Search for the associated production of Higgs bosons and top quarks at $\sqrt{s}$=7-8 TeV with the ATLAS detector at LHC

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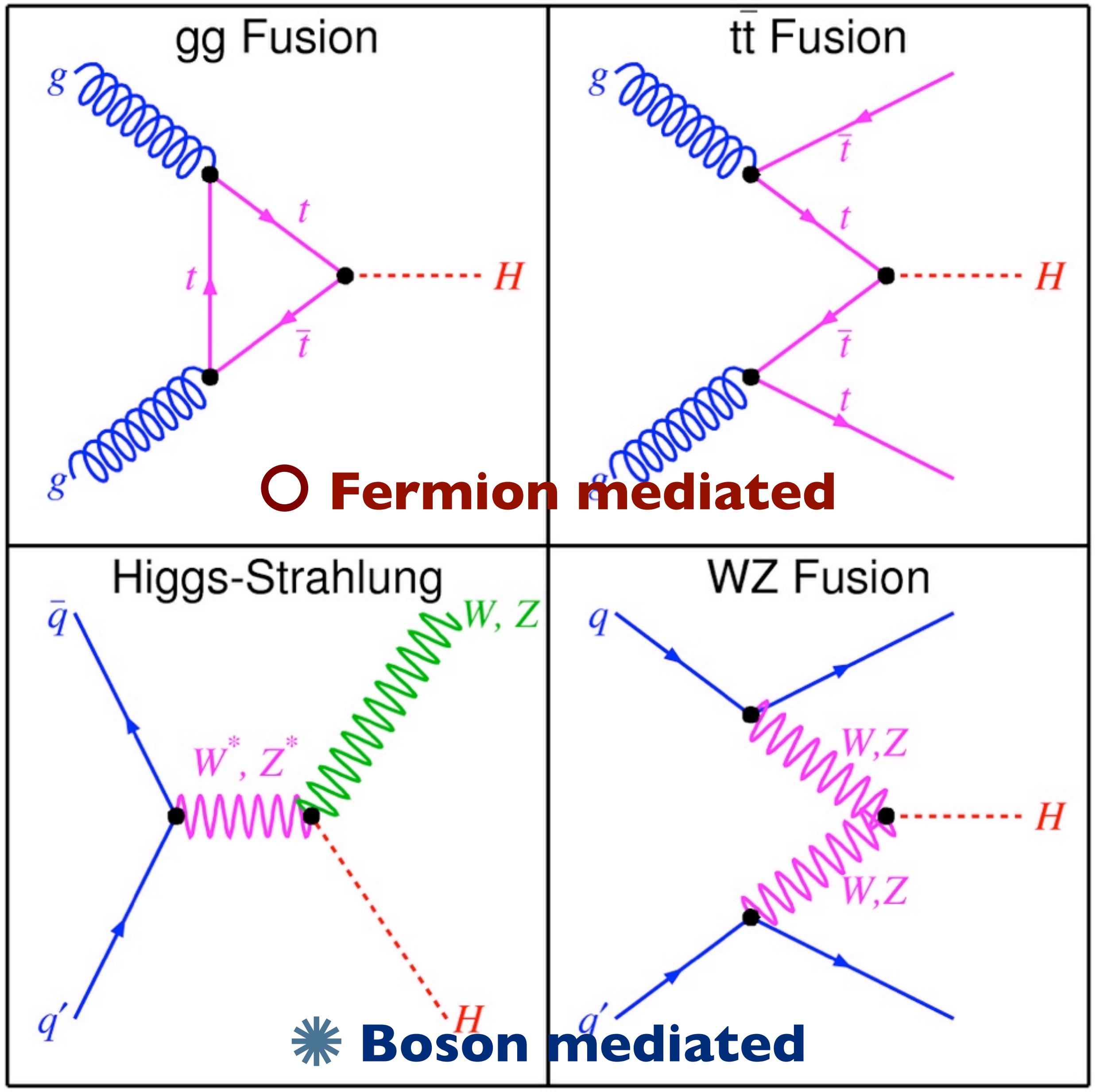
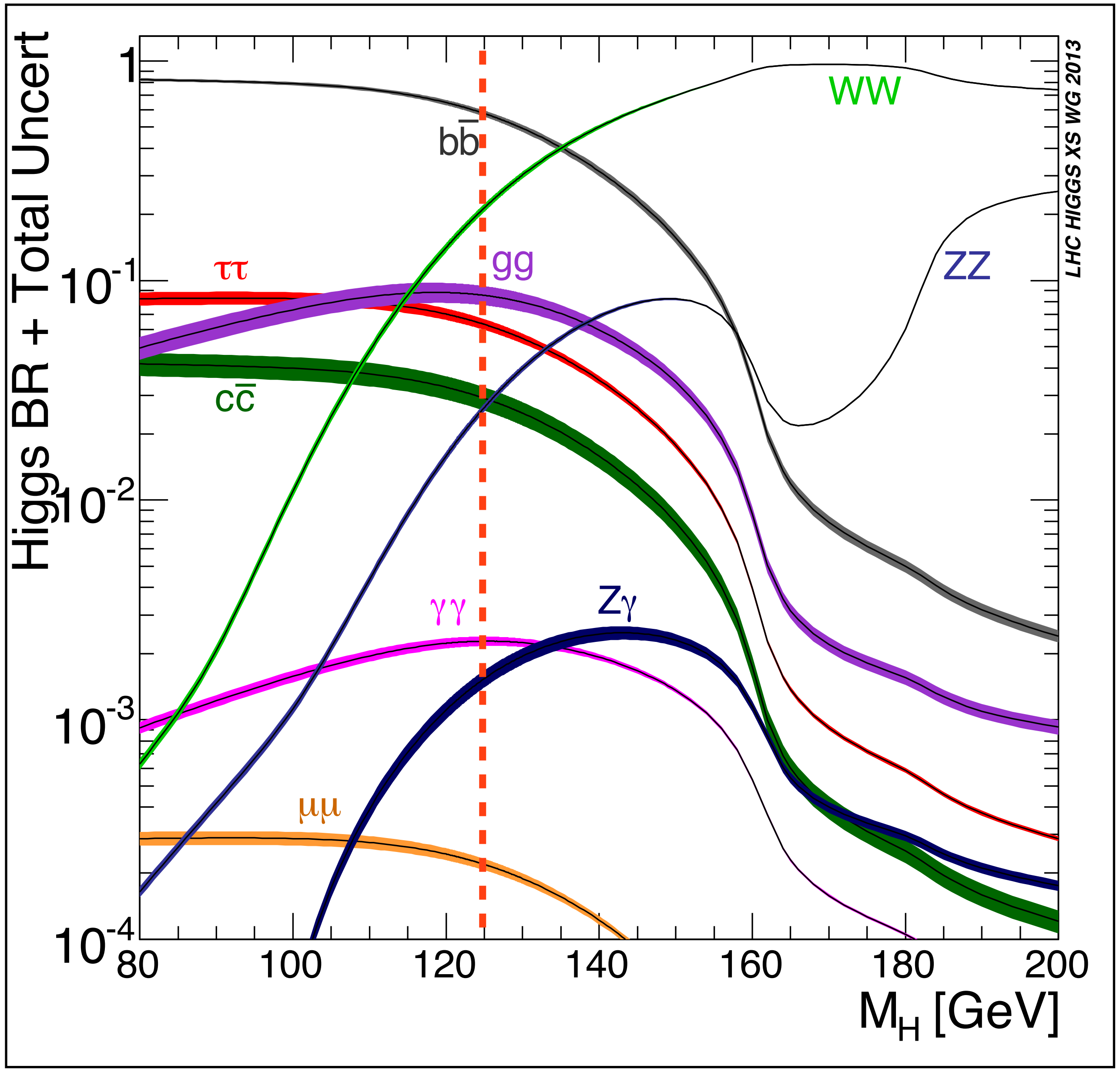
Outline

- General framework, motivations
  - Higgs couplings
  - Overview of present experimental situation
  - top-Higgs
- Channels/signatures in ATLAS
  - bb channels
  - multi-lepton channels
  - di-photon channels
- Conclusions

Higgs Bosons: generalities

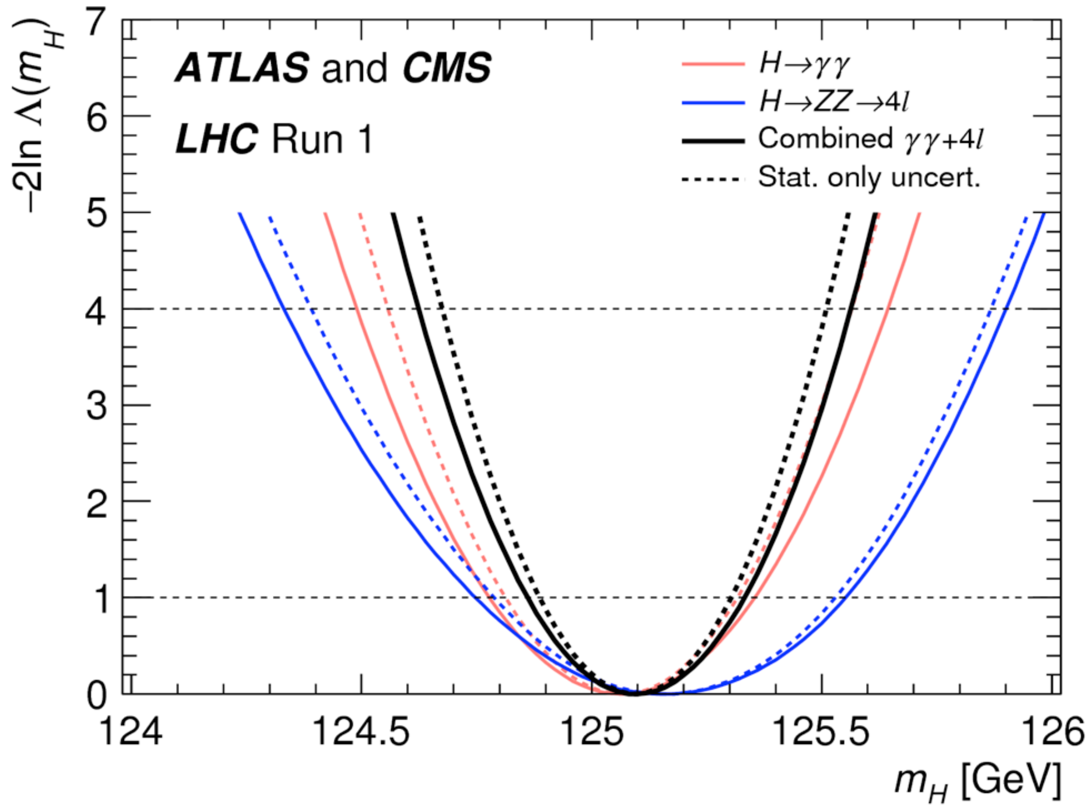




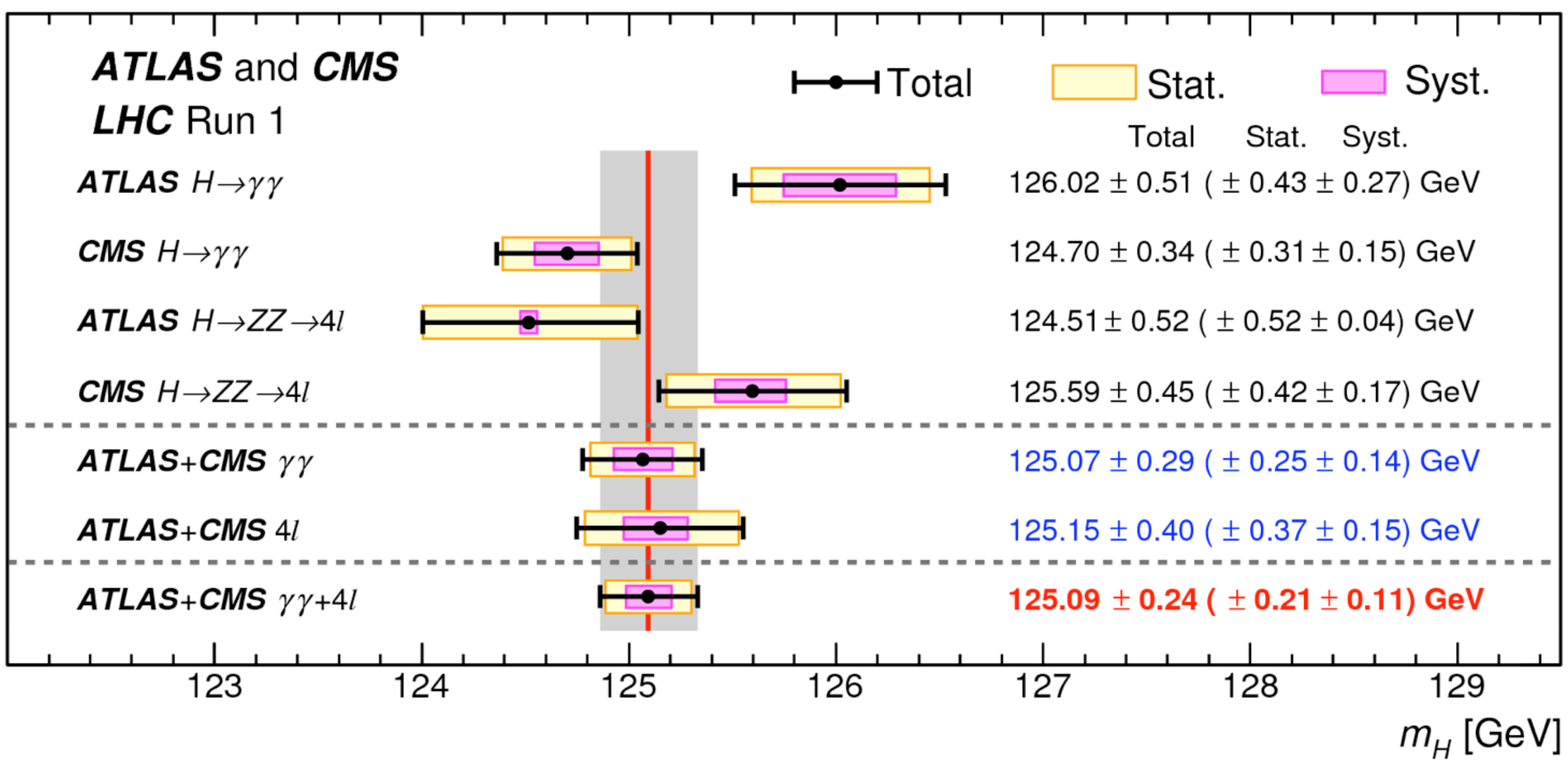
Production

Decay

Mass



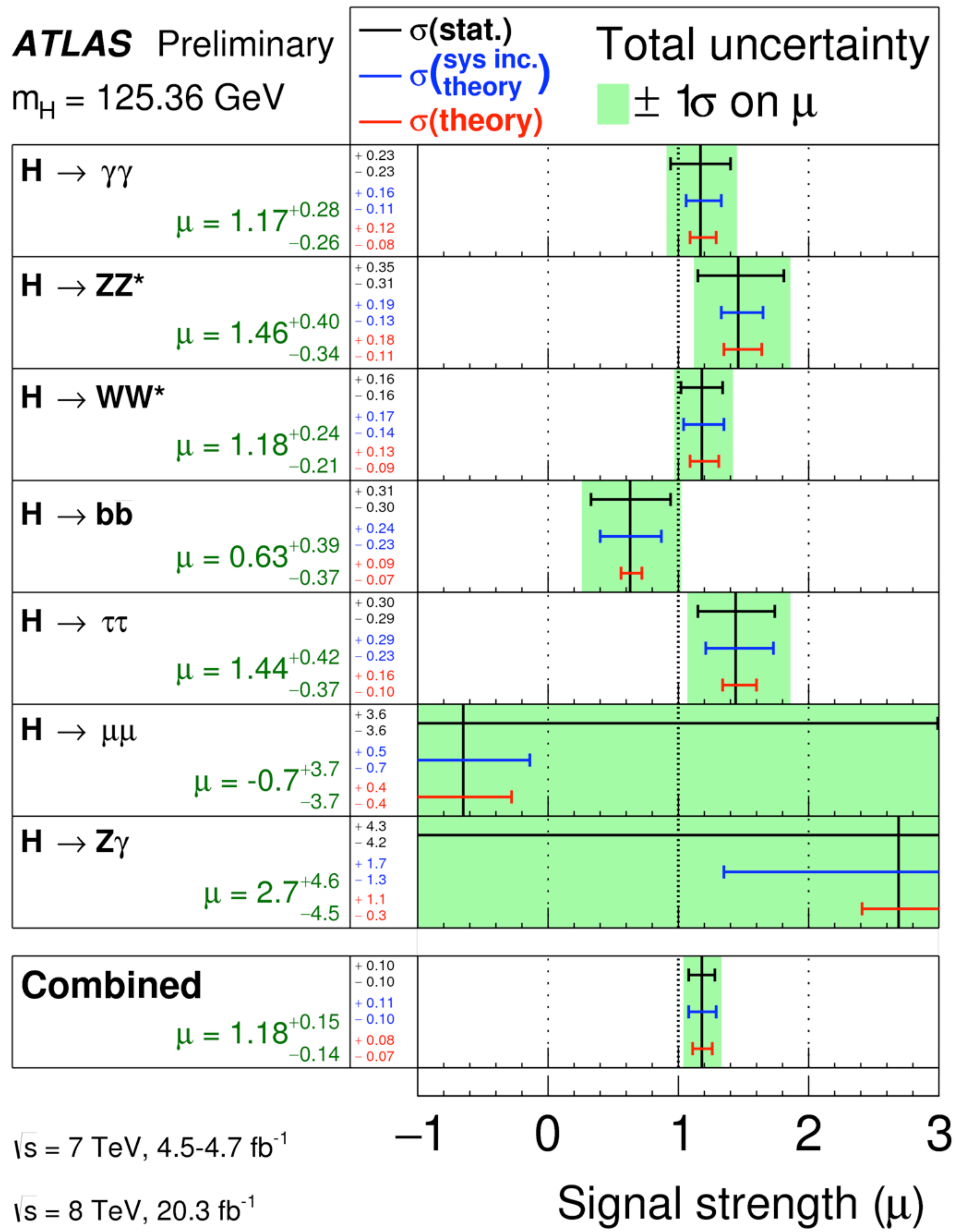
- Mass measured from "golden" channels for discovery
  - Fully determined kinematics
- Mass ~125 GeV
  - fair agreement across channels for ATLAS and CMS



Couplings

$$\mu = \frac{\sigma \times \mathrm{BR}}{(\sigma \times \mathrm{BR})_{\mathrm{SM}}}$$

$$1.18 \pm 0.10\,(\mathrm{stat.}) \pm 0.07(\mathrm{expt.})\,^{+0.08}_{-0.07}(\mathrm{theo.}).$$



- Expresses yield in several channels probed, relative to SM expectations
- Indirect determination of couplings to bosons and fermions from mix of modes (previous slide)

➡ Compatible with SM at ~20% level within 1sigma

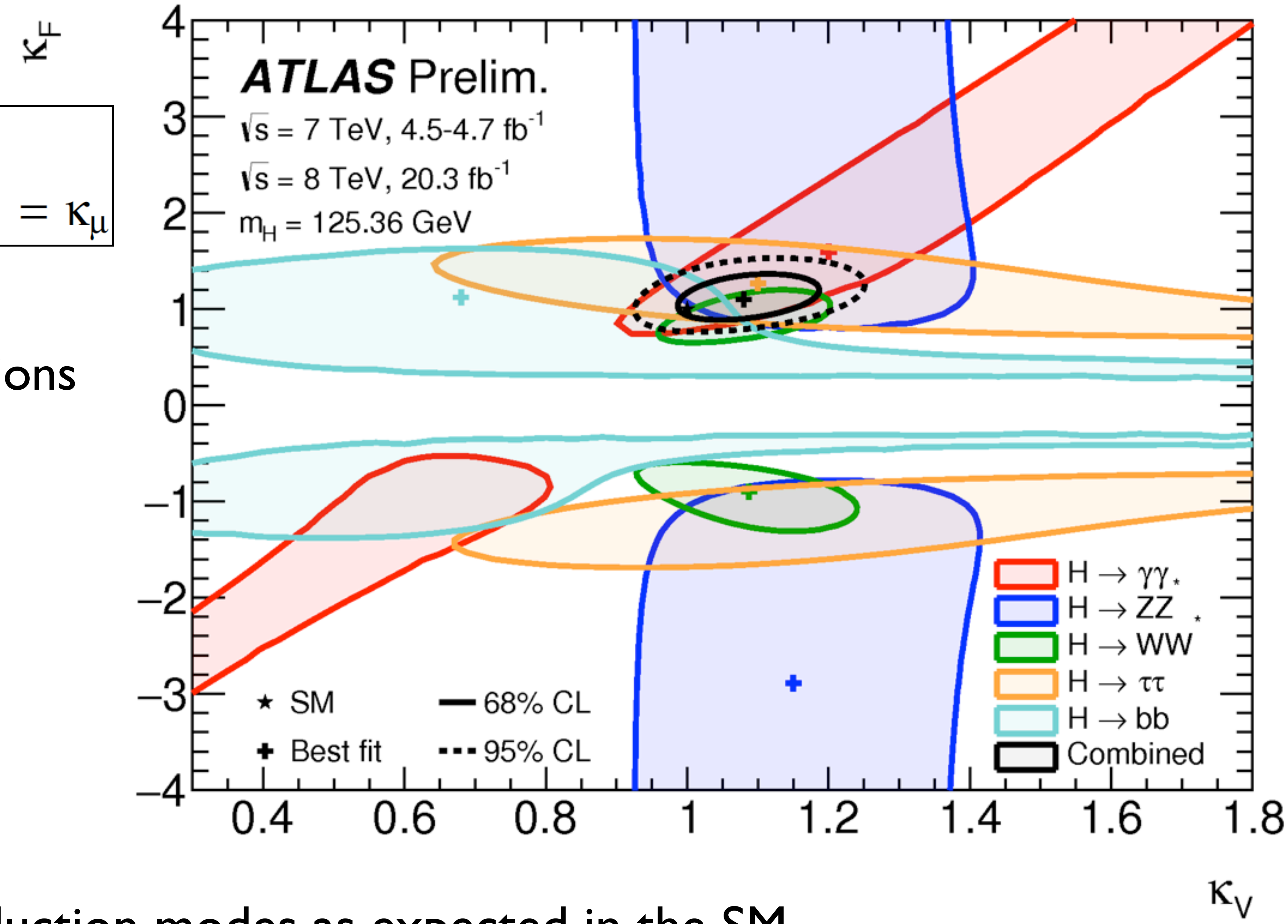
- All bosonic decay modes observed
- $H \rightarrow \tau\tau$ has 4.5σ significance

Couplings/2

$$\kappa_V = \kappa_W = \kappa_Z$$
$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g = \kappa_\mu$$

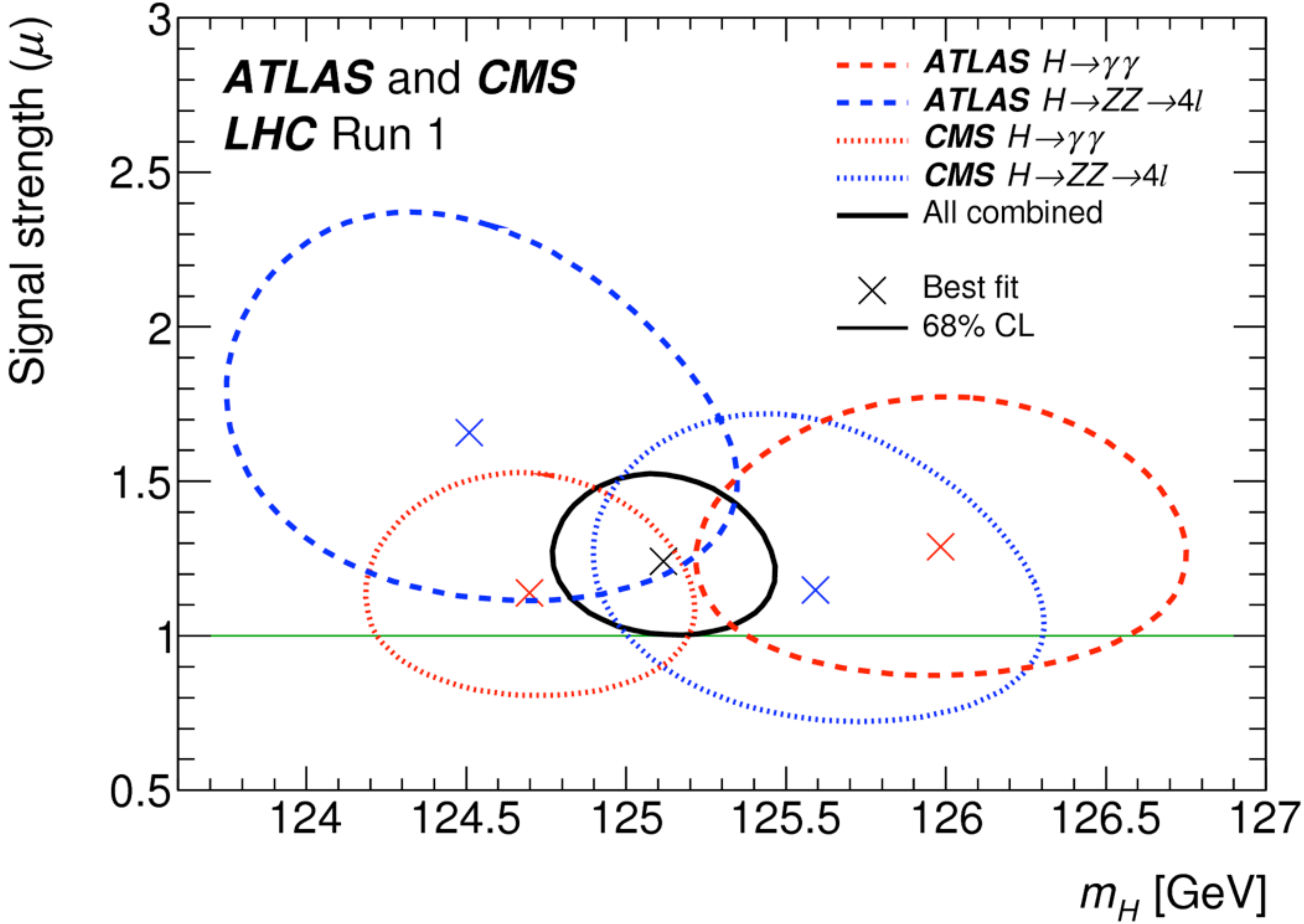
- "Effective" model with coupling strength to fermions and bosons fit separately

$$\kappa_V = 1.09^{+0.07}_{-0.07}$$
$$\kappa_F = 1.11^{+0.17}_{-0.15}.$$



- From production modes as expected in the SM
  - *e.g. gg fusion assumed sensitive to fermion loop only!*
- Relative sign V-to-F still not fully determined
  - but +1 (=SM) favourite

