a place of mind

THE UNIVERSITY OF BRITISH COLUMBIA

PHYSICS ASTRONOMY

Search for Vector-Like Quarks

Road Map

- *Motivation*
- *ATLAS Analyses*
- *Take Away*

BEACH 2018

XIII INTERNATIONAL CONFERENCE ON BEAUTY, CHARM & HYPERON HADRONS

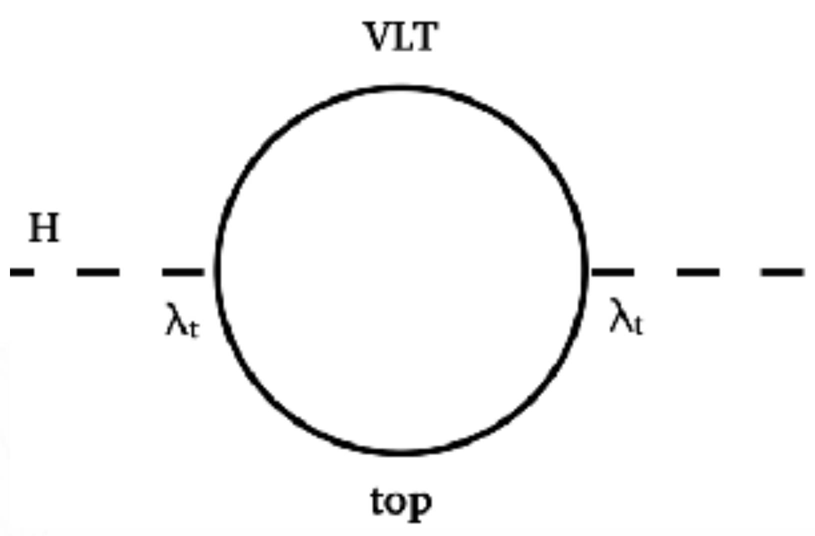
17 / 06 / 2018

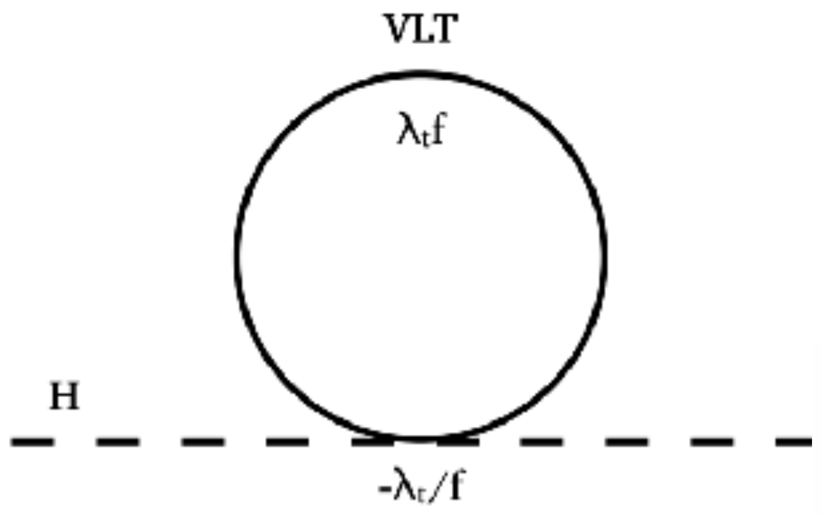
Steffen Henkelmann | On Behalf of the ***ATLAS*** Collaboration

Vector-Like Quarks (I)

Motivation

- Solution to big hierarchy problem
  - Cancelation of radiative corrections Δm_H^2





- Predicted by a number of BSM theories
  - Little Higgs, Composite Higgs, non-minimal SUSY

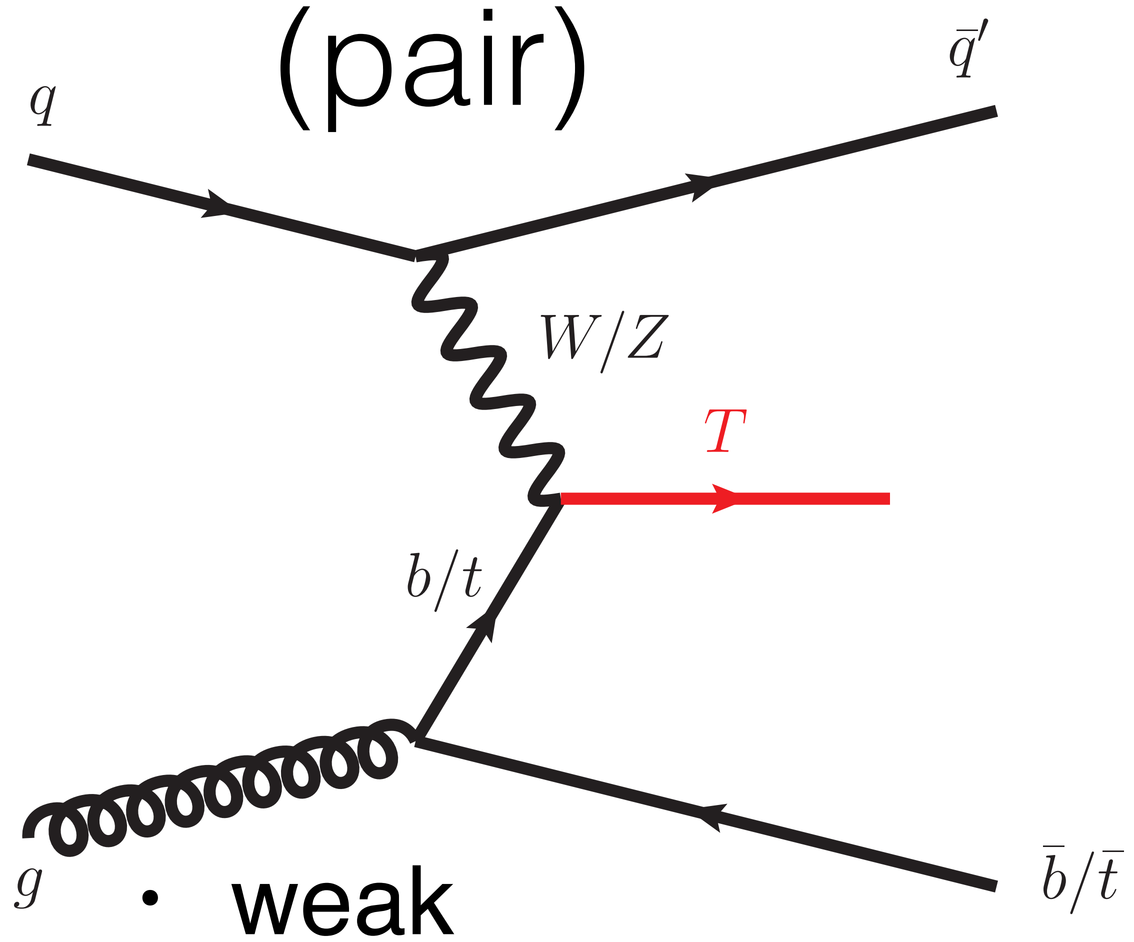
Q[e]	SM quarks (generation i)			VLQs singlets		VLQs doublets		
5/3						X		
2/3	u	c	t	(T)		T	T	
−1/3	d	s	b		(B)		B	B
−4/3								Y

Phenomenology

- VLQ's defined as colour-triplet spin 1/2 fermions
  - Mixing with SM quarks ➞ allows for flavour changing neutral currents (FCNC)
  - Different SU(2) multiplets allowed
    - Determines $\mathscr{B}$
    - Only small mass splitting allowed ➞ no cascade decays
  - Non-chiral: L and R same colour and transform same under SU(2) — vector coupling
    - Add bare mass term to SM Lagrangian
    - They do not get their masses through the EWSB
    - They can decouple from SM controled by mixing angle

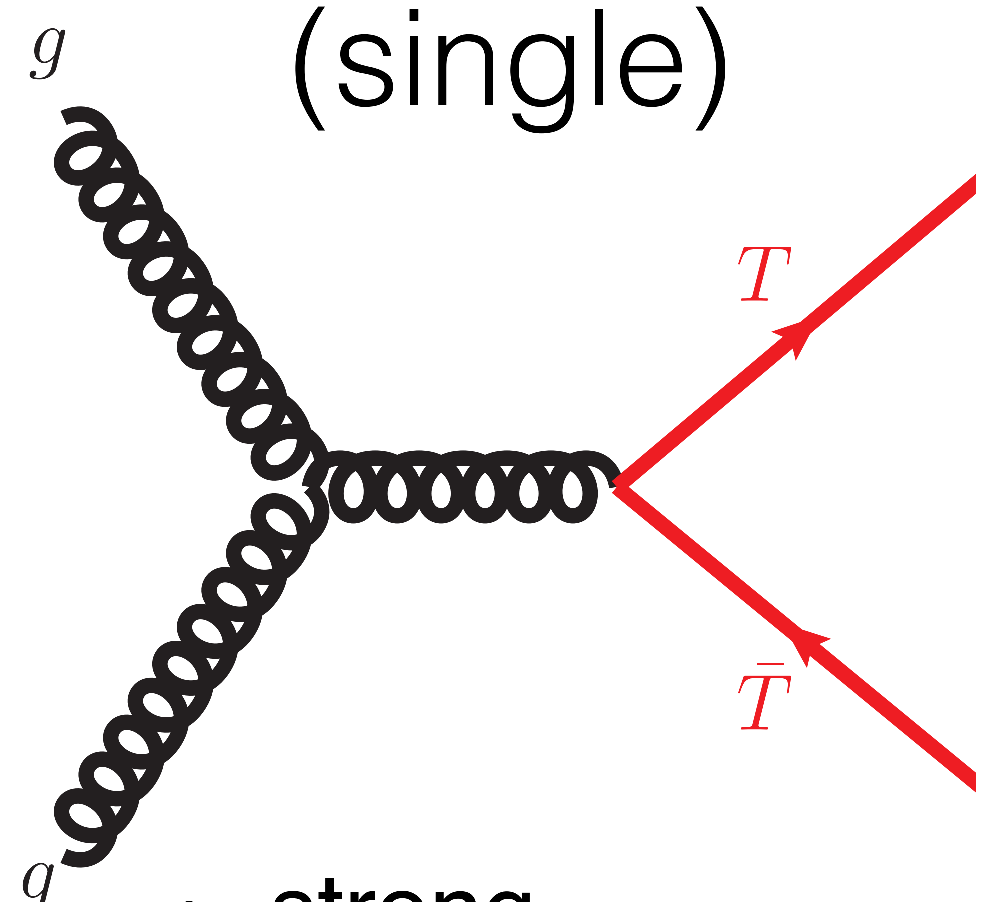
Production

(pair)



- weak
- σ depends on mass & SM quark mixing

(single)

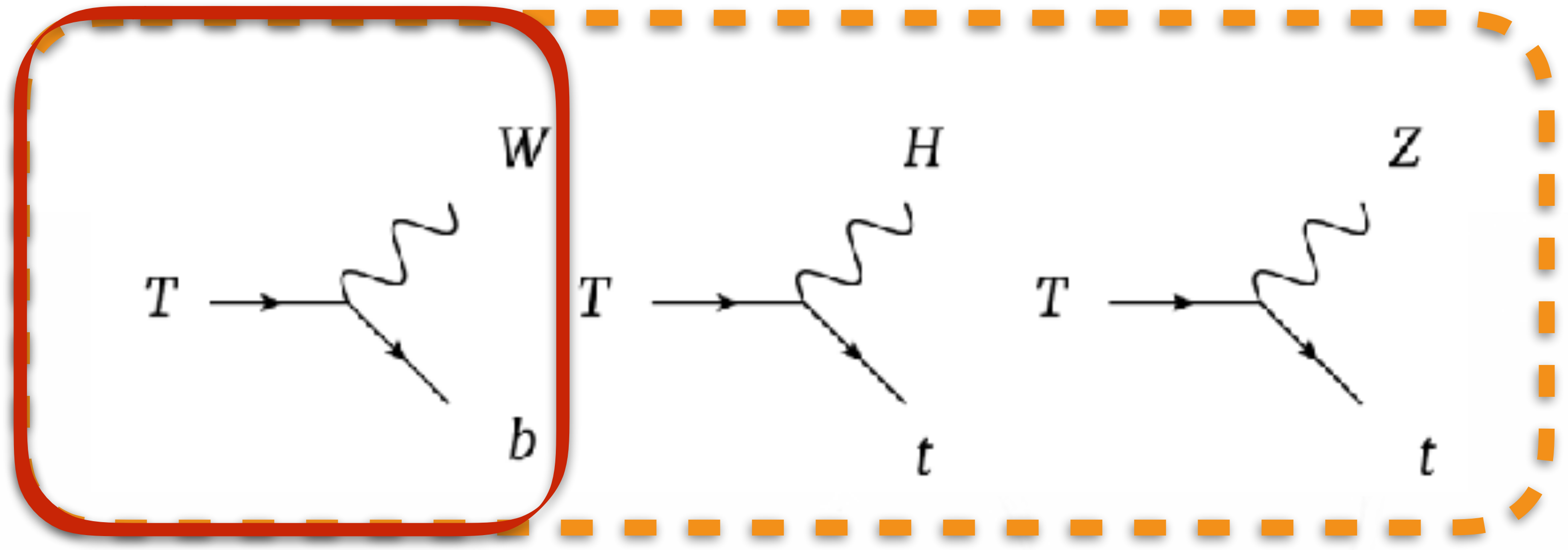


- strong
- σ depends on mass only

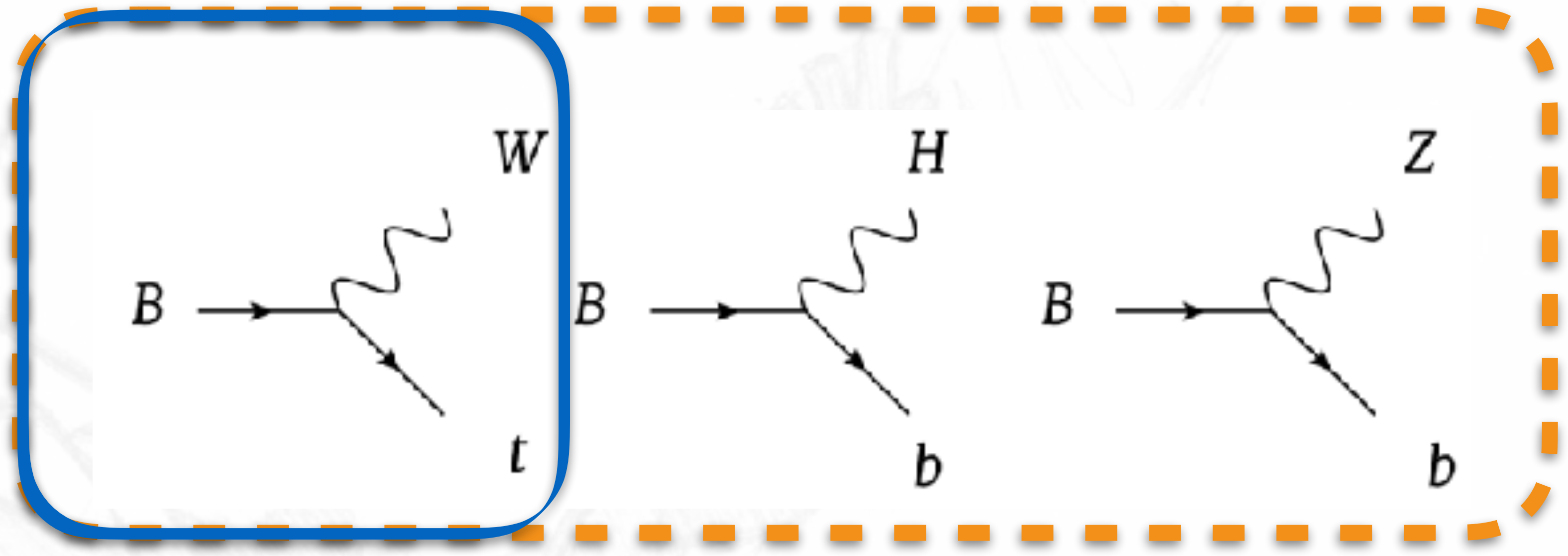
Decay

- pre-dominantly decay to 3rd generation quarks & bosons

VLT →Wb / Ht / Zt



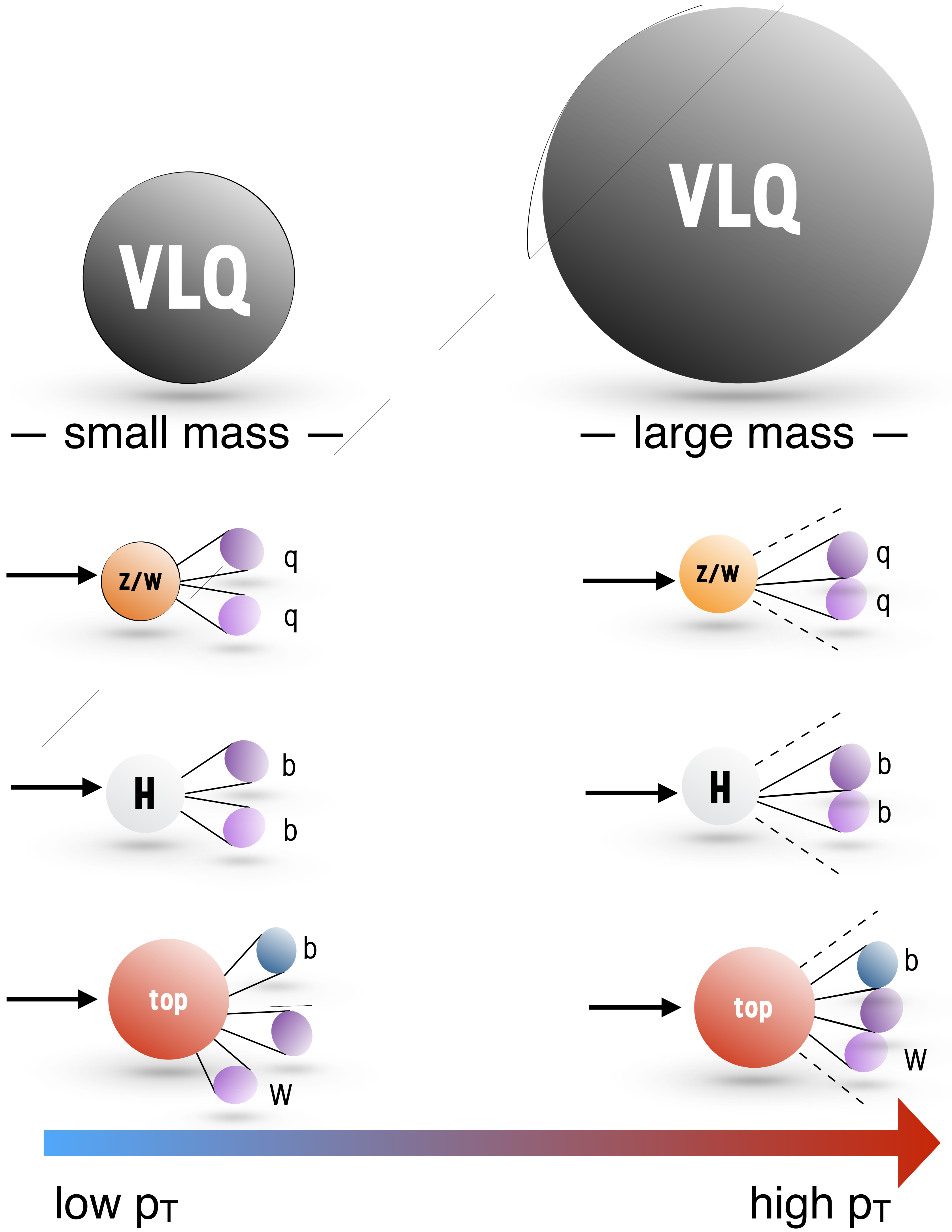
VLB →Wt / Hb / Zb



Rich decay phenomenology

(depends on mass and quantum numbers)

Signal Topologies



VLQ SEARCHES

Run-I results exclude VLT (VLB) masses below ~720 (740) GeV for any $\mathscr{B}$ combination

***Focus*: Run-II results**

- Take advantage of σ_{prod} increase at high masses
- based on combined 2015 + 2016 data set ($\mathcal{L}$=36.1 fb^{-1}) @13 TeV

Ht+X arXiv:1803.09678 I submitted to JHEP

- *Target*: 0ℓ & 1ℓ + moderate S_T* (m_{eff})

Zt+X JHEP 08 (2017) 052

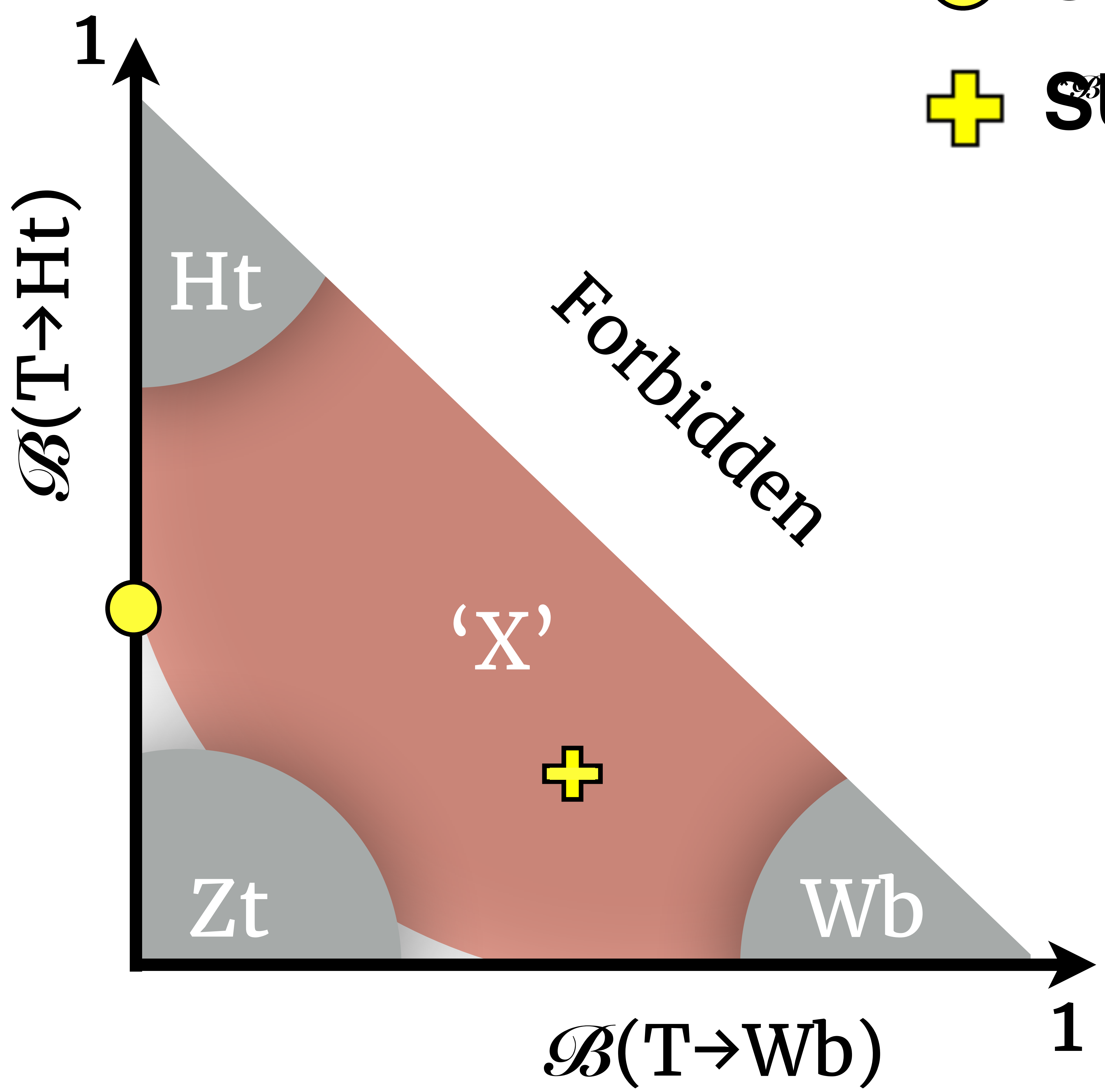
- *Target*: 1ℓ + high E_T^{miss}

Wb+X JHEP 10 (2017) 141

- *Target*: 1ℓ + high S_T

Benchmark Models

- **SU(2)** doublet *ℬ(T→Wt[Hb,Zb])=~.0[.55,.45]
- **SU(2)** singlet *ℬ(T→Wb[Ht,Zt])=~.5[.25,.25]



Assumption: **ℬ(T→Wb) + ℬ(T→Zt) + ℬ(T→Ht) =1**

$$^{*}\quad S_{\mathrm{T}} = m_{\mathrm{eff}} = \sum_{\ell,\mathrm{E_T^{miss}},\mathrm{jets}} p_{\mathrm{T}}$$

Run-I results exclude VLT (VLB) masses below ~720 (740) GeV for any $\mathscr{B}$ combination

***Focus*: Run-II results**

- Take advantage of σ_{prod} increase at high masses
- based on combined 2015 + 2016 data set ($\mathcal{L}$=36.1 fb^{-1}) @13 TeV

Ht+X

arXiv:1803.09678 | submitted to JHEP

- *Target*: 0ℓ & 1ℓ + moderate S_T* (m_{eff})

Zt+X

JHEP 08 (2017) 052

- *Target*: 1ℓ + high E_T^{miss}

Wb+X

JHEP 10 (2017) 141

- *Target*: 1ℓ + high S_T

Wt+X

new

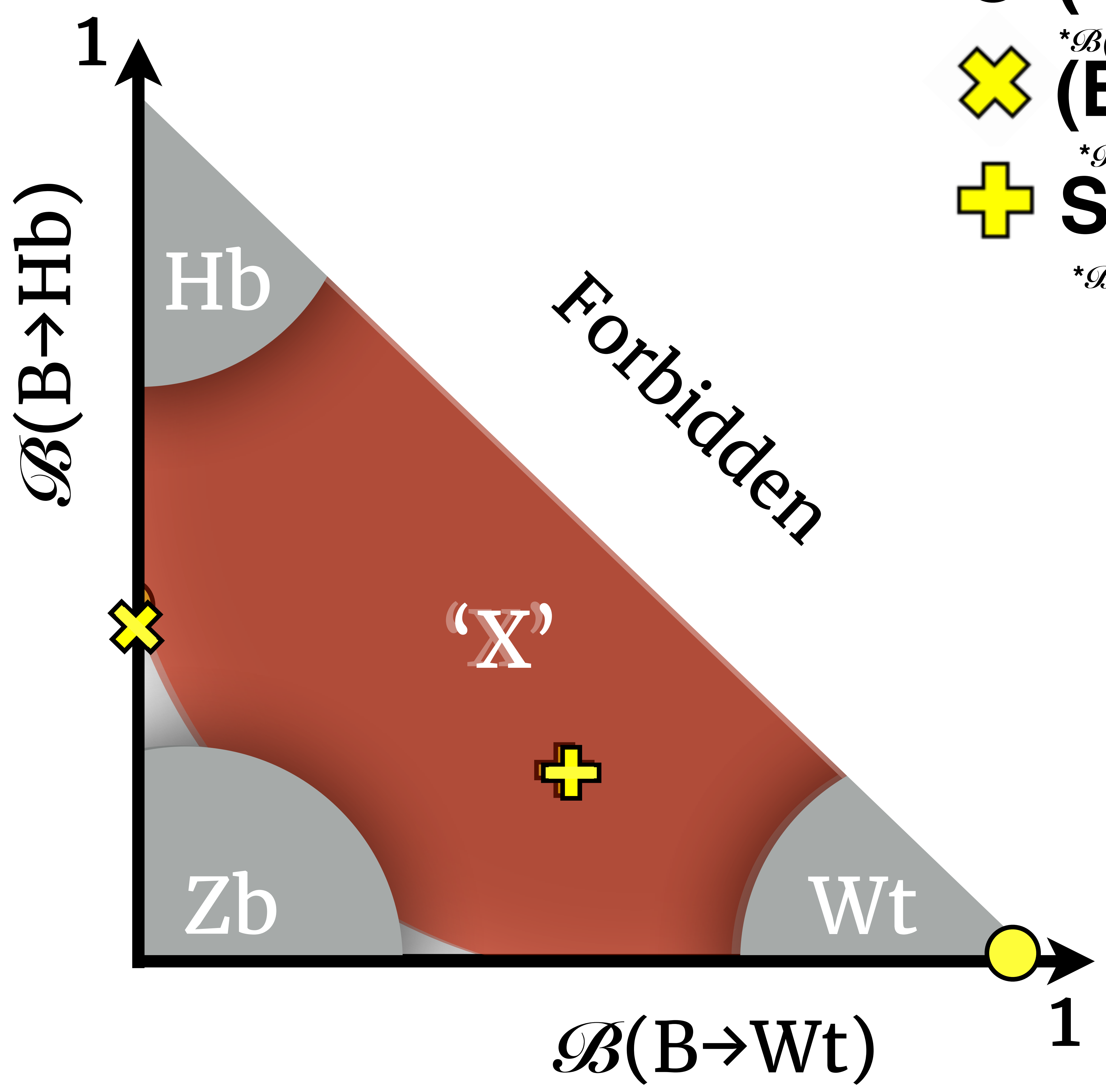
arXiv:1806.01762 | submitted to JHEP

- *Target*: 1ℓ + moderate to high S_T

* $$S_T = m_{eff} = \sum_{\ell, E_T^{miss}, jets} p_T$$

Benchmark Models

- (T B) doublet
  *$\mathscr{B}$(B→Wb[Ht,Zt])=~1
- (B Y) doublet
  *$\mathscr{B}$(B→Wt[Hb,Zb])=~.0[.5,.5]
- SU(2) singlet
  *$\mathscr{B}$(B→Wt[Hb,Zb])=~.5[.25,.25]

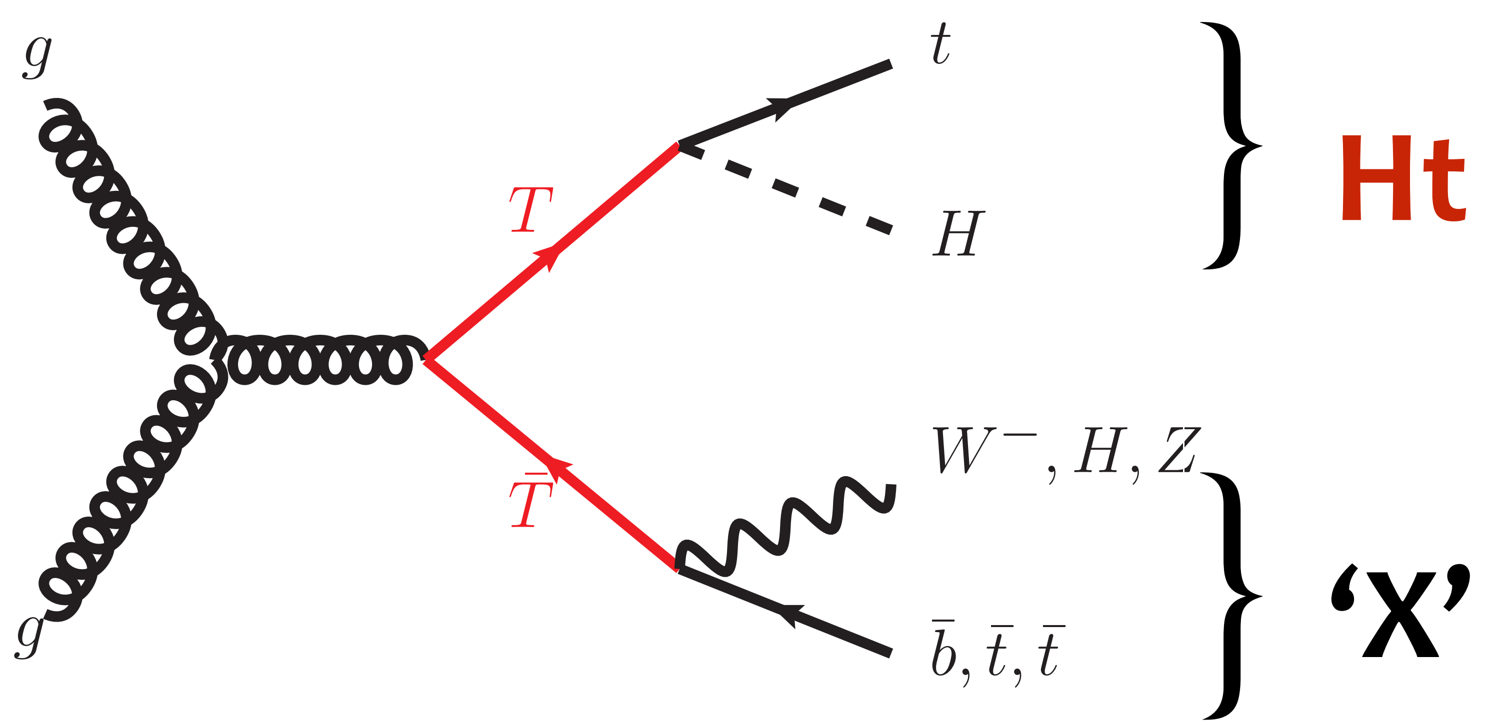


Assumption: $\mathscr{B}$**(B→Wt) +** $\mathscr{B}$**(B→Zb) +** $\mathscr{B}$**(B→Hb) =1**

Ht+X (I) — Analysis Overview

arXiv:1803.09678 | submitted to JHEP

$\mathcal{L}$=36.1 fb^{-1},13 TeV



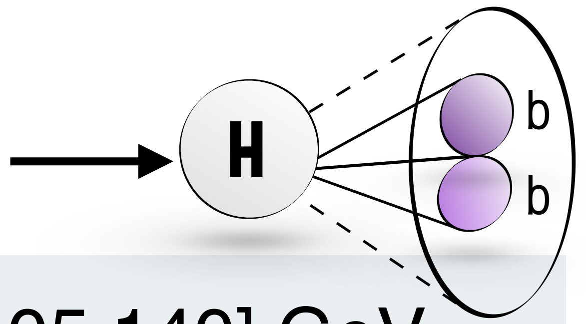
Target

- $\mathscr{B}$(T→Ht)=1 decay w/ H(→bb) — *broad VLT decay coverage*
  - 1ℓ — target HtHt corner
  - 0ℓ — sensitive also to Z(νν)t and W(ℓν)t (w/ mis-reconstructed ℓ's)

