Search for new physics in ttbb final states with the ATLAS detector: ttH(bb) and beyond

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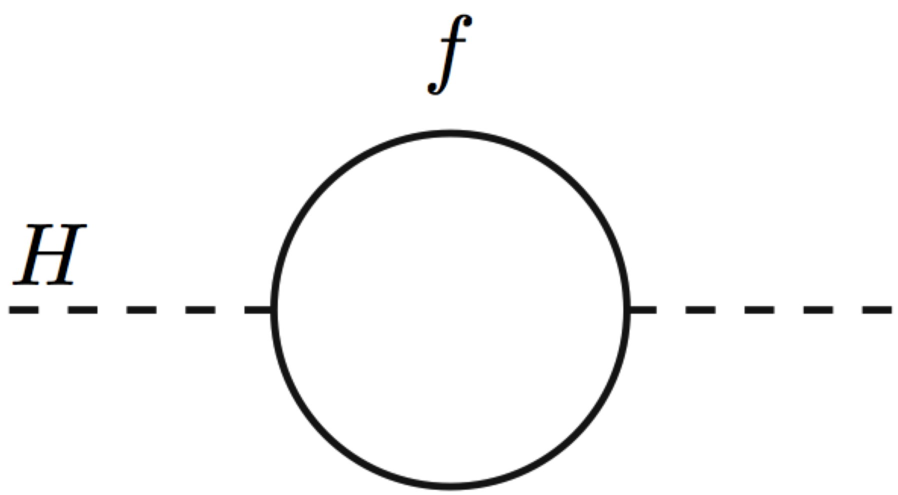
The hierarchy problem

- Why is the difference between M_{EW} (10^2 GeV) and M_P (10^{18} GeV) so large?
- The mass of the Higgs boson is at M_{EW} but radiative corrections are order M_P



$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{16\pi^2}\left[2\Lambda^2 + \mathcal{O}\left(m_f^2 \ln\left(\frac{\Lambda}{m_f}\right)\right)\right]$$

- Top quark is the most strongly-coupled SM particle with $Y_t \sim 1$
  - special role in electroweak symmetry breaking?

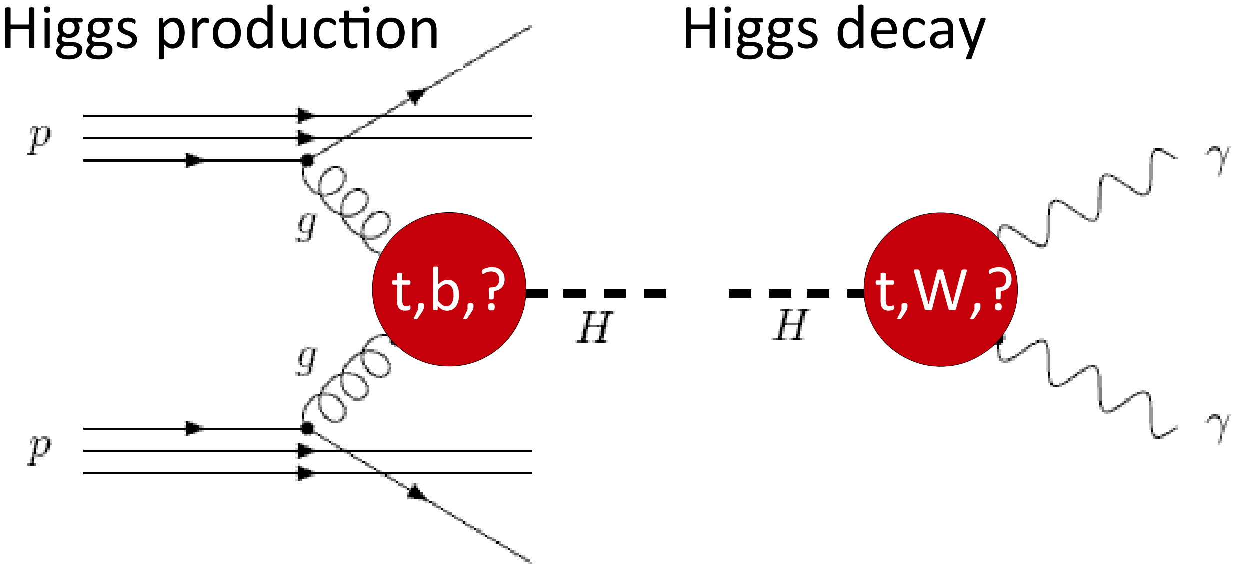
The top Yukawa coupling

- After the Higgs discovery, time to measure the couplings to fermions and gauge bosons

- Already indirect constraints on the top-Higgs Yukawa coupling
  - assumes no new particles in the loop

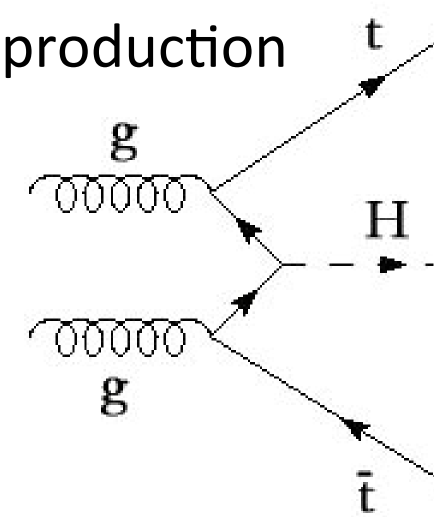
Higgs production

Higgs decay



- Direct measurement of Y_t in ttH production
  - allows probing new physics in ggH and γγH effective vertices

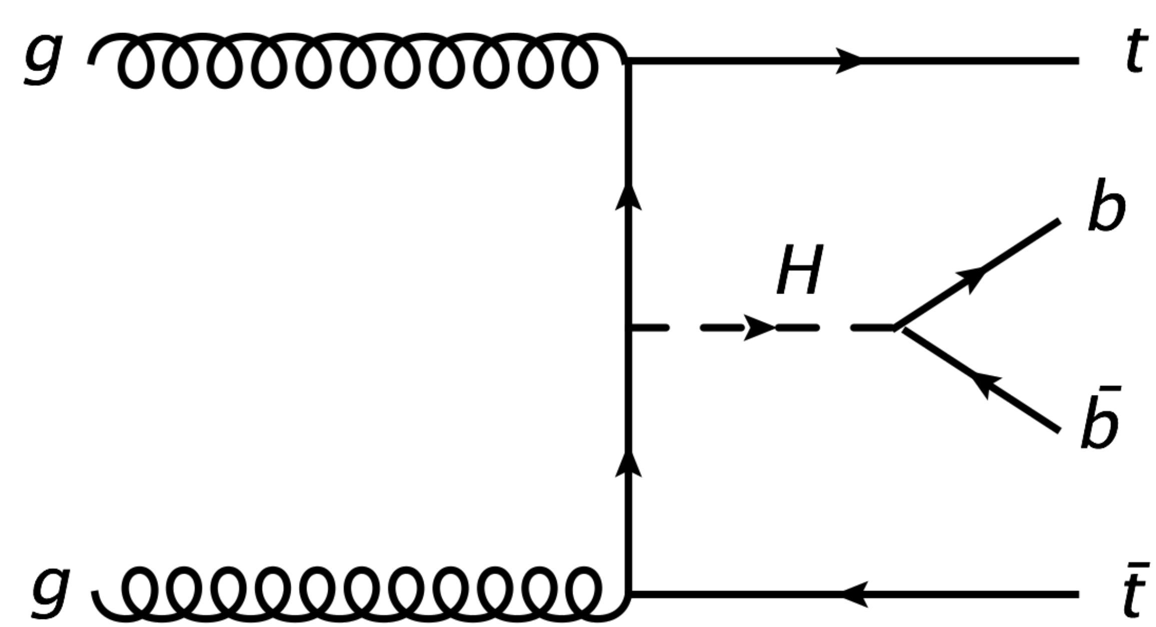
ttH production



$$\sigma(\mathbf{t\bar{t}H}) \propto \mathbf{g^2_{ttH}}$$

ttH production

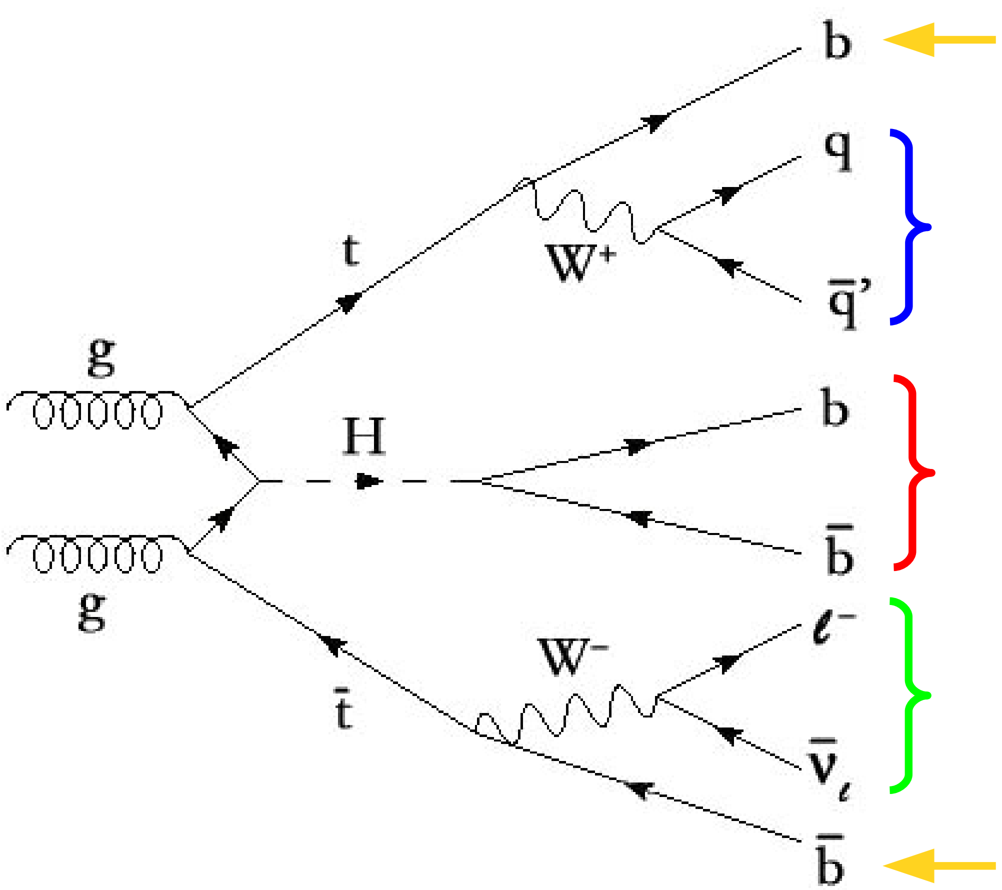
- **Production**
  - σ(ttH) is known at NLO QCD
  - suppressed compared to other Higgs production modes
  - ≈ 2600 events in 20.3 fb^{-1} at 8 TeV
- **Decay**
  - Focusing on the decay H → bb
  - Highest branching ratio (58%) but large backgrounds



- **Main background**
  - tt+X, 2000 times higher cross section
  - Very challenging final state, with high jet and b-tag multiplicity, large systematic uncertainties, both theoretical and experimental
- **Search for ttH focusing on the decay H → bb in the lepton+jets (and dilepton) channels**

http://arxiv.org/abs/1503.05066

ttH signal features

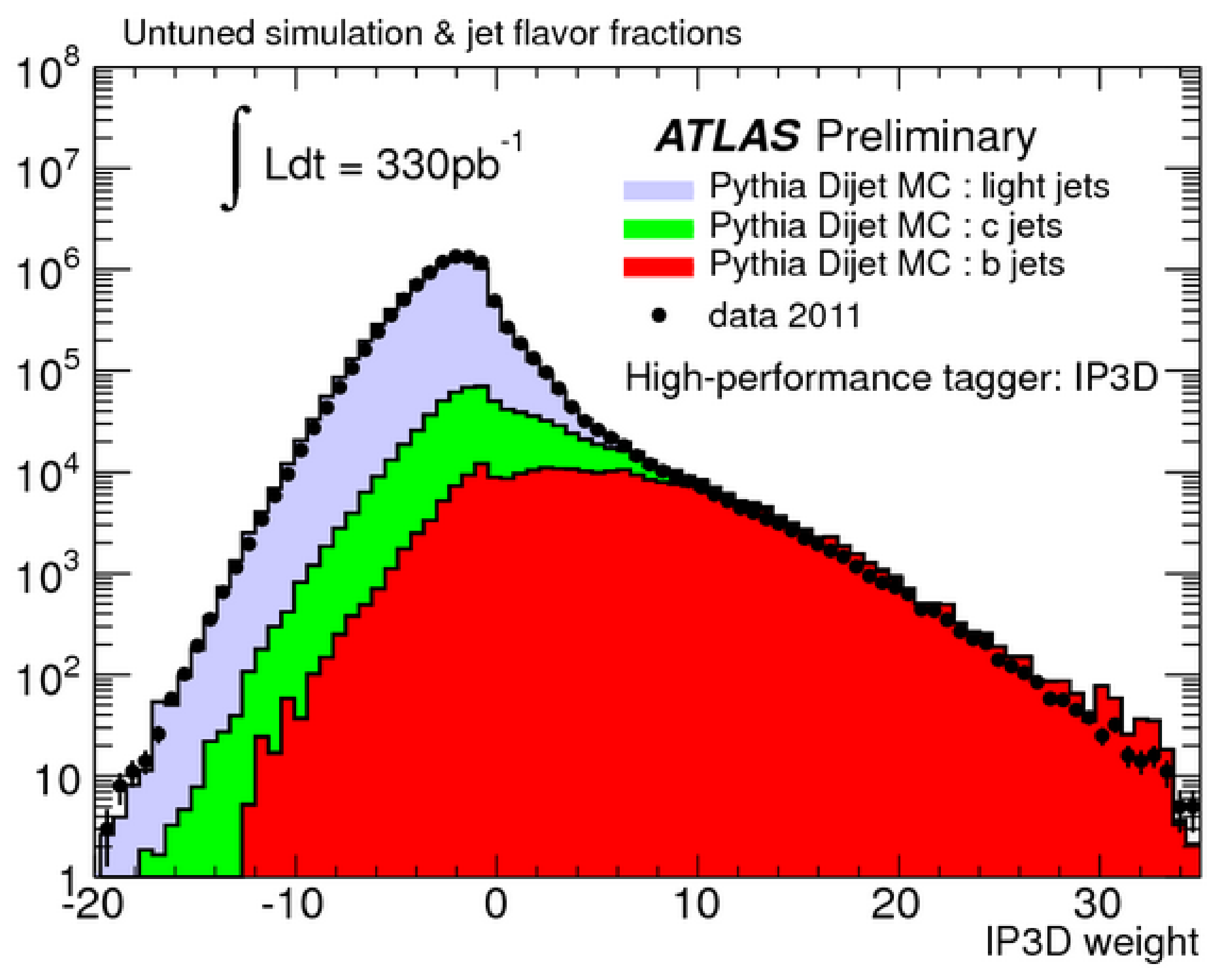


- **ttH(bb) in the lepton+jets channel**
  - 1 leptonic W, isolated electron or muon used to trigger the event
  - 1 hadronic W, produces two jets
  - 2 b's from top decays
  - 2 b's from Higgs decay

