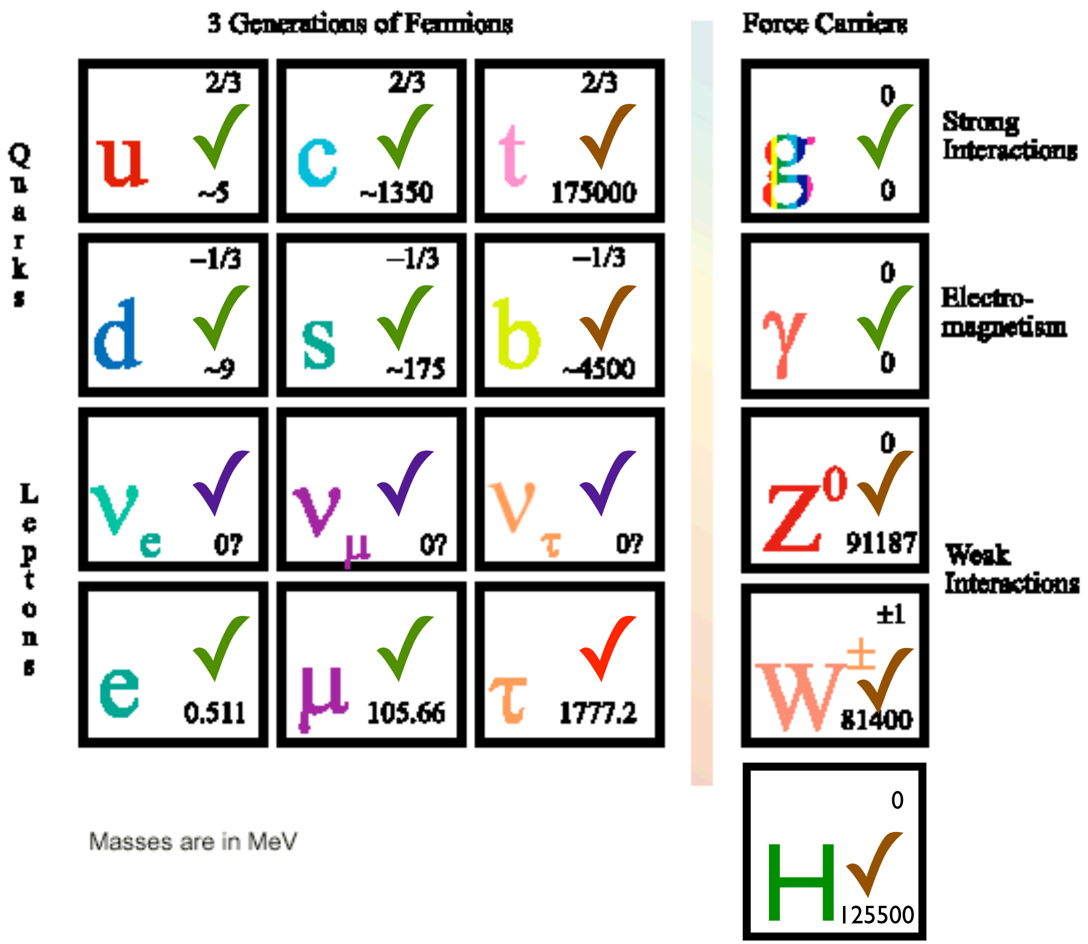
Detecting Particles



✓: Detect with high efficiency

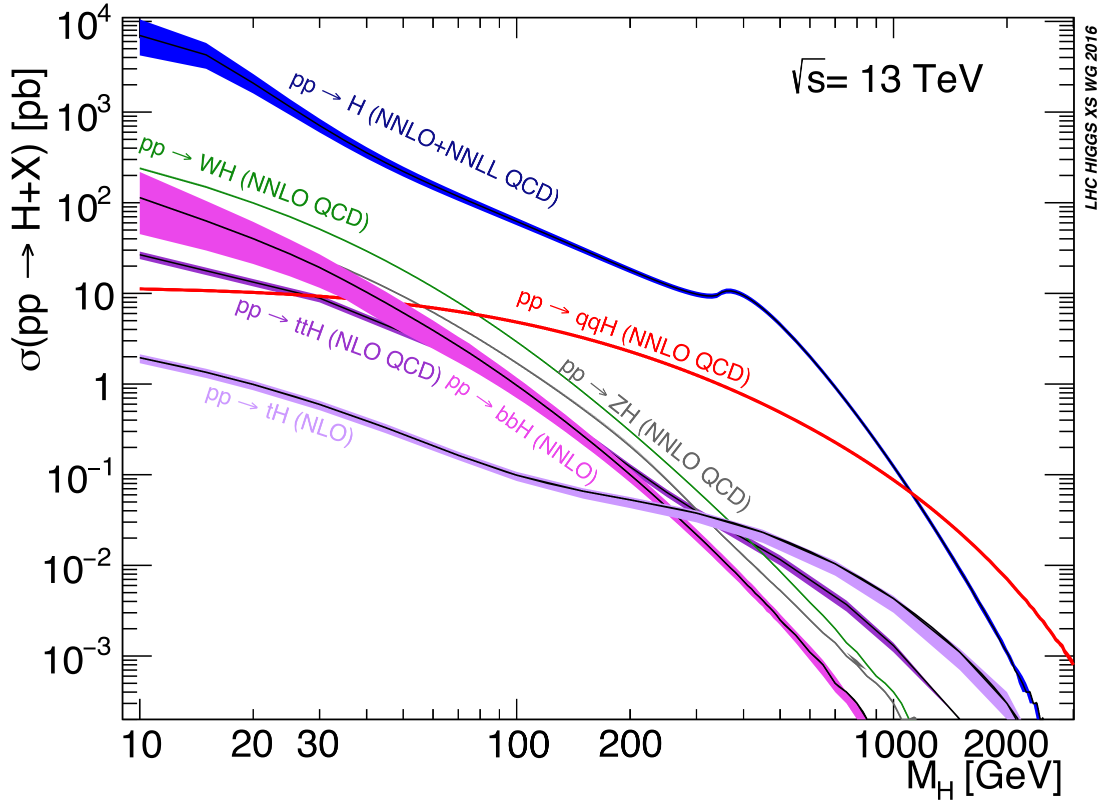
✓: Detect by missing transverse energy

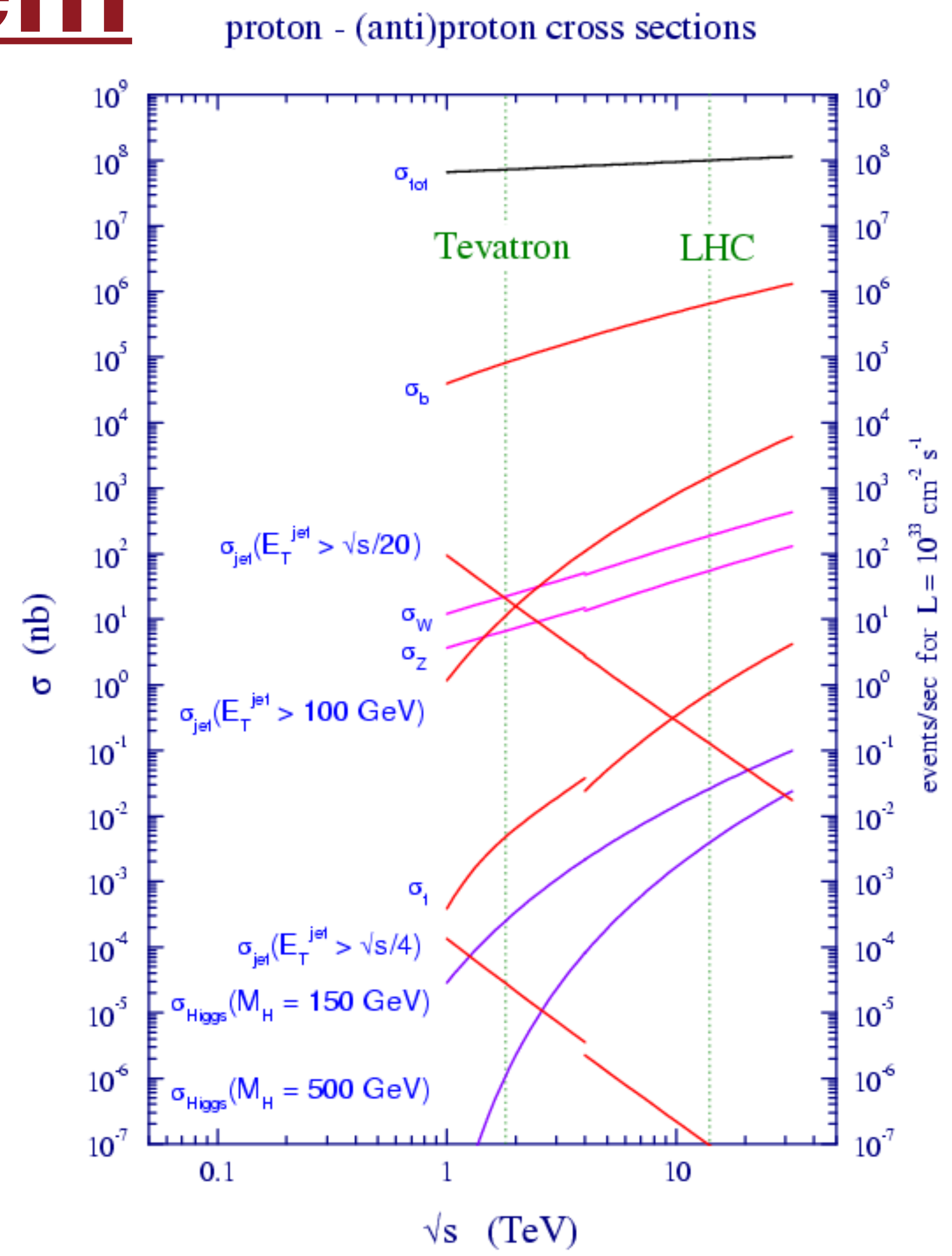
✓: Detect through decays: t→Wb, W/Z → leptons, ...

Hadron Colliders: Triggering

The Problem

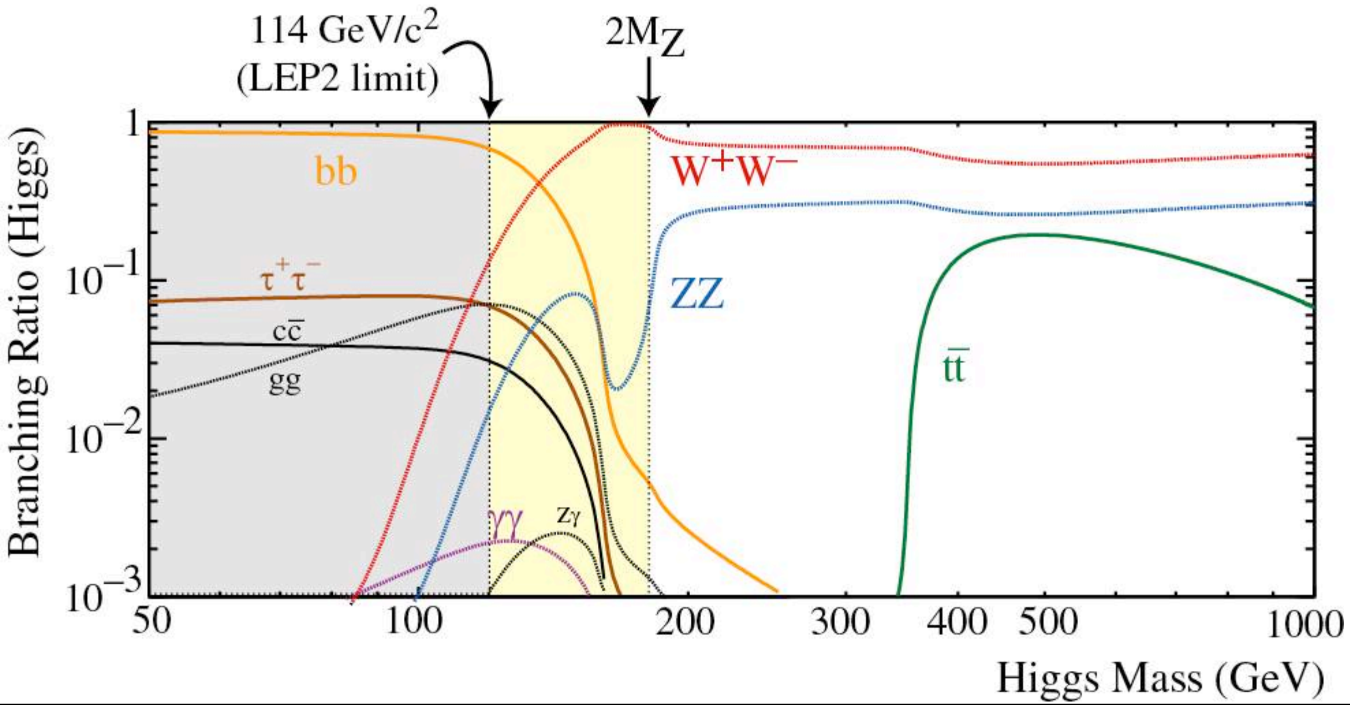
- Total cross-section is large
  - 80 mb at 10^{32} is 8 MHz!
  - H production, ~50 pb at 10^{32} is 5 Hz
    - But most of those are not detectable!

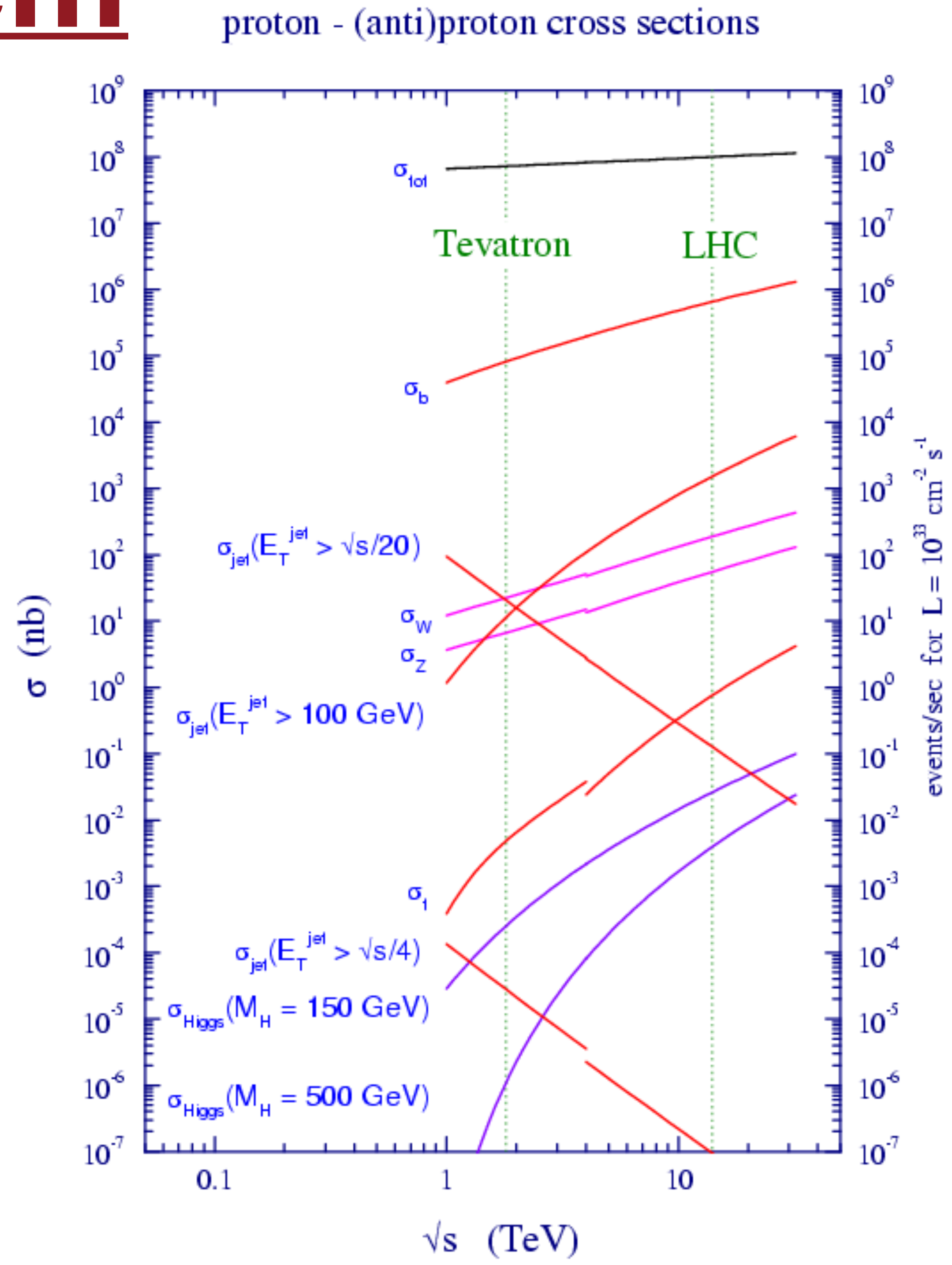




The Problem

- Total cross-section is large
  - 80 mb at 10^{32} is 8 MHz!
  - H production, ~50 pb at 10^{32} is 5 Hz
    - But most of those are not detectable!
    - LHC runs at ~2x10^{34}, ~0.5 fb^{-1} or 25k H bosons per day





Triggering

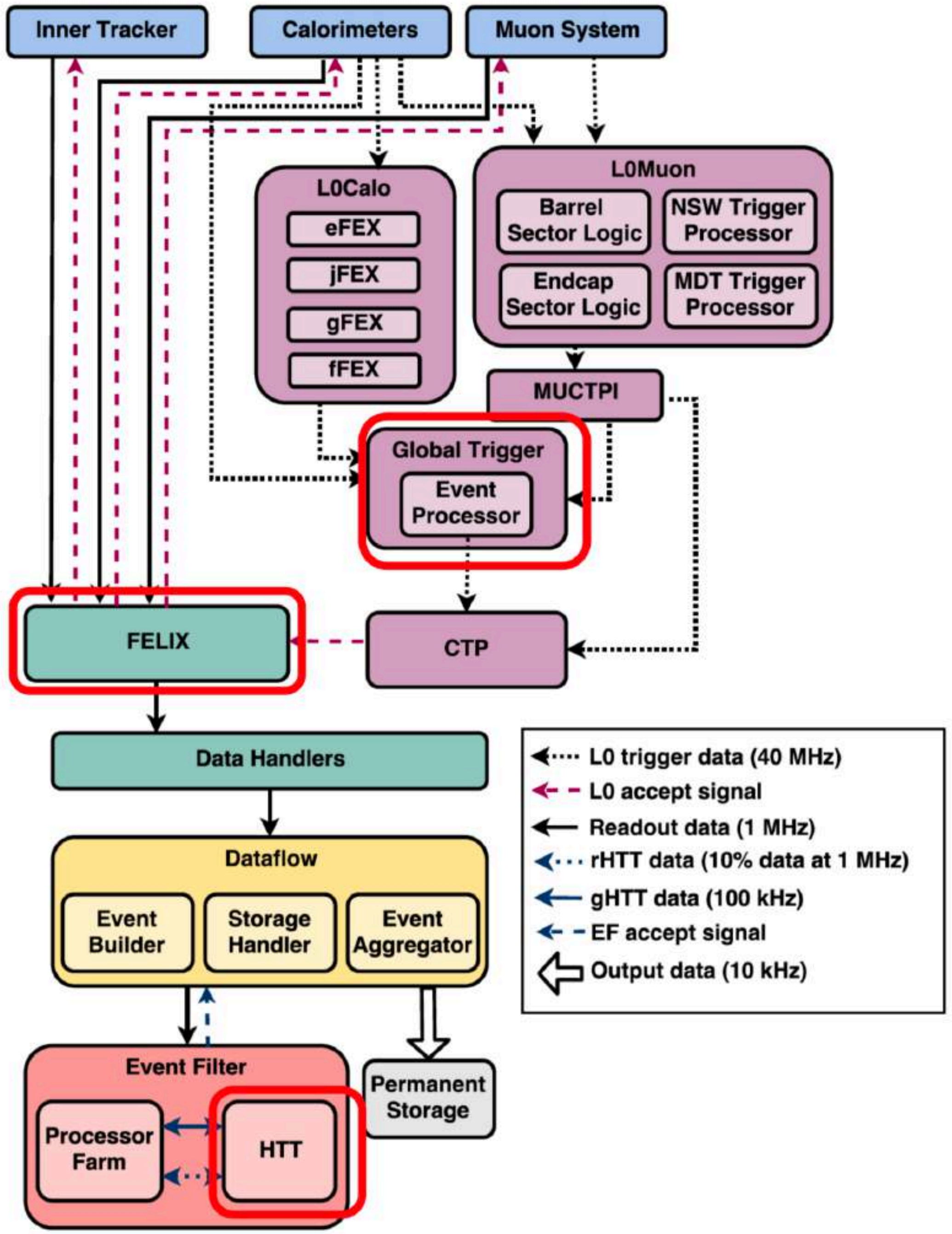
- Goal: select interesting events for offline analysis, while minimizing dead time
- "Interesting" is subjective
  - Depends on physics priorities (need for compromise in multi-purpose experiments)
  - Only interesting if event passes offline cuts
  - Includes events needed to validate analysis
    - Determination of efficiencies
    - Control samples
    - …

Constraints

- ❖ During decision-making process, data need to be “stored”
  - ATLAS produces 100s of Tbps
- ❖ Architectures are evolving
  - Closing in on shipping all data off-detector, where pipelines can be implemented in cheap RAM, not exposed to particle-induced upsets
    - For hermetic experiments, only inner tracker data still on-detector
  - Always at the forefront during design, antiquated during construction
    - E.g. HL-LHC, installation ~2025, will use mainly 10 Gbps links

Looking Forward

- ❖ Typical HL-LHC parameters:
  - Level-1 hardware trigger, ~10 μs latency
    - Access to fine-grained calorimeter and muon system data
  - High-level trigger (asynchronous)
    - Software with access to full detector data, run fast versions of offline algorithms
    - Track reconstruction may run on custom hardware, not clear if can be done in software…



Analyzing Data

Steps in a Physics Analysis

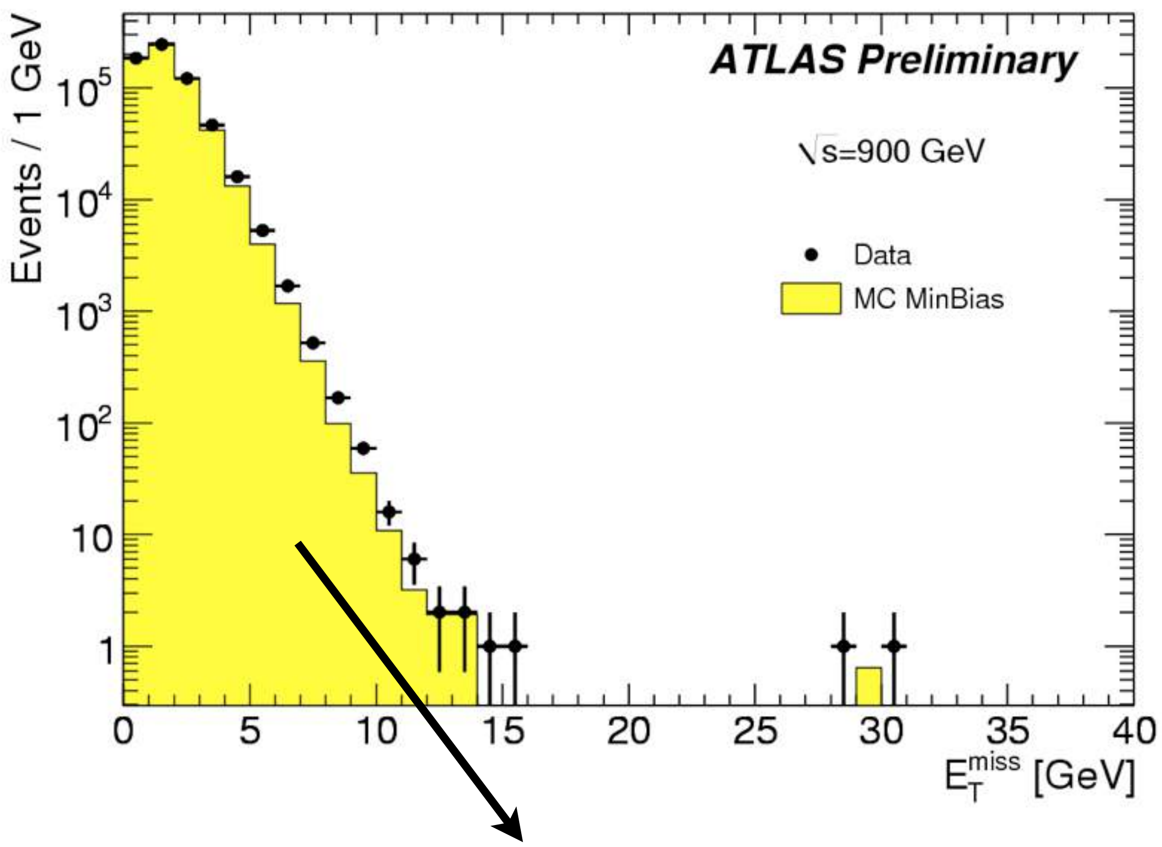
- ❖ Choose a topic (often theory-motivated)
- ❖ What is the final state? ⇒ "Preselection"
  - For a search, sufficiently loose to be signal-poor
    - Prove you understand the detector response, physics processes contributing
  - But sufficiently tight to have a manageable data volume
    - ATLAS/CMS write 1000 Hz × 1+ MB/event = 1+ GB/s
    - "4-vectors" is not enough, need some amount of detector info
    - In practice, often have preselected sample for frequent analysis, + looser sample for e.g. multijet background with rare passes
- ❖ Note that data volume ∝ running time, not $\int\mathcal{L}$

Steps (II)

- Determine preselected sample's composition
  - MC and data to understand each contribution
    - Multijet background to leptons often extracted from data: rejection factor ~10^{-4}, difficult for simulation to be that accurate
    - MC for most other processes, with corrections from data, since generators are (LO,) NLO, NNLO, (LL,) NLL, NNLL
  - Also need to correct MC for real-life data conditions
    - Different alignment, dead channels etc.
  - As statistics increase, more difficult, since mis-modelings not hidden by statistical uncertainties anymore
    - Mis-modelings often show up in tails

Anecdotes From the Field (I)

- Everybody wants experimenters to produce results fast
  - Lots of pressure in the early days of LHC...



