LCWS2012, International Workshop on Future Linear Colliders
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Searches for $t\bar{t}H$ at the LHC

(and some comparisons to the Linear Collider)

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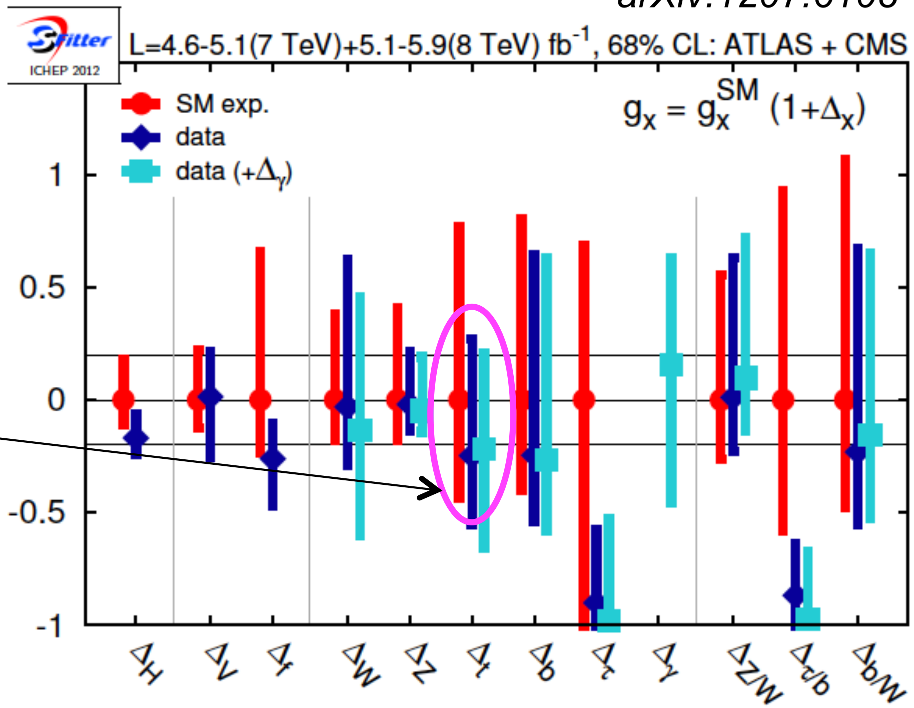
For the ATLAS and CMS Collaborations

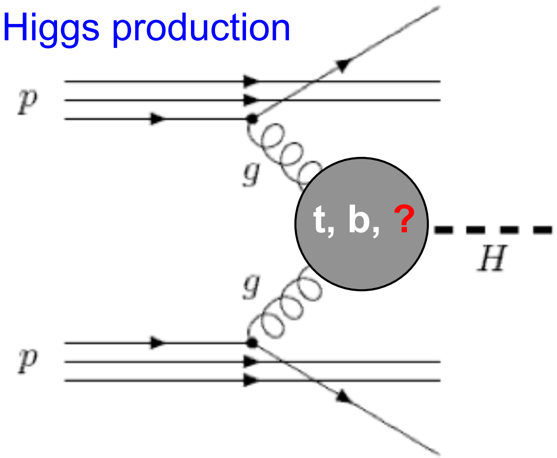
Motivation

- After the discovery of a new Higgs-like boson at mass of ~125 GeV, the focus now is on the precise measurement of its properties, in particular couplings to fermions and gauge bosons.
- 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 ➔ allows probing for NP contributions in the ggH and γγH vertices.

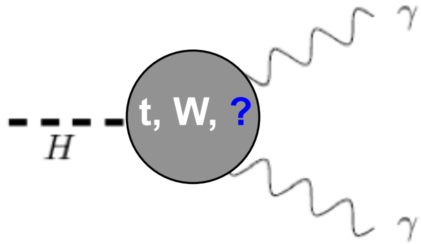
arXiv:1207.6108



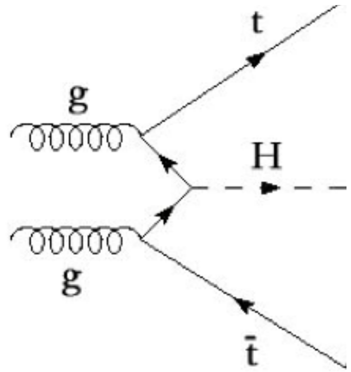
Higgs production



Higgs decay to photons



Higgstrahlung from top quark



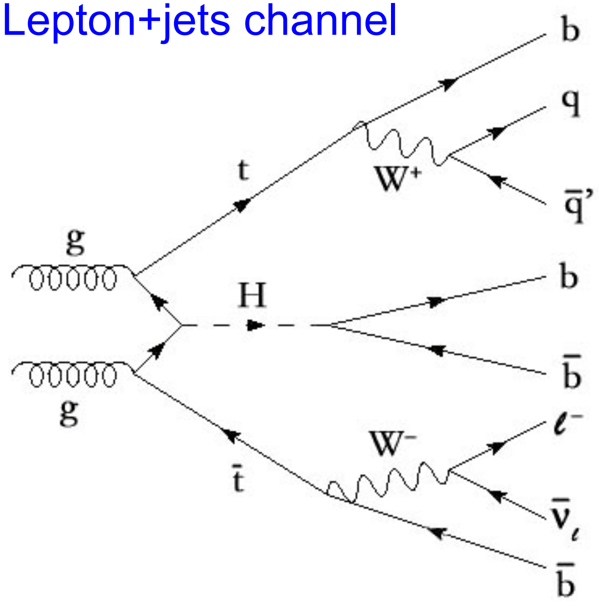
$$\sigma(t\bar{t}H) \propto g_{ttH}^2$$

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!
- Possibility to exploit several Higgs decay modes.
  - For M_H=125 GeV, H→b$\bar{b}$ dominates although e.g. H→W^+W^-,$\tau^+\tau^-$, can also contribute.
  - Other decay modes can be exploited at high integrated luminosity (e.g. H→$\gamma\gamma$).

Lepton+jets channel



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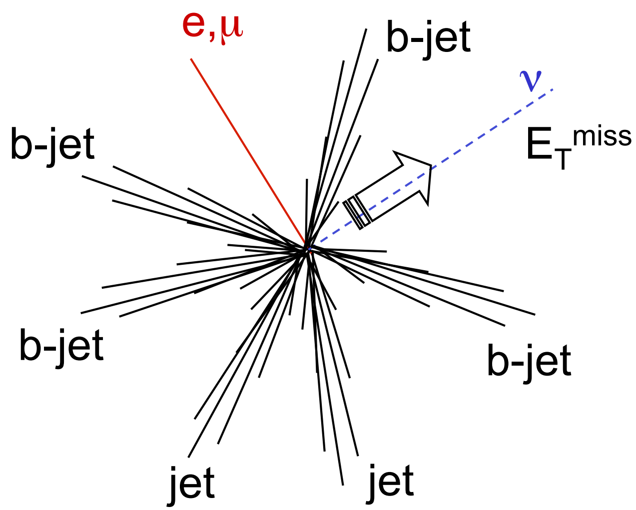
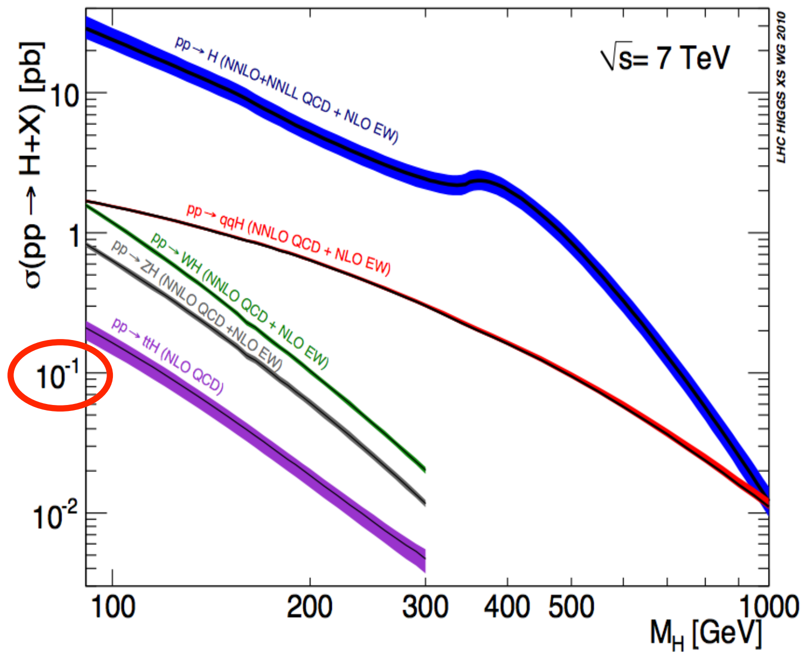


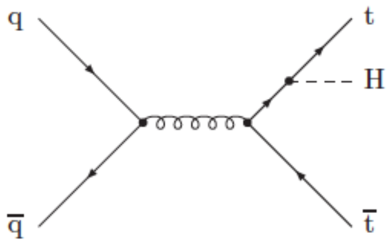
Challenges:

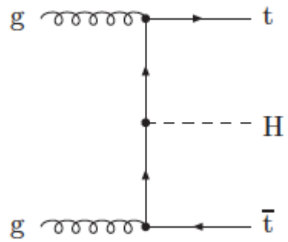
- Very busy events which are hard to reconstruct kinematically (large combinatorial background).
- Low production cross section.
- Huge background from $t\bar{t}$+jets affected by large systematic uncertainties, both theoretical and experimental.

