Challenges of Collider Measurements (and Searches!)

Gustaaf Brooijmans

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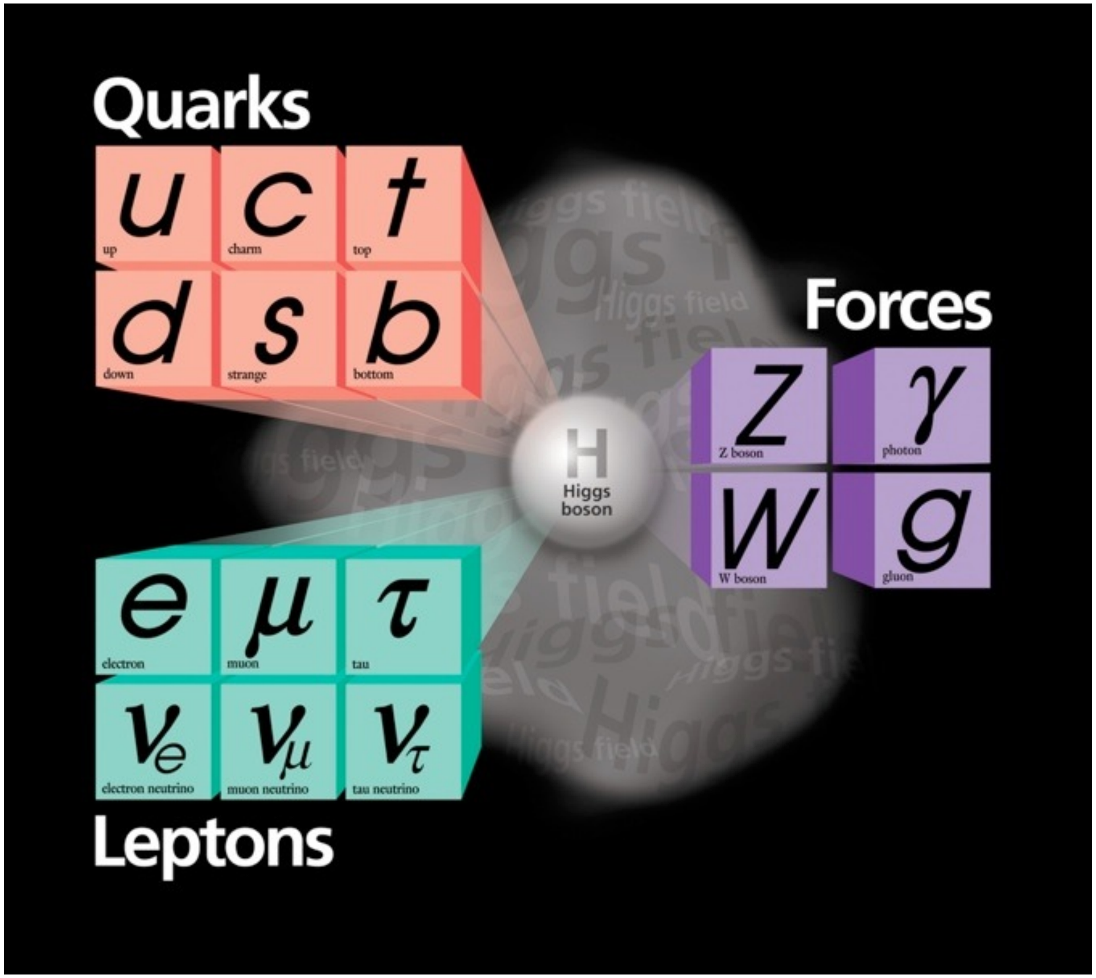
IN THE CITY OF NEW YORK

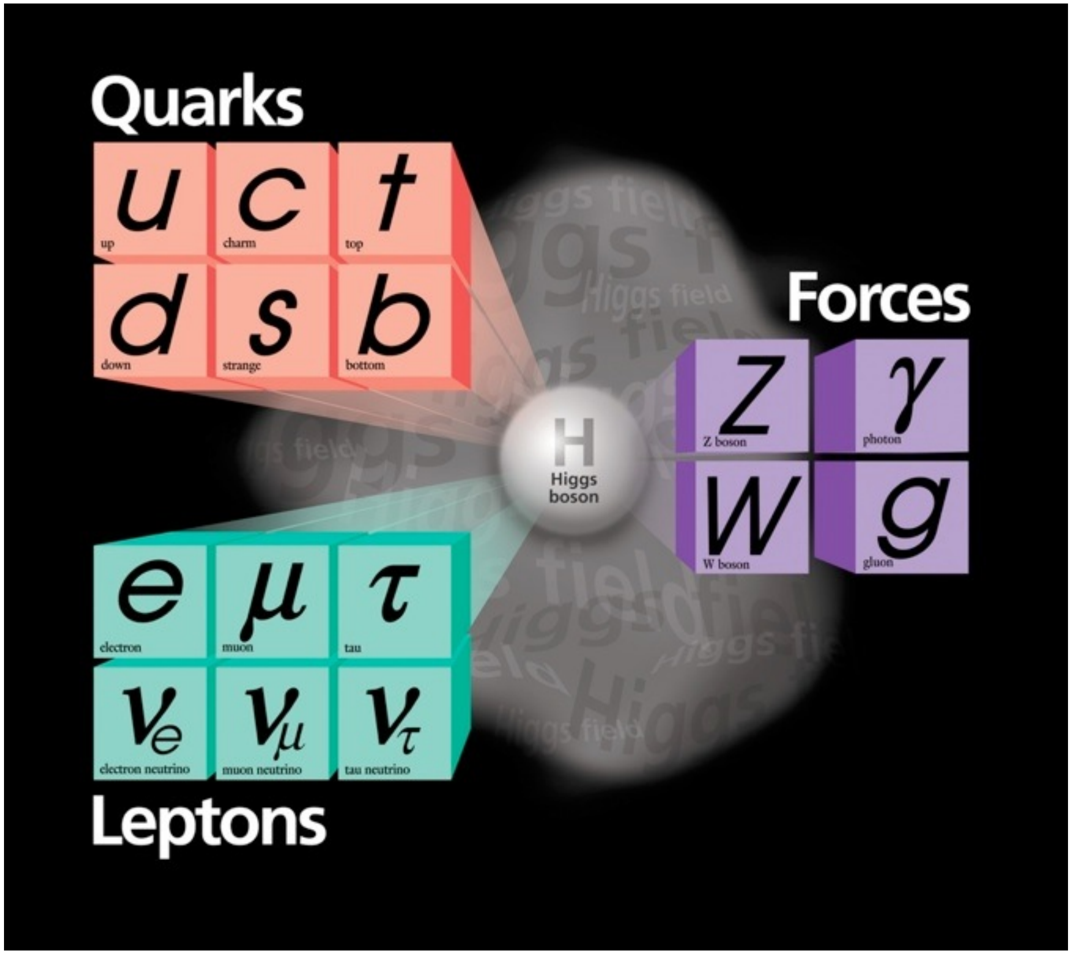
Standard Model Today



Triumph of Gauge Theories!

Standard Model Today

- Higgs discovery completes the Standard Model
  - Fully consistent, complete, precise description of strong, electromagnetic and weak interactions
- Even generate fermion masses
  - But that is the ***only*** property of fermions we "understand"



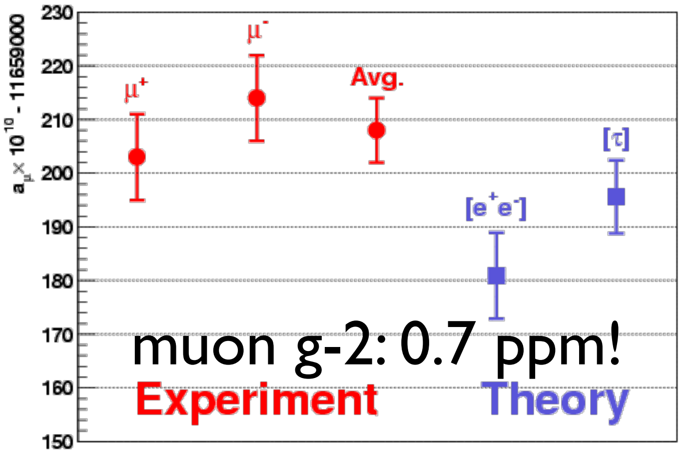
In Words

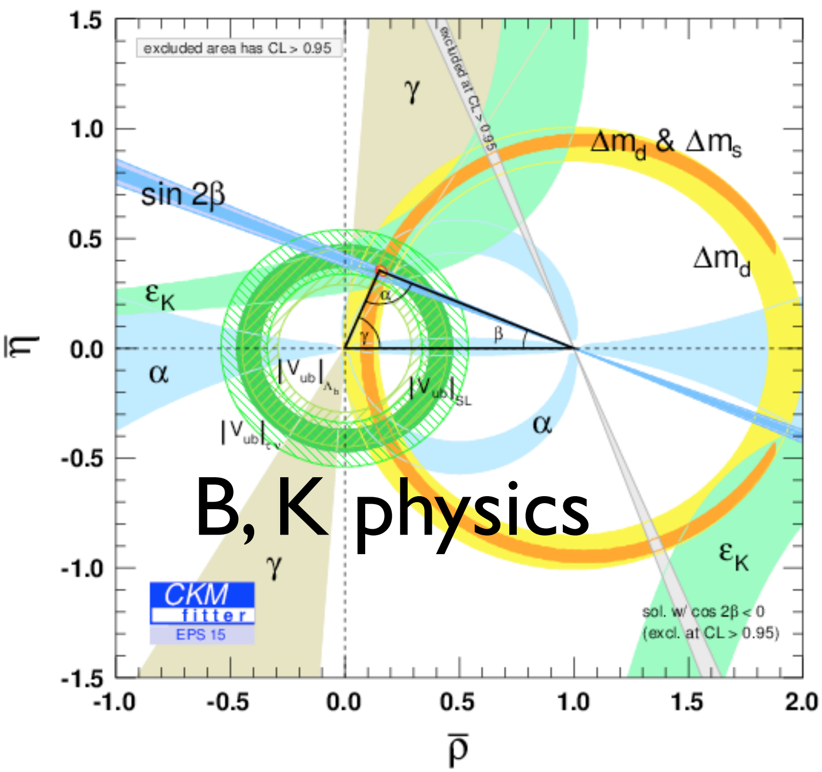
- Matter is built of spin 1/2 particles that interact by exchanging 3 different kinds of spin 1 particles corresponding to 3 different (gauge) interactions
- There appear to be 3 generations of matter particles
- The 4 different matter particles in each generation carry different combinations of quantized charges characterizing their couplings to the interaction bosons
- The matter fermions and the weak bosons have “mass”
- Gravitation is presumably mediated by spin 2 gravitons
- Gravitation is extremely weak for typical particle masses
- There appear to be 3 macroscopic space dimensions

