ttH(H->bb) searches in ATLAS and CMS

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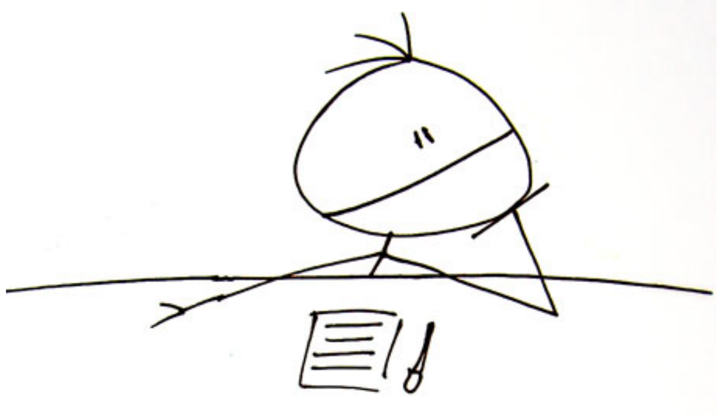
Collider Cross Talk, 18 October 2012

Plan

1. Intro
2. Refs.
3. ATLAS' analysis
4. CMS' analysis
5. Limits

- Other things to mention:
  - Theory uncertainty in ttbb/ttjj – mention Malgorzata's numbers
  - QCD background (ATLAS/CMS?)
  - Continuous b-tagging (ATLAS/CMS?)

Why?



- If ***particle X*** is the Standard Model Higgs, then we need to see fermionic couplings
- ttH, H->bb depends on couplings to two heaviest fermions in SM – large mass => large coupling
- Clear interest in measuring top Yukawa couplings at tree level, with no additional assumptions
- Can only be done in ttH
- Can access ttH, H→anything given enough lumi - Foremost is ttH, H→bb

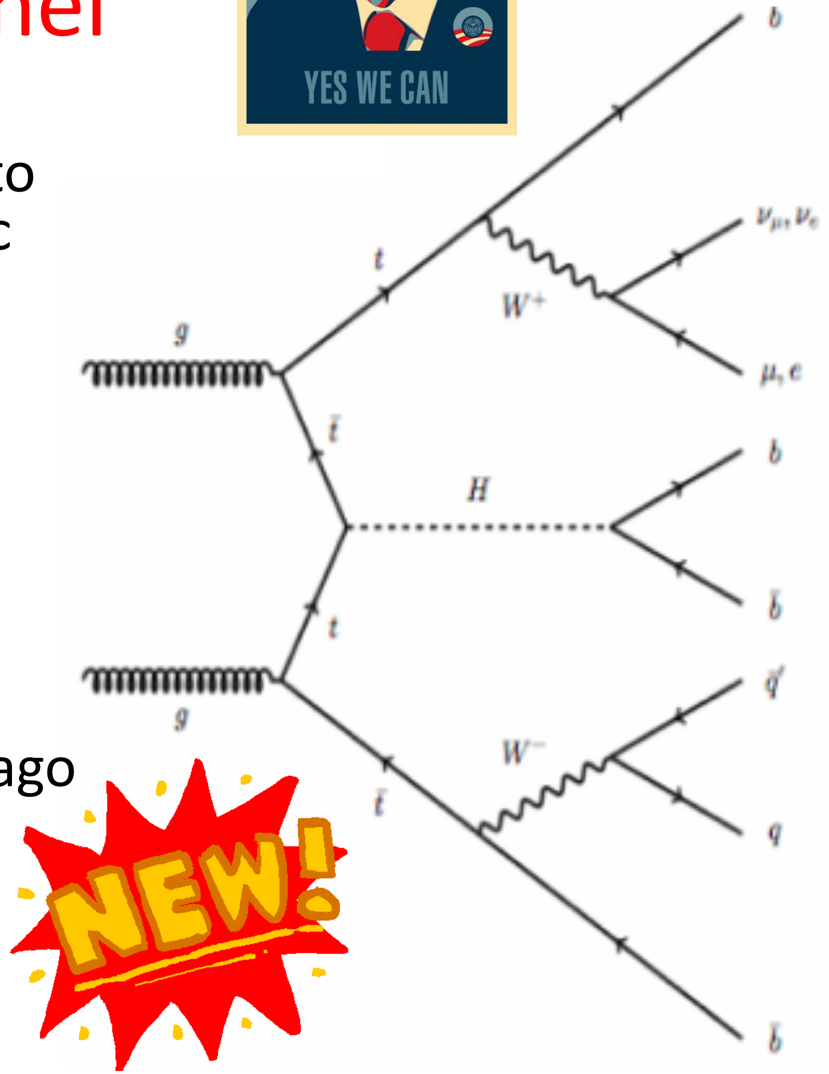
Early LHC ttH analyses:

A **yes we can!** channel

- Very difficult analysis, plagued by combinatorial "background", in addition to actual background from ttbar+X , QCD etc

- First LHC results shown by **CMS** at ICHEP
  - CMS-PAS-HIG-12-025: https://cdsweb.cern.ch/record/1460423/
  - **Single-lepton** and **di-lepton** modes
  - 2011 data (5fb^{-1})

- **ATLAS** released ttH analysis a few weeks ago
  - ATLAS-CONF-2012-135: https://cdsweb.cern.ch/record/1478423
  - **Single-lepton** mode
  - 4.7fb^{-1} of 2011 data



Theory input and uncertainty

- At NLO (mH=125GeV, 7TeV):
  - $\sigma(ttH) = 89.9\ \text{fb}^{+3.3\%}_{-9.3\%}$ (scale) $^{+4.3}_{-3.9}$ (PDF+α_s)

- Preliminary numbers from Malgorozata Worek & Giuseppe Bevilacqua
  - $\sigma(ttbb)_{NLO} = 458\ \text{fb}^{+26\%}_{-27\%}$ (O(90%) @ LO)
  - $\sigma(ttbb)_{NLO} = 982\ \text{pb}^{+15\%}_{-15\%}$ (O(80%) @ LO)
  - $R = \sigma(ttbb)/\sigma(ttjj)_{NLO} = 0.047^{+47\%}_{-15\%}$ (3-200% @ LO)

  Caveat: first estimates use rather different conditions for ttbb and ttjj, from PDFs to jet cones…

ttbb

Dynamical common scale:

$$\mu_R^2 = \mu_F^2 = \mu_0^2 = m_t \cdot \sqrt{p_T(b) \cdot p_T(\bar{b})}$$

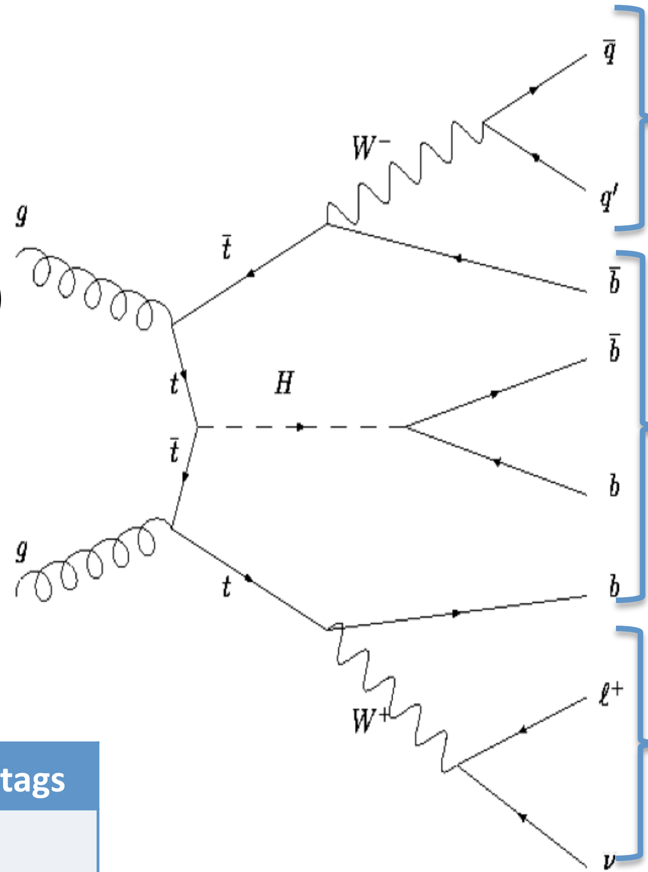
ttjj

Common fixed scale:

$$\mu_R = \mu_F = \mu_0 = m_t$$

ATLAS Analysis – lepton+jets

- Cut-based analysis
- For ≥6 jets & ≥3 b-tags:
  - Use m_{bb}, as discriminating variable
  - Kinematic fit to reconstruct ttbar
  - Use leftover b-jets for H->bb
- Elsewhere: use H_T^{had} (scalar sum of jet p_T)
- Fit Signal and Background regions to get limits
- Get final background normalizations and systematic uncertainties ("nuisance parameters") from fit to data – profiling
- Use control regions to check fit is ok



2 light jets (mostly)

