# Higgs Drawbacks

- So with the addition of a Higgs boson around 125 GeV particle physics could be “complete”
  - Like Mendeleev’s table for chemistry, but not understood. By itself, the Higgs is very unsatisfactory:
    - Why are the couplings to the fermions what they are?
      - Dumb luck (aka landscape)?
    - What is the link to gravity?
    - What about Dark Matter?
    - Why does the Higgs break the symmetry?
    - Why are there 3....?

# Hunting for Answers

- Get more information
  - Measure particles and their interactions in detail
    - Precision measurements (incl. flavor)
  - Observe new particles or interactions
    - Search in new areas in “phase space”
- Find the underlying pattern(s)
  - Hypothesize, build models
    - Internally consistent?  Consistent with data?
    - Suggestions on where to look

Experiment

Theory

# Where to Start?

- BSM physics **must** couple to SM (if it helps with the hierarchy problem), but is it
  - Resonant?
    - Does it have new massive particles decaying to electrons, muons, quarks, W, Z,…?
  - "SM-like"?
    - Same but includes some new long-lived particles in the decay chain… (e.g. dark matter candidate)
  - No new "particles" in reach
    - Hidden or too heavy (indirect searches) or…. don't exist (new paradigm needed)
  - Are there new interactions?

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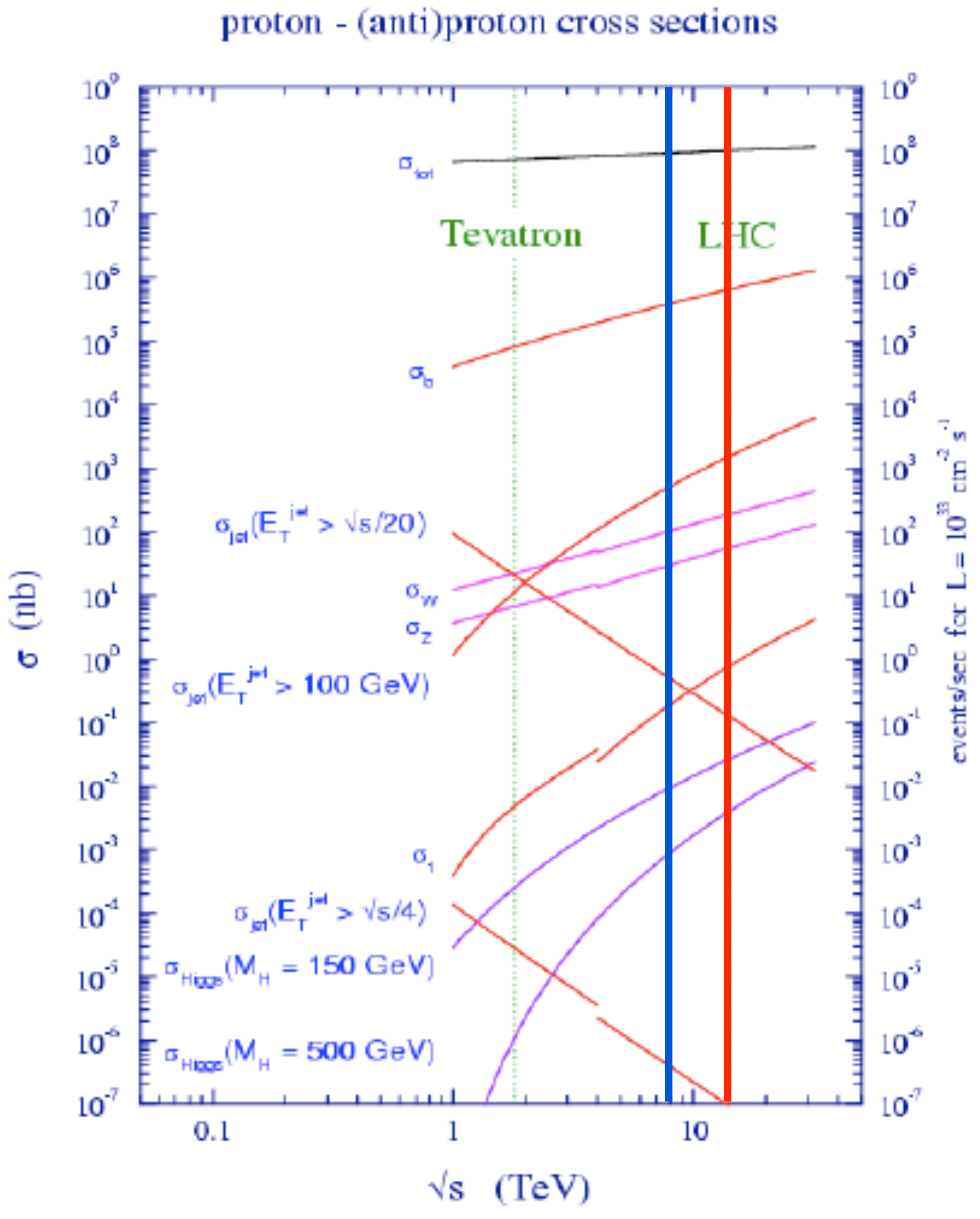
  - Are there new interactions?

Nobody could have predicted QCD

# Physics @ LHC

❖ LHC opened a new era:

- Tevatron was mega-W
- LHC is
  - Giga-W
  - Giga-Z
  - Top factory (~giga-top)
  - Higgs factory (mega-Higgs)
  - New physics factory?

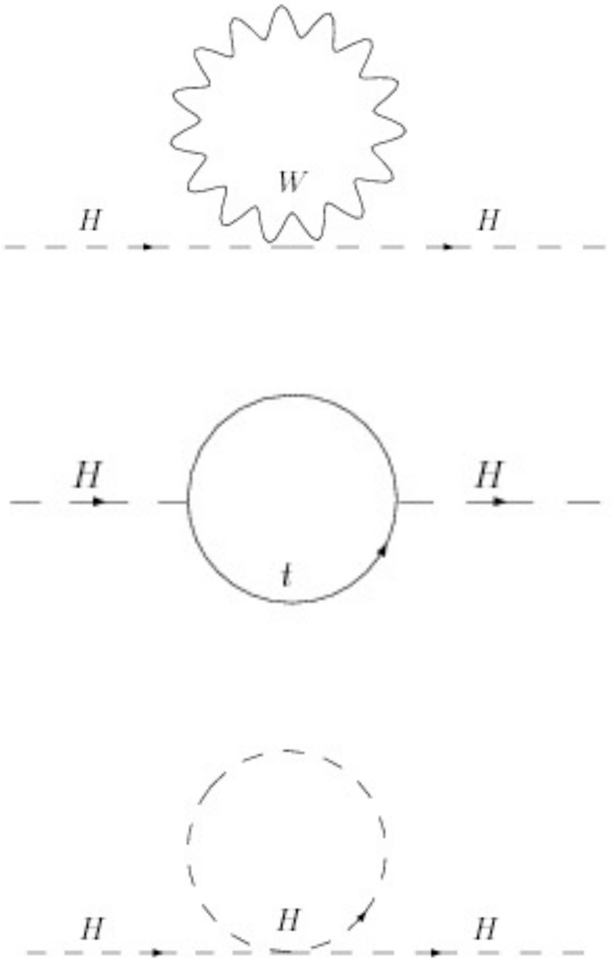


# Experimental Searches

- By final state, so main questions are
  - Does the new physics produce dark matter?
    - Something we basically know exists and interacts weakly at best with SM
    - ➡ Yes: signatures contain missing transverse energy
    - ➡ No: MET not generic signature
  - Are there new interactions?
    - ➡ No: we know how to calculate everything
    - ➡ Yes: strong (resonances) or very weak (long-lived particles) or...?
- e.g. SUSY is (Yes,No) if R-parity, technicolor (No,Yes)....

# With Dark Matter

# (Super)Symmetry Solution




$\rightarrow \frac{1}{16\pi^2} g^2 E^2$

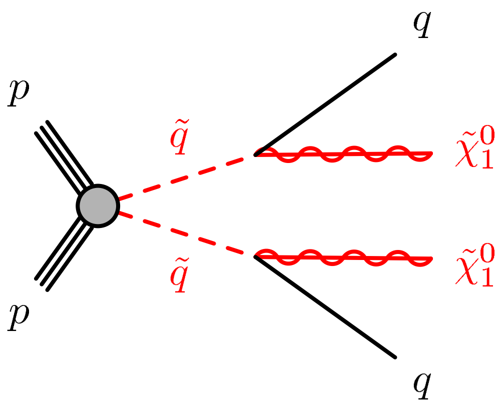
$\rightarrow \frac{3}{16\pi^2} y_t^2 E^2$

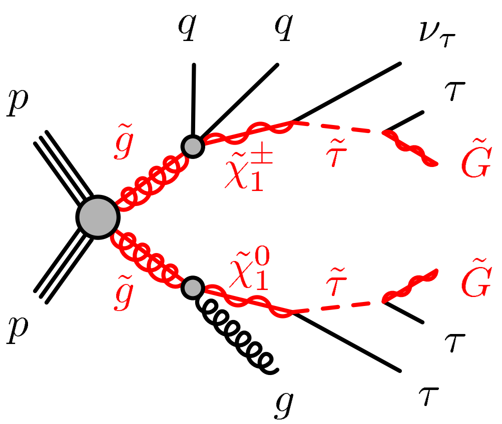
$\rightarrow \frac{1}{16\pi^2} \lambda E^2$

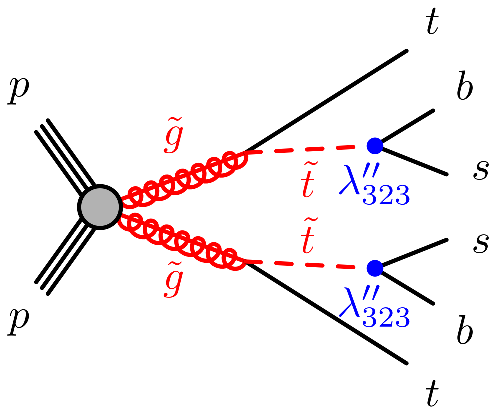
- If for every fermion there is a partner boson and vice-versa
  - Loops cancel each other
- Symmetry cannot be exact (no bosonic electron observed)
  - Symmetry breaking leads to "residual" Higgs mass
- This is supersymmetry
- With R-parity, get missing $E_T$
  - Generic to models with dark matter@LHC

# Canonical SUSY

- ❖ Wide range of signatures
  - Strong production… (large cross-section)

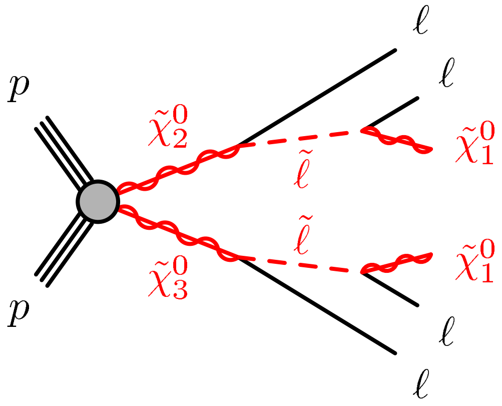


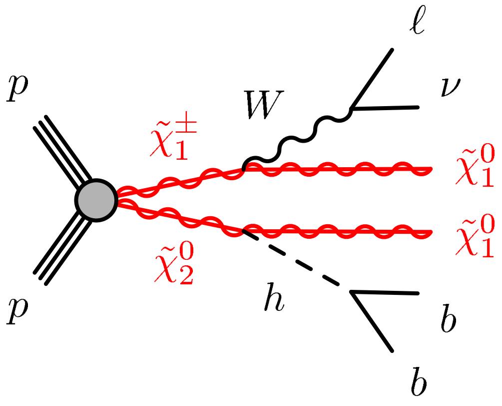



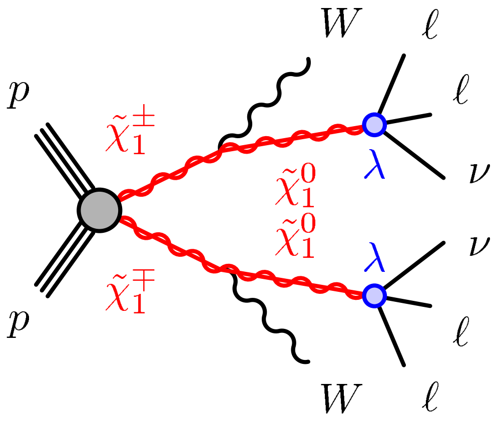




  - … or weak production

RPV



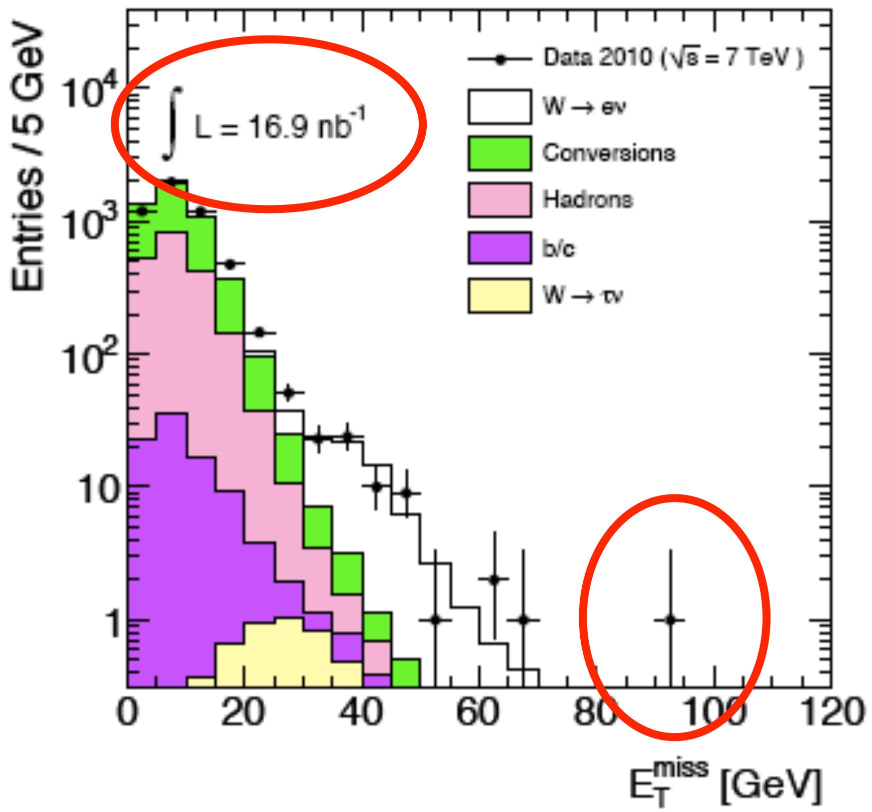



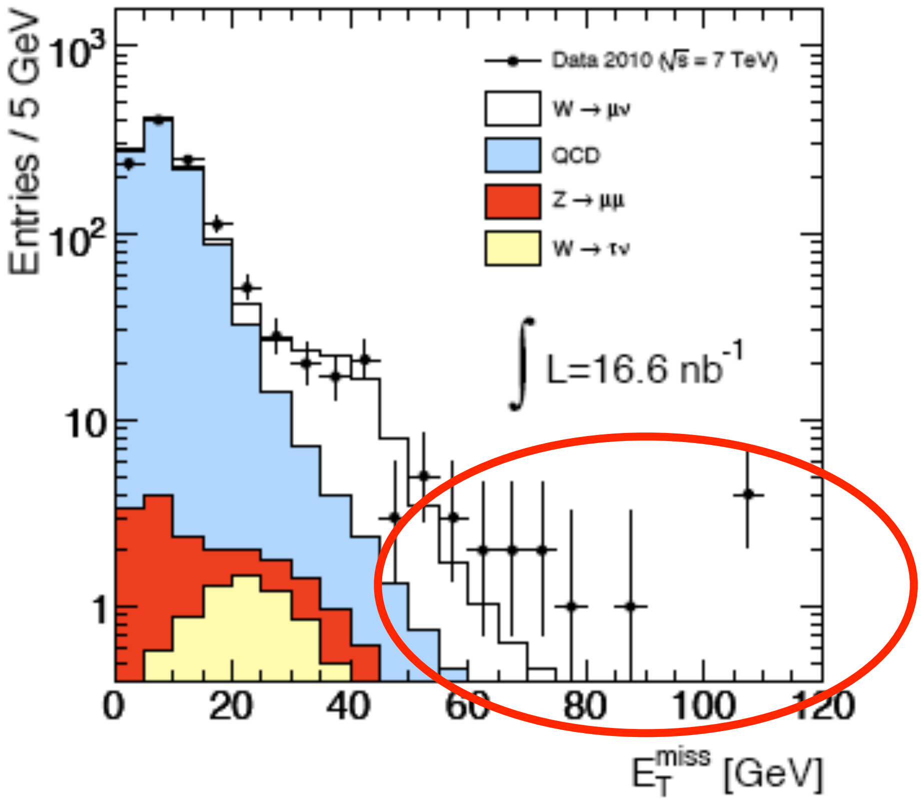



# Missing $E_T$

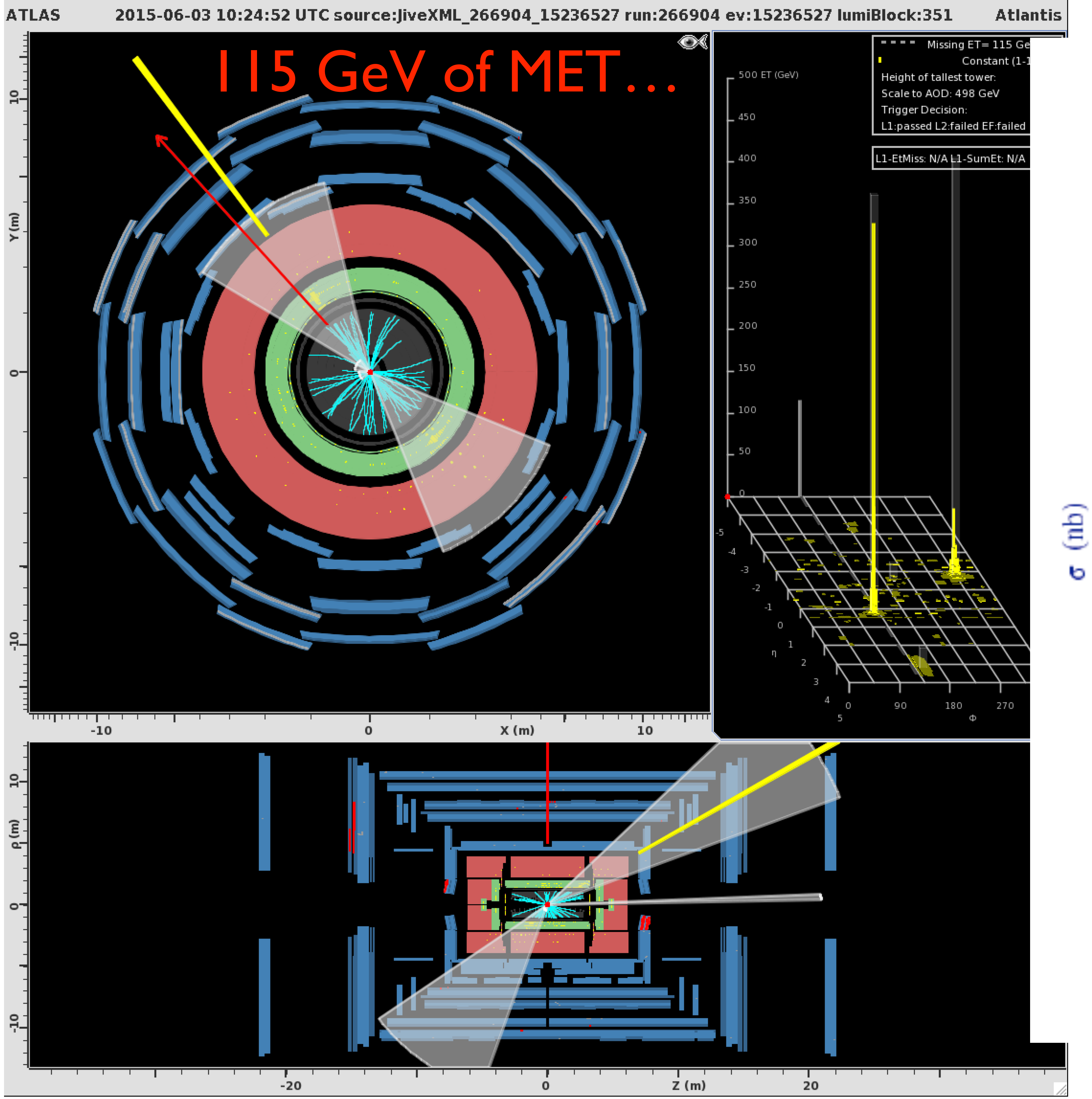
- "Evil" variable: - Σ (everything else)
  - Need to understand "everything else"
  - Good benchmark: leptonic W boson decays