Boosted Object Reconstruction

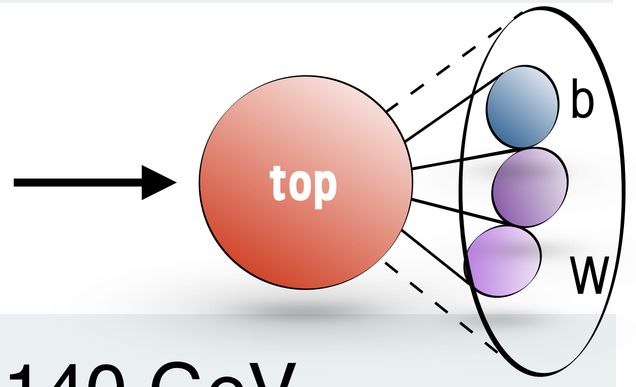
- L-jet$_{(R=1)}$ (m > 50 GeV / p_T > 200 GeV / |η| < 2.0)

+ Higgs



- p_T > 200 GeV / m ∈ [105,140] GeV
- =2 sub-jets for p_T < 500 GeV
- =1 or 2 sub-jets for p_T > 500 GeV

+ Top



- p_T > 300 GeV / m > 140 GeV
- ≥ 2 sub-jets

Pre-Selection

- lepton- (e or μ) or E_T^{miss}-trigger
- ≥ 5 or ≥ 6 jets (≥ 2 *b*-tagged jets)
- low or high E_T^{miss} (suppress multi-jet background in 0ℓ)

Backgrounds

- *Dominant*: $t\bar{t}$ + jets (from simulation validated in 'VR')
- Multi-jet: Matrix Method (1ℓ) or fit to $\Delta\phi_{min}^{4j}$ (0ℓ)
- $t\bar{t}$+V (V=W,Z), $t\bar{t}$+H, single top, VV, V+jets (from simulation)

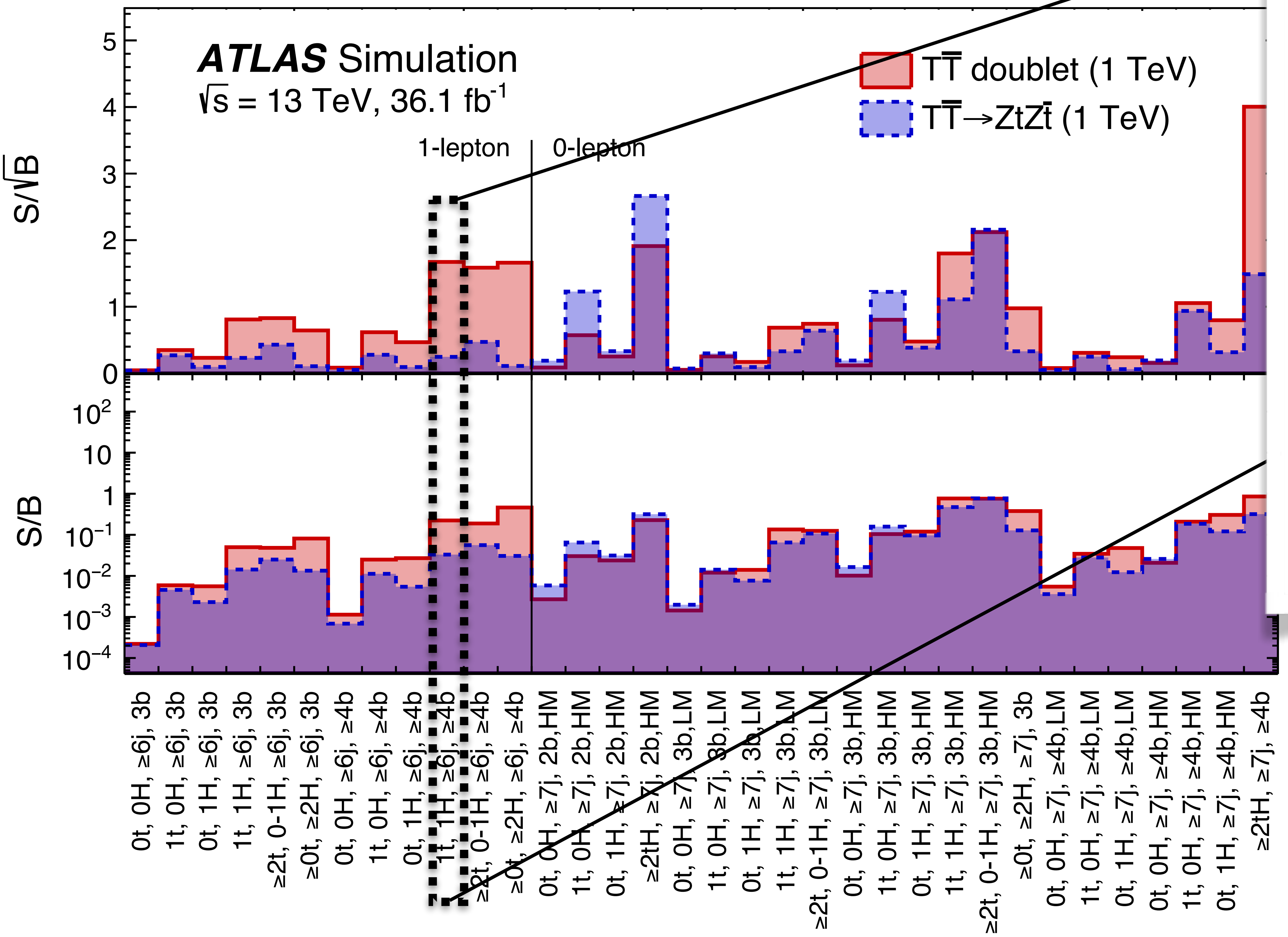
Ht+X (II) — Search Strategy

arXiv:1803.09678 | submitted to JHEP

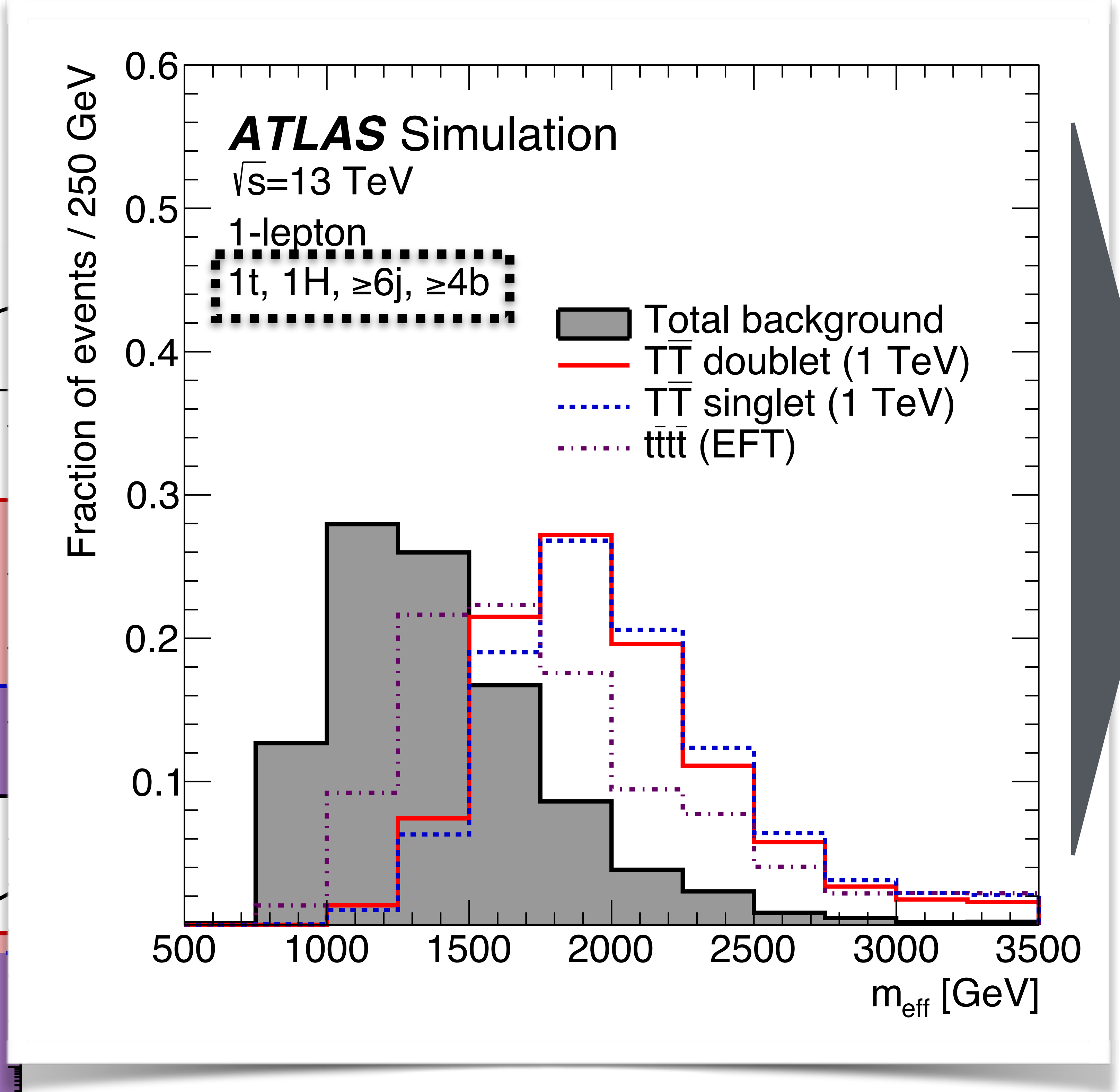
$\mathcal{L}$=36.1 fb^{-1},13 TeV

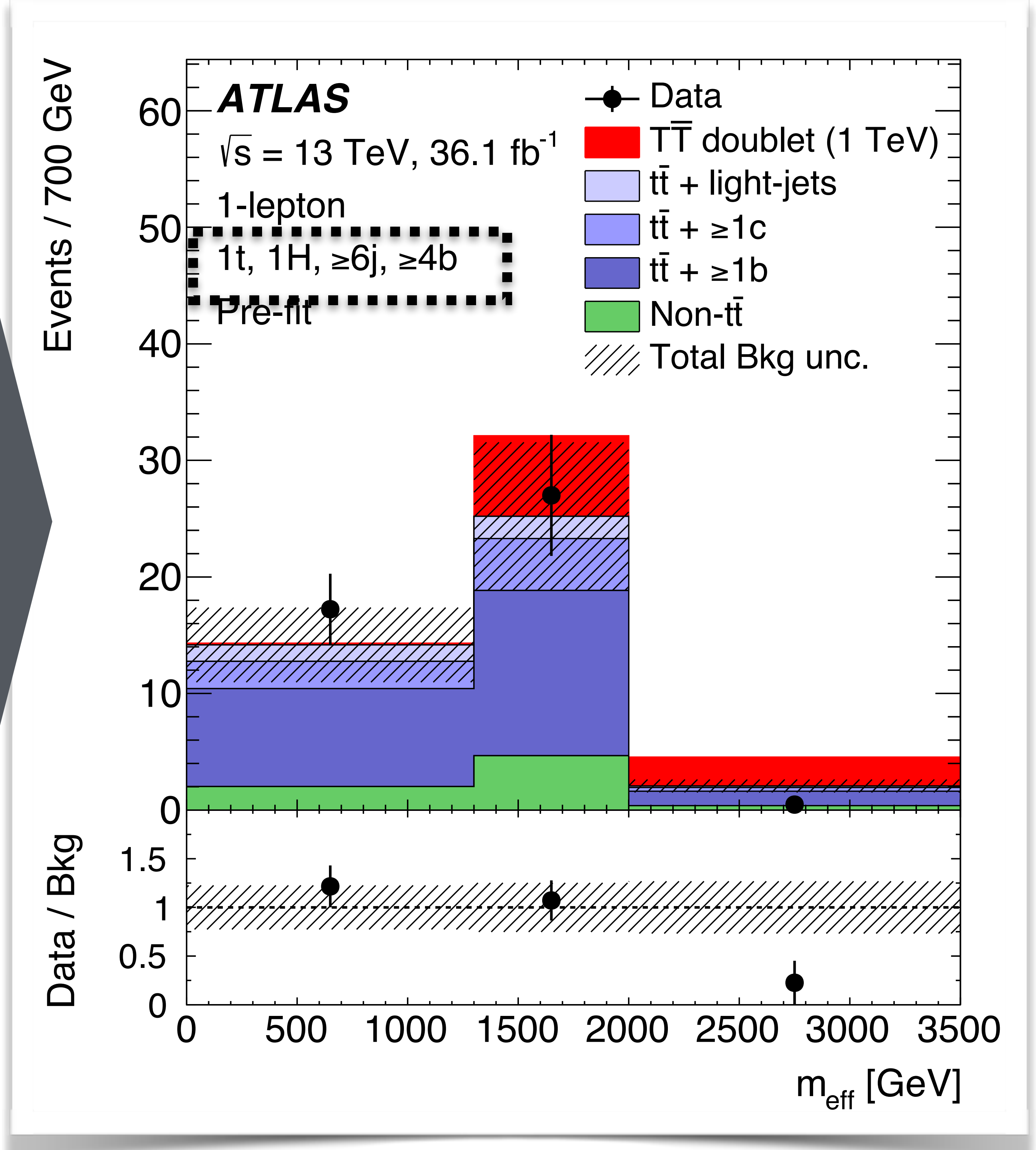
Search Regions

- 34 signal regions ('SR')
  - #jets / #b-jets / #Higgs- & top-quark candidates
- Simultaneous Profile Likelihood fit of **m_{eff}**
  - Signal depleted regions used to constrain bgr. uncertainty



Final Discriminant



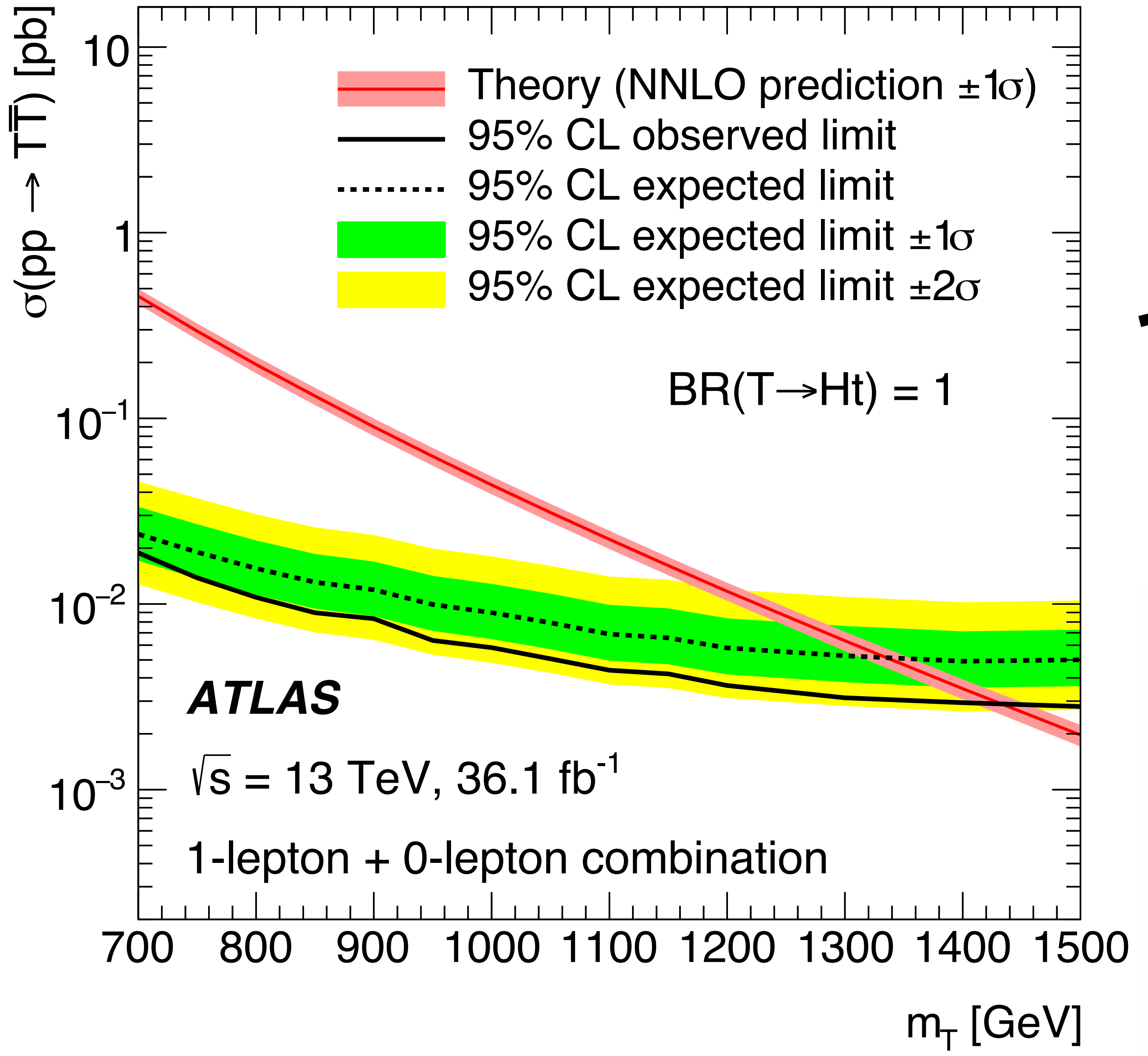


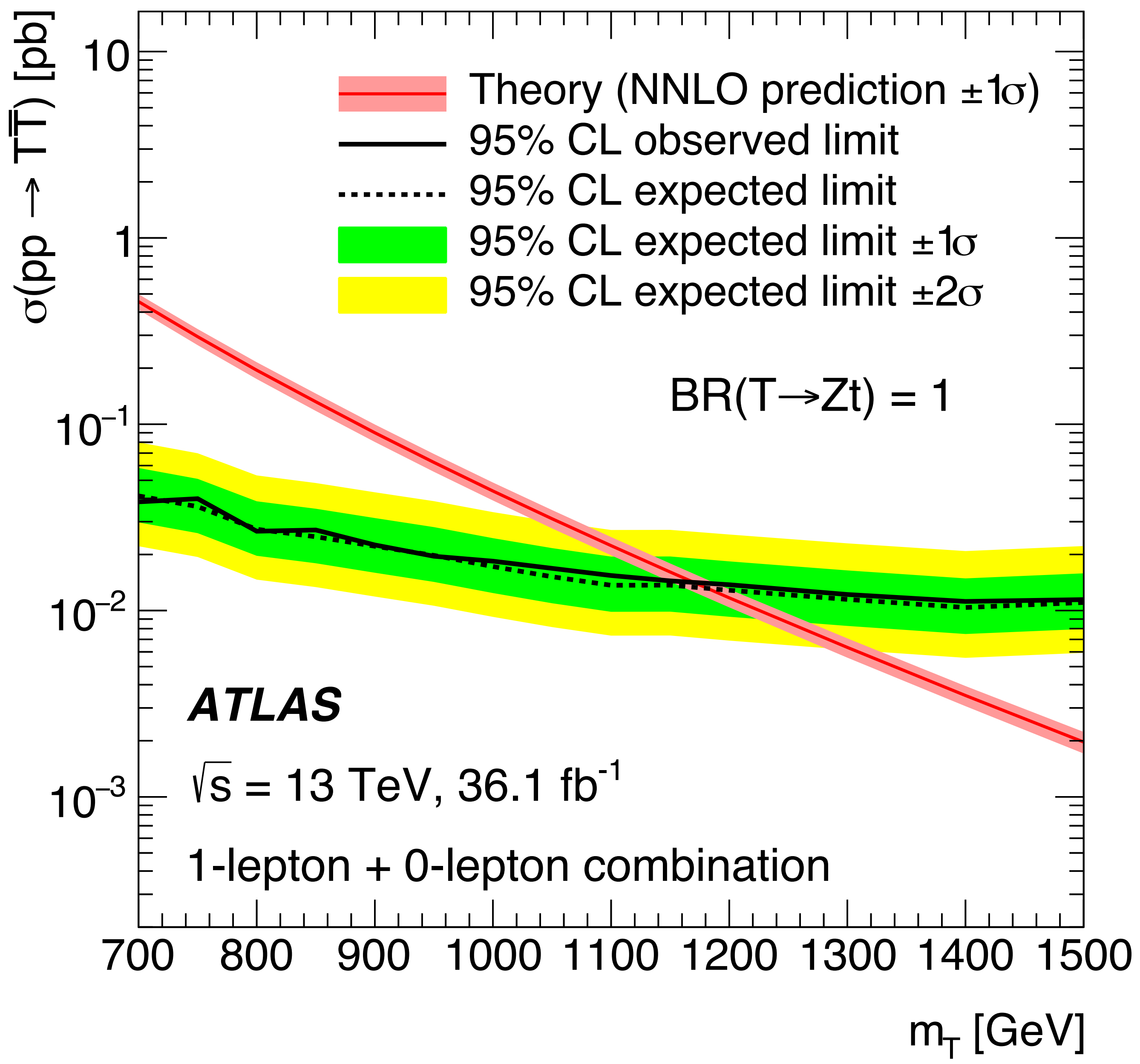
- optimized binning in all SRs

No excess above SM expectation

Ht+X (II) — Limits

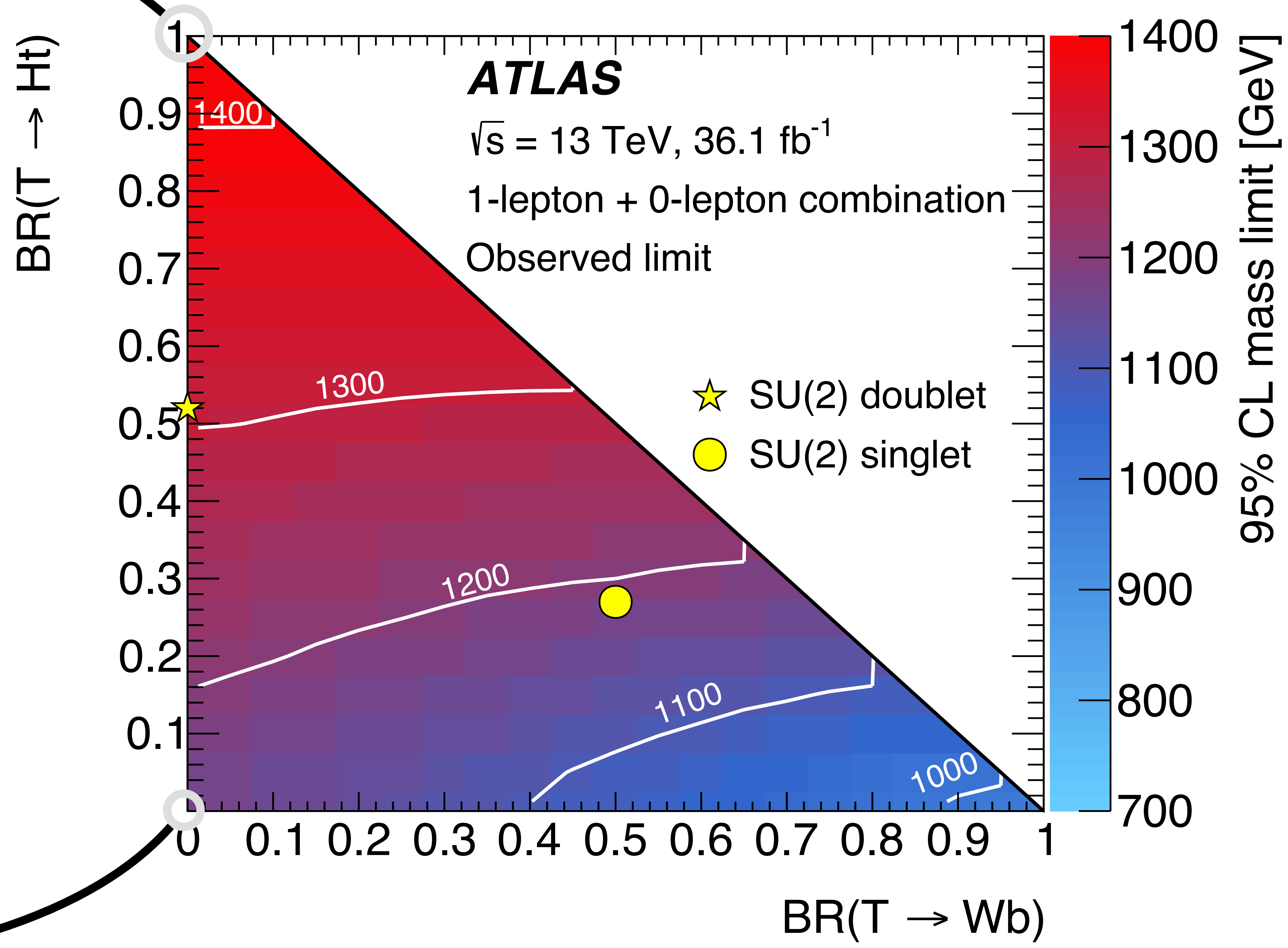
arXiv:1803.09678 | submitted to JHEP





Limit as function of $\mathscr{B}$

assuming $\mathscr{B}$(T→Wb) + $\mathscr{B}$(T→Zt) + $\mathscr{B}$(T→Ht) =1



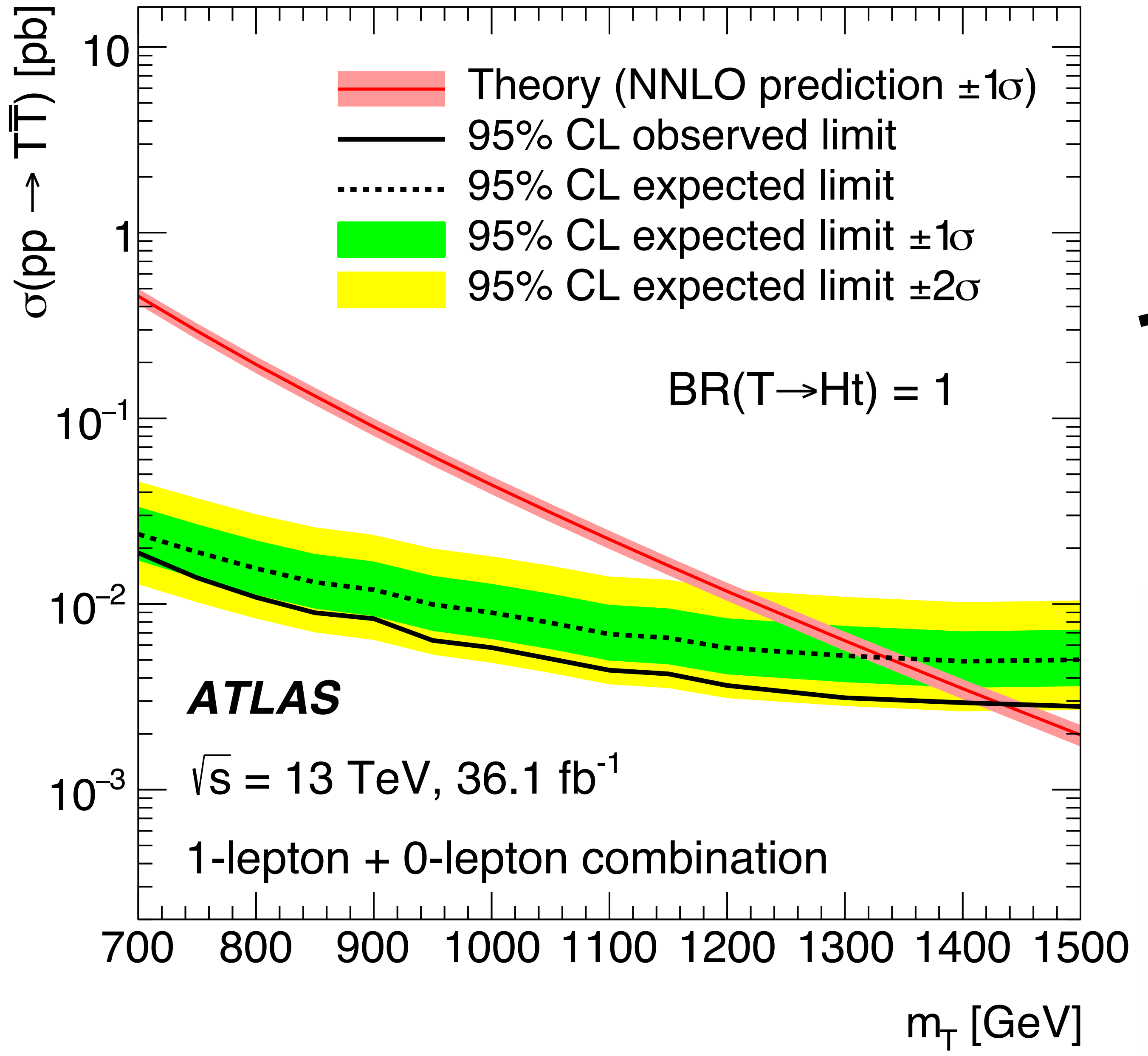
- Analysis sensitive to full $\mathscr{B}$-plane (≥1 TeV)
- *Dominant systematics*:
  - Data statistics limited

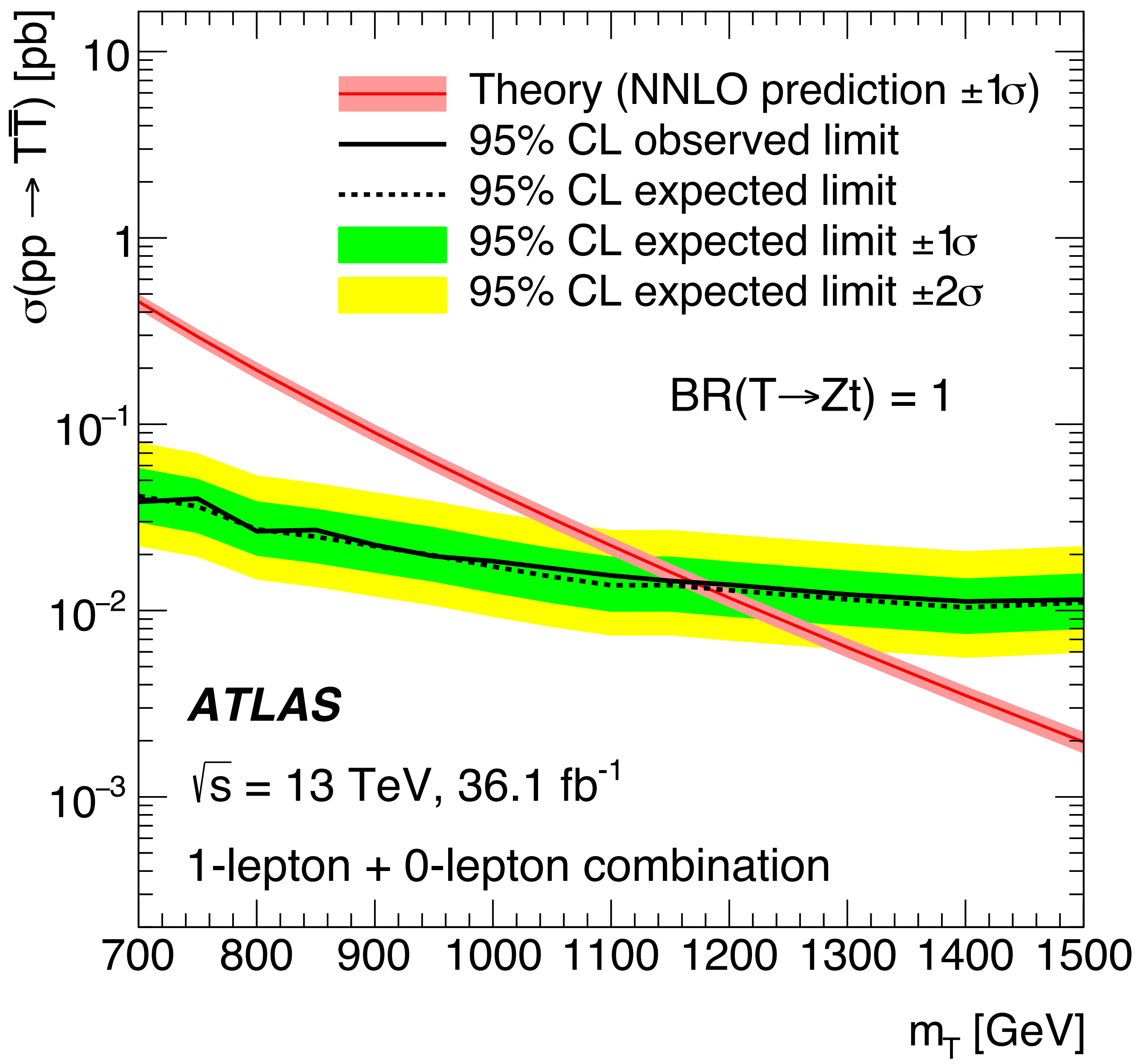
1ℓ + 0ℓ combined

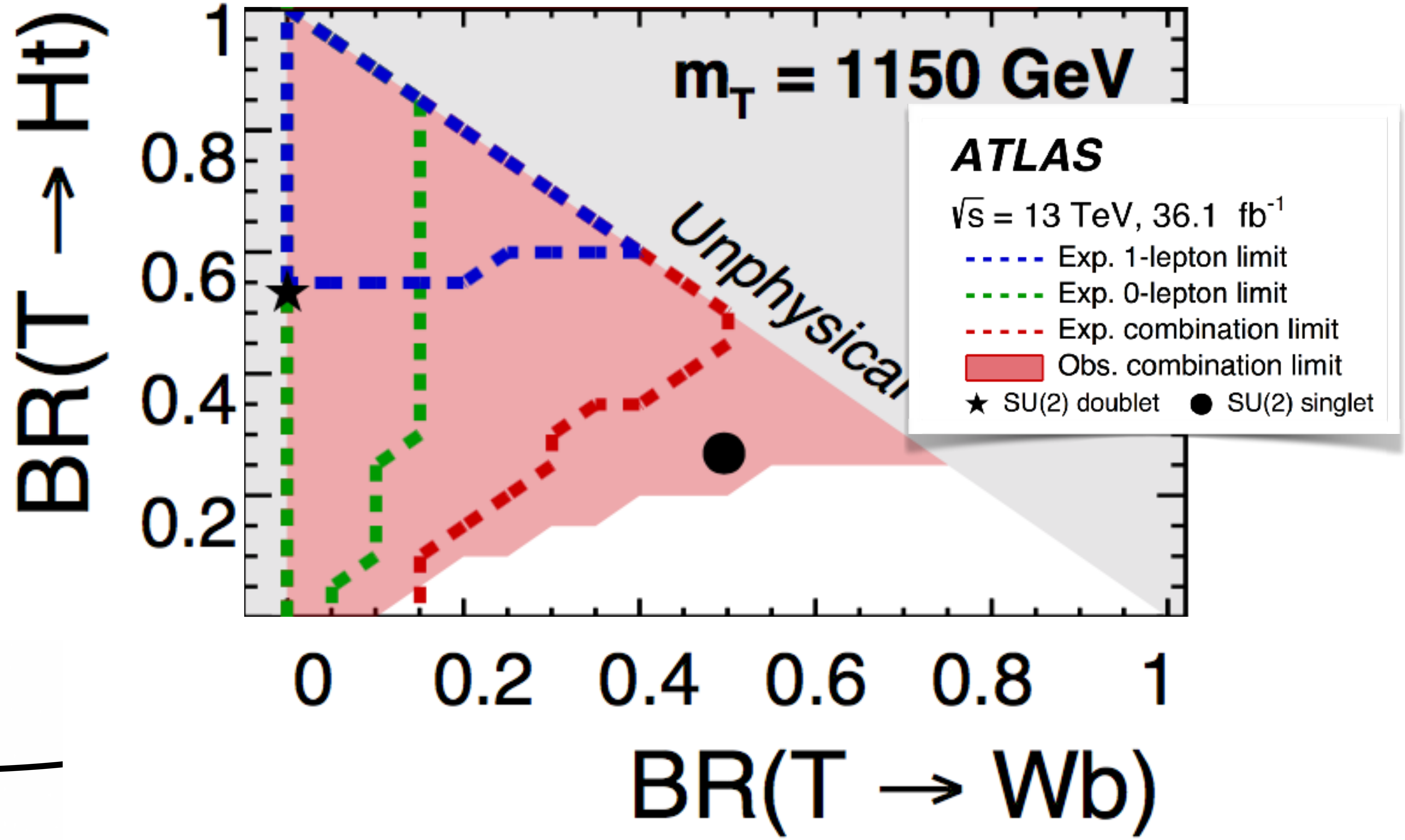
m^{limit} [GeV]	$\mathscr{B}$(T→Ht)=1
expected	1340
observed	**1430**

