UNIVERSITÉ DE GENÈVE

Search for vector-like quarks in ATLAS

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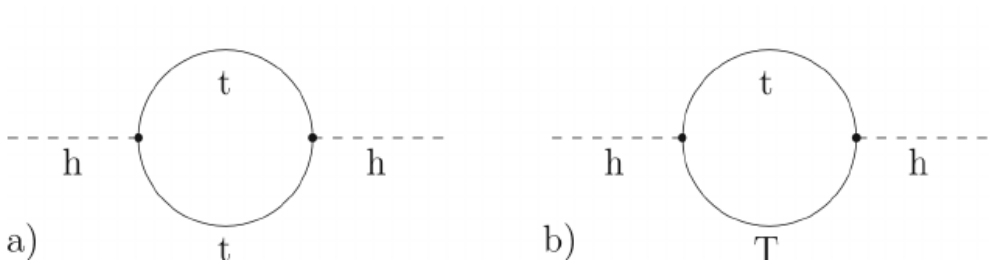
On behalf of the ATLAS Collaboration

30th Rencontres de Blois, June 3-8 2018

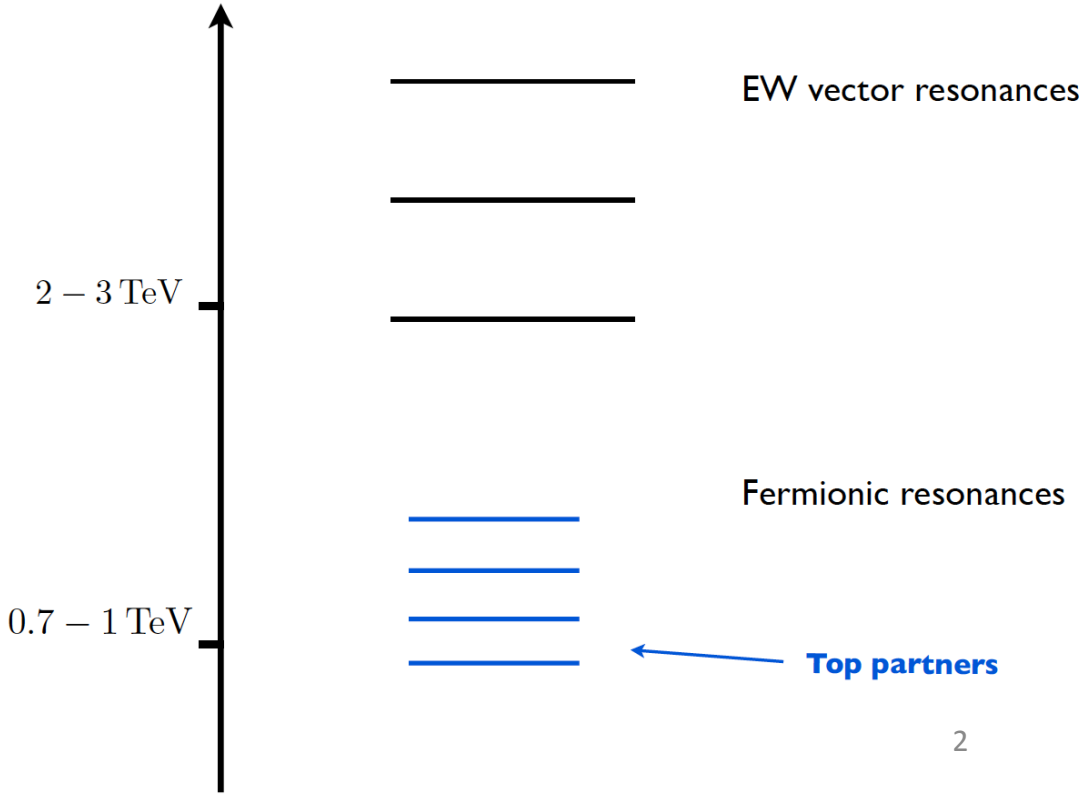
Motivation

- Natural solution to hierarchy problem



- ED, Little/composite Higgs models

- Top/bottom partners typically “light”



VLQs: Top/Bottom Partners

- Considering four different kinds of Vector-Like Quarks (VLQs) with different charge
  - T (+2/3)
  - B (-1/3)
  - X (+5/3) – aka $T_{5/3}$
  - Y (-4/3)

JHEP 11, 030 (2009) *(triplets not included)*

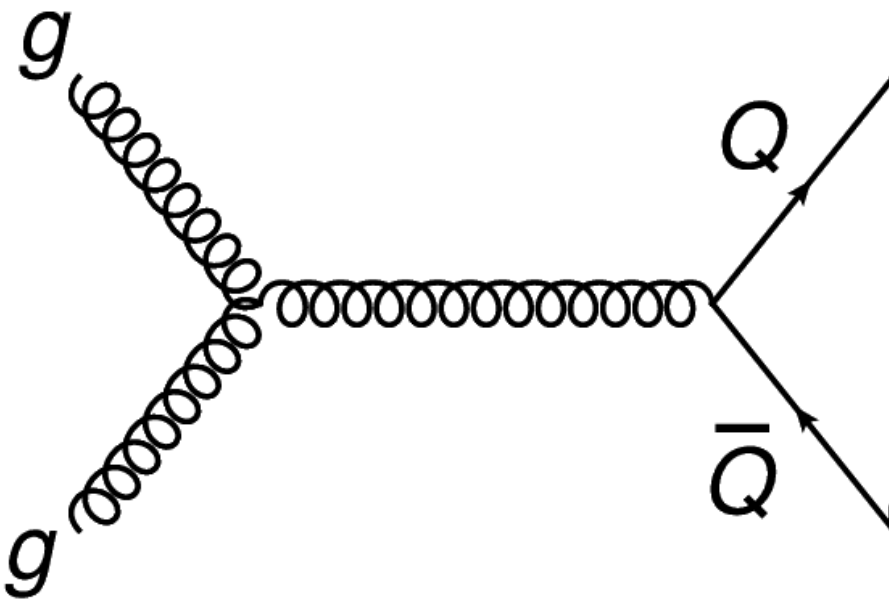
	Label	Charge	Decay mode
T singlet	T_S	+2/3	$T \to W^+b$, Zt, ht
B singlet	B_S	-1/3	$B \to W^-t$, Zb, hb
(T,B) doublet	TB_d	(+2/3, -1/3)	$T \to W^+b$, Zt, ht $B \to W^-t$, Zb, hb
(X,T) doublet	XT_d	(+5/3, +2/3)	$X \to W^+t$ $T \to Zt$, ht
(B,Y) doublet	BY_d	(-1/3, -4/3)	$B \to Zb$, hb $Y \to W^-b$

- Come in EW singlets, doublets, triplets

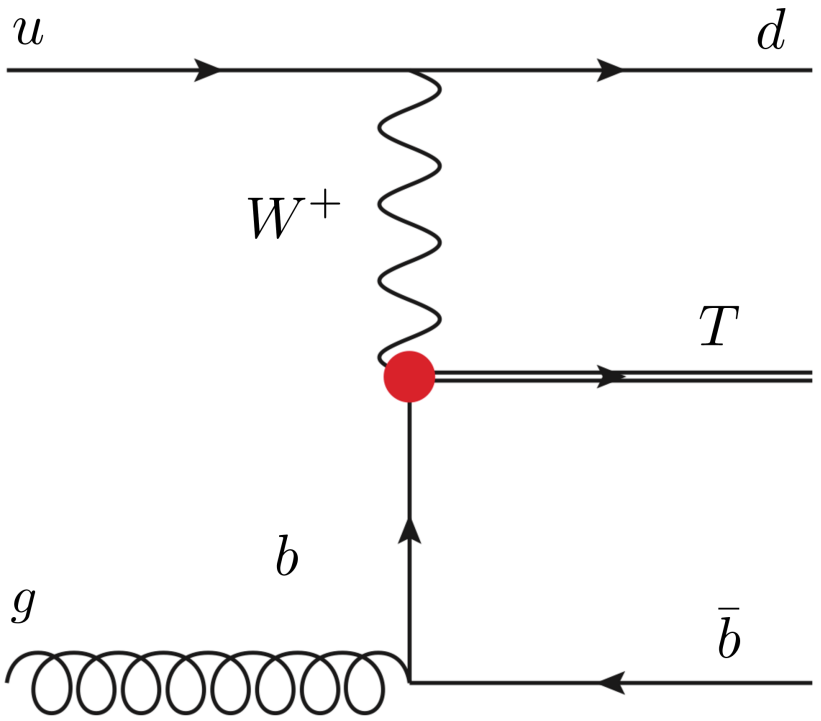
(VLQ: LH and RH components have the same properties under $SU(2)_L \times U(1)_Y$ transformation / weak-isospin gauge group)

VLQ Production Modes at the LHC

- **Strongly produced in pairs**: large $Q\bar{Q}$ cross-section only dependent on mass (just like $t\bar{t}$)