Only jets, background easy

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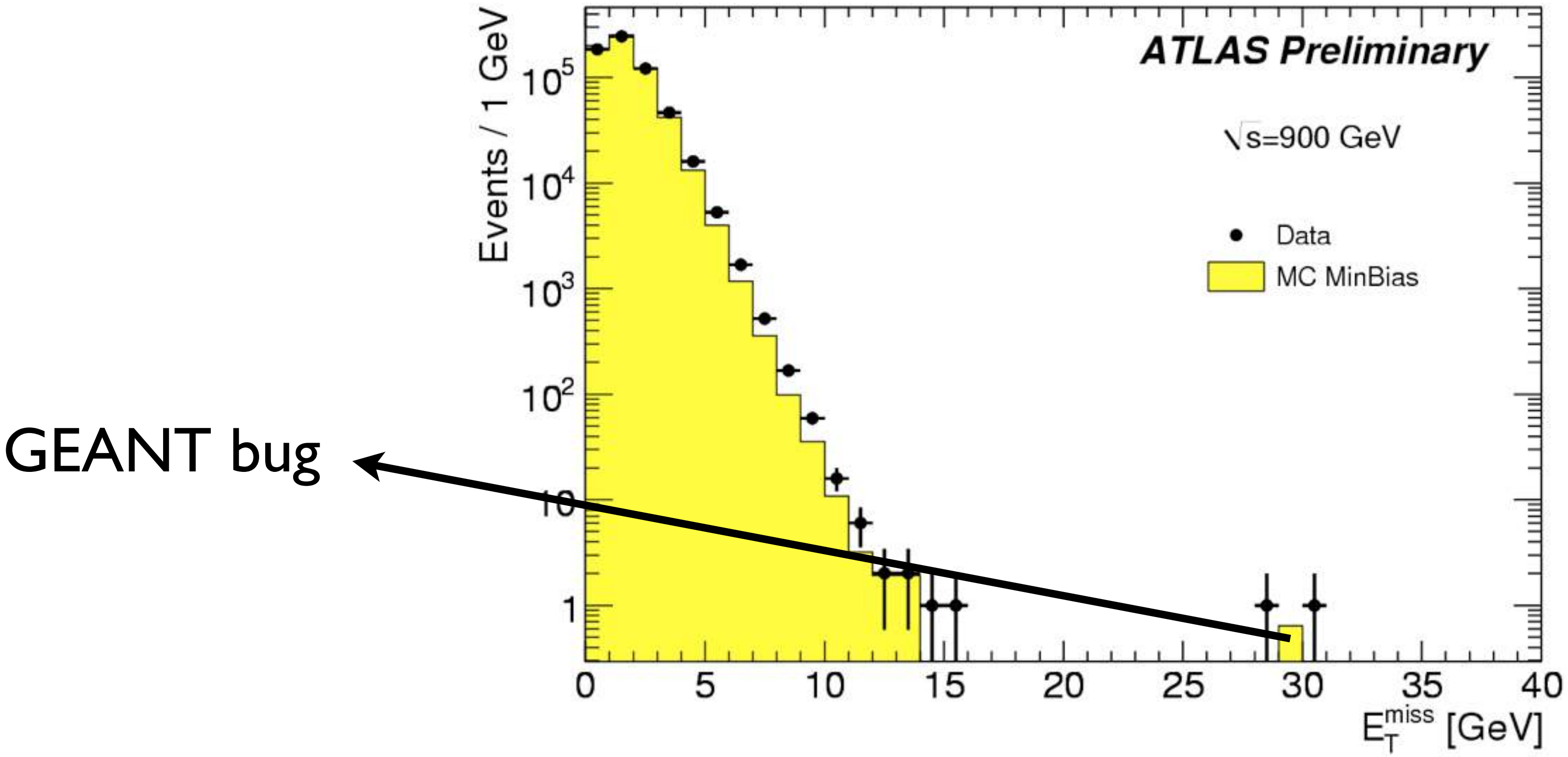

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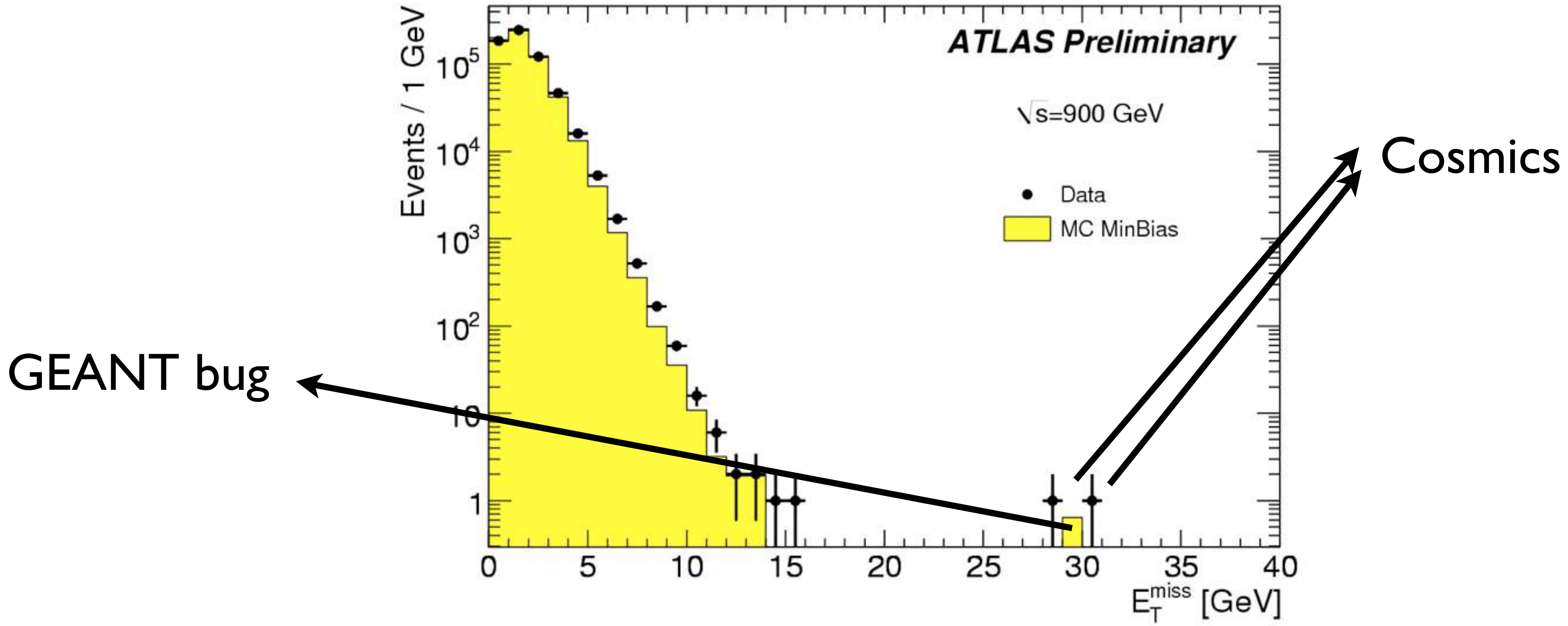
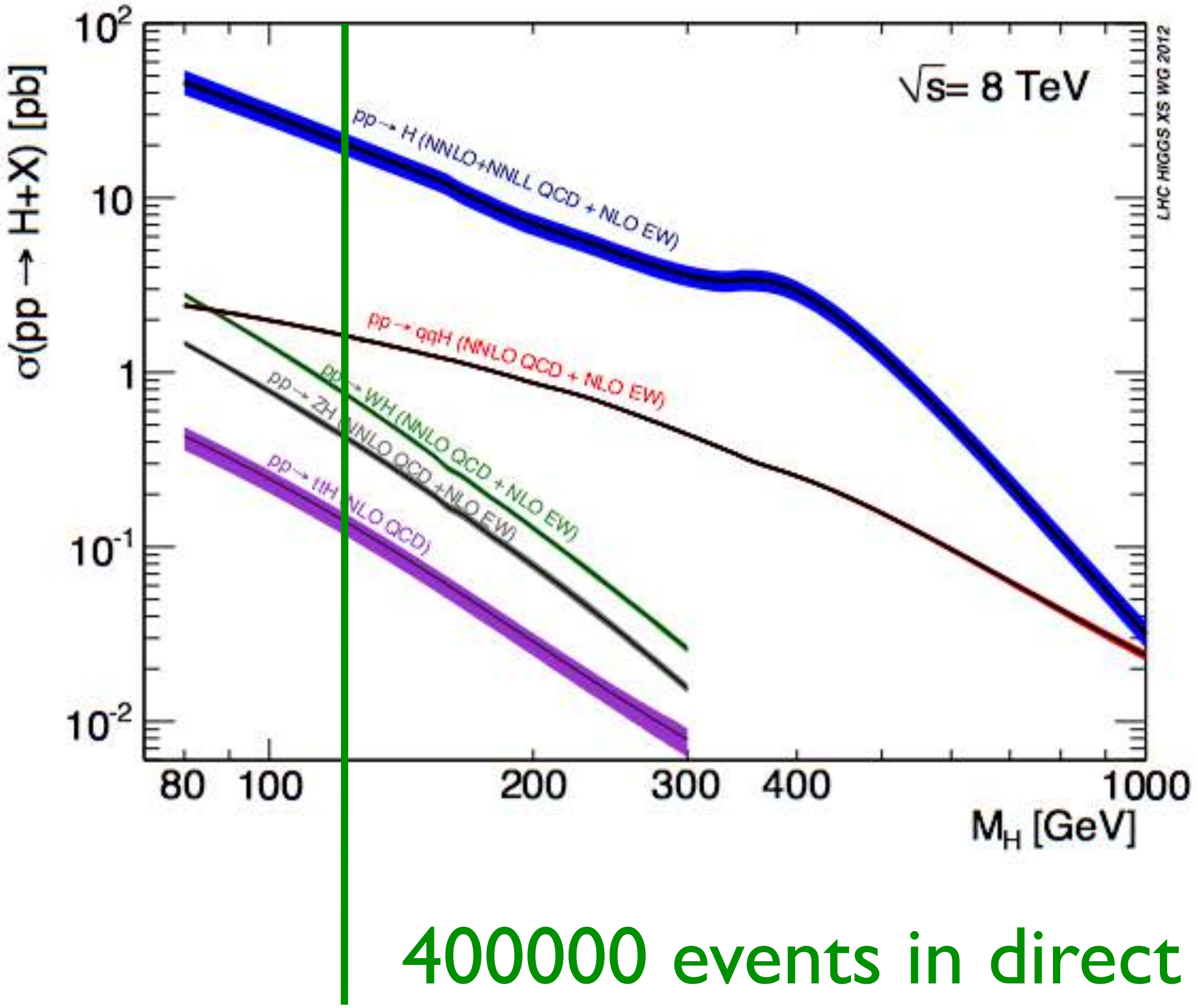


- Sometimes it's better to take the time needed to understand strange things…

A Semi-Challenging Search:
Higgs to $\tau\ \mu$

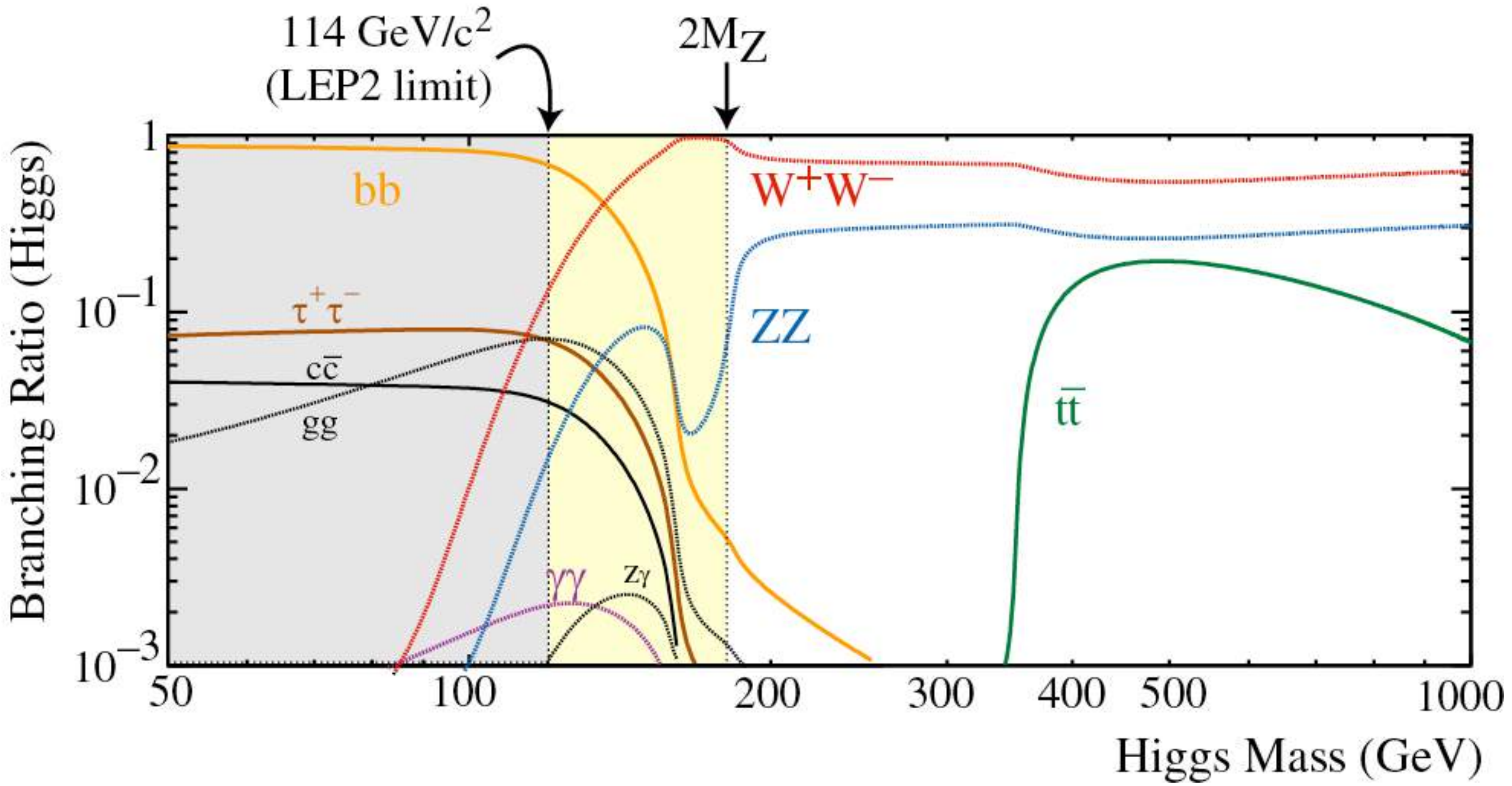
Producing Higgses

❖ 20 fb^{-1} collected by end 2012 at 8 TeV



400000 events in direct production
can look for rare decays!

Higgs Decay: 125 GeV is Golden



Low Mass

$H \to bb, \tau\tau, \gamma\gamma$

High Mass

$H \to WW, ZZ$

$\mu + \tau$

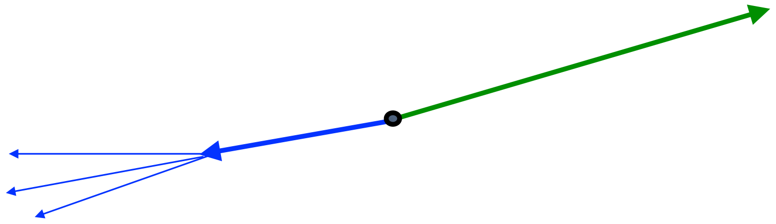
- Indirect constraints fairly weak (as opposed to e.g. $e+\mu$)
  - Indirect: BR($\mu\tau$) < ~10%; BR($e\mu$) < ~10^{-8}
- Lepton Flavor remains a mystery
  - Observing LFV crucial in understanding origin
  - Know it exists in the neutrino sector
- Experimentally:
  - With 400k Higgses produced, 1% BR yields 4000 signal events (x efficiency)
  - Two leptons ⇒ small to moderate background at hadron collider

Tau decays

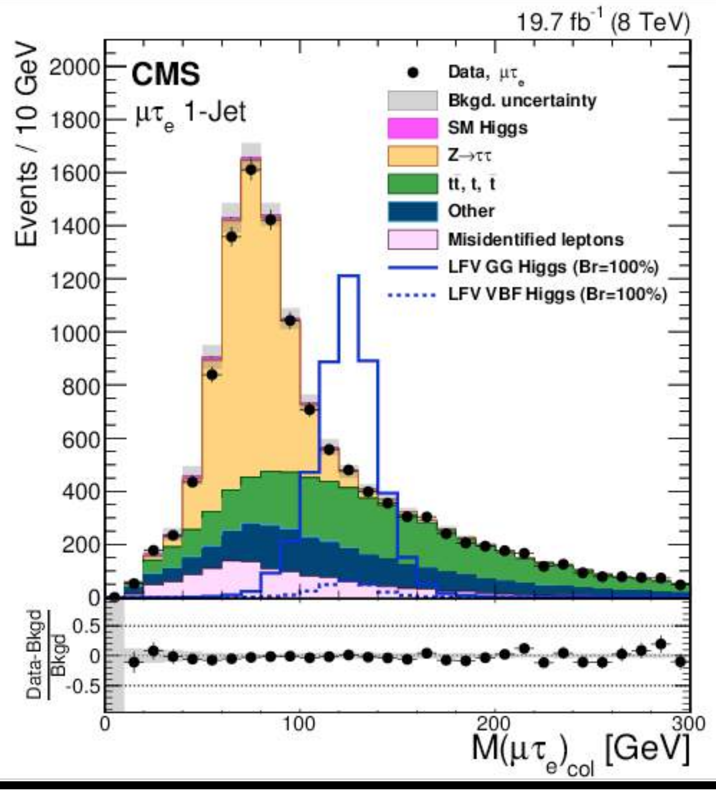
- Exploit two channels:
  - $\tau \rightarrow e\nu\nu$: BR = 18%
  - $\tau \rightarrow h\nu$: BR = 49% (one charged particle) + 15% (three charged particles)
  - Avoid $Z \rightarrow \mu\mu$ background
- Final states are $\mu\tau_e$ and $\mu\tau_h$
  - Irreducible background is $Z \rightarrow \tau\tau$
  - Primary discriminating variable is μ-τ invariant mass
    - Unfortunately not directly reconstructible: neutrinos escape!

