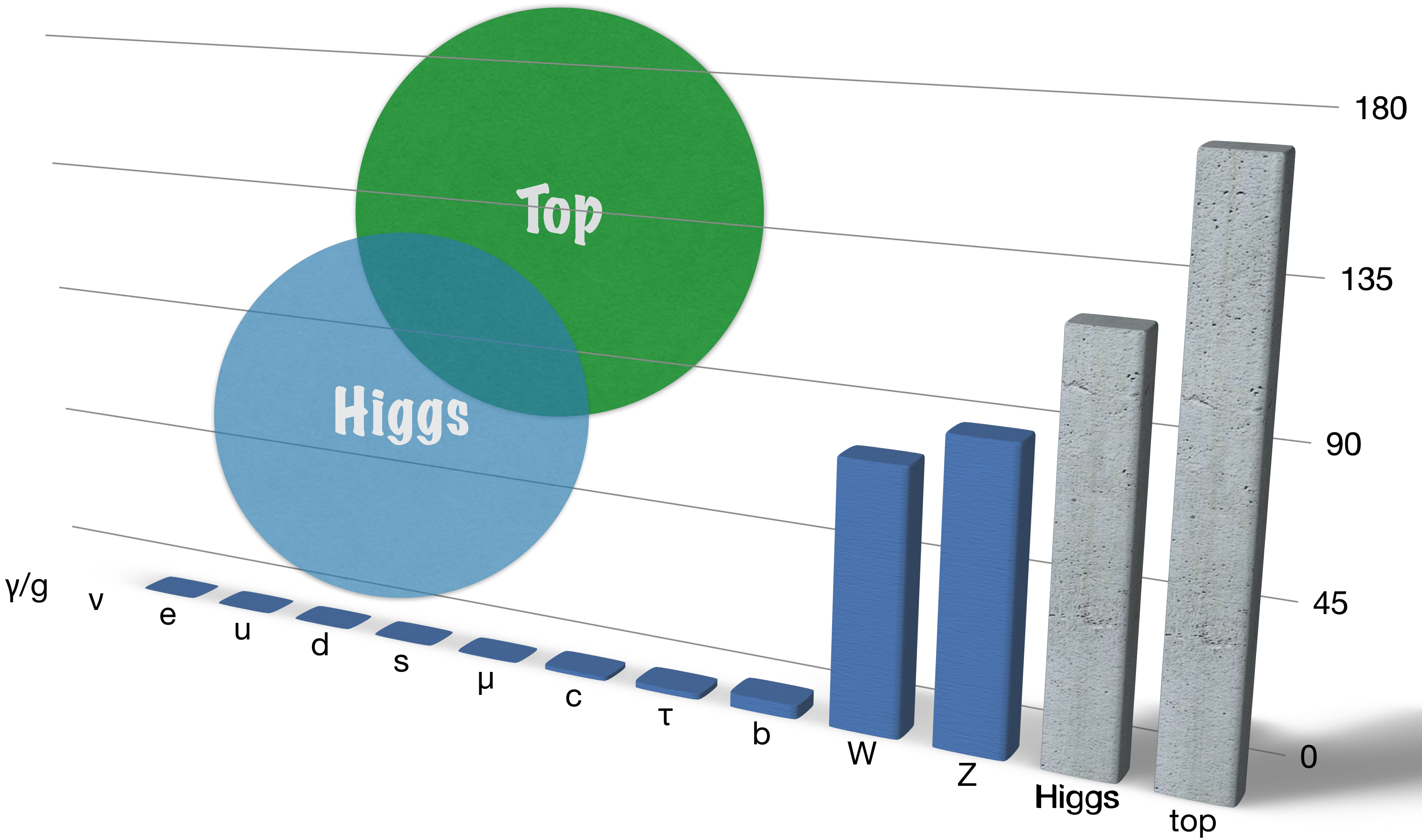
HIGGS PRODUCTION IN ASSOCIATION WITH TOP QUARKS IN CMS

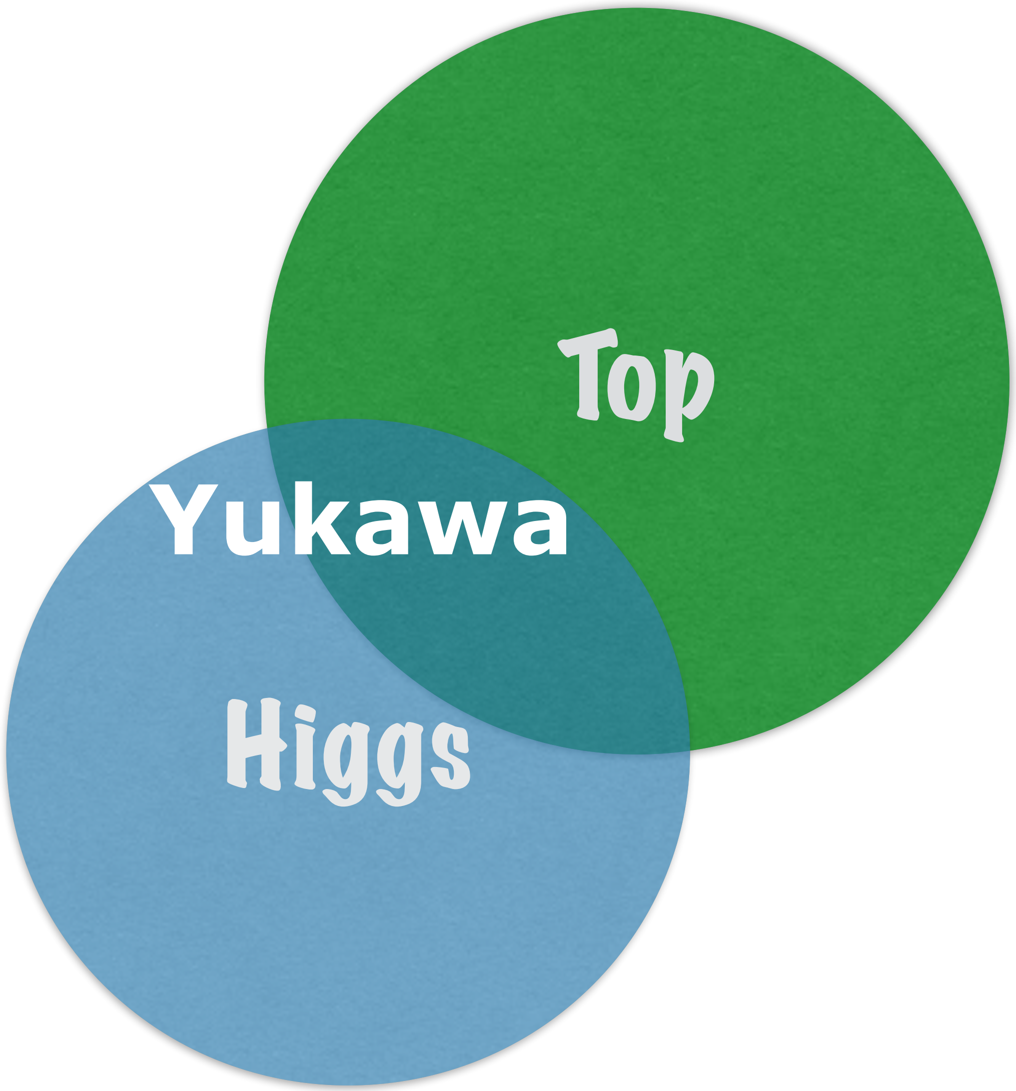
Fabrizio Margaroli
(for the CMS Collaboration)
Sapienza & INFN

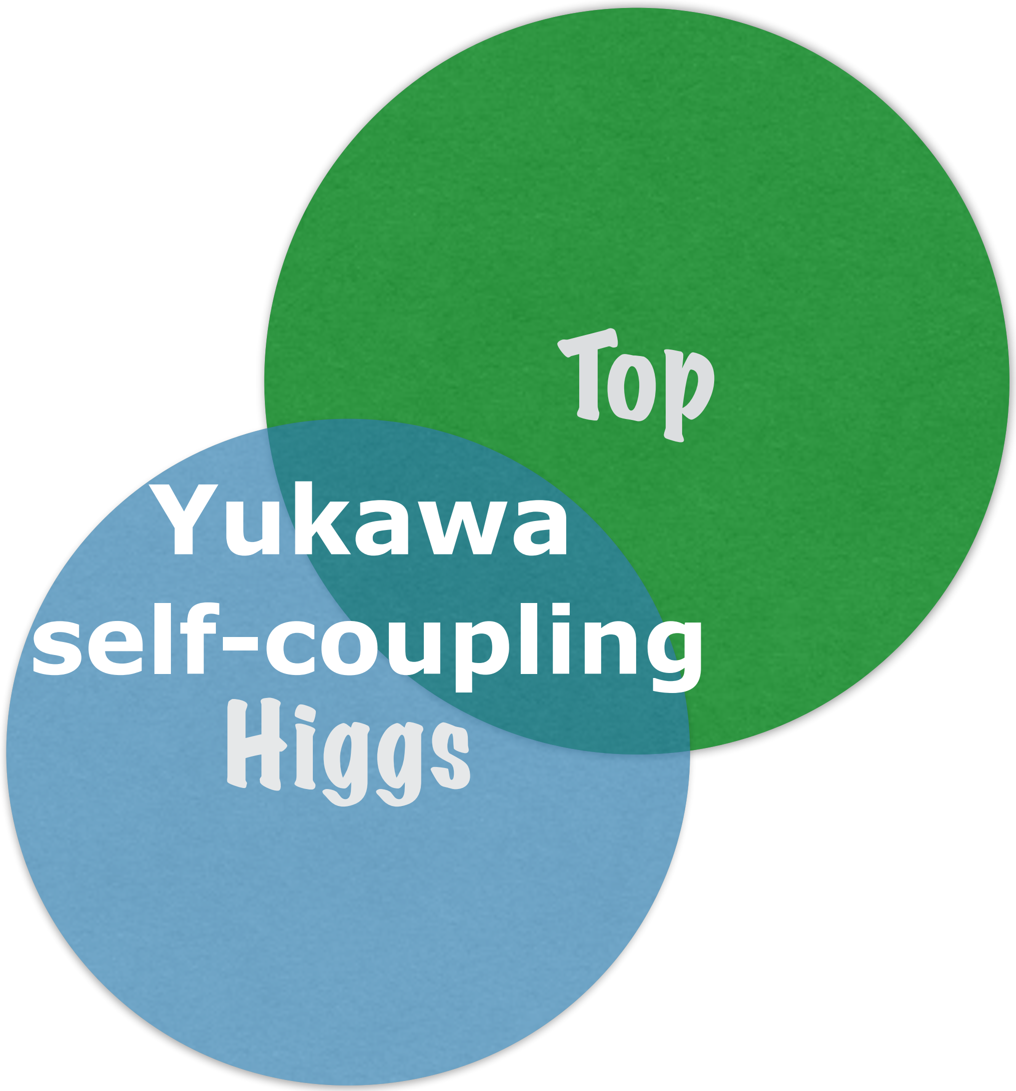
SAPIENZA
UNIVERSITÀ DI ROMA

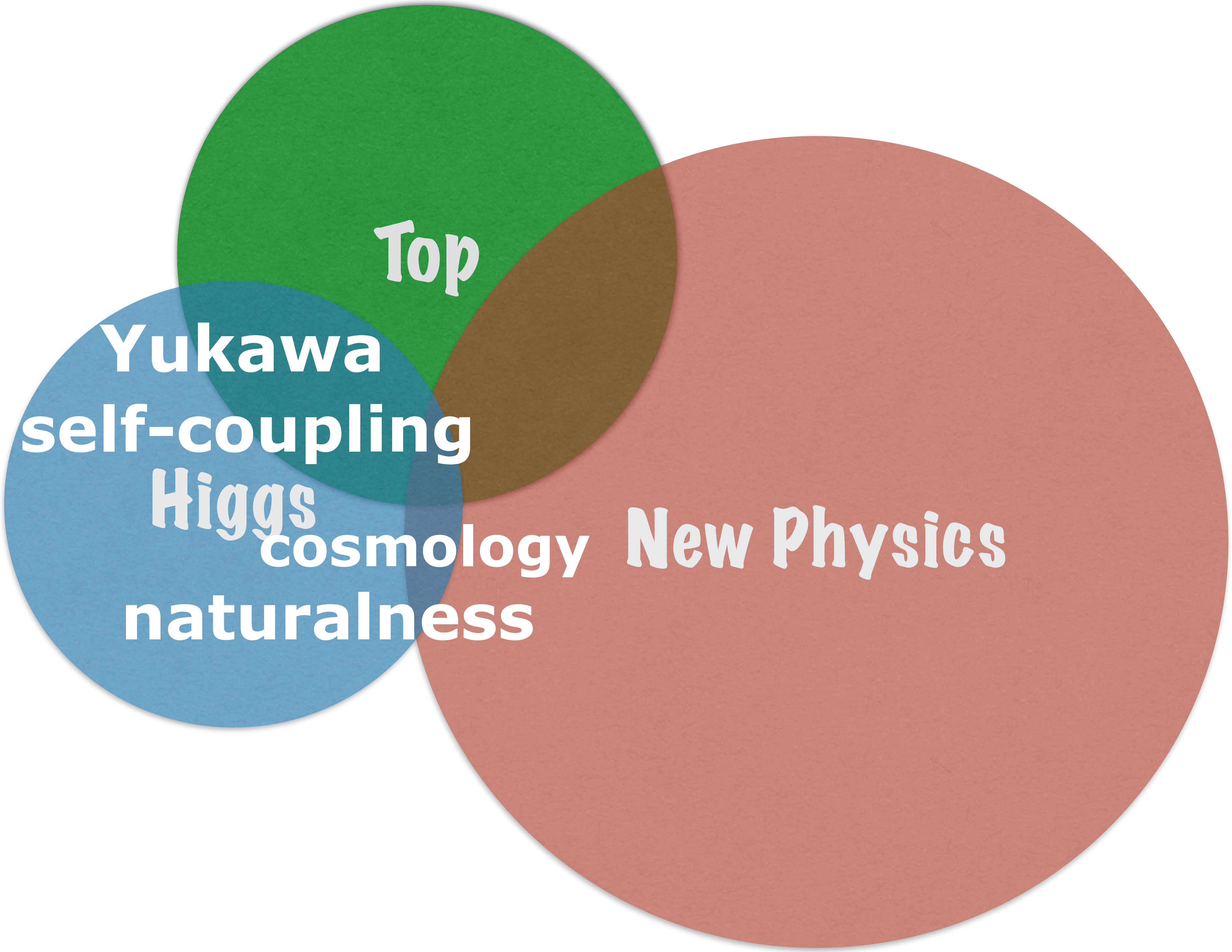
INFN
Istituto Nazionale di Fisica Nucleare

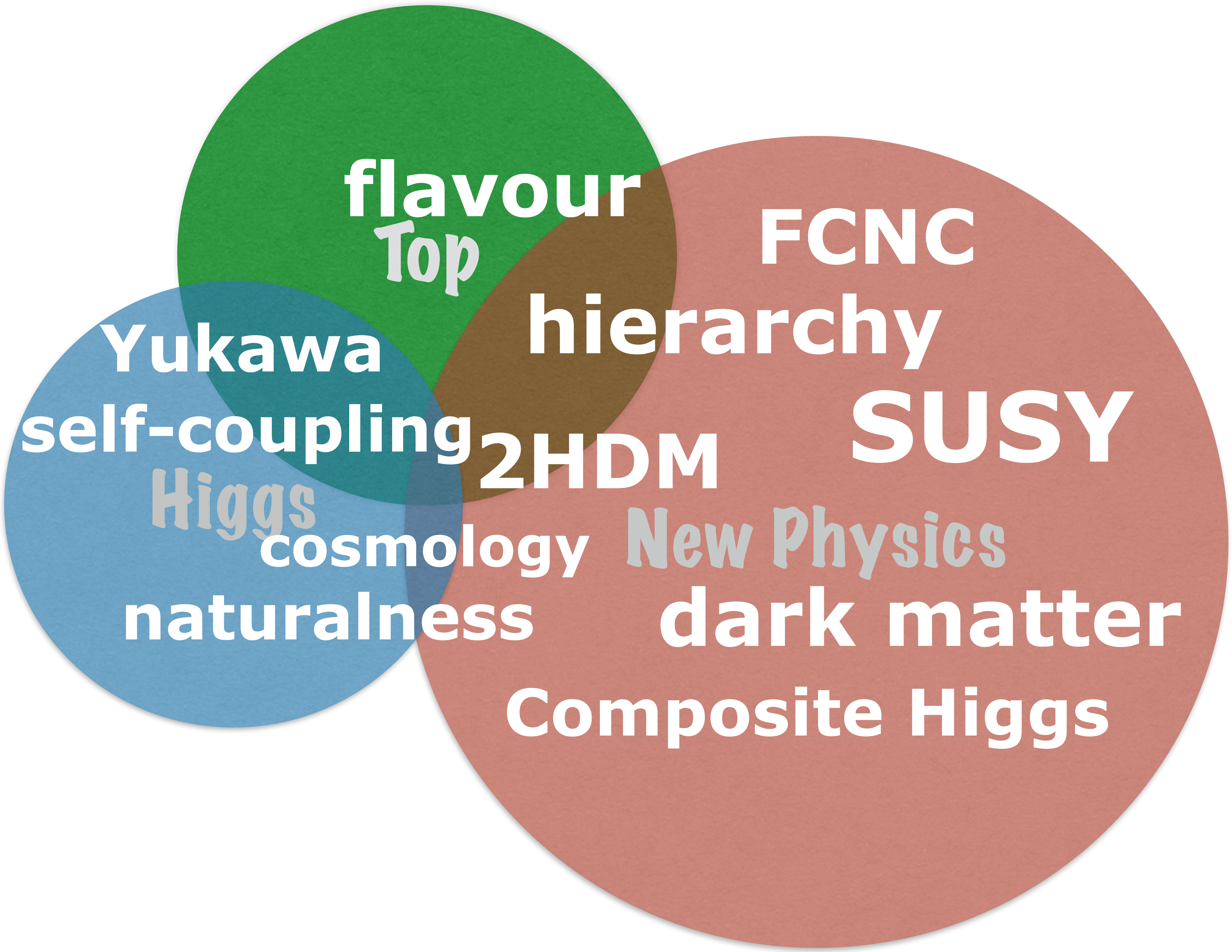
Why Top and Higgs?



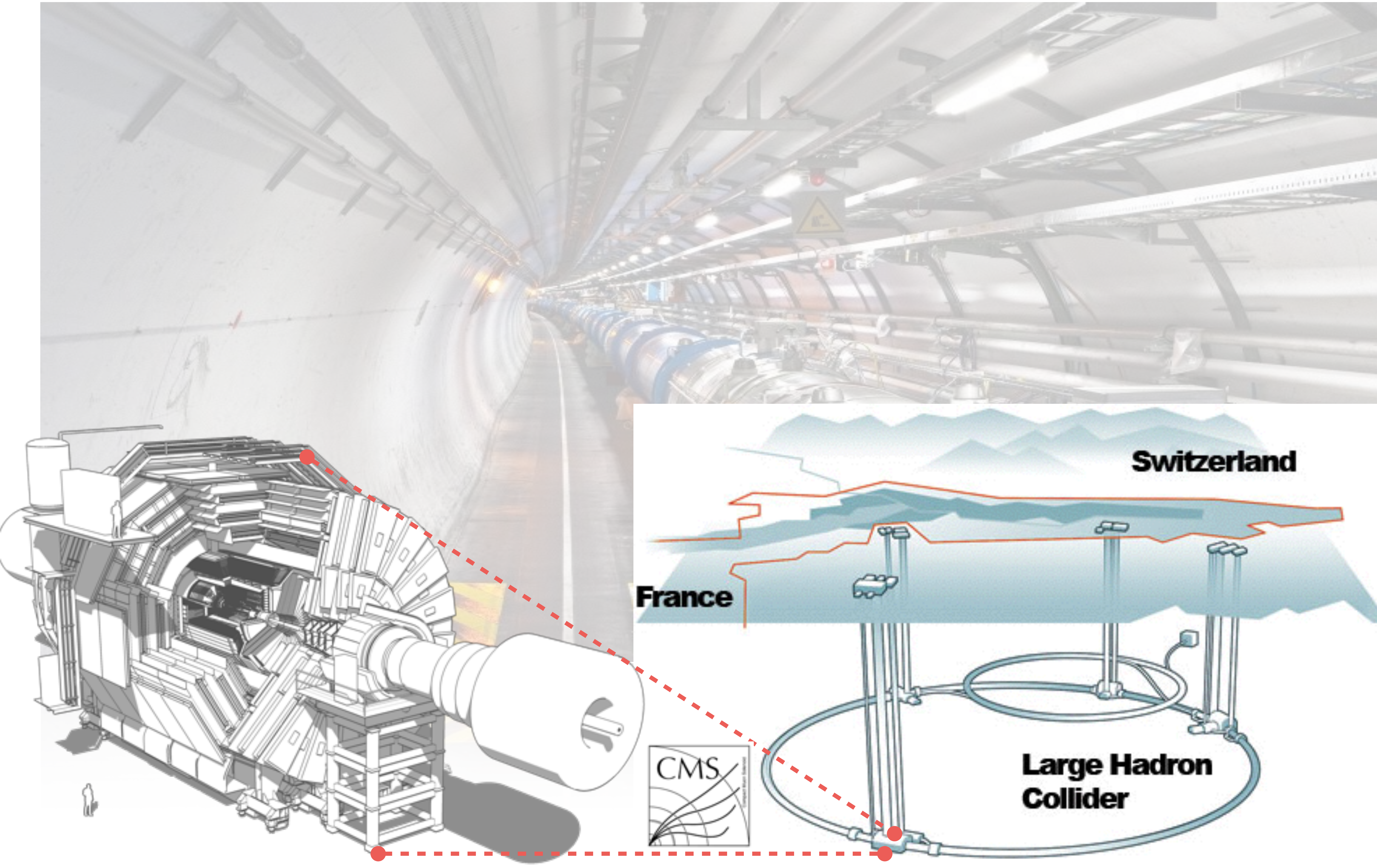

Top
Yukawa
Higgs


Top
Yukawa
self-coupling
Higgs

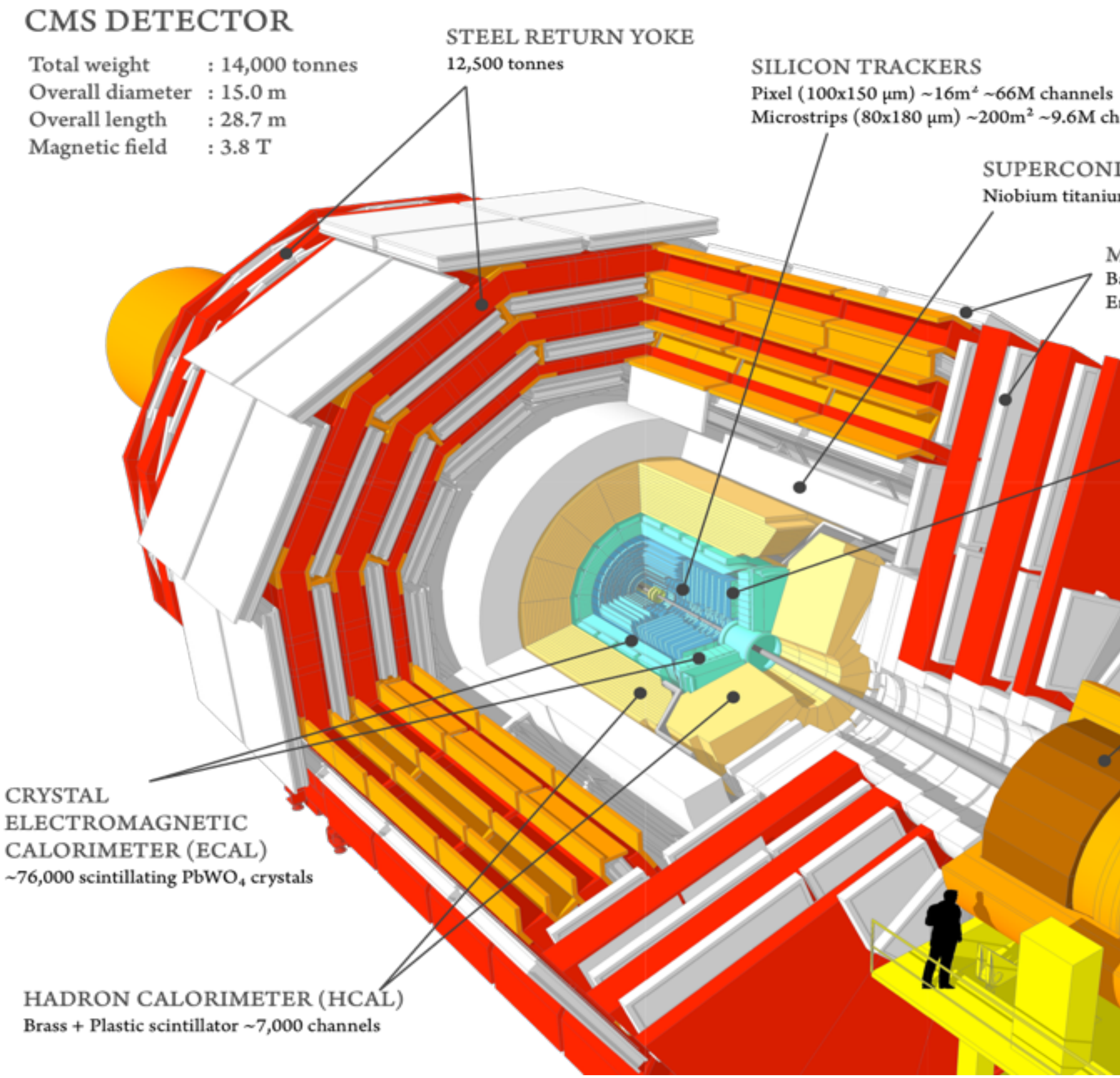

Top
Yukawa
self-coupling
Higgs
cosmology
New Physics
naturalness

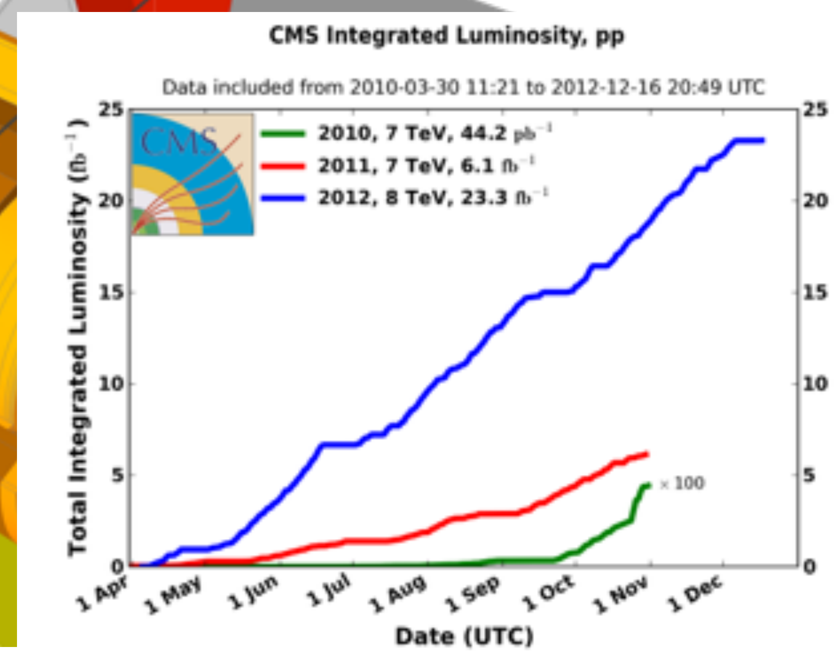

flavour
Top
FCNC
hierarchy
Yukawa
SUSY
self-coupling
2HDM
Higgs
cosmology
New Physics
naturalness
dark matter
Composite Higgs

WHERE



How (experimentally)

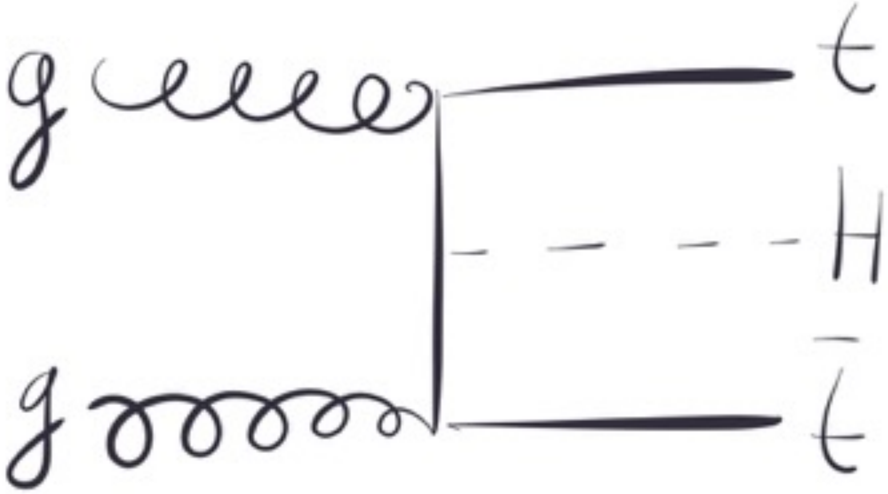




A THREEFOLD WAY TO TOP+HIGGS

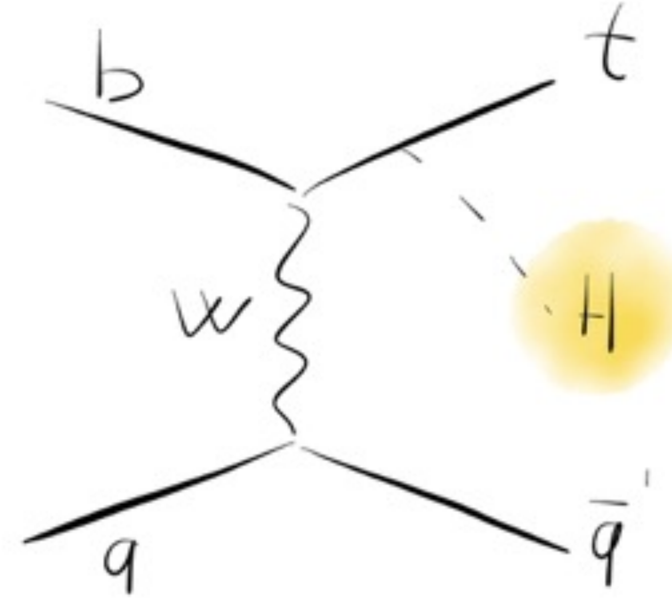
INDIRECT:
Direct Higgs Production
Higgs decay to photons

CMS EPJ. C 75 (2015) 212



DIRECT: absolute Yukawa
Top-antitop-Higgs Production

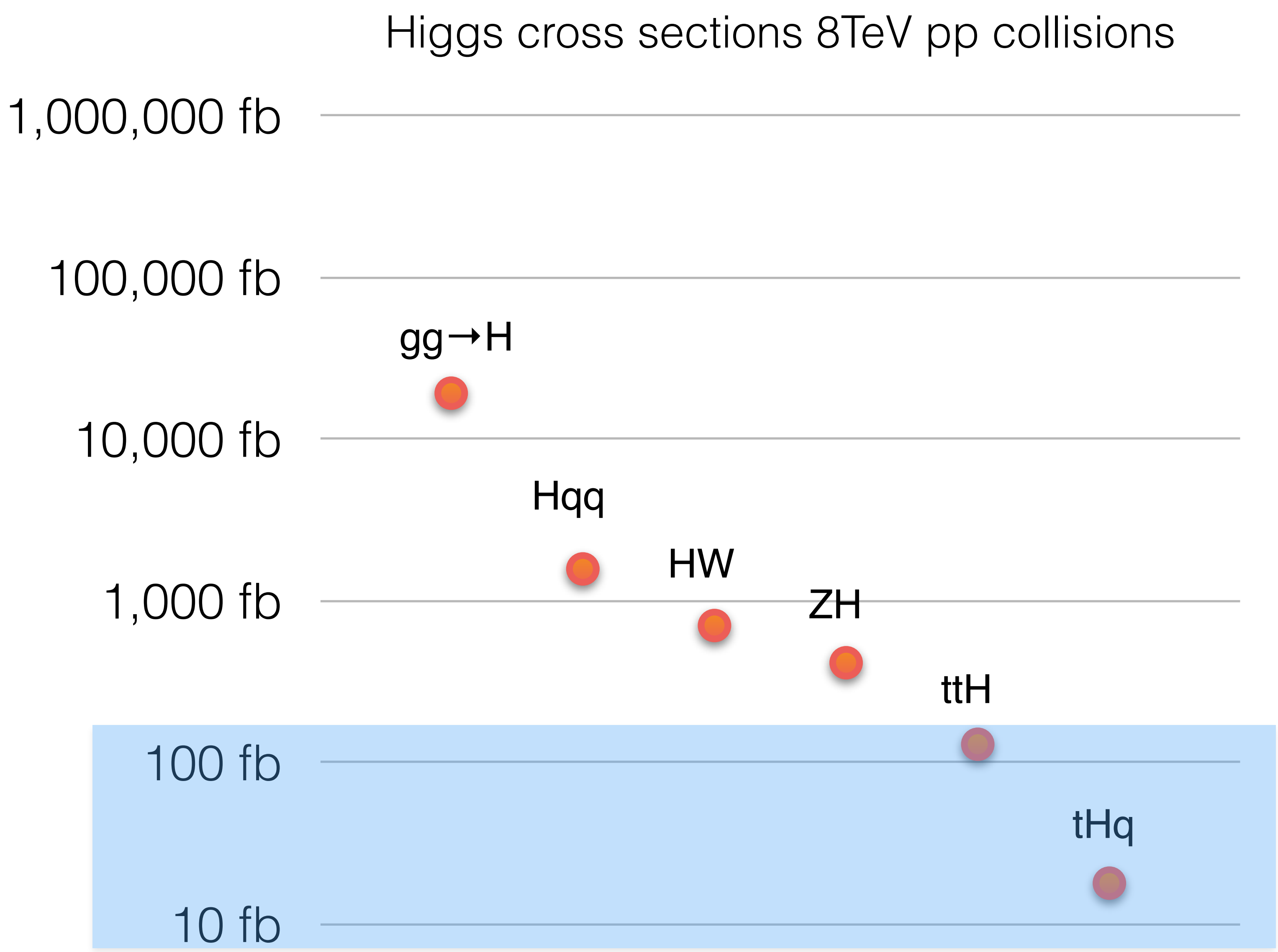
JHEP 09 (2014) 087 (*comb*)
EPJ C 75 (2015) (bb ME)



