Search for ttH and tH production with H to bb

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on behalf of the ATLAS and CMS collaborations

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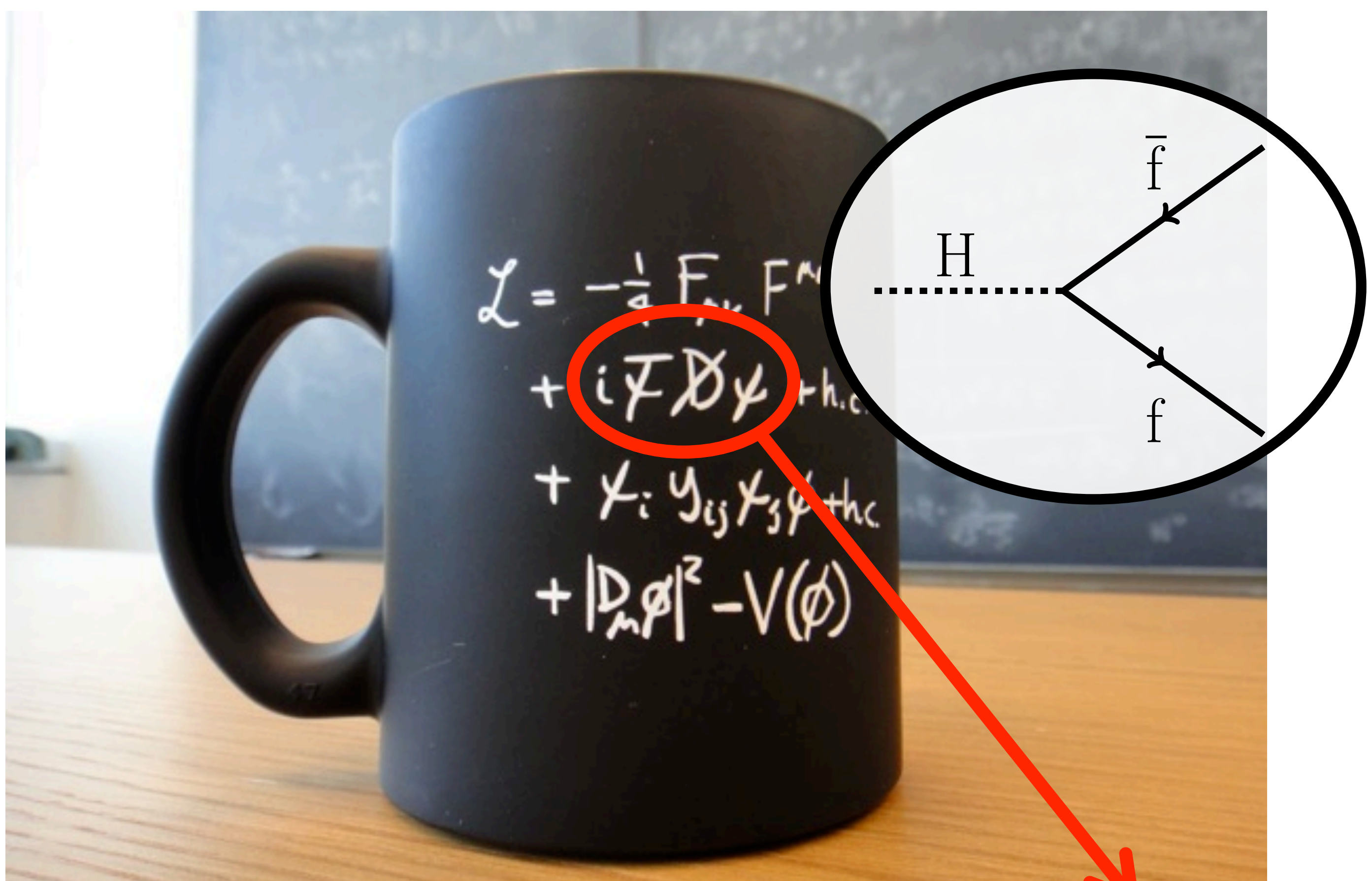
Introduction and motivation

- Focus of post-discovery Higgs physics is full characterization of new particle
- Precise knowledge of Higgs coupling to top quark essential
  - Large m_t implies relatively large coupling y_t
  - Strongest coupling among all known SM particles

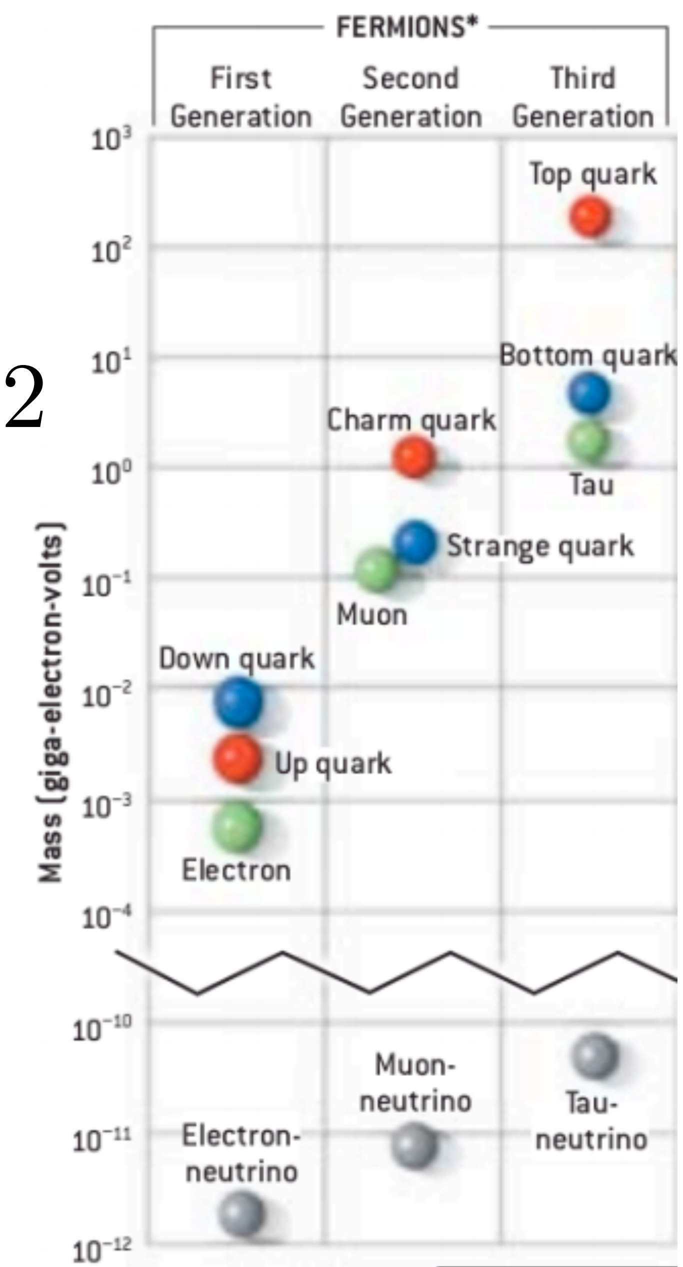


F. Tanedo

$$y_b \approx 0.02$$

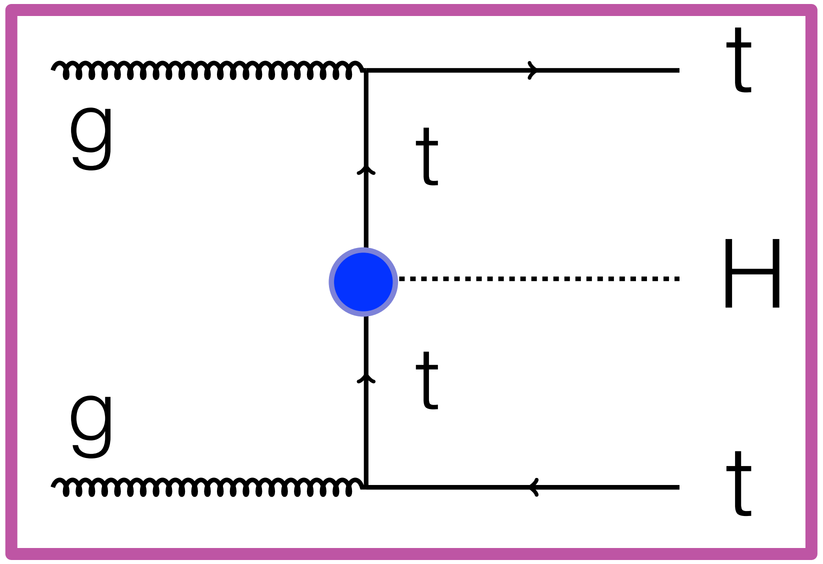
$$y_t \approx 1$$

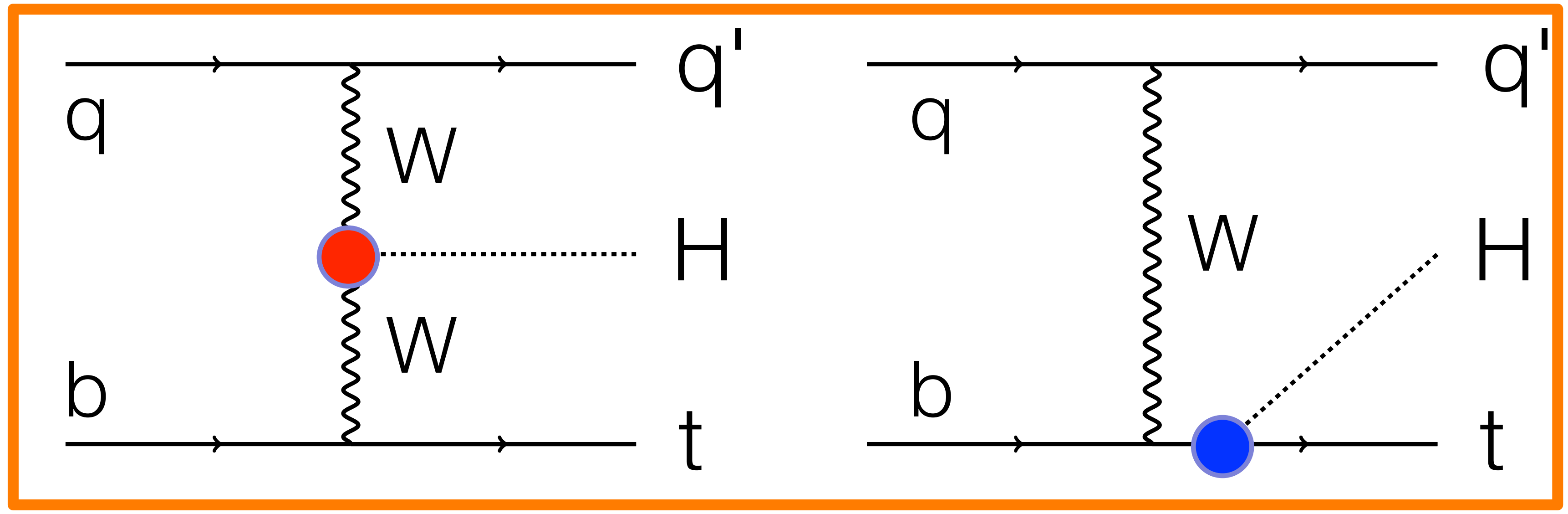
$$m_t = \frac{y_t\ \nu}{\sqrt{2}}$$



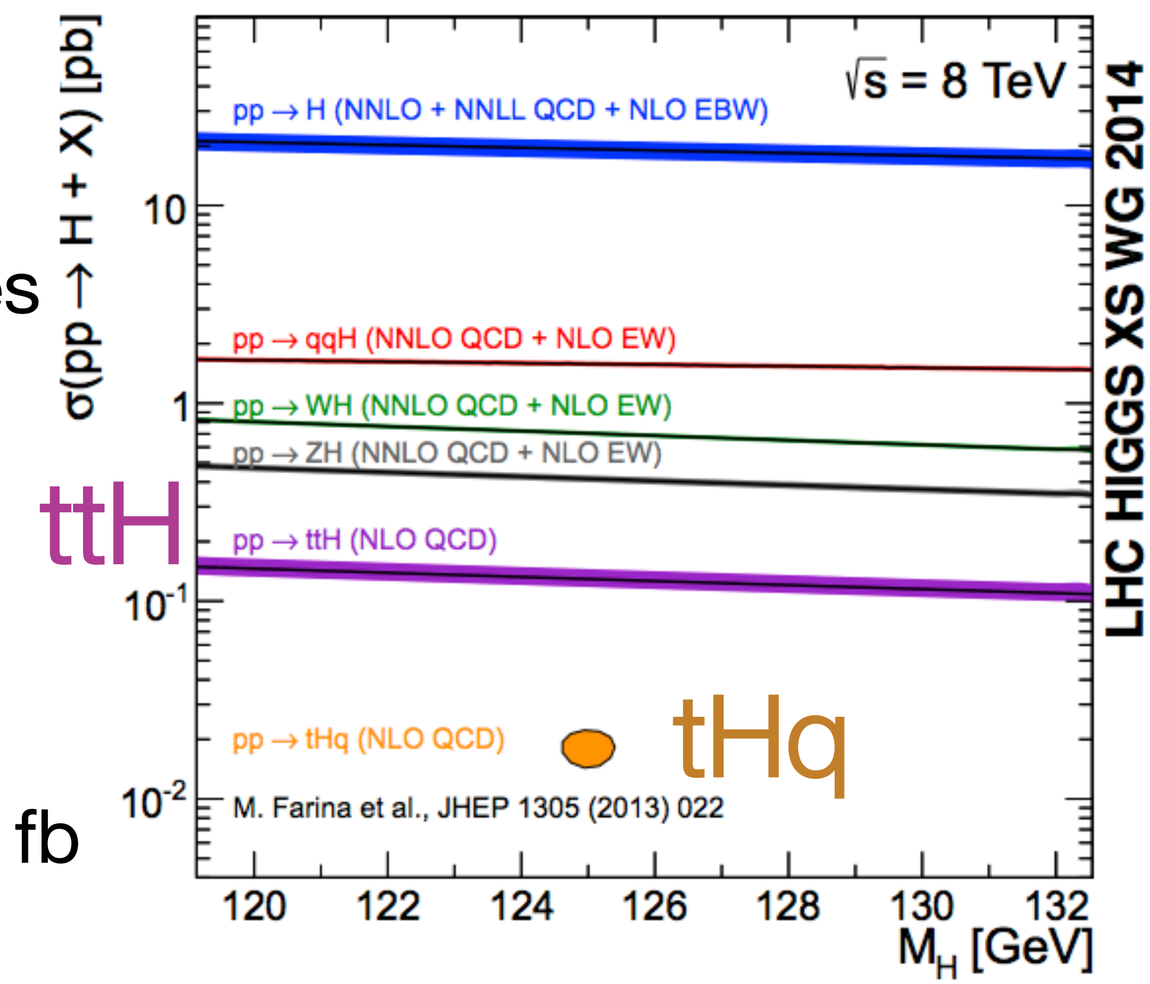
Experimental access to y_t

- Only directly accessible through Higgs produced with a top quark

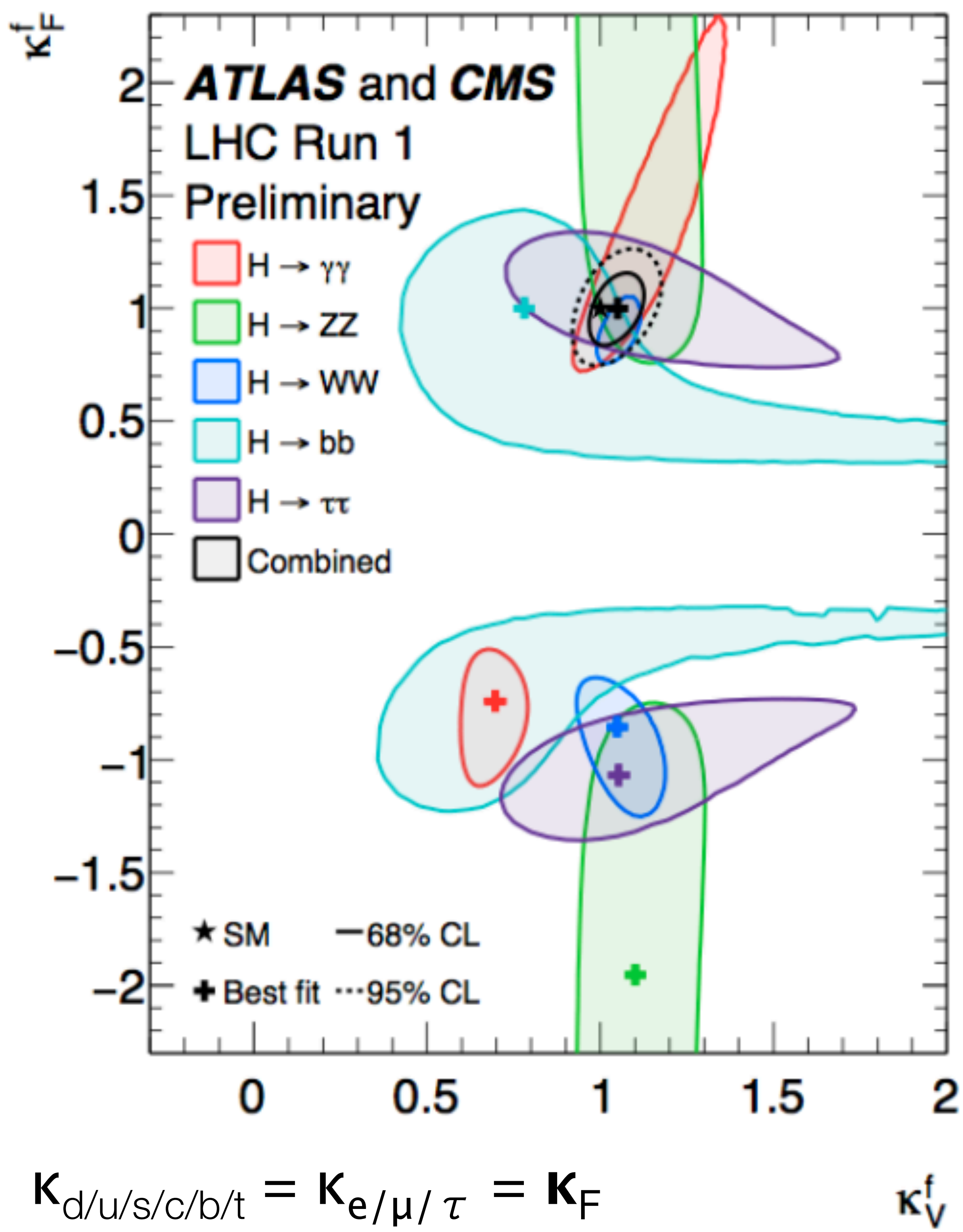




- Experimental challenges
  - Small signal cross section
    - Compared to Higgs production modes
    - Compared to tt+jets background
  - σ(tt+jets) = 245,800 fb
  - $\sigma(ttH_{125})$ = 129 fb
  - $\sigma(tHq)_{SM}$ = 18 fb
    - $\boldsymbol{\kappa_t = y_t/y_t^{SM} = -1}$ ⟶ $\sigma(tHq)_{\kappa t=-1}$ = 234 fb



Constraints on Higgs couplings from LHC



$\kappa_{d/u/s/c/b/t} = \kappa_{e/\mu/\tau} = \boldsymbol{\kappa}_F$

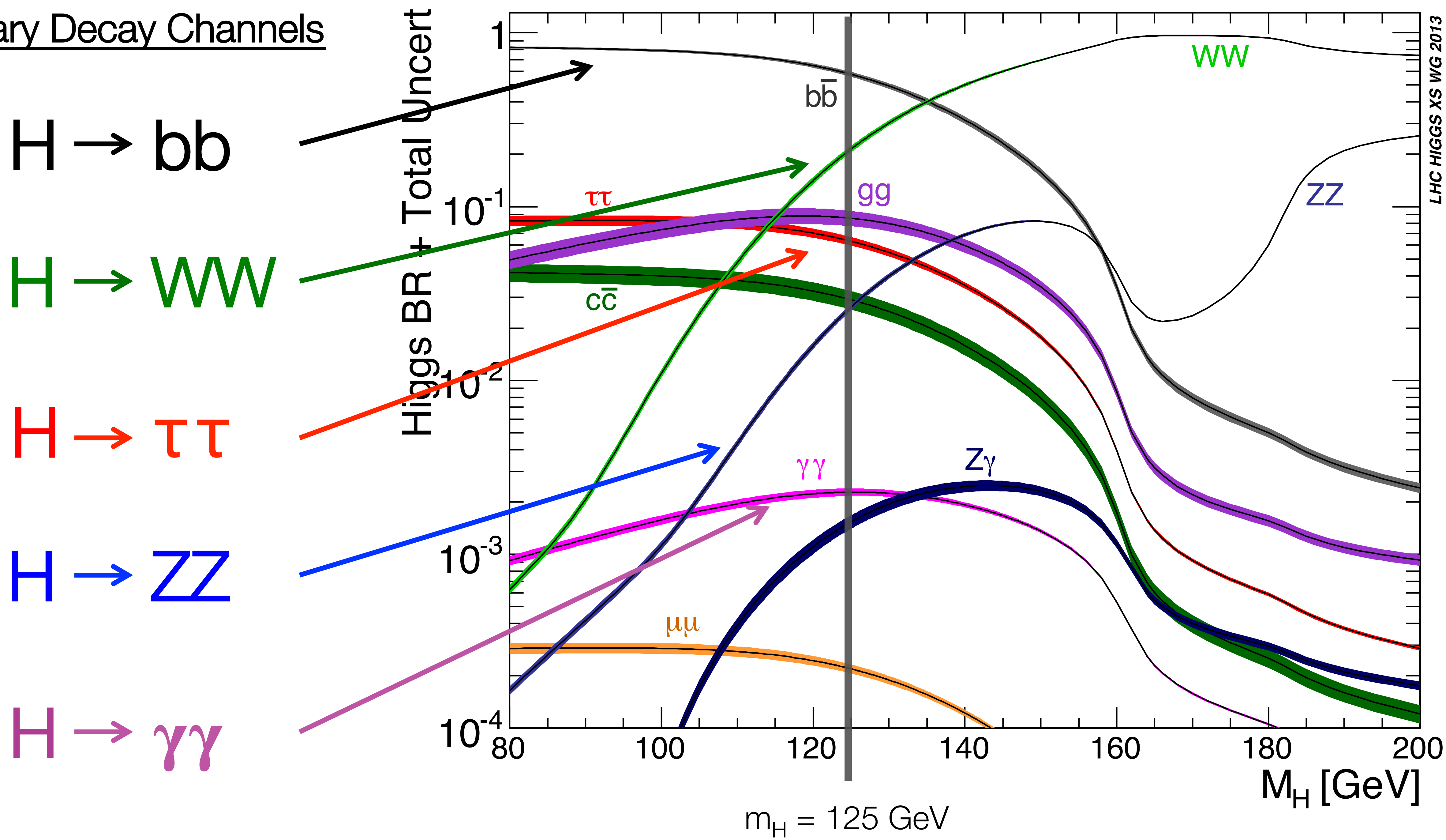
$\kappa_{W/Z} = \boldsymbol{\kappa}_V$

- Coupling constraints from ATLAS + CMS disfavor $\kappa_t = -1$
  - Assuming only SM contributions to the total width
- tHq also sensitive to other modifications of the SM
  - FCNCs, vector-like quarks, etc.
- $\kappa_t = -1$ still tolerated if allow BSM contributions to loops in $H \rightarrow \gamma\gamma$ and $H \rightarrow gg$ couplings

J. Ellis, T. You, JHEP 1306 (2013) 103
arXiv:1303.3879

Various Higgs decay modes

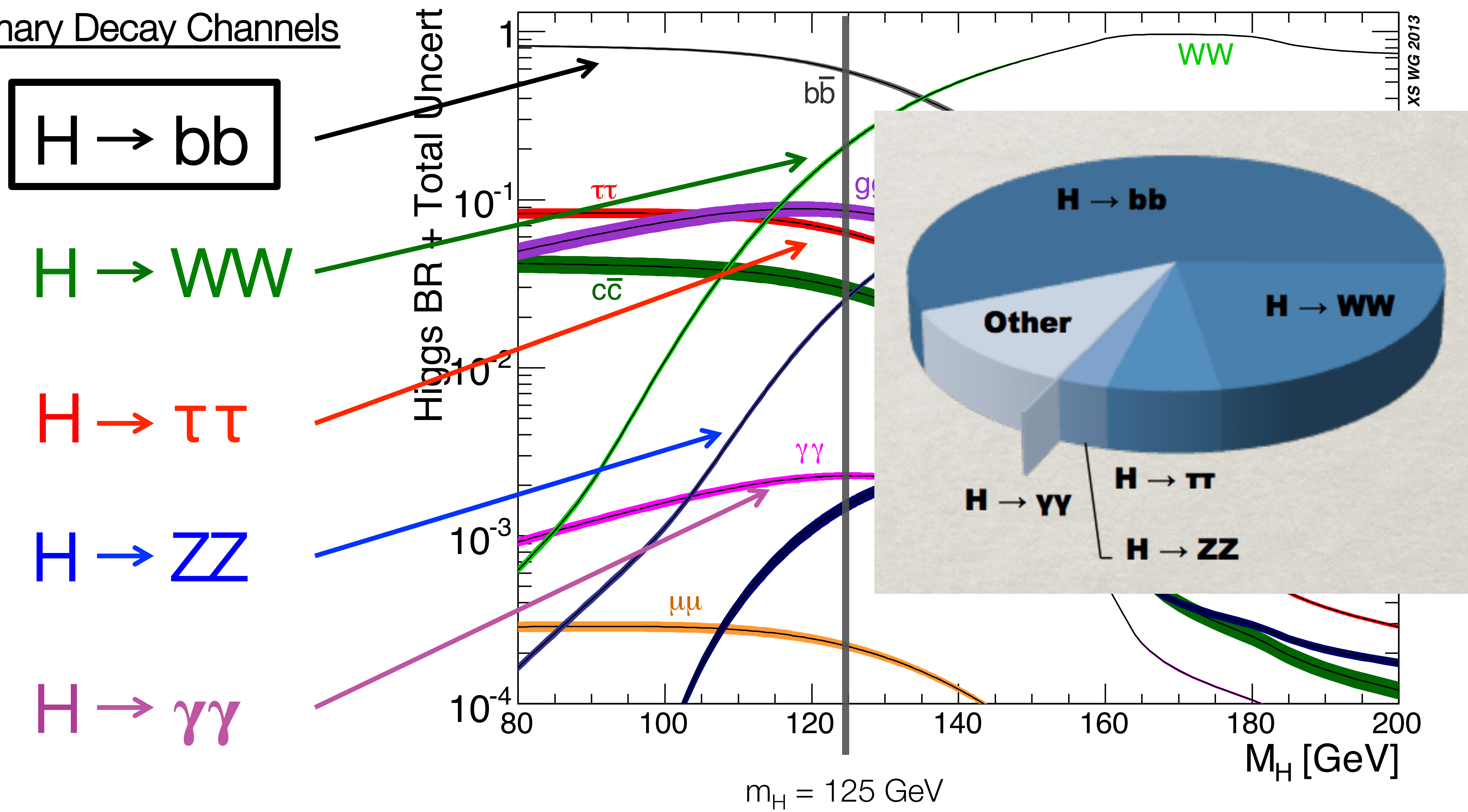
Primary Decay Channels



- For m_H = 125 GeV, many different decay modes possible
  - H ⟶ bb dominant (58%)

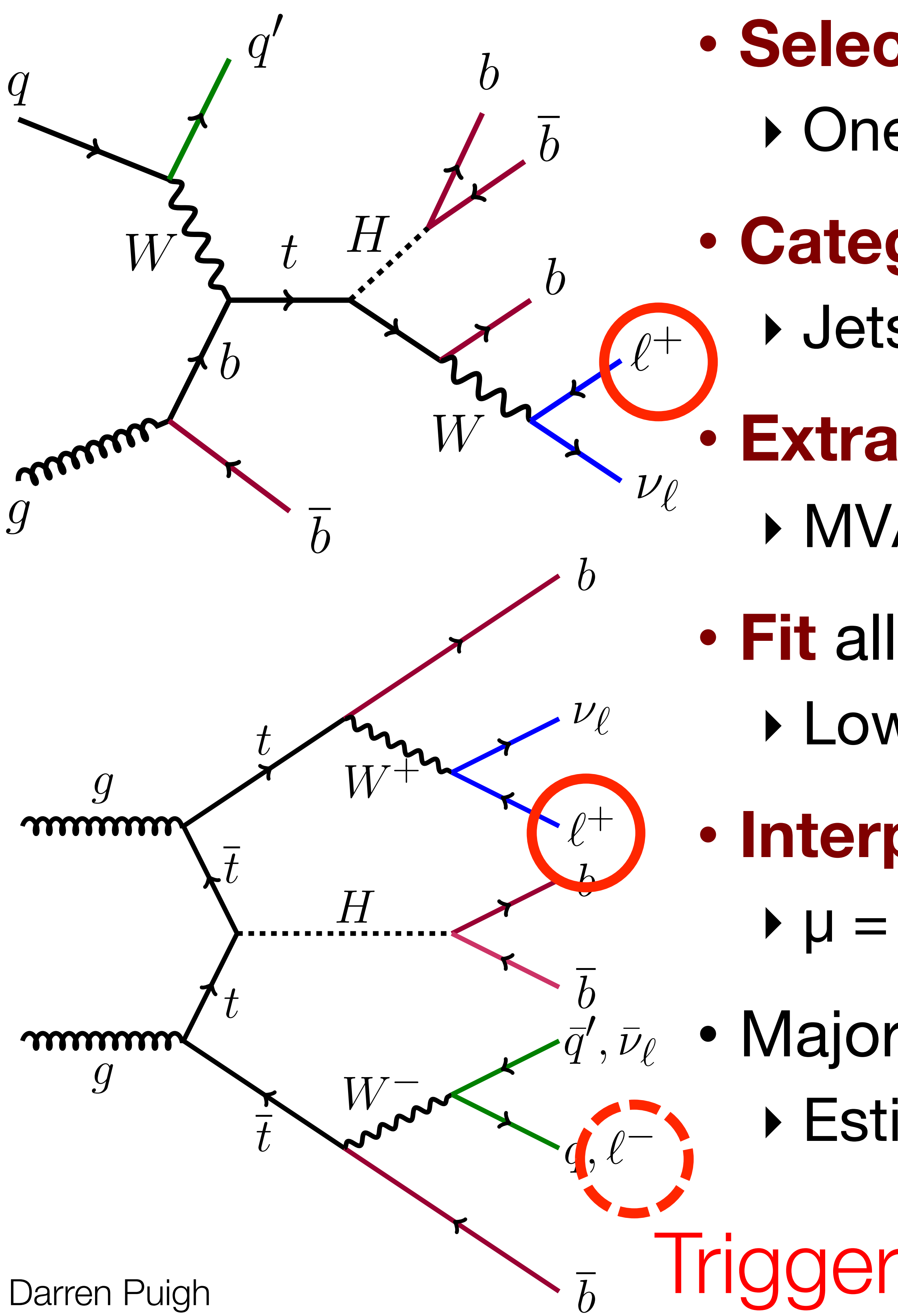
Various Higgs decay modes

Primary Decay Channels



- For m_H = 125 GeV, many different decay modes possible
  - H ⟶ bb dominant (58%)

Search strategy



- **Select** isolated, well-identified objects
  - One or two leptons, multiple (b-tag) jets
- **Categorize** based on number of objects
  - Jets, b-tag jets, lepton flavor, reco bosons
- **Extract** signal, separate from background
  - MVA: BDT, MEM, NN, etc.
- **Fit** all the categories simultaneously
  - Low S/B regions can constrain backgrounds
- **Interpret** fit as limit or best-fit signal
  - $\mu = \sigma / \sigma_{SM}$
- Major background in every case: **tt+jets**
  - Estimate using simulation with corrections

Overview of analyses

- **Search for ttH, H → bb with BDT (CMS)**
  - MVA to discriminate between between signal and background
- **Search for ttH, H → bb with MEM (CMS)**
  - Matrix elements and full event interpretation

Updated since Top2014!

- **Search for ttH, H → bb (ATLAS)**
  - Combining matrix elements and MVAs

NEW!

