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 (e.g. LHCb)
  - 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

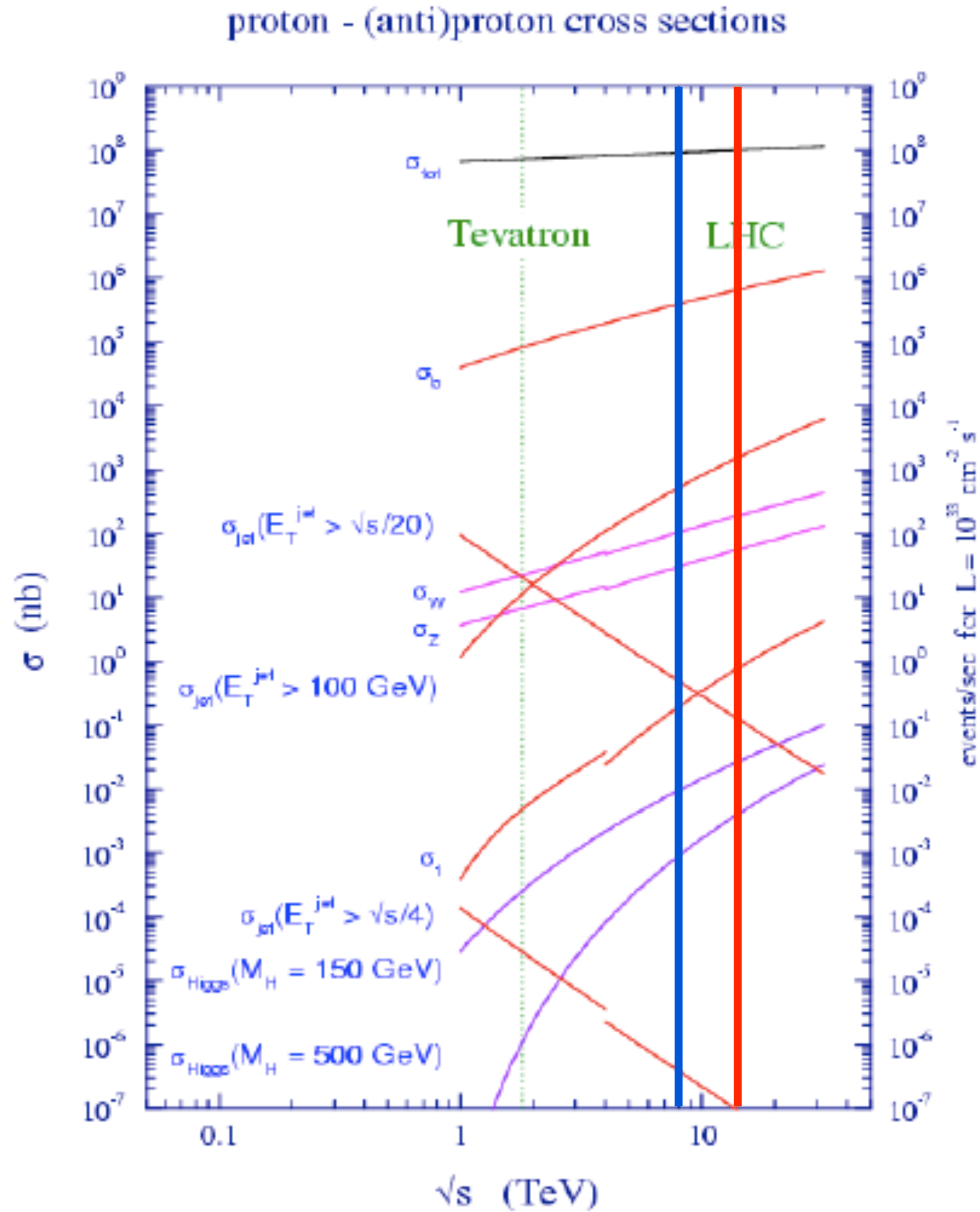
Theory

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 or.... don’t exist
  - Are there new interactions?

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?

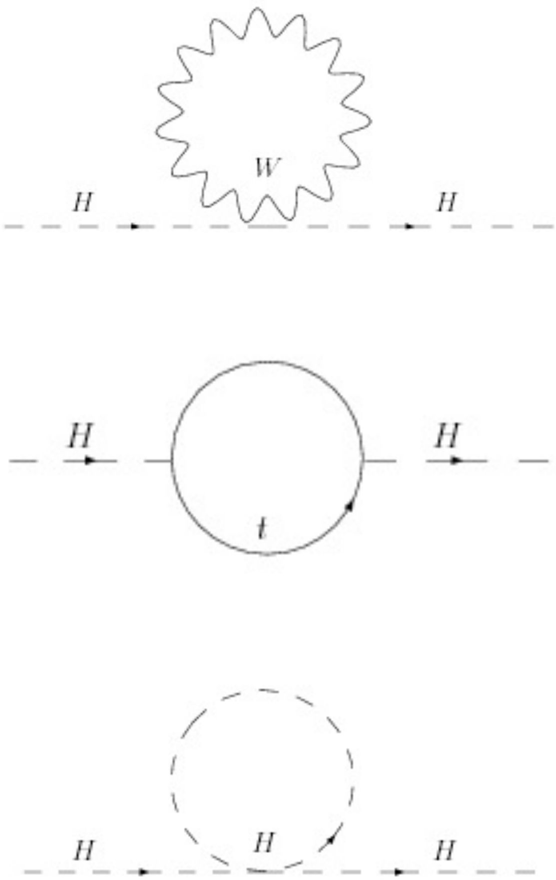


Experimental Searches

- 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



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

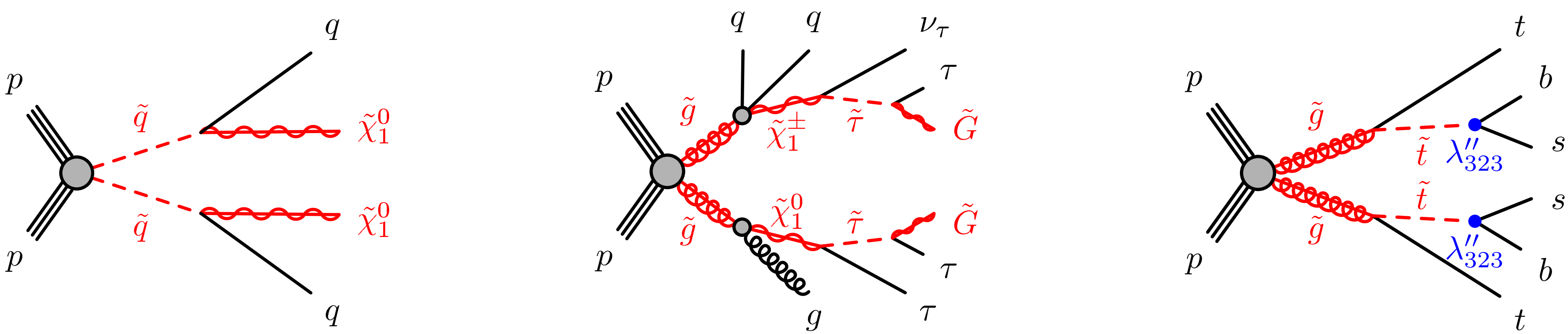
$$\rightarrow \frac{3}{16\pi^2} y_t^2 E^2$$

