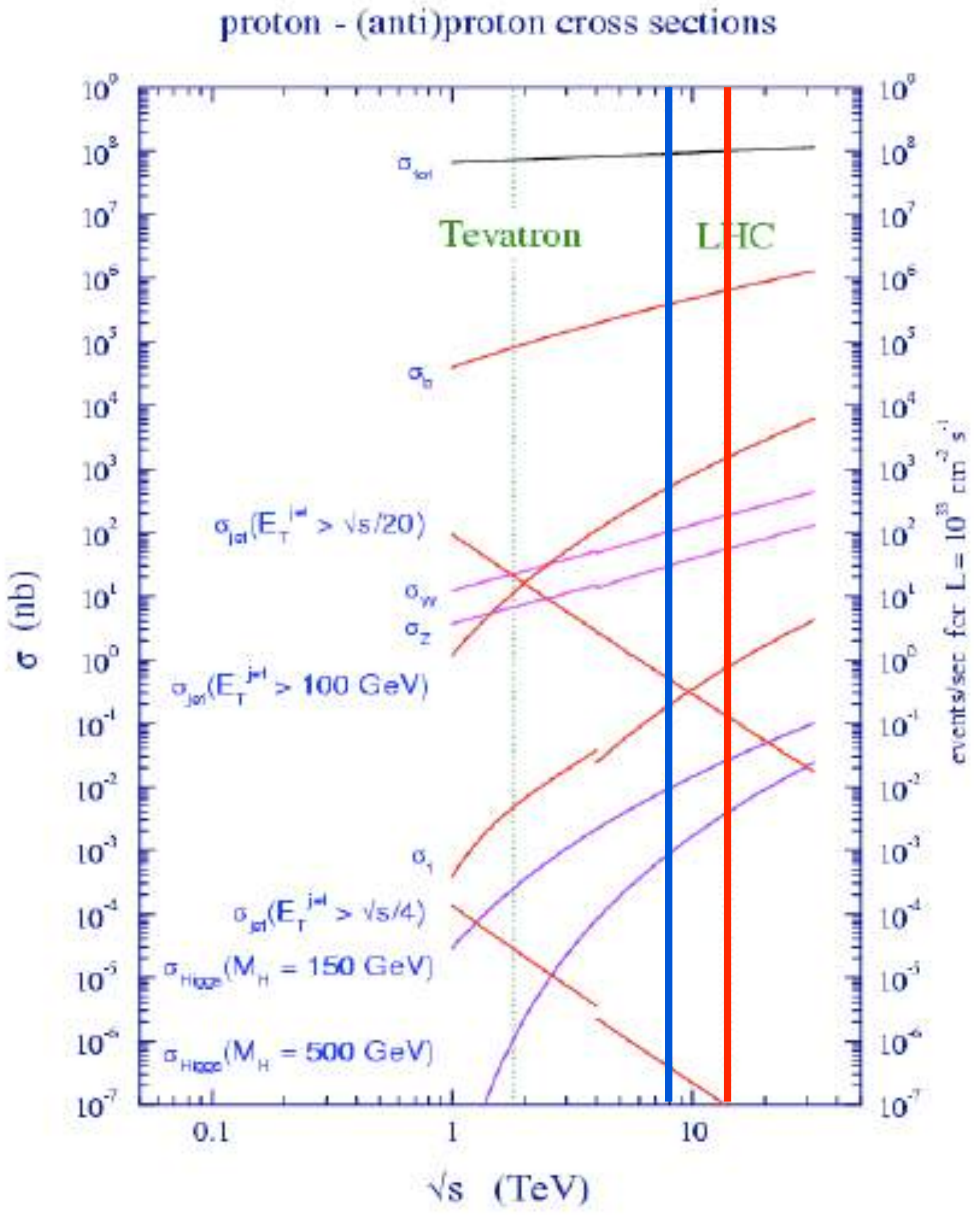
Physics @ LHC

- 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?

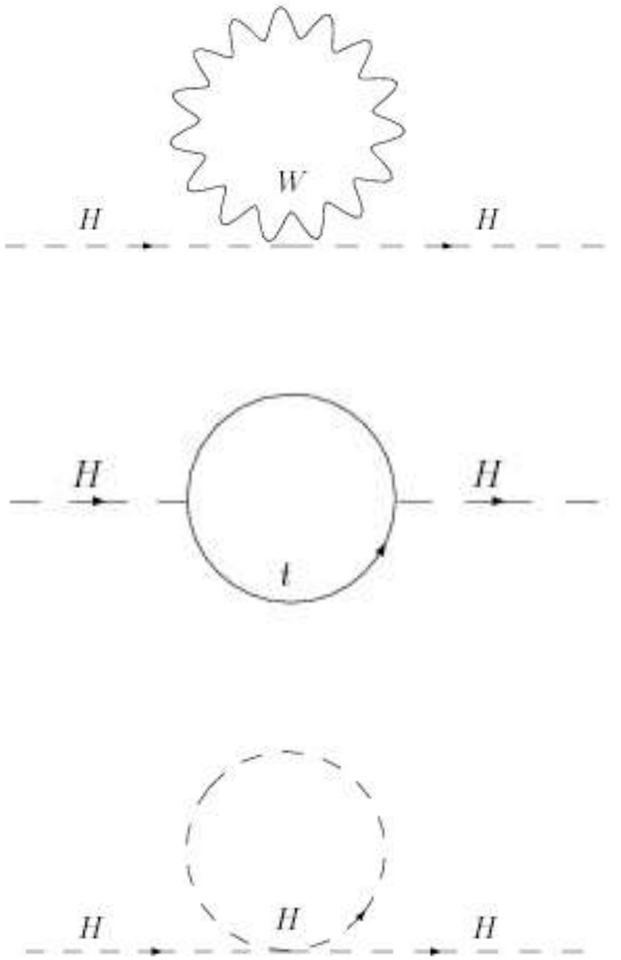


Experimental Searches

- 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



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

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

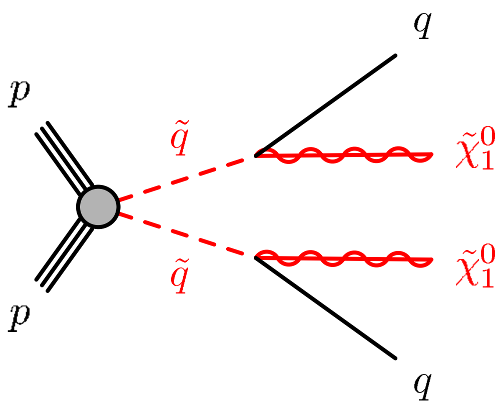
$$\rightarrow \frac{1}{16\pi^2} \lambda E^2$$

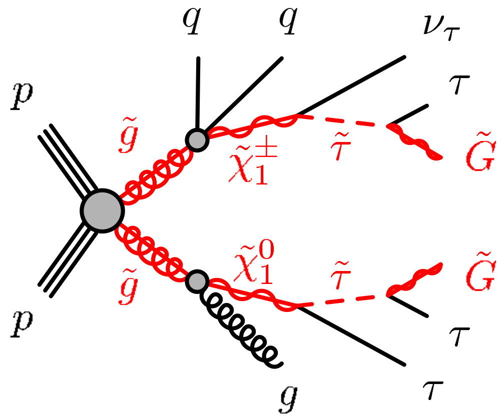
- If for every fermion there is a partner boson and vice-versa
  - Loops cancel each other
- Symmetry cannot be exact (no bosonic electron observed)
  - Symmetry breaking leads to “residual” Higgs mass
- This is supersymmetry
- With R-parity, get missing E_T
  - Generic to models with dark matter@LHC

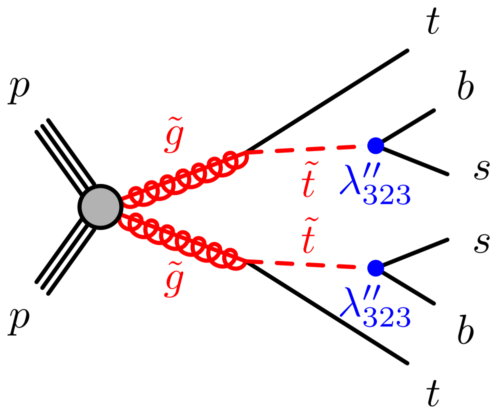
Canonical SUSY

❖ Wide range of signatures

- Strong production… (large cross-section)

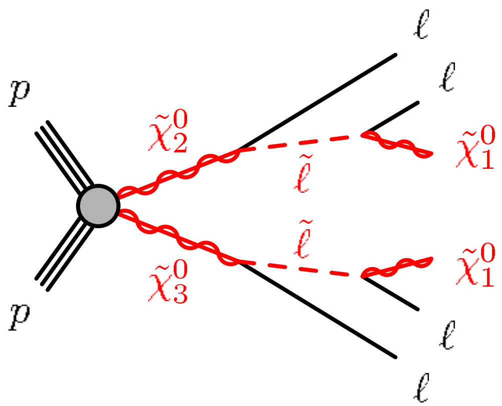


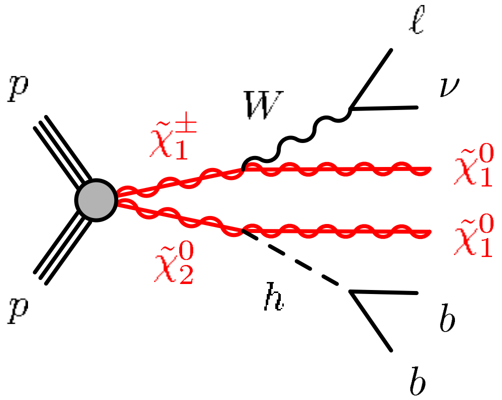


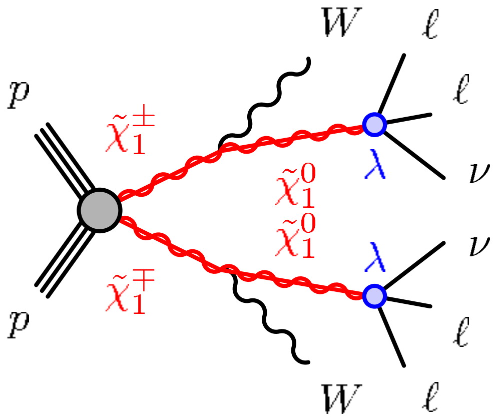


- … or weak production

RPV



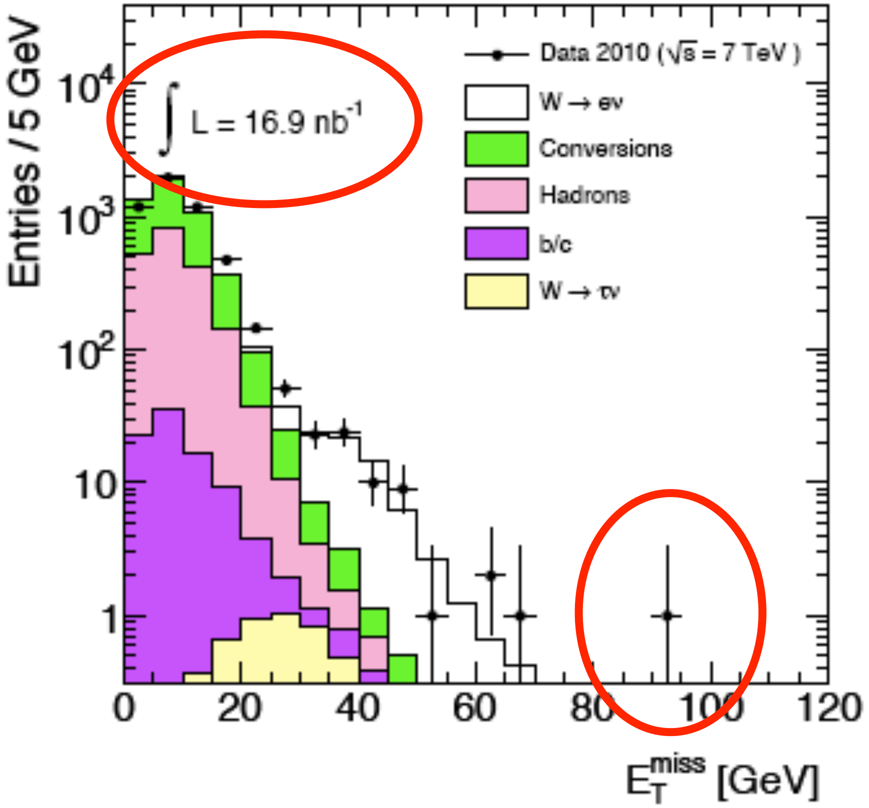


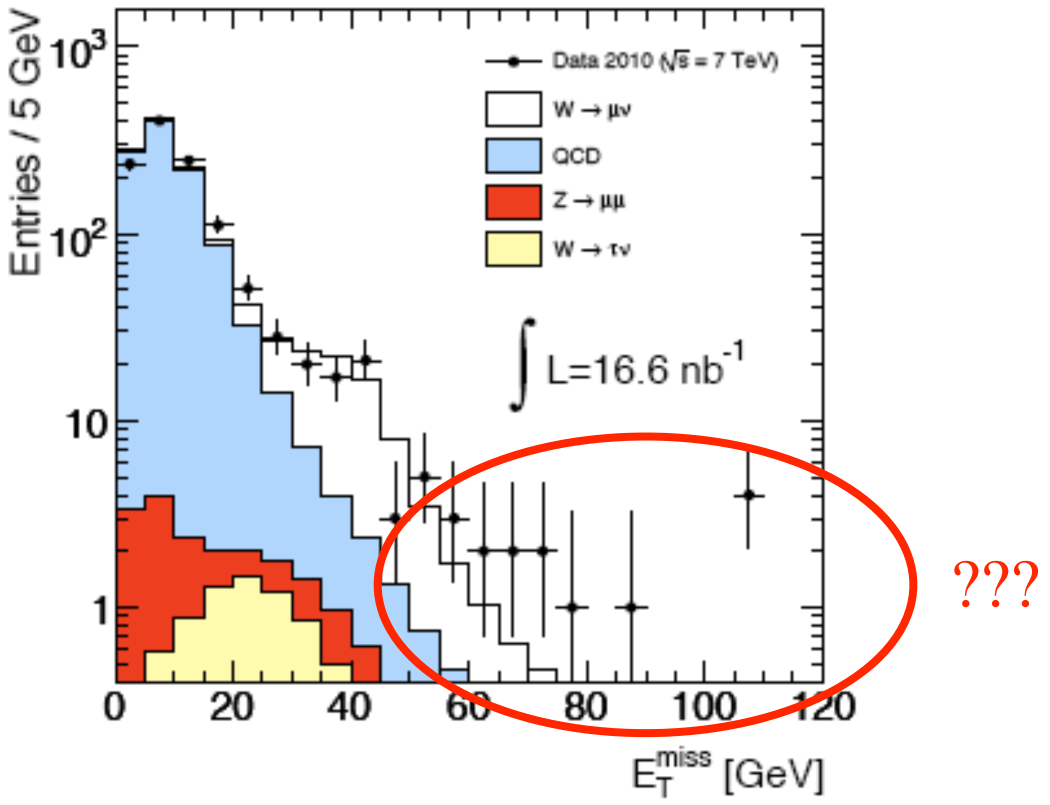


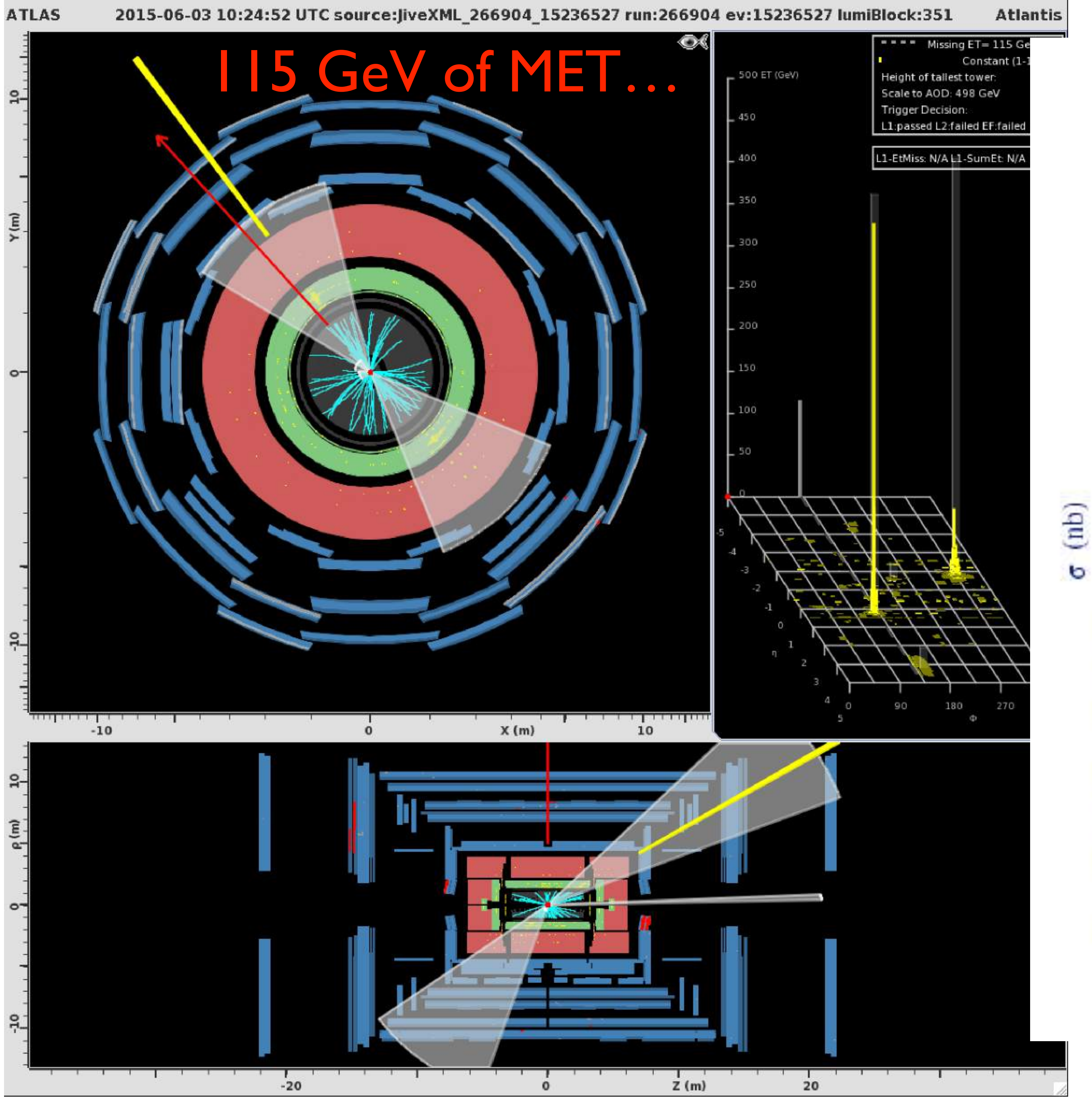
Missing E_T

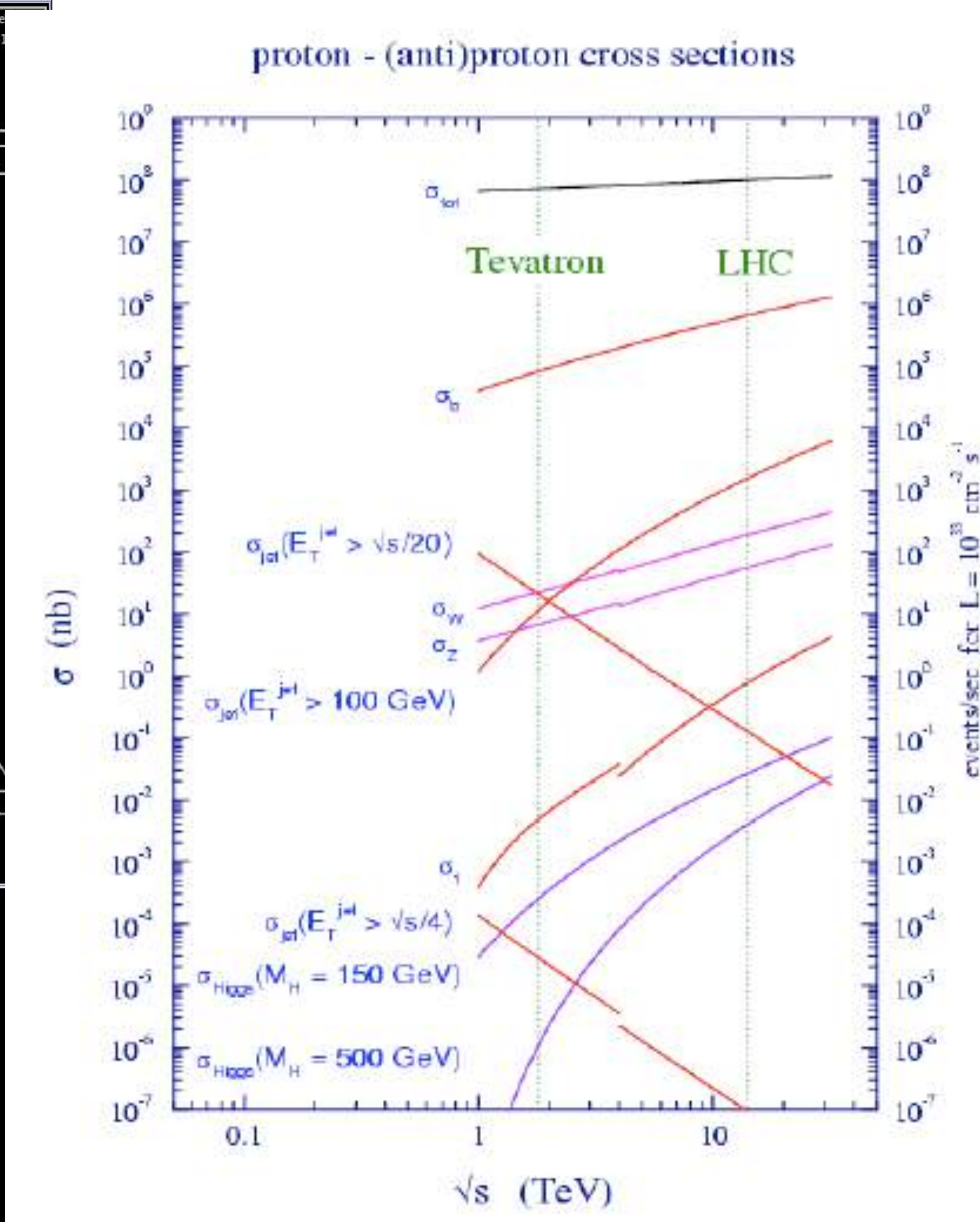
- "Evil" variable: - Σ (everything else)
  - Need to understand "everything else"
  - Good benchmark: leptonic W boson decays

Early 2010



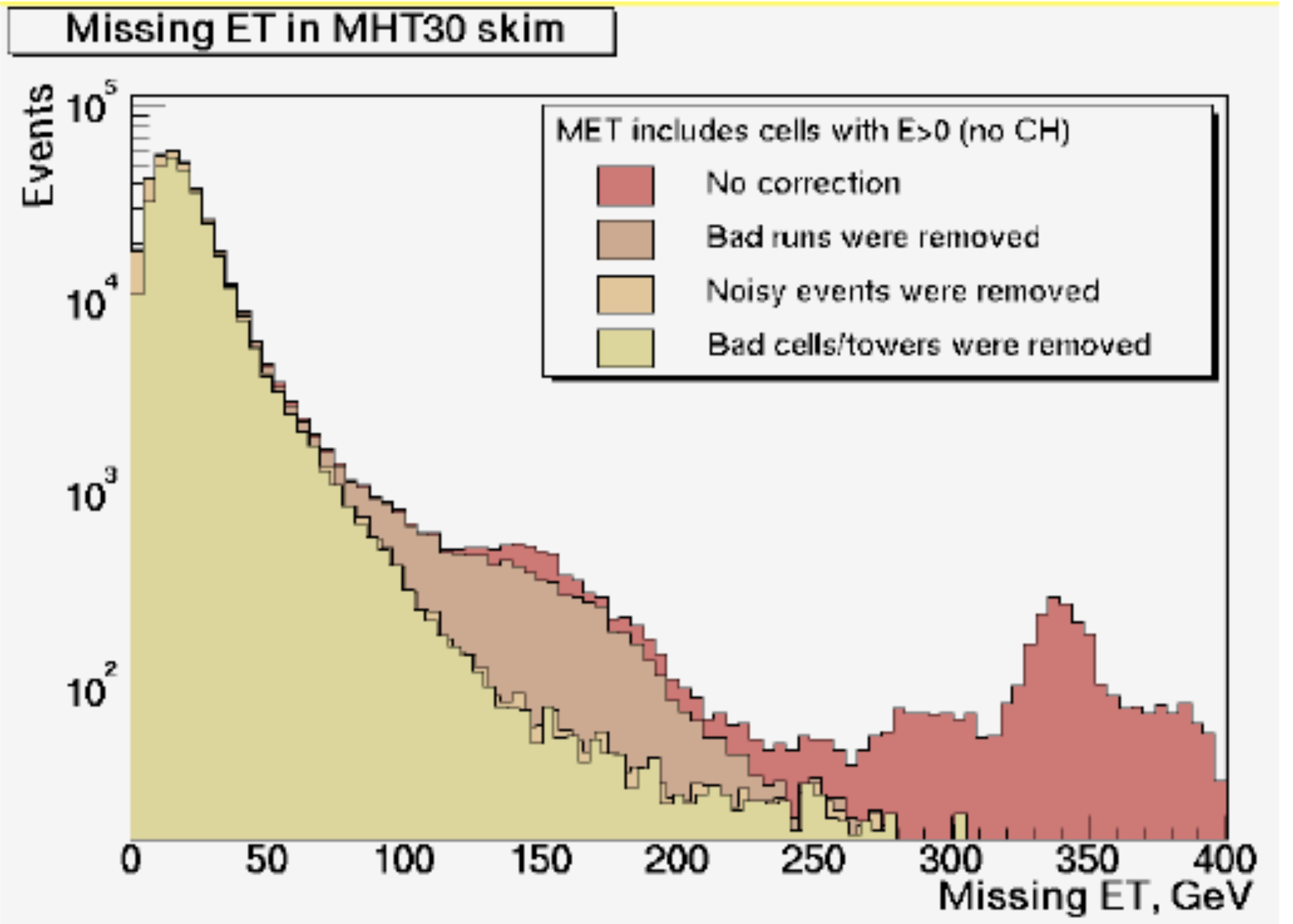



115 GeV of MET…
ATLAS 2015-06-03 10:24:52 UTC source:JiveXML_266904_15236527 run:266904 ev:15236527 lumiBlock:351 Atlantis
Height of tallest tower:
Scale to AOD: 498 GeV
Trigger Decision:
L1:passed L2:failed EF:failed
L1-EtMiss: N/A L1-SumEt: N/A
X (m)
Y (m)
Z (m)
ρ (m)