- **Search for tHq, H → bb with κ_t = -1 (CMS)**
  - Event interpretation and multiple MVAs

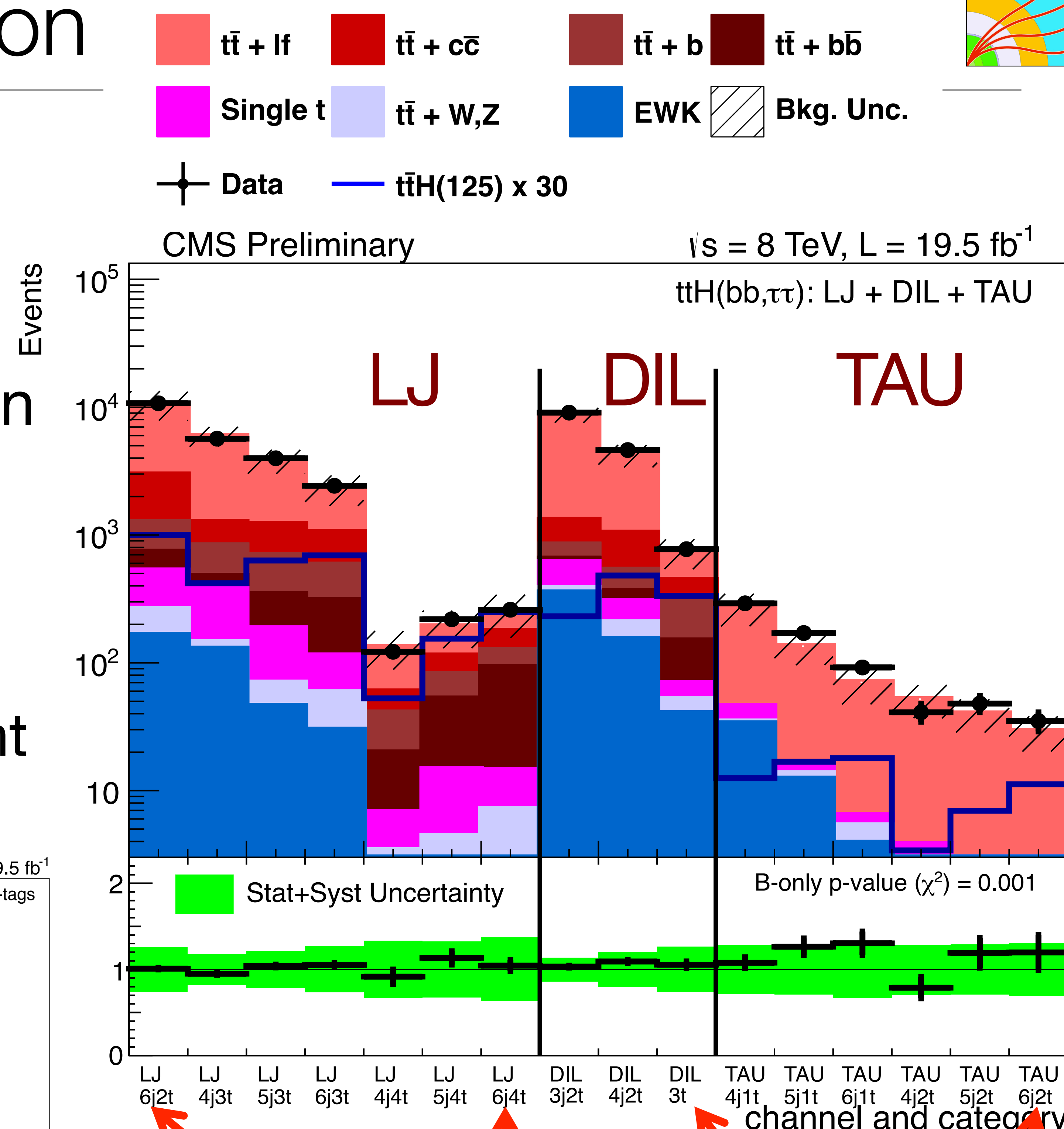
CMS: Search for ttH, H → bb with BDT

CMS-PAS-HIG-13-019
JHEP 09 (2014) 087

Better than cut-and-count: multivariate data analysis

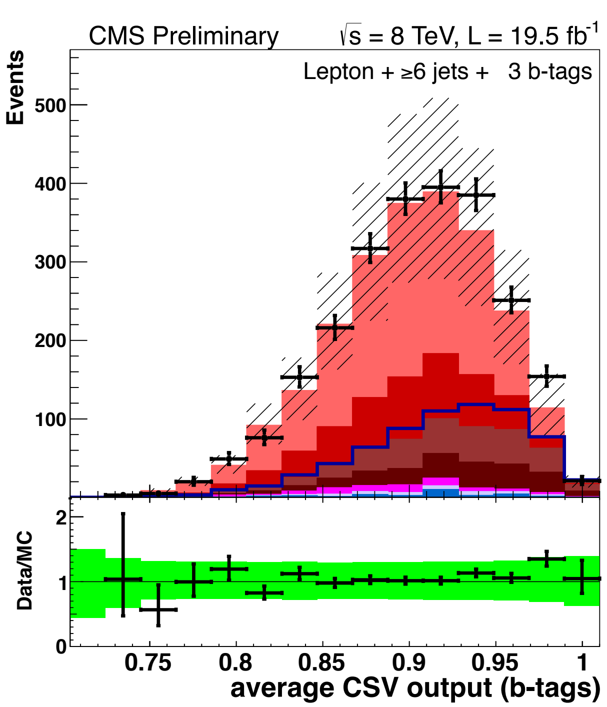
ttH event categorization

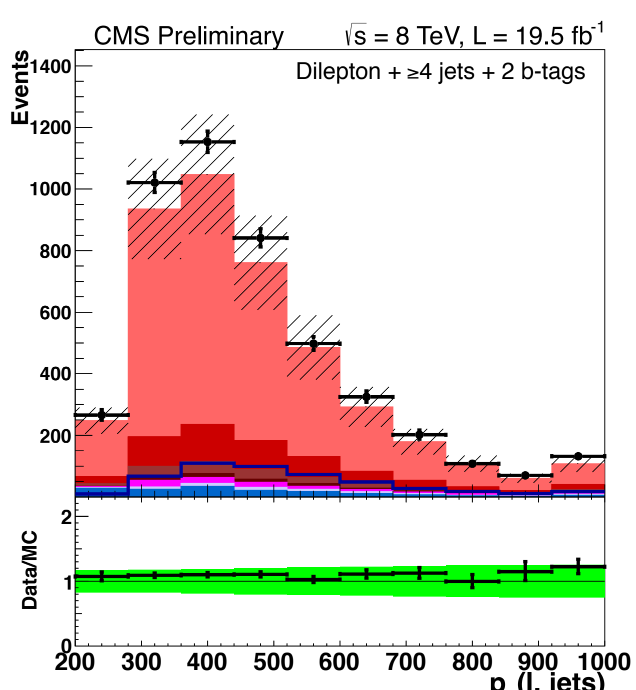
- Separate by **N_{jets}, $N_{b\text{-}jets}$**
  - Low S/B regions help constrain backgrounds
- Backgrounds from simulation
  - Main background: **tt+jets**
    - **tt+lf, tt+b, tt+bb, tt+cc**
- **BDT** to improve sensitivity
  - Kinematics, b-tag info, event shape, and angular info



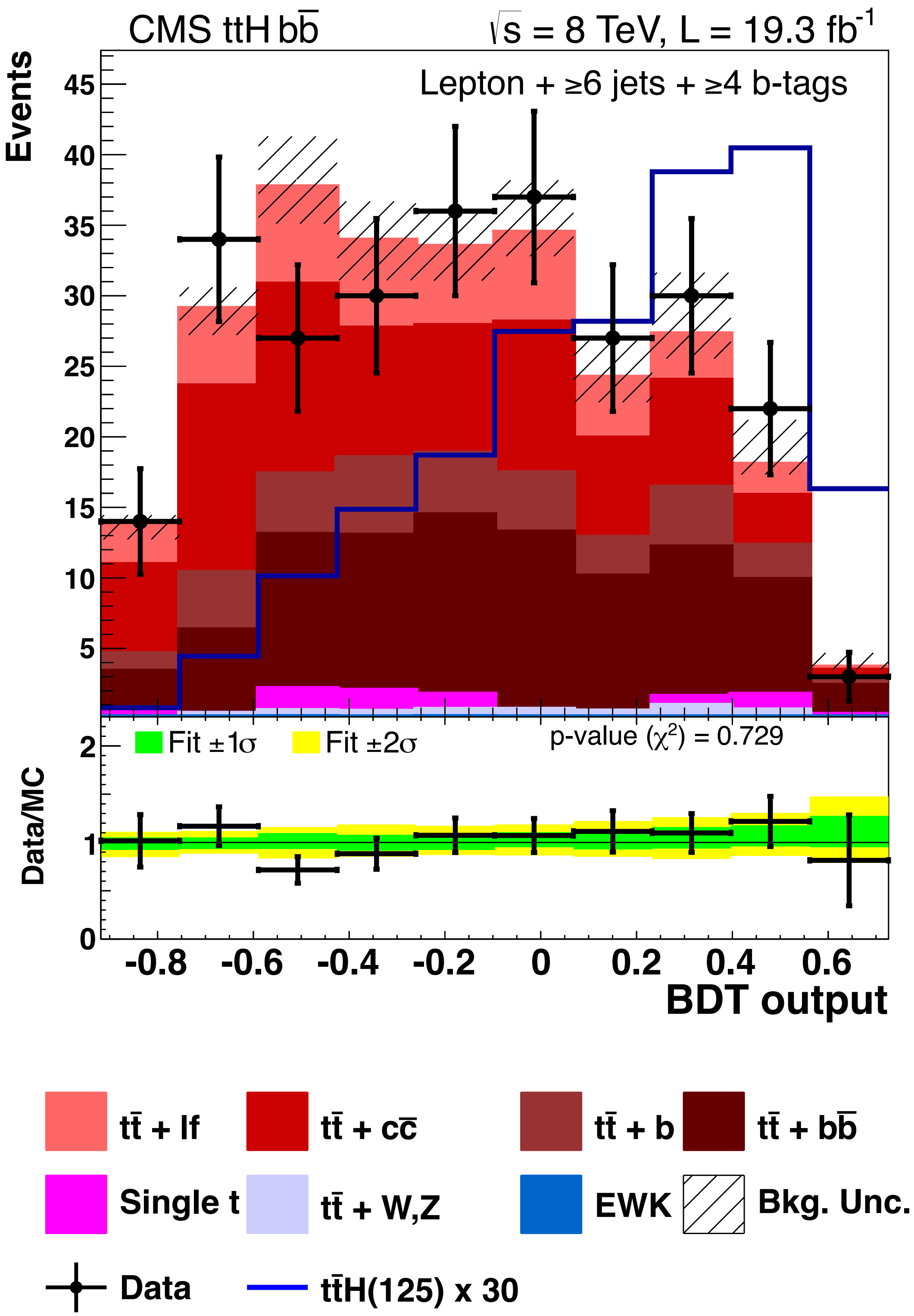
1/320 1/30 1/66 1/70

signal / background





CMS ttH Hbb with BDT



- MVA analysis using BDT
  - Take advantage of correlations among input variables
  - More discriminating than single input
- Simultaneous fit across all categories
  - **7+8 TeV, single lepton and dilepton**
- Not yet sensitive enough to signal
  - Set upper limit

Expected limit (no ttH): 3.5 x σ_{SM}
Expected limit (SM ttH): 5.0 x σ_{SM}
Observed limit: 4.1 x σ_{SM}

Fitted $\boldsymbol{\sigma/\sigma_{SM}}$: 0.7 ± 1.9

Updated since Top2014!

CMS: Search for ttH, H → bb with MEM

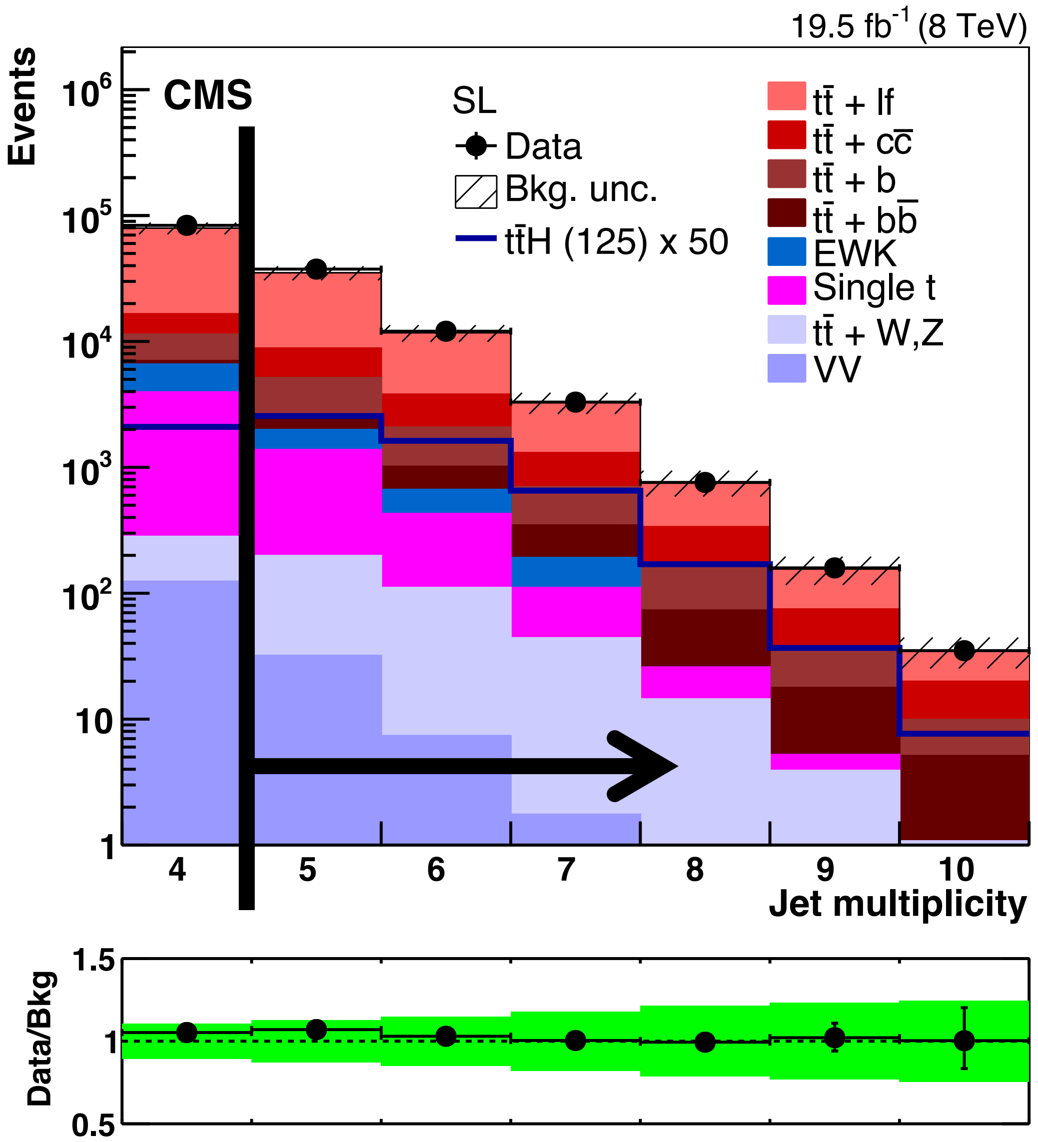
Eur Phys J C (2015) 75:251

Matrix elements and full event interpretation

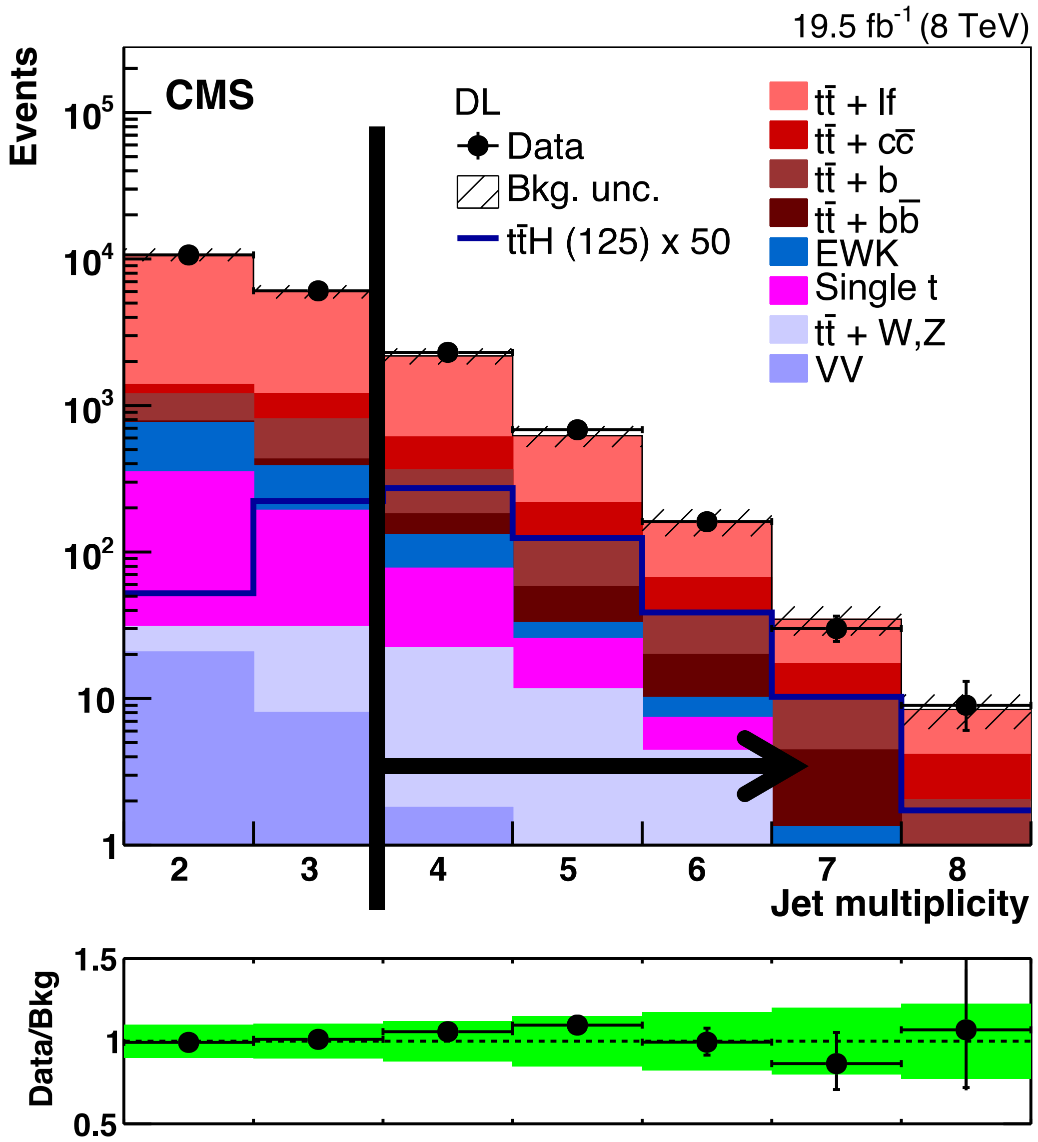
CMS ttH Hbb MEM

- **Select SL and DL events**

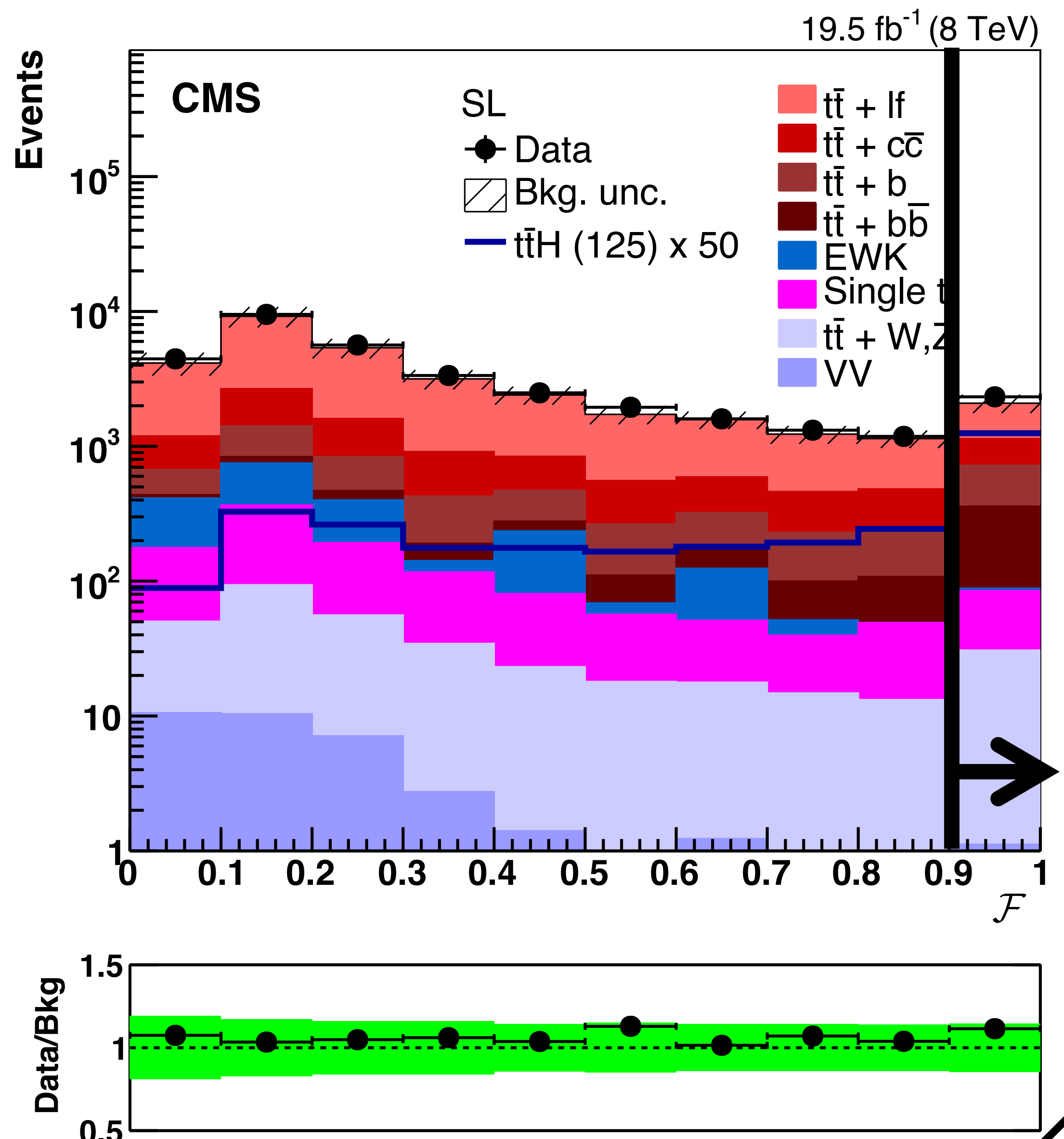
Single lepton: ≥5 jets



Dilepton: ≥4 jets



CMS ttH Hbb MEM



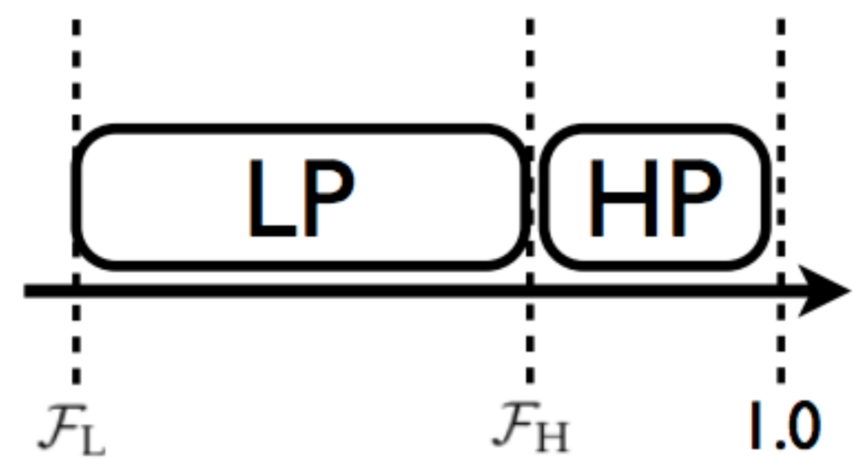
- Select SL and DL events
- **Assign events a b-tag likelihood**
  - **Based on b-tag value of jets**
  - **Separate into low- and high-purity categories**

Likelihood under tt+hf hypothesis

Likelihood under tt+lf hypothesis

$$\mathcal{F}(\xi) = \frac{f(\xi|t\bar{t}+\mathrm{hf})}{f(\xi|t\bar{t}+\mathrm{hf}) + f(\xi|t\bar{t}+\mathrm{lf})}$$

B-tag values of jets



CMS ttH Hbb MEM

SL Cat 1 tt → blν bqq All quarks reconstructed	**SL Cat 2** tt → blν bq q + g All quarks reconstructed – except for one W daughter – and ≥1 gluon
SL Cat 3 tt → blν bq q All quarks reconstructed – except for one W daughter	**DIL** tt → blν blν All quarks reconstructed

- Select SL and DL events
- Assign events a b-tag likelihood
  - Based on b-tag value of jets
  - Separate into low- and high-purity categories
- **Categorize events by reconstruction and interpretation**

CMS ttH Hbb MEM

Hypotheses $\mathcal{H}$:

S = ttH

B = tt+bb

$$w(\mathbf{y}|\mathcal{H}) = \sum_{i=1}^{N_a} \int \frac{\mathrm{d}x_a \mathrm{d}x_b}{2x_a x_b s} \int \prod_{k=1}^{8} \left(\frac{\mathrm{d}^3\mathbf{p}_k}{(2\pi)^3 2E_k} \right)$$
$$\times (2\pi)^4 \delta^{(E,z)} \left(p_a + p_b - \sum_{k=1}^{8} p_k \right)$$
$$\times \mathcal{R}^{(x,y)}(\rho_{\mathrm{T}}, \sum_{k=1}^{8} p_k)$$
$$\times g(x_a, \mu_{\mathrm{F}}) g(x_b, \mu_{\mathrm{F}})$$
$$\times |\mathcal{M}_{\mathcal{H}}(p_a, p_b, p_1, \ldots, p_8)|^2 \, W(\mathbf{y}, \mathbf{p})$$

- Select SL and DL events
- Assign events a b-tag likelihood
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- **Construct ME weights under ttH and tt+bb hypotheses**

CMS ttH Hbb MEM

Hypotheses $\mathcal{H}$:

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Observables

Integration over final-state particles and gluon energy fractions via VEGAS

$$w(\mathbf{y}|\mathcal{H}) = \sum_{i=1}^{N_a} \int \frac{\mathrm{d}x_a \mathrm{d}x_b}{2x_a x_b s} \int \prod_{k=1}^{8} \left(\frac{\mathrm{d}^3\mathbf{p}_k}{(2\pi)^3 2E_k} \right)$$
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$$\times \mathcal{R}^{(x,y)}(\rho_{\mathrm{T}}, \sum_{k=1}^{8} p_k)$$
$$\times g(x_a, \mu_{\mathrm{F}}) g(x_b, \mu_{\mathrm{F}})$$
$$\times |\mathcal{M}_{\mathcal{H}}(p_a, p_b, p_1, \ldots, p_8)|^2 W(\mathbf{y}, \mathbf{p})$$

Conservation of energy and longitudinal momentum

Resolution function to account for initial/final state radiation

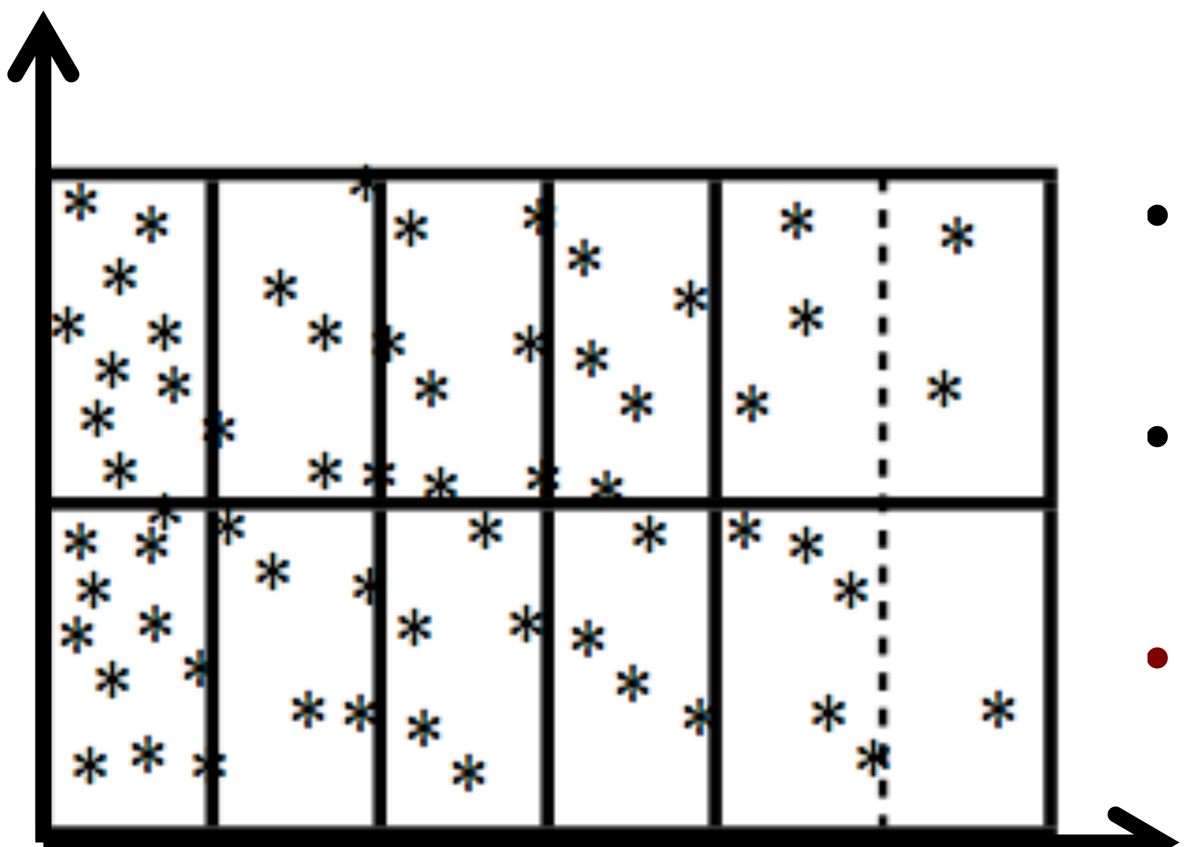
Gluon parton distribution function

Scattering amplitude via OpenLoops

Transfer function y->p

CMS ttH Hbb MEM

$$P_{h/l} = \frac{f(\xi|\mathrm{t\bar{t}+hf})}{f(\xi|\mathrm{t\bar{t}+hf}) + k_{h/l} f(\xi|\mathrm{t\bar{t}+lf})}$$



$$P_{s/b} = \frac{w(\mathbf{y}|\mathrm{t\bar{t}H})}{w(\mathbf{y}|\mathrm{t\bar{t}H}) + k_{s/b}\, w(\mathbf{y}|\mathrm{t\bar{t}+b\bar{b}})}$$

- Select SL and DL events
- Assign events a b-tag likelihood
  - Based on b-tag value of jets
  - Separate into low- and high-purity categories
- Categorize events by reconstruction and interpretation
- Construct ME weights under ttH and tt+bb hypotheses
- **Build 2D likelihood ratio disc combining ME and b-tag info**
  - Good a priori separation
  - Well-behaved in data

CMS ttH Hbb MEM

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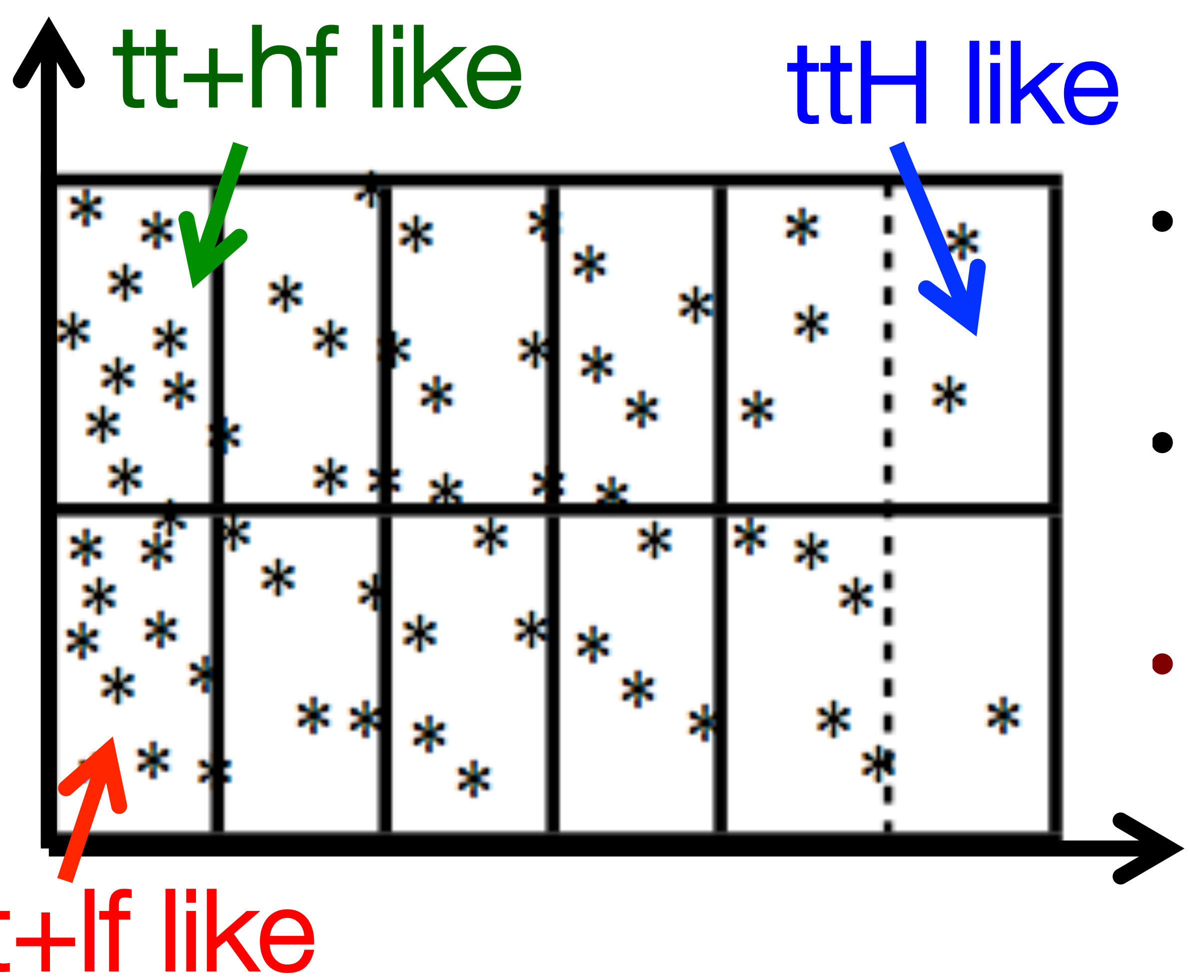

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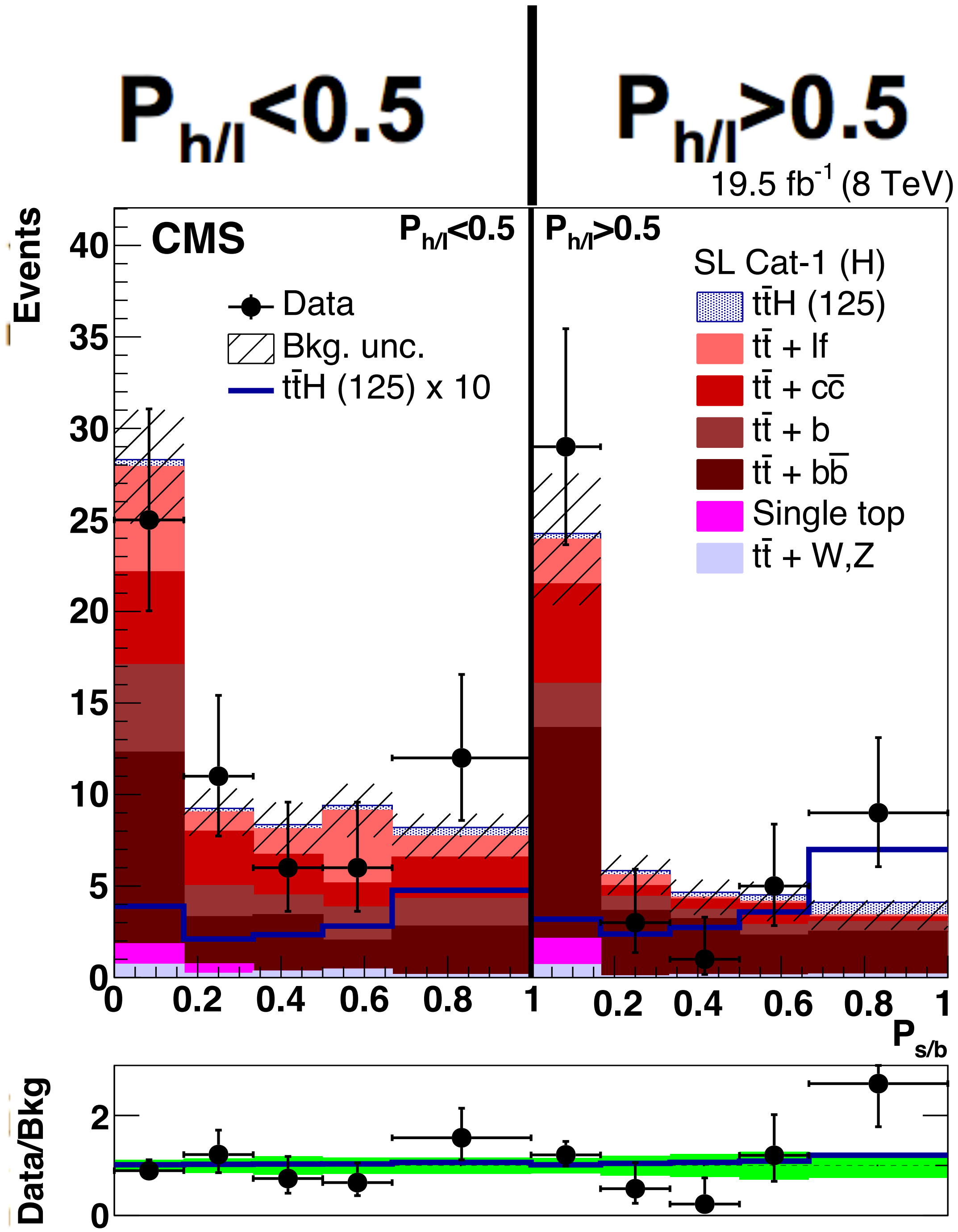

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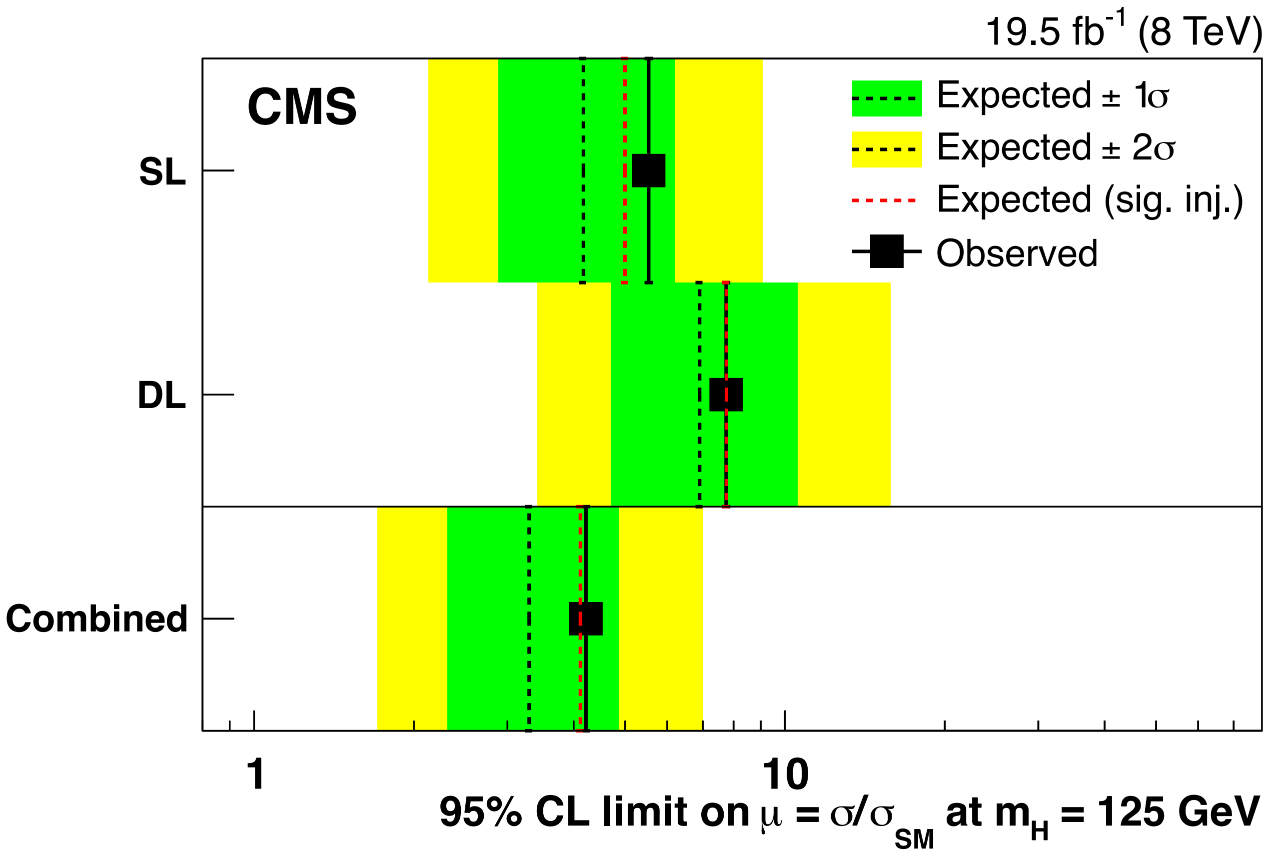
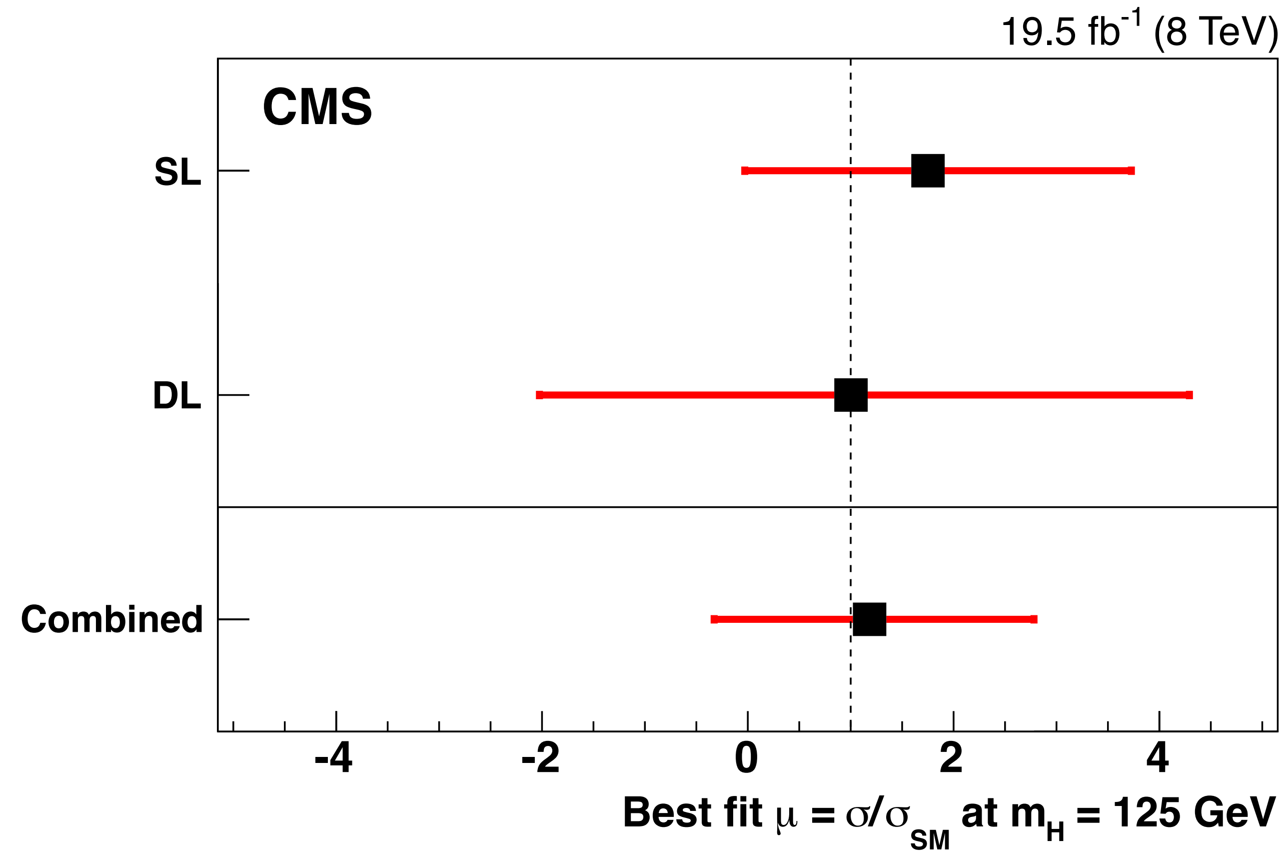
- Construct ME weights under ttH and tt+bb hypotheses
- Build 2D likelihood ratio disc combining ME and b-tag info
  - **Good a priori separation**
  - **Well-behaved in data**

ttH Hbb MEM fit and results

- Simultaneous fit to the discriminant in all 8 channels
  - No significant excess, set upper limit on $\mu = \sigma/\sigma_{SM}$





Combined obs (exp) limit:

$\mu < 4.2\ (3.3)$

Combined best-fit value:

$\hat{\mu} = 1.2^{+1.6}_{-1.5}$

- Improvement over BDT analysis of ~15% in expected limit

NEW!