About the Standard Model

- It's a theory of interactions:
  - Properties of fermions are inputs
    - In gauge paradigm, fermion properties "generate" interactions
  - Properties of interaction bosons in terms of couplings, propagations, masses are linked:
    - Measuring a few allows us to predict the rest, then measure and compare with expectation
- It's remarkably successful:
  - Predictions verified to be correct at sometimes incredible levels of precision
  - After ~40 years, still no serious cracks

Precision Results

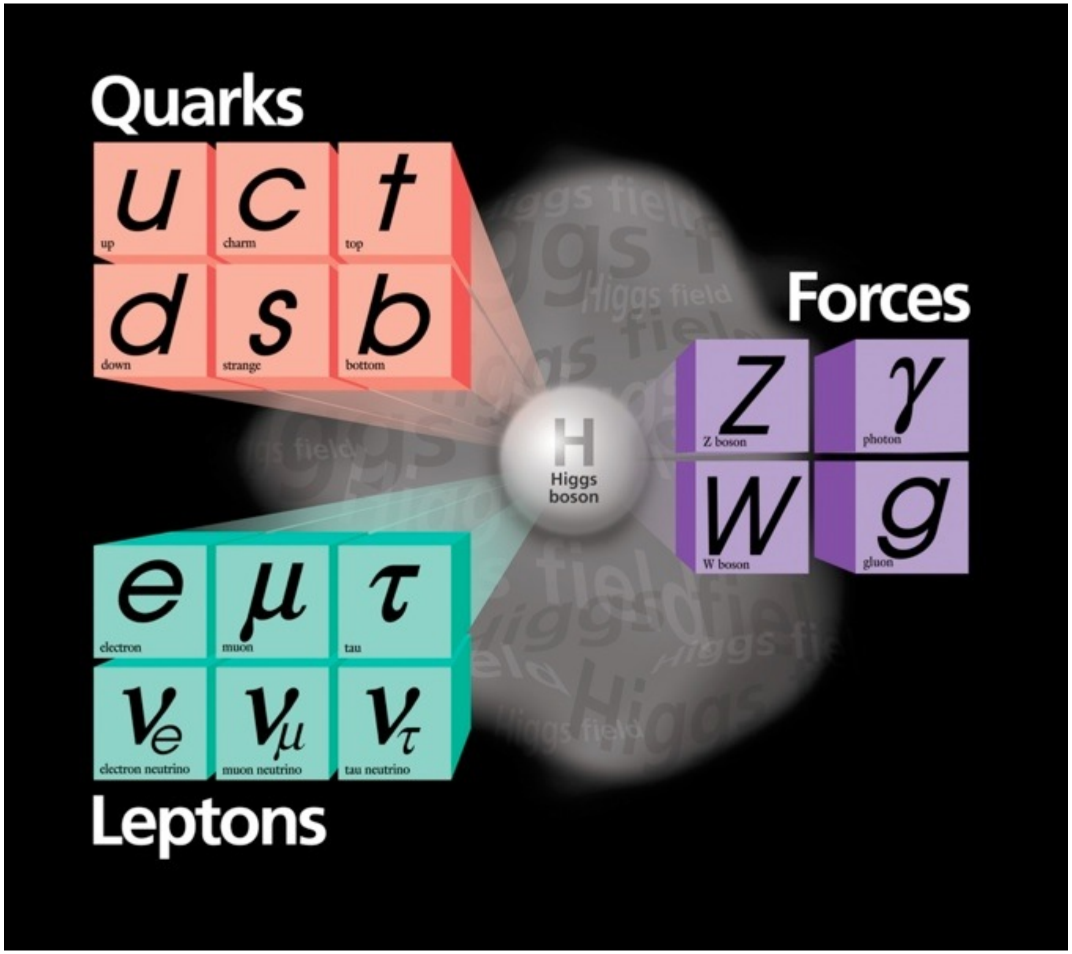




LEP, SLD & Tevatron

Lacking in the Standard Model

- Clear structure in fermionic sector unexplained
  - No understanding of the "charges"
  - Evidence of selective principle(s)
    - E.g. no neutral colored fermions
    - q(down) = q(e)/N_c
  - Interpreted as evidence for (grand) unification
    - Grand or less grand? (One or more scales?)



Lacking in the Standard Model

- Many cosmological issues
  - Dark matter and dark energy
  - Not enough CP violation in the quark sector for baryogenesis
  - Baryon number violation
    - Present in the SM through B-L (sphalerons)
    - Baryogenesis through leptogenesis and B-L?
      - Untestable?

Many Fundamental Questions

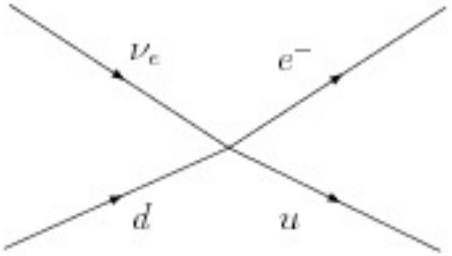
- What exactly *is* spin? Or color? Or electric charge? Why are they quantized?
- Are there only 3 generations? If so, why?
- Why are there e.g. no neutral, colored fermions?
- What is mass? Why are particles so light?
- Is there a link between particle and nucleon masses?
- How does all of this reconcile with gravitation? How many space-time dimensions are there really?
- ...

Particles Solve Problems

(Problems Predict Particles)

Vector Boson Scattering

- There was in fact one known problem with the Standard Model (+ a second, related, lesser one):
  - If we collide W's or Z's (not so easy...), the scattering cross-section grows with the center of mass energy, and gets out of control (violates unitarity) at about 1.7 TeV: $\sigma(WW \rightarrow WW) \sim s$
- This is similar to "low" energy neutrino scattering:
  - If $q^2 << (M_W)^2$, looks like a "contact interaction", and cross-section grows with center of mass energy: $\sigma \sim s$



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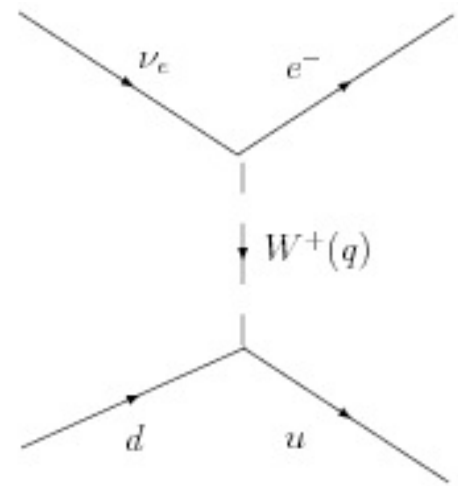
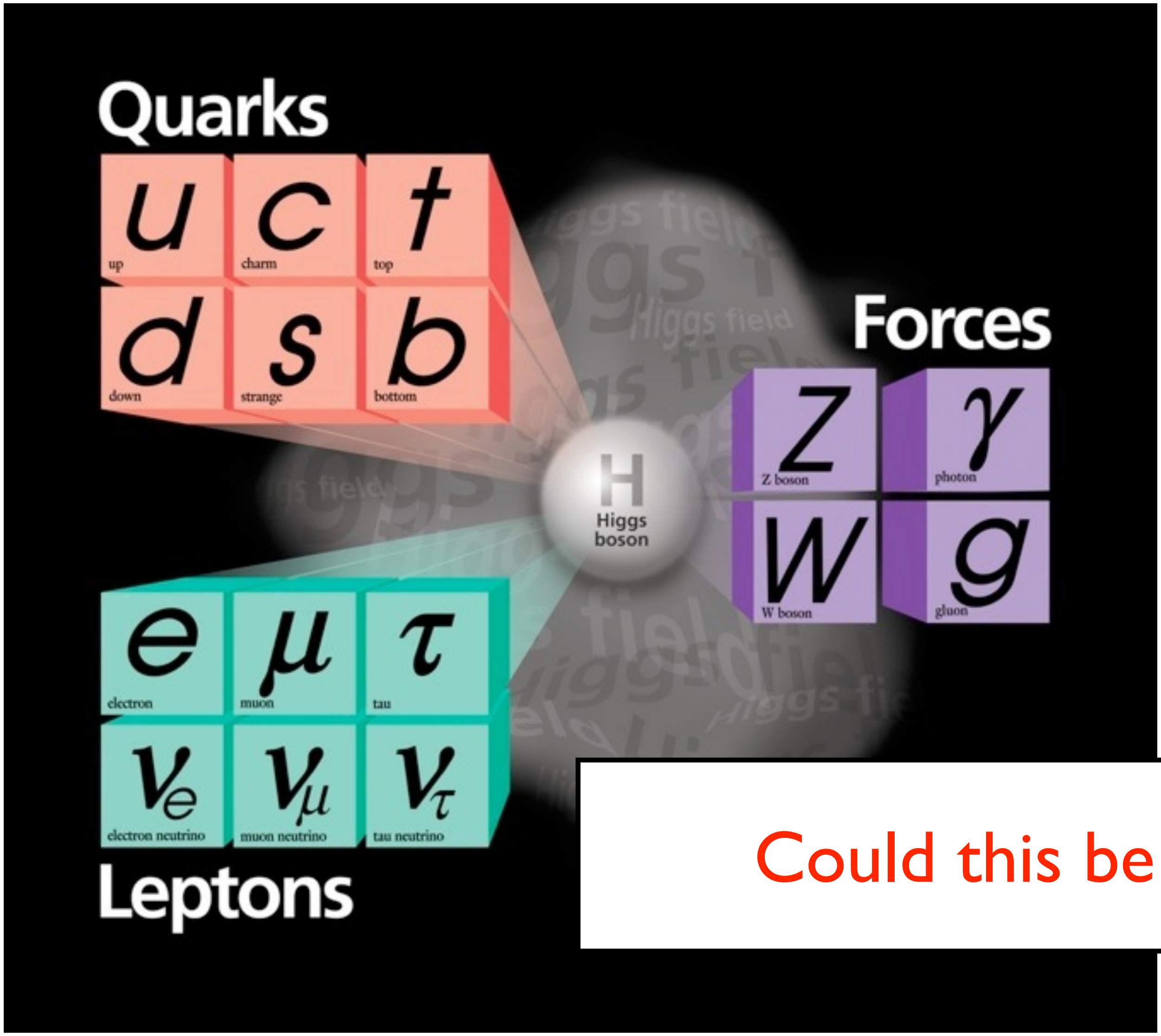


  - But when $q^2 \approx (M_W)^2$, W-boson propagation becomes visible, and "cures" this problem

The Higgs Boson

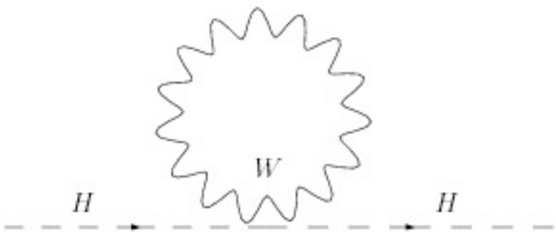
- One way to solve WW, is to introduce a massive, spinless particle (of mass < ~1 TeV)
  - Couplings to W and Z are fixed, quantum numbers are known...
  - .... to be those of the vacuum
  - Its mass is unknown, and its couplings to the fermions are unknown.... well, maybe
    - Fermions can acquire mass by coupling to this Higgs boson, so their couplings could be proportional to their masses. This is called the “Standard Model Higgs”

New Physics?