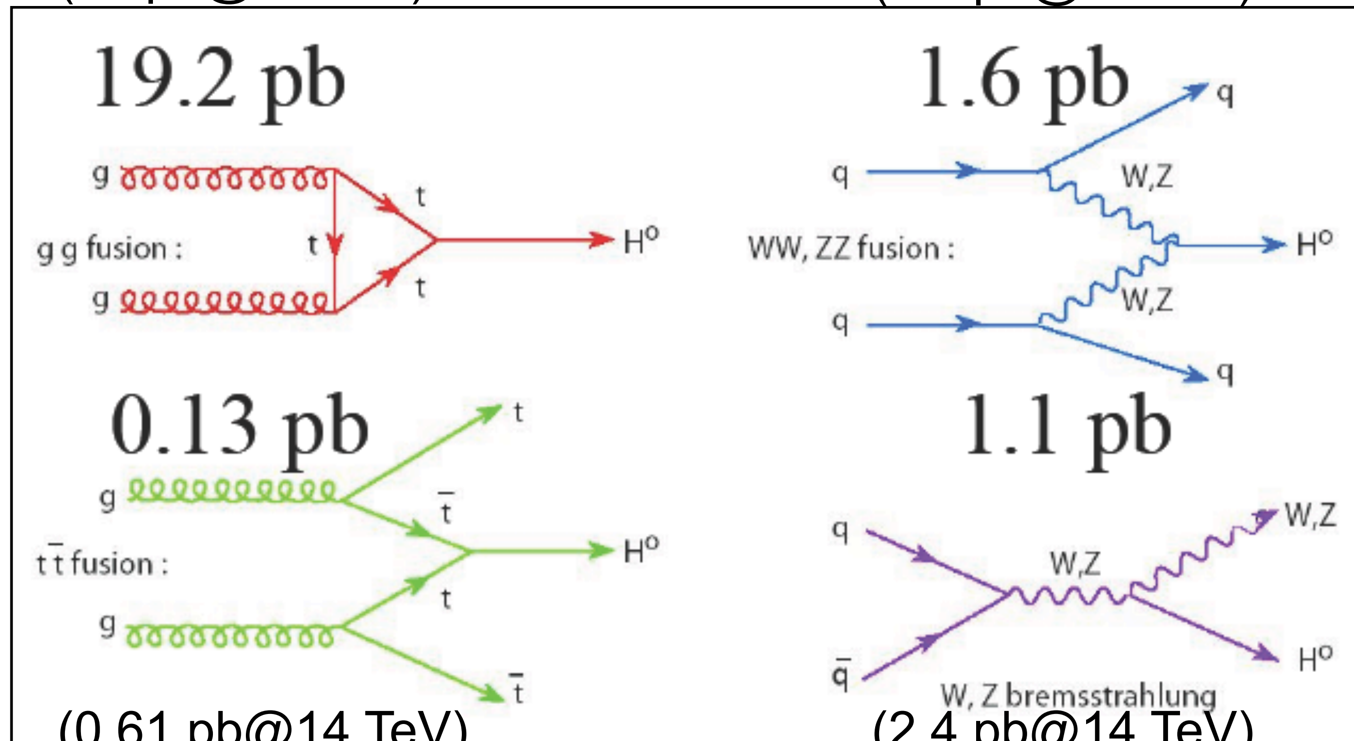
Combined picture - Run1



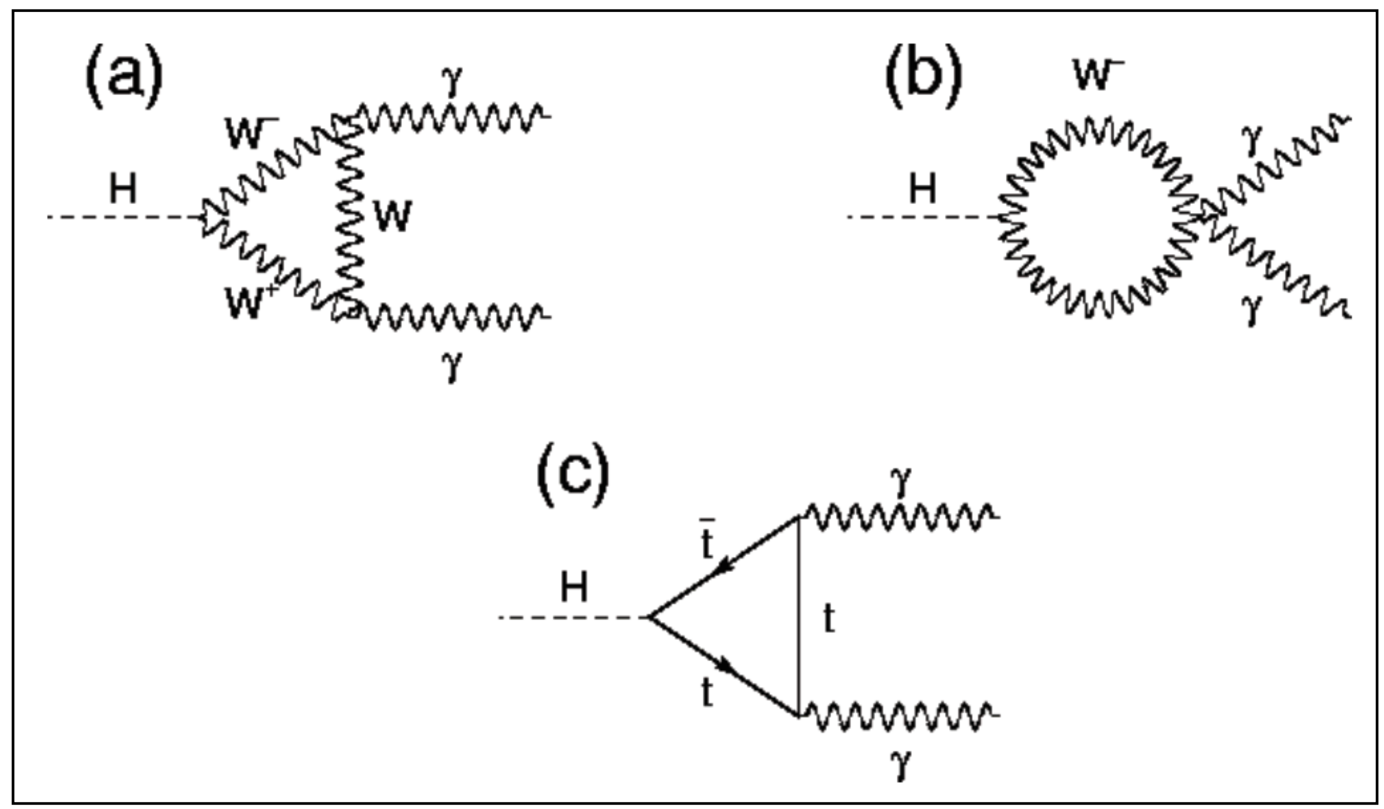
Higgs Boson coupling with top quarks

- t-H dominates gg fusion mechanism
  - but through loop process where...
  - ...new physics could also hide
  - *e.g. if no longer SM particle-only assumed in loops, $k_t \rightarrow \sim 1.3$*

(50 pb@14 TeV) (4.2 pb@14 TeV)



(0.61 pb@14 TeV) (2.4 pb@14 TeV)



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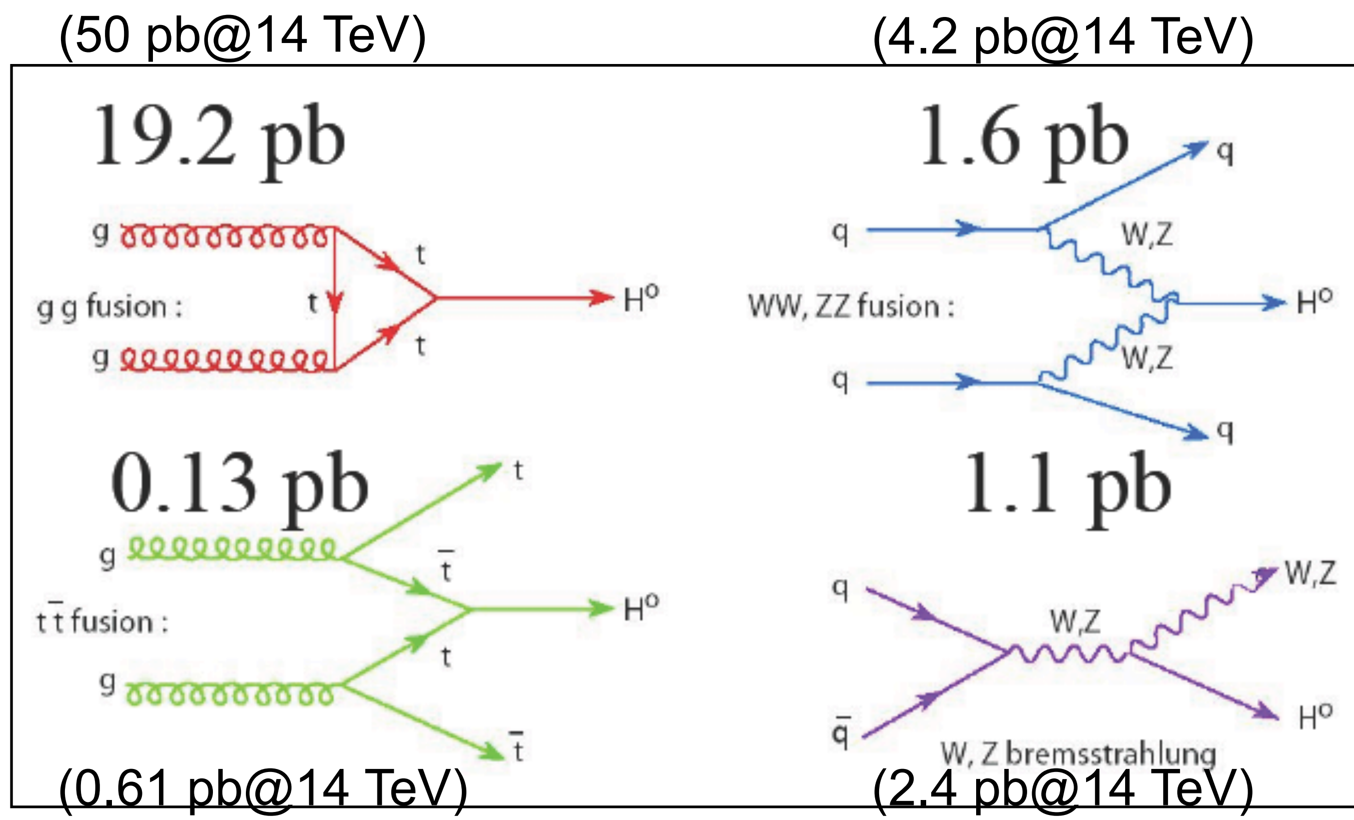
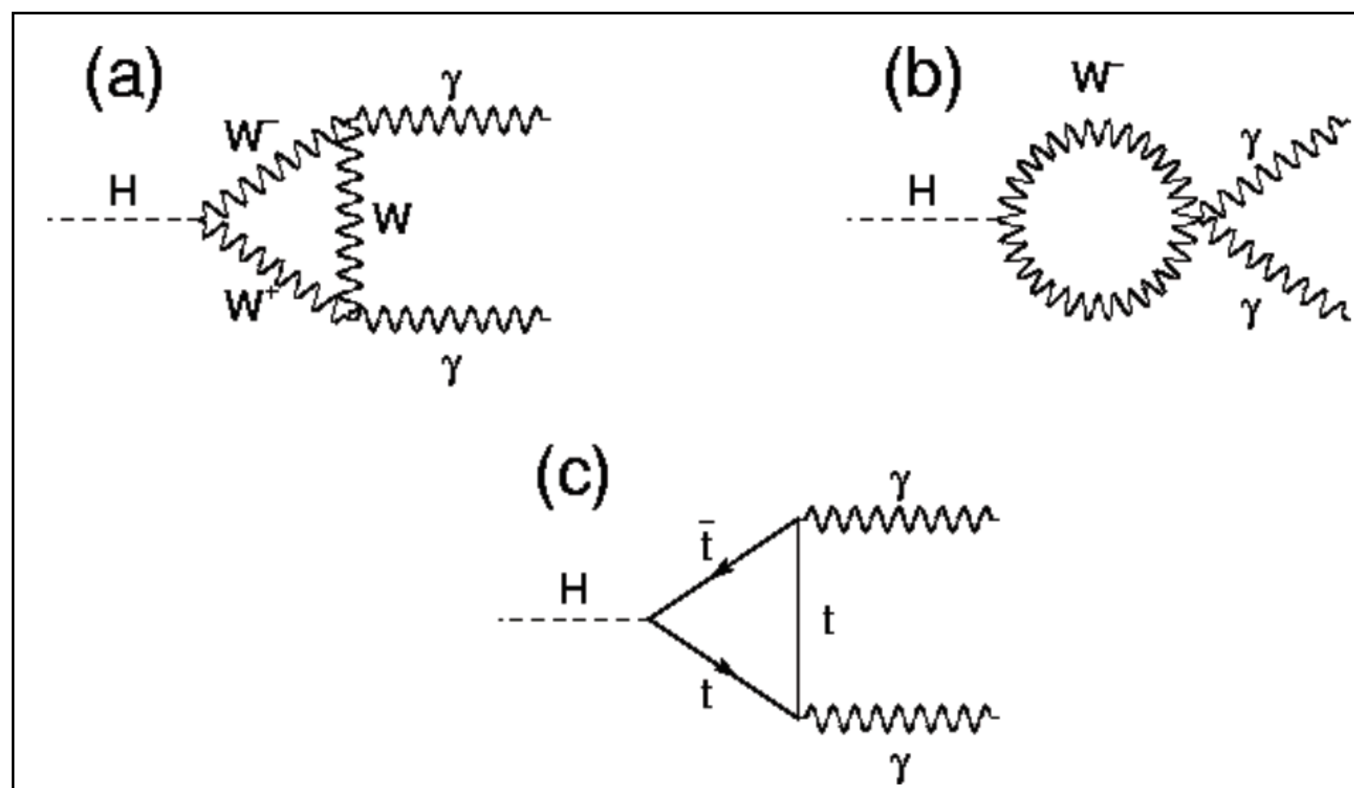
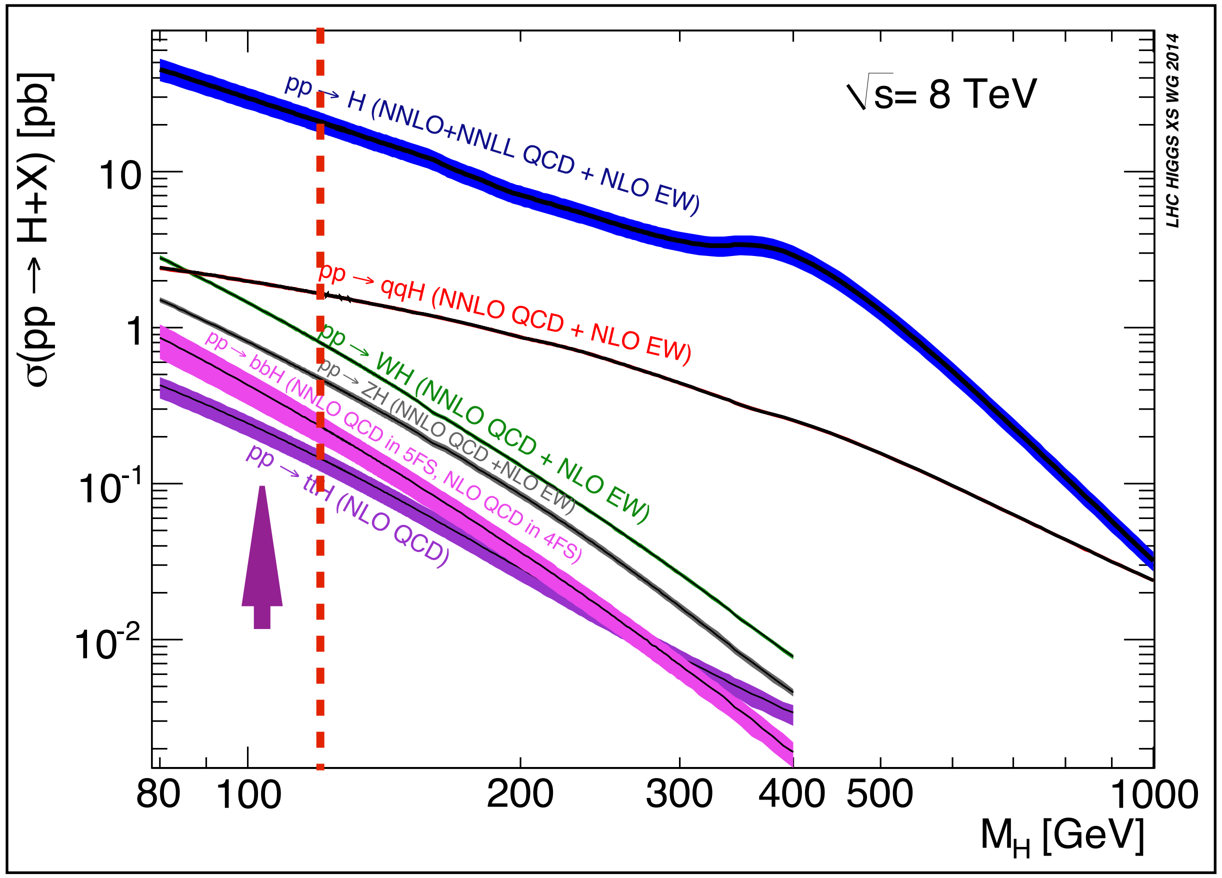


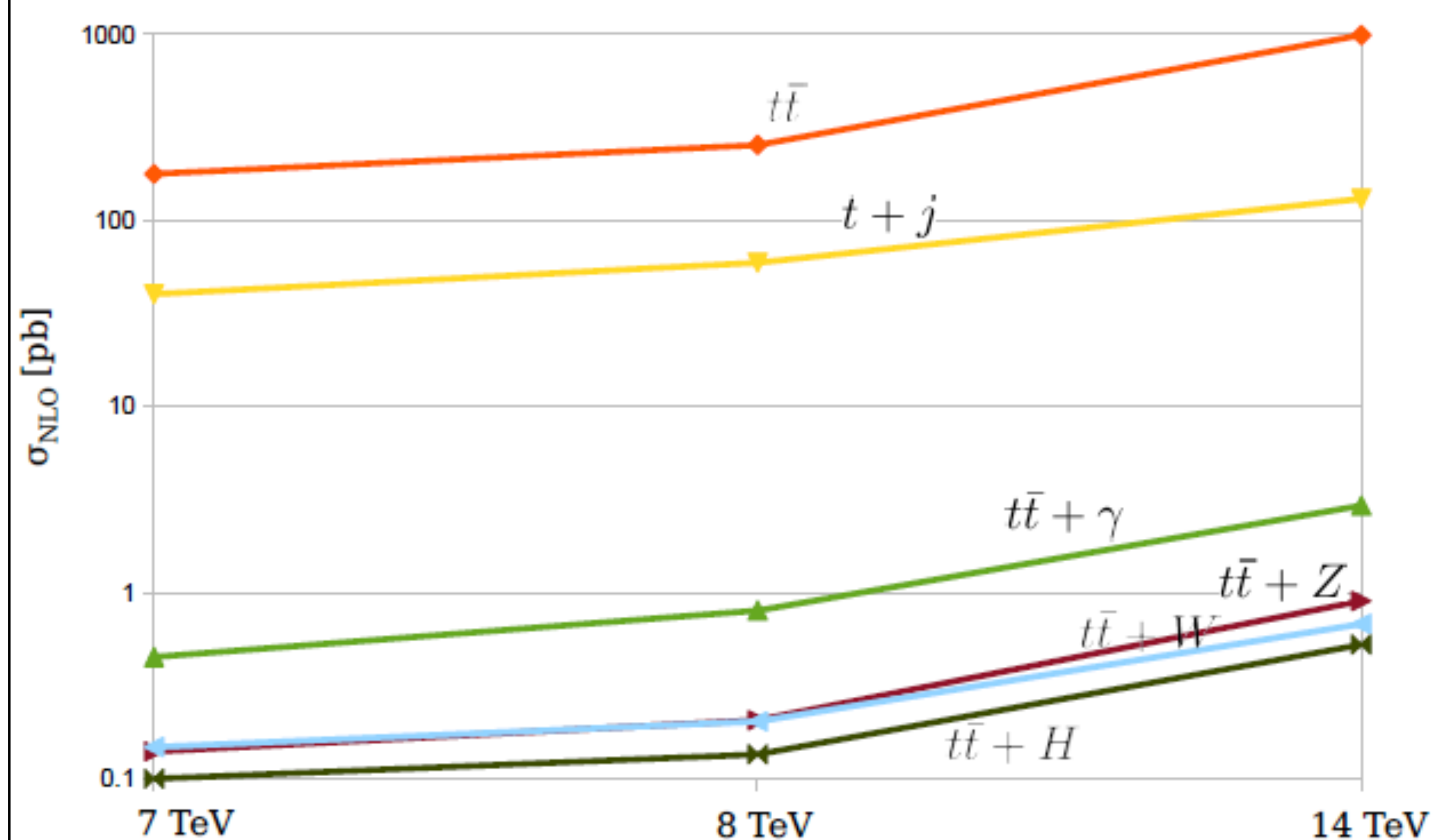
- By measuring ttH we have <u>direct</u> access to the coupling at production instead
  - independent, assumption-free check of t-H vertex strength



SM cross-section at 8 TeV



- At NLO, σ_{SM}=130 fb for m(H) =125 GeV@ 8 TeV
- @ 14 TeV ~5x increase in σ_{SM}

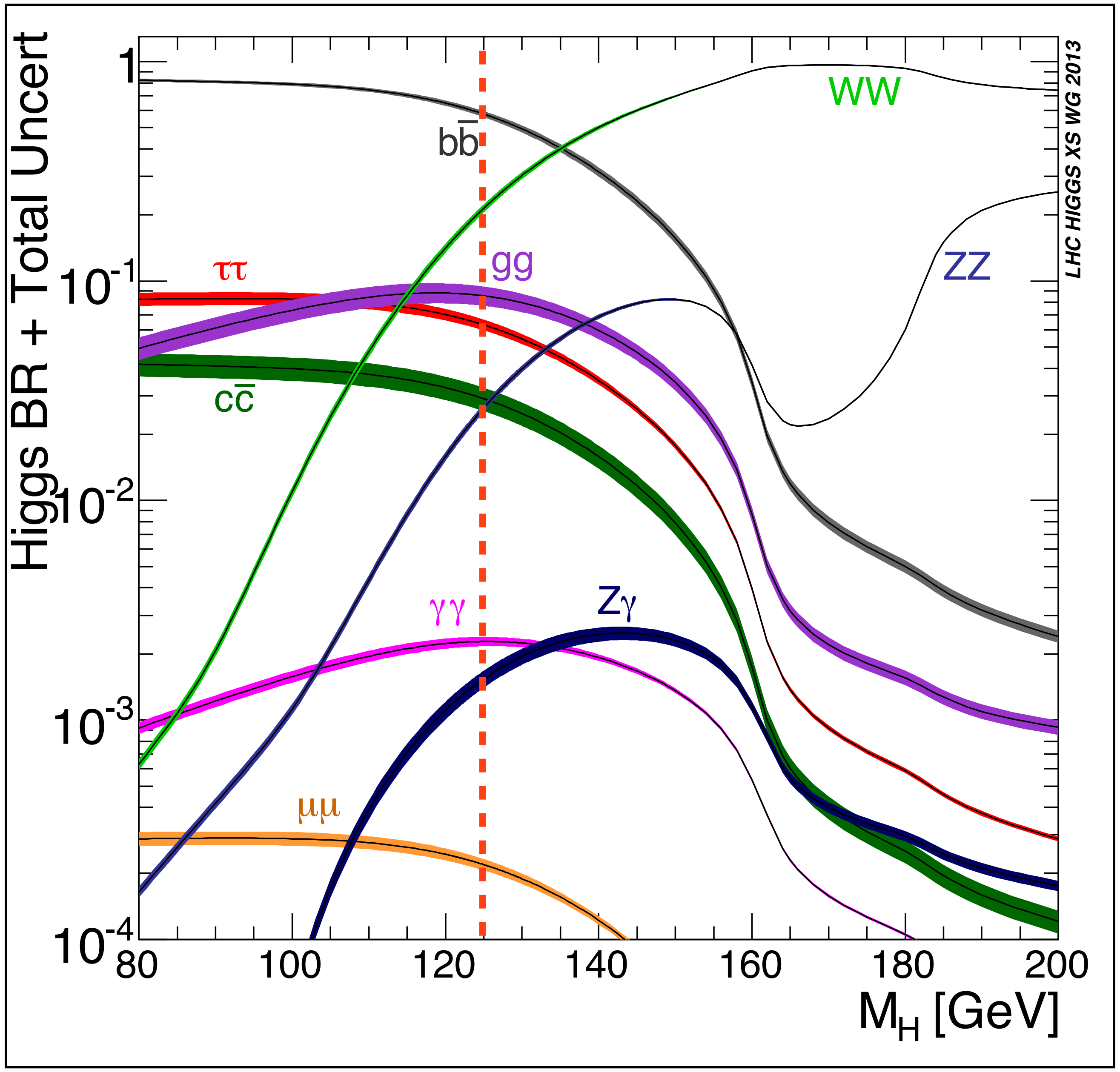


[Baernreuther,Czakon,Fiedler,Mitov],[Campbell,Ellis,Röntsch],
[Melnikov,Scharf,M.S.],[Garzelli,Kardos,Papadopoulos,Trocsanyi],
[Demartin,Maltoni,Mawatari,Page,Zaro]