Collinear Mass

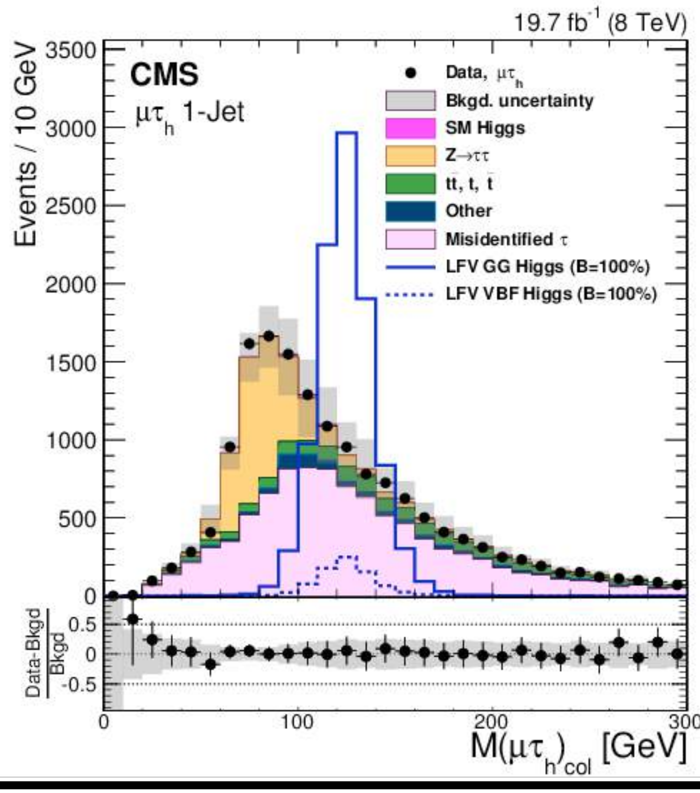
- ❖ m(H) = 125 GeV, m(τ) = 1.8 GeV
  - ➡ Tau is heavily boosted
  - ➡ Tau decay products are collinear with tau



- ❖ Under that assumption, know neutrino direction
  - From direction and missing transverse momentum infer neutrino longitudinal momentum



Preselection

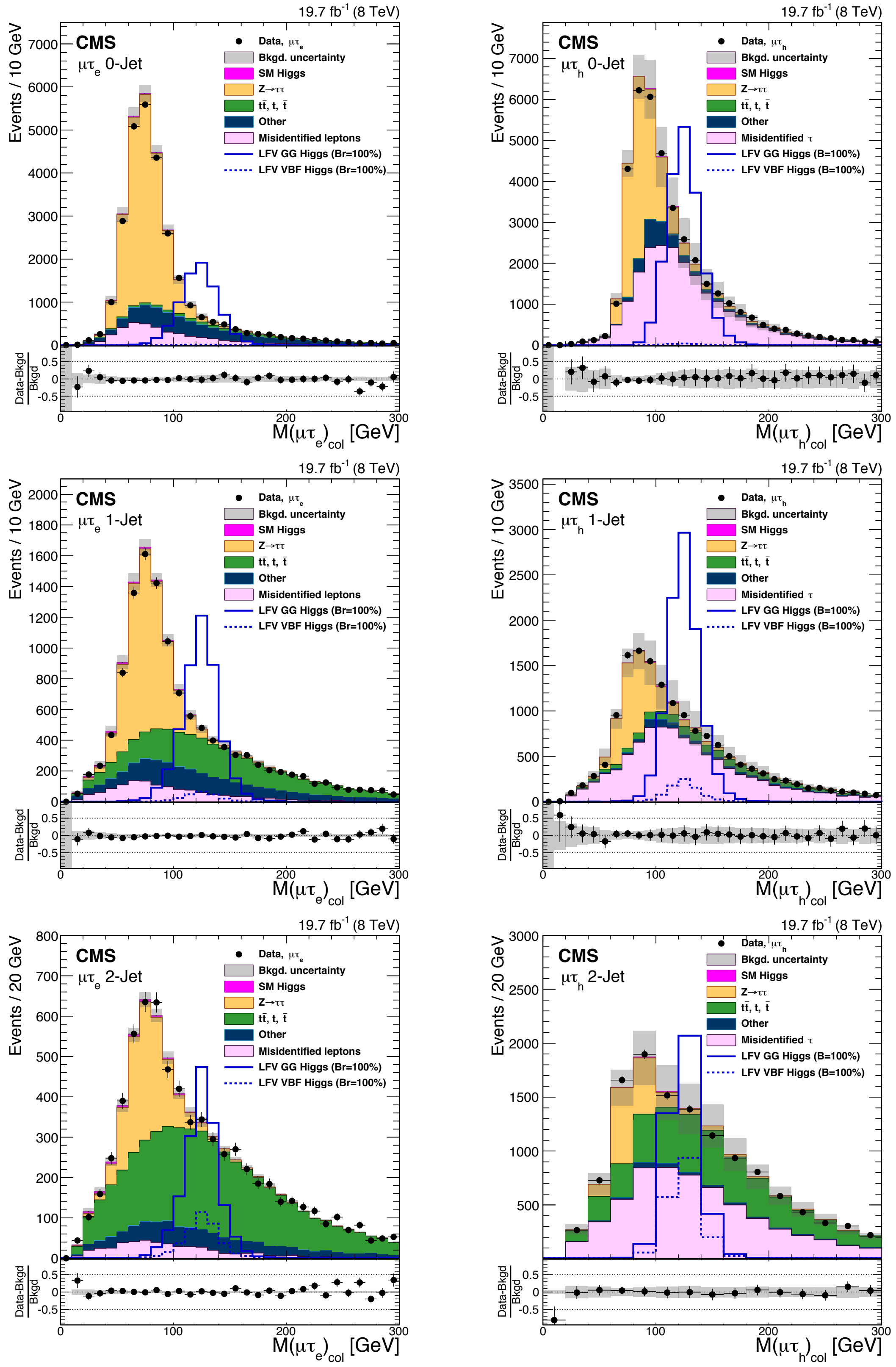


CMS: arXiv:1502.07400

Phys. Lett. B 749 (2015) 337

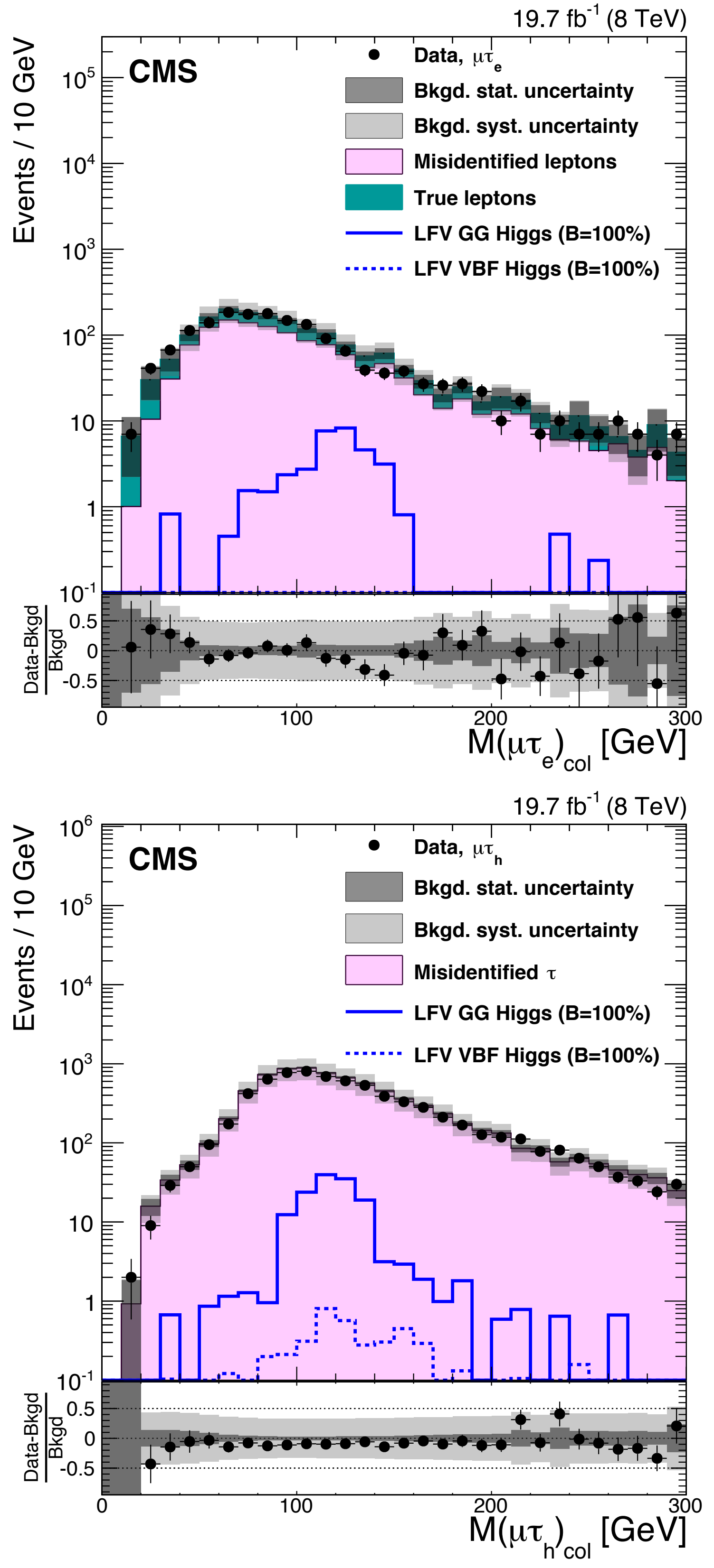
Categorize!

- ❖ Different production mechanism (gluon fusion vs. vector boson fusion) lead to different topologies
  - In practice number of jets
- ❖ Different decay channels have different reducible backgrounds
  - Hadronic tau decays are low multiplicity jets
- ❖ Categorize to exploit different S/B!
  - Assign corresponding weights (typically ln(1+S/B)), to increase sensitivity



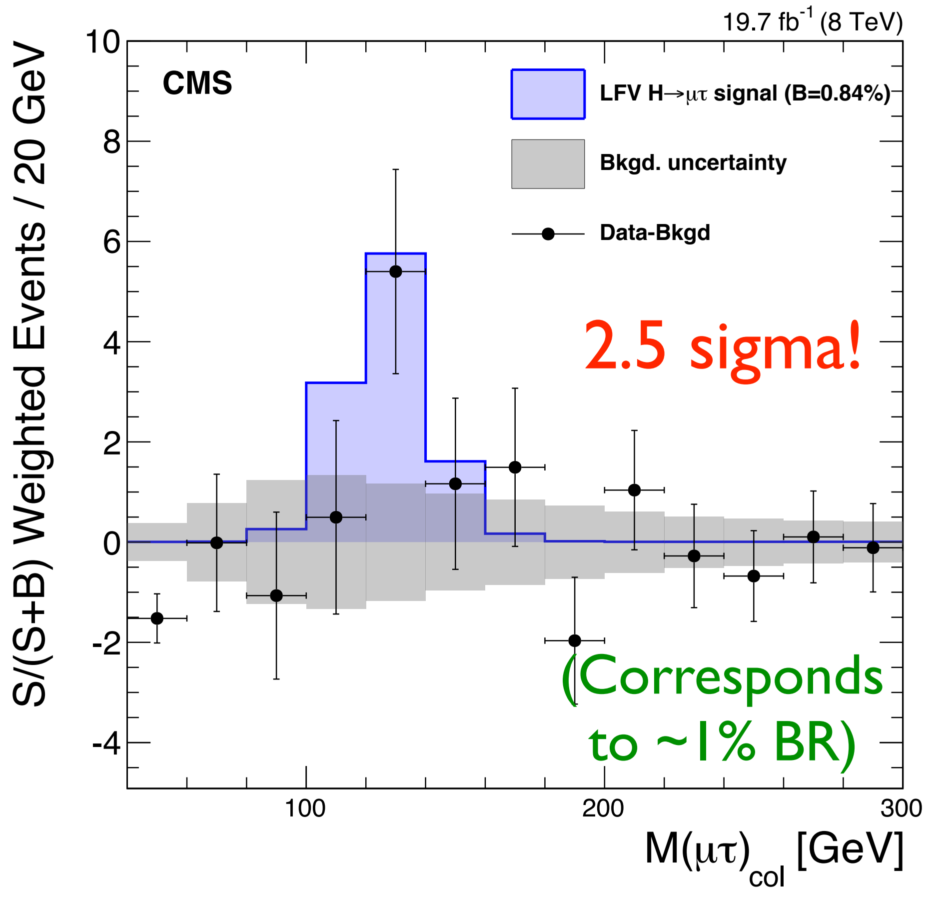
Backgrounds

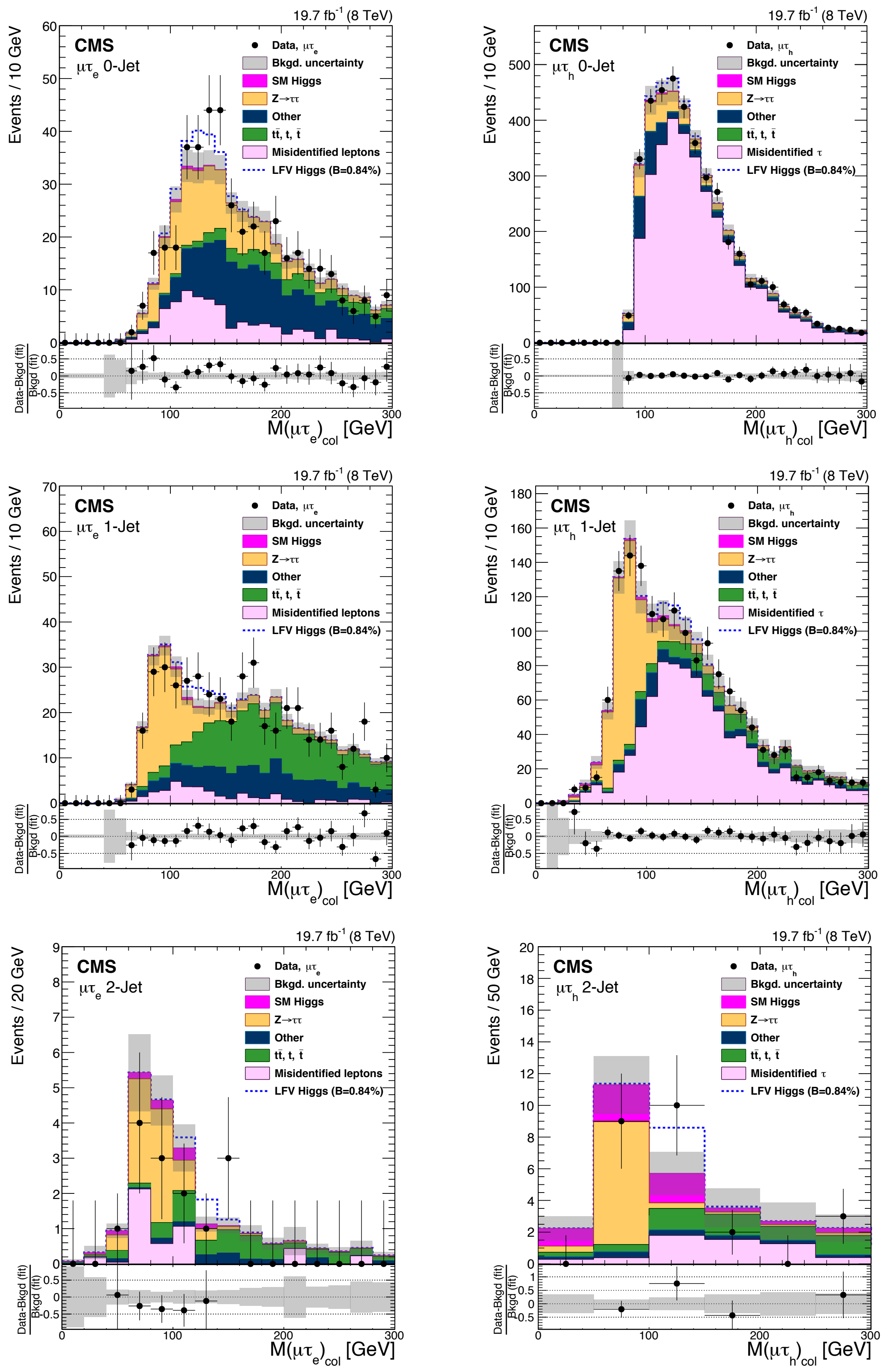
- Small signal ⇒ need very accurate background estimate
  - Use data where possible
- In this case:
  - $Z \to \tau\tau$ (irreducible): take $Z \to \mu\mu$ events from data, replace one muon with simulated tau
  - Misidentified leptons: get control sample, and independently measure probability to fake e or τ_h, check in control region
  - Rest: simulation



Finally

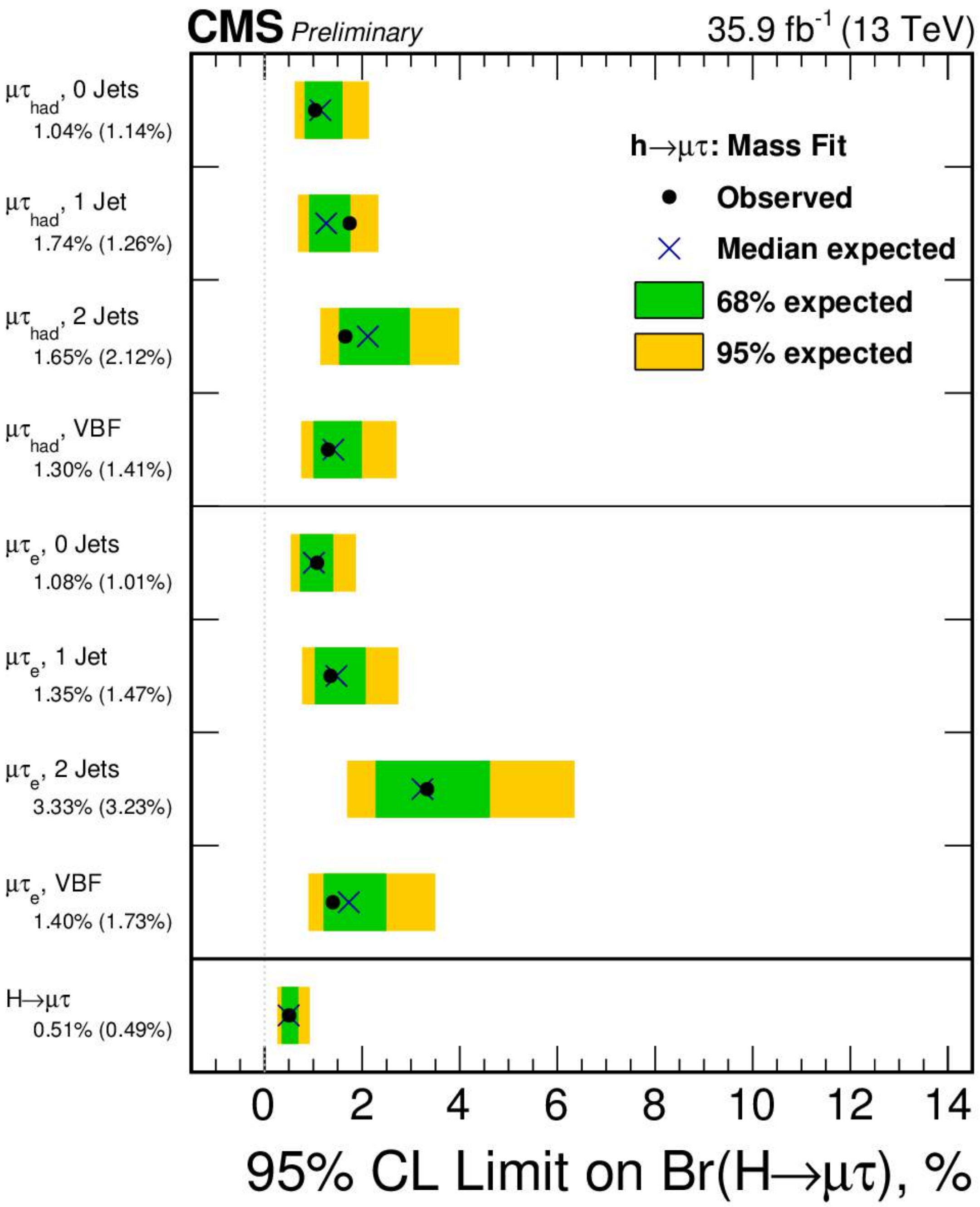
- ❖ Tighten cuts and look for signal
- ❖ Don't forget systematic uncertainties
  - Difficult topic: estimators often have known flaws, but “best we can do”

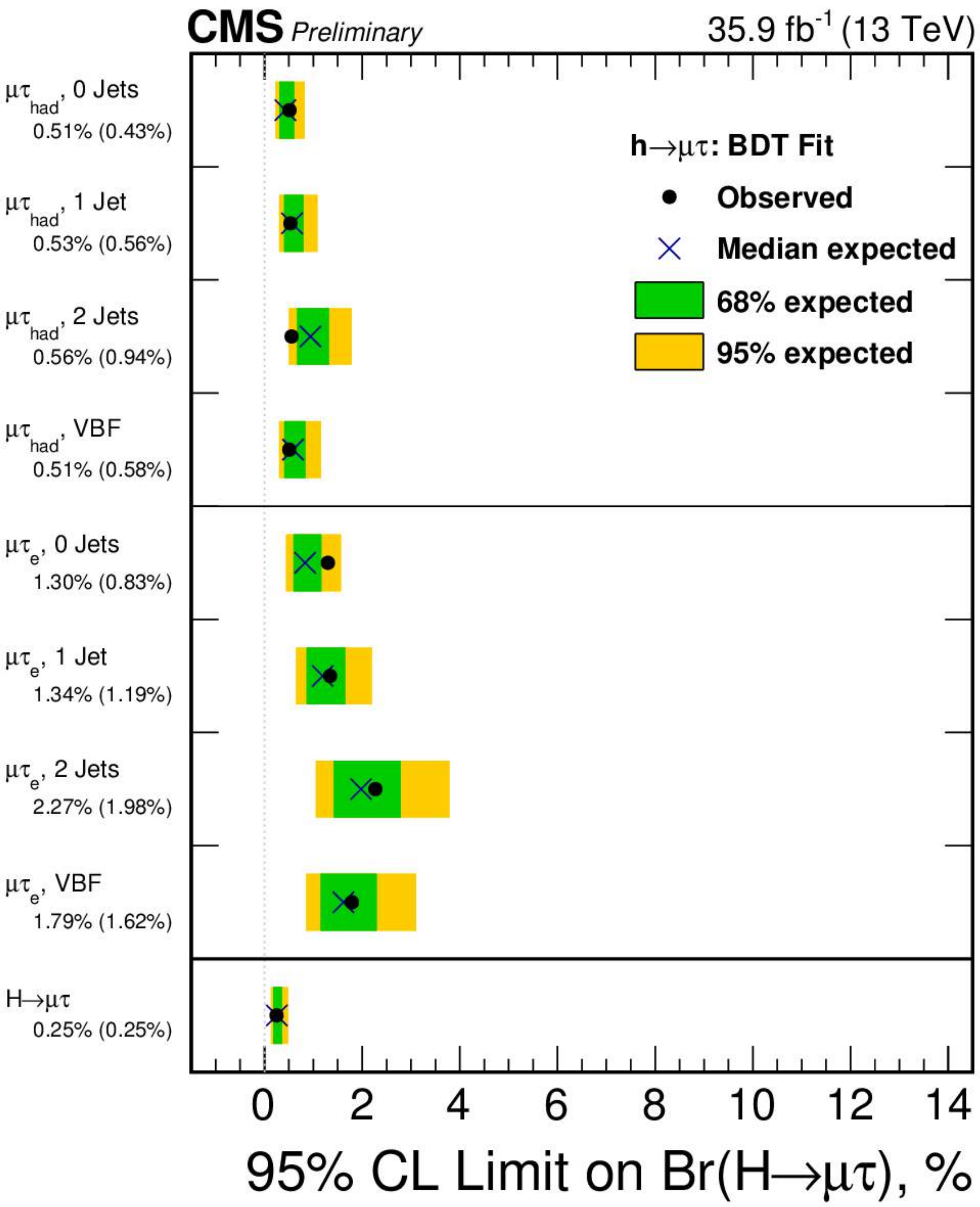




Run 2

CMS-PAS-HIG-17-001





So, Physics Analysis

- ❖ Start from:
  - “*How well* do we understand data *and* the SM?”
    - How confident are we in corrections we apply?
- ❖ Given that:
  - Which measurements can we make? What do we need to do to improve our understanding?
- ❖ Balance the work!
  - Early, low background searches
  - Detailed understanding/verification of SM predictions

Complementary measurements!

- ❖ Increasingly complex searches
  - Tough backgrounds, hard work
  - Don’t scorn multivariate and statistical tools

Sample Composition

- After preselection, low S/B allows to verify shapes of dominant backgrounds
  - E.g. for WH, first before b-tagging (W+light), then with 1 tag (W+b), then 2 tag but more jets (top)
- Determining the sample's composition
  - I.e. which processes contribute, and how
    - Diboson from MC simulation (usually small, + "trust" MC)
    - Z+jets from data & MC ("easy" to get a clean sample, correct MC)
    - QCD multijet from data (no choice)
    - Top from MC + data
    - W + jets from MC + data, but ....

