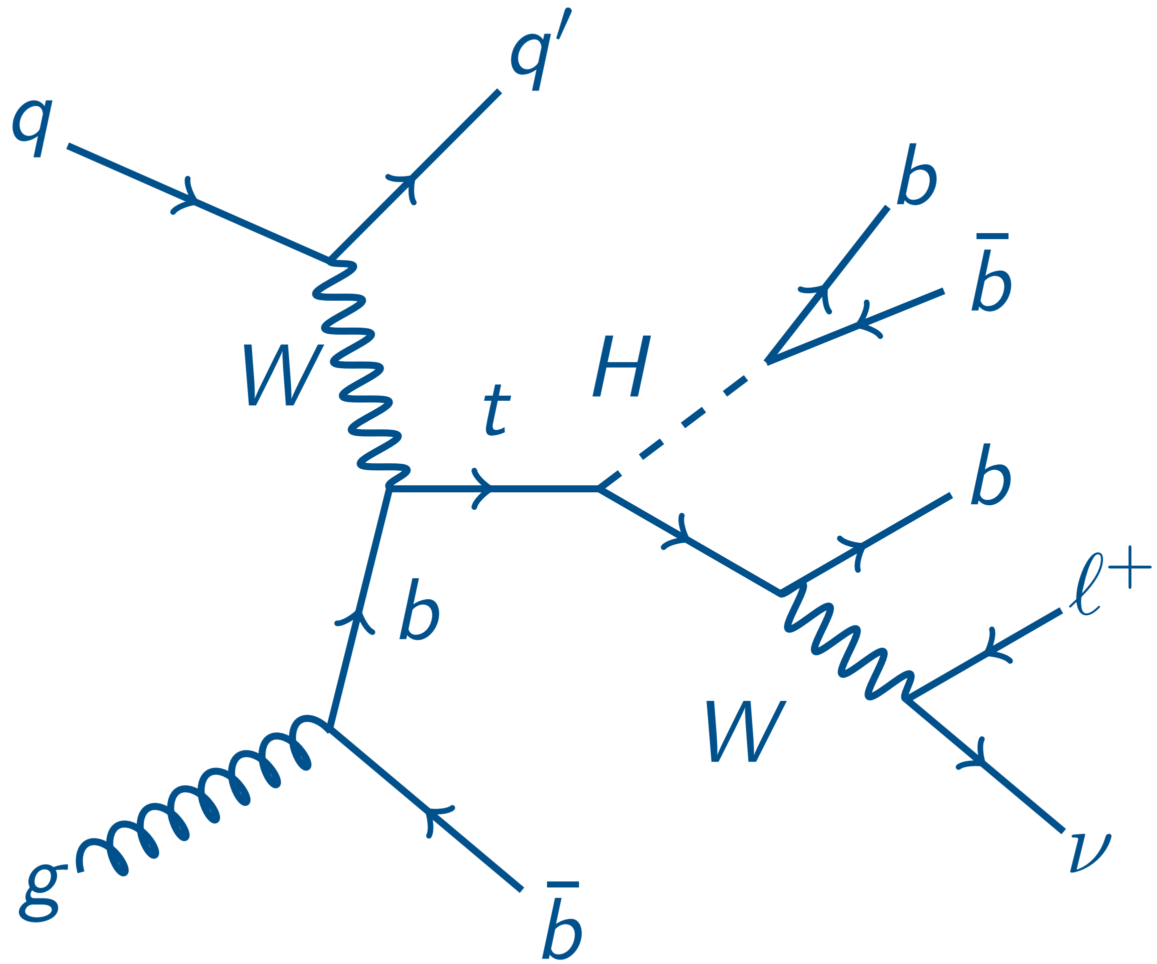
- Search for tHq production in four final states
  - H→γγ, bb, WW (multileptons), ττ
- Analyses only set limits for κ_t = -1 case
- Set limit of < 2.8 × $\sigma_{tHq}(\kappa_t = -1)$ at 95% CL



CMS HIG-14-027, JHEP 06 (2016) 177

Run 2 searches for tH at CMS

- Searches for tH production are even more promising in Run 2
  - tHq cross section ~x4 larger at 13 TeV than 8 TeV
  - Run 2 dataset has already exceeded Run 1 dataset
  - Searches now include tHW as signal
  - Improved analysis techniques, greater exploration of $\kappa_t \neq -1$
- CMS has released results for searches in two Higgs decay modes
  - $H \rightarrow b\bar{b}$: Largest branching ratio but very large $t\bar{t}$ background
  - $H \rightarrow WW$ multileptons: small branching ratio but better S/B, non-prompt lepton backgrounds
- Commonalities:
  - Both take advantage of top-quark semi-leptonic decay
  - Both have $t\bar{t}$ (including $t\bar{t}H$) as their most significant background



- One isolated high-pT lepton
- Missing energy from **ν**
- Three or four b jets
- One additional jet

- Lots of t$\bar{t}$ background!

