Wine & Cheese Seminar
October 27, 2017

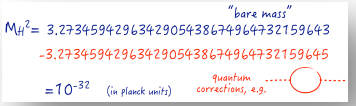
Fermilab
50 Years of Discovery

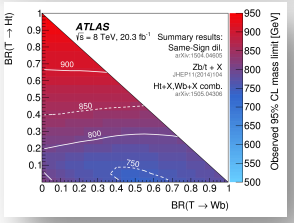
Searches for Vector-Like Quarks with ATLAS

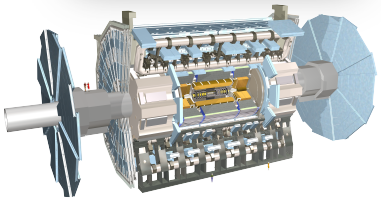
Joseph Haley
Oklahoma State University

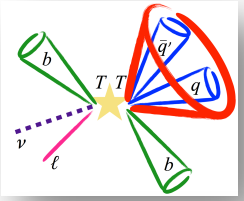
Supported by funding from the US Department of Energy

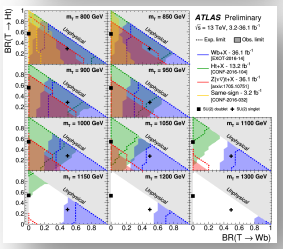
Outline











Vector-like quarks
- What are they?
- Why should you care?

General Search Strategy
- What will they look like?
- Run 1 Limits

ATLAS
- Particle Identification
- Simulated data

The Analyses
- $TT \rightarrow Ht+X$
- $TT \rightarrow Zt+X$
- $TT \rightarrow Wb+X$

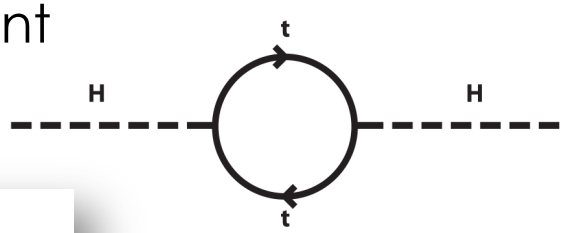
Results!

Conclusions

Hierarchy Problem

In the SM, Higgs mass is quadratically divergent

- Assuming no new physics until the Planck scale



"bare mass"

$$M_H^2 = 3.27345942963429054386749647321596 43$$

$$-3.27345942963429054386749647321596 45$$

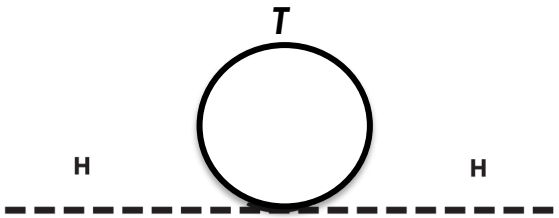
$$= 10^{-32}$$ (in planck units)

quantum corrections, e.g.

from Roni Harnik

This can be *naturally* cancelled by VLQs!

- Adding a ~400 GeV vector-like top (*T*):



$$M_H^2 \sim 10 - 9 = 1$$ (in units of ~100 GeV squared)

VLQs show up in many BSM scenarios

- Little/Composite Higgs, Topcolor, GUTs, …
- **Naturalness requires mass ~1 TeV ⇒ Accessible at the LHC!**

Vector-like Quarks (VLQs)

Colored, spin-½ particles ⇒ "Quarks"

Both chiralities transform the same under SM gauge groups ⇒ "Vector-like"

VLQ current $(\bar{Q}\gamma^\mu Q')$

SM V-A current $(\bar{q}\gamma^\mu(1-\gamma^5)q')$

Can have bare VLQ mass term

- Avoids constraints from Higgs measurements

Couple to SM through mixing with SM quarks

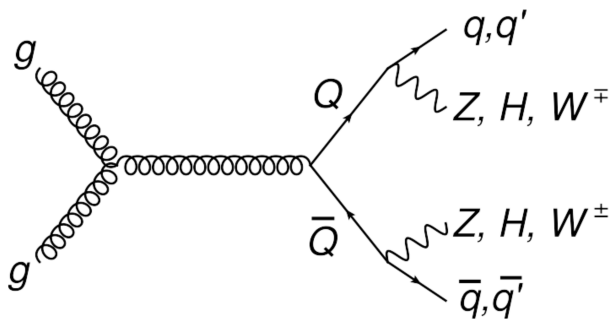
- Naturalness + FCNC constraints ⇒ mixing mostly with 3rd generation

	Q[e]	VLQs singlets	doublets			triplets	
	$5/3$		$\begin{pmatrix} X \\ T \end{pmatrix}$			$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$	
Top-partner →	$2/3$	(T)		$\begin{pmatrix} T \\ B \end{pmatrix}$			$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
Bottom-partner →	$-1/3$	(B)			$\begin{pmatrix} B \\ Y \end{pmatrix}$		
	$-4/3$						

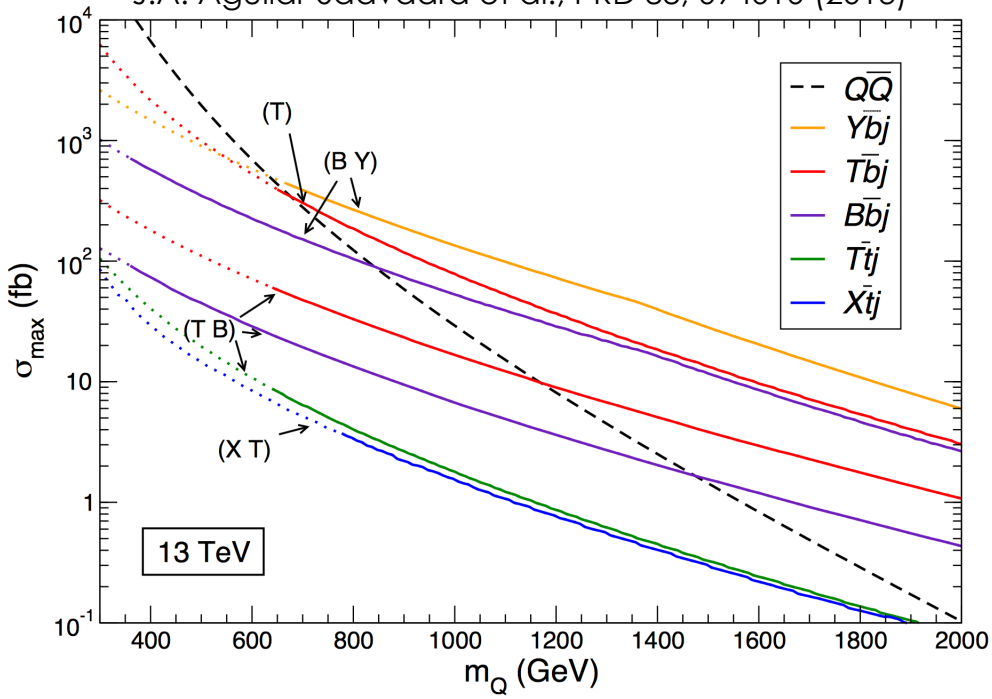
What will they look like?

Pair Production via QCD

- Depends only on mass
  ⇒ ~Model-independent

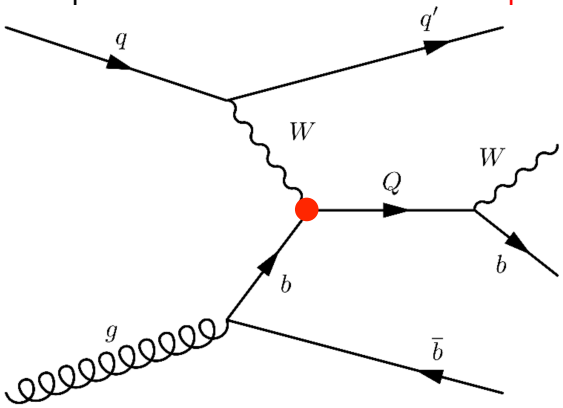


J.A. Aguilar-Saavadra et al., PRD 88, 094010 (2013)



Single production via EW boson

- Depends on mass and coupling



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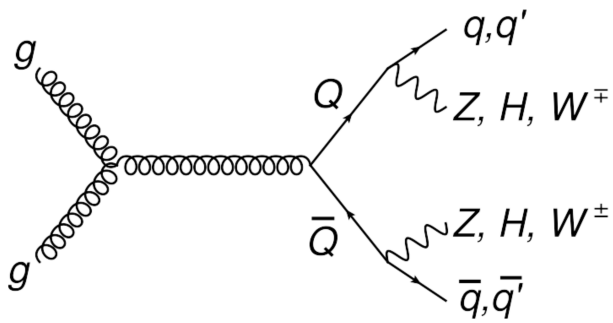

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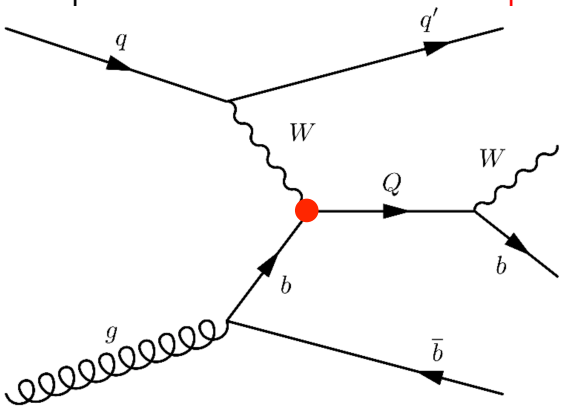
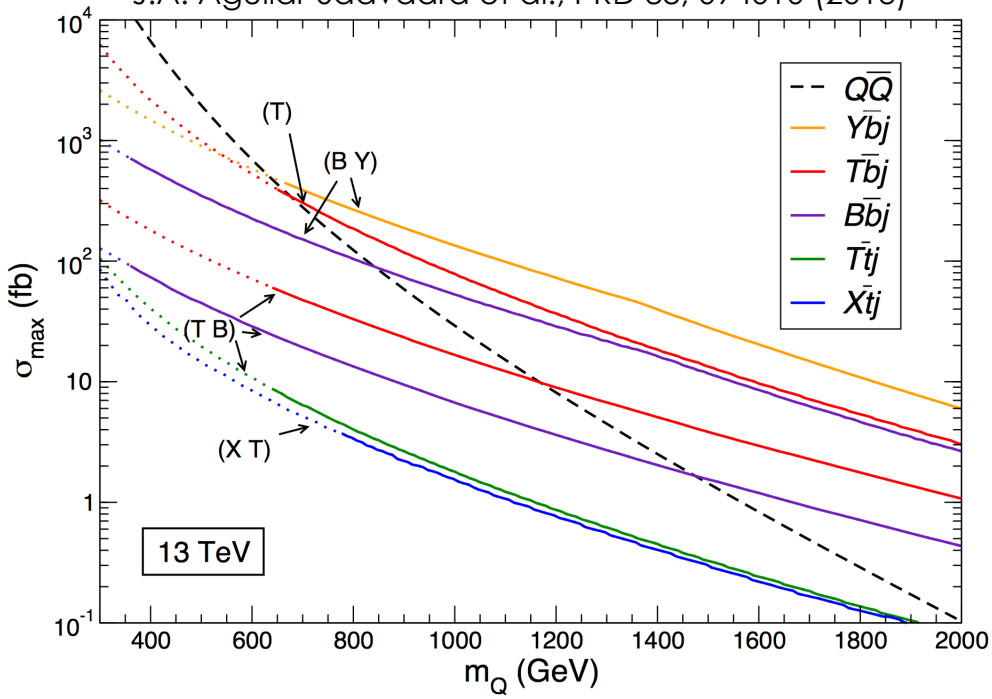


Still most sensitive & more recent results

J.A. Aguilar-Saavadra et al., PRD 88, 094010 (2013)



What will they look like?

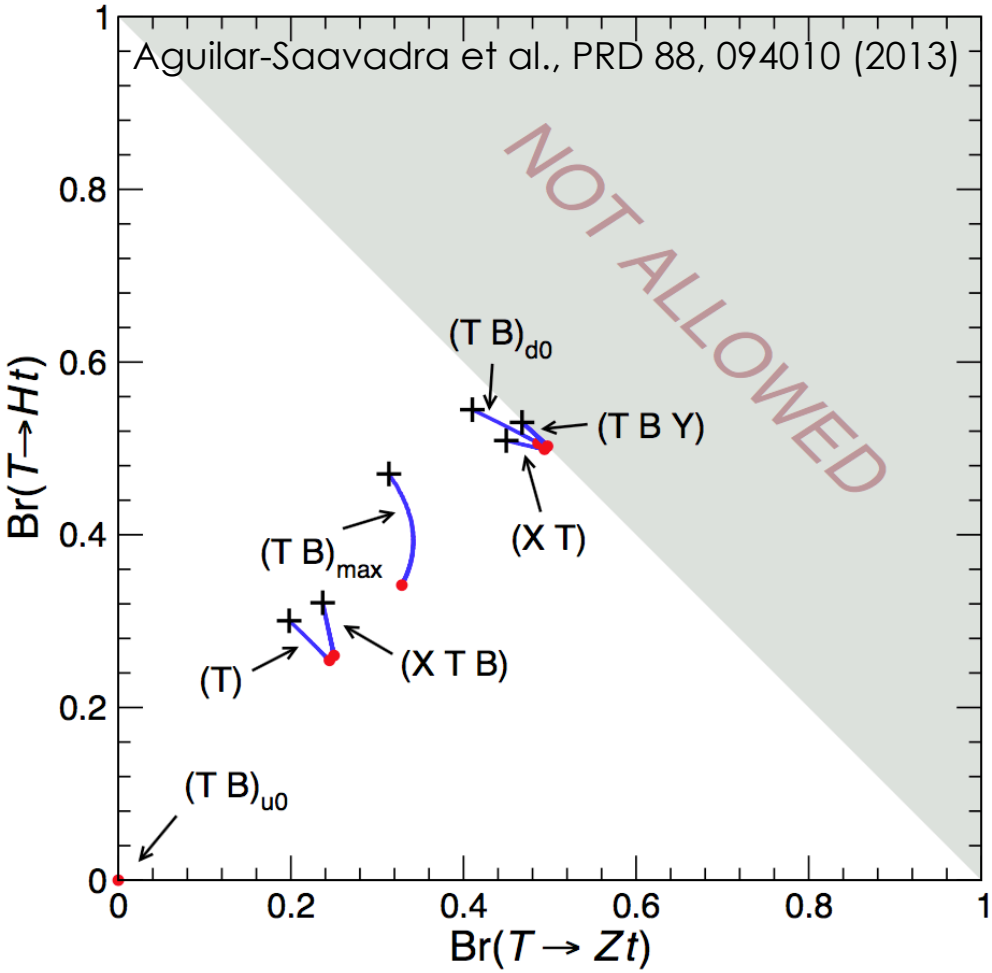
Possible decays dictated by quantum numbers

- $T \rightarrow Wb, Zt, Ht$
- $B \rightarrow Wt, Zb, Hb$

⇒ Rich phenomenology!

Branching ratios are model-dependent

- Constrained in some scenarios



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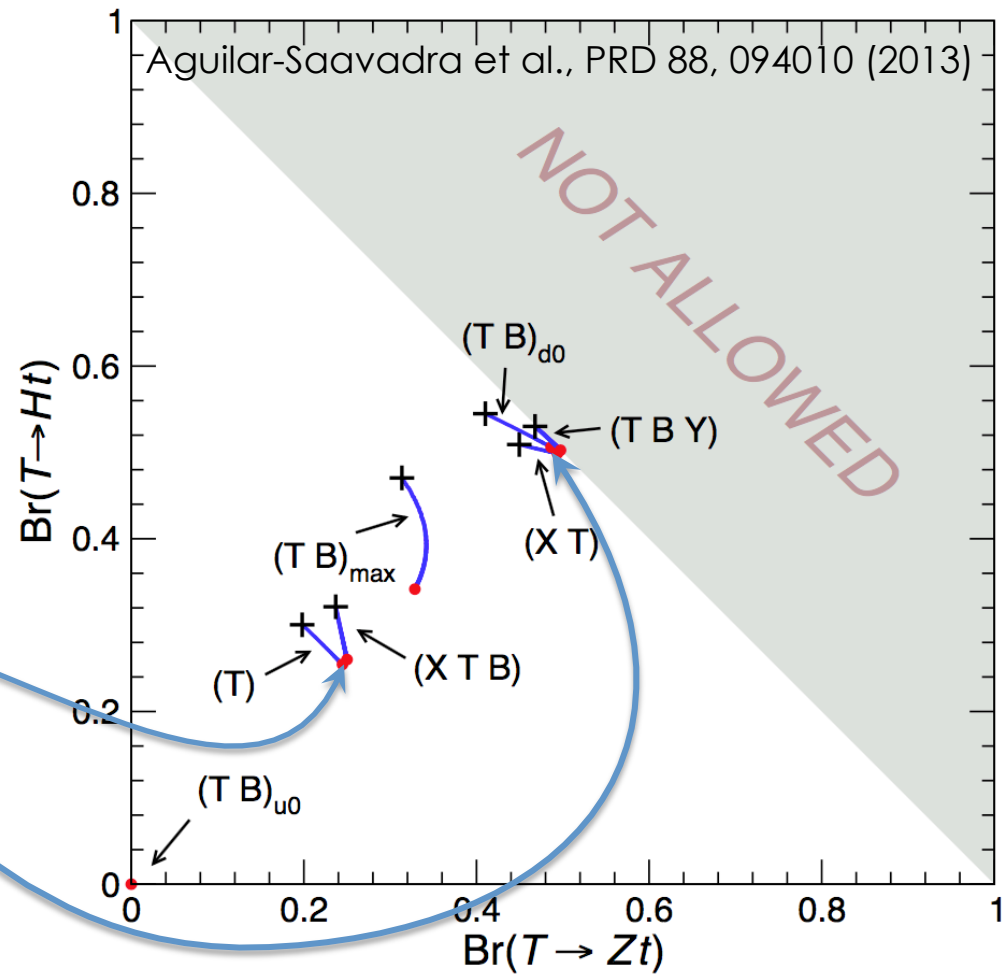
  - "Singlet" scenario
  - "Doublet" scenario (assuming mixing only in up sector)



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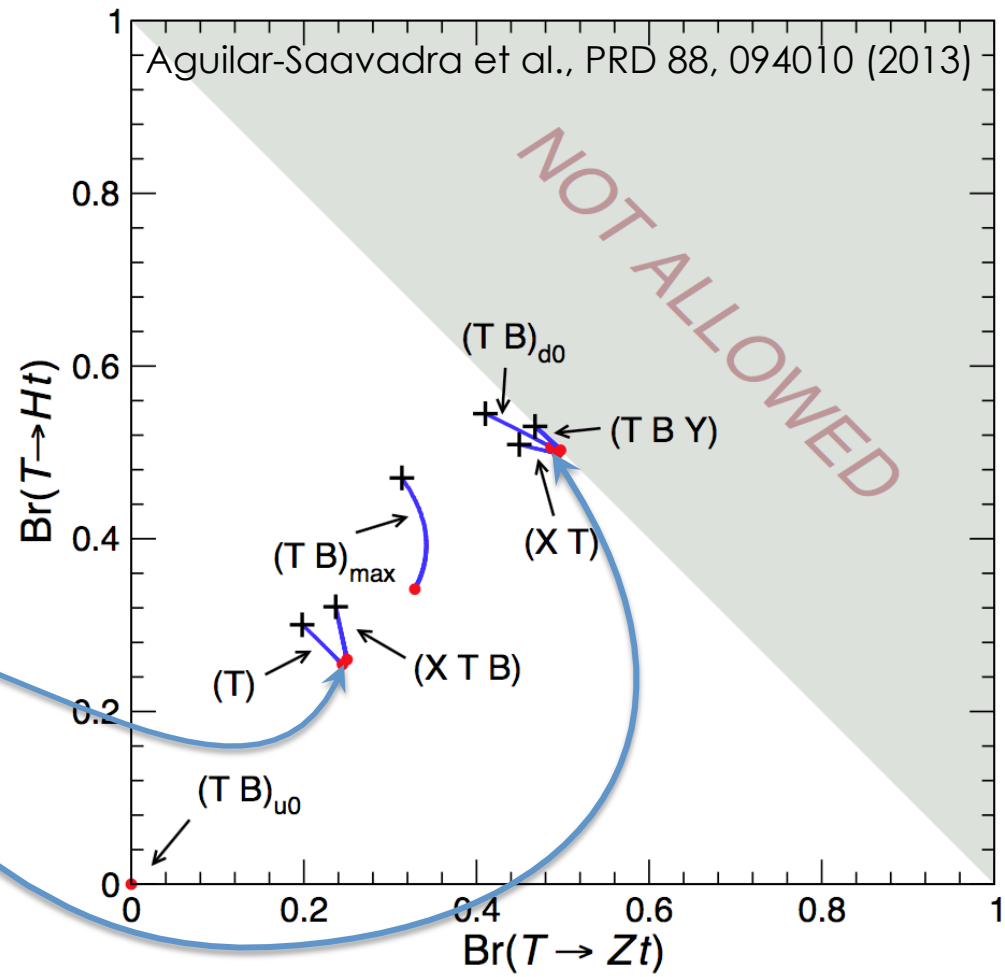
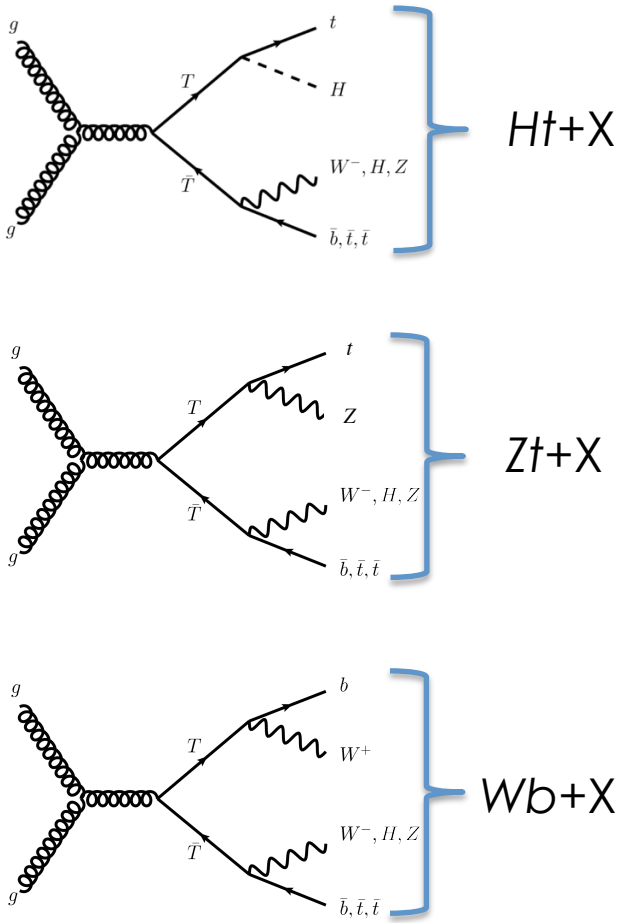


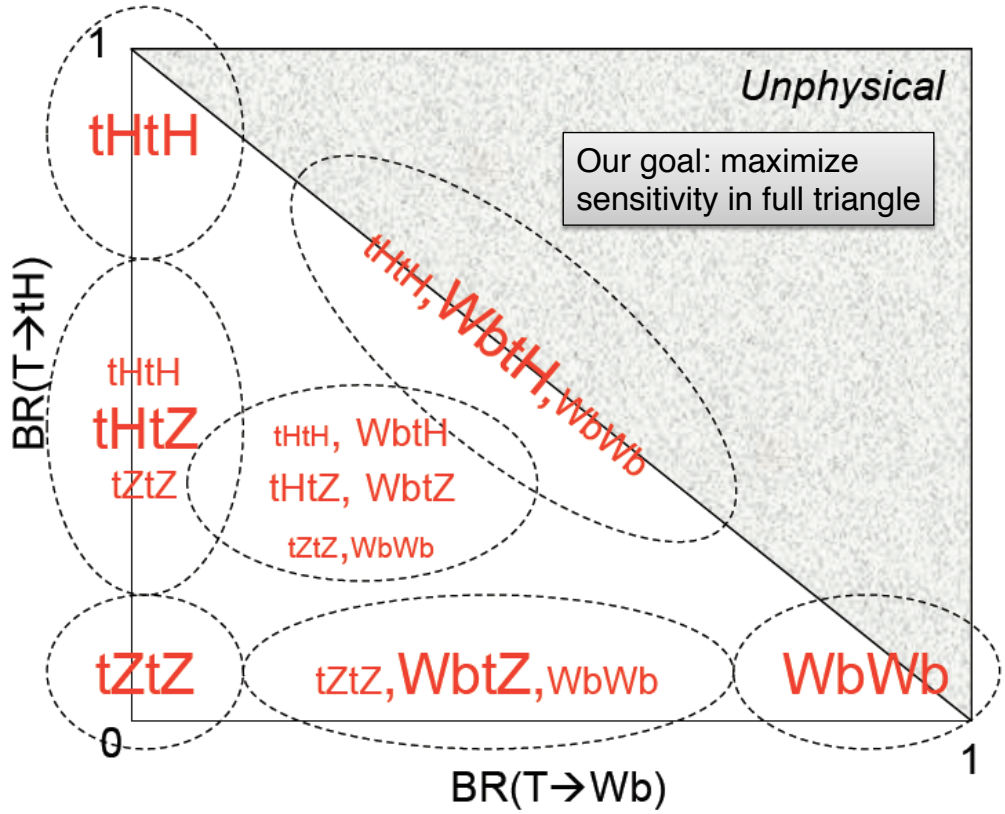
But need to test all possibilities!

General Search Strategy

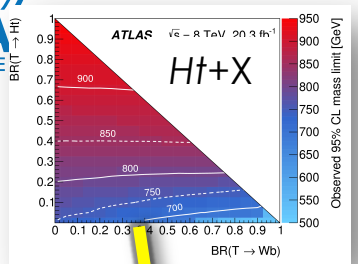
Multiple analyses to target each decay:

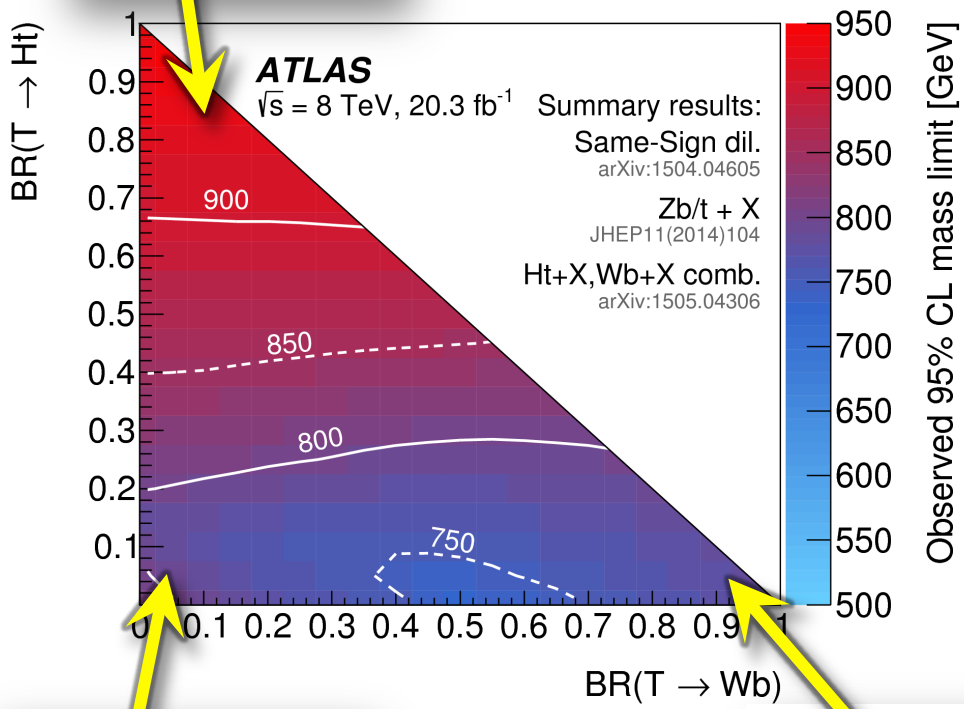


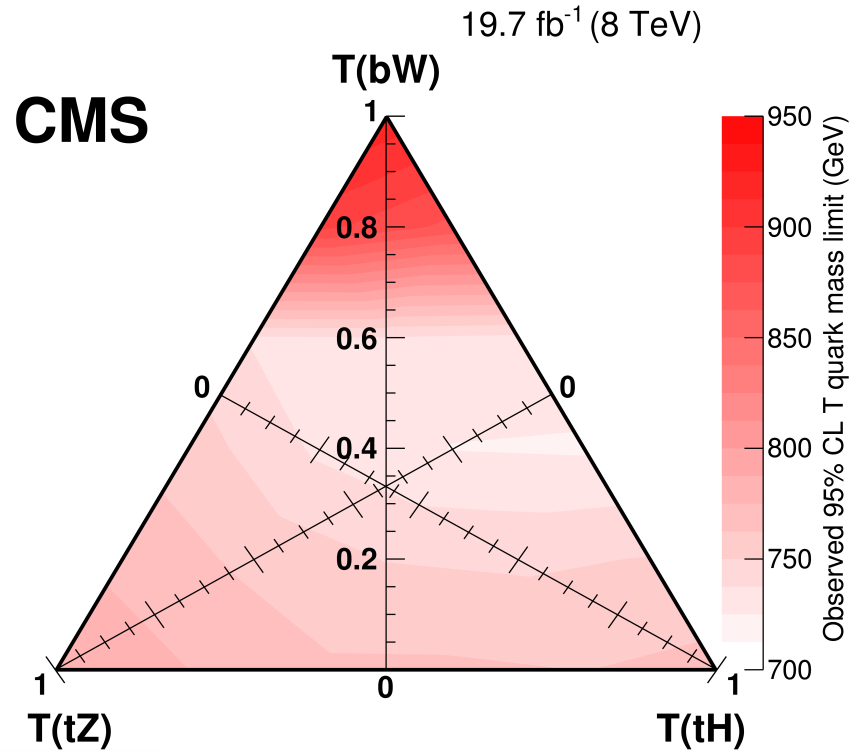
Set limits as a function of branching ratio

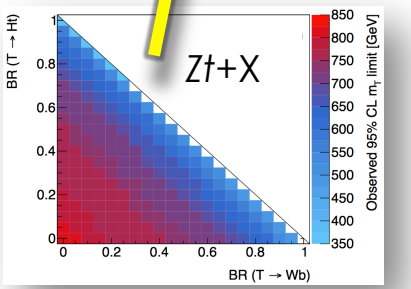


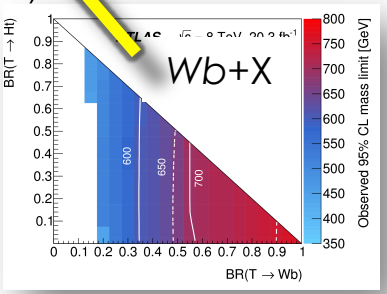
Run 1 Limits on *TT*







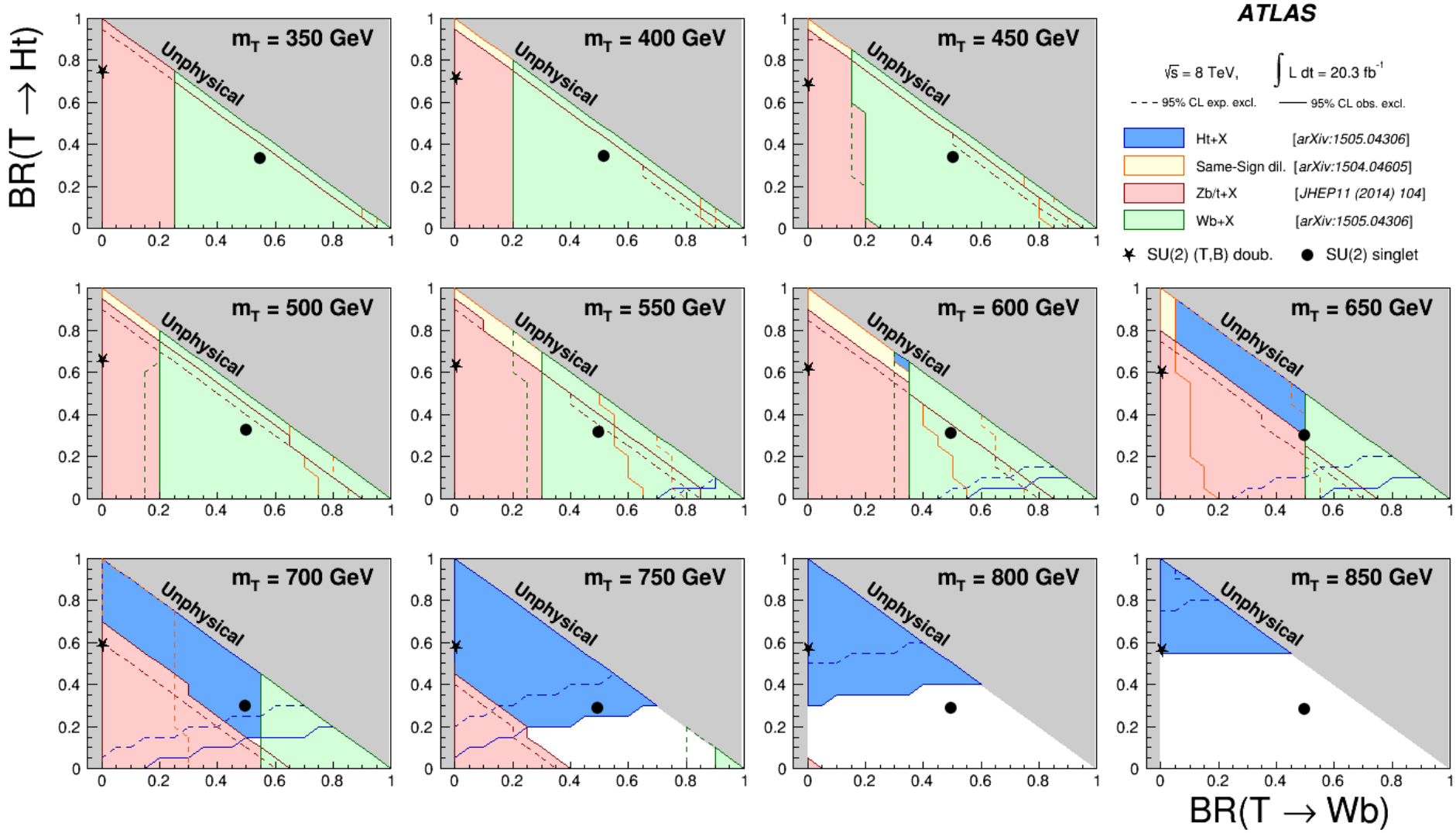




⇒ Almost all BR scenarios exclude for $m_T \lesssim 750$ GeV

arXiv:1505.04306

Run 1 Limits on *TT*



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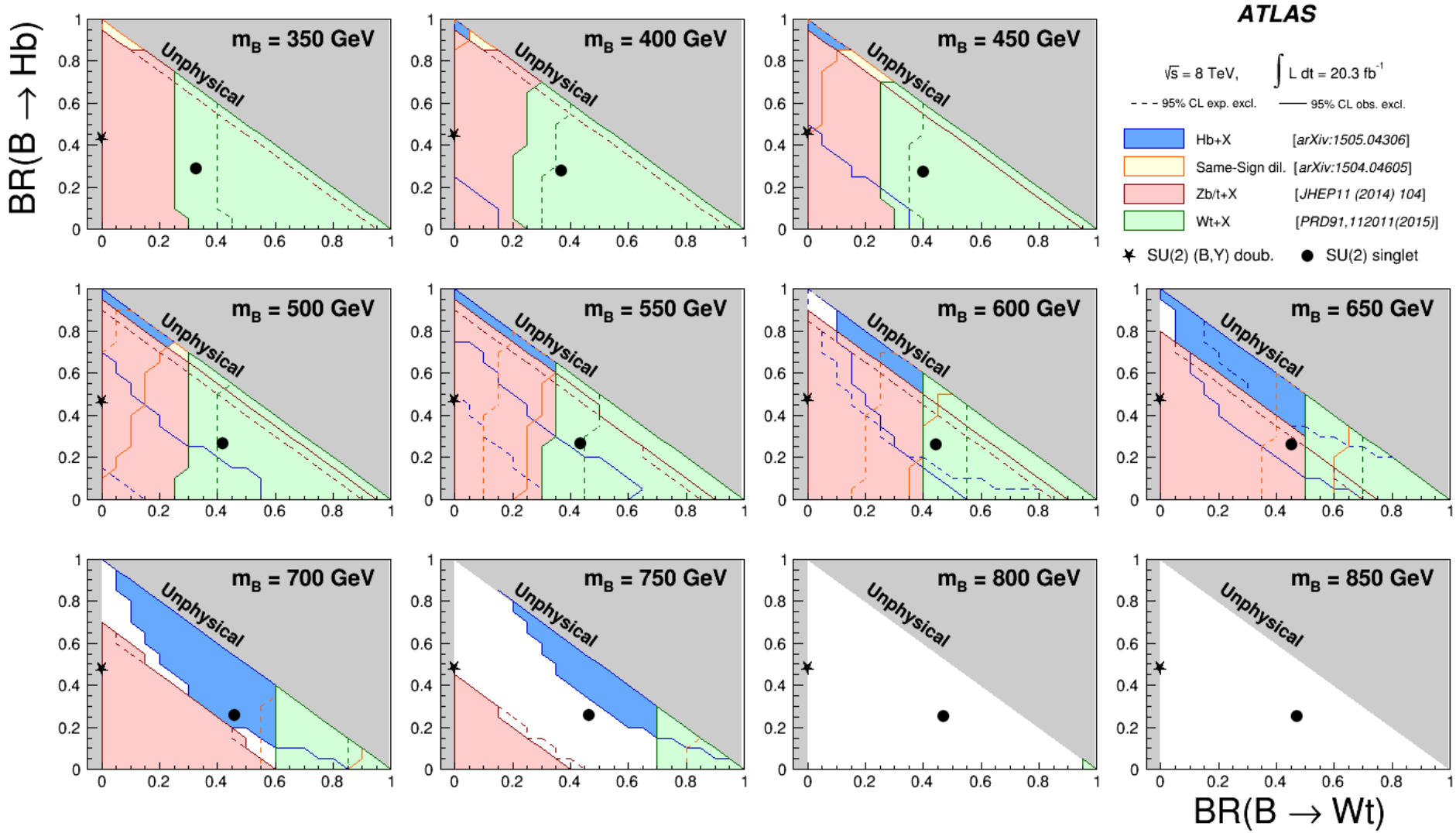
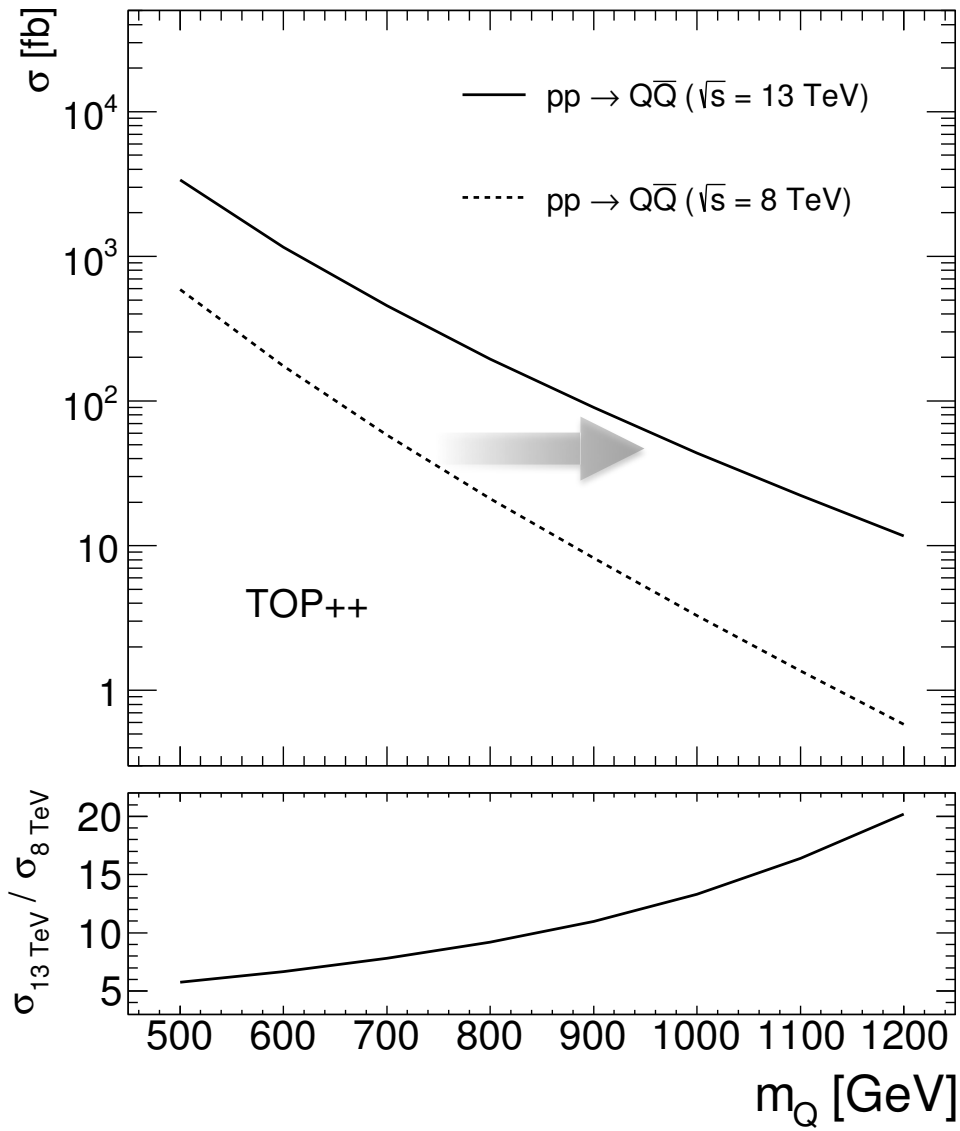
Run 1 Limits on *BB*