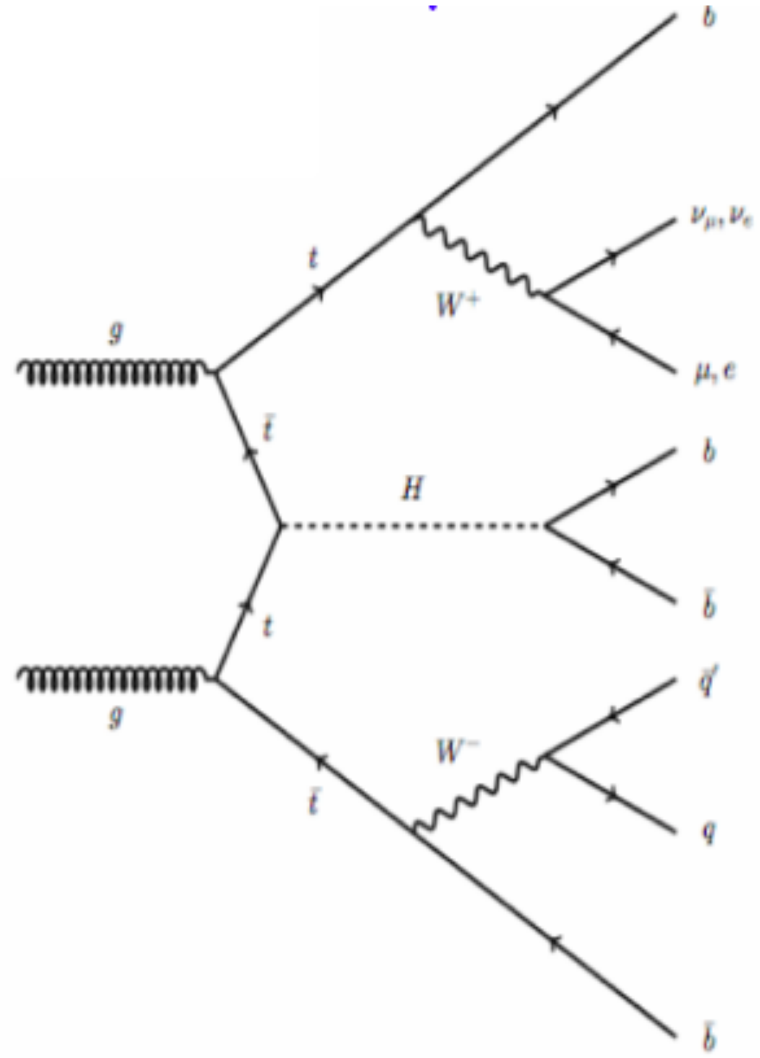
Up to 4 b-tags

e or μ, E_T^{miss}, M_T^W

	0 b-tags	1 b-tag	2 b-tags	3 b-tags	≥4 b-tags
4 jets	H_T^{had}	H_T^{had}		H_T^{had}	
5 jets	H_T^{had}	H_T^{had}	H_T^{had}	H_T^{had}	H_T^{had}
≥6 jets	H_T^{had}	H_T^{had}	H_T^{had}	m_{bb}	m_{bb}

Signal
Background
Control regions

ATLAS Event Selection



- Trigger:
- e: 20 / 22 GeV (+45GeVnon-isol)
- μ: 18GeV
- Leptons:
  - e: p_T>25GeV |η|<2.5
    - Tightest electron
  - μ: p_T>20GeV |η|<2.5
- Jets: (R=0.4): p_T>25GeV
- B-tag: 70% (b) 20% (c) 0.8% (lite)
- e ch.: E_T^{miss} > 30 GeV; M_T^W > 30GeV
- μ ch.:
  - E_T^{miss}> 20GeV
  - $E_T^{miss}+M_T^W$ > 60GeV

Object Defintions (Standard Top Group)

Electrons:

- tightPlusPlus
- author==1 or 3
- $|\eta_{clus}| < 2.47$ & excl 1.37-1.52
- Eiso90Etcone20 && Eiso90PtCone30
- Not flagged BADCLUSELECTRON (el_QQ && 1446==0)
- $E_t = E_{clus} / \cosh track\eta$
- Energy corrected in data (& smeared in MC) with eGamma tool.

Jets:

- AntiKt4TopEMJets
- E> 0
- Calibrate jets with ApplyOffsetEtaJES
- p_t, $|\eta|$, JVF requirements are applied later in cuts/overlap removal
- Remove jet overlappign with electron i.e. dR< 0.2 with a 'good electron'

Muons:

- MuID Combined
- tight
- author==12
- $\eta < 2.5$
- $p_t > 15$ GeV
- MCP ID Hits requirements
- Ptcone30< 2.5, Etcone20< 4 GeV
- not overlapping a jet having $p_t > 25$ GeV, $E > 0$ and JVF> 0.7
- Energy corrected with MCP tool.

b-tagging

- MV1 tagger @ $\varepsilon = 70\%$ (0.601713)

Missing ET:

- MET_RefFinal_em_tightpp
- Corrected with top WG tool before cuts applied

Samples and Yields for ≥ 6 jets ≥ 4 b's

Signal: 2.3 events

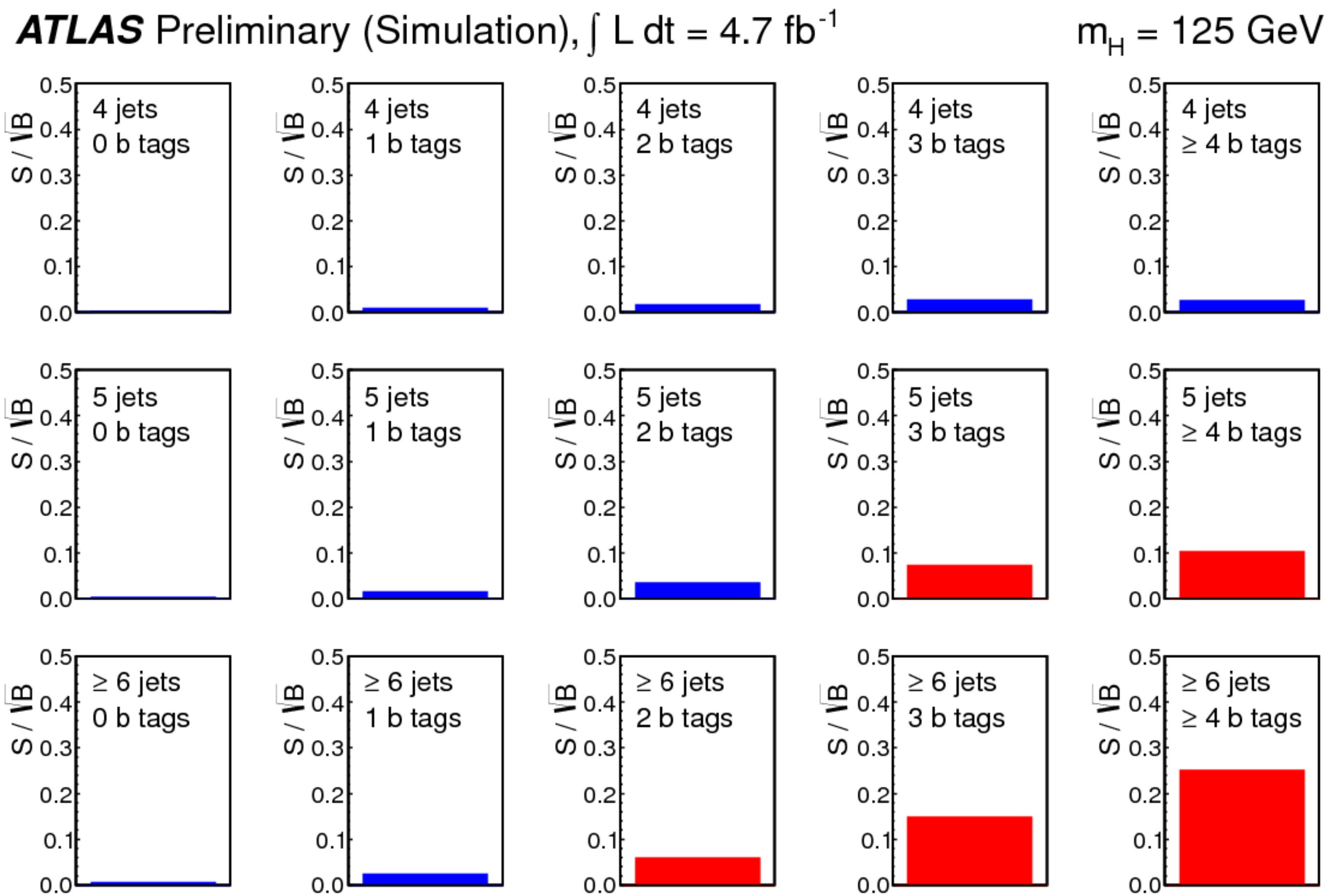
- PYTHIA 6.425, mt = 172.5 GeV. Charged lepton filter: $p_T > 5$, $|\eta| < 5$

Backgrounds:

- **Dominant** are **tt+jets** (16.4 events) and **ttbb** (26.5 events):
  - ALPGEN 2.13+HERWIG 6.520 HFOR overlap removal.
  - tt+jets: Npartons = 0−5, σ=73.08pb, K=1.755;
  - ttbb : σ = 0.856 pb, K=1.687 (biggest sys.)
- Multijets (data-driven): 6.22 events (5.67 e channel; 0.55 μ channel)
- ttV: 2.2 events
  - Madgraph 4 + PYTHIA 6.425 σ_{ttW}= 0.12pb, σ_{ttZ} = 0.096pb
- Single Top: 1.28 events
  - s-channel (1.5 pb) and Wt (15.74 pb): MC@NLO 4.01 with HERWIG 6.520 and Jimmy 4.31.
  - t-channel (20.92 pb, K=0.866): AcerMC 3.8 with PYTHIA 6.425
- W+jets: 0.54 events
  - ALPGEN 2.13+HERWIG 6.520: Wbb, Wcc, Wc, Z → ll, W → lv; HFOR overlap removal
  - Uses data to normalize and change mix of heavy flavours
- Minor backgrounds: 0.2 events
  - Dibosons and Z + jets;
  - Dibosons: HERWIG 6.520 and JIMMY 4.31; charged lepton filter $p_T > 10$GeV, $|\eta| < 2.8$.