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

- 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

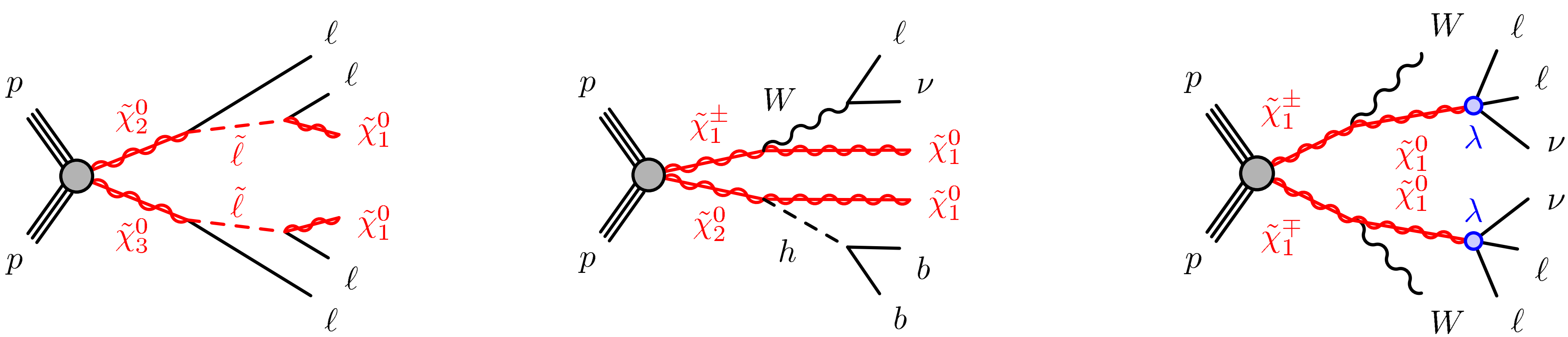
Canonical SUSY

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



  - … or weak production

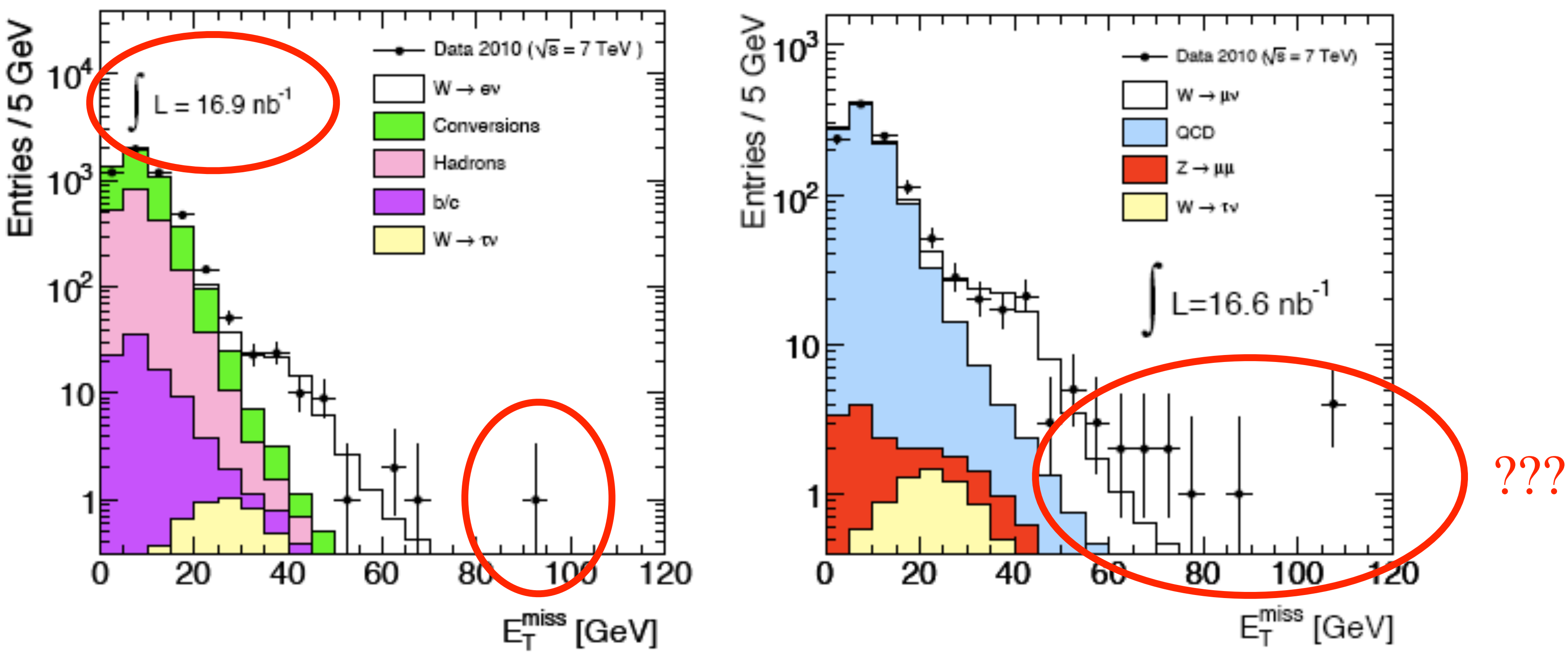
RPV

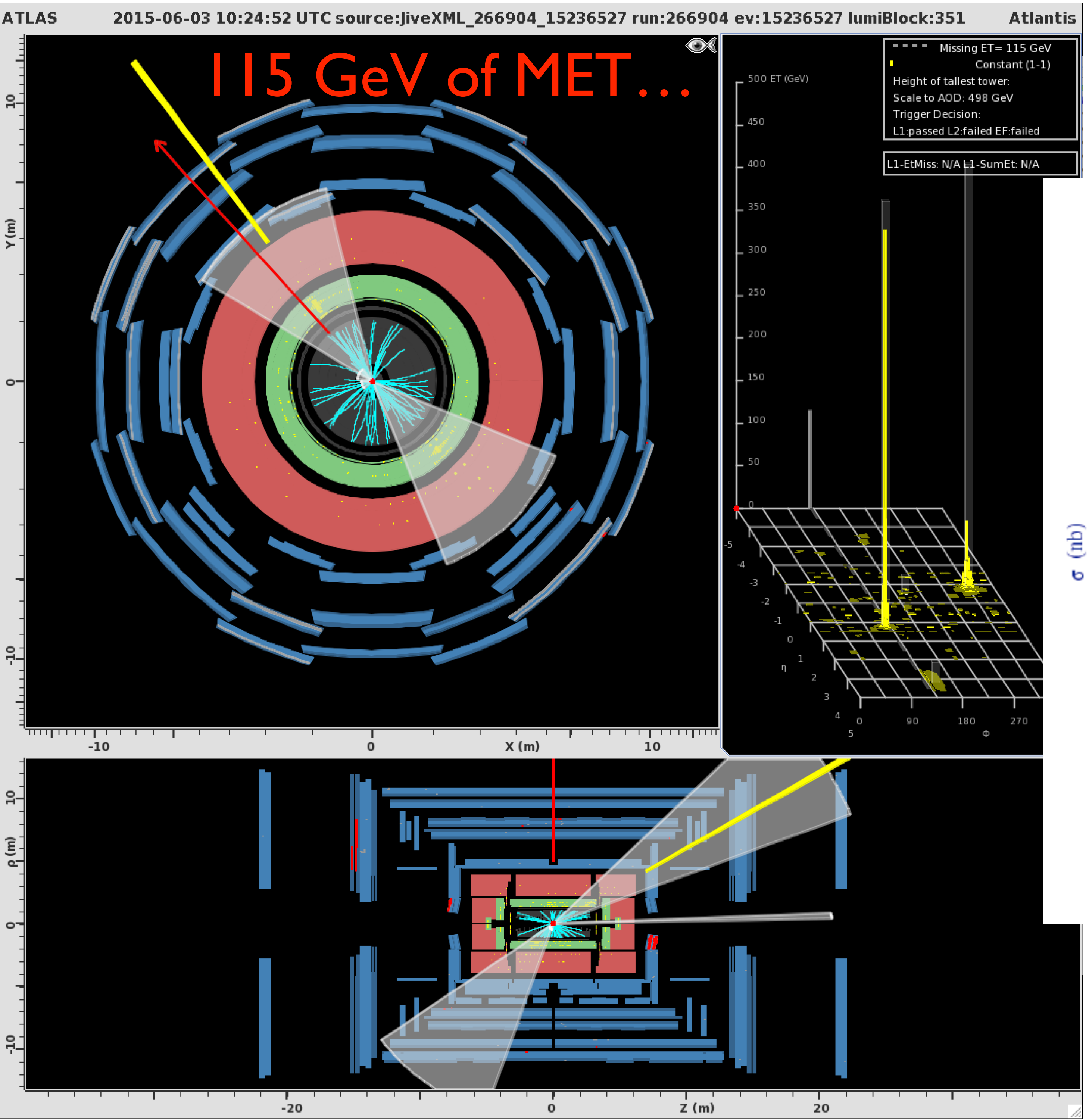


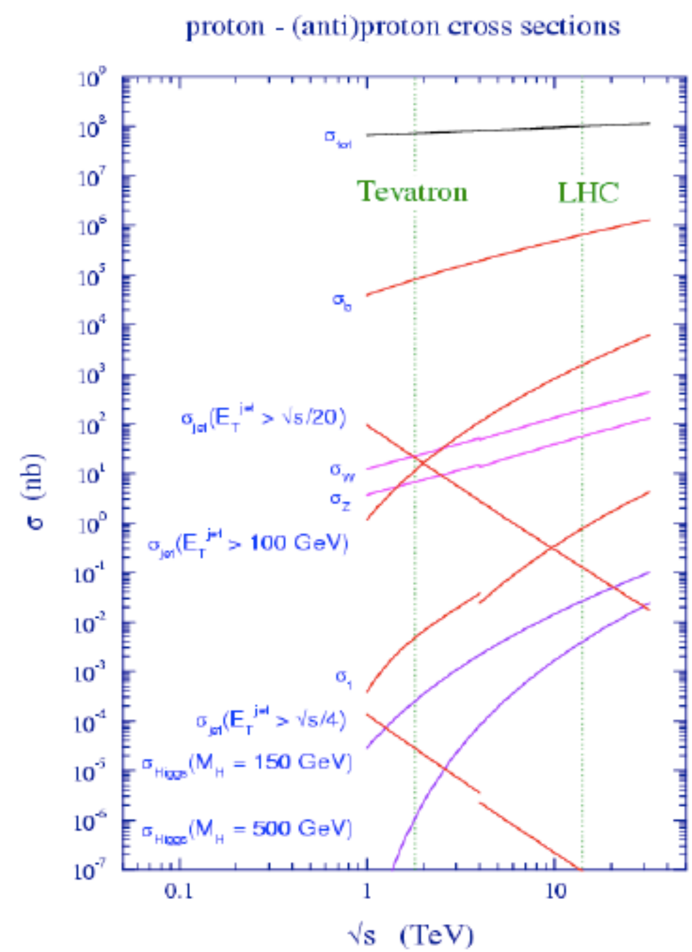
Missing ET

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

Early 2010

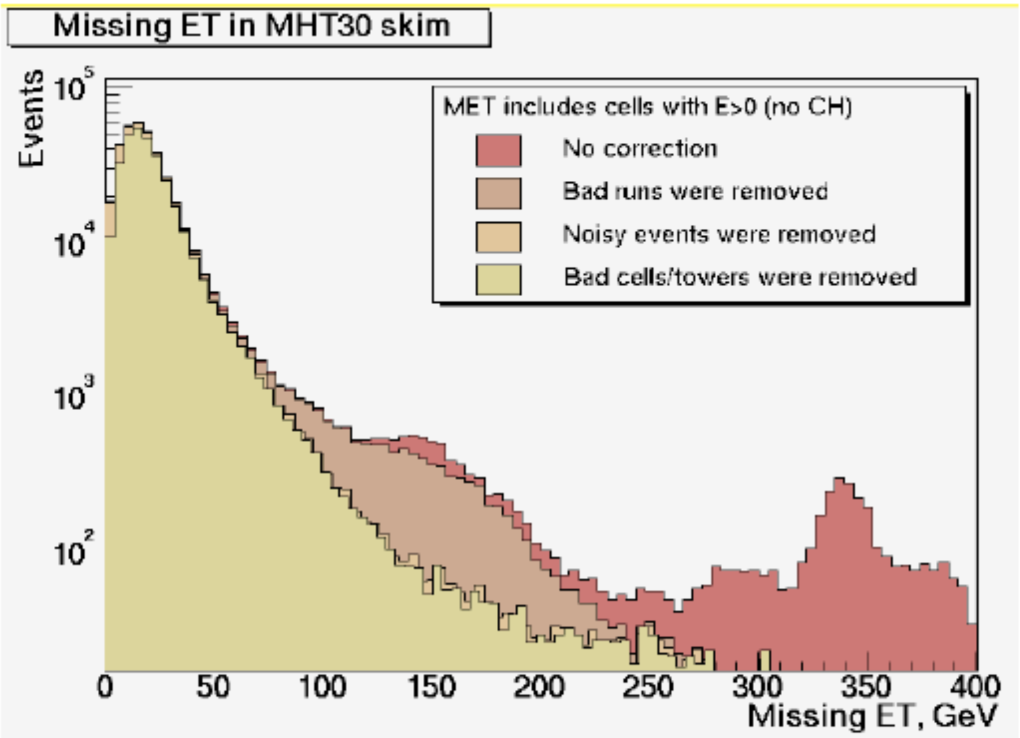



ATLAS
2015-06-03 10:24:52 UTC source:JiveXML_266904_15236527 run:266904 ev:15236527 lumiBlock:351
Atlantis
115 GeV of MET…
Missing ET= 115 GeV
Constant (1-1)
Height of tallest tower:
Scale to AOD: 498 GeV
Trigger Decision:
L1:passed L2:failed EF:failed
L1-EtMiss: N/A L1-SumEt: N/A
500 ET (GeV)
Y (m)
X (m)
ρ (m)
Z (m)
η
Φ

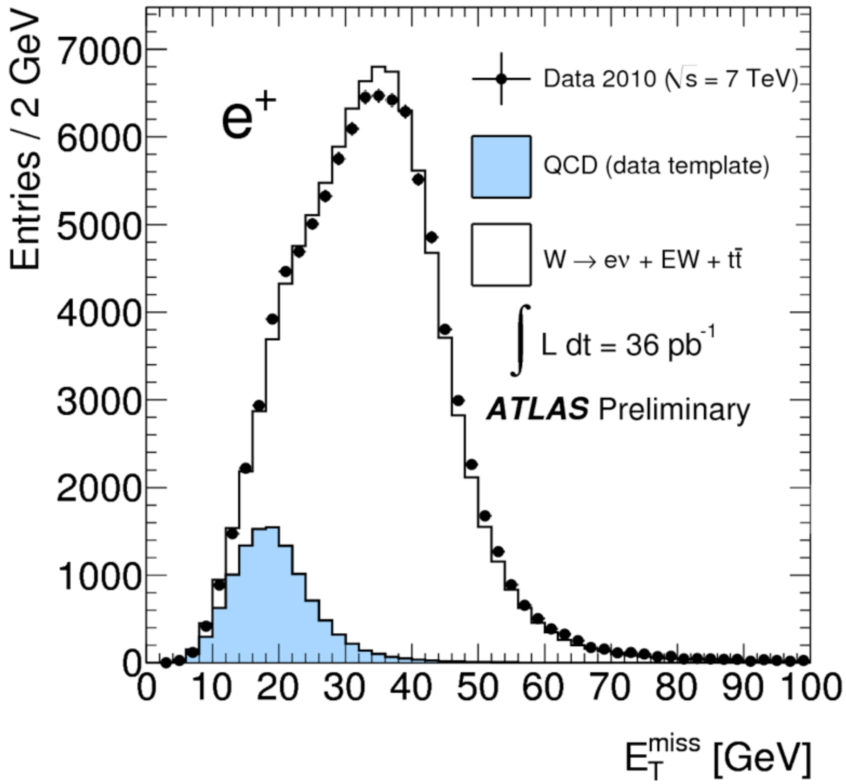

proton - (anti)proton cross sections
Tevatron
LHC
σ_{tot}
σ_b
$\sigma_{jet}(E_T^{jet} > \sqrt{s}/20)$
σ_W
σ_Z
$\sigma_{jet}(E_T^{jet} > 100$ GeV)
σ_t
$\sigma_{jet}(E_T^{jet} > \sqrt{s}/4)$
$\sigma_{Higgs}(M_H = 150$ GeV)
$\sigma_{Higgs}(M_H = 500$ GeV)
σ (nb)
√s (TeV)

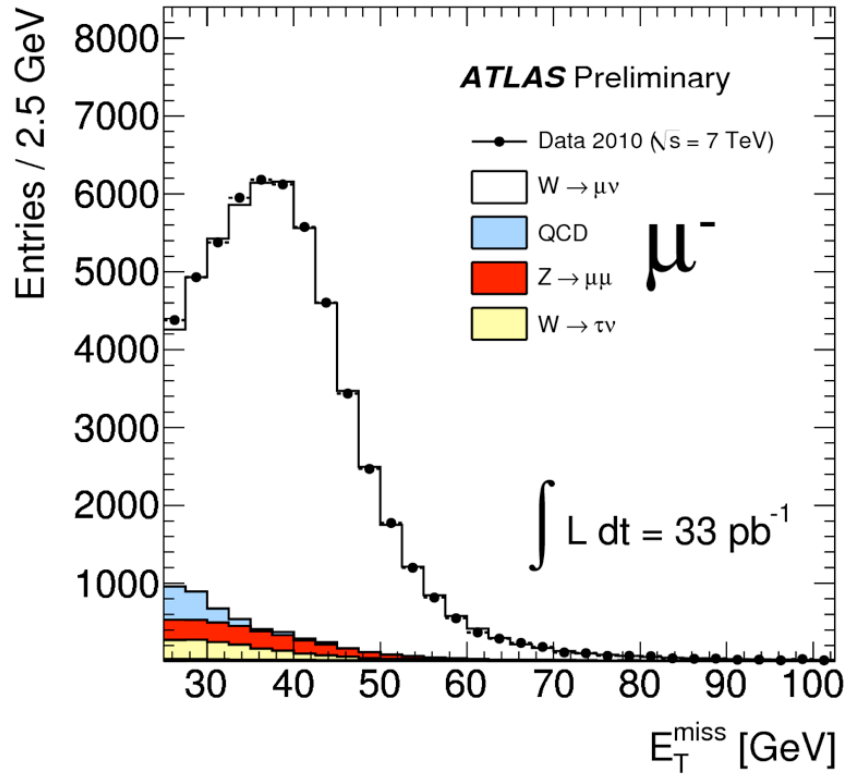
❖ Analyses using MET are particularly sensitive

- Requires the full calorimeter to behave, and calorimeter is generally the most sensitive subdetector (analog, ~16 bits)
- 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,…



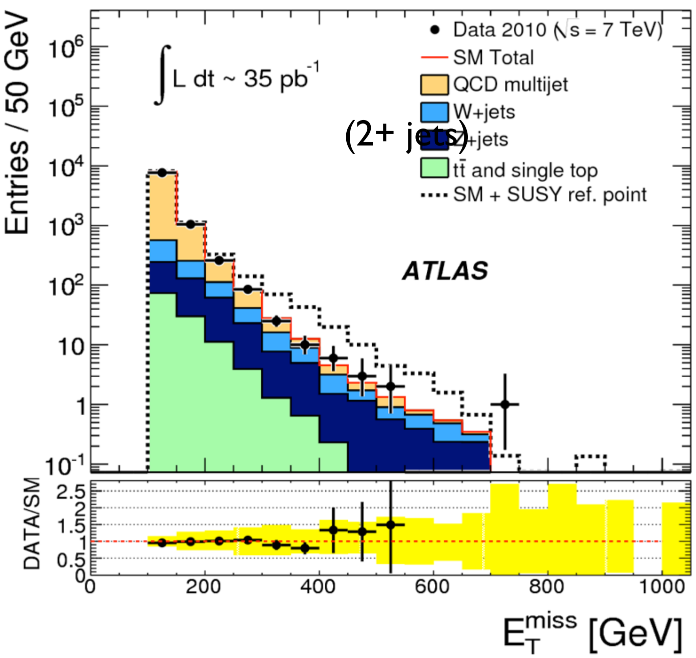


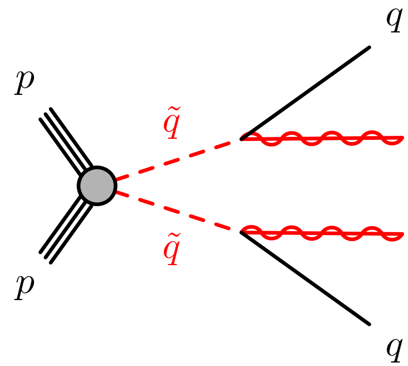
❖ Already ~200k clean W → $\ell\nu$ events in 2010

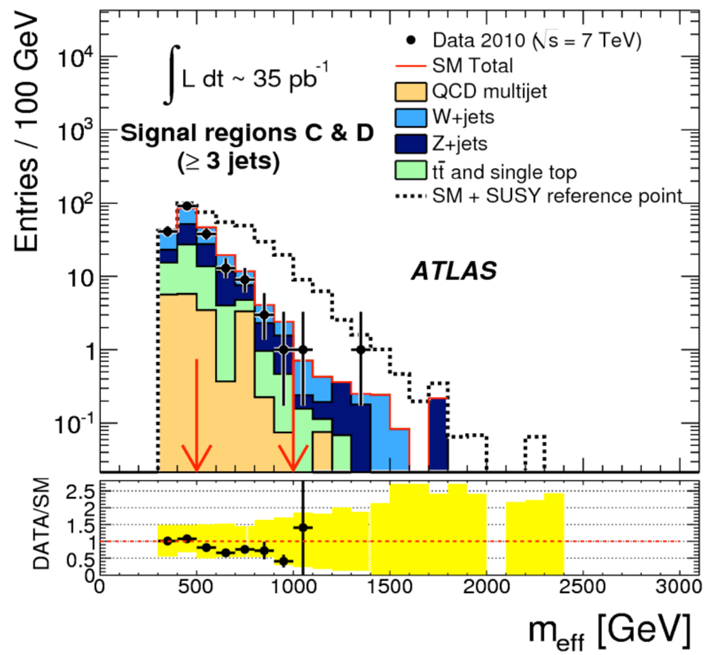
- Almost a billion now

SUSY as a Benchmark

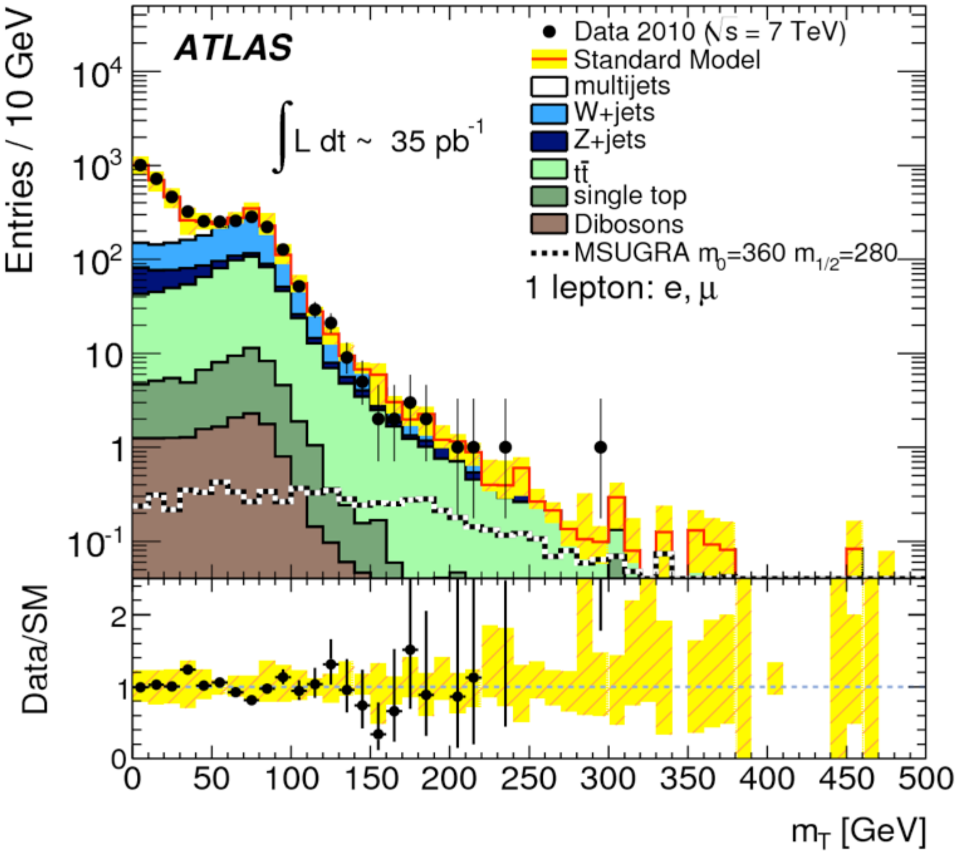
- Hadron collider ⇒ produce squarks and gluinos decaying to jets + MET
  - Optimize jet p_T & MET cuts for different scenarios, since gluinos produce more jets than squarks
    - Use M_{eff} to discriminate, measure of event Q^2