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

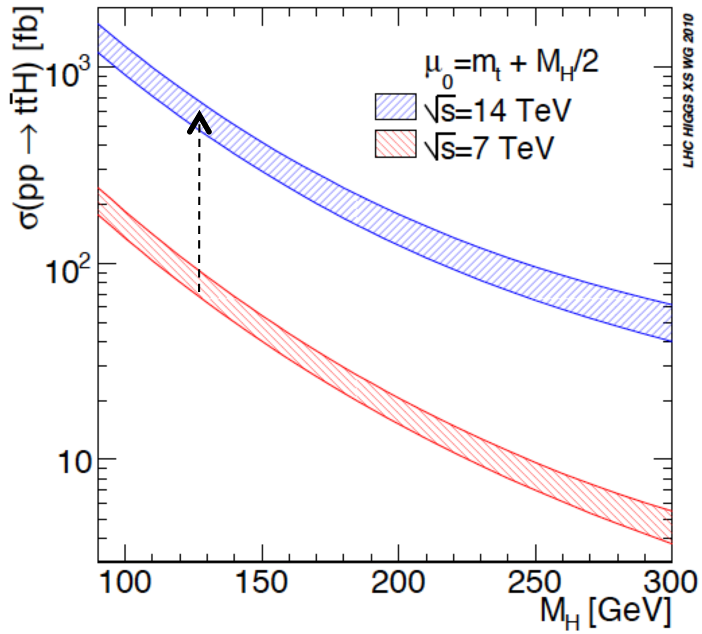


ttH Production



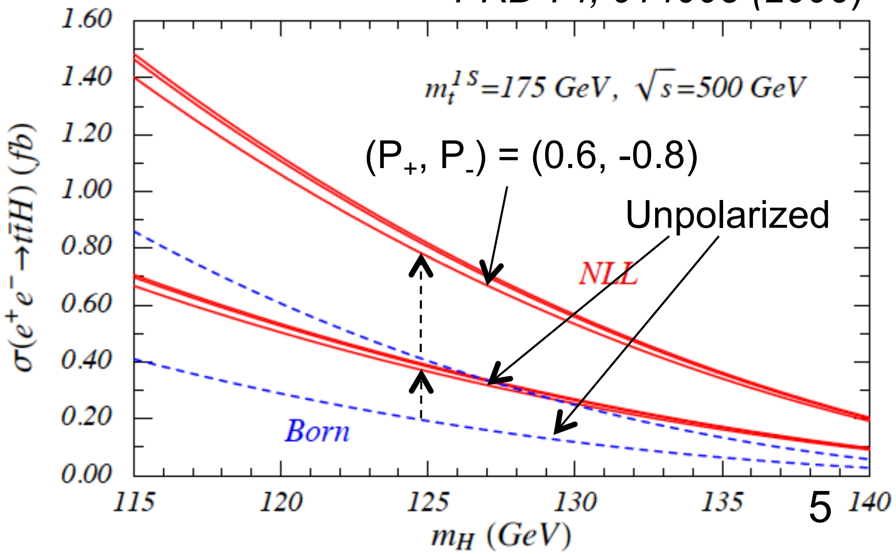


arXiv:1101.0593



- At the LHC, $\sigma(t\bar{t}H)$ known at NLO in QCD. For M_H=125 GeV:
  - $\sqrt{s}$=7 TeV: $\sigma(t\bar{t}H)$=86 fb
    Uncertainties: +3.3%/-9.3% (scale), ±8.5% (PDF)
  - $\sqrt{s}$=8 TeV: $\sigma(t\bar{t}H)$=130 fb (~x1.5 wrt $\sqrt{s}$=7 TeV)
  - $\sqrt{s}$=14 TeV: $\sigma(t\bar{t}H)$=611 fb (~x7 wrt $\sqrt{s}$=7 TeV)

PRD 74, 014008 (2006)

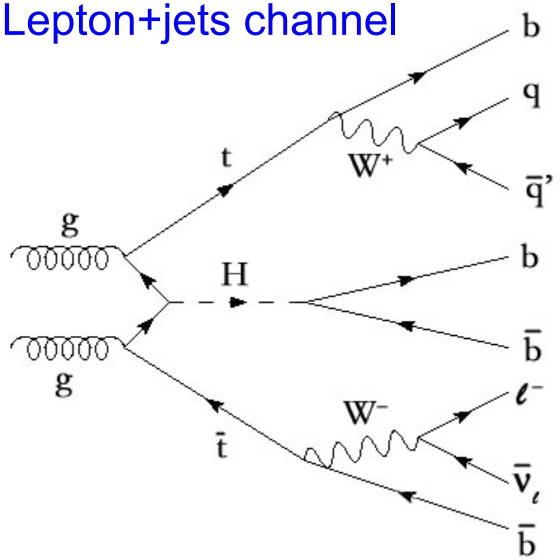


- At a LC with $\sqrt{s}$=500 GeV, the inclusion of non-relativistic QCD effects becomes crucial:
  - Increase $\sigma(t\bar{t}H)$ by x2 wrt Born prediction!
  - Another x2 increase can be achieved by using polarized beams.
  - Still, $\sigma(t\bar{t}H) \leq 1$ fb for M_H=125 GeV.

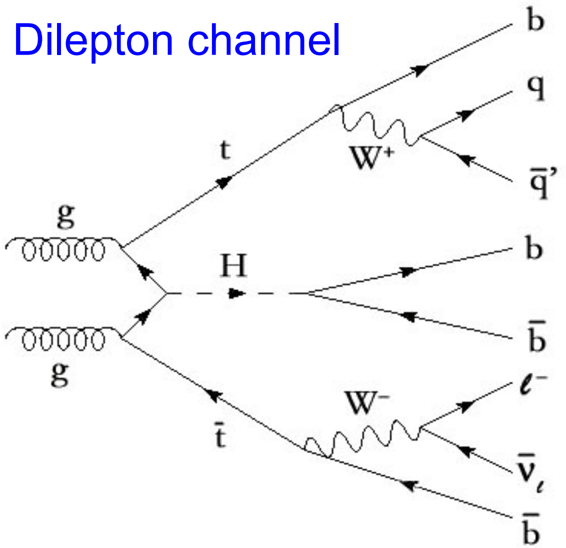
Analysis Strategy @ LHC

- Select $t\bar{t}$-enriched samples:
  - Lepton+jets (ATLAS, CMS) and opposite-sign dilepton (CMS) final states considered so far.
- Pick signals being targeted:
  - H→bb (ATLAS), H→anything (CMS).
- Categorize events by jet and b-tag multiplicities:
  - Improve sensitivity by keeping separate high and low S/√B channels.
  - Signal-depleted channels will be exploited to constrain systematic uncertainties.
- For each analysis channel, choose a discriminant variable:
  - ATLAS: single kinematic variables
  - CMS: multivariate discriminants
- Hypothesis testing including in-situ constraining of systematic uncertainties.

Lepton+jets channel



Dilepton channel



Event Selections

"Signal-rich" categories

Lepton+jets

ATLAS

- =1 isolated e (μ), p_T>25 (20) GeV
- ≥ 4 jets, p_T>25 GeV (anti-k_T R=0.4)
- e+jets: E_T^{miss}>30 GeV, $m_{T,W}$>30 GeV
- μ+jets: E_T^{miss}>20 GeV, $m_{T,W}$>60 GeV-E_T^{miss}

Divide into 9 categories:
- 4 jets (0, 1, ≥ 2 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)

Dileptons

CMS

- ee, $\mu\mu$, eμ final states
- 1 tight e/μ, p_T>20 GeV and
- 1 loose e/μ p_T>15/10 GeV
- ≥ 2 jets, p_T>30 GeV (anti-k_T R=0.5)
- ≥ 2 b-tags

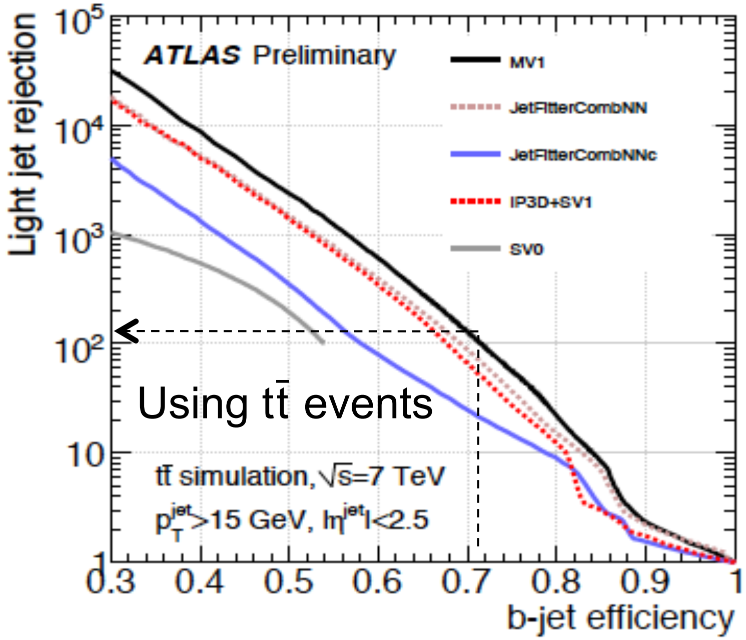
Divide into 2 categories:
- 2 jets (2 b-tags)
- ≥ 3 jets (≥ 3 b-tags)