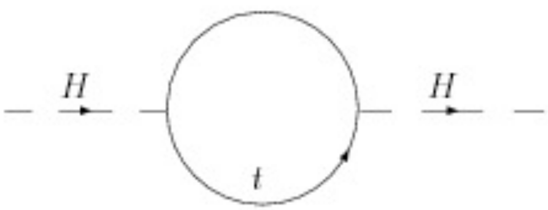


Could this be it?

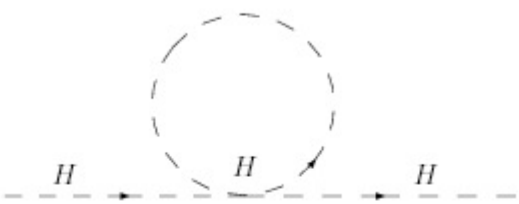
Higgs Mass



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



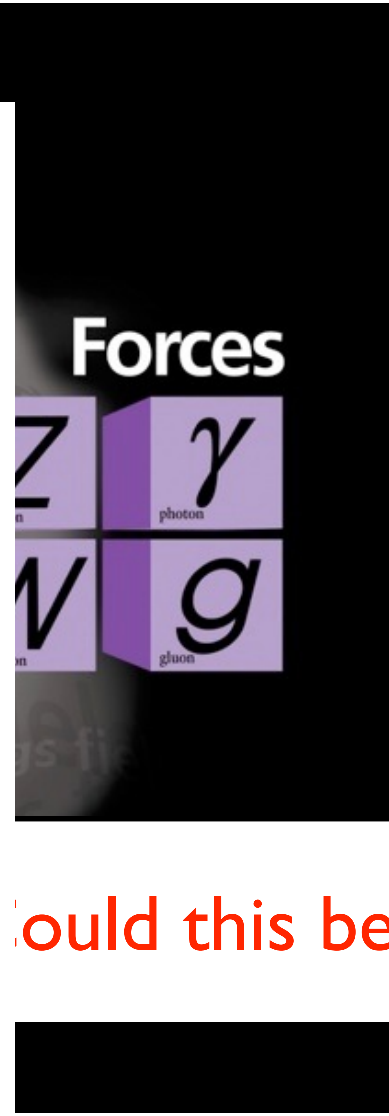
$$\rightarrow \frac{3}{16\pi^2} y_t^2 E^2$$



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

- Higgs, in fact, also acquires mass from coupling to W's, fermions, and itself!
  - These "mass terms" are quadratically divergent
  - Drive mass to limit of validity of the theory
- So we expect the Higgs mass to be close to the scale where new physics comes in....

New Physics?



The hierarchy problem of the electroweak Standard Model revisited

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Abstract

A careful renormalization group analysis of the electroweak Standard Model reveals that there is no hierarchy problem in the SM. In the broken phase a light Higgs turns out to be natural as it is self-protected and self-tuned by the Higgs mechanism. It means that the scalar Higgs needs not be protected by any extra symmetry, specifically super symmetry, in order not to be much heavier than the other SM particles which are protected by gauge- or chiral-symmetry. Thus the existence of quadratic cutoff effects in the SM cannot motivate the need for a super symmetric extensions of the SM, but in contrast plays an important role in triggering the electroweak phase transition and in shaping the Higgs potential in the early universe to drive inflation as supported by observation.

ould this be it?

New Physics?

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A careful renormalization group
that there is no hierarchy problem
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Natural Tuning: Towards A Proof of Concept

Sergei Dubovsky, Victor Gorbenko, and Mehrdad Mirbabayi

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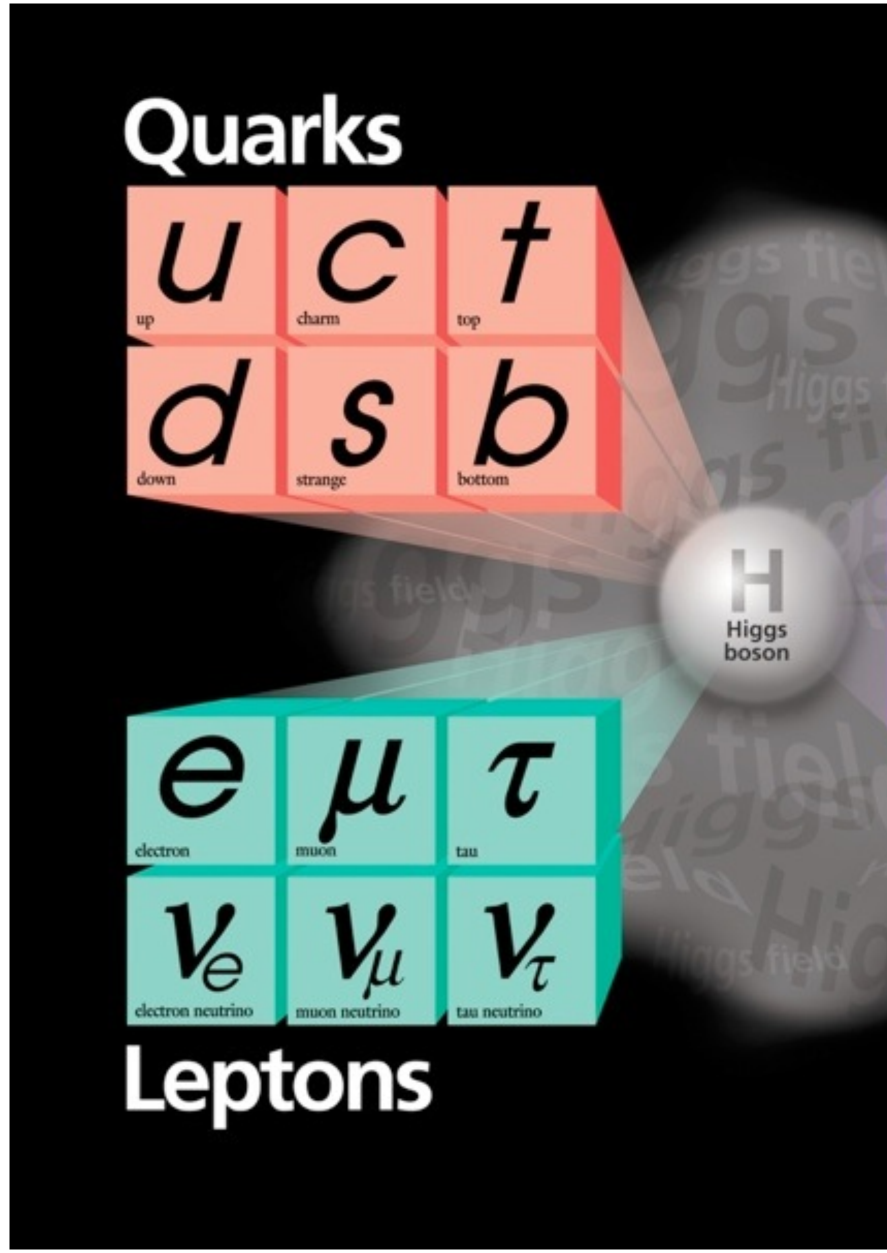
New York, NY, 10003, USA

Abstract

The cosmological constant problem and the absence of new natural physics at the electroweak scale, if confirmed by the LHC, may either indicate that the nature is fine-tuned or that a refined notion of naturalness is required. We construct a family of toy UV complete quantum theories providing a proof of concept for the second possibility. Low energy physics is described by a tuned effective field theory, which exhibits relevant interactions not protected by any symmetries and separated by an arbitrary large mass gap from the new "gravitational" physics, represented by a set of irrelevant operators. Nevertheless, the only available language to describe dynamics at all energy scales does not require any fine-tuning. The interesting novel feature of this construction is that UV physics is not described by a fixed point, but rather exhibits asymptotic fragility. Observation of additional unprotected scalars at the LHC would be a smoking gun for this scenario. Natural tuning also favors TeV scale unification.

Nevertheless

- Clear structure in fermionic sector unexplained
  - Evidence of some selective principle (why are there no neutral colored fermions?)
  - Proton stability, running of couplings suggestive of at least one other scale **relevant to SM particles and interactions**, $\sim 10^{15}$ GeV
    - Either fine-tuning, or a closer scale



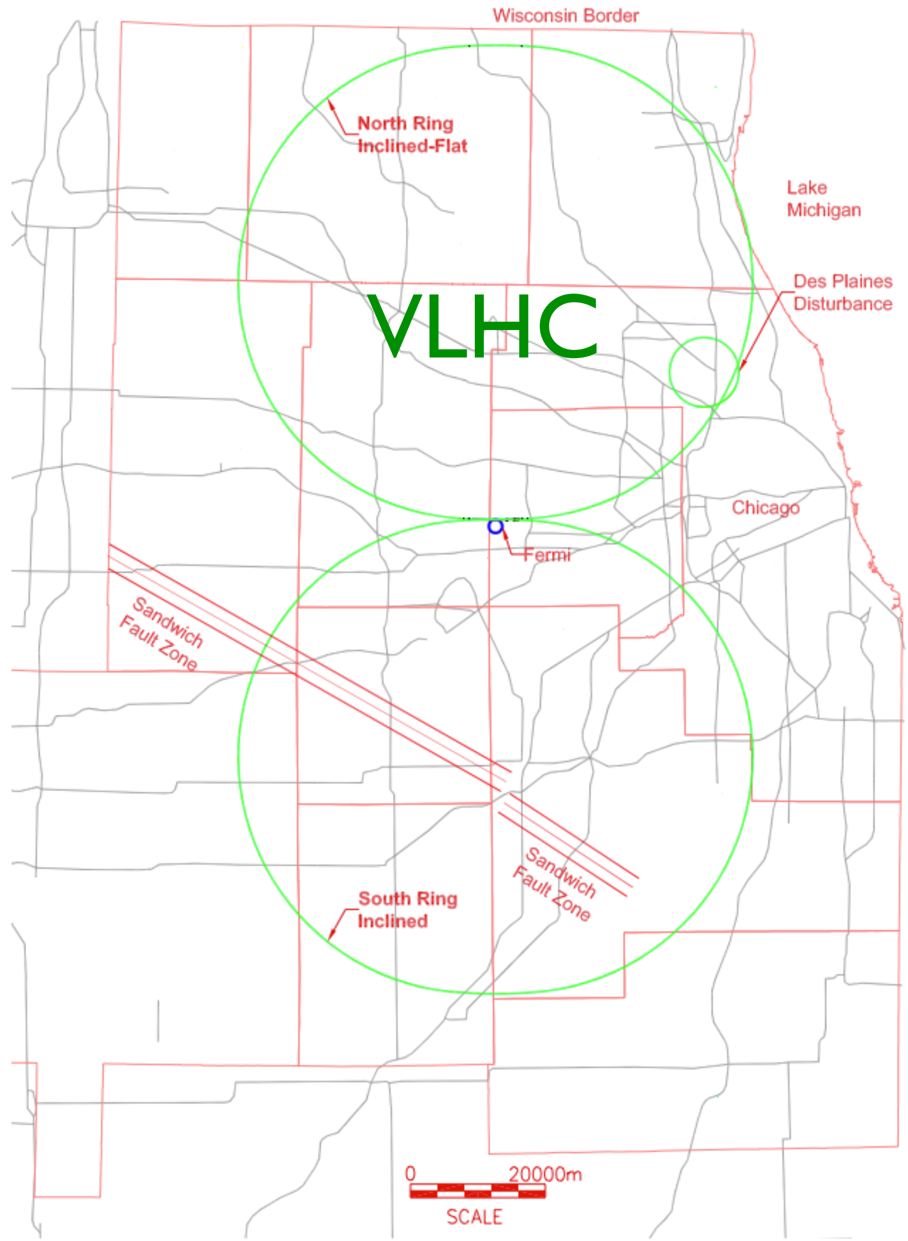
The Tools

Energy Frontier

- Currently, hadron colliders:
  - High energy implies probing of short distances, and production of other, massive particles