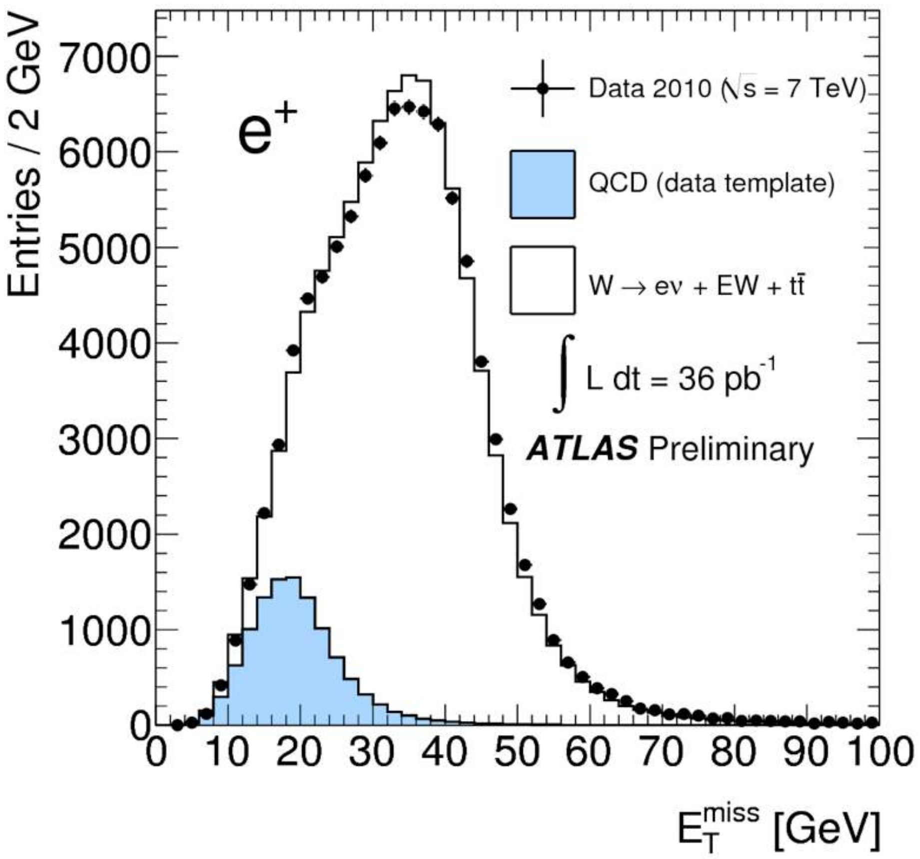

proton - (anti)proton cross sections
Tevatron
LHC
σ_{tot}
σ_b
$\sigma_{jet}(E_T^{jet} > \sqrt{s}/20)$
σ_W
σ_Z
$\sigma_{jet}(E_T^{jet} > 100$ GeV$)$
σ_t
$\sigma_{jet}(E_T^{jet} > \sqrt{s}/4)$
$\sigma_{Higgs}(M_H = 150$ GeV$)$
$\sigma_{Higgs}(M_H = 500$ GeV$)$
σ (nb)
√s (TeV)
events/sec for L = 10^{33} cm^{-2} s^{-1}

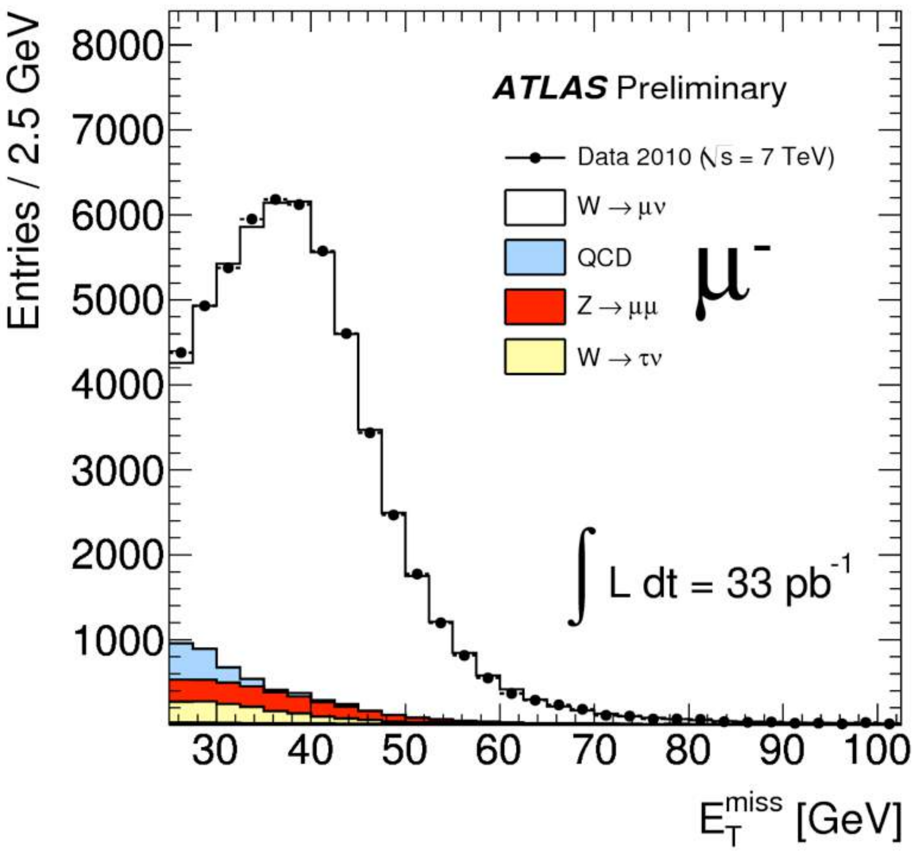
❖ Analyses using MET are particularly sensitive

- 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,…





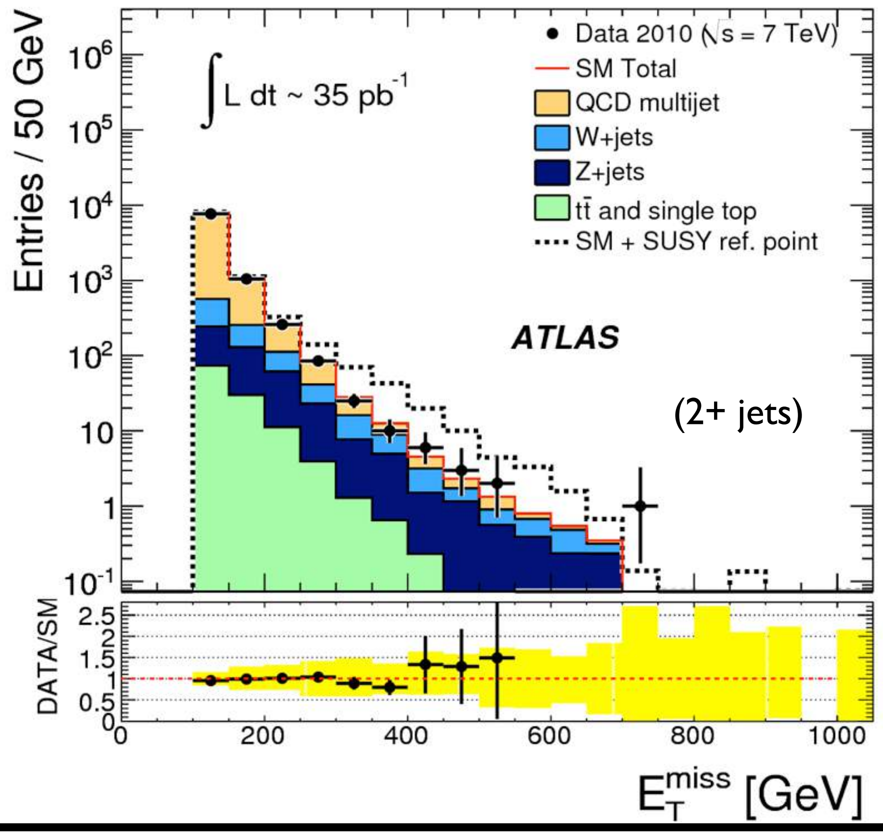
❖ Already ~200k clean W → $\ell\nu$ events in 2010

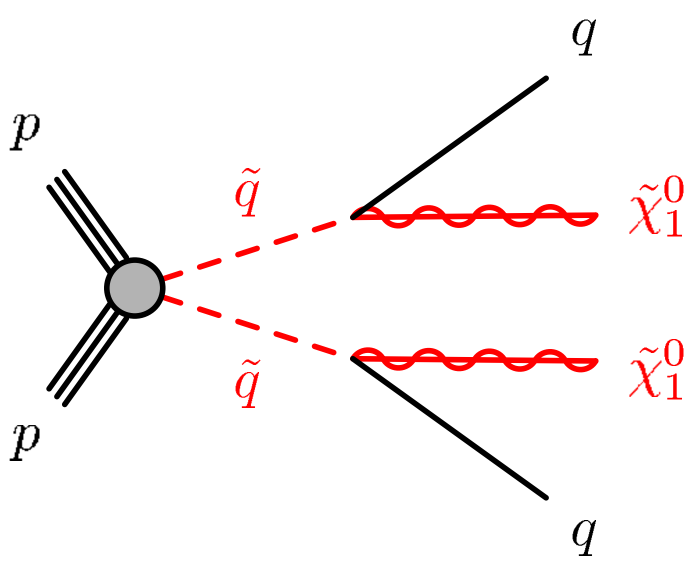
- Billions now

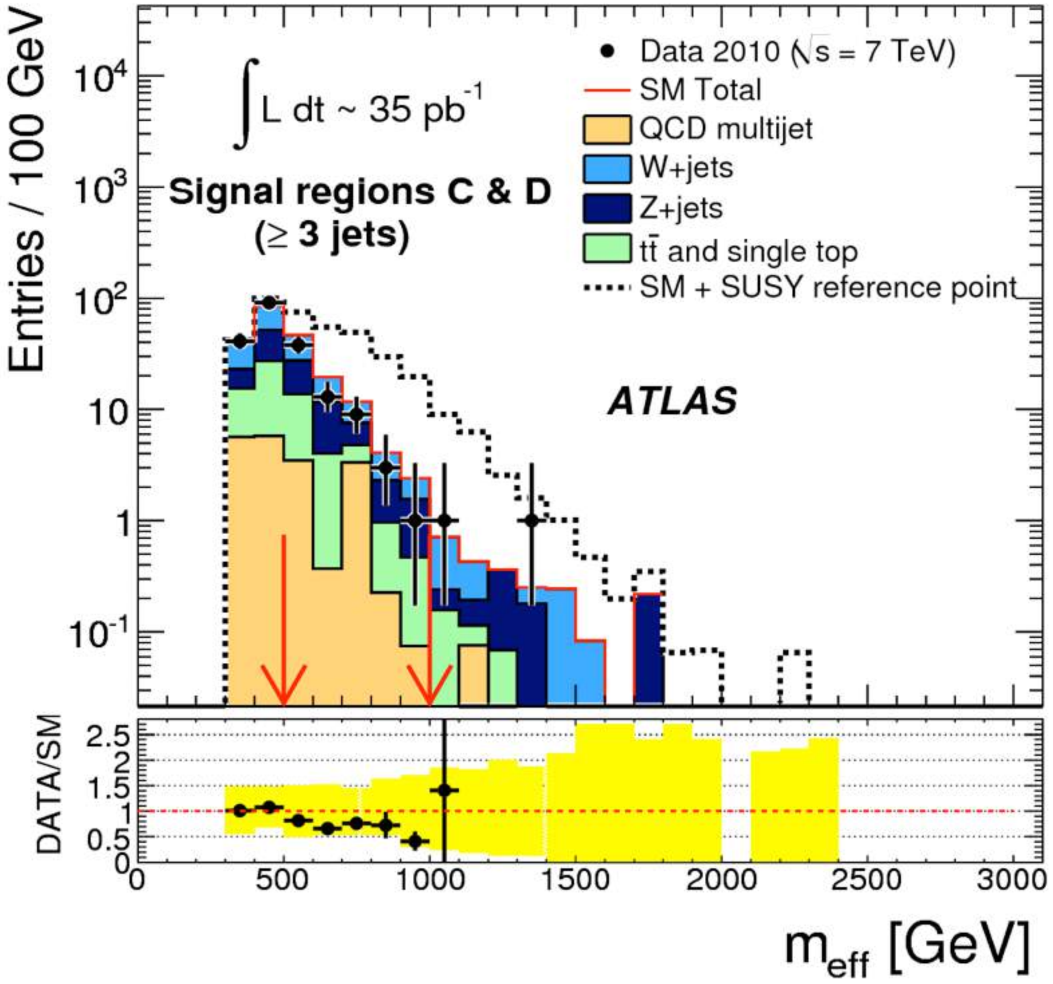
SUSY as a Benchmark

❖ Hadron collider ⇒ produce squarks and gluinos decaying to jets + MET

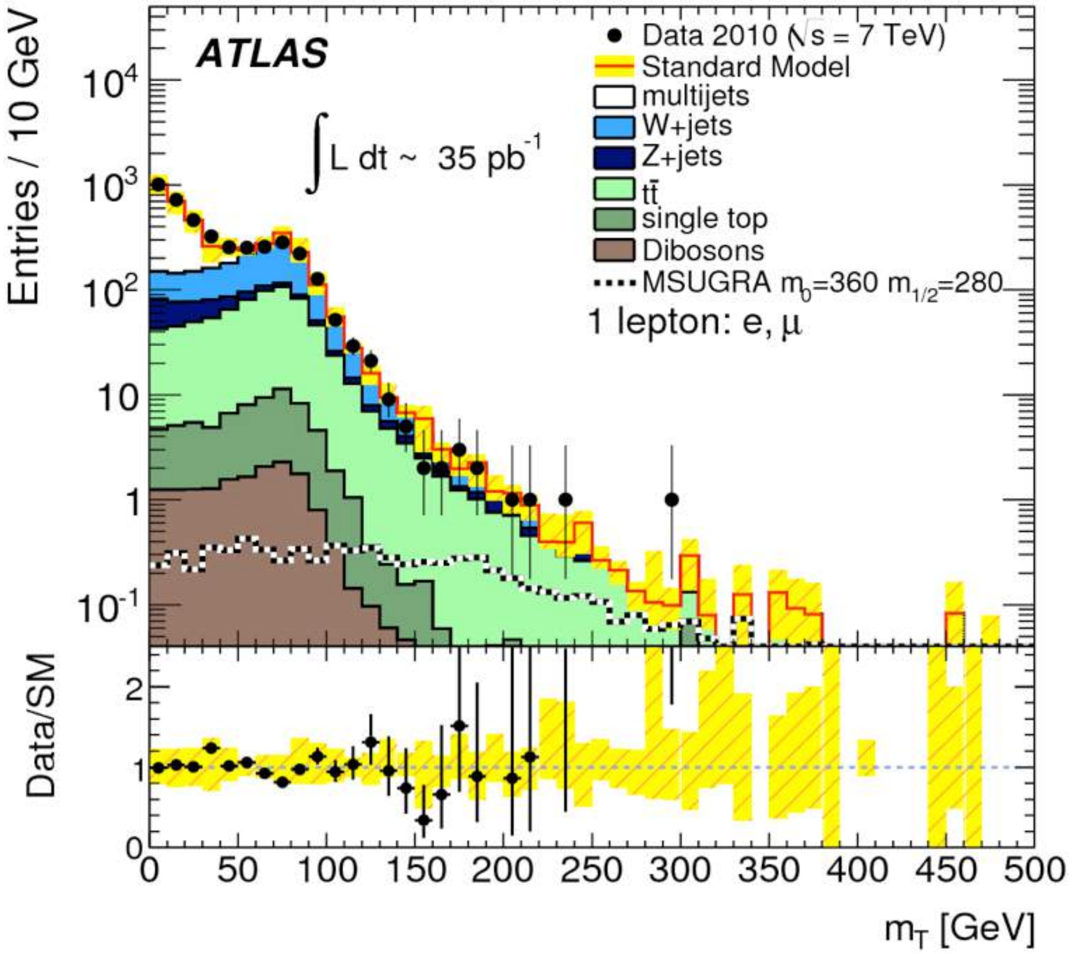
- Optimize jet p_T & MET cuts for different scenarios, since gluinos produce more jets than squarks
    - Use M_{eff} to discriminate, measure of event Q^2

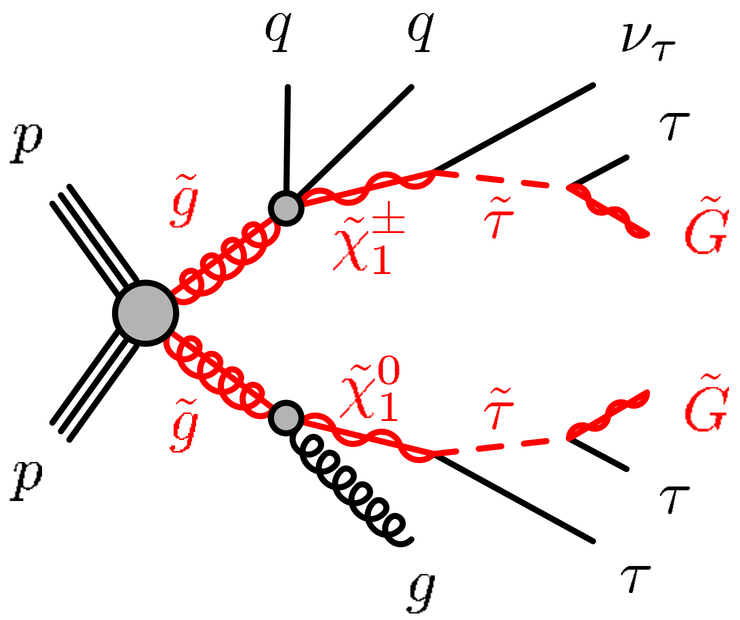


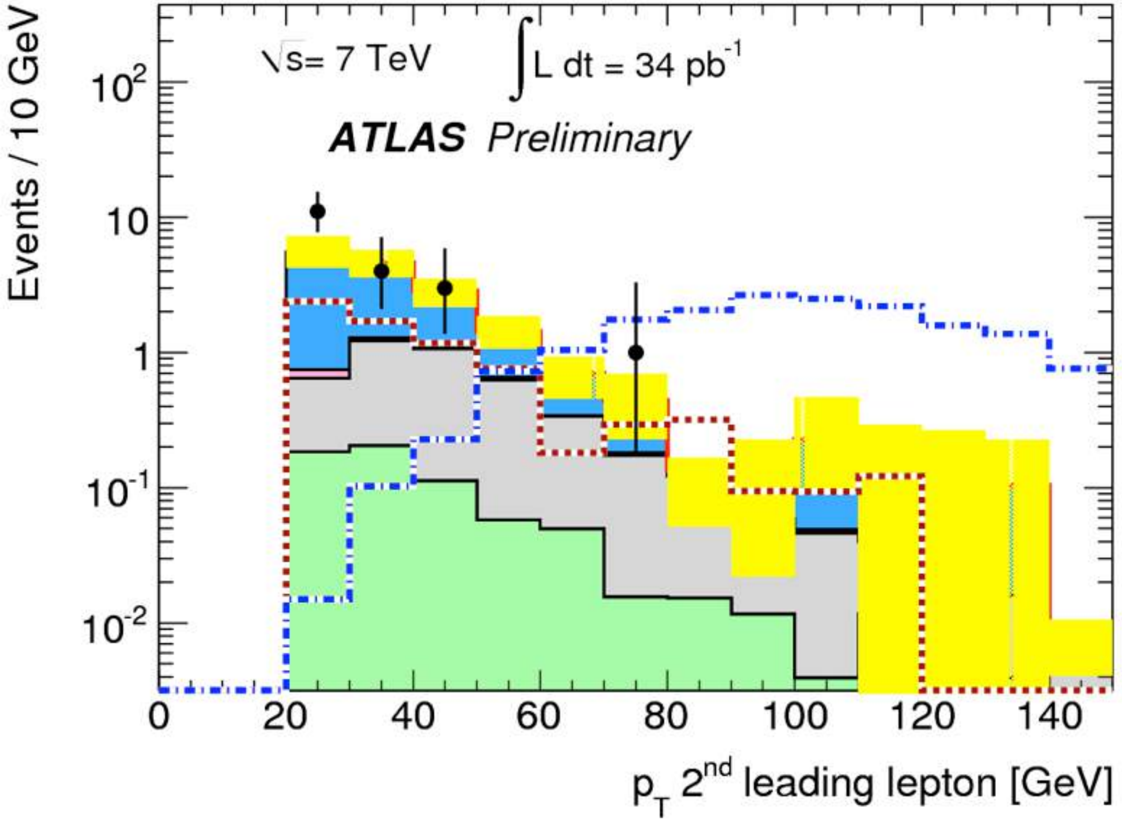




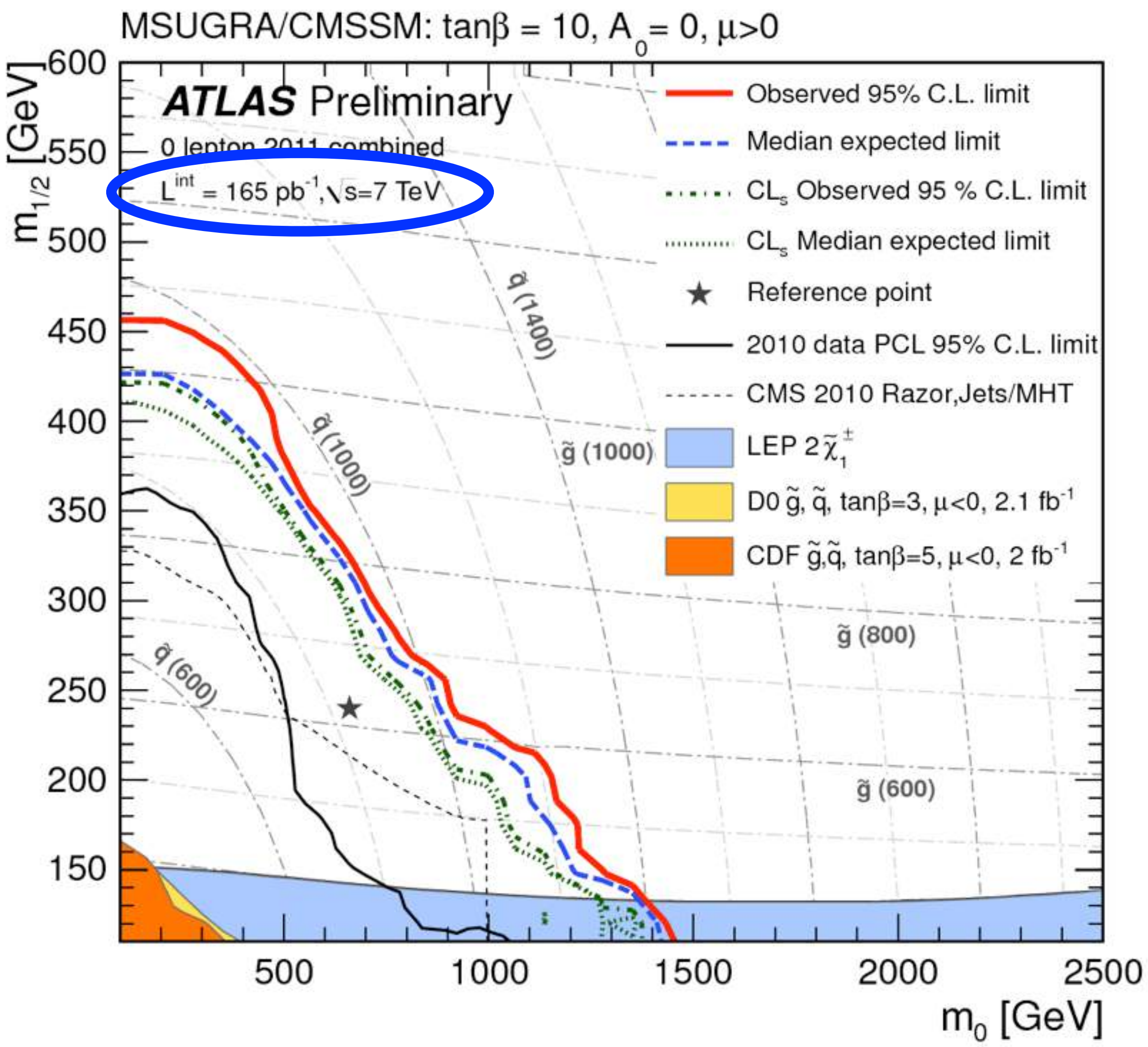
❖ Leptons in decay chains....