Increasing difficulty ↓

Generators Used

- We use four kinds of Monte Carlo generators
  - "Calculators" (often NNLO) do not actually generate events, they just calculate some (limited) distributions, like W p_T
  - Traditional 2 → 2 generators: LO, e.g. $q\bar{q}$ → WZ
    - Include parton shower, i.e. QCD radiation, and hadronization to jets
    - pythia and herwig
  - "Matrix Element" 2 → n (n < 9): LO, e.g. $q\bar{q}$ → eνjjjj
    - Necessary to generate events with multiple hard jets
    - Require matching to parton shower to avoid double counting
  - NLOwPS 2 → n generators: include NLO corrections
    - I.e. in a sense they are 2 → n with virtual corrections

Correction Factors

❖ Of course, the ME's are (N)LO, so "K-factors" needed

- Different ones for heavy flavor etc..... (DØ) convention

• K-factor is purely theoretical, and denotes a (N)NLO/LO ratio of cross sections;

• K'-factor is also theoretical, and denotes a (N)NLO/LL ratio of cross sections. According to Steve, ALPGEN cross sections are Leading Log;

• S-factor is empirical, and comes on top of K or K' to bring MC in agreement with data. MC should be initially normalized to luminosity, and all correction (a.k.a. scale) factors should be applied (trigger, ID...);

• HF-factor is, in principle, theoretical, but in practice only theory inspired. It tells you by how much heavy flavor production should be increased, on top of K or K', and possibly S;

• S_HF-factor is empirical, and comes on top of K or K', S, and HF, to bring MC in agreement with data, after b-tagging.

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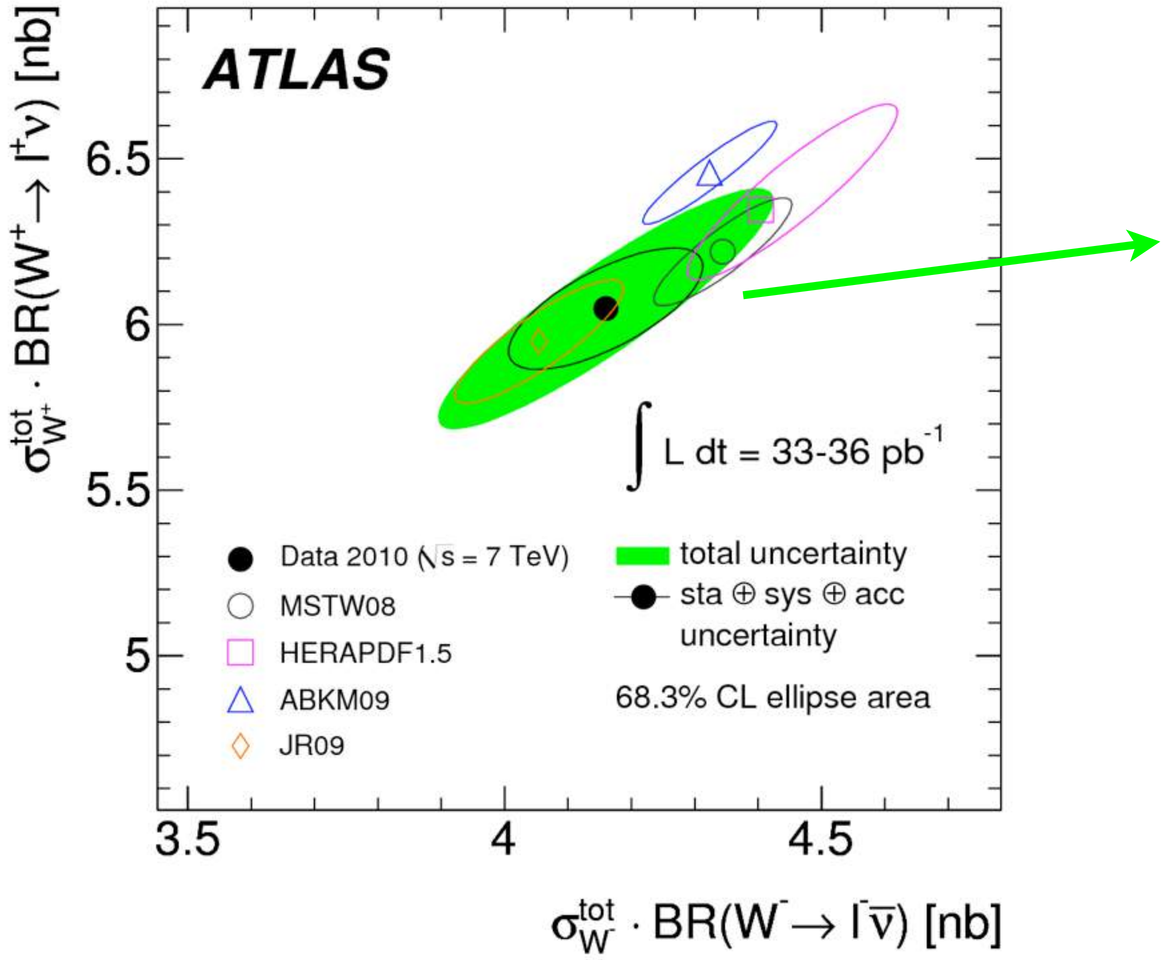
In addition to W/Z PT reweighting

Sometimes Physics Helps

- At the LHC, produce more W+ than W-
  - Can exploit that to normalize W+jets

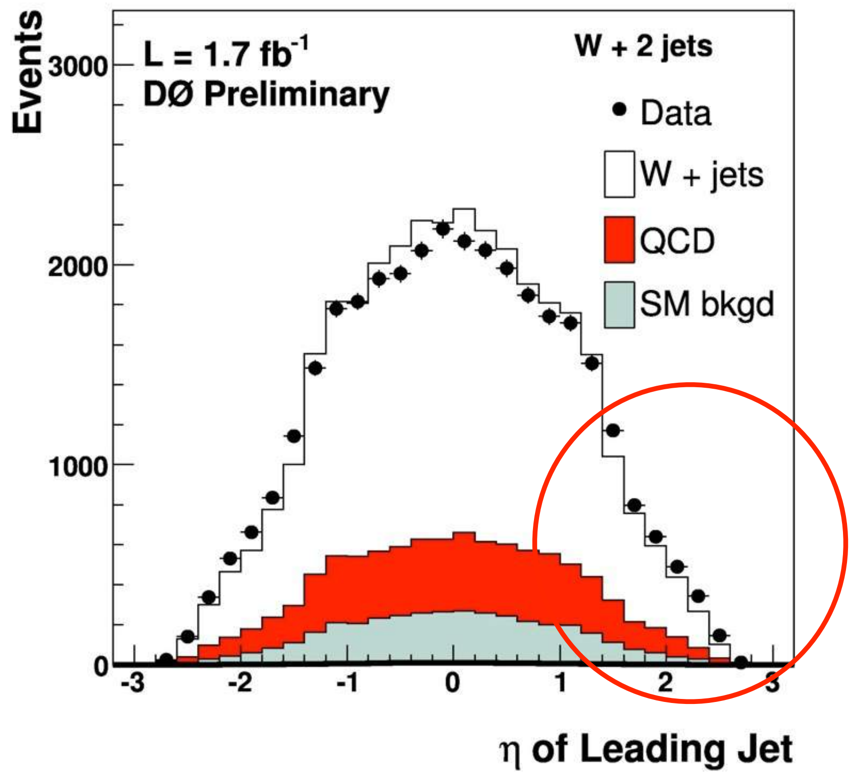


$$(N_{W^+} + N_{W^-})^{\text{exp}} = \left(\frac{r_{\text{MC}} + 1}{r_{\text{MC}} - 1}\right)(N_{W^+} - N_{W^-})^{\text{data}}$$

But what about shape??

Anecdotes From the Field (III)

- Pile-up events ("minimum bias") do produce jets



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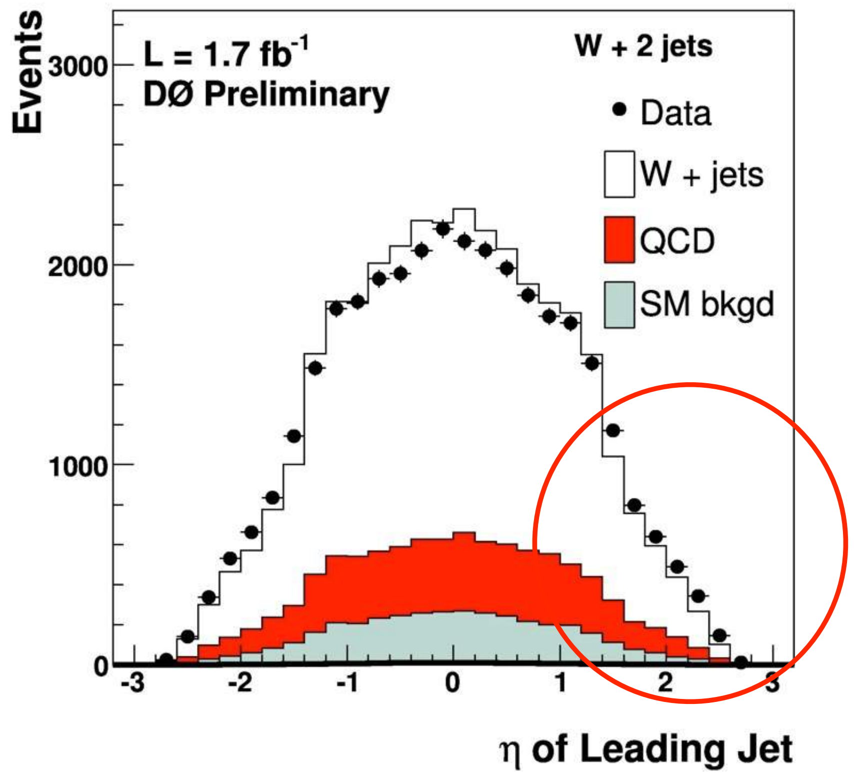
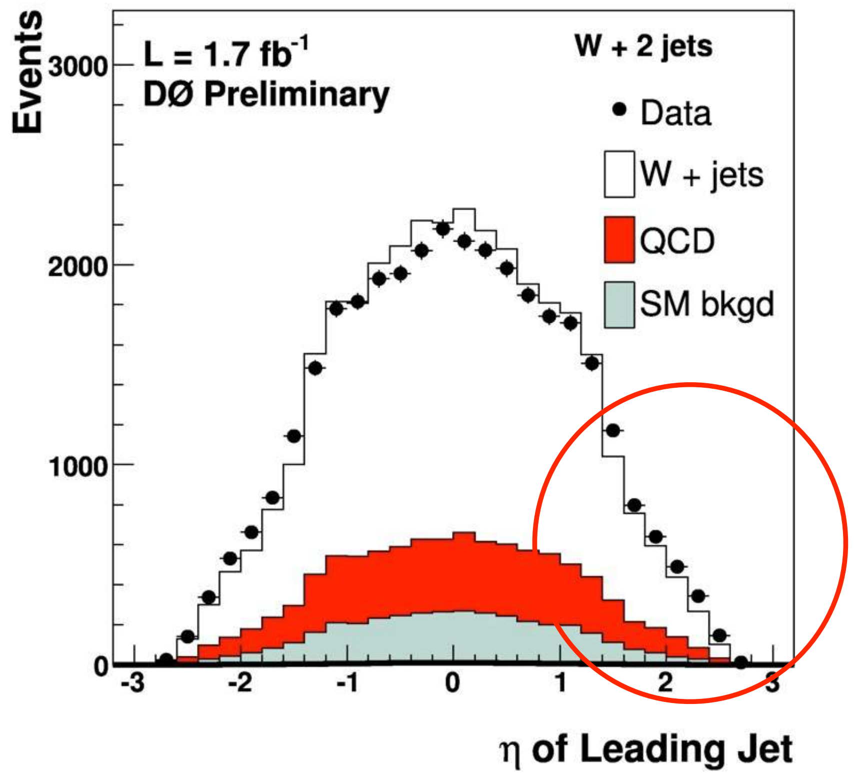
  - High η excess disappeared!



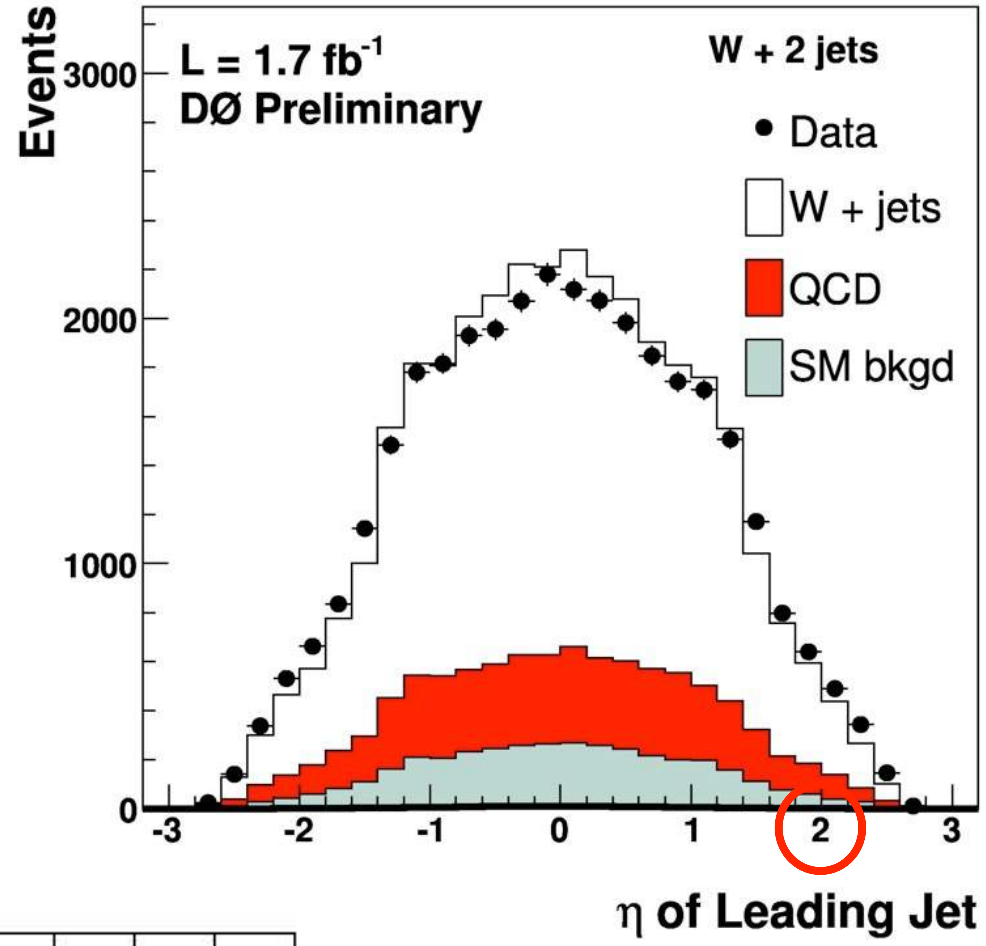
Anecdotes From the Field (III)

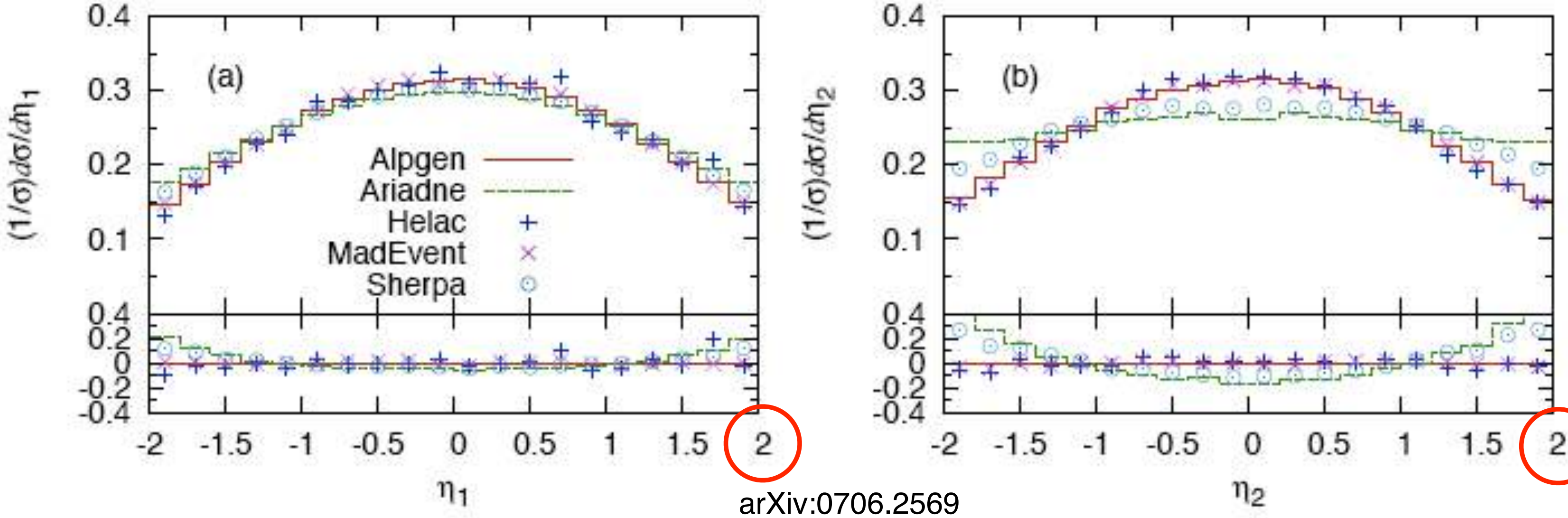
- Pile-up events ("minimum bias") do produce jets
  - At high $\mathscr{L}$, require that tracks pointing to jets originate from same vertex as lepton
  - High η excess disappeared!
  - Eta-dependence of jet-vertex match turns out to have shape very very similar to excess
  - After correcting for this, excess is back....



So…

- After all K/K'/S/HF-factors and boson p_T reweighing:
- Similar angular differences between generators: reweigh alpgen to sherpa





arXiv:0706.2569

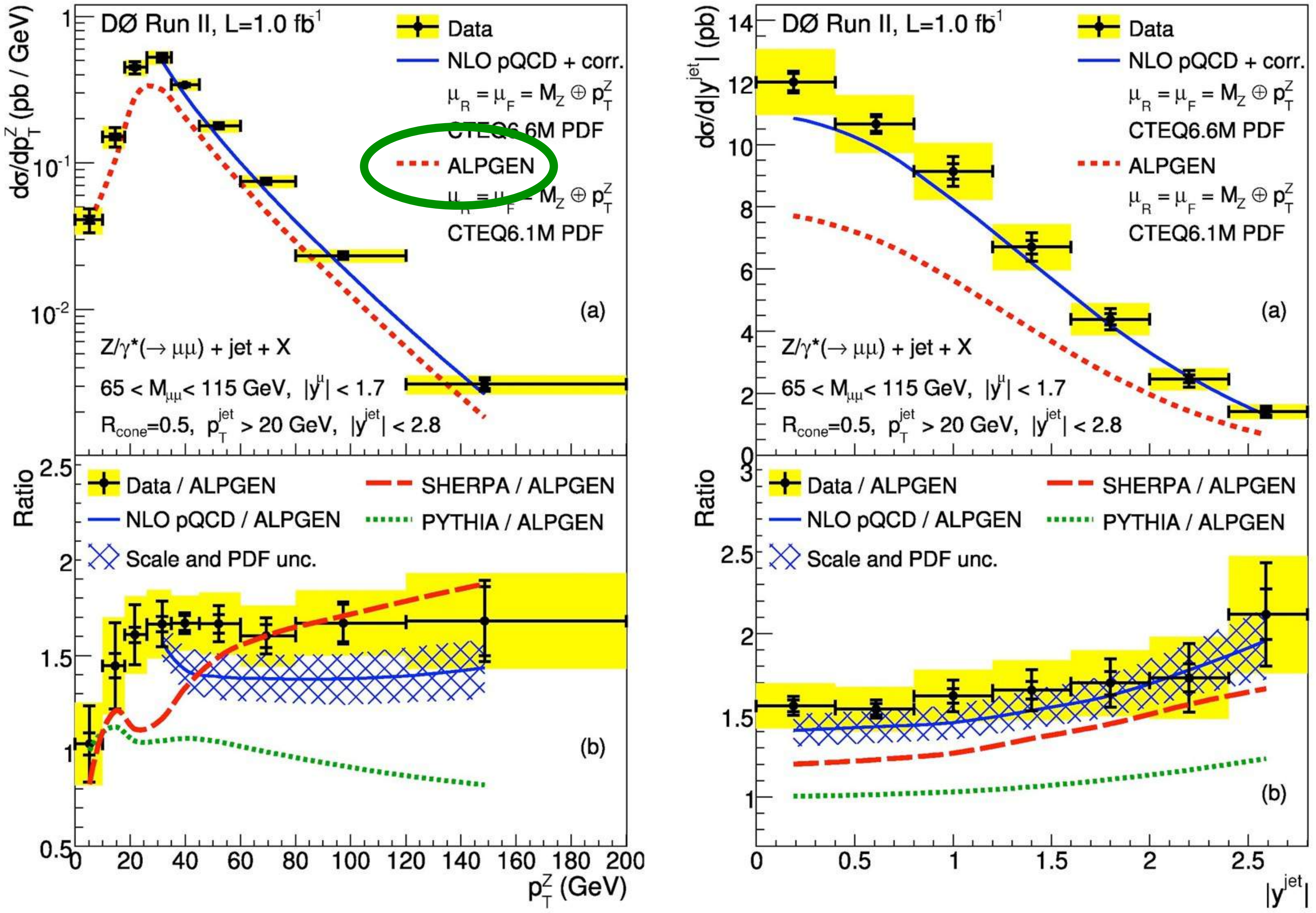
Alpgen, MadEvent, Helac with MLM, Sherpa and Ariadne with CKKW matching