- The signal in the detector is an isolated lepton, missing transverse energy from the escaping neutrino and 6 jets
  - 4 of the jets are originated from b-quarks

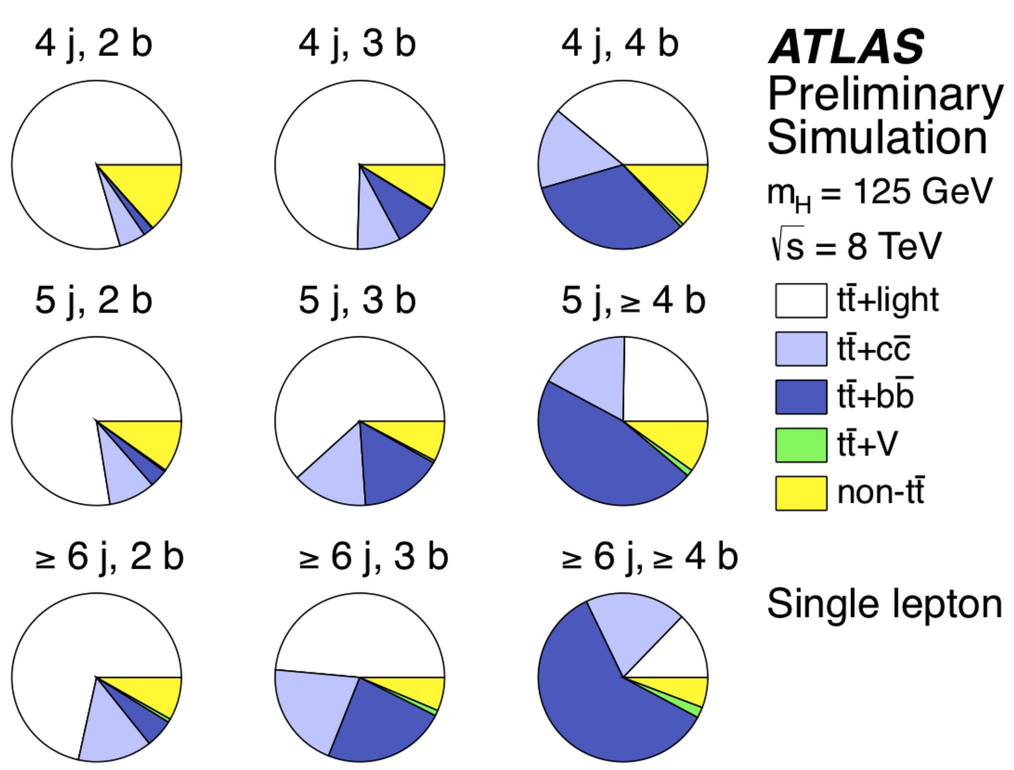
Identifying b-quarks

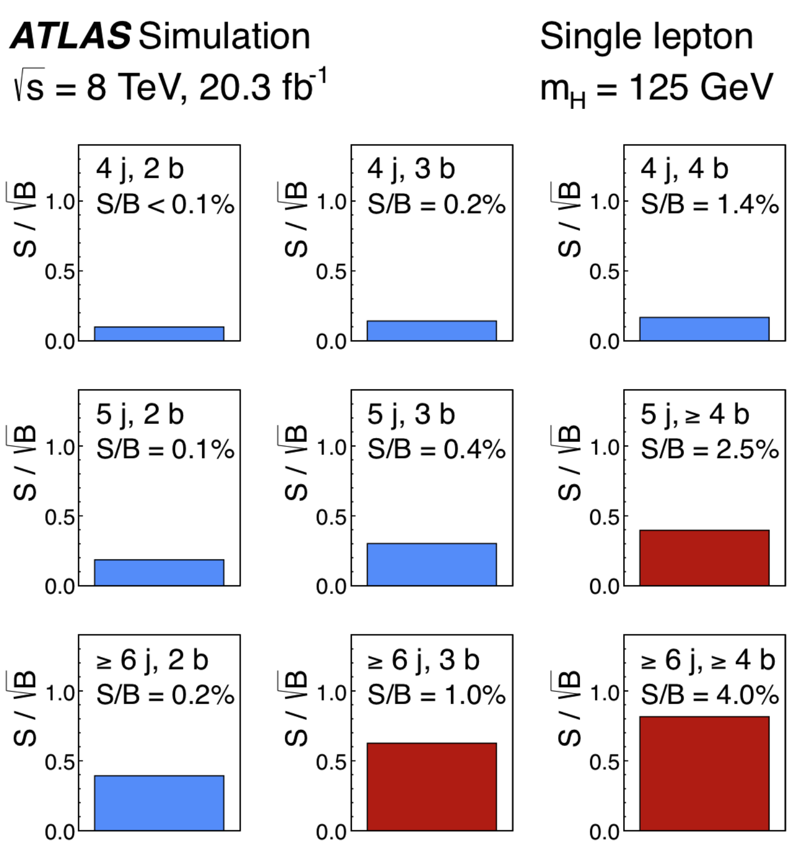
- B-hadrons have interesting properties compared to lighter hadrons
  - Long lived: $\tau \sim 1.5$ ps → decays several milimeters away from the interaction point
  - Massive: order 5 GeV → reconstruct mass with the tracks matched to the jet
- Several features can be used to identify jets originated from b-quarks



Analysis strategy

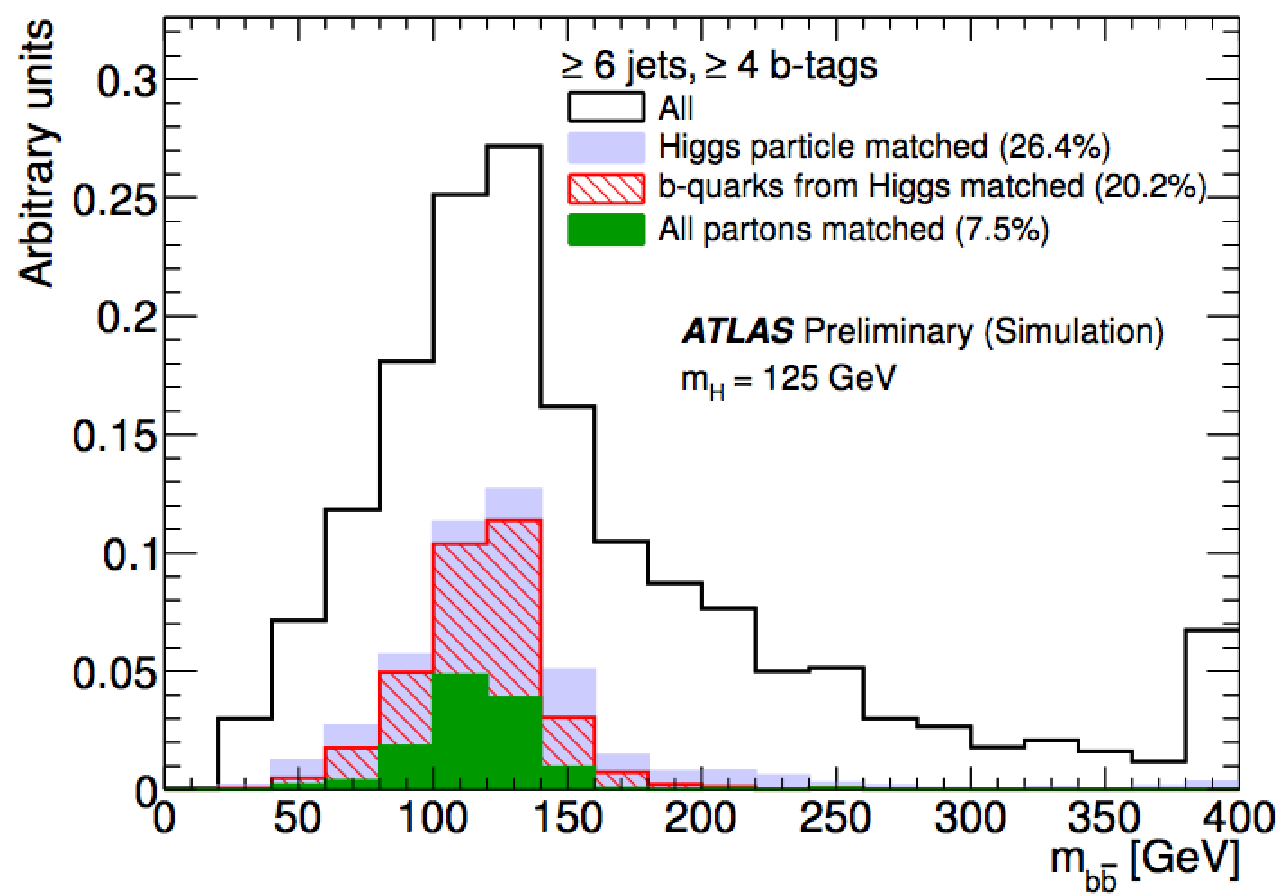
- Extract the ttH(bb) signal from a fit to data
- Very large systematics:
  - tt+heavy flavor modeling, b-tagging, JES
- **Profiled likelihood fit**, in order to constrain in-situ the leading systematics
- Analysis channels defined splitting in jet and b-tag multiplicities
- Signal-depleted channels play a key role constraining systematic uncertainties





Discriminant variable

- Main difference between ttH(bb) and ttbb → Higgs resonance
  - 4 b-jets in the event → 12 possibilities to build M_{bb}
  - Even with a kinematic likelihood fit of the event to identify the ttbar system, only 20% of the times we pick the correct permutation.



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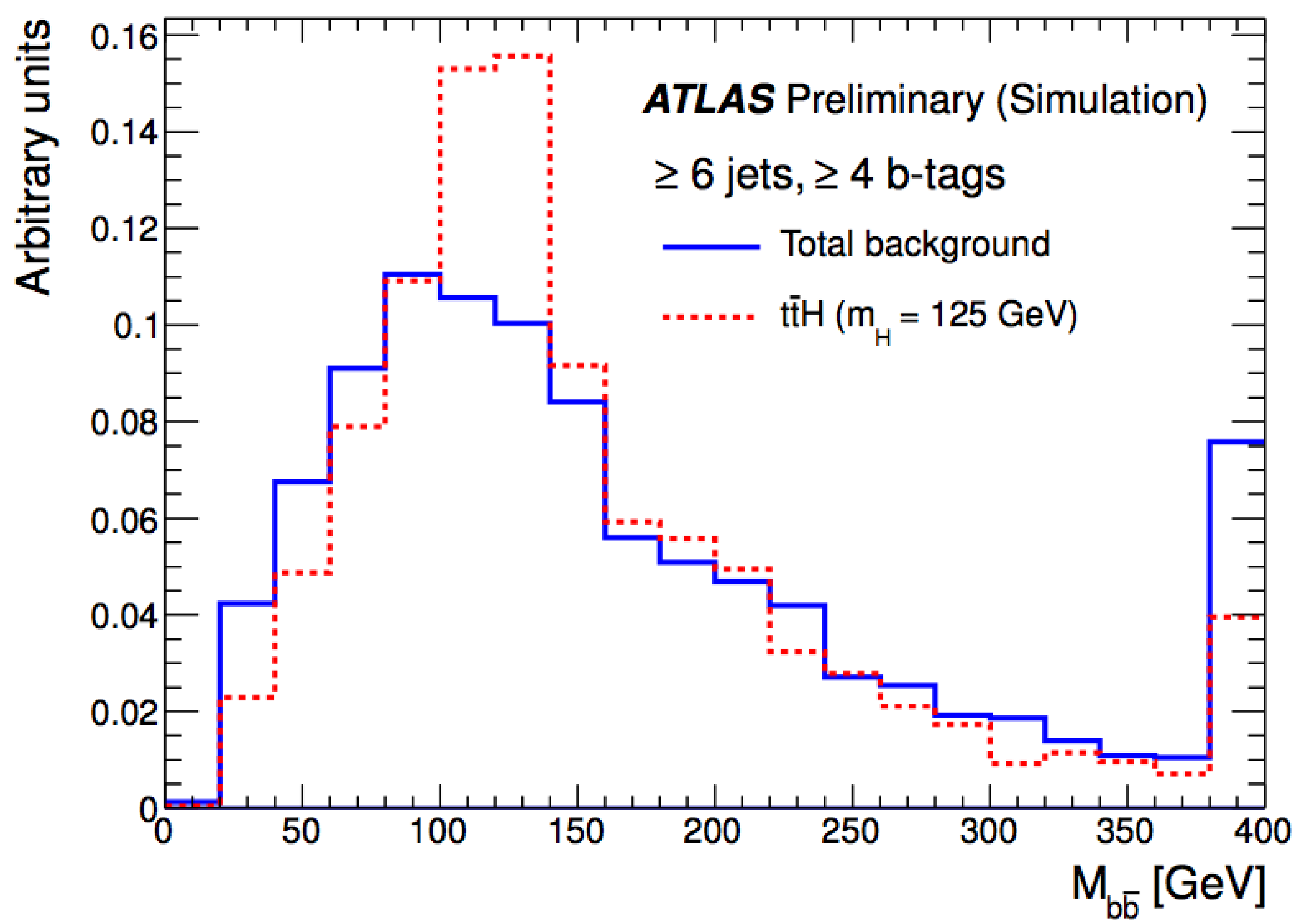
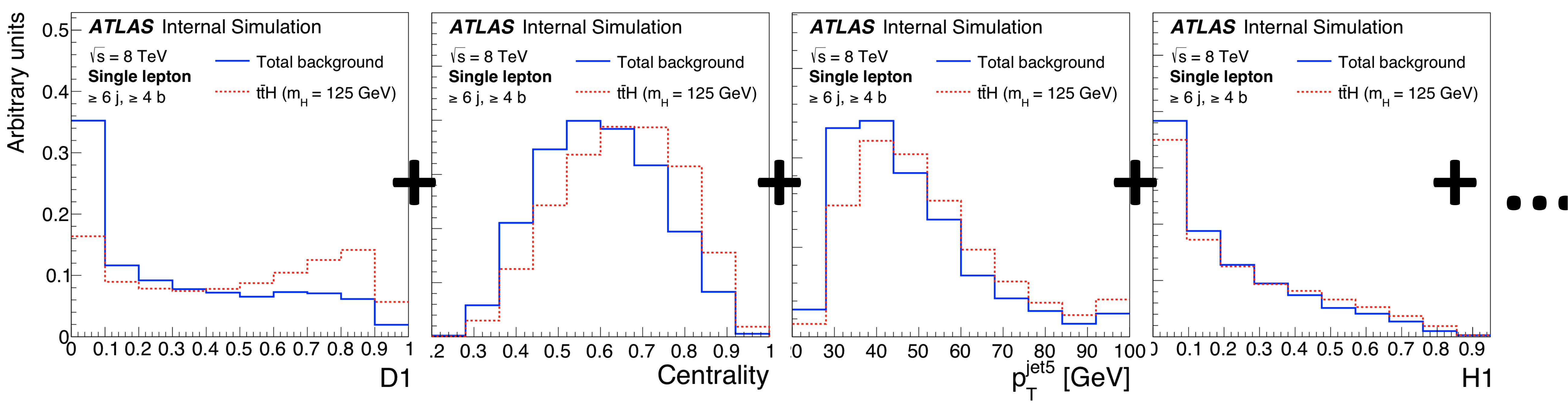