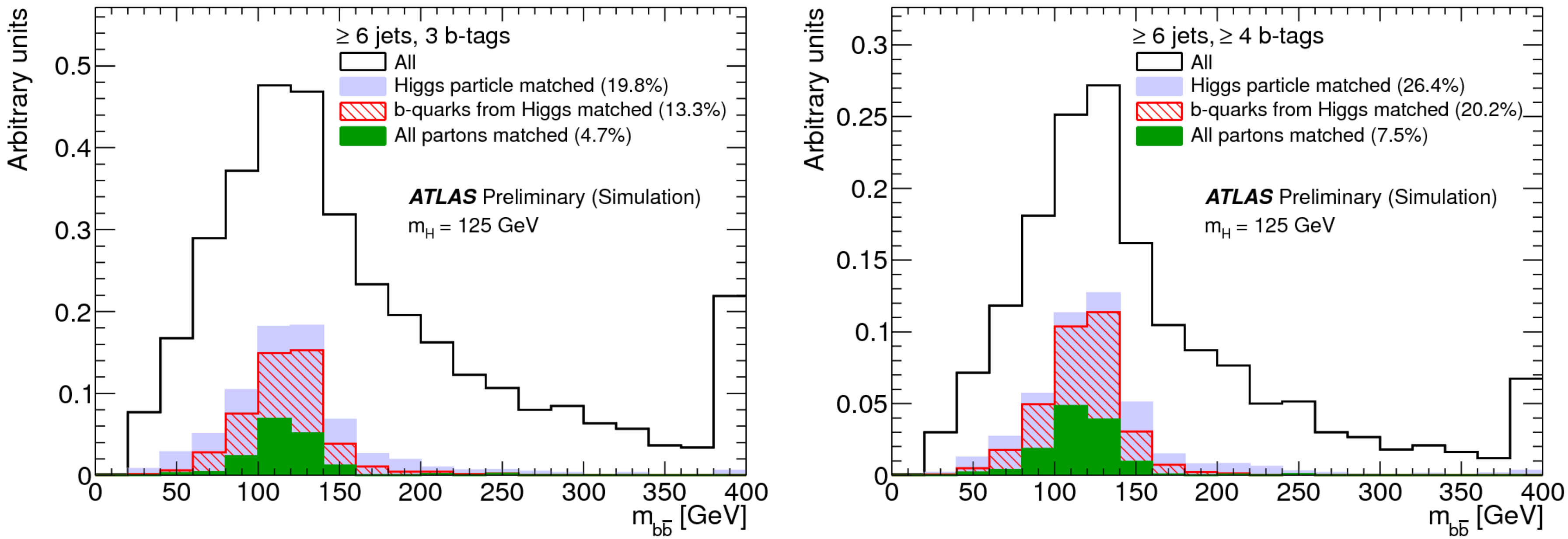
Category	signal (M=125) $H \to bb$	background	$S/\sqrt{B}$
4 jets, 0 tags	0.20	40200	0.001
4 jets, 1 tag	1.1	21240	0.008
4 jets, ≥ 2 tags	3.0	15040	0.02
5 jets, 2 tags	2.7	6640	0.03
≥ 6 jets, 2 tags	3.4	3360	0.06
5 jets, 3 tags	2.3	915	0.08
5 jets, ≥ 4 tags	0.74	45	0.11
≥ 6 jets, 3 tags	4.0	634	0.16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

Yields after the fit


ATLAS Preliminary (Simulation), ∫ L dt = 4.7 fb-1
mH = 125 GeV
S / √B
4 jets 0 b tags
4 jets 1 b tags
4 jets 2 b tags
4 jets 3 b tags
4 jets ≥ 4 b tags
5 jets 0 b tags
5 jets 1 b tags
5 jets 2 b tags
5 jets 3 b tags
5 jets ≥ 4 b tags
≥ 6 jets 0 b tags
≥ 6 jets 1 b tags
≥ 6 jets 2 b tags
≥ 6 jets 3 b tags
≥ 6 jets ≥ 4 b tags
0.0
0.1
0.2
0.3
0.4
0.5

Kinematic Fit

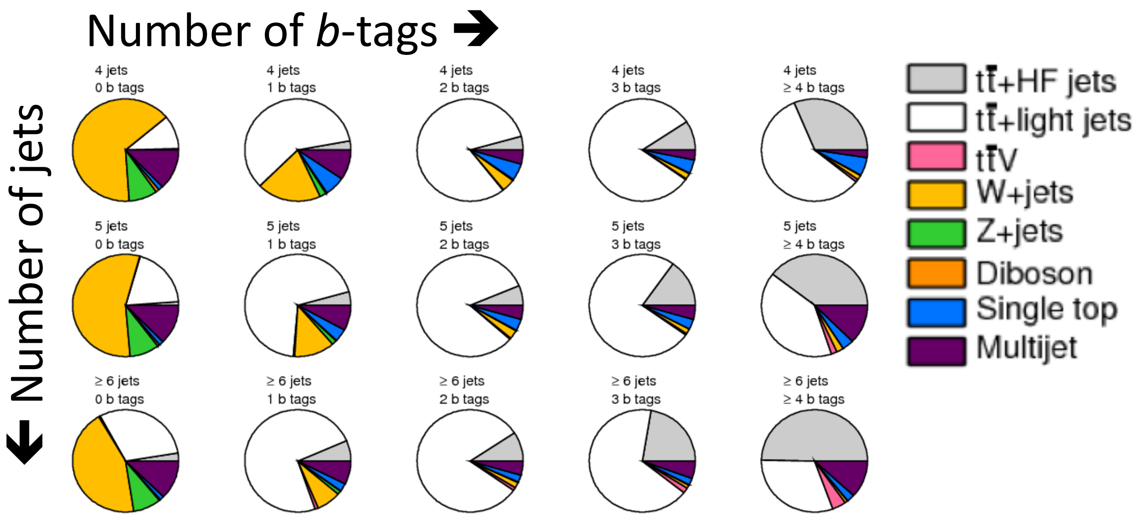
- Analysis sensitivity hampered by combinatorial background
- Reject bad combinations – e.g. where b-jet used in W reconstrucion – to reduce impact
- Selection purity still rather low => reconstructed mass spectrum in signal very broad



Profiling

Parameters strongly constrained:

- W+jets and QCD normalization, tt , b-tag:
  - 4 jet channels
- W+jet and tt:
  - 4 jet 0b (W+jet), 4 jet 1b and 2b
- b tagging:
  - 4 jet evolution across the number of b-tags
- tt modelling and rate uncertainties:
  - 4, 5 and 6 jets with 2 b-tags
- tt+HF fraction:
  - 5 channels with 3 and 4 b-tags

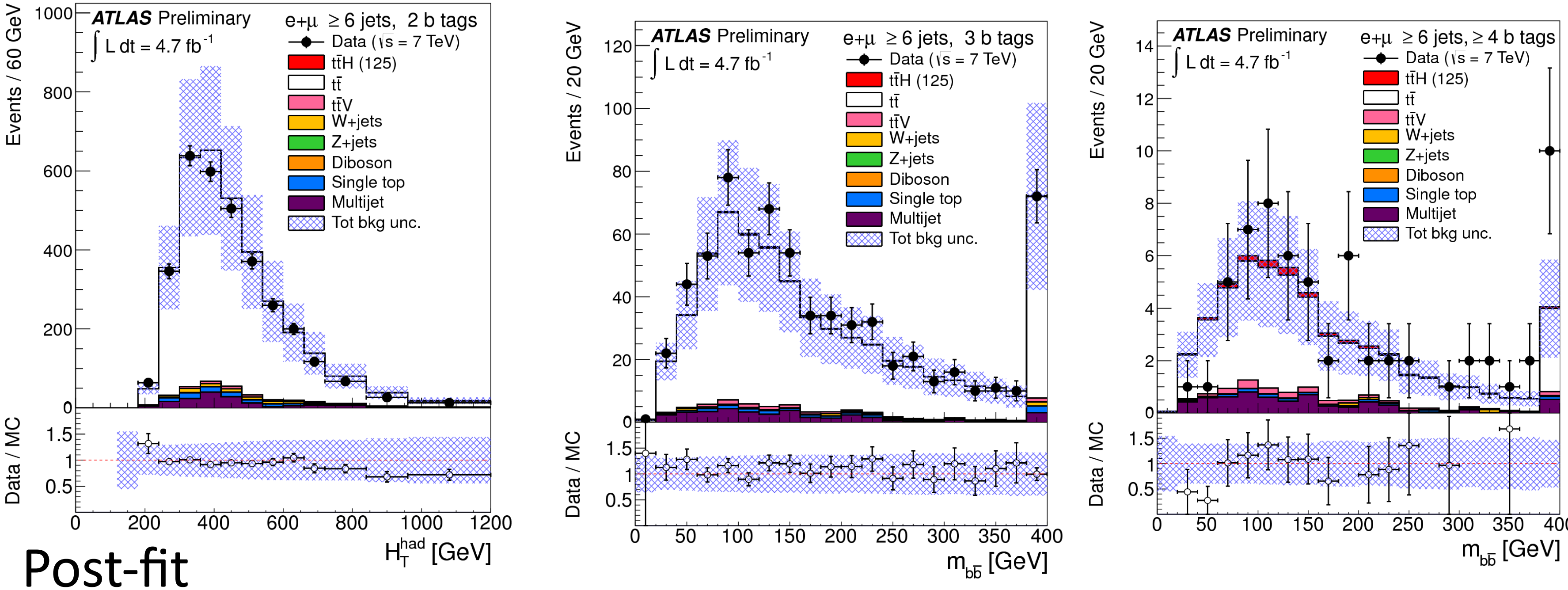


Ordered nuisance parameters:

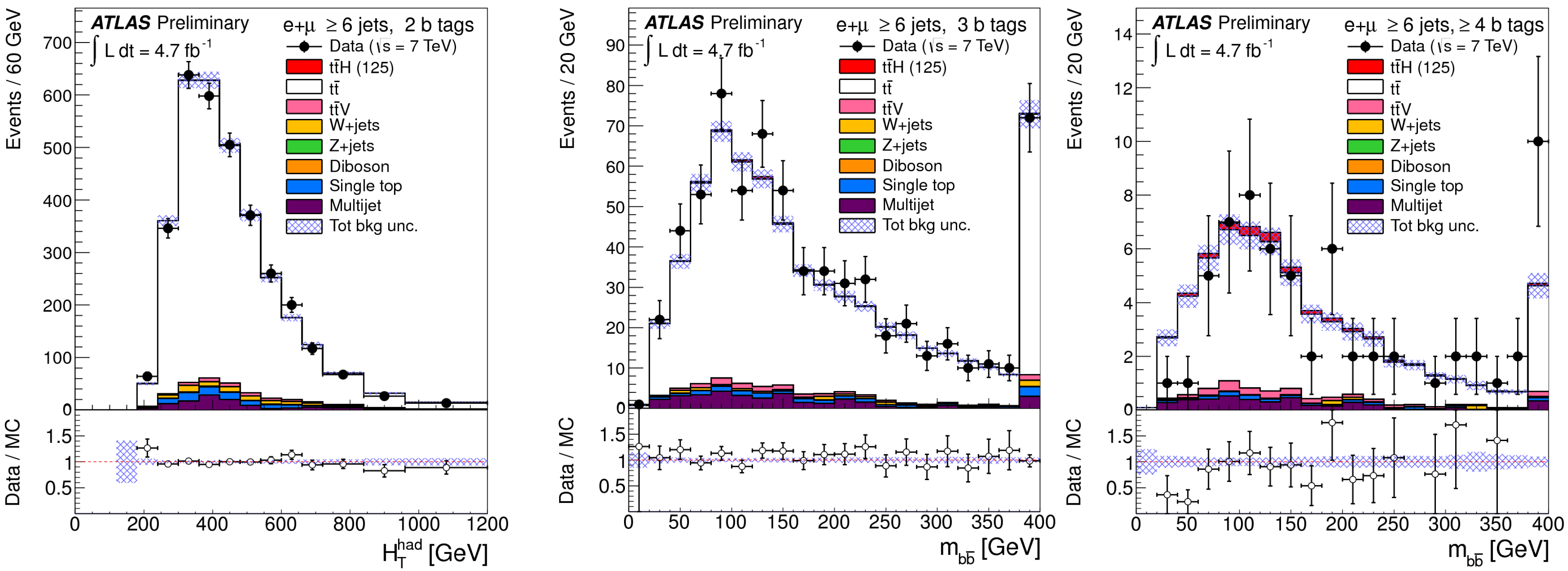
Level	Most Important	σ/σ_{SM}
N	Start	12.19
N-1	ttbar HF	9.77
N-2	Ltag	9.40
N-3	Ctag	8.08
N-4	QCD Norm	7.09
N-5	JES	6.94
All	Stat	6.10

- Effect of each systematic uncertainty evaluated with "N-1" test (and "N-m"):
  - Remove one, put back, remove next…
  - Largest impact: freeze (parameter set to the best fitted value) and repeat

Pre-fit



Post-fit

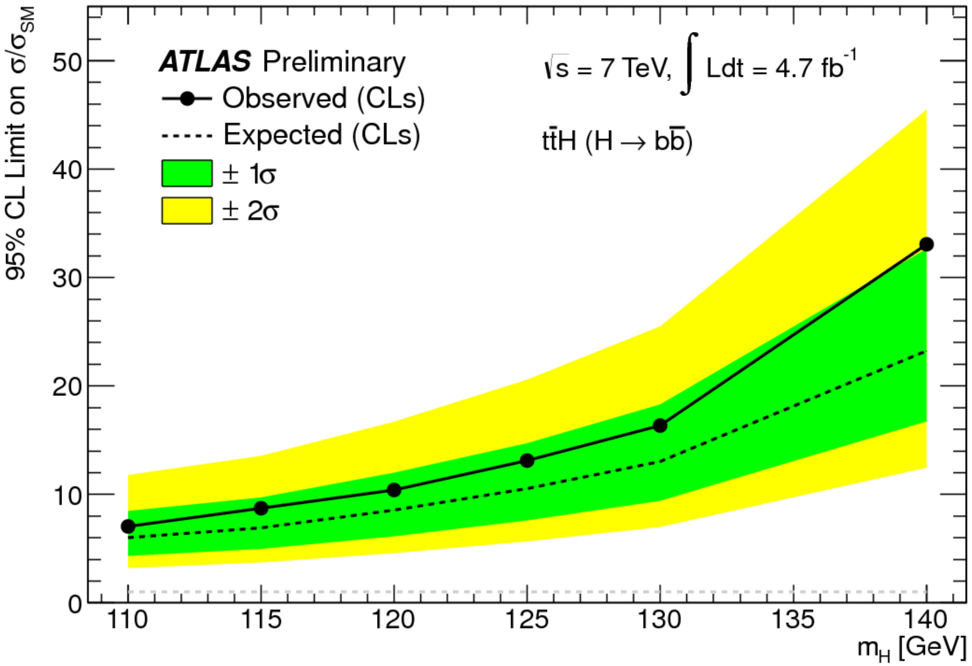


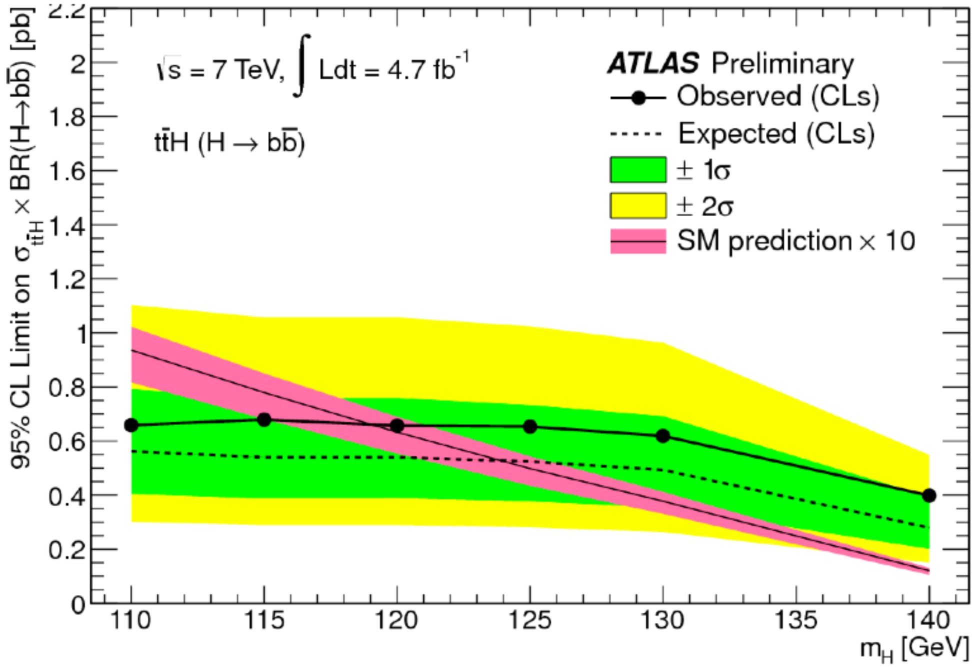
Systematic Uncertainties

- **tt+heavy-flavour** fractions: Vary by 50% - theory studies suggest cross section uncertainty is 75% ; should be weighted down by the fraction of this background. Fit puts it at 30%.

- **tt modeling** (Alpgen):
  - **Qfac**: (±2.3%) The **factorization scale** for the hard scatter is varied by a factor of two up and down relative to the original scale, $Q^2 = \Sigma_{partons} m^2 + p^2_T$
  - **kTfac**: (±9.2%) The **renormalisation scale** associated with the evaluation of α_s at each local vertex in the matrix element calculation is varied by a factor of two up and down relative to the original scale, k_T , between two partons.
  - Functional form of the **factorization scale** (**iqopt2**): (± 13%) Default choice (=1) for dynamic factorization scale, $Q^2 = \Sigma_{partons} m^2 + p^2_T$, changed to $Q^2 = x_1 x_2 s$. This has an order of magnitude larger effect than Qfac.

- **tt cross section**: +9.9 -10.7% using NNLO Hathor.
- **Jet Energy scale**: 16 eigenvectors recommended by the jet/ ETmiss group are varied.
- **b, c and light tagging**: 9 (btag),5(ctag) eigenvectors recommended by b-tagging group are varied for heavy flavours and the one value for light flavours.
- **QCD Multijets**: Mostly in the electron channel. Correlated 50% uncertainty plus uncorrelated statistical estimate in each channel (66% in 6 jet 4 b-tag)
- **ttH parton shower modelling**: 1-5% effect at mH = 120 GeV





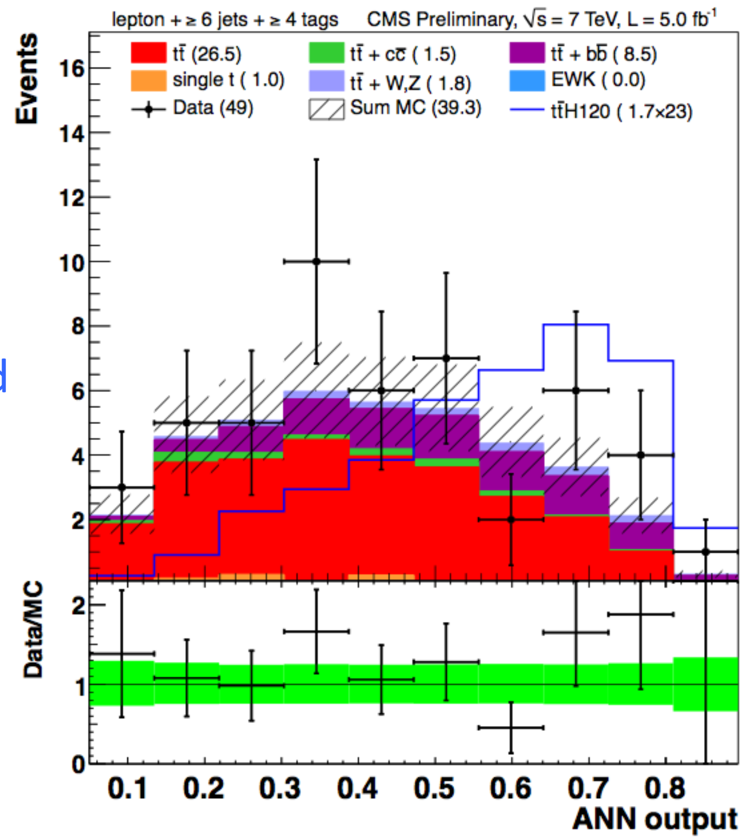
m_H (GeV)	observed	median	stat only
110	7.0	6.0	3.5
115	8.7	6.9	4.0
120	10.4	8.5	4.9
125	13.1	10.5	6.1
130	16.4	13.0	7.8
140	33.0	23.2	14.2