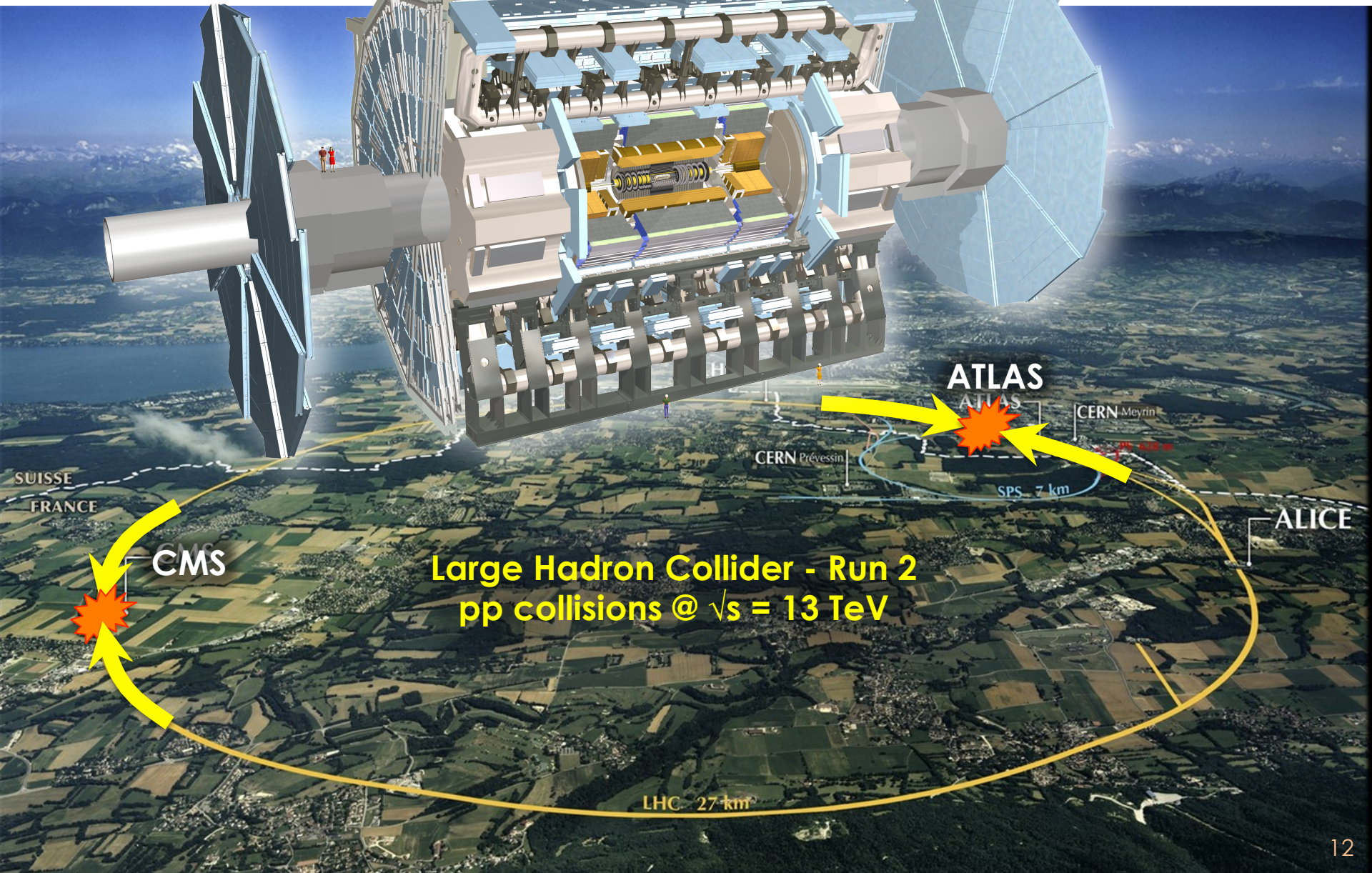
Run 1 ⇒ Run 2



8 TeV ⇒ 13 TeV

- Huge boost in *TT* cross section!
- Same amount of data will probe much higher masses

ATLAS


ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
Large Hadron Collider - Run 2
pp collisions @ √s = 13 TeV
LHC 27 km

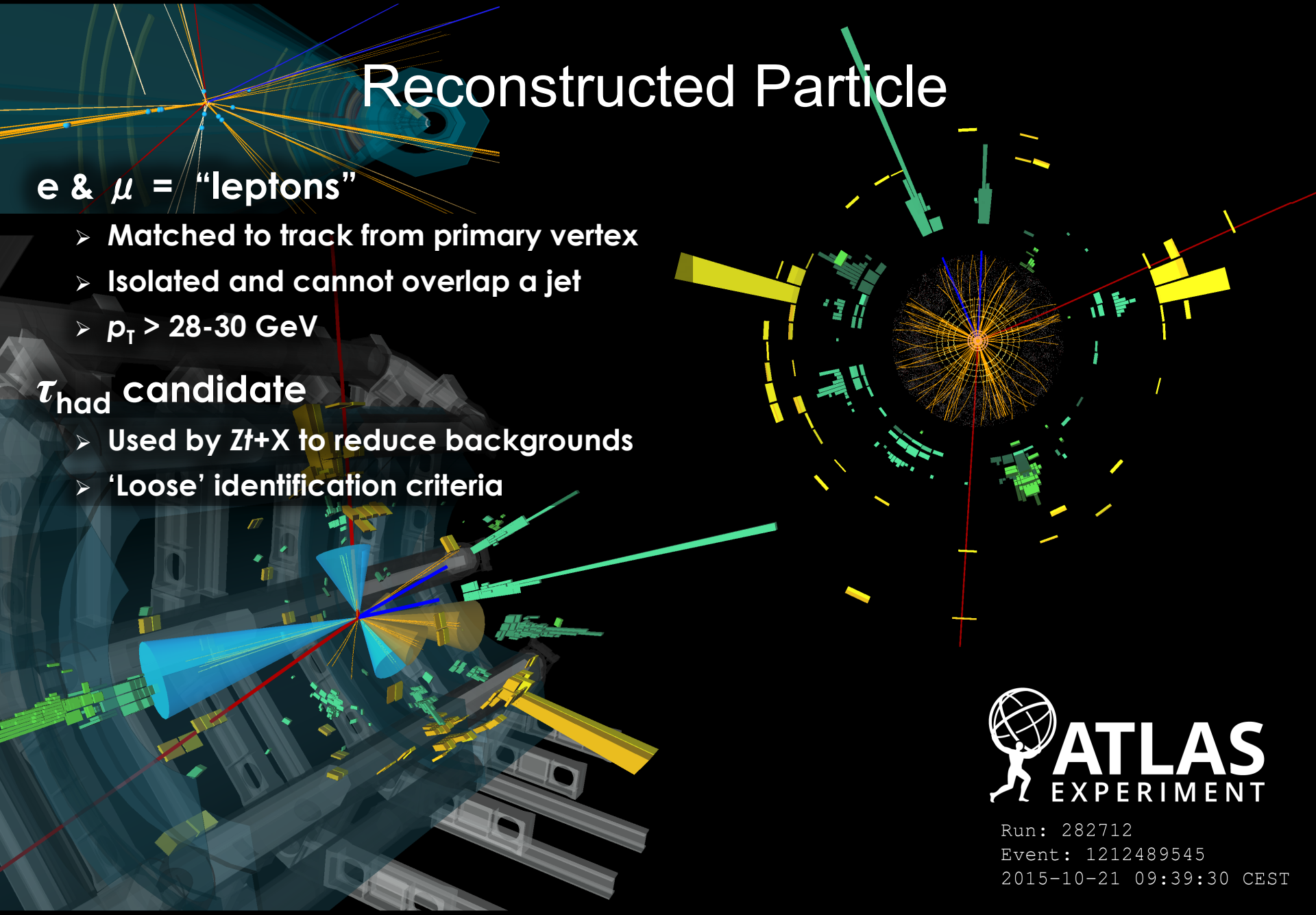
Reconstructed Particle

e & μ = "leptons"

- Matched to track from primary vertex
- Isolated and cannot overlap a jet
- p_T > 28-30 GeV

τ_{had} candidate

- Used by Zt+X to reduce backgrounds
- 'Loose' identification criteria



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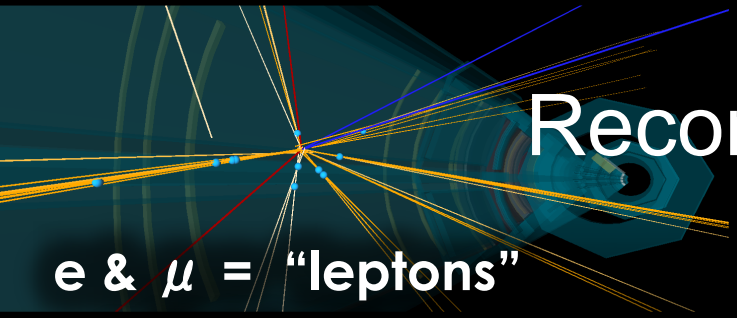

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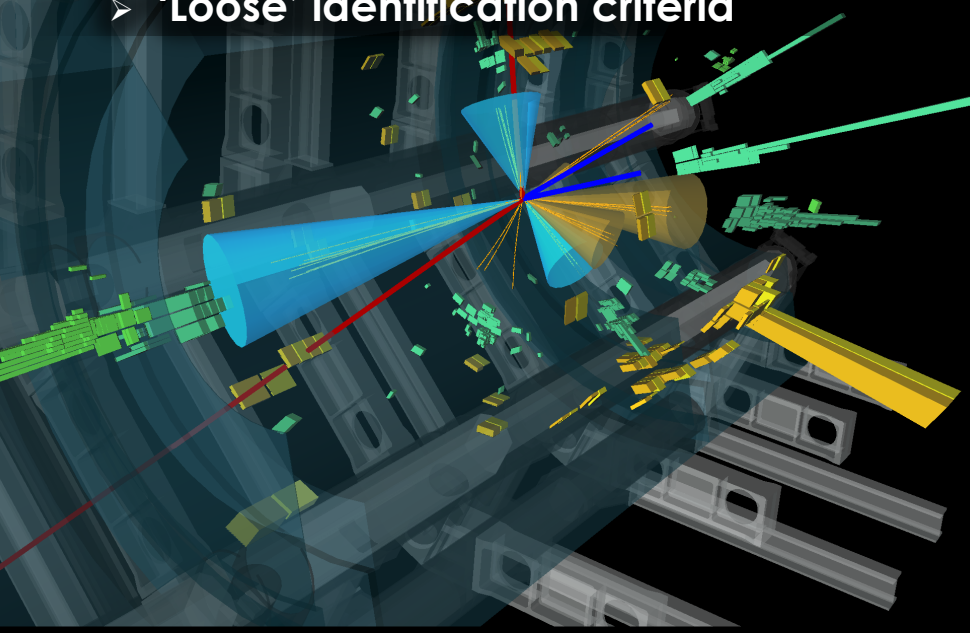

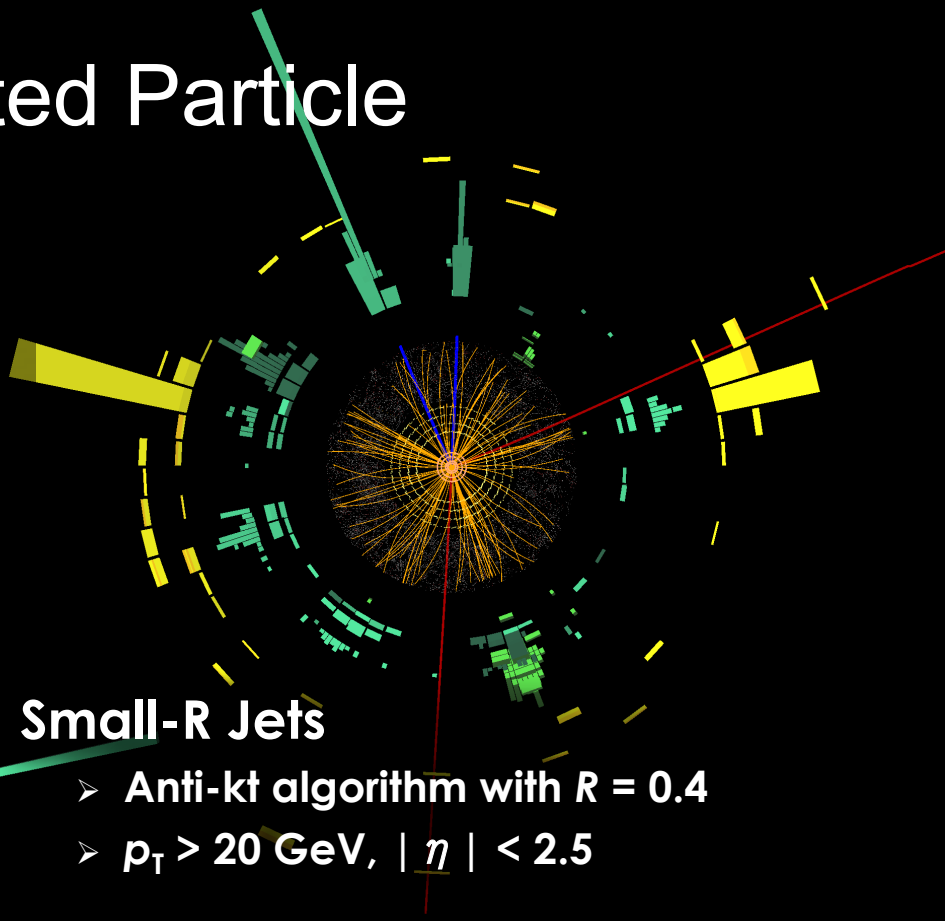

Small-R Jets

- Anti-kt algorithm with R = 0.4
- p_T > 20 GeV, $|\eta|$ < 2.5

ATLAS EXPERIMENT

Run: 282712
Event: 1212489545
2015-10-21 09:39:30 CEST

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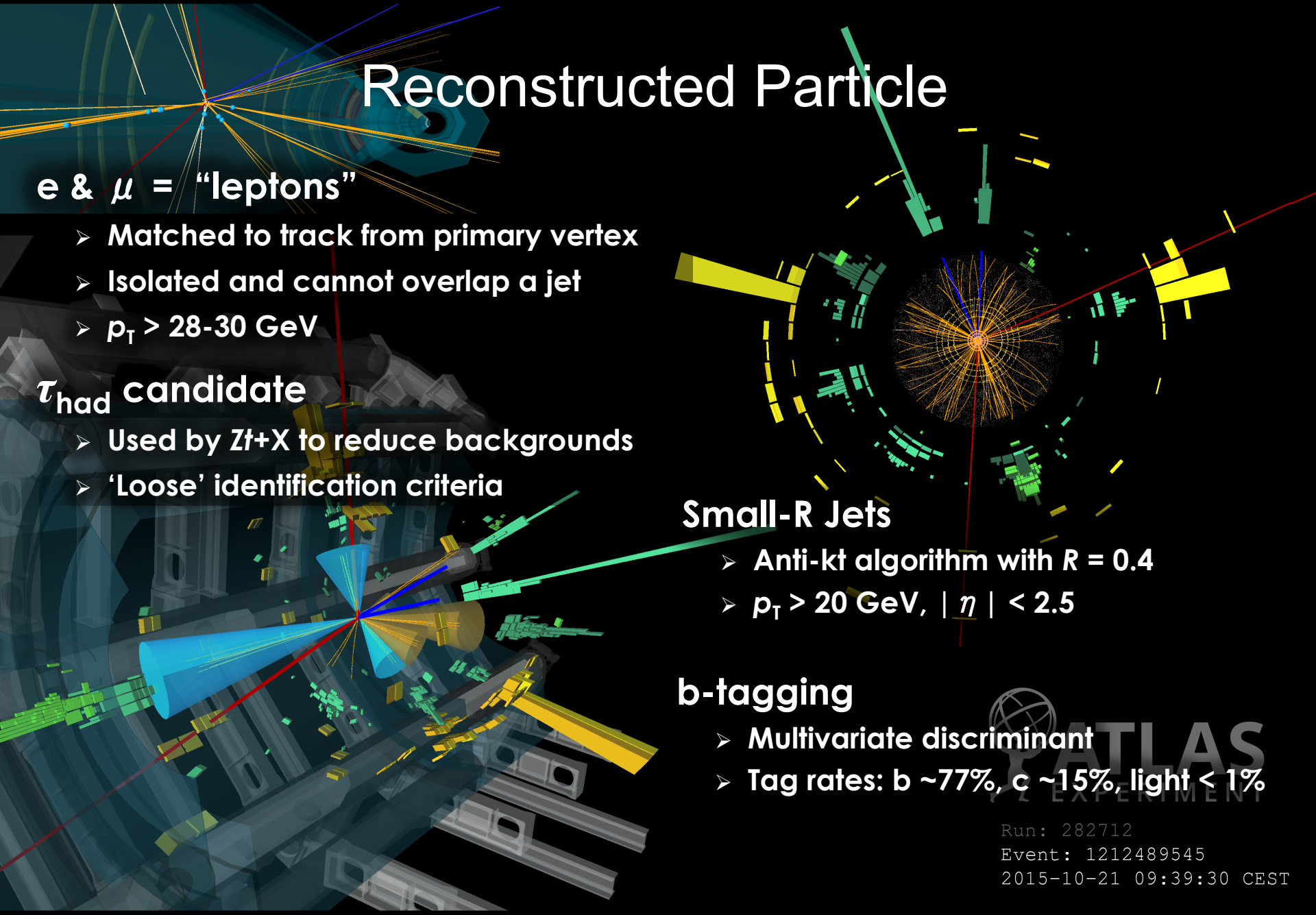

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b-tagging

- Multivariate discriminant
- Tag rates: b ~77%, c ~15%, light < 1%

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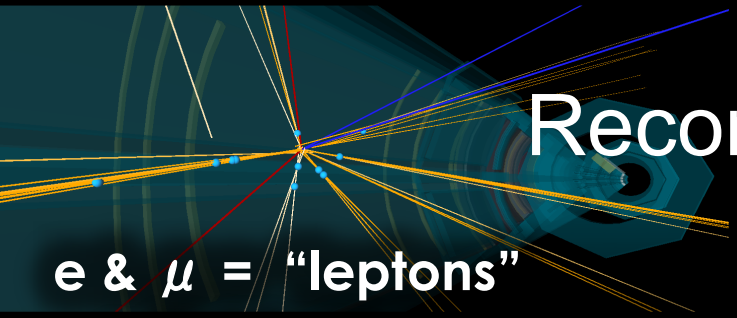

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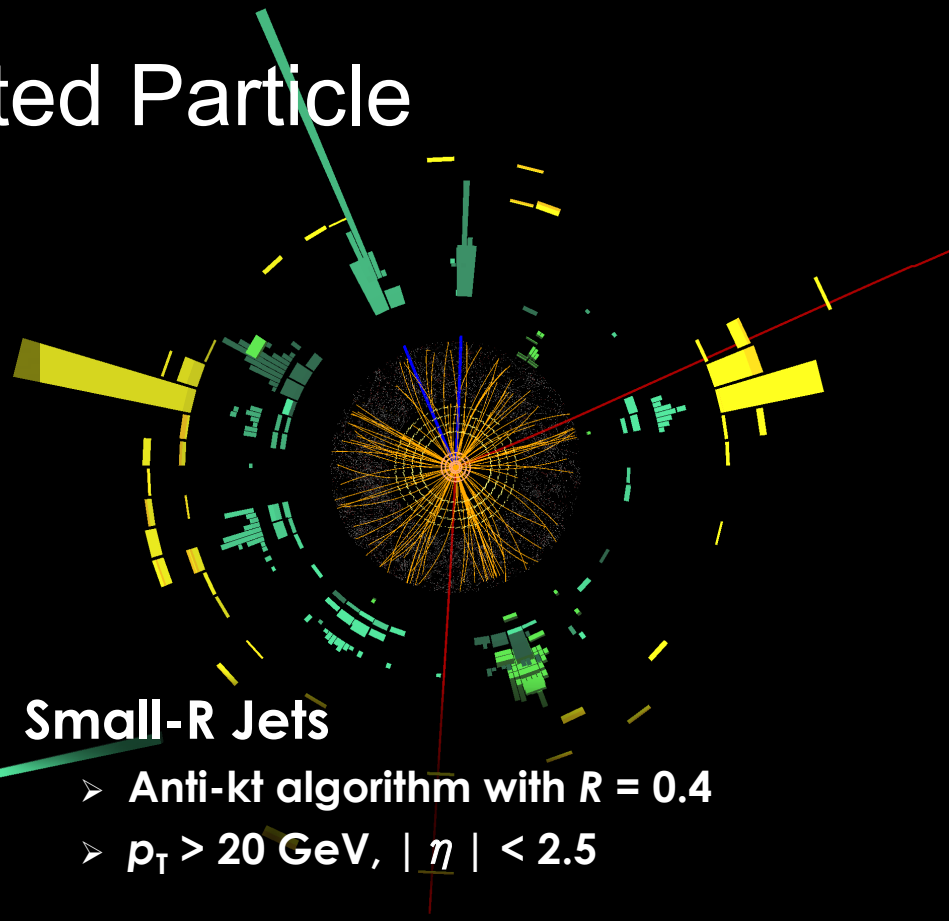

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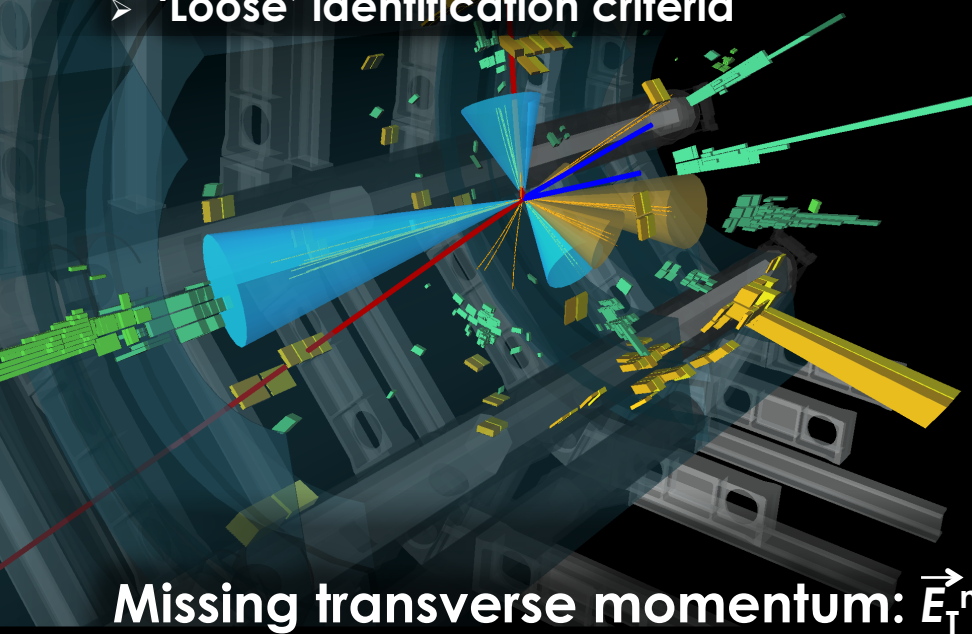

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EXPERIMENT
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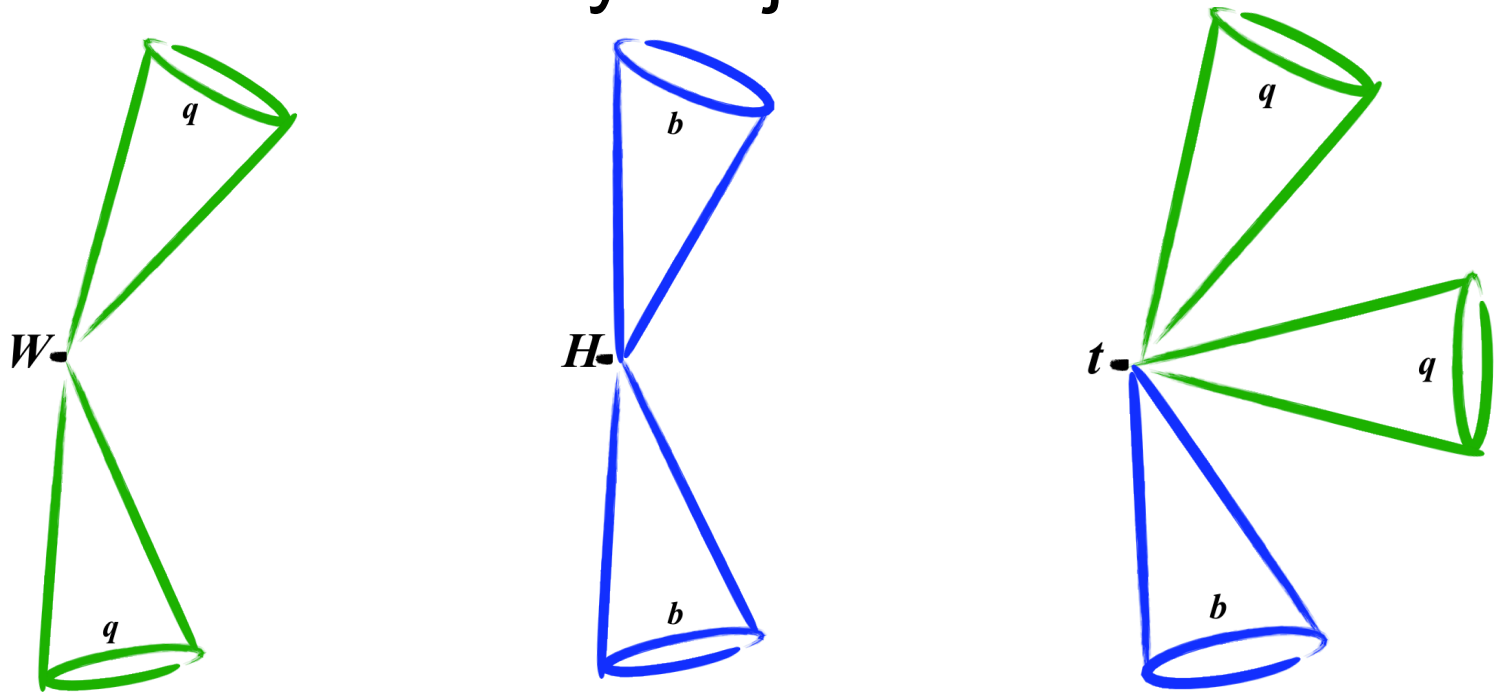
2015-10-21 09:39:30 CEST

Missing transverse momentum: $\vec{E}_T^{miss} = -\sum \vec{p}_T^{jets} - \sum p_T^{\mu} - \sum p_T^{e} - \sum p_T^{soft}$

Heavy Objects

With low-p_T:



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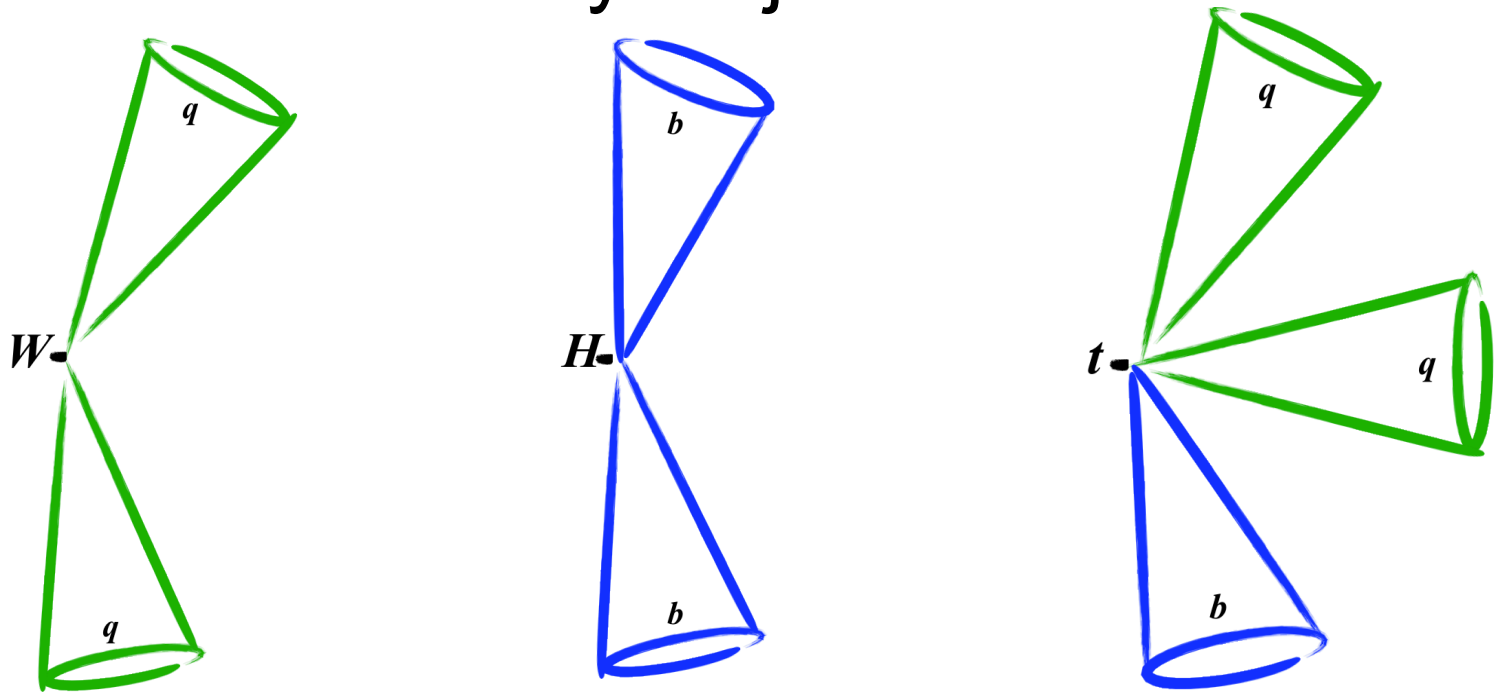
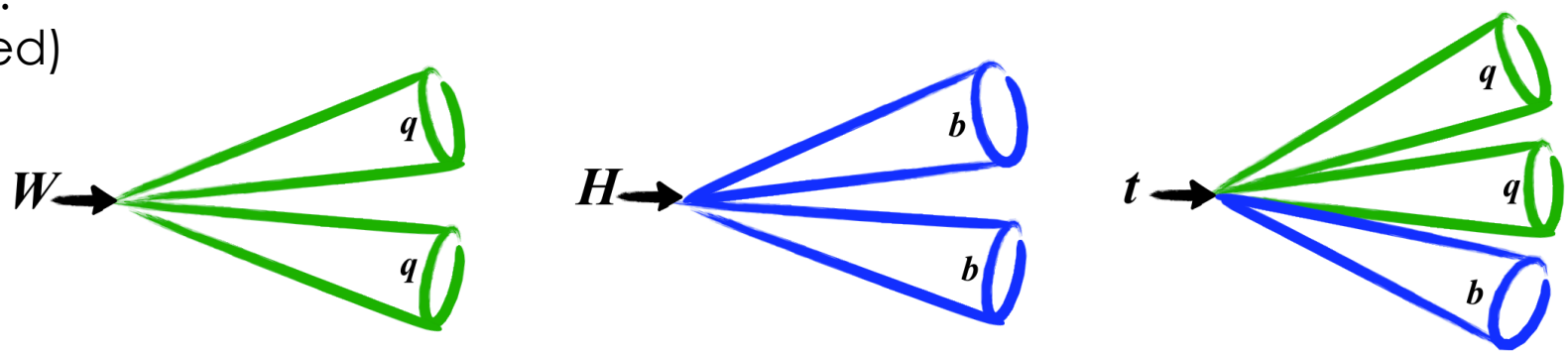


high-p_T: (boosted)



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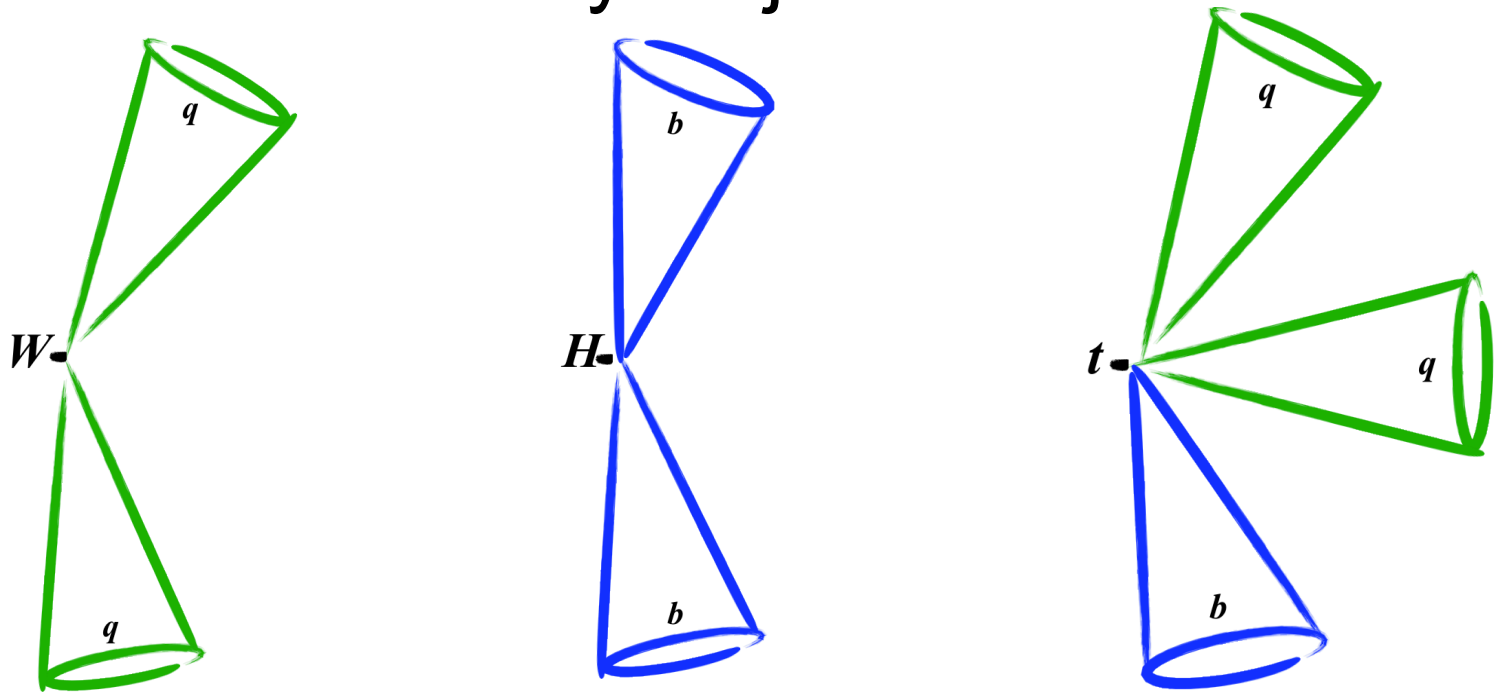