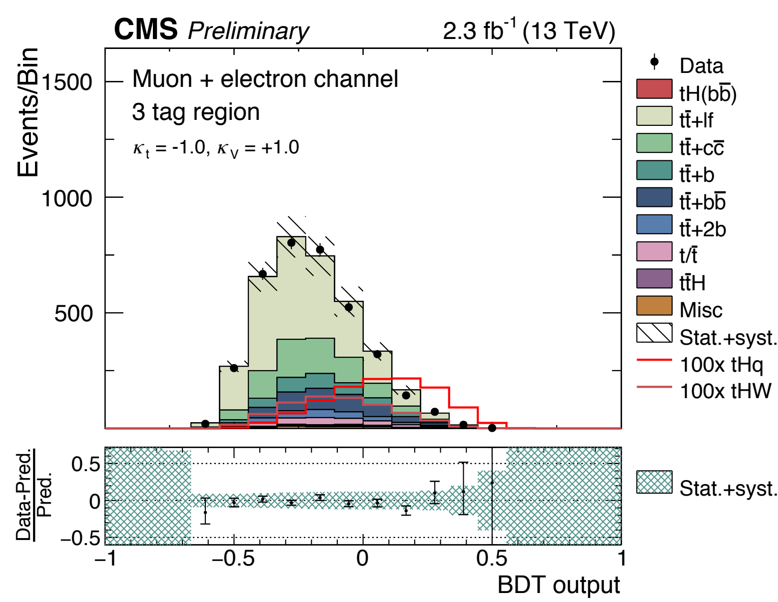
Sample	S(κ_t = -1)/B
3 b jets	17.9/4051
4 b jets	2.8/177

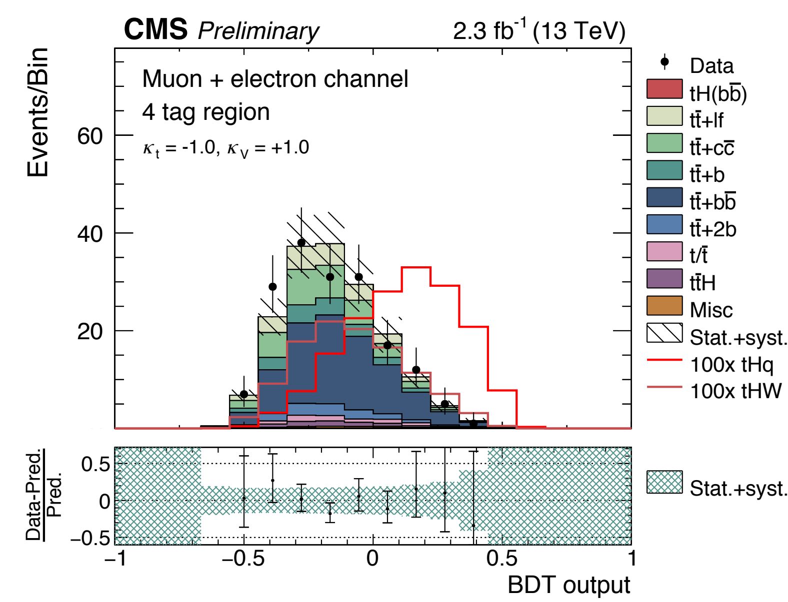
$H \rightarrow b\bar{b}$: multivariate approaches everywhere