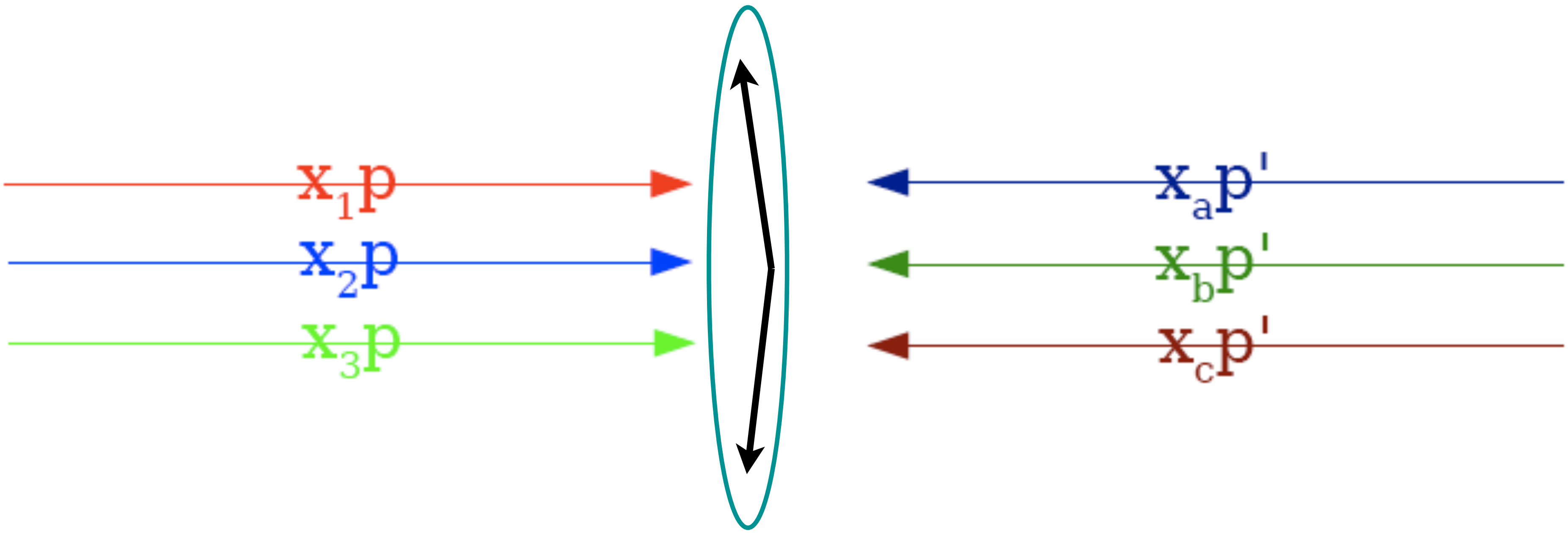
LHC

7 - 14 TeV center of mass energy



Hadron Colliders

- ❖ Incoming longitudinal momentum not known:
  - "Hard interaction" is between one of the quarks and/or gluons from each proton, other quarks/gluons are "spectators"
- ❖ Longitudinal boost "flattens" event to a pancake
- ➡ We usually work in the plane transverse to the beam