- Main backgrounds for analyses in this talk: tt+bb and tt+W/Z

M.Schulze (CERN), https://indico.cern.ch/event/375429/session/2/contribution/10/material/slides/0.pdf

Channels considered



- BR(H->bb) = 58%
- BR(H->WW+ZZ+ττ) = 30%
- BR(H->γγ) < 0.23%

- bb: by far most abundant, but overwhelmed by tt+(HF-)jets background and less easy *bb* reconstruction
- multi-lepton channels: good compromise, but sensitive to additional *tt+W/Z* backgrounds hard to control with data
- *γγ*: clear resonance peak but scarce

Event generation

- Signal ttH: Helac-One Loop+Powheg interface to parton shower (=”PowHel”)
  - inclusive in Higgs boson decays, cross-section and BR from http://arxiv.org/abs/1101.0593 and updates
  - CT10NLO Parton Distribution Function (PDF)
  - Pythia 8 for parton shower (PS) + CTEQ6L1 PDF
- (W)tH: MadGraph5_AMC@NLO, 5-flavour scheme
  - inclusive in Higgs boson decays, xsec and BR from Yellow Book
  - three different values of k_t = -1, 0, + 1.
  - CT10NLO PDF
  - Herwig++ for parton shower + CTEQ6L1 PDF
- tt+jets: Powheg
  - inclusive in flavour of additional partons
  - CT10NLO PDF
  - Pythia 6 for parton shower + CTEQ6L1 PDF
- tt+W/Z: MadGraph5
  - Pythia 6 for parton shower + CTEQ6L1 PDF
  - Up to 2 (ttW) or 1(ttZ) extra partons at Matrix Element

Other sources of background: simulation

- W/Z +jets : Alpgen + Pythia
- Dibosons : Alpgen + Herwig
- Single top : PowHeg / Acer +Pythia
- Multijets : Estimated by using data driven methods

Typical pre-selections on expt objects

- **e or μ** of good quality (track, track-cluster match) and isolated both in tracking and calorimetry
  - $E_T(e) > 15$-25 GeV, $p_T(\mu) > 10$-25 GeV according to channel
  - Additional requests on proximity to primary vertex (d_0, z_0) also applied
- Anti-k_T **jets** with R=0.4, calibrated at hadronic scale
  - $p_T(jet) > 25$ GeV, central
  - pile-up suppressing selection criteria for jets of $p_T(jet) < 50$ GeV
- **b-quark id**entification in jets with NN-based algorithm
  - 60, 70, 80% b-tag efficiency working points all used in this analysis
- **Photons** passing quality criteria on shower shape and isolated both in tracking and calorimetry
  - 2 photons with a reconstructed vertex required

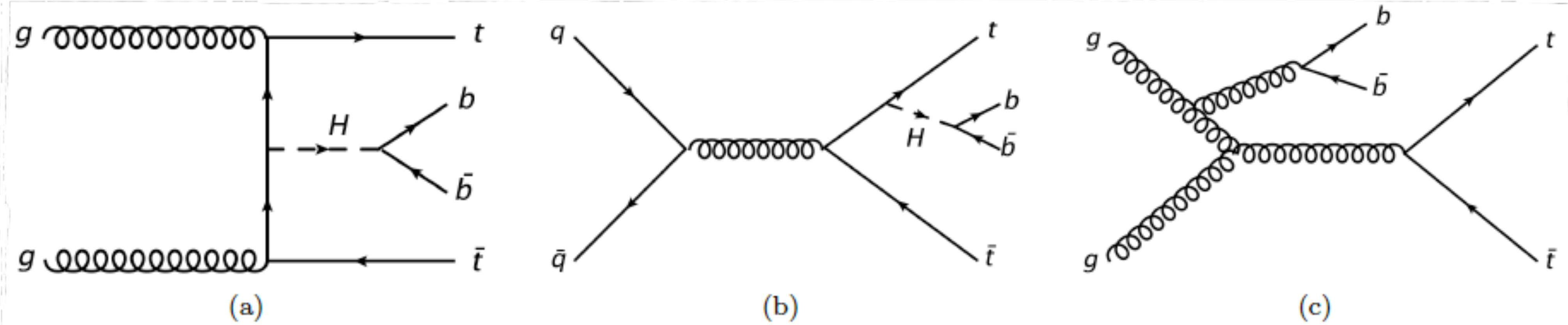


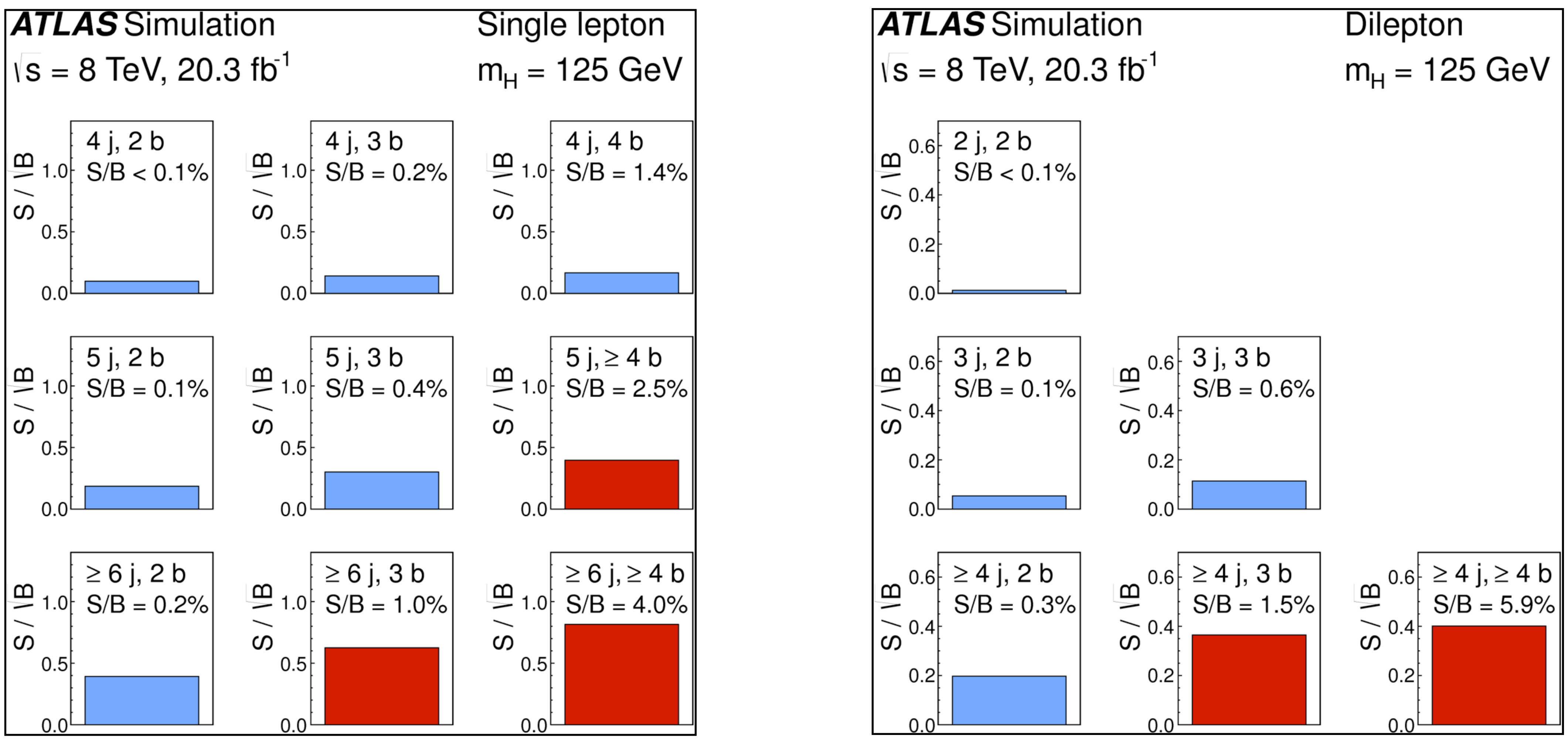
Fig. 1 Representative tree-level Feynman diagrams for the production of the Higgs boson in association with a top pair ($t\bar{t}H$) and the subsequent decay of the Higgs to $b\bar{b}$, (a) and (b), and for the main background $t\bar{t}+b\bar{b}$ (c).

$t\bar{t}H(b\bar{b})$

http://arxiv.org/abs/1503.05066
submitted to EPJC

Analysis strategy

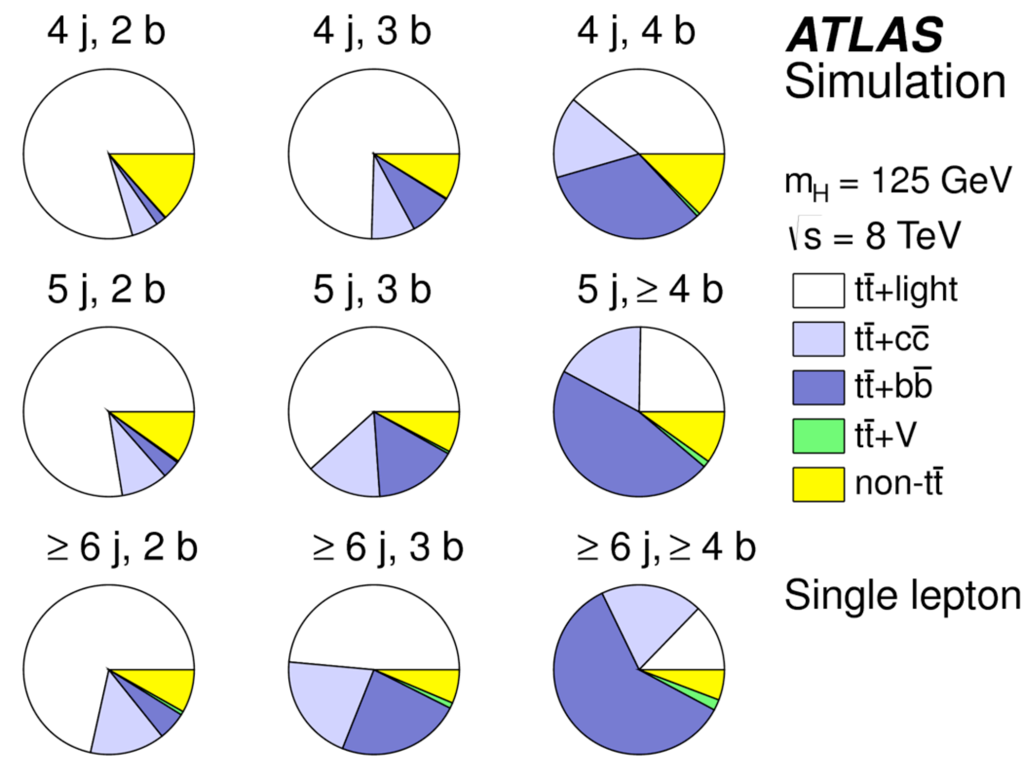
- Multi-variate analysis technique to reduce large bkg from $t\bar{t}$+X (esp. X=$b\bar{b}$)
- Construct matrix of N(jets)-N(b-tags) to characterize background
  - simultaneous fit for N_S (from signal-enriched regions, S/B>1%) and N_B (from control-enriched regions)

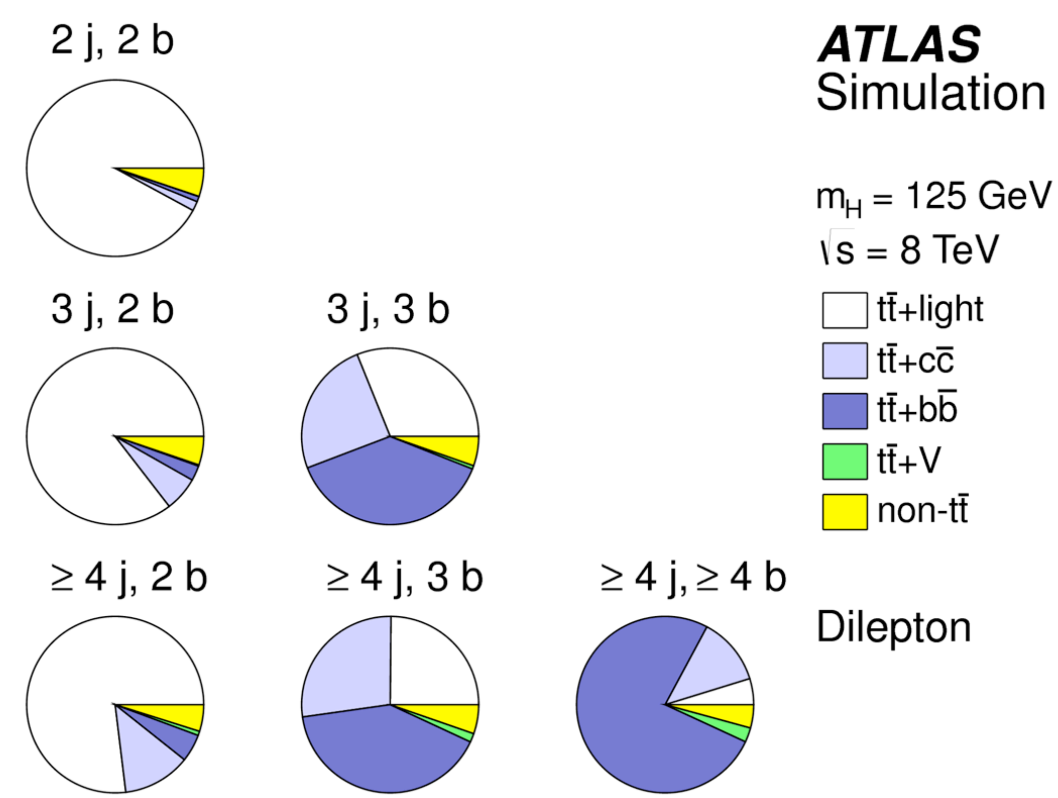


- dilepton channel: ee/μμ/eμ + (2, 3, ≥4 jets) and (2, 3, ≥4 b-tags)
- lepton+jets channel: 1 e or μ + (4, 5, ≥6 jets) and (2, 3, ≥4 b-tags)

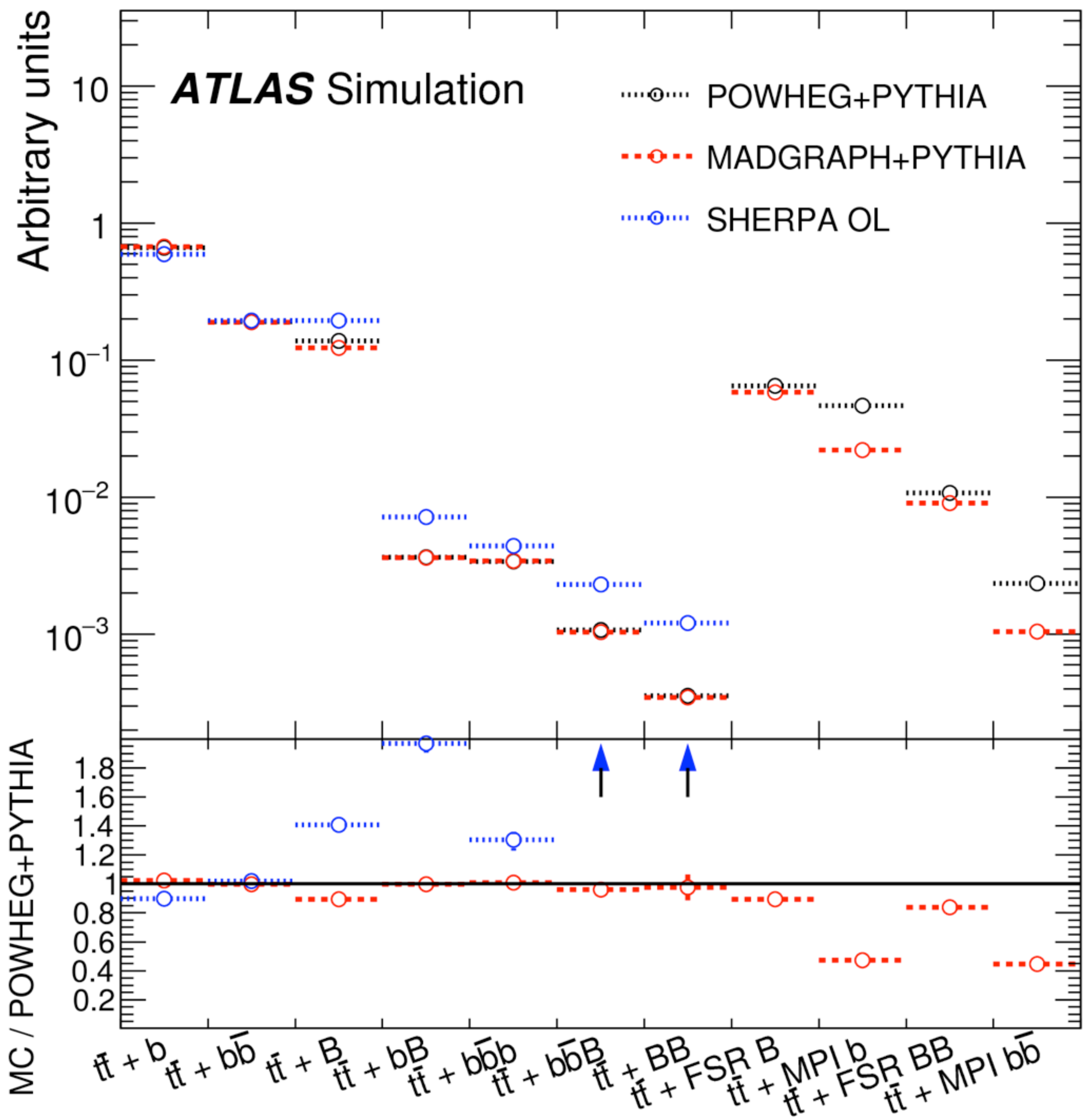
Background modeling

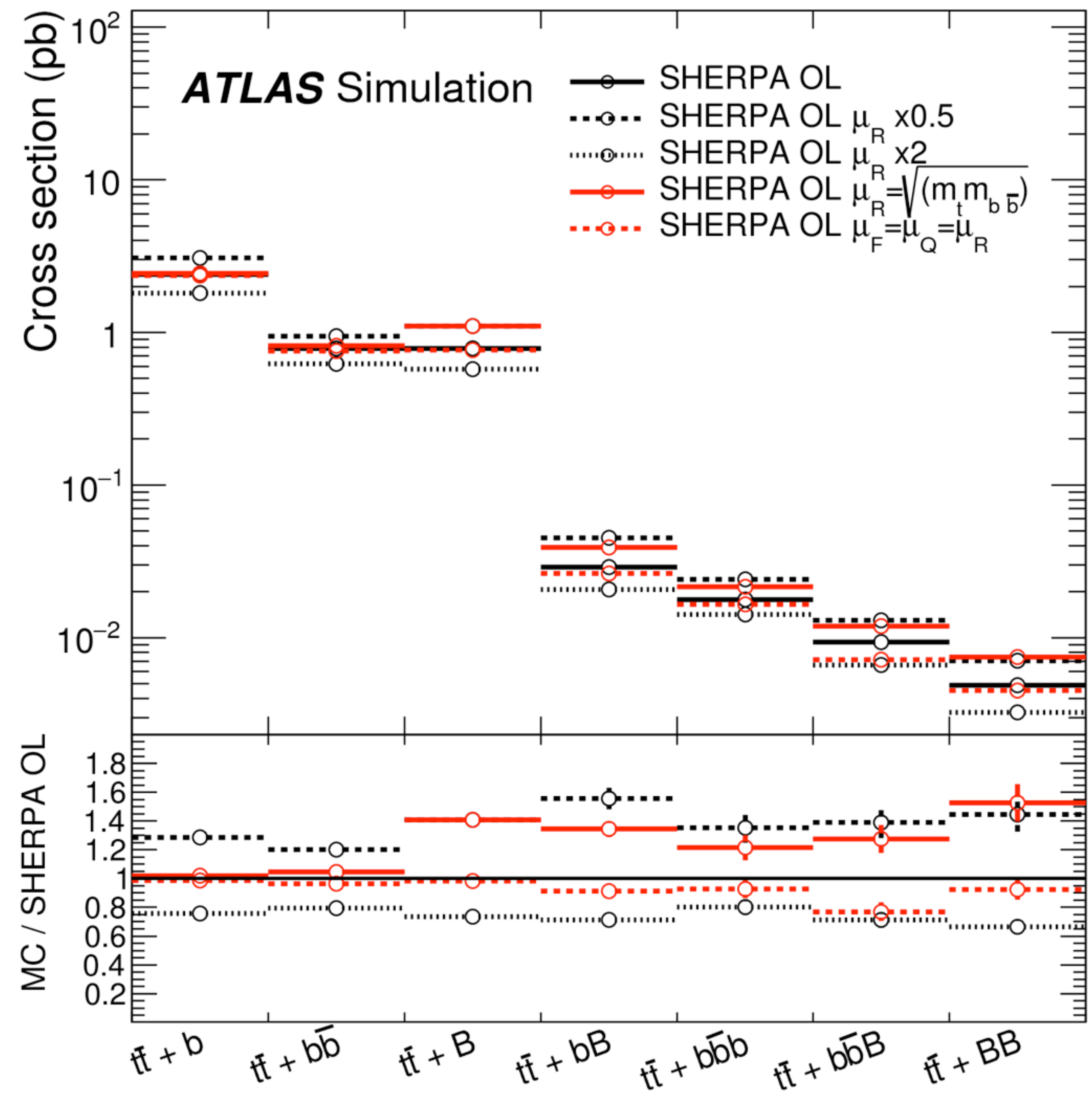
- Main bkg tt+HF in all regions for both channels
  - 50% normalization uncertainty on ttbb/cc
- Powheg + Pythia6 used to model it
- Madgraph and Sherpa+OpenLoops directly generate tt+bb/cc
  - HF kinematics in baseline reweighted to SherpaOL
  - expected to properly treat ME+PS matching of tt+HF
  - difference between generators taken as systematic uncertainty *(see later)*
- p_T of top quark and tt system reweighted in remaining tt+LF and tt+cc to reproduce spectra obtained in 7 TeV analysis *(see later)* (ATL-CONF-2013-099).





tt+bb theory modelling

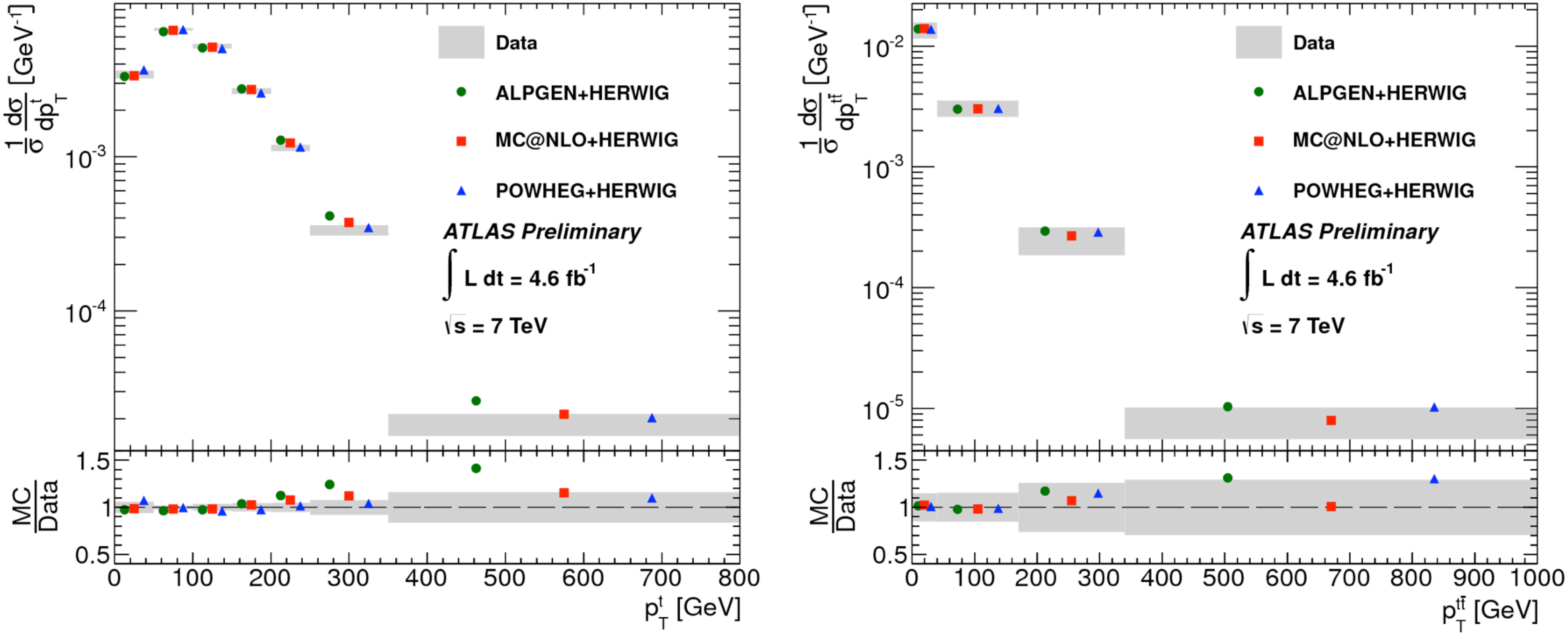




- A comparison between baseline MC set-up (Powheg+Pythia8) and multi-leg generators in 4-flavour (massive b quark) scheme suggests 50% uncertainty on inclusive tt+HF x-sec
  - anyway determined later from lower N(b-tags),N(jets) regions → 20/30%
- Additional unc. from parameters shaping the description of kine and final state particle multi (e.g. parton-shower tunes) also evaluated for several configurations

