

Vector-like quarks, leptoquarks and new gauge bosons searches in ATLAS

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Charleston, SC



Vector-like Quarks

| Gauge bosons | | |
|--|------------------------------|-----------------|
| SVM Z' → $\ell\ell$ | Z' mass | 5.1 TeV |
| SVM Z' → $\tau\tau$ | Z' mass | 2.42 TeV |
| Leptophobic Z' → $b\bar{b}$ | Z' mass | 2.1 TeV |
| Leptophobic Z' → $t\bar{t}$ | Z' mass | 4.1 TeV |
| SVM W' → $\ell\nu$ | W' mass | 6.0 TeV |
| SVM W' → $\tau\nu$ | W' mass | 3.7 TeV |
| HVT W' → WZ → $\ell\nu qq$ model B | W' mass | 4.3 TeV |
| HVT V' → WV → $qqqq$ model B | V' mass | 3.8 TeV |
| HVT V' → WH/ZH model B | V' mass | 2.93 TeV |
| HVT W' → WH model B | W_R mass | 3.2 TeV |
| LRSM W_R → $t\bar{b}$ | W_R mass | 3.25 TeV |
| LRSM W_R → μNR | W_R mass | 5.0 TeV |
| LQ | | |
| Scalar LQ 1 st gen | LQ mass | 1.4 TeV |
| Scalar LQ 2 nd gen | LQ mass | 1.56 TeV |
| Scalar LQ 3 rd gen | LQ ₃ mass | 1.03 TeV |
| Scalar LQ 3 rd gen | LQ ₃ mass | 970 GeV |
| Heavy quarks | | |
| VLQ TT → $Ht/Zt/Wb + X$ | T mass | 1.37 TeV |
| VLQ BB → $Wt/Zb + X$ | B mass | 1.34 TeV |
| VLQ $T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + X$ | T _{5/3} mass | 1.64 TeV |
| VLQ Y → $Wb + X$ | Y mass | 1.85 TeV |
| VLQ B → $Hb + X$ | B mass | 1.21 TeV |
| VLQ QQ → $WqWq$ | Q mass | 690 GeV |

Vector-like Quarks

“Quarks”: Color-triplet, spin- $\frac{1}{2}$ particles

“Vector-like”: Left and right chiralities have the same weak isospin

- Weak current is vector-like:

| | | | |
|-------|--------------------------|------------|---------------------------------------|
| VLQs: | $(\bar{Q}\gamma^\mu Q')$ | SM quarks: | $(\bar{q}\gamma^\mu(1 - \gamma^5)q')$ |
|-------|--------------------------|------------|---------------------------------------|
- Can have bare VLQ mass term
 \Rightarrow Avoids constraints from Higgs measurements

Couple to SM through mixing with SM quarks

Naturalness + FCNC constraints \Rightarrow mixing mostly with 3rd generation

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

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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:

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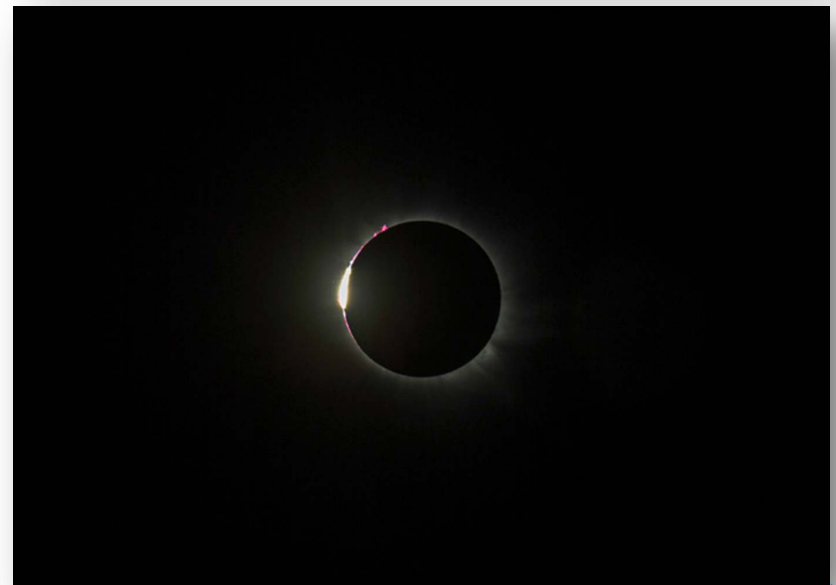
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The “Hierarchy Problem”

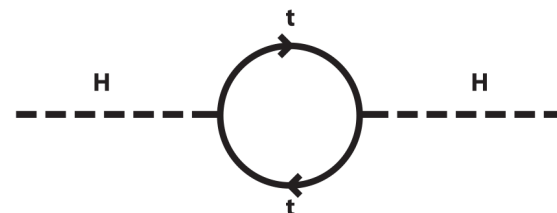
The mass (squared) of the Higgs gets quantum corrections from interacting with other particles: $M_H^2 = 2\mu^2 + (\delta m_1)^2 + (\delta m_2)^2 + \dots$

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

- If the SM is correct up to the Planck scale

$$M_H^2 = \overset{\text{“bare mass”}}{3.2734594296342905438674964732159643} - \overset{\text{quantum corrections, e.g.}}{3.2734594296342905438674964732159645}$$

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


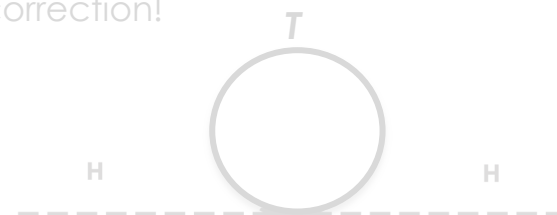


from
Roni Harnik

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

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

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




- Thus, VLQs show up in many BSM scenarios
 - Little/Composite Higgs, Topcolor, GUTs, ...
- **And naturalness requires mass ~1 TeV ⇒ Accessible at the LHC!**

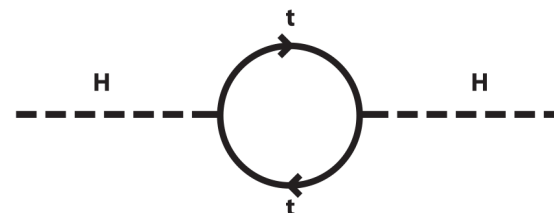
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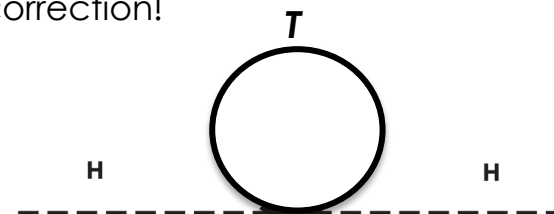


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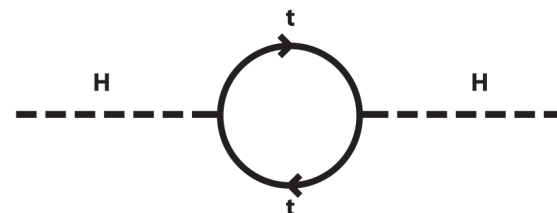
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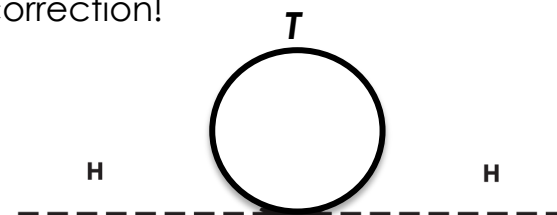


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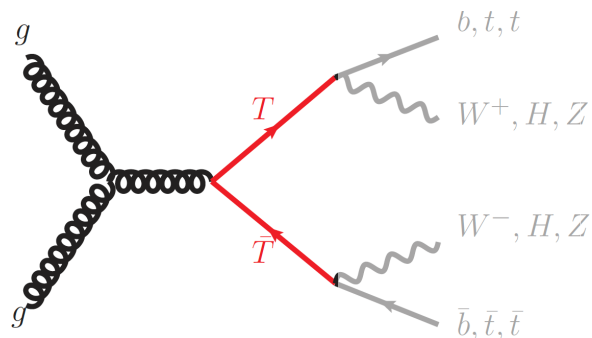
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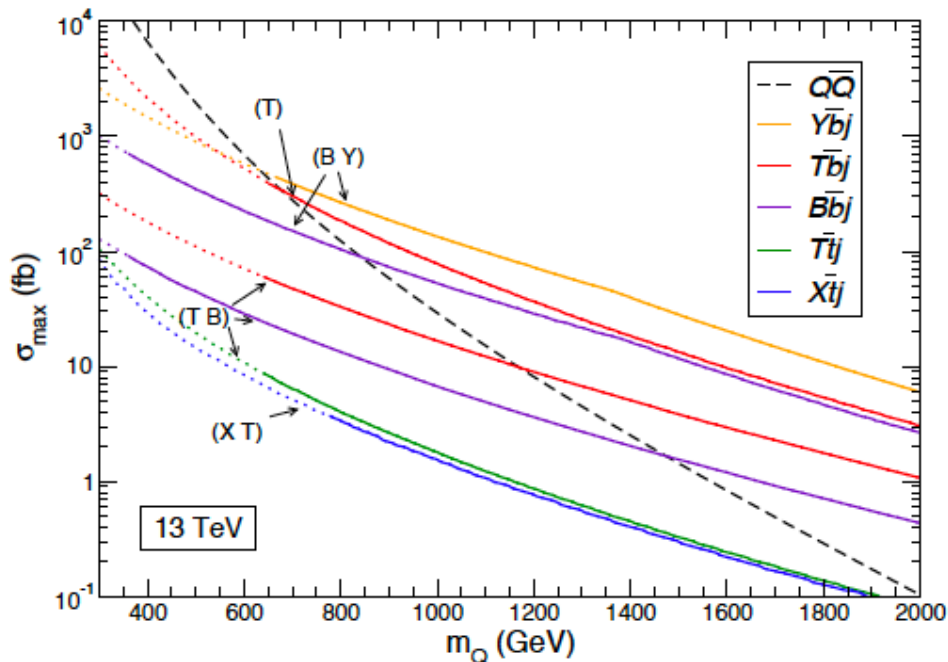
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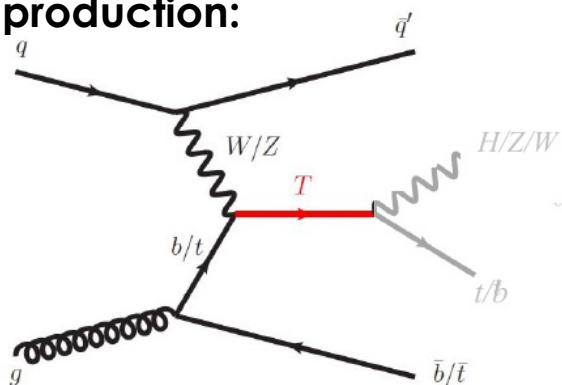
Pair Production:



- Via QCD \Rightarrow Depends only on VLQ mass
(Model-independent)



Single production:



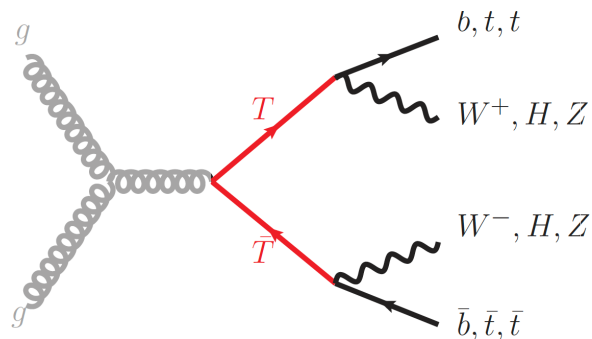
- Via mixing with SM quarks \Rightarrow Depends on mass and coupling (κ)
- **Could dominate** for large VLQ masses

Decays:

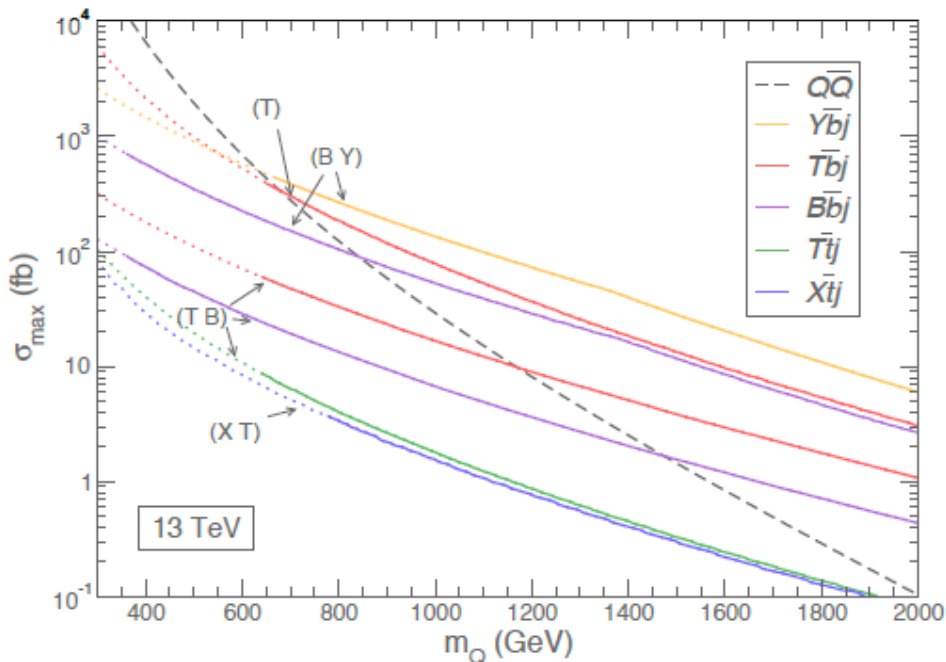
- Dictated by quantum numbers
 - $T \rightarrow Wb, Zt, Ht$
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 $(T), (T,B), (X,T), (X,T,B), \text{ etc.}$

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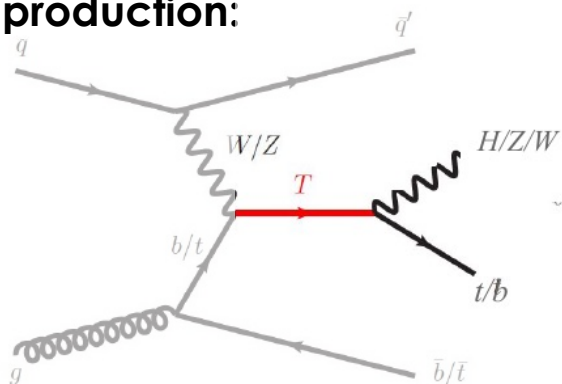
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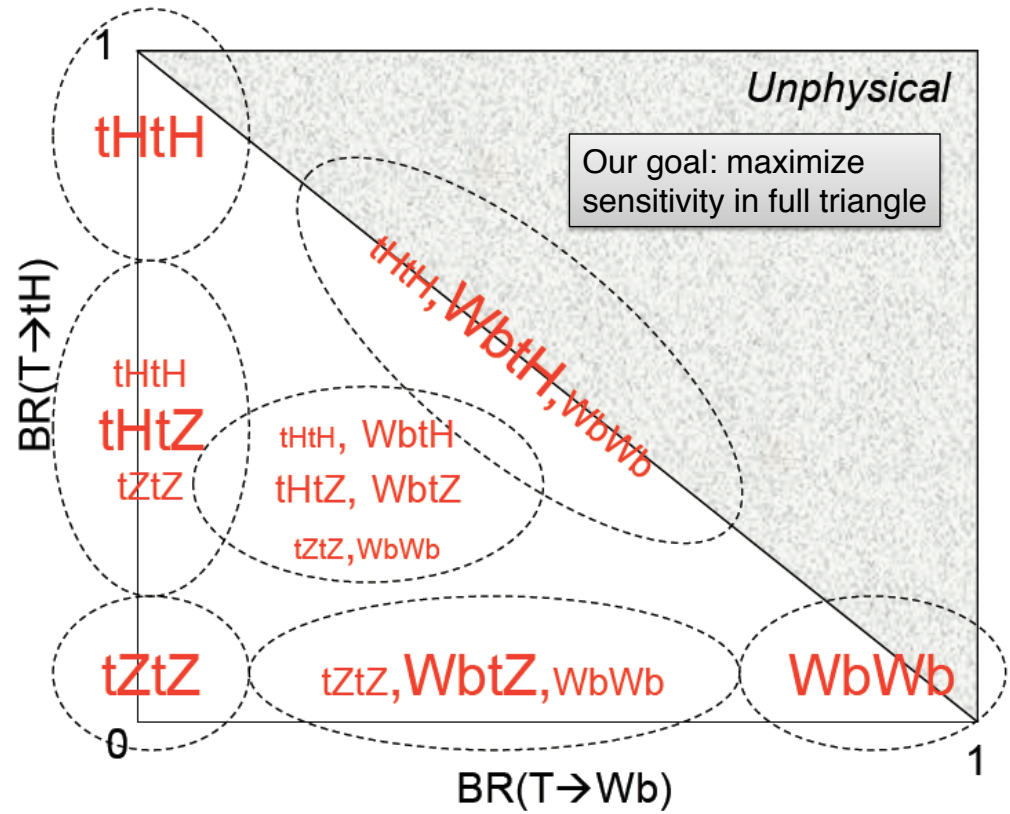
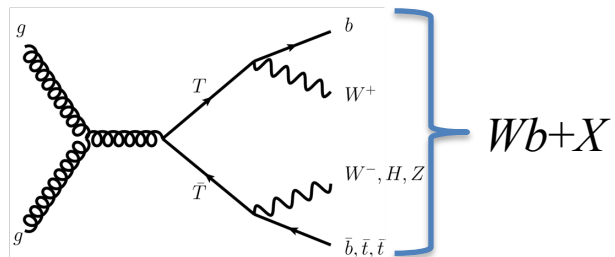
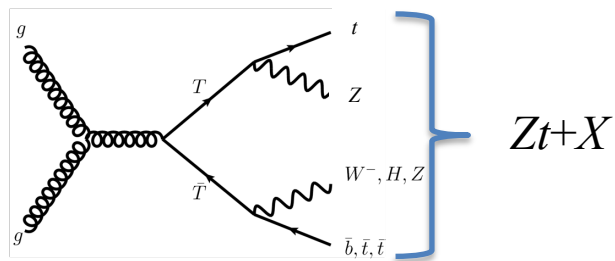
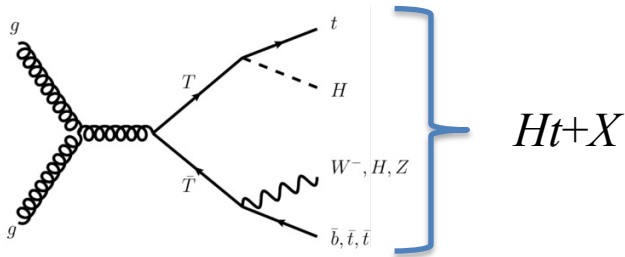
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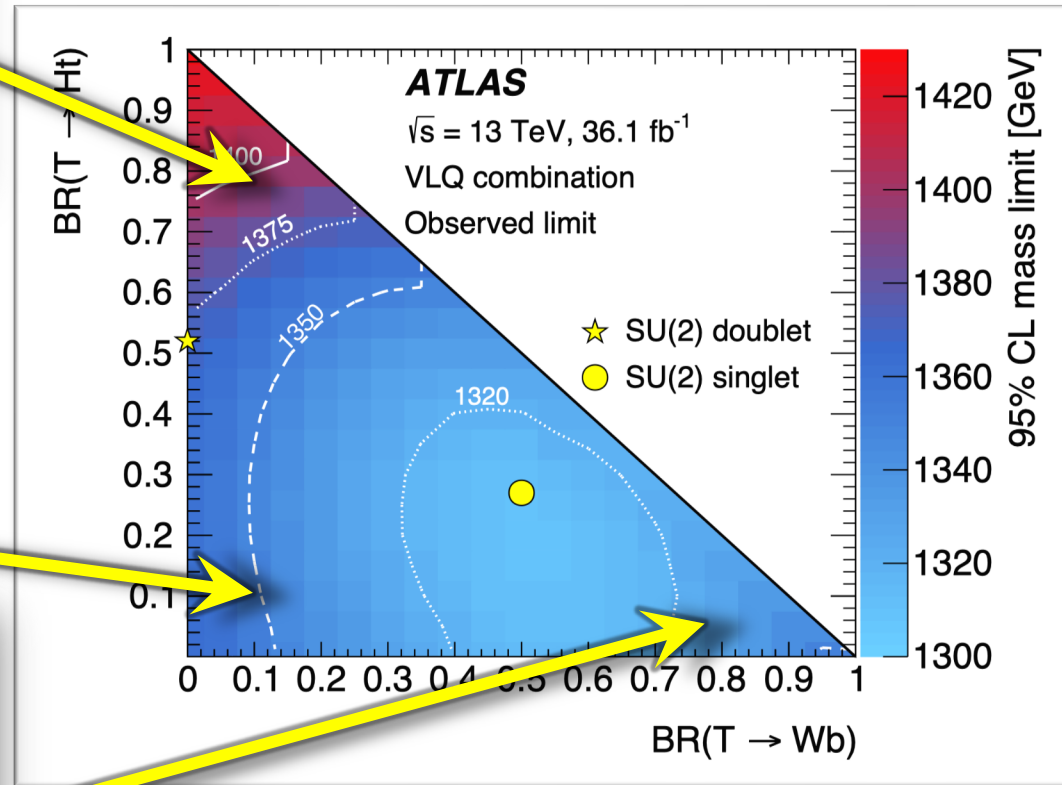
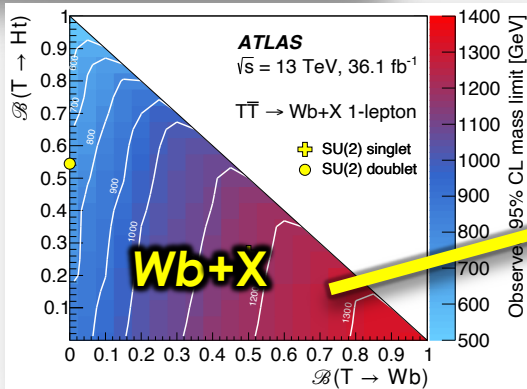
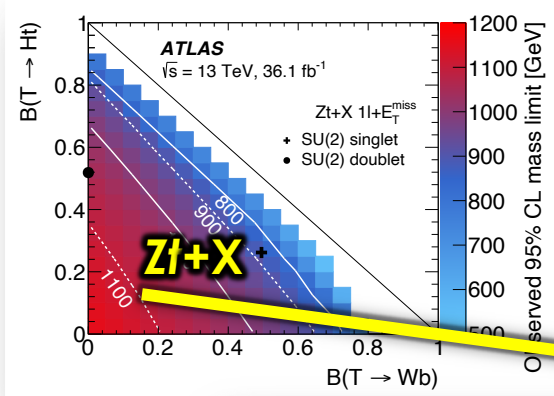
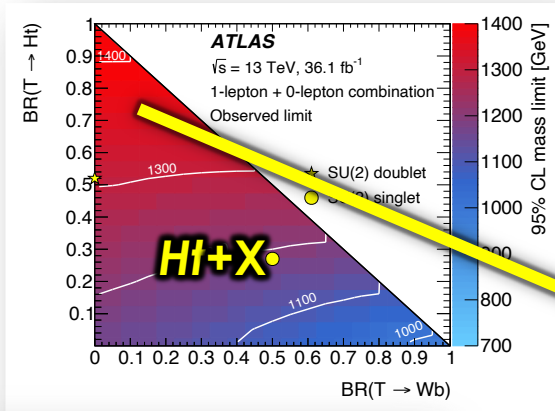
General Strategy