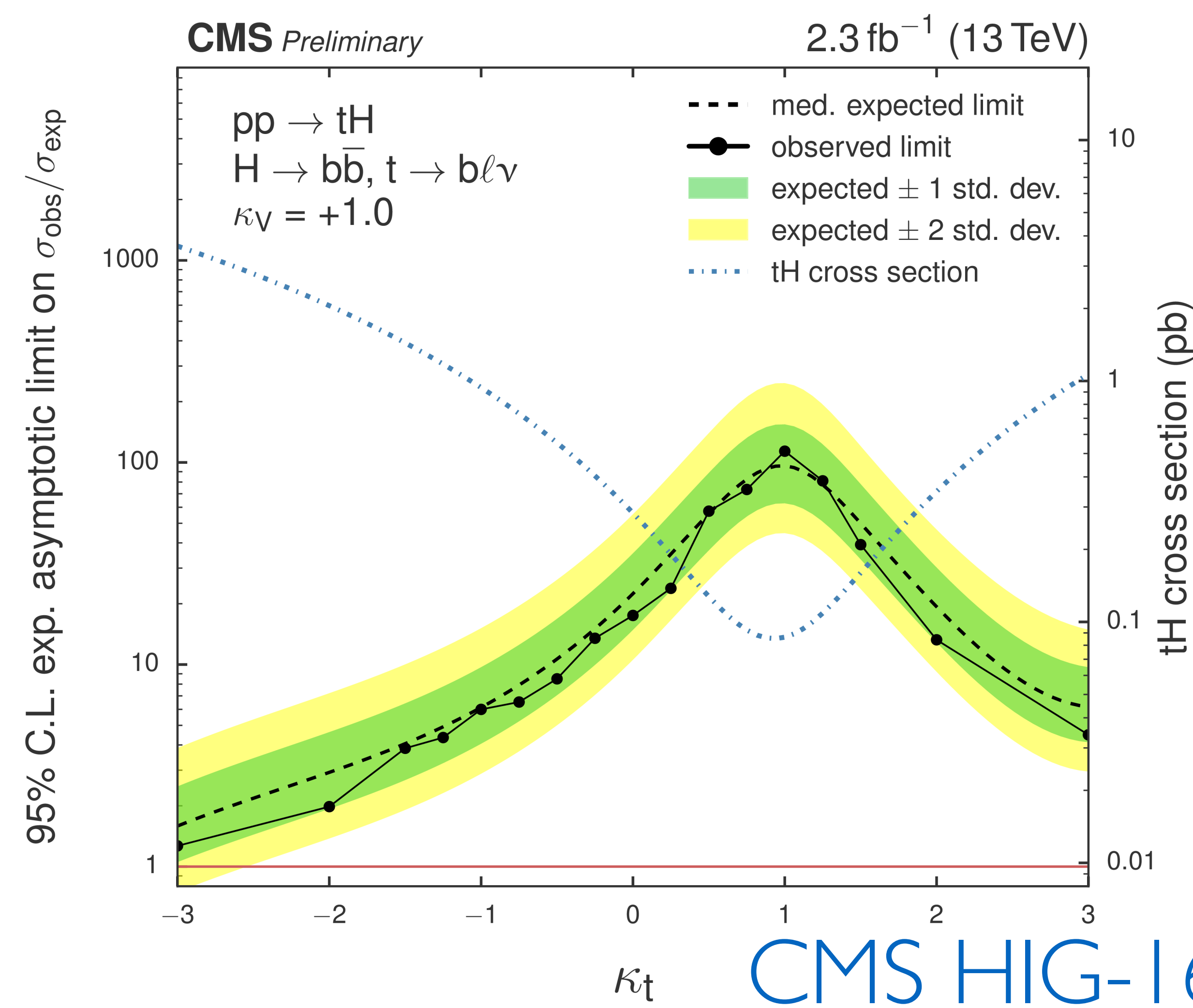
- Need to assign each of the jets to parent quarks of final state
  - Develop multivariate discriminator based event quantities such as invariant masses, ΔR's, jet η and pT values, jet charges and tagging info
  - Choose single best assignment of jets to quarks as reconstruction hypothesis
  - *Do this 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
  - Validated in two-tag event sample, enriched in $t\bar{t}$
- Fit distribution of that discriminator to templates from signal and background

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

- Expected upper limit: $6.4^{+3.7}_{-2.2} \times \sigma_{tH}(\kappa_t=-1)$ at 95% CL
- Observed upper limit: 6.0 $\times\ \sigma_{tH}(\kappa_t=-1)$ at 95% CL
- Comparable to 8 TeV result with much less integrated luminosity
  - Inclusion of tHW, increased cross section, looser b-tag requirement
- Largest systematic uncertainties from jet energy scale and shower modeling