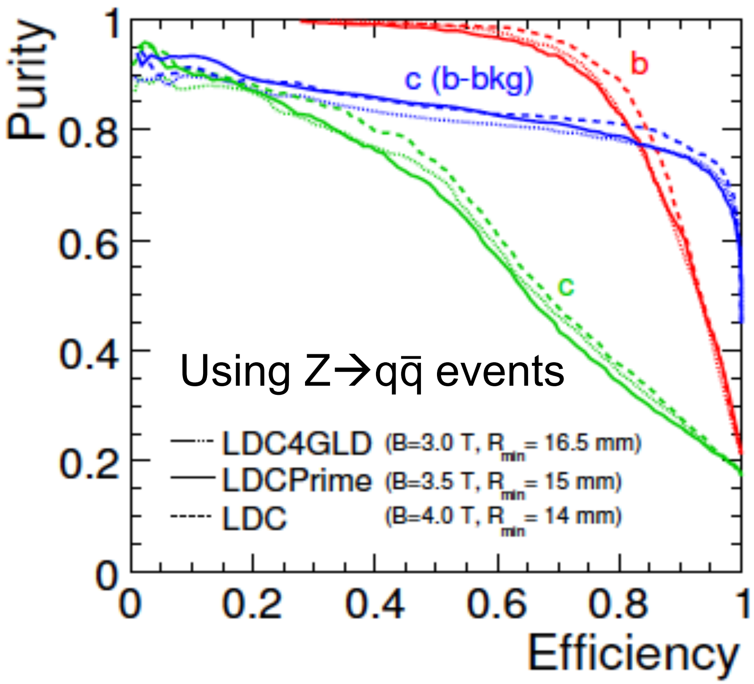
B-Jet Identification

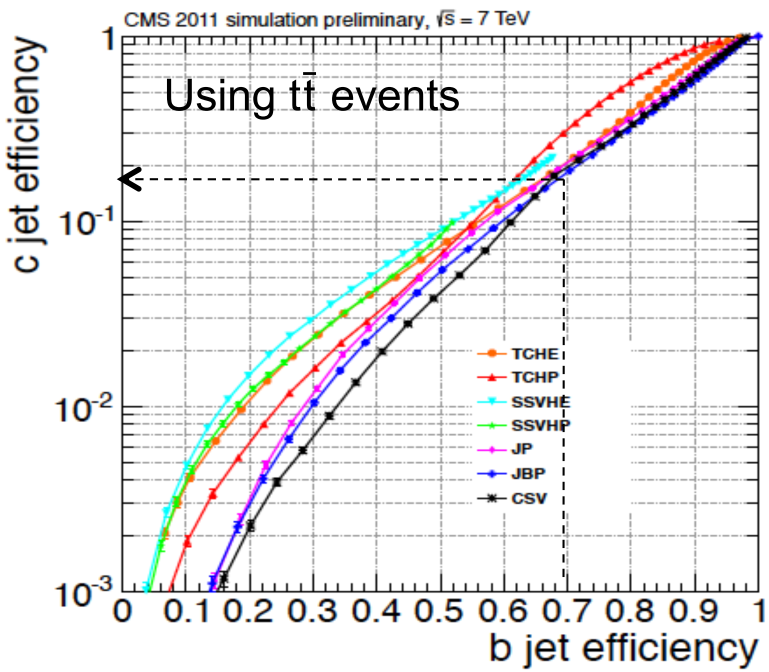
- Using multivariate techniques combining information from:
  - Lifetime: displaced tracks and/or vertices
  - Mass: secondary vertex mass
  - Decay chain reconstruction

  and calibrated in data control samples.
- Performance e.g. ε_b~70%, ε_c~20%, ε_{light}~1%.
- Much better b-to-c discrimination at a LC.

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

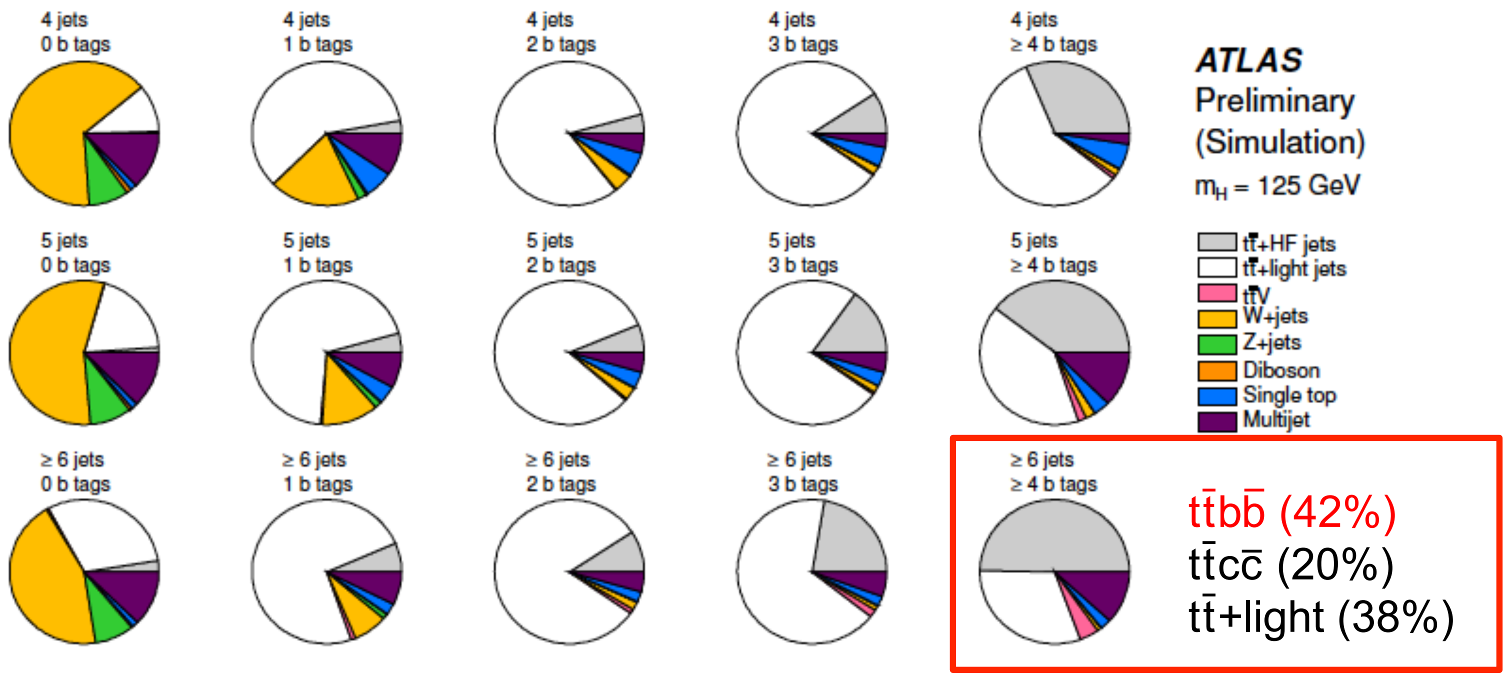






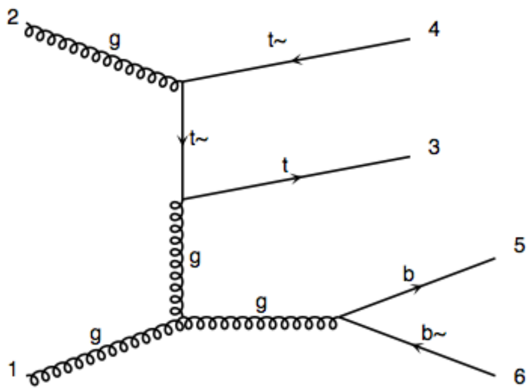
Signal and Background Modeling

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

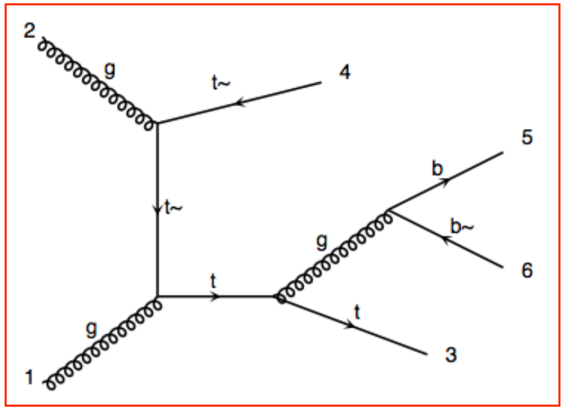


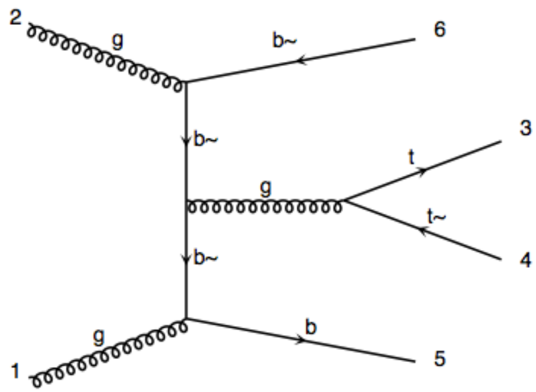
$t\bar{t}$+jets Modeling

- Based on state-of-art matrix element (ME)+parton shower (PS) MCs.
  Inclusive $t\bar{t}$+jets samples normalized to approx NNLO cross section
- *ALPGEN+HERWIG* → used by ATLAS
  - Separate samples for $t\bar{t}$+n light partons (n≤5), $t\bar{t}b\bar{b}$, and $t\bar{t}c\bar{c}$.
  - (Manual) heavy-flavor overlap removal between ME and PS based on ΔR separation between heavy quarks.
- *MADGRAPH+PYTHIA* → used by CMS
  - Separate samples for $t\bar{t}$+n partons (n≤4), including heavy quarks.
  - Heavy-flavor overlap (presumably) handled by *MADGRAPH*.
- Even at LO, $t\bar{t}b\bar{b}$ has many diagrams (36 diags for gg→$t\bar{t}b\bar{b}$, 7 diags for $q\bar{q}$→$t\bar{t}b\bar{b}$)!
  Examples:



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





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

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- What about NLO calculations?
  - NLO calculations exist for $t\bar{t}jj$ and $t\bar{t}b\bar{b}$ but they need to updated to $\sqrt{s}$=7, 8 TeV, using consistent set of kinematic cuts, PDFs, etc. *Underway.*
  - The first step will be to make the most consistent comparison possible between the ME+PS MCs and NLO calculations, and determine whether/how the NLO calculations can be used to improve the ME+PS MC description (e.g. to calibrate the $t\bar{t}b\bar{b}/t\bar{t}jj$ ratio).
  - Fully implementing NLO predictions into the analyses will likely have to wait for NLO+PS MCs under development.
  - *Discussions between theorists and experimentalists ongoing.*

Expected Yields

ATLAS EXPERIMENT

Lepton+jets

Category	signal (M=125) H→ bb	background	S/√B
4 jets, 0 tags	0.20	40200	0.001
4 jets, 1 tag	1.1	21240	0.008
4 jets, ≥ 2 tags	3.0	15040	0.02
5 jets, 2 tags	2.7	6640	0.03
≥ 6 jets, 2 tags	3.4	3360	0.06
5 jets, 3 tags	2.3	915	0.08
5 jets, ≥ 4 tags	0.74	45	0.11
≥ 6 jets, 3 tags	4.0	634	0.16
≥ 6 jets, ≥ 4 tags	2.2	62	0.28

CMS

Lepton+jets

Expected event yields in each Lepton plus jets category in 5 fb^{-1}

Category	signal (M=120) H→anything	background	S/√B
≥ 6 jets, 2 tags	6.3	2255.8	0.13
4 jets, 3 tags	3.5	1041.6	0.11
5 jets, 3 tags	4.7	666.7	0.18
≥ 6 jets, 3 tags	4.4	404.9	0.22
4 jets, ≥ 4 tags	0.5	20.0	0.11
5 jets, ≥ 4 tags	1.2	31.8	0.21
≥ 6 jets, ≥ 4 tags	1.7	39.3	0.27

Dileptons

Expected event yields in each Dilepton category in 5 fb^{-1}

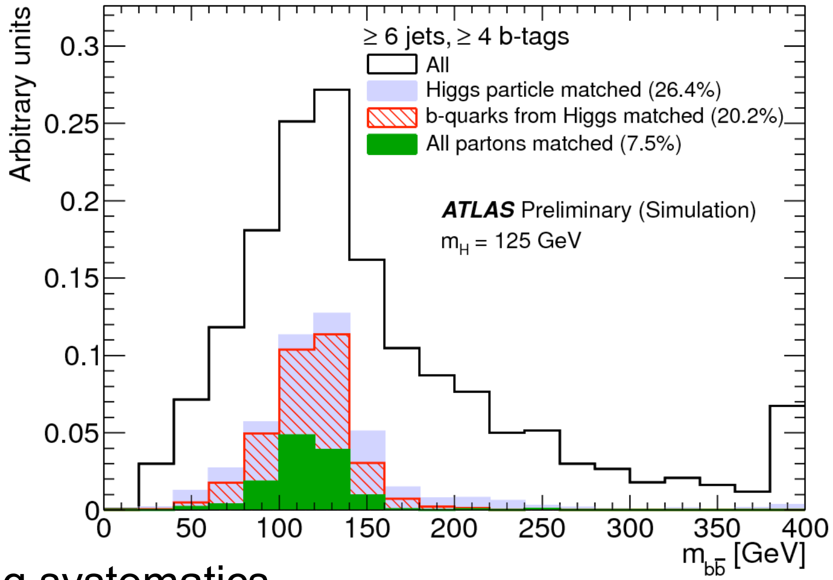
Category	signal (M=120) H→anything	background	S/√B
2 jets, 2 tags	0.7	4306.0	0.01
≥ 3 jets, ≥ 3 tags	2.9	167.6	0.22

- For M_H=120 GeV, the global S/√B (adding in quadrature S/√B per channel) in lepton+jets:
  - ATLAS: 0.40
  - CMS: 0.49

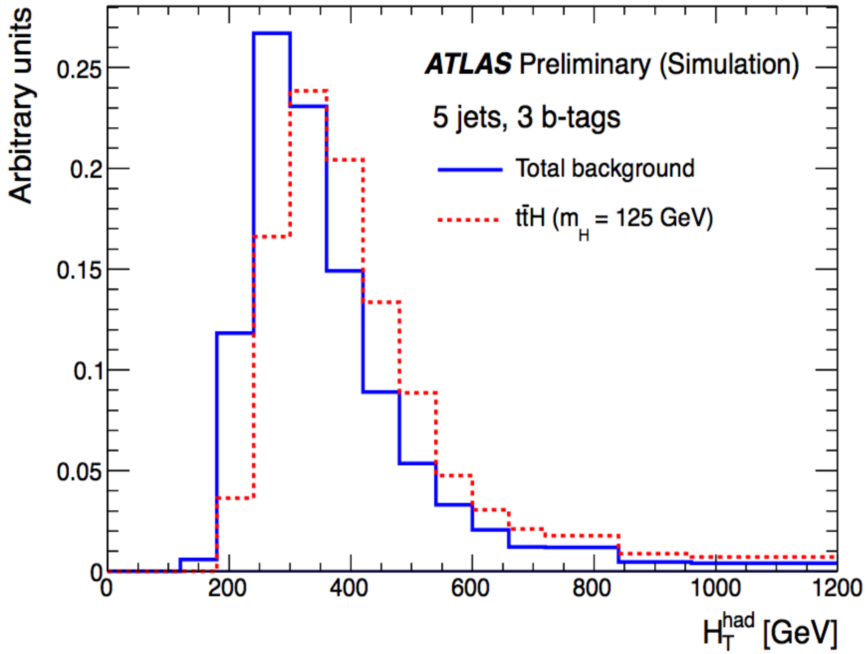
  ➔ ~22% higher for CMS mainly from additional (non H→b$\bar{b}$) signal as well as the inclusion of the 4 jet channel (3, ≥4 tags) as signal region.

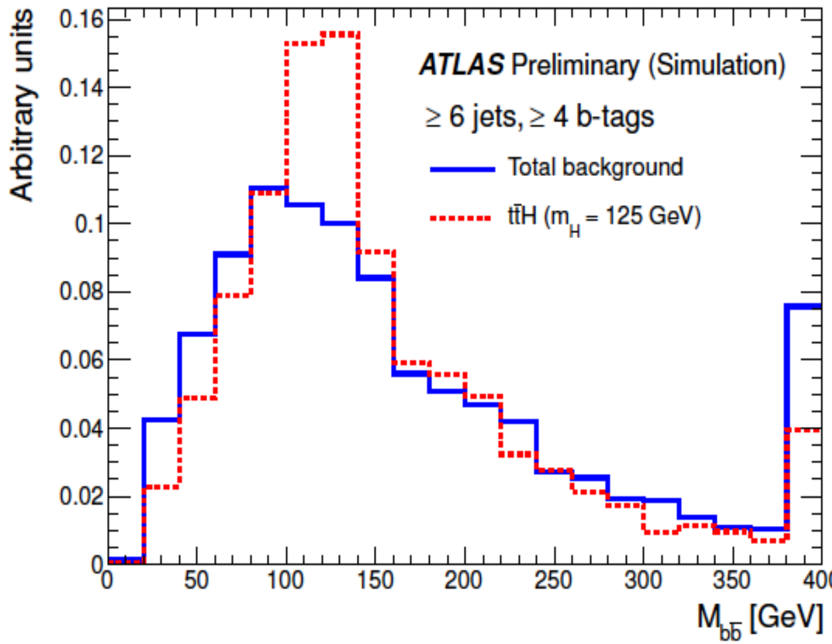
Signal-to-Background Discrimination

- ≥6 jets and 3 or ≥4 b-tags:
  m_{bb} via constrained kinematic fit
  - Hadronic W resonance: $m_{jj} \sim M_W$
  - Leptonic W resonance: $m_{l\nu} \sim M_W$
  - Top quark resonances: $m_{jjb} \sim m_{l\nu b} \sim m_t$
  - m_{bb} built from the two b-jet candidates not assigned to the $t\bar{t}$ system



- Rest of channels: $H_T^{had} = \Sigma\, p_{T,jet}$
  ➔ Mostly sensitive to jet-related and $t\bar{t}$ modeling systematics