CMS Analysis

- Neural Network analysis
- **Lepton+jets** & **di-lepton** analyses
- 10 best kinematic/event shape/ b-tagging variables chosen from "pool" of candidate variables
- Optimized for each #jets/#b-tags category
- Simultaneous fit for S and B on NN output distributions

Dilepton

	2 b-tags	≥3 b-tags
2 jets	✔	✗
≥3 jets	✗	✔

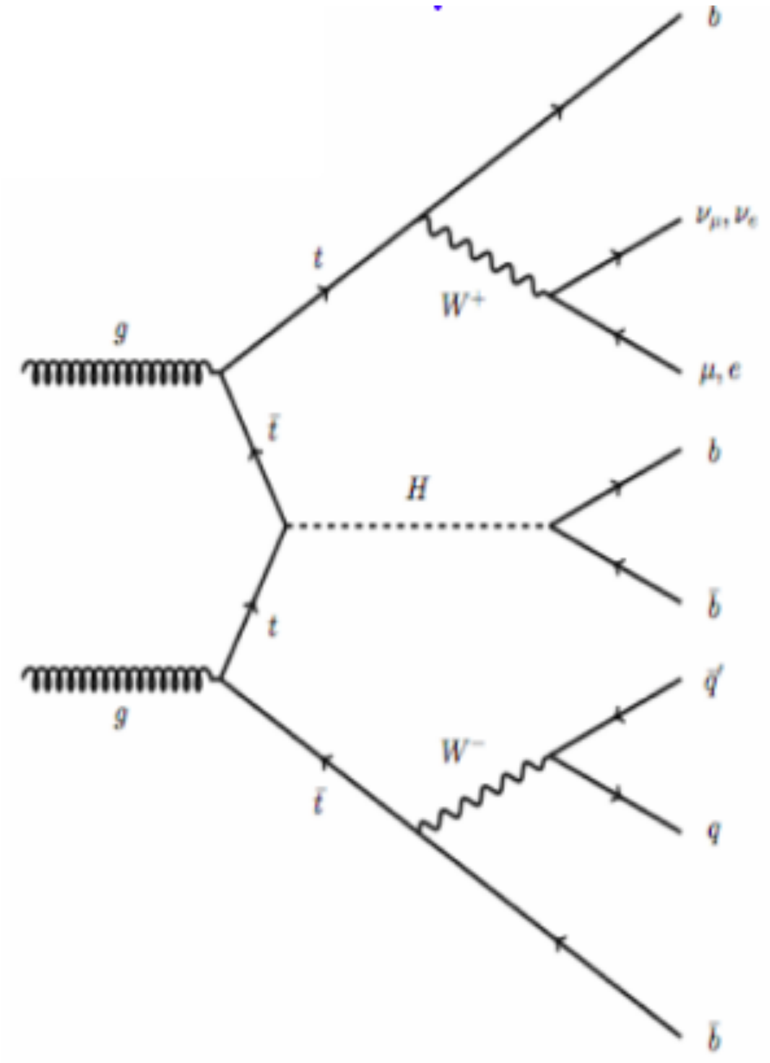


✔ Used
✗ Not used

Lepton+jets

	0 b-tags	1 b-tag	2 b-tags	3 b-tags	≥4 b-tags
4 jets	✗	✗	✗	✔	✔
5 jets	✗	✗	✗	✔	✔
≥6 jets	✗	✗	✔	✔	✔

CMS Event Selection



Trigger:

- l+jets: l+3 jet trigger
  - e: 25 GeV
  - μ: 18GeV
  - Jets: 30 GeV
- Dilepton:
  - 2-lepton trigger: leading >17GeV sublead >8GeV
- Leptons:
  - Isolation ratio dR<0.4
- l+jets:
  - Tight muon >30GeV |η|<2.1
  - Tight electron >30GeV |η|<2.5
- Dilepton:
  - Tight e or mu >20GeV + loose e or mu > 10GeV |η|<2.4
- Jets: (R=0.5): p_T>30GeV
  - For l+jets 3 leading jets >40GeV (trigger)
- B-tag: 70% (b) 20% (c) 2% (lite)

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

- **Included also, the dilepton channel**
  - μμ, ee, eμ channels
  - Require 1 tight muon/electron (20 GeV) and 1 loose muon/electron (10,15 GeV), at least 2 jets (30GeV) and 2 b-tags

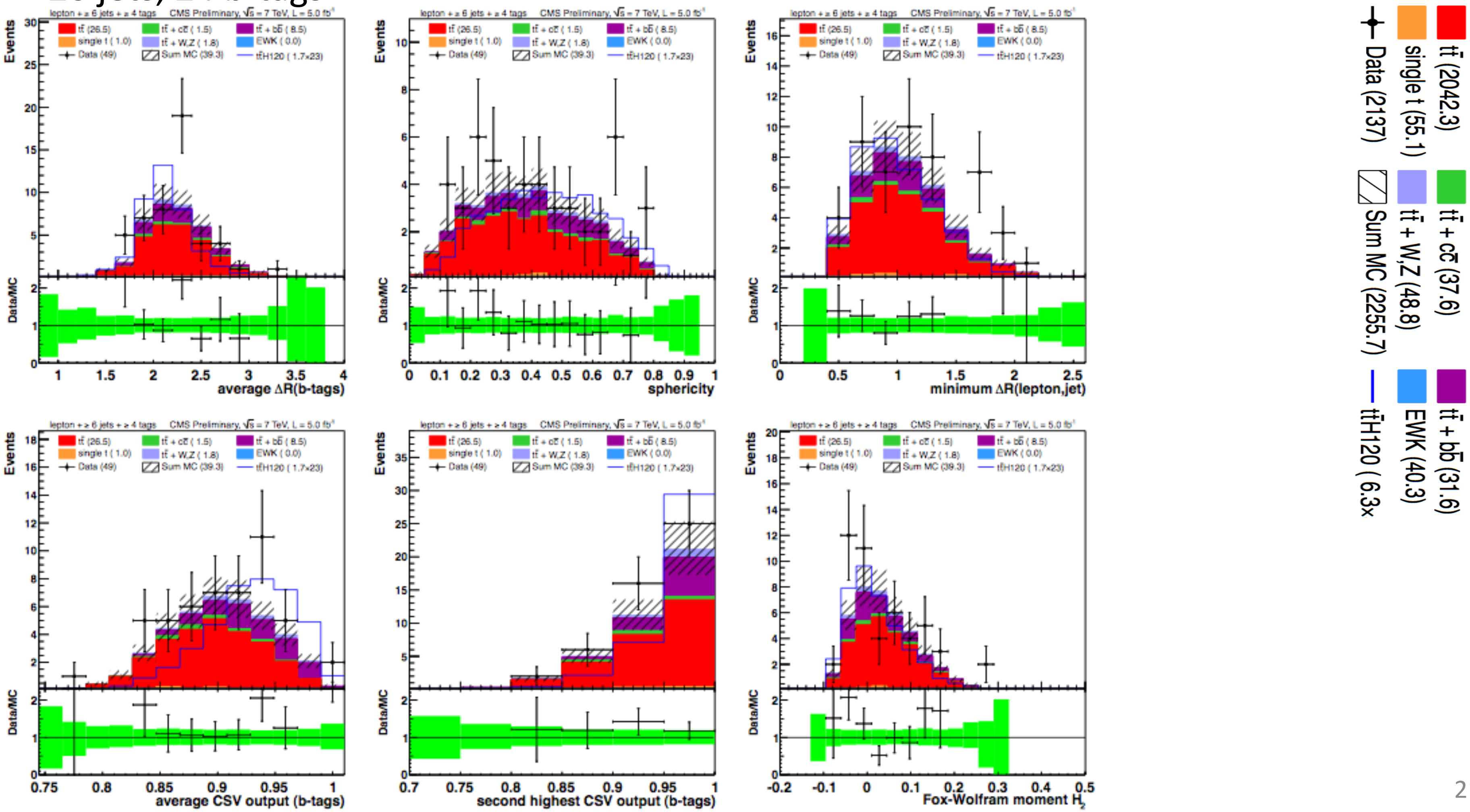
Expected event yields in each Dilepton category in 5 fb^{-1}