Neural networks

- Signal-rich regions: neural network trained to separate $t\bar{t}H$ from $t\bar{t}$+jets
- Doesn't require to have all partons reconstructed in the event
- Several types of variables:
  - Event shape: centrality
  - Object pair properties: $\Delta\eta_{jj}^{\max\Delta\eta}$
  - Object kinematics: p_T^{jet5}
  - Event kinematics: H_T
  - Matrix element method: D1



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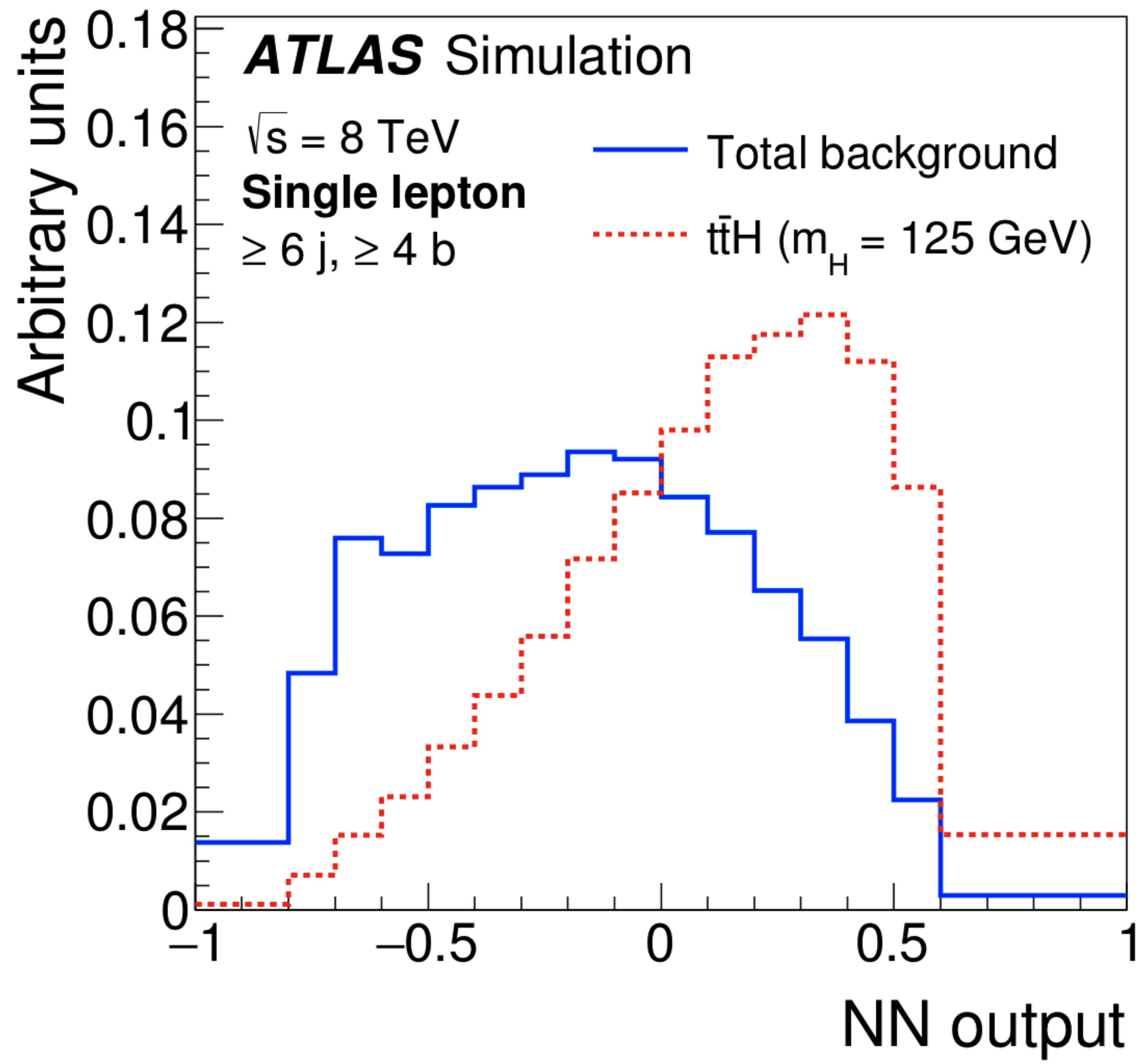
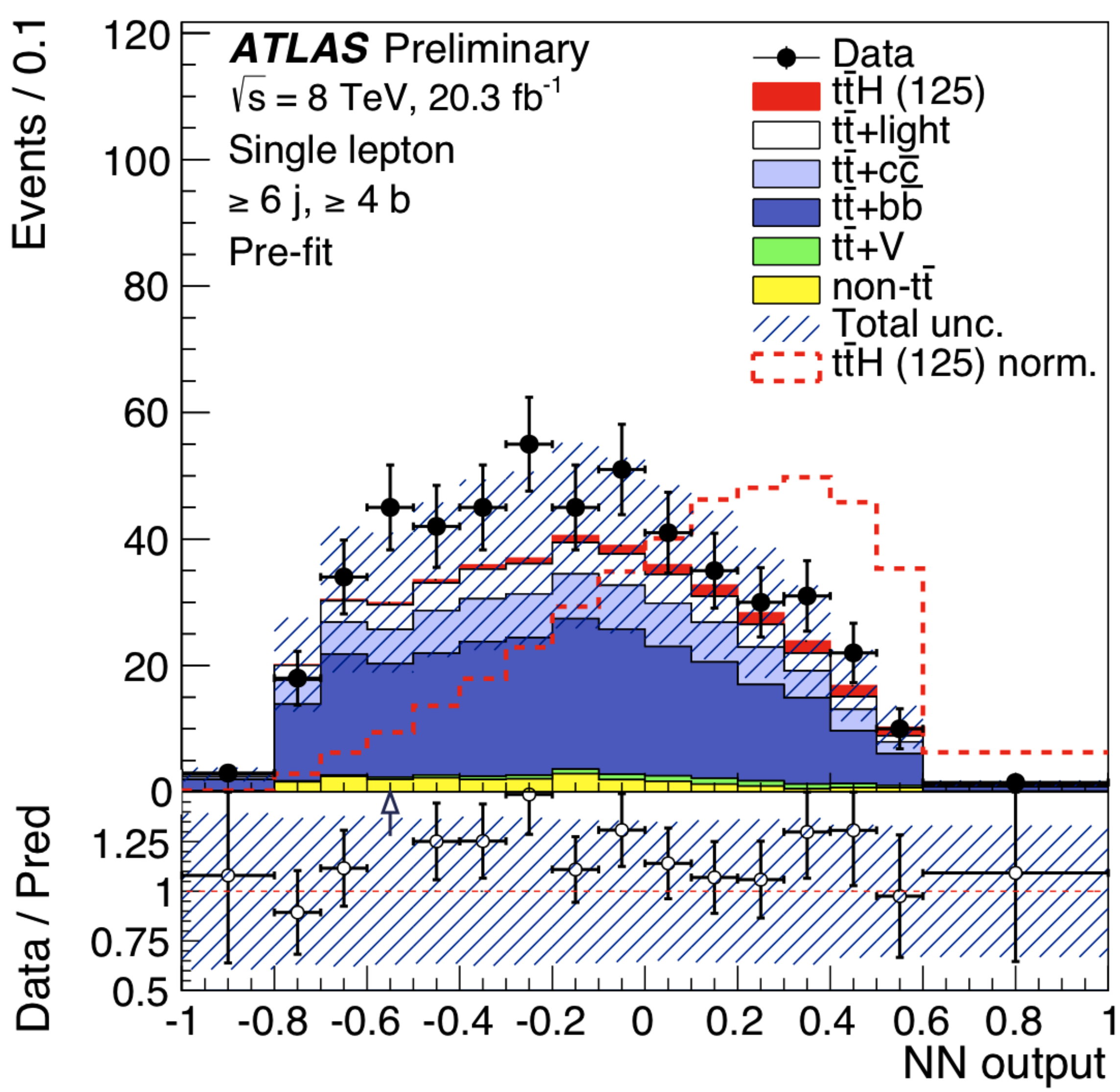


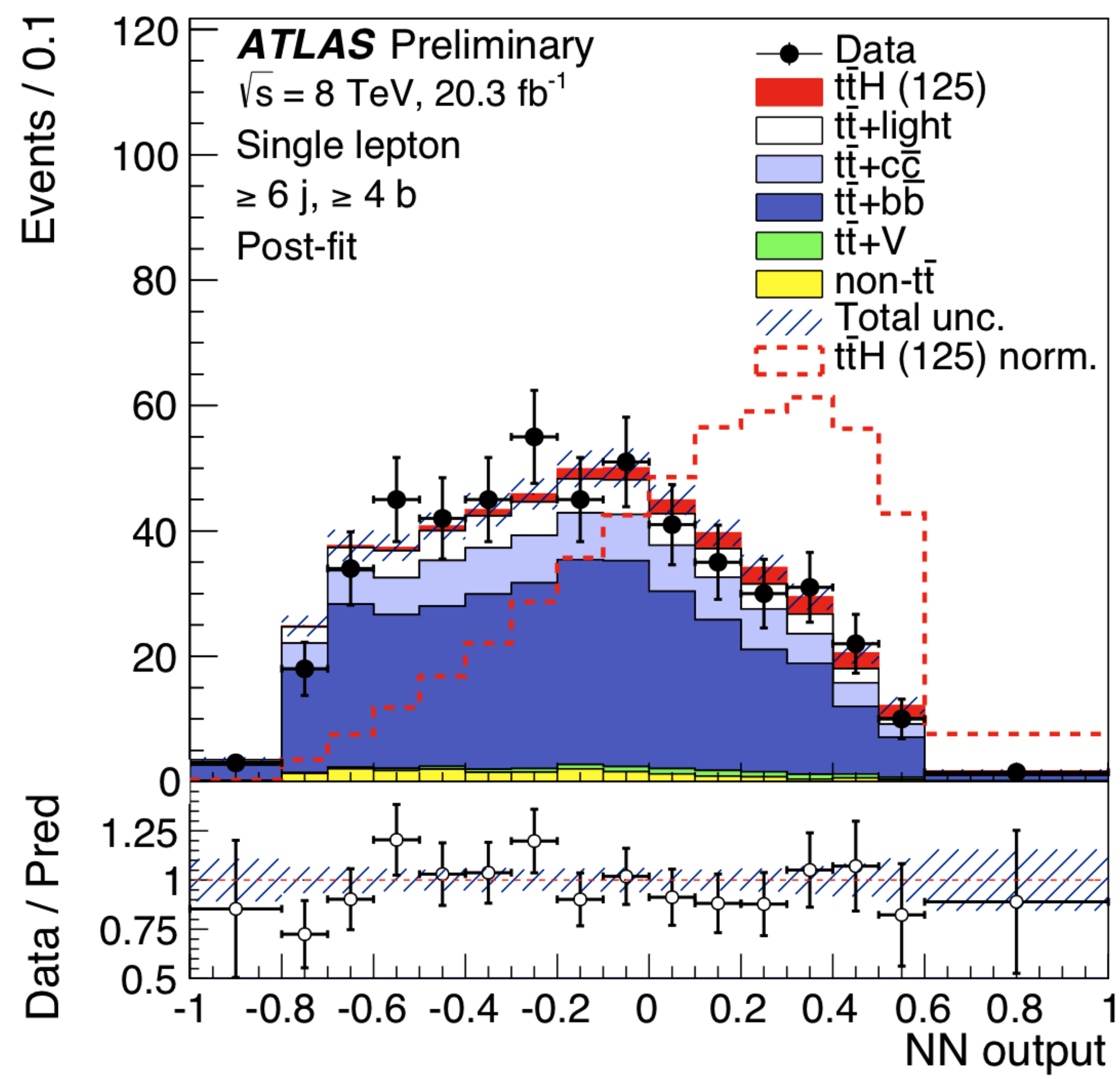
Profiling in action

- Signal extracted via simultaneous likelihood fit to the 9 regions under S+B hypothesis
- Impact of the systematic uncertainties are reduced