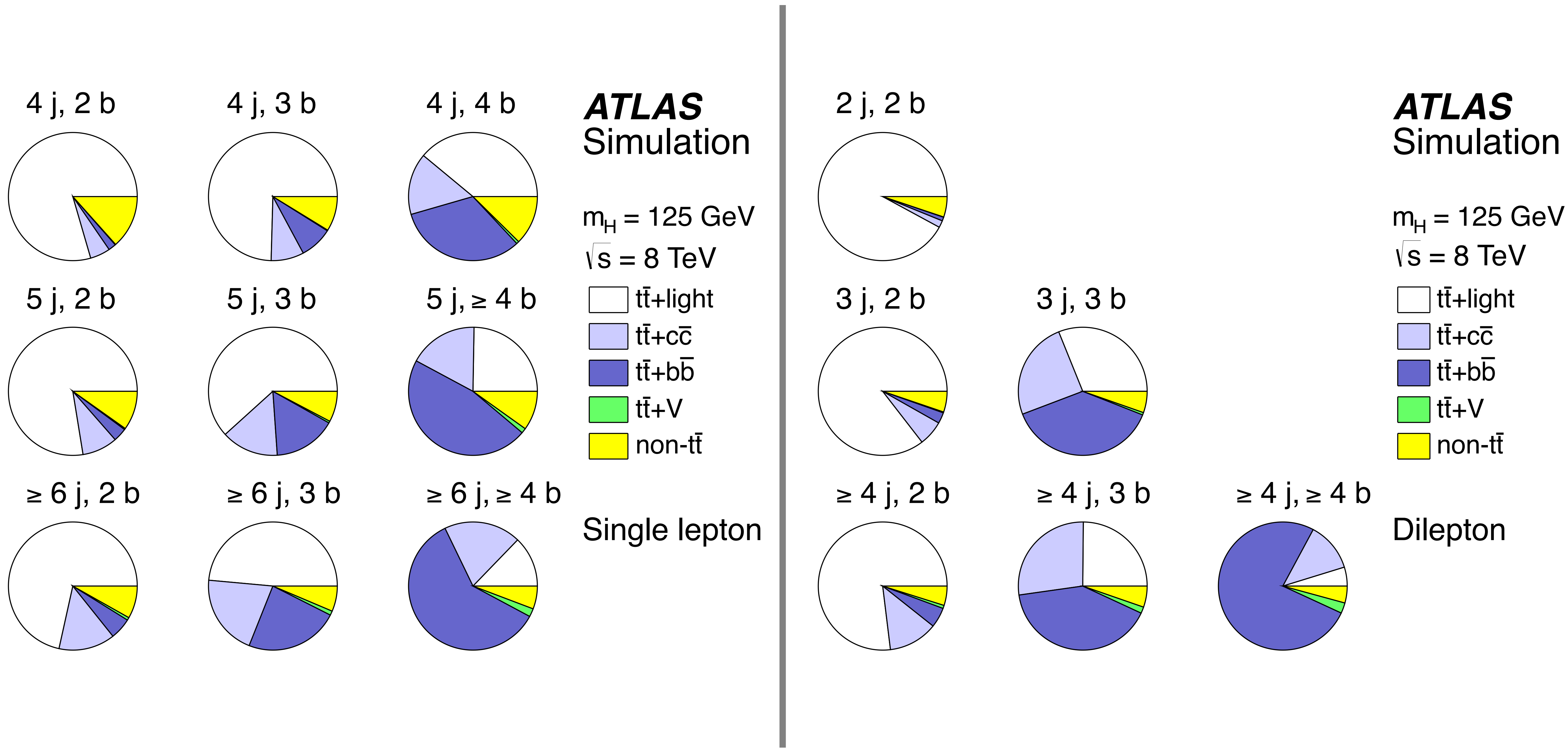
ATLAS: Search for ttH, H → bb with MEM and NN

Eur Phys J C (2015) 75:251

Putting it all together

ATLAS: Hbb

- Similar categorization scheme as in CMS BDT analysis
  - Separate into single- and di-lepton events, categorize by N_{jet}, $N_{b\text{-}tag}$



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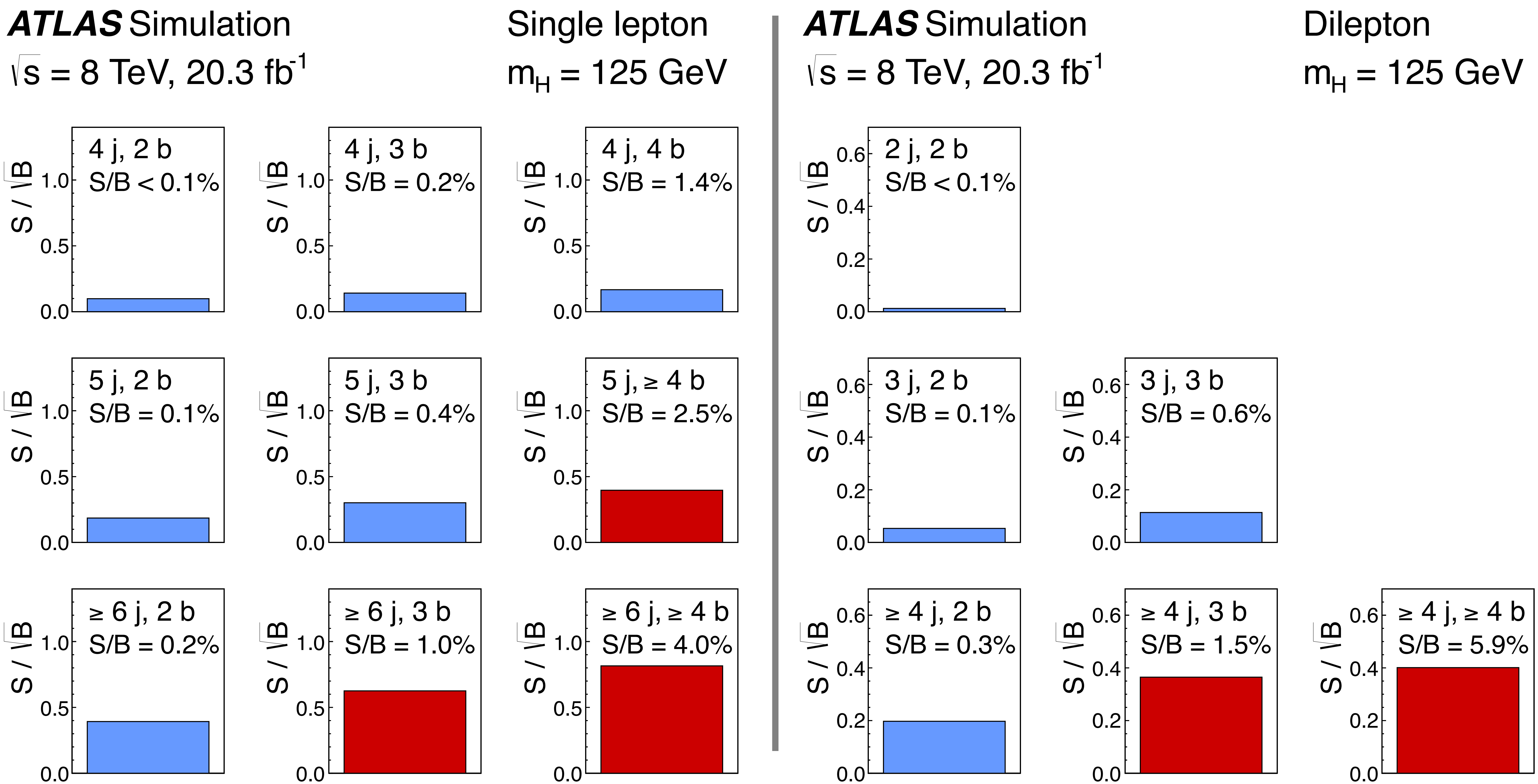


ATLAS: Hbb

- Similar categorization scheme as in CMS BDT analysis
  - Separate into single- and di-lepton events, categorize by N_{jet}, $N_{b\text{-}tag}$
- Signal extraction:
  - Use single variable H_T in background dominated categories
  - Use NN in signal rich categories
  - Special case of 5j3t: use NN for tt+HF / tt+LF

	2 tags	3 tags	≥ 4 tags
4 jets	HT	HT	HT
5 jets	HT	NNHF	NN
≥ 6 jets	HT	NN	NN

	2 tags	3 tags	≥ 4 tags
2 jets	HT		
3 jets	HT	NN	
≥ 4 jets	HT	NN	NN

In these two regions, two variables from MEM also used as input

HT: Scalar sum of p_T of jets and leptons
HT^{had}: Scalar sum of p_T of jets
NN: Neural network
NNHF: Neural network for separating tt+HF

ATLAS MEM variables

- Calculate pdf of event to be consistent with physics process

$$P_i(\mathbf{x}|\alpha) = \frac{(2\pi)^4}{\sigma_i^{\exp}(\alpha)} \int \mathrm{d}p_\mathrm{A}\mathrm{d}p_\mathrm{B}\ f(p_\mathrm{A})f(p_\mathrm{B})\ \frac{|\mathcal{M}_i(\mathbf{y}|\alpha)|^2}{\mathcal{F}}\ W(\mathbf{y}|\mathbf{x})\ \mathrm{d}\Phi_N(\mathbf{y})$$

ATLAS MEM variables

- Calculate pdf of event to be consistent with physics process

Observables

Matrix element / flux factor

Phase space element

$$P_i(\mathbf{x}|\alpha) = \frac{(2\pi)^4}{\sigma_i^{\exp}(\alpha)} \int \mathrm{d}p_\mathrm{A} \mathrm{d}p_\mathrm{B}\, f(p_\mathrm{A}) f(p_\mathrm{B}) \frac{|\mathcal{M}_i(\mathbf{y}|\alpha)|^2}{\mathcal{F}} W(\mathbf{y}|\mathbf{x})\, \mathrm{d}\Phi_N(\mathbf{y})$$

Parameters

Parton distribution function

Transfer function x->y

Normalization of P

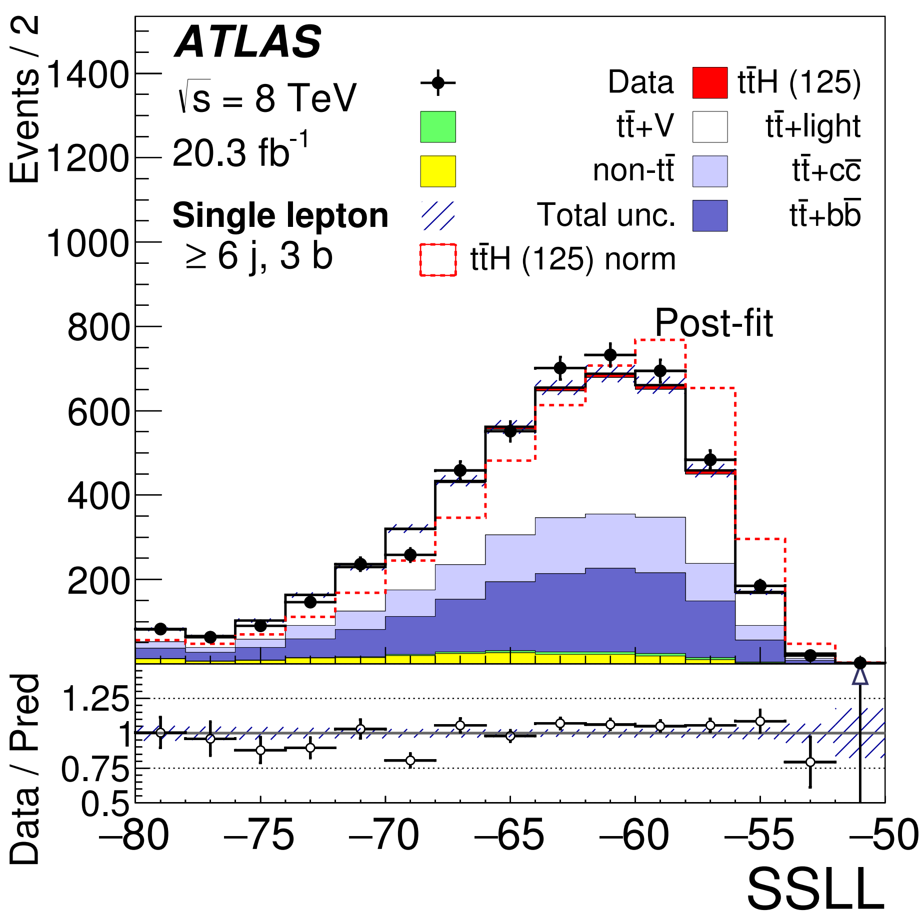
ATLAS MEM variables

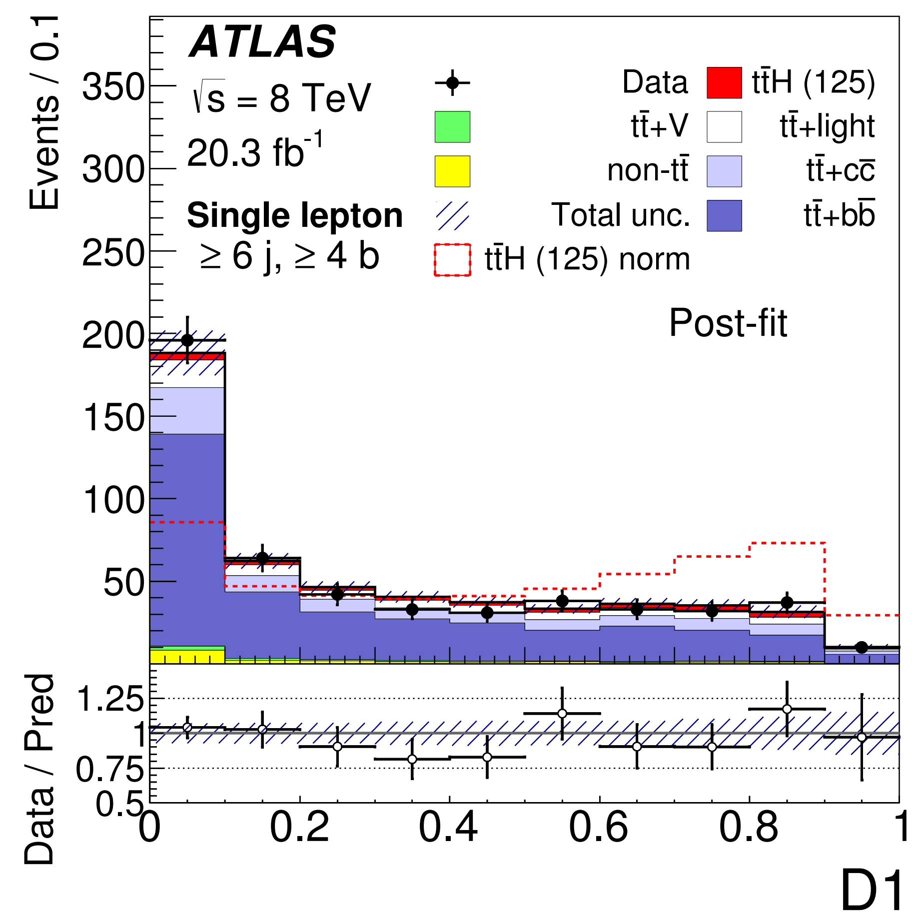
- Calculate pdf of event to be consistent with physics process

$$P_i(\mathbf{x}|\alpha) = \frac{(2\pi)^4}{\sigma_i^{\exp}(\alpha)} \int \mathrm{d}p_{\mathrm{A}}\mathrm{d}p_{\mathrm{B}}\ f(p_{\mathrm{A}})f(p_{\mathrm{B}})\ \frac{|\mathcal{M}_i(\mathbf{y}|\alpha)|^2}{\mathcal{F}}\ W(\mathbf{y}|\mathbf{x})\ \mathrm{d}\Phi_N(\mathbf{y})$$

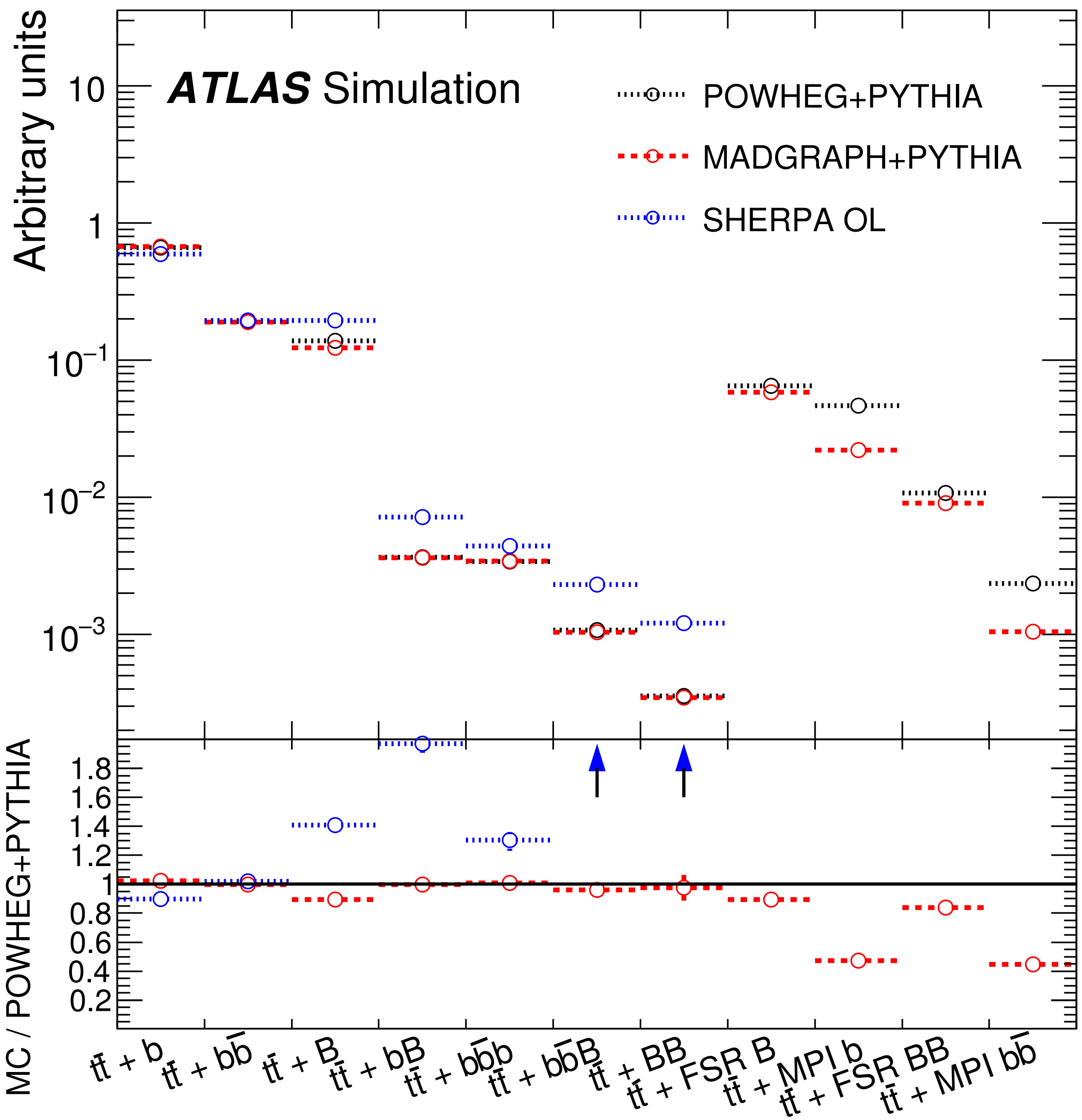
$$\mathcal{L}(\mathbf{x}|\alpha) = \sum_{p=1}^{N_p} P_i^p(\mathbf{x}|\alpha)$$

$$D1 = \frac{\mathcal{L}_{\mathrm{t\bar{t}H}}}{\mathcal{L}_{\mathrm{t\bar{t}H}} + \alpha\ \mathcal{L}_{\mathrm{t\bar{t}+b\bar{b}}}}$$





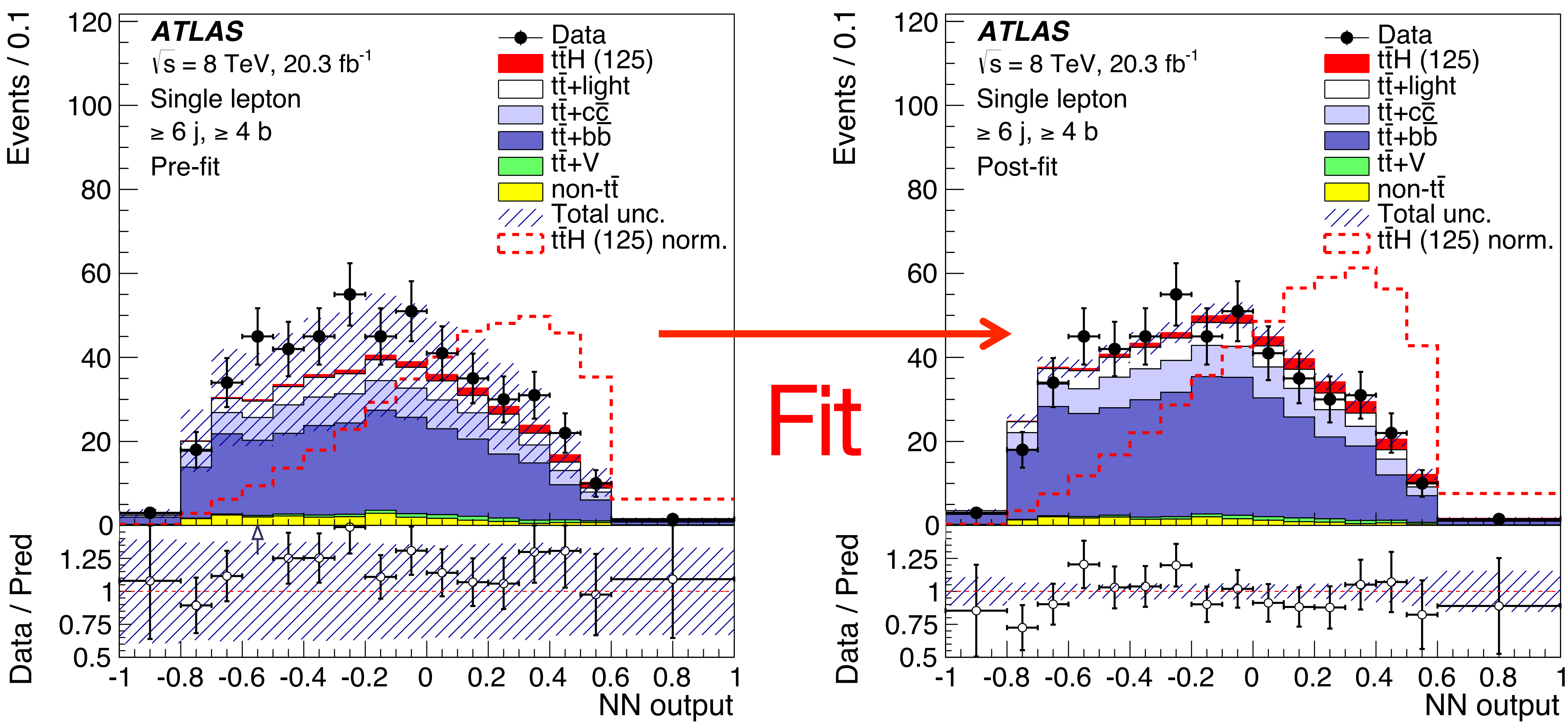
tt+jets MC and corrections



- tt+jets categorization
  - tt+bb: 2 gen jets match extra B's
  - tt+b: 1 gen jet match 1 B hadron
  - tt+B: 1 gen jet match bb pair
    - Unresolved gluon splitting
- **tt+jets MC: PowHeg+Pythia**
  - tt+bb only from PS
- Reweight at truth level to reproduce NLO tt+bb prediction from Sherpa+OpenLoops
  - p_T(t), p_T(tt), ΔR(bb), p_T(bb)
  - bb: dijet system not from tops

In-situ constraints

- Profile-likelihood fit in signal-rich and signal-depleted regions
  - Constrains systematic uncertainties and their influence on best-fit μ
  - Significant reduction in background uncertainties



Systematics

Systematic uncertainty	Type	Comp.
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	4
Light-jet tagging efficiency	SN	12
High-p_{T} tagging efficiency	SN	1
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	3
$t\bar{t}$+heavy-flavour: normalisation	N	2
$t\bar{t}+c\bar{c}$: p_{T} reweighting	SN	2
$t\bar{t}+c\bar{c}$: generator	SN	4
$t\bar{t}+b\bar{b}$: NLO Shape	SN	8
W+jets normalisation	N	3
W p_{T} reweighting	SN	1
Z+jets normalisation	N	3
Z p_{T} reweighting	SN	1
Lepton misID normalisation	N	3
Lepton misID shape	S	3
Single top cross section	N	1
Single top model	SN	1
Diboson+jets normalisation	N	3
$t\bar{t}+V$ cross section	N	1
$t\bar{t}+V$ model	SN	1
Signal Model		
$t\bar{t}H$ scale	SN	2
$t\bar{t}H$ generator	SN	1
$t\bar{t}H$ hadronisation	SN	1
$t\bar{t}H$ PDF	SN	1

Experimental uncertainties

Dominant: jet energy scale, b-tagging

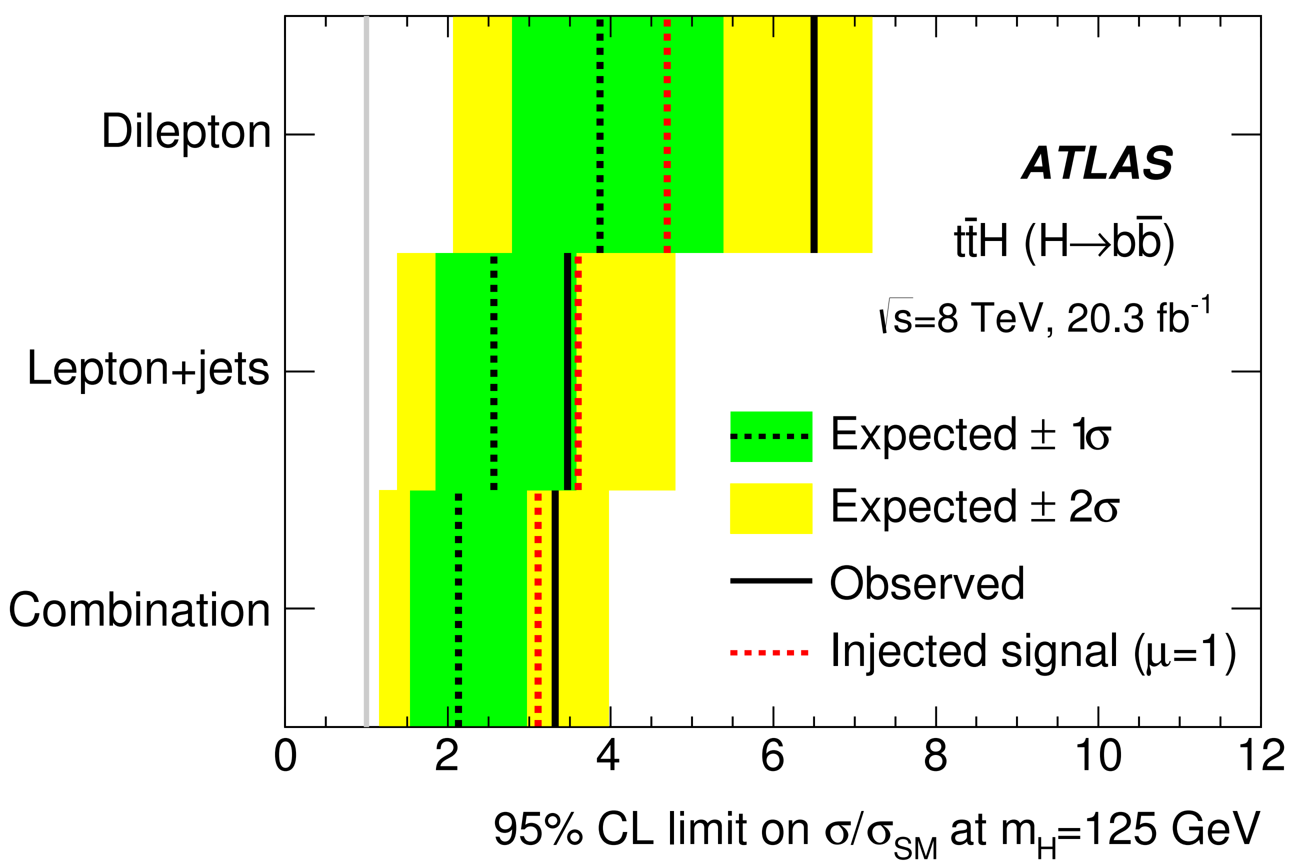
Background model uncertainties

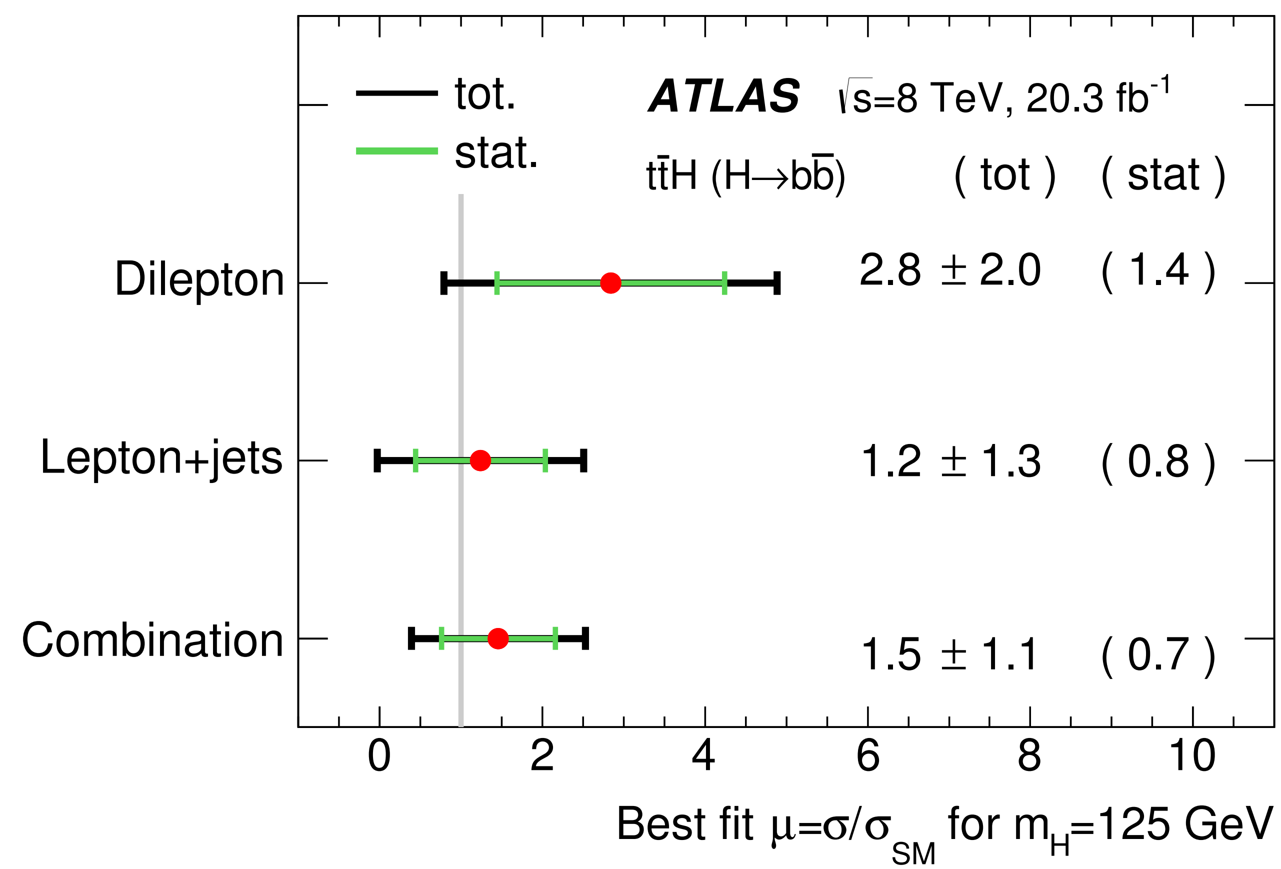
Dominant: tt+hf norm, tt+bb NLO shape

Signal model uncertainties

ttH Hbb limits and best-fit values

- Simultaneous fit to the discriminant in all 15 channels
  - No significant excess, set upper limit on $\mu = \sigma/\sigma_{SM}$





Obs (exp) limit: $\mu < 3.4$ (2.2)