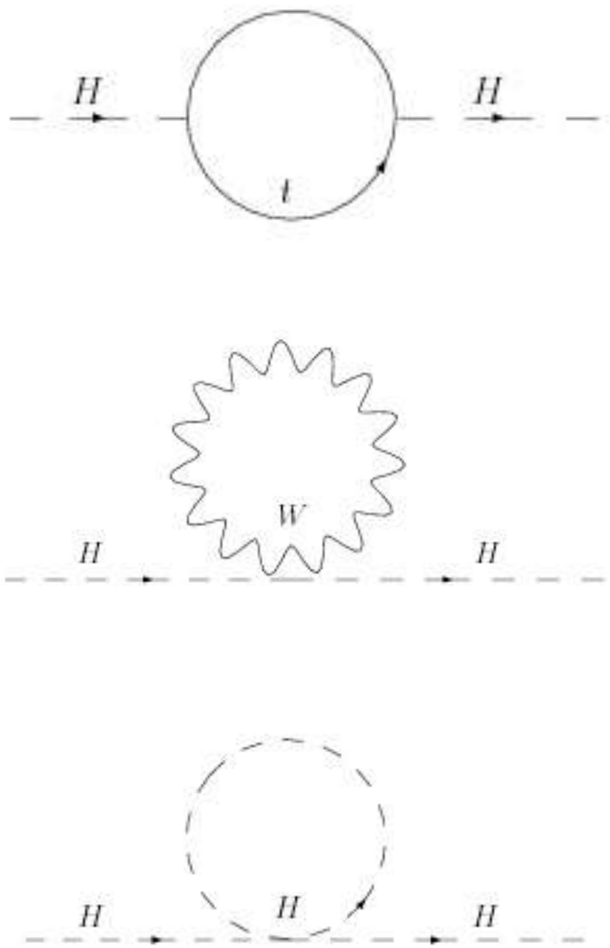
All Praise COM Energy!



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

But…

We’ve Found a Higgs!



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

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

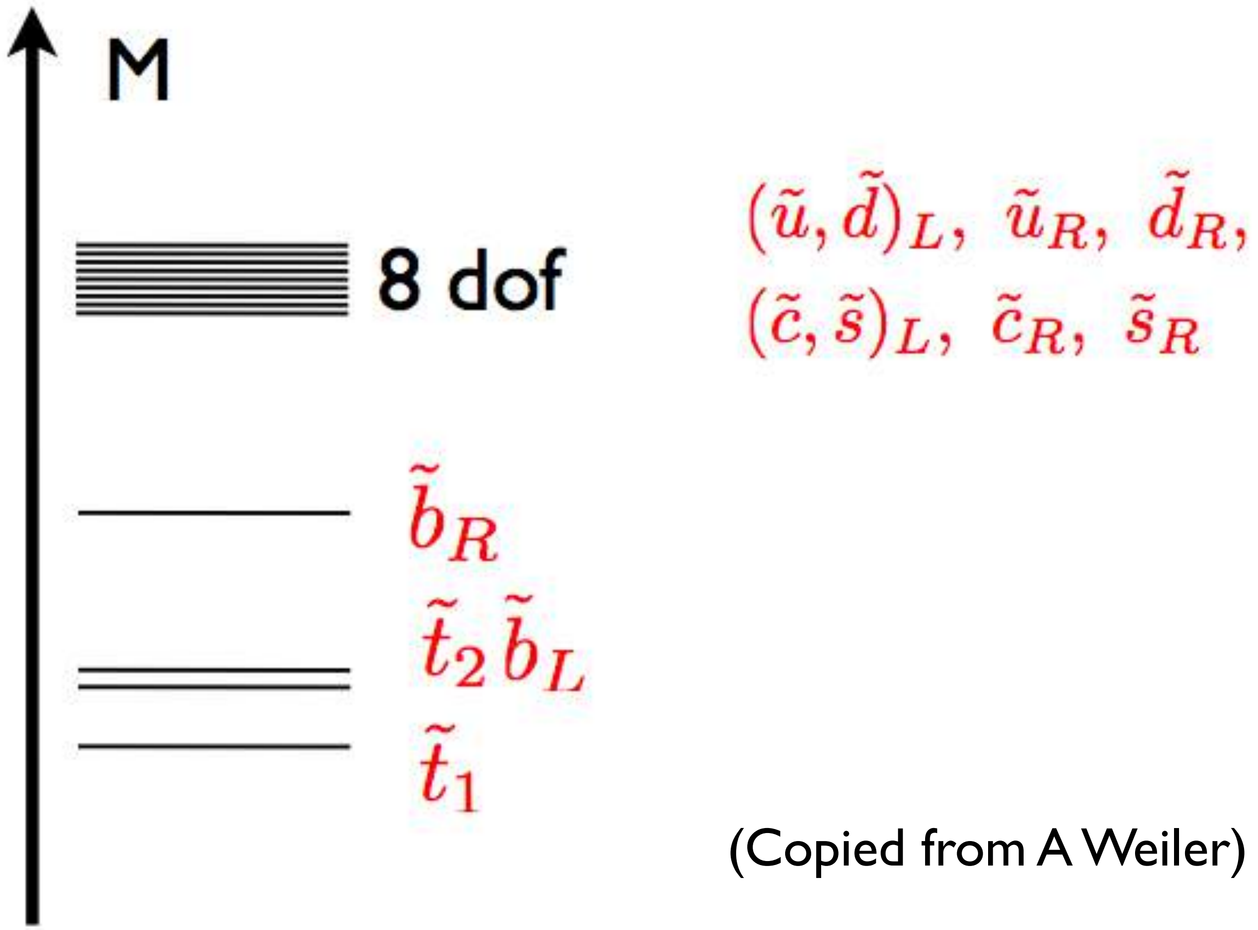
$$\frac{1}{16\pi^2} \lambda E^2$$

- ❖ 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**

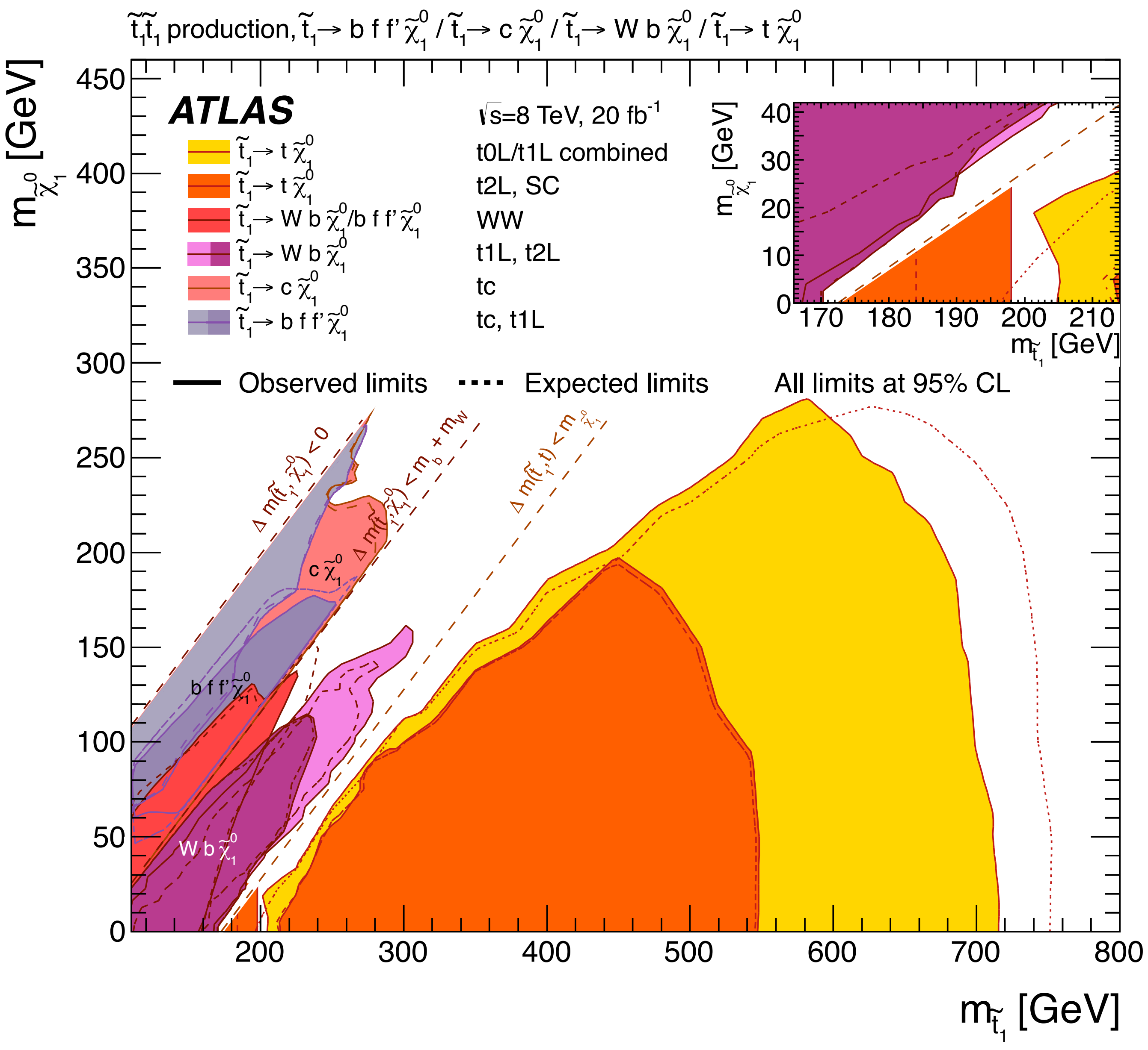
SUSY and the Higgs

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

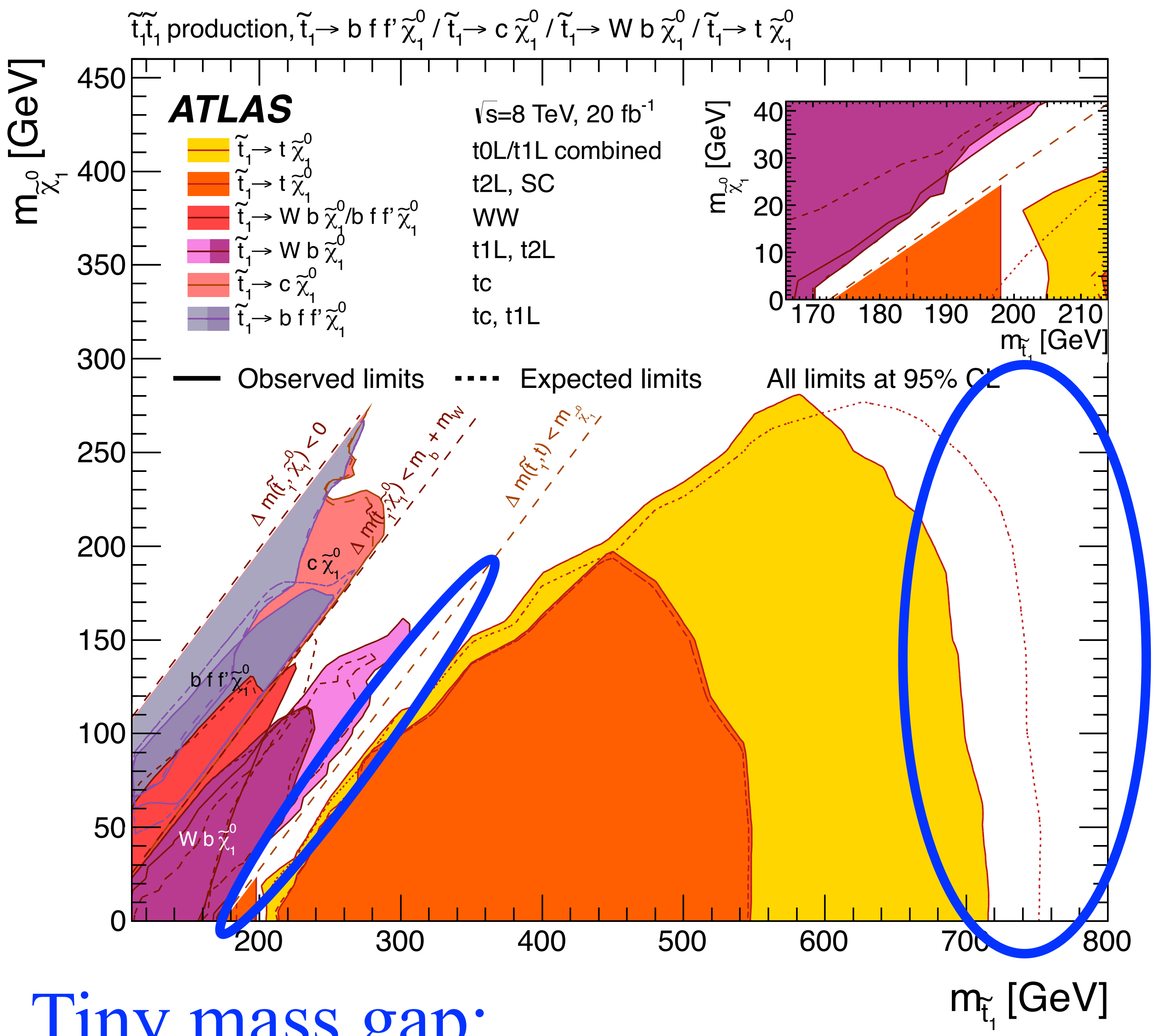


(Copied from A Weiler)

Stop Searching Anatomy



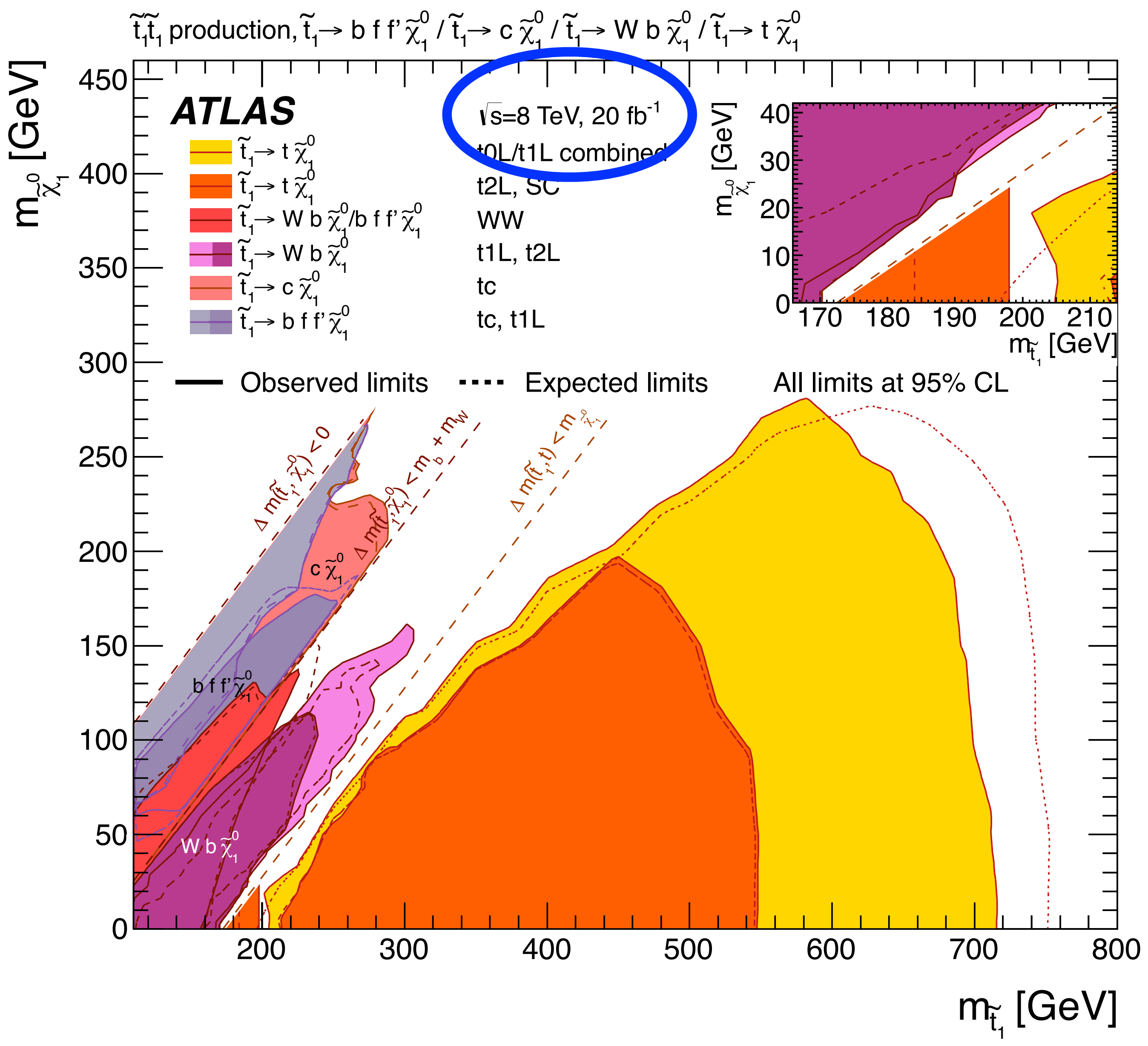
Stop Searching Anatomy

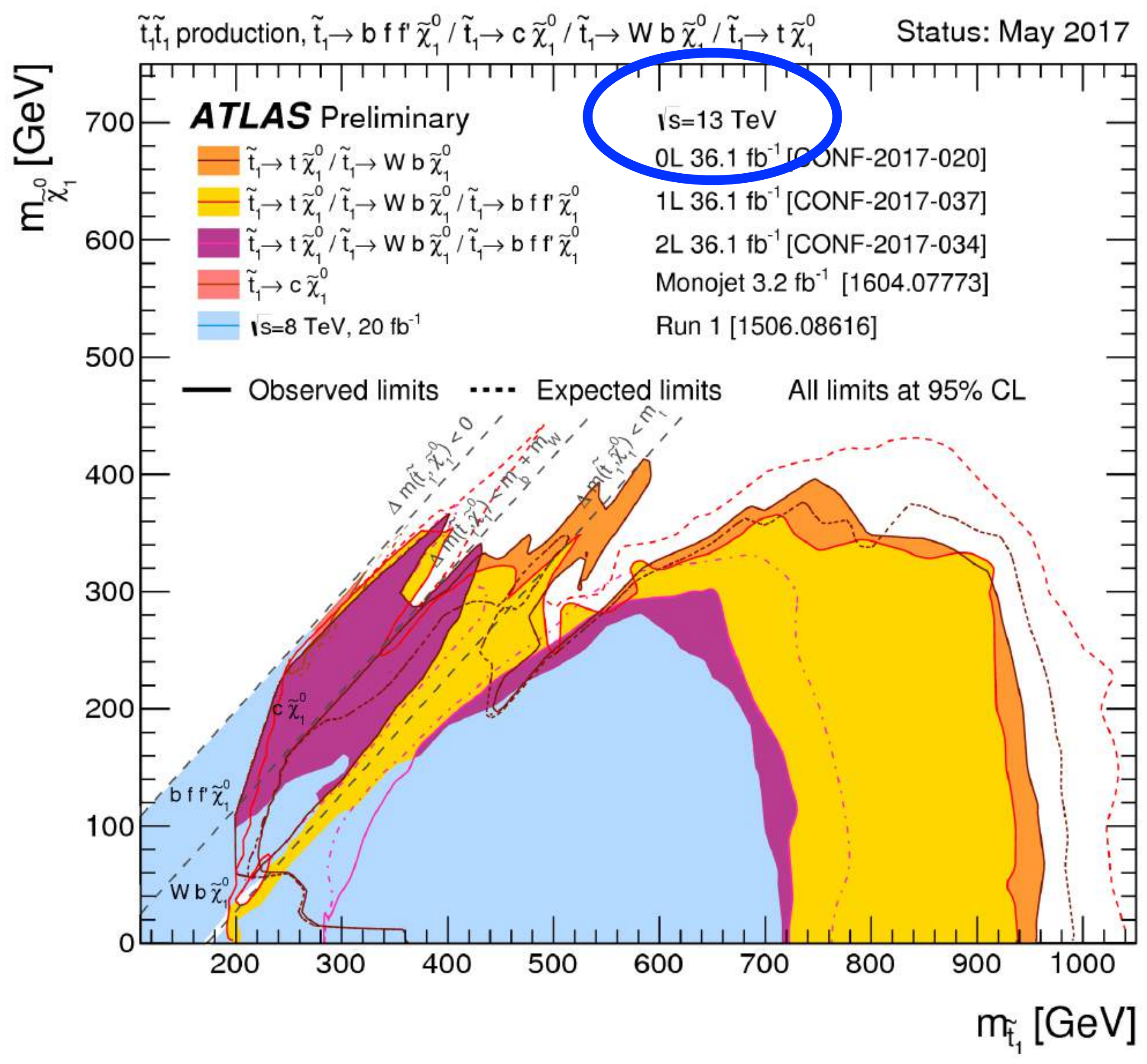


High mass: run out of cross-section

Tiny mass gap: soft decay products

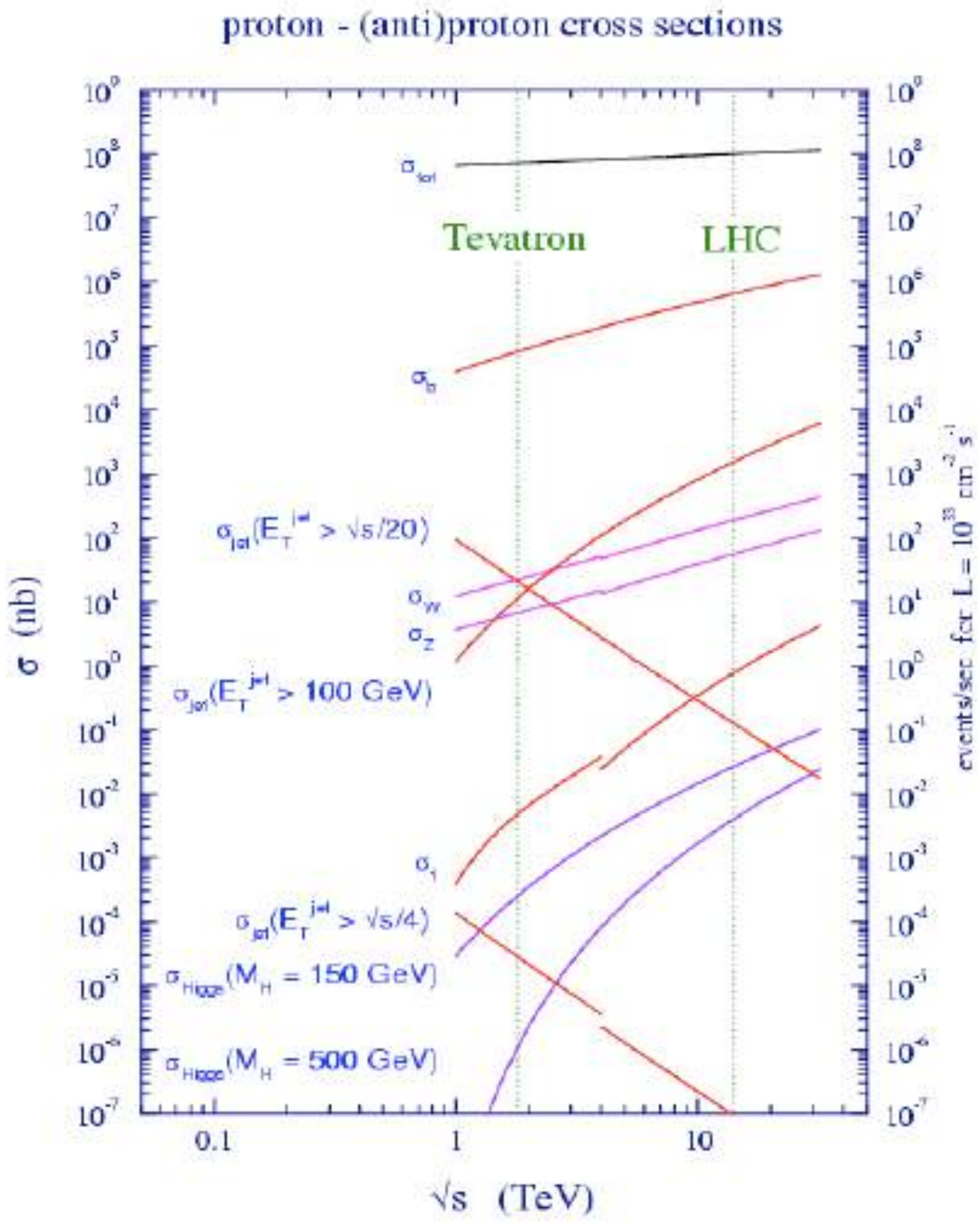
Stop Searching Anatomy



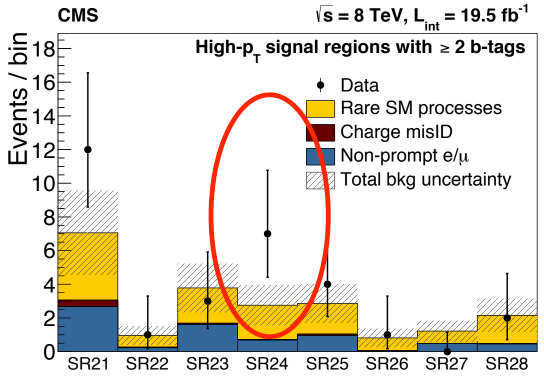


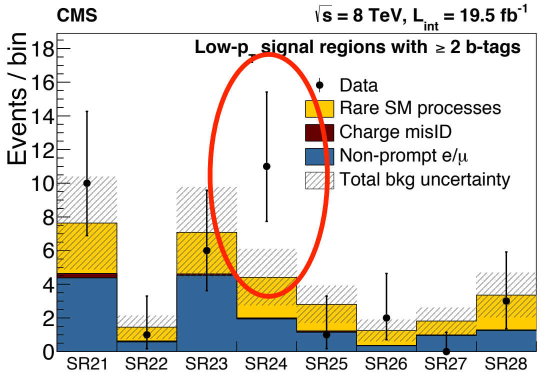
Same-Sign Leptons

- 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

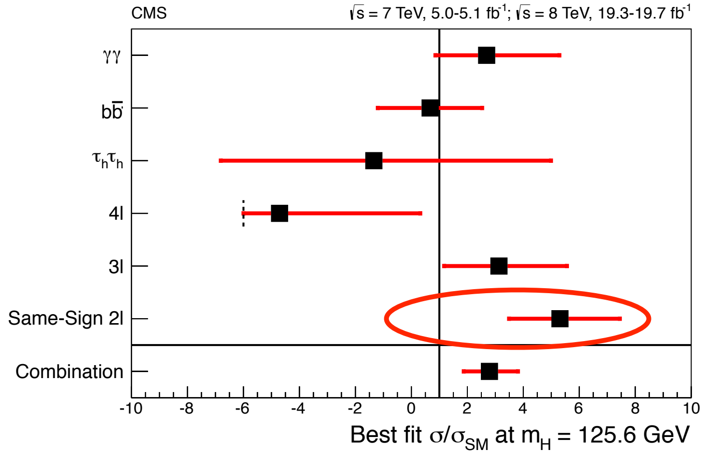




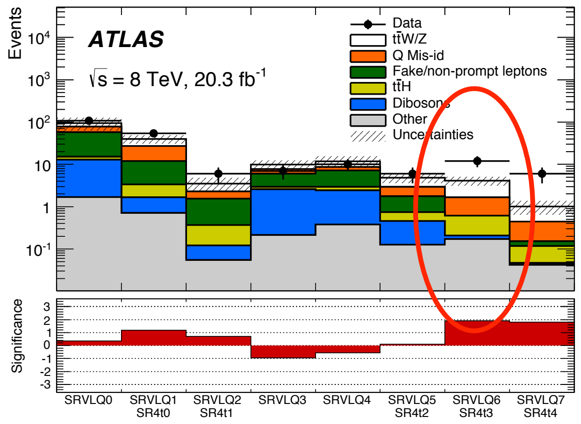
CMS (SUSY), http://arxiv.org/abs/1311.6736 (24 signal regions in paper)

