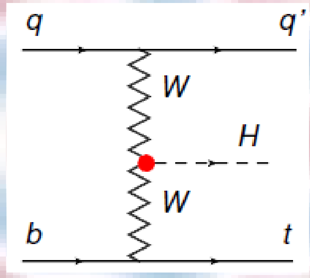
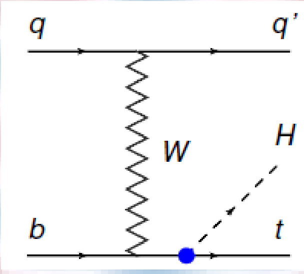
Single top + Higgs search with CMS data: quantum interference and the sign of y_t





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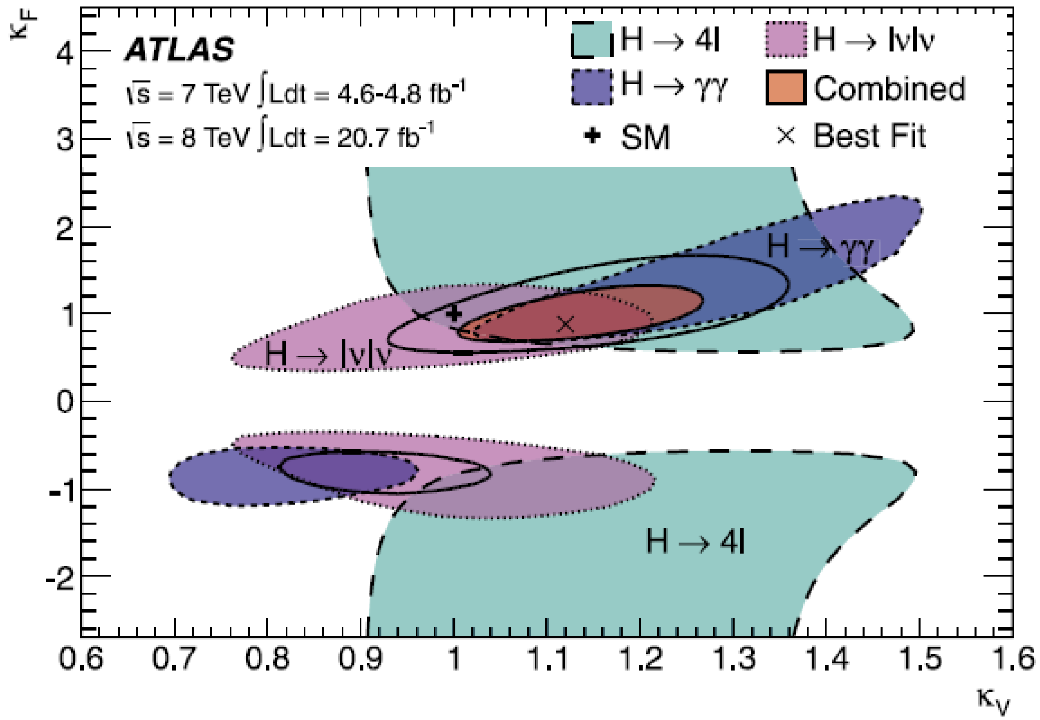
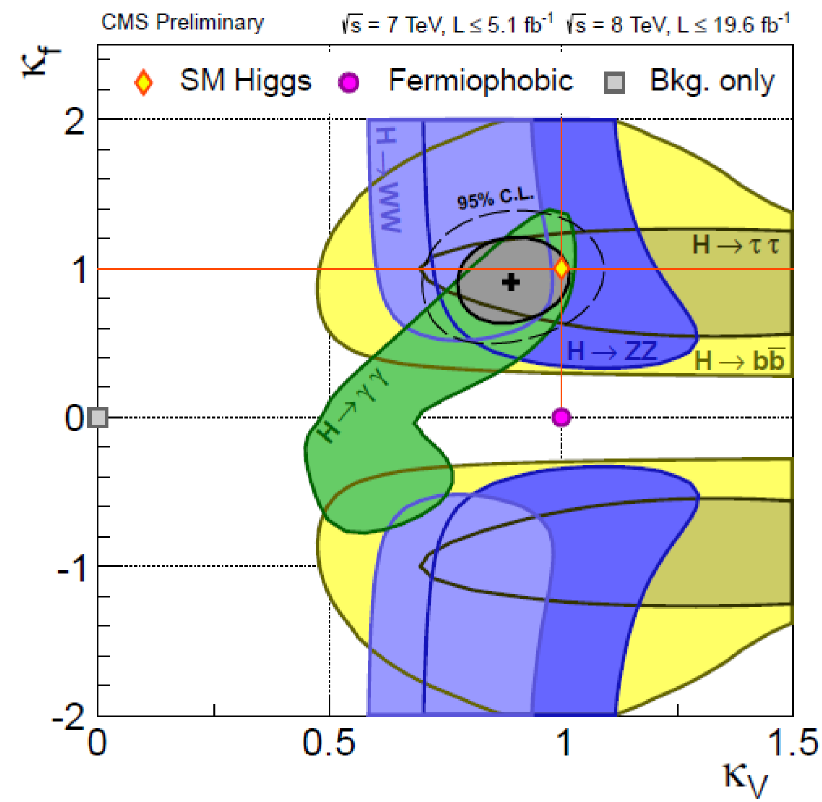
for the CMS collaboration

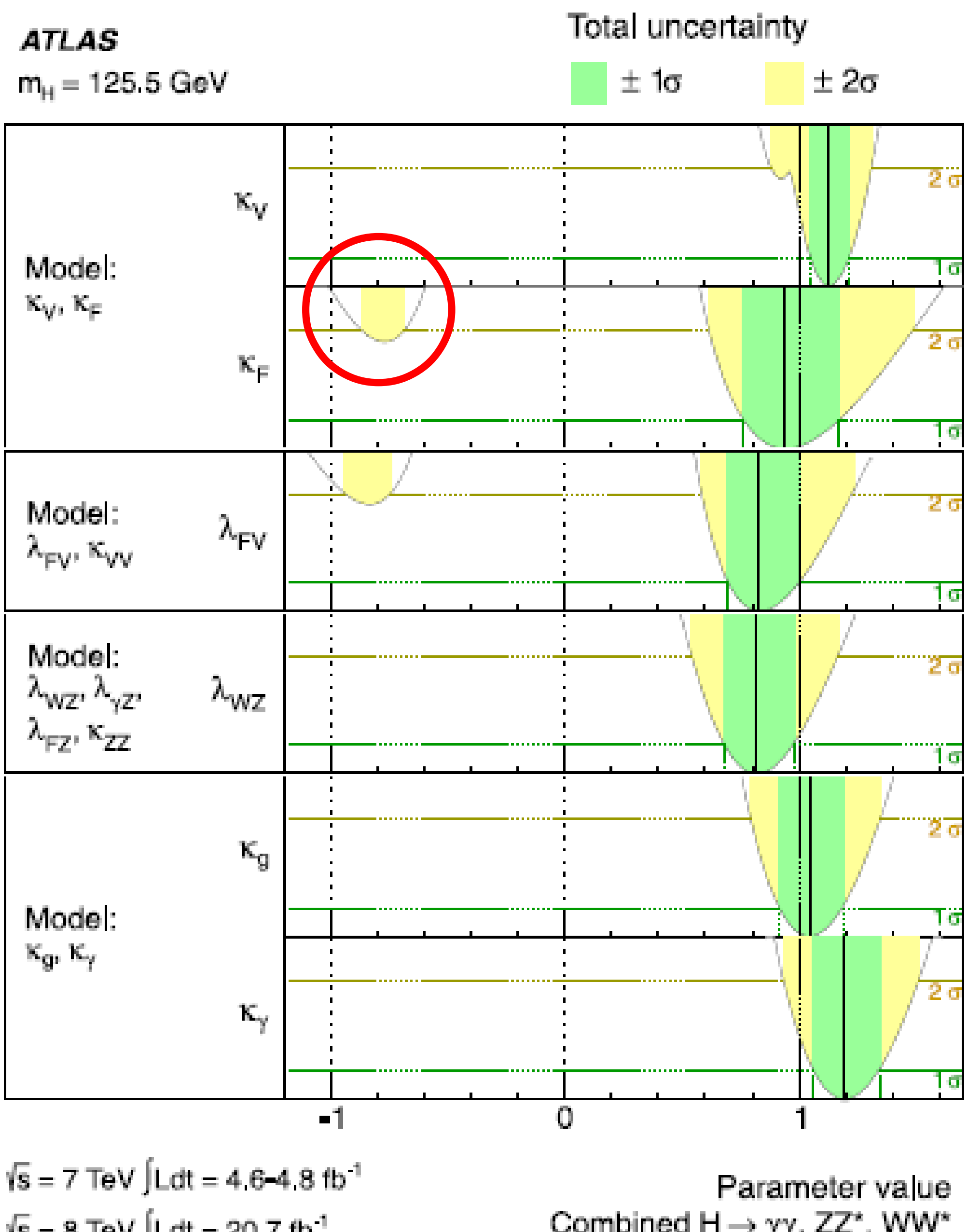
Motivation: a tale of two minima

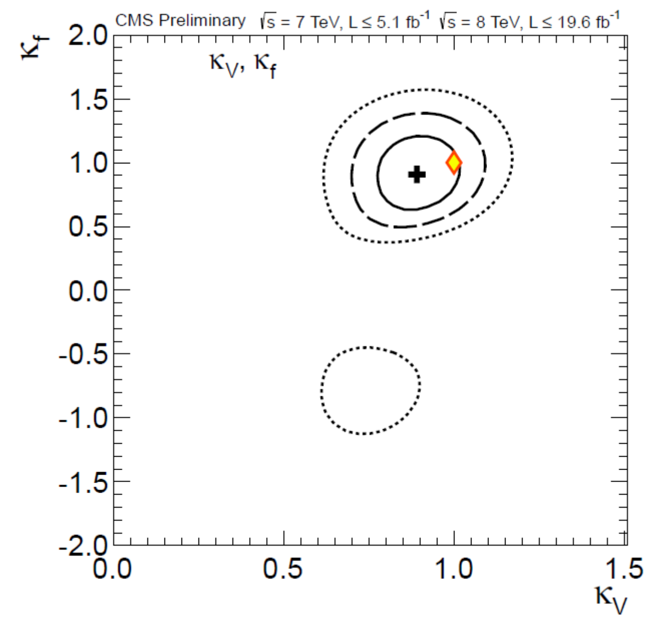


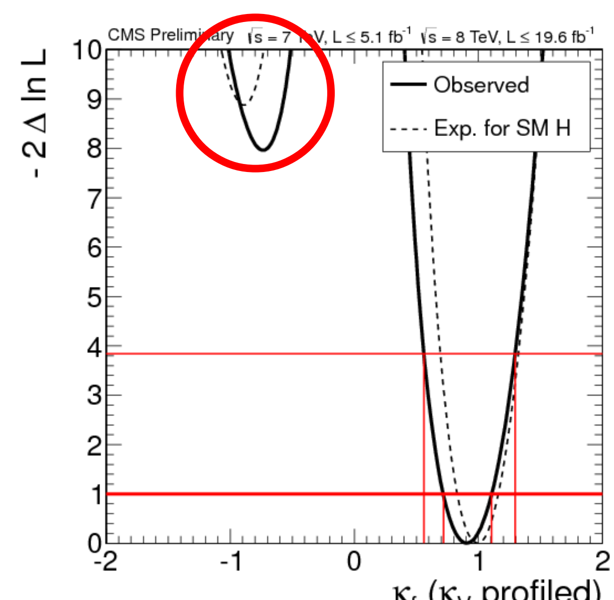


- Scale factors k_V, k_F multiplying the SM Higgs couplings to bosons and fermions, assuming no new particles
- Data disfavour the "wrong" minimum
  - Sensitivity to sign(Htt)*sign(HWW) comes only from H(125)→γγ