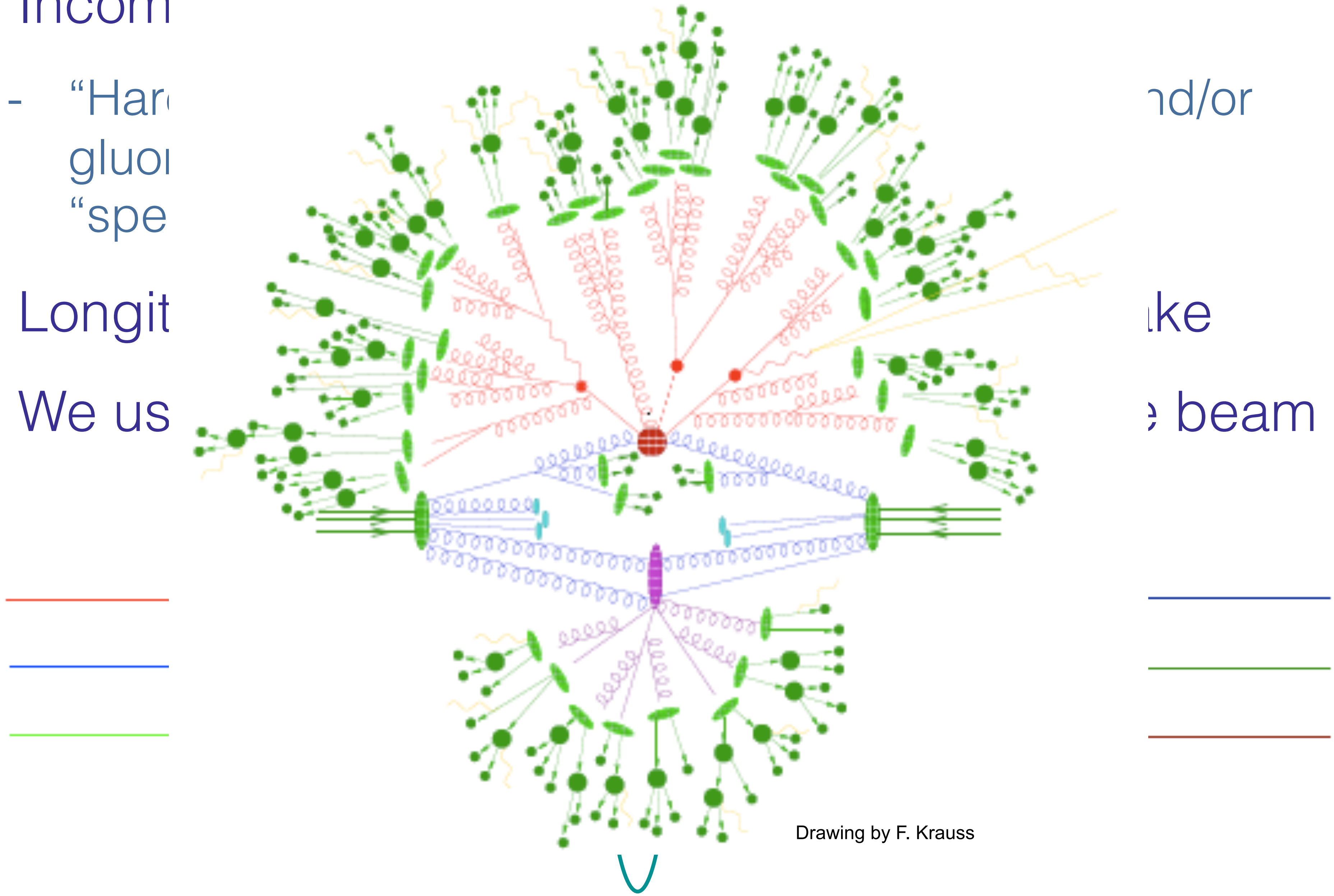
Hadron Colliders

❖ Incom

- “Har ... nd/or gluo ... “spe

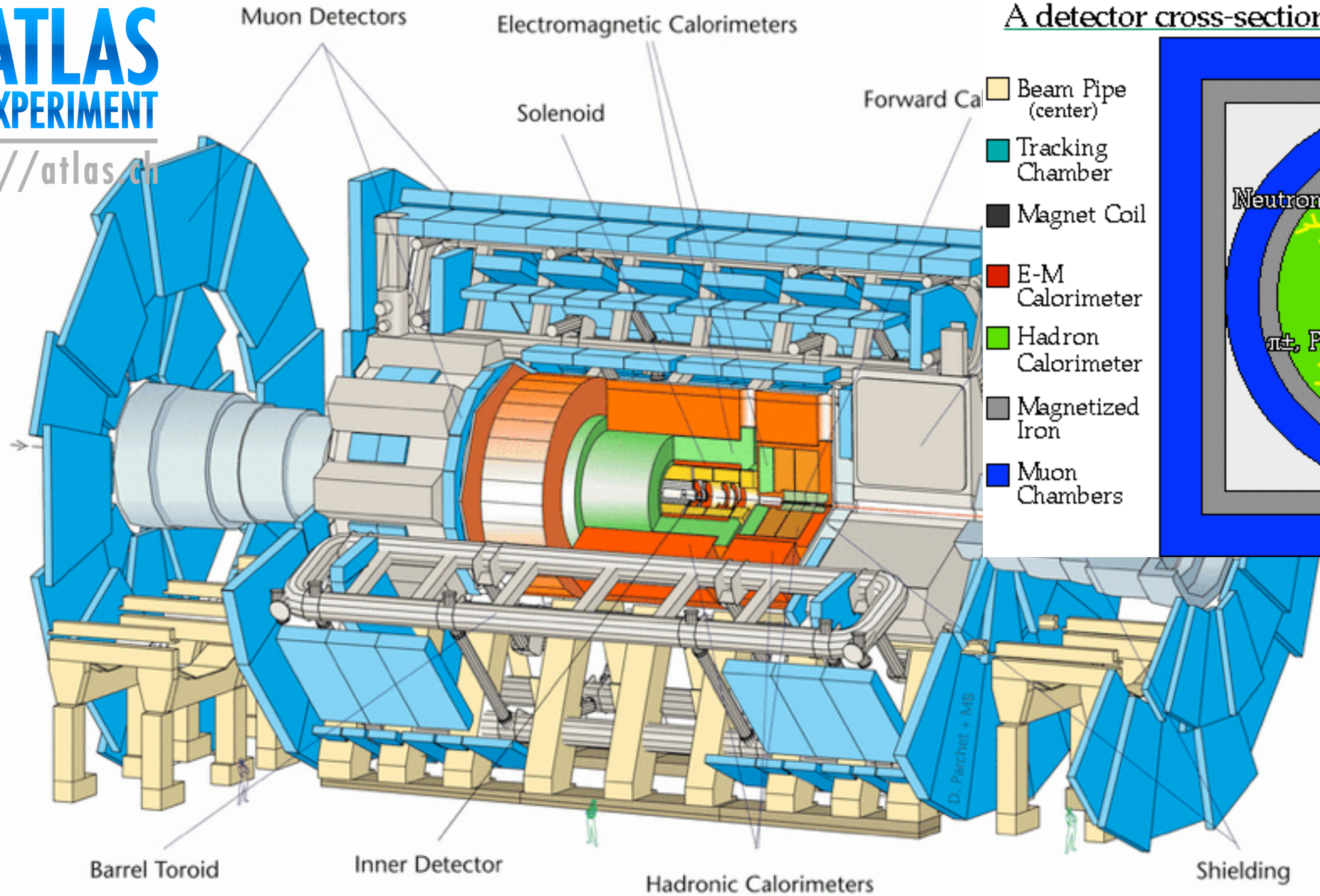
❖ Longit ... ke

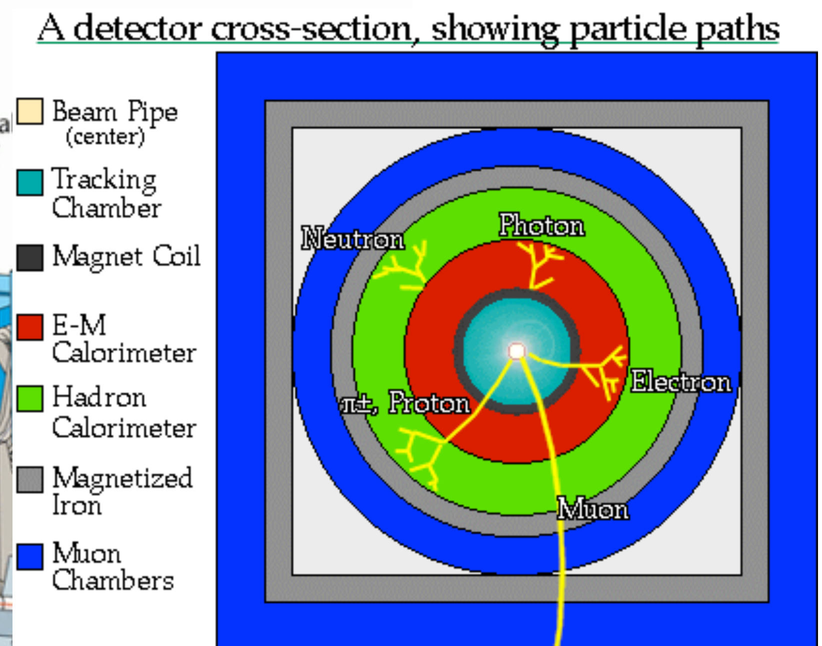
➡ We us ... e beam



Detectors

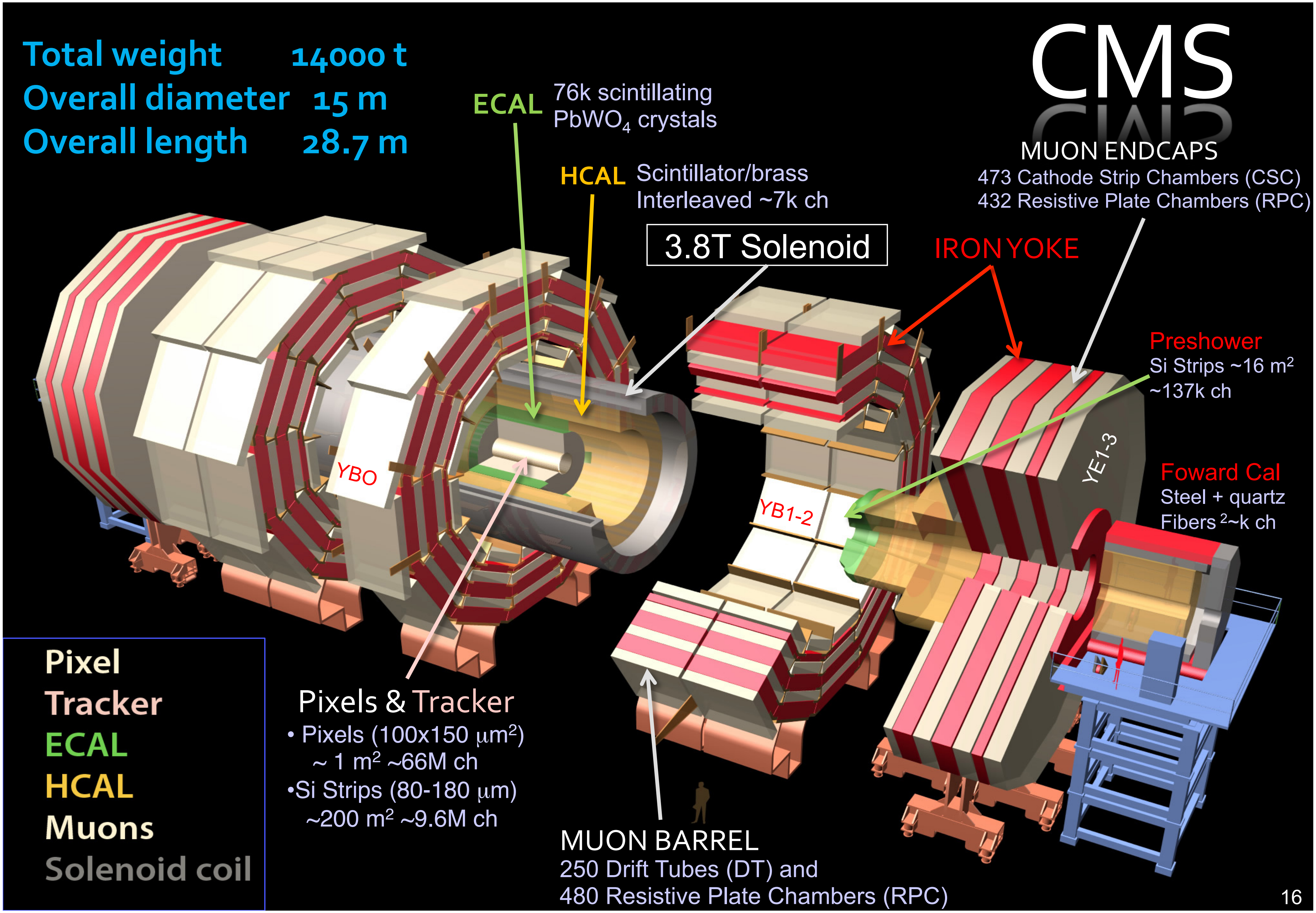
❖ Make best possible measurement of all particles coming out of collisions