SR1b $_{1bin}$	Total	ee	$e\mu$	$\mu\mu$
Observed events	10	6	4	0
Total expected background events	4.7 ± 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

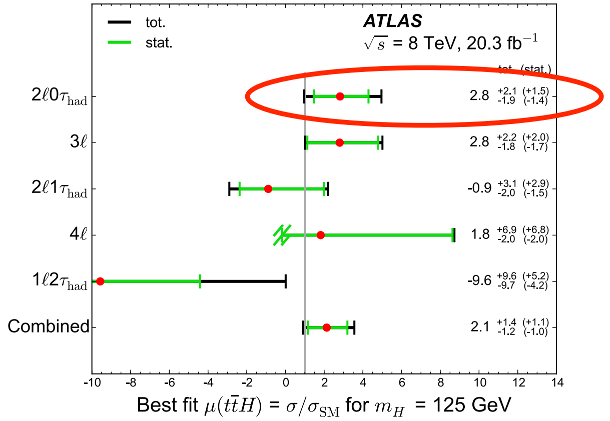
ATLAS (SUSY), http://arxiv.org/abs/1404.2500 (5 signal regions in paper)



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



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



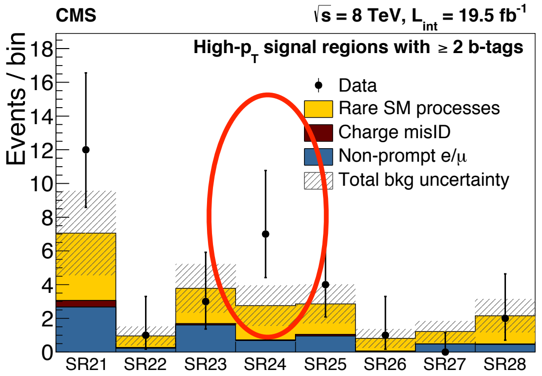
ATLAS (ttH), http://arxiv.org/abs/1506.05988

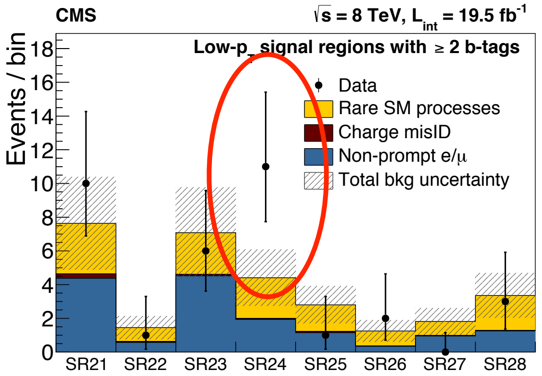
It certainly looks like multiple analyses looking at same sign leptons and b-jets see excesses!

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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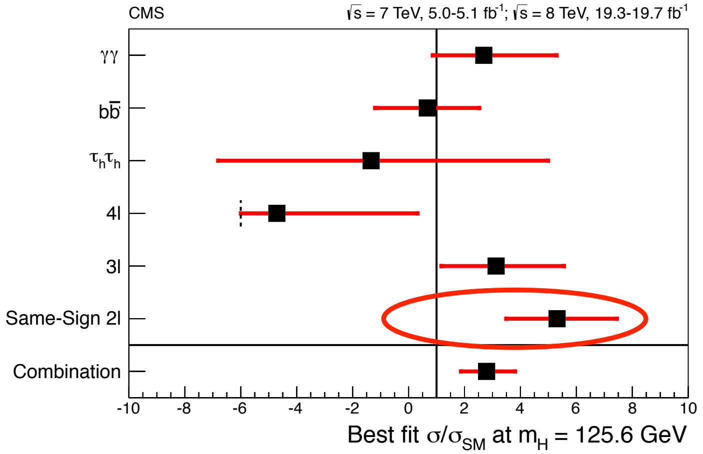

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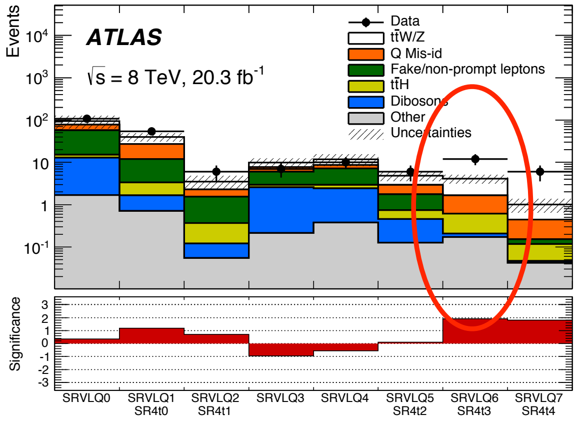
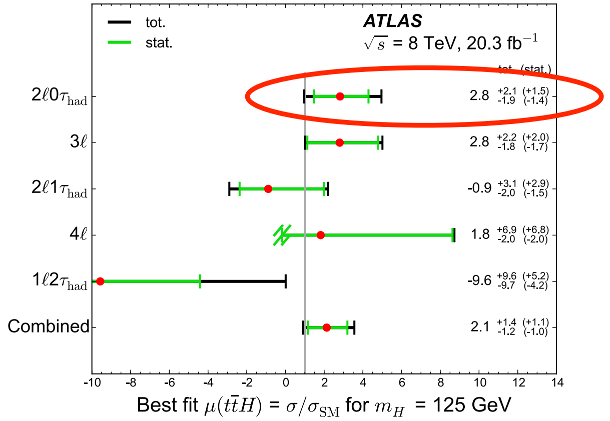


ATLAS (TT), http://arxiv.org/abs/1504.04605

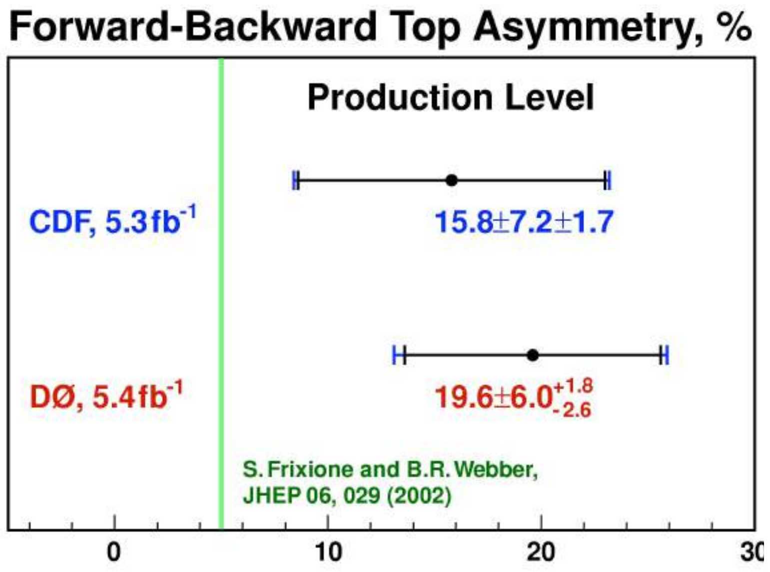


ATLAS (ttH), http://arxiv.org/abs/1506.05988

The ATLAS analyses are correlated, and same for CMS
So, ~2 analyses and excesses are < 3 σ…
Worth keeping an eye on? Sure.

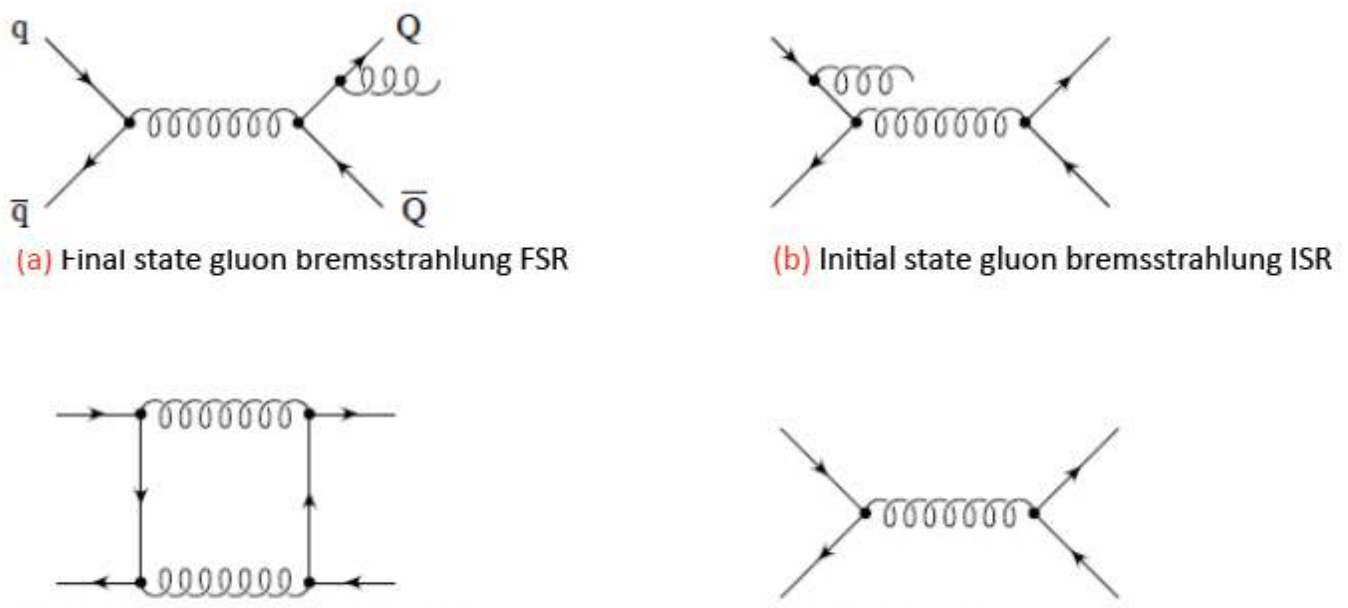
Anecdotes From the Field (II)

- 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!

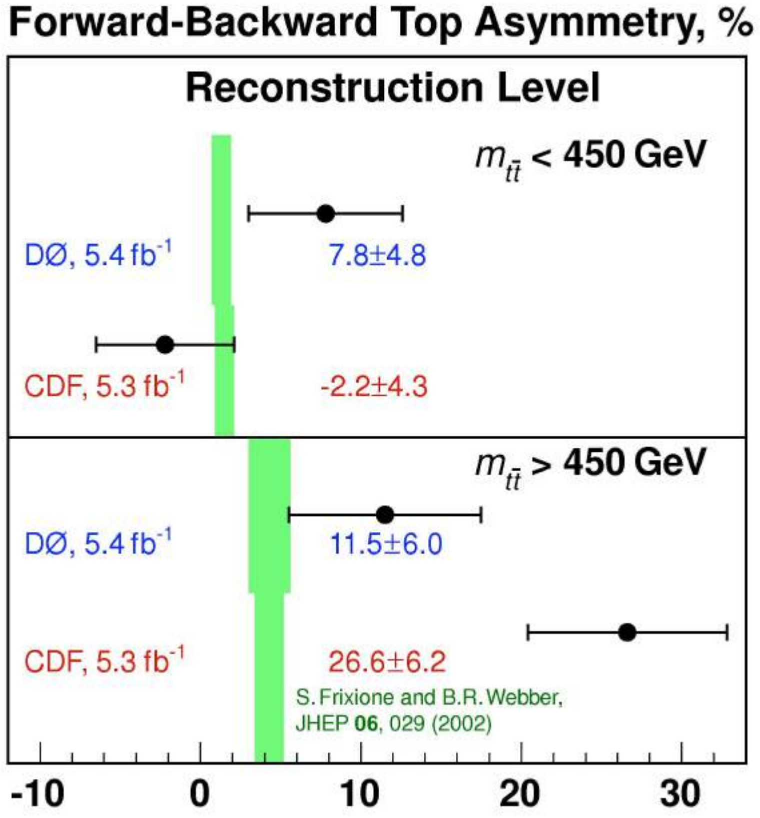


(a) Final state gluon bremsstrahlung FSR

(b) Initial state gluon bremsstrahlung ISR

(c) double virtual gluon exchange

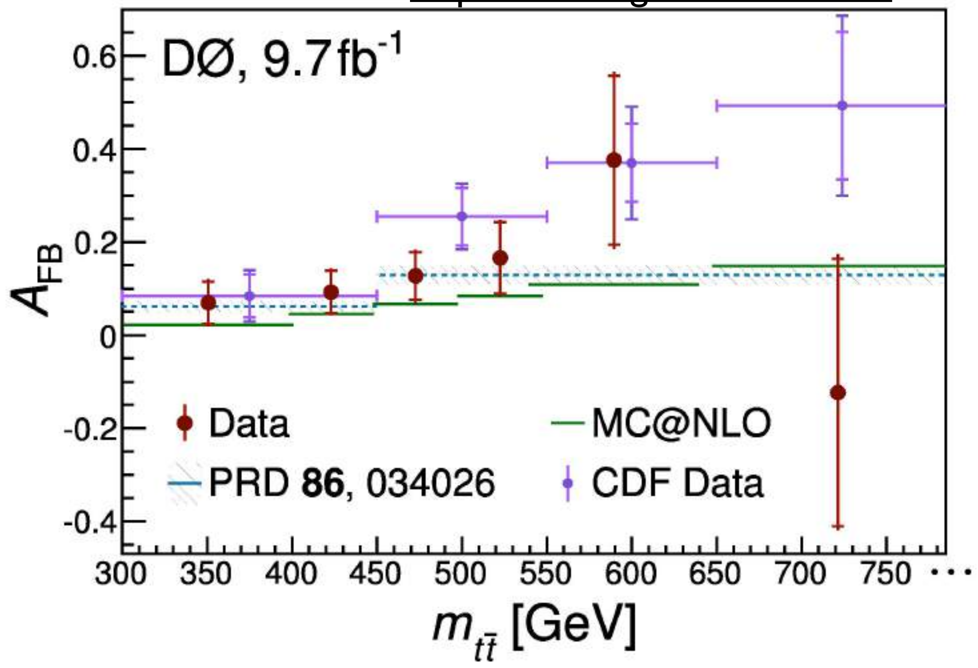
(d) Born diagram



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

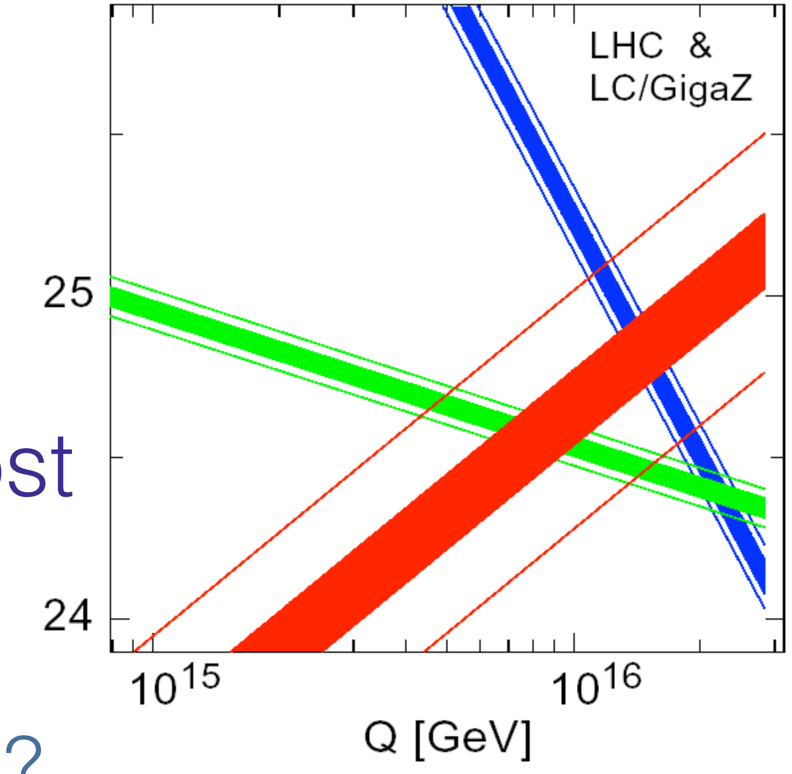


no BSM physics here:
-real life is not LO or NLO but NNN…LO
-many scales at work and this measurement crucially depends on multiple very different scales

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



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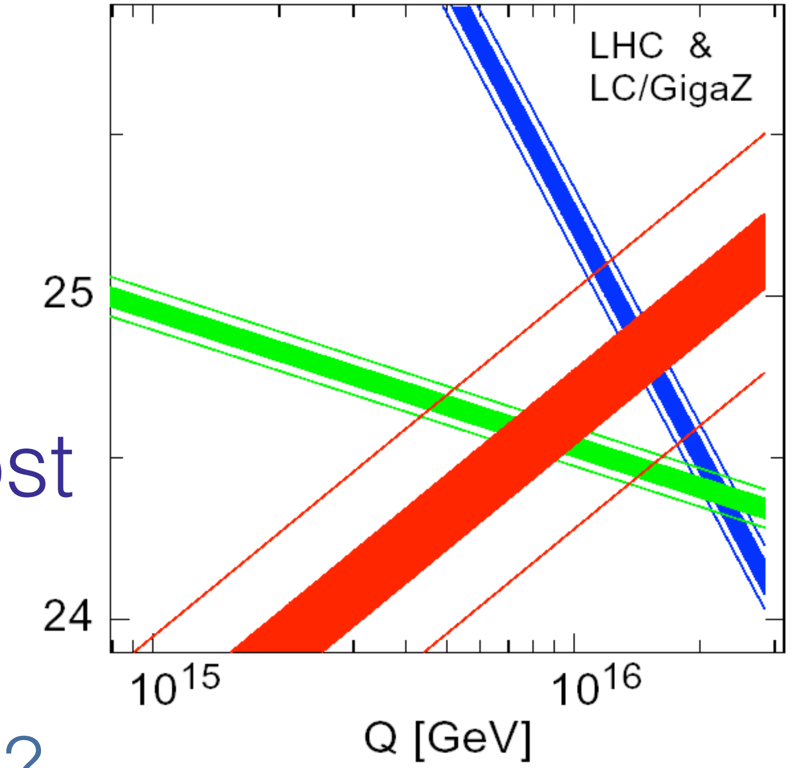
Dinosaurs on Venus?

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



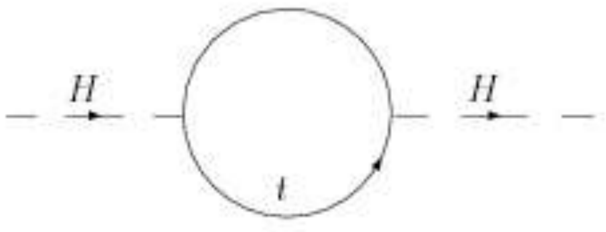
“We had a solution to the hierarchy problem, and it failed”

(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:

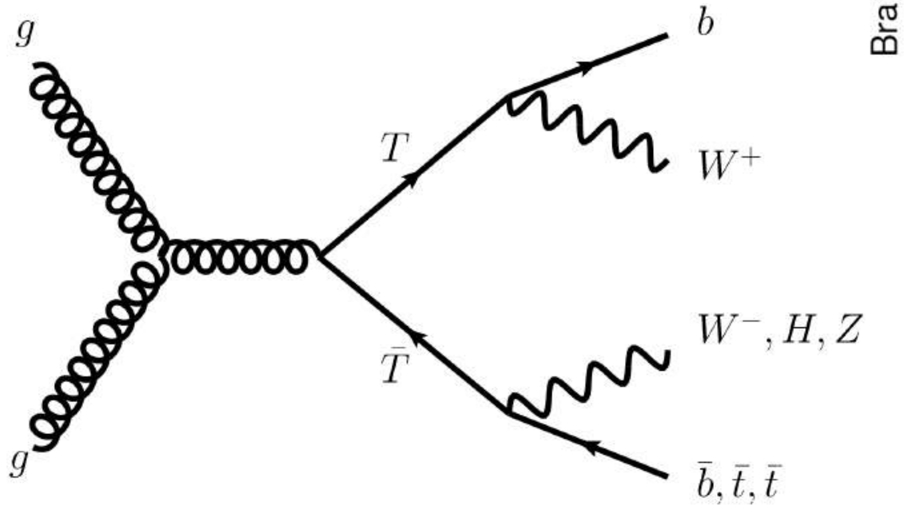


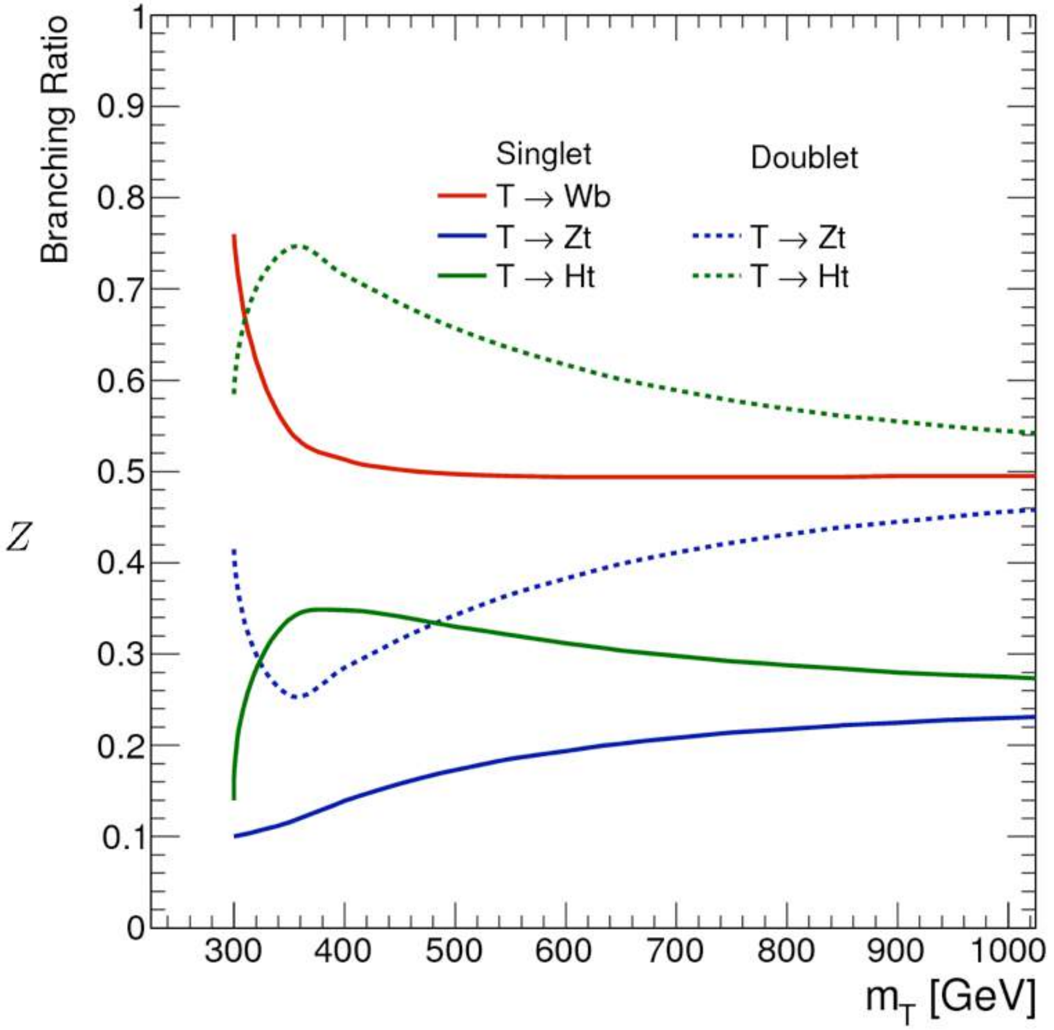
$$\rightarrow \frac{3}{16\pi^2} y_t^2 E^2$$

➡ Top partner!