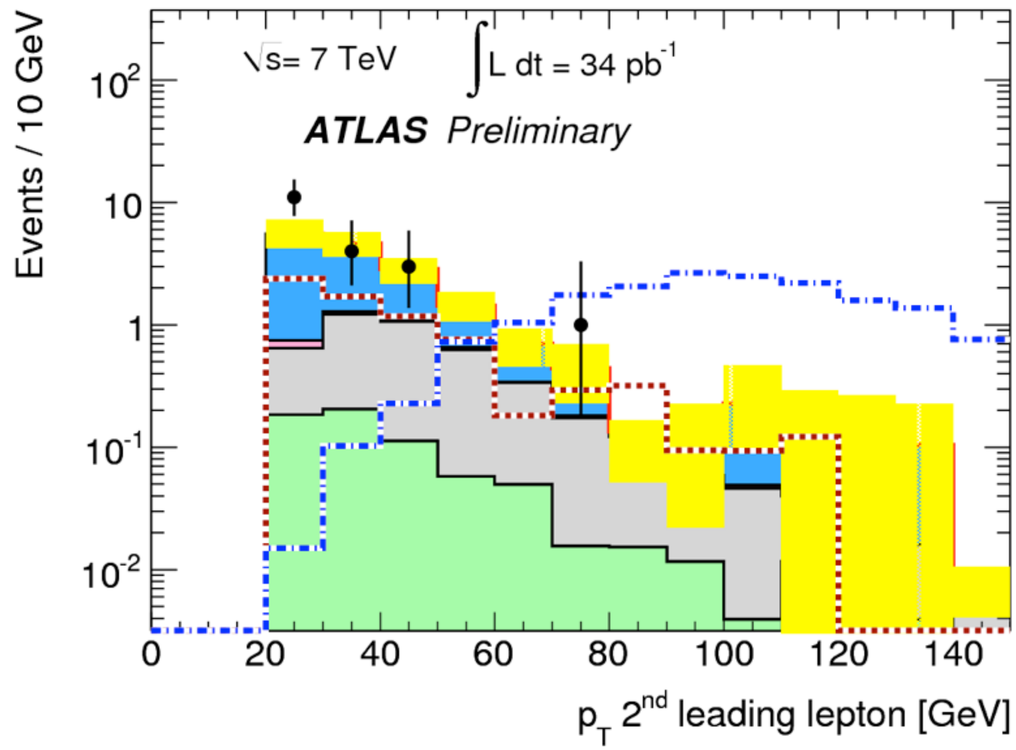




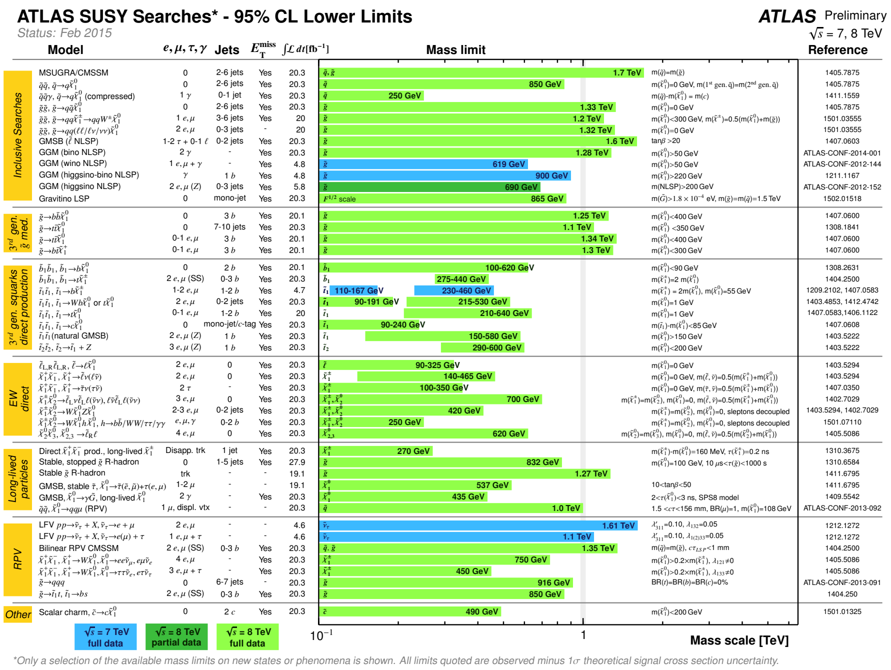


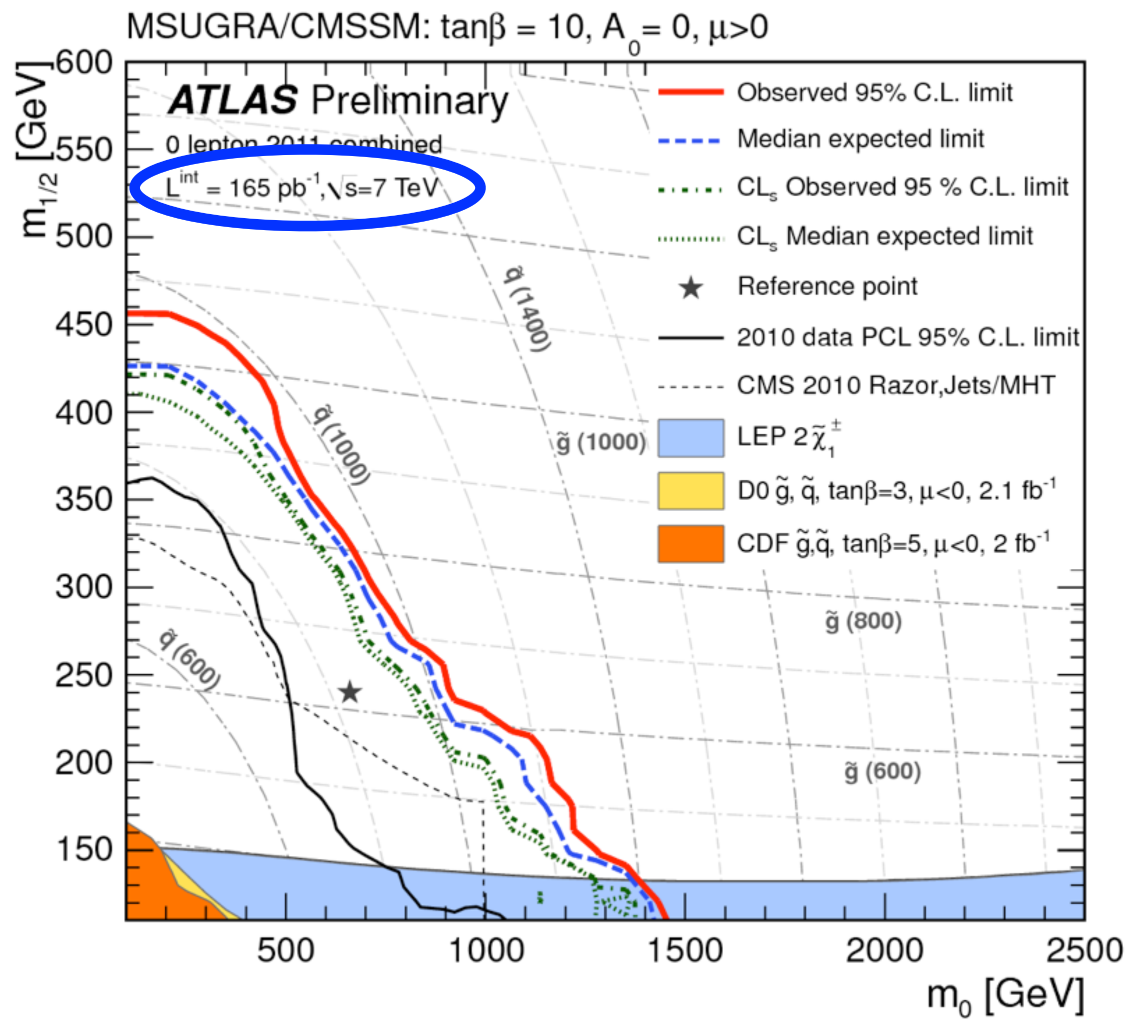
❖ Leptons in decay chains....





All Praise COM Energy!

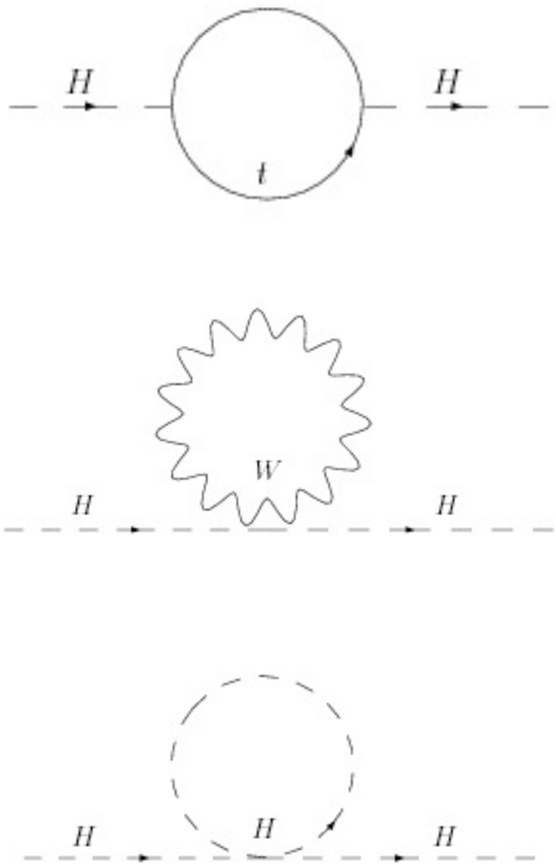




Tevatron blown away.... 8 (2016) hours of LHC data

But…

We've Found a Higgs!



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

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

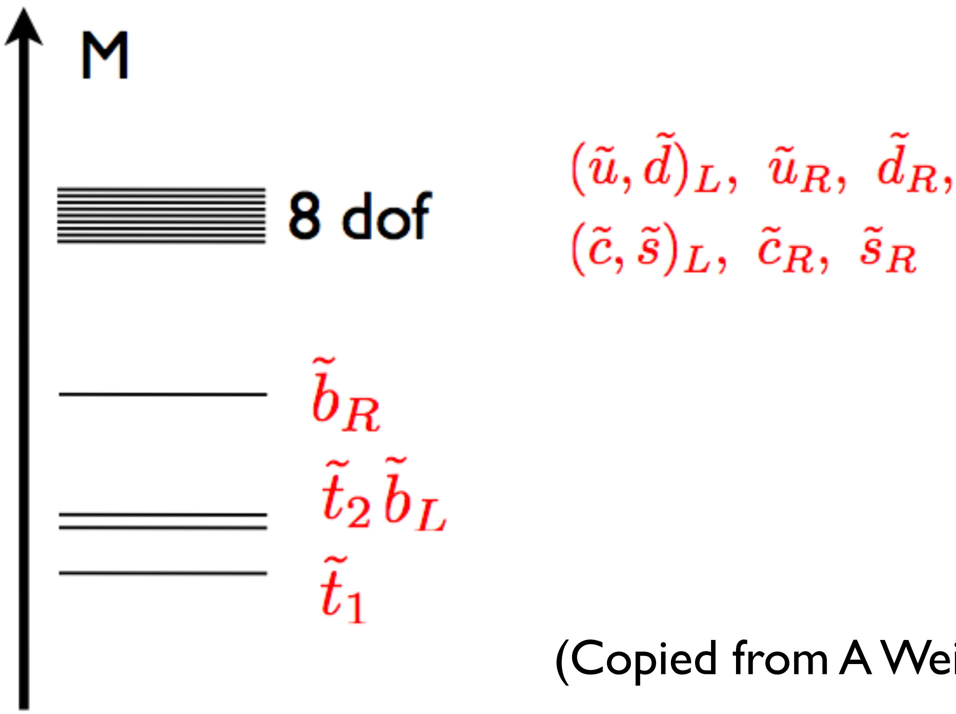
$$\rightarrow \frac{1}{16\pi^2} \lambda E^2$$