Z (→ ℓℓ) + jets

❖ Can get a clean sample, check if our simulation reproduces the data

⇒ yes, with ~expected deviations

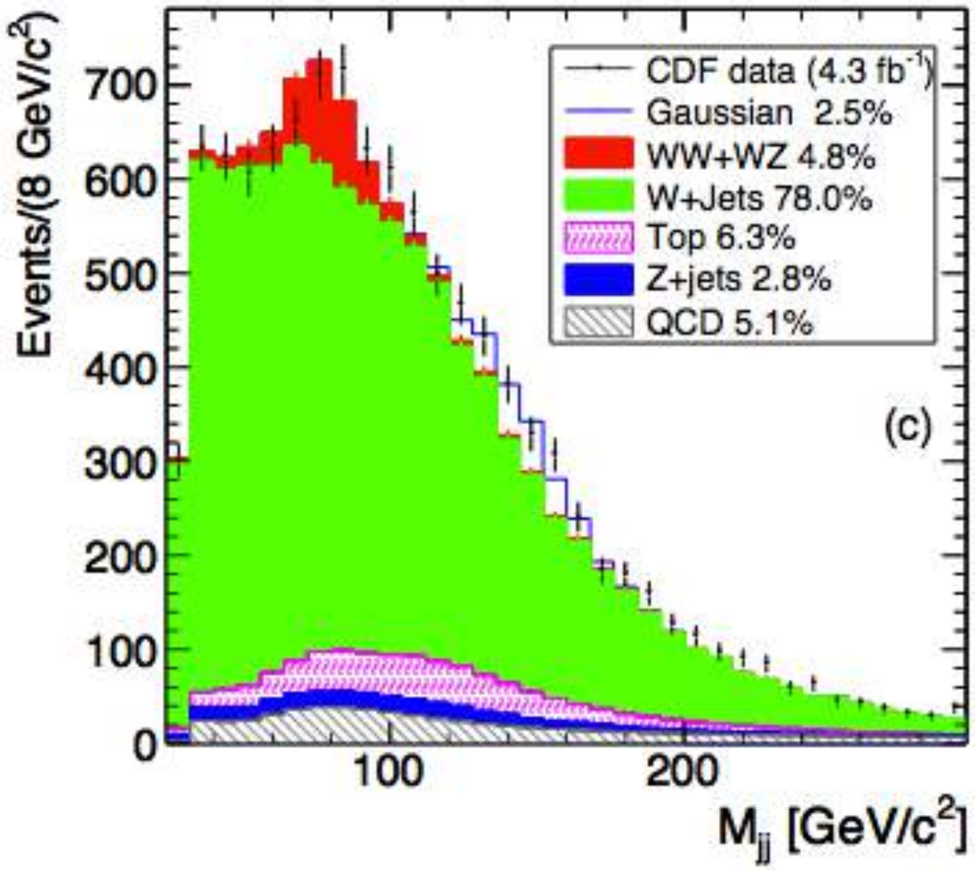
Need reweighing of MC

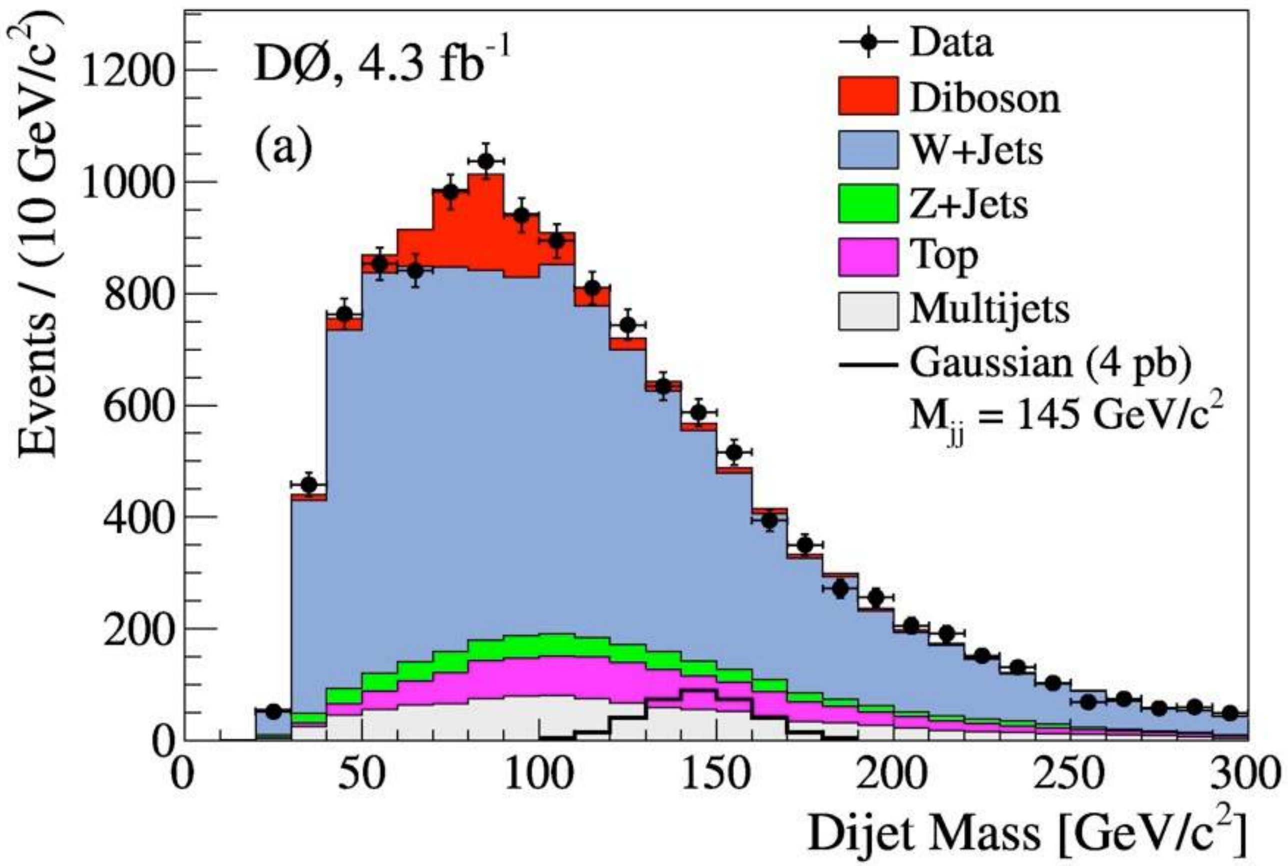


Anecdotes From the Field (IV)

❖ Searched for WW/WZ in $\ell\nu jj$

Phys.Rev.Lett.106:171801





❖ The background here is not SM, it is uncorrected alpgen!!

- But this is not the issue.....

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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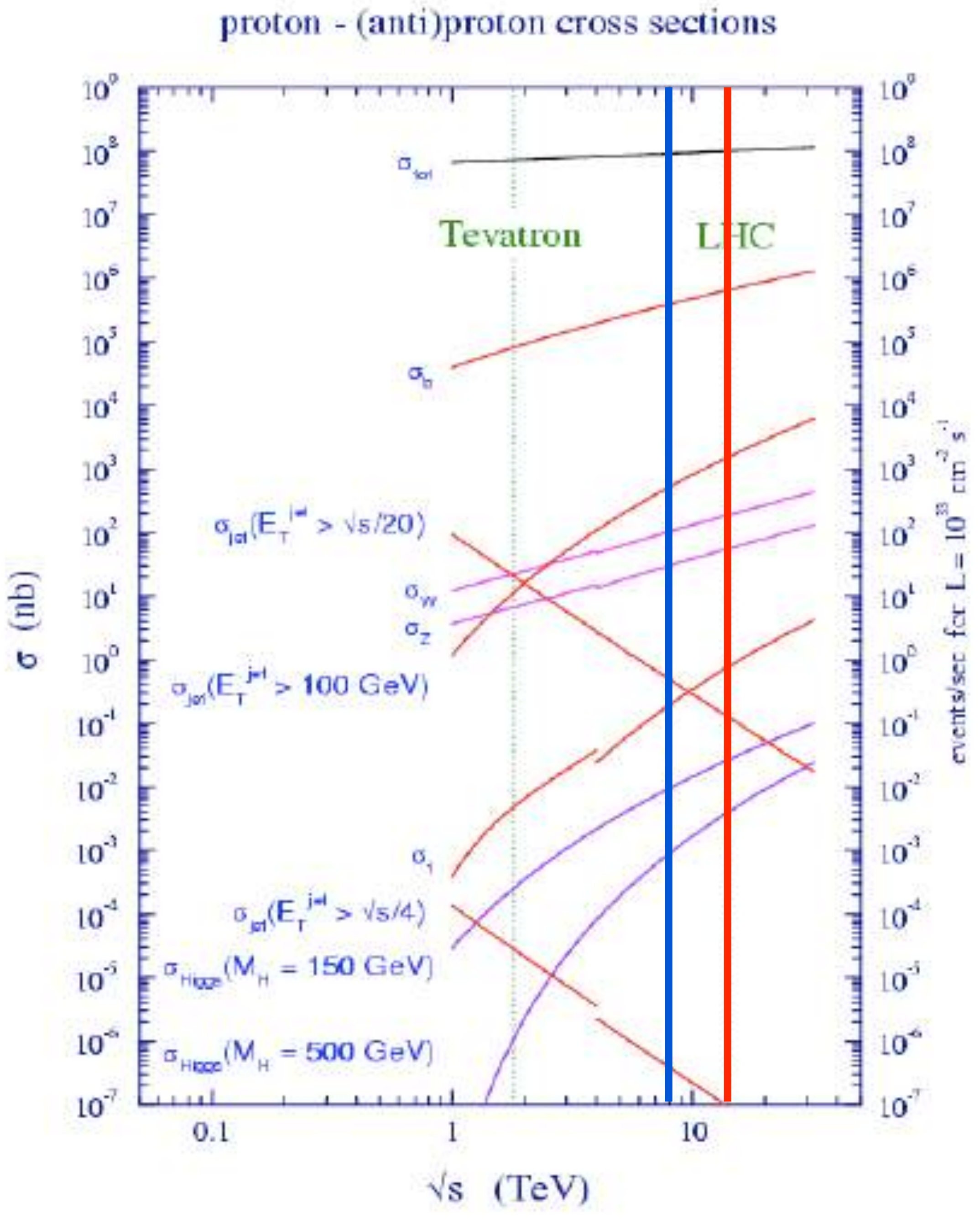
Nobody could have predicted QCD

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?

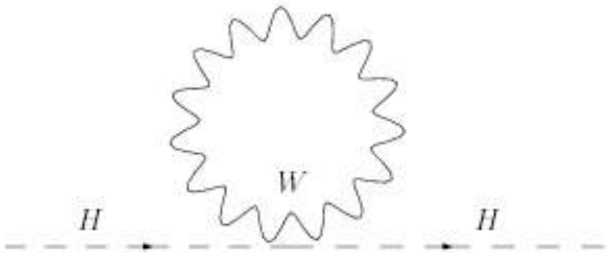


Experimental Searches

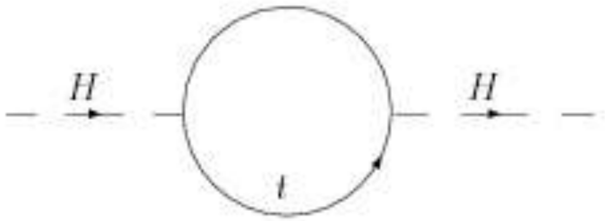
- By final state, so main questions are
  - Does the new physics produce dark matter?
    - Something we basically know exists and interacts weakly at best with SM
    - ➡ Yes: signatures contain missing transverse energy
    - ➡ No: MET not generic signature
  - Are there new interactions?
    - ➡ No: 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

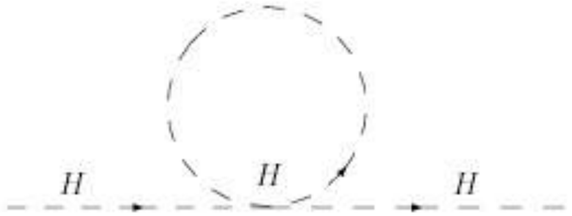
(Super)Symmetry Solution



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



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

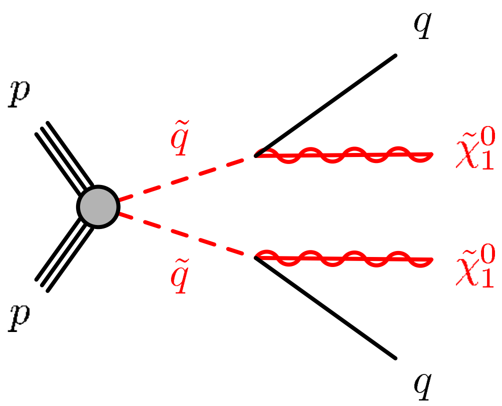


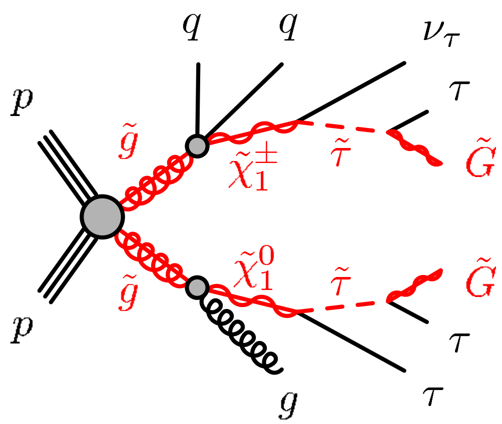
$$\rightarrow \frac{1}{16\pi^2} \lambda E^2$$

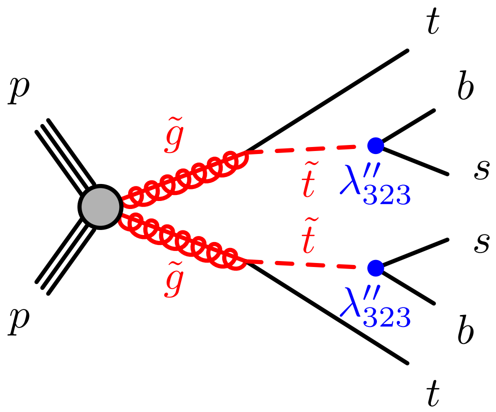
- ❖ If for every fermion there is a partner boson and vice-versa
  - Loops cancel each other
- ❖ Symmetry cannot be exact (no bosonic electron observed)
  - Symmetry breaking leads to “residual” Higgs mass
- ❖ This is supersymmetry
- ❖ With R-parity, get missing E_T
  - Generic to models with dark matter@LHC

Canonical SUSY

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

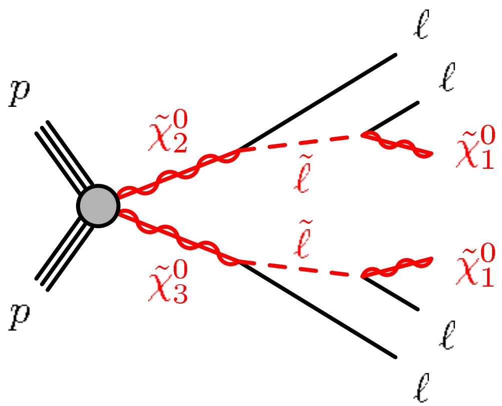


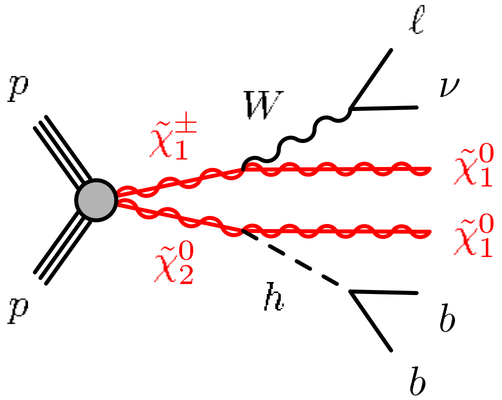


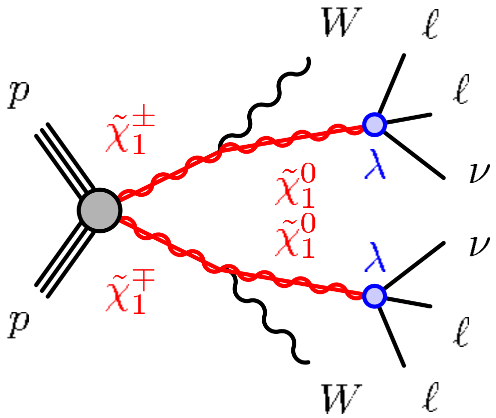


  - … or weak production

RPV





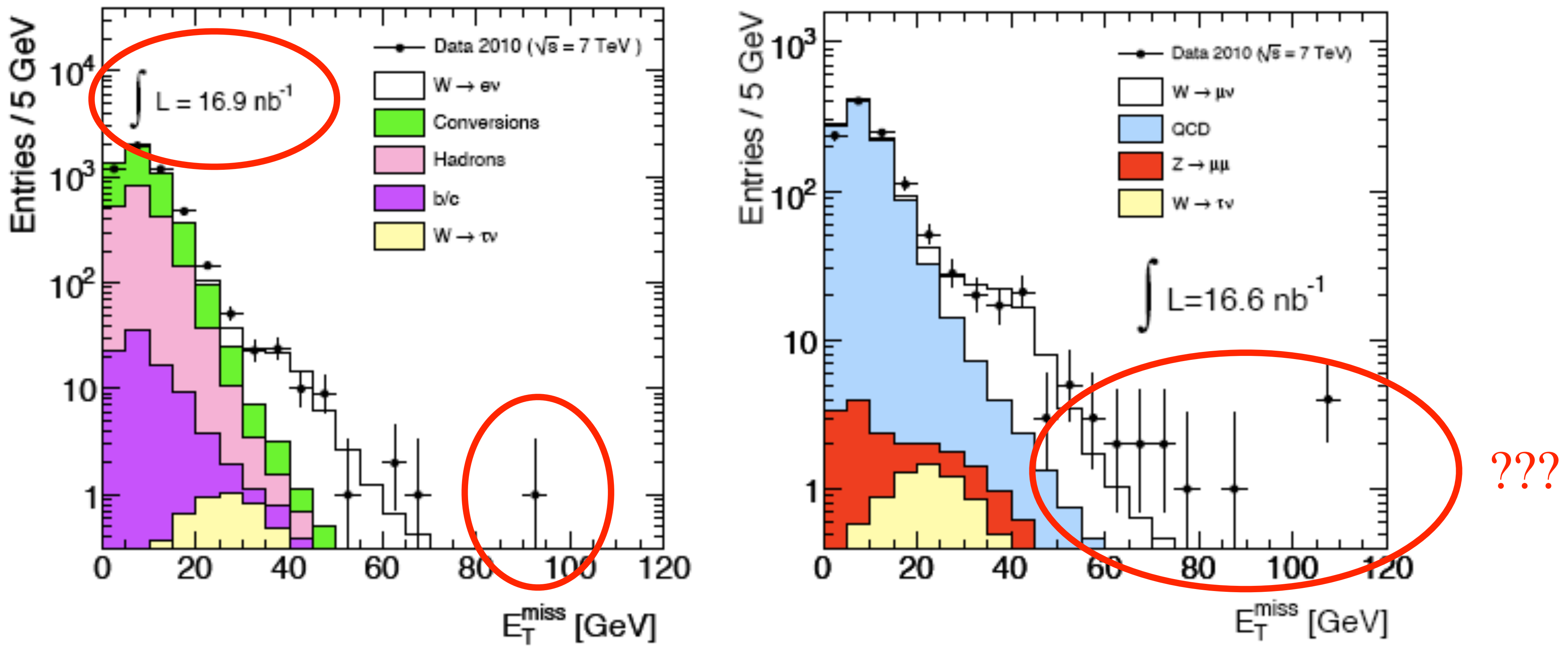


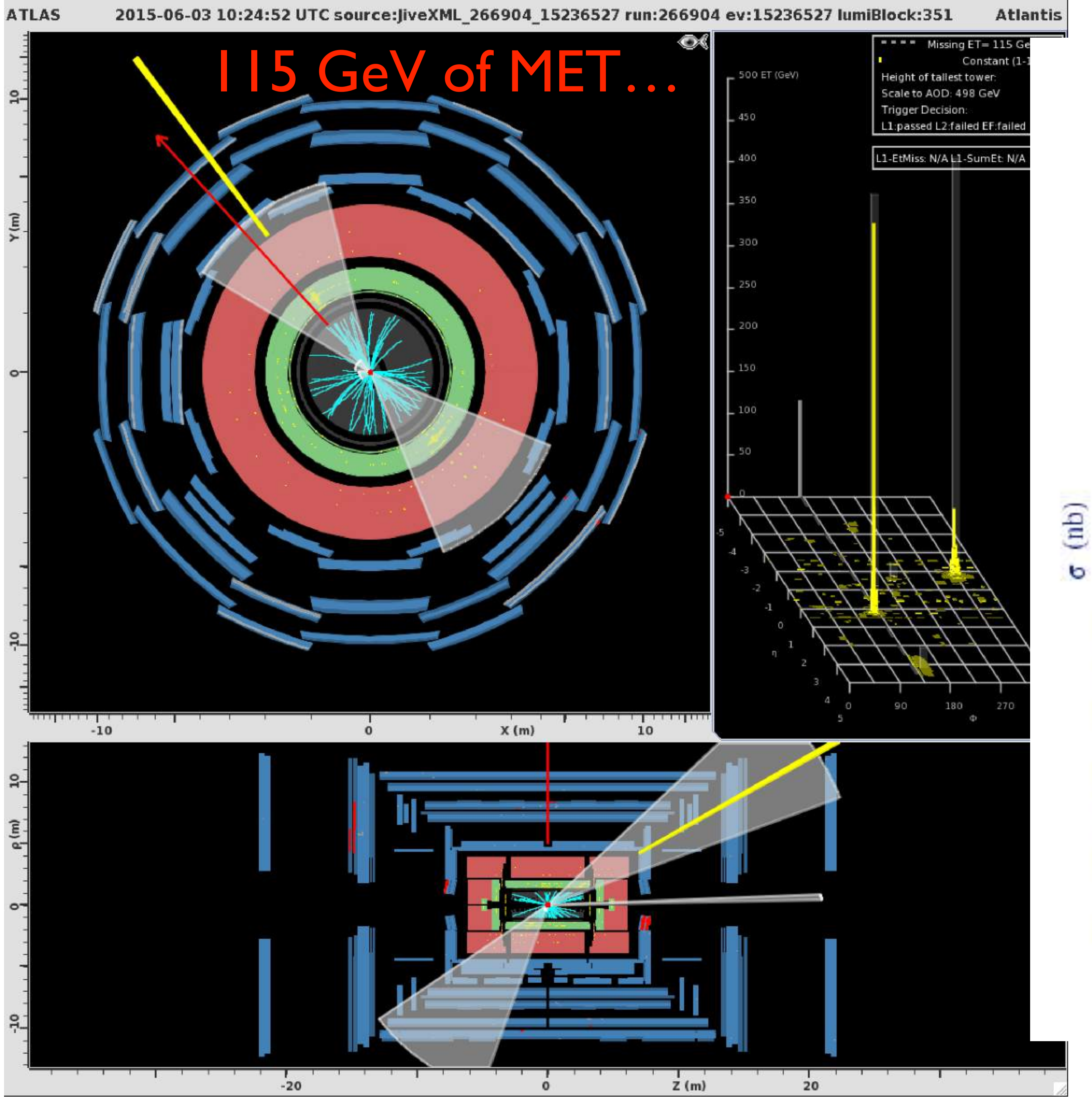
Missing E_T

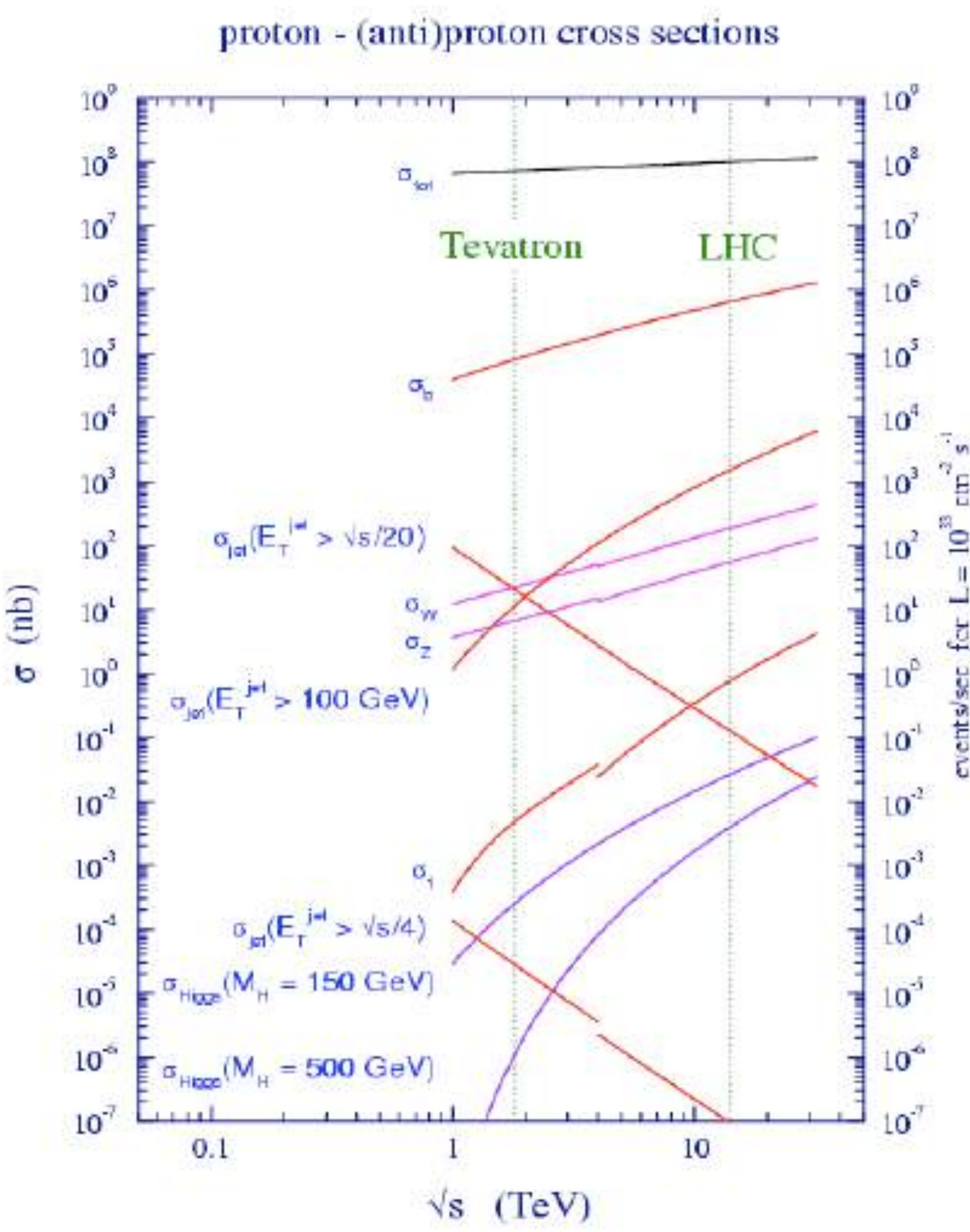
❖ "Evil" variable: - Σ (everything else)