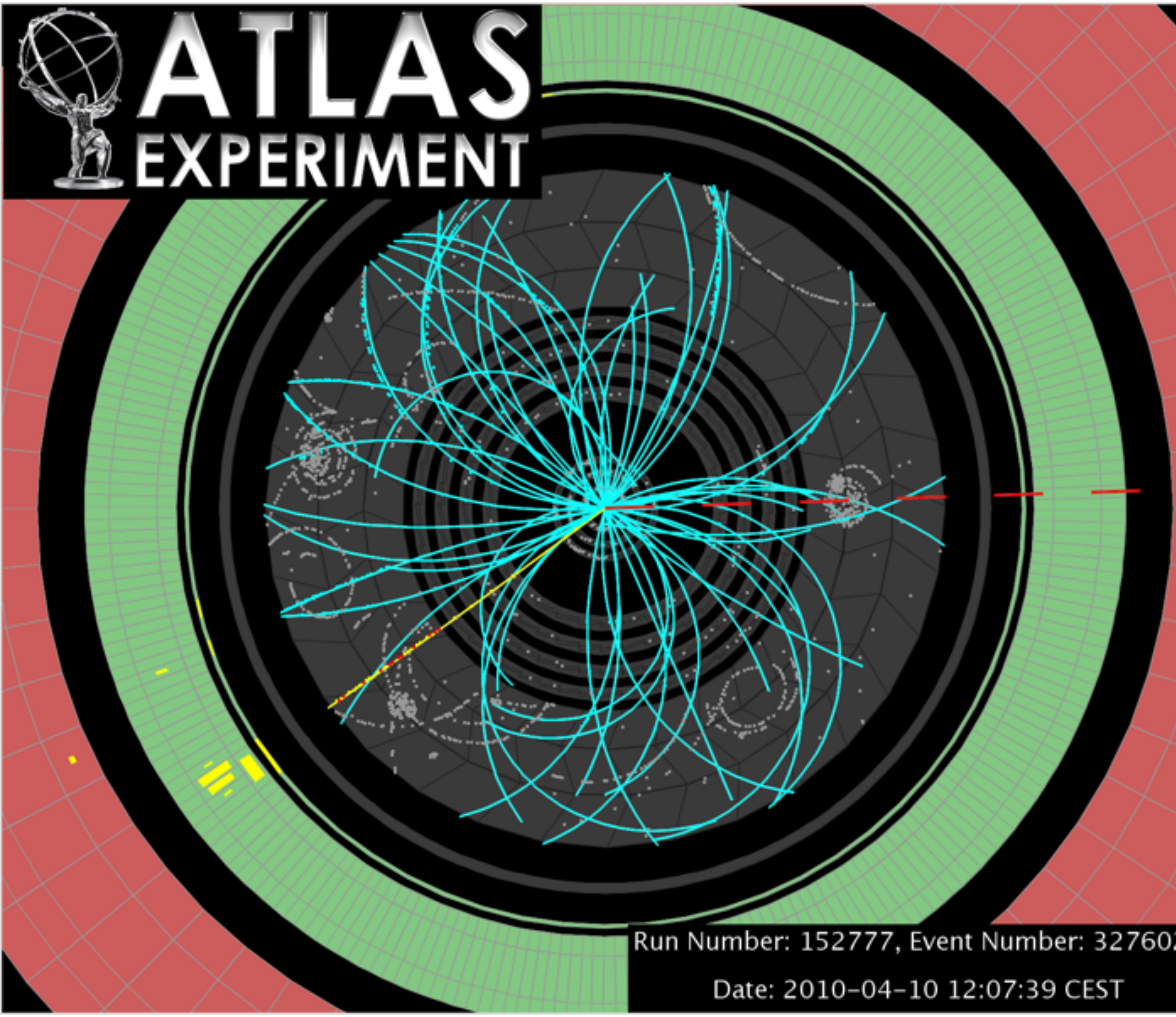
ATLAS EXPERIMENT
http://atlas.ch

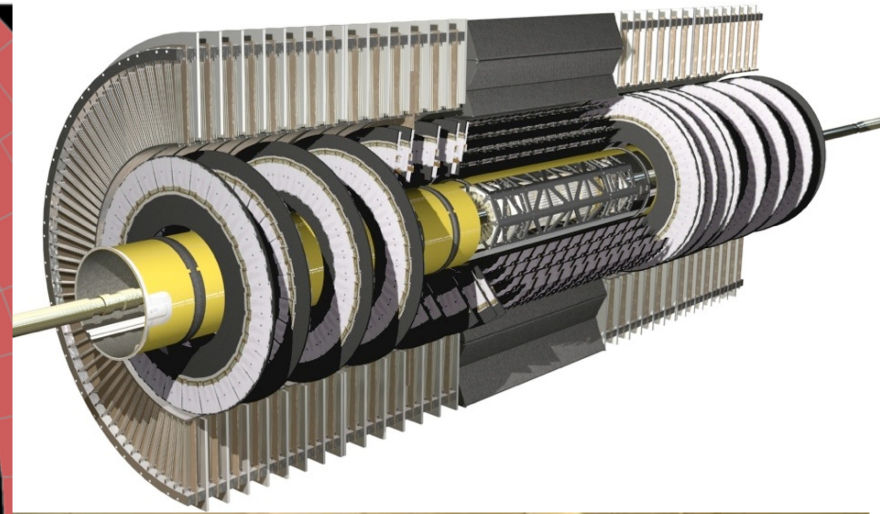
CMS


Total weight 14000 t
Overall diameter 15 m
Overall length 28.7 m
CMS
ECAL 76k scintillating $PbWO_4$ crystals
HCAL Scintillator/brass Interleaved ~7k ch
3.8T Solenoid
MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)
IRON YOKE
Preshower
Si Strips ~16 m^2
~137k ch
YE1-3
Foward Cal
Steel + quartz
Fibers ^{2}~k ch
YBO
YB1-2
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm^2)
~ 1 m^2 ~66M ch
•Si Strips (80-180 μm)
~200 m^2 ~9.6M ch
MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)
16

Charged Particles

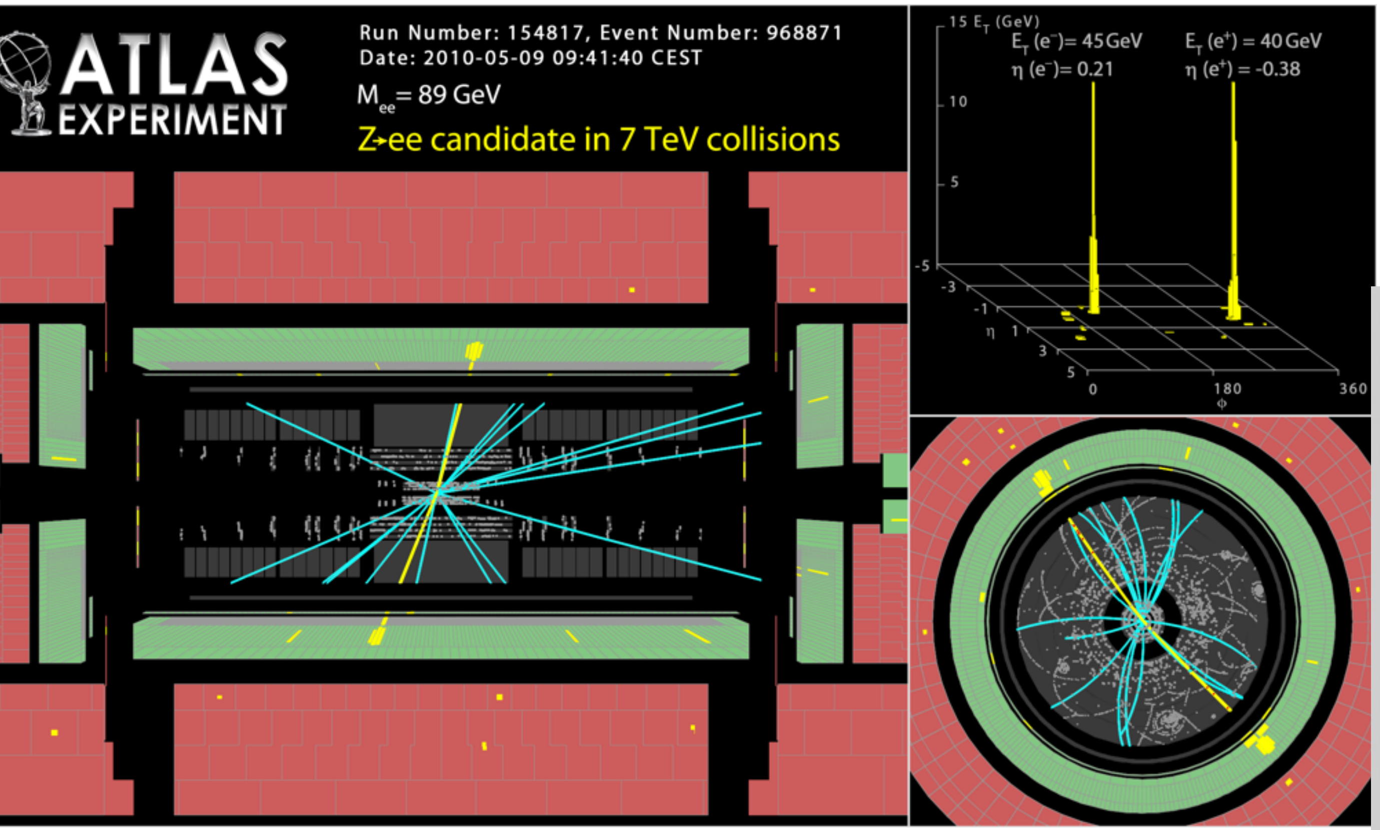
- Combination of pixels, silicon strips ("SCT") and straw tube transition radiation tracker (TRT)

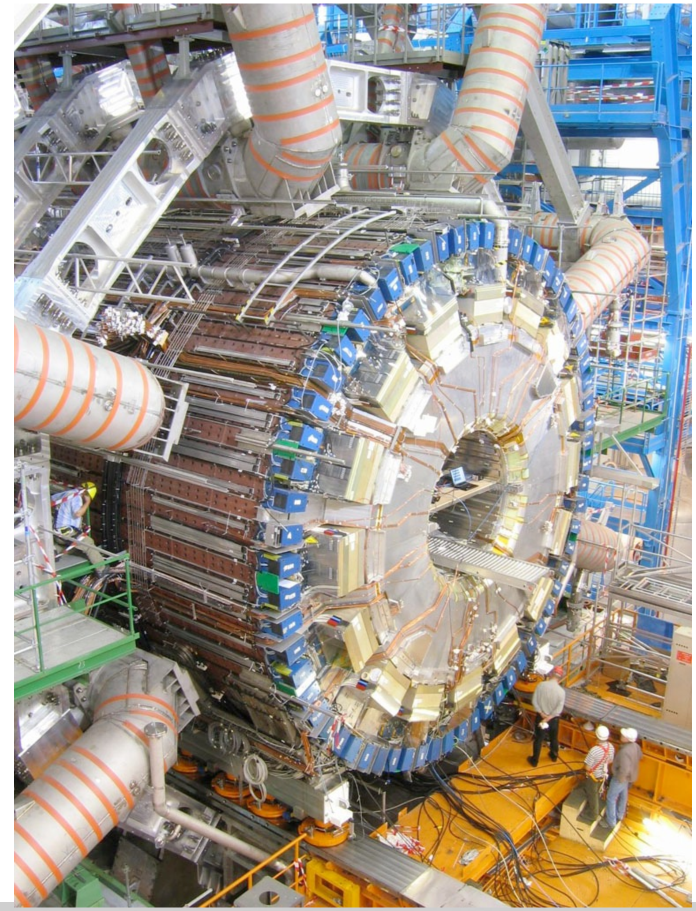


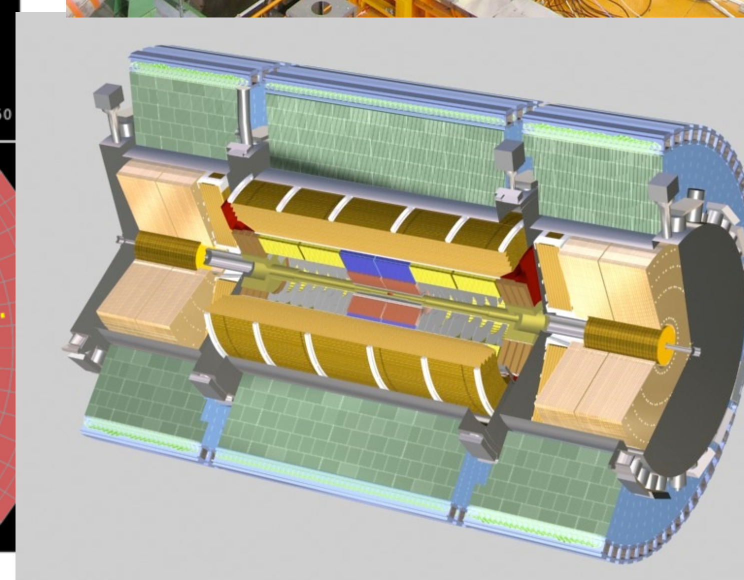


Calorimetry

- Liquid Argon & Pb accordion (EM & forward), crystals
- Scintillator & steel/copper/ tungsten (hadronic)