Reweighting tt+light/cc

ATL-CONF-2013-099



- *Study re-done internally including Powheg+Pythia6 set-up*
- Re-derived weights to bring MC to agree with data (unfolded with reference Alpgen) for tt+light flavour/cc *(which are not available with best theo prediction)*
- Found that sequential re-weighting of ttbar than top residual disagreement after first rew'ing gives best agreement on observables sensitive to α_s evolution and parton shower (e.g. Njets)

example

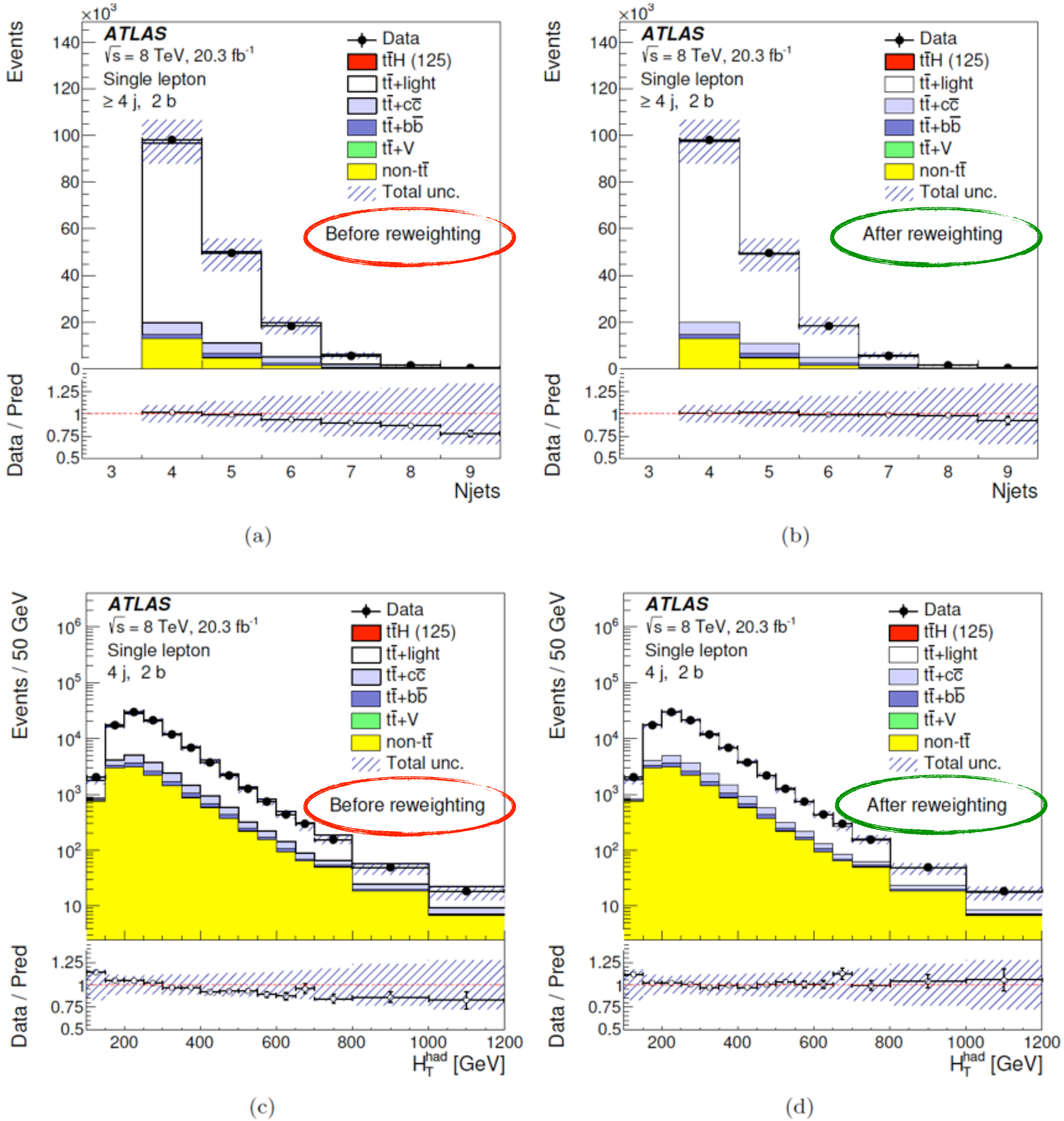


Fig. 5 The exclusive 2-b-tag region of the single-lepton channel before and after the reweighting of the p_{T} of the $t\bar{t}$ system and the p_{T} of the top quark of the POWHEG+PYTHIA $t\bar{t}$ sample. The jet multiplicity distribution (a) before and (b) after the reweighting; $H_{\mathrm{T}}^{\mathrm{had}}$ distributions (c) before and (d) after the reweighting.

Matrix Element method

- Recent addition (borrowed from Tevatron), used here for l+jets only
- PDF of an observed event to be consistent with process *i* described by a set of parameters α

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

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Amplitude of hard process

Kinematics/phase space

Transfer from parton-level (x) to detector quantities

- Demanding computing time-wise: approximations made on helicity states, angle expt. resolution and integration volume

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- Sum over all the possible assignments jets-partons ⇒ likelihood

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

- Provides highest S/B discrimination in ≥6 jets, ≥4 b-tags category

Variable ranking, bb l+j

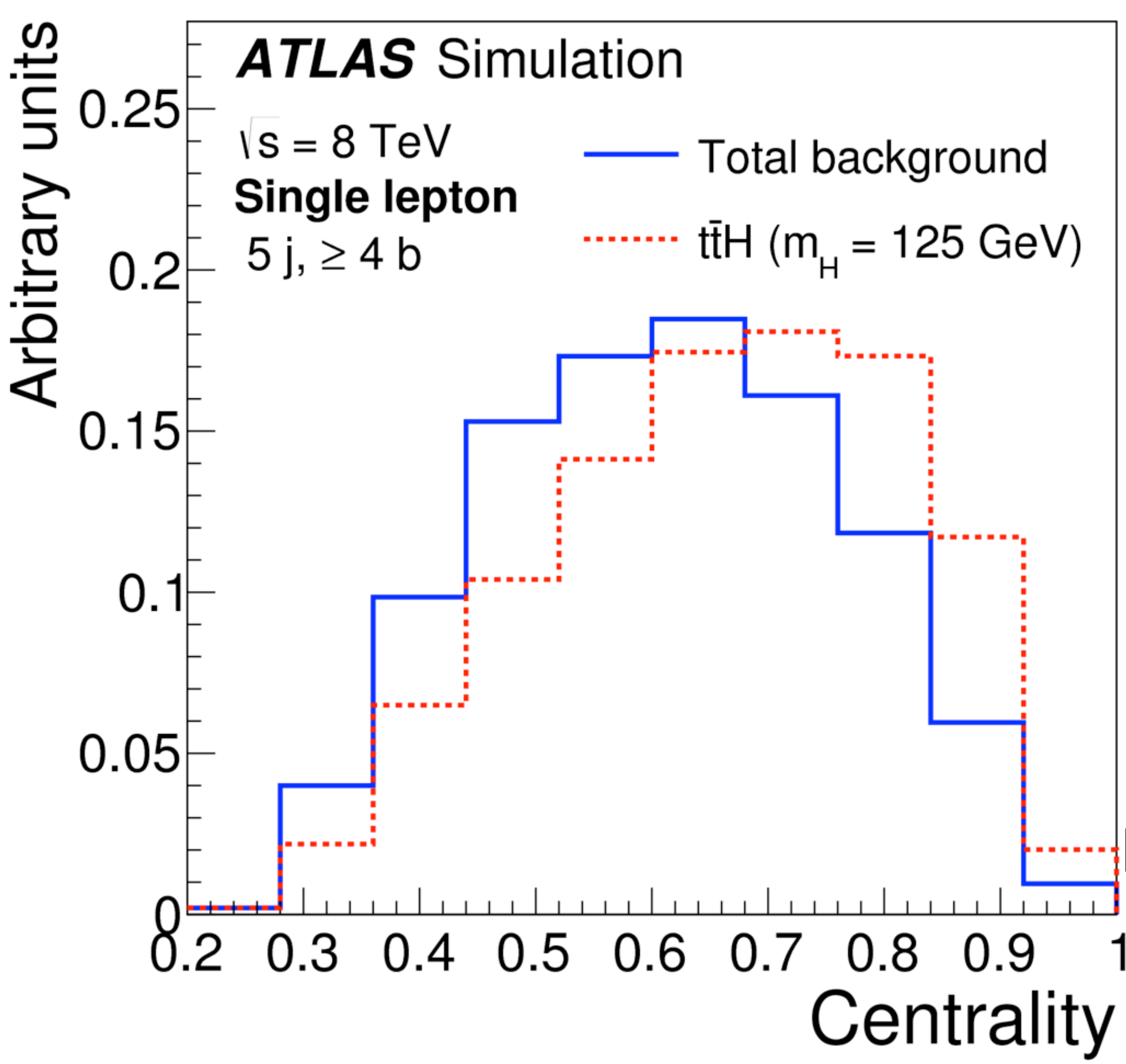
Variable	Definition	NN rank			
		$\geq$ 6j, $\geq$ 4b	$\geq$ 6j, 3b	5j, $\geq$ 4b	5j, 3b
$D1$	Neyman–Pearson MEM discriminant (Eq. (4))	1	10	-	-
Centrality	Scalar sum of the p_T divided by sum of the E for all jets and the lepton	2	2	1	-
p_T^{jet5}	p_T of the fifth leading jet	3	7	-	-
$H1$	Second Fox–Wolfram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

Variable ranking, bb 2l

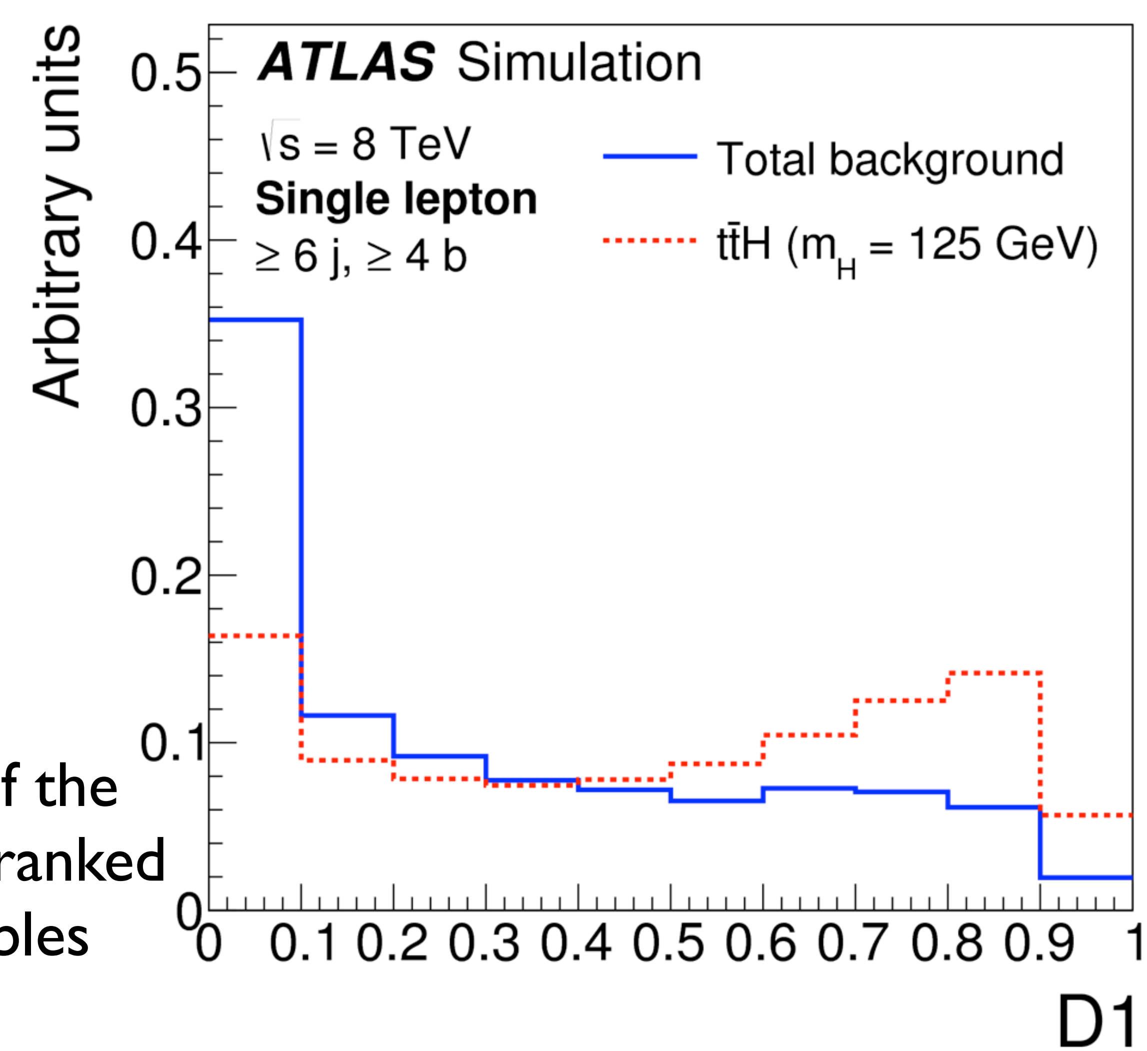
Variable	Definition	NN rank		
		$\geq$ 4j, $\geq$ 4b	$\geq$ 4j, 3b	3j, 3b
$\Delta\eta_{\mathrm{jj}}^{\max\ \Delta\eta}$	Maximum $\Delta\eta$ between any two jets in the event	1	1	1
$m_{\mathrm{bb}}^{\min\ \Delta\mathrm{R}}$	Mass of the combination of the two b-tagged jets with the smallest ΔR	2	8	-
$m_{b\bar{b}}$	Mass of the two b-tagged jets from the Higgs candidate system	3	-	-
$\Delta R_{\mathrm{hl}}^{\min\ \Delta\mathrm{R}}$	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
$\Delta R_{\mathrm{bb}}^{\max\ p_{\mathrm{T}}}$	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	-
$m_{\mathrm{jj}}^{\min\ \mathrm{m}}$	Minimum dijet mass between any two jets	8	3	2
$\Delta R_{\mathrm{hl}}^{\max\ \Delta\mathrm{R}}$	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
$\Delta R_{\mathrm{bb}}^{\max\ \mathrm{m}}$	ΔR between the two b-tagged jets with the largest invariant mass	-	9	-
$\Delta R_{\mathrm{lj}}^{\min\ \Delta\mathrm{R}}$	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
$m_{\mathrm{jj}}^{\max\ p_{\mathrm{T}}}$	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

MVA: S-B discrimination

- Train a Neural Network (NN) to separate S from B in each region
  - Uses a suite of variables from event shape and kinematics, single experimental object kinematics
  - uses also Matrix Element technique (variable D1)
- Lots of diagnostics on background shapes from control regions designed by cutting on **$H_T = \Sigma p_T$(selected jets)**



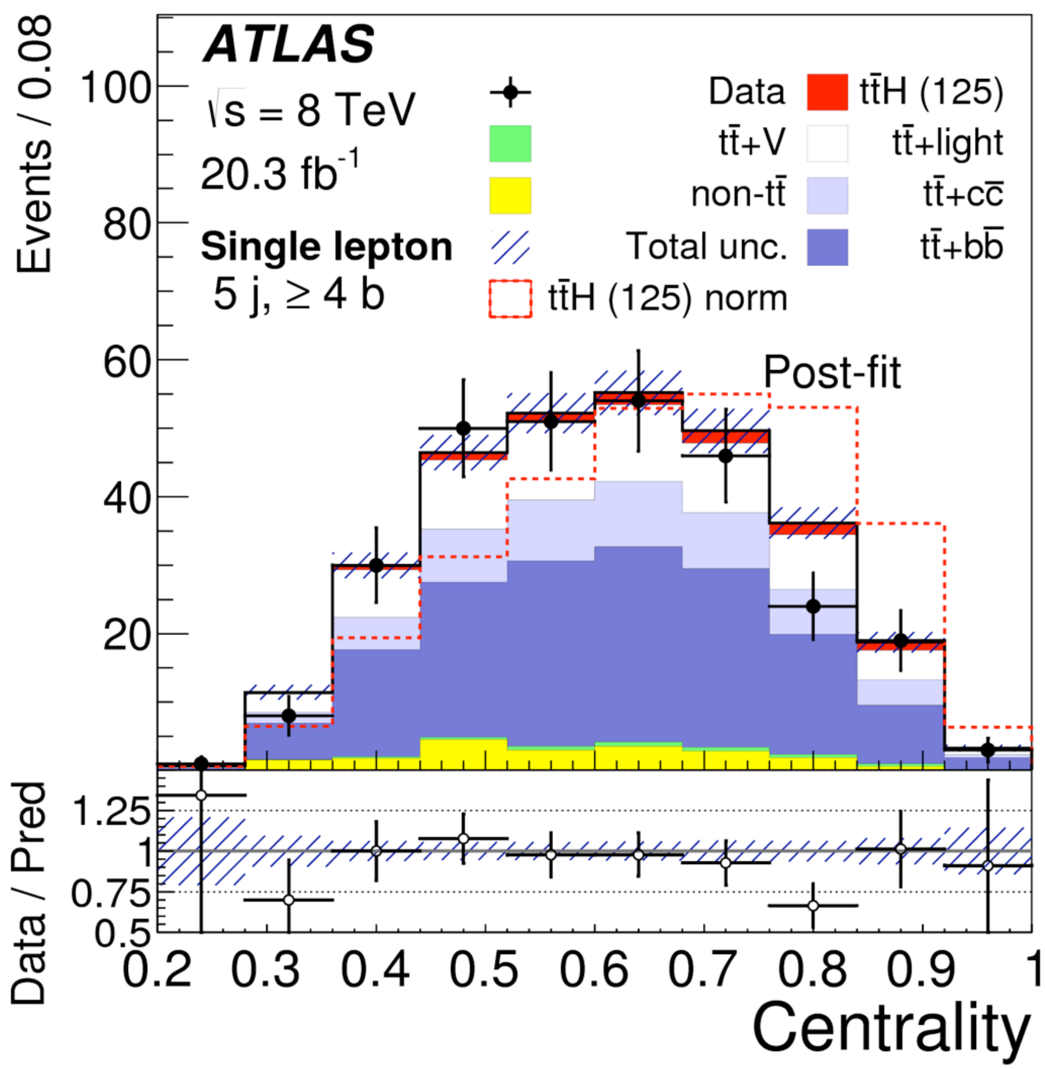
Two of the highest ranked variables

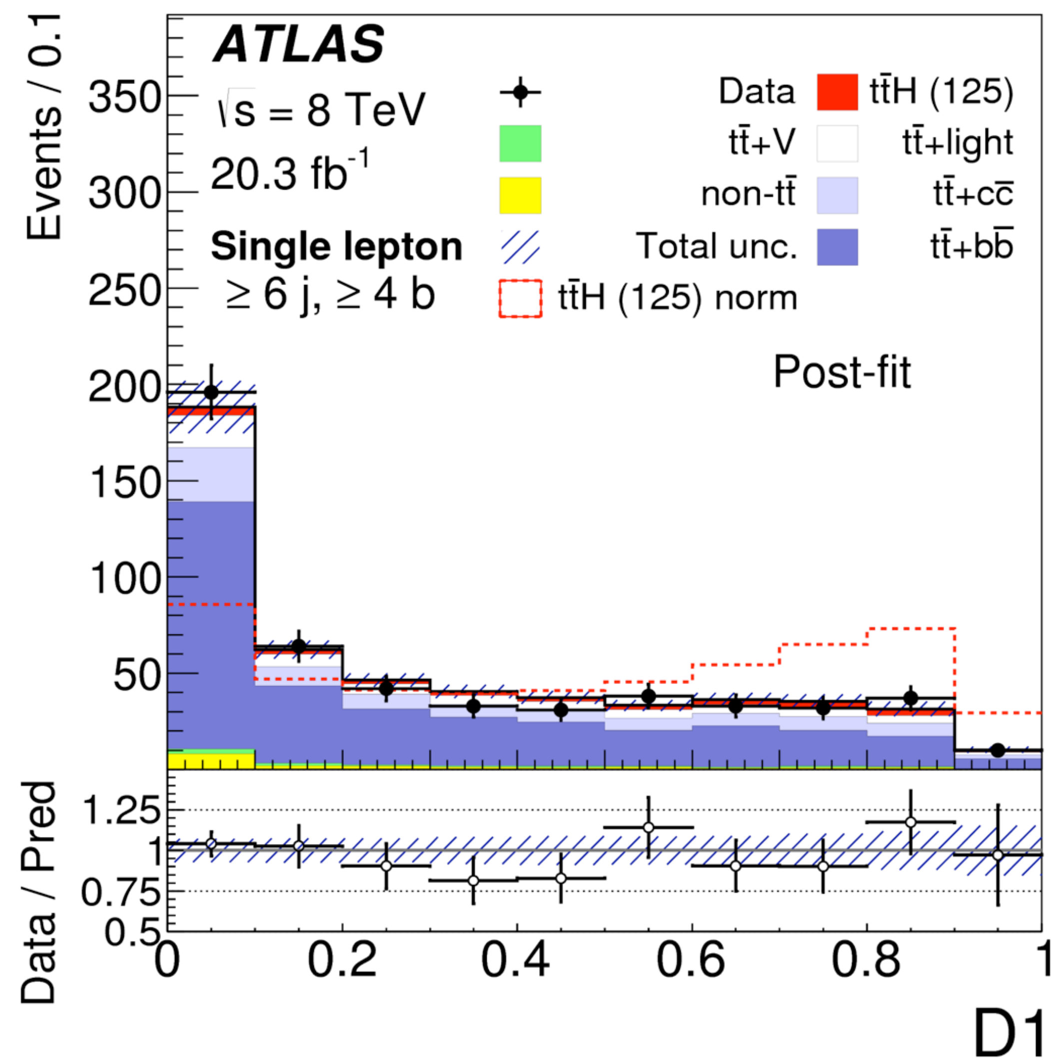


MVA: S-B discrimination

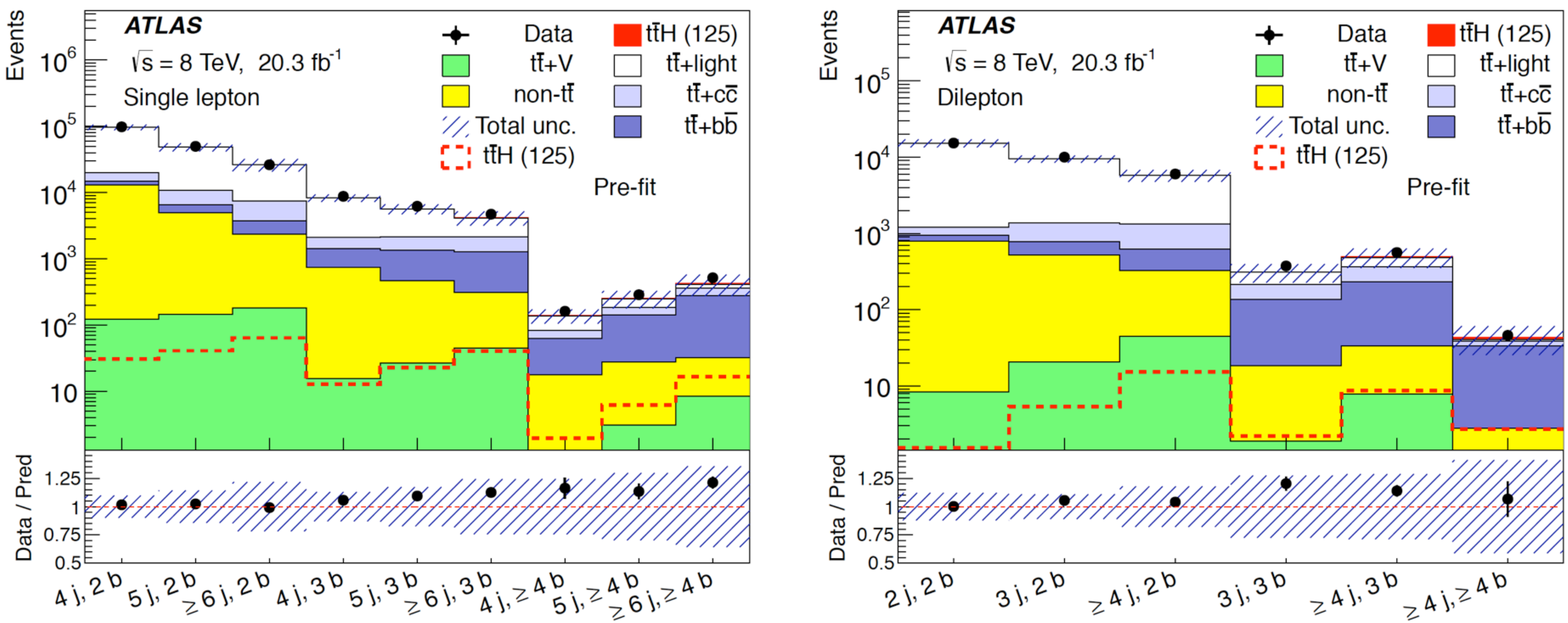
l+jets	2 b-tags	3 b-tags	4 b-tags
4 jets	CR (H_T cut)	CR (H_T cut)	CR (H_T cut)
5 jets	CR (H_T cut)	tt+HF vs LF NN	SR (NN cut)
≥ 6 jets	CR (H_T cut)	SR (NN cut)	SR (NN cut)

dilepton	2 b-tags	3 b-tags	4 b-tags
2 jets	CR (H_T cut)		
3 jets	CR (H_T cut)	SR (NN cut)	
≥ 4 jets	CR (H_T cut)	SR (NN cut)	SR (NN cut)