- Need to understand "everything else"
- Good benchmark: leptonic W boson decays

Early 2010

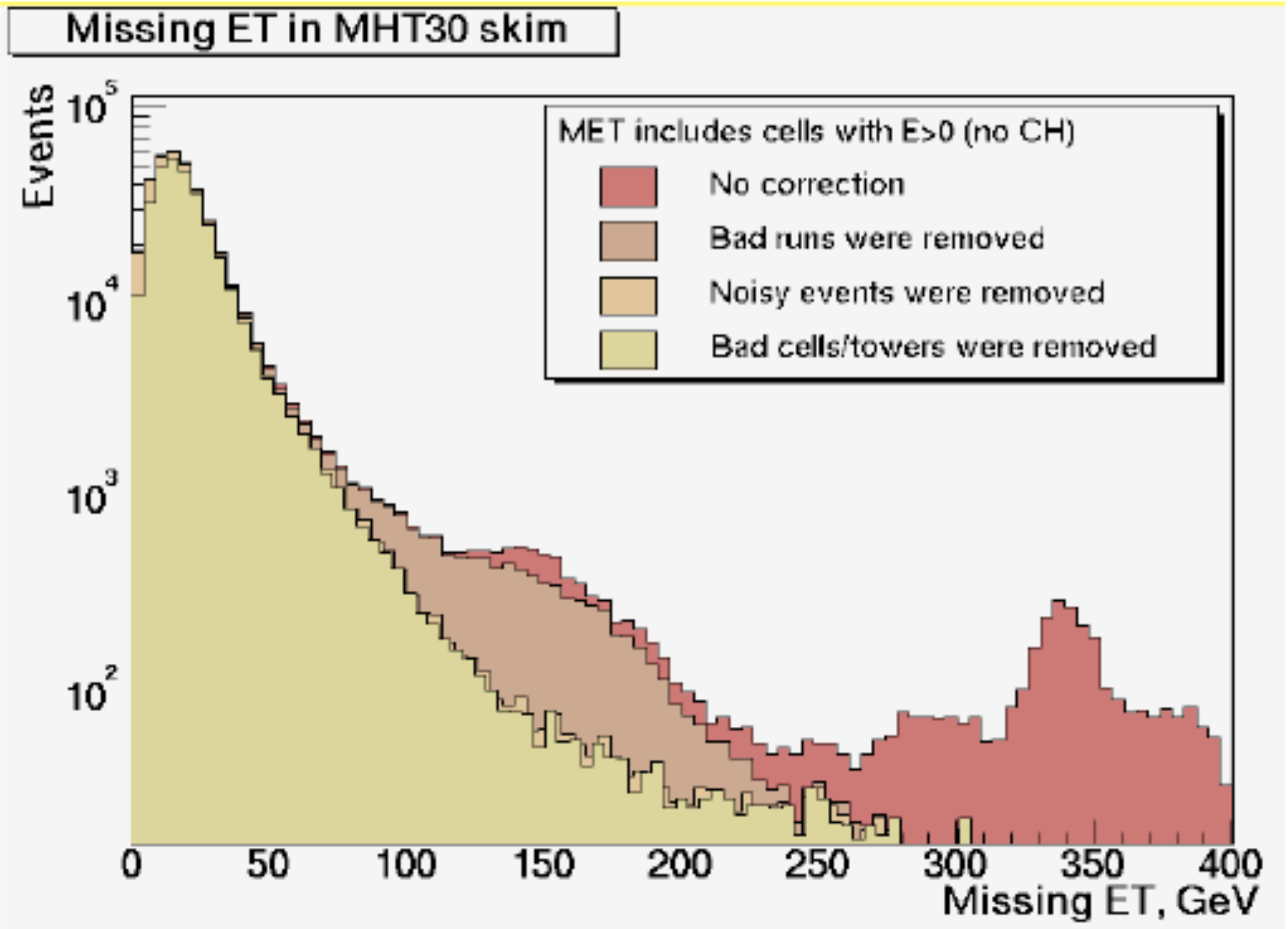



ATLAS
2015-06-03 10:24:52 UTC source:JiveXML_266904_15236527 run:266904 ev:15236527 lumiBlock:351
Atlantis
115 GeV of MET…
Missing ET= 115 GeV
Height of tallest tower:
Scale to AOD: 498 GeV
Trigger Decision:
L1:passed L2:failed EF:failed
L1-EtMiss: N/A L1-SumEt: N/A
X (m)
Y (m)
Z (m)
ρ (m)

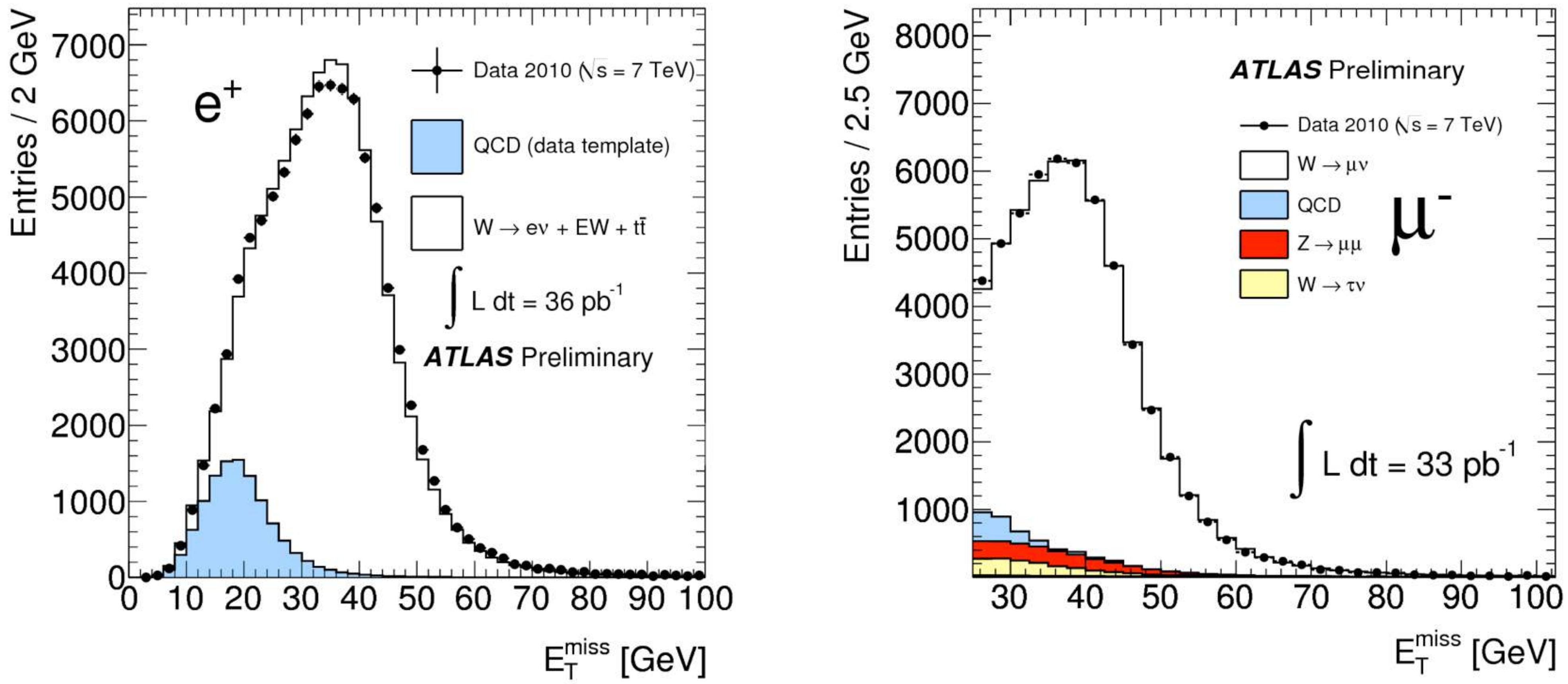

proton - (anti)proton cross sections
Tevatron
LHC
σ (nb)
√s (TeV)
events/sec for L = 10^33 cm^-2 s^-1
σ_tot
σ_b
σ_jet(E_T^jet > √s/20)
σ_W
σ_Z
σ_jet(E_T^jet > 100 GeV)
σ_t
σ_jet(E_T^jet > √s/4)
σ_Higgs(M_H = 150 GeV)
σ_Higgs(M_H = 500 GeV)

❖ 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,…

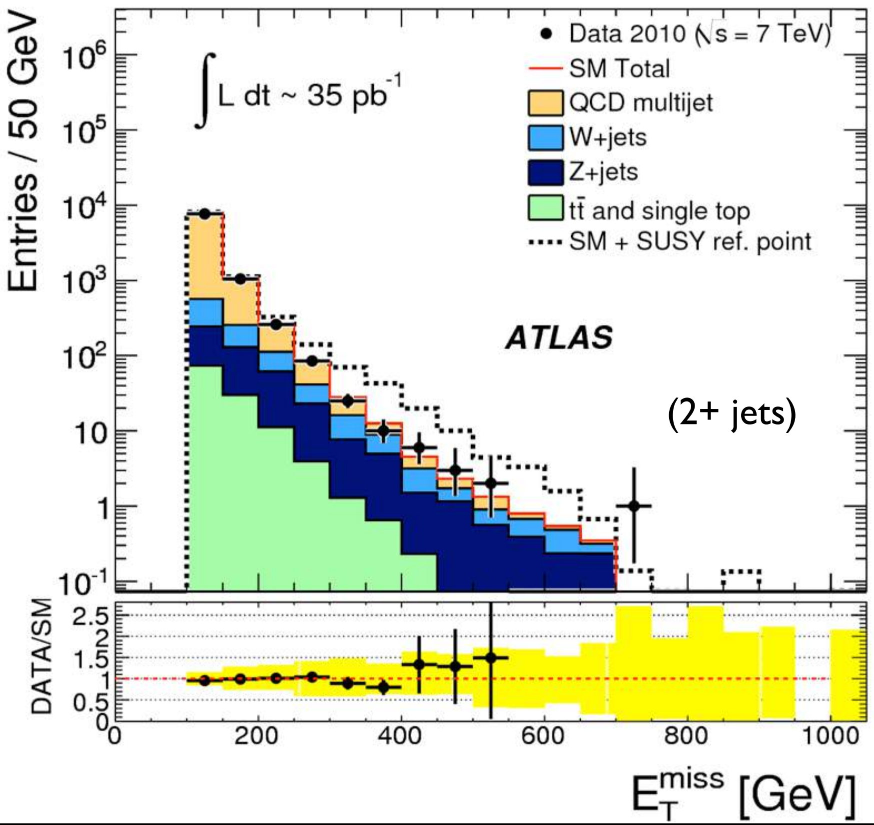


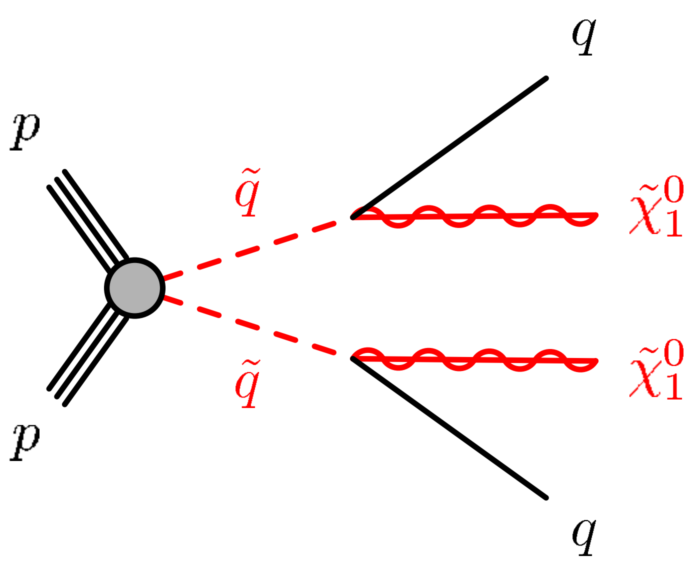
❖ Already ~200k clean W → $\ell\nu$ events in 2010

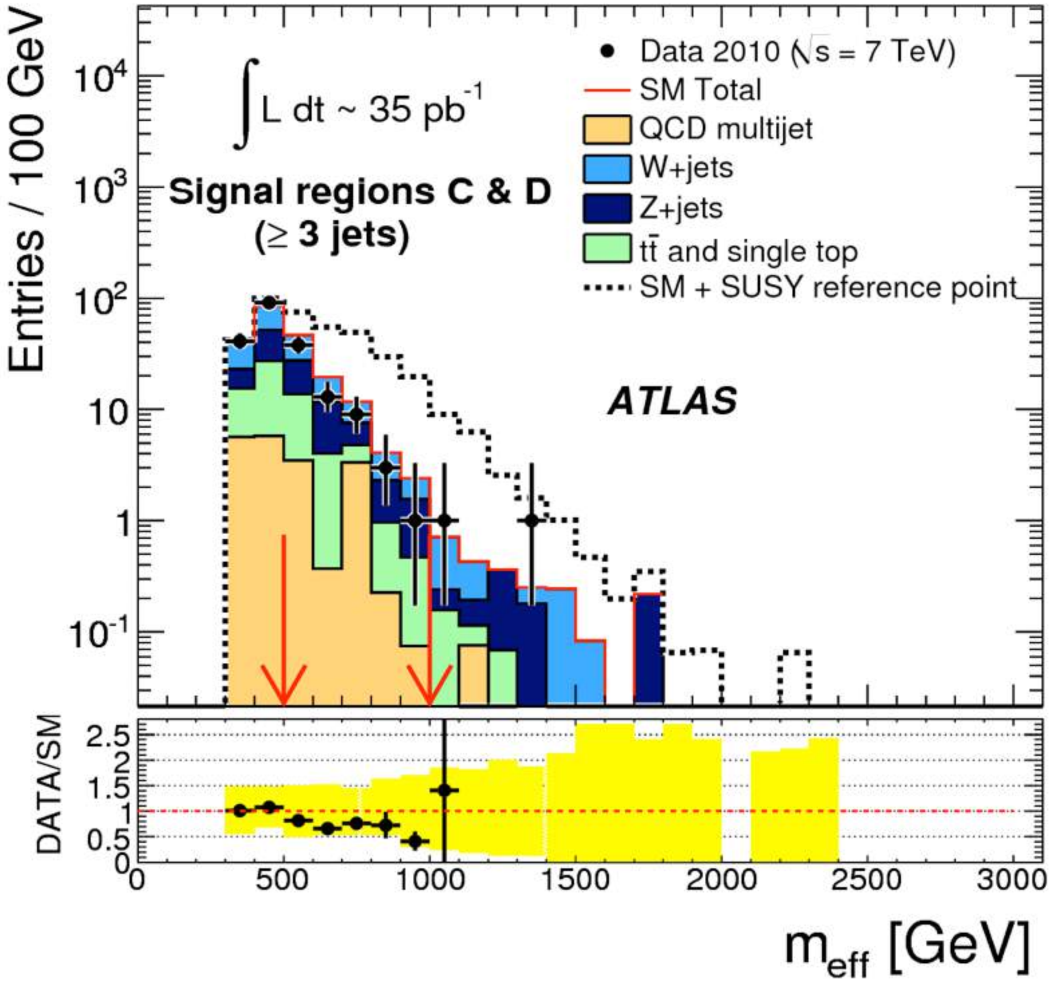
- Billions now

SUSY as a Benchmark

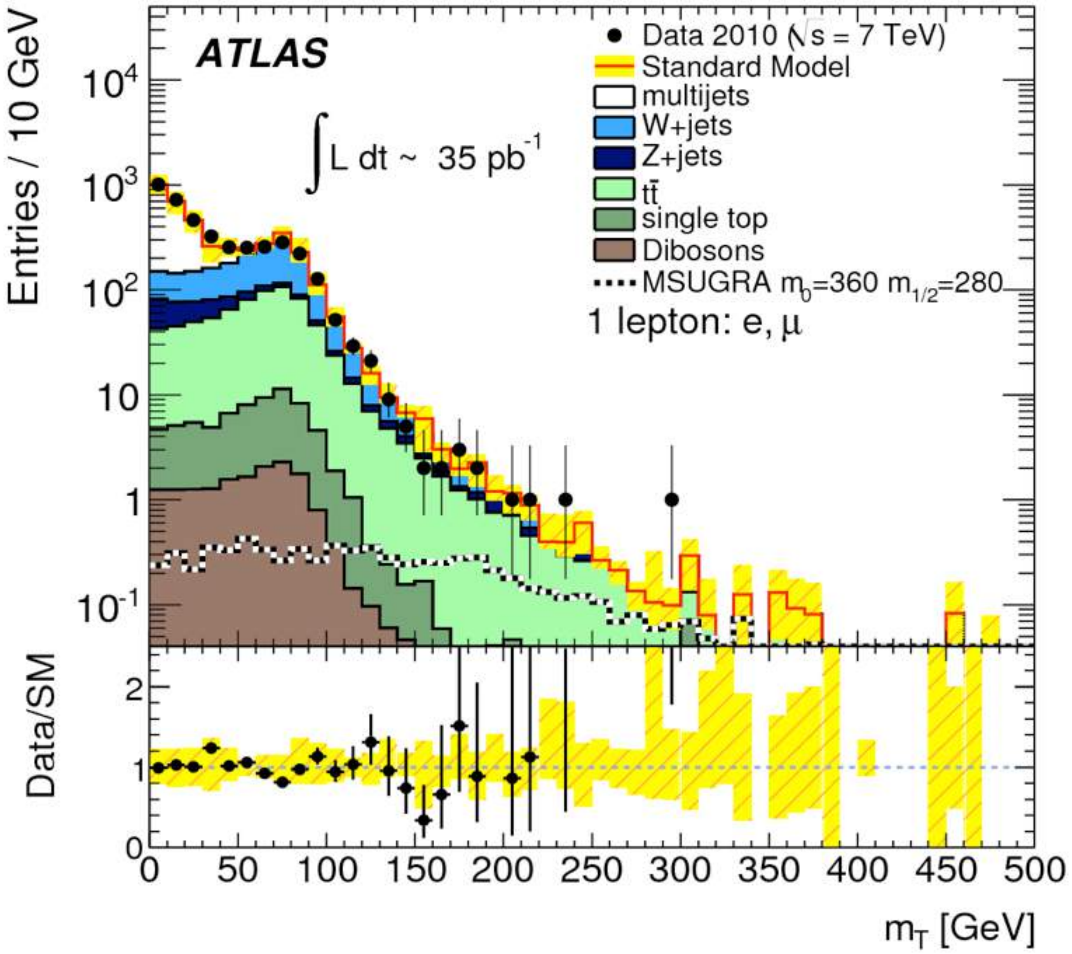
- ❖ Hadron collider ⇒ produce squarks and gluinos decaying to jets + MET
  - Optimize jet p_T & MET cuts for different scenarios, since gluinos produce more jets than squarks
    - Use M_{eff} to discriminate, measure of event Q^2