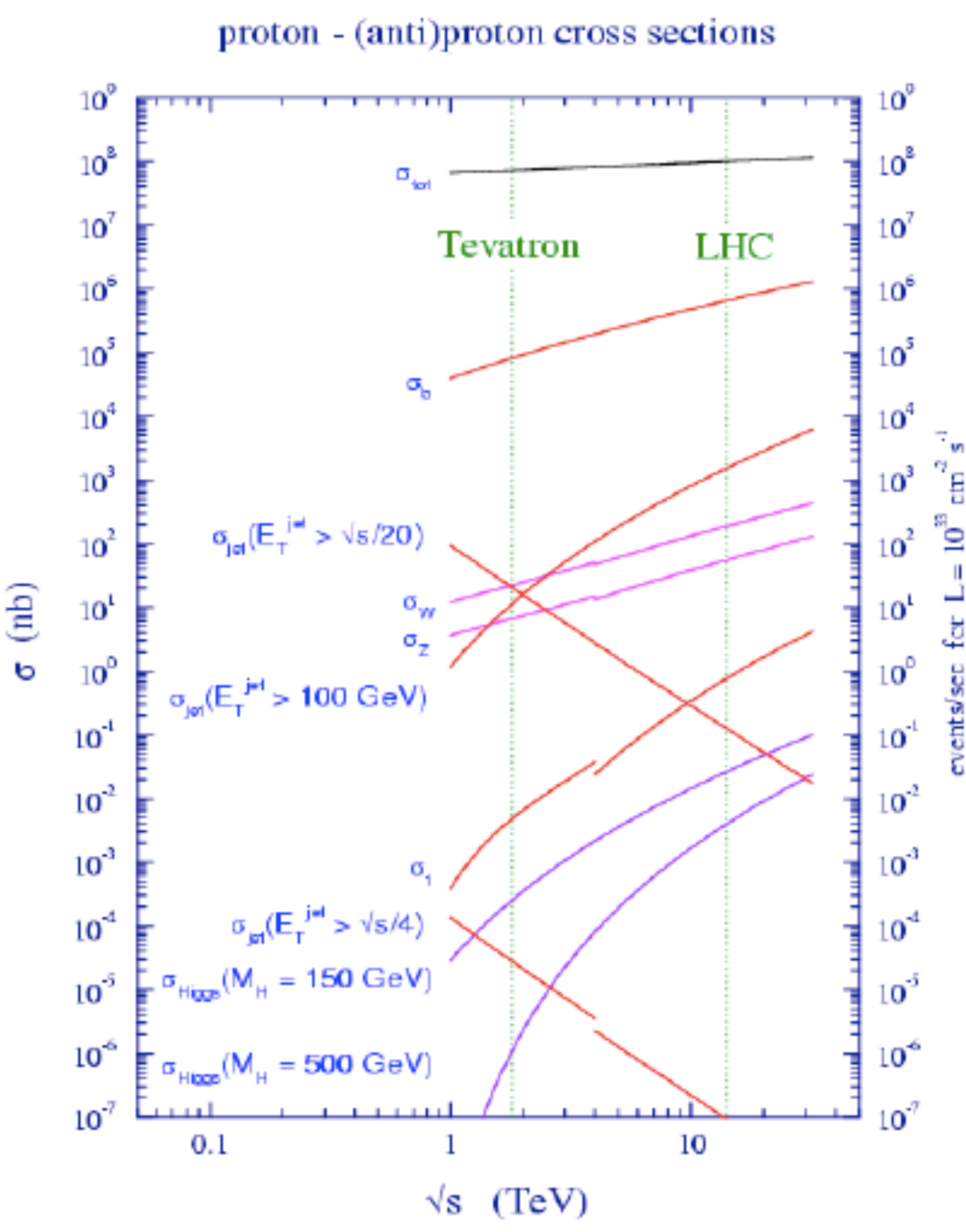
Early 2010



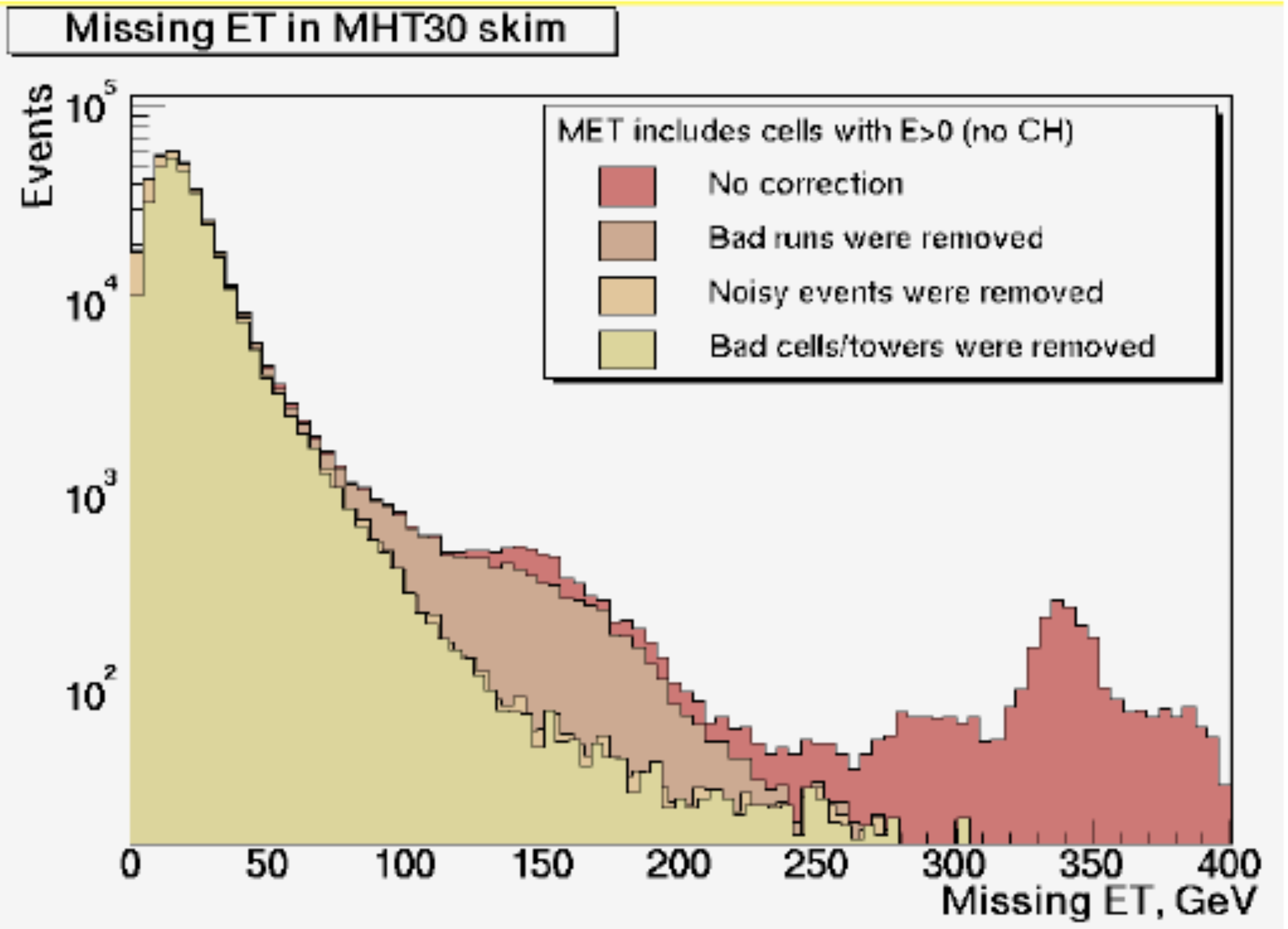

???


ATLAS
2015-06-03 10:24:52 UTC source:JiveXML_266904_15236527 run:266904 ev:15236527 lumiBlock:351
Atlantis
115 GeV of MET…
Missing ET= 115 Ge
Height of tallest tower:
Scale to AOD: 498 GeV
Trigger Decision:
L1:passed L2:failed EF:failed
L1-EtMiss: N/A L1-SumEt: N/A
Y (m)
X (m)
ρ (m)
Z (m)
η
Φ

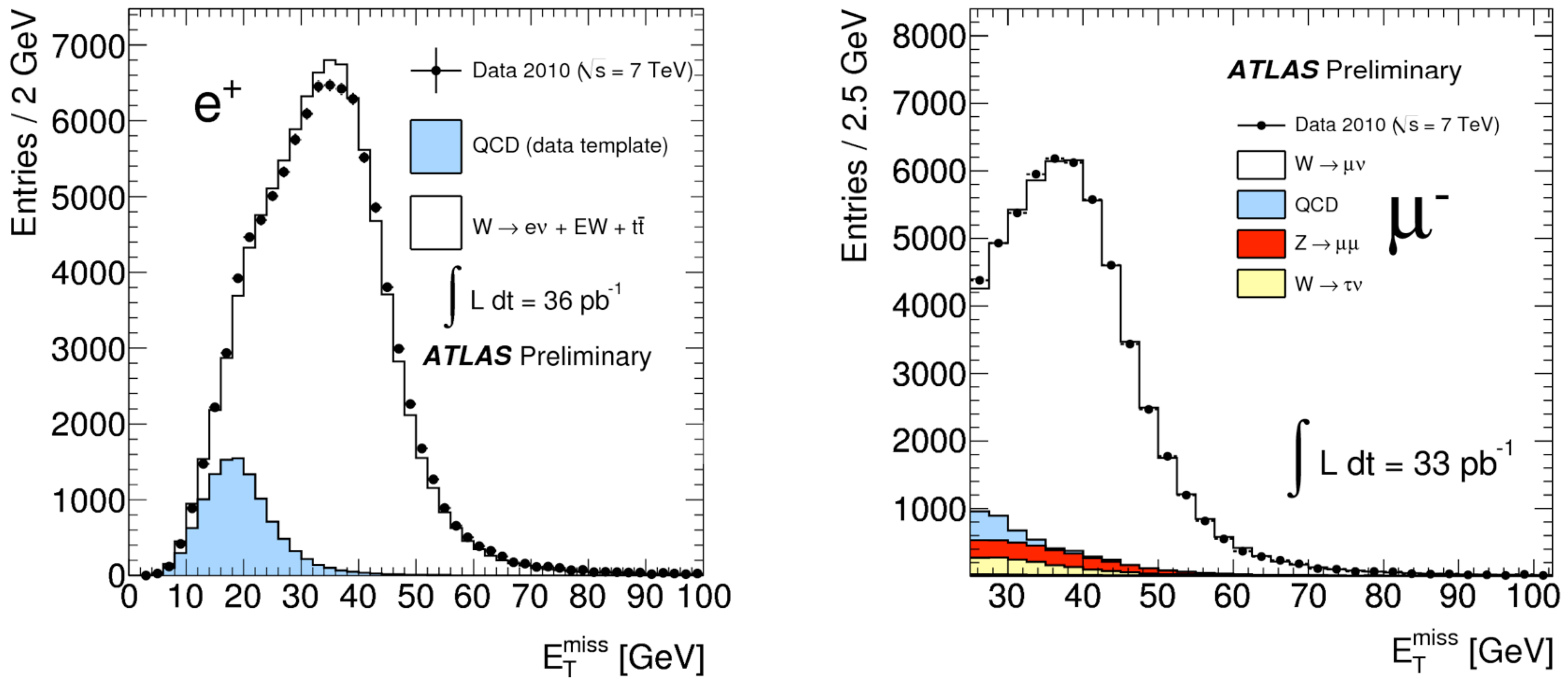

proton - (anti)proton cross sections
Tevatron
LHC
σ (nb)
events/sec for L = 10^33 cm^-2 s^-1
√s (TeV)
σ_tot
σ_b
σ_jet(E_T^jet > √s/20)
σ_W
σ_Z
σ_jet(E_T^jet > 100 GeV)
σ_t
σ_jet(E_T^jet > √s/4)
σ_Higgs(M_H = 150 GeV)
σ_Higgs(M_H = 500 GeV)

❖ Analyses using MET are particularly sensitive

- Requires the full calorimeter to behave, and calorimeter is generally the most sensitive subdetector (analog, ~16 bit dynamic range, 12 bit precision)
- Easy: basic DQ (high voltage trip, etc.)
- Hard: low frequency
- Can't spot a $10^{-5}$ Hz (once a day) effect online or in first pass DQ
  - But can be biggest part of dataset after cuts!



❖ With "cleaning", QCD evaluated from data,…

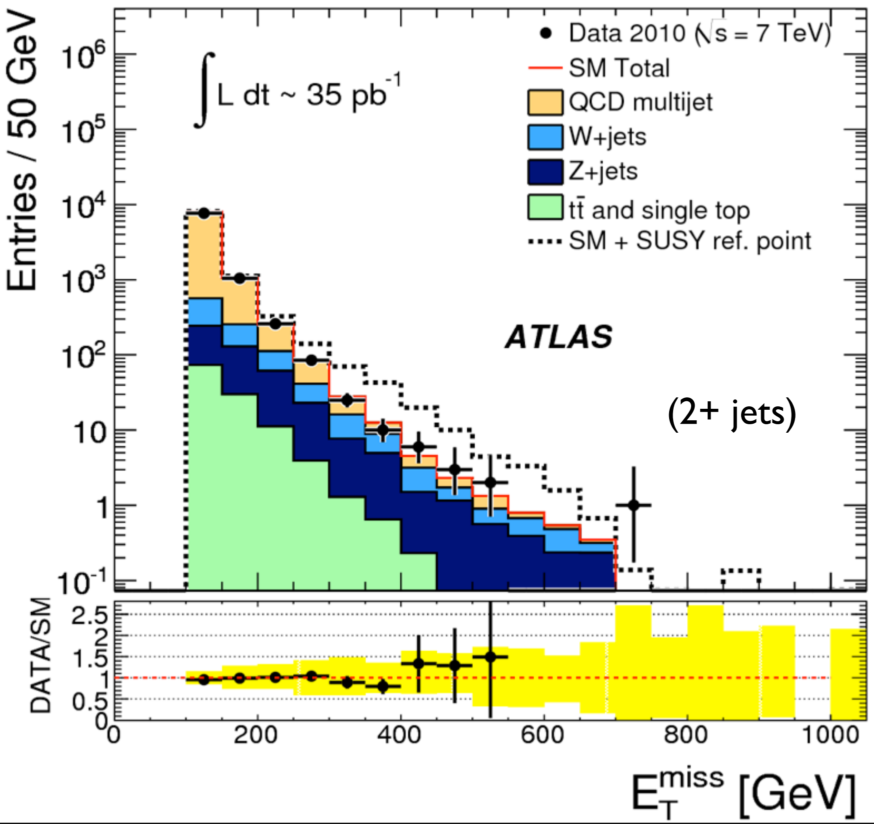


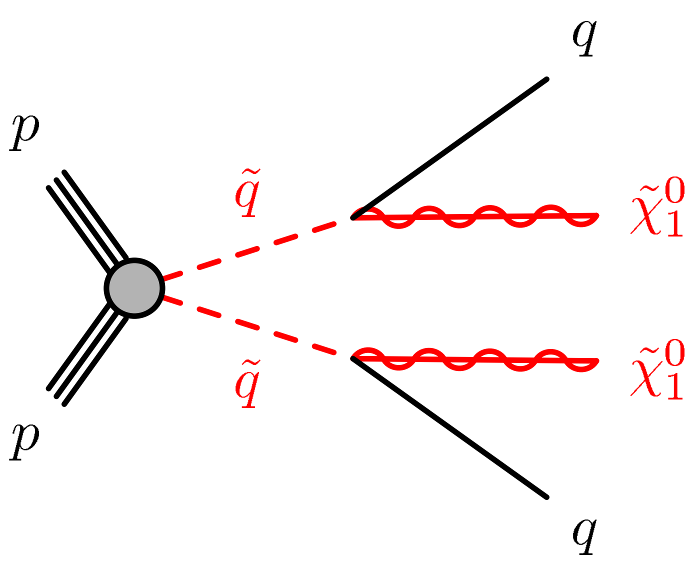

❖ Already ~200k clean W → $\ell\nu$ events in 2010

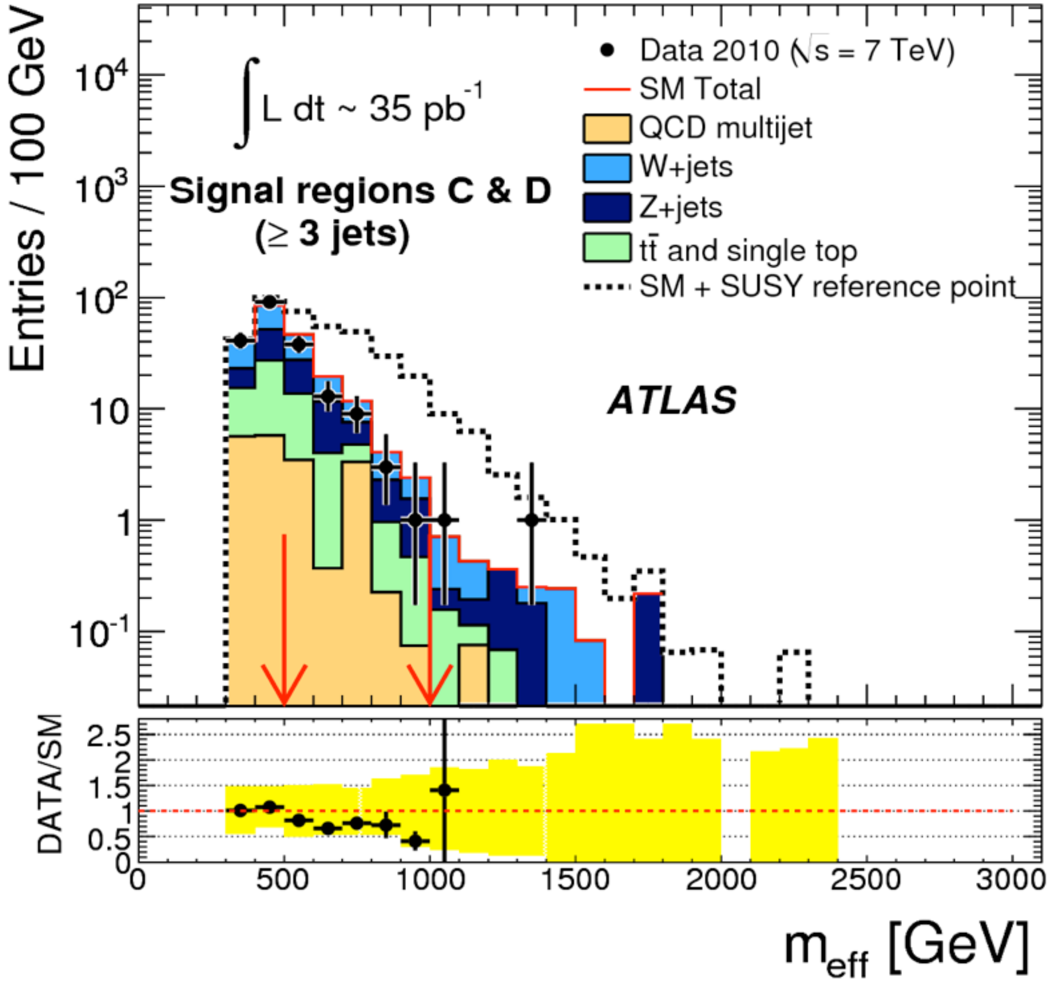
- Billions now

# SUSY as a Benchmark

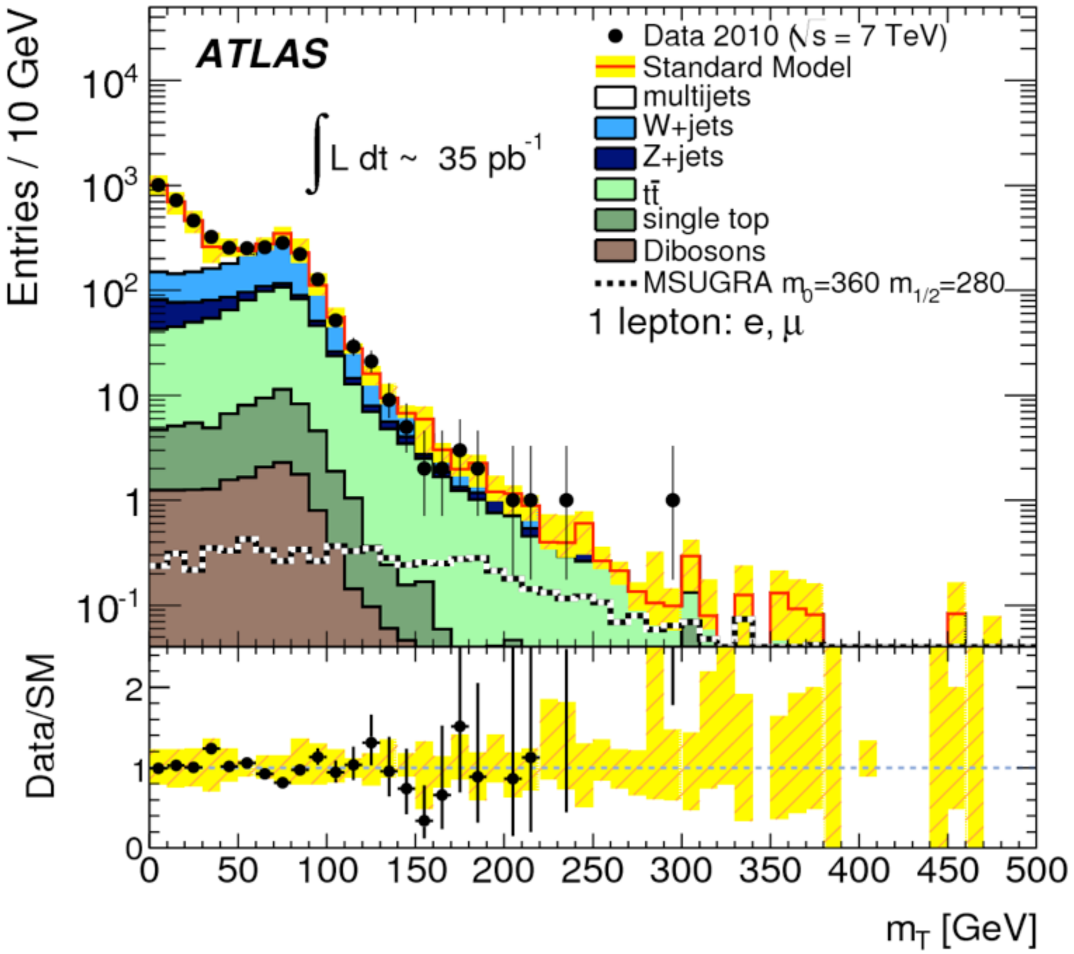
- ❖ Hadron collider ⇒ produce squarks and gluinos decaying to jets + MET
  - Optimize jet $p_T$ & MET cuts for different scenarios, since gluinos produce more jets than squarks
    - Use $M_{eff}$ to discriminate, measure of event $Q^2$