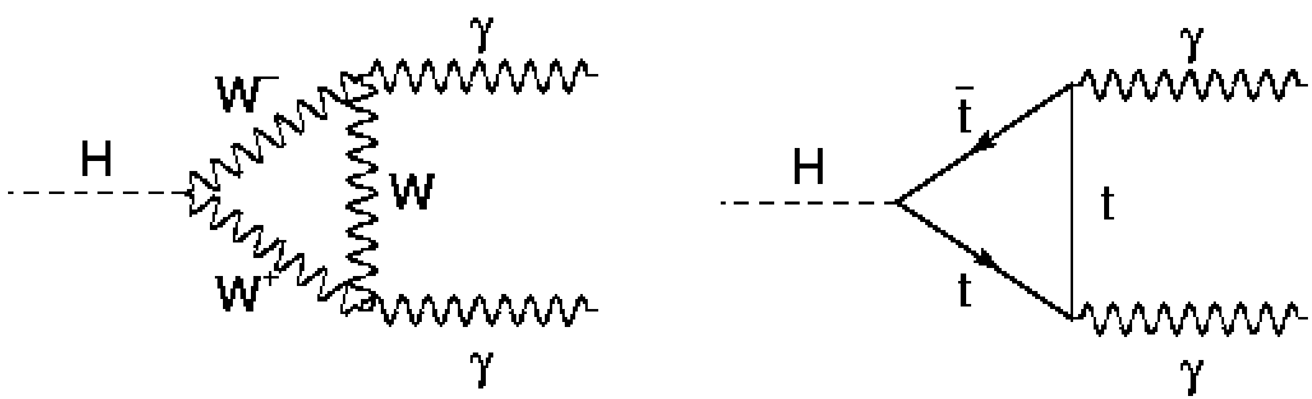
Motivation: a tale of two minima







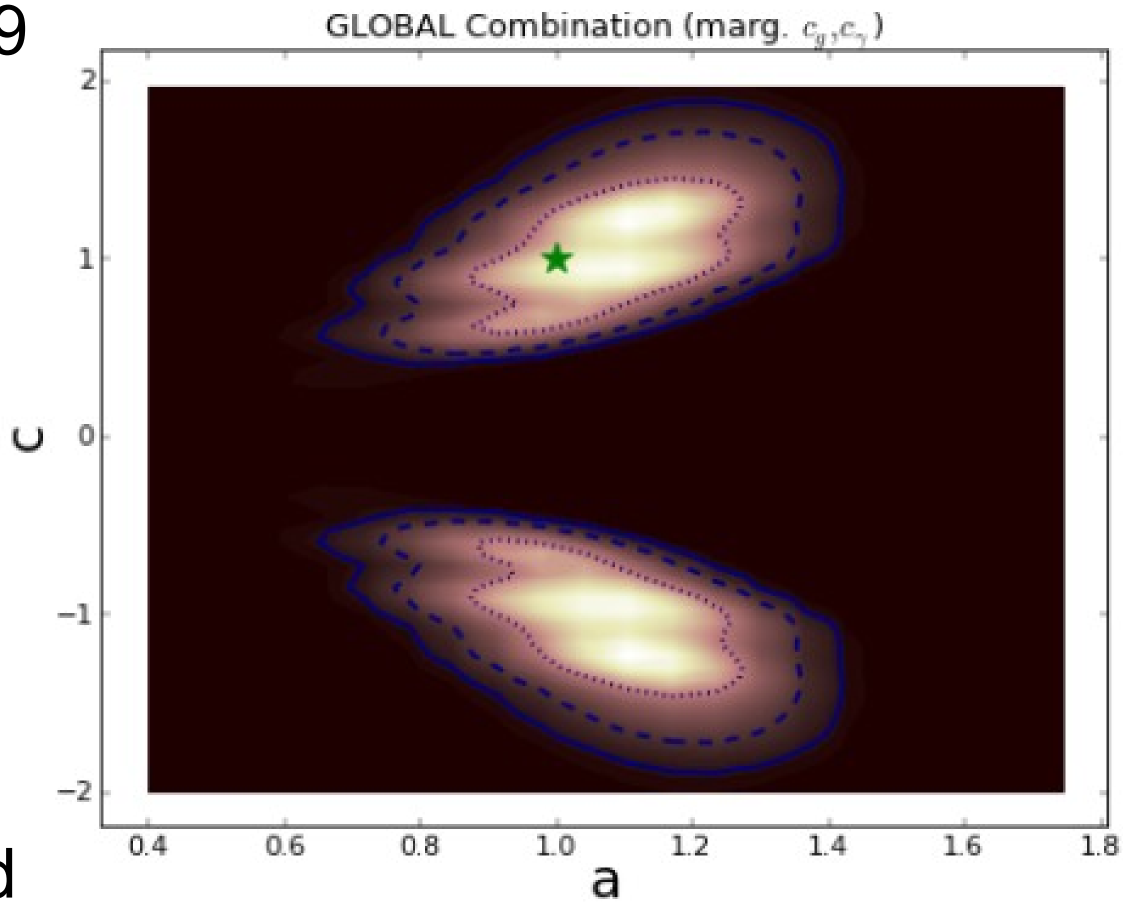
From where this sensitivity to the sign is coming from



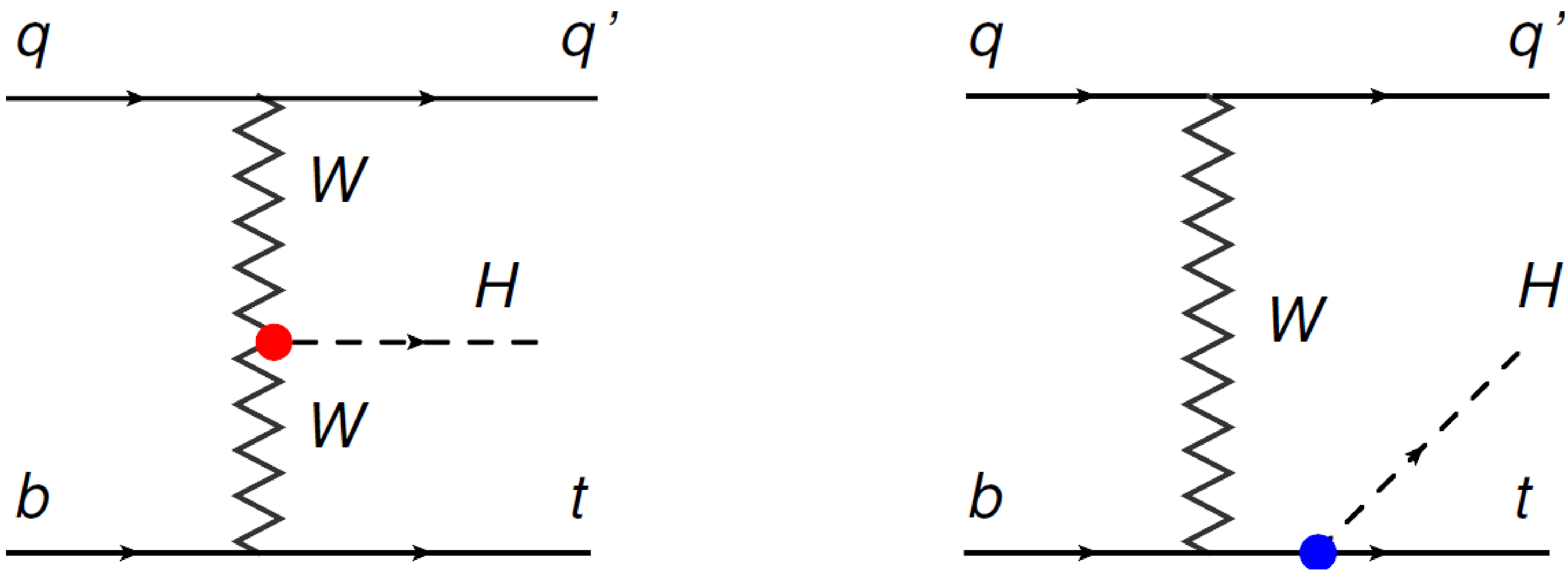
- Opposite sign amplitudes in the SM
  - Hence partial cancellation
- Switch the relative sign between y_t and g_{HWW} and you get constructive interference
  - It results in a ~2x enhancement in this branching ratio
  - No effect on ggF, VBF, VH, $t\bar{t}H$ cross sections

Disfavoured?

- J.Ellis, T.You, JHEP 06 (2013) 103, arXiv:1303.3879
- Combination of CMS, ATLAS, and Tevatron (still quite up to date)
- Here *a,c* have similar meaning as k_V, k_F
- In the plot reproduced here, BSM contributions are allowed in ggH and Hγγ loops and marginalised, and **the minima are degenerate**



Looking for a better "interferometer"



- In tHq production, accidentally strong cancellation between the LO diagrams in the SM (only 18 fb @ 8 TeV)
- Therefore, strong enhancement (~13x) if the relative sign between HWW and Htt couplings turns out to be negative

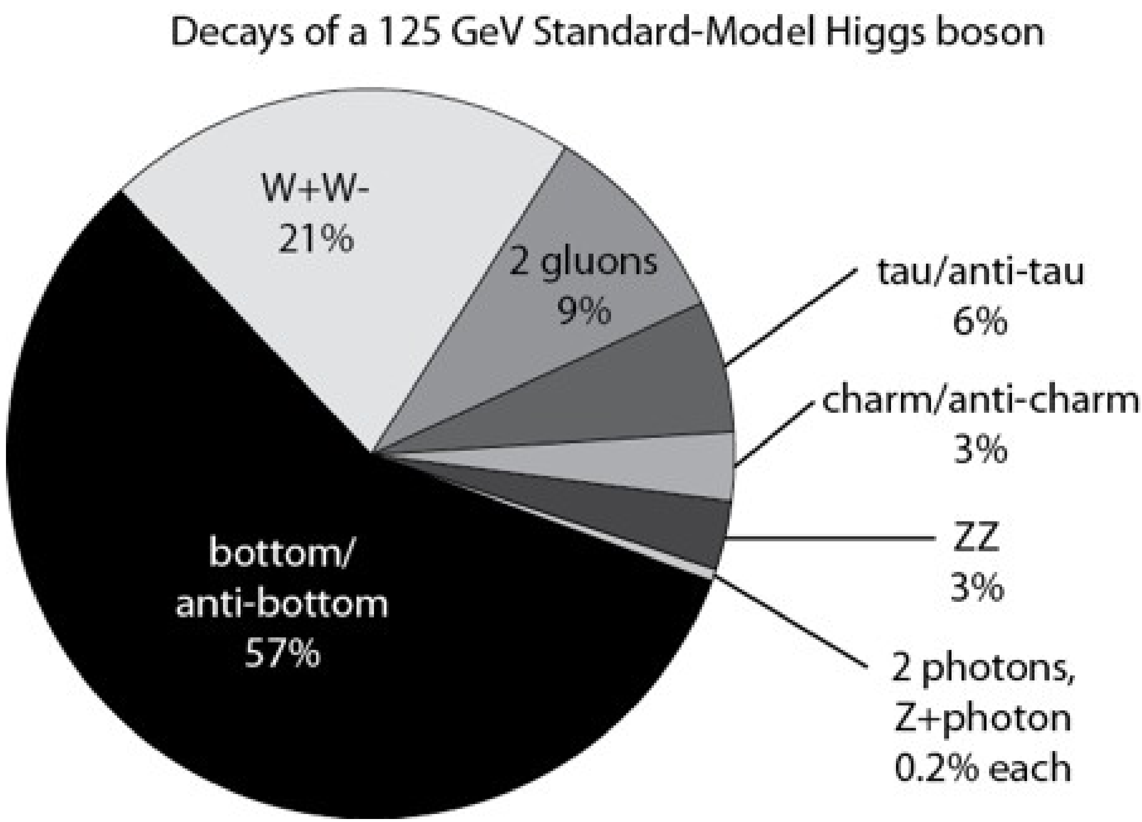
What we are looking for

- We call our signal model the tHq production with $y_t \sim -1$
  - Strawman model where all the rest of the SM parameters are still valid; not a realistic model, because something new must explain this weird sign
    - But useful to get a well defined prediction
    - A complete model may change numbers a bit, but switching sign is what makes the difference at first order
- Goals
  - In the short term (existing 8 TeV data set): set the first limits on signals in this final state
  - In the long term (Run II): strive to get enough sensitivity to conclusively discover or exclude the *"SM with y_t=-1"* model
  - Very long term: get sensitivity all the way down to SM x-sec.