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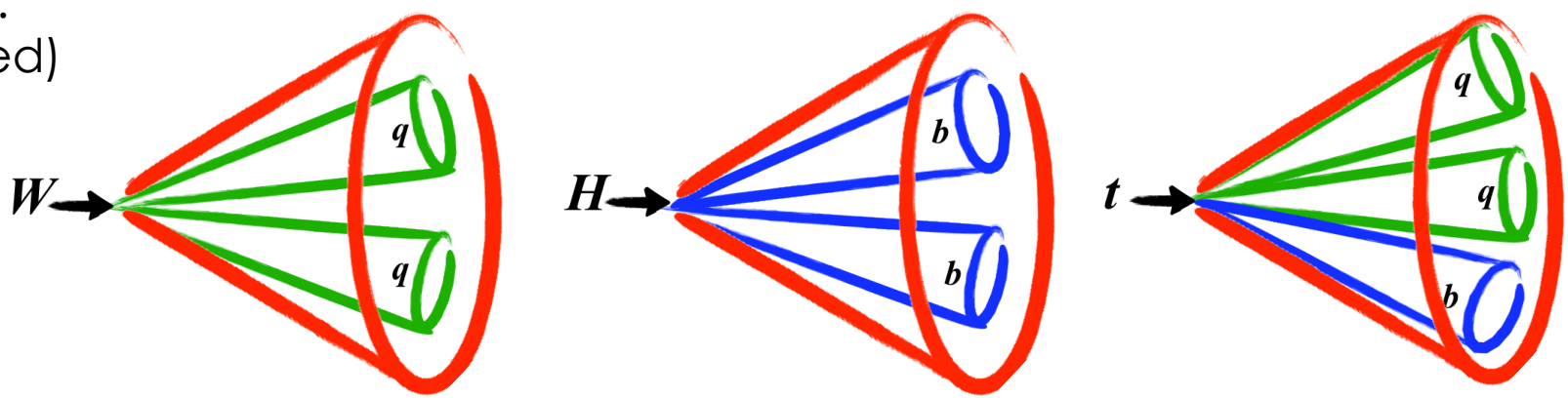
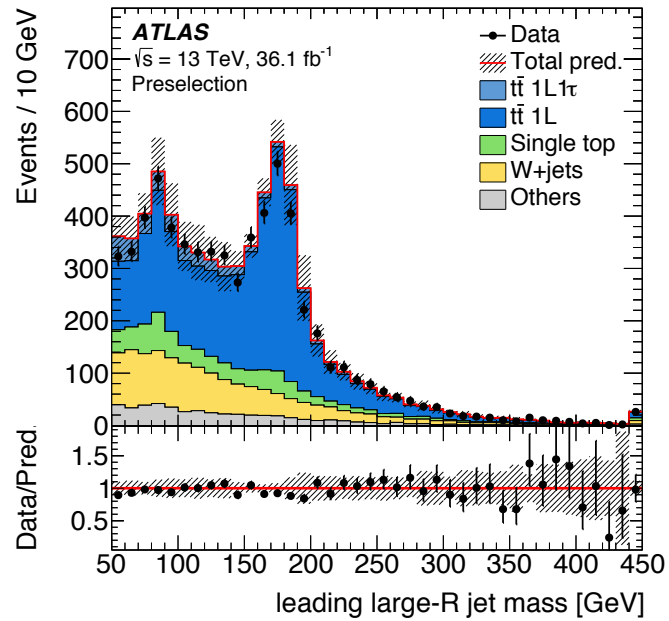
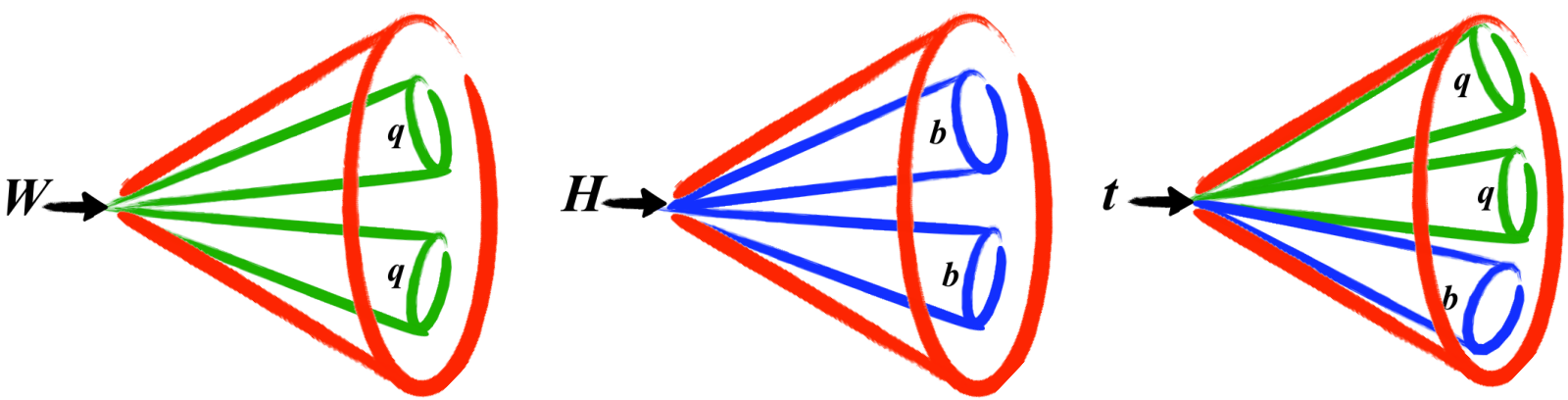


Heavy Objects

1) Large-R jets from calorimeter cells
   - *R*=1.0, C/A, trimmed jets
   - Dedicated calibrations and uncertainties
   - Use sub-structure to tag W bosons
2) Large-R "re-clustered" jets
   - Small-R jets are the input to *R*=1.0 clustering
   - Inherit calibration and uncertainties
   - Cut on large-R jet mass to "tag"



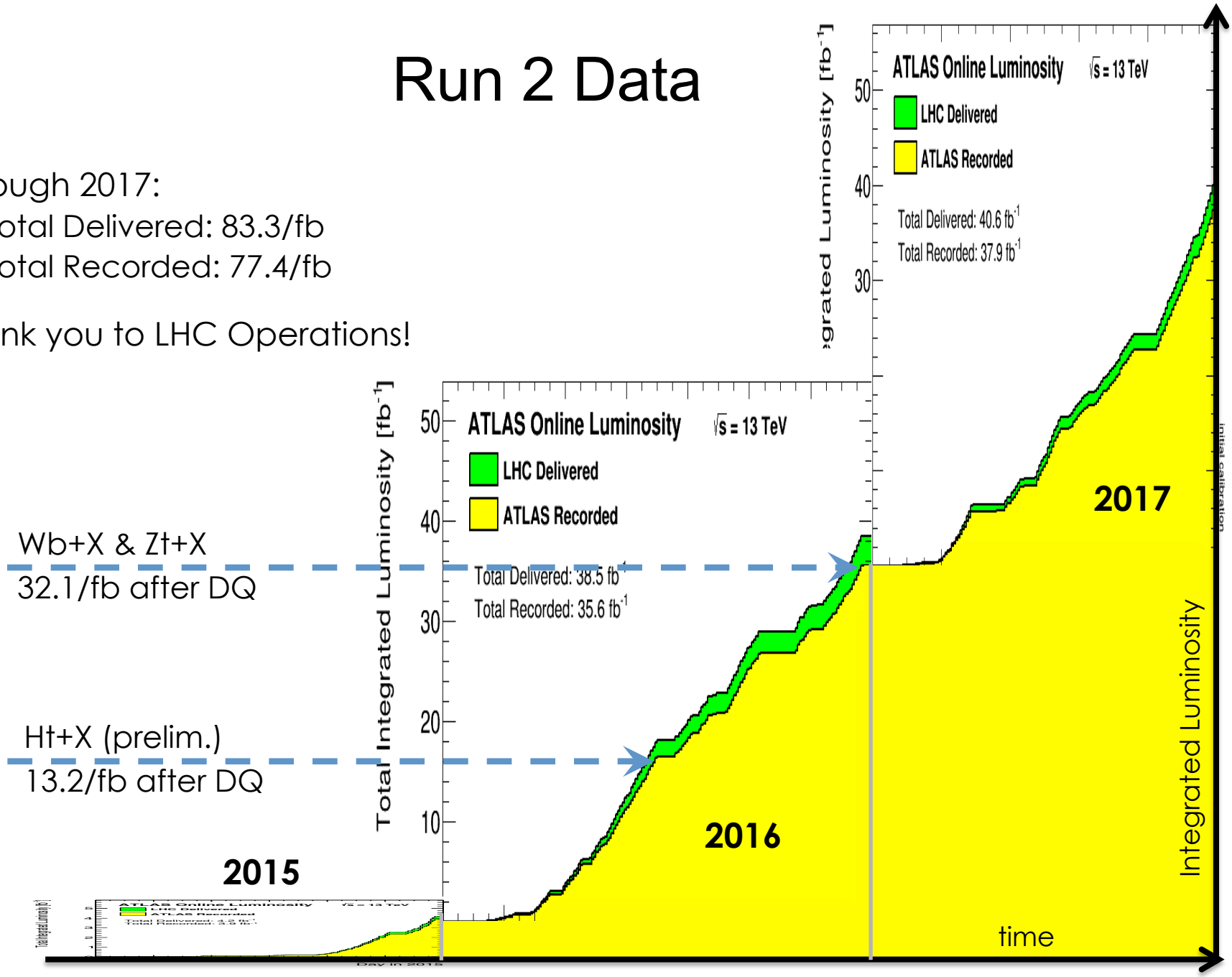


Run 2 Data

Through 2017:

- Total Delivered: 83.3/fb
- Total Recorded: 77.4/fb

Thank you to LHC Operations!



Signal and Background Samples

TT: PROTOS 2.2 (LO) + PYTHIA 8
- Check singlet vs. doublet

tt: POWHEG-BOX v2 + PYTHIA 6
- Uncertainties:
  POWHEG vs. MG5_aMC@NLO
  PYTHIA 6 vs. HERWIG++
  ISR/FSR

Normalized to NNLO (TOP++ v2.0)
- Uncertainties on scales, α_S, PDF

W/Z+jets: SHERPA 2.2
- NLO + up to 3 additional partons at LO

Normalized to NNLO (FEWZ)

Single-top: POWHEG-BOX v1/v2 + PYTHIA 6
- Overlap removal between *Wt* and NLO *tt*

Diboson: SHERPA 2.1

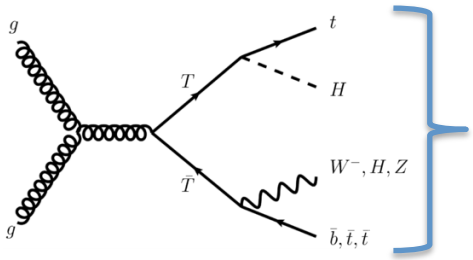
tt+V: MadGraph5_aMC@NLO 2.1 + PYTHIA 8

Normalized to NLO

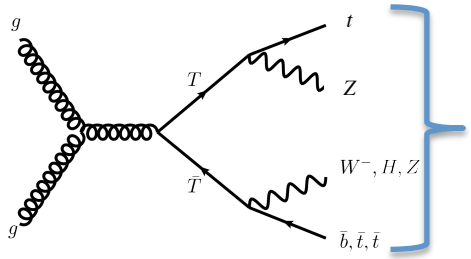
QCD Multijets: Estimated from data

Analyses

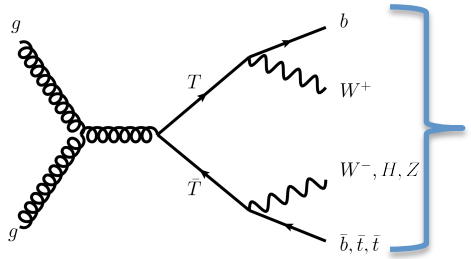
Multiple analyses to target each decay:



Ht+X



Zt+X



Wb+X

Different final states require different strategies:

- Divide and conquer
  - Many signal regions (SRs), control regions (CRs), and validation regions (VRs)
  - Fit m_{eff} distribution in SRs and CRs
- Cut-and-count w/ control regions
  - 1 SR, 2 CRs, and 3 VRs
  - Fit total yield in SR and CRs
- Mass bump search
  - 1 SR, 1 CR
  - Fit reconstructed m_{VLQ} distribution

Ht+X

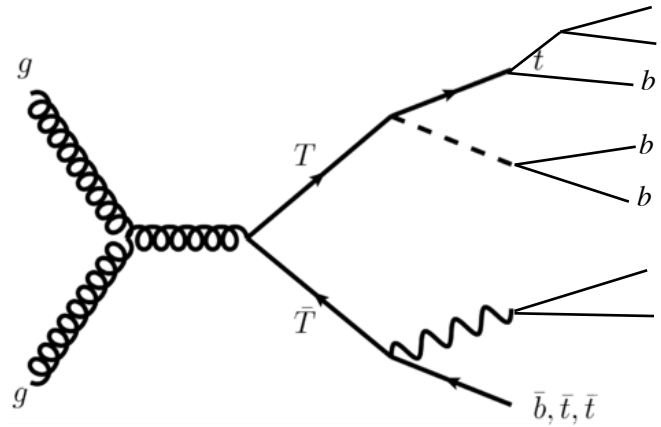
Main signals:

$TT \rightarrow Ht\ Ht \rightarrow bb\ Wb\ bb\ Wb$

$TT \rightarrow Ht\ Zt \rightarrow bb\ Wb\ Z\ Wb$

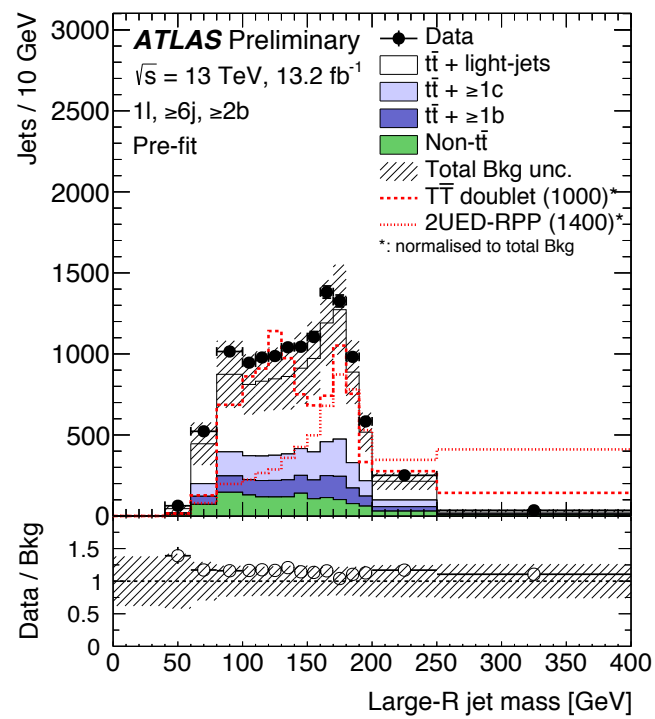
$TT \rightarrow Ht\ Wb \rightarrow bb\ Wb\ Wb$

- Many jets, many *b*-tags!



Initial selection:

- 0 / 1 charged lepton (e, μ)
- ≥6 / ≥5 small-R jets
  - ≥ 2 *b*-tagged
- E_T^{miss} > 200 GeV / 20 GeV



Ht+X: Strategy

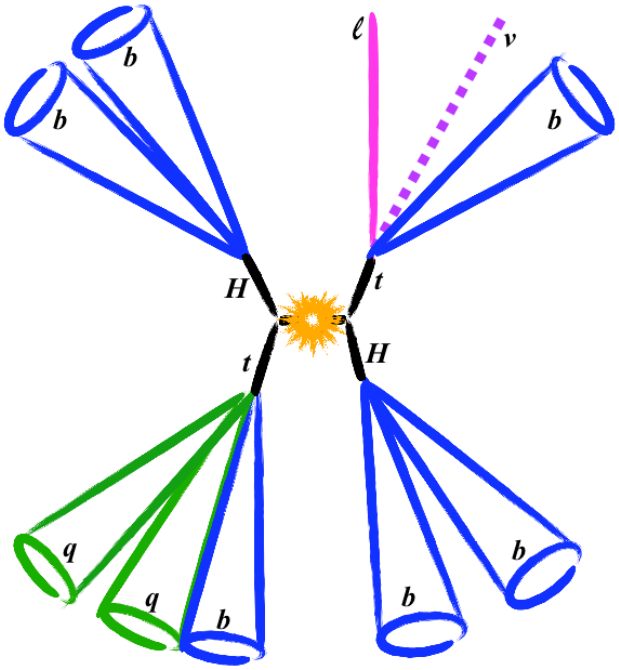
Main signals:

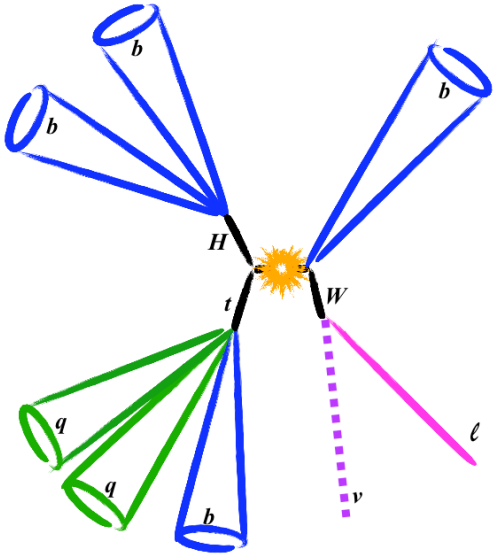
$TT \rightarrow Ht\ Ht \rightarrow bb\ Wb\ bb\ Wb$

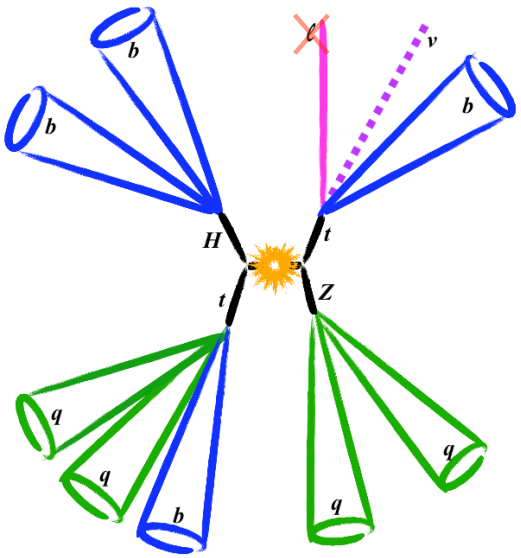
$TT \rightarrow Ht\ Zt \rightarrow bb\ Wb\ Z\ Wb$

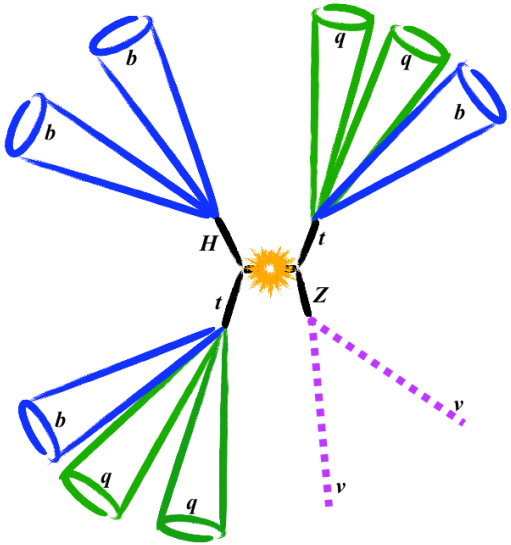
$TT \rightarrow Ht\ Wb \rightarrow bb\ Wb\ Wb$

- Many jets, many b-tags!





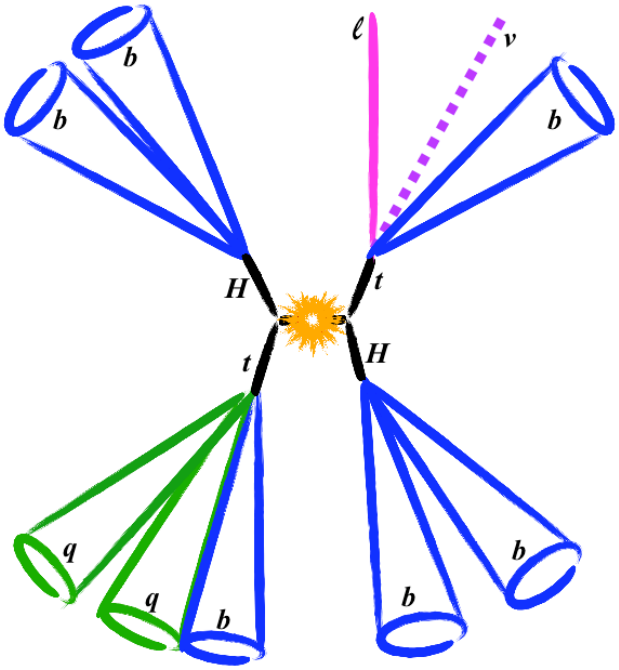


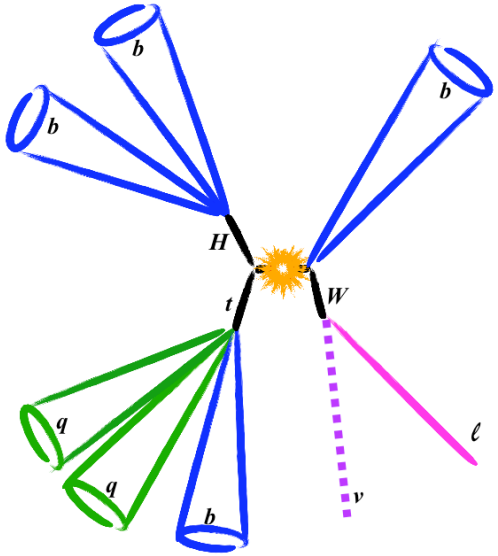


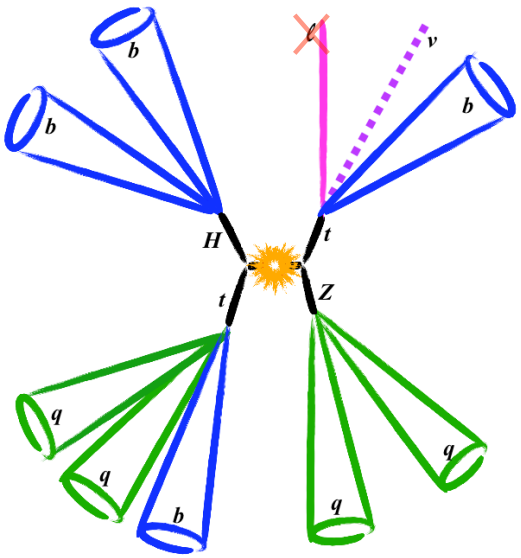
Ht+X: Strategy

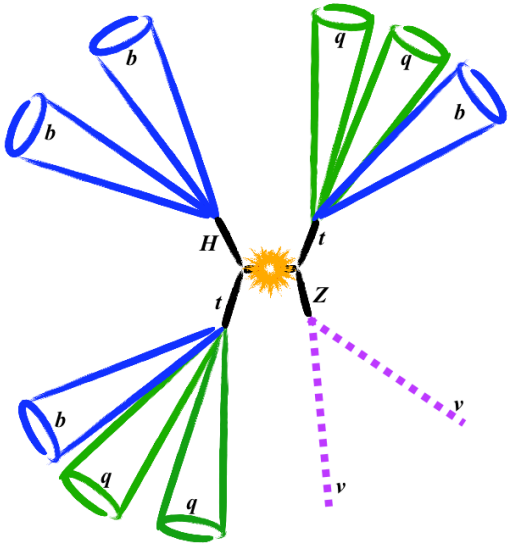
Categorize events by:

- # leptons (*l*)





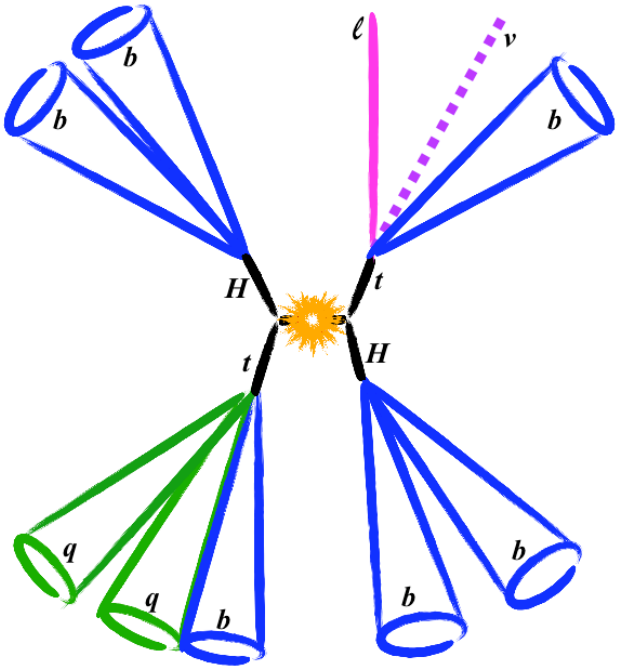


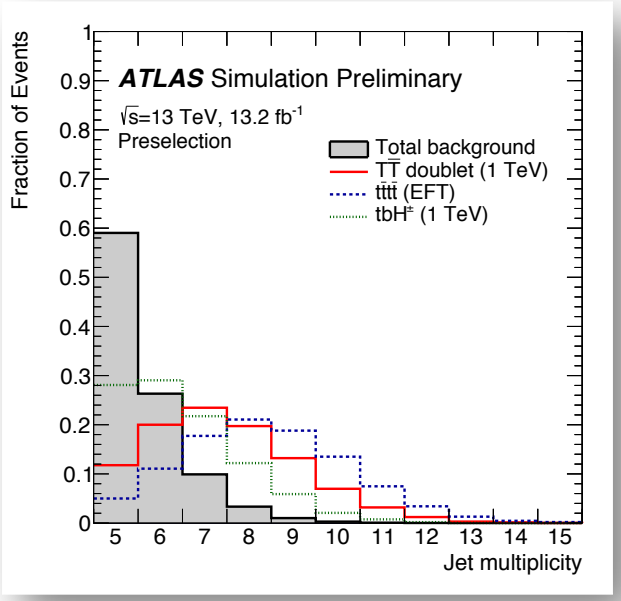


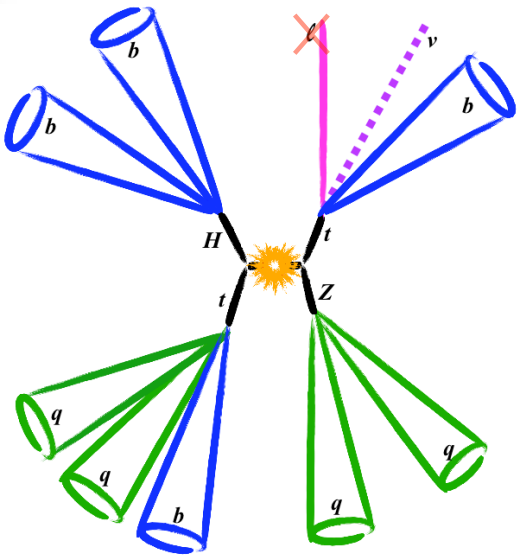
Ht+X: Strategy

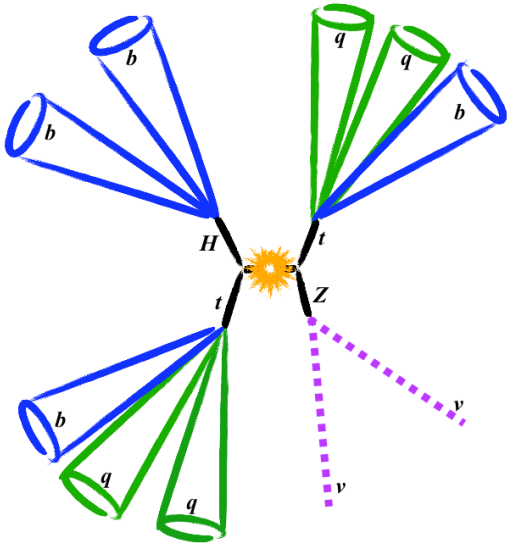
Categorize events by:

- # leptons (*l*)
- # small-R jets (*j*)





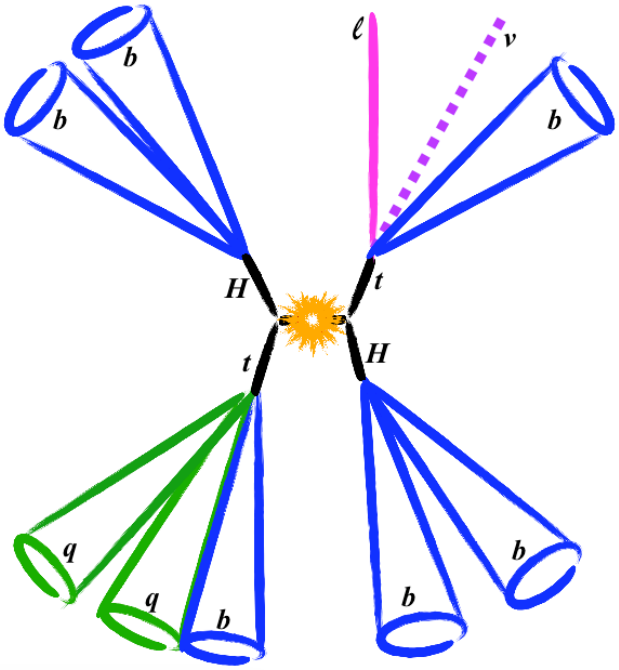


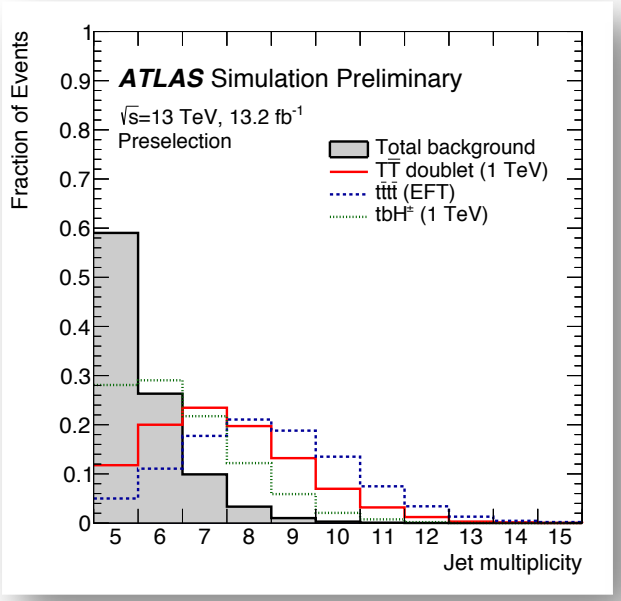


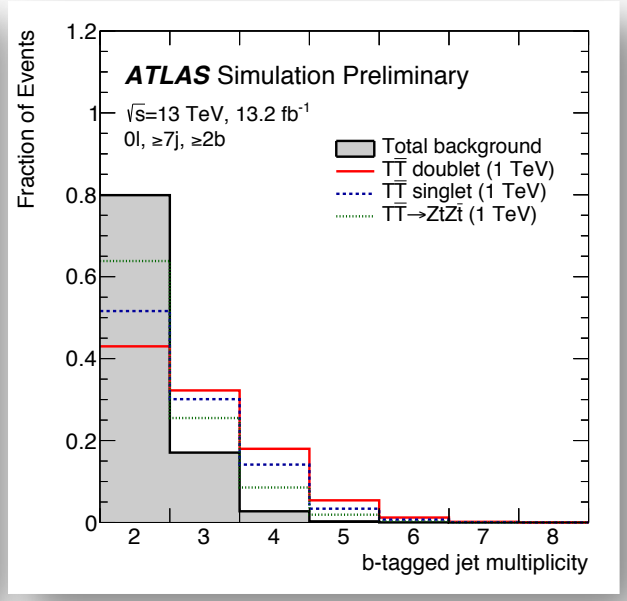
Ht+X: Strategy

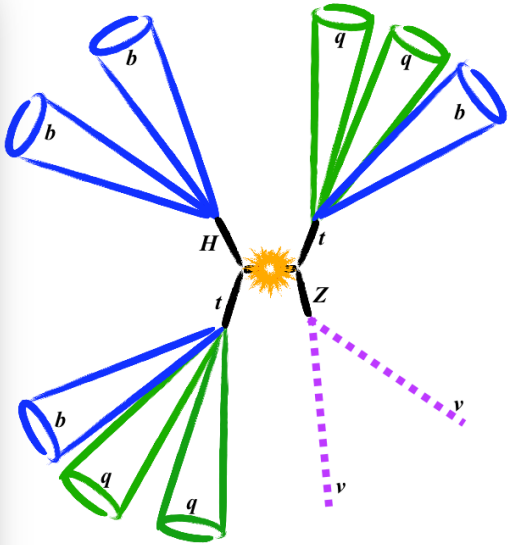
Categorize events by:

- # leptons (*l*)
- # small-R jets (*j*)
- # *b*-tags (*b*)







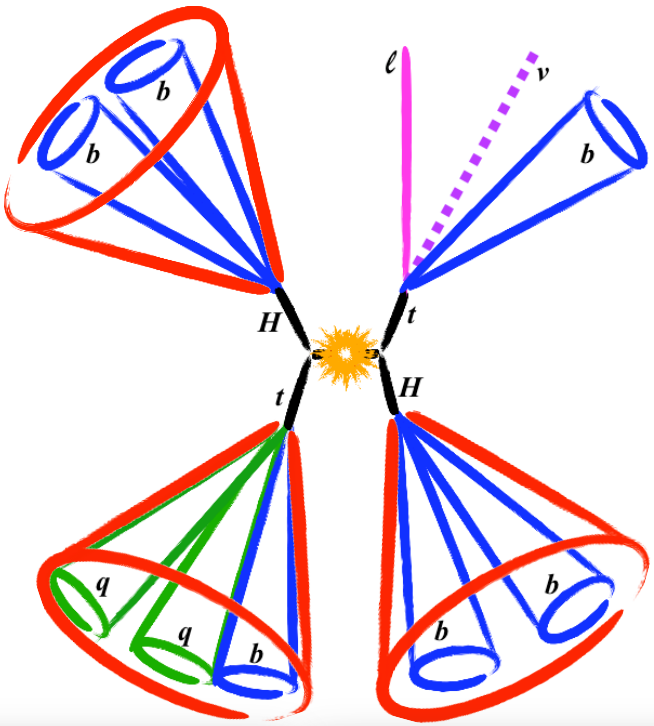


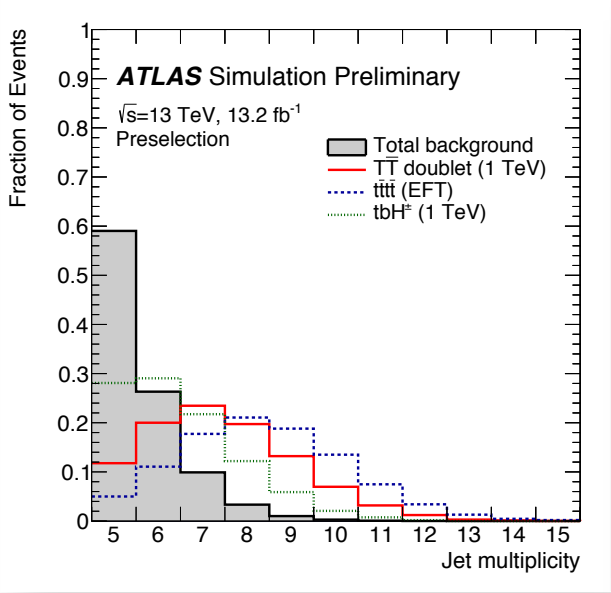
Ht+X: Strategy

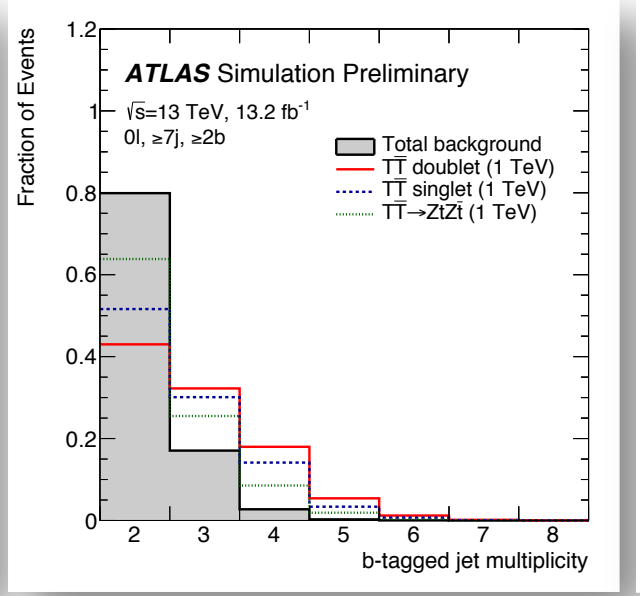
Categorize events by:

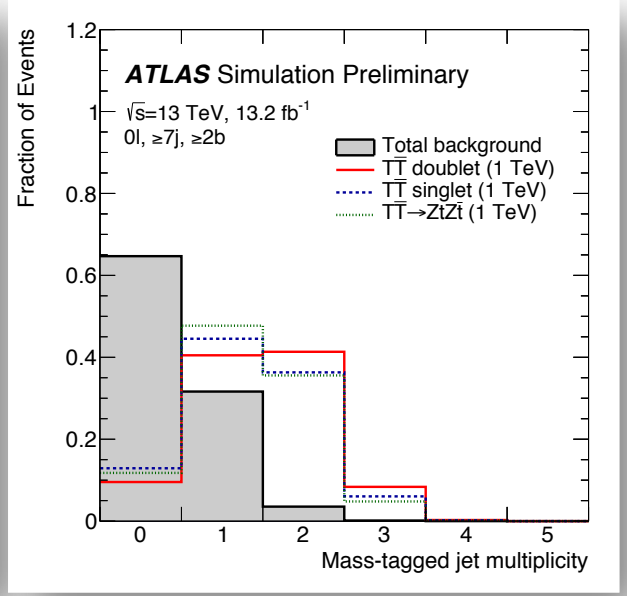
- # leptons (*l*)
- # small-R jets (*j*)
- # *b*-tags (*b*)
- # large-R jets (*J*)

  m > 100 GeV, p_T > 300 GeV





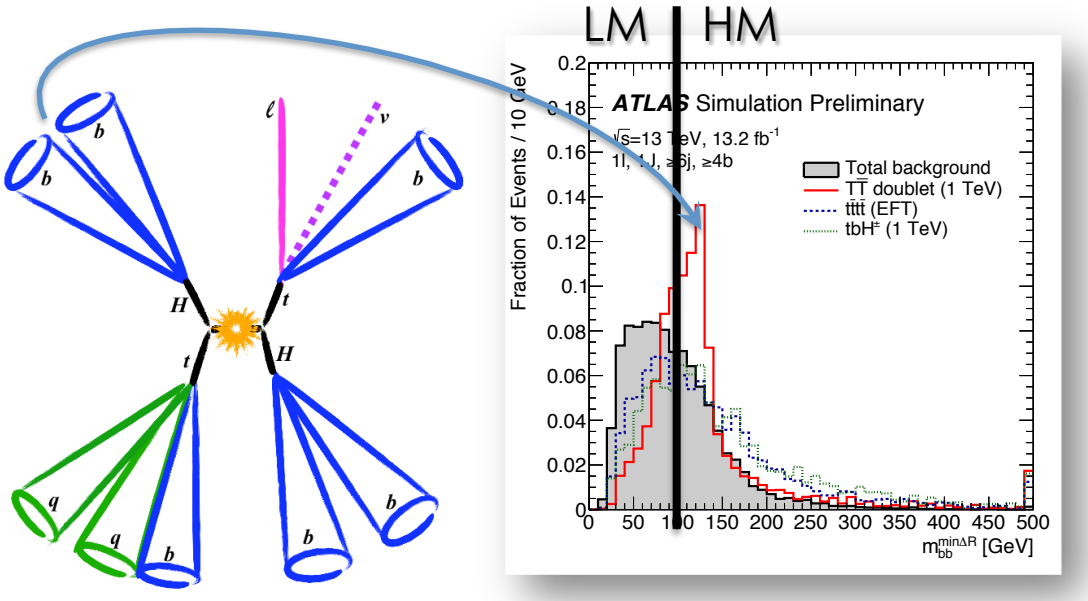


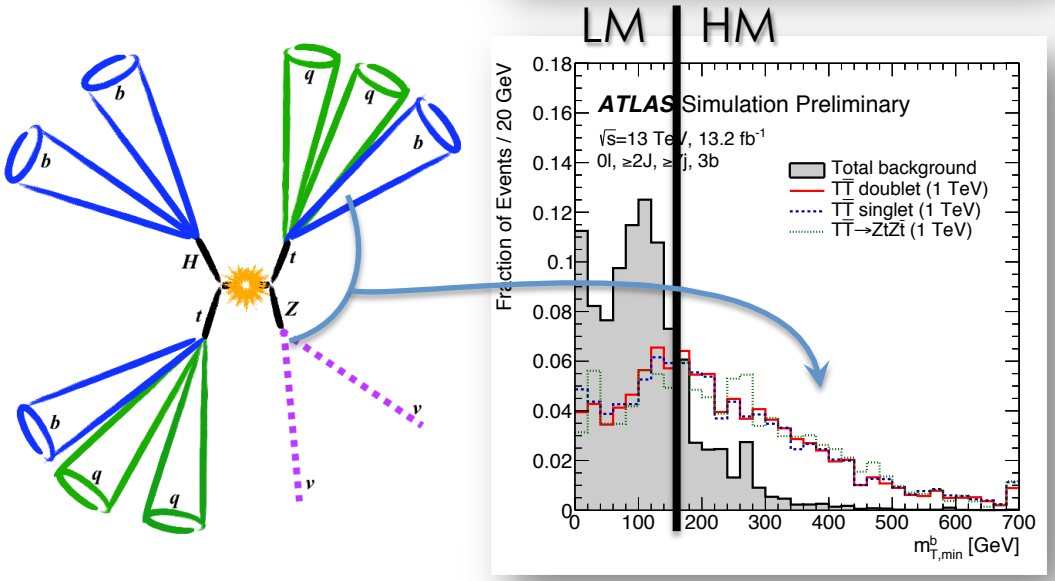


Ht+X: Strategy

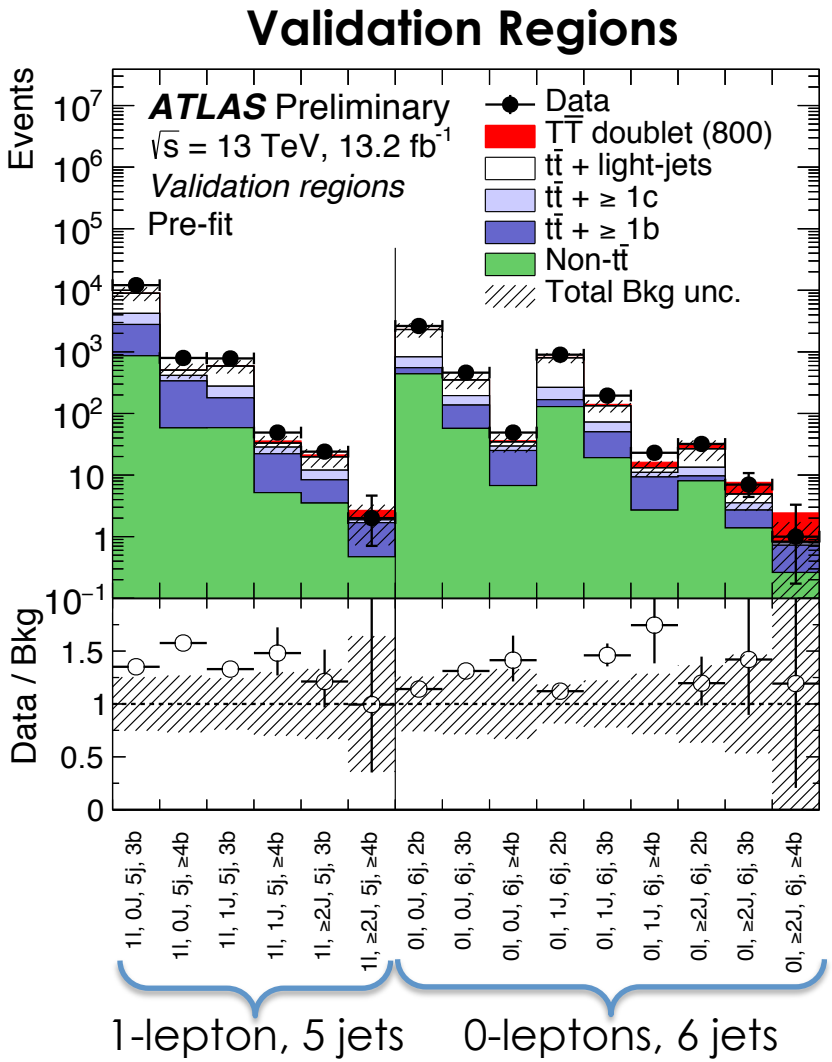
ategorize events by:

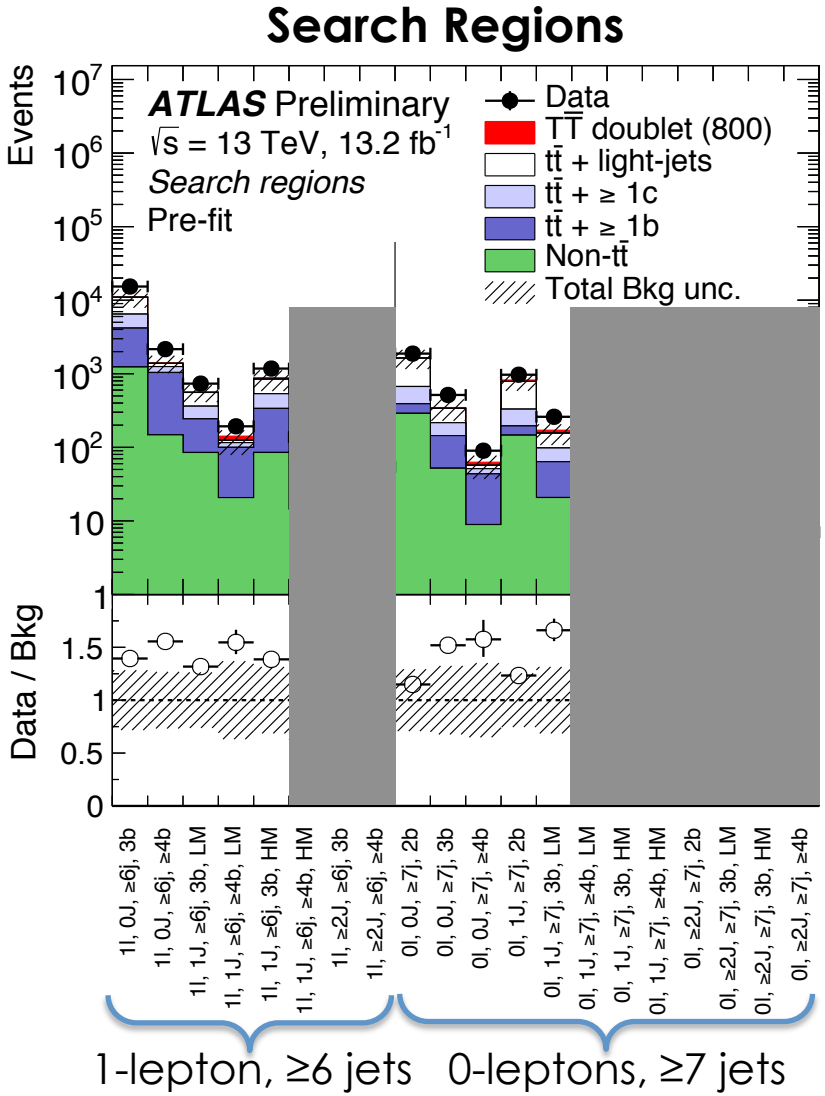
- # leptons (*l*)
- # small-R jets (*j*)
- # *b*-tags (*b*)
- # large-R jets (*J*)
  m > 100 GeV, p_T > 300 GeV
- Low/High mass
  - 0-lepton events:
    m_{bb} of closest *b*-pair
  - 1-lepton events:
    minimum $m_T(E_T^{miss}, b)$





Ht+X: Event Categories





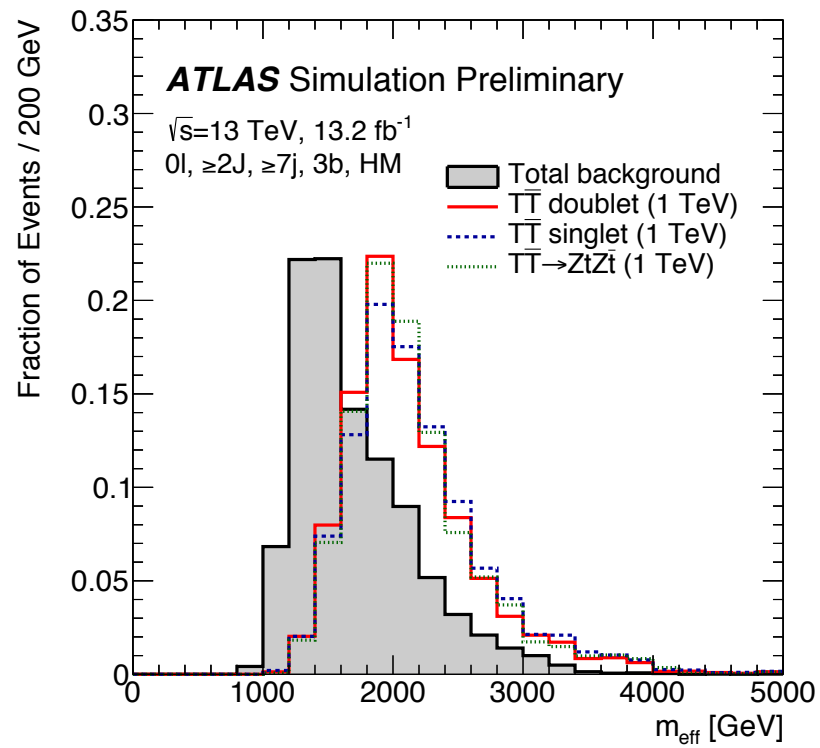
Ht+X: Statistical Analysis

Final discriminating variable: $m_{\mathrm{eff}} = \Sigma |p_T^{\mathrm{jets}}| + |p_T^{\ell}| + E_T^{\mathrm{miss}}$

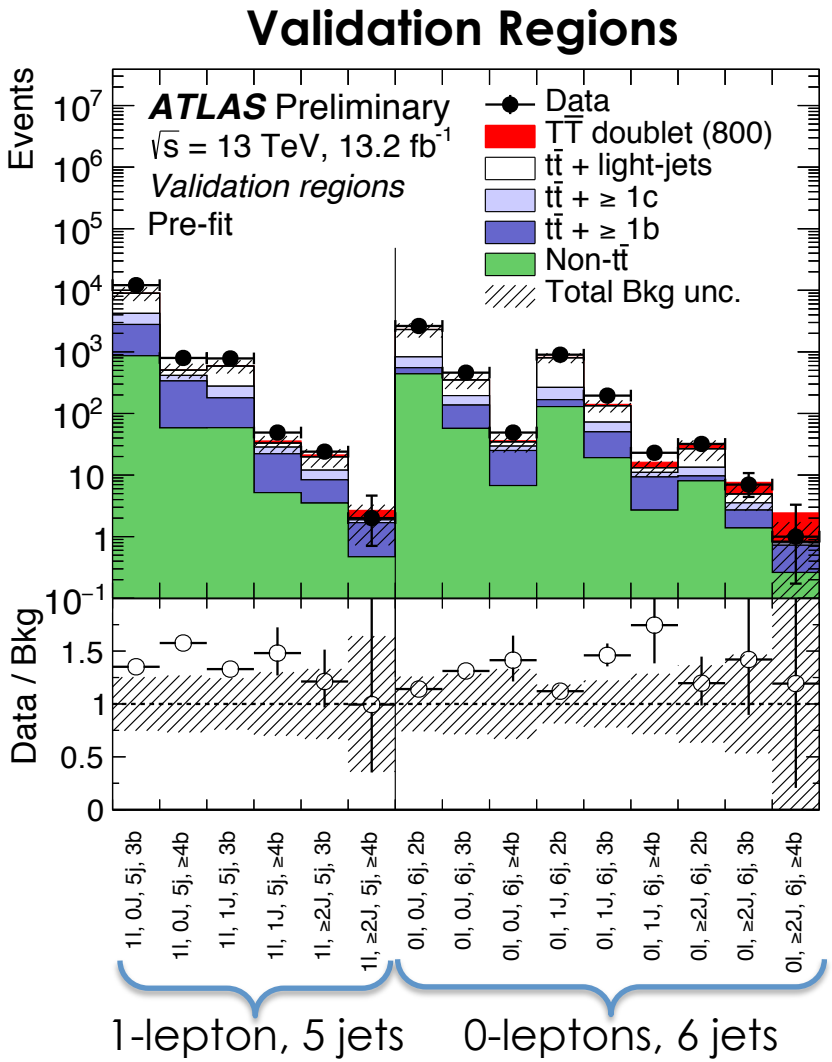
- Choose binning based on expected number of events

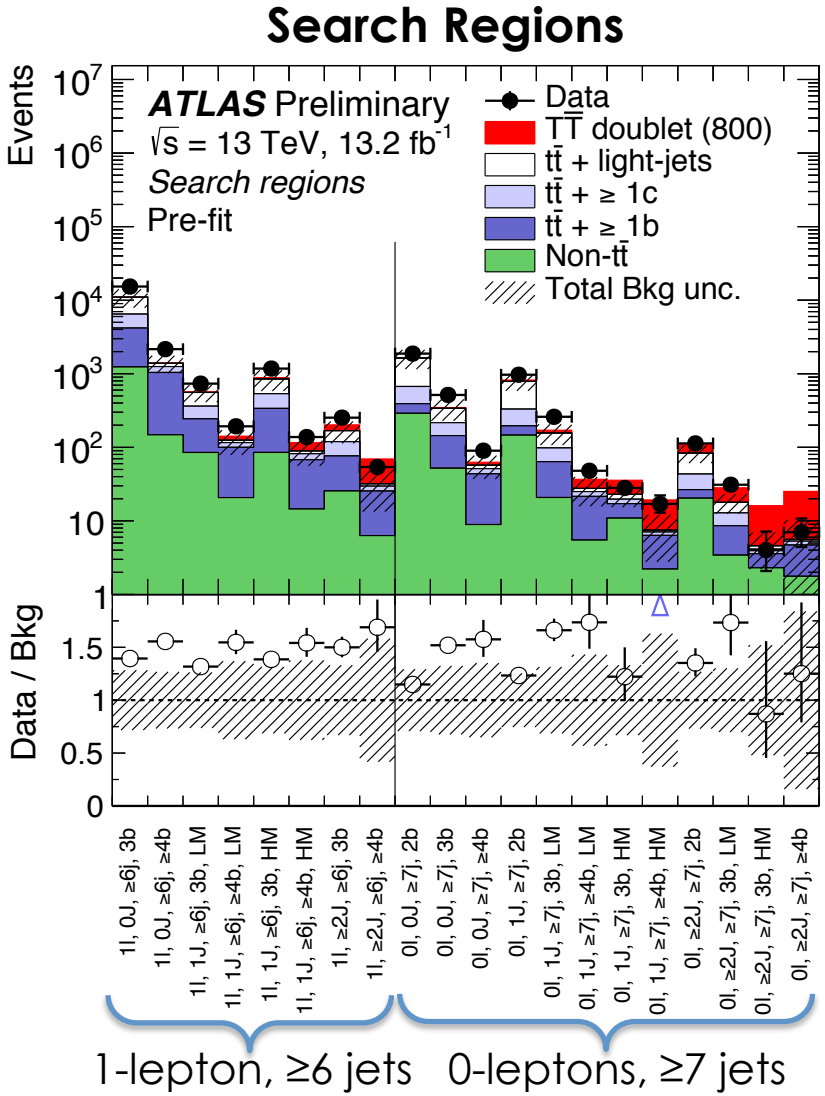
Perform a likelihood fit to m_{eff} in all "search regions"

- Systematic uncertainties treated as nuisance parameters
  - Can change shape and/or normalization of predictions
  - Dominant uncertainties:
    - *tt* and *tt*+heavy flavor modeling
    - *b*-tagging efficiencies
  - *tt*+≥1*b* normalization allowed to float ⇒ post-fit value: 1.2 ± 0.3

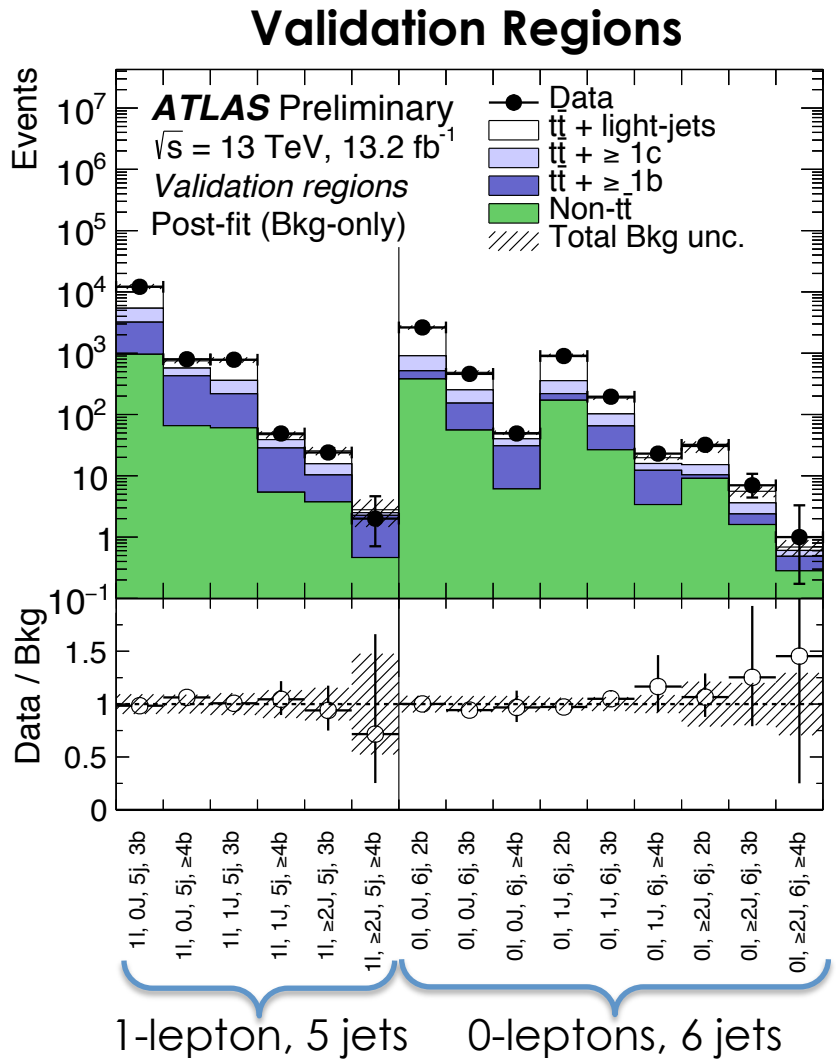


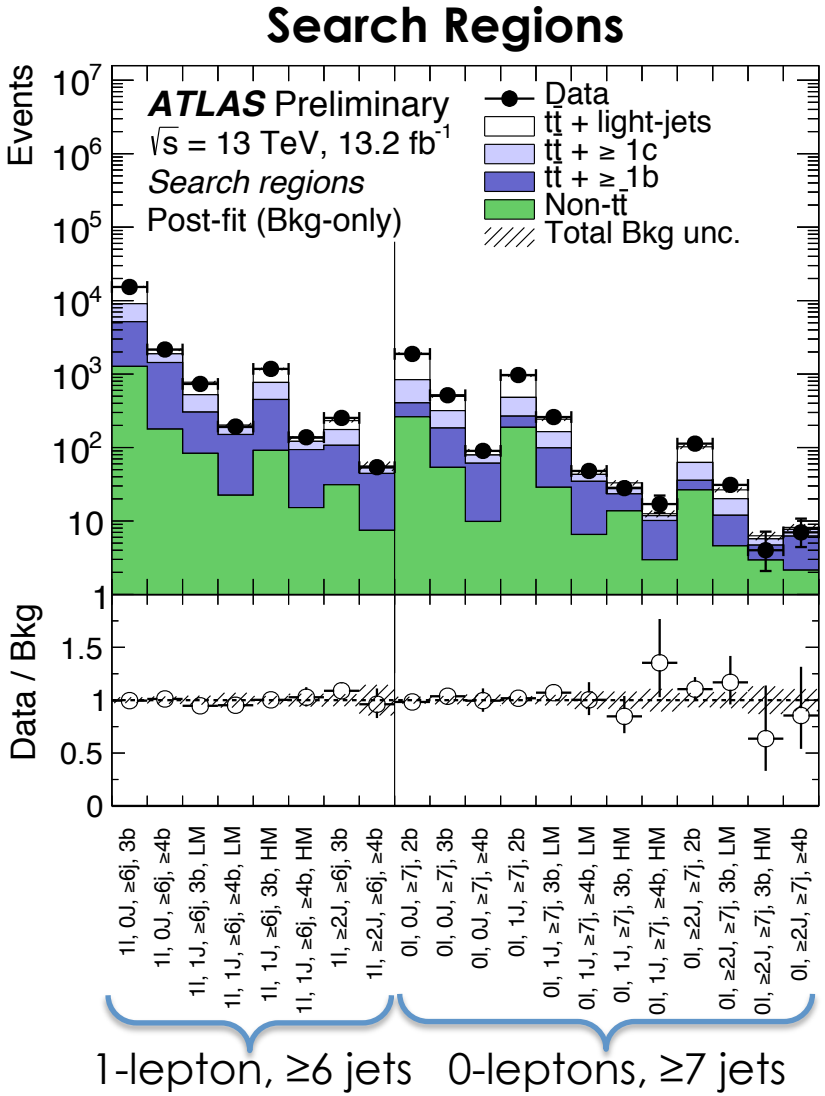
Ht+X: Pre-fit


Validation Regions
ATLAS Preliminary
√s = 13 TeV, 13.2 fb-1
Validation regions
Pre-fit
Data
TT̄ doublet (800)
tt̄ + light-jets
tt̄ + ≥ 1c
tt̄ + ≥ 1b
Non-tt̄
Total Bkg unc.
Events
Data / Bkg
1l, 0J, 5j, 3b
1l, 0J, 5j, ≥4b
1l, 1J, 5j, 3b
1l, 1J, 5j, ≥4b
1l, ≥2J, 5j, 3b
1l, ≥2J, 5j, ≥4b
0l, 0J, 6j, 2b
0l, 0J, 6j, 3b
0l, 0J, 6j, ≥4b
0l, 1J, 6j, 2b
0l, 1J, 6j, 3b
0l, 1J, 6j, ≥4b
0l, ≥2J, 6j, 2b
0l, ≥2J, 6j, 3b
0l, ≥2J, 6j, ≥4b
1-lepton, 5 jets
0-leptons, 6 jets


Search Regions
ATLAS Preliminary
√s = 13 TeV, 13.2 fb-1
Search regions
Pre-fit
Data
TT̄ doublet (800)
tt̄ + light-jets
tt̄ + ≥ 1c
tt̄ + ≥ 1b
Non-tt̄
Total Bkg unc.
Events
Data / Bkg
1l, 0J, ≥6j, 3b
1l, 0J, ≥6j, ≥4b
1l, 1J, ≥6j, 3b, LM
1l, 1J, ≥6j, ≥4b, LM
1l, 1J, ≥6j, 3b, HM
1l, 1J, ≥6j, ≥4b, HM
1l, ≥2J, ≥6j, 3b
1l, ≥2J, ≥6j, ≥4b
0l, 0J, ≥7j, 2b
0l, 0J, ≥7j, 3b
0l, 0J, ≥7j, ≥4b
0l, 1J, ≥7j, 2b
0l, 1J, ≥7j, 3b, LM
0l, 1J, ≥7j, ≥4b, LM
0l, 1J, ≥7j, 3b, HM
0l, 1J, ≥7j, ≥4b, HM
0l, ≥2J, ≥7j, 2b
0l, ≥2J, ≥7j, 3b, LM
0l, ≥2J, ≥7j, 3b, HM
0l, ≥2J, ≥7j, ≥4b
1-lepton, ≥6 jets
0-leptons, ≥7 jets

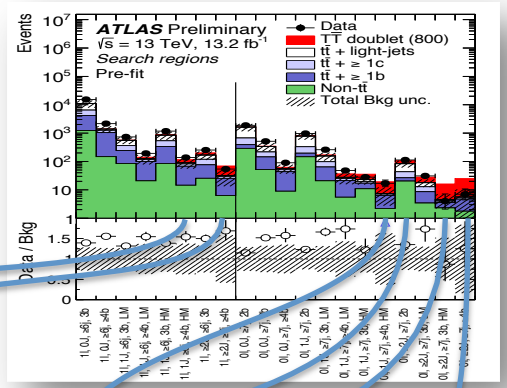
Ht+X: Post-fit

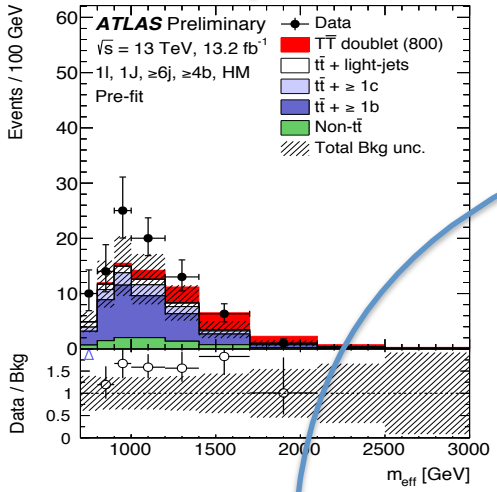

Validation Regions
ATLAS Preliminary
√s = 13 TeV, 13.2 fb-1
Validation regions
Post-fit (Bkg-only)
Data
tt̄ + light-jets
tt̄ + ≥ 1c
tt̄ + ≥ 1b
Non-tt̄
Total Bkg unc.
Events
Data / Bkg
1l, 0J, 5j, 3b
1l, 0J, 5j, ≥4b
1l, 1J, 5j, 3b
1l, 1J, 5j, ≥4b
1l, ≥2J, 5j, 3b
1l, ≥2J, 5j, ≥4b
0l, 0J, 6j, 2b
0l, 0J, 6j, 3b
0l, 0J, 6j, ≥4b
0l, 1J, 6j, 2b
0l, 1J, 6j, 3b
0l, 1J, 6j, ≥4b
0l, ≥2J, 6j, 2b
0l, ≥2J, 6j, 3b
0l, ≥2J, 6j, ≥4b
1-lepton, 5 jets
0-leptons, 6 jets

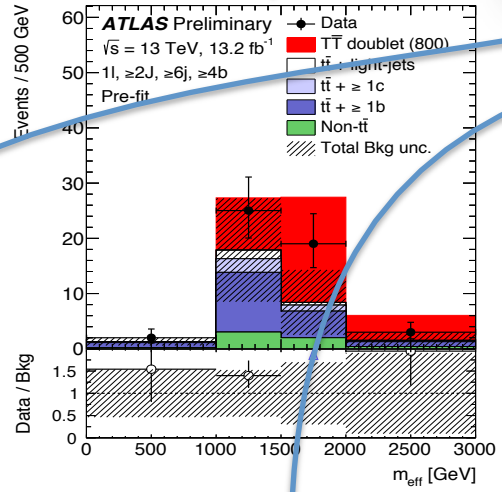

Search Regions
ATLAS Preliminary
√s = 13 TeV, 13.2 fb-1
Search regions
Post-fit (Bkg-only)
Data
tt̄ + light-jets
tt̄ + ≥ 1c
tt̄ + ≥ 1b
Non-tt̄
Total Bkg unc.
Events
Data / Bkg
1l, 0J, ≥6j, 3b
1l, 0J, ≥6j, ≥4b
1l, 1J, ≥6j, 3b, LM
1l, 1J, ≥6j, ≥4b, LM
1l, 1J, ≥6j, 3b, HM
1l, 1J, ≥6j, ≥4b, HM
1l, ≥2J, ≥6j, 3b
1l, ≥2J, ≥6j, ≥4b
0l, 0J, ≥7j, 2b
0l, 0J, ≥7j, 3b
0l, 0J, ≥7j, ≥4b
0l, 1J, ≥7j, 2b
0l, 1J, ≥7j, 3b, LM
0l, 1J, ≥7j, ≥4b, LM
0l, 1J, ≥7j, 3b, HM
0l, 1J, ≥7j, ≥4b, HM
0l, ≥2J, ≥7j, 2b
0l, ≥2J, ≥7j, 3b, LM
0l, ≥2J, ≥7j, 3b, HM
0l, ≥2J, ≥7j, ≥4b
1-lepton, ≥6 jets
0-leptons, ≥7 jets

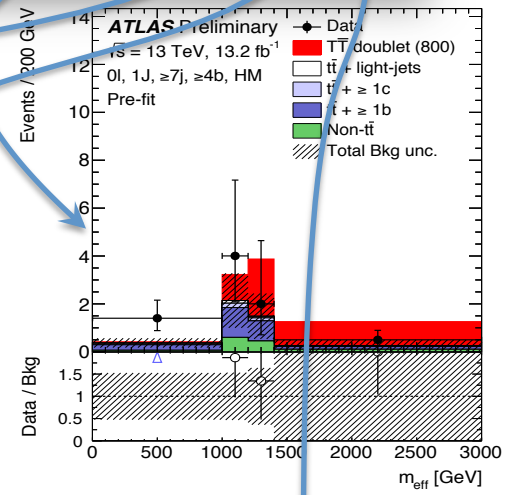
Ht+X: m_{eff}

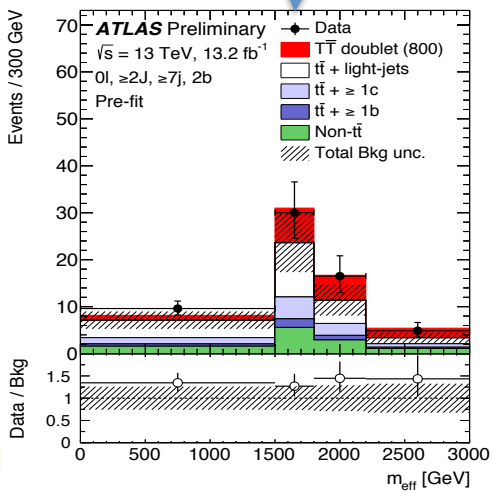
m_{eff} in most sensitive regions, pre-fit

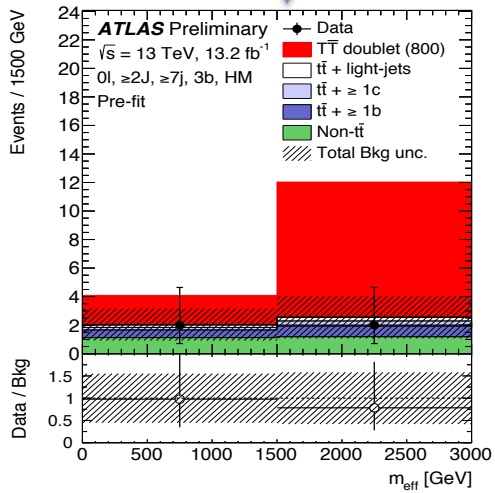


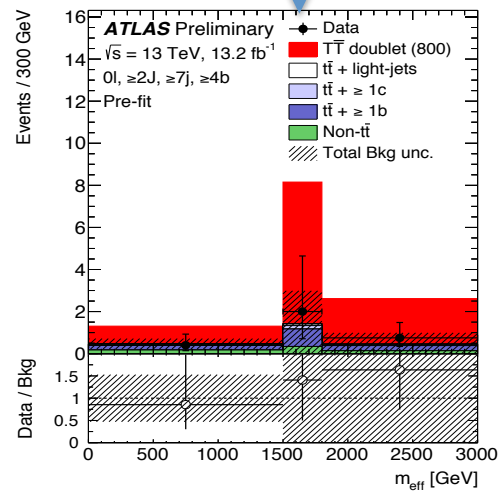






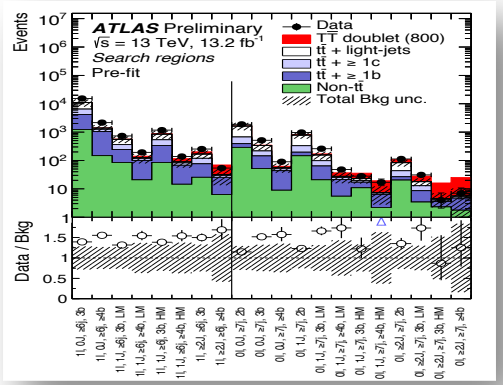


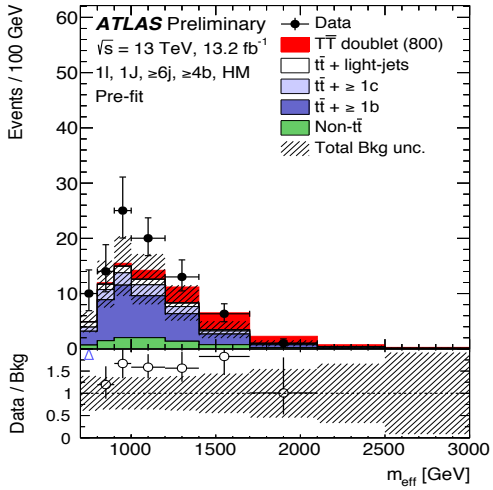


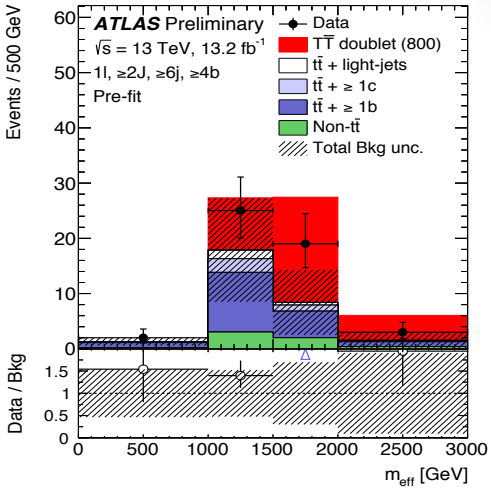


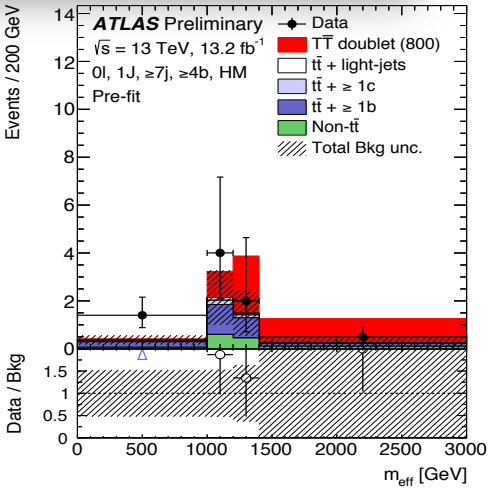
Ht+X: m_{eff}

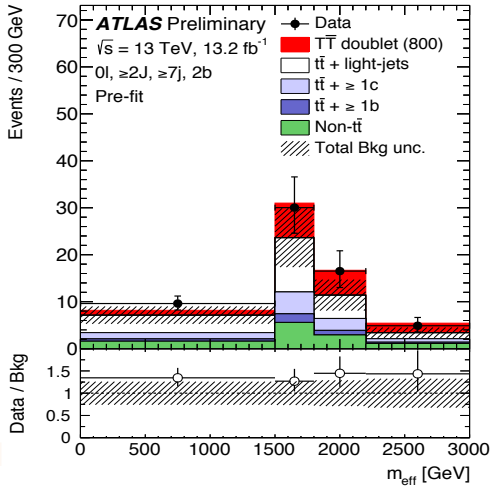
m_{eff} in most sensitive regions, pre-fit