Ht+X (II) — Limits

arXiv:1803.09678 | submitted to JHEP



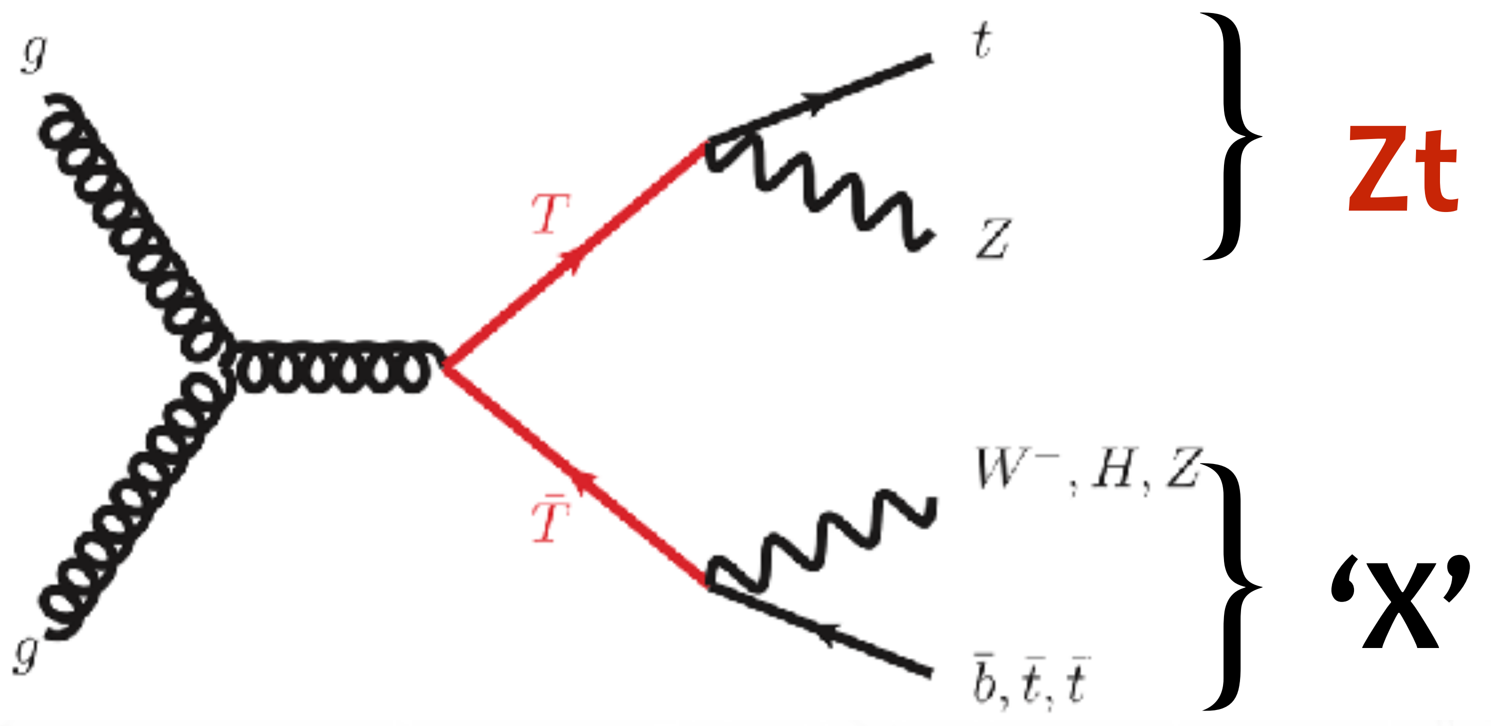




Analysis channels sensitive to different T decays

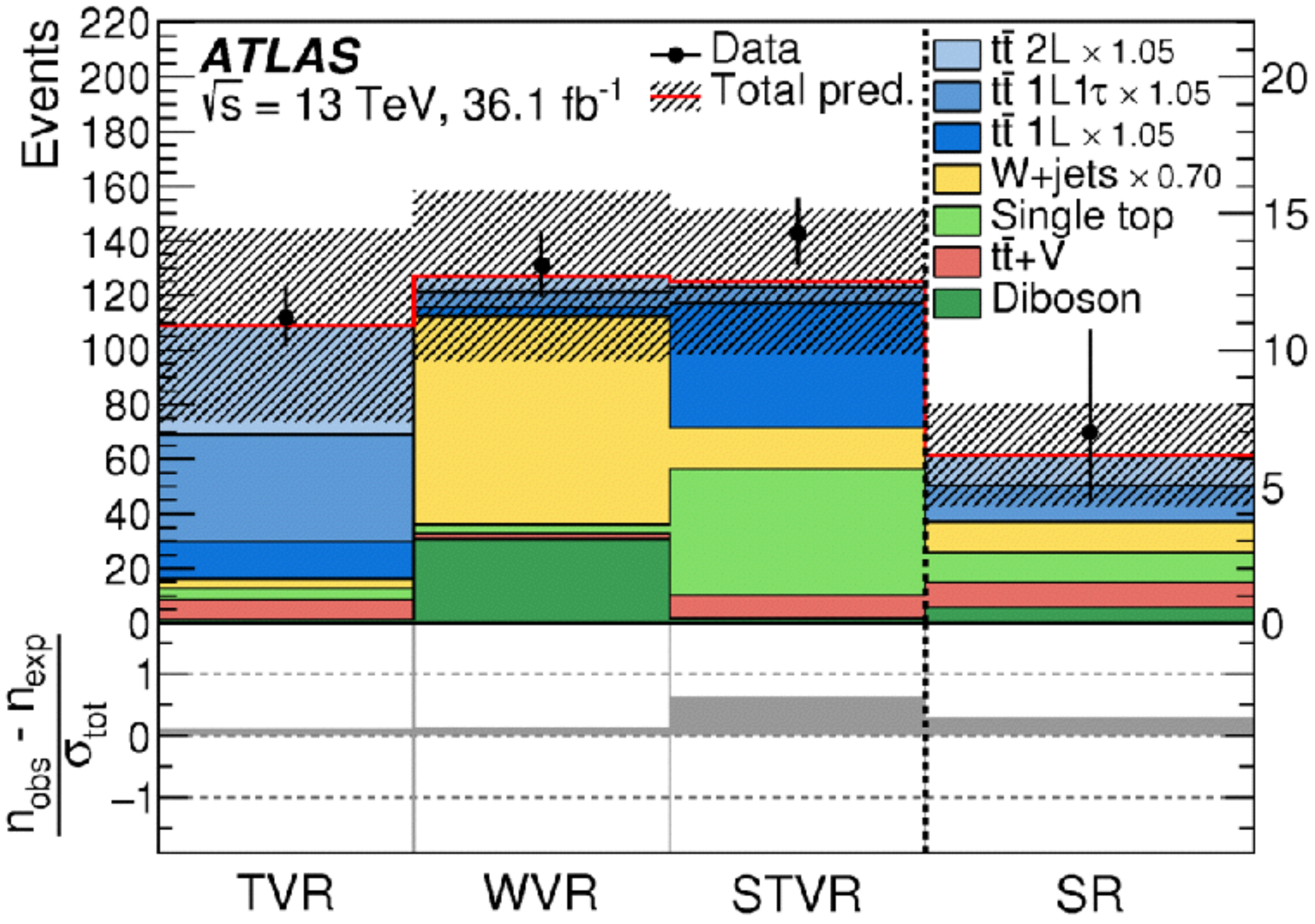
Zt+X (I) — Analysis Overview

JHEP 08 (2017) 052
$\mathcal{L}$=36.1 fb^{-1},13 TeV



Target

- $\mathscr{B}$(T→Zt[Hb,Wb])=0.8[0.1,0.1] decay w/ Z(→νν)
  - 1ℓ (e or μ) — target ZtZt corner at high E_T^{miss}



= 1 L-jet

Pre-Selection

- E_T^{miss}-trigger
- ≥ 4 jets (≥1 *b*-tagged jets)
- high E_T^{miss} (≥ 300 GeV)

Backgrounds

- tt̄ + jets (dedicated 'CR' ➧ VR)
- W+jets (dedicated 'CR' ➧ VR)
- Single-top (VR)

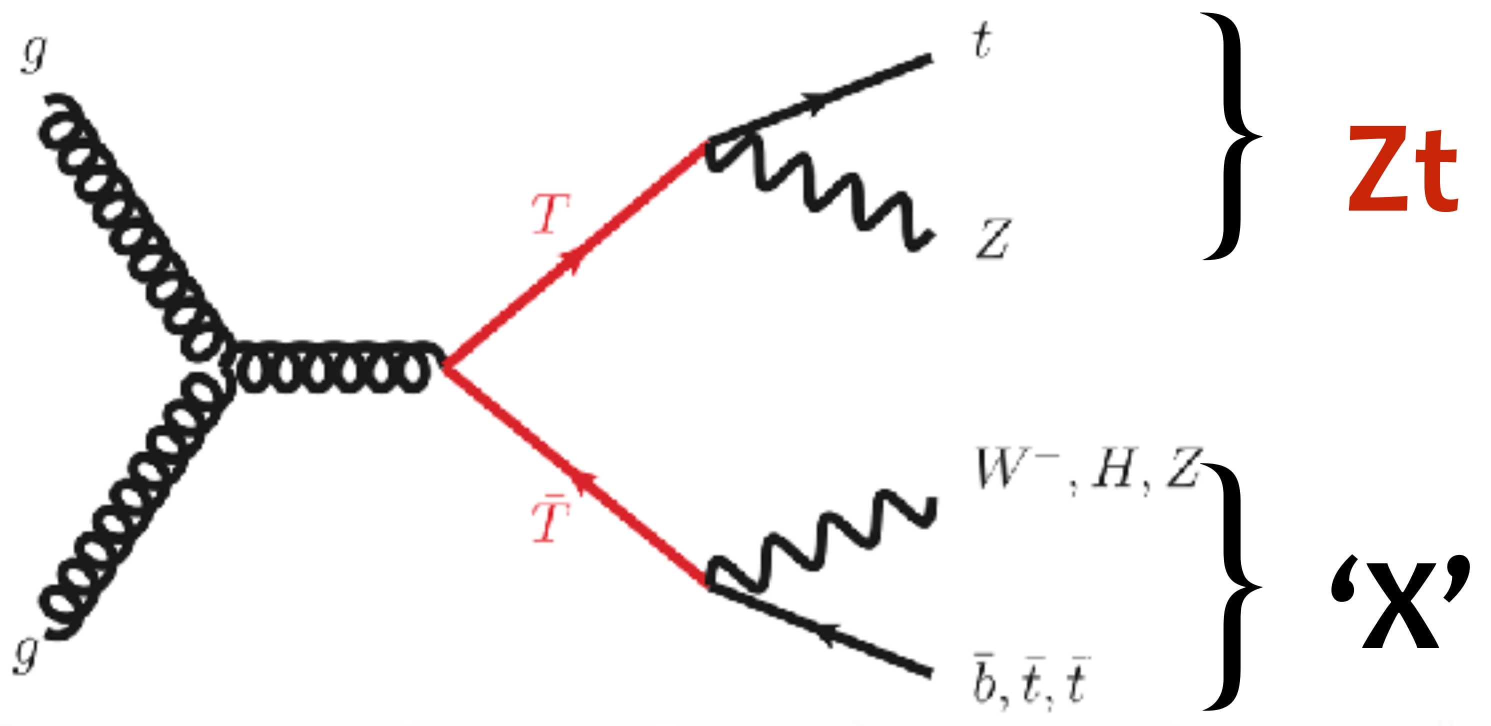
Search Regions

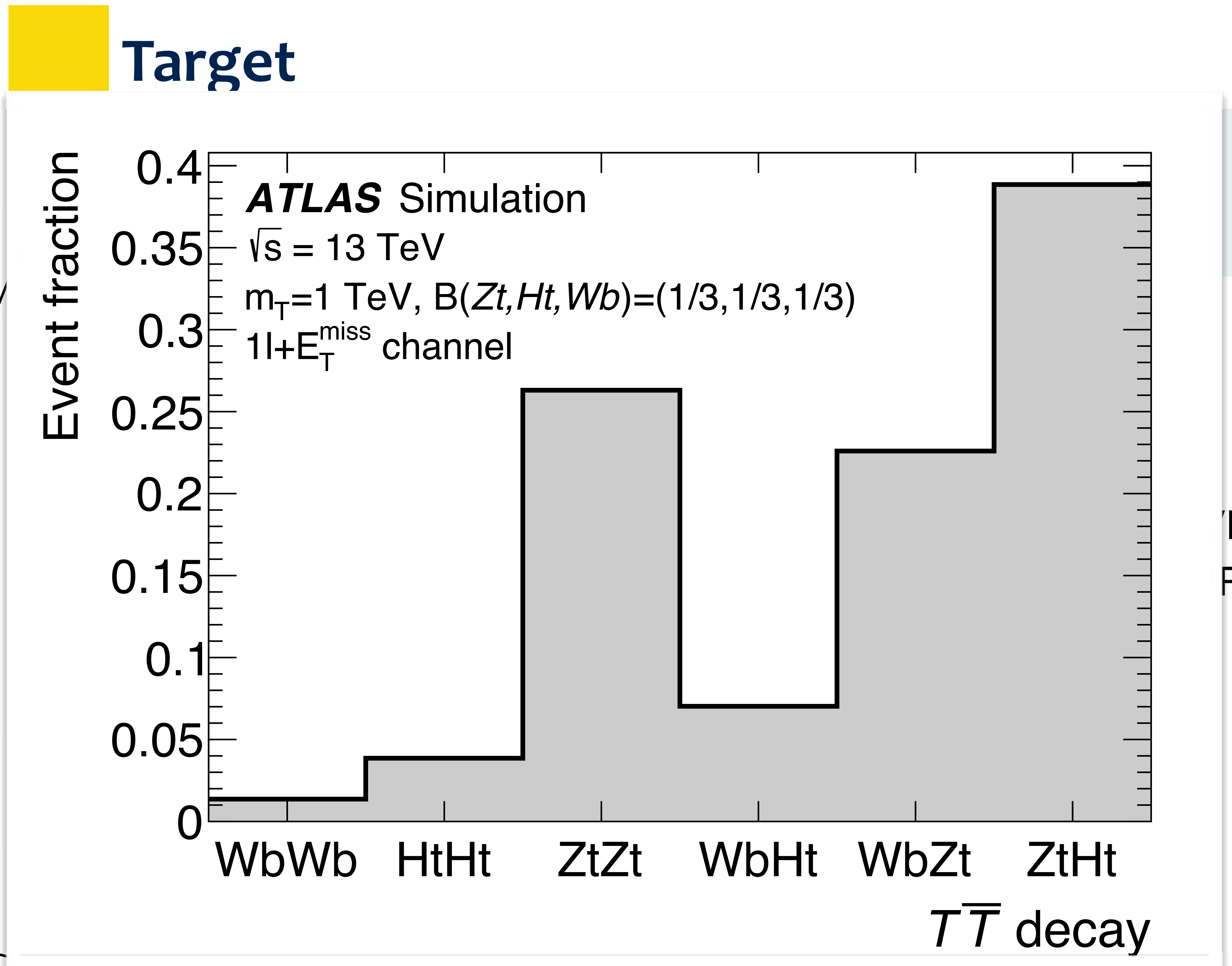
- 1 SR and 2 CR (*W*+jets & tt̄)
- Signal region defined through tight cuts to suppress tt̄ background (on $m_{T,W}$, am_{T2}, ≥2 large-R jets, etc)

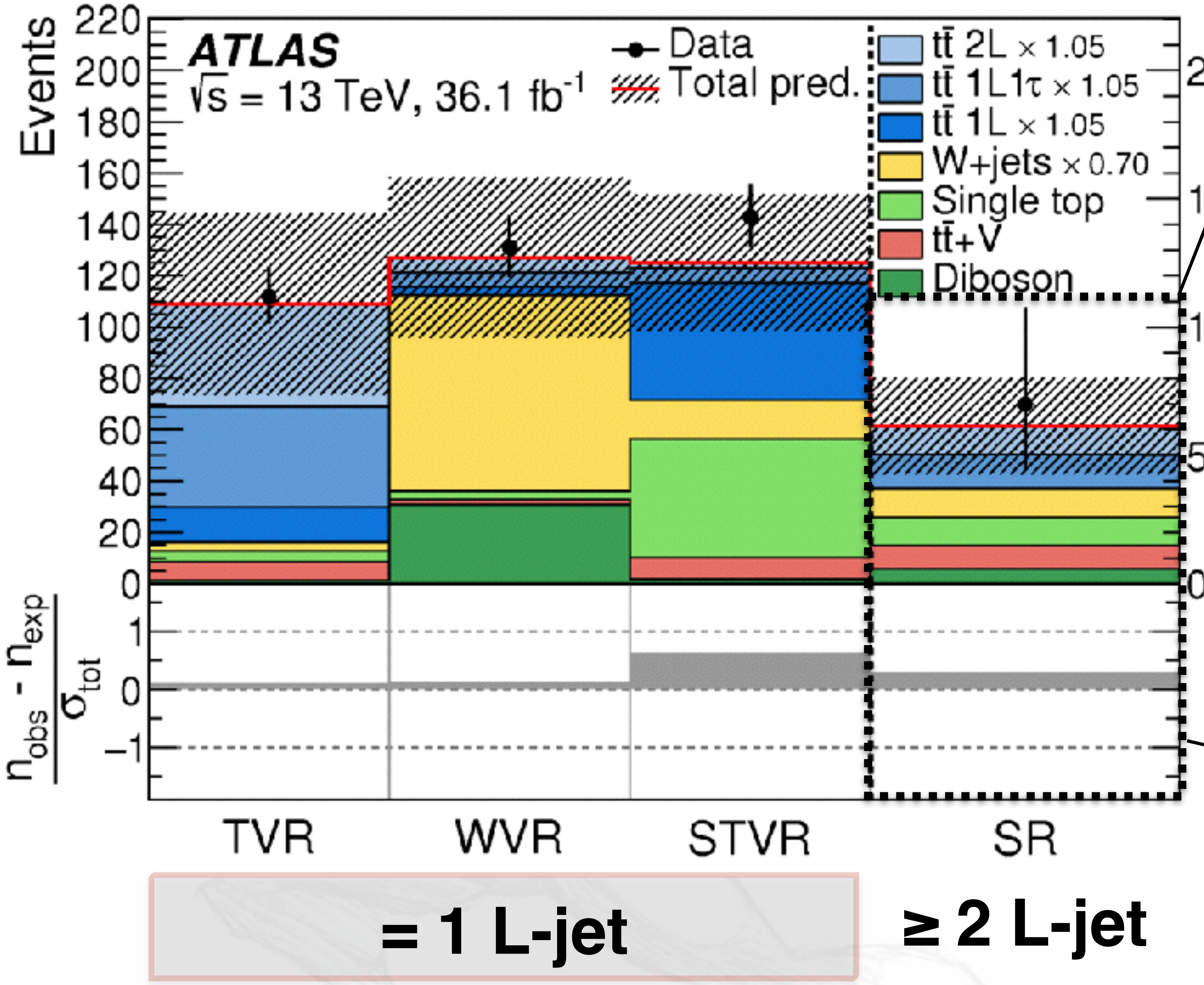
- Simultaneous Fit (**cut & count**)

Zt+X (I) — Analysis Overview

JHEP 08 (2017) 052
$\mathcal{L}$=36.1 fb^{-1},13 TeV





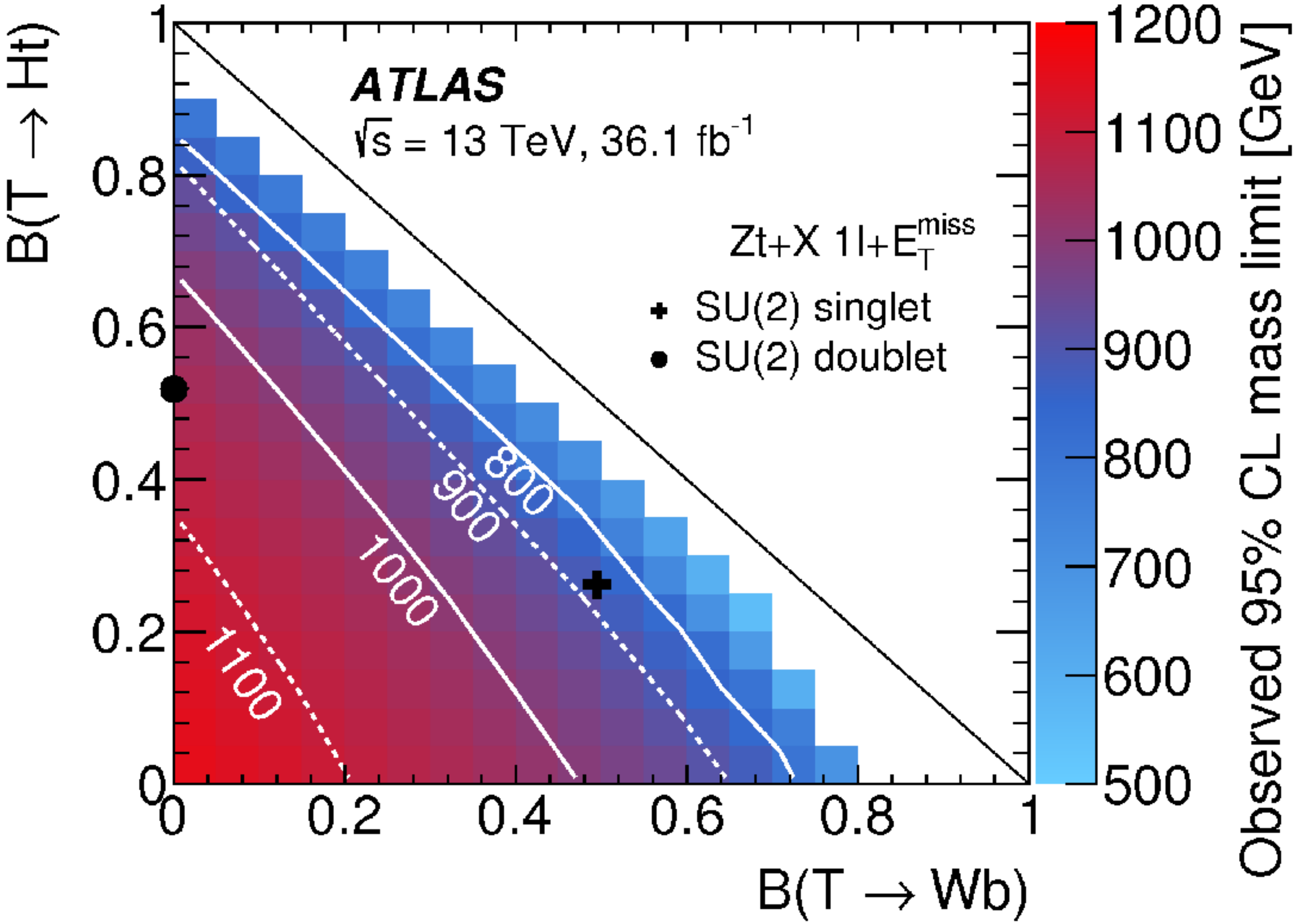


9 events expected for m_T=1.1 TeV, B(Zt,Ht,Wb)=(0.8,0.1,0.1)

No excess above SM expectation

Zt+X (II) — Limits

JHEP 08 (2017) 052

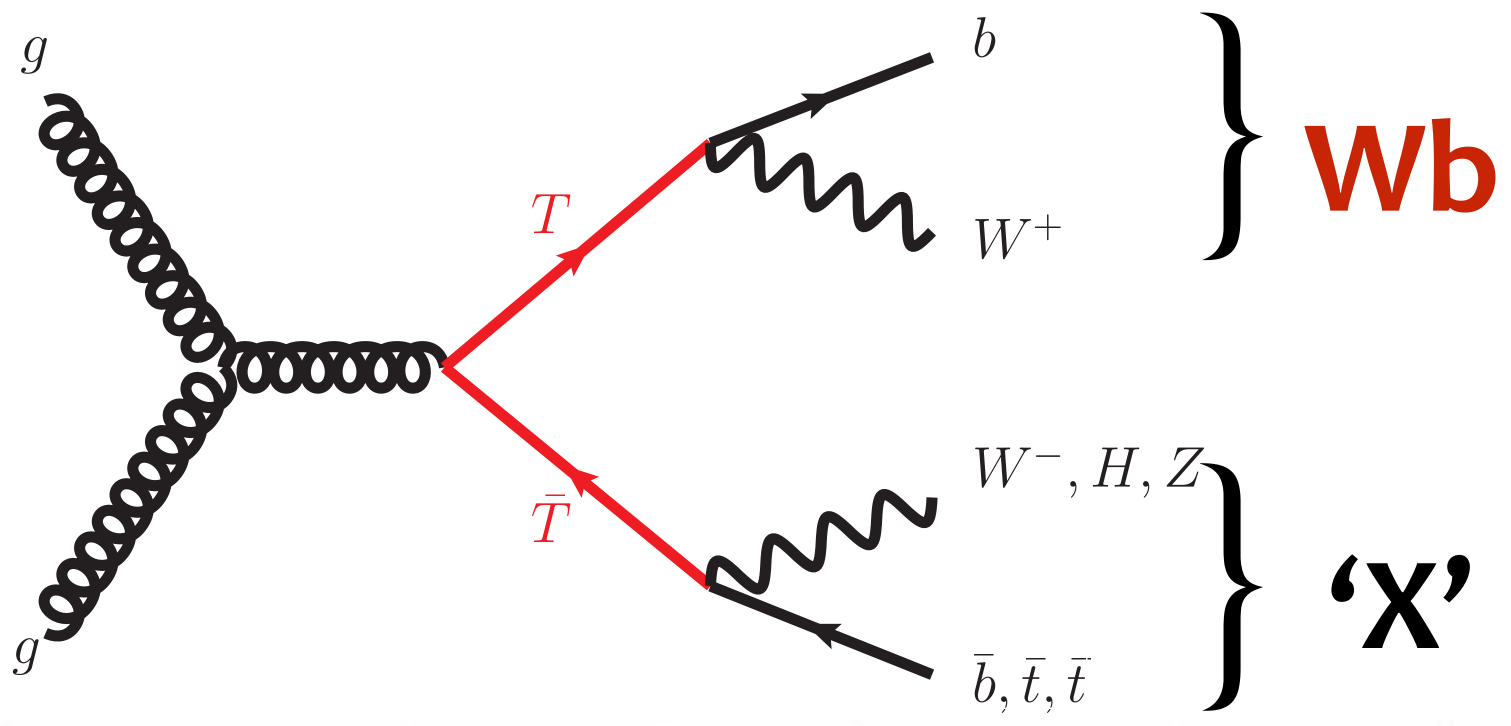


Signal	Obs. 95% CL lower mass limit	Exp. 95% CL lower mass limit
$T \to Zt$	1.16 TeV	1.17 TeV
✚ Singlet	0.87 TeV	0.89 TeV
● Doublet	1.05 TeV	1.06 TeV

- *Dominant systematics*
  - Data statistics
  - top-quark modelling

Wb+X (I) — Analysis Overview

JHEP 10 (2017) 141
$\mathcal{L}$=36.1 fb^{-1},13 TeV

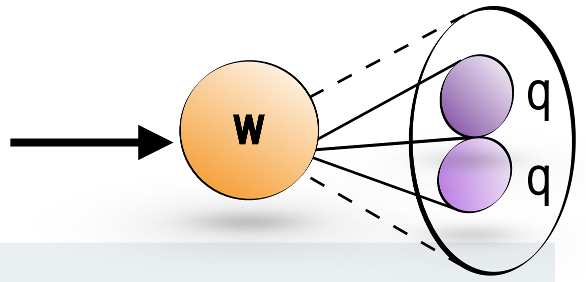


Target

- $\mathscr{B}$(T→Wb)=1
  - 1ℓ (e or μ) — target WbWb corner at high S_T
  - Mass range: m_T > 1 TeV
  - Same final state as $t\bar{t}$ background

W boson Reconstruction

W^{had}



- L-jet$_{(R=1)}$ (m > 50 GeV / p_T > 200 GeV / |η| < 2.0)
- $D2^{\beta=1}(p_T)$ cut & $m_W(p_T)$ window
- no b-tagged jet within ΔR<1.0

▸ *Key to suppress dominant $t\bar{t}$ background*

W^{lep}

- 1ℓ + E_T^{miss}
- Using m_W constraint to reconstruct ν

▸ *Helps VLT system reconstruction*

Pre-Selection

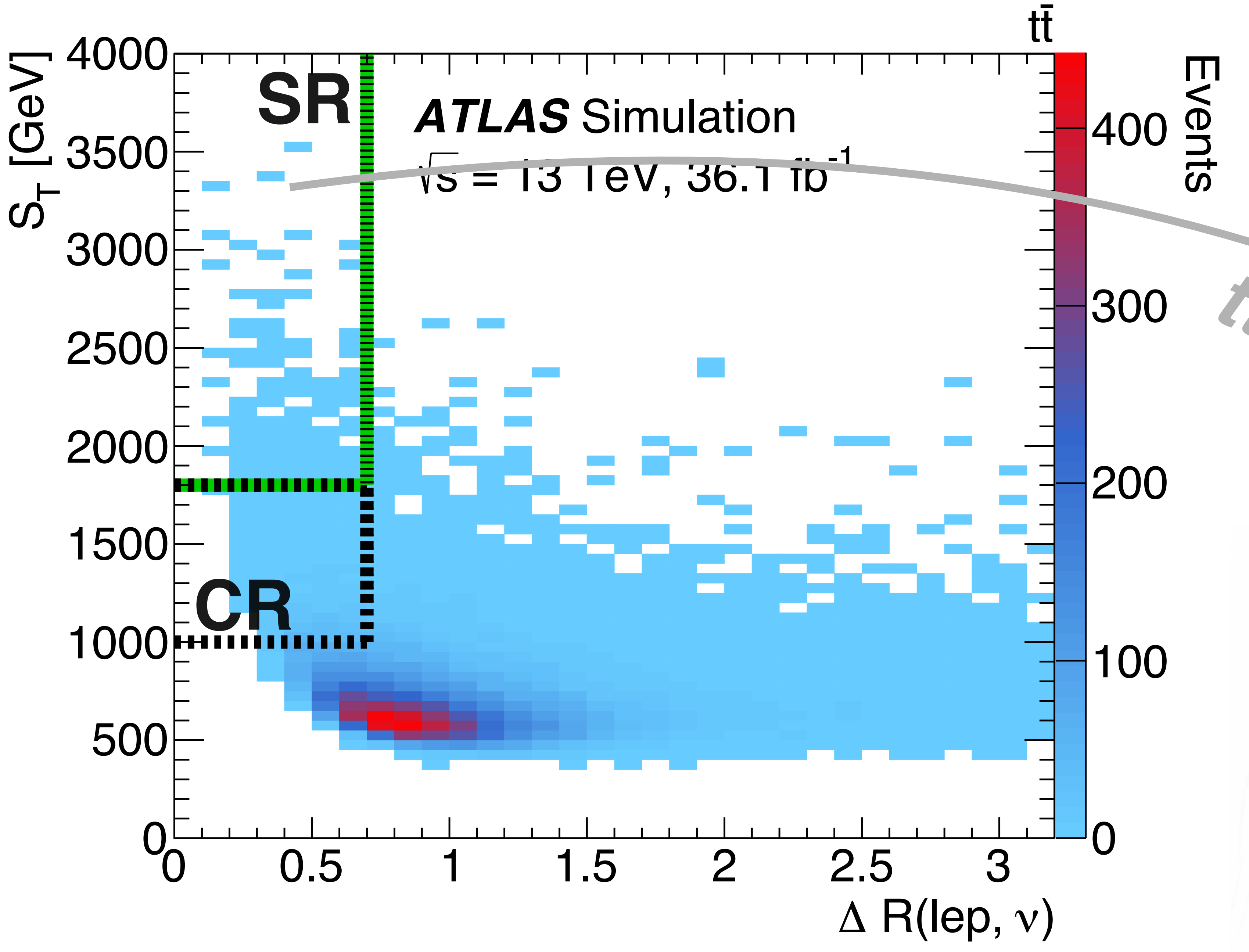
- lepton- (e or μ) trigger
- E_T^{miss} ≥ 60 GeV
- ≥ 3 jets (≥ 1 *b*-tagged jets)