Prefit 6 jets, 4 b-tags



Postfit 6 jets, 4 b-tags

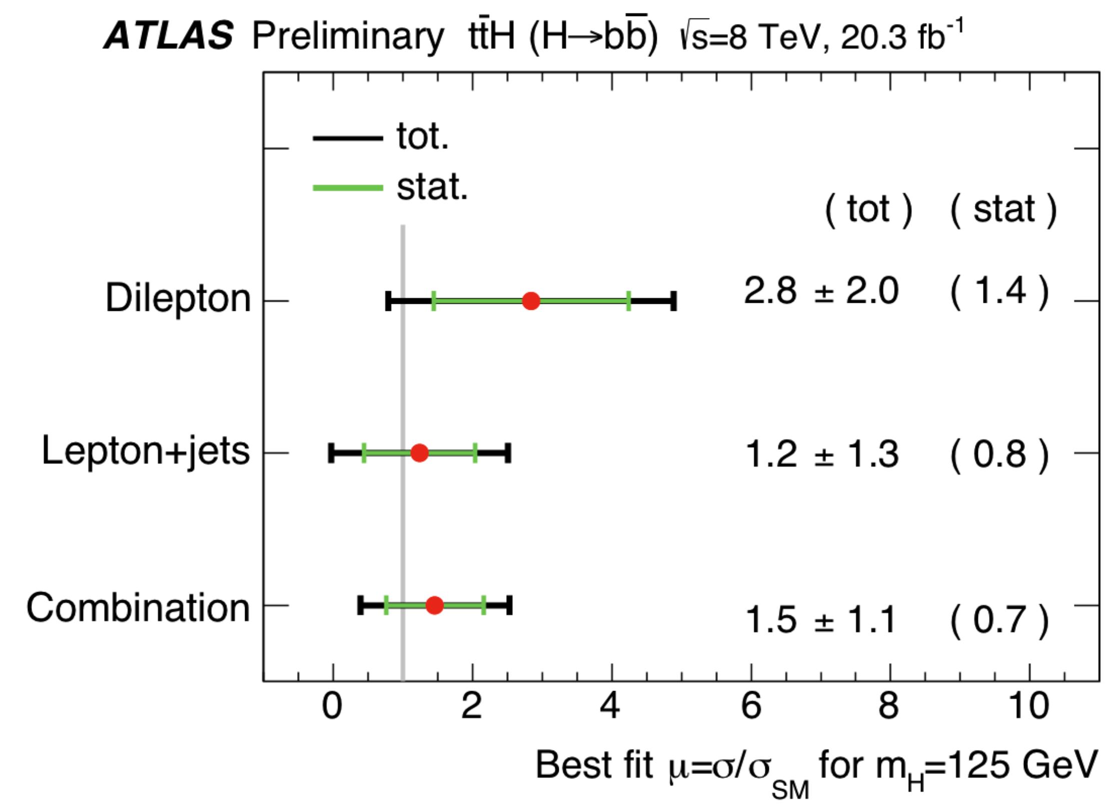


Results

- **Fitted signal strength:**

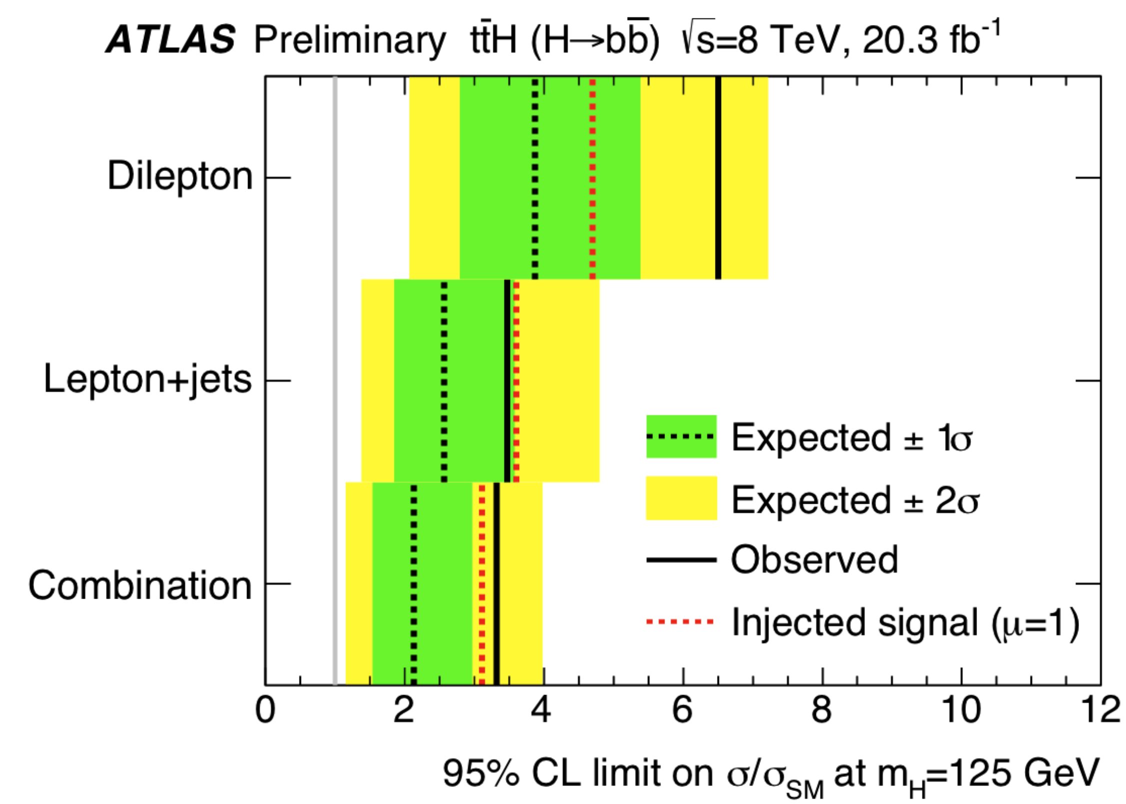
  $\mu = 1.5 \pm 1.1$

- In agreement with SM expectation



- **Observed (expected) exclusion limits:**

  $\sigma/\sigma_{SM} < 3.4$ (2.2)



Beyond the standard model

- Run I data is not enough to make a statement on the top Yukawa coupling
  - Besides “ttH signal strength in agreement with the SM prediction with 100% error”

- Back to the hierarchy problem, many BSM models addressing the hierarchy problem predict ttH-like final states
  - Little Higgs, GUT's, extra dimensions, composite top → Predict **vector-like quarks**
  - SUSY → top partner: **stops**

Vector-like quarks

- Both chiralities have the same transformation under the electroweak group SU(2) x U(1)
- Couple preferentially to 3rd generation quarks → three decay modes
  - T → Wb, **T → Ht**, T → Zt
- Pair production via QCD, only m_Q dependent.

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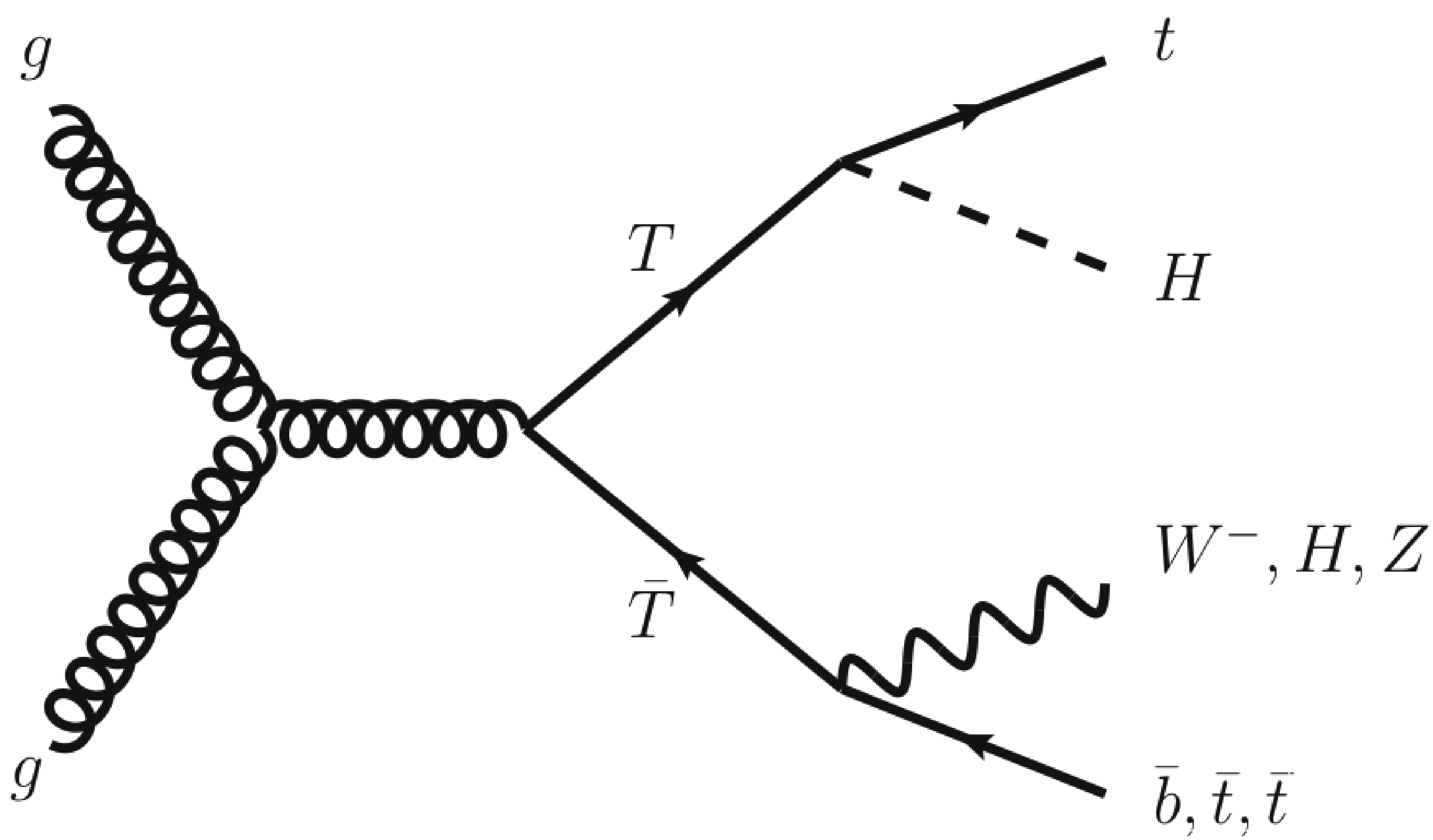
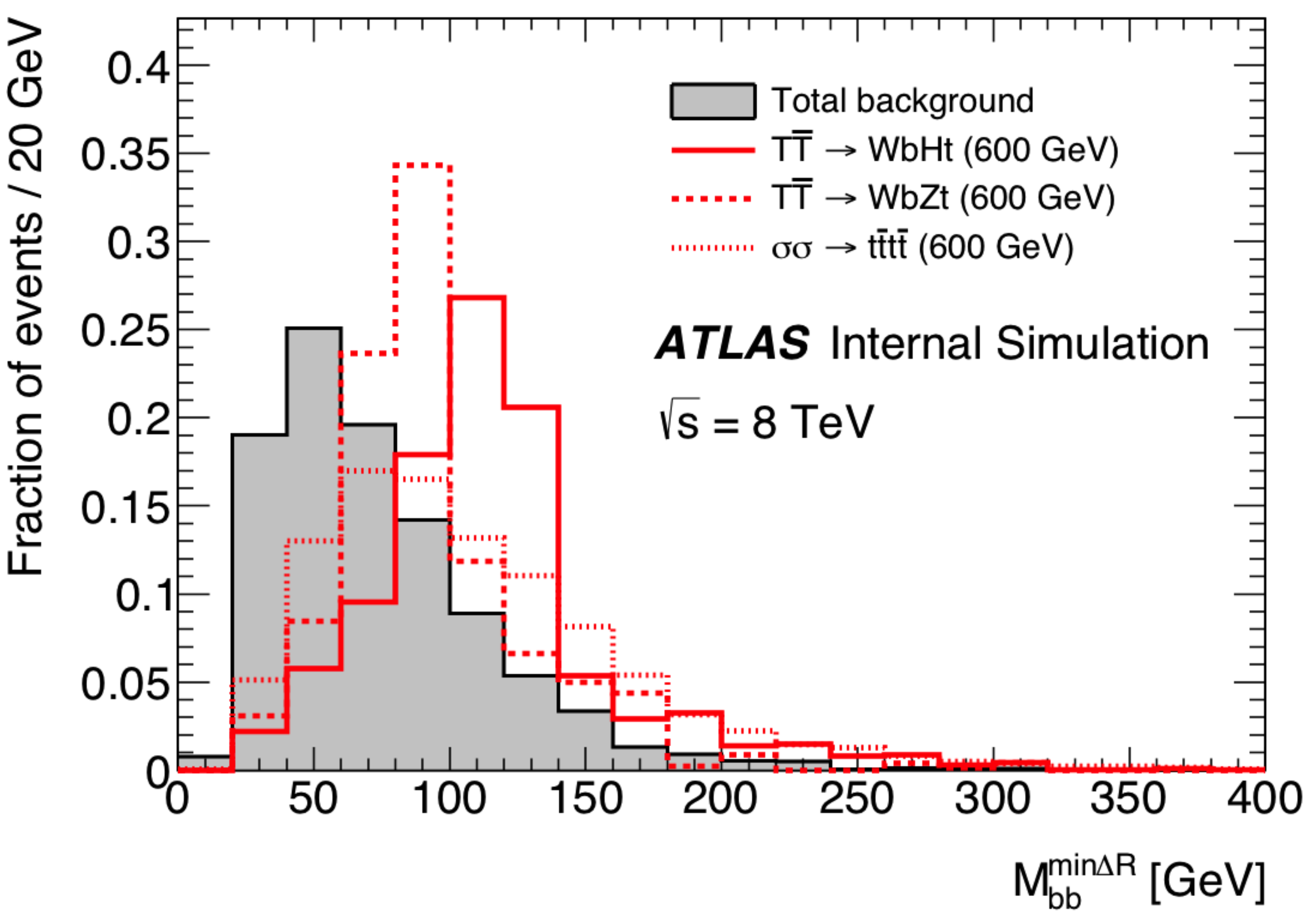
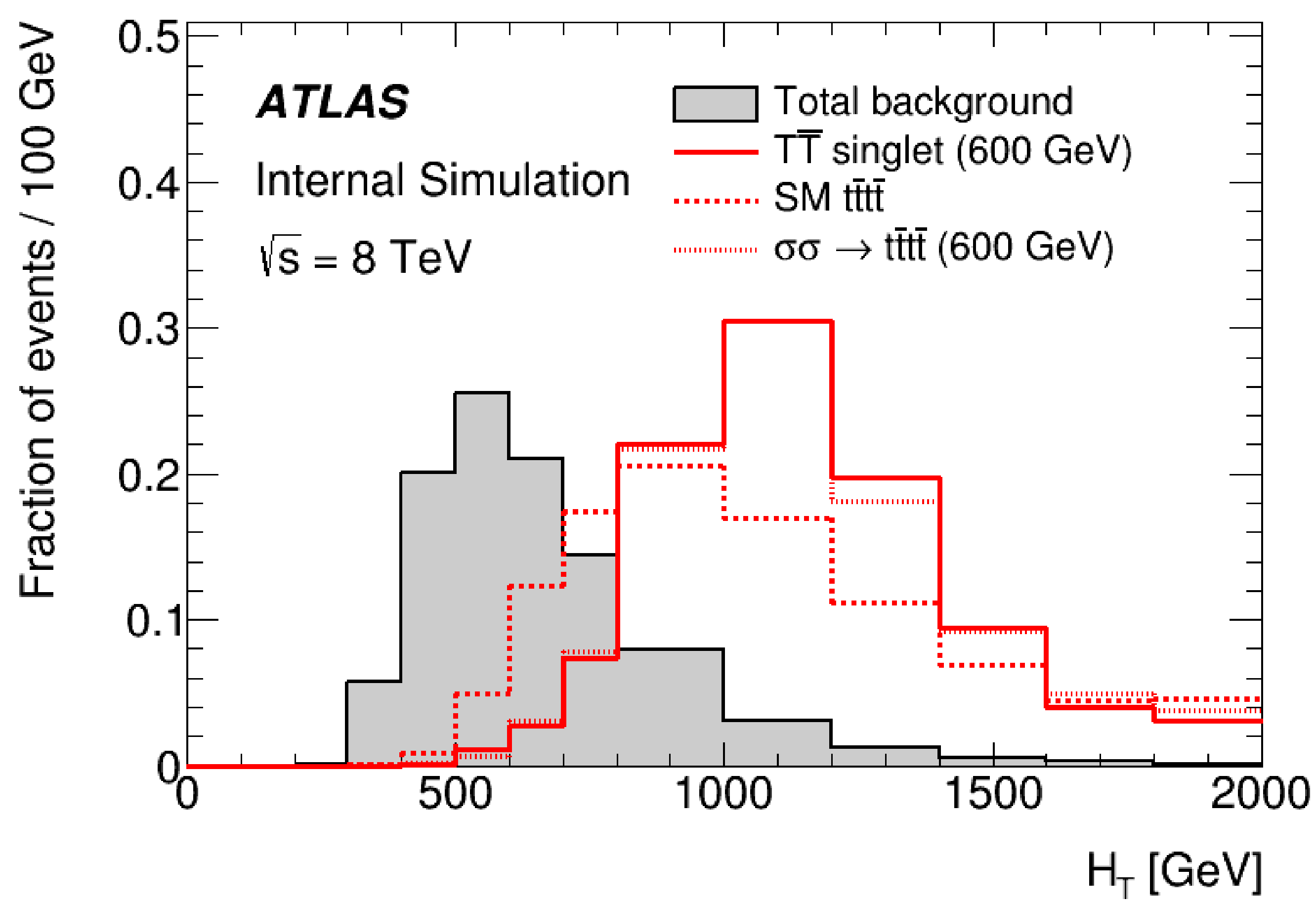