Multiple analyses to target each decay:

Test all possible branching ratios:



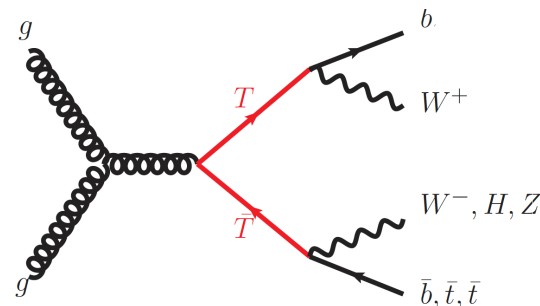
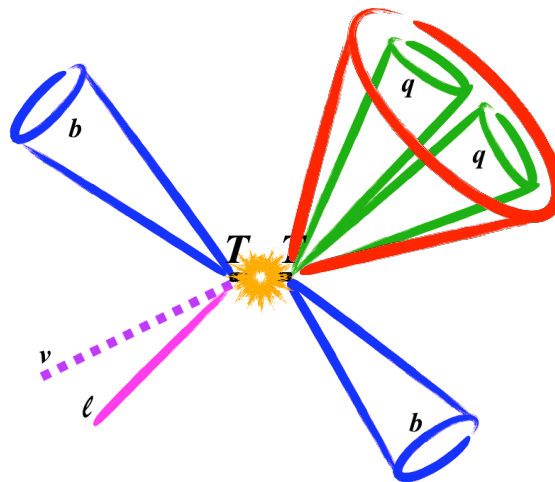
Previous Results (36.1 fb^{-1})



Pair-produced Top-partners: $TT \rightarrow Wb + X$

Optimized for $TT \rightarrow WbWb$, with $W \rightarrow \ell\nu$ and $W \rightarrow (qq)$

Primary event selection:

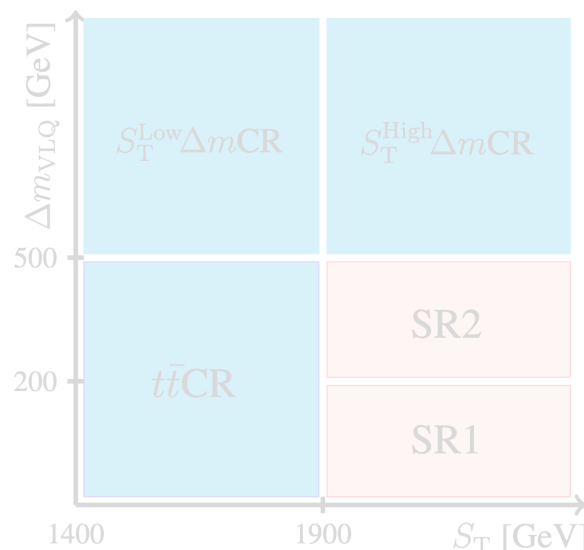


VLQ reconstruction:

- Find pairing of W_{had} and W_{lep} with b candidates that has smallest $\Delta m_{\text{VLQ}} = |m_T^{\text{lep}} - m_T^{\text{had}}|$

Final Signal Region requirements:

- $S_T = \sum_{\text{jets}, \ell, E_T^{\text{miss}}} |p_T| > 1900 \text{ GeV}$
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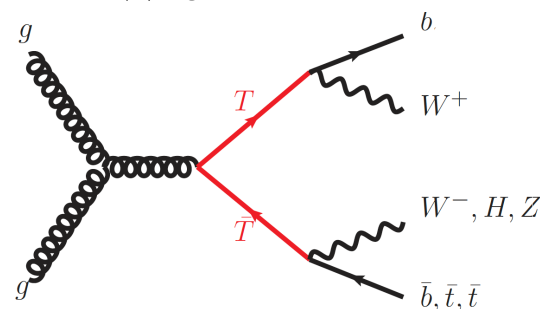
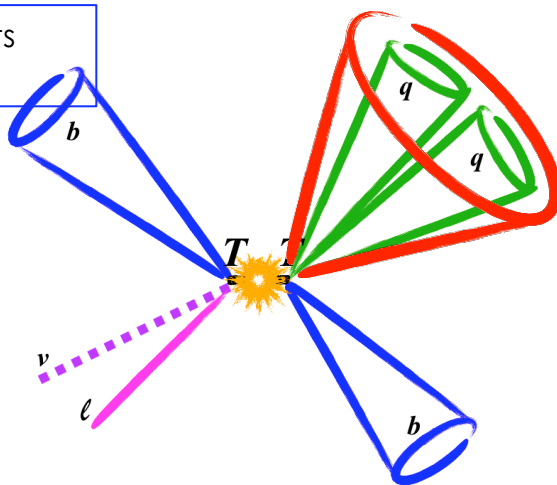


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Multiple small radius jets with ≥ 1 b -tagged

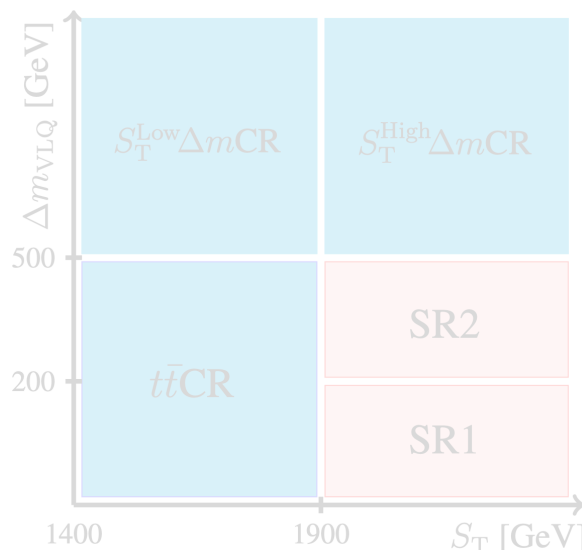


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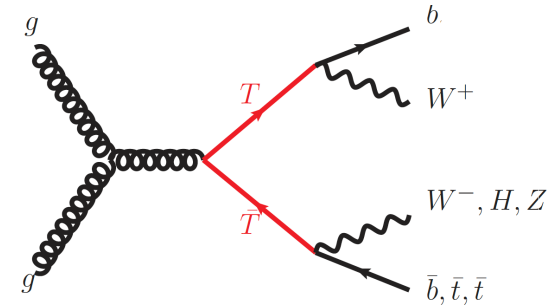
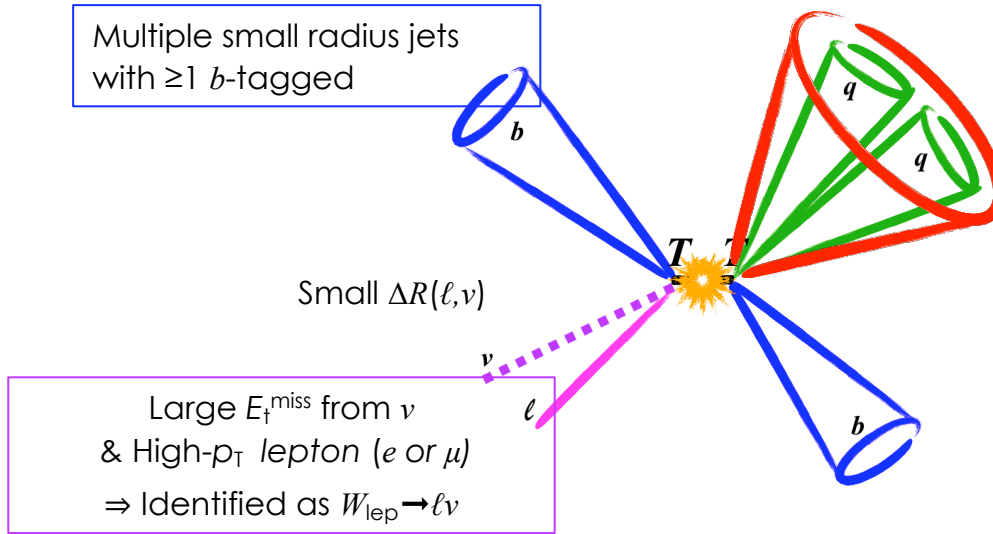
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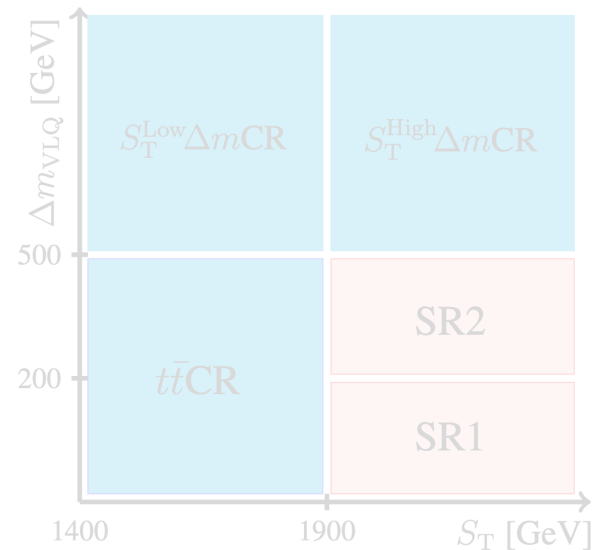


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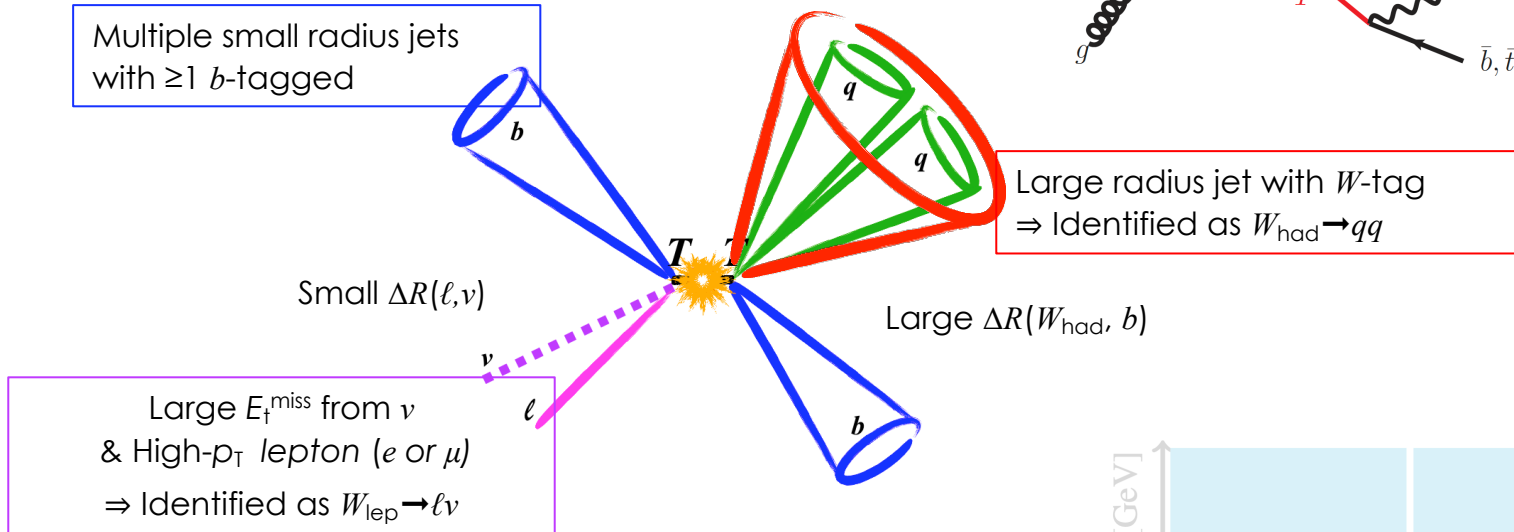
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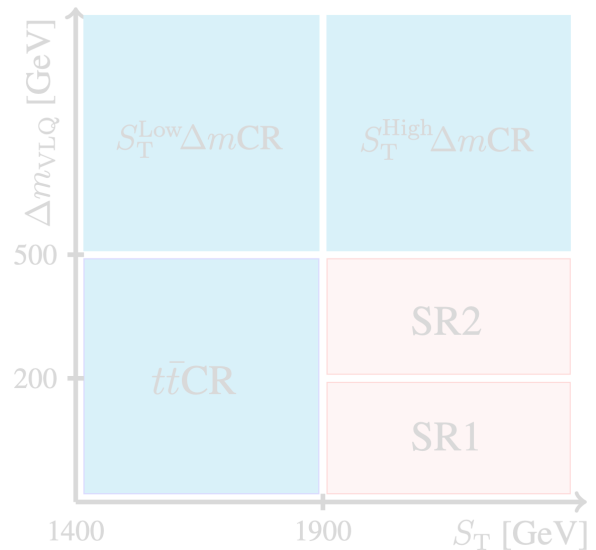


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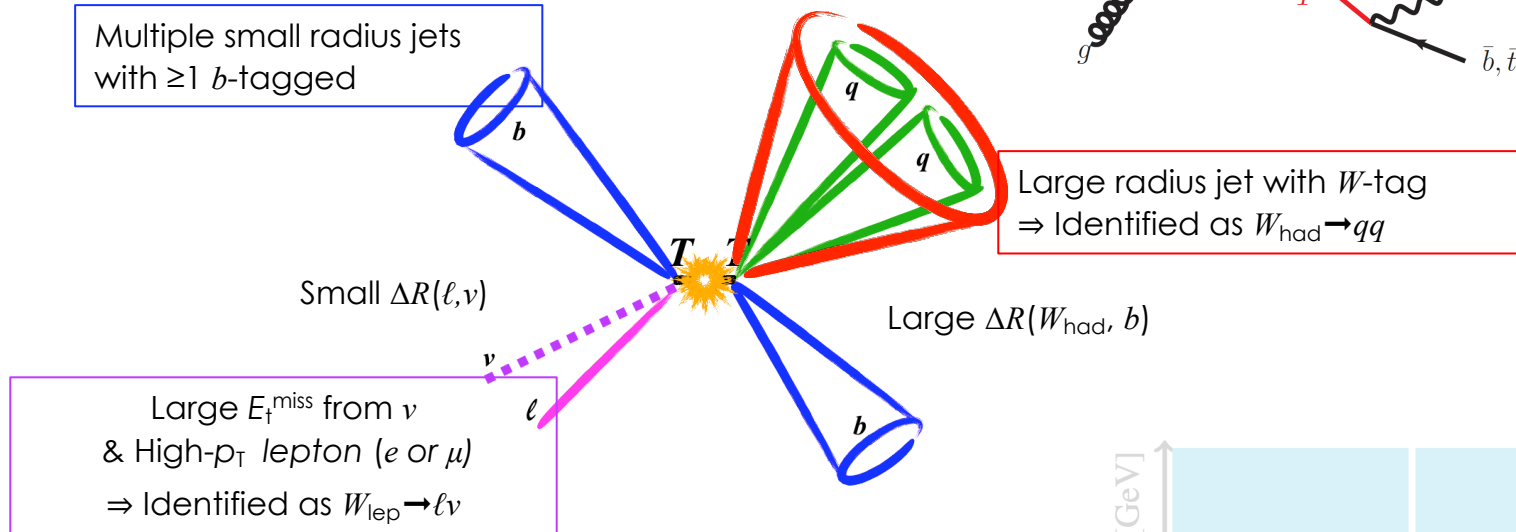
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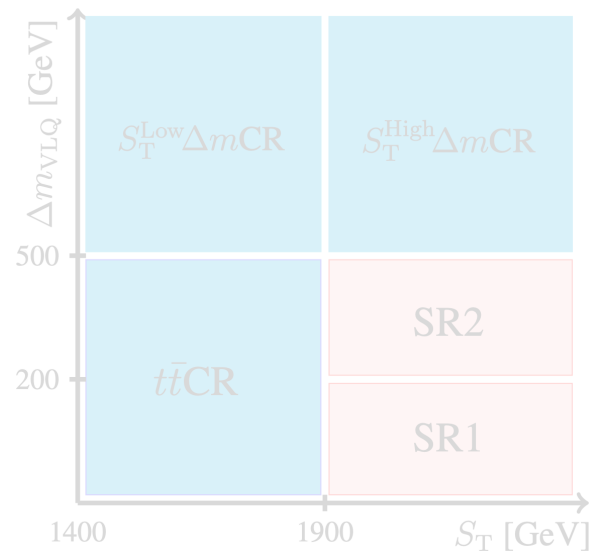
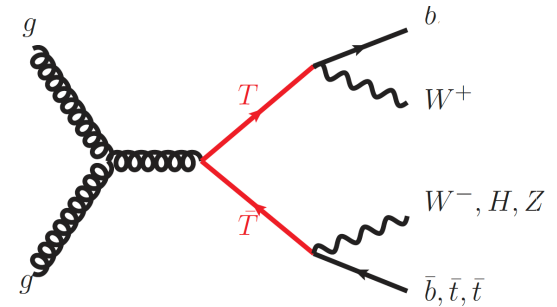