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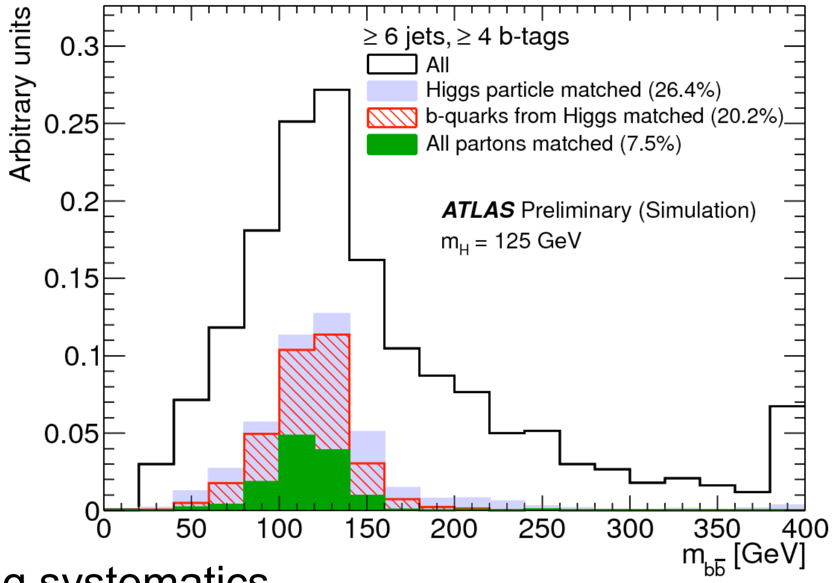

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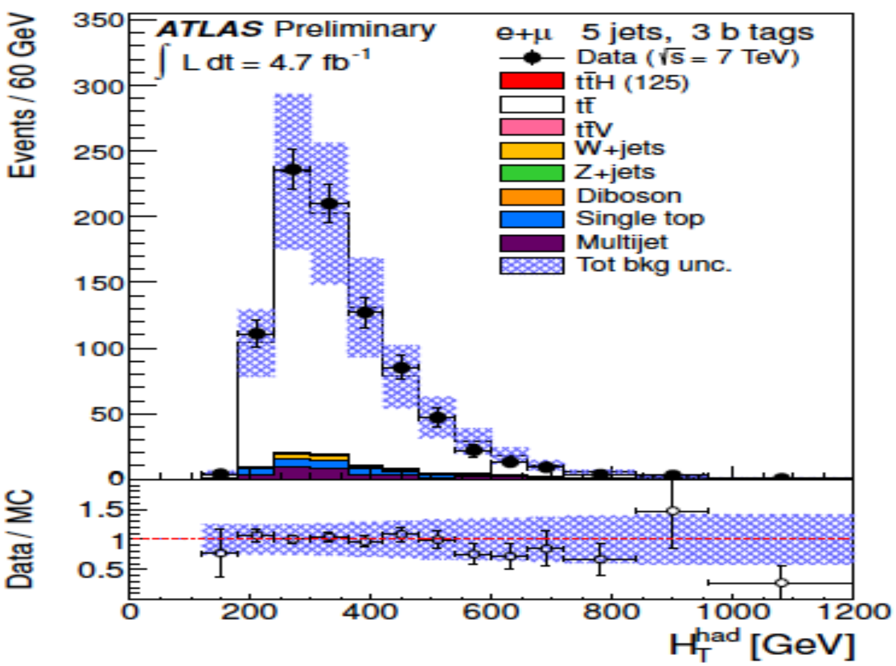
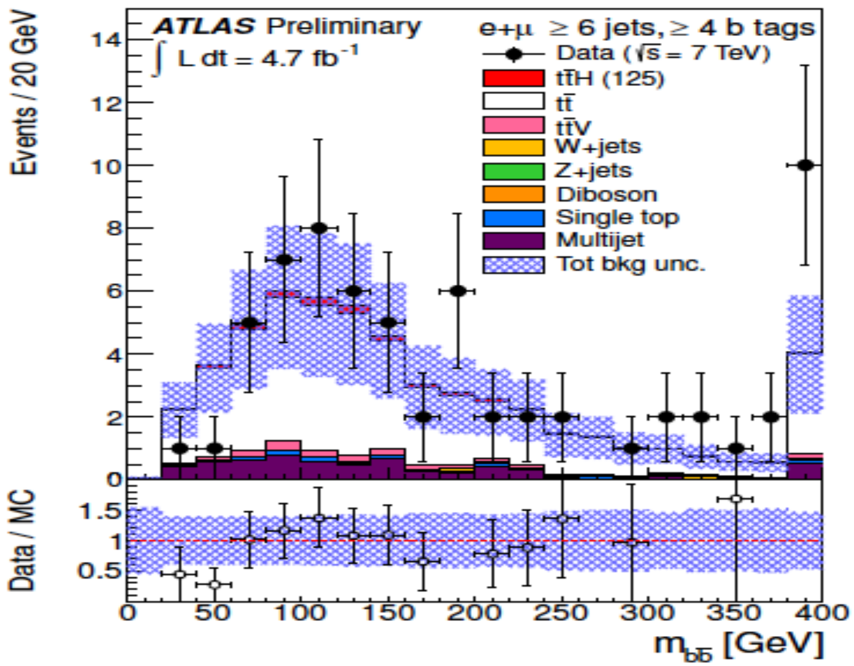
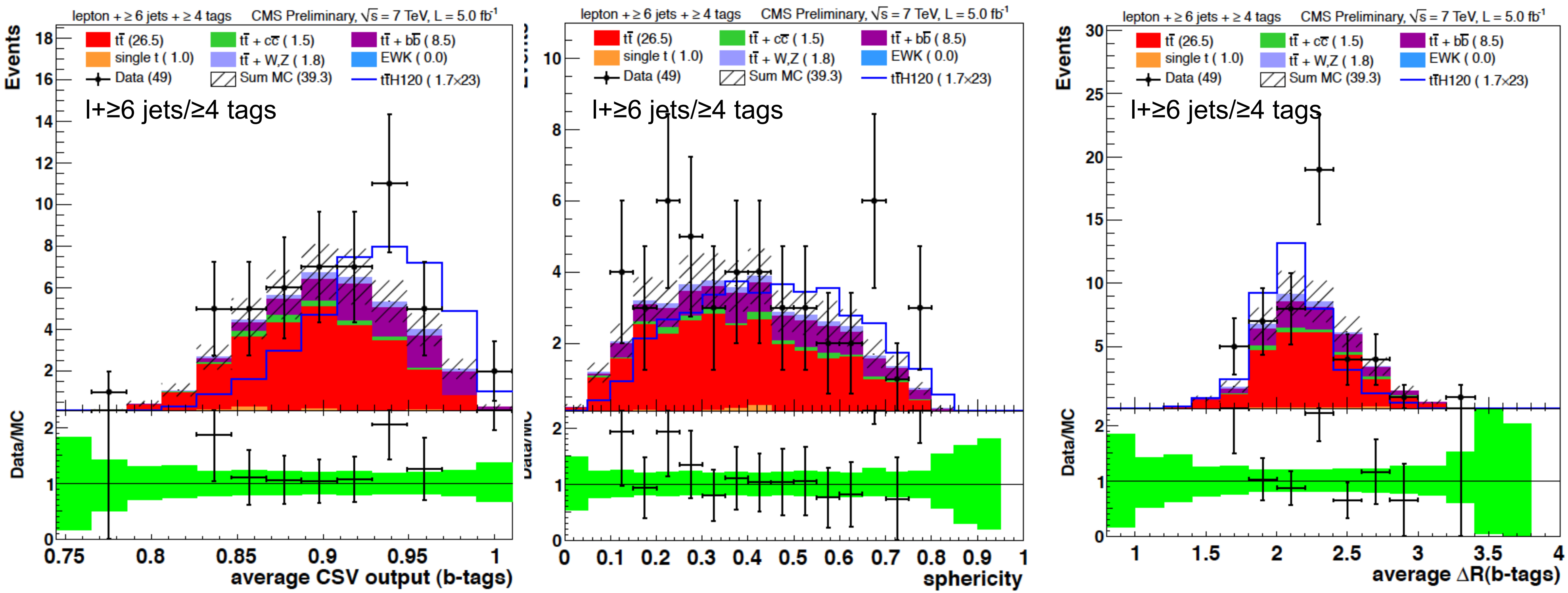




Signal-to-Background Discrimination

- Neural Networks trained for each category of the analysis.
- A total of 10 (5) variables are used in the lepton+jets (dilepton) channels.
  - B-tagging information: e.g. average b-tagging output variable
    ➔ some of the most powerful variables
  - Event kinematics: e.g sphericity
  - Angular correlations: e.g. average ΔR(b,b)