Singlets, Doublets, ...

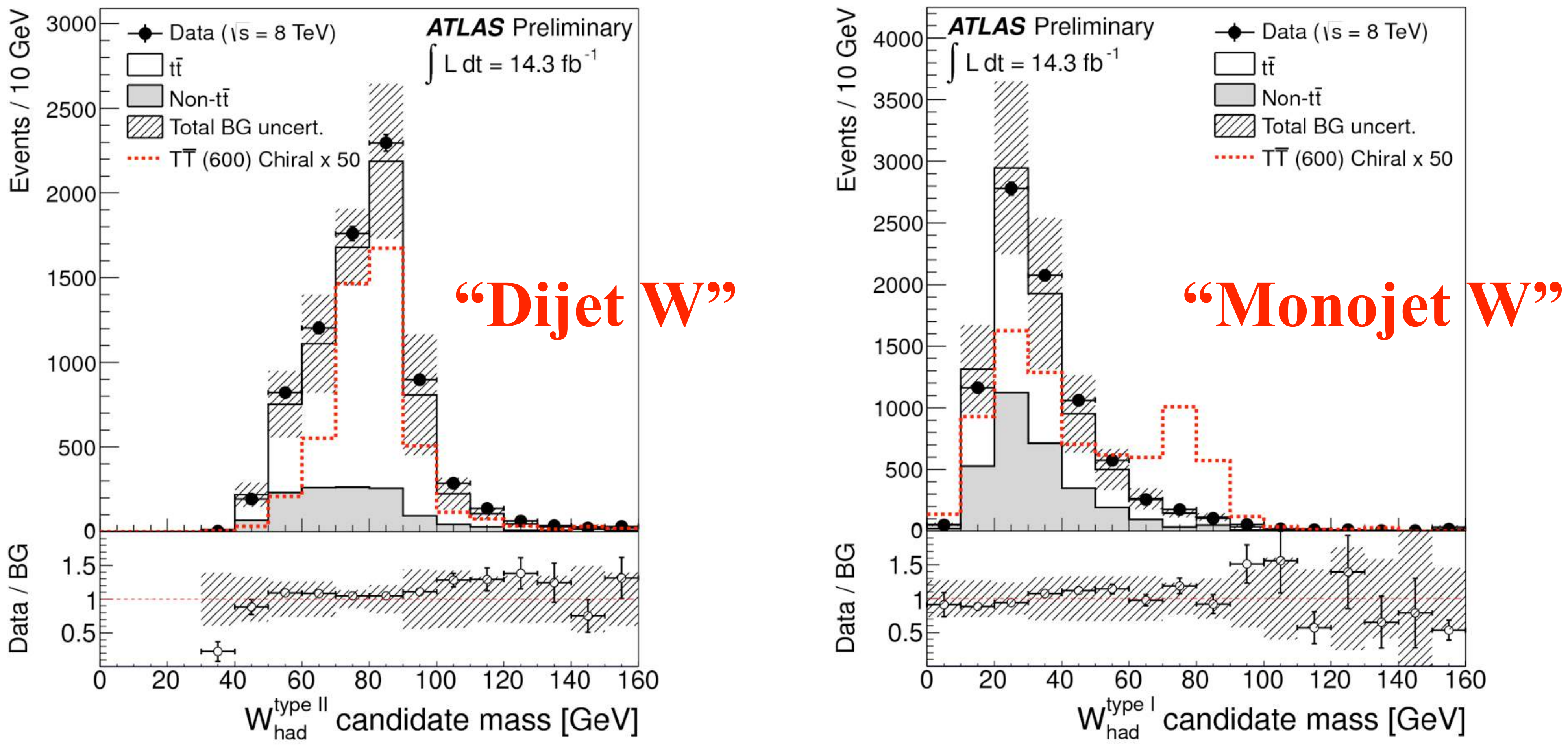
- Vector-like top partners (still fermions) less constrained by flavor....
  - Opens up decay modes
  - Top partner partners:
    - $T^{5/3}$
    - ...
- Rich set of signatures
  - Just no huge MET
  - At least not systematically





W's Can Be Light

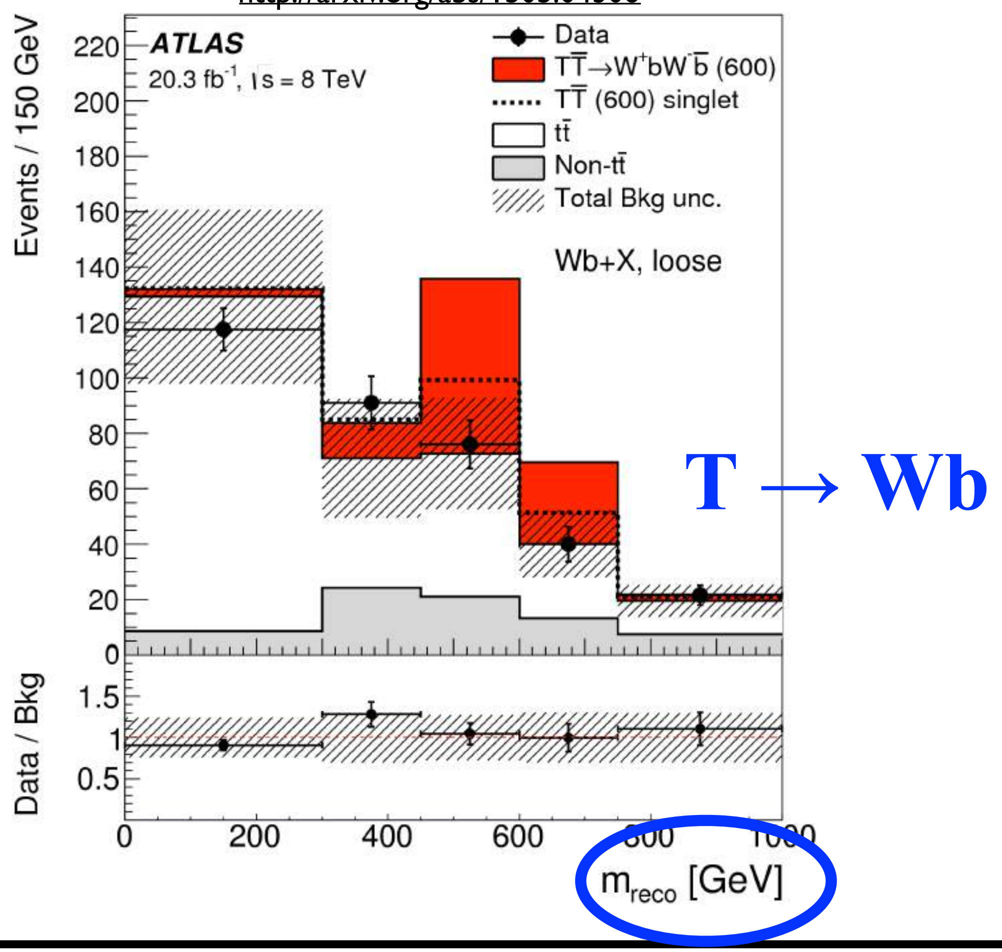
- ❖ T→Wb with m_T ~600 GeV
  - ➡ W will be boosted, and if decays hadronically → single jet



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



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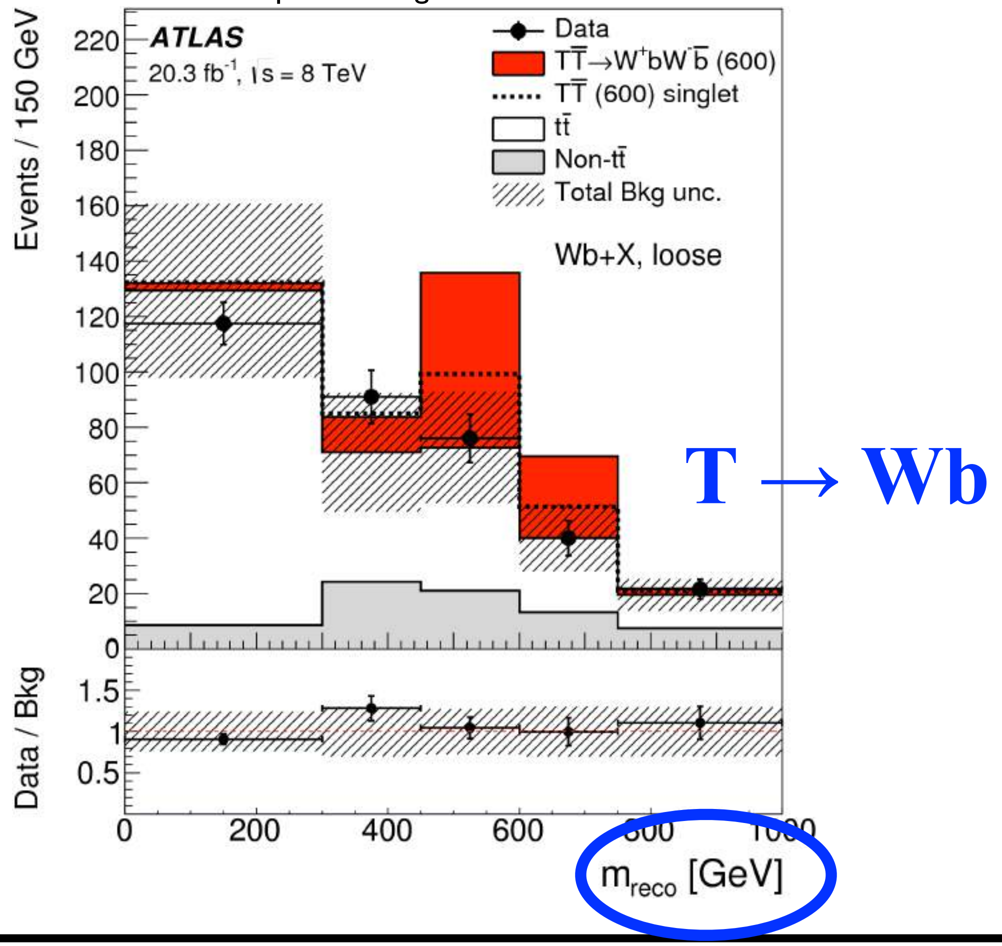

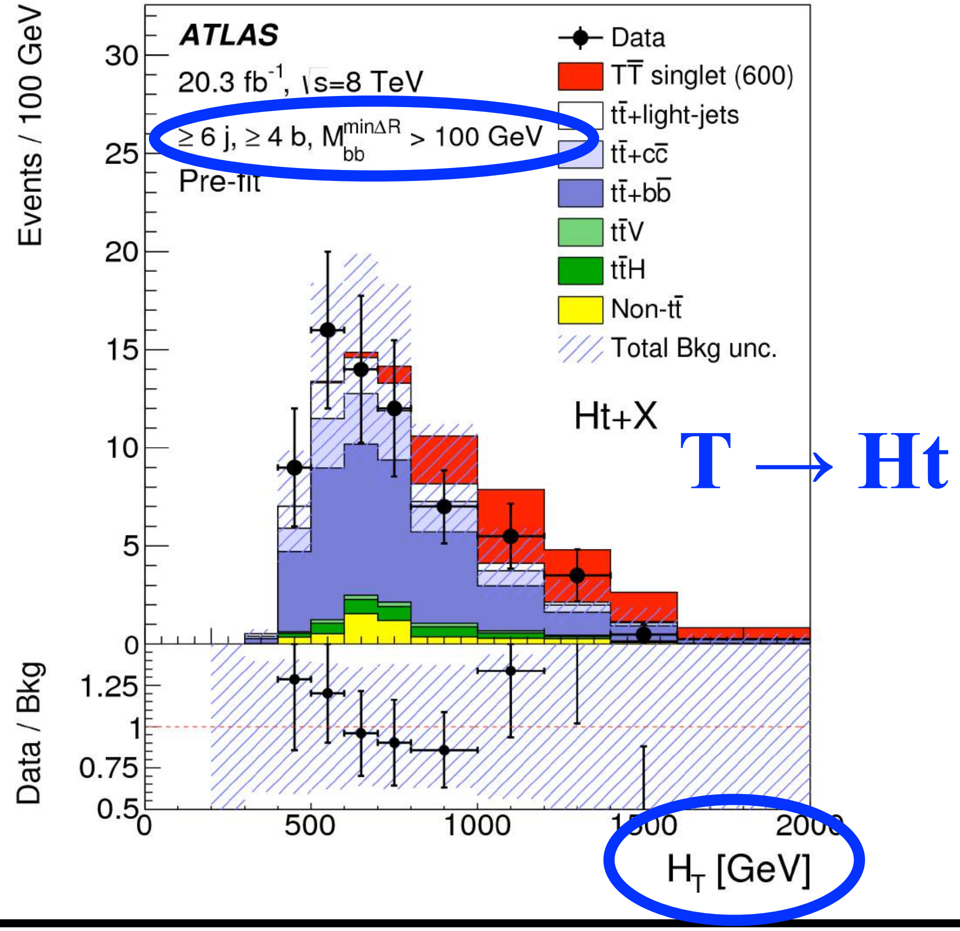

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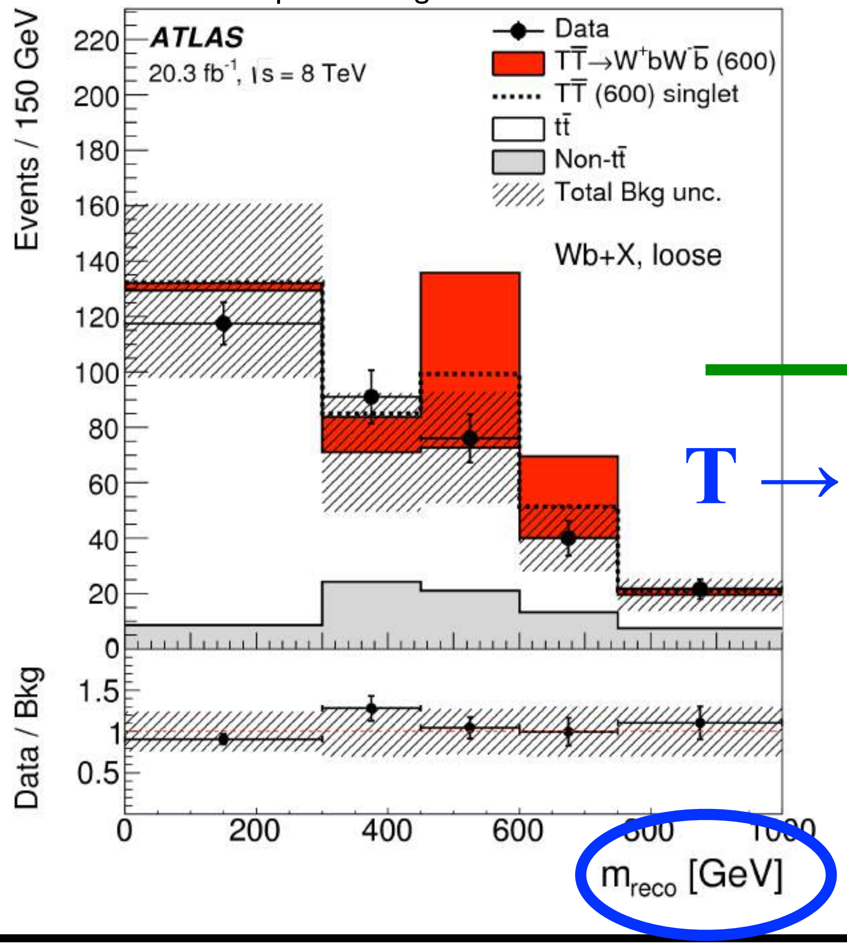
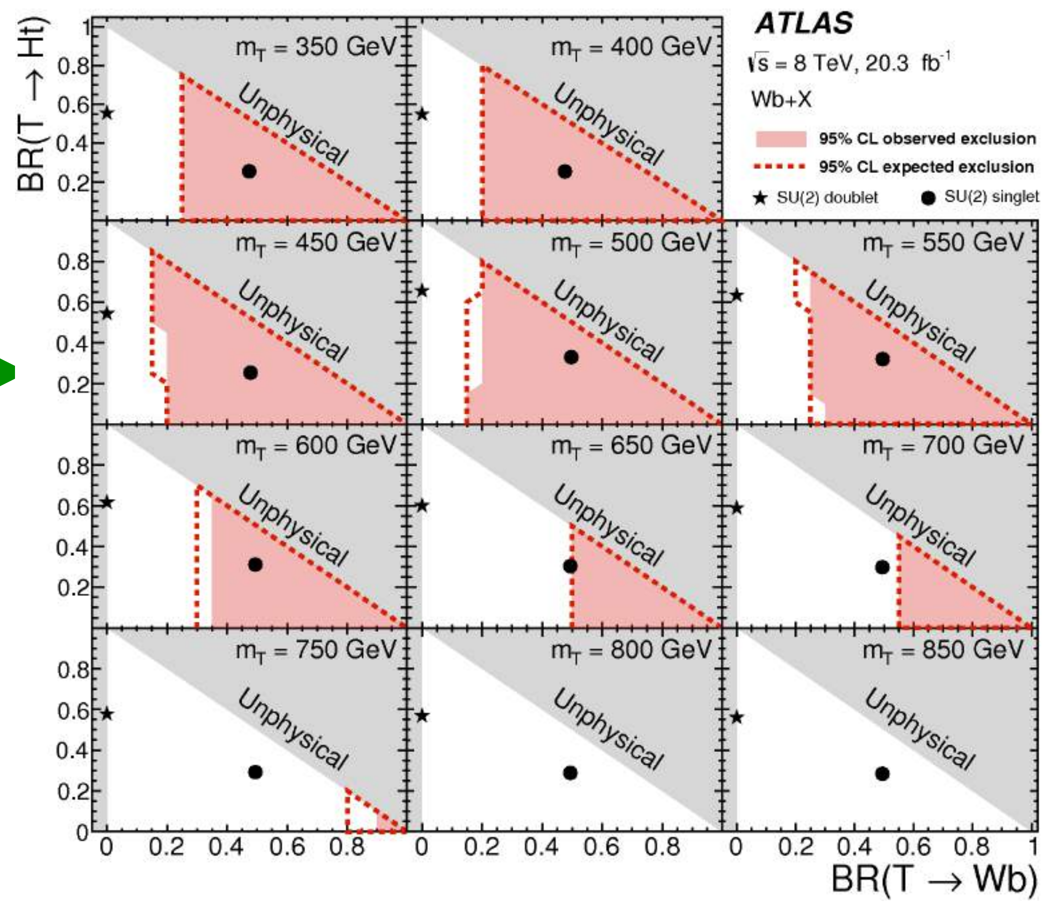


T → Wb



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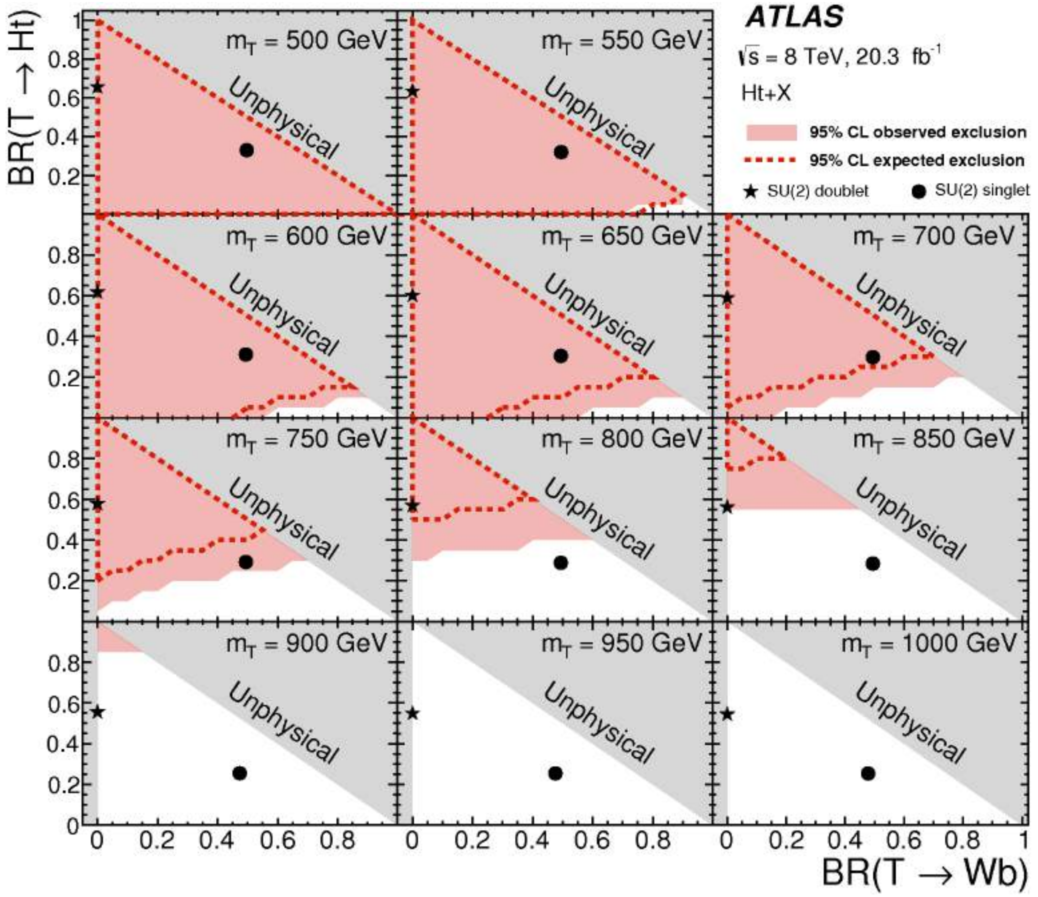