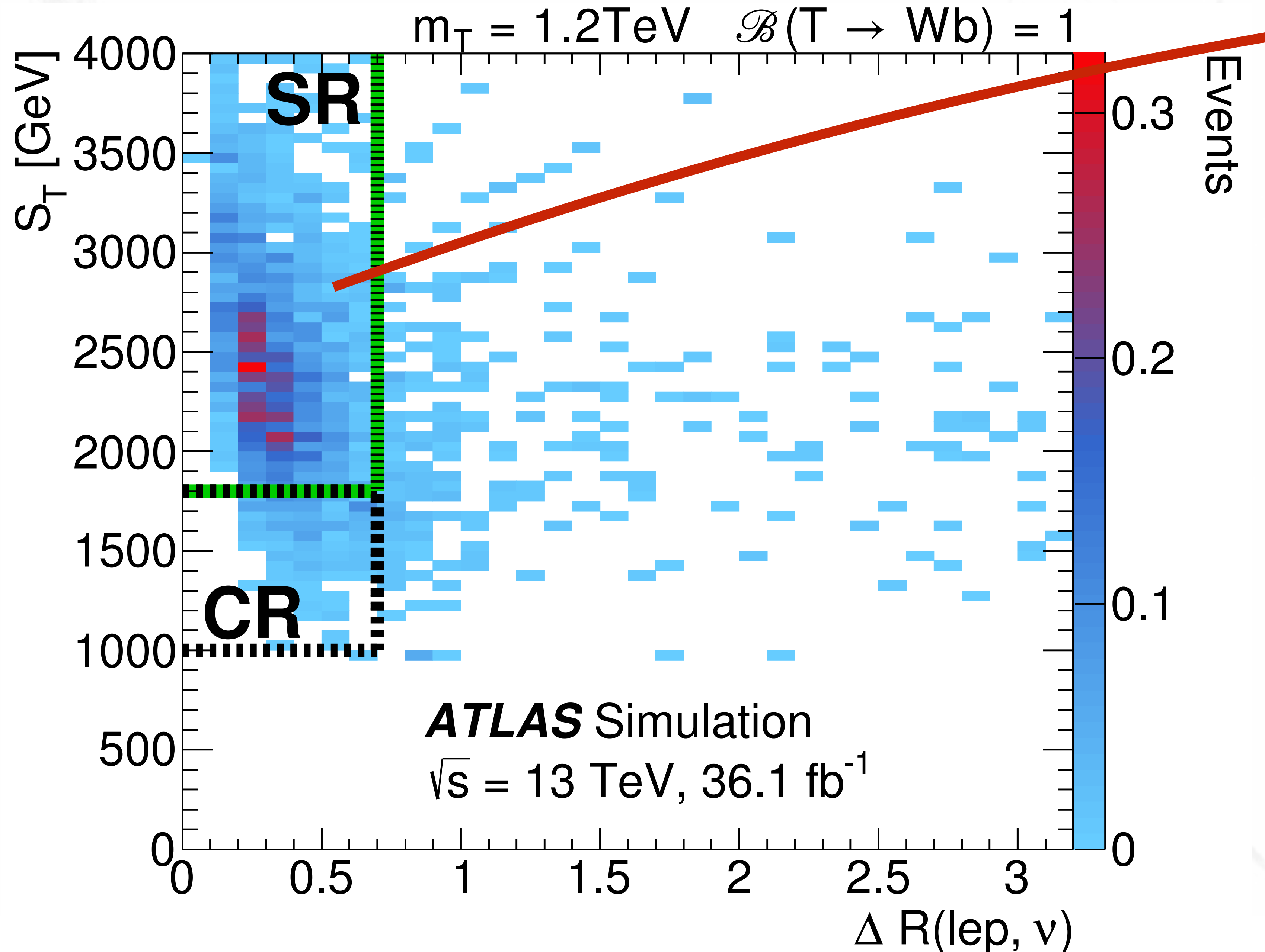
Backgrounds

- *Dominant*: $t\bar{t}$ + jets & single top (from simulation)
- W+jets (from simulation)
- Multi-jet: Matrix Method, $t\bar{t}$+V (V=W,Z), VV

Wb+X (II) — Search Regions

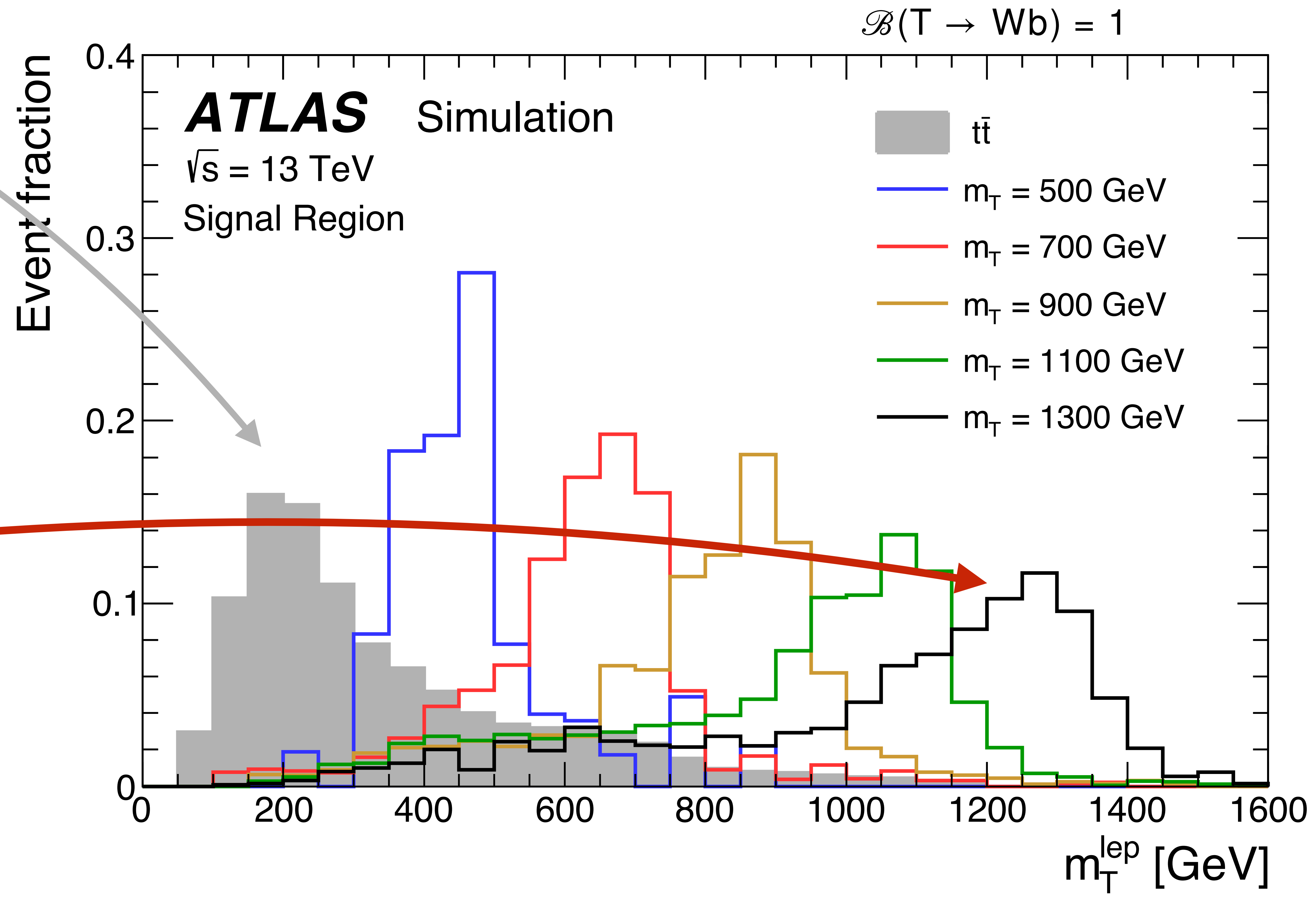
JHEP 10 (2017) 141





Search Regions

- 1 SR and 1 CR ($t\bar{t}$)
- Simultaneous Profile Likelihood Fit (reconstructed $\mathbf{m_T^{lep}}$)



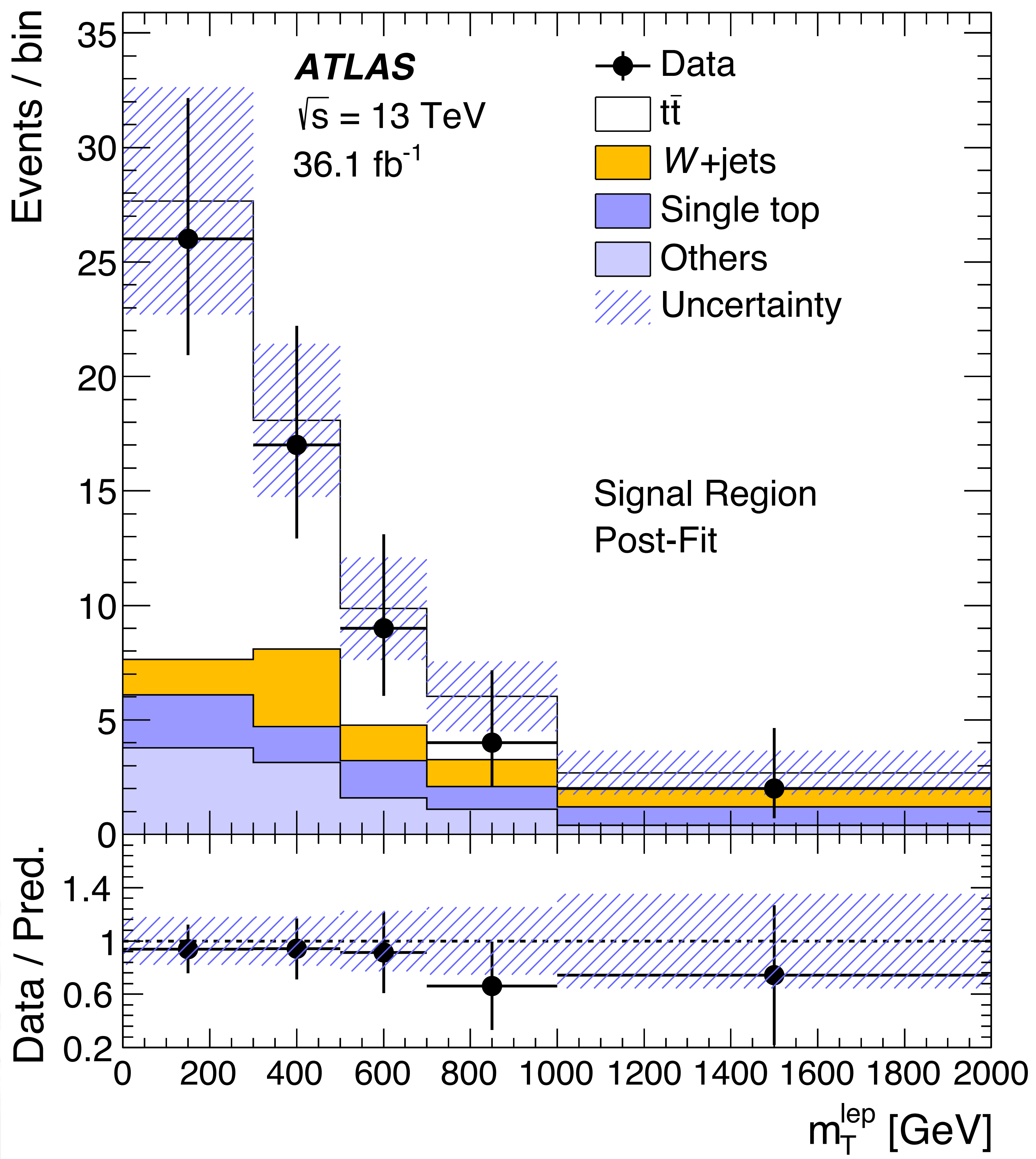
VLT system reconstruction

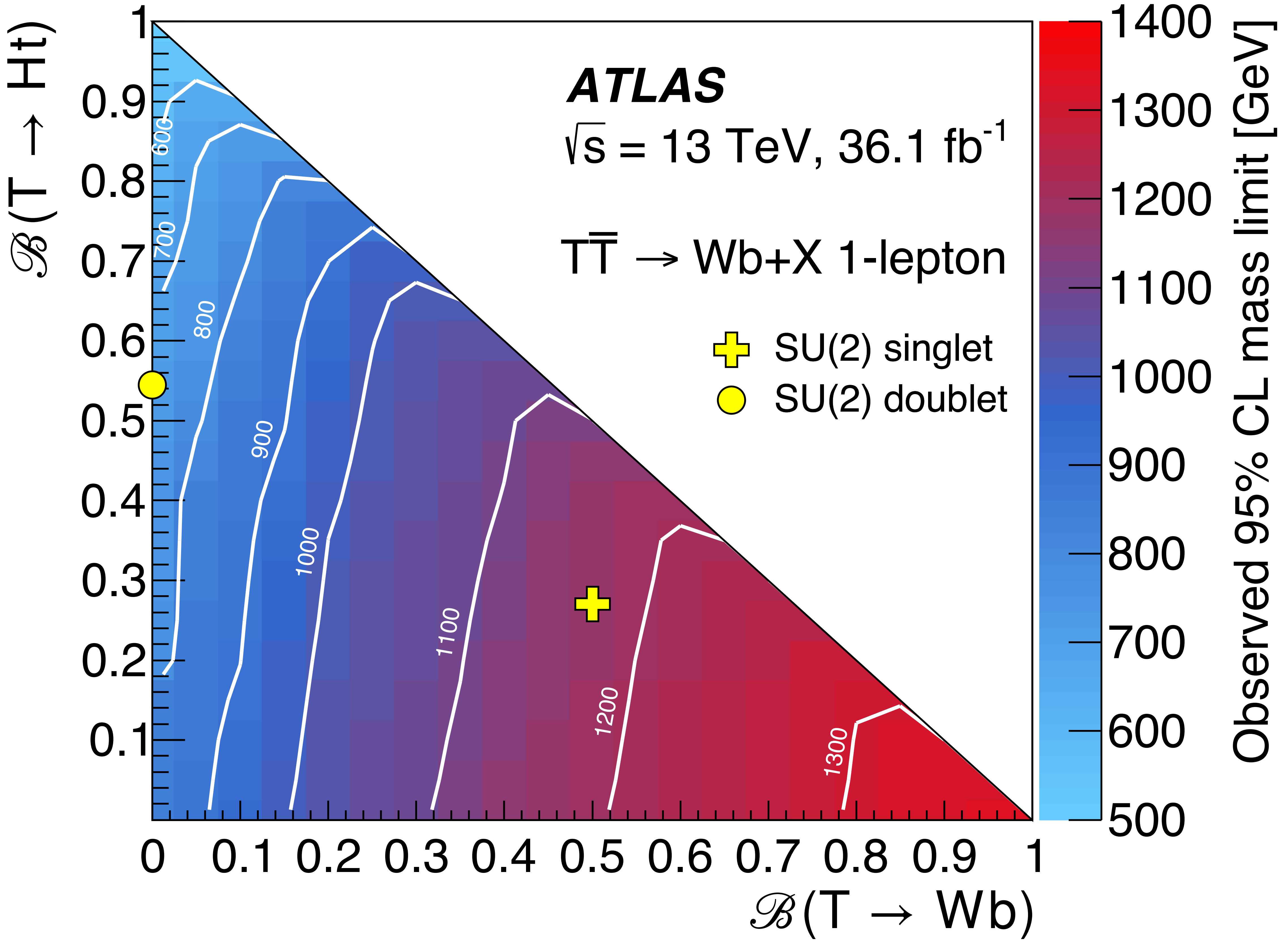
1. T_{lep}: Reco. W_{lep} paired with b-jet candidate
2. T_{had}: Reco. W_{had} paired with other b-jet candidate
3. All possible combinations are tried

▹ Choose combination with **min |ΔM(T_{lep}, T_{had})|**

Wb+X (III) — Limits

JHEP 10 (2017) 141





No excess above SM expectation

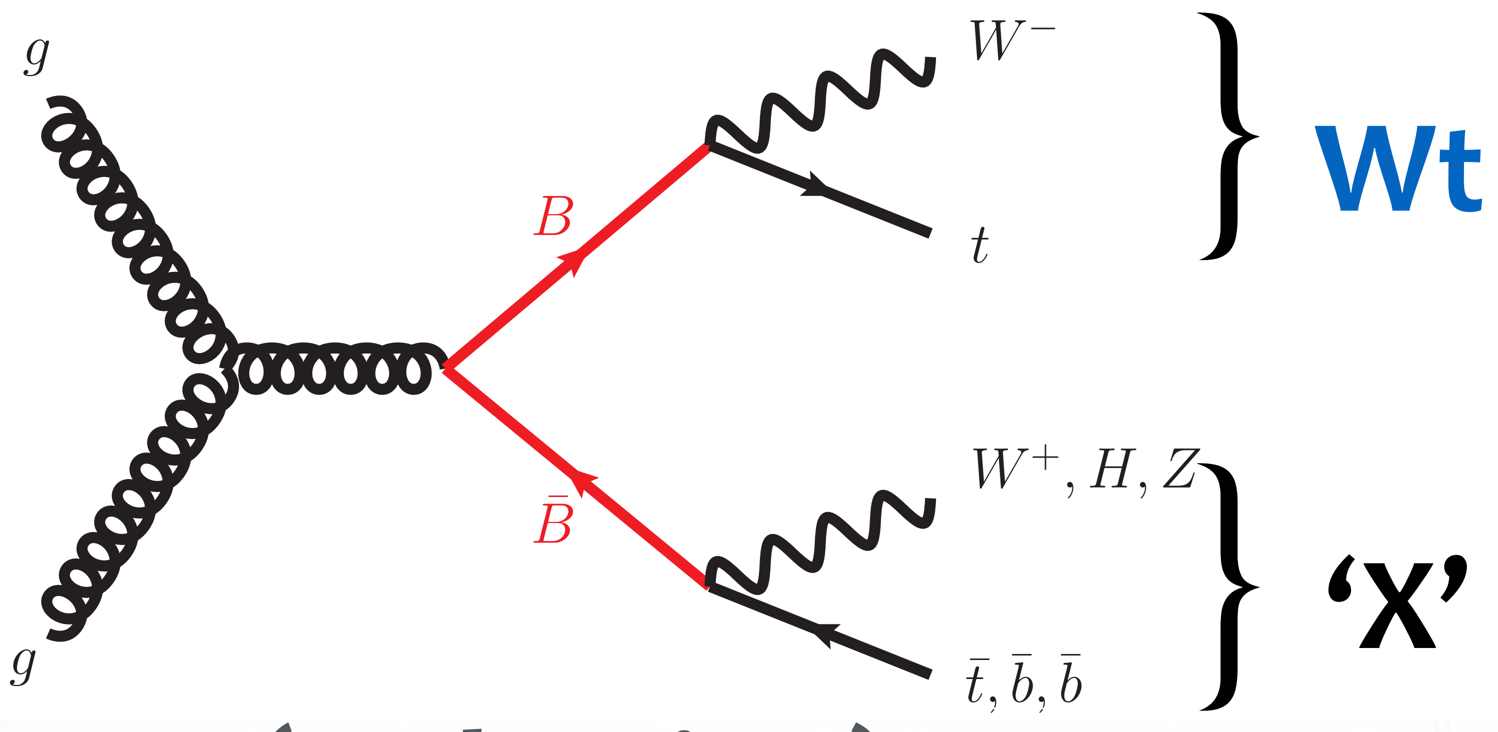
- *Dominant systematics*
  - Data statistics
  - top-quark modelling

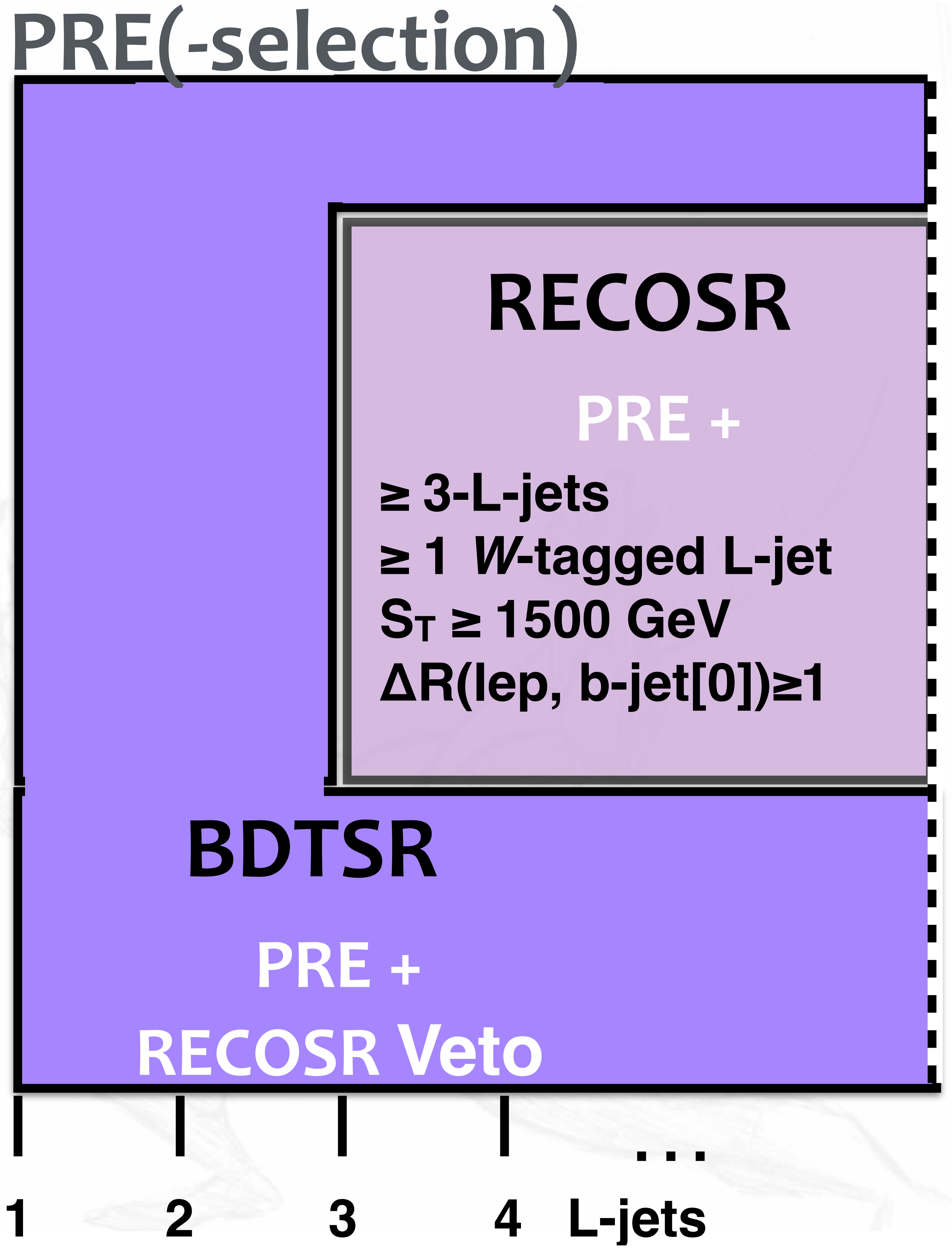
m^{limit} [GeV]	$\mathcal{B}(T\to Wb)=1$
expected	1310
observed	**1350**

Wt+X (I) — Analysis Overview

arXiv:1806.01762 | submitted to JHEP

$\mathcal{L}$=36.1 fb^{-1},13 TeV





Target

- $\mathscr{B}$(B→Wt)=1
  - 1ℓ (e or μ) — target WtWt corner at moderate to high S_T
  - Mass range: m_B > 1 TeV

Pre-Selection

- lepton- (e or μ) trigger
- E_T^{miss} ≥ 60 GeV
- ≥ 4 (≥ 1 *b*-tagged jets)
- ≥ 1 L-jet$_{(R=1)}$

Backgrounds

- $t\bar{t}$ + jets, W+jets & single-top (from simulation)
- Multi-jet: Matrix Method
- $t\bar{t}$+V (V=W,Z), VV, V+jets

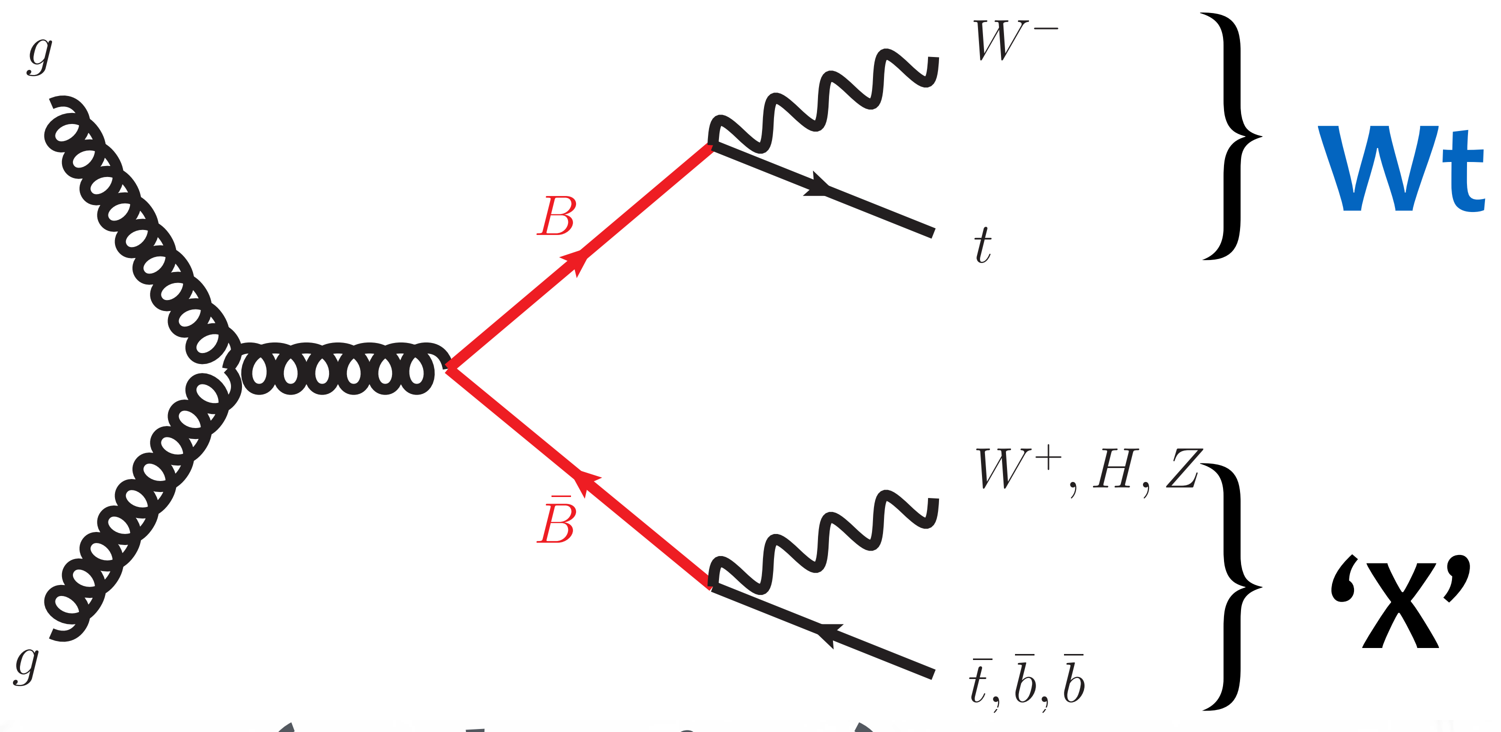
Search Regions

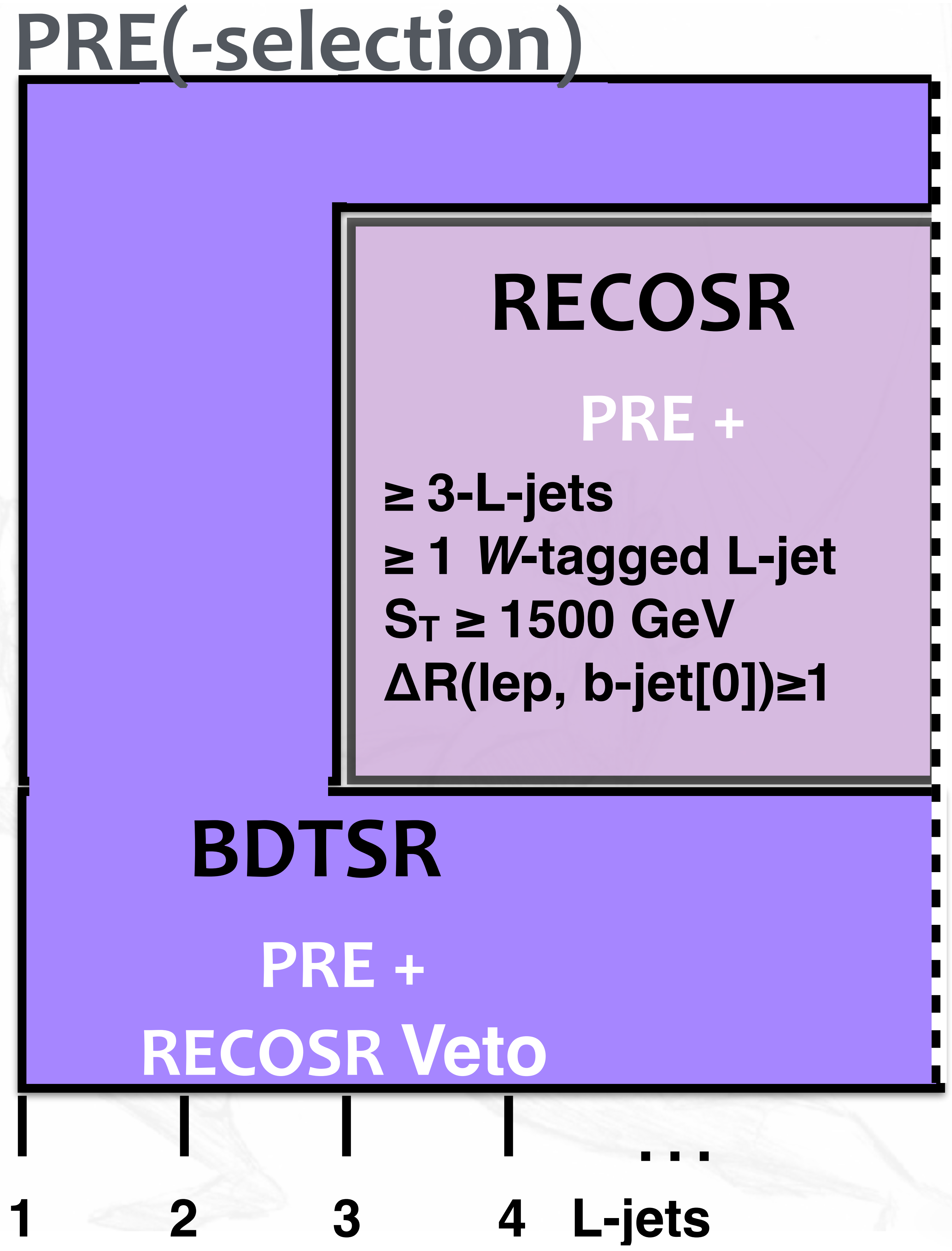
- 2 SRs
- Simultaneous Profile Likelihood Fit (reconstructed **m_B^{had} & BDT discriminant**)