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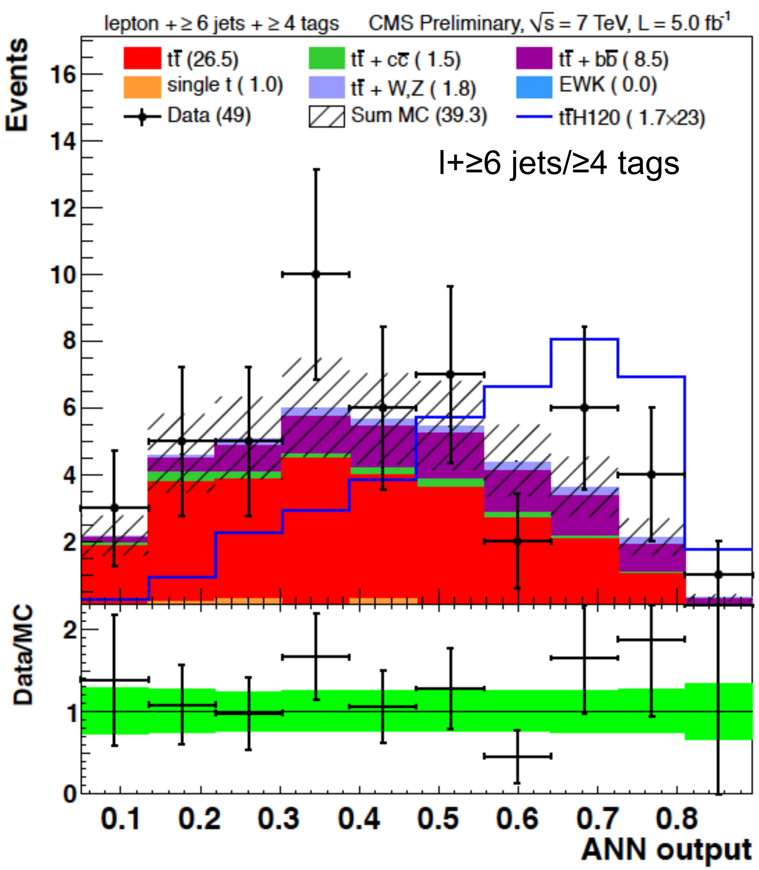
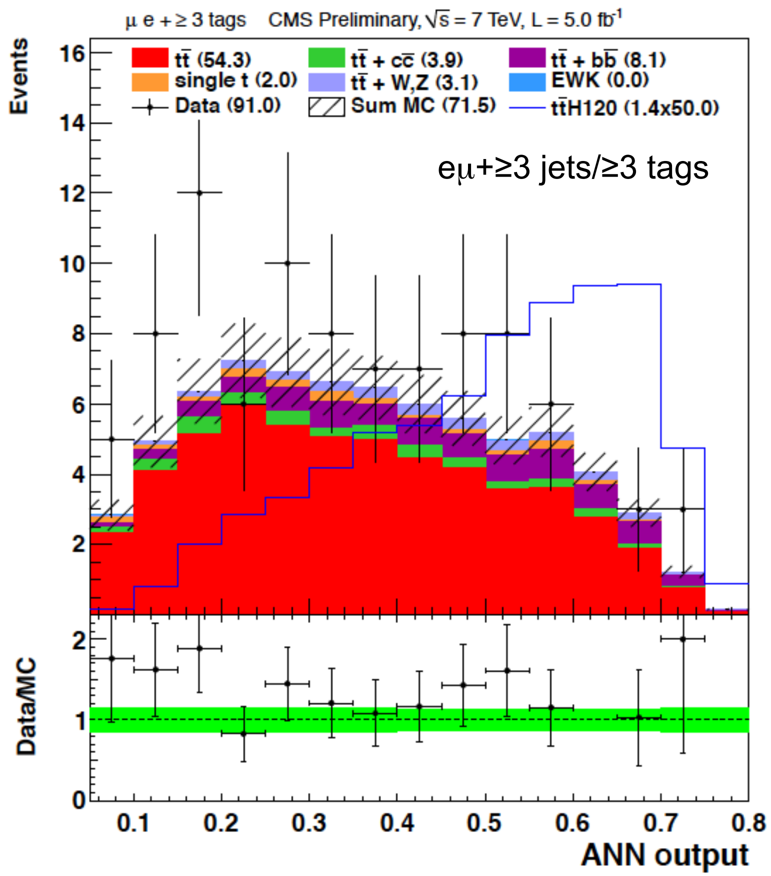




ATLAS EXPERIMENT

Systematic Uncertainties

	Systematic uncertainty	Status	Components
Object-related	Luminosity	N	1
	Lepton ID+reco+trigger	N	1
	Jet vertex fraction efficiency	N	1
	Jet energy scale	SN	16
	Jet energy resolution	N	1
	b-tagging efficiency	SN	9
	c-tagging efficiency	SN	5
	Light jet-tagging efficiency	SN	1
Bkg cross sections	$t\bar{t}$ cross section	N	1
	$t\bar{t}V$ cross section	N	1
	Single top cross section	N	1
	Dibosons cross section	N	1
	V+jets normalisation	N	3
	Multijet normalisation	N	7
Physics modeling	W+heavy-flavour fractions	SN	4
	$t\bar{t}$ modelling	SN	3
	$t\bar{t}$+heavy-flavour fractions	SN	1
	$t\bar{t}H$ modelling	N	1

- Many systematic uncertainties, both theoretical and experimental.
- Can effectively exploit high-statistics control samples to constrain the leading ones, but need sophisticated enough treatment to not artificially overconstrain them.

Systematic Uncertainties

% change in yield in ≥6 jets/≥4 tags — Prefit

	$t\bar{t}H(125)$	$t\bar{t}$
Luminosity	+1.8/-1.8	+1.8/-1.8
Lepton ID+reco+trigger	+1.3/-1.3	+1.3/-1.3
Jet vertex fraction efficiency	+2.4/-1.7	+2.5/-1.9
Jet energy scale	+9.6/-9.9	+13.5/-15.2
Jet energy resolution	+1.0/-1.0	+0.7/-0.7
b-tagging efficiency	+30.4/-34.8	+22.9/-25.2
c-tagging efficiency	+5.0/-5.0	+16.5/-17.3
Light jet-tagging efficiency	+1.3/-1.3	+11.4/-12.1
$t\bar{t}$ cross section	–	+9.9/-10.7
$t\bar{t}V$ cross section	–	–
Single top cross section	–	–
Diboson cross section	–	–
V+jets normalisation	–	–
Multijet normalisation	–	–
W+heavy-flavour fractions	–	–
$t\bar{t}$ modeling	–	+15.8/-20.2
$t\bar{t}$+heavy-flavour fractions	–	+25.9/-25.9
$t\bar{t}H$ modeling	+1.3/-1.5	–
Total	+32.5/-36.7	+46.3/-50.1

Dominant uncertainties

- Many systematic uncertainties, both theoretical and experimental.
- Can effectively exploit high-statistics control samples to constrain the leading ones, but need sophisticated enough treatment to not artificially overconstrain them.