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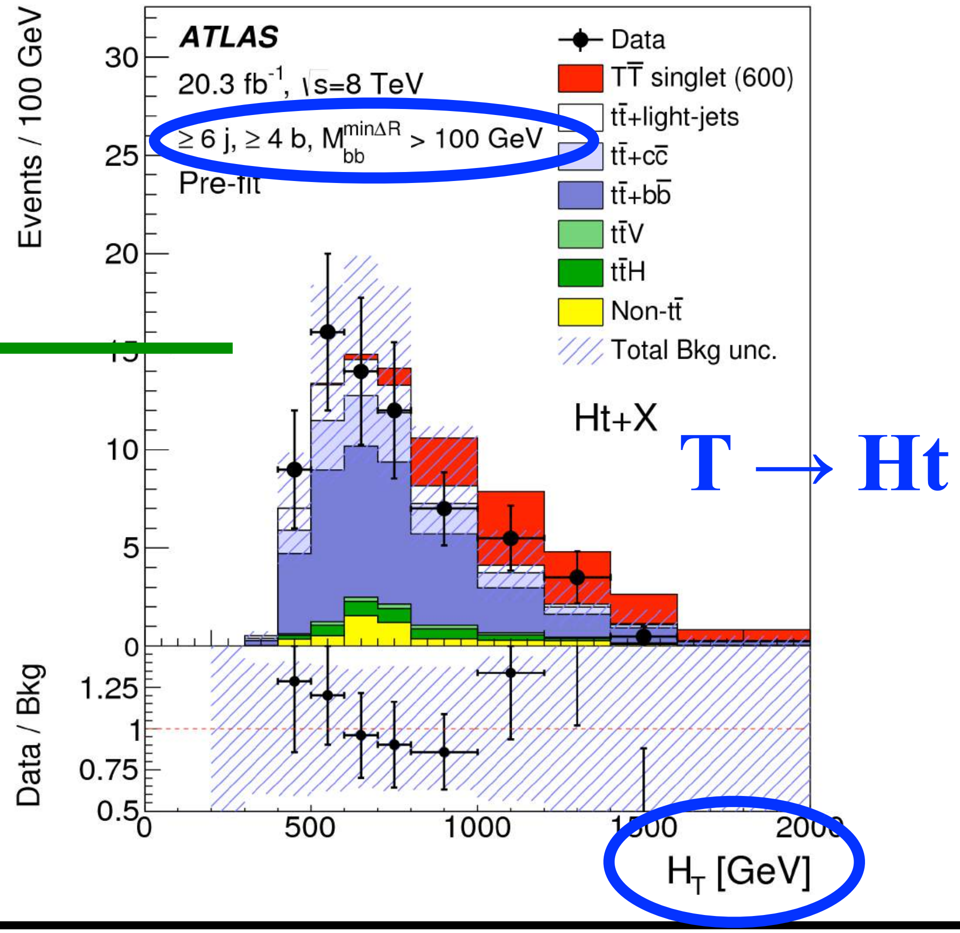
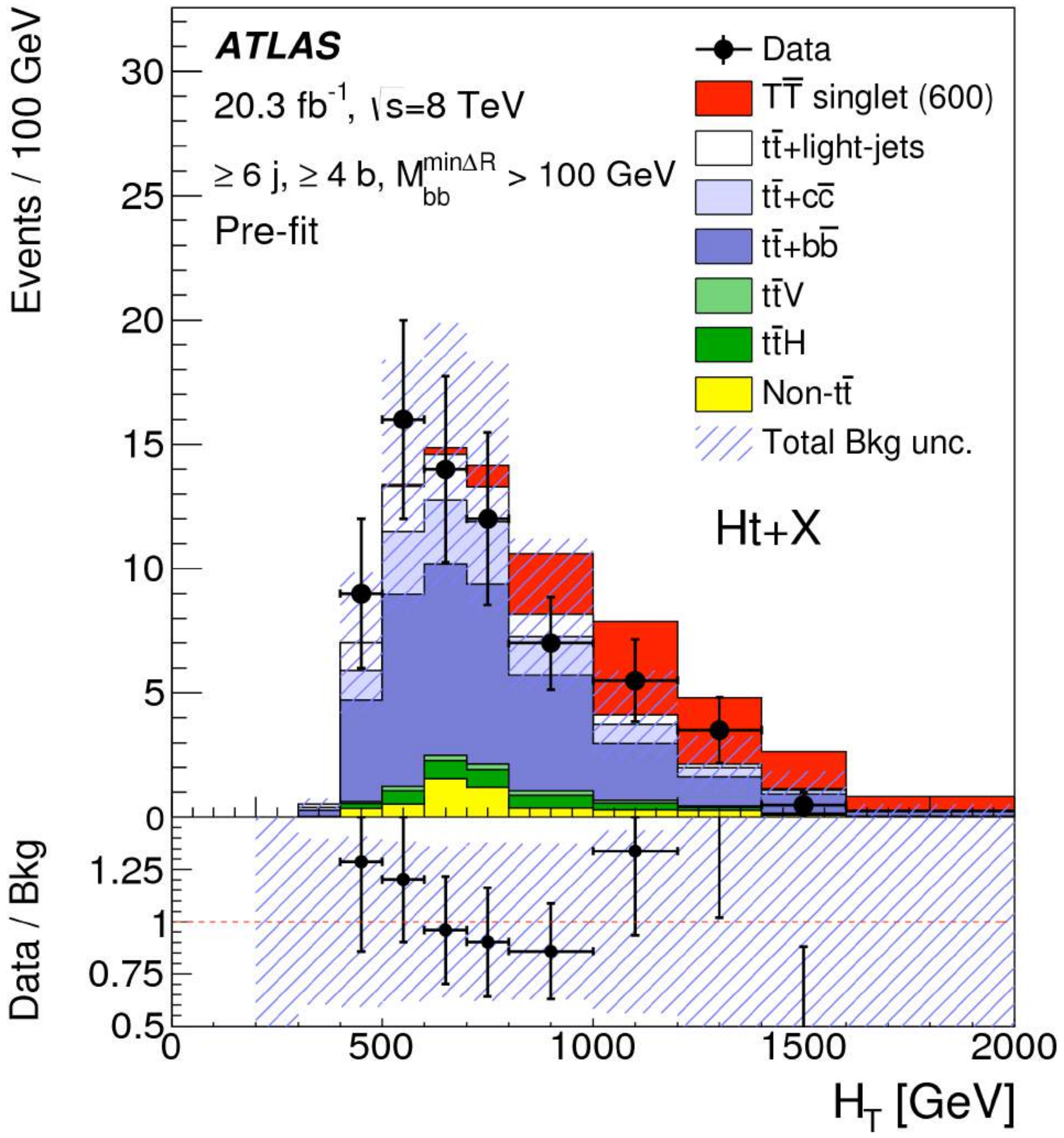


Systematic Uncertainties

- 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_{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



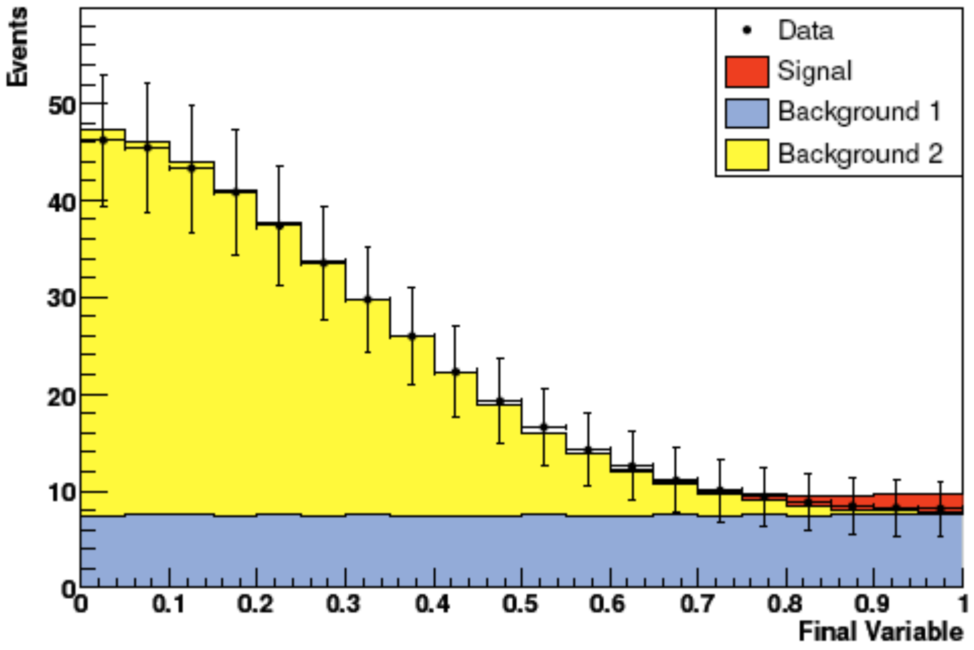
- ❖ H_T is the sum of scalar energies of jets, leptons,…
  - If the jet energy scale is different between data and MC, comparison is wrong
  - If the jet energy scale dependence on jet energy is wrong, distort shape
  - etc.
- ❖ But how do I determine the jet energy scale uncertainty?
  - testbeams (single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

Systematics Profiling

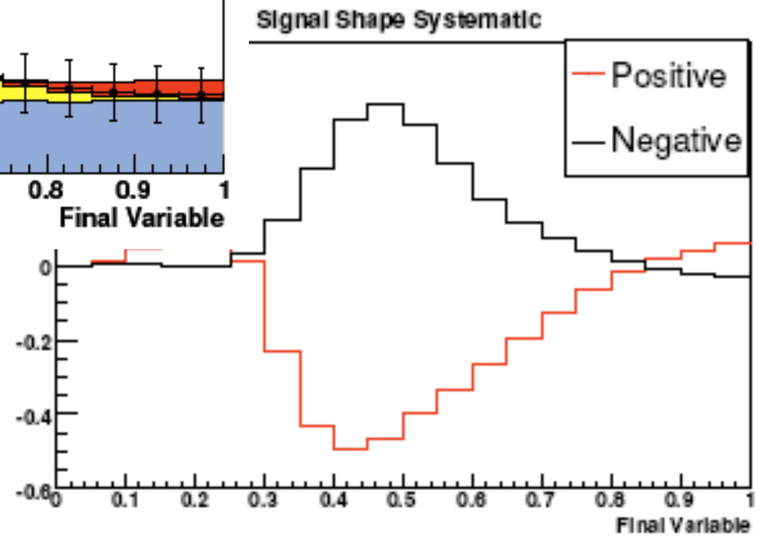
- Systematic uncertainties are propagated through the full analysis chain to the discriminating distribution
  - E.g. we repeat the analysis with jet energy scale shifted up & down by 1σ
  - Some systematic uncertainties affect shape (jet/lepton/photon reconstruction efficiency, energy scale and resolution,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

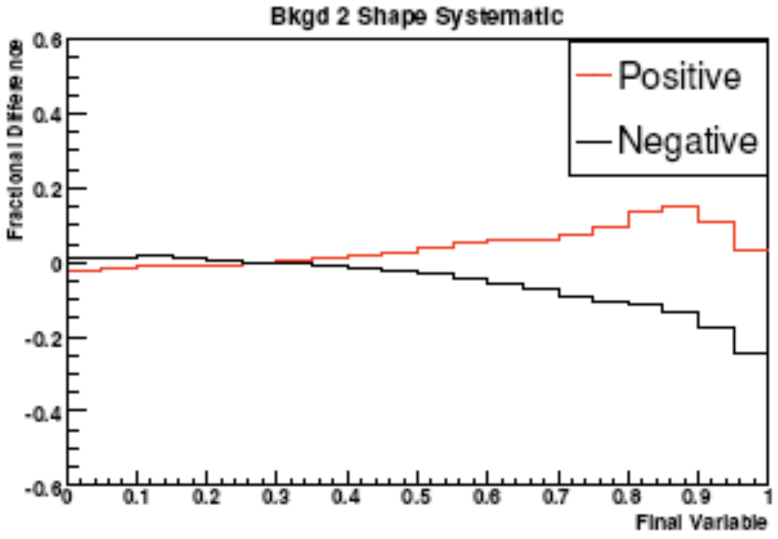
Systematics Profiling

- 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)



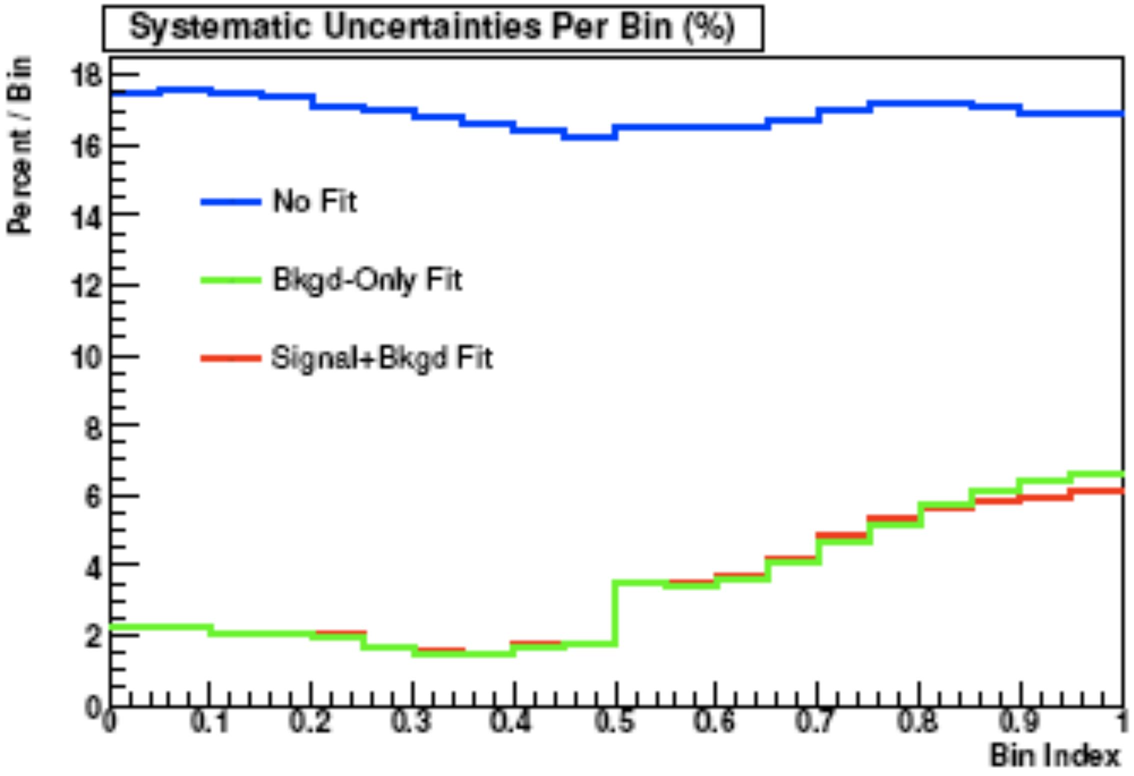


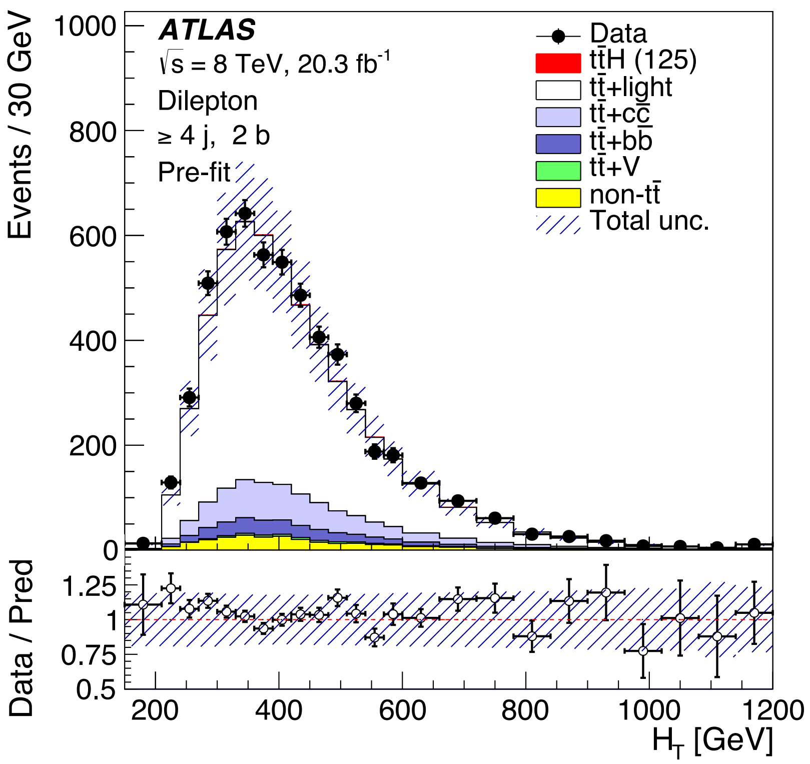
- Generate pseudo-experiments (events in bins according to poisson), then for each experiment vary nuisance parameters
  - Variations in background (& S+B) prediction
    - Compare results to data using log-likelihood ratio
- We can maximize likelihood ratio as a function of nuisance parameters → constrain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

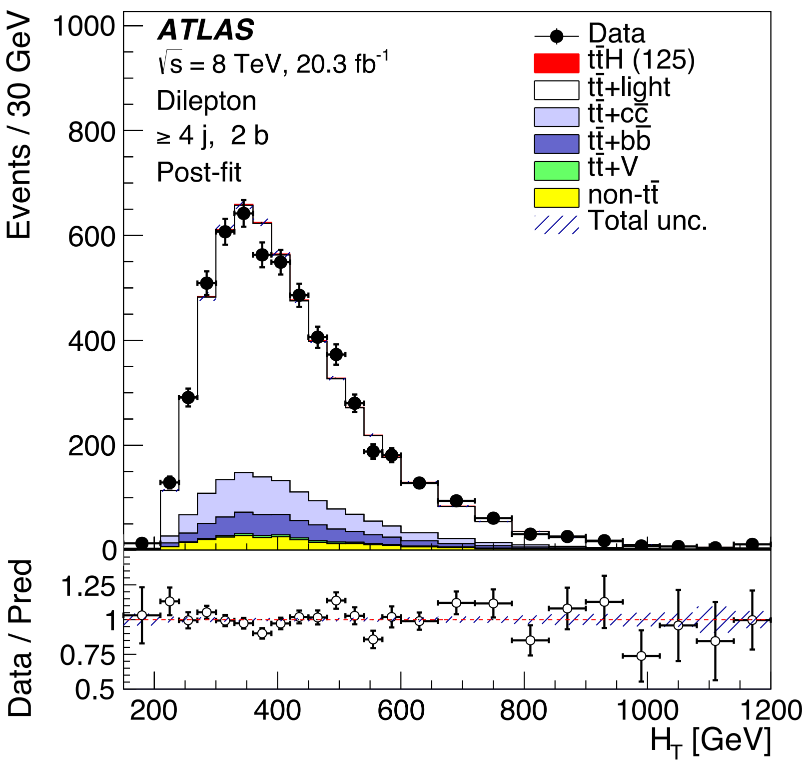
❖ Test example:

- 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



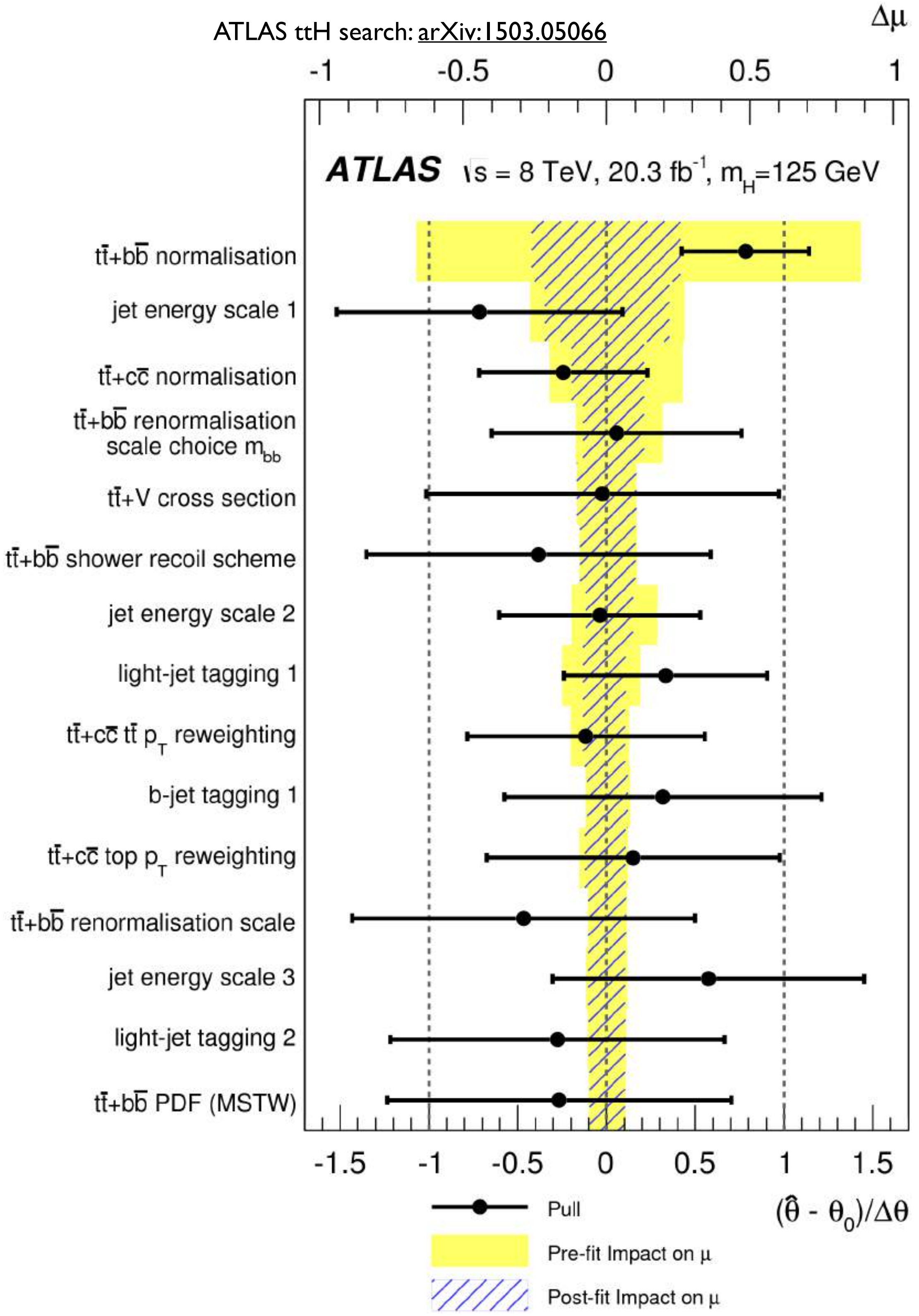




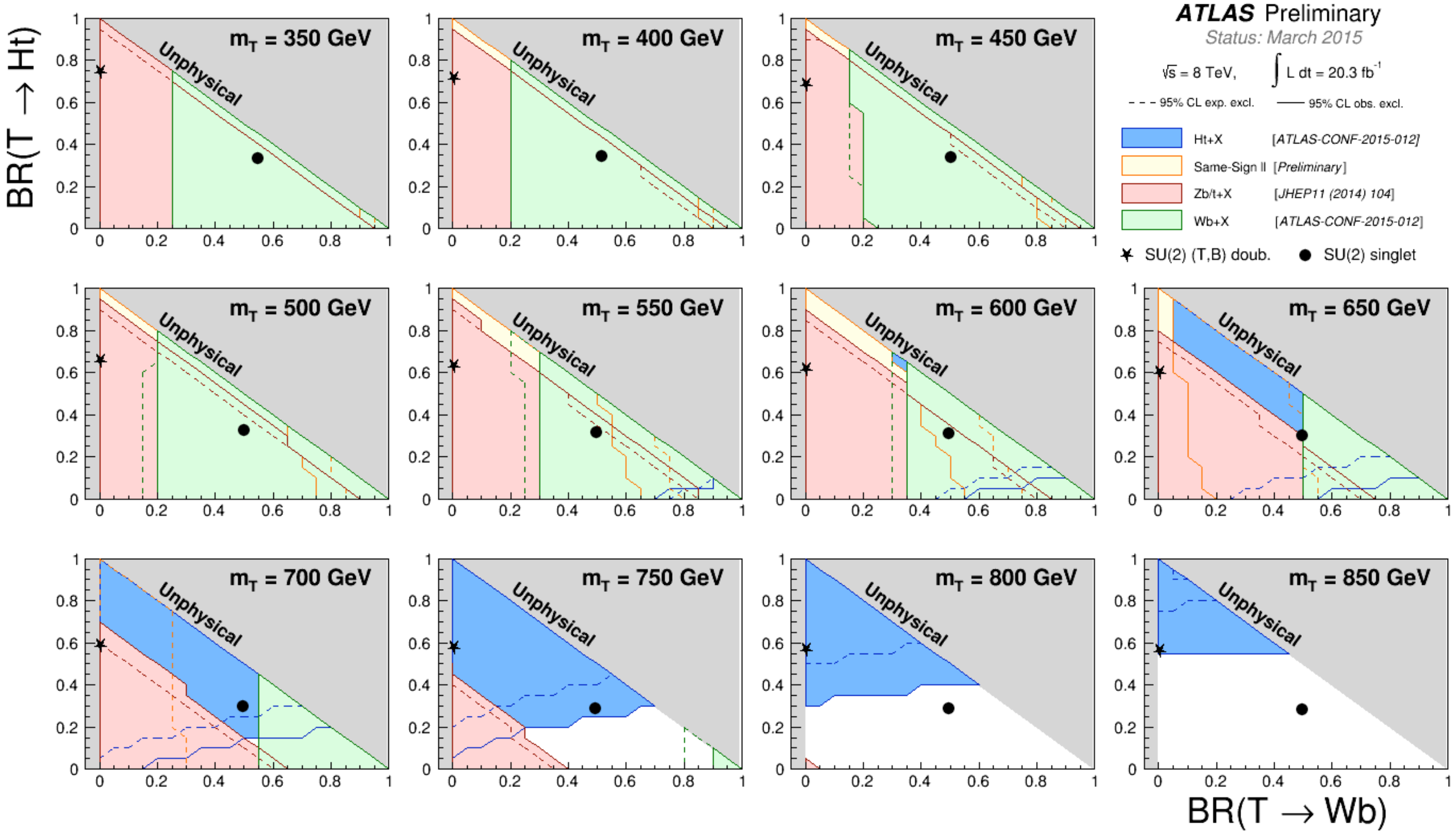
Fit Results

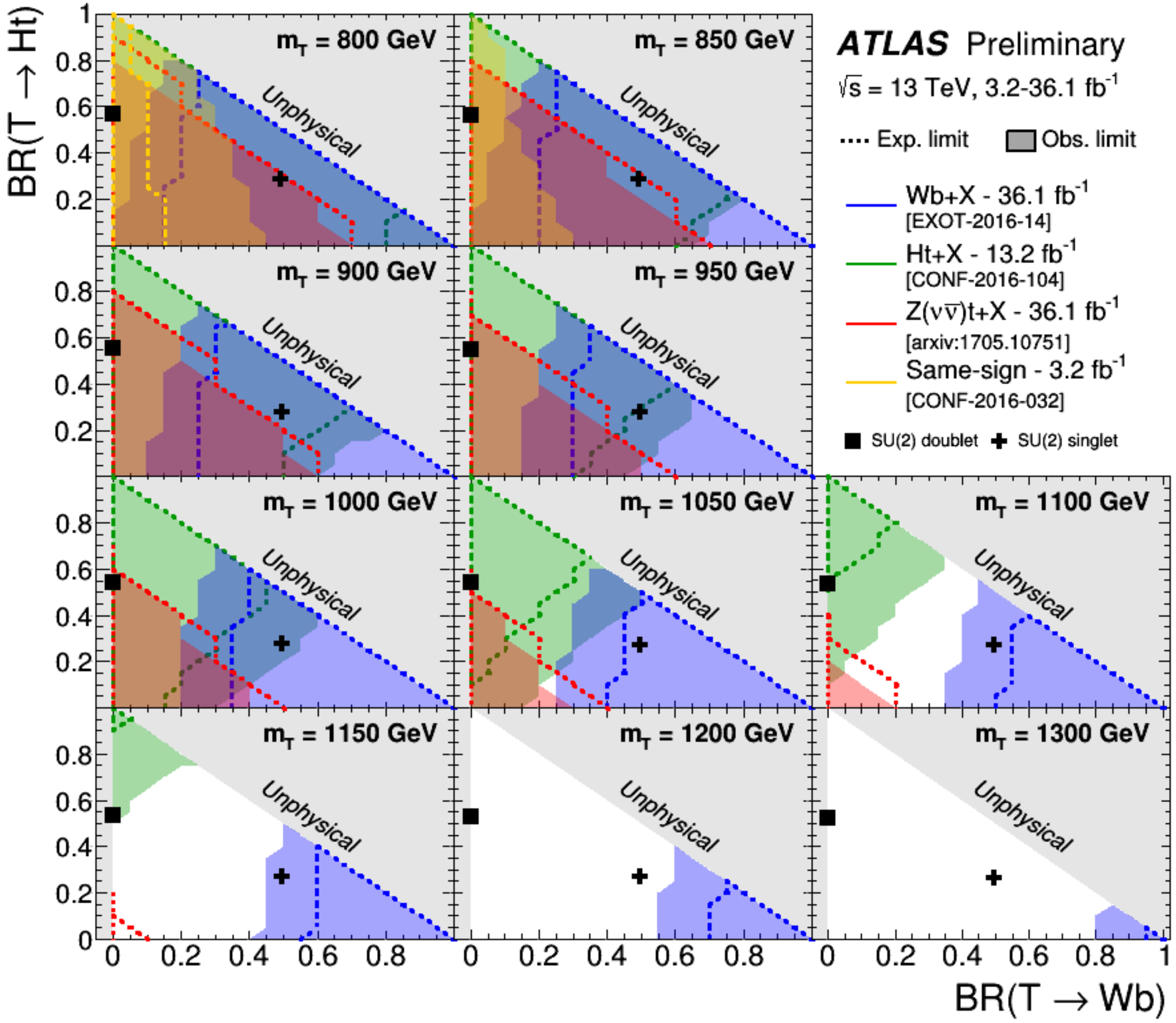
- Need to compare starting point and results
  - Pathologies due to lack of MC stats in some areas, strong correlations, …
- Crucial to design analysis with good control regions the fit can use to address least understood systematics