Analyses in CMS

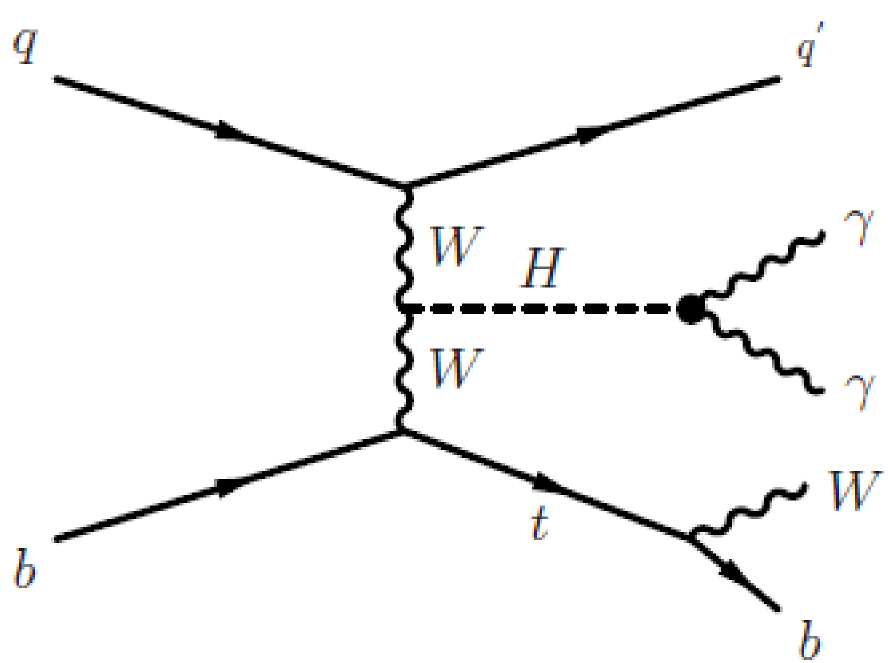
- CMS-HIG-14-001: **$H\to\gamma\gamma$**
  - BR = 0.2% in SM, but would ~ double if our signal is true
  - Very clean signature
- CMS-HIG-14-015 (public soon): **$H\to b\bar{b}$**
  - BR = 56-58% in SM, not much affected in principle
  - Very unclean signature (dominated by $t\bar{t}$ background), and very messy combinatorics
  - I will just sketch some analysis elements, not the results
- Both use the leptonic decay of the top (BR~2/9)
- The background from $t\bar{t}H$ is not negligible
  - Implication on what you call signal and background in the $\gamma\gamma$ analysis: if our model is true, other Higgs modes grow too

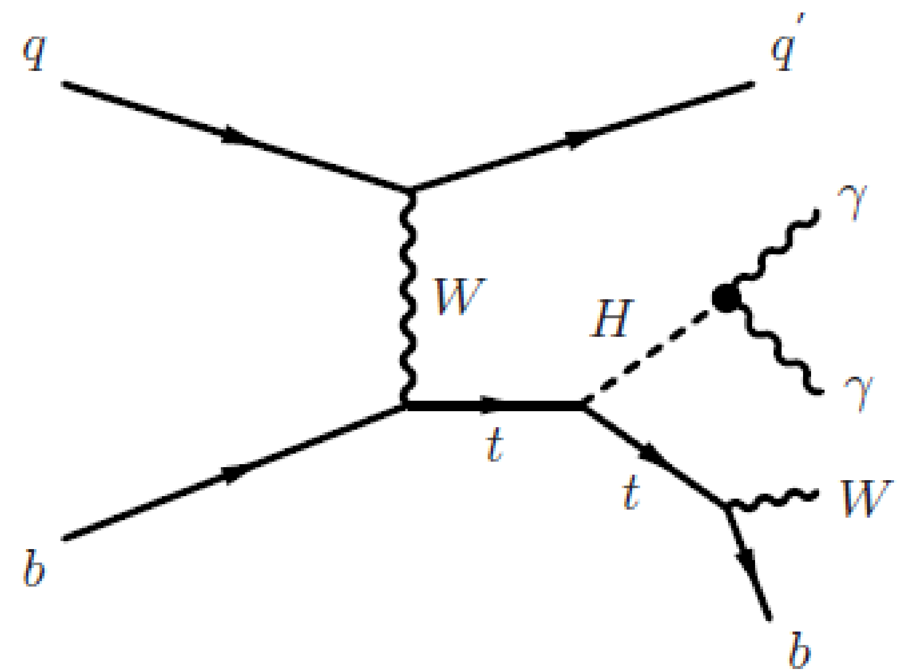
About branching ratios



- We are assuming that these BR's only need to be corrected for the photon channel enhancement
- Strong assumption but supported by direct measurements

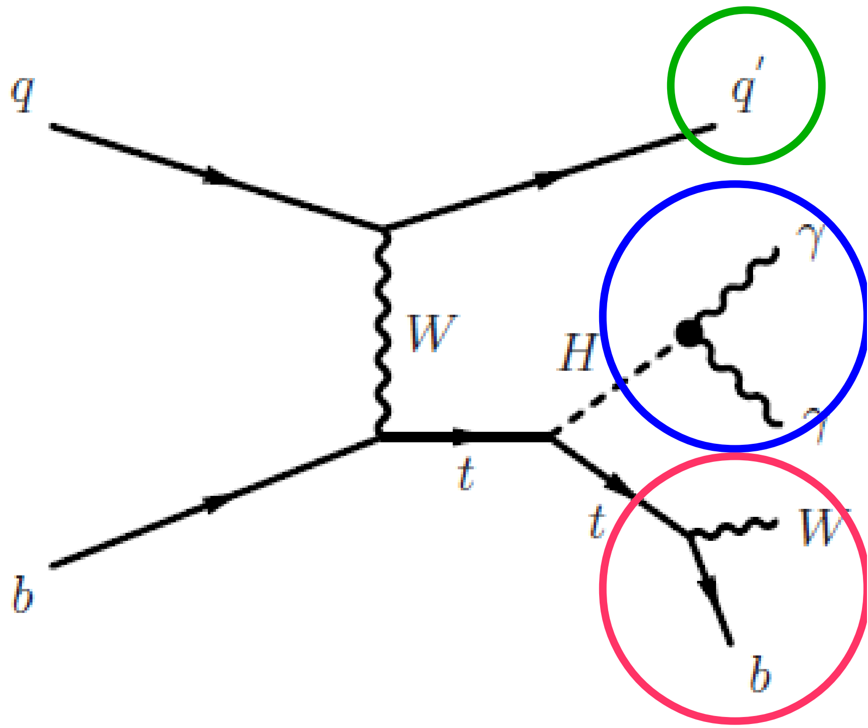
H→γγ analysis, CMS-HIG-14-001





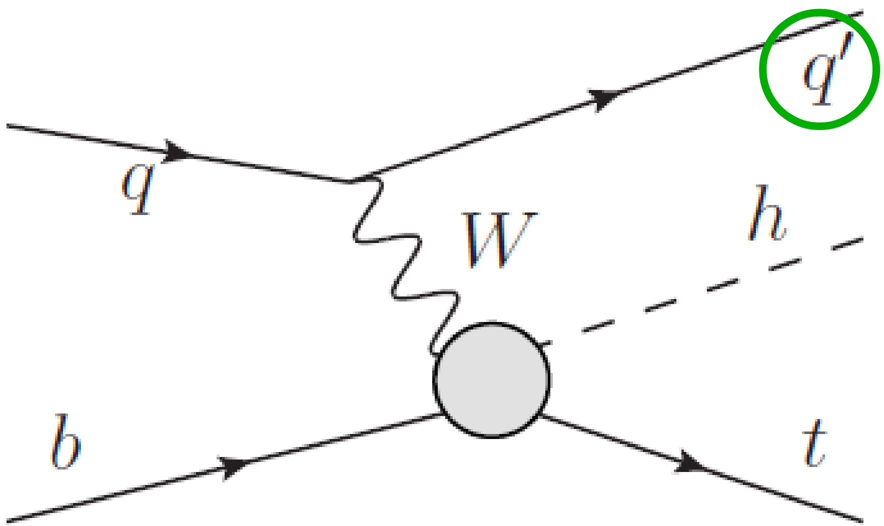
Event pre-selection

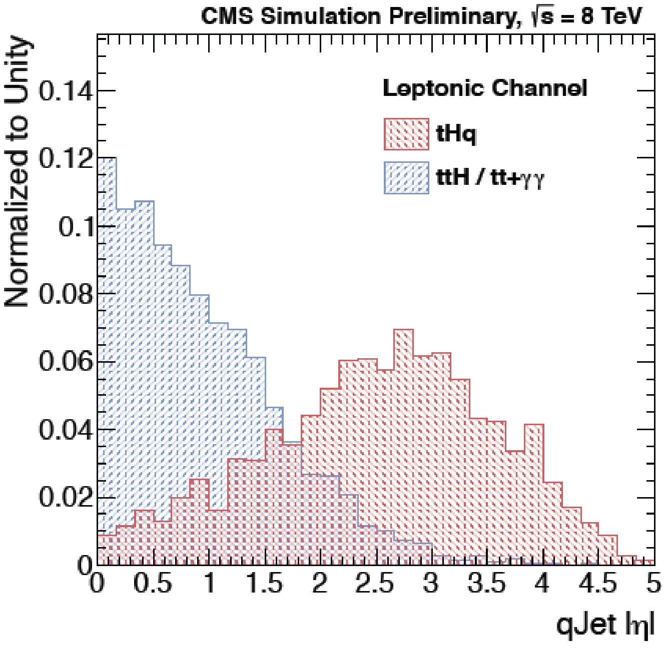
- Di-photon trigger
- Leading photon: $p_T > 50*m_{\gamma\gamma}/120$ GeV
- Sub-leading photon: $p_T > 25$ GeV
- Exactly 1 lepton (e/μ), $p_T > 10$ GeV
- At least 2 jets, $p_T > 20$ GeV
- At least one passes a tight b tagging
- The hardest non-b-tagged jet has $|\eta|>1$