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

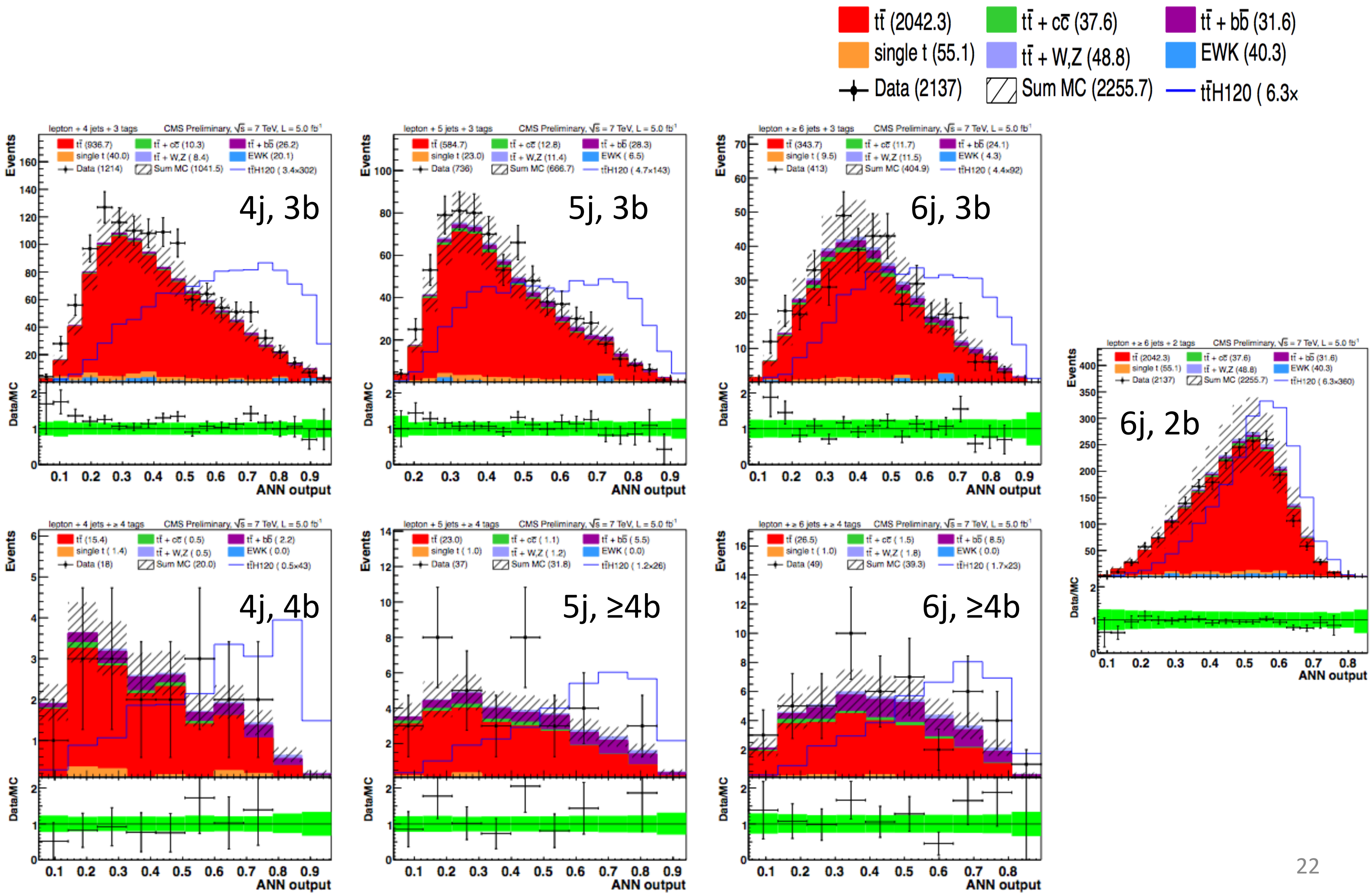
CMS Analysis

- Neural-net based analysis of 2011 data
- Separate events into categories of #jets and #b-tagged jets
- 10 best kinematic/event shape/b-tagging variables chosen from "pool of candidates"
- Optimized for each #jets/#b-tags category
- Simultaneous fit for S and B on NN output distributions

≥6 jets, ≥4 b-tags

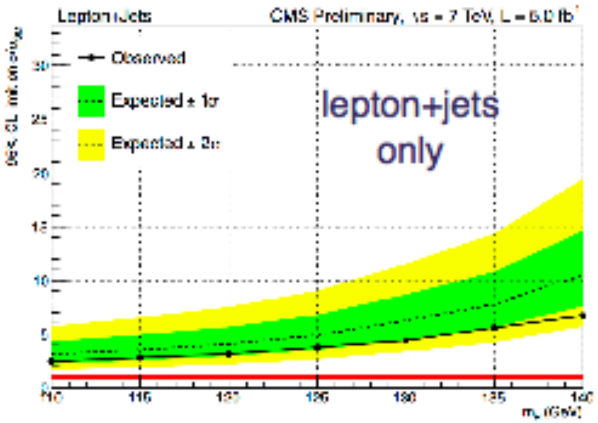


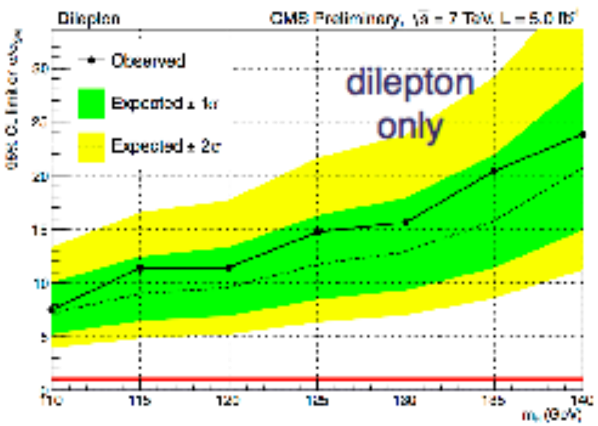
CMS Analysis

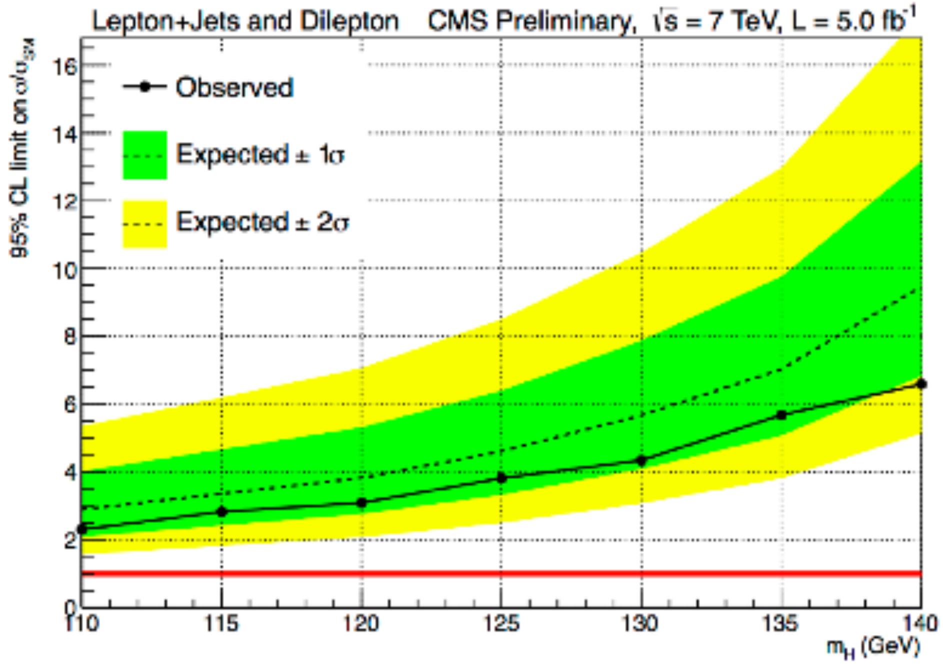


At Higg's mass 125 GeV

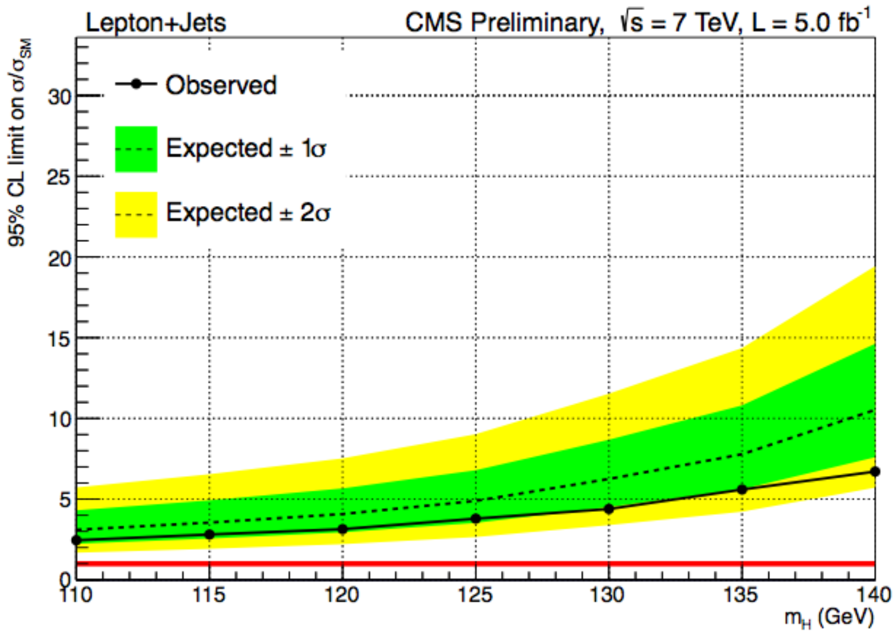
- expect to set a limit of 4.6 x σ_{SM}
- observed upper limit: 3.8 x σ_{SM}







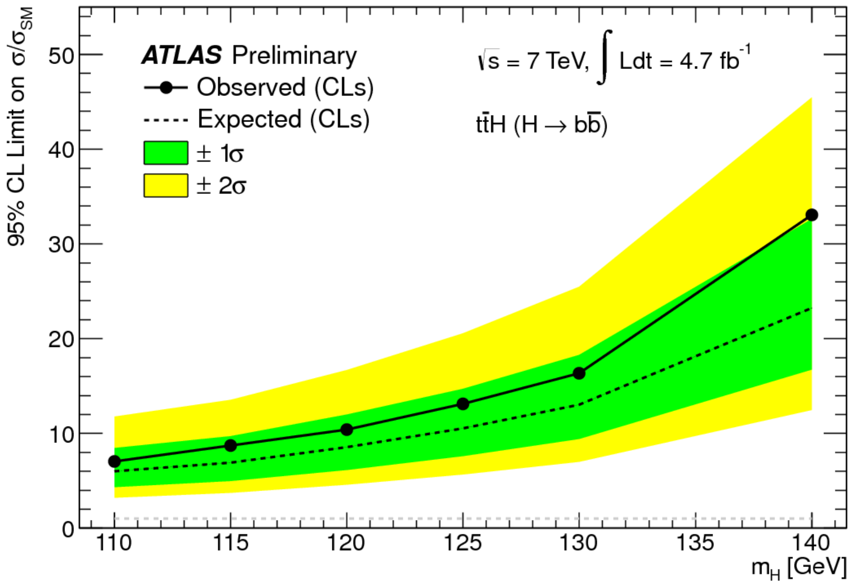
Source	Rate	Shape?	Notes
Luminosity	2.2%	No	All signal and backgrounds
Lepton ID/Trig	1.8%	No	All signal and backgrounds
Pileup	1%	No	All signal and backgrounds
Jet Energy Resolution	1.5%	No	All signal and backgrounds
Jet Energy Scale	0-66%	Yes	All signal and backgrounds
QCD Scale ($t\bar{t}H$)	12.5%	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



CMS

m_H (GeV/c^2)	Obs limit	Median Exp limit
110	2.5	3.1
115	2.8	3.6
120	3.1	4.1
125	3.8	4.9
130	4.4	6.3
135	5.6	7.8
140	6.7	10.5

Lepton+jets mode



ATLAS

m_H (GeV)	observed	median	stat only
110	7.0	6.0	3.5
115	8.7	6.9	4.0
120	10.4	8.5	4.9
125	13.1	10.5	6.1
130	16.4	13.0	7.8
140	33.0	23.2	14.2

Very big difference!...