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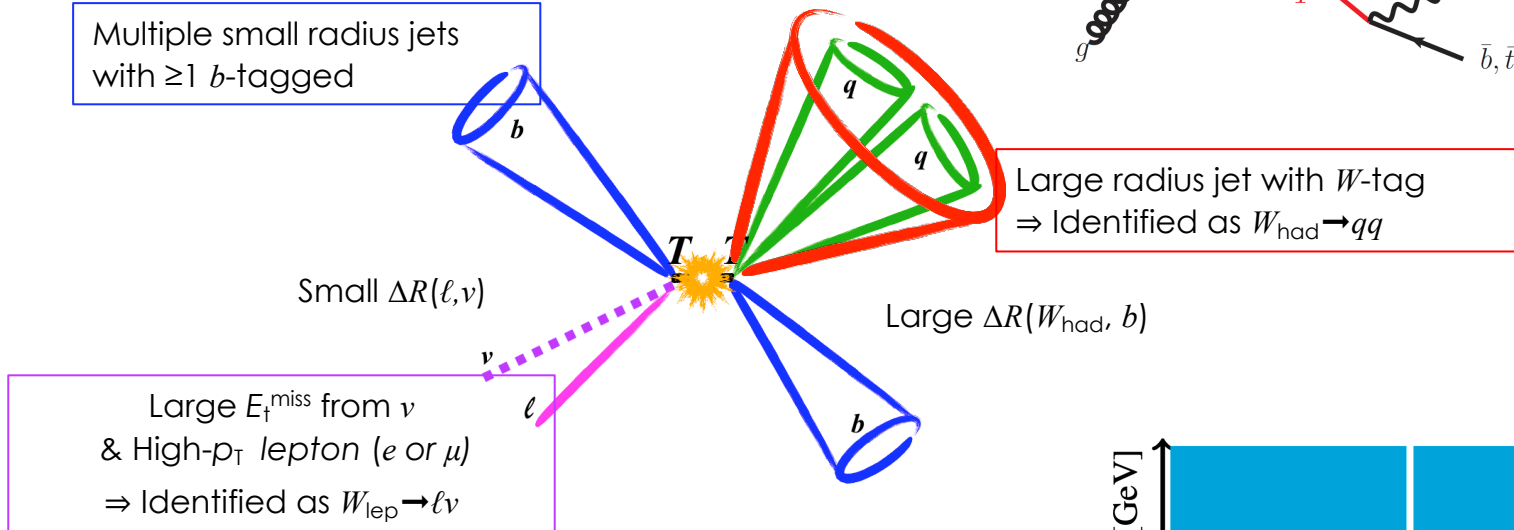
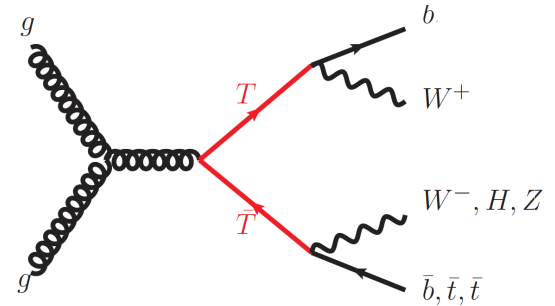
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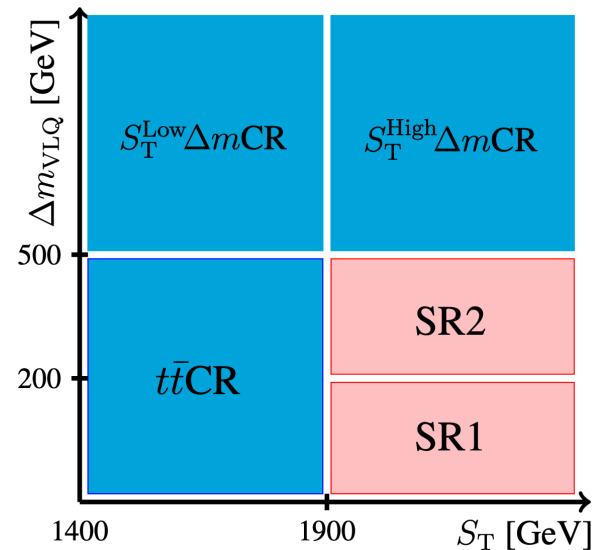


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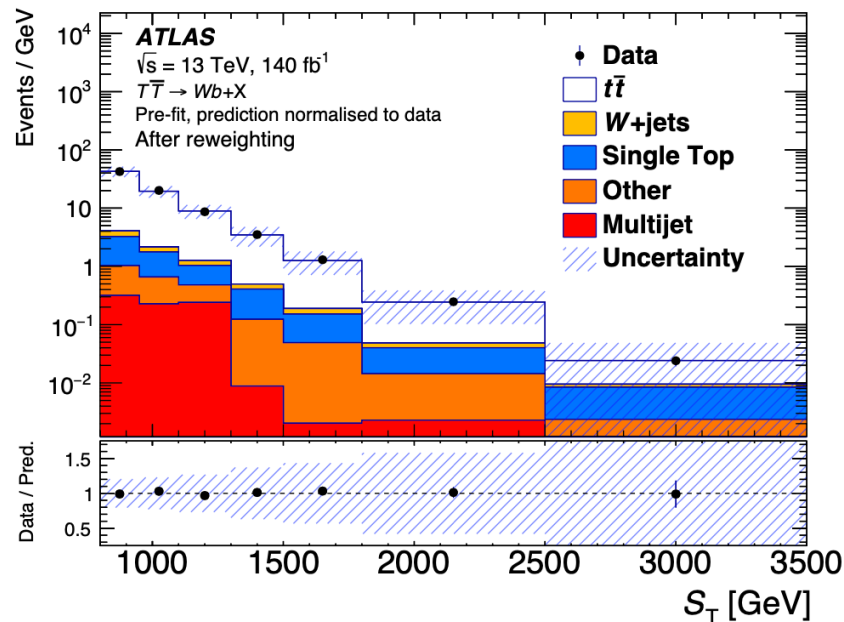
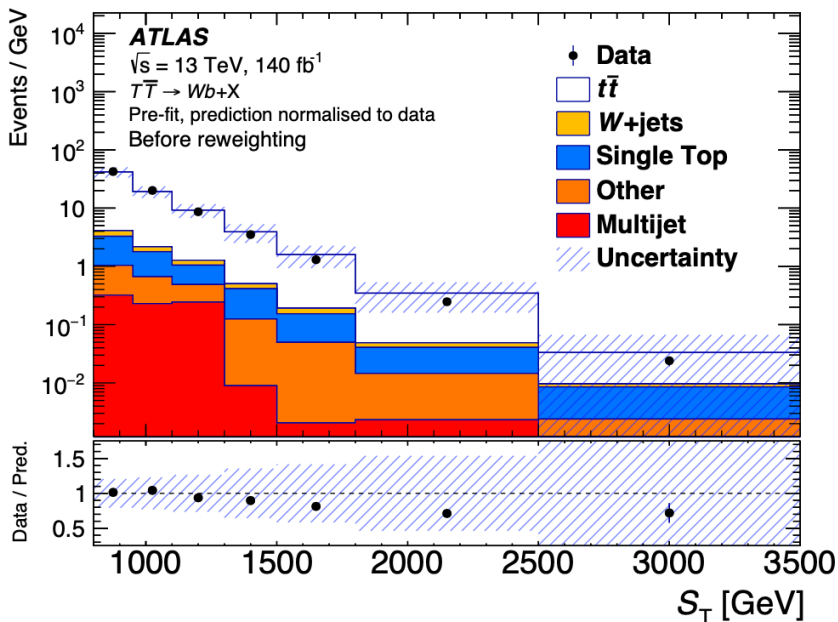
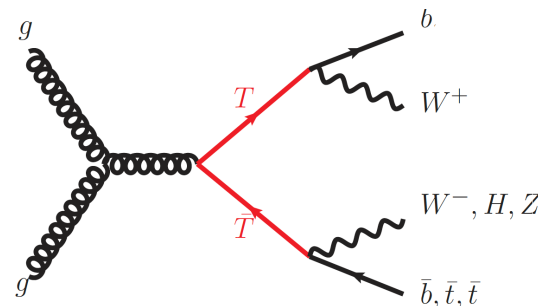
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Pair-produced Top-partners: $T\bar{T} \rightarrow Wb + X$

Background dominated by SM $t\bar{t}$

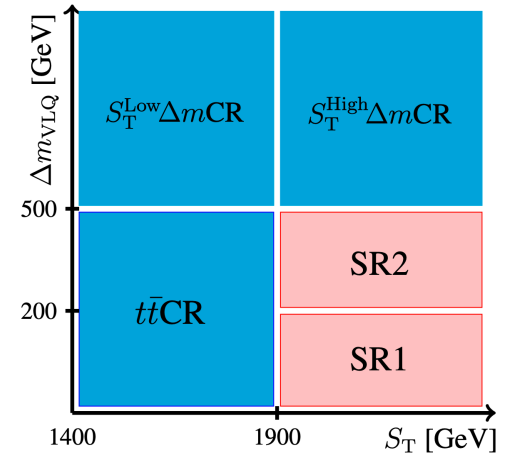
- Estimated with Monte Carlo simulation, but with data-driven correction to improve modeling
- Derive S_T correction in dedicate re-weighting region
- Similar kinematics to SRs, but low signal



Pair-produced Top-partners: $TT \rightarrow Wb + X$

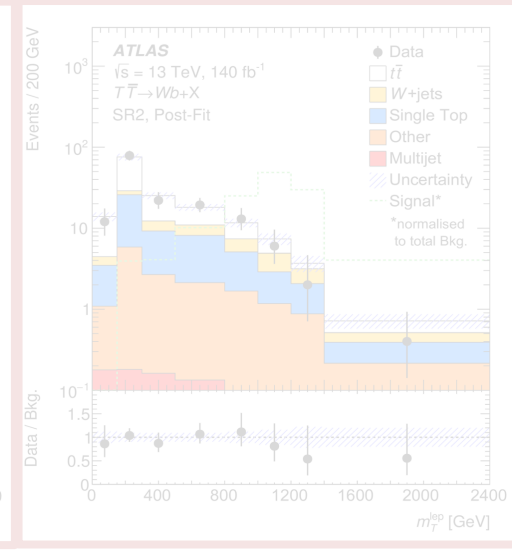
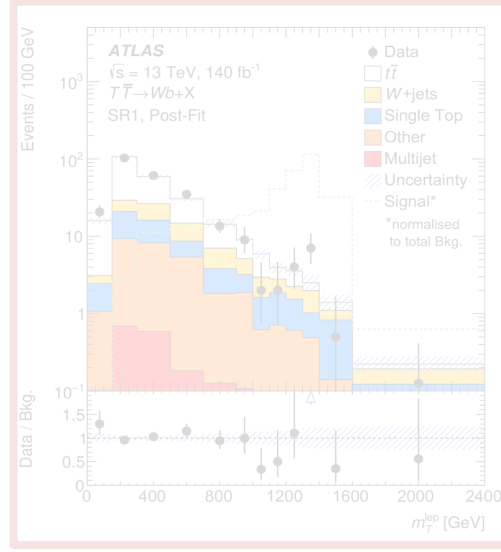
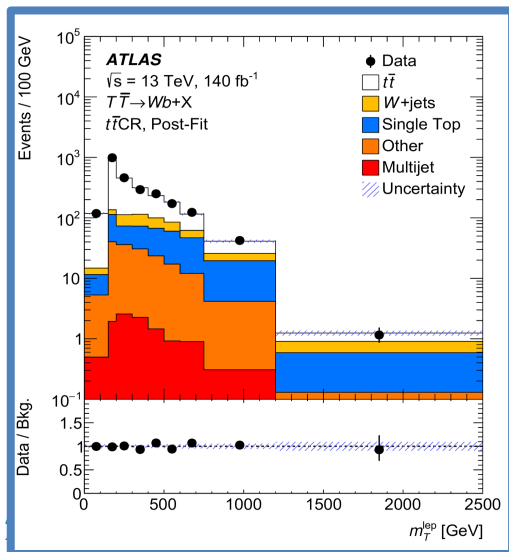
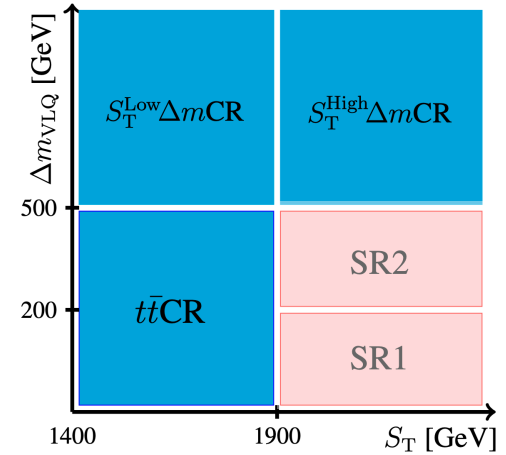
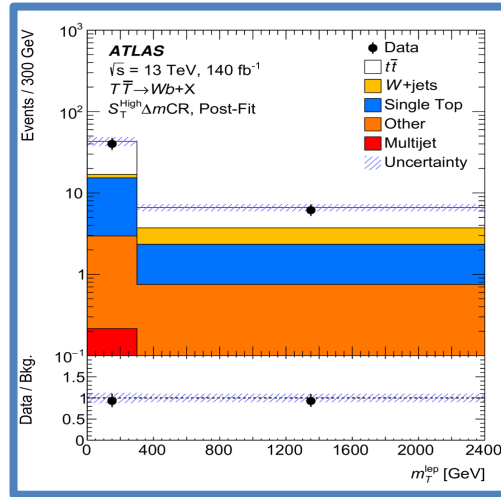
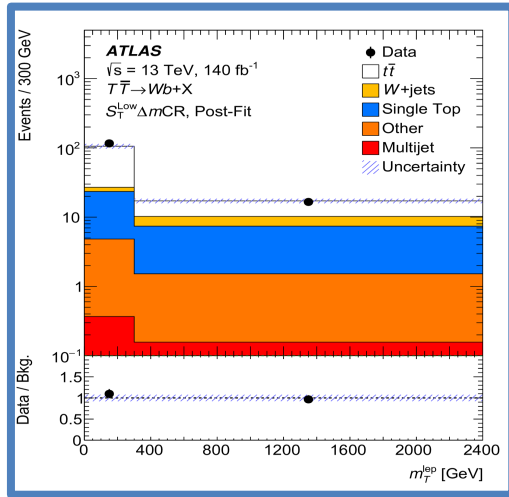
Perform simultaneous fit to data of reconstructed VLQ mass using:

- **2 Signal Regions**
- **3 Control Regions**
 - $t\bar{t}$ CR: Constrains dominate $t\bar{t}$ background
 - Δm CRs with Low and High S_T : Provides extrapolation between $t\bar{t}$ CR and SRs



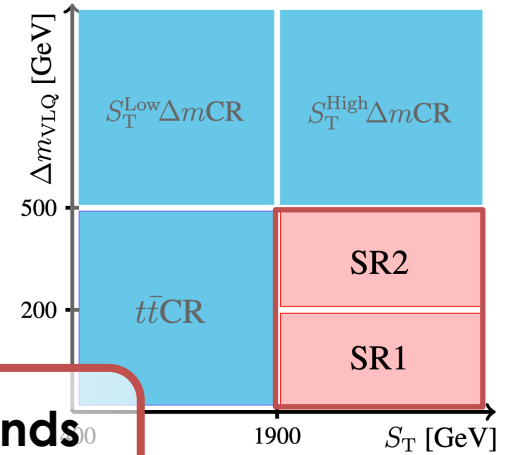
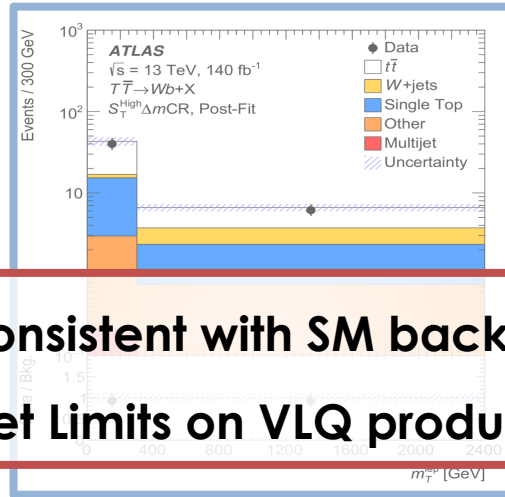
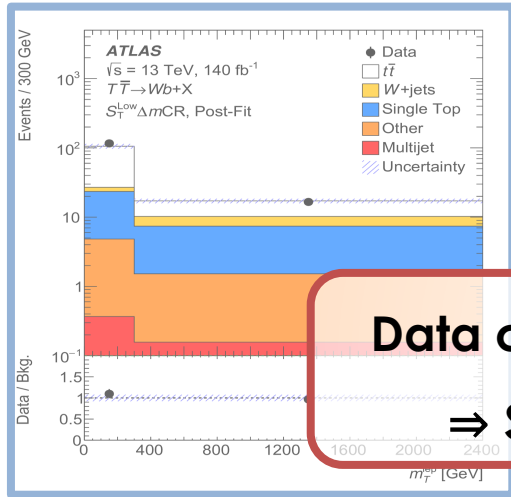
Pair-produced Top-partners: $T\bar{T} \rightarrow Wb + X$

Perform simultaneous fit to data of reconstructed VLQ mass in **3 CRs**

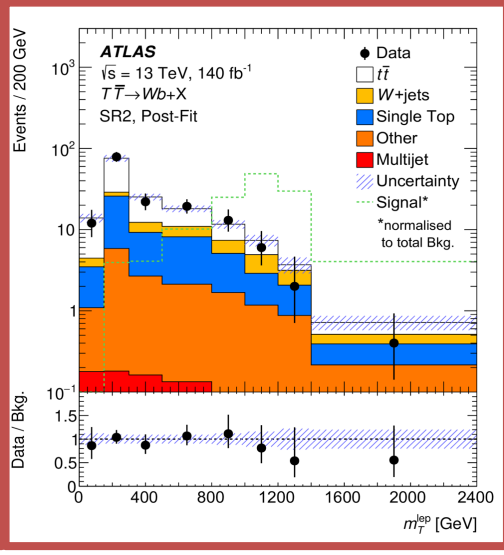
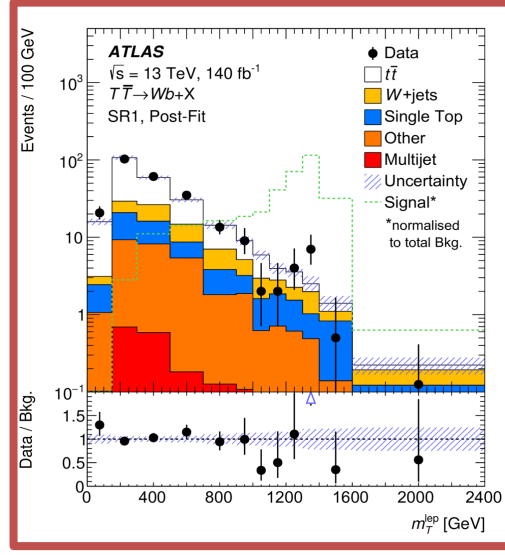
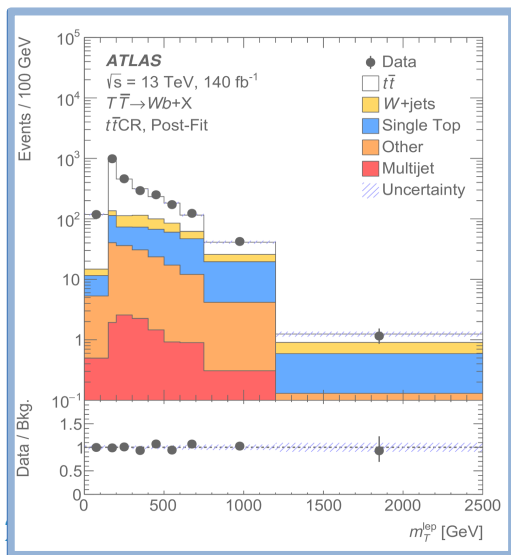


Pair-produced Top-partners: $T\bar{T} \rightarrow Wb + X$

Perform simultaneous fit to data of reconstructed VLQ mass in **3 CRs** and **2 SRs**



Data consistent with SM backgrounds
⇒ Set Limits on VLQ production



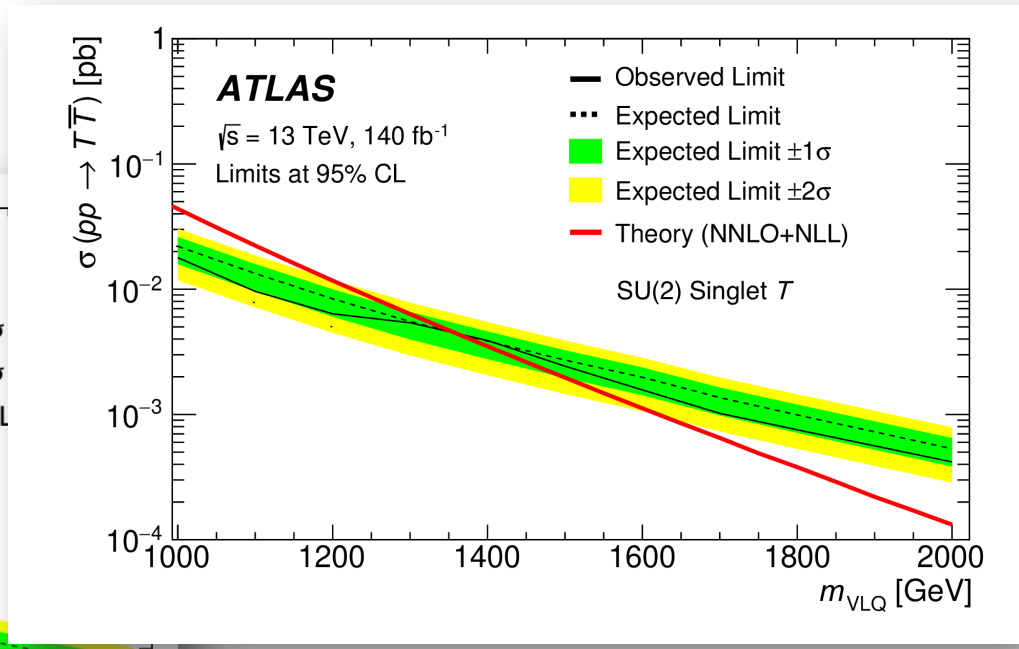
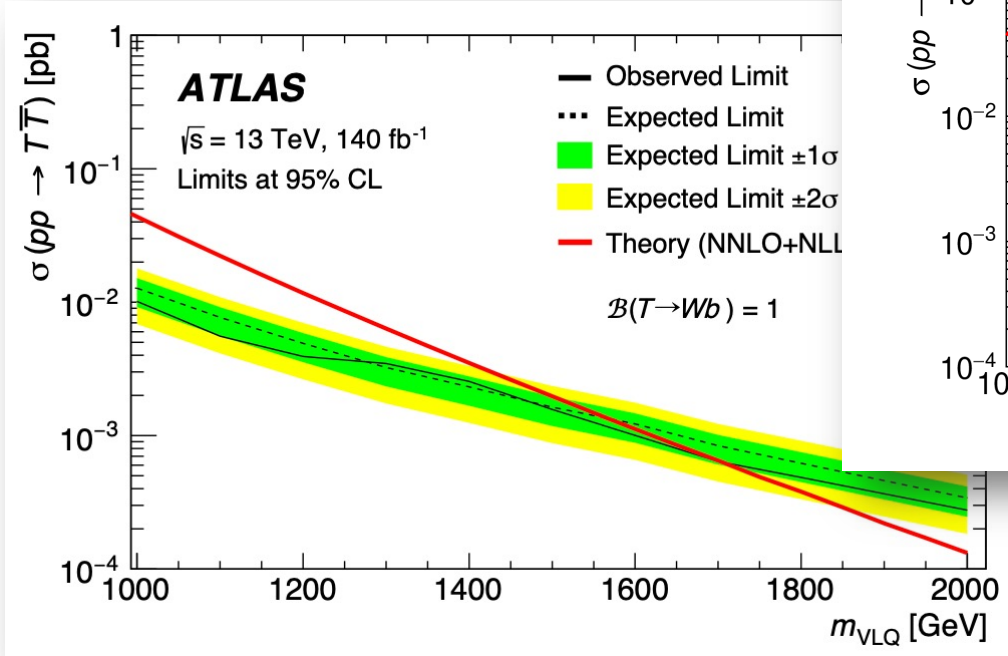
Pair-produced Top-partners: $TT \rightarrow Wb + X$