H(125) selection – Top selection – specific of tHq

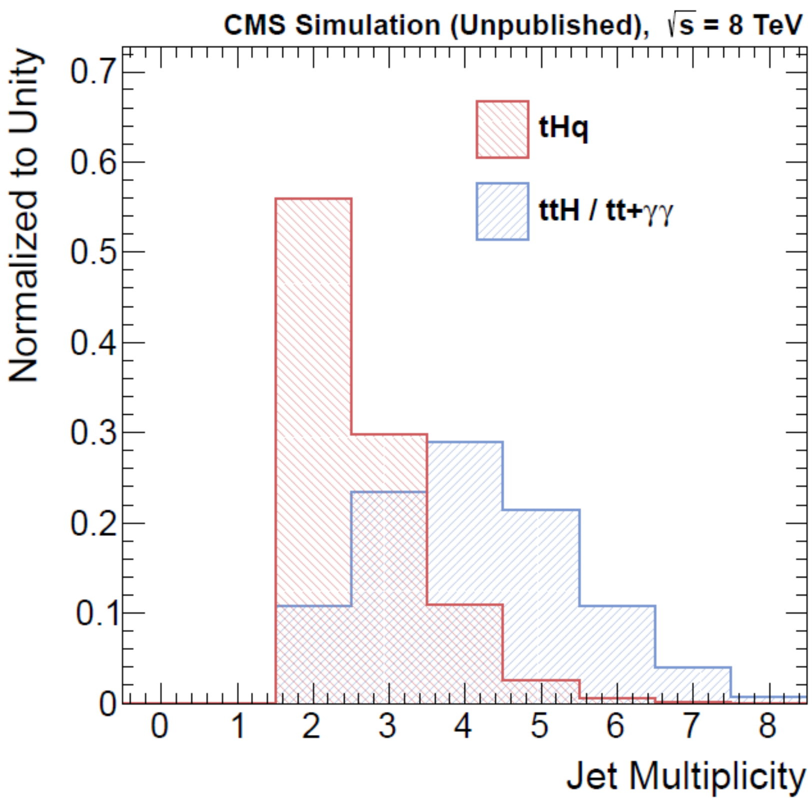
Robust discriminators

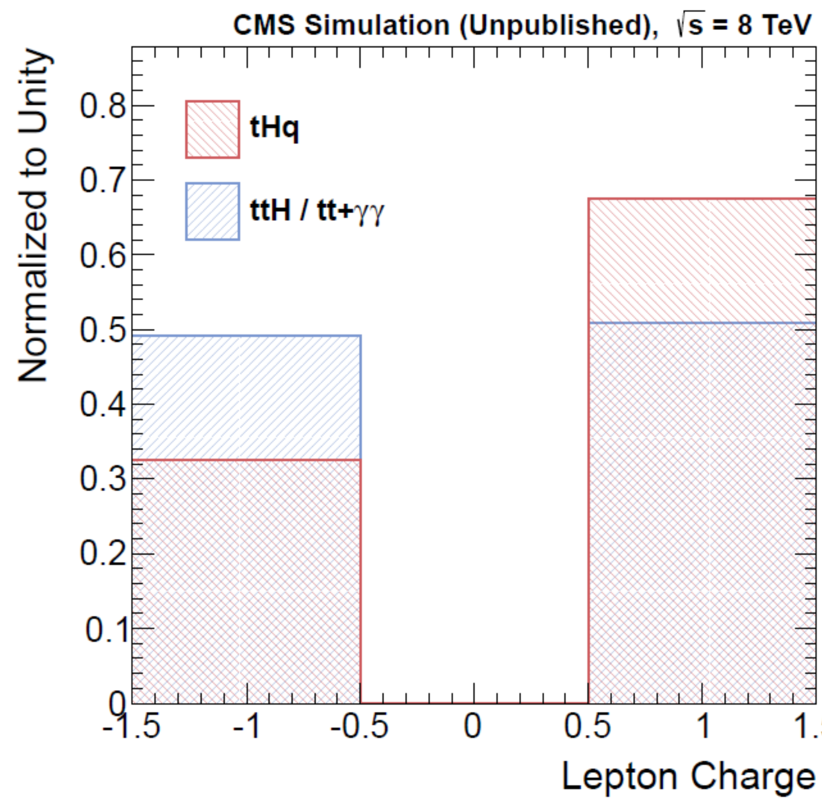




The recoil quark, which gives the only light jet in the event, has a rather characteristic pseudorapidity distribution.
This is dictated by mere kinematics (it depends on the PDF and on the mass of the system it is recoiling against) and it is, therefore, a rather robust prediction of any suitable model.
Similar considerations apply to the next variables, which are all arguably independent of the top-Higgs coupling

Other discriminating variables (after $|\eta|>1$)

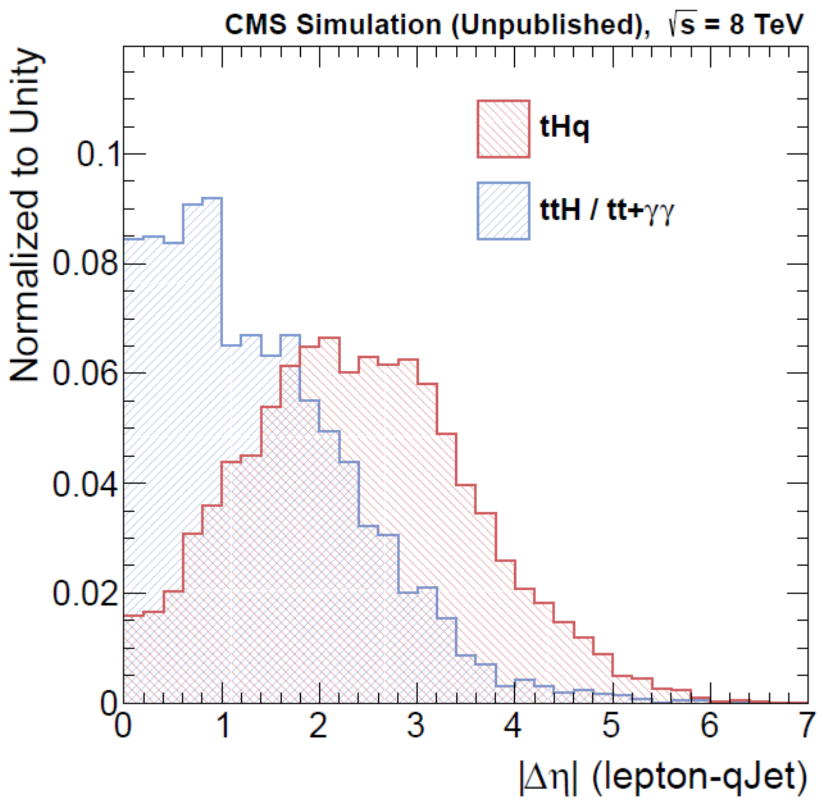


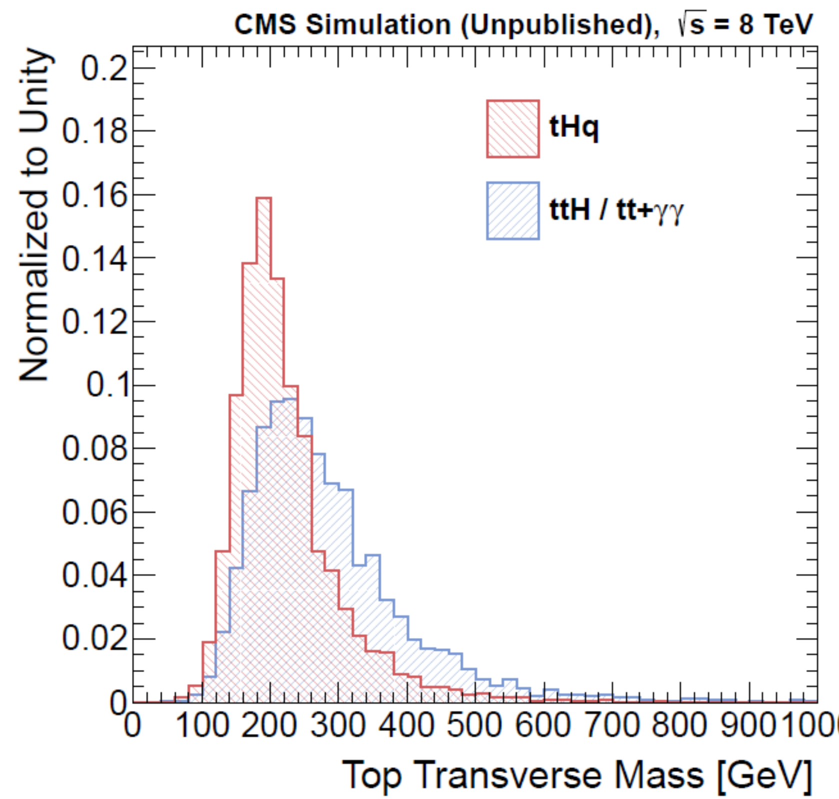


Signal has less jets than $t\bar{t}$+photons and $t\bar{t}H$

No charge symmetry: more up than down, hence $\sigma(tHd) > \sigma(\bar{t}Hu)$

Other discriminating variables (after $|\eta|>1$)

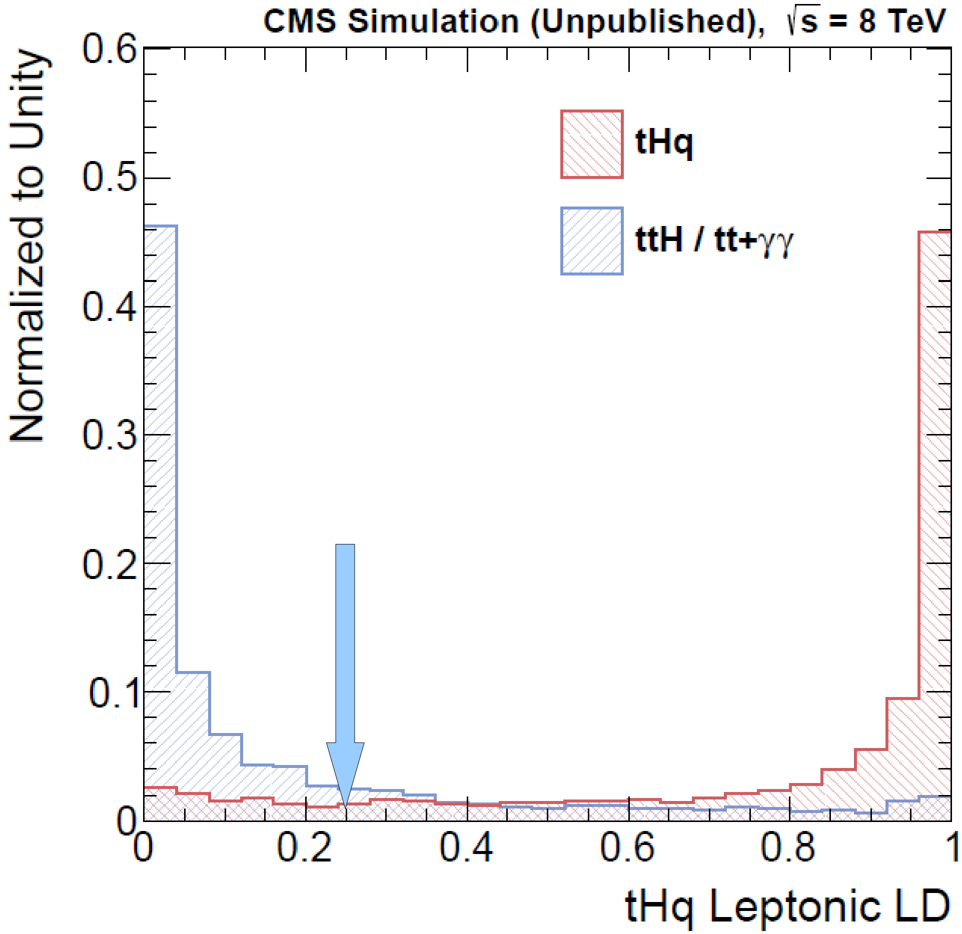




Lepton and light jet tend to have small $|\Delta\eta|$ if coming both from top decay, large if the jet is from recoil

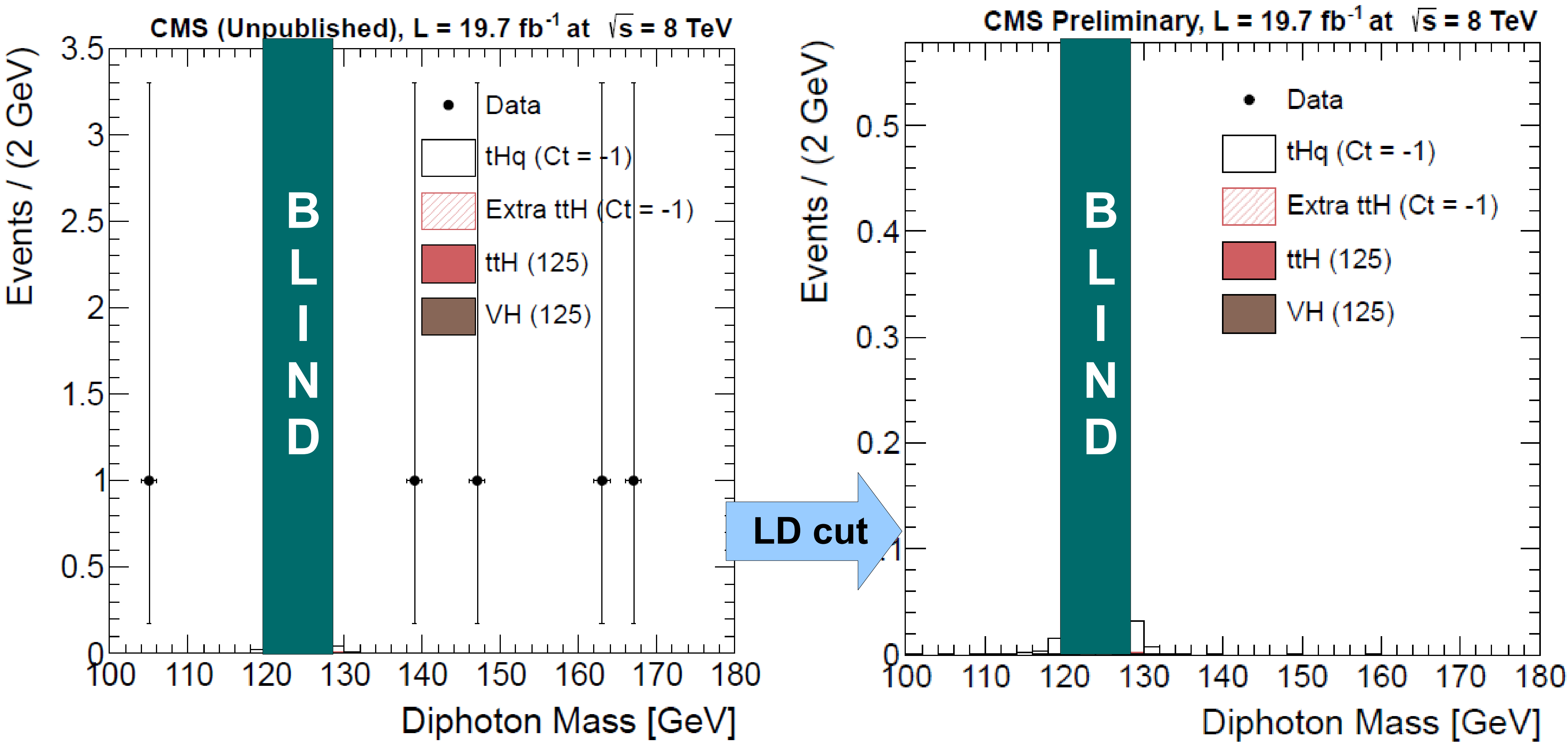
Top transverse mass distribution (from l, b, MET) broader if there are two tops

Likelihood discriminant (LD)



All previous variables are combined in this discriminant.
Cut chosen in MC, before looking at any data, to give
#($t\bar{t}H$)/#(tHq) < 10% @ y_t=-1

A bit of suspence...