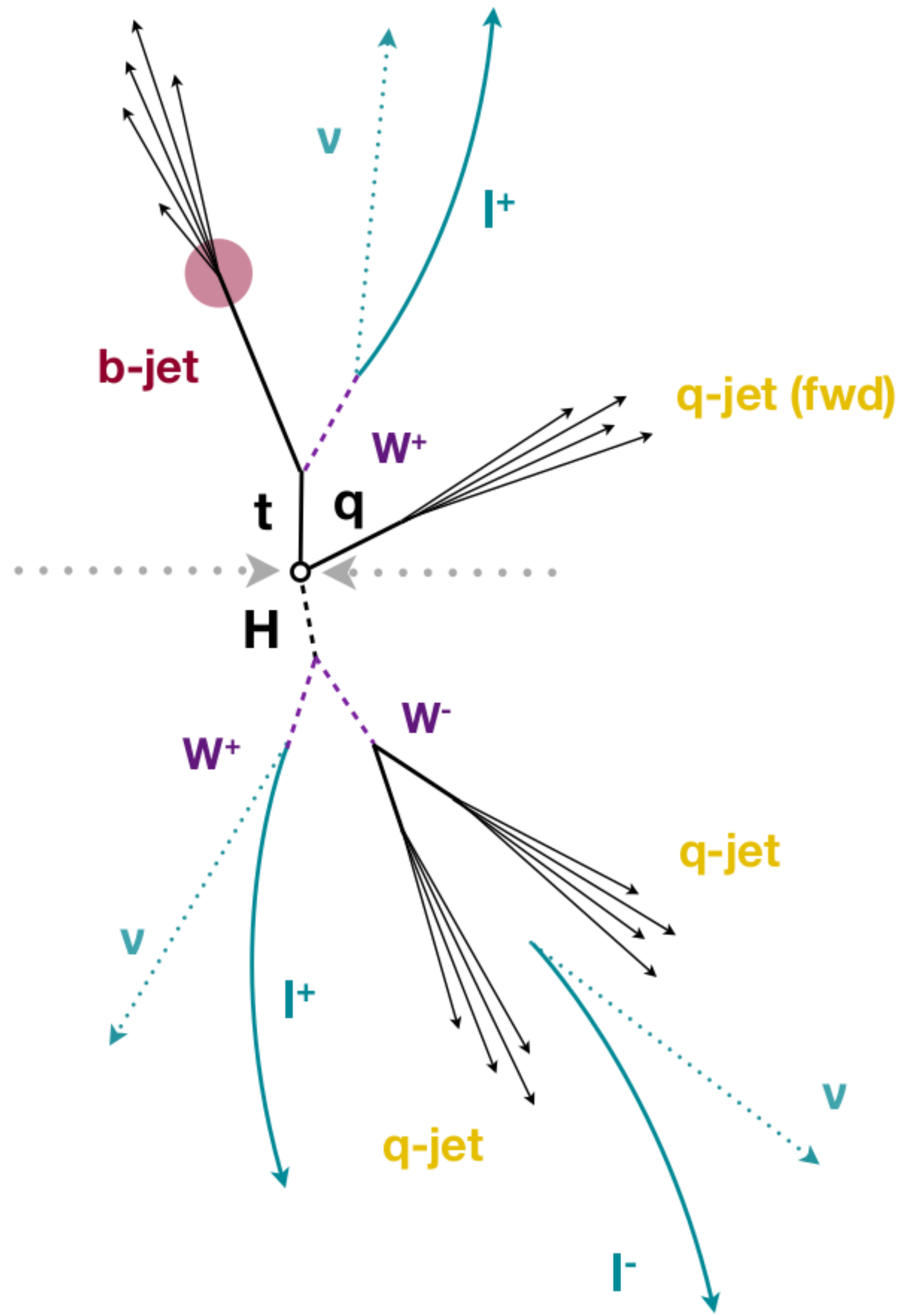




CMS HIG-16-019

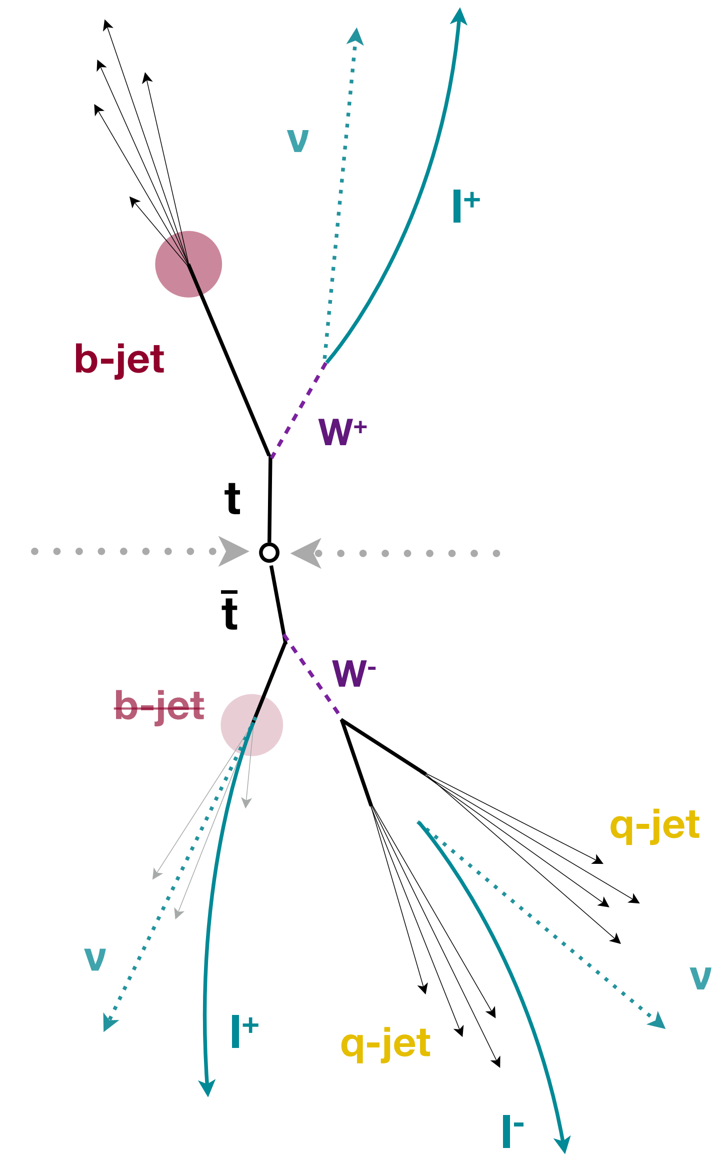
H→WW→leptons: selection

- Trilepton final state
  - μμμ, μμe, μee, eee
  - Z veto
- Same-sign dilepton final state
  - μμ, μe
- Both cases
  - At least one b-tagged jet
  - At least one non-tagged jet
- ~75% H→WW, ~20% H→ZZ, ~5% H→ττ
- Significant fraction of selected data events also pass selections for $t\bar{t}H$ analysis, counted as signal