⇒ Limits on cross-section vs. mass
for benchmark scenarios

Electroweak Singlet T

$$\Rightarrow \mathcal{B}(T \rightarrow Wb : Ht : Zt) = 1/2 : 1/4 : 1/4$$

Pure $TT \rightarrow WbWb$
⇒ $\mathcal{B}(T \rightarrow Wb) = 1$



Pair-produced Top-partners: $TT \rightarrow Wb + X$

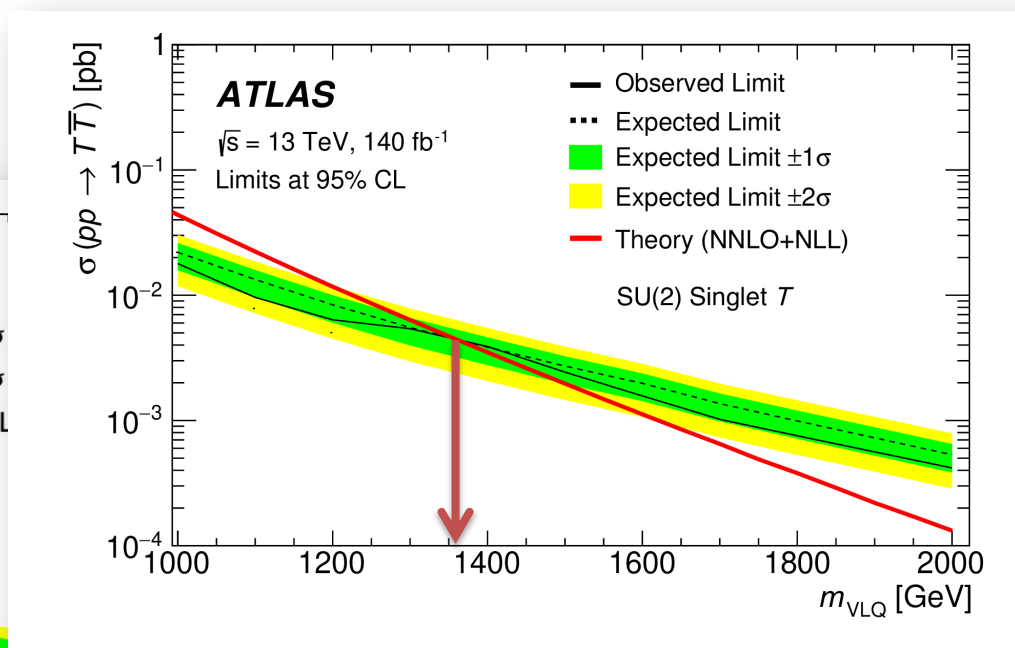
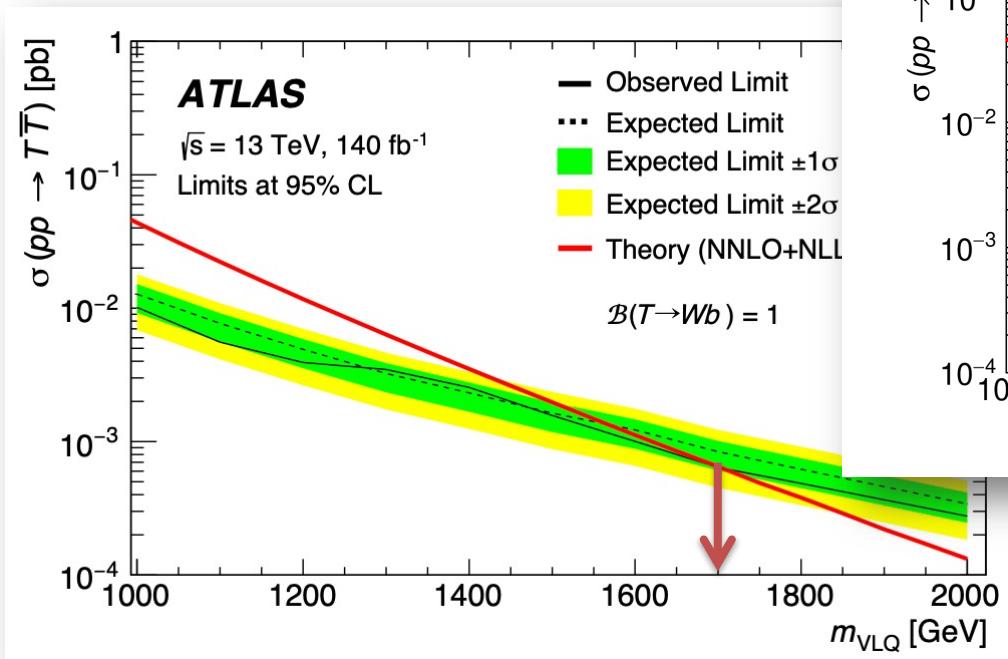
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Singlet excluded for $m_{VLQ} \leq 1360 \text{ GeV}$

$\mathcal{B}(T \rightarrow Wb) = 1$ excluded for $m_{VLQ} \leq 1700 \text{ GeV}$

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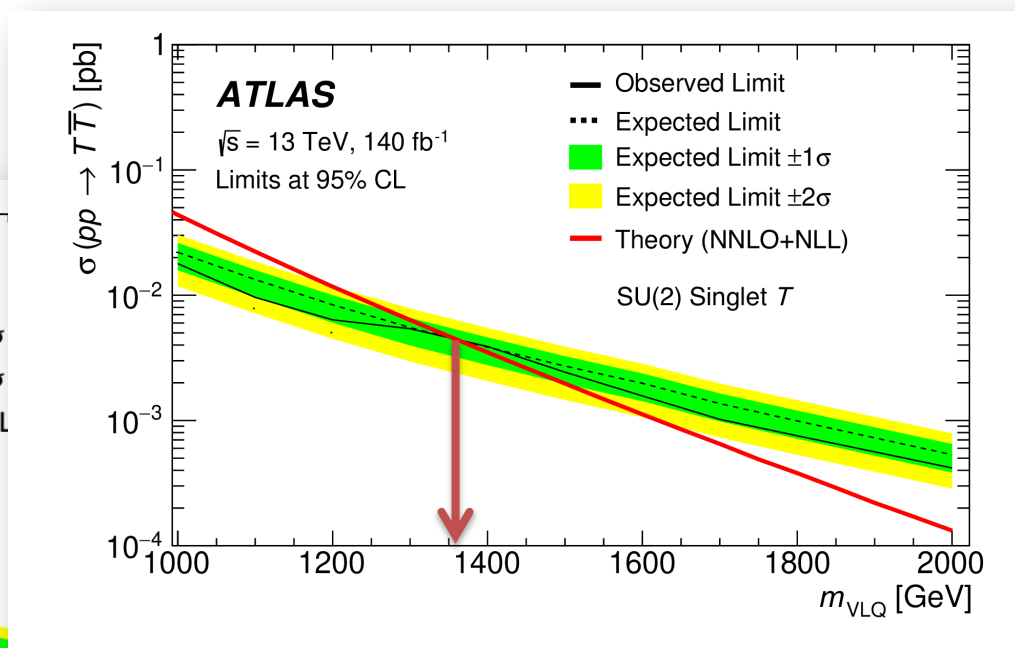
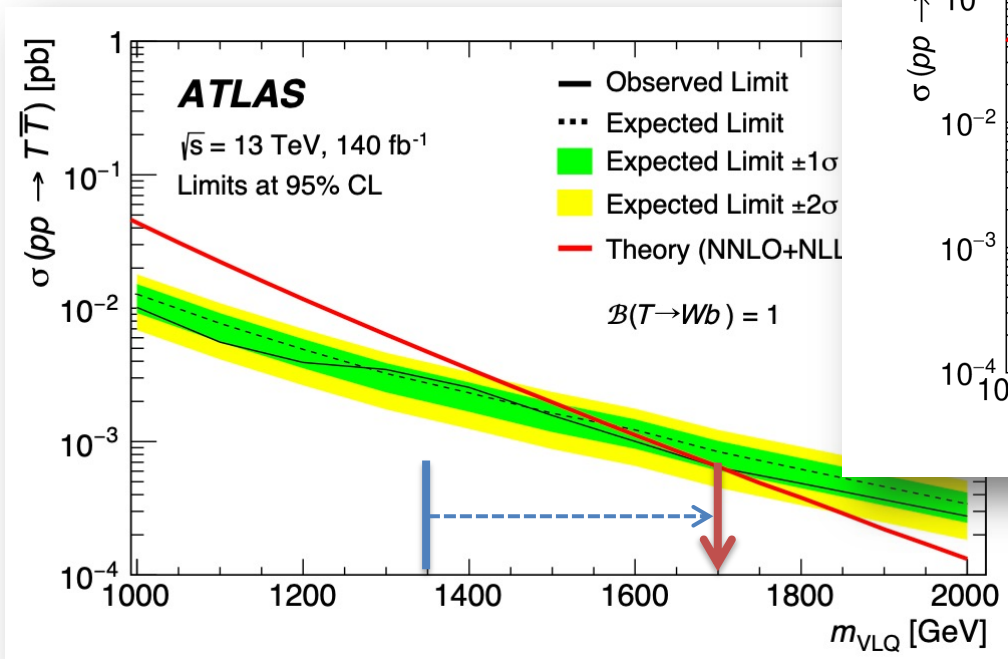
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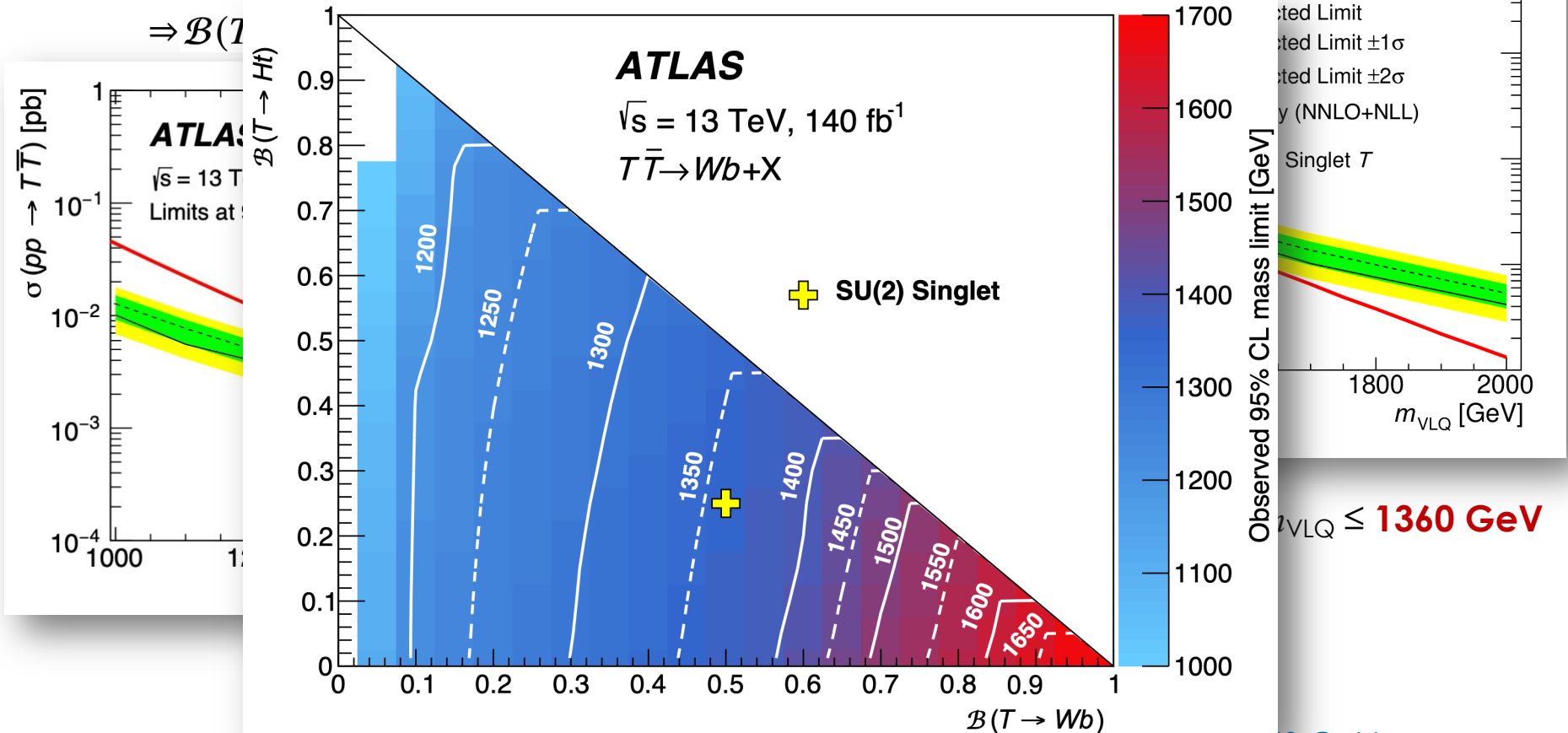
350 GeV increase from previous limit $m_{VLQ} \leq 1350 \text{ GeV}$

Pair-produced Top-partners: $TT \rightarrow Wb + X$

⇒ Limits on cross-section vs. mass

Electroweak Singlet T

⇒ Limits on T mass for any combination of branching ratios $\mathcal{B}(T \rightarrow Wb) : \mathcal{B}(T \rightarrow Zt) : \mathcal{B}(T \rightarrow Ht) = 1/4 : 1/4$
 (assuming T decays to SM particles: $T \rightarrow Wb/Zt/Ht$)



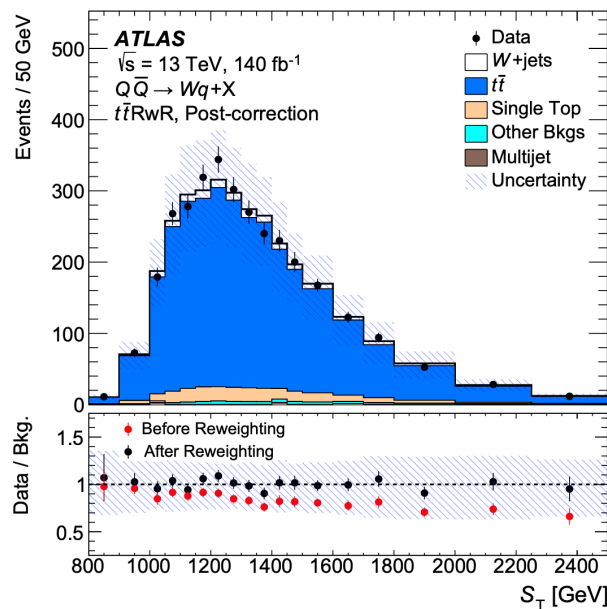
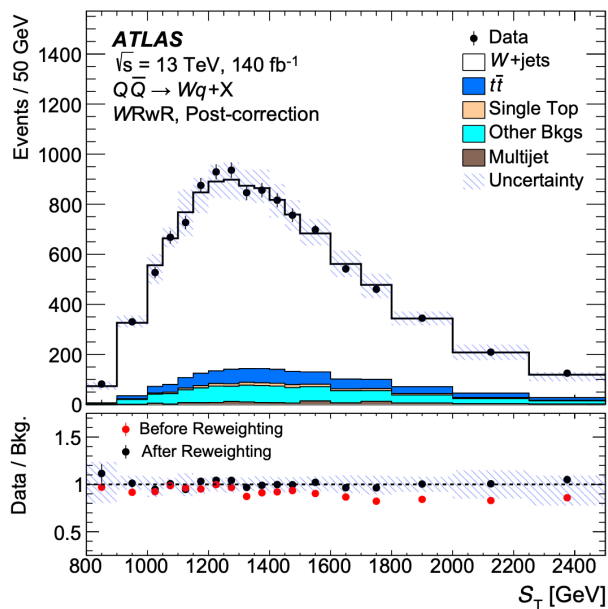
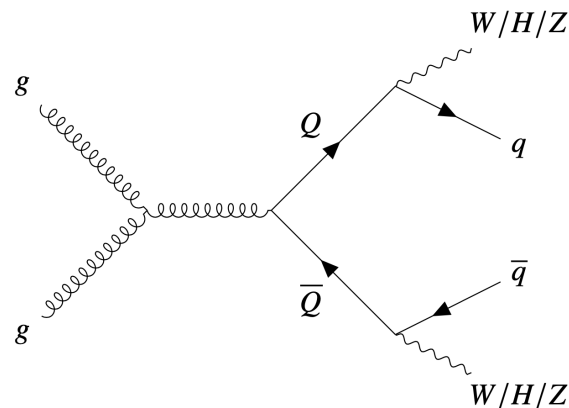
$m_{VLQ} \leq 1360 \text{ GeV}$

350 GeV increase from previous limit $m_{VLQ} \geq 1350 \text{ GeV}$

Pair-produced Light-partners: $Q\bar{Q} \rightarrow Wq + X$

Very much like $T\bar{T} \rightarrow Wb + X$, but a few significant differences:

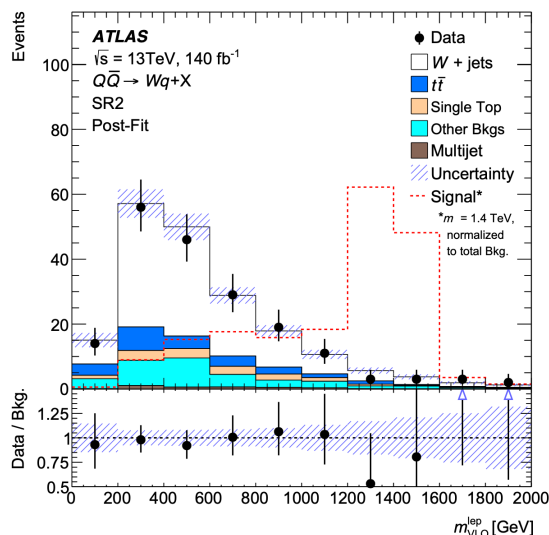
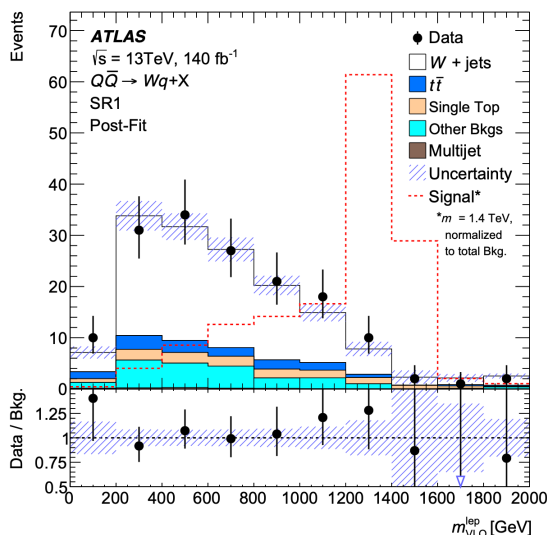
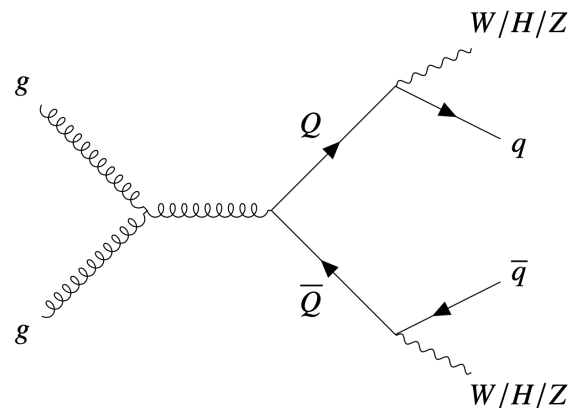
- Require zero b -tagged jets
 - Background dominated by W +jets
- \Rightarrow Data-driven S_T correction for both W +jets and $t\bar{t}$ backgrounds