- 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**

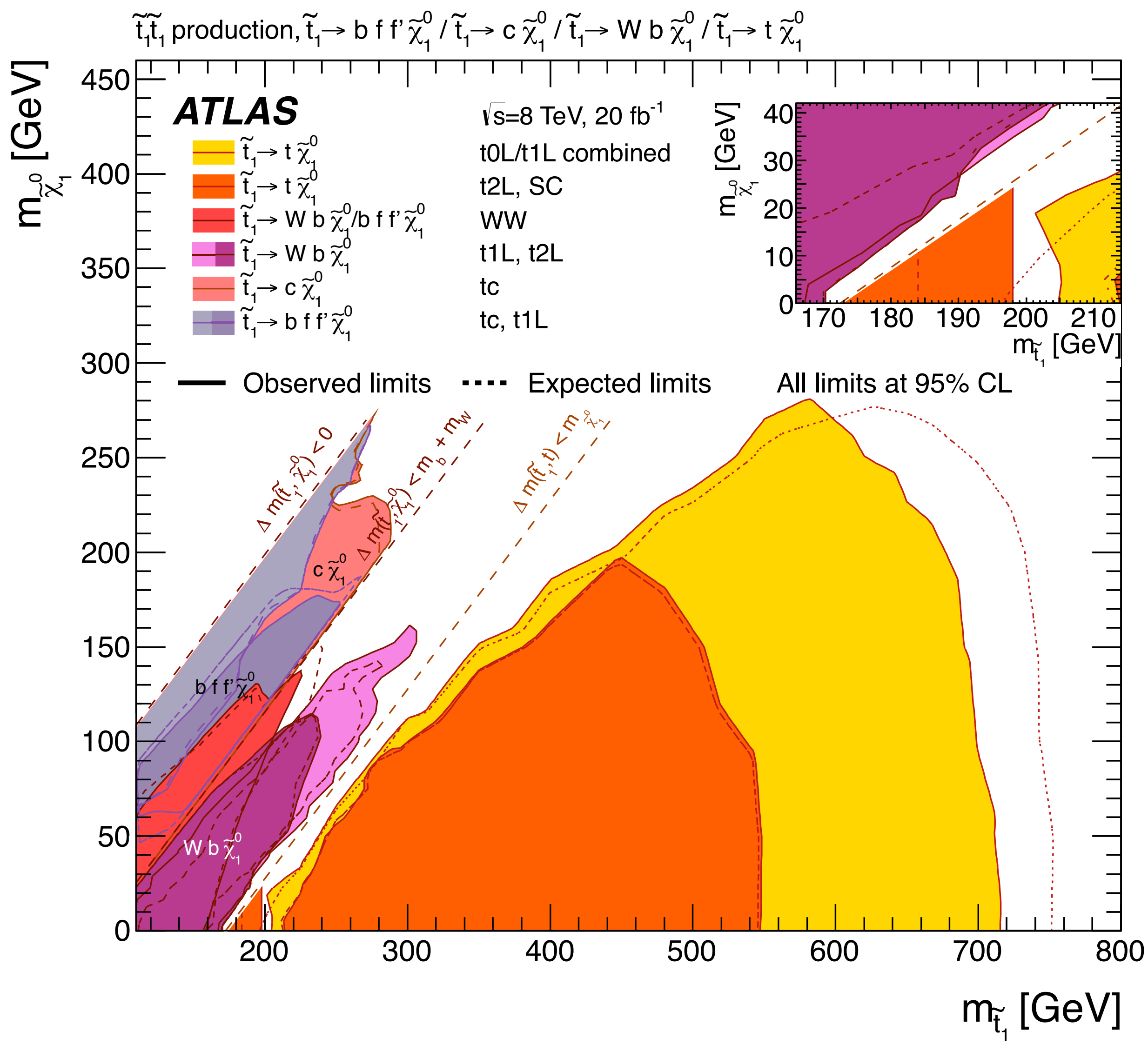
SUSY and the Higgs

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

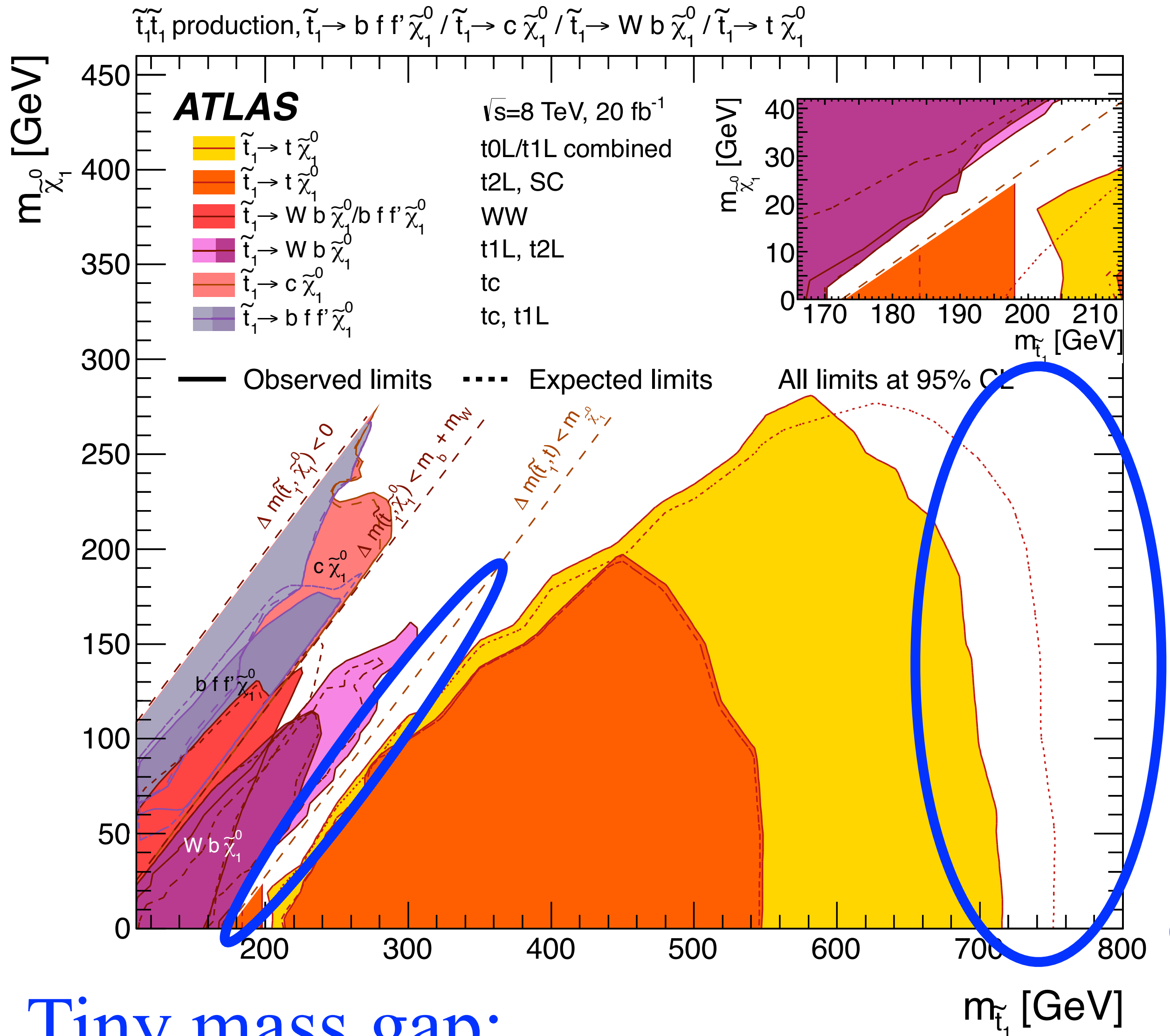


(Copied from A Weiler)

