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Top-Higgs Couplings Measurements at the LHC and Beyond

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Today's Presentation

- Motivation for top-Higgs Yukawa coupling measurement
- Light overview of $t\bar{t}H$ production at hadron and lepton colliders
- Review of $t\bar{t}H$ searches at LHC Run 1
- Prospects at the LHC and other future colliders
- Summary and outlook

Motivation

- After the discovery of h(125), the focus is on the precise measurement of its properties, in particular couplings to fermions and gauge bosons.
- The top quark is the most strongly-coupled SM particle to the Higgs boson.
  For m_t=173.34 ± 0.76 GeV:
  $$\lambda_t = \frac{\sqrt{2}m_t}{v} = 0.996 \pm 0.004$$

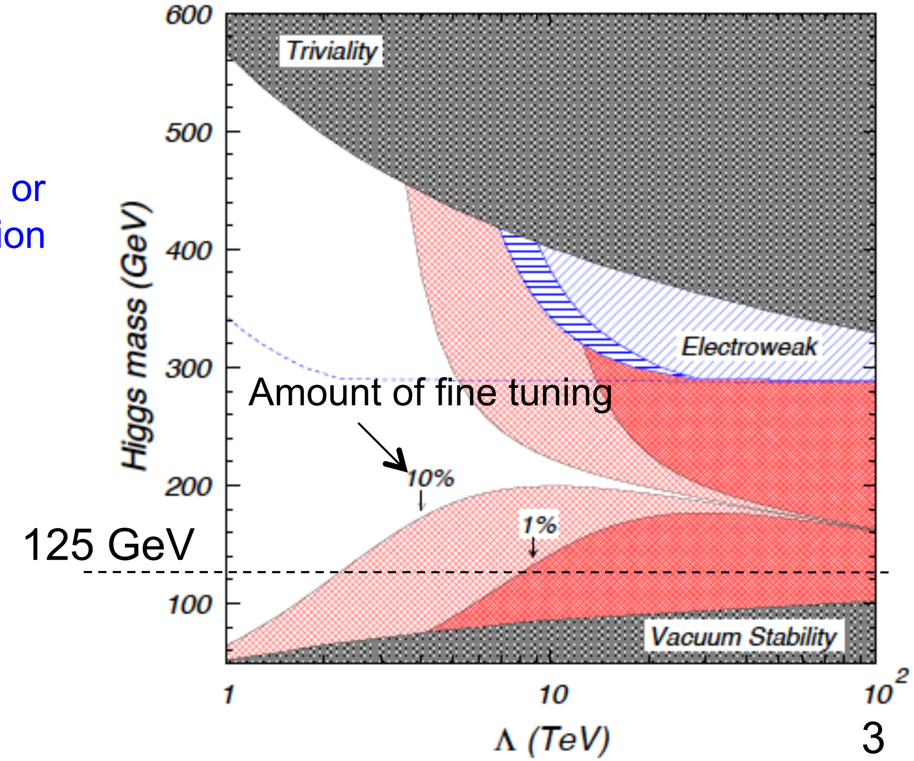
$$(125\,\mathrm{GeV})^2 = m_{H0}^2 + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right]\left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

➔ Only quark with a “natural mass”.

➔ Main responsible for instability of Higgs mass against radiative corrections.

Either New Physics appears at a scale Λ or there has to be a very delicate cancellation

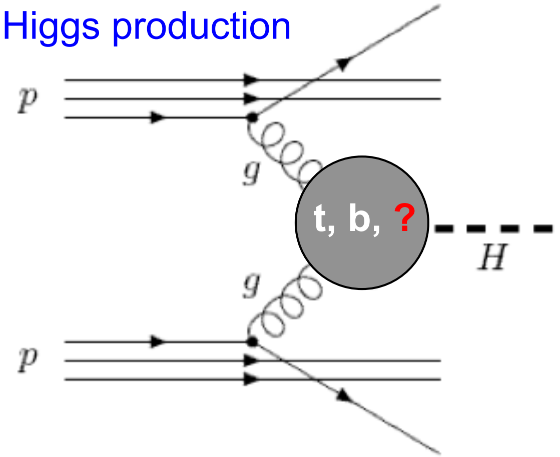
➔ May either play a key role in EWSB, or serve as a window to New Physics related to EWSB which might be preferentially coupled to it.



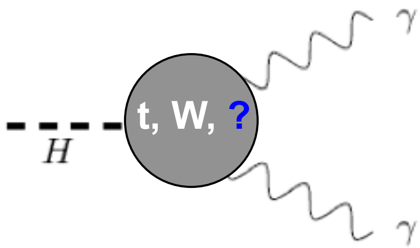
- Big incentive to measure top Yukawa coupling as precisely as possible!

Motivation

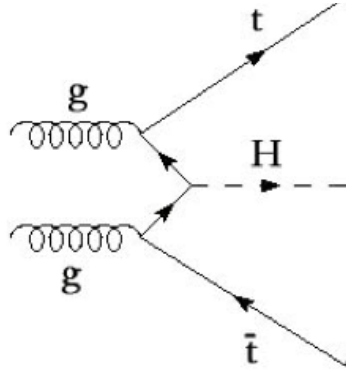
Higgs production



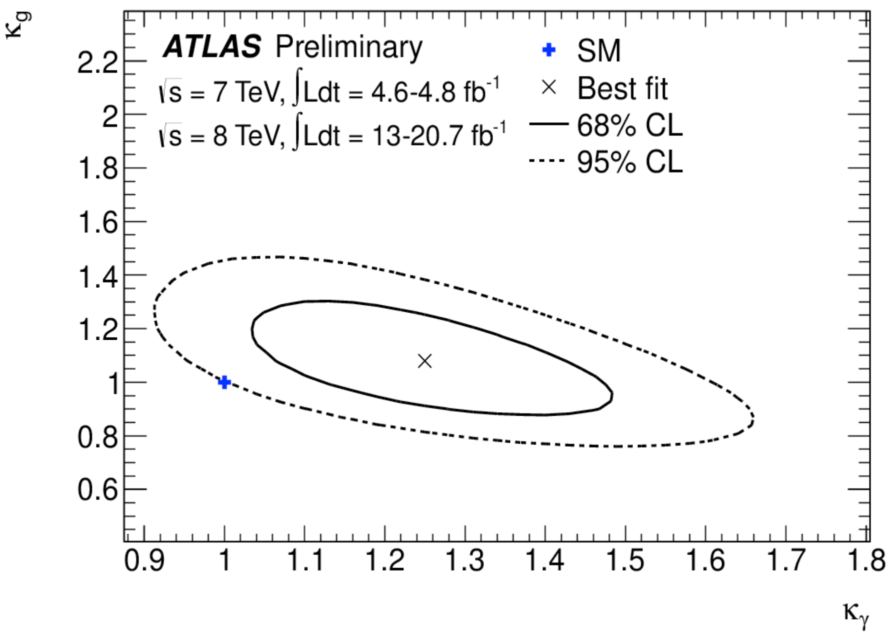
Higgs decay to photons



Higgsstrahlung from top quark



ATLAS-CONF-2013-034



- Indirect constraints on the top-Higgs Yukawa coupling can be extracted from channels involving the ggH and γγH vertices

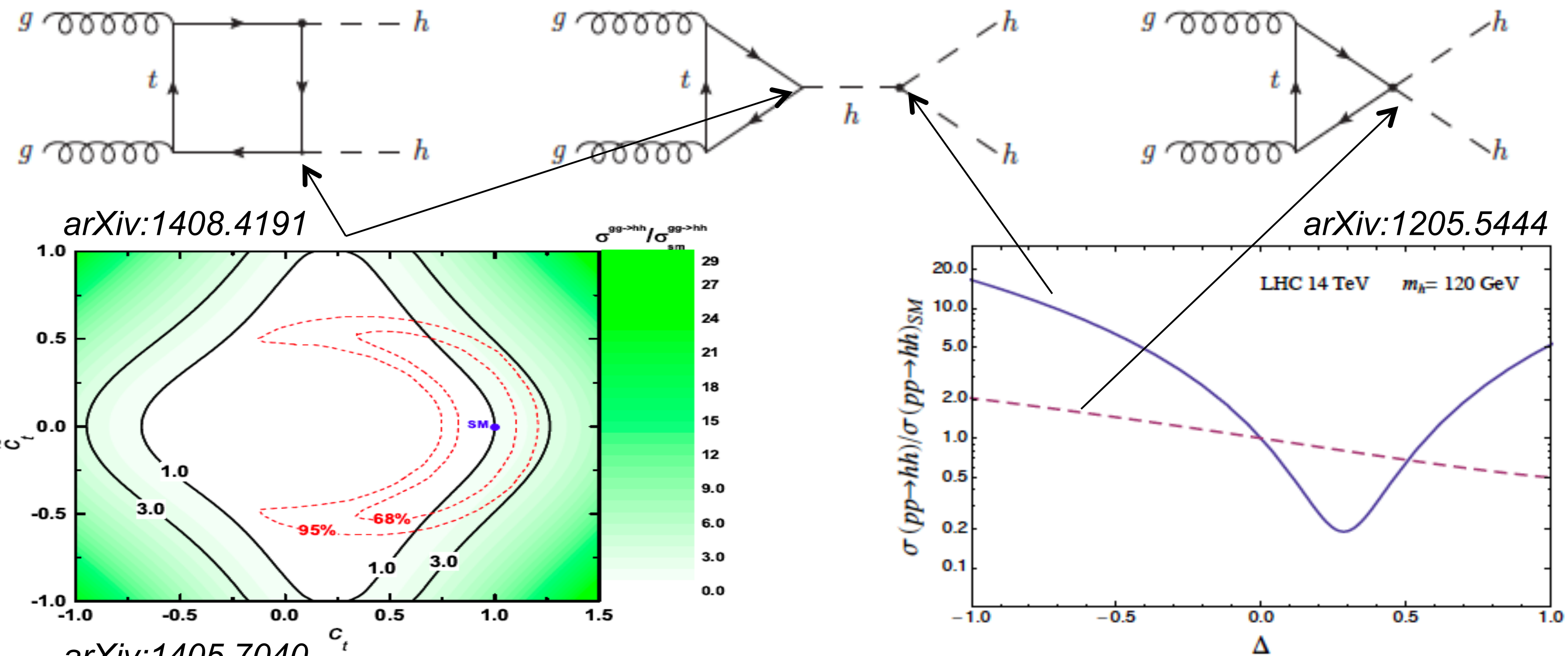
  ➔ assumes no new particles.

- Top-Higgs only Yukawa coupling that can be measured directly:

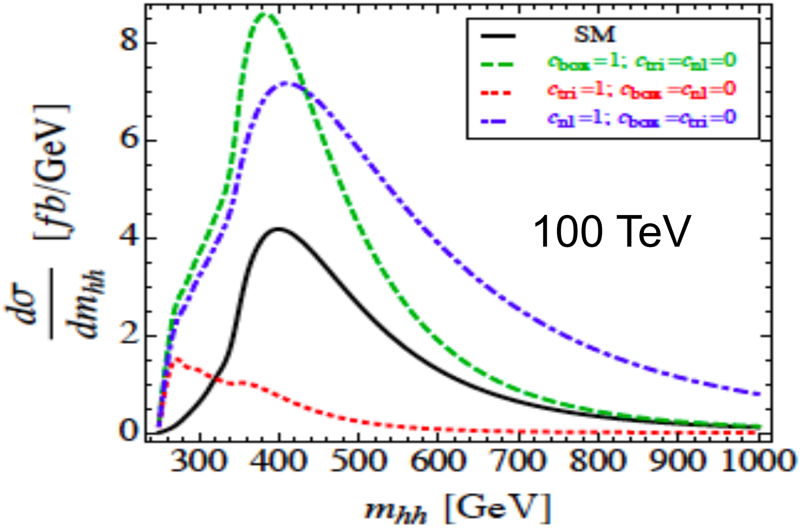
$$\sigma(t\bar{t}H) \propto g_{ttH}^2$$

➔ allows probing for NP contributions in the ggH and γγH vertices.

Motivation



arXiv:1405.7040



- Similarly, model-independent measurements of the Higgs self-coupling will require precise knowledge of the top-Higgs interactions.
- Will eventually need a global approach to resolve contributions. ttHH production may contribute (see T. Liu's talk).
- High-stats at a 100 TeV collider may allow to exploit kinematic distributions in HH production.

Motivation

- Higher-dimension operators that involve the top and Higgs fields:
  - are little tested so far, and
  - are particularly sensitive to New Physics associated with EWSB.

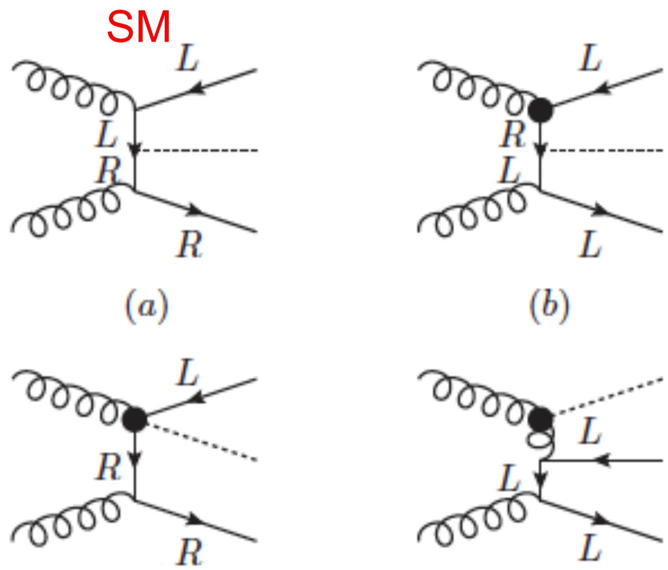
- Effective top-Higgs Yukawa coupling can deviate from SM prediction due to contributions from dimension-6 operators.

  Example: $\sigma(ttH)$ at $\sqrt{s}$=14 TeV:

SM

$$\frac{\sigma(pp \to t\bar{t}h)}{\text{fb}} = 611^{+92}_{-110} + \left[457^{+127}_{-91}\Re c_{hg} - 49^{+15}_{-10} c_G + 147^{+55}_{-32} c_{HG} - 67^{+23}_{-16} c_y\right]\left(\frac{\text{TeV}}{\Lambda}\right)^2 + \left[543^{+143}_{-123}(\Re c_{hg})^2 + 1132^{+323}_{-232} c_G^2 + 85.5^{+73}_{-21} c_{HG}^2 + 2^{+0.7}_{-0.5} c_y^2 + 233^{+81}_{-144}\Re c_{hg} c_{HG} - 50^{+16}_{-14}\Re c_{hg} c_y - 3.2^{+8}_{-8}\Re c_{Hy} c_{HG} - 1.2^{+8}_{-8} c_H c_{HG}\right]\left(\frac{\text{TeV}}{\Lambda}\right)^4$$

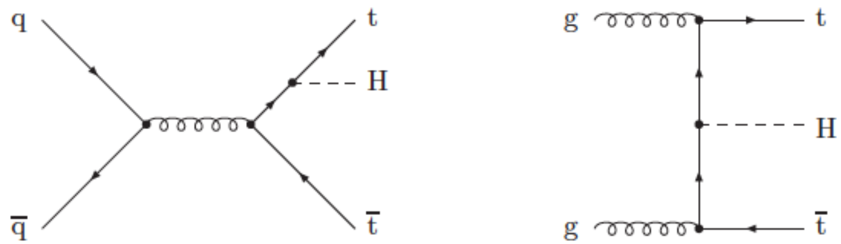
arXiv:1205.1065



Complementary to $\sigma(gg \to H)$ and $\sigma(t\bar{t})$ measurements, which are sensitive to a different combination of operators.

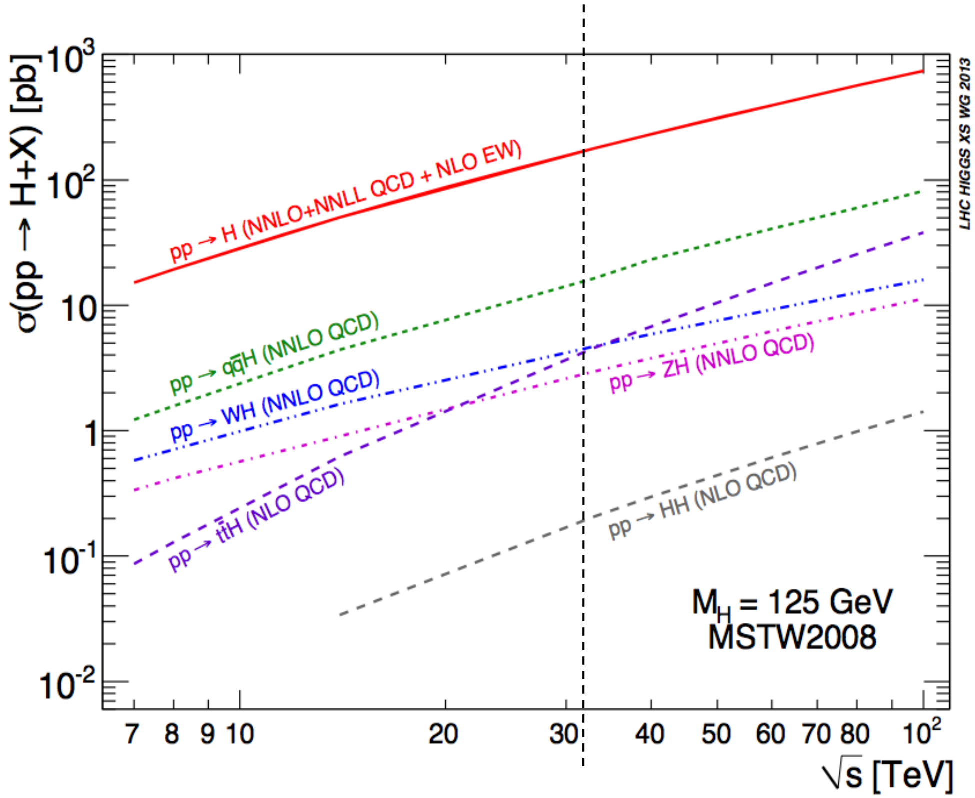
ttH Production in pp Collisions

- $t\bar{t}H$ production has the lowest cross section for a SM-like Higgs boson at LHC.
- Interestingly, the phase-space suppression effect is overcome at $\sqrt{s}$>30-40 TeV, where $t\bar{t}H$ becomes the 3rd most important production mechanism.



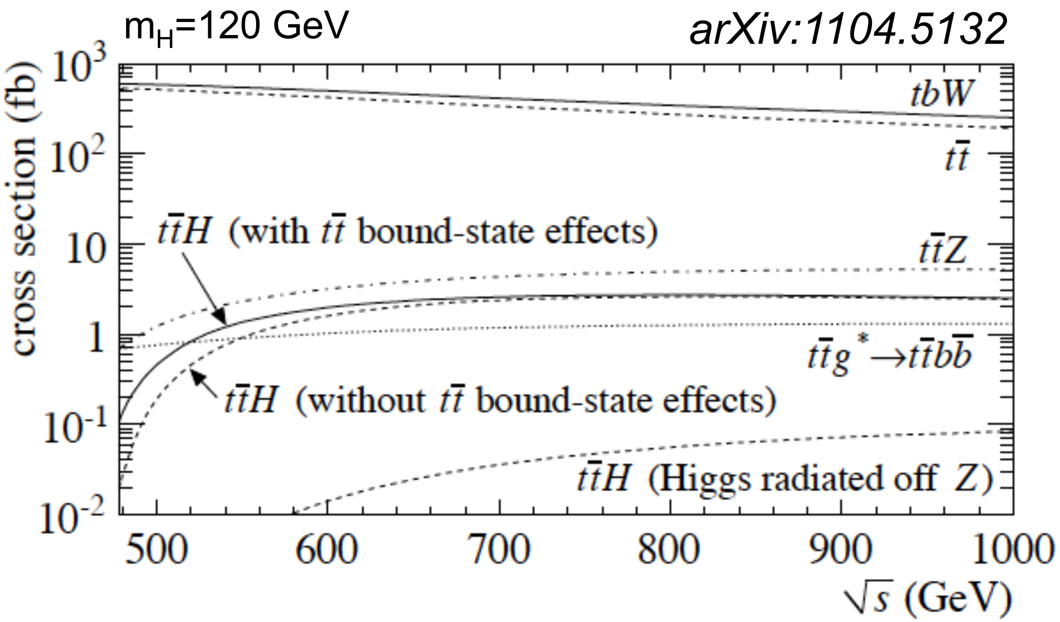
- $\sigma(t\bar{t}H)$ known at NLO in QCD.
  For M_H=125 GeV:
  $\sqrt{s}$=8 TeV: $\sigma(t\bar{t}H)$=130 fb
  $\sqrt{s}$=14 TeV: $\sigma(t\bar{t}H)$=611 fb
  (~x5 wrt $\sqrt{s}$=8 TeV)
  $\sqrt{s}$=100 TeV: $\sigma(t\bar{t}H)$=38 pb
  (~x60 wrt $\sqrt{s}$=14 TeV)

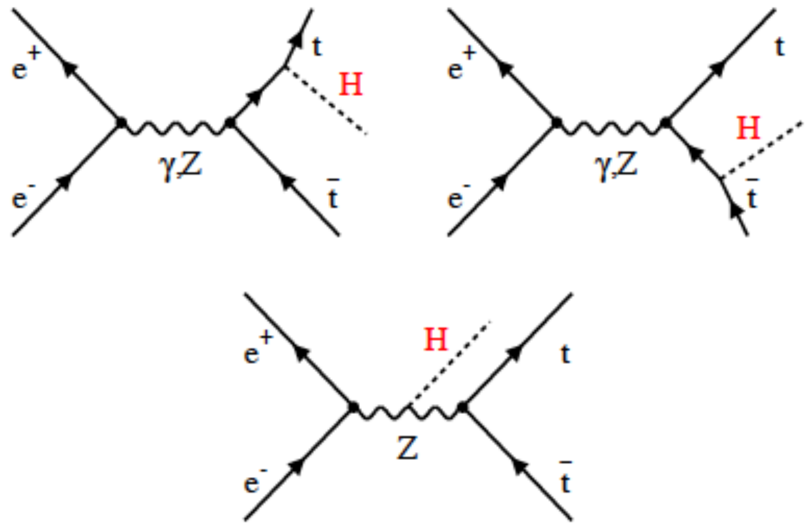
  Uncertainties at $\sqrt{s}$=14 TeV:
  +5.9%/-9.3% (scale), ±8.9% (PDF)
  ➔ Adds a ~8% uncertainty to the top-Higgs Yukawa.



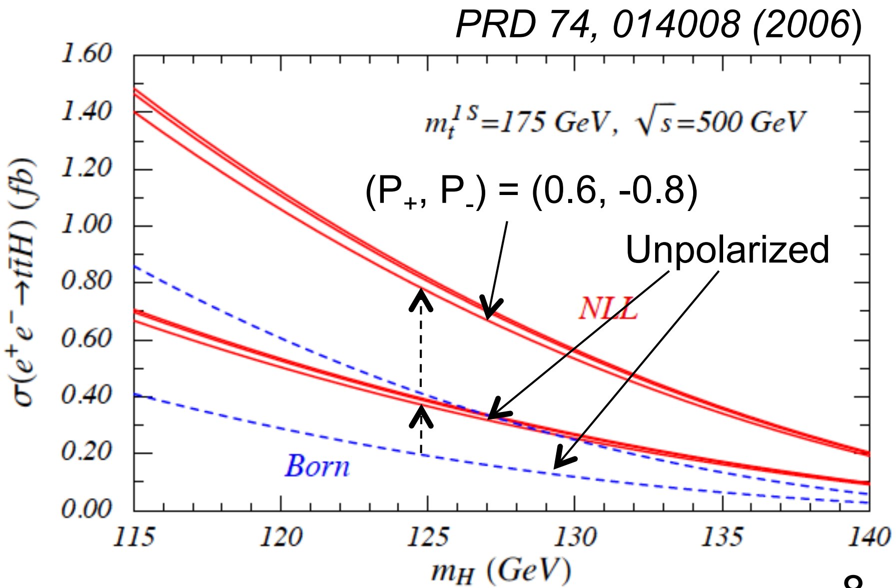
May eventually need to be improved! (measuring the ratio of ttH/ttZ also promising)

ttH Production in e^+e^- Collisions





- The optimal √s to extract the top-Higgs Yukawa coupling at an e^+e^- collider is ~800 GeV.
- At √s=500 GeV, barely enough phase-space and $\sigma(t\bar{t}H)$ significantly reduced by radiative effects in initial state (ISR, beamstrahlung).
- Fortunately, there are a couple of x2 gains possible
  - $t\bar{t}$ bound-state effects near threshold
  - beam polarization
- Still, challenging: $\sigma(t\bar{t}H) \leq 1$ fb for M_H=125 GeV.