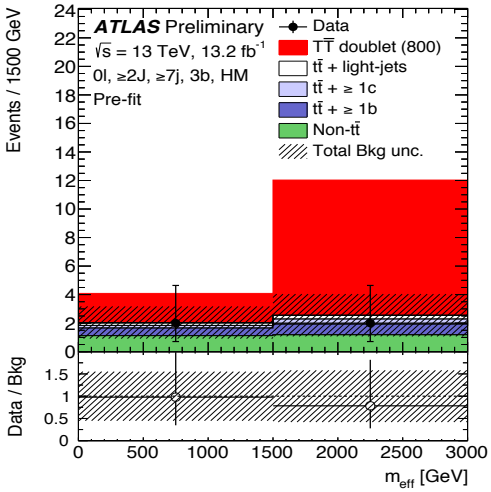


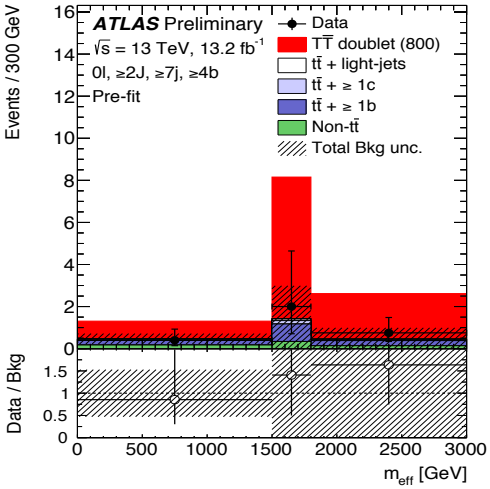








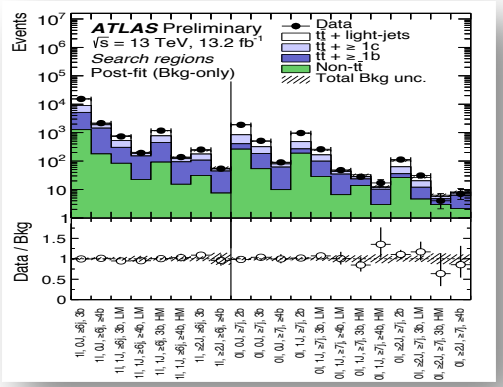


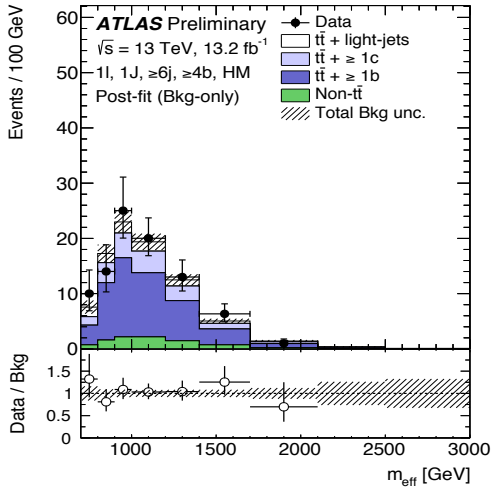


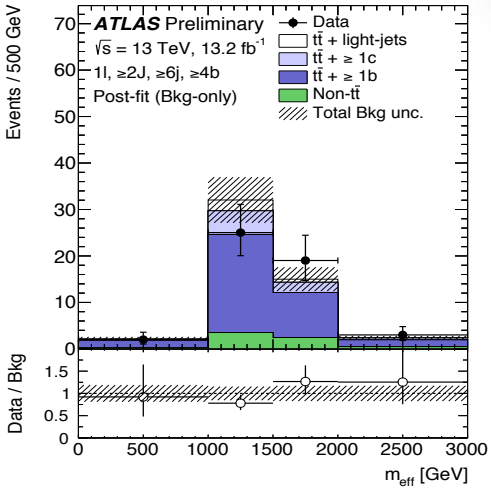
Ht+X: m_{eff}

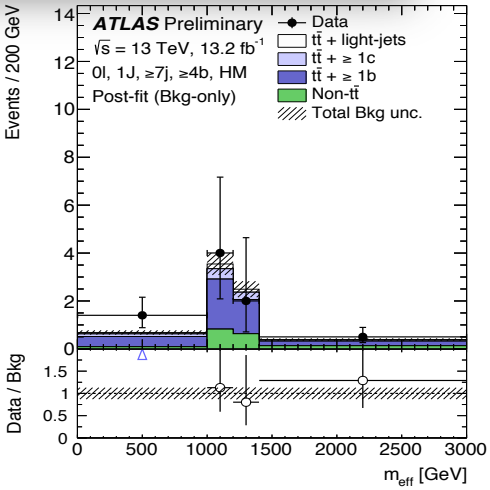
m_{eff} in most sensitive regions, post-fit

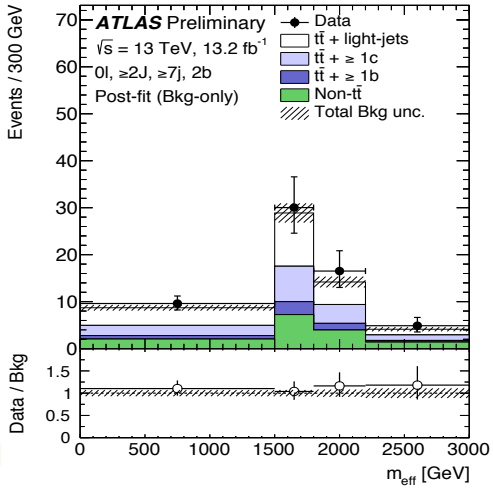
⇒ Looks to be consistent with SM

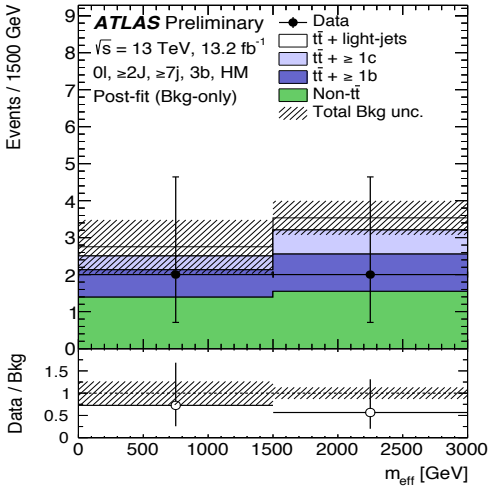


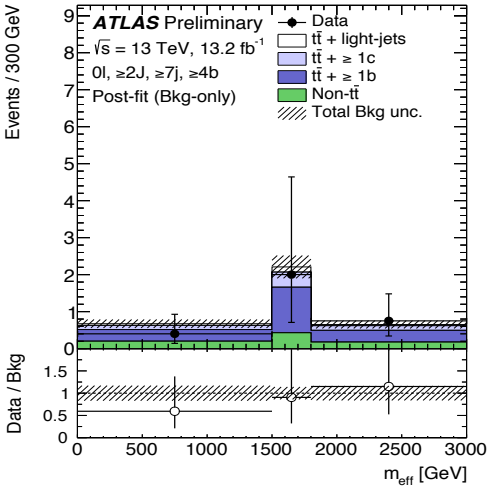








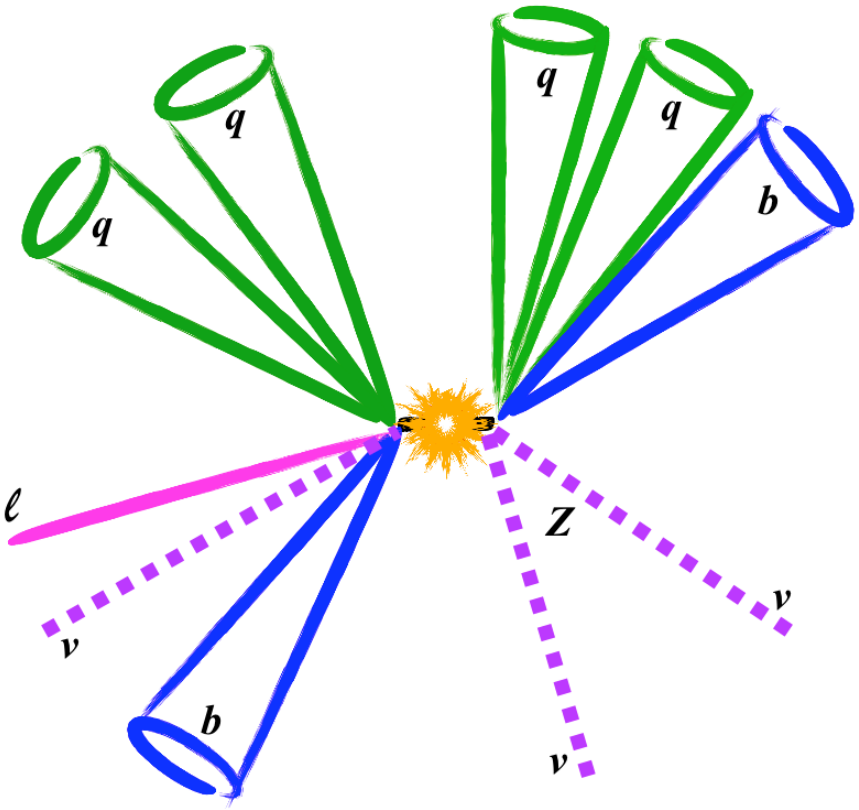




Before going to the limits, let's see if there are any hints in the other decay modes…

Accepted by JHEP [arXiv:1705.10751]

Zt+X



Targeting $Z \rightarrow \nu\nu$ decay

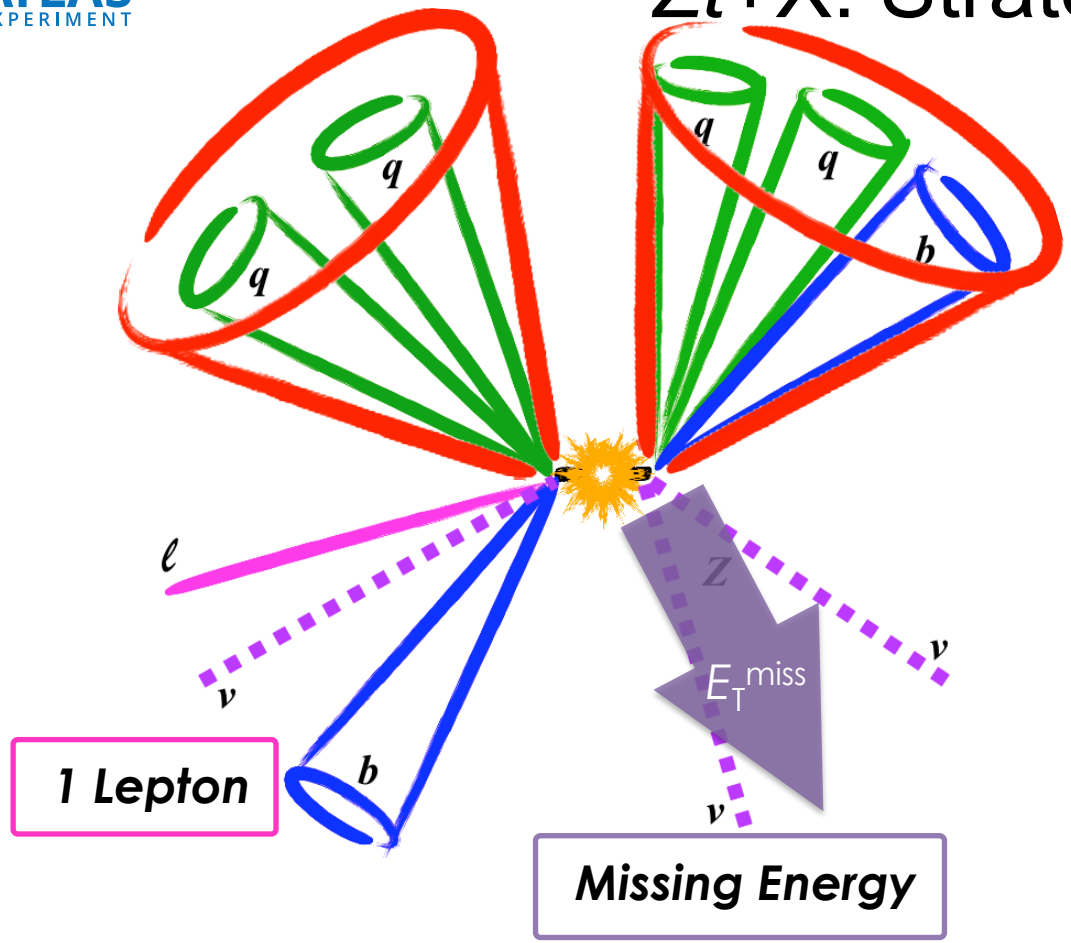
$TT \rightarrow ZtZt \rightarrow \nu\nu\ Wb\ qq\ Wb$

$TT \rightarrow ZtHt \rightarrow \nu\nu\ Wb\ bb\ Wb$

$TT \rightarrow ZtWb \rightarrow \nu\nu\ Wb\ Wb$

- With one $W \rightarrow \ell\nu$

Zt+X: Strategy



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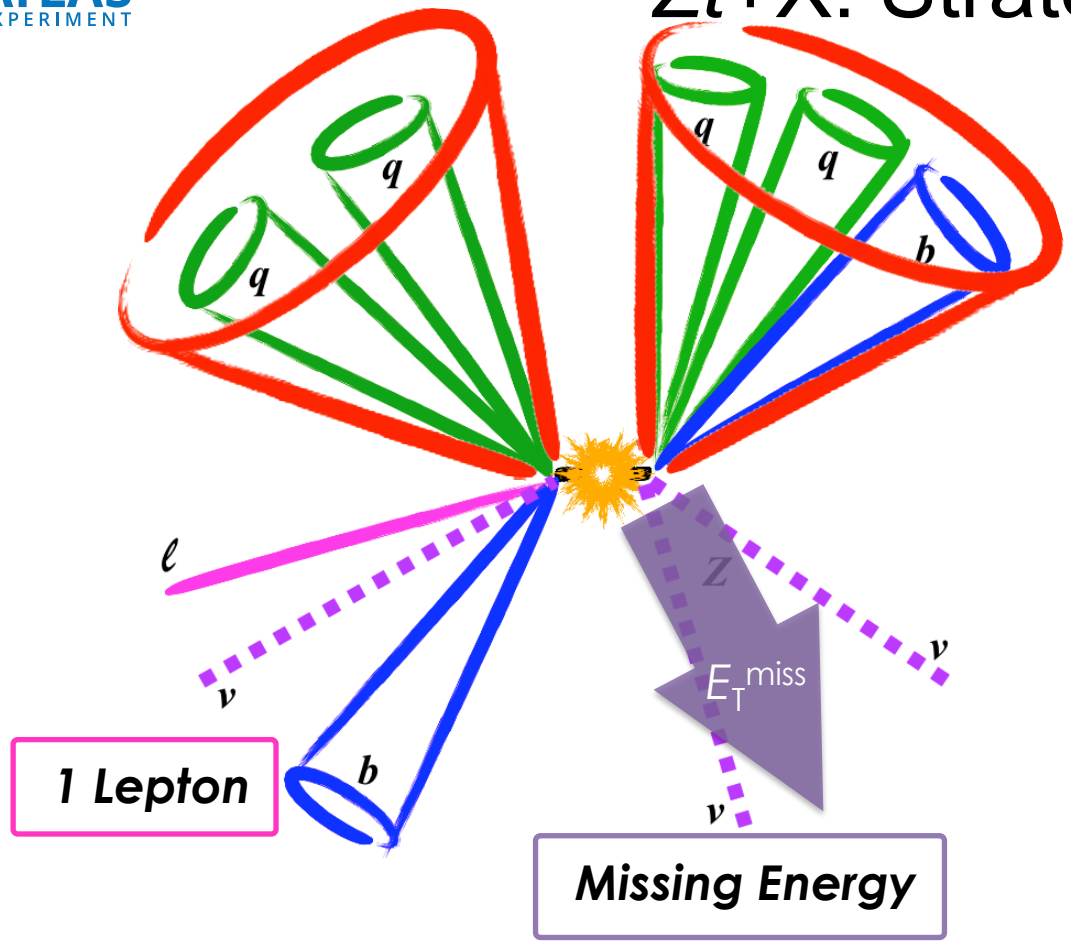
- With one $W \rightarrow \ell\nu$

≥ 4 small-R jets
- ≥ 1 b-tagged

2 large-R jets

Zt+X: Strategy



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- With one $W \rightarrow \ell\nu$

≥ 4 small-R jets
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2 large-R jets

Cut-and-count analysis
- Signal Region (Bin) – Kinematic cuts to optimize VLQ sensitivity
- Control Regions – To fit *tt* and *W*+jets normalizations
- Validation Regions – To check modeling of backgrounds

Zt+X: Regions

Variable	Signal Region
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 350 GeV
m_{T}^{W}	> 170 GeV
am_{T2}	> 175 GeV
m_{T2}^{τ}	> 80 GeV
$H_{\mathrm{T,sig}}^{\mathrm{miss}}$	> 12
Jet p_{T}	$> 120, 80, 50, 25$ GeV
$\lvert\Delta\phi(j_i, E_{\mathrm{T}}^{\mathrm{miss}})\rvert$, $i = 1, 2$	> 0.4
# b-tagged jets	≥ 1
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Large-radius jet mass	$> 80, 60$ GeV
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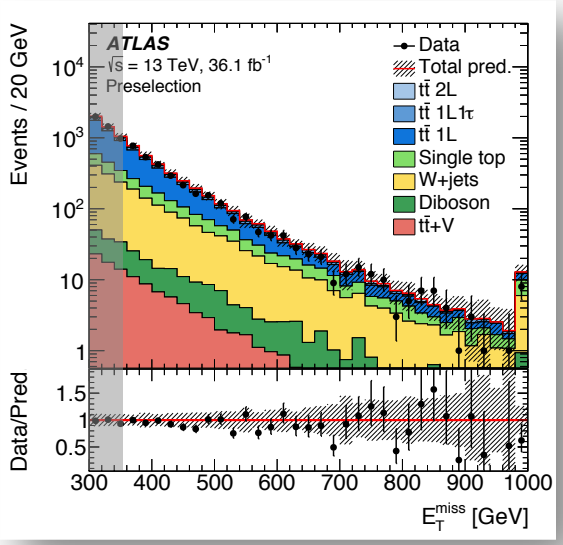

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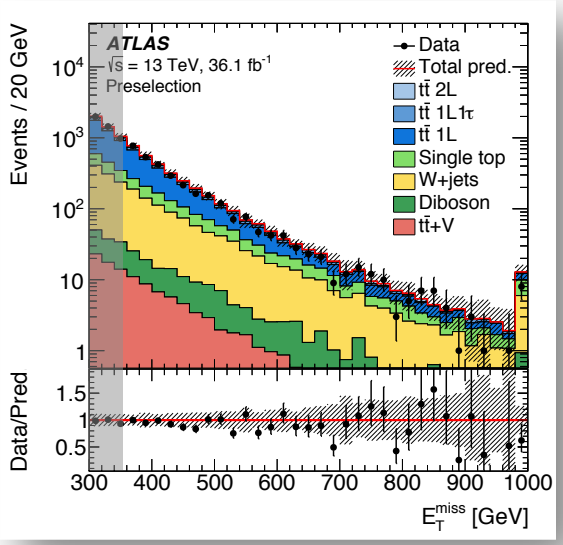

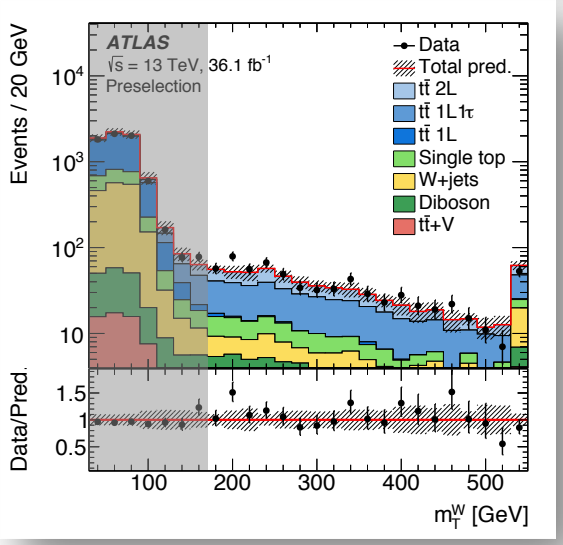

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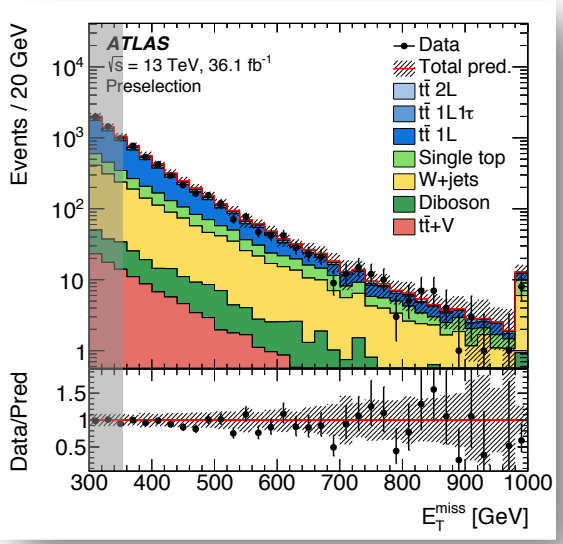

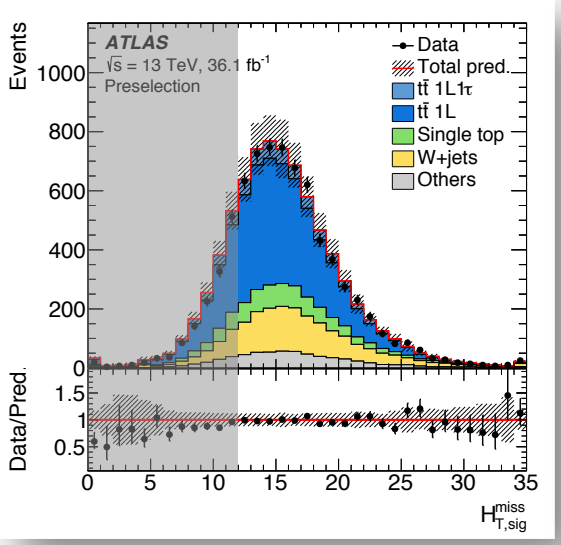

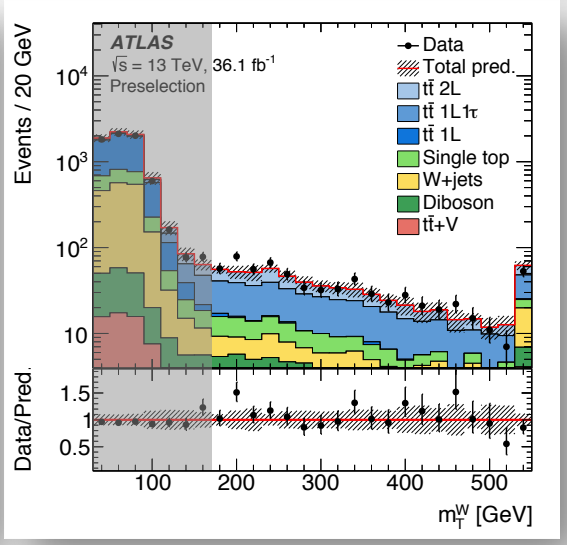

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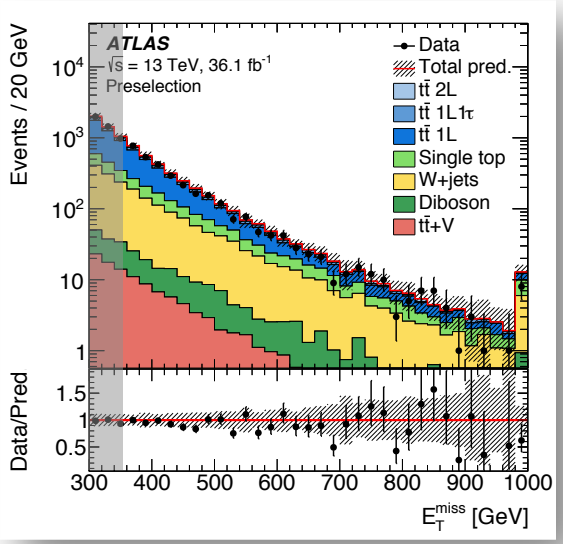

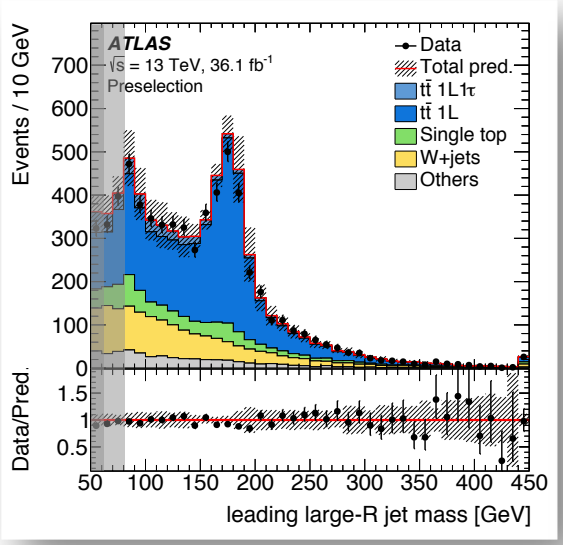

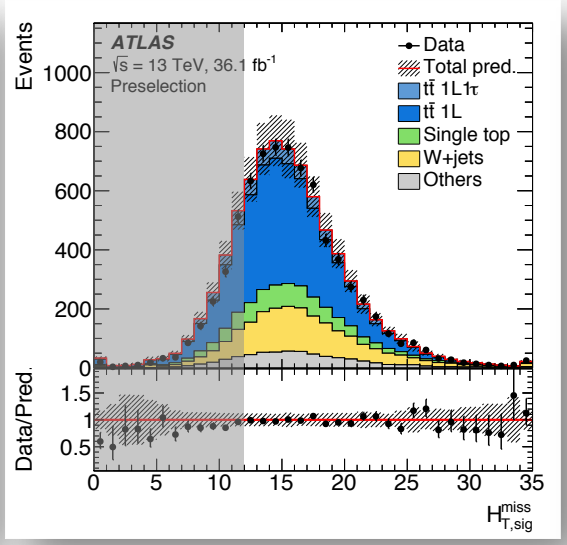

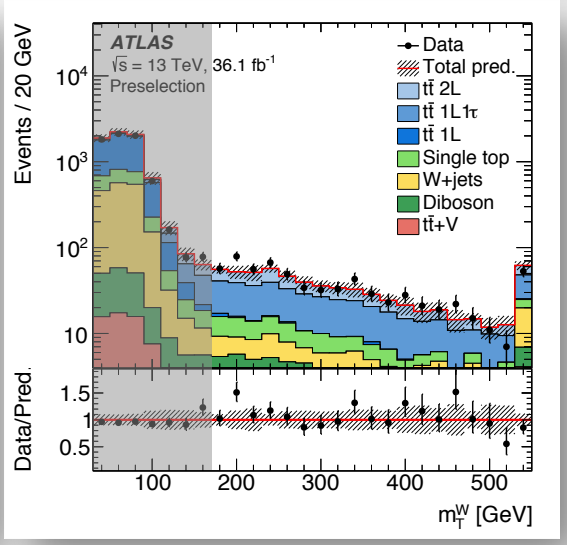

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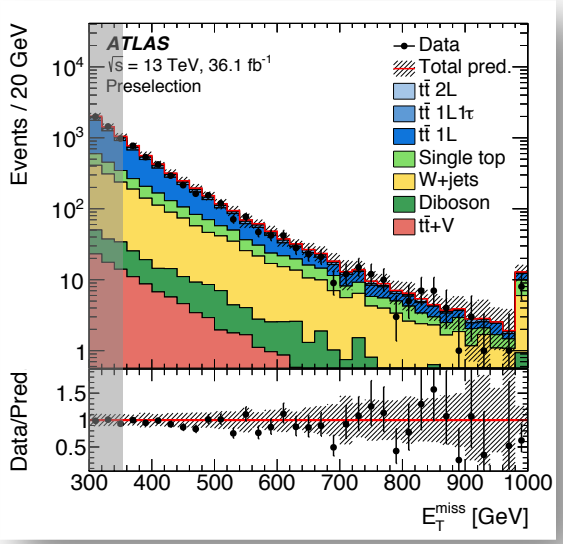
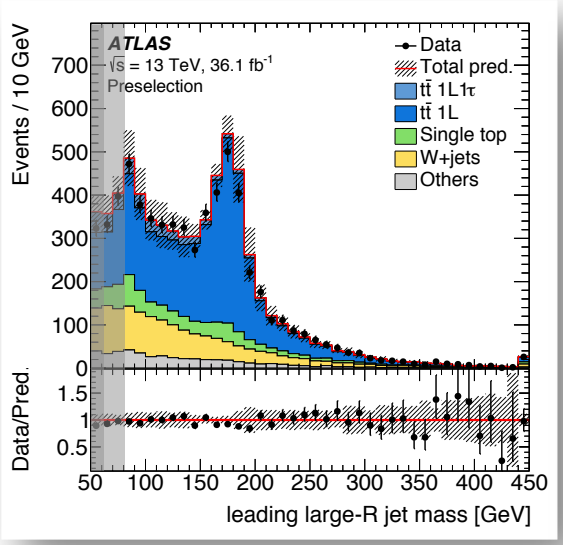
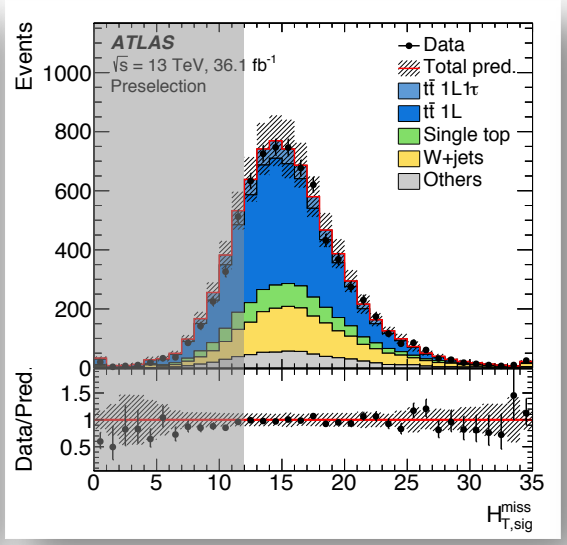
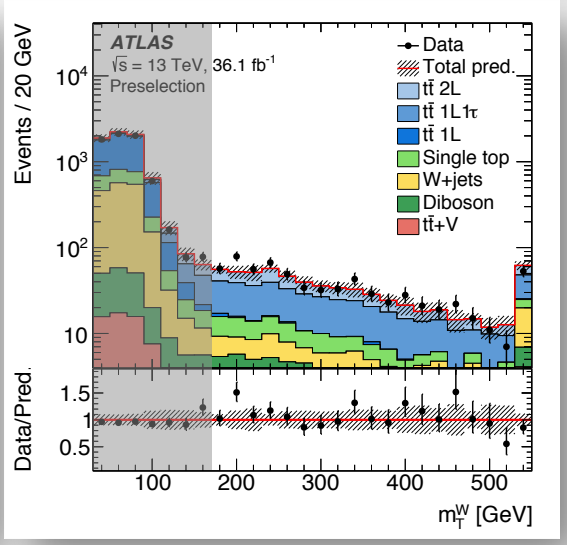
Next slide...