Best-fit value: $\hat{\mu} = 1.5 \pm 1.1$

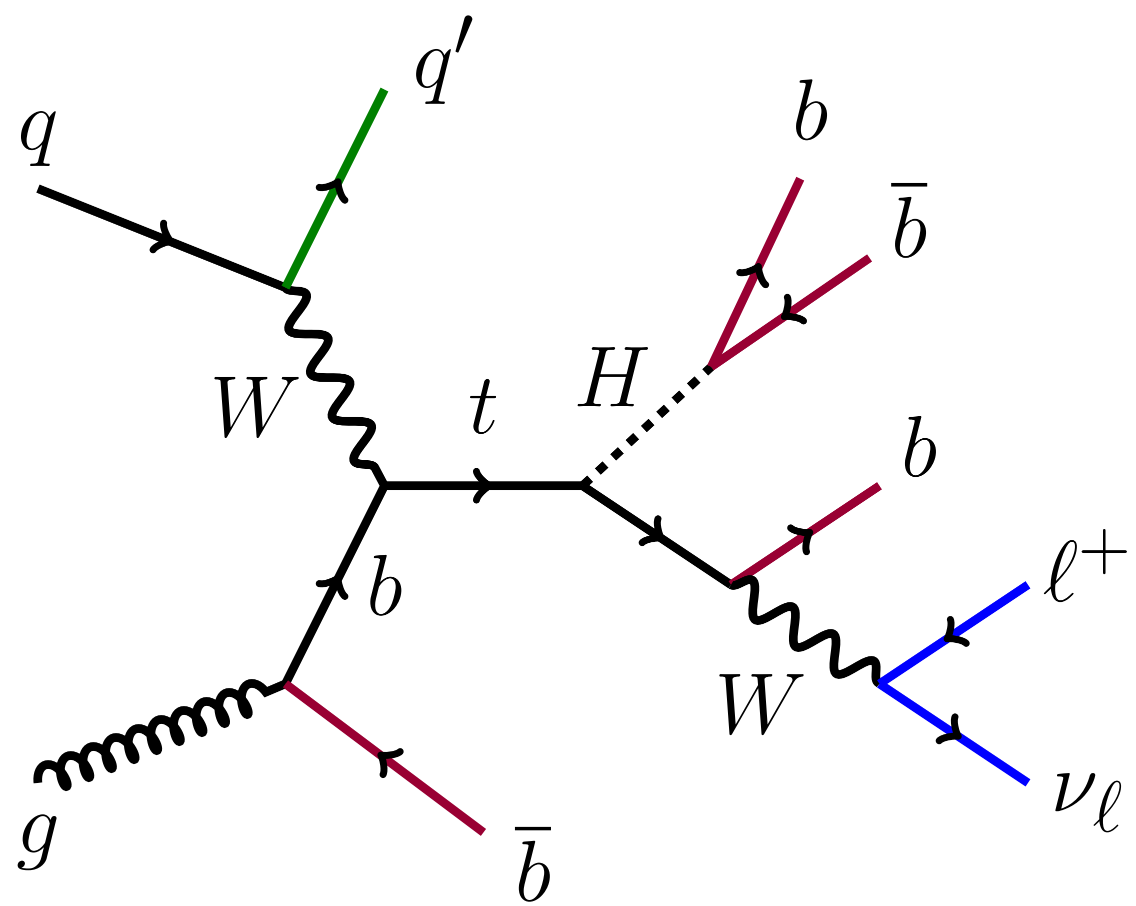
- Improvement over previous analyses
  - More efficient b-tagging, looser object selection (p_T), NLO tt+bb corrections, combining event interpretation MEs and NN

CMS: Search for tHq, $H \to bb$ with $\kappa_t = -1$

CMS-PAS-HIG-14-015

Event interpretation and multiple MVAs

CMS tHq Hbb



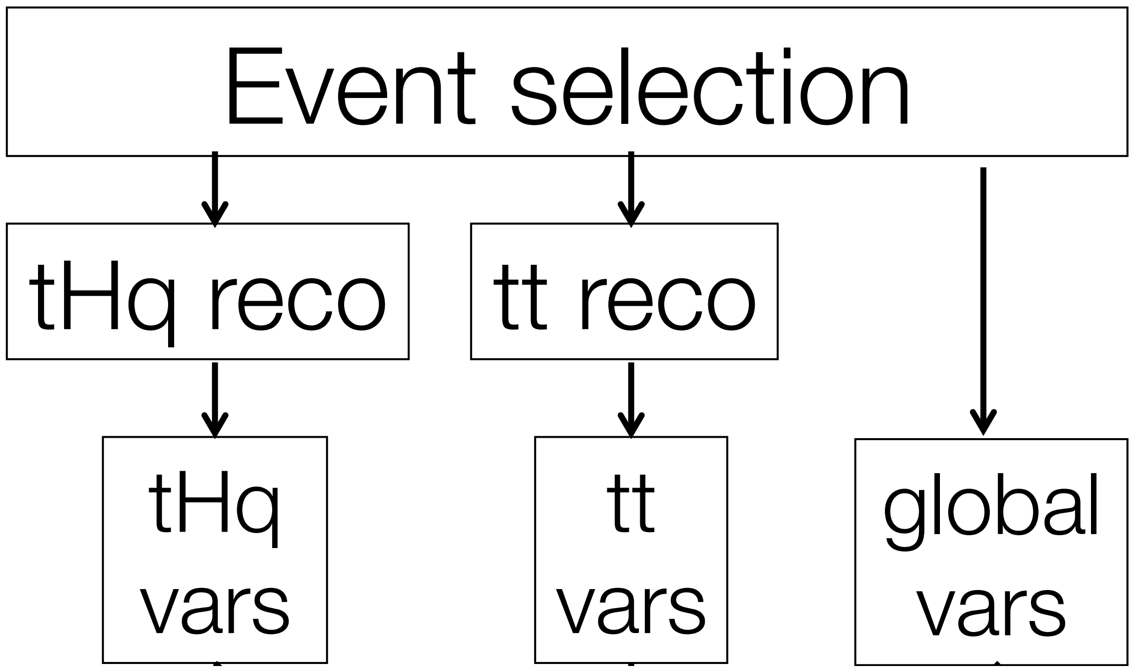
1 isolated lepton + MET

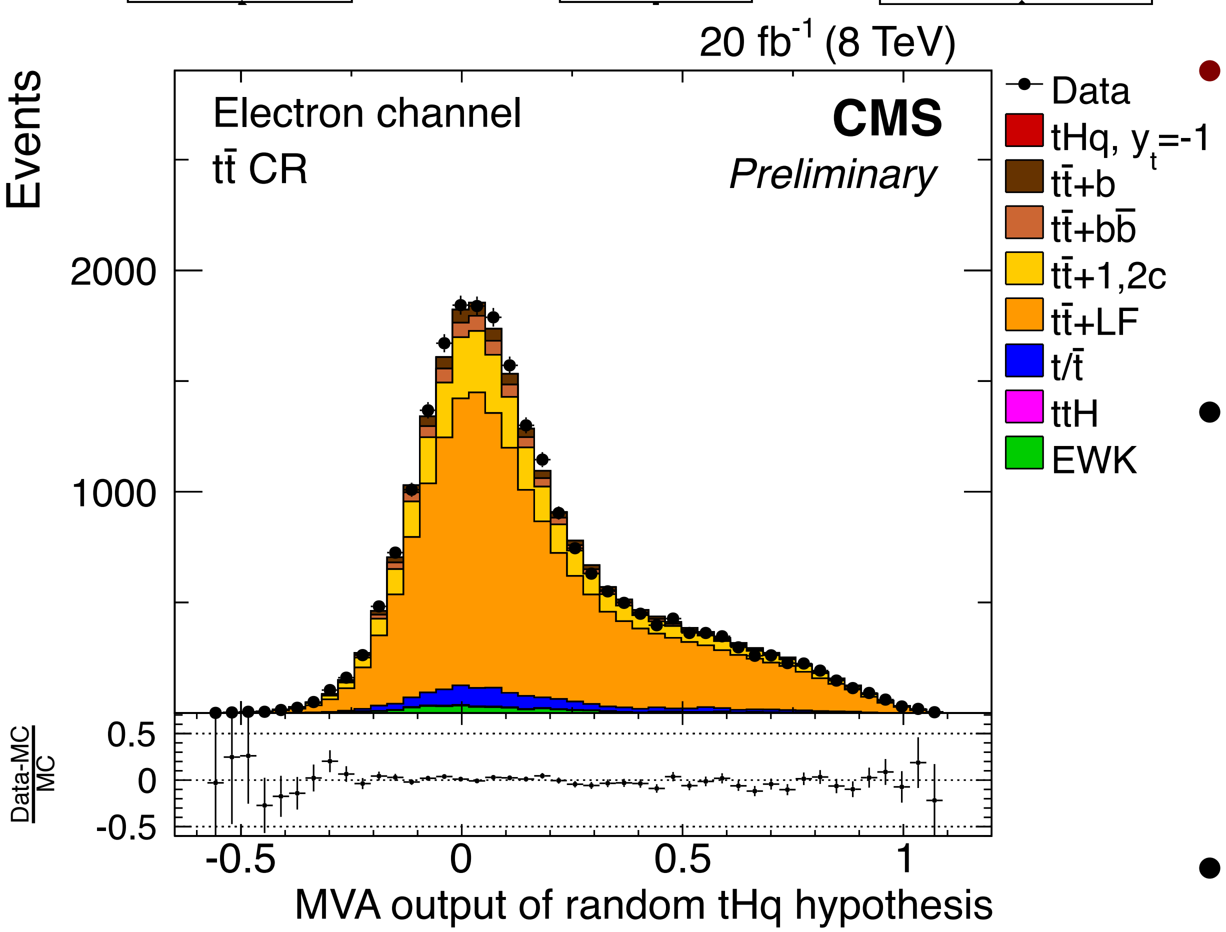
1 forward, light jet

3 or 4 b-tagged jets

- **Select events with lepton + jets**
- **Separate events by e/μ, 3/4 b-tag**
- Train two MVAs for jet assignment
  - Under tt+jets hypothesis
  - Under signal hypothesis
  - Jet ⟶ parton assignment
- Define variables for hypotheses
  - Reconstruct all jet combinations
  - Take assignment with largest MVA
- Final MVA for S/B discrimination
  - Variables in tHq interpretation
  - Variables in tt+jets interpretation
  - Global observables (lepton charge)
- Data-driven tt+jets for cross check

CMS tHq Hbb





- Select events with lepton + jets
- Separate events by e/μ, 3/4 b-tag
- **Train two MVAs for jet assignment**
  - **Under tt+jets hypothesis**
  - **Under tHq signal hypothesis**
  - **Jet → parton assignment**
- **Define variables for hypotheses**
  - **Reconstruct all jet combinations**
  - **Take assignment with largest MVA**
- Final MVA for S/B discrimination
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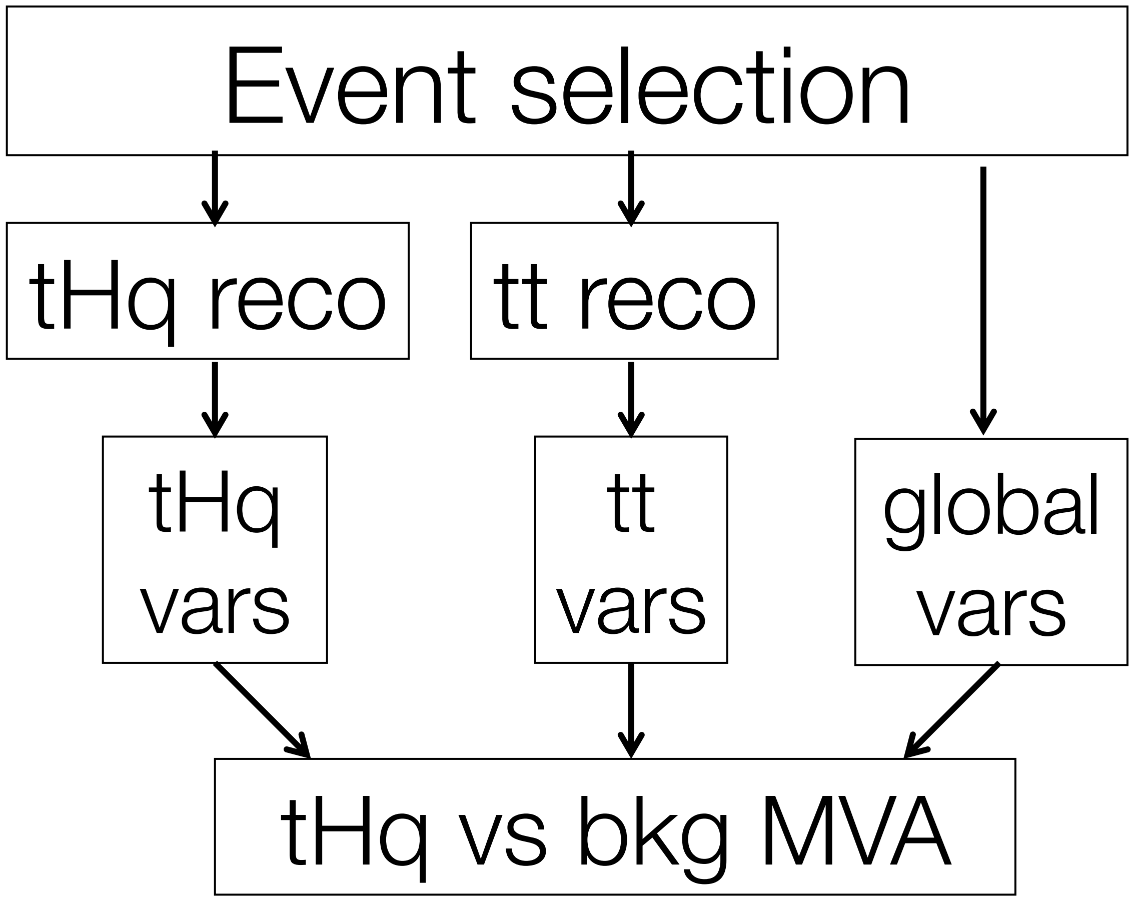
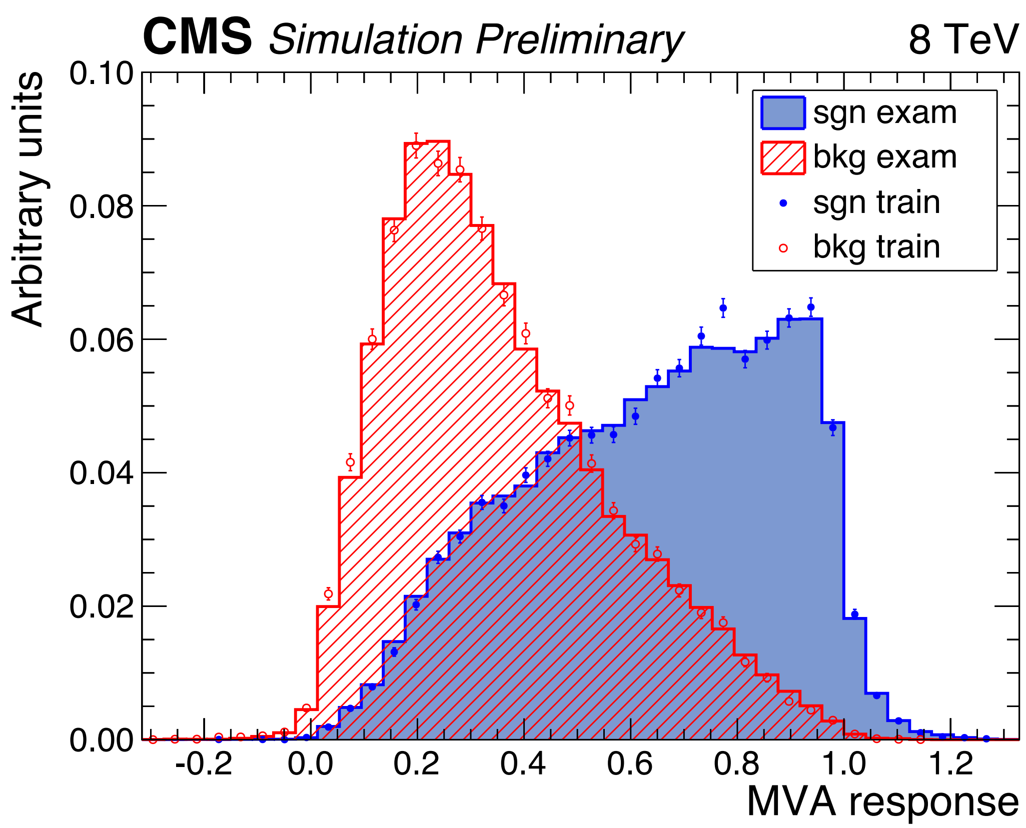
CMS tHq Hbb





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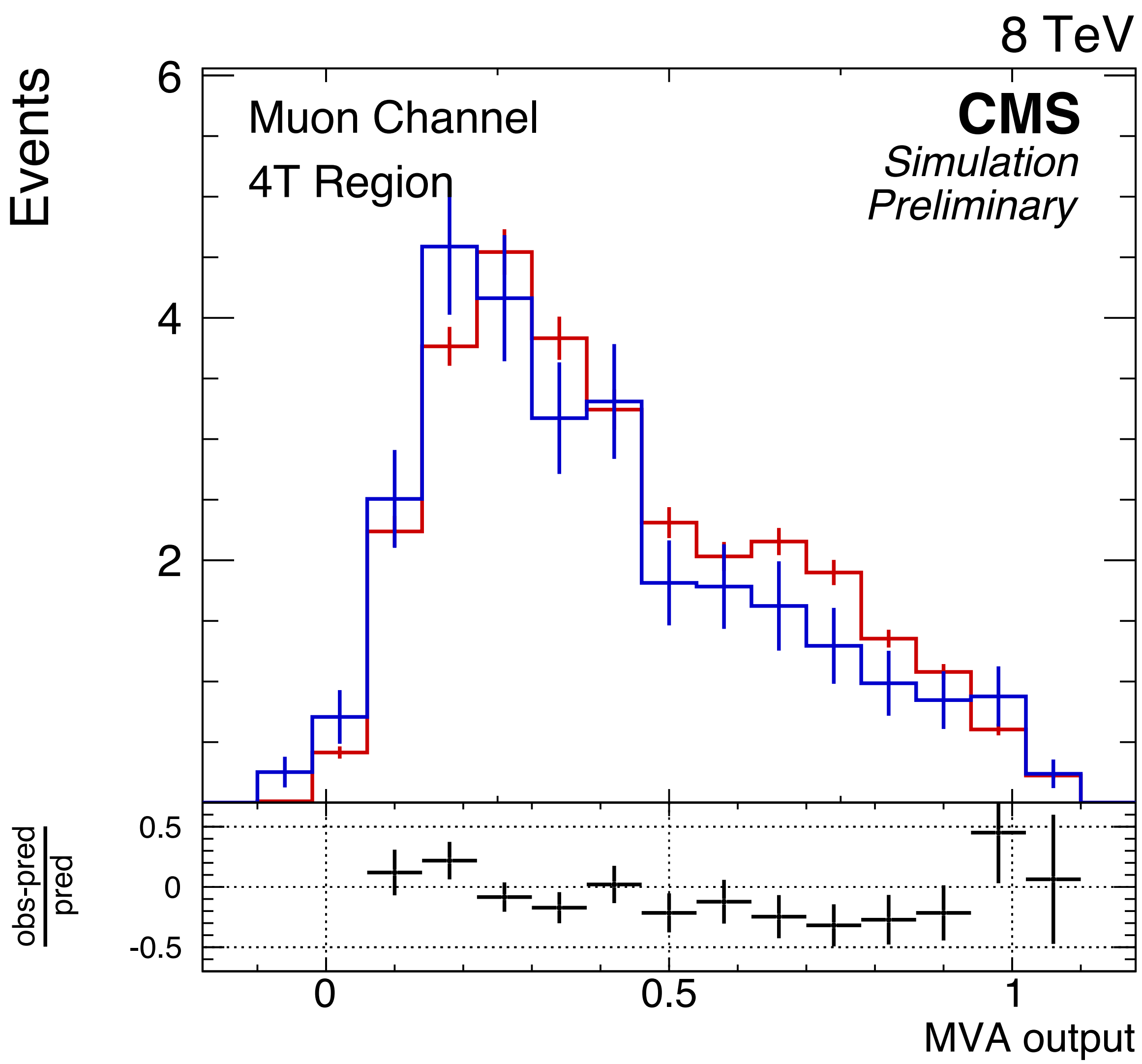
- **Final MVA for S/B discrimination**
  - **Variables in tHq interpretation**
  - **Variables in tt+jets interpretation**
  - **Global observables (lepton charge)**
- Data-driven tt+jets for cross check

CMS tHq Hbb

MC closure test



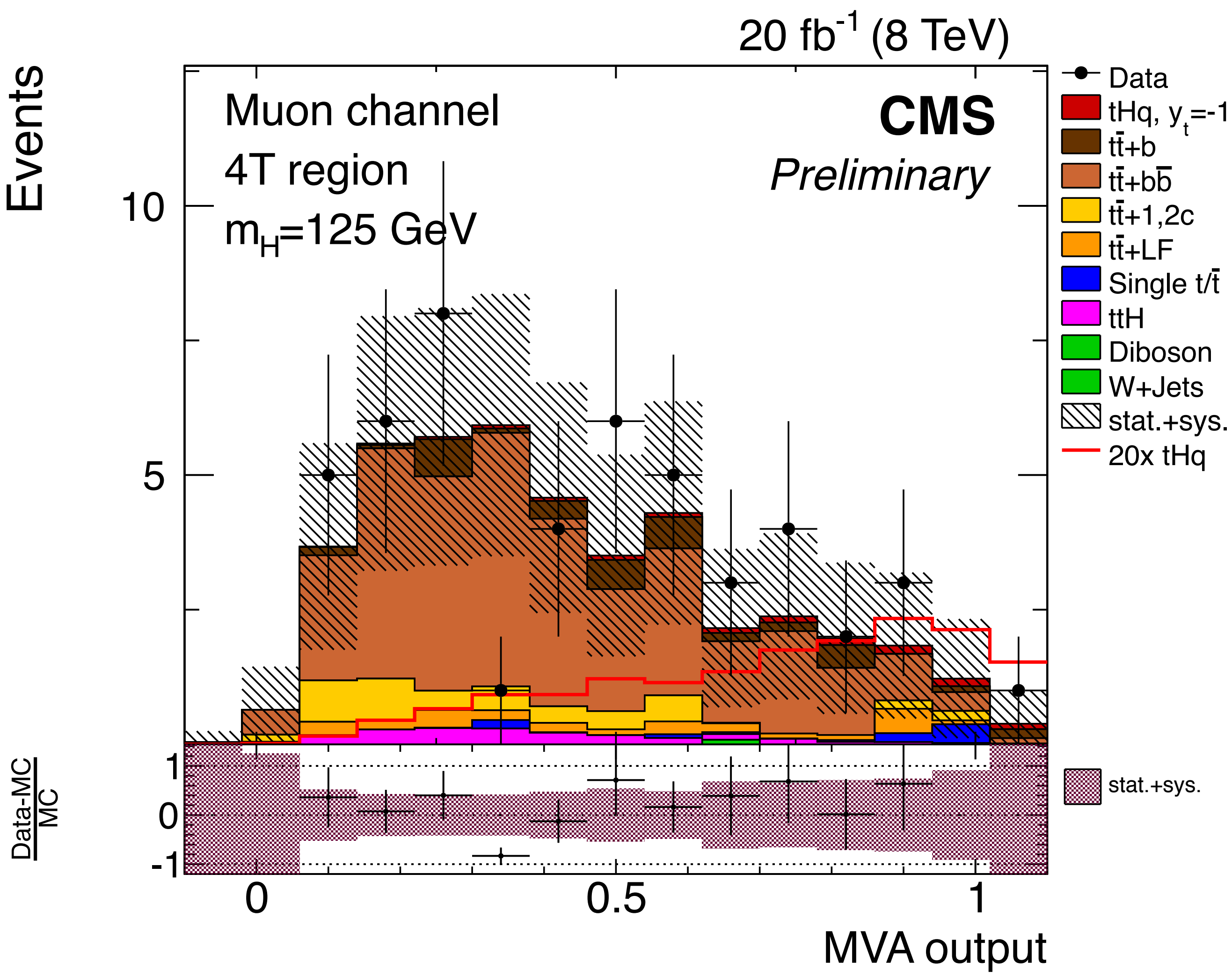
tt+jets **prediction**

tt+jets **true**

- Select events with lepton + jets
- Separate events by e/μ, 3/4 b-tag
- Train two MVAs for jet assignment
  - Under tt+jets hypothesis
  - Under signal hypothesis
  - Jet ⟶ parton assignment
- Define variables for hypotheses
  - Reconstruct all jet combinations
  - Take assignment with largest MVA
- Final MVA for S/B discrimination
  - Variables in tHq interpretation
  - Variables in tt+jets interpretation
  - Global observables (lepton charge)
- **Data-driven tt+jets for cross check**

tHq Hbb fit and results

- Simultaneous fit to the discriminant in all 4 channels
  - No significant excess, set upper limit



95% CL upper limits on $\mu = \sigma/\sigma_{\kappa_t=-1}$		
Approach	Observed	Expected
MC	**7.57**	$\mathbf{5.14^{+2.14}_{-1.44}}$
Data driven	6.95	$6.24^{+2.26}_{-1.71}$

- Higher expected limit with data driven cross check than MC
  - Quote both values for comparison

Summary and future work

- ttH and tH are only avenues to directly extract top quark Yukawa
  - Hbb decay has largest branching ratio, difficult tt+jets background
- Sophisticated searches have been performed at 7 and 8 TeV
  - **Rapidly approaching standard model sensitivity!**
  - Analyses have evolved over time
    - MEM, BDTs, 2D discriminants, improved background modeling
- Work ongoing to coordinate between ATLAS and CMS
  - Same definition of tt+jets categories: tt+b, tt+bb, tt+2b, tt+cc, tt+lf
  - Same treatment of signal and major background, e.g NLO ttH, tt+bb
- Larger cross section increase for ttH than backgrounds at 13 TeV
- **Looking forward to interesting results with 13 TeV data!**

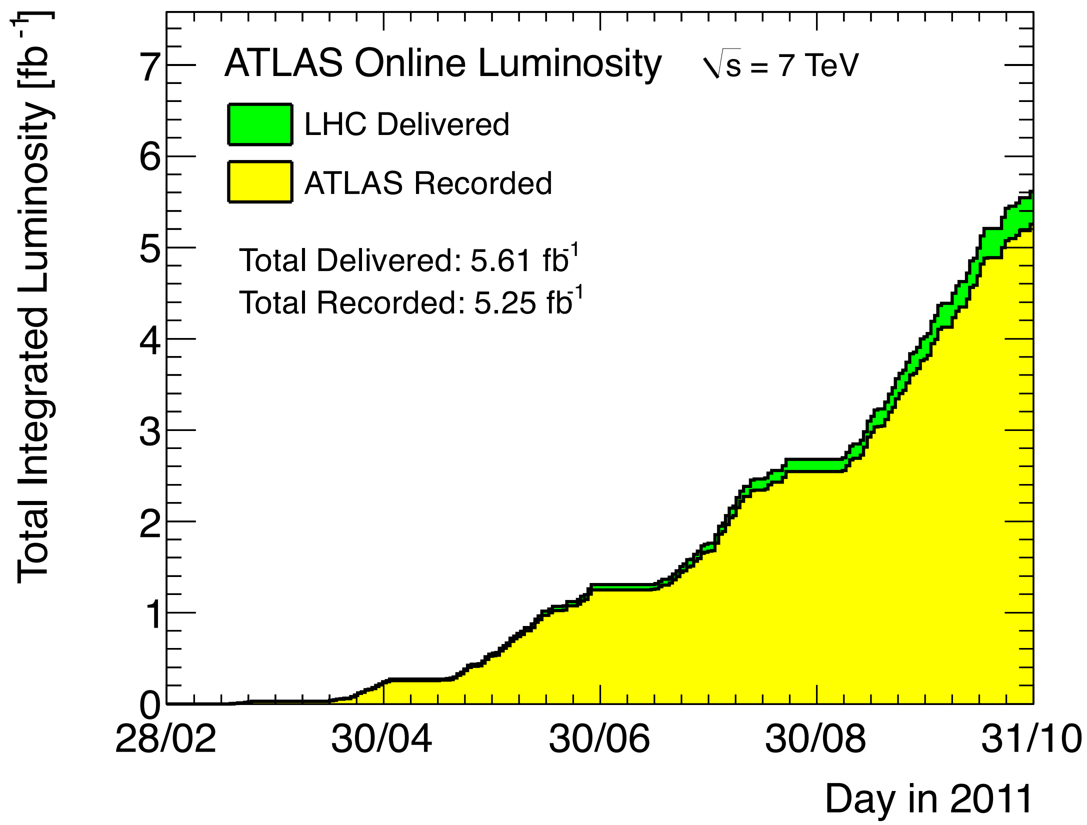
THANK YOU

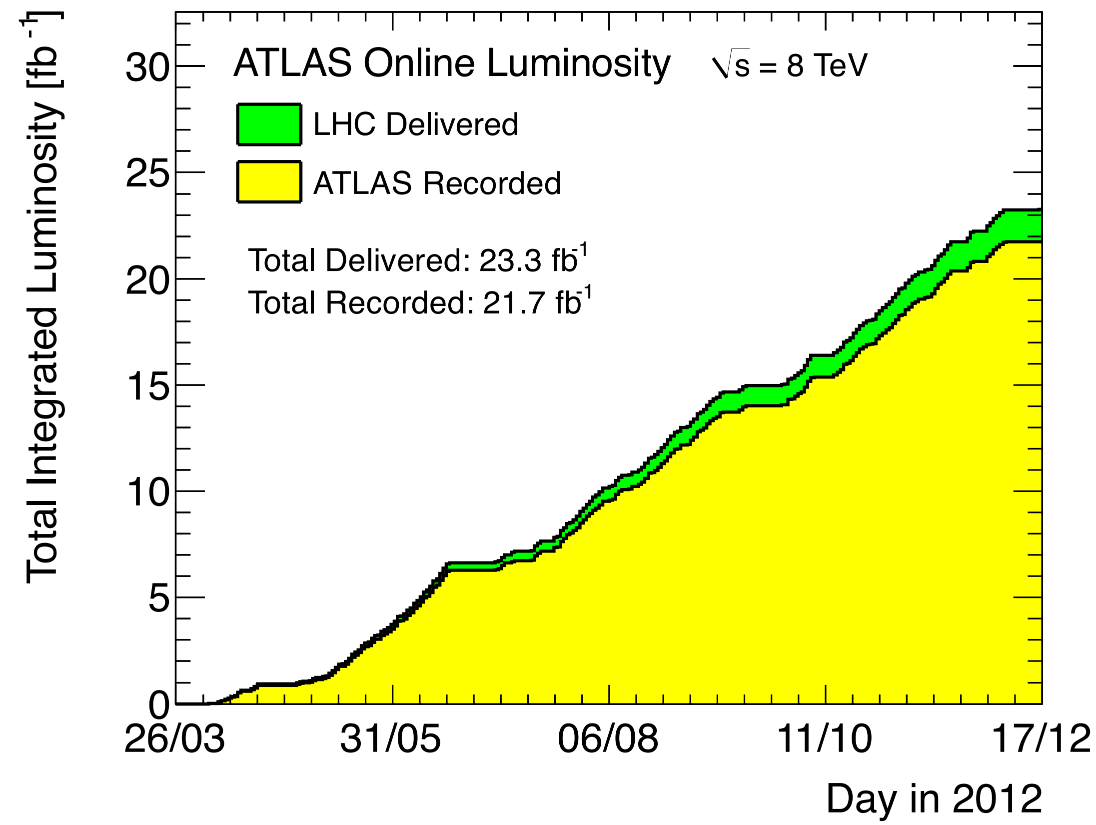
Backup Slides

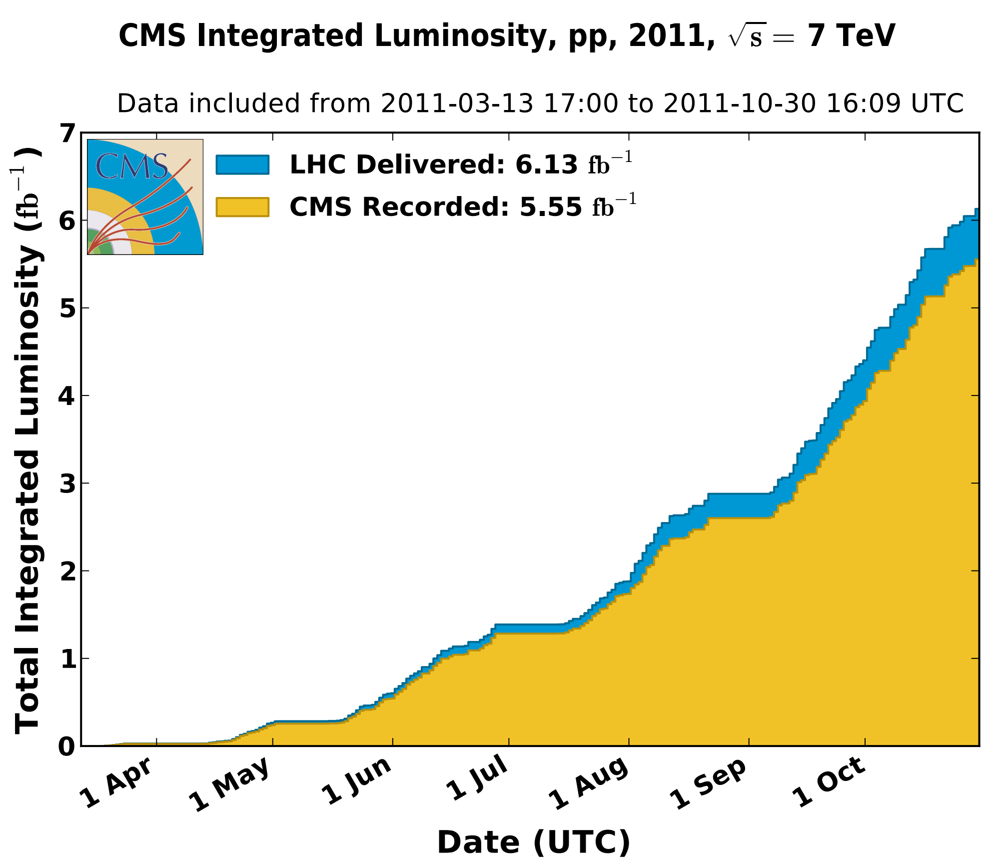
Thank you!