Stop Searching Anatomy



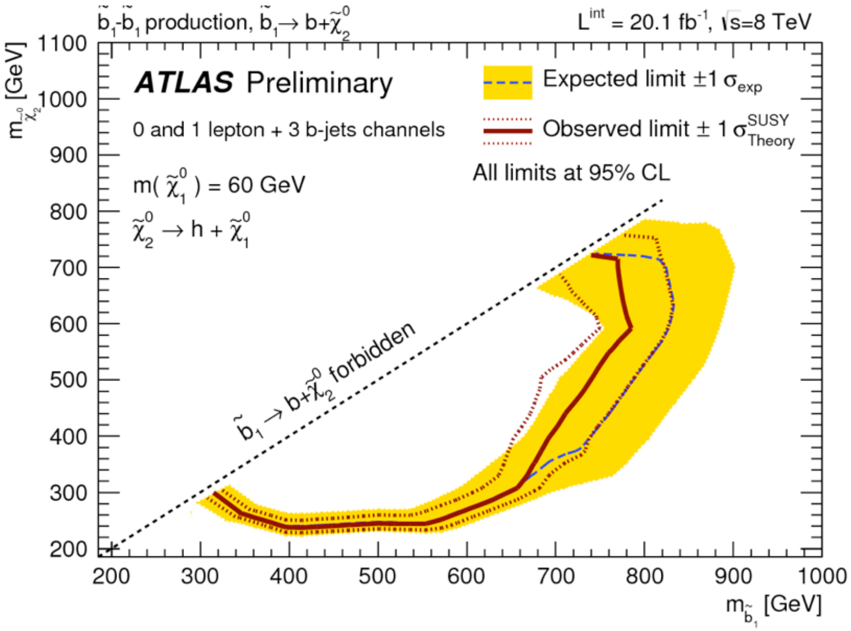
Stop Searching Anatomy

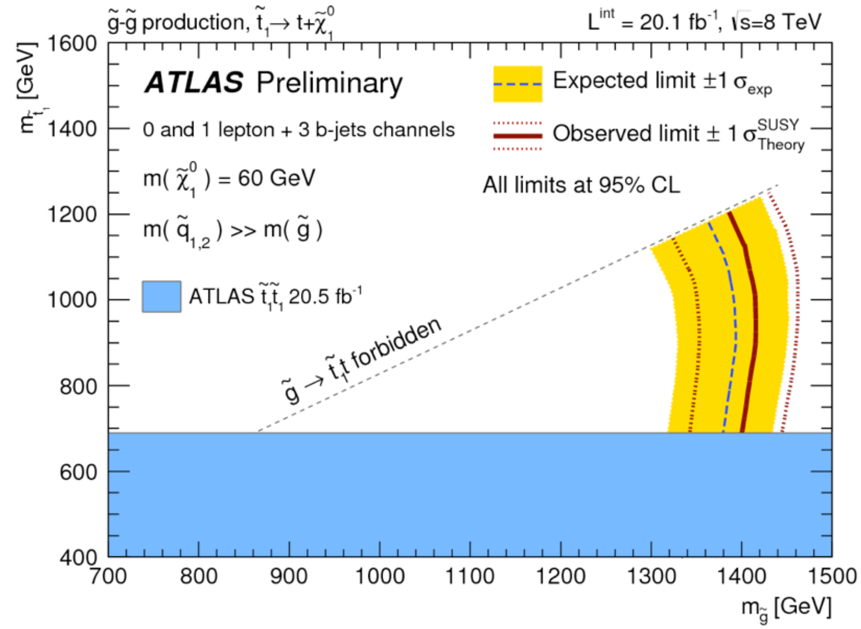


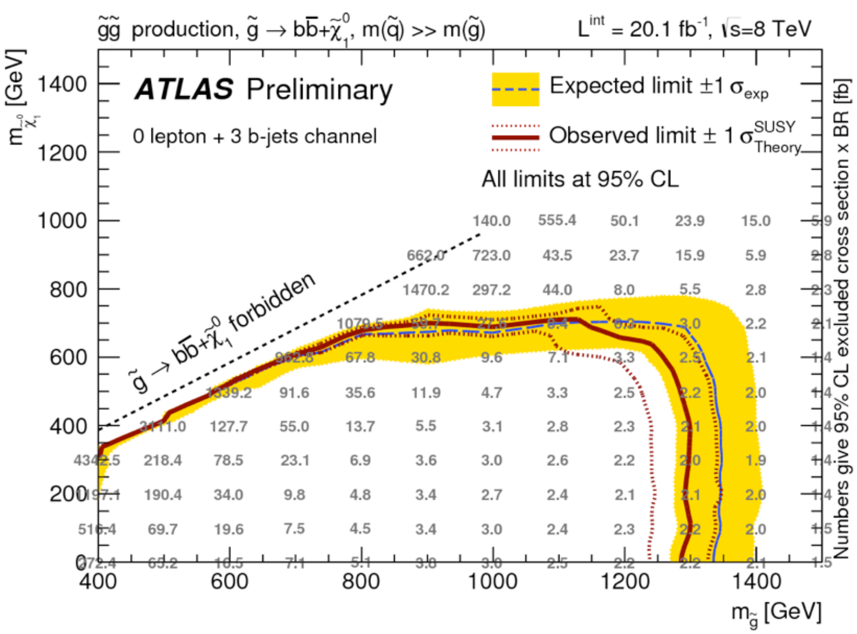
High mass: run out of cross-section

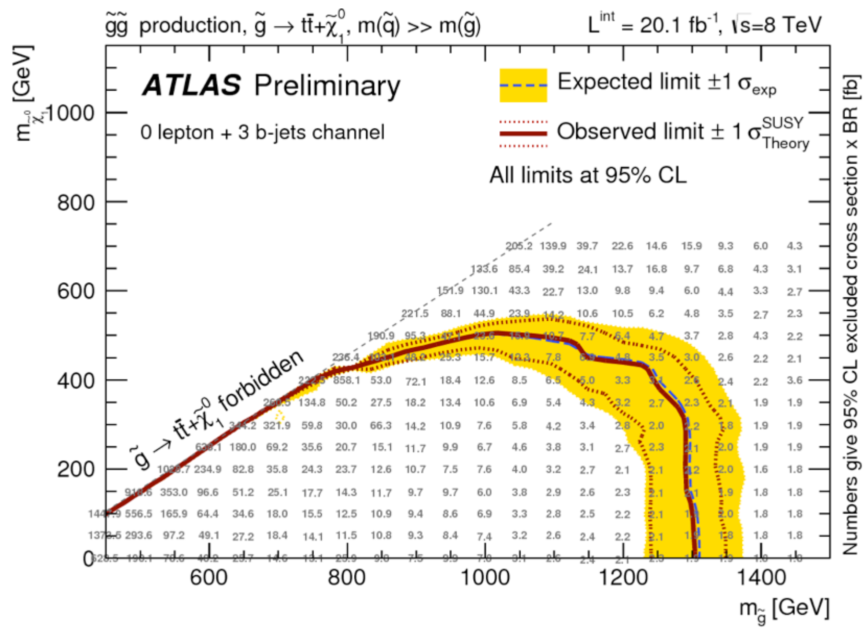
Tiny mass gap: soft decay products

Many Many Limits… Sigh



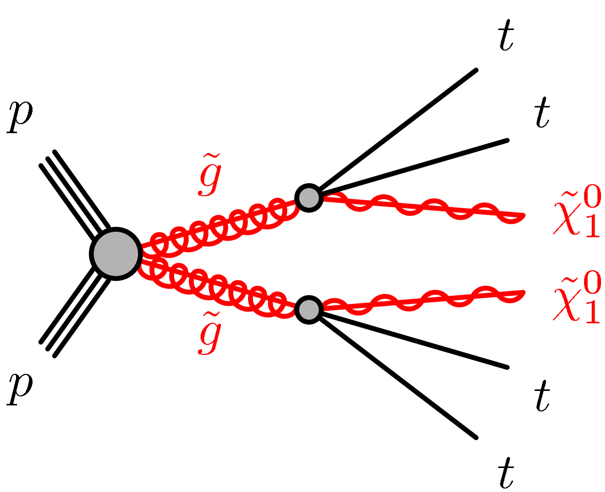


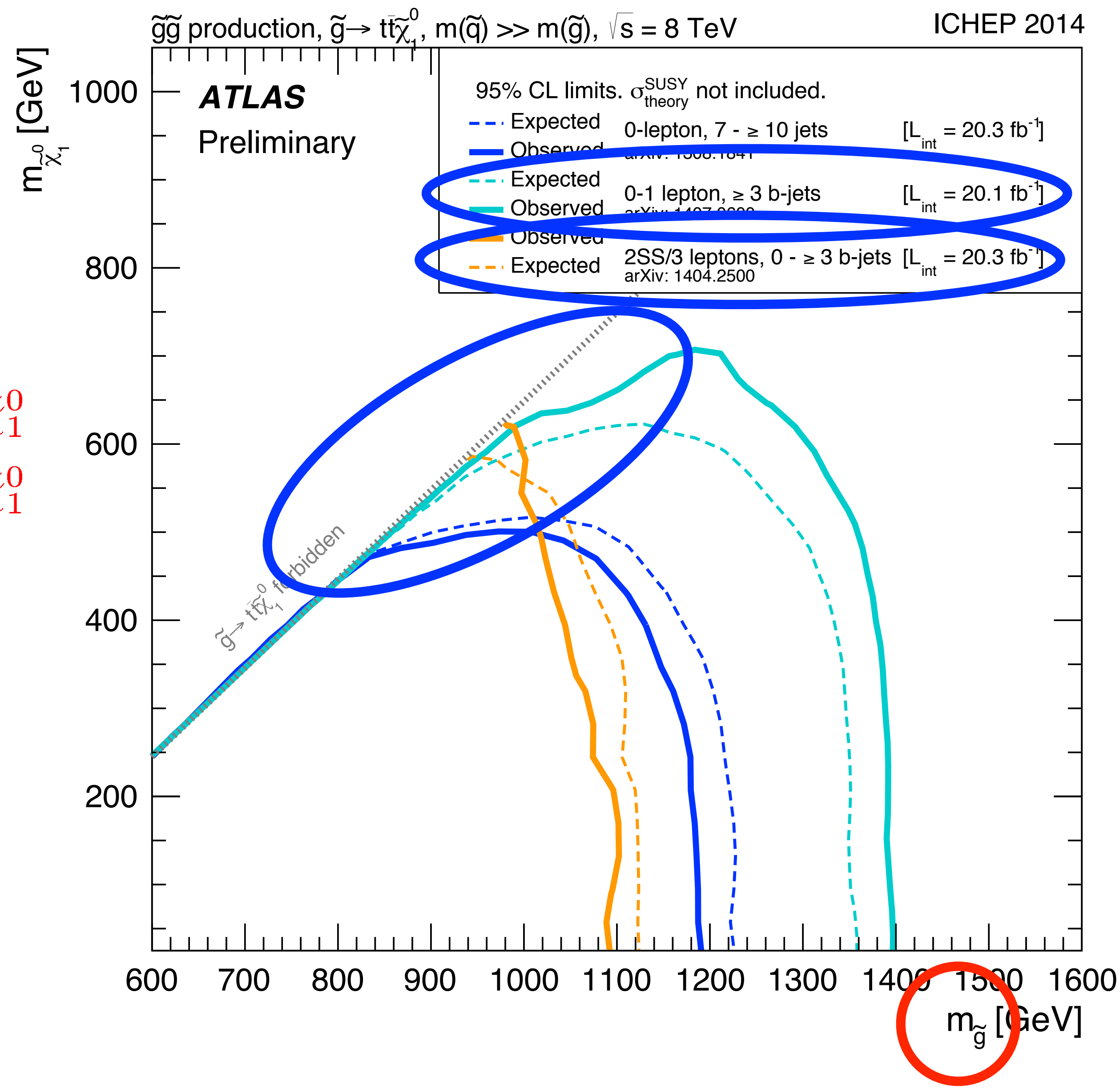




Stop Searching Anatomy

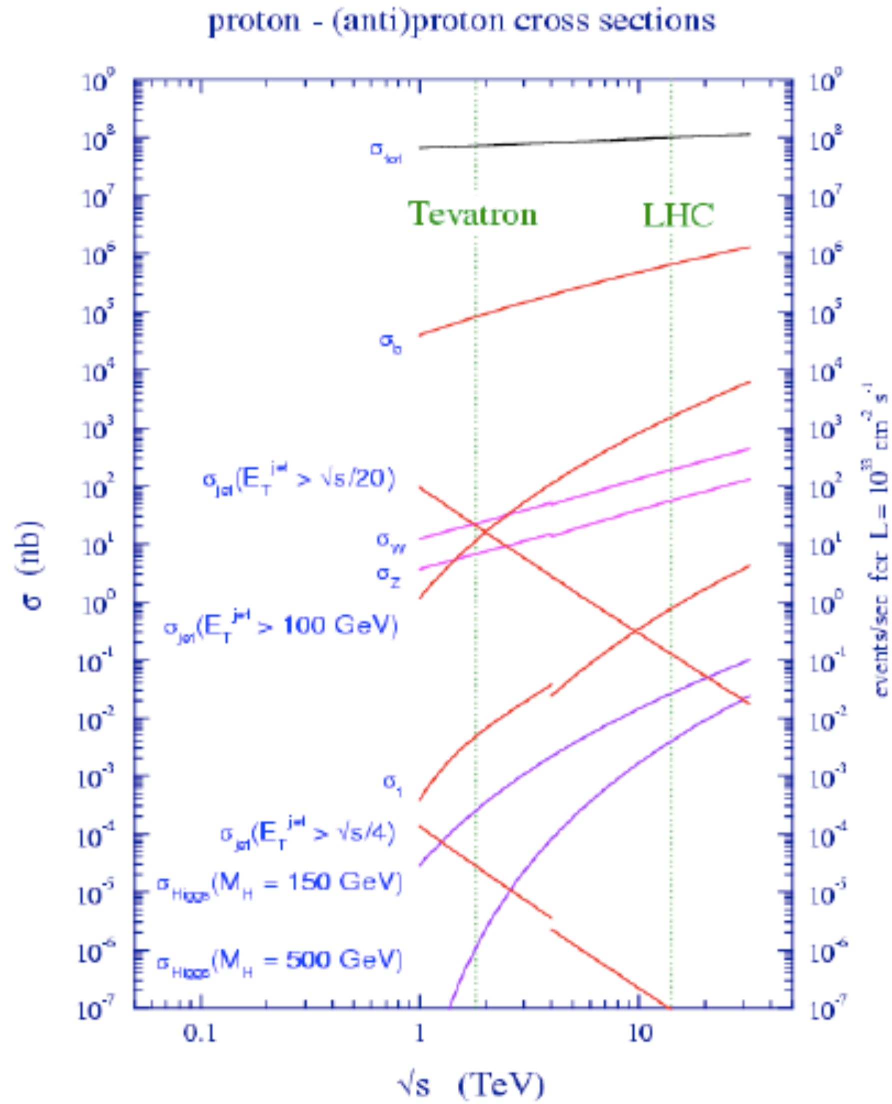
(Off-shell intermediate stop)



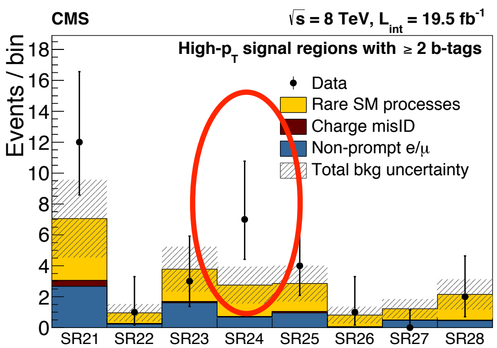


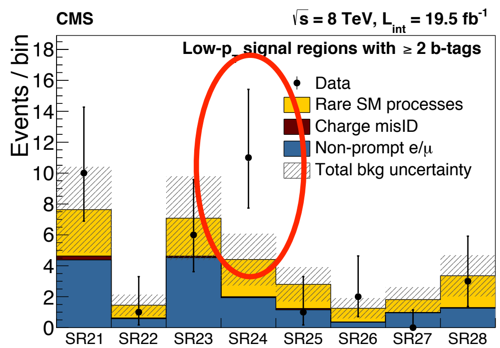
Same-Sign Leptons

- ❖ 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



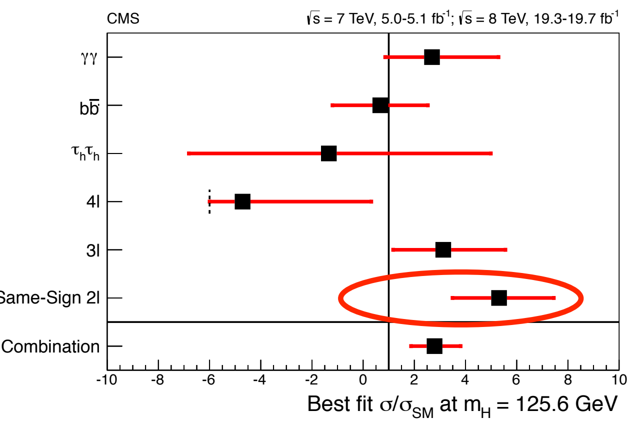
Same Sign Lepton Excesses



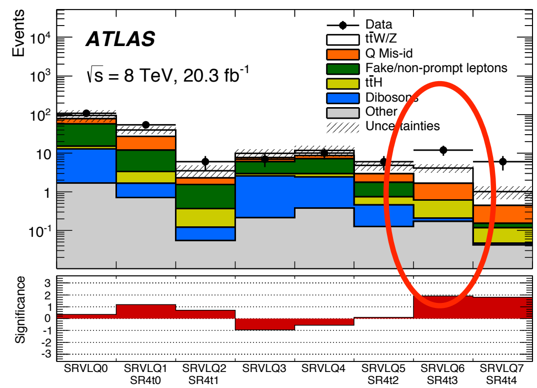


SR1b $_{1bin}$	Total	ee	$e\mu$	$\mu\mu$
Observed events	10	6	4	0
Total expected background events	4.7 ± 2.1	1.4 ± 0.8	2.1 ± 1.1	1.2 ± 0.4
Components of the background				
$t\bar{t}V$, $t\bar{t}H$, tZ and $t\bar{t}t\bar{t}$	2.5 ± 1.7	0.6 ± 0.3	1.2 ± 1.0	0.7 ± 0.3
Dibosons and tribosons	0.9 ± 0.4	0.10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

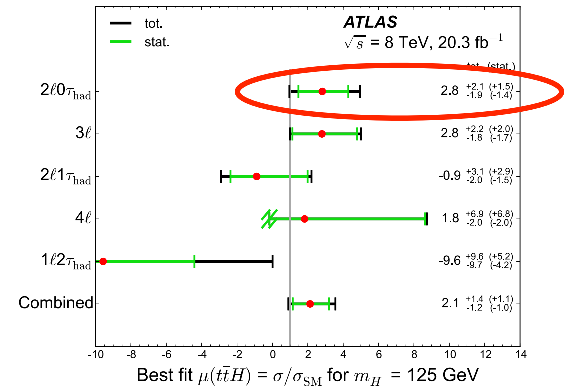
CMS (SUSY), http://arxiv.org/abs/1311.6736 (24 signal regions in paper) ATLAS (SUSY), http://arxiv.org/abs/1404.2500 (5 signal regions in paper)



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



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



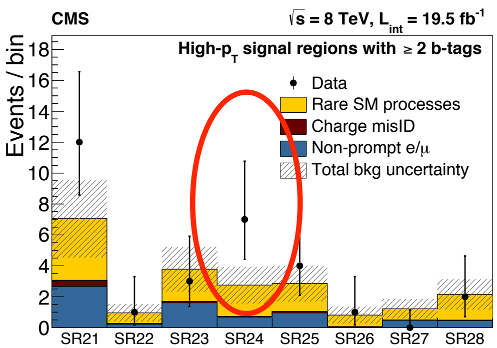
ATLAS (ttH), http://arxiv.org/abs/1506.05988

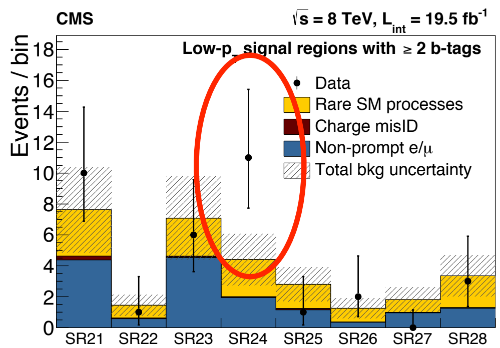
It certainly looks like multiple analyses looking at same sign leptons and b-jets see excesses!

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

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

Same Sign Lepton Excesses





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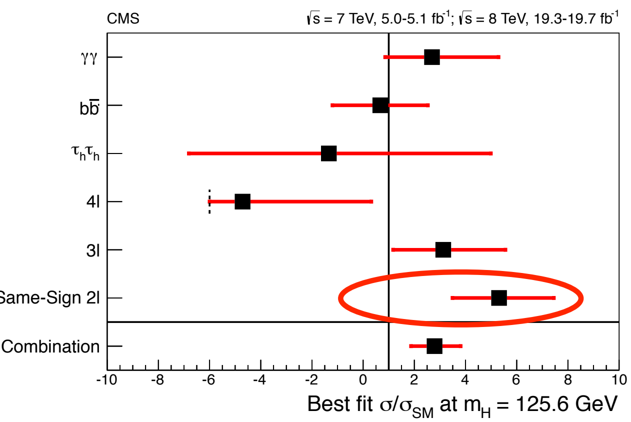

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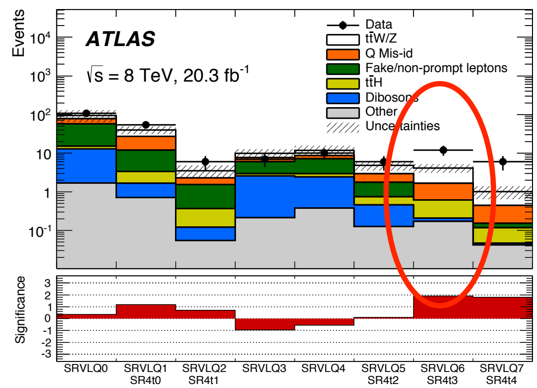

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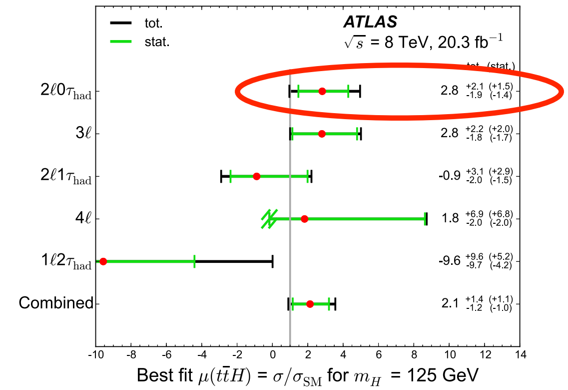


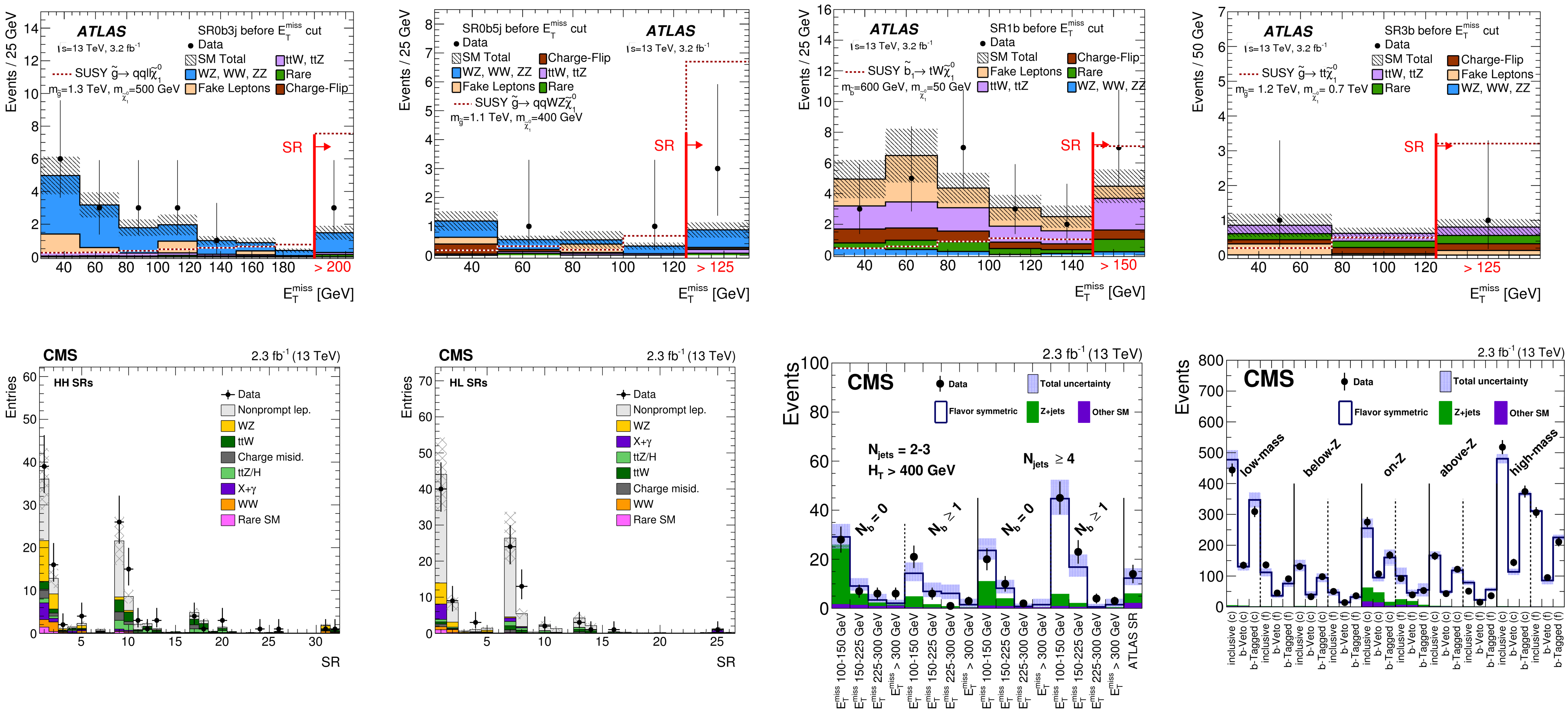
ATLAS (ttH), http://arxiv.org/abs/1506.05988

The ATLAS analyses are correlated, and same for CMS

So, ~2 analyses and excesses are < 3 σ

Worth keeping an eye on? Sure.

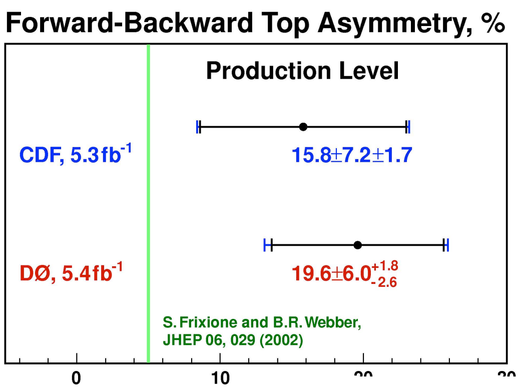
13 TeV



Not much there…. so far

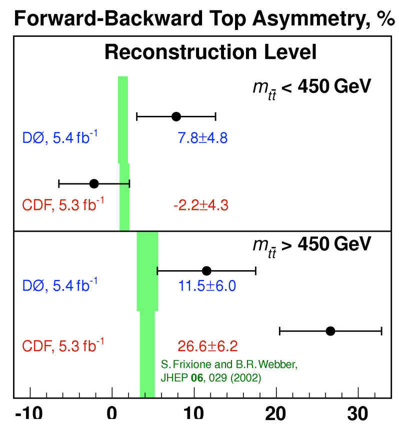
Anecdotes From the Field (II)

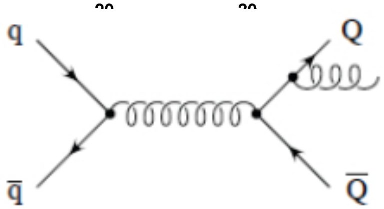
- ttbar charge asymmetry at the Tevatron
  - At Feynman diagram level, NLO effect (Tevatron is proton-anti-proton collider)



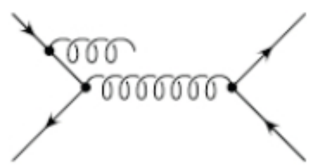
http://arxiv.org/abs/1107.4995

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

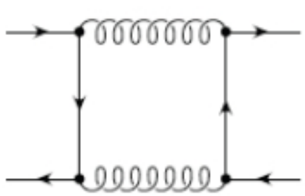




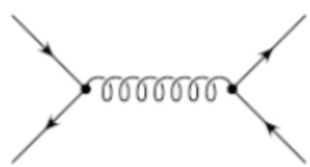
(a) Final state gluon bremsstrahlung FSR



(b) Initial state gluon bremsstrahlung ISR



(c) double virtual gluon exchange



(d) Born diagram

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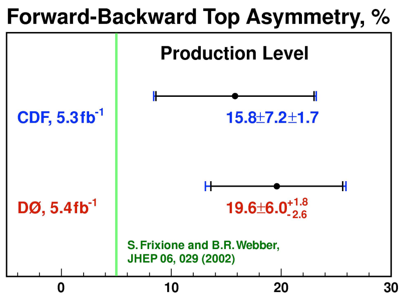

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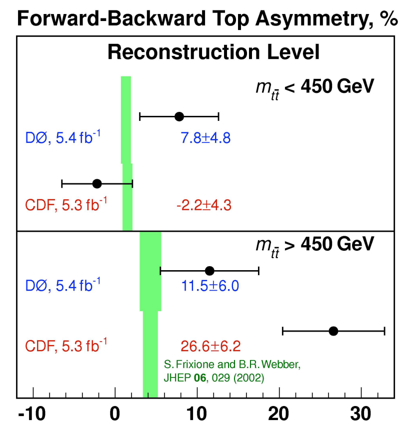
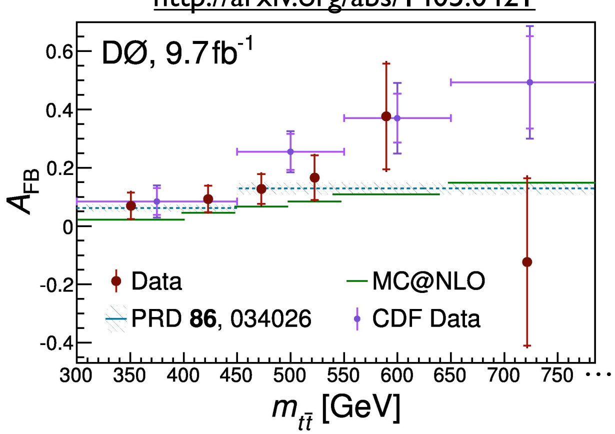


  - In real life, already exists at ~LO!
    - Shown it is there in Pythia: parton shower, recoils! http://arxiv.org/abs/1205.1466

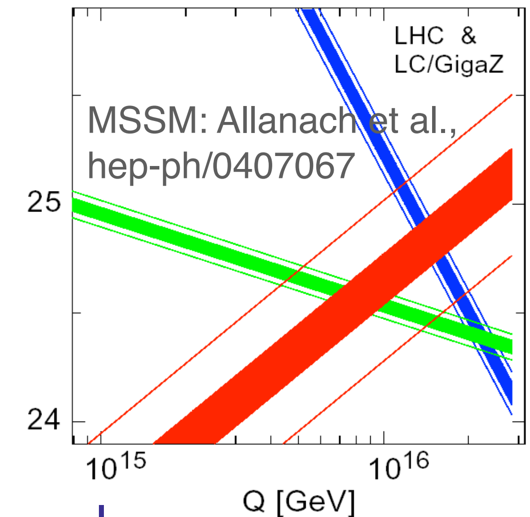
http://arxiv.org/abs/1405.0421



(My) current conclusion: no BSM physics here: just (N)NLO + non-perturbative effects at work

Not SUSY?

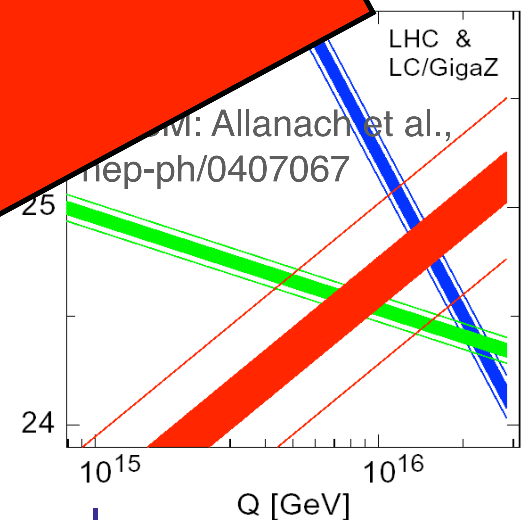
- SUSY theories (and others with full or partial set of SM-partners) have a number of attractive features
  - "Explanation" for low Higgs mass (and sometimes EWSB)
  - Gauge coupling unification (often)
  - Dark matter candidate (if introduce a new parity, natural in UED, ~ad-hoc in SUSY)
  - No new 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?

Not SUSY?

- SUSY theories (and others with full or partial set of SM-partners) have a number of attractive fea… s
  - "Explanation" for low Higgs mass (and s… B)
  - Gauge coupling unification (often)
  - Dark matter candidate (if i… parity, natural in UED…)
  - No new inter…



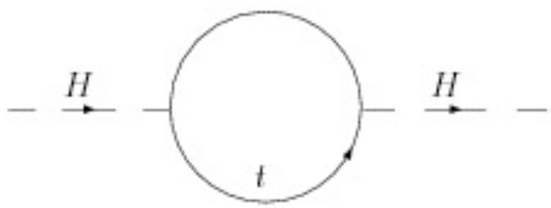
Dinosaurs on Venus?

- But a… questions comes at a large cos…
  - Ma… w particles, with masses and mixing angles
  - Need to explain why mass scale is so low (or high), spin?

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:



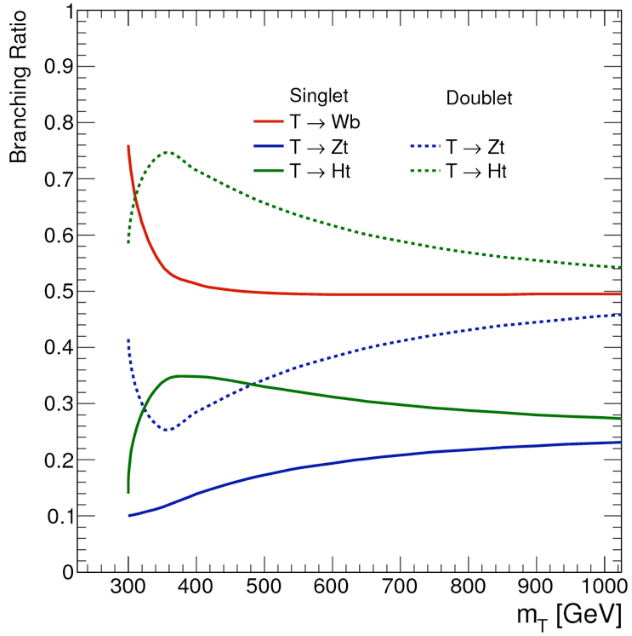
$$\longrightarrow \frac{3}{16\pi^2} y_t^2 E^2$$

➡ Top partner!

Singlets, Doublets, ...

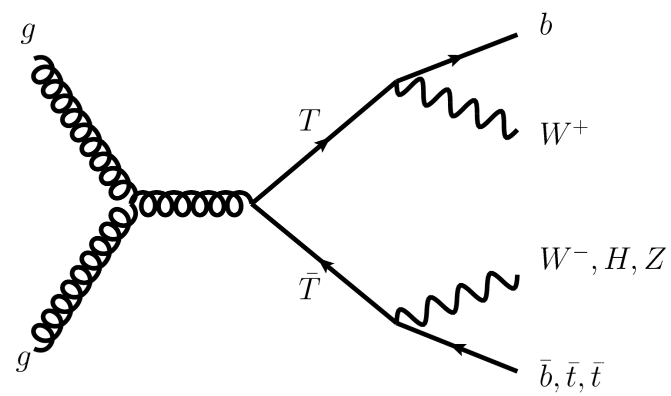
❖ Vector-like top partners (still fermions) less constrained by flavor....

- Opens up decay modes
- Top partner partners:
  - $T^{5/3}$
  - ...



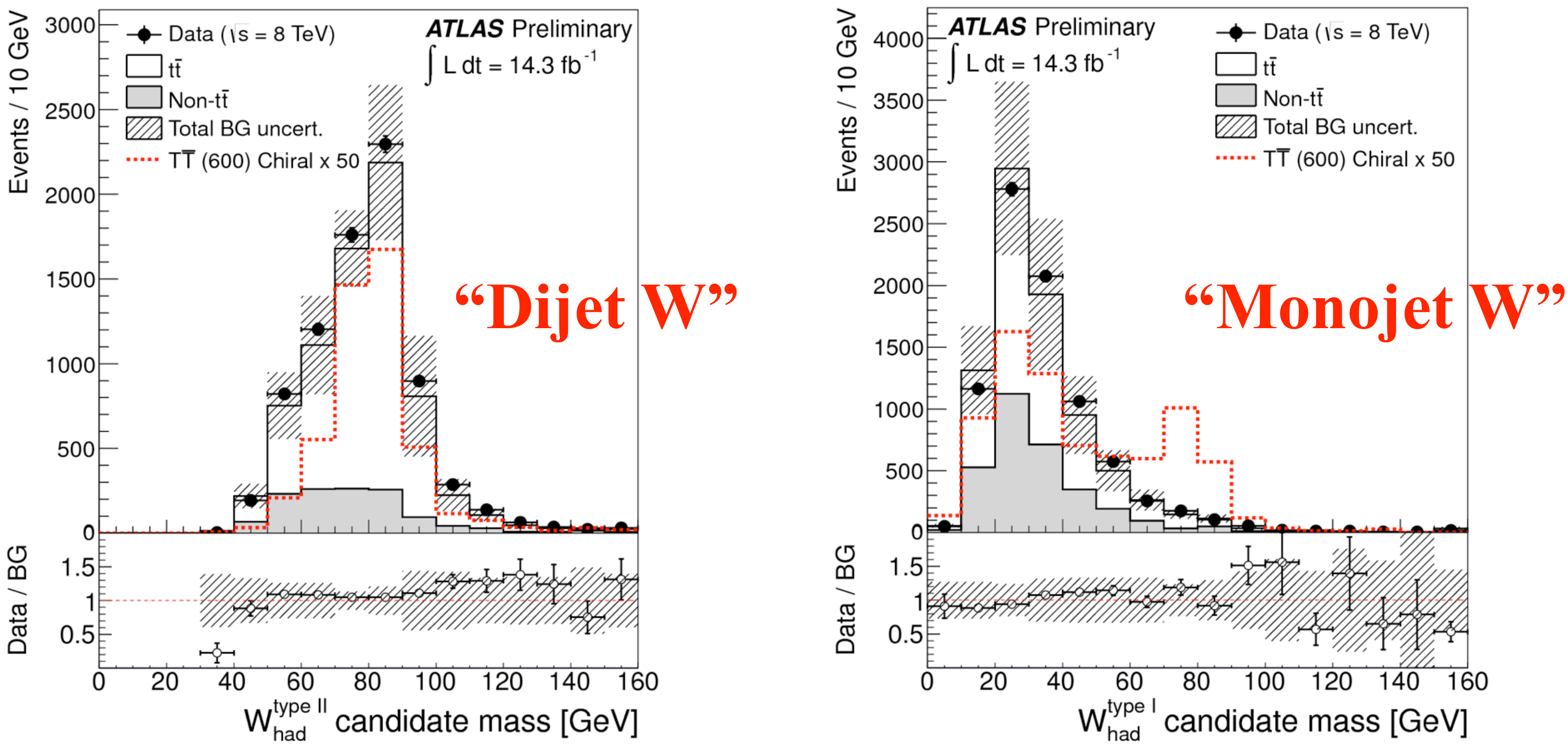
❖ Rich set of signatures

- Just no huge MET
- At least not systematically



W's Can Be Light

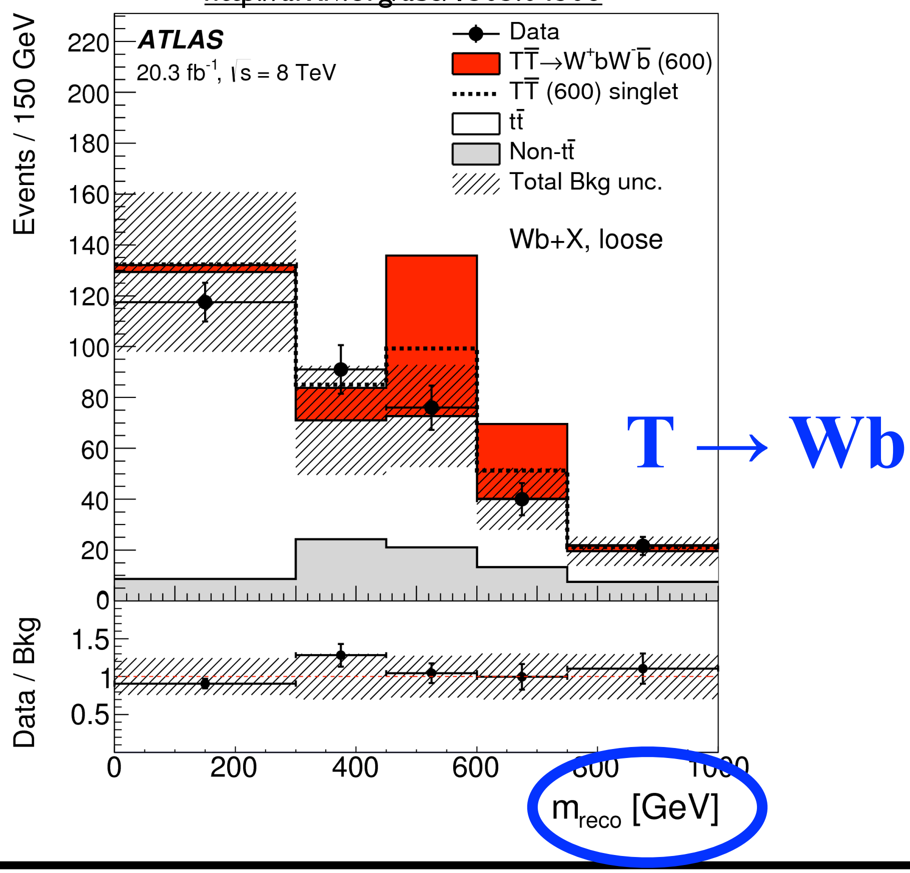
- T→Wb with m_T ~600 GeV
  - ➡ W will be boosted, and if decays hadronically → single jet



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



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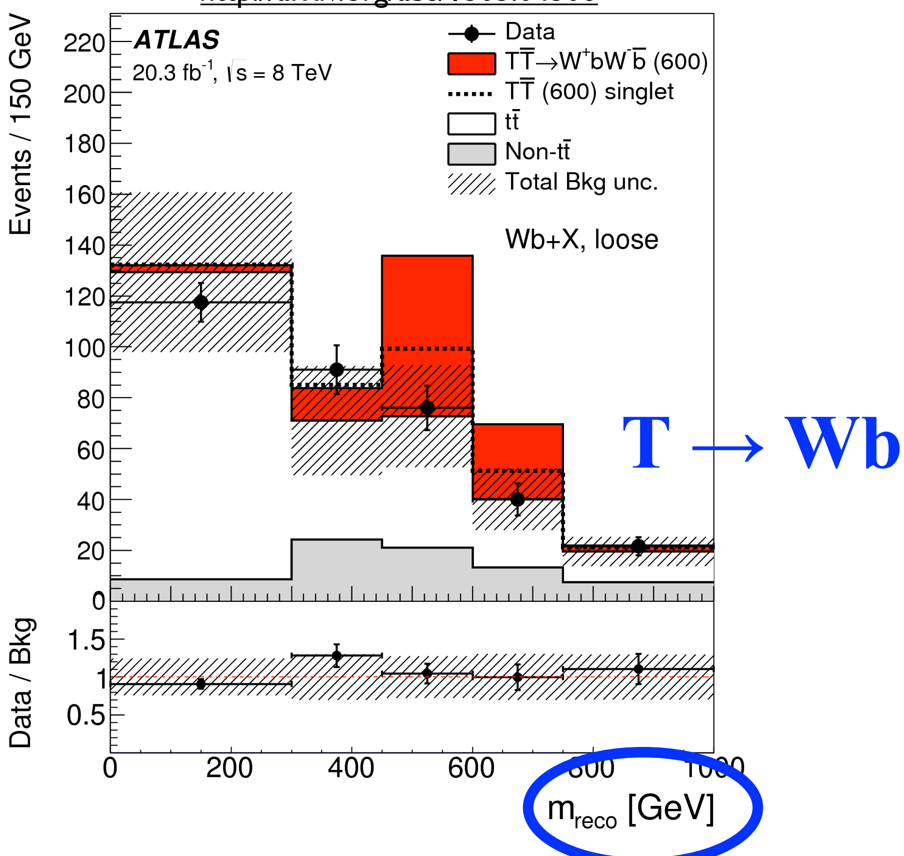