Wt+X (I) — Analysis Overview

arXiv:1806.01762 | submitted to JHEP

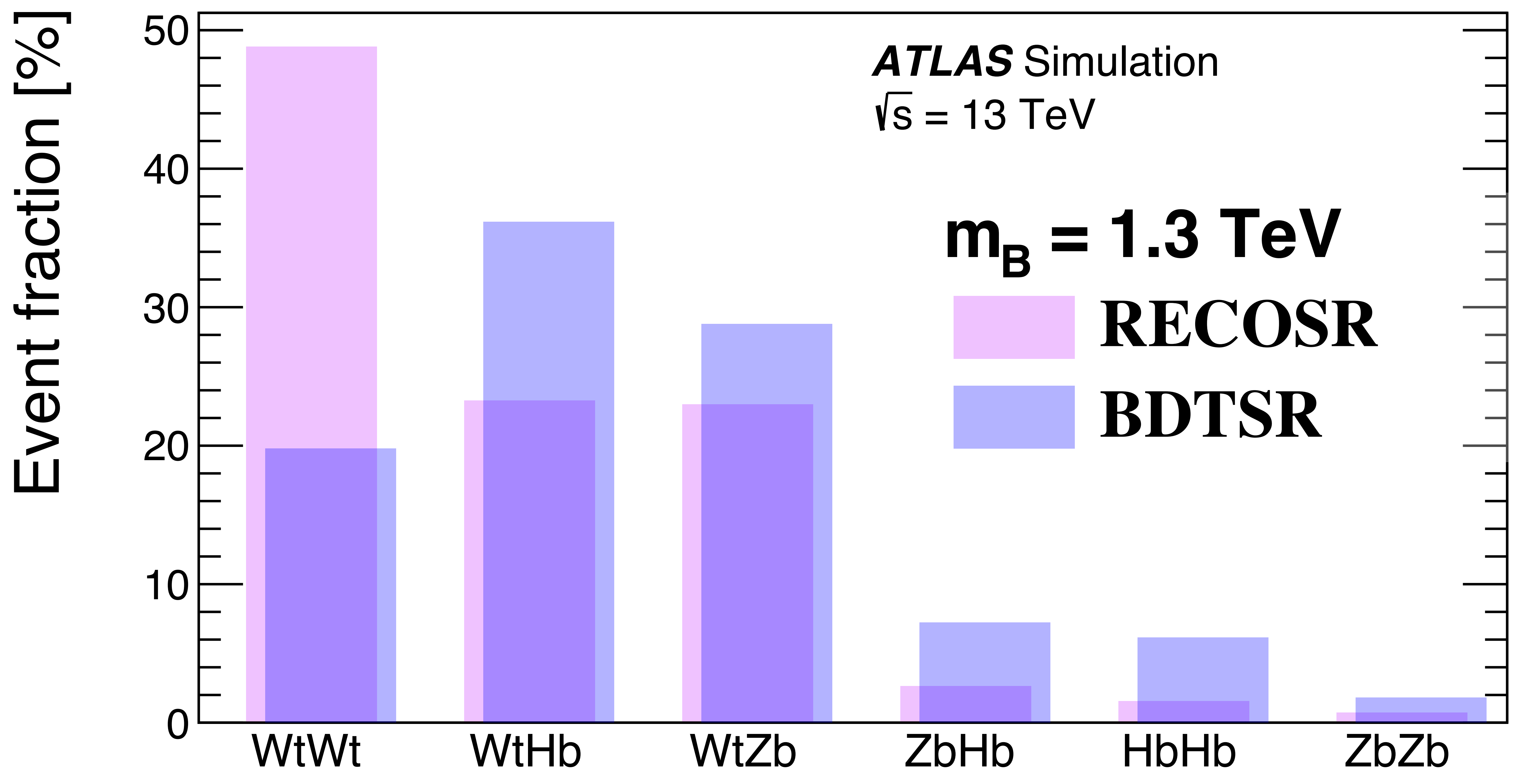
$\mathcal{L}$=36.1 fb^{-1},13 TeV





Target

- $\mathscr{B}$(B→Wt)=1
  - 1ℓ (e or μ) — target WtWt corner at moderate to high S_T
  - Mass range: m_B > 1 TeV

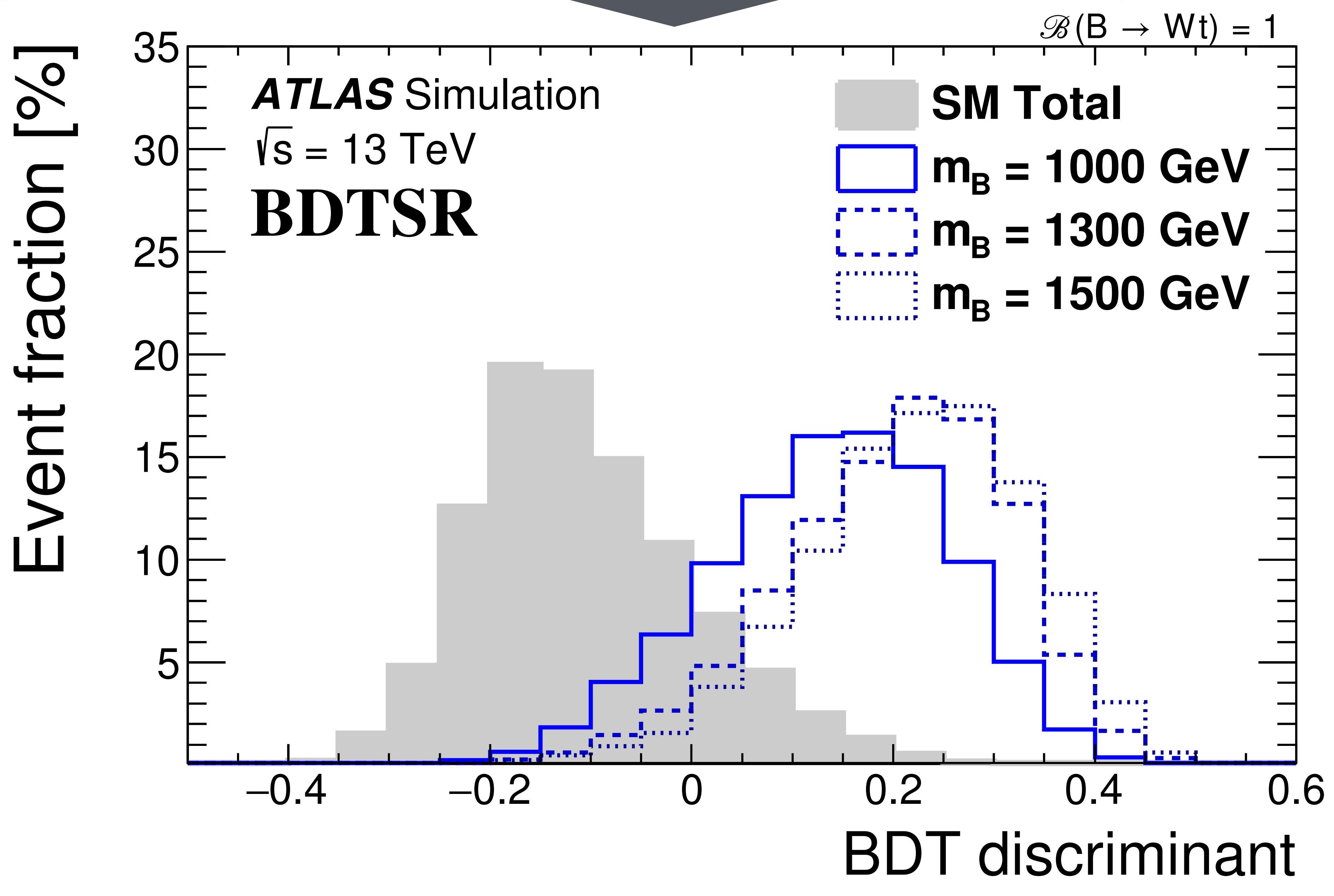


arXiv:1806.01762 | submitted to JHEP

BDTSR

BDT classifier

- TMVA (AdaBoost)
- Background: $t\bar{t}$
- Signal: $m_B^{WtWt} \in [1.05, \ldots, 1.6]$ TeV
- 20 input variables
  - global event characteristics
  - kinematic and angular distributions



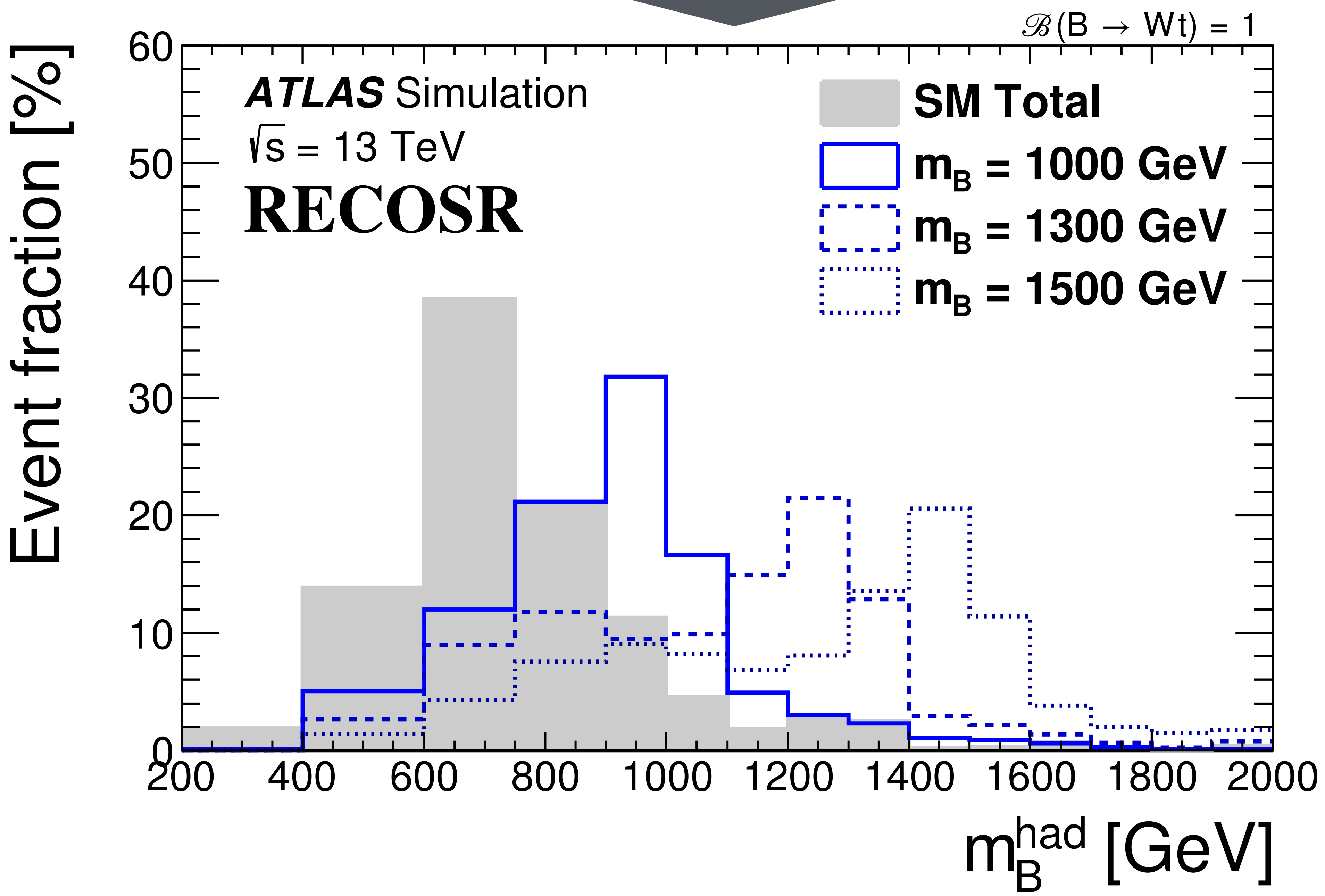
- Significant acceptance to other branching ratios, 'X'

RECOSR

BB system reconstruction

1. Reco. W_{lep} paired with L-jet as proxy for B_{lep} candidate
2. Two additional L-jets paired as proxy for B_{had} candidate
3. All possible combinations are tried

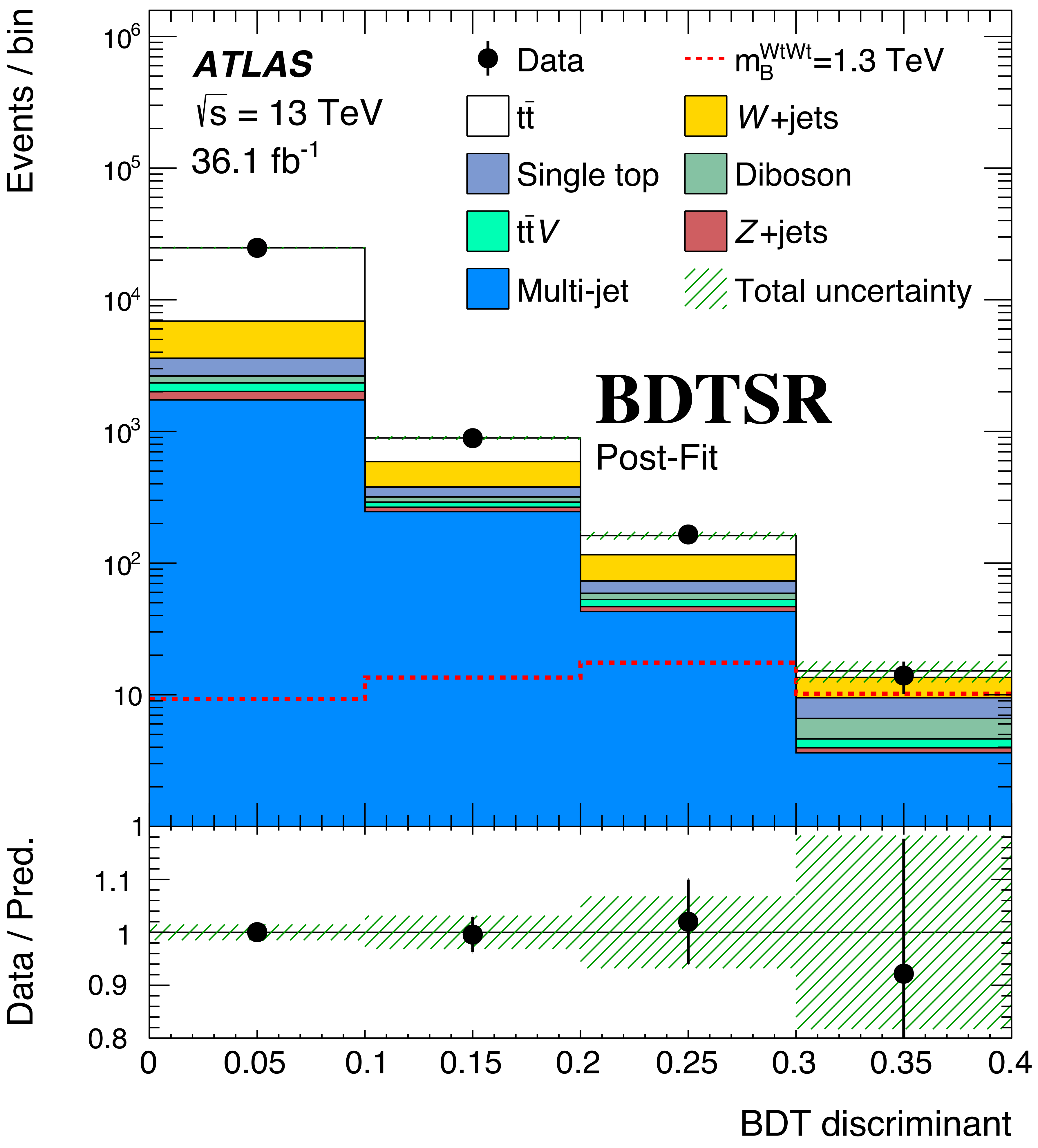
▶ Choose combination with min $|\Delta M(B_{lep}, B_{had})|$

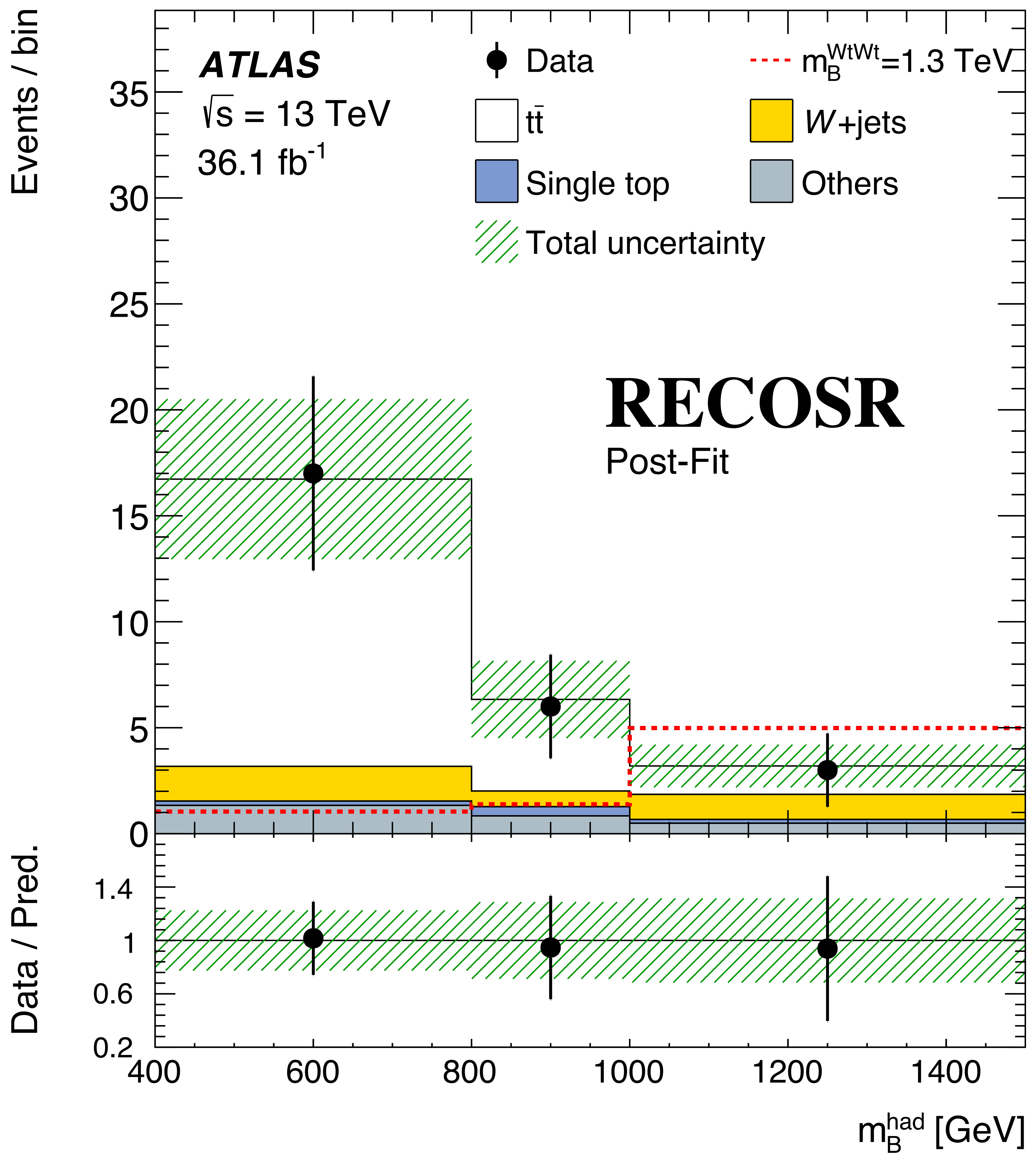


- BB system fully reconstructable
- Designed to look for 'bump' targeting $\mathcal{B}(B\to Wt)=1$

Wt+X (II) — Discriminants

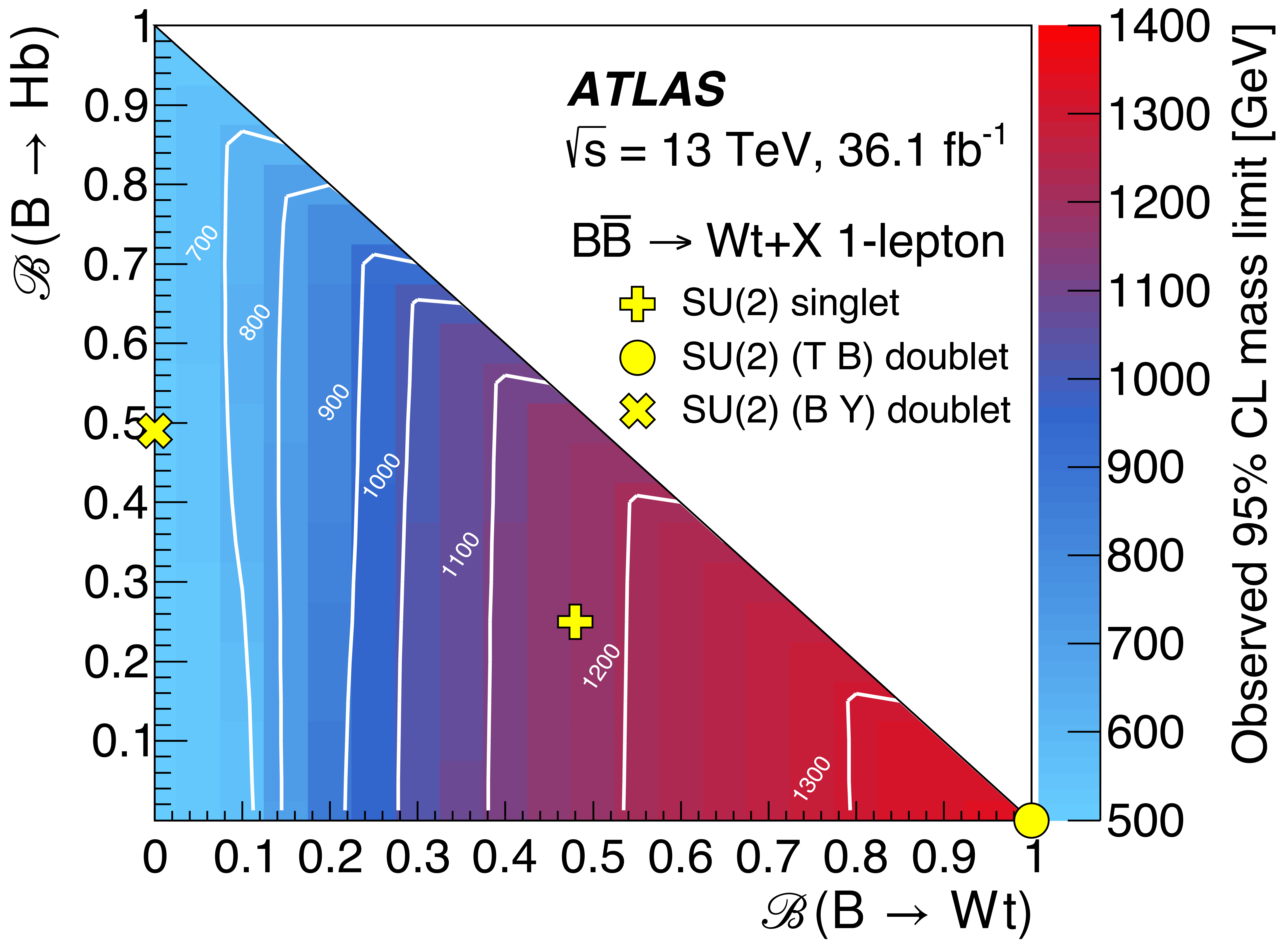
arXiv:1806.01762 | submitted to JHEP





No excess above SM expectation

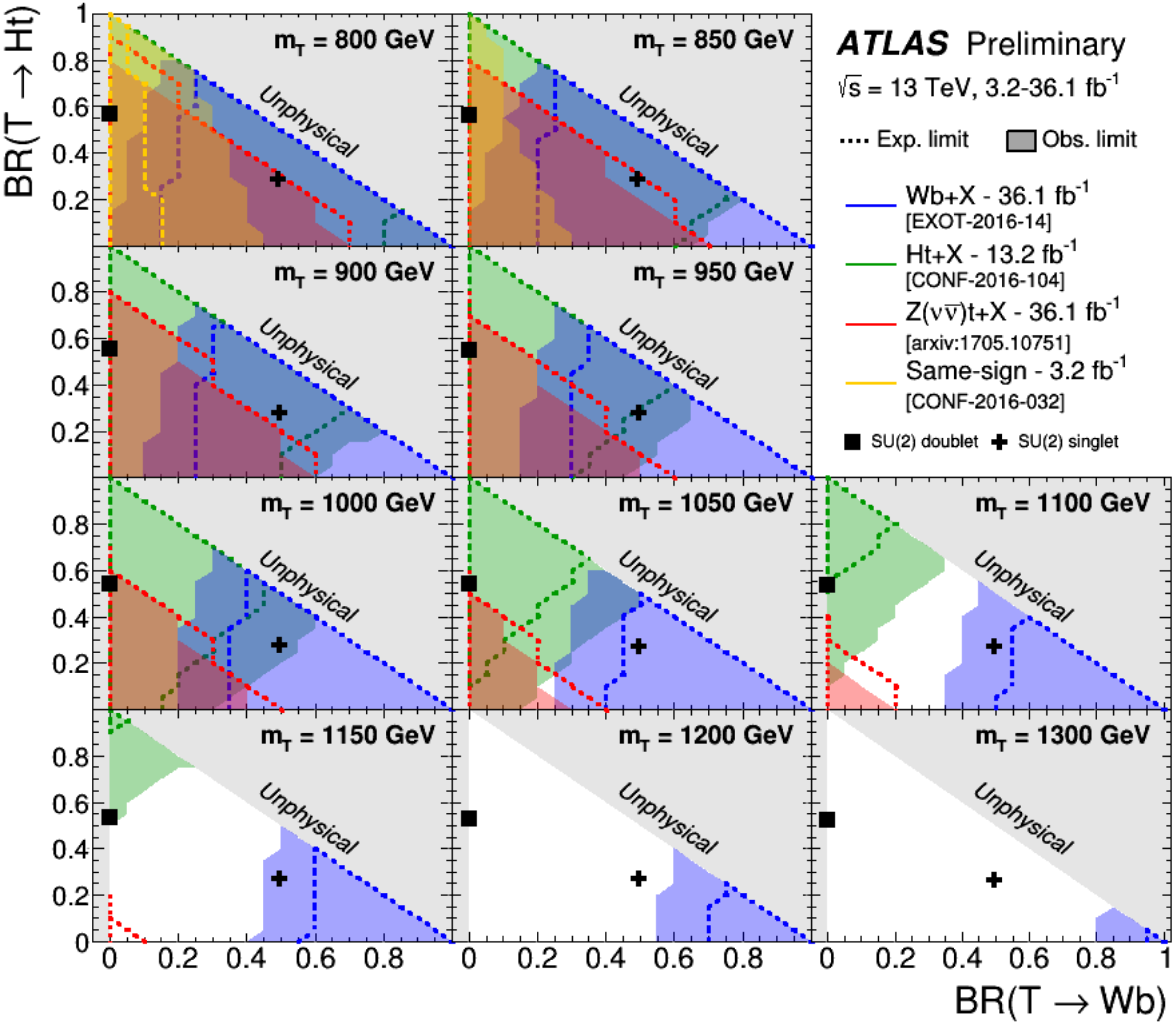
Wt+X (III) — Limits



- *Dominant systematics*
  - Top-quark modelling
  - Data statistics

m^{limit} [GeV]	ℬ(B→Wt)=1
expected	1330
observed	**1350**

The Bigger Picture



Take Away

No discovery of new physics

Comprehensive Search Program @ ATLAS Experiment

- Various VLQ decay mode coverage by numerous *ATLAS* analyses
- Strategy established to maximise sensitivity in full $\mathscr{B}$-plane
- Significant improvements of lower VLQ mass limits compared to Run-1

m^{limit} [GeV]	VLT $\mathscr{B}(T\rightarrow Ht)=1$	VLT $\mathscr{B}(T\rightarrow Wb)=1$	VLT $\mathscr{B}(T\rightarrow Zt)=1$	VLB $\mathscr{B}(B\rightarrow Wt)=1$
expected	1340	1310	1170	1330
observed	**1430**	**1350**	**1160**	**1350**
Run-I	950	780	750	810

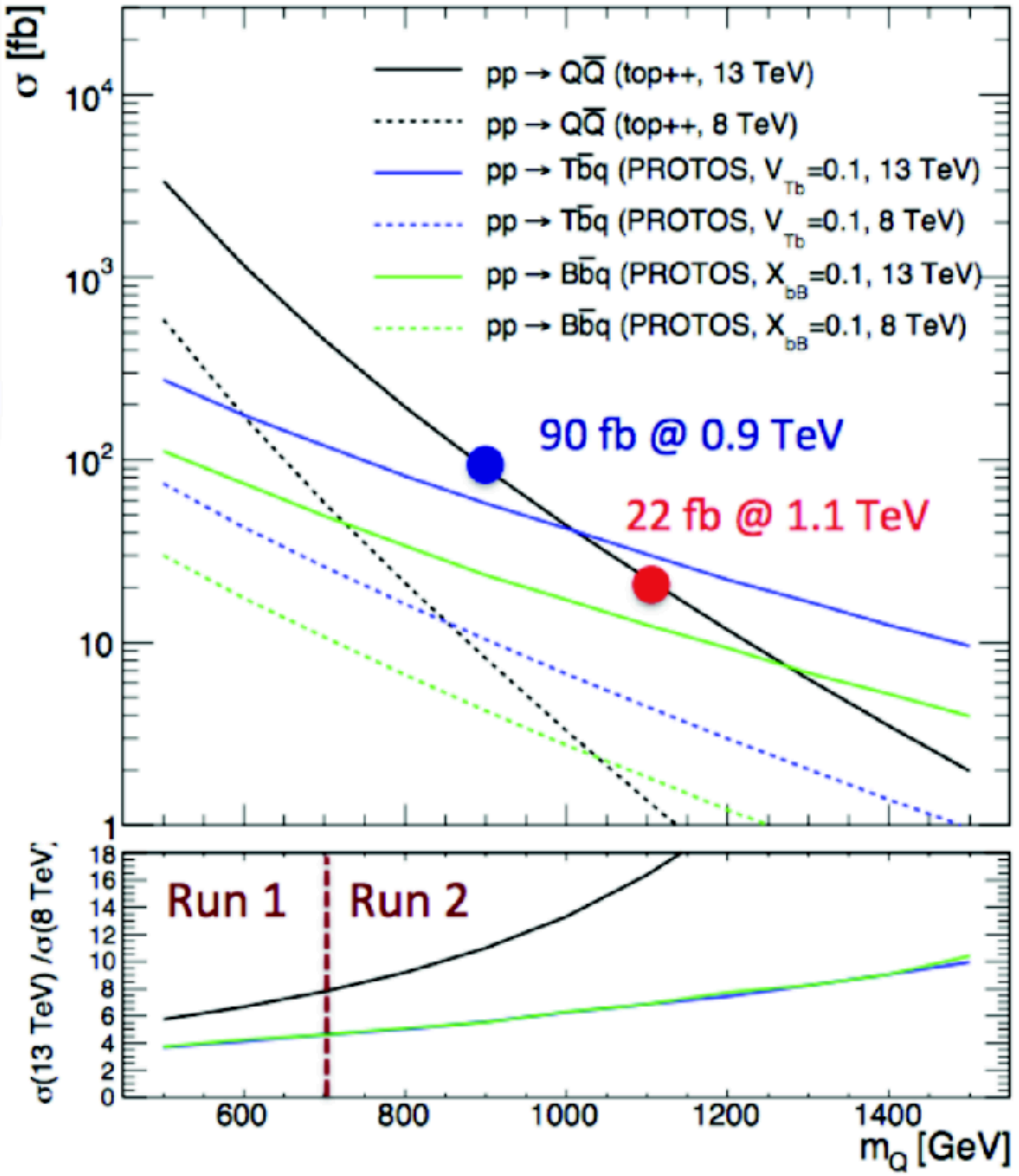
Run-II results exceed 1 TeV

Future Challenges

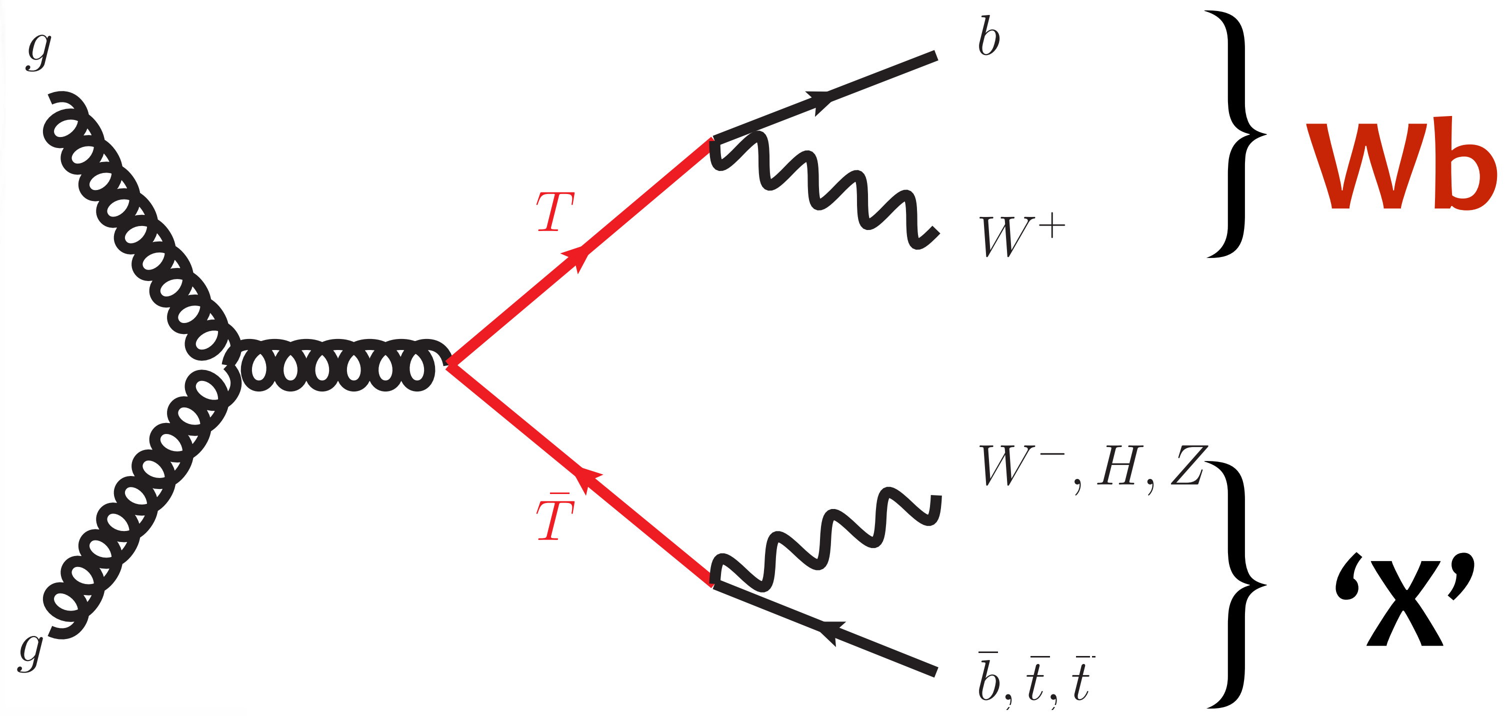
- Only mild gain in sensitivity with luminosity increase

Probing new & interesting regions of phase space

- *Theory*: Reliable SM background process modelling in 'extreme' regions of phase space
- *Experiment*: Modern reconstruction & identification techniques for boosted particles