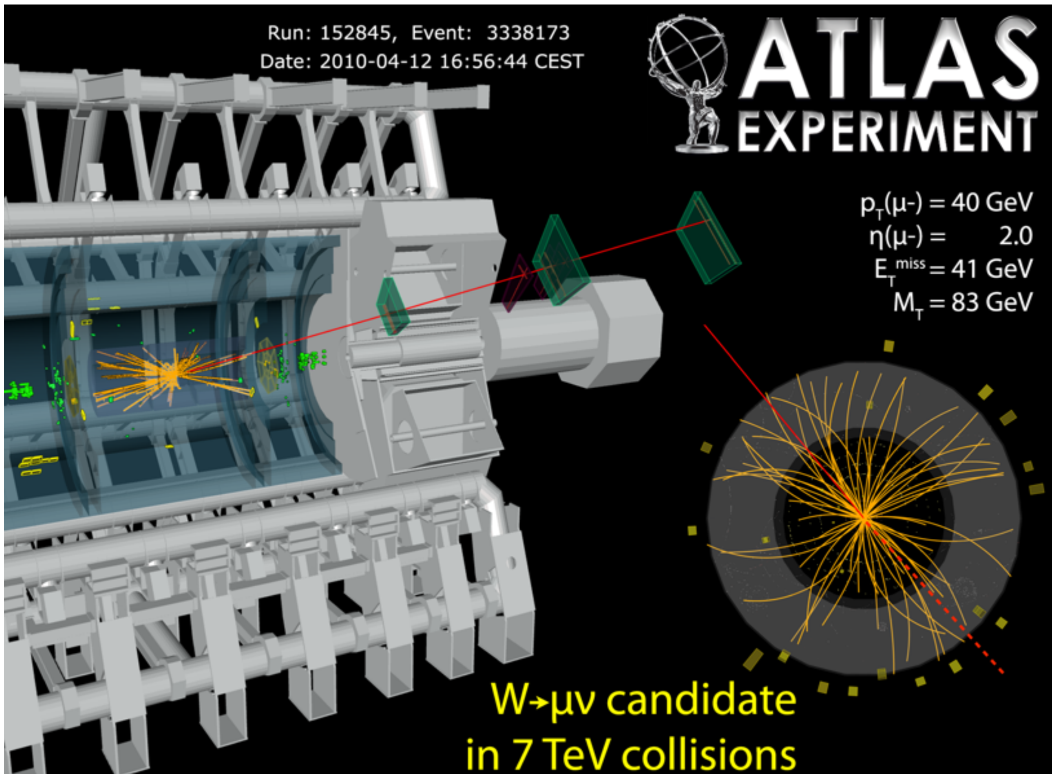


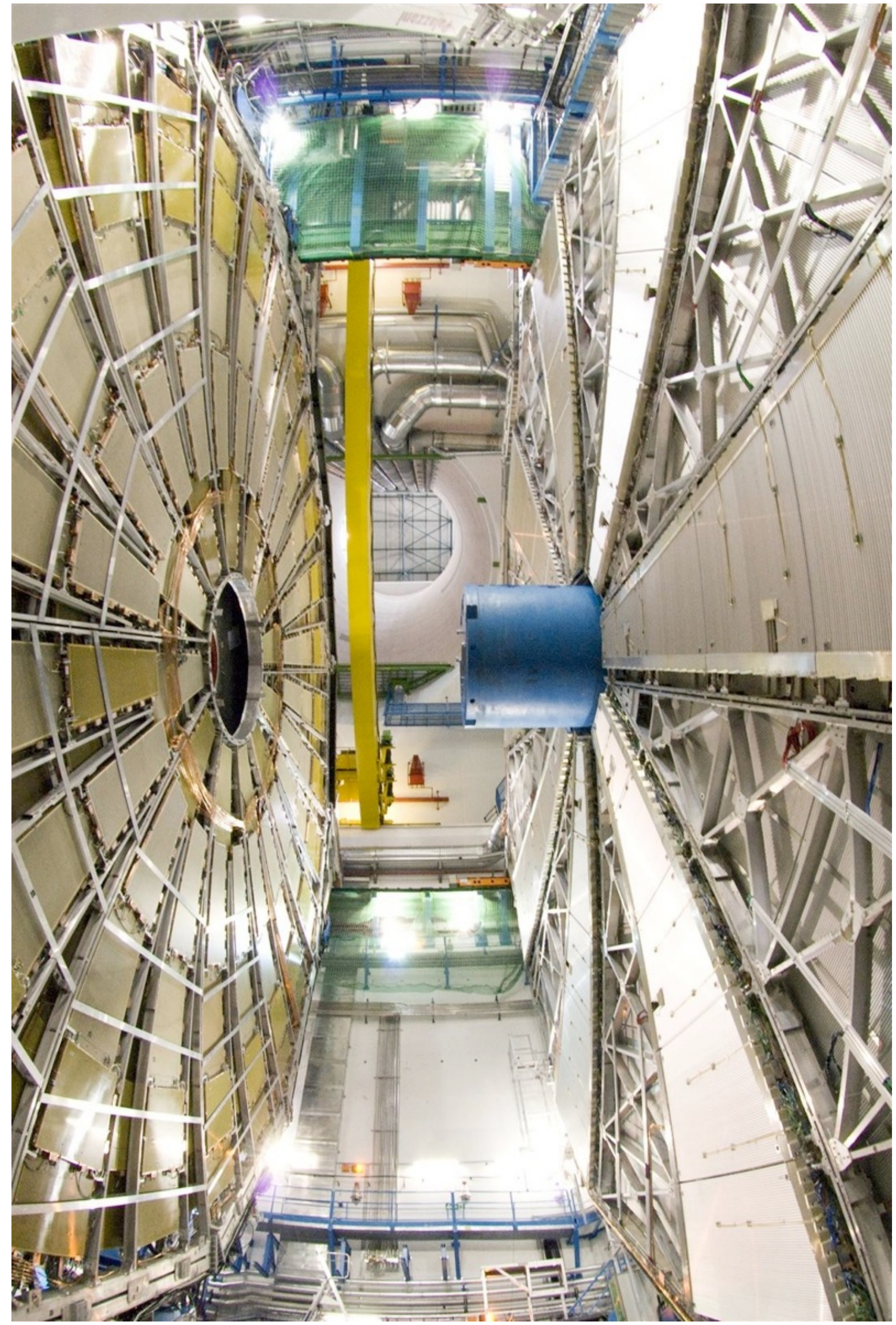




Muons

- Air-core toroids/flux return; wire chambers and RPCs

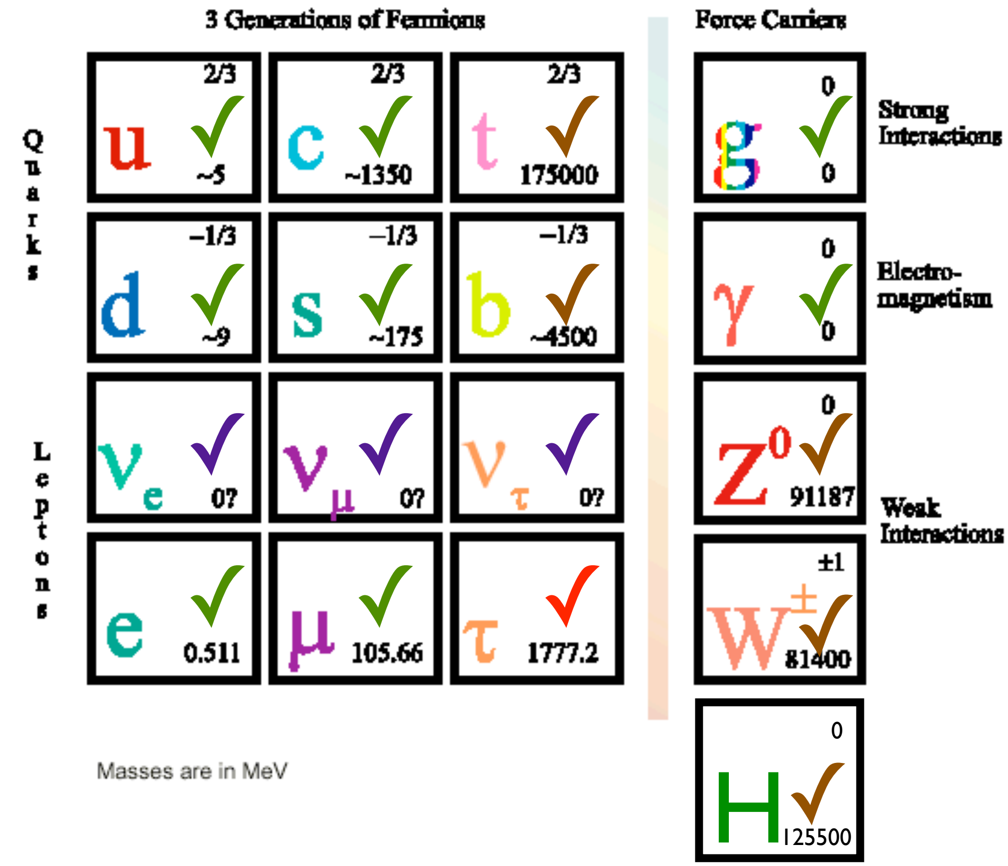




Neutrinos*

*(100% acceptance)

Detecting Particles



√ : Detect with high efficiency

√ : Detect by missing transverse energy

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

The Work

Steps in a Physics Analysis

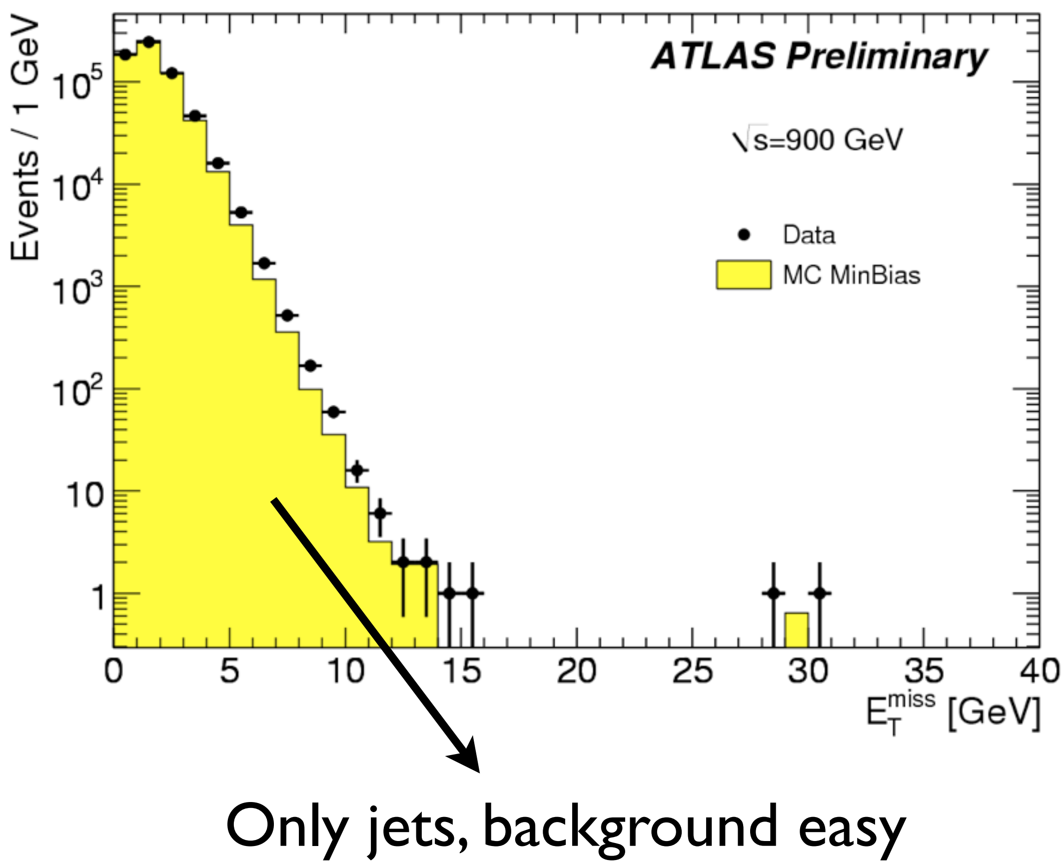
- Choose a topic (often theory-motivated)
- What is the final state? ⇒ "Preselection"
  - For a search, sufficiently loose to be signal-poor
    - Prove you understand the detector response, physics processes contributing
  - But sufficiently tight to have a manageable data volume
    - ATLAS/CMS write 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 $\propto$ 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 $\sim 10^{-4}$, 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...