Conclusions & Outlook

Should get to the bottom of ttH differences…

– **BUT** Nice problem to have: ttH can be done at LHC!! (Yes we can!)

Uncertainties:

– Background matters!
– Theory uncertainty matters!
– Background theory uncertainty matters!
– Discussion ongoing within LHC Higgs XS WG

The path ahead:

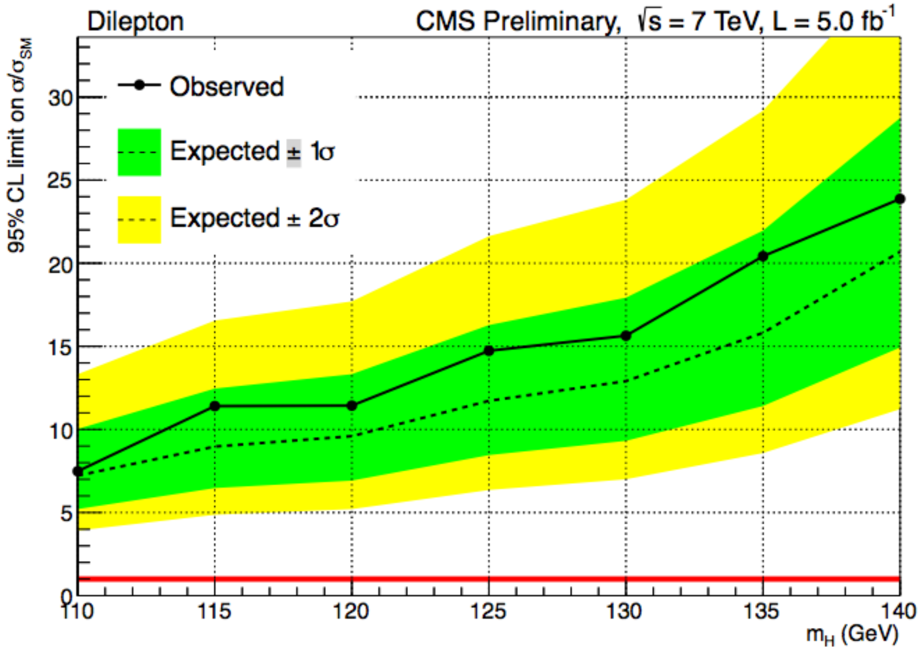
- **Approximate** expected limits extrapolating current analysis:
  – $4.7fb^{-1}$@7TeV + $15fb^{-1}$@8TeV: $\sigma/\sigma_{SM} \approx 4.9$ (stats); $\sigma/\sigma_{SM} = 6.0^{+2.4}_{-1.7}$ (+syst)
  – $4.7fb^{-1}$@7TeV + $25fb^{-1}$@8TeV: $\sigma/\sigma_{SM} \approx 3.8$ (stats); $\sigma/\sigma_{SM} \approx 4.6$ (stats+syst)
- But we can do better!
  – Developing several MV analyses
  – Improving b-jet resolution in energy and angle
- Must keep in mind goal of measuring top Yukawa coupling!

Bonus slides

Monte Carlo

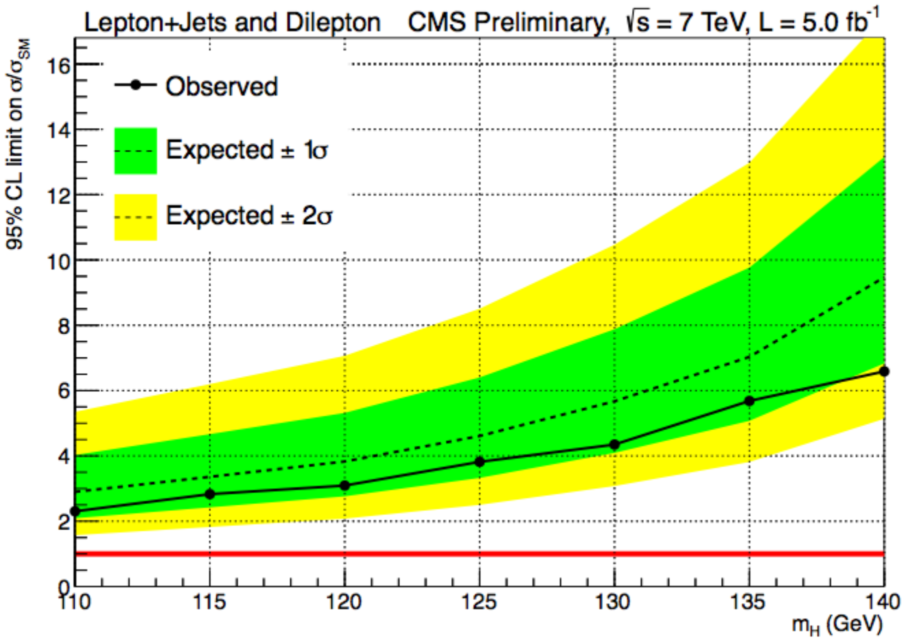
- ATLAS:
- Main backgrounds:
  - tt+jets (ALPGEN+HERWIG)
  - ttW, ttZ (MADGRAPH+PYTHIA)
  - Drell-Yan (ALPGEN+HERWIG)
  - W+jets normalization: data-derived, shape: (ALPGEN +HERWIG)
  - single-t (MC@NLO+HERWIG/ AcerMC+PYTHIA)
  - diboson (HERWIG)
  - Multijet: Data-derived model
- Signal:
  - ttH with H→bb (PYTHIA)

- CMS:
  - Main backgrounds:
  - tt+jets (MADGRAPH+PYTHIA)
  - ttW, ttZ (MADGRAPH+PYTHIA)
  - W+jets, Drell-Yan (MADGRAPH+PYTHIA)
  - single-t (POWHEG+PYTHIA)
  - diboson (PYTHIA)
- Signal:
  - ttH with H→anything (PYTHIA)



Di-lepton channel

m_H (GeV/c^2)	Obs limit	Median Exp limit
110	7.5	7.2
115	11.4	8.9
120	11.4	9.6
125	14.7	11.7
130	15.6	12.8
135	20.4	15.8
140	23.8	20.6



Single-lepton + Di-lepton channels combined
(di-lepton improves expected limit by 6.5%)

m_H (GeV/c^2)	Obs limit	Median Exp limit
110	2.3	2.9
115	2.8	3.5
120	3.1	3.8
125	3.8	4.6
130	4.4	5.7
135	5.7	7.0
140	6.6	9.5

ATLAS/CMS differences

Systematics:

- No QCD systematics (no QCD background?!)
- No ttH modeling
- No W+jets/HF systematic
- No JVF systematic (pileup suppression)
- Different treatment of Jet Energy Scale (ATLAS 16 NP), b-tag sys. (ATLAS 9 NP) and c-tag sys (ATLAS 5 NP): CMS one Nuis. Par.
- b and c tagging correlated
- One tt systematic uncertainty (ATLAS 3 NP)
- ttbar+HF 20% instead of 50% uncertainty

Summary:

- ATLAS using CMS systematics: 35% better
- 20% improvement from more signal
- Remaining improvement from use of Multivariate analysis (22%)

In numbers:

- σ/σ_{SM} = 10.5 -> 7.8 from systematics
- Take 22% improvement from MVA: -> 6.1
- Take 20% additional signal: σ/σ_{SM} -> 5.1 (expect)
- CMS: 4.9 (expected)

Cuts:

- Electrons and muon:
  - ATLAS p_T>20/25GeV
  - CMS p_T > 30 GeV
- Jets:
  - ATLAS pT>25GeV
  - CMS 3 leading jets pt > 40 GeV (otherwise 30 GeV)
- More signal and higher cuts. Not clear what signal sources are used

Channel	Signal		Background		$S/\sqrt{(B)}$		Ratio: $S/\sqrt{(B)}$
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS	CMS/ATLAS
6jet, 2tag	4.45	6.3	3567.38	2255.8	0.0745	0.133	1.78
4jet, 3tag	1.23	3.5	1294.14	1041.6	0.0341	0.108	3.17
5jet, 3tag	2.8	4.7	887.25	666.7	0.0940	0.182	1.94
6jet, 3tag	4.61	4.4	622.88	404.9	0.1847	0.219	1.18
4jet, 4tag	0.16	0.5	19.94	20	0.0358	0.112	3.12
5jet, 4tag	0.83	1.2	38.33	31.8	0.1341	0.213	1.59
6jet, 4tag	2.28	1.7	53.12	39.3	0.3128	0.271	0.86
Total	16.4	22.3			0.4084	0.492	1.20

ATLAS vs CMS Comparison

ATLAS	CMS
e: p_T>25GeV |η|<2.5	e: p_T>30GeV |η|<2.5
μ: p_T>20GeV |η|<2.5	μ: p_T>30GeV |η|<2.1
jets: (0.4): p_T>25GeV	Jets (0.5): p_T>30/40GeV |η|<2.4
B-tag: 70% (b) 20% (c) 0.8% (lite)	B-tag: 70% (b) 20% (c) 2% (lite)
e ch.: E_T^{miss} > 30 GeV M_T^W > 30GeV	
μ ch.: E_T^{miss}> 20GeV $E_T^{miss}+M_T^W$ > 60GeV	

ttbb – new generated results

@ 7 TeV
b massless

$m_t = 172.5$ GeV

PDFs via LHAPDF:
CT09MC1 at LO
CT10 at NLO

b-quarks excluded from PDFs

Dynamical common scale:
$$\mu_R^2 = \mu_F^2 = \mu_0^2 = m_t \cdot \sqrt{p_T(b) \cdot p_T(\bar{b})}$$