σ [fb]
pp → QQ̄ (top++, 13 TeV)
pp → QQ̄ (top++, 8 TeV)
pp → Tb̄q (PROTOS, V_Tb=0.1, 13 TeV)
pp → Tb̄q (PROTOS, V_Tb=0.1, 8 TeV)
pp → Bb̄q (PROTOS, X_bB=0.1, 13 TeV)
pp → Bb̄q (PROTOS, X_bB=0.1, 8 TeV)
90 fb @ 0.9 TeV
22 fb @ 1.1 TeV
Run 1
Run 2
σ(13 TeV) /σ(8 TeV)
m_Q [GeV]

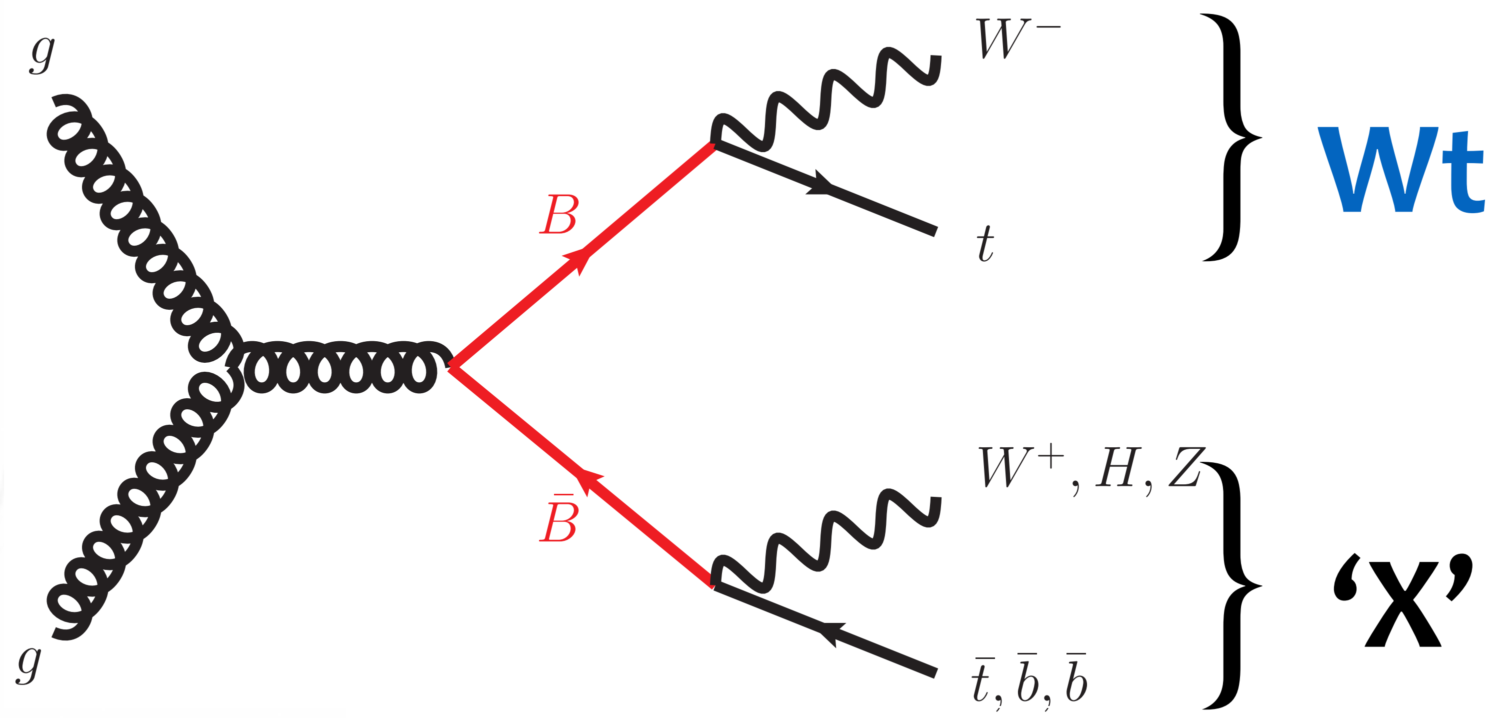
JHEP 10 (2017) 141



Wb+X — pre-selection

<ADD>

arXiv:1806.01762 | submitted to JHEP



Wt+X — pre-selection

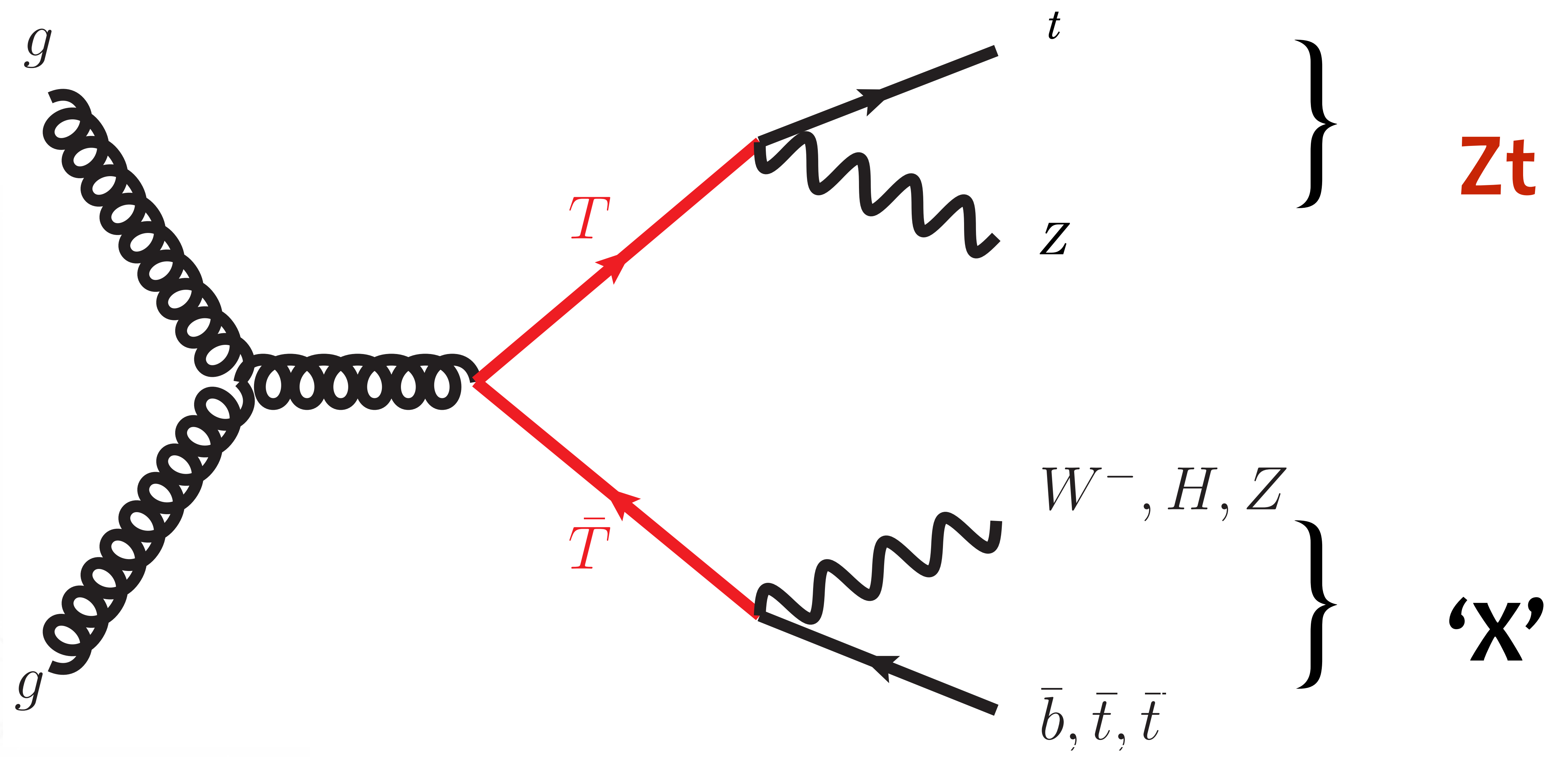
<ADD>

BDT Input Variable Definitions

Table 3: List of the 20 BDT input variables used in the training of the BDTSR signal region, ordered by their respective TMVA ranking. The terms leading, sub-leading, etc. refer to the p_T ordering of the objects.

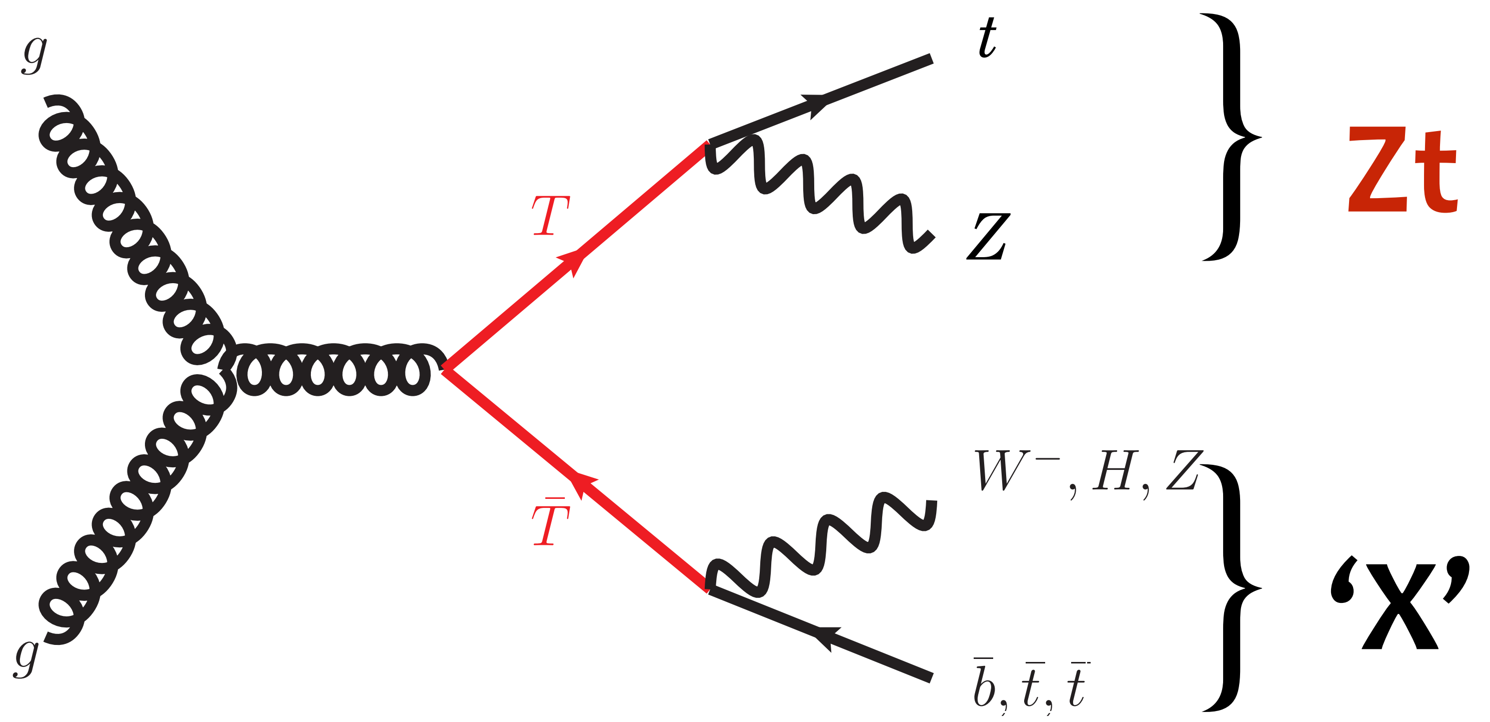
Variable	Description
S_T	Scalar sum of E_T^{miss}, the p_T of the lepton and the p_T of all small-R jets
m (leading large-R jet)	Mass of the leading large-R jet
Sphericity	Sphericity [70] ($\mathcal{S} = \frac{2}{3}(\lambda_2 + \lambda_3)$) is a measure of the total transverse momentum with respect to the sphericity axis defined by the four-momenta used for the event shape measurement; $\lambda_{2,3}$ are the two smallest eigenvalues of the normalised momentum tensor of the small-R jets
ΔR(lep, sub-leading small-R jet)	Angular separation between the lepton and the sub-leading small-R jet
ΔR(leading b-jet, leading large-R jet)	Angular separation between the leading b-tagged jet and the leading large-R jet
min[ΔR(lep, b-jet)]	Minimum angular separation between the lepton and all b-tagged jets
Aplanarity ($\mathcal{A} = \frac{3}{2}\lambda_3$)	Aplanarity [70], where λ_3 is the smallest eigenvalue of the norm. momentum tensor of small-R jets
min[M(W_{lep}, b-jet)]	Minimum invariant mass of W_{lep} and all b-tagged jets
ΔR(lep, third-leading small-R jet)	Angular separation between the lepton and the third-leading small-R jet
ΔR(W_{lep}, large-R jet closest to leading b-jet)	Angular separation between the W_{lep} and the large-R jet closest to the leading b-tagged jet
p_T (sub-leading large-R jet)	Transverse momentum of the sub-leading large-R jet
M_T^W	Transverse mass of the W_{lep}
Sphericity (large-R jets)	Sphericity, using normalised momentum tensor of the large-R jets
ΔR(lep, leading small-R jet)	Angular separation between the lepton and the leading small-R jet
ΔR(W_{lep}, leading large-R jet)	Angular separation between the W_{lep} and the leading large-R jet
ΔR(lep, sub-leading b-jet)	Angular separation between the lepton and the sub-leading b-tagged jet
E_T^{miss}	Missing transverse energy
p_T (W_{had})	Transverse momenta of the leading W_{had} candidate
N_{jets}	Small-R jet multiplicity
p_T (sub-leading small-R jet)	Transverse momentum of the sub-leading small-R jet

JHEP 08 (2017) 052



Zt+X — pre-selection / Search Regions (I)

JHEP 08 (2017) 052

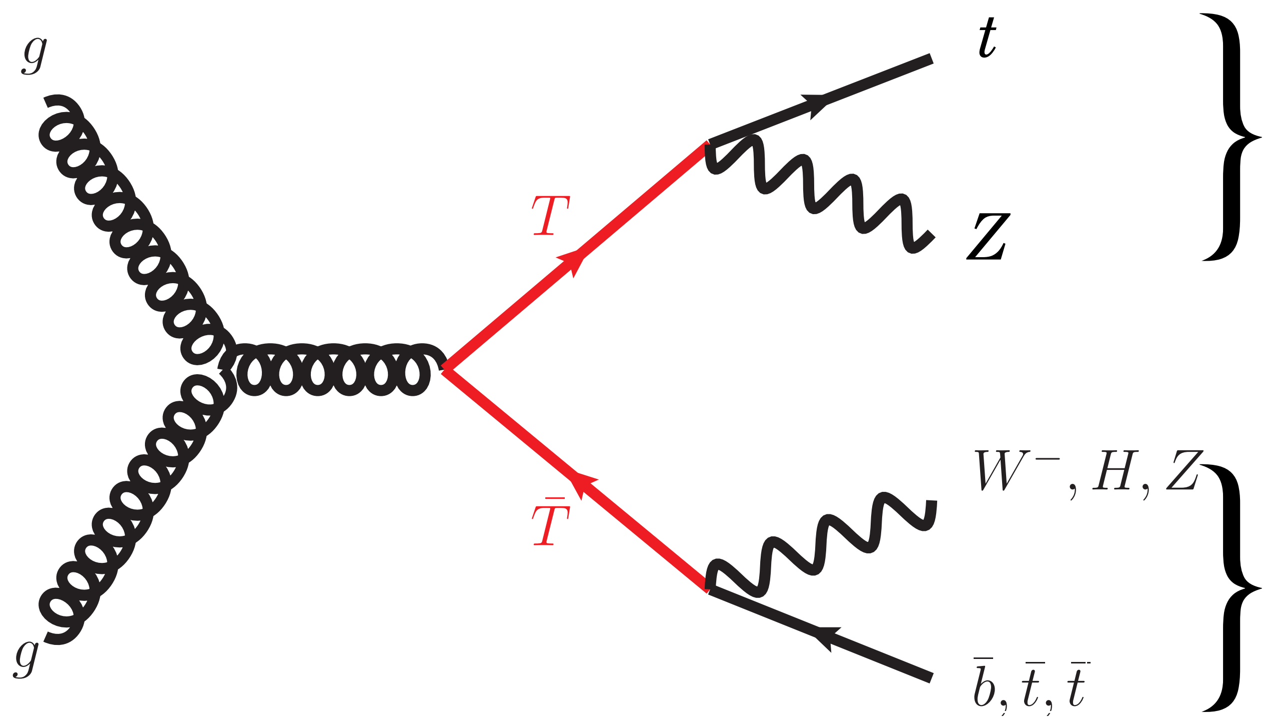


Variable	Preselection	SR	TCR	WCR
E_T^{miss}	> 300 GeV	> 350 GeV	> 300 GeV	
m_T^W	> 30 GeV	> 170 GeV	$\in [30, 90]$ GeV	
am_{T2}	–	> 175 GeV	> 100 GeV	
m_{T2}^{τ}	–	> 80 GeV	> 80 GeV	
$H_{T,sig}^{miss}$	–	> 12	–	
Jet p_T	> 25 GeV	$> 120, 80, 50, 25$ GeV	$> 120, 80, 50, 25$ GeV	
$\lvert\Delta\phi(j_i, E_T^{miss})\rvert$, $i = 1, 2$	> 0.4	> 0.4	> 0.4	
# b-tagged jets	≥ 1	≥ 1	≥ 1	$= 0$
# large-radius jets	–	≥ 2	≥ 2	
Large-radius jet mass	–	$> 80, 60$ GeV	$> 80, 60$ GeV	
Large-radius jet p_T	–	> 290 GeV if $E_T^{miss} < 450$ GeV > 200 GeV if $E_T^{miss} > 450$ GeV	> 200 GeV	

- Zt+X
  - m_T^W : transverse mass of leptonic W $\quad m_T^W = \sqrt{2 p_T^{lep} E_T^{miss} [1 - \cos(\Delta\phi)]}$
  - am_{T2} : transverse mass with two invsible particle $\quad m_{T2} \equiv \min_{\vec{q}_{Ta} + \vec{q}_{Tb} = \vec{E}_T^{miss}} \{\max(m_{Ta}, m_{Tb})\}$
    - a,b = lepton, two b-jets with highest weight
  - $H_{T,sig}^{miss}$: significance of H_t^{miss} $\quad H_{T,sig}^{miss} \equiv (H_T^{miss} - 100\,\text{GeV})/\sigma_{H_T^{miss}}$ (used to reduce events w/ mis-reconstructed E_T^{miss})
    - H_T^{miss} : magnitude of vectorial sum of jets and lepton p_T

Zt+X — pre-selection / Search Regions (II)

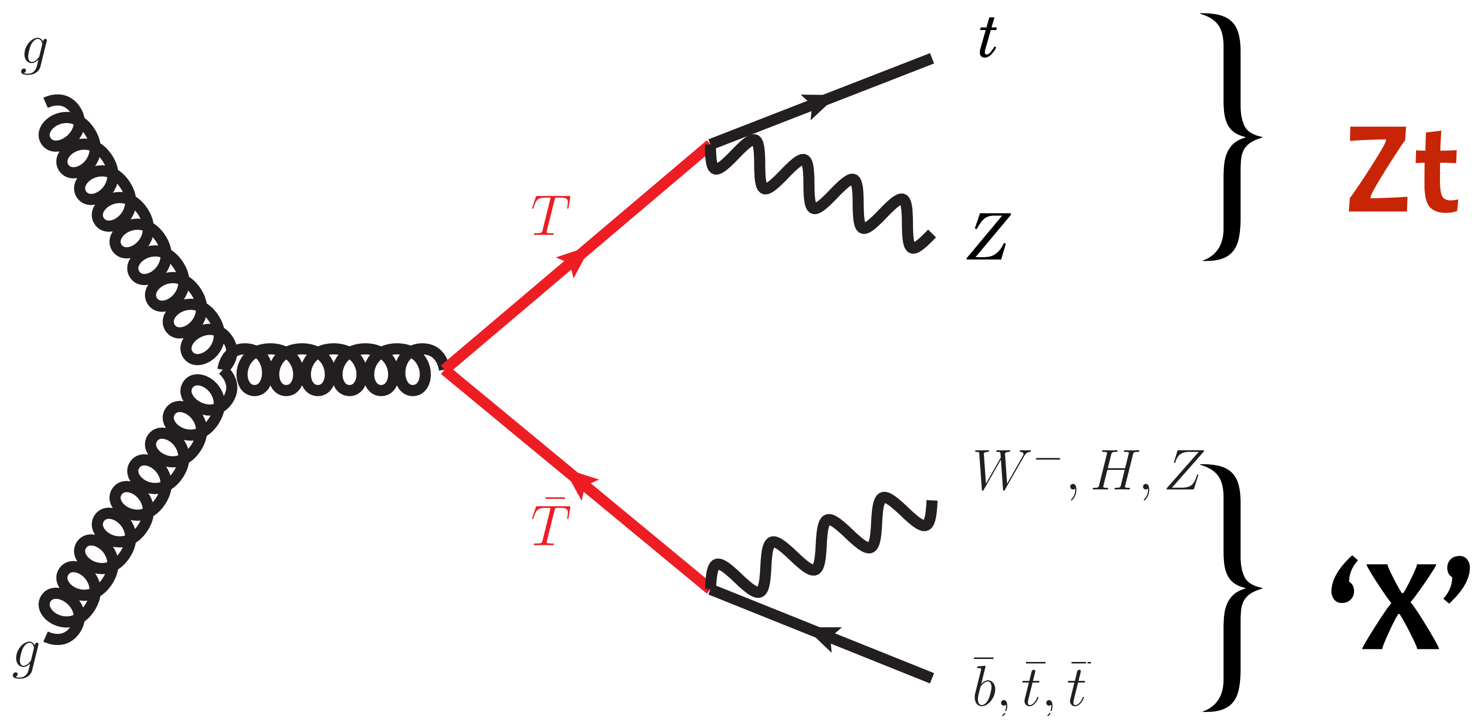
JHEP 08 (2017) 052



Variable	Signal Region	TVR	WVR	STVR
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 350 GeV	> 300 GeV		
m_{T}^{W}	> 170 GeV	> 120 GeV		> 60 GeV
am_{T2}	> 175 GeV	$\in [100, 200]$ GeV	> 100 GeV	> 200 GeV
m_{T2}^{τ}	> 80 GeV	> 80 GeV		
$H_{\mathrm{T,sig}}^{\mathrm{miss}}$	> 12	–		
Jet p_{T}	$> 120, 80, 50, 25$ GeV	$> 120, 80, 50, 25$ GeV		
$\lvert\Delta\phi(j_i, E_{\mathrm{T}}^{\mathrm{miss}})\rvert$, $i = 1, 2$	> 0.4	> 0.4		
# b-tagged jets	≥ 1	≥ 1	$= 0$	≥ 2
# large-radius jets	≥ 2	$= 1$		
Large-radius jet mass	$> 80, 60$ GeV	> 80 GeV		
Large-radius jet p_{T}	> 290 GeV if $E_{\mathrm{T}}^{\mathrm{miss}} < 450$ GeV > 200 GeV if $E_{\mathrm{T}}^{\mathrm{miss}} > 450$ GeV	> 200 GeV		

Zt+X — Yields / Limits (III)

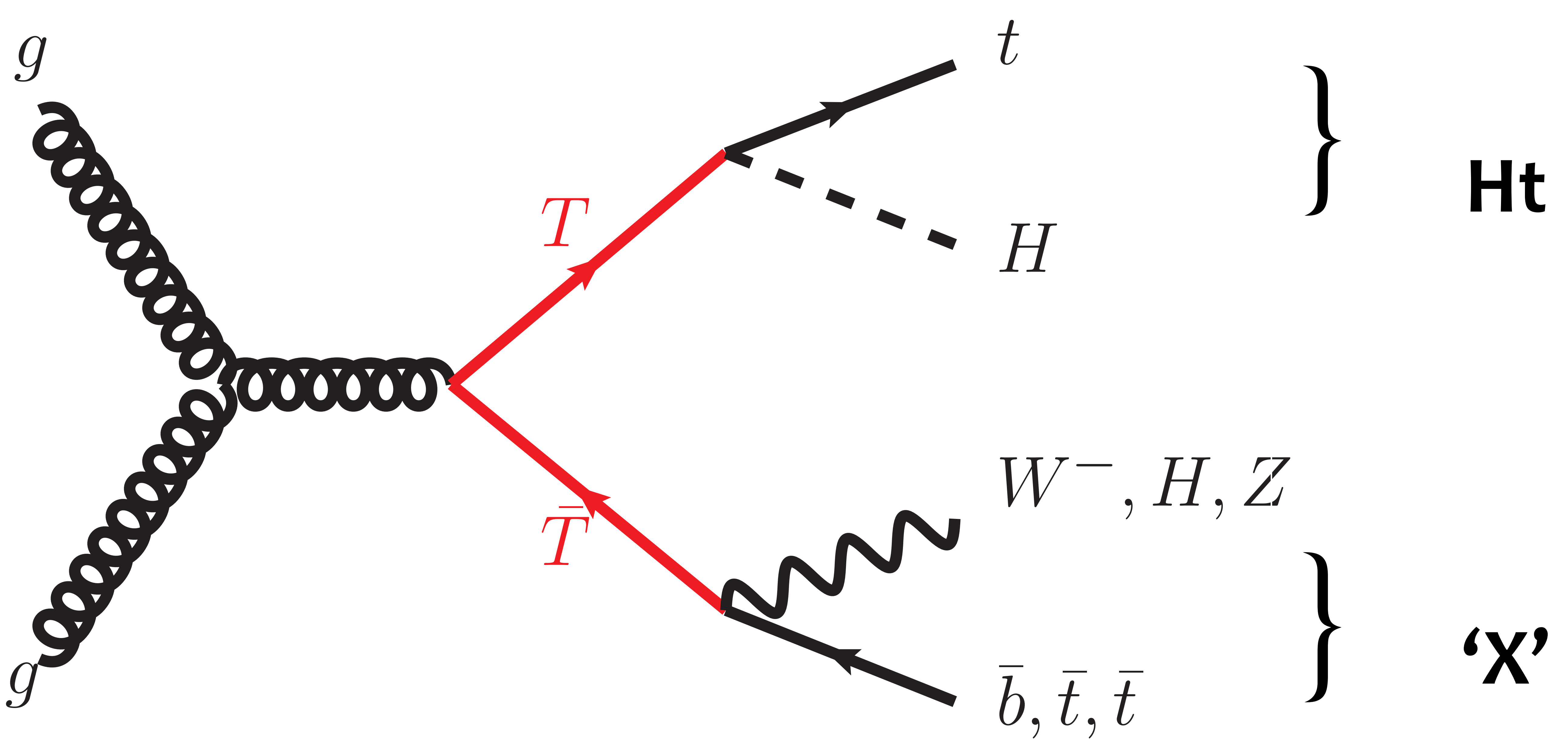
JHEP 08 (2017) 052



Region	SR	TCR	WCR	TVR	WVR	STVR
Observed events	7	437	303	112	131	143
Fitted bkg events	6.1 ± 1.9	437 ± 21	303 ± 17	109 ± 35	127 ± 31	125 ± 27
Fitted $t\bar{t}$ events	2.5 ± 1.7	280 ± 40	38 ± 15	90 ± 40	15 ± 8	53 ± 23
Fitted W + jets events	1.1 ± 0.7	70 ± 28	224 ± 27	3.5 ± 2.0	77 ± 30	15 ± 7
Fitted singletop events	1.1 ± 0.7	63 ± 24	10 ± 5	4.2 ± 2.6	$3.3^{+3.5}_{-3.3}$	46 ± 17
Fitted $t\bar{t} + V$ events	0.91 ± 0.20	9.7 ± 1.6	1.03 ± 0.30	7.0 ± 1.4	1.9 ± 0.7	8.3 ± 1.4
Fitted diboson events	0.6 ± 0.6	11 ± 5	30 ± 12	1.3 ± 1.3	31 ± 9	1.7 ± 1.1
MC exp. bkg events	6.5	450	398	106	160	129

Signal	Obs. 95% CL lower mass limit	Exp. 95% CL lower mass limit
$T \to Zt$	1.16 TeV	1.17 TeV
Singlet	0.87 TeV	0.89 TeV
Doublet	1.05 TeV	1.06 TeV

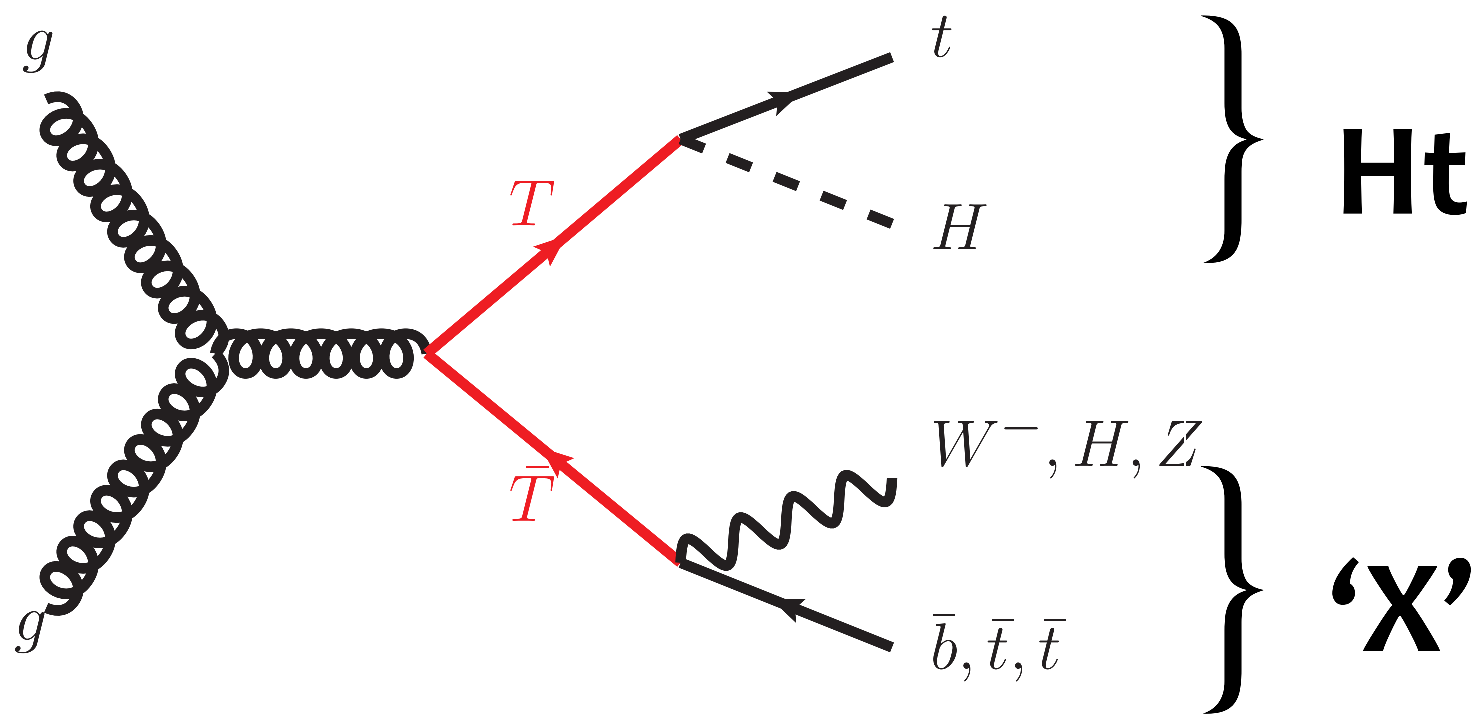
arXiv:1803.09678 I submitted to JHEP



Ht+X — pre-selection (I)

arXiv:1803.09678 I submitted to JHEP

Preselection requirements		
Requirement	1-lepton channel	0-lepton channel
Trigger	Single-lepton trigger	E_T^{miss} trigger
Leptons	=1 isolated e or μ	=0 isolated e or μ
Jets	≥5 jets	≥6 jets
b-tagging	≥2 b-tagged jets	≥2 b-tagged jets
E_T^{miss}	$E_T^{miss} > 20$ GeV	$E_T^{miss} > 200$ GeV
Other E_T^{miss}-related	$E_T^{miss} + m_T^W > 60$ GeV	$\Delta\phi_{min}^{4j} > 0.4$