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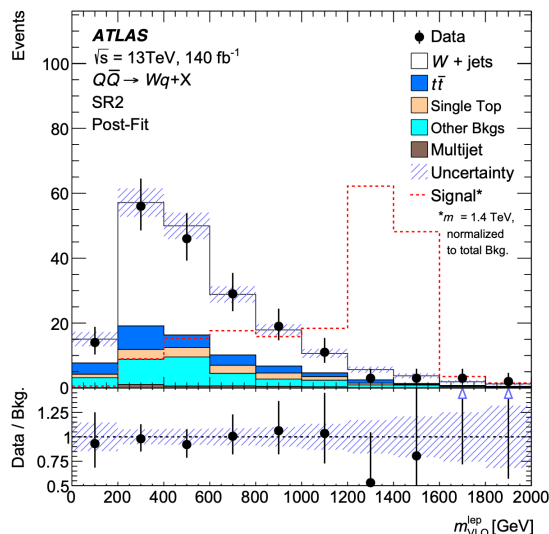
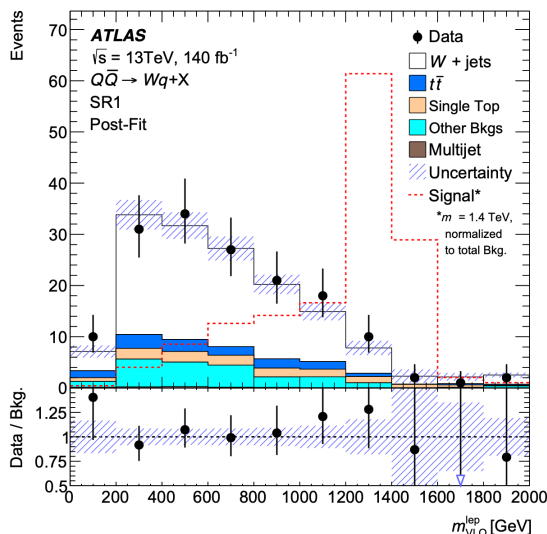
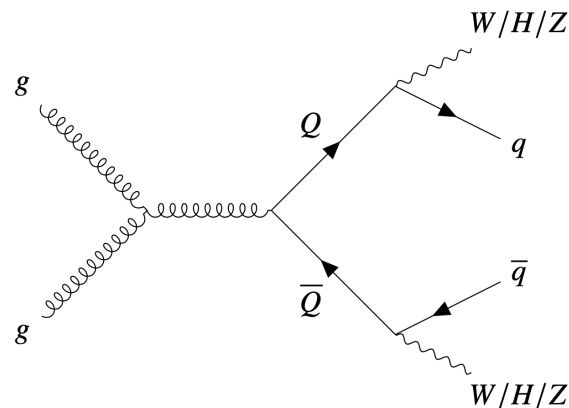
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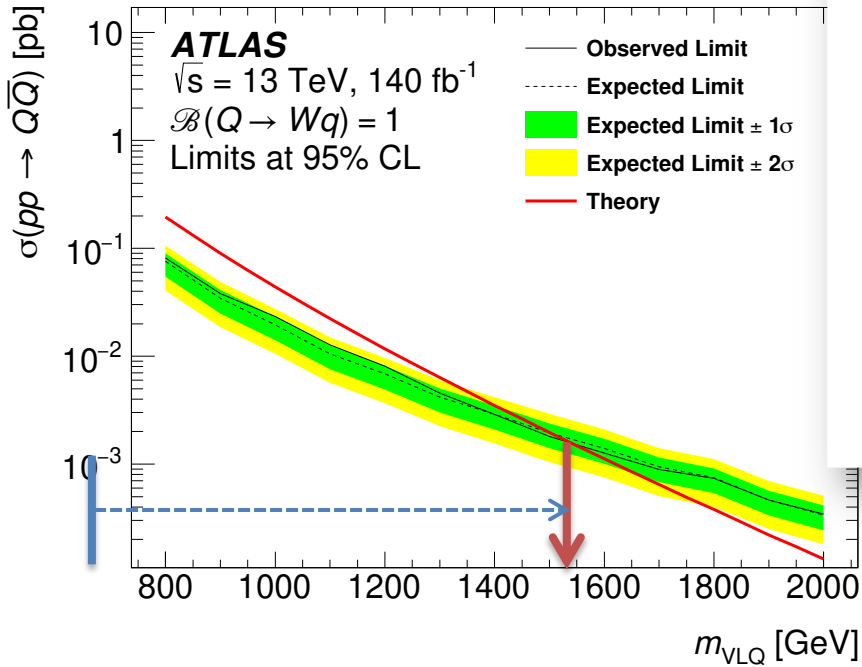


No signs of new physics
 \Rightarrow Set limits

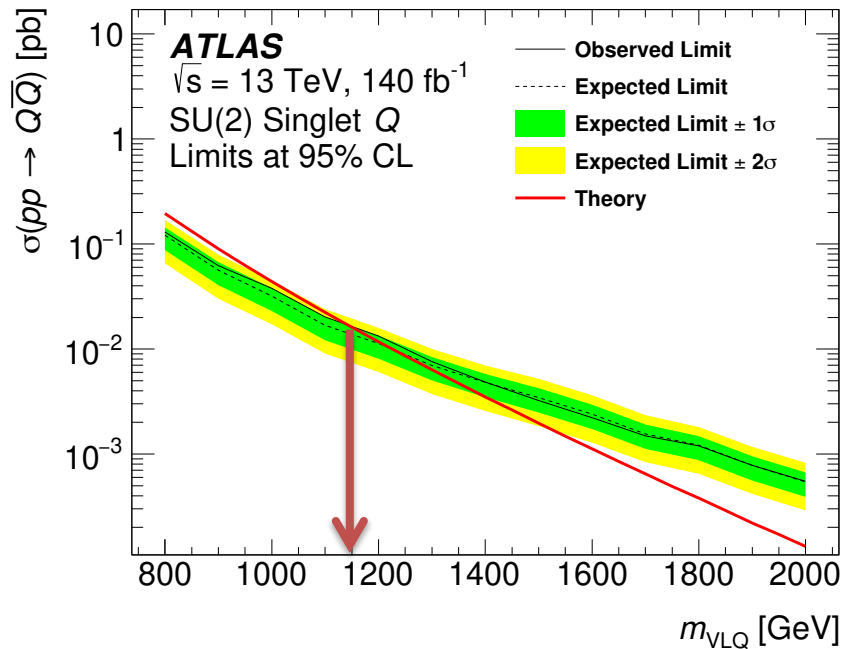
Pair-produced Light-partners: $QQ \rightarrow Wq + X$

⇒ Limits on cross-section vs. mass
for benchmark scenarios

Pure $QQ \rightarrow WqWq$



Electroweak Singlet Q



Excluded for $m_{VLQ} \leq 1150 \text{ GeV}$

Excluded for $m_{VLQ} \leq 1530 \text{ GeV}$

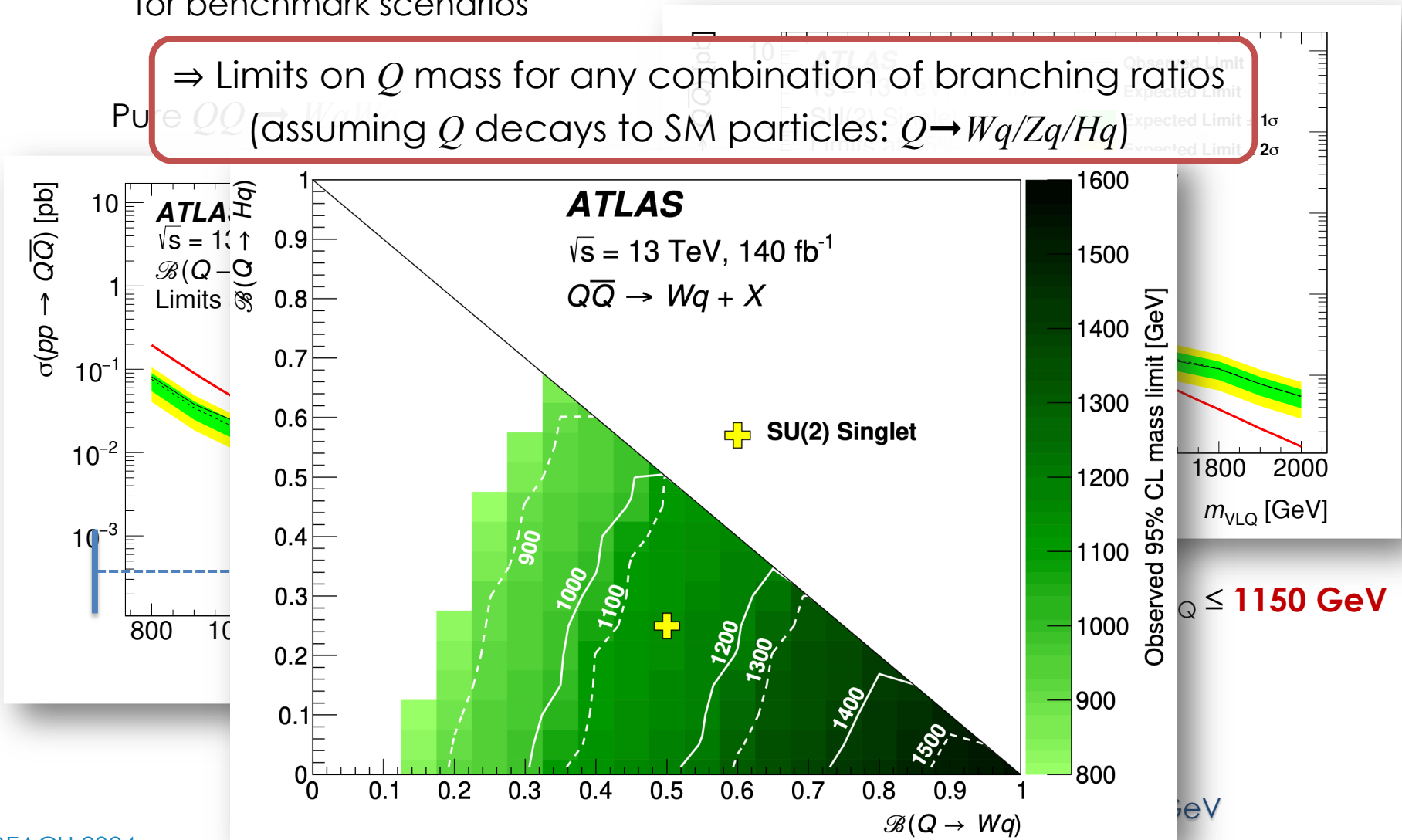
840 GeV increase from previous limit $m_{VLQ} \leq 690 \text{ GeV}$

Pair-produced Light-partners: $QQ \rightarrow Wq + X$

⇒ Limits on cross-section vs. mass
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Electroweak Singlet Q

⇒ Limits on Q mass for any combination of branching ratios
(assuming Q decays to SM particles: $Q \rightarrow Wq/Zq/Hq$)



Single-produced Bottom-partner: $B \rightarrow Hb \rightarrow bbb$

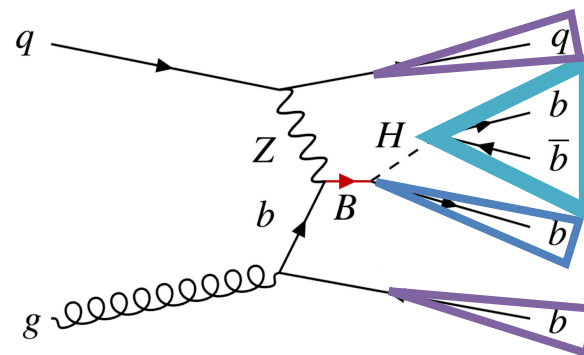
Large-R jet with mass $\approx m_H$ & 2 b -tagged track jet

\Rightarrow Identified as boosted $H \rightarrow bb$

High- p_T **b -tagged small-R jet** from B decay

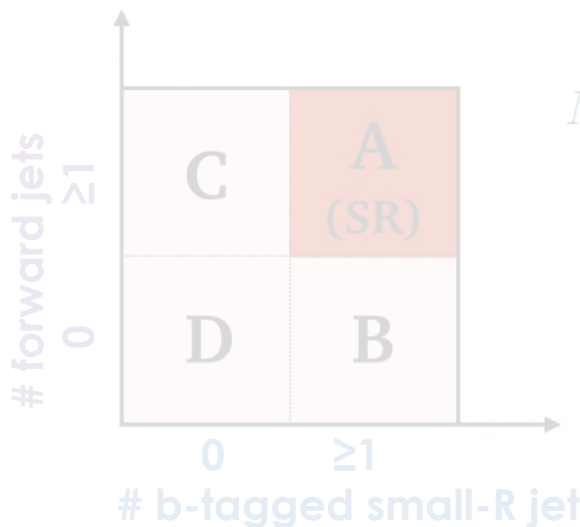
\Rightarrow Critical to reduce huge multijet background

At least one **“forward” jet** from spectator quarks



Purely data-driven background estimate using “ABCD” method

- Extrapolate background from control region (B) to search region (A) using transfer functions measured in neighboring regions (C/D)
- Validate by applying method in two orthogonal regions



$$N_A = N_B \times \frac{N_C}{N_D}$$

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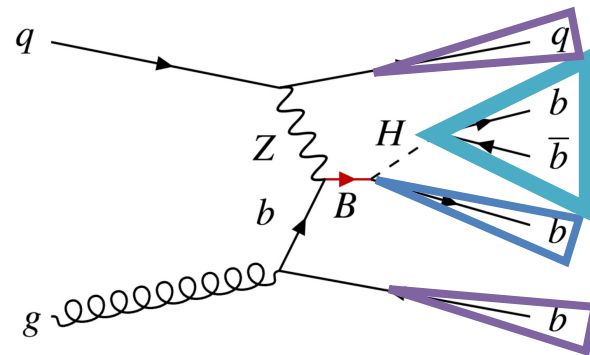
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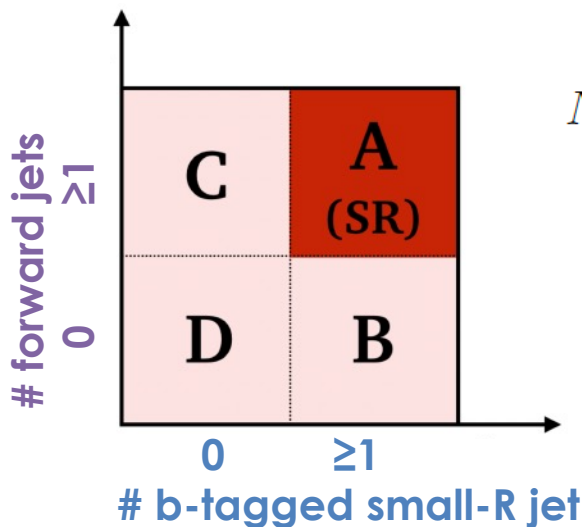
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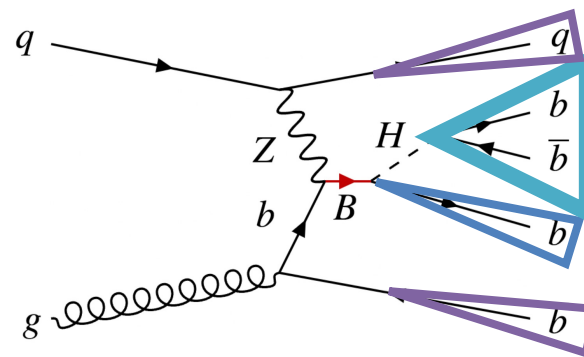
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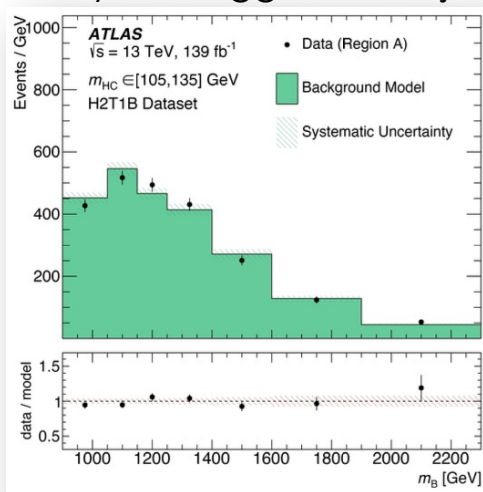
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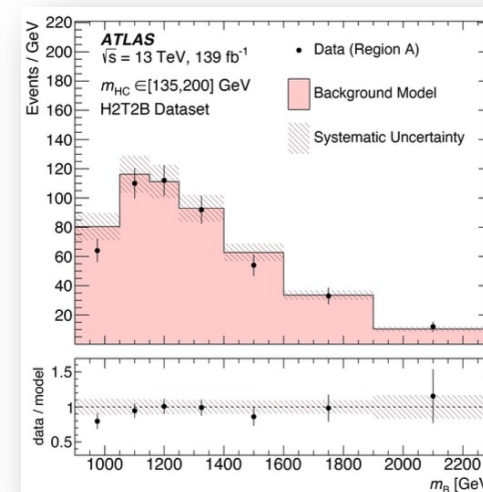
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Only 1 b -tagged track jet



Large-R jet mass sideband



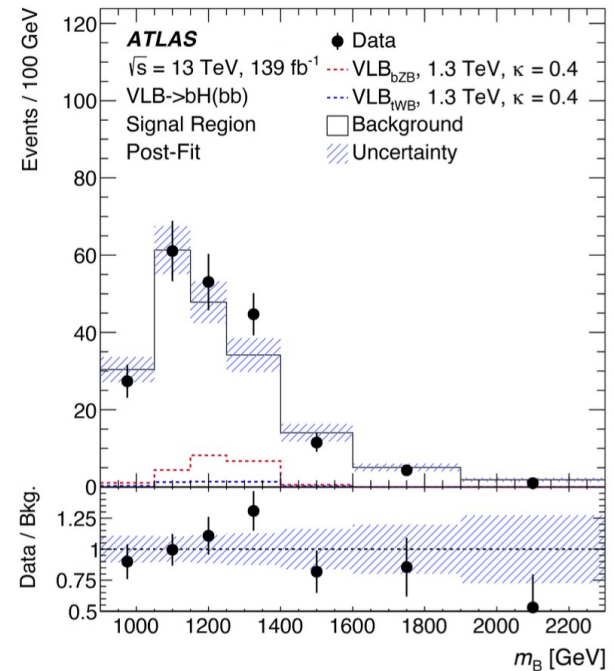
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Binned maximum-likelihood fit to reconstructed B mass distribution m_B

No significant excesses found in full Run 2 dataset

⇒ Set limits

- Limits on coupling κ as a function of the VLB mass for B singlet or (B, Y) doublet
- Lower bounds on VLB mass for given BR and width