Pre-fit yields in comparison



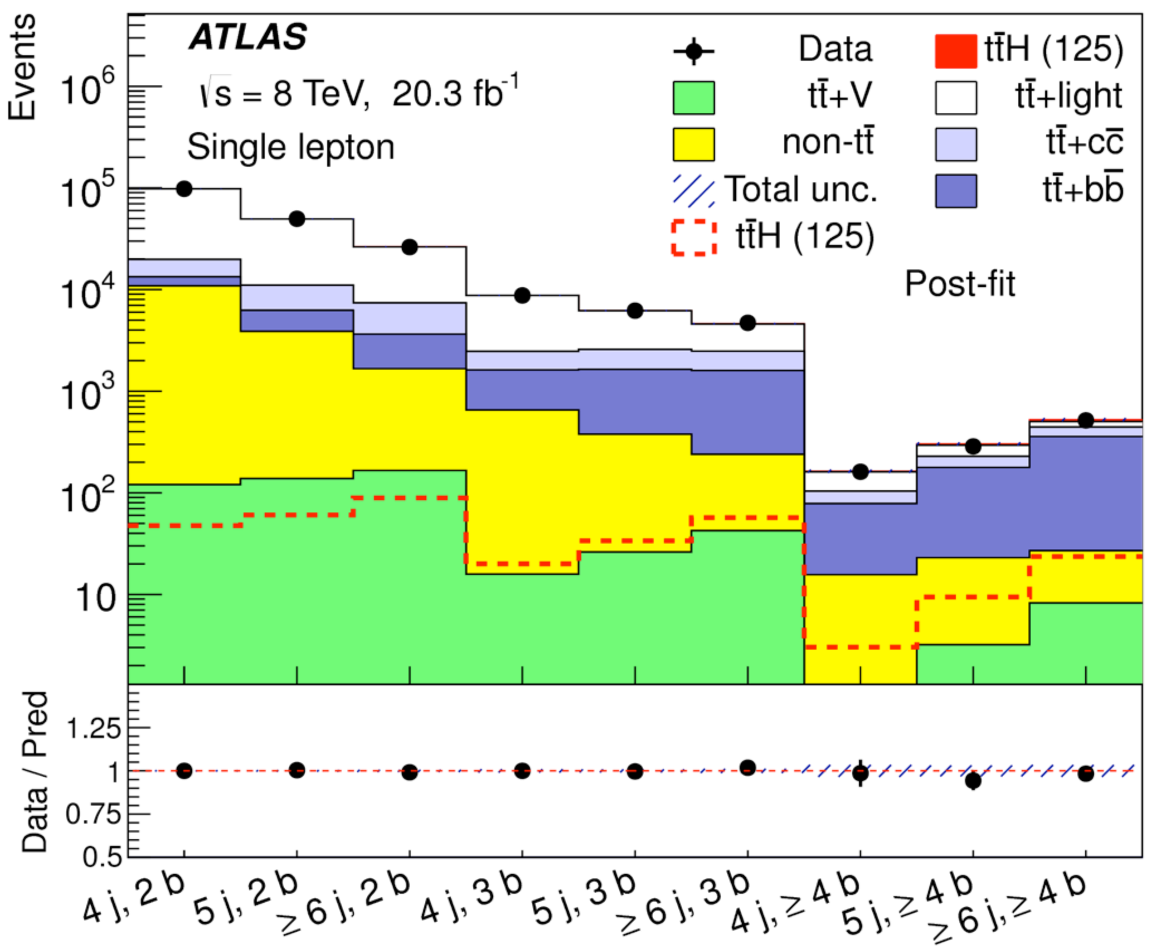
l+jets

dilepton

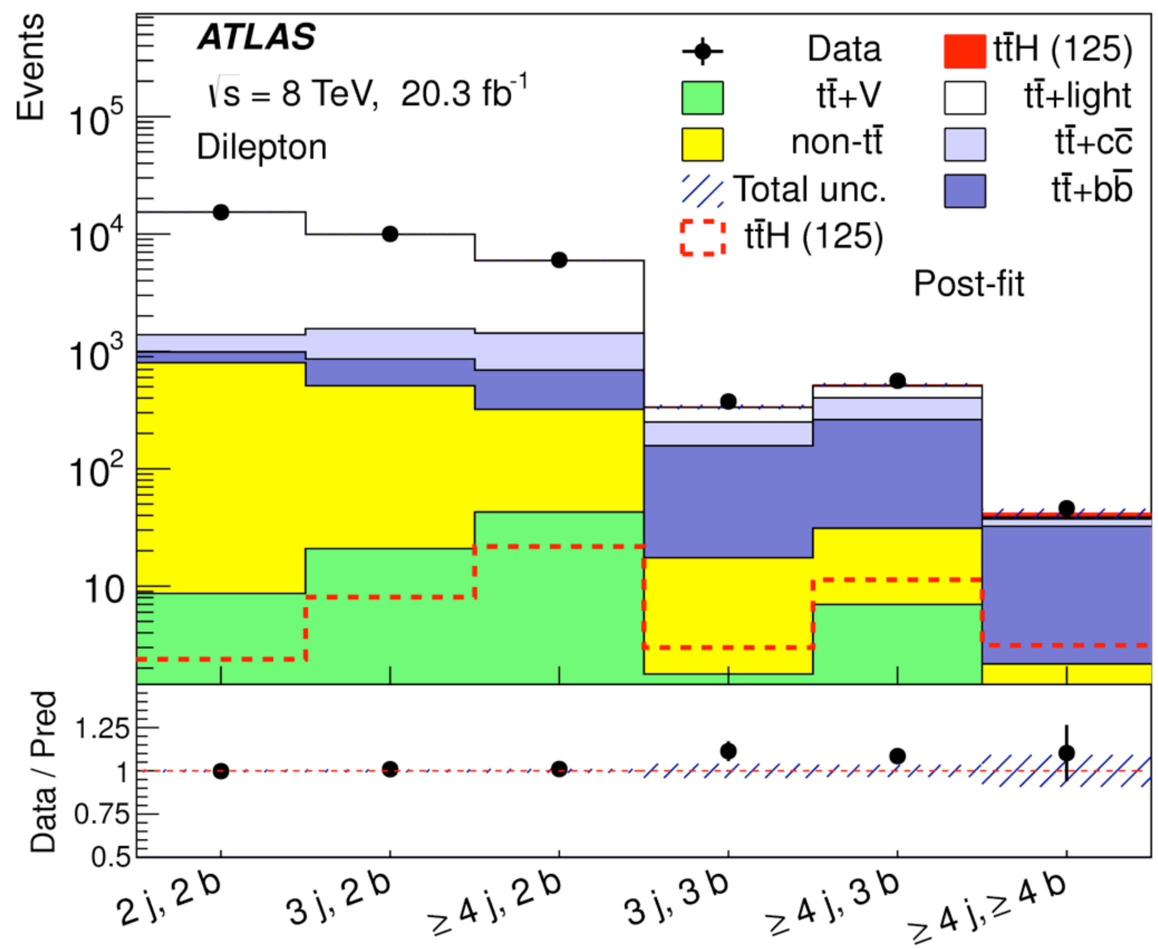
- Nominal (i.e. as evaluated from full variations) systematic uncertainties included

Post-fit description

- A profile likelihood fit is performed simultaneously considering all the events passing the cuts in the various analysis regions
  - reduces effect of systematic uncertainties thanks to high-stats, bkg enriched control regions



l+jets

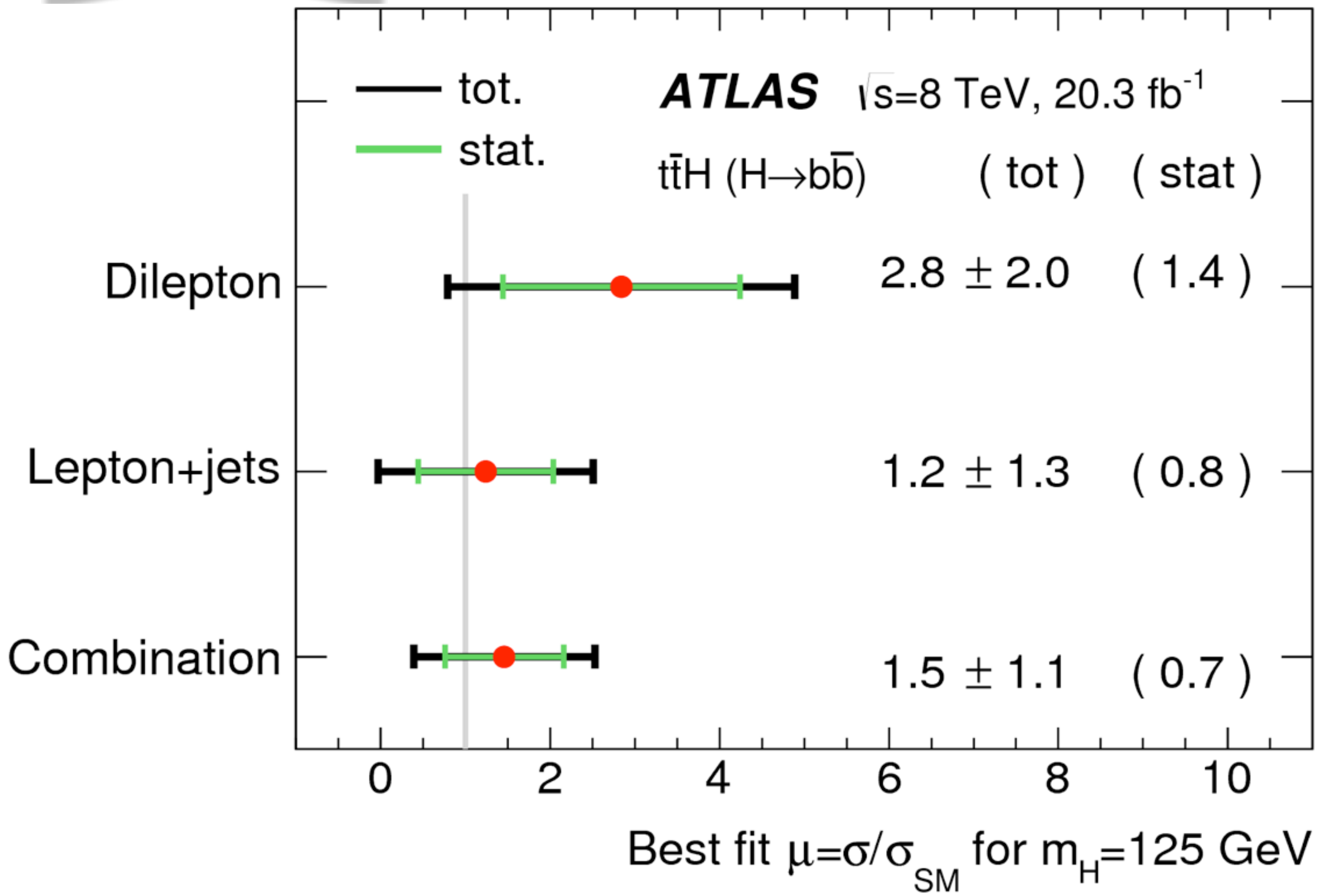


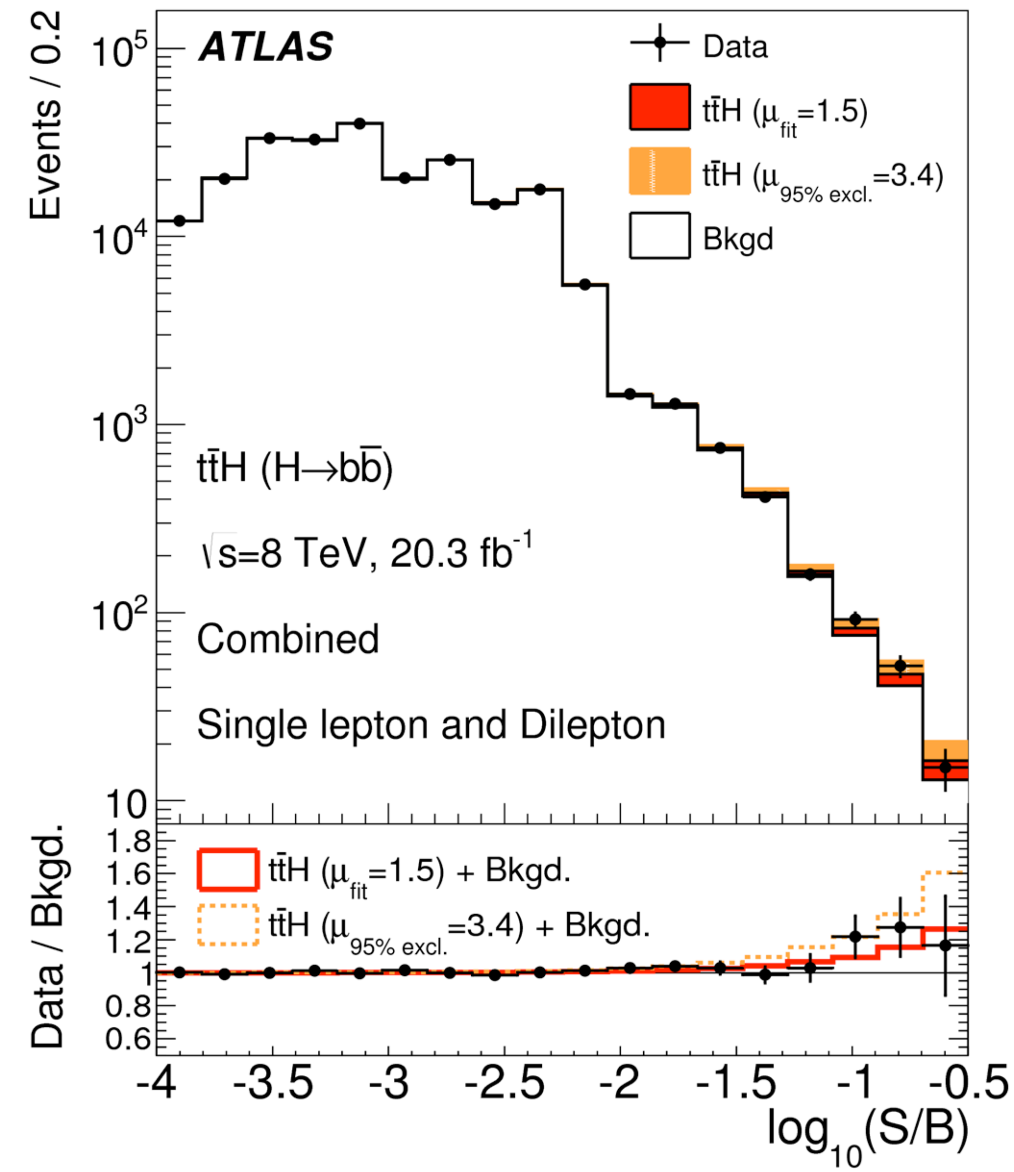
dilepton

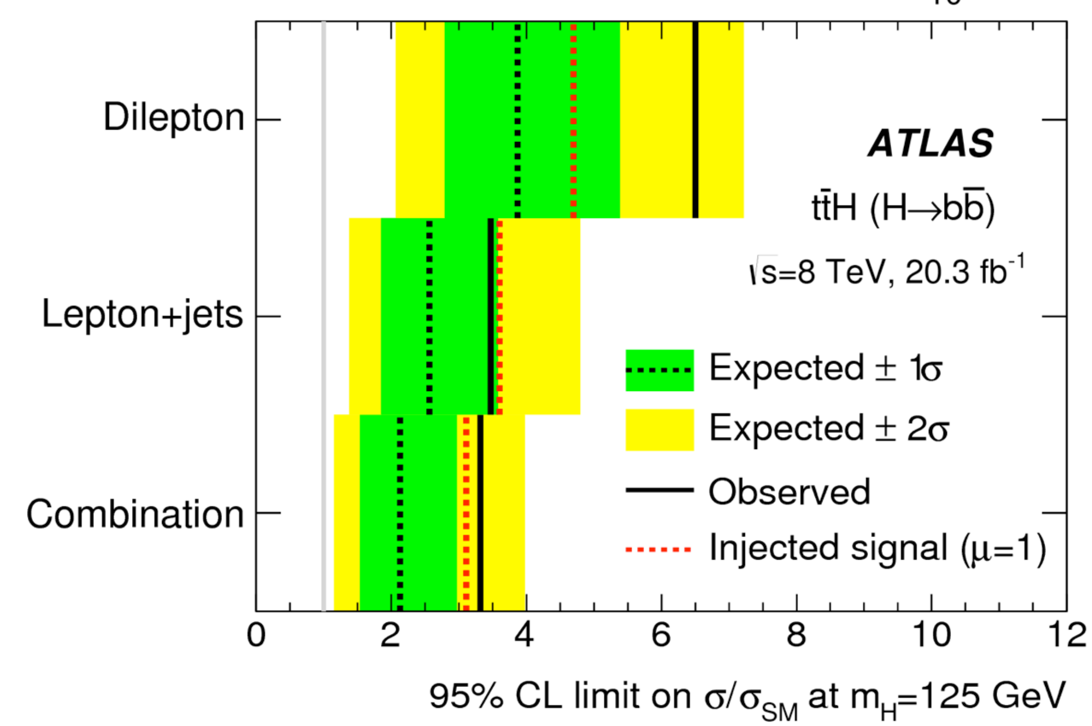
- Fit to data *under the signal-plus-background hypothesis*
- Signal normalised to the fitted μ (=1.7)

Results

$\mu_{ttH} = \sigma/\sigma_{SM}$







- Expected 95% CL: 2.6 x SM, m(H) = 125 GeV
- Best fit signal strength μ_{ttH} = 1.7 ± 1.0
- Significance Observed (Exp'd) : 1.3 σ (0.8 σ)

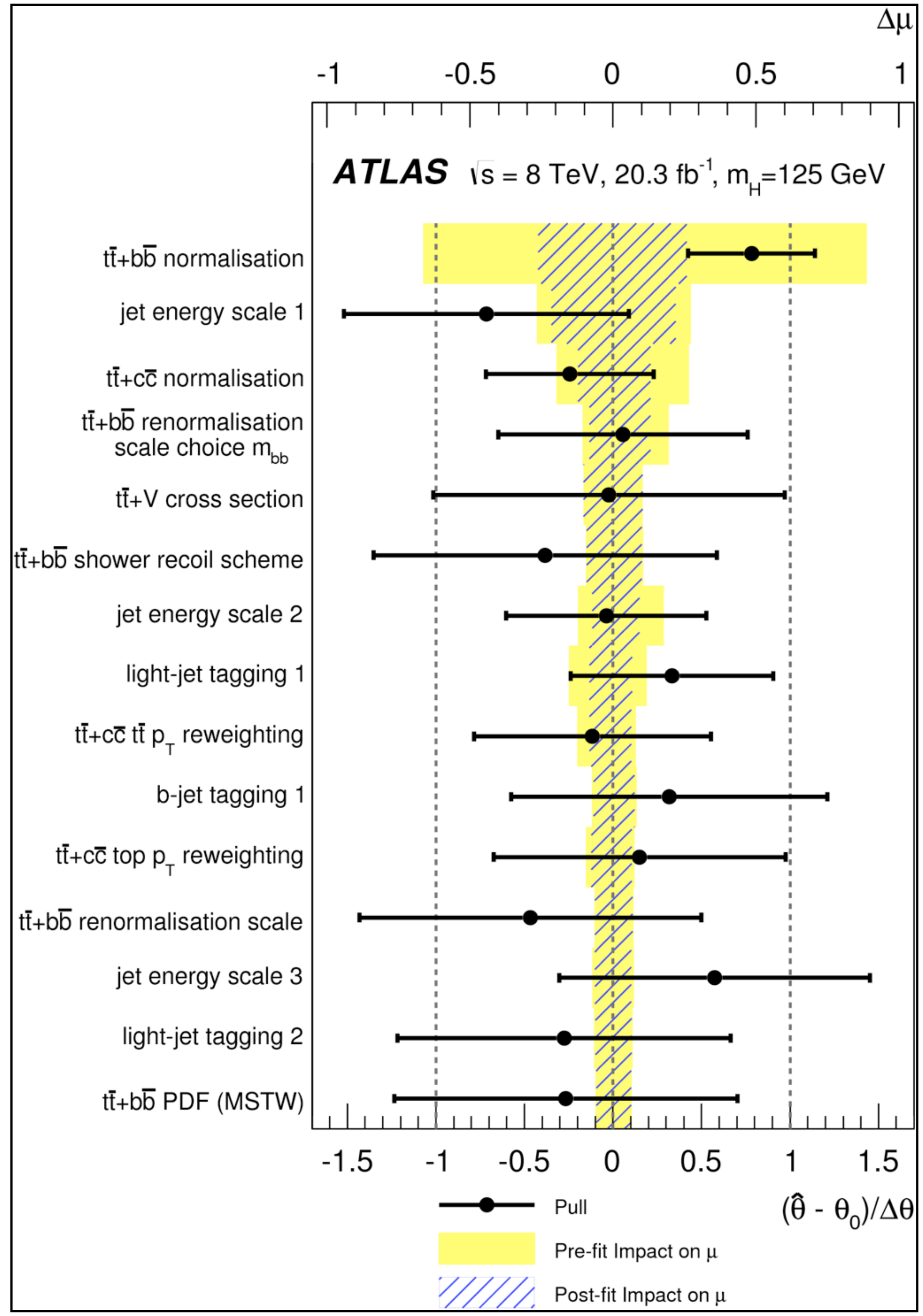
Systematic uncertainties

Pre-fit

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

S=shape, N=normalization

Sources with biggest impact on μ, as constrained by data



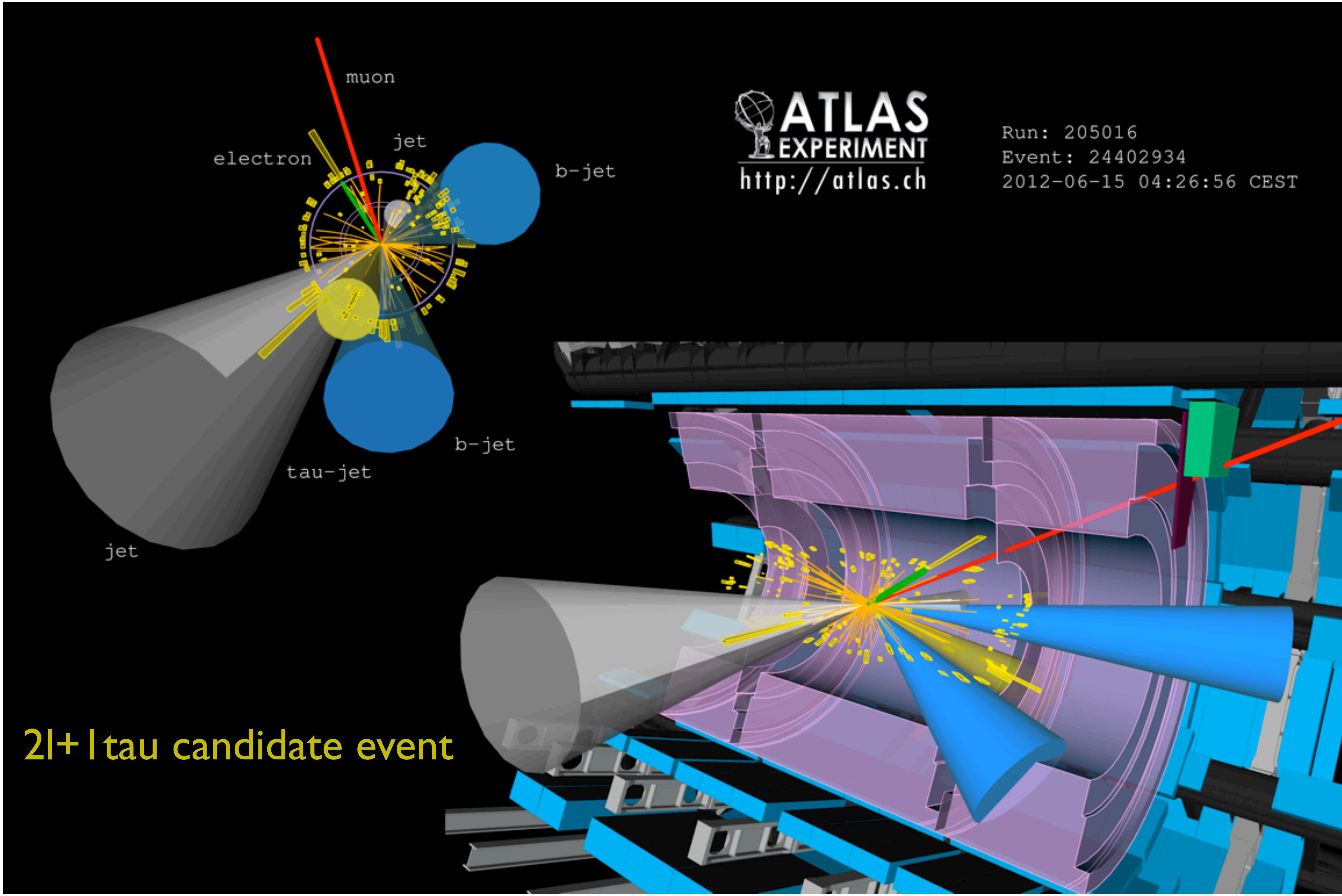
- Main experimental syst is from jet energy scale
- Main theo syst is from tt+bb normalization, but constrained by profile LL fit

ttH(multi-lepton)

	Higgs boson decay mode			
Category	WW^*	$\tau\tau$	ZZ^*	Other
$2\ell 0\tau_{\text{had}}$	80%	15%	3%	2%
3ℓ	74%	15%	7%	4%
$2\ell 1\tau_{\text{had}}$	35%	62%	2%	1%
4ℓ	69%	14%	14%	4%
$1\ell 2\tau_{\text{had}}$	4%	93%	0%	3%

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2015-006/

paper in preparation



2l+1tau candidate event

Topologies

- high N(lep), which suppresses ttbar background
  - only contributing if secondary lepton from HF decays identified as "prompt"
- mostly irreducible tt+V(=W/Z) background
  - after experimental selections on lepton p_T, tracking and calorimeter isolation
- N(jets, pt>25 GeV) and N(b-tags) selections based on S/B optimizations and
  - reflecting different jet multiplicity in various signal channels
  - additional M(l,l) veto for 3lep to suppress ttZ (but $tt\gamma^*$ remains relevant bkg)

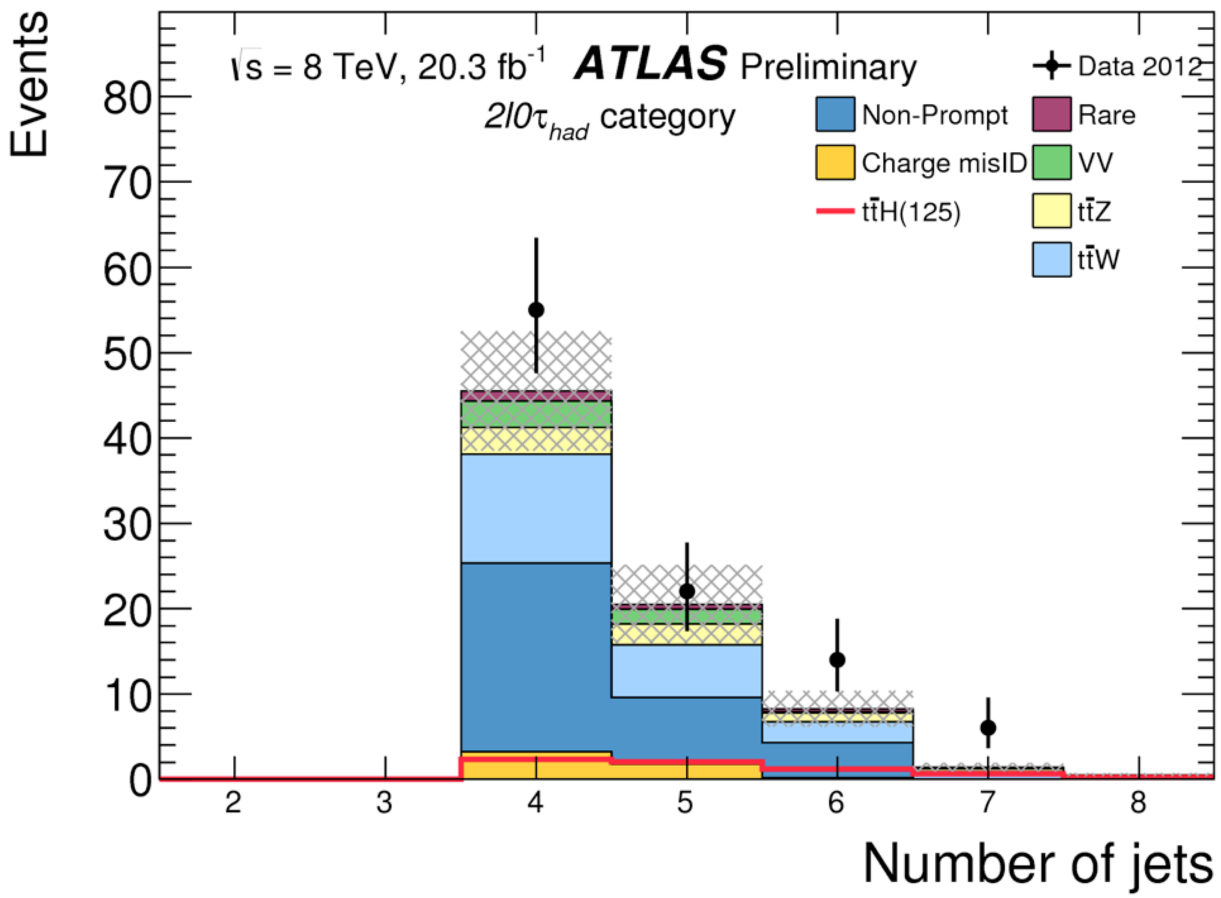
Event categories

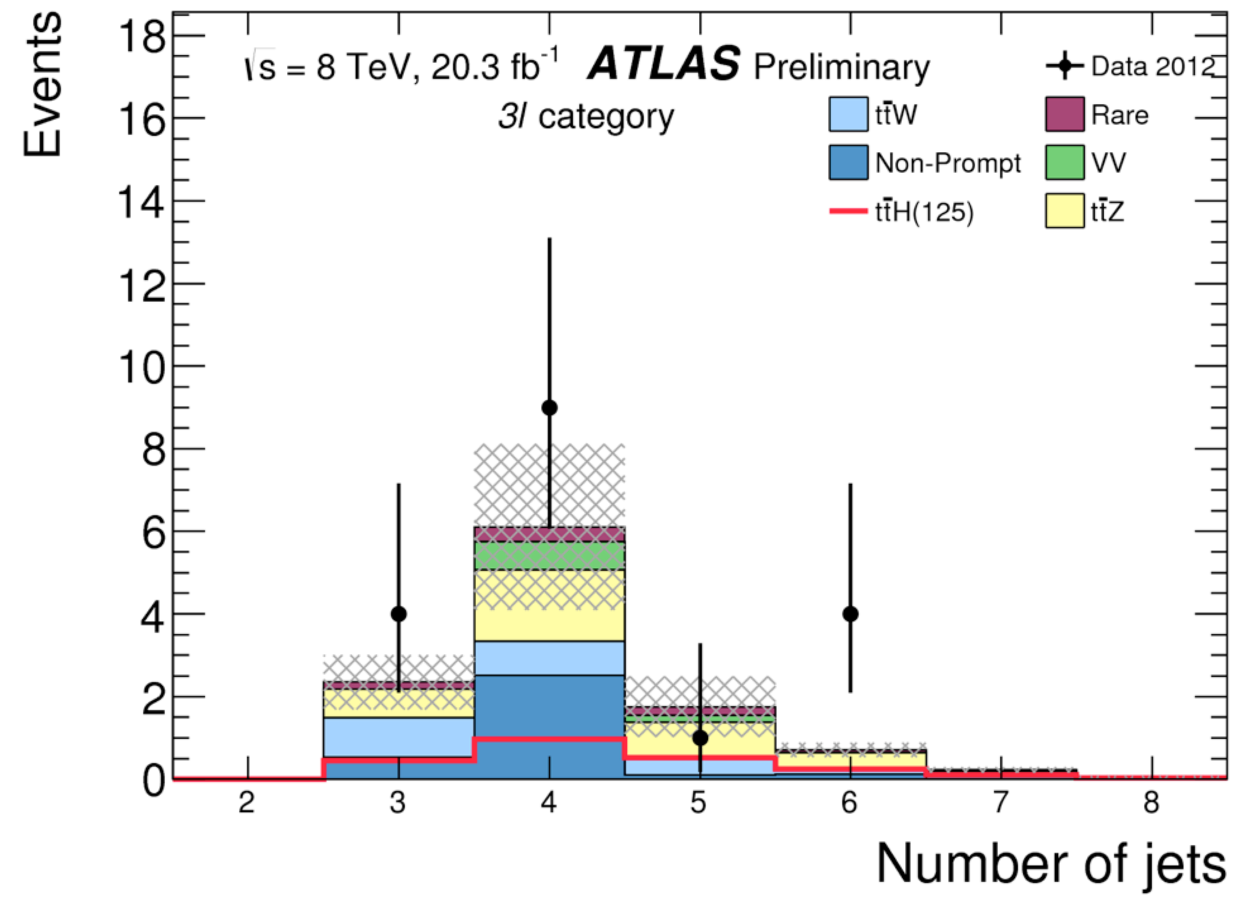
- "Cut and count" strategy: events categorized into 5 channels and further split to maximize signal sensitivity
- Divided into "signal regions": by N(e/μ), and w/ or w/o a hadronically decaying τ

Category	q mis-id	Non-prompt	$t\bar{t}W$	$t\bar{t}Z$	Diboson	Expected Bkg.	$t\bar{t}H$ ($\mu = 1$)	Observed
$ee + \geq 5j$	1.1 ± 0.5	2.3 ± 1.2	1.4 ± 0.4	0.98 ± 0.32	0.47 ± 0.42	6.5 ± 2.0	0.73 ± 0.11	10
$e\mu + \geq 5j$	0.85 ± 0.35	6.7 ± 2.4	4.8 ± 1.4	2.1 ± 0.7	0.38 ± 0.32	15 ± 4	2.13 ± 0.31	22
$\mu\mu + \geq 5j$	–	2.9 ± 1.4	3.8 ± 1.1	0.95 ± 0.31	0.69 ± 0.63	8.6 ± 2.5	1.41 ± 0.21	11
$ee + 4j$	1.8 ± 0.7	3.4 ± 1.7	2.0 ± 0.4	0.75 ± 0.25	0.74 ± 0.58	9.1 ± 2.3	0.44 ± 0.06	9
$e\mu + 4j$	1.4 ± 0.6	12 ± 4	6.2 ± 0.9	1.5 ± 0.2	1.9 ± 1.2	24.0 ± 4.5	1.16 ± 0.14	26
$\mu\mu + 4j$	–	6.3 ± 2.6	4.7 ± 0.9	0.80 ± 0.26	0.53 ± 0.30	12.7 ± 3.0	0.74 ± 0.10	20
3ℓ	–	3.2 ± 0.7	2.3 ± 0.9	3.9 ± 0.9	0.86 ± 0.59	11.4 ± 3.1	2.34 ± 0.32	18
$2\ell 1\tau_{\rm had}$	–	$0.4\,^{+0.6}_{-0.4}$	0.38 ± 0.15	0.37 ± 0.09	0.12 ± 0.15	1.4 ± 0.6	0.47 ± 0.02	1
$1\ell 2\tau_{\rm had}$	–	15 ± 5	0.17 ± 0.07	0.37 ± 0.10	0.41 ± 0.42	16 ± 6	0.68 ± 0.07	10
4ℓ Z-enr.	–	$\lesssim 10^{-3}$	$\lesssim 3 \times 10^{-3}$	0.43 ± 0.13	0.05 ± 0.02	0.55 ± 0.17	0.17 ± 0.01	1
4ℓ Z-dep.	–	$\lesssim 10^{-4}$	$\lesssim 10^{-3}$	0.002 ± 0.002	$\lesssim 2 \times 10^{-5}$	0.007 ± 0.005	0.03 ± 0.00	0

- *3l accepts events with ≥4j,≥1b-tag and 3j,≥2b-tag*
- "Non-prompt" (mainly ttbar) remains largest bkg
- except for μμ+5j and especially 3lep,
  - where non-resonant tt+ll expected to be hardest entry to beat down in Run 2

Jet multiplicities





- Plots illustrate different relative contributions from ttbar vs tt+V in the two main channels

- Electrons with charge sign mis-determined ~20% of same-sign ee bkg
  - Mainly from Z→ee + jets events
  - Estimated on data by means of likelihood binned in electron (p_T,eta)
  - calibrated on ad-hoc sample of opposite sign dilepton events under Z peak

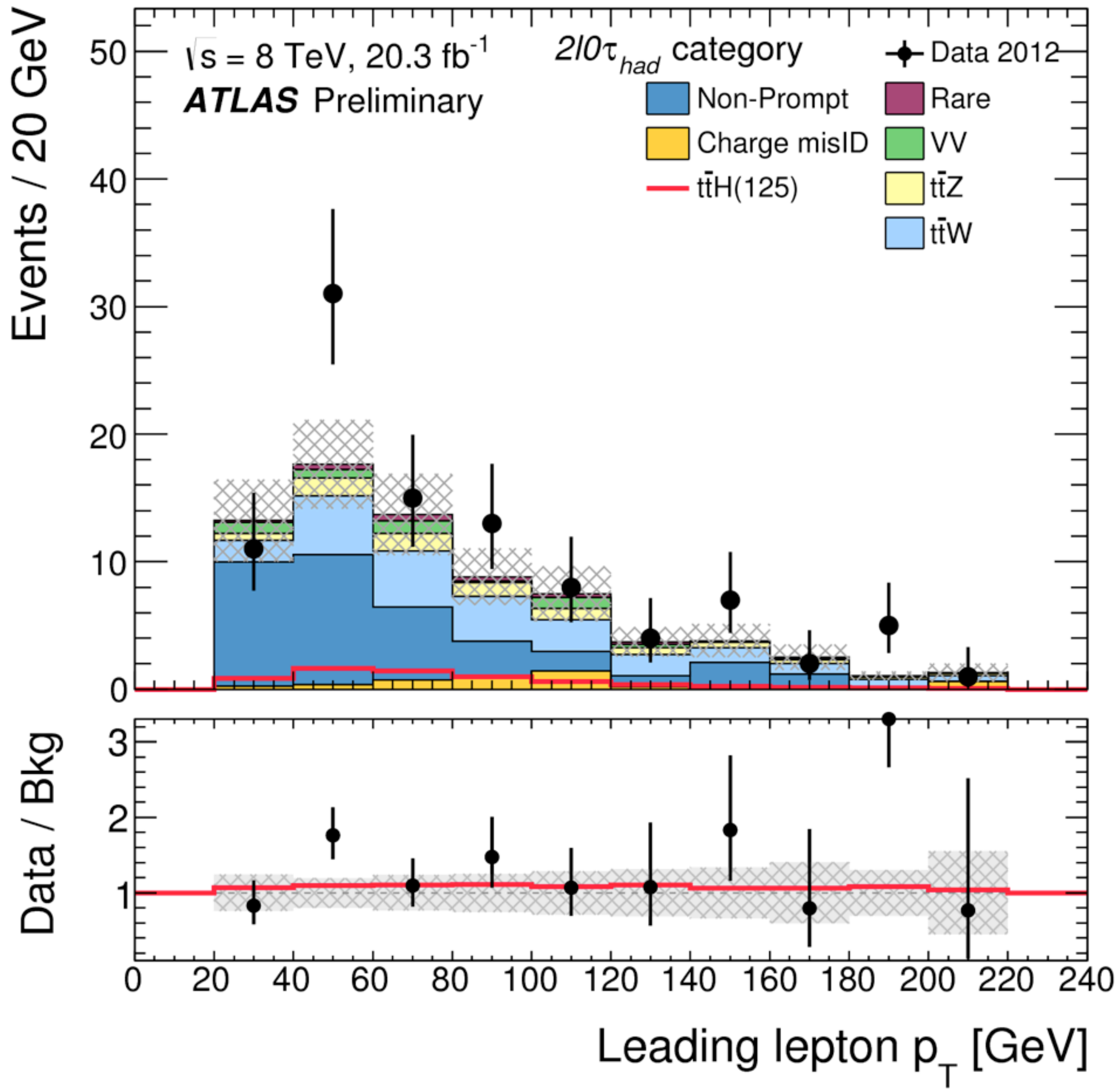
Main backgrounds: non-prompt e/mu

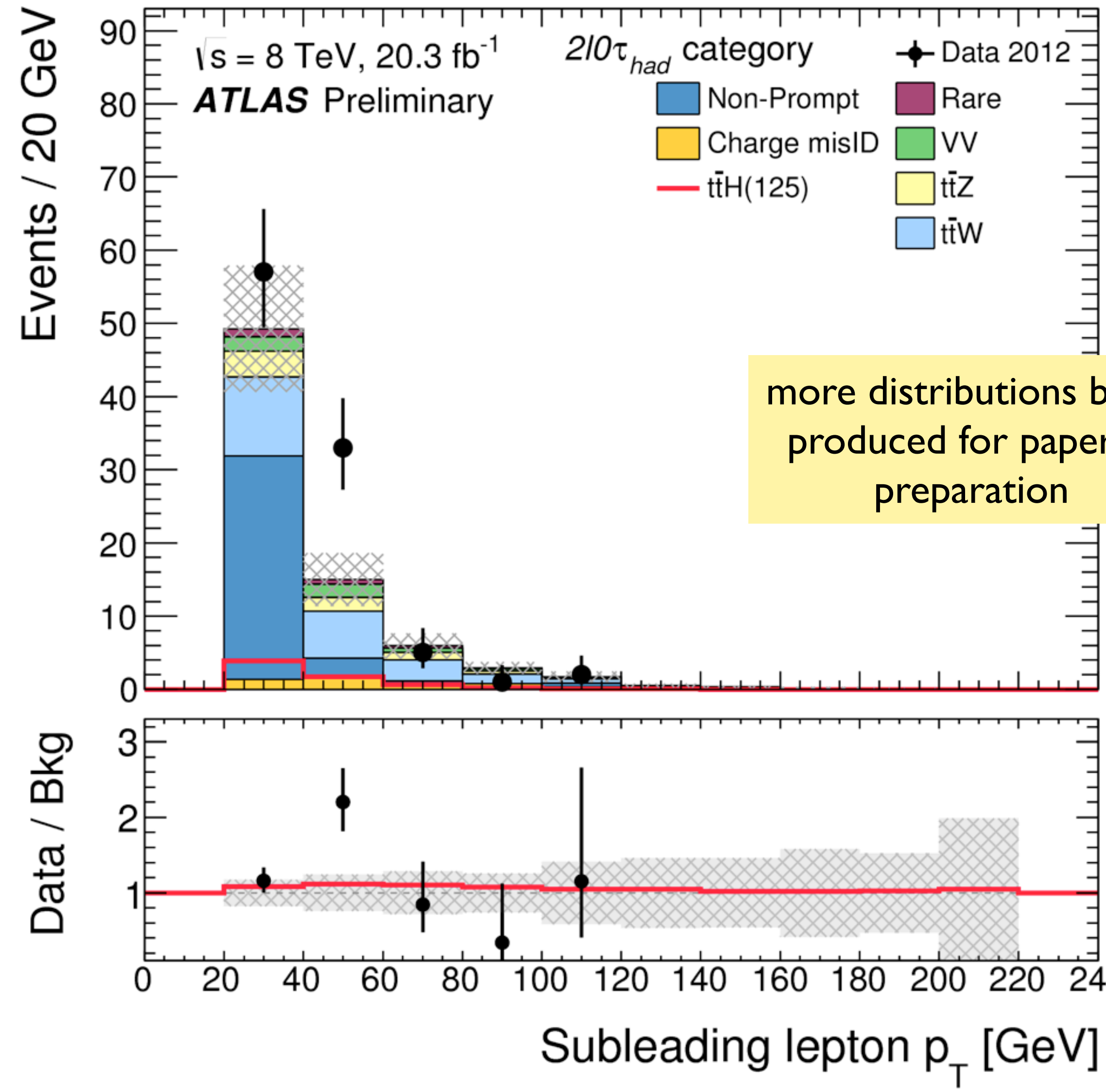
- *In situ* method: estimate normalization from data in non-prompt (ttbar) enriched region ("Loose")
  - by reverting selection on isolation, pt, tracking, tau Id
- then extrapolate back into signal region

> - Method:
>   - Define a transfer factor in control region:
> $$\theta = (N_{Data} - N_{prompt})^{tight\text{-}tight} / (N_{Data} - N_{prompt})^{tight\text{-}loose}$$
>   - Predict number of non-prompts:
> $$N_{fakes} = \theta \times (N_{Data} - N_{prompt})^{tight\text{-}tloose}$$

- Theta from 2-3 jet events or MC *(reproduces relevant variable distr. within 20% in "auxiliary" region orthogonal to both signal and loose selections)*
  - flavour composition same across regions *(checked on MC that >95% of non-prompt leptons are from heavy flavour decays)*
  - jet multiplicity same in signal and loose regions *(true at 10% level)*
- All *deviations* from above assumptions are taken as systematic uncertainties

Main backgrounds: non-prompt e/mu





more distributions being produced for paper in preparation

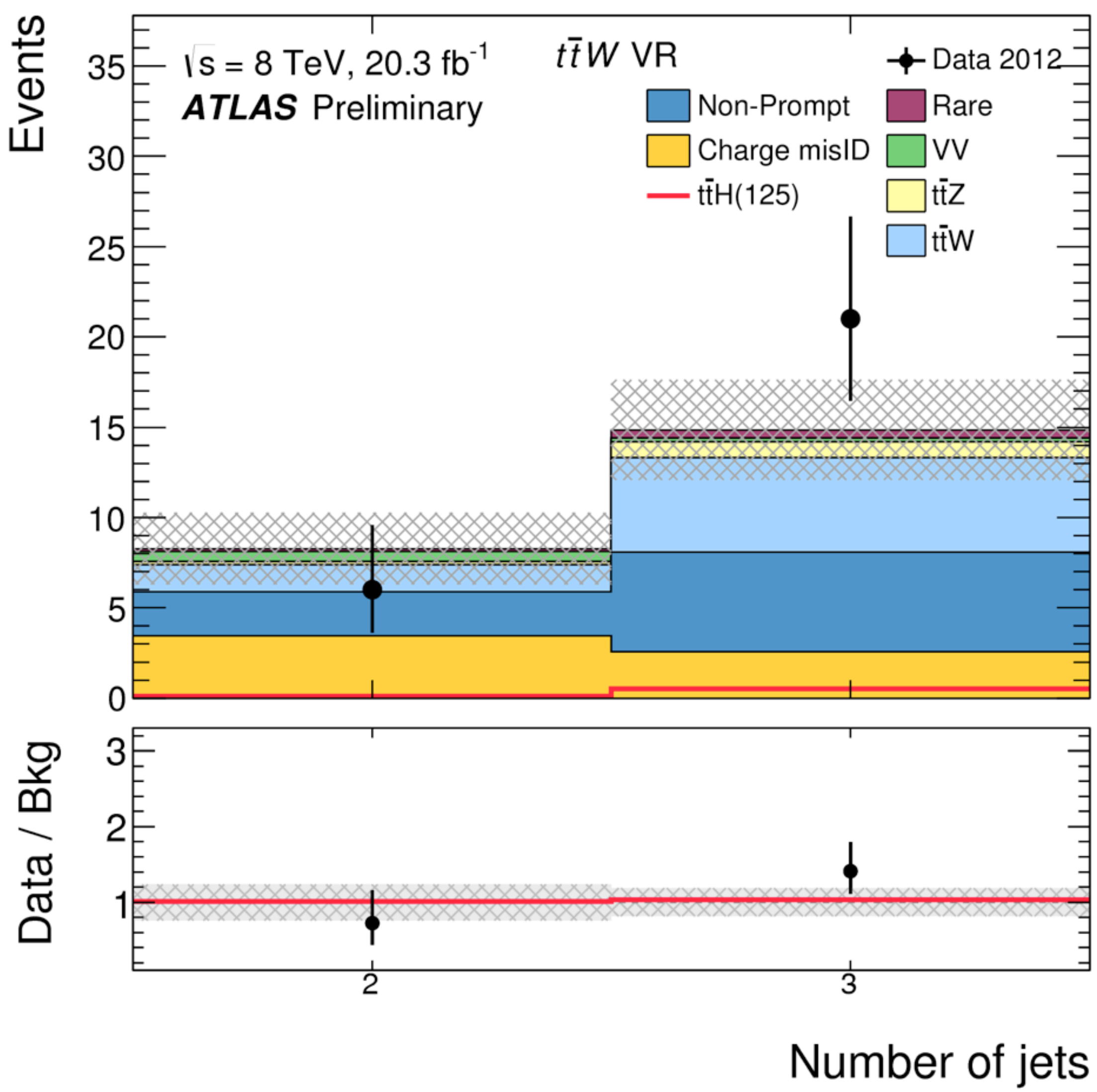
Total uncertainties on non-prompt estimates:
30-50% for 2lSS
25% for 3l
50% on very small (<2%) bkg for 4l

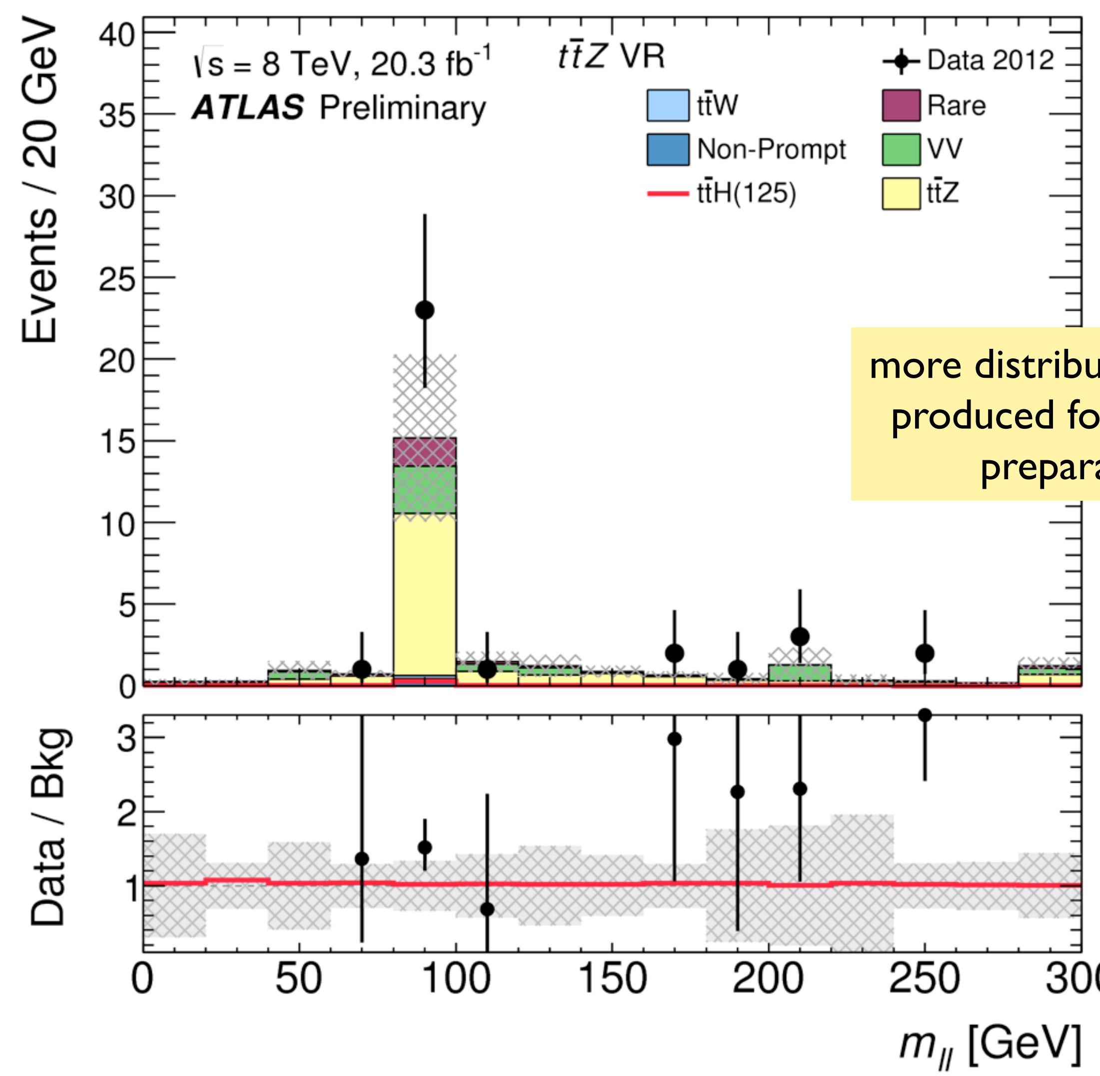
Main backgrounds: non-prompt τ_{had}

- Similar method in 2l+1τ_{had} as for e/μ
  - fake factor from ≤3 jet events
  - assuming "fake" τ_{had} rate independent of e/μ one
  - 100% unc.
- 1l+2τ_{had} takes ttbar from MC
  - too low yields, but cross-check with data-driven method
  - MC validated to 50% level with data from sideband in τ_{had} τ_{had} visible mass
  - 35% unc

Main backgrounds: ttV

- ttV taken from MC and normalized to NLO x-sec calculations
  - hard to extract from data (low yield and/or ttbar contamination) and degenerate with signal region
  - e.g. attempted to extract ttW from W charge asymmetry in 2l, but large ttbar subtraction results in >50% uncertainty on yields
- validation in ttV enriched regions (using events at Z pole for ttZ and looking at same-sign 2l events with 2 ≤ N(jets) ≤ 3)





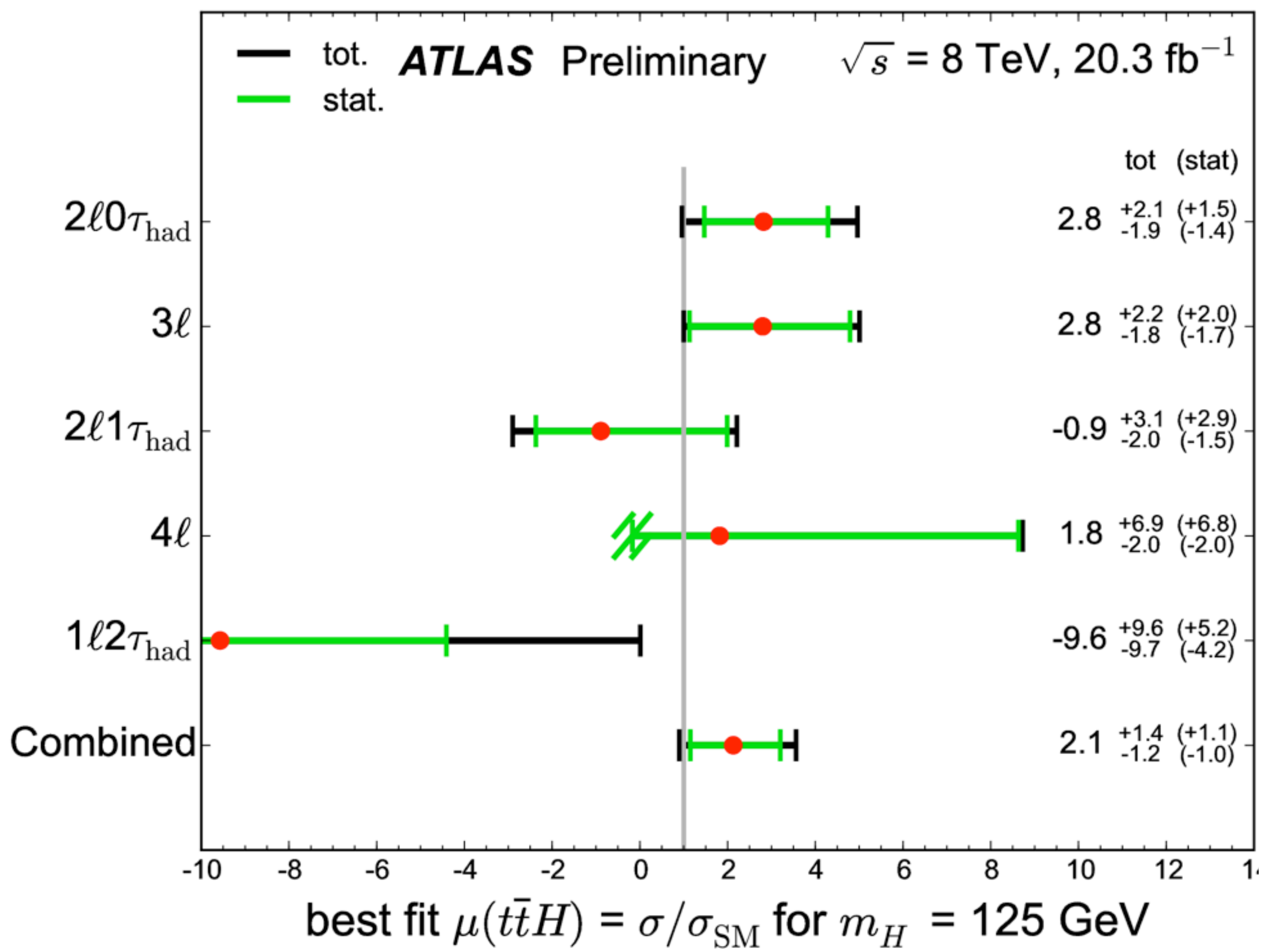
more distributions being produced for paper in preparation

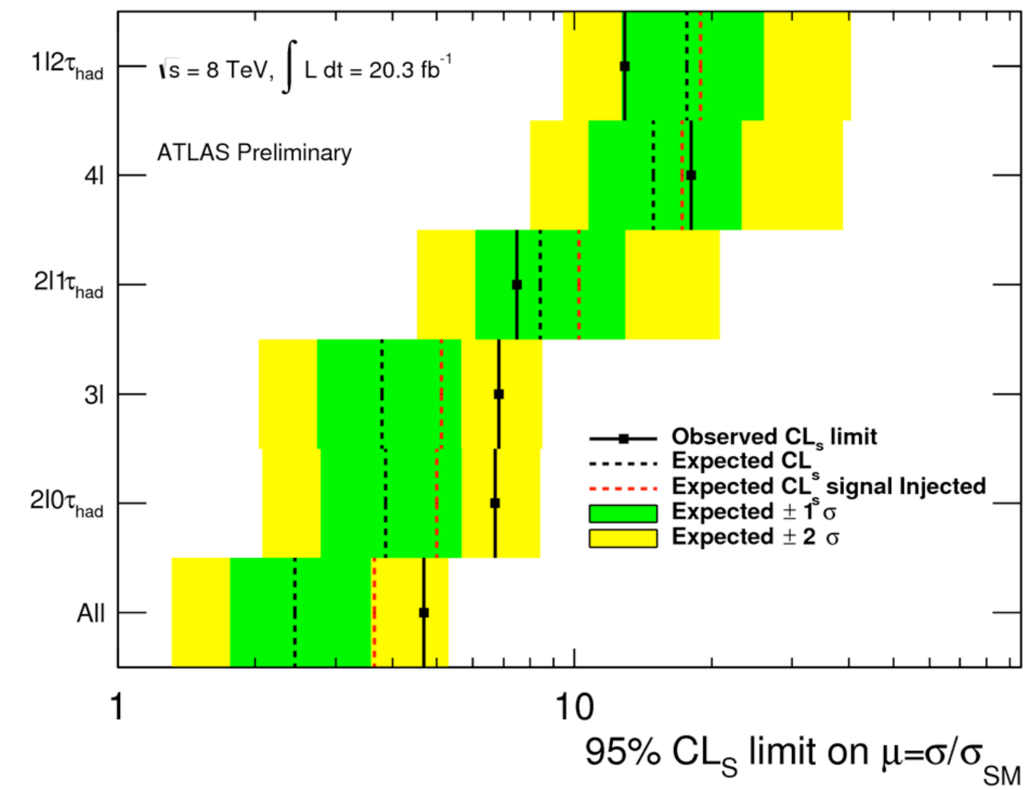
Other backgrounds: VV

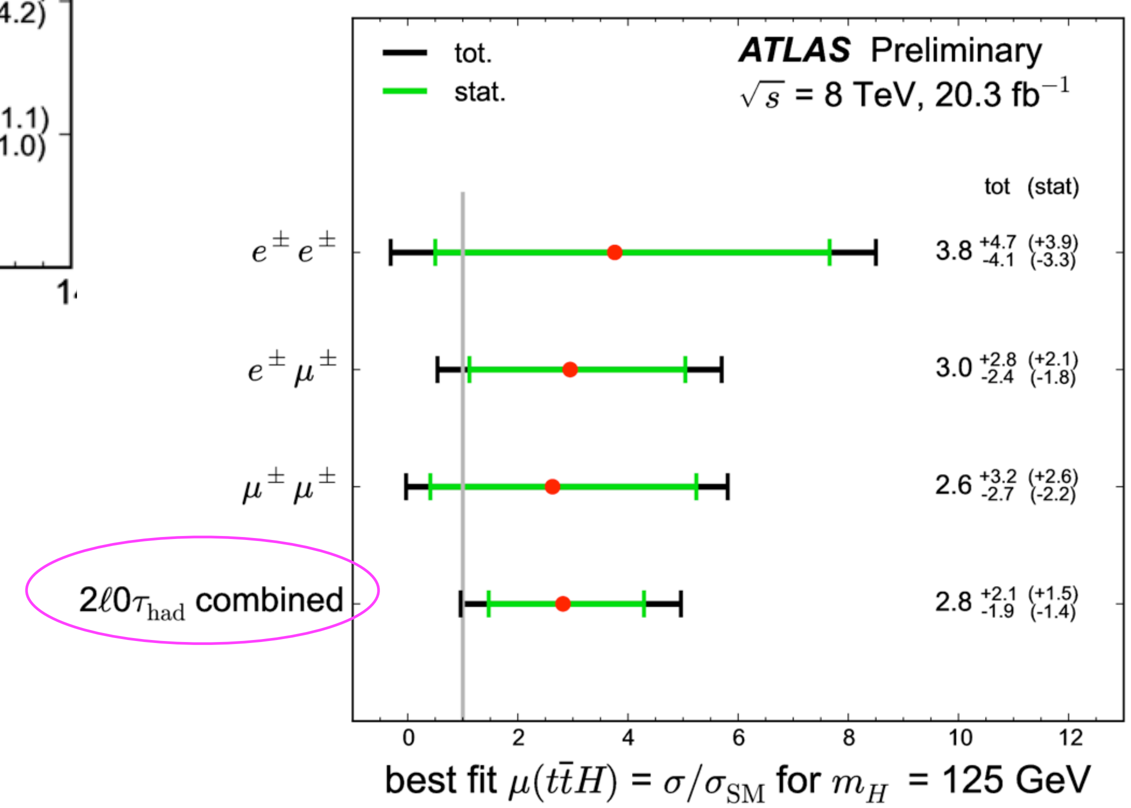
- VV (ZZ,WZ) taken from MC
  - less important backgrounds (but for sub-leading 4l channel)
  - measurements of x-sec exist only for inclusive production, while here VV+b component is relevant
    - e.g. WZ+b is 50% of all WZ in 3l channel
  - MC estimate checked with data around Z peak with 0 or 1 b-tags
    - WZ inclusive jet spectrum well described in MC
    - WZ+b is constrained to 100% level and therefore a 50% uncertainty on WZ is applied for 3l

Results

$\mu_{ttH} = \sigma/\sigma_{SM}$







- Expected 95% CL: 2.4 x SM, m(H) = 125 GeV
- Best fit signal strength $\mu_{ttH} = 2.1^{+1.4}_{-1.2}$
- Significance Observed (Exp'd) : 1.8 σ (0.9 σ)
- *tHj and WtH treated as bkg here and added to signal in global ATLAS coupling fit*

Systematic uncertainties

Table 3: Leading sources of systematic uncertainty and their impact on the measured value of μ.

Source	$\Delta\mu$	
$2\ell 0\tau_{\text{had}}$ non-prompt muon transfer factor	+0.38	−0.35
$t\bar{t}W$ acceptance	+0.26	−0.21
$t\bar{t}H$ inclusive cross section	+0.28	−0.15
Jet energy scale	+0.24	−0.18
$2\ell 0\tau_{\text{had}}$ non-prompt electron transfer factor	+0.26	−0.16
$t\bar{t}H$ acceptance	+0.22	−0.15
$t\bar{t}Z$ inclusive cross section	+0.19	−0.17
$t\bar{t}W$ inclusive cross section	+0.18	−0.15
Muon isolation efficiency	+0.19	−0.14
Luminosity	+0.18	−0.14

- Main experimental syst is from secondary lepton bkg in 2l0tau
- Main theo syst are from cross-section of ttV and acceptance of ttW +additional jets (parton shower for higher number of jets)

ttH(γγ)

http://arxiv.org/abs/1409.3122
Phys. Rev. D 90, 112015

Overall strategy

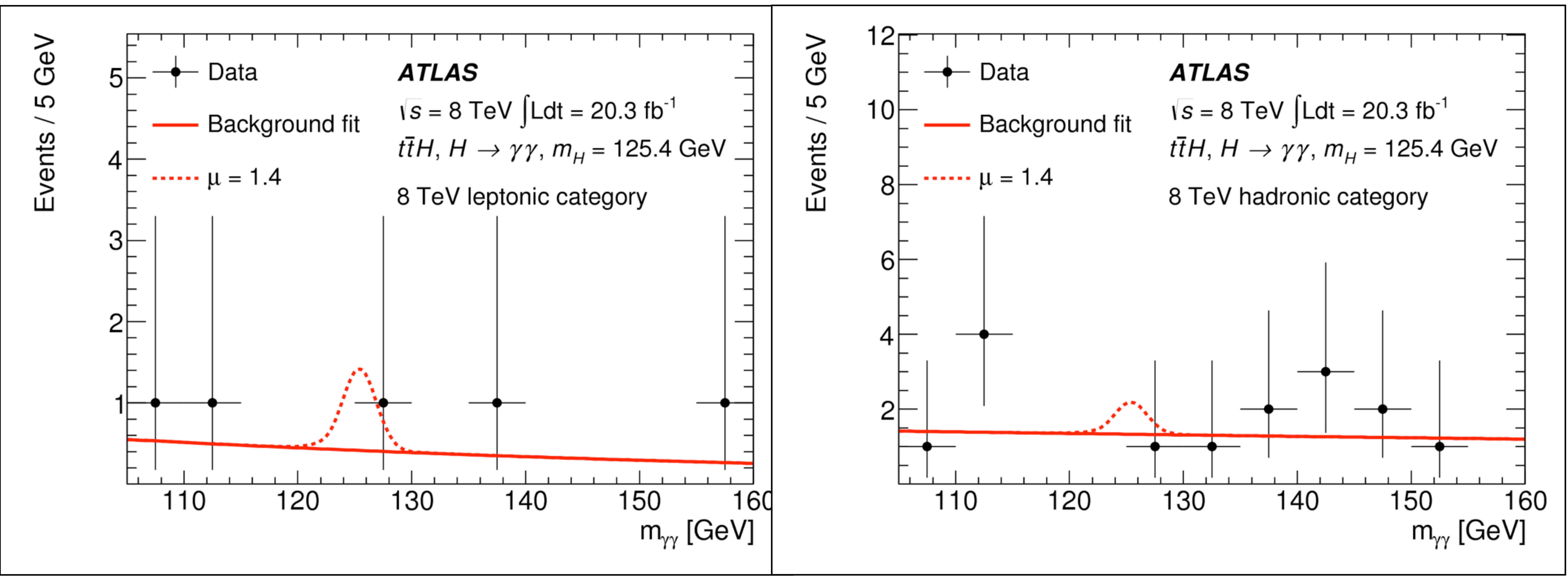
- 2 isolated, high-p_T photons for Higgs boson mass reconstruction
  - leading (sub-leading) photon required to have $E_T > 0.35\ m_{\gamma\gamma}$ ($0.25\ m_{\gamma\gamma}$), and the di-photon mass to be between 105 GeV and 160 GeV ("Signal Region")
- Categorize events according to top quark decay:
  - Optimized on the expected limit on μ_{ttH}
  - leptonic channel: ≥ 1 leptons (e or μ), ≥ 1 b-tagged jet
  - hadronic channel: ≥ 6 jets, ≥ 2 b-tagged jet
  - Combined signal selection: eff ~ 15%, purity ~80%

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

absolute numbers (N_H) — fractions (ggF … WtH) — absolute numbers (N_B)

Analysis

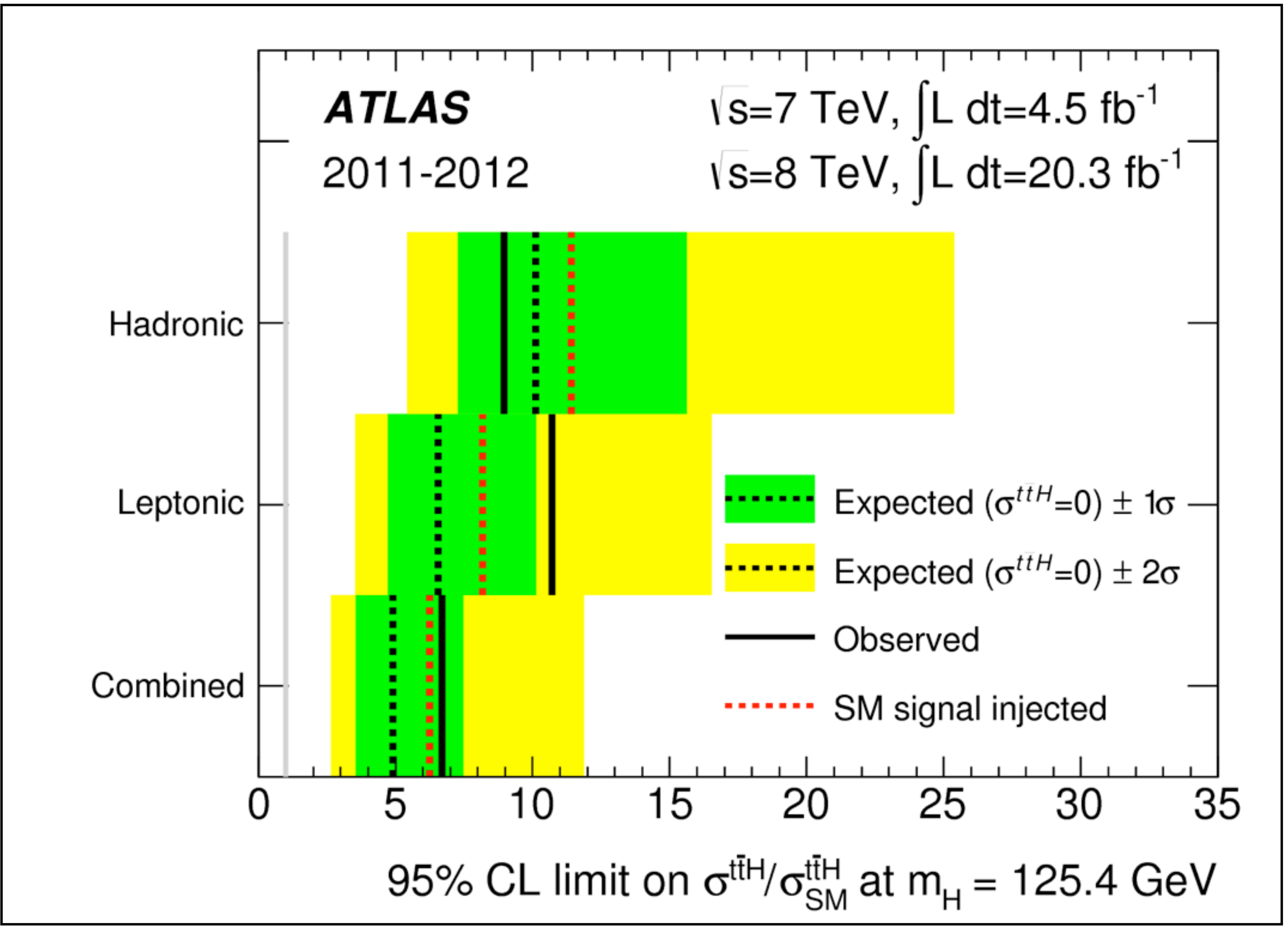
- Look for localized excess around $m_{\gamma\gamma}$=125.4 GeV
- Unbinned LL fit to background and signal in signal region
  - signal: Gaussian core portion and a power-law low-end tail + Gaussian (tails)
  - background: exponential function tested on ad-hoc control region (loosening photon ID) sensitive to jets faking γ



- $m_{\gamma\gamma}$ resolution dominated by resolution on E_γ

Results

$\mu_{ttH} = \sigma/\sigma_{SM}$



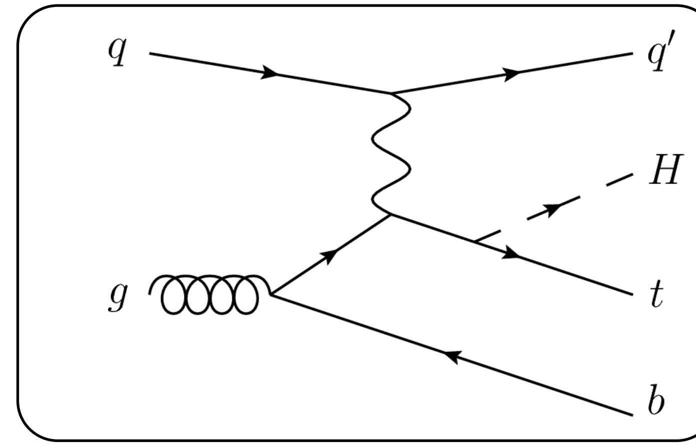
- m_H=125.4 GeV
- Expected limit on μ_{ttH} = 4.9
- Observed limit on μ_{ttH} = 6.5

- Comparable impact of theory and experimental systematic uncertainties on final yield of events

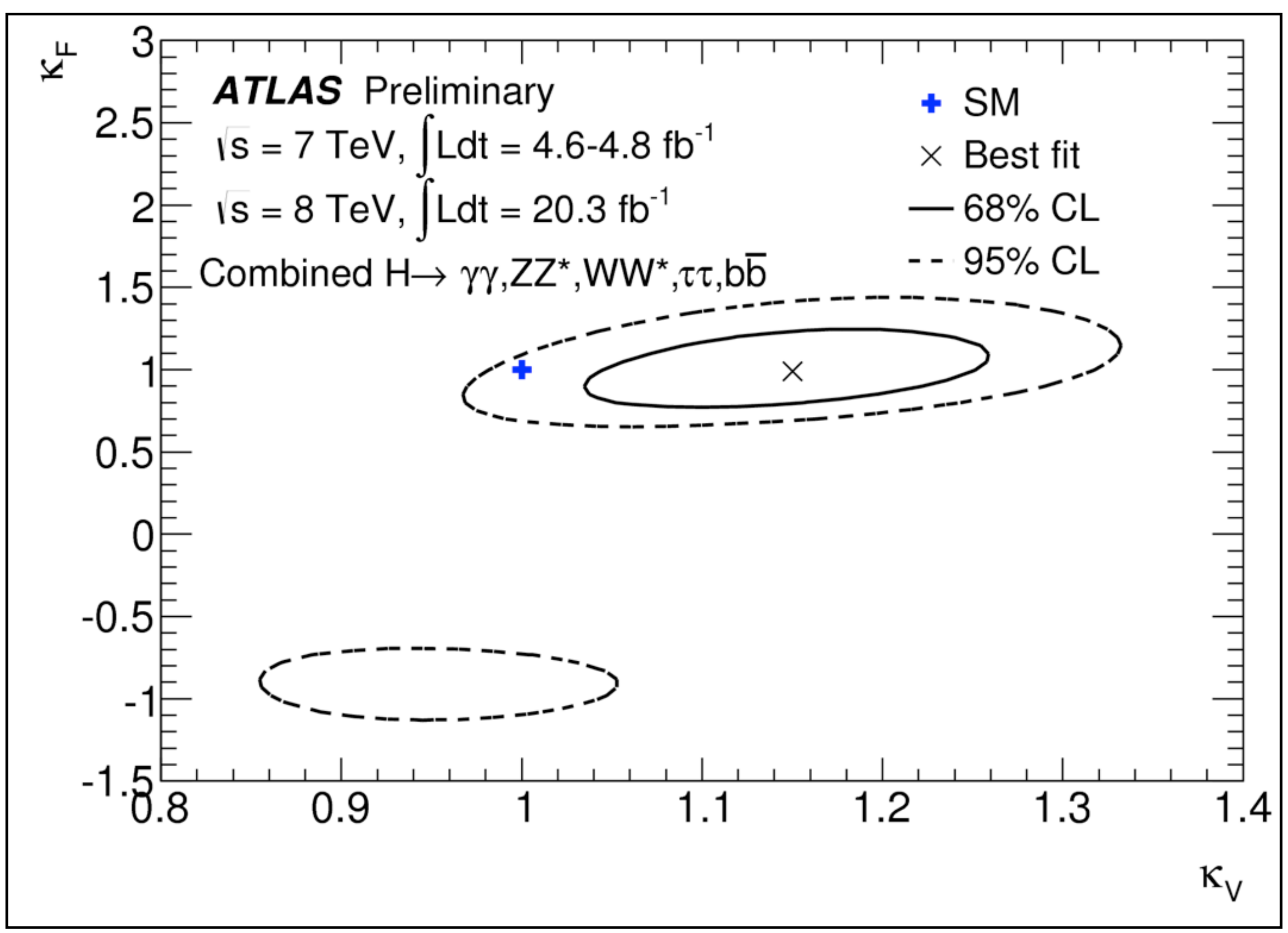
	$t\bar{t}H$ [%]		$tHqb$ [%]		WtH [%]		ggF [%]	WH [%]
	had.	lep.	had.	lep.	had.	lep.	had.	lep.
Luminosity	±1.8							
Photons	±10.0	±10.0	±10.0	±10.0	±10.0	±10.0	±10.0	±10.0
Leptons	< 0.1	±0.7	< 0.1	±0.7	< 0.1	±0.6	< 0.1	±0.7
Jets and E_T^{miss}	±9.1	±1.6	±19	±2.4	±13	±2.9	±30	±10
Bkg. modeling	0.12 evt.	0.01 evt.	applied on the sum of all Higgs boson production processes					
Theory ($\sigma \times$ BR)	+10,−13		+8,−7		+12,−12		+11,−12	+5.5,−5.5
MC Modeling	±11	±3.3	±12	±4.4	±13	±5.2	±130	±100

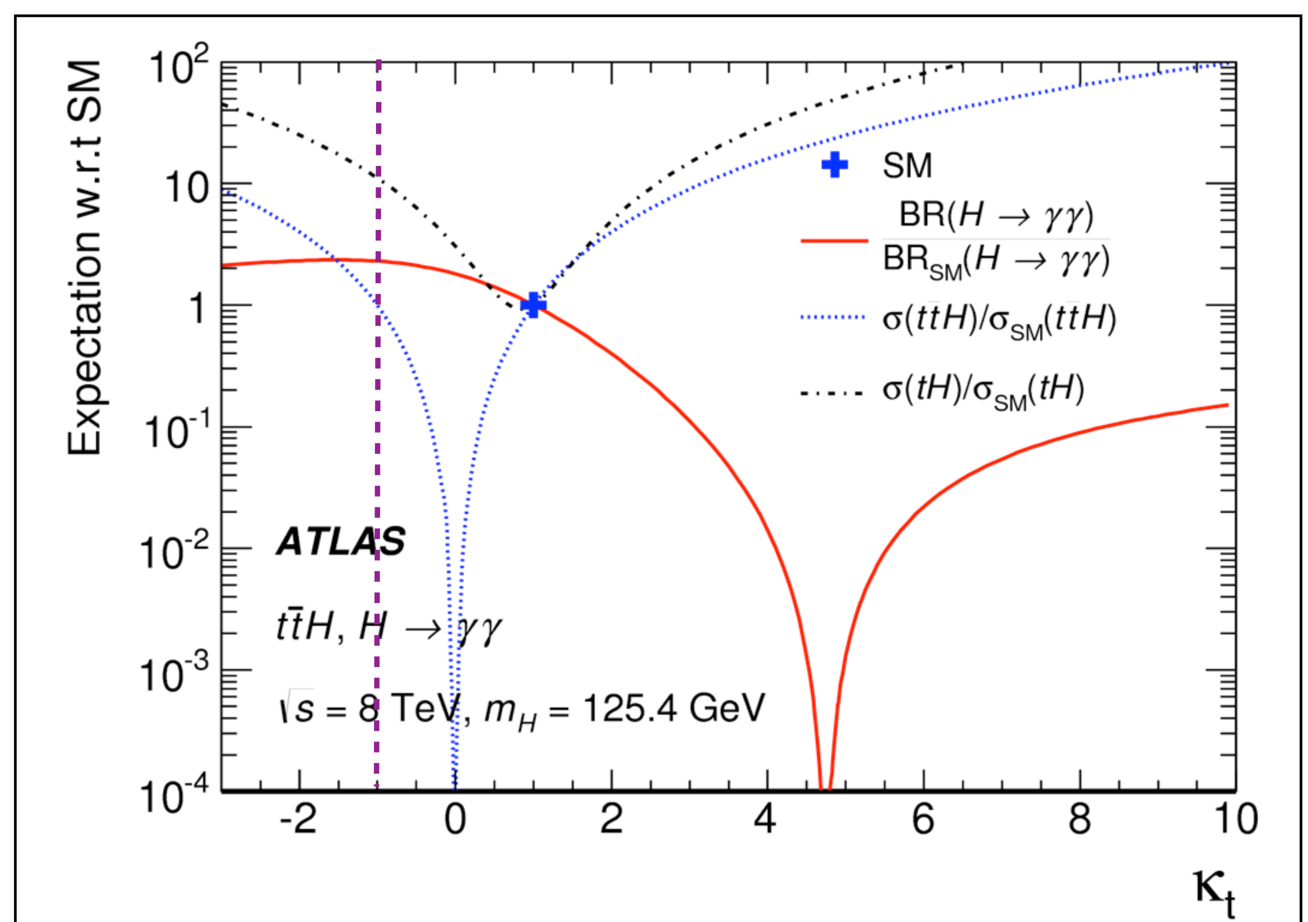
(W)tH with γγ channel

- Residual sign ambiguity between fermionic and couplings



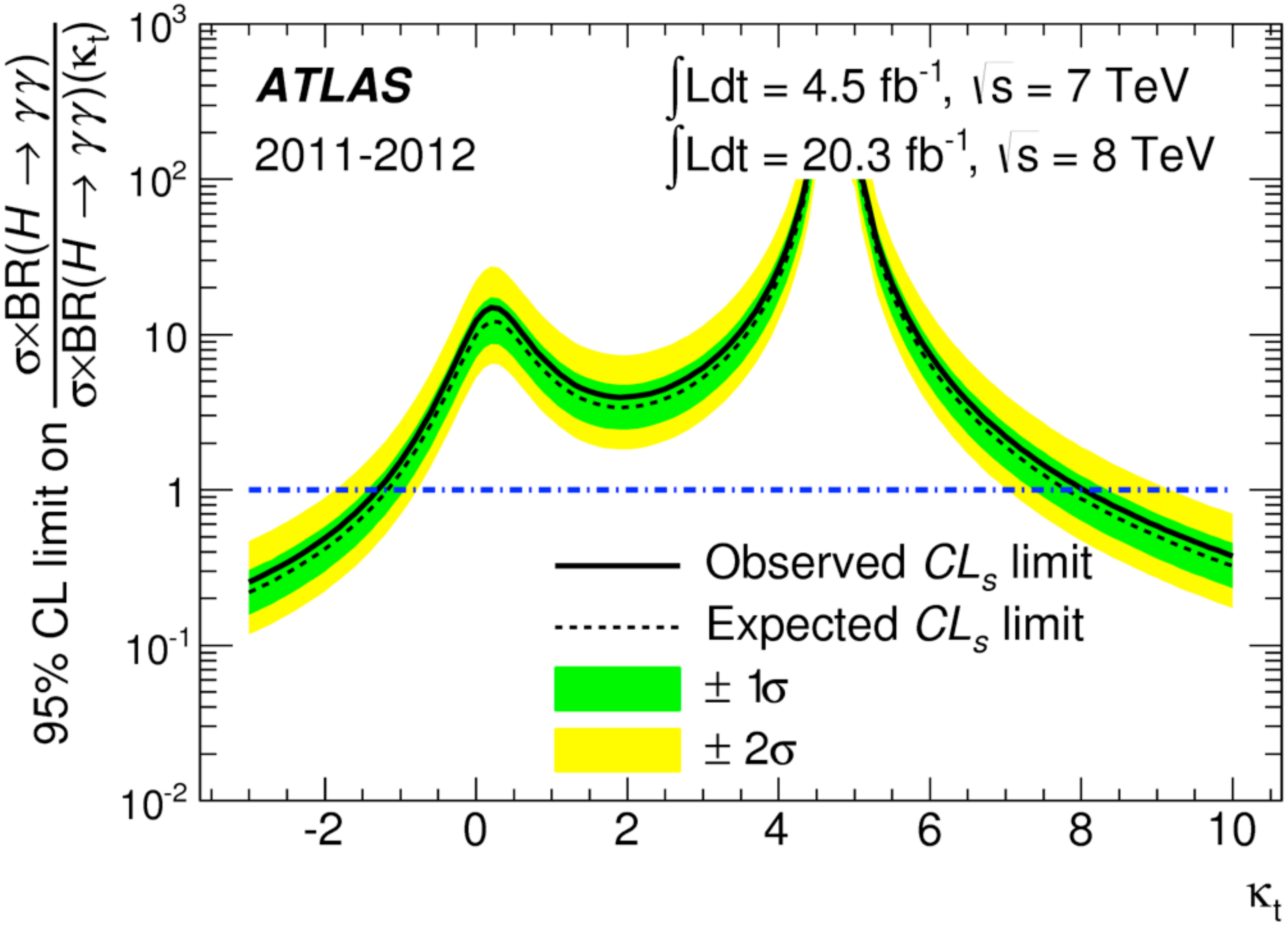
- Single top + Higgs production probes this sign
  - SM has destructive interference between H emission from top and from W: if relative sign of top coupling flips, large constructive interference
  - Also affects BR(H-> γγ): double-sensitivity of this channel





Analysis tHj+WtHj

- Exactly same analysis/samples as ttH, but including tH+j and WtH
- scanning also limit in top-H Yukawa coupling k_t
  - tH+WtH selection efficiencies extrapolated from 3 benchmark k_t values/MC samples (variations up to 15/20%)



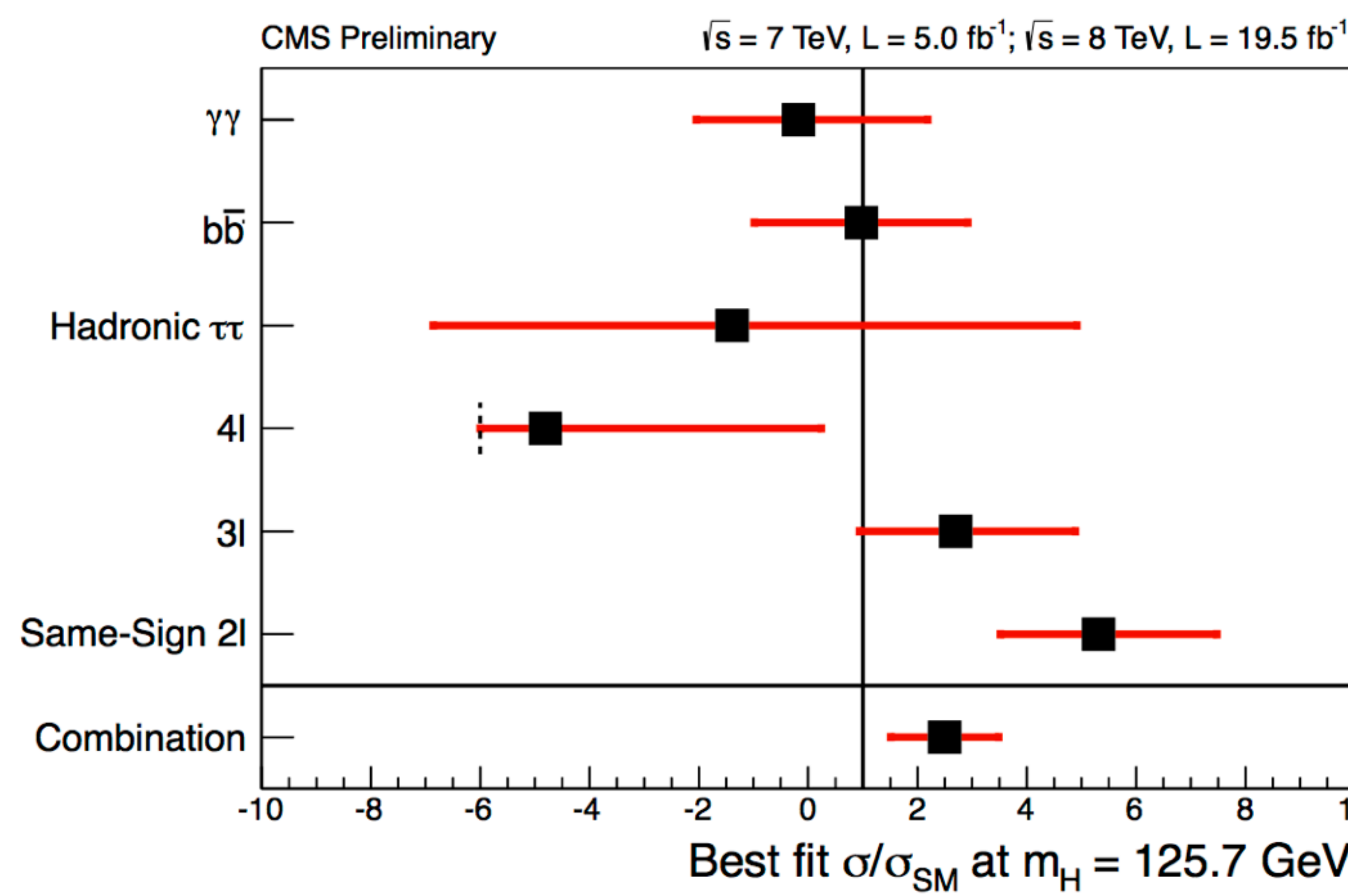
Observed range at 95% CL: [-1.3, 8.0]
expected: [-1.2, 7.8]

Will repeat in Run II
(at least as cross-check of main coupling fit)

A peek at CMS..

ttH Channel	95% CL upper limits on $\mu = \sigma/\sigma_{SM}$ ($m_H = 125.7$ GeV)				
		Expected			
	Observed	Median Signal Injected	Median	68% CL Range	95% CL Range
$\gamma\gamma$	5.4	6.7	5.5	[3.5,8.9]	[2.4,14.1]
$b\bar{b}$	4.5	5.2	3.7	[2.6,5.2]	[2.0,7.0]
$\tau\tau$	12.9	16.2	14.2	[9.5,21.7]	[6.9,32.5]
4l	6.8	11.9	8.8	[5.7,14.2]	[4.0,22.4]
3l	6.7	4.7	3.8	[2.5,5.8]	[1.8,8.7]
Same-sign 2l	9.1	3.6	3.4	[2.3,5.0]	[1.7,7.2]
Combined	4.3	2.9	1.8	[1.2,2.6]	[0.9,3.6]

- Similar excess as ATLAS seen in the 2lSS and 3l channels
- Not significant in either case but let's keep an eye on these..
- Work has started to combine ATLAS +CMS



Run II prospects

- Higher E_{CM} beneficial for ttH search:
  - @ 13(14) TeV ~4x (5x) increase in σ_{SM} for signal
  - same for ttV
  - ~3x (4x) increase in σ_{SM} for tt+jets background
- Additional techniques (e.g. more multi variate analysis) in development to maximize signal-bkg discrimination

- Not many prospect studies exist for RunII/future

- expect to measure ttH at 3σ with 300 fb^{-1} from di-photon channel alone (ATL-PHYS-PUB-2014-016)
- much earlier from bb and multi-lepton channels
- *tens fb^{-1} at 13 TeV?*

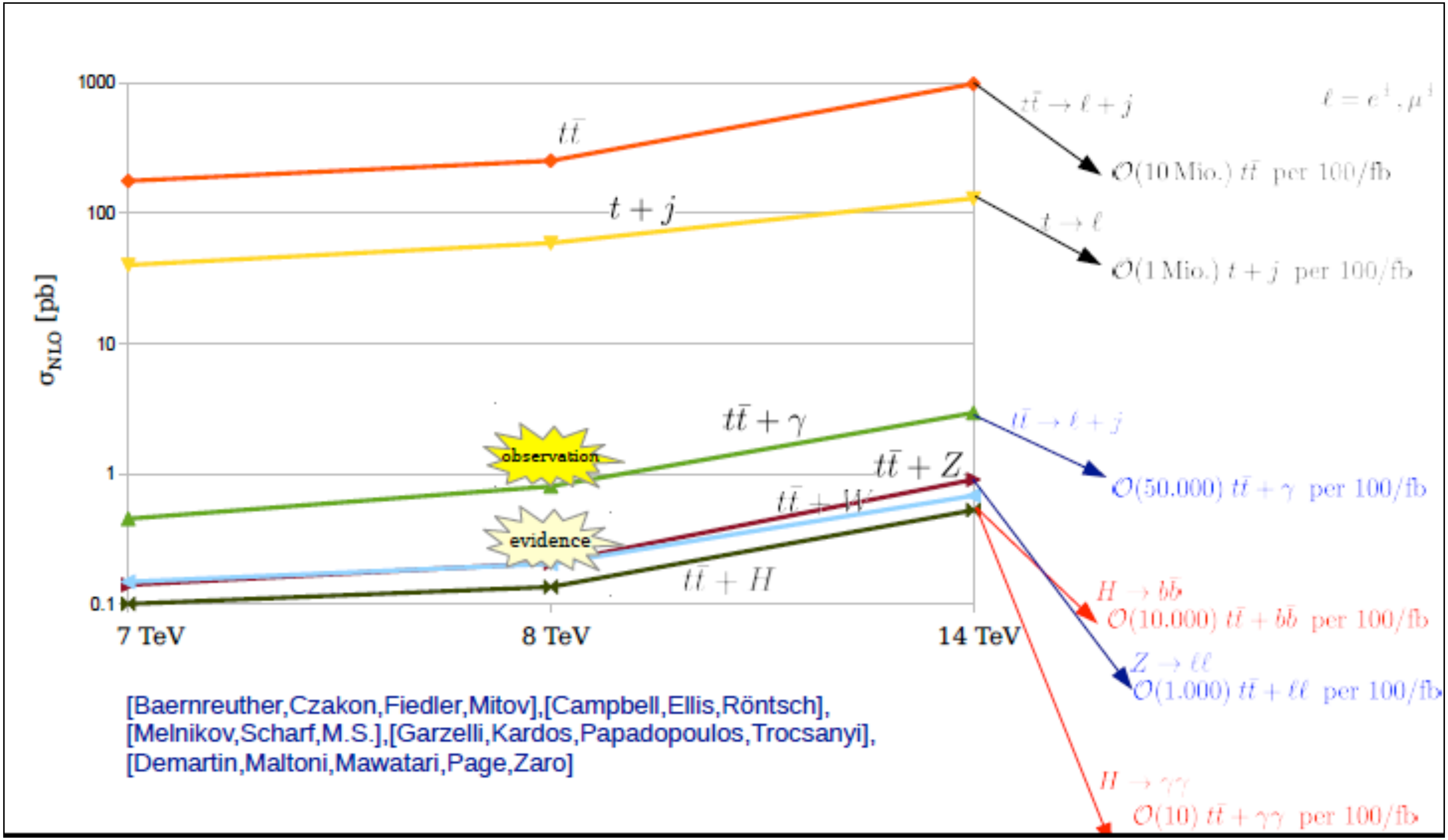
$\Delta\mu/\mu$	300 fb^{-1}		3000 fb^{-1}	
	All unc.	No theory unc.	All unc.	No theory unc.
$gg \to H$	0.12	0.06	0.11	0.04
VBF	0.18	0.15	0.15	0.09
WH	0.41	0.41	0.18	0.18
$qqZH$	0.80	0.79	0.28	0.27
$ggZH$	3.71	3.62	1.47	1.38
► ttH	0.32	0.30	0.16	0.10

Outlook

- ttH production mode being looked at with several, different final states
- Challenging both from detector and backgrounds point of view
- Closing on to SM xsec value
- This will be one of the first hot topics in Run II

Back-up

Evolution of x-sec



Charge confusion

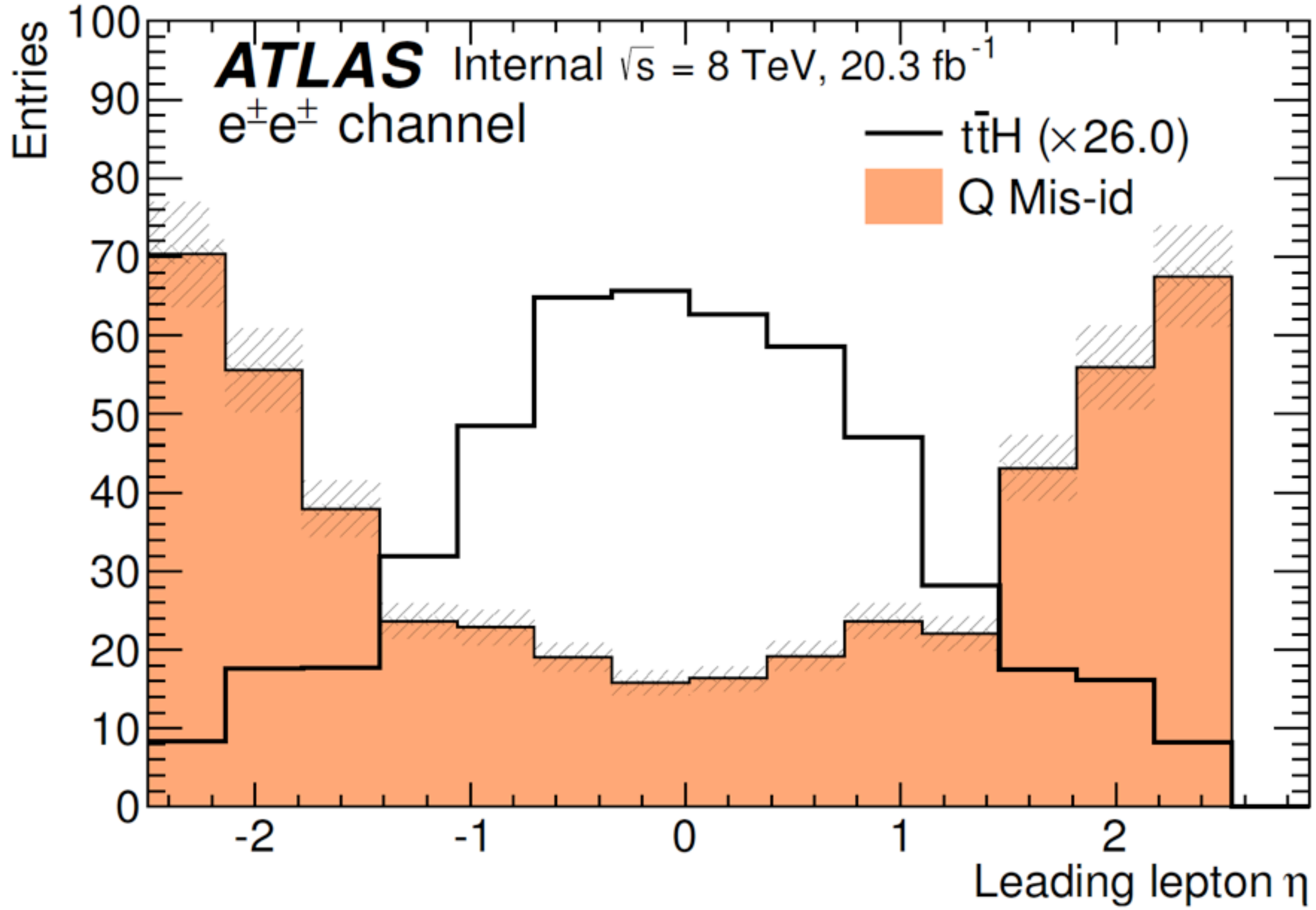


Figure A.6: Pseudorapidity η distribution of the higher p_T lepton in the $2\ell 0\tau_{had}$ *ee* categories, comparing *q* mis-id background and $t\bar{t}H$ signal expectation. The rapid rise of the *q* mis-id contribution at high η motivates the selection requirement $\eta < 1.37$ for electrons in the $2\ell 0\tau_{had}$ categories.

Orange is from 2l SS events weighted by Q Mis-id probability