Zt+X: m_{T2}

E_T^{miss} can be coming from multiple decays

- Use a generalization of m_T that allows the missing momentum to come from two decays:

$$m_{T2} \equiv \min\{ \max[m_{Ta}, m_{Tb}] \}$$

- m_{Ta} and m_{Tb} are calculated from given visible particles, plus part of the missing momentum

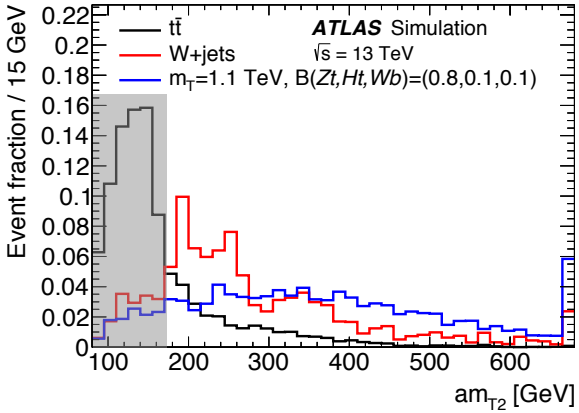
This analysis uses two such variables:

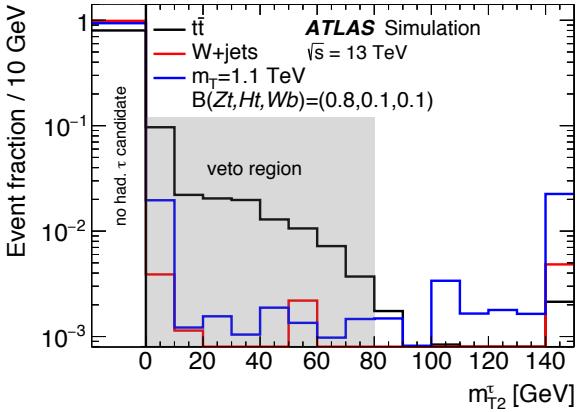
am_{T2} : $m_{Ta}(\ell + b + E_t^{miss,a})$, $m_{Tb}(b + E_T^{miss,b})$

- Reduce dileptonic tt events
- Kinematic endpoint at m_{top}

m_{T2}^{τ} : $m_{Ta}(\ell + E_t^{miss,a})$, $m_{Tb}(\tau + E_t^{miss,b})$

- Reduce dileptonic tt with $W \rightarrow \tau\nu$ (only constructed if τ is found)
- Kinematic endpoint at m_W





Zt+X: Signal Region (SR)

Variable	Signal Region
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 350 GeV
m_{T}^{W}	> 170 GeV
am_{T2}	> 175 GeV
m_{T2}^{τ}	> 80 GeV
$H_{\mathrm{T,sig}}^{\mathrm{miss}}$	> 12
Jet p_{T}	$> 120, 80, 50, 25$ GeV
$\lvert\Delta\phi(j_i, E_{\mathrm{T}}^{\mathrm{miss}})\rvert$, $i = 1, 2$	> 0.4
# b-tagged jets	≥ 1
# large-radius jets	≥ 2
Large-radius jet mass	$> 80, 60$ 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

Region	SR
Observed events	
Fitted bkg events	6.1 ± 1.9
Fitted $t\bar{t}$ events	2.5 ± 1.7
Fitted W + jets events	1.1 ± 0.7
Fitted singletop events	1.1 ± 0.7
Fitted $t\bar{t} + V$ events	0.91 ± 0.20
Fitted diboson events	0.6 ± 0.6
MC exp. bkg events	6.5
Singlet (Doublet) *T* w/ *m*=1 TeV	5 (10)

Main background is *tt*
Followed by *W*+jets and single-top

⇒ Use Control Regions to determine normalization of *tt* and *W*+jets

Zt+X: Control Regions

Variable	Signal Region	TCR	WCR
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 350 GeV	> 300 GeV	
m_{T}^{W}	> 170 GeV	$\in [30, 90]$ GeV	
am_{T2}	> 175 GeV	> 100 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	$= 0$
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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	

CRs:

- Enhanced in *tt* or *W*+jets
- Orthogonal to SR

Region	SR	TCR	WCR
Observed events		437	303
Fitted bkg events	6.1 ± 1.9	437 ± 21	303 ± 17
Fitted $t\bar{t}$ events	2.5 ± 1.7	280 ± 40	38 ± 15
Fitted W + jets events	1.1 ± 0.7	70 ± 28	224 ± 27
Fitted singletop events	1.1 ± 0.7	63 ± 24	10 ± 5
Fitted $t\bar{t} + V$ events	0.91 ± 0.20	9.7 ± 1.6	1.03 ± 0.30
Fitted diboson events	0.6 ± 0.6	11 ± 5	30 ± 12
MC exp. bkg events	6.5	450	398

Singlet (Doublet) *T* w/ *m*=1 TeV 5 (10)

Zt+X: Control Regions

Variable	Signal Region	TCR	WCR
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 350 GeV	> 300 GeV	
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Singlet (Doublet) *T* w/ *m*=1 TeV 5 (10)

CRs:

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- Orthogonal to SR

Perform simultaneously fit in SR and CRs

- *tt* scaled by 1.05 ± 0.17
- *W*+jets scaled by 0.70 ± 0.10
- Sensitivity dominated by stat. uncertainty: $\sqrt{6.1} = 2.5$

Zt+X: Control Regions

Variable	Signal Region	TCR	WCR
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Perform simultaneously fit in SR and CRs

- *tt* scaled by 1.05 ± 0.17
- *W*+jets scaled by 0.70 ± 0.10
- Sensitivity dominated by stat. uncertainty: √6.1 = 2.5

Use Validation Regions to check modeling of *tt*, *W*+jets, and single-top…

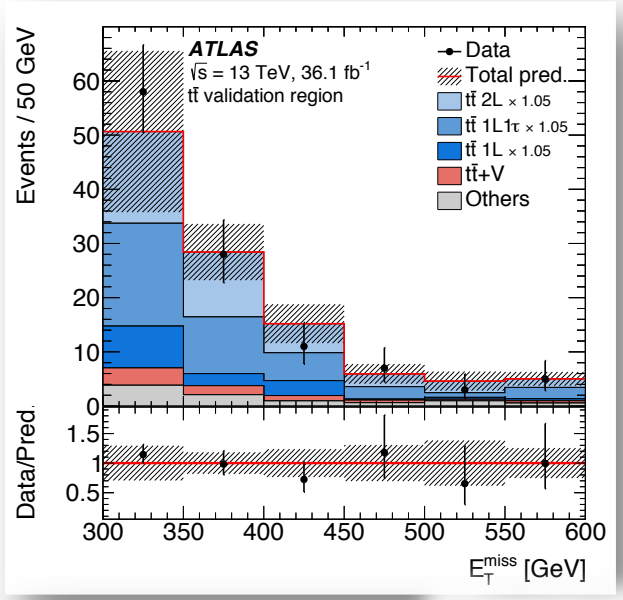
Zt+X: Validation Regions

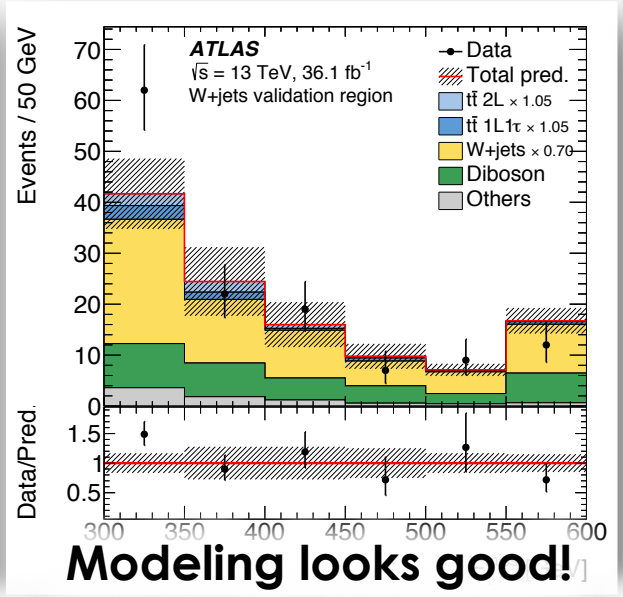
Variable	Signal Region	TCR	WCR	TVR	WVR	STVR
$E_{\mathrm{T}}^{\mathrm{miss}}$	> 350 GeV	> 300 GeV		> 300 GeV		
m_{T}^{W}	> 170 GeV	$\in [30, 90]$ GeV		> 120 GeV		> 60 GeV
am_{T2}	> 175 GeV	> 100 GeV		$\in [100, 200]$ GeV	> 100 GeV	> 200 GeV
m_{T2}^{τ}	> 80 GeV	> 80 GeV		> 80 GeV		
$H_{\mathrm{T,sig}}^{\mathrm{miss}}$	> 12	–		–		
Jet p_{T}	$> 120, 80, 50, 25$ GeV	$> 120, 80, 50, 25$ GeV		$> 120, 80, 50, 25$ GeV		
$\lvert\Delta\phi(j_i, E_{\mathrm{T}}^{\mathrm{miss}})\rvert$, $i = 1, 2$	> 0.4	> 0.4		> 0.4		
# b-tagged jets	≥ 1	≥ 1	$= 0$	≥ 1	$= 0$	≥ 2
# large-radius jets	≥ 2	≥ 2		$= 1$		
Large-radius jet mass	$> 80, 60$ GeV	$> 80, 60$ 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		> 200 GeV		

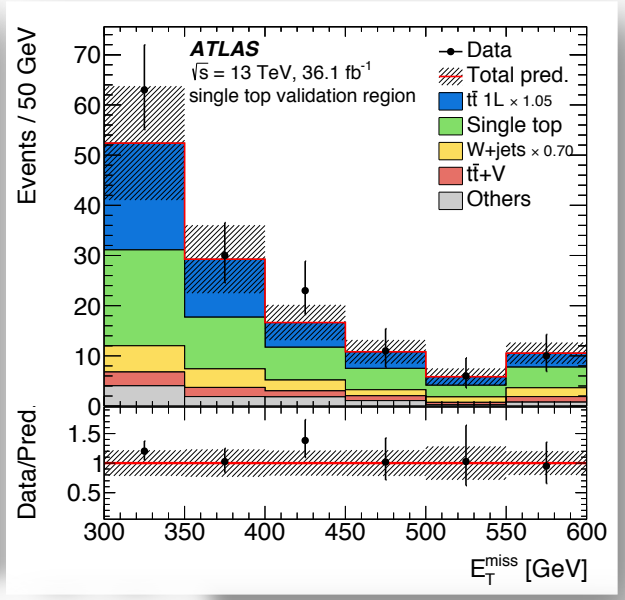
Region	SR	TCR	WCR	TVR	WVR	STVR
Observed events		437	303	112	131	143
Fitted bkg events	6.1 ± 1.9	437 ± 21	303 ± 17	109 ± 35	127 ± 31	125 ± 27
Fitted $t\bar{t}$ events	2.5 ± 1.7	280 ± 40	38 ± 15	90 ± 40	15 ± 8	53 ± 23
Fitted W + jets events	1.1 ± 0.7	70 ± 28	224 ± 27	3.5 ± 2.0	77 ± 30	15 ± 7
Fitted singletop 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

Singlet (Doublet) T w/ m=1 TeV 5 (10)

Zt+X: Validation Regions

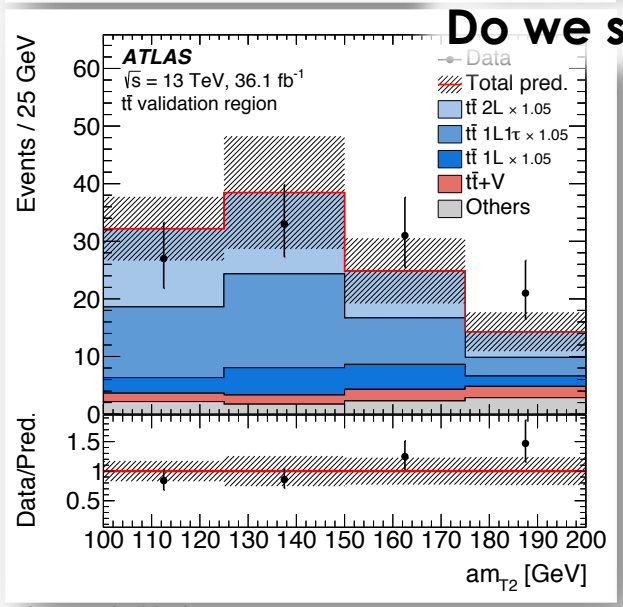


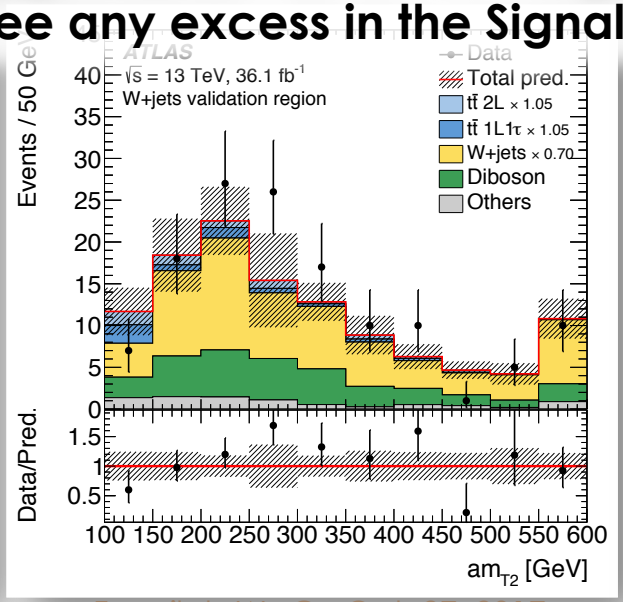


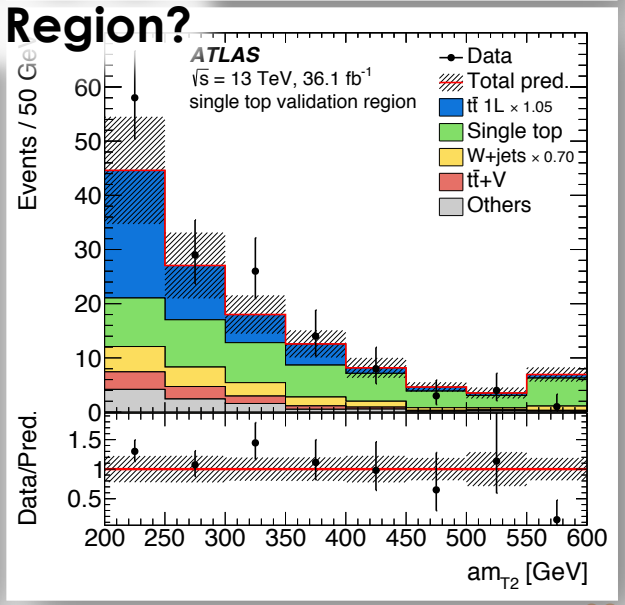


Modeling looks good!

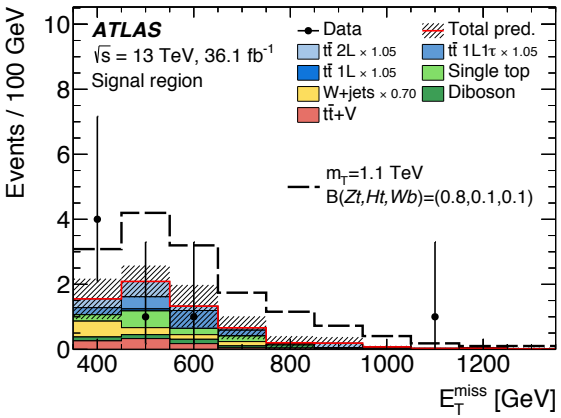
Do we see any excess in the Signal Region?

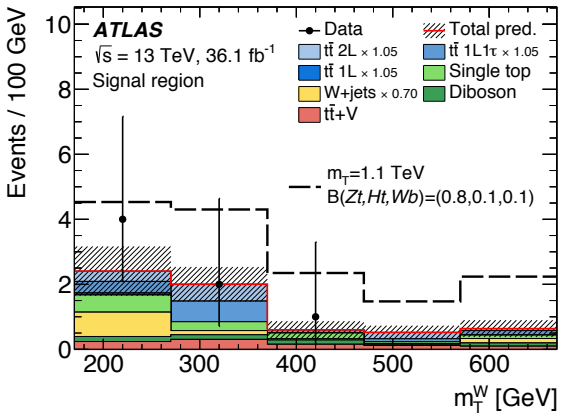


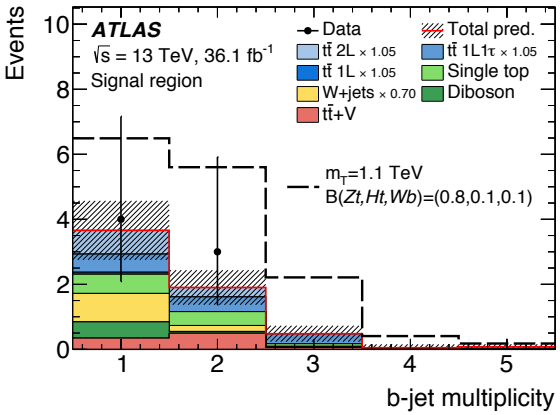




Zt+X: Signal Region







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Singlet (Doublet) *T* w/ *m*=1 TeV 5 (10)

⇒ Also consistent with SM

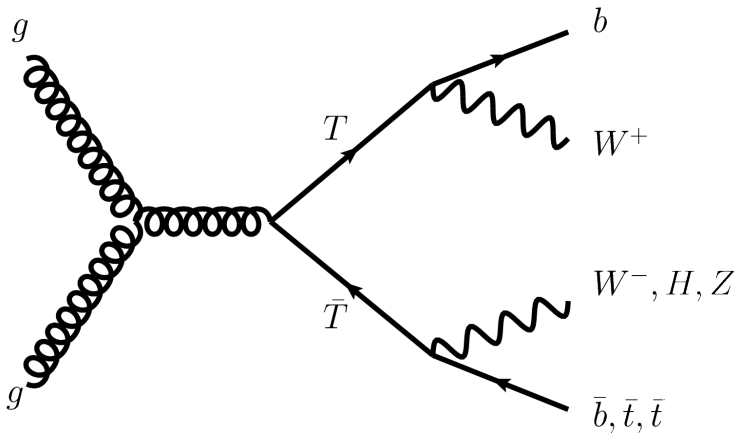
Wb+X

Targeting W→ℓν decay

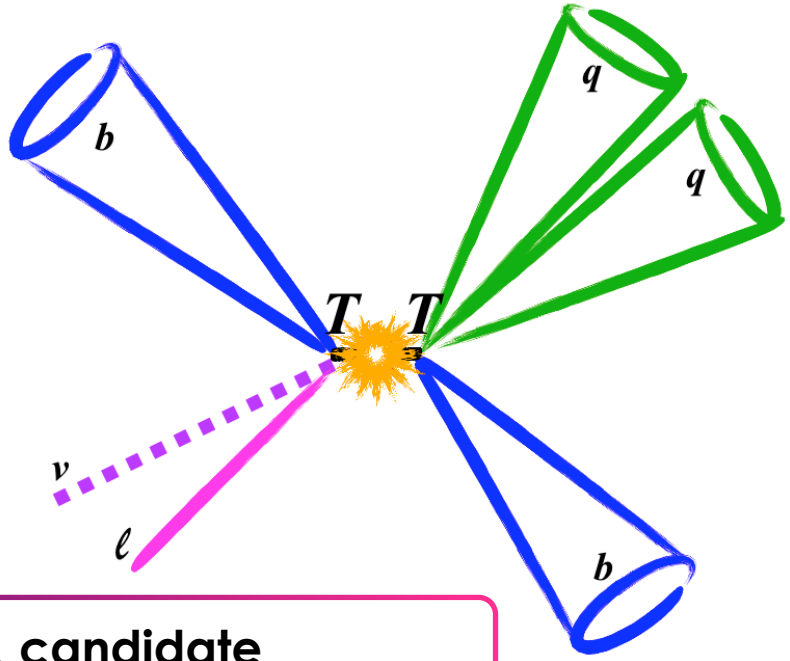
TT → WbWb → ℓν b qq b

TT → WbHt → ℓν b bb Wb

TT → WbZt → ℓν b qq Wb



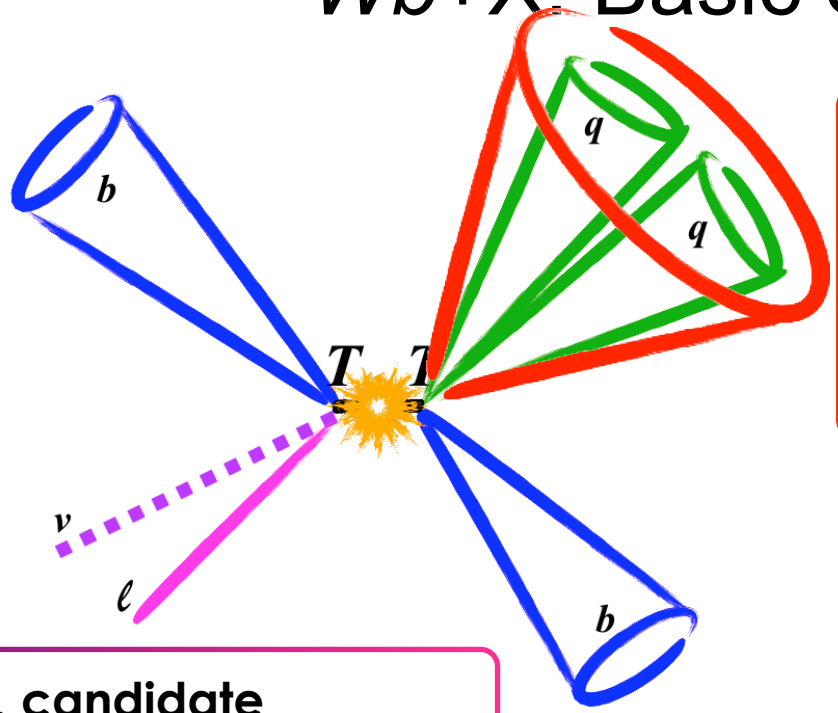
Wb+X: Basic Selection



W_{lep} candidate

- $\equiv 1\ e/\mu$, $p_T > 30$ GeV
- $E_T^{miss} > 60$ GeV
- Use m_W constraint to reconstruct neutrino

Wb+X: Basic Selection



Boosted W_{had} candidate

- R=1.0, anti-k_t jet trimmed
- m > 50 GeV, p_T > 200 GeV
- Jet substructure W-tag (50% efficiency)

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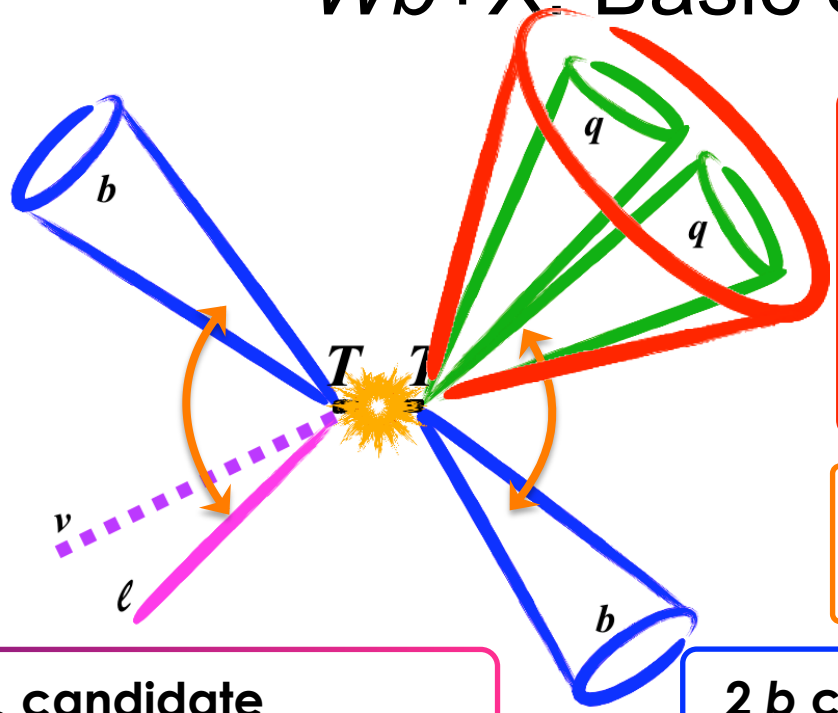

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$\Delta R(W_{had}, b) > 1.0$
$\Delta R(\ell, b) > 1.0$

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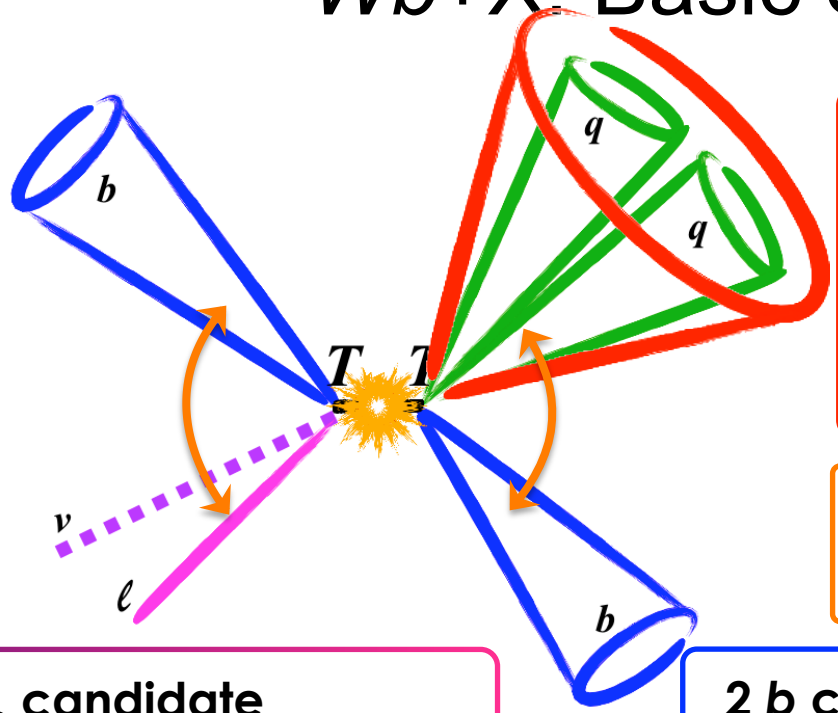
- Use m_W constraint to reconstruct neutrino

2 *b* candidates
- ≥ 2 additional small-R jets
  - p_T > 25 GeV
  - ≥ 1 *b*-tagged

Wb+X: Basic Selection



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  - ≥ 1 *b*-tagged

T_{had} *and* T_{lep} candidates
- Test all parings of *b* candidates with W_{had} or W_{lep}
- Pick combinaiton with smallest $|m_T^{lep} - m_T^{had}|$ < 300 GeV

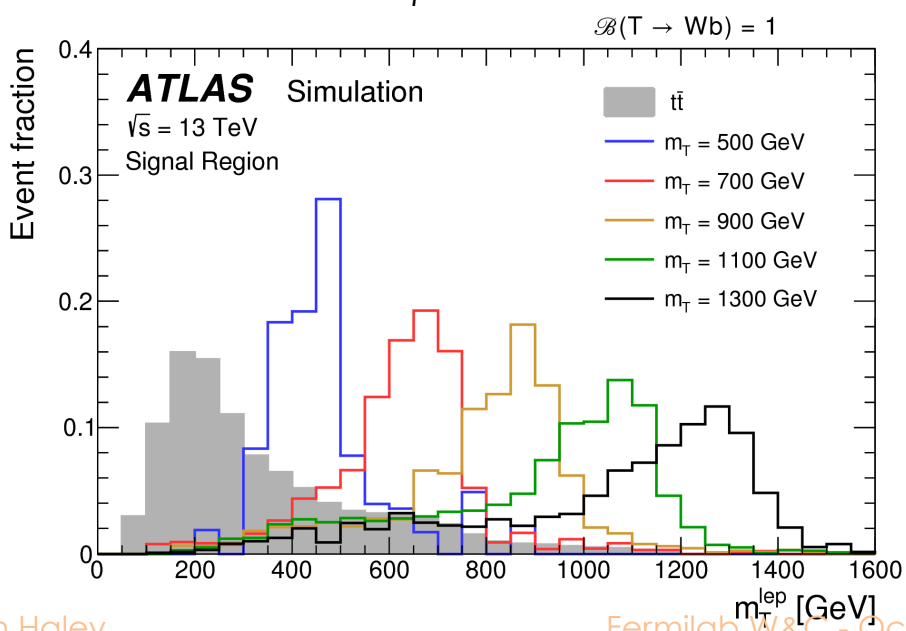
Wb+X: Final Selection

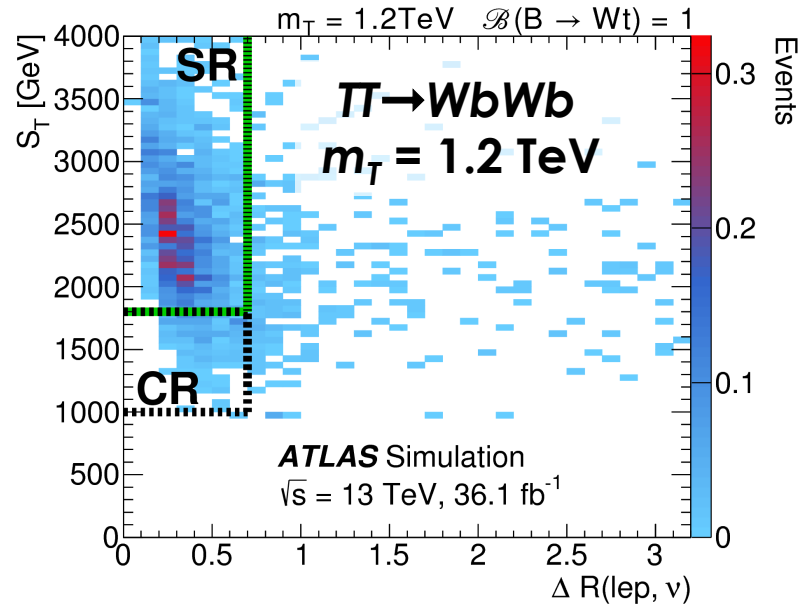
Signal Region (SR)

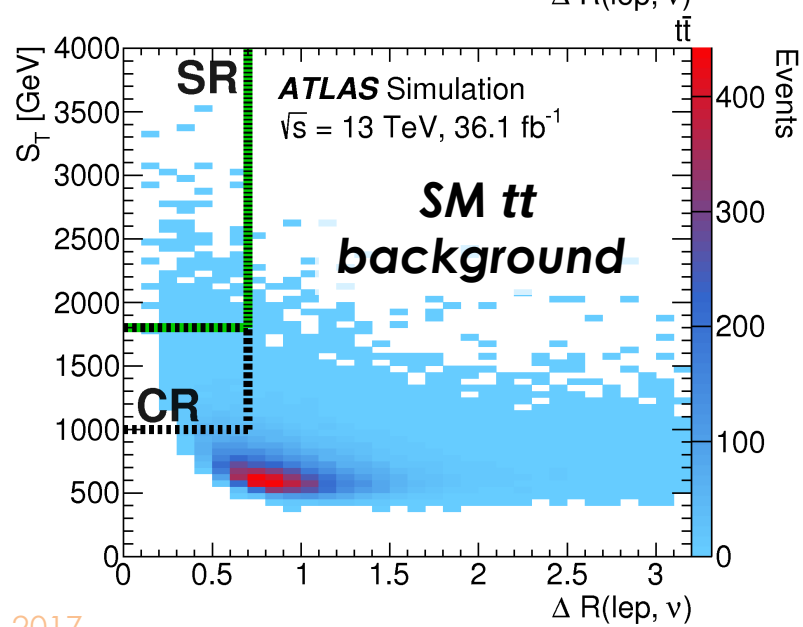
- Optimized for VLQ masses $\gtrsim$ 1 TeV
  - $\Delta R(\ell, \nu) < 0.7$
  - $S_T \equiv \sum p_T^{jets} + p_T^{\ell} + E_T^{miss} > 1200$ GeV

Control Region (CR) to constrain *tt*

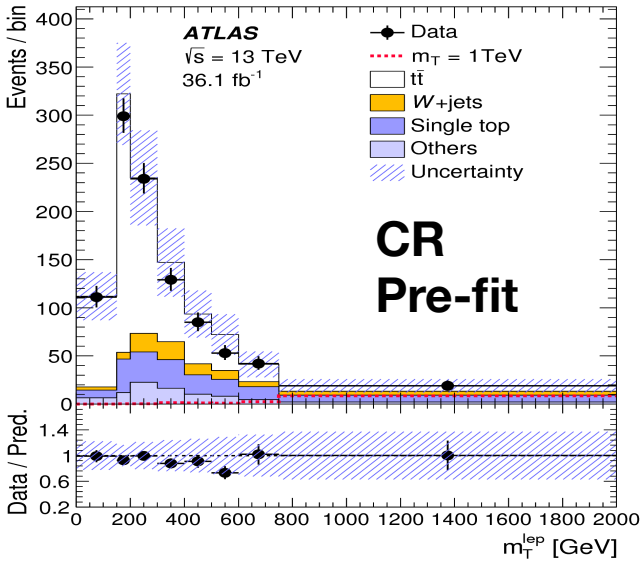
Final variable: m_T^{lep}







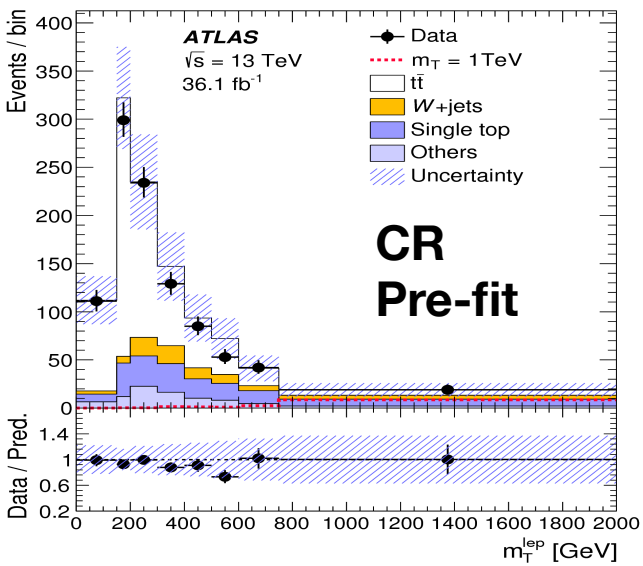
Wb+X: Backgrounds

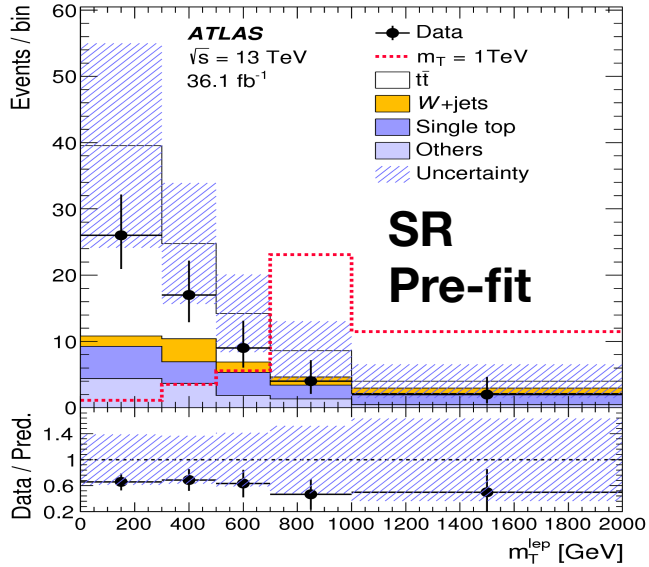


- Backgrounds estimated with MC simulations (expect multijet)
- Dominant uncertainties
  - Poisson uncertainty of data
  - Single-top *Wt* removal scheme
  - *tt* parton shower and generator
  - Jet energy resolution

Sample	Signal region	Control region
$t\bar{t}$	55 ± 26	720 ± 130
W+jets	9 ± 4	78 ± 41
Single top	15 ± 15	160 ± 110
Others (Z+jets, diboson, ttV, multijet)	12 ± 10	82 ± 66
Total Background	91 ± 35	$1\,040 \pm 200$
Signal ($m_T = 1$ TeV, $T \rightarrow Wb = 100\%$)	45 ± 4	15 ± 2
Signal ($m_T = 1$ TeV, SU(2) singlet)	21 ± 2	8 ± 1

Wb+X: Pre-fit





No sign of VLQs

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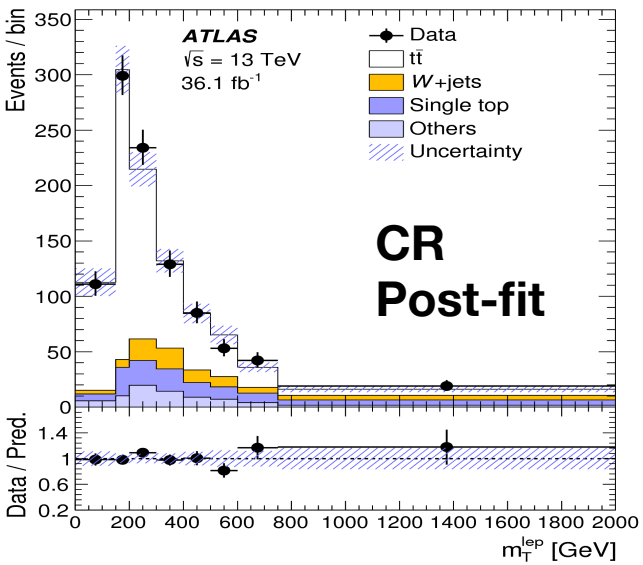
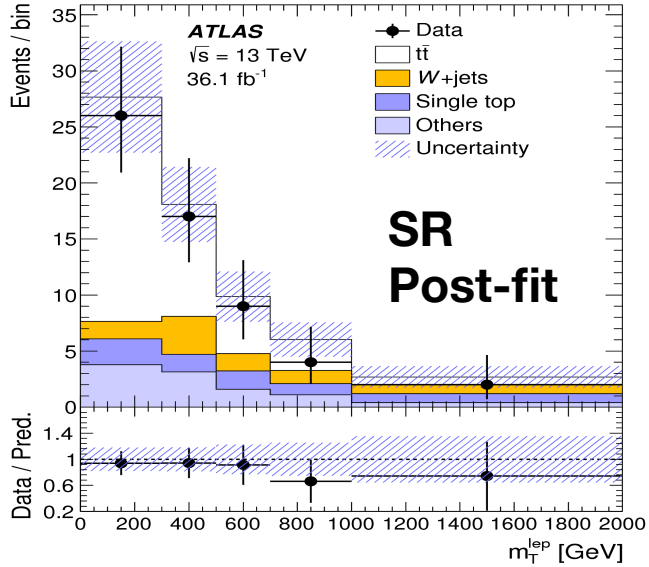
Wb+X: Post-fit





No sign of VLQs

- Data compatible with SM prediction
- Time to set limits!

Limits!