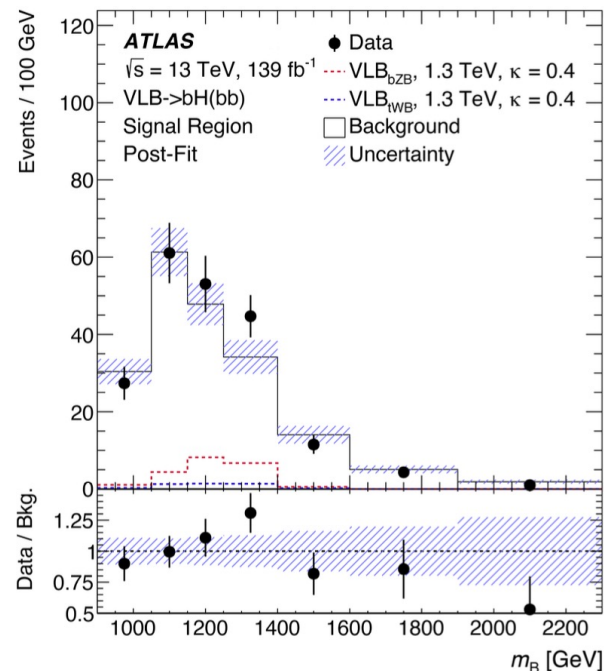
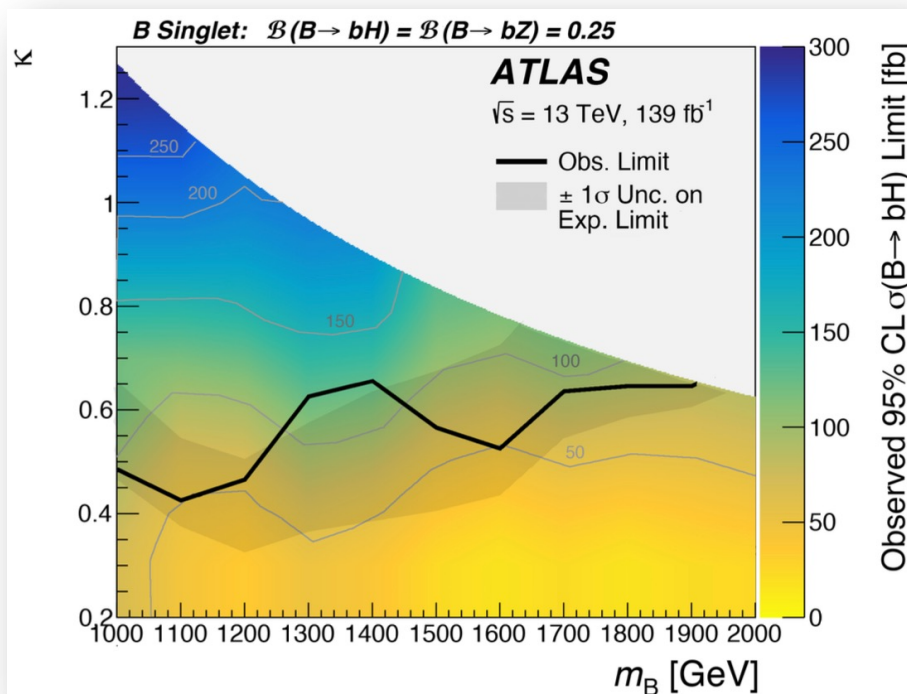
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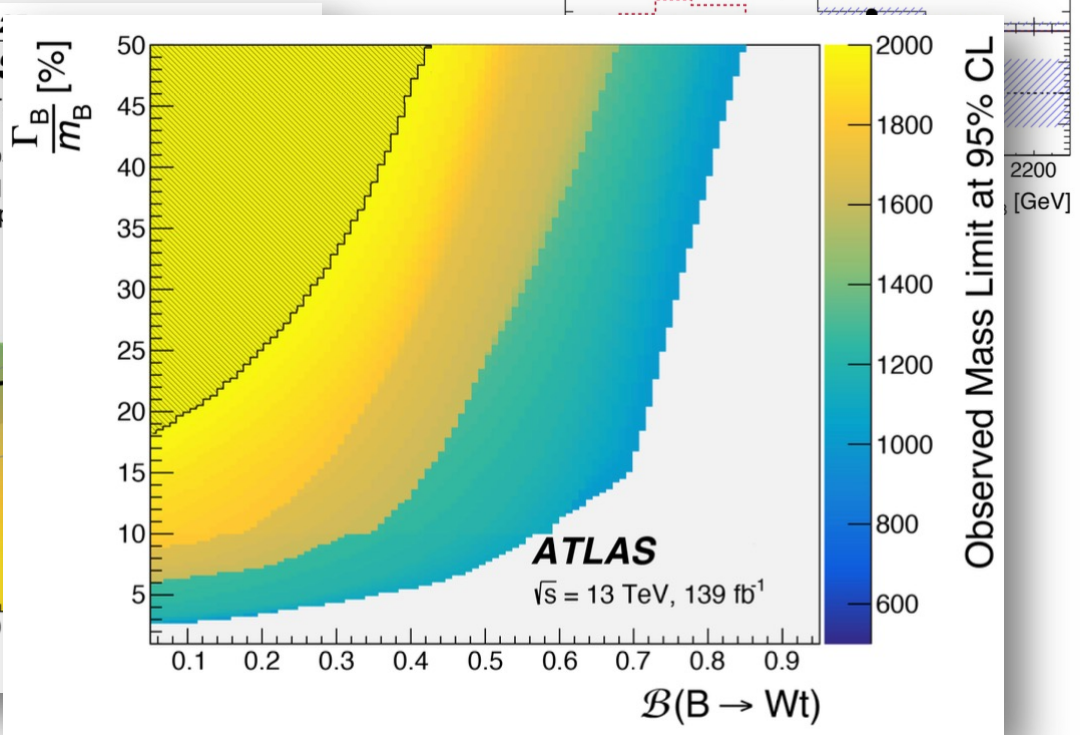
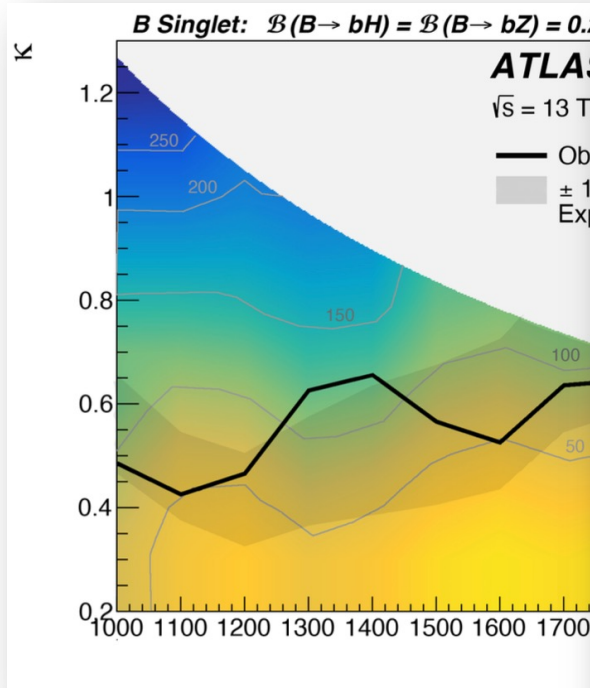
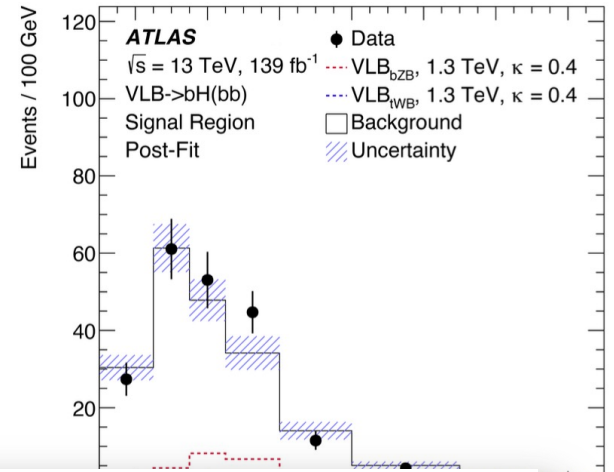
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Leptoquarks

| | | |
|--|----------------------|----------|
| <i>Gauge bosons</i> | | |
| SMS $Z' \rightarrow \ell\ell$ | Z' mass | 5.1 TeV |
| SMS $Z' \rightarrow \tau\tau$ | Z' mass | 2.42 TeV |
| Leptophobic $Z' \rightarrow b\bar{b}$ | Z' mass | 2.1 TeV |
| Leptophobic $Z' \rightarrow t\bar{t}$ | Z' mass | 4.1 TeV |
| SMS $W' \rightarrow \ell\nu$ | W' mass | 6.0 TeV |
| SMS $W' \rightarrow \tau\nu$ | W' mass | 3.7 TeV |
| HVT $W' \rightarrow WZ \rightarrow \ell\nu q\bar{q}$ model B | W' mass | 4.3 TeV |
| HVT $V' \rightarrow W\nu \rightarrow qq\bar{q}q$ model B | V' mass | 3.8 TeV |
| HVT $V' \rightarrow WH/ZH$ model B | V' mass | 2.93 TeV |
| HVT $W' \rightarrow WH$ model B | W' mass | 3.2 TeV |
| LRSM $W_R \rightarrow tb$ | W_R mass | 3.25 TeV |
| LRSM $W_R \rightarrow \mu NR$ | W_R mass | 5.0 TeV |
| LQ | | |
| Scalar LQ 1 st gen | LQ mass | 1.4 TeV |
| Scalar LQ 2 nd gen | LQ mass | 1.56 TeV |
| Scalar LQ 3 rd gen | LQ ₃ mass | 1.03 TeV |
| Scalar LQ 3 rd gen | LQ ₃ mass | 970 GeV |
| <i>Heavy quarks</i> | | |
| VLQ $TT \rightarrow Ht/Zt/Wb + X$ | T mass | 1.37 TeV |
| VLQ $BB \rightarrow Wt/Zb + X$ | B mass | 1.34 TeV |
| VLQ $T_{5/3} T_{5/3} / T_{5/3} T_{5/3} \rightarrow Wt + X$ | $T_{5/3}$ mass | 1.64 TeV |
| VLQ $Y \rightarrow Wb + X$ | Y mass | 1.85 TeV |
| VLQ $B \rightarrow Hb + X$ | B mass | 1.21 TeV |
| VLQ $QQ \rightarrow WqWq$ | Q mass | 690 GeV |

Leptoquarks (LQ)

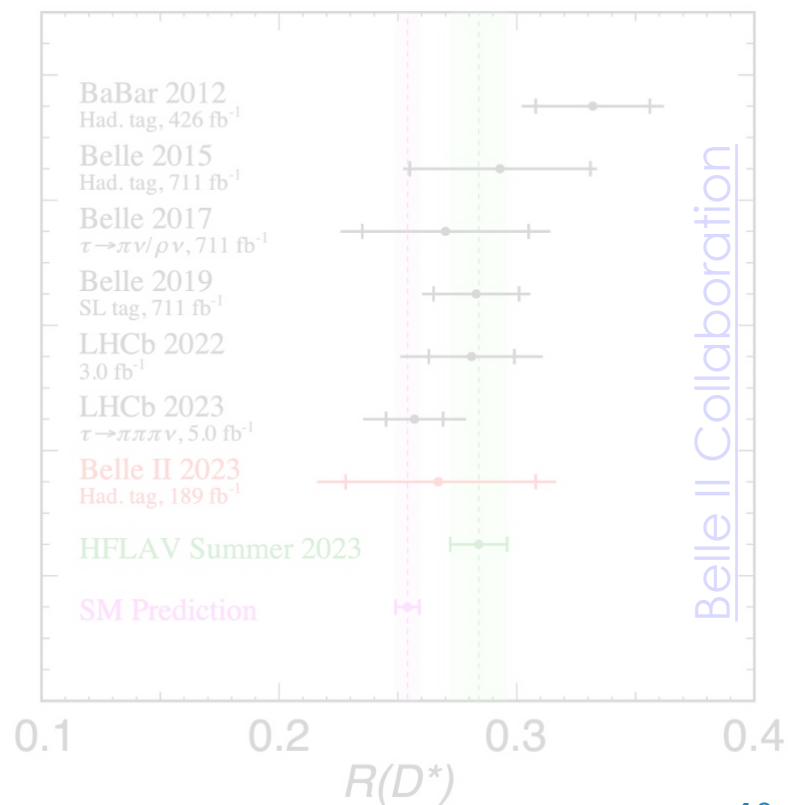
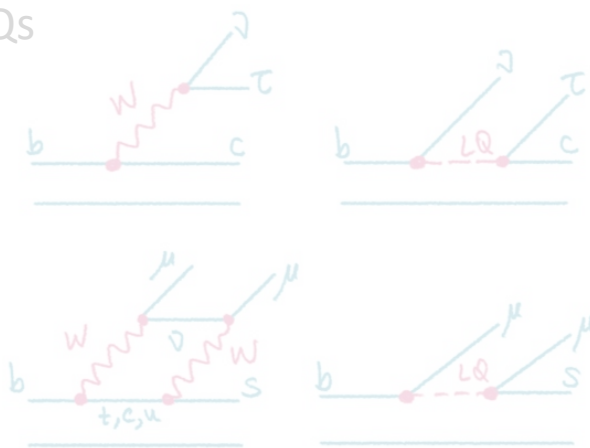
New scalar or vector particles that appear in many Grand Unified Theories

- Carry color charge, fractional electric charge, and both baryon and lepton number
- Provide direct coupling between leptons and quarks
⇒ Can explain many SM problems

Hints of lepton flavor universality violation from B-physics

- R_D/R_{D^*} : 3.2 σ deviation in global average
- R_K/R_{K^*} : Now SM consistent?
- $B \rightarrow K \mu \mu$ angular variable discrepancies, muon g-2, and more...

The size of the anomalies suggests a tree-level mediators like LQs



Belle II Collaboration

Leptoquarks (LQ)

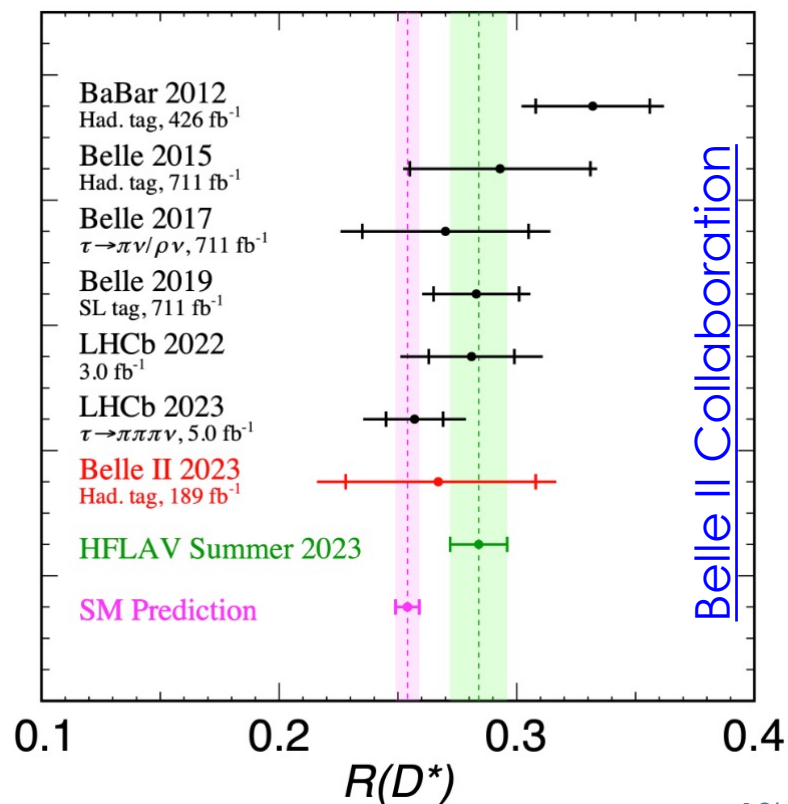
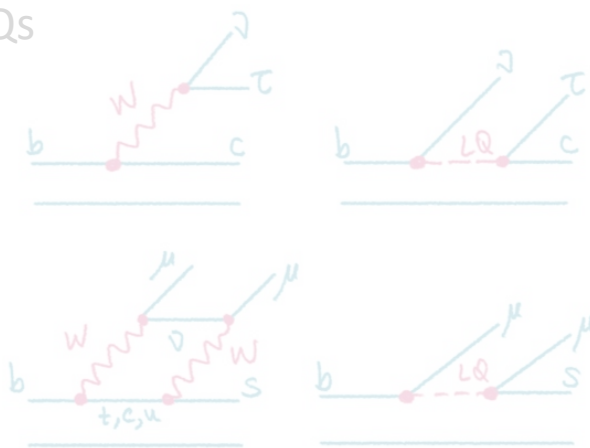
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Belle II Collaboration

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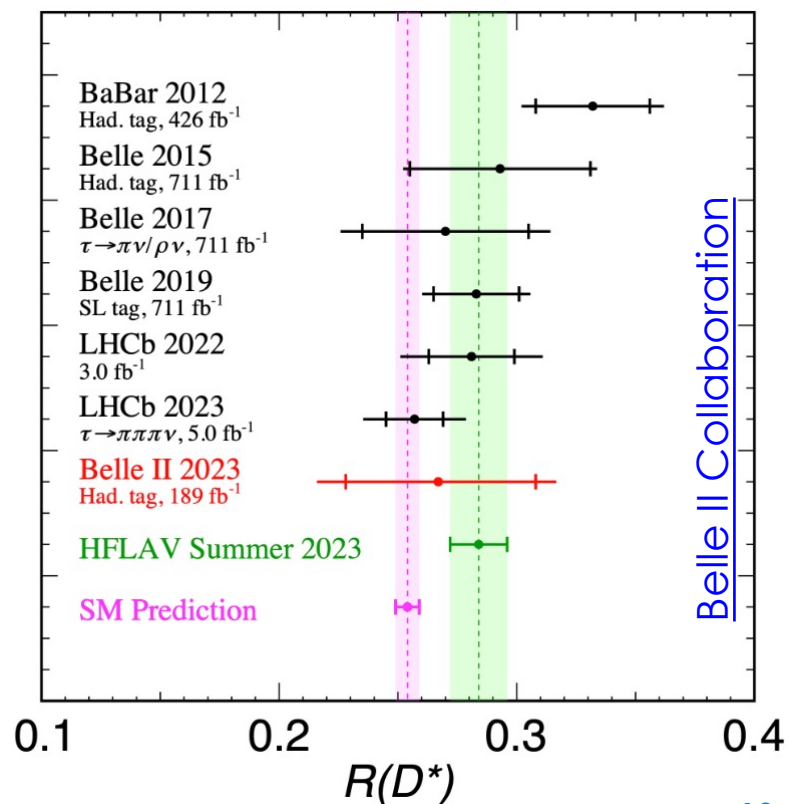
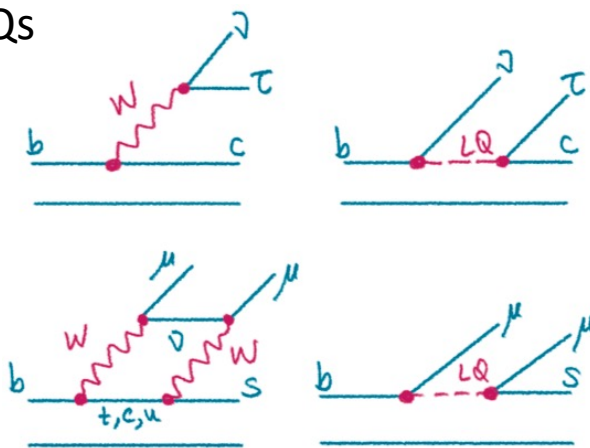
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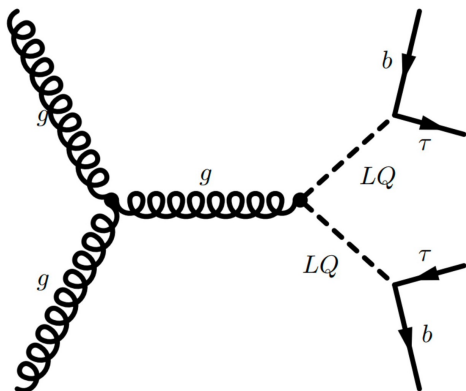


Belle II Collaboration

What do we look for?

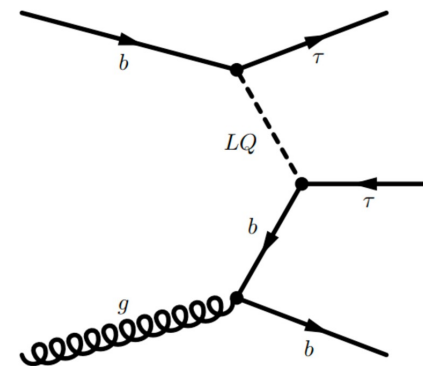
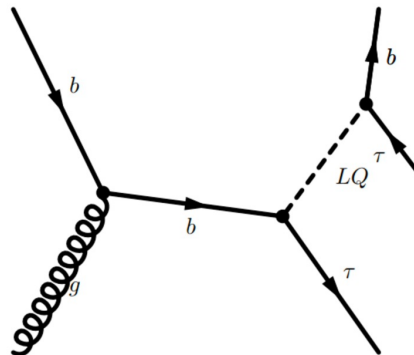
Like VLQs, pair or single production:

Pair Production:



- ~Model independent (via QCD)
- Dominate for lower masses

Single (and non-resonant) Production:



- Depends on coupling
- Can dominate at high masses

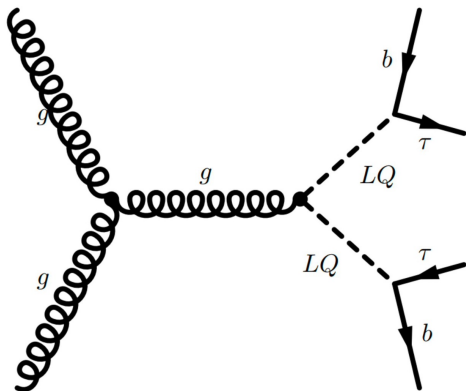
Two general types of LQs

- $LQ_{1,2,3}$: Couple only within given generation
 - Most searches focus on LQ_3 , with final states containing b , t , τ and/or ν
- LQ_{mix} : Allow coupling across generations
 - Lepton Flavor Violation!

What do we look for?