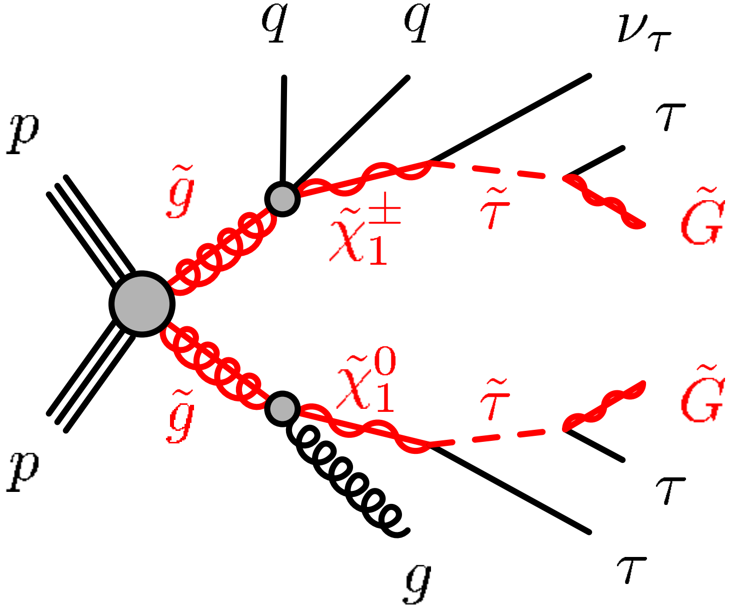


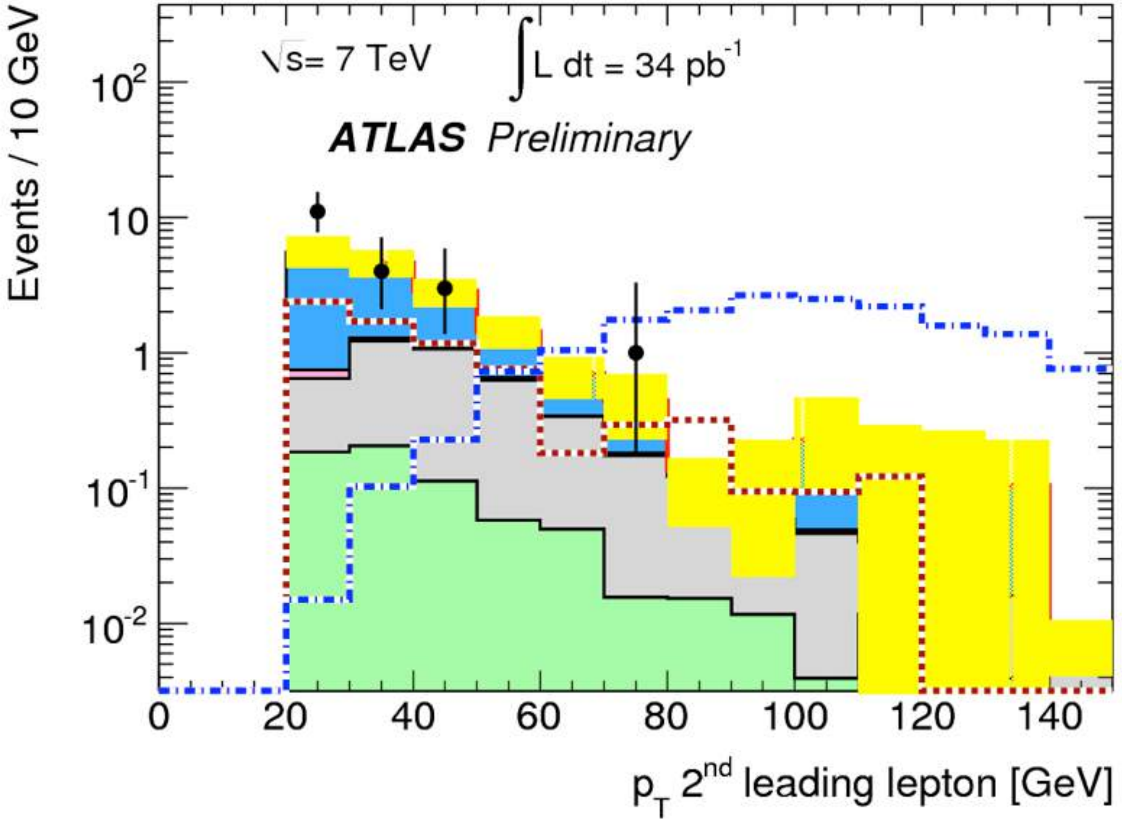




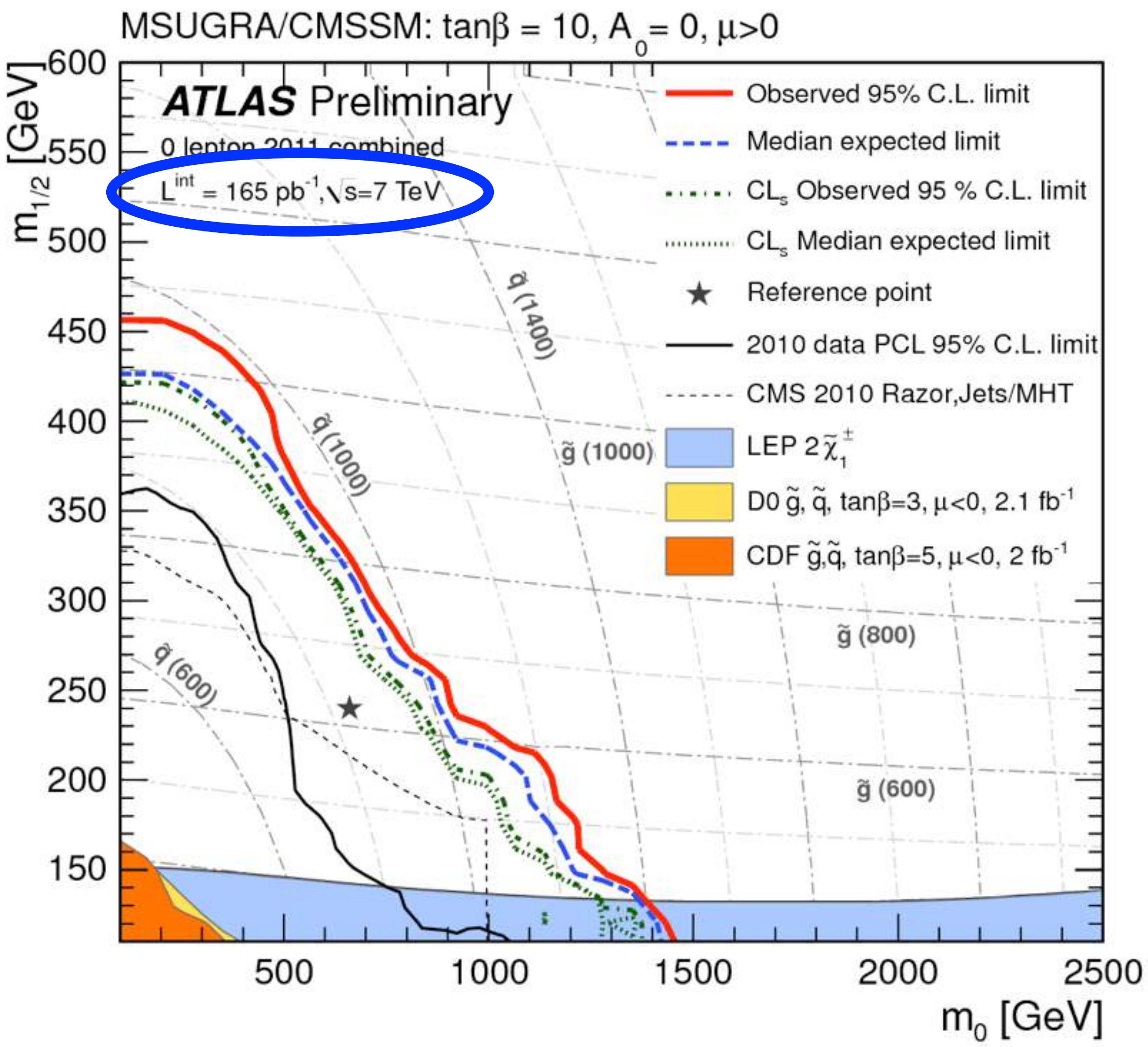
❖ Leptons in decay chains....







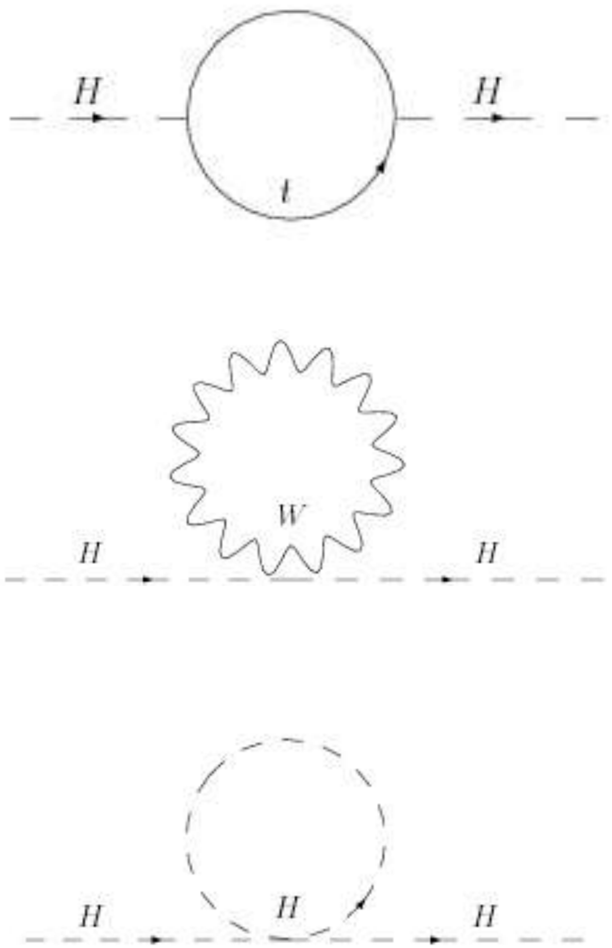
All Praise COM Energy!



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

But…

We’ve Found a Higgs!



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

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

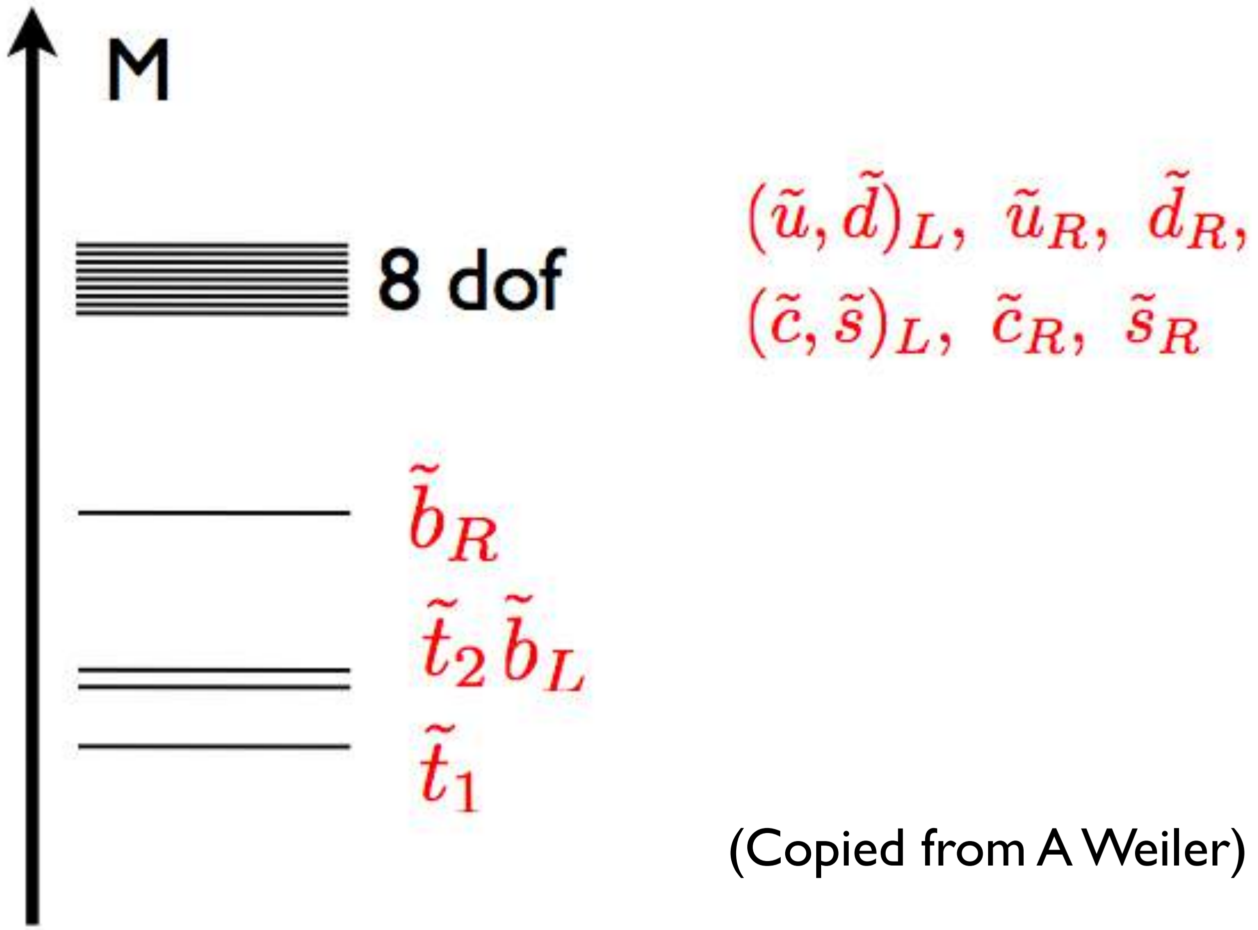
$$\rightarrow \frac{1}{16\pi^2} \lambda E^2$$

- ❖ 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**

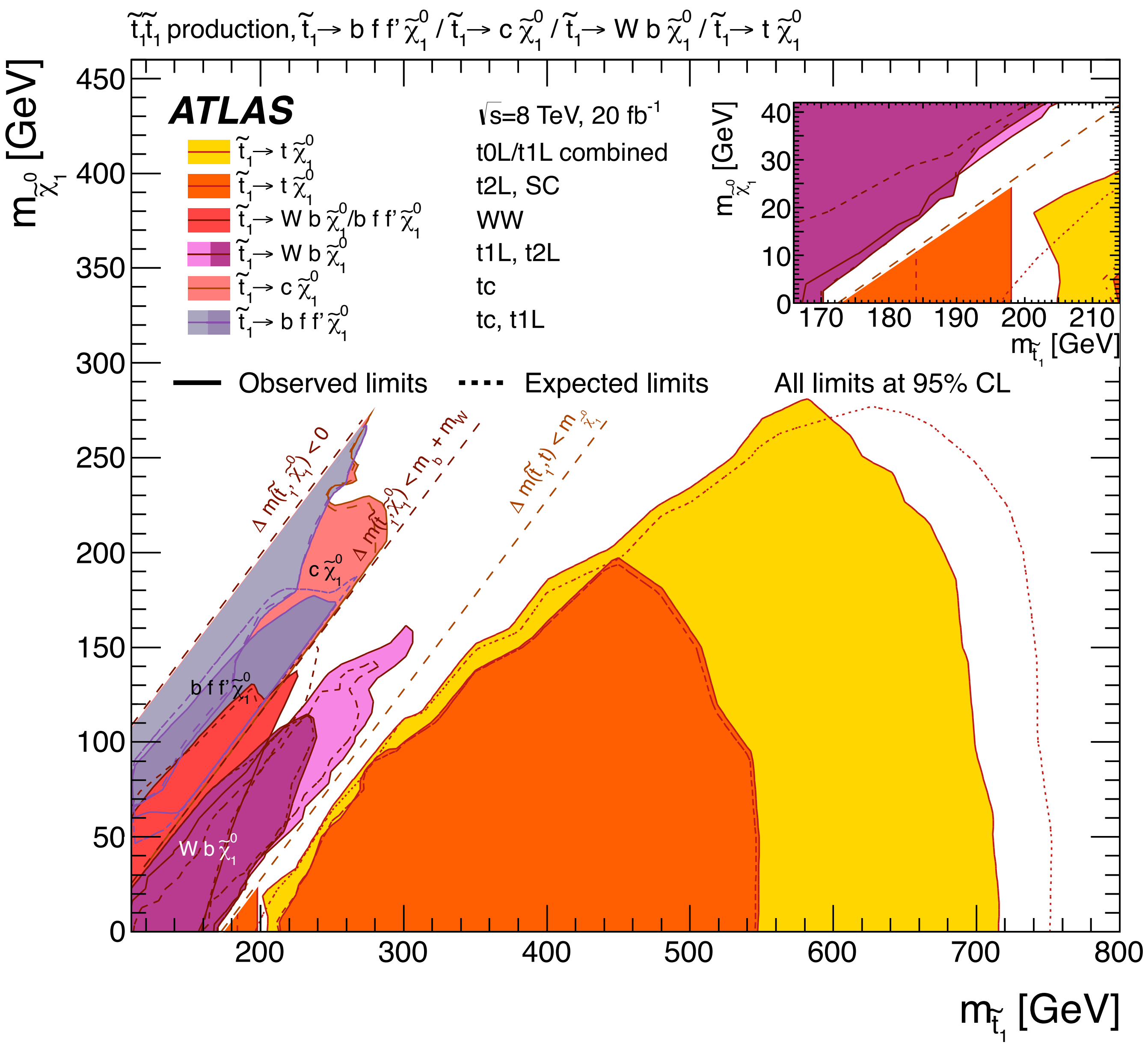
SUSY and the Higgs

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

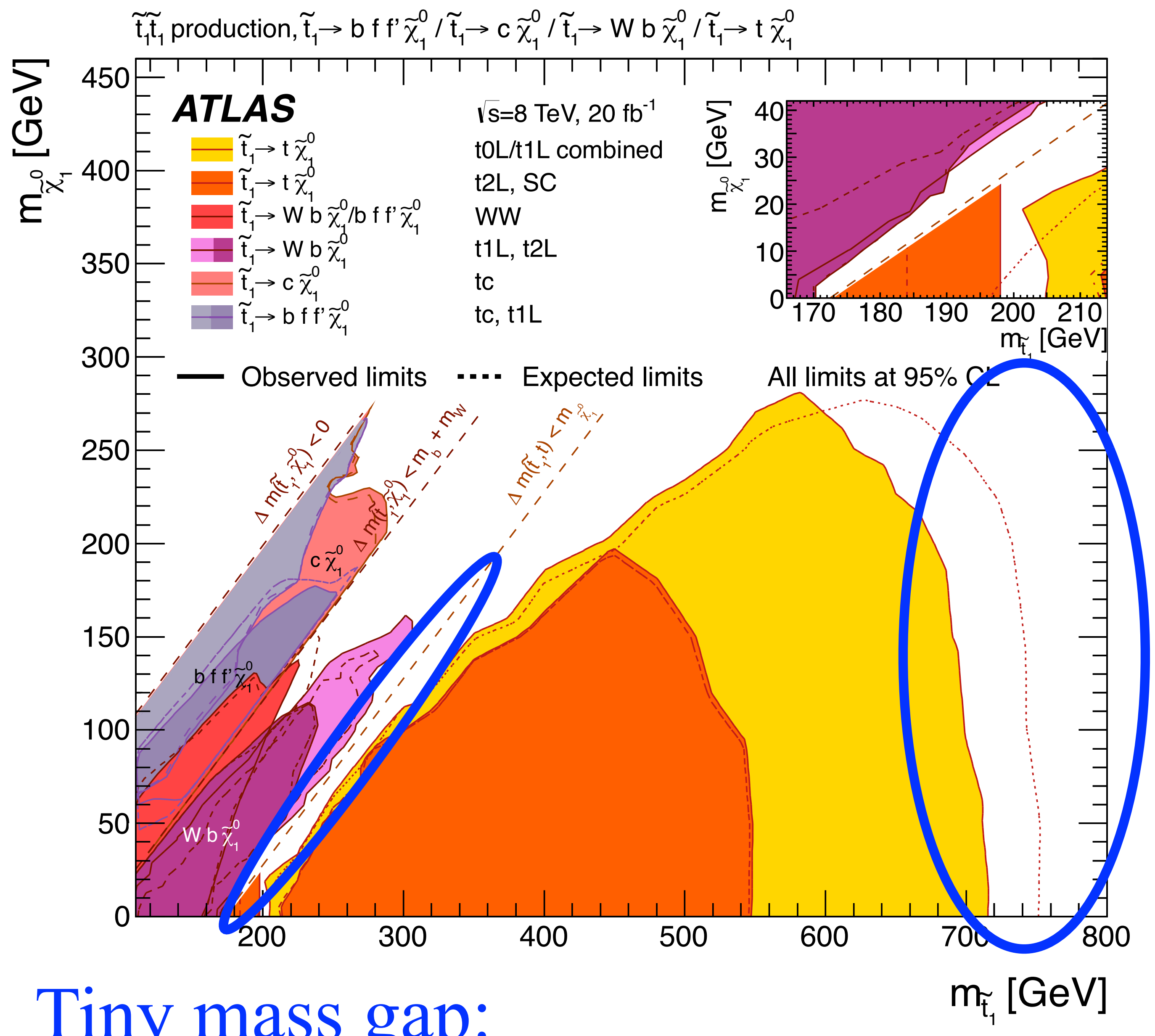


(Copied from A Weiler)