Cross Section Limits

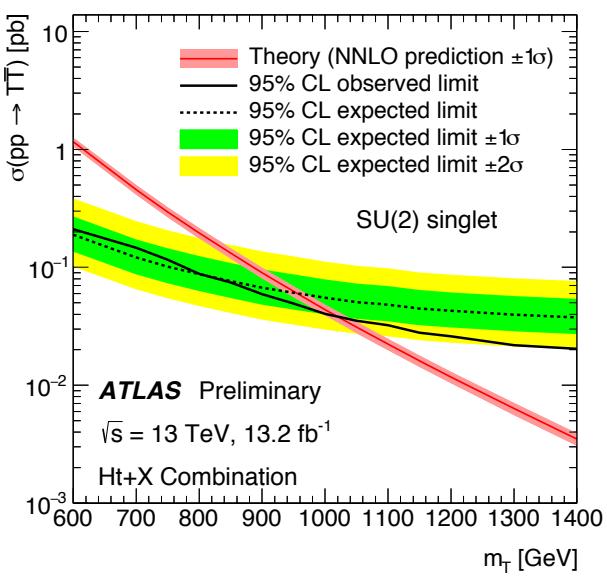
Use CL_S method to set 95% CL limits on $T\bar{T}$ cross section

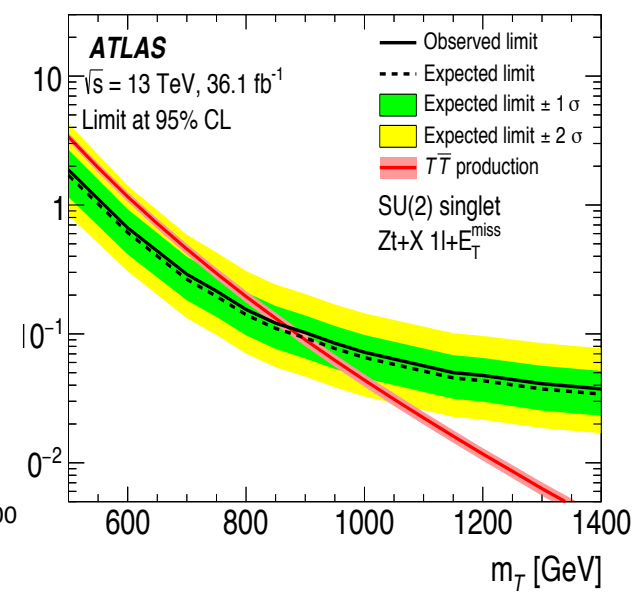
- **For singlet *T*:** $\mathcal{B}(T \rightarrow Wb{:}Ht{:}Zt) \sim ½ : ¼ : ¼$

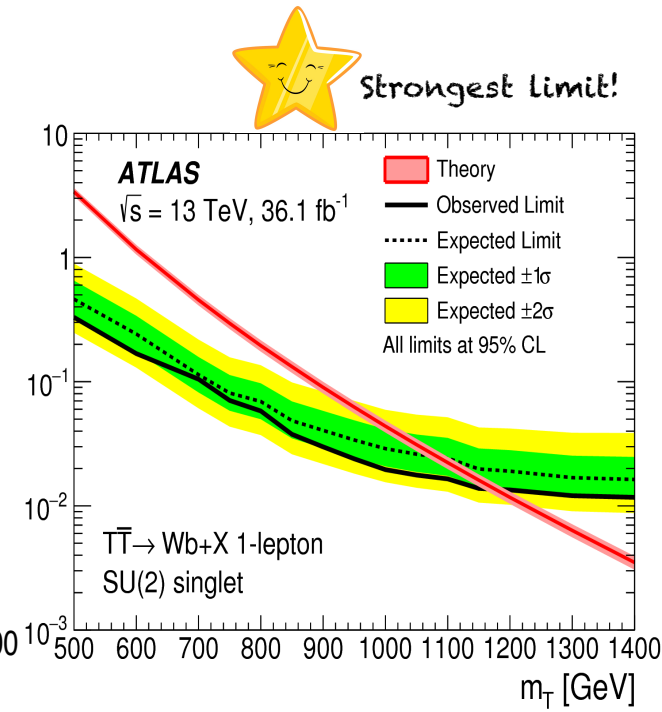
  Ht+X ⇒ $m_T \geq$ 1020 GeV (960 GeV expected)

  Zt+X ⇒ $m_T \geq$ 870 GeV (890 GeV expected)

  Wb+X ⇒ $m_T \geq$ **1170 GeV** (1080 GeV expected)







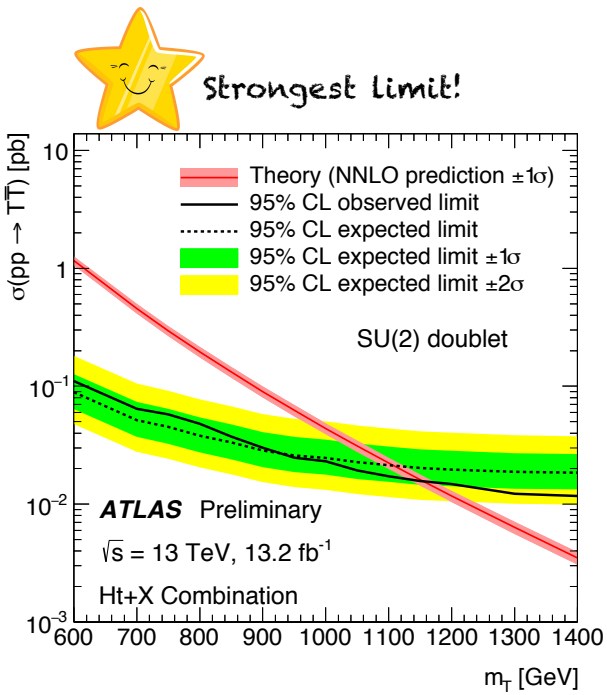
Cross Section Limits

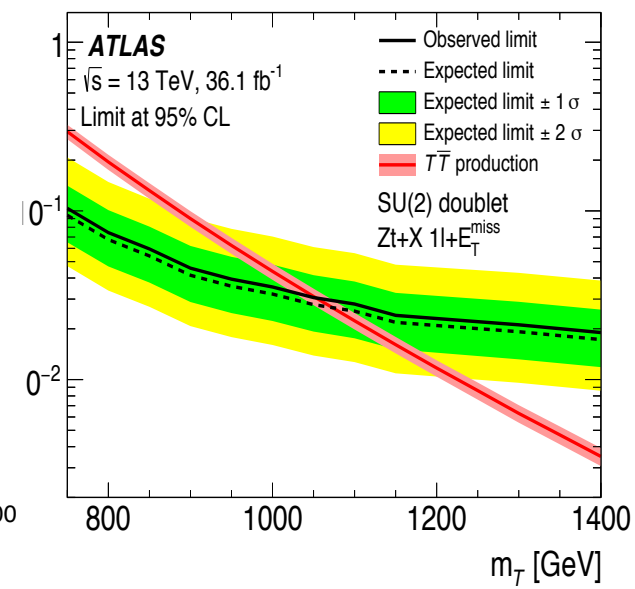
Use CL_S method to set 95% CL limits on $T\bar{T}$ cross section

- **For doublet *T*:** $\mathcal{B}(T \rightarrow Wb{:}Ht{:}Zt) \sim 0 : ½ : ½$

  Ht+X $\Rightarrow m_T \geq$ **1160 GeV** (1110 GeV expected)

  Zt+X $\Rightarrow m_T \geq$ 1050 GeV (1060 GeV expected)



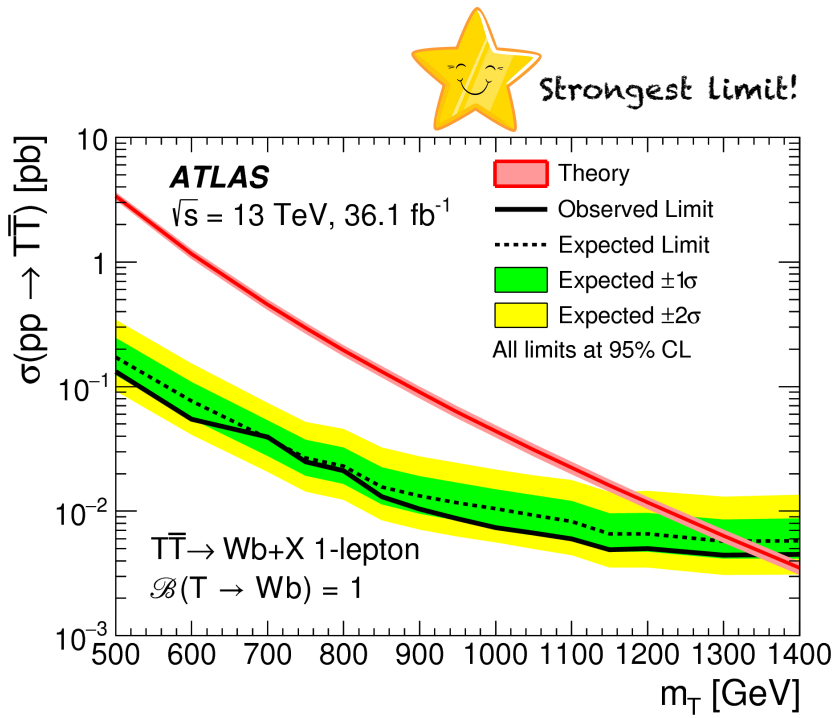


Cross Section Limits

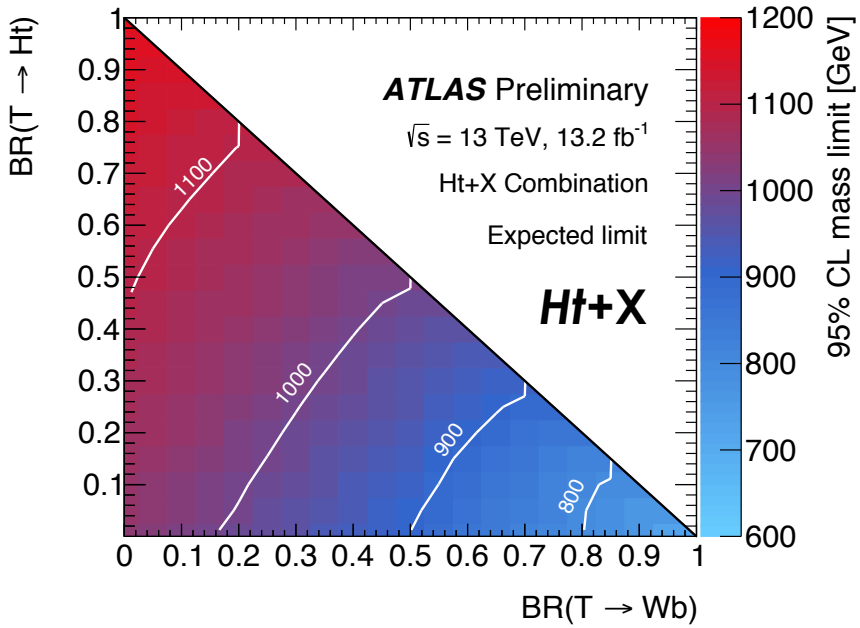
Use CL_S method to set 95% CL limits on *TT* cross section

- $\mathcal{B}(T \rightarrow Wb{:}Ht{:}Zt) \sim 1 : 0 : 0$ ⇒ Can be interpreted as $\boldsymbol{Y^{-4/3} \rightarrow Wb}$

  Wb+X ⇒ $m_Y \geq$ **1350 GeV** (1310 GeV expected)



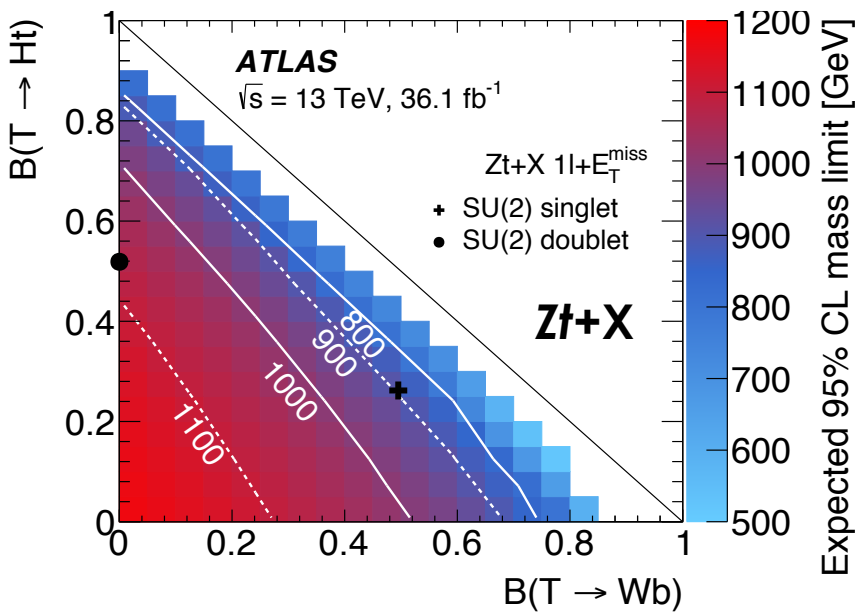
Mass Limits vs. Branching Ratio

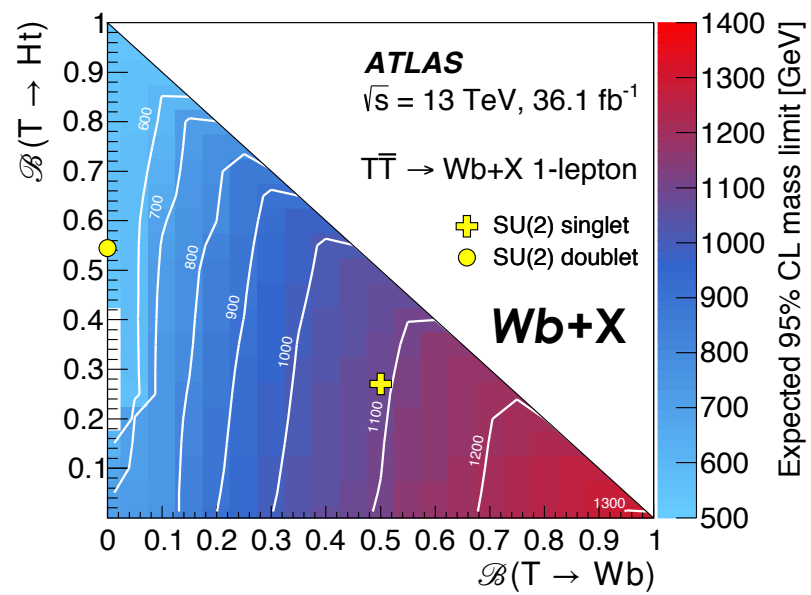


Assuming $\mathcal{B}(T \rightarrow Wb+Zt+Ht) = 1$, set model-independent lower bound on the mass of T

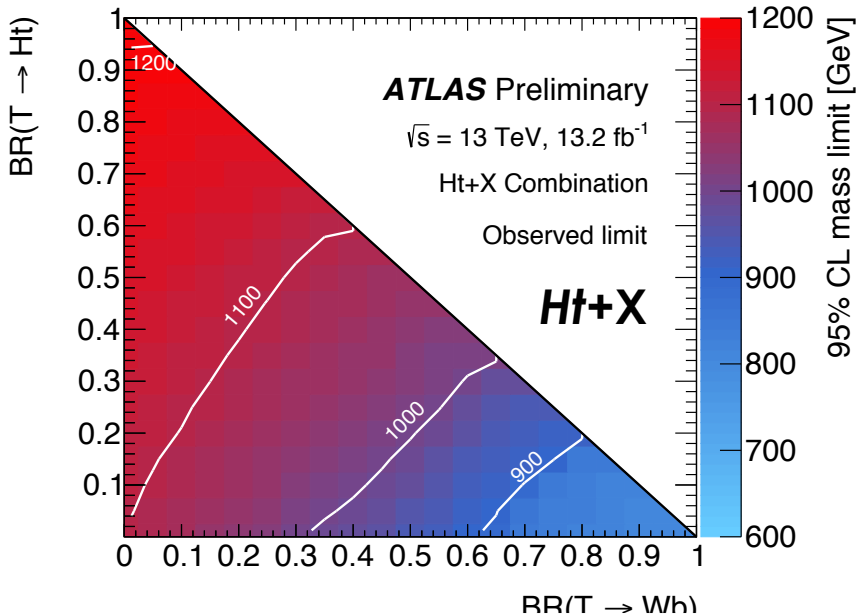
- Make a grid of possible branching ratios
- Find the lower mass limit at each point

Expected Limits





Mass Limits vs. Branching Ratio



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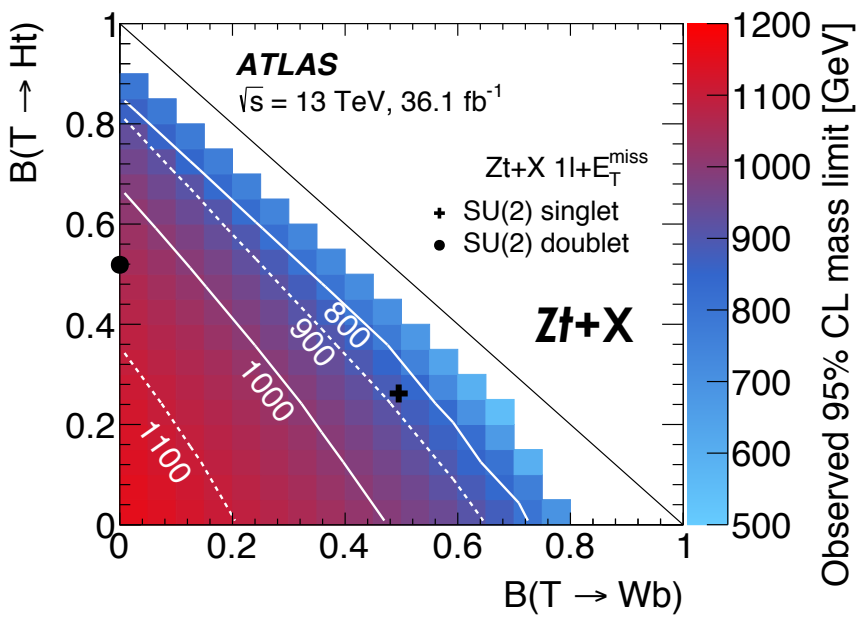
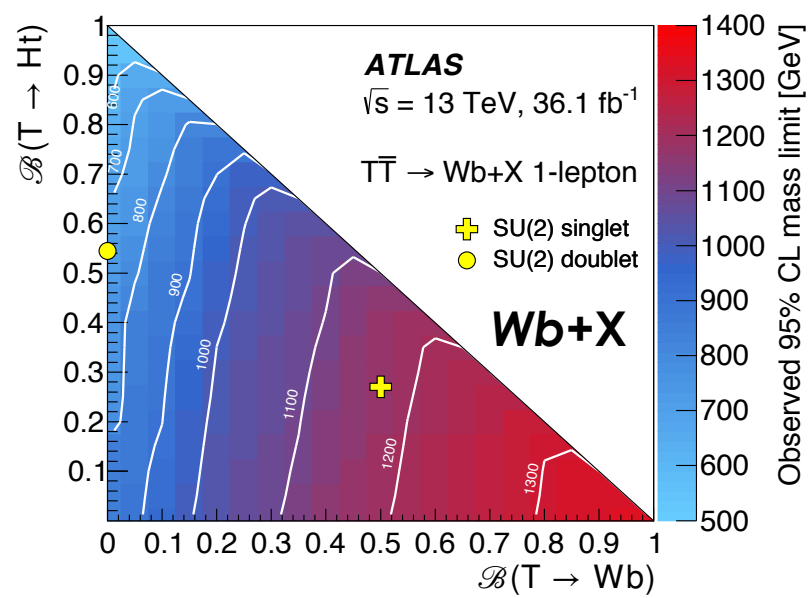
Observed Limits





Wb+X: Reinterpretation

What if this analysis tries to look for *BB*→*Wt*+X?

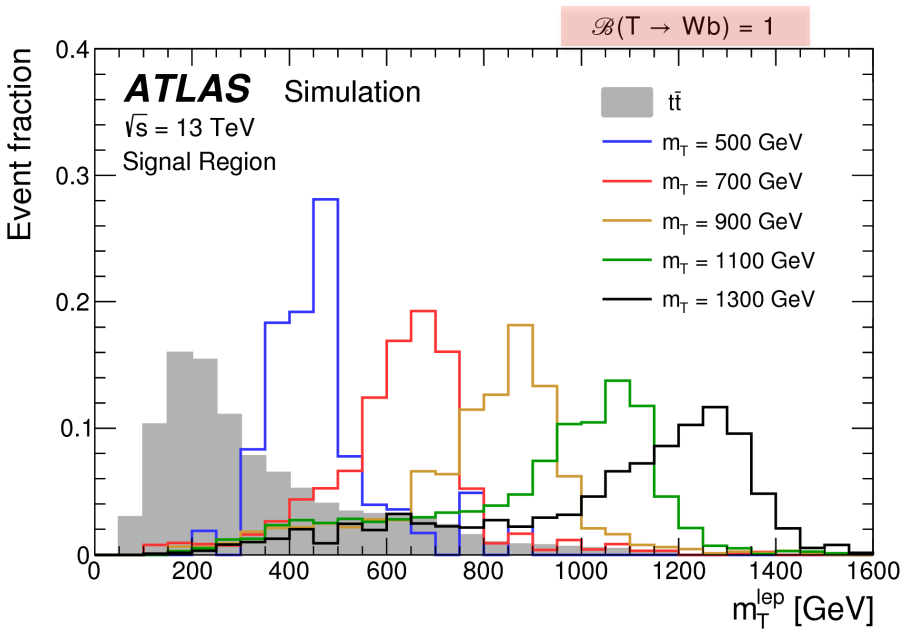
- Selection efficiency is basically the same as the *TT* signal:

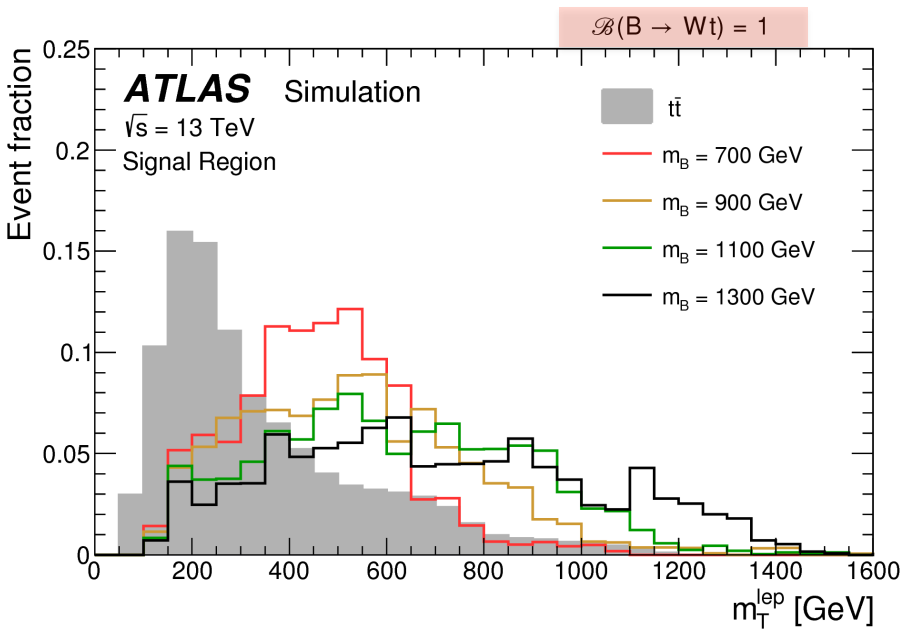
Selection criteria	$t\bar{t}$ [%]	Vector-like T $\mathcal{B}(T \to Wb)$ =1 [%]	Vector-like T SU(2) singlet [%]	Vector-like B $\mathcal{B}(B \to Wt)$ =1 [%]	Vector-like B SU(2) singlet [%]
Base selection	5.9	28	25	33	22
$\geq$ 1 W_{had} cand.	1.3	24	23	29	20
$E_{\mathrm{T}}^{\mathrm{miss}} > 60\ GeV$	66	94	68	92	91
$\geq$ 1b-tagged jet	74	80	85	89	88
$S_T \geq 1800\ GeV$	0.6	71	68	64	64
$\Delta R(\mathrm{lep}, \nu) \leq 0.7$	71	90	75	72	68
$\lvert\Delta m\rvert < 300\ GeV$	81	90	83	82	80
Total acceptance	$1.1 \cdot 10^{-4}$	2.9	1.4	3.0	1.2

Wb+X: Reinterpretation

What if this analysis tries to look for *BB*→*Wt*+X?

- Selection efficiency is basically the same as the *TT* signal
- Final variable, m_T^{lep}, does not reconstruct m_B:





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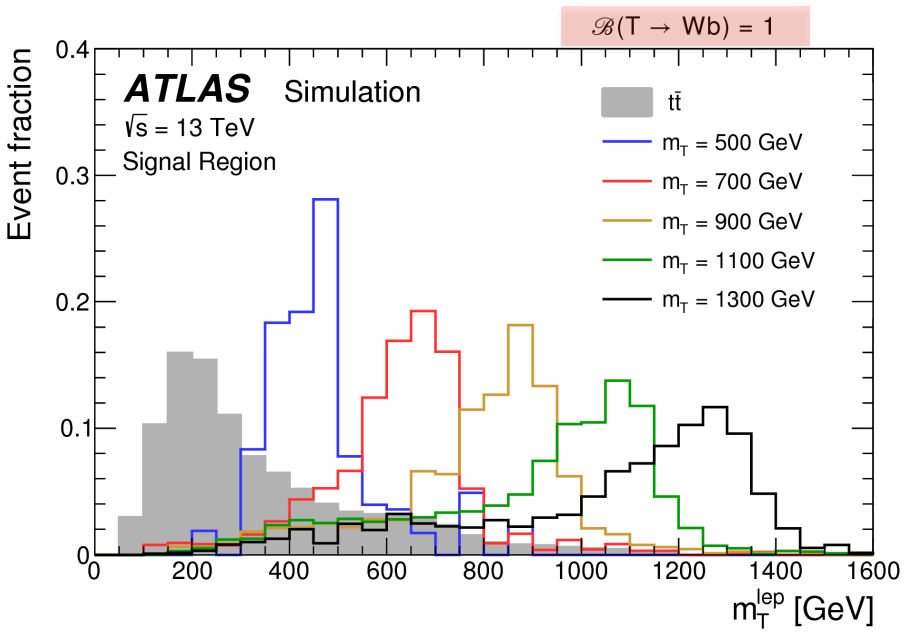
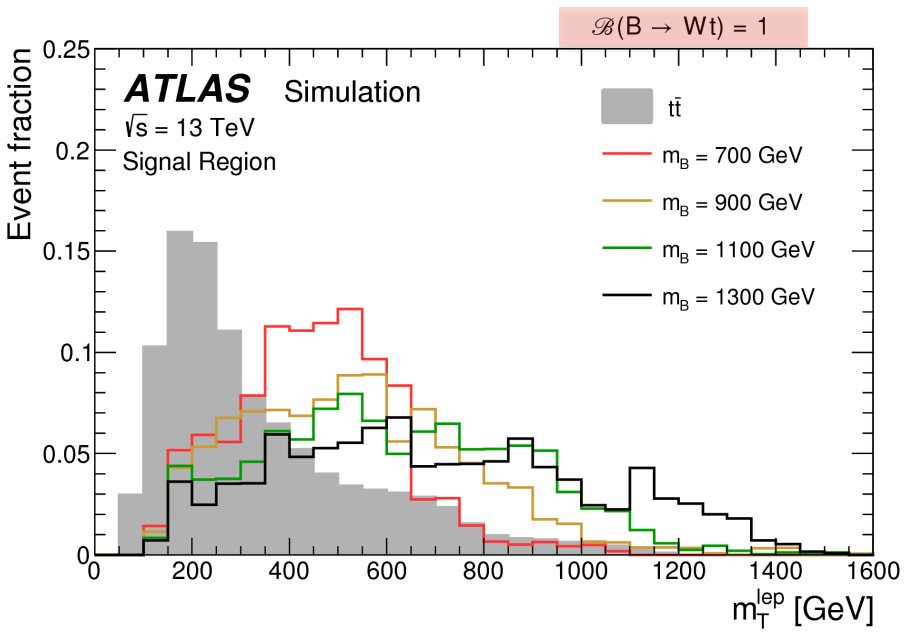
- Final variable, m_T^{lep}, does not reconstruct m_B:

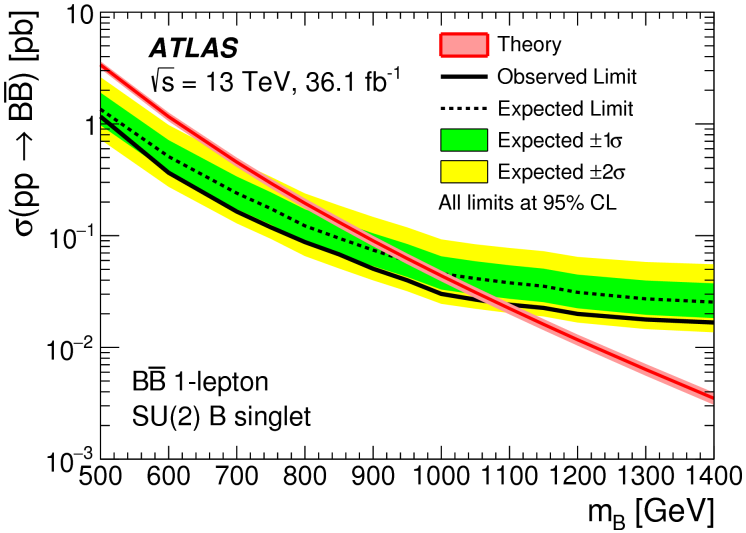


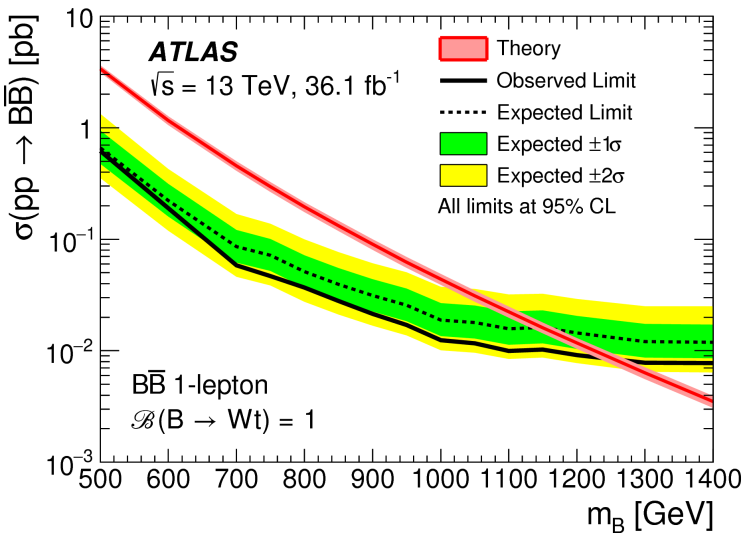


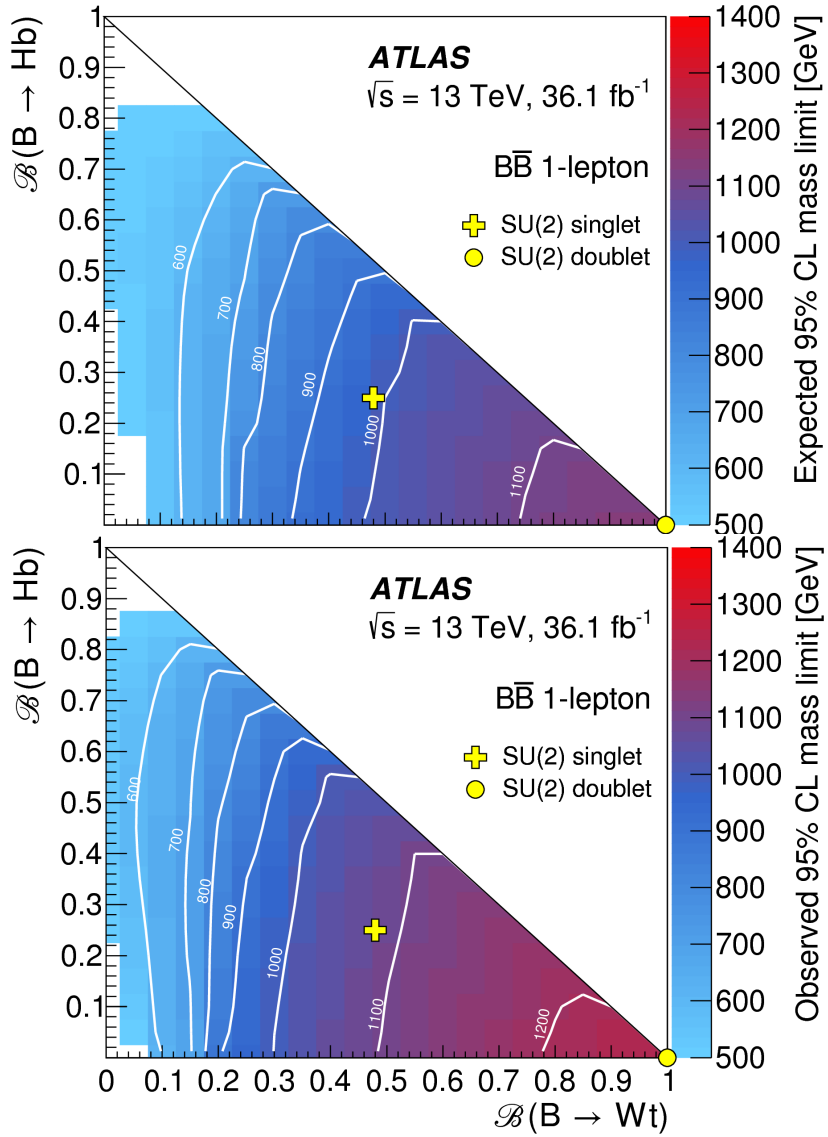
- But still provides discrimination between signal and background

⇒ Set limits on *BB* production

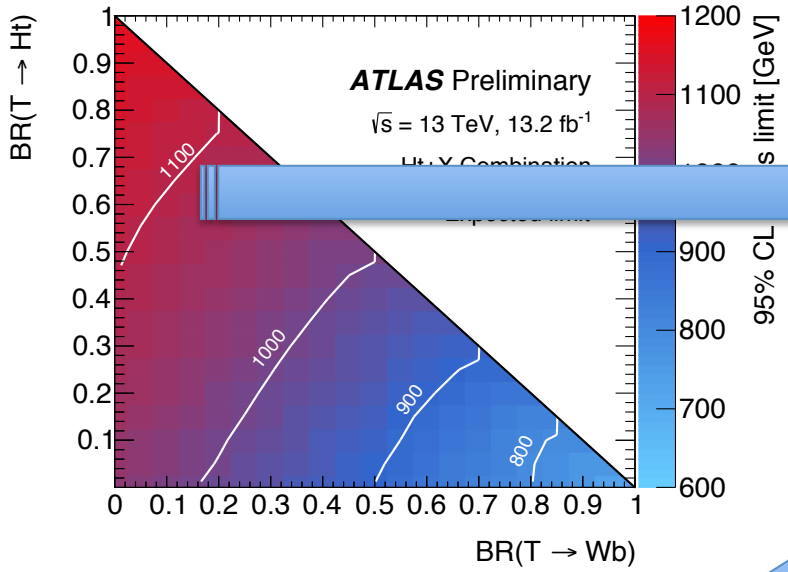
Wb+X: Limits on *BB*





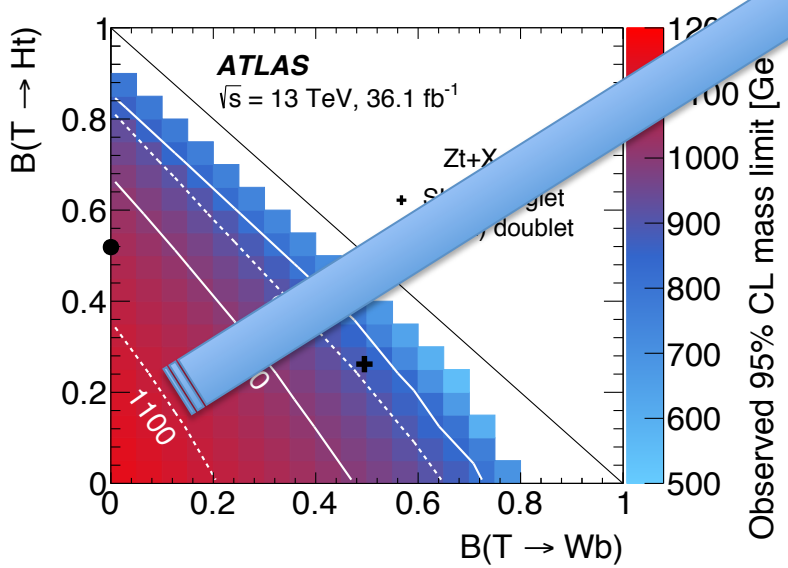


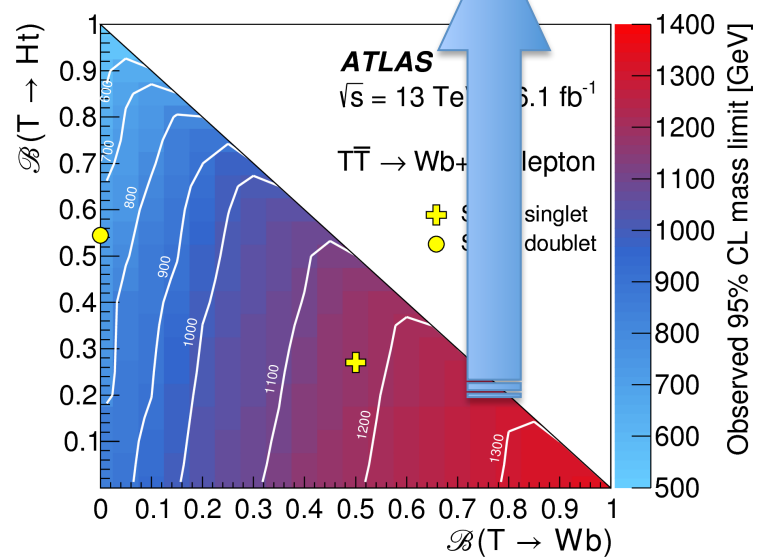
Stronger Together



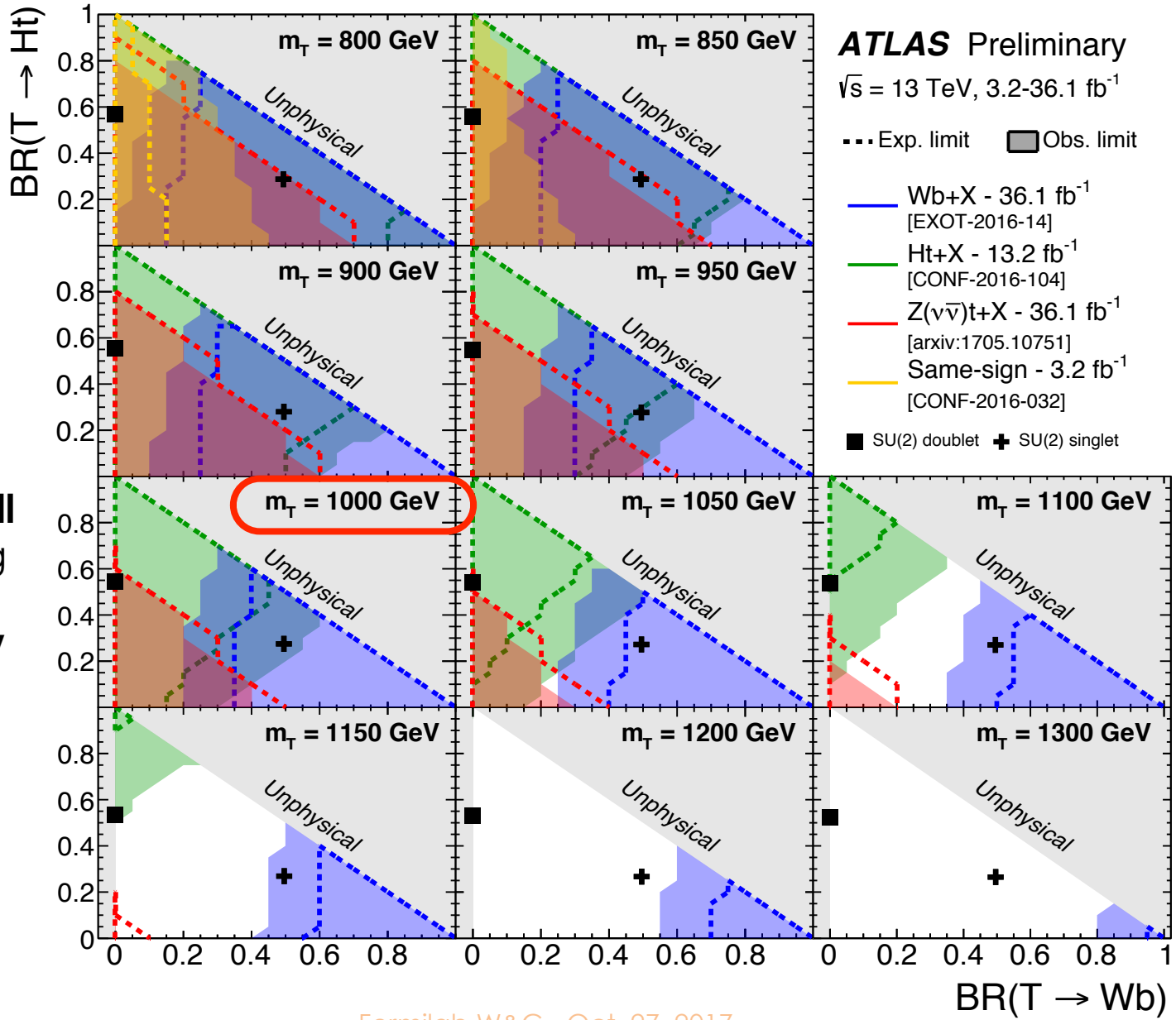
Combination!