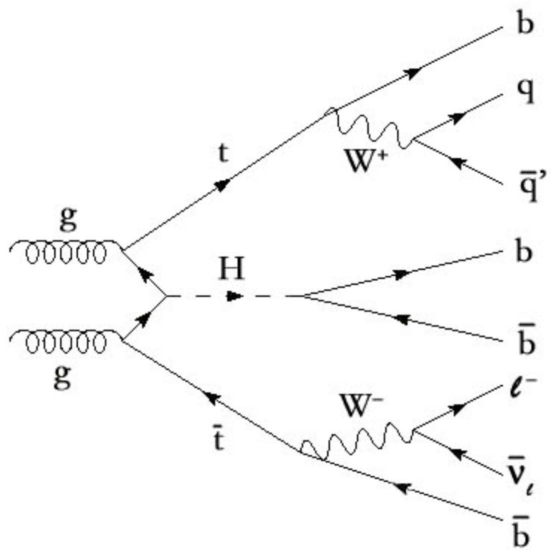
Direct Searches for ttH Production

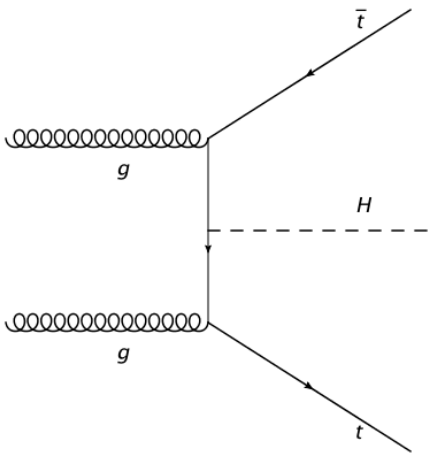
Virtues:

- Distinctive final states with high jet/b-tag multiplicity and multiple heavy resonances
  - A priori many handles against backgrounds!
- For M_H=125 GeV, $H \to b\bar{b}$ dominates, although other decay modes can also be exploited: $H \to \tau^+\tau^-$, W^+W^-, ZZ, and even $\gamma\gamma$!
- Many possible final states to consider!

  Need to find the best combinations of top and Higgs decays to isolate the signal.

Lepton+jets channel ($H \to b\bar{b}$)





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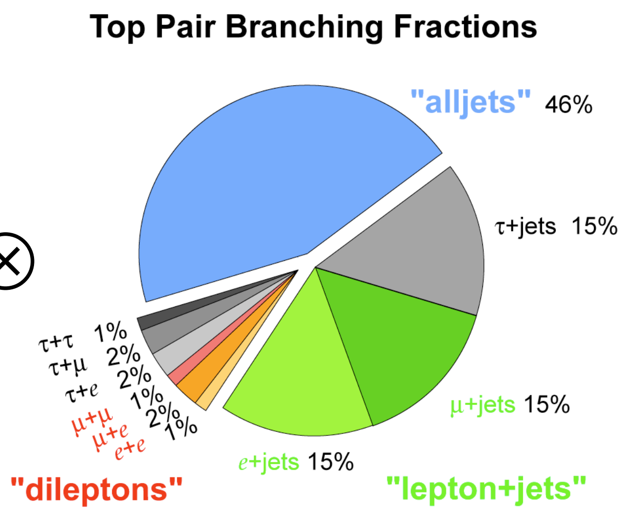

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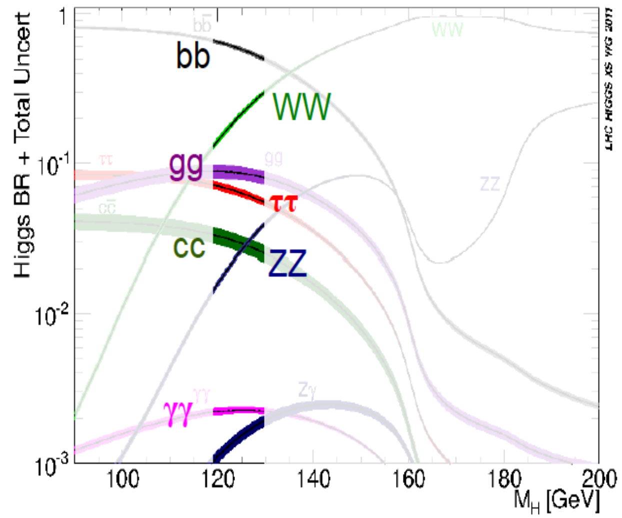
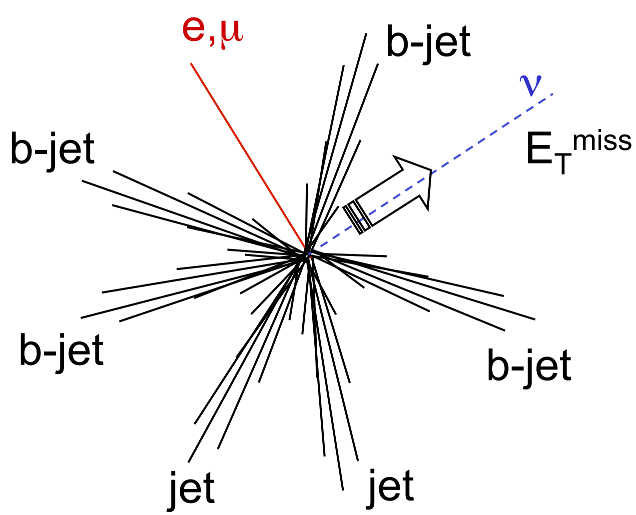


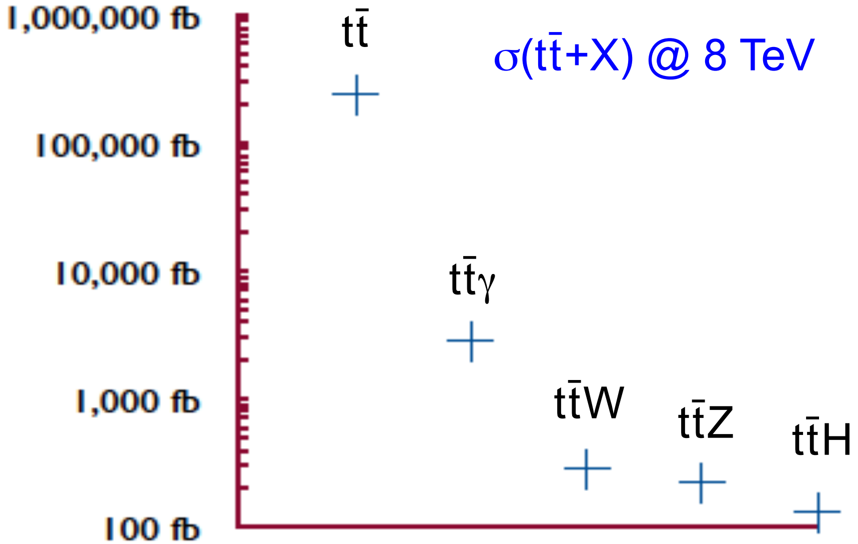
Direct Searches for ttH Production

Challenges:

- Low production cross section.
- H→b$\bar{b}$, $\tau^+\tau^-$: large combinatorial and physics backgrounds (mainly t$\bar{t}$+jets), affected by large systematic uncertainties.
- H→W^+W^-, ZZ: typically focus on multilepton final states, which have smaller backgrounds but also small signal rate.
- H→$\gamma\gamma$: small signal rate.

Lepton+jets channel (H→b$\bar{b}$)





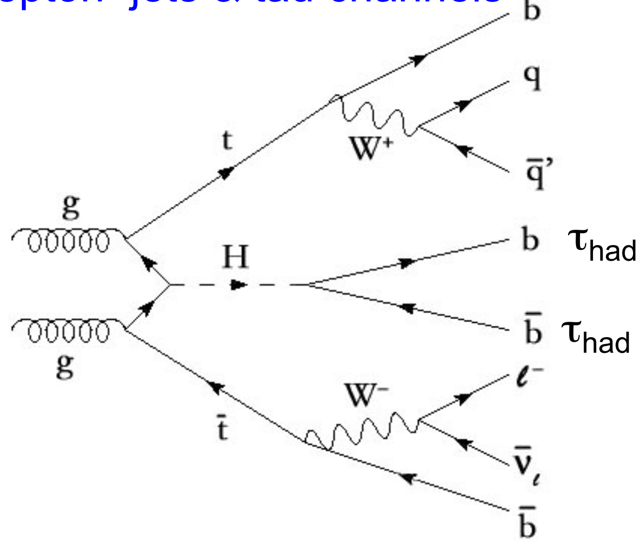
Cross section ratio for M_H=125 GeV:
LHC: σ(t$\bar{t}$)/σ(t$\bar{t}$H)~2000(1500) for √s=7 TeV(14 TeV)
LC: σ(t$\bar{t}$)/σ(t$\bar{t}$H)~500(100) for √s=500 GeV(1 TeV)

ttH, H→bb/ττ

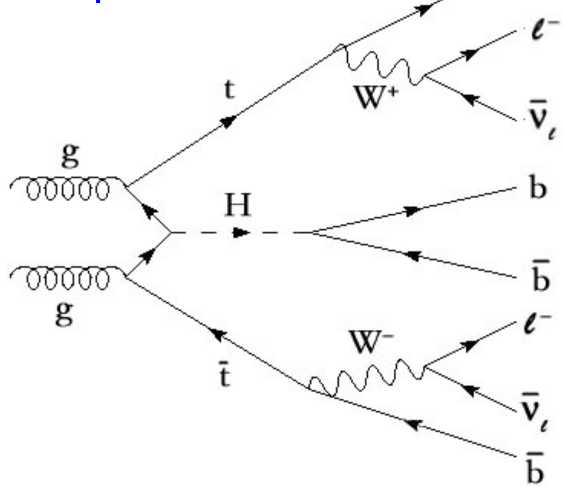
Basic Analysis Strategy

- Select $t\bar{t}$-enriched samples:
  - Lepton+jets and OS dilepton (ATLAS, CMS)
- Pick signals being targeted:
  - $H \rightarrow b\bar{b}$ (ATLAS, CMS), $H \rightarrow \tau\tau$ (CMS).
- Categorize events by jet and b-tag multiplicities:
  - Improve sensitivity by keeping separate high and low $S/\sqrt{B}$ channels.
  - Signal-depleted channels will be exploited to constrain systematic uncertainties.
- For each analysis channel, choose a discriminant variable:
  - ATLAS: single kinematic variable or multivariate discriminant
  - CMS: multivariate discriminant
- Hypothesis testing including in-situ constraining of systematic uncertainties.

Lepton+jets & tau channels



Dilepton channel



Event Selections

"Signal-rich" categories

Lepton+jets channel

ATLAS

=1 isolated e or μ, p_T>25 GeV
≥ 4 jets, p_T>25 GeV (anti-k_T R=0.4)
≥ 2 b-tags
No E_T^{miss} or $m_{T,W}$ requirements

Divide into 9 categories:
4 jets (2, 3, ≥ 4 b-tags)
5 jets (2, 3, ≥ 4 b-tags)
≥ 6 jets (2, 3, ≥ 4 b-tags)

CMS

=1 isolated e or μ, p_T>30 GeV
≥ 4 jets, p_T>30 GeV (anti-k_T R=0.5)
≥ 3 jets, p_T>40 GeV
≥ 2 b-tags
No E_T^{miss} or $m_{T,W}$ requirements

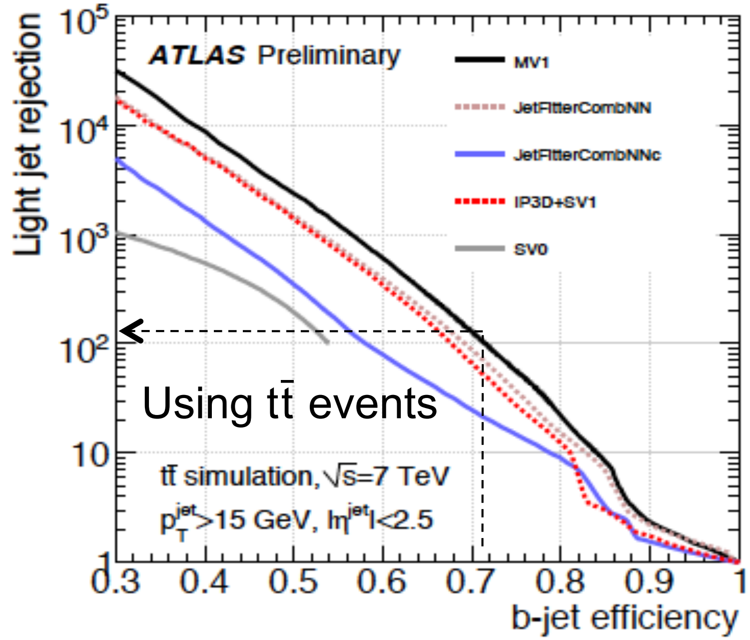
Divide into 7 categories:
4 jets (3, ≥ 4 b-tags)
5 jets (3, ≥ 4 b-tags)
≥ 6 jets (2, 3, ≥ 4 b-tags)

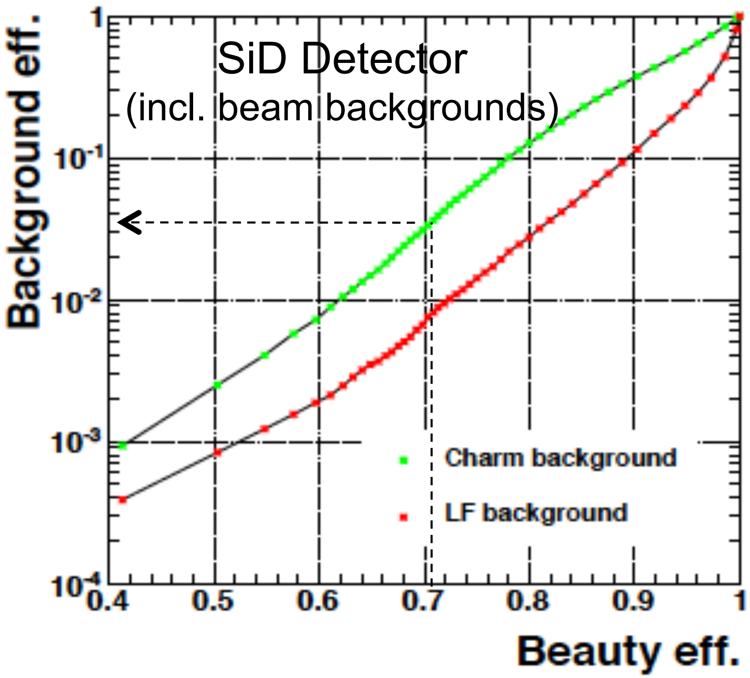
B-Jet Identification

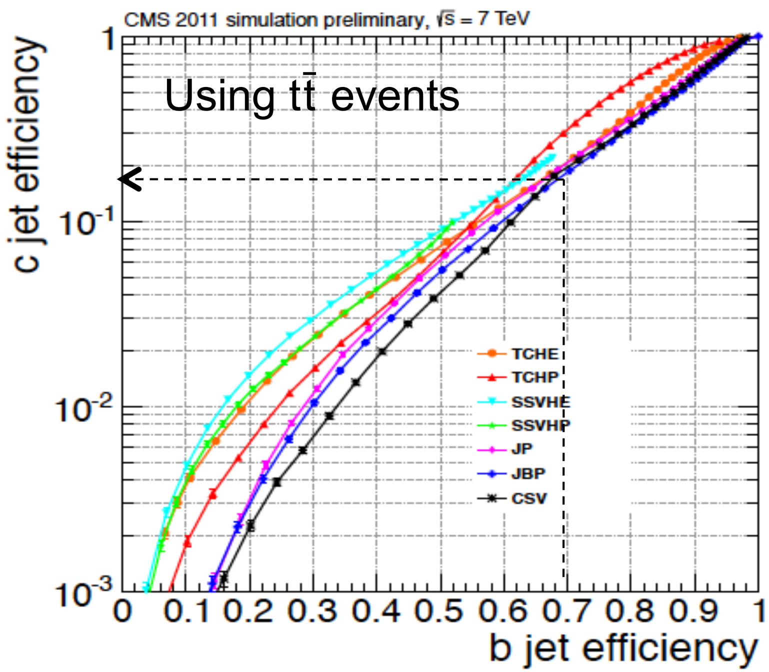
- Using multivariate techniques combining information from:
  - Lifetime: displaced tracks and/or vertices
  - Mass: secondary vertex mass
  - Decay chain reconstruction

  and calibrated in data control samples.
- Performance at LHC: $\varepsilon_b \sim 70\%$, $\varepsilon_c \sim 20\%$, $\varepsilon_{light} \sim 1\%$.
- Much better b-to-c discrimination at a LC.

  ➔ Important to suppress non-$t\bar{t}b\bar{b}$ background!

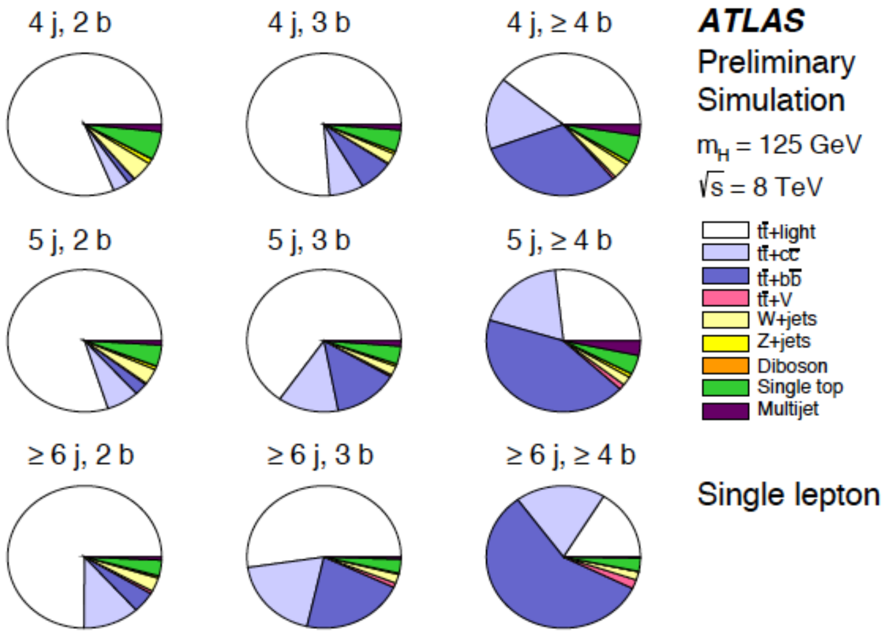


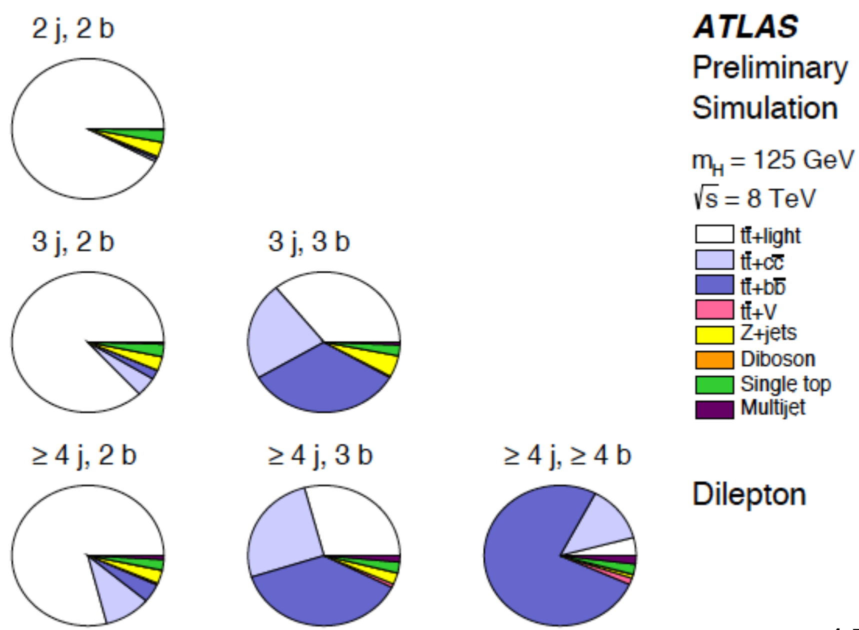




Signal and Background Modeling

- $t\bar{t}H$ Signal: *POWHEL+PYTHIA* (ATLAS), *PYTHIA* (CMS)
- Backgrounds:
  - $t\bar{t}$+jets: *POWHEG+PYTHIA* (ATLAS), *MADGRAPH+PYTHIA* (CMS)
  - $t\bar{t}W$, $t\bar{t}Z$: *MADGRAPH+PYTHIA*
  - W/Z/γ*+jets: *ALPGEN+PYTHIA* (ATLAS), *MADGRAPH+PYTHIA* (CMS)
  - Single top: *POWHEG+PYTHIA/AcerMC+PYTHIA* (ATLAS), *POWHEG+PYTHIA* (CMS)
  - Dibosons: *ALPGEN+HERWIG* (ATLAS), *PYTHIA* (CMS)
  - Multijets: normalization and shape data-driven
- **After requiring ≥1 b-tag background dominated by $t\bar{t}$.**





$t\bar{t}$+jets Modeling

- Based on matrix element (ME)+parton shower (PS) MCs.
  Inclusive $t\bar{t}$+jets samples normalized to approx NNLO cross section.
- *MADGRAPH+PYTHIA* ➔ used by CMS
  - Separate samples for $t\bar{t}$+n partons ($n \leq 3$), including heavy quarks (5F scheme).
  - Matched samples. Heavy-flavor overlap removal automatically handled.
- *POWHEG+PYTHIA* ➔ used by ATLAS
  - Good modeling of $t\bar{t}$+jets production, including jet multiplicity and kinematics.
  - Modeling of $t\bar{t}$+HF comparable (in normalization and kinematics) to *MADGRAPH.*
- Modeling further improved by applying MC corrections based on differential cross section measurements (e.g. ATLAS: as a function of top p_T and $t\bar{t}$ p_T; ATL-CONF-2013-099).
- Overall rate of $t\bar{t}+b\bar{b}$ and $t\bar{t}+c\bar{c}$ calibrated to data using background-enriched bins in signal-rich regions.

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- Overall rate of $t\bar{t}+b\bar{b}$ and $t\bar{t}+c\bar{c}$ calibrated to data using background-enriched bins in signal-rich regions.

