Search for associated production of a Higgs boson and a single top quark in proton-proton collisions at $\sqrt{s}$= 13 TeV

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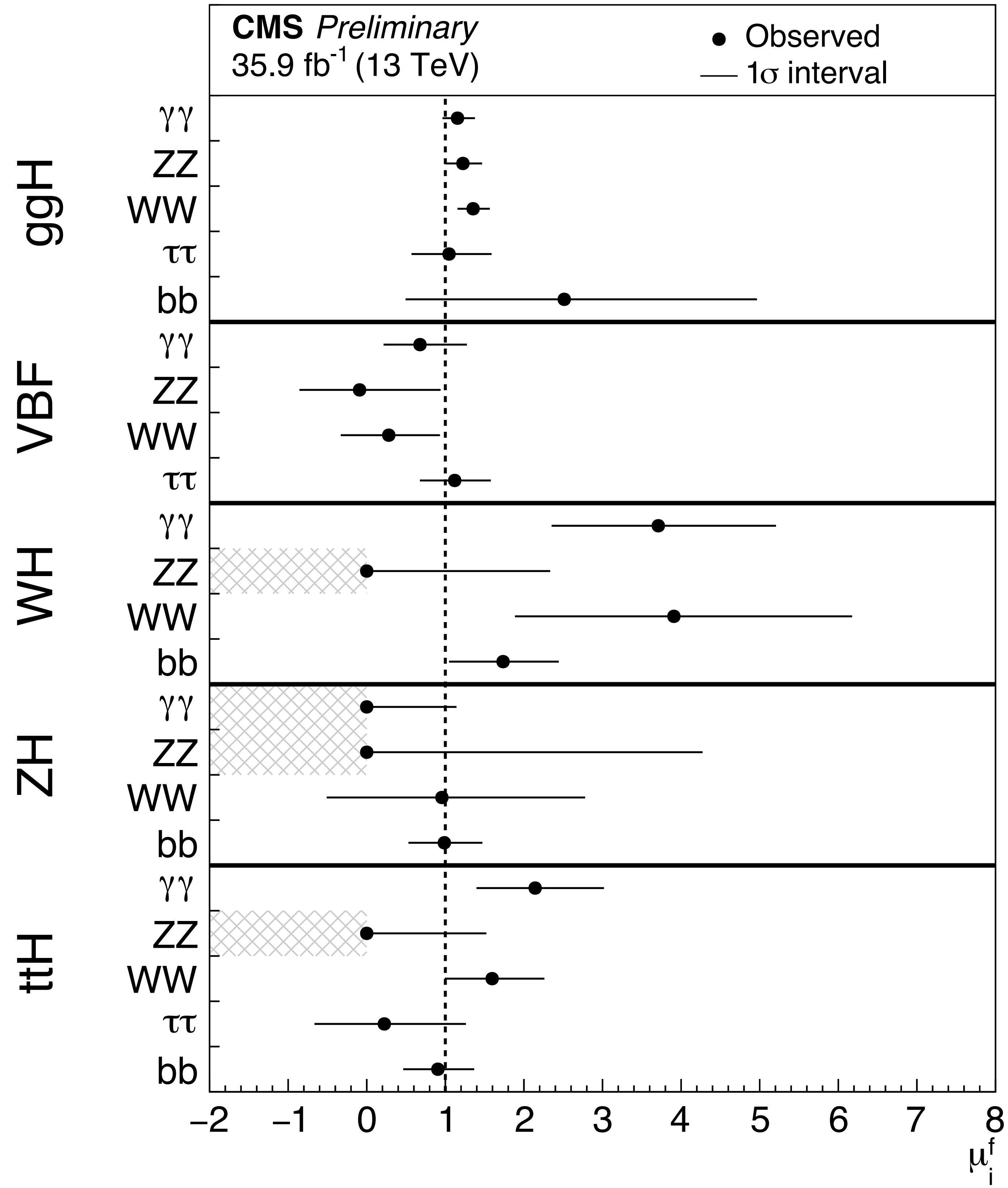
- We all know the five favorite Higgs production mechanisms and tend to forget about another
- The SM cross section for single top plus Higgs production is ~500x smaller than that for gluon fusion
  - σ(tHq) = 71 fb
  - σ(tHW) = 16 fb
- Why even bother looking?



CMS HIG-17-031, EPJC 79 (2019) 421

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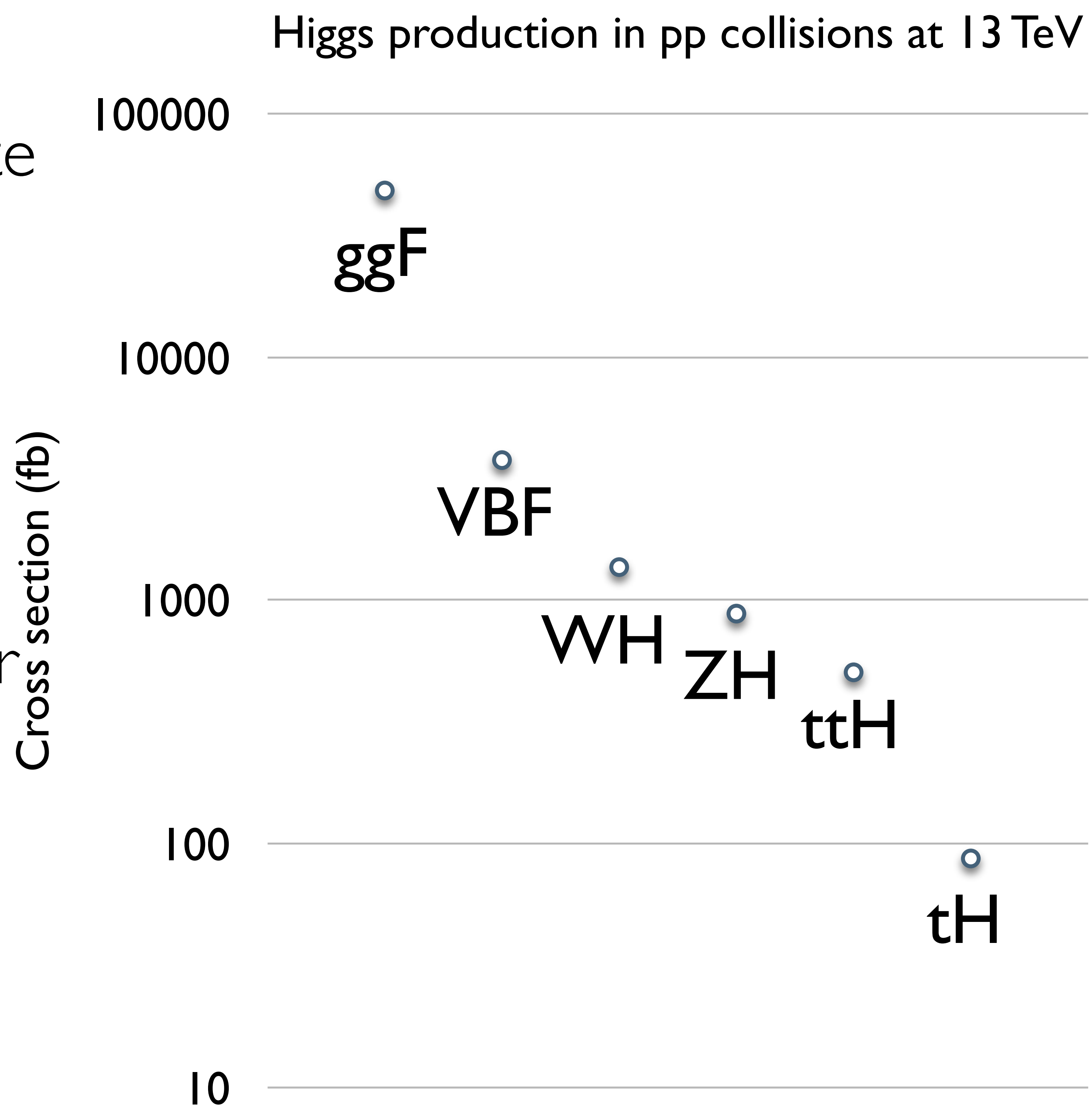
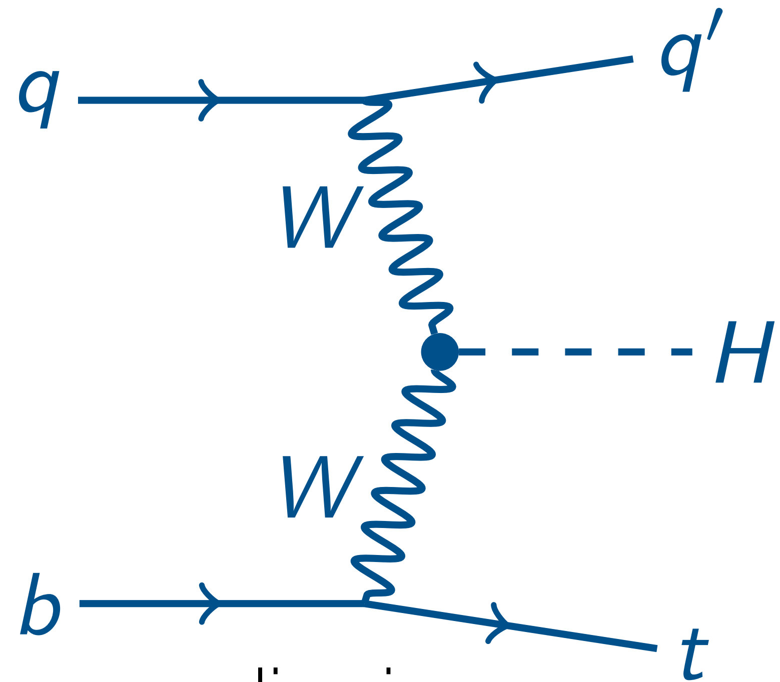
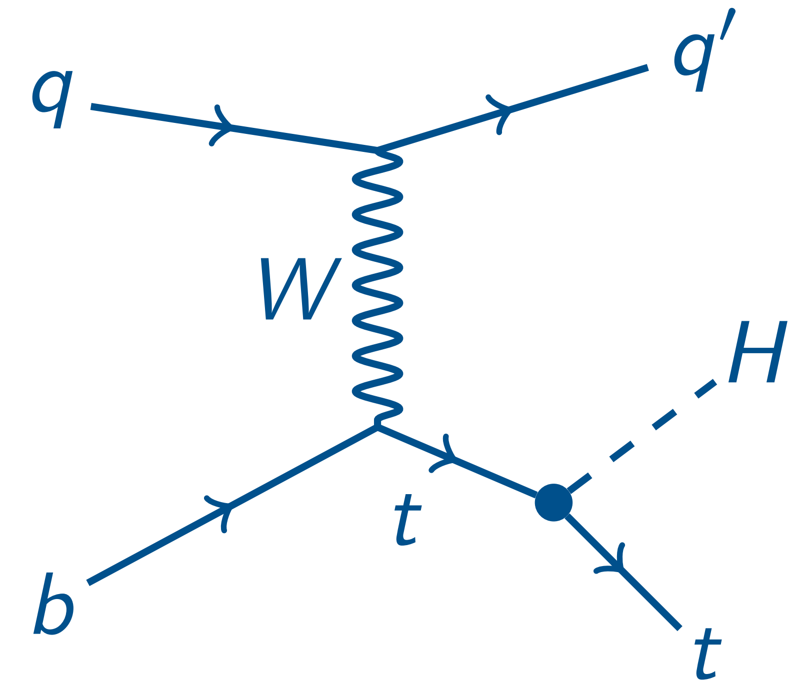


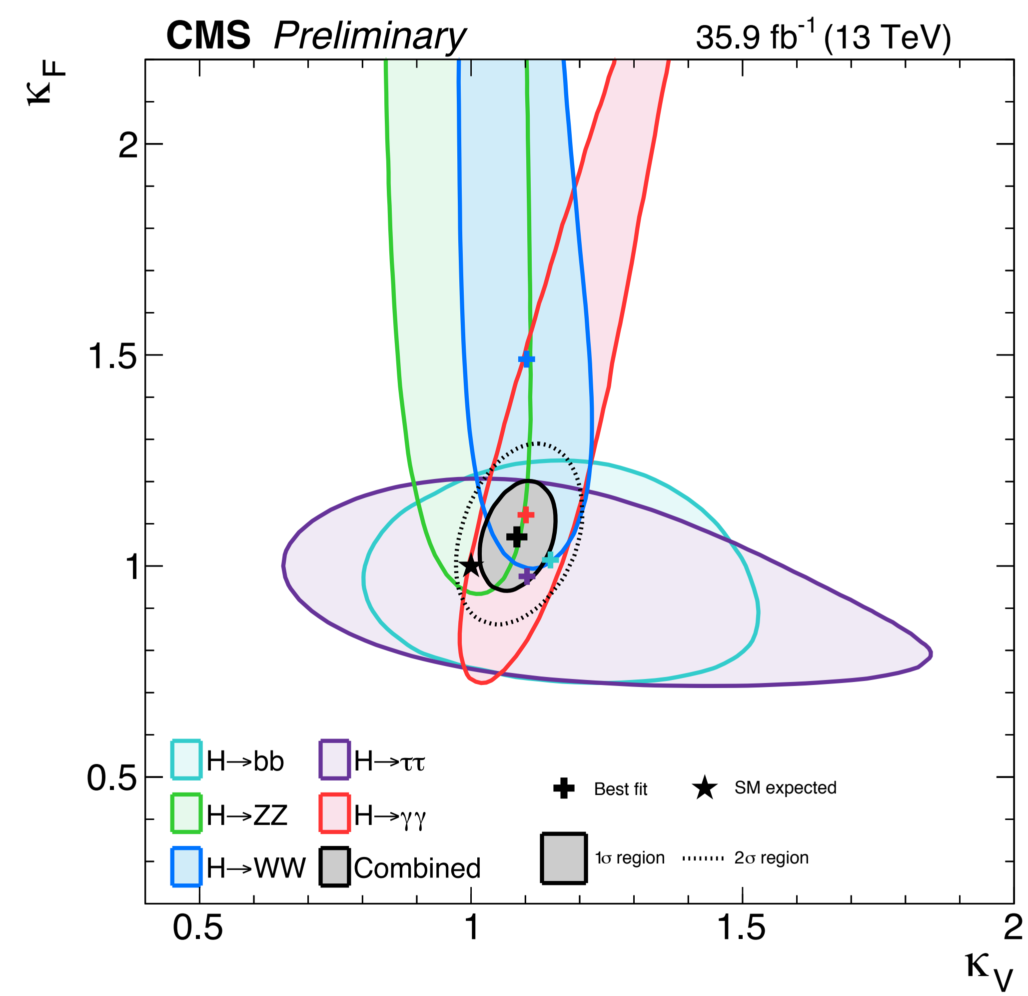
arXiv:1610.07922

Discovery through interference

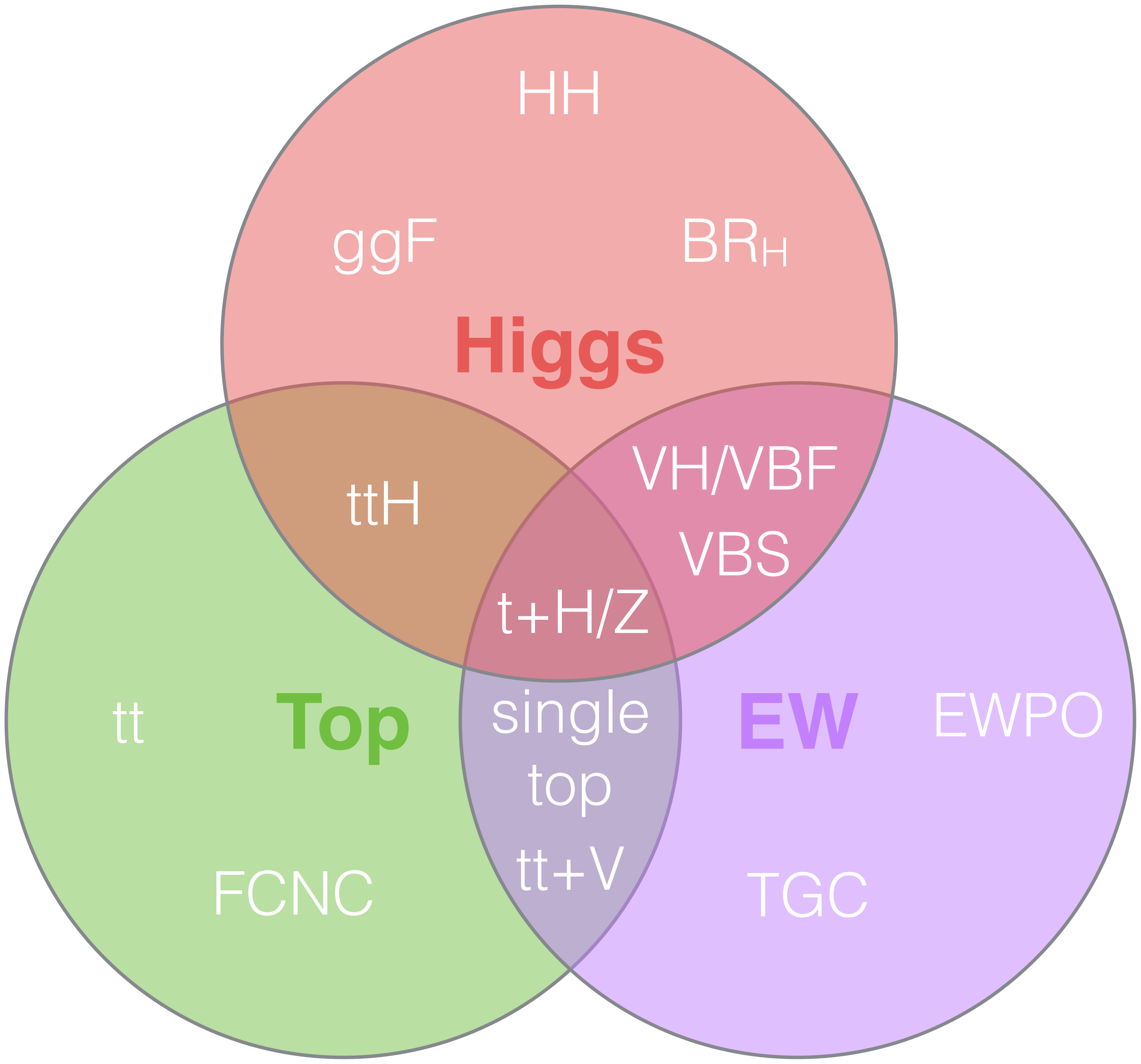
- Small cross section due to destructive interference between two diagrams
  - Similar for tHW production
- If the sign of the top Yukawa coupling is inverted (κ_t = -1), interference is constructive, and cross section is ×10 larger!
- Most production modes depend on the square of the coupling, insensitive to sign
- Bounds on κ_t largely derived from decays
  - Constraints assume no new particles in loops
  - Composite Higgs, FCNC processes could enhance cross section further







- tH production has recently gained attention in the context of standard model effective field theory
- "opens up the rather unique possibility of accessing top-Higgs, top-gauge, triple gauge, gauge-Higgs interactions in the same final state."
- See JHEP 1810 (2018) 005 and arXiv:1904.05637

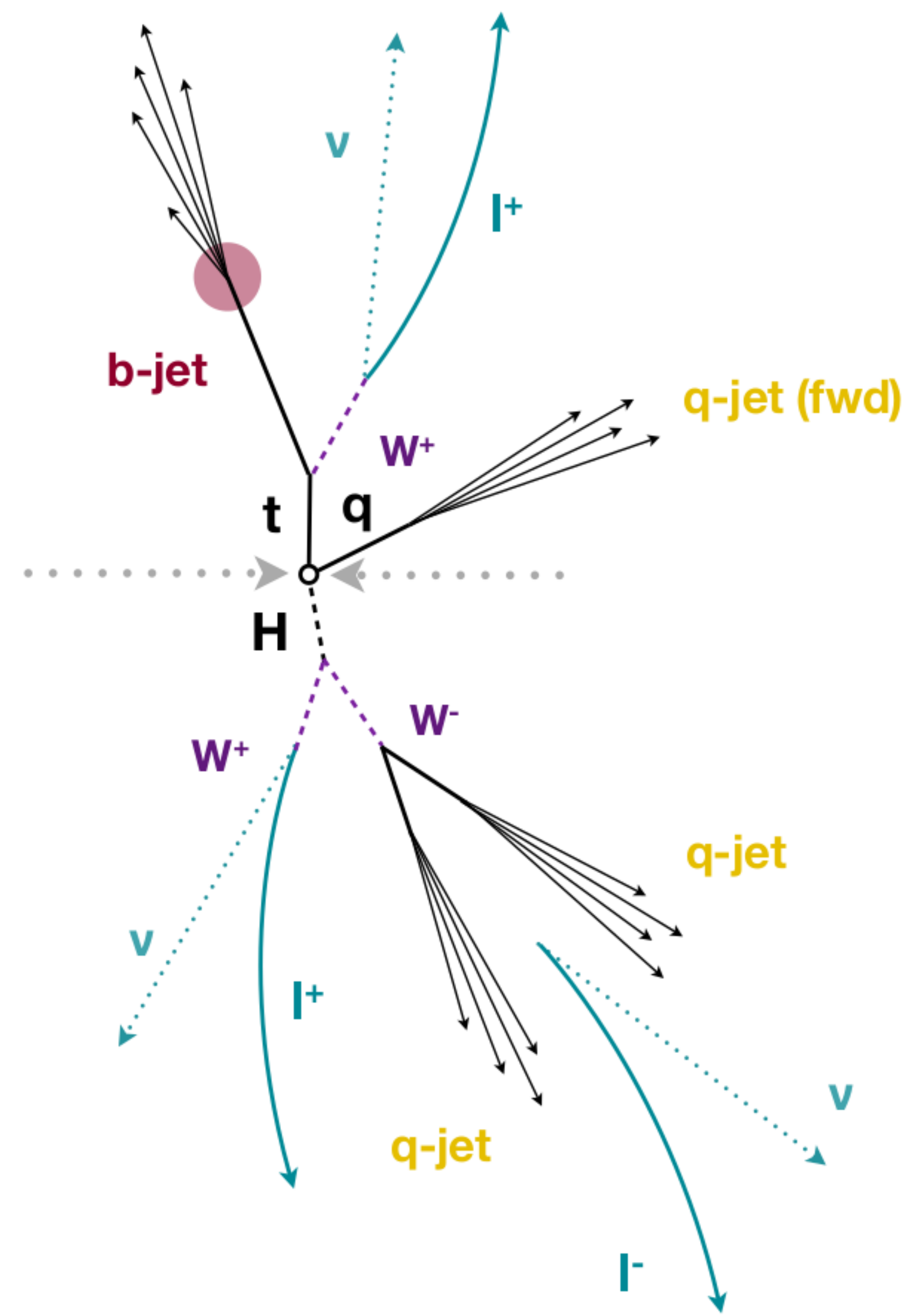


K. Mimasu, "EFT in Top Physics", CMS TOP PAG, 6/27/18

CMS Run 2 searches for tH

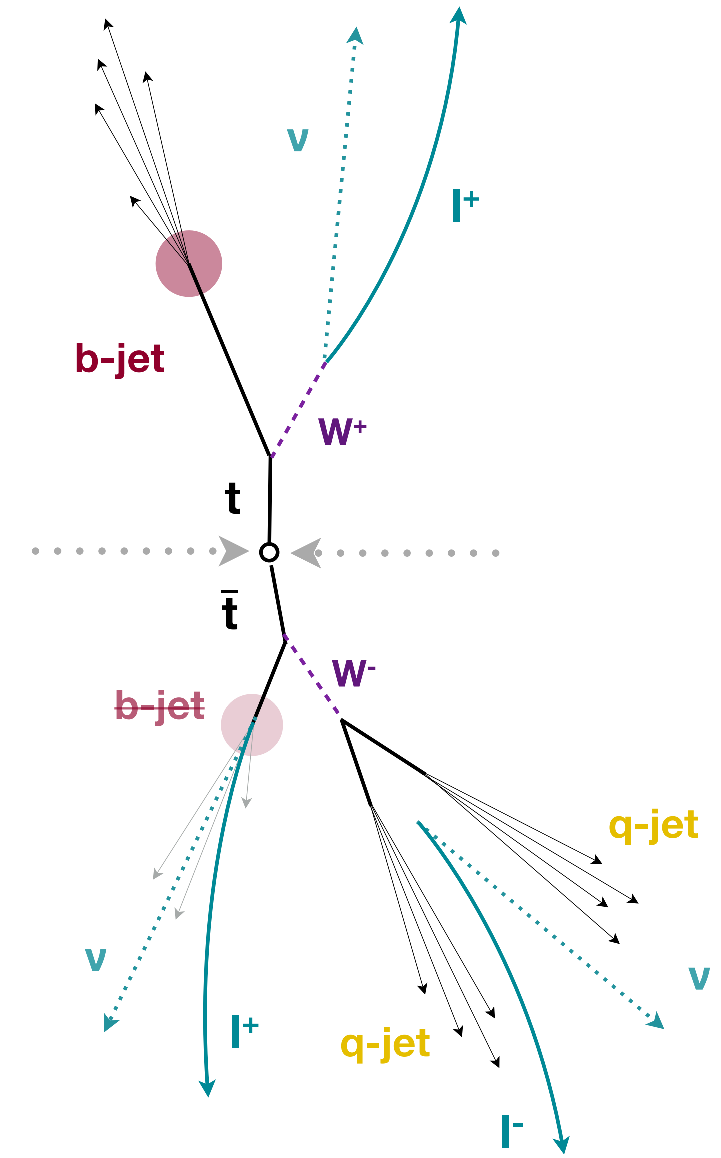
- Excellent opportunity to search for tH in LHC Run 2 data
  - CMS Run 1 result (JHEP 06 (2016) 177) only explored $\kappa_t = -1$
  - tHq cross section ~x4 larger at 13 TeV than 8 TeV
  - Include tHW as signal, improved analysis techniques, greater exploration of $\kappa_t \neq -1$
- Two CMS searches for tH production (PRD 99 (2019) 092005)
  - $H \rightarrow WW$ multileptons: small branching ratio but better S/B, non-prompt lepton backgrounds
  - $H \rightarrow b\bar{b}$: Largest branching ratio but very large $t\bar{t}$ background
- Commonalities:
  - Both take advantage of top semi-leptonic decay and forward light jet
  - Both have $t\bar{t}$ (including $t\bar{t}H$) as their most significant background
- Plus: reinterpretation of $H \rightarrow \gamma\gamma$ in the tHq context

- 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

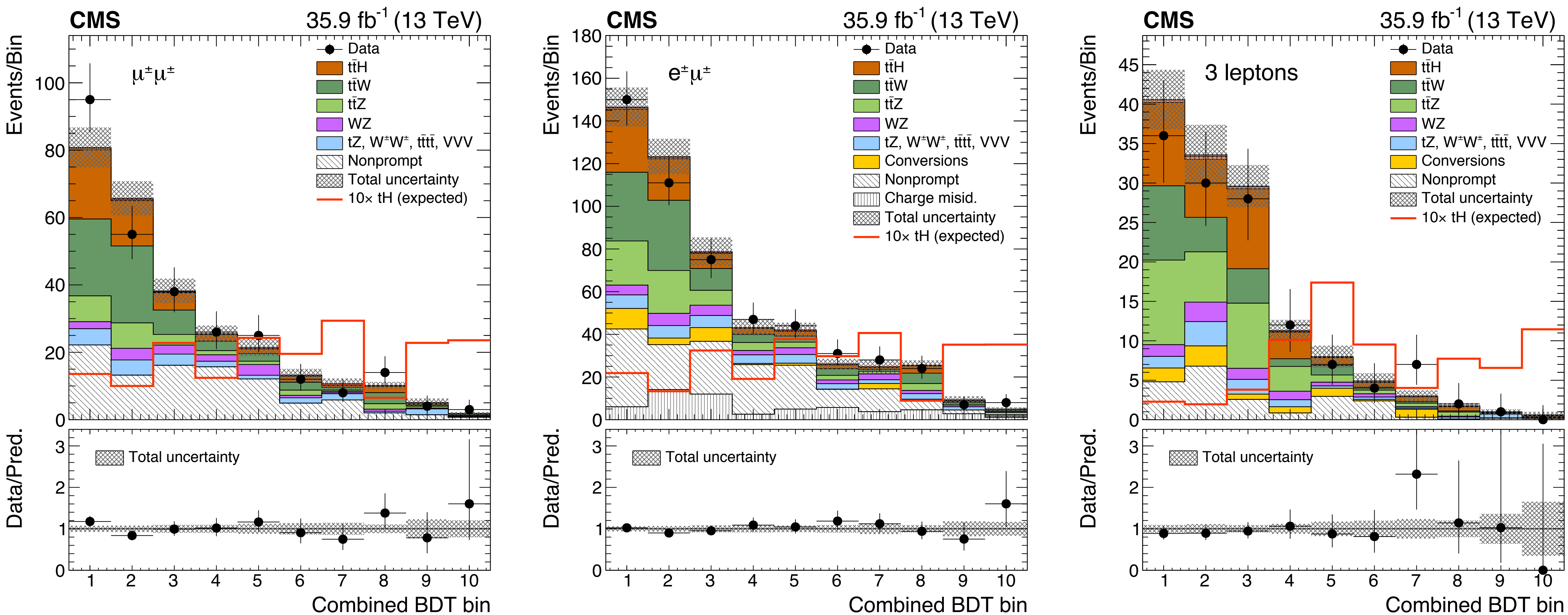


H→WW→leptons: backgrounds

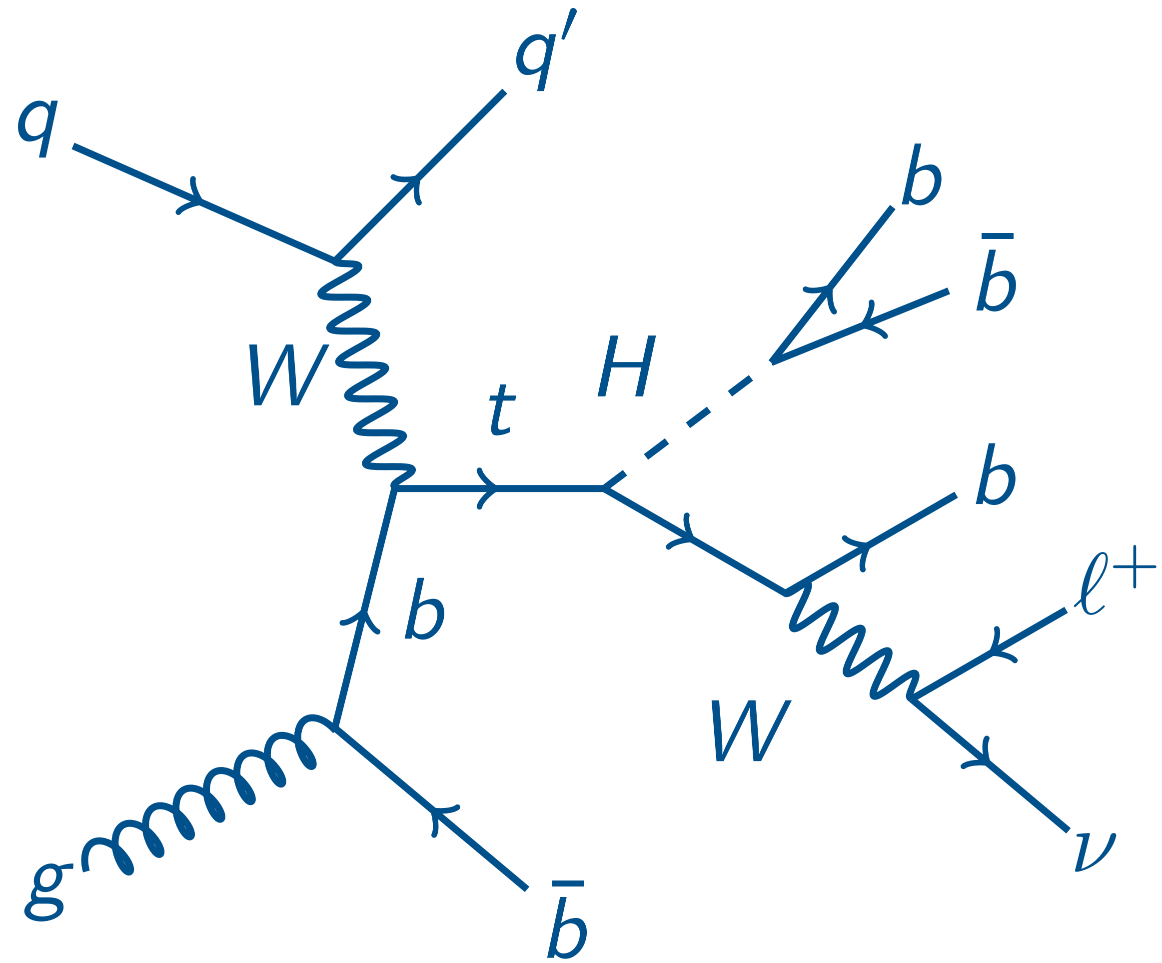
- Two dominant sources of background
  - $t\bar{t}$+(W/Z/H/γ) with prompt leptons
    - Modeled with simulations
  - $t\bar{t}$ with non-prompt leptons
    - Modeled with data using loose-to-tight extrapolation from control regions
- Separate multivariate discriminators for two main backgrounds, using 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



- Classifier output distributions from combined maximum likelihood fit
- Uncertainties dominated by normalization of non-prompt lepton backgrounds, scale variations for $t\bar{t}V$ and $t\bar{t}H$ processes, lepton selection efficiencies



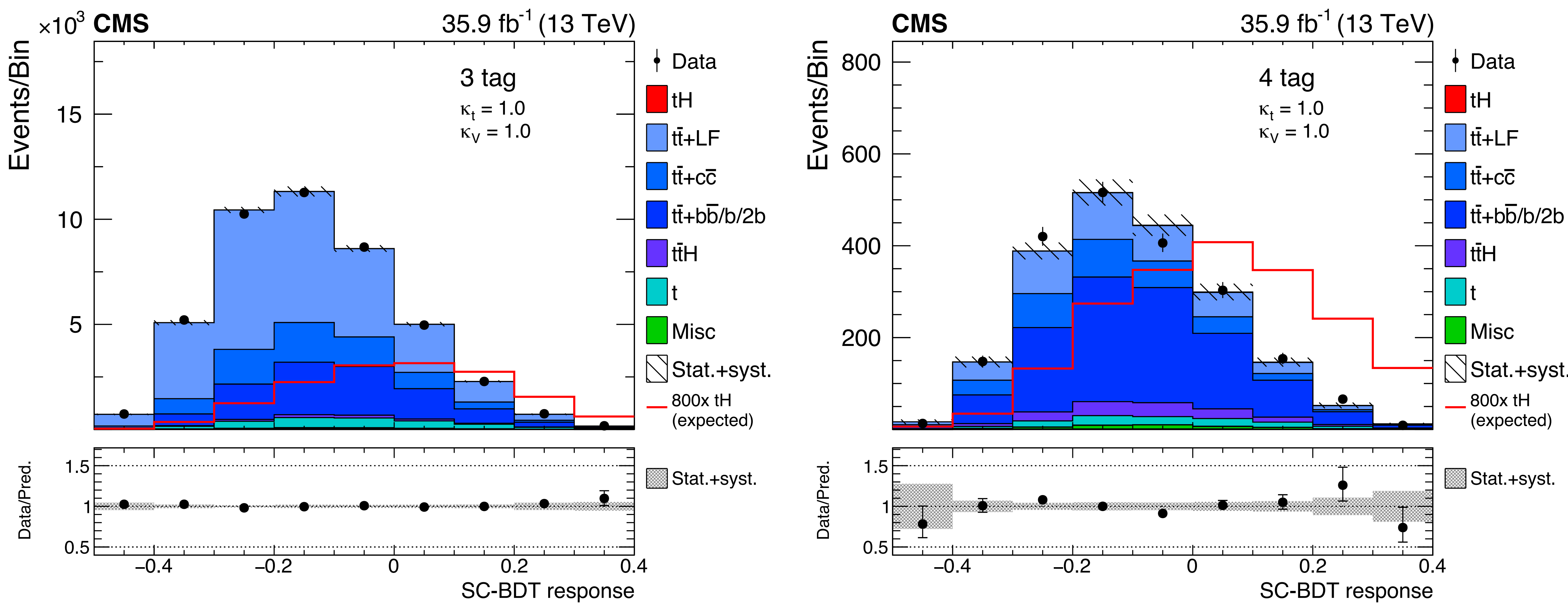
- One isolated high-pT lepton
- Missing energy from ν
- Three or four b jets
- One additional jet

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

Sample	$S(\kappa_t = -1)/B$
3 b jets	252/45300
4 b jets	32.8/1880

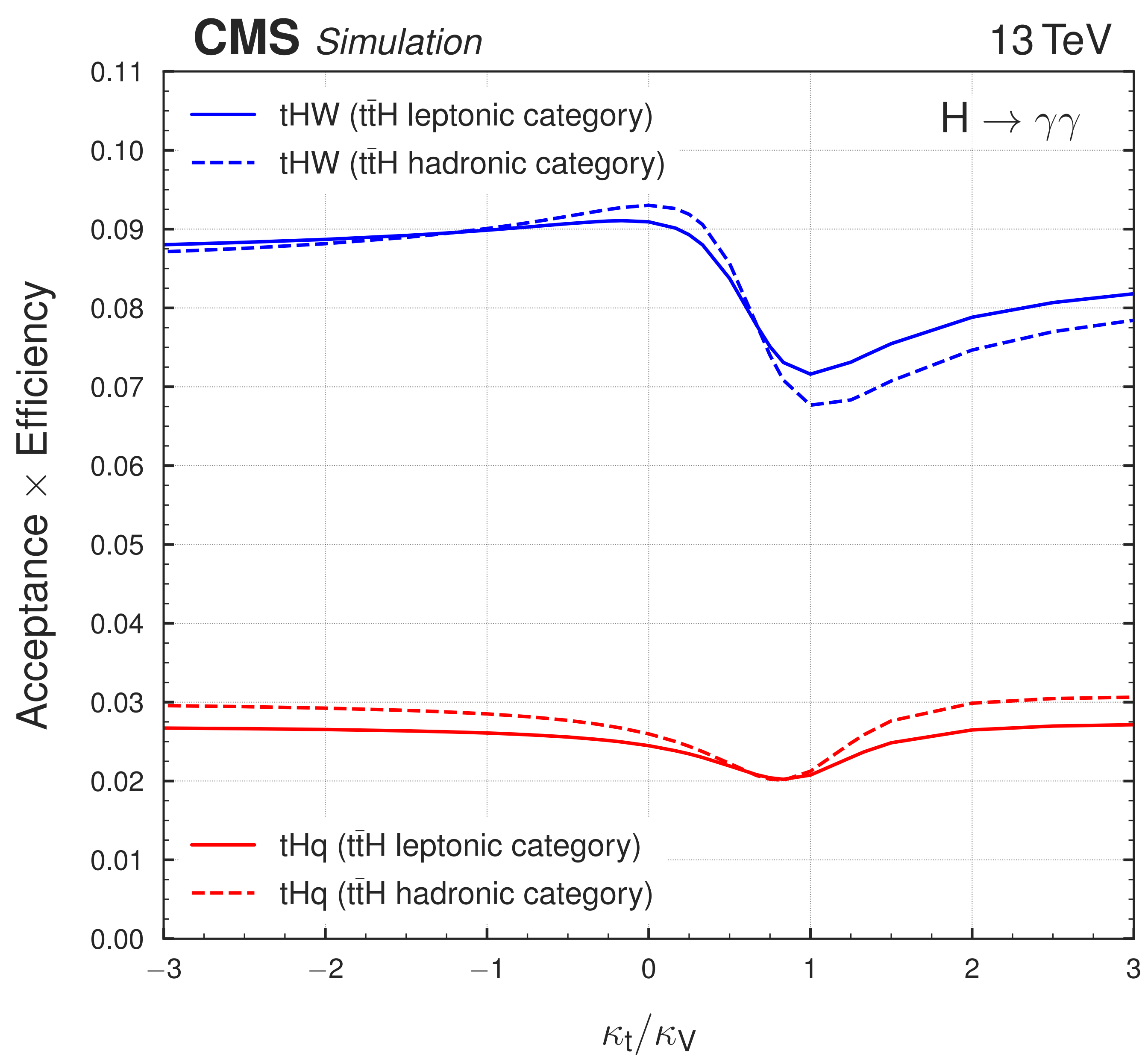
$H \to b\bar{b}$: multivariate approaches everywhere

- Need to assign each of the jets to parent quarks of final state
  - Develop multivariate discriminator based on 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 three different assumptions of initial state: tHq and tHW signal and $t\bar{t}$ background*
- With tH 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 processes
  - Validated in two-tag event sample, enriched in $t\bar{t}$
- Fit distribution of that discriminator to templates from signal and background
- Simultaneously, use a $t\bar{t}$-enriched dilepton sample to constrain the heavy flavor content of the $t\bar{t}$ background, using (yet) another discriminator



- Classification discriminator from maximum likelihood fit
- Dominant systematic uncertainties from renormalization and factorization scales, overall normalization of $t\bar{t}$+HF processes, and jet energy corrections

- tH already included in CMS inclusive H→γγ analysis (JHEP 11 (2018) 185), with events mostly populating the "ttH hadronic" and "ttH leptonic" categories
- Use these categories to constrain κ_t and tH production cross section
  - κ_t, κ_V affect tH and ttH cross sections and Higgs branching fractions
- Correct changes in acceptance as a function of κ_t/κ_V due to changes in kinematics



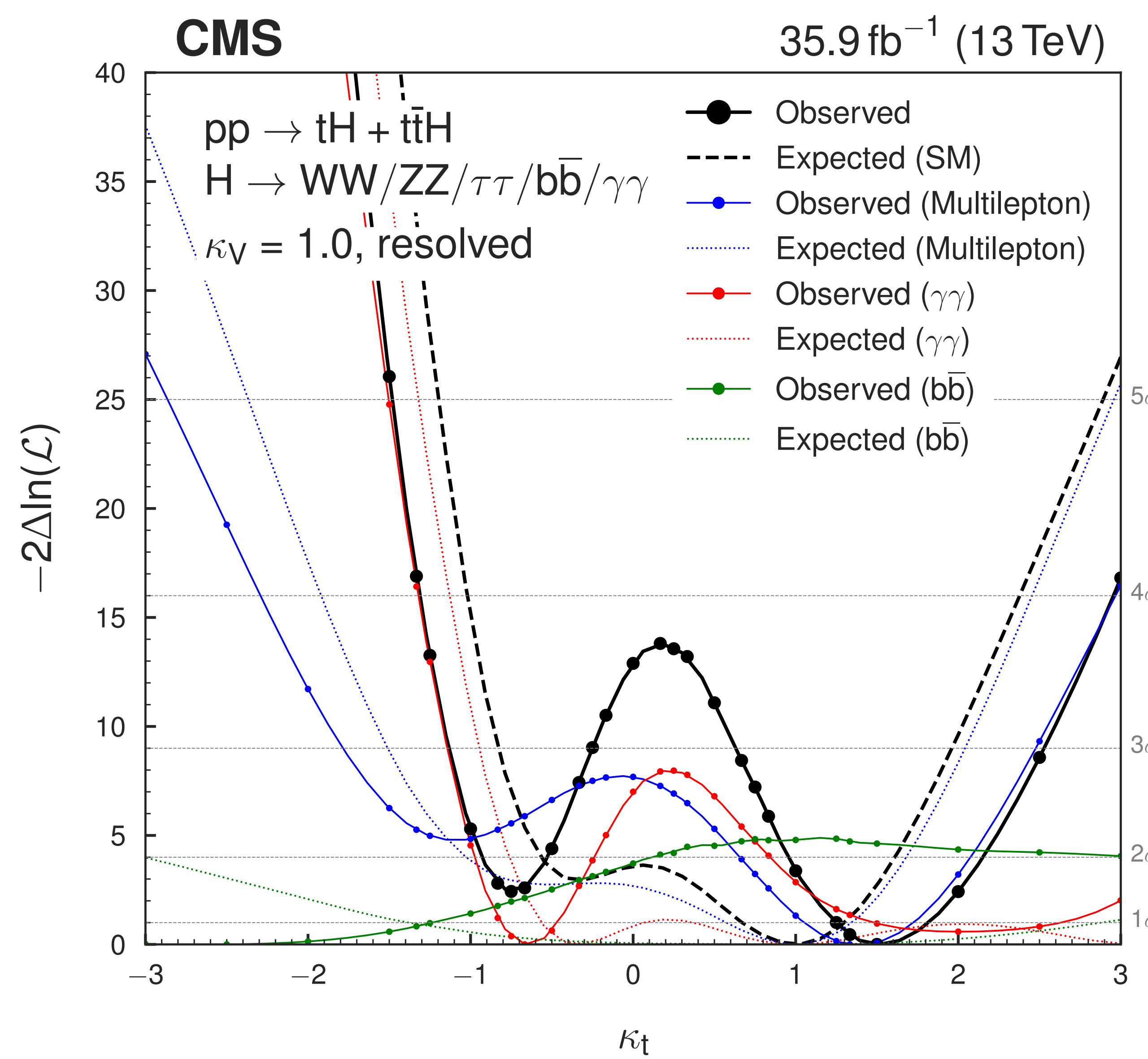
Constraints on Higgs couplings

- tH production cross sections go as

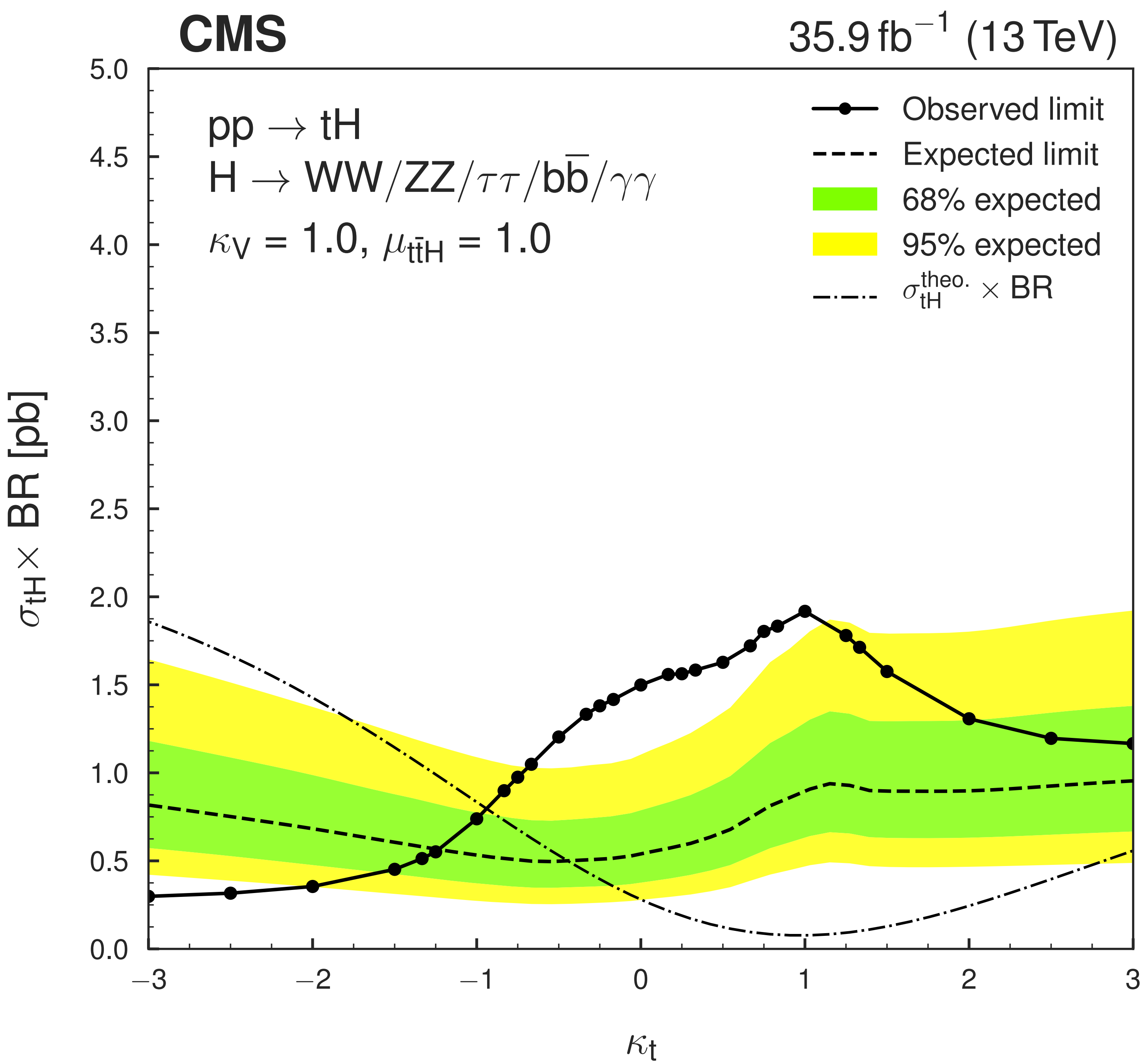
$$\sigma_{tHq} = (2.63\kappa_t^2 + 3.58\kappa_V^2 - 5.21\kappa_t\kappa_V)\sigma_{tHq}^{SM},$$

$$\sigma_{tHW} = (2.91\kappa_t^2 + 2.31\kappa_V^2 - 4.22\kappa_t\kappa_V)\sigma_{tHW}^{SM}$$

- Perform profile likelihood scan as a function of κ_t (with $\kappa_V = 1$), which affects tH and tt̄H cross sections and Higgs branching fractions
- Expect to favor $\kappa_t = 1$ over $\kappa_t = -1$ by 4σ, exclude κ_t outside [-0.5, 1.6] at 95% CL
- Data favor $\kappa_t > 0$ over $\kappa_t < 0$ by 1.5σ, exclude κ_t outside [-0.9, -0.5] and [1.0, 2.1] at 95% CL
- 2σ excess of events over expectations in multilepton and $\gamma\gamma$ channels; combined tH+tt̄H rate is (2.00 ± 0.53) x SM expectations
  - Consistent with dedicated tt̄H searches



- Introduce separate signal strength parameter for tH, excluding $t\bar{t}H$
  - Fix $t\bar{t}H$ to its κ_t-dependent cross section
- Expected limit of 12x SM production cross section; observe limit of 25x SM



Future?

- Results presented are derived from data collected in 2016
- Full Run 2 (2016-18) result will be more strongly integrated with $t\bar{t}H$ result, as there are significant overlaps in the event selection
- Other analyses:
  - tH cross section is also sensitive to Higgs CP mixing phase, expect to set limits on admixture of CP-odd Higgs in future analyses
  - Search for Higgs-mediated FCNC process tHq with q = u, c
- Very (very?) far future: tHHq has strong dependence on Higgs self coupling, but unfortunately an extremely small cross section
- Much to learn yet from this process at the center of everything!