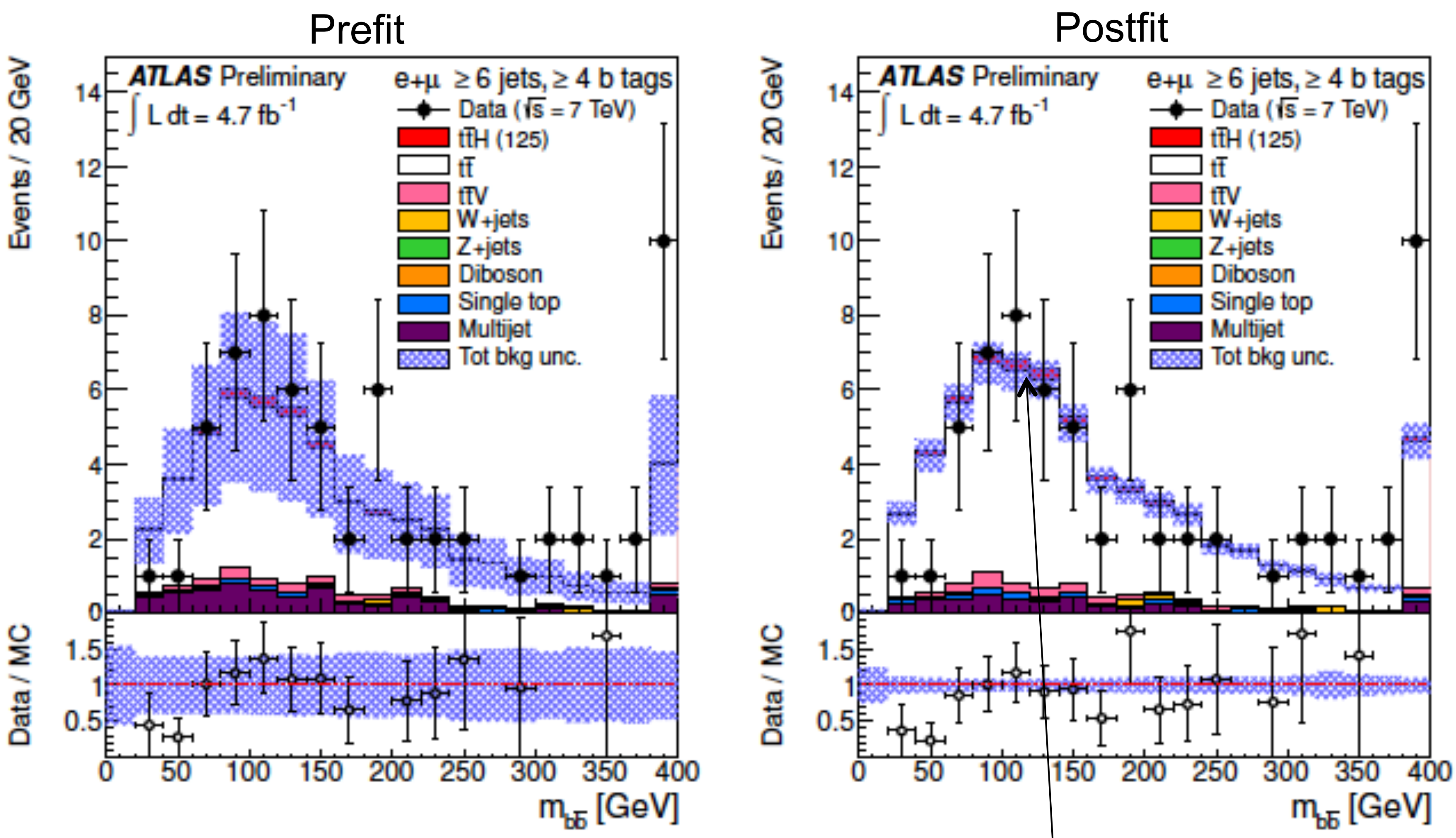
Systematic Uncertainties

Source	Rate	Shape?	Notes
Luminosity	2.2%	No	All signal and backgrounds
Lepton ID/Trig	1.8%	No	All signal and backgrounds
Pileup	1%	No	All signal and backgrounds
Jet Energy Resolution	1.5%	No	All signal and backgrounds
Jet Energy Scale	0-66%	Yes	All signal and backgrounds
QCD Scale ($t\bar{t}H$)	12.5%	No	Scale uncertainty for NLO $t\bar{t}H$ prediction
QCD Scale ($t\bar{t}$)	2-12%	No	Scale uncertainty for NLO $t\bar{t}$, $t\bar{t}V$, and single top predictions
QCD Scale (V)	1.2-1.3%	No	Scale uncertainty for NNLO W and Z prediction
QCD Scale (VV)	3.5%	No	Scale uncertainty for NLO diboson prediction
pdf (gg)	9%	No	Pdf uncertainty for gg initiated processes ($t\bar{t}$, $t\bar{t}Z$, $t\bar{t}H$)
pdf ($q\bar{q}$)	4.2-7%	No	Pdf uncertainty for $q\bar{q}$ initiated processes ($t\bar{t}V$, W, Z)
pdf (qg)	4.6%	No	Pdf uncertainty for qg initiated processes (single top)
Factorization scale ($t\bar{t}$)	0-20%	Yes	Uncorrelated between $t\bar{t}$+jets/$b\bar{b}$/$c\bar{c}$; varies by jet bin
Factorization scale (V)	20-60%	No	Varies by jet bin
b-Tag SF (b/c)	0-15.2%	Yes	All signal and backgrounds
b-Tag SF (mistag)	0-10.6%	Yes	All signal and backgrounds

- Many systematic uncertainties, both theoretical and experimental.
- Can effectively exploit high-statistics control samples to constrain the leading ones, but need sophisticated enough treatment to not artificially overconstrain them.

Profiling in Action: Example Plots

≥6 jets, ≥4 tags (signal-rich)



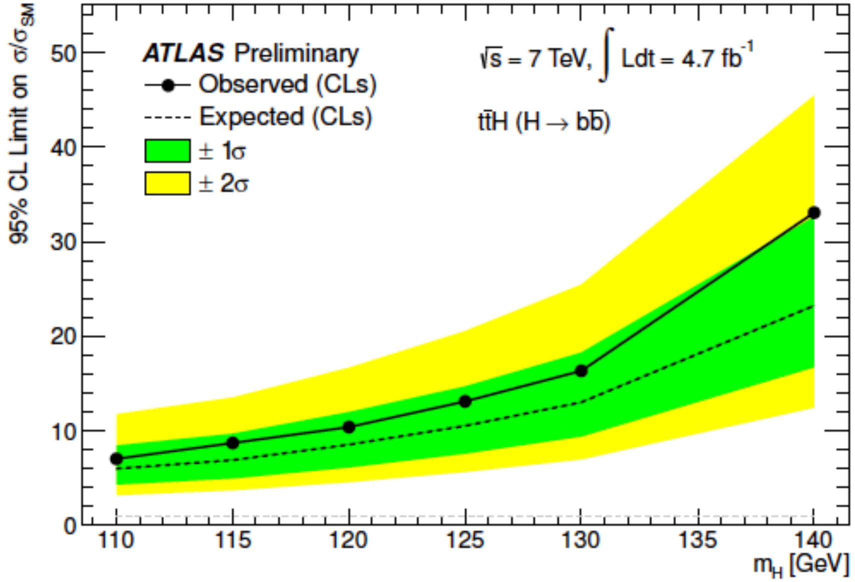
Measured $t\bar{t}$+HF scaling factor: 1.34±0.21

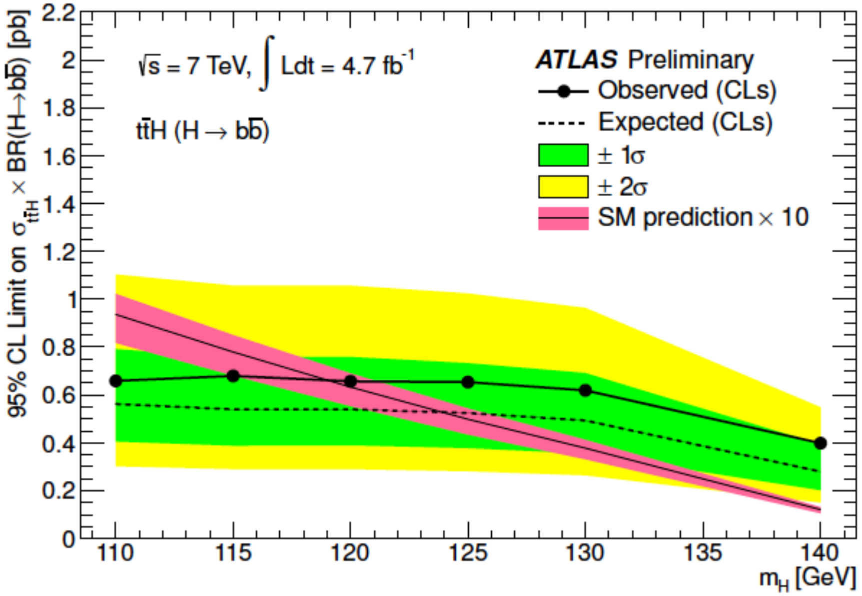
$t\bar{t}H$ signal still x2 smaller than post-fit background uncertainties

Results

- Observed (expected) limit @ M_H=125 GeV: 13.1xSM (10.5xSM)
- Effect of systematic uncertainties is to degrade expected limit/SM by 72% (6.1xSM ➔ 10.5xSM).
- Leading uncertainties are:
  - $t\bar{t}$+HF fraction
  - Light tagging efficiency
  - C tagging efficiency
  - Multijet normalization
  - Jet energy scale

  They alone degrade sensitivity by 55%. Almost half of this degradation (25%) comes from $t\bar{t}$+HF.



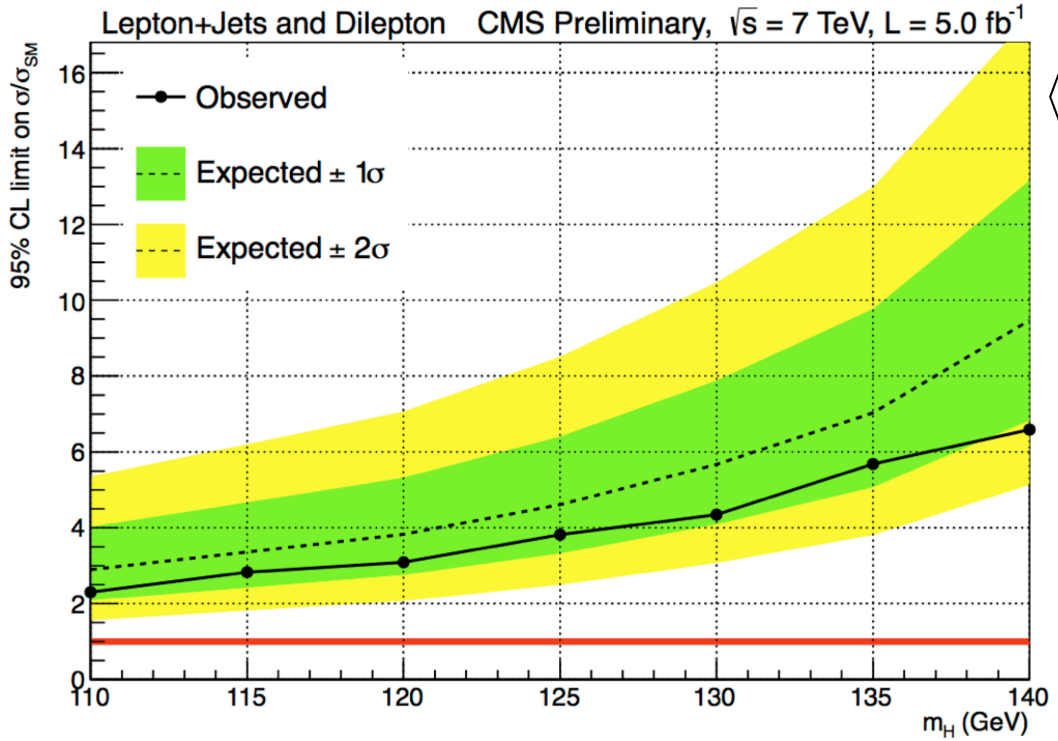


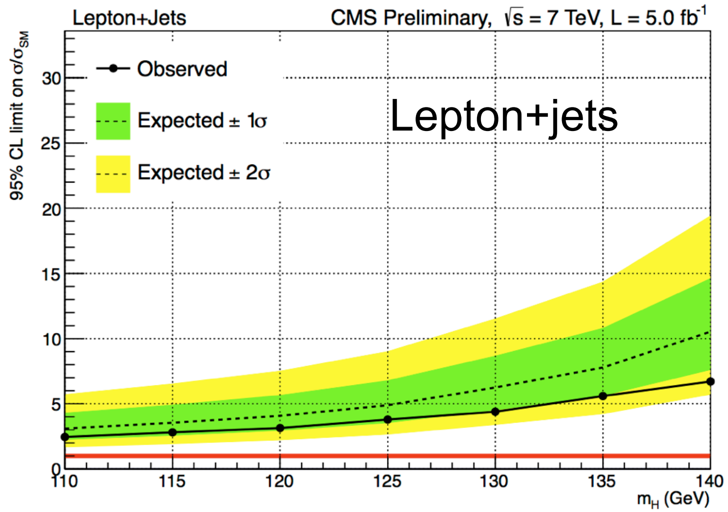
*Limits on $\sigma(t\bar{t}H)$*$BR(H \to b\bar{b})$/SM*