- Major recent progress in the theoretical description of the background that will be exploited for Run 2 analyses.

	matrix elements	$0j$	$1j$	$2j$	$3j$	$\geq 4j$
LO+PS	$t\bar{t}+2$ jets	-	-	LO	PS	PS
MEPS@LO	$t\bar{t}+0,1,2,3$ jets	LO	LO	LO	LO	PS
MC@NLO	$t\bar{t}+2$ jets	-	-	NLO	LO	PS
MEPS@NLO	$t\bar{t}+0,1,2$ jets	NLO	NLO	NLO	LO	PS

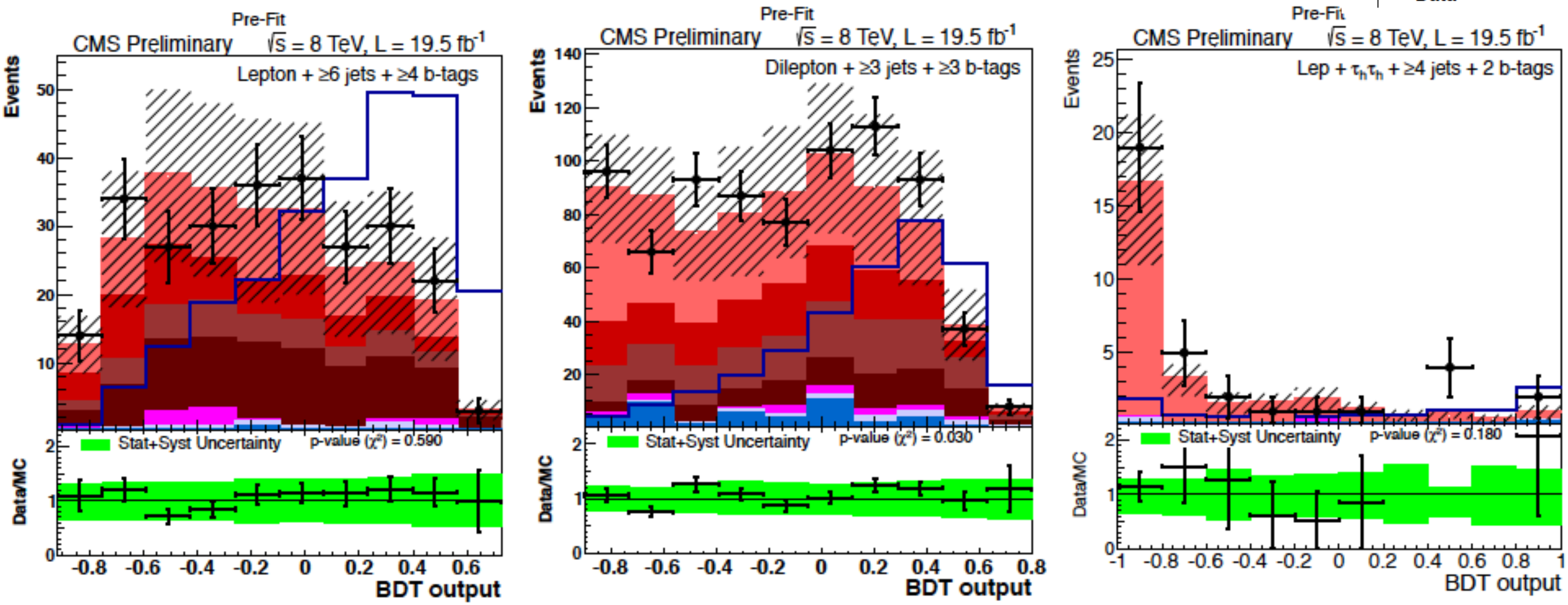
Run 1

Run 2

Signal-to-Background Discrimination

- NNs or BDTs trained for each category of the analysis.
- Different discriminating variables being exploited. E.g. CMS:
  - Angular correlations: e.g. average $\Delta R(b,b)$
  - Event kinematics: e.g sphericity
  - B-tagging information: e.g. average b-tagging output variable
  - $t\bar{t}b\bar{b}/t\bar{t}H$ BDT in signal-rich lepton+jets channels
  - Tau isolation and kinematics (tau channel)

CMS PAS HIG-13-019



Systematic Uncertainties

ATLAS-CONF-2014-011

Systematic uncertainty	Type	Components
Luminosity	N	1
Physics Objects		
Electron	SN	5
Muon	SN	6
Jet energy scale	SN	22
Jet vertex fraction	SN	1
Jet energy resolution	SN	1
Jet reconstruction	SN	1
b-tagging efficiency	SN	6
c-tagging efficiency	SN	6
Light jet-tagging efficiency	SN	12
Background Model		
$t\bar{t}$ cross section	N	1
$t\bar{t}$ modelling: p_T reweighting	SN	9
$t\bar{t}$ modelling: parton shower	SN	2
$t\bar{t}$+heavy-flavour: normalisation	N	2
$t\bar{t}$+heavy-flavour: HF reweighting	SN	2
$t\bar{t}$+heavy-flavour: generator	SN	5
W+jets normalisation	N	3
W p_T reweighting	SN	1
Z+jets normalisation	N	2
Z p_T reweighting	SN	1
Multijet normalisation	N	3
Multijet shape dilepton	S	1
Single top cross section	N	1
Dibosons cross section	N	1
$t\bar{t}V$ cross section	N	1
Signal Model		
$t\bar{t}H$ modelling	SN	2

% change in yield in ≥6 jets/≥4 tags

≥ 6 j, ≥ 4 b	Pre-fit			
	$t\bar{t}H$ (125)	$t\bar{t}$ + light	$t\bar{t} + c\bar{c}$	$t\bar{t} + b\bar{b}$
Luminosity	±2.8	±2.8	±2.8	±2.8
Lepton efficiencies	±1.4	±1.4	±1.4	±1.5
Jet energy scale	±6.5	±14	±10	±8.2
Jet efficiencies	±1.6	±5.4	±2.5	±2.4
Jet energy resolution	±0.1	±8.5	±4.1	±4.3
b-tagging efficiency	±9.0	±5.8	±5.1	±9.2
c-tagging efficiency	±1.9	±7.3	±14	±2.8
Light jet-tagging efficiency	±1.0	±17	±4.4	±1.5
$t\bar{t}$ modelling: reweighting	–	±11	±13	±13
$t\bar{t}$ modelling: parton shower	–	±7.5	±1.8	±10
$t\bar{t}$ heavy-flavour: normalisation	–	–	±50	±50
$t\bar{t}$ heavy-flavour: reweighting	–	–	±11	±12
$t\bar{t}$ heavy-flavour: generator	–	–	±2.2	±2.9
Theoretical cross sections	–	±6.2	±6.3	±6.3
$t\bar{t}H$ modelling	±1.9	–	–	–
Total	±12	±30	±57	±56

- Many systematic uncertainties, both theoretical and experimental.
- Background systematics much larger than expected signal yield!

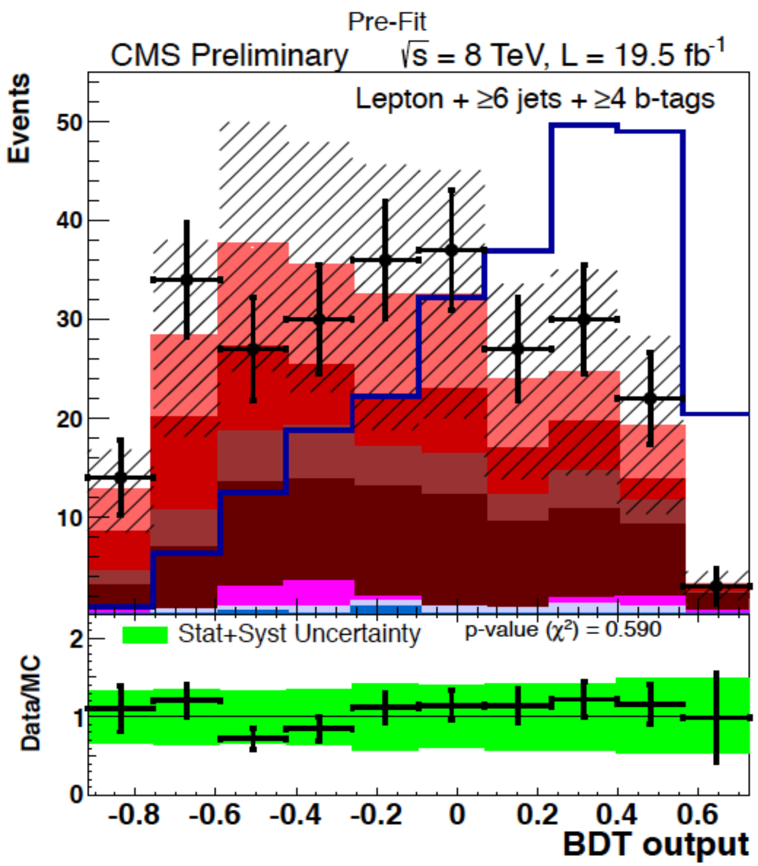
Total background uncertainty: ~37%
Expected S/B: ~3%

Profiling in Action: Example Plots

- Can exploit high-statistics control samples to constrain the leading syst. uncertainties.
- But need sophisticated enough treatment to not artificially overconstrain them!

CMS PAS HIG-13-019

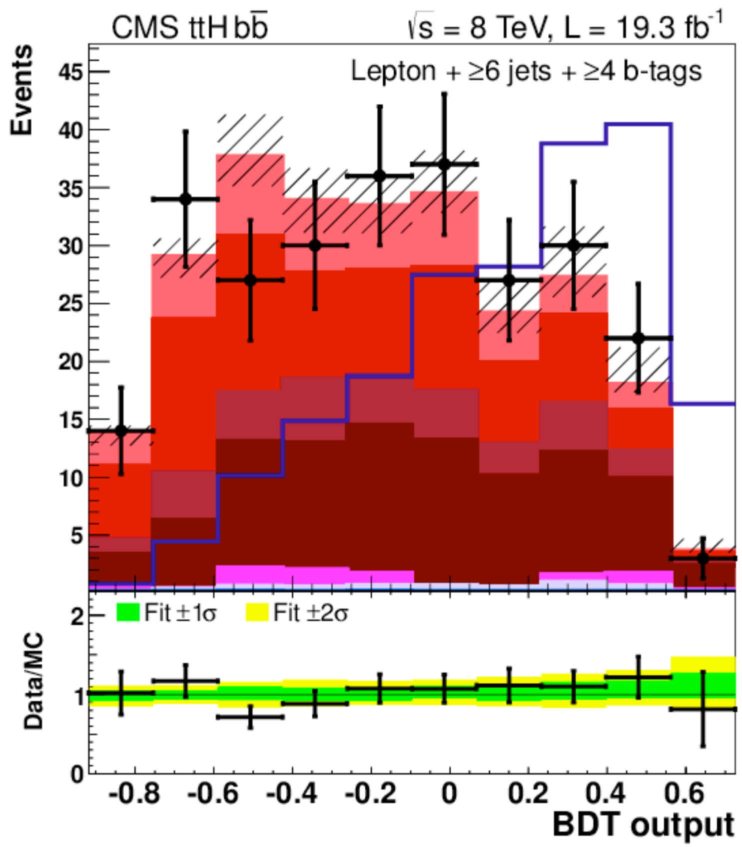
Pre-Fit



Total background uncertainty: ~37%

arXiv:1408.1682

Post-Fit (S+B)

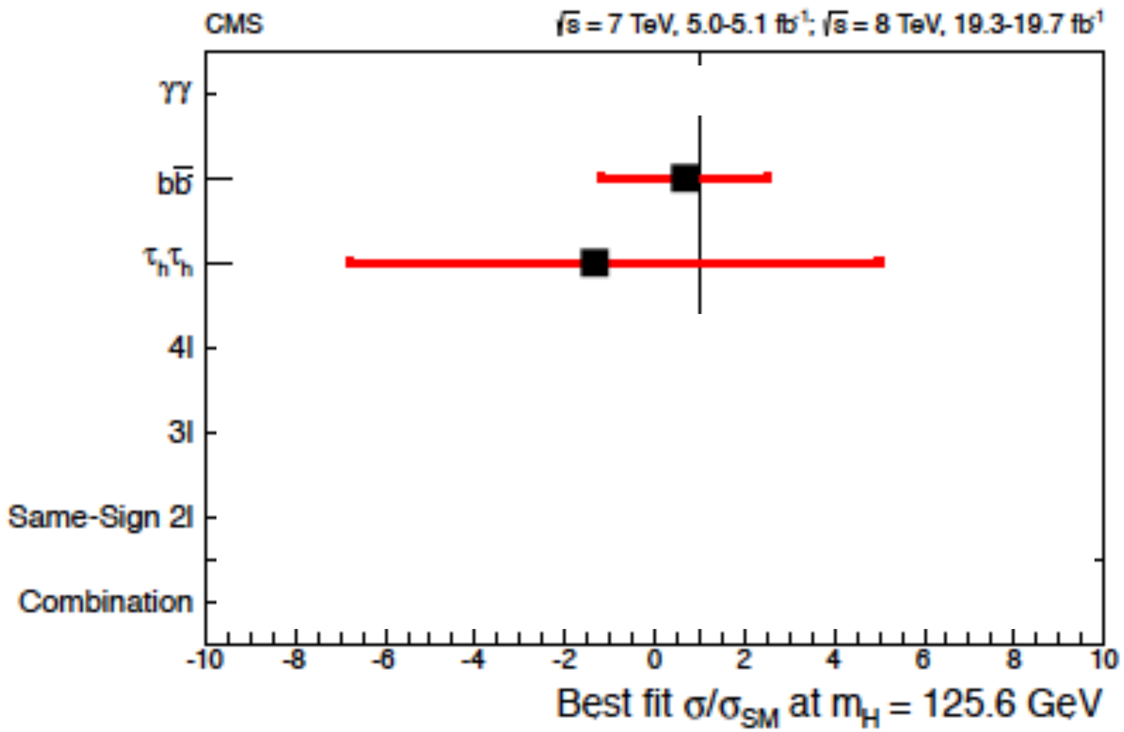


Total background uncertainty: ~6%

CMS H→bb/ττ Results (7+8 TeV)

arXiv:1408.1682

$t\bar{t}$H channel	Best-fit μ	95% CL upper limits on $\mu = \sigma/\sigma_{SM}$ ($m_H = 125.6$ GeV)				
			Expected			
	Observed	Observed	Median signal-injected	Median	68% CL range	95% CL range
$b\bar{b}$	$+0.7^{+1.9}_{-1.9}$	4.1	5.0	3.5	[2.5, 5.0]	[1.9, 6.7]
$\tau_h\tau_h$	$-1.3^{+6.3}_{-5.5}$	13.0	16.2	14.2	[9.5, 21.7]	[6.9, 32.5]

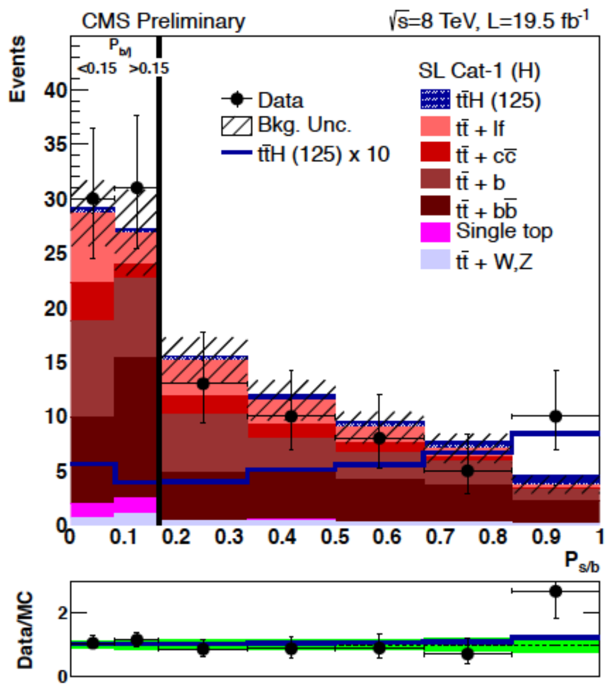


CMS H→bb Search with the ME Method (8 TeV)

CMS-PAS-HIG-14-010

- .Basic event selection:
  - Lepton + ≥5 jets
  - Dilepton + ≥4 jets
  - Cut on an event-wide likelihood variable to select 4b-enriched sample.
- Define different event categories and build suitable ME discriminant:

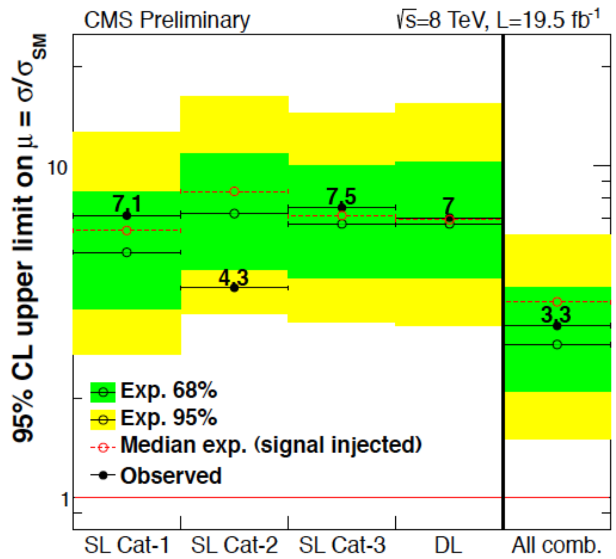
single-lepton			di-lepton
"SL Cat-1"	"SL Cat-3"	"SL Cat-2"	"DL"
$tt \to b\ell\nu\ bqq$	$tt \to b\ell\nu\ bqq$	$tt \to b\ell\nu\ bqq + g$	$tt \to b\ell\nu\ b\ell\nu$
all quarks reconstructed (+ *gluon(s)*)	all quarks *but one W-quark* reconstructed	all quarks *but one W-quark* reconstructed + ≥ *1 gluon(s)*	all quarks reconstructed



- Combination of lepton+jets and dileptons:

  Observed (expected) limit @ M_H=125 GeV: 3.3xSM (2.9xSM)

  ➔ Significant improvement relative to pub result at 8 TeV (exp: ~4.1xSM)

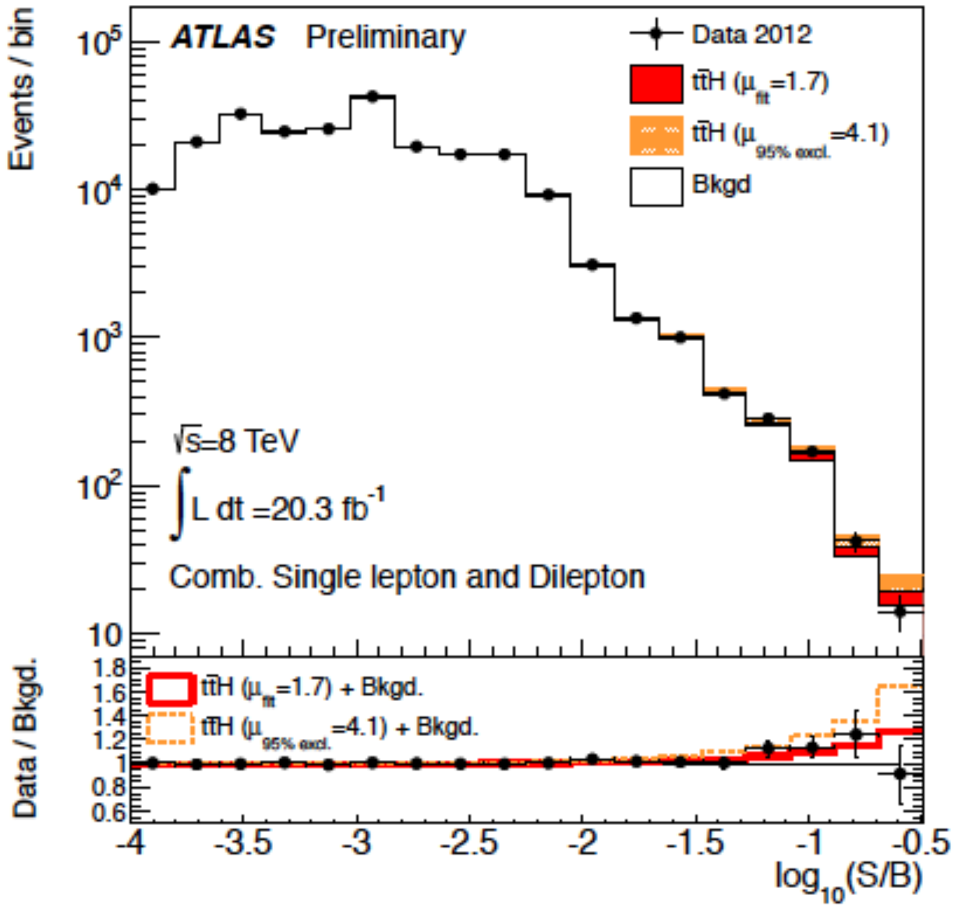


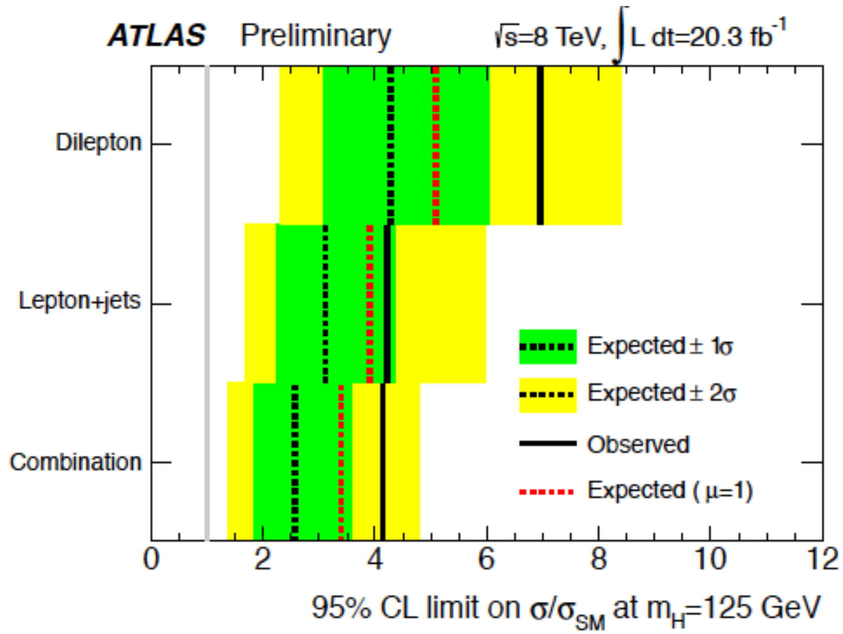
- Best-fit signal strength: $\boxed{\mu_{comb} = 0.7 \pm 1.3}$

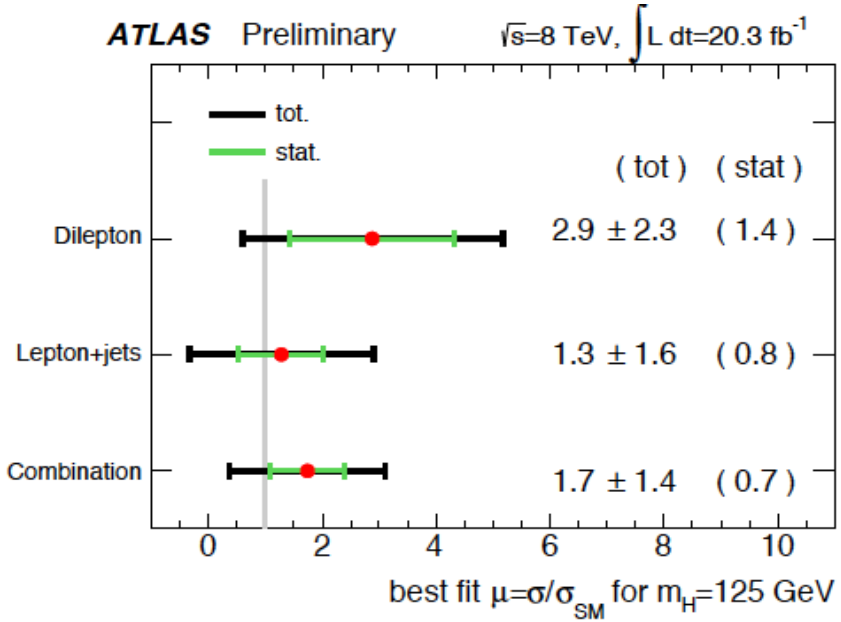
ATLAS H→bb Result (8 TeV)

- Combination of lepton+jets and dileptons:
  Observed (expected) limit @ M_H=125 GeV:
  4.1xSM (2.6xSM)
- Best-fit signal strength: $\boxed{\mu_{comb} = 1.7 \pm 1.4}$

ATLAS-CONF-2014-011







ttH, Multileptons

Basic Analysis Strategy

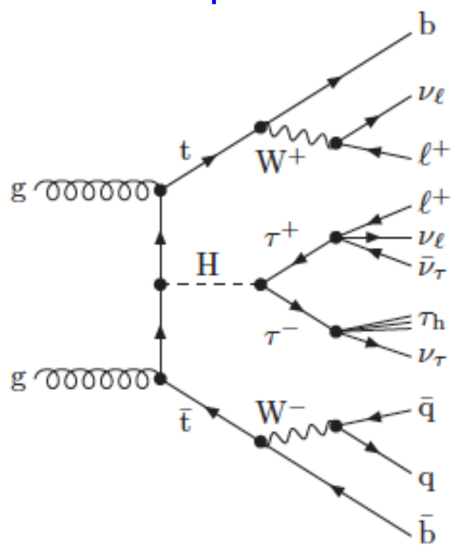
- Mainly probe H→WW, but also non-negligible contributions from H→ττ and H→ZZ.

- Categorize channels by number of leptons.
  Ideal signatures for H→WW:
  - SS 2-leptons + 6 jets (2 b jets)
  - 3-leptons + 4 jets (2 b jets)
  - 4-leptons + 2 jets (2 b jets)

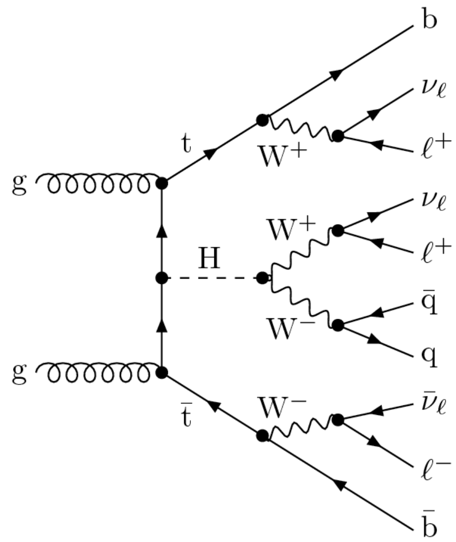
- Low signal rate but also low background, dominated by $t\bar{t}W/Z/\gamma^*$.
  Additional contributions from WZ and ZZ.
  For SS 2-lepton and 3-lepton analyses, sizable contribution from $t\bar{t}$+jets, with jets misidentified as leptons.