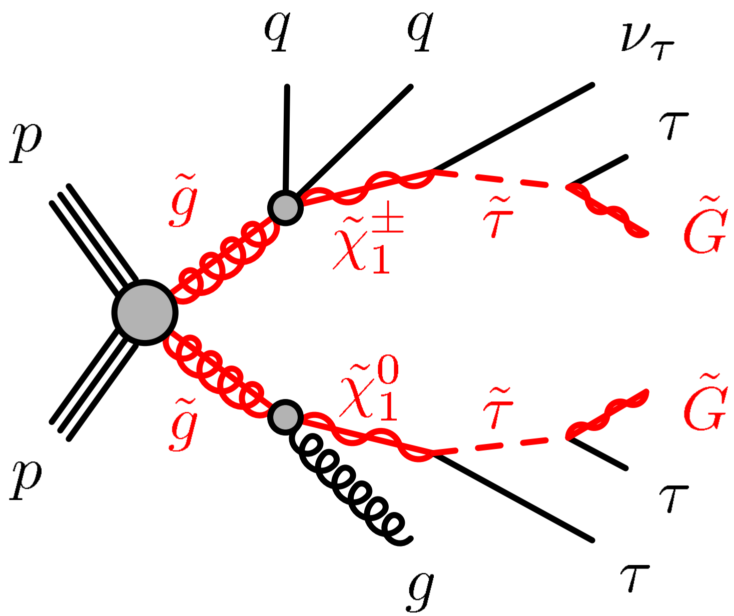


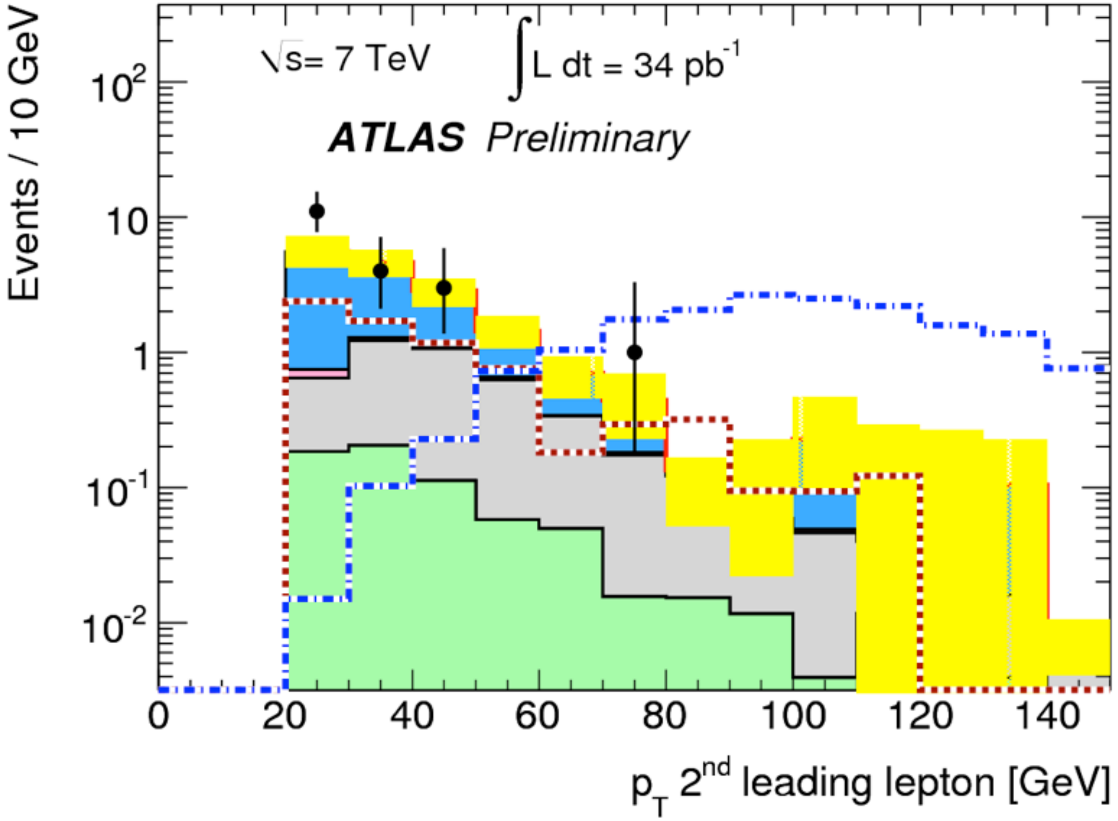



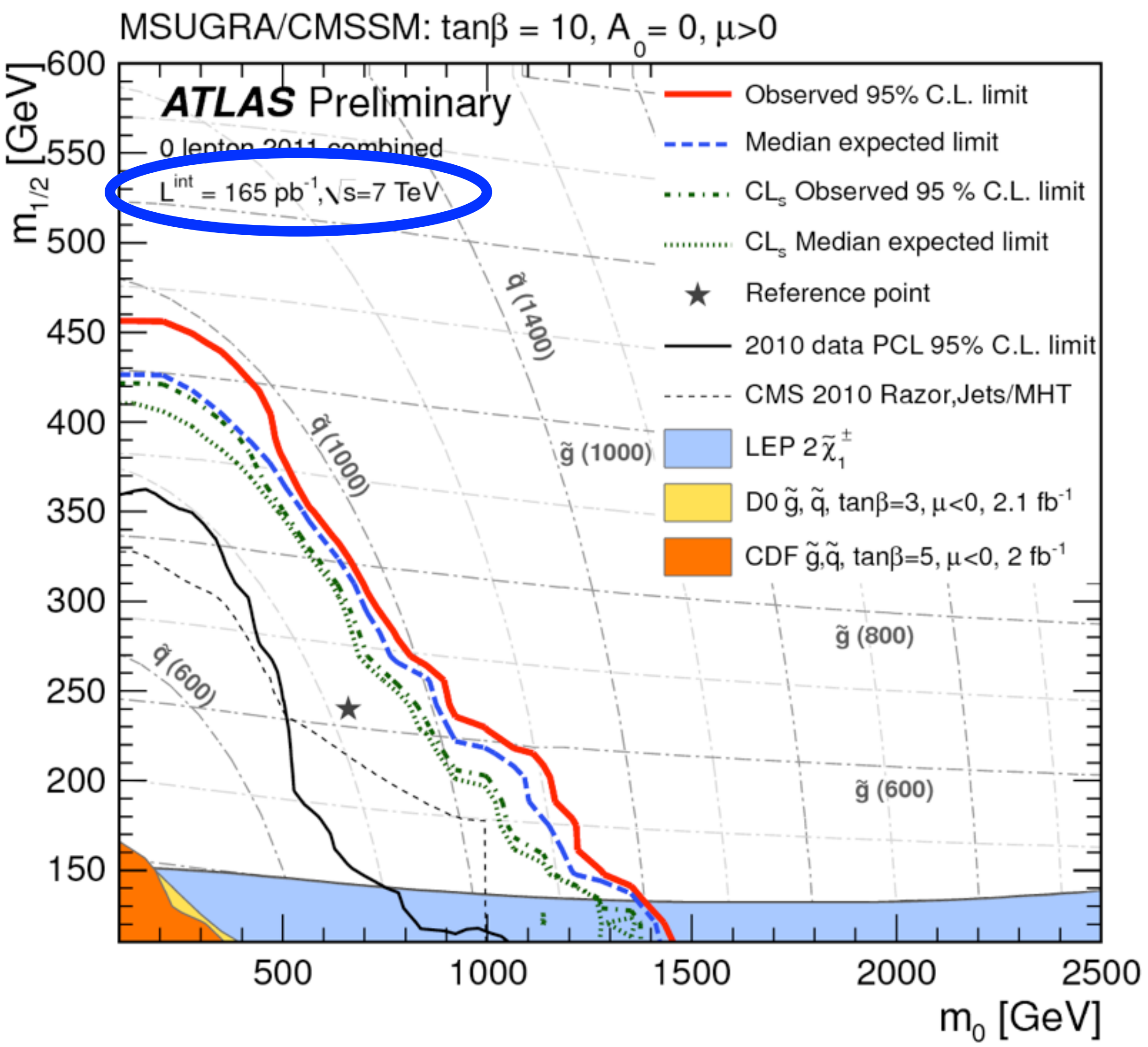
# ❖ Leptons in decay chains....



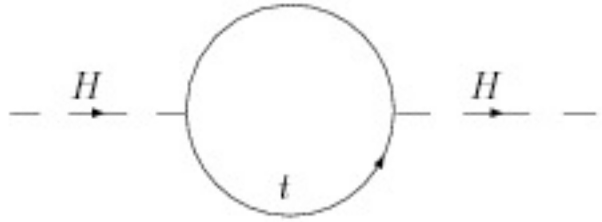
# All Praise COM Energy!



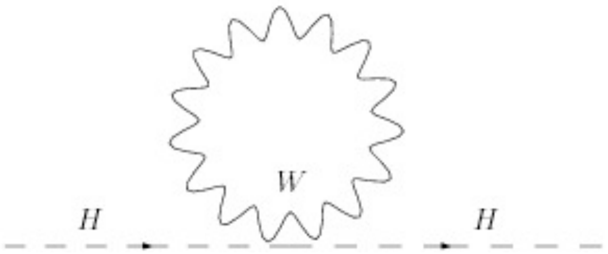

Tevatron blown away.... 8 (2016) hours of LHC data

# But…

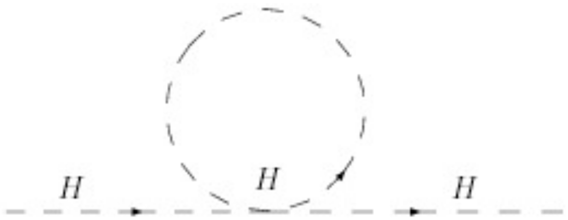
# We’ve Found a Higgs!




$\rightarrow \frac{3}{16\pi^2} y_t^2 E^2$




$\rightarrow \frac{1}{16\pi^2} g^2 E^2$



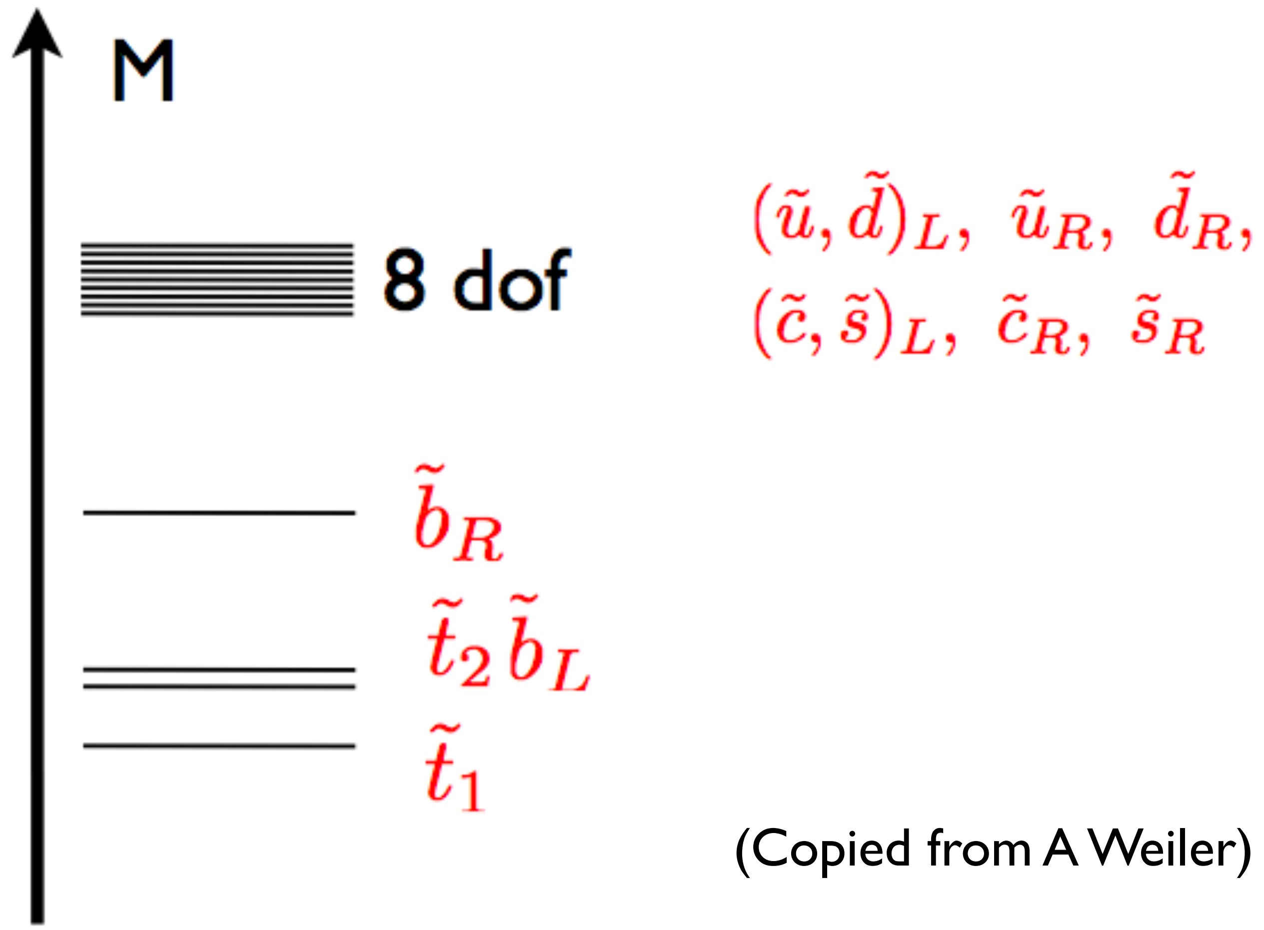

$\rightarrow \frac{1}{16\pi^2} \lambda E^2$

- ❖ If new scale, these go to the new scale...
- ❖ To ~cancel these, need to primarily compensate for
  - Top
  - W/Z
  - H

➡ **Discovery of the light Higgs refocuses new physics search**

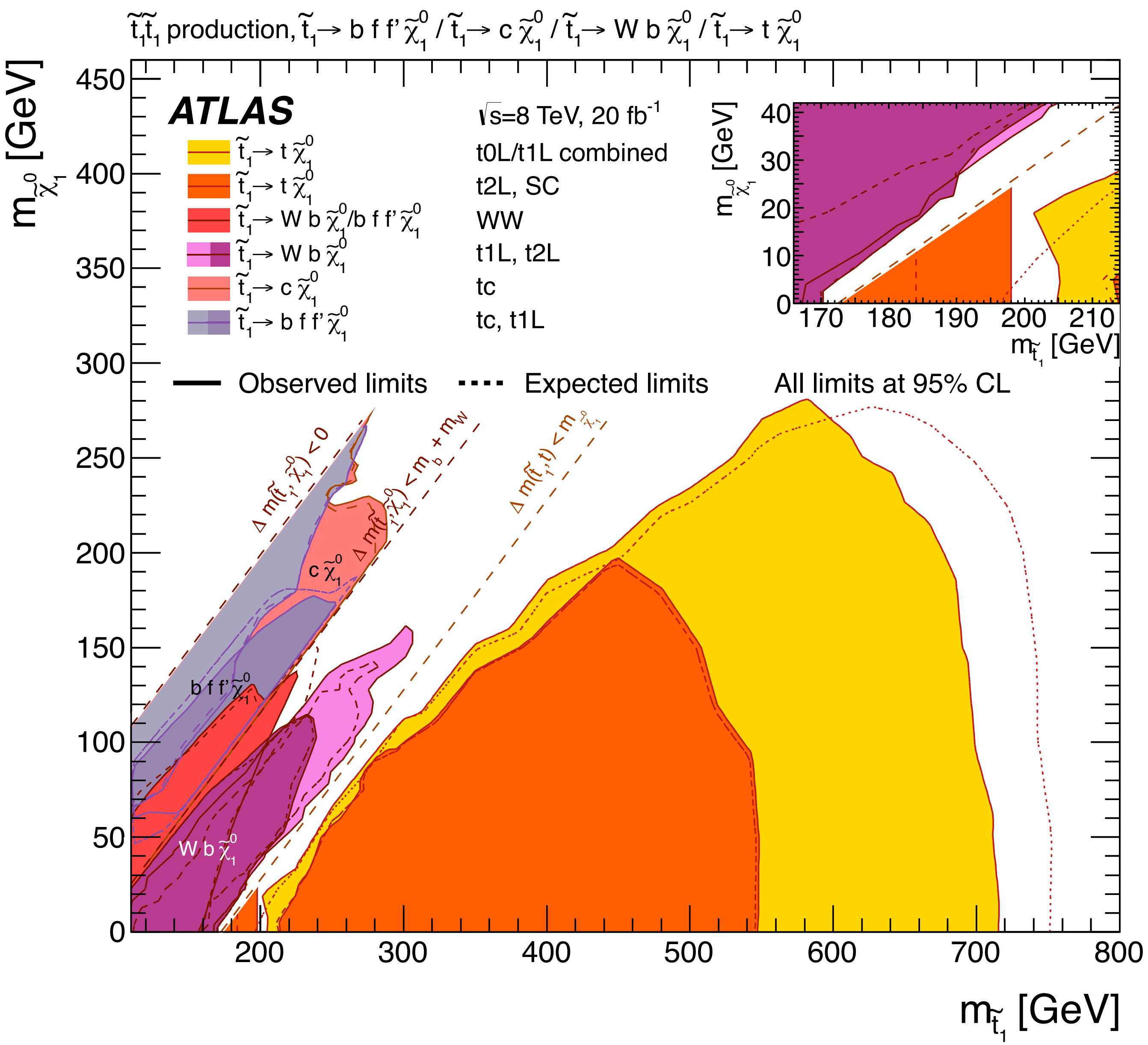
# SUSY and the Higgs

- For SUSY, 125 GeV is rather heavy!
  - Need light higgsinos, stops, sbottoms... but heavy "light" squarks ok ⇒ "natural SUSY"
  - Stop at the forefront!