ATLAS ttH search: arXiv:1503.05066



All Together Now

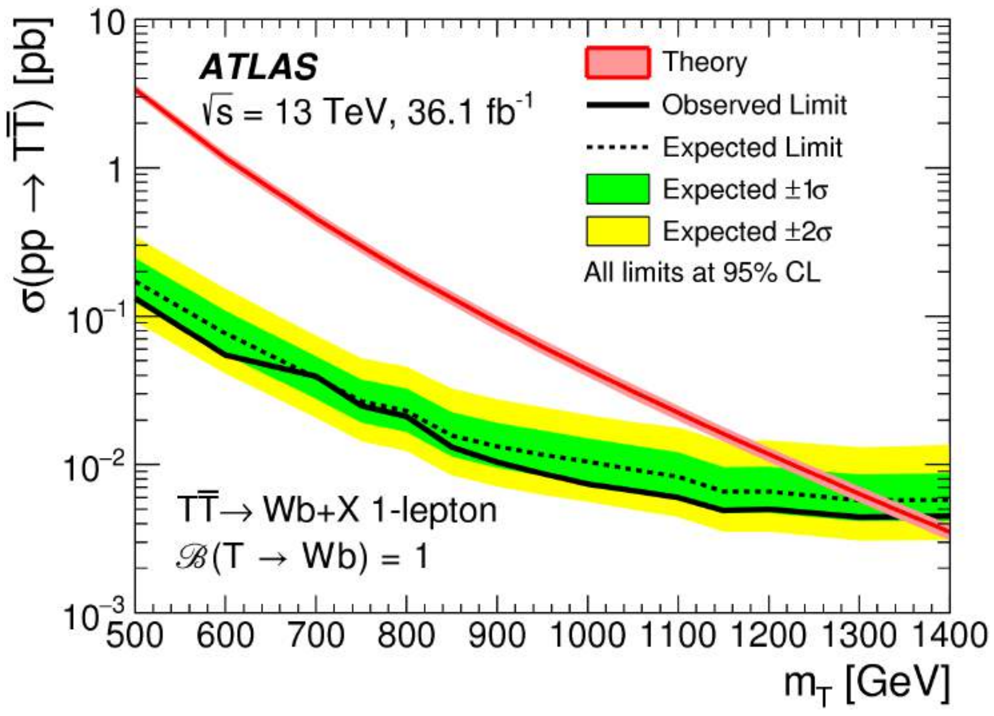




Numbers very similar as for stop….

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
    - Low background at high mass
- What about overlaps?
  - Turns out SUSY searches have good sensitivity to vector-like quarks!
    - SUSY large MET requirement maps to e.g. $Z \rightarrow \nu\nu$



arXiv:1608.01312

TTK-16

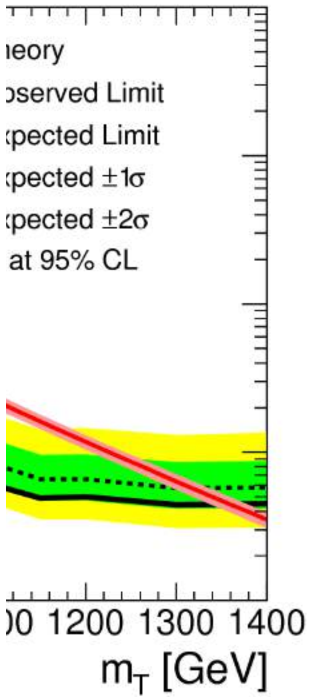
Complementarity of Resonant Scalar, Vector-Like Quark and Superpartner Searches in Elucidating New Phenomena

Anke Biekötter,[1] JoAnne L. Hewett,[2] Jong Soo Kim,[3] Michael Krämer,[1]
Thomas G. Rizzo,[2] Krzysztof Rolbiecki,[4] Jamie Tattersall,[1] and Torsten Weber[1]

[1] *Institut für Theoretische Teilchenphysik und Kosmologie, RWTH Aachen, Germany*
[2] *SLAC National Accelerator Laboratory, Menlo Park 94025, CA, USA*
[3] *Instituto de Fisica Teorica UAM/CSIC, Madrid, Spain*
[4] *Instytut Fizyki Teoretycznej, Uniwersytet Warszawski, Warsaw, Poland*

(Dated: August 30, 2016)

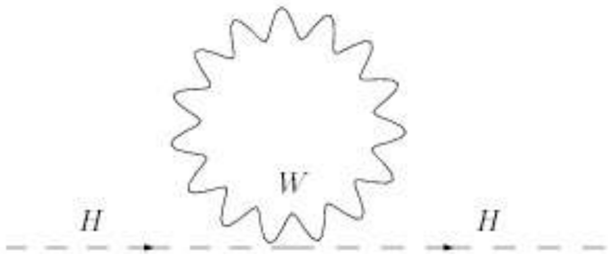
The elucidation of the nature of new phenomena requires a multi-pronged approach to understand the essential physics that underlies it. As an example, we study the simplified model containing a new scalar singlet accompanied by vector-like quarks, as motivated by the recent diphoton excess at the LHC. 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.



Parity

V-A is The Problem!

- Violation of parity in weak interactions is The Problem
  - What, really, *is* (weak iso)spin?
- What if the fermion mass scale ~ parity restoration scale? (and the Higgs mass flows from that)
  - Can we then, as a next step, hope to understand relative fermion masses?
  - BTW, did you notice that inside a generation, the more a fermion interacts the heavier it is?
    - Eek! (The whole point of the Higgs mechanism is to decouple masses from interactions!)
    - But even the Higgs wants W/Z partners!



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

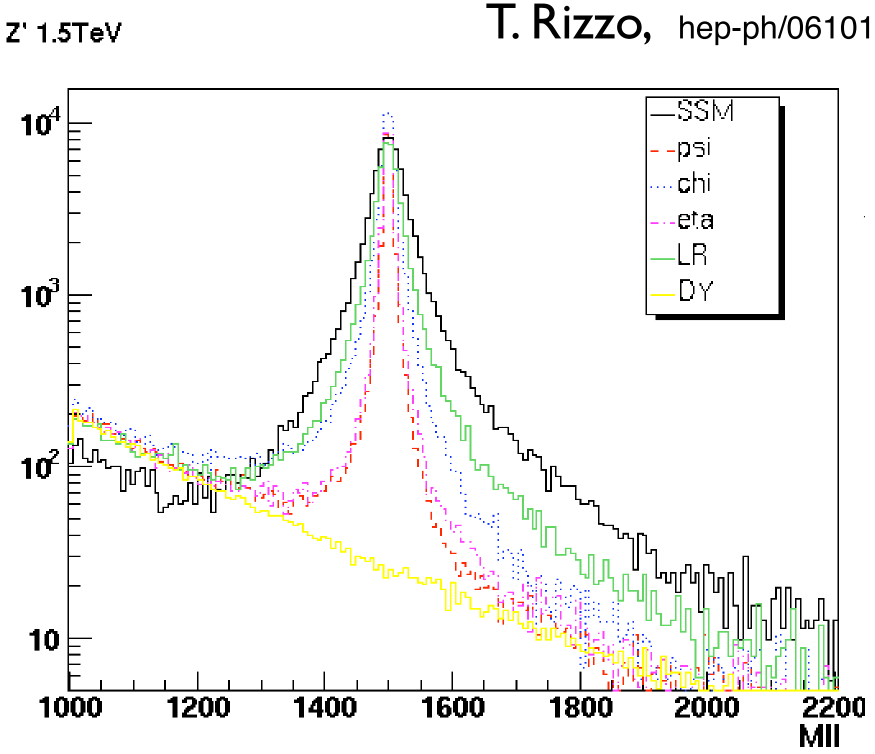
Parity Restoration: Signals

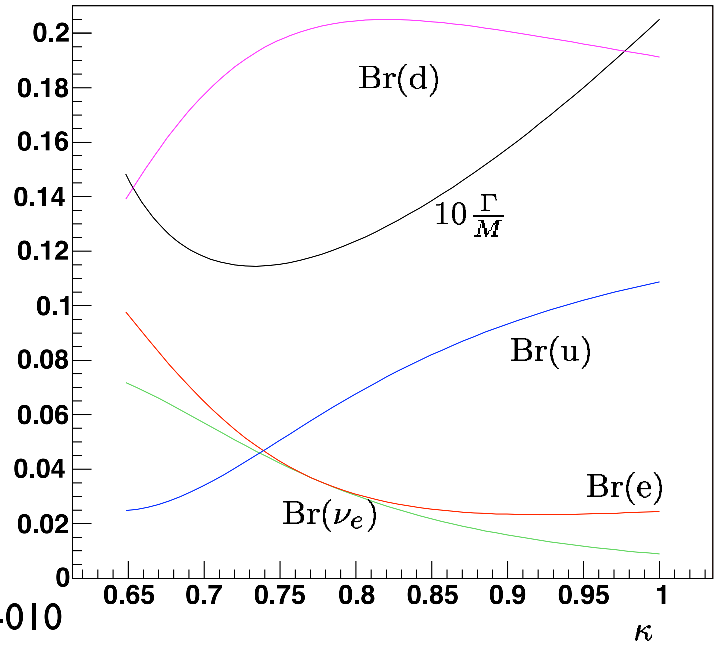
- Primary signals are (right-handed) W' (+ Z')
  - Dilepton resonances (Z') offer clean signals, well-understood backgrounds
    - At LHC, some concern about extrapolation of calibration from Z to very high energies
    - Electron/muon resolution improves/degrades with p_T
  - $t\bar{t}$ decays visible
  - ν_R is presumably heavy, W' may not decay to leptons
    - Only dijet or diboson
    - If ν_R lighter than W'/Z', ν_R decays become important
- Note: many kinds of Z' - review by Langacker arXiv:0801.1345
  - W'/Z' would also require new fermions…

Z' Production and Decay

- ❖ Production from u, d quarks is dominant at LHC
  - Couplings vary by model
  - E.g. for LR symmetric models, $\kappa = g_R/g_L$ drives production cross-section (convolute with PDFs) and branching ratios
- ❖ Decays somewhat similar to Z (but almost no BR to light neutrinos, decays to top open up), plot assumes ν_R heavier

T. Rizzo, hep-ph/0610104



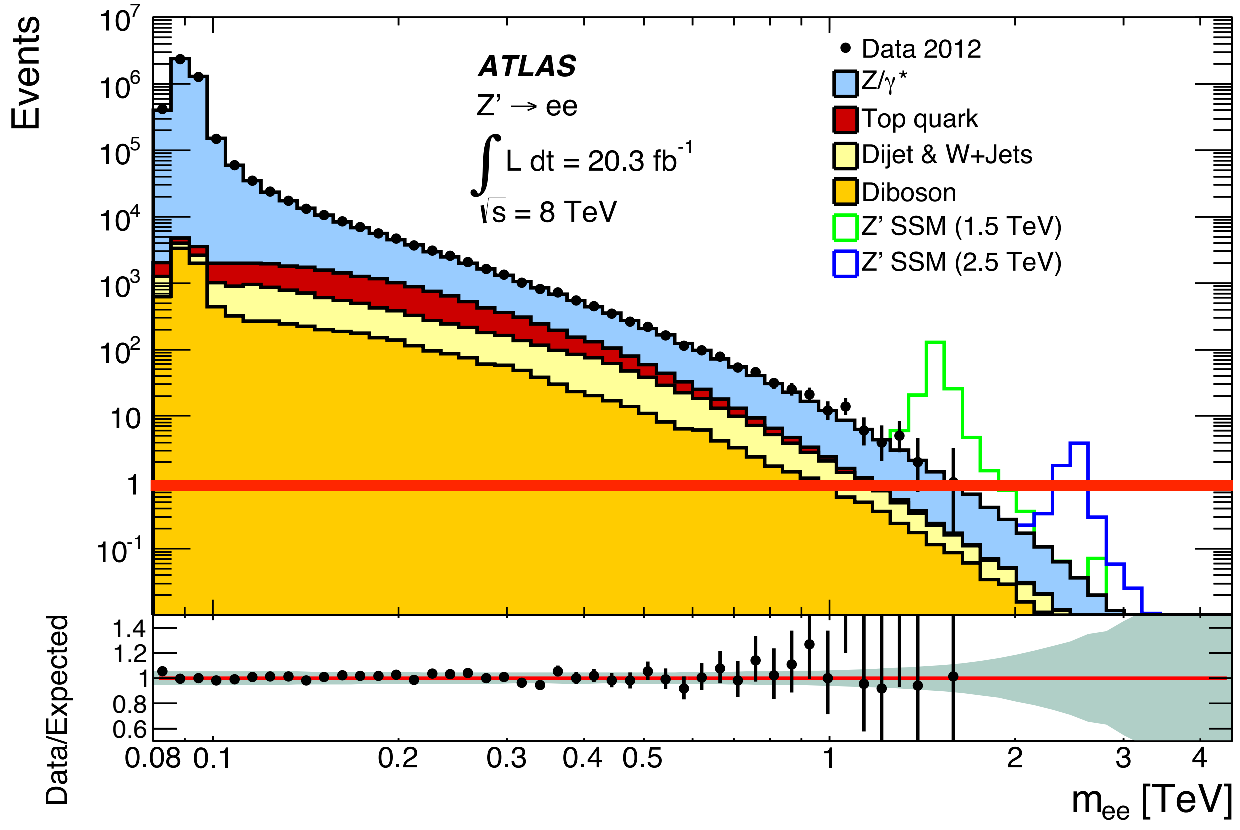


ATL-PHYS-PUB-2005-010

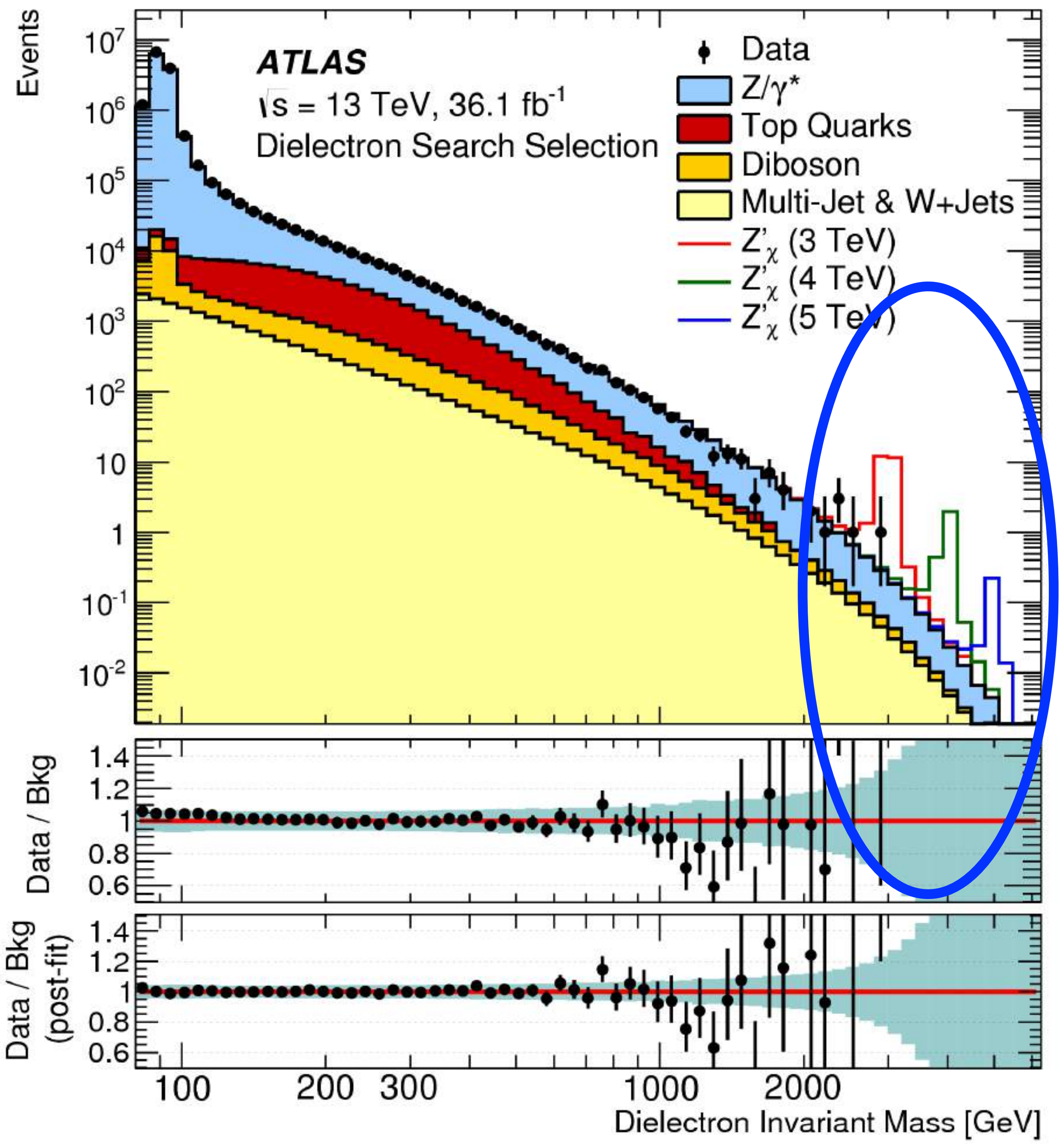
Z’ → ee/μμ

- Most promising channels:
  - Backgrounds very low!
  - “Self-calibrating”
  - In ee, at high masses, energy resolution dominated by constant term
    - 10 GeV for 1.5 TeV electron
    - Could measure width!
- LHC extended Tevatron reach immediately!
  - Limits now hitting 4+ TeV

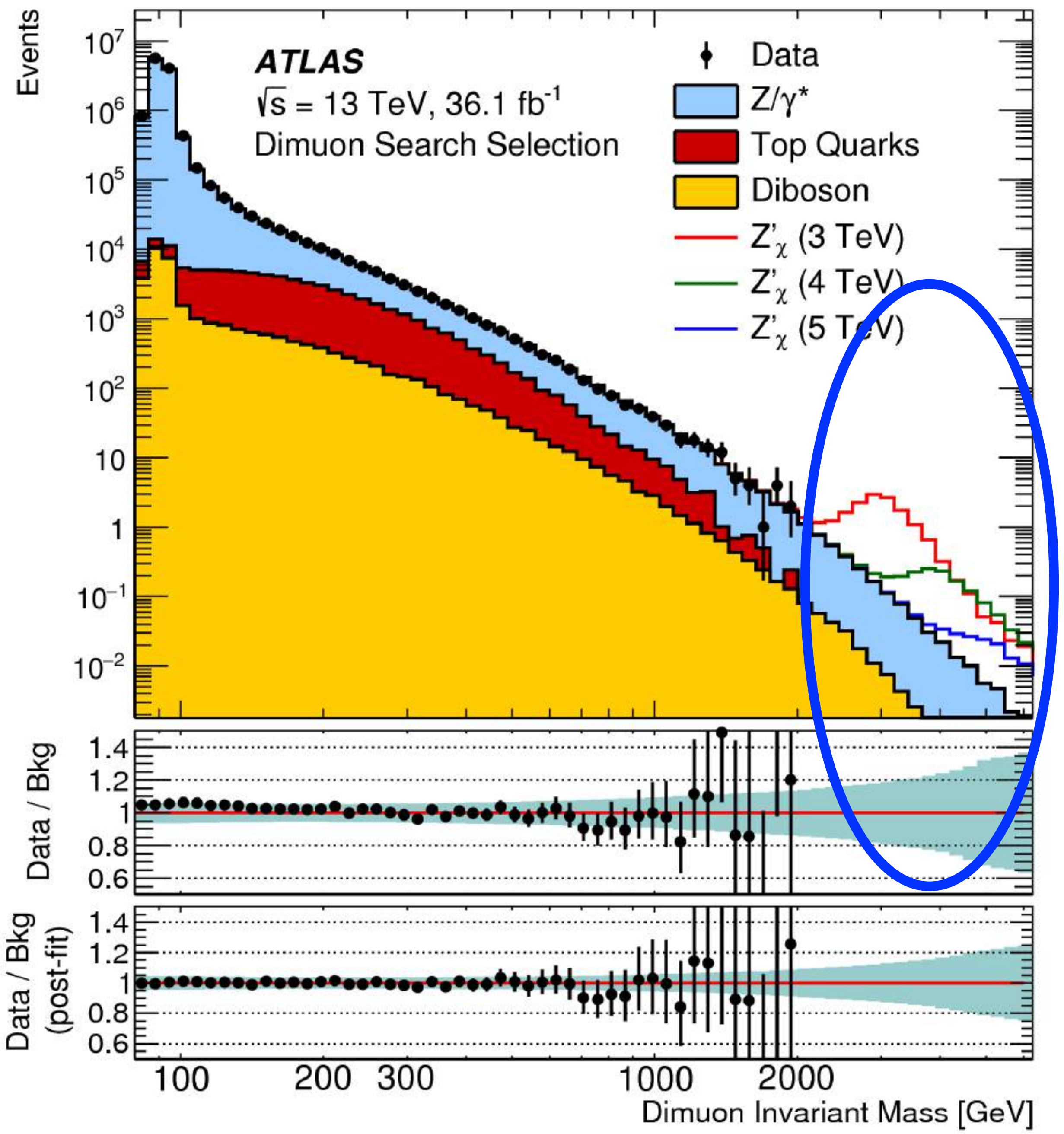
ATLAS, Phys. Rev. D. 90, 052005 (2014)



e vs μ



ATLAS
√s = 13 TeV, 36.1 fb-1
Dielectron Search Selection
Data
Z/γ*
Top Quarks
Diboson
Multi-Jet & W+Jets
Z'χ (3 TeV)
Z'χ (4 TeV)
Z'χ (5 TeV)
Events
Data / Bkg
Data / Bkg (post-fit)
Dielectron Invariant Mass [GeV]