- Use multivariate discriminants to separate signal from backgrounds.

SS 2-leptons channel



3-leptons channel



Event Selections

SS 2-leptons channel

- $e^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$, $e^{\pm}\mu^{\pm}$ final states
- 2 tight e/μ, p_T>20 GeV; Z veto
- ≥ 4 jets, p_T>25 GeV (anti-k_T R=0.5)
- ≥ 2 b-tags
- E_T^{miss} LD>0.2, $\Sigma\ p_T^{lep}+E_T^{miss}$>100 GeV

3-leptons channel

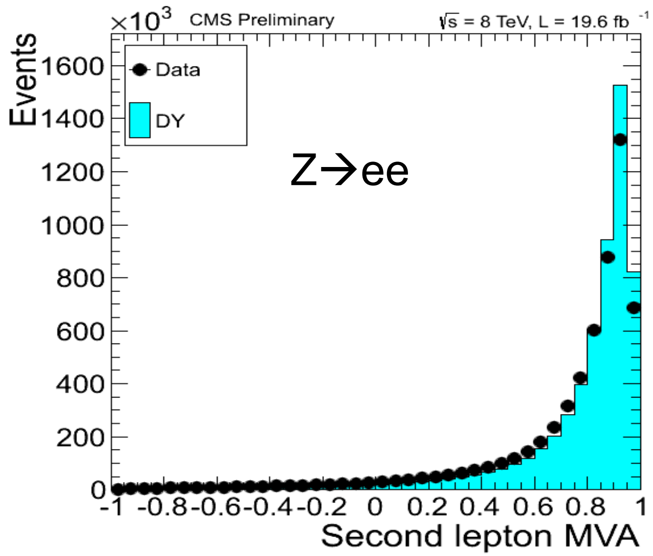
- 3 tight e/μ, p_T>20/10/10 GeV; Z veto
- ≥ 2 jets, p_T>25 GeV (anti-k_T R=0.5)
- ≥ 2 b-tags
- E_T^{miss} LD cut if SF/OS pair and <4 jets

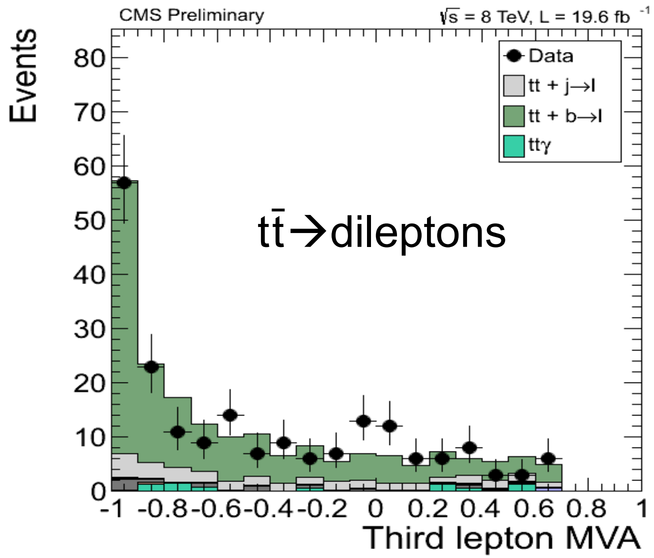
4-leptons channel

- 4 loose e/μ, p_T>20/10/10/10 GeV; Z veto
- ≥ 2 jets, p_T>25 GeV (anti-k_T R=0.5)
- ≥ 2 b-tags

• MVA-based lepton identification (trained on ttH vs tt+jets MC):

CMS PAS HIG-13-020

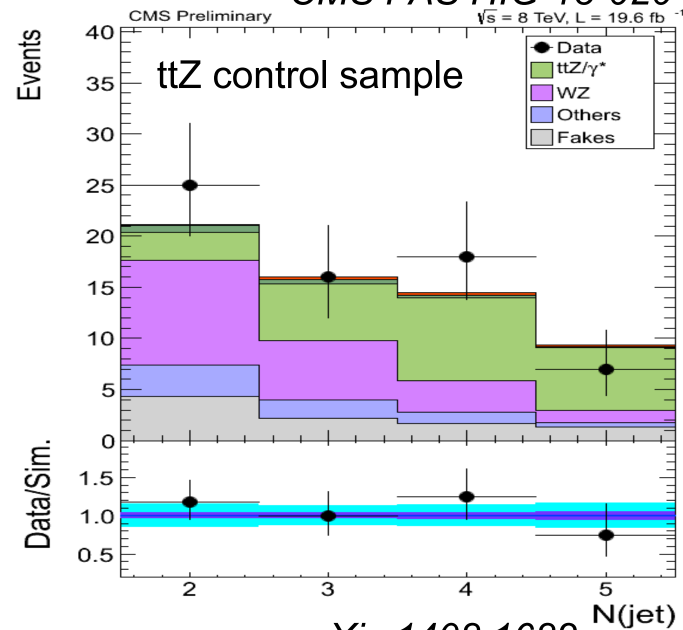




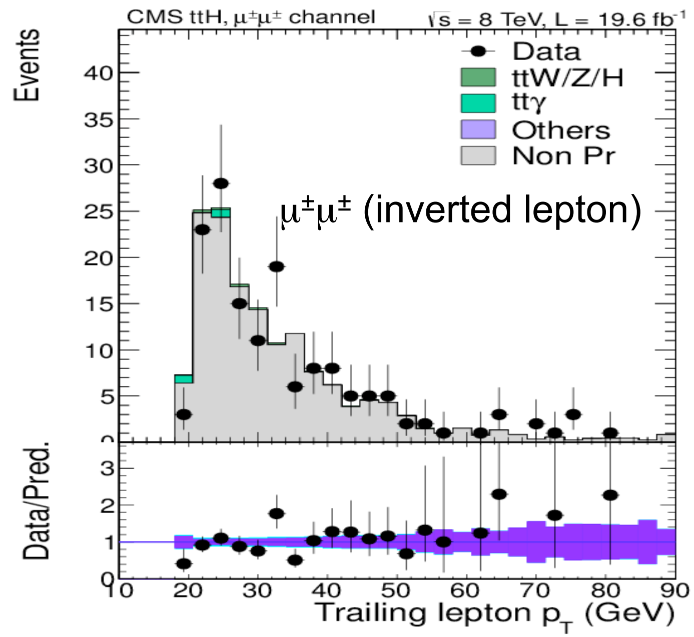
Background Estimation

- ttV+jets (V=W, Z, WW)
  - Predicted using Madgraph+Pythia MC normalized to NLO cros section (~13% uncertainty). Additional uncertainties from varying scale choices in the MC.
  - ttZ prediction validated in data control sample (~35% statistical uncertainty).
- Dibosons+jets (WZ,ZZ)
  - Predicted using Madgraph+Pythia MC calibrated in data control samples (WZ+≥2+non-b jets and ZZ+≥1+non-b jets).
  - Total uncertainty ~20% (includes uncertainty in extrapolation from control to signal region).
- tt+jets instrumental
  - Fake leptons: data events with inverted lepton MVA corrected with per-lepton fake rate. Uncert. ~50%.
  - Charge misID (SS 2-leptons): OS 2-leptons data events corrected with per-lepton charged misID rate. Uncert. ~30%.

CMS PAS HIG-13-020



arXiv:1408.1682

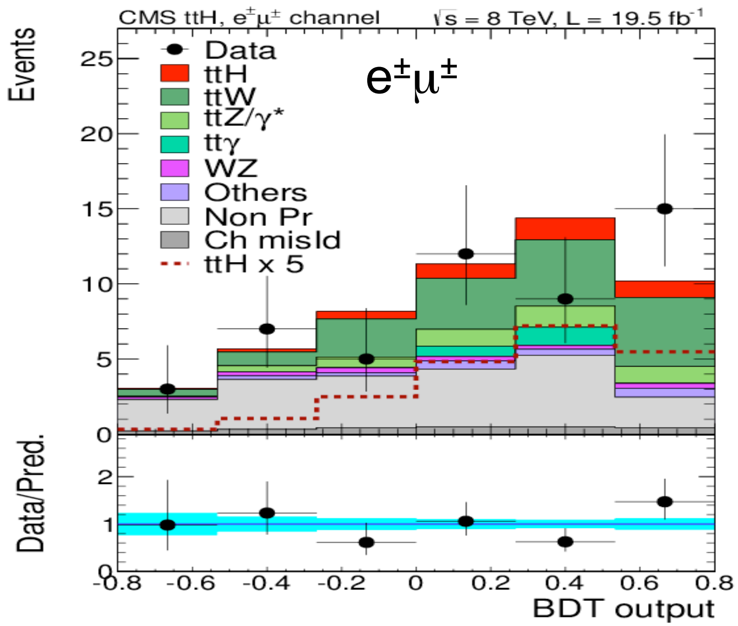


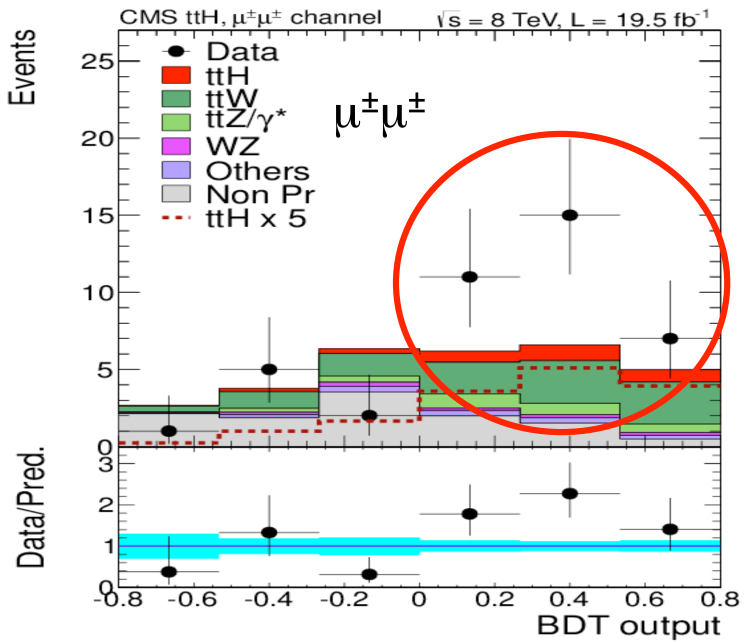
SS 2-Leptons

arXiv:1408.1682

- Analyze separately $e^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$, $e^{\pm}\mu^{\pm}$ events.
- Events categorized according to lepton charge sum (exploit charge correlation in ttW).
- BDT trained between ttH signal and tt+jets background MC (6 vars: e.g. H_T).
- ~2σ excess (wrt SM) in $\mu^{\pm}\mu^{\pm}$ channel.
  Cross-checks performed show no issues with data quality or background mismodeling.

	ee	eμ	μμ
$t\bar{t}H$, $H \to WW$	1.0 ± 0.1	3.2 ± 0.4	2.4 ± 0.3
$t\bar{t}H$, $H \to ZZ$	—	0.1 ± 0.0	0.1 ± 0.0
$t\bar{t}H$, $H \to \tau\tau$	0.3 ± 0.0	1.0 ± 0.1	0.7 ± 0.1
$t\bar{t}W$	4.3 ± 0.6	16.5 ± 2.3	10.4 ± 1.5
$t\bar{t}Z/\gamma^*$	1.8 ± 0.4	4.9 ± 0.9	2.9 ± 0.5
$t\bar{t}WW$	0.1 ± 0.0	0.4 ± 0.1	0.3 ± 0.0
$t\bar{t}\gamma$	1.3 ± 0.3	1.9 ± 0.5	—
WZ	0.6 ± 0.6	1.5 ± 1.7	1.0 ± 1.1
ZZ	—	0.1 ± 0.1	0.1 ± 0.0
Rare SM bkg.	0.4 ± 0.1	1.6 ± 0.4	1.1 ± 0.3
Non-prompt	7.6 ± 2.5	20.0 ± 4.4	11.9 ± 4.2
Charge misidentified	1.8 ± 0.5	2.3 ± 0.7	—
All signals	1.4 ± 0.2	4.3 ± 0.6	3.1 ± 0.4
All backgrounds	18.0 ± 2.7	49.3 ± 5.4	27.7 ± 4.7
Data	19	51	41





3-Leptons and 4-Leptons

arXiv:1408.1682

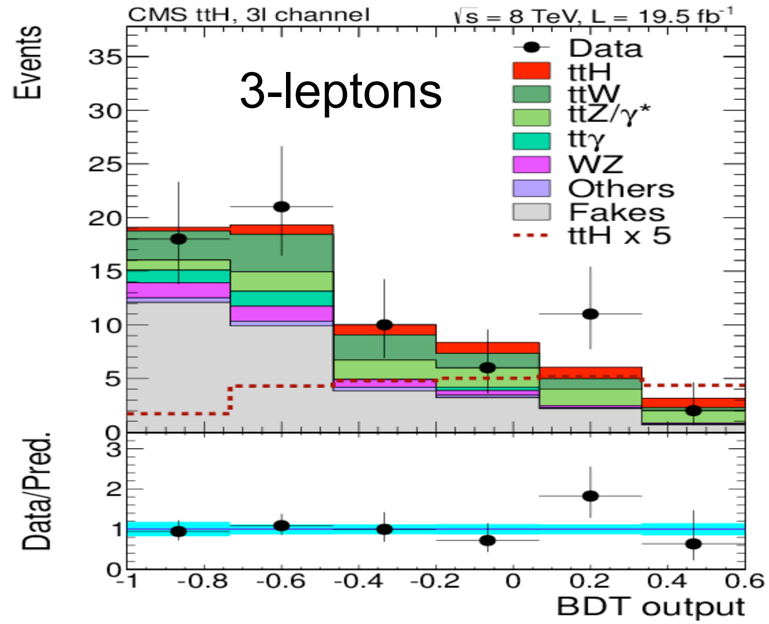
3-leptons:

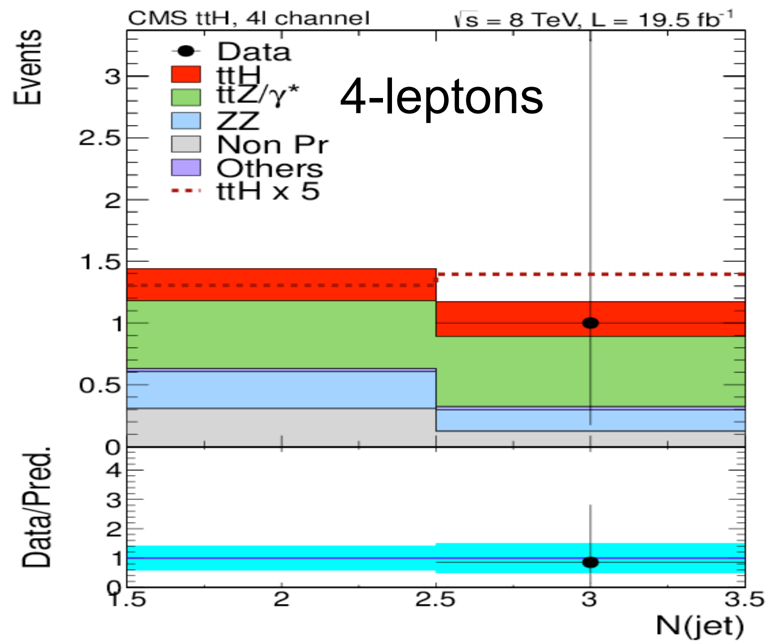
- Events categorized according to lepton charge sum (exploit charge correlation in ttW).
- BDT trained between ttH signal and mixture of tt+jets and ttV+jets background MC (7 vars: e.g. N_{jets}).

4-leptons:

- Use N_{jets} as discriminating variable.

	3ℓ	4ℓ
$t\bar{t}H, H \to WW$	3.4 ± 0.5	0.29 ± 0.04
$t\bar{t}H, H \to ZZ$	0.2 ± 0.0	0.09 ± 0.02
$t\bar{t}H, H \to \tau\tau$	1.1 ± 0.2	0.15 ± 0.02
$t\bar{t}W$	10.3 ± 1.9	—
$t\bar{t}Z/\gamma^*$	8.4 ± 1.7	1.12 ± 0.62
$t\bar{t}WW$	0.4 ± 0.1	0.04 ± 0.02
$t\bar{t}\gamma$	2.6 ± 0.6	—
WZ	3.9 ± 0.7	—
ZZ	0.3 ± 0.1	0.47 ± 0.10
Rare SM bkg.	0.8 ± 0.3	0.01 ± 0.00
Non-prompt	33.3 ± 7.5	0.43 ± 0.22
Charge misidentified	—	—
All signals	4.7 ± 0.7	0.54 ± 0.08
All backgrounds	59.8 ± 8.0	2.07 ± 0.67
Data	68	1



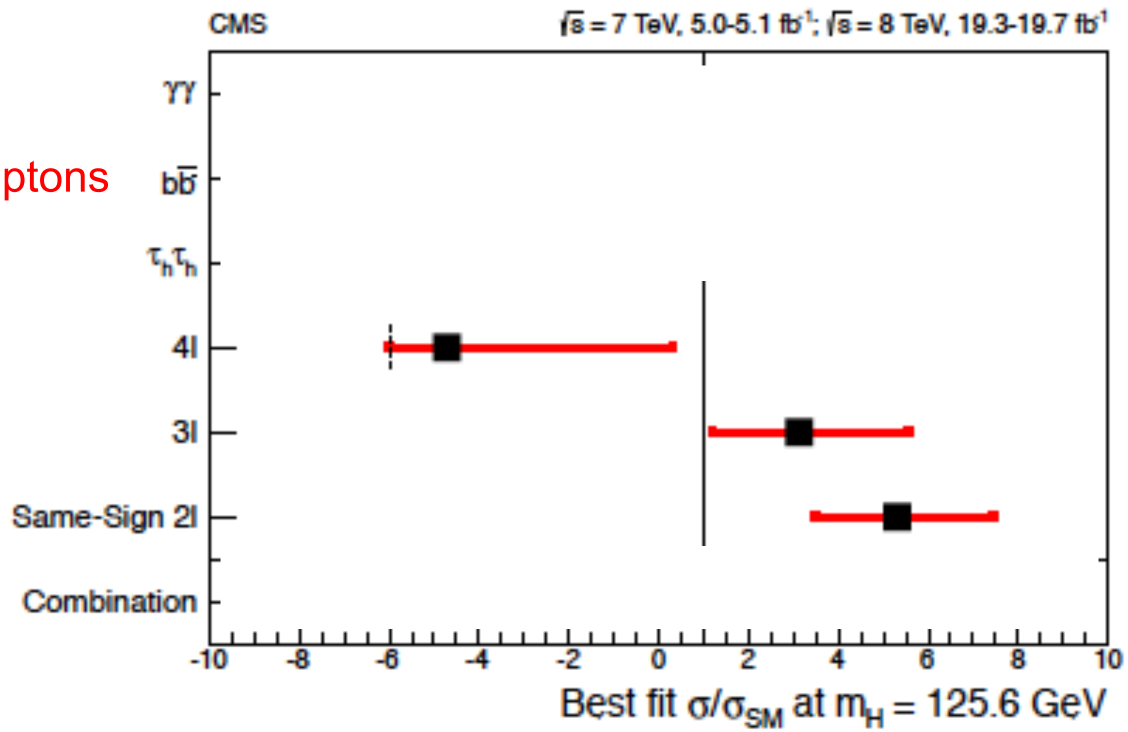


CMS Multilepton Result

arXiv:1408.1682

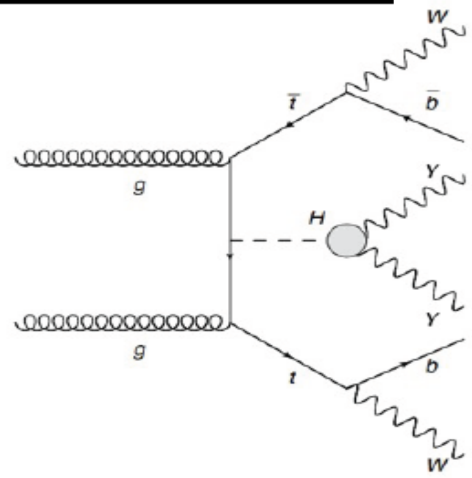
$t\bar{t}$H channel	Best-fit μ	95% CL upper limits on $\mu = \sigma/\sigma_{SM}$ ($m_H = 125.6$ GeV)				
				Expected		
	Observed	Observed	Median signal-injected	Median	68% CL range	95% CL range
4l	$-4.7^{+5.0}_{-1.3}$	6.8	11.9	8.8	[5.7, 14.3]	[4.0, 22.5]
3l	$+3.1^{+2.4}_{-2.0}$	7.5	5.0	4.1	[2.8, 6.3]	[2.0, 9.5]
Same-sign 2l	$+5.3^{+2.1}_{-1.8}$	9.0	3.6	3.4	[2.3, 5.0]	[1.7, 7.2]

- Excellent sensitivity of SS 2-leptons and 3-lepton channels!



ttH, H→$\gamma\gamma$

Basic Analysis Strategy



- Small BR(H→γγ) is compensated by the much smaller backgrounds and the good diphoton mass resolution.

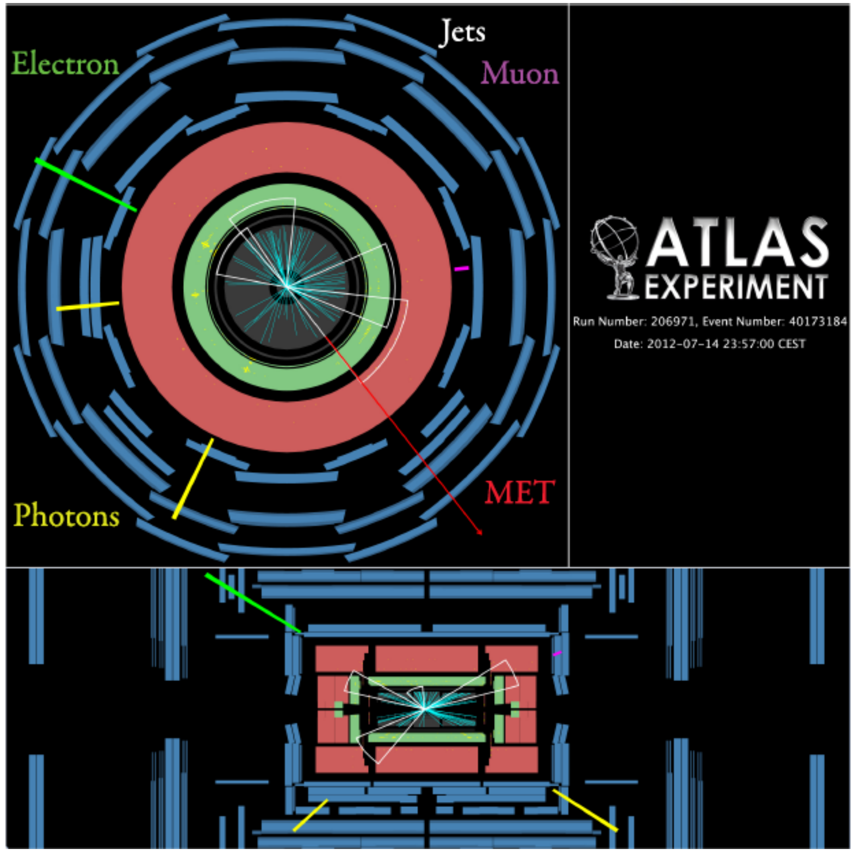
- Capitalize on well-understood H→γγ analyses.

- Categorize signal events according to the $t\bar{t}$ decay mode (leptonic or hadronic).
  Exploit high jet multiplicity and b-jet content of signal to optimize sensitivity.

- Discriminant variable: $m_{\gamma\gamma}$
  No need (for now) to estimate complicated background composition. Can perform sideband analysis as in standard H→γγ analyses.