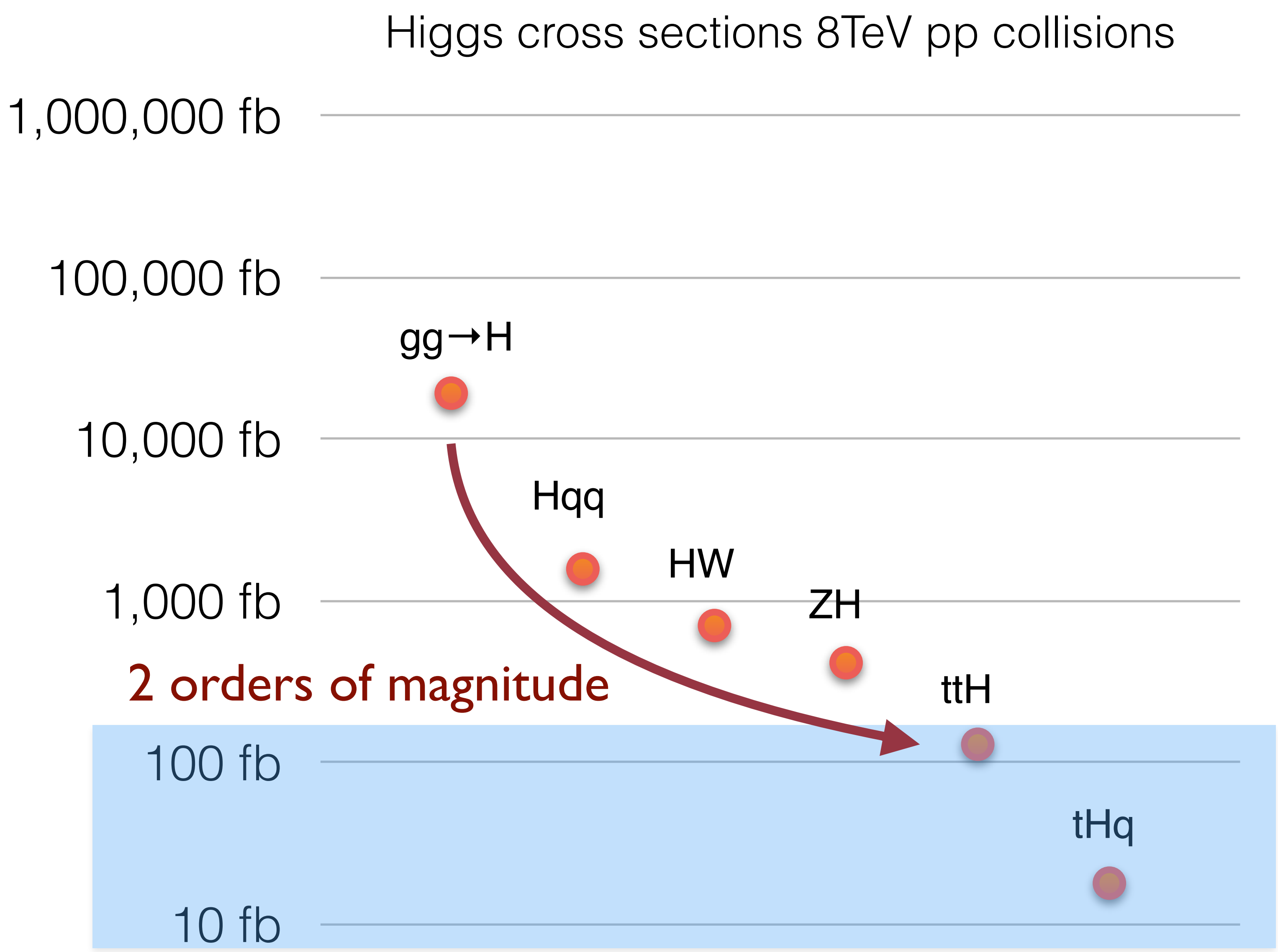
DIRECT: Yukawa sign
Top(antitop)-Higgs Production

CMS-HIG-14-001 (*γγ*)
CMS-HIG-14-015 (*bb*)
CMS-HIG-14-026 (*leptons*)
CMS-HIG-14-027 (*tau+combination*)

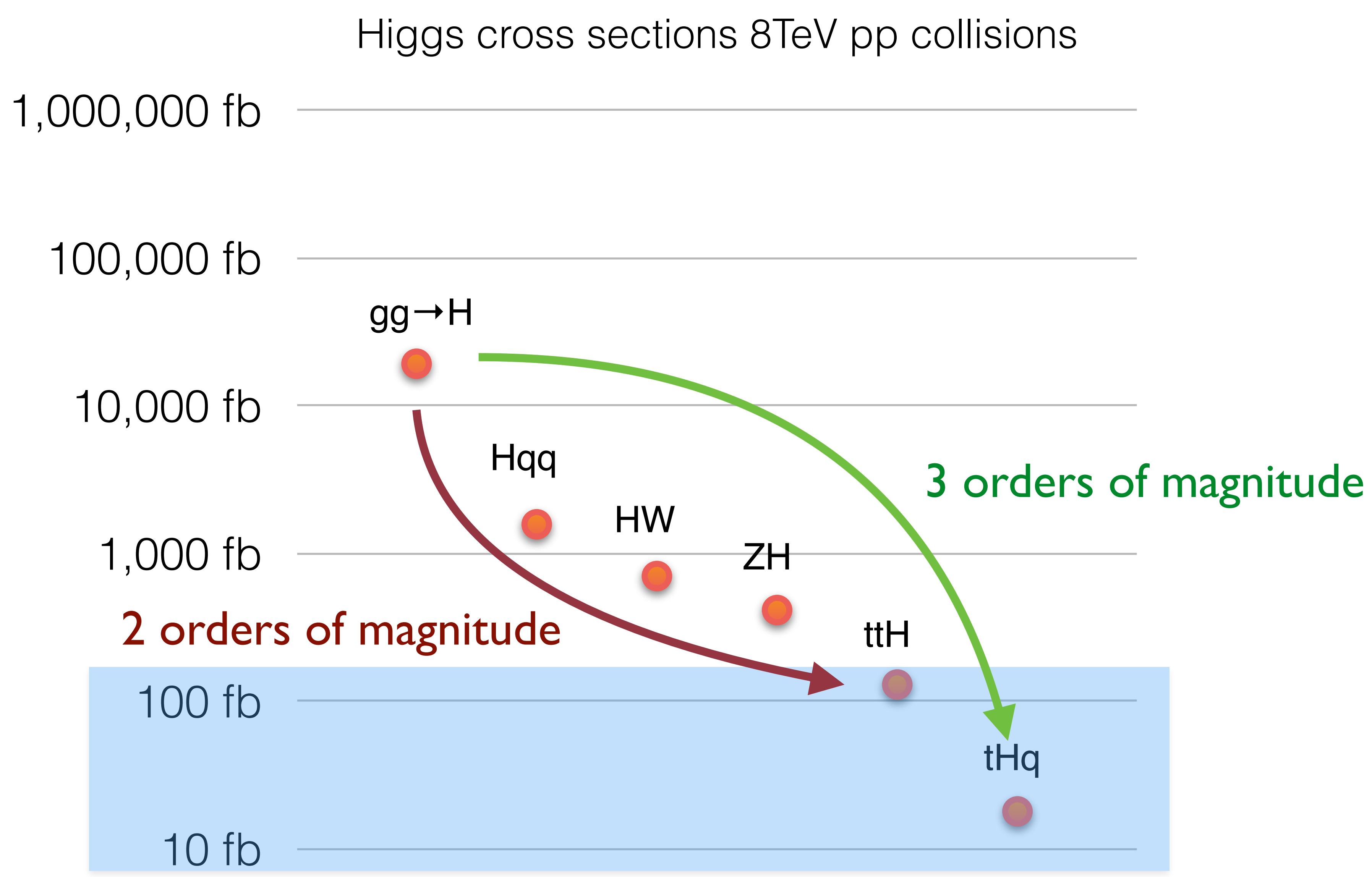
DIG DEEPER INTO THE LHC GOLD



DIG DEEPER INTO THE LHC GOLD

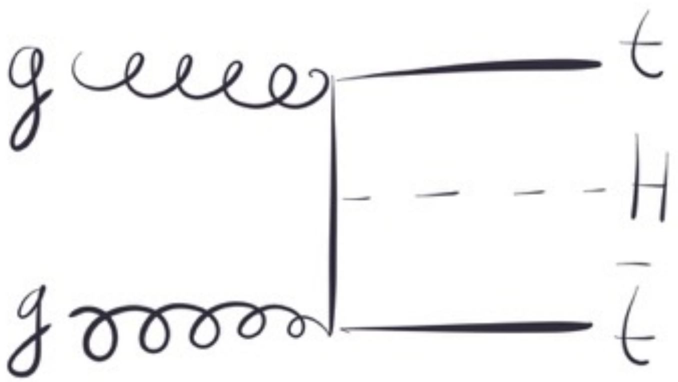


DIG DEEPER INTO THE LHC GOLD



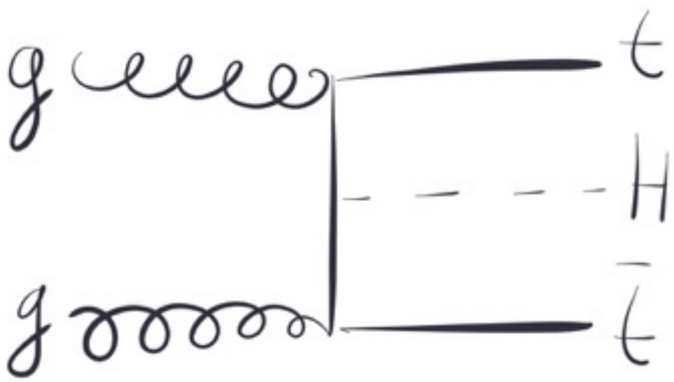
TTH: ***VERY*** COMPLEX FINAL STATE

- Cross section is only ~1/200 of the inclusive Higgs production cross section
- Large multiplicity of objects in the final state
  - top quarks decay to Wb, W bosons decay in turn leptonically (lnu) or hadronically (qq)
  - Higgs bosons decay to anything but top quarks…
- Need to find the best combination of top and Higgs decays to isolate the small signal (130fb)

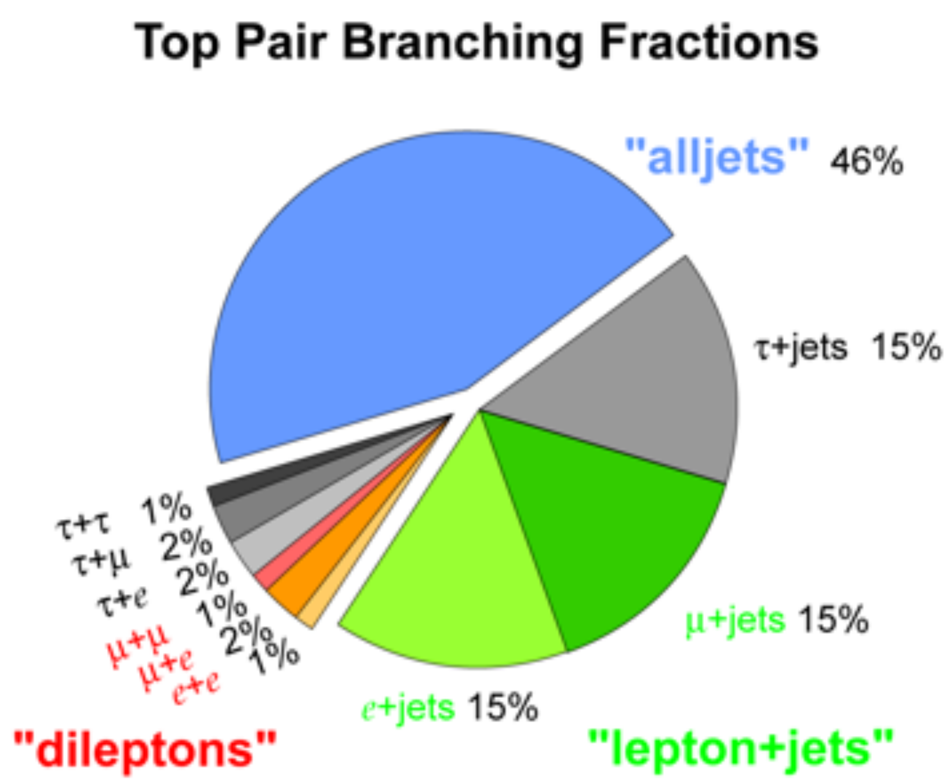


TTH: ***VERY*** COMPLEX FINAL STATE

- Cross section is only ~1/200 of the inclusive Higgs production cross section
- Large multiplicity of objects in the final state
  - top quarks decay to Wb, W bosons decay in turn leptonically (lnu) or hadronically (qq)
  - Higgs bosons decay to anything but top quarks…
- Need to find the best combination of top and Higgs decays to isolate the small signal (130fb)

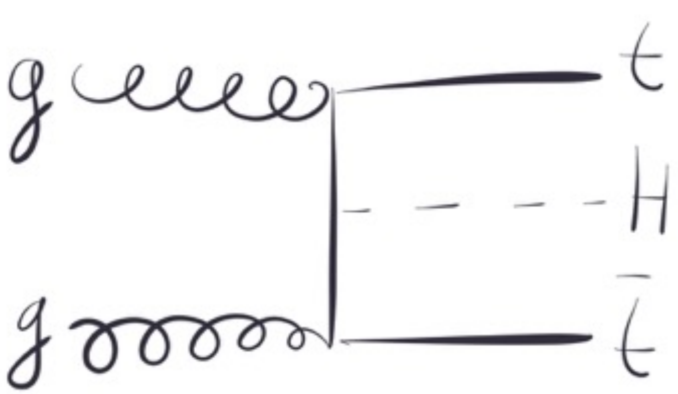


x

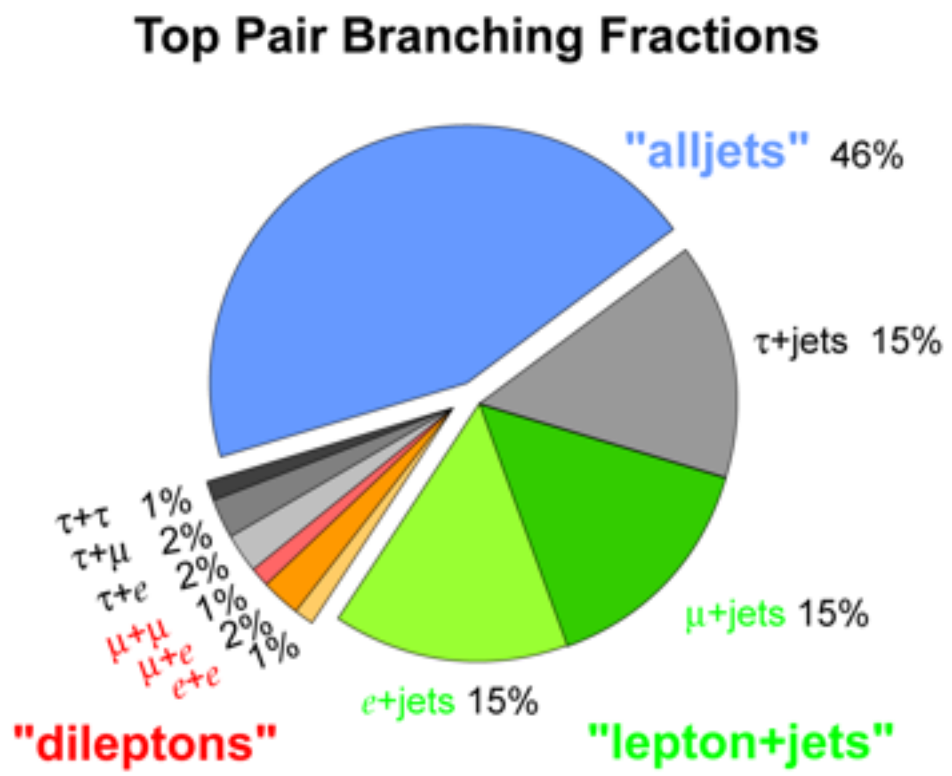


TTH: ***VERY*** COMPLEX FINAL STATE

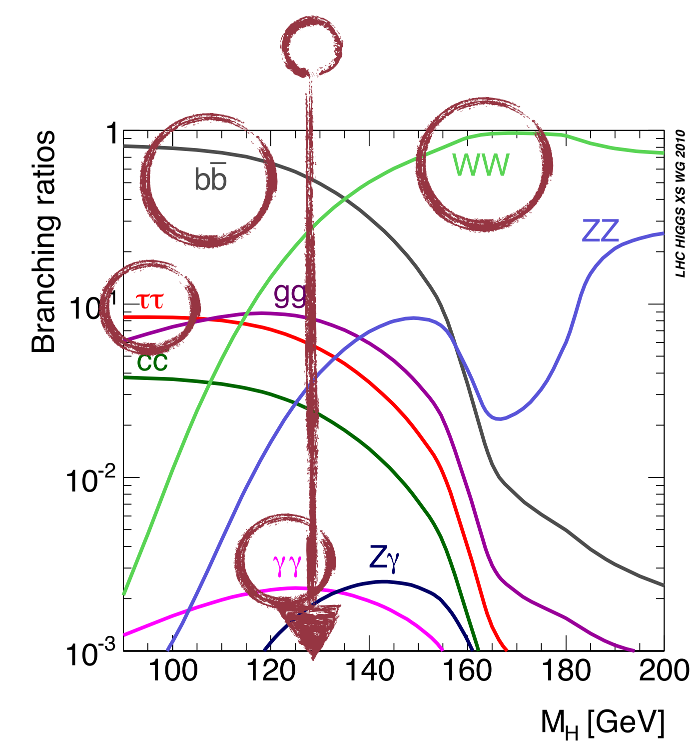
- Cross section is only ~1/200 of the inclusive Higgs production cross section
- Large multiplicity of objects in the final state
  - top quarks decay to Wb, W bosons decay in turn leptonically (lnu) or hadronically (qq)
  - Higgs bosons decay to anything but top quarks…
- Need to find the best combination of top and Higgs decays to isolate the small signal (130fb)



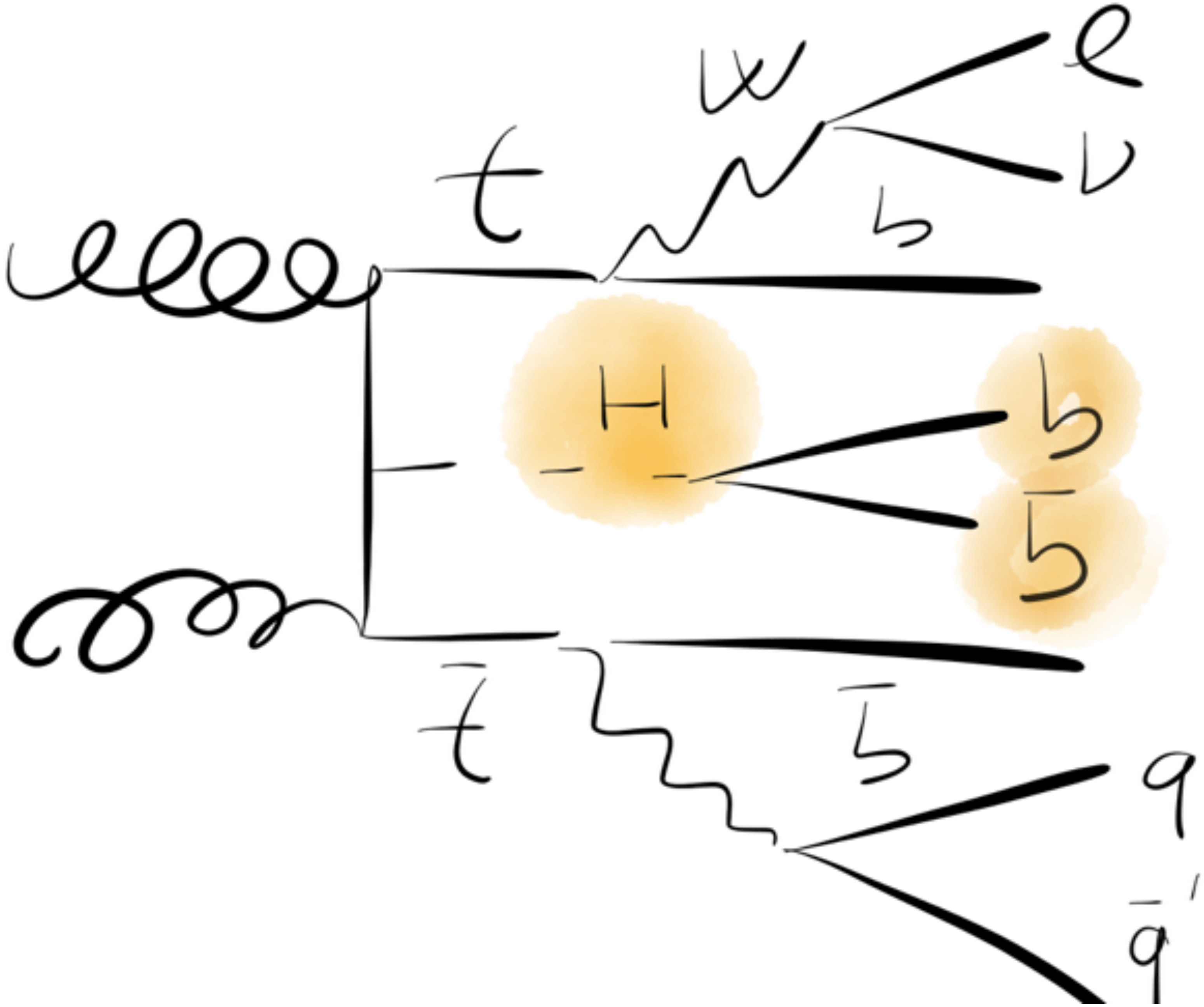
x



x



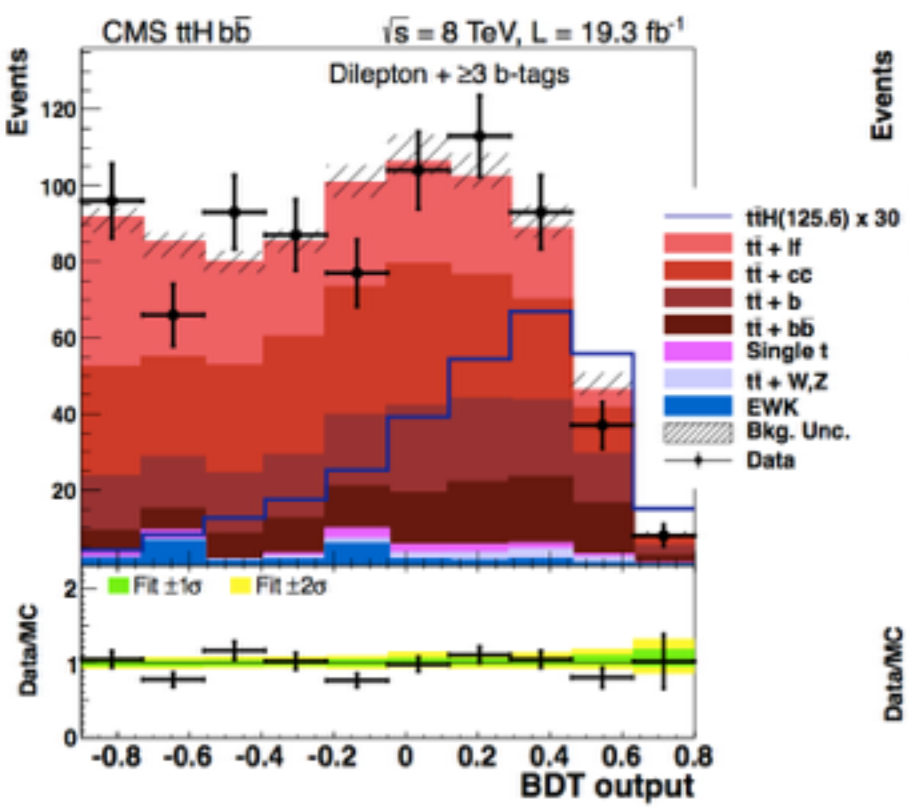
TTH, HIGGS TO B ANTIB

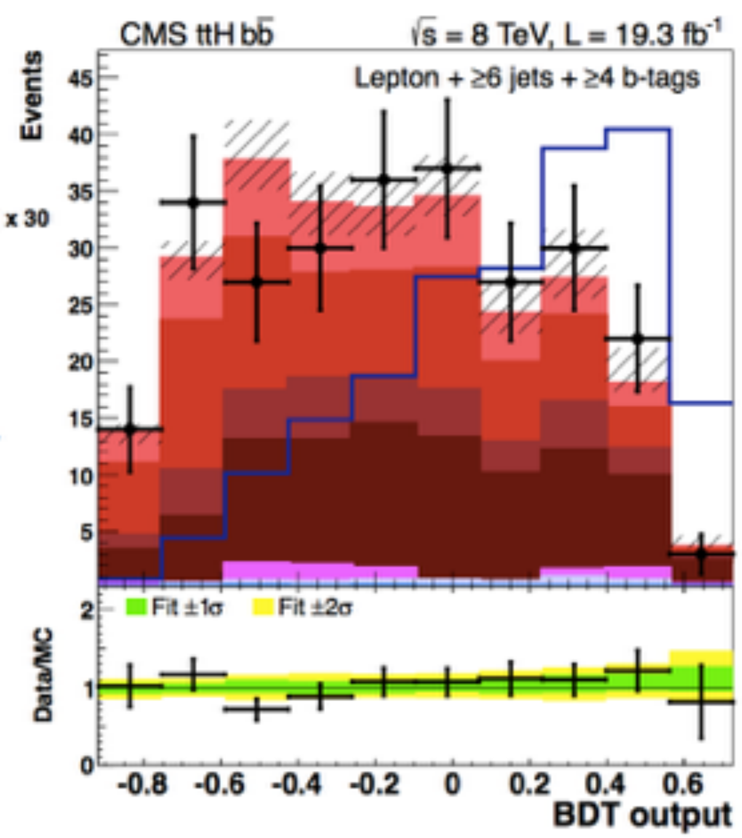


TTH, HIGGS TO B ANTIB

- Single lepton and dilepton selections to suppress large multi-jet background
- Remaining backgrounds dominated by **tt+bb**, mis-tagged **tt+light** and **tt+cc**
- Categorise on number of leptons/jets/b-tagged jets
- CMS has 2 analyses: first discriminates through boosted decision trees, second through matrix element technique

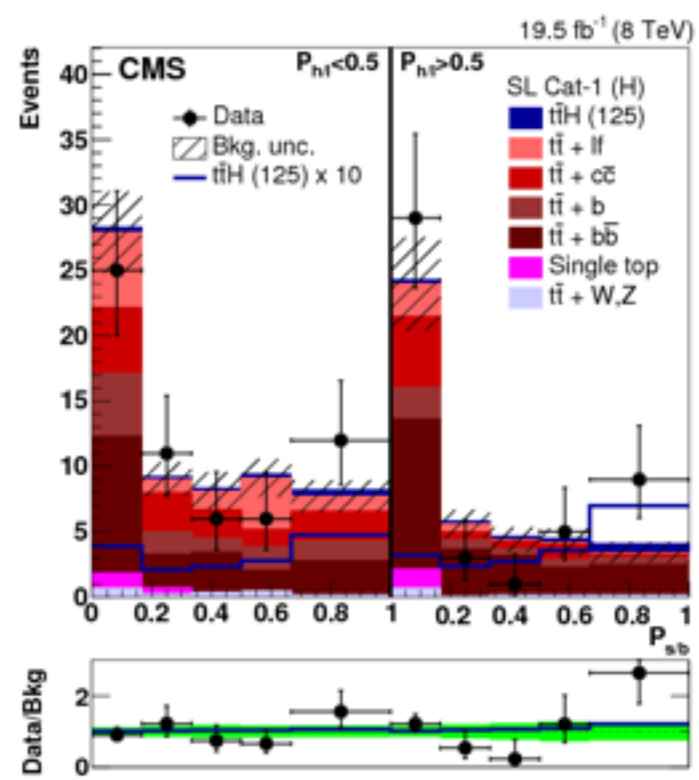
Boosted decision trees





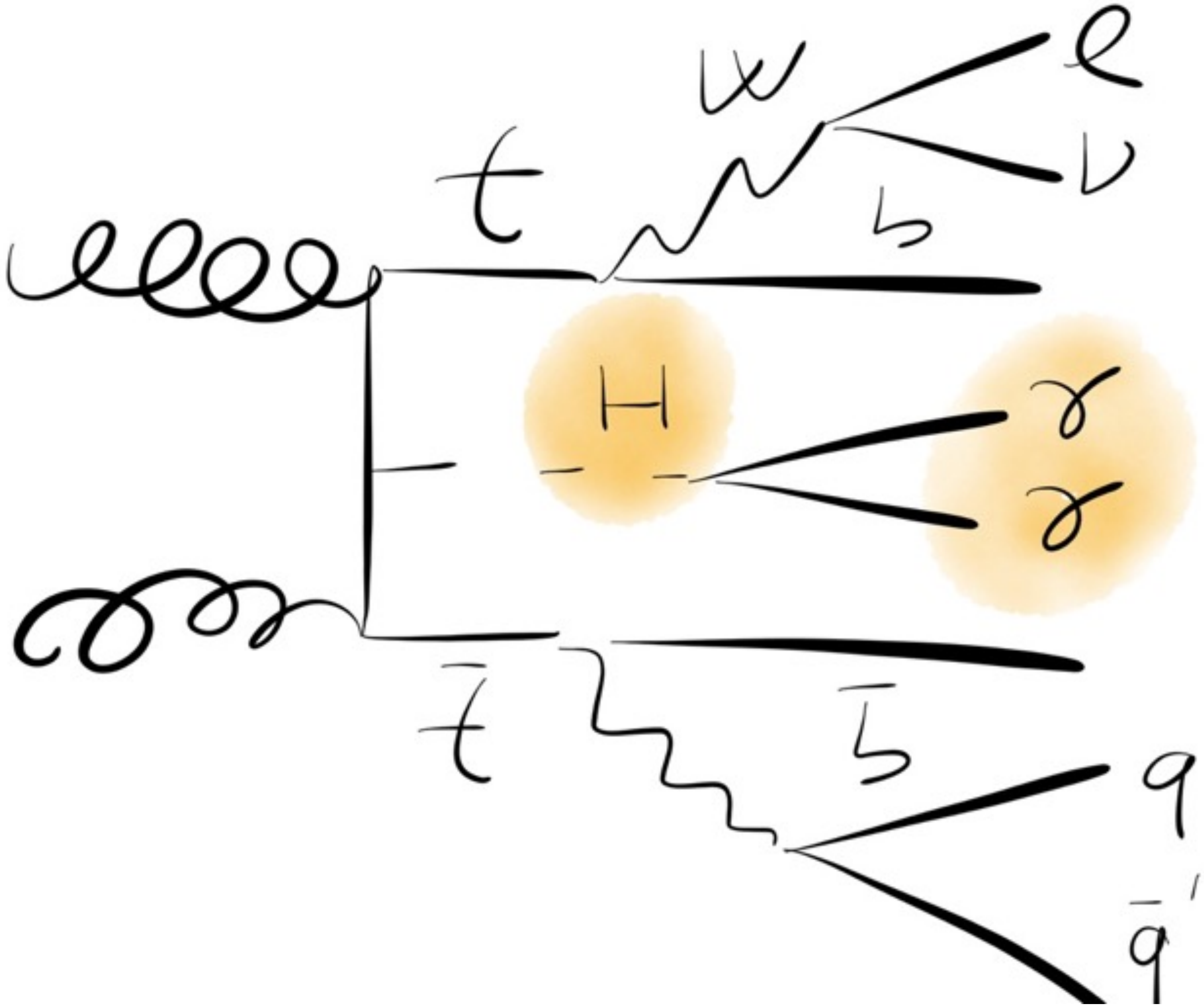
Exp(obs) upper limit of 3.5(4.1) the SM cross section