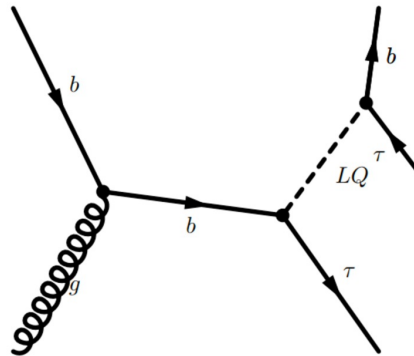
Like VLQs, pair or single production:

Pair Production:

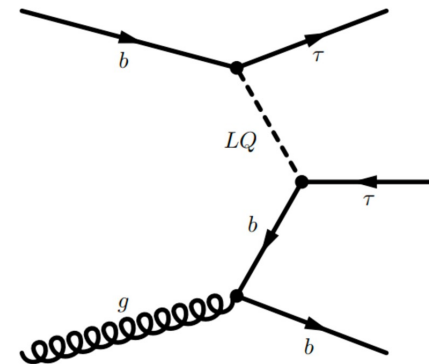


- \sim Model independent (via QCD)
- Dominate for lower masses

Single (and non-resonant) Production:



- Depends on coupling
- Can dominate at high masses

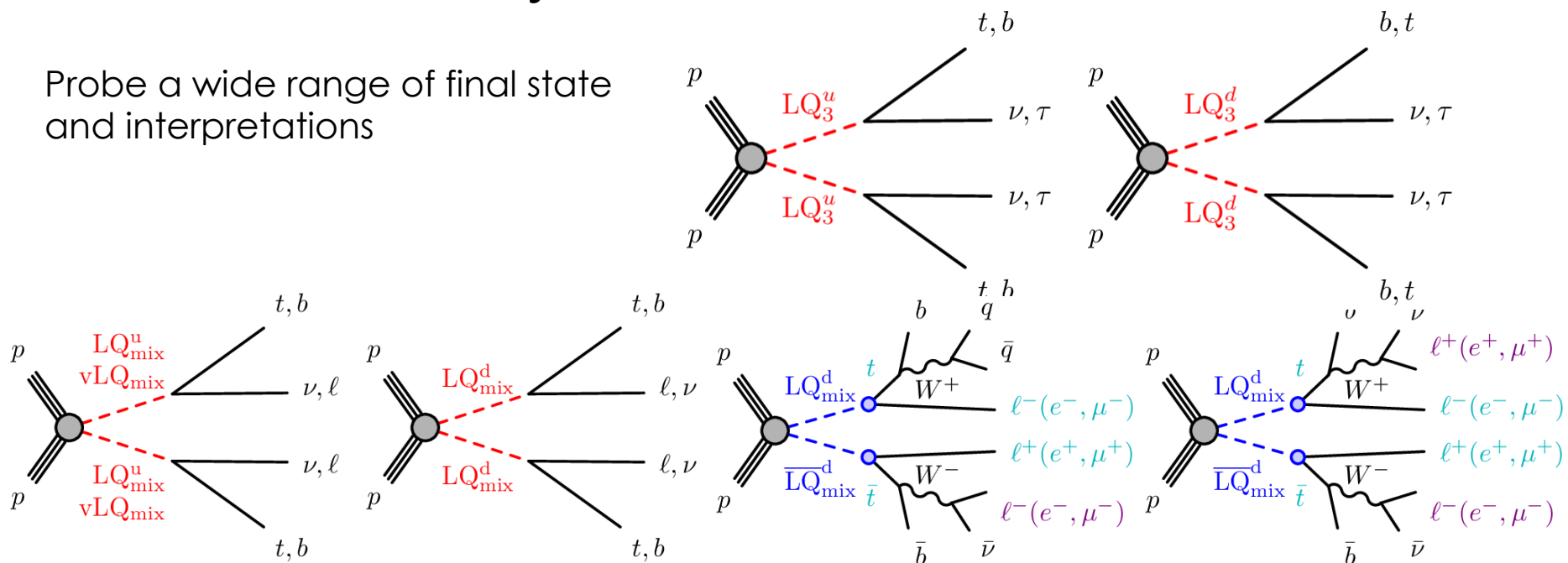


Two general types of LQs

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Many Individual Searches

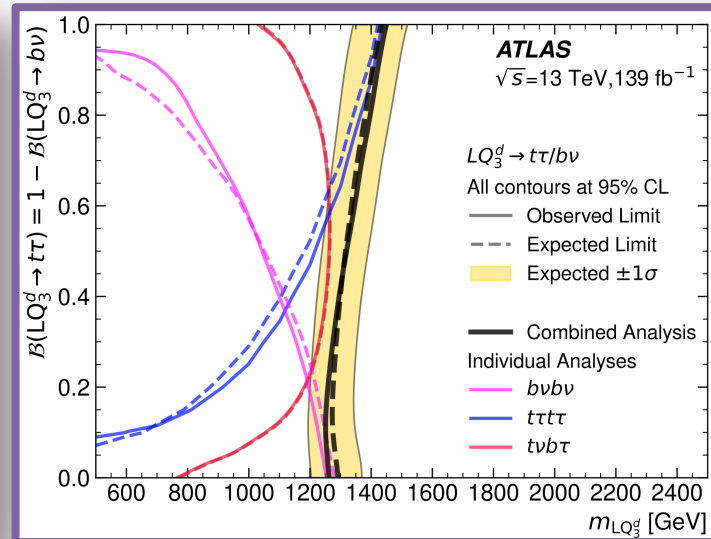
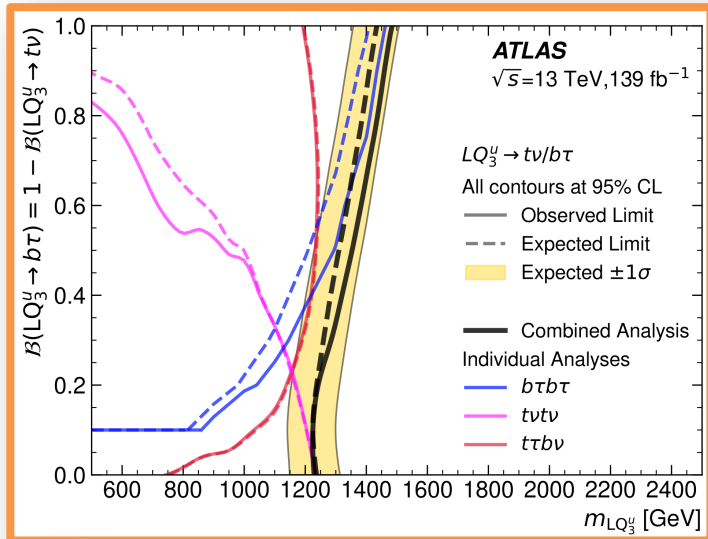
Probe a wide range of final state and interpretations



| Search | | Scalar | | | | Vector | | Signal Region | | |
|----------------------------|----------|----------|----------|--------------|--------------|---------------|-----------------------|---------------|----------------|-------------|
| Final State | Citation | LQ_3^u | LQ_3^d | LQ_{mix}^u | LQ_{mix}^d | $U_1^{YM/MC}$ | $\tilde{U}_1^{YM/MC}$ | N_ℓ | $N_{\tau had}$ | N_{bjets} |
| $t\nu b\tau$ | [54] | ✓ | ✓ | - | - | ✓ | - | 0 | 1 | ≥ 2 |
| $b\tau b\tau$ | [55] | ✓ | - | - | - | ✓ | - | {0, 1} | {1, 2} | {1, 2} |
| $t\tau t\tau$ | [57] | - | ✓ | - | - | - | ✓ | {1, 2, 3} | ≥ 1 | ≥ 1 |
| $t\nu b\ell$ | [40] | - | - | ✓ | ✓ | - | - | 1 | - | ≥ 1 |
| $b\ell b\ell$ | [58] | - | - | ✓ | - | - | - | 2 | - | {0, 1, 2} |
| $t\ell t\ell (2\ell)$ | [59] | - | - | - | ✓ | - | - | 2 | - | - |
| $t\ell t\ell (\geq 3\ell)$ | [61] | - | - | - | ✓ | - | - | {3, 4} | - | ≥ 2 |
| $t\nu t\nu$ | [62] | ✓ | - | ✓ | - | ✓ | - | 0 | 0 | ≥ 2 |
| $b\nu b\nu$ | [64] | - | ✓ | - | ✓ | - | - | 0 | - | ≥ 2 |

New LQ Combination

Perform a statistical combination of searches for pair-produced leptoquarks that decay into a third-generation quark and any charged or neutral lepton

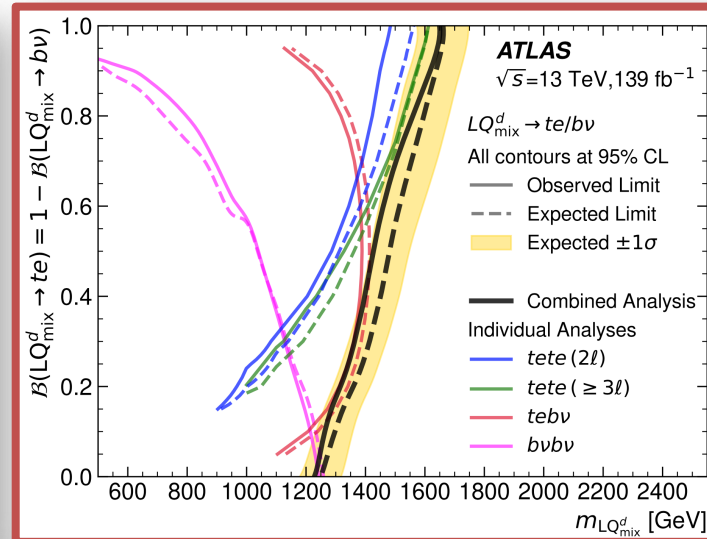
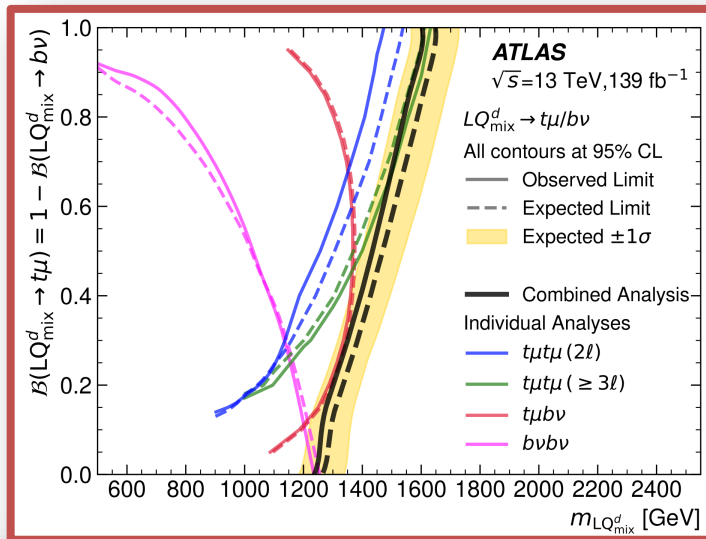


| Search | Final State | Citation | Scalar | | | | Vector | | Signal Region | | N_{bjets} |
|--------|----------------------------|----------|----------|----------|--------------|--------------|---------------|--------------------|---------------|-----------|-------------|
| | | | LQ_3^u | LQ_3^d | LQ_{mix}^u | LQ_{mix}^d | $U_1^{YM/MC}$ | \tilde{U}_1^{YM} | | | |
| | $tvb\tau$ | [54] | ✓ | ✓ | — | — | ✓ | | | ≥ 2 | |
| | $b\tau b\tau$ | [55] | ✓ | — | — | — | ✓ | | | {1, 2} | |
| | $t\tau t\tau$ | [57] | — | ✓ | — | — | — | | | ≥ 1 | |
| | $tvbl$ | [40] | — | — | ✓ | ✓ | — | | | ≥ 1 | |
| | $blbl$ | [58] | — | — | ✓ | — | — | | | {0, 1, 2} | |
| | $t\ell t\ell (2\ell)$ | [59] | — | — | — | ✓ | — | | | — | |
| | $t\ell t\ell (\geq 3\ell)$ | [61] | — | — | — | ✓ | — | | {3, 4} | ≥ 2 | |
| | $tv tv$ | [62] | ✓ | — | ✓ | — | ✓ | | 0 | ≥ 2 | |
| | $b\nu b\nu$ | [64] | — | ✓ | — | ✓ | — | | 0 | ≥ 2 | |

⇒ Best limits to date for any combination of parameters!

New LQ Combination

Perform a statistical combination of searches for pair-produced leptoquarks that decay into a third-generation quark and any charged or neutral lepton



| Search | | Scalar | | | | Vector | | Signal Region | | |
|--------------------|----------|------------------------------|------------------------------|--------------------------------|--------------------------------|---------------------------------|-------------------------------|---------------|--------------------|-----|
| Final State | Citation | LQ ₃ ^u | LQ ₃ ^d | LQ _{mix} ^u | LQ _{mix} ^d | U ₁ ^{YM/MC} | Ũ ₁ ^{YM} | | N _{bjets} | |
| <i>tνbτ</i> | [54] | ✓ | ✓ | – | – | ✓ | – | | ≥ 2 | |
| <i>bτbτ</i> | [55] | ✓ | – | – | – | ✓ | – | | {1, 2} | |
| <i>tτtτ</i> | [57] | – | ✓ | – | – | – | – | | ≥ 1 | |
| <i>tνbl</i> | [40] | – | – | ✓ | ✓ | – | – | | ≥ 1 | |
| <i>blbl</i> | [58] | – | – | ✓ | – | – | – | | {0, 1, 2} | |
| <i>tlll (2l)</i> | [59] | – | – | – | ✓ | – | – | | – | |
| <i>tlll (≥ 3l)</i> | [61] | – | – | – | ✓ | – | – | {3, 4} | ≥ 2 | |
| <i>tvtv</i> | [62] | ✓ | – | ✓ | – | ✓ | – | 0 | 0 | ≥ 2 |
| <i>bνbν</i> | [64] | – | ✓ | – | ✓ | – | – | 0 | – | ≥ 2 |

⇒ Best limits to date for any combination of parameters!

New Gauge Bosons

| Gauge bosons | SSM $Z' \rightarrow \ell\ell$ | Z' mass | 5.1 TeV | |
|-----------------------------------|--|-------------------------------|----------|----------|
| | SSM $Z' \rightarrow \tau\tau$ | Z' mass | 2.42 TeV | |
| | Leptophobic $Z' \rightarrow bb$ | Z' mass | 2.1 TeV | |
| | Leptophobic $Z' \rightarrow tt$ | Z' mass | 4.1 TeV | |
| | SSM $W' \rightarrow \ell\nu$ | W' mass | 6.0 TeV | |
| | SSM $W' \rightarrow \nu\nu$ | W' mass | 3.7 TeV | |
| | HVT $W' \rightarrow WZ \rightarrow \ell\nu qq$ model B | W' mass | 4.3 TeV | |
| | HVT $V' \rightarrow WV \rightarrow qq qq$ model B | V' mass | 3.8 TeV | |
| | HVT $V' \rightarrow WH/ZH$ model B | V' mass | 2.93 TeV | |
| | HVT $W' \rightarrow WH$ model B | W' mass | 3.2 TeV | |
| | LRSM $W_R \rightarrow tb$ | W_R mass | 3.25 TeV | |
| | LRSM $W_R \rightarrow \mu N_R$ | W_R mass | 5.0 TeV | |
| | LQ | Scalar LQ 1 st gen | LQ mass | 1.4 TeV |
| | | Scalar LQ 2 nd gen | LQ mass | 1.56 TeV |
| Scalar LQ 3 rd gen | | LQ ₃ mass | 1.03 TeV | |
| Scalar LQ 3 rd gen | | LQ ₃ mass | 970 GeV | |
| VLQ $TT \rightarrow Ht/Zt/Wb + X$ | | T mass | 1.37 TeV | |
| Heavy quarks | VLQ $BB \rightarrow Wt/Zb + X$ | B mass | 1.34 TeV | |
| | VLQ $T_{5/3} T_{5/3} T_{5/3} \rightarrow Wt + X$ | T _{5/3} mass | 1.64 TeV | |
| | VLQ $Y \rightarrow Wb + X$ | Y mass | 1.85 TeV | |
| | VLQ $B \rightarrow Hb + X$ | B mass | 1.21 TeV | |
| | VLQ $QQ \rightarrow WqWq$ | Q mass | 690 GeV | |

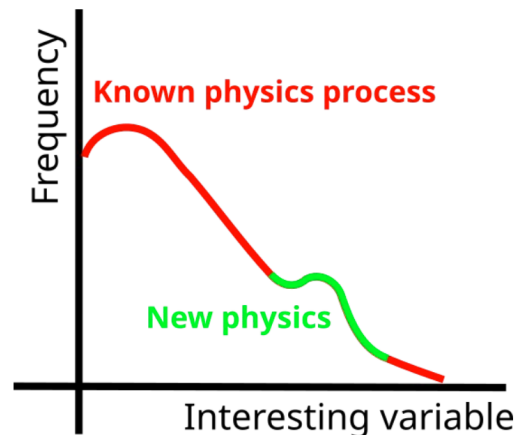
New vector bosons

Large category of models that predict new W'/Z' bosons with different properties. Sometimes they appear as DM mediators and sometimes they couple strongly to specific generations (3rd for example), among many other possibilities

Both collaborations have looked for W' and Z' in **many different final states** and are exploring new ones with some regularity

Typical benchmark models for general searches
Sequential Standard Model (SSM) or Heavy Vector Triplet (HVT)

Often searches in the invariant mass of the expected decay (dijet, tt , bb , tb , e^+e^- , etc...). Very good coverage at high mass, Low mass still has uncovered phase-space !



New Gauge Bosons

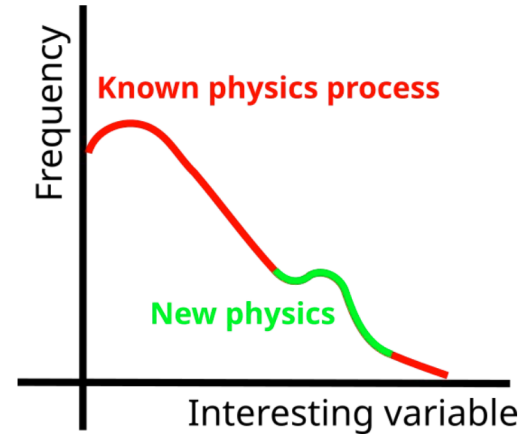
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17

| Gauge bosons | Model | Mass (TeV) |
|--------------|--|------------|
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| | SSM $Z' \rightarrow \tau\tau$ | 2.42 TeV |
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| | $W_R \rightarrow \mu N_R$ | 5.0 TeV |

University of Illinois

New Gauge Bosons

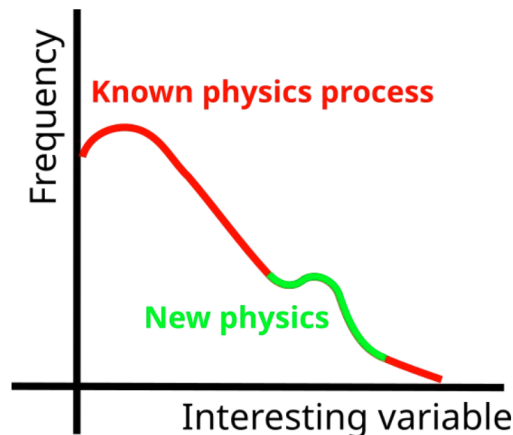
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Gauge bosons

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LRSM $W_R \rightarrow tb$
LRSM $W_R \rightarrow \mu N_R$

| | |
|------------|----------|
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| W' mass | 3.2 TeV |
| W_R mass | 3.25 TeV |
| W_R mass | 5.0 TeV |

⇒ Brand new search for low mass resonance

Low Mass Resonance Search

Search for $Z' \rightarrow jj$ resonance with mass from 200 GeV to 650 GeV

- Consider two types of ISR (photon or jet) and two Z' decays (jj or bb)
 - Four selections: γjj , γbb , jjj , jbb
 - Search for bump in dijet mass distribution m_{jj}
 - jbb : use the two b -jets
 - jjj : use pair with smallest $\Delta\phi$ and not two highest p_T
 - Clear peaks for $Z' \rightarrow qq$ events
 - Smoothly falling distribution for **background**

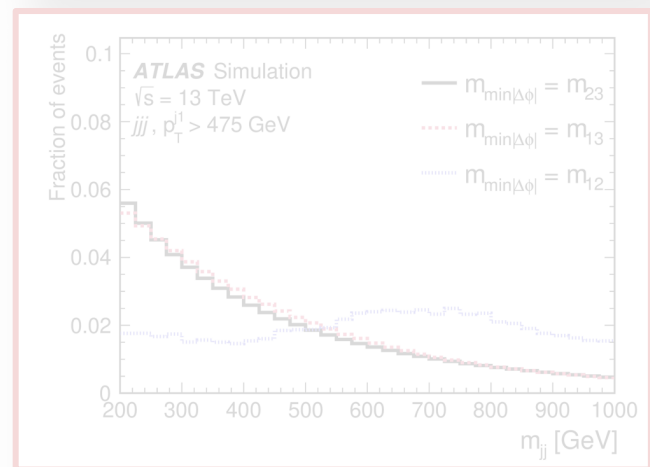
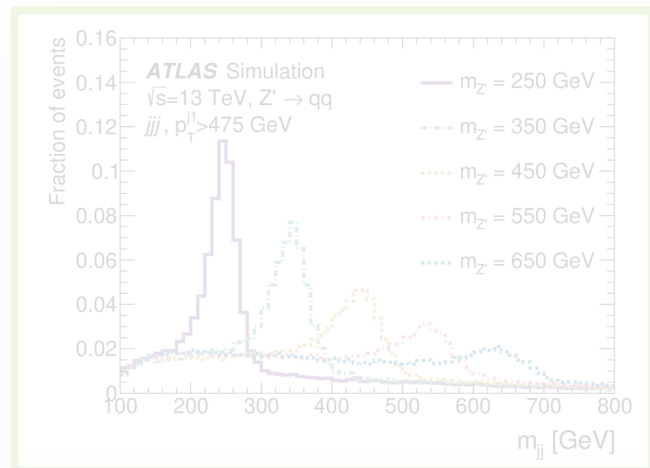
Dominant backgrounds from multijet and γ +jet

- Smoothly-falling m_{jj} distribution
- Estimate by function form fit to data

$$f_B(x) = p_1(1-x)^{p_2} x^{p_3+p_4} \ln(x) + p_5 \ln^2(x) + p_6 \ln^3(x)$$

with $x = m_{jj}/\sqrt{s}$.