Five events in the sidebands before LD cut, none left after!
Unusual for hadron colliders, more typical of ν and DM experiments; how to estimate the non-resonant bkg?

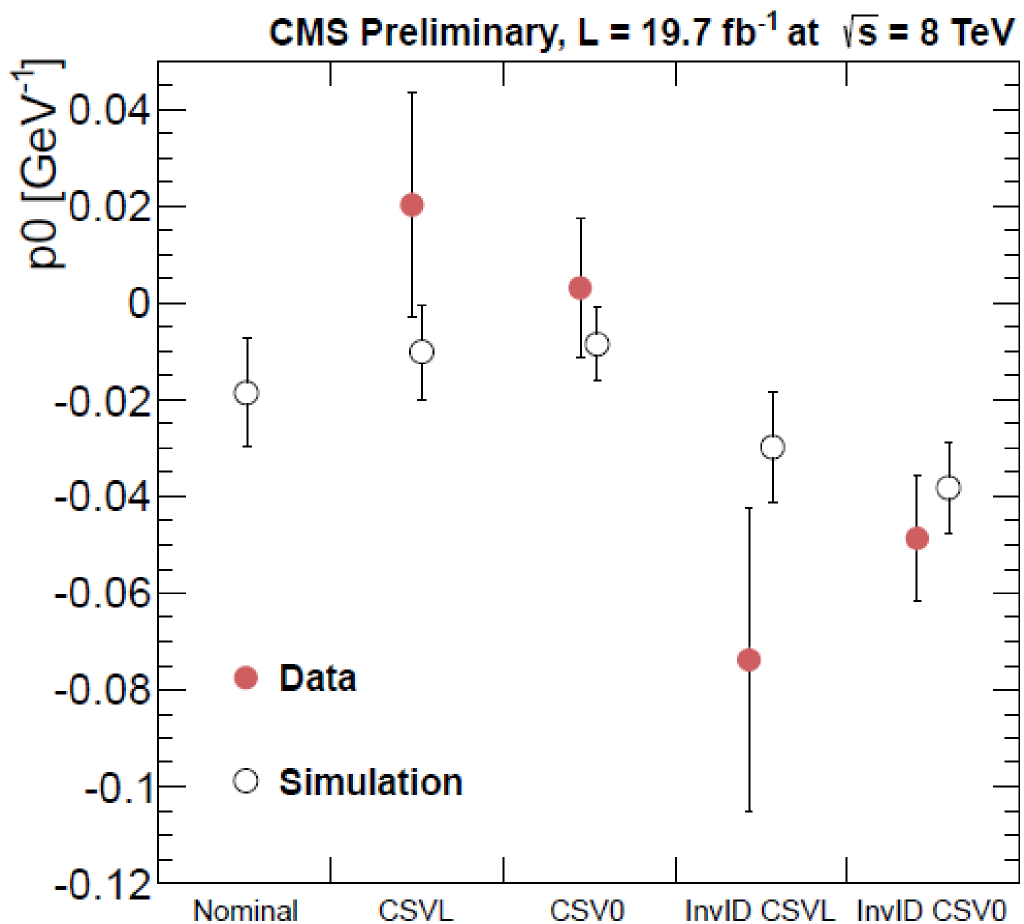
Non-resonant background estimation from data

- Interpolate from sidebands to signal window ([122,128] GeV) via a multiplicative factor α, assuming a $m_{\gamma\gamma}$ shape f_{bg}

$$\alpha = \frac{\int_{signal\ region} f_{bg}(x)\mathrm{d}x}{\int_{sideband\ region} f_{bg}(x)\mathrm{d}x}$$

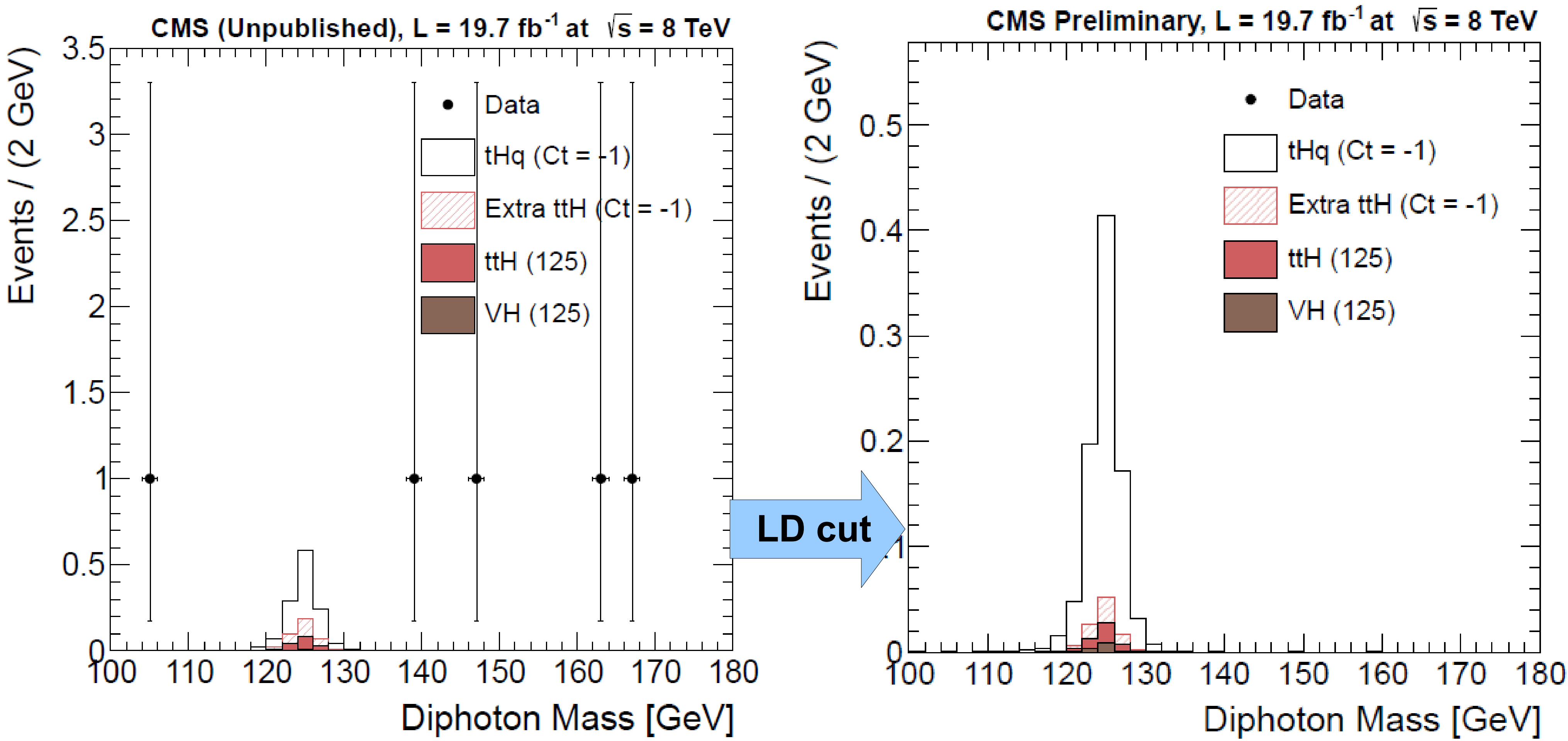
- f_{bg} from exponential fit in 4 (non-empty) control regions:
  - *CSVL*: same as signal region, but loose < b-tagging < tight
  - *CSV0*: looser b-tagging than *CSVL* (note: is a superset of it)
  - *InvID CSVx*: same as *CSVx*, but with inverted ID criteria on one of the two photons; orthogonal to *CSVx*; reweighted to correct for a kinematic bias coming from ID inversion

Non-resonant background estimation from data



Fair stability of the slope of the fitted exponential.
Maximum difference on α is 16%, taken as systematic

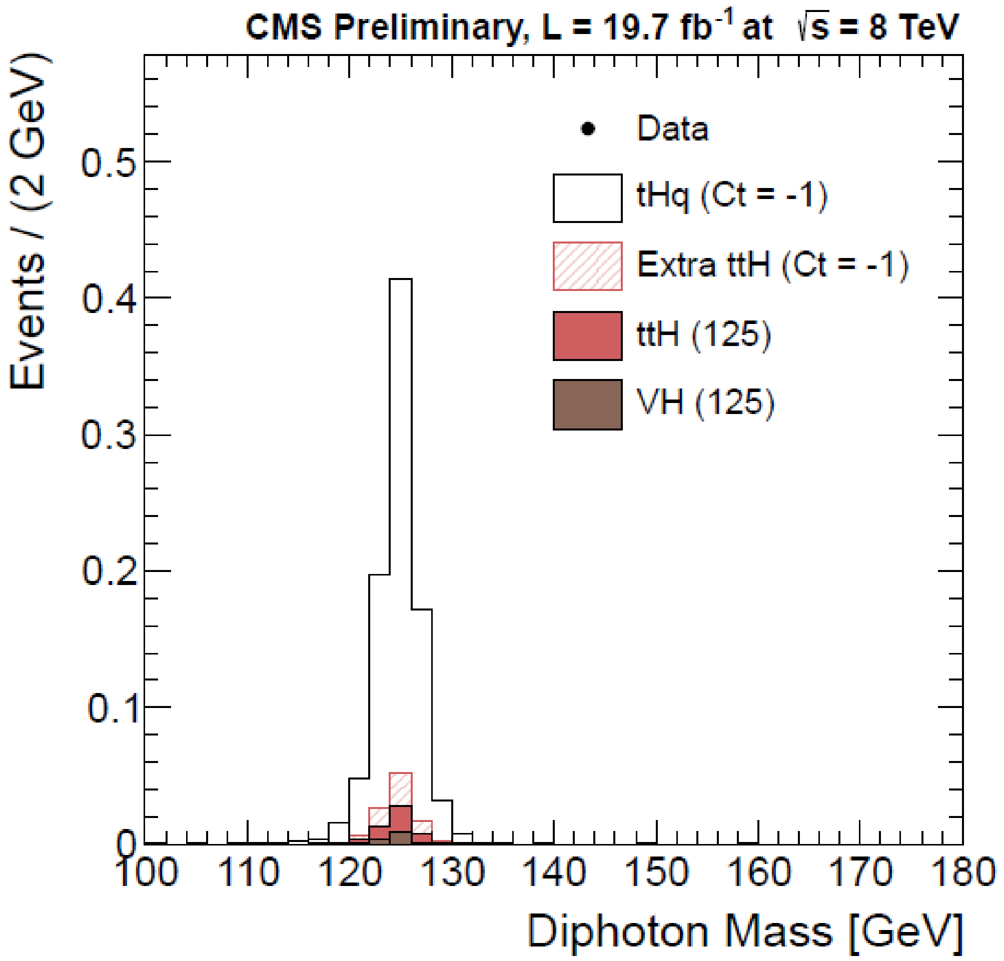
Now let's unblind



No event in signal window

Event yield

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



The extra $t\bar{t}$H and VH (†) are accounted as part of signal.
Yields are counted in [122, 128] GeV.
Less than 1 event expected even in the y_t=-1 hypothesis

Systematics

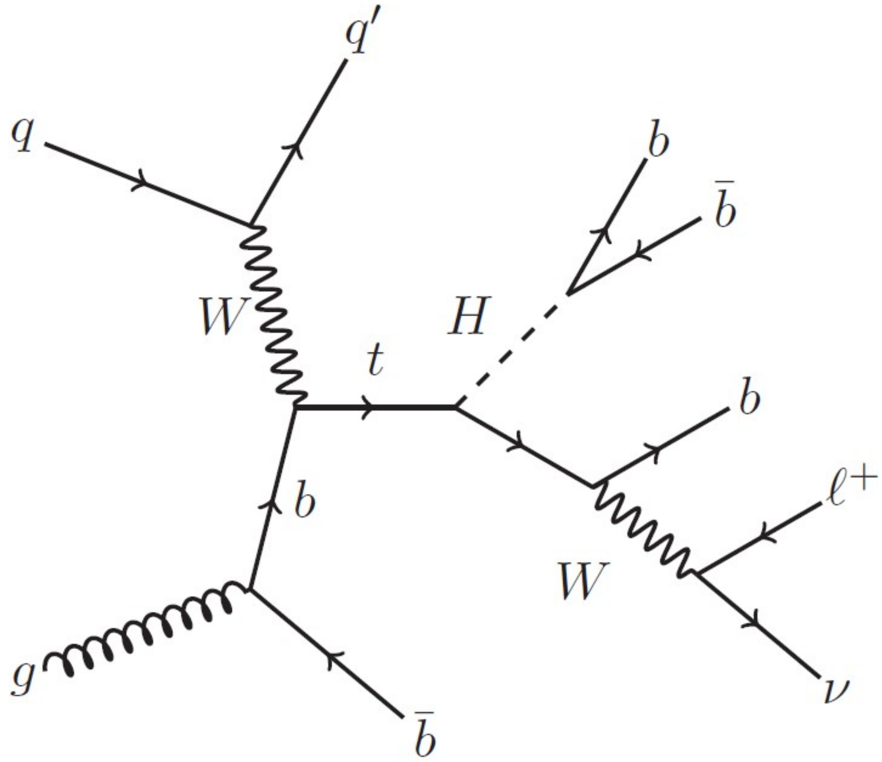
	tHq	$t\bar{t}H$	VH	Continuous BG
Luminosity	$\pm 2.6\%$	$\pm 2.6\%$	$\pm 2.6\%$	-
PDF	+3.1/-2.5 %	$\pm 8\%$	$\pm 11\%$	-
QCD Scale	+4.8/-4.3 %	+11/-14 %	$\pm 2.3\%$	-
Signal Model **(*)**	$\pm 5.5\%$	-	-	-
Photon Energy Resolution	+4/-2 %	+4/-2 %	+4/-2 %	-
Photon Energy Scale	+1/-4 %	+1/-4 %	+1/-4 %	-
Photon ID Efficiency	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$	-
Vertex Efficiency	$\pm 0.1\%$	$\pm 0.1\%$	$\pm 0.1\%$	-
HLT	$< 0.1\%$	$< 0.1\%$	$< 0.1\%$	-
JEC	$\pm 1.5\%$	+3/-5 %	$\pm 8\%$	-
JER	$\pm 0.5\%$	$\pm 3\%$	+8/-0 %	-
b-tagging	$\pm 2\%$	$\pm 1.5\%$	$\pm 0.1\%$	-
PU ID	$\pm 2\%$	$\pm 0.5\%$	$\pm 2\%$	-
Lepton Reconstruction	$\pm 1\%$	$\pm 1\%$	$\pm 1\%$	-
BG shape	-	-	-	33%

(*) In this context it means 4-flavor vs 5-flavor scheme

Result

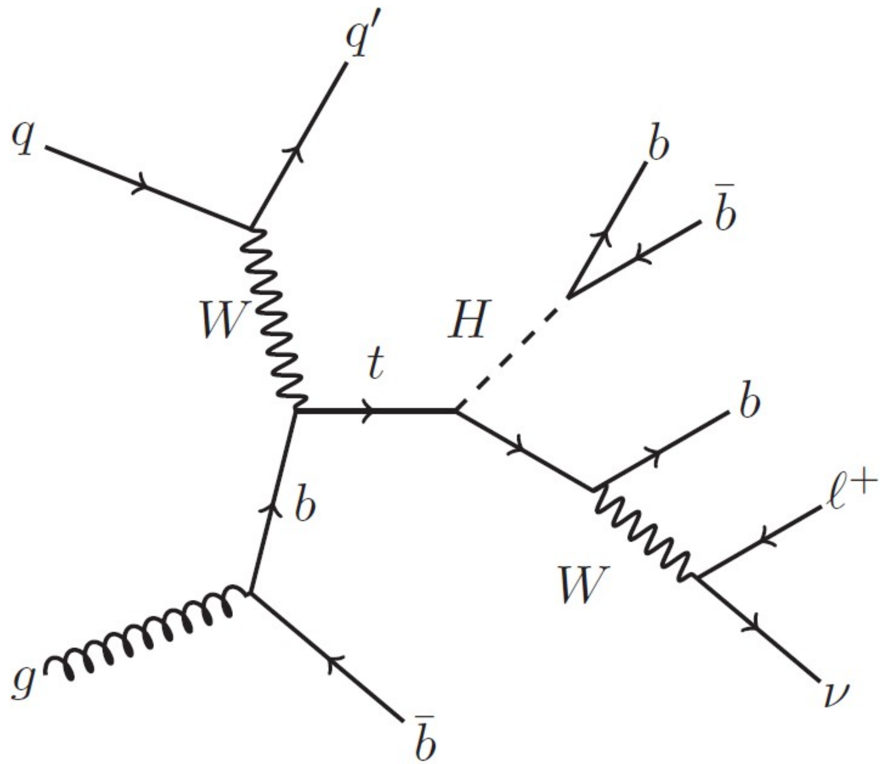
- Combined Frequentist-Bayesian method
- Upper limit @ 95%CL: σ_{prod} < 74 fb
  - (Expected and observed limit coincide)
- Nice, but still 4.1 times the expectation for the *"SM with y_t=-1"* hypothesis
- Hungry for more data...

H→b$\bar{b}$ analysis, HIG-14-015



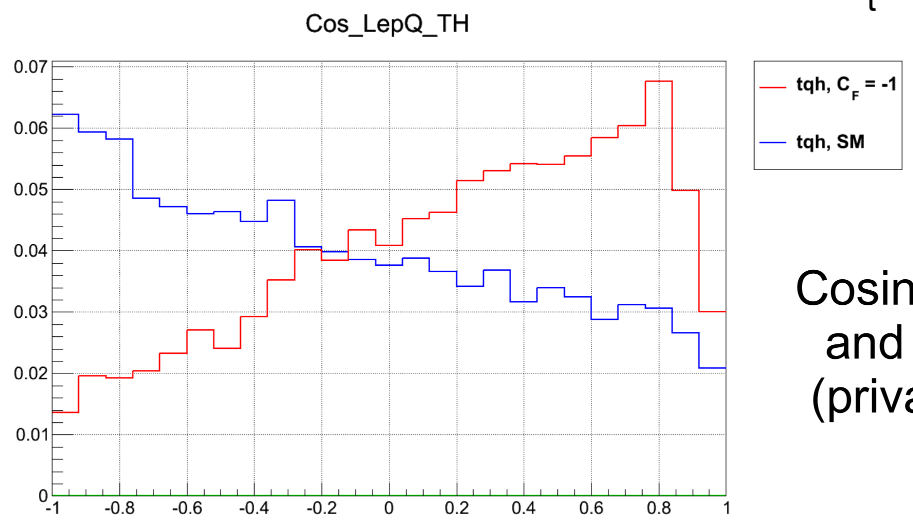
Baseline event selection

- Single-lepton trigger
- Tight muon/electron, $p_T > 26/30$ GeV
  - Veto additional loose leptons
  - MET > 35/45 GeV
- At least 4 jets with $p_T > 30$ GeV
  - But we consider all jets above 20
  - Jets in $|\eta|>2.5$: $p_T > 40$ GeV
- At least one jet must **fail** b tagging
- From this point on, we classify events by number of tags (3T, 4T)



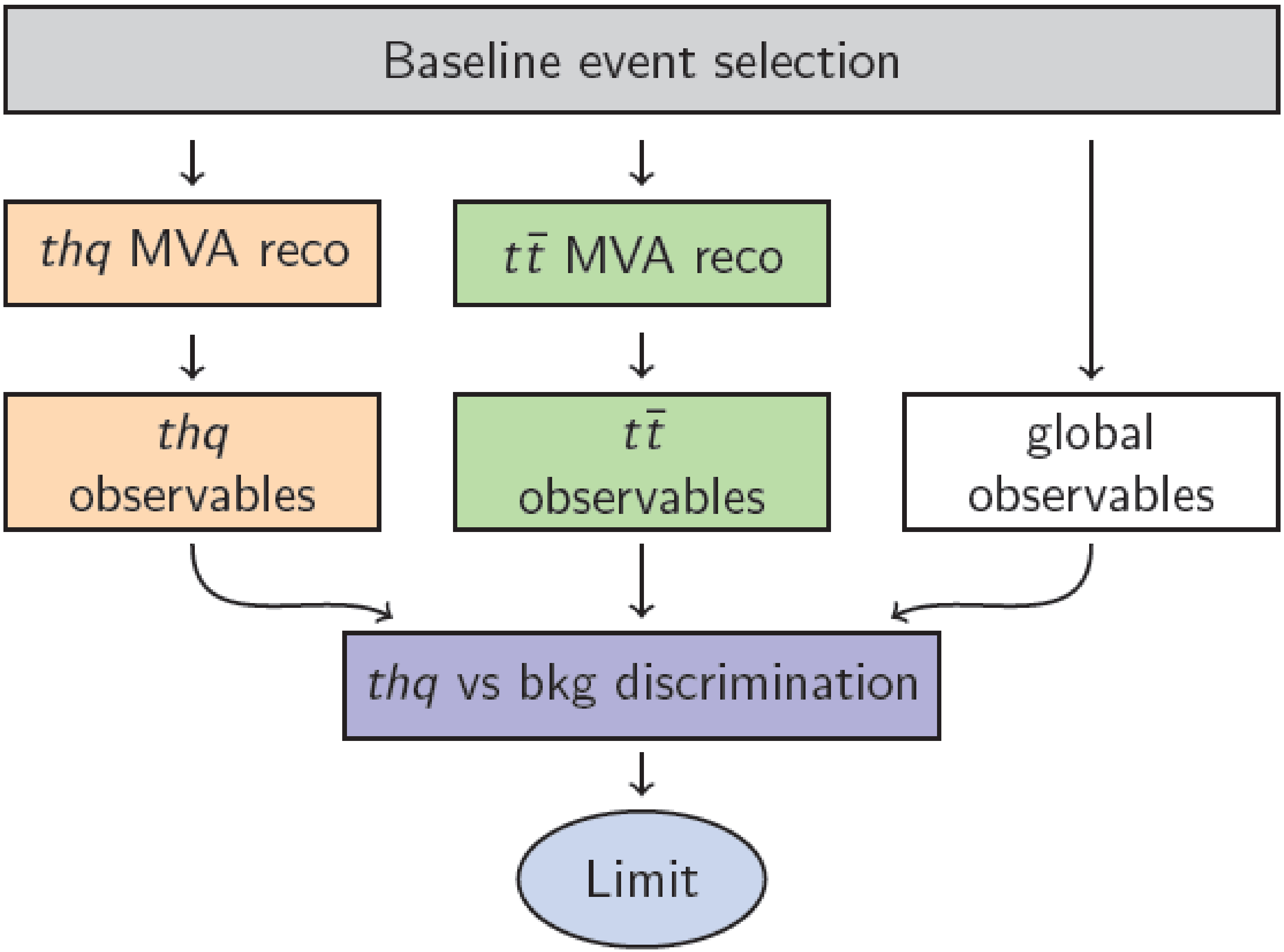
Designing our MVA analysis

- Technically, we choose a Neural Network
  - BDT proven to be equivalent, Likelihood discriminant sub-optimal because of large correlations between the inputs we consider
- Some powerful discriminating variables (mostly angles) depend on degree of interference, hence on y_t
  - Choicee between optimizing for most "discoverable" case ($y_t \sim -1$) or keeping MVA y_t-independent (as the $\gamma\gamma$ analysis)
  - y_t-independent MVA is not optimal for any y_t

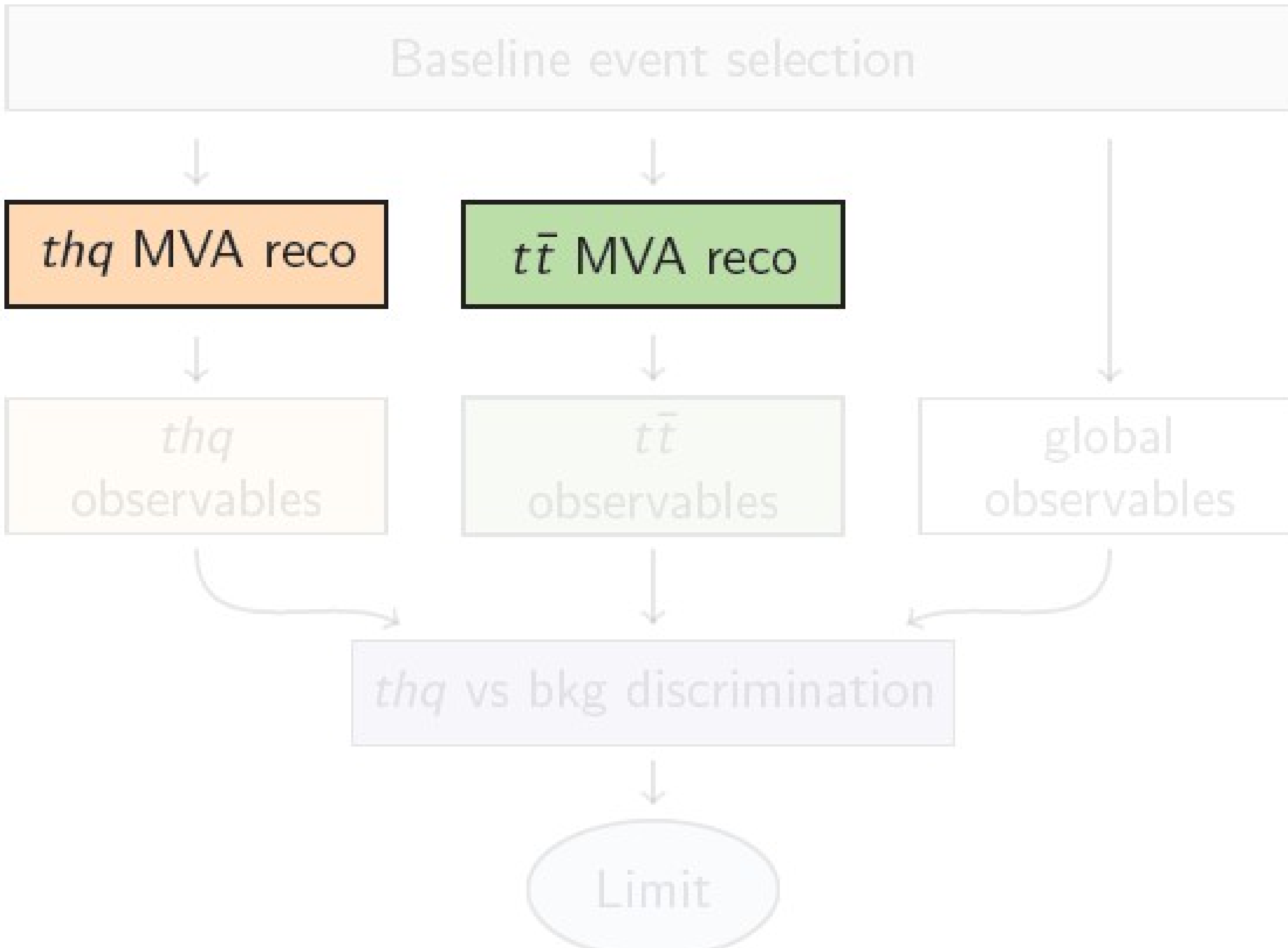


Cosine of the angle between l and q in the t+H rest frame (private generator-level plot)

Strategy


Baseline event selection
thq MVA reco
$t\bar{t}$ MVA reco
thq observables
$t\bar{t}$ observables
global observables
thq vs bkg discrimination
Limit

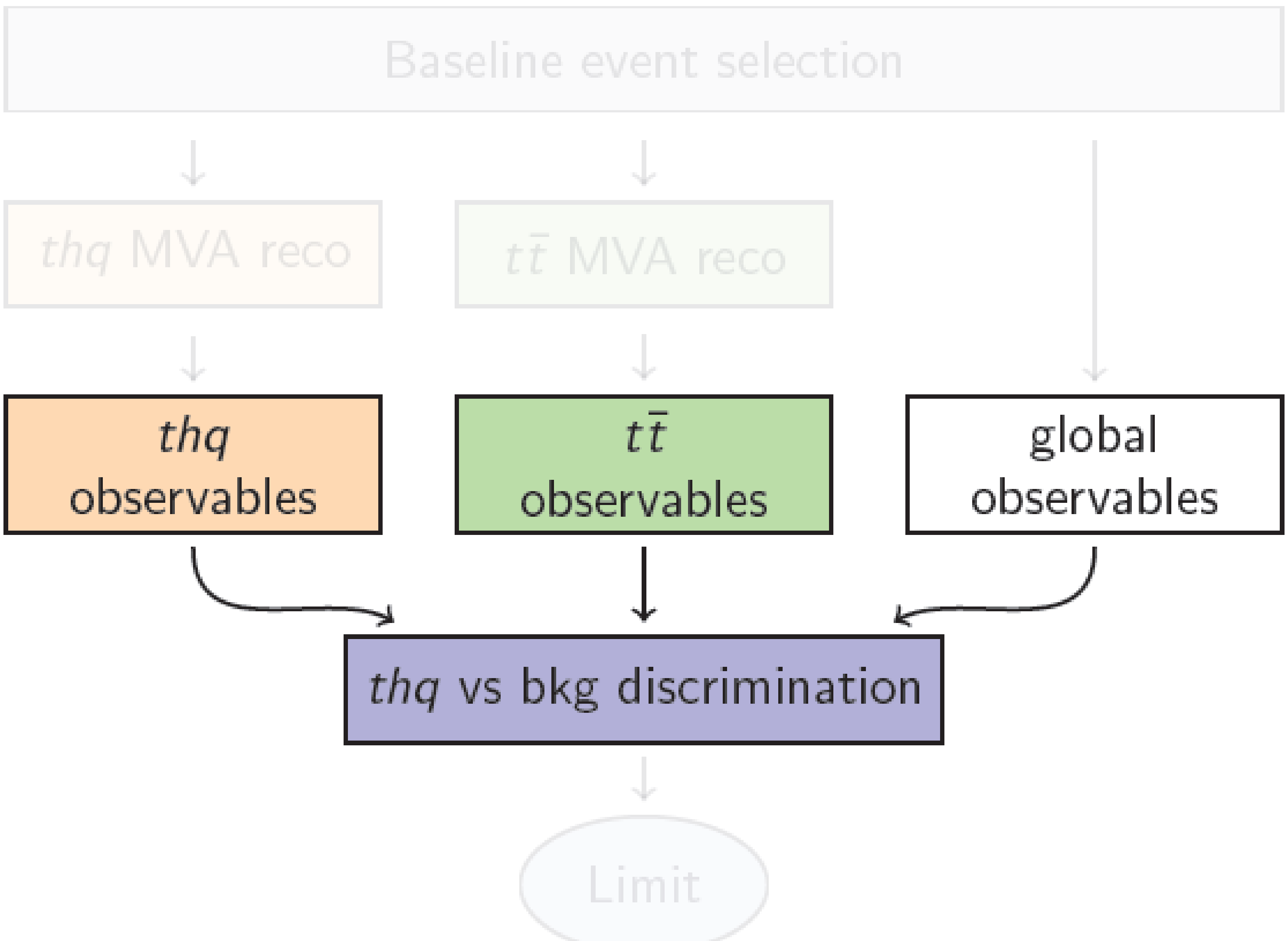
Event interpretations



Event interpretations

- Jets are associated to their originators (t_{lep}, t_{had}, H, q_{recoil}), in the "tHq hypothesis" and in the "$t\bar{t}$ hypothesis"
  - Goal is to be then able to define observables like "angle between H and t in the tHq hypothesis"
- NN trained to recognize the "best" combination
  - One combination per event treated as "signal" in the training, based on jet-parton matching ($\Delta R<0.3$)
  - At least one jet mismatched → "background"

Signal-vs-background MVA



Data-driven model for $t\bar{t}$

- MC modeling of $t\bar{t}$ in signal regions carries large uncertainties (m_F, m_R, JES) that swamp the signal
- Data-driven model has a different set of uncertainties
- We use 2T region and the known b-tagging efficiencies
- Event weights P_3/P_2 and P_4/P_2 calculated from:

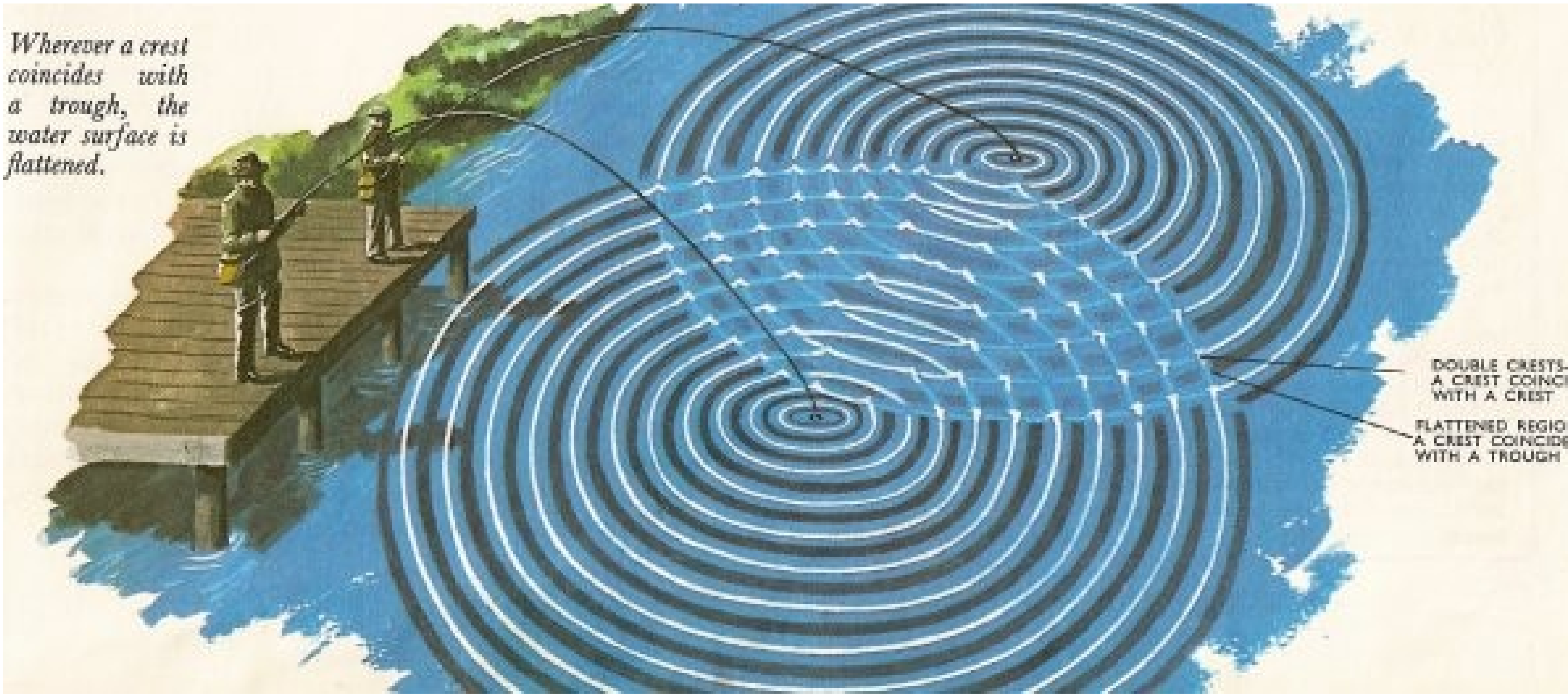
$$\mathcal{P}_m = \sum_{\text{comb}} \prod_{i=1}^{m} \epsilon(p_i, f_i) \cdot \prod_{j=m+1}^{n} (1 - \epsilon(p_j, f_j))$$