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Dimuon Search Selection
Data
Z/γ*
Top Quarks
Diboson
Z'χ (3 TeV)
Z'χ (4 TeV)
Z'χ (5 TeV)
Events
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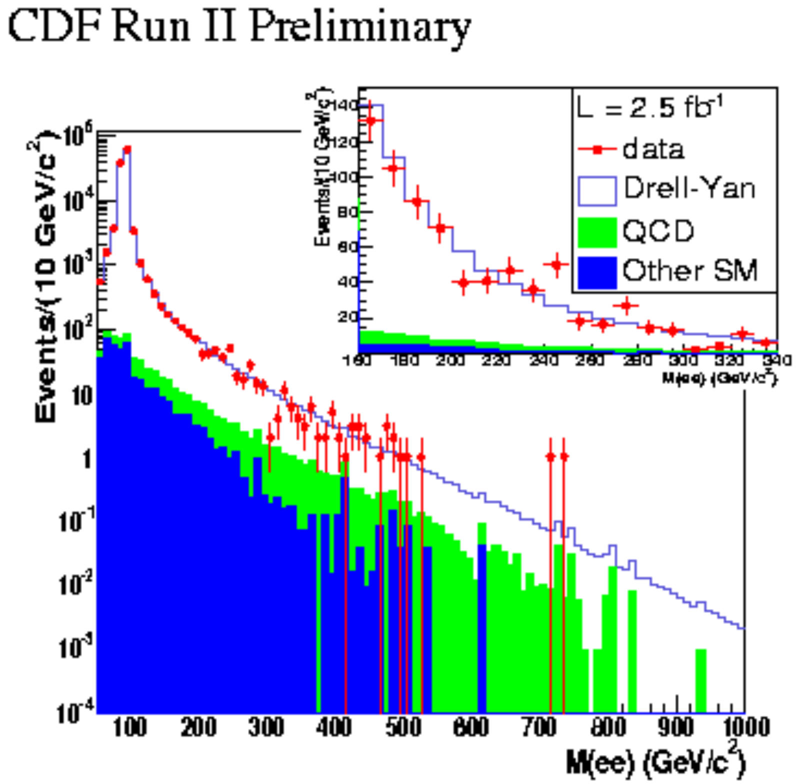
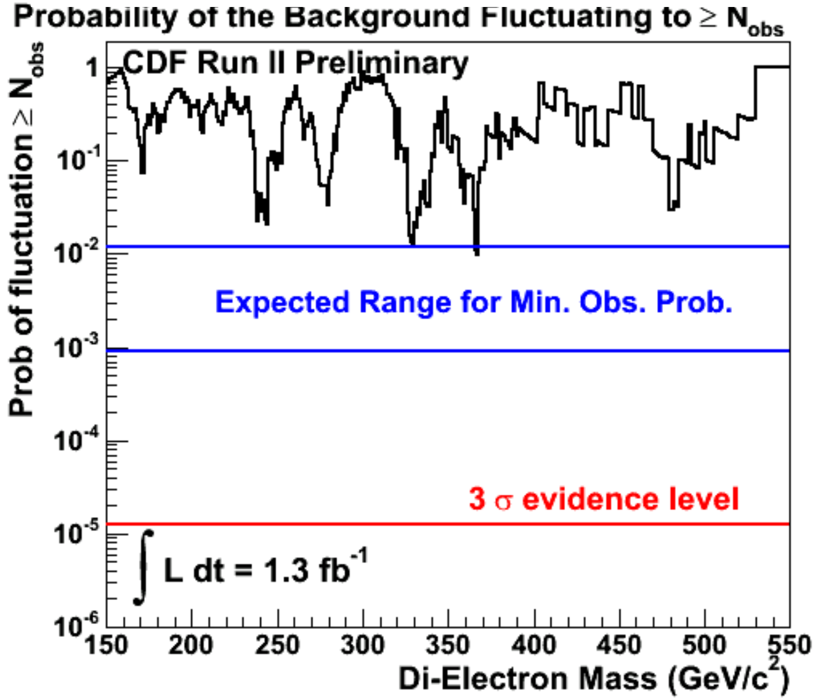
Data / Bkg (post-fit)
Dimuon Invariant Mass [GeV]

"Look Elsewhere" Effect

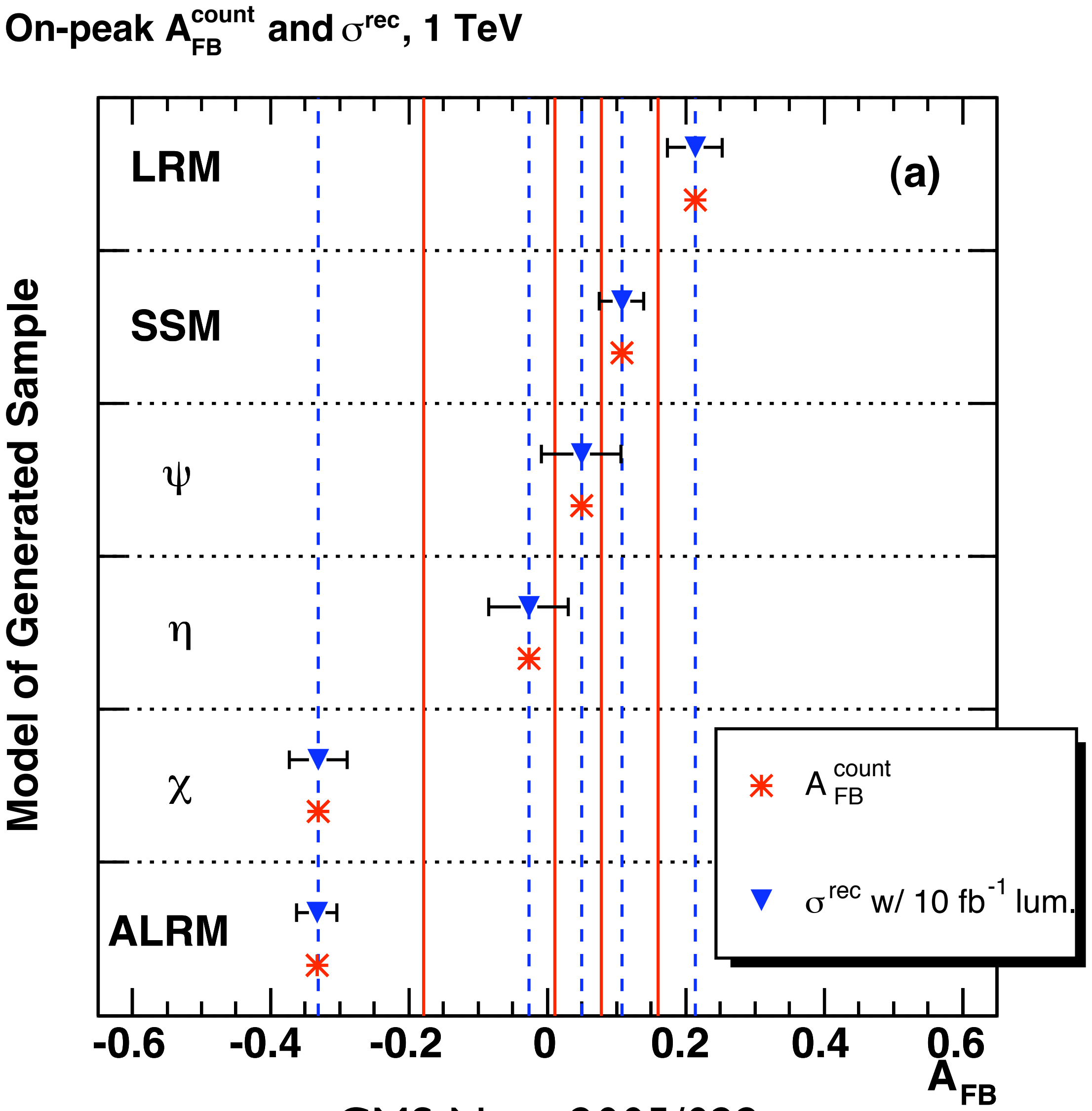


- If search is done by counting experiment in a shifting mass window, need to factor in "look elsewhere" effect (∝ # of windows)
  - Always an excess if look at enough distributions...
- Global fit to the (DY) spectrum is another approach
  - Let fit find the mass
  - Shape analysis more sensitive
- Run pseudo-experiments!



Model Determination

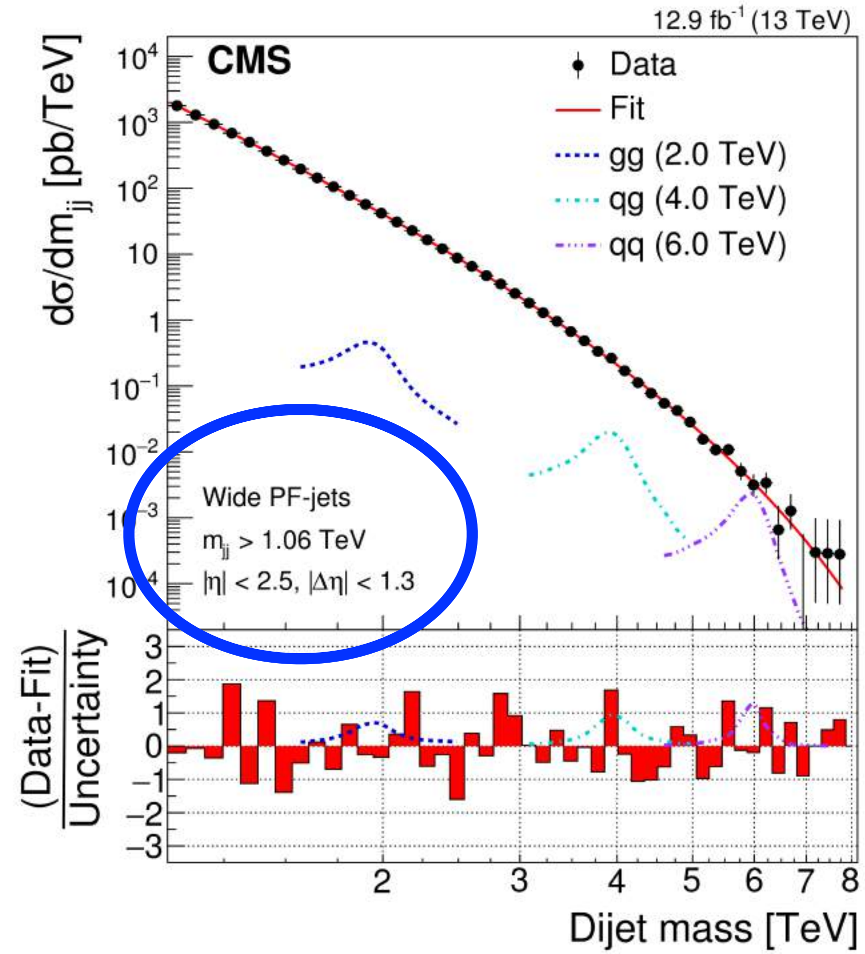
- ❖ Angular distribution gives excellent handle on g_V, g_A for various fermions
  - Charm may be possible
- ❖ This will come after an initial determination of branching ratios (obviously)
  - Complementary information in determining nature of resonance



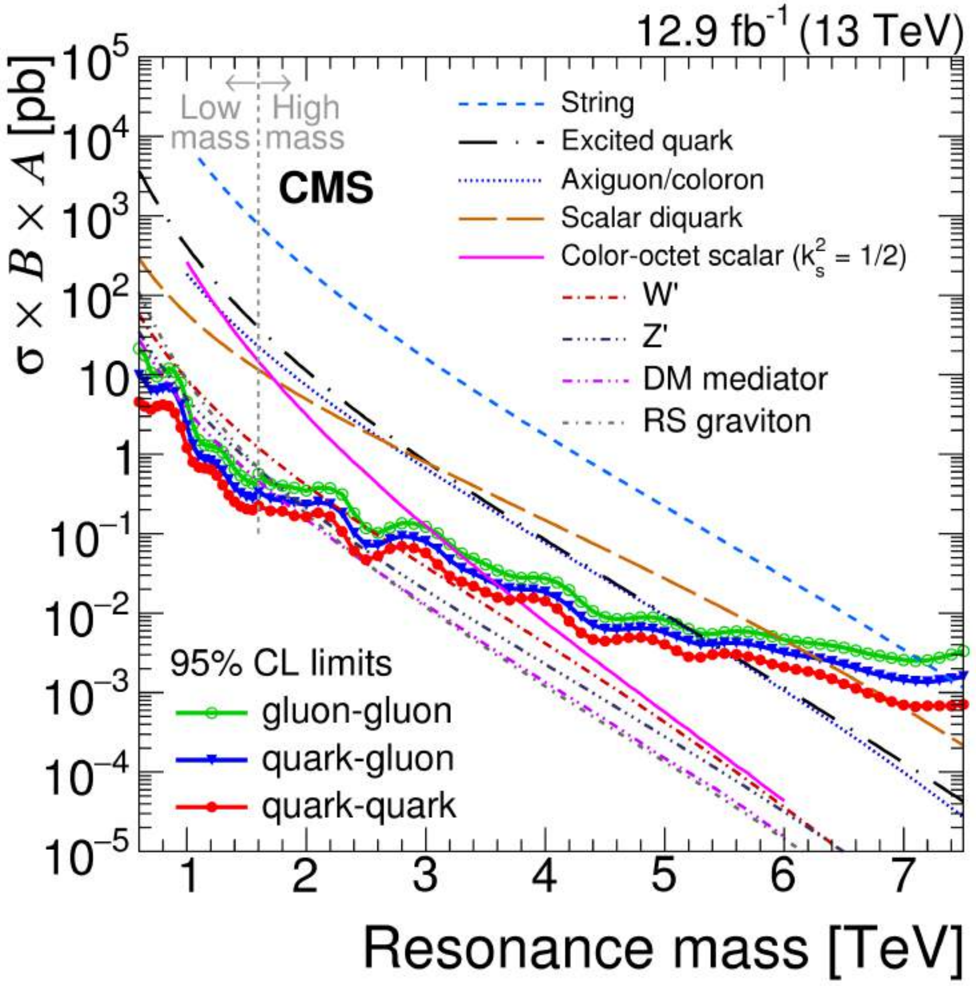
CMS Note 2005/022

Dijets

- ❖ SM Background obviously much larger
  - But single source
  - And opens the door to strongly interacting objects

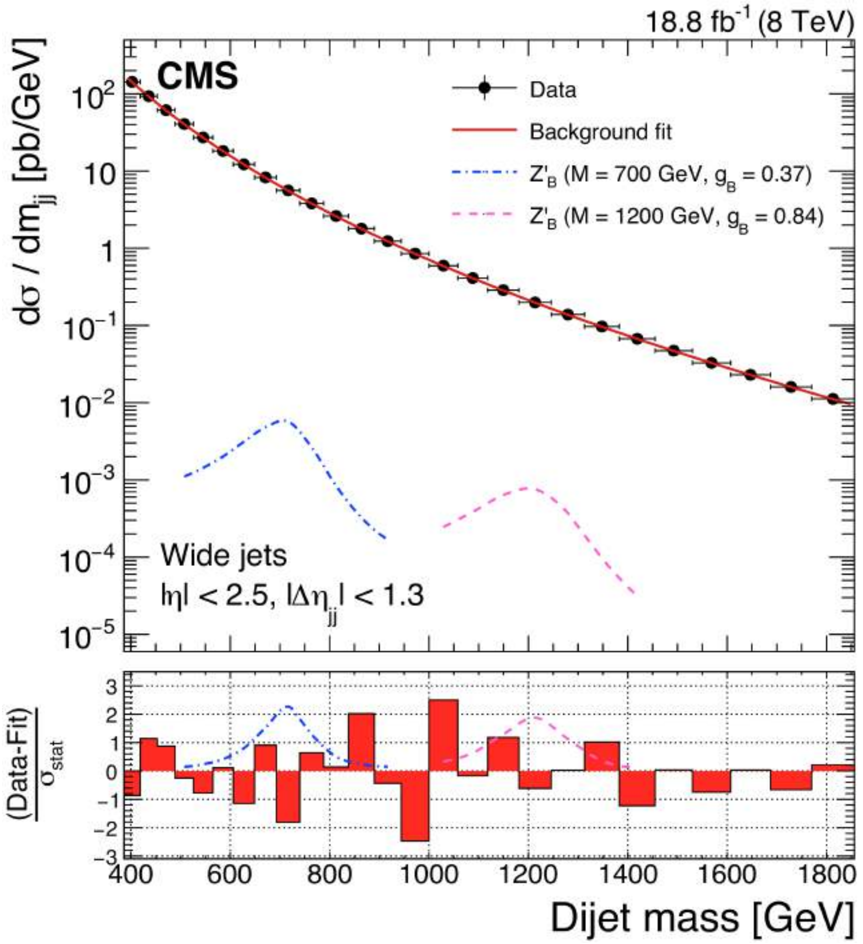


CMS
Phys. Lett. B 769 (2017) 520



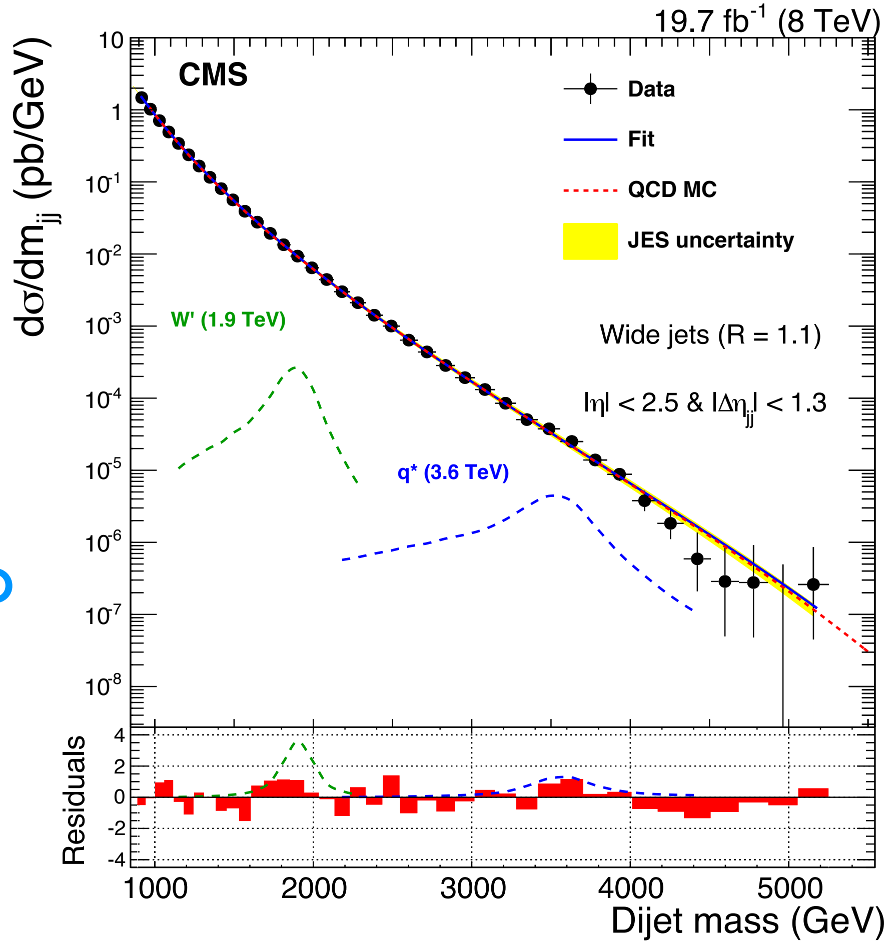
Scouting

- ❖ Dijet resonances at moderate masses are tough
  - Unprescaled single jet trigger thresholds now > 400 GeV → below m = 1 TeV no sensitivity!
- ❖ Both experiments now implement "data scouting"
  - Only keep jet information in high level trigger to make events small



CMS, arXiv:1604.08907

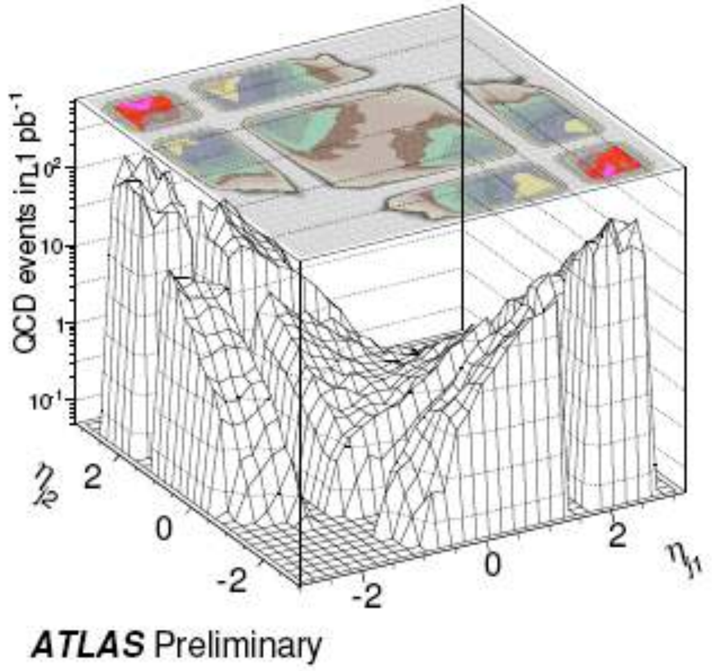
Compare to

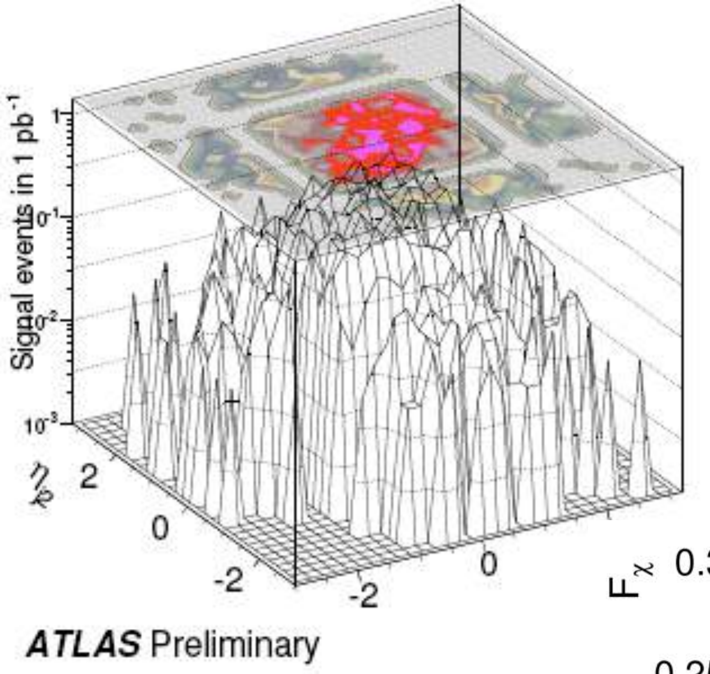


Angles

875 GeV < m_{jj} < 1020 GeV

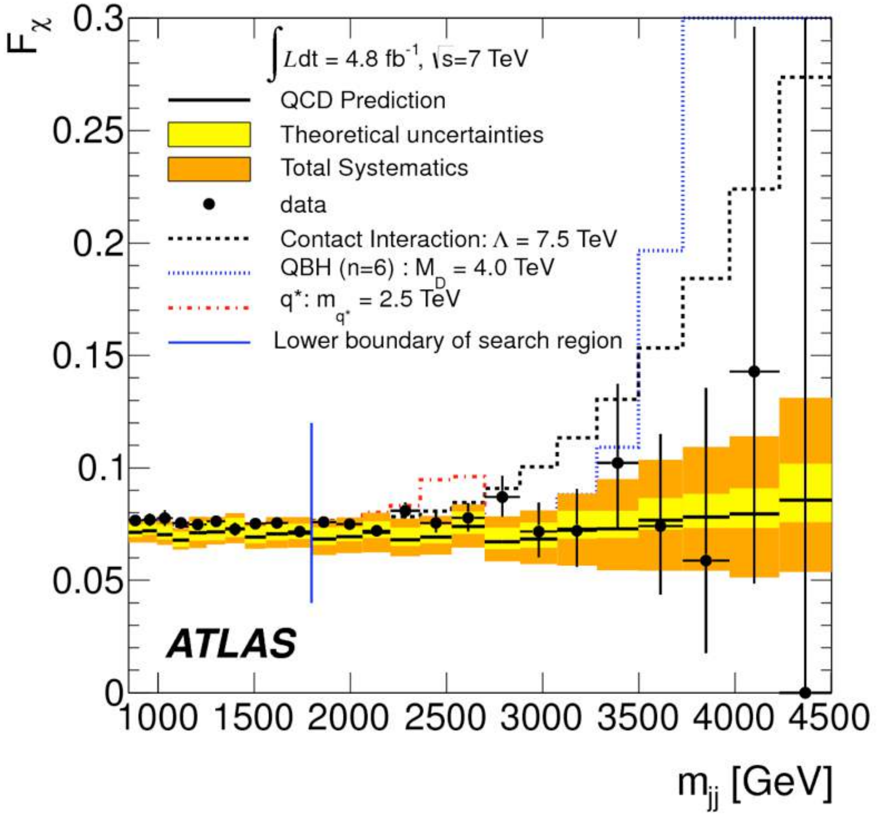
QCD





q^*

$$F_\chi(m_{jj}) \equiv \frac{dN_{central}/dm_{jj}}{dN_{total}/dm_{jj}}$$



- ❖ High mass object → large boost → central
  - But background dominated by QCD "elastic" scatters and larger angle = higher mass
  - "Δη" cuts used in many analyses