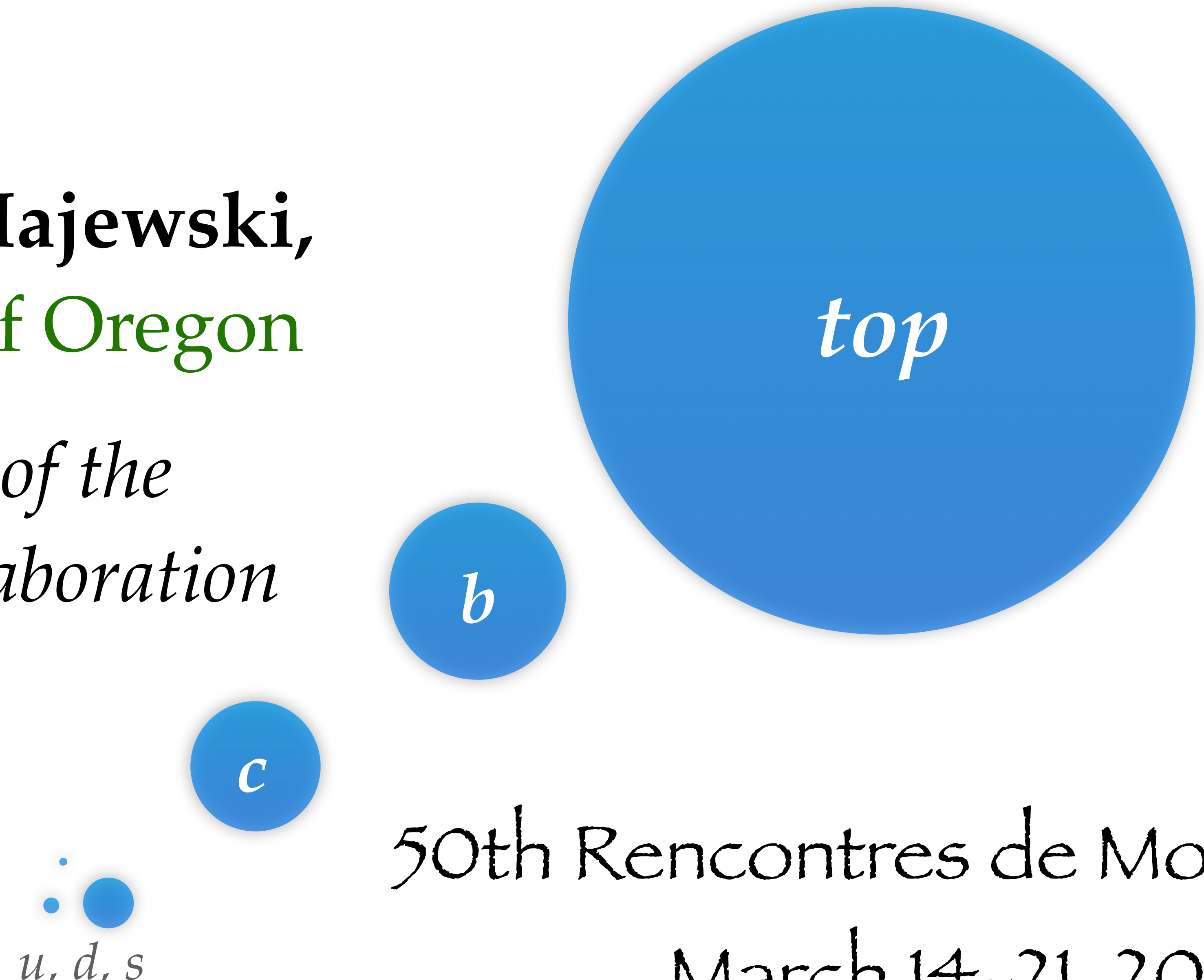
Top quarks in ATLAS: bridging measurements and searches

Stephanie Majewski,
University of Oregon

on behalf of the ATLAS Collaboration



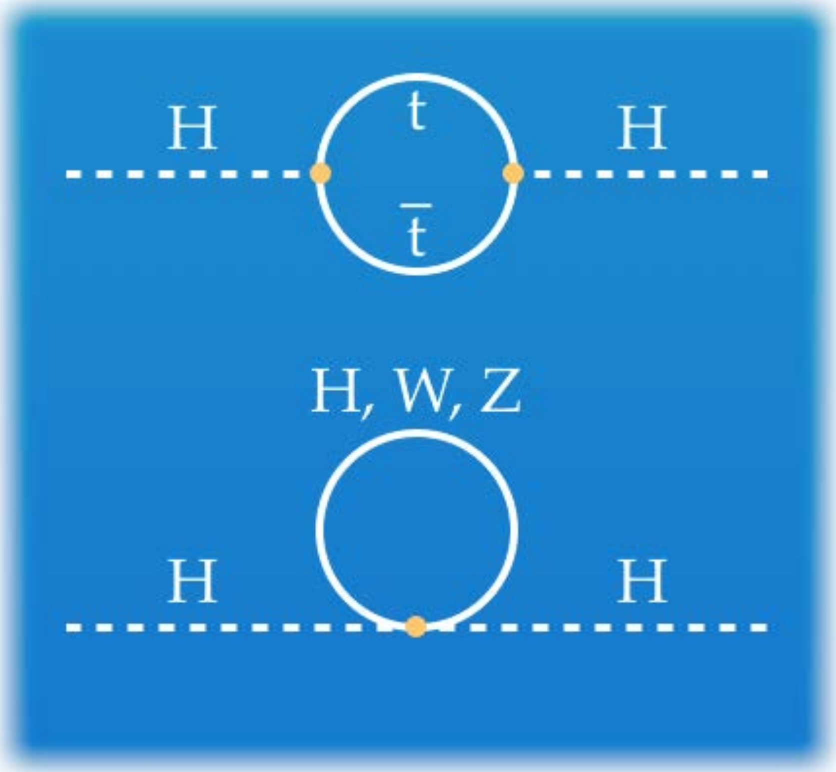
50th Rencontres de Moriond EW,
March 14-21, 2015

Introduction

- The interplay between top quark measurements and searches is essential to fully explore avenues for new physics

1. "Classic" SM top cross-section measurements have played a key role to understanding $t\bar{t}$ backgrounds

2. The top Yukawa coupling can be measured at tree-level in $t\bar{t}H$ → important for understanding EW symmetry breaking & sensitive to new physics



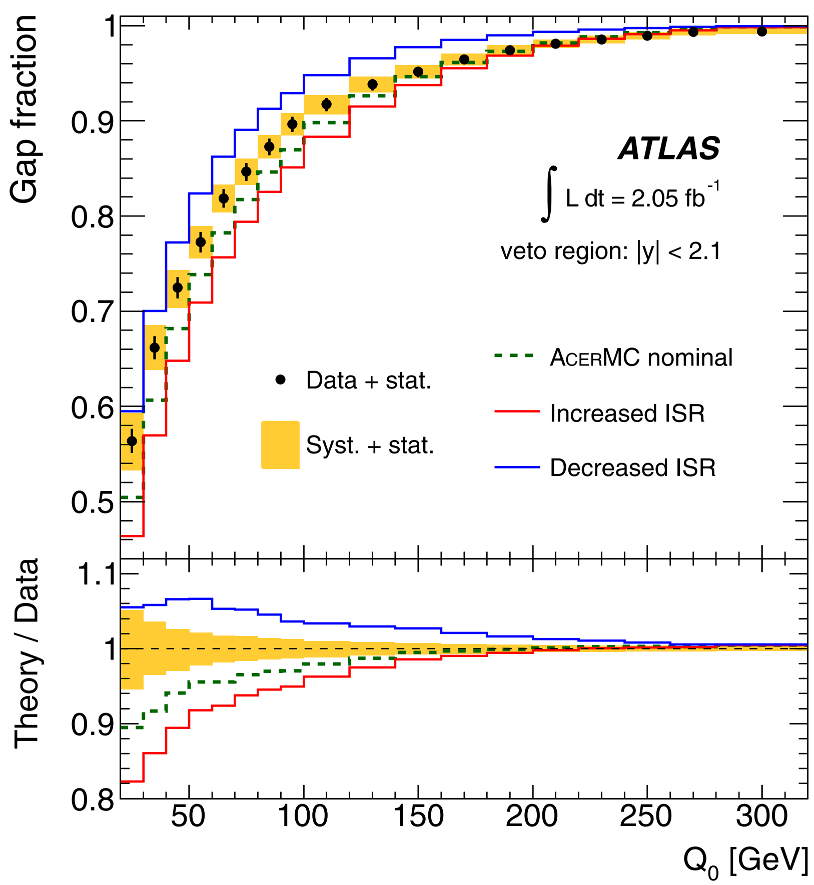
3. Strong motivation (*naturalness*) for top partner searches:
vector-like quarks, SUSY stop (including "stealth" stop)

Measurements → Searches

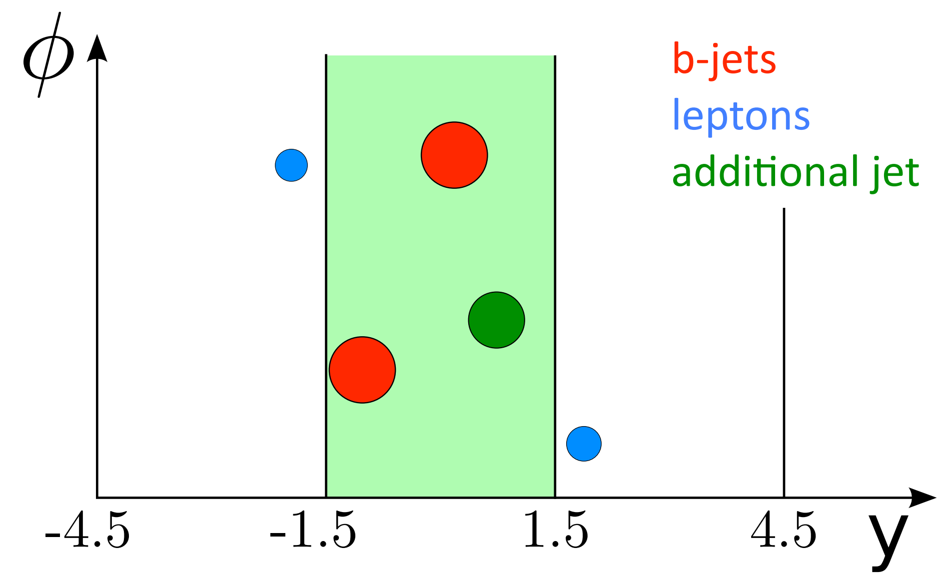
Rapidity Gap in $t\bar{t}$ events

- Study the fraction of dilepton $t\bar{t}$ events that do not contain an additional central rapidity jet

Eur.Phys.J. C72 (2012) 2043



Updated: ATL-PHYS-PUB-2014-005



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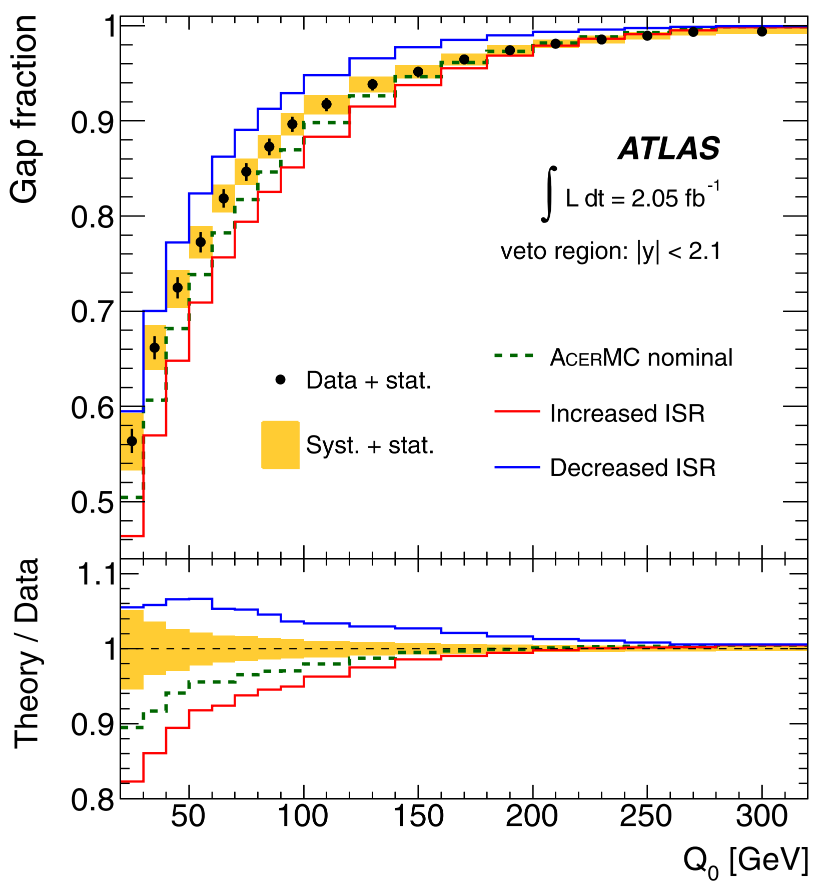
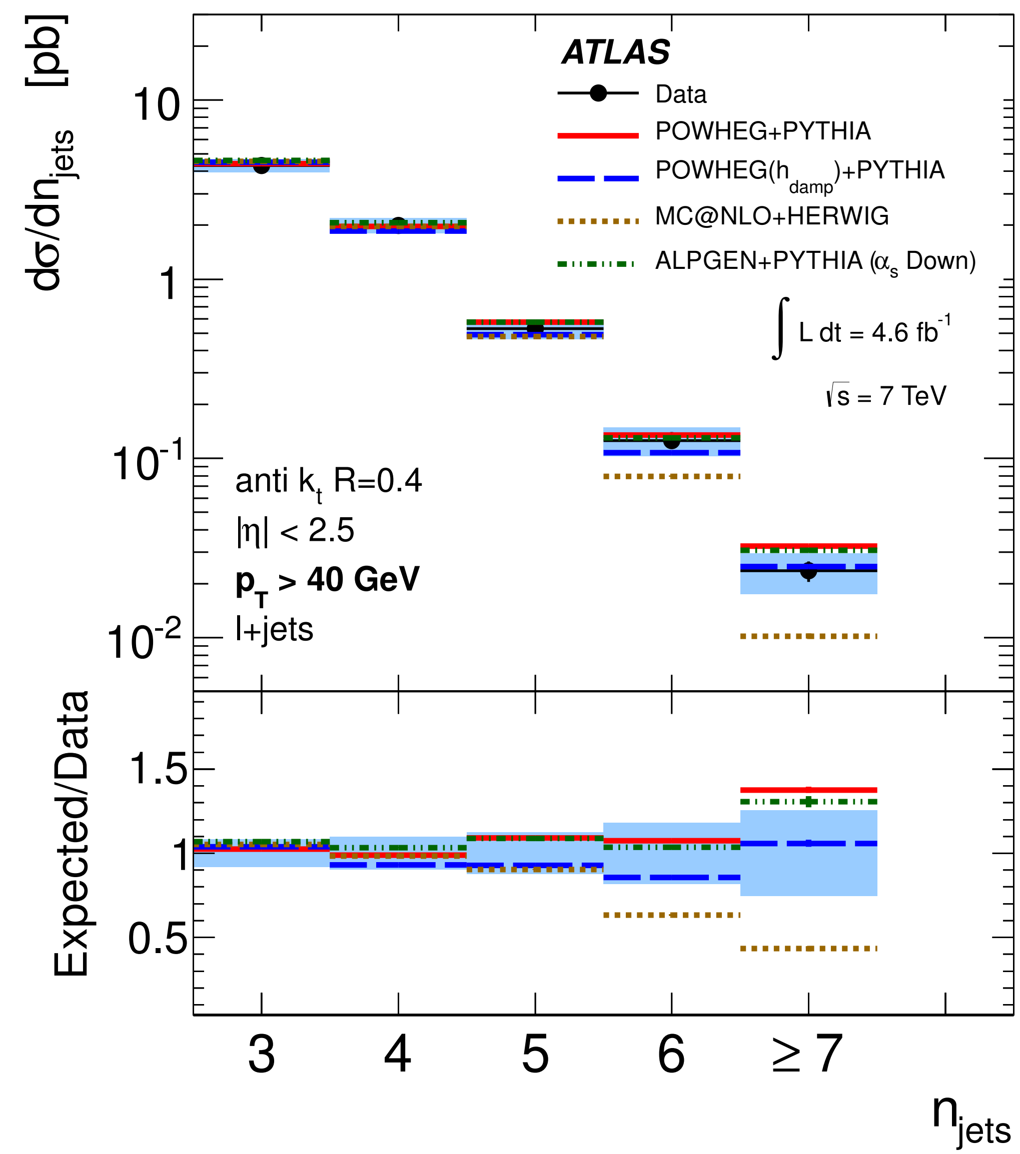


Updated: ATL-PHYS-PUB-2014-005

$t\bar{t}$ differential cross sections

- Jet multiplicity dependence

JHEP 01 (2015) 020



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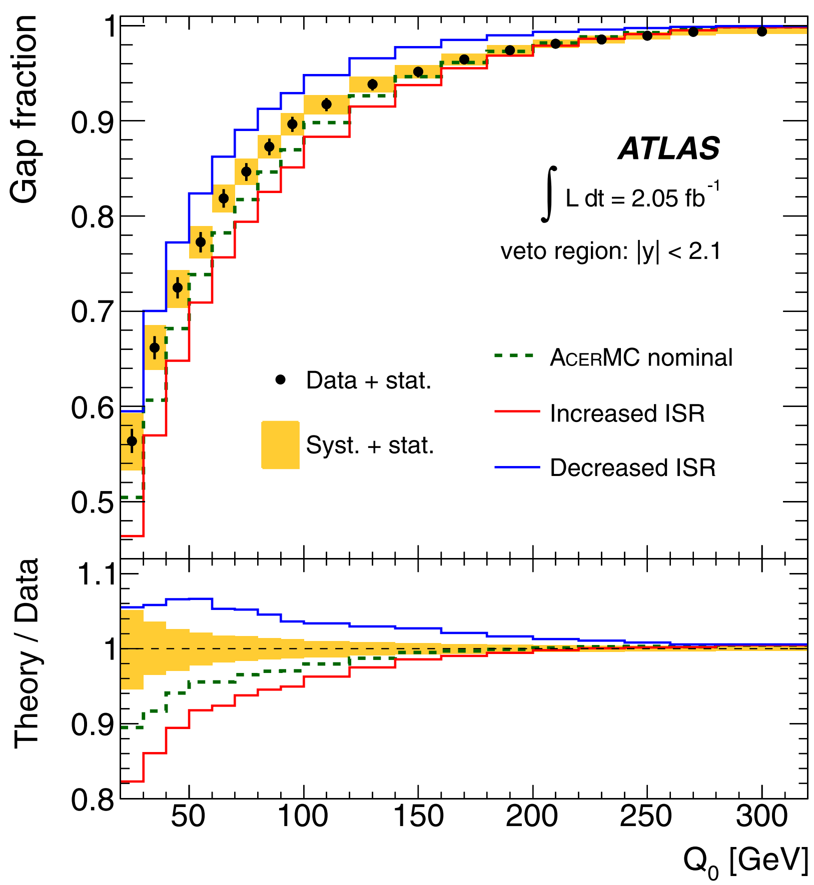

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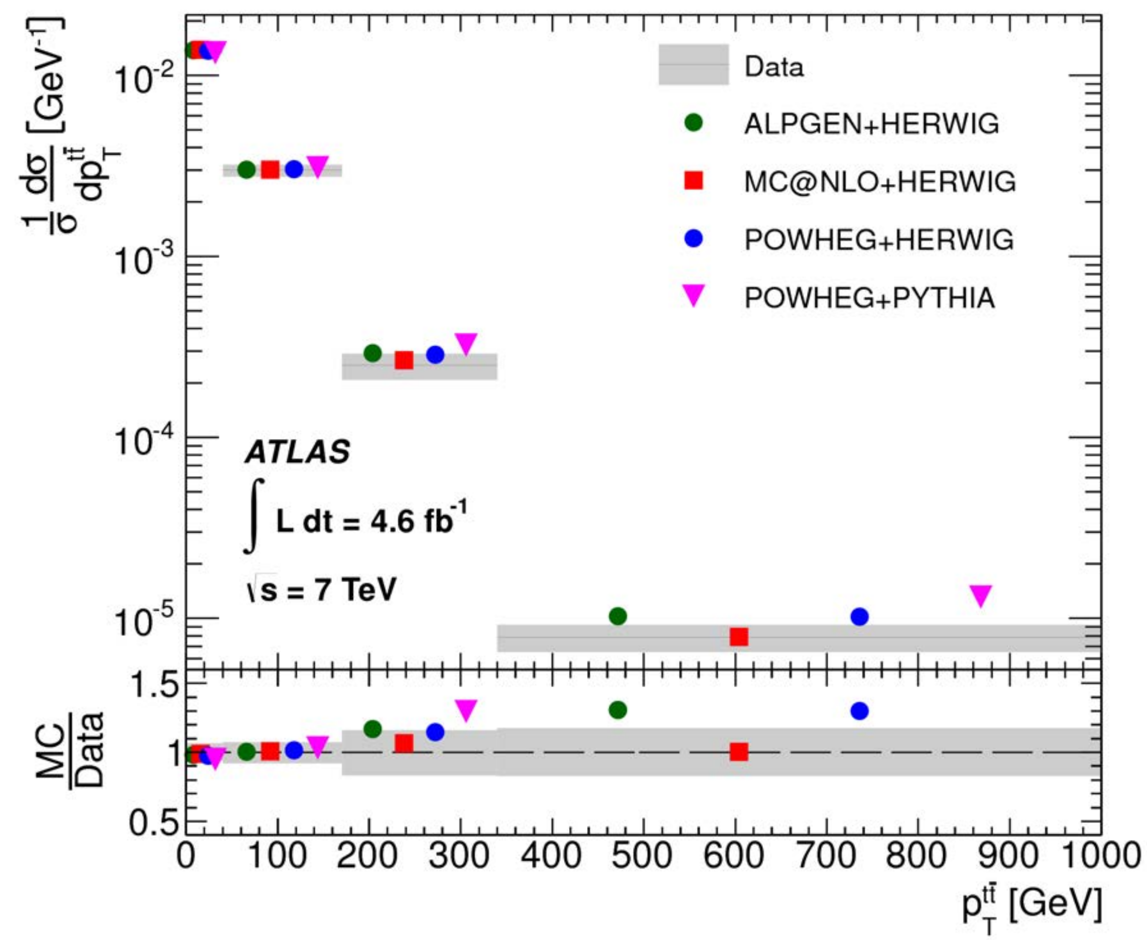
$t\bar{t}$ differential cross sections

- Jet multiplicity dependence
  JHEP 01 (2015) 020
- Dependence on $p_T(t\bar{t})$
  Phys. Rev. D90 (2014) 072004