Matrix element



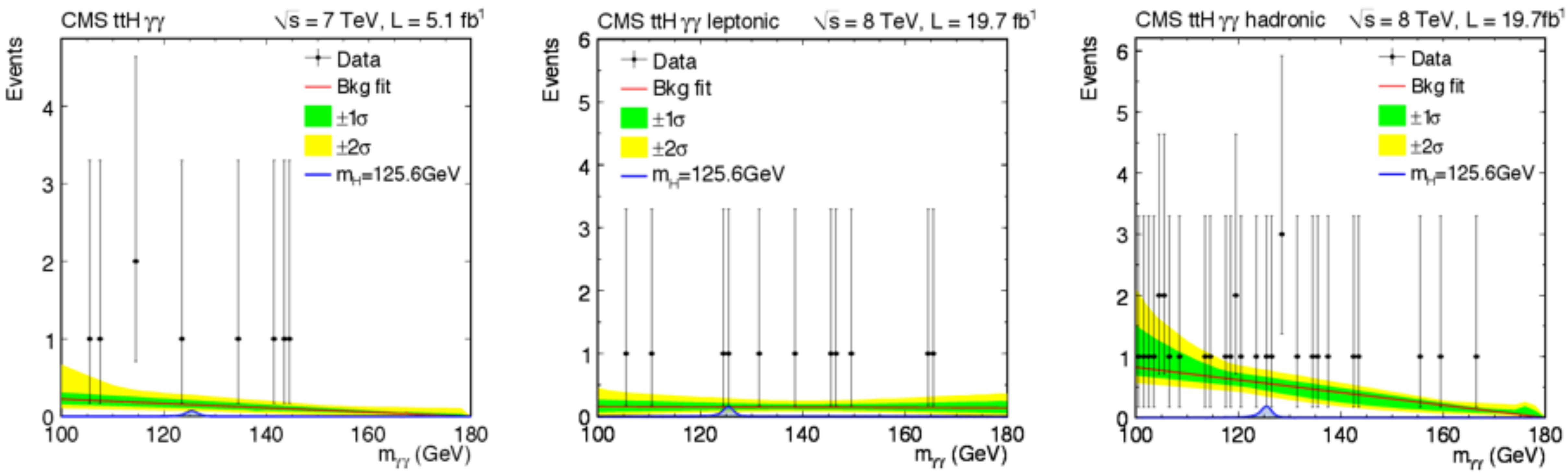
Exp(obs) upper limit of 3.3(4.2) the SM cross section

TTH, HIGGS TO GAMMA GAMMA



HIGGS TO GAMMA GAMMA

- Very low rate, but distinctive signature of the Higgs peak. Backgrounds are coming from top(s) +photon(s), or photons+(b)jets, latter poorly known at theoretical level
- Split into events with leptons and few jets (leptonic) or no leptons and many jets (hadronic)

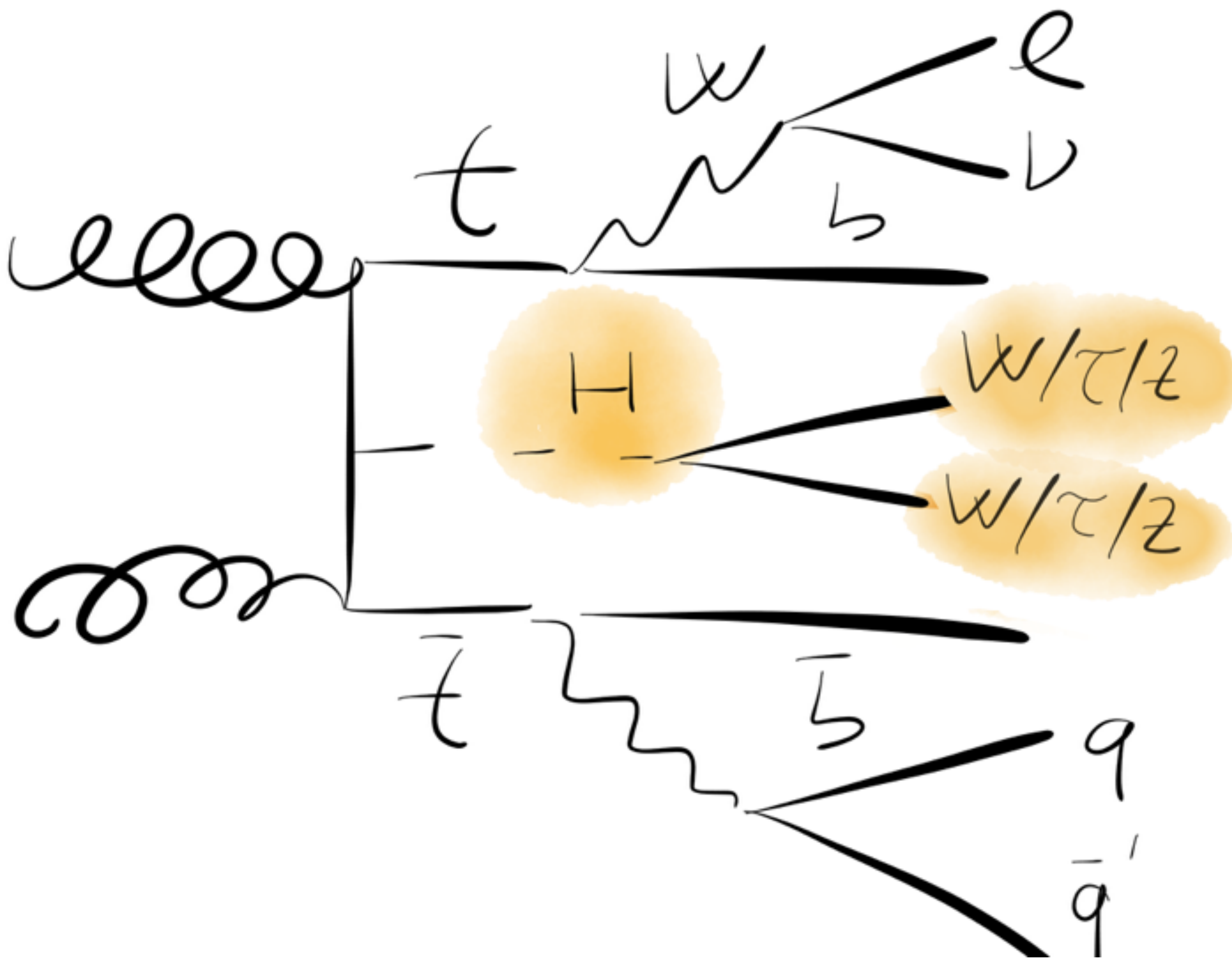


Event selection minimizes contamination from other Higgs sources

Process	Hadronic Channel	Leptonic Channel
$t\bar{t}H$	0.567 (87%)	0.429 (97%)
$gg \to H$	0.059 (9%)	0 (0%)
VBF H	0.006 (1%)	0 (0%)
WH/ZH	0.019 (3%)	0.013 (3%)
Total signal	0.65	0.44

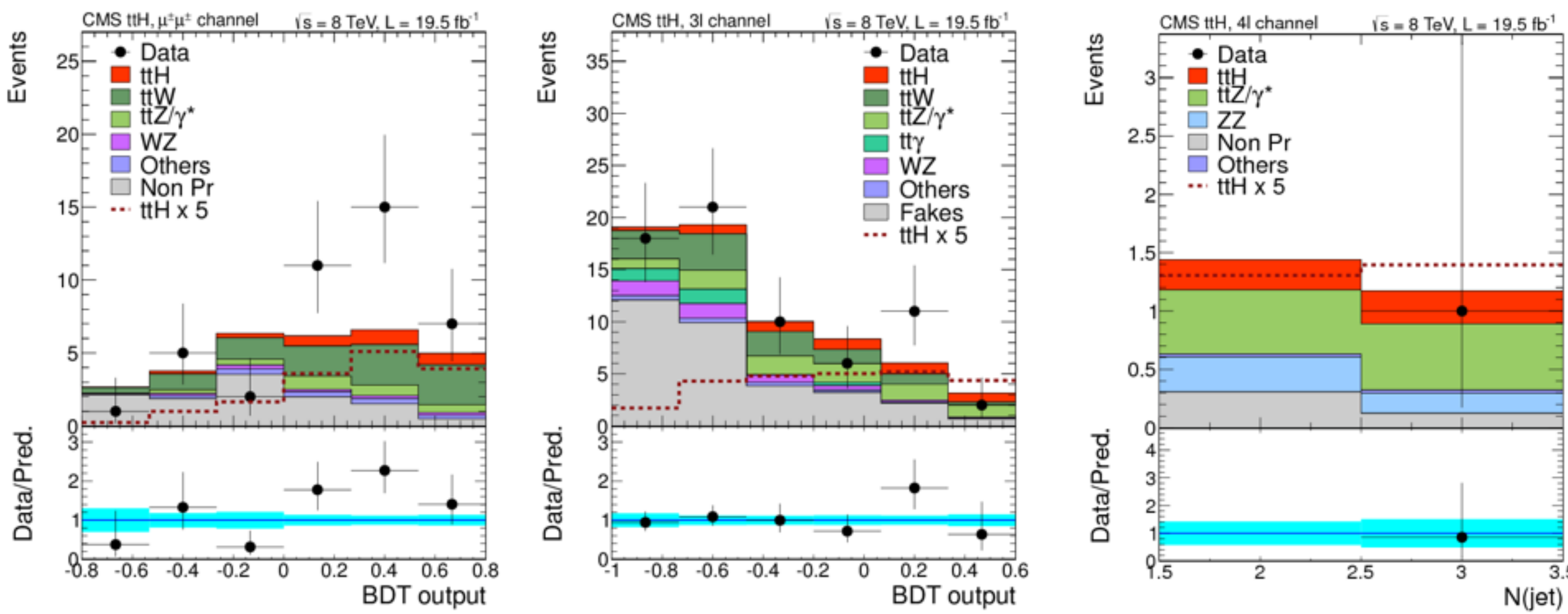
- fitting the diphoton peak greatly reduce sensitivity to background systematics

TTH TO MULTILEPTON

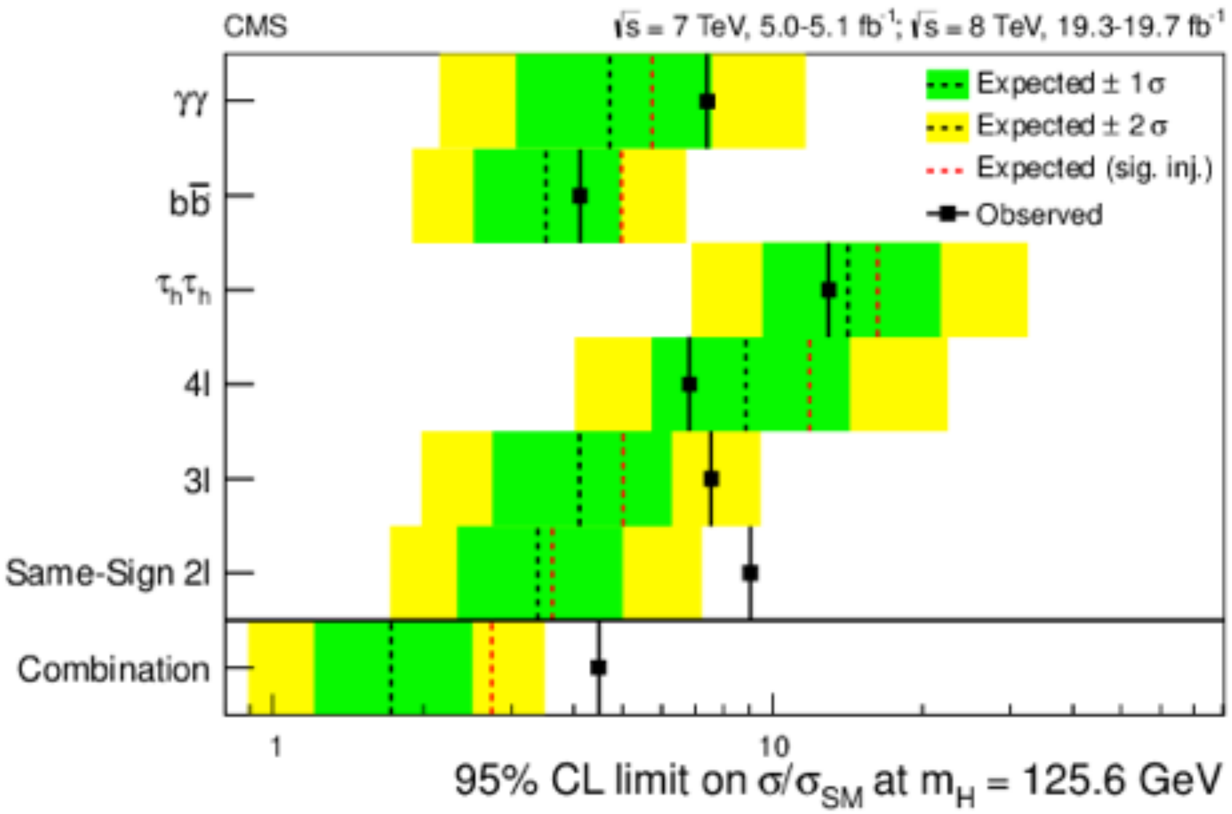


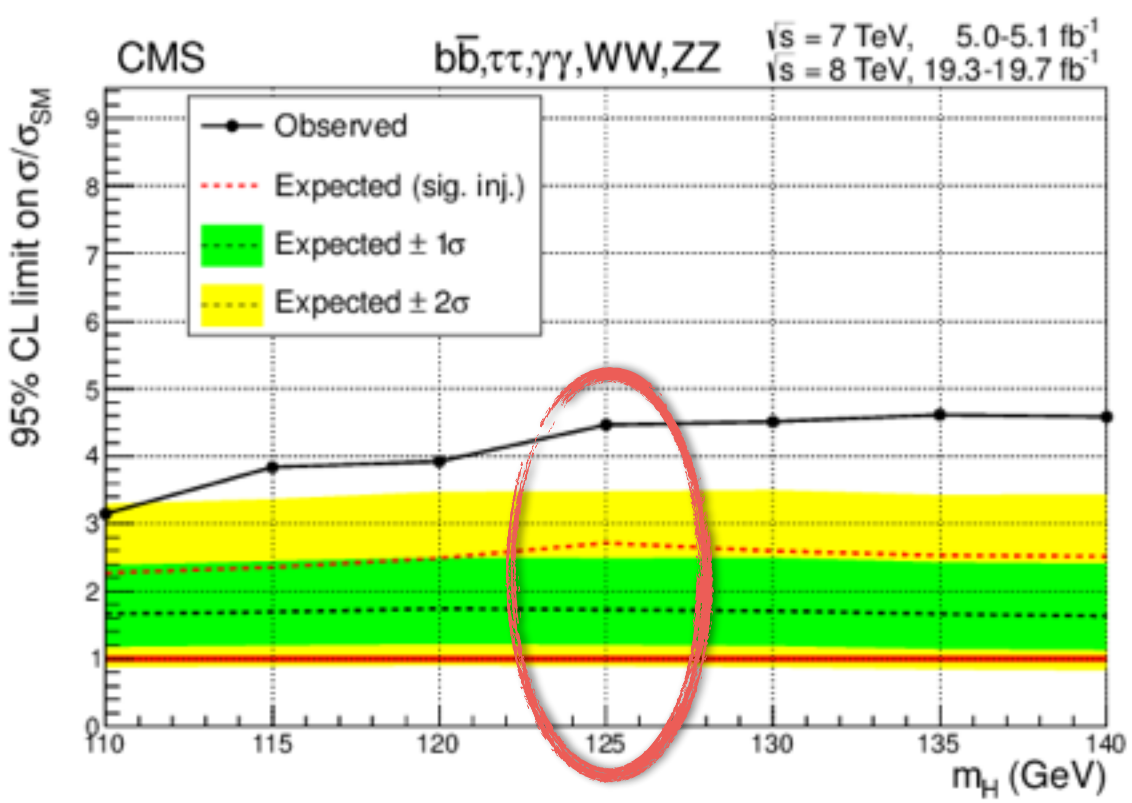
TTH TO MULTILEPTON

- Strategy for H->WW/tautau: same sign dilepton, trilepton, four leptons
- Pretty high acceptance rate, good signal-to-background ratio
- Dedicated multivariate lepton identification to suppress ttbar backgrounds
- divide into subchannels, optimize S-B discrimination to maximize sensitivity to the signal



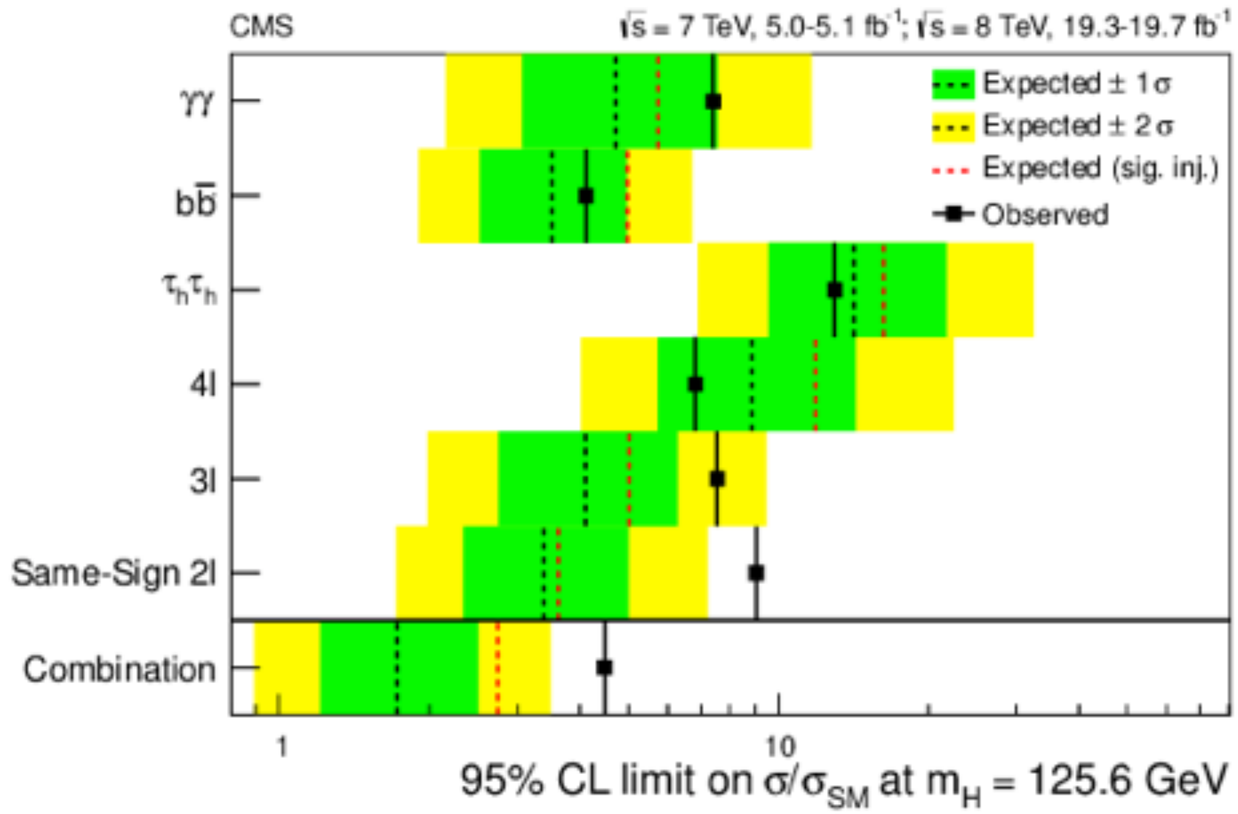
CMS COMBINATION ON TTH

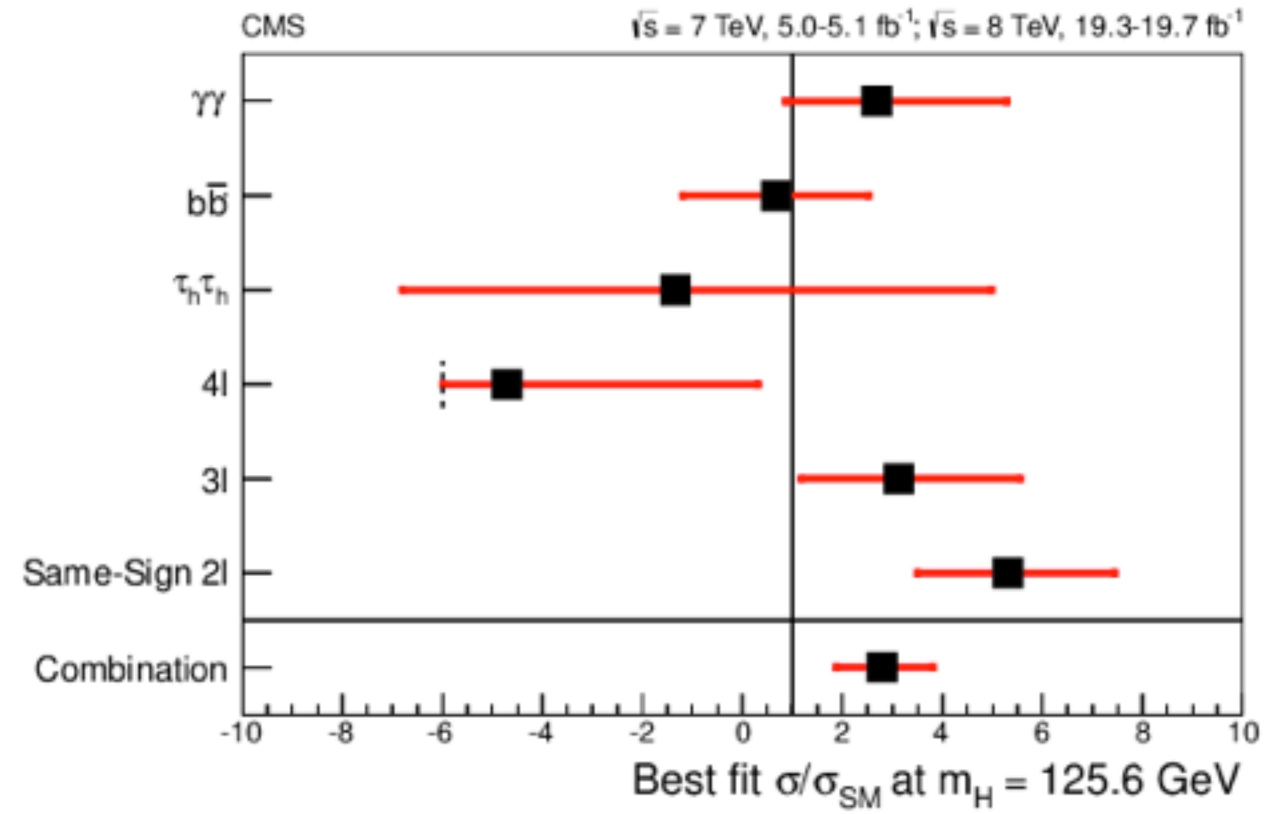


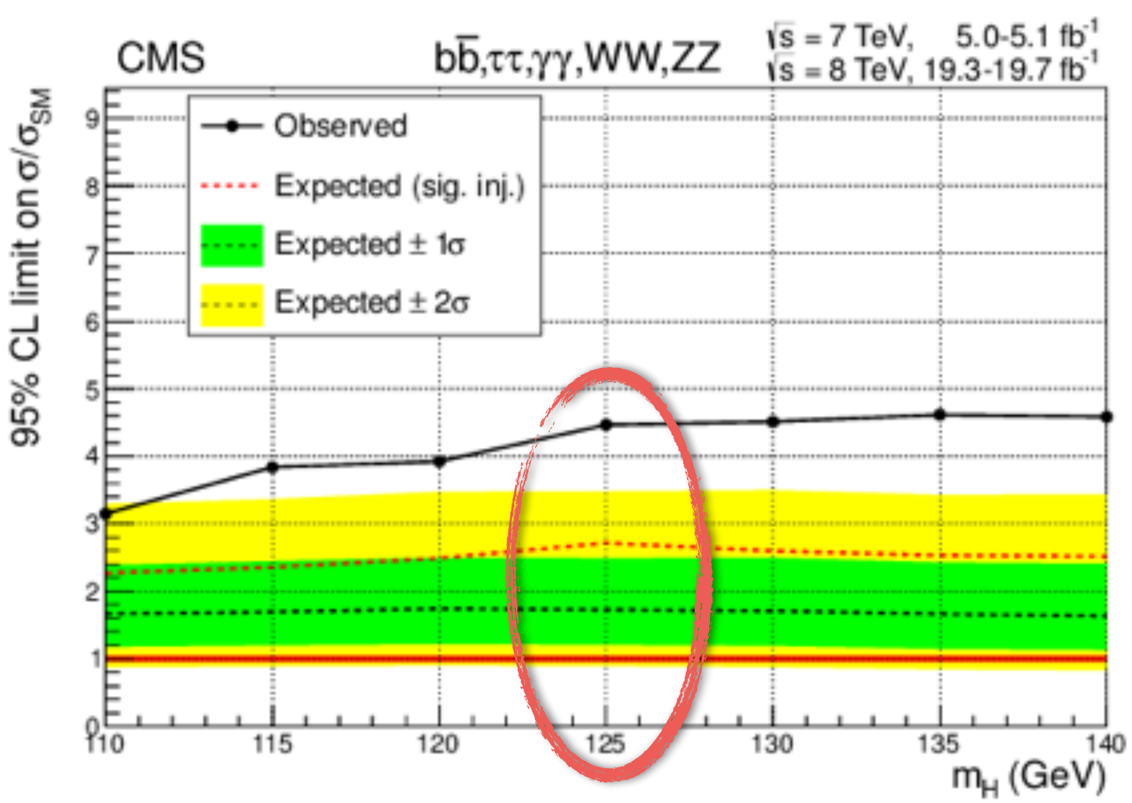


- Set 95% confidence level limits on ttH
- Combined exp(obs) limit of 1.7(4.5) X SM

CMS COMBINATION ON TTH



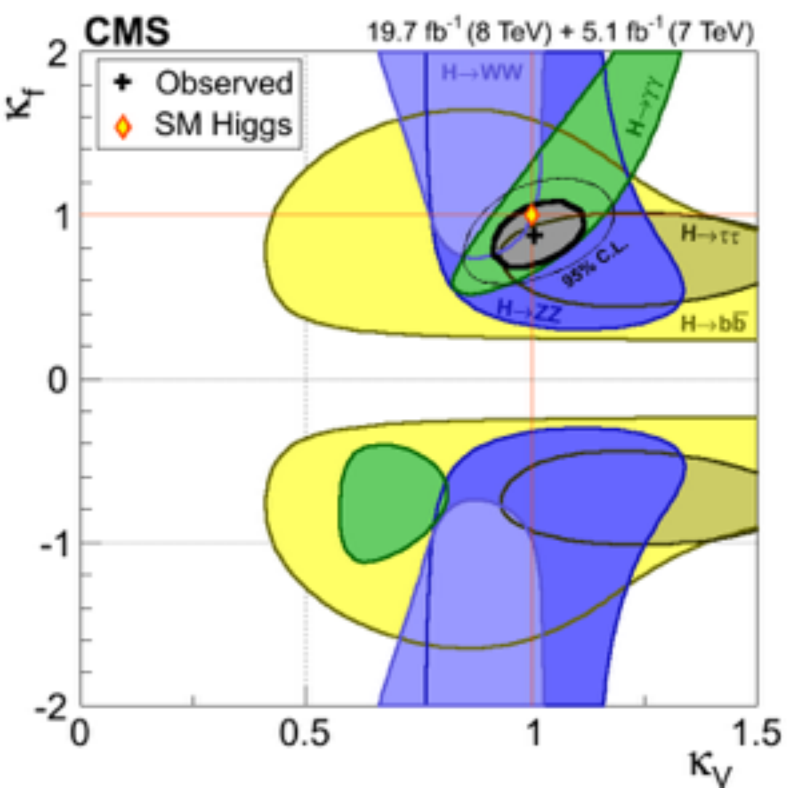


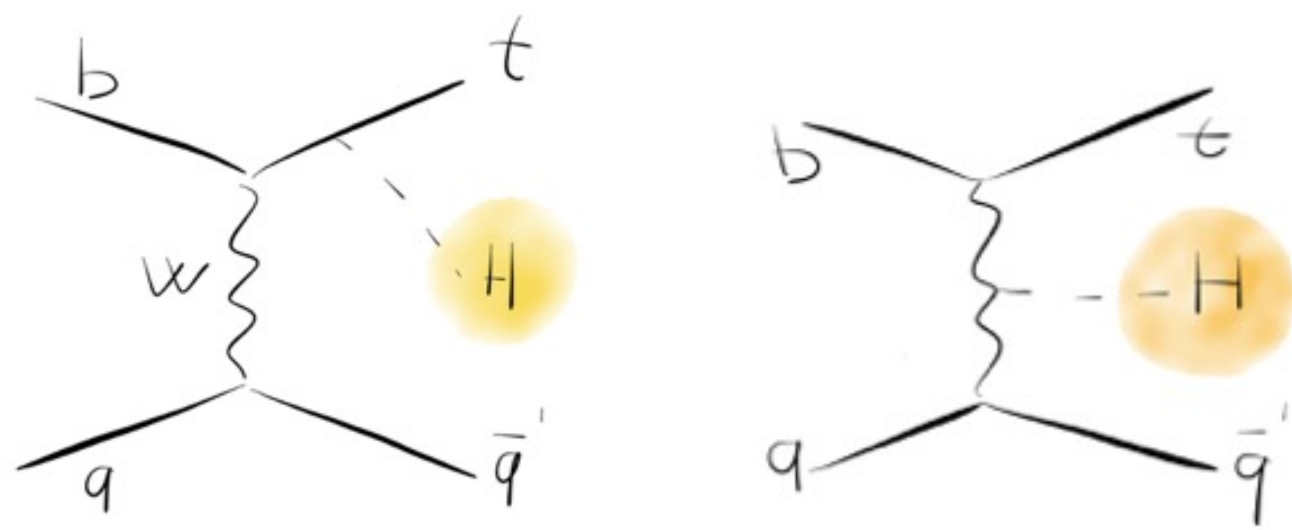


- Set 95% confidence level limits on ttH
- Combined exp(obs) limit of 1.7(4.5) X SM
- Intepreting the result as a cross section measurement
- Combined signal strength multiplier $\mu = 2.8^{+1.0}_{-0.9}$ X SM

Single top plus Higgs

- Early Higgs data allowed inverted sign of the coupling of Higgs to fermions, relative to Higgs to bosons, due to interference between Htt and HWW in the Higgs to diphoton decay
- Single top plus Higgs production would be severely enhanced if that was the case

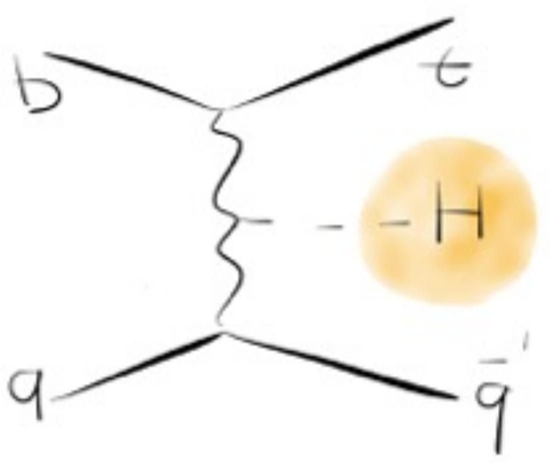




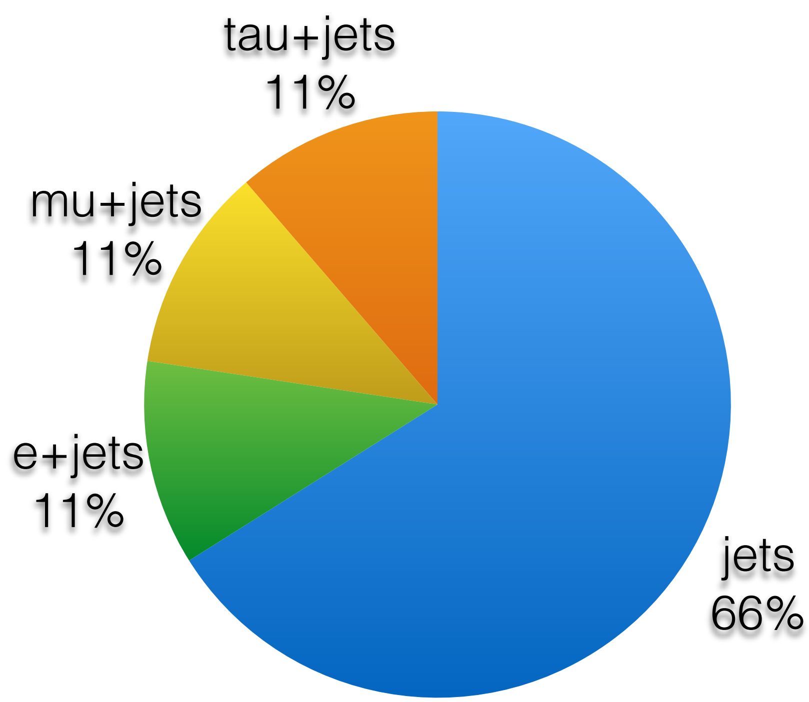
- t-channel tHq production especially sensitive to sign of Yukawa coupling, as it would bring large enhancement in cross section (x10-20, would exceed ttH production)
- single top plus Higgs would be sensitive to other new physics greatly enhancing its rates:
  - non-diagonal Yukawa/new physics in tHu/tHc flavor-changing-neutral-currents

tHq: *very* complex final state

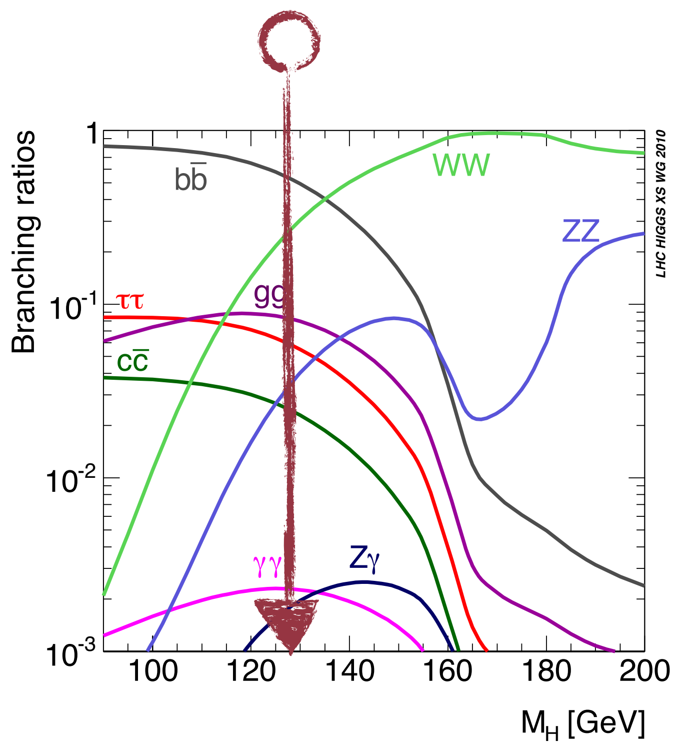
- Cross section is only ~1/1000 of the inclusive Higgs production cross section
- Large multiplicity of objects in the final state (signature is dominated by the t/tbar decays)
- Best combination of top and Higgs decays to isolate the small signal - apply lessons learned for ttH!



x



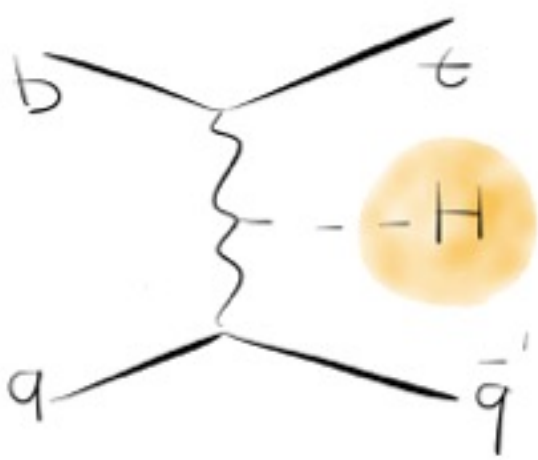
x



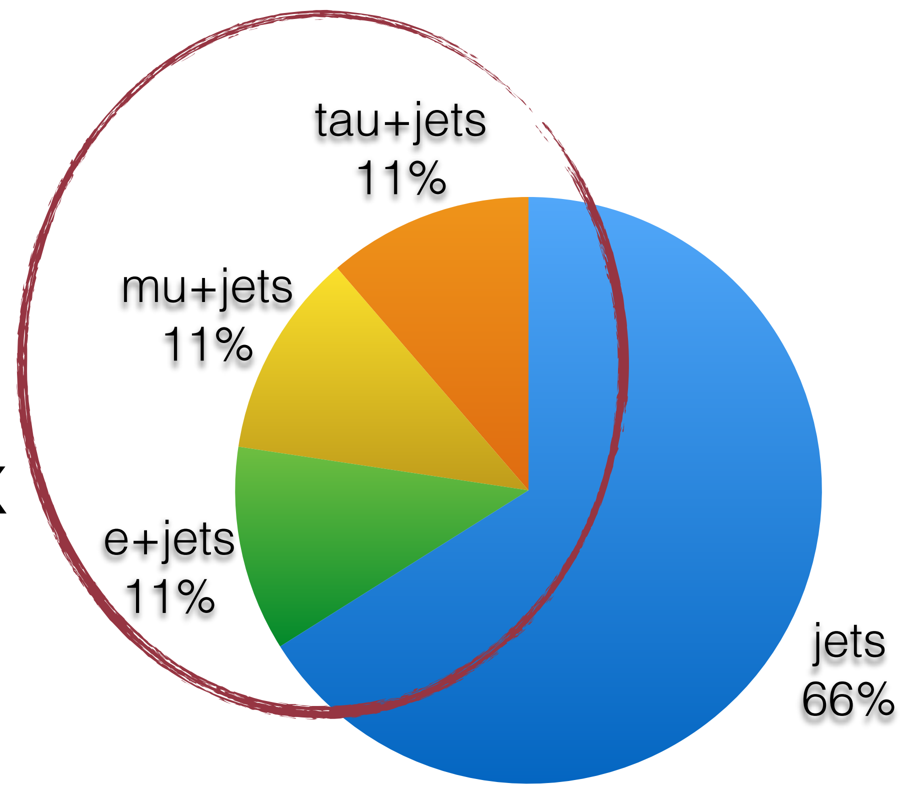
- For the time being, focus on negative Yukawa scenario: cross section O(200fb)
- use only leptonic top quark decay to increase signal-to-background ratio
- now combined result as well! new

tHq: *very* complex final state

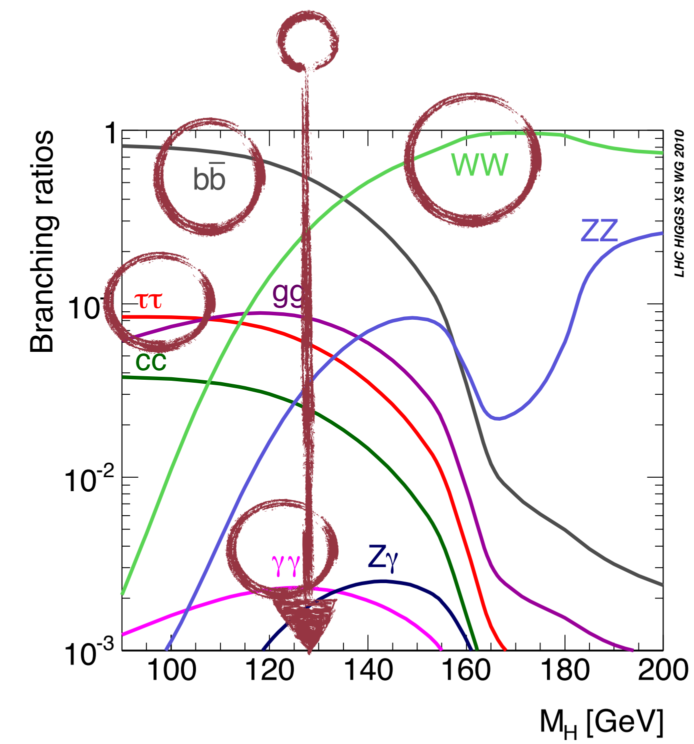
- Cross section is only ~1/1000 of the inclusive Higgs production cross section
- Large multiplicity of objects in the final state (signature is dominated by the t/tbar decays)
- Best combination of top and Higgs decays to isolate the small signal - apply lessons learned for ttH!



X



X

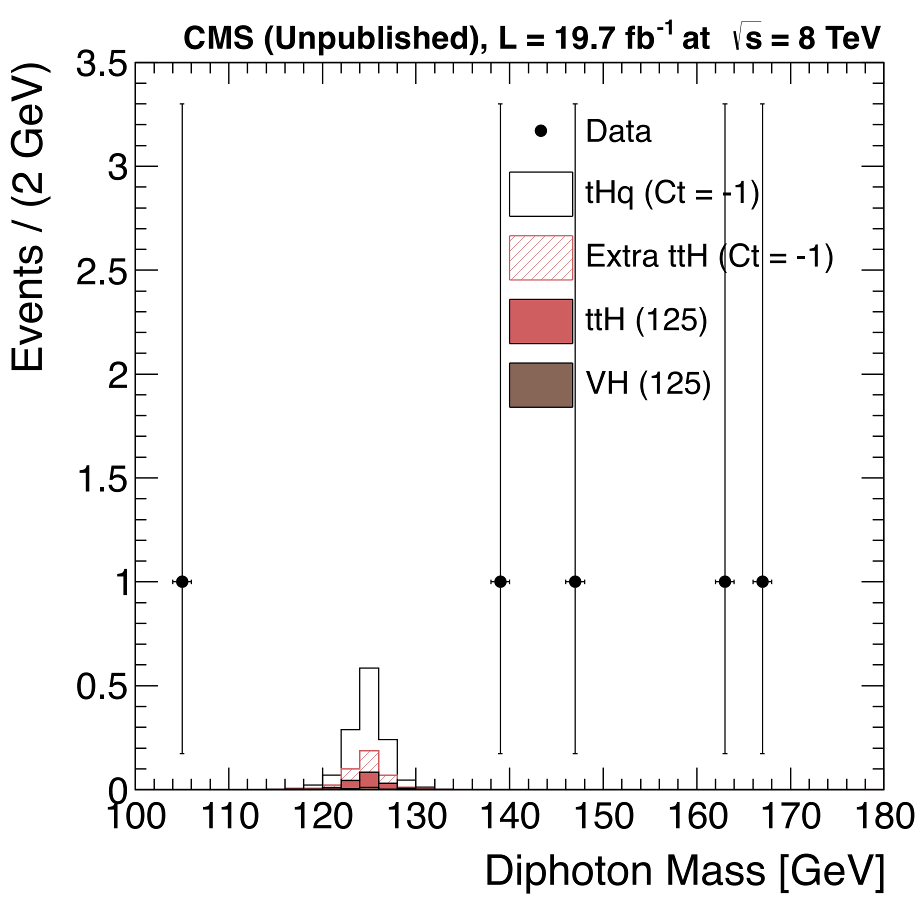


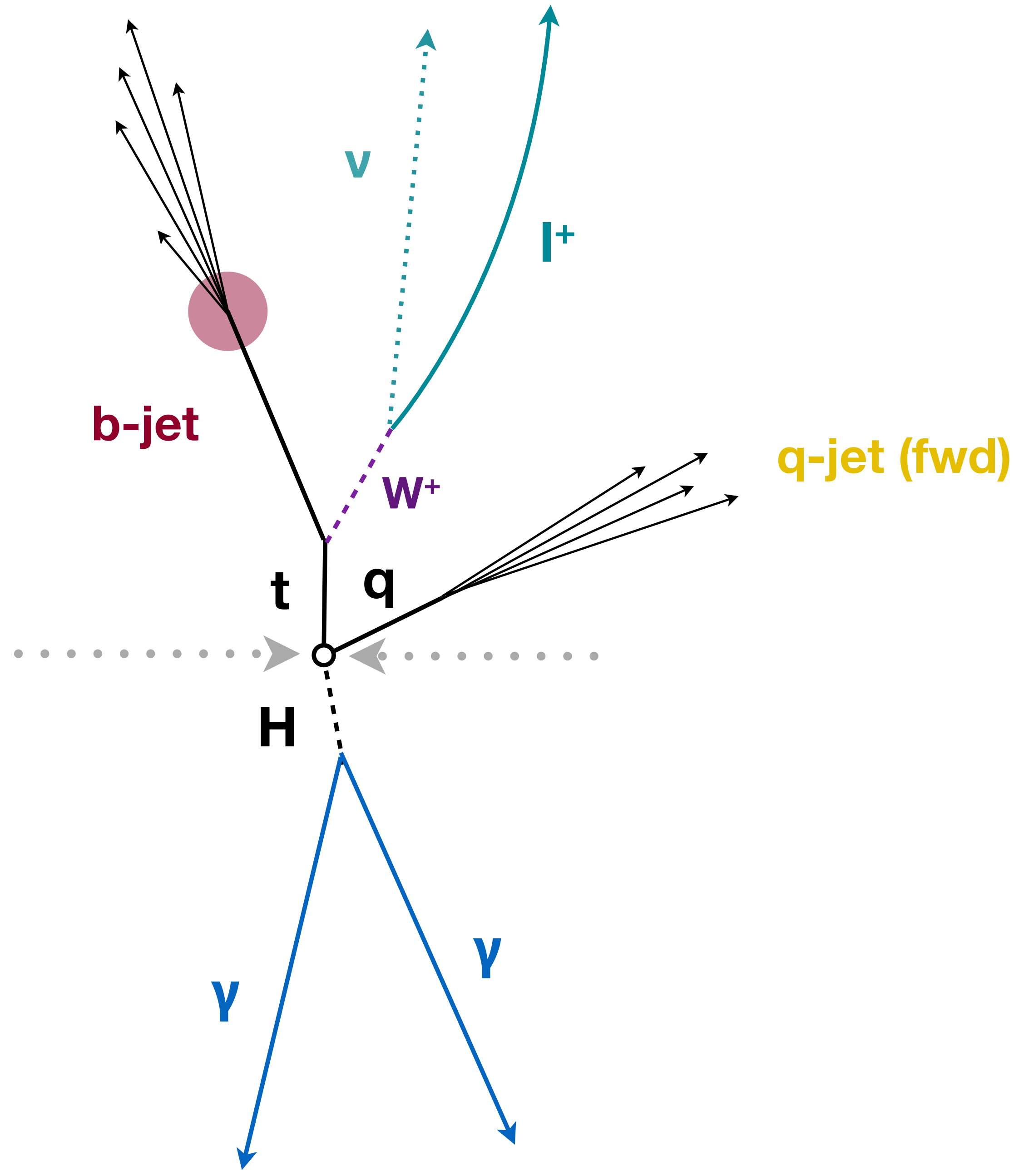
- For the time being, focus on negative Yukawa scenario: cross section O(200fb)
- use only leptonic top quark decay to increase signal-to-background ratio
- now combined result as well! **new**

tHq, Higgs to photons

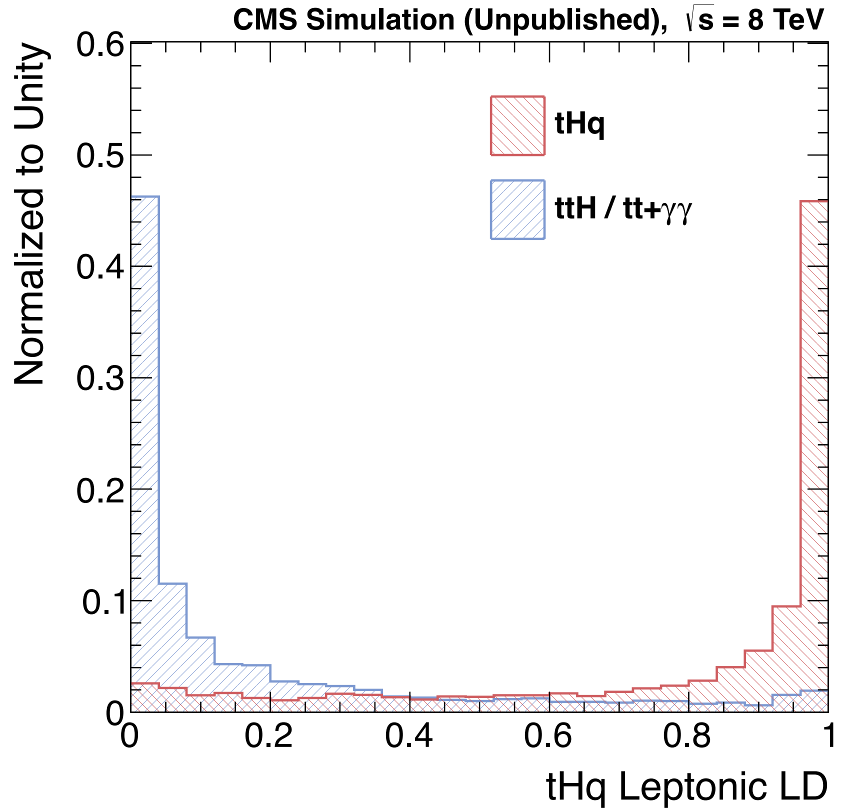
Two step analysis: first cut and count selection

- 2photons with pT >50 ·mγγ/120 and 25GeV
- 1 lepton with > 10 GeV and ΔR > 0.5 w.r.t. photons
- 1 b-tagged jet with > 20 GeV
- No cut on E/T
- Hardest additional jet, must have pT > 20 GeV and |η| > 1





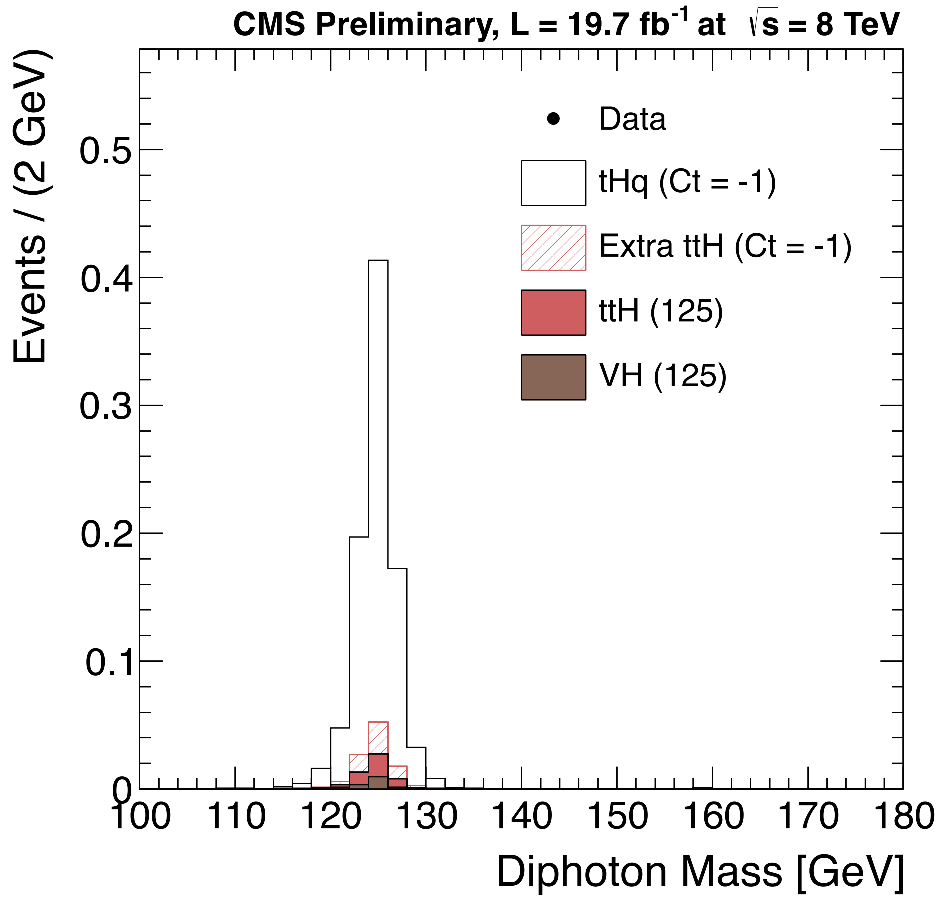
tHq, Higgs to photons



Then multivariate selection to suppress backgrounds further

- No events in the signal region
- Non-resonant background estimation via fit in loosened m(γγ)-sideband regions
- Set 95% upper level confidence limit of 4.1 the sigmaXBR for tHq production with negative Yukawa

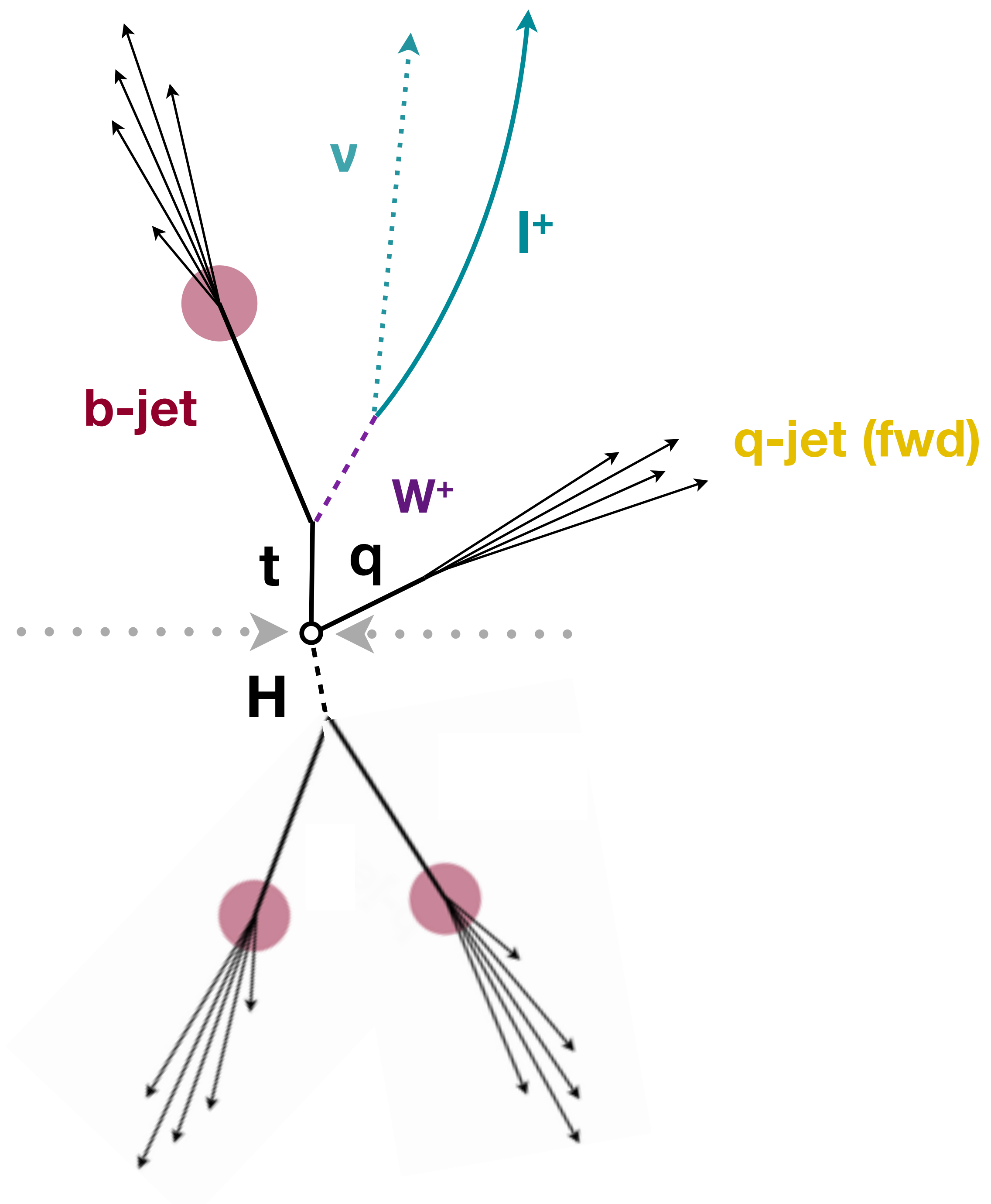
Process	Yield
tHq ($C_t = -1$)	0.67
$t\bar{t}$H	$0.03 + 0.05^{\dagger}$
VH	$0.01 + 0.01^{\dagger}$
other H	0



THQ, H → BBAR

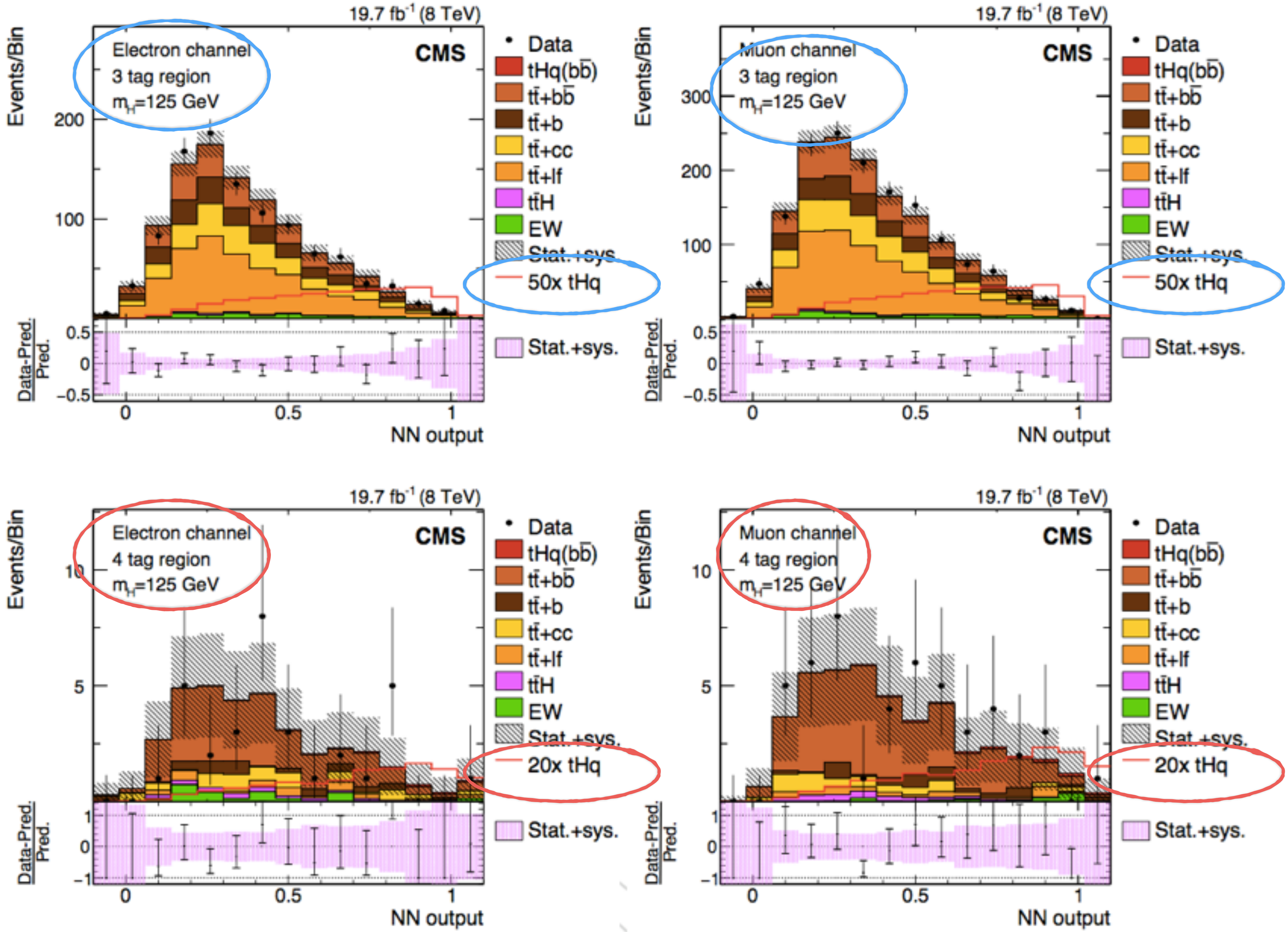
- The most advanced analysis of the set
- 1 lepton
- split events according to number of identifyied b-jets (a forth b-jet may arise from gluon splitting)
- two multivariate discriminator to assign jets to decaying particles (regression)
- one more multivariate technique to discriminate signal from background (classification)

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



tHq, H → bbar

3btags, higher acceptance



4btags, better S/B

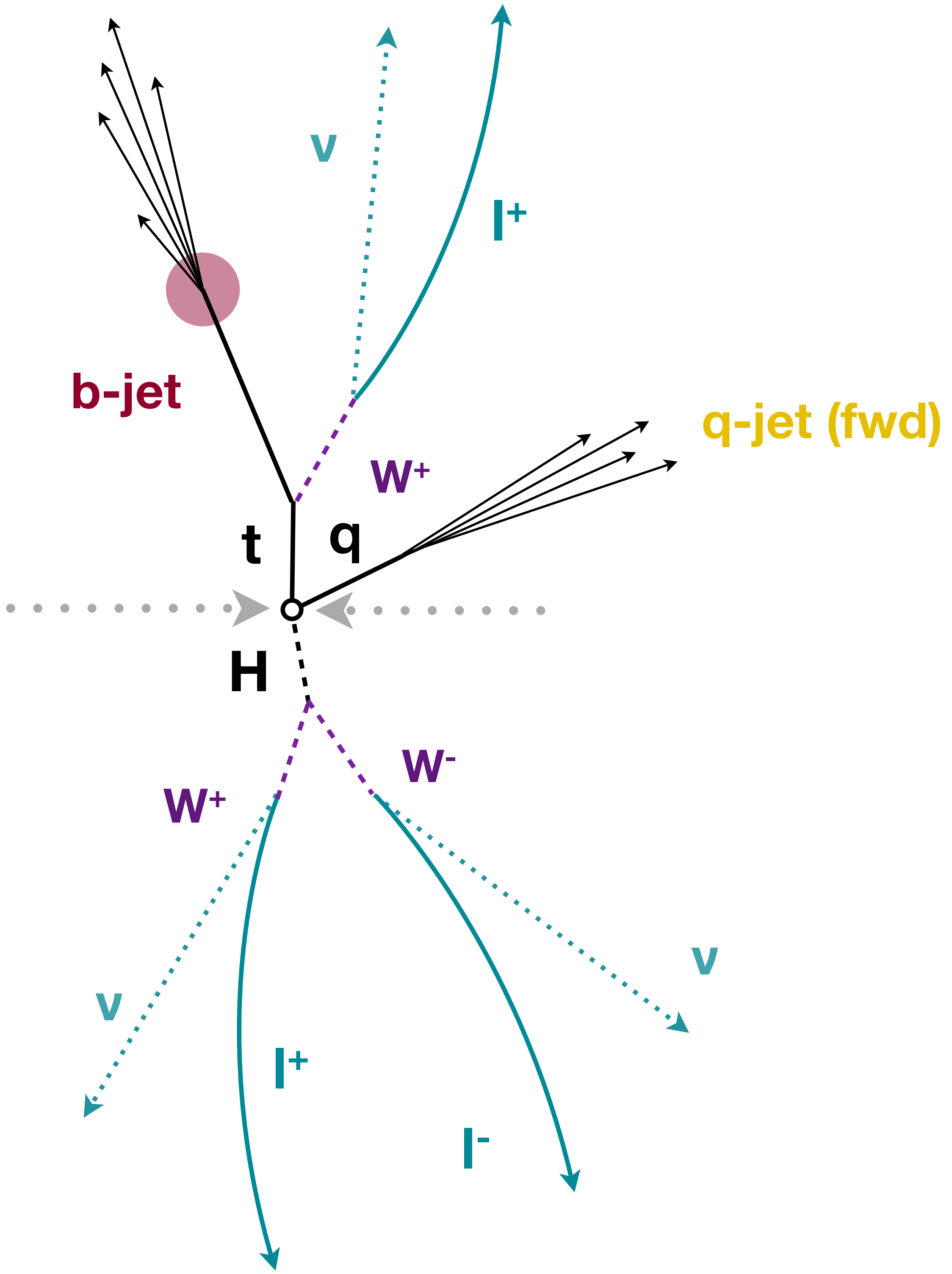
tHQ TO MULTILEPTON

- Three W bosons
- One b-jet
- One light (forward) jet

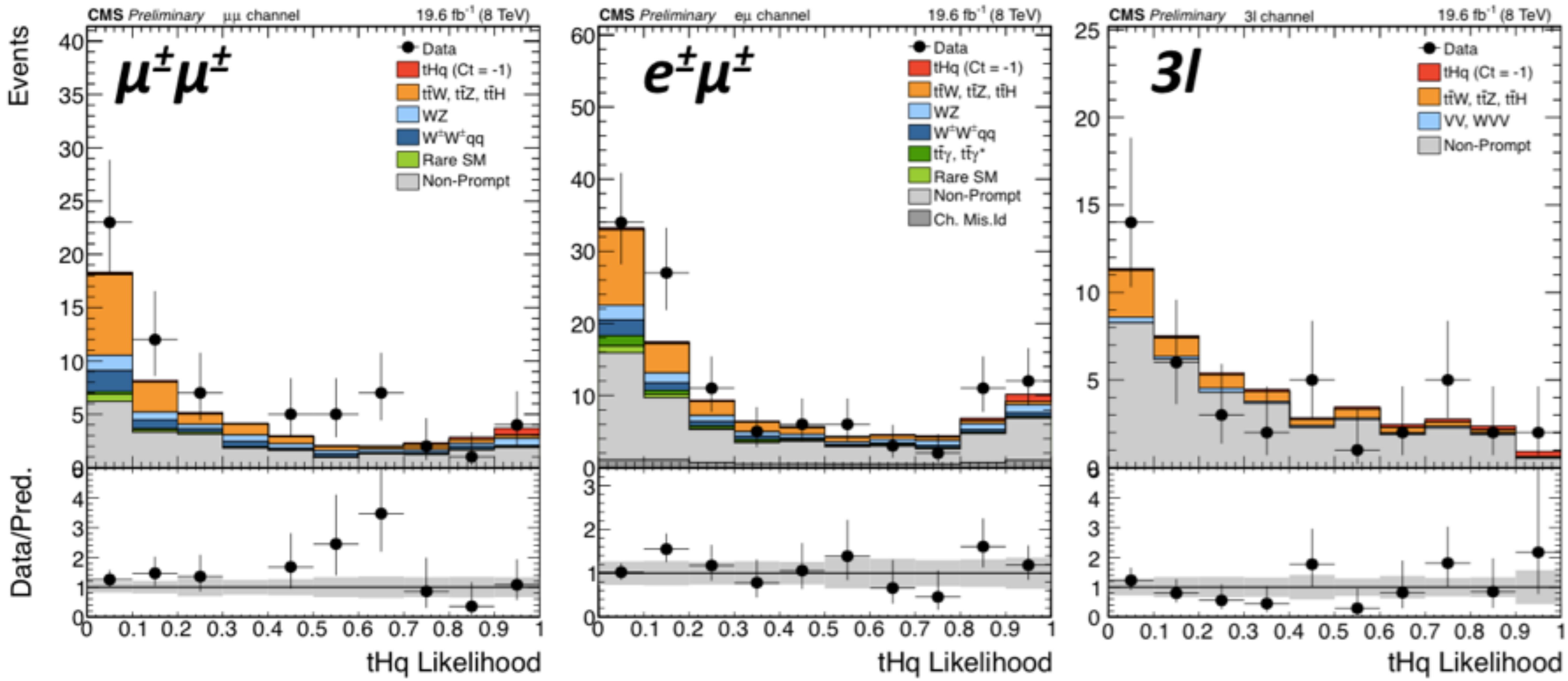
- Best channels for H->WW
  - same sign dileptons
  - three leptons

- Leptons:
  - pt>20GeV(SS2L) 10GeV (3L)
  - ttH derived machine-learning-optimized lepton identification (SS2L)

- Jets
  - pt>25GeV η < 4.7
  - b-tagging



tHQ TO MULTILEPTON



No significant signal - setting 95% confidence level upper limits

Channel	Observed	Expected	68% prob. band	95% prob. band
SS $\mu\mu$	9.3	8.1	[6.0, 11.8]	[4.7, 16.7]
SS $e\mu$	11.4	9.3	[7.0, 13.5]	[5.4, 18.8]
3ℓ	11.5	8.6	[6.6, 12.4]	[5.7, 18.0]
combined	6.7	5.0	[3.6, 7.1]	[2.9, 10.3]

expected (observed) limit at 5 (6.7) times cross section on sigma(tHq, Ct=-1)

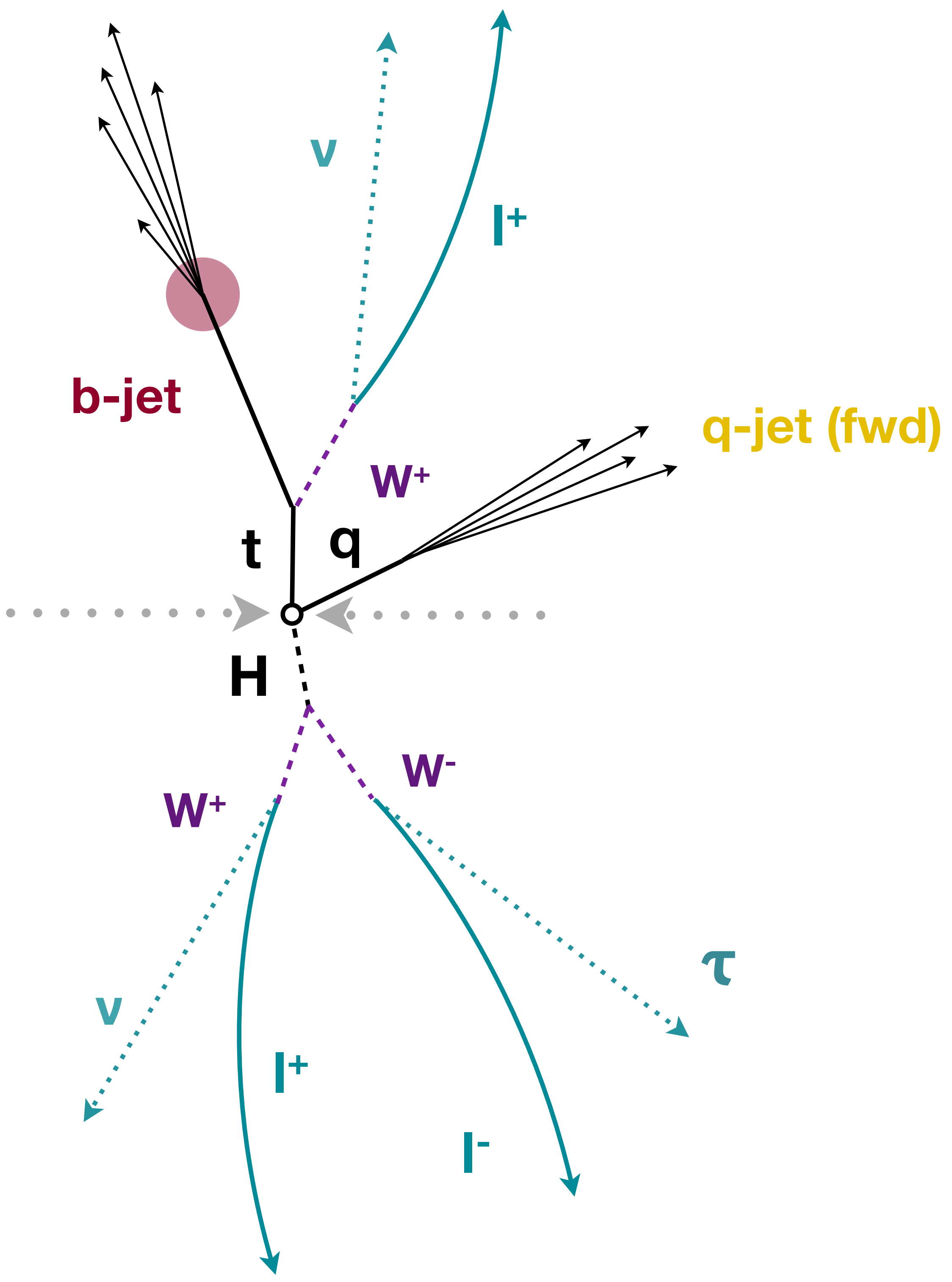
tHq to multilepton + tau

- Three W bosons
- One b-jet
- One light (forward) jet

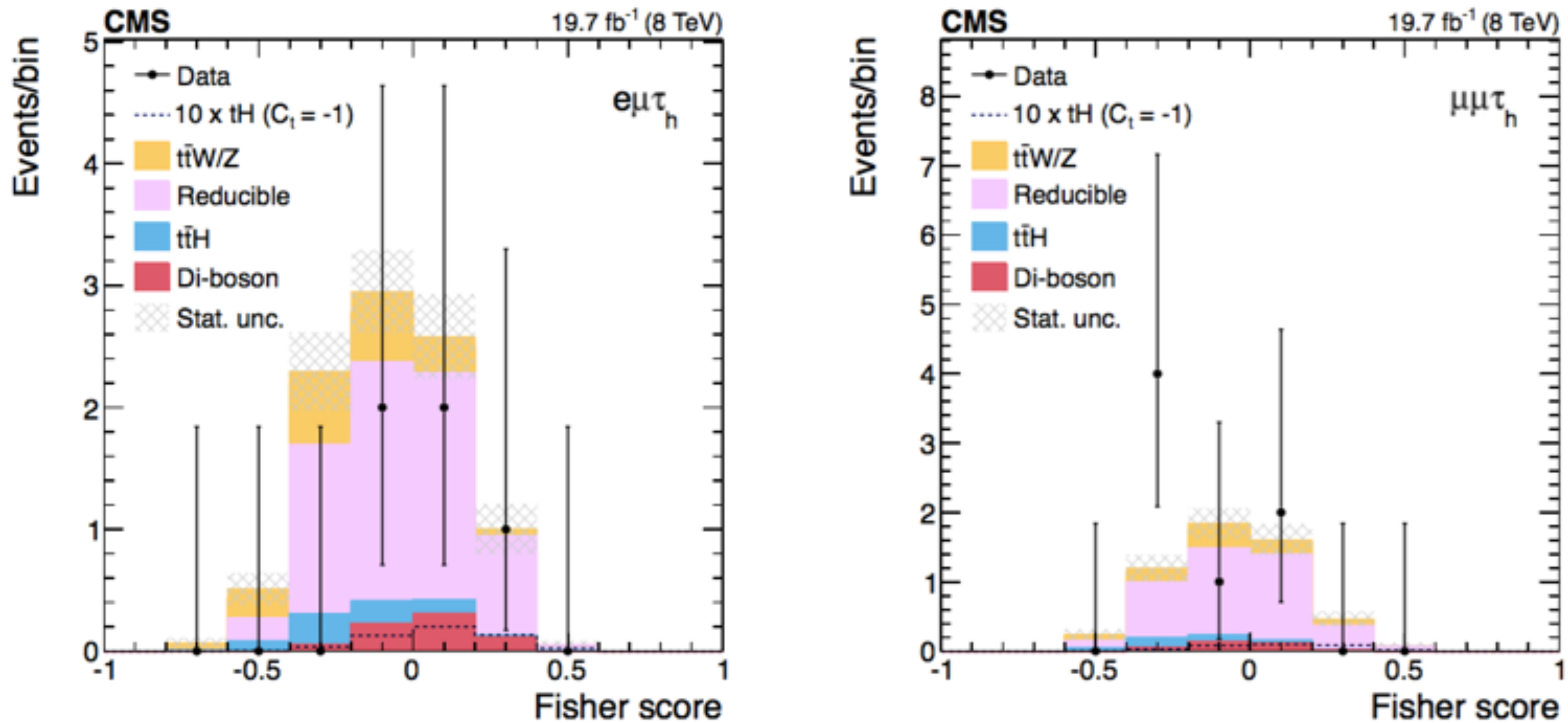
- Best channels for H->tautau:
  - same sign dileptons+hadronic tau

- Leptons:
  - pt>20GeV(SS2L) 10GeV (3L)
  - ttH derived machine-learning-optimized lepton identification (SS2L)
  - tau ID experience from H → tautau

- Jets
  - pt>25GeV η < 4.7
  - b-tagging



tHq TO MULTILEPTON + TAU



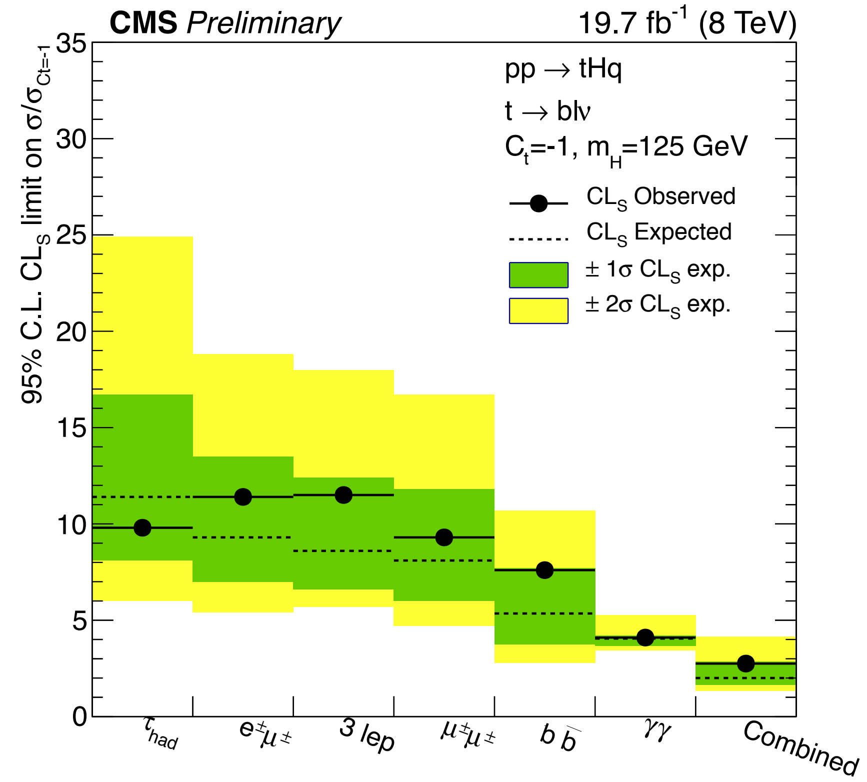
Process	$e\mu\tau_h$	$\mu\mu\tau_h$
tHq, $C_t = -1$	0.42 ± 0.05	0.26 ± 0.03
tHW, $C_t = -1$	0.06 ± 0.01	0.04 ± 0.01
$t\bar{t}H$	0.6 ± 0.1	0.3 ± 0.1
$t\bar{t}V$	1.8 ± 0.4	0.9 ± 0.2
VV	0.7 ± 0.1	0.3 ± 0.1
Reducible	6.3 ± 3.1	4.5 ± 1.9
Tot. background	9.5 ± 3.7	5.4 ± 2.4
Data	5	7

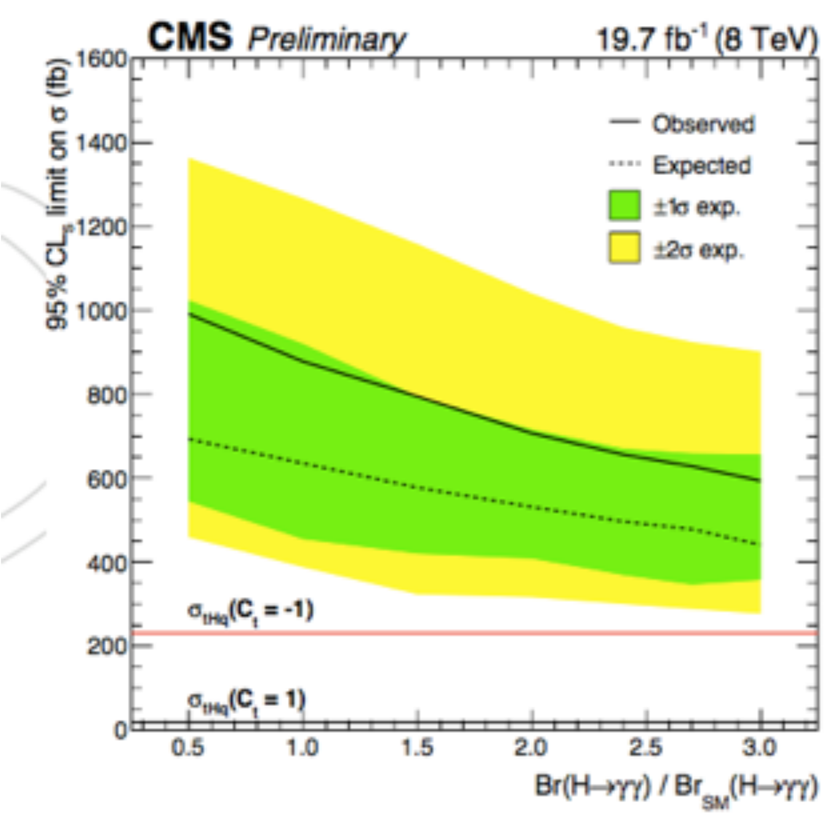
COMBINATION AND INTERPETATIONS

Interpretation #1

Limits on the event yields on the analyzed channels, predicted by the inverted Yukawa sign hypothesis:

2.1 (2.8) exp (obs) on Yt=-1 event yields prediction





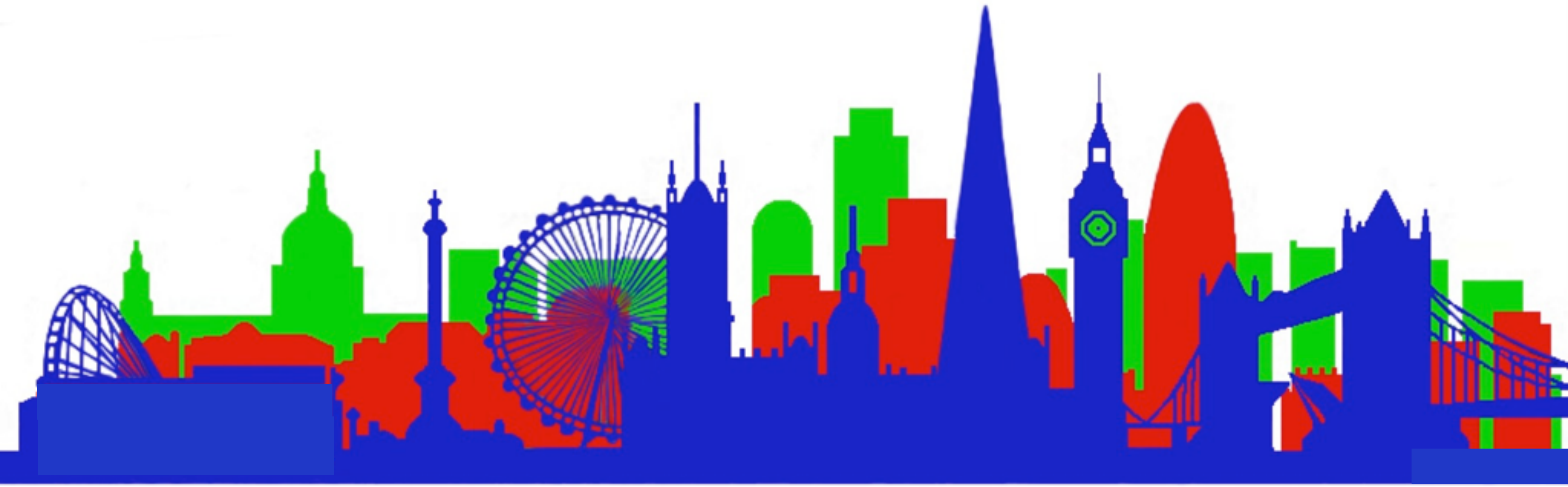
Interpretation #2

generic limits on single top plus Higgs production scanning values around SM Higgs to diphoton decay:

Upper limit of 700(1000) - 425(600)fb exp(obs) depending on assumed Higgs to diphoton branching ratio

CONCLUSIONS

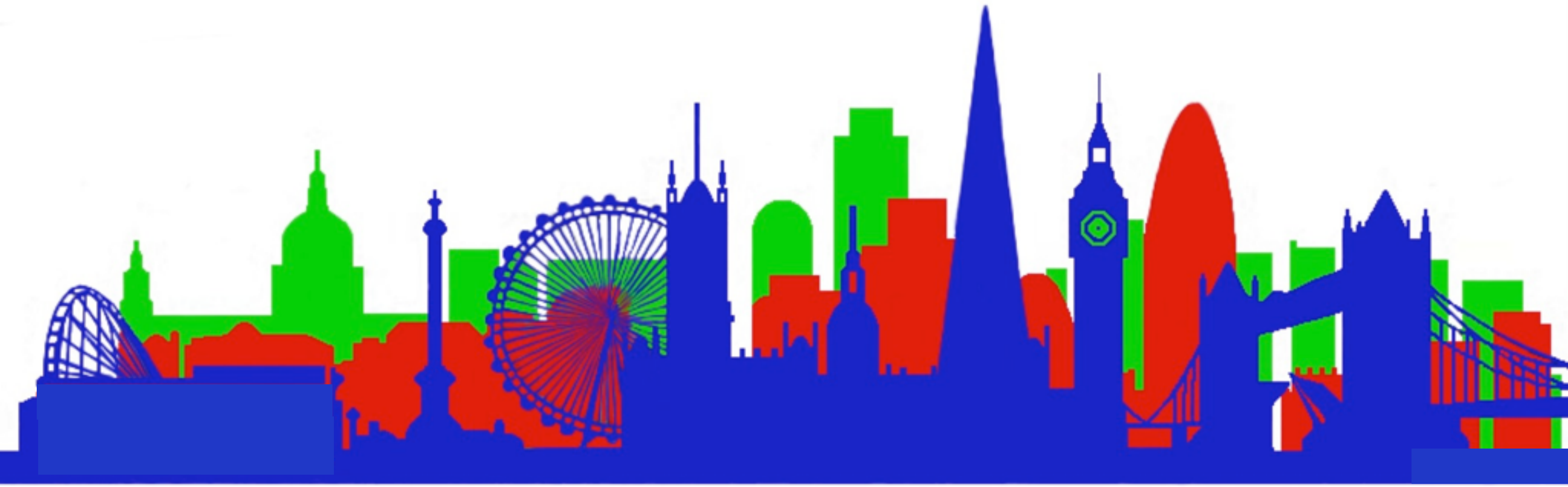
- Each way to probe top-Higgs has his own th+exp. advantages/disadvantages - CMS is developing a *strong, synergic effort* to exploit different production and decay modes
- *Direct exploration* of top-Higgs coupling will soon allow *independent probe on SM*
- New physics would modify direct Higgs production, ttH, and tH in *different* ways



CONCLUSIONS

- Each way to probe top-Higgs has his own th+exp. advantages/disadvantages - CMS is developing a *strong, synergic effort* to exploit different production and decay modes
- *Direct exploration* of top-Higgs coupling will soon allow *independent probe on SM*
- New physics would modify direct Higgs production, ttH, and tH in *different* ways

The coming data will allow us to navigate uncharted top and Higgs territories!



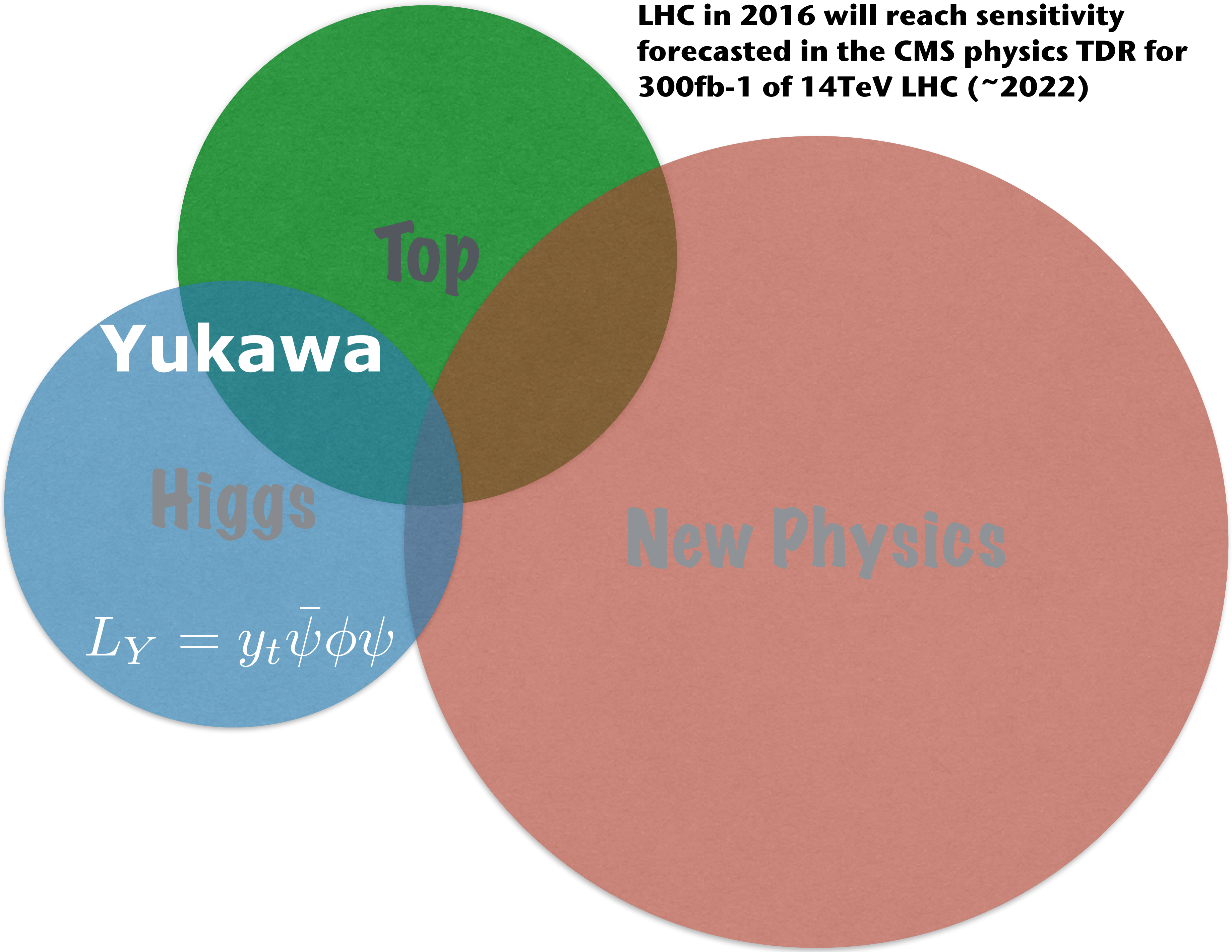
Conclusions

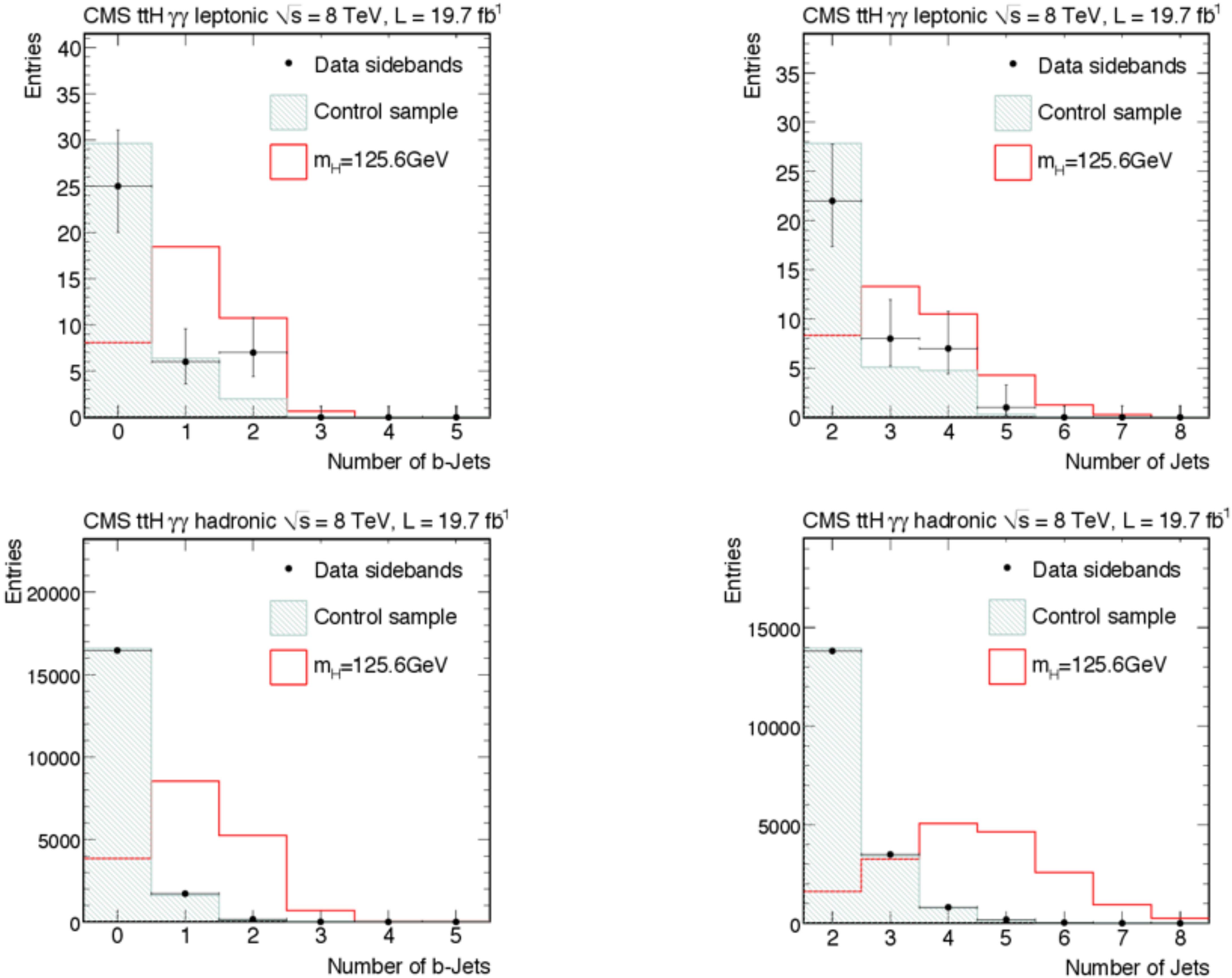
- Each way to probe top-Higgs has his own th+exp. advantages/disadvantages - CMS is developing a *strong, synergic effort* to exploit different production and decay modes
- *Direct exploration* of top-Higgs coupling will soon allow *independent probe on SM*
- New physics would modify direct Higgs production, ttH, and tH in *different* ways

The coming data will allow us to navigate uncharted top and Higgs territories!

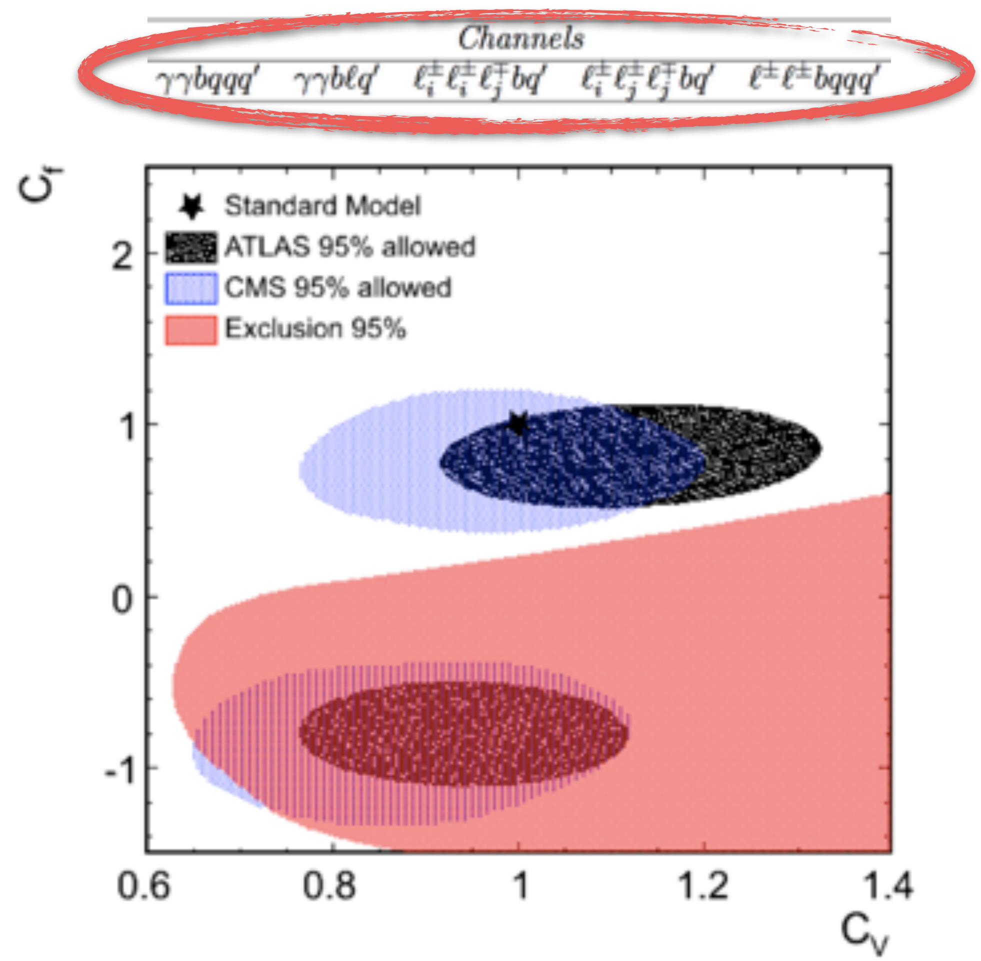
BACKUP

LHC in 2016 will reach sensitivity forecasted in the CMS physics TDR for 300fb-1 of 14TeV LHC (~2022)

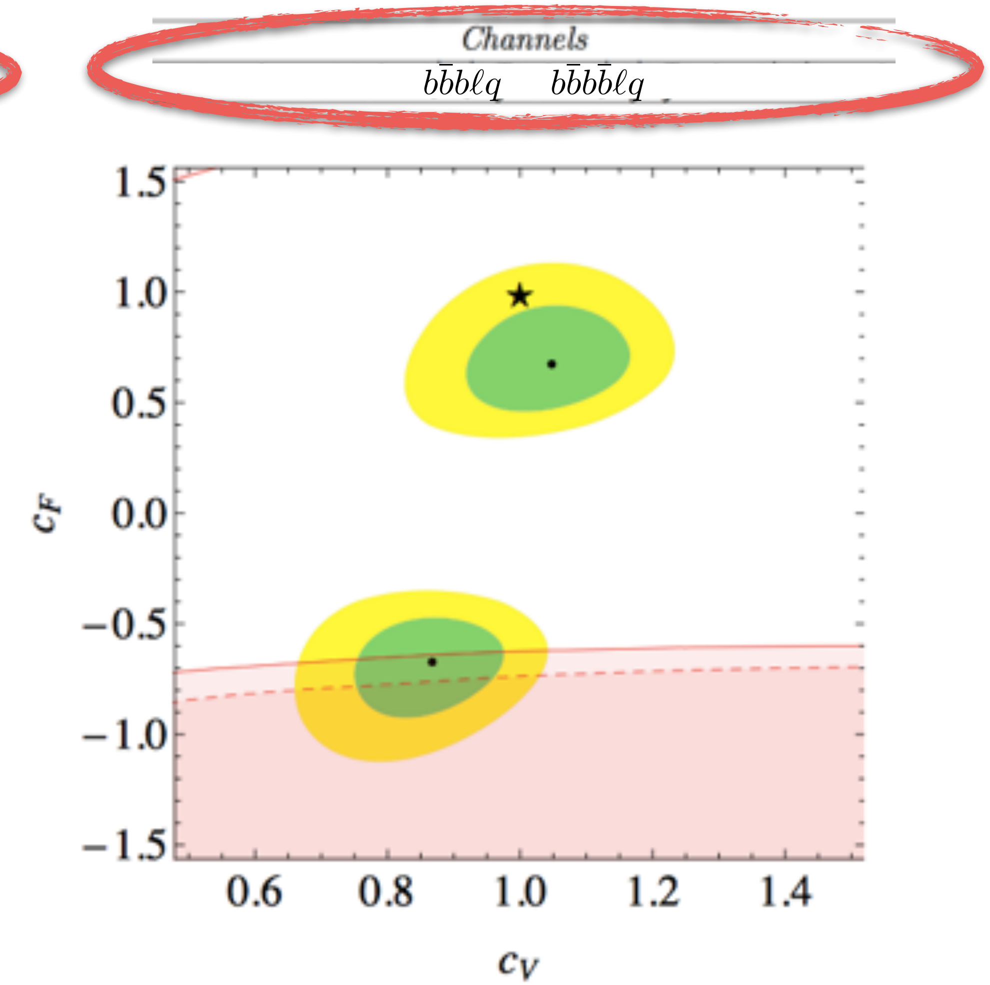



CMS ttH γγ leptonic √s = 8 TeV, L = 19.7 fb-1
Entries
Data sidebands
Control sample
mH=125.6GeV
Number of b-Jets
CMS ttH γγ leptonic √s = 8 TeV, L = 19.7 fb-1
Entries
Data sidebands
Control sample
mH=125.6GeV
Number of Jets
CMS ttH γγ hadronic √s = 8 TeV, L = 19.7 fb-1
Entries
Data sidebands
Control sample
mH=125.6GeV
Number of b-Jets
CMS ttH γγ hadronic √s = 8 TeV, L = 19.7 fb-1
Entries
Data sidebands
Control sample
mH=125.6GeV
Number of Jets

HIGGS COUPLING AND MORE



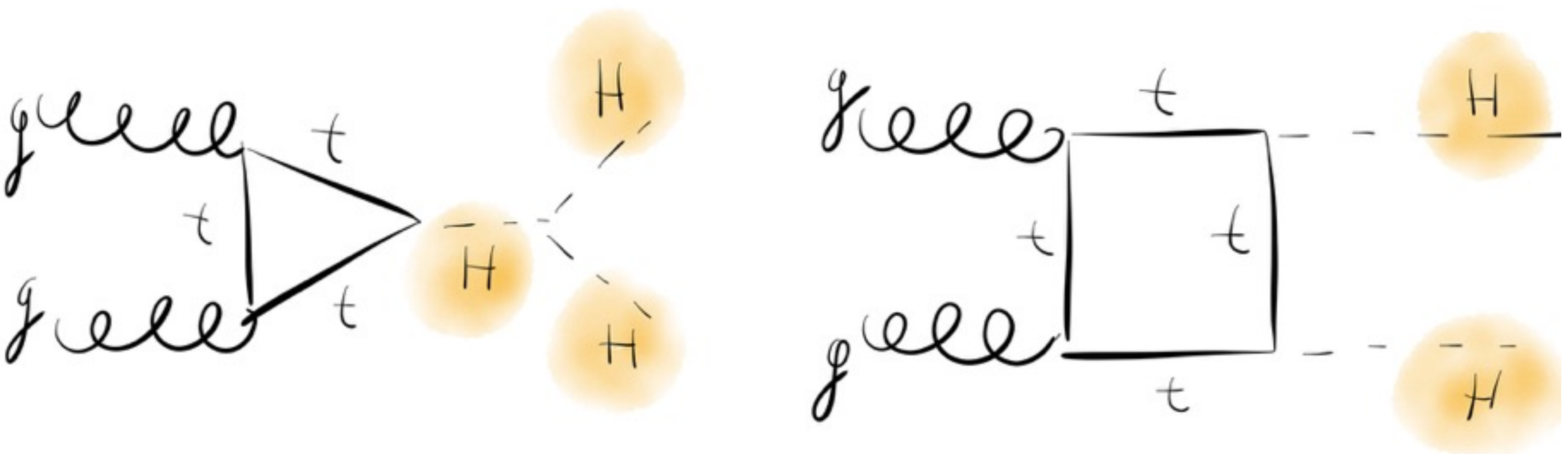
S.Biswas,E.Gabrielli,FM,B.Mele JHEP 07 (2013) 073



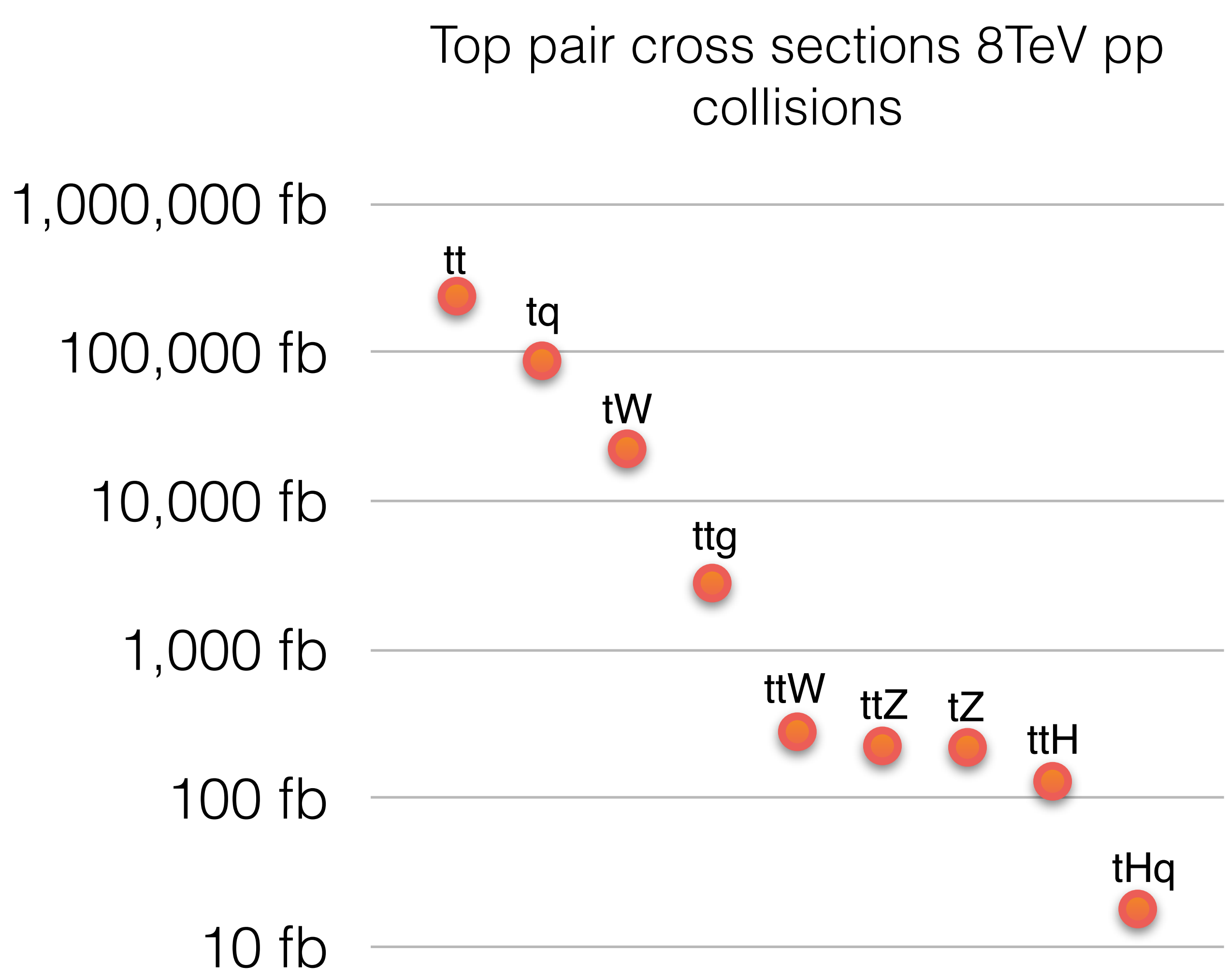
Farina,Grojean,Maltoni,Salvioni,Thamm JHEP 05 (2013) 022

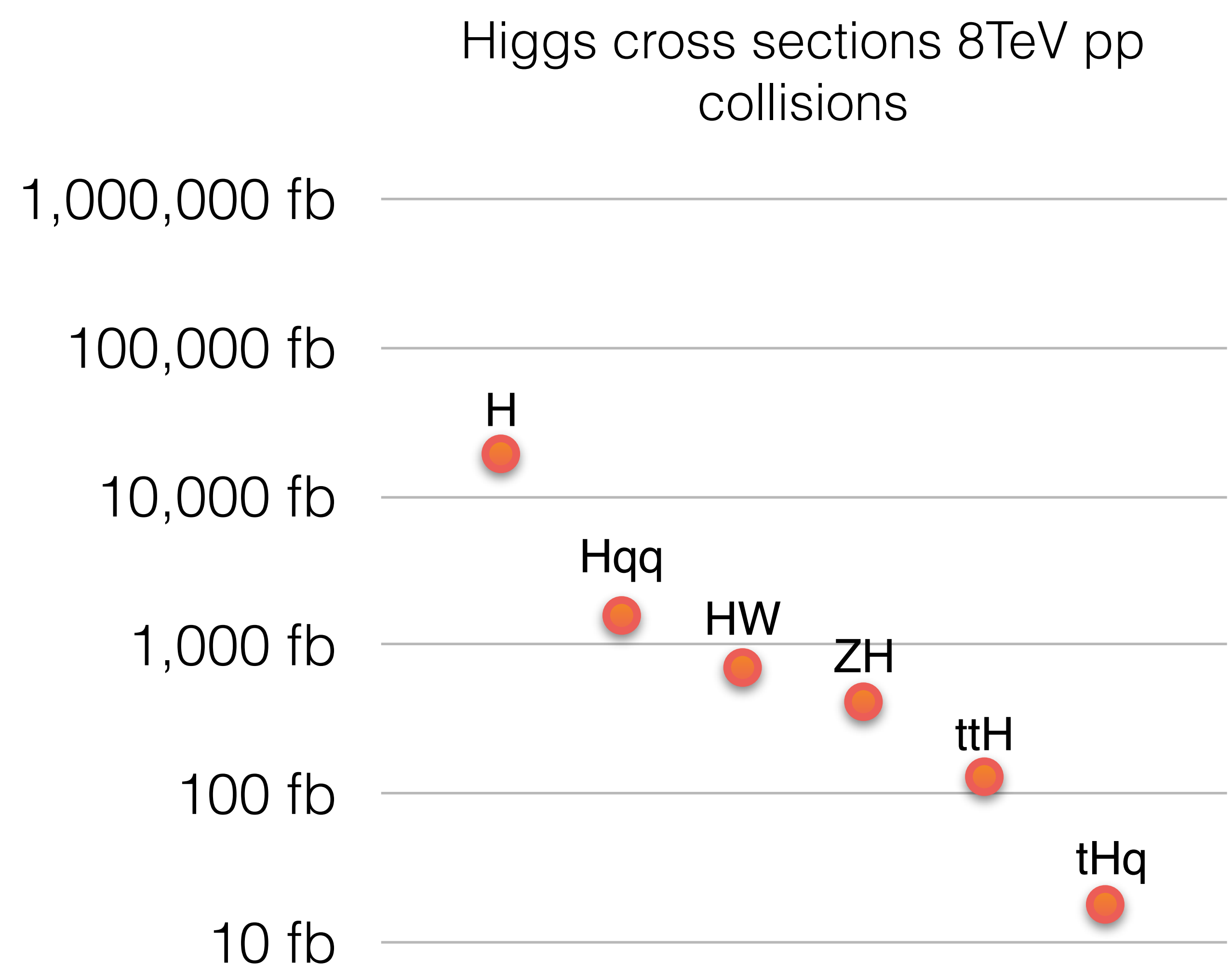
- Several other new physics models could alter single top plus Higgs production rates and/or kinematics:
  - FCNC
  - Composite Higgs
  - CP violation
  - who knows?

HIGGS SELF-COUPLING



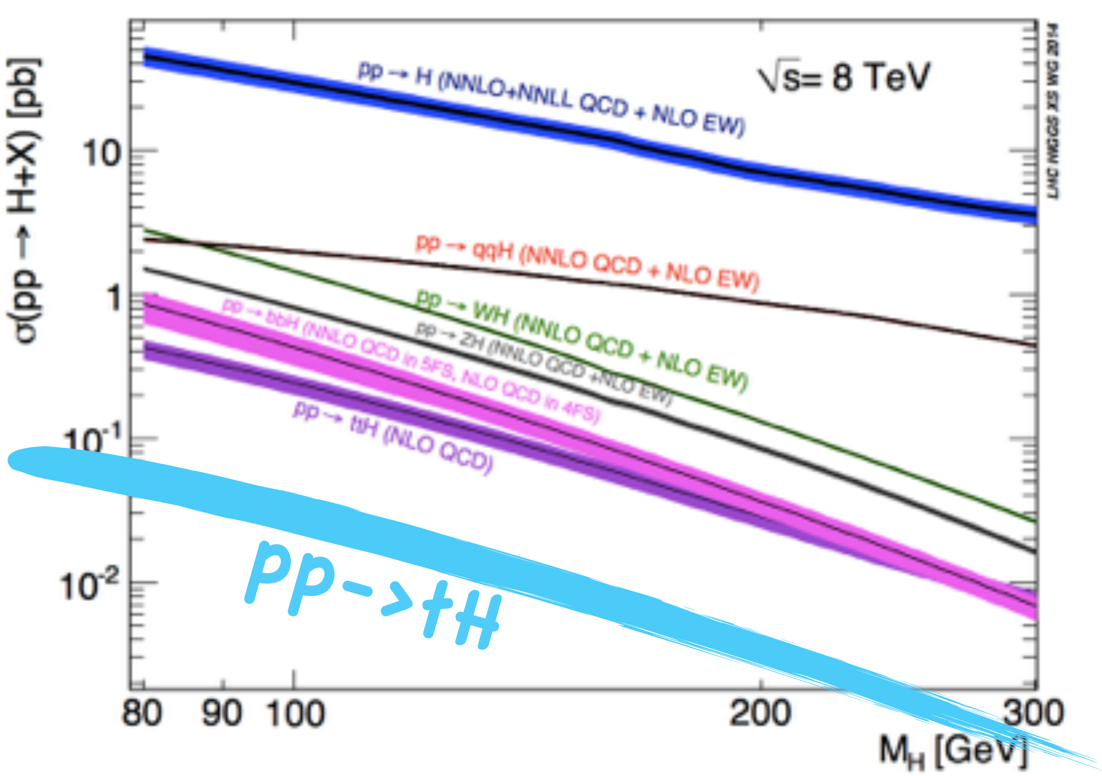
DIG DEEPER INTO THE LHC GOLD

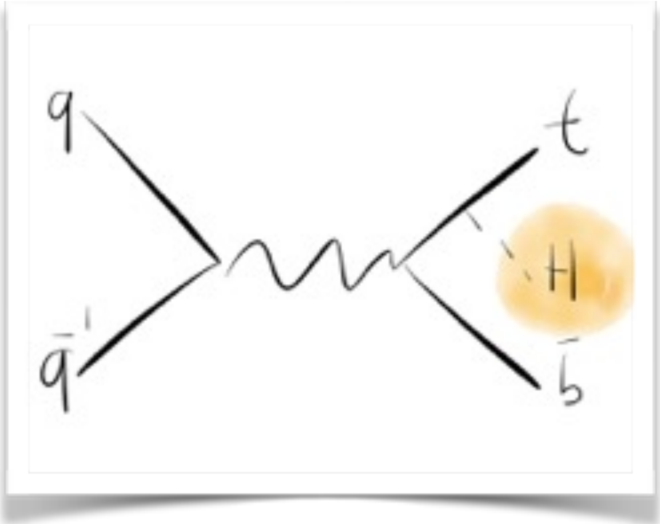


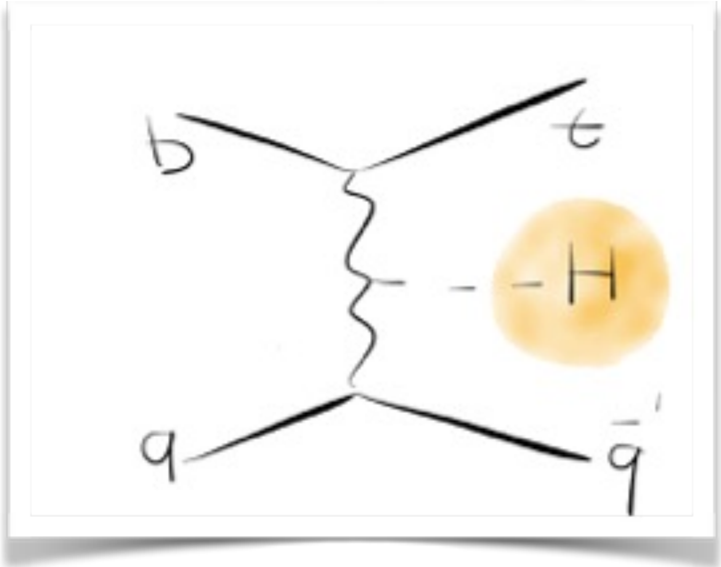


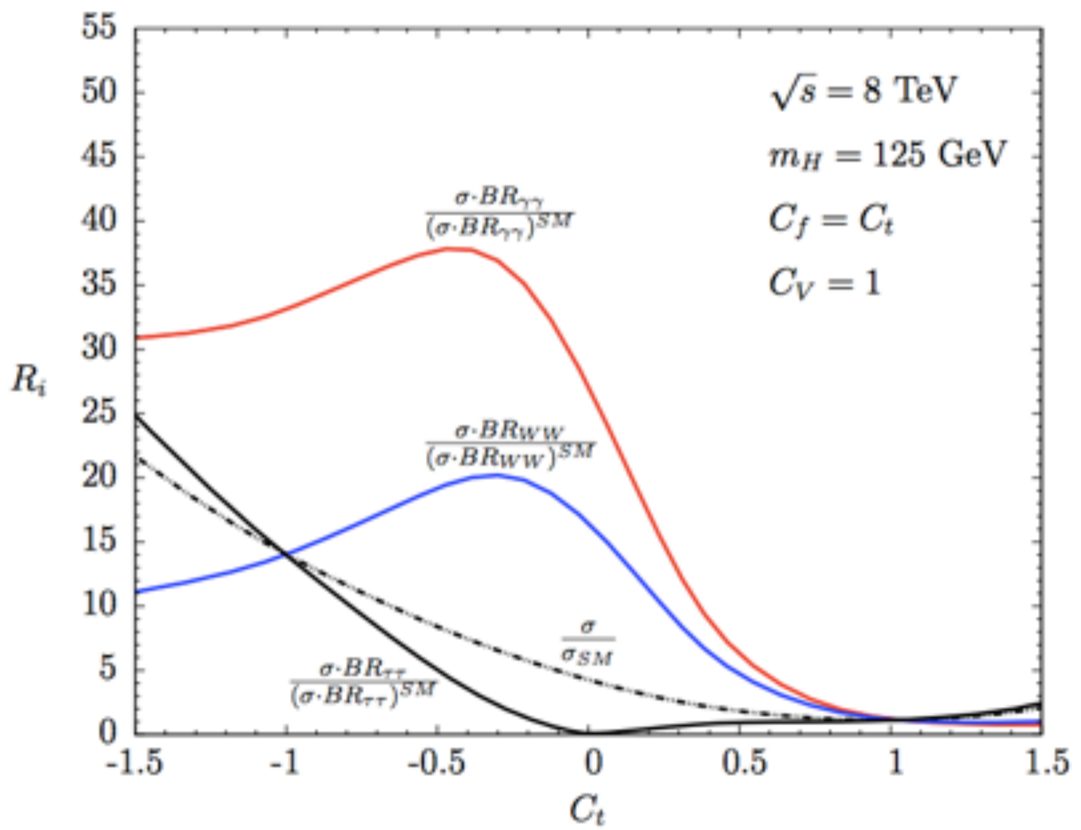
t+H is the next goal in both Higgs physics, <u>and</u> in top physics

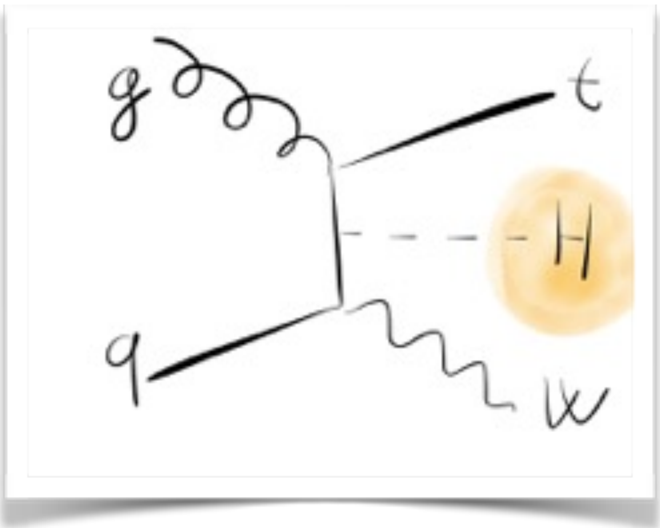
SINGLE TOP PLUS HIGGS



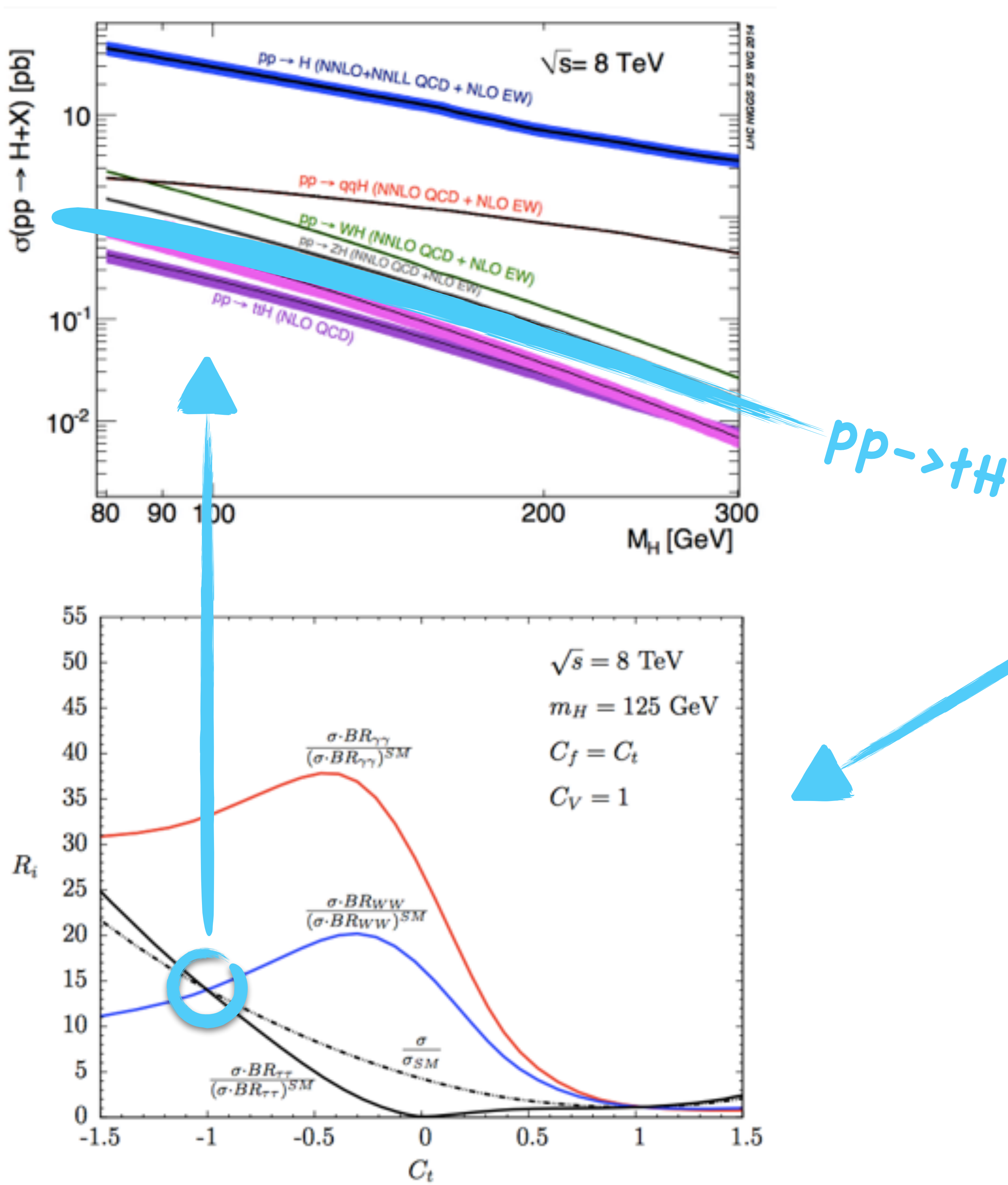


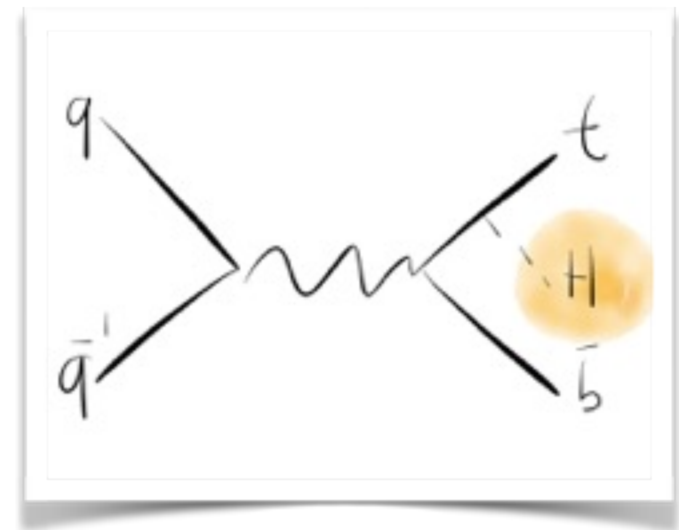


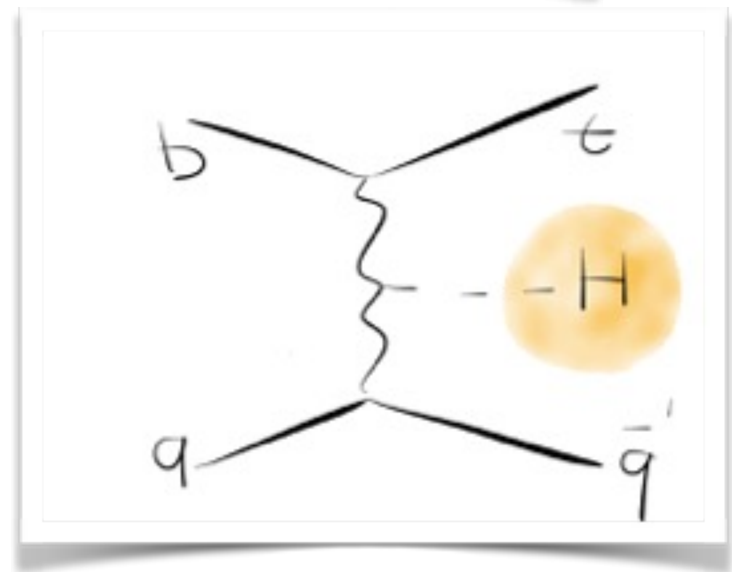


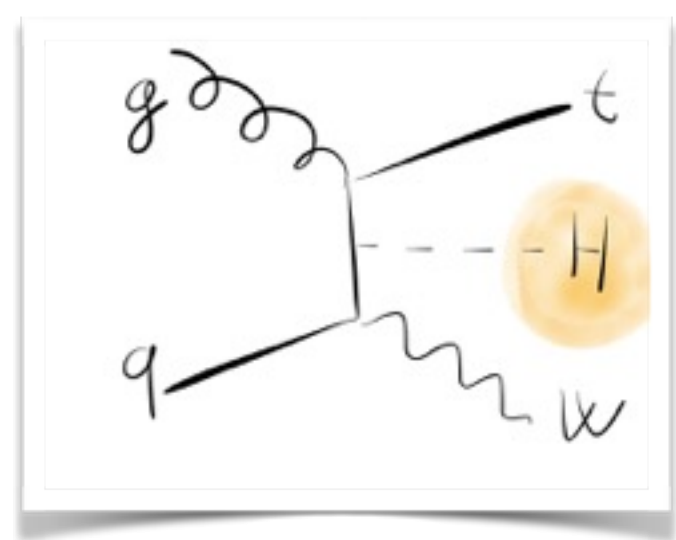


Single top plus Higgs



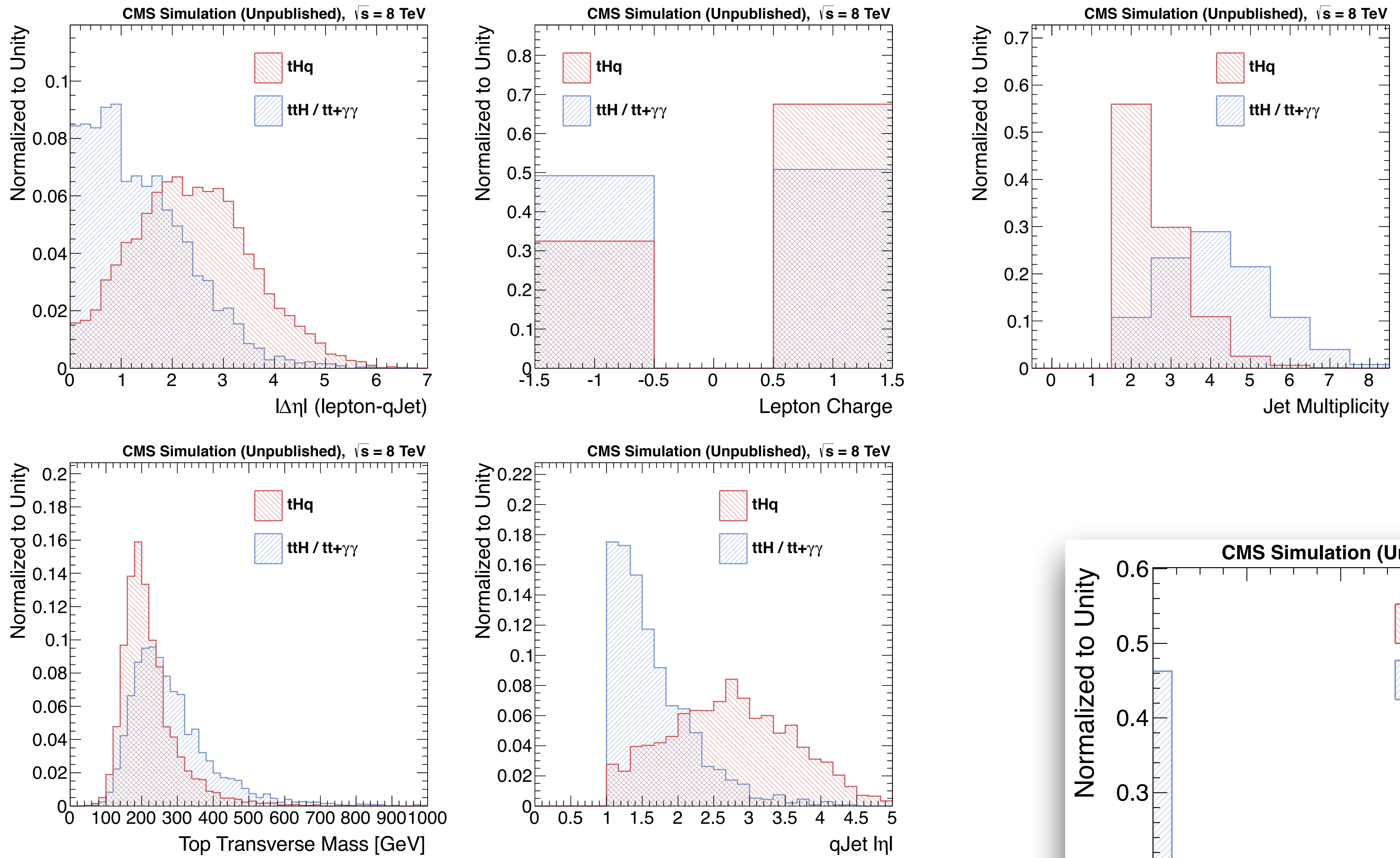


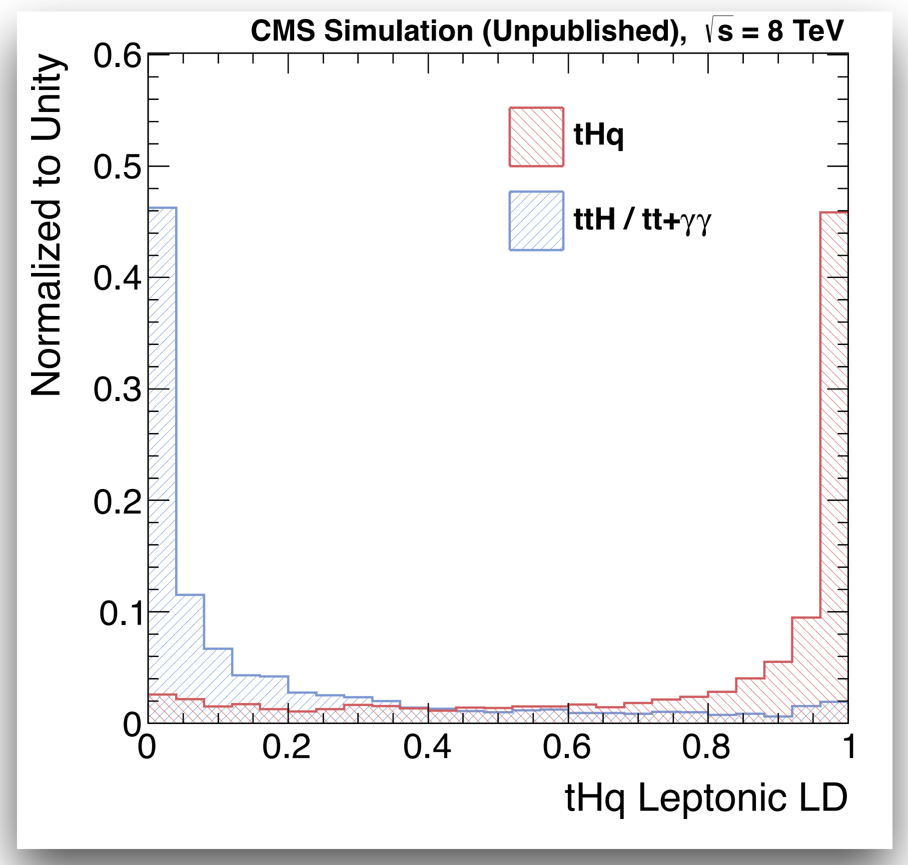




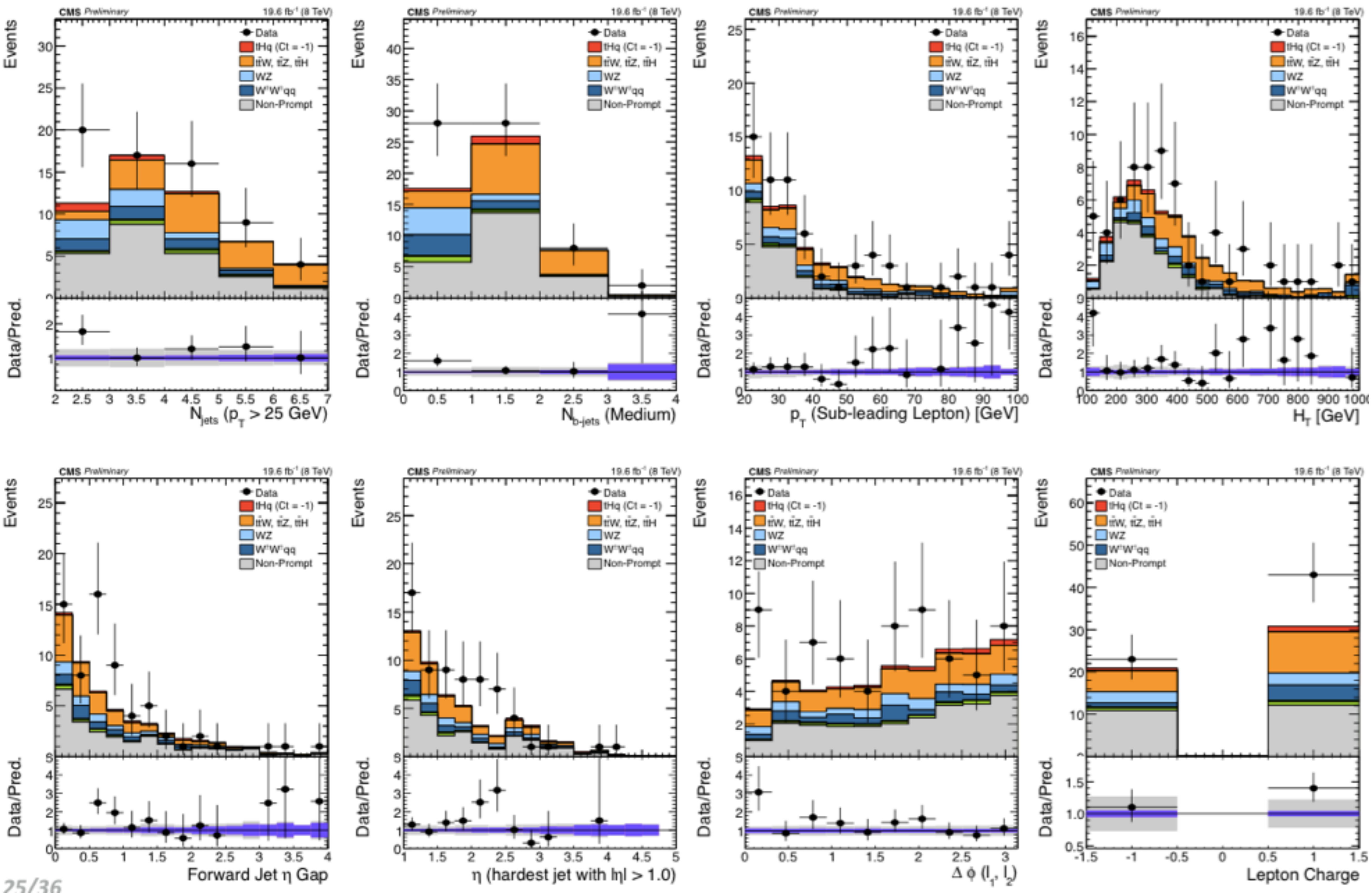
tHq, Higgs to photons

CMS-HIG-14-001

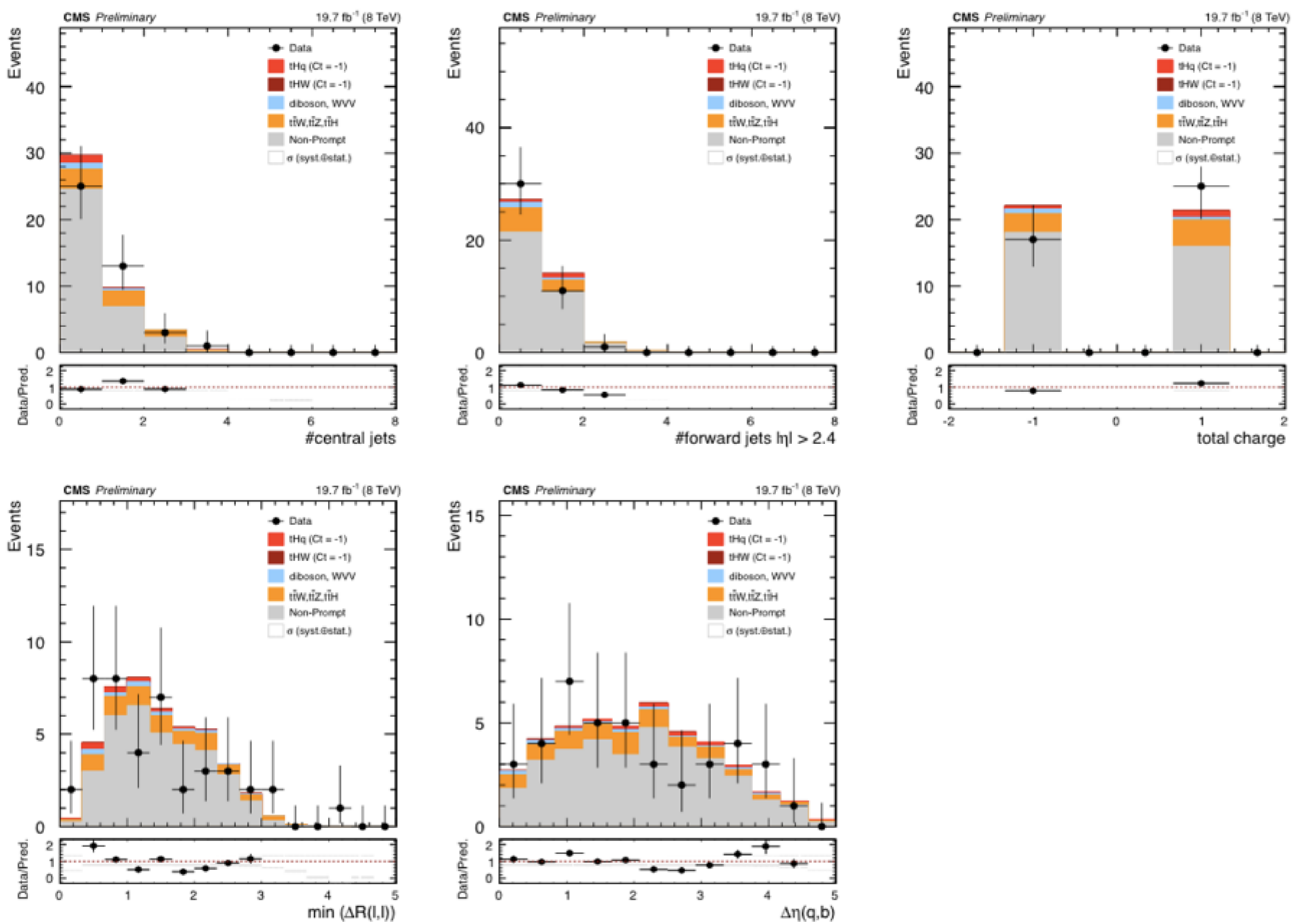




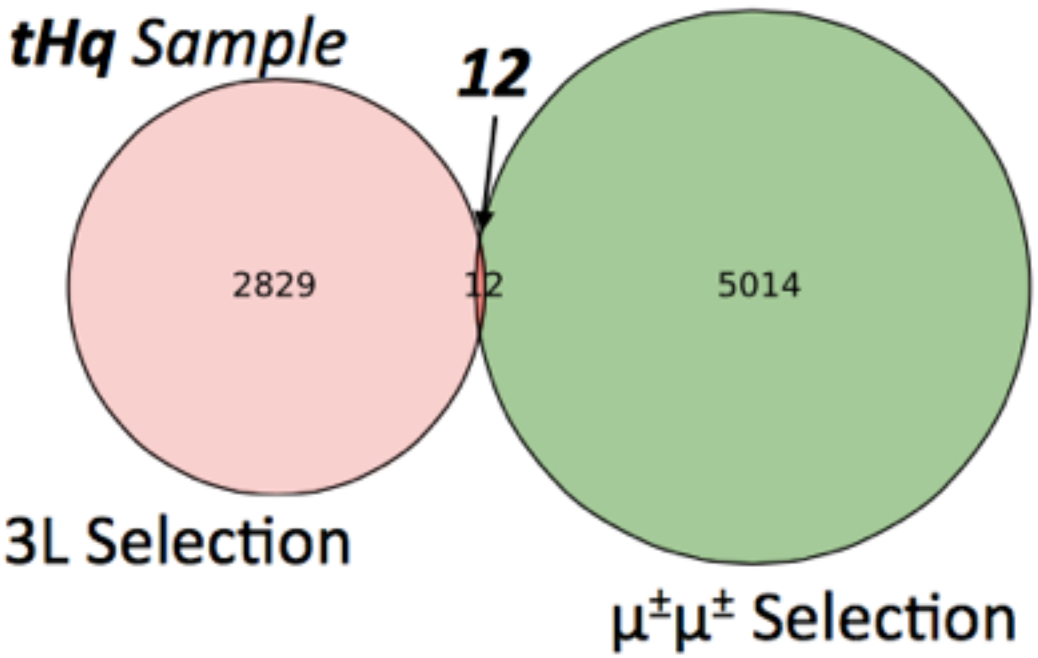
tHQ TO MULTILEPTON

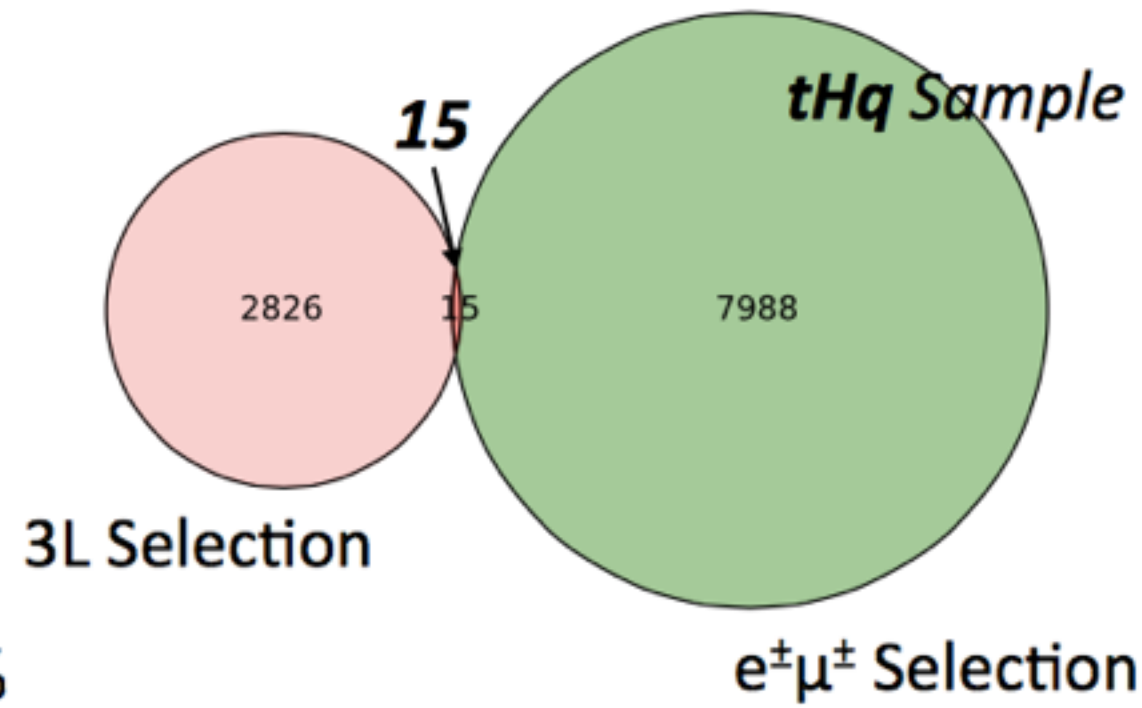


tHq to multilepton



Interchannel Overlap?





- Residual overlap well below 1%
- No common events on data

TTH AND THQ MULTILEPTON

In the dilepton channels ($\mu\mu/e\mu$), ttH* has a tighter selection than tHq, but does not require forward jets

tHq 2lSS Selection

- **≥ 1 jet with |η| > 1**
- ≥ 1 jet with |η| < 1
- ≥ 1 jet with loose CSV tag
- Veto hadronic τ's

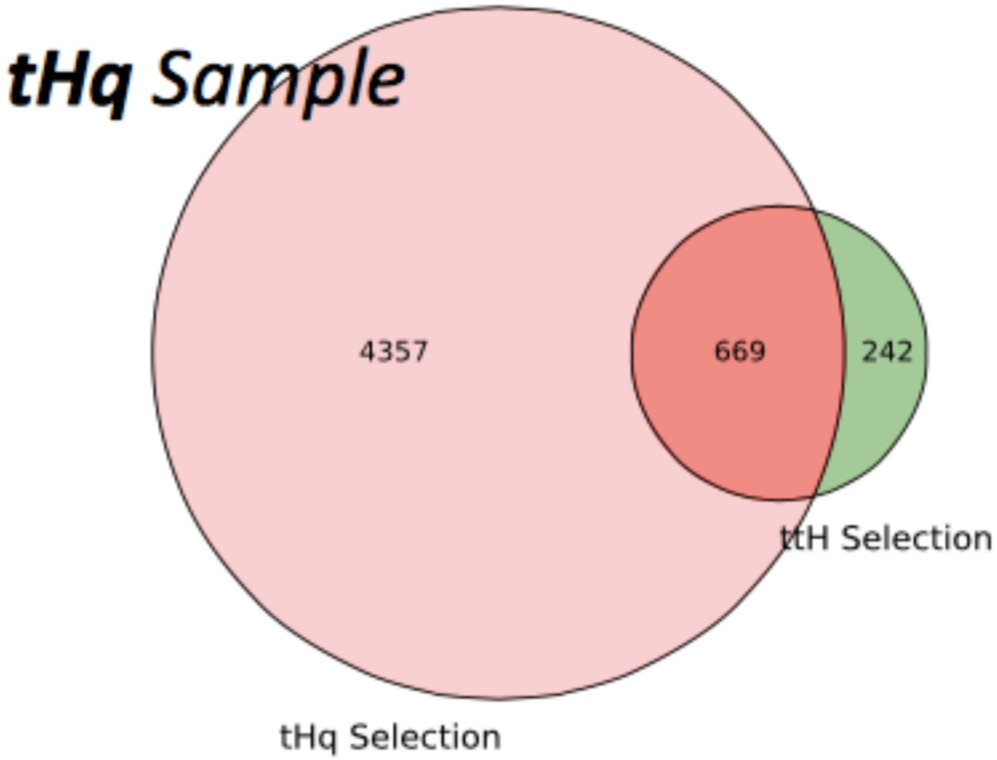
ttH 2lSS Selection

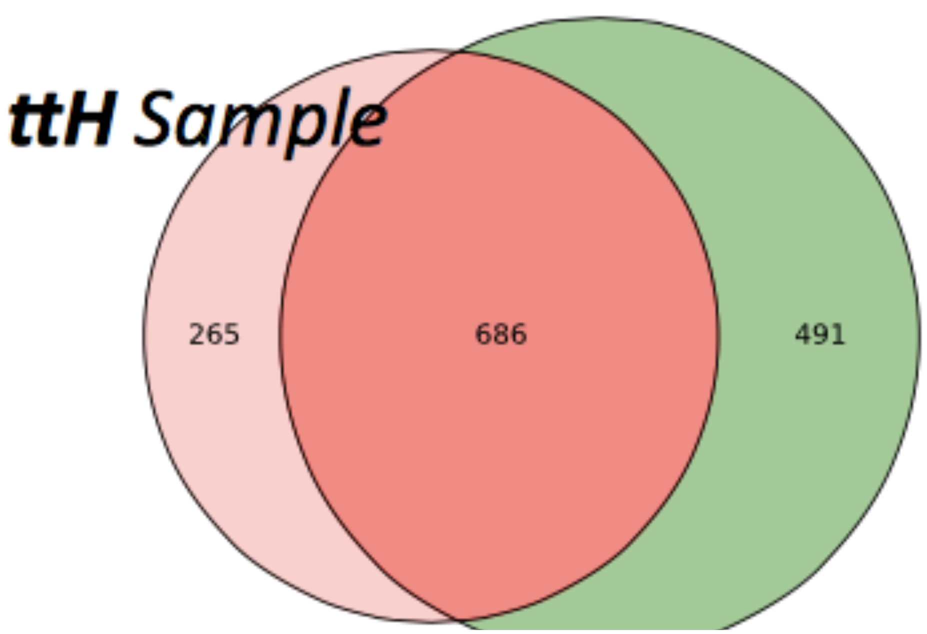
- $p_{T,1} + p_{T,2} + ME_T > 100$ GeV
- **≥ 4 jets (|η| < 2.4)**
- ≥ 2 jets with loose CSV **OR** ≥ 1 jet with medium CSV

- Remaining selection is identical
- By construction, no migration between tHq dilepton and ttH channels

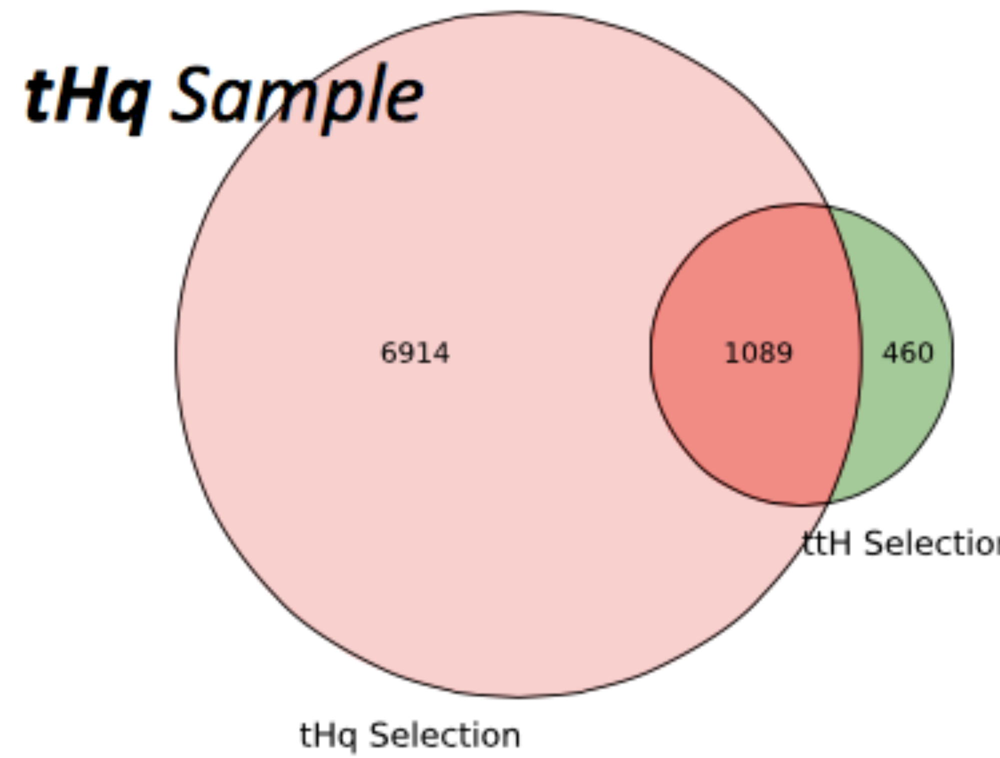
TITLE

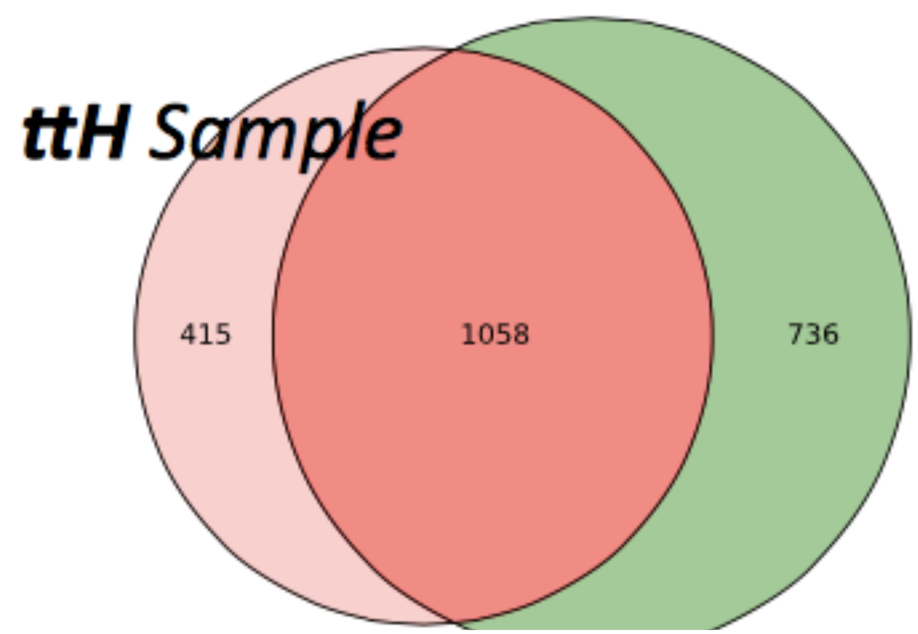
μμ Channel





eμ Channel





OVERLAP FOR 3L ANALYSIS

tHq 3l Selection

- ≥ 1 (non-tagged) fwd-jet ($|\eta| > 1.5$)
- ME_T > 30 GeV
- == 1 jet with med. CSV tag

ttH 3l Selection

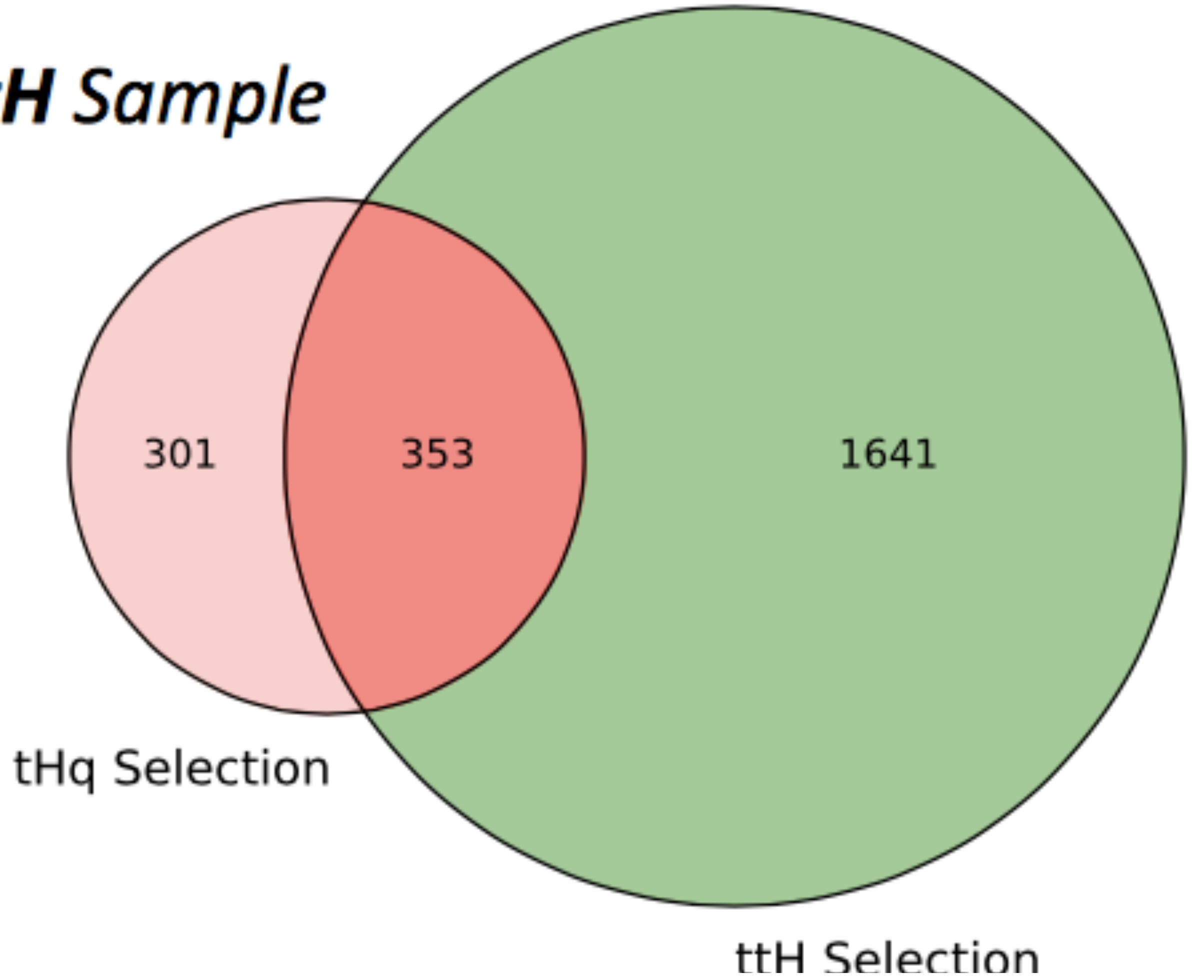
- ≥ 2 jets ($|\eta| < 2.4$)
- ME_TLD* > 0.2 **OR** ≥ 4 jets
- ≥ 2 jets with loose CSV **OR** ≥ 1 jet with medium CSV

- Remaining selection very similar (Z-veto, m_{ll} cuts, add. lep veto)
- Different lepton object selections
- Possible migration between tHq-3l and ttH-2l channels (see sl. 50)

TITLE

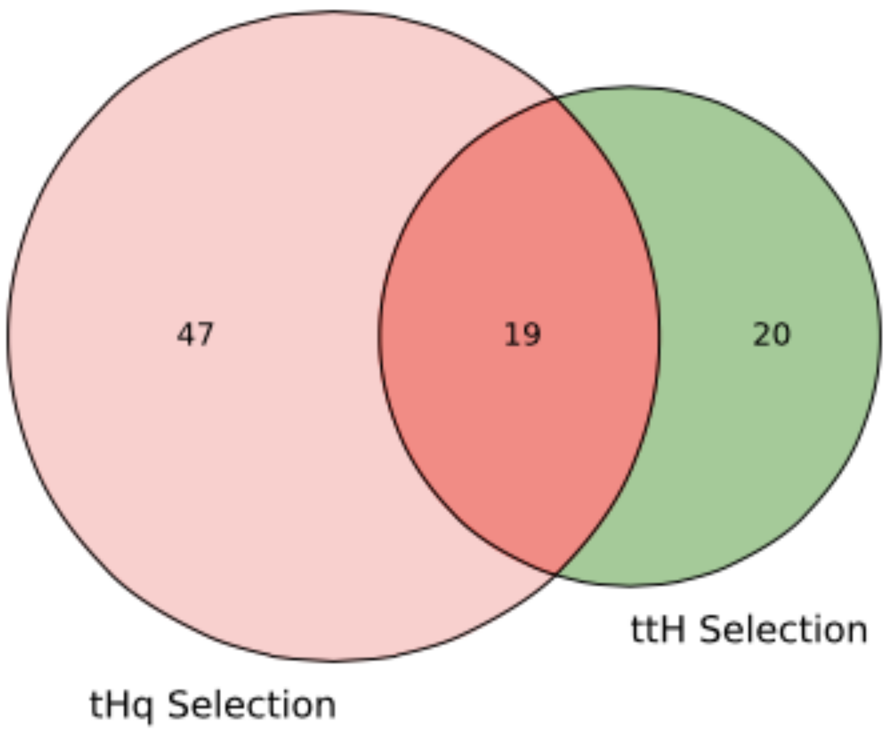
3l Channel

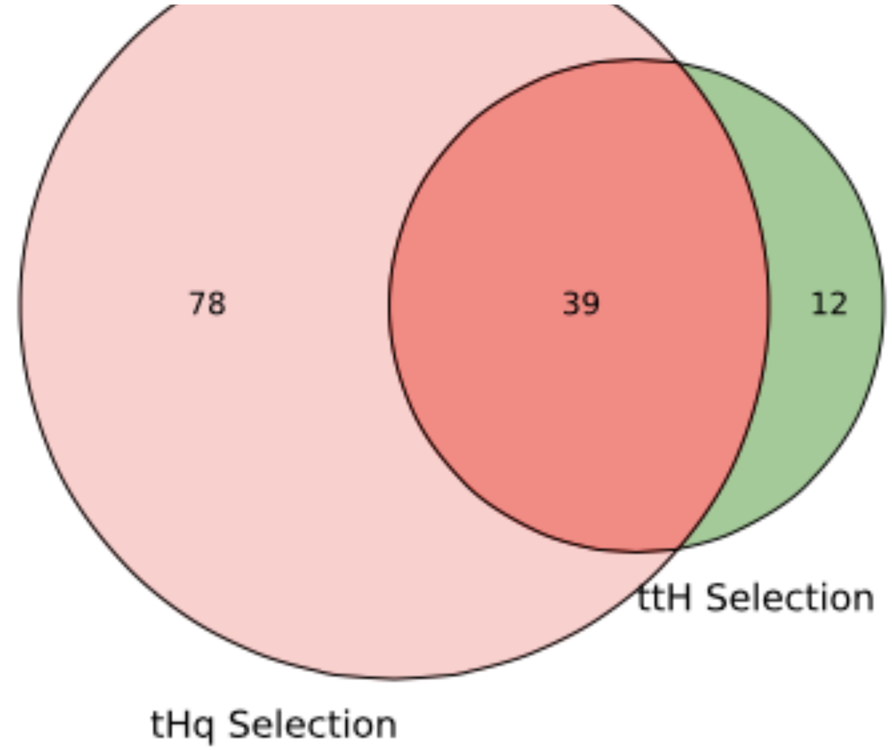
***ttH** Sample*



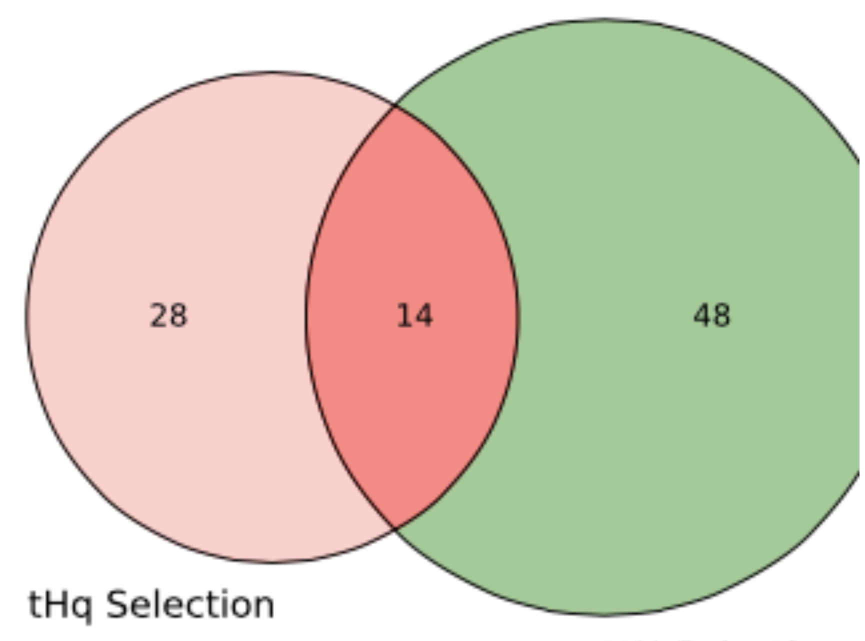
Title

μμ Channel





3l Channel



- Slight difference in yields of ttH selection compared to **HIG-13-020** PAS due to ReReco: 41 → 39 (μμ), 51 → 51 (eμ), 68 → 62 (3l)

TECHNICALITIES

Signal and background modeling

- ttH, WW, WZ, ZZ Pythia
- ttW/ttZ/ttgamma/ttgammagamma/gamma+jets/gammagamma+jets MadGraph
- tq/tW Powheg

Triggers used:

- Diphoton trigger
- Electron trigger
- Muon trigger
- ee/emu/mumu triggers

btagging

- Combined secondary vertex, medium OP
- H->bb also uses full CSV spectrum

SYSTEMATICS THQ MULTILEPTON

- PDF and QCD scales (*rate*)
  - tHq: 4.6% from PDF, 1.1% from Q^2 scale
  - 10/11/6 % for ttW/ttZ/ttH from Q^2 scale
  - 7-9% for ttV from PDFs, 8% for ttH
- 4 vs 5 flavor scheme (*rate*)
  - Study difference in selection efficiency and cross section on parton level, assign 10% (SS2L), 16% (3L)
- Pileup reweighting (*rate*)
  - Vary total inelastic cross section by 5%

SYSTEMATICS THQ MULTILEPTON

- SS2L non-prompt estimate: **about 50%**
  - Data/MC agreement of fake rates: 50% (μμ), 40 % ⊕ 20 % (eμ) (rate)
  - Variations of fake rate by p_T/η (10-20%) (shape)

- SS2L charge mis-identification estimate: **about 30%**
  - Propagated uncertainty on measured probabilities (rate)

- 3L non-prompt estimate: **about 35%**
  - MC closure test (30%) (rate)
  - Statistical errors of measured fake rates (shape)
  - Varying the ME_T cut in control region (shape)

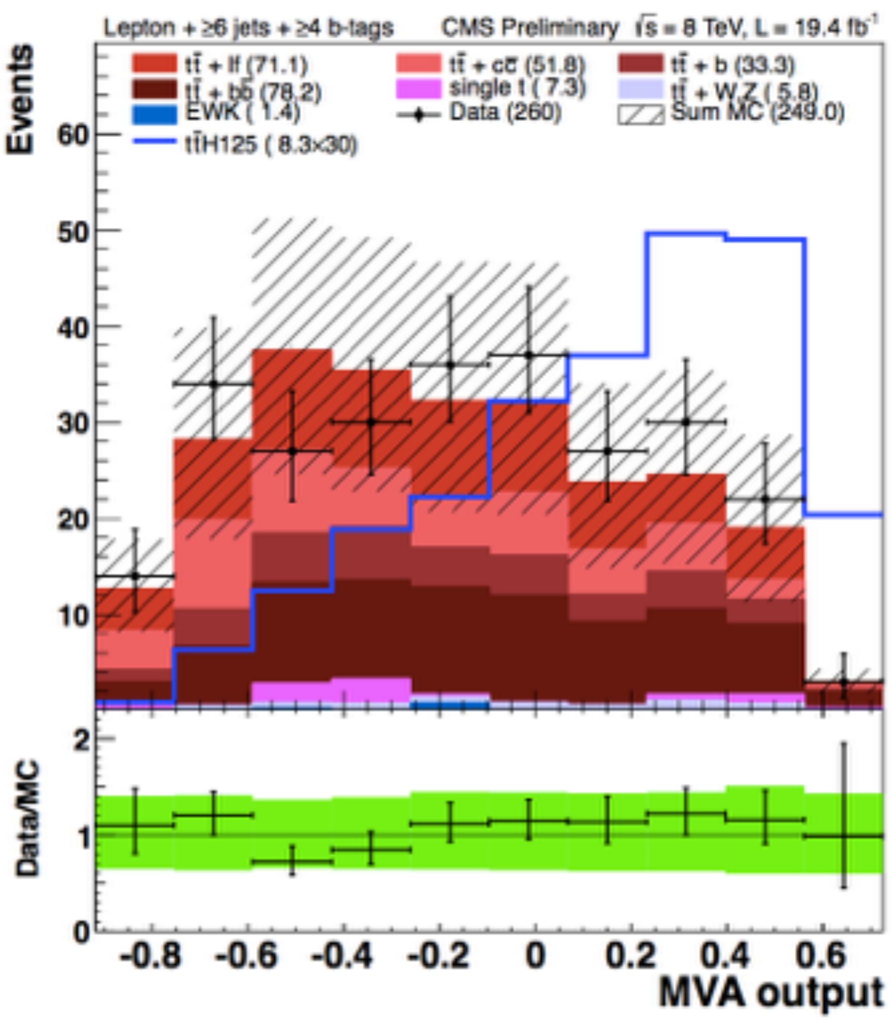
Lepton MVA

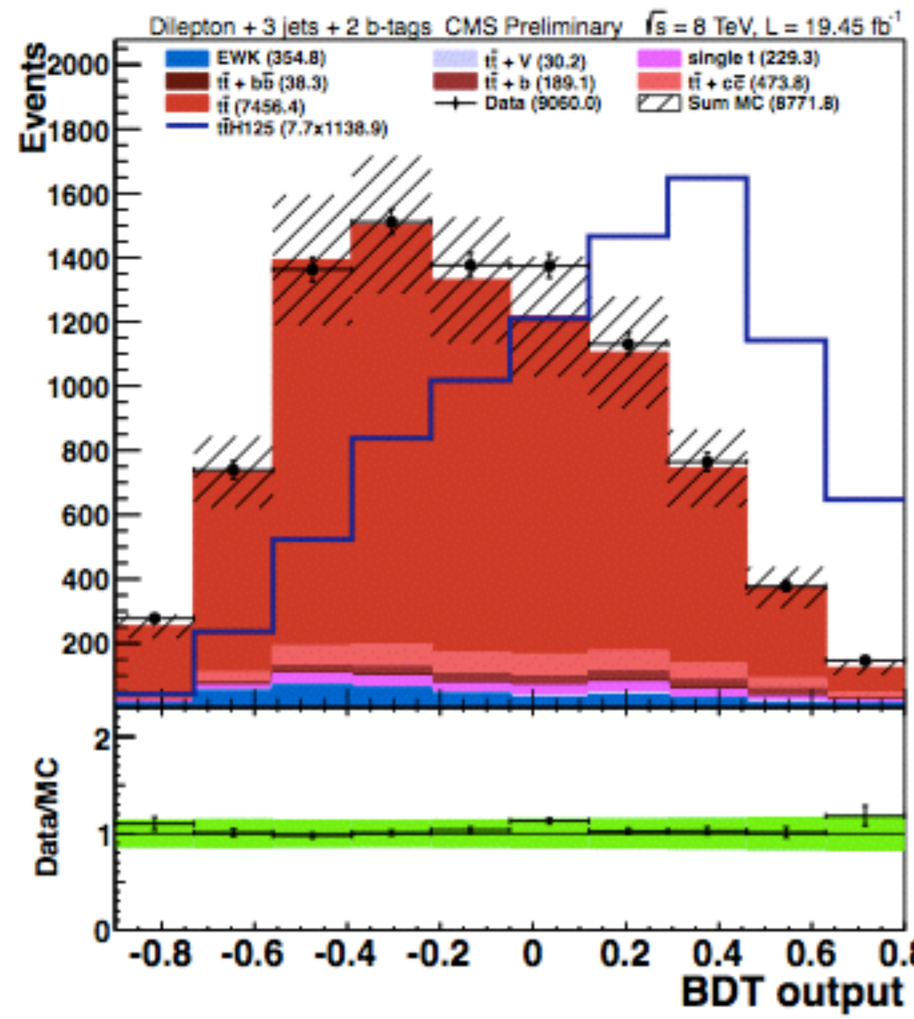
Next, a multivariate discriminator based on BDT techniques is used to distinguish prompt from non- prompt leptons. This discriminator, referred to as the lepton MVA, is trained with simulated prompt leptons from the ttH MC sample and non-prompt leptons from the tt+jets MC sample, separately for electrons and muons and for several bins in pT and η.

The lepton MVA input variables relate to the lepton IP, isolation, and the properties of the nearest jet, within $\Delta R < 0.5$. A tight working point on the lepton MVA output is used for the search in the dilepton and trilepton final states, and a loose working point is used for the four-lepton final state. For the tight working point, the efficiency to select prompt electrons is of order 35% for peT ~ 10 GeV and reaches a plateau of 85% at peT ~ 45 GeV; for prompt muons it is of order 55% for pTμ ~ 10 GeV, and reaches a plateau of about 97% at pTμ ~ 45 GeV. The efficiency to select electrons (muons) from the decay of b hadrons is between 5–10% (around 5%).

H → BB, TT → LJETS OR DILEPTON

- Identify tops and Higgs via multiple b-tagged jets, leptons (ele/muons) and light flavor jets
- Split into Njet/Nbtag categories to further increase sensitivity
- For each category, use machine learning techniques to discriminate signal from dominant tt +bb/cc/b backgrounds

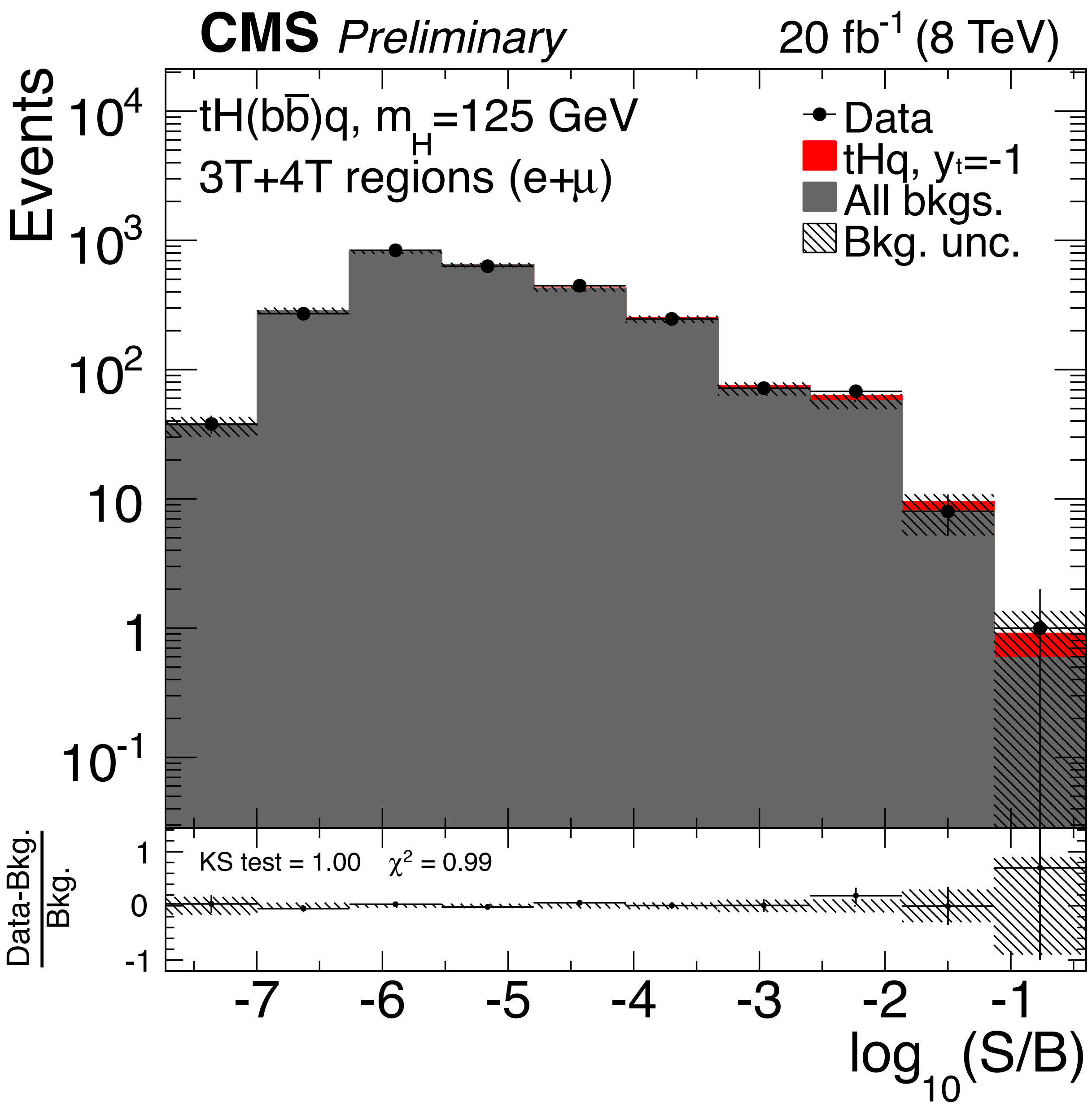




- Fit over resulting shapes, systematics modify relative normalization and shapes themselves
  - largest systematic is on the poorly known tt+bb/cc/b background

tHq, Higgs to bottoms

CMS-HIG-14-001



Process	Muon channel	Electron channel
$t\bar{t}$	1058 ± 5	718 ± 4
Single top	39 ± 3	27 ± 3
Electroweak	17^{+7}_{-5}	11 ± 7
$t\bar{t}H$	12.87 ± 0.17	9.35 ± 0.15
Total background	1128 ± 9	767 ± 10
tHq, $y_t = -1$	7.54 ± 0.03	5.15 ± 0.02
S/B ratio	0.7%	0.7%

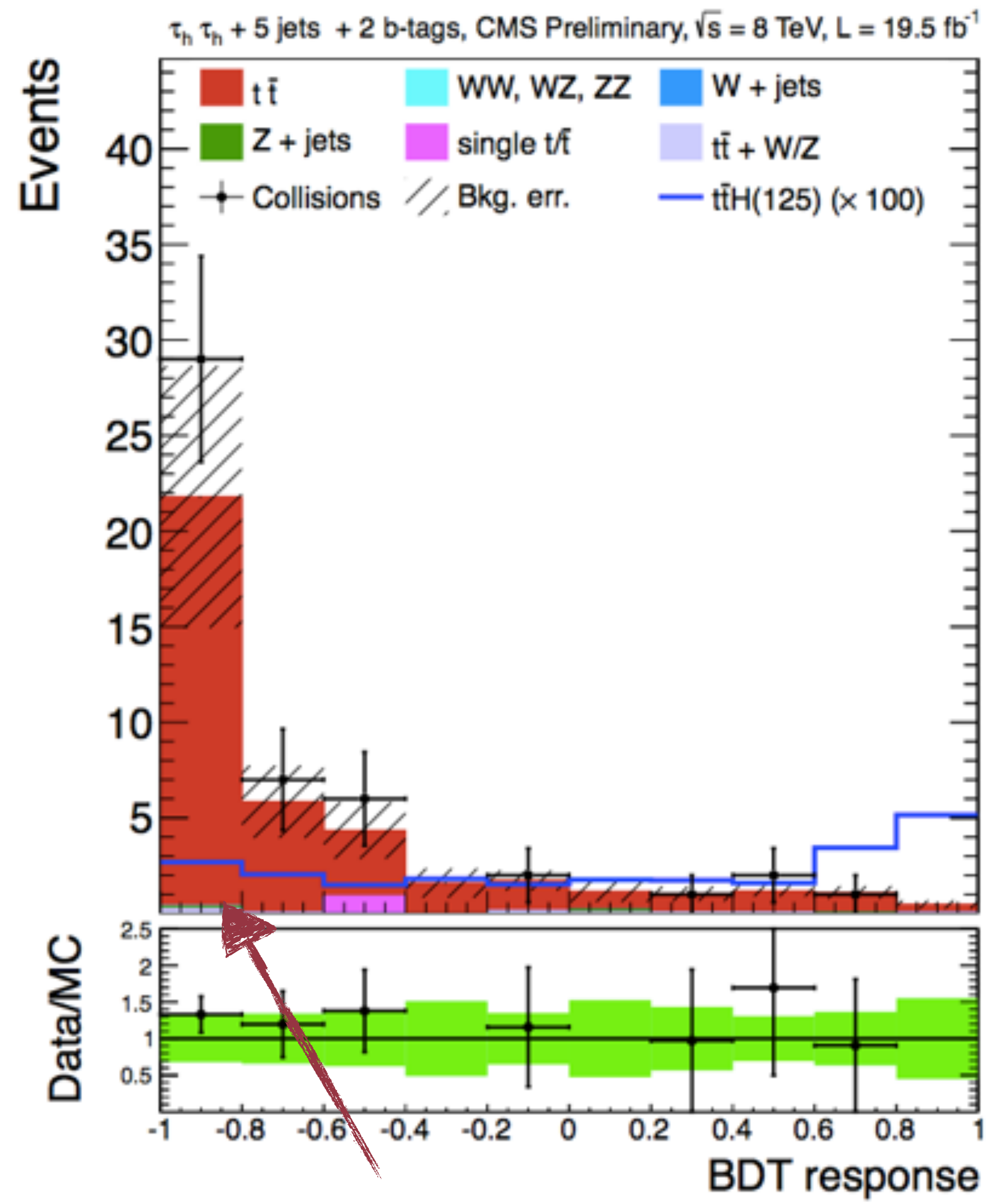
Process	Muon channel	Electron channel
$t\bar{t}$	29.1 ± 0.8	19.8 ± 0.7
Single top	$1.1^{+0.8}_{-0.6}$	1.2 ± 1.0
Electroweak	4^{+6}_{-4}	5^{+6}_{-4}
$t\bar{t}H$	1.72 ± 0.06	1.43 ± 0.05
Total background	37^{+6}_{-4}	29^{+7}_{-4}
tHq, $y_t = -1$	0.835 ± 0.010	0.580 ± 0.009
S/B ratio	2.3%	2.0%

- Set 95% expected (observed) upper level confidence limit of 5.1 (7.6) the sigmaXBR for tHq production with negative Yukawa

TTH, H → TAUTAU

- Select hadronically decaying taus, coming from the Higgs decay, reconstructed via a Particle Flow algorithm
- Select additional b-jets, leptons, light flavor jets consistent with ttbar decays, split into Njets and Nbtags categories

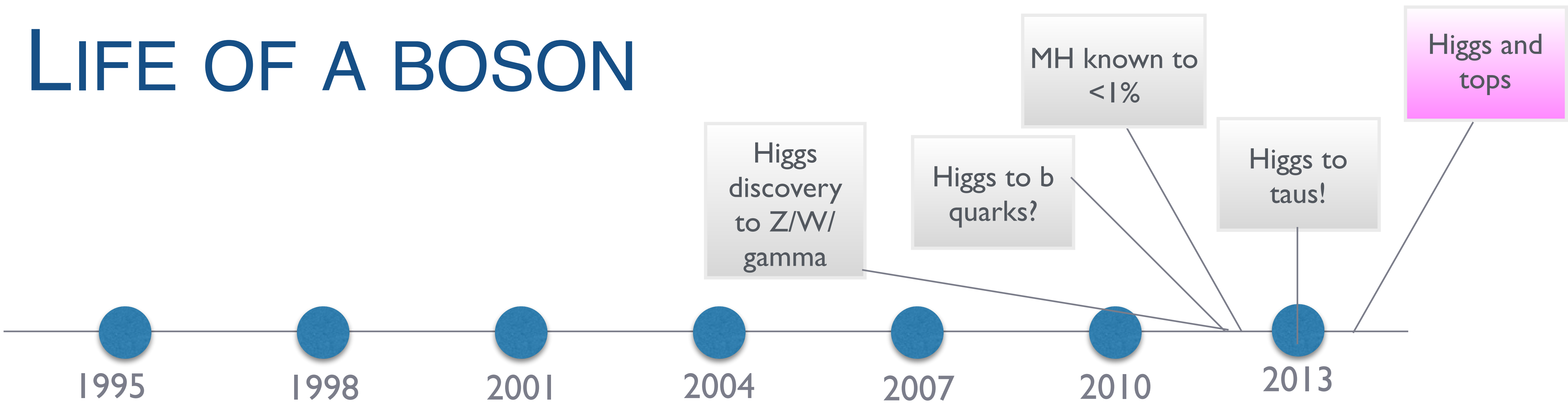
	4 jets 1 b-tag	5 jets 1 b-tag	≥6 jets 1 b-tag	4 jets 2 b-tags	5 jets 2 b-tags	≥6 jets 2 b-tags
$t\bar{t}H(125)$	0.4 ± 0.1	0.6 ± 0.1	0.6 ± 0.2	0.1 ± 0.0	0.2 ± 0.1	0.4 ± 0.1
$t\bar{t}$	225 ± 69	119 ± 38	64 ± 22	48 ± 15	38 ± 12	27.0 ± 9.1
$t\bar{t}V$	1.1 ± 0.3	1.3 ± 0.3	1.4 ± 0.4	0.4 ± 0.1	0.6 ± 0.2	1.1 ± 0.3
Single t	11.2 ± 4.0	3.0 ± 1.4	1.1 ± 1.0	1.9 ± 1.1	0.9 ± 0.6	0.6 ± 0.7
V+jets	33 ± 17	11.7 ± 6.8	3.8 ± 2.8	1.4 ± 0.9	0.4 ± 0.3	0.5 ± 0.6
Diboson	0.9 ± 0.2	0.7 ± 0.2	0.1 ± 0.0	0.0 ± 0.0	0.1 ± 0.0	0.1 ± 0.1
Total bkg	271 ± 82	135 ± 41	71 ± 24	52 ± 16	40 ± 12	29.2 ± 9.4
Data	292	171	92	41	48	35



Non H→tautau ttH component

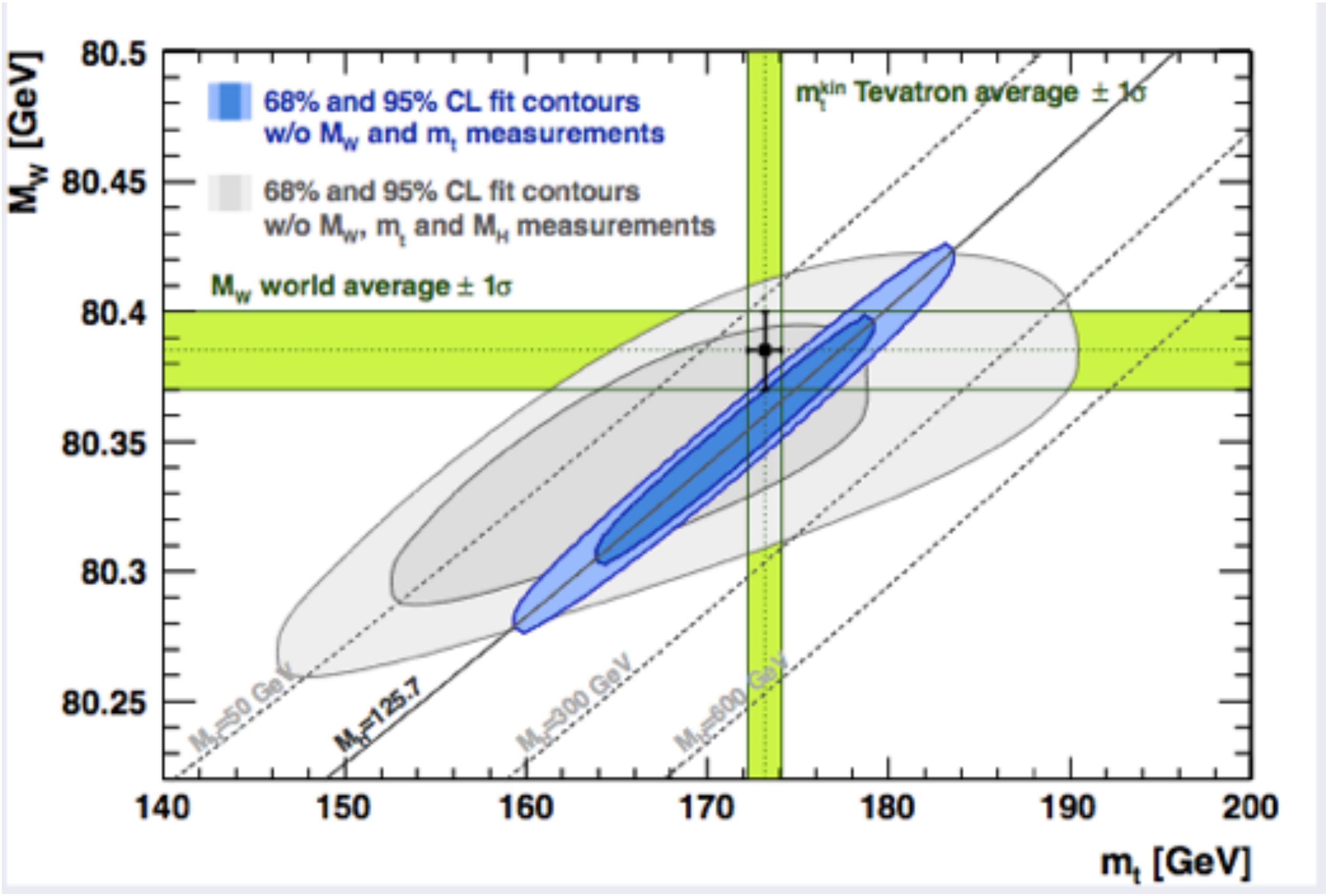
- Here tt+jets is again dominant background
  - multivariate discriminants exploit mostly tau-related informations
- Total Ns~2.5 evts
  - x10 (H → bb, ttbar → dilepton)
  - x100 (H → bb, ttbar → l+jets)

LIFE OF A BOSON



TOP, HIGGS, AND ALL OF US

- Precise top quark mass (and W boson mass) measurements provides a predictions for a SM Higgs boson mass: mH=94±24GeV



EPJ C72 2205

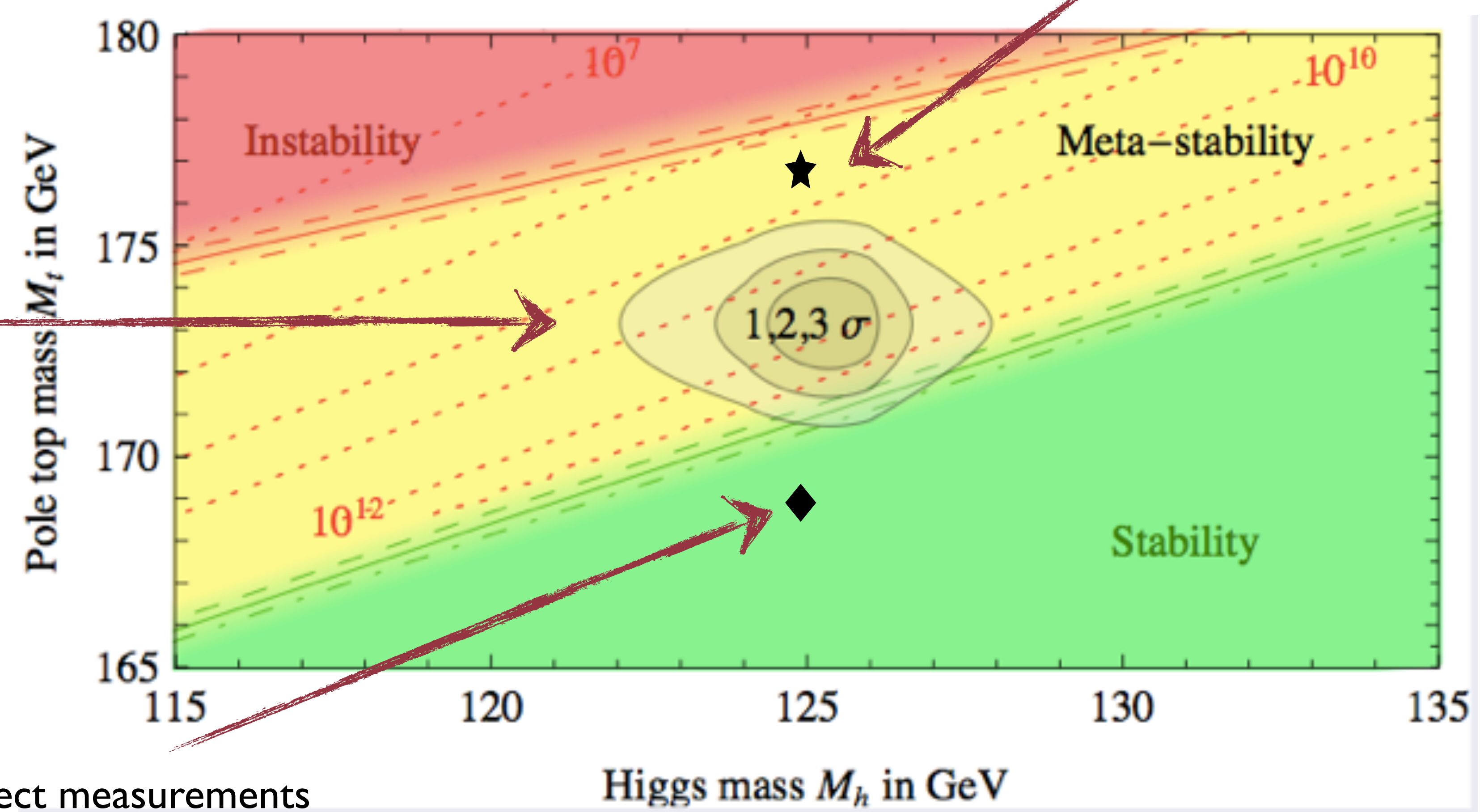
Predicted Higgs boson to be within 1sigma to where we found it!
Knowledge of Higgs mass allows prediction of Mtop to 1% level: Mtop=175.8±2.5GeV

TOP, HIGGS, AND ALL OF US

- Precise top quark mass (and W boson mass) measurements provides a predictions for a SM Higgs boson mass: mH=94±24GeV
- Oh BTW, it also helps us predict the fate of the universe…

From EWK fits (incl Higgs)

Mtop from direct measurements



JHEP 1208 098

From indirect measurements (until recently)

THE ATLAS WAY TO YUKAWA

- ATLAS uses a different approach to negative Yukawa:
- take existing ttH analysis, consider all tH contributions to it, study the dependence of the sum of tH+X processes as a function of Ct