Vector-like quarks

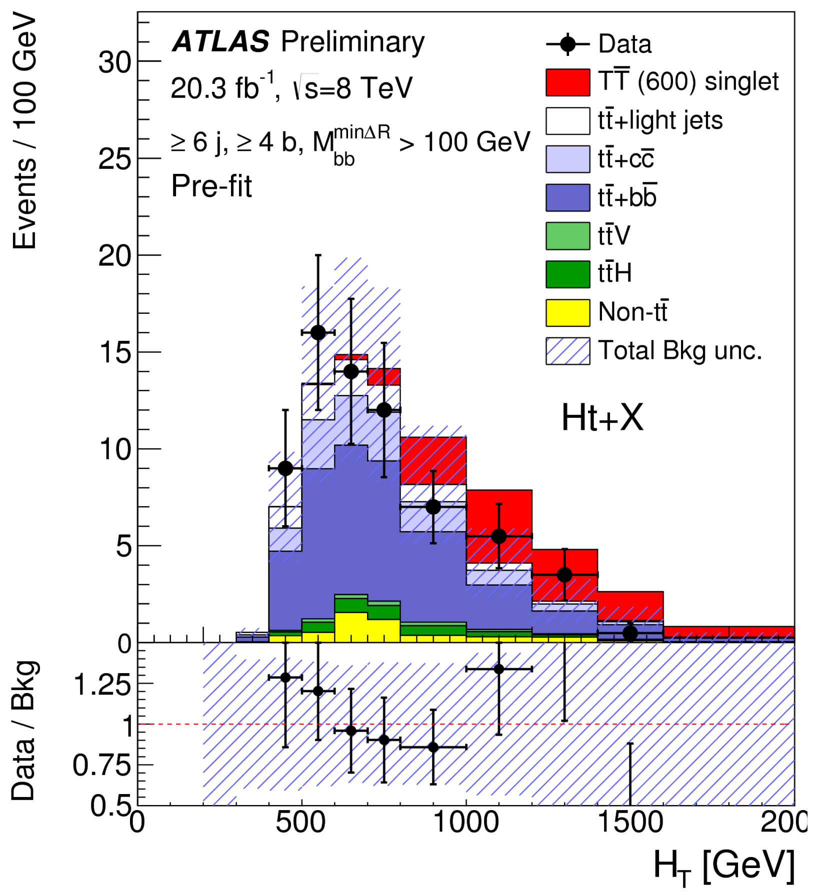
- TT → Ht+X can produce up to 8 jets (6 b-jets)
- Higgs from the VLQ decay is moderately boosted, reconstruct using bb pair with min dR
- Analyze HT = Scalar sum of jet pt + MET + lepton pT

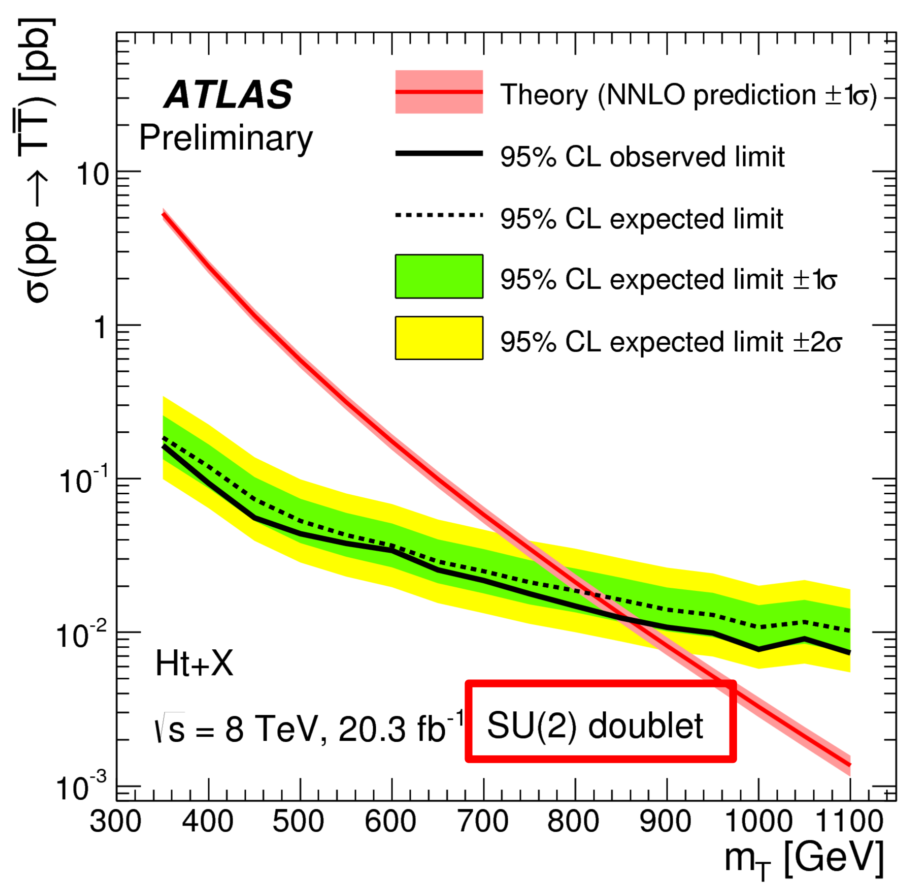


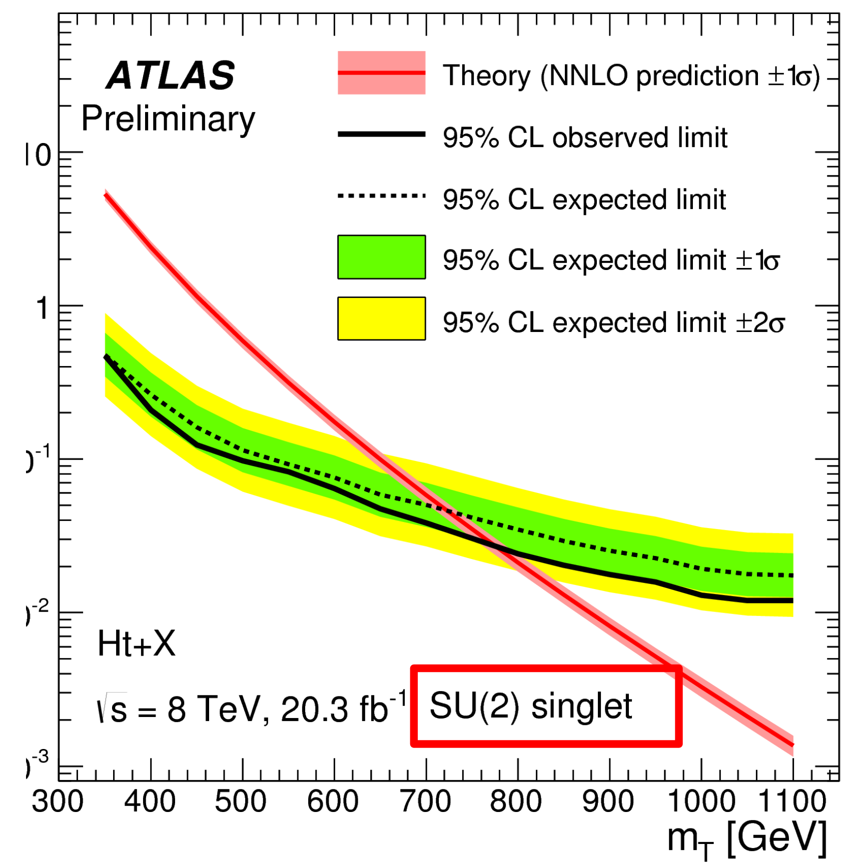


Results

- No excess observed, place limits on VLQ production







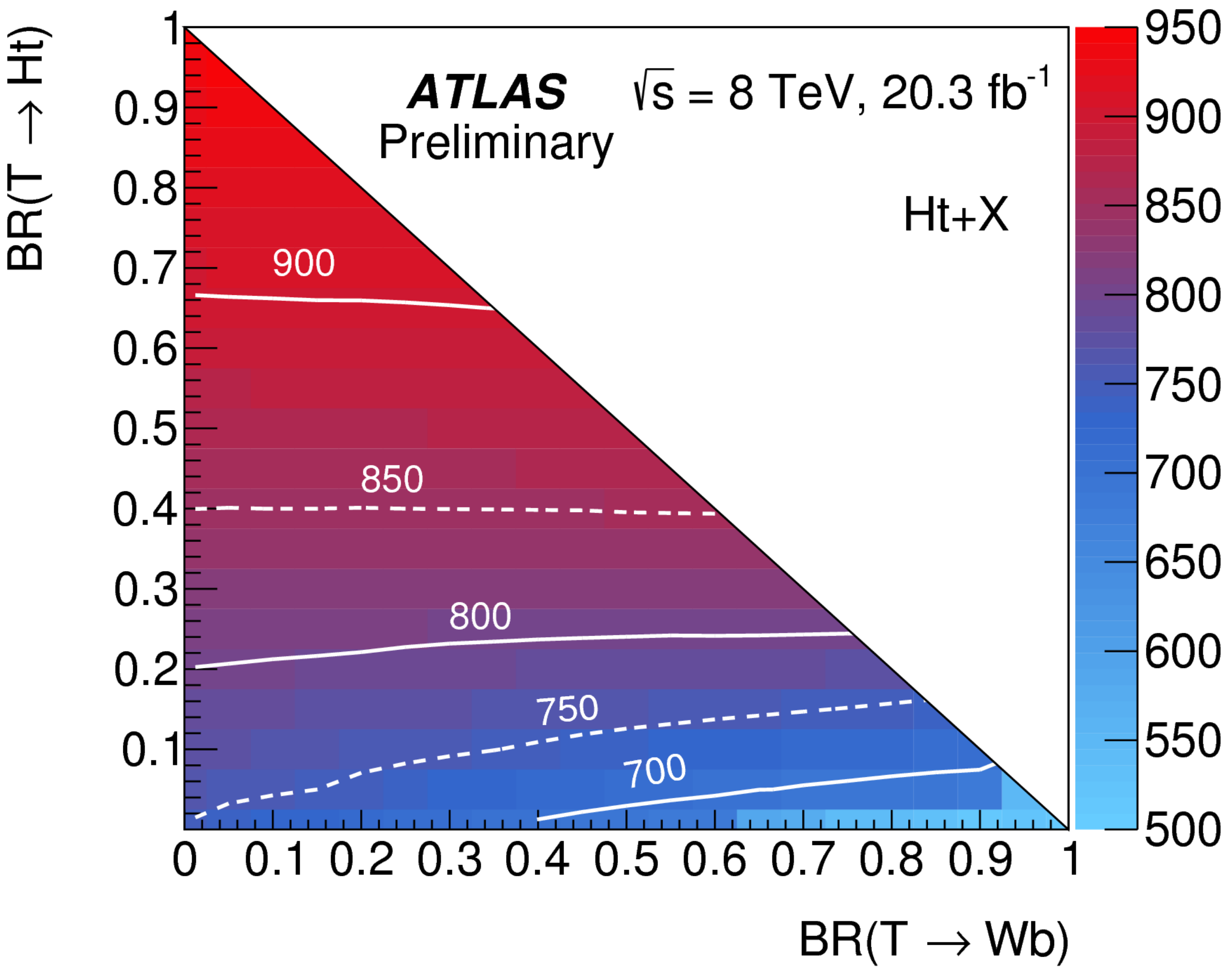
Branching ratio to Wb, Ht, Zt determined by the model