Stop Searching Anatomy



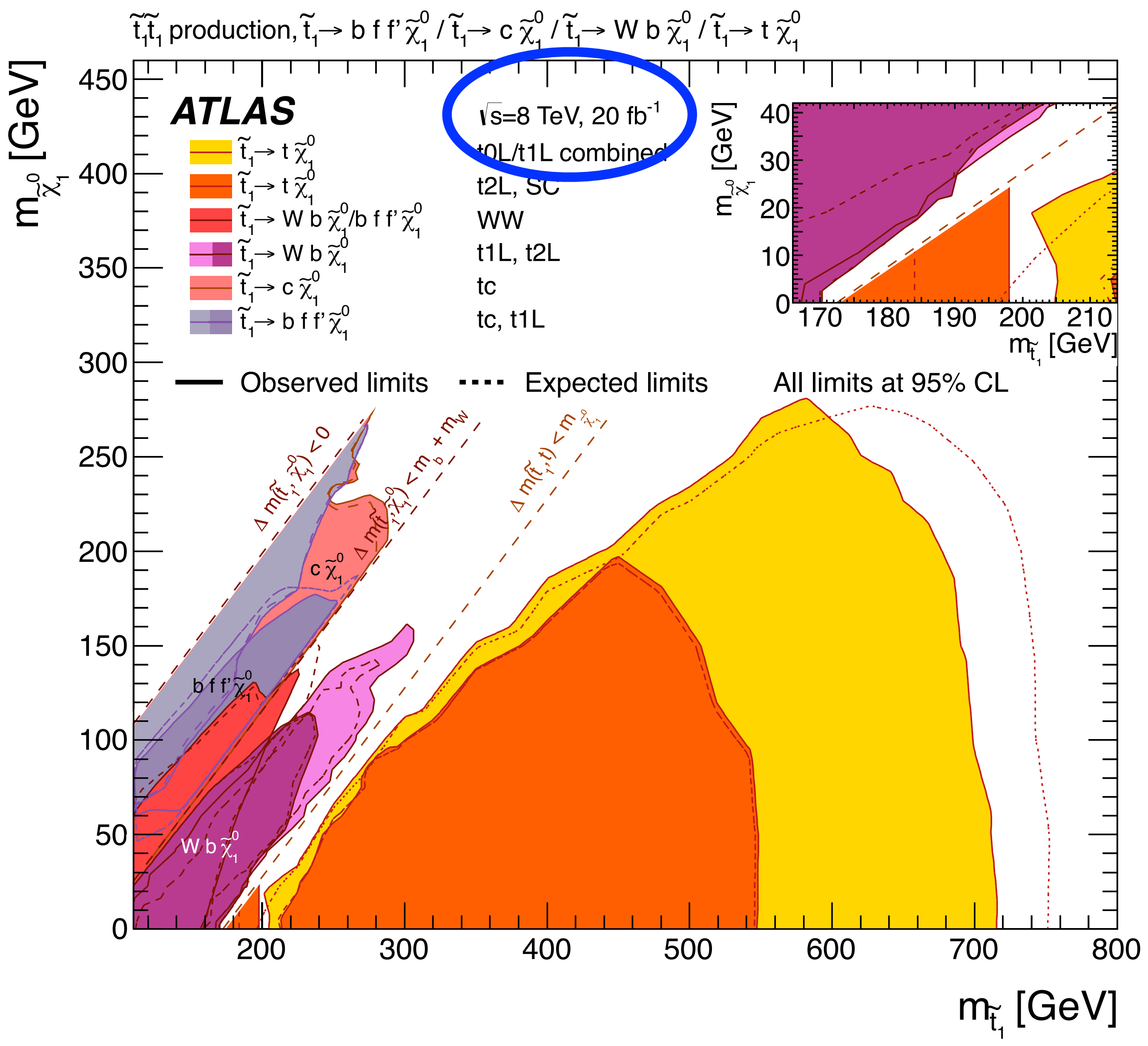
Stop Searching Anatomy

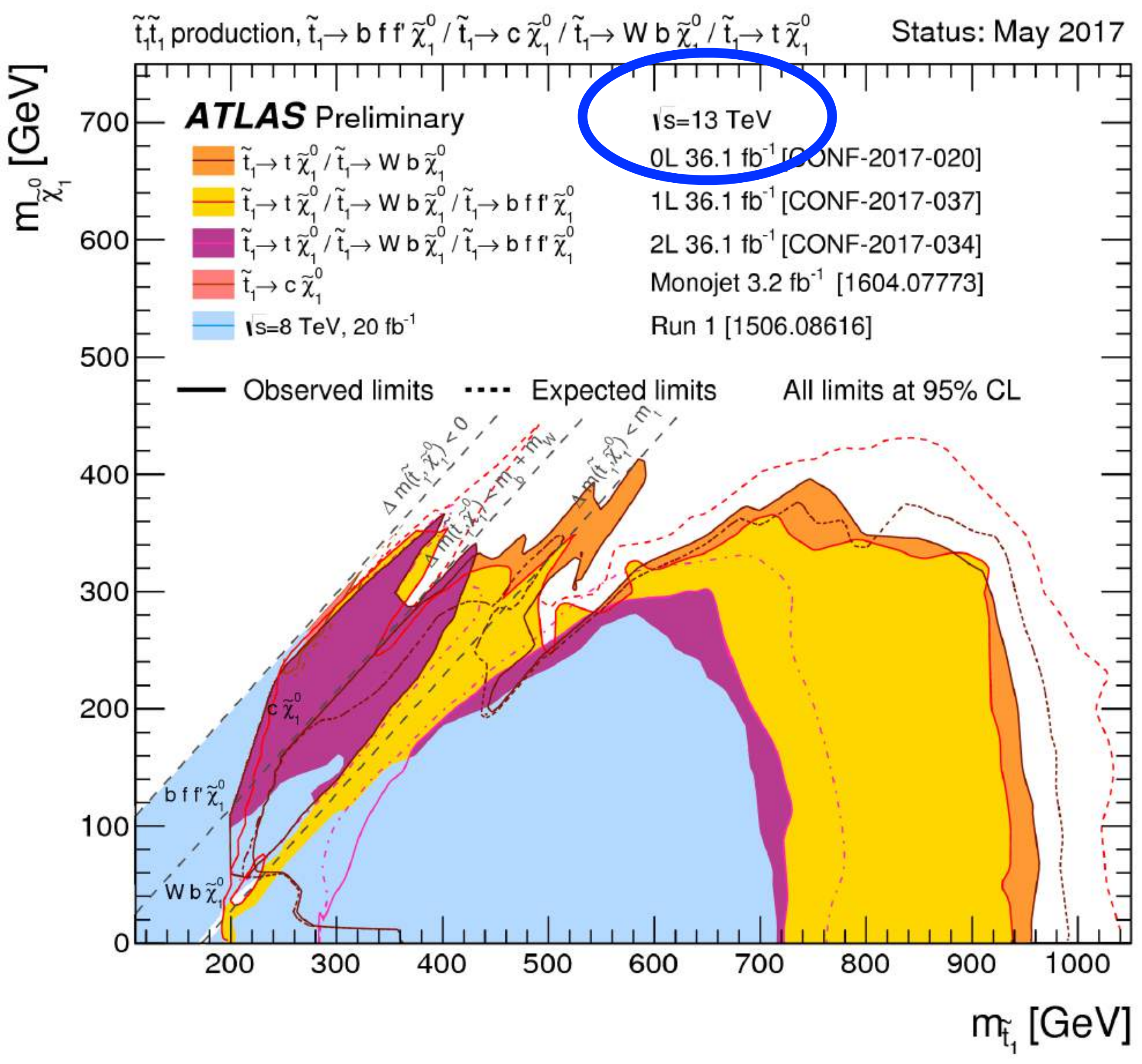


Tiny mass gap: soft decay products

High mass: run out of cross-section

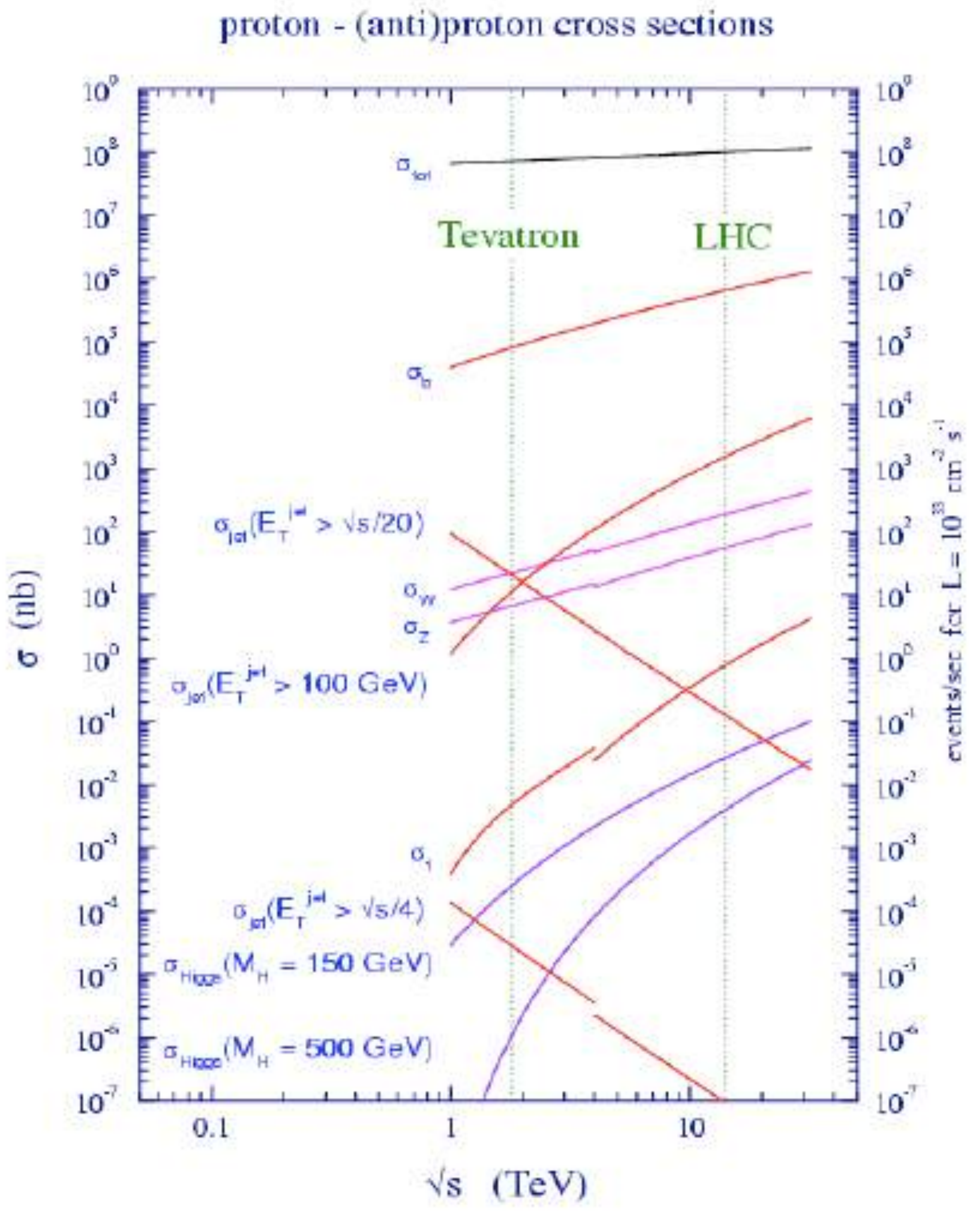
Stop Searching Anatomy



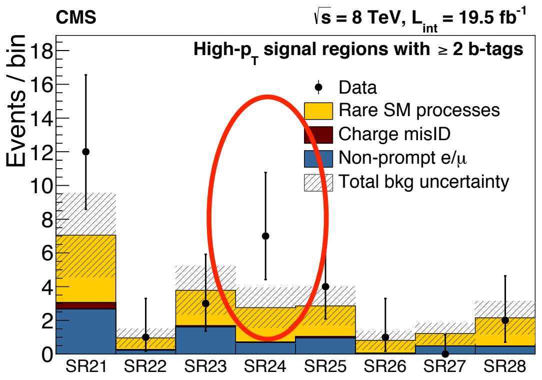


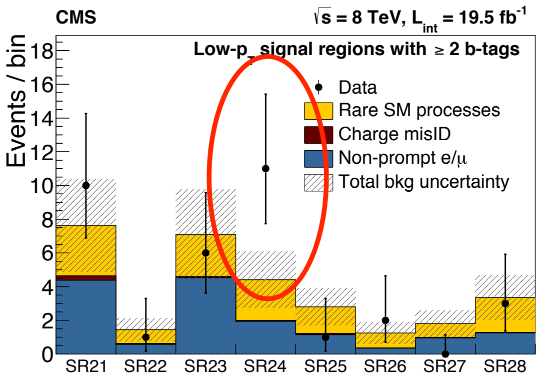
Same-Sign Leptons

- 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

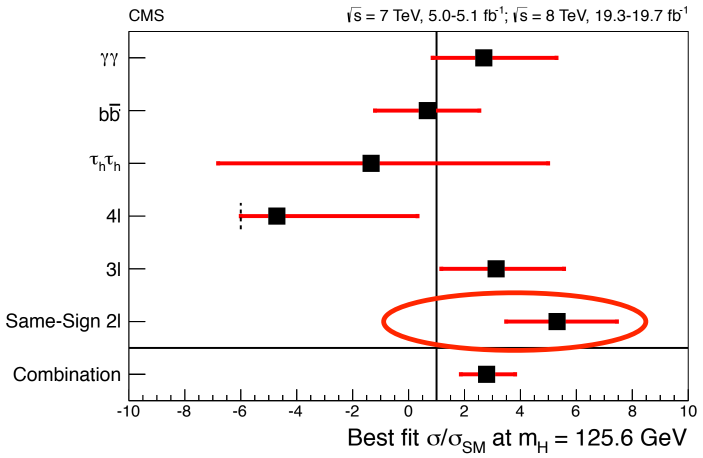




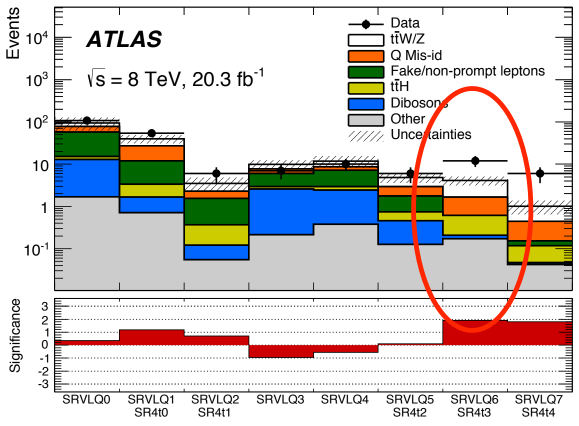
CMS (SUSY), http://arxiv.org/abs/1311.6736 (24 signal regions in paper)

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

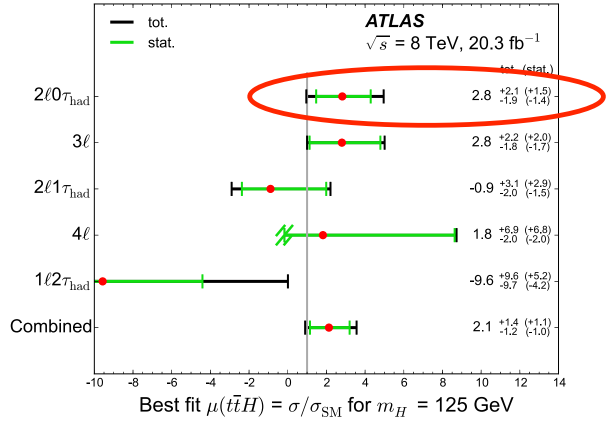
ATLAS (SUSY), http://arxiv.org/abs/1404.2500 (5 signal regions in paper)



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



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



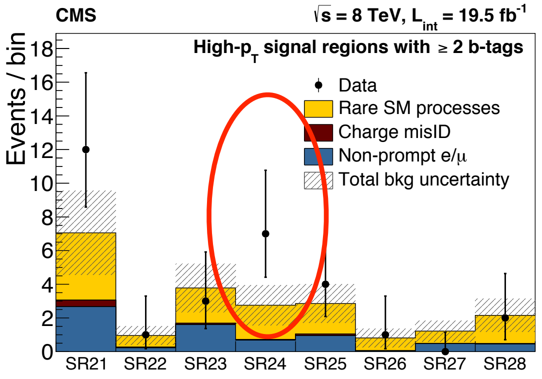
ATLAS (ttH), http://arxiv.org/abs/1506.05988

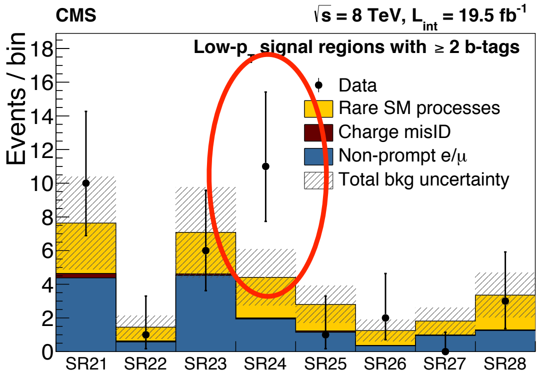
It certainly looks like multiple analyses looking at same sign leptons and b-jets see excesses!

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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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
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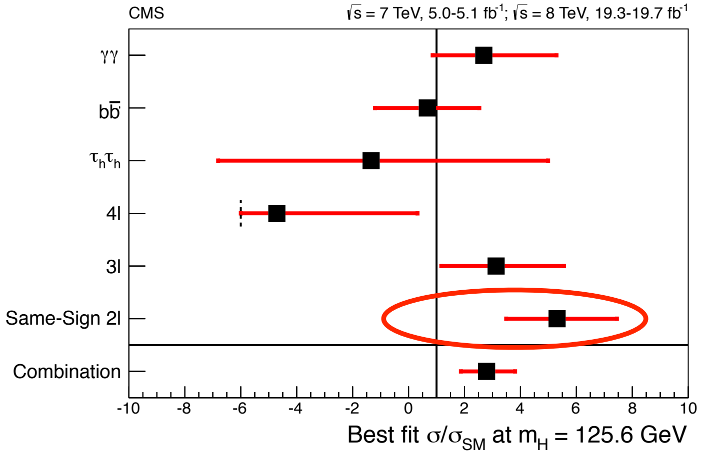

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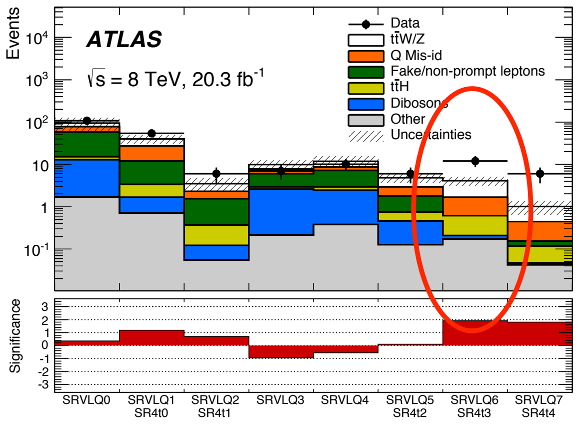
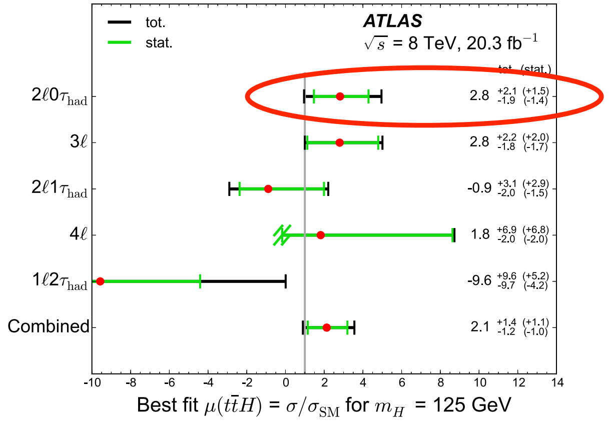


ATLAS (TT), http://arxiv.org/abs/1504.04605

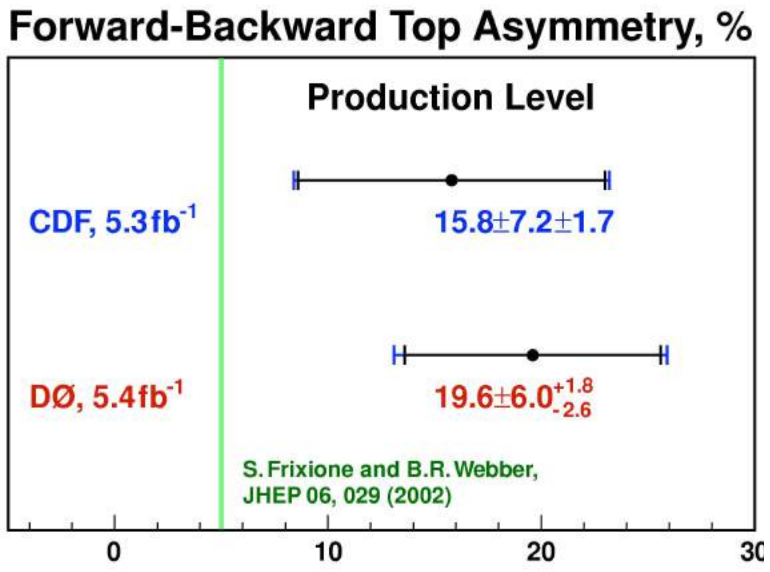


ATLAS (ttH), http://arxiv.org/abs/1506.05988

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

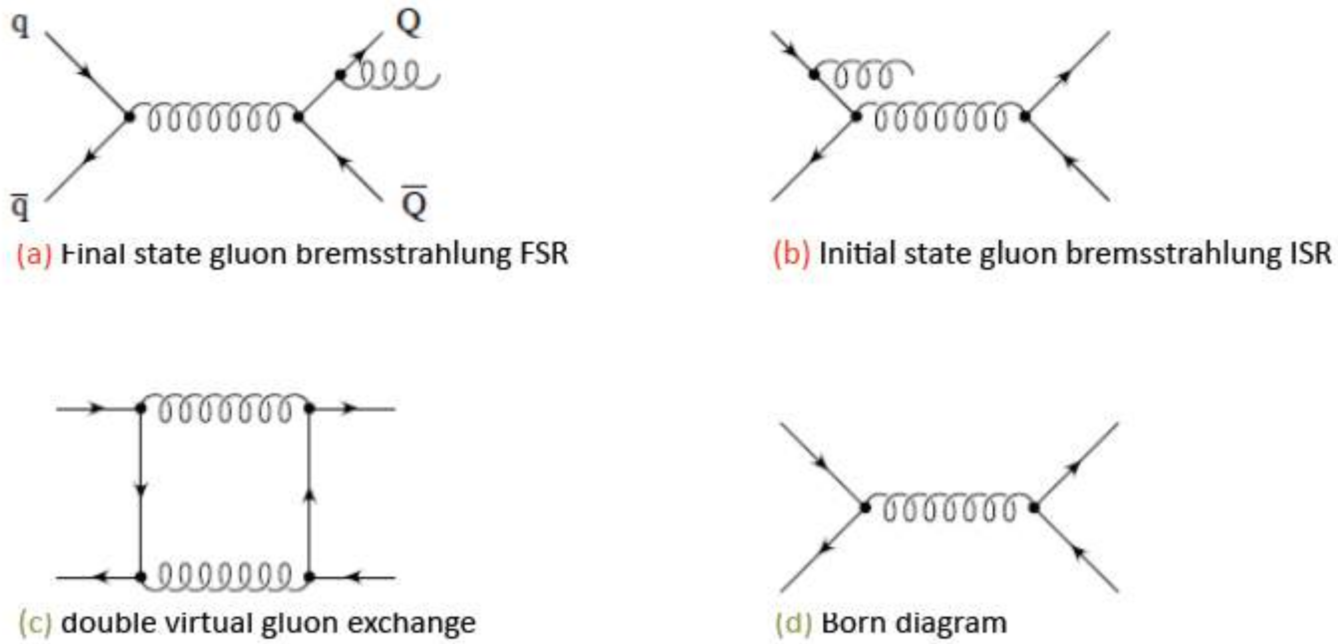
Anecdotes From the Field (II)

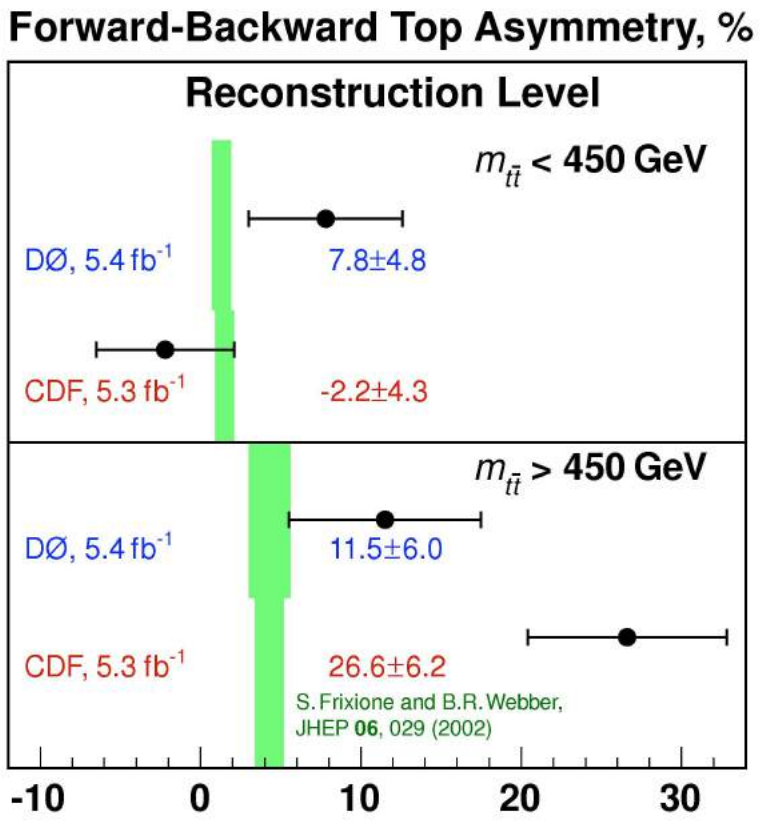
- ttbar charge asymmetry at the Tevatron
  - At Feynman diagram level, NLO effect (Tevatron is proton-anti-proton collider)



http://arxiv.org/abs/1107.4995

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

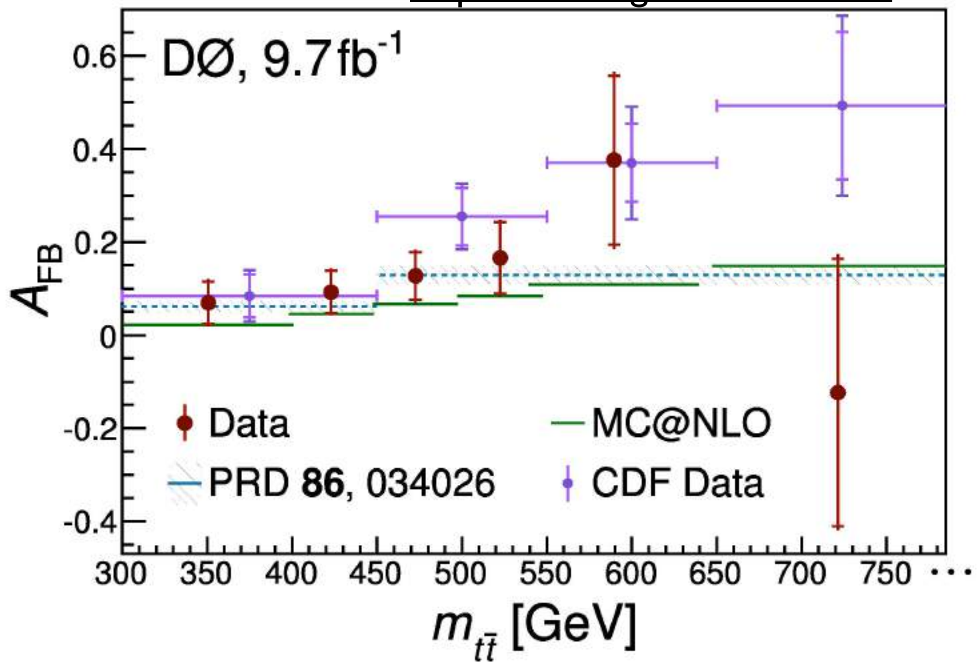




Anecdotes From the Field (II)

- 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