- A few more analyses are being finalized, then ATLAS could produce a full combination of all VLQ pair searches
- For now, we have a simple overlay of the available results





Run 2 *TT* Mass Limits

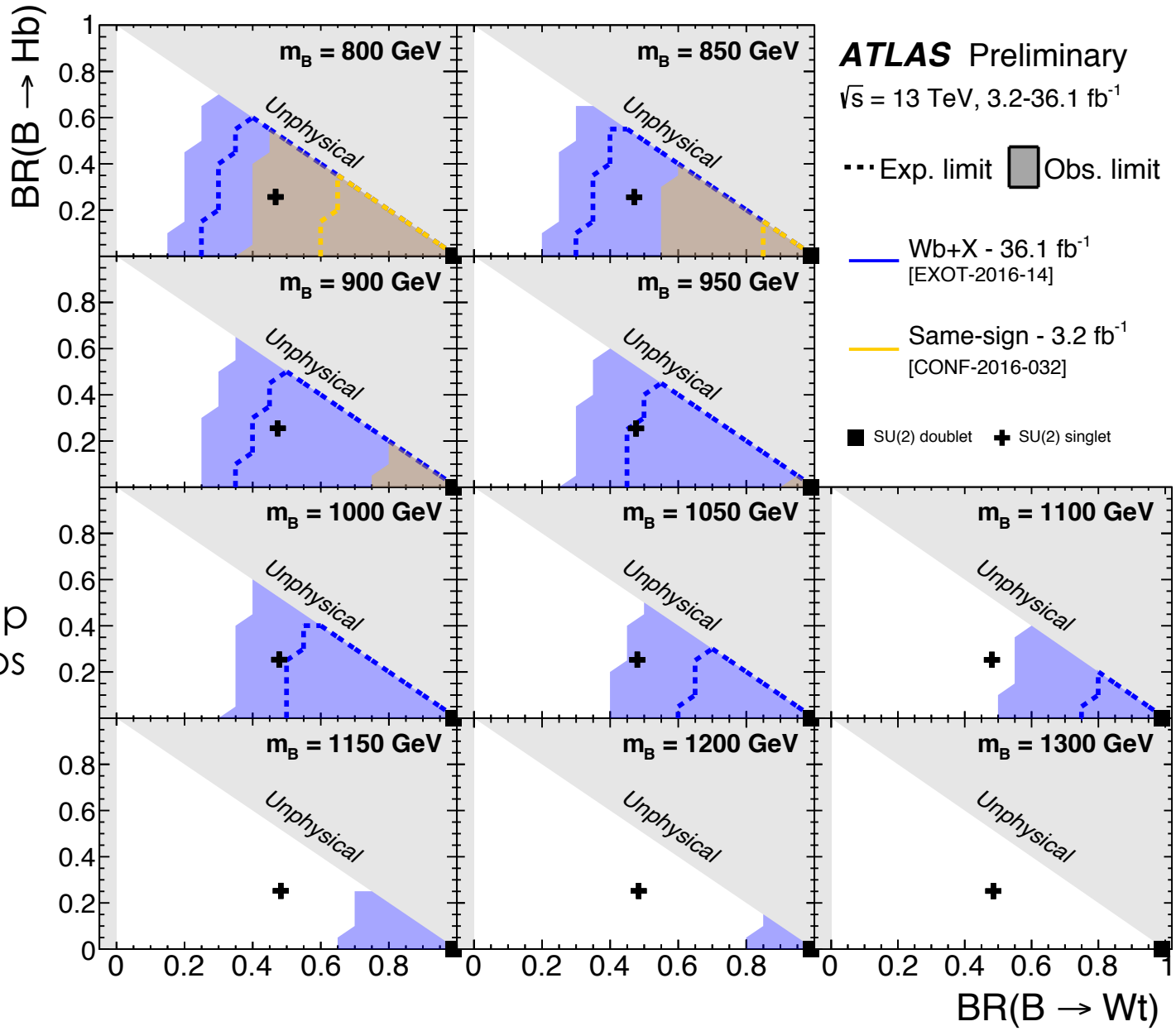


Exclude **all** branching ratios for m_T < 1 TeV

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html

Run 2 *BB* Mass Limits

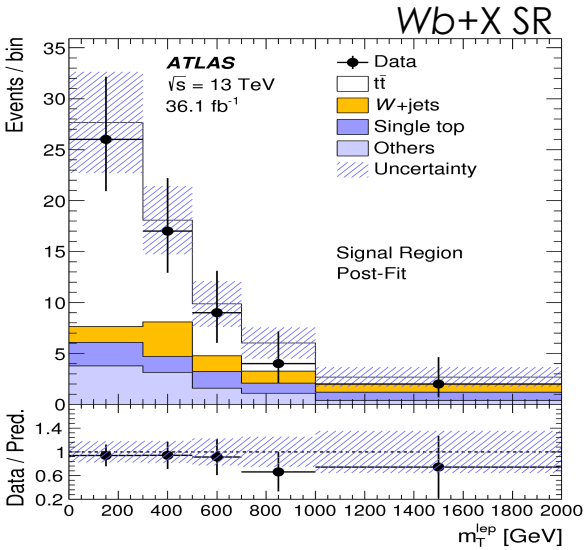
Pending analyses should help fill the gaps

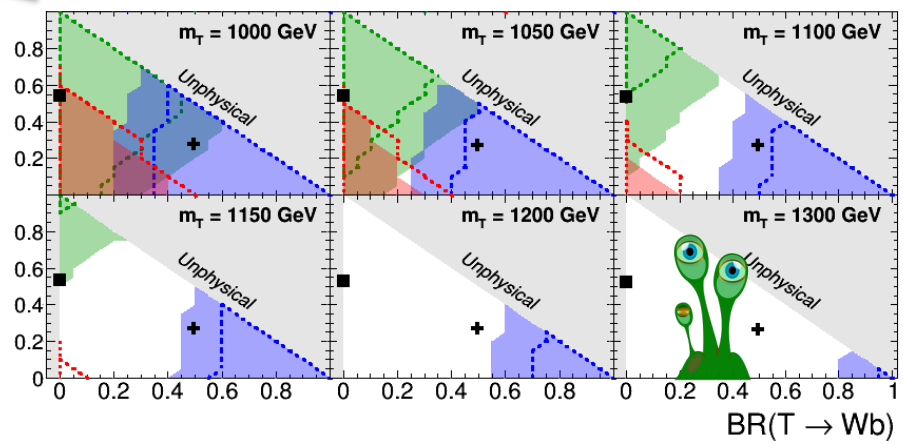


https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/index.html

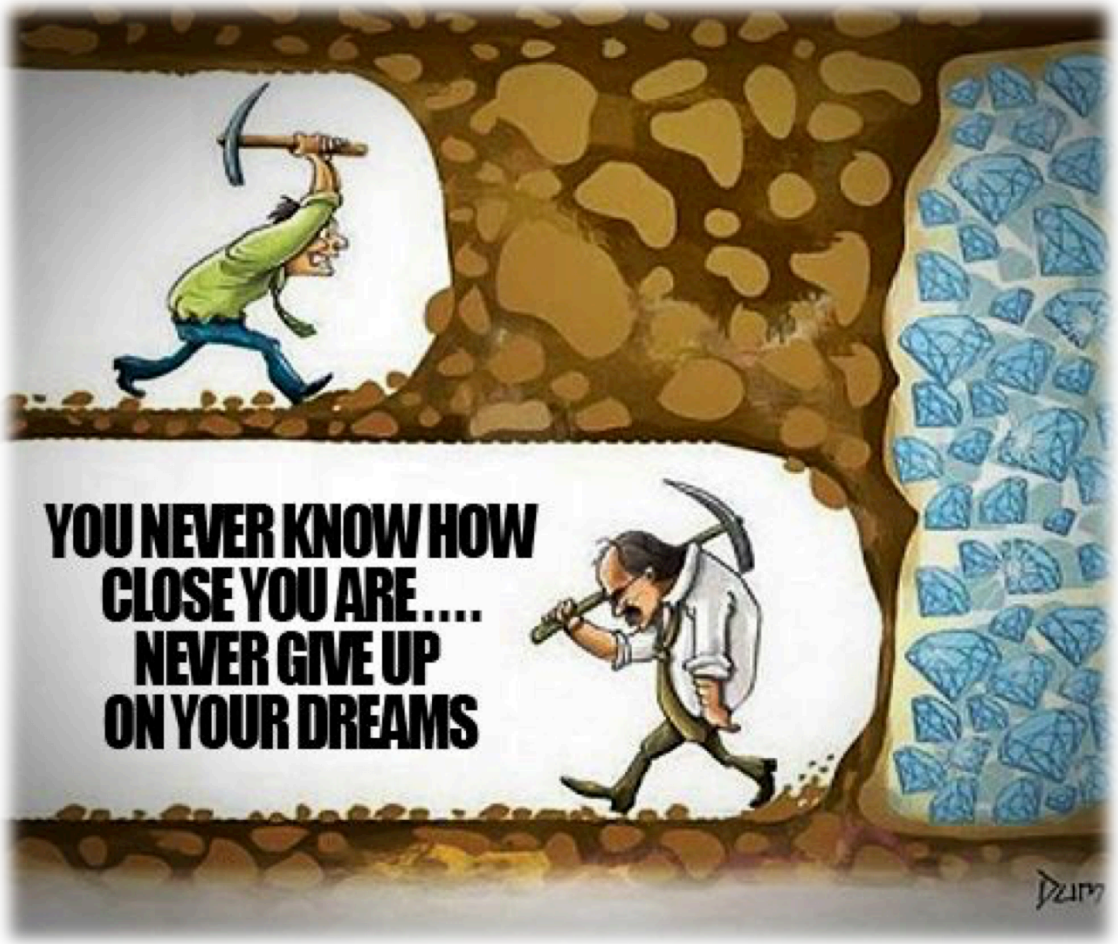
Conclusions

- VLQs can provide a natural solution to the hierarchy problem … but only if their mass is near ~1 TeV
- Presented latest ATLAS searches for *TT*
  - Data consistent with background-only
  - Strongest limits for many cases
- Current analyses excluding *T* masses up to 1 TeV for any branching ratios
  - Similar results from CMS
- If VLQs solve the hierarchy problem, they are starting to feel the heat of Run 2!
- More VLQ analyses are in the pipeline …





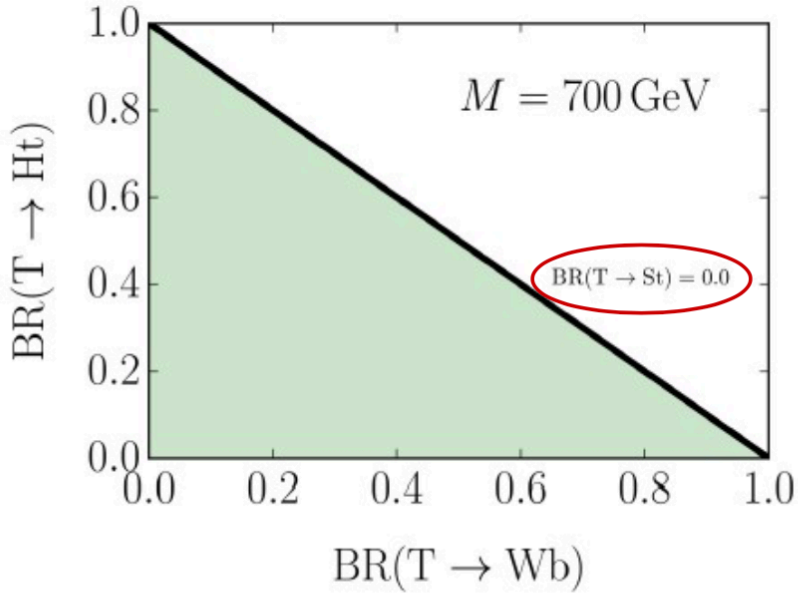
Thank you!

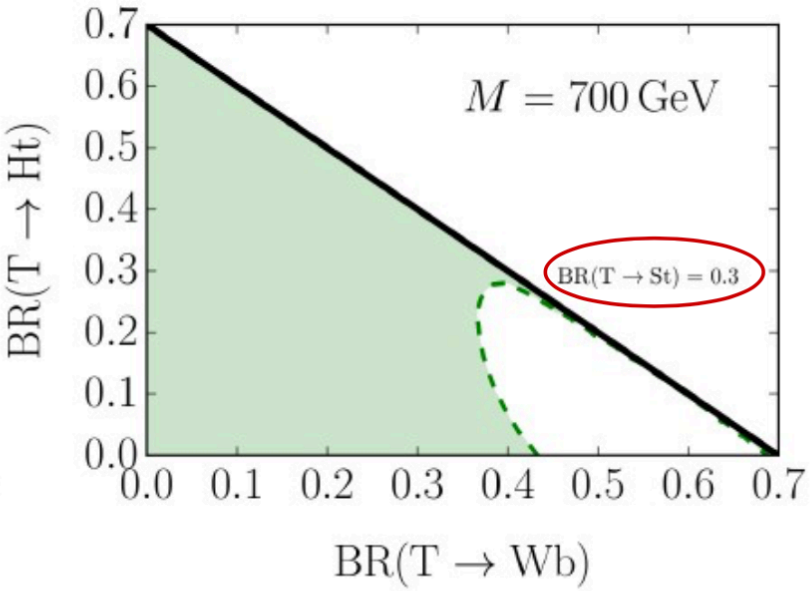


Complete list of ATLAS exotic results:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Beyond $\mathcal{B}(T \rightarrow Wb+Zt+Ht) = 1$ Assumption

- In the triangular BR plots we assume that VLQs only decay to SM particles
  - This is not the case in most of the composite Higgs models (e.g. arXiv:1704.07388)





→ A non-negligible decay to a non-SM particle (e.g. the new scalar S) can significantly change the limits in the BR plane

[arXiv:1705.03013]

(Slide from Nuno Castro)

Beyond $\mathcal{B}(T \rightarrow Wb+Zt+Ht) = 1$ Assumption

- Depending on the model S can be ~ stable, evading detection, or decay e.g. to bb, tt, HH
  - Ideally we would have dedicated searches for these channels
  - Some of our current searches might even be (partially) sensitive to S, depending on its decay modes
    - We might even be able to tailor our analysis to increase the sensitivity to these additional final states
  - Nonetheless, providing the BR plane limits for relaxed Σ(BR) assumptions gives a conservative hint on the impact of S (i.e. gives us the maximum effect in the degradation of our results)
    - As long as we provide enough information and are very clear about the assumptions, this would fit well as a complementary result for our papers (in particular the combination one)

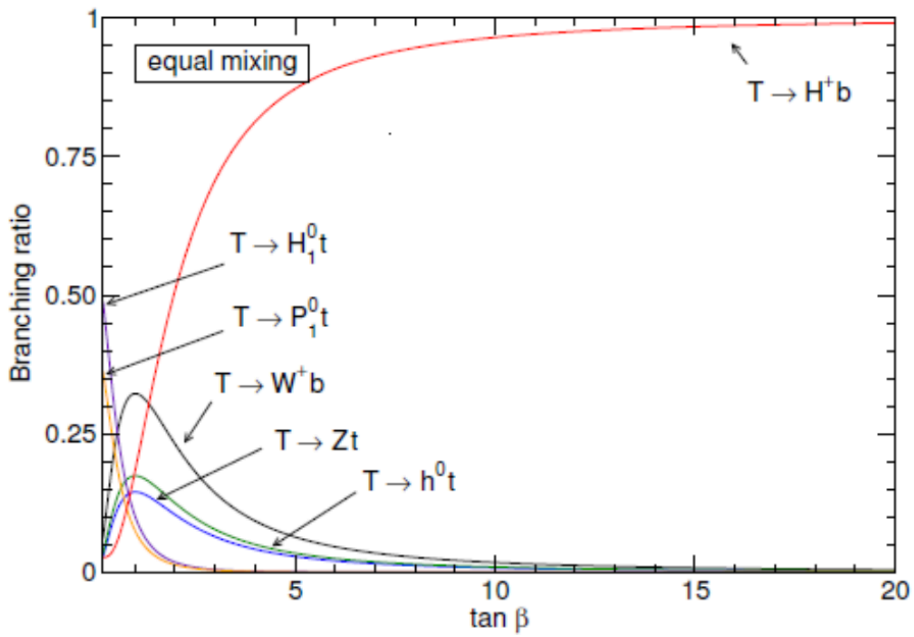
(Slide from Nuno Castro)

Beyond $\mathcal{B}(T \rightarrow Wb+Zt+Ht) = 1$ Assumption

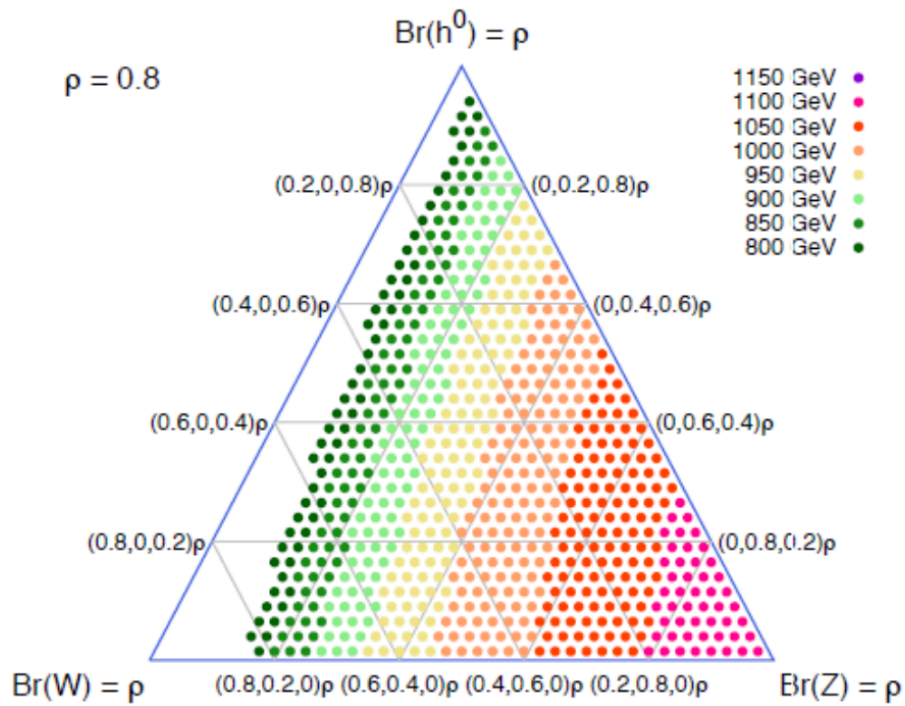
- Another recent proposal: arXiv:1705.02526

one example:

$$T \rightarrow H_k^0 t\,, \quad T \rightarrow P_k^0 t\,, \quad T \rightarrow H^+ b\,,$$



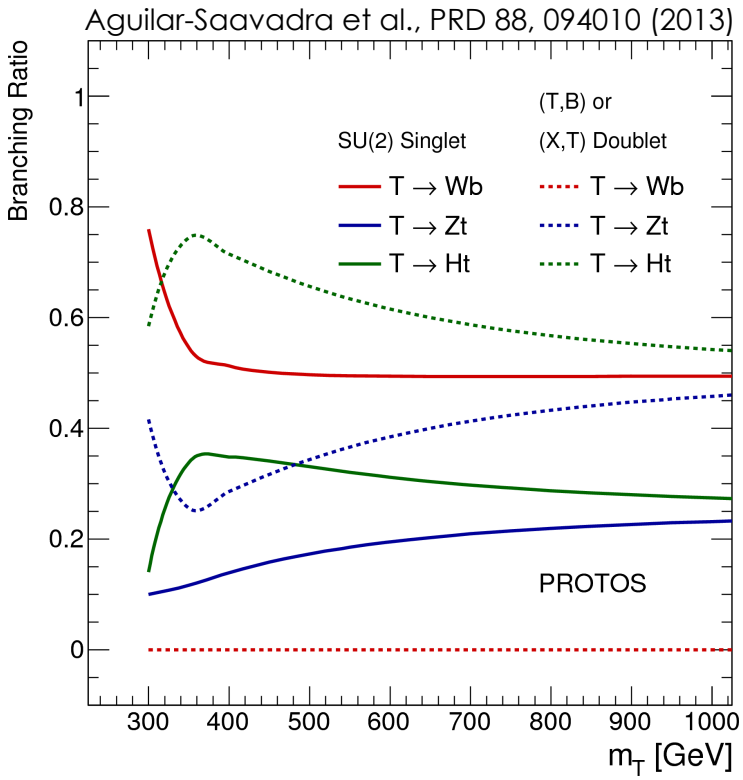
$$\boxed{\mathrm{Br}(W) + \mathrm{Br}(Z) + \mathrm{Br}(h^0) \leq 1}$$



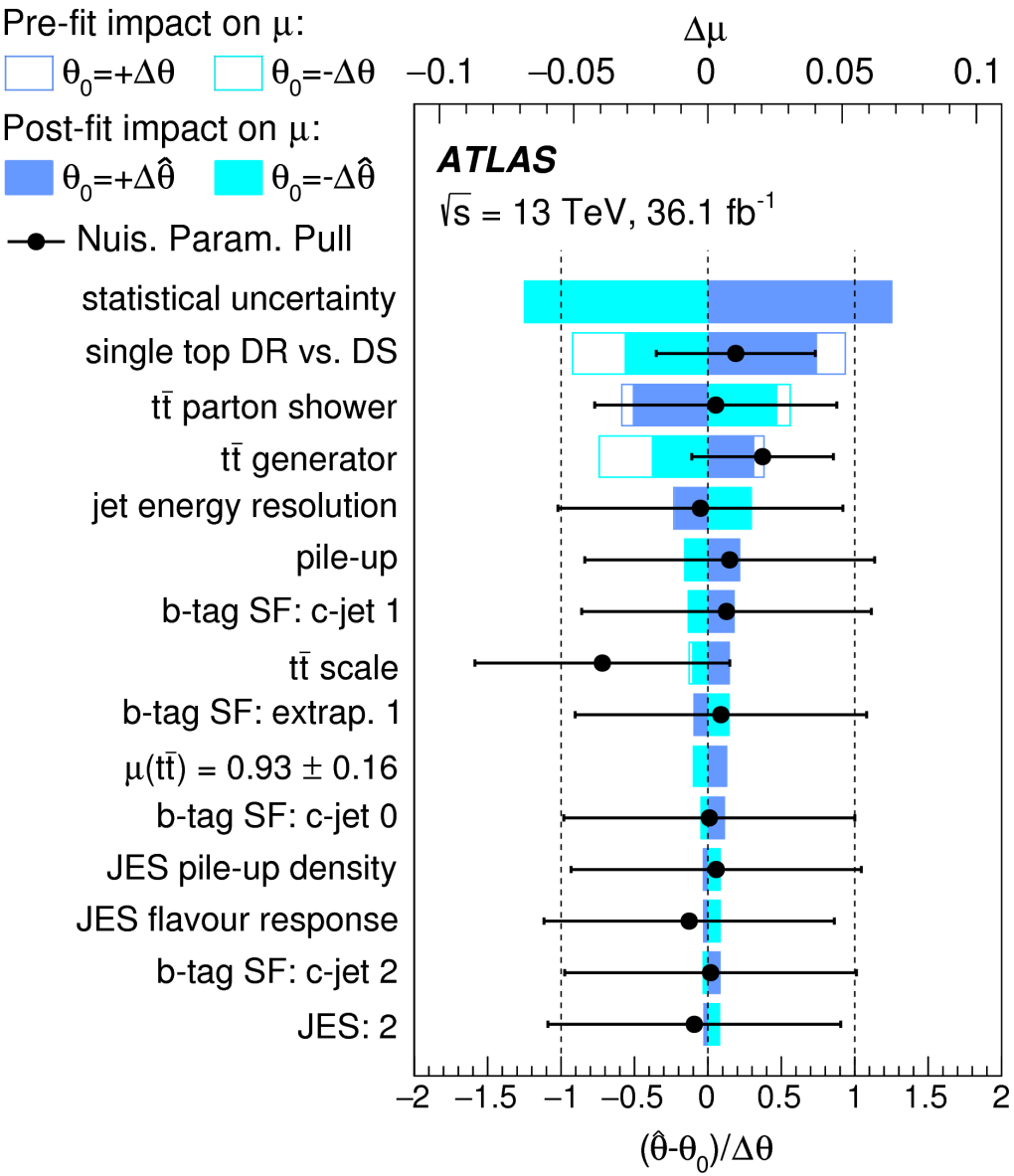
$$\mathrm{Br}(W) + \mathrm{Br}(Z) + \mathrm{Br}(h^0) = \rho$$

(Slide from Nuno Castro)

Branching Ratios



Wb+X: Uncertainties



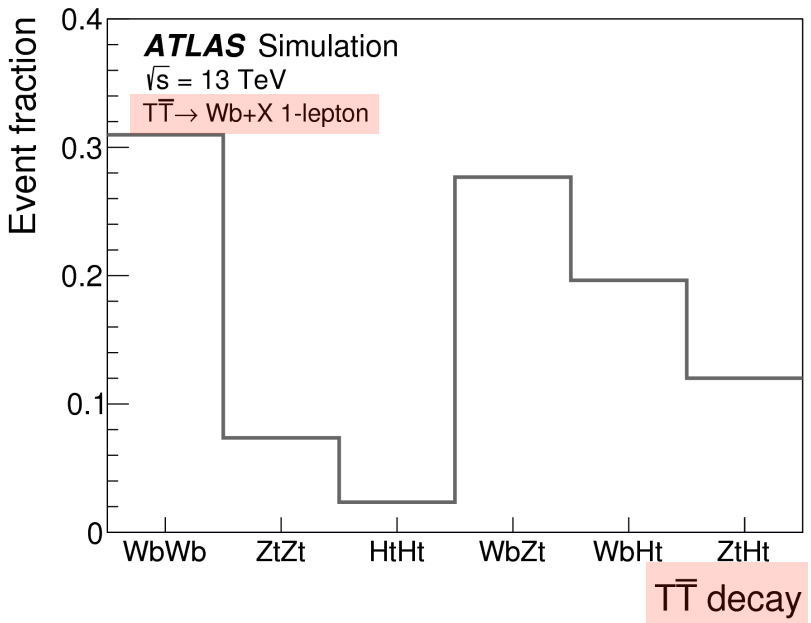
Post-fit

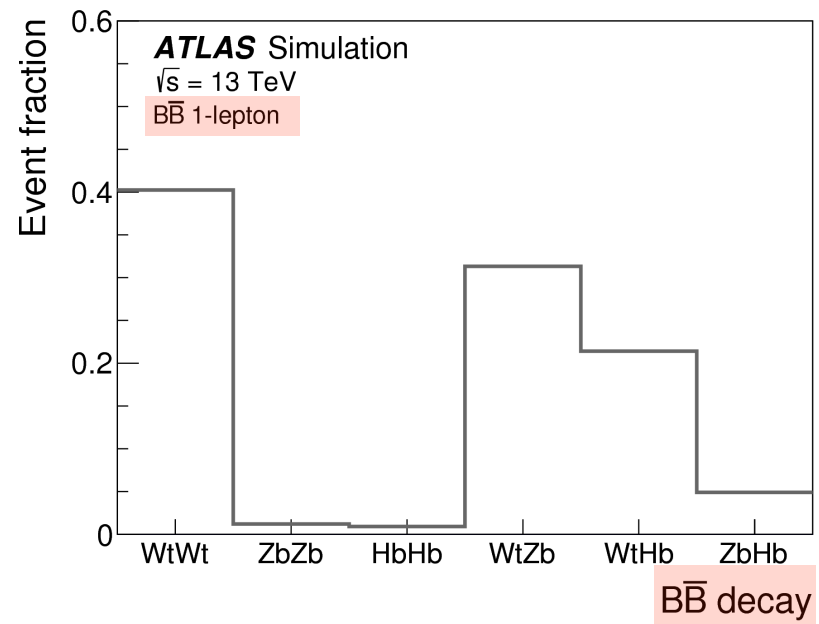
Sample	Signal region	Control region
$t\bar{t}$	39 ± 10	700 ± 70
W+jets	8 ± 4	78 ± 38
Single top	7 ± 4	110 ± 40
Others	10 ± 7	72 ± 48
Total background	64 ± 9	970 ± 50
Data	58	972

Submitted to JHEP [arXiv:1707.03347]

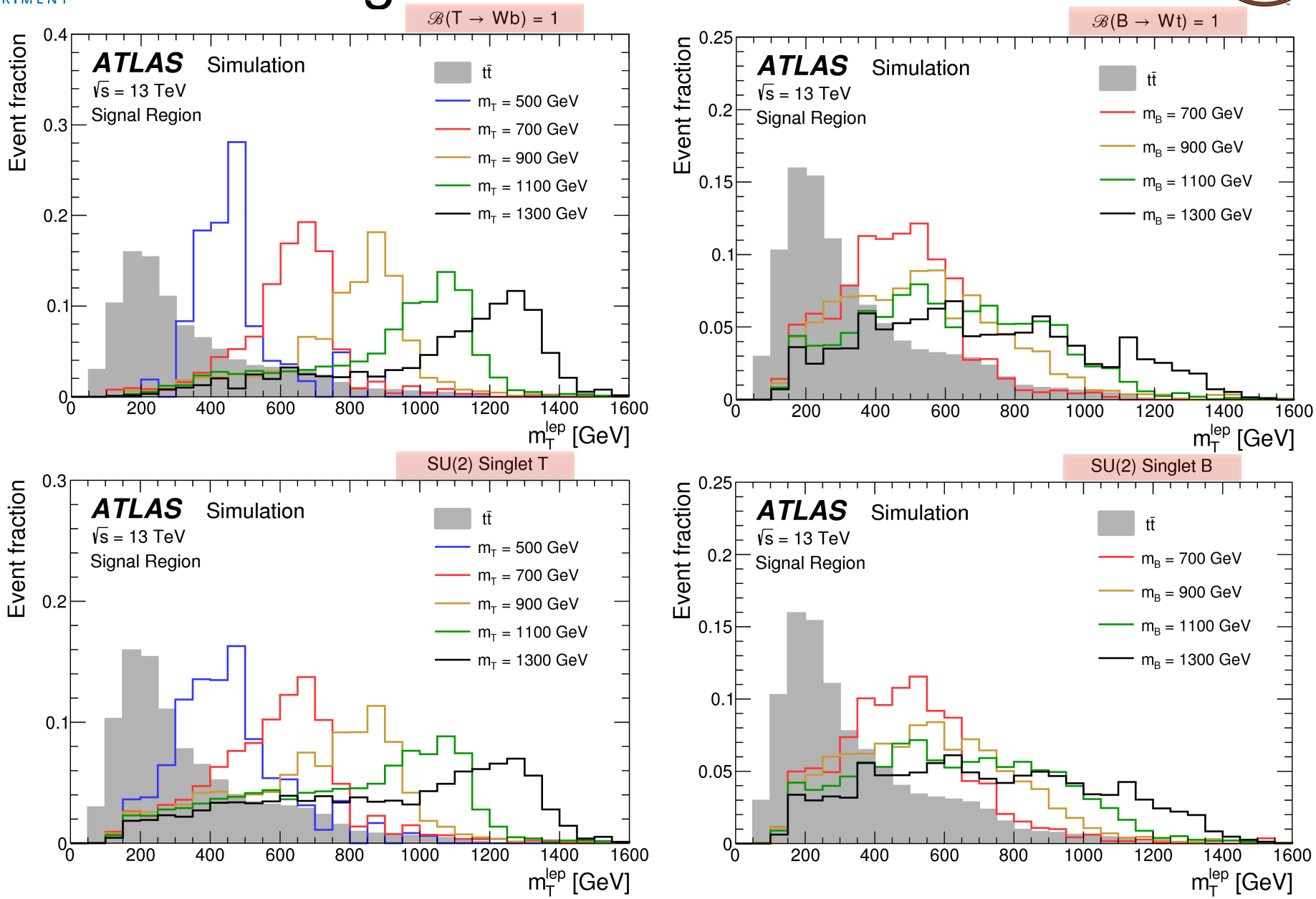
Acceptance

Selection criteria	$t\bar{t}$ [%]	Vector-like T $\mathcal{B}(T \to Wb)$ =1 [%]	Vector-like T SU(2) singlet [%]	Vector-like B $\mathcal{B}(B \to Wt)$ =1 [%]	Vector-like B SU(2) singlet [%]
Base selection	5.9	28	25	33	22
$\geq$ 1 W_{had} cand.	1.3	24	23	29	20
$E_{\text{T}}^{\text{miss}} > 60\ GeV$	66	94	68	92	91
$\geq$ 1b-tagged jet	74	80	85	89	88
$S_T \geq 1800\ GeV$	0.6	71	68	64	64
$\Delta R(\text{lep}, \nu) \leq 0.7$	71	90	75	72	68
$\lvert\Delta m\rvert < 300\ GeV$	81	90	83	82	80
Total acceptance	$1.1 \cdot 10^{-4}$	2.9	1.4	3.0	1.2

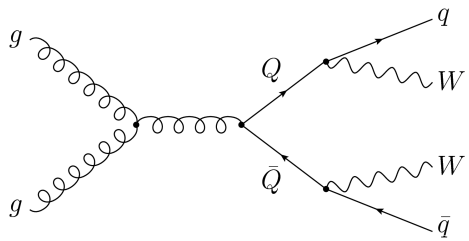


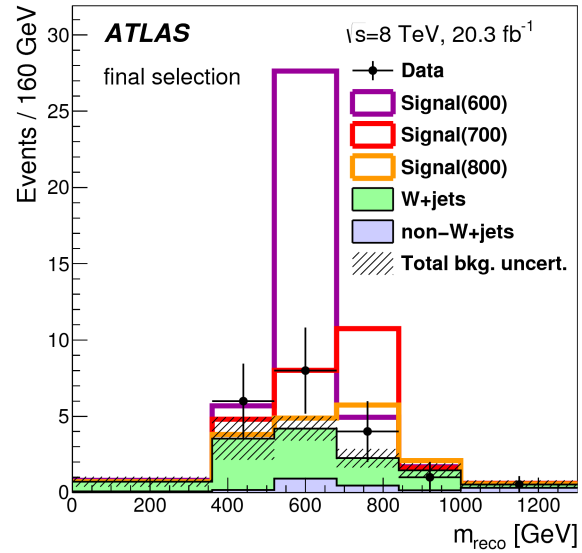


Signal Mass Distribution



VLQs decaying to light quarks

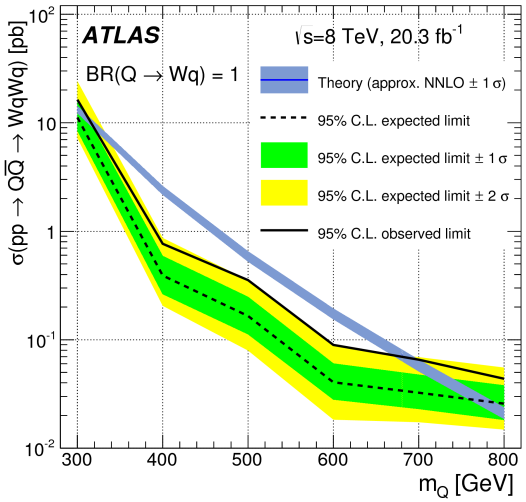
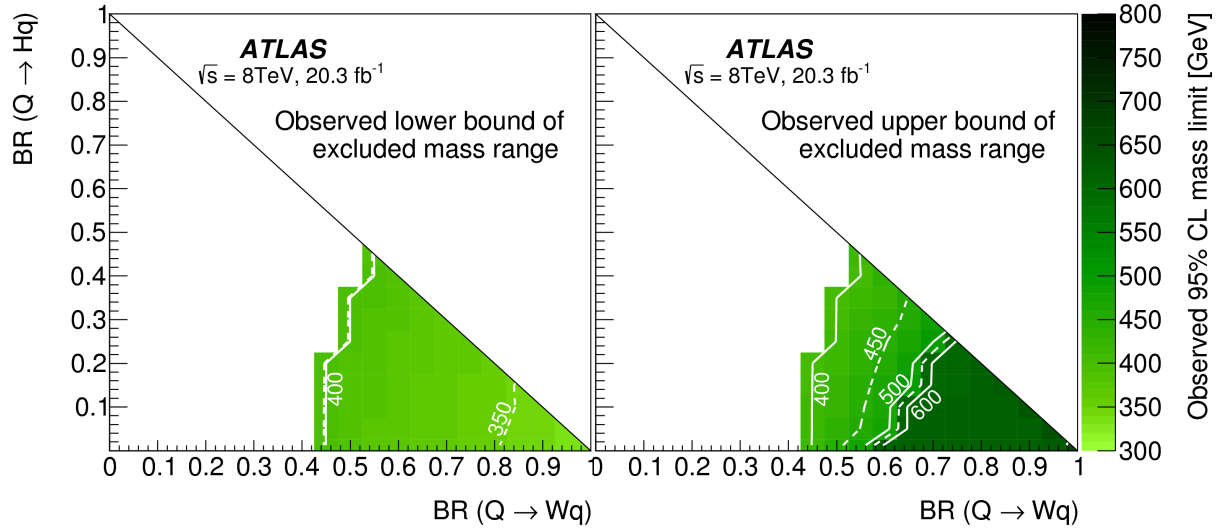




Select $\ell\nu qqqq$

- Reconstruct Q candidates
- Look for bump in mass of $Q \rightarrow Wq \rightarrow qqq$ candidate

Limit on cross section for BR(Q→Wq)=1:



Excluded masses for given choice of BRs: