



The search for vector-like quarks with the ATLAS experiment

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HEP Seminar
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Outline

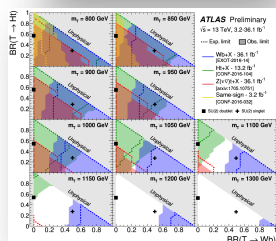
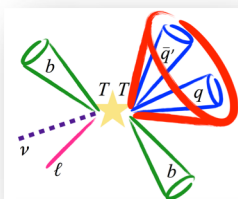
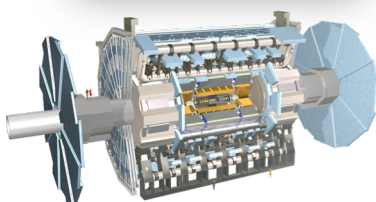
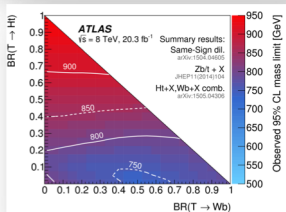
"bare mass"

$$M_H^2 = 3.2734594296342905438674964732159643$$

$$- 3.2734594296342905438674964732159645$$

$$= 10^{-32} \text{ (in Planck units)}$$

quantum corrections, e.g.



Vector-like quarks

- What are they?
- Why should you care?
- What will vector-like quarks look like?
- Previous results

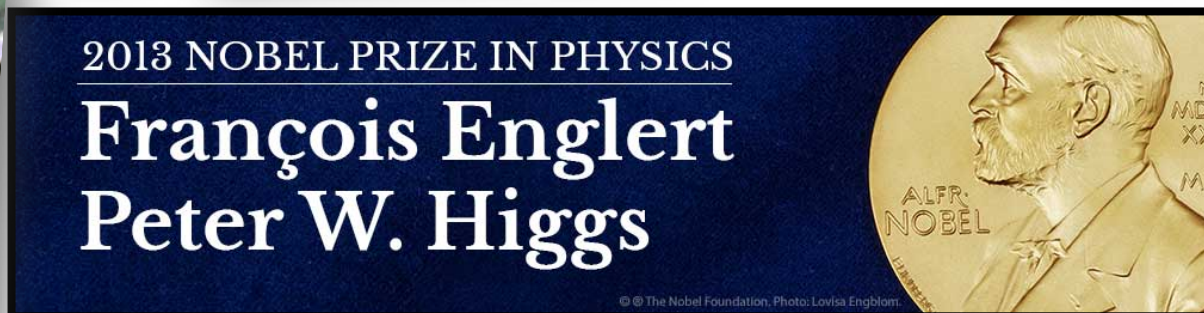
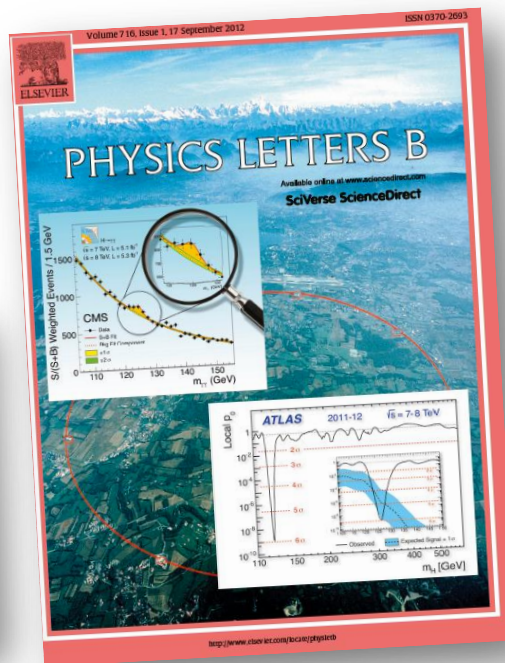
The ATLAS Experiment

- Particle Identification
- Searching for VLQs in the data
 - $T\bar{T} \rightarrow Wb + X$ analysis
- The results!

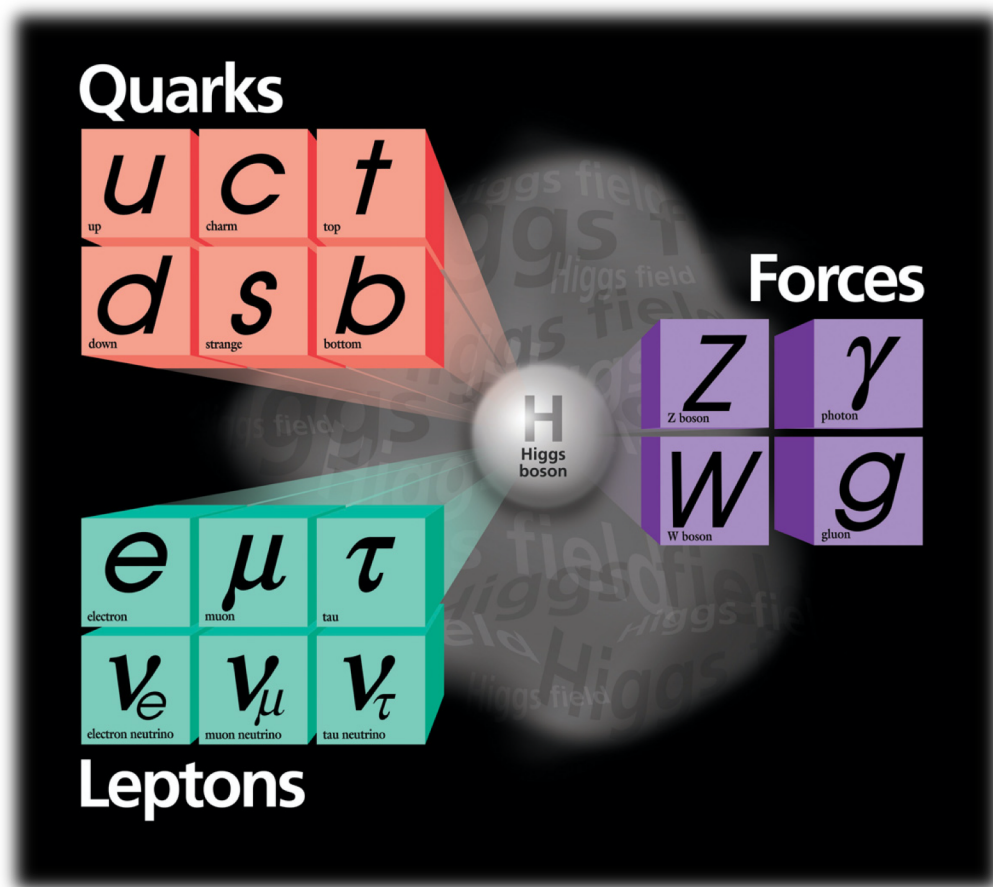
Conclusions

Higgs Boson Discovered

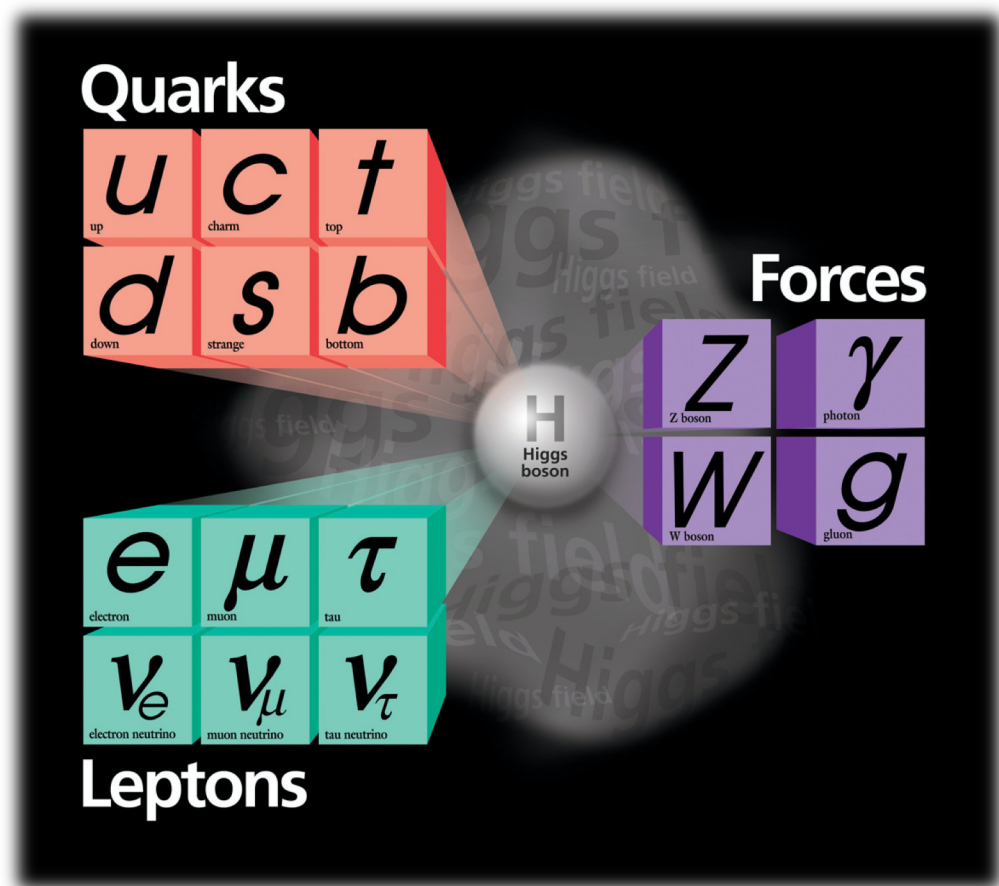
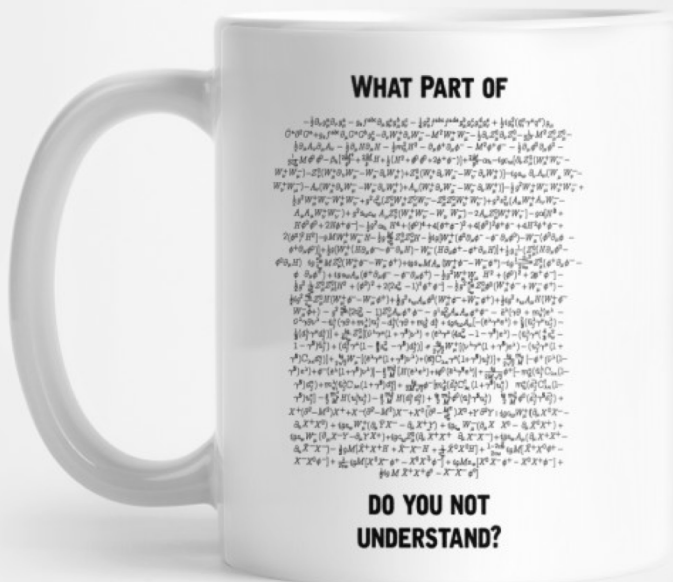
ATLAS and CMS announce discovery on July 4, 2012



The Standard Model is Confirmed!



The Standard Model is Confirmed!



The Standard Model is Complete?



calamitiesofnature.com © 2011 Tony Piro

The Higgs boson completed the Standard Model,
but the Standard Model is not complete!

Why are there
three generations?
Are there more?

Why these
masses?

Is there are larger
symmetry?

What is dark
matter?

What is dark
energy?

Why are
neutrinos so
light?

How can gravity
be included?

Why is gravity
so weak?

.....

Naturalness

What is naturalness?

If X is an observable that depends on n independent inputs, a_i :

$$X = a_1 + a_2 + \dots + a_n$$

It would be unnatural to have some $|a_i| \gg |X|$

Natural:

$$a_1 = 4$$

$$a_2 = 2,098,572,309,800$$

$$a_3 = -1,099,785$$

$$\Rightarrow X = 2,098,571,210,019$$

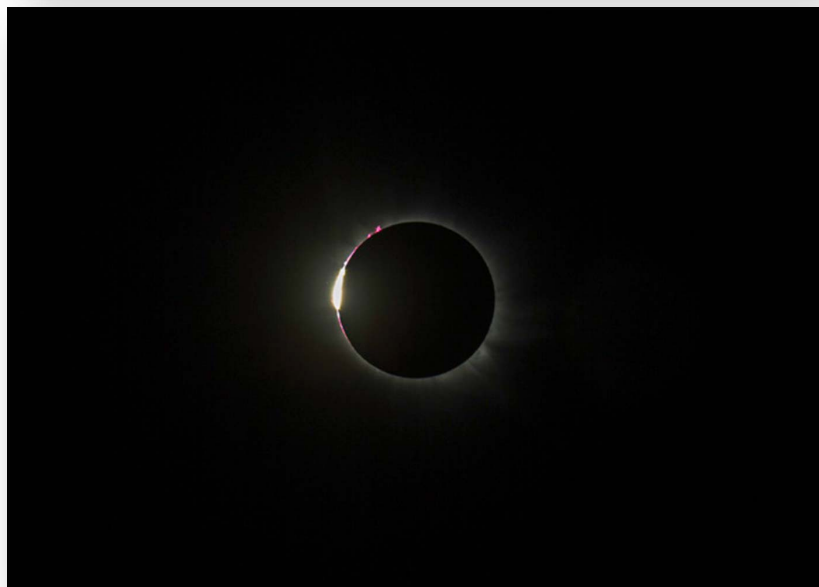
Unnatural:

$$a_1 = 4$$

$$a_2 = 2,098,572,309,800$$

$$a_3 = -2,098,572,309,885$$

$$\Rightarrow X = -81$$



The “Hierarchy Problem”

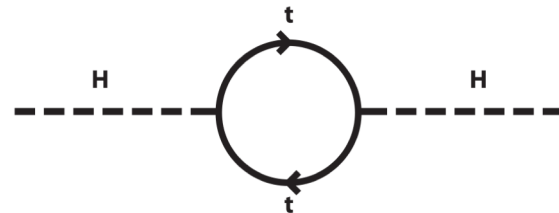
The mass (squared) of the Higgs gets quantum corrections from interacting with other particles: $M_H^2 = 2\mu^2 + (\delta m_1)^2 + (\delta m_2)^2 + \dots$

The most significant correction comes from top quarks, which causes a quadratic divergence!

- If the SM is correct (up to quantum gravity)

$M_H^2 = 3.2734594296342905438674964732159643$
 - $3.2734594296342905438674964732159645$
 = 10^{-32} (in planck units)

"bare mass"
 quantum corrections, e.g. 



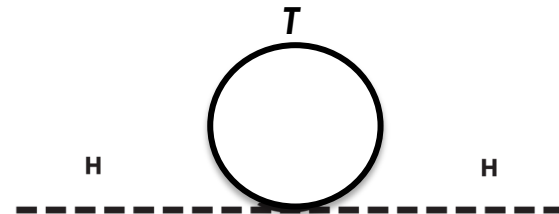
from
Roni Harnik

Having vector-like quarks could naturally cancel the divergent top correction!

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

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

- But only if they are not too heavy (mass ~ 1 TeV)



Therefore, many theories for physics beyond the Standard Model predict vector-like quarks that should be accessible at the LHC!

Vector-like Quarks (VLQs)

Spin- $\frac{1}{2}$ particles with color-charge $\Rightarrow$ “Quarks”

Both left and right chiralities behave the same $\Rightarrow$ “Vector-like”

What are “left and right chiralities”?

- A spin- $\frac{1}{2}$ particle can be written as:

➤ A superposition of a spin-up and spin-down particle: $\psi = \psi_{\uparrow} + \psi_{\downarrow}$

➤ OR a superposition of a left and right-handed particle: $\psi = \psi_L + \psi_R$

$$\psi_{R/L} = \frac{1}{2}(1 \pm \gamma^5)\psi$$

- In the SM, left and right-handed fermions behave very differently

Weak force doesn't interact with
right-handed SM quarks

$\Rightarrow$ Right-handed singlets:

$$(u_R), (c_R), (t_R)$$

$$(d_R), (s_R), (b_R)$$

Weak force does interact with
left-handed SM quarks

$\Rightarrow$ Left-handed doublets:

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} t_L \\ b_L \end{pmatrix}$$

W bosons flip between
upper and lower type

- The SM quarks are “chiral particles”

Vector-like Quarks (VLQs)

Mathematically, this means:

- In the Lagrangian: The ‘current’ for SM quarks is chiral: $\bar{\psi}\gamma^\mu\frac{1}{2}(1-\gamma^5)\psi$

The ‘current’ for VLQs is vector-like: $\bar{\psi}\gamma^\mu\psi$

Physically, this means:

- Chiral fermions can only get mass through coupling to the Higgs boson
- VLQs fermions can have mass without coupling to the Higgs boson
 - Important: This avoids strong constraints from Higgs measurements!

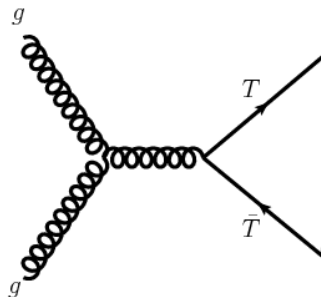
If a VLQ and SM quark have the same quantum numbers, they can “mix”

- ⇒ A physical VLQ will actually be a mixture of VLQ and SM quark
- To solve the hierarchy problem, we need a “top-partner” VLQ

		Q[e]	VLQs				
			singlets	doublets			triplets
Top-partner →	5/3			$\begin{pmatrix} X \\ T \end{pmatrix}$			$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$
	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						

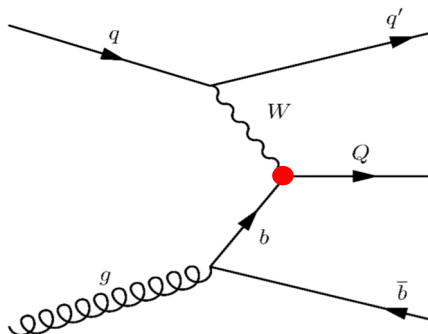
How can we make VLQs?

Pair Production via strong force



- Depends on mass and QCD
 $\Rightarrow \sim$ Model-independent

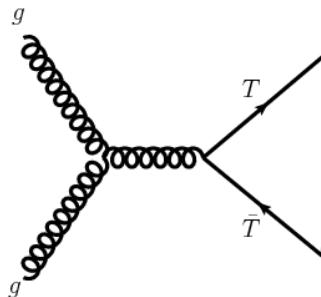
Also could make a single VLQ



- Depends on mass and **VLQ coupling**
 $\Rightarrow$ Model-dependent

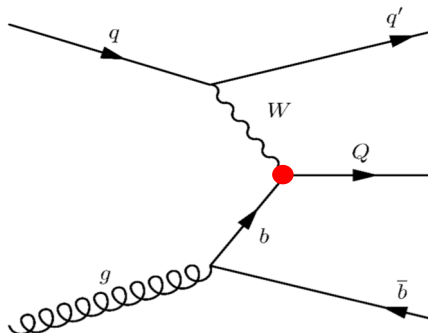
How can we make VLQs?

Pair Production via strong force



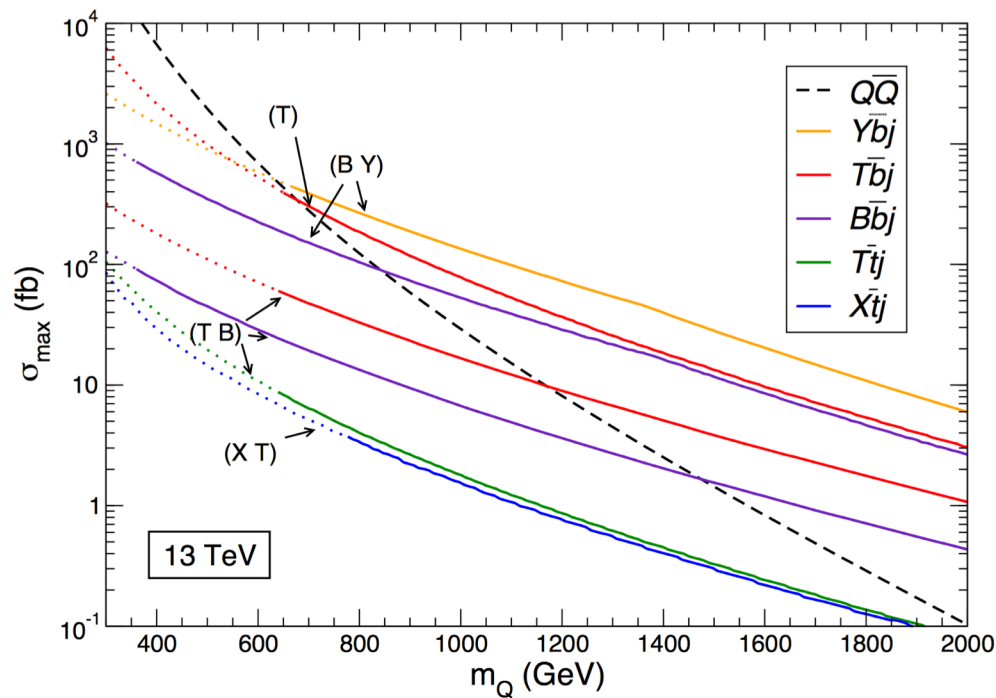
- Depends on mass and QCD
⇒ ~Model-independent

Also could make a single VLQ



- Depends on mass and **VLQ coupling**
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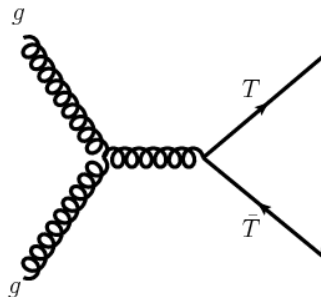
Cross section vs. VLQ mass:
(Production rate)



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

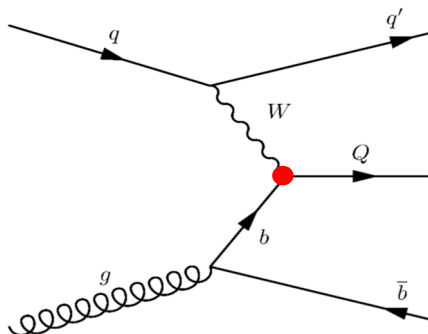
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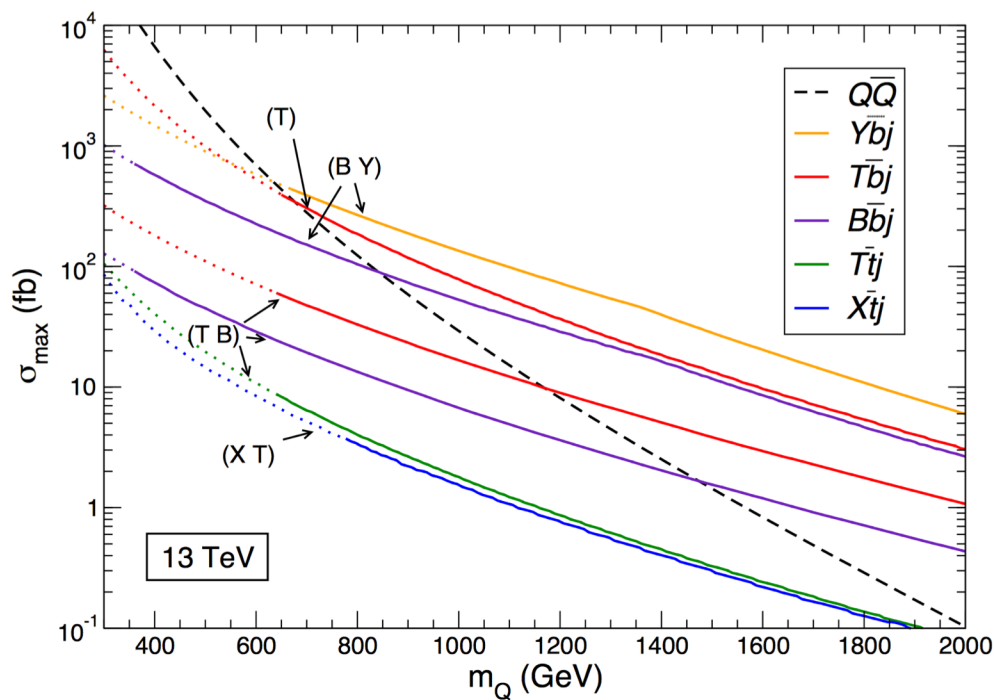
Also could make a single VLQ



- Depends on mass and **VLQ coupling**
⇒ Model-dependent

Still most sensitive

Cross section vs. VLQ mass:
(Production rate)



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

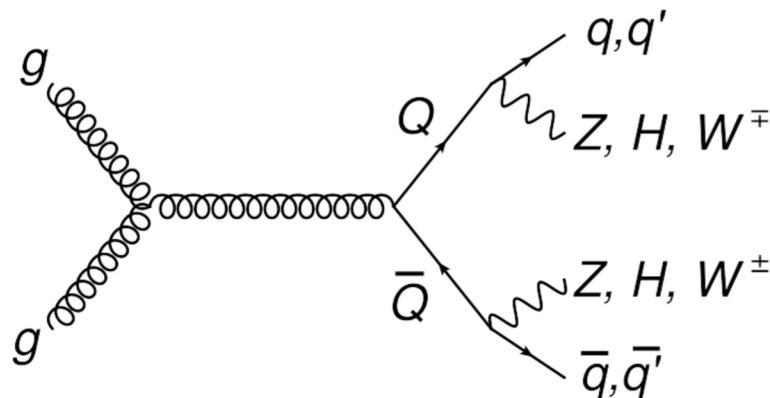
How will they decay?

Possible decays dictated by quantum numbers

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

⇒ Rich phenomenology!

Branching ratios are
model-dependent



How will they decay?

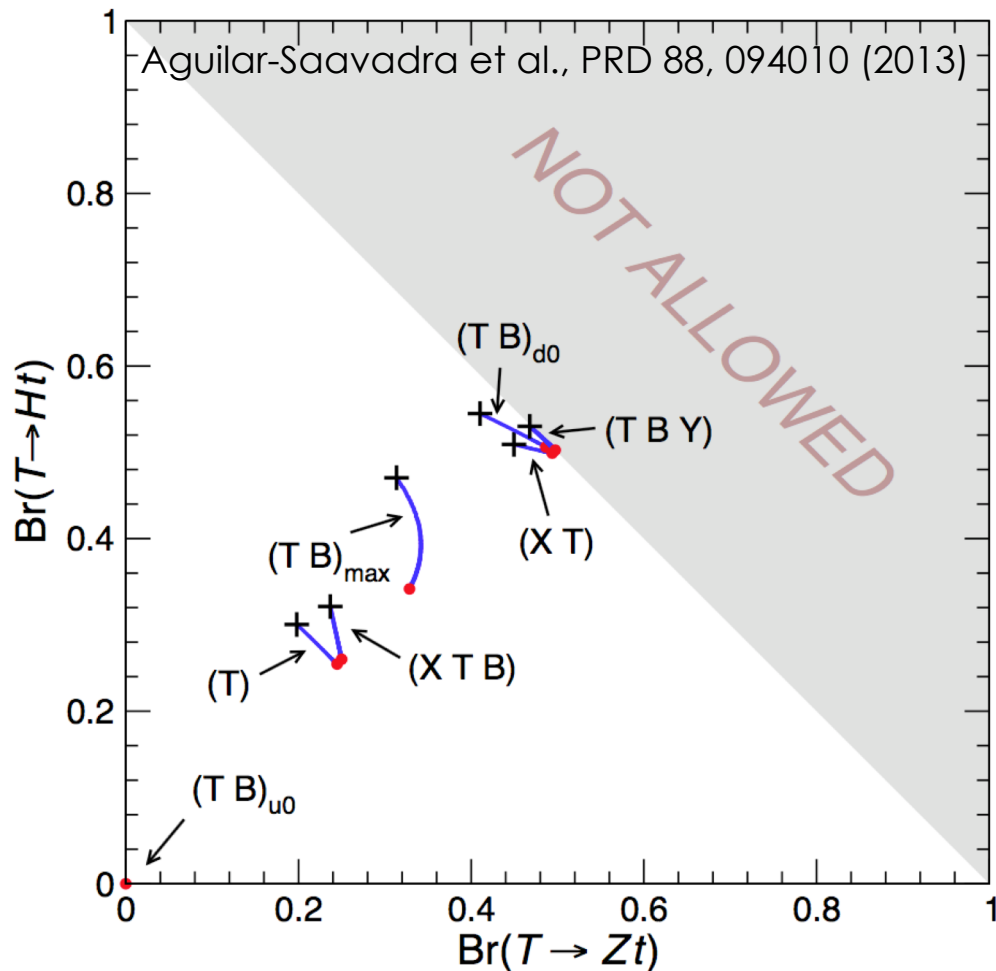
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How will they decay?

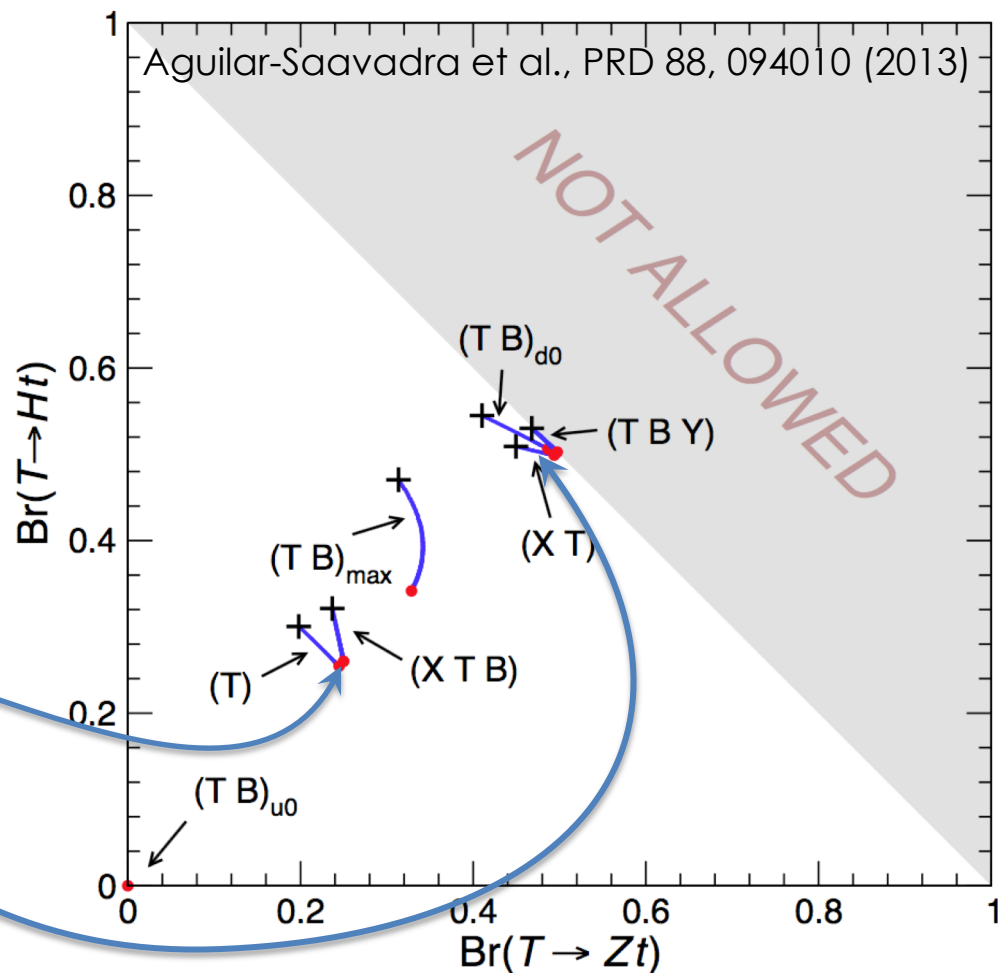
Possible decays dictated by quantum numbers

- $T \rightarrow Wb, Zt, Ht$
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⇒ Rich phenomenology!

Branching ratios are model-dependent

- Constrained in some scenarios
 - “Singlet” T
 - “Doublet” T
(assuming mixing only in up sector)



How will they decay?

Possible decays dictated by quantum numbers

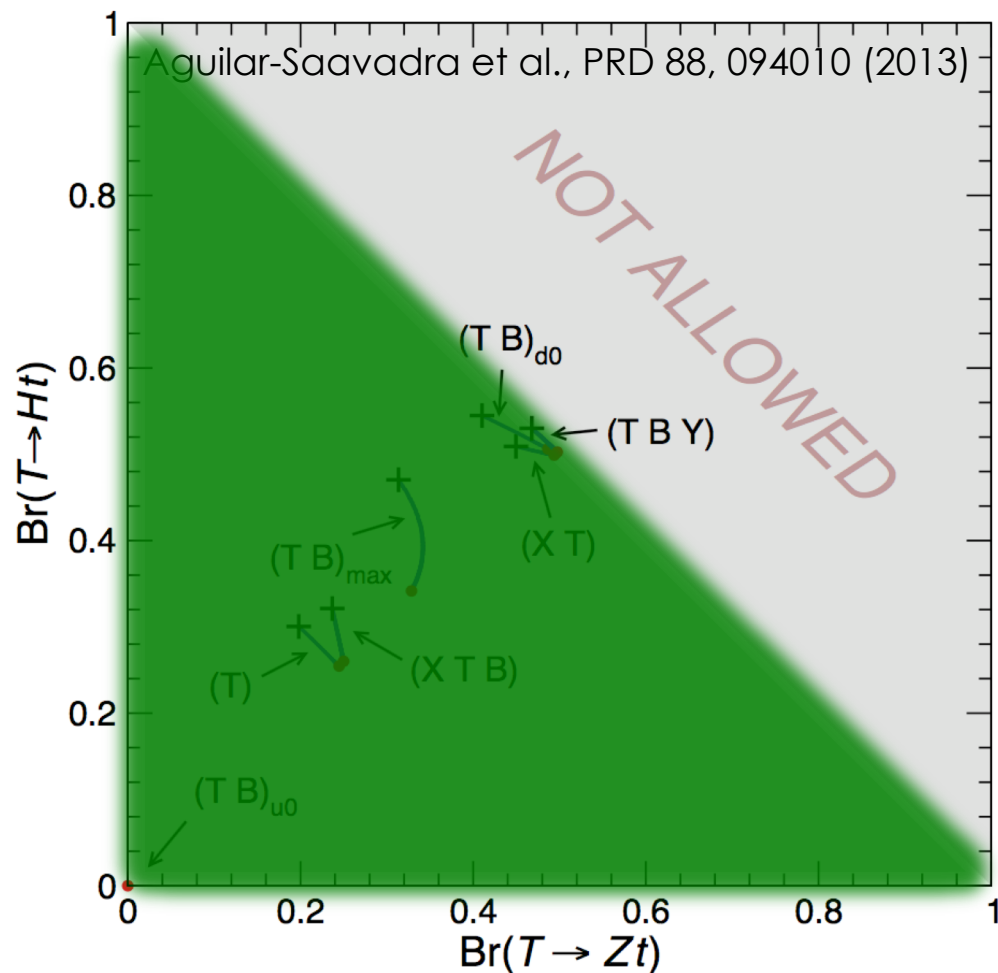
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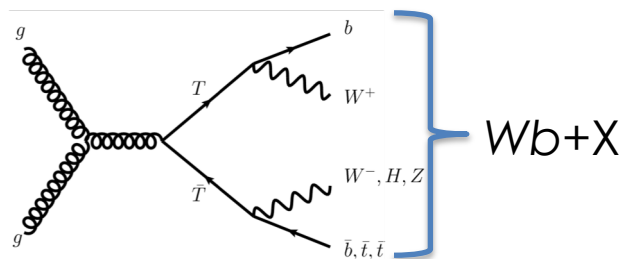
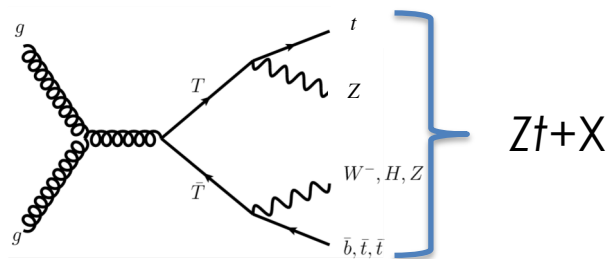
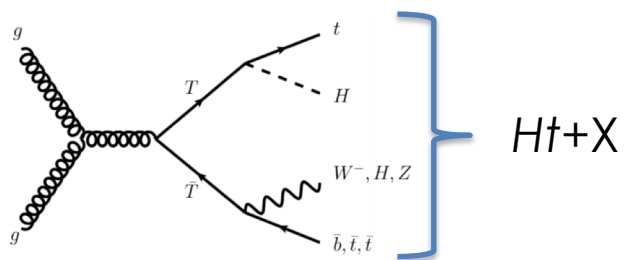
- Constrained in some scenarios
 - “Singlet” T
 - “Doublet” T
(assuming mixing only in up sector)

But need to test **all** possibilities!

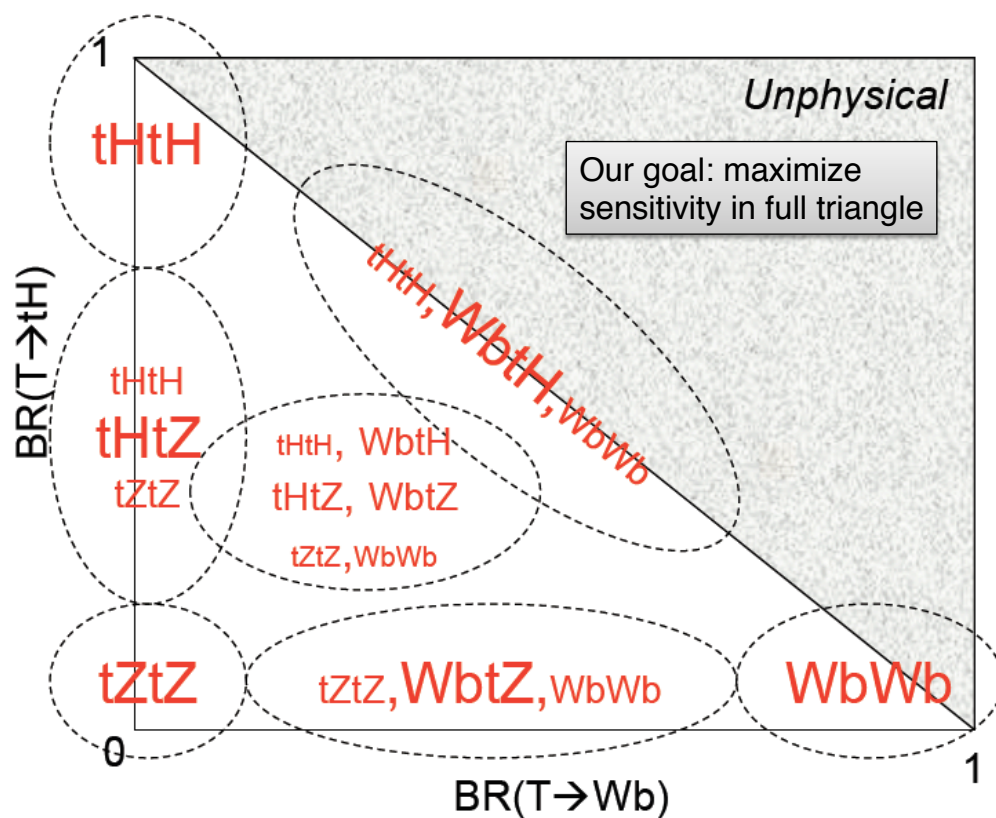


General Search Strategy

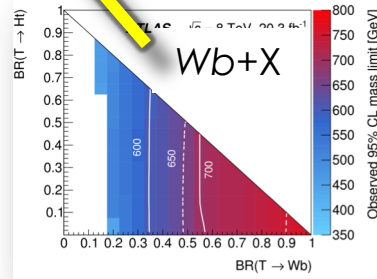
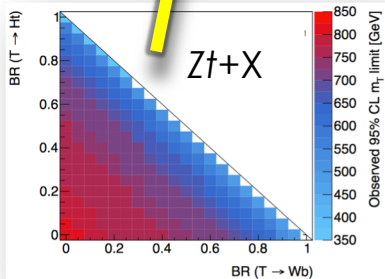
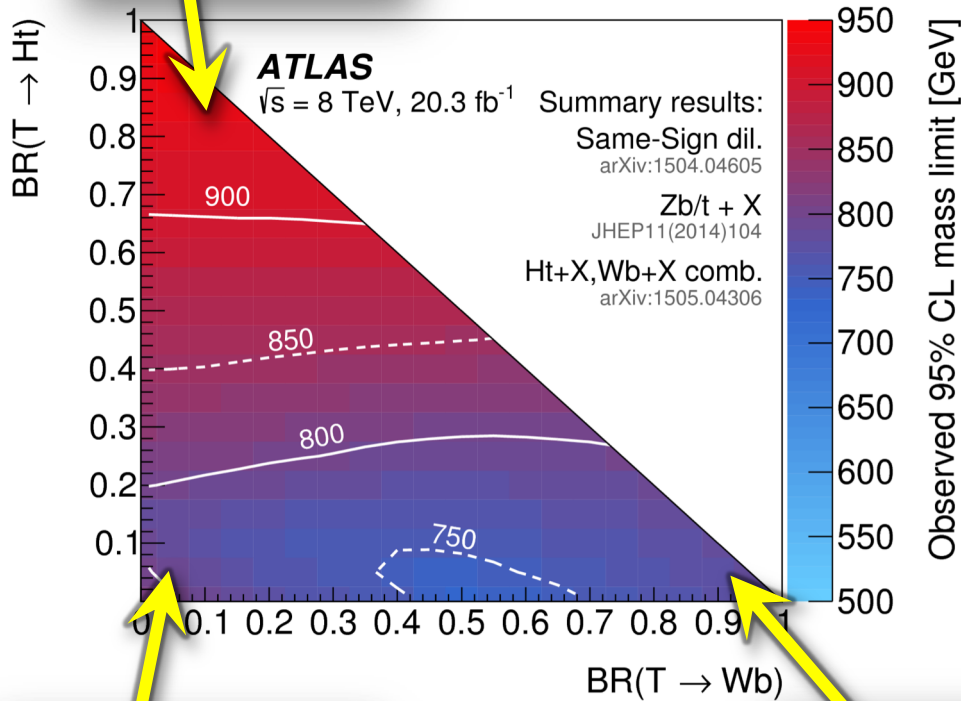
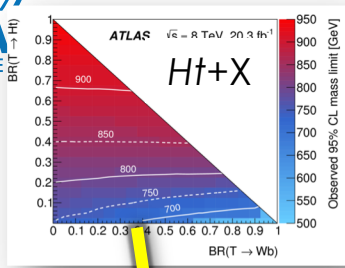
Multiple analyses to target each decay:



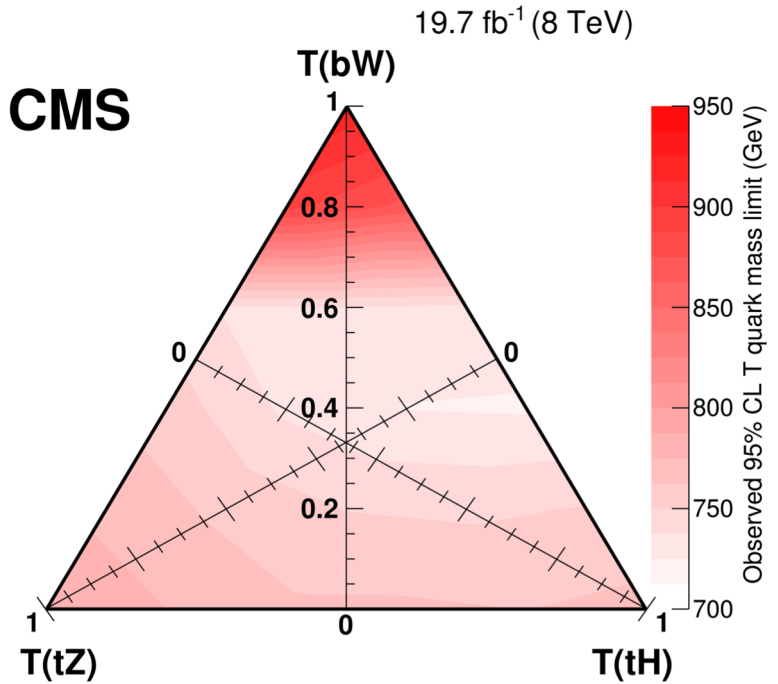
Check all possible branching ratios:



Run 1 Limits on T mass

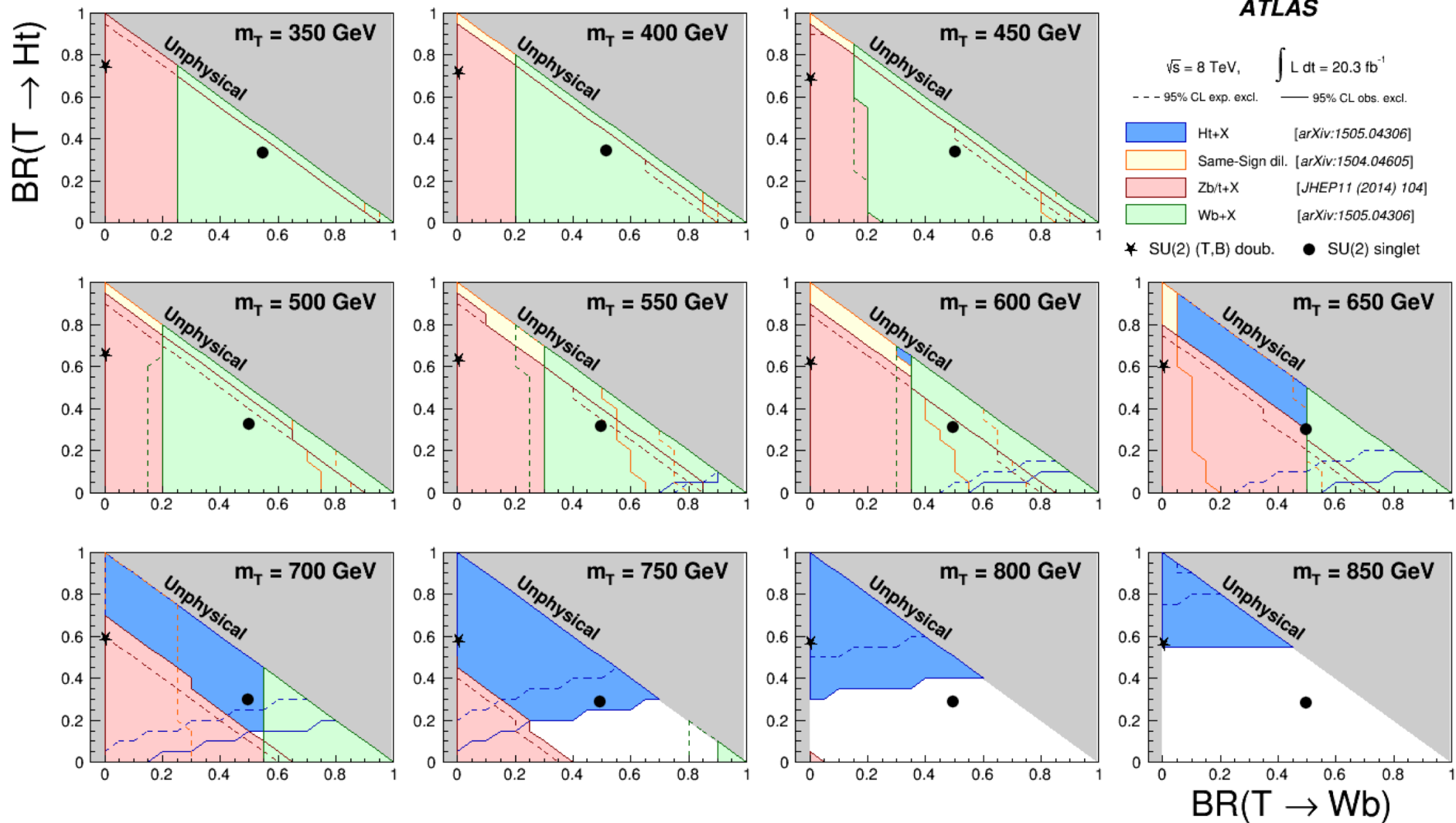


CMS



$\Rightarrow$ Almost all BR scenarios exclude for $m_T \lesssim 750 \text{ GeV}$

Run 1 Limits on T mass

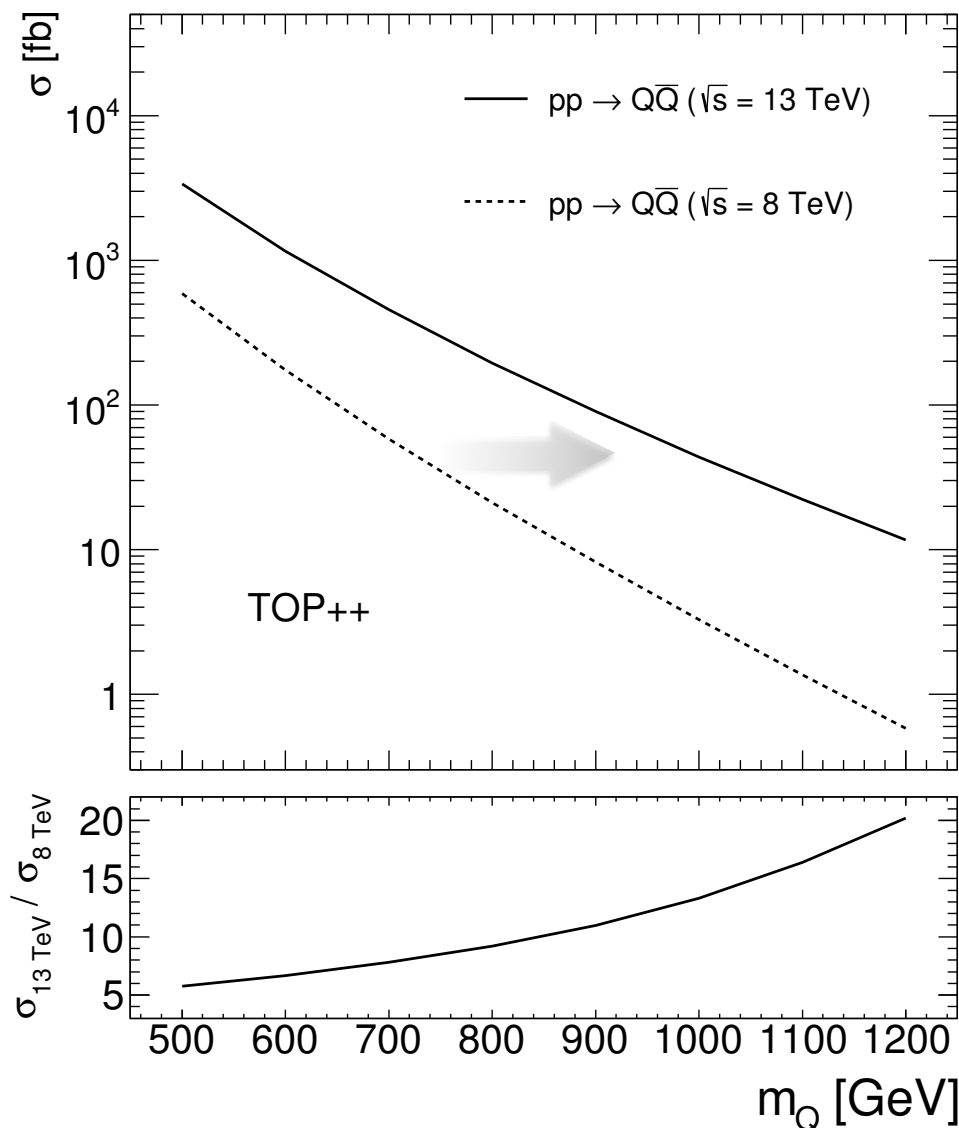


Run 1 $\Rightarrow$ Run 2

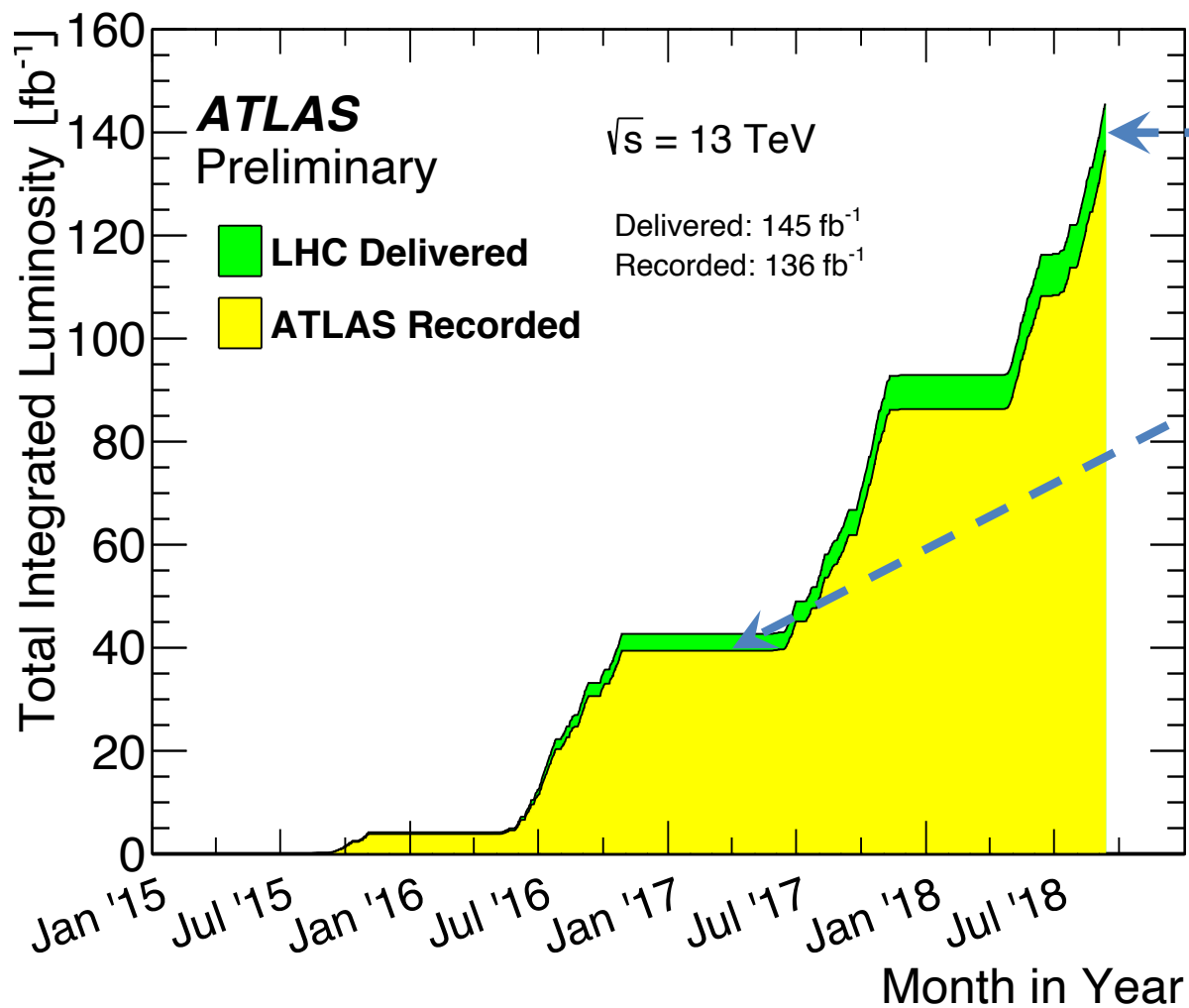
8 TeV $\Rightarrow$ 13 TeV

- Huge increase in $pp \rightarrow T\bar{T}$ cross section!

$\Rightarrow$ Same amount of data will probe much higher masses



Run 2 Data



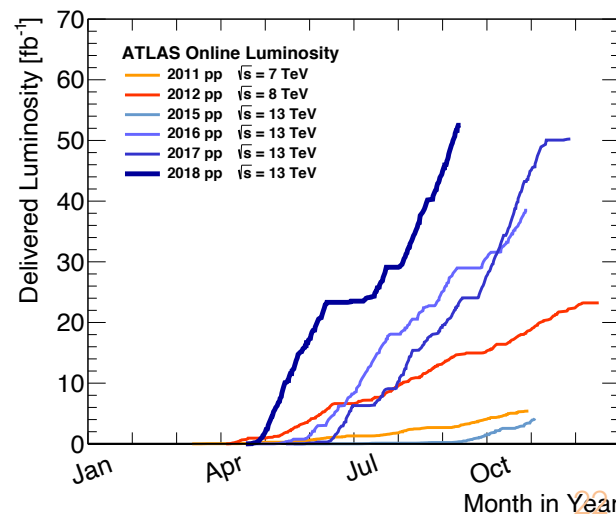
To date

- Total Delivered: $\sim 145/\text{fb}$
- Total Recorded: $\sim 135/\text{fb}$

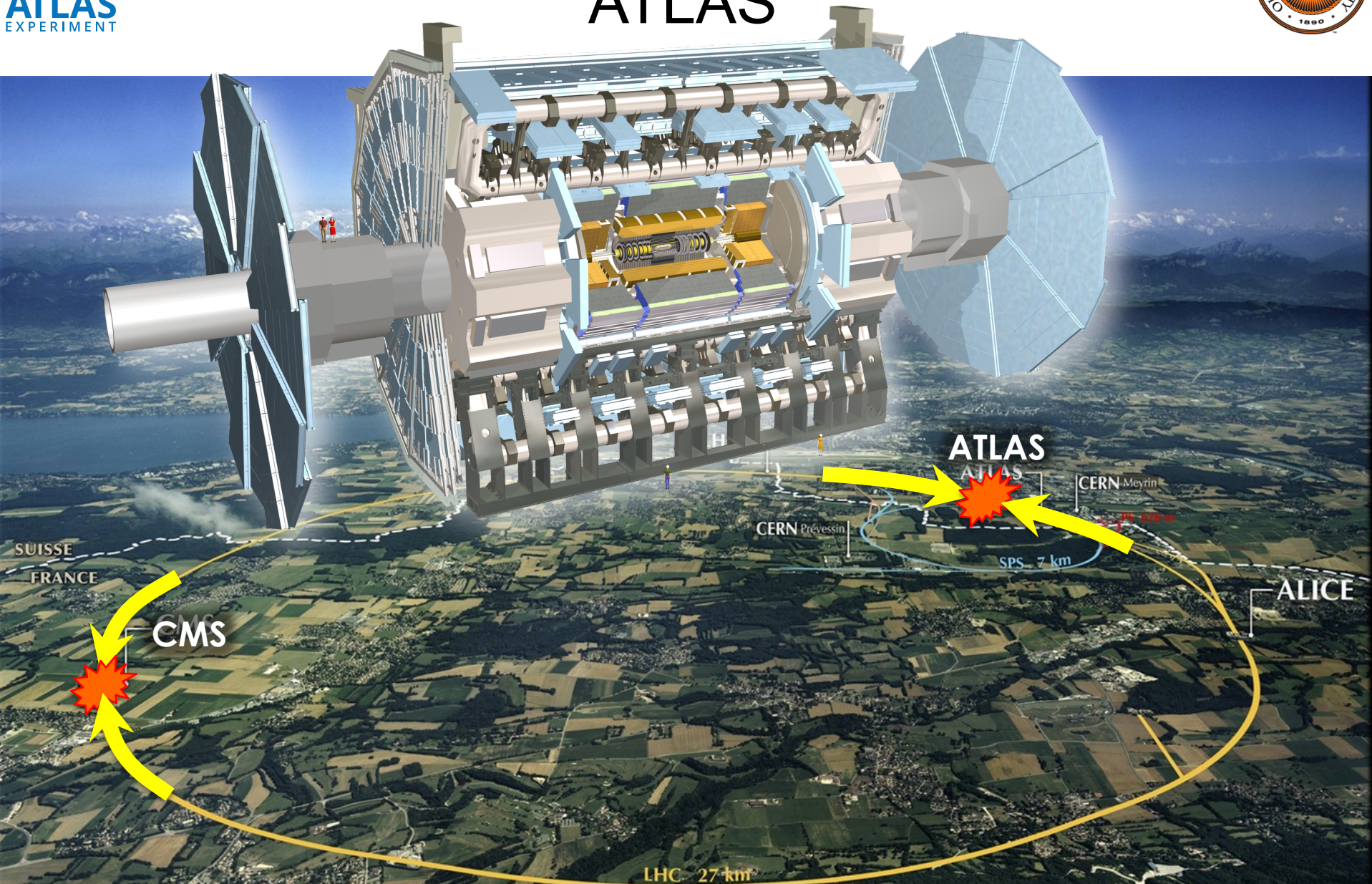
VLQ searches

(36/ fb after DQ)

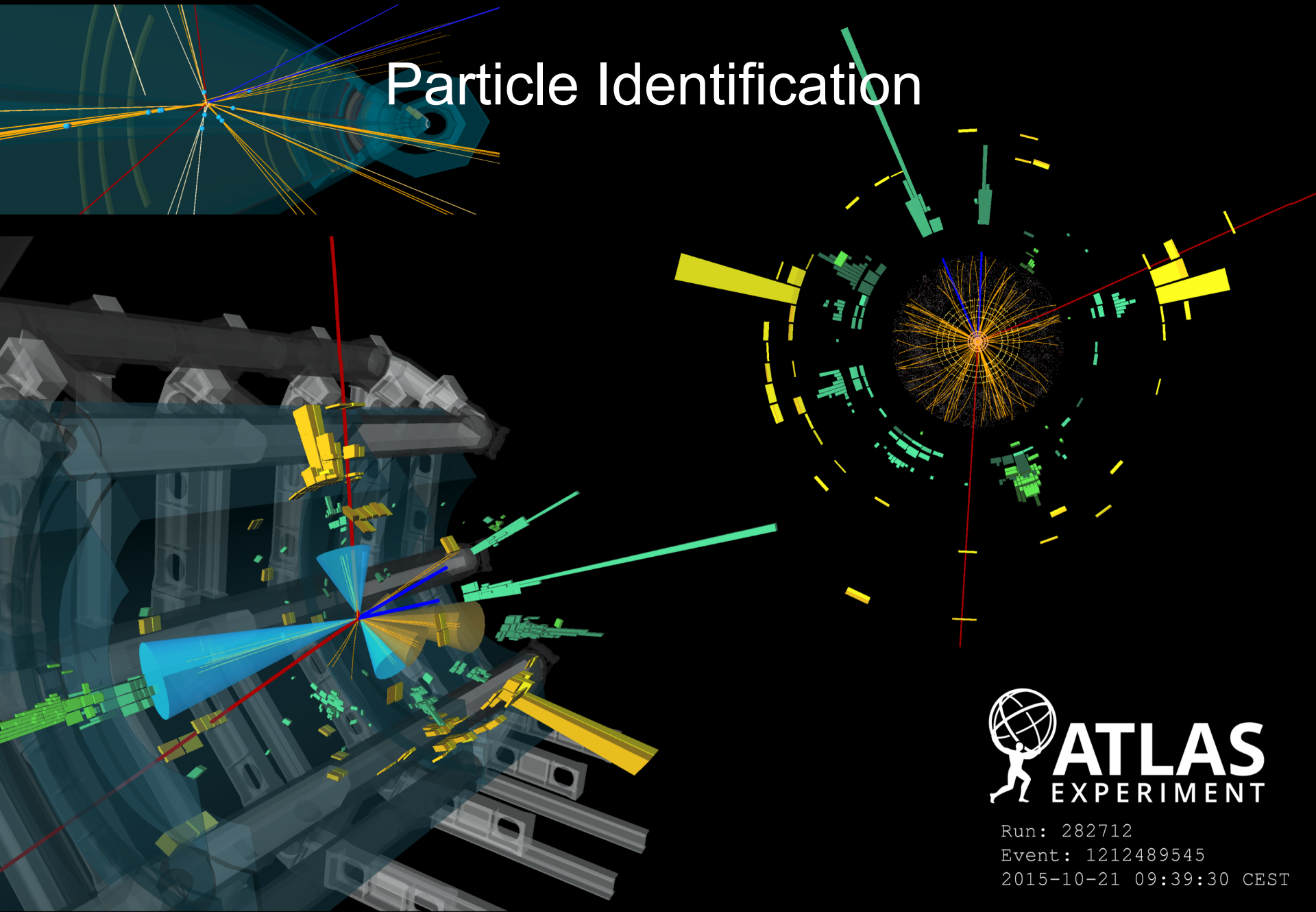
**Huge thank you to
LHC Operations!**



ATLAS



Particle Identification



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

Particle Identification

Electrons

- Tracks leading to isolated EM energy deposits

Muons

- Tracks passing through entire detector



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

Particle Identification

b-quarks

- Tagged by multivariate discriminant
- b ~77%, c ~15%, light < 1%

Electrons

- Tracks leading to isolated EM energy deposits

Muons

- Tracks passing through entire detector

Quarks and gluons $\Rightarrow$ Jets

- Collimated showers of particles

Neutrinos $\Rightarrow$ Missing transverse momentum ($E_{\text{T}}^{\text{miss}}$)

Run: 282712

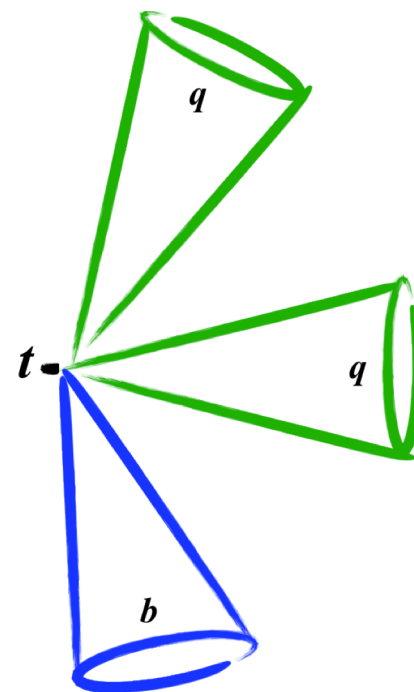
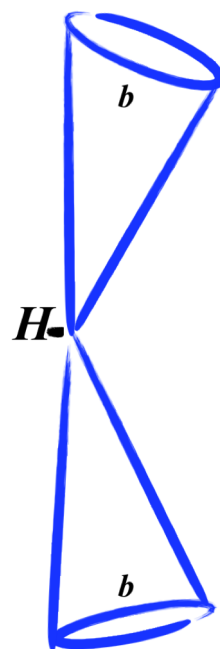
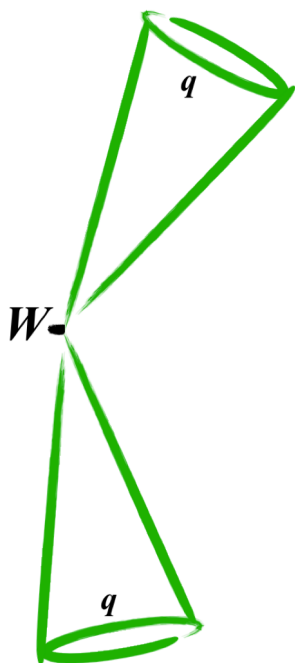
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2012-08-21 09:39:30 CEST

ATLAS
EXPERIMENT

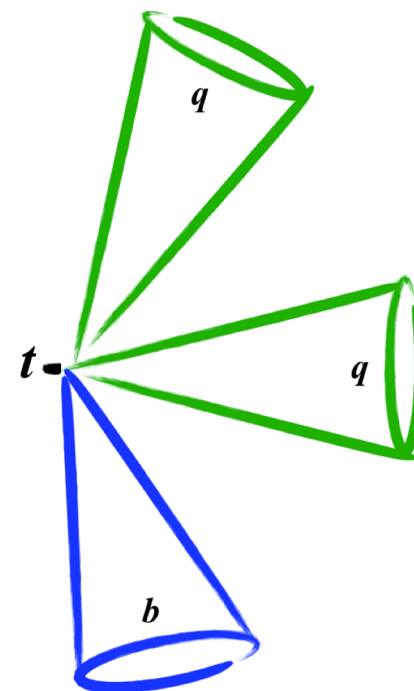
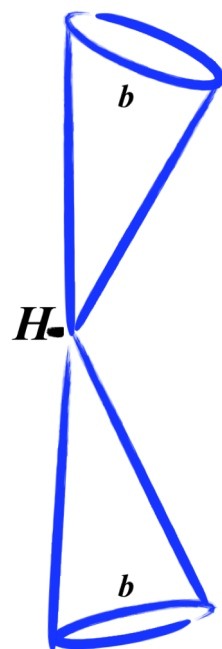
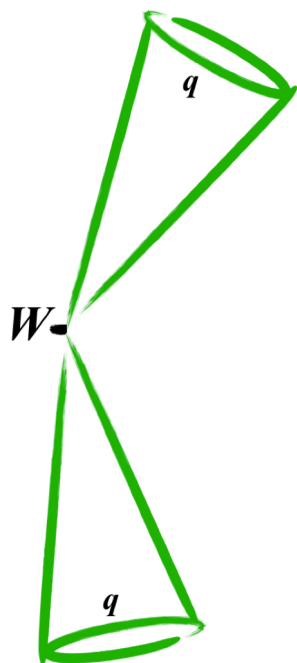
Heavy Objects

With
low- p_T :

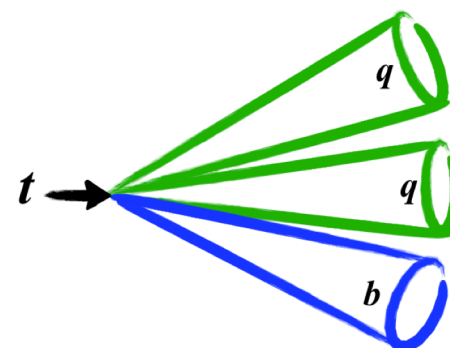
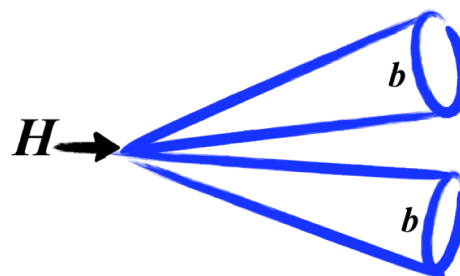
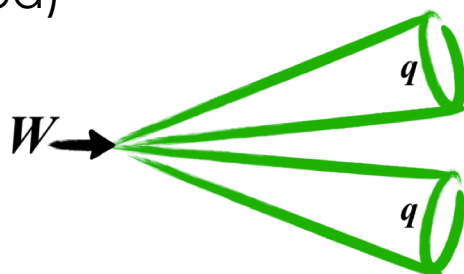


Heavy Objects

With
low- p_T :

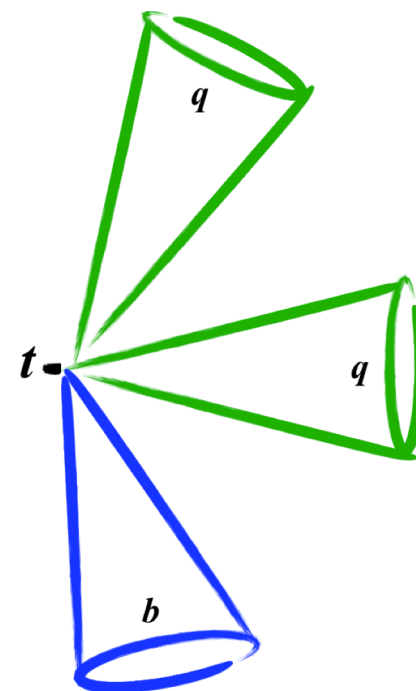
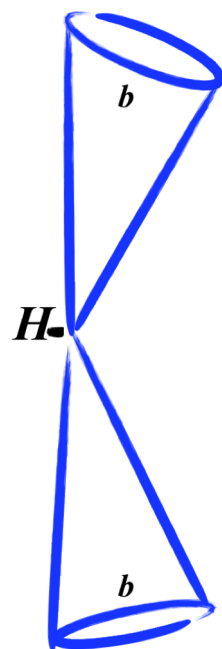
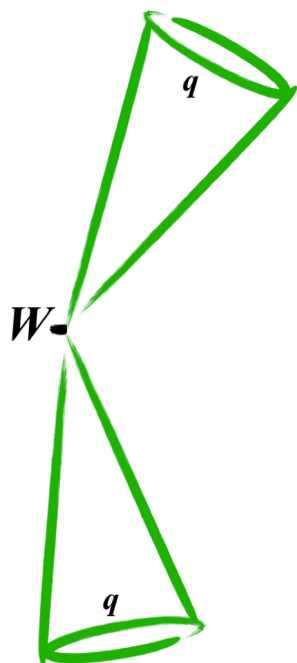


high- p_T :
(boosted)

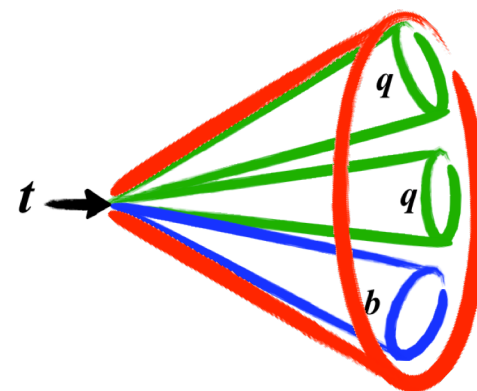
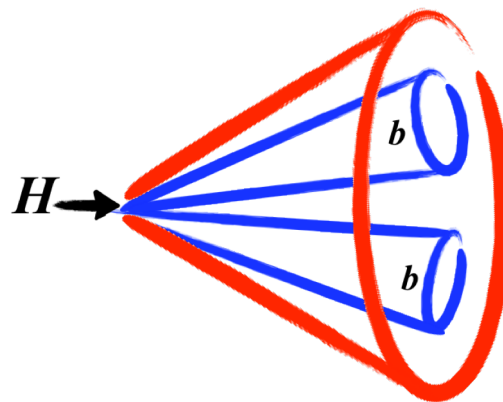
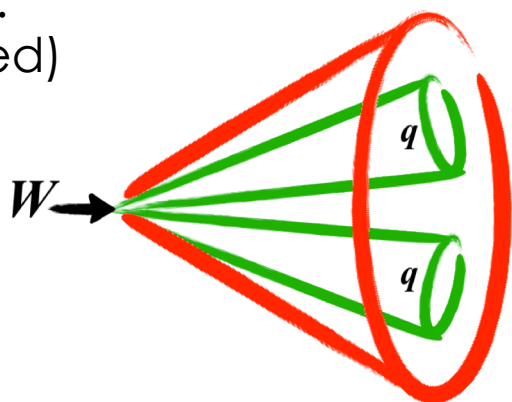


Heavy Objects

With
low- p_T :



high- p_T :
(boosted)



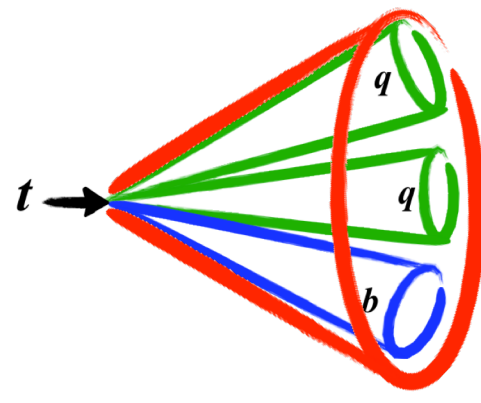
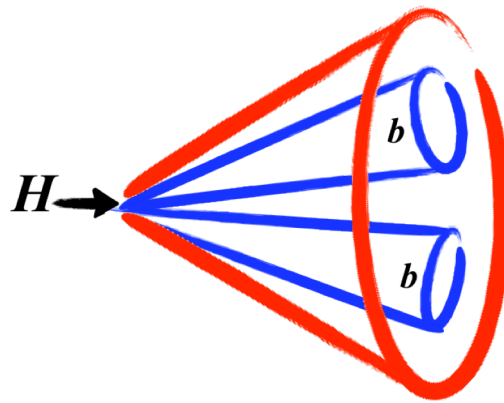
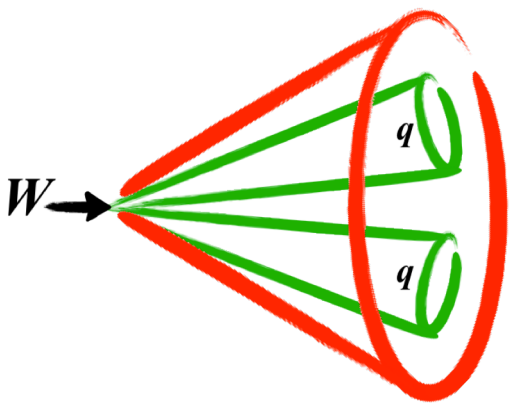
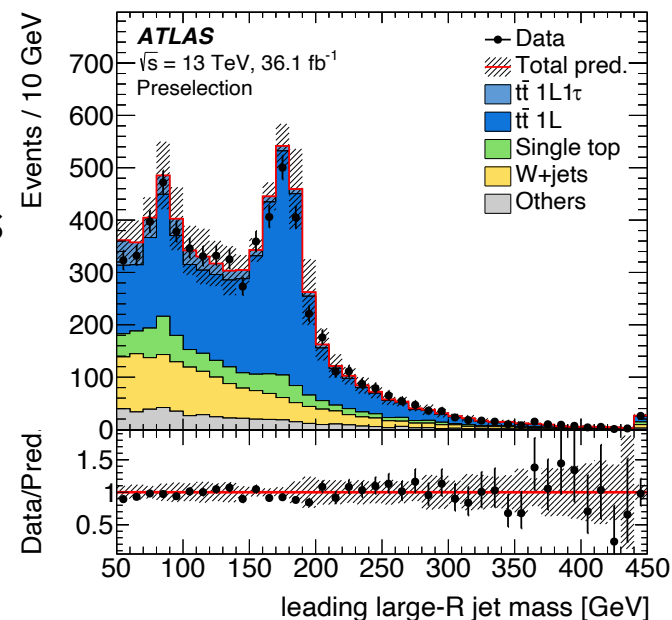
Heavy Objects

1) “Large-R jets” from calorimeter cells

- $R=1.0$ ‘trimmed’ jets
- Dedicated calibrations and uncertainties
- Use sub-structure to tag $W \rightarrow qq$ candidates

2) “Large-R re-clustered jets”

- Group regular jets inside $R=1.0$
- Inherit calibration and uncertainties
- Use mass of large-R jet to “tag”



Analyses

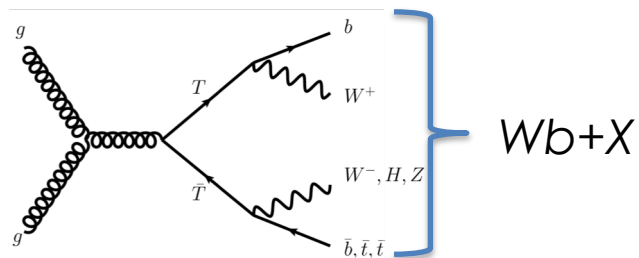
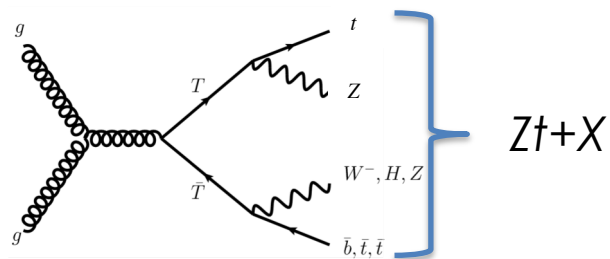
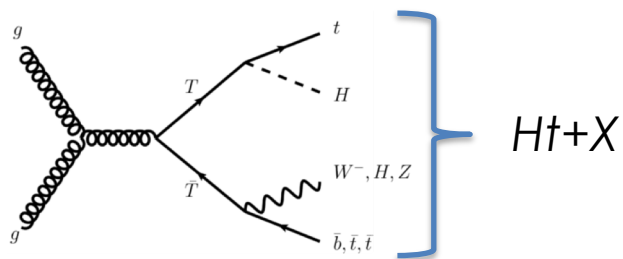
Multiple analyses to target the various decays:

Analysis	$T\bar{T}$ decay	$B\bar{B}$ decay
$H(bb)t + X$ [16]	$HtH\bar{t}$	-
$W(\ell\nu)b + X$ [30]	$WbW\bar{b}$	-
$W(\ell\nu)t + X$ [32]	-	$WtW\bar{t}$
$Z(\nu\nu)t + X$ [33]	$ZtZ\bar{t}$	-
$Z(\ell\ell)t/b + X$ [35]	$ZtZ\bar{t}$	$ZbZ\bar{b}$
Tril./s.s. dilepton [36]	$HtH\bar{t}$	$WtW\bar{t}$
Fully hadronic [37]	$HtH\bar{t}$	$HbH\bar{b}$

Analyses

Multiple analyses to target each decay:

Different final states require different strategies:

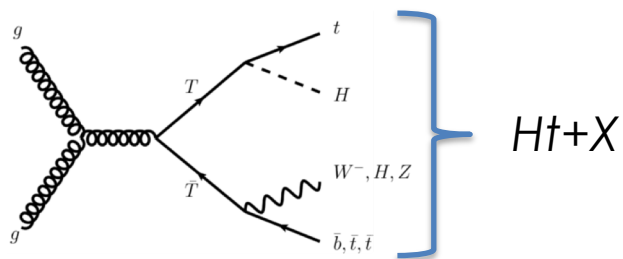


- Divide and conquer
 - Many signal regions (SRs), control regions (CRs), and validation regions (VRs)
 - Fit m_{eff} distribution in SRs and CRs
- Cut-and-count w/ control regions
 - 1 signal-, 2 control-, 3 validation-regions
 - Fit total yield in SR and CRs
- Mass bump search
 - 1 signal-region, 1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

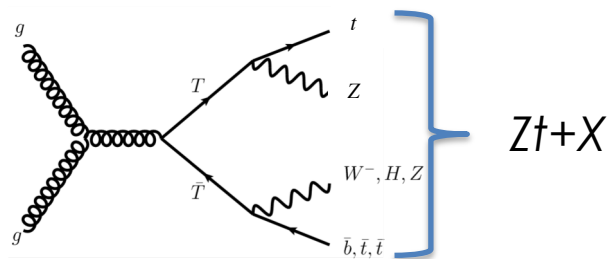
Analyses

Multiple analyses to target each decay:

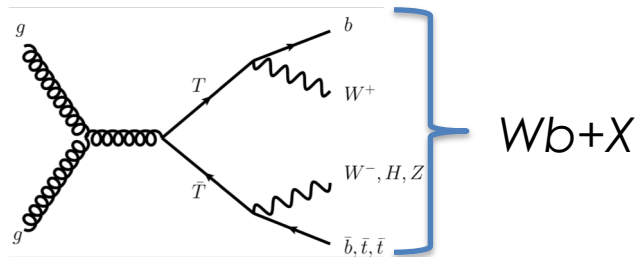
Different final states require different strategies:



- 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 signal-, 2 control-, 3 validation-regions
 - Fit total yield in SR and CRs



- Mass bump search
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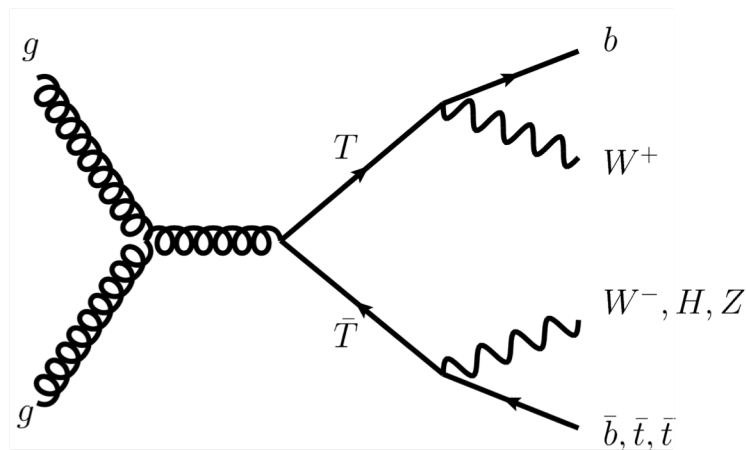
Targeting $W \rightarrow \ell \nu$ decay

$$T\bar{T} \rightarrow WbWb \rightarrow \ell \nu b qq b$$

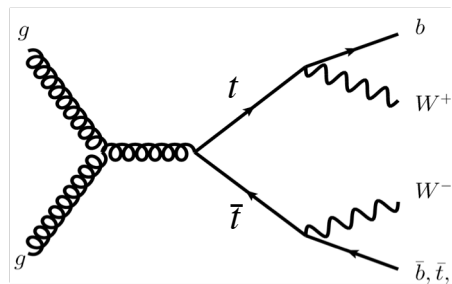
$$T\bar{T} \rightarrow WbHt \rightarrow \ell \nu b bb Wb$$

$$T\bar{T} \rightarrow WbZt \rightarrow \ell \nu b qq Wb$$

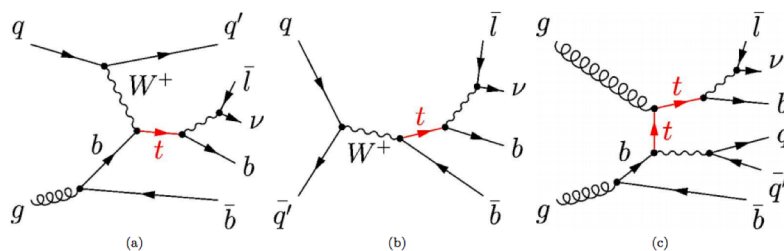
Backgrounds



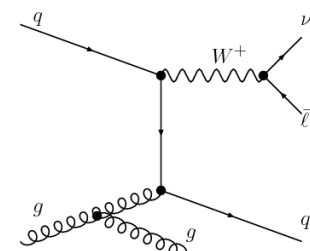
$t\bar{t} \rightarrow WbWb$:



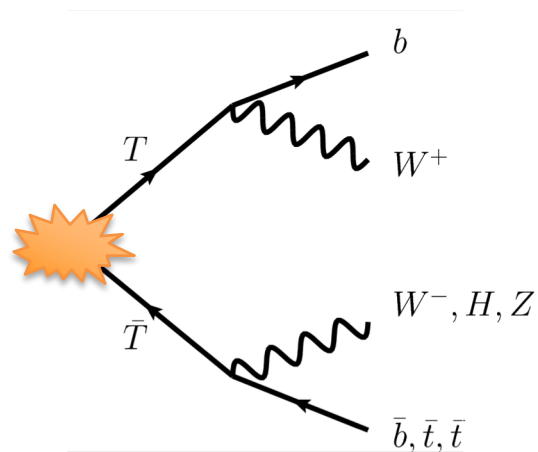
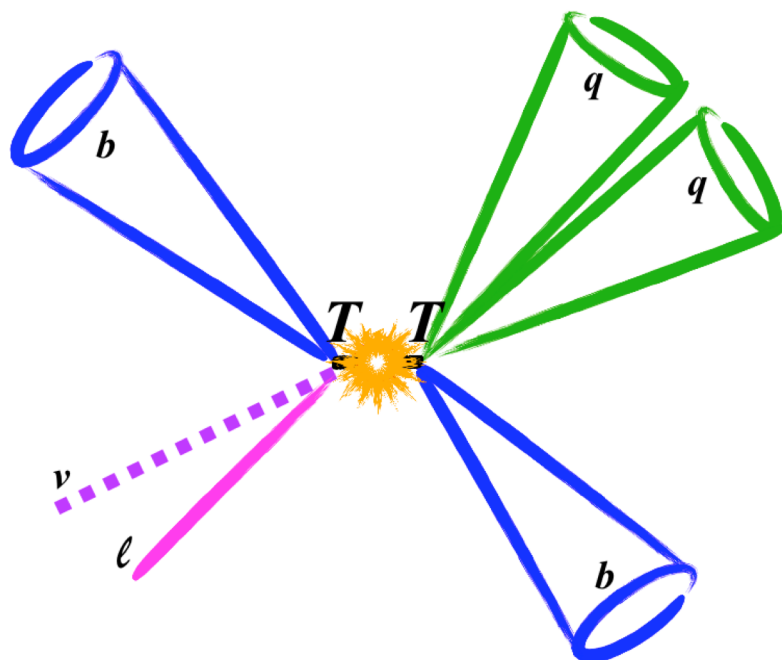
Single top:



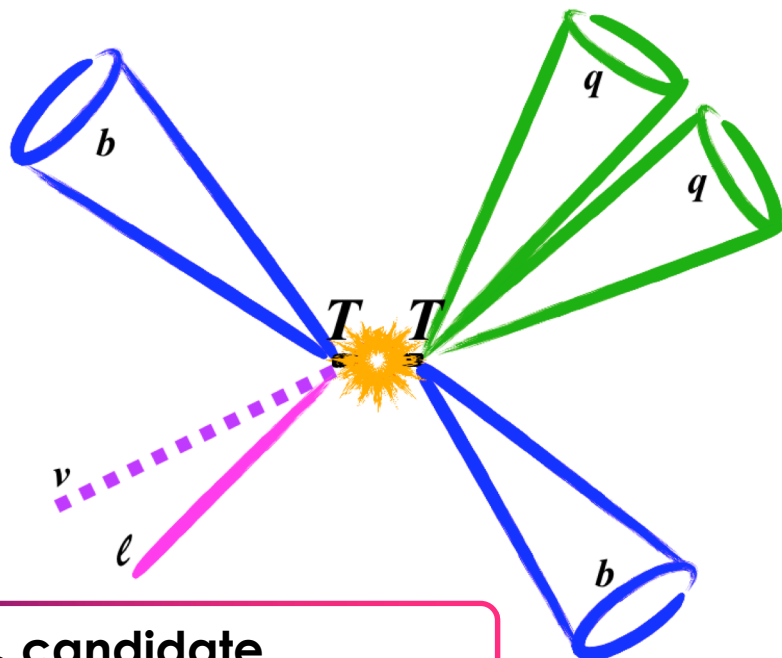
W +jets:



Basic Selection



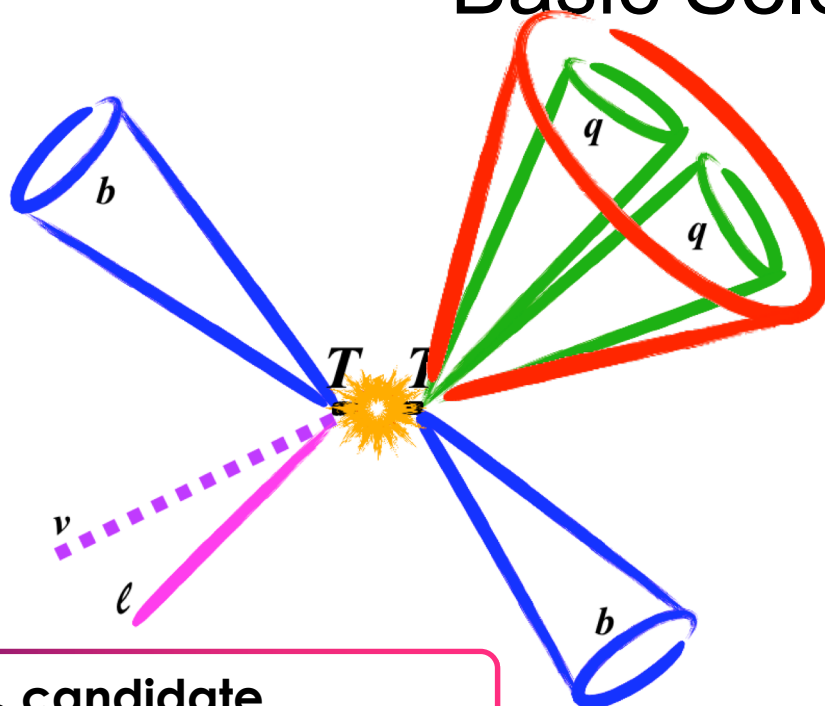
Basic Selection



W_{lep} candidate

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

Basic Selection



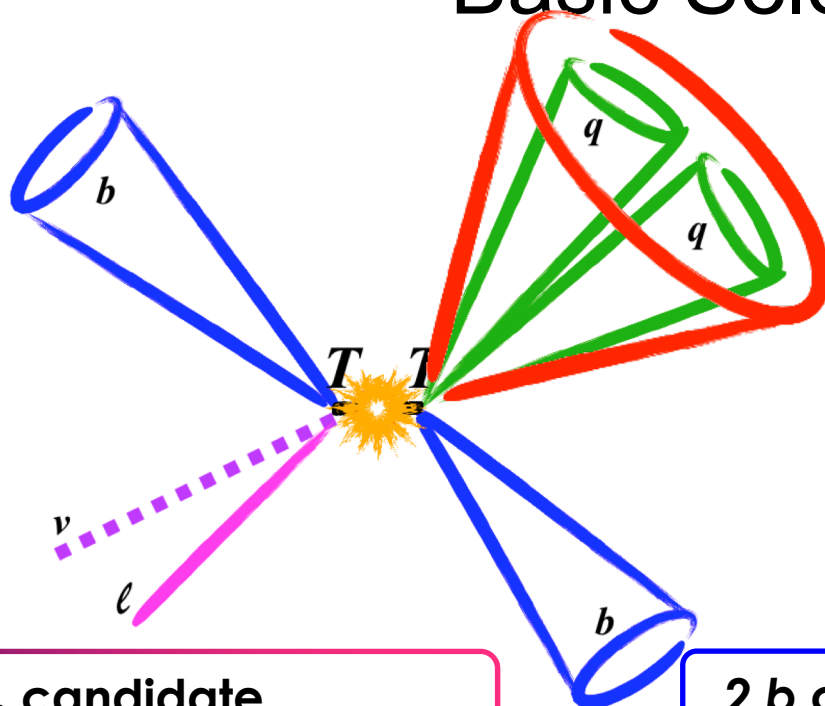
Boosted W_{had} candidate

- $R=1.0$ 'trimmed' jet
- $m > 50 \text{ GeV}$, $p_T > 200 \text{ GeV}$
- Jet substructure W-tag (50% efficiency)

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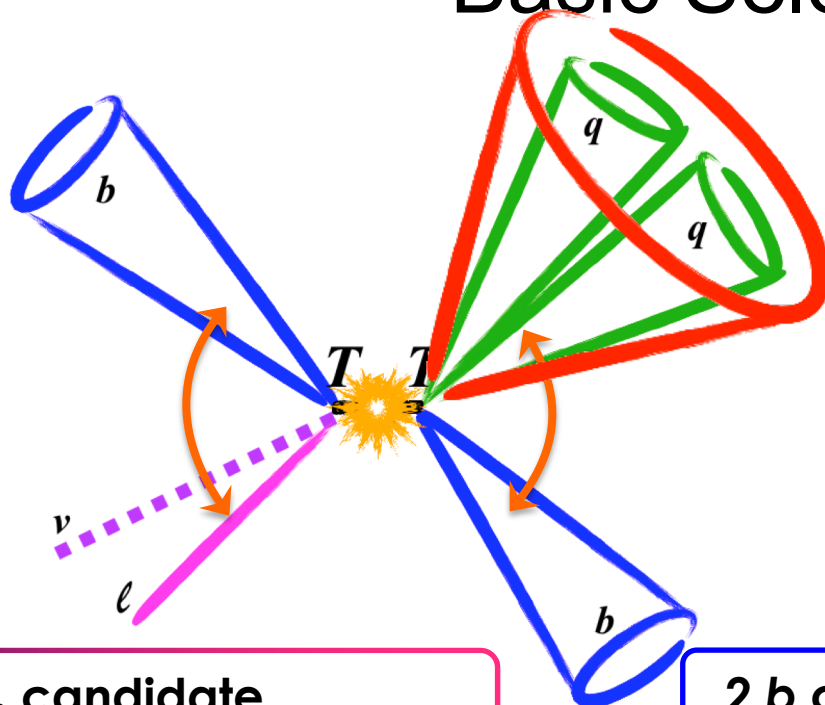
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2 b candidates

- ≥ 2 additional small-R jets
 - $p_T > 25 \text{ GeV}$
 - ≥ 1 b -tagged

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

$$\Delta R(\ell, b) > 1.0$$

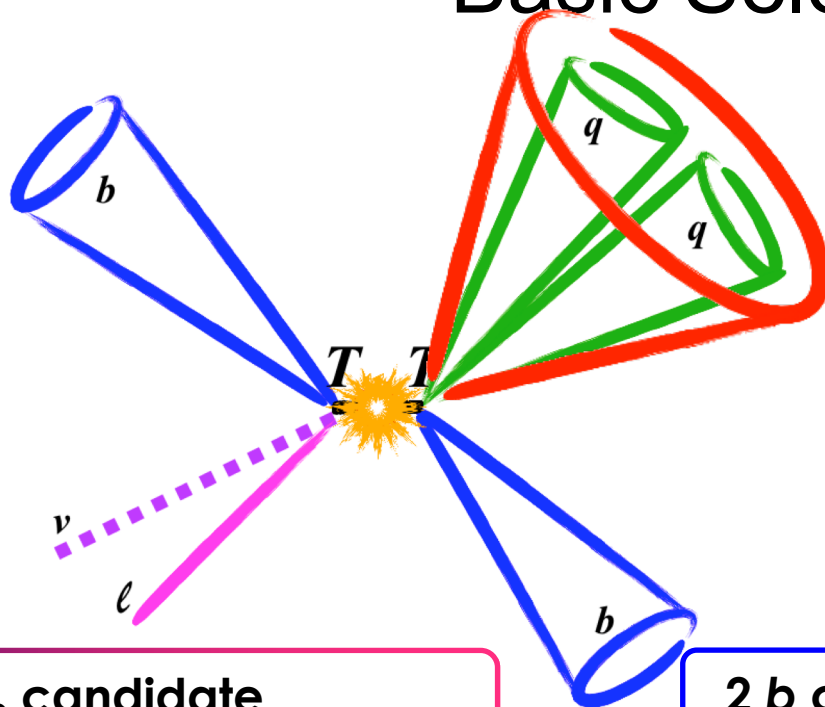
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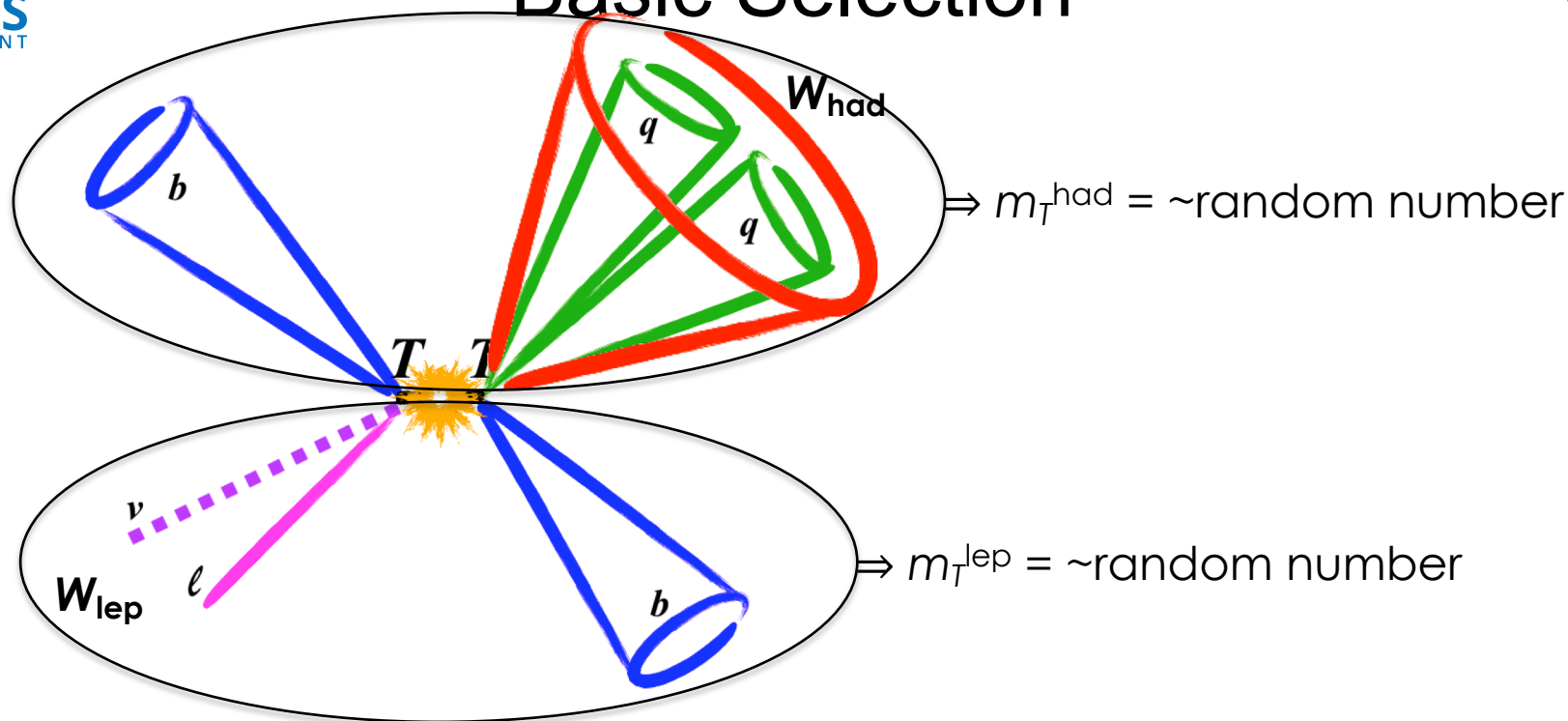
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T_{had} and T_{lep} candidates

- Test all pairings of b candidates with W_{had} or W_{lep}
- Pick combination with smallest $|m_T^{\text{lep}} - m_T^{\text{had}}| < 300 \text{ GeV}$

Basic Selection

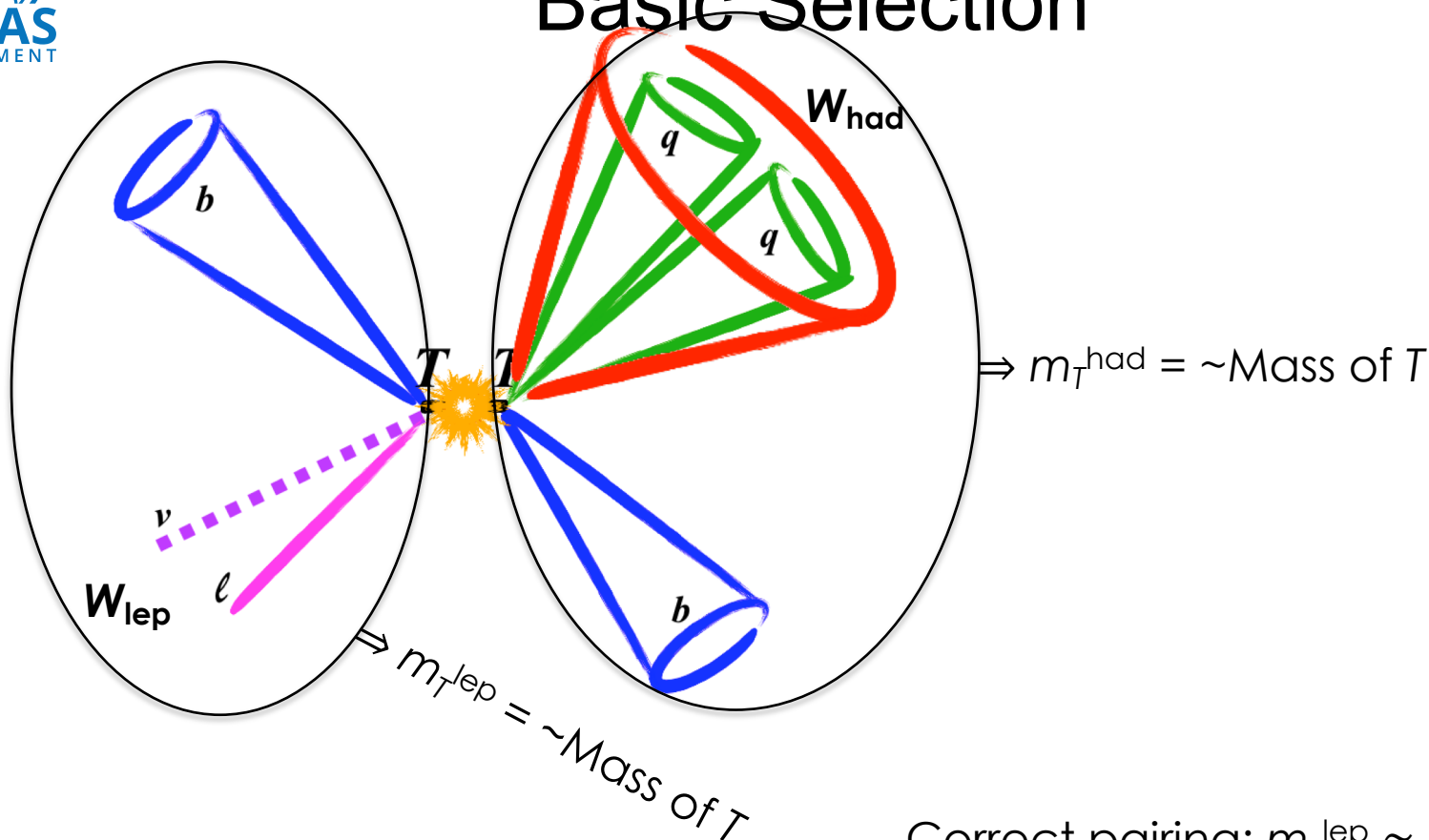


Incorrect pairing: $m_T^{\text{lep}} \neq m_T^{\text{had}}$

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Basic Selection



Correct pairing: $m_T^{\text{lep}} \simeq m_T^{\text{had}}$

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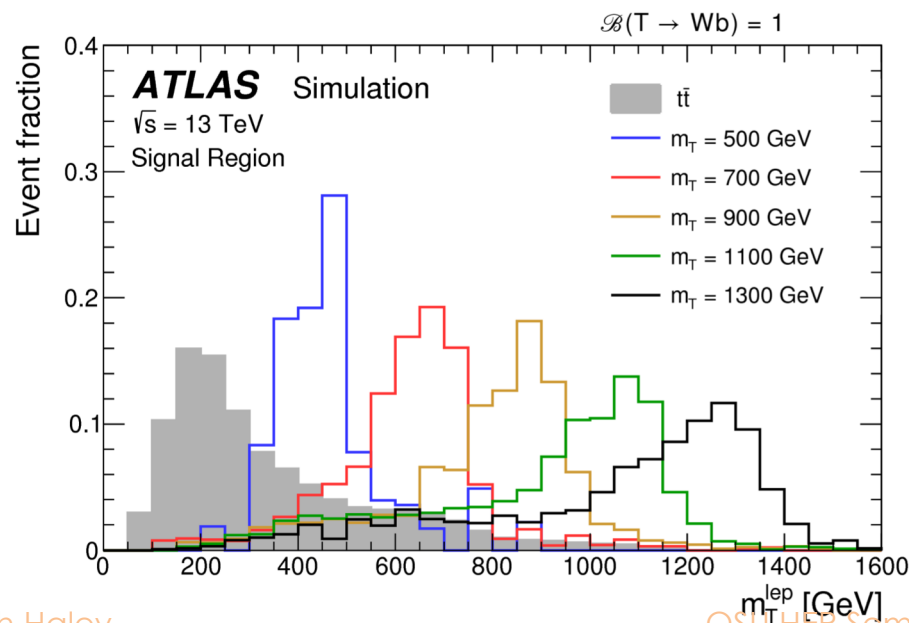
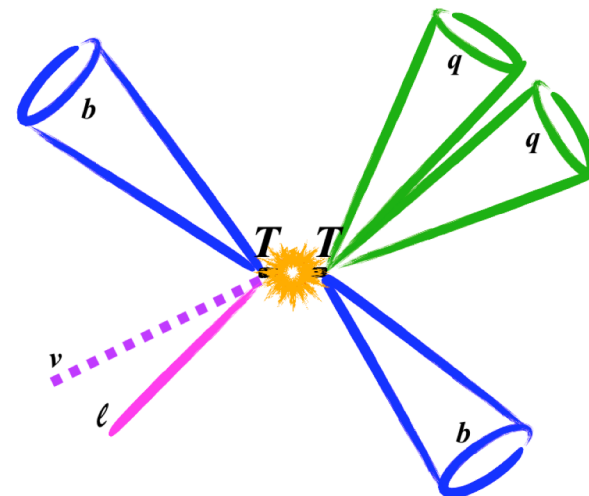
Final Selection

Signal Region (SR)

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

Control Region (CR) to constrain $t\bar{t}$

Final variable: m_T^{lep}



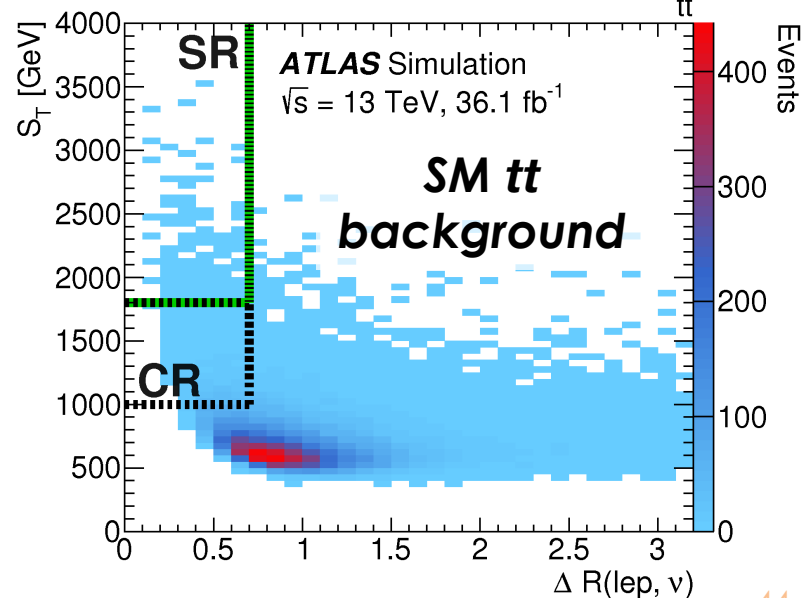
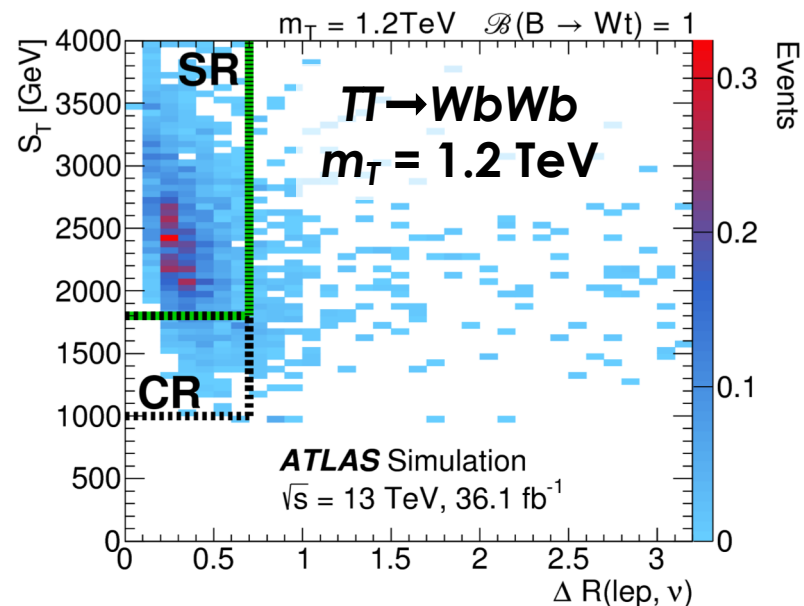
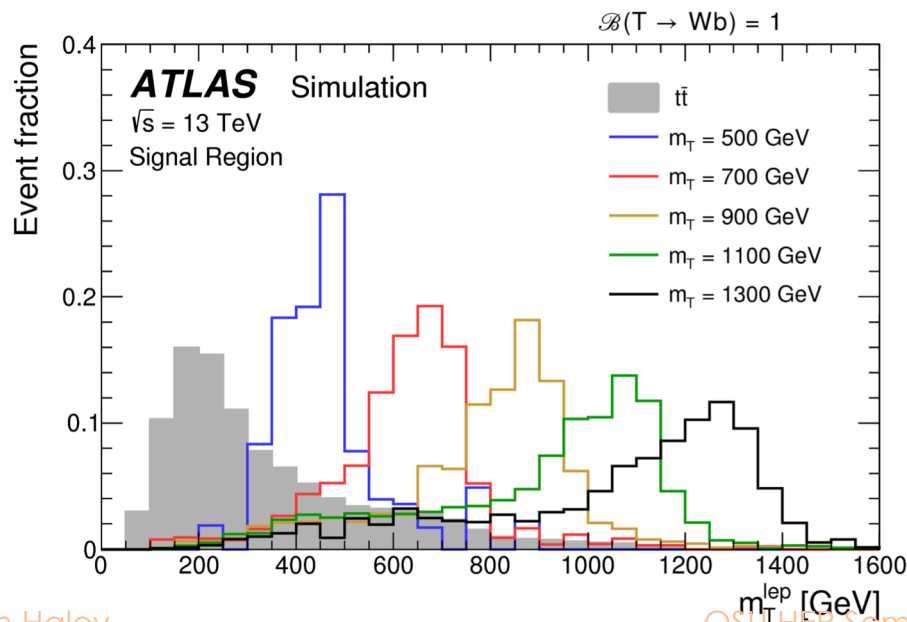
Final Selection

Signal Region (SR)

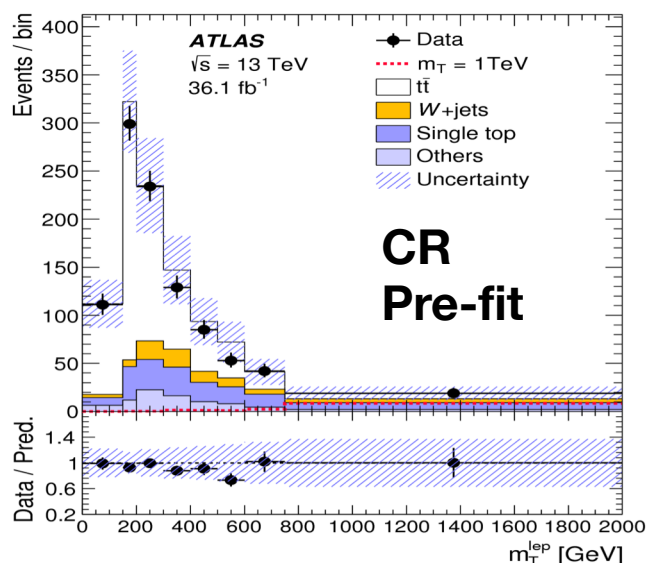
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Control Region (CR) to constrain $t\bar{t}$

Final variable: m_T^{lep}



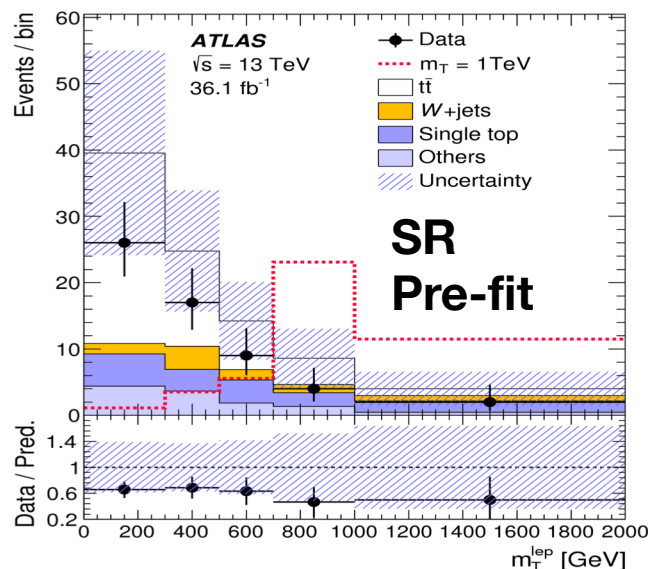
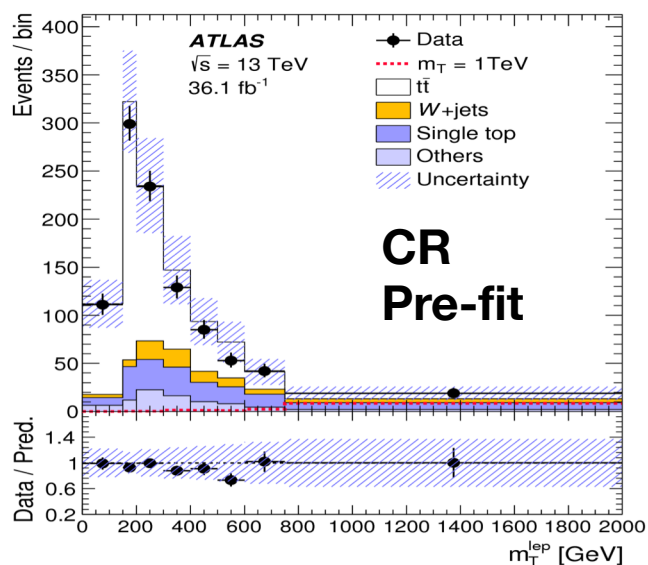
Control Region



- Backgrounds estimated with MC simulations (expect multijet)
- Dominant uncertainties
 - Poisson uncertainty of data
 - Single-top Wt removal scheme
 - $t\bar{t}$ 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, $t\bar{t}V$, multijet)	12 ± 10	82 ± 66
Total Background	91 ± 35	$1\,040 \pm 200$
Signal ($m_T = 1 \text{ TeV}$, $T \rightarrow Wb = 100\%$)	45 ± 4	15 ± 2
Signal ($m_T = 1 \text{ TeV}$, SU(2) singlet)	21 ± 2	8 ± 1

Signal Region: Pre-fit

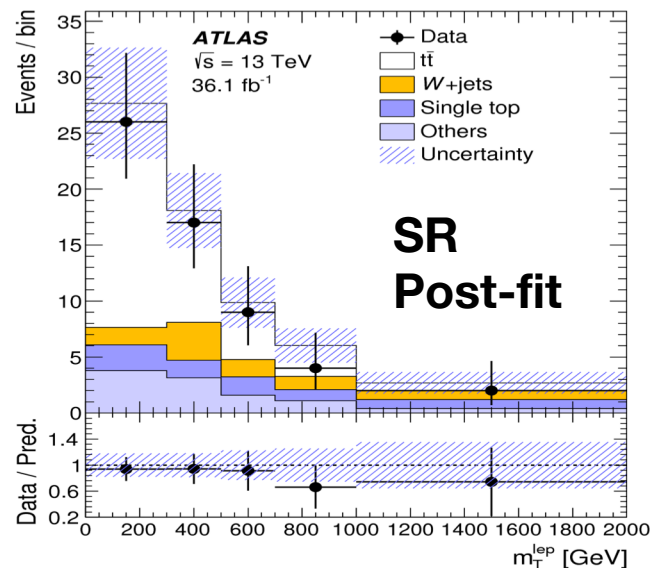
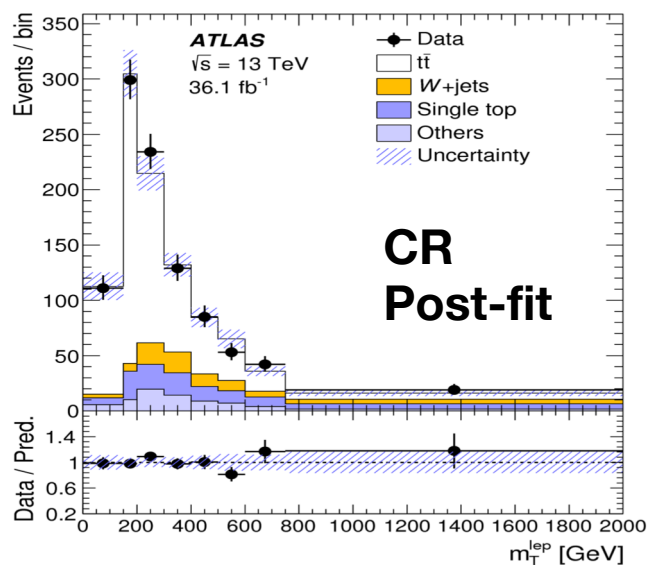


No sign of
VLQs



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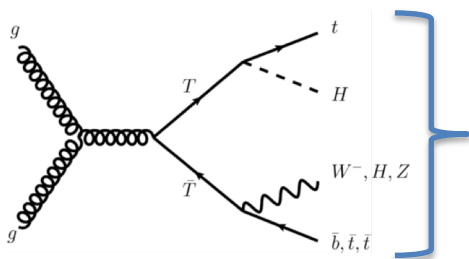
No sign of
VLQs



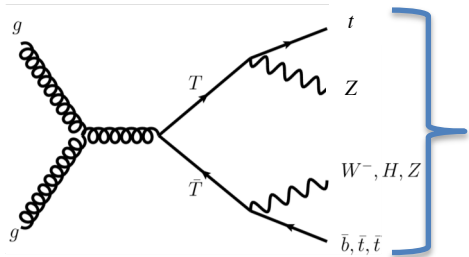
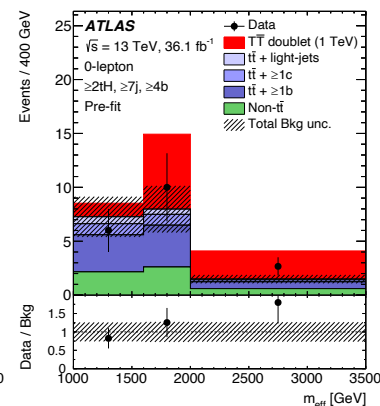
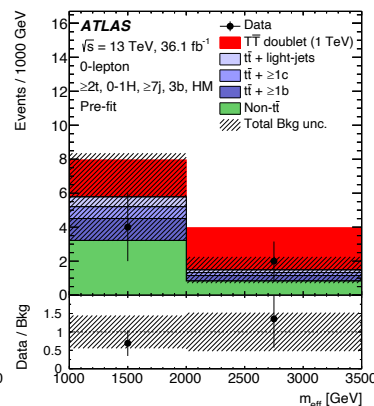
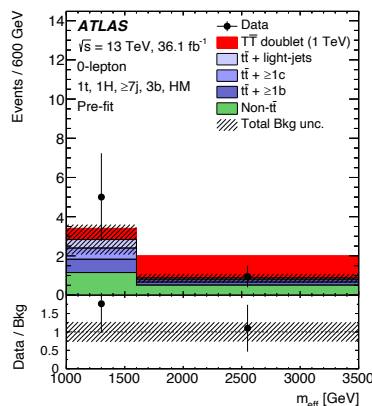
- Data compatible with SM prediction

What about the other decays?

Most sensitive $Ht+X$ signal regions:



$Ht+X$



$Zt+X$

Region	SR
Observed events	7
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)

$\Rightarrow$ All consistent with SM

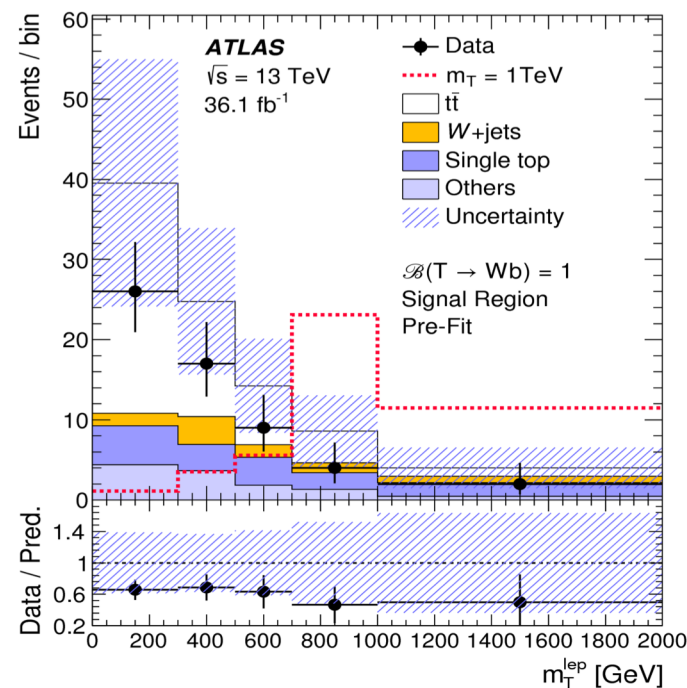
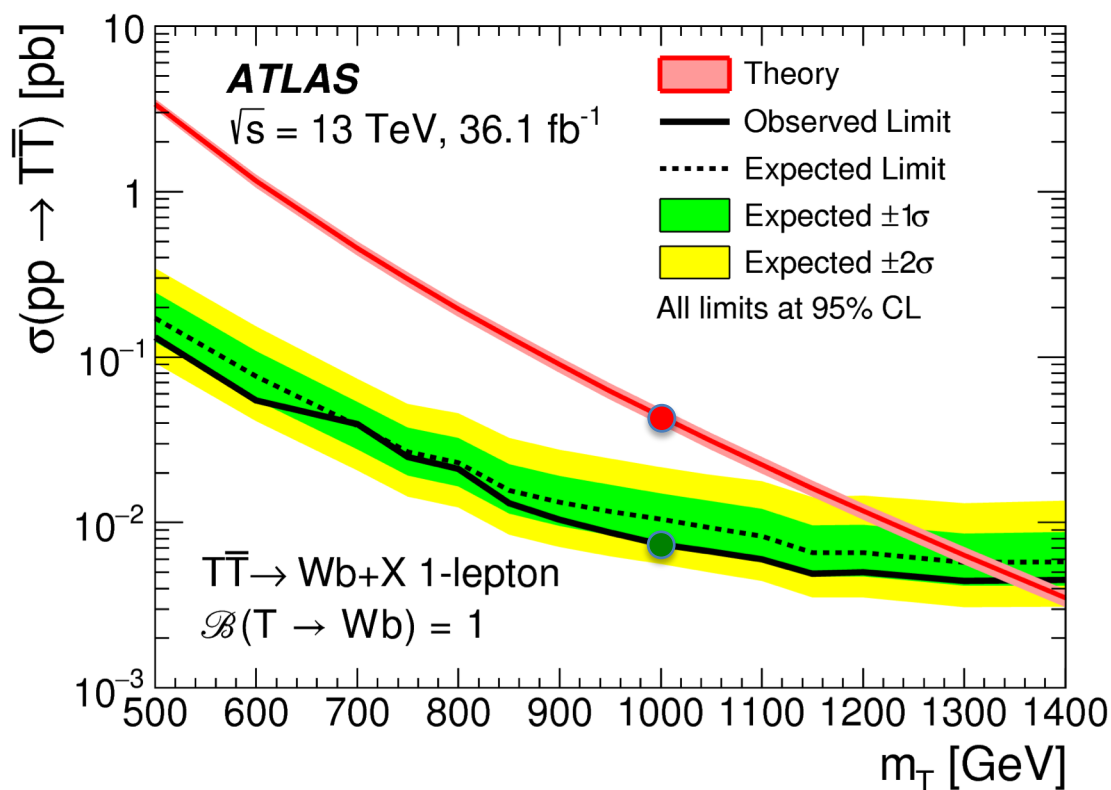


Set Limits!

Cross Section Limits

Set limits on $pp \rightarrow T\bar{T}$ cross section for a given scenario

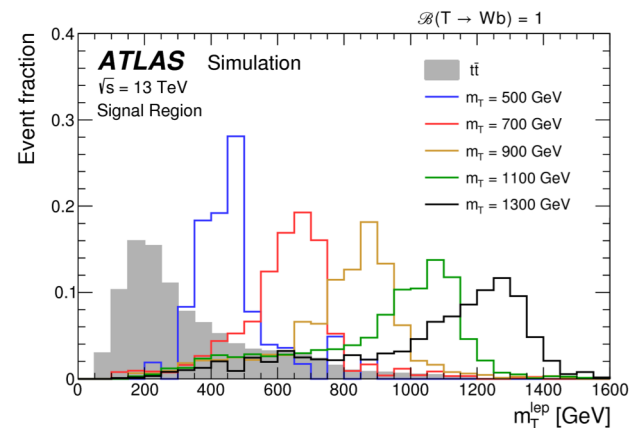
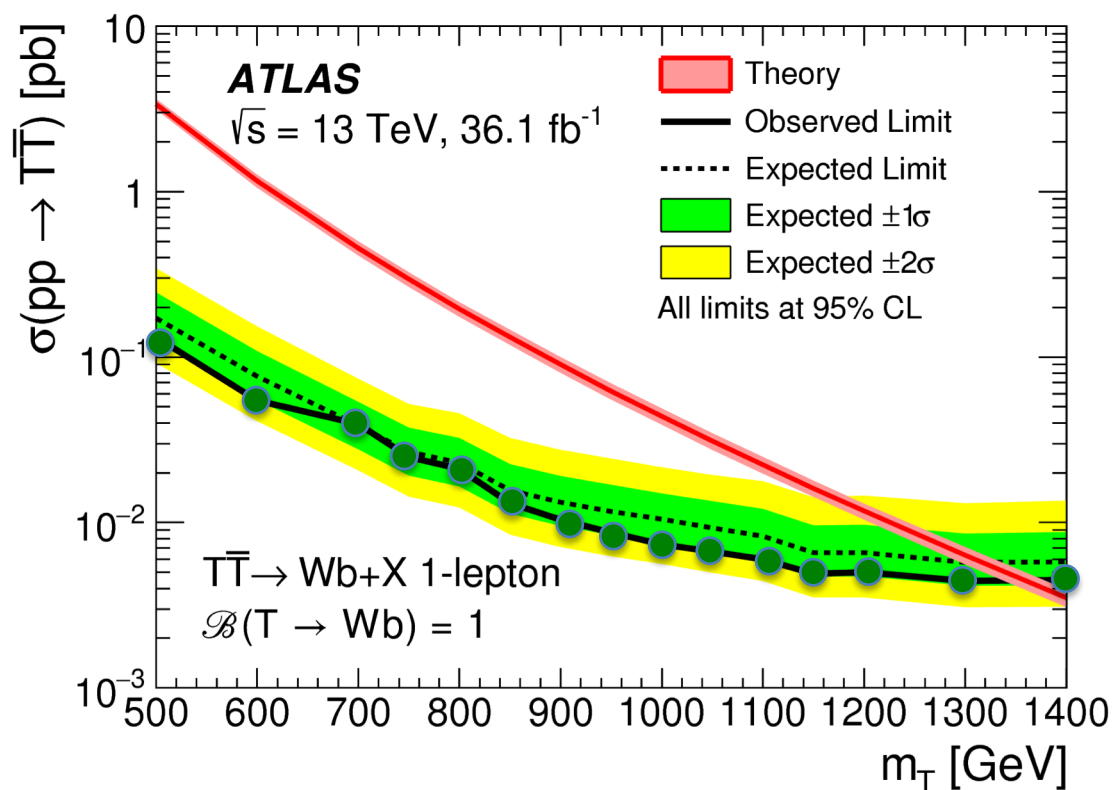
- First consider the branching ratio scenario: $\mathcal{B}(T \rightarrow Wb) = 100\%$



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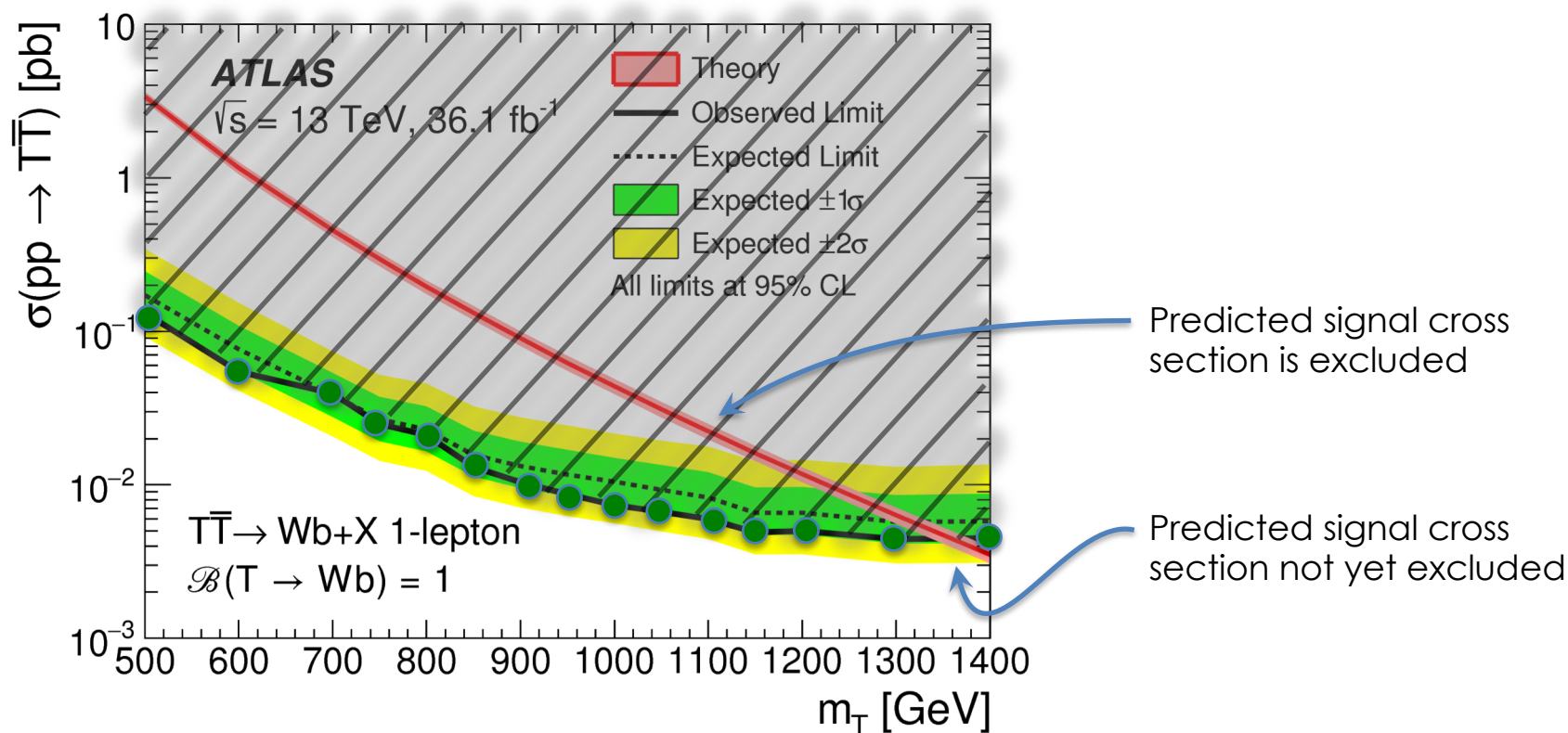
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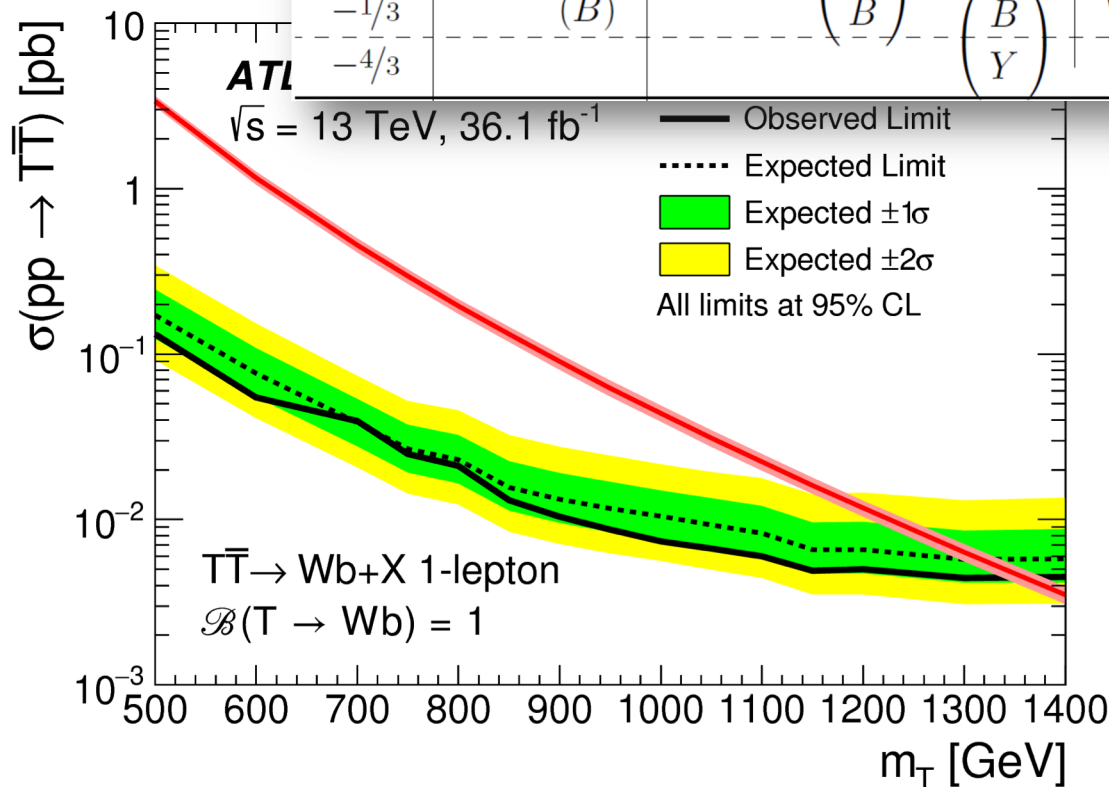


Cross Section Limits

Set limits on

- First constraints

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



Conclusion:

If $\mathcal{B}(T \rightarrow Wb) = 100\%$, it must have a mass higher than 1350 GeV

“Y” VLQ can only decay to Wb :

$$Y^{-4/3} \rightarrow W^{-1} b^{-1/3}$$

This result can also be interpreted as a limit on $pp \rightarrow YY$

$\Rightarrow m_Y \geq 1350 \text{ GeV}$ (1310 GeV expected)



Strongest Limit!