$t\bar{t}H$, H→γγ Candidate

2 photons, p_{T1}=61 GeV, p_{T2}=39 GeV
$m_{\gamma\gamma}$=126.6 GeV
1 electron, p_T=90 GeV
E_T^{miss} = 43 GeV
4 jets, p_T=75, 71, 50, 39 GeV, 1 muon-tagged jet



Event Selections

Leptonic channel

ATLAS

2 photons, $p_T > 0.35m_{\gamma\gamma}/0.25m_{\gamma\gamma}$
≥ 1 e/μ, $p_T > 15/10$ GeV
$E_T^{miss} > 20$ GeV (only for 1 b-tag)
≥ 1 jets, $p_T > 25$ GeV
≥ 1 b-tags (80% WP)

CMS

2 photons, $p_T > 0.5m_{\gamma\gamma}/25$ GeV
≥ 1 e or μ, $p_T > 20$ GeV
No E_T^{miss} cut
≥ 2 jets, $p_T > 25$ GeV
≥ 1 b-tags (70% WP)

Hadronic channel

ATLAS

2 photons, $p_T > 0.35m_{\gamma\gamma}/0.25m_{\gamma\gamma}$
0 leptons
≥ 6 jets, $p_T > 25$ GeV, ≥ 2 b-tags (80% WP)
or
≥ 5 jets, $p_T > 30$ GeV, ≥ 2 b-tags (70% WP)
or
≥ 6 jets, $p_T > 30$ GeV, ≥ 1 b-tags (60% WP)

CMS

2 photons, $p_T > 0.5m_{\gamma\gamma}/25$ GeV
0 leptons
≥ 4 jets, $p_T > 25$ GeV, ≥ 1 b-tags (70% WP)

High ttH purity selections

ATLAS — $120 < m_{\gamma\gamma} < 130$ GeV

Category	N_H	ggF	VBF	WH	ZH	$t\bar{t}H$	$tHqb$	WtH	N_B
7 TeV leptonic selection	0.10	0.6	0.1	14.9	4.0	72.6	5.3	2.5	$0.5^{+0.5}_{-0.3}$
7 TeV hadronic selection	0.07	10.5	1.3	1.3	1.4	80.9	2.6	1.9	$0.5^{+0.5}_{-0.3}$
8 TeV leptonic selection	0.58	1.0	0.2	8.1	2.3	80.3	5.6	2.6	$0.9^{+0.6}_{-0.4}$
8 TeV hadronic selection	0.49	7.3	1.0	0.7	1.3	84.2	3.4	2.1	$2.7^{+0.9}_{-0.7}$

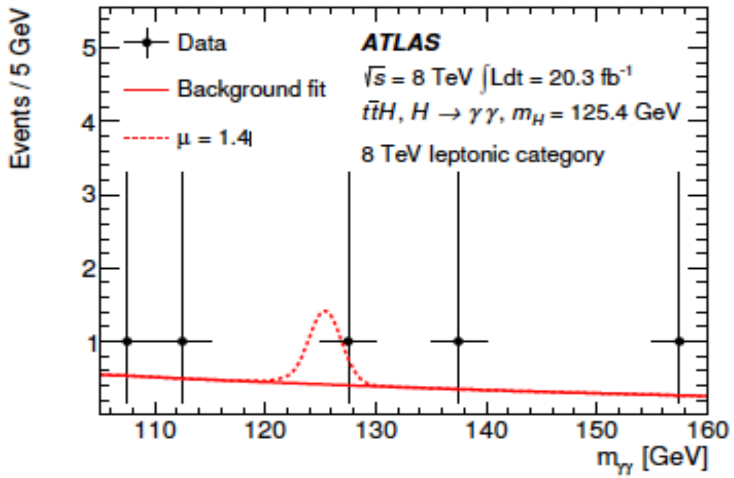
CMS — $100 < m_{\gamma\gamma} < 180$ GeV

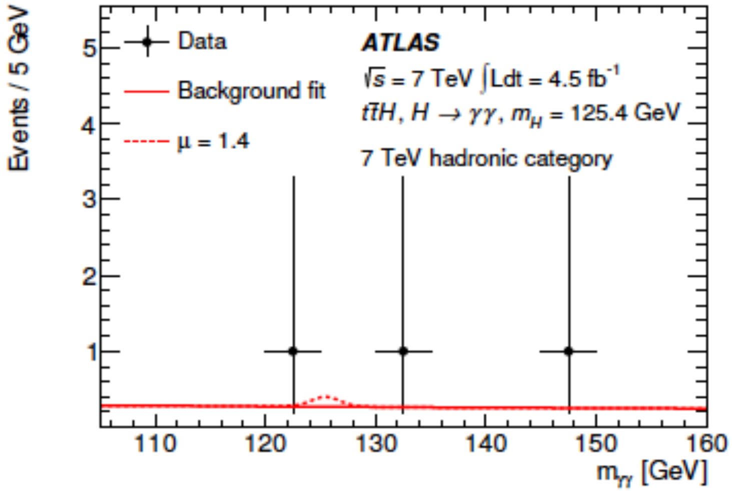
	7 TeV	8 TeV	
	All decays	Hadronic channel	Leptonic channel
$t\bar{t}$H	0.21	0.51	0.45
gg $\rightarrow$ H	0.01	0.02	0
VBF H	0	0	0
WH/ZH	0.01	0.01	0.01
Total H	0.23	0.54	0.46
Data	9	32	11

Background Estimation

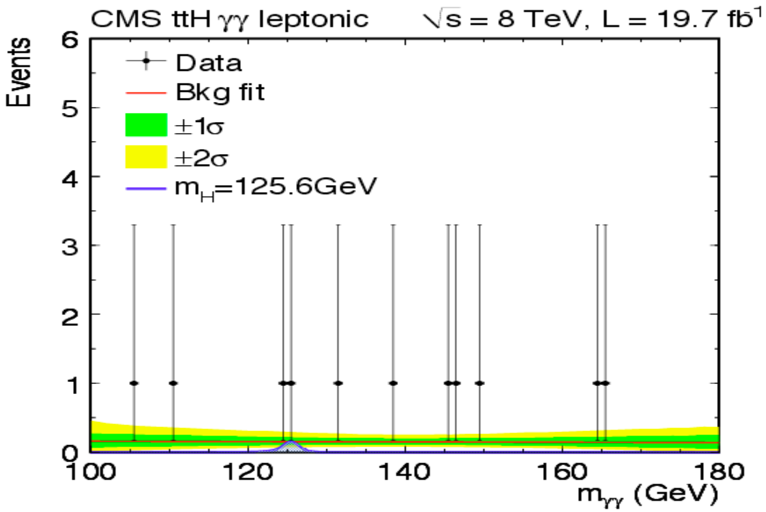
- **ATLAS:** fit with exponential function
- **CMS:** actual functional form included as a discrete nuisance parameter; exponentials, power-law functions, polynomials (in the Bernstein basis), and Laurent series are considered; all functions tried in the fit, with a penalty term added to 2NLL to account for number of free parameters in the fitted function.

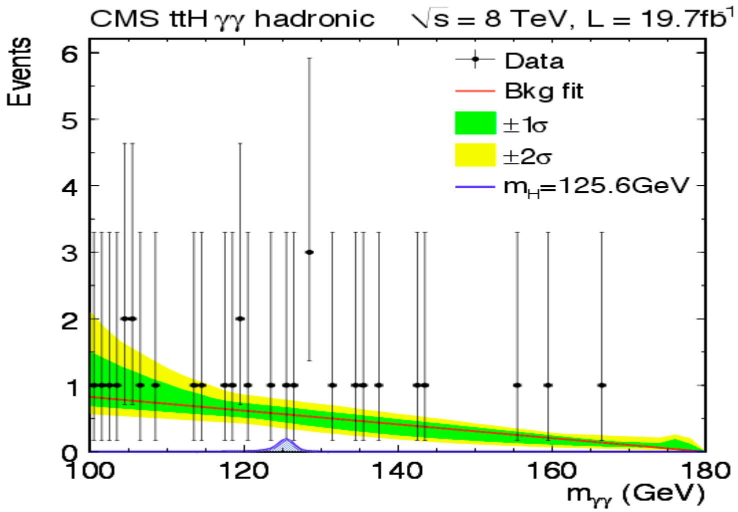
arXiv:1409.3122





arXiv:1408.1682





H→γγ Results

arXiv:1409.3122

- Observed (expected) limit @ M_H=125.4 GeV: 6.7xSM (4.9xSM)

Best-fit signal strength:

$$\boxed{\mu_{ttH} = 1.3^{+2.6}_{-1.8}}$$

Limits @ M_H=125.4 GeV

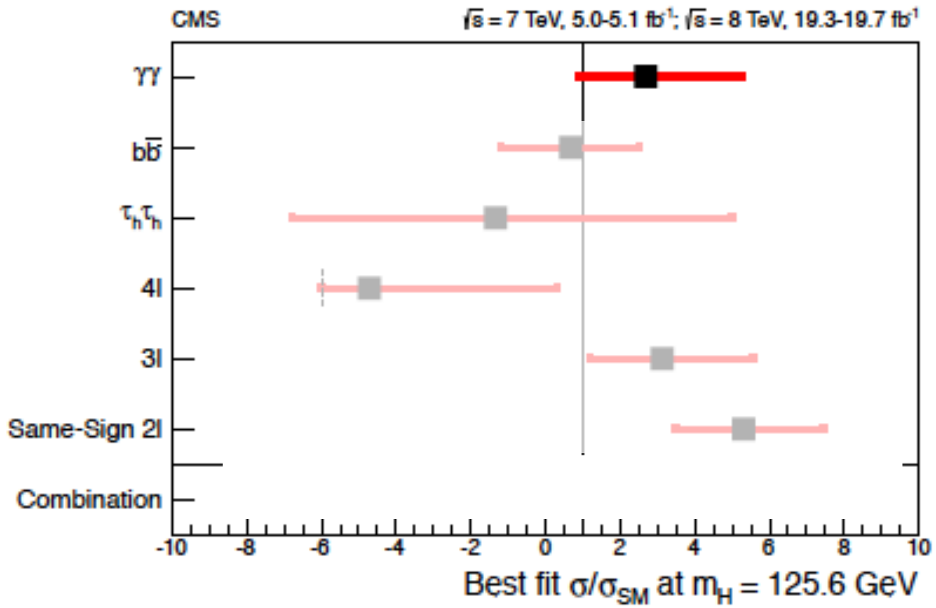
	Observed limit	Expected limit	$+2\sigma$	$+1\sigma$	-1σ	-2σ
Combined (with systematics)	6.7	4.9	11.9	7.5	3.5	2.6
Combined (statistics only)	6.3	4.7	10.5	7.0	3.4	2.5
Leptonic (with systematics)	10.7	6.6	16.5	10.1	4.7	3.5
Leptonic (statistics only)	10.2	6.4	15.1	9.6	4.6	3.4
Hadronic (with systematics)	9.0	10.1	25.4	15.6	7.3	5.4
Hadronic (statistics only)	8.5	9.5	21.4	14.1	6.8	5.1

arXiv:1408.1682

- Observed (expected) limit @ M_H=125.6 GeV: 7.4xSM (4.7xSM)

Best-fit signal strength:

$$\boxed{\mu_{ttH} = 2.7^{+2.6}_{-1.8}}$$



- Searches statistically-limited.
  Very small impact from systematic uncertainties.

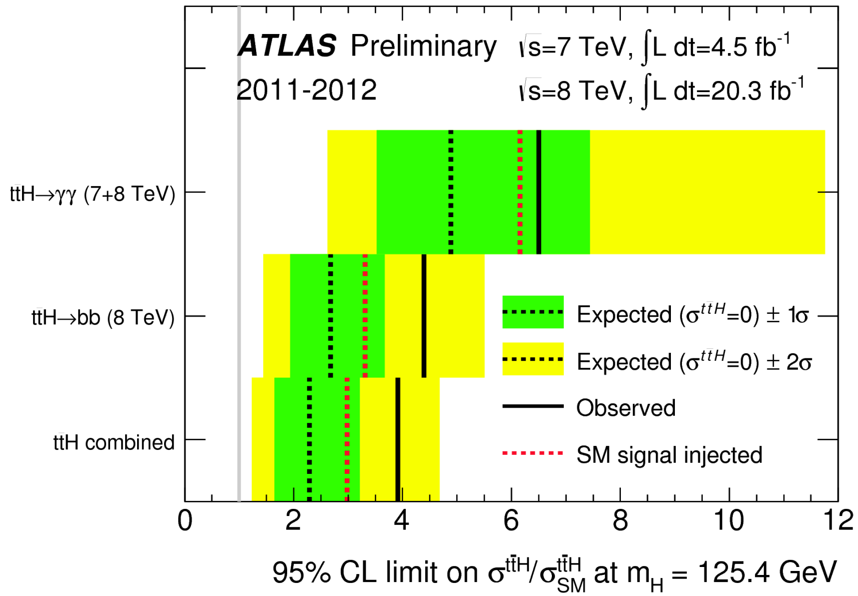
ATLAS γγ+bb Combination

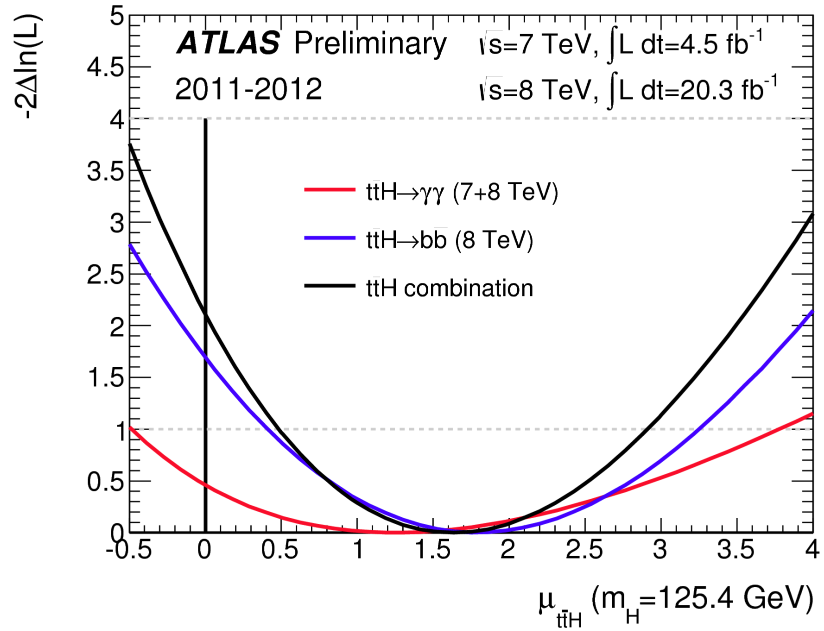
ATLAS-CONF-2014-043

- Combination of ttH(bb) and ttH(γγ) preliminary results.
- Observed (expected) limit @ M_H=125.4 GeV: 3.9xSM (2.3xSM)
- Best-fit signal strength @ M_H=125.4 GeV:

$$\boxed{\mu_{comb} = 1.6 \pm 1.2}$$

- Observed (expected) significance (wrt B-only hypothesis): 1.5σ (1.0σ)



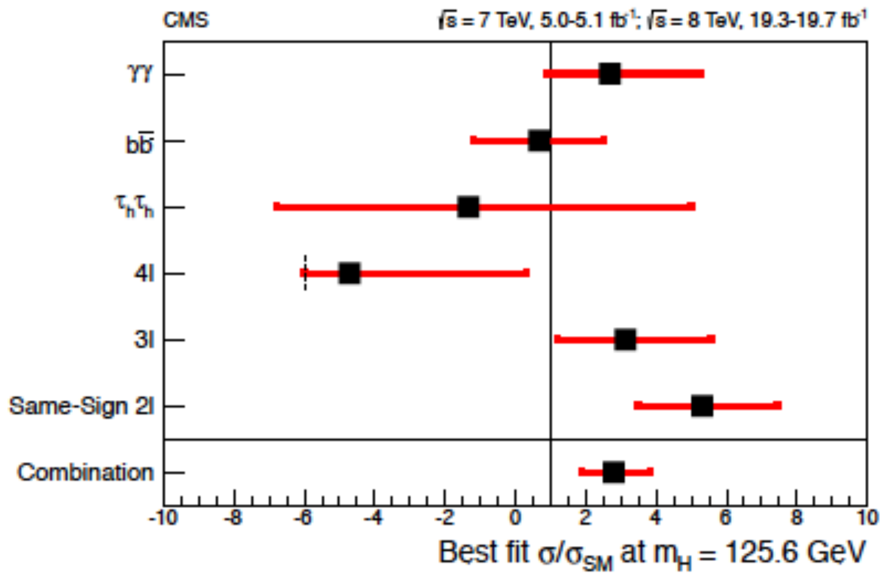


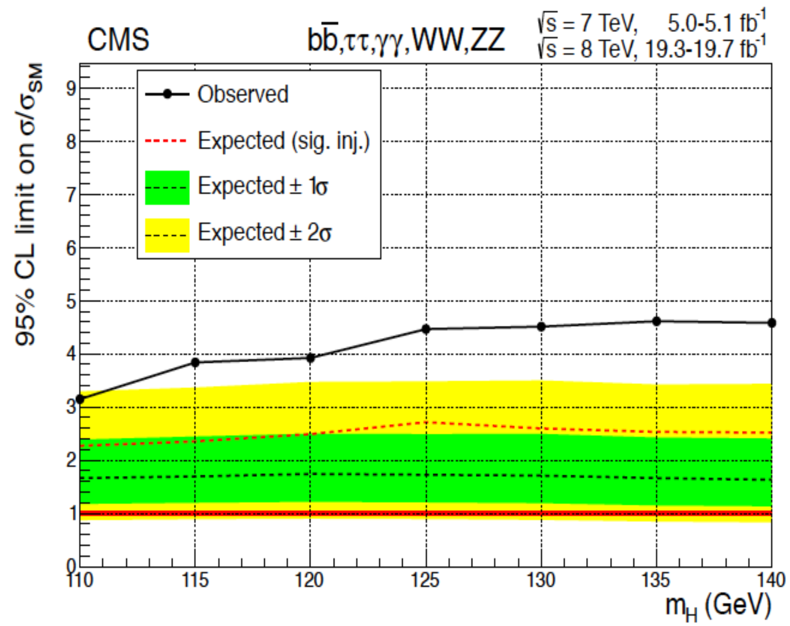
CMS Grand Combination

arXiv:1408.1682

- **Combination of CMS results (all pub results):**
  - H→bb (7+8 TeV)
  - H→ττ (8 TeV)
  - SS 2-lep, 3-lep, 4-lep (8 TeV)
  - H→γγ (7+8 TeV)
- Obs (exp) limit @ M_H=125.6 GeV: 4.5xSM (1.7xSM)
- Best-fit: $\boxed{\mu_{comb} = 2.8^{+1.1}_{-0.9}}$
  - Obs p-value(B)=0.04% →3.4σ
  - Obs p-value(SM)=2.0%

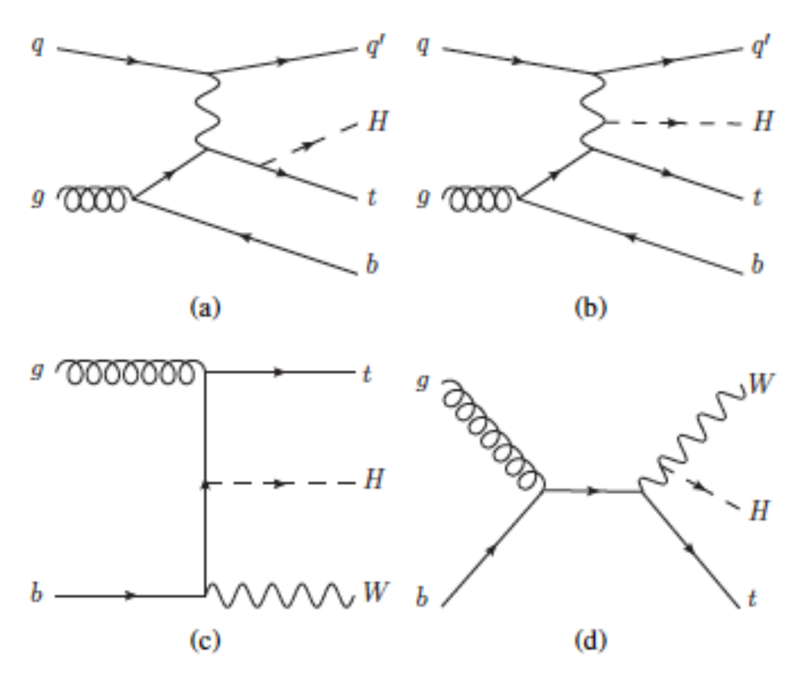
$t\bar{t}H$ channel	Best-fit μ	95% CL upper limits on $\mu = \sigma/\sigma_{SM}$ ($m_H = 125.6$ GeV)				
			Expected			
	Observed	Observed	Median signal-injected	Median	68% CL range	95% CL range
$\gamma\gamma$	$+2.7^{+2.6}_{-1.8}$	7.4	5.7	4.7	[3.1, 7.6]	[2.2, 11.7]
$b\bar{b}$	$+0.7^{+1.9}_{-1.9}$	4.1	5.0	3.5	[2.5, 5.0]	[1.9, 6.7]
$\tau_h\tau_h$	$-1.3^{+6.3}_{-5.5}$	13.0	16.2	14.2	[9.5, 21.7]	[6.9, 32.5]
4l	$-4.7^{+5.0}_{-1.3}$	6.8	11.9	8.8	[5.7, 14.3]	[4.0, 22.5]
3l	$+3.1^{+2.4}_{-2.0}$	7.5	5.0	4.1	[2.8, 6.3]	[2.0, 9.5]
Same-sign 2l	$+5.3^{+2.1}_{-1.8}$	9.0	3.6	3.4	[2.3, 5.0]	[1.7, 7.2]
Combined	$+2.8^{+1.0}_{-0.9}$	4.5	2.7	1.7	[1.2, 2.5]	[0.9, 3.5]

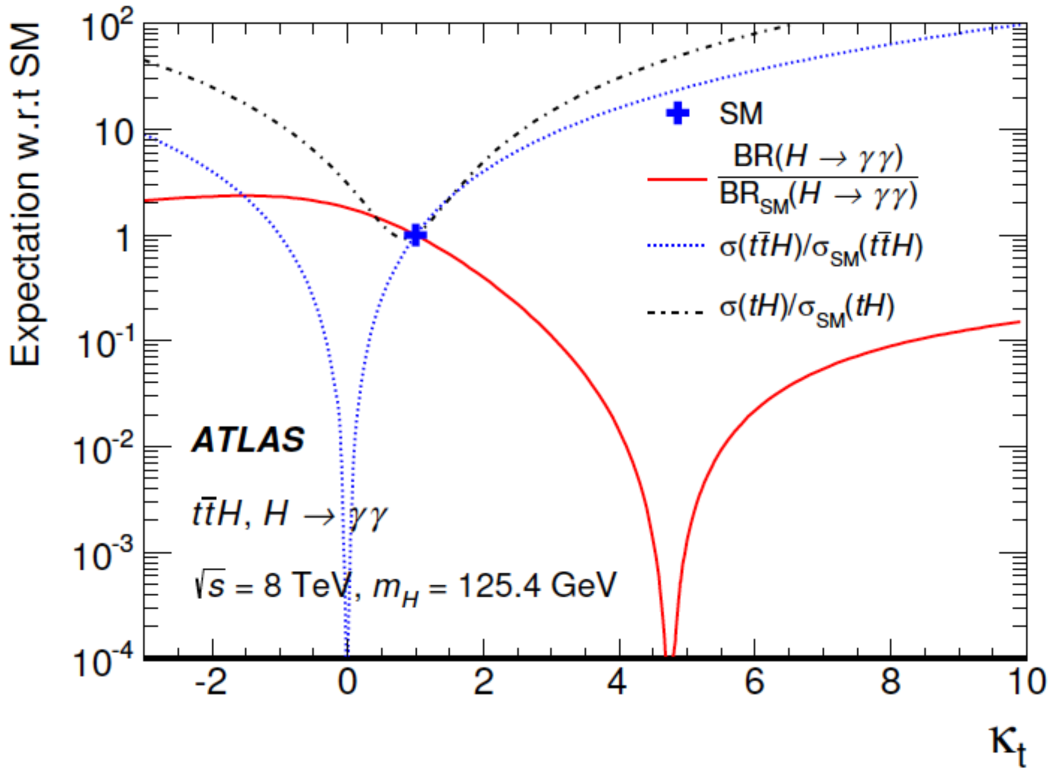


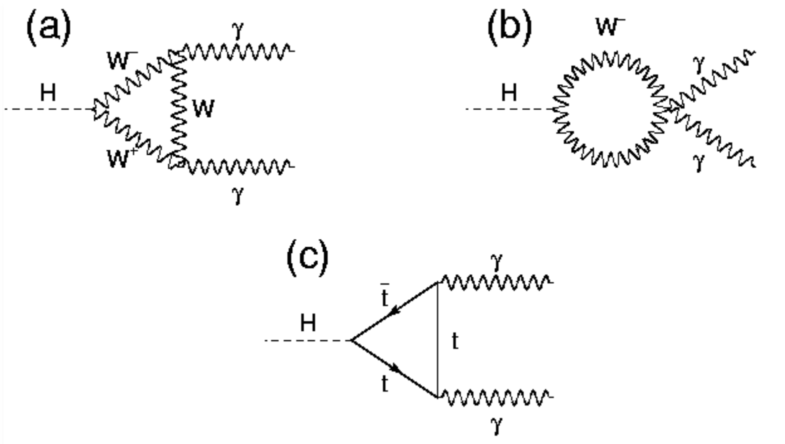


tH+X Production

- tH+X production highly suppressed in the SM.
  - Much smaller than ttH production.
- In the case of negative relative sign of the top-Higgs and W-Higgs coupling, destructive interference becomes constructive:
  - Increase in BR(H→γγ) by ~x2
  - Increase in σ(tH+X) by ~x10