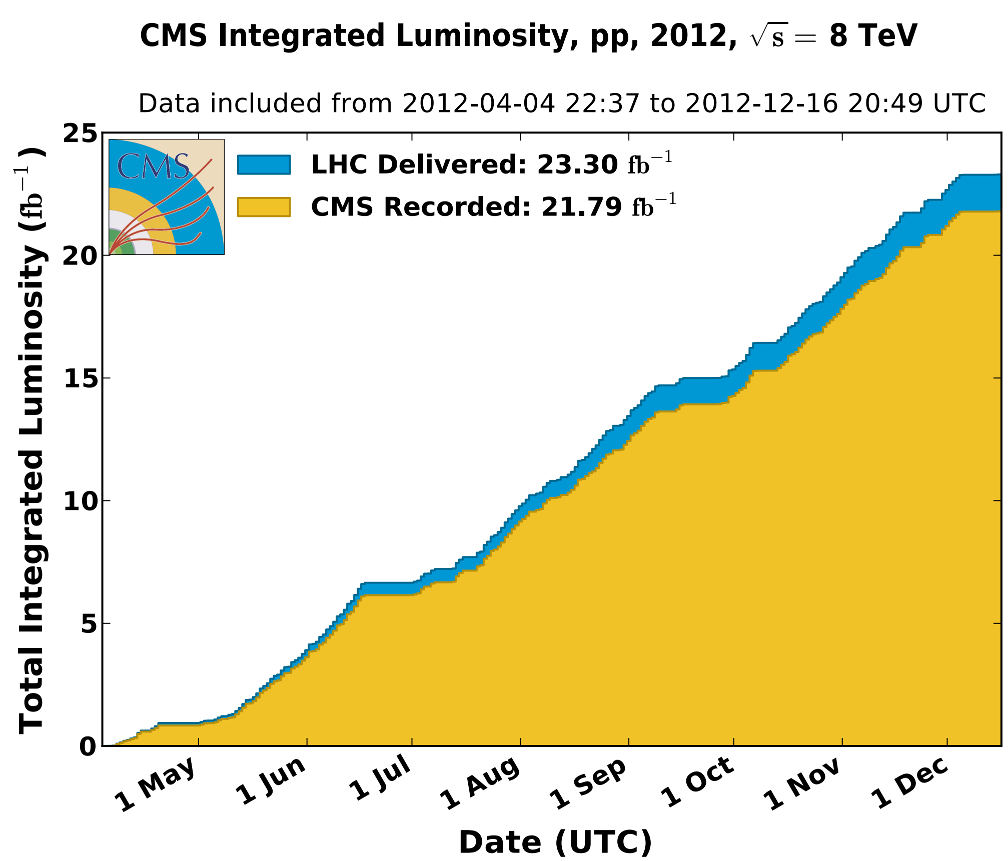
- With help and inspiration from
  - Lorenzo Bianchini
  - Christian Böser
  - Sarah Boutle
  - Stefan Guindon
  - Satoshi Hasegawa
  - Mark Owen
  - Tamara Vázquez Schöder

Integrated luminosity



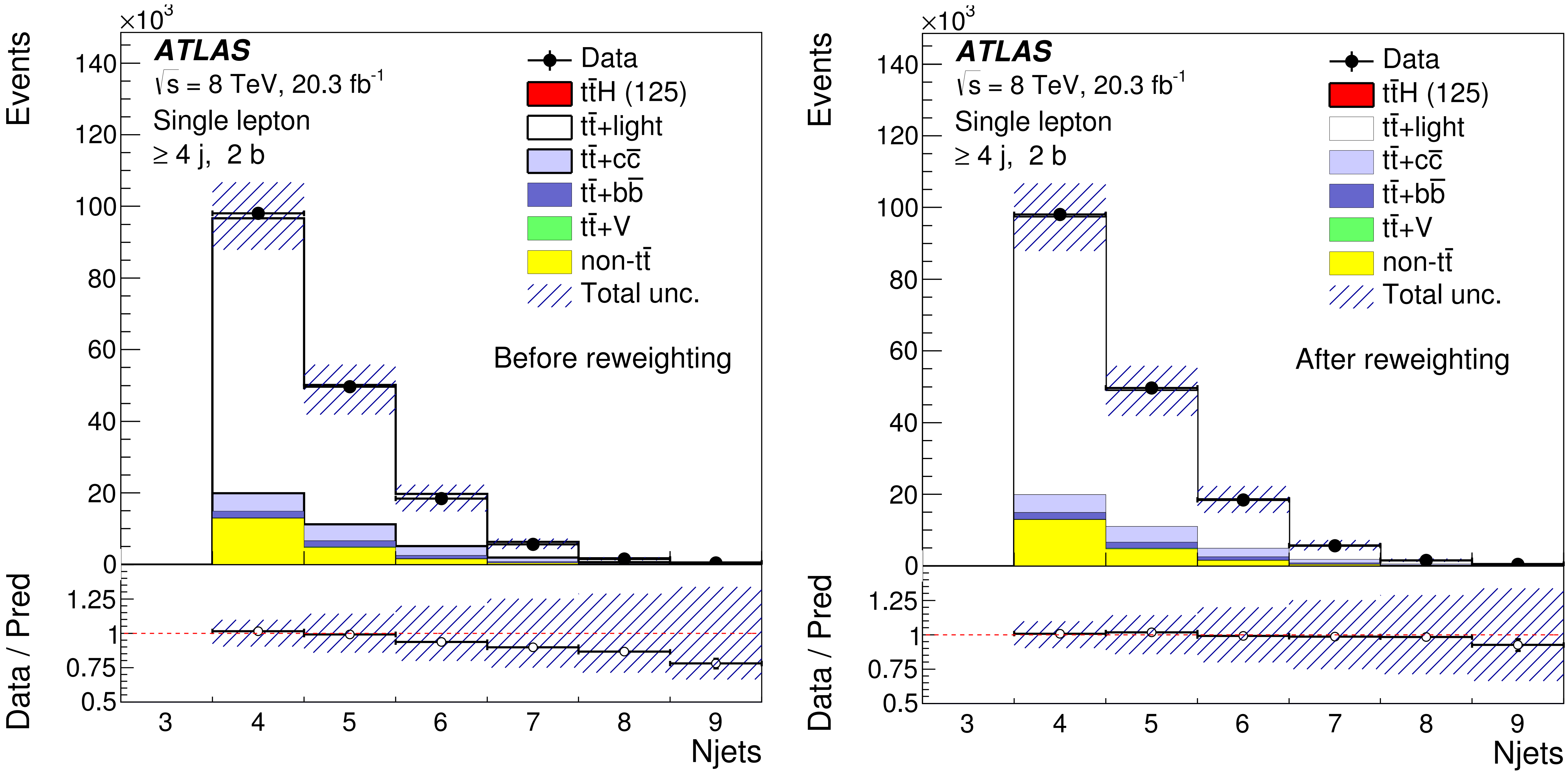






Correcting tt+light and tt+cc

- Corrections on top and tt+jets p_T from differential XS measurement
  - Data softer than tt+jets simulation -> predict more/harder jets
  - Good agreement between data and MC after correction



Object selection

	ATLAS ttH Hbb	CMS ttH Hbb BDT	CMS ttH Hbb MEM	CMS tHq Hbb
Muons or Electrons	p_T > 25 (15) GeV |η| < 2.5 id, isolation	p_T > 30/20 (10) GeV |η| < 2.1 or 2.5 id, isolation	p_T > 30/20 (20) GeV |η| < 2.1 or 2.5 id, isolation	p_T > 26 or 30 GeV |η| < 2.1 or 2.5 id, isolation
Jets	p_T > 25 GeV |η| < 2.5 Anti-k_T, R=0.4 JVF > 0.5	p_T > 30 GeV |η| < 2.4 Anti-k_T, R=0.5 PU / noise id	p_T > 30 GeV |η| < 2.4 Anti-k_T, R=0.5 PU / noise id	p_T > 30 GeV |η| < 2.4 Anti-k_T, R=0.5 PU / noise id
B-tag	B-eff = 70% Mis-tag = 1% Charm = 20%	B-eff = 70% Mis-tag = 2% Charm = 20%	B-eff = 70% Mis-tag = 2% Charm = 20%	B-eff = 50% Mis-tag = 0.4% Charm = 7%

tt+jets MC and corrections

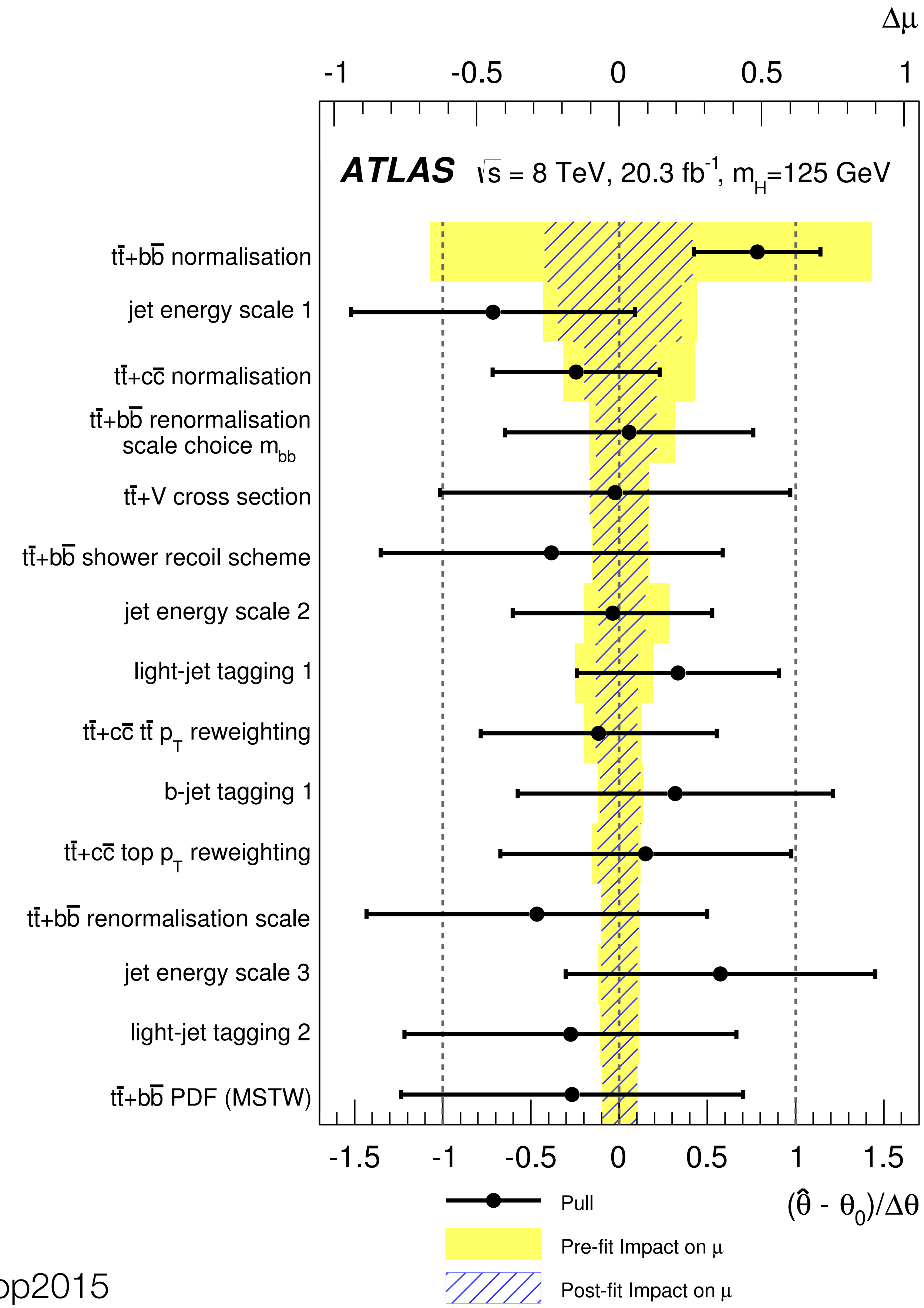
tt+jets	ATLAS	CMS
Generator	PowHeg-Box Normalized to NNLO+NLLL	MadGraph5 5F + 0,1,2,3p (incl b,c) Normalized to NNLO+NLLL
PS, PDF	Pythia6, CTEQ6L1	Pythia6, CTEQ6L1
Top Mass	172.5 GeV	172.5 GeV
Reweight	p_T(t), p_T(ttbar) SherpaOL (tt+bb)	p_T(t)
Model uncertainty	Vary reweighting (9 comp) Pythia vs Herwig	Vary reweighting Vary scales in MC
Additional HF modeling uncertainty	On/off reweight (tt+cc) Vary scales in MadGraph Compare MadGraph+Pythia to PowHeg+Pythia tt+bb NLO shape (8 comp)	Scale variations uncorrelated tt+0,1,2p, and tt+b, tt+bb, tt+cc
Additional HF normalization unc	50% (2 comp) tt+bb, tt+cc	50% (3 comp) tt+b, tt+bb, tt+cc

Other MC generators

MC sample	ATLAS	CMS
Single top	PowHeg+Pythia	PowHeg+Pythia
Diboson (WW,WZ,ZZ)	Alpgen+Herwig	Pythia6 (normalized to NLO)
tt+Z/W	MadGraph+Pythia	MadGraph+Pythia

Systematics and ranking

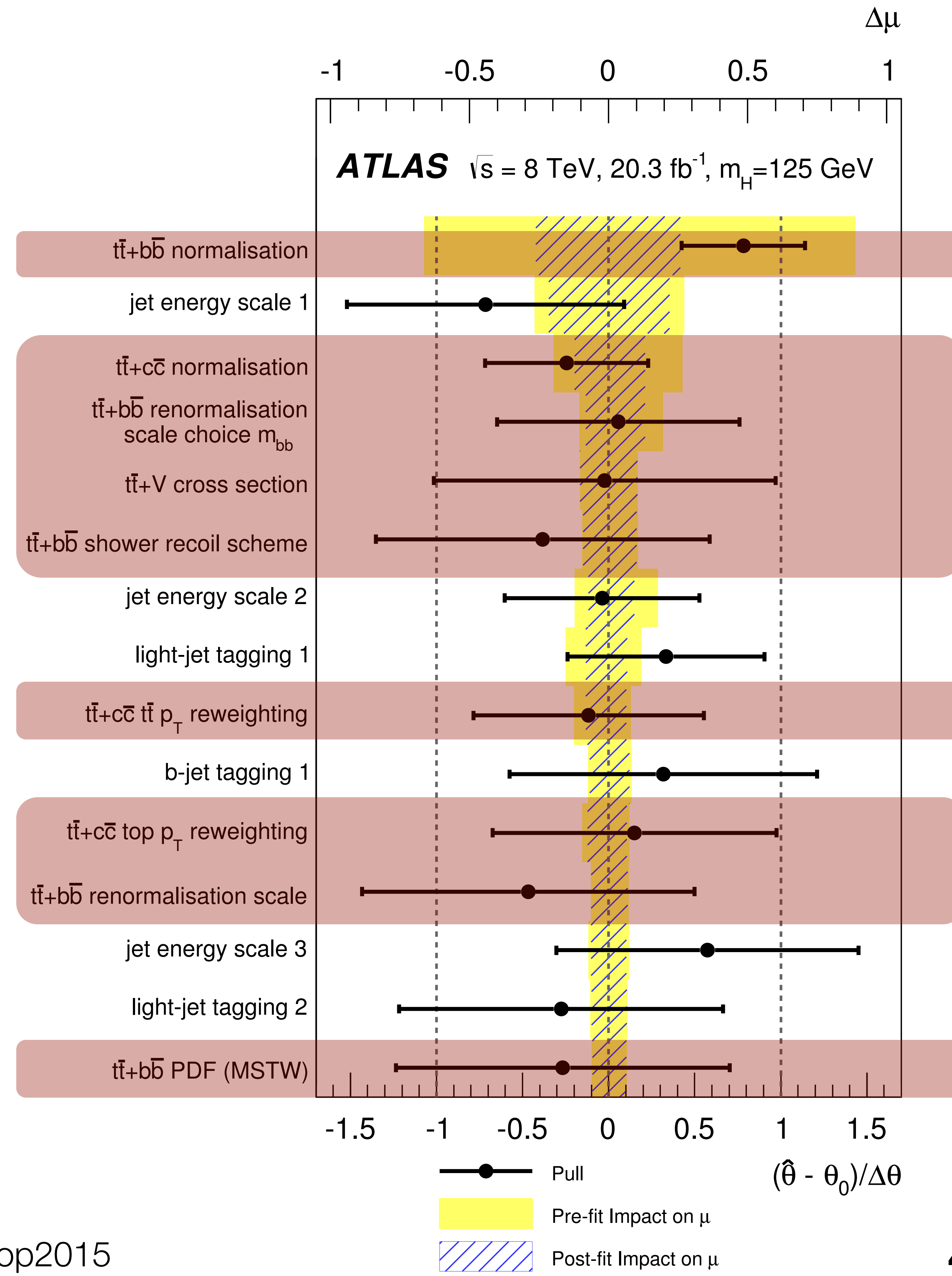
Systematic uncertainty	Type	Comp.
Luminosity	N	1
Physics Objects		
Electron	SN	5
Muon	SN	6
Jet energy scale	SN	22
Jet vertex fraction	SN	1
Jet energy resolution	SN	1
Jet reconstruction	SN	1
b-tagging efficiency	SN	6
c-tagging efficiency	SN	4
Light-jet tagging efficiency	SN	12
High-p_{T} tagging efficiency	SN	1
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	3
$t\bar{t}$+heavy-flavour: normalisation	N	2
$t\bar{t}+c\bar{c}$: p_{T} reweighting	SN	2
$t\bar{t}+c\bar{c}$: generator	SN	4
$t\bar{t}+b\bar{b}$: NLO Shape	SN	8
W+jets normalisation	N	3
W p_{T} reweighting	SN	1
Z+jets normalisation	N	3
Z p_{T} reweighting	SN	1
Lepton misID normalisation	N	3
Lepton misID shape	S	3
Single top cross section	N	1
Single top model	SN	1
Diboson+jets normalisation	N	3
$t\bar{t}+V$ cross section	N	1
$t\bar{t}+V$ model	SN	1
Signal Model		
$t\bar{t}H$ scale	SN	2
$t\bar{t}H$ generator	SN	1
$t\bar{t}H$ hadronisation	SN	1
$t\bar{t}H$ PDF	SN	1



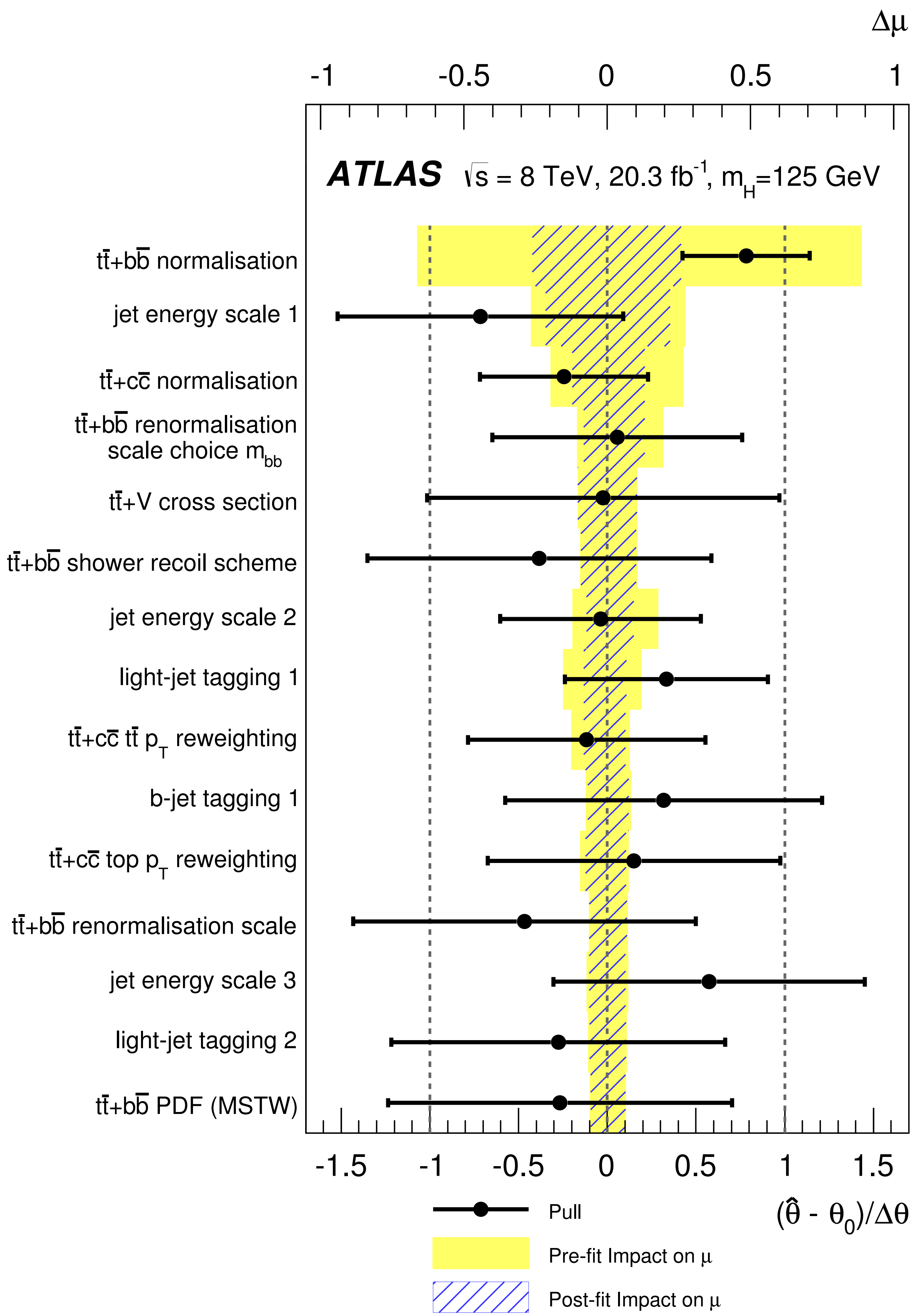
Systematics and ranking

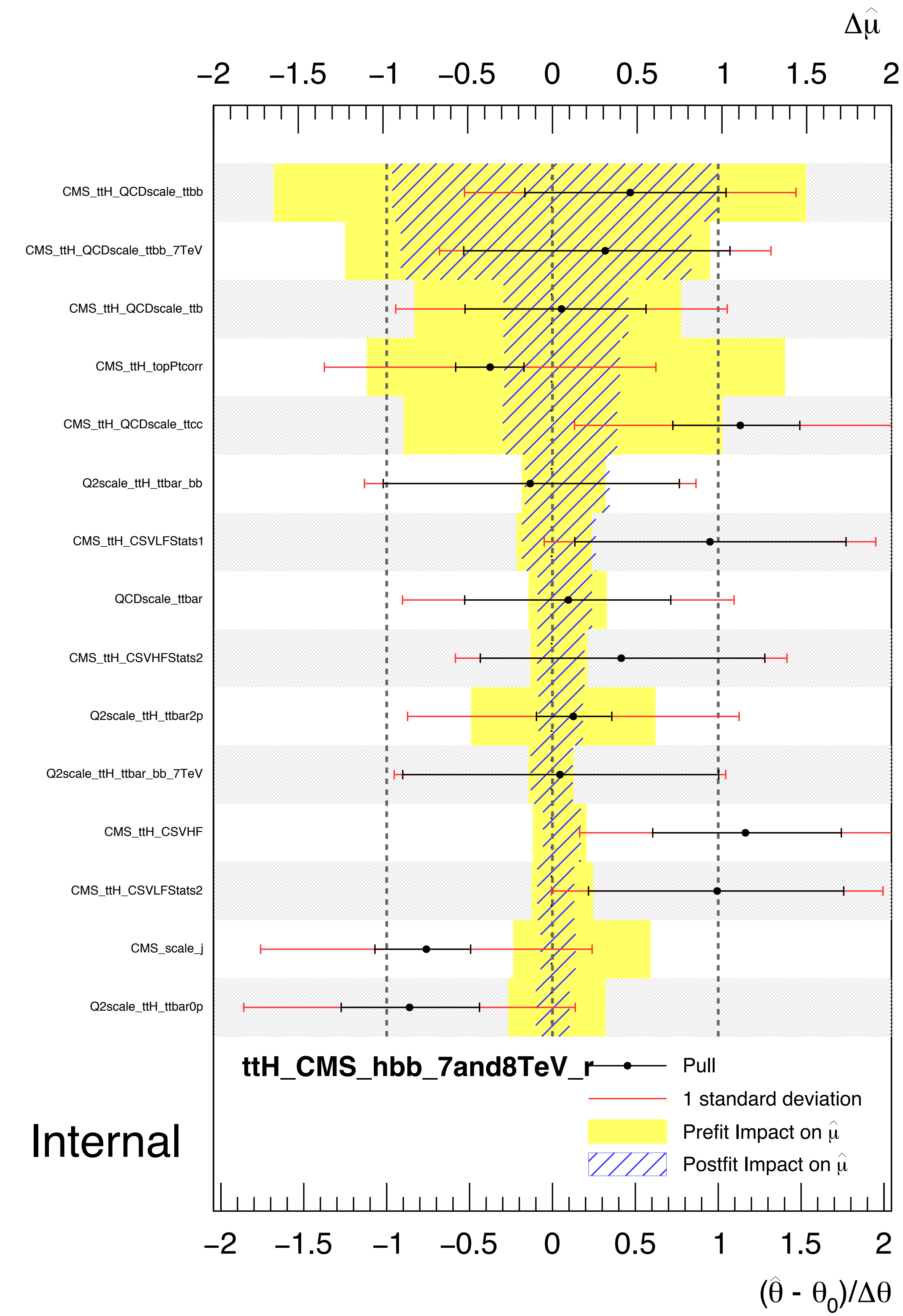
Systematic uncertainty	Type	Comp.
Luminosity	N	1
Physics Objects		
Electron	SN	5
Muon	SN	6
Jet energy scale	SN	22
Jet vertex fraction	SN	1
Jet energy resolution	SN	1
Jet reconstruction	SN	1
b-tagging efficiency	SN	6
c-tagging efficiency	SN	4
Light-jet tagging efficiency	SN	12
High-p_T tagging efficiency	SN	1
W p_T reweighting	SN	1
Z+jets normalisation	N	3
Z p_T reweighting	SN	1
Lepton misID normalisation	N	3
Lepton misID shape	S	3
Single top cross section	N	1
Single top model	SN	1
Diboson+jets normalisation	N	3
$t\bar{t}+V$ cross section	N	1
$t\bar{t}+V$ model	SN	1
Signal Model		
$t\bar{t}H$ scale	SN	2
$t\bar{t}H$ generator	SN	1
$t\bar{t}H$ hadronisation	SN	1
$t\bar{t}H$ PDF	SN	1

<u>Largest uncertainties</u>:
tt+hf norm, tt+bb modeling, top/tt p_T correction



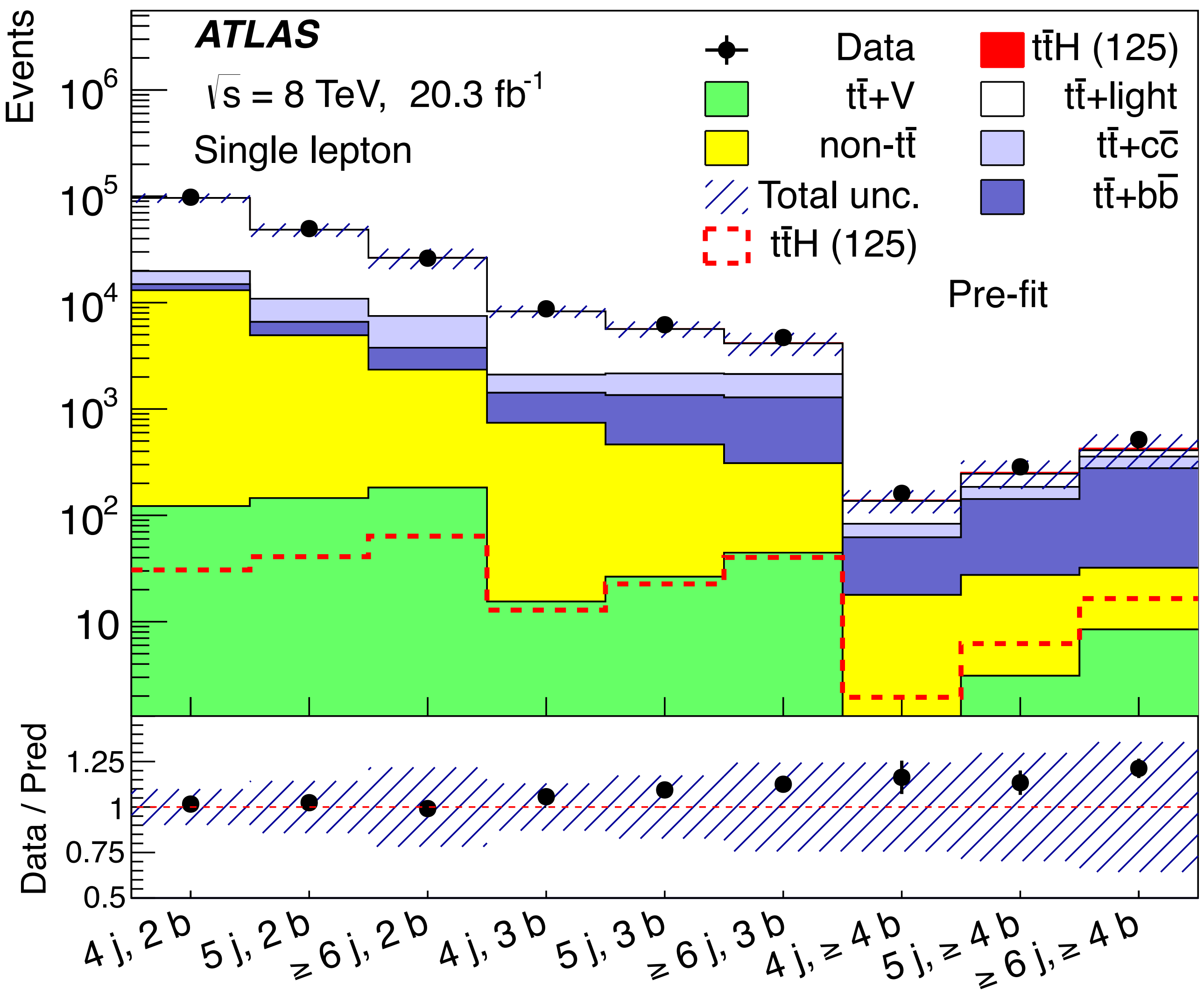
Nuisance pulls



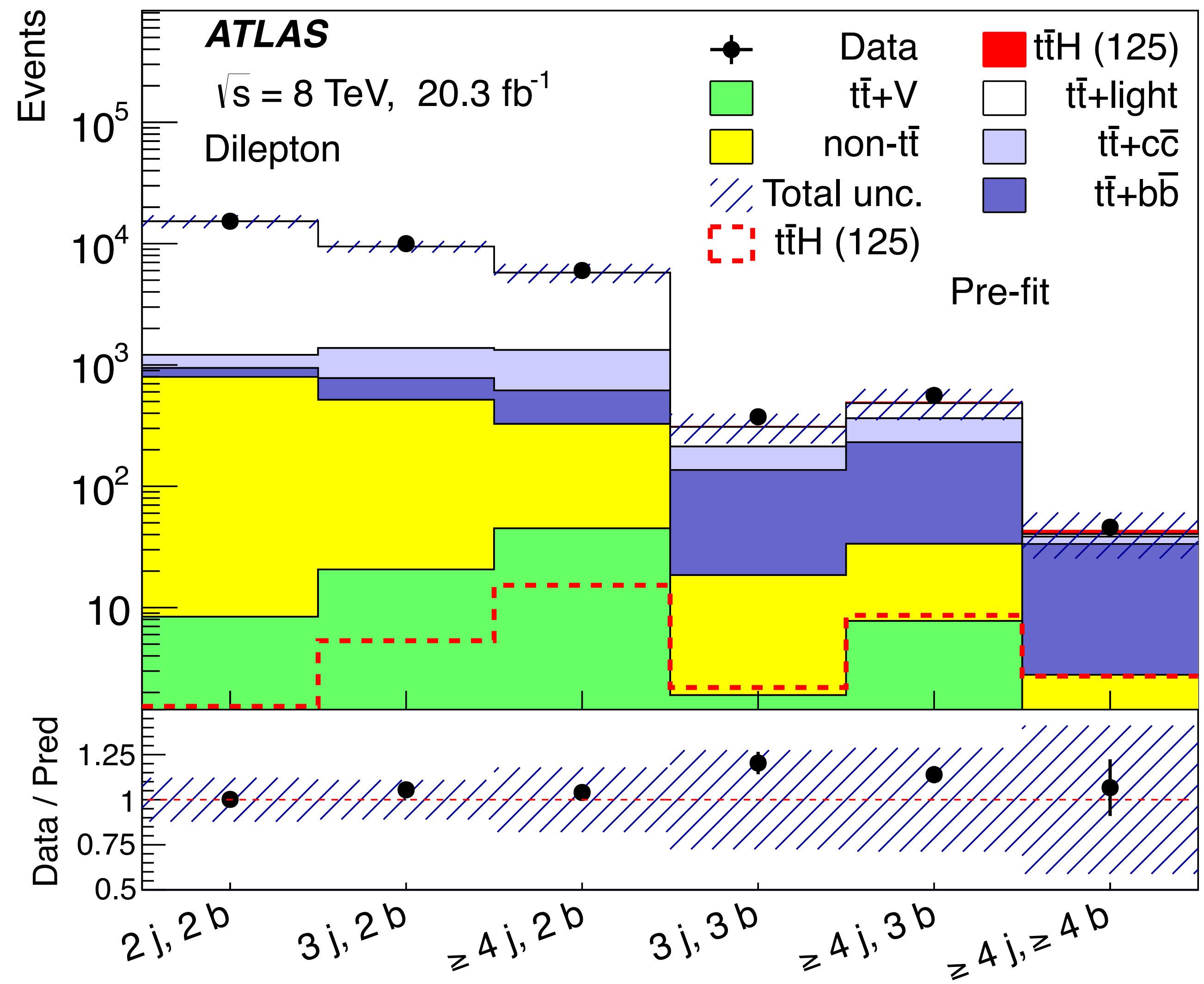


Event yields (pre-fit)

Single lepton

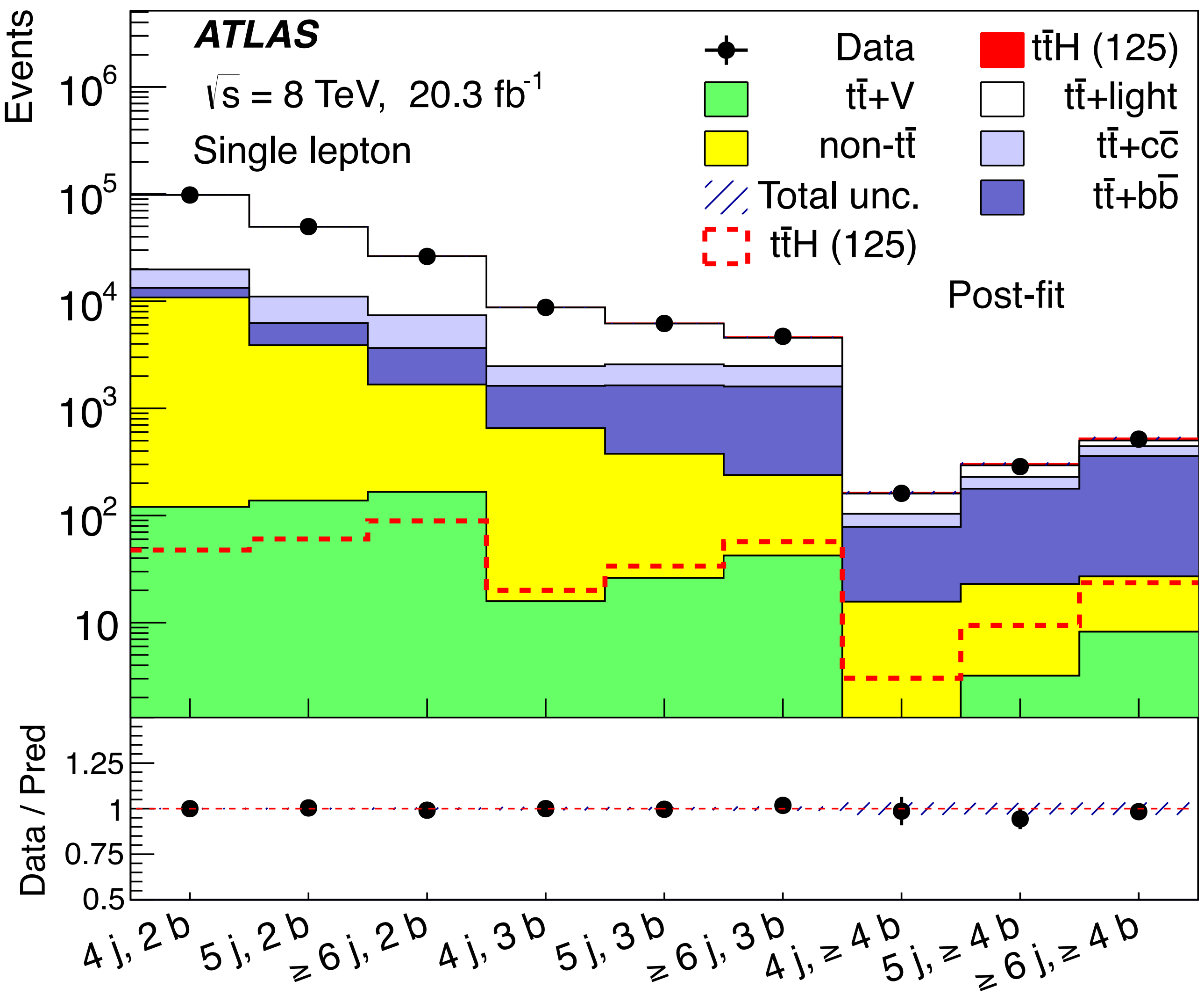


Dilepton

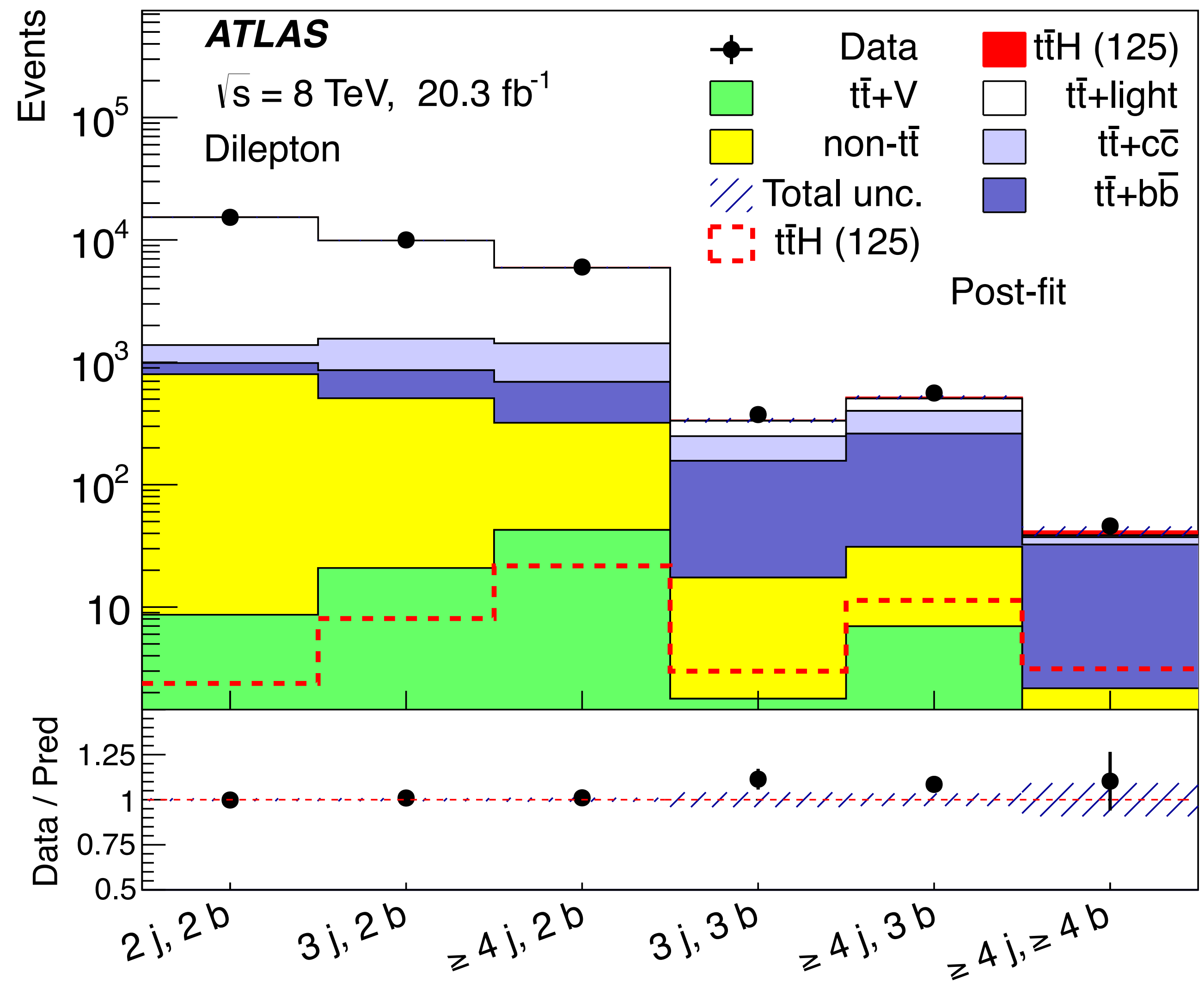


Event yields (post-fit)