Measurements → Searches

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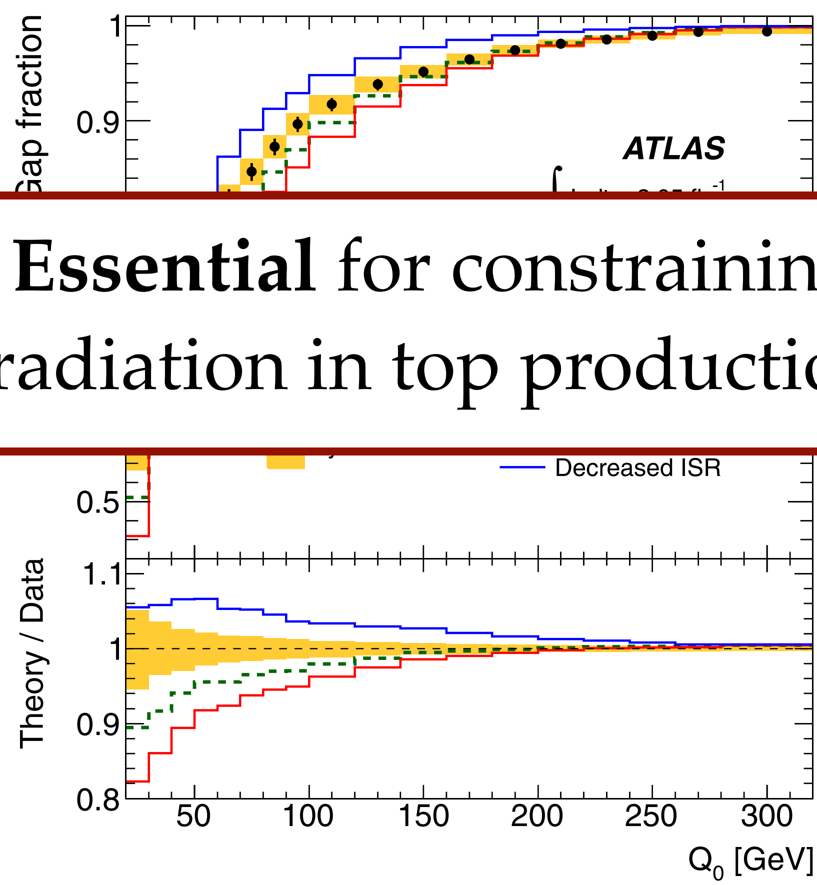

Essential for constraining radiation in top production

Updated: ATL-PHYS-PUB-2014-005

$t\bar{t}$ differential cross sections

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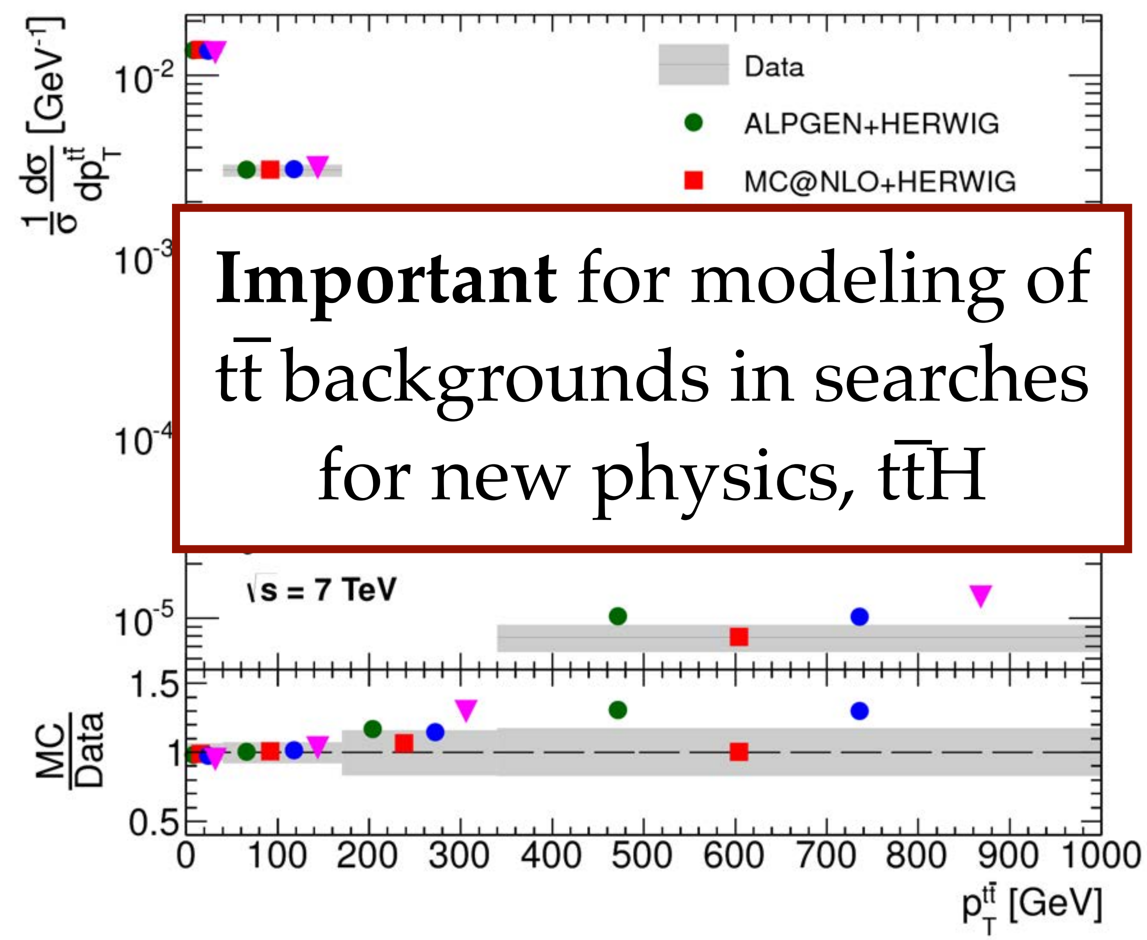


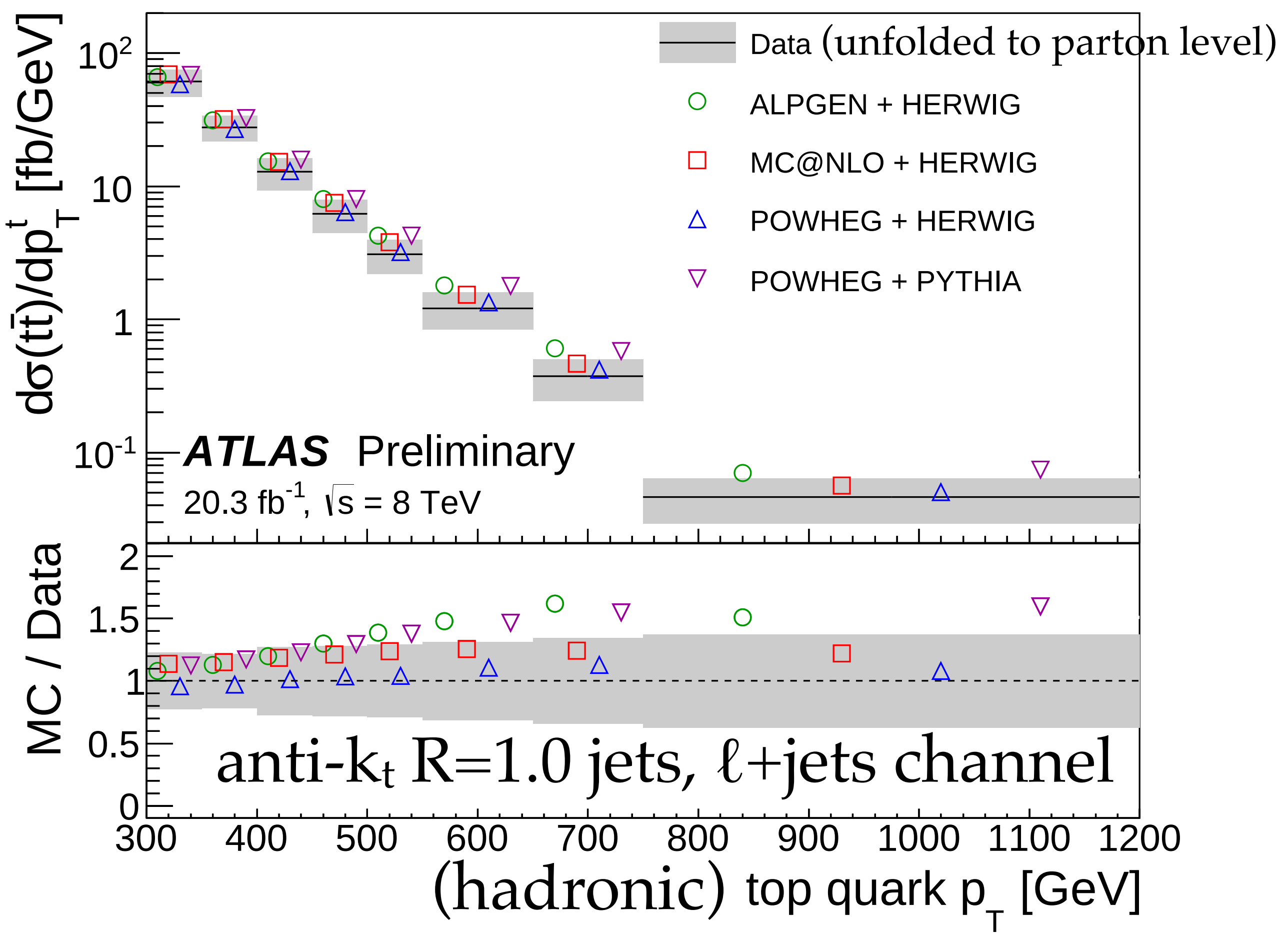
Important for modeling of $t\bar{t}$ backgrounds in searches for new physics, $t\bar{t}H$

see also talk by A. Loginov

Measurements → Searches

Boosted $t\bar{t}$ differential cross section

ATLAS-CONF-2014-057

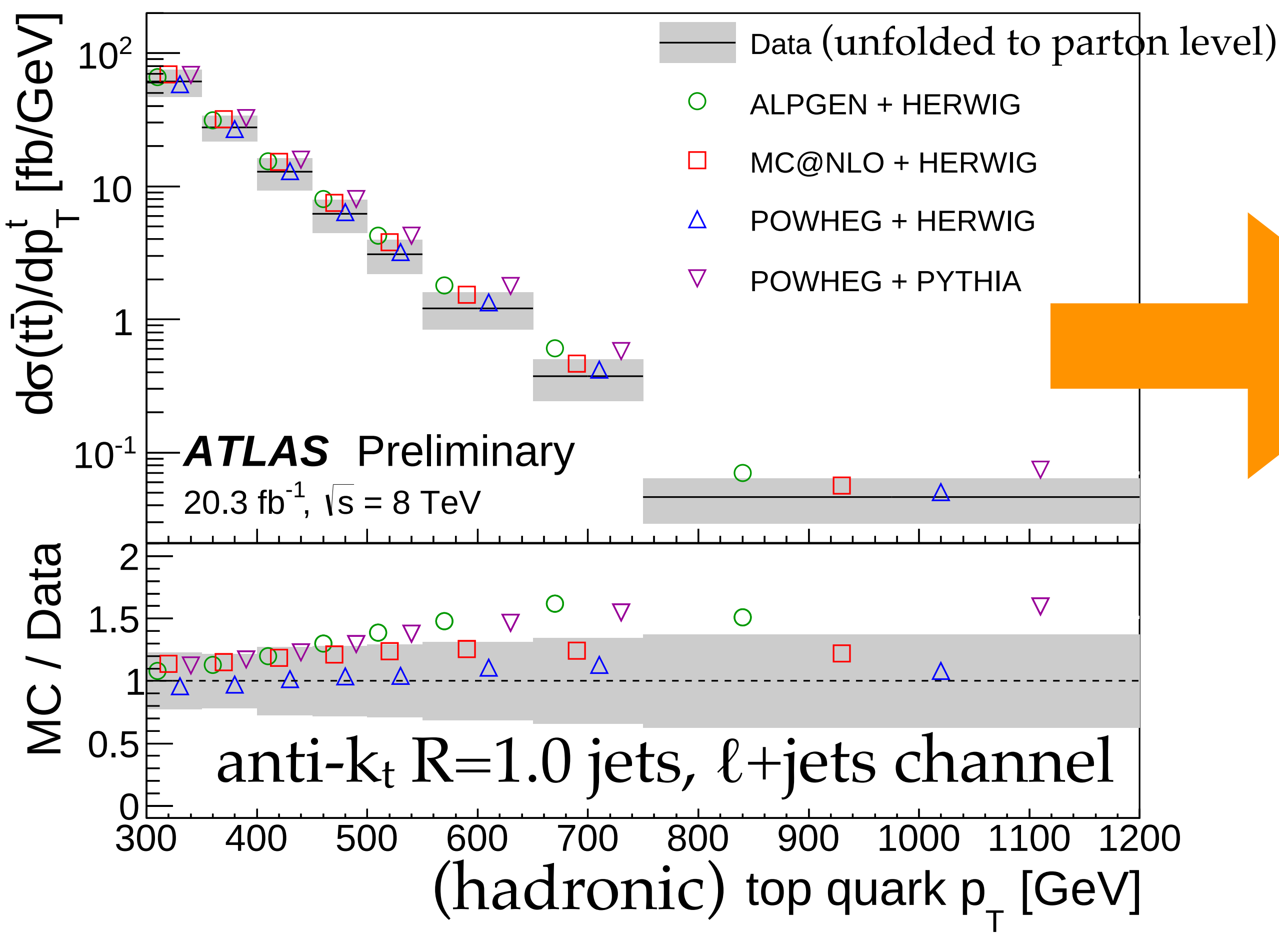


- lepton+jets $t\bar{t}$ events, unfolded to particle & parton level

Measurements → Searches

Boosted $t\bar{t}$ differential cross section

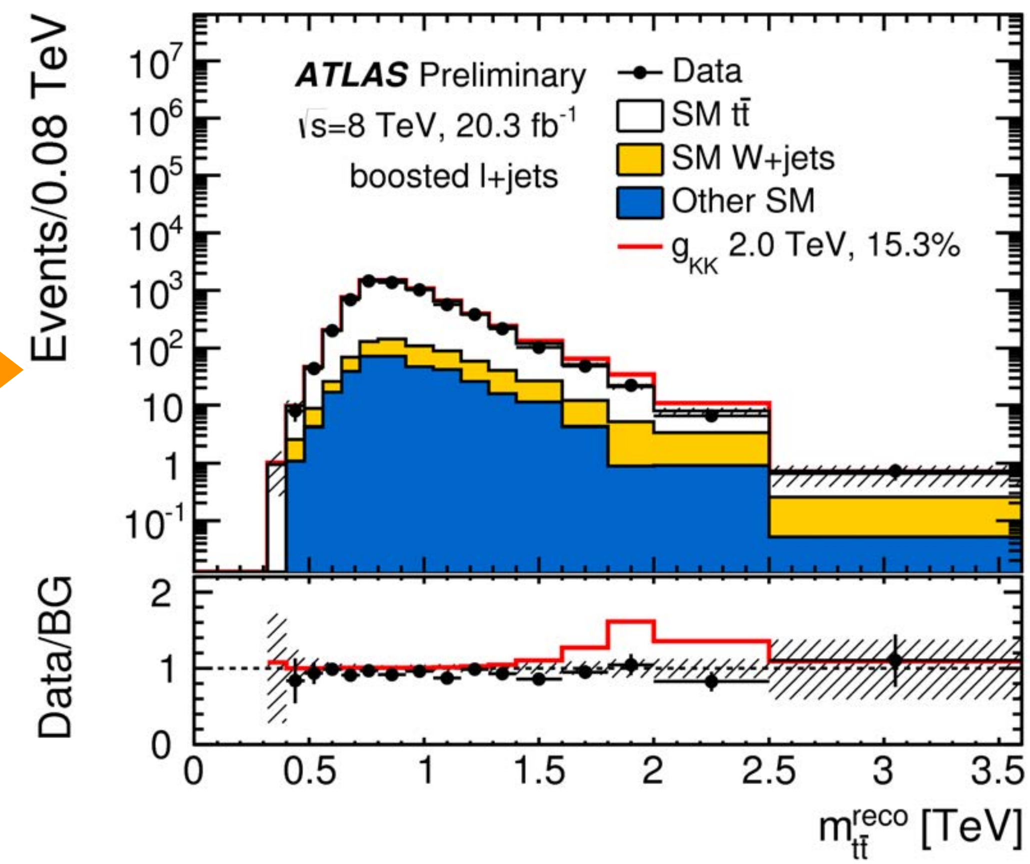
ATLAS-CONF-2014-057



- lepton+jets $t\bar{t}$ events, unfolded to particle & parton level

$t\bar{t}$ resonance search New!

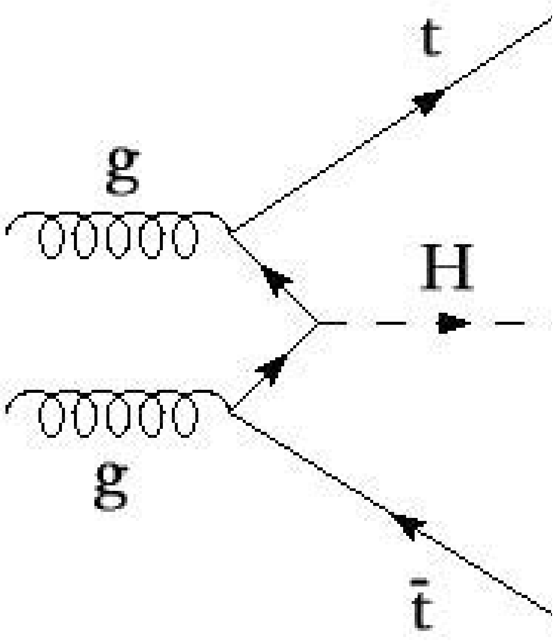
ATLAS-CONF-2015-009



- combined boosted+resolved $(\sigma \times \mathscr{B}) < 0.03$ pb for 3 TeV Z′
- excludes narrow leptophobic Z′ < 1.8 TeV

see also talk by J. Stupak

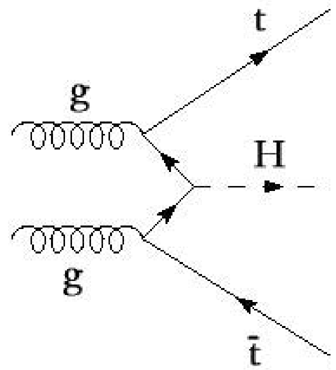
Top Yukawa Coupling



- SM Higgs predicted to have a large Yukawa coupling to tops
  - can be probed through Higgs production in association with top quark(s): tH and **$t\bar{t}H$**
- Three channels explored:

$H \to b\bar{b}$ New! $t\bar{t} \to \ell + \text{jets, dilepton}$	$H \to \gamma\gamma$ $t\bar{t} \to \ell + \text{jets, dilepton, all-had}$	Multi-lepton final states (including τ s) New!
HIGG-2013-27, submitted to EPJC	**Physics Letters B 740 (2015) 222-242**	**ATLAS-CONF-2015-006**

$$\sigma_{t\bar{t}H}(\sqrt{s} = 8\,\text{TeV}) = 129.3^{+\,4.9}_{-12.0}\,(\text{scale}) \pm 10.5\,(\text{PDF})\,\text{fb}$$



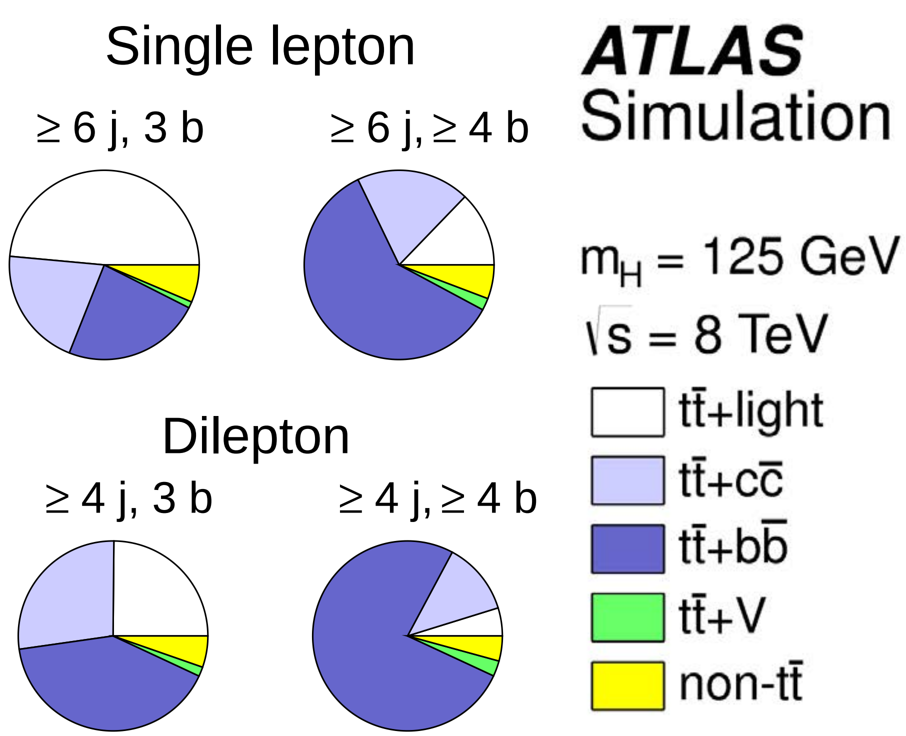
Top Yukawa Coupling

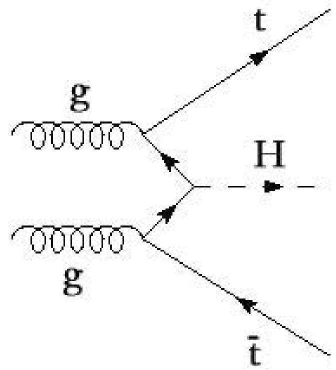
$H \to b\bar{b}$

$t\bar{t} \to \ell + \text{jets, dilepton}$

- Events categorized according to jet and b-jet multiplicities into signal-rich & bkg-rich regions

- Most sensitive regions:





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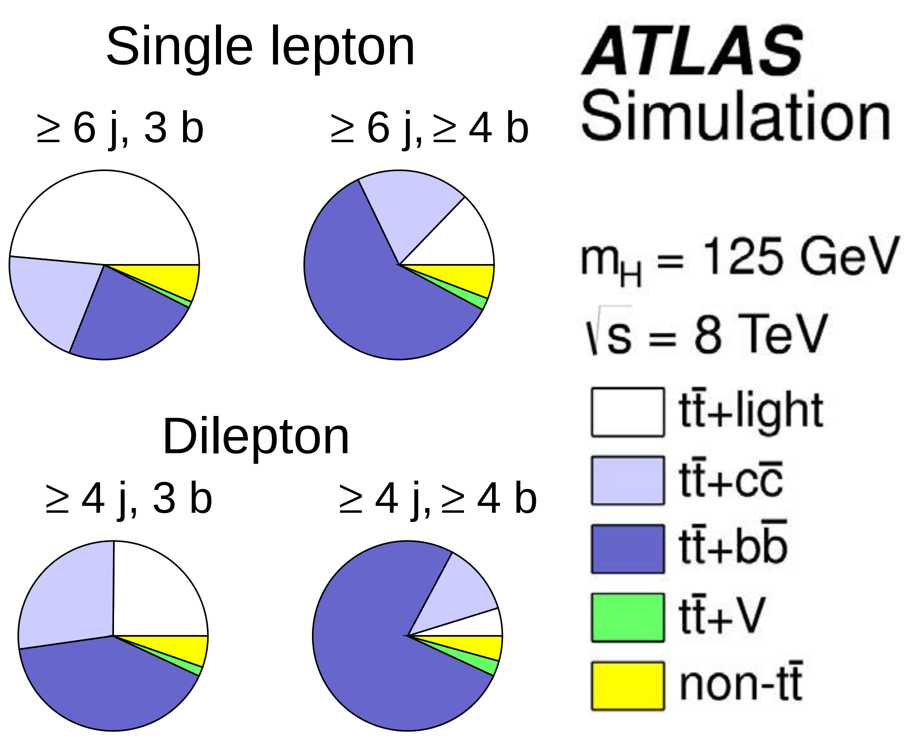
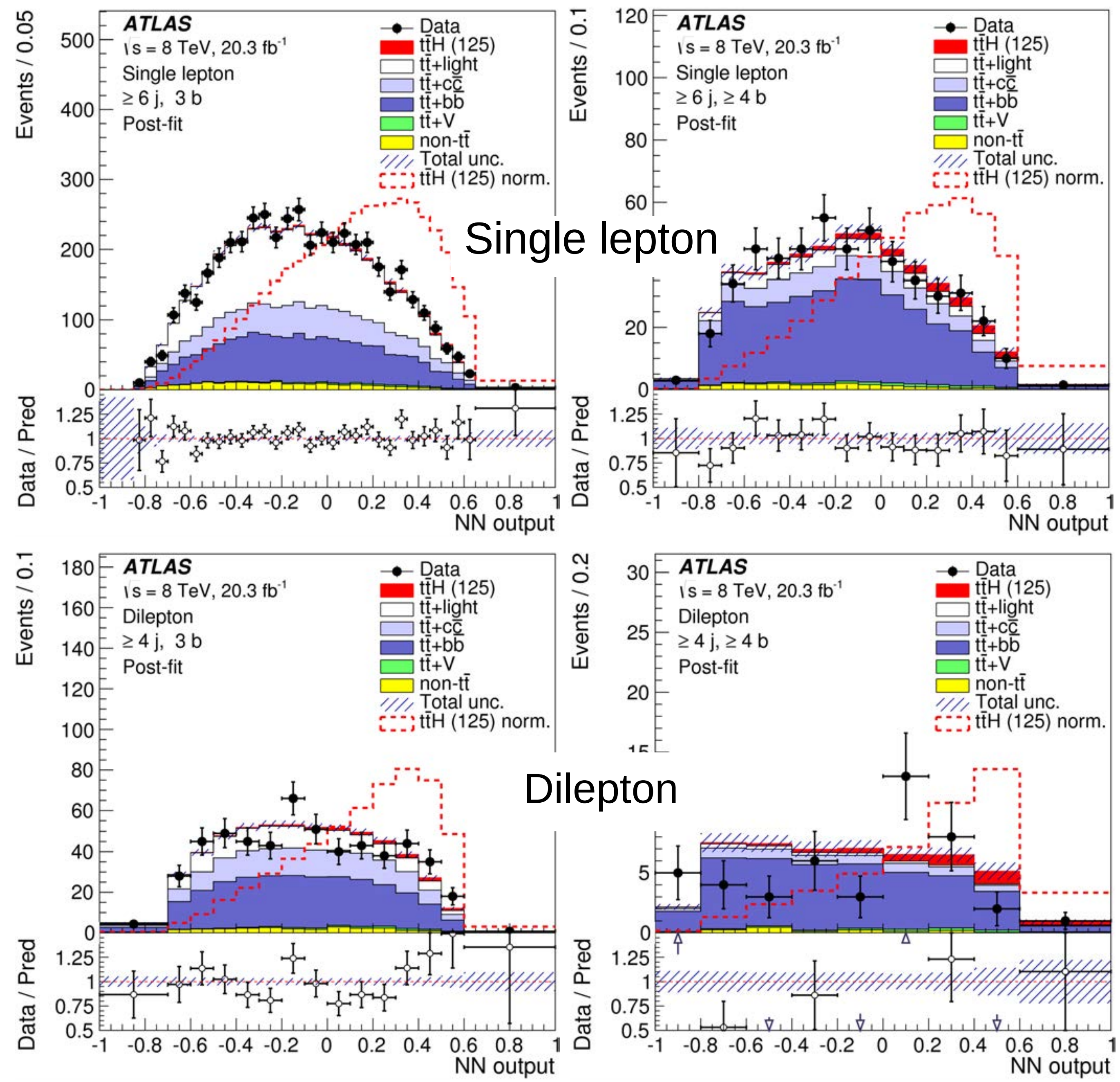
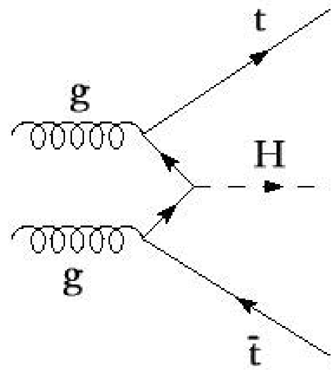




S. Majewski, University of Oregon



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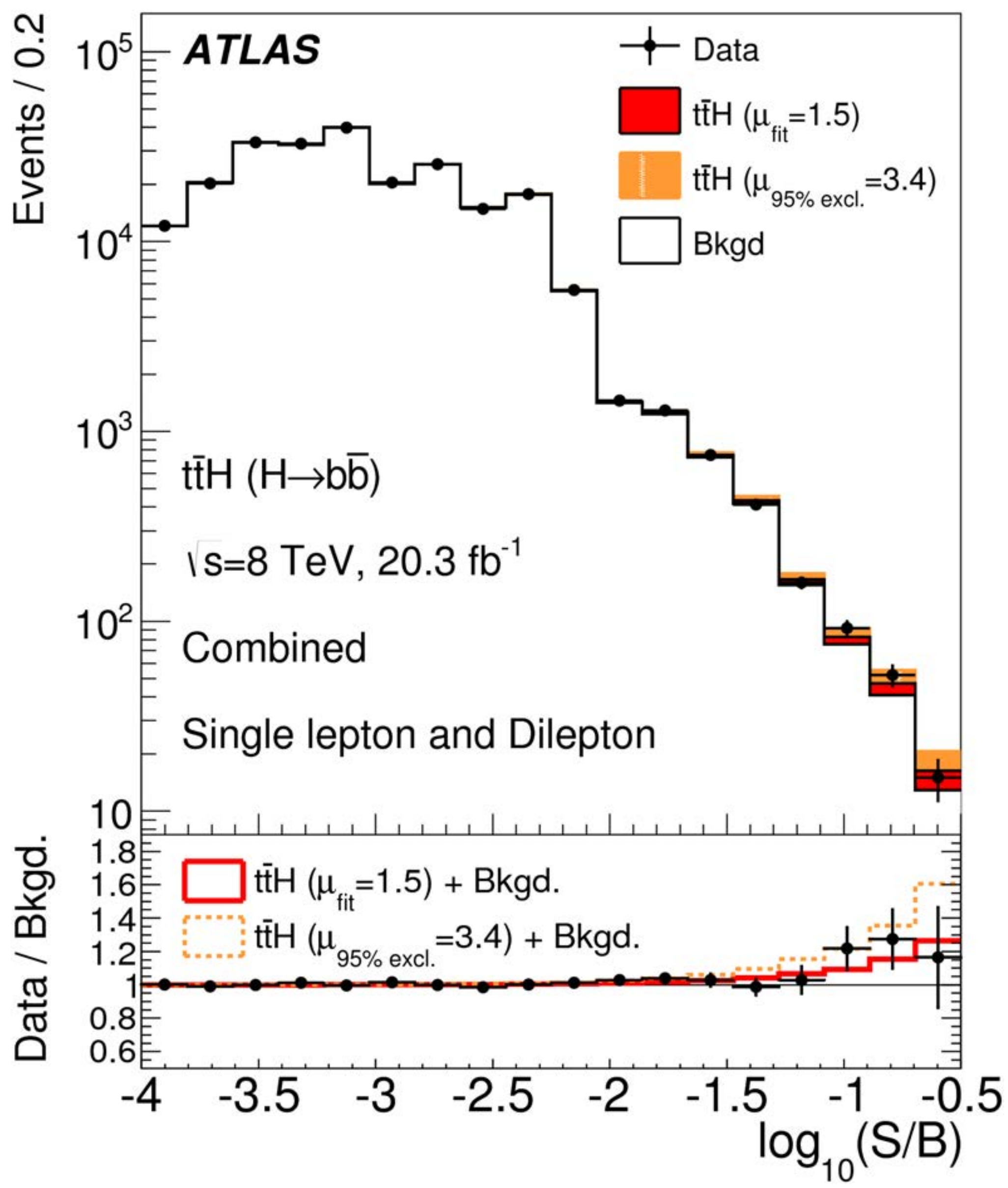
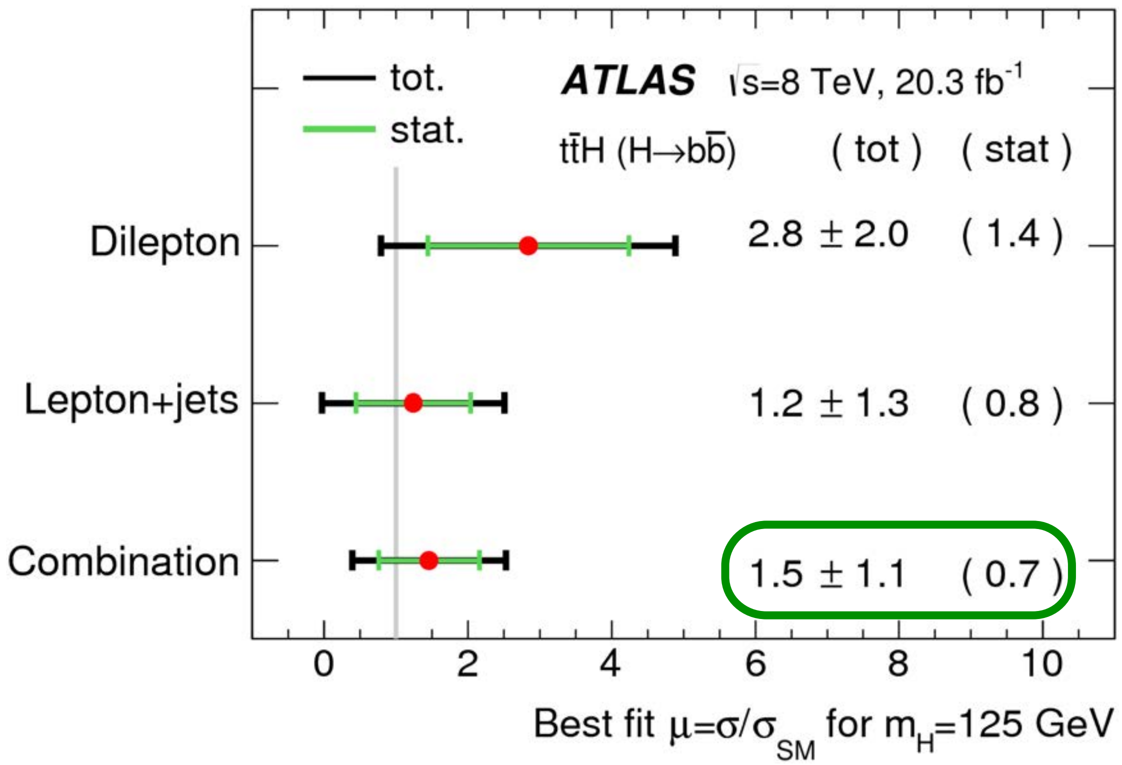
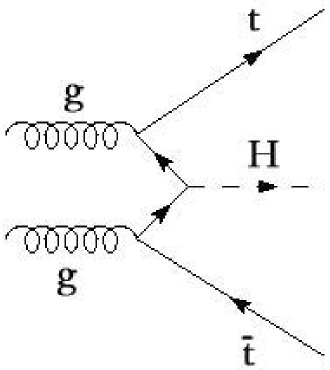




- Dominant systematics: $t\bar{t} + b\bar{b}$ background modeling, jet energy scale

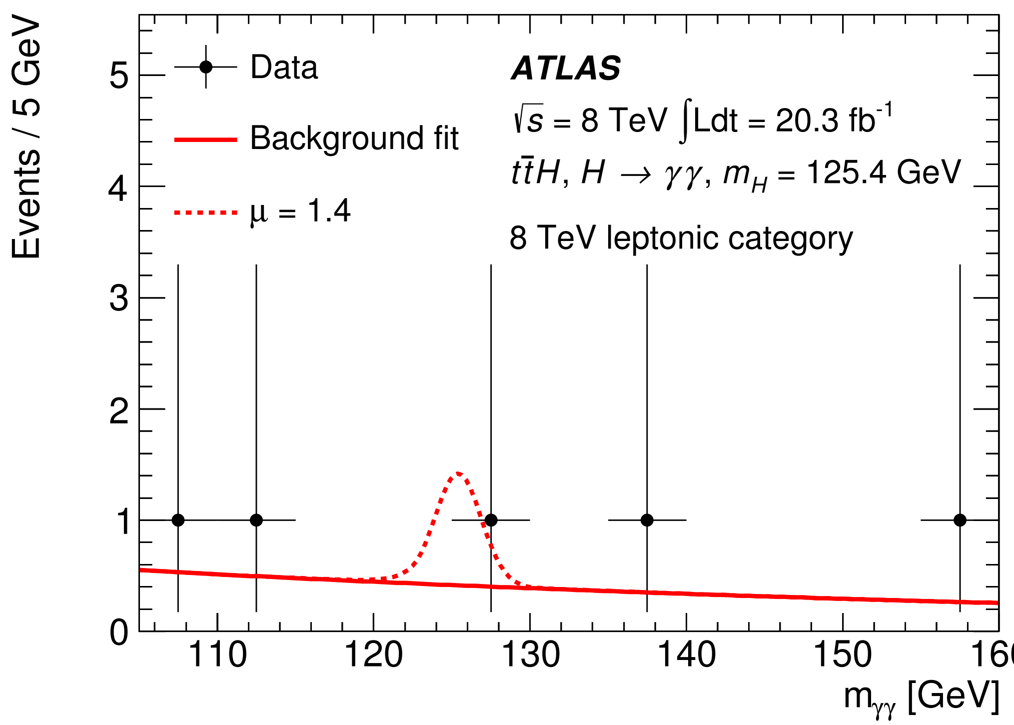


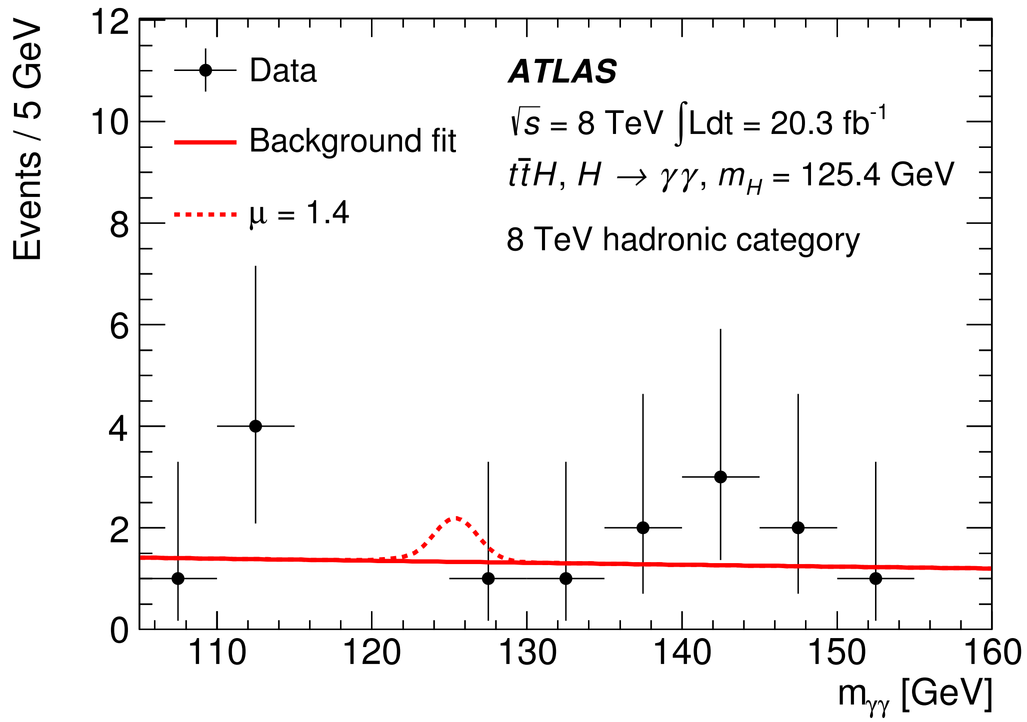
Top Yukawa Coupling

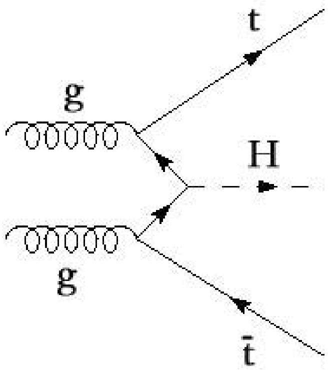
$H \rightarrow \gamma\gamma$

$t\bar{t} \rightarrow \ell + \text{jets, dilepton, all-had}$

- $m_{\gamma\gamma}$ mass spectrum provides discrimination 1.42 GeV (1.56 GeV) resolution for 7 TeV (8 TeV) data
- Best fit value (m_H = 125.4 GeV): $\mu_{t\bar{t}H} = 1.3^{+2.5}_{-1.7}(\text{stat})^{+0.8}_{-0.4}(\text{syst})$







Top Yukawa Coupling

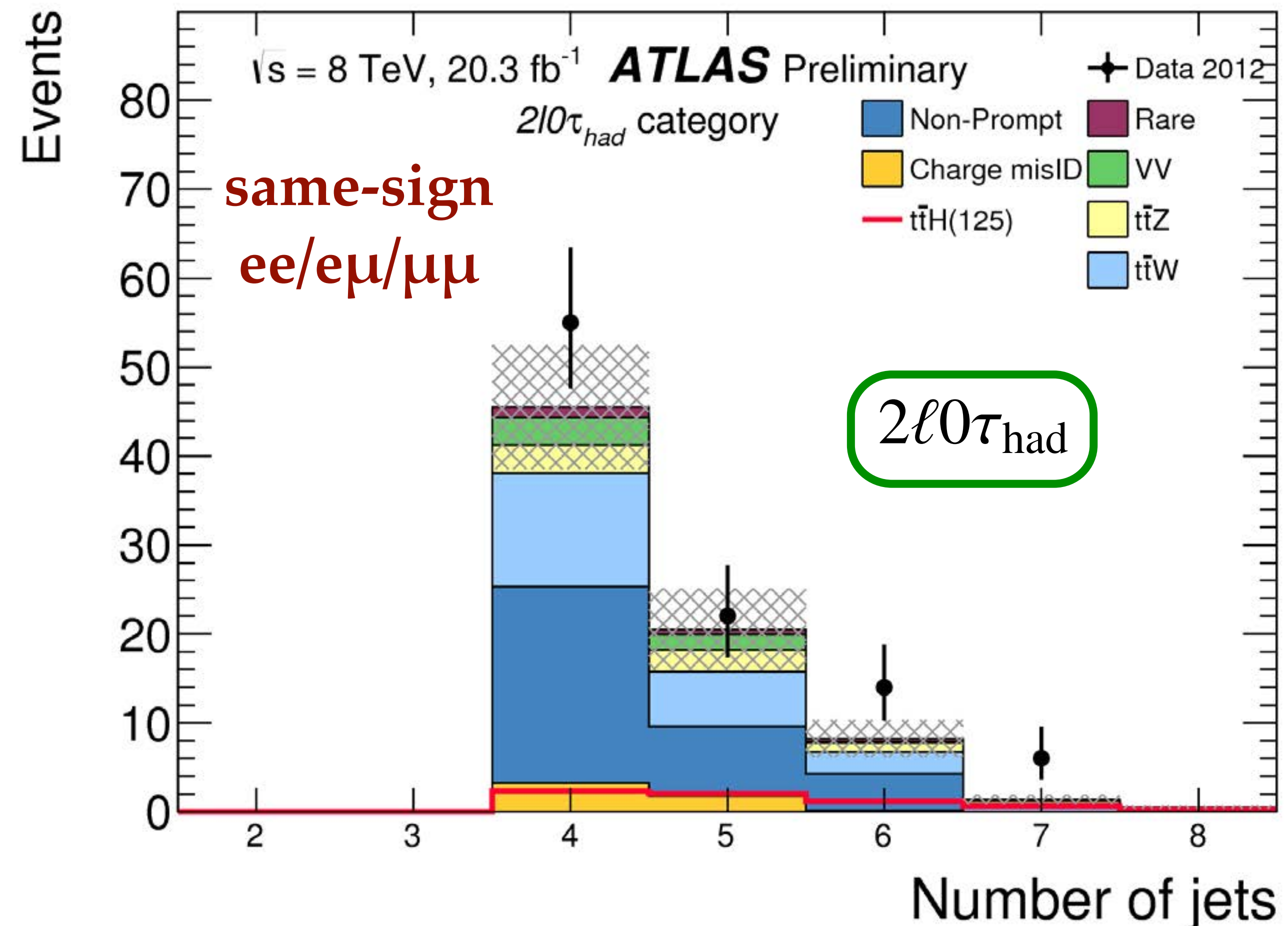
Multi-lepton final states (including τ s)

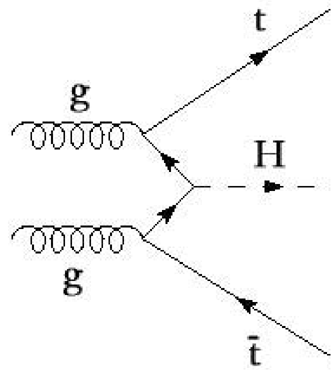
- Five different multi-lepton final states (2ℓ are same-sign):

Higgs decay mode fraction

Category	WW	$\tau\tau$	ZZ	other
$2\ell 0\tau_{\rm had}$	80%	15%	3%	2%
3ℓ	74%	15%	7%	4%
$2\ell 1\tau_{\rm had}$	35%	62%	2%	1%
4ℓ	69%	14%	14%	4%
$1\ell 2\tau_{\rm had}$	4%	93%	0%	3%

- Main backgrounds:
  $t\bar{t}Z$, $t\bar{t}W$ (all categories)
  diboson (3 ℓ)
  $t\bar{t}$+jets, Z+jets (e charge mis-id)
  $t\bar{t}$ with non-prompt leptons





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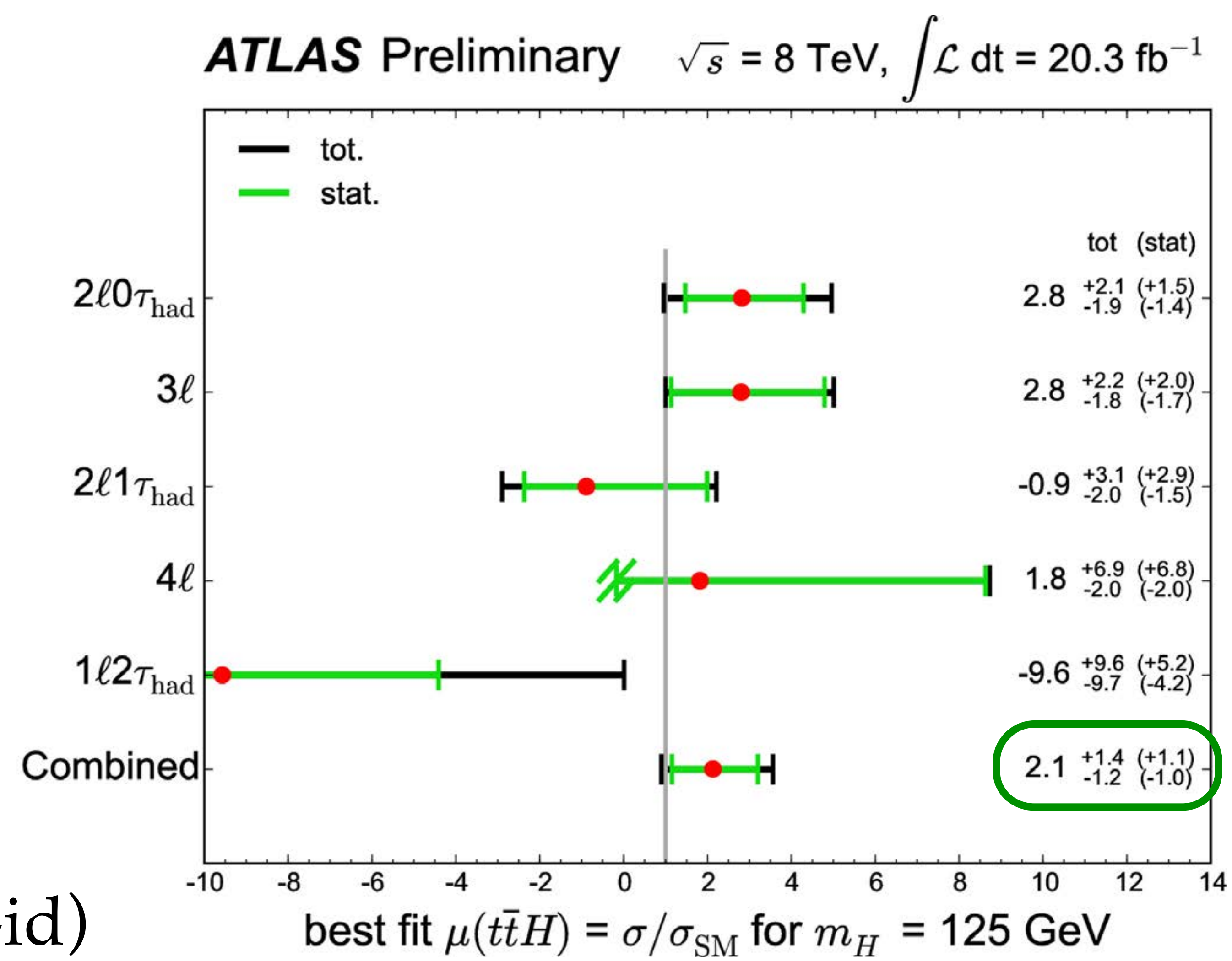
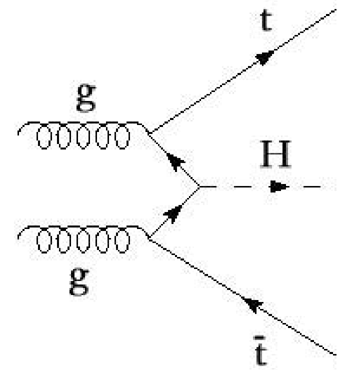


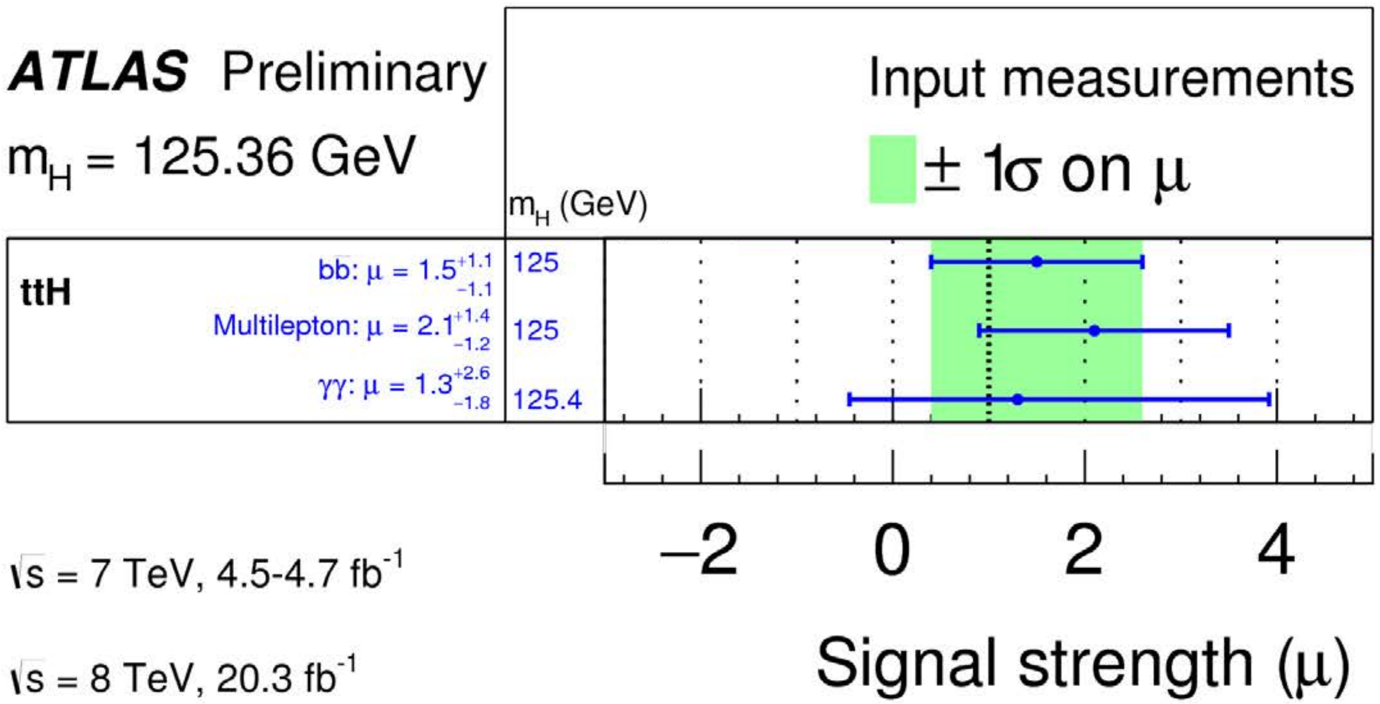


Top Yukawa Coupling

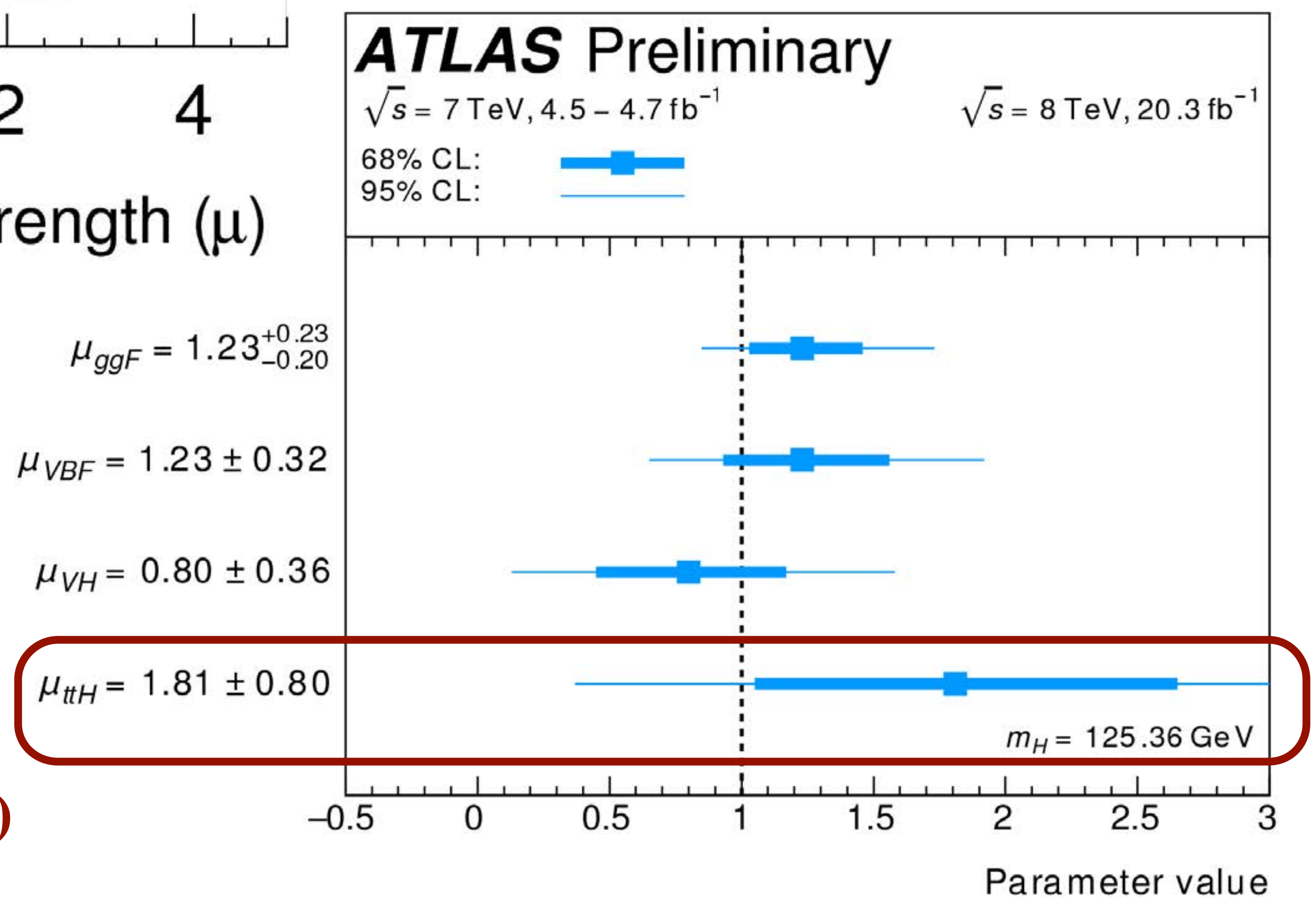
Combined Results

ATLAS-CONF-2015-007

New!



see also talk by M. Duehrssen



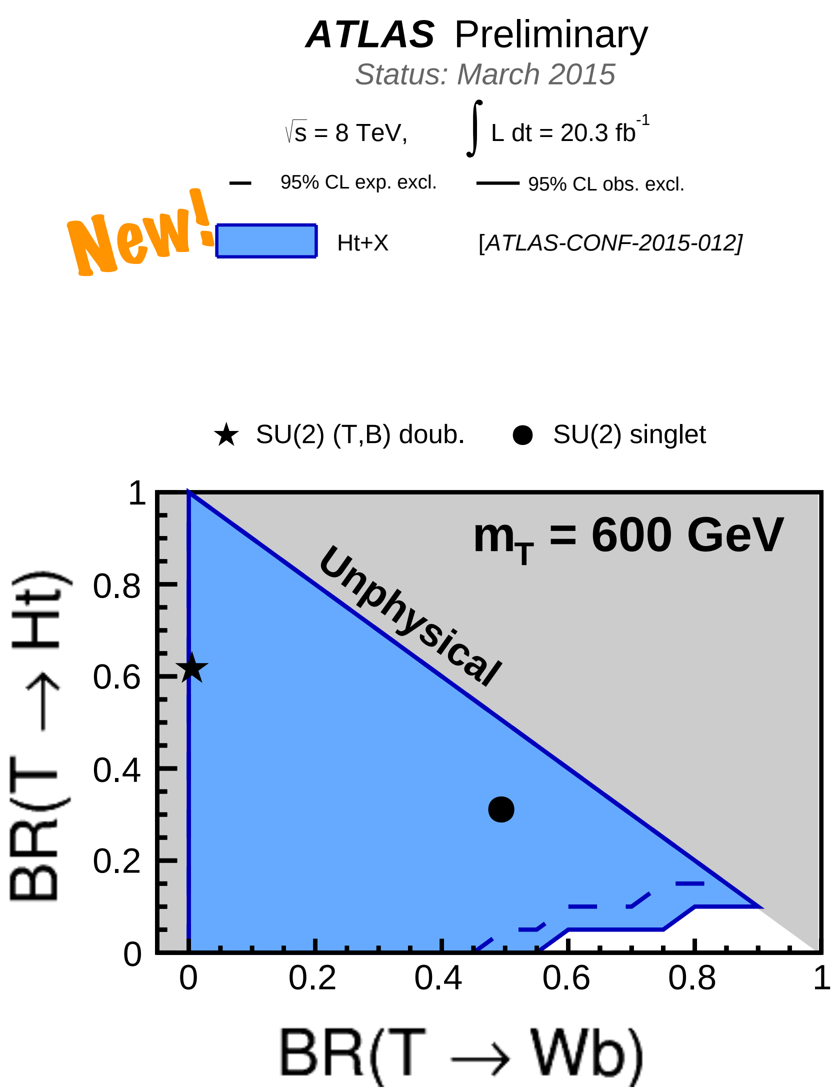
3 channels combined:
>2σ from 0

$\mu_{ttH} < 3.2$ (obs), 1.4 (exp)

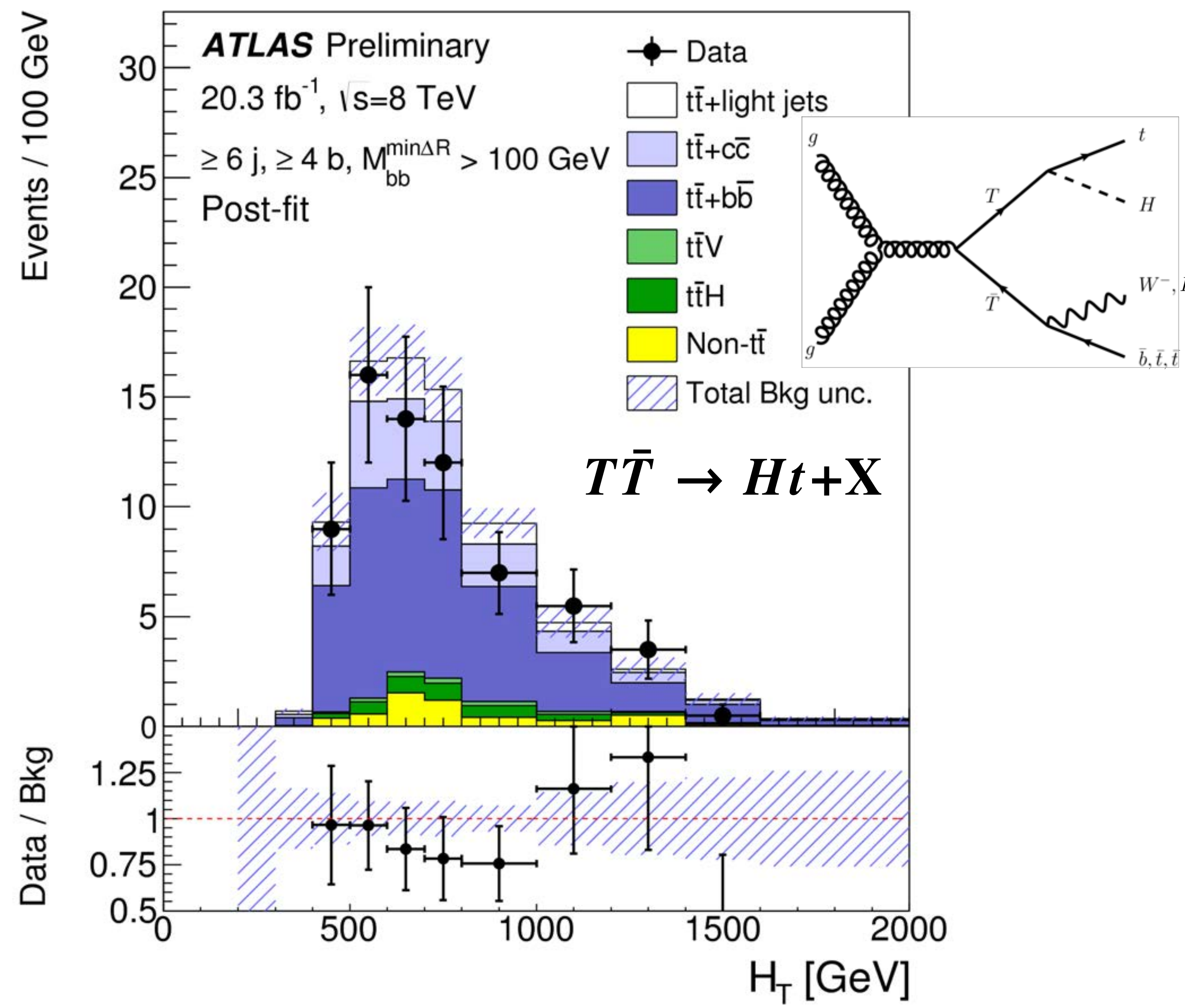
Vector-Like Quarks

- color-triplet spin-1/2 fermions; L & R components transform the same way under weak isospin
  - flavor-changing neutral current decays allowed: **T → W b, Z t, H t**

Four search channels:



ATLAS-CONF-2015-012



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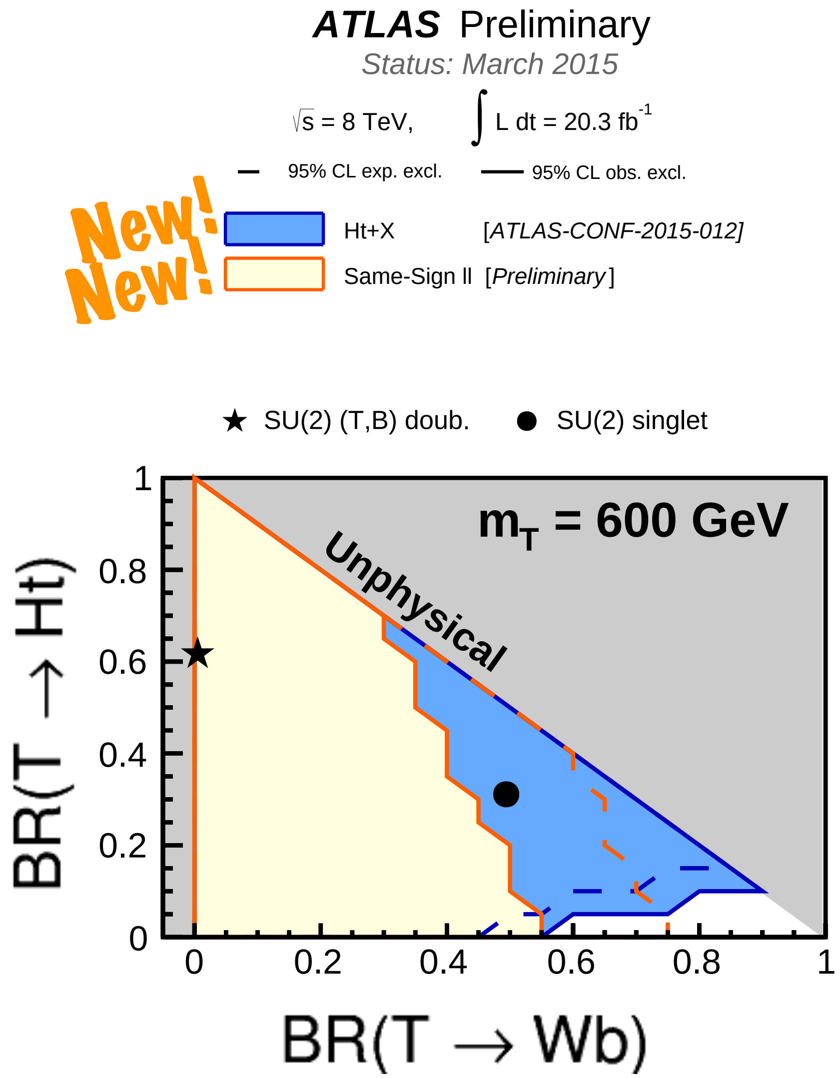
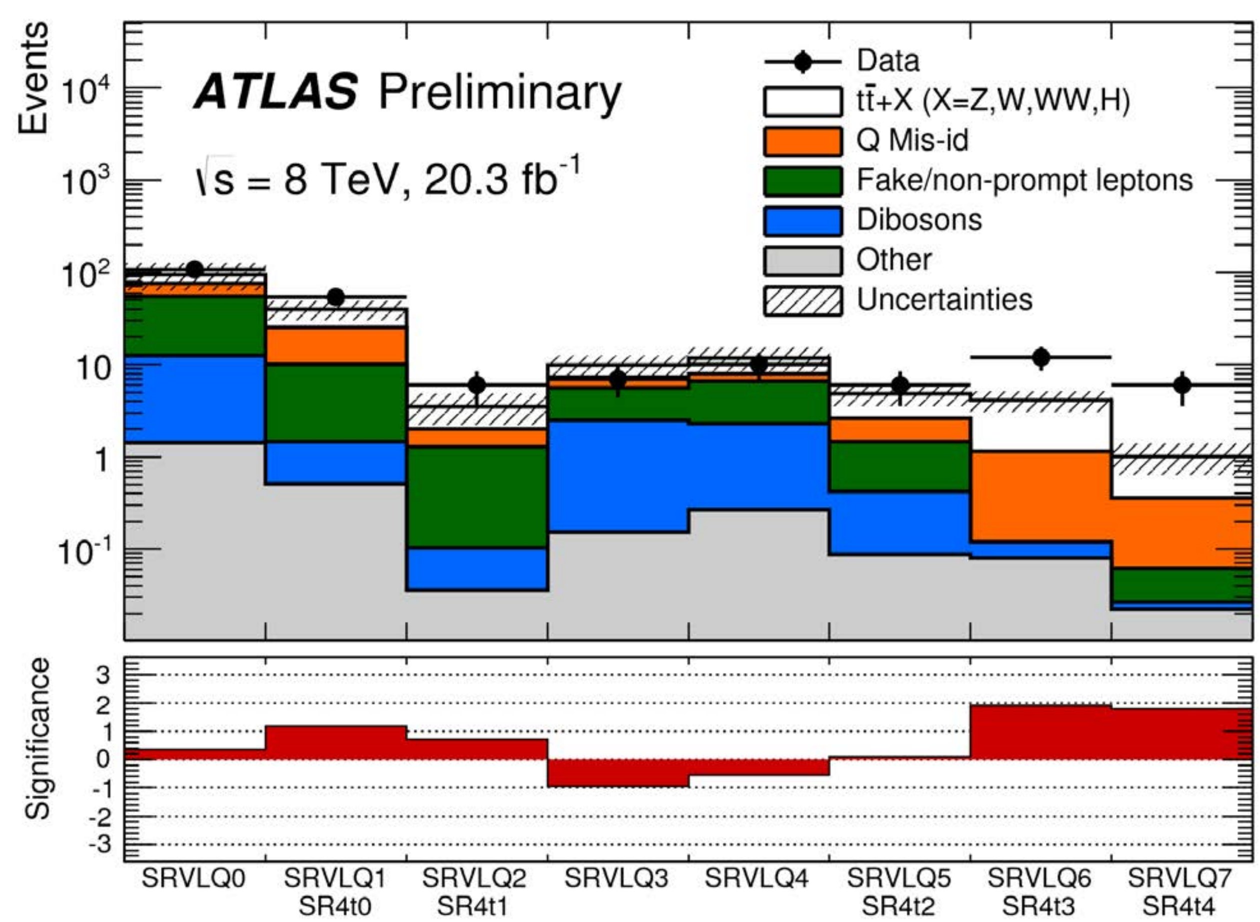


Same-Sign Dilepton/Trilepton (+*b*-jets)



2.2σ 2.4σ

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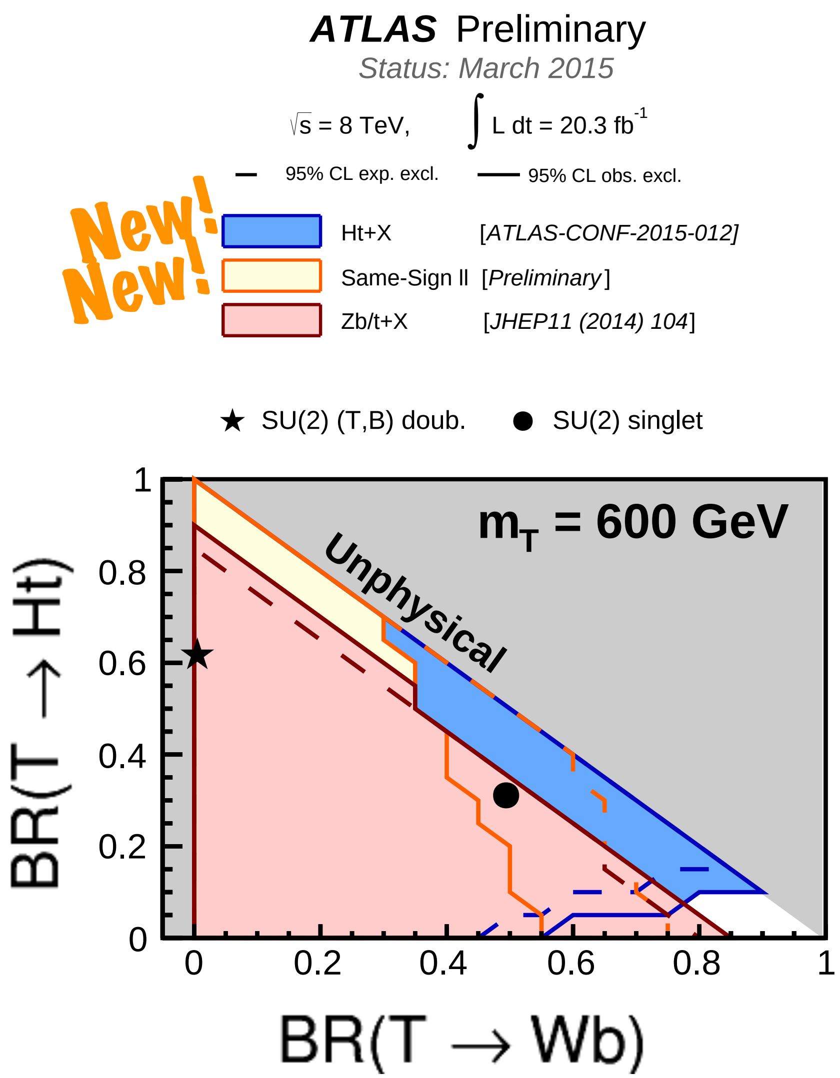
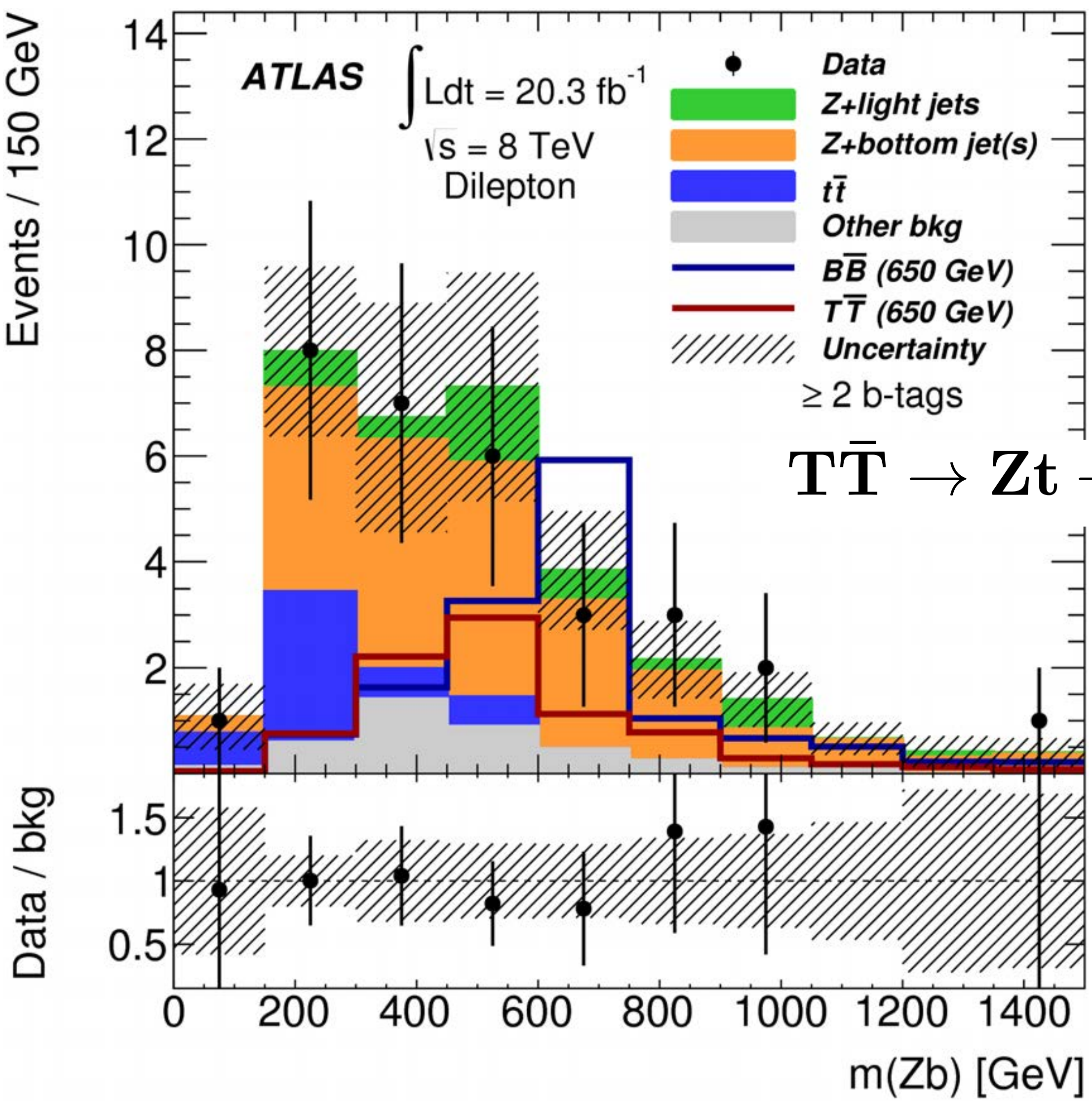


JHEP 11 (2014) 104

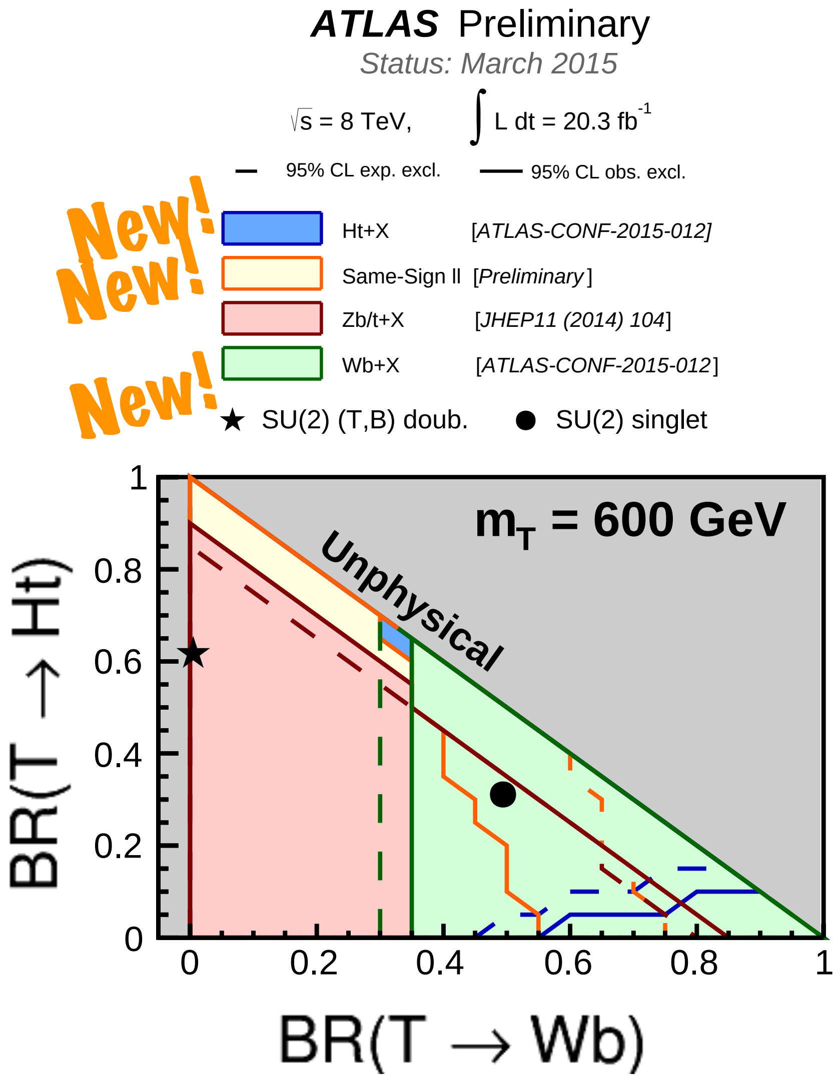


$T\bar{T} \to Zt + X$

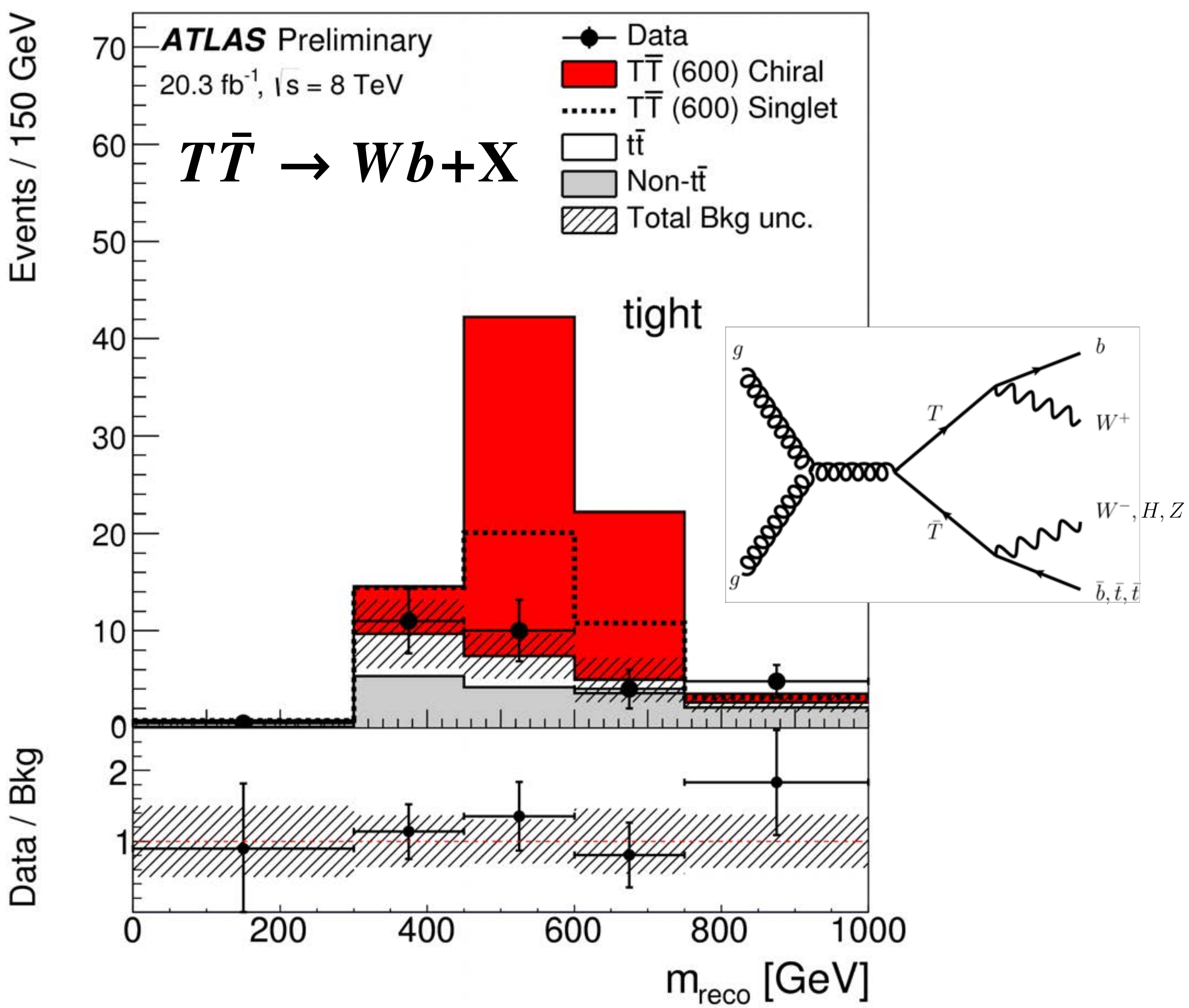
Vector-Like Quarks

- color-triplet spin-1/2 fermions; L & R components transform the same way under weak isospin
  - flavor-changing neutral current decays allowed: **T → W b, Z t, H t**

Four search channels:

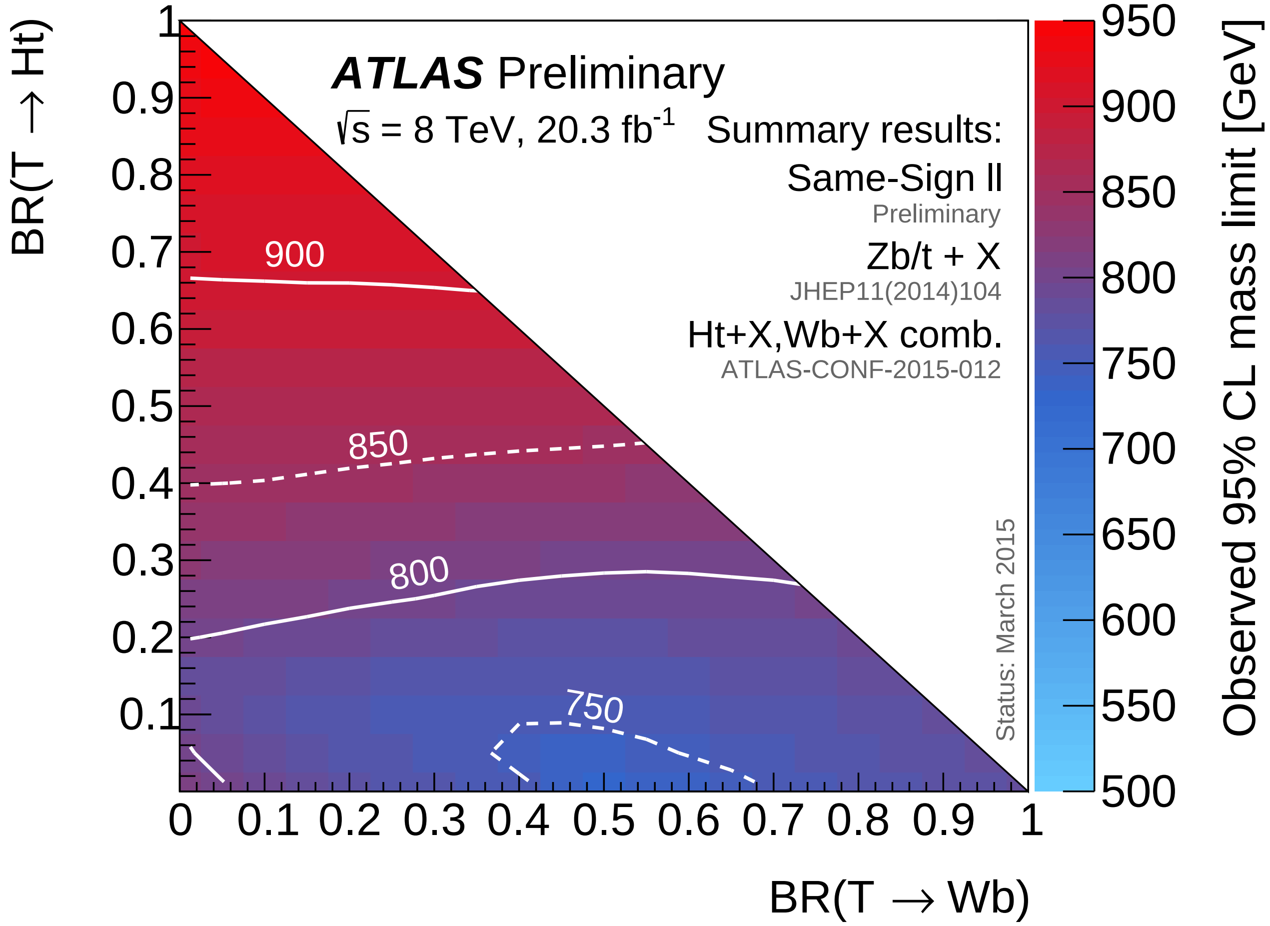


ATLAS-CONF-2015-012



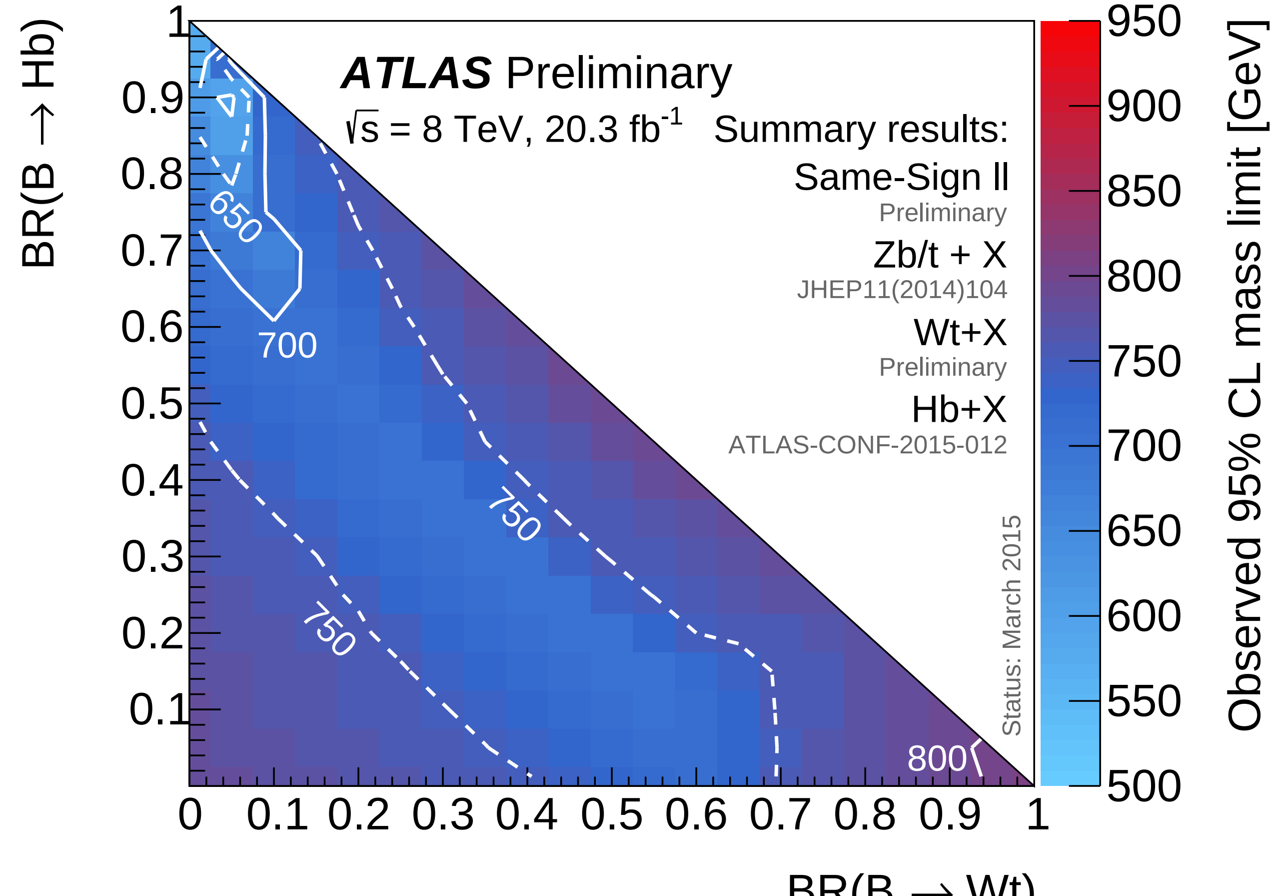
Vector-Like Quarks

New!



New results also available for vector-like B searches!

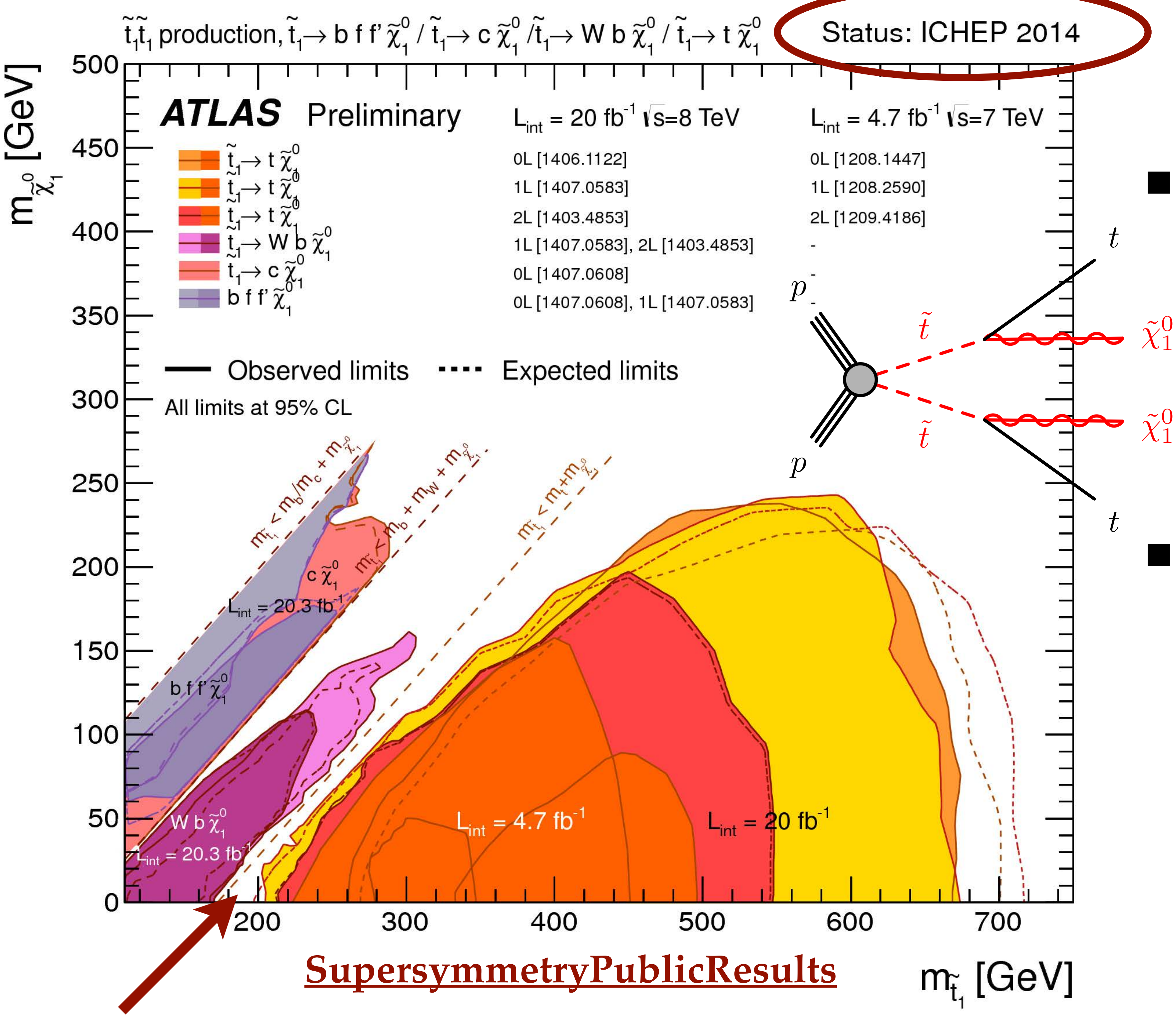
New!



(submitted to arxiv yesterday)

See the full set of summary plots: ExoticsPublicResults

Direct Stop Searches

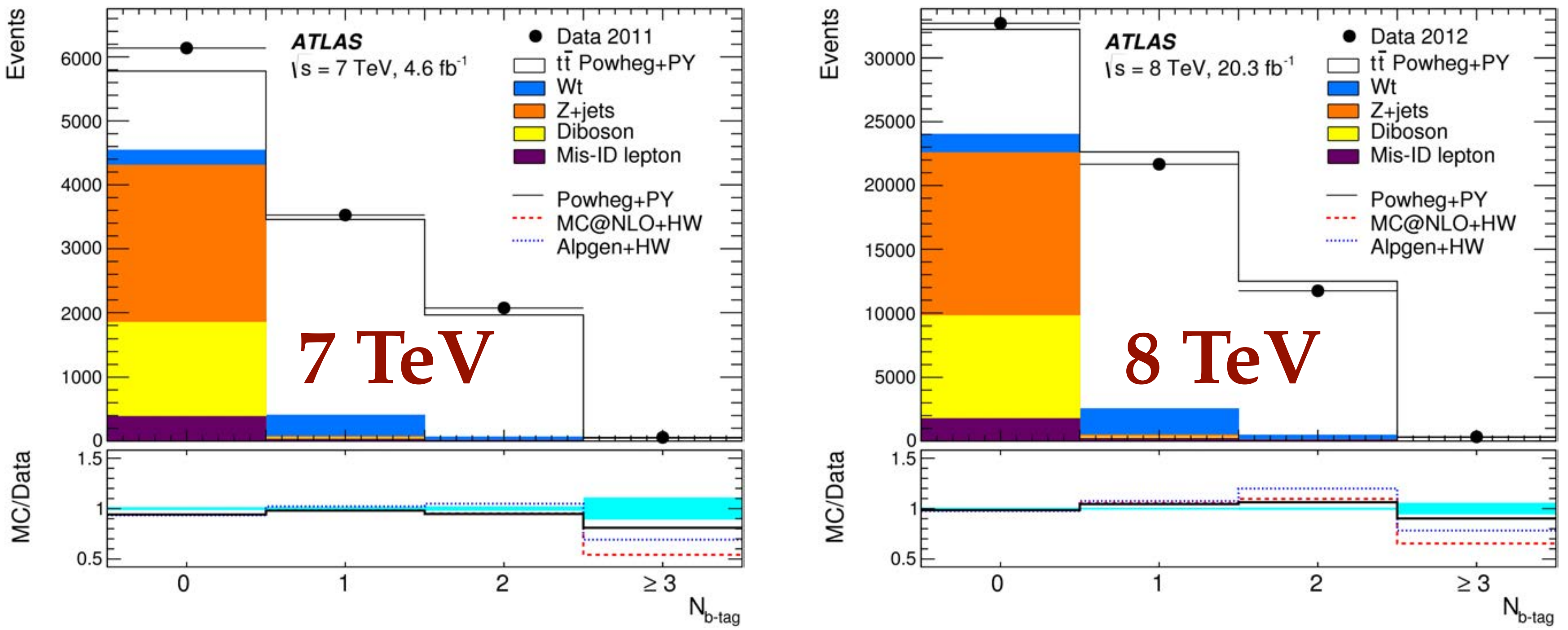


SupersymmetryPublicResults

- As of ICHEP 2014, direct stop searches provided impressive phase space coverage
- But detailed $t\bar{t}$ measurements were needed to investigate the region $m_{\tilde{t}} \sim m_t$

Precise $t\bar{t}$ Cross Sections

- 7 TeV and 8 TeV $t\bar{t}$ cross sections measured in $e^{\pm}\mu^{\mp}$ events
  - Reduced systematic uncertainties due to simultaneous fit and extraction of b-tagging efficiency EPJC 74 (2014) 3109



$$\sigma_{t\bar{t}} = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3\,\mathrm{pb}\ (\sqrt{s} = 7\,\mathrm{TeV})$$

$$\sigma_{t\bar{t}} = 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2\,\mathrm{pb}\ (\sqrt{s} = 8\,\mathrm{TeV})$$

stat syst lumi beam energy

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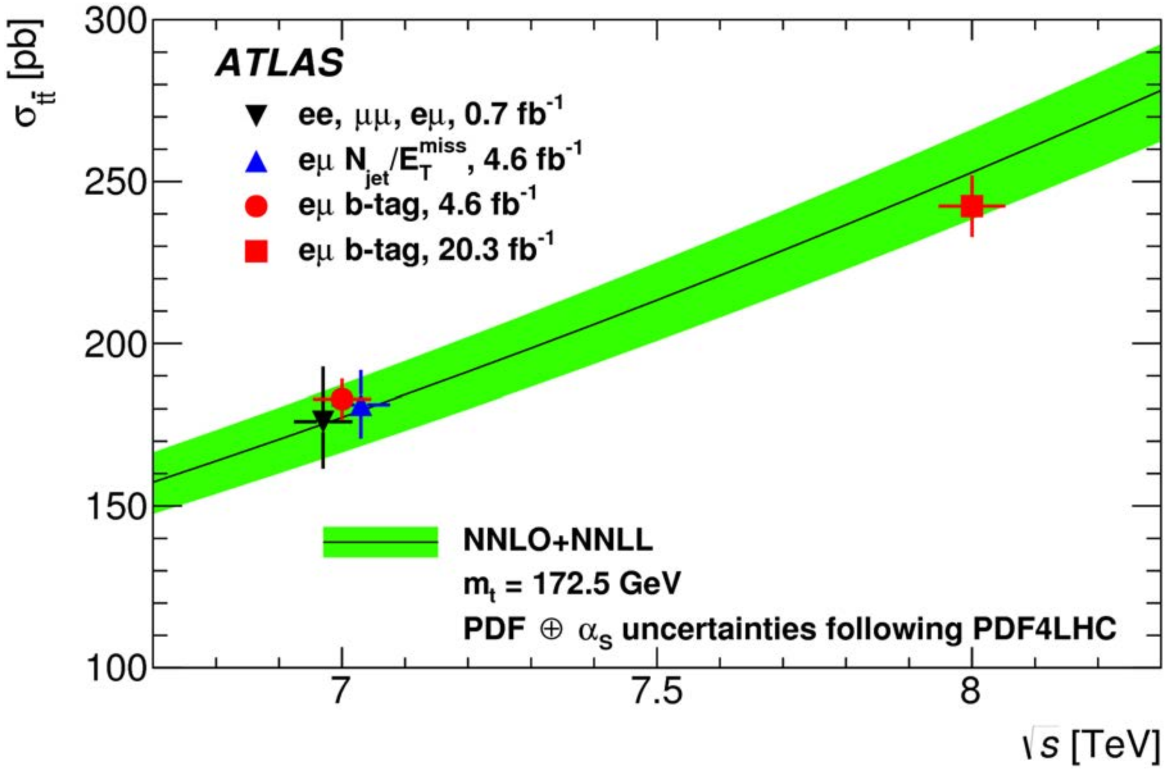
EPJC 74 (2014) 3109



total uncertainties:

$$\sigma_{t\bar{t}} = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3\,\text{pb}\ (\sqrt{s} = 7\,\text{TeV})$$ **7.1 pb (3.9%)**

$$\sigma_{t\bar{t}} = 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2\,\text{pb}\ (\sqrt{s} = 8\,\text{TeV})$$ **10.3 pb (4.3%)**

stat syst lumi beam energy

Precise $t\bar{t}$ Cross Sections

- 7 TeV and 8 TeV $t\bar{t}$ cross sections measured in $e^{\pm}\mu^{\mp}$ events
  - Reduced systematic uncertainties due to simultaneous fit and extraction of b-tagging efficiency

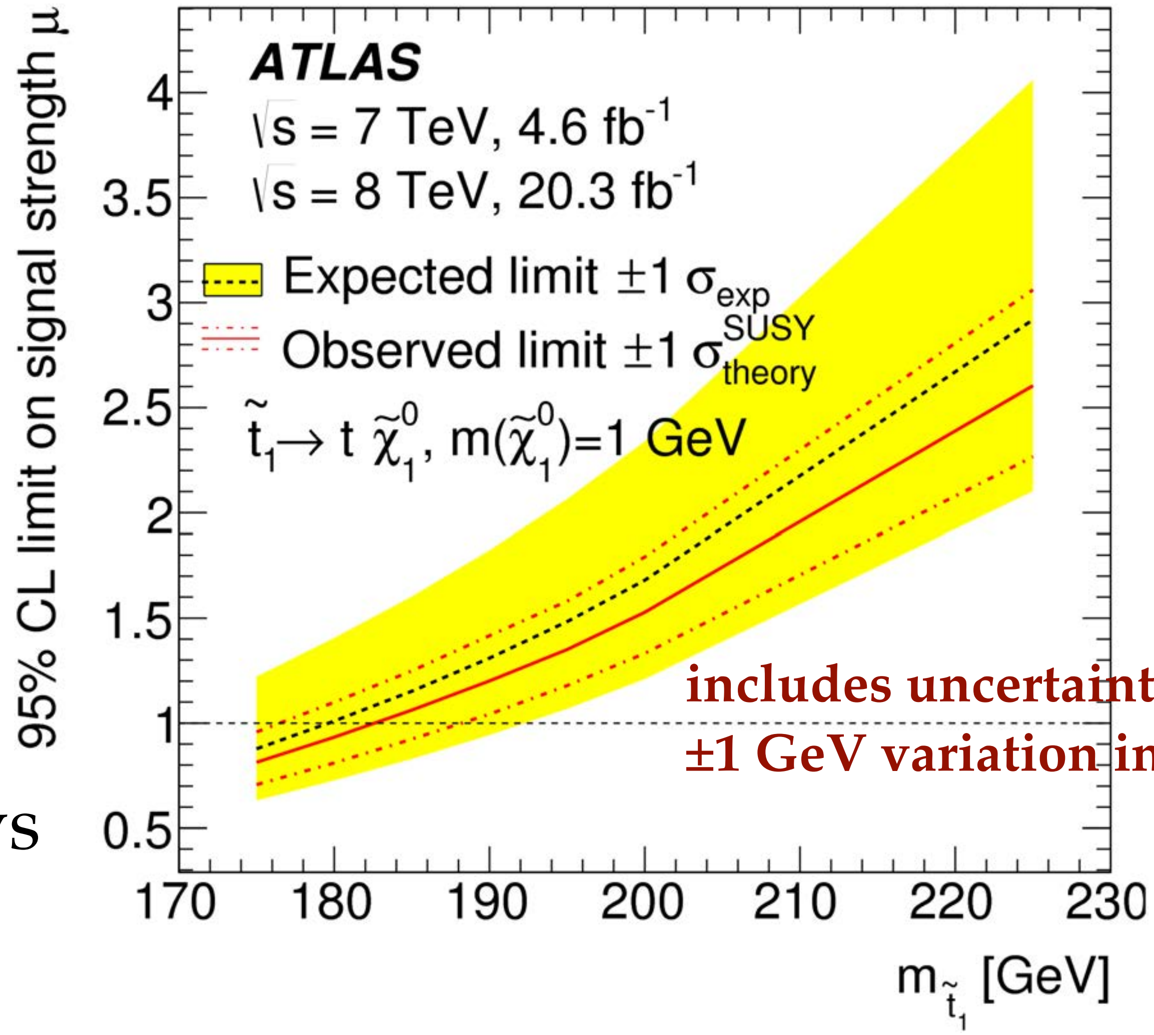
EPJC 74 (2014) 3109

  - **Also constrains "stealth" stop pair production**

    for $m_{\tilde{t}} = 175\,\mathrm{GeV}$,

    $\sigma_{\tilde{t}\tilde{t}^*}\,(8\,\mathrm{TeV}) = 40\,\mathrm{pb}$

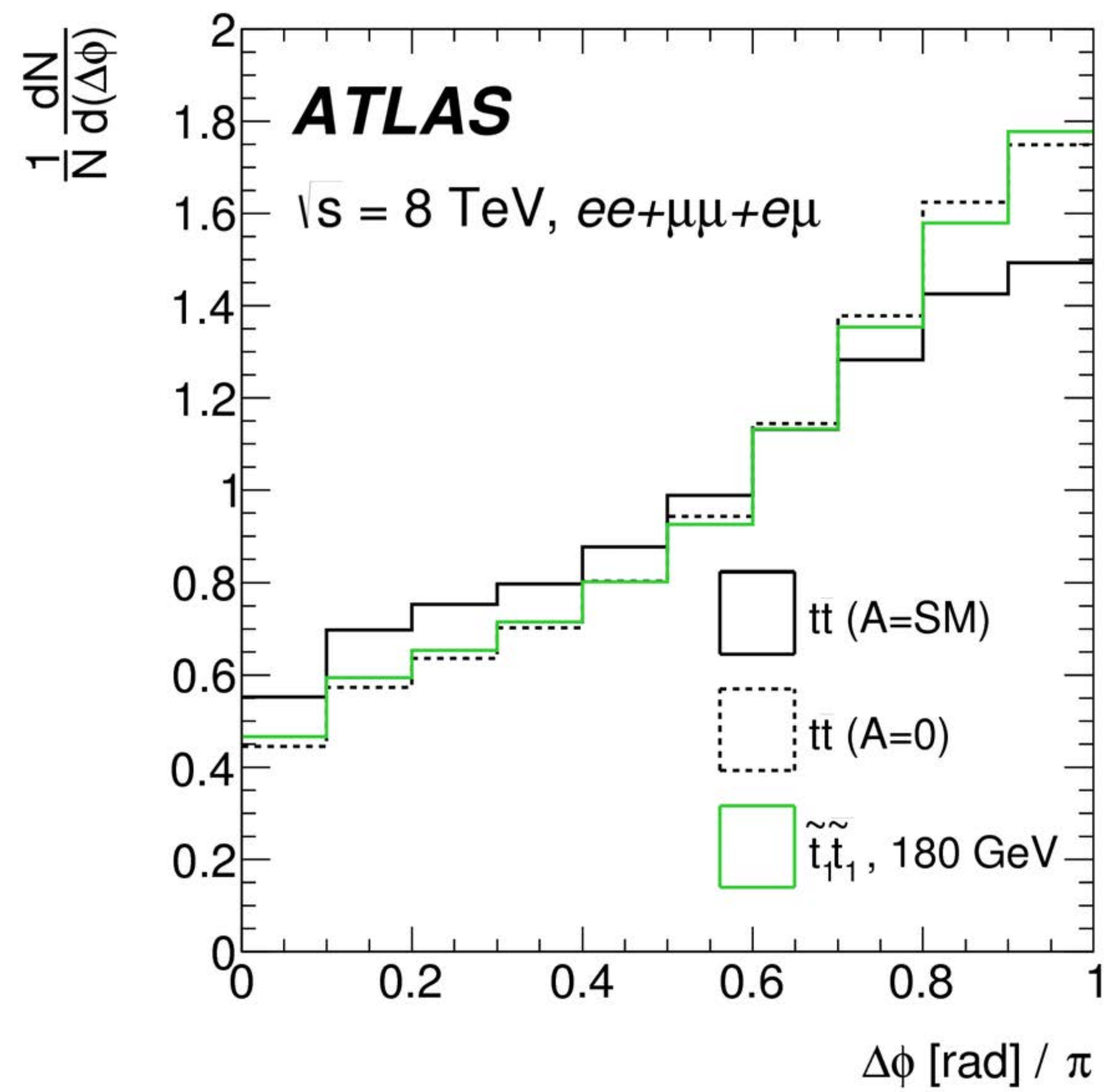
  - results sensitive to top polarization in stop decays



includes uncertainty due to ±1 GeV variation in m_{top}

$t\bar{t}$ Spin Correlation

- Top—antitop spin correlation extracted from dilepton $t\bar{t}$ events using $\Delta\Phi(\ell^+,\ell^-)$
- Analysis sensitive to changes in yield and shape → can detect admixture of $t\bar{t} + \tilde{t}\tilde{t}^*$



arxiv:1412.4742, accepted by PRL

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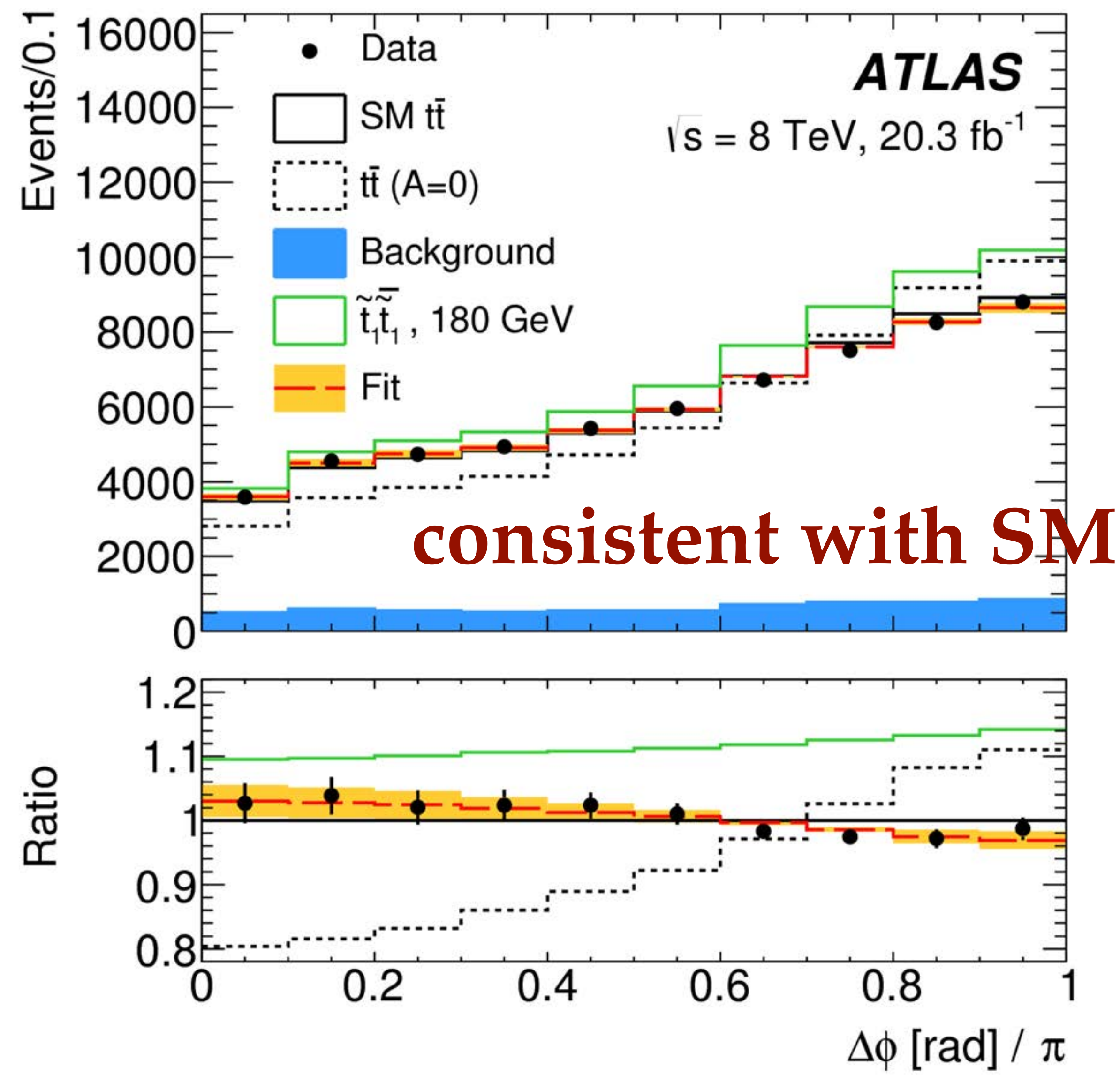
Process	Yield
$t\bar{t}$	$54000\ ^{+\ 3400}_{-\ 3600}$
Z/γ^*+jets	2800 ± 300
tV (single top)	2600 ± 180
$t\bar{t}V$	80 ± 11
WW, WZ, ZZ	180 ± 65
Fake leptons	780 ± 780
Total non-$t\bar{t}$	6400 ± 860
Expected	$60000\ ^{+\ 3500}_{-\ 3700}$
Observed	60424
$\tilde{t}_1\bar{\tilde{t}}_1$ ($m_{\tilde{t}_1} = 180$ GeV, $m_{\tilde{\chi}^0_1} = 1$ GeV)	7100 ± 1100



arxiv:1412.4742, accepted by PRL

$t\bar{t}$ Spin Correlation

- Top—antitop spin correlation extracted from dilepton $t\bar{t}$ events using $\Delta\Phi(\ell^+,\ell^-)$
- Analysis sensitive to changes in yield and shape → can detect admixture of $t\bar{t} + \tilde{t}\tilde{t}^*$

Process	Yield
$t\bar{t}$	$54000\ ^{+\ 3400}_{-\ 3600}$
Z/γ^*+jets	2800 ± 300
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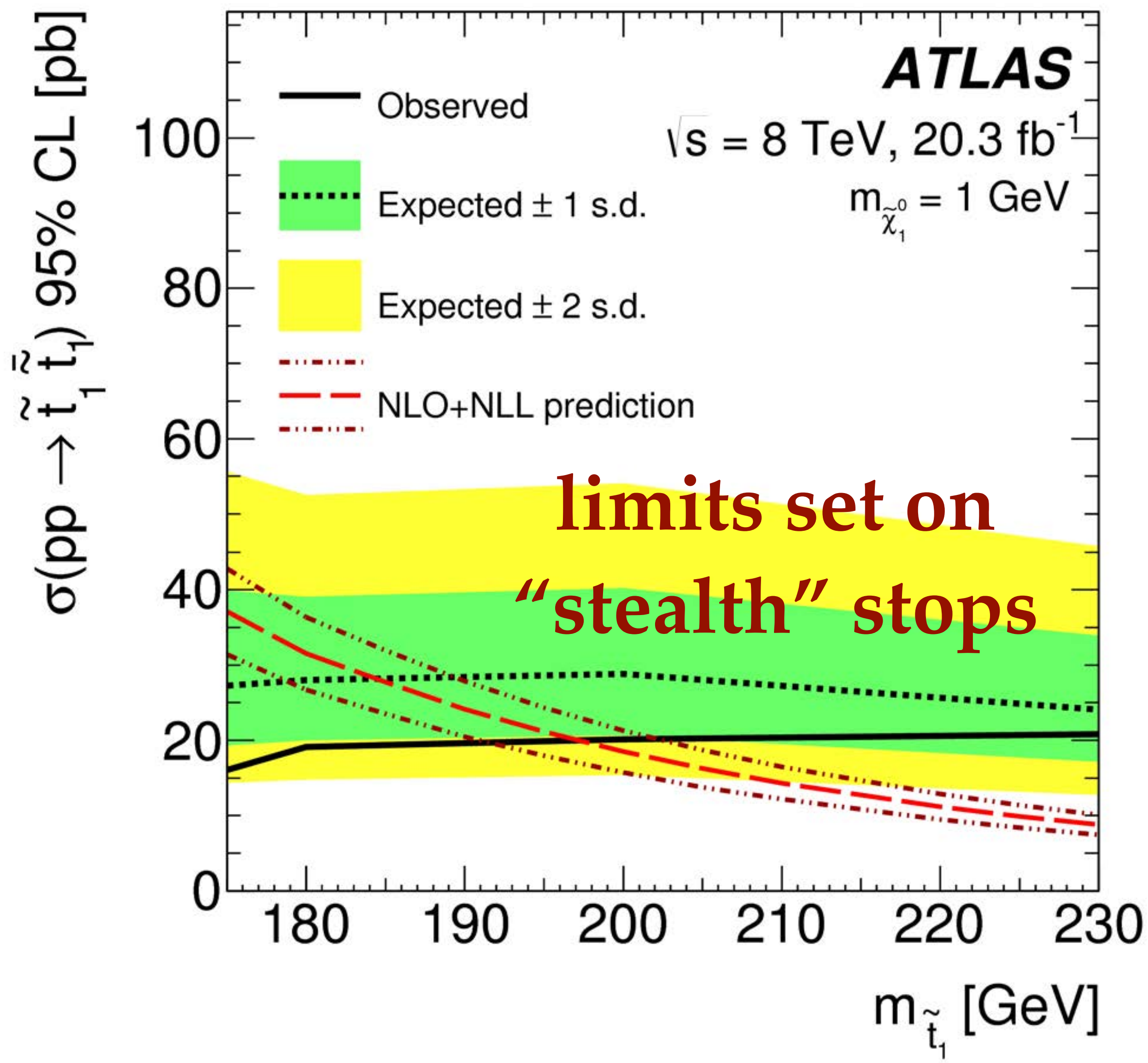
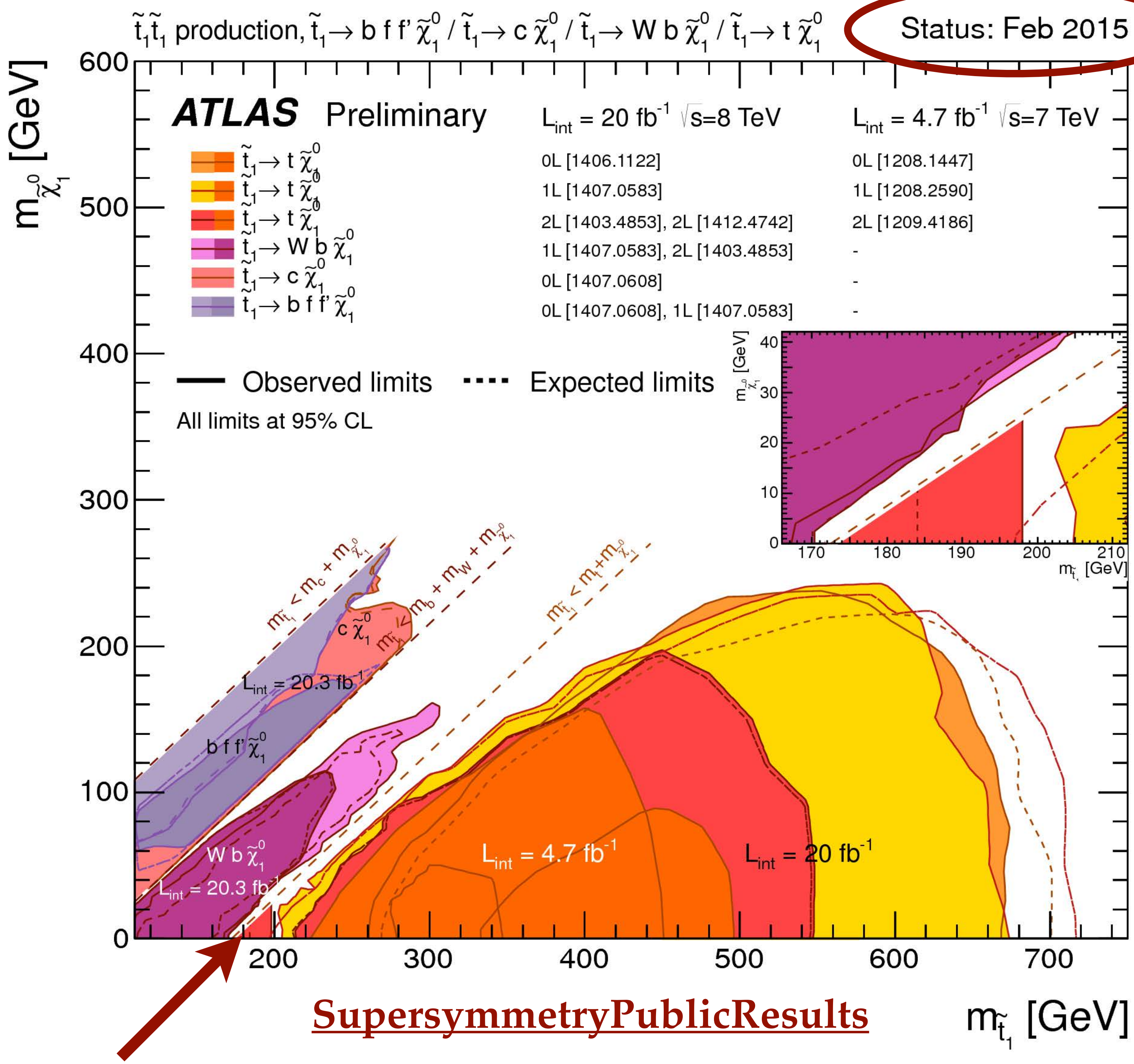
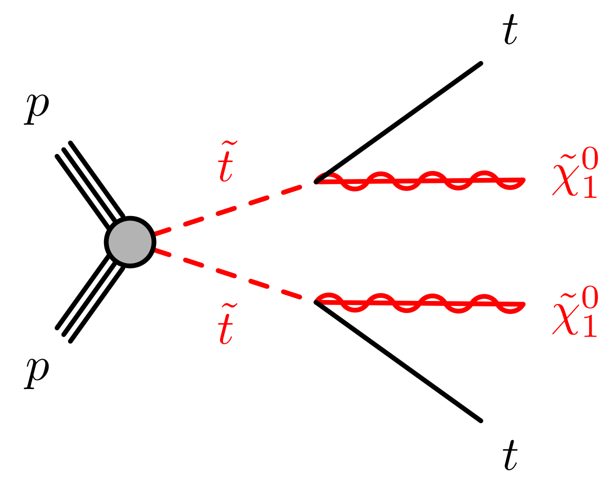


arxiv:1412.4742, accepted by PRL

Direct Stop Searches



SupersymmetryPublicResults

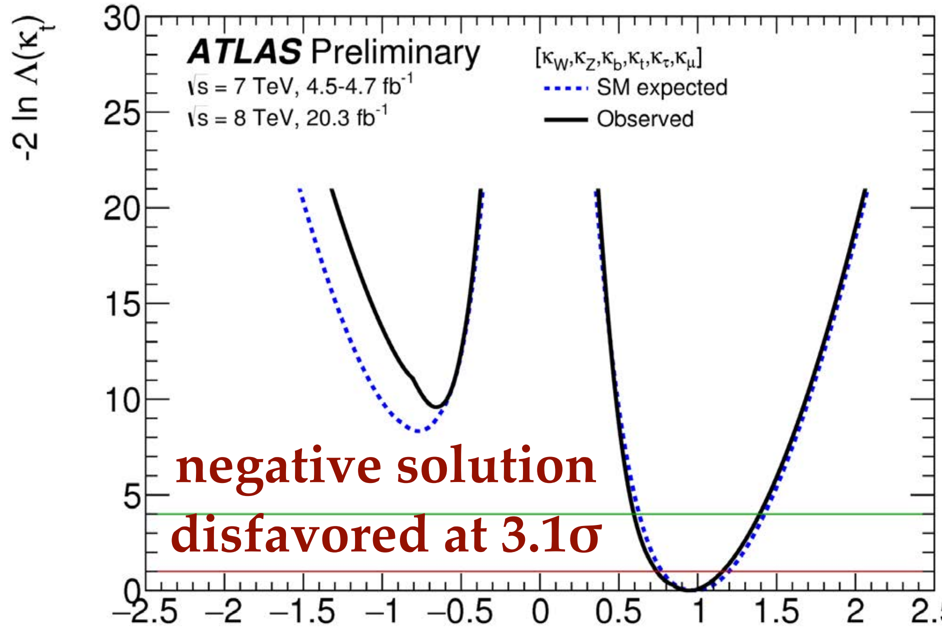


- Stealth stop region ($m_{\tilde{t}} \sim m_t$) nearly closed by precision $t\bar{t}$ measurements!

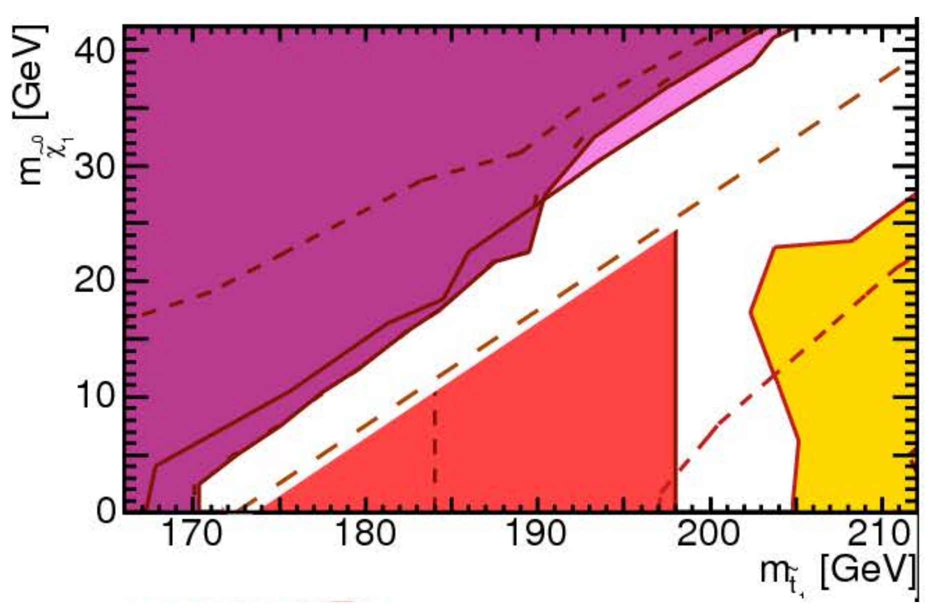
see also talk by G. Polesello

Summary & Outlook

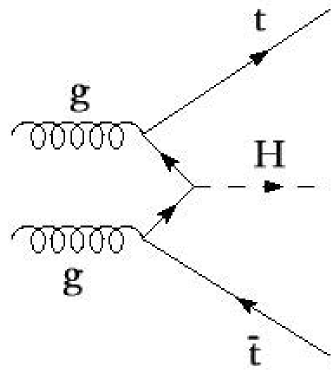
- On the 20th anniversary of its discovery, the massive top quark plays a central role in searching for new physics at the LHC
- Measurements have **improved our background estimates** and **increased our sensitivity to new physics** in *challenging* regions of phase space
- Looking forward to continued synergy between measurements and searches in Run 2!



$\kappa_t \equiv \frac{Y_t}{Y_t^{SM}}$



Additional Material

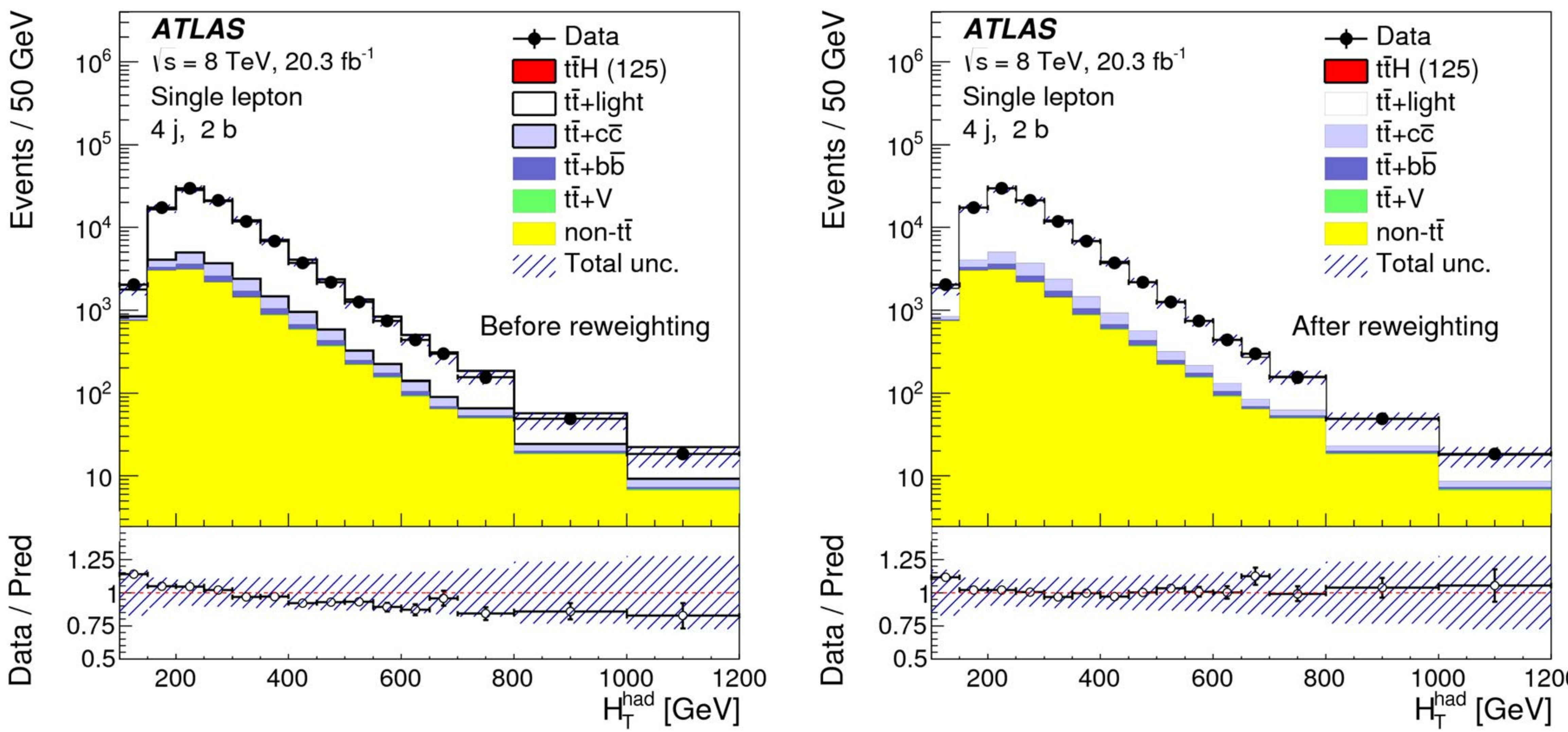


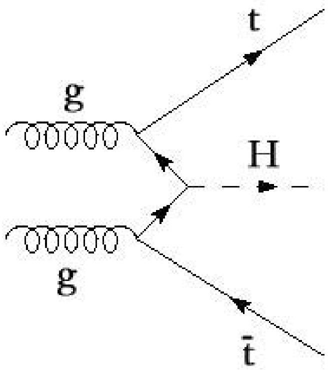
Top Yukawa Coupling

$H \to b\bar{b}$

$t\bar{t} \to \ell + \text{jets, dilepton}$

- impact of reweighting Powheg+Pythia based on $p_T(tt)$:



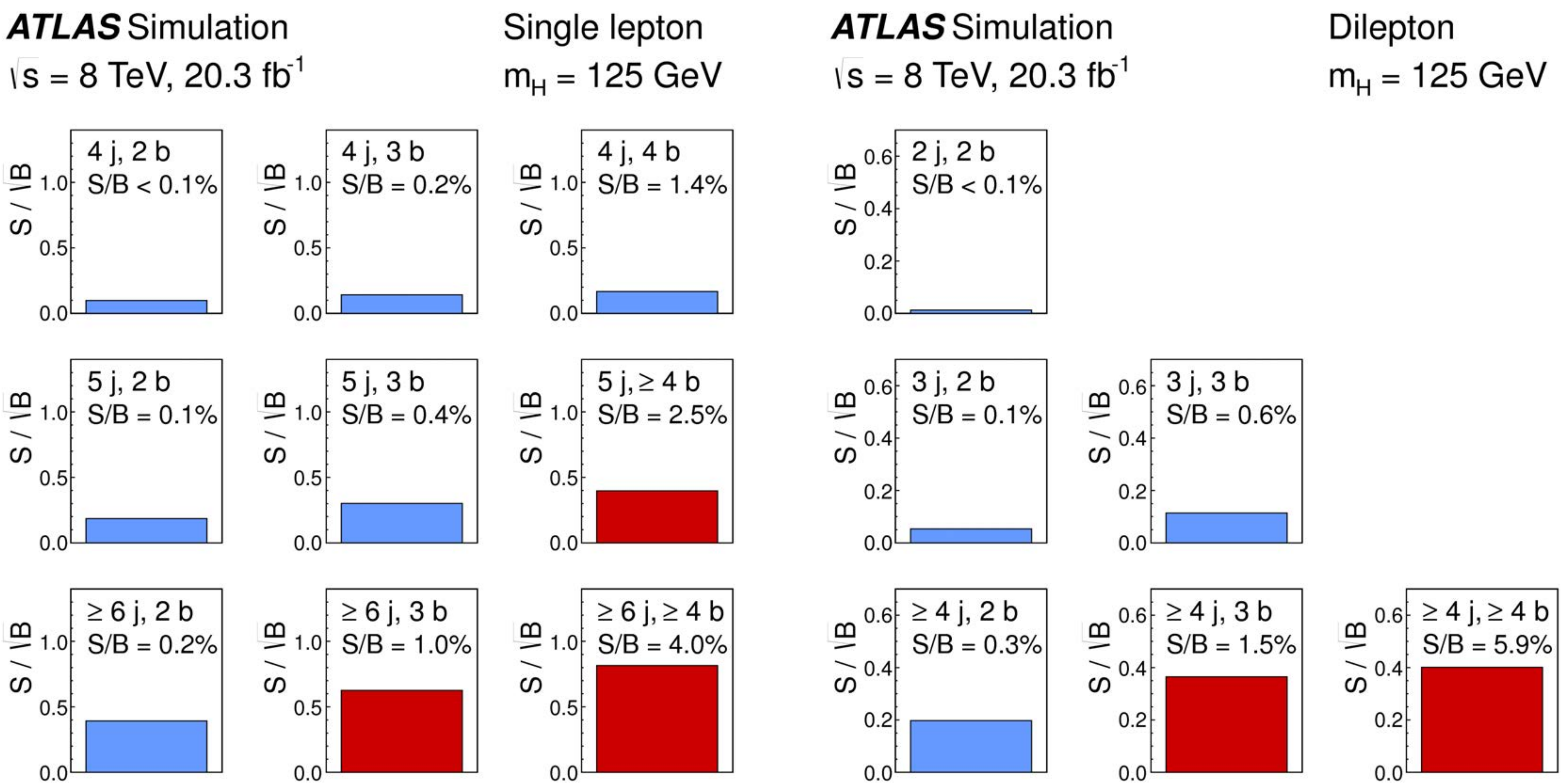


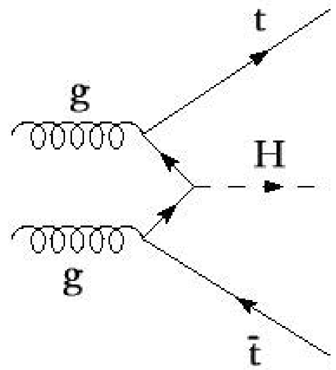
Top Yukawa Coupling

$H \to b\bar{b}$

$t\bar{t} \to \ell + \text{jets, dilepton}$

- full set of signal-rich and background-rich regions:





Top Yukawa Coupling

$H \to \gamma\gamma$

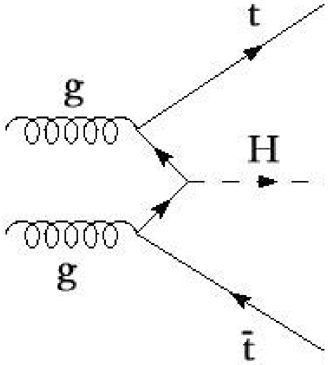
$t\bar{t} \to \ell +$ jets, dilepton, all-had

Table 2
Expected numbers of $H \to \gamma\gamma$ events (N_H) from an SM Higgs boson with $m_H = 125.4$ GeV after the event selection. These combined yields are normalized to 4.5 fb^{-1} for the 7 TeV data and to 20.3 fb^{-1} for the 8 TeV data, and are listed in the table along with the percent contribution of each Higgs boson production process with respect to the sum of all Higgs boson production processes. The numbers of fitted continuum background events (N_B) for the 7 TeV and 8 TeV data are also shown, where N_B is the integral of the continuum background in the $m_{\gamma\gamma}$ range 120–130 GeV, which is determined by an unbinned signal-plus-background fit to all categories with one common scale factor for the $H \to \gamma\gamma$ normalization. The uncertainty on N_B is the statistical uncertainty calculated from $\delta N_B = \delta N_{\text{tot}} N_B / N_{\text{tot}}$, where N_{tot} is the total number of background events in the full $m_{\gamma\gamma}$ range 105–160 GeV estimated from an unbinned signal-plus-background likelihood fit, and δN denotes the Poisson uncertainty on N.

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	$2.7^{+0.9}_{-0.7}$

$4.6^{+1.3}_{-0.9}$

5 candidate events observed in $120 < m_{\gamma\gamma} < 130$ GeV, consistent with 1.3 expected from ttH + 4.6 from bkg



Top Yukawa Coupling

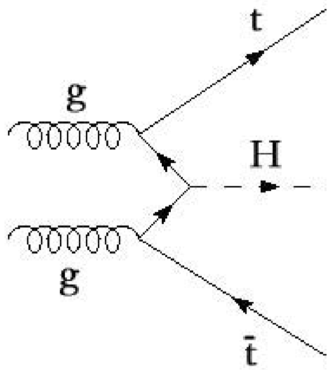
Multi-lepton final states (including τ s)

- Expected and observed yields in each channel

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
$2\ell 1\tau_{\text{had}}$	–	$0.4\,^{+0.6}_{-0.4}$	0.38 ± 0.15	0.37 ± 0.09	0.12 ± 0.15	1.4 ± 0.6	0.47 ± 0.02	1
$1\ell 2\tau_{\text{had}}$	–	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

- Systematic uncertainties:

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

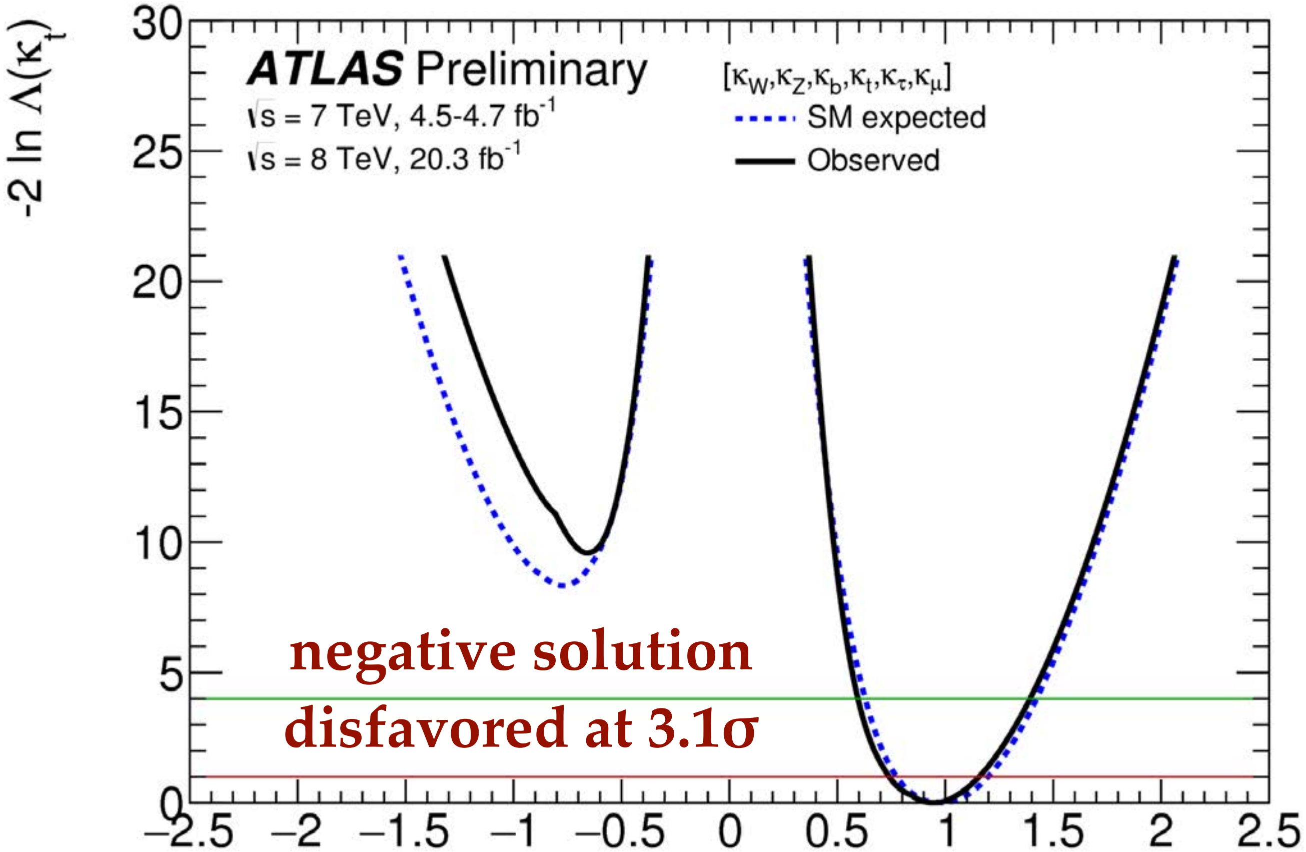


Top Yukawa Coupling

Combined Results

ATLAS-CONF-2015-007

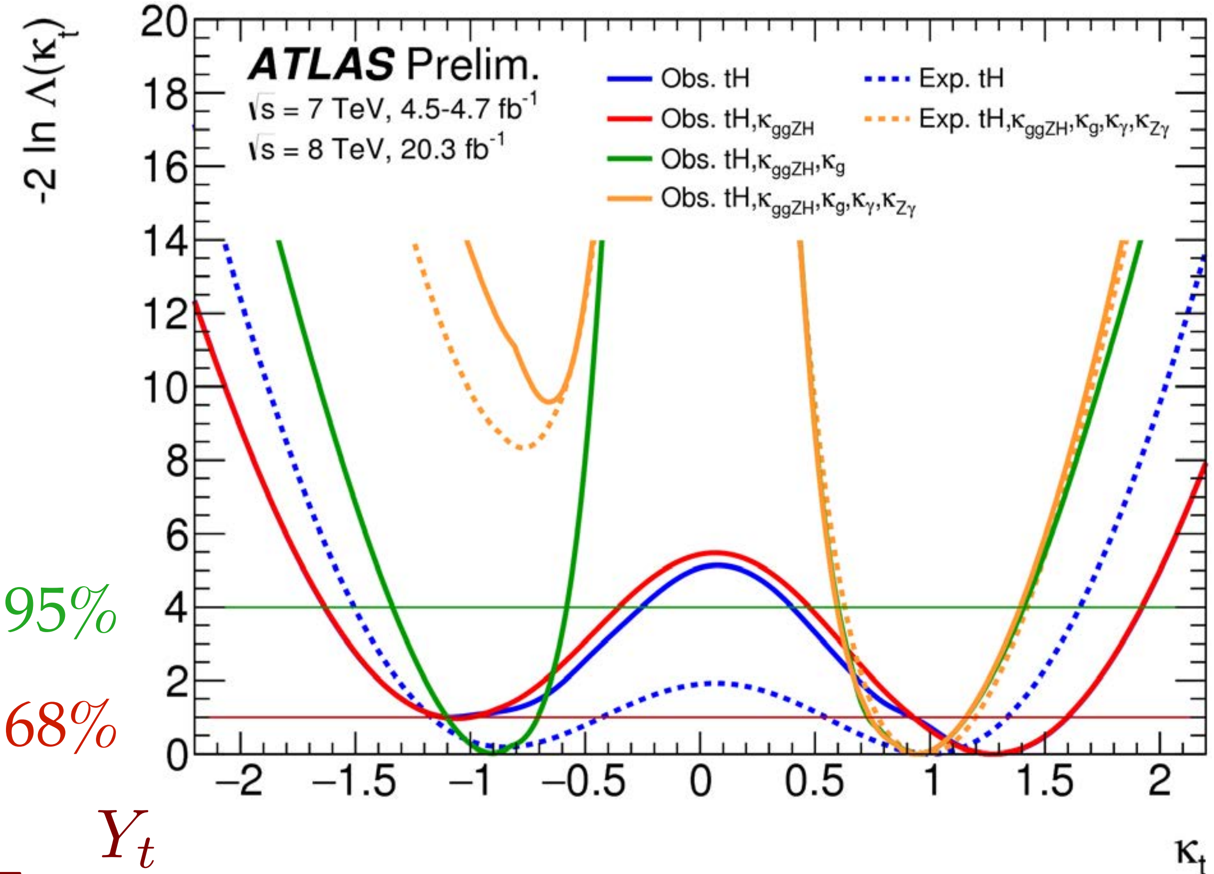
New!



negative solution disfavored at 3.1σ

95%

68%



$$\kappa_t \equiv \frac{Y_t}{Y_t^{\mathrm{SM}}}$$

only SM particles in loops, no invisible or undetected Higgs decays

Vector-Like Quarks

$T\bar{T} \rightarrow Ht$+X

Common preselection:

1 e or 1 μ, ≥ 4 jets

$E_T^{miss} > 20$ GeV

$E_T^{miss} + m_T^W > 60$ GeV

	5 j, 2 b	5 j, 3 b	5 j, ≥4 b	≥6 j, 2 b
$T\bar{T}$ (m_T = 600 GeV)				
Singlet	52.5 ± 4.2	19.0 ± 2.3	5.8 ± 1.2	123.3 ± 6.2
Doublet	25.8 ± 2.0	14.0 ± 1.4	5.0 ± 1.0	154.1 ± 6.4
$\sigma\sigma \rightarrow t\bar{t}t\bar{t}$ (m_σ = 800 GeV)	2.0 ± 0.3	1.4 ± 0.3	0.3 ± 0.1	64.8 ± 4.6
$t\bar{t}t\bar{t}$+X (Tier (1,1), m_{KK} = 800 GeV)	1.0 ± 0.4	0.6 ± 0.3	0.06 ± 0.05	180 ± 29
$t\bar{t}$+light jets	32400 ± 5300	2930 ± 520	48 ± 12	16200 ± 4000
$t\bar{t} + c\bar{c}$	3800 ± 2100	730 ± 410	42 ± 24	3300 ± 1800
$t\bar{t} + b\bar{b}$	1530 ± 800	800 ± 420	108 ± 58	1300 ± 700
$t\bar{t}V$	140 ± 46	24.9 ± 8.1	2.9 ± 1.0	172 ± 56
$t\bar{t}H$	39.2 ± 1.7	20.8 ± 1.6	5.6 ± 0.7	60.2 ± 4.5
W+jets	1600 ± 1000	111 ± 71	5.0 ± 3.4	770 ± 530
Z+jets	360 ± 120	24.8 ± 8.4	1.2 ± 0.5	185 ± 67
Single top	1630 ± 320	169 ± 36	7.0 ± 1.0	730 ± 200
Diboson	85 ± 27	7.3 ± 2.5	0.4 ± 0.2	45 ± 15
Multijet	133 ± 48	33 ± 12	6.9 ± 2.6	56 ± 20
Total background	41700 ± 6400	4840 ± 900	228 ± 69	22800 ± 5200
Data	43319	5309	244	23001

	≥6 j, 3 b low $M_{bb}^{\min\Delta R}$	≥6 j, 3 b high $M_{bb}^{\min\Delta R}$	≥6 j, ≥4 b low $M_{bb}^{\min\Delta R}$	≥6 j, ≥4 b high $M_{bb}^{\min\Delta R}$
$T\bar{T}$ (m_T = 600 GeV)				
Singlet	29.5 ± 2.0	44.0 ± 3.6	17.7 ± 1.9	24.1 ± 3.7
Doublet	50.2 ± 2.5	68.9 ± 4.1	41.0 ± 3.9	53.8 ± 7.3
$\sigma\sigma \rightarrow t\bar{t}t\bar{t}$ (m_σ = 800 GeV)	22.5 ± 1.6	50.7 ± 3.5	9.3 ± 1.0	16.2 ± 2.6
$t\bar{t}t\bar{t}$+X (Tier (1,1), m_{KK} = 800 GeV)	33.6 ± 2.8	132.5 ± 5.9	27.7 ± 2.3	75 ± 13
$t\bar{t}$+light jets	1280 ± 350	440 ± 110	38 ± 14	9.3 ± 3.9
$t\bar{t} + c\bar{c}$	550 ± 320	220 ± 120	53 ± 31	14.7 ± 9.0
$t\bar{t} + b\bar{b}$	620 ± 330	250 ± 140	178 ± 95	46 ± 25
$t\bar{t}V$	28.7 ± 9.2	12.5 ± 4.2	6.2 ± 2.0	1.5 ± 0.5
$t\bar{t}H$	24.9 ± 1.9	11.6 ± 1.3	10.6 ± 1.2	4.1 ± 0.6
W+jets	68 ± 46	16 ± 10	6.6 ± 4.8	0.6 ± 0.4
Z+jets	15.7 ± 6.3	3.3 ± 1.3	1.6 ± 0.6	0.3 ± 0.1
Single top	74 ± 22	32 ± 12	7.8 ± 2.2	2.1 ± 1.3
Diboson	4.2 ± 1.6	1.2 ± 0.5	0.4 ± 0.1	0.2 ± 0.1
Multijet	1.9 ± 0.8	4.8 ± 2.1	< 0.01	2.8 ± 1.0
Total background	2670 ± 680	990 ± 260	300 ± 110	81 ± 30
Data	3015	1085	362	84

Vector-Like Quarks

$T\bar{T} \rightarrow Wb$+X

Selection	Requirements
Preselection	One electron or muon $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}} > 60$ GeV $\geq$4 jets, $\geq$1 b-tagged jets
Loose selection	Preselection $\geq$1 W_{had} candidate (type I or type II) $H_{\mathrm{T}} > 800$ GeV $p_{\mathrm{T}}(b_1) > 160$ GeV, $p_{\mathrm{T}}(b_2) > 110$ GeV (type I) or $p_{\mathrm{T}}(b_2) > 80$ GeV (type II) $\Delta R(\ell,\nu) < 0.8$ (type I) or $\Delta R(\ell,\nu) < 1.2$ (type II)
Tight selection	Loose selection $\min(\Delta R(\ell, b_{1,2})) > 1.4$, $\min(\Delta R(W_{\mathrm{had}}, b_{1,2})) > 1.4$ $\Delta R(b_1,b_2) > 1.0$ (type I) or $\Delta R(b_1,b_2) > 0.8$ (type II) $\Delta m < 250$ GeV (type I)

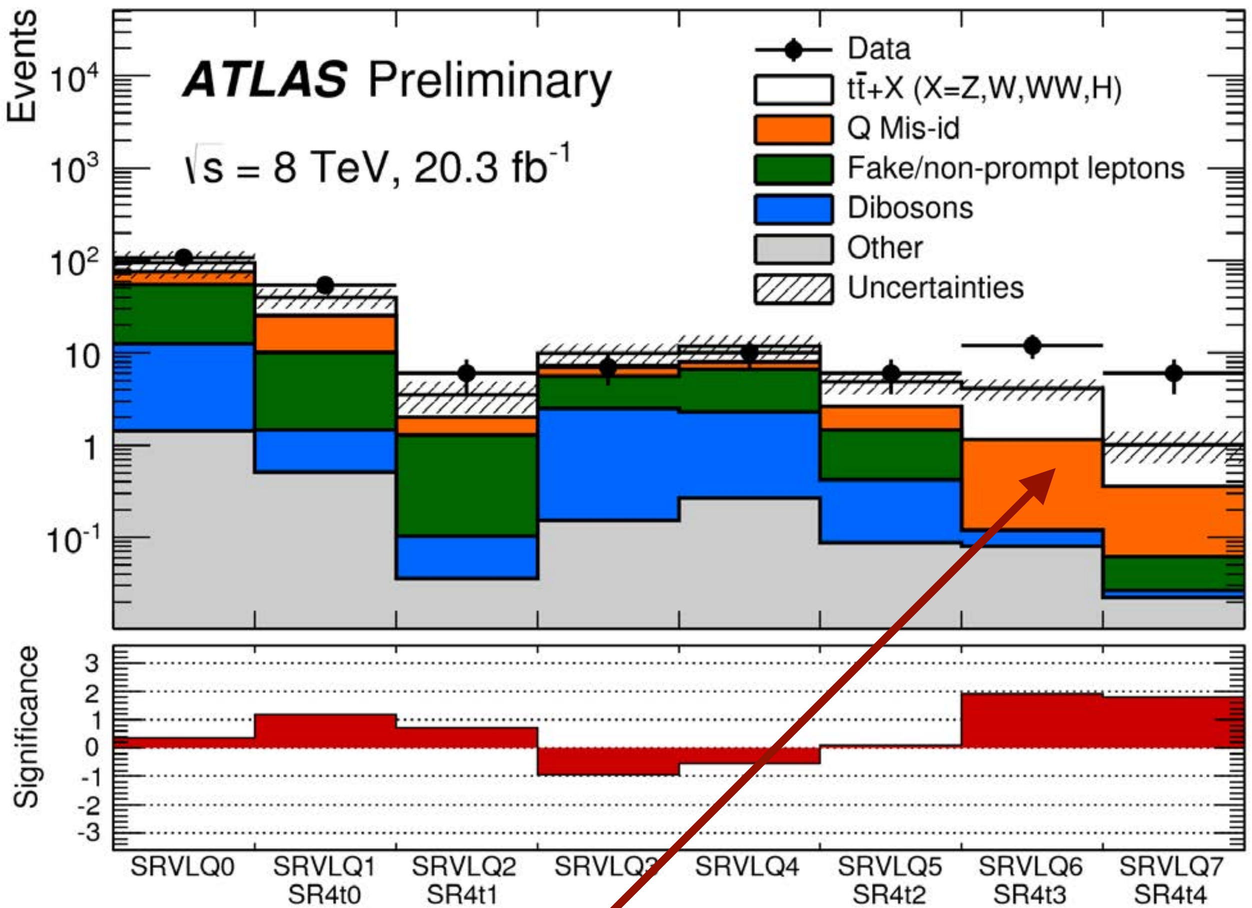
	Loose selection	Tight selection
$T\bar{T}(m_T = 600$ GeV$)$		
Chiral fourth-generation	115 ± 10	58.9 ± 5.9
Vector-like singlet	60.3 ± 5.1	24.5 ± 2.3
$t\bar{t}$	390 ± 110	10.7 ± 4.3
$t\bar{t}V$	6.5 ± 2.5	0.4 ± 0.2
W+jets	38 ± 19	11.4 ± 6.2
Z+jets	1.5 ± 1.2	0.4 ± 0.4
Single top	36 ± 17	2.2 ± 1.5
Diboson	5.6 ± 1.4	1.5 ± 0.6
Multijet	0.3 ± 1.6	0.8 ± 0.7
Total background	480 ± 120	27.5 ± 8.6
Data	478	34

Vector-Like Quarks

Same-sign dilepton/trilepton

SR4t3: $H_T > 700$ GeV, $N_{b\text{-jets}} = 2$, $E_T^{miss} > 100$ GeV

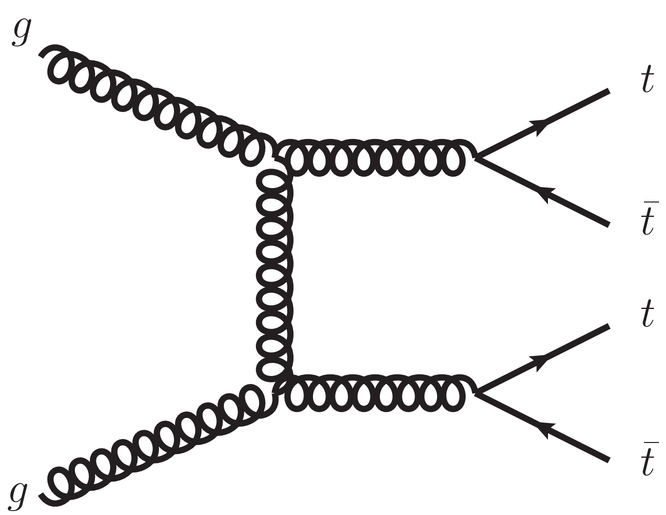
SR4t4: $H_T > 700$ GeV, $N_{b\text{-jets}} >= 3$, $E_T^{miss} > 40$ GeV



2.2σ 2.4σ

6/18 events in common with ttH multilepton analysis

Search for 4-top production



- SM σ_{tttt} ~ 1 fb @ 8 TeV
- Same channels as vector-like quark searches: Ht+X, ss dilepton/trilepton
  - Ht+X limit: 23 fb (obs), 32 fb (exp)
  - ss dilepton/trilepton limit: 27 fb (exp)