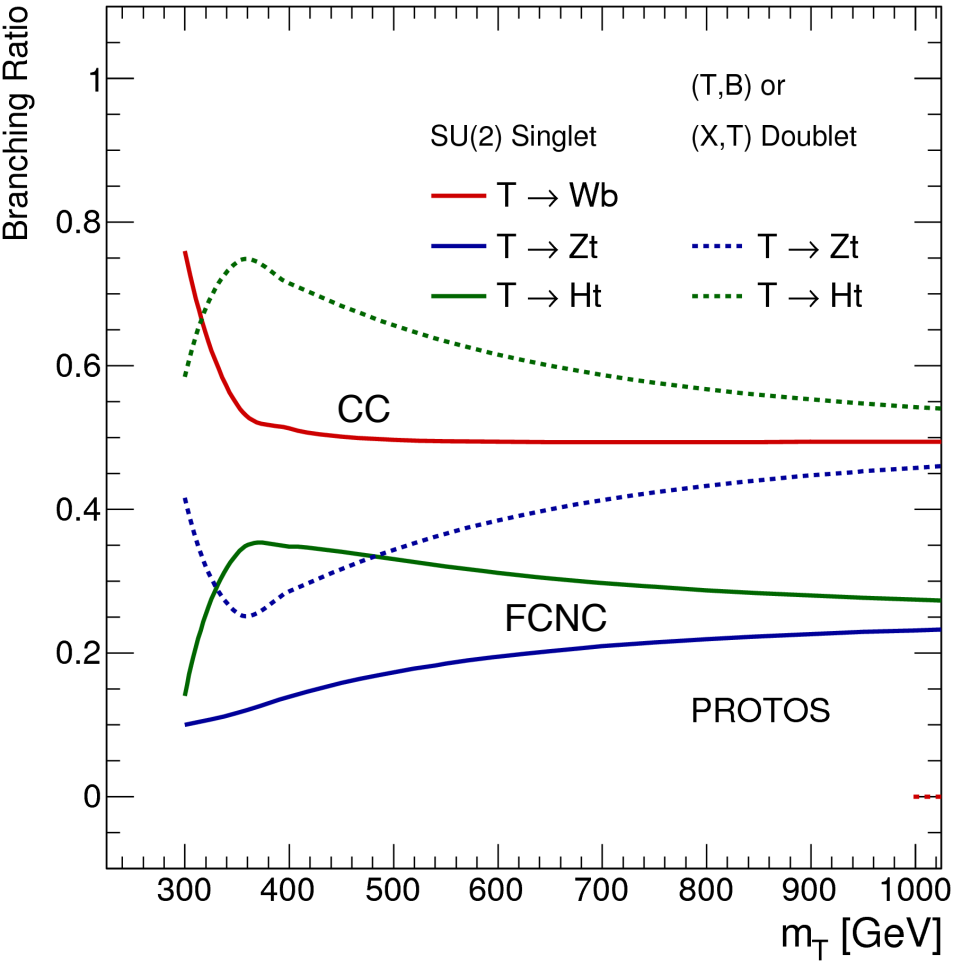


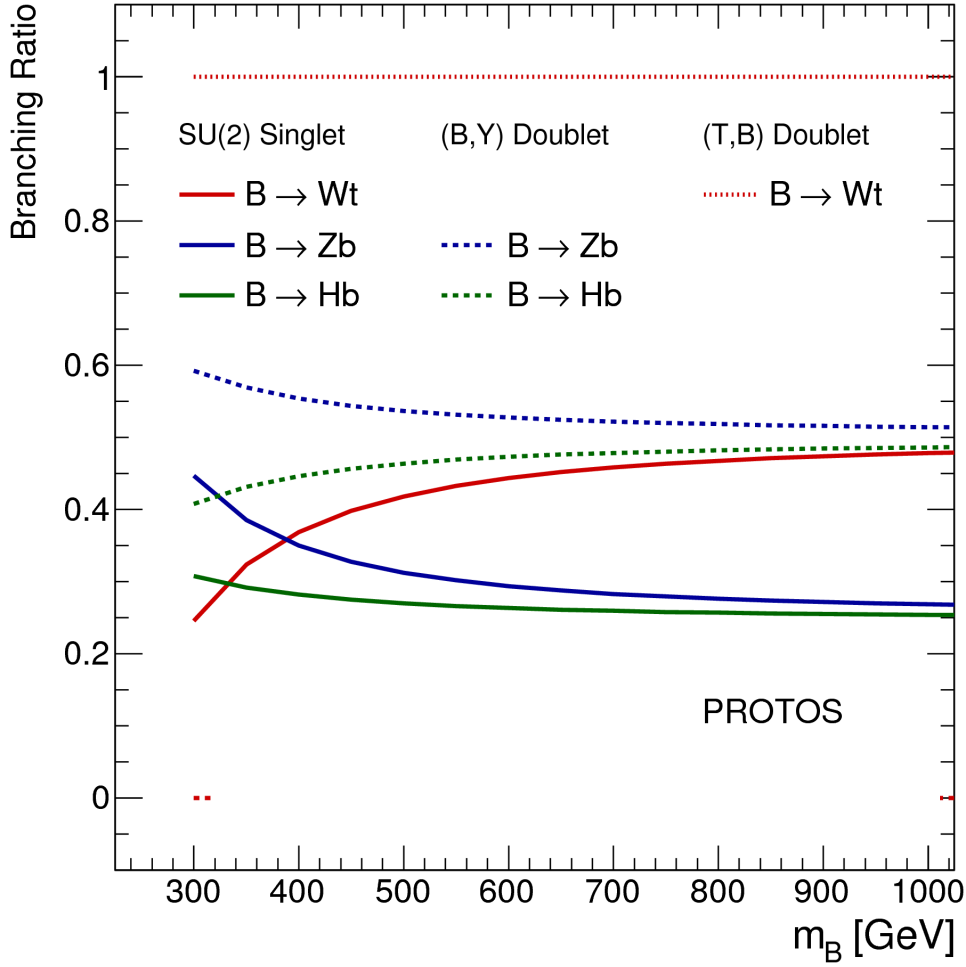
- **Single production** dependent on mass, charge, coupling (like single top)



VLQ Decay Modes

For (T,B) doublet assume $V_{Tb} << V_{tB}$

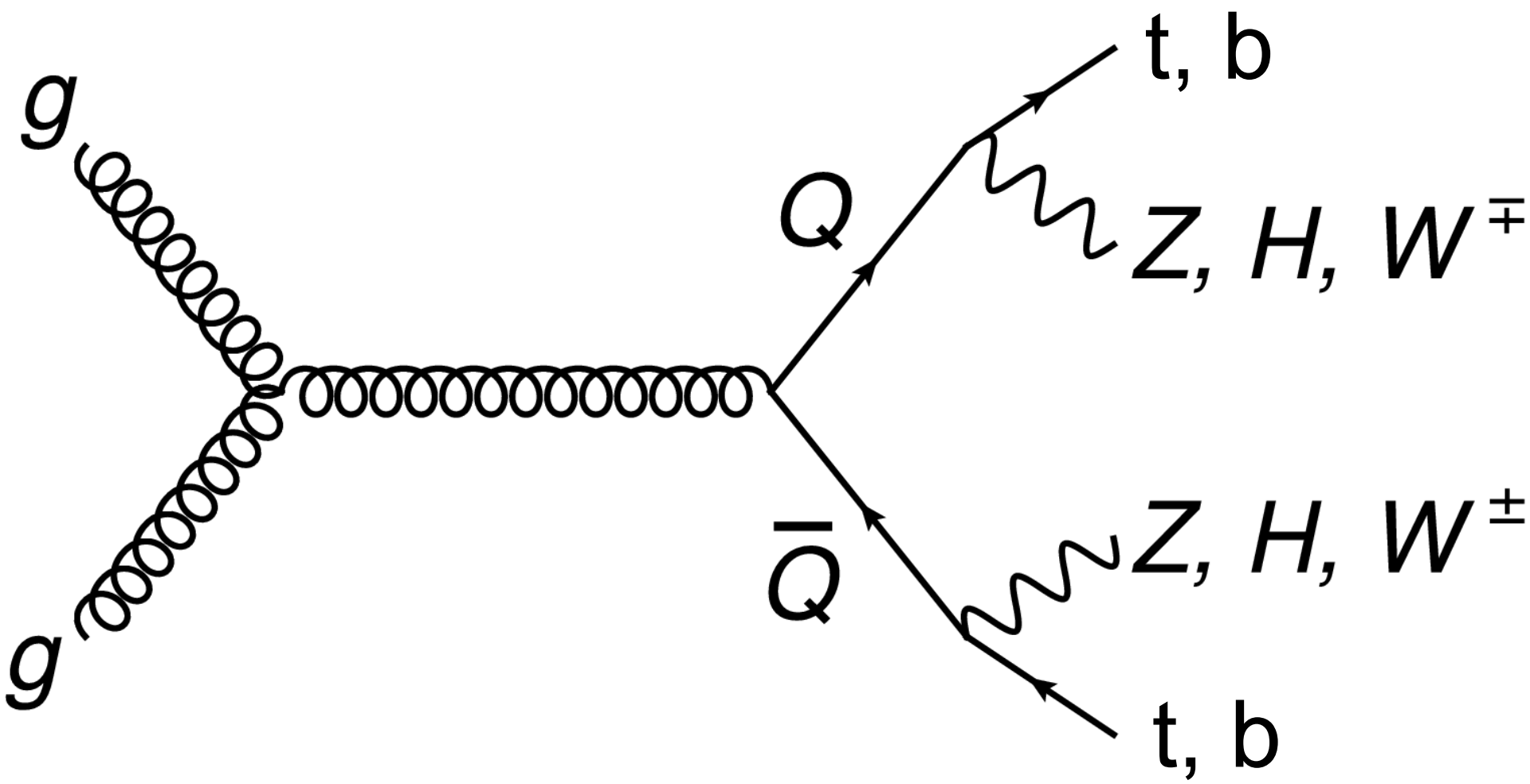




Difference in chirality of singlet and doublet couplings and interference with SM processes are negligible in the presented analyses

VLQ Pair Signature

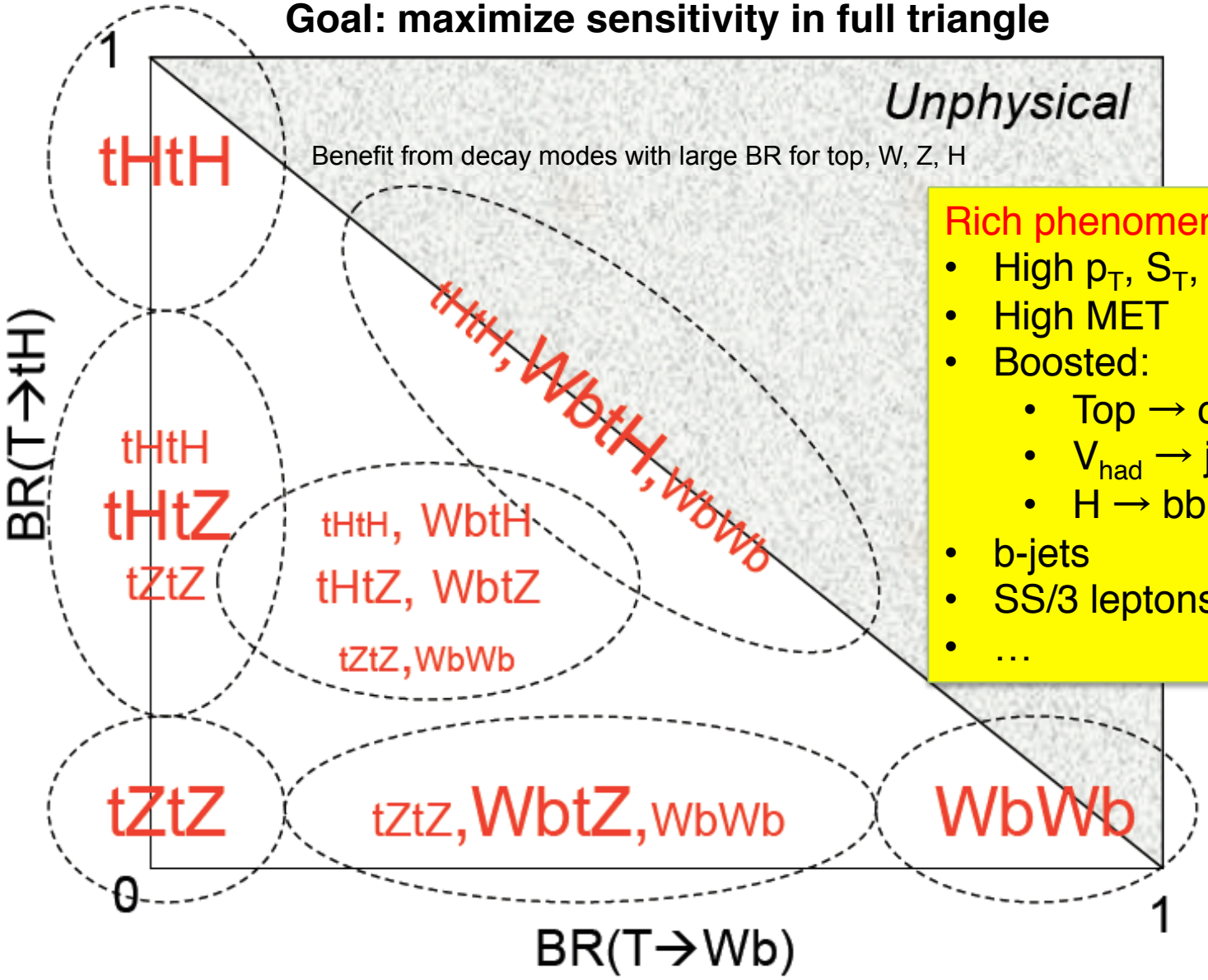
Spectacular signatures: boosted b-jets, tops, W, Z, H bosons



(decay to 3rd generation quarks favored)

VLQ Pair Production: $T\bar{T}$

Goal: maximize sensitivity in full triangle

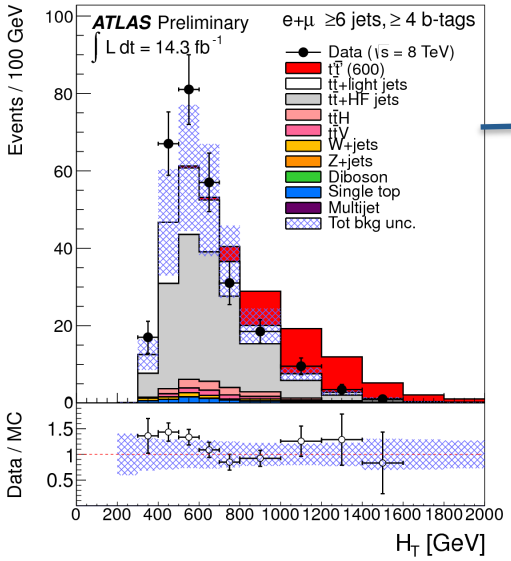


Rich phenomenology:

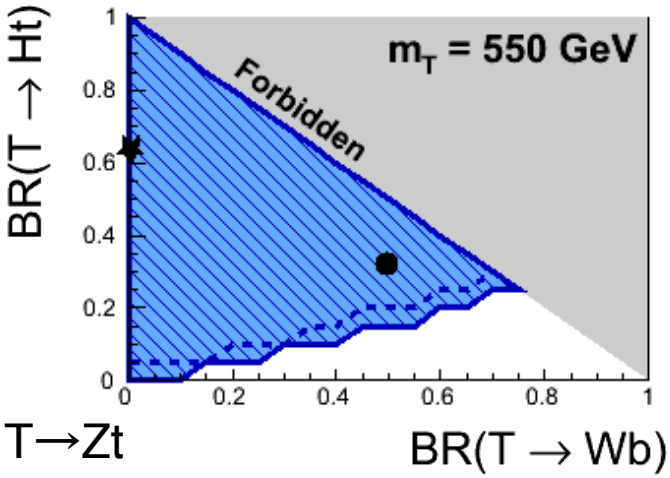
- High p_T, S_T, H_T, m_{eff}
- High MET
- Boosted:
  - Top → qqb
  - V_{had} → jj / J
  - H → bb
- b-jets
- SS/3 leptons
- …

$BR(T \rightarrow Wb) + BR(T \rightarrow Ht) + BR(T \rightarrow Zt) = 1$

VLQ Strategy Established in Run I

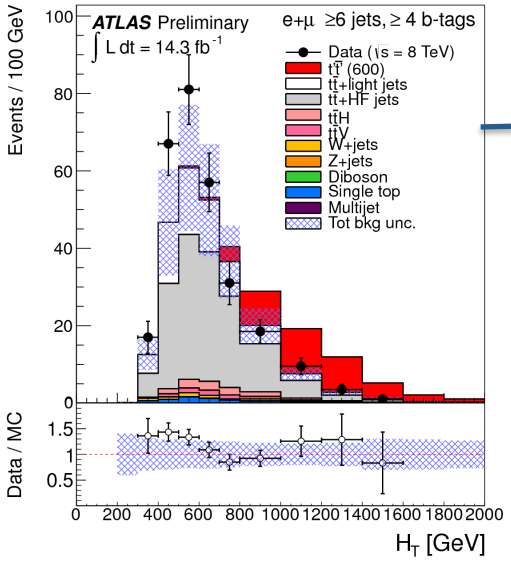


Ht+X (l+jets)



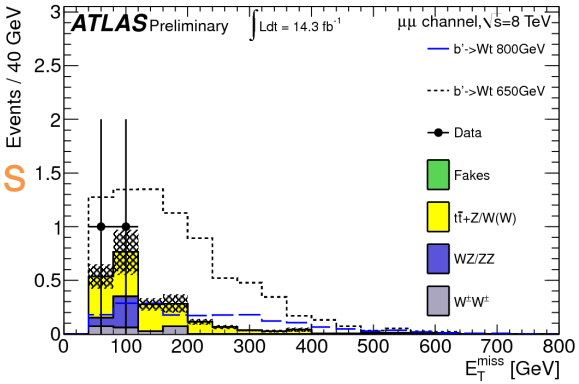
- Exclusive vs. inclusive, compromise: 1 VLQ exclusive (e.g. T→Ht), the other inclusive (T→X)
- Highlight doublet ★ and singlet ●

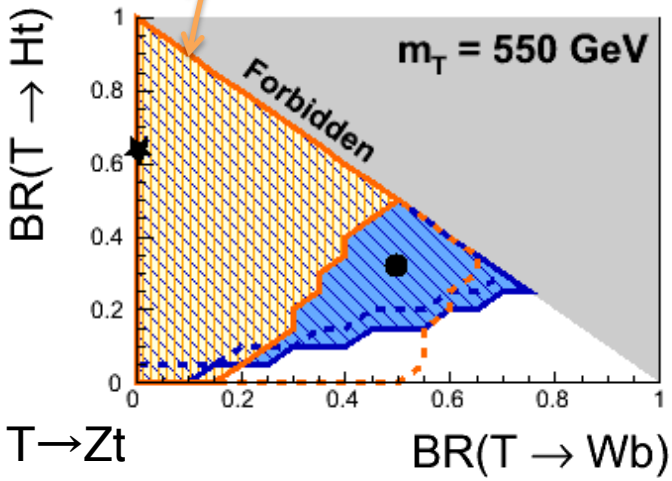
VLQ Strategy Established in Run I



Ht+X (l+jets)

Same-sign leptons

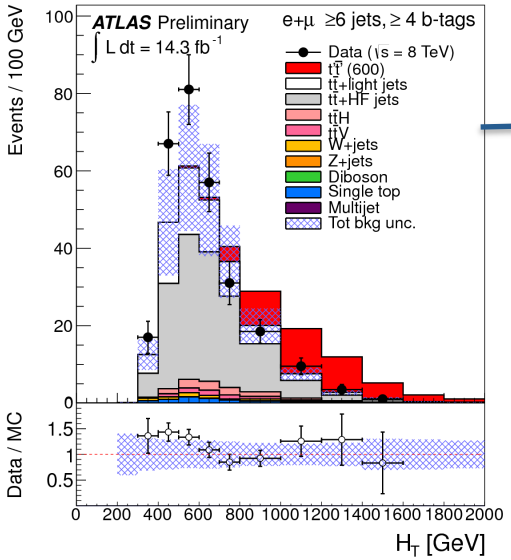




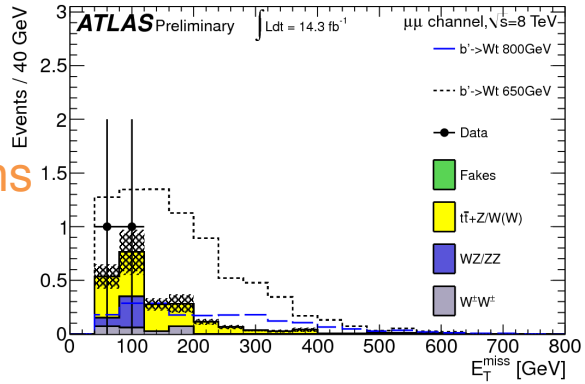
(not a combination, just overlaying results)

VLQ Strategy Established in Run I

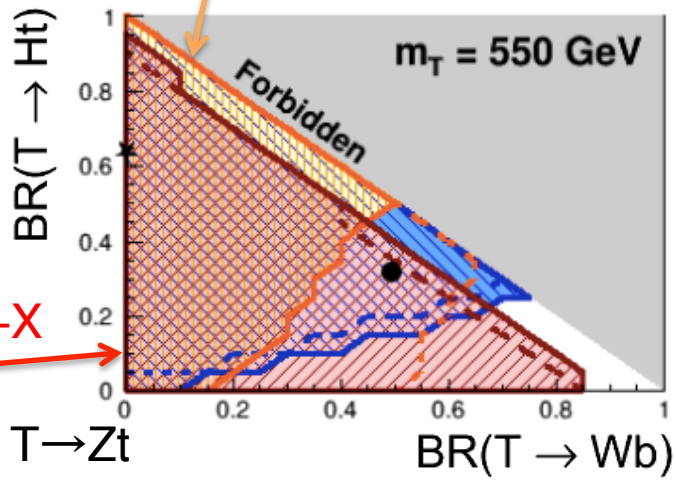
Ht+X (l+jets)

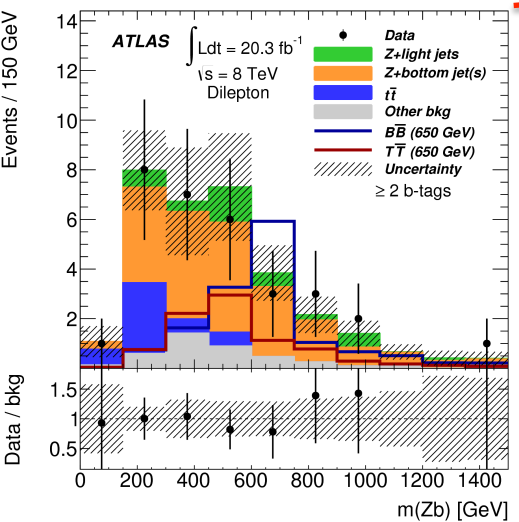


Same-sign leptons



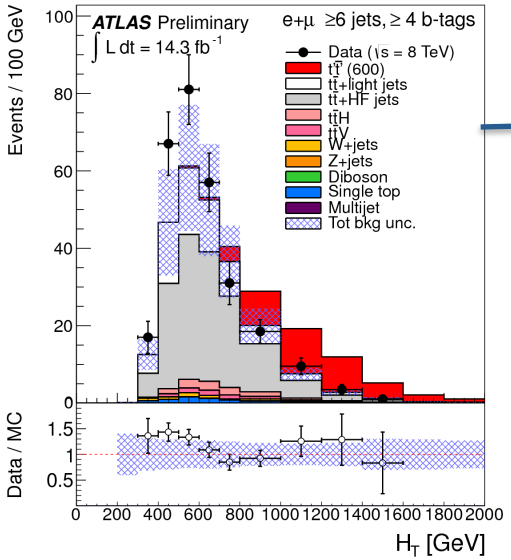
Z(→ll)t+X



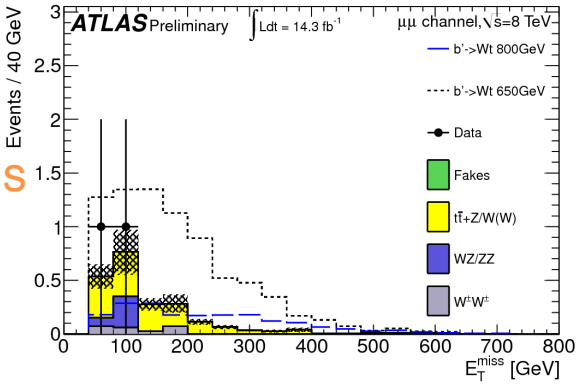


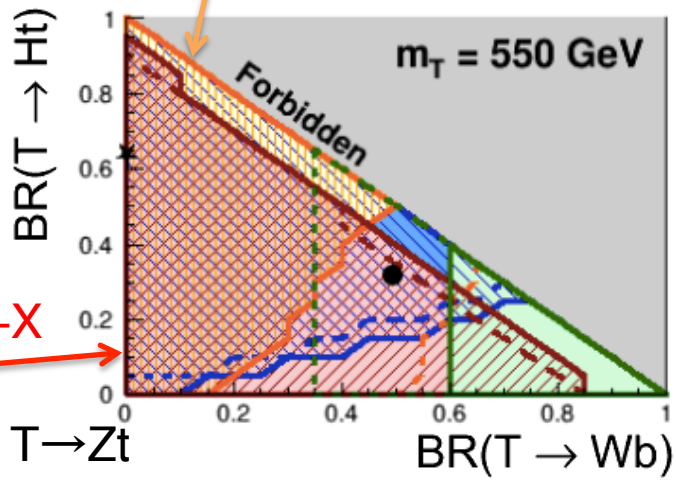
VLQ Strategy Established in Run I

Ht+X (l+jets)

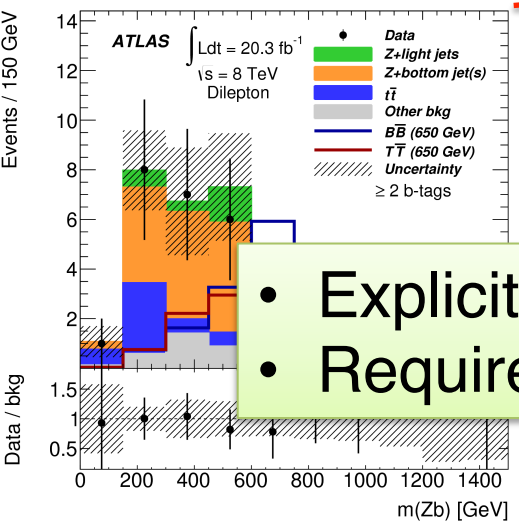


Same-sign leptons

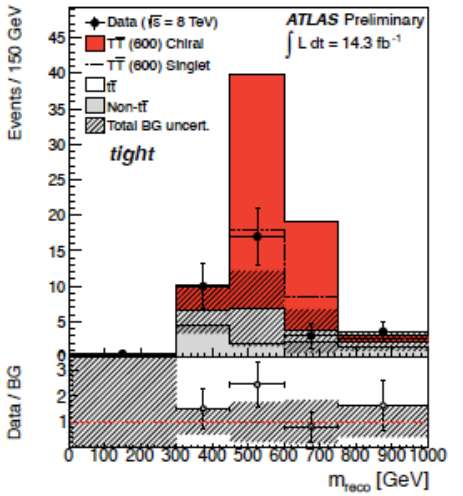




Z(→ll)t+X

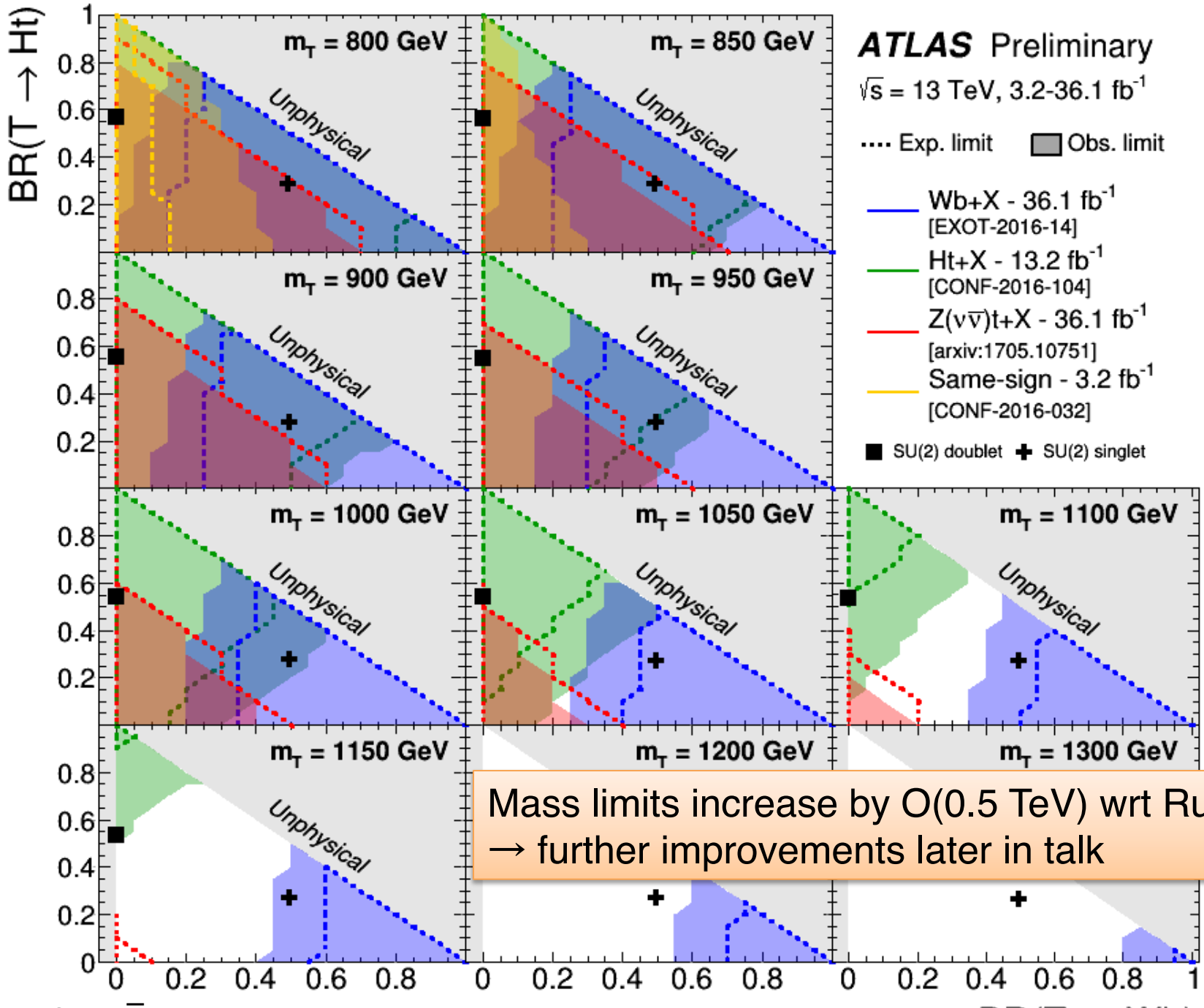


Wb+X (l+jets)



- Explicitly reconstruct VLQ mass
- Require both masses to be the same

Now with Run II data…



Mass limits increase by O(0.5 TeV) wrt Run 1
→ further improvements later in talk

(results for $B\bar{B}$ in backup)

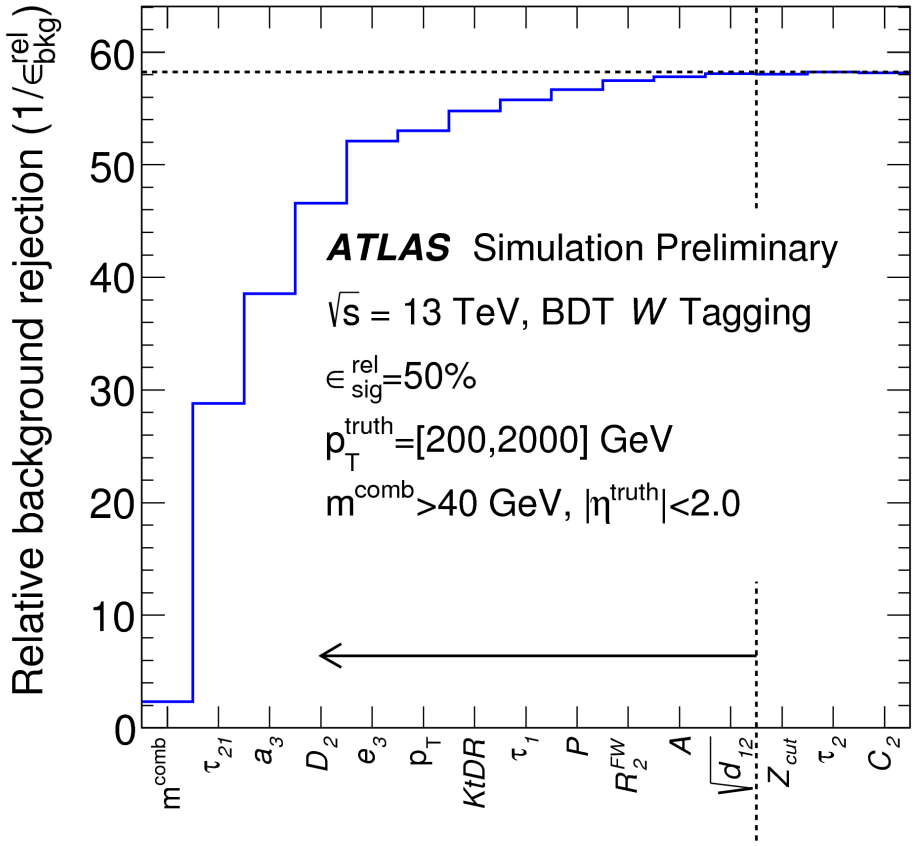
Refined Strategy for Run II & beyond

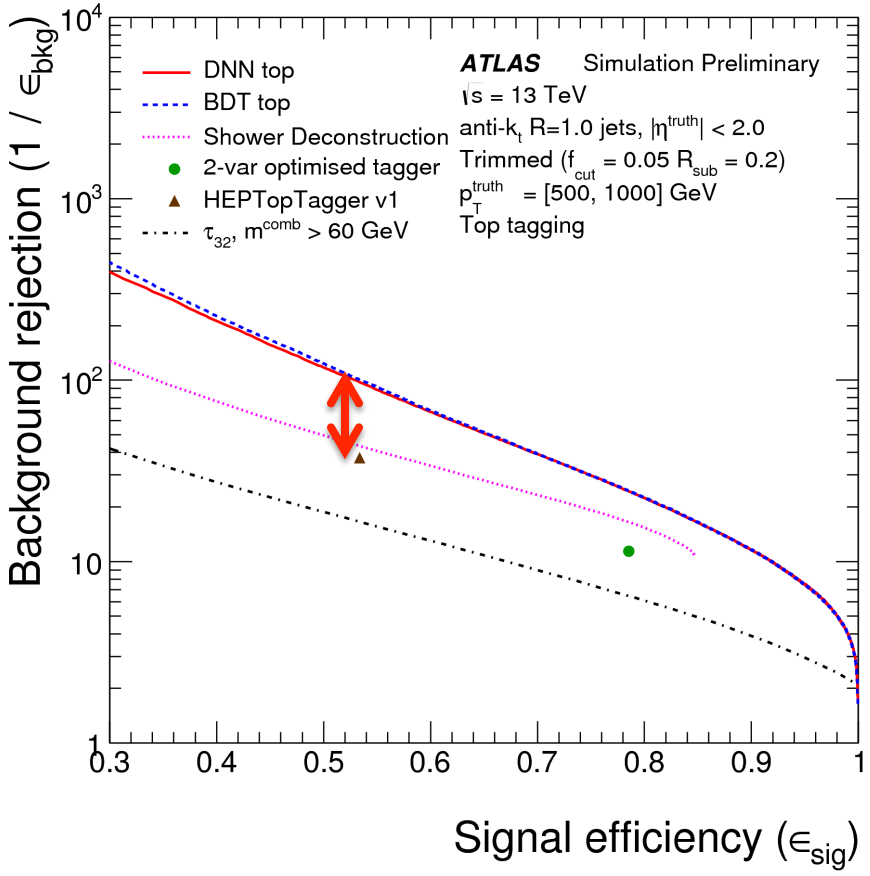
- Improved boosted hadronic top, W, Z and Higgs tagging
  - Large-R jets built from reclustered small-R jets → propagate systematic uncertainties [1803.09678]
  - BDT and DNN [ATLAS-CONF-2017-064]
  - Track-CaloCluster [ATL-PHYS-PUB-2017-015]
    - Mitigate the calorimeter angular resolution limitations by combining tracks and caloclusters before jet finding

- Improved high-p_T b-tagging [ATL-PHYS-PUB-2017-013]
  - RNN and DNN
  - Train algorithm on large statistics of high p_T jets

- Include Z(→νν) final states [1705.10751]
- Include all-hadronic final states [1803.09678]

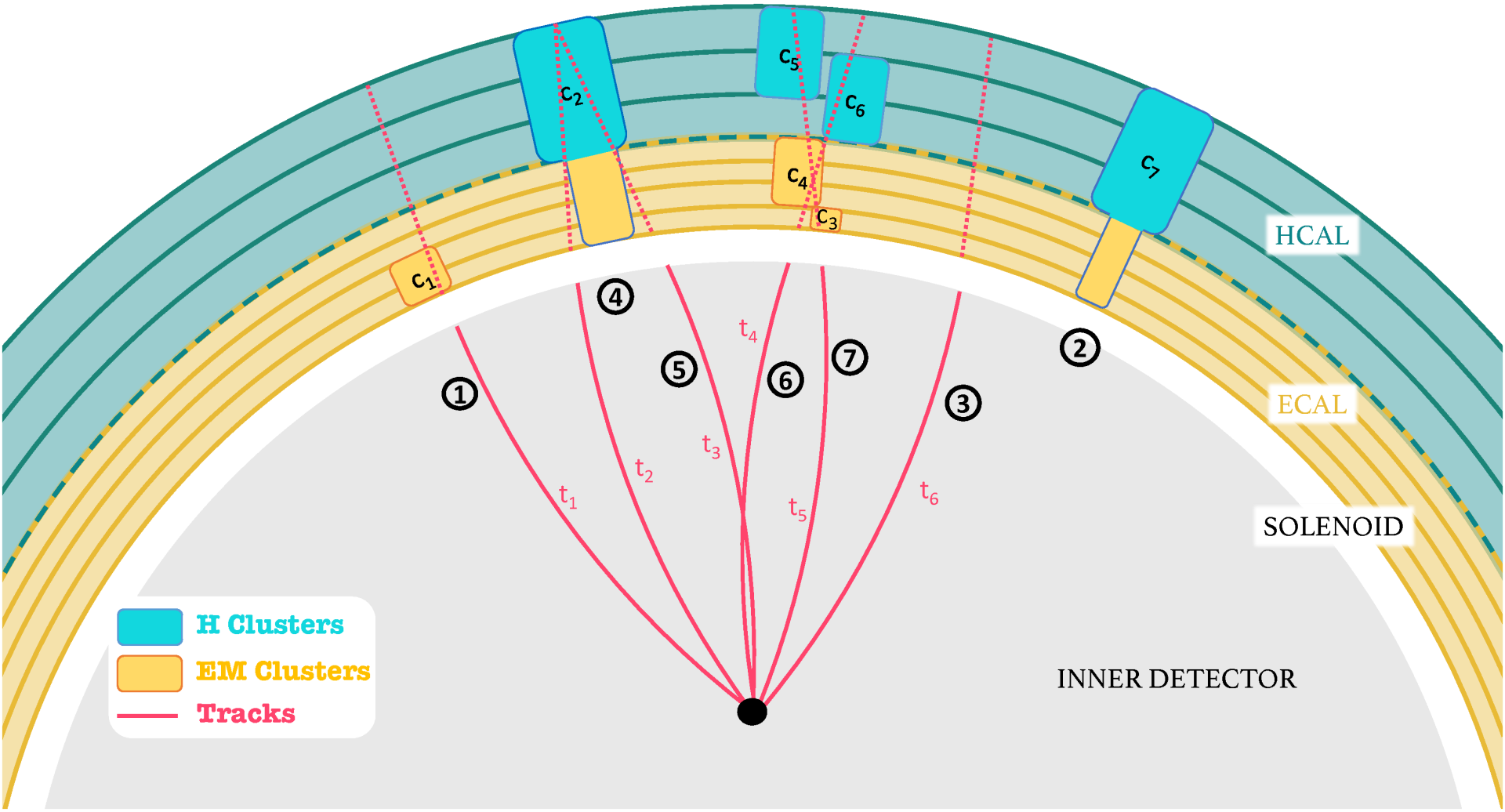
Improved boosted object tagging with BDT & DNN





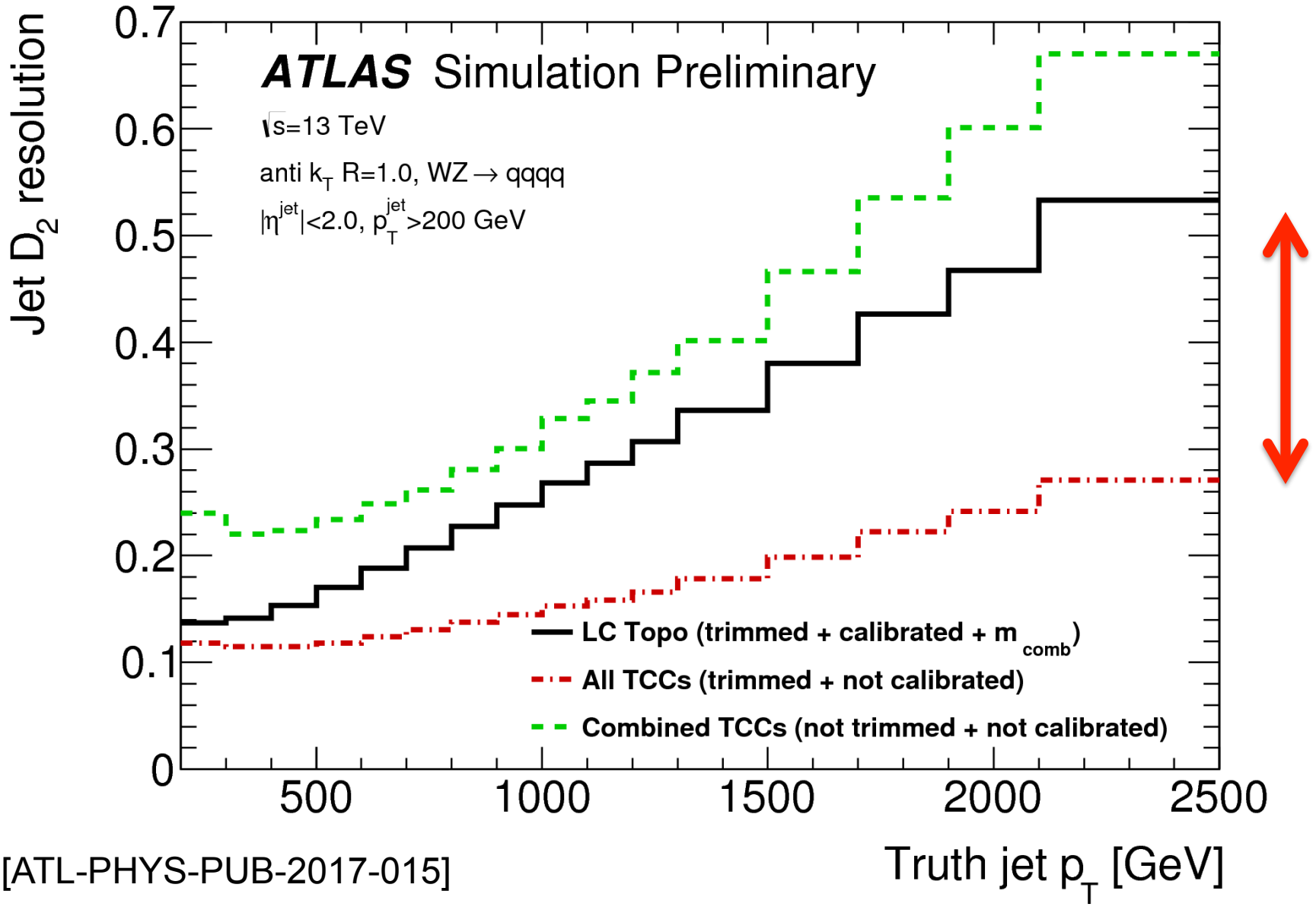
[ATLAS-CONF-2017-064]

Track-CaloCluster (TCC) matching



[ATL-PHYS-PUB-2017-015]

Improved resolution with TCC

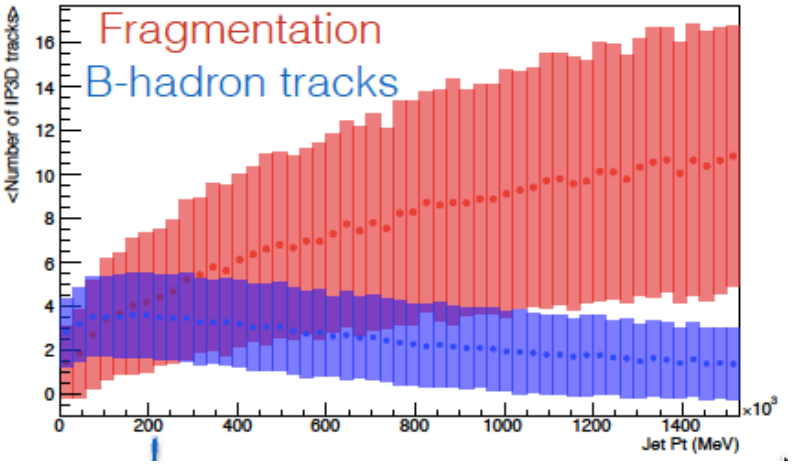


[ATL-PHYS-PUB-2017-015]

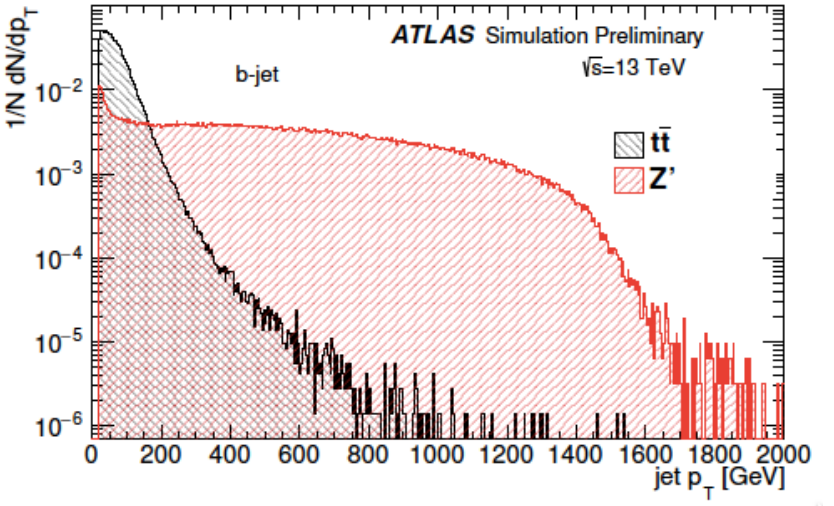
Improved high-p_T b-tagging

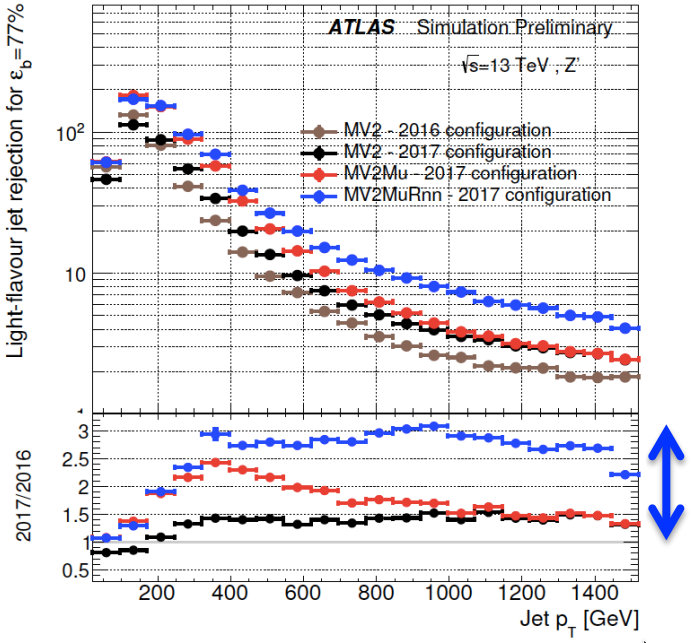
[ATL-PHYS-PUB-2017-013]

B-tagging very challenging at high p_T



Development of new training sample that populates high p_T

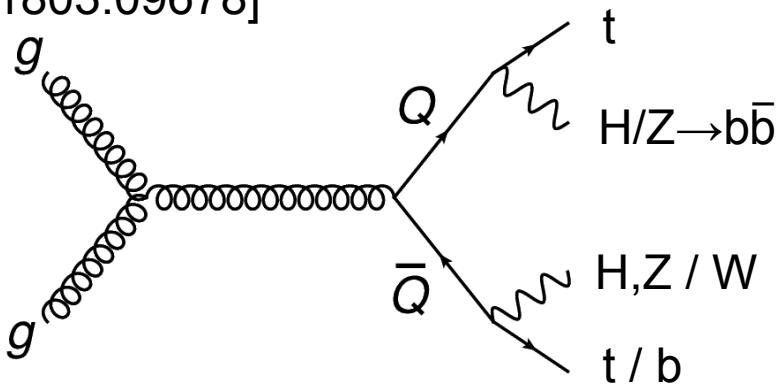




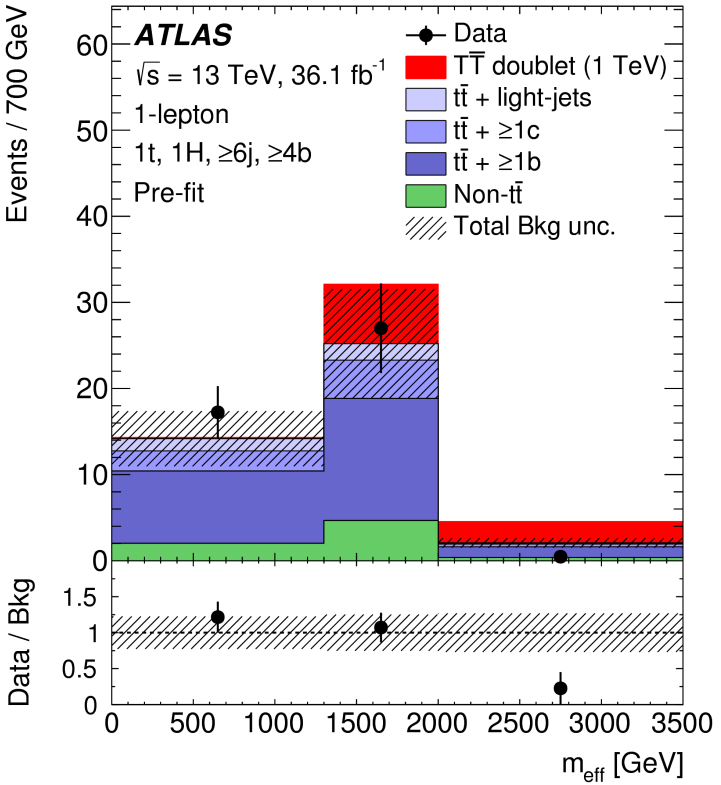
+ RNN and DNN tagging:
all in all **factor 3**
improvement at high p_T

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

[1803.09678]



- 1-lepton-trigger or **0-lepton** MET trigger
- At least 5 jets
- At least 2 b-tags,
- **Reclustered** large-R jets (top, H)
- Final discriminant: m_{eff}



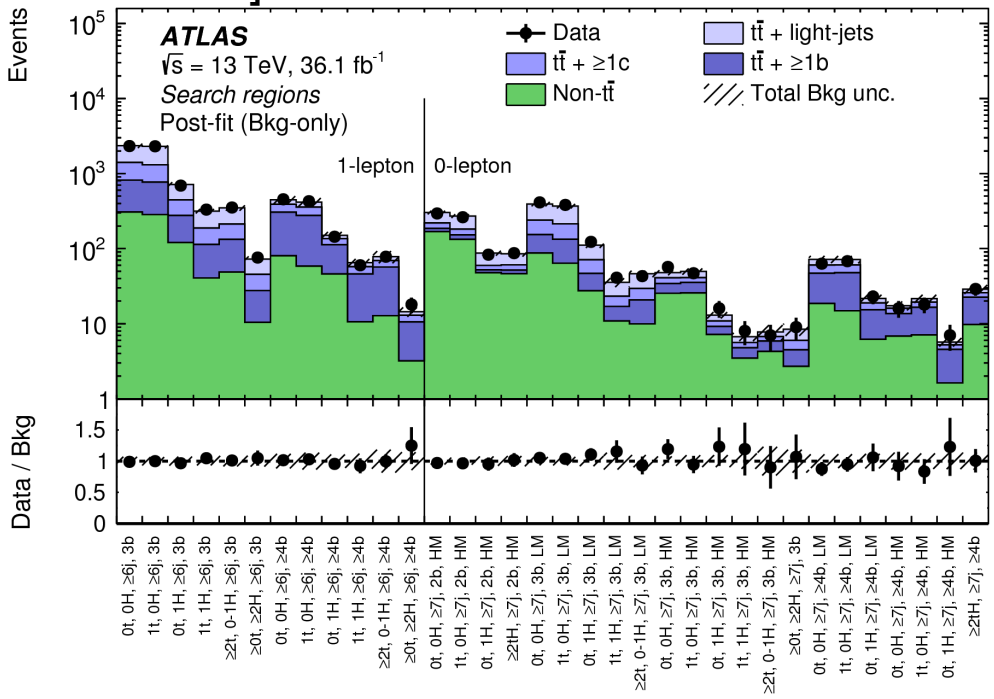
Top-tags
- p_T> 300 GeV
- m> 140 GeV
- ≥ 2 subjets

Higgs-tags
- p_T> 200 GeV
- 105 < m < 140 GeV
- = 2 subjets (p_T< 500 GeV)
- 1 or 2 subjets (p_T> 500 GeV)

(analysis also sensitive to BSM 4top production and decays of KK excitations)

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

[1803.09678]



- 34 signal regions
  - Jet multiplicity
  - B-tags
  - Top-tags
  - Higgs-tags

Maximum likelihood fit to m_{eff} in all search regions

Largest background: $t\bar{t}$+jets
- Use validation regions

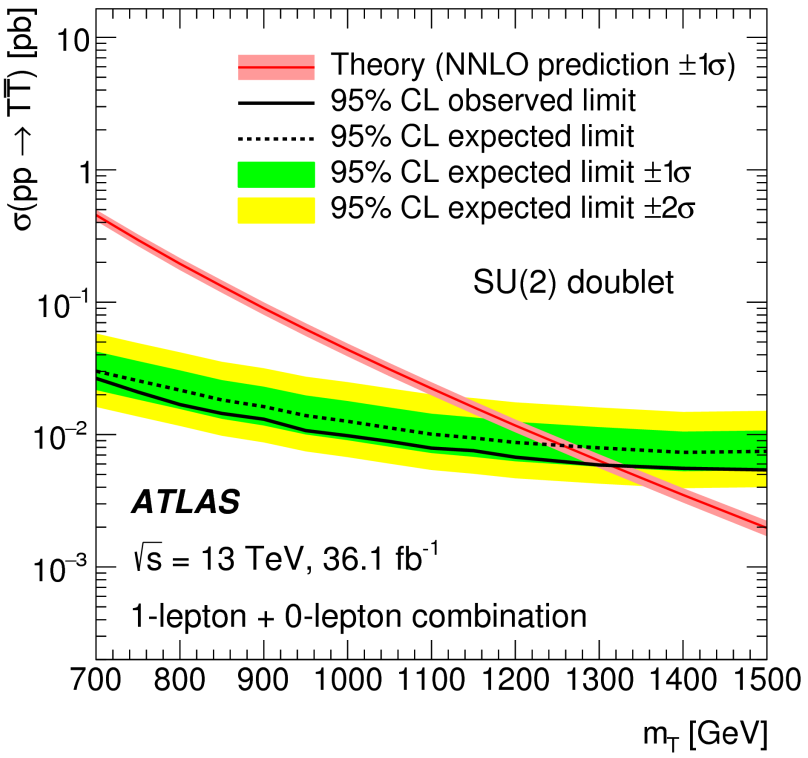
Multi-jet BG: data-driven
- matrix method (1-lep)
- fit to $\Delta\phi$min(4j) (0-lep)

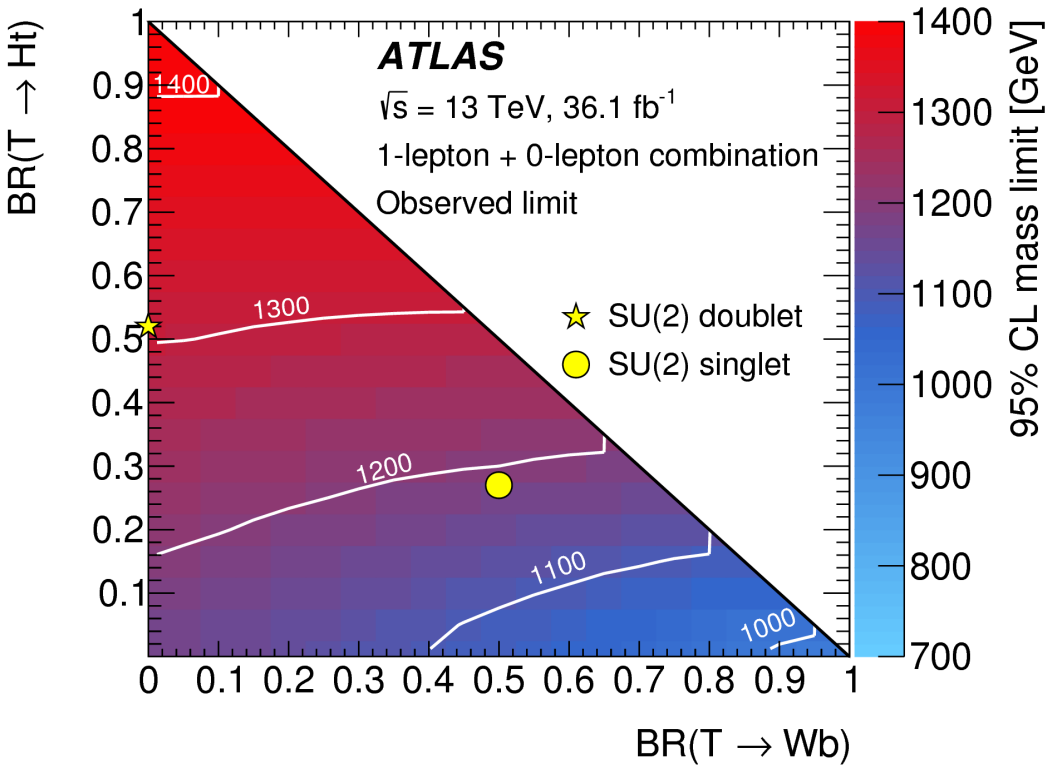
Other small BG from MC: $t\bar{t}$+V, $t\bar{t}$+H, single top, VV, W/Z+jets

Dominant systematics:
- $t\bar{t}$ modeling
- b- top- Higgs-tagging
- background normalization

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

[1803.09678]

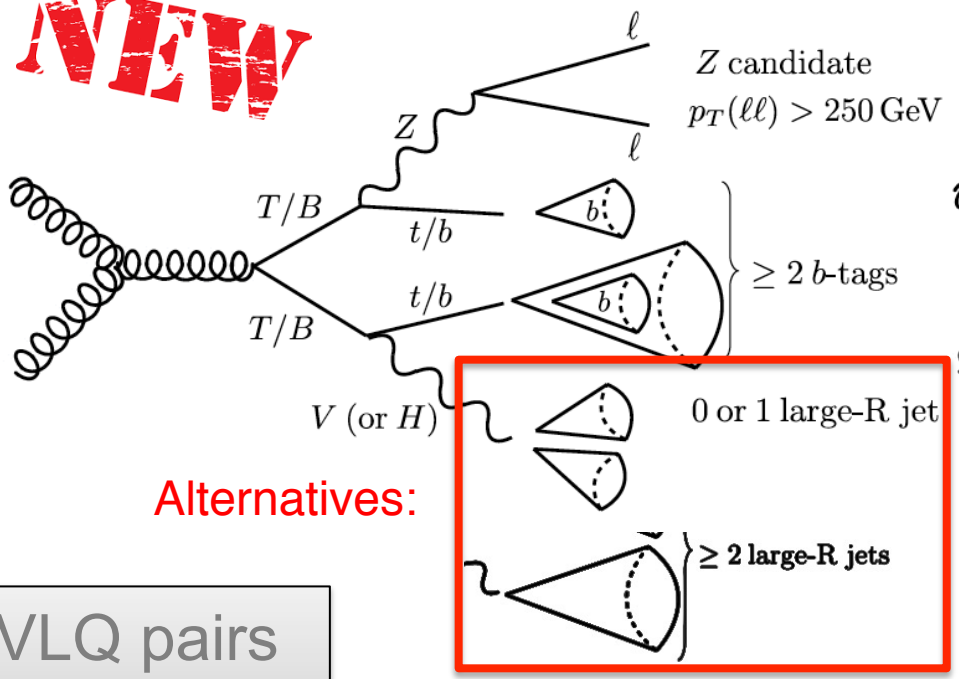




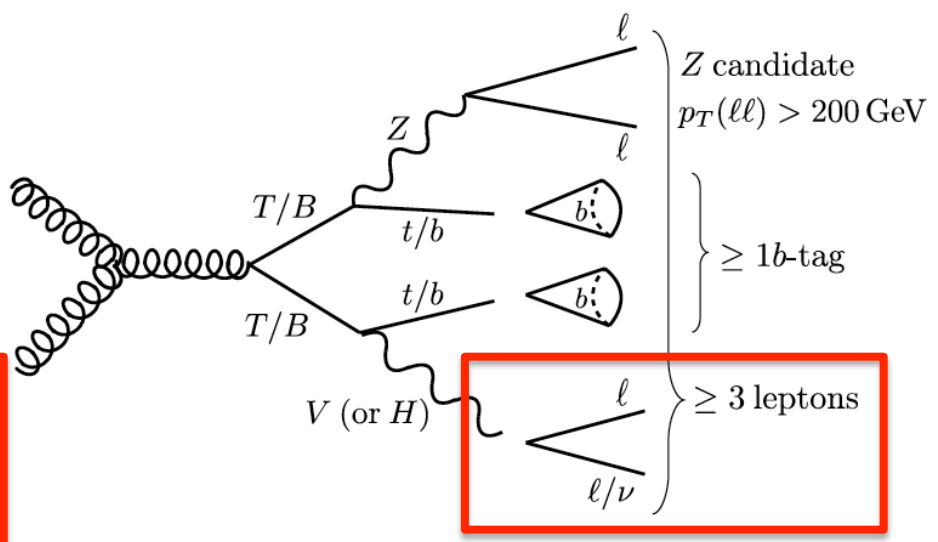
- Limits set per channel and then combined
- VLQ masses excluded up to:
  - 1.4 TeV (100% BR T→Ht)
  - 1.3 TeV (doublet)

Single and pair VLQs with Z→ll

NEW

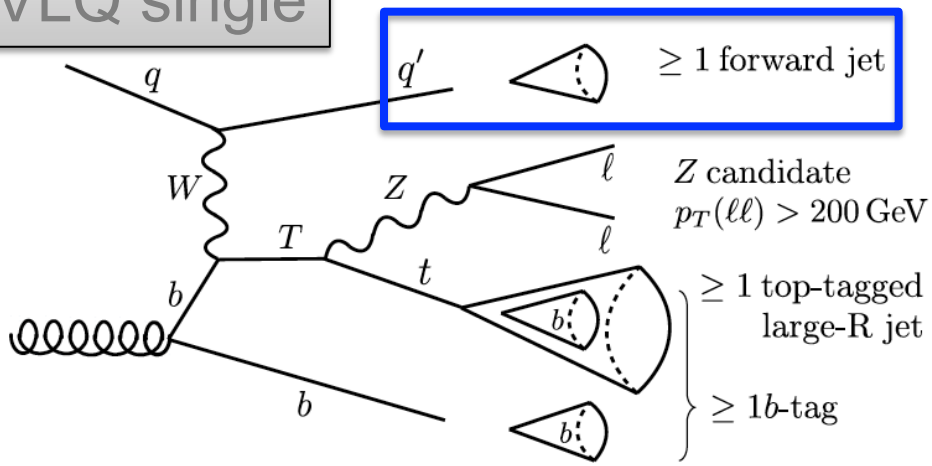


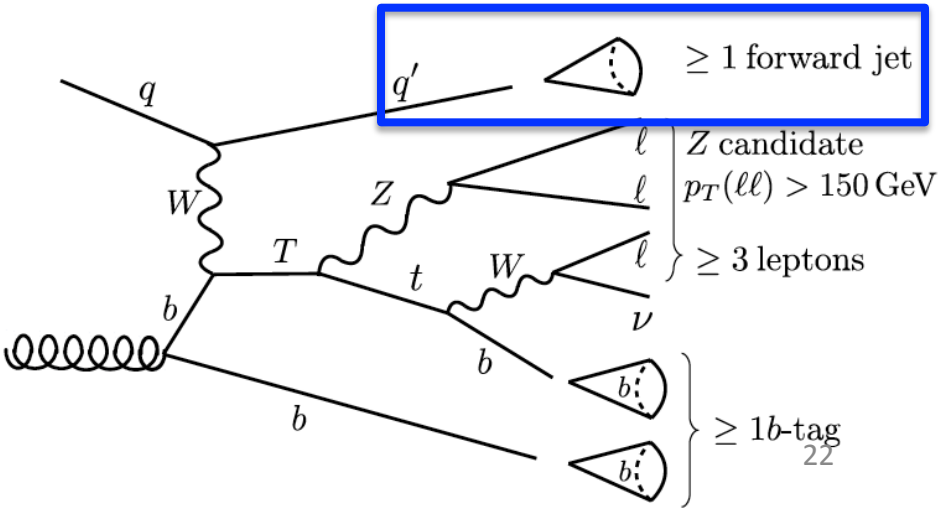
Alternatives:



VLQ pairs

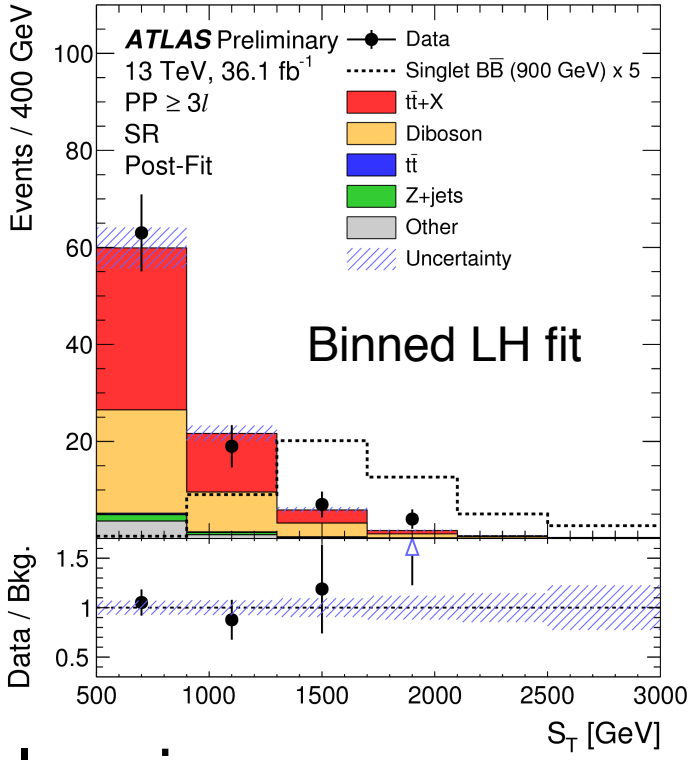
VLQ single





VLQ search with Z→ll

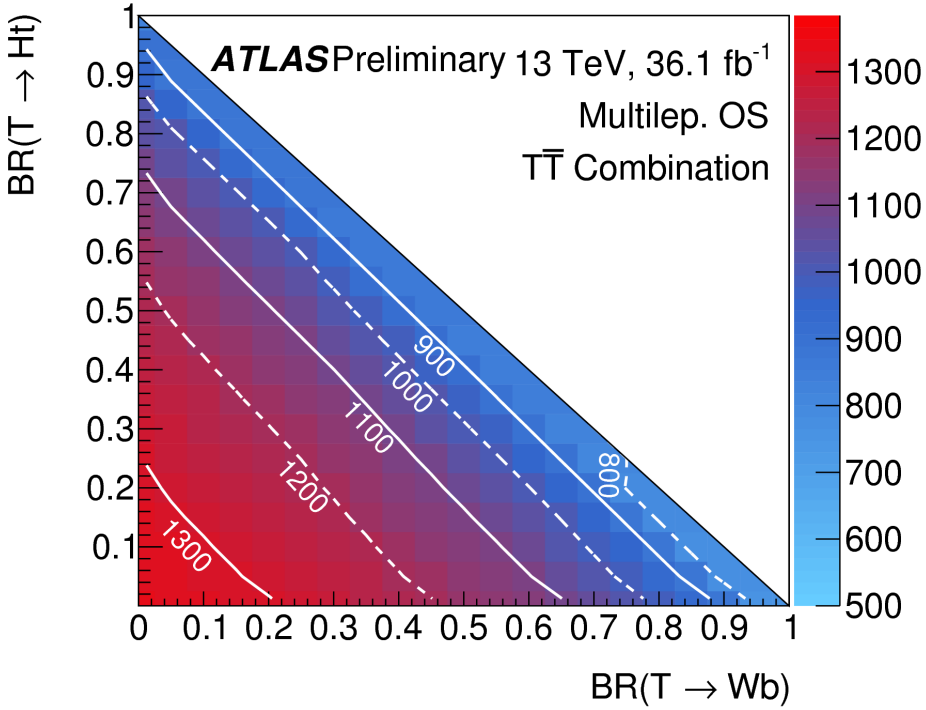
- Major background
  - 2 lepton search
    - Z+jets
    - $t\bar{t}$
  - 3 lepton search
    - VV
    - $t\bar{t}$+Z

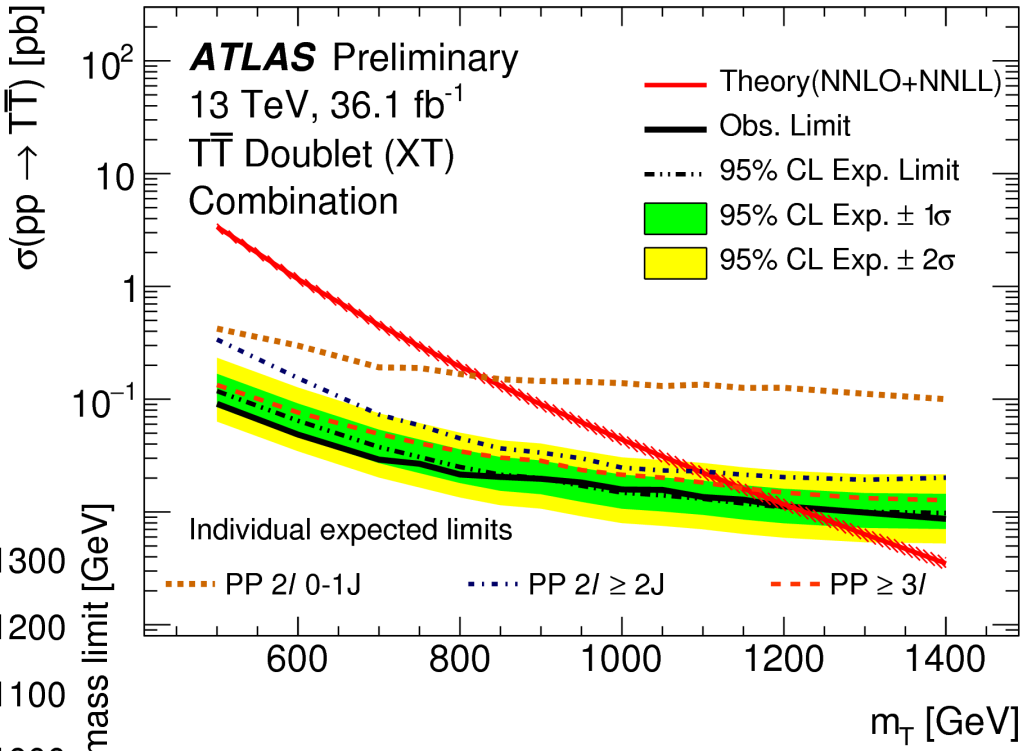


- Backgrounds validated in control regions
  - Outside Z window / fewer b-tags / lower H_T or $p_T(ll)$
- Search limited by statistical uncertainties
- Dominant systematics: background modeling

Z→ll: TT̄ limits

No excess ⇒
limits at 95% CL

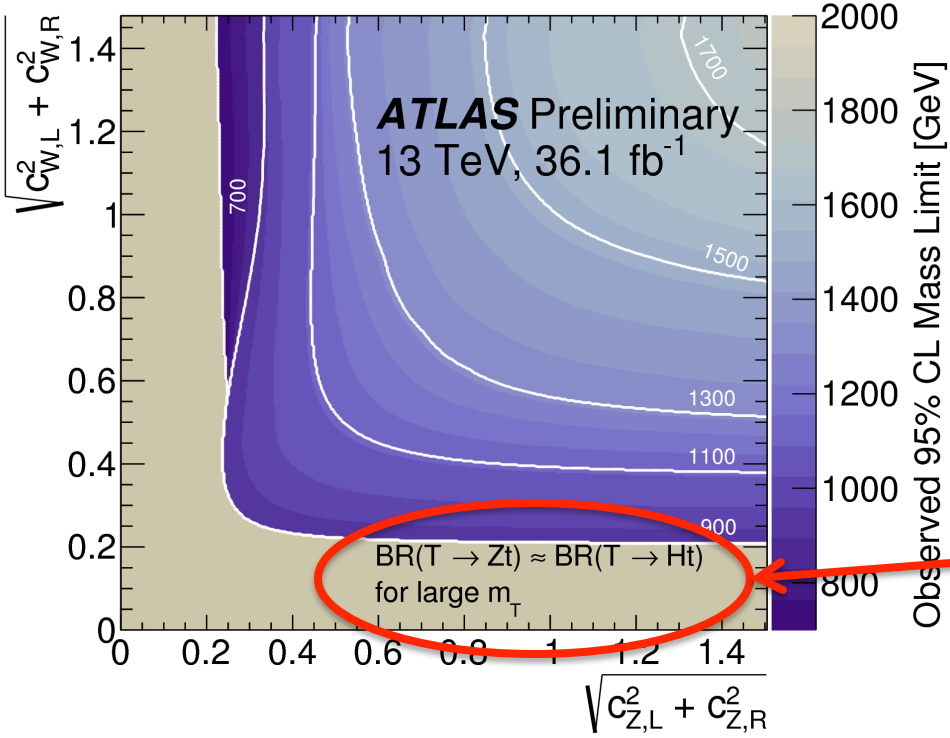


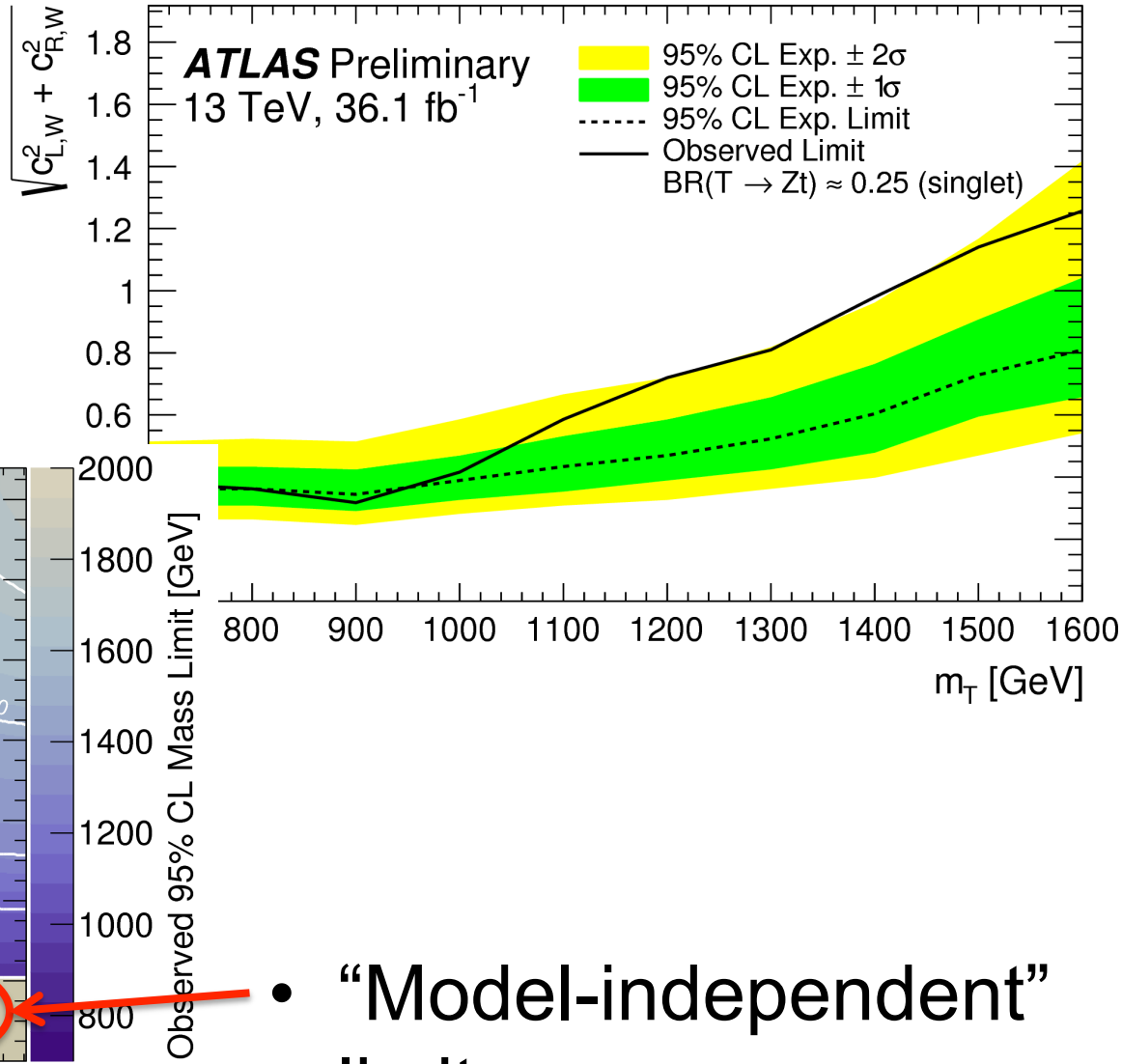


(results for BB̄ in backup)

Z→ll: Single VLQ T limits

- Assuming singlet model



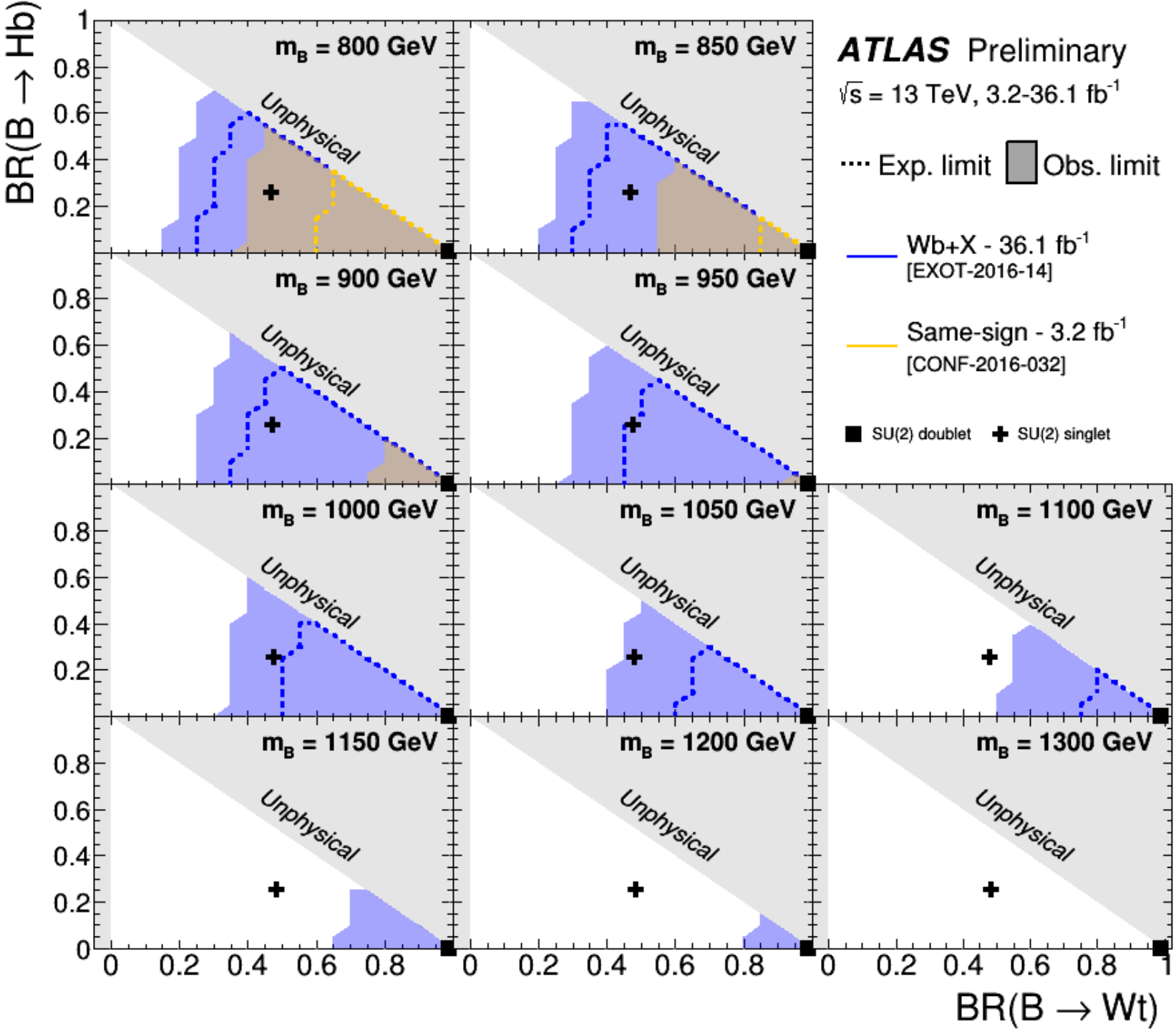


- "Model-independent" limits

Summary

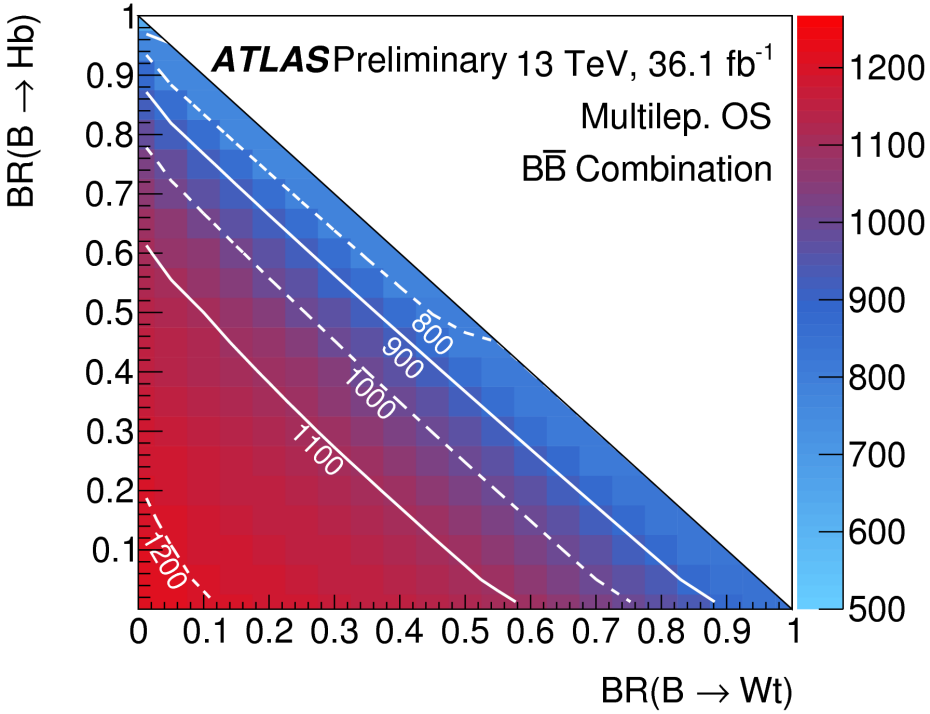
- Broad search program for VLQs at ATLAS
  - All important decay modes considered
  - Boosted objects & high-p_T b-tagging becoming more and more important
- No evidence for new physics yet
  - Mass exclusions @ 95% CL in Run I: ~800 GeV → Run II: up to 1.4 TeV (pair production)
- Still many analyses in the pipeline

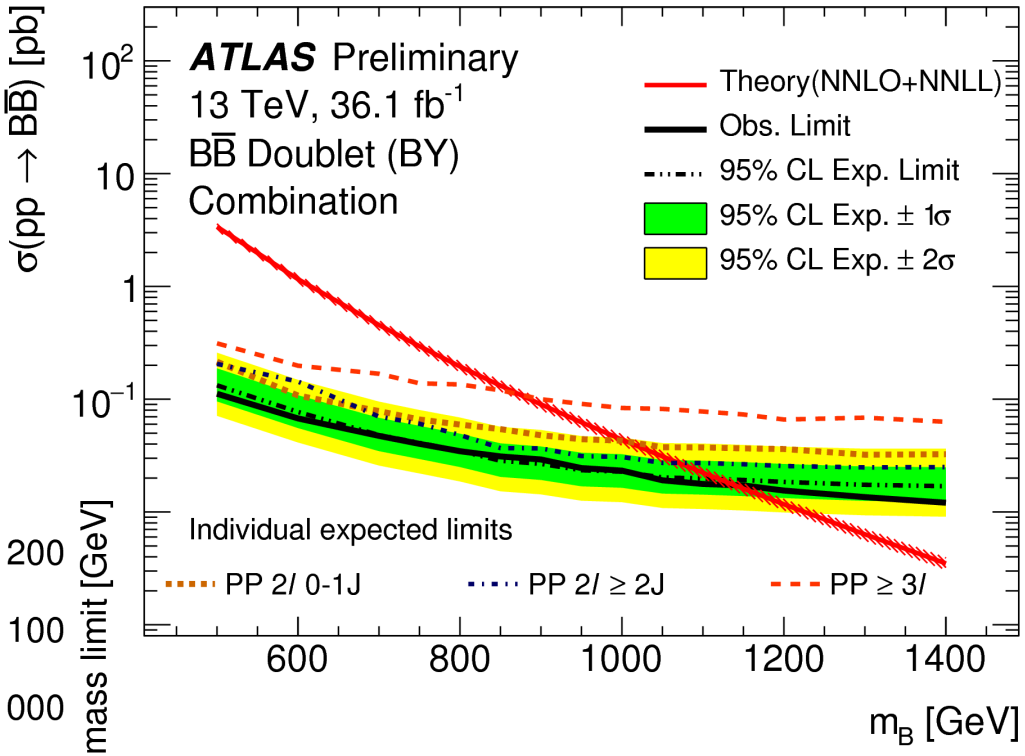
Backup

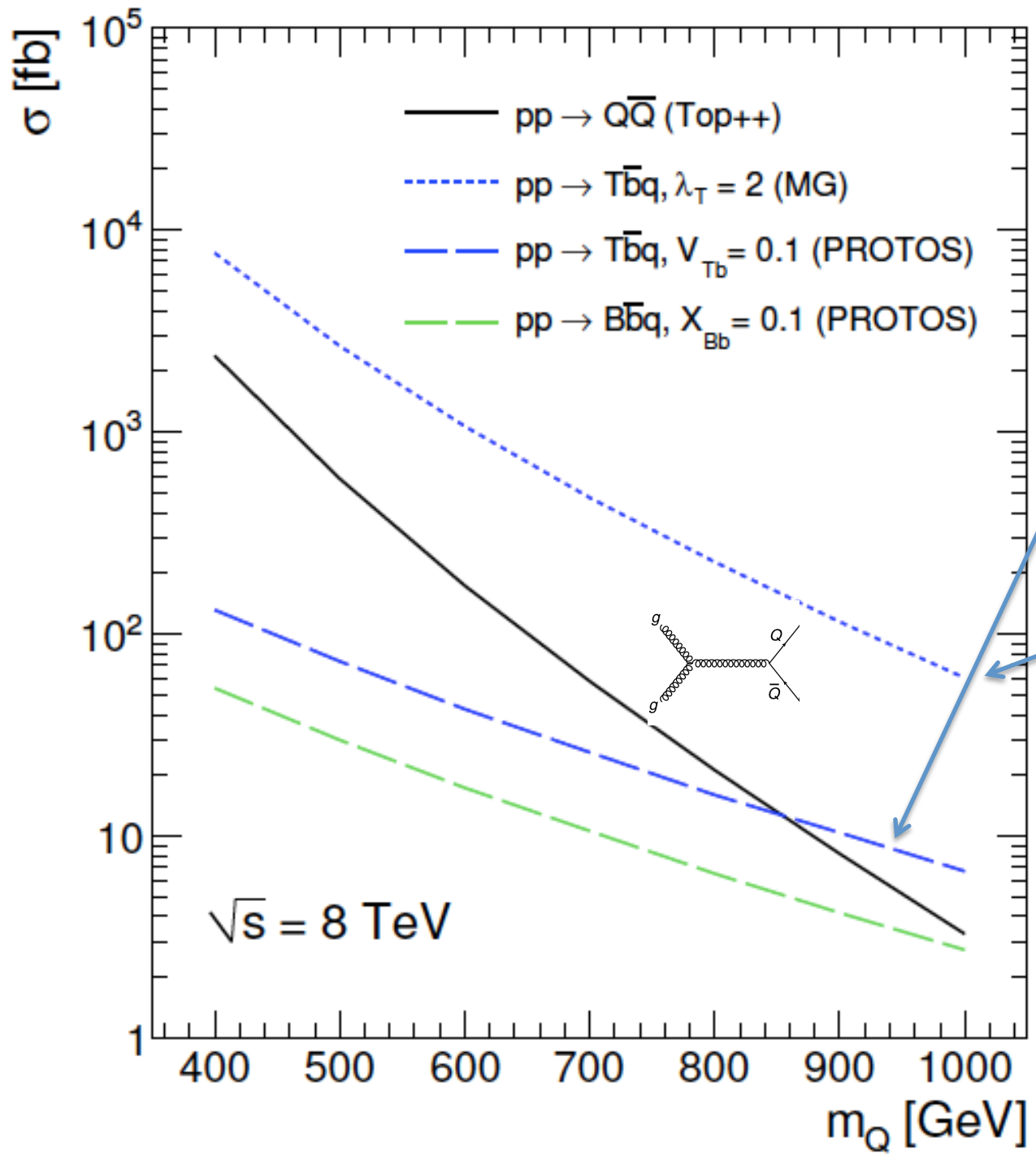

ATLAS Preliminary
√s = 13 TeV, 3.2-36.1 fb-1
Exp. limit
Obs. limit
Wb+X - 36.1 fb-1
[EXOT-2016-14]
Same-sign - 3.2 fb-1
[CONF-2016-032]
SU(2) doublet
SU(2) singlet
mB = 800 GeV
mB = 850 GeV
mB = 900 GeV
mB = 950 GeV
mB = 1000 GeV
mB = 1050 GeV
mB = 1100 GeV
mB = 1150 GeV
mB = 1200 GeV
mB = 1300 GeV
Unphysical
BR(B → Hb)
BR(B → Wt)

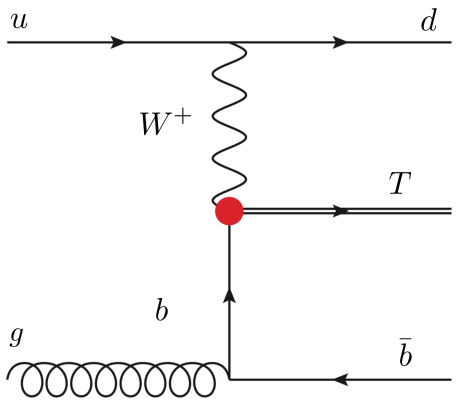
Z→ll: BB̄ limits

No excess ⇒
limits at 95% CL









EWPTs:
$V_{Tb} \leq 0.1$ (applies to single multiplet)

Relaxed for >1 multiplet (well motivated in CH models)