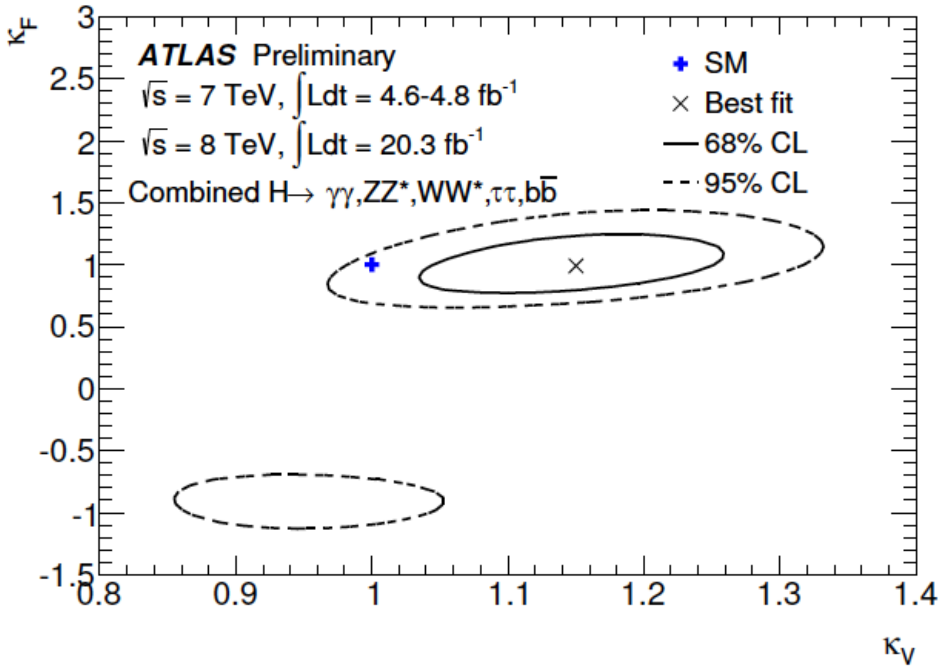


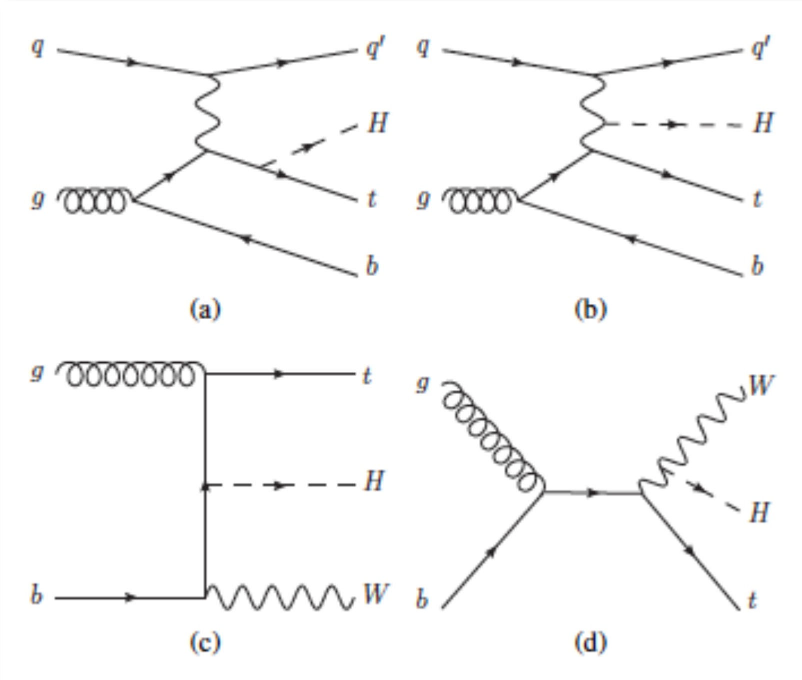


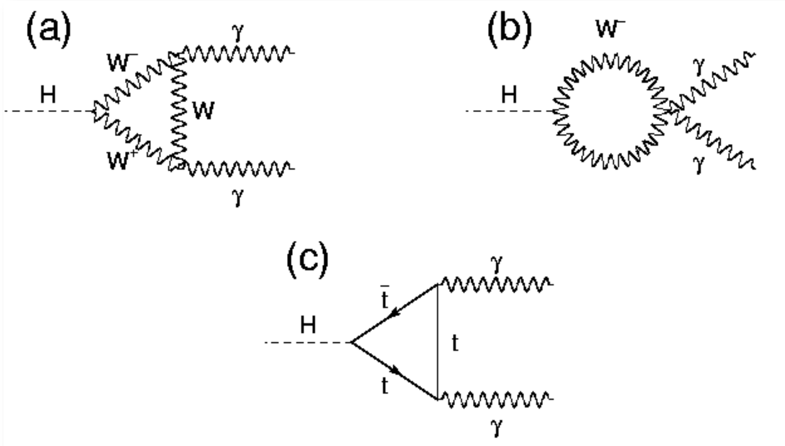
tH+X Production

- tH+X production highly suppressed in the SM.
  - Much smaller than ttH production.
- In the case of negative relative sign of the top-Higgs and W-Higgs coupling, destructive interference becomes constructive:
  - Increase in BR(H→$\gamma\gamma$) by ~x2
  - Increase in σ(tH+X) by ~x10
- Allows to break degeneracy in relative sign in coupling measurements:

ATLAS-CONF-2014-009



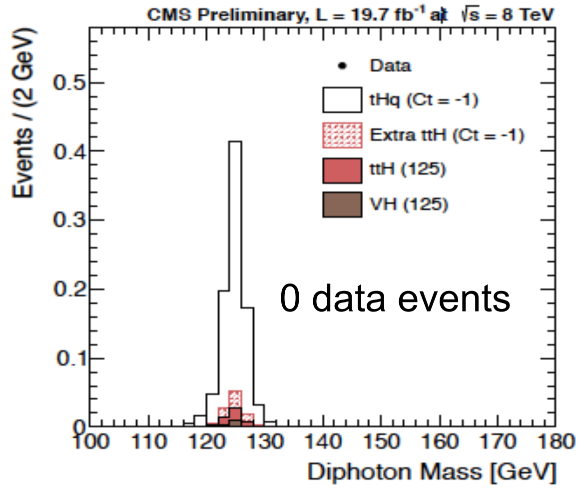




tH+X Production

- Dedicated analysis searching for tHq, H→γγ in the leptonic decay mode of the top quark.

Leading photon with $p_T > 50 \cdot m_{\gamma\gamma}/120$ GeV
Subleading photon with $p_T > 25$ GeV
Exactly one lepton (e/μ) with $p_T > 10$ GeV
At least one b-jet with $p_T > 20$ GeV
The hardest jet in the event which is not the b-Jet must have $p_T > 20$ GeV and $\lvert\eta\rvert > 1$
LD> 0.25

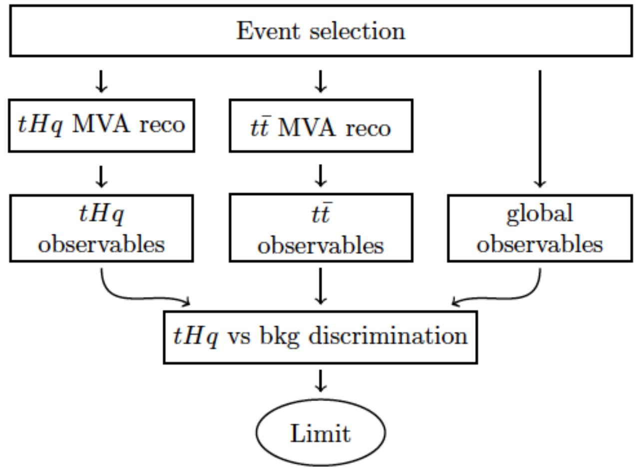


- Observed (exp) cross section limit: 4.1(4.1)$\sigma_{tHq}(\kappa_t=-1)$

CMS-PAS-HIG-14-001

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

- Dedicated analysis searching for tHq, H→bb in the leptonic decay mode of the top quark.
  - 1 lepton, E_T^{miss}>35/45 GeV, ≥4 jets p_T>30 GeV
    Consider ≥4 jets/≥3 tags or ≥5 jets/≥4 tags
    $S(\kappa_t=-1)/B$~0.7%-2%
  - Very sophisticated MVA analysis.



- Observed (exp) cross section limit: 7.6(5.1)$\sigma_{tHq}(\kappa_t=-1)$

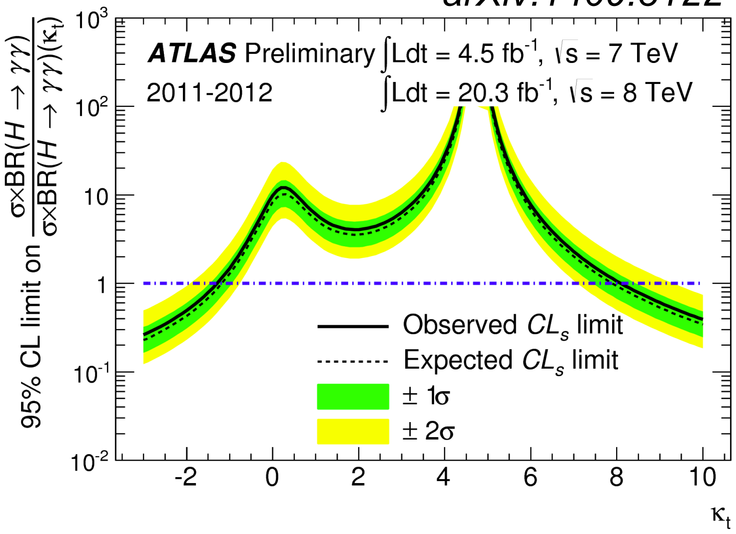
CMS-PAS-HIG-14-015

tH+X Production

- Reinterpretation of the inclusive ttH($\gamma\gamma$) search:
  - includes the tHqb and WtH signals (~+50% contribution from the latter)
  - Exploits effect on BR(H→$\gamma\gamma$) on both ttH and tH+X

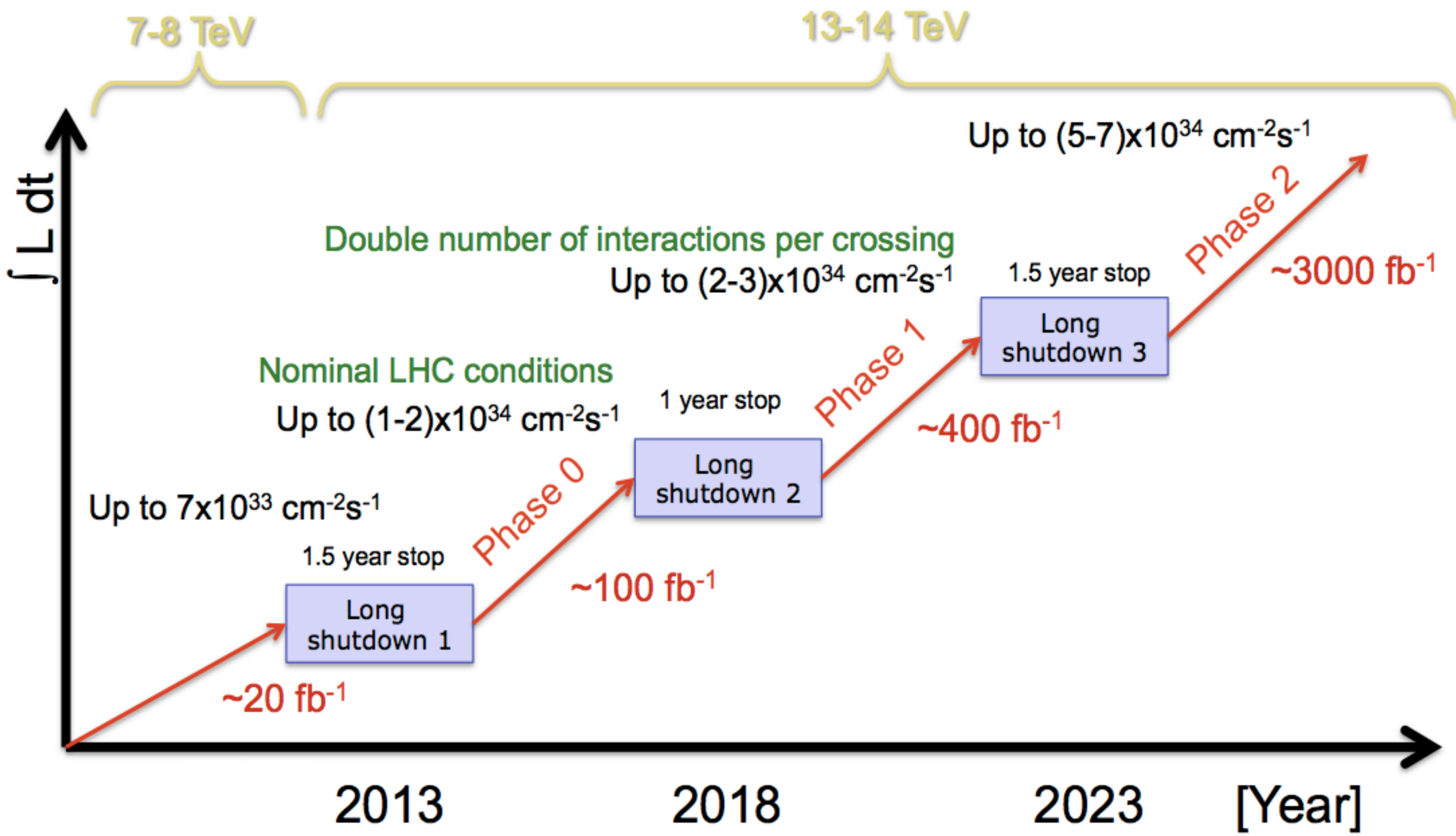
- 95% CL lower and upper observed (expected) limits on κ_t: $\kappa_t > -1.3$ (-1.2) and $\kappa_t < +8.1$ (+7.9)
  ➔ κ_t=-1 could be excluded with Run 1 data

arXiv:1409.3122



LHC Prospects

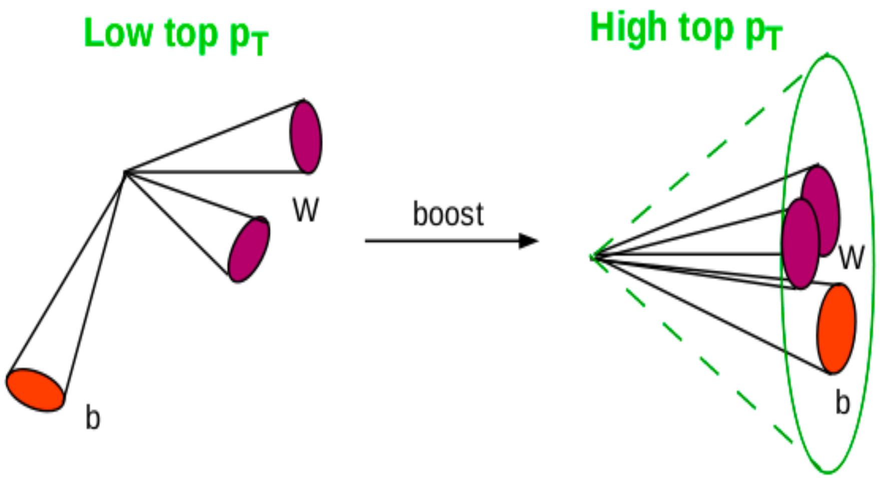
- Short term:
  - ATLAS searches using full Run 1 dataset ongoing in similar channels as for CMS. Expect results to be available before end of 2014.
  - Combination of ATLAS+CMS Run 1 results should be close to SM sensitivity!
- Longer term:
  - We are at the beginning of a 20-year program! Much potential to be exploited.



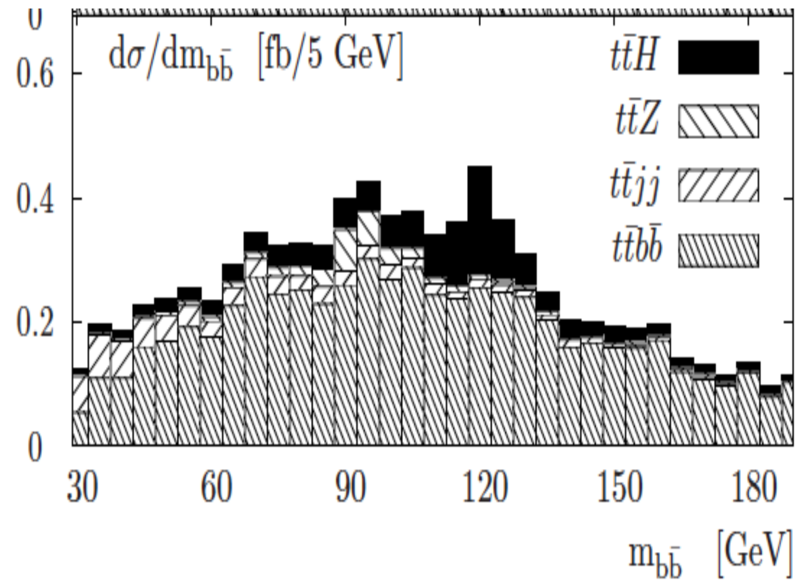
LHC Prospects

H→bb

- It has been pointed out that √s=14 TeV "boosted" analyses can potentially achieve ~5σ statistical significance with 100 fb^{-1}.
  - Requiring high enough p_T for hadronic top quark and/or Higgs boson allows to significantly reduce both physics and combinatorial backgrounds.
  - These techniques have by now become "standard" at the LHC experiments in searches for boosted bosons and top quarks.
  - Experimental searches for boosted ttH just starting. "Resolved" and "boosted" analyses will likely co-exists and be combined at the end.



PRL 104, 111801 (2010)



LHC Prospects

Multilepton (3-leptons and 4-leptons)

- Recently studied in the context of the European Strategy and Snowmass.
- Analysis still statistically limited with 300 fb^{-1}.
- At very high-luminosity (and pileup), sensitivity may be dominated by 4-leptons due to significant contribution from fake leptons in 3-leptons analysis.
- For 3000 fb^{-1}, experimental uncertainty on top Yukawa ~5%.
- Theoretical uncertainty on σ(ttH) adds 8% in quadrature!

arXiv:1307.7280

Stat. uncert. on σ(ttH)

Channel	300 fb^{-1}	3000 fb^{-1}
3ℓ only	25%	—%
4ℓ only	34%	12%
Combined	21%	9%

Syst. uncert. on σ(ttH)

Channel	300 fb^{-1}	3000 fb^{-1}
Top fake rate	17%	2%
$\sigma(t\bar{t}H)_{\mathrm{SM}}$	16%	16%
Other cross-section systematics	8%	3%
All systematics	27%	17%
Systematics without $\sigma(t\bar{t}H)_{\mathrm{SM}}$	18%	4%

H→γγ

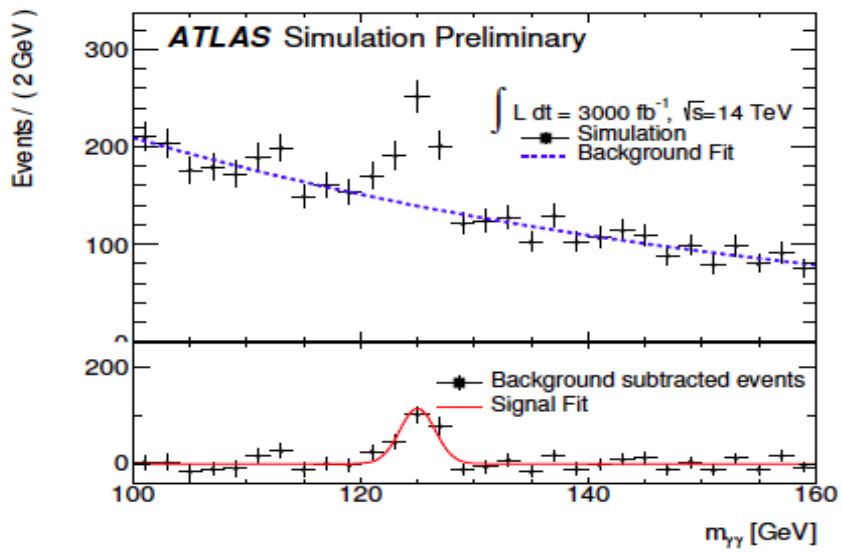
- Analysis statistically limited but theoretical uncertainty comparable:

  For 3000 fb^{-1} at $\sqrt{s}$=14 TeV:

  Expected uncertainty on signal strength ~20%

  ➔ 10% uncertainty on top Yukawa coupling

ATL-PHYS-PUB-2014-012

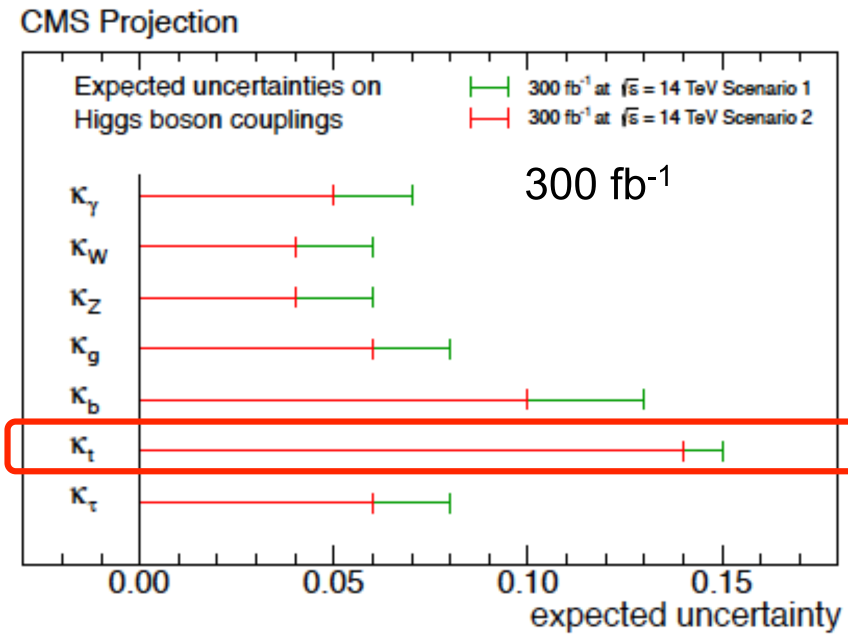


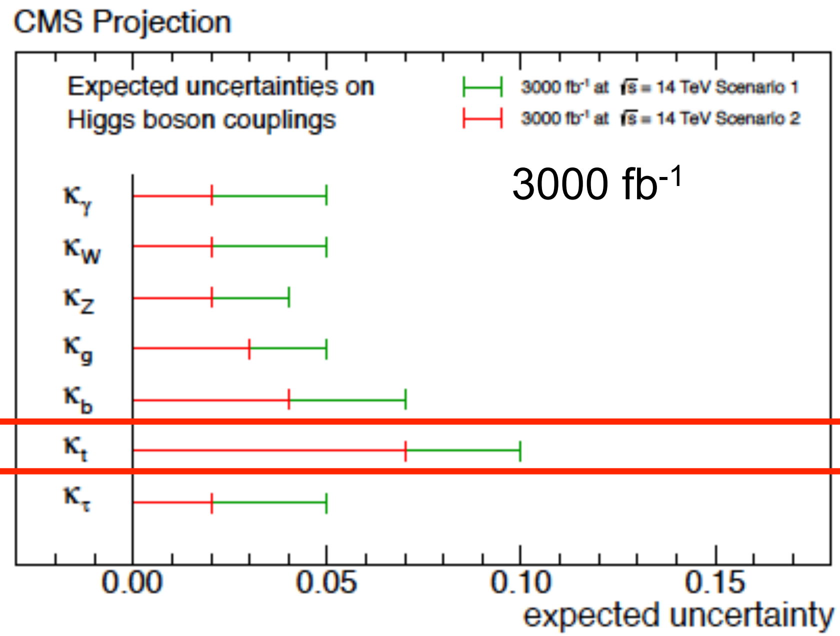
LHC Prospects

arXiv:1307.7135

Global Fit Analysis

- Extrapolation of global fit to Higgs couplings based on existing CMS Higgs analyses.
  - ttH: only considering H→γγ and H→bb. Will get better after including multileptons.
- Consider two scenarios:
  - Scenario 1: all systematic uncertainties are left unchanged.
  - Scenario 2: theoretical uncertainties are scaled by a factor of 1/2, while other systematic uncertainties are scaled by the square root of the integrated luminosity.