No T → Wb decays in the doublet scenario

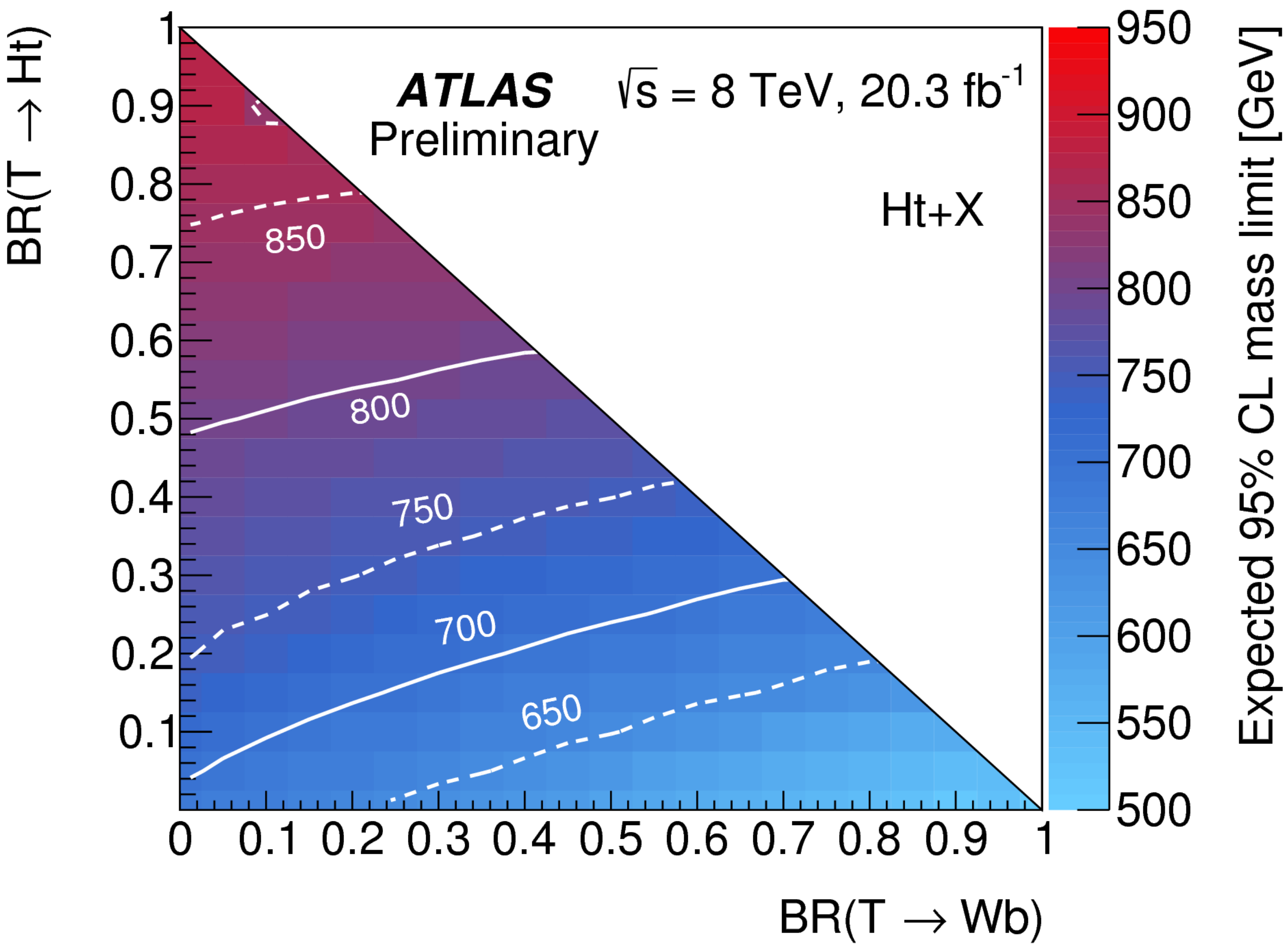
Results

- Without assuming any model, scan the BR plane

Observed limit

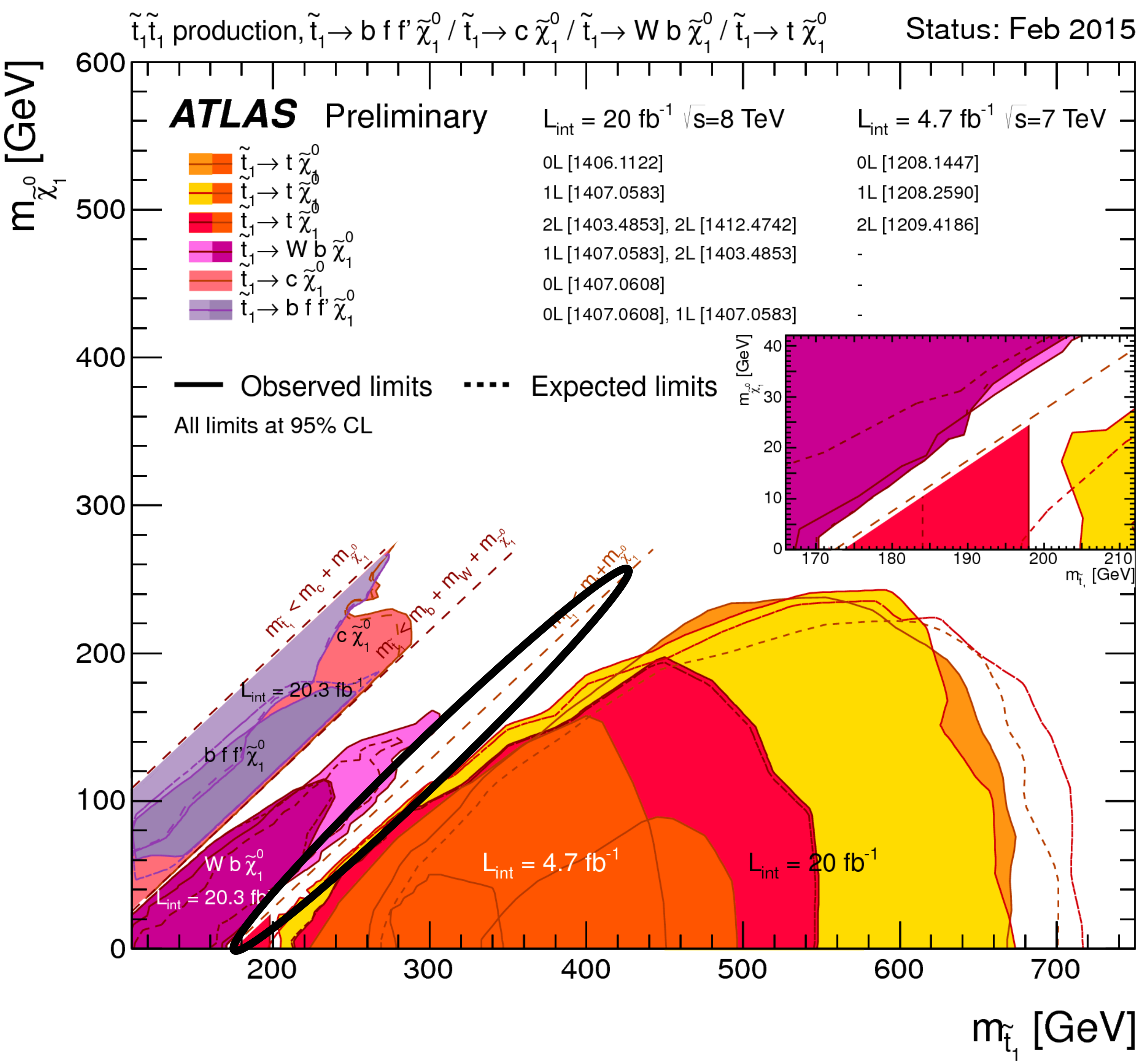


Expected limit



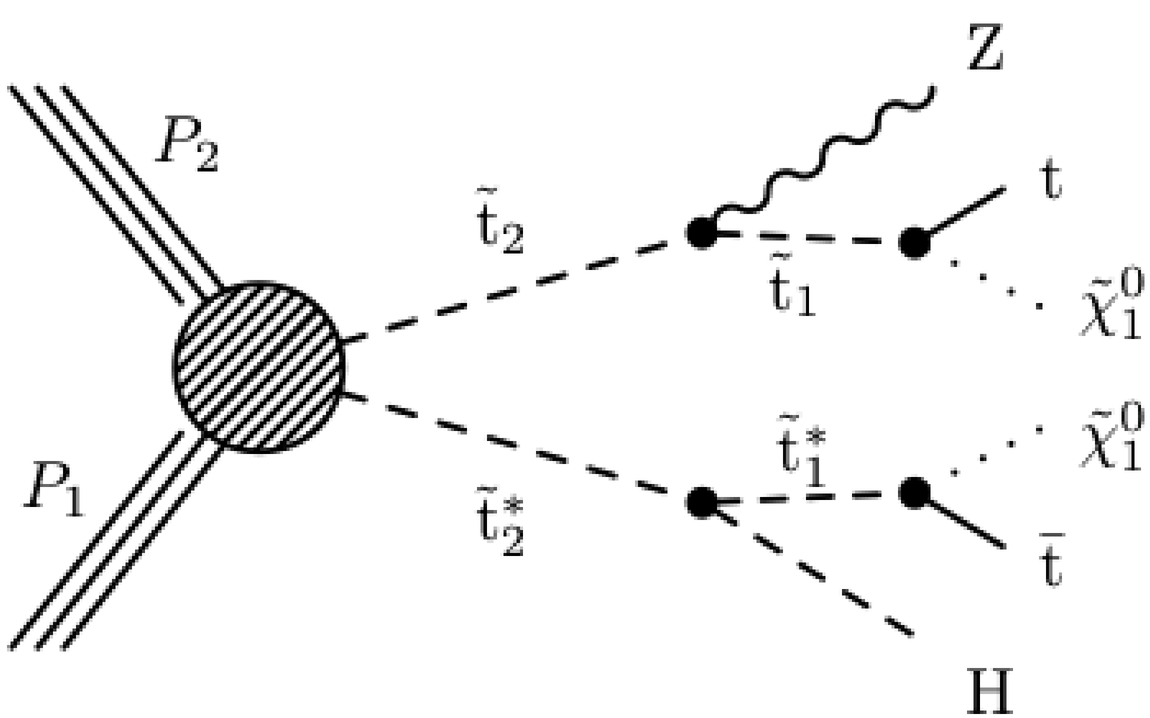
SUSY

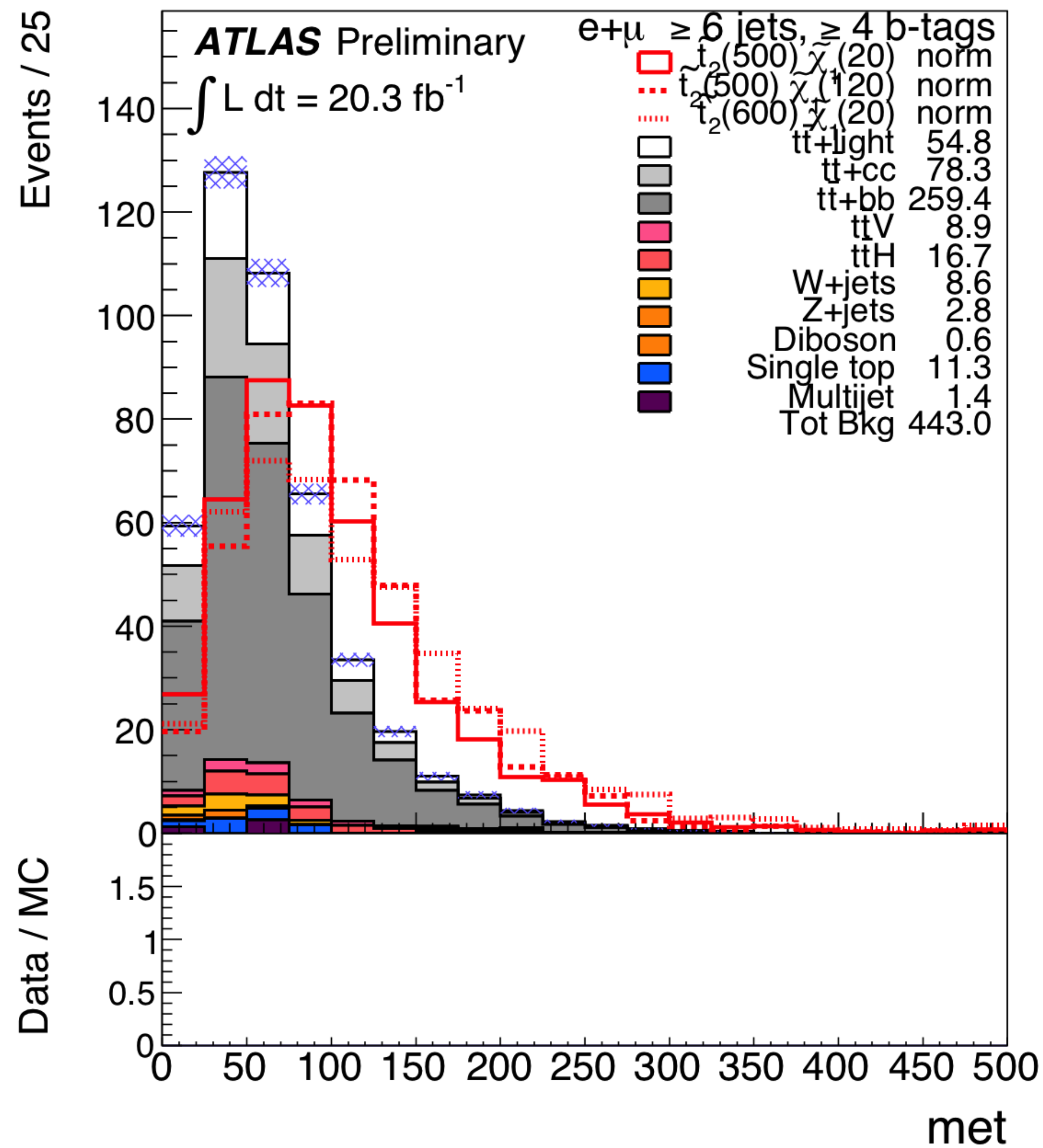
- Many analysis in ATLAS looking for 3rd generation squarks
- Traditional SUSY searches have little sensitivity when m(stop1) ≈ m(top) + m(LSP)
- Target those scenarios looking for the heavier stop partner
  - **stop2 → stop1 + H/Z**



SUSY

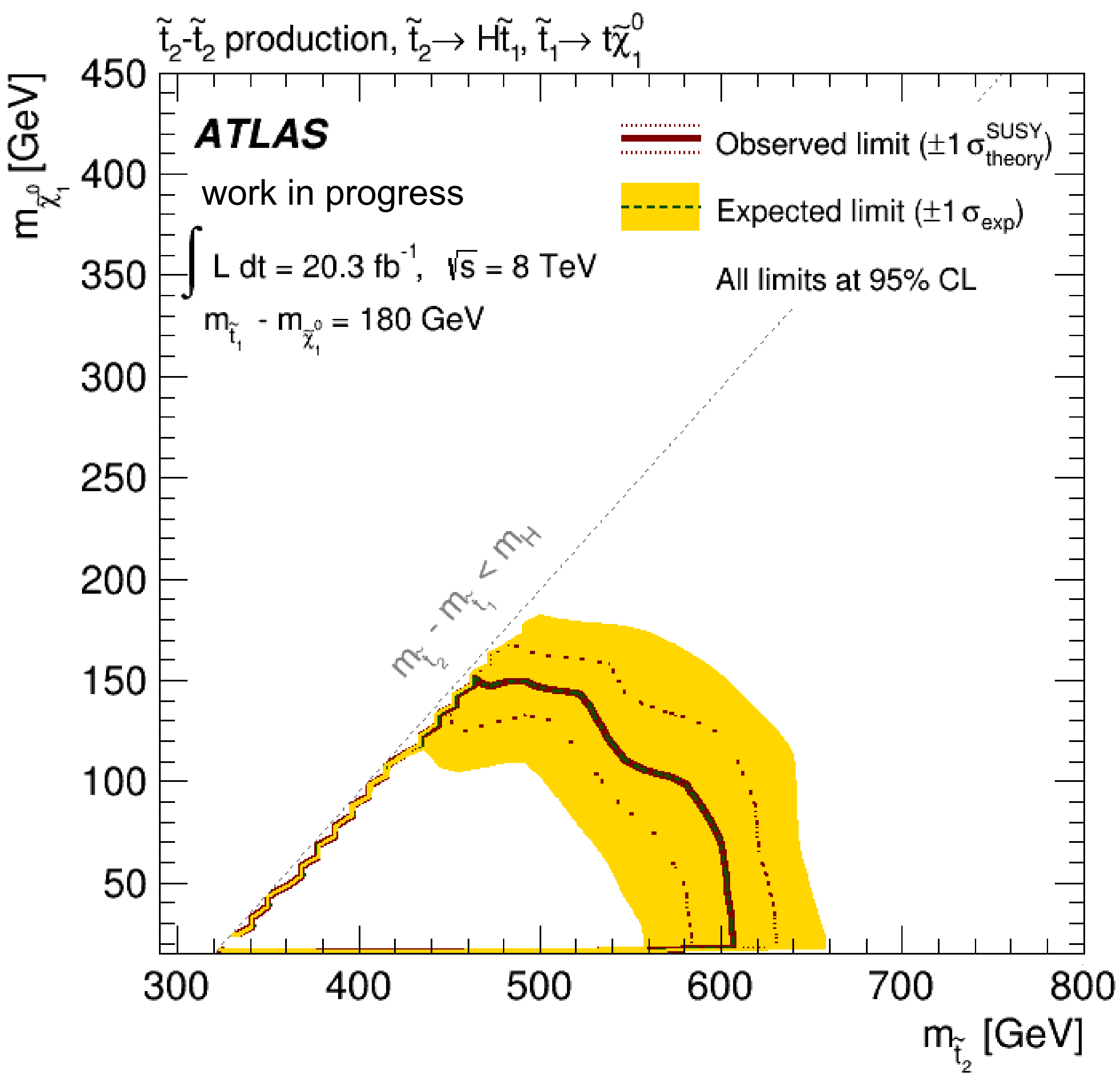
- Final state with lepton, neutrino, 8 jets, up to 6 b-tags and **2 neutralinos**
- Cut on missing transverse energy
- Split channels in high/low $m_T(W)$





Results

- Place limits on the 2D plane stop2 vs neutralino mass
- Analysis not public yet :(



Summary

- ttbb is a very challenging final state but with plenty of potential
  - ttH(bb) not yet observed
  - Run II will be able to measure top Yukawa coupling to 20% accuracy
  - Plenty of new physics scenarios predicting an increase in ttbb or tttt
  - They will all benefit from the increase in energy
    - With higher bounds on VLQ masses, single production starts to become relevant

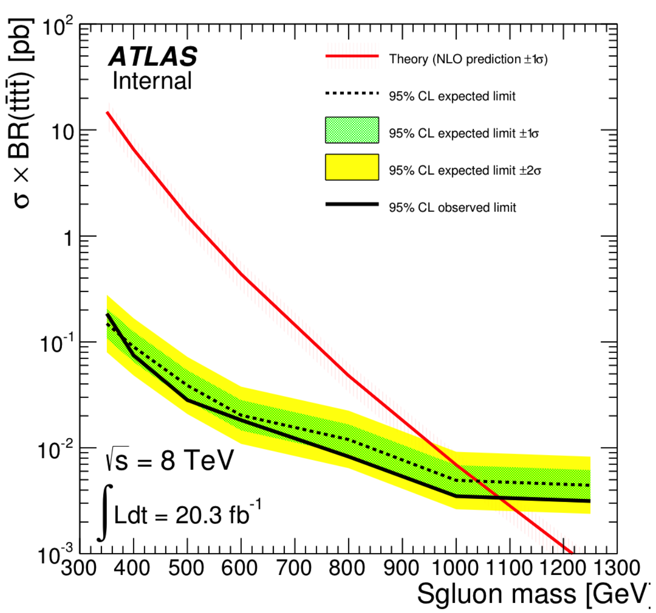
- Top quark is a very special particle, hopefully also a window to new physics

Backup

4 tops interpretations

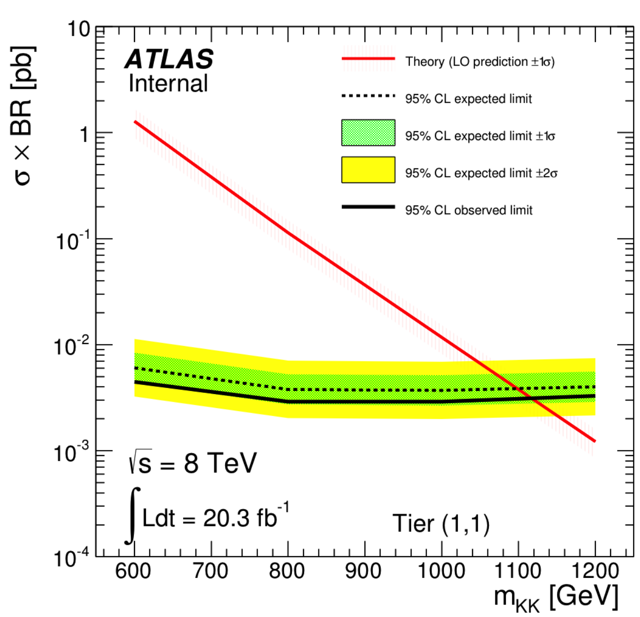
- The Ht+X analysis is reinterpreted in the context of 4 top final states:
- Observed (expected) limits:
  - **SM 4 top production**: 23 fb (32 fb), $\sigma/\sigma_{SM} < 34$ (47)
  - **EFT with 4 top contact interaction**: 12 fb (16 fb), $|C_{4t}|/\Lambda^2 < 6.6$ (7.7)

Sgluon pair production with decay to ttbar



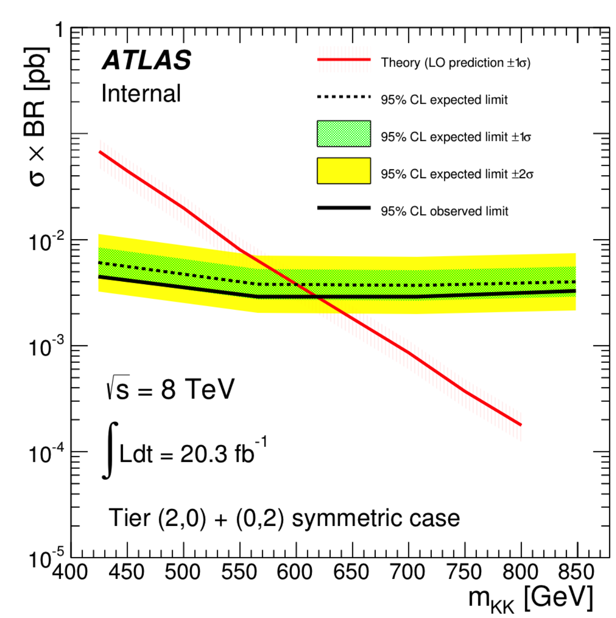
$m_{Sgluon} > 1.06$ (1.02) TeV

UED, tier(1,1)



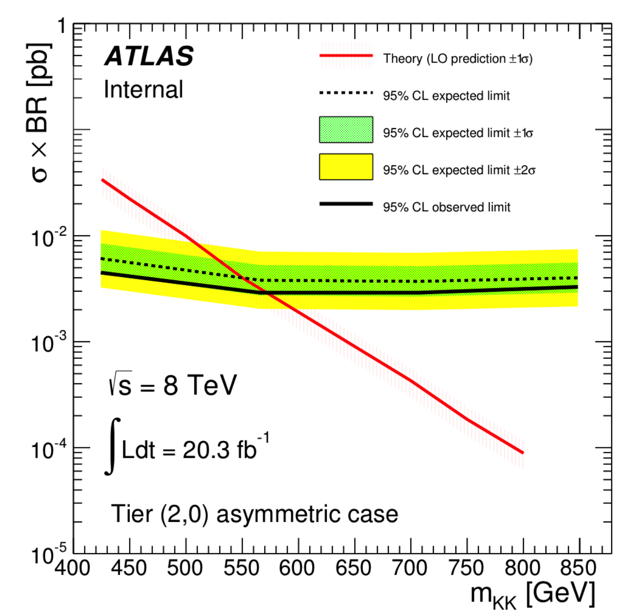
$m_{KK} > 1.12$ (1.10) TeV

UED, tier(2,0) + tier(0,2) symmetric case



$m_{KK} > 0.61$ (0.60) TeV

UED, tier(2,0) asymmetric case



$m_{KK} > 0.57$ (0.55) TeV

Matrix element method

- The Matrix Element Method (MEM) is used to compute the likelihood for an event to be originated from a certain theoretical hypothesis.
- Compute the likelihood respect to the ttH or ttbb hypothesis

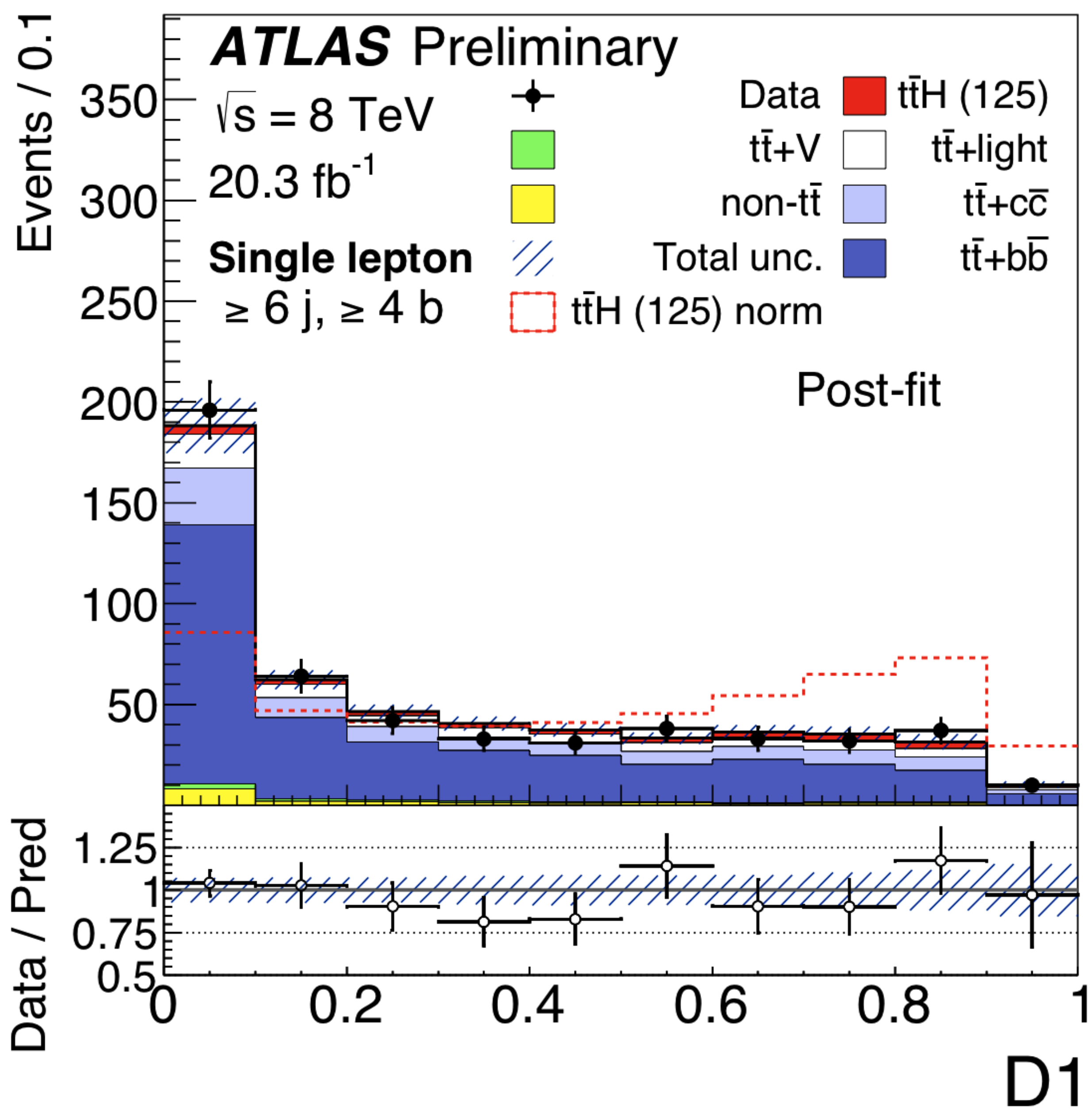
$$\underbrace{P_{t\bar{t}H}\left(\vec{x}_{\text{Detector}}, m_H\right)}_{\text{probability}} = \frac{1}{\underbrace{\sigma_{t\bar{t}H}\left(m_H\right)}_{\text{normalization}}} \int \boxed{\underbrace{\mathrm{dp_{g1}dp_{g2}f\left(p_{g1}\right)f\left(p_{g2}\right)}}_{\text{parton density function}}} \boxed{\underbrace{\mathrm{d}\sigma_{\mathrm{t\bar{t}H}}\left(\tilde{\mathrm{x}}_{\mathrm{Parton}}, \mathrm{m_H}\right)}_{\text{differential cross section}}} \boxed{\underbrace{W\left(\vec{x}_{\text{Parton}}, \vec{x}_{\text{Detector}}\right)}_{\text{transfer functions}}}$$

  - PDFs account for production mechanism
  - Differential cross section proportional to $|M|^2$, consider only LO ME. Test ttbb and ttH hypothesis
  - Transfer functions map detector response to parton level
- Likelihood ratio of ttH/ttbb (**D1**) is the most discriminating variable against ttbb in 6j4b.
- Sum of likelihood under signal hypothesis (**SSLL**) is discriminating against the rest of the backgrounds