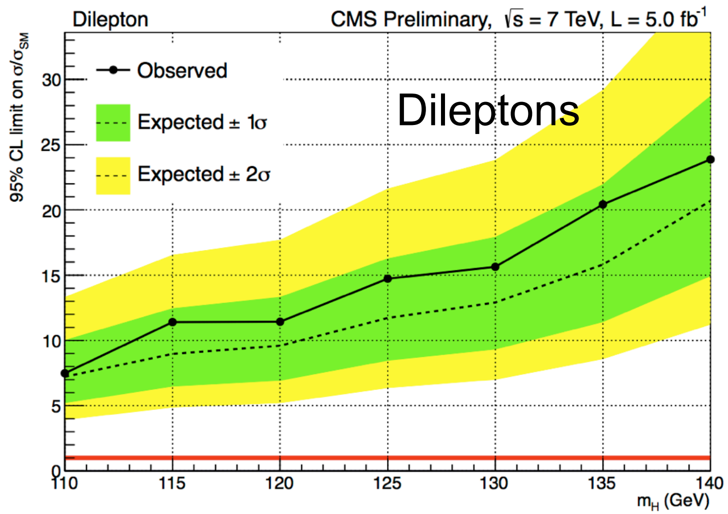
m_H (GeV)	observed	-2 s.d.	-1 s.d.	median	+1 s.d.	+2 s.d.	stat only
110	7.0	3.2	4.3	6.0	8.5	11.8	3.5
115	8.7	3.7	5.0	6.9	9.7	13.6	4.0
120	10.4	4.6	6.2	8.5	12.0	16.7	4.9
125	13.1	5.7	7.6	10.5	14.7	20.6	6.1
130	16.4	7.0	9.4	13.0	18.3	25.5	7.8
140	33.0	12.5	16.7	23.2	32.7	45.5	14.2

Results

- Combination of lepton+jets and dileptons:
  Observed (expected) limit @ M_H=125 GeV: 3.8xSM (4.6xSM)
  Since all Higgs decay modes considered, assume SM prediction for ratio of BRs.
- Addition of dilepton channel improves sensitivity by ~5-10% depending on M_H.

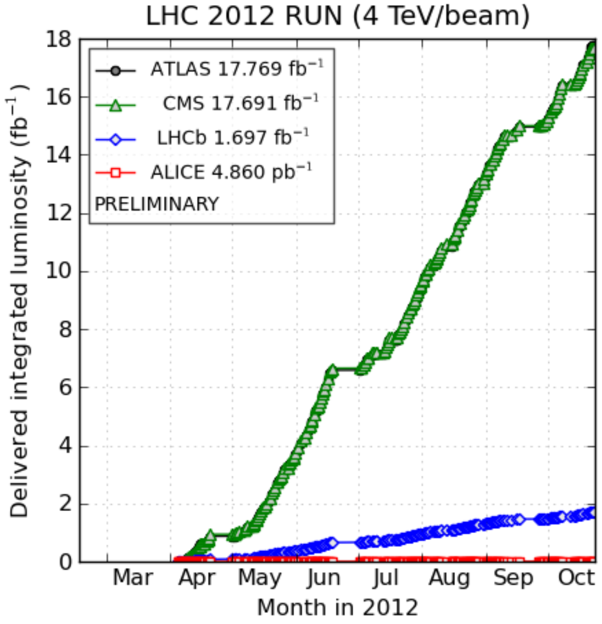




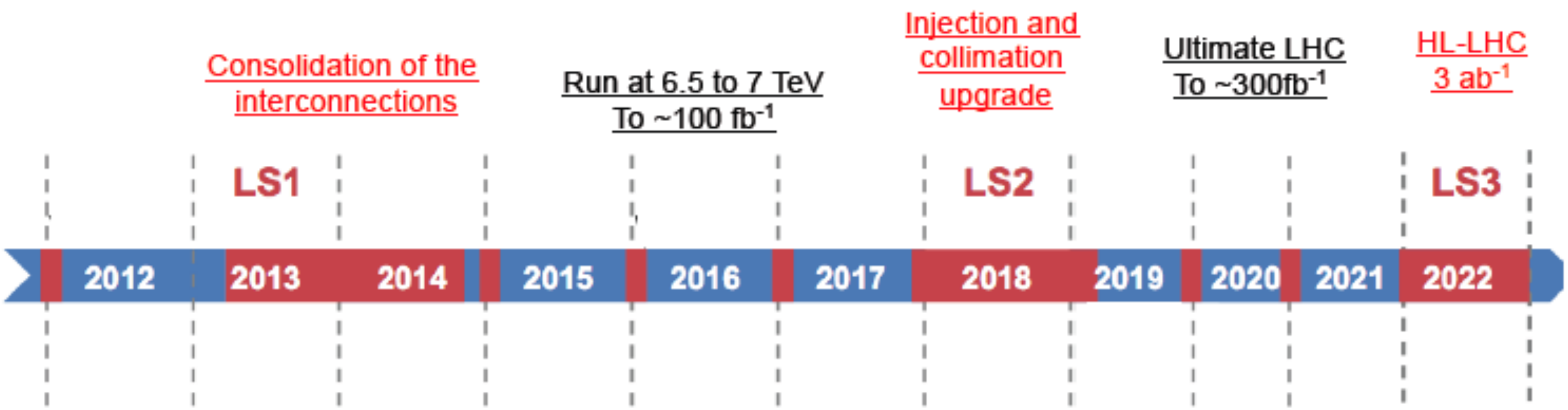


What Lies Ahead

- Have already collected almost 18 fb^{-1} at $\sqrt{s}$=8 TeV, and expect a total of ~25 fb^{-1} by the end of the 2012 run.
  - 50% increase in $\sigma(t\bar{t}H)$ and 5 times more data than analyzed at $\sqrt{s}$=7 TeV.
  - Analysis optimizations underway.
  - ➔ Expect significant improvements by Moriond 2013 conference!



- The LHC time schedule beyond 2012:



➔ Large datasets (with lots of pileup) upcoming!

LC vs LHC Discussion

- Feasibility studies at the LC have shown that a precision on the top-Higgs Yukawa coupling of 10%(5%) can be achieved at $\sqrt{s}$=500 GeV (800 GeV) with 1 ab^{-1}. However:
  - those studies were largely based on fast simulation and did not use ME+PS MCs to predict $t\bar{t}$+jets background
  - often ad-hoc uncertainties on the background of 5-10% were assigned. Can those be motivated?

    [On the other hand, profiling of systematic uncertainties at the LHC already predict background to 15%, with large statistical component!]

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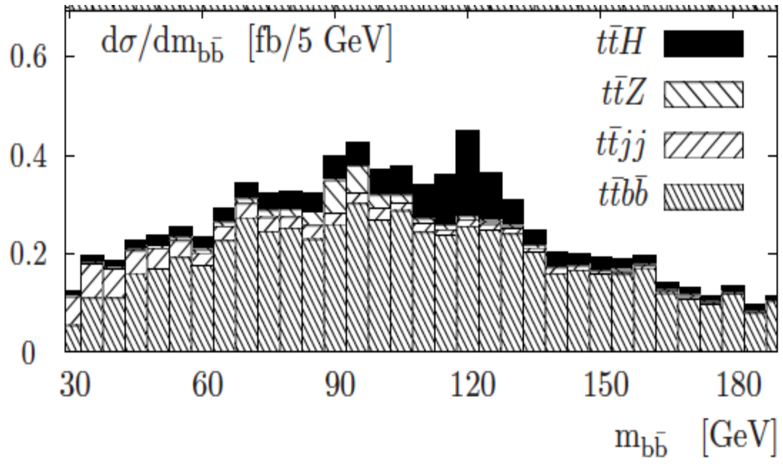

- Can the LHC measure the top-Higgs Yukawa coupling to ~10% or better?
  - A 10% measurement means ~5σ significance.
  - Current analyses have more potential than anticipated through a combination of improved signal-to-background discrimination and in-situ constraining of uncertainties.
  - At $\sqrt{s}$=14 TeV "boosted" $t\bar{t}H$ analyses can potentially achieve ~5σ significance with 100 fb^{-1}. This may also be the only way to maintain sensitivity at high pileup.

Summary and Outlook

- The program of searches for $t\bar{t}H$ production at the LHC has just started.
  These searches should start approaching SM sensitivity with the full 2012 dataset.

- Much experience has been gained on how to overcome limitations from systematic uncertainties that led to abandon this channel in the past, by exploiting the high-statistics data samples. Further progress needed on the theoretical description of the dominant $t\bar{t}$+jets background.

- Great prospects for this search using the large datasets at $\sqrt{s}$=14 TeV, including the application of jet substructure techniques in this channel, already successfully commissioned.

- It may be useful to apply some of these developments/lessons learned towards a more realistic evaluation of the sensitivity at the LC.