Single lepton



Dilepton



Event yields (single lepton)

	4 j, 2 b	4 j, 3 b	4 j, 4 b
$t\bar{t}H$ (125)	31 ± 3	13 ± 2	2.0 ± 0.3
$t\bar{t}$+ light	$77\,000 \pm 7500$	6200 ± 750	53 ± 12
$t\bar{t} + c\bar{c}$	4900 ± 3000	680 ± 390	21 ± 12
$t\bar{t} + b\bar{b}$	1800 ± 1100	680 ± 380	44 ± 25
W+jets	5100 ± 3000	220 ± 130	5.5 ± 3.3
Z+jets	1100 ± 600	50 ± 27	0.9 ± 0.6
Single top	4900 ± 640	340 ± 60	6.8 ± 1.6
Diboson	220 ± 71	11 ± 4.1	0.2 ± 0.1
$t\bar{t} + V$	120 ± 40	15 ± 5.1	0.9 ± 0.3
Lepton misID	1600 ± 620	100 ± 37	3.5 ± 1.3
Total	$96\,000 \pm 9500$	8300 ± 1100	140 ± 34
Data	98 049	8752	161
S/B	< 0.001	0.002	0.014
S/$\sqrt{\text{B}}$	0.099	0.141	0.167

	5 j, 2 b	5 j, 3 b	5 j, $\geq$ 4 b
$t\bar{t}H$ (125)	41 ± 2	23 ± 2	6.2 ± 0.8
$t\bar{t}$+ light	$38\,000 \pm 5500$	3500 ± 520	61 ± 15
$t\bar{t} + c\bar{c}$	4300 ± 2400	810 ± 460	43 ± 25
$t\bar{t} + b\bar{b}$	1700 ± 880	890 ± 480	110 ± 63
W+jets	1900 ± 1200	140 ± 87	5.9 ± 3.9
Z+jets	410 ± 240	29 ± 17	1.5 ± 0.9
Single top	1900 ± 360	190 ± 41	8.3 ± 1.3
Diboson	97 ± 39	8.0 ± 3.4	0.4 ± 0.2
$t\bar{t} + V$	150 ± 48	26 ± 9	3.1 ± 1.0
Lepton misID	460 ± 170	70 ± 28	8.3 ± 3.7
Total	$49\,000 \pm 7000$	5700 ± 980	250 ± 75
Data	49 699	6199	286
S/B	0.001	0.004	0.025
S/$\sqrt{\text{B}}$	0.186	0.301	0.397

	$\geq$ 6 j, 2 b	$\geq$ 6 j, 3 b	$\geq$ 6 j, $\geq$ 4 b
$t\bar{t}H$ (125)	64 ± 5	40 ± 3	16 ± 2
$t\bar{t}$+ light	$19\,000 \pm 4400$	2000 ± 460	52 ± 17
$t\bar{t} + c\bar{c}$	3700 ± 2100	850 ± 480	79 ± 46
$t\bar{t} + b\bar{b}$	1400 ± 770	970 ± 530	250 ± 130
W+jets	910 ± 620	97 ± 66	8.6 ± 6.2
Z+jets	180 ± 120	19 ± 12	1.5 ± 1.0
Single top	840 ± 220	120 ± 35	12 ± 3.7
Diboson	50 ± 24	6.0 ± 3.0	0.5 ± 0.3
$t\bar{t} + V$	180 ± 59	45 ± 14	8.5 ± 2.8
Lepton misID	180 ± 66	21 ± 8	1.1 ± 0.5
Total	$26\,000 \pm 5800$	4200 ± 1000	430 ± 150
Data	26 185	4701	516
S/B	0.002	0.01	0.04
S/$\sqrt{\text{B}}$	0.393	0.63	0.815

	4 j, 2 b	4 j, 3 b	4 j, 4 b
$t\bar{t}H$ (125)	48 ± 35	20 ± 15	3.0 ± 2.2
$t\bar{t}$+ light	$78\,000 \pm 1600$	6300 ± 160	56 ± 5
$t\bar{t} + c\bar{c}$	6400 ± 1800	850 ± 220	26 ± 7
$t\bar{t} + b\bar{b}$	2500 ± 490	970 ± 150	63 ± 8
W+jets	3700 ± 1100	170 ± 51	4.0 ± 1.2
Z+jets	1100 ± 540	49 ± 25	1.1 ± 0.6
Single top	4700 ± 320	330 ± 28	6.8 ± 0.7
Diboson	220 ± 65	11 ± 4	0.3 ± 0.1
$t\bar{t} + V$	120 ± 38	16 ± 5	0.9 ± 0.3
Lepton misID	1100 ± 370	78 ± 26	2.6 ± 1.0
Total	$98\,000 \pm 340$	8800 ± 82	160 ± 6
Data	98 049	8752	161

	5 j, 2 b	5 j, 3 b	5 j, $\geq$ 4 b
$t\bar{t}H$ (125)	60 ± 44	34 ± 25	9.4 ± 6.9
$t\bar{t}$+ light	$38\,000 \pm 1000$	3600 ± 120	65 ± 6
$t\bar{t} + c\bar{c}$	4800 ± 1200	930 ± 230	51 ± 12
$t\bar{t} + b\bar{b}$	2400 ± 360	1300 ± 180	150 ± 20
W+jets	1200 ± 420	87 ± 31	4.0 ± 1.5
Z+jets	370 ± 200	28 ± 16	1.4 ± 0.8
Single top	1700 ± 150	190 ± 18	8.2 ± 0.7
Diboson	94 ± 35	8.0 ± 3.1	0.5 ± 0.2
$t\bar{t} + V$	140 ± 43	26 ± 8	3.2 ± 1.0
Lepton misID	340 ± 110	44 ± 16	5.7 ± 2.2
Total	$50\,000 \pm 220$	6200 ± 54	300 ± 10
Data	49 699	6199	286

	$\geq$ 6 j, 2 b	$\geq$ 6 j, 3 b	$\geq$ 6 j, $\geq$ 4 b
$t\bar{t}H$ (125)	89 ± 65	57 ± 42	24 ± 17
$t\bar{t}$+ light	$19\,000 \pm 700$	2100 ± 87	58 ± 5
$t\bar{t} + c\bar{c}$	3700 ± 890	890 ± 210	85 ± 21
$t\bar{t} + b\bar{b}$	2000 ± 310	1400 ± 190	330 ± 37
W+jets	450 ± 170	51 ± 19	4.4 ± 1.9
Z+jets	150 ± 86	16 ± 9	1.2 ± 0.7
Single top	730 ± 83	110 ± 14	11 ± 2
Diboson	45 ± 20	5.6 ± 2.6	0.5 ± 0.2
$t\bar{t} + V$	170 ± 52	42 ± 13	8.2 ± 2.5
Lepton misID	120 ± 41	14 ± 5	1.1 ± 0.5
Total	$26\,000 \pm 160$	4600 ± 55	520 ± 18
Data	26 185	4701	516

Event yields (dilepton)

	2 j, 2 b	3 j, 2 b	3 j, 3 b
$t\bar{t}H$ (125)	1.5 ± 0.2	5.3 ± 0.5	2.2 ± 0.3
$t\bar{t}$+ light	14 000 ± 1800	8100 ± 880	96 ± 21
$t\bar{t}+c\bar{c}$	270 ± 170	600 ± 320	76 ± 44
$t\bar{t}+b\bar{b}$	150 ± 87	260 ± 130	120 ± 65
Z+jets	330 ± 30	190 ± 49	8.2 ± 3.1
Single top	430 ± 71	270 ± 30	7.6 ± 3.5
Diboson	6.8 ± 2.2	4.2 ± 1.5	≤ 0.1 ± 0.1
$t\bar{t}+V$	8.4 ± 2.7	21 ± 6	1.9 ± 0.6
Lepton misID	21 ± 10	33 ± 17	0.8 ± 0.4
Total	15 000 ± 1900	9500 ± 1000	310 ± 85
Data	15 296	9996	374
S/B	< 0.001	0.001	0.006
$S/\sqrt{B}$	0.012	0.053	0.114

	2 j, 2 b	3 j, 2 b	3 j, 3 b
$t\bar{t}H$ (125)	2.4 ± 1.8	8.1 ± 5.9	3.0 ± 2.2
$t\bar{t}$+ light	14 000 ± 160	8300 ± 170	84 ± 9.6
$t\bar{t}+c\bar{c}$	400 ± 110	700 ± 160	92 ± 22
$t\bar{t}+b\bar{b}$	190 ± 36	350 ± 49	140 ± 19
Z+jets	330 ± 22	200 ± 43	7.3 ± 2.4
Single top	430 ± 35	260 ± 21	7.6 ± 1.5
Diboson	6.8 ± 2.1	4.5 ± 1.4	≤ 0.1 ± 0.1
$t\bar{t}+V$	8.7 ± 2.7	21 ± 6	1.8 ± 0.6
Lepton misID	19 ± 10	30 ± 15	0.7 ± 0.4
Total	15 000 ± 120	9900 ± 82	340 ± 14
Data	15 296	9996	374

	≥ 4 j, 2 b	≥ 4 j, 3 b	≥ 4 j, ≥ 4 b
$t\bar{t}H$ (125)	15 ± 1	8.6 ± 0.6	2.7 ± 0.3
$t\bar{t}$+ light	4400 ± 810	120 ± 31	1.9 ± 0.8
$t\bar{t}+c\bar{c}$	710 ± 380	130 ± 74	5.0 ± 3.0
$t\bar{t}+b\bar{b}$	290 ± 150	200 ± 100	31 ± 17
Z+jets	100 ± 39	10 ± 4	0.6 ± 0.2
Single top	140 ± 55	11 ± 5	0.8 ± 0.2
Diboson	4.0 ± 1.3	0.4 ± 0.1	≤ 0.1 ± 0.1
$t\bar{t}+V$	45 ± 14	7.8 ± 2.4	1.1 ± 0.4
Lepton misID	38 ± 19	4.3 ± 2.2	0.4 ± 0.2
Total	5800 ± 1000	490 ± 140	43 ± 18
Data	6006	561	46
S/B	0.003	0.015	0.059
$S/\sqrt{B}$	0.197	0.365	0.401

	≥ 4 j, 2 b	≥ 4 j, 3 b	≥ 4 j, ≥ 4 b
$t\bar{t}H$ (125)	22 ± 16	11 ± 8	3.1 ± 2.3
$t\bar{t}$+ light	4500 ± 150	100 ± 12	1.4 ± 0.3
$t\bar{t}+c\bar{c}$	740 ± 170	140 ± 30	4.8 ± 1.1
$t\bar{t}+b\bar{b}$	370 ± 59	230 ± 31	30 ± 4
Z+jets	100 ± 33	9.5 ± 3.1	0.4 ± 0.2
Single top	140 ± 23	11 ± 2	0.6 ± 0.1
Diboson	4.2 ± 1.3	0.3 ± 0.1	≤ 0.1 ± 0.1
$t\bar{t}+V$	43 ± 13	7.0 ± 2.1	0.9 ± 0.3
Lepton misID	34 ± 18	3.5 ± 1.8	0.2 ± 0.1
Total	5900 ± 65	520 ± 18	42 ± 4
Data	6006	561	46

Systematics (single lepton)

$\geq$ 6 j, $\geq$ 4 b

	Pre-fit				Post-fit			
	$t\bar{t}H$ (125)	$t\bar{t}$ + light	$t\bar{t}+c\bar{c}$	$t\bar{t}+b\bar{b}$	$t\bar{t}H$ (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	±2.6	±2.6	±2.6	±2.6
Lepton efficiencies	±1.4	±1.4	±1.4	±1.5	±1.3	±1.3	±1.3	±1.3
Jet energy scale	±6.4	±13	±11	±9.2	±2.3	±5.3	±4.7	±3.6
Jet efficiencies	±1.7	±5.2	±2.7	±2.5	±0.7	±2.3	±1.2	±1.1
Jet energy resolution	±0.1	±4.4	±2.5	±1.6	±0.1	±2.3	±1.3	±0.8
b-tagging efficiency	±9.2	±5.6	±5.1	±9.3	±5.0	±3.1	±2.9	±5.0
c-tagging efficiency	±1.7	±6.0	±12	±2.4	±1.4	±5.1	±10	±2.1
l-tagging efficiency	±1.0	±19	±5.2	±2.1	±0.6	±11	±3.0	±1.1
High p_{T} tagging efficiency	±0.6	–	±0.7	±0.6	±0.3	–	±0.4	±0.3
$t\bar{t}$: p_{T} reweighting	–	±5.4	±6.1	–	–	±4.7	±5.4	–
$t\bar{t}$: parton shower	–	±13	±16	±11	–	±3.6	±10	±6.0
$t\bar{t}$+HF: normalisation	–	–	±50	±50	–	–	±28	±14
$t\bar{t}$+HF: modelling	–	±11	±16	±8.3	–	±3.6	±9.1	±7.1
Theoretical cross sections	–	±6.3	±6.3	±6.3	–	±4.1	±4.1	±4.1
$t\bar{t}H$ modelling	±2.7	–	–	–	±2.6	–	–	–
Total	±12	±32	±59	±54	±6.9	±9.2	±23	±12

Systematics (dilepton)

$\geq$ 4 j, $\geq$ 4 b

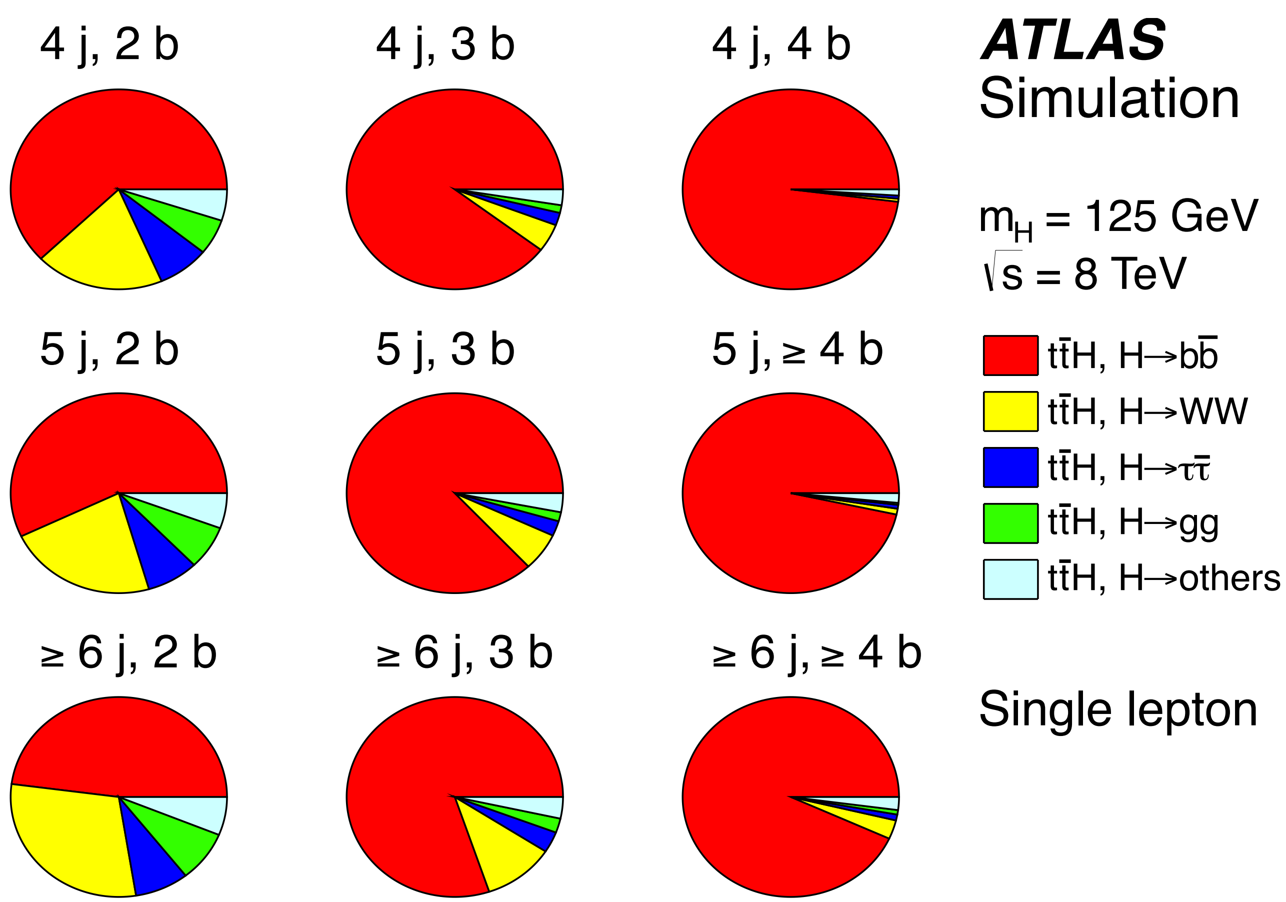
	Pre-fit				Post-fit			
	$t\bar{t}H$ (125)	$t\bar{t}$ + light	$t\bar{t}+c\bar{c}$	$t\bar{t}+b\bar{b}$	$t\bar{t}H$ (125)	$t\bar{t}$ + light	$t\bar{t}+c\bar{c}$	$t\bar{t}+b\bar{b}$
Luminosity	±2.8	±2.8	±2.8	±2.8	±2.6	±2.6	±2.6	±2.6
Lepton efficiencies	±2.5	±2.5	±2.5	±2.5	±1.8	±1.8	±1.8	±1.8
Jet energy scale	±4.5	±12	±9.4	±7.0	±2.0	±5.5	±4.5	±3.3
Jet efficiencies	–	±5.9	±1.6	±0.9	–	±2.6	±0.7	±0.4
Jet energy resolution	±0.1	±4.5	±1.1	–	±0.1	±2.3	±0.6	–
b-tagging efficiency	±10	±5.5	±5.4	±11	±5.6	±3.1	±3.0	±5.8
c-tagging efficiency	±0.5	–	±12	±0.6	±0.3	–	±10	±0.3
l-tagging efficiency	±0.7	±34	±7.0	±1.6	±0.4	±21	±4.2	±0.9
High p_{T} tagging efficiency	–	–	±0.6	–	–	–	±0.3	–
$t\bar{t}$: p_{T} reweighting	–	±5.8	±6.2	–	–	±5.0	±5.4	–
$t\bar{t}$: parton shower	–	±14	±18	±14	–	±4.8	±11	±8.1
$t\bar{t}$+HF: normalisation	–	–	±50	±50	–	–	±28	±14
$t\bar{t}$+HF: modelling	–	±11	±16	±12	–	±3.8	±10	±10
Theoretical cross sections	–	±6.3	±6.3	±6.2	–	±4.1	±4.1	±4.1
$t\bar{t}H$ modelling	±1.9	–	–	–	±1.8	–	–	–
Total	±12	±40	±59	±55	±6.7	±22	±22	±13

Systematics on tt+jets

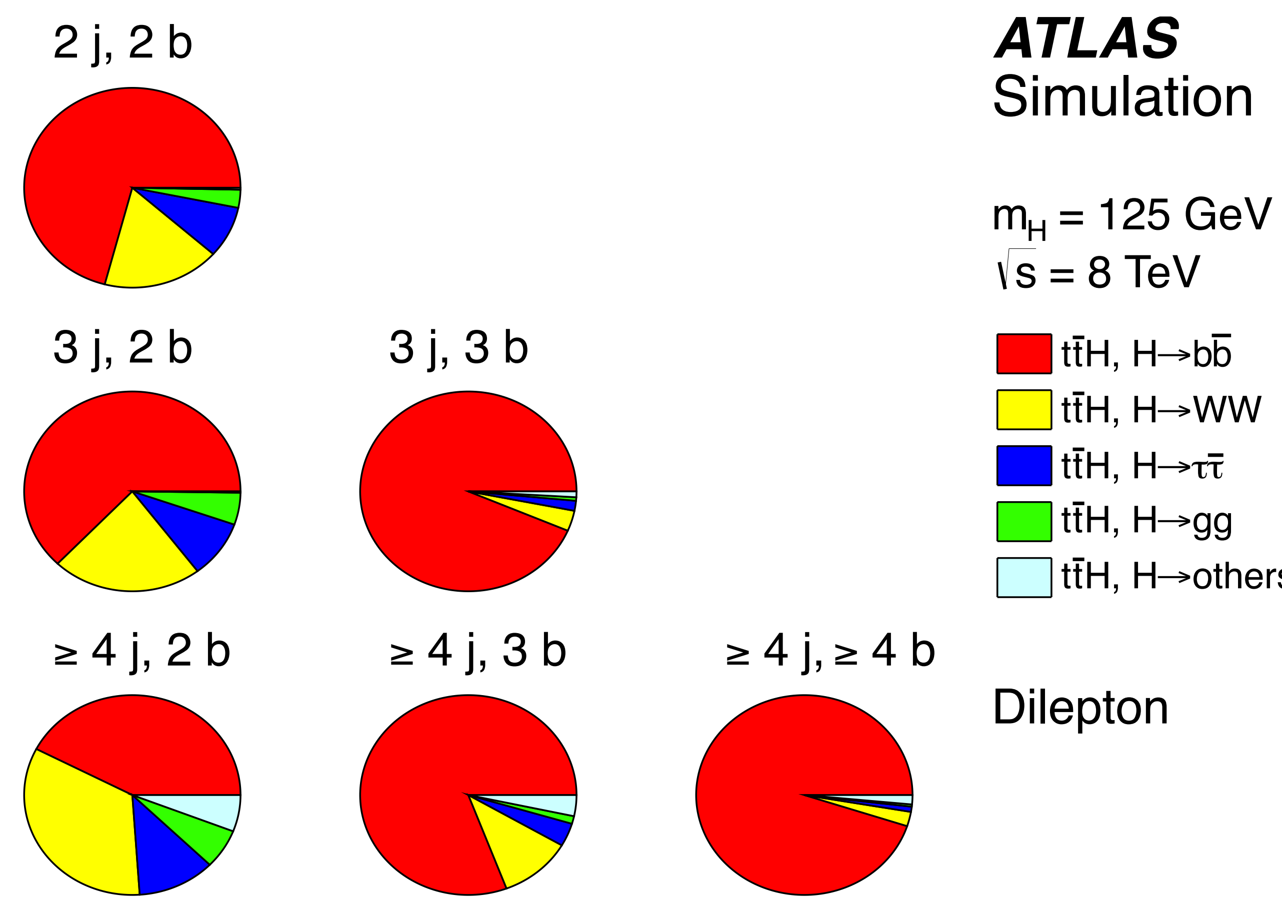
- Uncertainties
  - Cross section uncertainty: ~6%
  - 2 xsec uncertainties on tt+hf, uncorrelated for tt+bb, cc: 50%
  - 3 uncorrelated uncertainties for PS (PowHeg+Pythia vs PowHeg +Herwig), uncorrelated for tt+lf, bb, cc
- tt+lf and tt+cc: corrections on top and ttbar p_T differential xsec
  - 9 uncertainties from method, correlated tt+lf and tt+cc
  - 2 uncorrelated uncertainties for full difference w/wo rewgt: tt+cc
  - 4 uncertainties on tt+cc
    - 3 MadGraph uncertainties: factor+renorm scale, matching, c mass
    - 1 generator uncertainty: MadGraph+Pythia vs Powheg+Pythia
- tt+bb: 8 uncertainties on NLO shape
  - 3 scale variation uncertainties: factor, renorm, resummation
  - Shower recoil method (1), PDF choice (2), MPI & FSR in SherpaOL (2)

Event yields (post-fit)

Single lepton



Dilepton



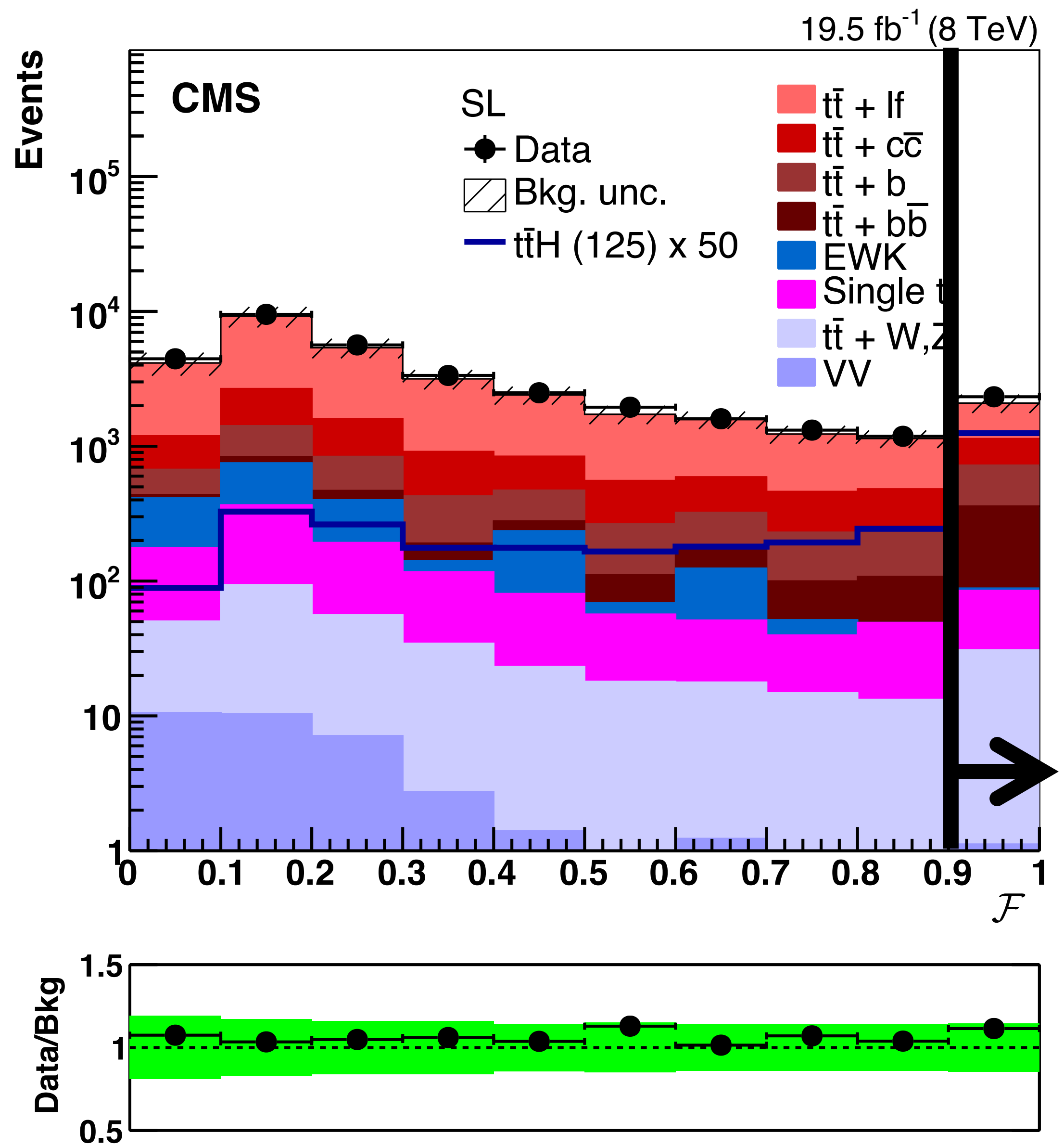
MVA input variables (single lepton)

Variable	Definition	NN rank			
		$\geq$ 6j, $\geq$ 4b	$\geq$ 6j, 3b	5j, $\geq$ 4b	5j, 3b
$D1$	Neyman–Pearson MEM discriminant (Eq. (4))	1	10	-	-
Centrality	Scalar sum of the p_{T} divided by sum of the E for all jets and the lepton	2	2	1	-
$p_{\mathrm{T}}^{\mathrm{jet5}}$	p_{T} of the fifth leading jet	3	7	-	-
$H1$	Second Fox–Wolfram moment computed using all jets and the lepton	4	3	2	-
$\Delta R_{\mathrm{bb}}^{\mathrm{avg}}$	Average ΔR for all b-tagged jet pairs	5	6	5	-
SSLL	Logarithm of the summed signal likelihoods (Eq. (2))	6	4	-	-
$m_{\mathrm{bb}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of the two b-tagged jets with the smallest ΔR	7	12	4	4
$m_{\mathrm{bj}}^{\mathrm{max}\ p_{\mathrm{T}}}$	Mass of the combination of a b-tagged jet and any jet with the largest vector sum p_{T}	8	8	-	-
$\Delta R_{\mathrm{bb}}^{\mathrm{max}\ p_{\mathrm{T}}}$	ΔR between the two b-tagged jets with the largest vector sum p_{T}	9	-	-	-
$\Delta R_{\mathrm{lep-bb}}^{\mathrm{min}\ \Delta\mathrm{R}}$	ΔR between the lepton and the combination of the two b-tagged jets with the smallest ΔR	10	11	10	-
$m_{\mathrm{uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of the two untagged jets with the smallest ΔR	11	9	-	2
$\mathrm{Aplan}_{b-\mathrm{jet}}$	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor[92] built with only b-tagged jets	12	-	8	-
N_{40}^{jet}	Number of jets with $p_{\mathrm{T}} \geq 40GeV$	-	1	3	-
$m_{\mathrm{bj}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of a b-tagged jet and any jet with the smallest ΔR	-	5	-	-
$m_{\mathrm{jj}}^{\mathrm{max}\ p_{\mathrm{T}}}$	Mass of the combination of any two jets with the largest vector sum p_{T}	-	-	6	-
$H_{\mathrm{T}}^{\mathrm{had}}$	Scalar sum of jet p_{T}	-	-	7	-
$m_{\mathrm{jj}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of any two jets with the smallest ΔR	-	-	9	-
$m_{\mathrm{bb}}^{\mathrm{max}\ p_{\mathrm{T}}}$	Mass of the combination of the two b-tagged jets with the largest vector sum p_{T}	-	-	-	1
$p_{\mathrm{T,uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Scalar sum of the p_{T} of the pair of untagged jets with the smallest ΔR	-	-	-	3
$m_{\mathrm{bb}}^{\mathrm{max}\ \mathrm{m}}$	Mass of the combination of the two b-tagged jets with the largest invariant mass	-	-	-	5
$\Delta R_{\mathrm{uu}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Minimum ΔR between the two untagged jets	-	-	-	6
m_{jjj}	Mass of the jet triplet with the largest vector sum p_{T}	-	-	-	7

MVA input variables (dilepton)

Variable	Definition	NN rank		
		$\geq$ 4j, $\geq$ 4b	$\geq$ 4j, 3b	3j, 3b
$\Delta\eta_{\mathrm{jj}}^{\mathrm{max}\ \Delta\eta}$	Maximum $\Delta\eta$ between any two jets in the event	1	1	1
$m_{\mathrm{bb}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Mass of the combination of the two b-tagged jets with the smallest ΔR	2	8	-
$m_{b\bar{b}}$	Mass of the two b-tagged jets from the Higgs candidate system	3	-	-
$\Delta R_{\mathrm{hl}}^{\mathrm{min}\ \Delta\mathrm{R}}$	ΔR between the Higgs candidate and the closest lepton	4	5	-
$\mathrm{N}_{30}^{\mathrm{Higgs}}$	Number of Higgs candidates within 30 GeV of the Higgs mass of 125 GeV	5	2	5
$\Delta R_{\mathrm{bb}}^{\mathrm{max}\ p_{\mathrm{T}}}$	ΔR between the two b-tagged jets with the largest vector sum p_{T}	6	4	8
$\mathrm{Aplan}_{\mathrm{jet}}$	$1.5\lambda_2$, where λ_2 is the second eigenvalue of the momentum tensor built with all jets	7	7	-
$m_{\mathrm{jj}}^{\mathrm{min}\ \mathrm{m}}$	Minimum dijet mass between any two jets	8	3	2
$\Delta R_{\mathrm{hl}}^{\mathrm{max}\ \Delta\mathrm{R}}$	ΔR between the Higgs candidate and the furthest lepton	9	-	-
$m_{\mathrm{jj}}^{\mathrm{closest}}$	Dijet mass between any two jets closest to the Higgs mass of 125 GeV	10	-	10
H_{T}	Scalar sum of jet p_{T} and lepton p_{T} values	-	6	3
$\Delta R_{\mathrm{bb}}^{\mathrm{max}\ \mathrm{m}}$	ΔR between the two b-tagged jets with the largest invariant mass	-	9	-
$\Delta R_{\mathrm{lj}}^{\mathrm{min}\ \Delta\mathrm{R}}$	Minimum ΔR between any lepton and jet	-	10	-
Centrality	Sum of the p_{T} divided by sum of the E for all jets and both leptons	-	-	7
$m_{\mathrm{jj}}^{\mathrm{max}\ p_{\mathrm{T}}}$	Mass of the combination of any two jets with the largest vector sum p_{T}	-	-	9
$H4$	Fifth Fox–Wolfram moment computed using all jets and both leptons	-	-	4
$p_{\mathrm{T}}^{\mathrm{jet3}}$	p_{T} of the third leading jet	-	-	6

CMS ttH Hbb MEM



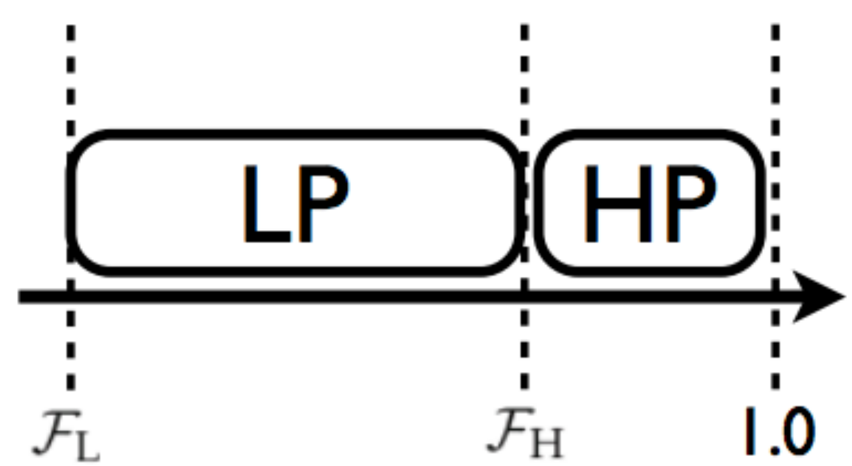
- Select SL and DL events
- **Assign events a b-tag likelihood**
  - **Based on b-tag value of jets**
  - **Separate into low- and high-purity categories**

heavy flavor jet b-tag pdf

light flavor jet b-tag pdf

$$f(\xi|t\bar{t}+\mathrm{hf}) = \sum_{i_1}\sum_{i_2\neq i_1}\cdots\sum_{i_6\neq i_1,\ldots,i_5}\left\{\prod_{k\in\{i_1,i_2,i_3,i_4\}} f_{\mathrm{hf}}(\xi_k)\prod_{m\in\{i_5,i_6\}} f_{\mathrm{lf}}(\xi_m)\right\}$$

$$\mathcal{F}(\xi) = \frac{f(\xi|t\bar{t}+\mathrm{hf})}{f(\xi|t\bar{t}+\mathrm{hf}) + f(\xi|t\bar{t}+\mathrm{lf})}$$



Channels and signatures

H decay	Top pair decay	Trigger	Selection
bb	semileptonic ℓνqqbb	Single lepton p_T > 27 (e) GeV p_T > 24 (μ) GeV	1 e/μ p_T > 30 GeV ≥4 jets, ≥2 b-jets, p_T > 30 GeV **Nsig ~ 90, S/B ~ 0.004**
bb	dileptonic ℓνℓνbb	Double lepton p_T > 17,8 GeV	1 e/μ p_T > 20 GeV 1 e/μ p_T > 10 GeV ≥3 jets, ≥2 b-jets, p_T > 30 GeV **Nsig ~ 30, S/B ~ 0.002**
$\tau_h\tau_h$	semileptonic ℓνqqbb	Single lepton p_T > 27 (e) GeV p_T > 24 (μ) GeV	1 e/μ p_T > 30 GeV 2 τ_h p_T > 30 GeV ≥4 jets, ≥1 b-jets, p_T > 30 GeV **Nsig ~ 2, S/B ~ 0.003**

Event yield (single lepton)

	$\geq$6 jets + 2 b-tags	4 jets + 3 b-tags	5 jets + 3 b-tags	$\geq$6 jets + 3 b-tags	4 jets + 4 b-tags	5 jets + $\geq$4 b-tags	$\geq$6 jets + $\geq$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

Event yield (dilepton)

	3 jets + 2 b-tags	$\geq$4 jets + 2 b-tags	$\geq$3 b-tags
$t\bar{t}H(125.6\,\mathrm{GeV})$	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

Systematics

Source	Shape	Remarks
Luminosity	No	Signal and all backgrounds
Lepton ID/Trigger efficiency	No	Signal and all backgrounds
Pileup	No	Signal and all backgrounds
Top p_{T} reweighting	Yes	Only $\mathrm{t\bar{t}}$ background
Jet Energy Resolution	No	Signal and all backgrounds
Jet Energy Scale	Yes	Signal and all backgrounds
b-Tag bottom-flavor contamination	Yes	Signal and all backgrounds
b-Tag bottom-flavor statistics (linear)	Yes	Signal and all backgrounds
b-Tag bottom-flavor statistics (quadratic)	Yes	Signal and all backgrounds
b-Tag light-flavor contamination	Yes	Signal and all backgrounds
b-Tag light-flavor statistics (linear)	Yes	Signal and all backgrounds
b-Tag light-flavor statistics (quadratic)	Yes	Signal and all backgrounds
b-Tag Charm uncertainty (linear)	Yes	Signal and all backgrounds
b-Tag Charm uncertainty (quadratic)	Yes	Signal and all backgrounds
QCD Scale ($\mathrm{t\bar{t}H}$)	No	Scale uncertainty for NLO $\mathrm{t\bar{t}H}$ prediction
QCD Scale ($\mathrm{t\bar{t}}$)	No	Scale uncertainty for NLO $\mathrm{t\bar{t}}$ and single top predictions
QCD Scale (V)	No	Scale uncertainty for NNLO W and Z prediction
QCD Scale (VV)	No	Scale uncertainty for NLO diboson prediction
PDF (gg)	No	Parton distribution function (PDF) uncertainty for gg initiated processes ($\mathrm{t\bar{t}}$, $\mathrm{t\bar{t}Z}$, $\mathrm{t\bar{t}H}$)
PDF ($\mathrm{q\bar{q}}$)	No	PDF uncertainty for $\mathrm{q\bar{q}}$ initiated processes ($\mathrm{t\bar{t}W}$, W, Z).
PDF (qg)	No	PDF uncertainty for qg initiated processes (single top)
Madgraph Q^2 Scale ($\mathrm{t\bar{t}}$+0p,1p,2p)	Yes	Madgraph Q^2 scale uncertainty for $\mathrm{t\bar{t}}$+jets split by parton number. There is one nuisance parameter per parton multiplicity and they are uncorrelated.
Madgraph Q^2 Scale ($\mathrm{t\bar{t}}$+b/$\mathrm{b\bar{b}}$/$\mathrm{c\bar{c}}$)	Yes	Madgraph Q^2 scale uncertainty for $\mathrm{t\bar{t}}$+b/$\mathrm{b\bar{b}}$/$\mathrm{c\bar{c}}$.
Madgraph Q^2 Scale (V)	No	Varies by jet bin.
Extra $\mathrm{t\bar{t}}$+hf rate uncertainty	No	A 50% uncertainty in the rate of $\mathrm{t\bar{t}}$+b, $\mathrm{t\bar{t}} + \mathrm{b\bar{b}}$, $\mathrm{t\bar{t}} + \mathrm{c\bar{c}}$.
τ Energy Scale	Yes	Tau signal and background
τ ID efficiency	Yes	Tau signal and background
τ Jet Fake Rate	Yes	Tau signal and background
τ Electron Fake Rate	Yes	Tau signal and background

Systematics

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

Input variables

Variable	Description
abs $\Delta\eta$ (leptonic top, bb)	Delta-R between the leptonic top reconstructed by the best Higgs mass algorithm and the b-jet pair chosen by the algorithm
abs $\Delta\eta$ (hadronic top, bb)	Delta-R between the hadronic top reconstructed by the best Higgs mass algorithm and the b-jet pair chosen by the algorithm
aplanarity	Event shape variable equal to $\frac{3}{2}(\lambda_3)$, where λ_3 is the third eigenvalue of the sphericity tensor as described in [31].
ave CSV (tags/non-tags)	Average b-tag discriminant value for b-tagged/non-b-tagged jets
ave ΔR(tag,tag)	Average ΔR between b-tagged jets
best Higgs boson mass	A minimum-chi-squared fit to event kinematics is used to select two b-tagged jets as top-decay products. Of the remaining b-tags, the invariant mass of the two with highest E_t is saved.
best ΔR(b,b)	The ΔR between the two b-jets chosen by the best Higgs boson mass algorithm
closest tagged dijet mass	The invariant mass of the two b-tagged jets that are closest in ΔR
dev from ave CSV (tags)	The square of the difference between the b-tag discriminant value of a given b-tagged jet and the average b-tag discriminant value among b-tagged jets, summed over all b-tagged jets
highest CSV (tags)	Highest b-tag discriminant value among b-tagged jets
H_0, H_1, H_2, H_3	The first few Fox-Wolfram moments [32] (event shape variables)
HT	Scalar sum of transverse momentum for all jets with $p_T > 30$ GeV/c
$\sum p_T$(jets,leptons,MET)	The sum of the p_T of all jets, leptons, and MET
$\sum p_T$(jets,leptons)	The sum of the p_T of all jets, leptons
jet 1, 2, 3, 4 p_T	The transverse momentum of a given jet, where the jet numbers correspond to rank by p_T
lowest CSV (tags)	Lowest b-tag discriminant value among b-tagged jets
mass(lepton,jet,MET)	The invariant mass of the 4-vector sum of all jets, leptons, and MET
mass(lepton,closest tag)	The invariant mass of the lepton and the closest b-tagged jet in ΔR (LJ channel)
max $\Delta\eta$ (jet, ave jet η)	max difference between jet eta and avg deta between jets
max $\Delta\eta$ (tag, ave jet η)	max difference between tag eta and avg deta between jets
max $\Delta\eta$ (tag, ave tag η)	max difference between tag eta and avg deta between tags
median inv. mass (tag pairs)	median invariant mass of all combinations of b-tag pairs
M3	The invariant mass of the 3-jet system with the largest transverse momentum.
MHT	Vector sum of transverse momentum for all jets with $p_T > 30$ GeV/c
MET	Missing transverse energy
min ΔR(lepton,jet)	The ΔR between the lepton and the closest jet (LJ channel)
HiggsLike dijet mass(2)	the invariant mass of a jet pair(at least one is b-tagged) ordered in closeness to a Higgs boson mass (DIL channel)
number of HiggsLike dijet 15	number of jet pairs(at least one is b-tagged) whose invariant mass is within 15 GeV window of a Higgs boson mass (DIL channel)
min ΔR(tag,tag)	The ΔR between the two closest b-tagged jets
min ΔR(jet,jet)	The ΔR between the two closest jets
$\sqrt{\Delta\eta(t^{lep},bb)\times\Delta\eta(t^{had},bb)}$	square root of the product of abs $\Delta\eta$ (leptonic top, bb) and abs $\Delta\eta$ (hadronic top, bb)
second-highest CSV (tags)	Second-highest b-tag discriminant value among b-tagged jets
sphericity	Event shape variable equal to $\frac{3}{2}(\lambda_2+\lambda_3)$, where λ_2 and λ_3 are the second and third eigenvalues of the sphericity tensor as described in [31]
(Σ jet p_T)/(Σ jet E)	The ratio of the sum of the transverse momentum of all jets and the sum of the energy of all jets
tagged dijet mass closest to 125	The invariant mass of the b-tagged pair closest to 125 GeV/c^2
$t\bar{t}b\bar{b}/t\bar{t}H$ BDT	BDT used to discriminate between $t\bar{t}b\bar{b}$ and $t\bar{t}H$ in the LJ ≥ 6 jets, ≥ 4 tags, $\geq$6 jets + 3 tags, and 5 jets + $\geq$4 tags categories. See text for description and table 15 for list of variables

Input variables (ttH vs tt+jets)

	4 jets, 3 b-tags	4 jets, 4 b-tags
	jet 1 p_{T}	jet 1 p_{T}
	jet 2 p_{T}	jet 2 p_{T}
	jet 3 p_{T}	jet 4 p_{T}
	jet 4 p_{T}	HT
	M3	$\sum p_{\mathrm{T}}$(jets,lepton,MET)
	$\sum p_{\mathrm{T}}$(jets,lepton,MET)	M3
	HT	ave CSV (tags)
	lowest CSV (tags)	second-highest CSV (tags)
	MHT	third-highest CSV (tags)
	MET	lowest CSV (tags)
	5 jets, 3 b-tags	5 jets, $\geq$ 4 b-tags
	jet 1 p_T	max $\Delta\eta$ (tag, ave jet η)
	jet 2 p_T	$\sum p_T$(jets,lepton,MET)
	jet 3 p_T	(Σ jet p_T)/(Σ jet E)
	jet 4 p_T	ave ΔR(tag,tag)
	$\sum p_T$(jets,lepton,MET)	ave CSV (tags)
	(Σ jet p_T)/(Σ jet E)	dev from ave CSV (tags)
	HT	second-highest CSV (tags)
	ave CSV (tags)	third-highest CSV (tags)
	third-highest CSV (tags)	lowest CSV (tags)
	fourth-highest CSV (jets)	ttbb/ttH BDT
$\geq$ 6 jets, 2 tags	$\geq$ 6 jets, 3 tags	$\geq$ 6 jets, $\geq$ 4 tags
$\sum p_T$(jets,lepton,MET)	H_0	(Σ jet p_T)/(Σ jet E)
HT	sphericity	ave ΔR(tag,tag)
mass(lepton,closest tag)	(Σ jet p_T)/(Σ jet E)	product($\Delta\eta$(leptonic top, bb), $\Delta\eta$(hadronic top, bb))
max $\Delta\eta$ (jet, ave jet η)	max $\Delta\eta$ (jet, ave jet η)	closest tag mass
min ΔR(lepton,jet)	$\sum p_T$(jets,lepton,MET)	max $\Delta\eta$ (tag, ave tag η)
H_2	ave CSV (tags)	ave CSV (tags)
sphericity	second-highest CSV (tags)	third-highest CSV (tags)
(Σ jet p_T)/(Σ jet E)	third-highest CSV (tags)	fourth-highest CSV (tags)
third-highest CSV (jets)	fourth-highest CSV (jets)	best Higgs boson mass
fourth-highest CSV (jets)	ttbb/ttH BDT	ttbb/ttH BDT

Input variables (ttH vs ttbb)

5 jets, ≥ 4 tags	≥ 6 jets, 3 tags	≥ 6 jets, ≥ 4 tags
ave ΔR(tag,tag)	tagged dijet mass closest to 125	H_3
max $\Delta\eta$ (tag, ave tag η)	(Σ jet p_T)/(Σ jet E)	ave ΔR(tag,tag)
(Σ jet p_T)/(Σ jet E)	$\sqrt{\Delta\eta(t^{lep}, bb) \times \Delta\eta(t^{had}, bb)}$	closest tagged dijet mass
tagged dijet mass closest to 125	H_1	sphericity
H_1	H_3	max $\Delta\eta$ (tag, ave jet η)
H_3	M3	max $\Delta\eta$ (tag, ave tag η)
$\sum p_T$(jets,lepton,MET)	max $\Delta\eta$ (tag, ave tag η)	mass(lepton,jet,MET)
fourth-highest CSV (tags)	max $\Delta\eta$ (tag, ave jet η)	(Σ jet p_T)/(Σ jet E)
aplanarity	max $\Delta\eta$ (jet, ave jet η)	abs $\Delta\eta$ (leptonic top, bb)
MET	abs $\Delta\eta$ (hadronic top, bb)	abs $\Delta\eta$ (hadronic top, bb)
	abs $\Delta\eta$ (leptonic top, bb)	$\sqrt{\Delta\eta(t^{lep}, bb) \times \Delta\eta(t^{had}, bb)}$
	sphericity	ave CSV (tags)
	aplanarity	best ΔR(b,b)
	min ΔR(tag,tag)	best Higgs boson mass
	jet 3 p_T	median inv. mass (tag pairs)

Input variables (tHq)

Electric charge of b-quark jet from decay of top quark, multiplied by lepton's charge. The jet charge is defined as in Eq. (1) in Ref. [37], with $\kappa = 1$
ΔR between the two jets from decay of Higgs boson
ΔR between b-quark jet and W boson from decay $t \rightarrow bW$
ΔR between reconstructed top quark and Higgs boson
Pseudorapidity of recoil jet
Invariant mass of b-quark jet from decay of top quark and charged lepton
Mass of reconstructed Higgs boson
Pseudorapidity of the most forward jet from decay of H
Tranverse momentum of the softest jet from decay of H
Number of b-tagged jets among the two jets from decay of H
Boolean variable that equals 1 if the b-quark jet from decay of t is b-tagged, 0 otherwise
Relative H_T, $(p_T(t) + p_T(H))/H_T$

Input variables (tt+jets)

Difference of electric charges of b-quark jets from decays of t_{had} and t_{lep}, multiplied by lepton's charge
ΔR between the two light-flavor jets from decay of t_{had}
ΔR between b-quark jet and W boson from decay $t_{had} \to bW$
ΔR between b-quark jet and W boson from decay $t_{lep} \to bW$
Difference between masses of t_{had} and W from decay of t_{had}
Pseudorapidity of t_{had}
Invariant mass of b-quark jet from decay of t_{lep} and charged lepton
Mass of W from decay of t_{had}
Number of b-tagged jets among the two light-flavor jets from decay of t_{had}
Boolean variable that equals 1 if the b-quark jet from decay of t_{had} is b-tagged, 0 otherwise
Boolean variable that equals 1 if the b-quark jet from decay of t_{lep} is b-tagged, 0 otherwise
Transverse momentum of t_{had}
Transverse momentum of t_{lep}
Relative H_T, $(p_T(t_{had}) + p_T(t_{lep}))/H_T$
Sum of electric charges of the two light-flavor jets from decay of t_{had}, multiplied by lepton's charge

Input variables (tHq vs tt+jets)

Electric charge of the lepton
Pseudorapidity of the recoil jet
Number of b-tagged jets among the two jets from the Higgs boson decay
Transverse momentum of the Higgs boson
Transverse momentum of the recoil jet
ΔR between the two light-flavor jets from the decay of t_{had}
Mass of t_{had}
Number of b-tagged jets among the two light-flavor jets from the decay of t_{had}

Event yields

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

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

NT	Predicted	Observed	Ratio
3	1093.6 ± 1.9	1082.5 ± 8.9	0.990 ± 0.008
4	29.71 ± 0.45	28.16 ± 1.39	0.948 ± 0.049

Systematics

Process	pdf			QCD Scale			
	gg	$q\bar{q}$	qg	$t\bar{t}$	V	VV	$t\bar{t}H$
tHq			2%				
$t\bar{t}H$	9%						12.5%
$t\bar{t}$	2.6%			3%			
Single top			4.6%	2%			
W+jets		4.8%			1.3%		
Z+jets		4.2%			1.2%		
Dibosons						3.5%	

Systematics (MC approach)

Source	Type	impact as exclusive source on final limit [%]	improvement of final limit after removal [%]
JES	shape	17	3
JER	shape	< 1	< 1
BTag light flavor	shape	13	< 1
BTag heavy flavor	shape	17	< 1
Pile up	normalization	< 1	< 1
Unclustered energy	shape	3	1
Lepton efficiency	normalization	5	< 1
Luminosity	normalization	10	< 1
Cross section (PDF)	normalization	8	< 1
Cross section (Scale)	normalization	9	< 1
MC Bin-by-Bin unc.	shape	< 1	< 1
Q^2 scale ($tHq + t\bar{t}$)	shape	20	4
Matching	shape	2	2
Top p_T reweighting	shape	19	2
$t\bar{t}$ HF rates (b)	normalization	13	< 1
$t\bar{t}$ HF rates ($b\bar{b}$)	normalization	15	< 1
$t\bar{t}$ HF rates (c / $c\bar{c}$)	normalization	13	1

Systematics (data-driven approach)

Source	Type	impact as exclusive source on final limit [%]	improvement of final limit after removal [%]
JES	shape	< 1	< 1
JER	shape	< 1	< 1
BTag light flavor (MC)	shape	< 1	< 1
BTag heavy flavor (MC)	shape	6	3
Pile up	normalization	< 1	< 1
Unclustered energy	shape	< 1	< 1
Lepton efficiency	normalization	< 1	< 1
Luminosity	normalization	< 1	< 1
Cross section (PDF)	normalization	< 1	< 1
Cross section (Scale)	normalization	< 1	< 1
Q^2 scale (tHq)	shape	< 1	< 1
MC Bin-by-Bin unc.	shape	< 1	< 1
BTag light flavor (DD $t\bar{t}$)	shape	4	< 1
BTag heavy flavor (DD $t\bar{t}$)	shape	< 1	< 1
$t\bar{t}$ contamination	shape	9	16
Method bias	shape	9	3
Scale	shape	< 1	< 1
$t\bar{t}$ HF rates (b)	shape	12	3
$t\bar{t}$ HF rates ($b\bar{b}$)	shape	15	5
$t\bar{t}$ HF rates (c / $c\bar{c}$)	shape	< 1	< 1

Data-driven model

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

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

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

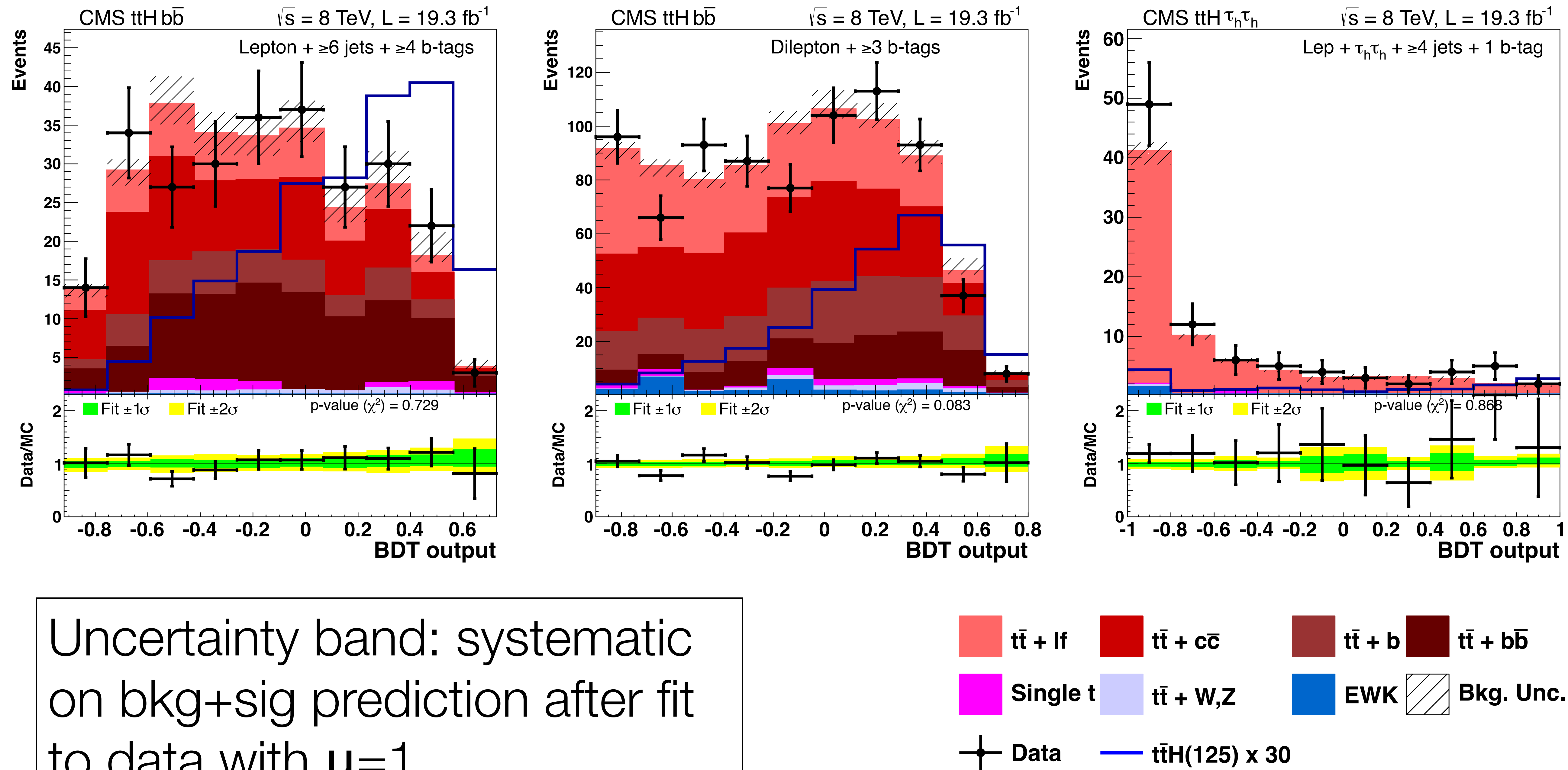
Signal discriminant

- Extract signal by fitting BDT discriminants

bb: lep+≥6 jets+≥4 b-jets

bb: 2 lep+≥3 b-jets

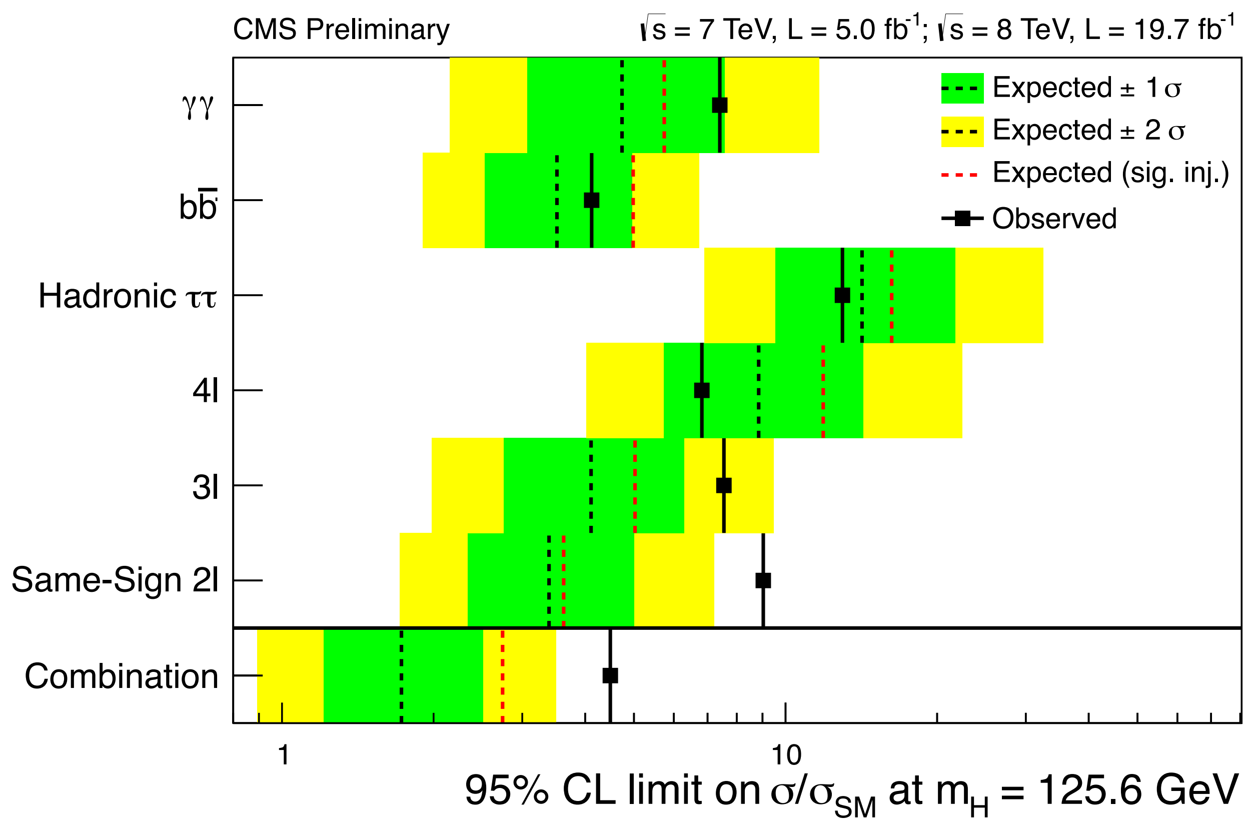
$\tau_h\tau_h$: lep+≥4 jets+1 b-jets

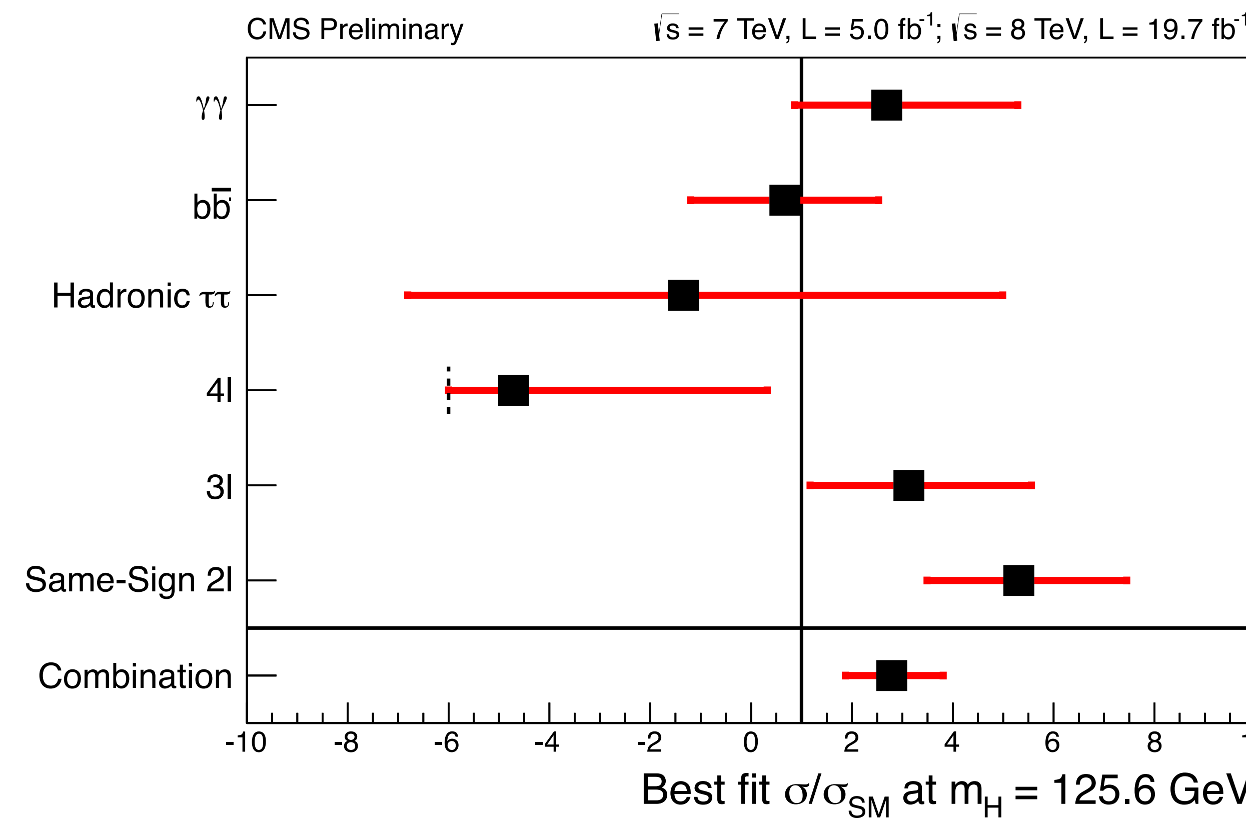


Uncertainty band: systematic on bkg+sig prediction after fit to data with μ=1

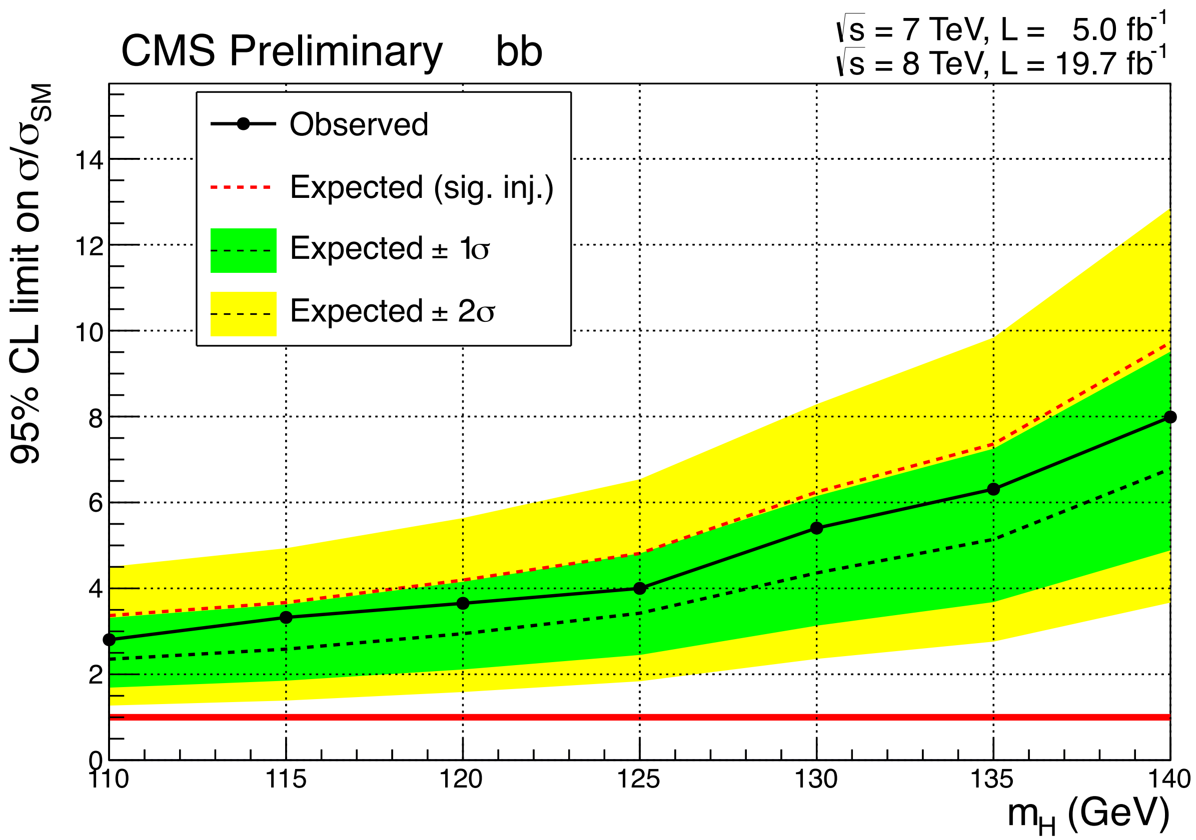
ttH combination results

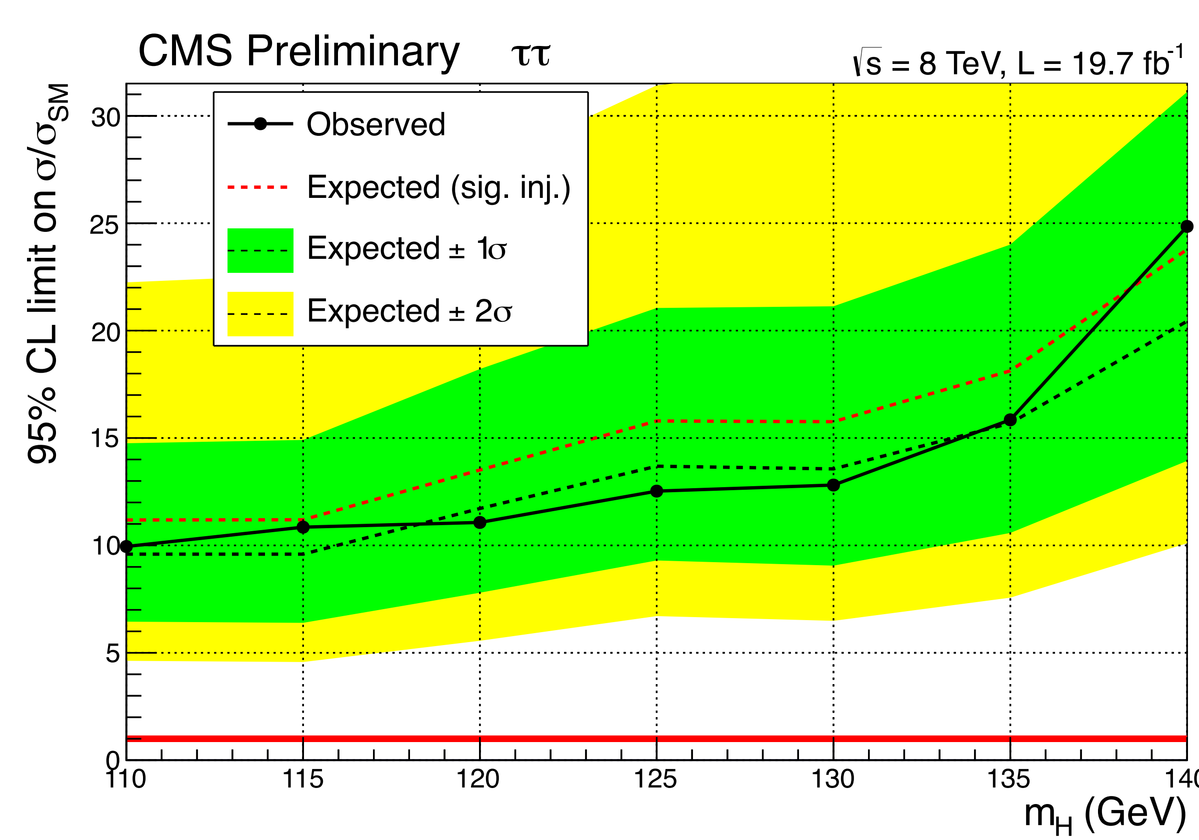
$t\bar{t}H$ channel	Best-fit μ	95% CL upper limits on $\mu = \sigma/\sigma_{SM}$ ($m_H = 125.6$ GeV)				
			Expected			
	Observed	Observed	Median signal-injected	Median	68% CL range	95% CL range
$\gamma\gamma$	$+2.7^{+2.6}_{-1.8}$	7.4	5.7	4.7	[3.1, 7.6]	[2.2, 11.7]
$b\bar{b}$	$+0.7^{+1.9}_{-1.9}$	4.1	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]