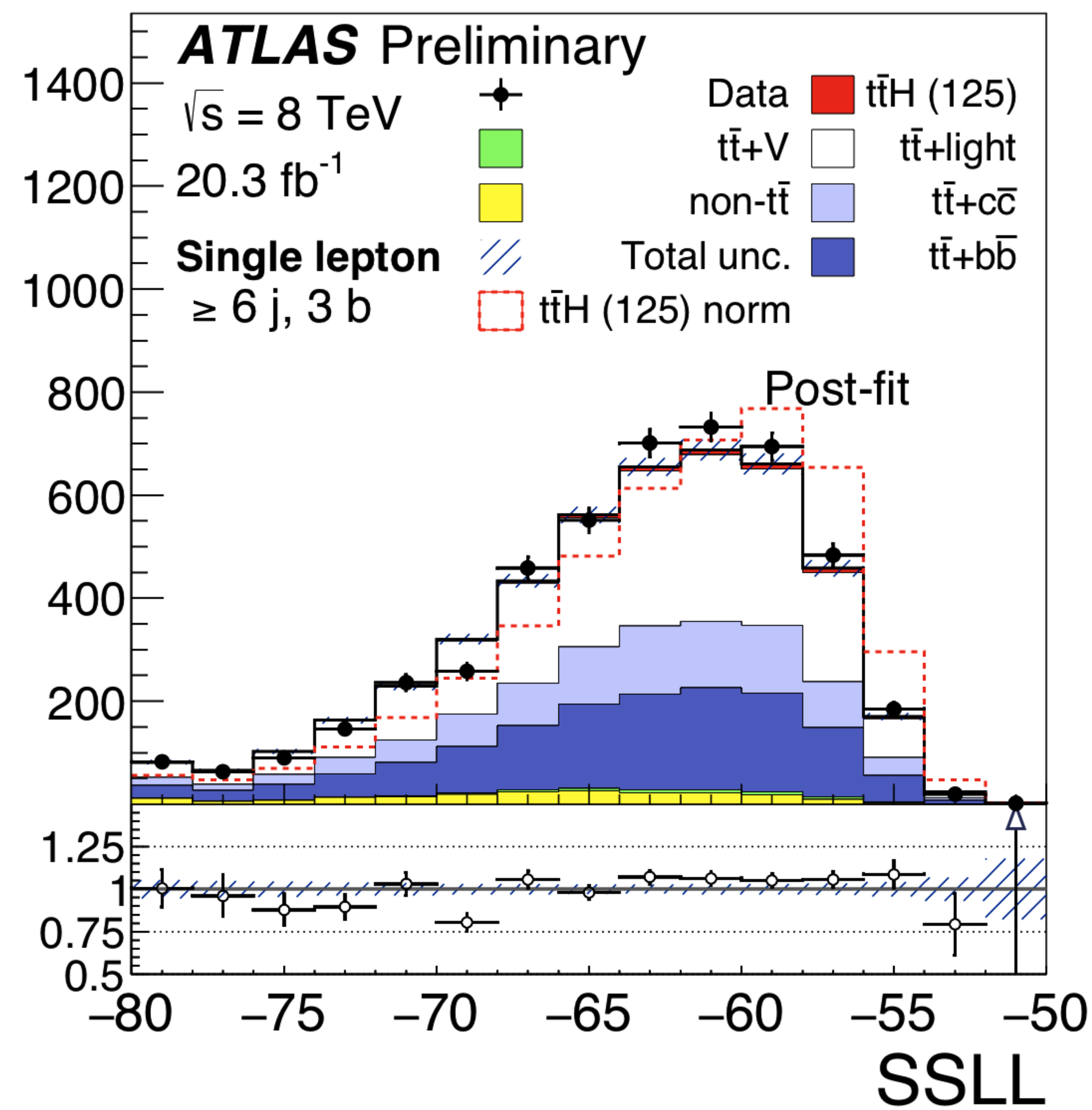
Matrix element method

- Good modeling of MEM variables and good separation power, especially in D1

D1, 1st ranked variable in 6j4b

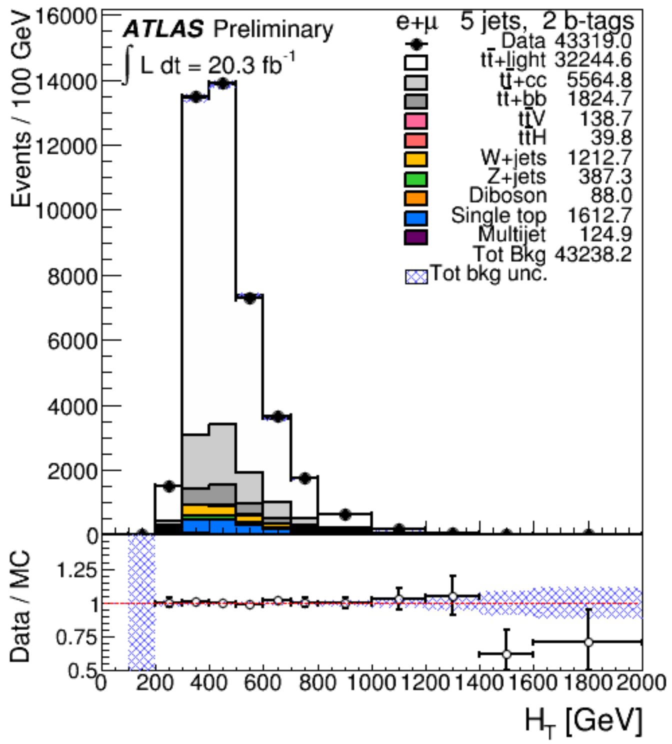


SSLL, 4th ranked variable in 6j3b

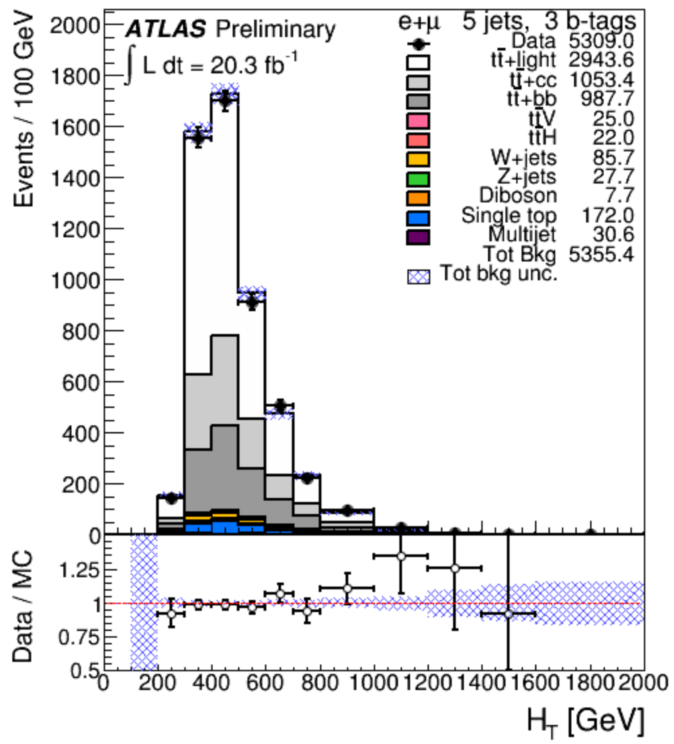


Ht+X plots

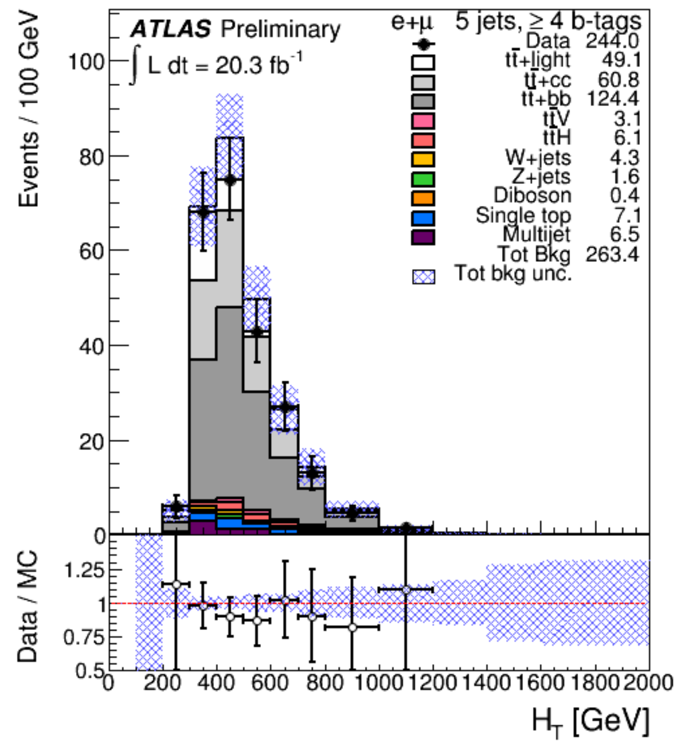
5 jet 2 btag



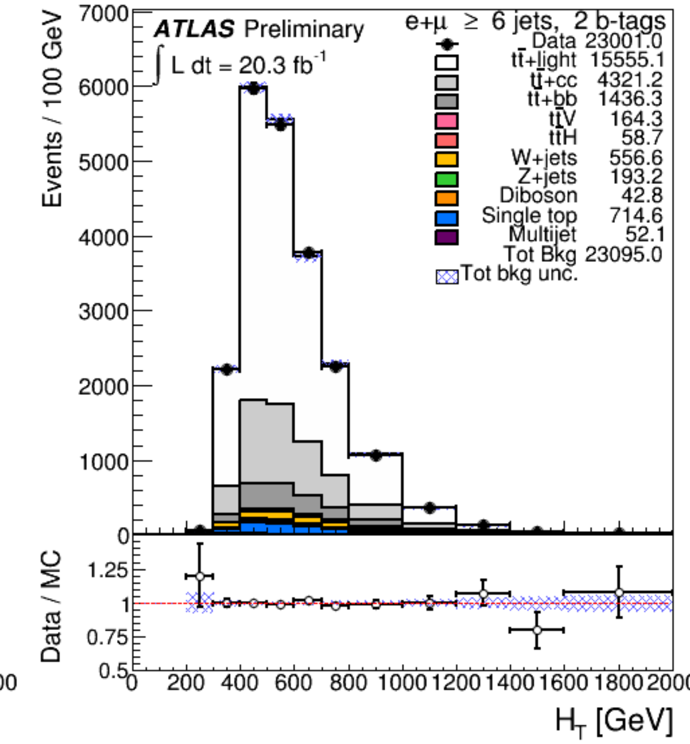
5 jet 3 btag



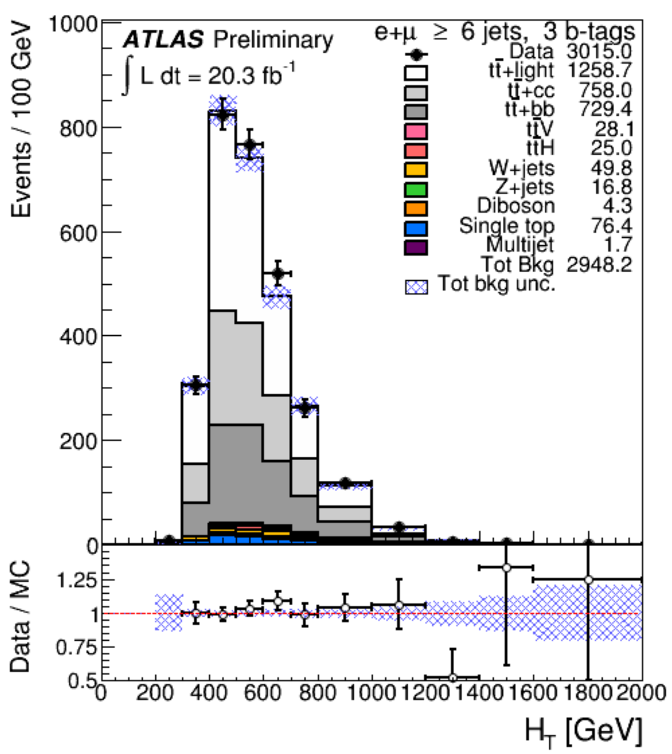
5 jet 4 btag



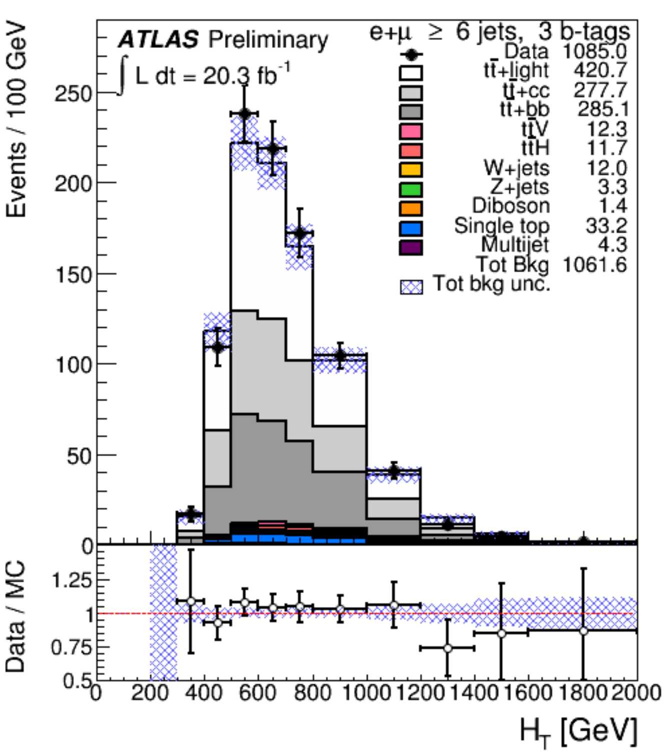
6 jet 2 btag



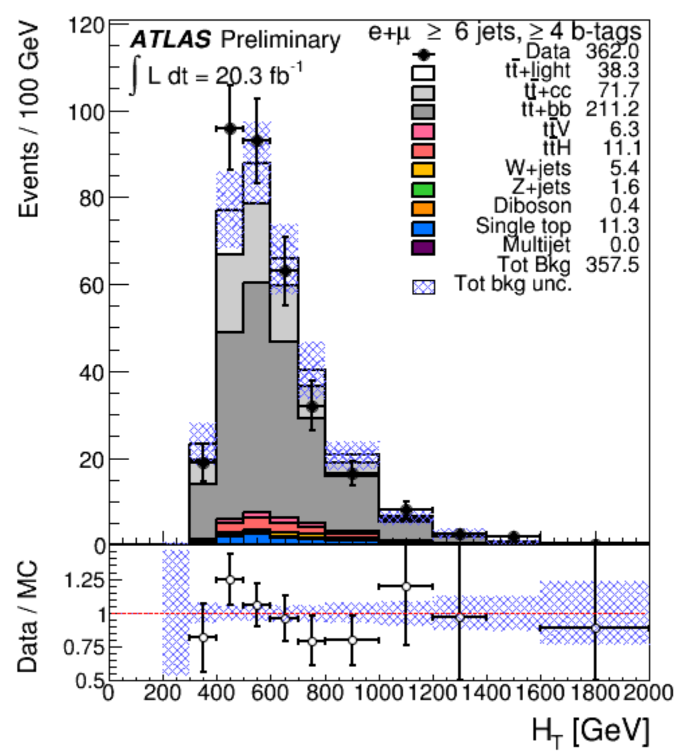
6 jet 3 btag, Mbb < 100



6 jet 3 btag, Mbb > 100



6 jet 4 btag, Mbb < 100



6 jet 4 btag, Mbb > 100