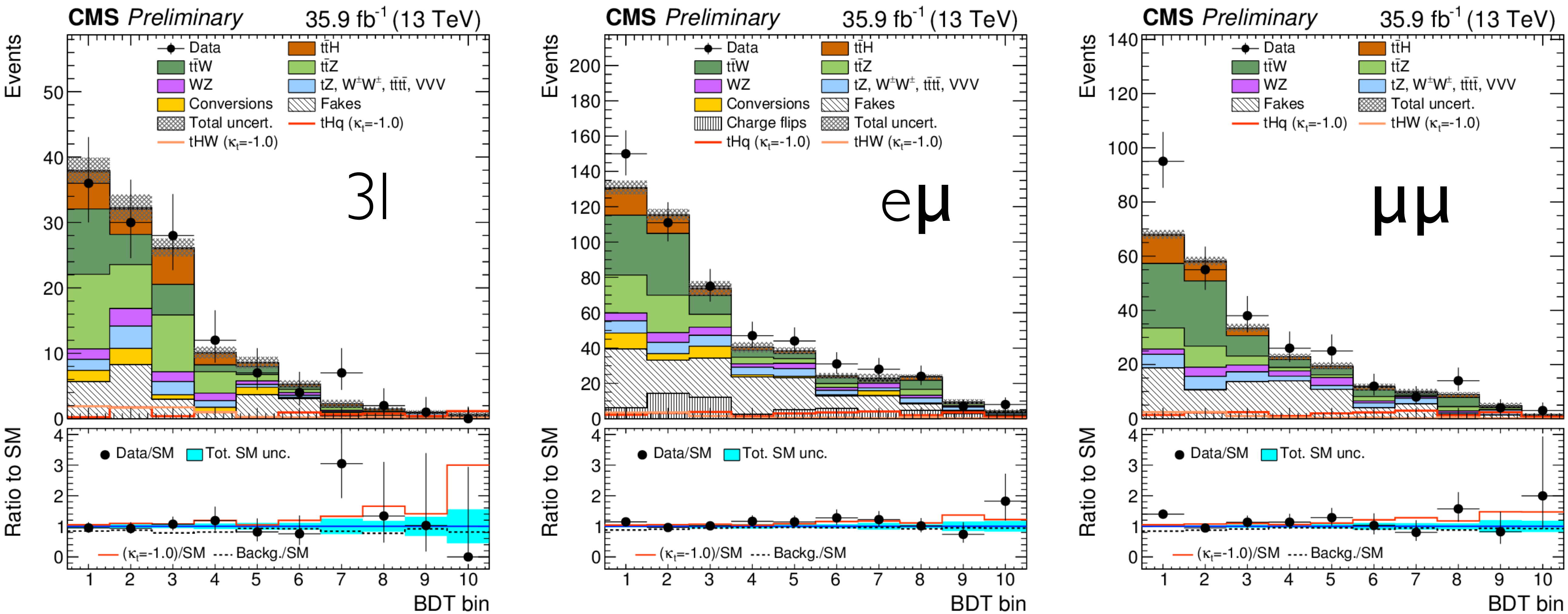
H→WW→leptons: backgrounds

- Two dominant sources of background
  - $t\bar{t}$+(W/Z/H/γ) with prompt leptons
    - Modeled with simulations
  - $t\bar{t}$ with non-prompt leptons
    - Modeled with data using loose-to-tight extrapolation from control regions
- Separate multivariate discriminators for two main backgrounds, using info on jet and b-jet multiplicities, forward jet activity and kinematic properties of leptons
- Combine information from two discriminators into one variable



Prediction	eμ	μμ	3l
Signal (κ_t = -1)	39	26	15
ttH (κ_t^2 = 1)	35	24	18
Background	443	211	106