Cross Section Limits

More realistic scenarios:

➤ **For singlet T :** $\mathcal{B}(T \rightarrow Wb : Ht : Zt) \sim 1/2 : 1/4 : 1/4$

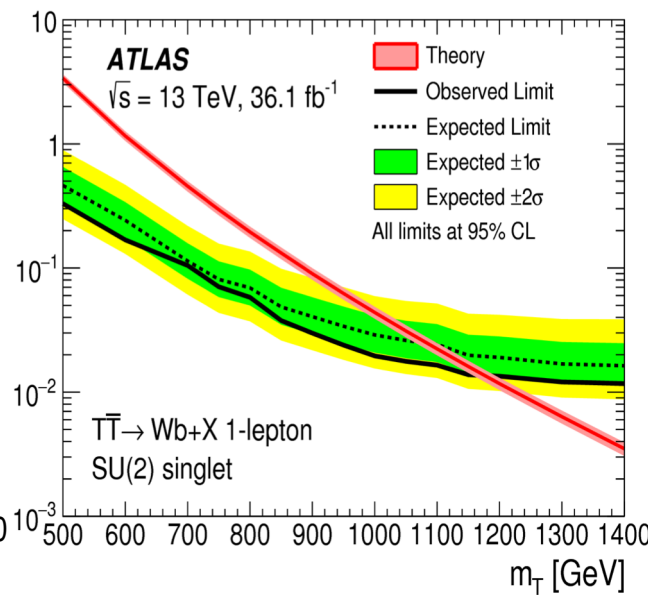
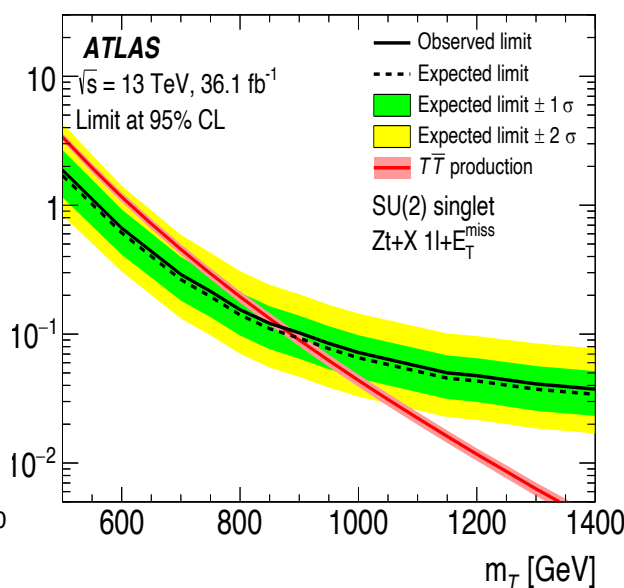
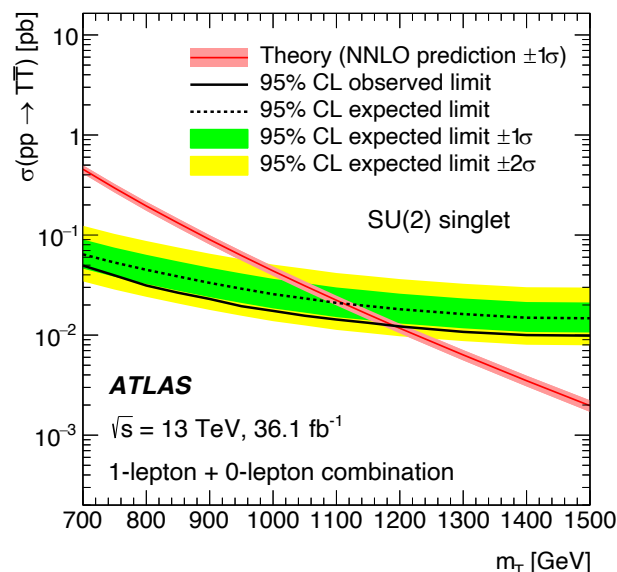
$Ht+X \Rightarrow m_T \geq 1190 \text{ GeV}$ (1110 GeV expected)

$Zt+X \Rightarrow m_T \geq 870 \text{ GeV}$ (890 GeV expected)

$Wb+X \Rightarrow m_T \geq 1170 \text{ GeV}$ (1080 GeV expected)



Strongest Limits!



Cross Section Limits

More realistic scenarios:

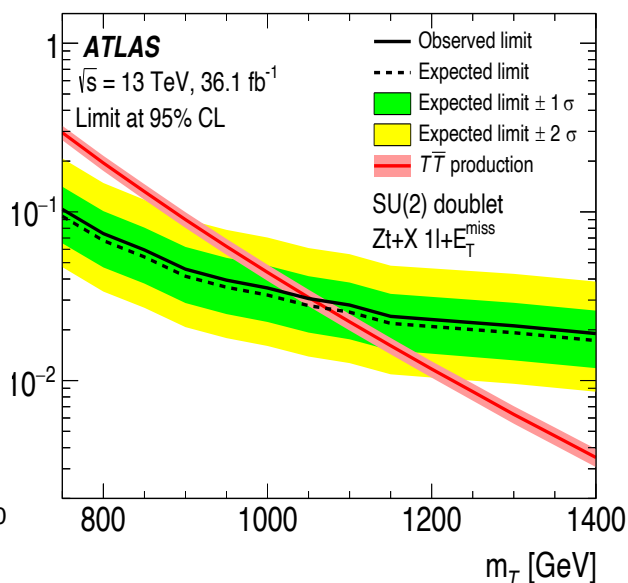
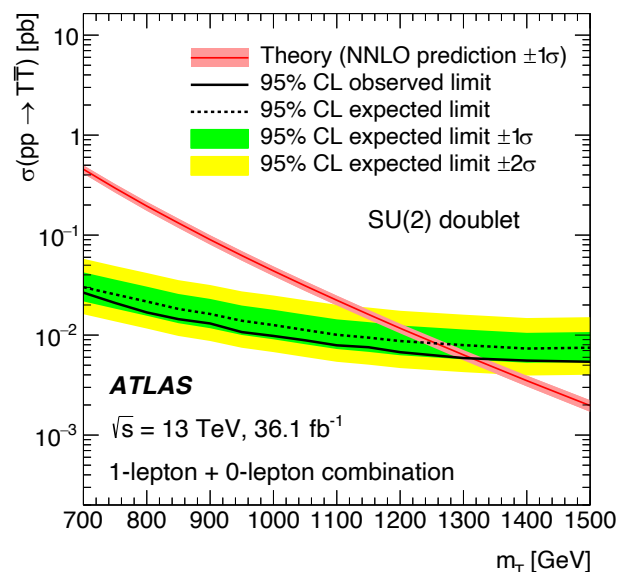
➤ **For doublet T :** $\mathcal{B}(T \rightarrow Wb:Ht:Zt) \sim 0 : \frac{1}{2} : \frac{1}{2}$

$Ht+X \Rightarrow m_T \geq 1310 \text{ GeV}$ (1260 GeV expected)

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



Strongest Limit!

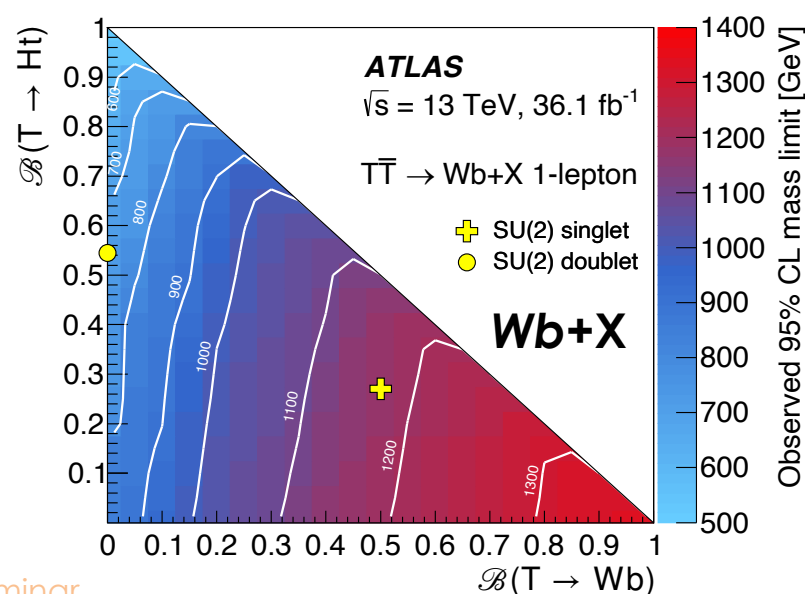
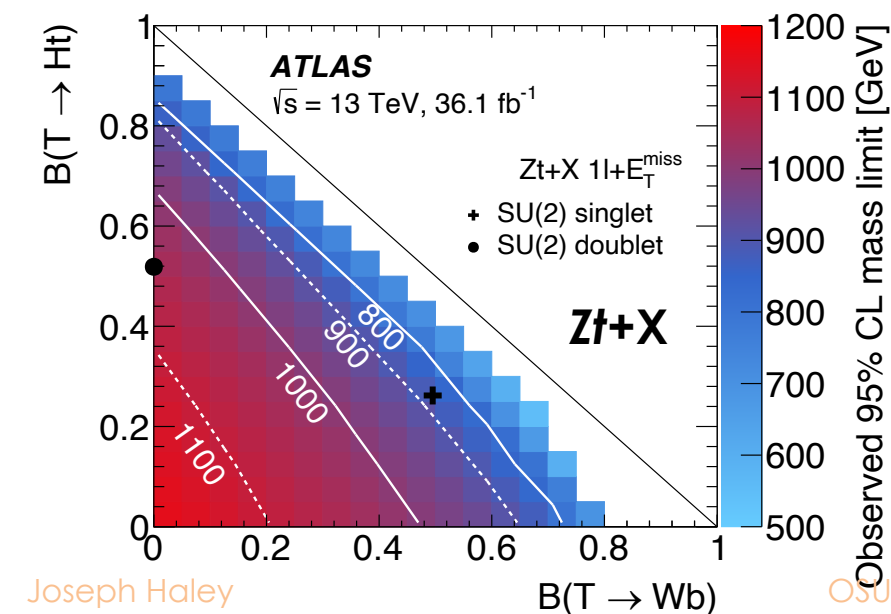
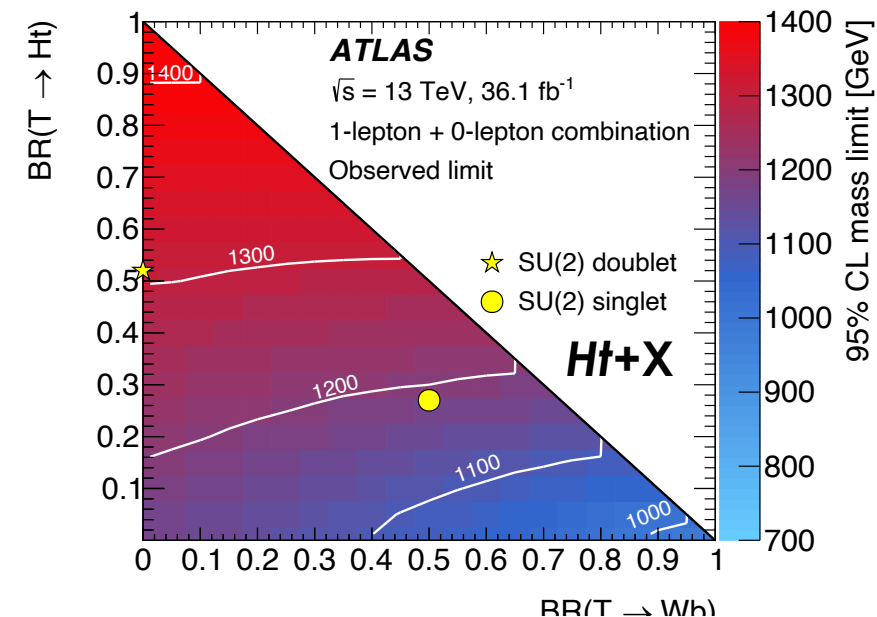


Mass Limits vs. Branching Ratio

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

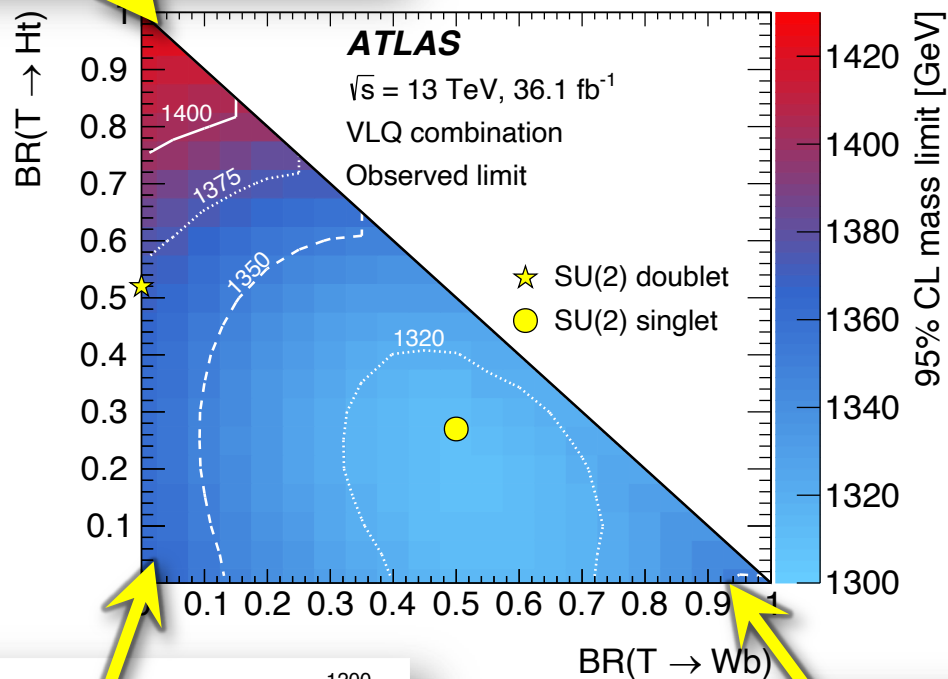
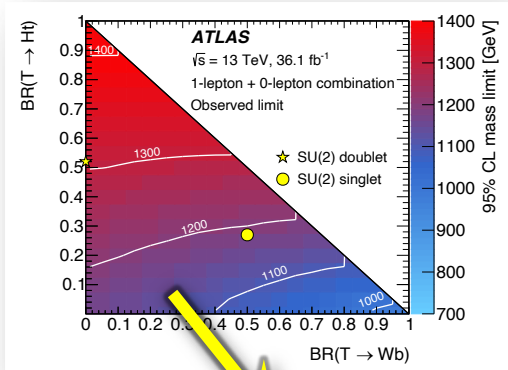
- Make a grid of possible branching ratios
- Find the lower mass limit at each point

Observed Limits

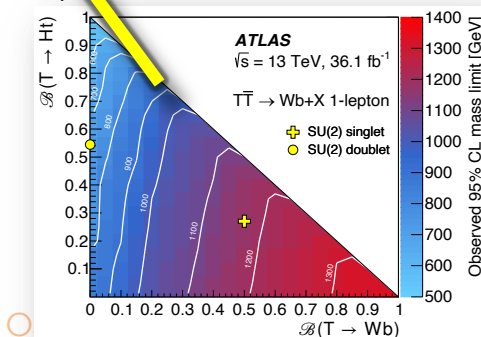
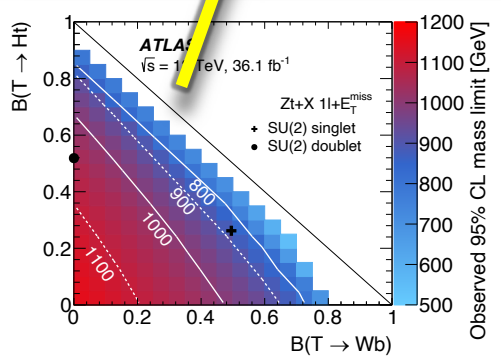


Combination!

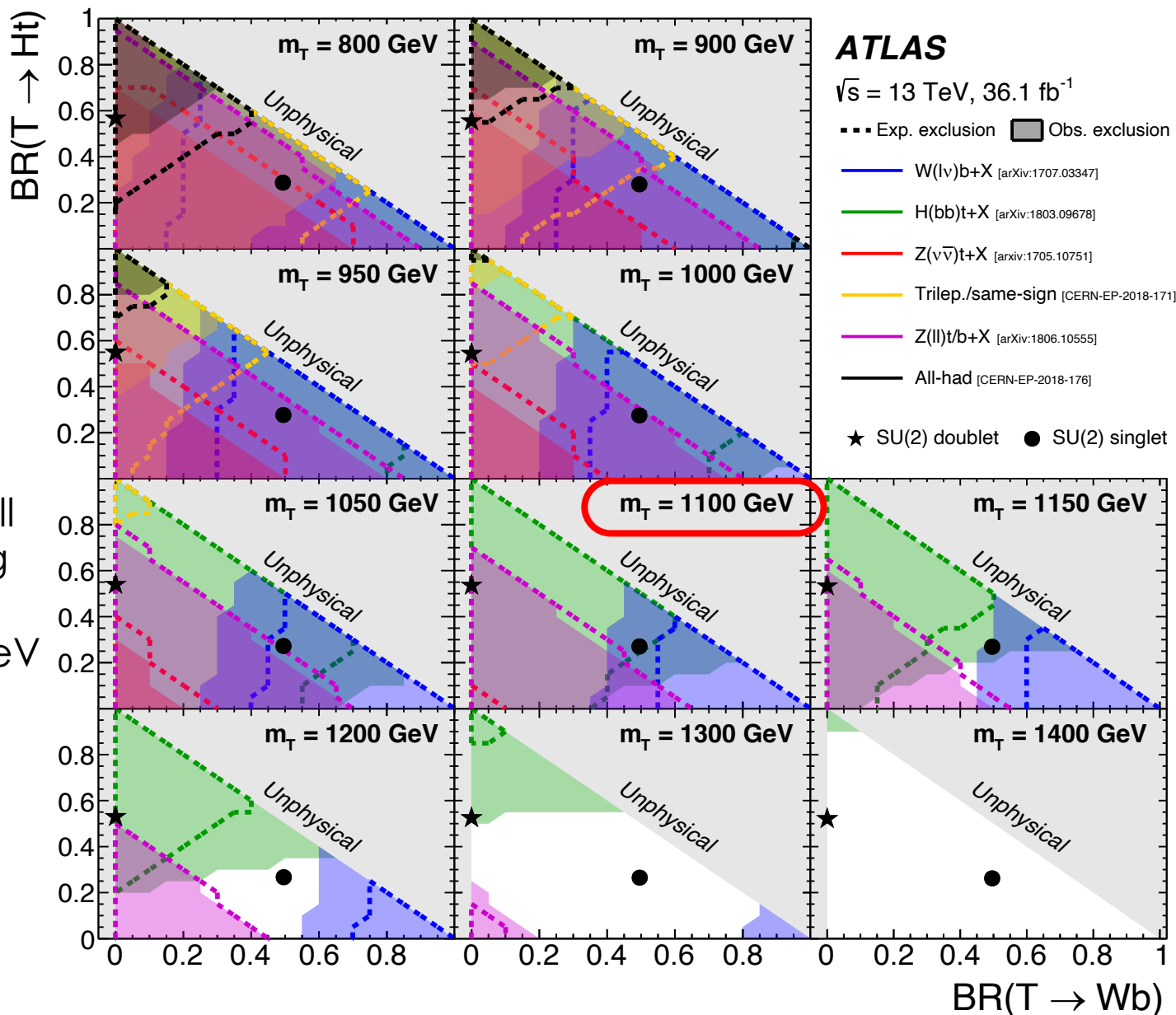
Statistical combination
of all VLQ searches



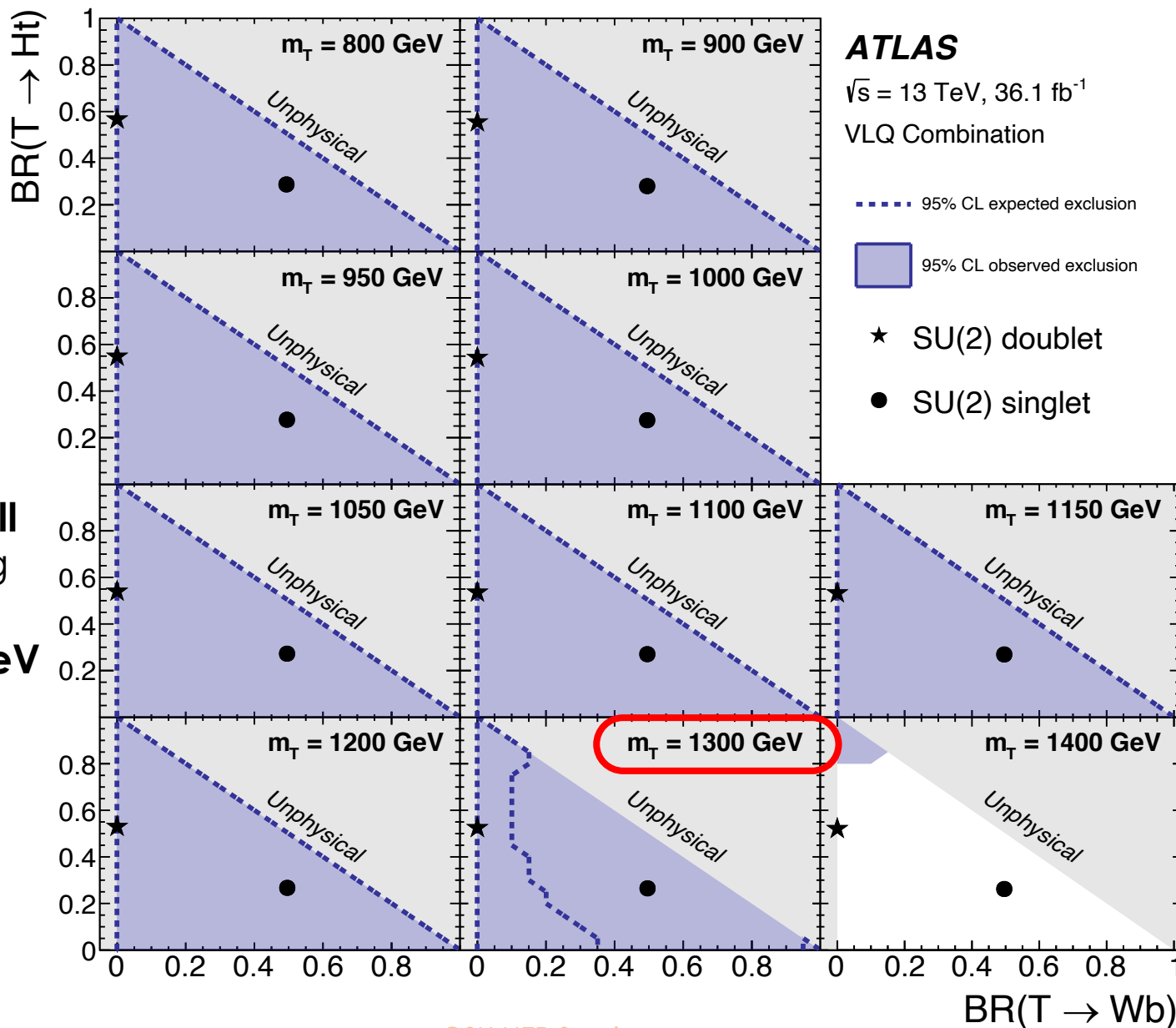
Analysis	$T\bar{T}$ decay	$B\bar{B}$ decay
$H(bb)t + X$ [16]	$HtH\bar{t}$	-
$W(\ell\nu)b + X$ [30]	$WbW\bar{b}$	-
$W(\ell\nu)t + X$ [32]	-	$WtW\bar{t}$
$Z(\nu\nu)t + X$ [33]	$ZtZ\bar{t}$	-
$Z(\ell\ell)t/b + X$ [35]	$ZtZ\bar{t}$	$ZbZ\bar{b}$
Tril./s.s. dilepton [36]	$HtH\bar{t}$	$WtW\bar{t}$
Fully hadronic [37]	$HtH\bar{t}$	$HbH\bar{b}$