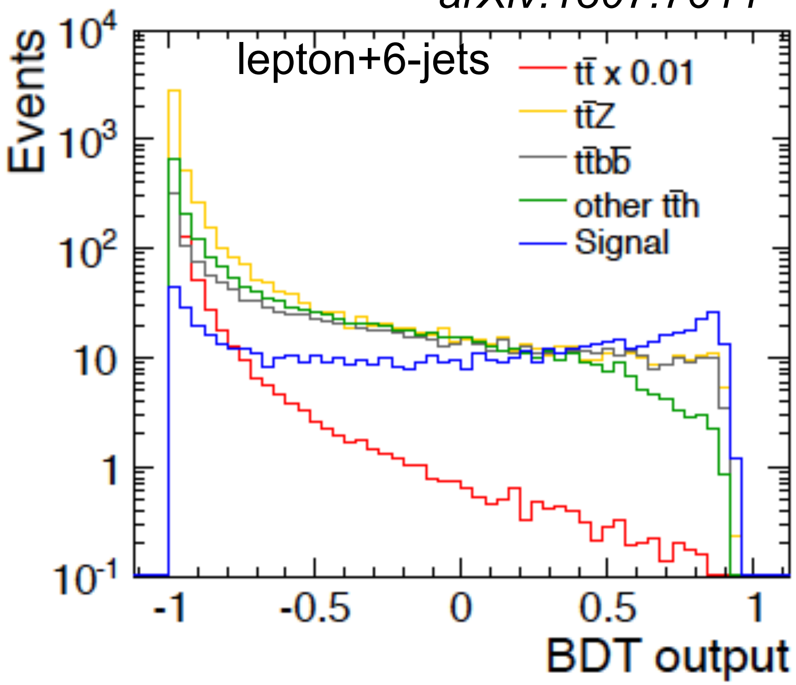
Tentative conclusion: a ~5% uncertainty on the top Yukawa coupling at the LHC should be achievable!

LC Prospects

- The precise measurement of the top Yukawa coupling has traditionally been considered as something that only the LC could do.
- The most recent feasibility studies are finally based on full simulation and employing realistic reconstruction algorithms.
- Example: ttH, H→bb
  - √s=1 TeV, and 1 ab^{-1} equally split between (P_{e-},P_{e+})=(-0.8,+0.2) and (+0.8,-0.2)
  - Consider lepton+6-jets and 8-jets channels.
  - Train BDT to separate signal from background.
  - Apply BDT cut to maximize S/√S+B.
  - ➔ Expected stat. error on top Yukawa: 4.5%

- At √s=500 GeV it becomes more challenging:
  - σ($t\bar{t}$H) down by x10, σ($t\bar{t}$) up by x2.5
  - However, $t\bar{t}$H is enhanced by x2 due to $t\bar{t}$ bound effects, and $t\bar{t}$H and $t\bar{t}$ another x2 if using beam polarization.
  - ➔ Expected stat. error on top Yukawa: ~10%

arXiv:1307.7644



After BDT cut *arXiv:1307.7644*

Final state	BDT trained to select 6 jets
$t\bar{t}H$, $H \to b\bar{b}$ (6 jets)	264.9
$t\bar{t}H$, $H \to b\bar{b}$ (8 jets)	72.6
$t\bar{t}H$, H not $b\bar{b}$ (6 jets)	11.7
$t\bar{t}H$, H not $b\bar{b}$ (8 jets)	4.3
$t\bar{t}H$ (4 jets)	32.8
$t\bar{t}Z$	188.4
$t\bar{t}g^* \to t\bar{t}b\bar{b}$	185.0
$t\bar{t}$	459.3

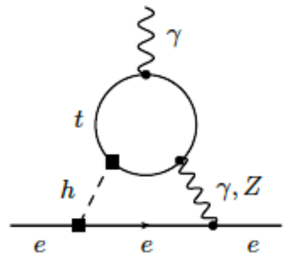
S/B~1/3

Exciting Opportunities at High Lumi/Energy

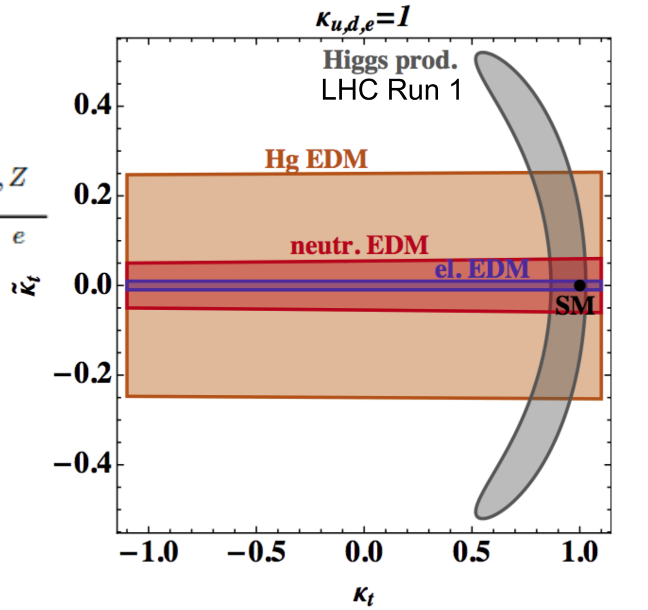
- High statistics samples will allow to probe a CP mixing in the top-Higgs interaction.

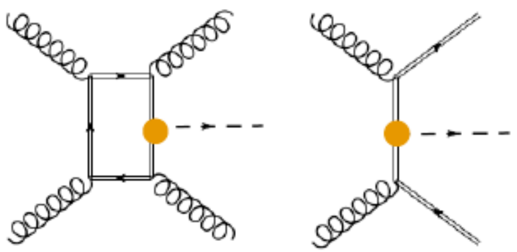
$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}}\left(\kappa_f \bar{f} f + i\tilde{\kappa}_f \bar{f}\gamma_5 f\right) h$$

- Inclusive gg→H production only probes a combination of both couplings.
- Indirect constraints from-eEDM very strong, yet assume:
  - SM couplings for the light fermions
  - No other states present in the spectrum
- There are ways to directly access CP mixing.



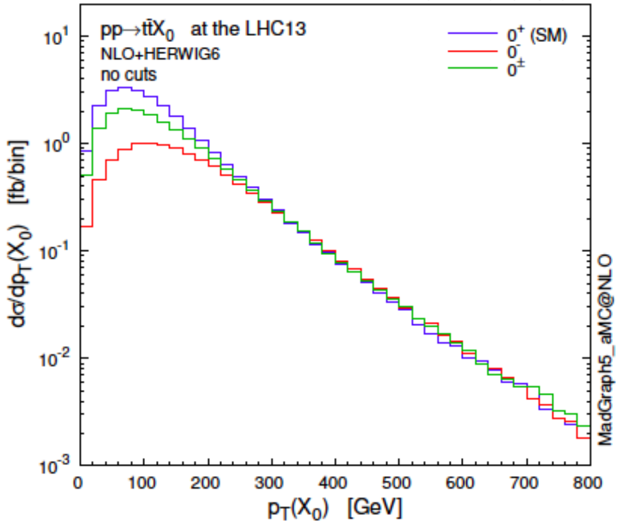
arXiv:1310.1385



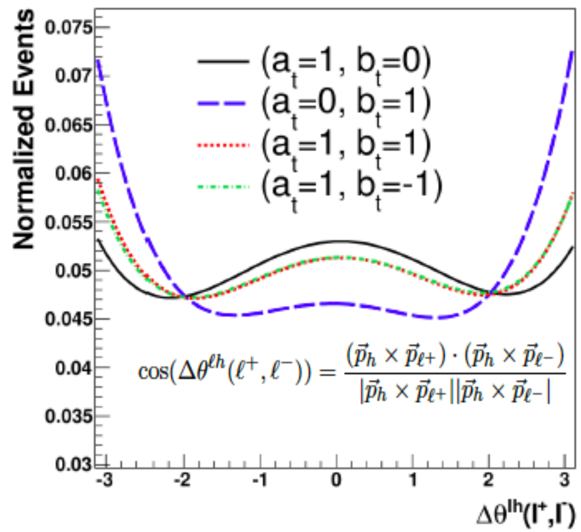


pp→Hjj pp→ttH

arXiv:1407.5089



arXiv:1501.03157



Exciting Opportunities at High Lumi/Energy

- In addition to the total rate, exploit kinematic distributions, which can be affected significantly at high p_T by some operators

  E.g. chromomagnetic dipole moment

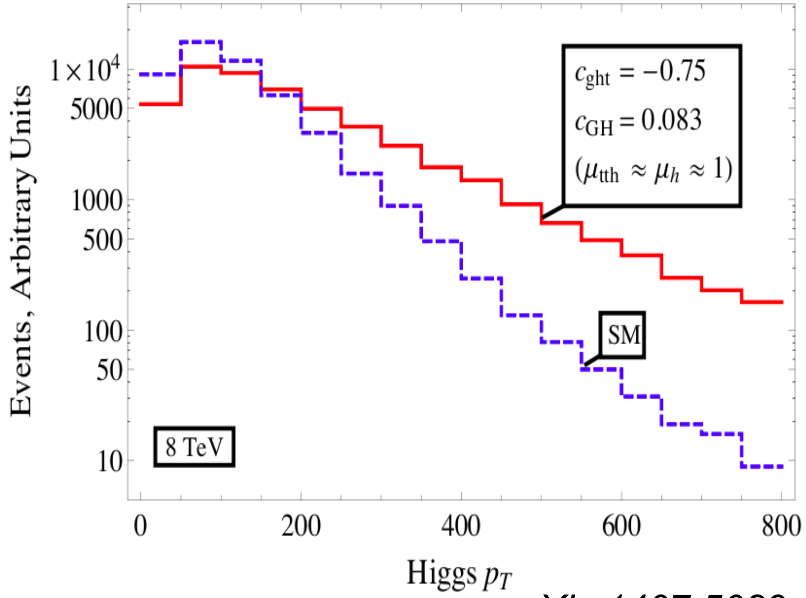
$$\frac{Q^\dagger \, H \, \sigma_{\mu\nu} \, t^c \, G^{\mu\nu}}{\Lambda^2}$$

- Combination of resolved and boosted ttH analyses should allow to probe anomalous top-Higgs couplings. E.g. from signal strength as a function of Higgs p_T.

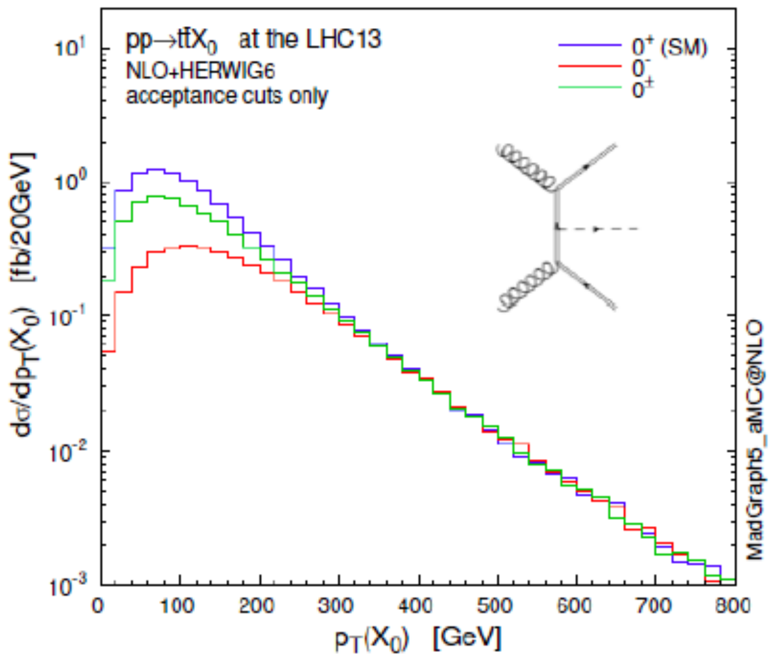
- Eventually should plan on grand combination from complete set of sensitive measurements for more model-indep interpretation within EFT.

- At a 100 TeV collider a large fraction of ttH events will have tops and Higgs boosted, representing a change in paradigm on how to analyze these events and bringing new opportunities for studies. Studies barely starting.

arXiv:1402.5985



arXiv:1407.5089



Summary and Outlook

- The precise measurement of the top Yukawa coupling may provide insights on the underlying mechanism for EWSB and whether or not the top quark plays a role in it.

- The program of searches for $t\bar{t}H$ production at the LHC is well underway, with all main decay modes being explored ($H \rightarrow b\bar{b}$, $\tau\tau$, WW and ZZ):
  - $H \rightarrow b\bar{b}$ has turned out to be just as challenging as anticipated. Much experience has been gained on how to reduce the impact from systematic uncertainties that led to abandon this channel in the past, by exploiting high-statistics data samples.

    Recent progress on the theoretical description of the dominant $t\bar{t}$+jets background should be exploited moving forward. Jet substructure techniques potentially promising in this channel.
  - At the same time, searches for $t\bar{t}H$ in diphoton and multilepton final states are showing interesting sensitivity that can be competitive with (or even exceed) that of $H \rightarrow b\bar{b}$.

  ➔ Very exciting prospects for LHC Run 2!

- The very high-statistics samples at the HL-LHC will allow incisive tests of top-Higgs interactions. Studies are starting on what opportunities would a 100 TeV collider bring.

Extra

Event Selections

"Signal-rich" categories

Dileptons channel

ATLAS EXPERIMENT

ee, $\mu\mu$, eμ final states
lepton p_T>25/15 GeV
≥ 2 jets, p_T>25 GeV (anti-k_T R=0.4)
≥ 2 b-tags

Divide into 6 categories:
2 jets (2 b-tags)
3 jets (2, 3 b-tags)
≥ 4 jets (2, 3, ≥ 4 b-tags)

CMS

ee, $\mu\mu$, eμ final states
tight/loose lepton, p_T>20/10 GeV
≥ 2 jets, p_T>30 GeV (anti-k_T R=0.5)
≥ 2 b-tags

Divide into 3 categories:
3 jets (2 b-tags)
≥ 4 jets (2 b-tags)
≥ 3 jets (≥ 3 b-tags)

Tau channel

CMS

=1 isolated e or μ, p_T>30 GeV and
≥2 1-prong τ_{had}, p_T>20 GeV
≥ 2 jets, p_T>30 GeV (anti-k_T R=0.5)
1 or 2 b-tags

Divide into 6 categories:
2 jets (1, 2 b-tags)
3 jets (1, 2 b-tags)
≥ 4 jets (1, 2 b-tags)

LC Prospects

- Feasibility studies at the LC have shown that a precision on the top Yukawa coupling of 10%(5%) can be achieved at $\sqrt{s}$=500 GeV (1 TeV) with 1 ab^{-1}.

  However:

  - Studies were largely based on fast simulation and not using ME+PS MCs to predict $t\bar{t}$+jets background
  - In the best case scenario ad-hoc uncertainties on the background of 5-10% were assigned. Are those justified?

  On the bright side, much of the experience and developments necessary to carry out this measurement at the LHC will be beneficial to the ILC:

  - Precise theoretical predictions for signal and backgrounds via e.g. MEPS@NLO.
  - Profiling of systematic uncertainties.

- Can the LHC measure the top-Higgs Yukawa coupling to ~10% or better?
  - A 10% measurement means ~5σ significance.
  - Advanced analysis techniques may resurrect H→bb as a discovery mode.
  - New channels not considered before (H→$\gamma\gamma$, multileptons), have irrupted into the scene with surprisingly good sensitivity and have great potential.

Systematic Uncertainties

% change in background yield in ≥6 jets/≥4 tags

Uncertainties of the sum of $t\bar{t}$+lf, $t\bar{t}$+b, $t\bar{t}+b\bar{b}$, and $t\bar{t}+c\bar{c}$ events with ≥ 6 jets and ≥ 4 b-tags		
Source	Rate	Shape?
QCD Scale (all $t\bar{t}$+hf)	35%	No
QCD Scale ($t\bar{t}+b\bar{b}$)	17%	No
b-Tag bottom-flavor contamination	17%	Yes
QCD Scale ($t\bar{t}+c\bar{c}$)	11%	No
Jet Energy Scale	11%	Yes
b-Tag light-flavor contamination	9.6%	Yes
b-Tag bottom-flavor statistics (linear)	9.1%	Yes
QCD Scale ($t\bar{t}$+b)	7.1%	No
Madgraph Q^2 Scale ($t\bar{t}+b\bar{b}$)	6.8%	Yes
b-Tag Charm uncertainty (quadratic)	6.7%	Yes
Top p_T Correction	6.7%	Yes
b-Tag bottom-flavor statistics (quadratic)	6.4%	Yes
b-Tag light-flavor statistics (linear)	6.4%	Yes
Madgraph Q^2 Scale ($t\bar{t}+2$ partons)	4.8%	Yes
b-Tag light-flavor statistics (quadratic)	4.8%	Yes
Luminosity	4.4%	No
Madgraph Q^2 Scale ($t\bar{t}+c\bar{c}$)	4.3%	Yes
Madgraph Q^2 Scale ($t\bar{t}$+b)	2.6%	Yes
QCD Scale ($t\bar{t}$)	3%	No
pdf (gg)	2.6%	No
Jet Energy Resolution	1.5%	No
Lepton ID/Trigger efficiency	1.4%	No
Pileup	1%	No
b-Tag Charm uncertainty (linear)	0.6%	Yes

CMS PAS HIG-13-019

Assume 50% uncertainty on $t\bar{t}b\bar{b}$, $t\bar{t}b$ and $t\bar{t}c\bar{c}$ (uncorrelated among them) **AD-HOC!!**

- Many systematic uncertainties, both theoretical and experimental.
- Background systematics much larger than expected signal yield!

Total background uncertainty: ~37%
Expected S/B: ~3.3%

ttH, H→bb Event Yields: Lepton+Jets

ATLAS EXPERIMENT

μ=1.7

	5 jets, ≥ 4 b-tags	≥ 6 jets, 3 b-tags	≥ 6 jets, ≥ 4 b-tags
$t\bar{t}H$ (125)	$11 \pm 1 \pm 9$	$69 \pm 3 \pm 57$	$28 \pm 2 \pm 23$
$t\bar{t}$+ light	78 ± 9	2380 ± 130	78 ± 11
$t\bar{t} + c\bar{c}$	45 ± 12	750 ± 190	75 ± 19
$t\bar{t} + b\bar{b}$	149 ± 20	1160 ± 170	300 ± 40
$t\bar{t} + V$	3.3 ± 1.0	44 ± 13	8.9 ± 2.7
non-$t\bar{t}$	23.2 ± 2.5	218 ± 23	18.8 ± 2.2
Total	309 ± 11	4620 ± 80	507 ± 27
Data	283	4671	516

CMS

μ=1.0

	≥6 jets + 2 b-tags	4 jets + 3 b-tags	5 jets + 3 b-tags	≥6 jets + 3 b-tags	4 jets + 4 b-tags	5 jets + ≥4 b-tags	≥6 jets + ≥4 b-tags
$t\bar{t}$H(125.6 GeV)	28.5 ± 2.5	12.4 ± 1.0	18.1 ± 1.5	18.9 ± 1.5	1.5 ± 0.2	4.4 ± 0.4	6.7 ± 0.6
$t\bar{t}$+lf	7140 ± 310	4280 ± 150	2450 ± 130	1076 ± 74	48.4 ± 10.0	54 ± 12	44 ± 11
$t\bar{t}$+b	570 ± 170	364 ± 94	367 ± 98	289 ± 87	20.0 ± 5.5	28.6 ± 8.0	33 ± 10
$t\bar{t} + b\bar{b}$	264 ± 59	123 ± 29	193 ± 42	232 ± 49	15.8 ± 3.6	45.2 ± 9.7	86 ± 18
$t\bar{t} + c\bar{c}$	2420 ± 300	690 ± 130	800 ± 130	720 ± 110	29.7 ± 5.6	55 ± 11	81 ± 13
$t\bar{t}$+W/Z	85 ± 11	15.0 ± 2.0	20.9 ± 2.8	24.7 ± 3.3	1.0 ± 0.2	2.1 ± 0.4	4.7 ± 0.8
Single t	236 ± 18	213 ± 17	101.7 ± 10.0	47.7 ± 6.7	2.8 ± 1.4	7.5 ± 3.8	6.7 ± 2.6
W/Z+jets	75 ± 27	46 ± 30	13 ± 12	7.7 ± 8.8	1.1 ± 1.2	0.9 ± 1.0	0.3 ± 0.8
Diboson	4.5 ± 1.0	5.4 ± 0.9	2.0 ± 0.5	1.0 ± 0.4	0.2 ± 0.2	0.1 ± 0.1	0.2 ± 0.1
Total bkg	10790 ± 200	5730 ± 110	3935 ± 74	2394 ± 65	119.0 ± 8.2	193.4 ± 10.0	256 ± 16
Data	10724	5667	3983	2426	122	219	260

ttH, H→bb Event Yields: Dileptons

ATLAS EXPERIMENT

μ=1.7

	2 jets, 2 b-tags	3 jets, 2 b-tags	3 jets, 3 b-tags	$\geq$ 4 jets, 2 b-tags	$\geq$ 4 jets, 3 b-tags	$\geq$ 4 jets, $\geq$ 4 b-tags
$t\bar{t}H$ (125)	$2.7 \pm 0.2 \pm 2.2$	$9.4 \pm 0.5 \pm 7.7$	$3.7 \pm 0.3 \pm 3.0$	$27 \pm 1 \pm 22$	$14.9 \pm 0.6 \pm 12.3$	$4.7 \pm 0.3 \pm 3.9$
$t\bar{t}$+ light	14140 ± 150	8700 ± 140	122 ± 14	4810 ± 130	161 ± 20	2.0 ± 0.4
$t\bar{t} + c\bar{c}$	99 ± 29	390 ± 110	67 ± 18	520 ± 140	119 ± 31	4.9 ± 1.2
$t\bar{t} + b\bar{b}$	121 ± 19	270 ± 40	153 ± 23	320 ± 50	242 ± 35	39 ± 5
$t\bar{t} + V$	4.7 ± 1.4	11.2 ± 3.3	1.0 ± 0.3	24 ± 7	4.2 ± 1.3	0.59 ± 0.18
non-$t\bar{t}$	920 ± 100	570 ± 60	22.3 ± 3.2	340 ± 40	31 ± 4	2.0 ± 0.4
Total	15290 ± 110	9960 ± 80	369 ± 14	6040 ± 60	572 ± 17	53 ± 4
Data	15296	9997	374	6026	561	46

CMS

μ=1.0

	3 jets + 2 b-tags	$\geq$4 jets + 2 b-tags	$\geq$3 b-tags
$t\bar{t}H(125.6\,GeV)$	7.4 ± 0.6	14.5 ± 1.2	10.0 ± 0.8
$t\bar{t}$+lf	7650 ± 170	3200 ± 120	227 ± 35
$t\bar{t}$+b	210 ± 55	198 ± 57	160 ± 43
$t\bar{t} + b\bar{b}$	50 ± 13	76 ± 17	101 ± 21
$t\bar{t} + c\bar{c}$	690 ± 110	761 ± 97	258 ± 46
$t\bar{t}$+W/Z	29.5 ± 3.8	50.5 ± 6.4	10.9 ± 1.5
Single t	218 ± 16	95.2 ± 8.8	14.6 ± 3.6
W/Z+jets	217 ± 52	98 ± 28	21 ± 15
Diboson	9.5 ± 0.9	2.9 ± 0.4	0.6 ± 0.1
Total bkg	9060 ± 130	4475 ± 82	793 ± 28
Data	9060	4616	774

Probing Higgs Couplings

- Several production and decay mechanisms contribute to signal rates per channel
  ➔ interpretation is difficult
- A better option: measure deviations of couplings from the SM prediction (*arXiv:1209.0040*).
  Basic assumptions:
  - there is only one underlying state with m_H=125.5 GeV,
  - it has negligible width,
  - it is a CP-even scalar (only allow for modification of coupling strengths, leaving the Lorentz structure of the interaction untouched).
- Under these assumptions all production cross sections and branching ratios can be expressed in terms of a few common multiplicative factors to the SM Higgs couplings.
  Examples:

$$\sigma(gg \to H)BR(H \to WW) = \sigma_{SM}(gg \to H)BR_{SM}(H \to WW)\frac{\kappa_g^2\kappa_W^2}{\kappa_H^2}$$

$$\sigma(WH)BR(H \to bb) = \sigma_{SM}(WH)BR_{SM}(H \to bb)\frac{\kappa_W^2\kappa_b^2}{\kappa_H^2}$$

$$\kappa_g = f(\kappa_t, \kappa_b, m_H)$$

$$\kappa_H = f'(\kappa_t, \kappa_b, \kappa_\tau, \kappa_W, \kappa_Z, m_H)$$

$t\bar{t}$+jets Modeling: A Long Road Ahead

Disclaimer: this is my personal view

- **The Problem**:
  - No good feeling for how accurate current $t\bar{t}$+jets/HF ME+PS MCs are.
  - Assigned systematic uncertainties are “ad-hoc”. No good understanding for what normalization and shape systematics should be considered and correlations among topologies. Unclear whether we are being too conservative or too aggressive.
  - We’ll need a solid quantitative understanding before we can confidently establish a signal in this channel.