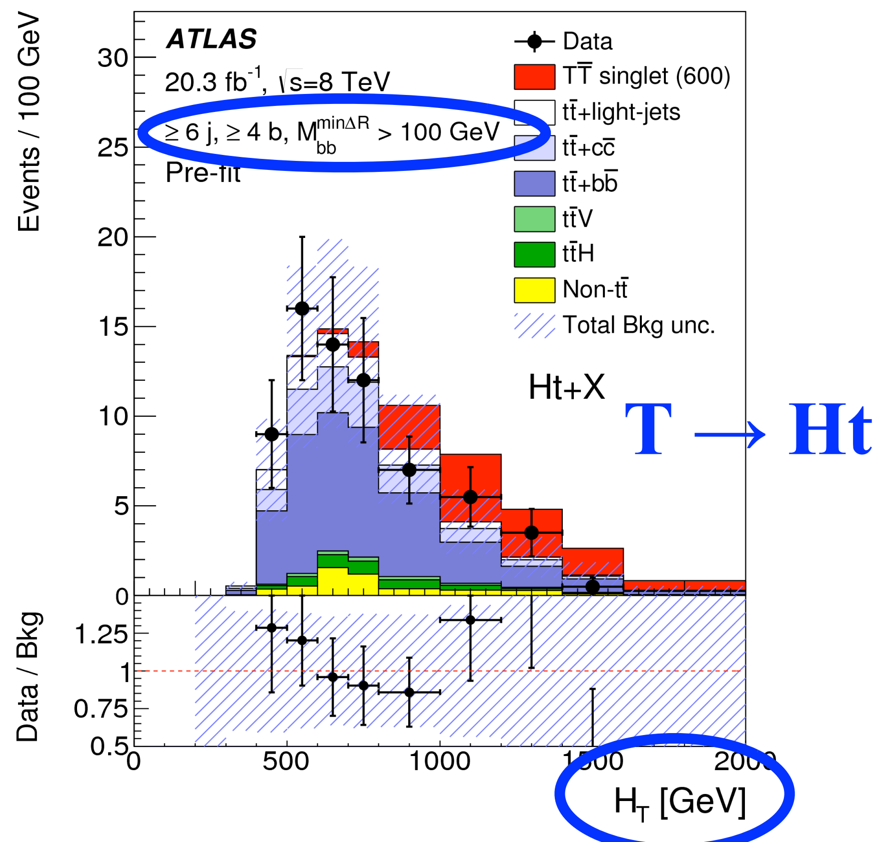

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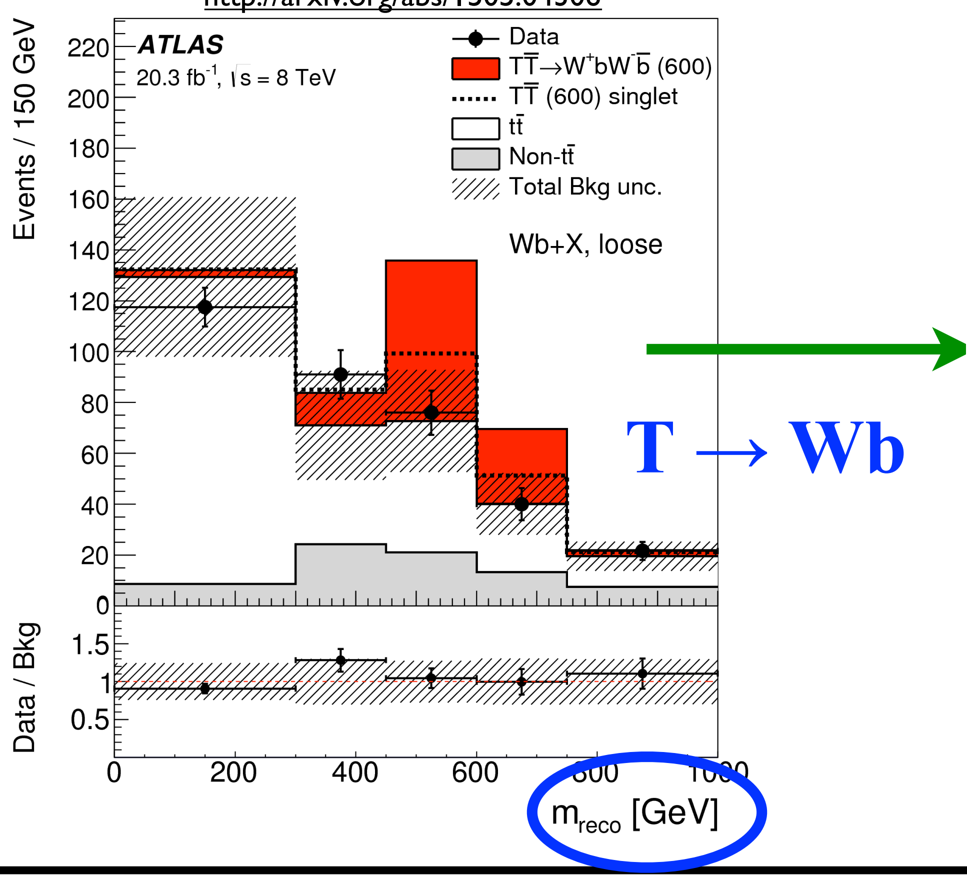

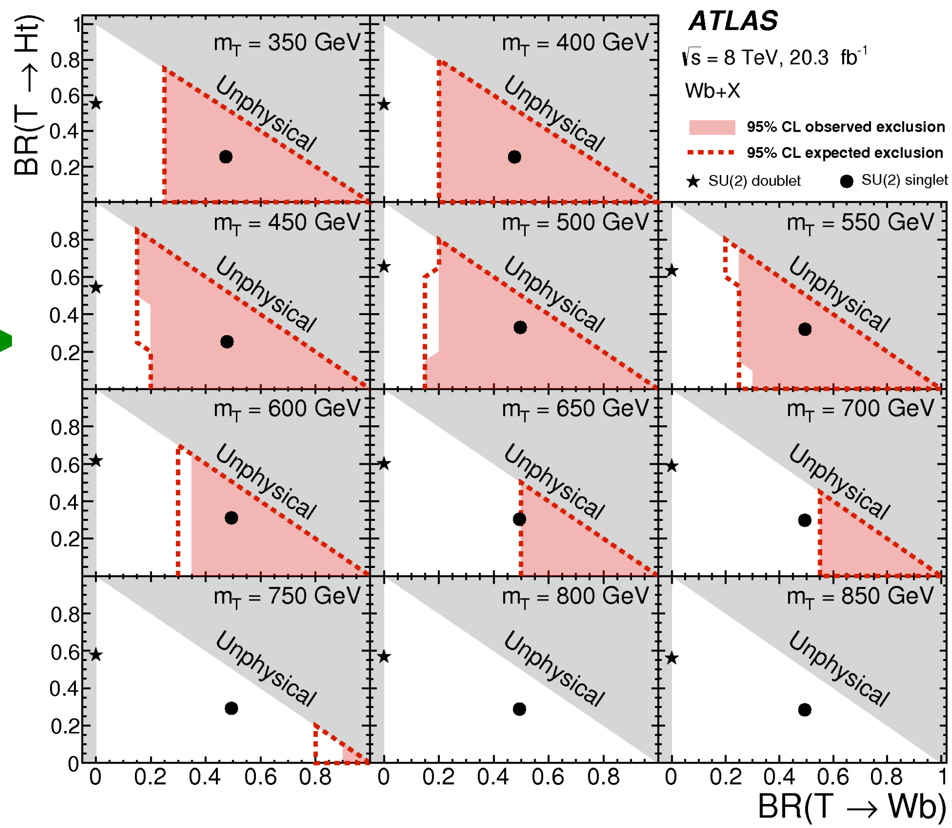

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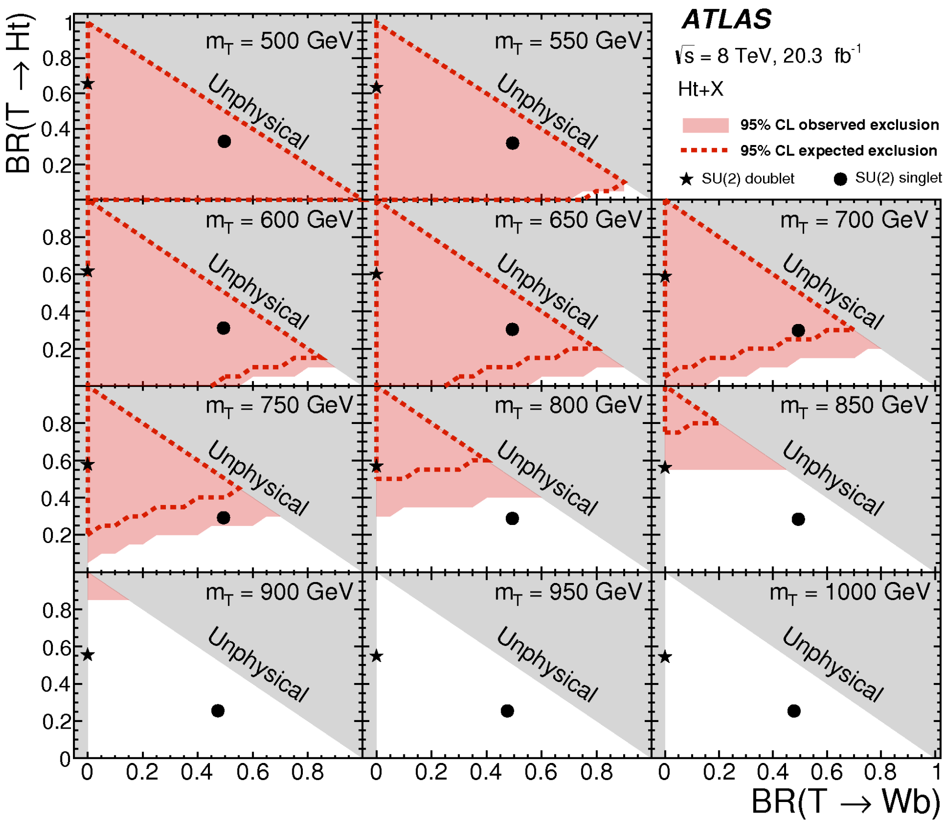
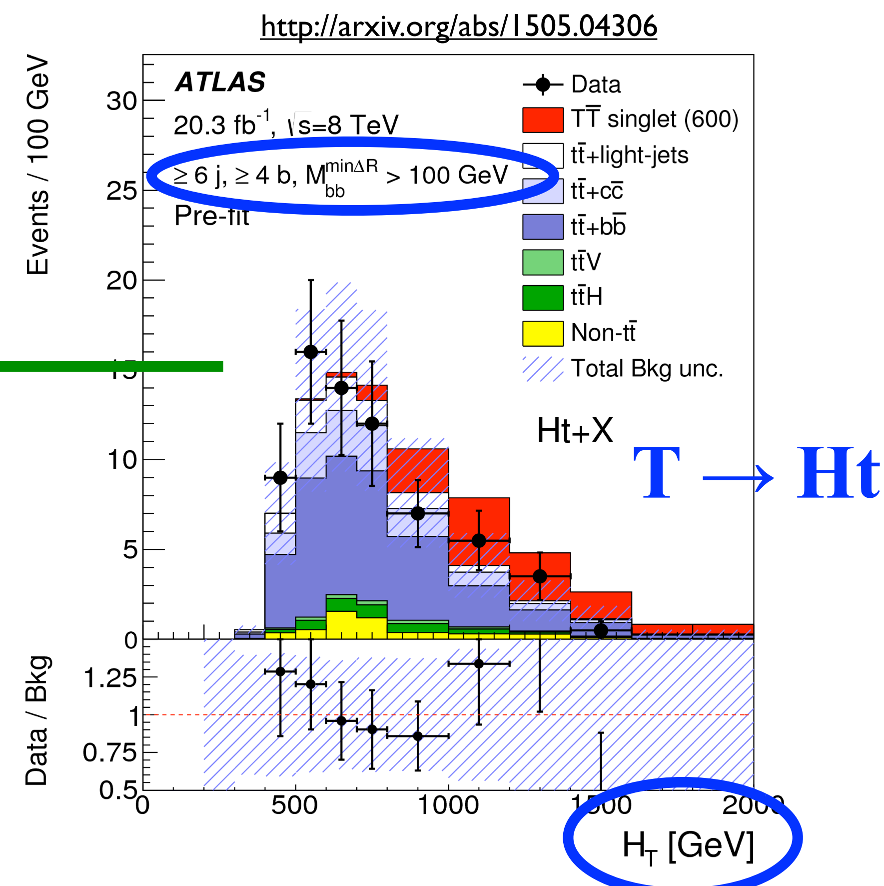
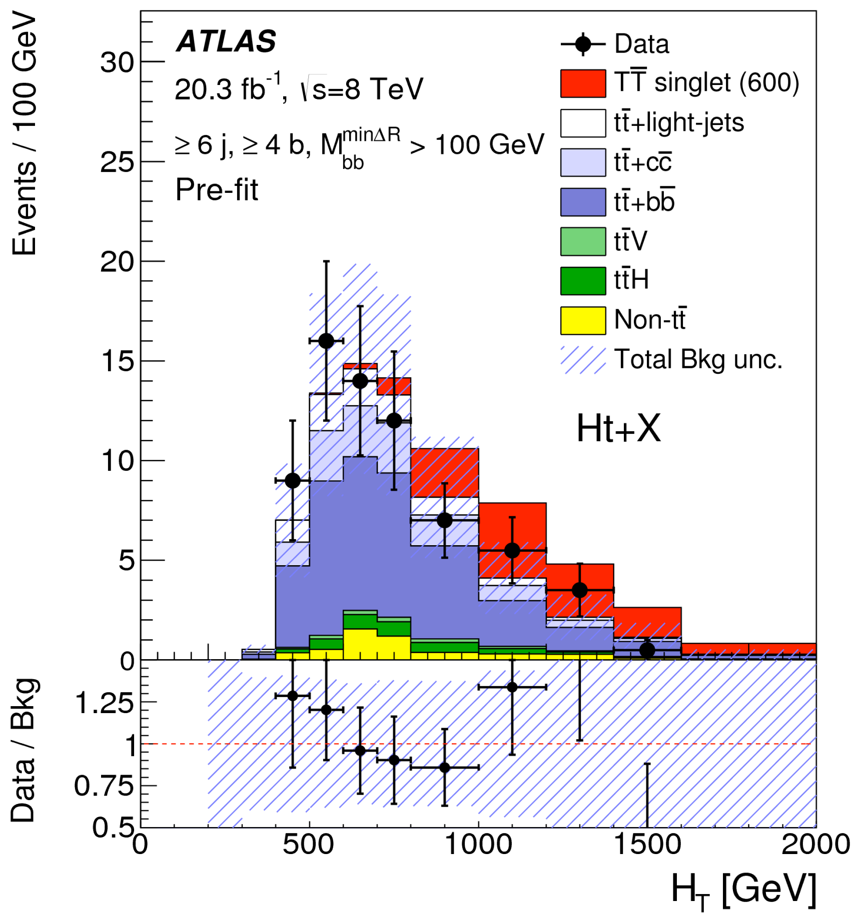