- This is the probability that an event with *n* jets with momentum p_i and flavour f_i has *m* of them b-tagged
- Here $\varepsilon(p,f)$ is the b-tagging efficiency and the sum is taken over all the possible ways to choose *m* tagged jets

Conclusions

- Study of tHq production can provide an unambiguous measurement of the relative sign of Htt and HWW couplings
- Started two analyses to search for tHq
  - Both very challenging, and quite complementary: rare & clean versus abundant & messy
  - The $H\rightarrow\gamma\gamma$ analysis is already public, $H\rightarrow b\bar{b}$ expected to be realeased very soon
  - Sensitivity still far from our strawman scenario, but Run-II is near and we have two well-oiled analyses ready to be unleashed over 13 TeV data

Thanks for your attention



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Francesco Pandolfi, Andrey Popov, Benedikt Maier, Christian Boser, Dan Knowlton, for outstanding analysis work

Pheno bibliography (only < 2 years)

- Biswas, Gabrielli, Mele, "Single top and Higgs associated production as a probe of the Htt coupling sign at the LHC", arXiv:1211.0499, JHEP 01 (2013) 088
- Farina, Grojean, Maltoni, Salvioni, Thamm, "Lifting degeneracies in Higgs couplings using single top production in association with a Higgs boson", arXiv:1211.3736
- Biswas, Gabrielli, Margaroli, Mele, "Direct constraints on the top-Higgs coupling from the 8 TeV LHC data", arXiv:1304.1822, JHEP 07 (2013) 073
- El Hedri, Fox, Wacker, "Exploring the dark side of the top Yukawa", arXiv:1311.6488
- Englert, Re, "Bounding the top Yukawa with Higgs-associated single-top production", arXiv:1402.0445, Phys. Rev. D 89, 073020 (2014)
- Ellis, Hwang, Sakurai, Takeuchi, "Disentangling Higgs-Top Couplings in Associated Production", arXiv:1312.5736
- Chang, Cheung, Lee, Lu, "Probing the Top-Yukawa Coupling in Associated Higgs production with a Single Top Quark", arXiv:1403.2053
- Greljo, Kamenik, Kopp, "Disentangling Flavor Violation in the Top-Higgs Sector at the LHC", arXiv:1404.1278
- Kobakhidze, Wu, Yue, "Anomalous Top-Higgs Couplings and Top Polarisation in Single Top and Higgs Associated Production at the LHC", arXiv:1406.1961

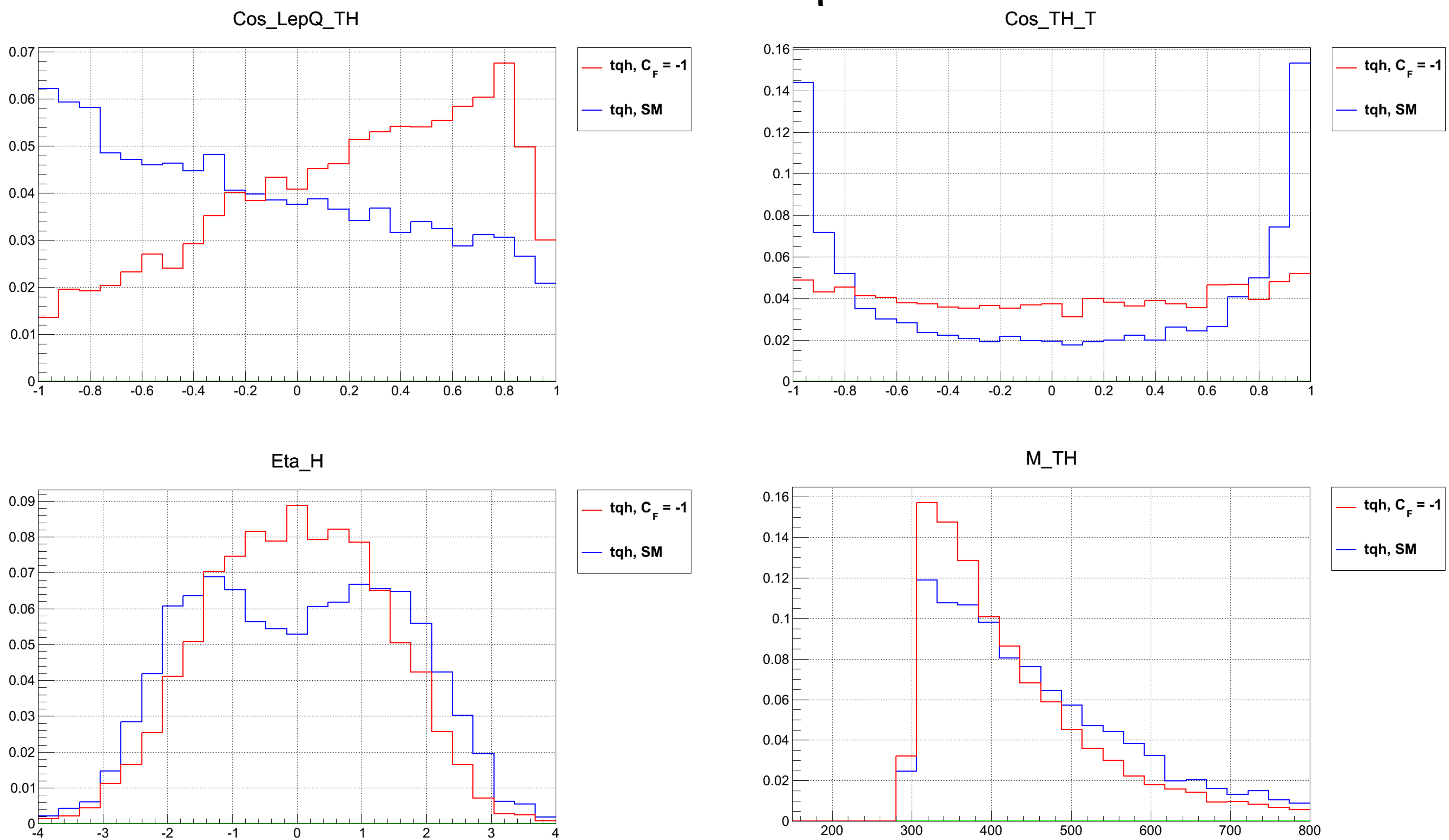
Any motivation for a "wrong sign"?

- Our ideology: let's not think too much of what kind of new physics can give a "wrong sign"
  - Just see which of the two minima survives, with sufficient data and minimum assumptions
- However, there are models that accomodate it:
  - S.El Hedri, P.J.Fox, J.G.Wacker, arXiv:1311.6488
    - "One possible scenario (...) is a Georgi-Machacek model (*) with one additional Higgs doublet. This model would predict a large number of new charged and neutral Higgses with sizable couplings to the top quark." (*) H.Georgi, M.Machacek, Nucl.Phys.B262, 463 (1985)
  - Ellis & You, JHEP 06 (2013) 103, arXiv:1303.3879
    - They mention an anti-dilaton model, defined as yielding the opposite of the dilaton model

Beyond the "binary analysis": limits as function of a parameter?

- Originally thought about limits as function of the relative phase between k_V and k_F
  - It makes sense if CP is not assumed
- Suggested to provide limits as function of k_F/k_V
  - Technically: by reweighting the events, rather than by the brute force approach of generating many MCs; there is even a routine in aMC@NLO that does that (although at LO)
  - Of course one should validate the reweighting versus the brute force method; e.g. one could just generate the y_t=-1 and +1 samples, reweight the -1 MC to the +1 case and compare to the +1 MC

Parton-level: y_t=-1 vs +1

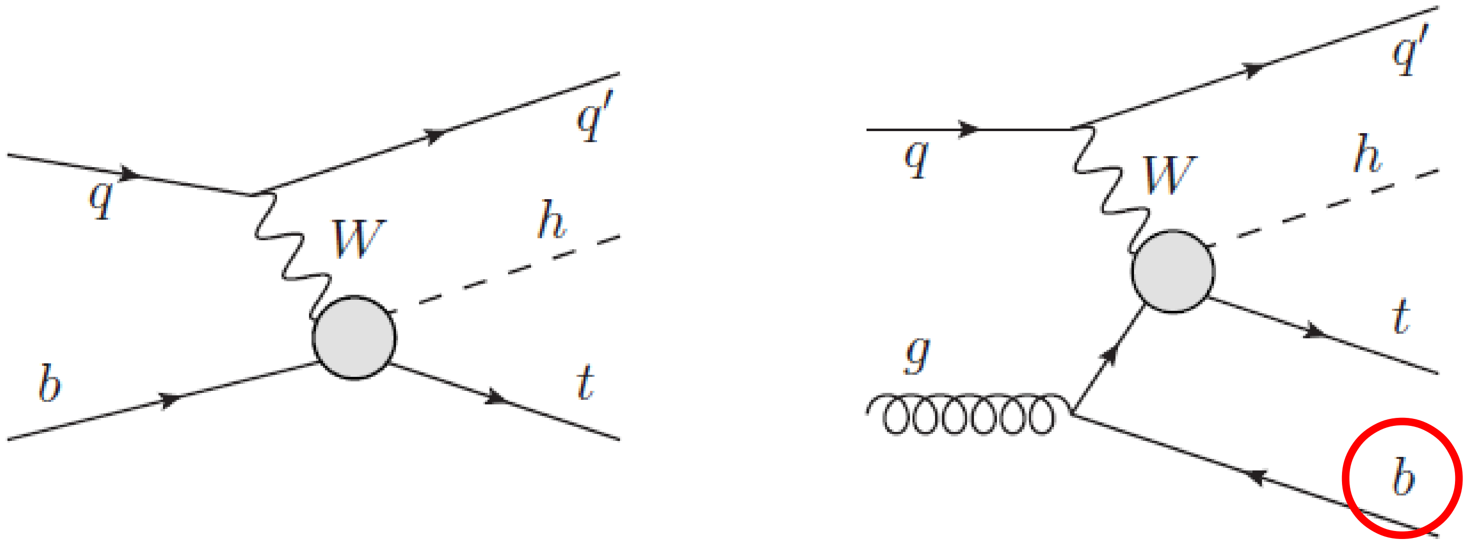


Conclusion: we cannot optimize a MVA for both at the same time

The pheno papers that motivated us to start these analyses

- Biswas, Gabrielli, Mele, arXiv:1211.0499, JHEP 01 (2013) 088
  - They propose to look at $H \to \gamma\gamma$ (interference also in decay) and hadronic top decay; topology: 2γ+4j(1b,1fwd)
  - Follow-up paper, arXiv:1304.1822, JHEP 07 (2013) 073, with the inclusion of the channels 2γ+1l+2j(1b,1fwd) and multi-lepton (WW,ZZ,$\tau\tau$)
- Farina, Grojean, Maltoni, et al., arXiv:1211.3736, JHEP 05 (2013) 022
  - They propose $H \to b\bar{b}$ (best branching ratio) and leptonic top decay; topology: 1l+4/5j(3/4b,1fwd)
  - My group (Louvain-Karlsruhe-Nebraska) chose this strategy, mostly because of our own experimental expertise

An important detail



The b must be created with a $\bar{b}$. This is usually soft and almost collinear with the beam, but sometimes it enters acceptance:

	$\sigma(pp \to thj)$ [fb]		$\sigma(pp \to thjb)$ [fb]	
	$c_F = 1$	$c_F = -1$	$c_F = 1$	$c_F = -1$
8 TeV	17.4	252.7	5.4	79.2
14 TeV	80.4	1042	26.9	363.5