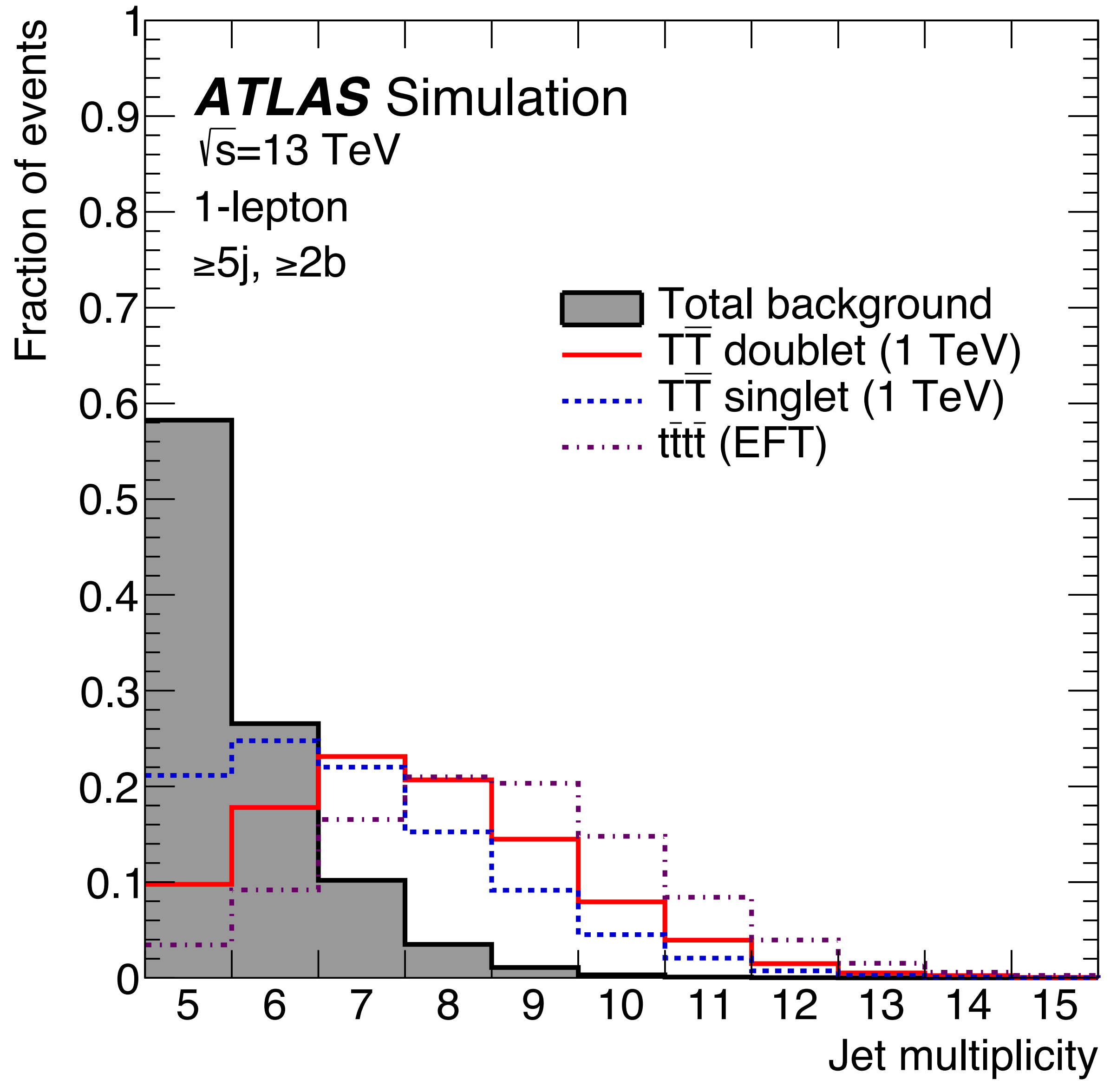


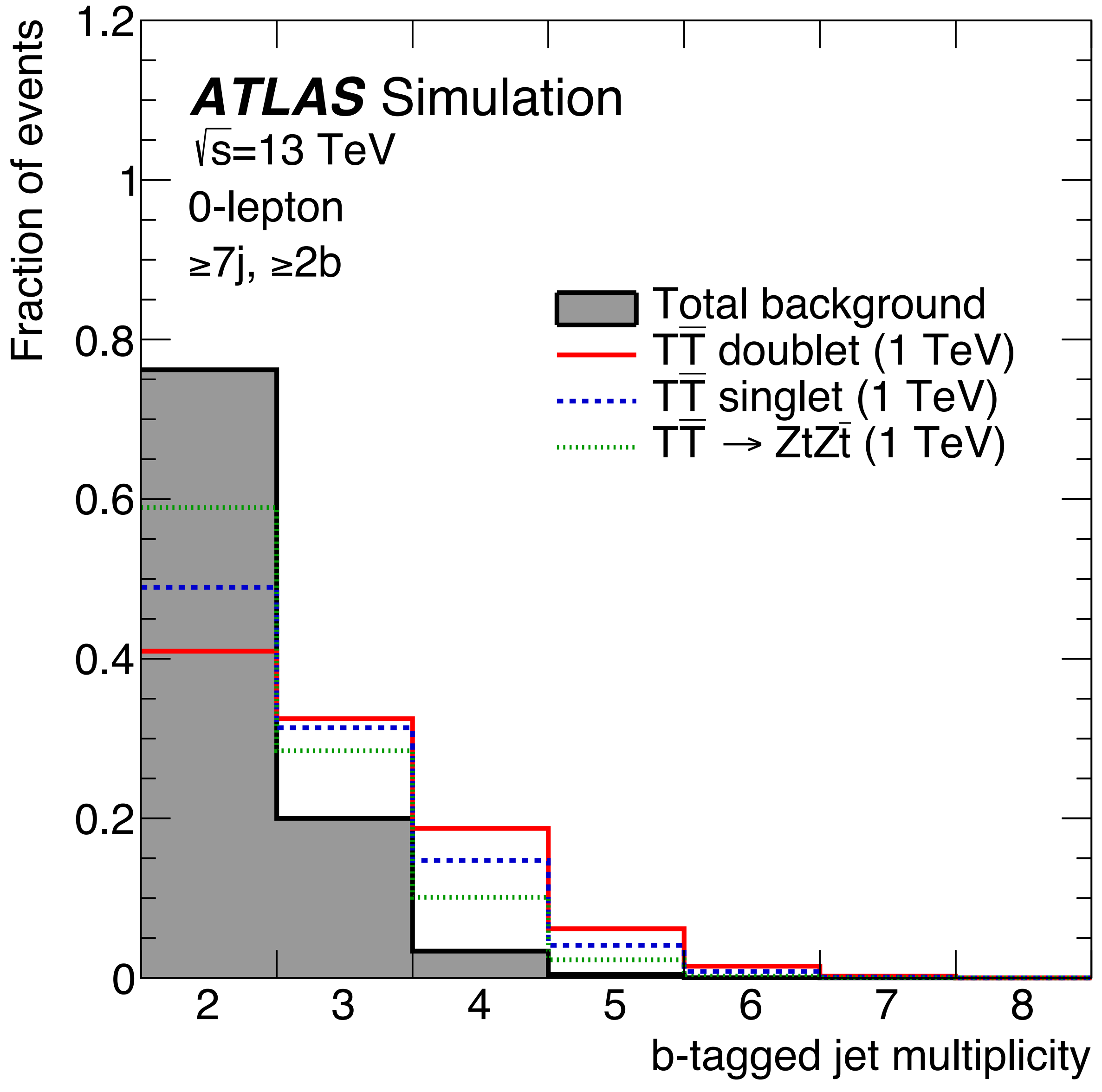
$\Delta\phi_{min}^{4j}$ is the minimum azimuthal separation between the E_T^{miss} vector and each of the four highest-p_T jets.

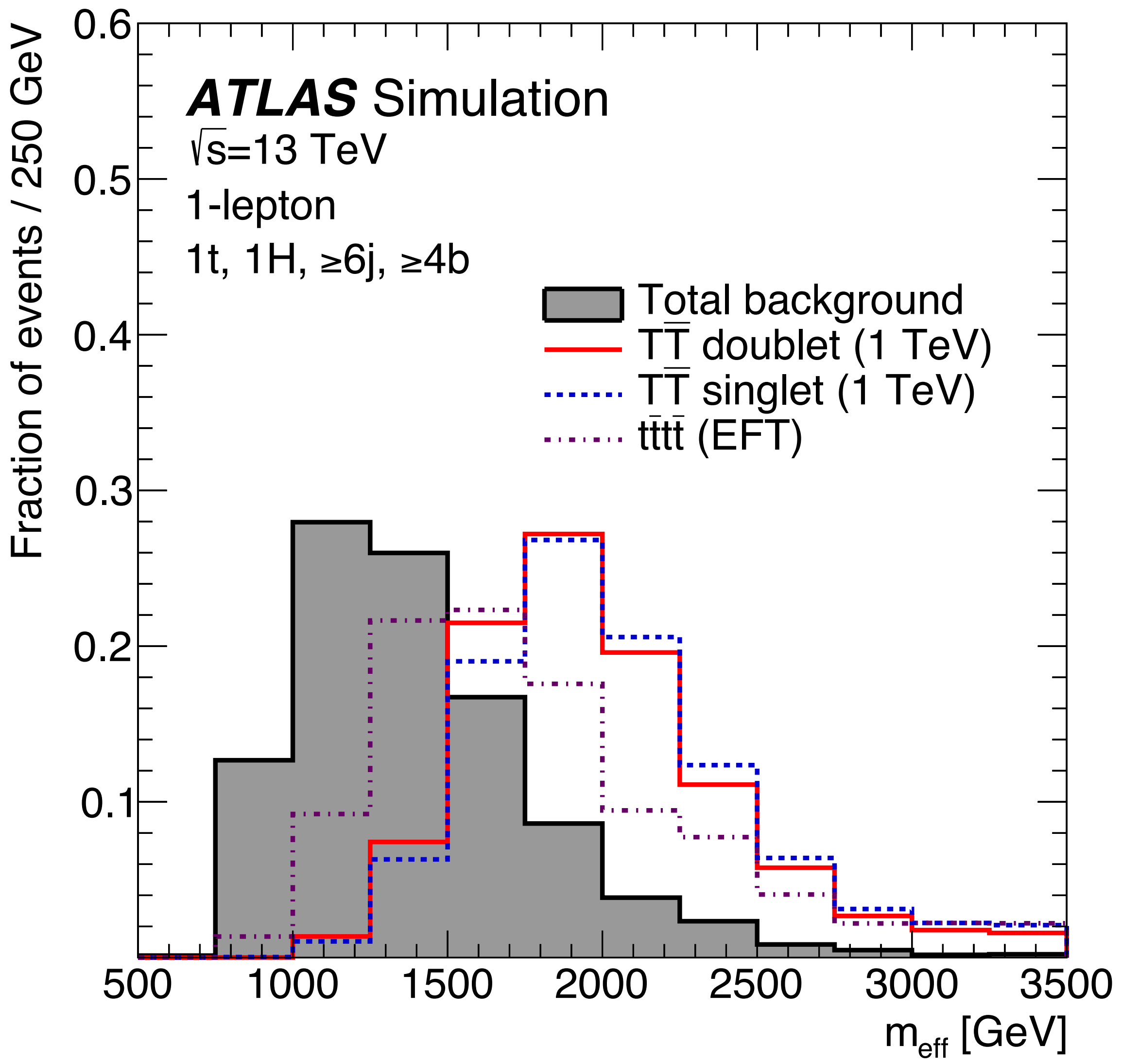
The latter requirement in the 0-lepton channel is very effective in suppressing multijet events, where the large E_T^{miss} results from the mismeasurement of a high-p_T jet or the presence of neutrinos emitted close to a jet axis.

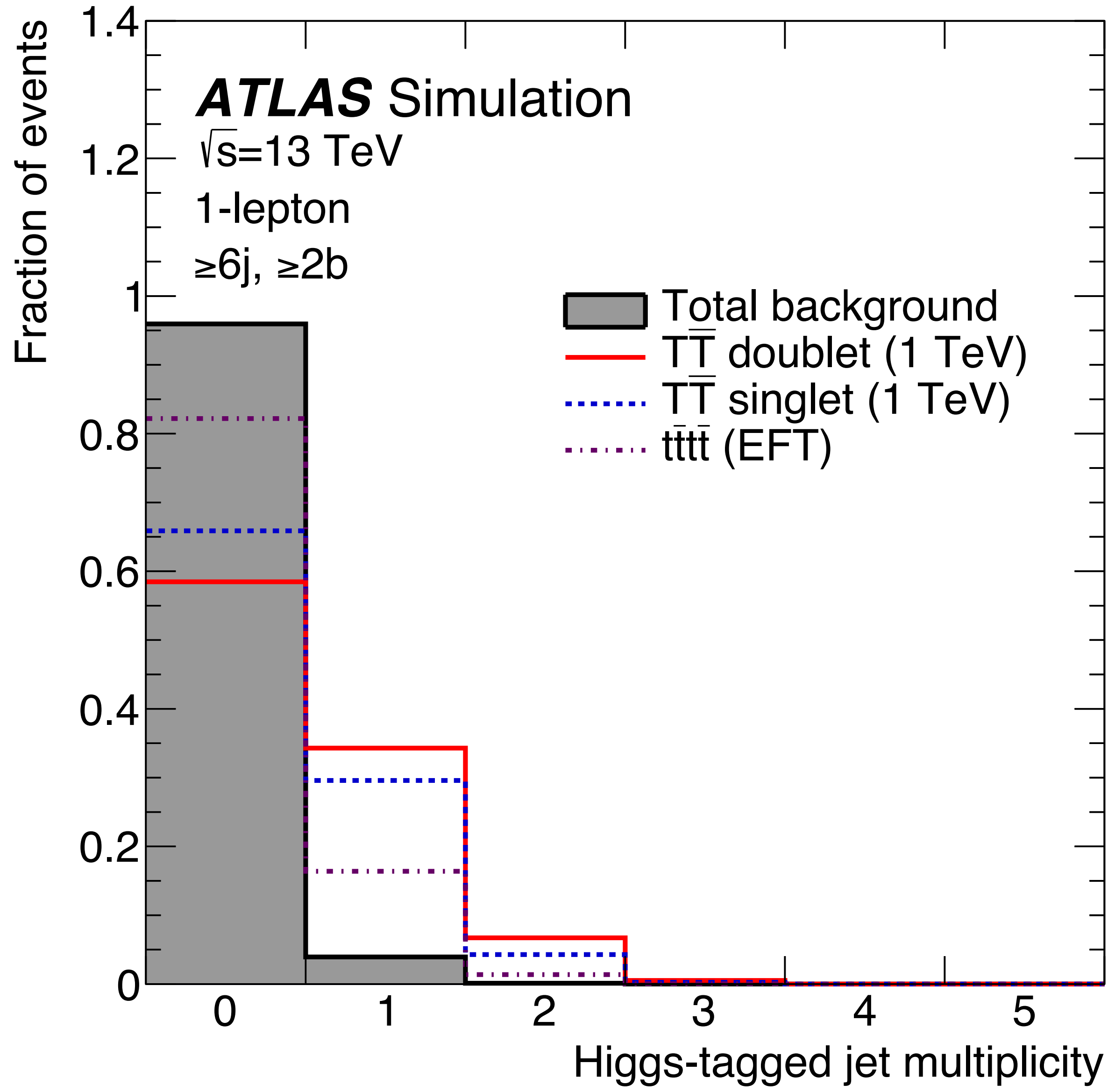
Ht+X — Kinematics (II)

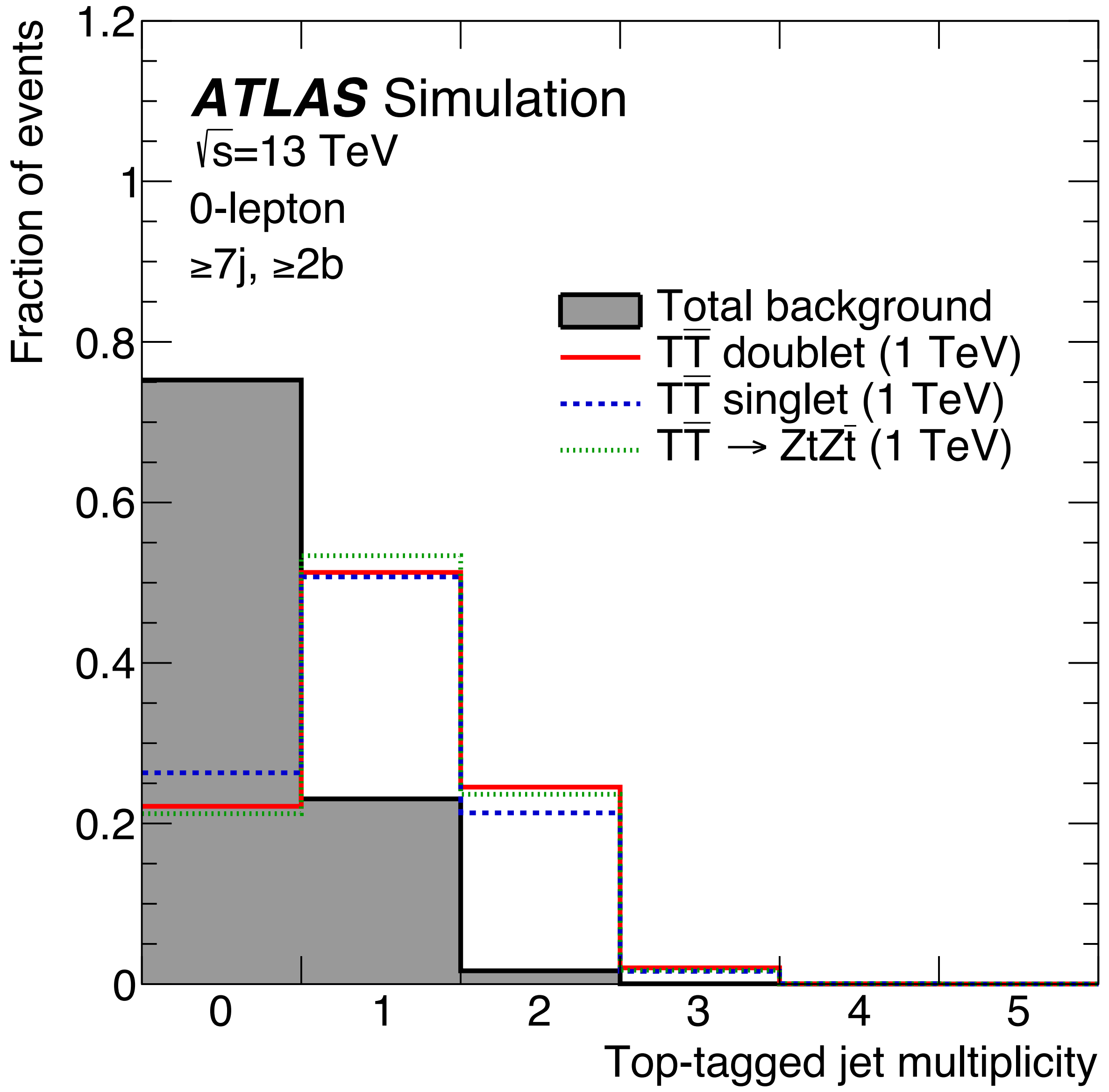
arXiv:1803.09678 I submitted to JHEP

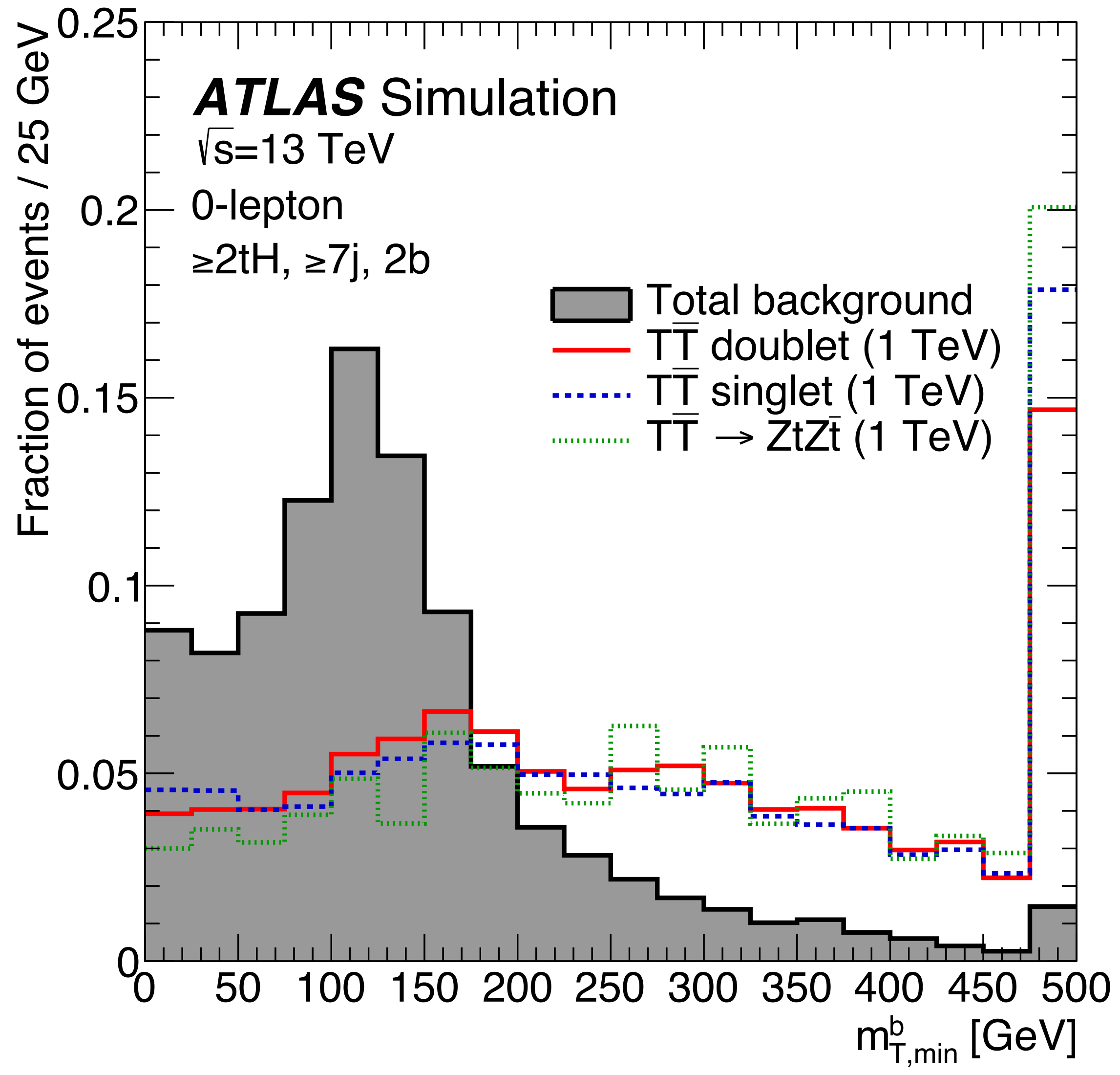


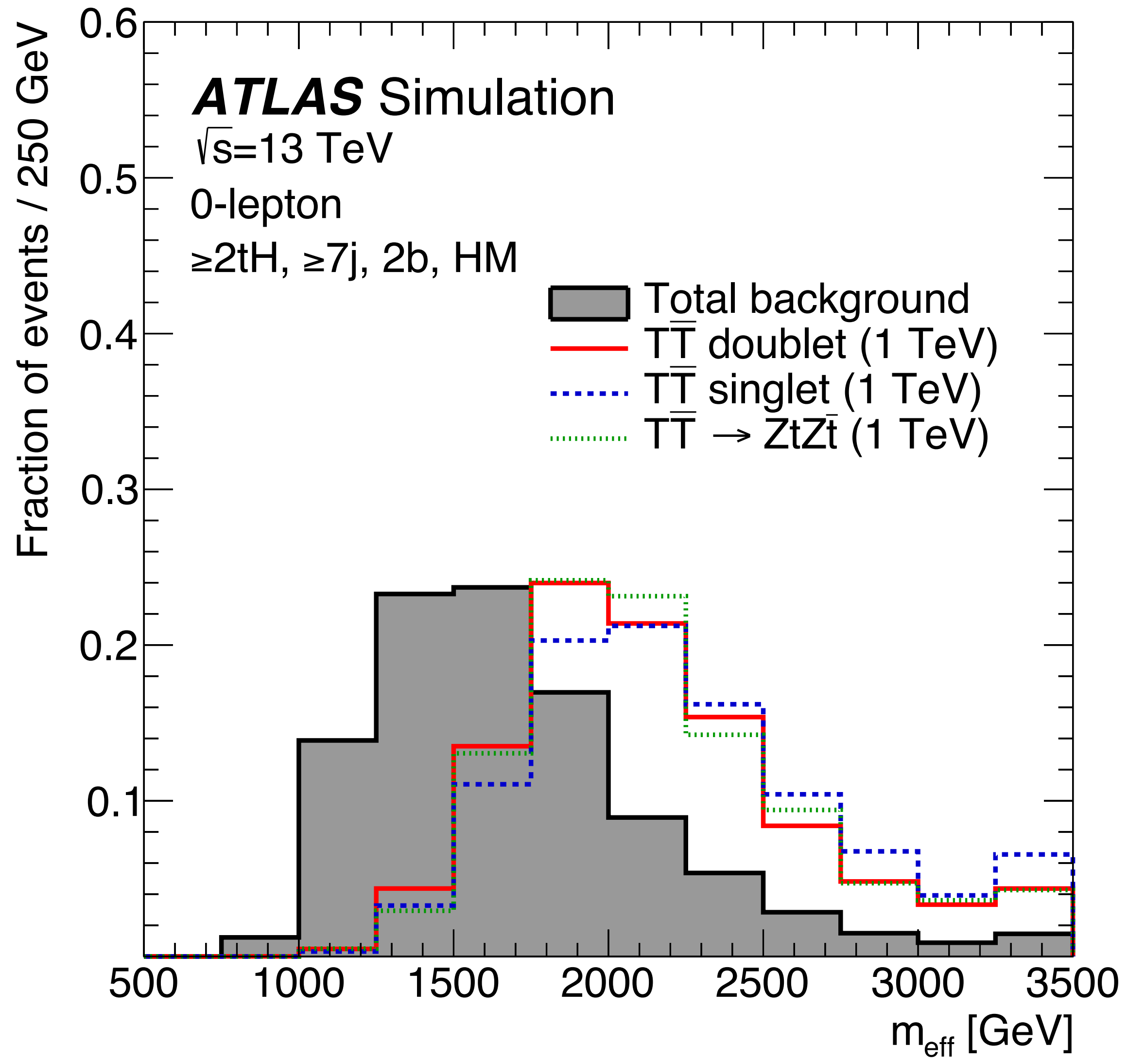












Ht+X — Search Regions (III)

arXiv:1803.09678 I submitted to JHEP

1-lepton channel				
Search regions (≥6 jets)				
N_t	N_H	b-tag multiplicity	m_eff	Channel name
0	0	3	>1 TeV	0t, 0H, ≥6j, 3b
0	0	≥4	>1 TeV	0t, 0H, ≥6j, ≥4b
1	0	3	>1 TeV	1t, 0H, ≥6j, 3b
1	0	≥4	>1 TeV	1t, 0H, ≥6j, ≥4b
0	1	3	>1 TeV	0t, 1H, ≥6j, 3b
0	1	≥4	>1 TeV	0t, 1H, ≥6j, ≥4b
1	1	3	–	1t, 1H, ≥6j, 3b
1	1	≥4	–	1t, 1H, ≥6j, ≥4b
≥2	0 or 1	3	–	≥2t, 0–1H, ≥6j, 3b
≥2	0 or 1	≥4	–	≥2t, 0–1H, ≥6j, ≥4b
≥0	≥2	3	–	≥0t, ≥2H, ≥6j, 3b
≥0	≥2	≥4	–	≥0t, ≥2H, ≥6j, ≥4b
Validation regions (5 jets)				
N_t	N_H	b-tag multiplicity	m_eff	Channel name
0	0	3	>1 TeV	0t, 0H, 5j, 3b
0	0	≥4	>1 TeV	0t, 0H, 5j, ≥4b
1	0	3	>1 TeV	1t, 0H, 5j, 3b
1	0	≥4	>1 TeV	1t, 0H, 5j, ≥4b
0	1	3	>1 TeV	0t, 1H, 5j, 3b
0	1	≥4	>1 TeV	0t, 1H, 5j, ≥4b
1	1	3	–	1t, 1H, 5j, 3b
≥2	0 or 1	3	–	≥2t, 0–1H, 5j, 3b
≥0	≥2	3	–	≥0t, ≥2H, 5j, 3b
$N_\mathrm{t}+N_\mathrm{H}\geq 2$		≥4	–	≥2tH, 5j, ≥4b

0-lepton channel					
Search regions (≥7 jets)					
N_t	N_H	b-tag multiplicity	$m^{\mathrm{b}}_{\mathrm{T,\,min}}$	m_eff	Channel name
0	0	2	>160 GeV	>1 TeV	0t, 0H, ≥7j, 2b, HM
0	0	3	<160 GeV	>1 TeV	0t, 0H, ≥7j, 3b, LM
0	0	3	>160 GeV	>1 TeV	0t, 0H, ≥7j, 3b, HM
0	0	≥4	<160 GeV	>1 TeV	0t, 0H, ≥7j, ≥4b, LM
0	0	≥4	>160 GeV	>1 TeV	0t, 0H, ≥7j, ≥4b, HM
1	0	2	>160 GeV	>1 TeV	1t, 0H, ≥7j, 2b, HM
1	0	3	<160 GeV	>1 TeV	1t, 0H, ≥7j, 3b, LM
1	0	3	>160 GeV	>1 TeV	1t, 0H, ≥7j, 3b, HM
1	0	≥4	<160 GeV	>1 TeV	1t, 0H, ≥7j, ≥4b, LM
1	0	≥4	>160 GeV	>1 TeV	1t, 0H, ≥7j, ≥4b, HM
0	1	2	>160 GeV	>1 TeV	0t, 1H, ≥7j, 2b, HM
0	1	3	<160 GeV	>1 TeV	0t, 1H, ≥7j, 3b, LM
0	1	3	>160 GeV	>1 TeV	0t, 1H, ≥7j, 3b, HM
0	1	≥4	<160 GeV	>1 TeV	0t, 1H, ≥7j, ≥4b, LM
0	1	≥4	>160 GeV	>1 TeV	0t, 1H, ≥7j, ≥4b, HM
1	1	3	<160 GeV	>1 TeV	1t, 1H, ≥7j, 3b, LM
1	1	3	>160 GeV	>1 TeV	1t, 1H, ≥7j, 3b, HM
≥2	0 or 1	3	<160 GeV	>1 TeV	≥2t, 0–1H, ≥7j, 3b, LM
≥2	0 or 1	3	>160 GeV	>1 TeV	≥2t, 0–1H, ≥7j, 3b, HM
≥0	≥2	3	–	>1 TeV	≥0t, ≥2H, ≥7j, 3b
$N_\mathrm{t}+N_\mathrm{H}\geq 2$		2	>160 GeV	>1 TeV	≥2tH, ≥7j, 2b, HM
$N_\mathrm{t}+N_\mathrm{H}\geq 2$		≥4	–	>1 TeV	≥2tH, ≥7j, ≥4b
Validation regions (6 jets)					
N_t	N_H	b-tag multiplicity	$m^{\mathrm{b}}_{\mathrm{T,\,min}}$	m_eff	Channel name
0	0	2	>160 GeV	>1 TeV	0t, 0H, 6j, 2b, HM
0	0	3	<160 GeV	>1 TeV	0t, 0H, 6j, 3b, LM
0	0	3	>160 GeV	>1 TeV	0t, 0H, 6j, 3b, HM
0	0	≥4	<160 GeV	>1 TeV	0t, 0H, 6j, ≥4b, LM
0	0	≥4	>160 GeV	>1 TeV	0t, 0H, 6j, ≥4b, HM
1	0	2	>160 GeV	>1 TeV	1t, 0H, 6j, 2b, HM
1	0	3	<160 GeV	>1 TeV	1t, 0H, 6j, 3b, LM
1	0	3	>160 GeV	>1 TeV	1t, 0H, 6j, 3b, HM
1	0	≥4	–	>1 TeV	1t, 0H, 6j, ≥4b
0	1	2	>160 GeV	>1 TeV	0t, 1H, 6j, 2b, HM
0	1	3	<160 GeV	>1 TeV	0t, 1H, 6j, 3b, LM
0	1	3	>160 GeV	>1 TeV	0t, 1H, 6j, 3b, HM
0	1	≥4	–	>1 TeV	0t, 1H, 6j, ≥4b
$N_\mathrm{t}+N_\mathrm{H}\geq 2$		2	>160 GeV	>1 TeV	≥2tH, 6j, 2b, HM
$N_\mathrm{t}+N_\mathrm{H}\geq 2$		3	–	>1 TeV	≥2tH, 6j, 3b
$N_\mathrm{t}+N_\mathrm{H}\geq 2$		≥4	–	>1 TeV	≥2tH, 6j, ≥4b

Ht+X — Search Regions (III)

pre-fit

1-lepton channel	≥2t, 0–1H, ≥6j, 3b	1t, 0H, ≥6j, ≥4b	1t, 1H, ≥6j, ≥4b	≥2t, 0–1H, ≥6j, ≥4b	≥0t, ≥2H, ≥6j, ≥4b
$T\bar{T}$ ($m_T = 1$ TeV)					
$\mathcal{B}(T \to Ht) = 1$	19.6 ± 1.5	21.5 ± 2.6	24.3 ± 2.7	23.9 ± 2.8	14.6 ± 2.0
T doublet	14.2 ± 1.0	15.2 ± 1.6	12.5 ± 1.4	13.3 ± 1.5	5.96 ± 0.62
T singlet	7.88 ± 0.58	8.13 ± 0.94	5.47 ± 0.62	5.51 ± 0.69	2.18 ± 0.23
$t\bar{t}t\bar{t}$					
EFT ($\lvert C_{4t}\rvert/\Lambda^2 = 4\pi$ TeV^{-2})	535 ± 30	706 ± 80	171 ± 19	468 ± 55	34.3 ± 5.0
2UED/RPP ($m_{\mathrm{KK}} = 1.6$ TeV)	9.77 ± 0.46	1.84 ± 0.35	1.00 ± 0.19	8.9 ± 1.4	0.39 ± 0.09
$t\bar{t}$+light-jets	91 ± 46	38 ± 17	4.8 ± 2.4	5.4 ± 3.3	0.99 ± 0.49
$t\bar{t}$+≥1c	75 ± 45	64 ± 38	9.5 ± 5.6	11.8 ± 7.5	2.1 ± 1.3
$t\bar{t}$+≥1b	86 ± 41	215 ± 83	32.4 ± 9.5	42 ± 22	7.1 ± 2.2
$t\bar{t}V$	9.7 ± 1.8	11.4 ± 2.4	1.73 ± 0.39	2.46 ± 0.53	0.41 ± 0.10
$t\bar{t}H$	4.90 ± 0.78	15.0 ± 2.8	3.79 ± 0.65	2.84 ± 0.62	1.19 ± 0.20
W+jets	9.4 ± 4.4	8.2 ± 4.2	0.69 ± 0.50	1.32 ± 0.71	0.54 ± 0.48
Z+jets	1.31 ± 0.64	0.95 ± 0.48	0.10 ± 0.07	0.13 ± 0.08	0.06 ± 0.05
Single top	13.1 ± 5.5	16.6 ± 7.0	1.69 ± 0.76	1.97 ± 0.95	0.26 ± 0.21
Diboson	1.8 ± 1.1	0.99 ± 0.55	0.11 ± 0.09	0.22 ± 0.14	0.01 ± 0.04
$t\bar{t}t\bar{t}$ (SM)	2.82 ± 0.86	4.9 ± 1.6	1.12 ± 0.36	2.55 ± 0.82	0.23 ± 0.07
Total background	299 ± 83	380 ± 110	56 ± 13	71 ± 25	12.9 ± 3.2
Data	353	428	60	78	18