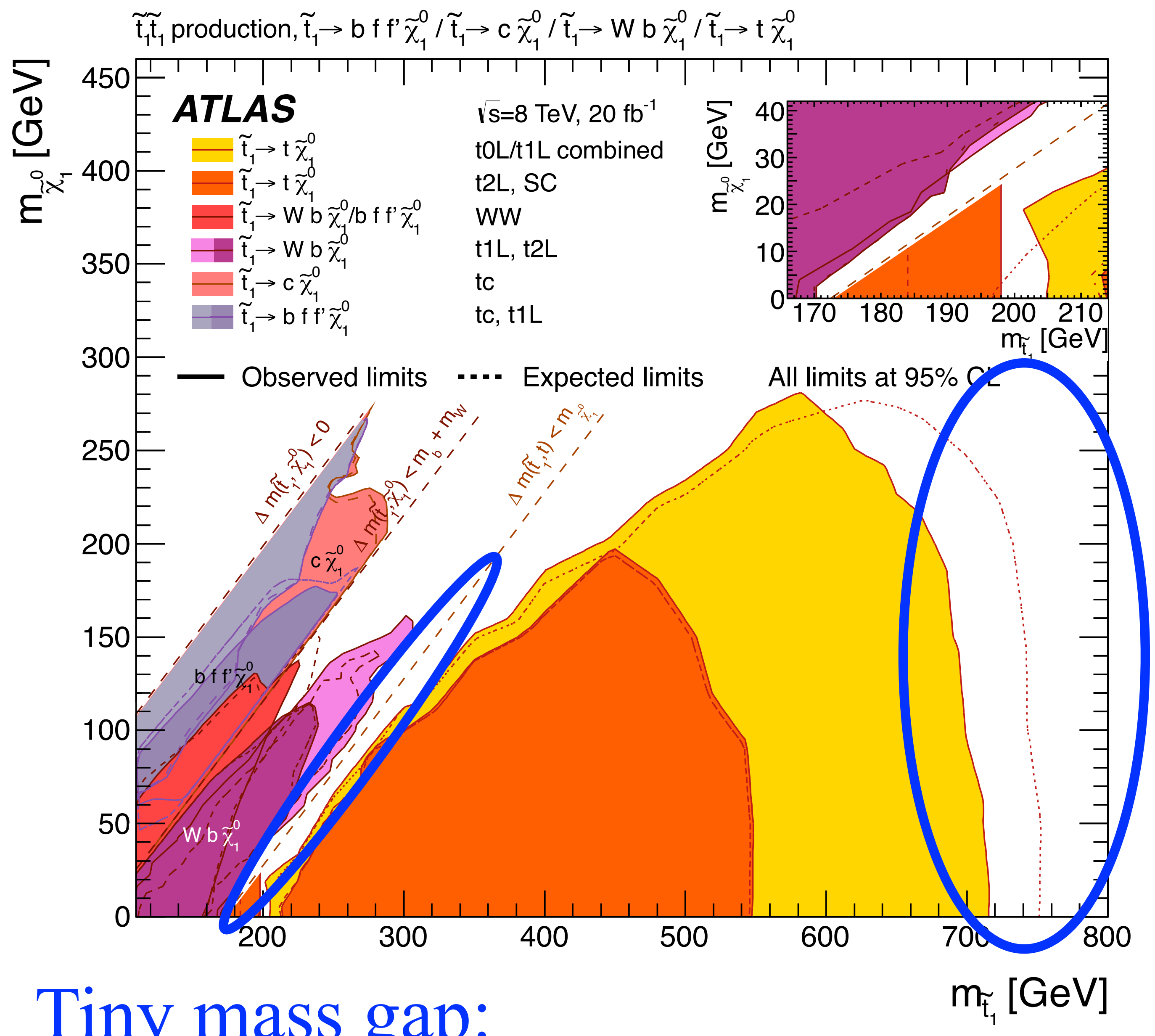



(Copied from A Weiler)

# Stop Searching Anatomy



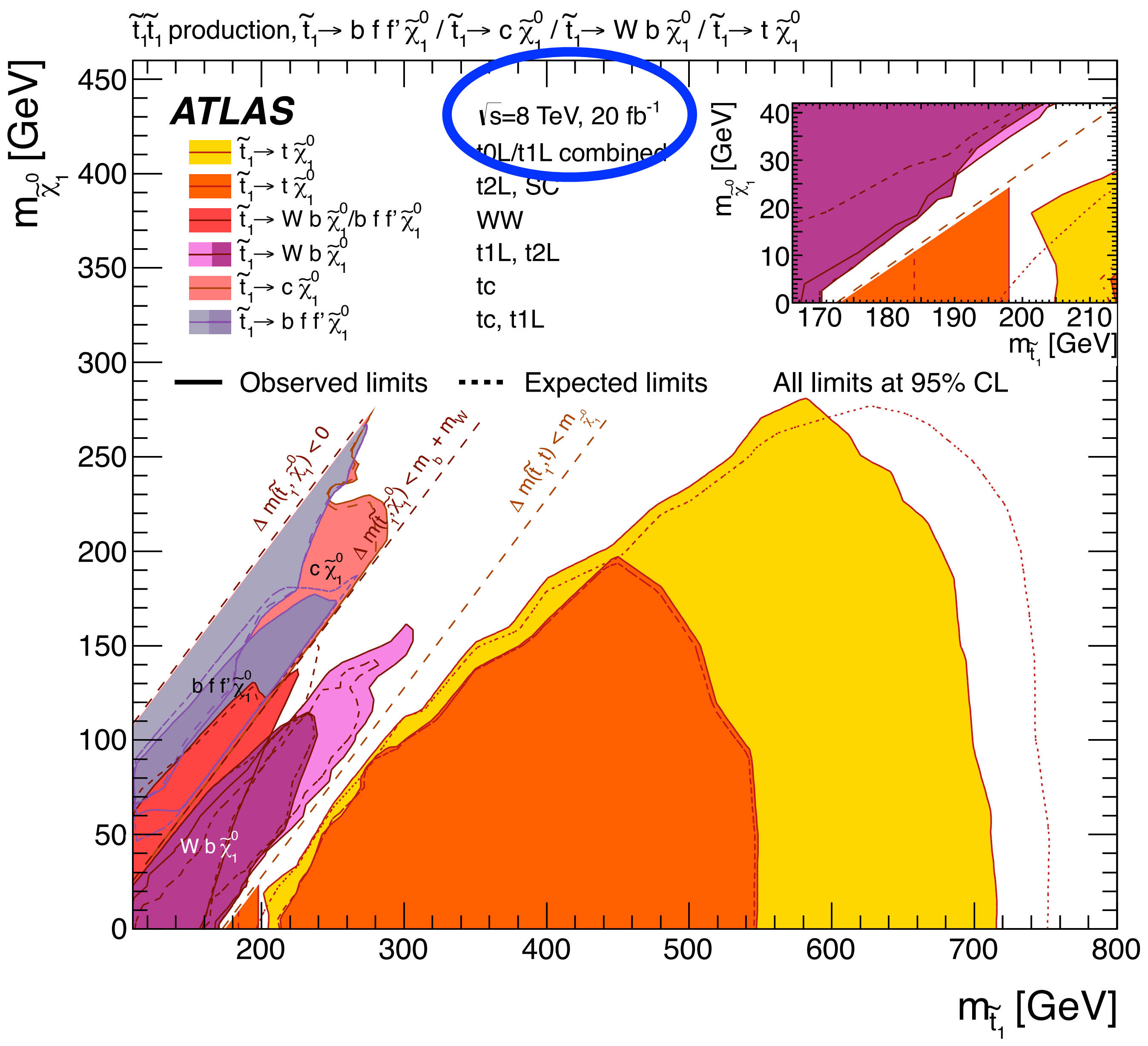
# Stop Searching Anatomy

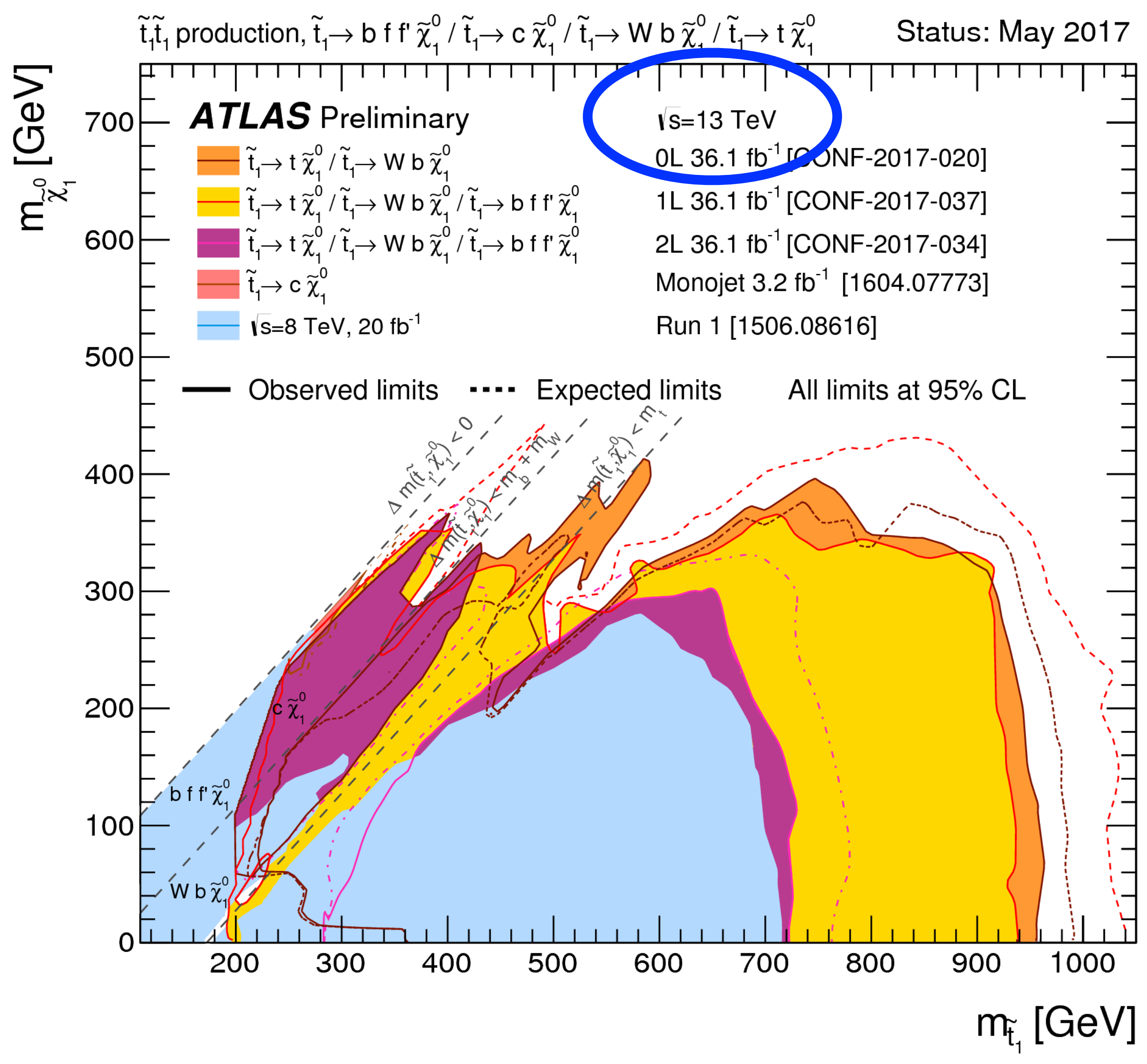



High mass: run out of cross-section

Tiny mass gap: soft decay products

# Stop Searching Anatomy



# Same-Sign Leptons

❖ At hadron colliders, leptons signify something interesting happened

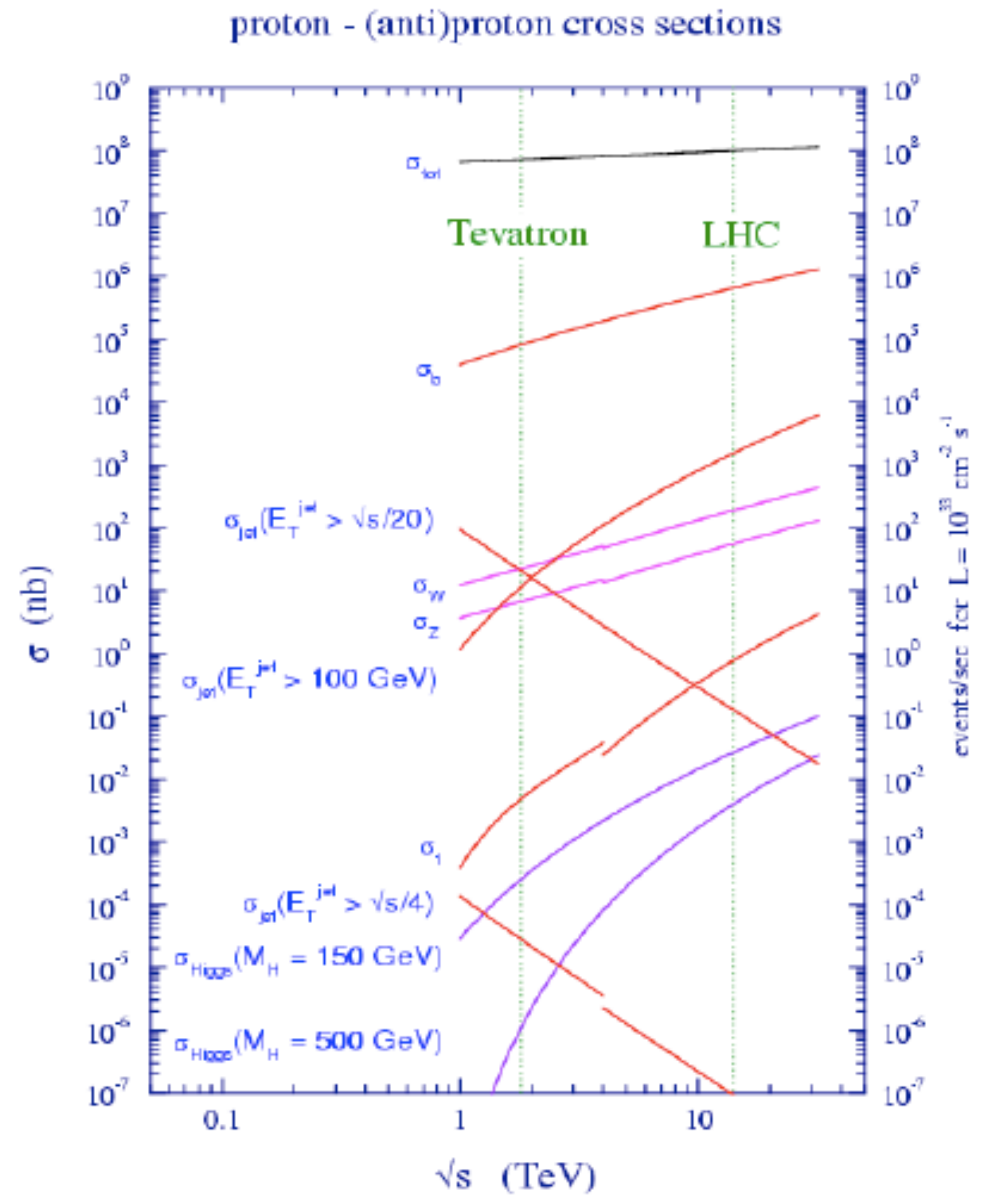
- E.g. Z production

❖ Same-sign leptons even more interesting? Lower background?

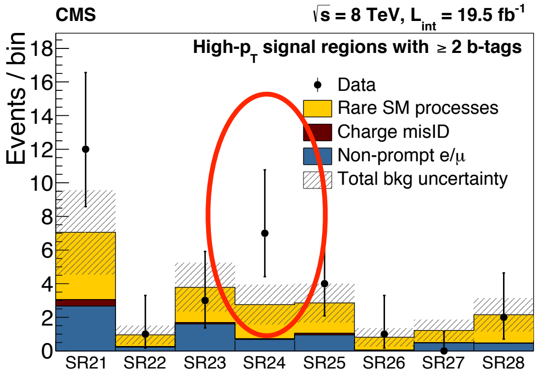
- $W^{\pm} W^{\pm}$
- but also B/D meson oscillations
  - mostly low $p_T$
- and wrong charge measurement

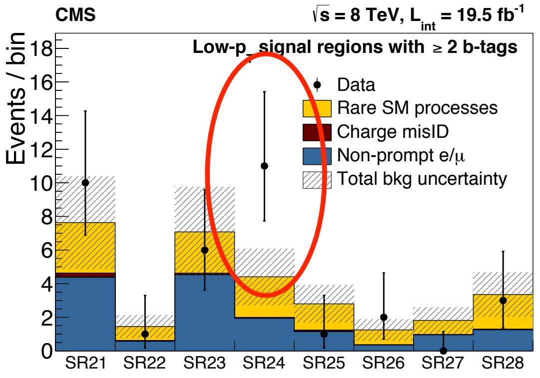
❖ With lower background, access to smaller cross-sections, smaller mass gaps

- At the cost of small branching ratio



# Same Sign Lepton Excesses

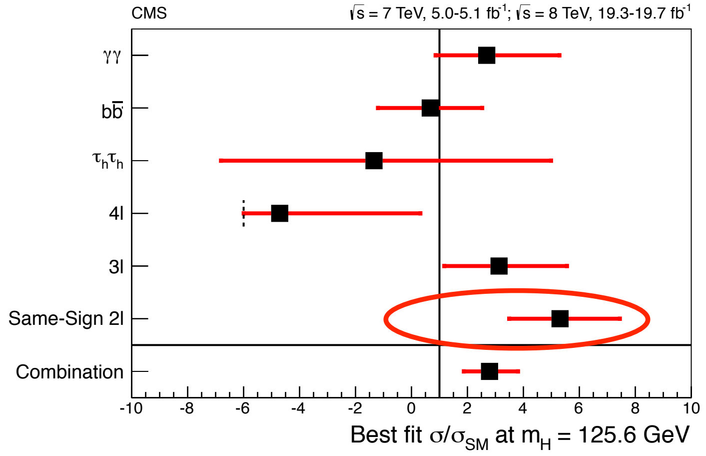


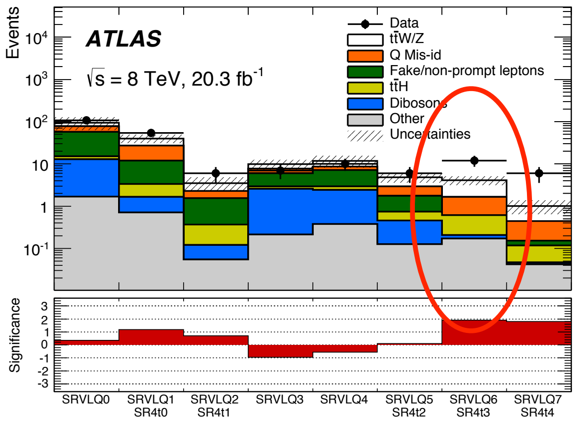

CMS (SUSY), http://arxiv.org/abs/1311.6736 (24 signal regions in paper)

| SR1b $_{1bin}$ | Total | $ee$ | $e\mu$ | $\mu\mu$ |
|---|---|---|---|---|
| **Observed events** | 10 | 6 | 4 | 0 |
| **Total expected background events** | $4.7 \pm 2.1$ | $1.4 \pm 0.8$ | $2.1 \pm 1.1$ | $1.2 \pm 0.4$ |
| **Components of the background** | | | | |
| $t\bar{t}V$, $t\bar{t}H$, $tZ$ and $t\bar{t}t\bar{t}$ | $2.5 \pm 1.7$ | $0.6 \pm 0.3$ | $1.2 \pm 1.0$ | $0.7 \pm 0.3$ |
| Dibosons and tribosons | $0.9 \pm 0.4$ | $0.10 \pm 0.04$ | $0.3 \pm 0.1$ | $0.5 \pm 0.3$ |
| Fake leptons | $0.8^{+1.2}_{-0.8}$ | $0.4^{+0.7}_{-0.4}$ | $0.4^{+0.5}_{-0.4}$ | $< 0.1$ |
| Charge-flip electrons | $0.5 \pm 0.1$ | $0.3 \pm 0.1$ | $0.3 \pm 0.1$ | – |
| $p(s = 0)$ | 0.07 | 0.01 | 0.18 | 0.50 |

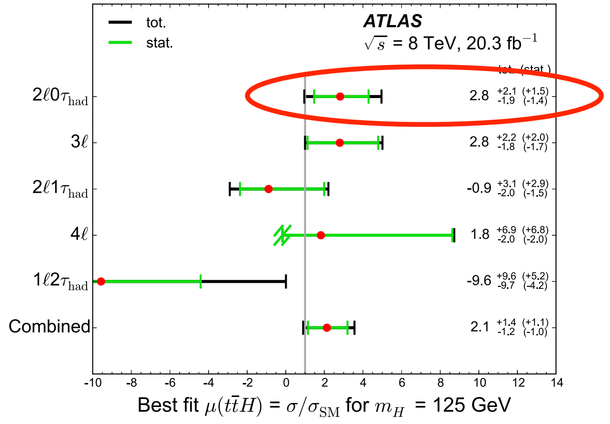
ATLAS (SUSY), http://arxiv.org/abs/1404.2500 (5 signal regions in paper)




CMS (ttH), http://arxiv.org/abs/1408.1682




ATLAS (TT), http://arxiv.org/abs/1504.04605



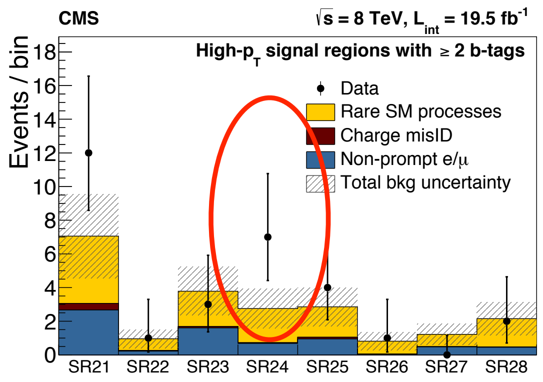

ATLAS (ttH), http://arxiv.org/abs/1506.05988

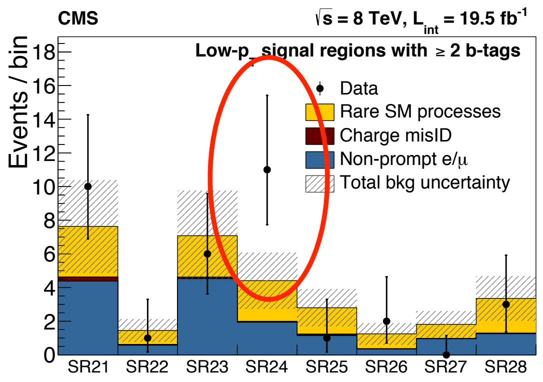
**It certainly looks like multiple analyses looking at same sign leptons and b-jets see excesses!**

Could it be SUSY? E.g. $\tilde{t}_R \to t + \tilde{B} \to t + (\tilde{W}^{\pm} + W^{\mp})$

Huang et al, http://arxiv.org/abs/1507.01601

# Same Sign Lepton Excesses

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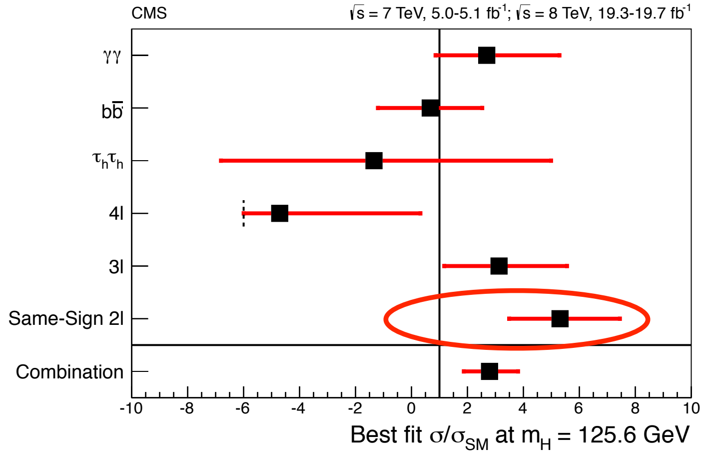
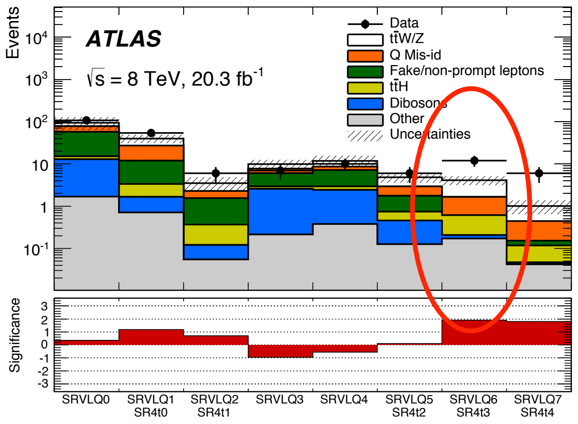



CMS (ttH), http://arxiv.org/abs/1408.1682

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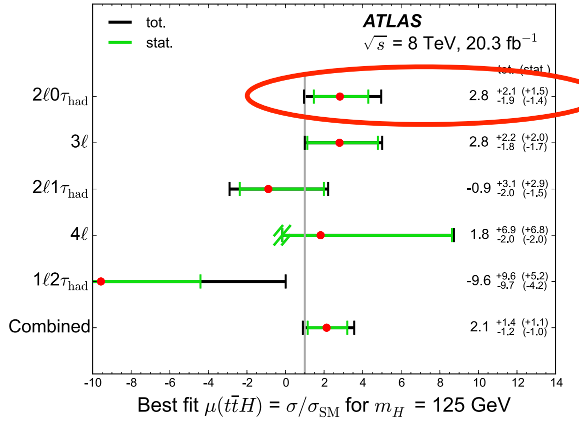



ATLAS (ttH), http://arxiv.org/abs/1506.05988

**The ATLAS analyses are correlated, and same for CMS**

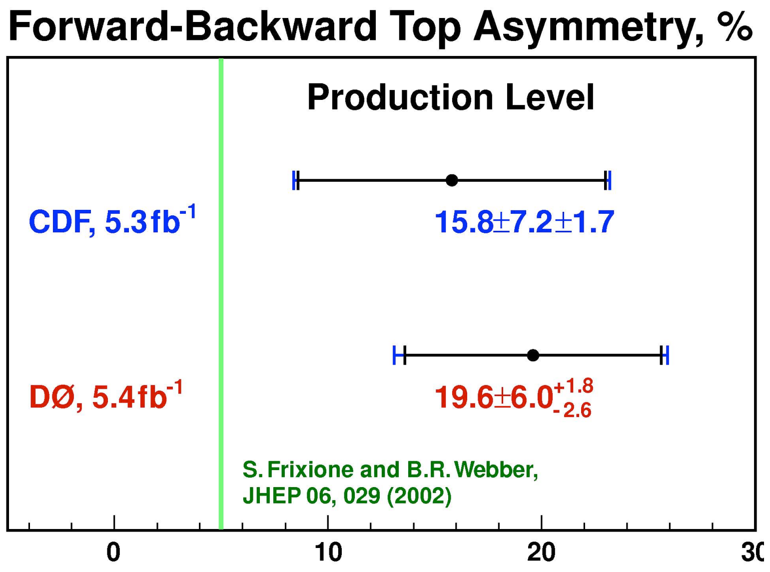
**So, ~2 analyses and excesses are < 3 σ…**

**Worth keeping an eye on? Sure.**

# Anecdotes From the Field (II)

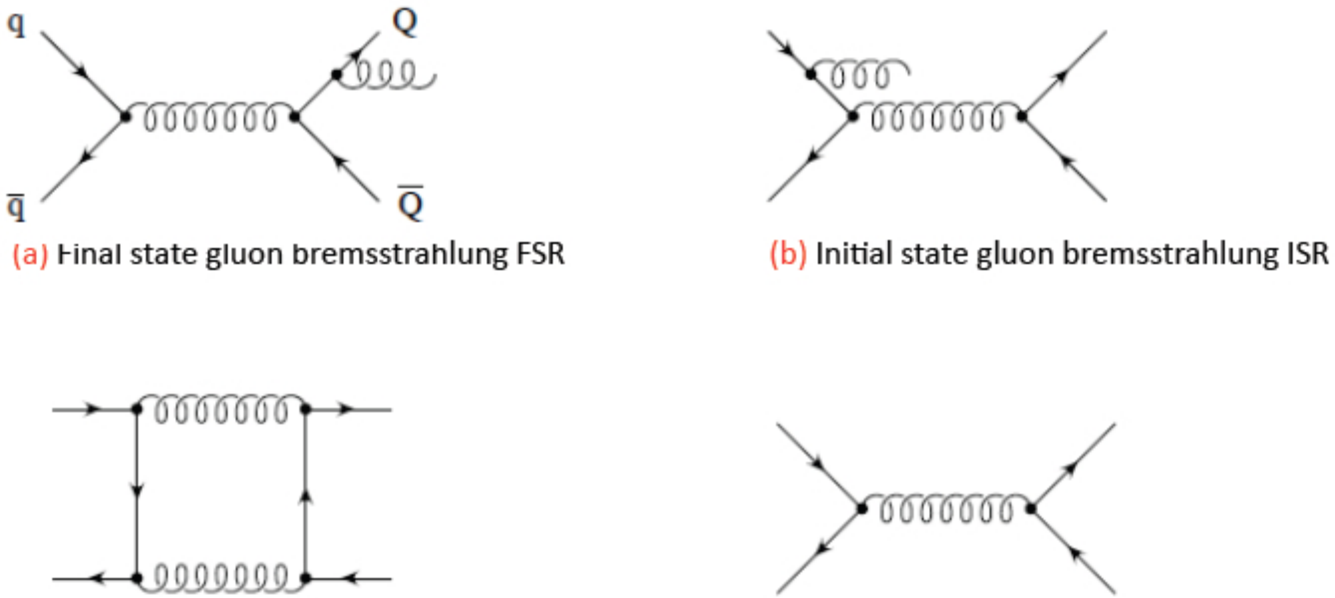
❖ ttbar charge asymmetry at the Tevatron

- At Feynman diagram level, NLO effect (Tevatron is proton-anti-proton collider)




http://arxiv.org/abs/1107.4995

Ca. 2010, big fuss: much larger than SM!

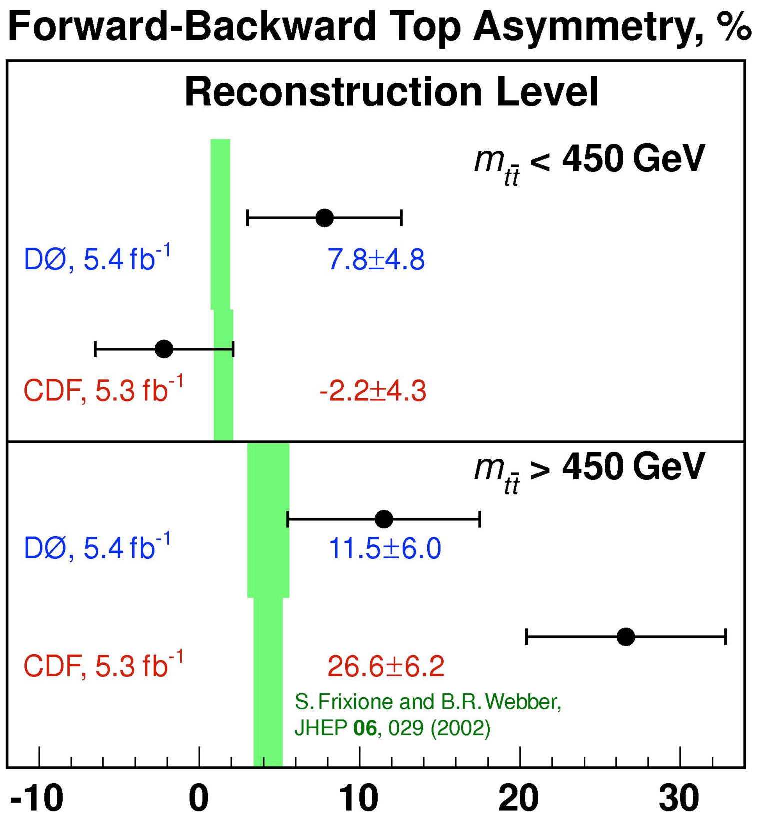



(a) Final state gluon bremsstrahlung FSR

(b) Initial state gluon bremsstrahlung ISR

(c) double virtual gluon exchange

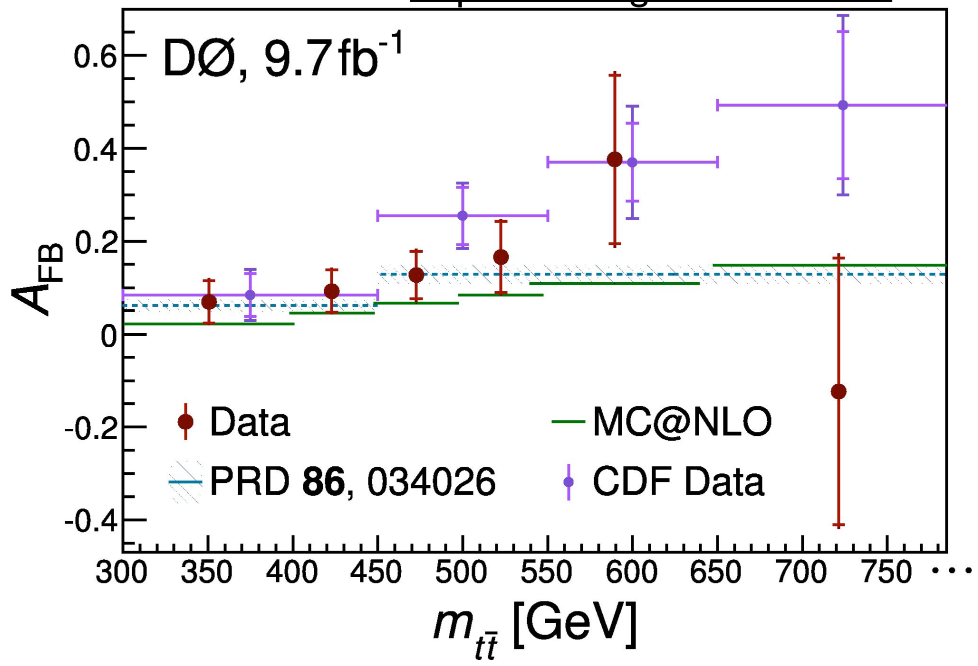
(d) Born diagram



# Anecdotes From the Field (II)

- ttbar charge asymmetry at the Tevatron
  - At Feynman diagram level, NLO effect (Tevatron is proton-anti-proton collider)
  - But in real life, already exists at ~LO!
    - Shown it is there in Pythia: parton shower, recoils!  http://arxiv.org/abs/1205.1466

http://arxiv.org/abs/1405.0421

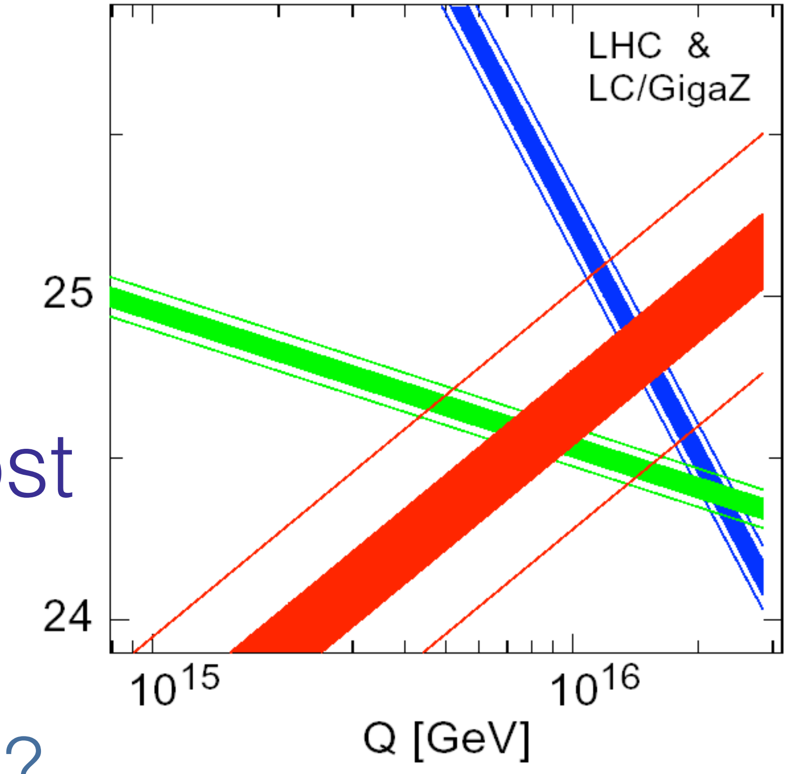



no BSM physics here:
-real life is not LO or NLO but NNN…LO
-many scales at work and this measurement crucially depends on multiple very different scales

# Not SUSY?

- ❖ SUSY theories (and others with full or partial set of SM-partners) have a number of attractive features
  - "Explanation" for low Higgs mass (and sometimes EWSB)
  - Gauge coupling unification (often)
  - Dark matter candidate (if introduce a new parity, natural in UED, ~ad-hoc in SUSY)
  - No new interactions (often)
- ❖ But answering those questions comes at a large cost
  - Many new particles, with masses and mixing angles
  - Need to explain why mass scale is so low (or high), spin?

MSSM: Allanach et al., hep-ph/0407067

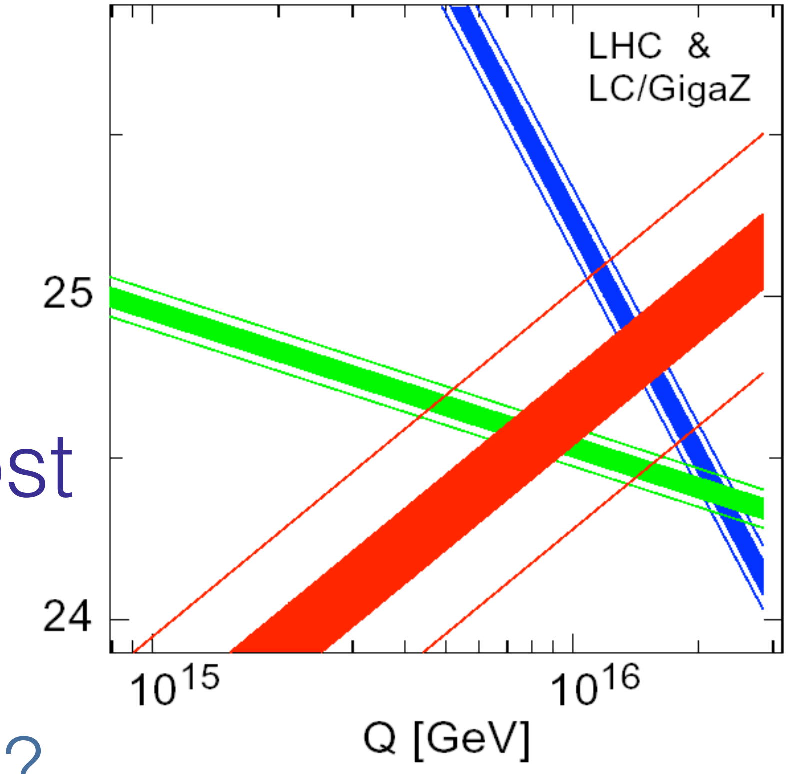


# Not SUSY?

- SUSY theories (and others with full or partial set of SM-partners) have a number of attractive features
  - "Explanation" for low Higgs mass (and someti
  - Gauge coupling unification (often)
  - Dark matter candidate (if introd parity, natural in UED, ~ad
  - No new interaction
- But answeri stions comes at a large cost
  - Many new pa , with masses and mixing angles
  - Need to explain why mass scale is so low (or high), spin?

Dinosaurs on Venus?

MSSM: Allanach et al., hep-ph/0407067



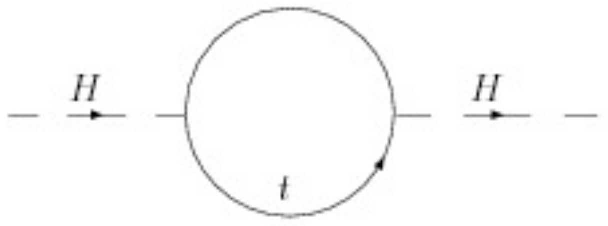
“We had a solution to the hierarchy problem, and it failed”

(Guido Altarelli, 2013)

# Less Ambitious

# Giving up on Dark Matter

- Electroweak-scale WIMPs fit the data well
  - But maybe hard/impossible to produce at colliders
- Or dark matter not WIMPs at all
- Back to problem #1:

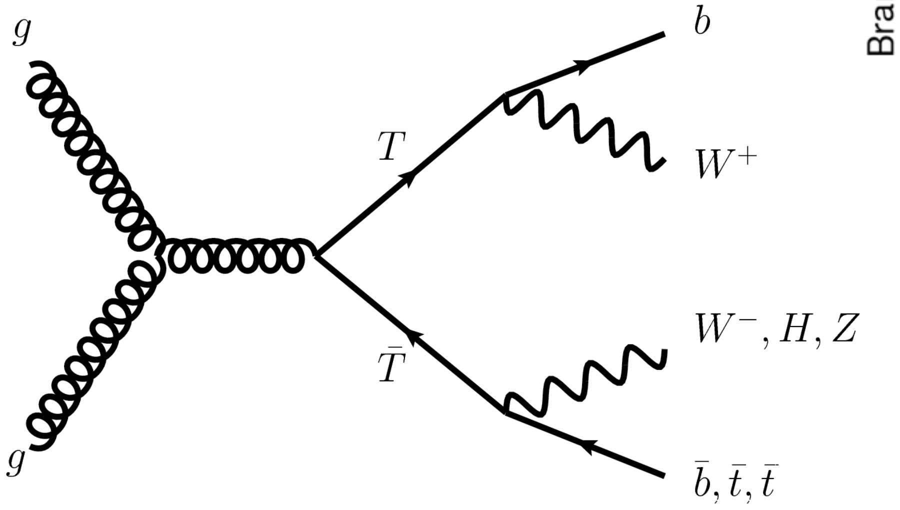


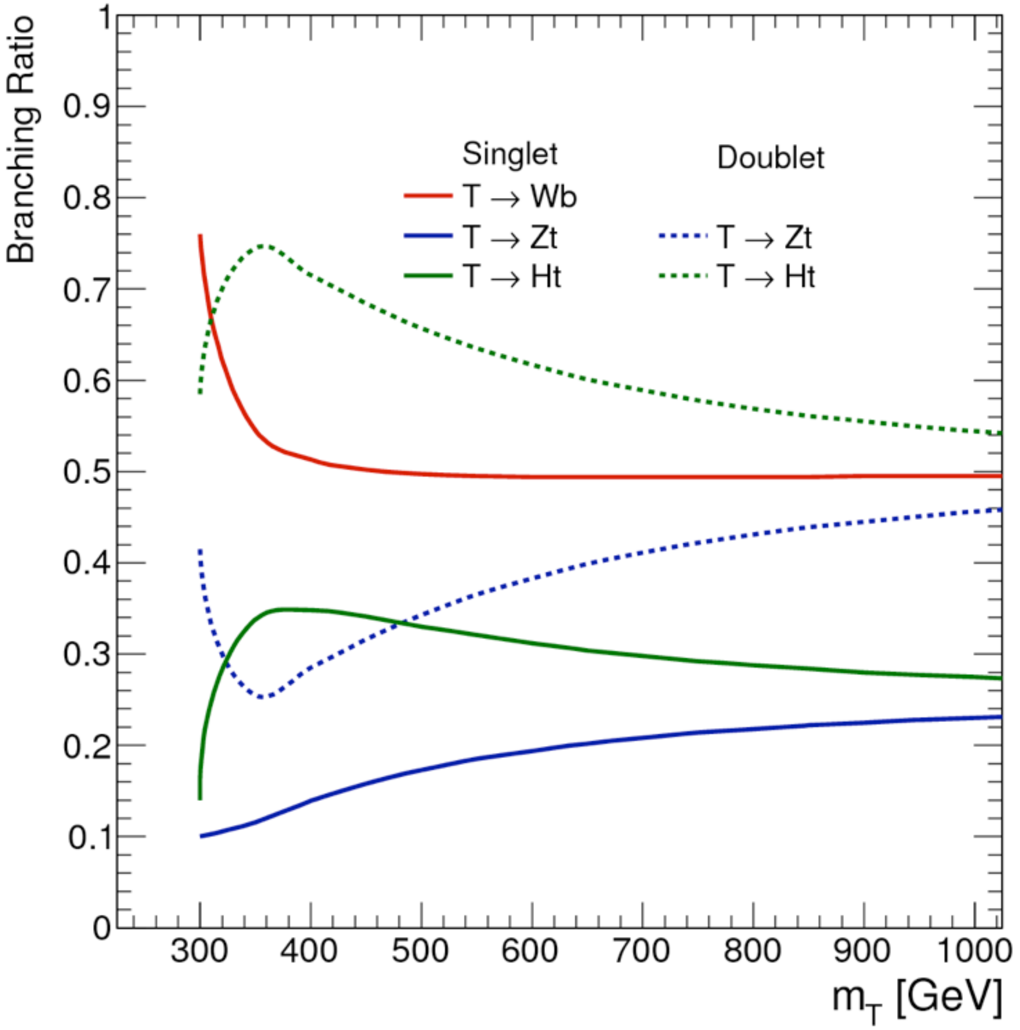

$$\rightarrow \frac{3}{16\pi^2} y_t^2 E^2$$

➡ Top partner!

# Singlets, Doublets, ...

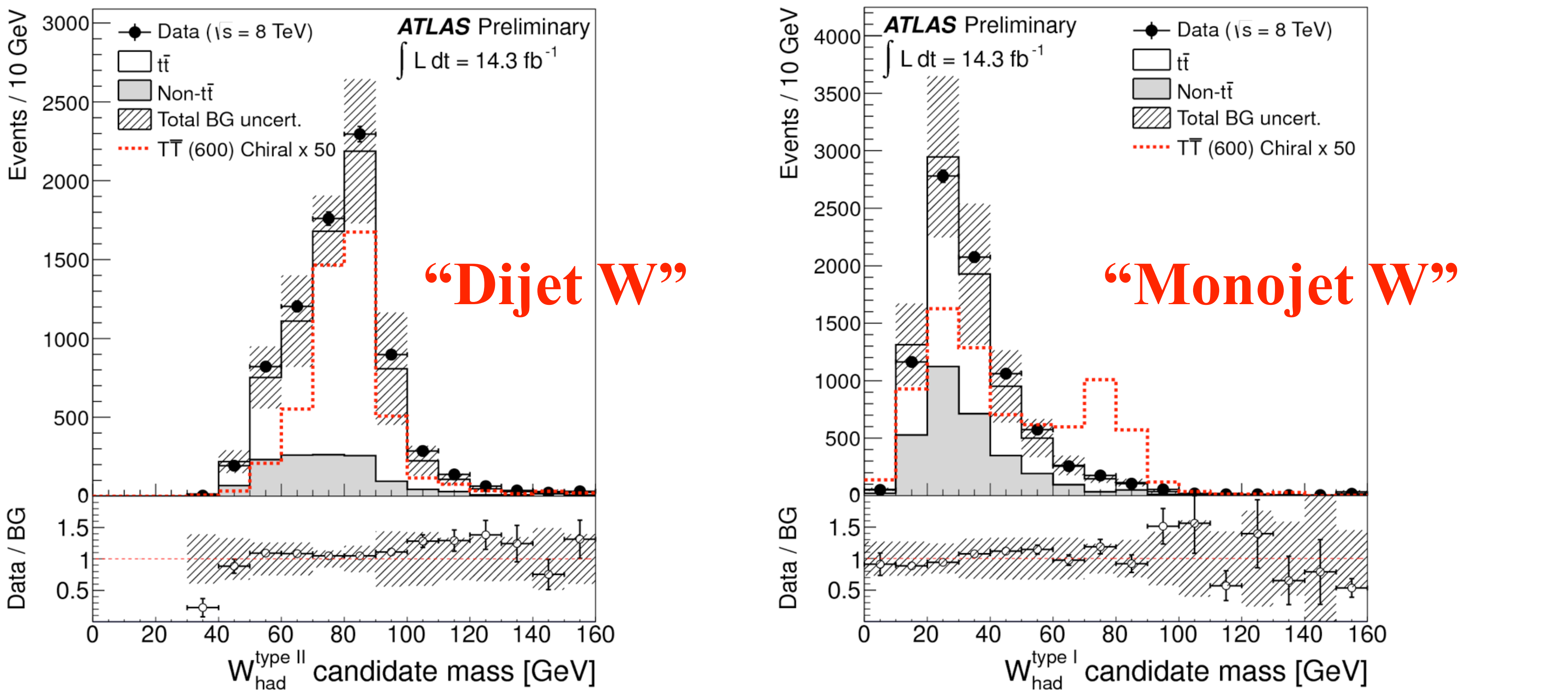
- Vector-like top partners (still fermions) less constrained by flavor....
  - Opens up decay modes
  - Top partner partners:
    - $T^{5/3}$
    - ...
- Rich set of signatures
  - Just no huge MET
  - At least not systematically



# W's Can Be Light

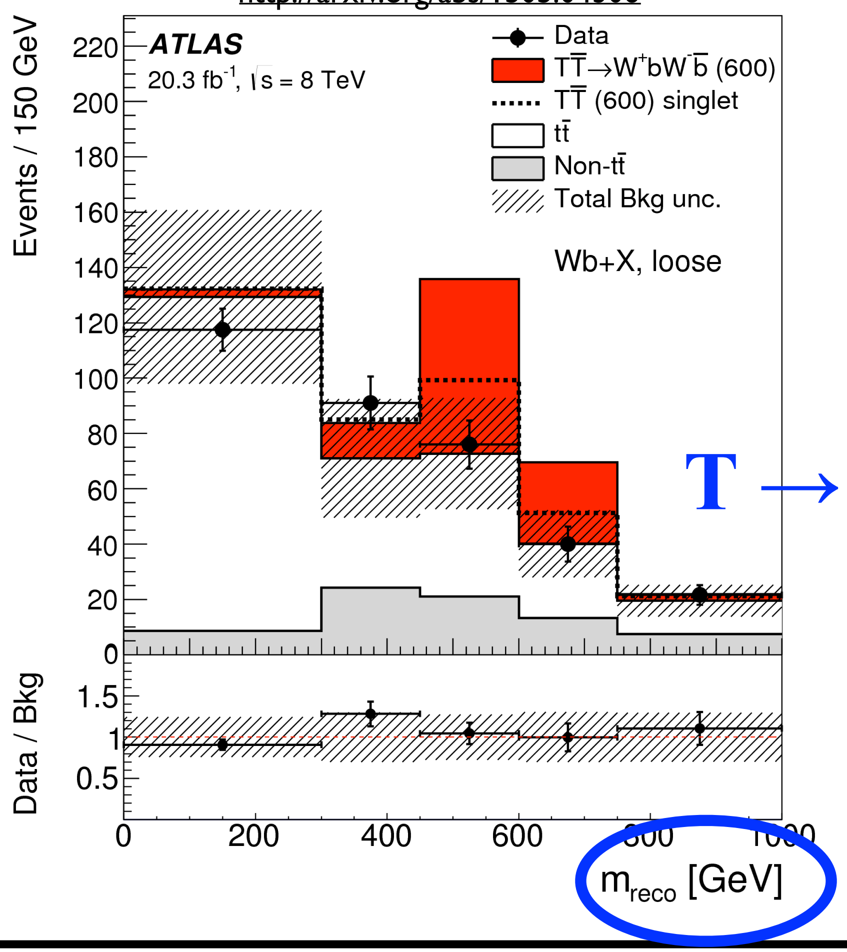
- T→Wb with $m_T$ ~600 GeV
  - ➡ W will be boosted, and if decays hadronically → single jet



# Wb versus Ht

- ❖ T→Wb yields the same final state as t→Wb
  - Need to discriminate, e.g. reconstruct $m_T$

http://arxiv.org/abs/1505.04306




T → Wb

# Wb versus Ht

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- ❖ T→Ht: ttHH, so WWbbbb

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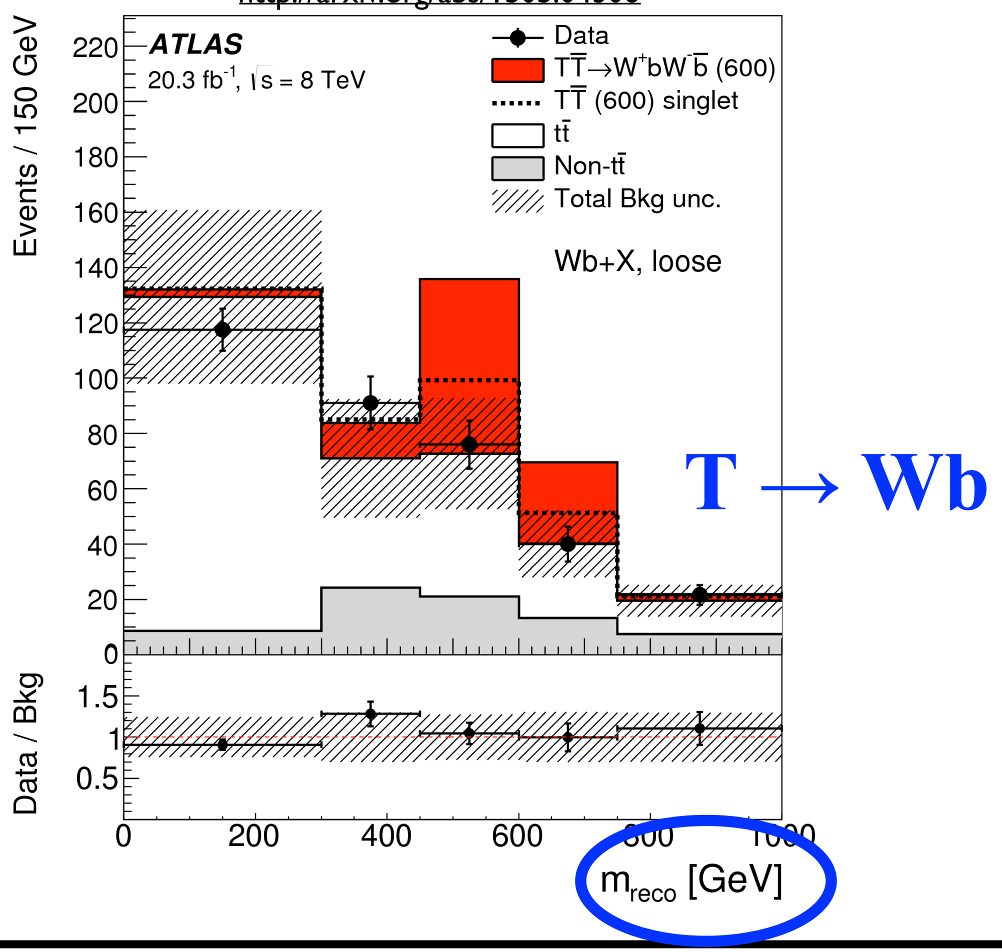


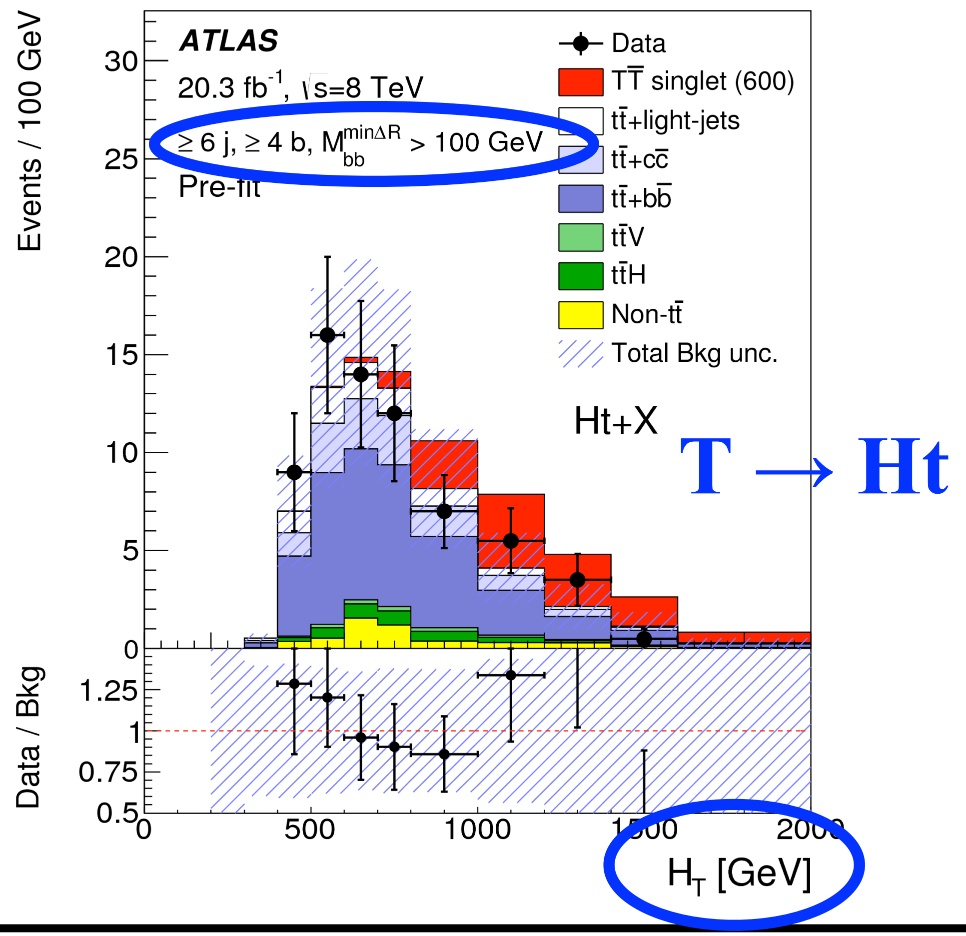

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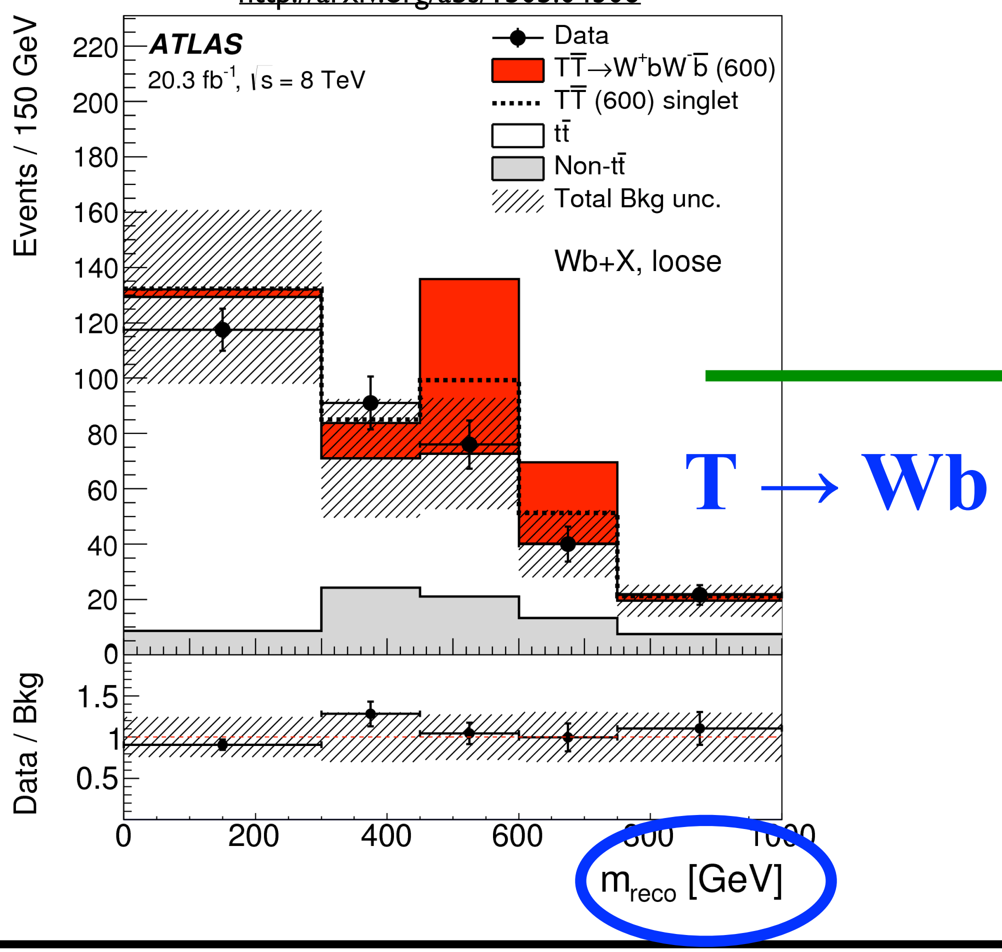


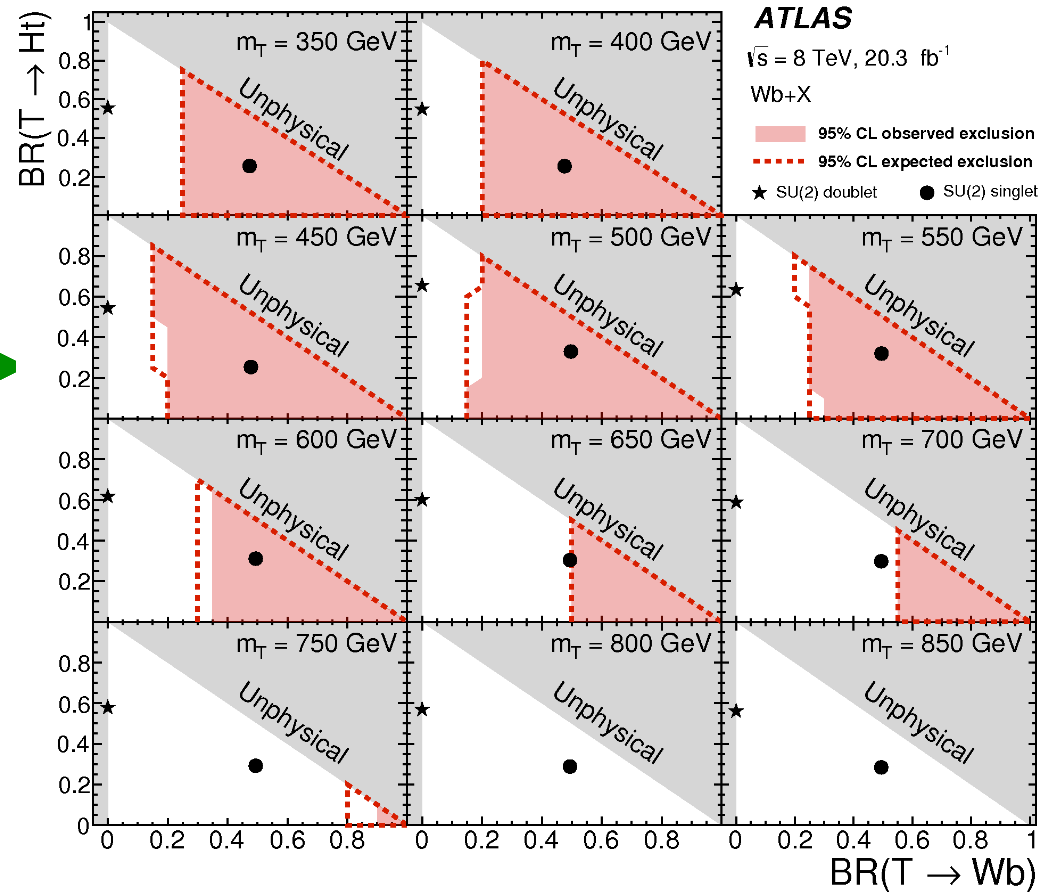

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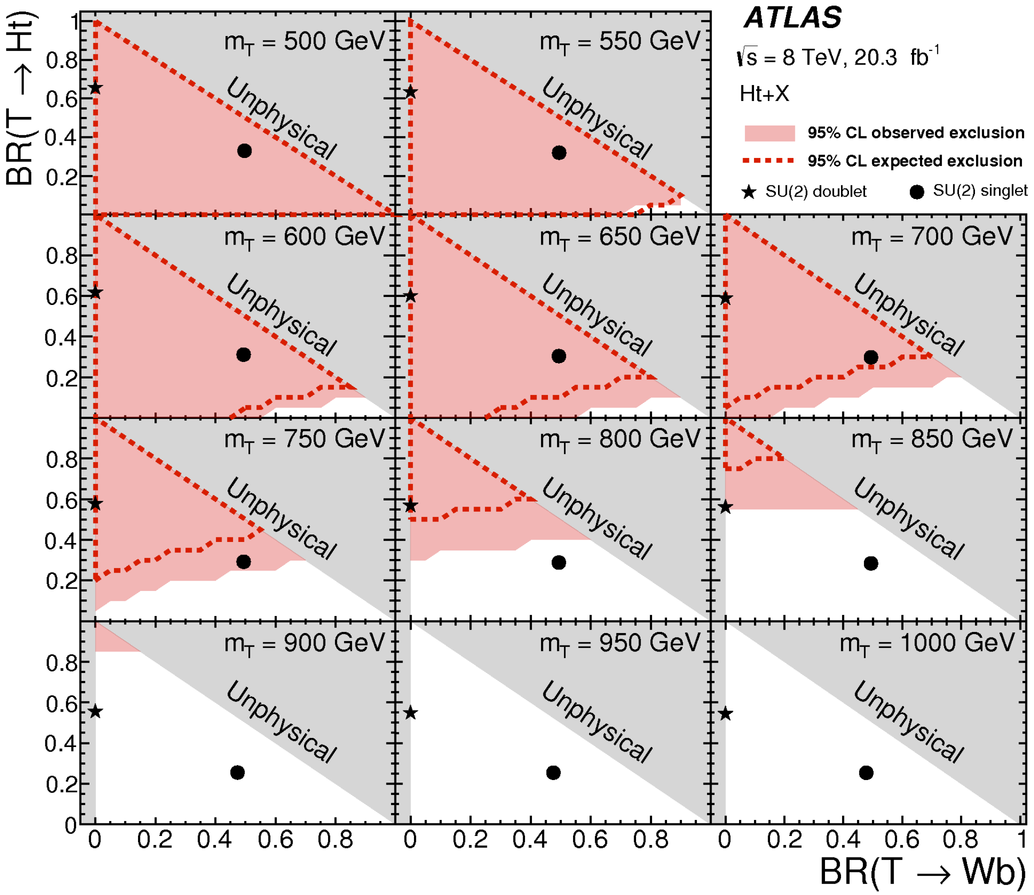


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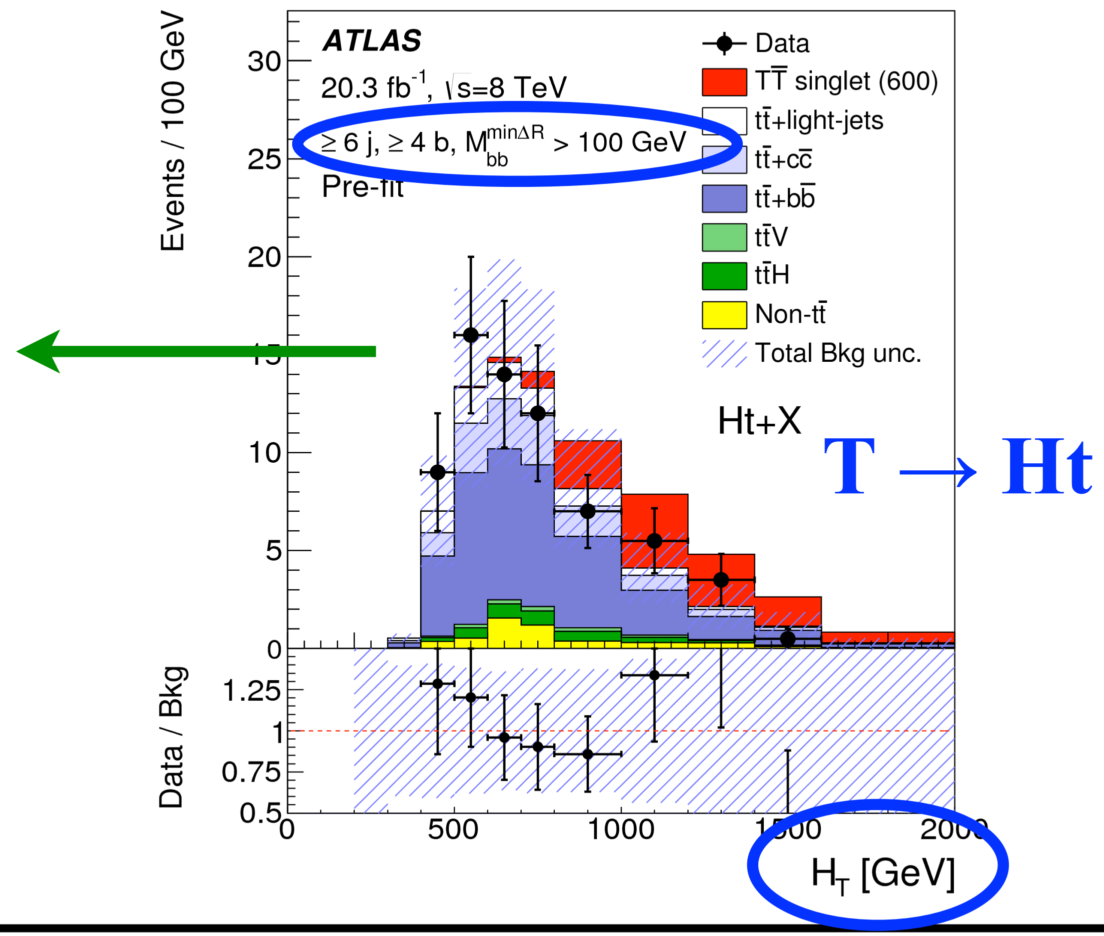
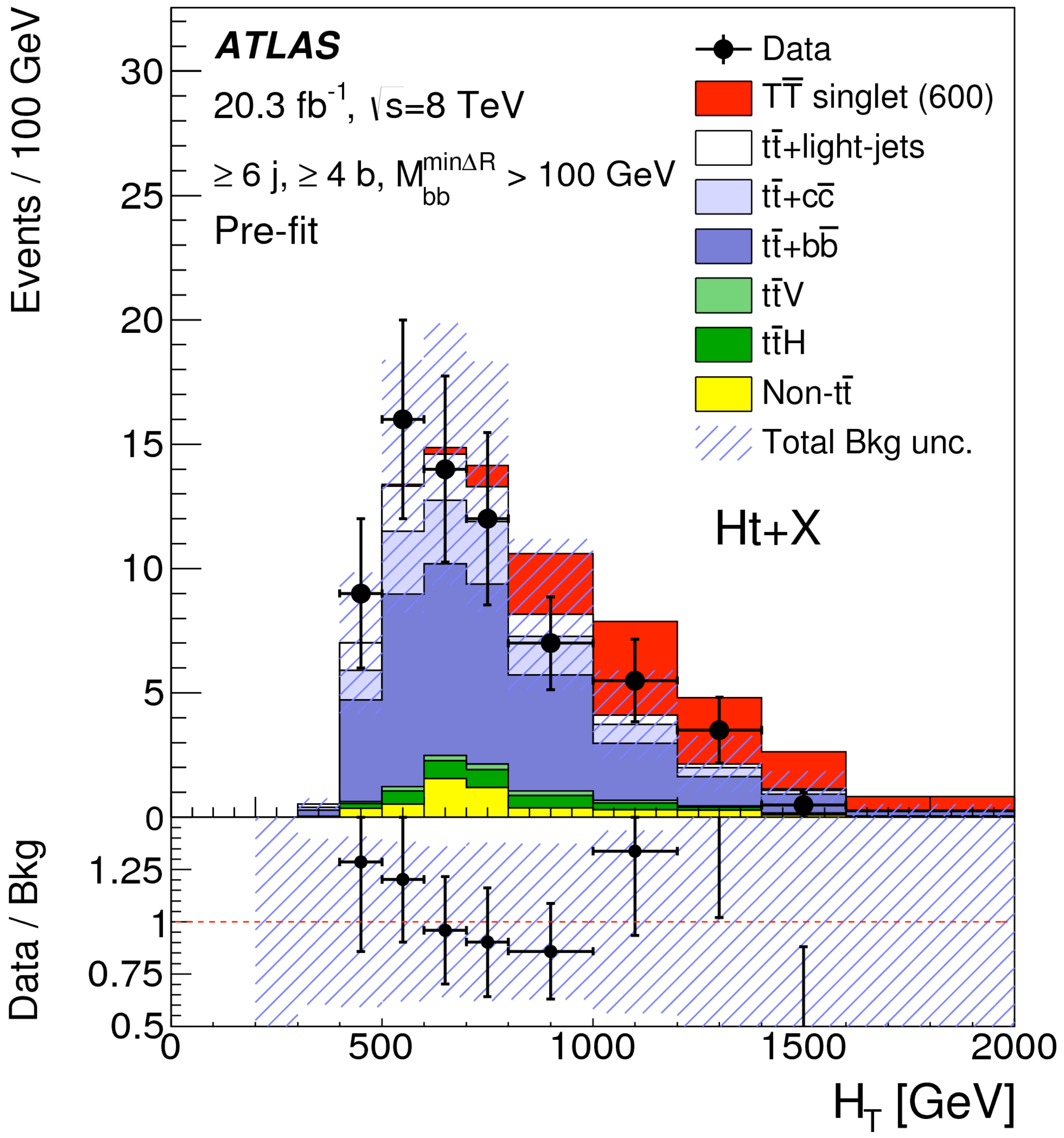


# Systematic Uncertainties

- Statistical uncertainties are easy: with limited number of events (and experiments), precision on a measurement is limited
- Systematic uncertainties vastly more complex
  - Example: measure a cross-section: $$\sigma = \frac{N_{\text{events}}}{\mathrm{L}A\epsilon}$$
  - L is the integrated luminosity, A the acceptance, ε the efficiency
    - Statistical uncertainty comes from $N_{\text{events}}$
    - Systematic uncertainties arise from limited knowledge of L, A and ε
      - L is estimated from Van der Meer scans
      - A typically depends on parton distribution functions
      - efficiency is a convolution of many experimental uncertainties

# Example




- ❖ $H_T$ is the sum of scalar energies of jets, leptons,…
  - If the jet energy scale is different between data and MC, comparison is wrong
  - If the jet energy scale dependence on jet energy is wrong, distort shape
  - etc.
- ❖ But how do I determine the jet energy scale uncertainty?
  - testbeams (single pions)
  - dijet balance
  - γ/Z+jet balance
  - …

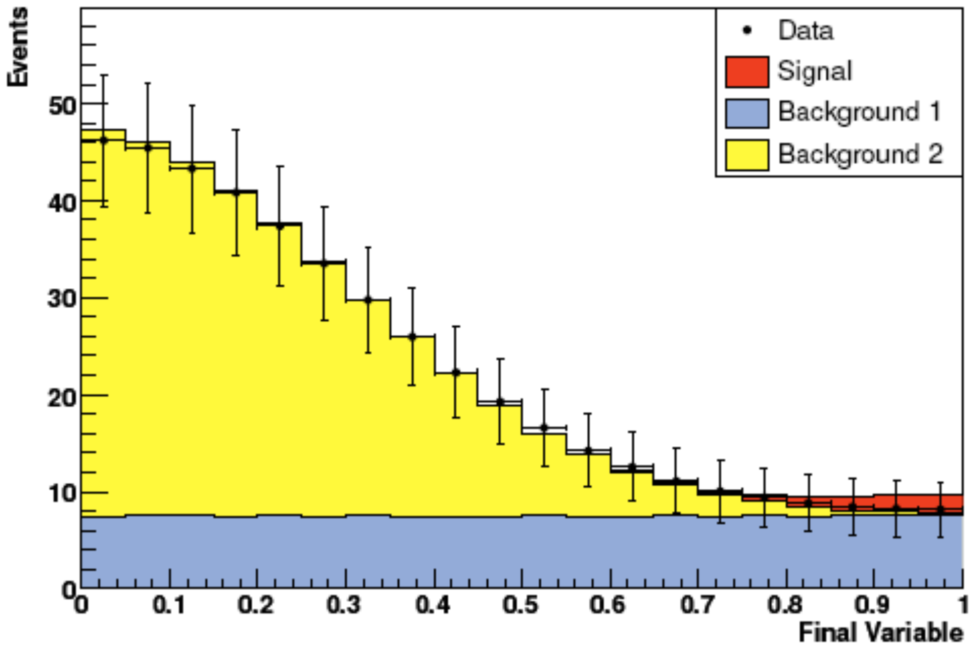
# Systematics Profiling

- ❖ Systematic uncertainties are propagated through the full analysis chain to the discriminating distribution
  - E.g. we repeat the analysis with jet energy scale shifted up & down by 1σ
  - Some systematic uncertainties affect shape (jet/lepton/photon reconstruction efficiency, energy scale and resolution, $p_T$ distributions, background models), others only normalization (lepton reconstruction efficiencies and momentum calibration, background normalizations, theoretical cross-sections and luminosity)
  - Systematic uncertainties are treated as nuisance parameters when fitting signal+background to the data
    - I.e. modify signal and background shape
    - Can be fixed, or allowed to change

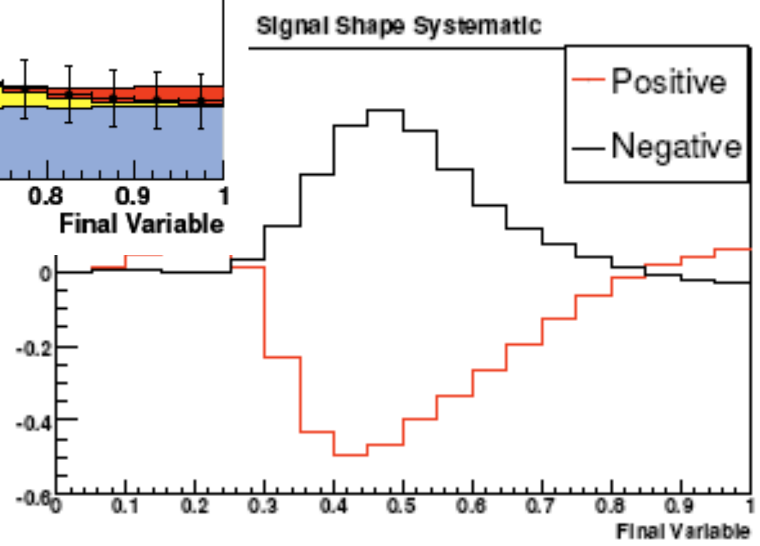
# Systematics Profiling

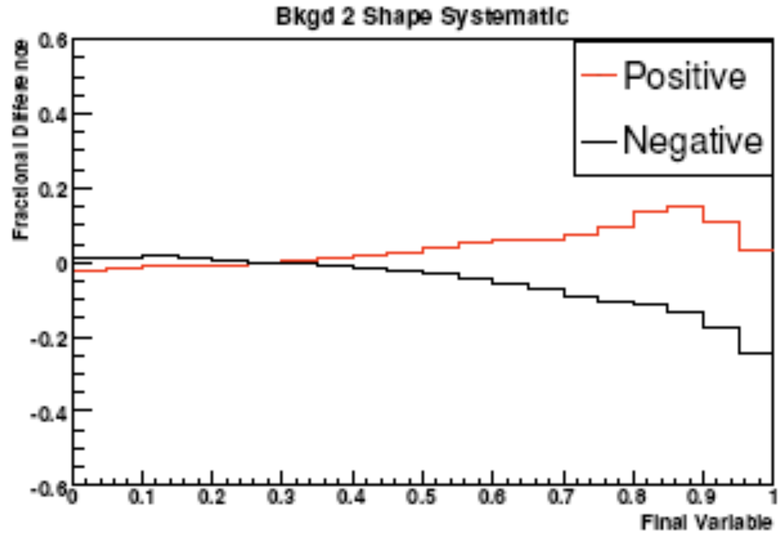
❖ Nuisance parameters tend to be correlated, but not 100%, among backgrounds

- Can affect rates, shapes, or both (in any distribution), and often asymmetric and non-gaussian




Toy Example (W. Fisher)