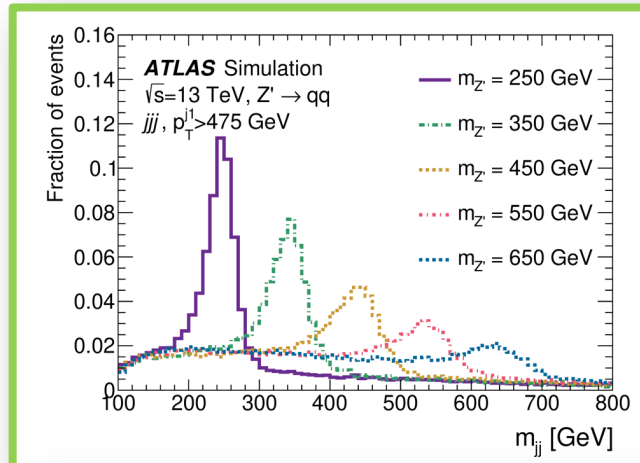
- Validated with signal injection and spurious signal tests with simulation and partial data



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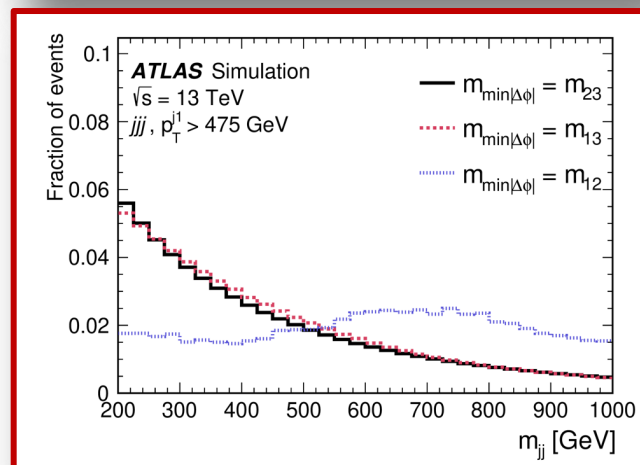
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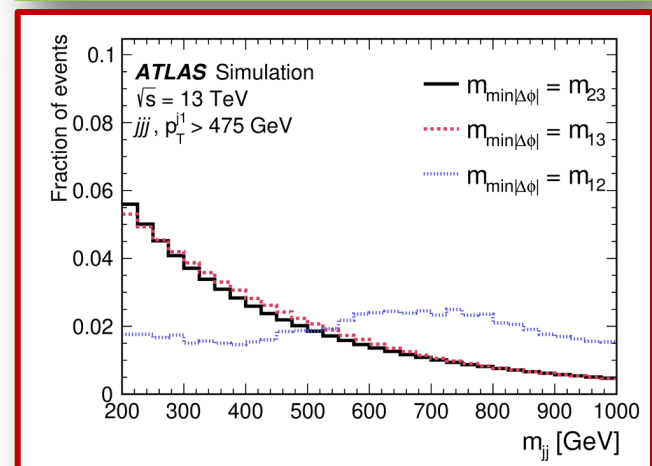
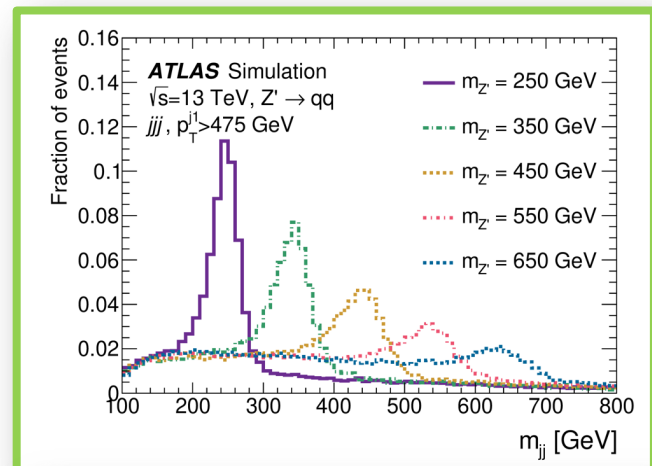
Dominate backgrounds from multijet and γ +jet

- Smoothly-falling m_{jj} distribution
- Estimate by function form fit to data

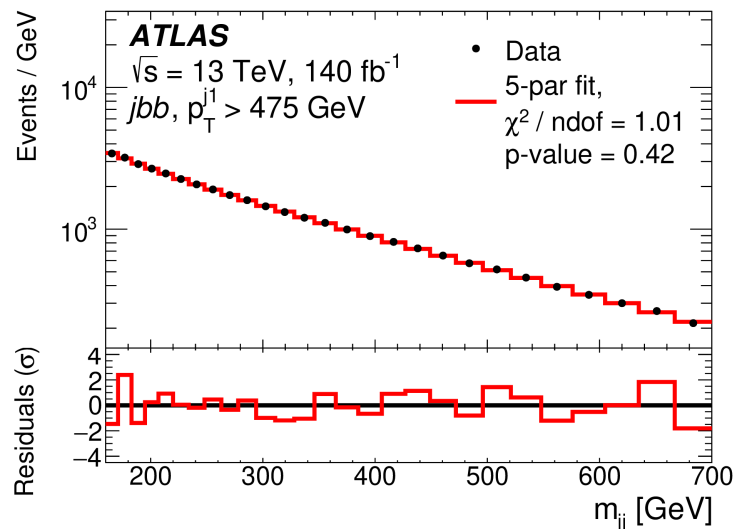
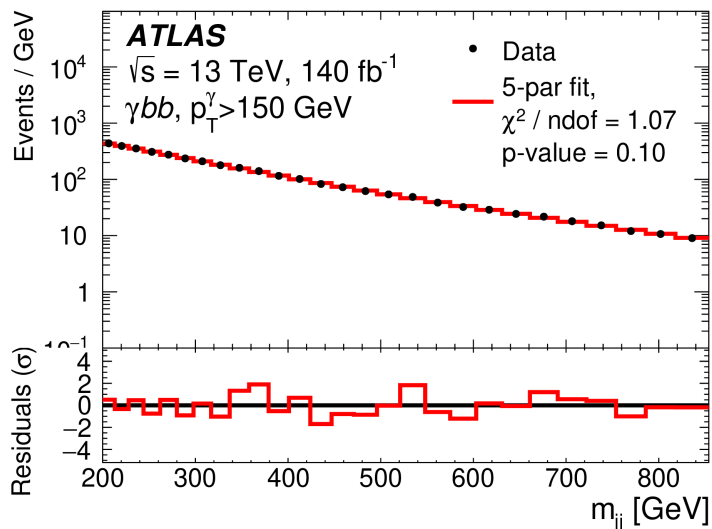
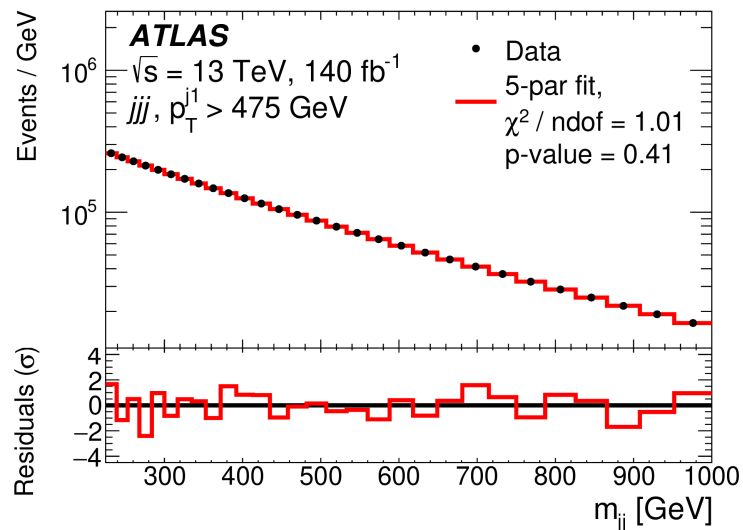
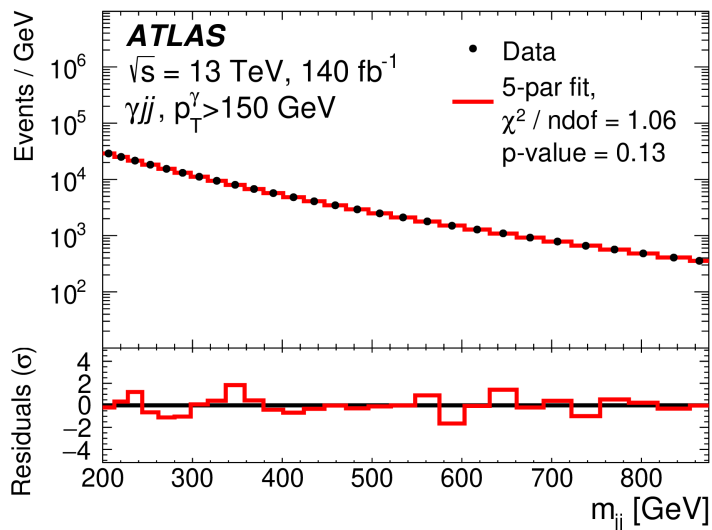
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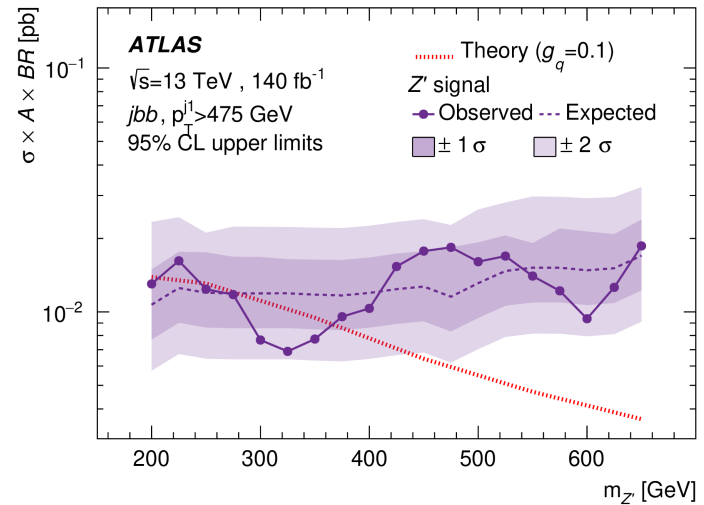
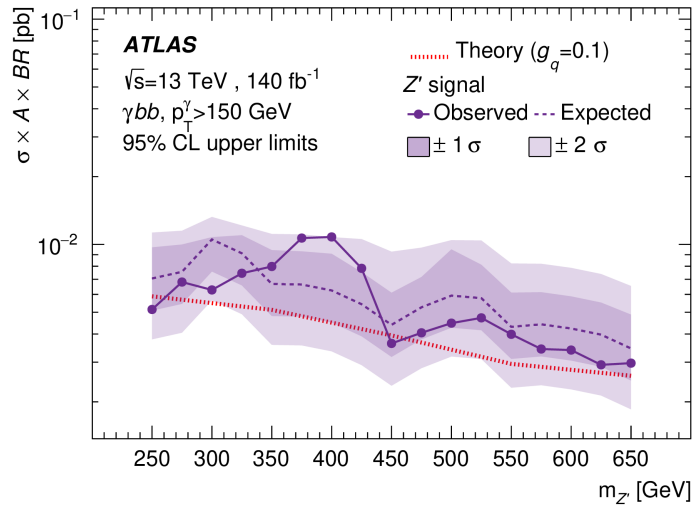
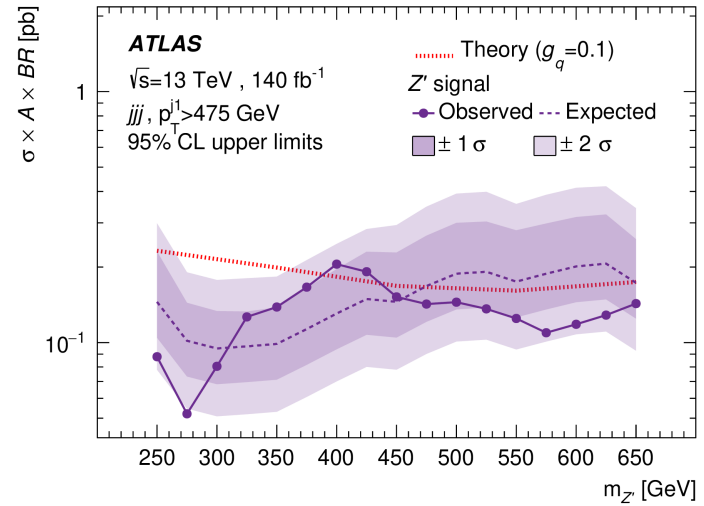
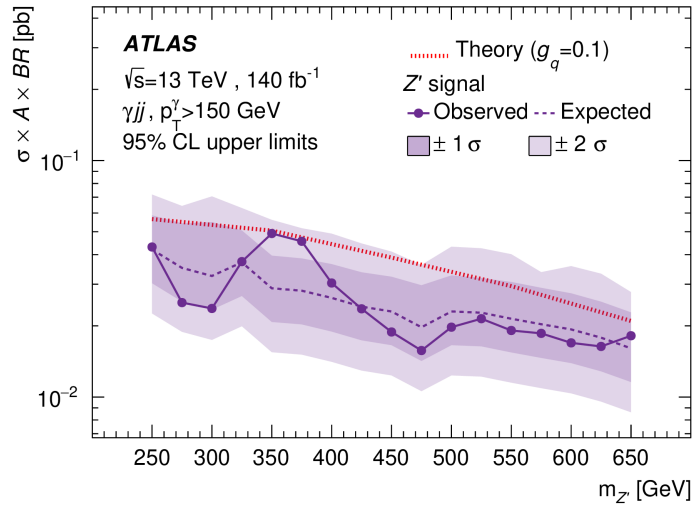
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Low Mass Resonance Search



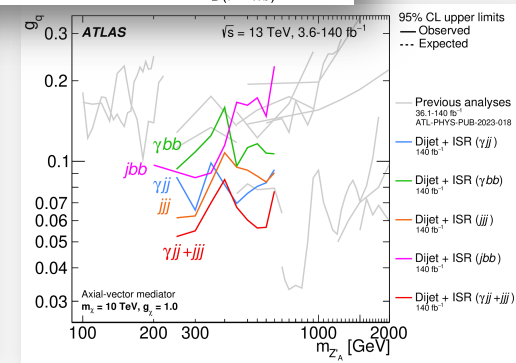
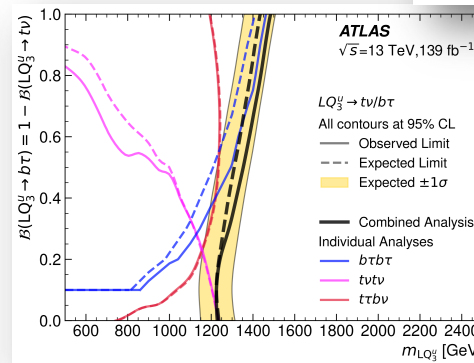
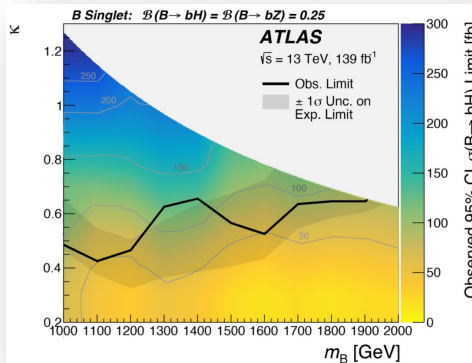
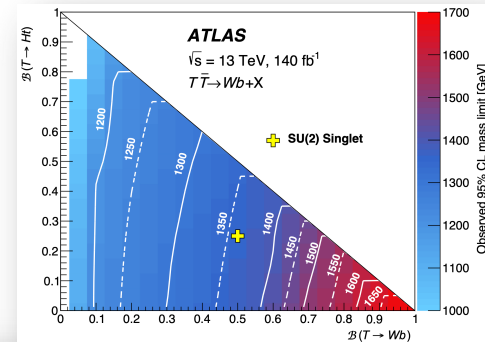
Low Mass Resonance Search



Conclusion

Many recent results from searches for VLQs, LQ, and gauge bosons

- Significant gains in sensitivity
 - Full Run 2 data set
 - Improved analysis techniques e.g. b -, W -, Higgs-, and top-tagging
 - Improved background modeling
- Most results are best limits to date



- Unfortunately, still no direct signs of VLQs, LQs, or new gauge bosons

Run 3 currently underway, bring much more data, plus many entirely new searches!

Thank you!

And special thank you to:



DOE for supporting this research



The ATLAS Collaboration

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



The BEACH 2024 Organizers!

List of presented analyses

- Search for pair-production of vector-like quarks in lepton+jets final states containing at least one b-tagged jet using the Run 2 data from the ATLAS experiment ([Phys. Lett. B 854 \(2024\) 138743](#))
- Search for single vector-like B -quark production and decay via $B \rightarrow bH(bb)$ in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector ([JHEP11 \(2023\) 168](#))
- Search for pair-produced vector-like quarks coupling to light quarks in the lepton plus jets final state using 13 TeV pp collisions with the ATLAS detector (Submitted to Phys. Rev. D June 2024)
- Combination of searches for pair-produced leptoquarks at $\sqrt{s} = 13$ TeV with the ATLAS detector ([Submitted to Phys. Lett. B March 2024](#))
- Search for low-mass resonances decaying into two jets and produced in association with a photon or a jet at $\sqrt{s} = 13$ TeV with the ATLAS detector ([Submitted to Phys. Rev. D January 2024](#))

ATLAS Detector

The LHC is a “top factory” (~ 1 tt /second)

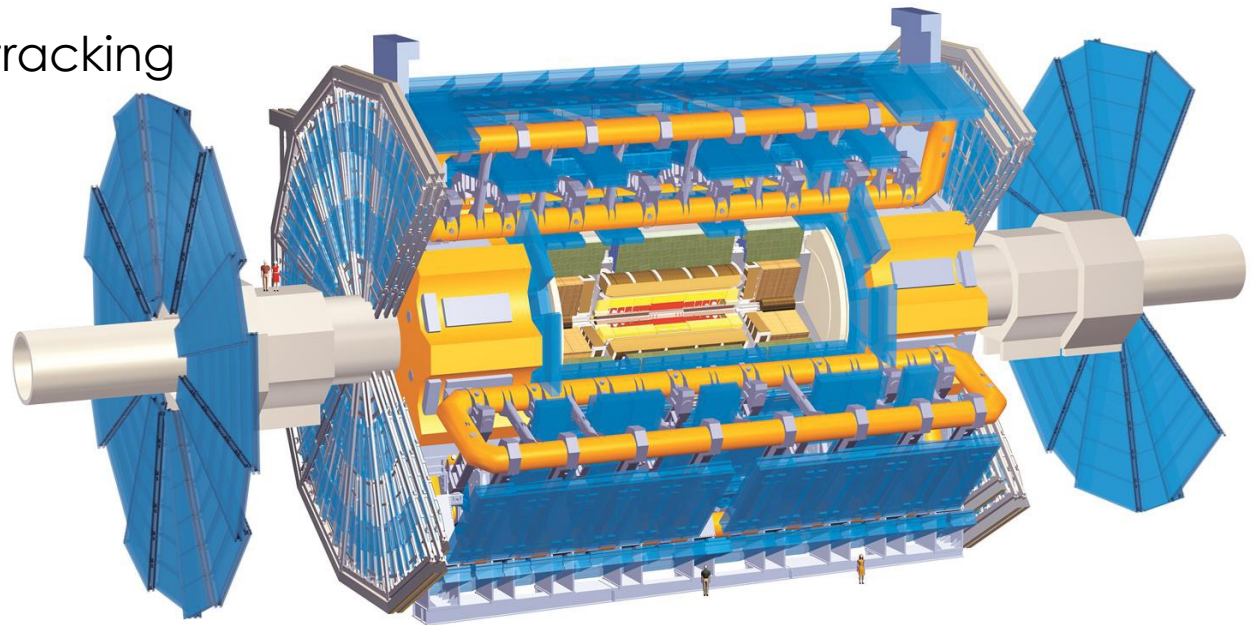
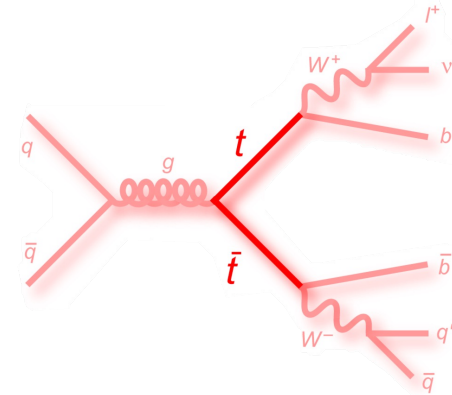
ATLAS is a “top detector”

Efficient e/μ identification

Nearly 4π coverage $\Rightarrow E_T^{\text{miss}}$

High granularity tracking

$\Rightarrow b$ -tagging



All results using the ATLAS Run 2 data set ($L = 139 \text{ fb}^{-1}$, $\sqrt{s} = 13 \text{ TeV}$)