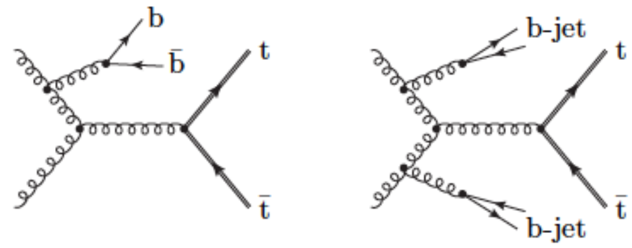
- S. Pozzorini: *“What’s needed to quantify $t\bar{t}$+jets/HF systematics in a meaningful way and reduce it to a decent (say 10-30%) level is MEPS@NLO $t\bar{t}$+0,1,2 jets (plus extra LO MEs up to 4,5 jets).”*

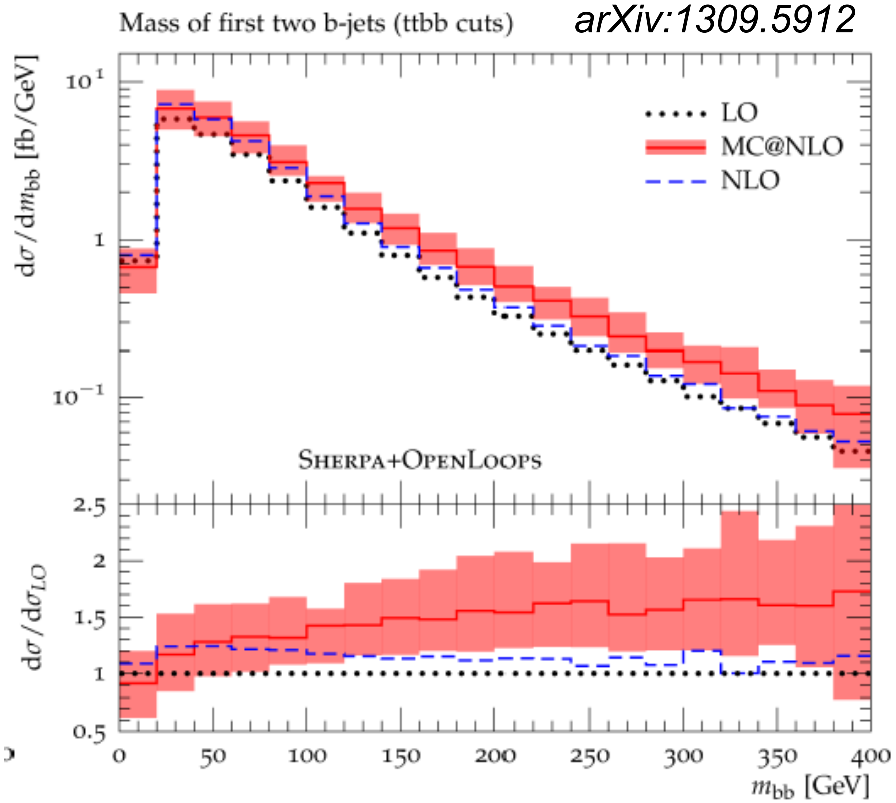
Current state-of-art

	matrix elements	$0j$	$1j$	$2j$	$3j$	$\geq 4j$
LO+PS	$t\bar{t}+2$ jets	-	-	LO	PS	PS
MEPS@LO	$t\bar{t}+0,1,2,3$ jets	LO	LO	LO	LO	PS
MC@NLO	$t\bar{t}+2$ jets	-	-	NLO	LO	PS
MEPS@NLO	$t\bar{t}+0,1,2$ jets	NLO	NLO	NLO	LO	PS

$t\bar{t}$+jets Modeling: A Long Road Ahead

- As a first step towads MEPS@NLO, it'd be quite important to perform detailed comparisons of various LO and NLO accurate simulations (w/ PS).
- **Recent progress:**
  - First complete MC@NLO simulation (within Sherpa/OpenLoops) for $t\bar{t}b\bar{b}$ at the LHC, including mass effects.
  - Allows covering the full ttbb phase space at NLO accuracy including collinear g→$b\bar{b}$ splitting.





arXiv:1309.5912

Parton-level jets:
p_T>25 GeV, |η|<2.5, Anti-kT R=0.4
No hadronization, no underlying event

	ttb	ttbb	ttbb($m_{bb} > 100$)
σ_{LO}[fb]	$2547^{+71\%\,+14\%}_{-37\%\,-11\%}$	$463.9^{+66\%\,+15\%}_{-36\%\,-12\%}$	$123.7^{+62\%\,+17\%}_{-35\%\,-13\%}$
σ_{NLO}[fb]	$3192^{+33\%\,+4.6\%}_{-25\%\,-4.9\%}$	$557^{+28\%\,+5.6\%}_{-24\%\,-4.0\%}$	$141^{+25\%\,+8.6\%}_{-22\%\,-3.8\%}$
σ_{NLO}/σ_{LO}	1.25	1.20	1.14
σ_{MC}[fb]	$3223^{+33\%\,+4.3\%}_{-25\%\,-2.5\%}$	$607^{+25\%\,+2.2\%}_{-22\%\,-2.8\%}$	$186^{+21\%\,+5.4\%}_{-20\%\,-4.7\%}$
σ_{MC}/σ_{NLO}	1.01	1.09	1.32
σ^{2b}_{MC}[fb]	3176	539	145
$\sigma^{2b}_{MC}/\sigma_{NLO}$	0.99	0.97	1.03

Significant contribution from double collinear g→$b\bar{b}$ splitting at high m_{bb} (one of them from the parton shower)

Profiling in Action: Example Plots

- Can exploit high-statistics control samples to constrain the leading syst. uncertainties.
- But need sophisticated enough treatment to not artificially overconstrain them!

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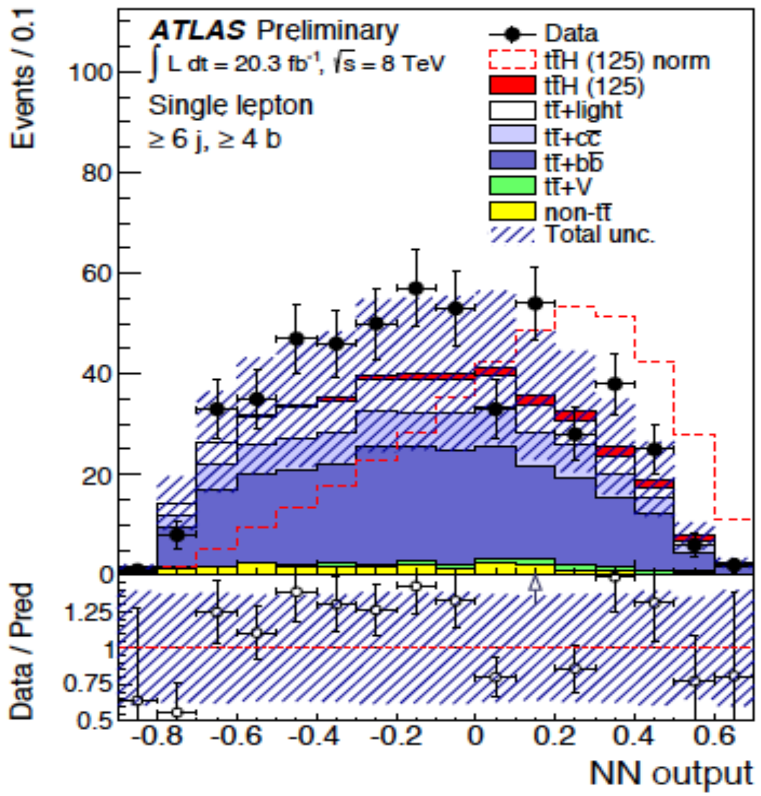
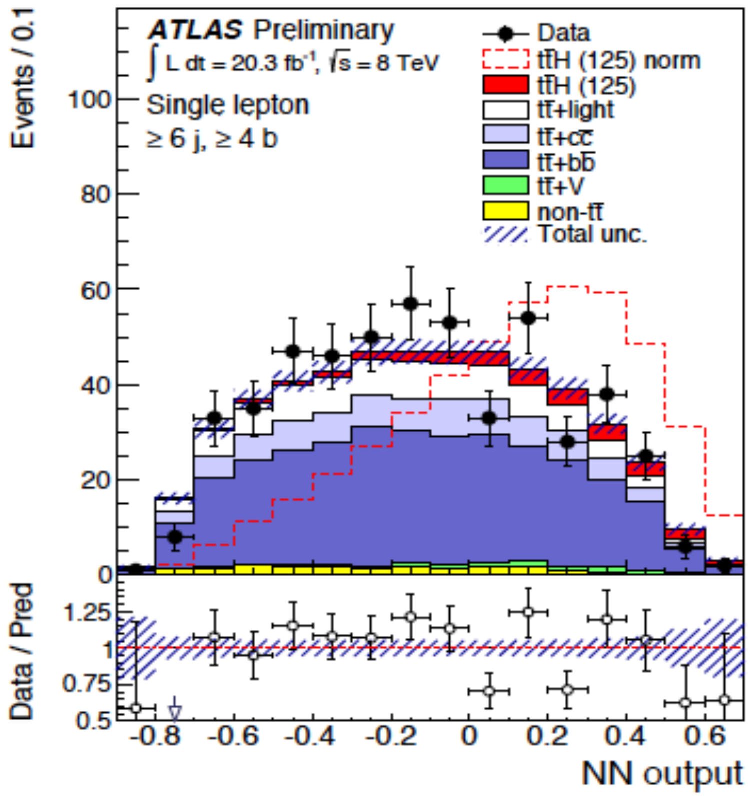
Pre-Fit



Post-Fit (S+B)

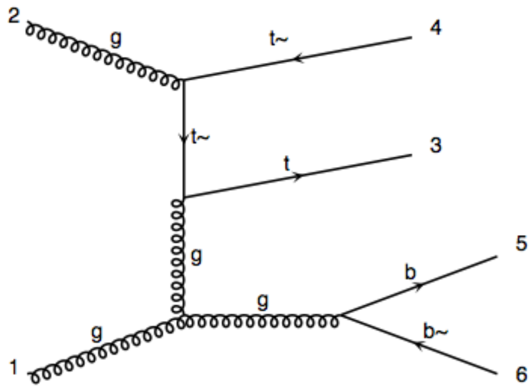


Total background uncertainty: ~37%

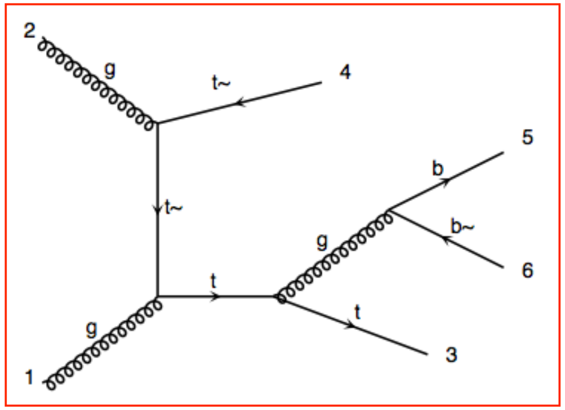
Total background uncertainty: ~5%

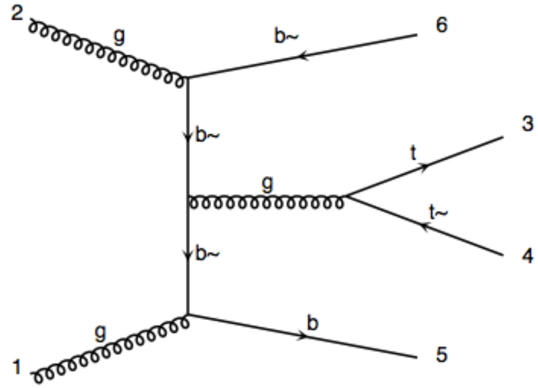
$t\bar{t}$+jets Modeling

- Even at LO, $t\bar{t}b\bar{b}$ has many diagrams (36 diags for $gg \rightarrow t\bar{t}b\bar{b}$, 7 diags for $q\bar{q} \rightarrow t\bar{t}b\bar{b}$)!
  Examples:



$t\bar{t}g^*$ ($g^* \rightarrow b\bar{b}$) diagram (e^+e^--like)



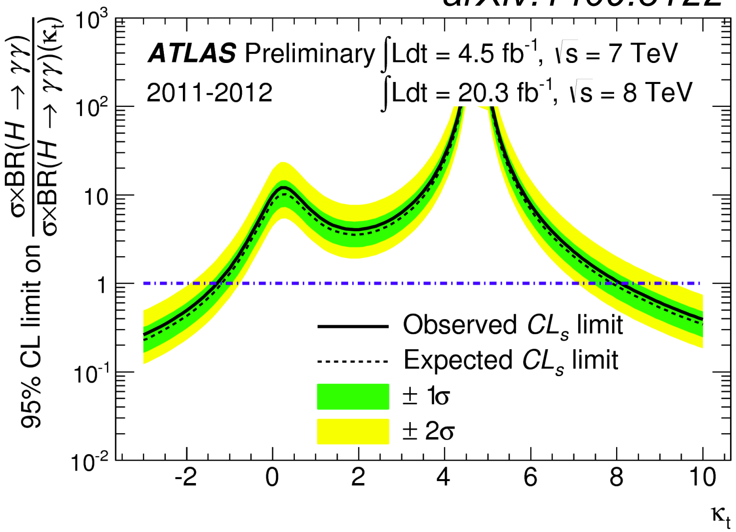


In comparison, only 8 diagrams for $e^+e^- \rightarrow t\bar{t}b\bar{b}$.
Expect $t\bar{t}b\bar{b}$ fraction in $t\bar{t}$+jets to be larger at the LHC!

tH+X Production

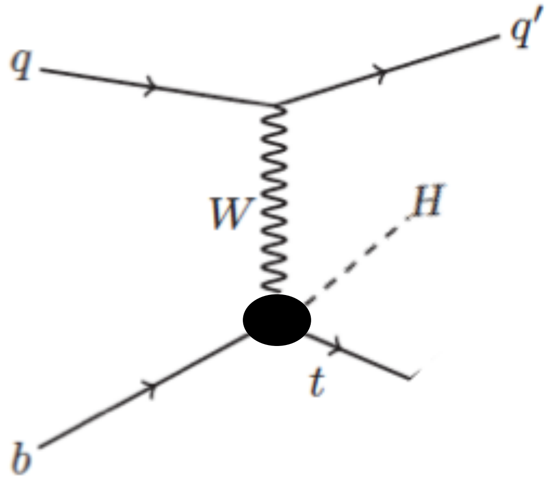
- Reinterpretation of the inclusive ttH($\gamma\gamma$) search:
  - includes the tHqb and WtH signals (~+50% contribution from the latter)
  - Exploits effect on BR(H→$\gamma\gamma$) on both ttH and tH+X

arXiv:1409.3122



- 95% CL lower and upper observed (expected) limits on κ_t: $\kappa_t > -1.3$ (-1.2) and $\kappa_t < +8.1$ (+7.9)
  ➔ κ_t=-1 could be excluded with Run 1 data

- It seems dedicated analyses just to rule out the κ_t=-1 hypothesis are pointless…
- The main interest of dedicated analyses may be to check the dim-6 operator contributing to a WbtH interaction. A-priori one does not expect a deviation from the SM since that's the same operator that contributes to the tbW vertex...



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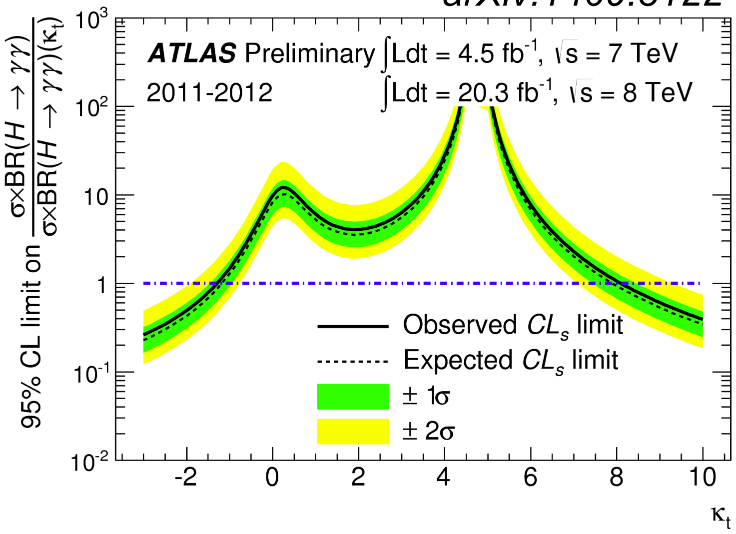

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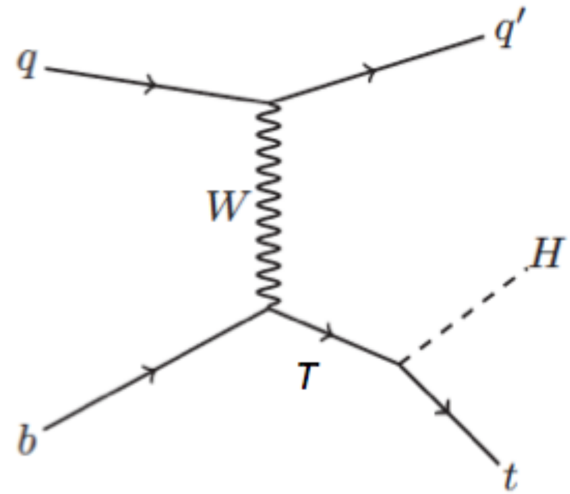
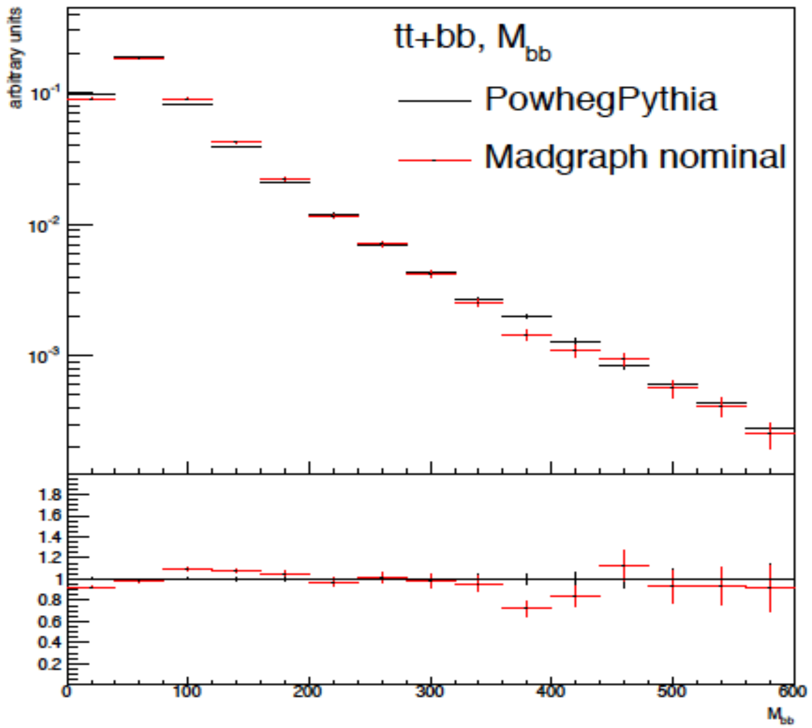
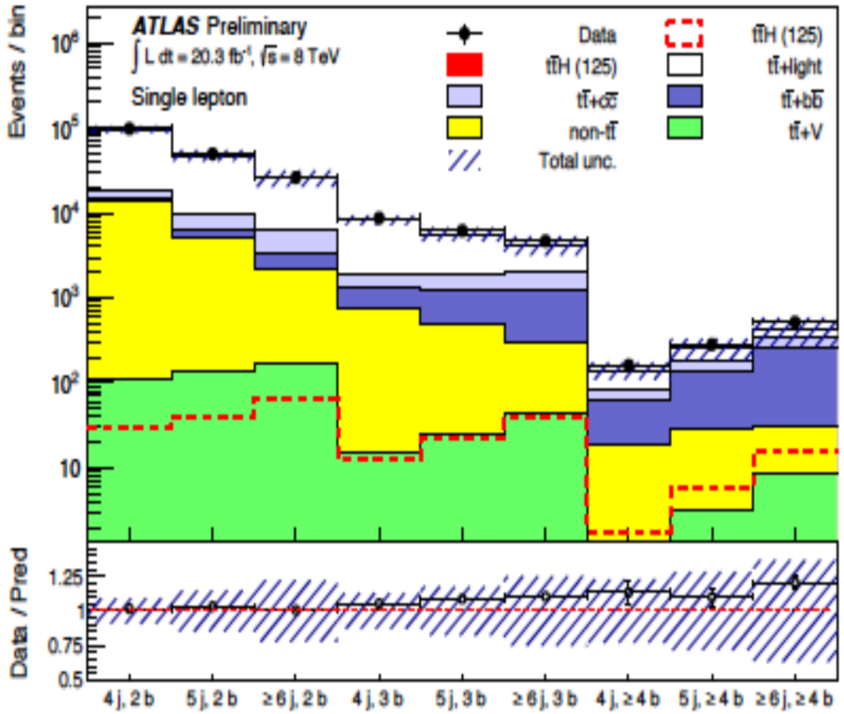
- The main interest of dedicated analyses may be to check the dim-6 operator contributing to a WbtH interaction. A-priori one does not expect a deviation from the SM since that's the same operator that contributes to the tbW vertex…
- Unless the LHC energy allows us to start probing some "light" degrees of freedom…



$t\bar{t}$+jets Modeling

- Based on matrix element (ME)+parton shower (PS) MCs.
  Inclusive $t\bar{t}$+jets samples normalized to approx NNLO cross section.
- *MADGRAPH+PYTHIA* ➔ used by CMS
  - Separate samples for $t\bar{t}$+n partons (n≤3), including heavy quarks (5F scheme).
  - Matched samples. Heavy-flavor overlap removal automatically handled.
- *POWHEG+PYTHIA* ➔ used by ATLAS
  - Good modeling of $t\bar{t}$+jets production, including jet multiplicity and kinematics.
  - Modeling of $t\bar{t}$+HF comparable (in normalization and kinematics) to *MADGRAPH.*





Signal-to-Background Discrimination

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- Signal-depleted regions: use $H_T^{had} = \sum p_T^{jets}$ for ℓ+jets and $H_T = \sum p_T^{jets} + \sum p_T^{\ell}$ for dilepton
- ℓ+jets, 5 jets, 3 b-tags region: use NN trained to separate $t\bar{t} + b\bar{b}/c\bar{c}$ from $t\bar{t}$+light jets
- Signal-rich regions: use NN trained to separate $t\bar{t}H$ from $t\bar{t}$+jets in each of the region

Lepton+jets

	2 b-tags	3 b-tags	$\geq$ 4 b-tags
4 jets	H_T^{had}	H_T^{had}	H_T^{had}
5 jets	H_T^{had}	NN	NN
$\geq$ 6 jets	H_T^{had}	NN	NN

Make use of event kinematics
- Object kinematics: p_T^{jet5}, ...
- Global event variables: H_T^{had}, $N^{jet}_{p_T>40GeV}$, ...
- Event shape variables: centrality, Fox-Wolfram moments, ...
- Object pair properties: $M_{bb}^{\min\Delta R}$, ΔR_{bb}^{avg}, ...