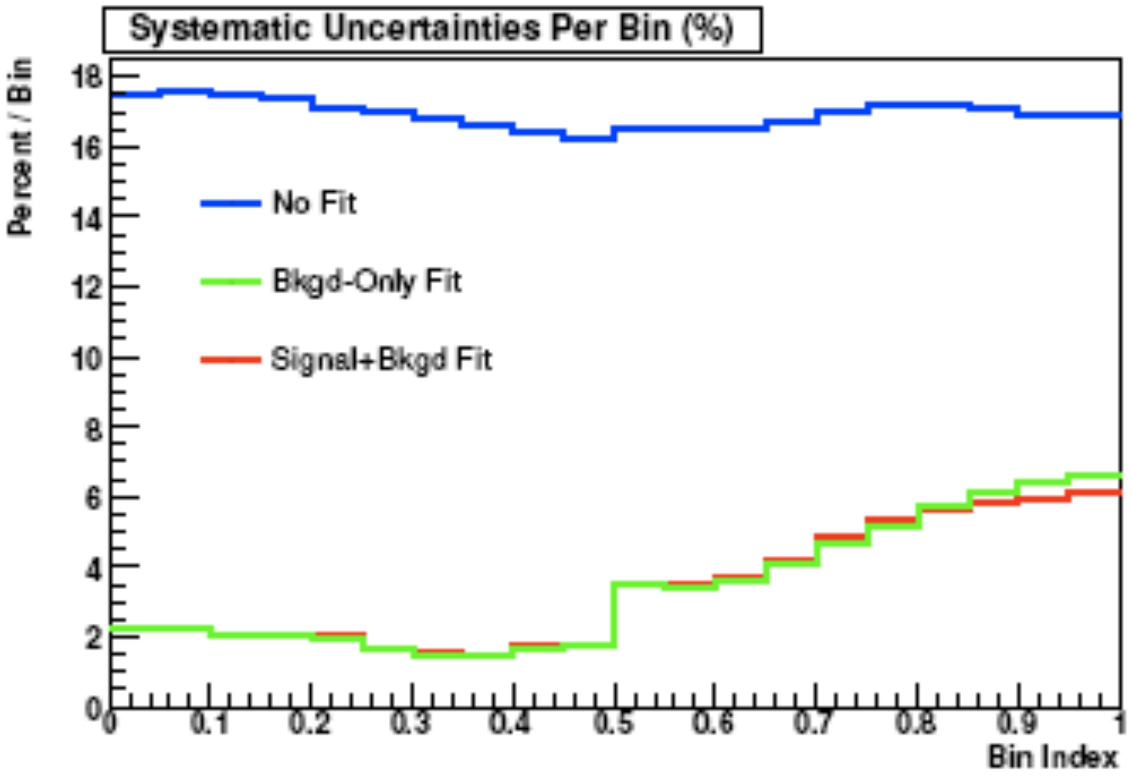



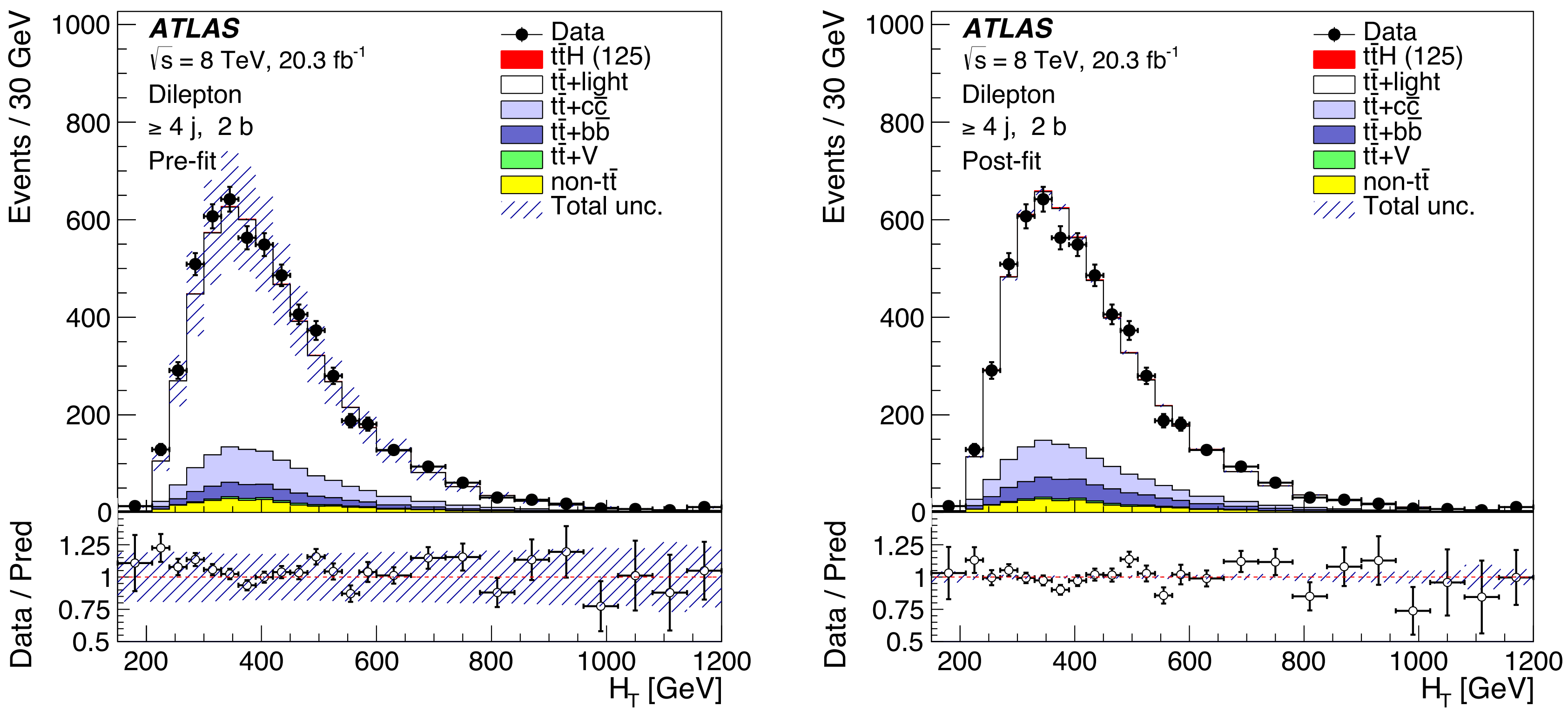
- Generate pseudo-experiments (events in bins according to poisson), then for each experiment vary nuisance parameters
  - Variations in background (& S+B) prediction
    - Compare results to data using log-likelihood ratio
- We can maximize likelihood ratio as a function of nuisance parameters → constrain them
  - I.e. use full shape of distribution(s) to see which background uncertainties are over/underestimated
    - Of course limited to size of statistical fluctuations
  - Can remove bins with large S/B if needed
    - Mostly important if uncertainties lead to similar shape distortions
  - Want enough background-rich phase space in fit!
    - Even include control regions

# ❖ Test example:

- Data constructed to disagree with background-only hypothesis (wrong estimates for background uncertainties)
- But to agree with background-only better than signal+ background
  - Improvement quite spectacular (by construction in example)

ATLAS ttH search: arXiv:1503.05066

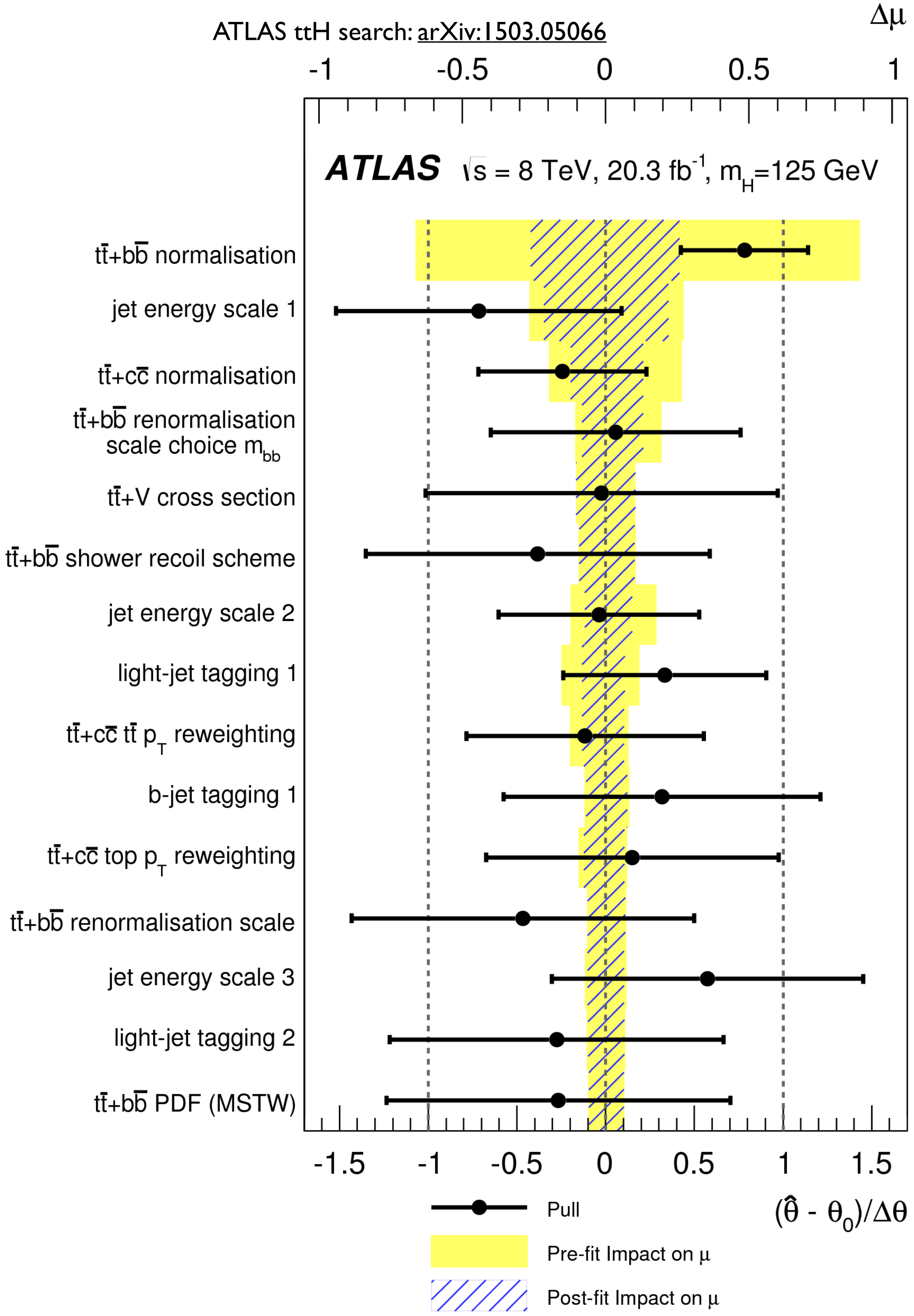


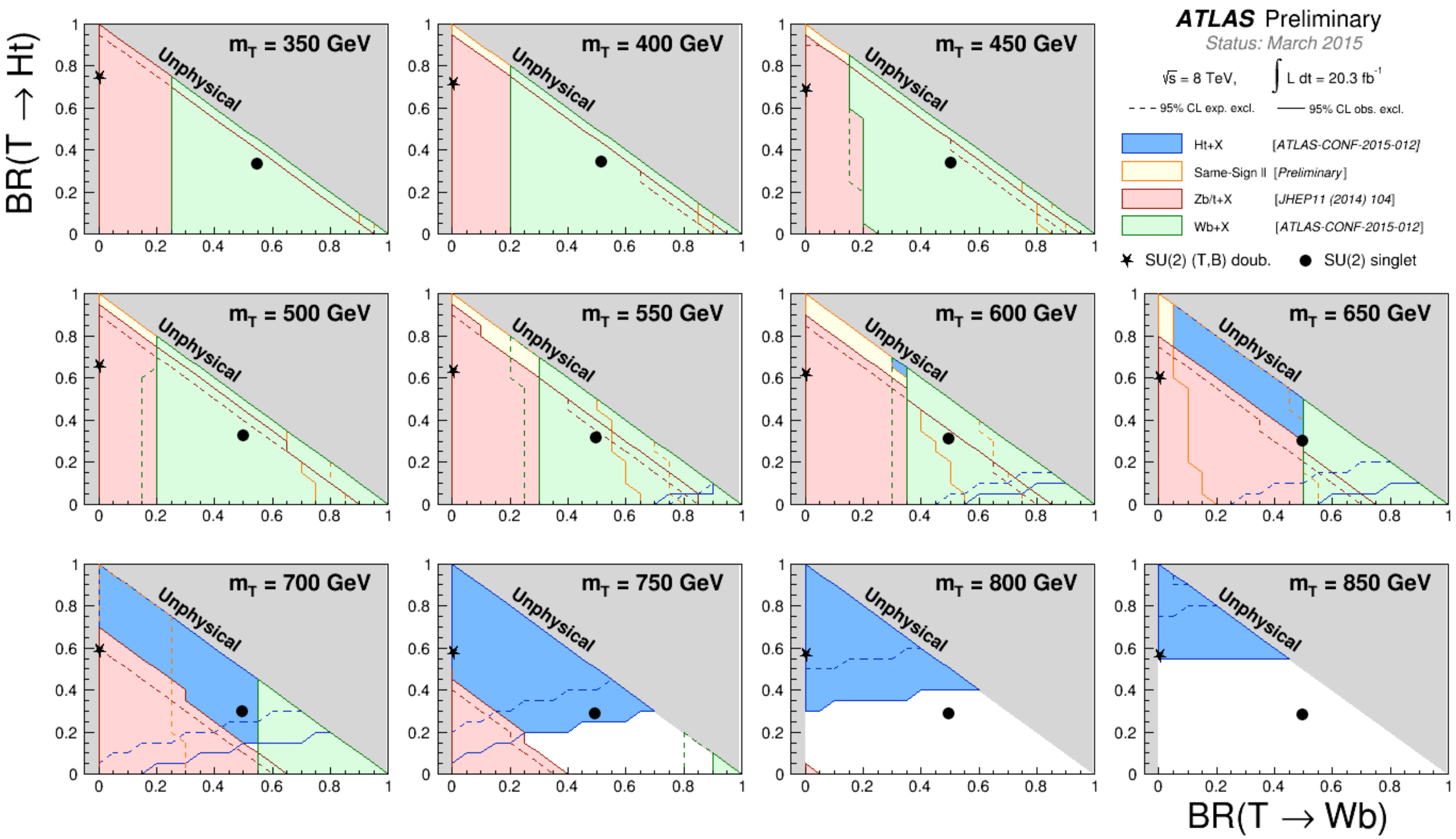
# Fit Results

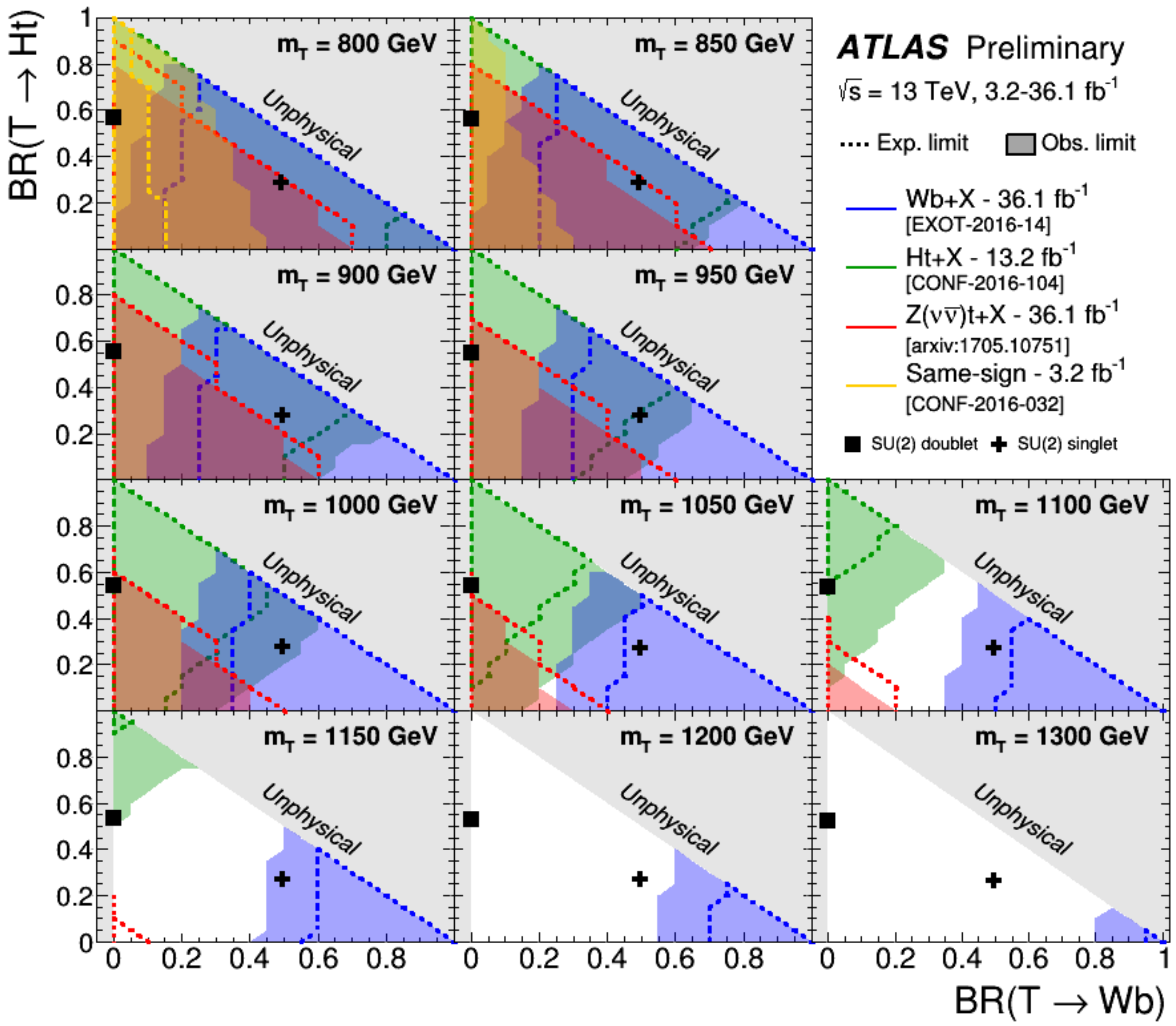
- ❖ Need to compare starting point and results
  - Pathologies due to lack of MC stats in some areas, strong correlations, …
- ❖ Crucial to design analysis with good control regions the fit can use to address least understood systematics

ATLAS ttH search: arXiv:1503.05066



# All Together Now

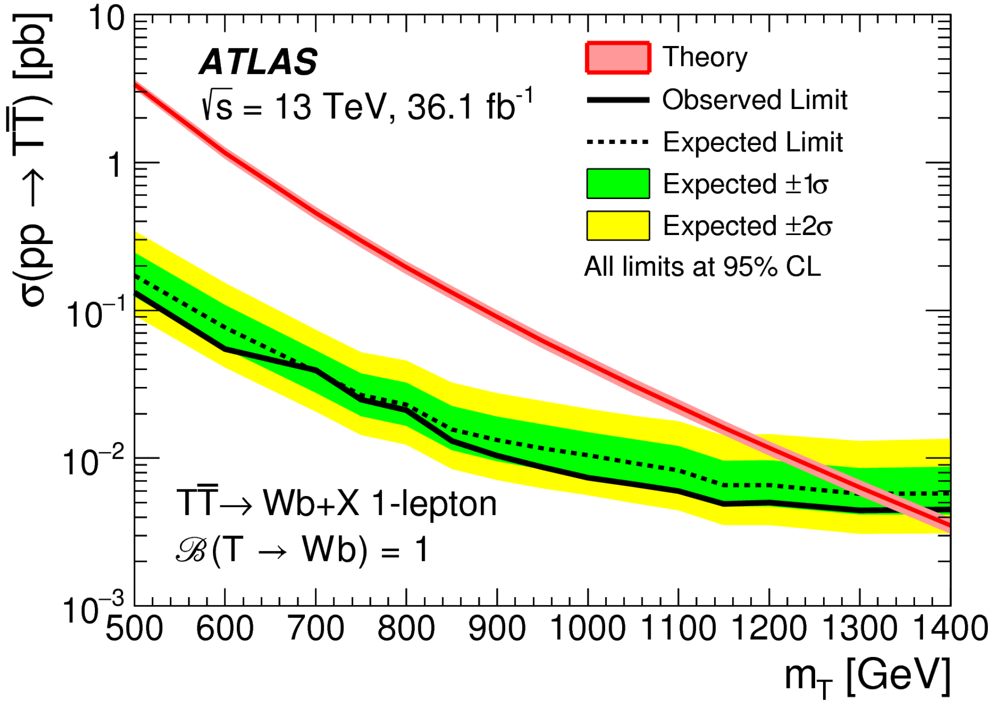




Numbers very similar as for stop….

# Choosing a Topic

- ❖ Scalar and fermionic top partner searches have very similar high mass sensitivity
  - Not surprising: cross-section higher for fermions, but mass limit only moderately sensitive to that
- ❖ What about overlaps?
  - Turns out SUSY searches have good sensitivity to vector-like quarks!
    - SUSY large MET requirement maps to e.g. $Z \to \nu\nu$



arXiv:1608.01312

TTK-16

# Complementarity of Resonant Scalar, Vector-Like Quark and Superpartner Searches in Elucidating New Phenomena

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(Dated: August 30, 2016)

The elucidation of the nature of new phenomena requires a multi-pronged approach to understand the essential physics that underlies it. As an example, we study the simplified model containing a new scalar singlet accompanied by vector-like quarks, as motivated by the recent diphoton excess at the LHC. To be specific, we investigate three models with $SU(2)_L$-doublet, vector-like quarks with Yukawa couplings to a new scalar singlet and which also couple off-diagonally to corresponding Standard Model fermions of the first or third generation through the usual Higgs boson. We demonstrate that three classes of searches can play important and complementary roles in constraining this model. In particular, we find that missing energy searches designed for superparticle production, supply superior sensitivity for vector-like quarks than the dedicated new quark searches themselves.

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