Overlaying Separate Analyses

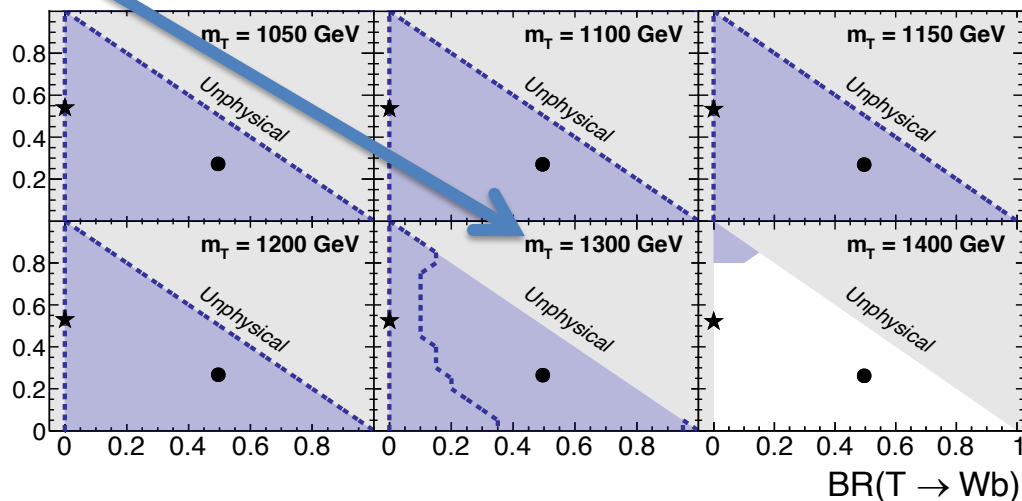
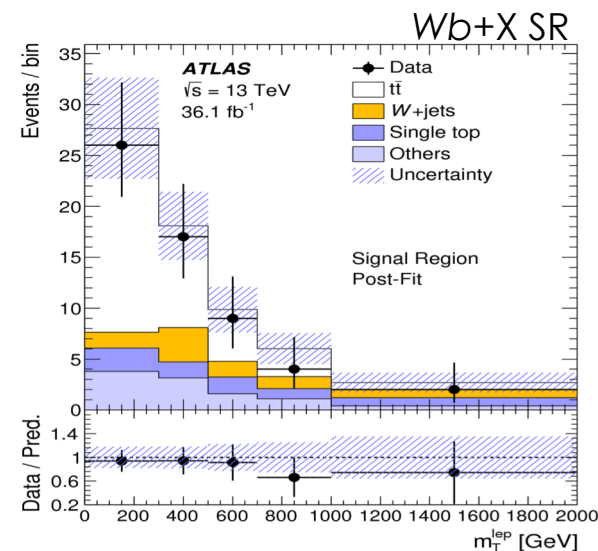


Statistical Combination of Analyses



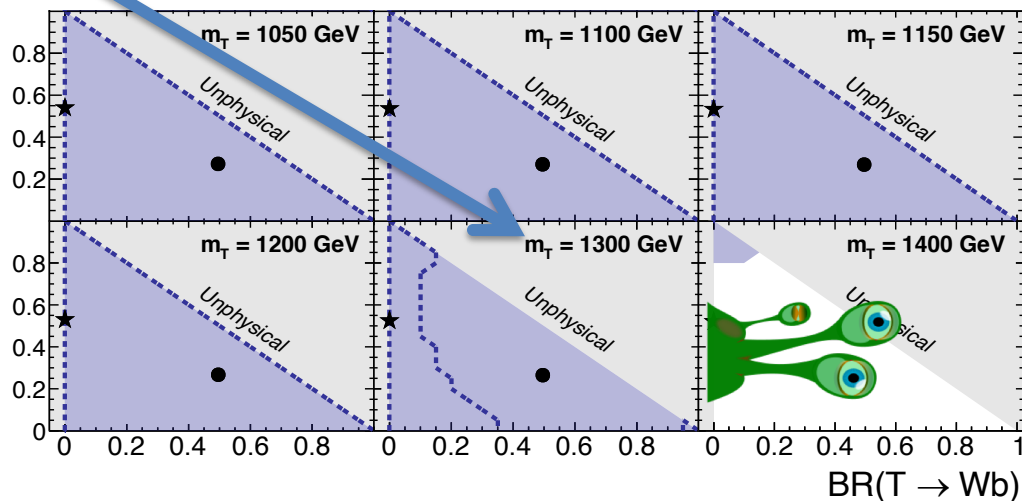
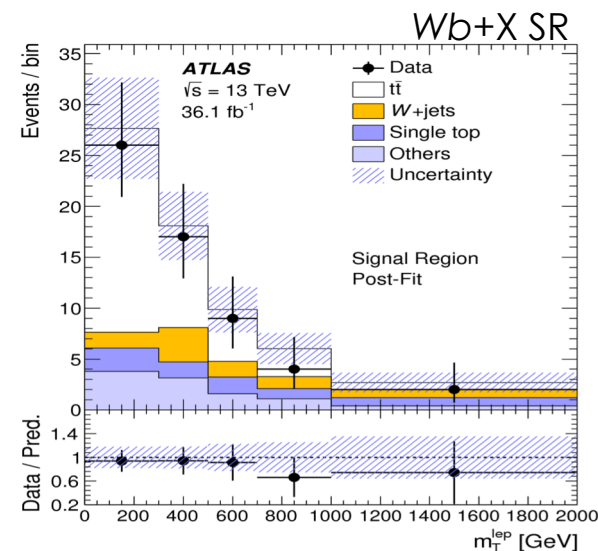
Conclusions

- VLQs can provide a natural solution to the hierarchy problem
... but only if their mass is near ~ 1 TeV
- Presented latest ATLAS searches for T
 - Data consistent with background-only
 - Strongest limits for many cases
- Current analyses excluding T masses up to 1.3 TeV for any branching ratios
 - Similar results from CMS



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 - Strongest limits for many cases
- Current analyses excluding T masses up to 1.3 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!
- With more data in the pipeline, maybe discovery is just around the corner...



Thank you

And special thanks to:



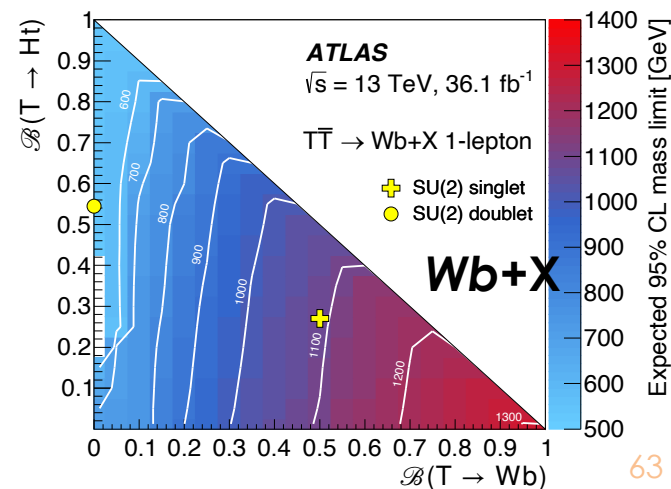
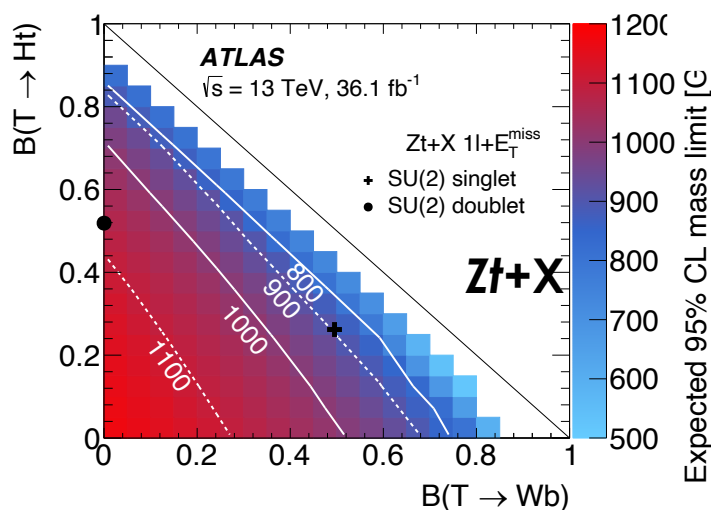
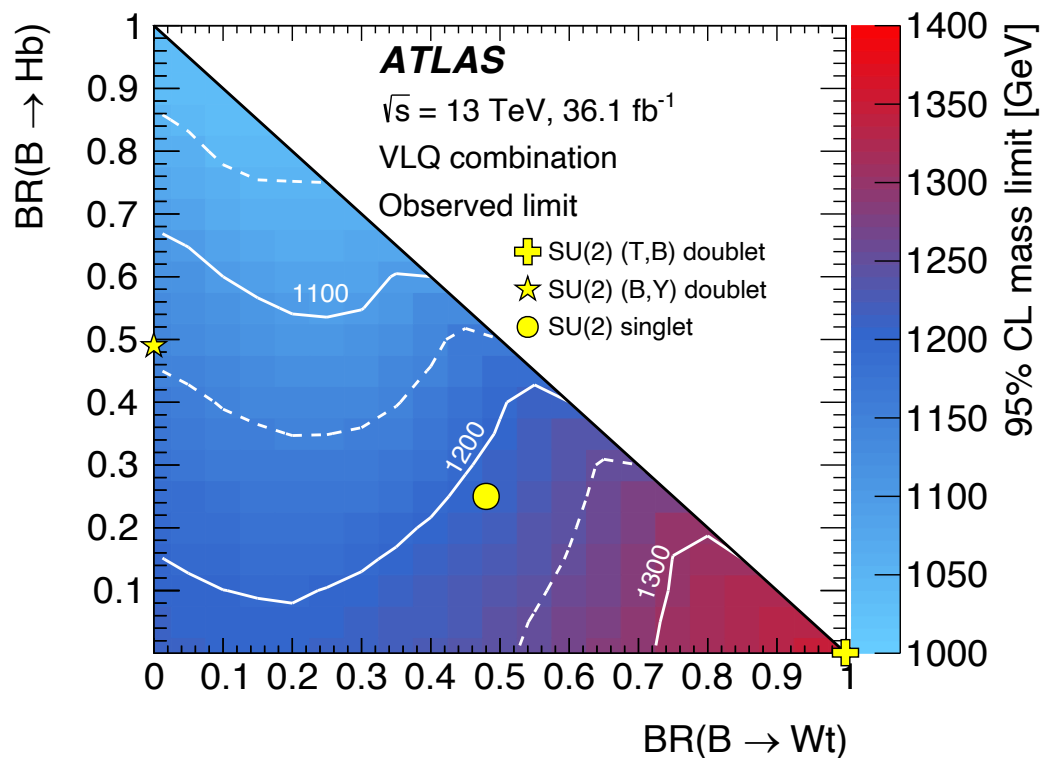
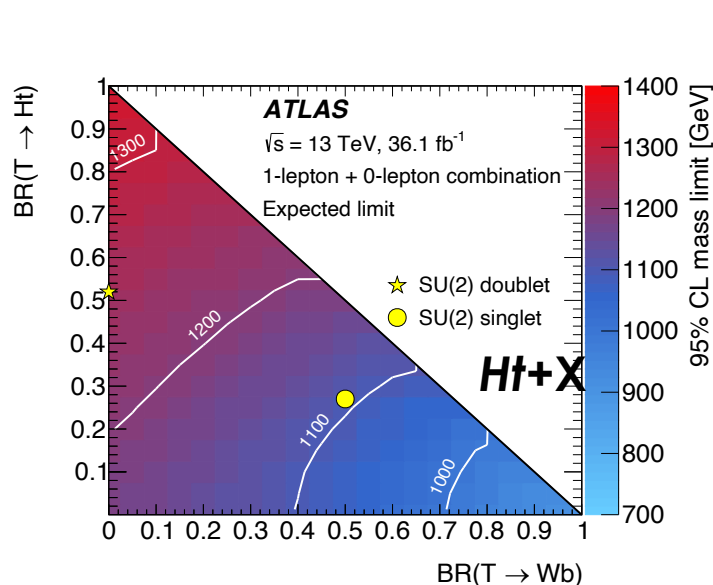
DOE for supporting this research



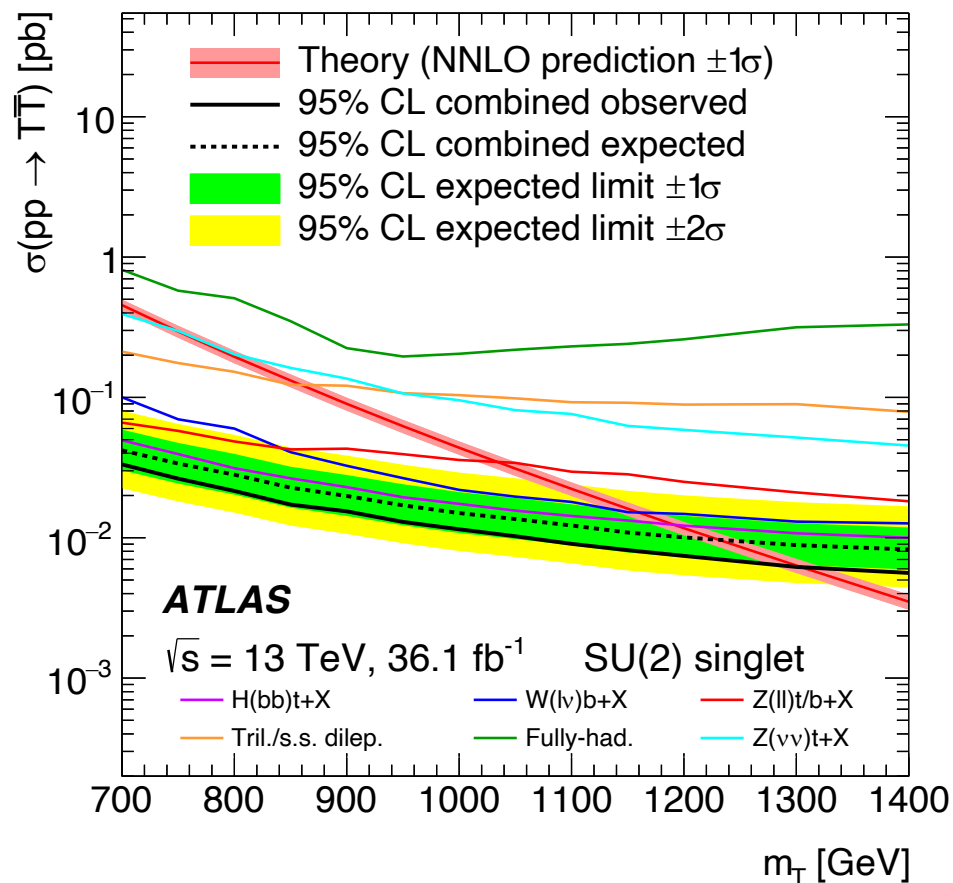
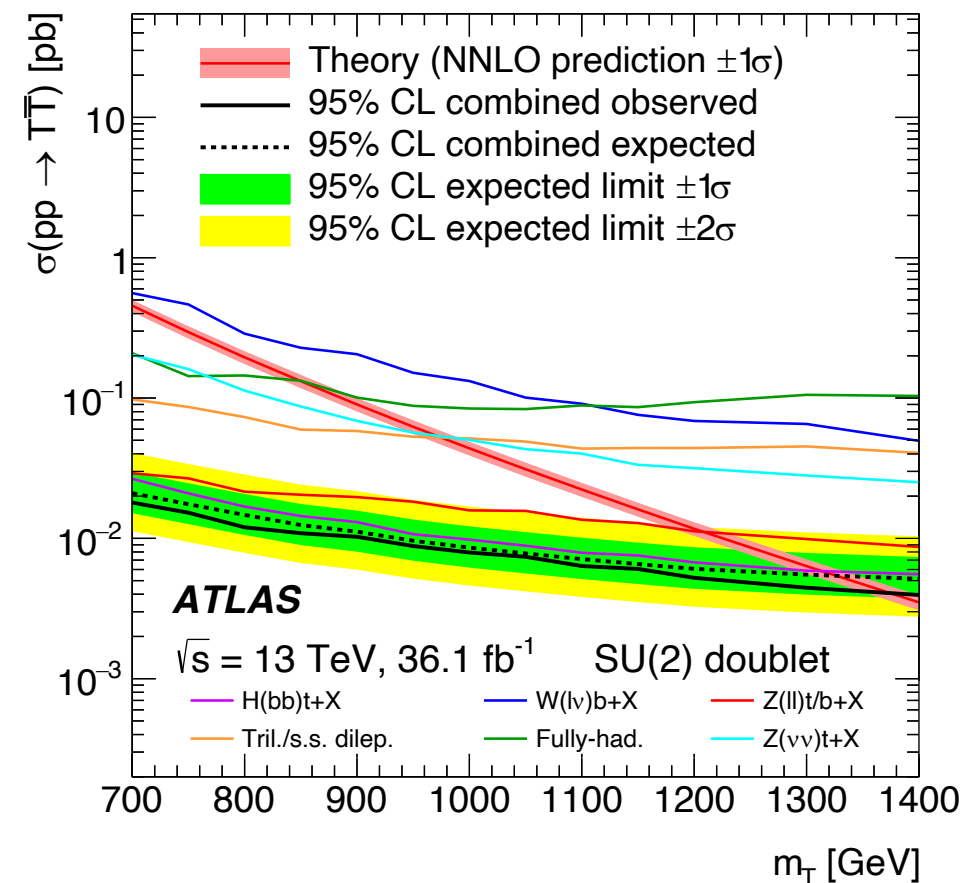
To the ATLAS Collaboration

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

Expected Limit vs. Branching Ratio



Combination: Cross section limits



Signal and Background Samples

$T\bar{T}$: PROTONS 2.2 (LO) + PYTHIA 8

- Check singlet vs. doublet

$t\bar{t}$: 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 $t\bar{t}$

Diboson: SHERPA 2.1

$t\bar{t}+V$: MadGraph5_aMC@NLO 2.1 + PYTHIA 8

Normalized to NLO

QCD Multijets: Estimated from data

$Ht+X$

Main signals:

$$\pi\pi \rightarrow Ht Ht \rightarrow bb Wb bb Wb$$

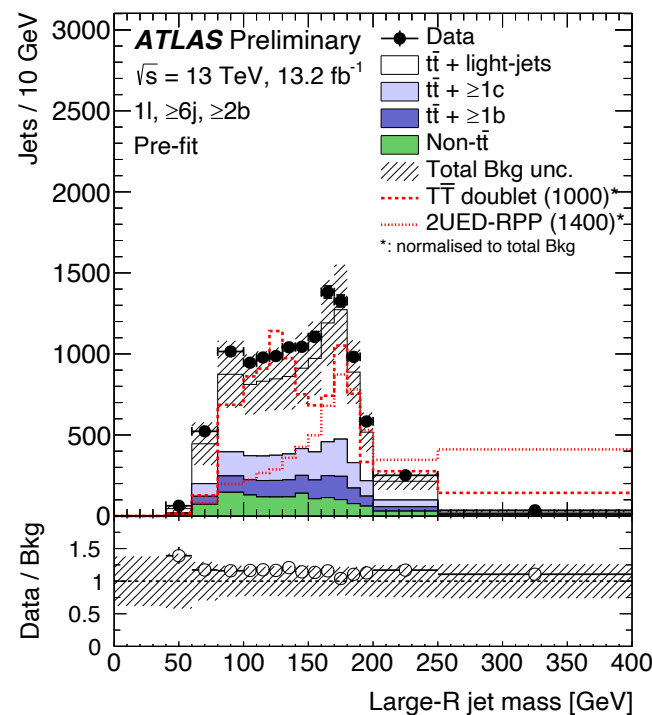
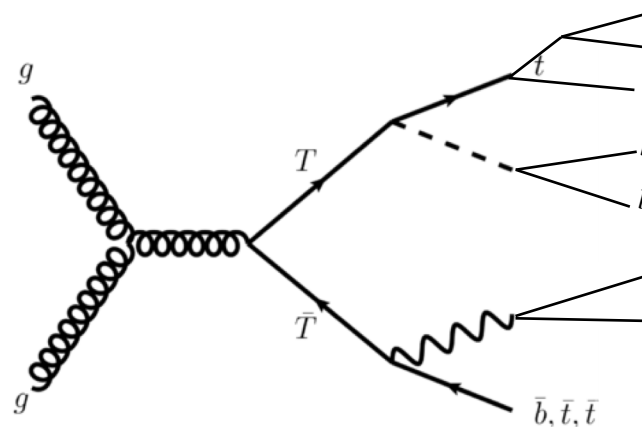
$$\pi\pi \rightarrow Ht Zt \rightarrow bb Wb Z Wb$$

$$\pi\pi \rightarrow Ht Wb \rightarrow bb Wb Wb$$

- Many jets, many b -tags!

Initial selection:

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



$Ht+X$: Strategy

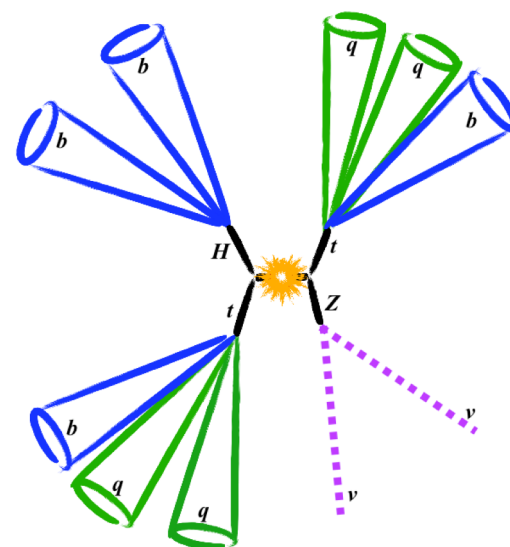
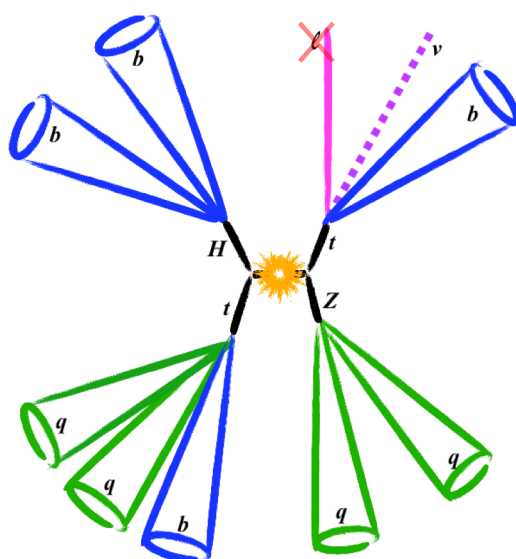
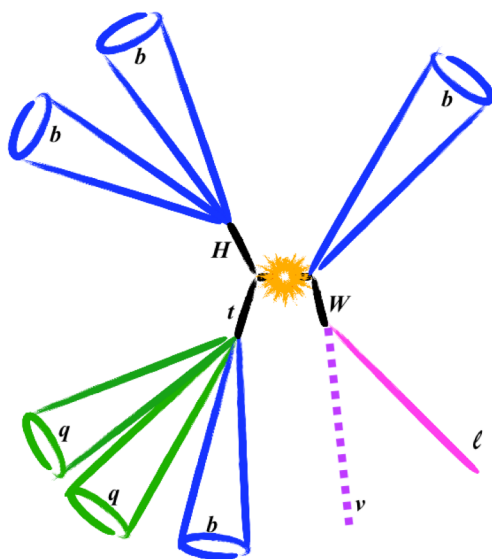
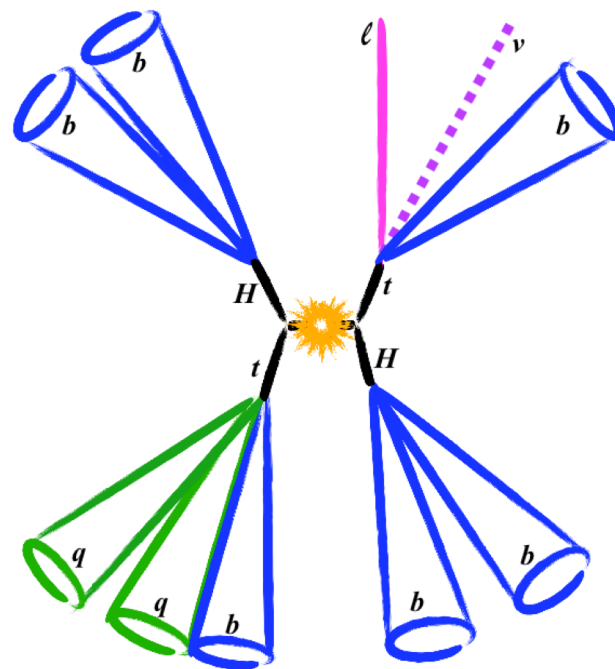
Main signals:

$$\pi\pi \rightarrow Ht Ht \rightarrow bb Wb bb Wb$$

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

$$\pi\pi \rightarrow Ht Wb \rightarrow bb Wb Wb$$

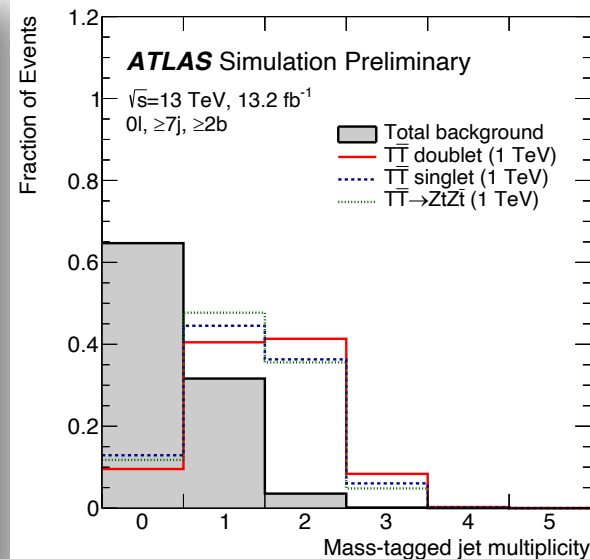
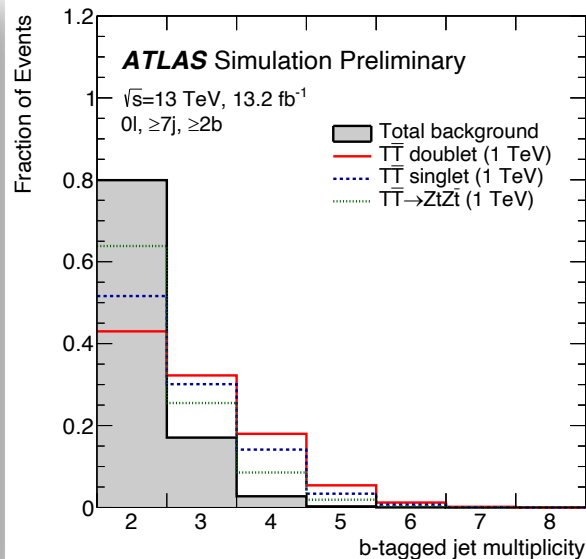
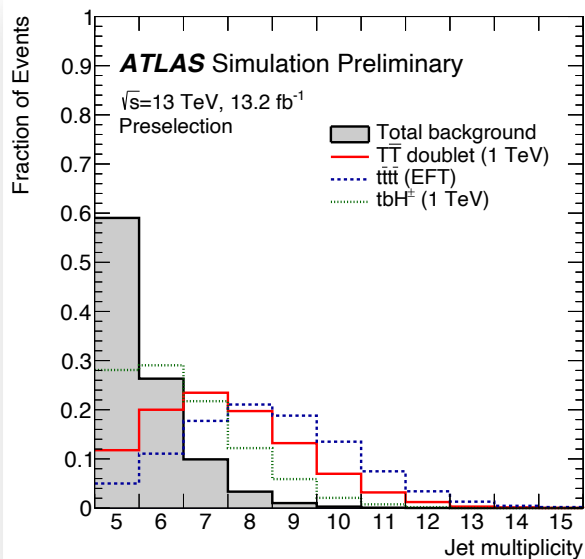
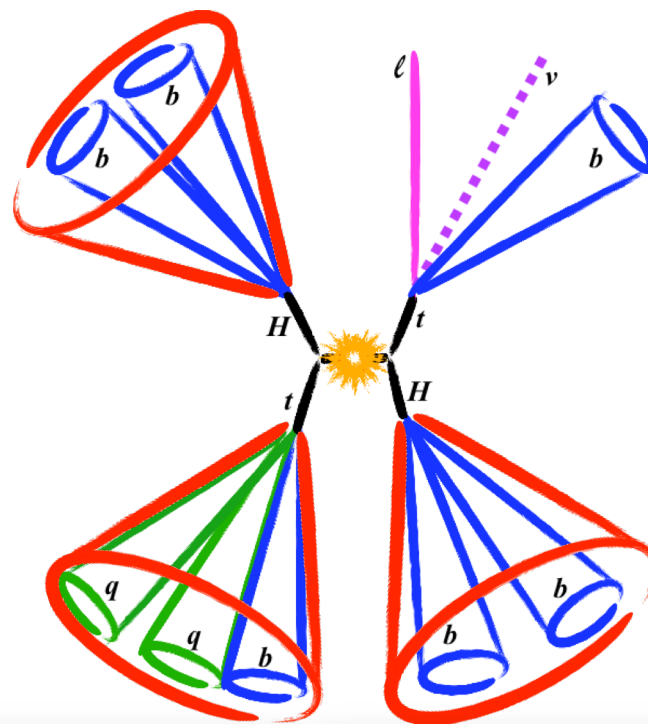
- Many jets, many b-tags!