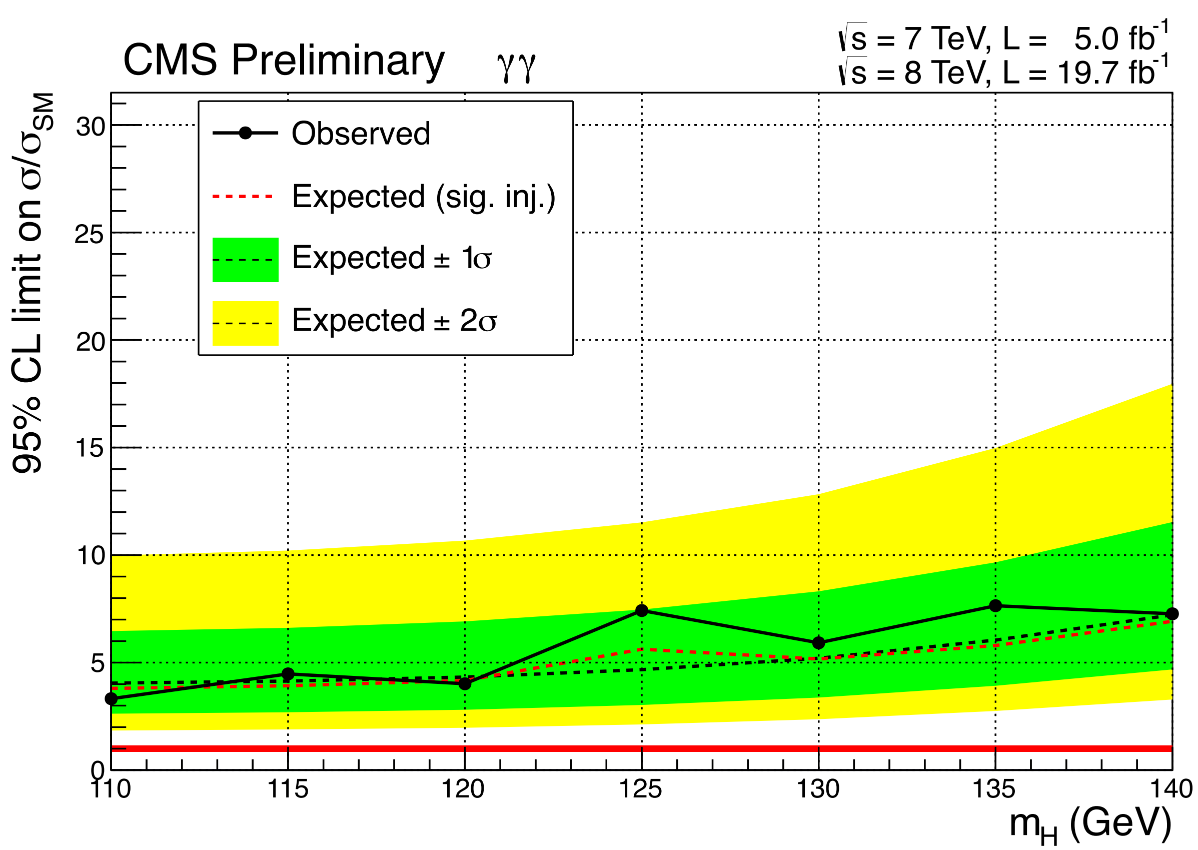


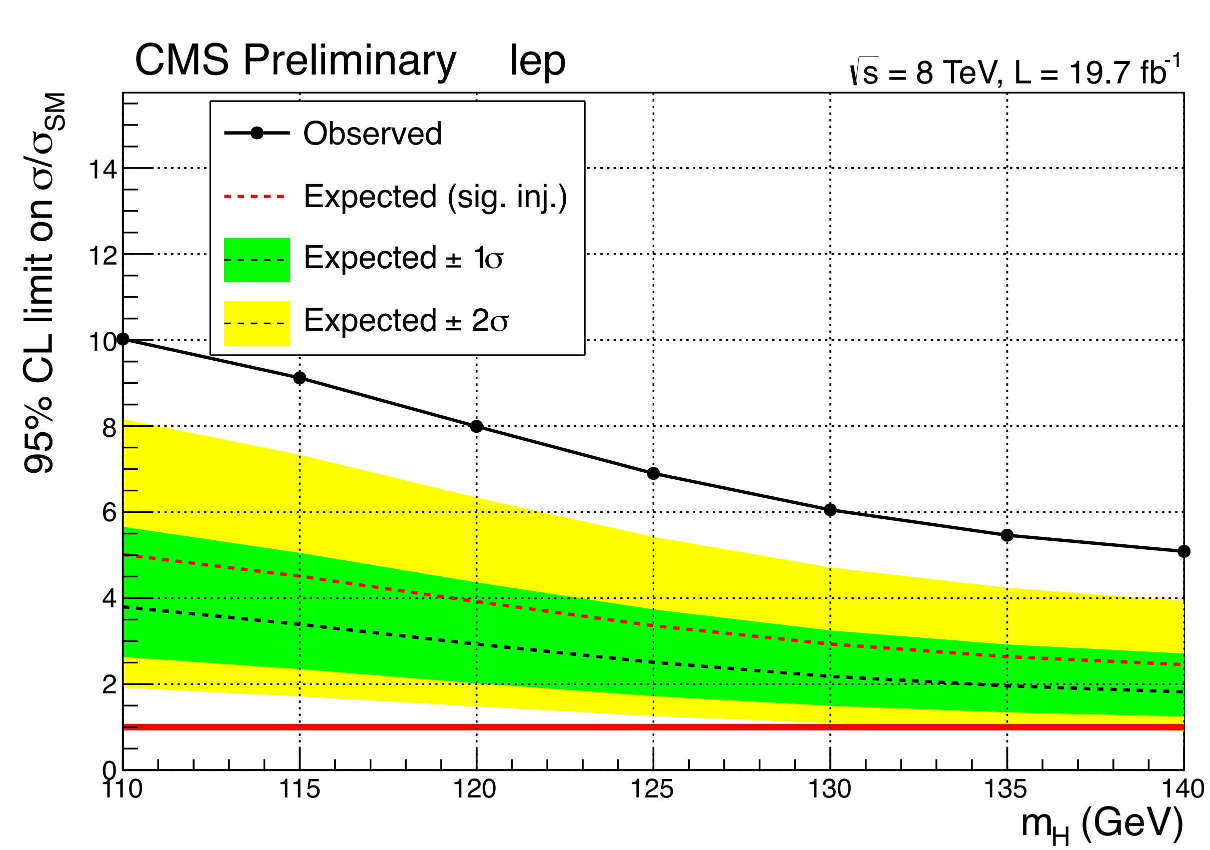


Limit vs mass for individual channels



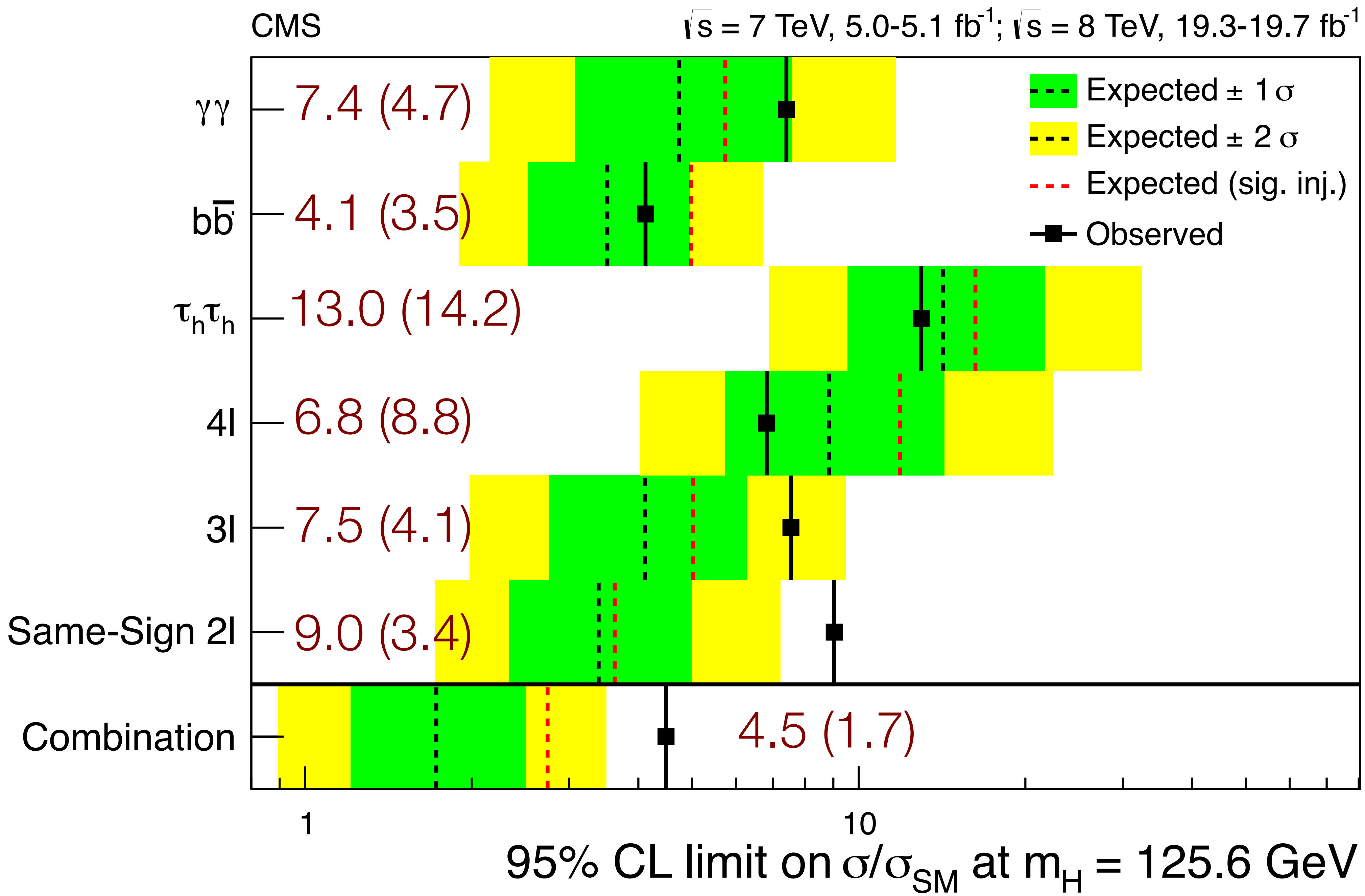






Limits: characterizing the absence of a signal

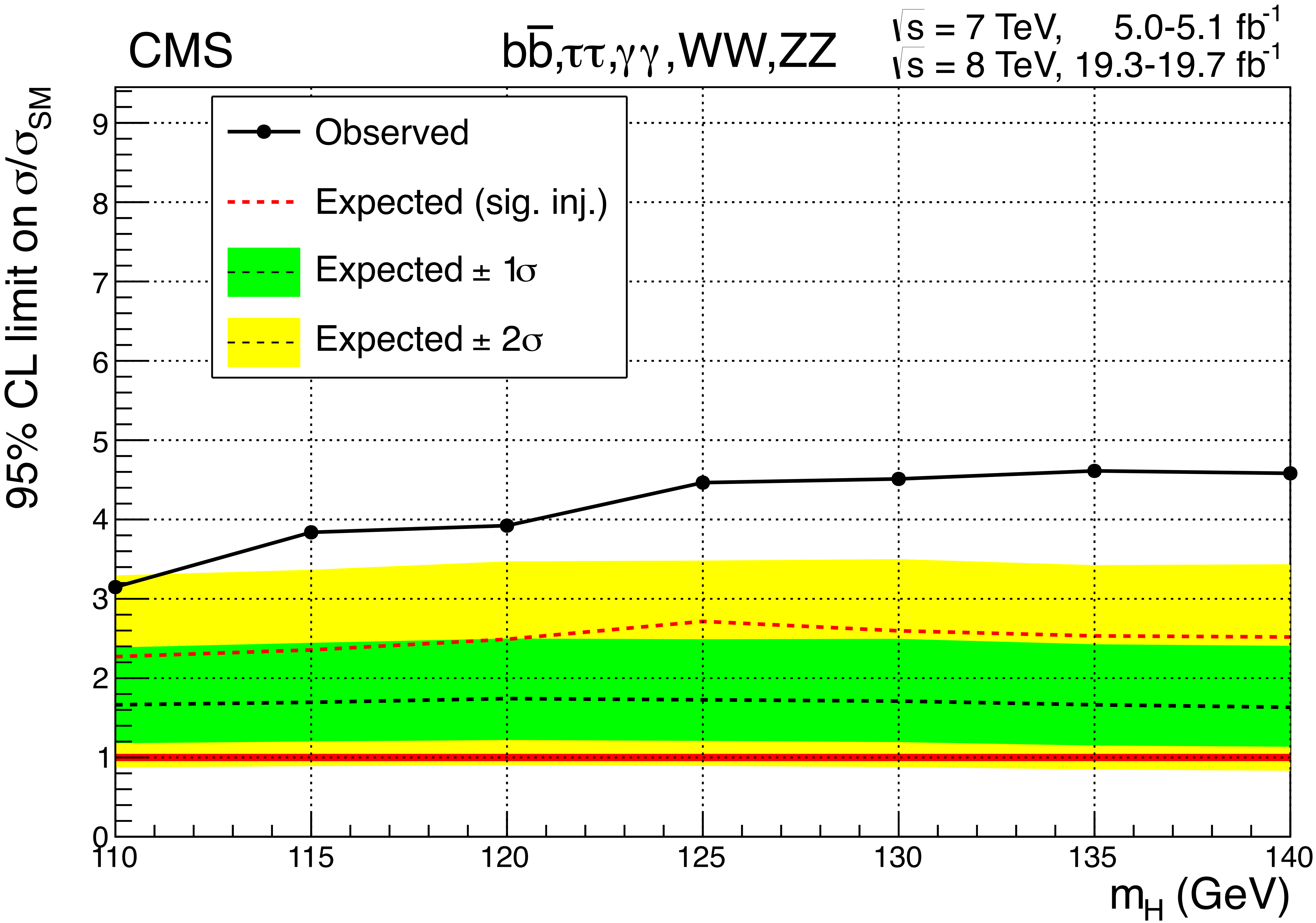
- Expectation for a SM Higgs with m_H = 125.6 GeV
  - Observed limits mainly driven by excess in SS μμ channel



Obs (exp) limit

Limits as a function of m_H

- Generalized excess over all masses



Signal strength, p-value

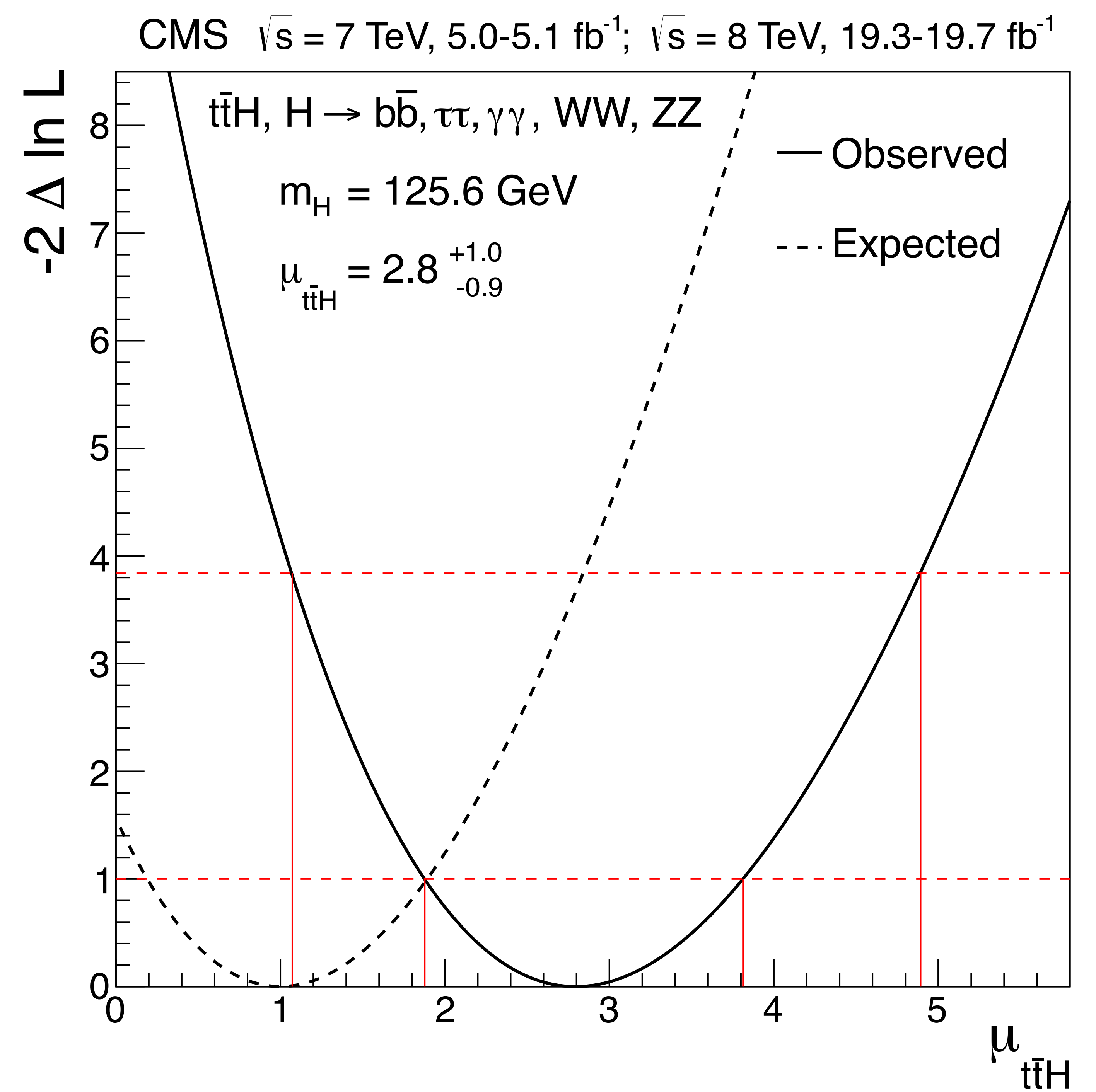
- All channels, m_H = 125.6 GeV

- Best-fit value

$$\hat{\mu} = 2.8^{+1.0}_{-0.9}$$

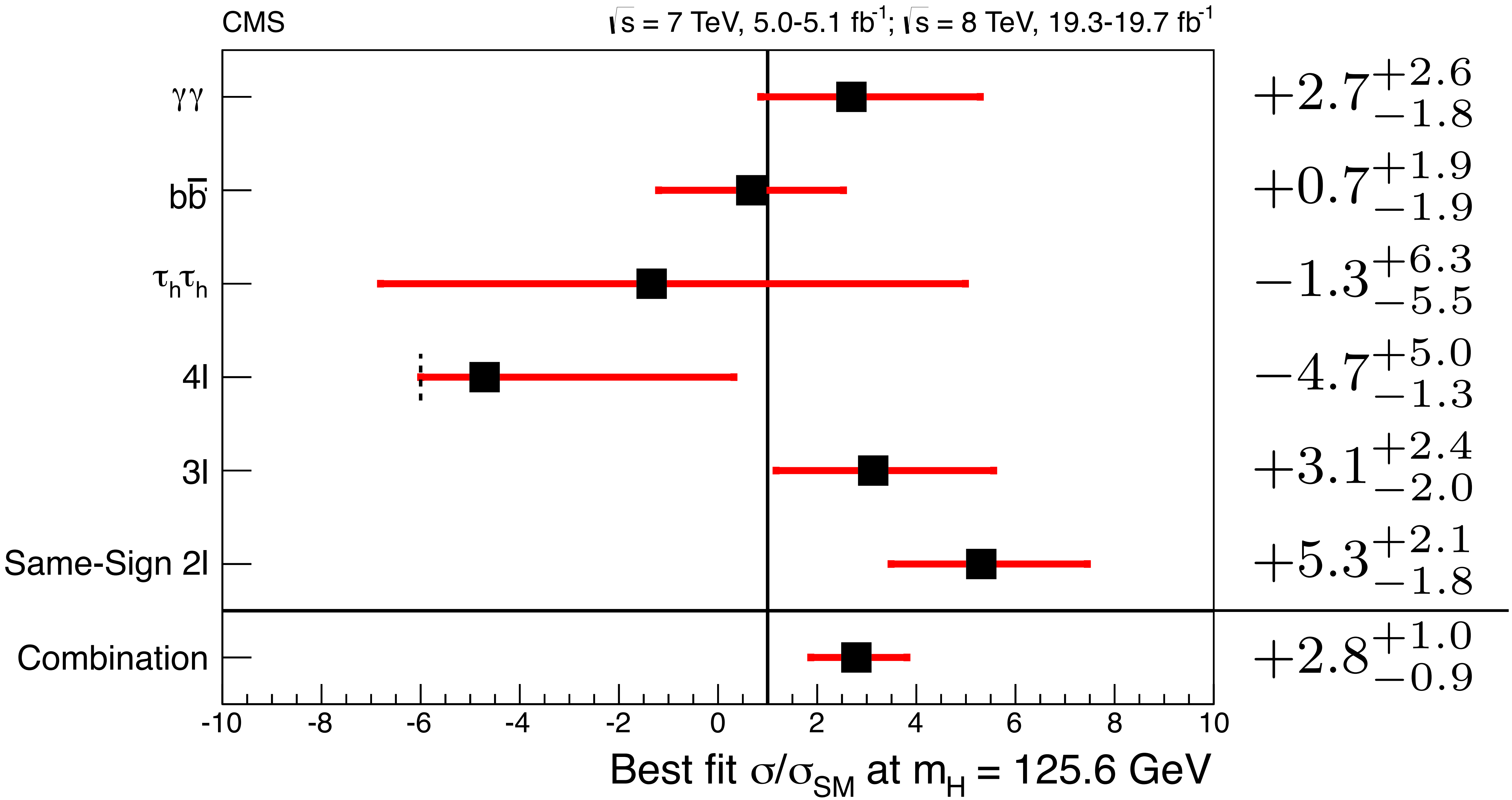
- Background fluctuation
  - p-value (μ=0) = 0.04%
  - Local significance = 3.4σ
    - Expected sig = 1.2σ

- Signal fluctuation
  - p-value (μ=1) = 2%

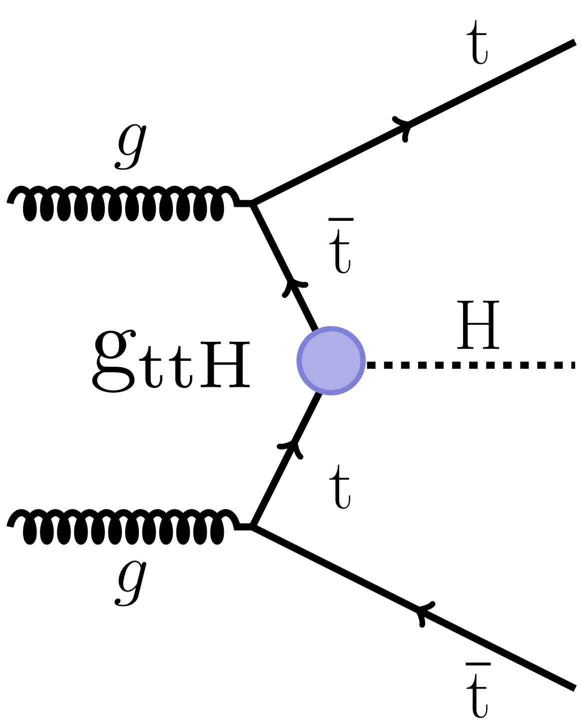


Signal strength compatibility

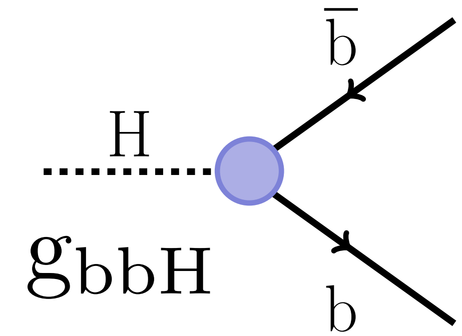
- Results in the six final states are consistent with a common signal strength at the **29% level compatibility**

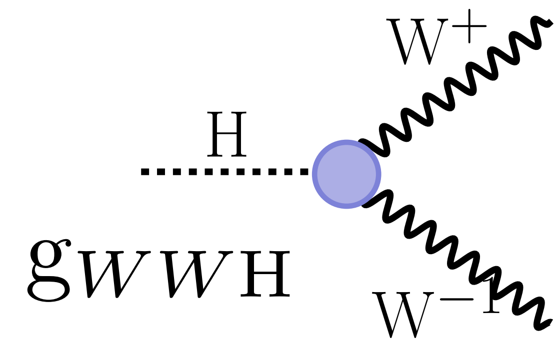


Coupling fit model



$$\kappa = \frac{g}{g_{\mathrm{SM}}}$$





$$\sigma \cdot BR(i \rightarrow \mathrm{H} \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_{\mathrm{H}}} \qquad \Gamma_{\mathrm{H}} << m_{\mathrm{H}}$$

Production xsec through initial state *i*: gg, qq

Partial decay width to the final state *f*

Total decay width

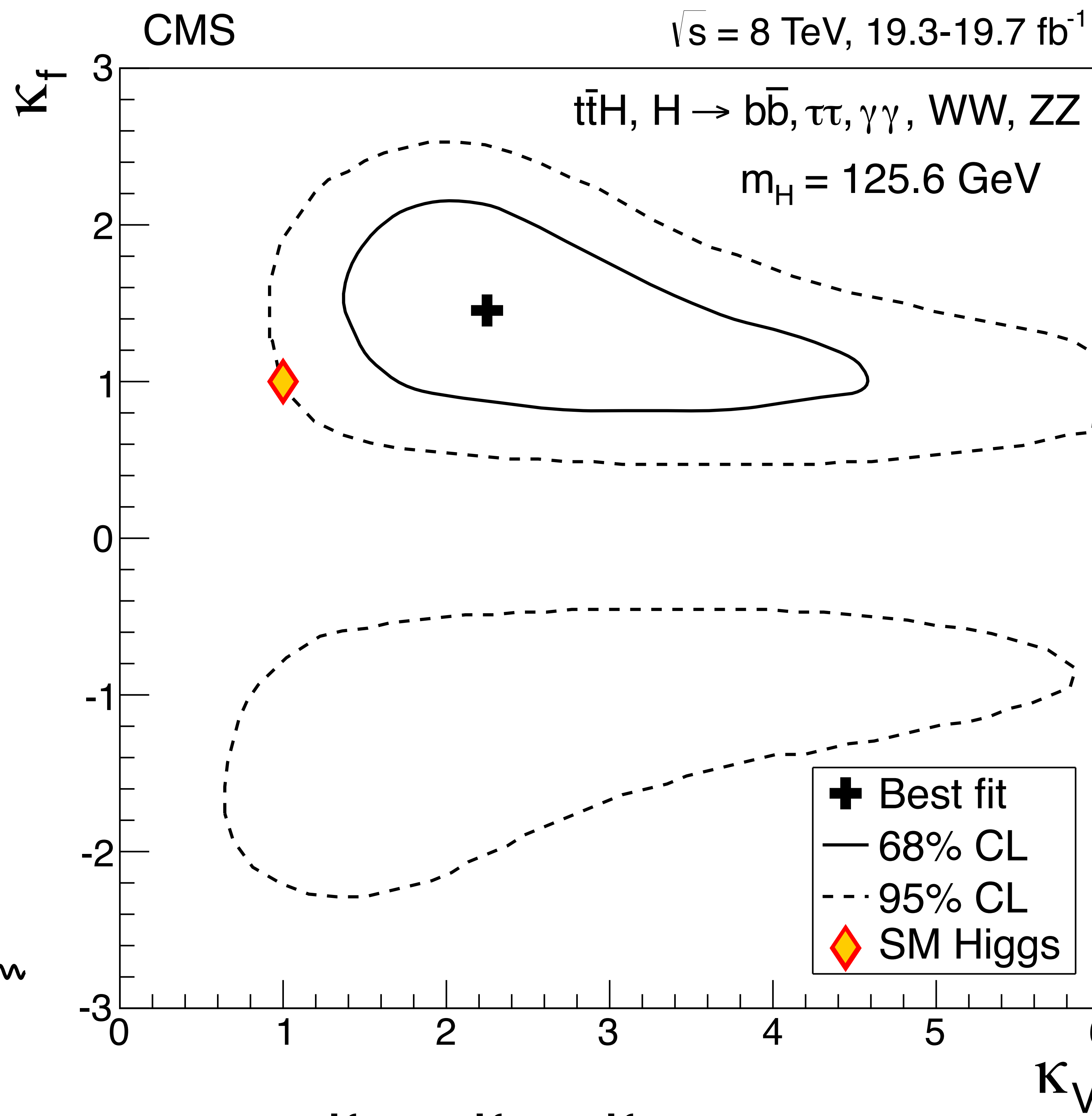
Coupling to fermions and vector bosons

2D scan of -2ΔlnL vs coupling modifiers of Higgs to vector bosons (κ_V) and fermions (κ_f), profiling all other nuisances

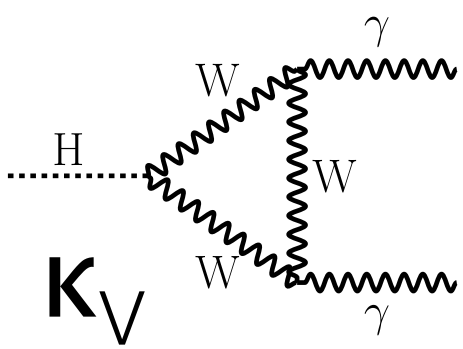
- Best-fit

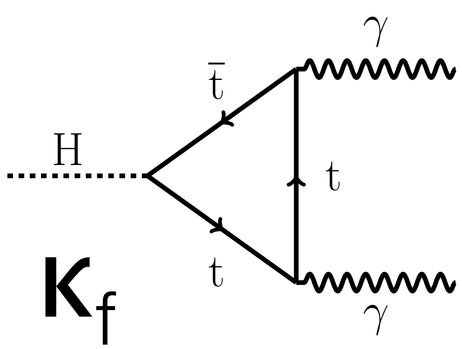
$$\kappa_V = 2.2$$
$$\kappa_f = 1.5$$

- Only H → γγ sensitive to sign of κ_V x κ_f
  - Take $\kappa_V > 0$



$$\kappa_W = \kappa_Z = \kappa_V$$
$$\kappa_t = \kappa_b = \kappa_\tau = \kappa_f$$





Statistical machinery

- Methodology developed by ATLAS and CMS collaborations
  - Done in the context of LHC Higgs Combination Group

- Build a **likelihood function** ~ probability of observed outcome

- What is the expected outcome?
  - Binned likelihood function (used for all but $\gamma\gamma$)

$$E[n_i] = \mu s_i + b_i$$

Statistical machinery

- Methodology developed by ATLAS and CMS collaborations
  - Done in the context of LHC Higgs Combination Group
- Build a **likelihood function** ~ probability of observed outcome
- What is the expected outcome?
  - Binned likelihood function (used for all but $\gamma\gamma$)

Signal — Background

$$E[n_i] = \mu s_i + b_i$$

Expected number of events

Signal strength modifier

$\mu \geq 0$

$\mu = 1$, SM ttH

$\mu = 0$, no ttH

The likelihood function

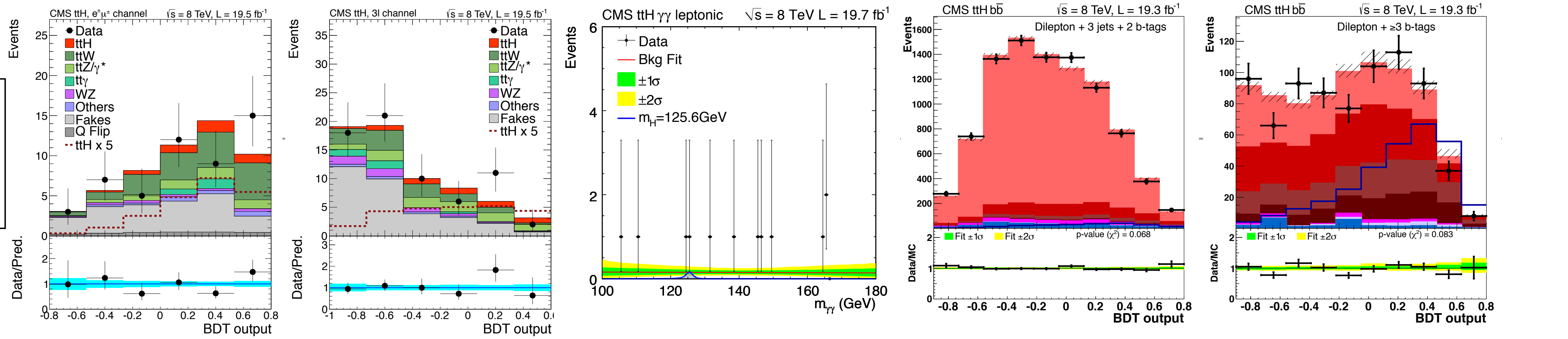
Poisson probabilities

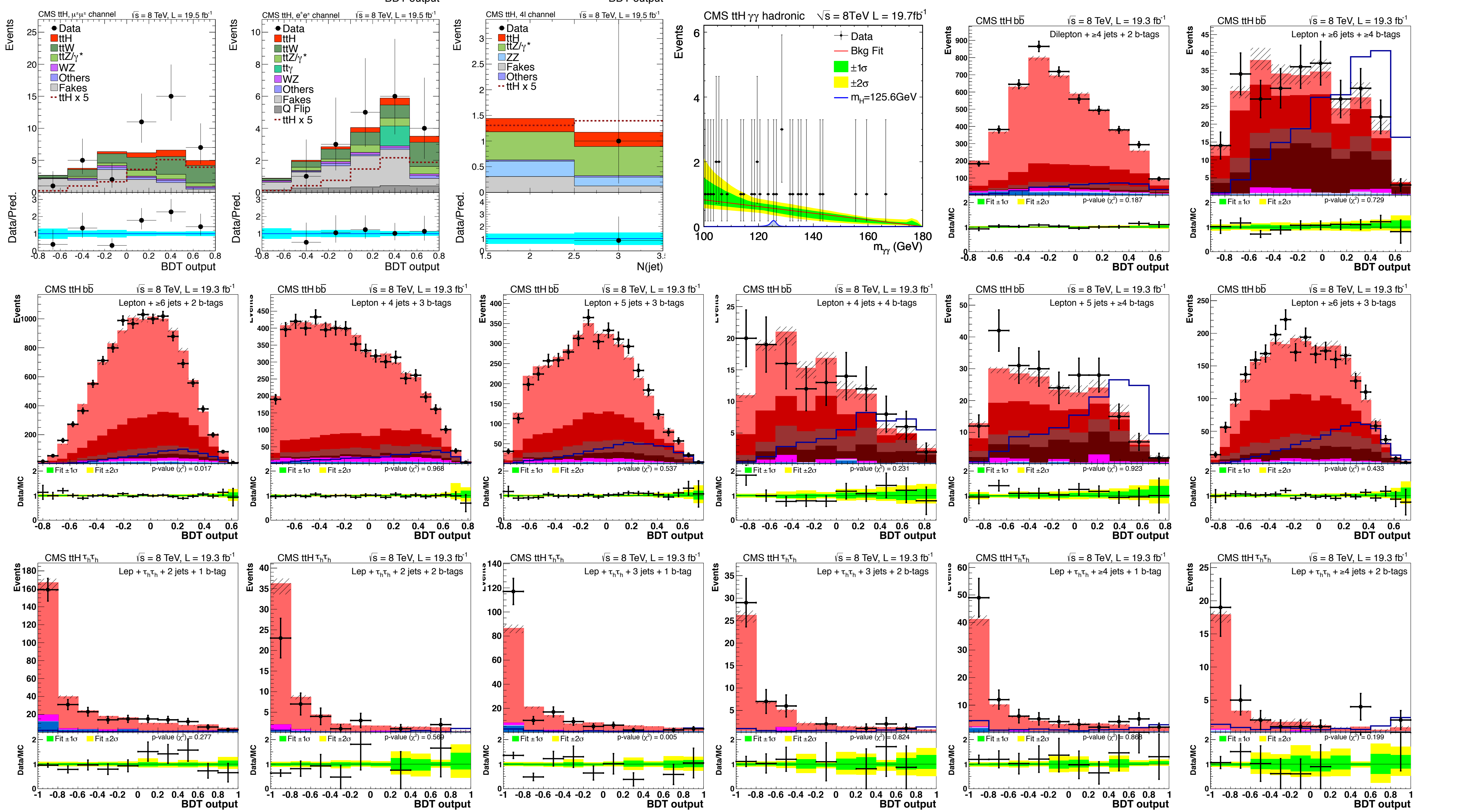
$$\mathcal{L}(\text{data}|\mu, \boldsymbol{\theta}) = \prod_i \underbrace{\frac{(\mu s_i + b_i)^{n_i}}{n_i!} e^{-(\mu s_i + b_i)}}_{\text{Poisson probabilities}} \underbrace{p(\tilde{\boldsymbol{\theta}}|\boldsymbol{\theta})}_{\text{Probability distribution function of nuisances}}$$

Probability distribution function of nuisances

- Systematic uncertainties treated as nuisance parameters
  - Affects both signal and background expectations
- Nuisance correlations used to account for category migration
  - e.g. shifting b-tag SF and JES done in correlated way so that $N_{jets}/N_{b\text{-}jets}$ variations capture migrations into / out of bins

8 TeV


CMS ttH, e±μ± channel √s = 8 TeV, L = 19.5 fb⁻¹
CMS ttH, 3l channel √s = 8 TeV, L = 19.5 fb⁻¹
CMS ttH γγ leptonic √s = 8 TeV L = 19.7 fb⁻¹
CMS ttH bb̄ √s = 8 TeV, L = 19.3 fb⁻¹
Dilepton + 3 jets + 2 b-tags
Dilepton + ≥3 b-tags
Data
ttH
ttW
ttZ/γ*
ttγ
WZ
Others
Fakes
Q Flip
ttH x 5
Bkg Fit
±1σ
±2σ
m_H=125.6GeV
Events
Data/Pred.
Data/MC
BDT output
m_γγ (GeV)
Fit ±1σ
Fit ±2σ
p-value (χ²) = 0.068
p-value (χ²) = 0.083


CMS ttH, μ±μ± channel √s = 8 TeV, L = 19.5 fb⁻¹
CMS ttH, e±e± channel √s = 8 TeV, L = 19.5 fb⁻¹
CMS ttH, 4l channel √s = 8 TeV, L = 19.5 fb⁻¹
CMS ttH γγ hadronic √s = 8TeV L = 19.7fb⁻¹
CMS ttH bb̄ √s = 8 TeV, L = 19.3 fb⁻¹
Dilepton + ≥4 jets + 2 b-tags
Lepton + ≥6 jets + ≥4 b-tags
Lepton + ≥6 jets + 2 b-tags
Lepton + 4 jets + 3 b-tags
Lepton + 5 jets + 3 b-tags
Lepton + 4 jets + 4 b-tags
Lepton + 5 jets + ≥4 b-tags
Lepton + ≥6 jets + 3 b-tags
CMS ttH τ_hτ_h √s = 8 TeV, L = 19.3 fb⁻¹
Lep + τ_hτ_h + 2 jets + 1 b-tag
Lep + τ_hτ_h + 2 jets + 2 b-tags
Lep + τ_hτ_h + 3 jets + 1 b-tag
Lep + τ_hτ_h + 3 jets + 2 b-tags
Lep + τ_hτ_h + ≥4 jets + 1 b-tag
Lep + τ_hτ_h + ≥4 jets + 2 b-tags
Data
ttH
ttW
ttZ/γ*
ZZ
ttγ
WZ
Others
Fakes
Q Flip
ttH x 5
Bkg Fit
±1σ
±2σ
m_H=125.6GeV
Events
Data/Pred.
Data/MC
BDT output
N(jet)
m_γγ (GeV)
Fit ±1σ
Fit ±2σ

The test statistic

- All channels and categories analyzed and fit simultaneously
  - Low S/B regions help constrain some nuisance parameters
- Find best-fit values of parameters that minimize log-likelihood

$$-2\ \ln\mathcal{L}(\text{data}|\mu s + b, \boldsymbol{\theta})$$

- Minimum of log-likelihood for parameter estimators: $\hat{\mu}, \hat{\boldsymbol{\theta}}$
- Test statistic to compare compatibility of data with hypotheses
  - **Background-only** and **signal + background** hypotheses

$$q_\mu = -2\ \ln\frac{\mathcal{L}(\text{data}|\mu s + b, \hat{\boldsymbol{\theta}}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu} s + b, \hat{\boldsymbol{\theta}})} \qquad 0 \leq \hat{\mu} \leq \mu$$

Setting upper limits on μ

- Characterize the absence of signal by putting limit on μ
- Calculated with CLs method, widely used at Tevatron and LHC
- Criterion for excluding signal at 1 – α confidence level (CL)

$$\mathrm{CL_s}(\mu) = \frac{\mathrm{P}(q_\mu \geq q_\mu^{\mathrm{obs}} | \mu s + b)}{\mathrm{P}(q_\mu \geq q_\mu^{\mathrm{obs}} | b)} \leq \alpha$$

- Use “asymptotic” approach, an analytic approximation
- Signal with cross section $\sigma = \mu\, \sigma_{SM}$ is **excluded at 95% CL**

$$\mathrm{CL_s}(\mu) \leq 0.05$$