Systematic Uncertainties

- 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: $\sigma = \frac{N_{\mathrm{events}}}{\mathrm{L}A\epsilon}$
  - L is the integrated luminosity, A the acceptance, ε the efficiency
    - Statistical uncertainty comes from N_{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



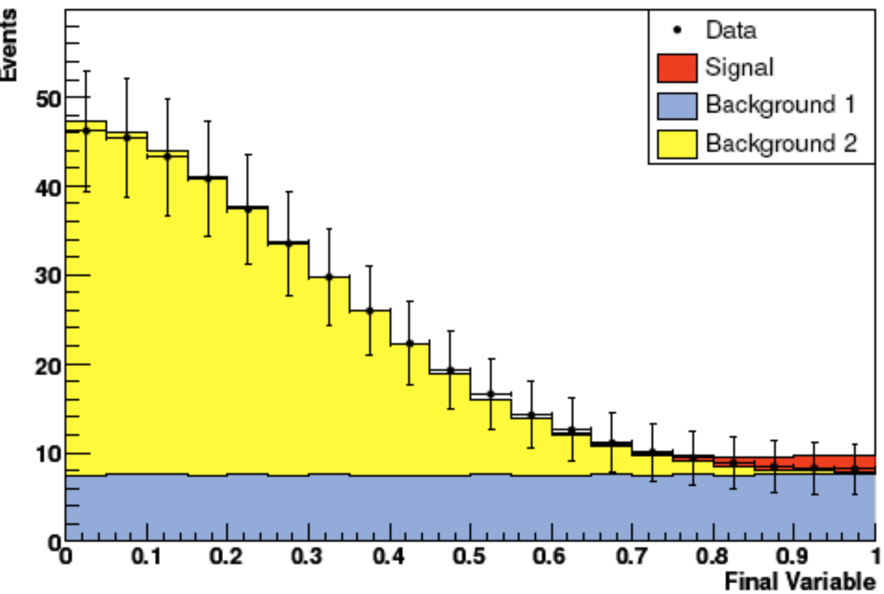
- ❖ H_T is the sum of scalar energies of jets, leptons,…
  - If the jet energy scale is different between data and MC, comparison is wrong
  - If the jet energy scale dependence on jet energy is wrong, distort shape
  - etc.
- ❖ But how do I determine the jet energy scale uncertainty?
  - testbeams (single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

Systematics Profiling

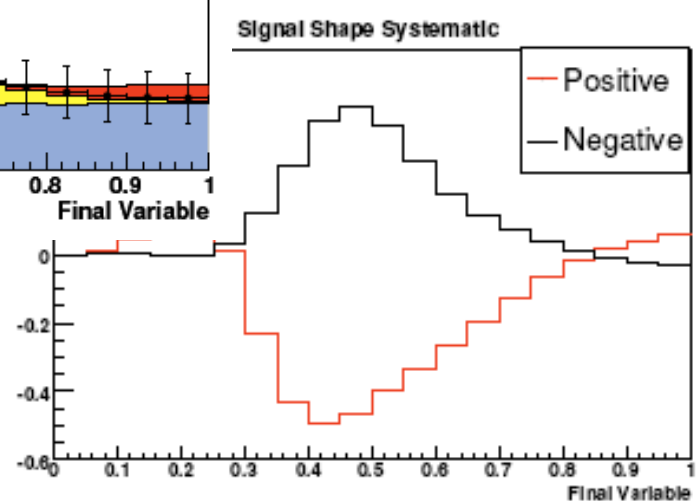
- Systematic uncertainties are propagated through the full analysis chain to the discriminating distribution
  - E.g. we repeat the analysis with jet energy scale shifted up & down by 1σ
  - Some systematic uncertainties affect shape (jet/lepton/photon reconstruction efficiency, energy scale and resolution, 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

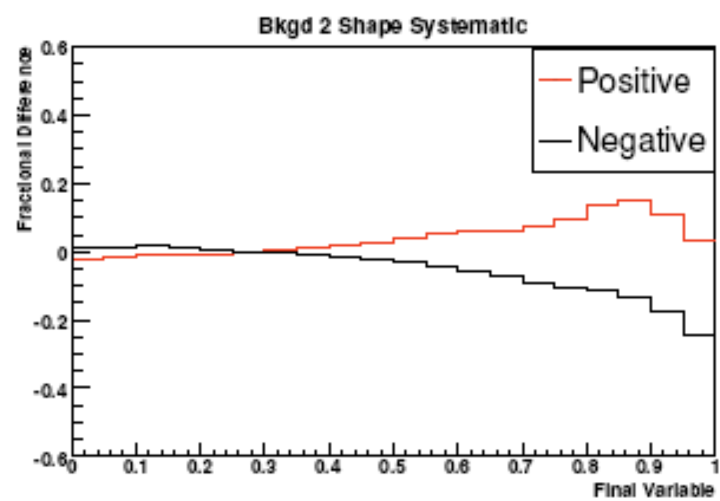
Systematics Profiling

- 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)

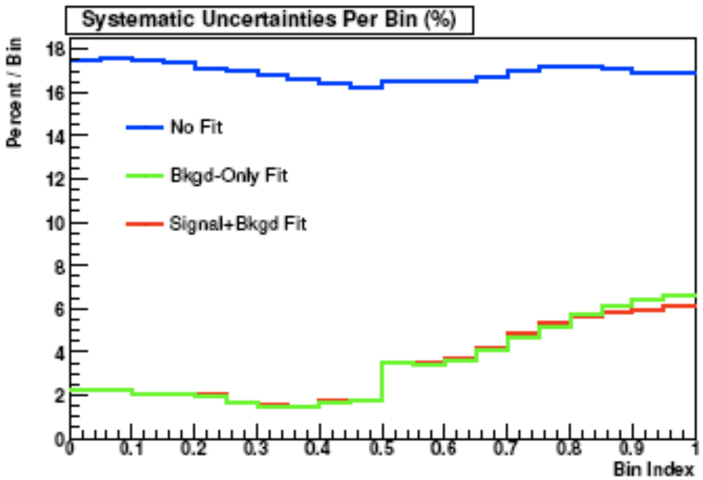




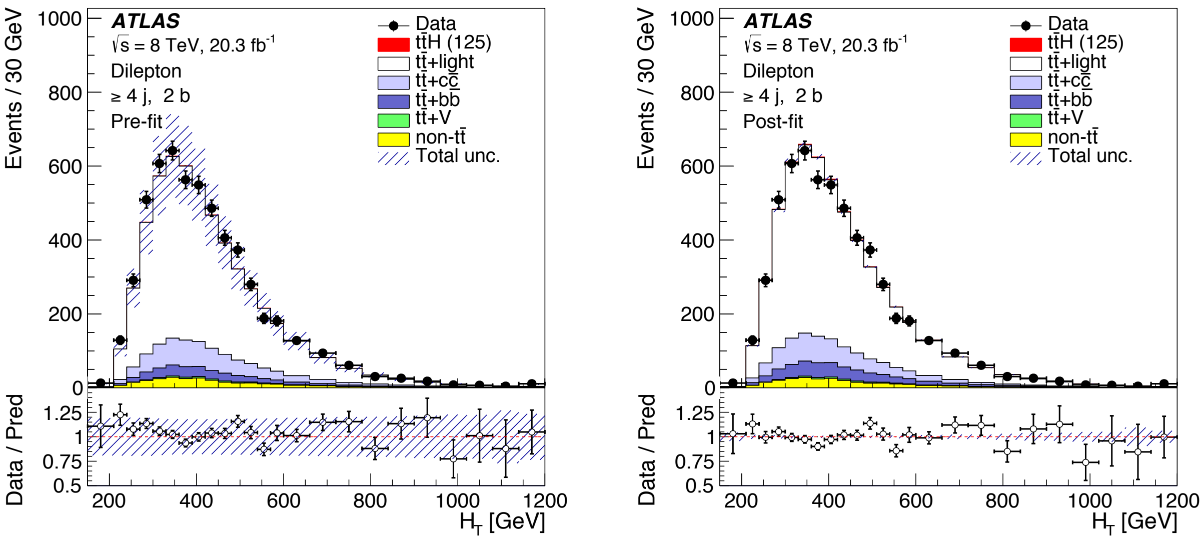
- ❖ Generate pseudo-experiments (events in bins according to poisson), then for each experiment vary nuisance parameters
  - Variations in background (& S+B) prediction
    - Compare results to data using log-likelihood ratio
- ❖ We can maximize likelihood ratio as a function of nuisance parameters → 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)

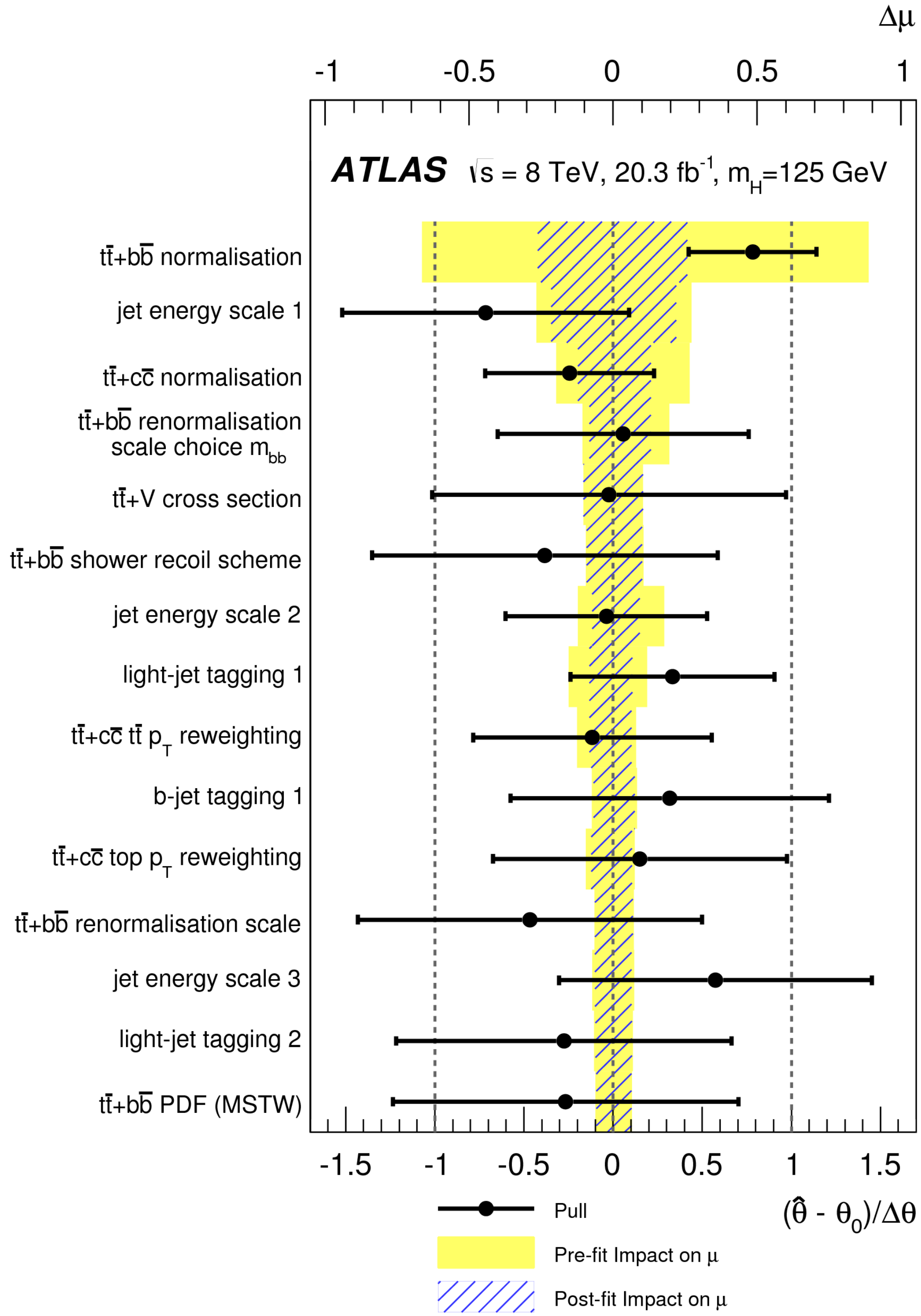


ATLAS ttH search: arXiv:1503.05066



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



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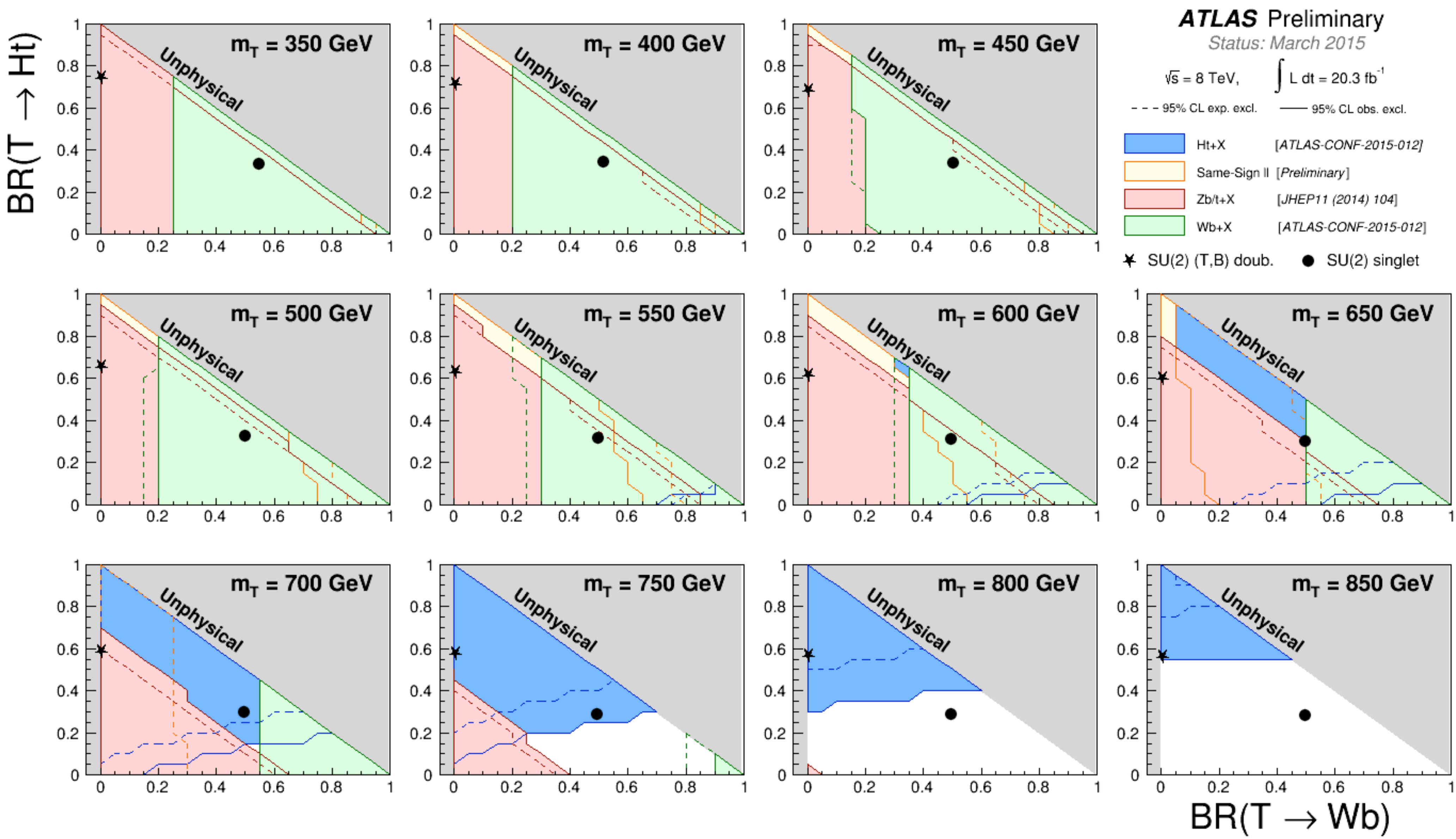
All Together Now



Presented Differently