IR-safe anti-k_T algorithms with separation R = 0.7

pT (b) > 20 GeV
| y(b) | < 2.5
R(b, b) > 0.7

ttjj – already existing results

@ 7 TeV
where j = u, d, c, s, b – all massless
Processes like ttbb, ttbg, etc. included
$m_t = 173.3$ GeV

PDFs via LHAPDF:
MSTW2008LO at LO
MSTW2008NLO at NLO

b-quarks included in PDFs

Common fixed scale:
$$\mu_R = \mu_F = \mu_0 = m_t$$

IR-safe anti-k_T algorithms with separation R = 0.5

pT (j) > 50 GeV
| y(j) | < 2.5
R(j, j) > 0.5

Fairly inconsistent (for now) !!!

ttjj

7 TeV

Process	$\sigma_{\rm LO}$ [pb]	$\sigma_{\rm NLO}^{\alpha_{\max}=1}$ [pb]	$\sigma_{\rm NLO}^{\alpha_{\max}=0.01}$ [pb]	K-Factor	[%]
$pp \to t\bar{t}jj + X$	13.398 (4)	9.81 (1)	9.82 (2)	0.73	−27

$$\sigma_{\rm LO}^{t\bar{t}jj}({\rm LHC}_{7{\rm TeV}}, m_t = 173.3 \text{ GeV}, {\rm MSTW2008lo}) = 13.398\,^{+11.713(87\%)}_{-5.788(43\%)} \text{ pb}$$

$$\sigma_{\rm NLO}^{t\bar{t}jj}({\rm LHC}_{7{\rm TeV}}, m_t = 173.3 \text{ GeV}, {\rm MSTW2008nlo}) = 9.82\,^{-1.48(15\%)}_{-1.47(15\%)} \text{ pb}\,.$$

$\xi \cdot \mu_0$	$0.5 \cdot \mu_0$	$1 \cdot \mu_0$	$2 \cdot \mu_0$
$\sigma_{\rm LO}$ [pb]	25.111 (8)	13.398 (4)	7.610 (2)
$\sigma_{\rm NLO}$ [pb]	8.34 (4)	9.82 (2)	8.35 (1)

NLO QCD Corrections
K = NLO/LO = 0.73 (-27%)

Scale dependence
LO 87% (65%) → NLO 15%

ttbb

7 TeV

PROCESS	σ_{LO} [fb]	$\sigma_{NLO}^{\alpha_{max}=1}$ [fb]	$\sigma_{NLO}^{\alpha_{max}=0.01}$ [fb]	K-FACTOR	[%]
$pp \to t\bar{t}b\bar{b} + X$	416.7 (5)	458.3 (8)	458 (1.4)	1.10	+10

$$\sigma_{LO}^{tt\bar{b}\bar{b}}(\mathrm{LHC}_{7\mathrm{TeV}}, m_t = 172.5 \text{ GeV}, \mathrm{CT09MC1}) = 416.7^{+380.7(91\%)}_{-183.2(44\%)} \text{ fb}$$

$$\sigma_{NLO}^{tt\bar{b}\bar{b}}(\mathrm{LHC}_{7\mathrm{TeV}}, m_t = 172.5 \text{ GeV}, \mathrm{CT10}) = 458.3^{+119.7(26\%)}_{-123.1(27\%)} \text{ fb} .$$

$\xi \cdot \mu_0$	$0.5 \cdot \mu_0$	$1 \cdot \mu_0$	$2 \cdot \mu_0$
σ_{LO} [fb]	797.4 (9)	416.7 (5)	233.5 (3)
σ_{NLO} [fb]	578 (3)	458.3 (8)	335.2 (8)

NLO QCD Corrections
K = NLO/LO = 1.10 (+10%)

Scale dependence
LO 91% (68%) → NLO 27%

ttbb/ttjj – First Crude Estimate

7 TeV

$$\mathcal{R}_{\rm LO} = \sigma^{t\bar{t}b\bar{b}}_{\rm LO}(\mu_0)/\sigma^{t\bar{t}jj}_{\rm LO}(\mu_0) = 0.031 = 3.1\%$$

$$\mathcal{R}_{\rm NLO} = \sigma^{t\bar{t}b\bar{b}}_{\rm NLO}(\mu_0)/\sigma^{t\bar{t}jj}_{\rm NLO}(\mu_0) = 0.047 = 4.7\%$$

$$\mathcal{R} = \sigma^{t\bar{t}b\bar{b}}(2\mu_0)/\sigma^{t\bar{t}jj}(2\mu_0)$$

$$\mathcal{R} = \sigma^{t\bar{t}b\bar{b}}(2\mu_0)/\sigma^{t\bar{t}jj}(0.5\mu_0)$$

$$\mathcal{R} = \sigma^{t\bar{t}b\bar{b}}(0.5\mu_0)/\sigma^{t\bar{t}jj}(2\mu_0)$$

$$\mathcal{R} = \sigma^{t\bar{t}b\bar{b}}(0.5\mu_0)/\sigma^{t\bar{t}jj}(0.5\mu_0)$$

For the individual NLO cross sections scale uncertainty of the order of 27% & 15%

For the ttbb/ttjj ratio asymmetric scale uncertainty @ NLO 47% & 15%

After symmetrization 31%

$$\mathcal{R}_{\rm LO} = 0.031^{+0.062(200\%)}_{-0.001(\ \ 3\%)}$$

$$\mathcal{R}_{\rm NLO} = 0.047^{+0.022(47\%)}_{-0.007(15\%)}$$

Expected Reach

- Approximate limit at m_H=125GeV for 4.7fb^{-1}@7TeV + 15fb^{-1}@8TeV:
  - Approximated all cross sections scaling to 1.4x the 7TeV values
  - Gives factor of 4.5 (15x1.4/4.7) multiplying the 7TeV yields
  - Statistics only should give expected limit $\sigma/\sigma_{SM} \approx 10.5/\sqrt{(4.5)} = 4.9$
  - Including systematics, got expected limit $\sigma/\sigma_{SM} = 6.0^{+2.4}_{-1.7}$

- Extrapolating to 4.7fb^{-1}@7TeV + 25fb^{-1}@8TeV:
  - Factor multiplying yields: 25x1.4/4.7 = 7.45
  - Expected limit (2011+2012) $\approx 10.5/\sqrt{7.45} = 3.8$
  - Penalty of ≈20% with respect to no systematics gives expected limit: $\sigma/\sigma_{SM} \approx 4.6$

- Even assuming CMS' improvement of factor 2 this gives ≈2.3

Data-driven background detemination

- **Multijets (5.6 e and 0.6 μ)**
  - Matrix Method (MM): "tight" and "loose" where tight is subset of loose

$$
\begin{aligned}
N^{loose} &= N^{loose}_{real} + N^{loose}_{fake} \\
N^{tight} &= \varepsilon_{real} N^{loose}_{real} + \varepsilon_{fake} N^{loose}_{fake}
\end{aligned}
$$

  - Problem: correlated with data and statistics low with more than 2 b tags.
  - Solution: Use $N_b \geq 2$ to get shape and matrix method in each region to get rate.

- **W+ jets (0.55)**
  - Exploit asymmetry in W^+ & W^- (ATL-COM-PHYS-2012-1197):
  - Measure $(N_{W+} - N_{W-})_{meas}$, use $r_{MC} = W^+/W^-$ to get $N_W = \left(\frac{r_{MC}+1}{r_{MC}-1}\right)(N_{W+} - N_{W-})_{meas}$.
  - Flavour fractions from:
  - $N^{W^{\pm},tag} = N^{W^{\pm},pre-tag}(P_{bb}F_{W^{\pm}bb} + P_{bb}F_{W^{\pm}cc} + P_{bb}F_{W^{\pm}c} + P_{bb}F_{W^{\pm}light})$
  - $F_{W^{\pm}bb} + F_{W^{\pm}cc} + F_{W^{\pm}c} + F_{W^{\pm}light} = 1$
  - 20% correction to pre-tag sample
  - $W_{b\bar{b}}$,$W_{c\bar{c}}$, W_c, W+light jets also in similar way from data.
  - Scale $W_{b\bar{b}}$,$W_{c\bar{c}}$, by 1.13(1.22) for e (μ).
  - Scale W_c by K=1.52 and then 0.88(0.95) for e (μ).
  - Preserve normalisation: Scale W+light by 1.01(0.98) for e (μ).

Systematics

- No QCD systematics
- No ttH modeling
- No Wjets HF systematic
- No JVF systematic

- JES(16), BTag(9) and CTag(5):One Nuis. Param
- One $t\bar{t}$ sys (3)
- ttbarHF 20% instead of 50%
- B and C Tagging correlated

Condition	σ/σ_{SM}
Atlas	10.5
No breakdown	10.2
20% ttbarHF	9.3
CMS-like (Btag/Ctag)	7.9
CMS-like (BCtag)	7.8

ATLAS results using CMS systematics:(35% better)

Systematics: N-m test $m_H = 125$ GeV

- Remove one, put back, remove next: largest impact; freeze and repeat. All sys=12.19; (Param set to the best fitted value then vary others)

Systematic	Remove NuisP	Change
– **ttbar HF**	**9.77**	**-20%**
– $t\bar{t}$ modeling	11.88	-3%
– JES	11.73	-4%
– ktfac	11.97	-2%
– Btag	12.08	-1%
– Ctag	12.06	-1%
– normalizations	12.16	0%
– Ltag	12.11	-1%
– iqopt2	12.20	0%
– wjets HF	12.17	0%
– qfac	12.21	0%