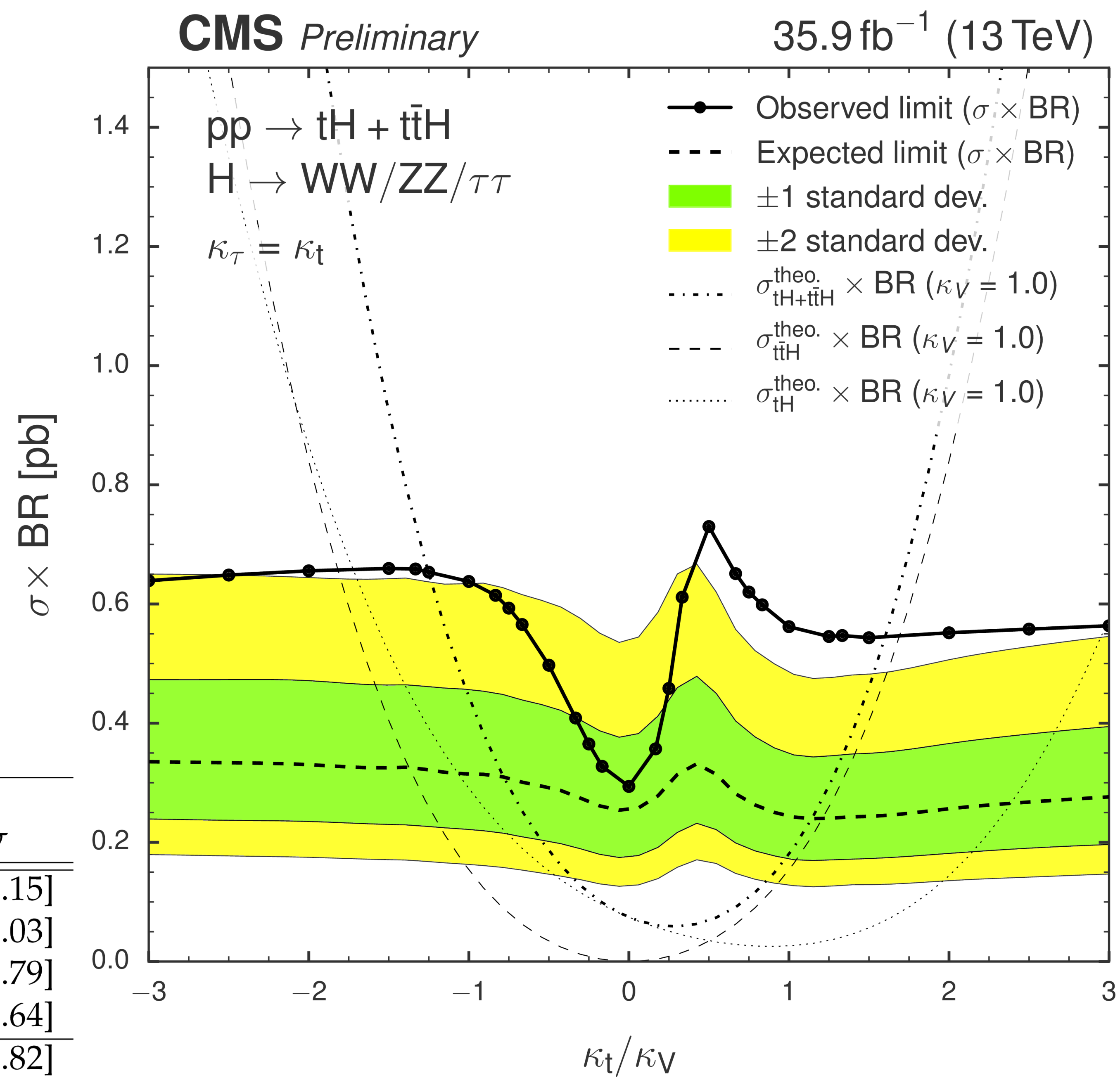
$H \to WW \to$ leptons: results



- Simultaneous maximum likelihood fit for all three channels, separately for different values of κ_t/κ_V
- Uncertainties dominated by background estimates, lepton ID
- Assume $\kappa_{tau} = \kappa_t$ and all other parameters at SM values, and then combined $tH+t\bar{t}H$ signal strength is uniquely defined by κ_t/κ_V

- κ_t/κ_V = -1: set limit of 1.4 × expected tH+tt̄H cross section
- κ_t/κ_V = 1: set limit of 3.1 × expected tH+tt̄H cross section
- κ_t/κ_V constrained to about [-1.25, 1.60]

Scenario	Channel	Obs. Limit (pb)	Exp. Limit (pb) Median	$\pm1\sigma$	$\pm2\sigma$
$\kappa t/\kappa_V = -1$	$\mu\mu$	1.00	0.58	[0.42, 0.83]	[0.31, 1.15]
	$e\mu$	0.84	0.54	[0.39, 0.76]	[0.29, 1.03]
	$\ell\ell\ell$	0.70	0.38	[0.26, 0.56]	[0.19, 0.79]
	Combined	**0.64**	**0.32**	[0.22, 0.46]	[0.16, 0.64]
$\kappa t/\kappa_V = 1$ (SM-like)	$\mu\mu$	0.87	0.41	[0.29, 0.58]	[0.22, 0.82]
	$e\mu$	0.59	0.37	[0.26, 0.53]	[0.20, 0.73]
	$\ell\ell\ell$	0.54	0.31	[0.22, 0.43]	[0.16, 0.62]
	Combined	**0.56**	**0.24**	[0.17, 0.35]	[0.13, 0.49]



CMS HIG-17-005

Conclusions/Outlook

- tH production rate is sensitive to the sign of the top Yukawa couplings and other new physics
- CMS has searched for tH production in Run 2 data with two final states
  - Results are already superseding those of Run 1 thanks to larger cross section at 13 TeV and improved analysis techniques
- Still to do:
  - Increase $H \to b\bar{b}$ statistics ×10 with 2016 dataset
  - Complete $H \to \gamma\gamma$ analysis, should be most sensitive final state
  - Obtain limits in the (κ_t, κ_V) plane
  - Use same process to search for admixture of CP-odd Higgs boson
  - Search for Higgs-mediated FCNC process tHq with q = u, c
  - Combine results from all channels, publish…
- Many interesting opportunities ahead!