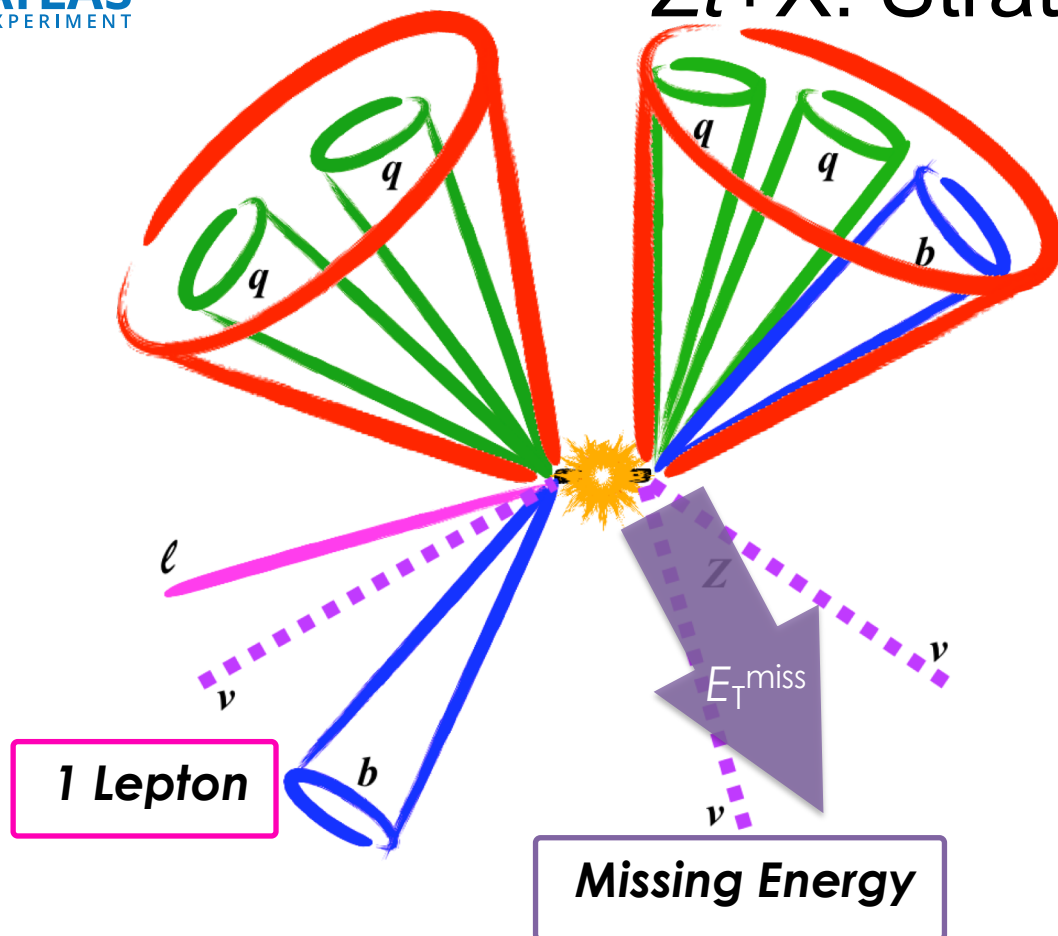
$Ht+X$: Strategy

Categorize events by:

- # leptons (l)
- # small-R jets (j)
- # b -tags (b)
- # large-R jets (J)
 $m > 100 \text{ GeV}, p_T > 300 \text{ GeV}$



Zt+X: Strategy



Targeting $Z \rightarrow \nu\nu$ decay

$$t\bar{t} \rightarrow ZtZt \rightarrow \nu\nu Wb qq Wb$$

$$t\bar{t} \rightarrow ZtHt \rightarrow \nu\nu Wb bb Wb$$

$$t\bar{t} \rightarrow ZtWb \rightarrow \nu\nu Wb Wb$$

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

≥ 4 small-R jets

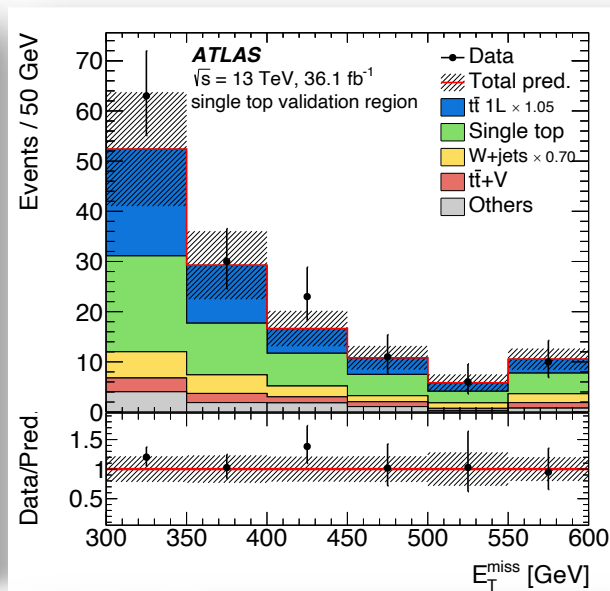
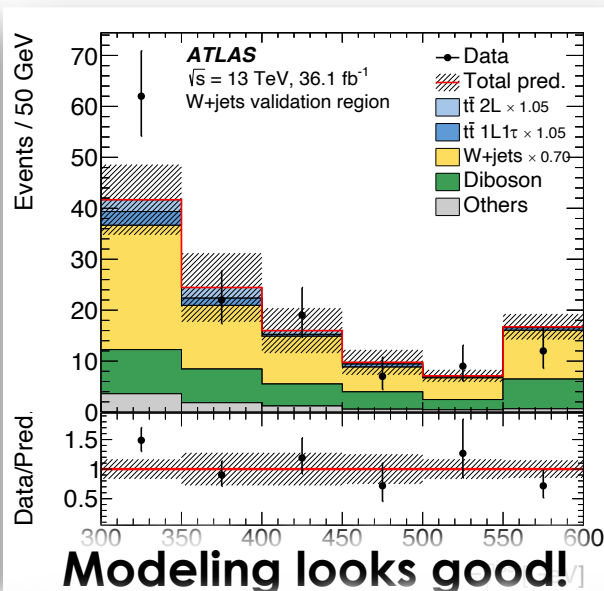
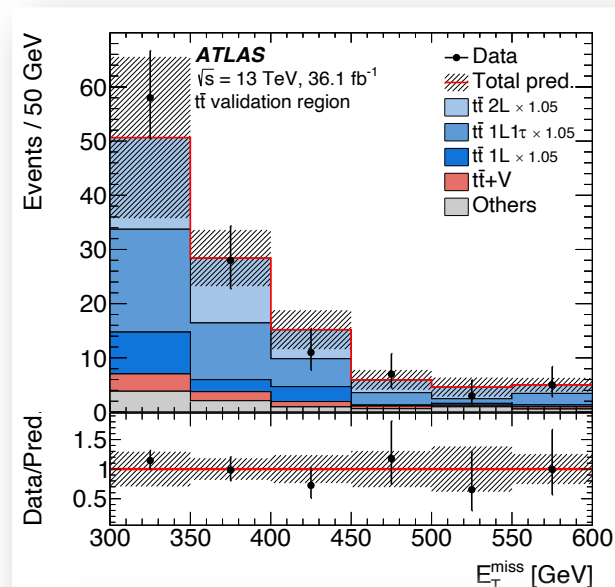
- ≥ 1 b-tagged

2 large-R jets

Cut-and-count analysis

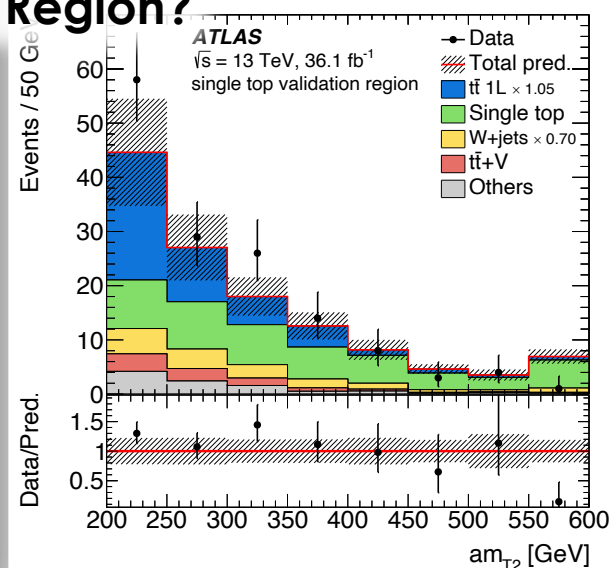
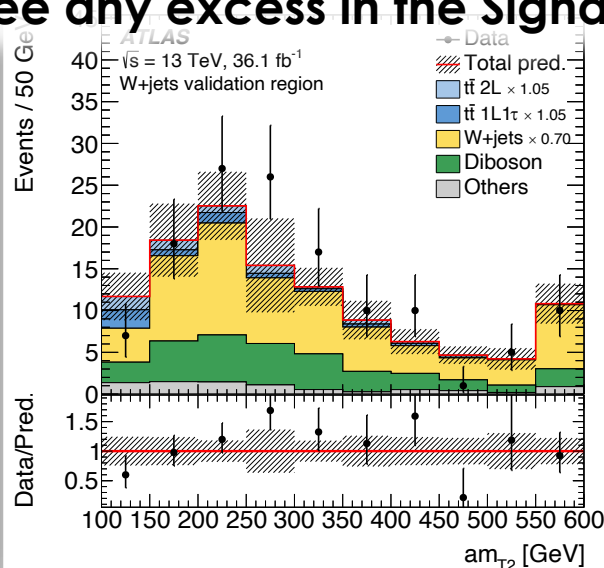
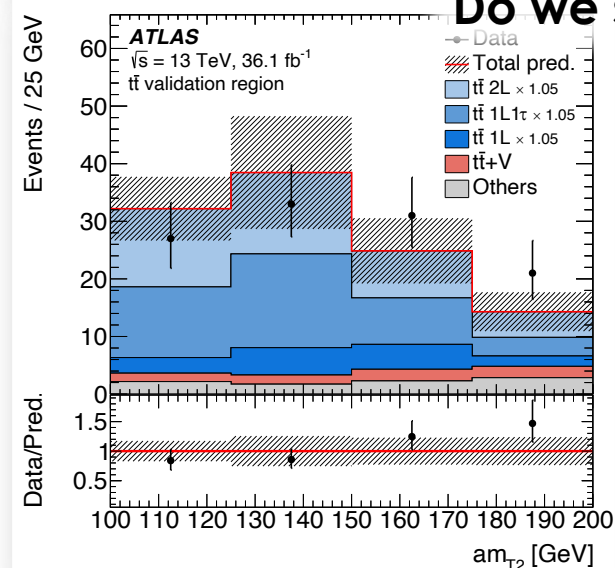
- Signal Region (Bin) – Kinematic cuts to optimize VLQ sensitivity
- Control Regions – To fit $t\bar{t}$ and W +jets normalizations
- Validation Regions – To check modeling of backgrounds

Zt+X: Validation Regions



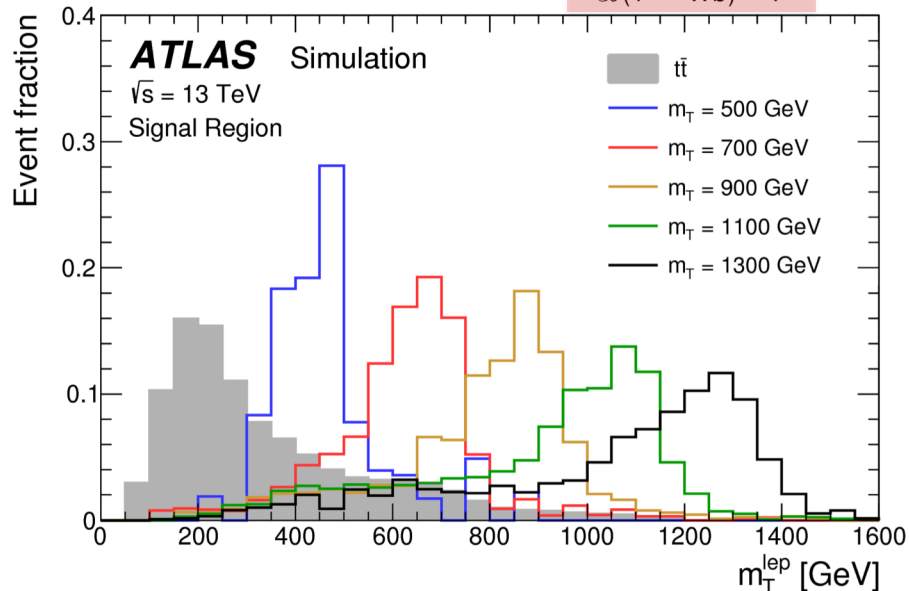
Modeling looks good!

Do we see any excess in the Signal Region?

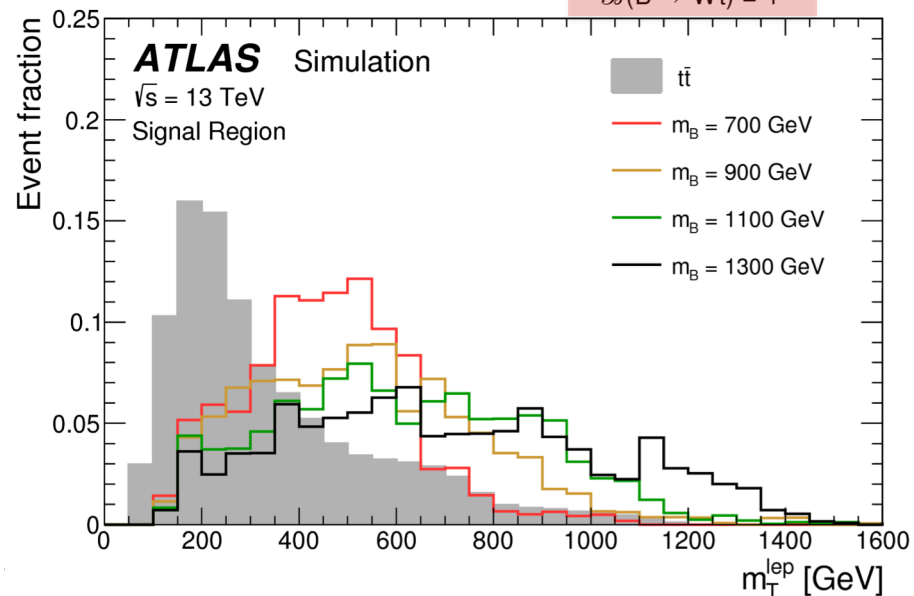


Signal Mass Distribution

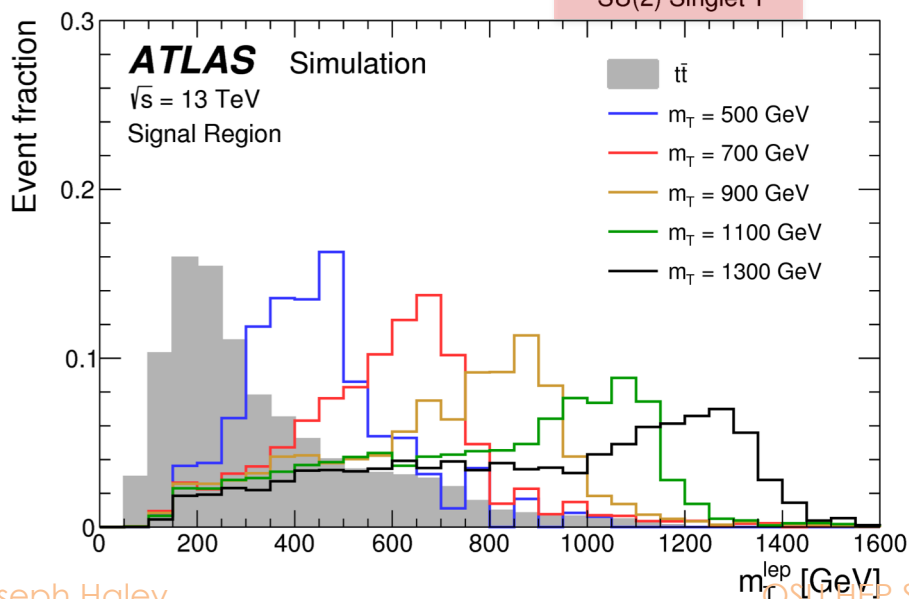
$\mathcal{B}(T \rightarrow Wb) = 1$



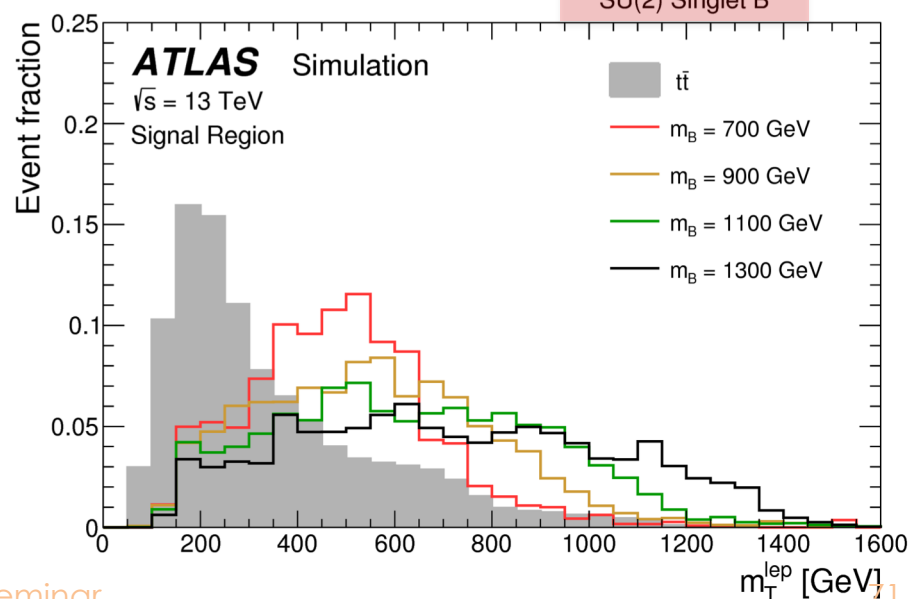
$\mathcal{B}(B \rightarrow Wt) = 1$



SU(2) Singlet T



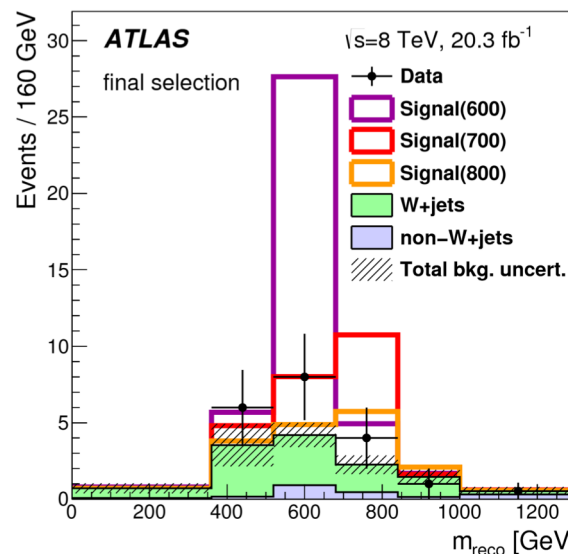
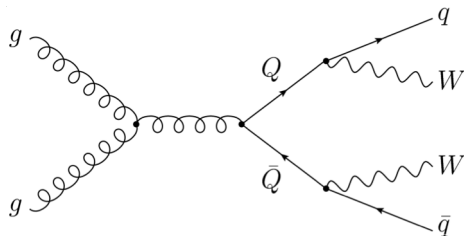
SU(2) Singlet B



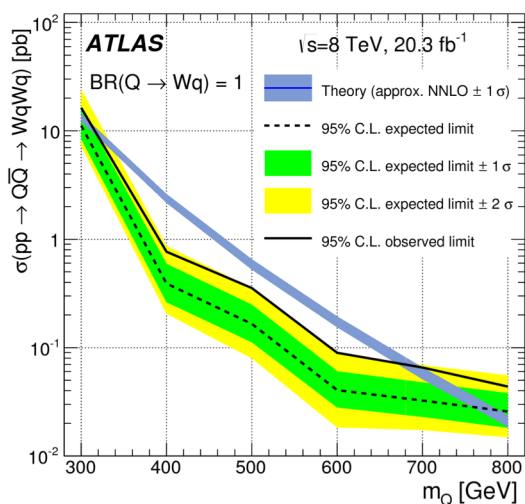
VLQs decaying to light quarks

Select $lvqqqq$

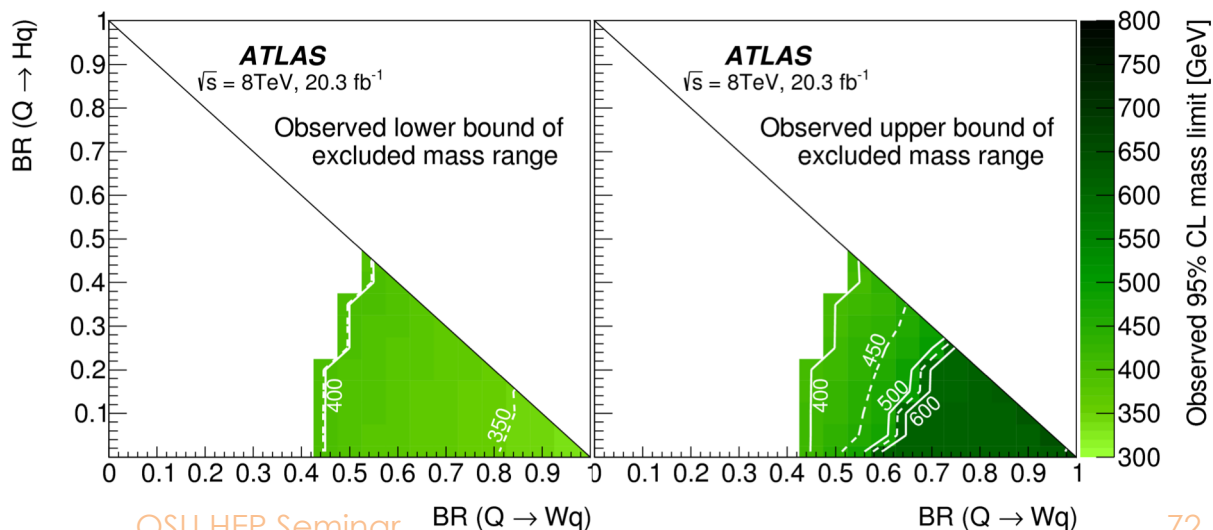
- Reconstruct Q candidates
- Look for bump in mass of $Q \rightarrow Wq \rightarrow qqq$ candidate



Limit on cross section
for $BR(Q \rightarrow Wq)=1$:



Excluded masses for given choice of BRs:



Cross Section Limits

Set limits on $pp \rightarrow T\bar{T}$ cross section for a given scenario

- Pick a branching ratio scenario: $\mathcal{B}(T \rightarrow Wb) = 100\%$
- Pick a mass: 1000 GeV

- Ask the question:

What is the largest amount of this signal that cannot be ruled out at 95% confidence level?

- Perform likelihood fit to data
- Signal and background predictions allowed to vary within uncertainties
- Exclude signal if probability $< 5\%$