0-lepton channel	≥2tH, ≥7j, 2b, HM	1t, 1H, ≥7j, 3b, HM	≥2t, 0–1H, ≥7j, 3b, HM	1t, 0H, ≥7j, ≥4b, HM	≥2tH, ≥7j, ≥4b
$T\bar{T}$ ($m_T = 1$ TeV)					
$\mathcal{B}(T \to Zt) = 1$	22.3 ± 2.3	2.60 ± 0.57	6.02 ± 0.61	4.72 ± 0.66	6.94 ± 0.98
T doublet	16.0 ± 1.1	4.22 ± 0.34	5.92 ± 0.49	5.32 ± 0.61	18.7 ± 2.0
T singlet	8.52 ± 0.61	1.81 ± 0.16	2.63 ± 0.22	2.32 ± 0.29	6.91 ± 0.80
$t\bar{t}$+light-jets	17.8 ± 9.8	0.72 ± 0.40	0.80 ± 0.53	1.30 ± 0.72	1.71 ± 0.98
$t\bar{t}$+≥1c	9.7 ± 6.4	0.92 ± 0.65	0.95 ± 0.71	2.4 ± 1.6	3.2 ± 2.0
$t\bar{t}$+≥1b	6.3 ± 4.2	1.17 ± 0.59	1.78 ± 0.74	9.4 ± 3.2	11.4 ± 4.1
$t\bar{t}V$	5.5 ± 1.0	0.49 ± 0.12	0.88 ± 0.19	1.19 ± 0.27	1.01 ± 0.24
$t\bar{t}H$	0.61 ± 0.12	0.17 ± 0.05	0.13 ± 0.04	0.85 ± 0.17	1.08 ± 0.25
W+jets	9.6 ± 4.1	0.52 ± 0.27	0.80 ± 0.37	0.81 ± 0.40	0.56 ± 0.28
Z+jets	8.6 ± 4.5	0.59 ± 0.28	0.8 ± 2.1	0.80 ± 0.40	0.63 ± 0.42
Single top	8.3 ± 4.4	0.69 ± 0.43	0.97 ± 0.59	1.8 ± 1.0	1.10 ± 0.61
Diboson	2.9 ± 1.9	0.11 ± 0.20	0.55 ± 0.66	0.24 ± 0.25	0.14 ± 0.15
$t\bar{t}t\bar{t}$ (SM)	0.22 ± 0.07	0.06 ± 0.02	0.12 ± 0.04	0.31 ± 0.10	0.77 ± 0.25
Multijet	3.9 ± 3.9	0.13 ± 0.17	0.20 ± 0.24	0.64 ± 0.68	2.8 ± 2.8
Total background	73 ± 19	5.6 ± 1.4	8.0 ± 3.7	19.7 ± 5.0	24.4 ± 6.3
Data	87	8	7	18	29

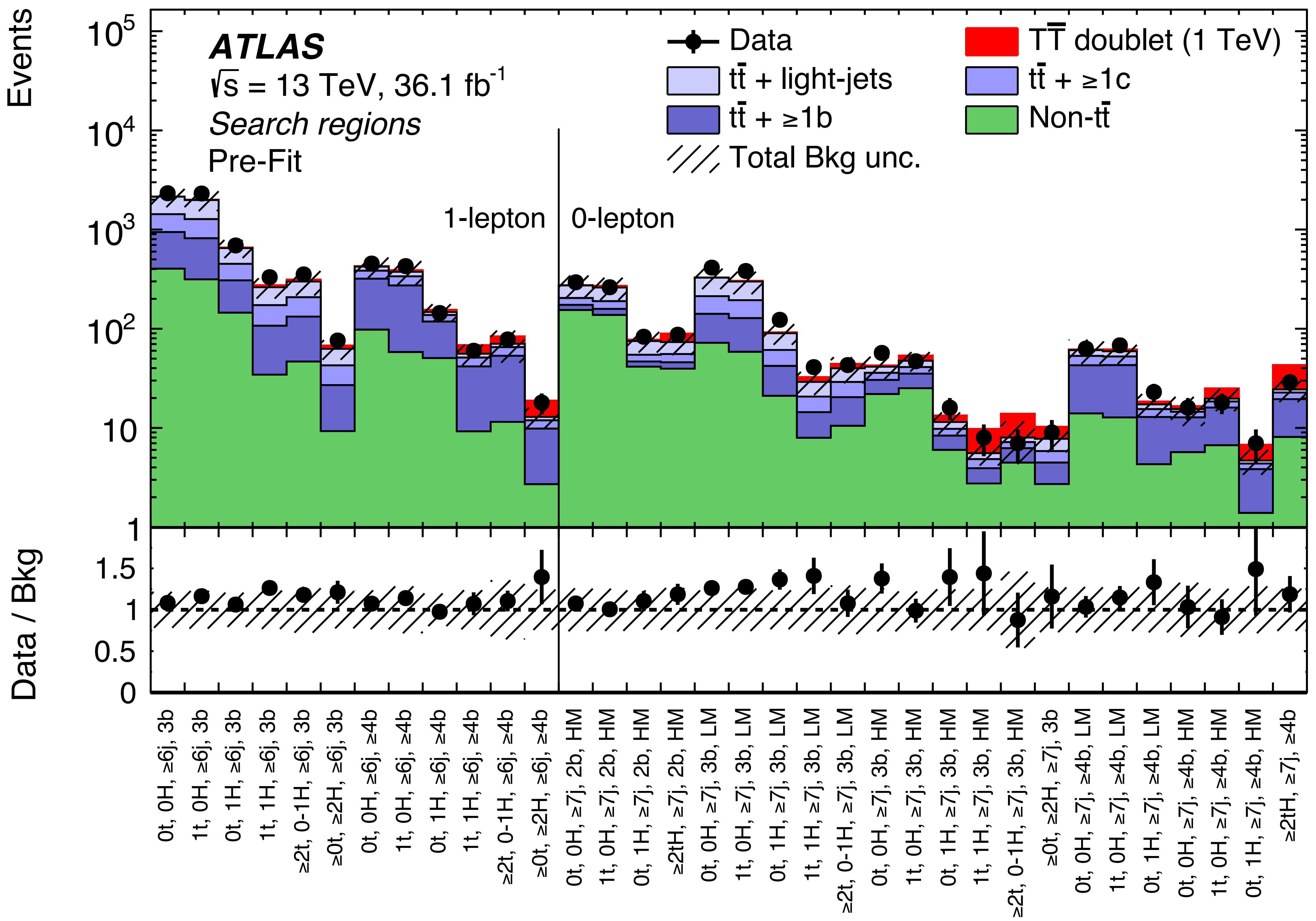
post-fit

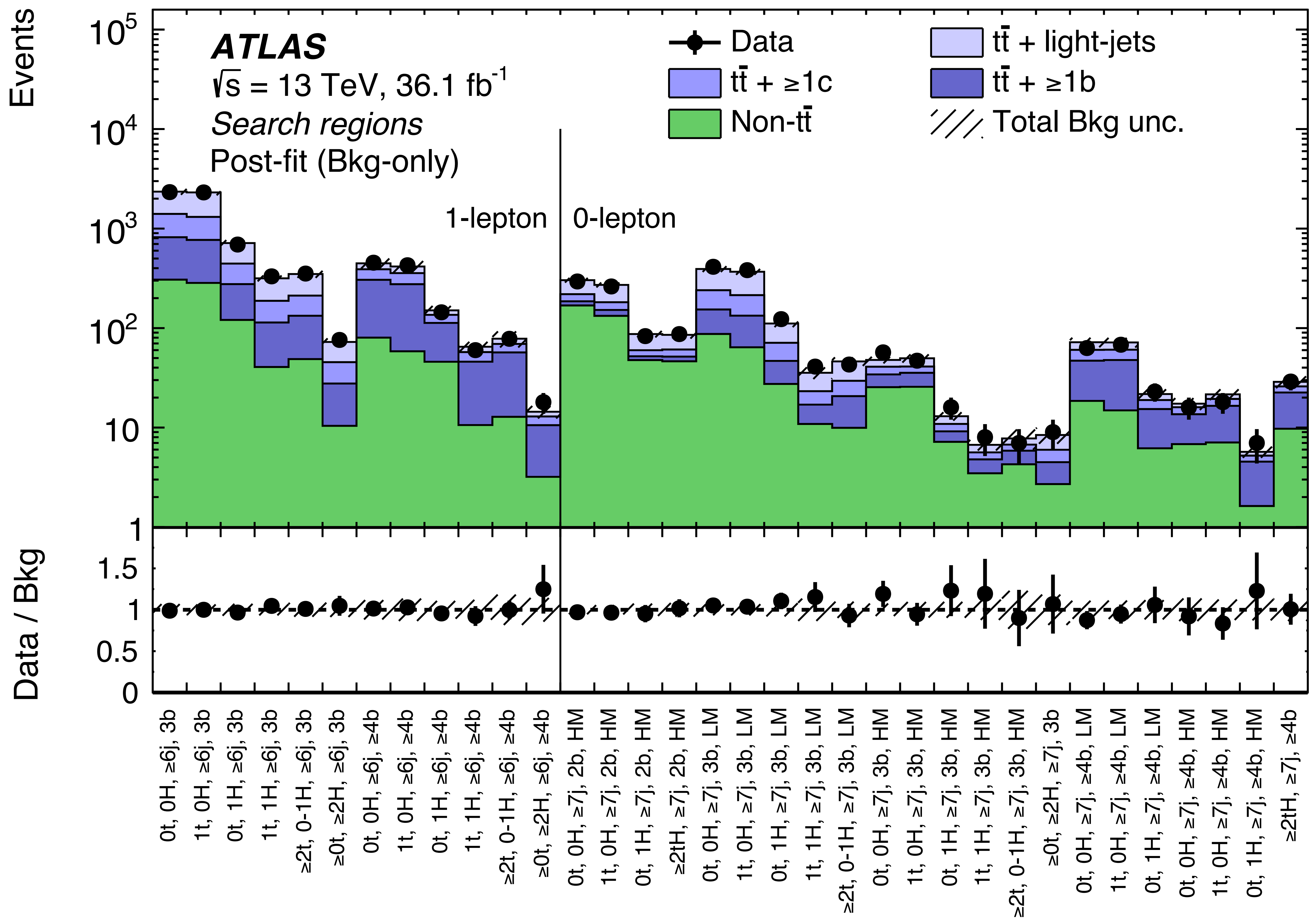
1-lepton channel	≥2t, 0–1H, ≥6j, 3b	1t, 0H, ≥6j, ≥4b	1t, 1H, ≥6j, ≥4b	≥2t, 0–1H, ≥6j, ≥4b	≥0t, ≥2H, ≥6j, ≥4b
$t\bar{t}$+light-jets	137 ± 24	59 ± 11	7.6 ± 1.6	9.0 ± 2.0	1.50 ± 0.34
$t\bar{t}$+≥1c	79 ± 34	81 ± 26	11.4 ± 3.8	12.4 ± 5.1	2.36 ± 0.84
$t\bar{t}$+≥1b	84 ± 20	217 ± 27	35.3 ± 5.6	44.1 ± 9.1	7.4 ± 1.2
$t\bar{t}V$	10.7 ± 1.6	13.2 ± 2.1	2.12 ± 0.34	2.82 ± 0.46	0.50 ± 0.08
$t\bar{t}H$	5.26 ± 0.61	17.4 ± 2.3	4.28 ± 0.56	3.25 ± 0.46	1.33 ± 0.17
W+jets	11.4 ± 4.0	9.5 ± 3.4	0.71 ± 0.36	1.68 ± 0.59	0.78 ± 0.31
Z+jets	1.56 ± 0.55	1.11 ± 0.41	0.08 ± 0.06	0.16 ± 0.06	0.07 ± 0.04
Single top	11.3 ± 5.6	10.8 ± 6.2	2.01 ± 0.62	1.85 ± 0.90	0.24 ± 0.15
Diboson	2.20 ± 0.91	1.10 ± 0.50	0.20 ± 0.08	0.30 ± 0.12	0.03 ± 0.07
$t\bar{t}t\bar{t}$ (SM)	2.83 ± 0.84	5.3 ± 1.5	1.20 ± 0.35	2.74 ± 0.79	0.24 ± 0.07
Total background	349 ± 20	416 ± 18	64.9 ± 4.7	78.2 ± 8.0	14.4 ± 1.2
Data	353	428	60	78	18

0-lepton channel	≥2tH, ≥7j, 2b, HM	1t, 1H, ≥7j, 3b, HM	≥2t, 0–1H, ≥7j, 3b, HM	1t, 0H, ≥7j, ≥4b, HM	≥2tH, ≥7j, ≥4b
$t\bar{t}$+light-jets	24.7 ± 5.0	1.08 ± 0.20	1.04 ± 0.25	2.20 ± 0.43	2.91 ± 0.57
$t\bar{t}$+≥1c	9.2 ± 4.9	0.85 ± 0.44	0.89 ± 0.48	2.9 ± 1.1	3.4 ± 1.4
$t\bar{t}$+≥1b	5.3 ± 1.9	1.31 ± 0.39	1.58 ± 0.55	9.4 ± 1.3	12.8 ± 2.4
$t\bar{t}V$	5.96 ± 0.88	0.59 ± 0.09	1.00 ± 0.15	1.46 ± 0.23	1.25 ± 0.19
$t\bar{t}H$	0.61 ± 0.08	0.19 ± 0.03	0.13 ± 0.02	1.02 ± 0.13	1.16 ± 0.17
W+jets	12.0 ± 3.2	0.63 ± 0.22	0.92 ± 0.34	0.71 ± 0.27	0.86 ± 0.22
Z+jets	10.6 ± 3.1	0.69 ± 0.26	0.4 ± 1.3	0.65 ± 0.29	0.94 ± 0.29
Single top	8.9 ± 3.2	0.77 ± 0.36	0.95 ± 0.48	1.84 ± 0.82	1.17 ± 0.47
Diboson	3.9 ± 1.6	0.41 ± 0.39	0.53 ± 0.44	0.37 ± 0.15	0.23 ± 0.10
$t\bar{t}t\bar{t}$ (SM)	0.20 ± 0.07	0.05 ± 0.02	0.12 ± 0.04	0.36 ± 0.10	0.87 ± 0.24
Multijet	4.1 ± 3.7	0.14 ± 0.13	0.18 ± 0.19	0.67 ± 0.62	3.3 ± 2.6
Total background	85.5 ± 6.8	6.70 ± 0.75	7.8 ± 1.7	21.6 ± 1.4	28.8 ± 3.1
Data	87	8	7	18	29

Ht+X — Search Regions (IV)

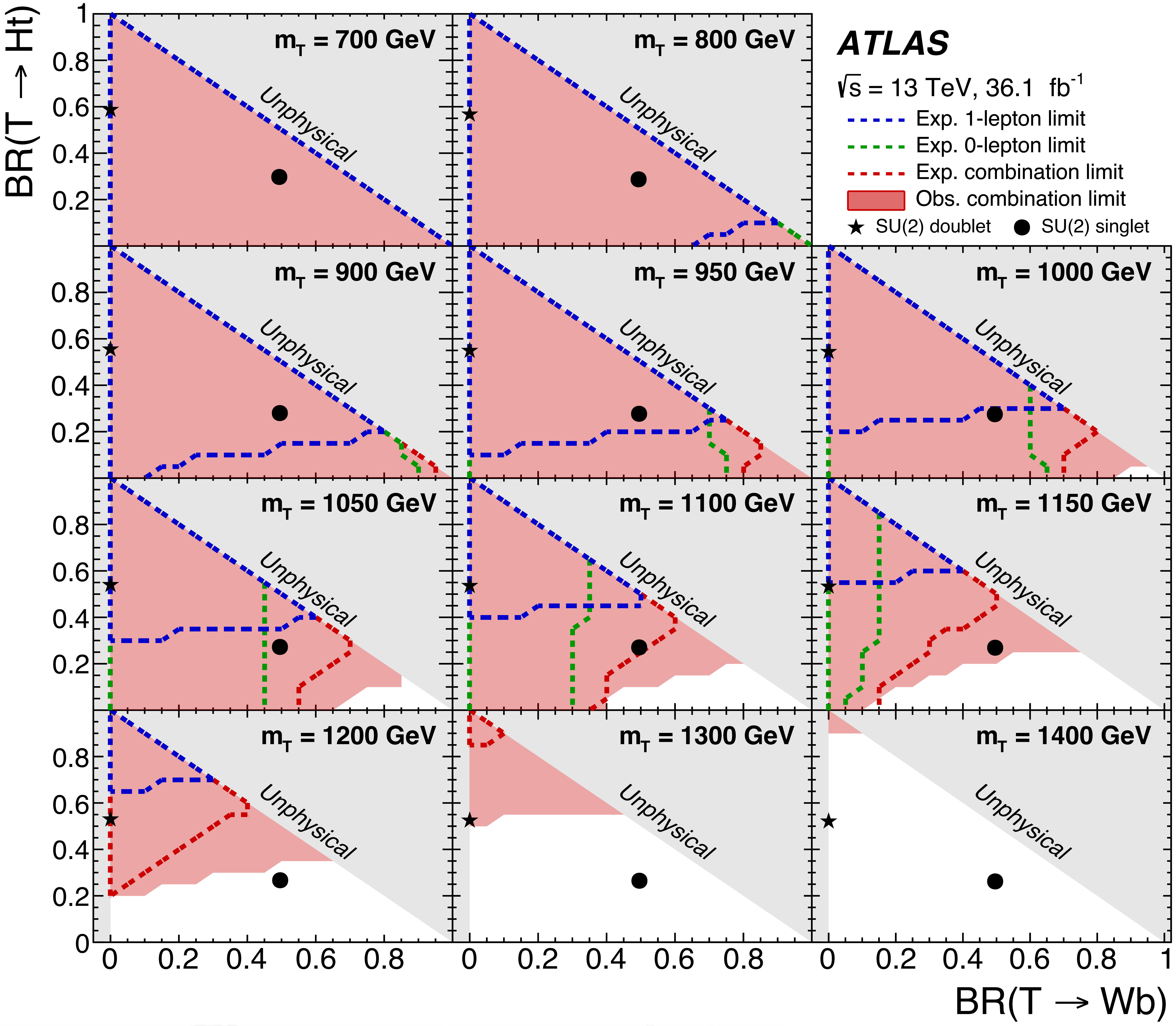
arXiv:1803.09678 | submitted to JHEP





Ht+X — Limits (V)

arXiv:1803.09678 | submitted to JHEP



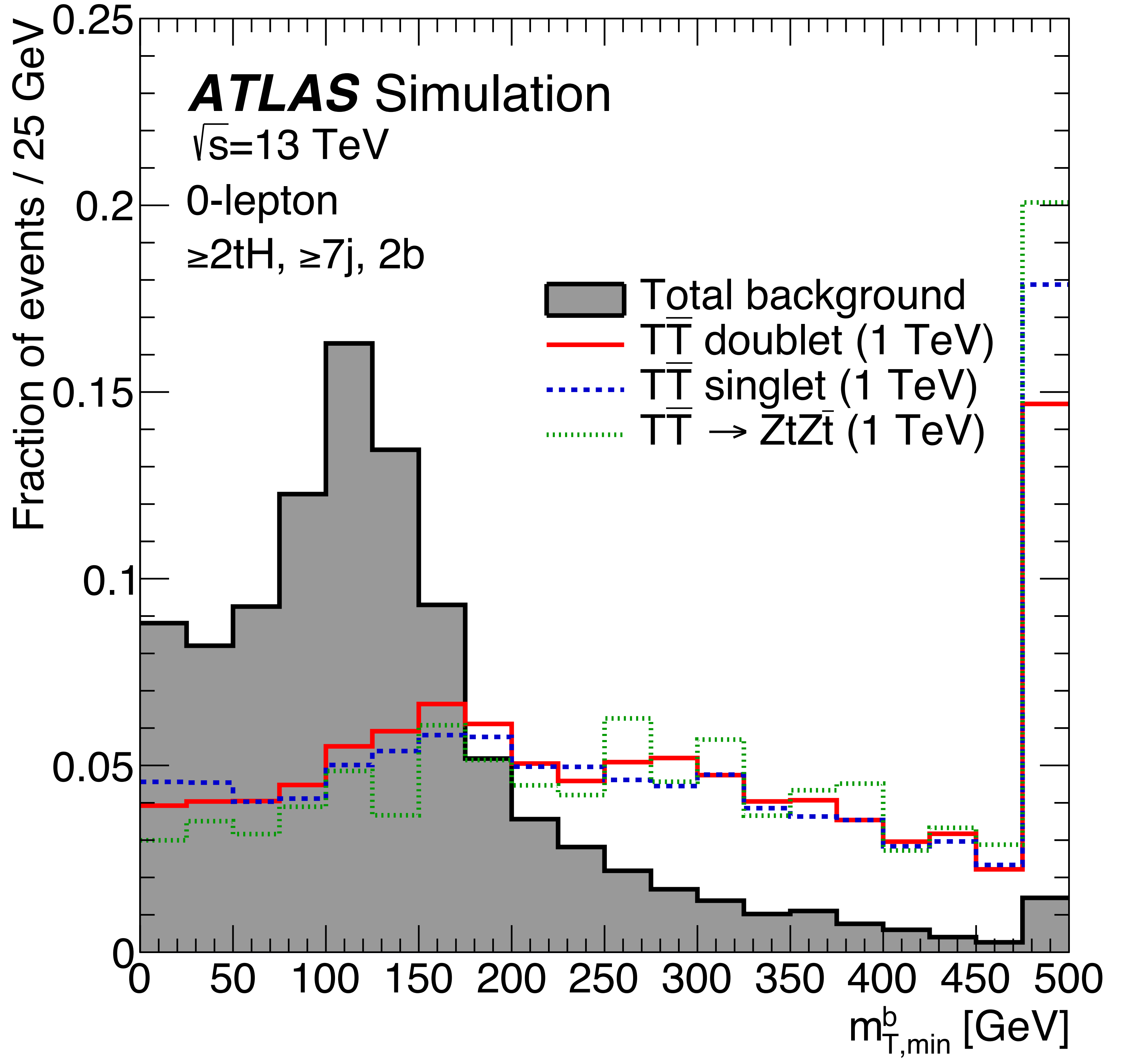
95% CL lower limits on T quark mass [TeV]				
Search	$\mathcal{B}(T \to Ht) = 1$	$\mathcal{B}(T \to Zt) = 1$	Doublet	Singlet
1-lepton channel	1.47 (1.30)	1.12 (0.91)	1.36 (1.16)	1.23 (1.02)
0-lepton channel	1.11 (1.20)	1.12 (1.17)	1.12 (1.19)	0.99 (1.05)
Combination	1.43 (1.34)	1.17 (1.18)	1.31 (1.26)	1.19 (1.11)
Previous Run-1 ATLAS $T\bar{T} \to Ht$+X search [25]				
1-lepton channel	0.95 (0.88)	0.75 (0.69)	0.86 (0.82)	0.76 (0.72)

Kinematic Variable Definitions

- Zt+X
  - m_T^W: transverse mass of leptonic W $m_T^W = \sqrt{2p_T^{lep} E_T^{miss}[1-\cos(\Delta\phi)]}$
  - am_{T2} : transverse mass with two invsible particle $m_{T2} \equiv \min_{\vec{q}_{Ta}+\vec{q}_{Tb}=\vec{E}_T^{miss}} \{\max(m_{Ta}, m_{Tb})\}$
    - a,b = lepton, two b-jets with highest weight
  - $H_{T,sig}^{miss}$: significance of H_t^{miss} $H_{T,sig}^{miss} \equiv (H_T^{miss} - 100\,\text{GeV})/\sigma_{H_T^{miss}}$ (used to reduce events w/ mis-reconstructed E_T^{miss})
    - H_T^{miss} : magnitude of vectorial sum of jets and lepton p_T
- Ht+X
  - M_{eff} : scalar sum of jet & lepton p_T and MET
  - M_{bb} : 1 lep - minΔR (bjet,bjet)
  - $m_{T,min}^b$: 0 lep - leading 3-bjets and MET

$m_{T,\,min}^{b}$, the minimum transverse mass of E_T^{miss} and any of the three (or two, in events with exactly two b-tagged jets) leading b-tagged jets in the event

- Wb+X
  - m_T^{lep} : Full $T\bar{T}$(W,b,lep,MET,b) reconstruction minimizing $|\Delta m_T|$
  - S_T : scalar sum of jet & lepton p_T and MET
- SS lepton
  - H_T : scalar sum of jet & lepton p_T
- Single VLQ
  - M_{VLQ} : Reconstruct Q(b,lep,MET)



$m^{\mathrm{b}}_{\mathrm{T,\,min}}$, the minimum transverse mass of $E_{\mathrm{T}}^{\mathrm{miss}}$ and any of the three (or two, in events with exactly two b-tagged jets) leading b-tagged jets in the event

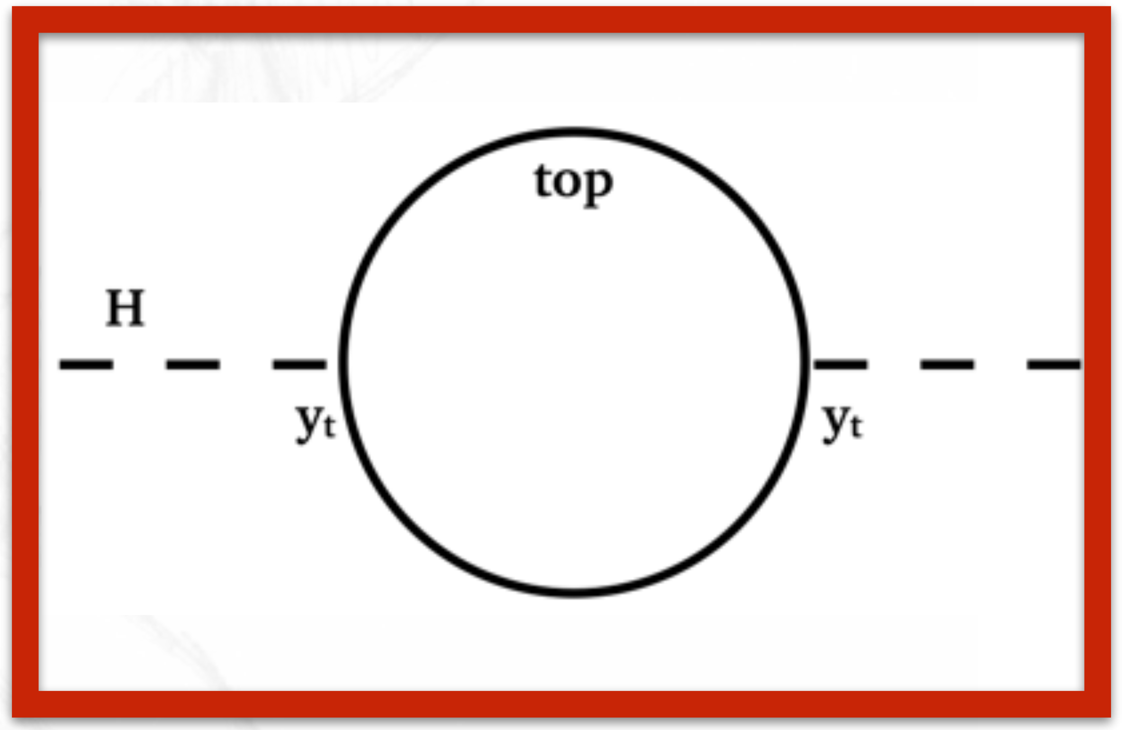
Λ: new physics scale

If SM describes nature up to say $\Lambda \sim M_{Planck}$

- Then, **divergent radiative corrections Δm_H^2** to bare Higgs mass suggest:

$$(m_H)_{bare}^2 \sim 10^{32}\ \text{GeV}$$ (appears 'unnatural')

Dominant radiative corrections
stem from **top-quark** loops



Assume Λ~10 TeV: $\Delta m_H^2 \sim -(2\ \text{TeV})^2$

Big Hierarchy Problem

Λ: new physics scale

If SM describes nature up to say $\Lambda \sim M_{Planck}$

- Then, **divergent radiative corrections Δm_H^2** to bare Higgs mass suggest:

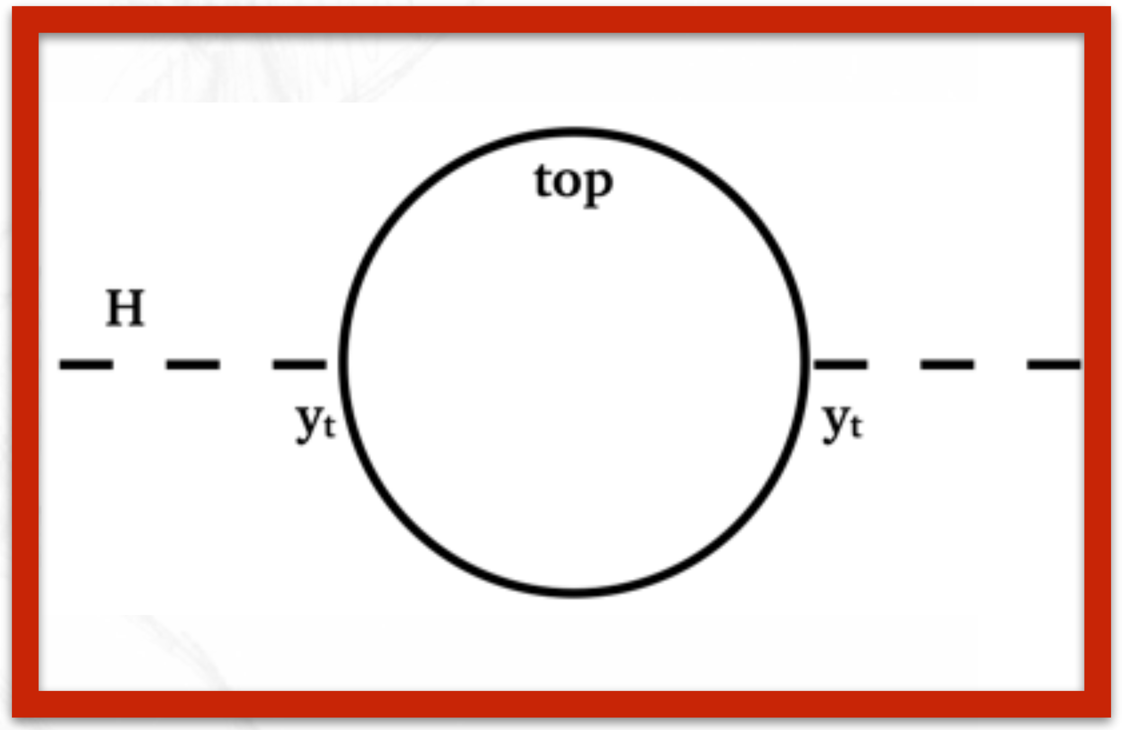
$$(m_H)_{bare}^2 \sim 10^{32}\ \text{GeV}$$ (appears 'unnatural')

Solve:

A. If SM is only effective theory at low energy scales up to say Λ~TeV

- $\Delta m_H^2 \sim O((m_H)_{bare}^2)$, i.e. amount of necessary fine-tuning needed in SM is O(few %)

Dominant radiative corrections
stem from **top-quark** loops



Assume Λ~10 TeV: **Δm_H^2**$\sim -(2\ \text{TeV})^2$

Λ: new physics scale

If SM describes nature up to say $\Lambda \sim M_{Planck}$

- Then, **divergent radiative corrections Δm_H^2** to bare Higgs mass suggest:

$$(m_H)_{bare}^2 \sim 10^{32}\ \text{GeV}$$ (appears 'unnatural')

Solve:

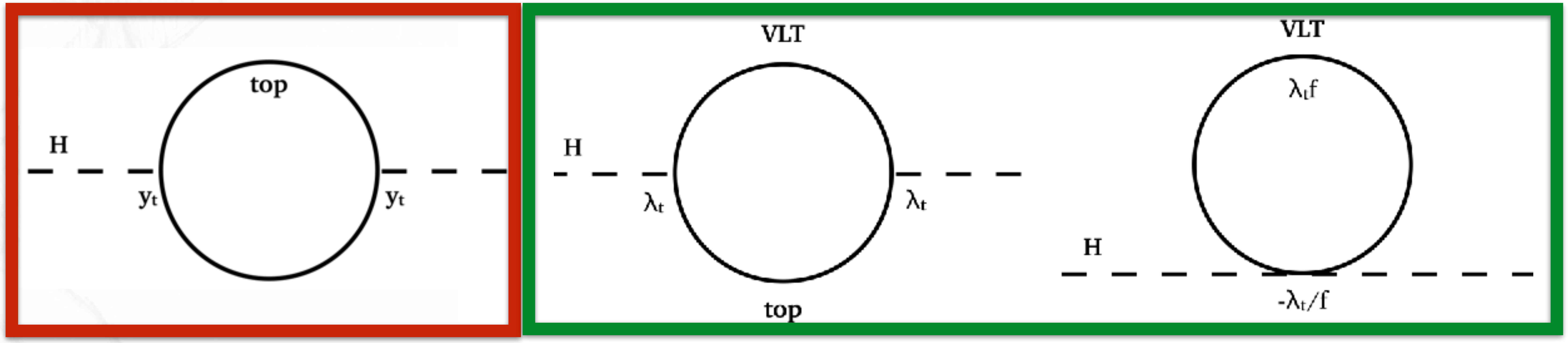
A. If SM is only effective theory at low energy scales up to say Λ~TeV

- $\Delta m_H^2 \sim O((m_H)_{bare}^2)$, i.e. amount of necessary fine-tuning needed in SM is O(few %)

B. Add **new particles** that lead to cancelation of Δm_H^2

Dominant radiative corrections stem from **top-quark** loops

Cancelation through **new particles** of **dominant** corrections to Higgs mass



Assume Λ~10 TeV: **Δm_H^2**~ —(2 TeV)²   **δm_H^2**~ +(2 TeV)²

Comment: Magnitude of cancelation depends on mass of new particles