Search for vector- like quarks in ATLAS

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BLV2017
Case Western Reserve University
15/May/2017

Introduction: Vector like quarks(VLQ)

- Vector like quark (VLQ): the quark that left- and right-handed chirality have the same transition components under weak SU(2).
  - SM quarks: left- is SU(2) doublet and right- is singlet.

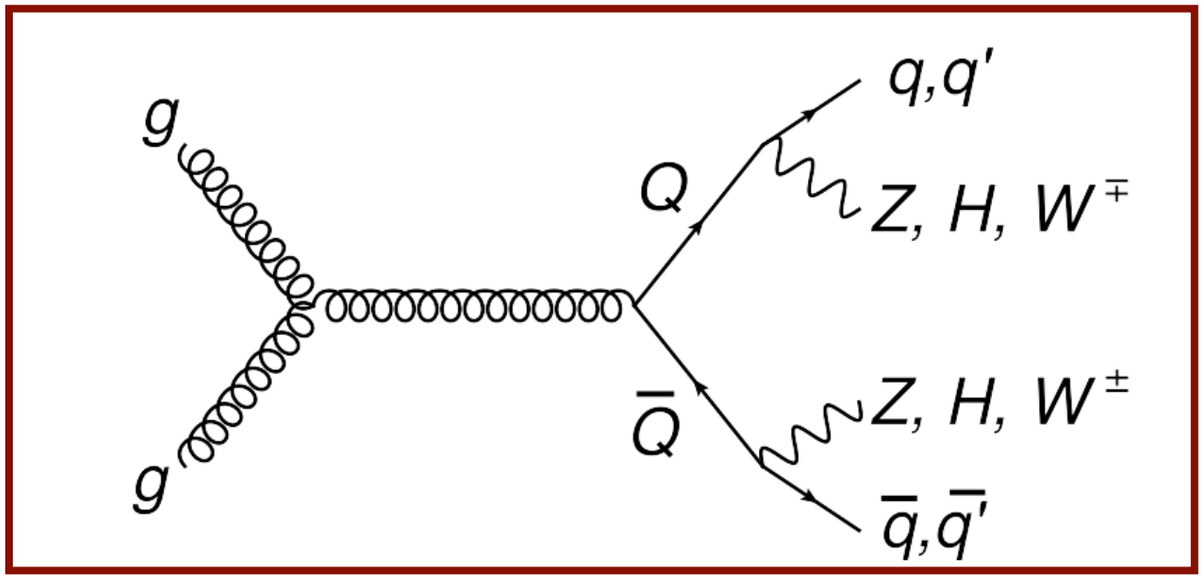
- Many BSM theories introduce VLQ existence.
  - composite Higgs, Little Higgs, and others.

- 4 possible VLQ are introduced.
  - X(+5/3), T(+2/3), B(-1/3), Y(-4/3)

- 3 possible SU(2) transitions are taken into account.
  - singlet, doublet, triplet

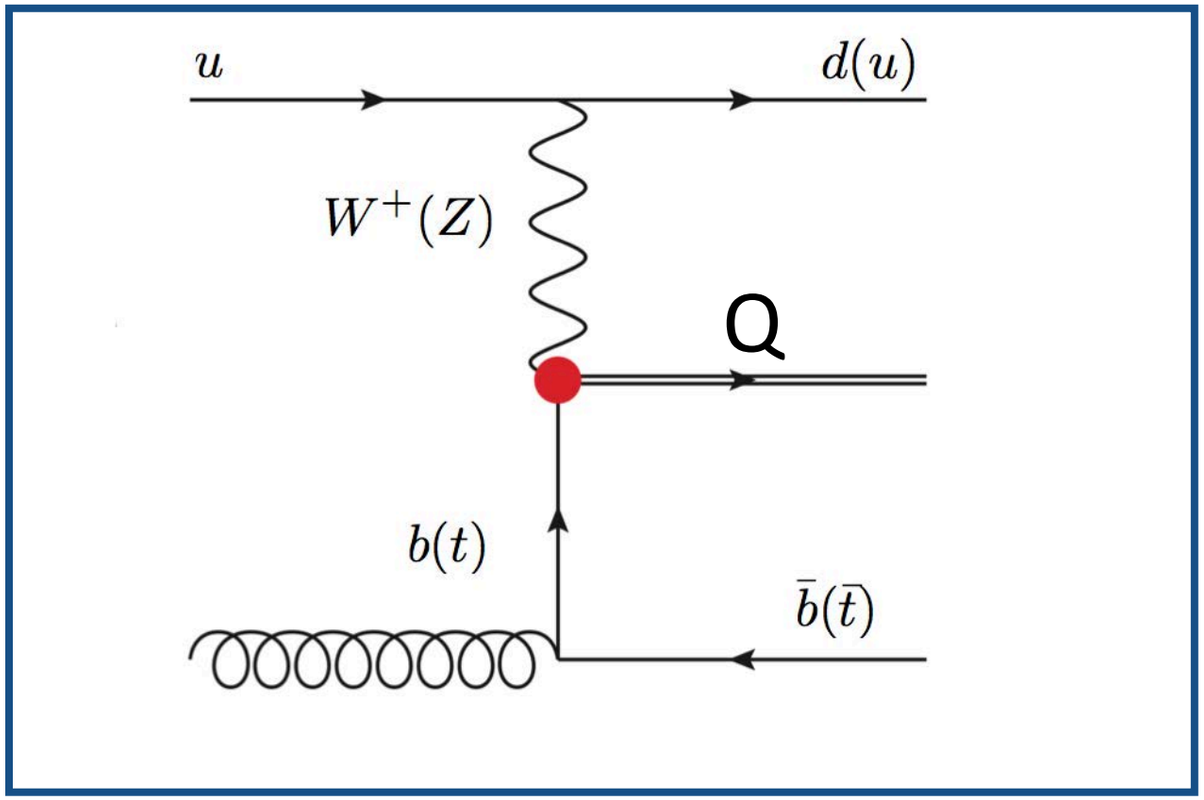
VLQ production by LHC

2 VLQ production channels exist.



(1) pair production

- Via QCD
- The cross section depends only on VLQ mass.



(2) single production

- Via Electro-Weak
- The cross section depends on VLQ mass and mixing with SM particles.
- Can be dominant if both VLQ mass and mixing is large.

VLQ search in ATLAS

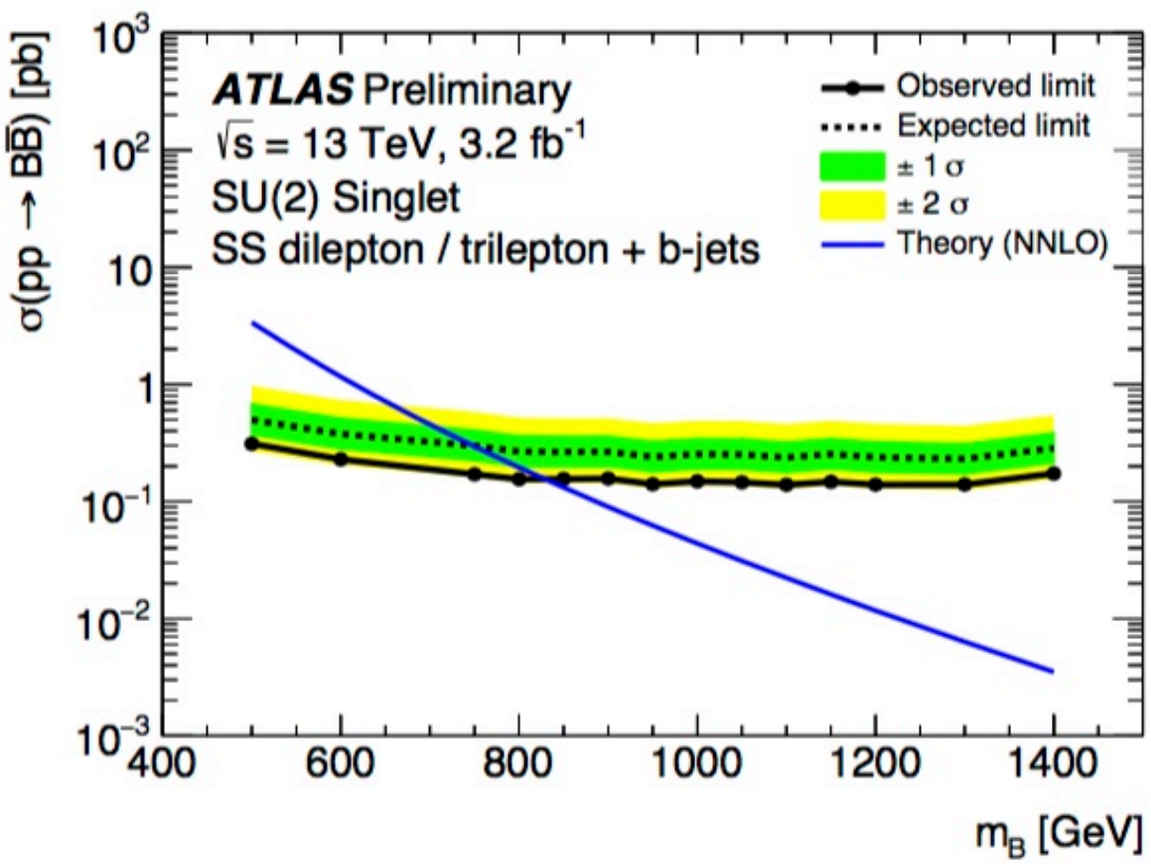
ATLAS collaborators search for VLQs using the LHC Run2 data ($\sqrt{s}$ = 13 TeV).

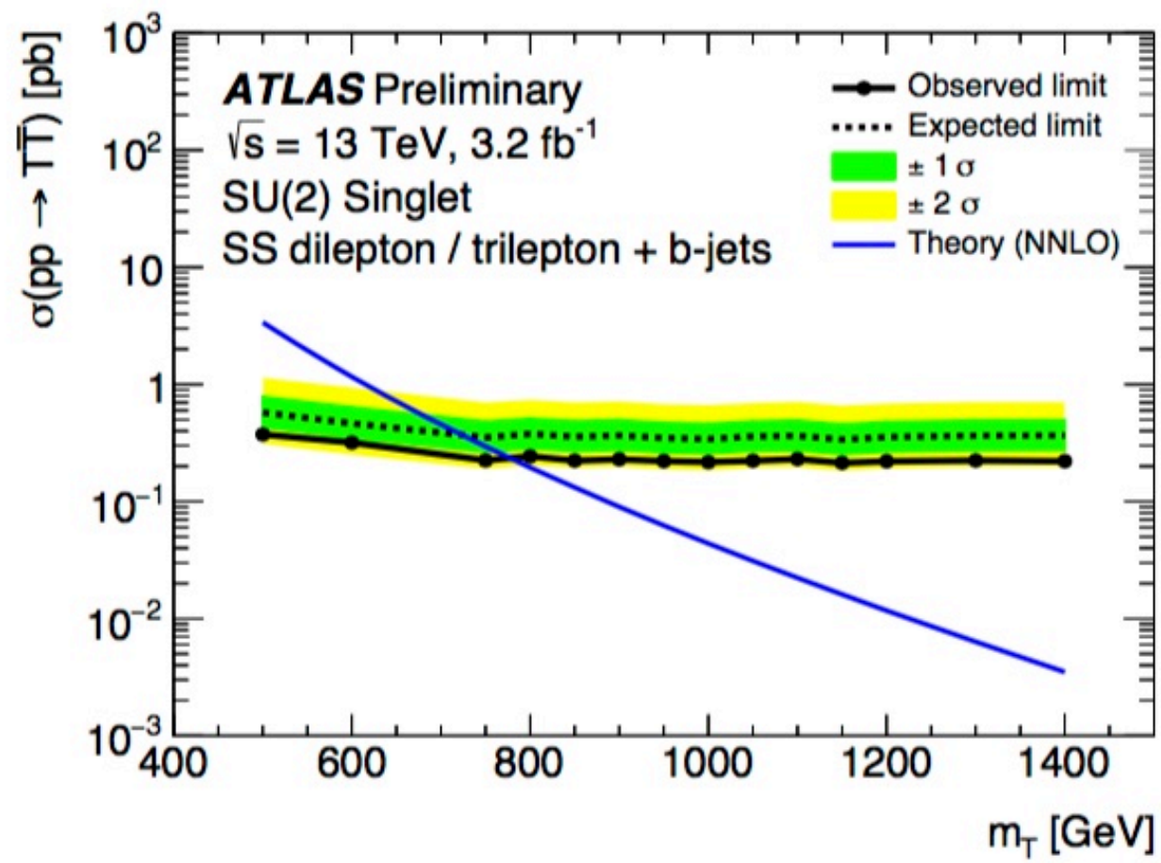
- 2015 data only (I do not introduce details today):
  - pair production, b + same sign leptons channel, 3.2 fb^{-1} (ATLAS-CONF-2016-032)
  - single production, W+b channel, 3.2 fb^{-1} (ATLAS-CONF-2016-072)
- 2015+2016 data:
  - pair production, Zt+X channel, 36.1 fb^{-1} (ATLAS-CONF-2017-015)
  - pair production, Ht+X channel, 13.3 fb^{-1} (ATLAS-CONF-2016-104)
  - pair production, Wb channel, 13.3 fb^{-1} (ATLAS-CONF-2016-102)

Results of 2015 data

No signal excess over the background was observed.
Cross section limit was set.

W+same sign channel





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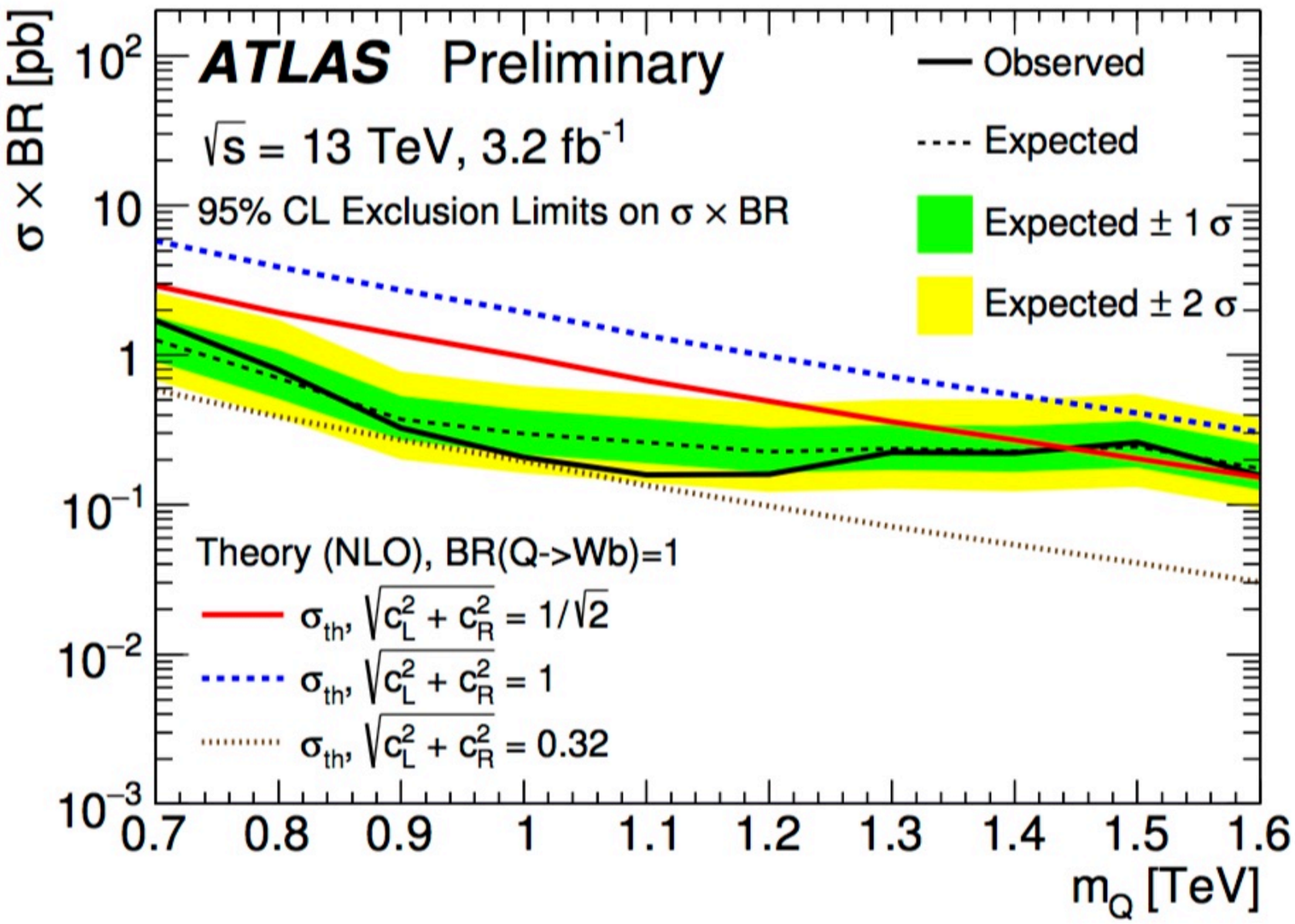
W+b channel



Zt+X channel

- Target:
  - TT -> Zt + X
  - Z decays into a pair of neutrinos
  - t or the other T produces exactly 1 charged lepton.

- The final state contains
  - large missing transverse momentum(E_T^{miss}) mainly due to the invisibly decaying Z.
  - multiple jets.
  - exactly 1 charged lepton.
  - at least 1 b-tagged jet.

Zt+X: strategy

- First, events are required to pass the pre-selection.

Pre-selection

- ✦ At least 4 jets are reconstructed
- ✦ Exactly 1 charged lepton is reconstructed
- ✦ $E_T^{miss} > 200$ GeV

- Then, events are categorised into control regions(CRs), validation regions(VRs), and signal region(SR).

CRs

- ✦ WCR: enriched in W+b
- ✦ TCR: enriched in $t\bar{t}$

VRs

- ✦ WVR: enriched in W+b
- ✦ TVR: enriched in $t\bar{t}$
- ✦ SRVR: enriched in single top

Zt+X: Background estimation

- The main background process in the SR is tt and W+jets, and single top.
- tt, W+jets contribution is estimated using the data in TCR, single top contribution is estimated based on MC, and then validated using the data in VRs.

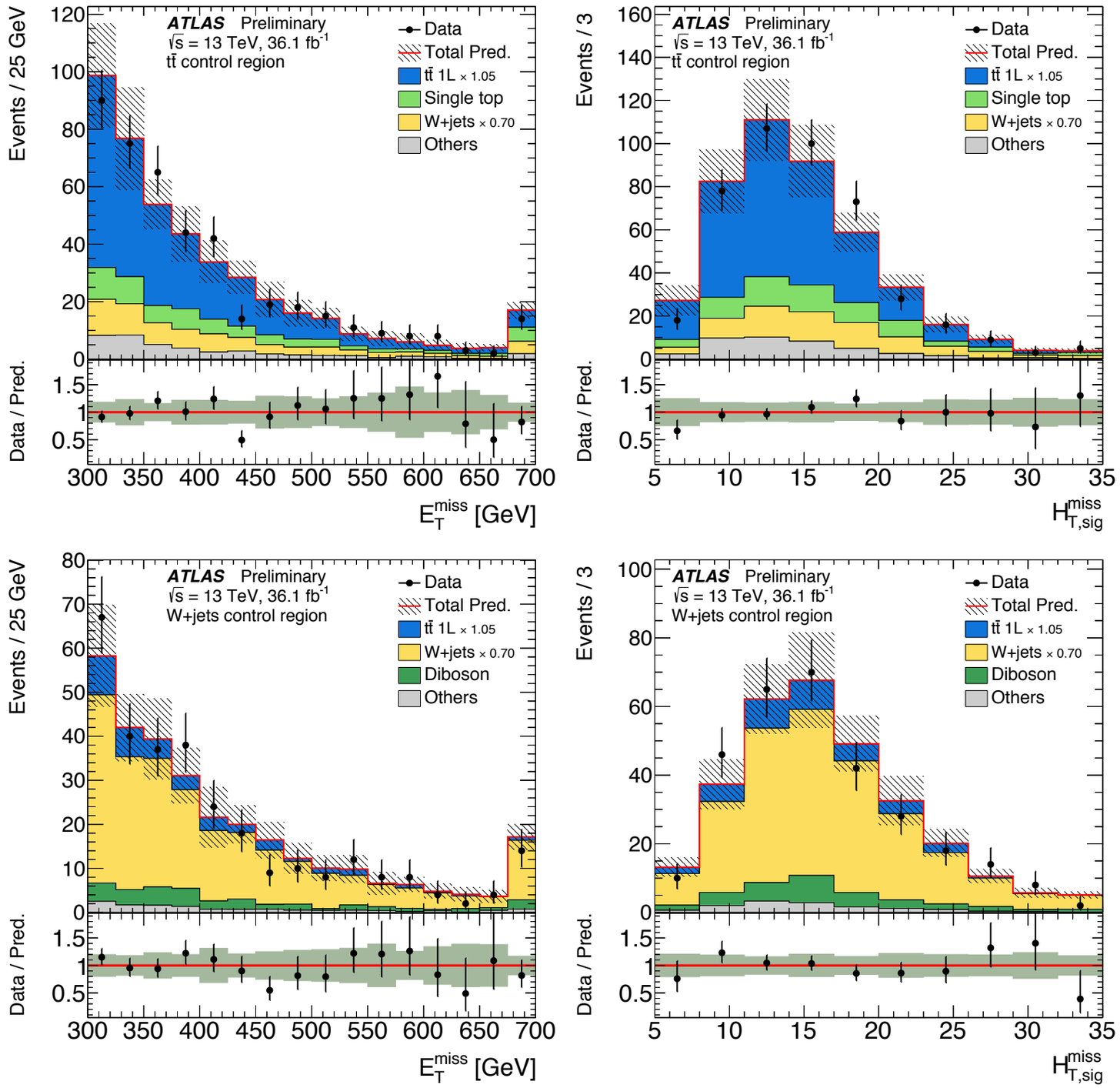
Zt+X: Background estimation

Data/MC comparison in CRs(after estimation)

and s ts,

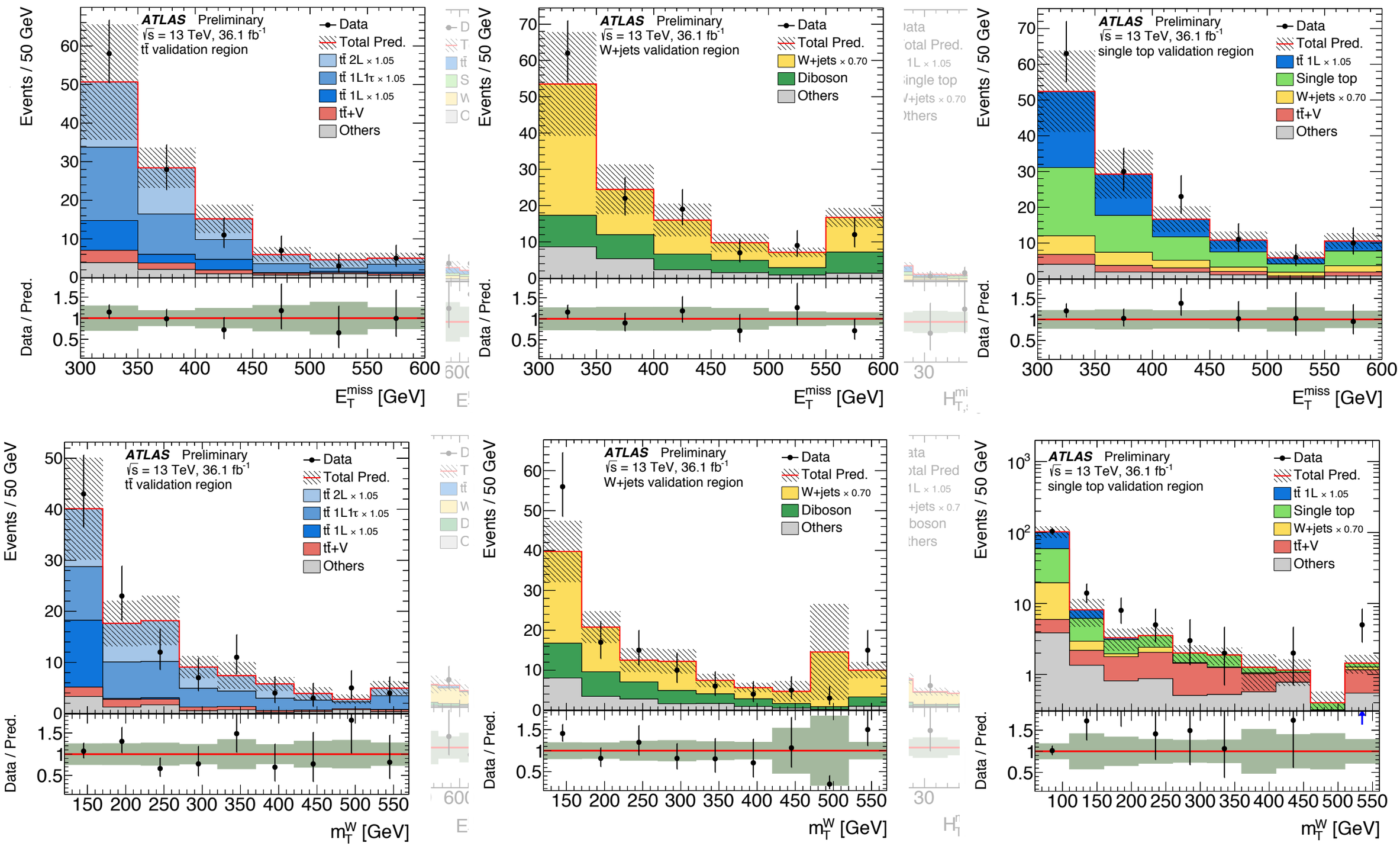
- tt, W
single
valid

the data in TCR, on MC, and then



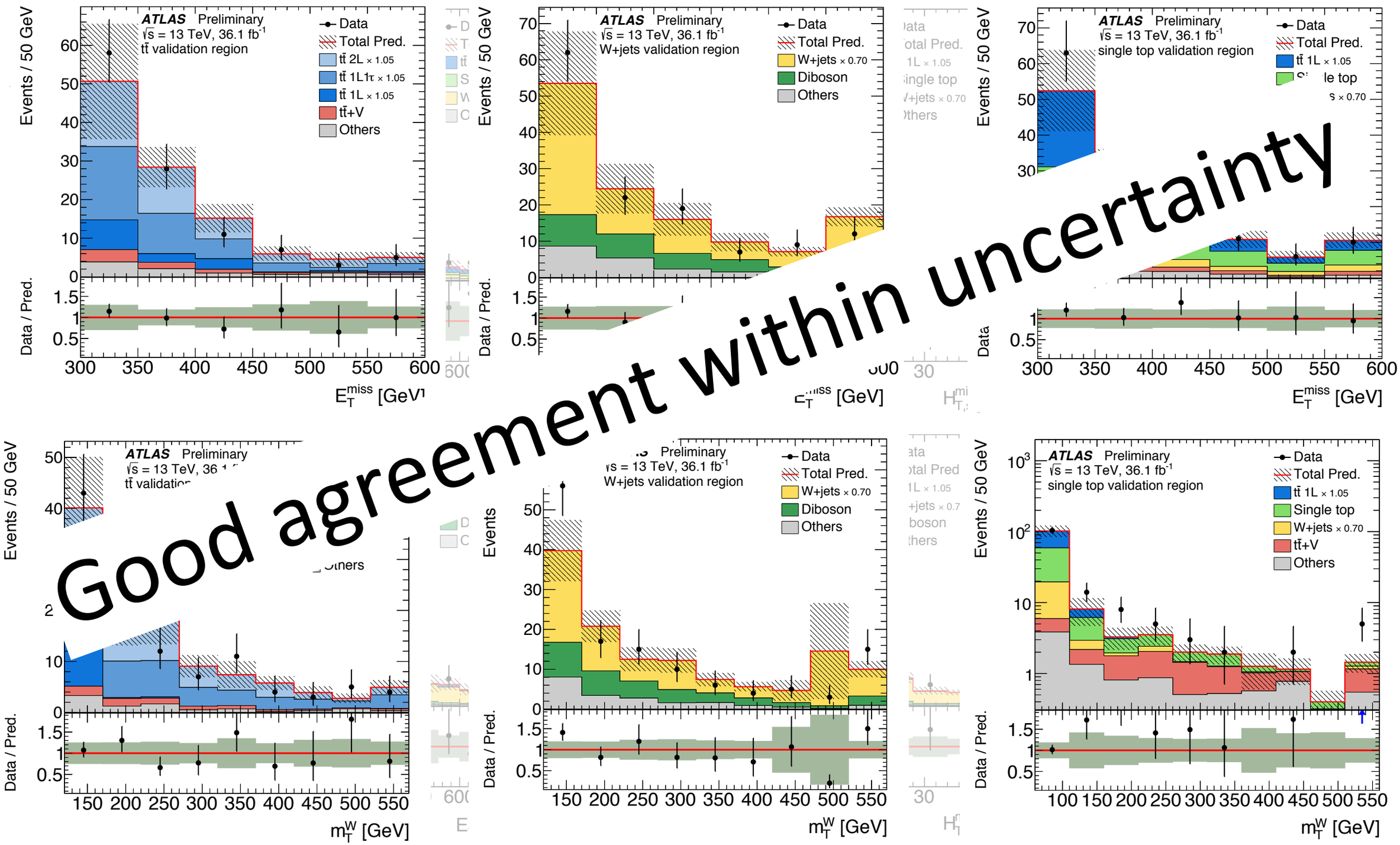
Zt+X: Background estimation

Data/MC comparison in VRs(after estimation)



Zt+X: Background estimation

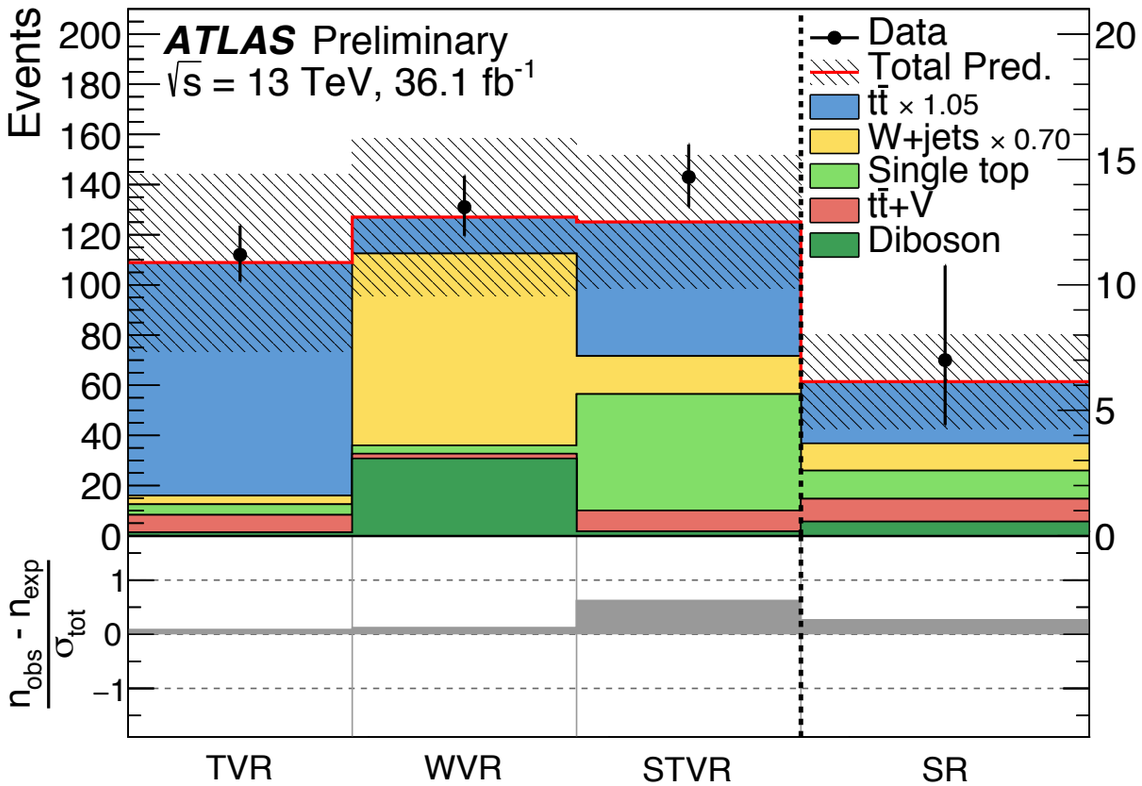
- Data/MC comparison in CRs(after estimation)

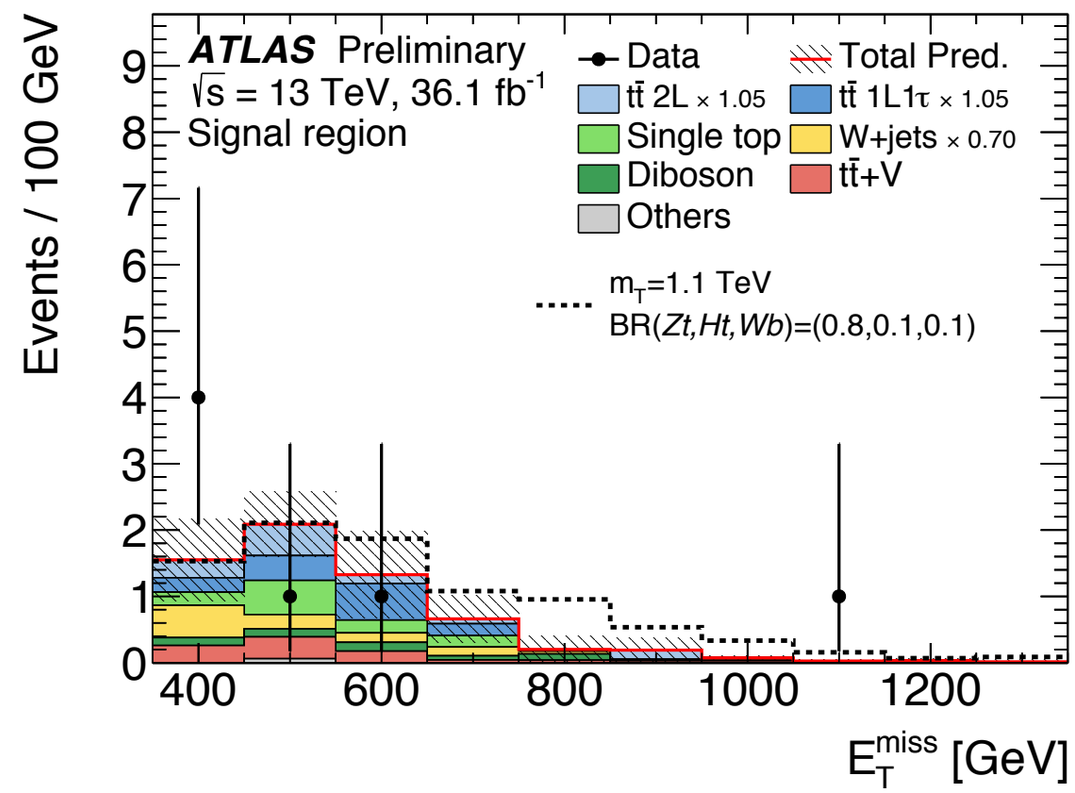


Good agreement within uncertainty

Zt+X: Event yields in the SR

- After the background estimation, data in SR was compared to MC expectation.



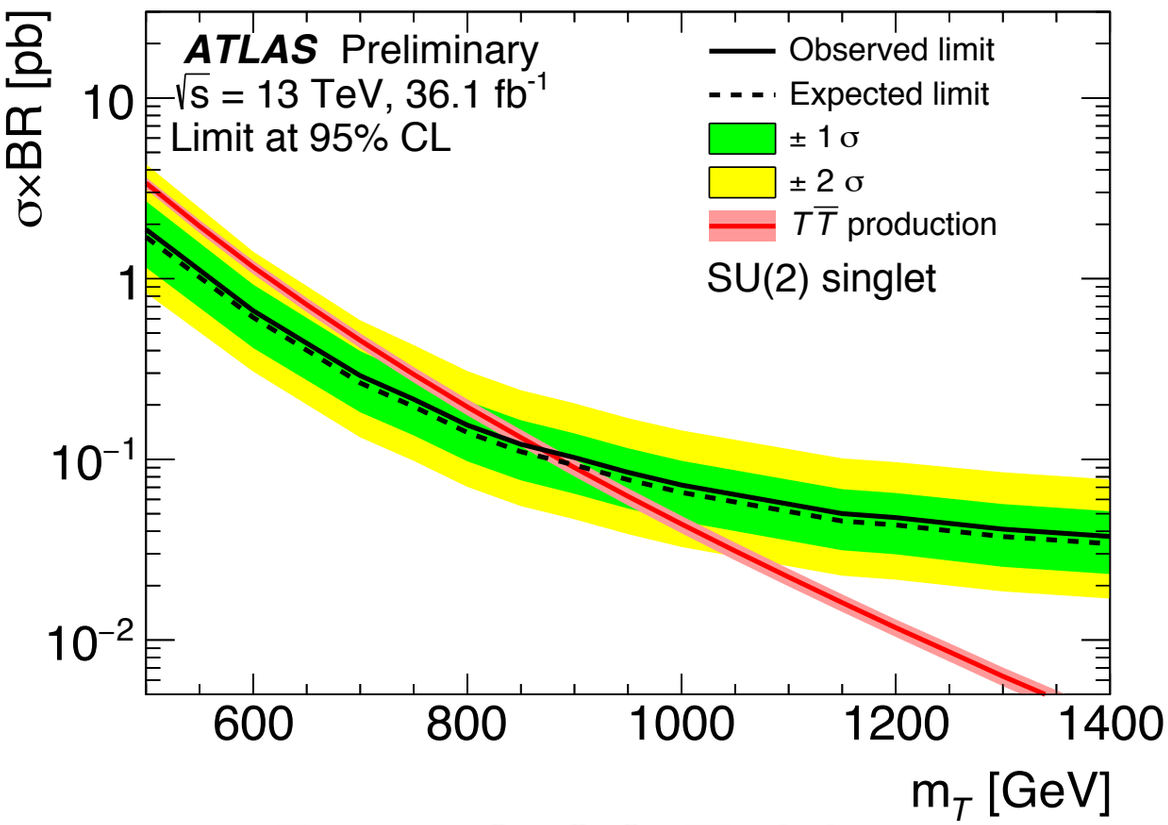


- **MC expectation: 6.1 ± 1.9 events**
- **Data : 7 events**

No excess was observed.

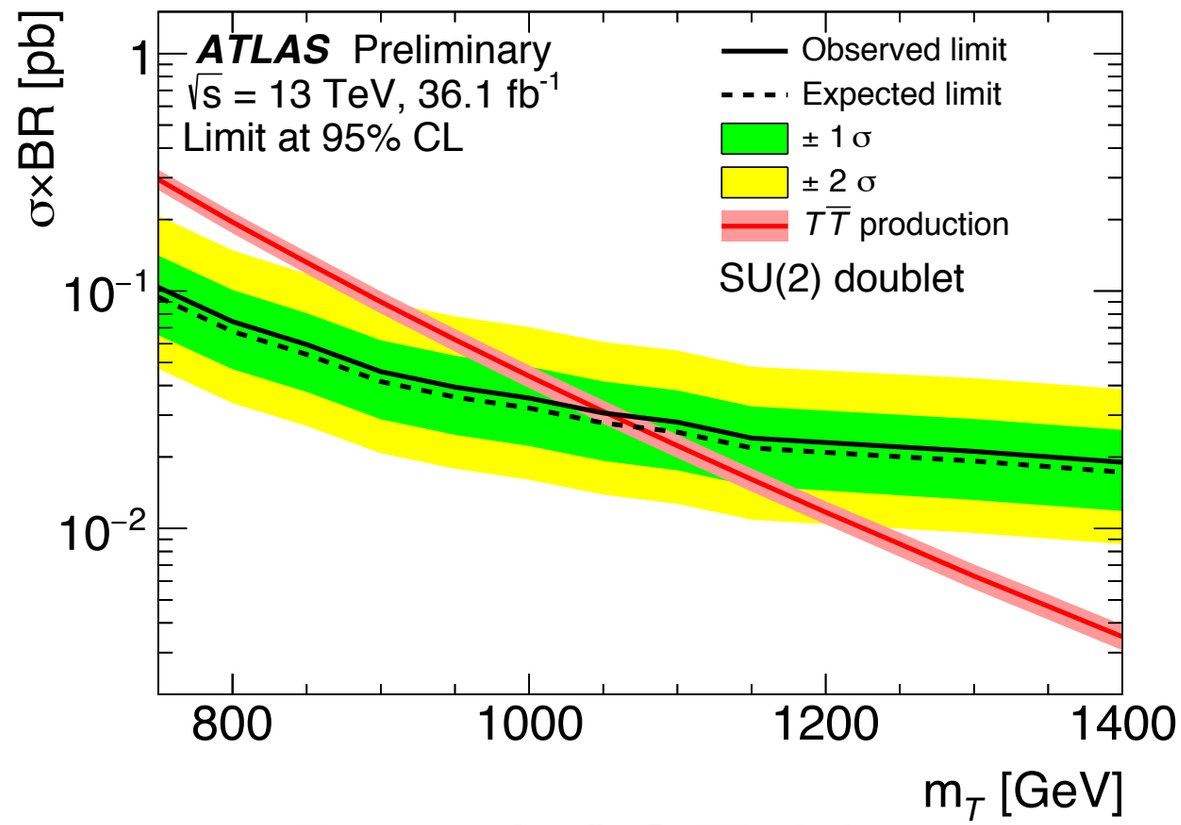
Zt+X: Limits on mass

- Since no excess was observed, the cross section times branching ratio limit was calculated.
- 2 VLQ models (SU(2) singlet and doublet) were taken into account.



Exp: 0.89 TeV

Obs: 0.87 TeV



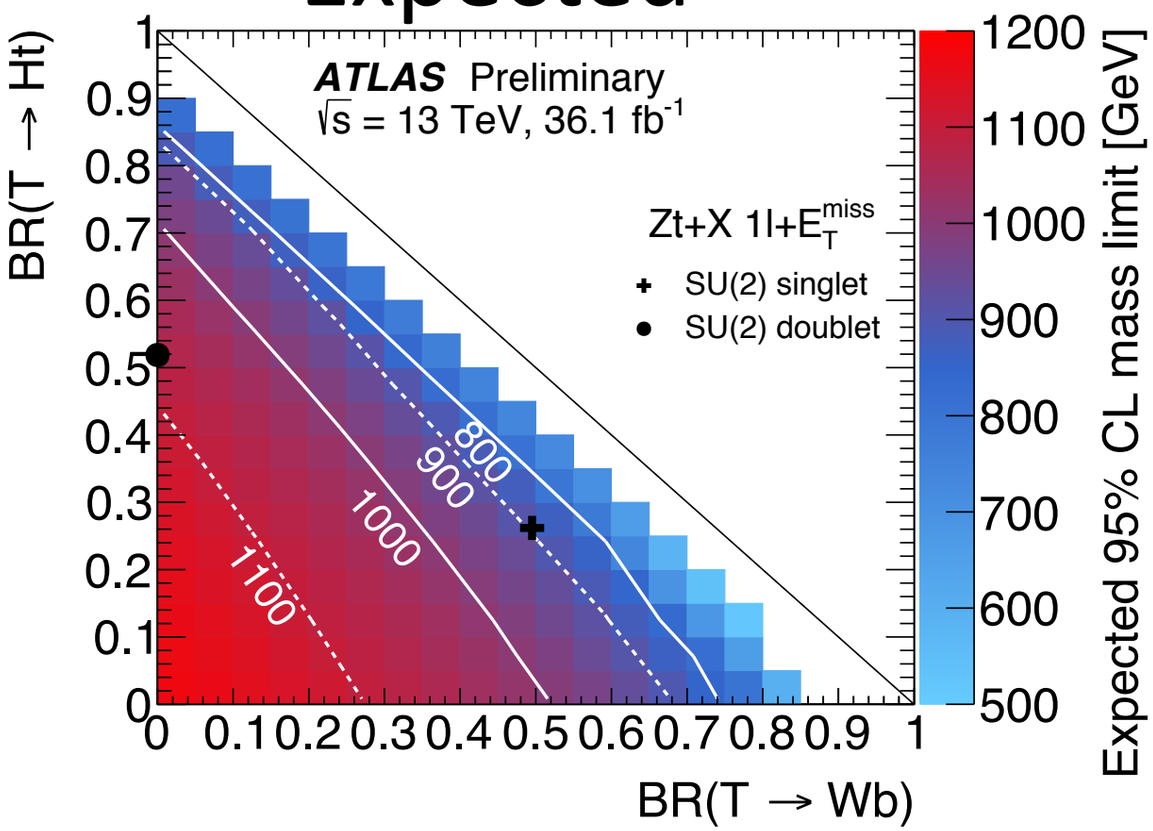
Exp: 1.06 TeV

Obs: 1.05 TeV

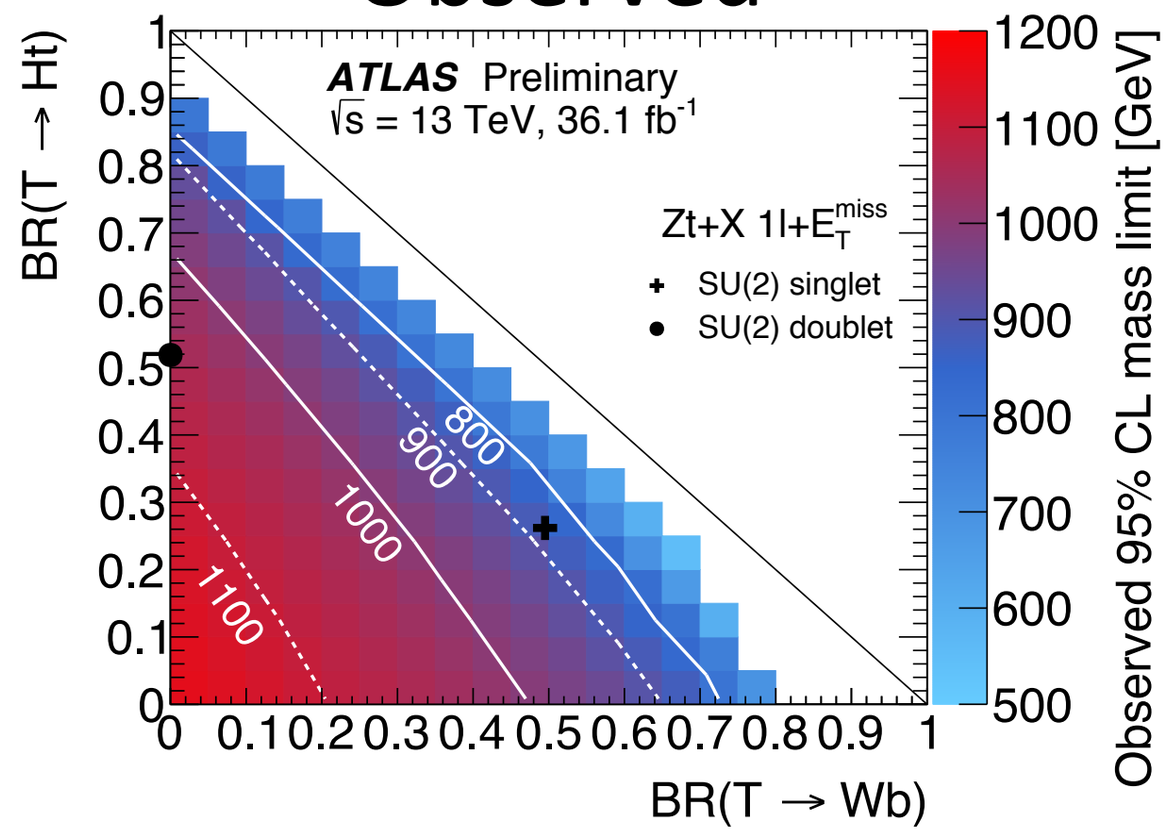
Zt+X: Limits on branching ratio

- Limits on T branching ratio was also calculated.
- Assuming that BR(T->Ht) + BR(T->Wb) + BR(T->Zt)=1

Expected



Observed



Ht+X channel

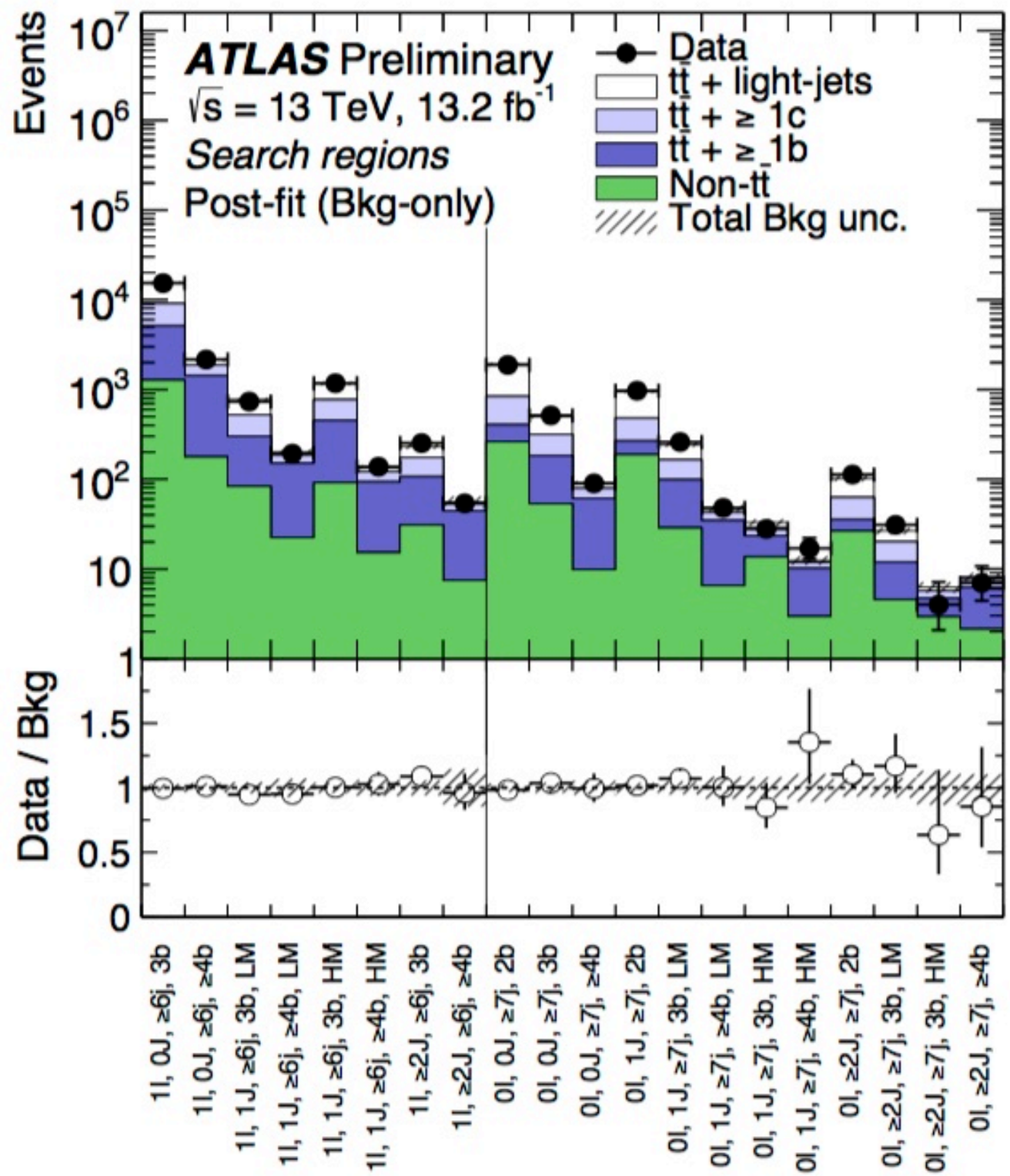
- Target:
  - TT -> Ht + X
  - H decays into a pair of b quarks

- The final state contains
  - large missing transverse momentum
  - multiple jets.
  - 0 or exactly 1 charged leptons.
  - at least 2 b-tagged jet.

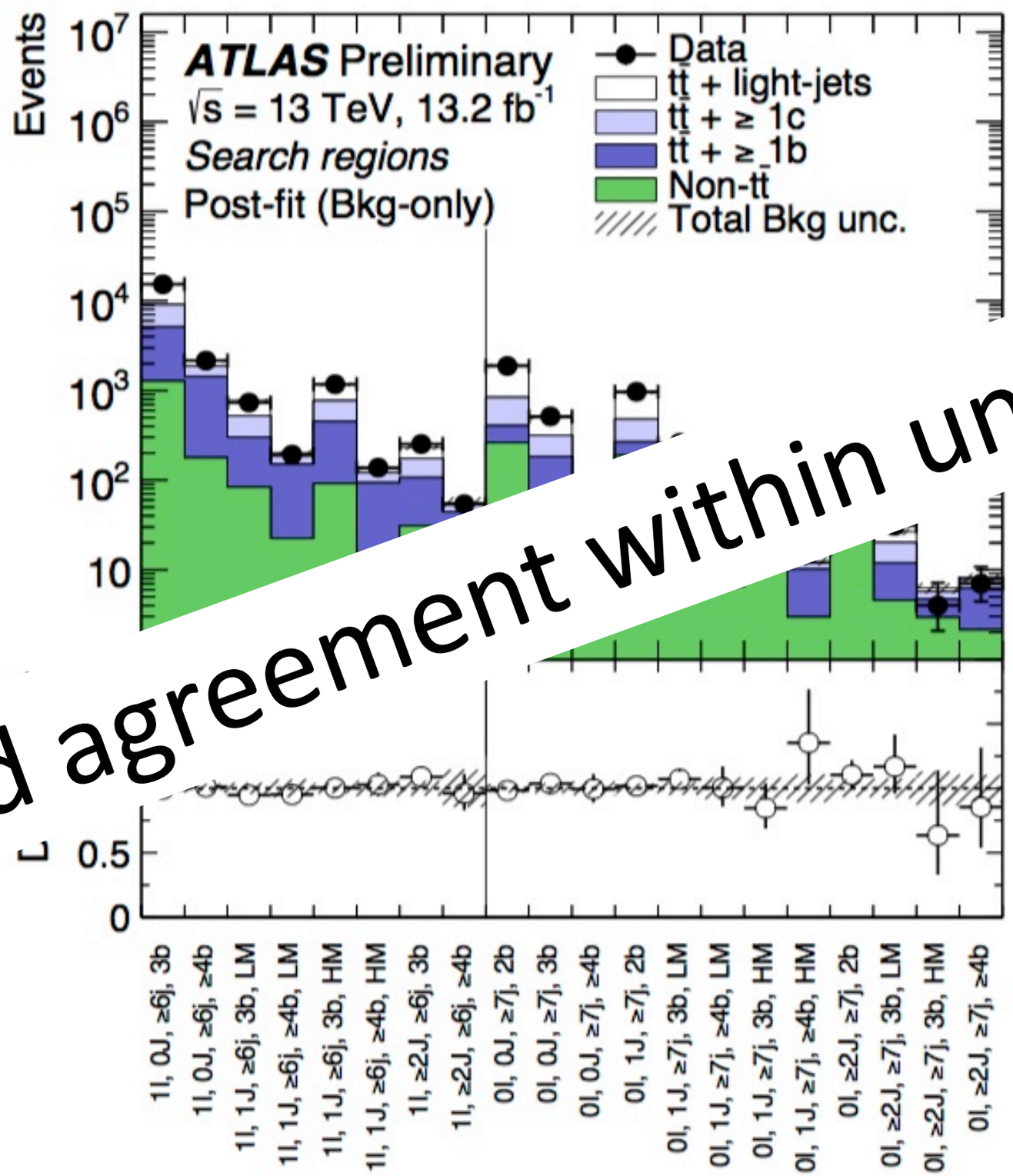
Ht+X: Analysis strategy

- Signal and background are estimated using 0-lepton and 1-lepton channel independently.
  - 1-lepton:
    - background is estimated using 8 search regions and validated using 6 validation regions.
  - 0-lepton:
    - background is estimated using 12 search regions and validated using 9 validation regions.

Ht+X: Data/MC in search regions



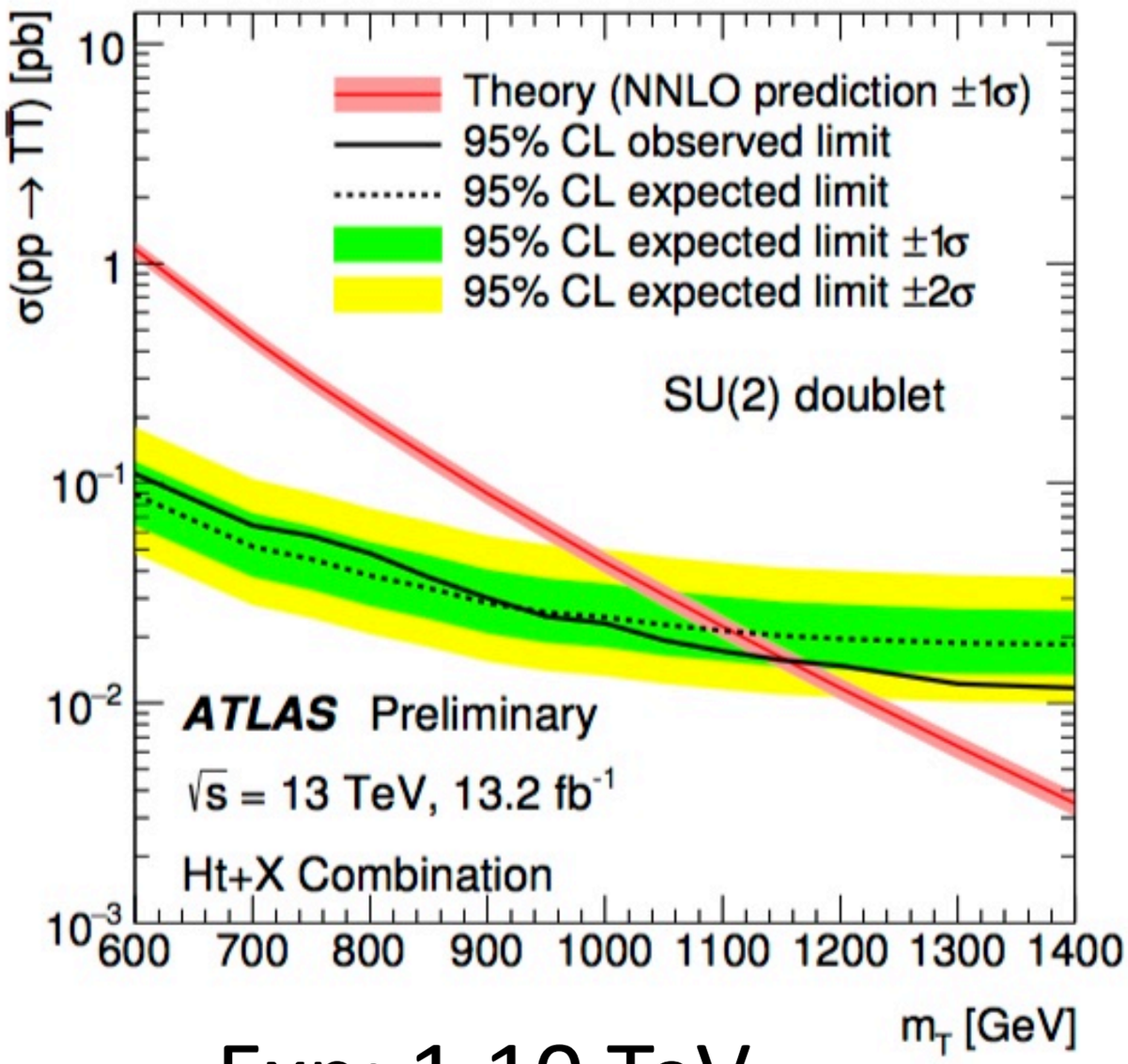
Ht+X: Data/MC in search regions



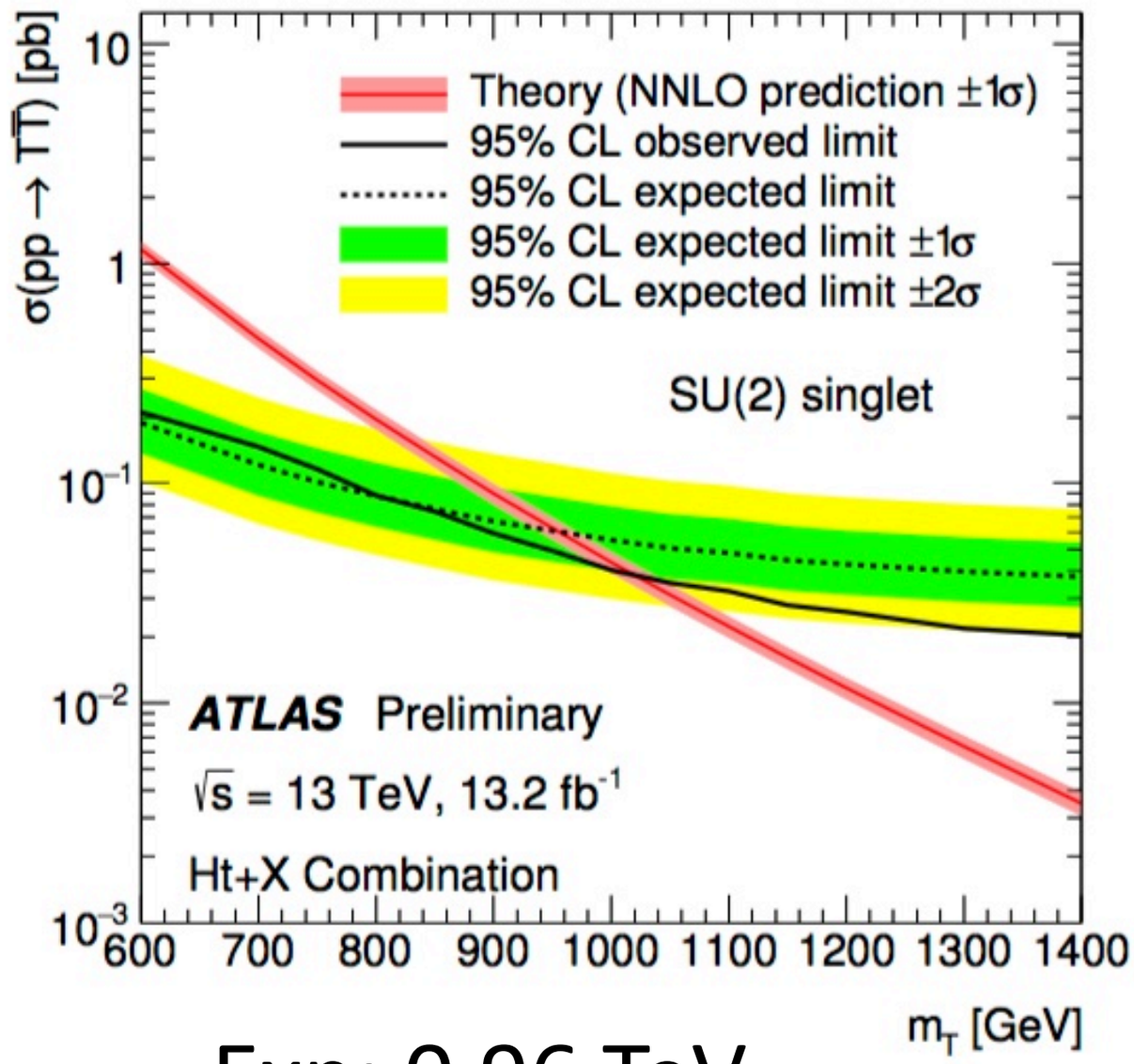
Good agreement within uncertainty

Ht+X: cross section limits

No signal excess over the background was observed in neither 0-lepton nor 1-lepton.
0- and 1-lepton results are combined to set limits.



Exp: 1.10 TeV
Obs: 1.16 TeV

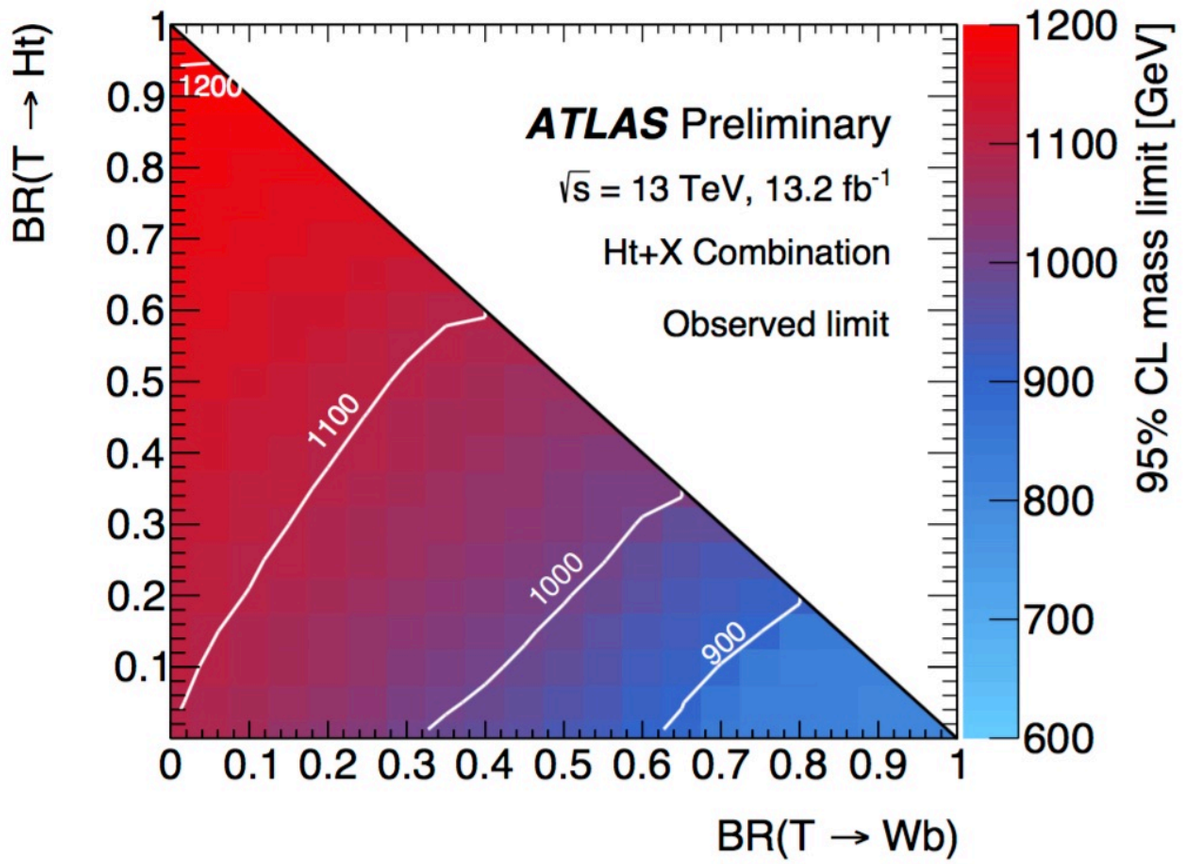


Exp: 0.96 TeV
Obs: 1.02 TeV

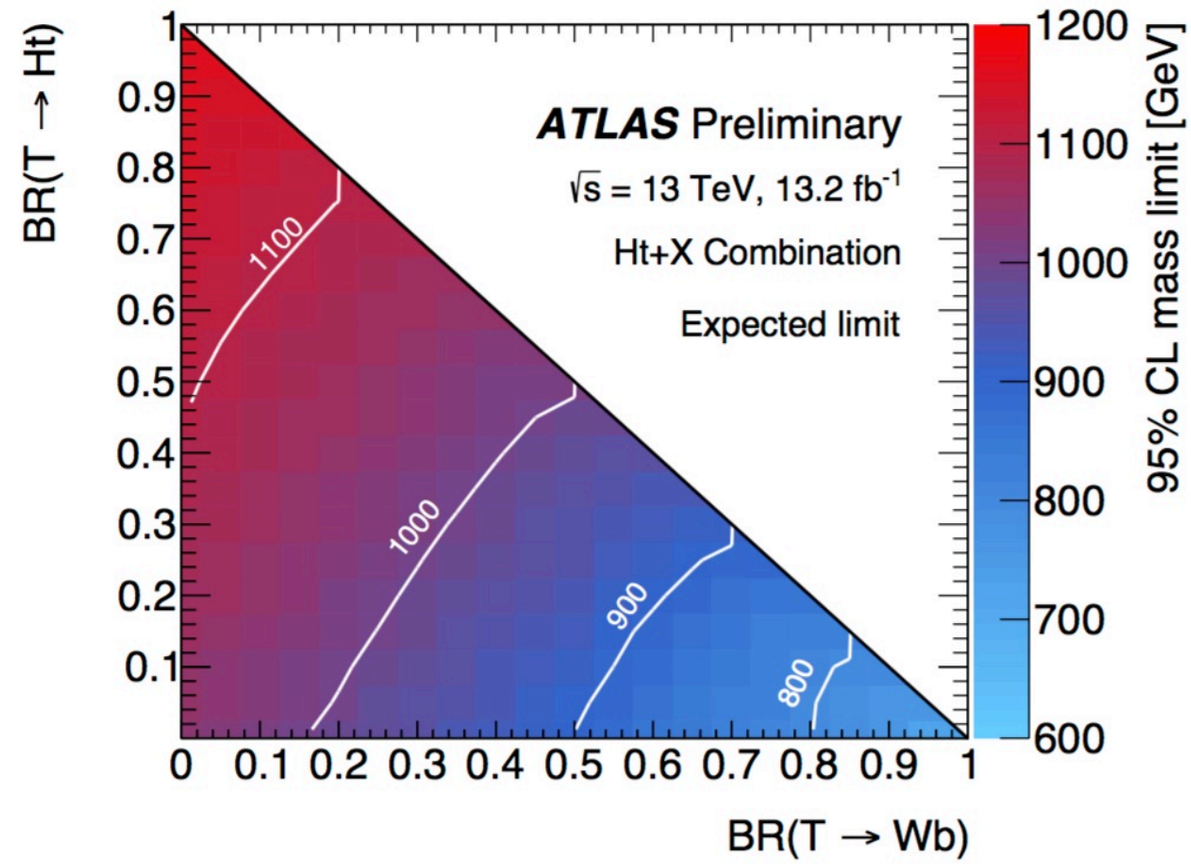
Ht+X: Limits on branching ratio

- Limits on T branching ratio was also calculated.
- Assuming that BR(T->Ht) + BR(T->Wb) + BR(T->Zt)=1

Expected



Observed



Wb channel

- Wb channel search was done using 14.7 fb^{-1} LHC data.

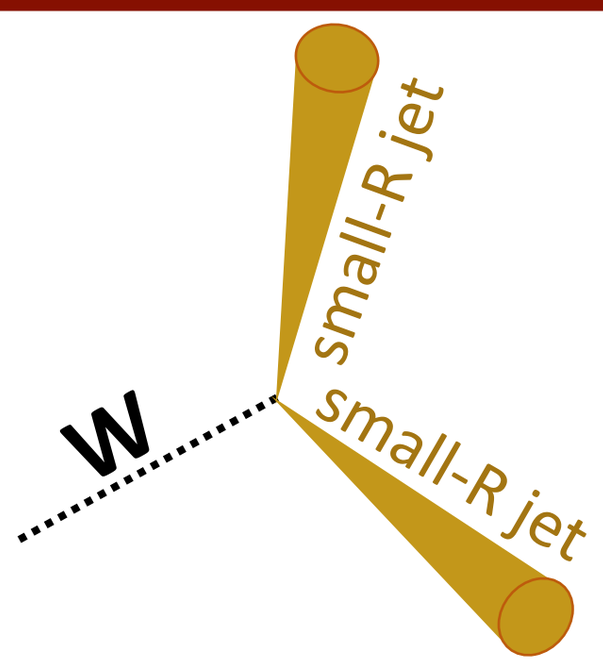
- Target:
  - TT -> Wb+Wb
  - One of W decays leptonically, the other hadronically

- The final state contains
  - large missing transverse momentum(E_T^{miss}) mainly due to the neutrino from W.
  - at least 1 jet.
  - exactly 1 charged lepton.
  - at least 2 b-tagged jet.

Wb: W jet topology

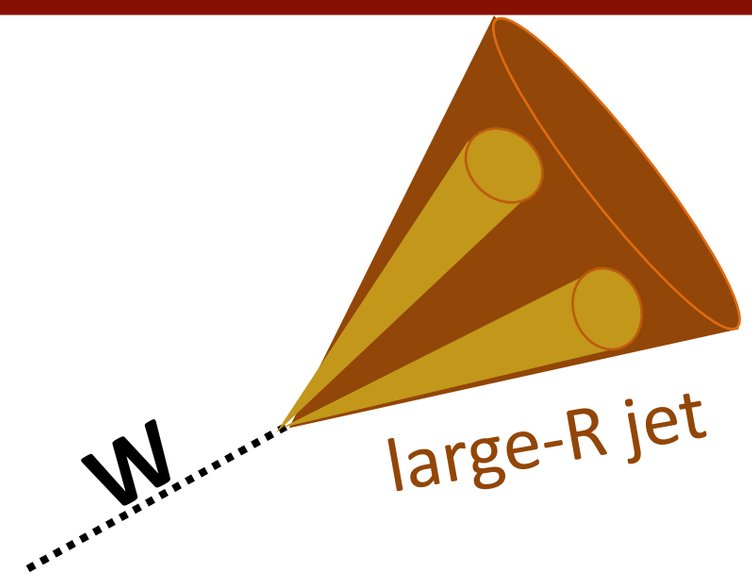
- Boosted and non-boosted(resolved) hadronic W have quite different topology.

Resolved



Hadrons are reconstructed as 2 small-R (R=0.4) jets

Boosted



Hadrons are reconstructed as 1 large-R (R=1.0) jet

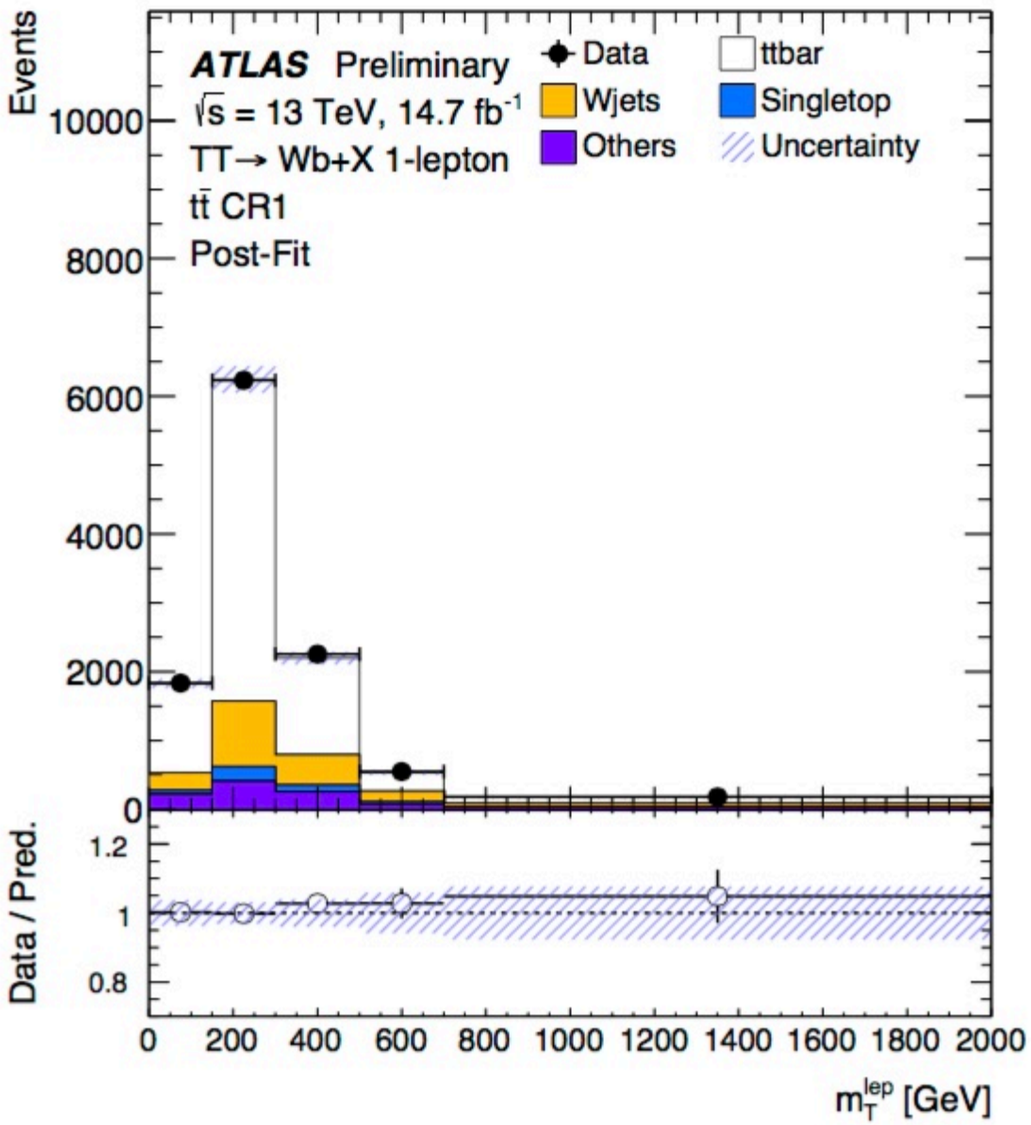
2 signal regions are defined to use both topology.

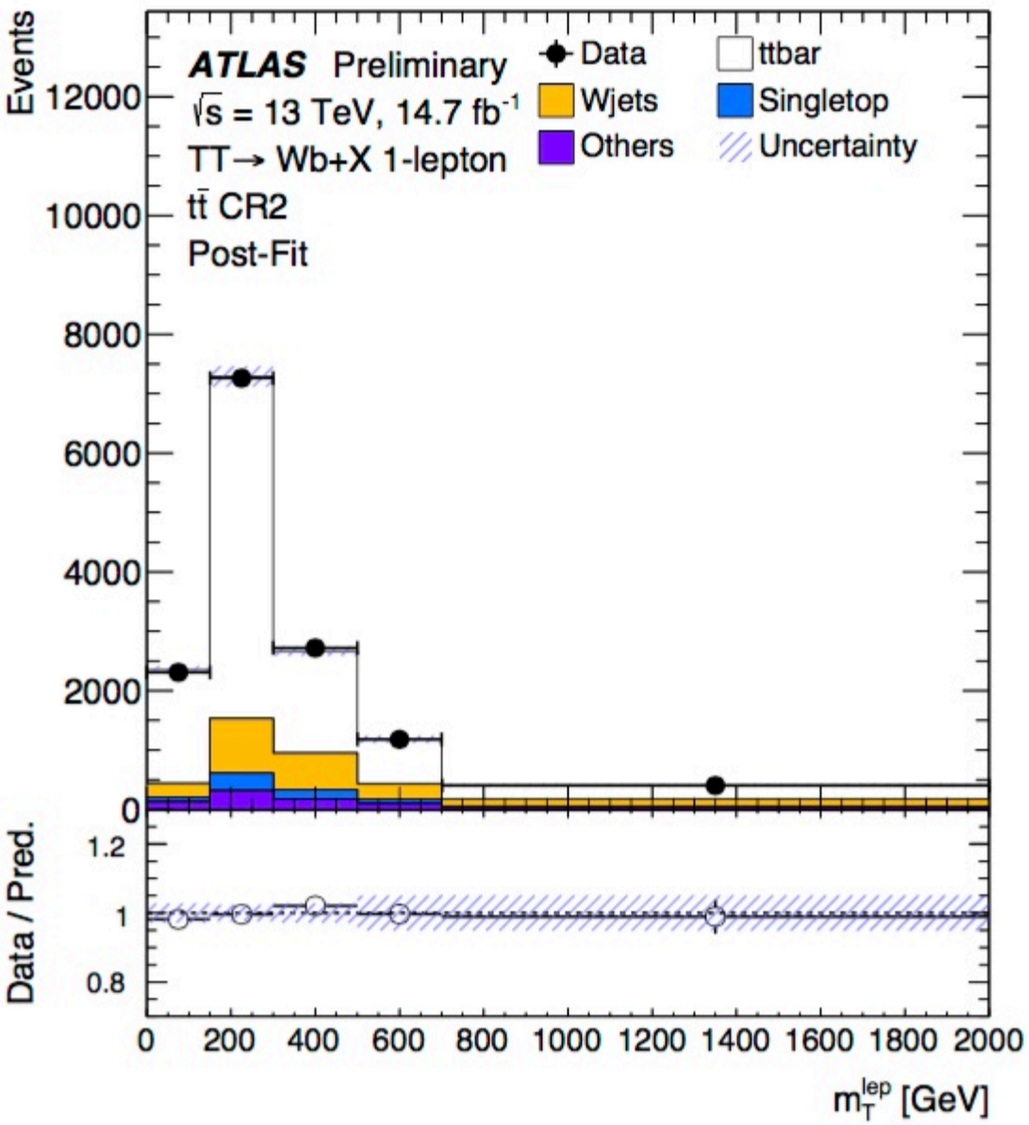
Wb: background estimation

- The dominant background in the Wb channel is $t\bar{t}$.
  Other background W+jet, single top, Diboson, $t\bar{t}$+V, Z+jets, and multi-jets are taken into account.
  - $t\bar{t}$: Estimated by MC.
    Dedicated control regions are used in order to constrain the systematic uncertainty.
  - multi-jets: Estimated with data-driven method.
  - Others: Estimated with MC.

Wb: background estimation

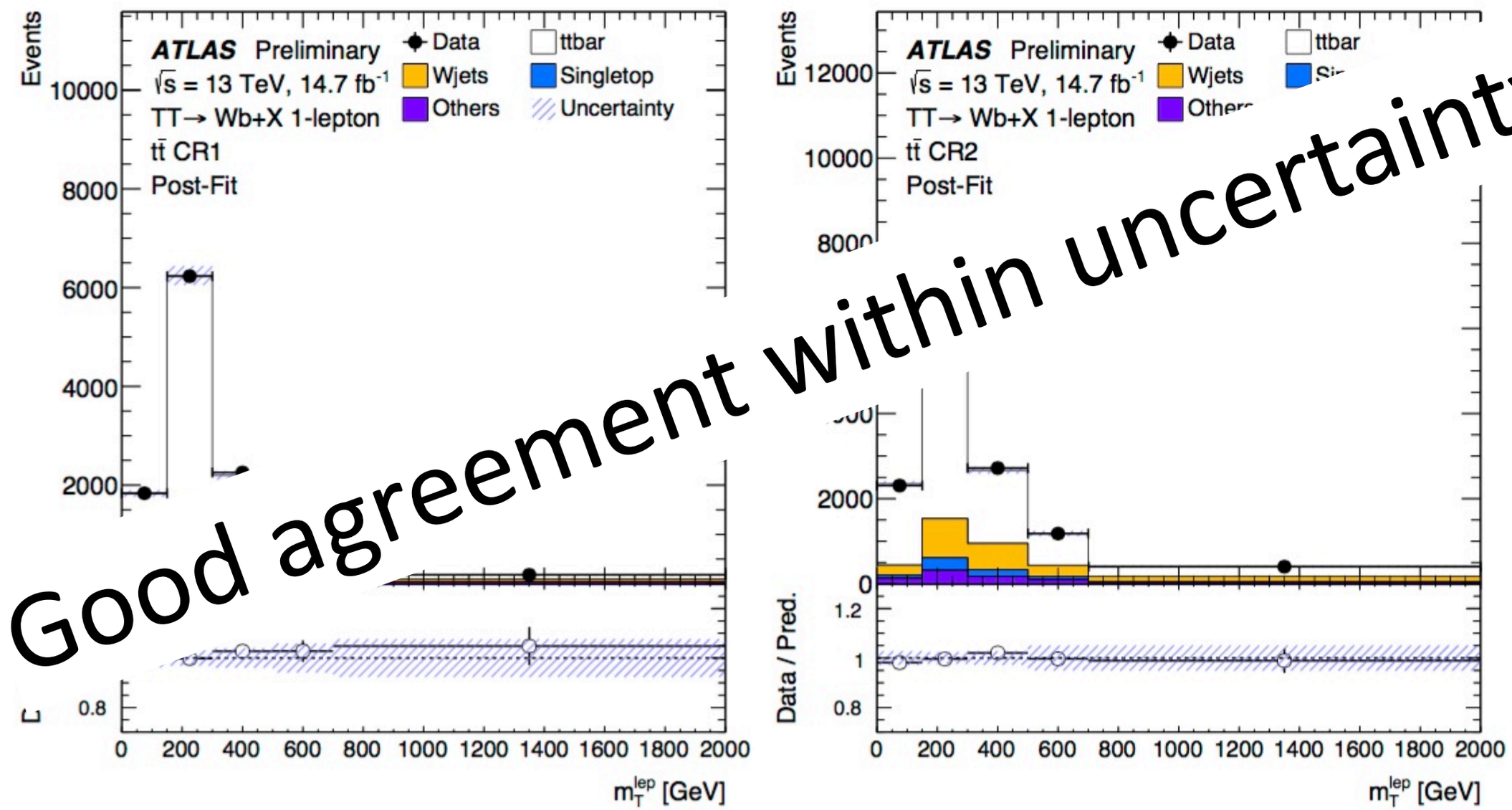
Data/MC comparison in CRs(after estimation)





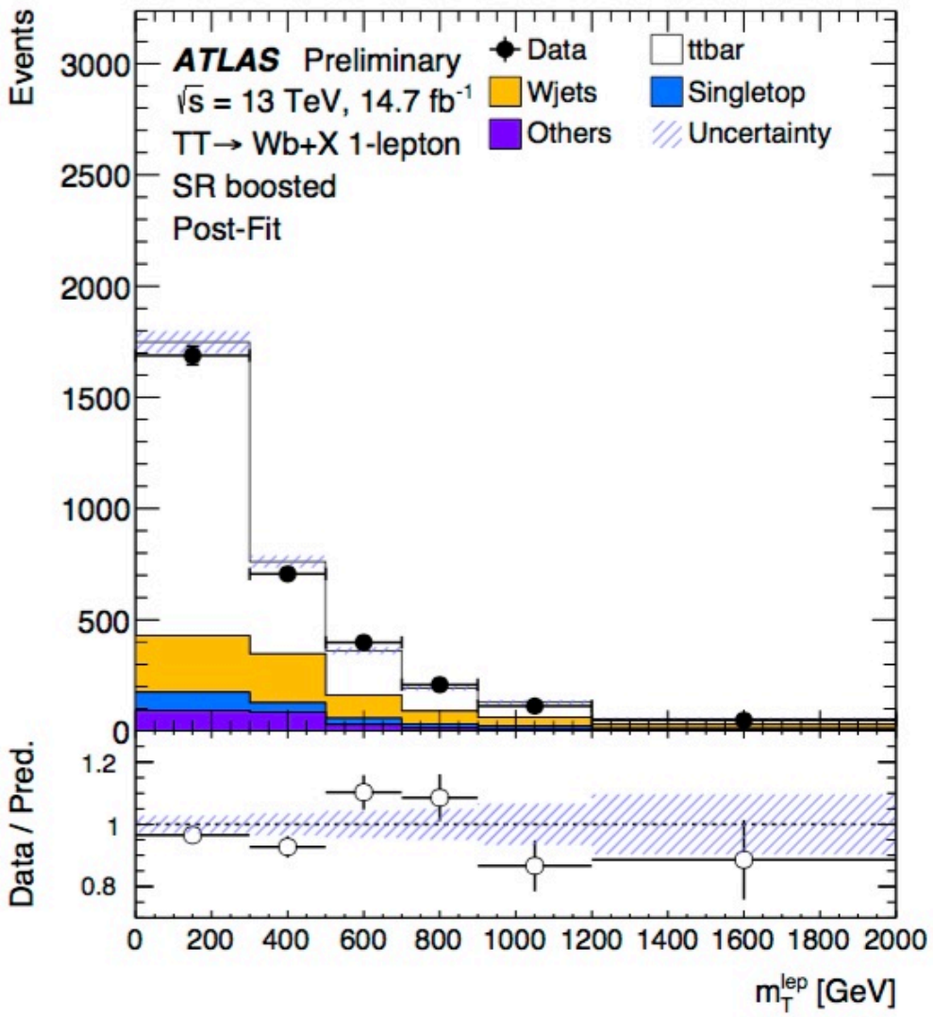
Wb: background estimation

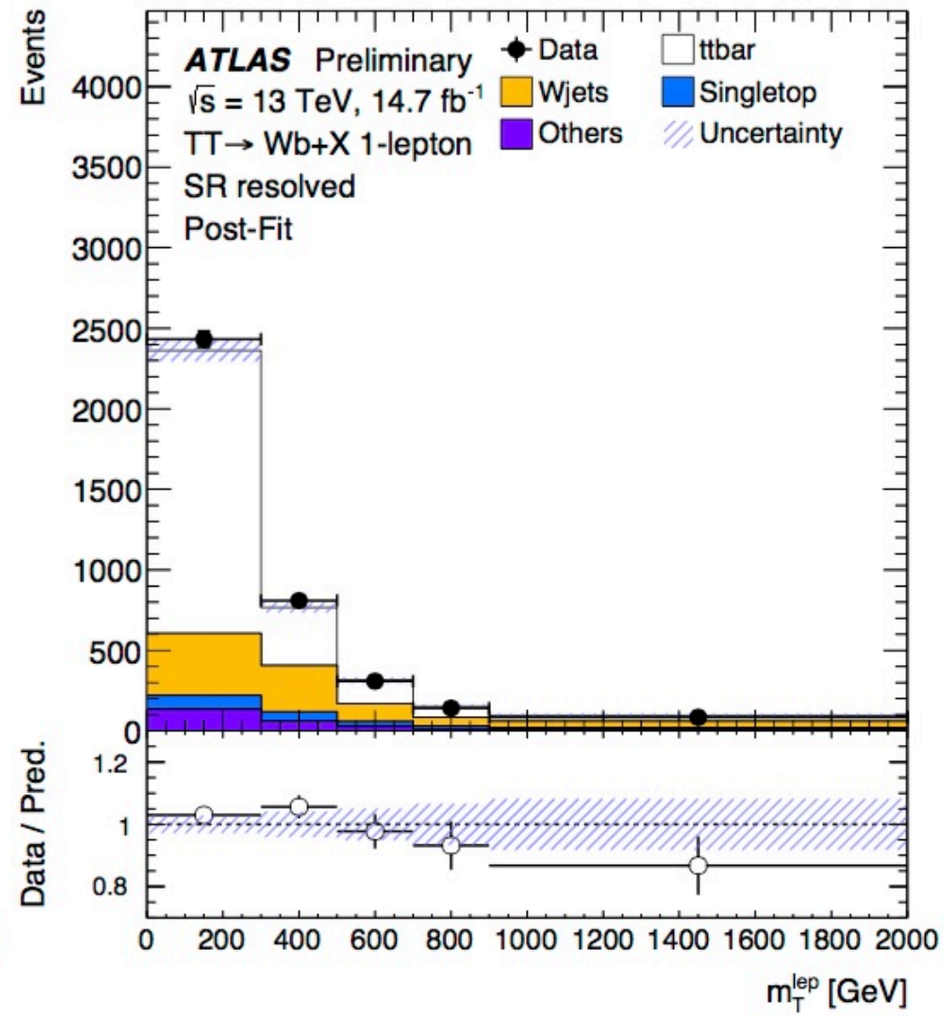
Data/MC comparison in CRs(after estimation)



Good agreement within uncertainty

Wb: Event yields in the SRs





SR boosted

- MC: 3246±81
- Data: 3160

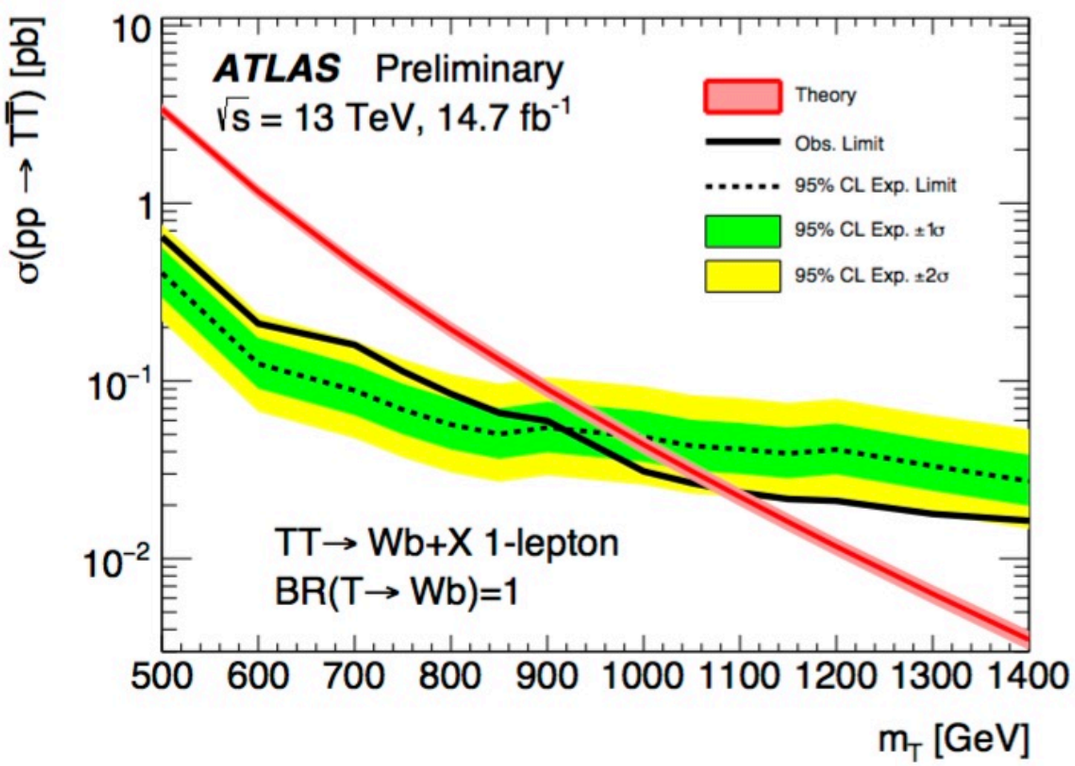
SR resolved

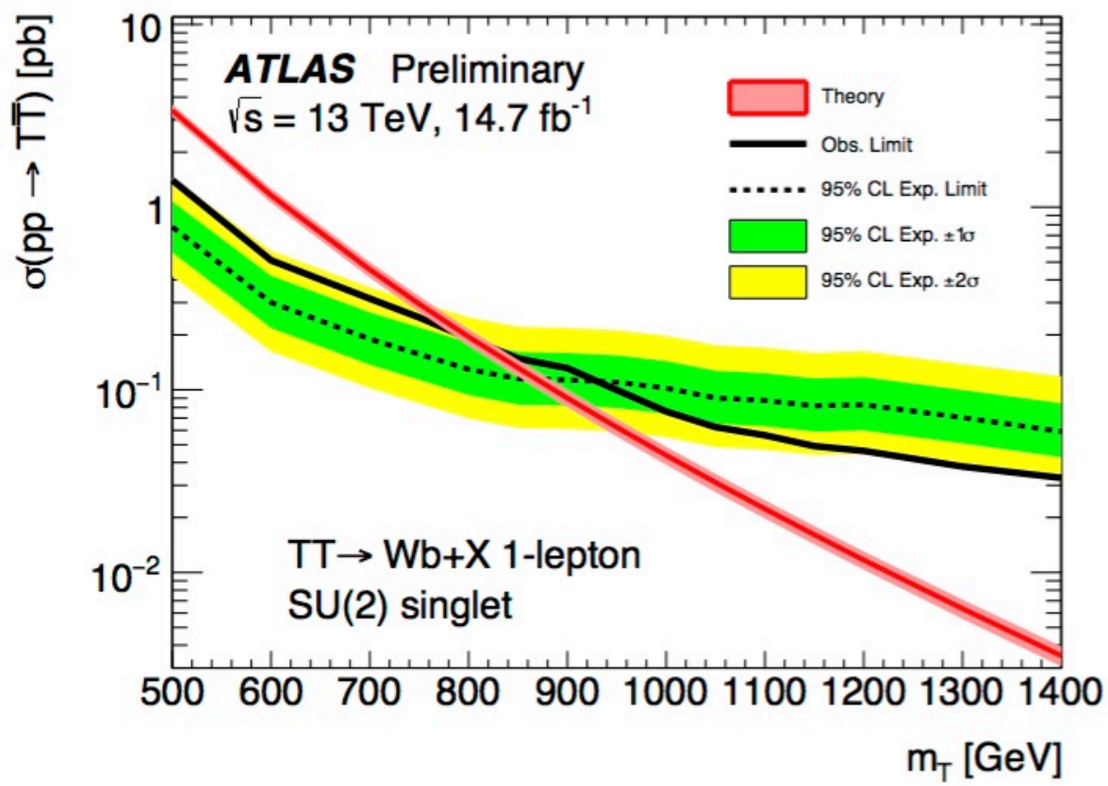
- MC: 3690±100
- Data: 3777

No excess was observed.

Wb: Limits on mass

- Since no excess was observed, the cross section times branching ratio limit was calculated.
- SU(2) singlet model and BR(T->Wb)=1 model are taken into account.





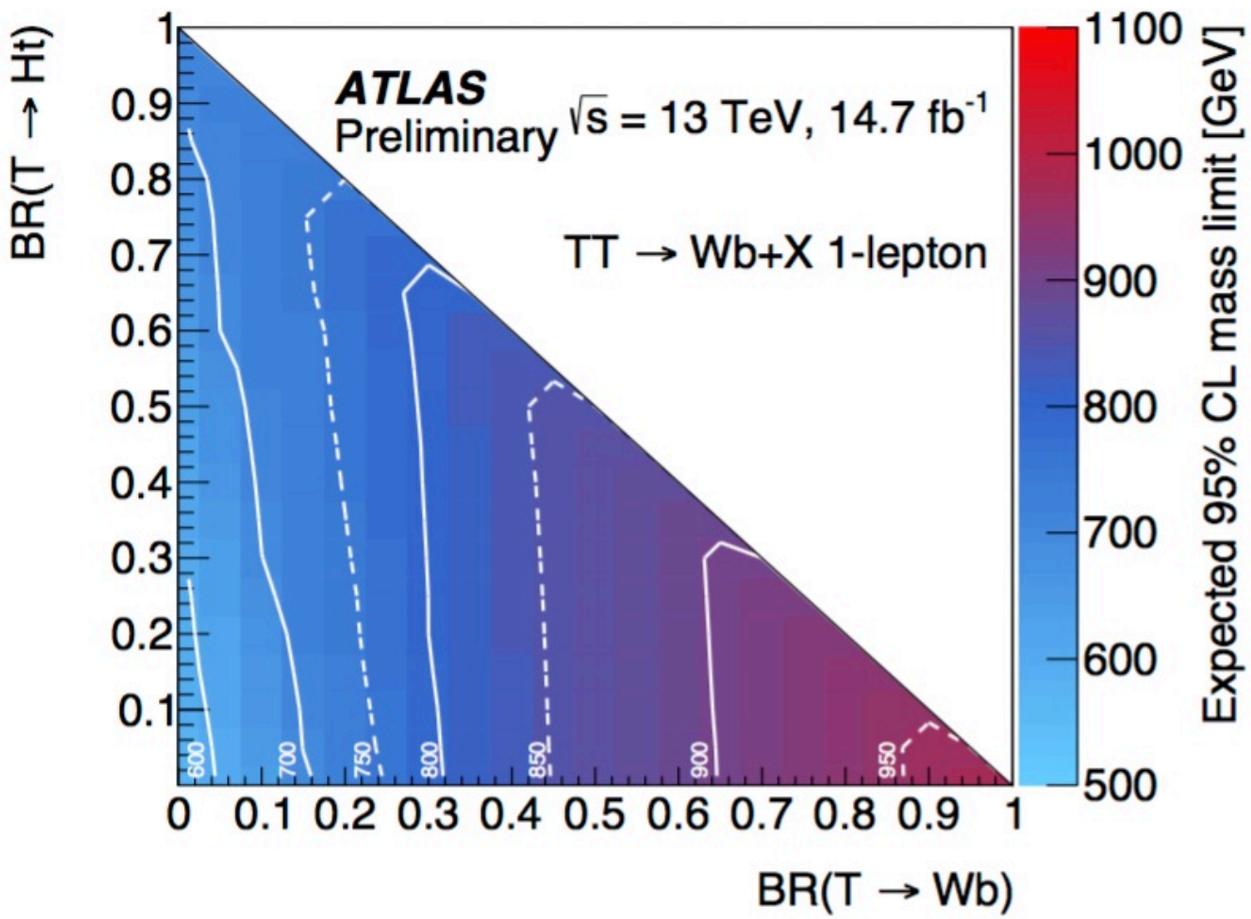
Exp: 0.98 TeV
Obs: 1.09 TeV

Exp: 0.87 TeV
Obs: 0.81 TeV

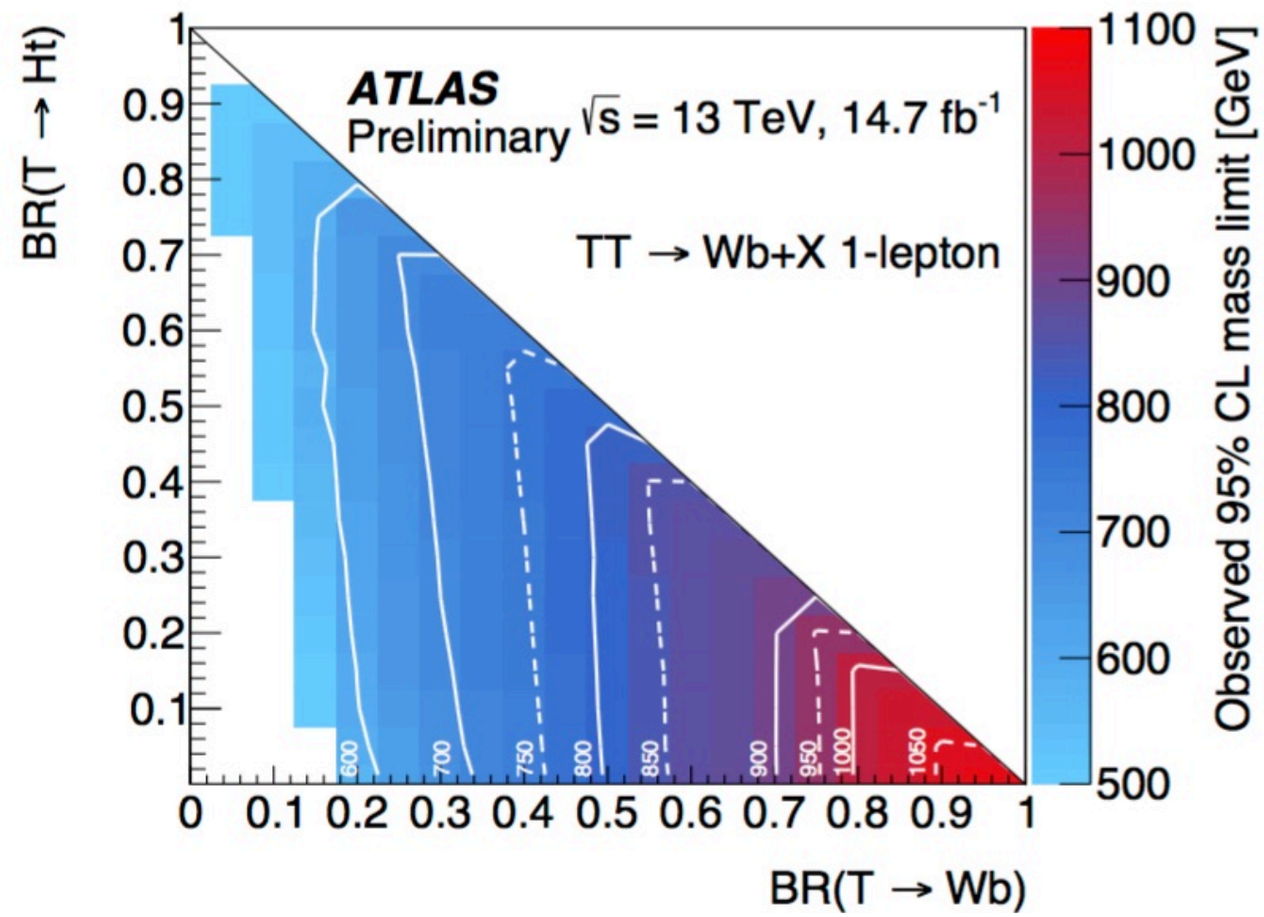
Wb: Limits on branching ratio

- Limits on T branching ratio was also calculated.
- Assuming that BR(T->Ht) + BR(T->Wb) + BR(T->Zt)=1

Expected



Observed



Summary

- ATLAS VLQ search was done using the LHC 13TeV data.
- Search was done using many channels.
- No excess over MC expectation was observed.
- 95% CL limit was set:
  - 0.87 TeV (Zt+X channel, SU(2) singlet)
  - 1.05 TeV(Zt+X channel, SU(2) doublet)
  - 1.02 TeV(Ht+X channel, SU(2) singlet)
  - 1.16 TeV(Ht+X channel, SU(2) doublet)
  - 1.09 TeV (Wb channel, BR(T->Wb)=1)
  - 0.81 TeV (Wb channel, SU(2) singlet)

Back up

VLQ production cross section