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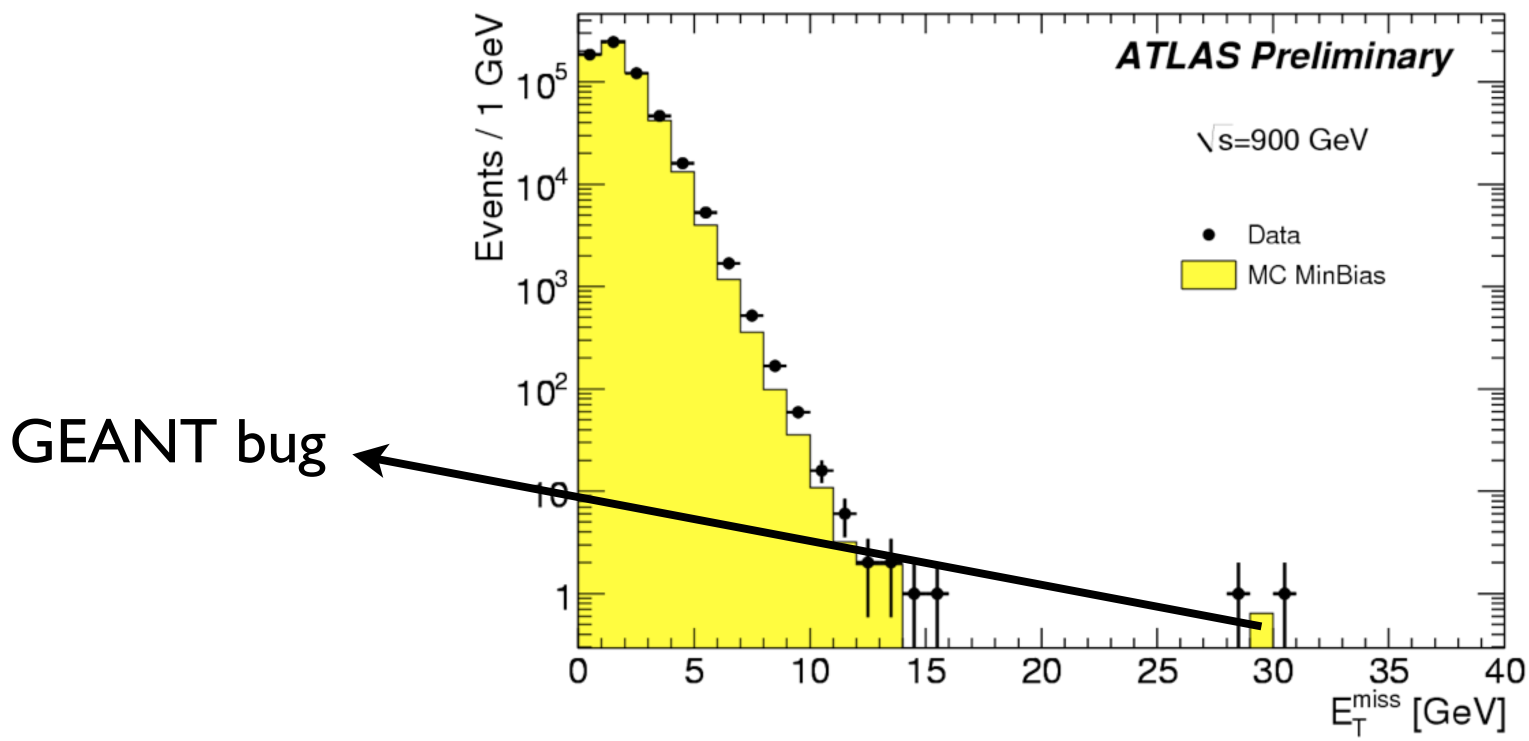

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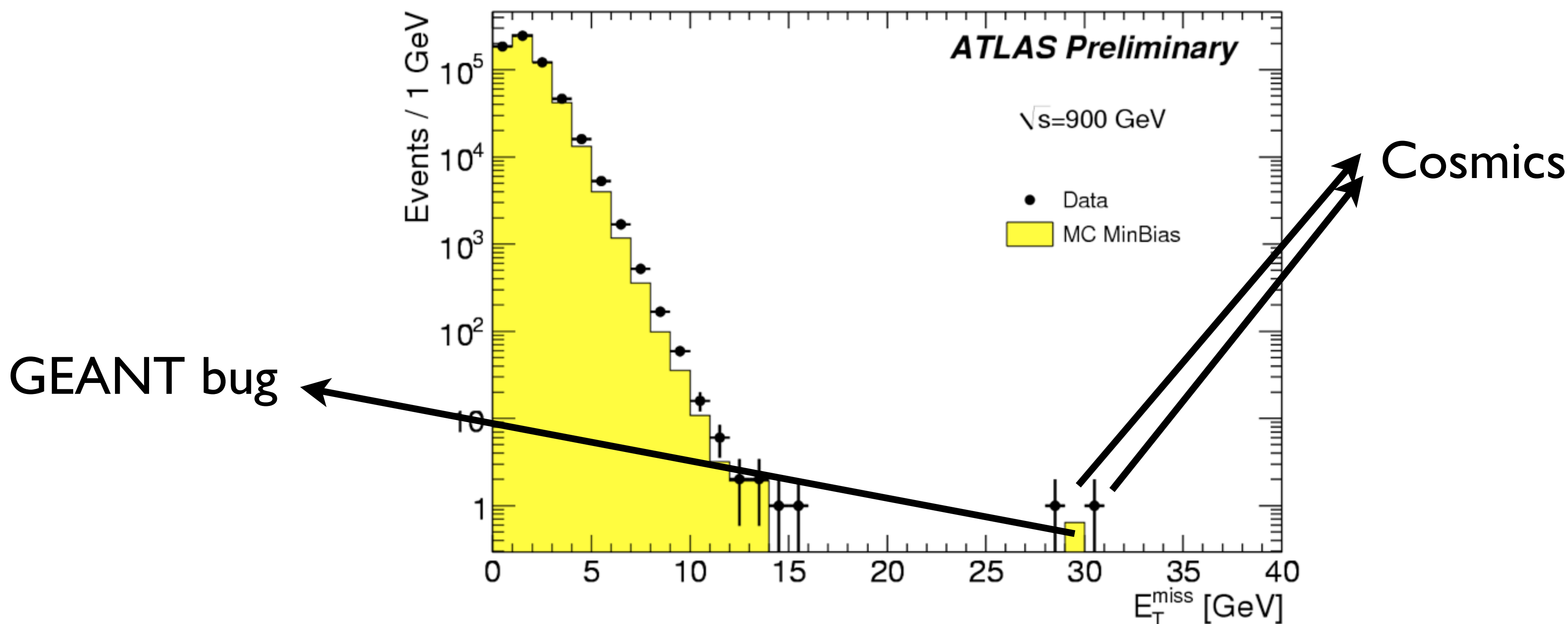
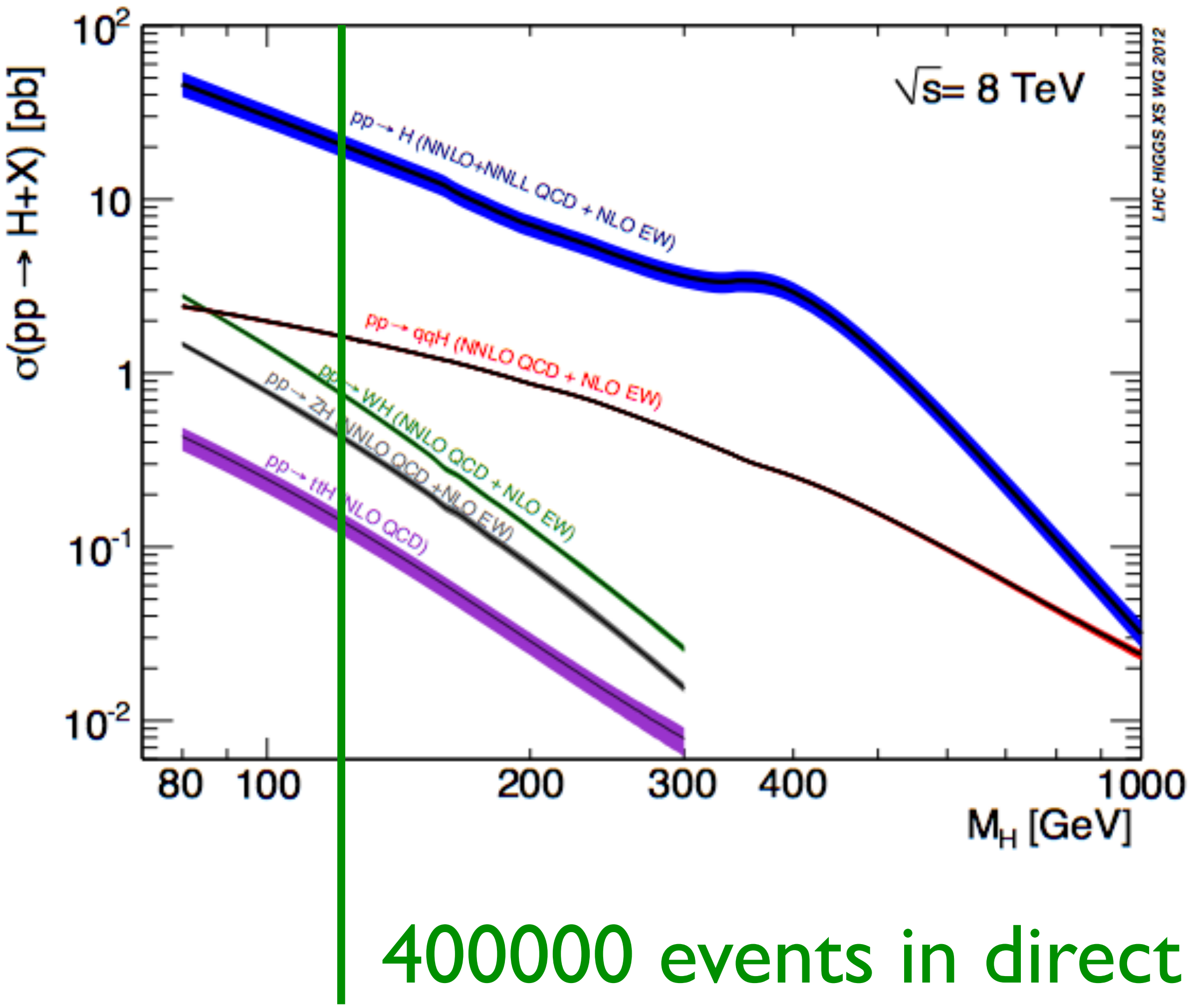


- Sometimes, it's better to take the appropriate time to investigate

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

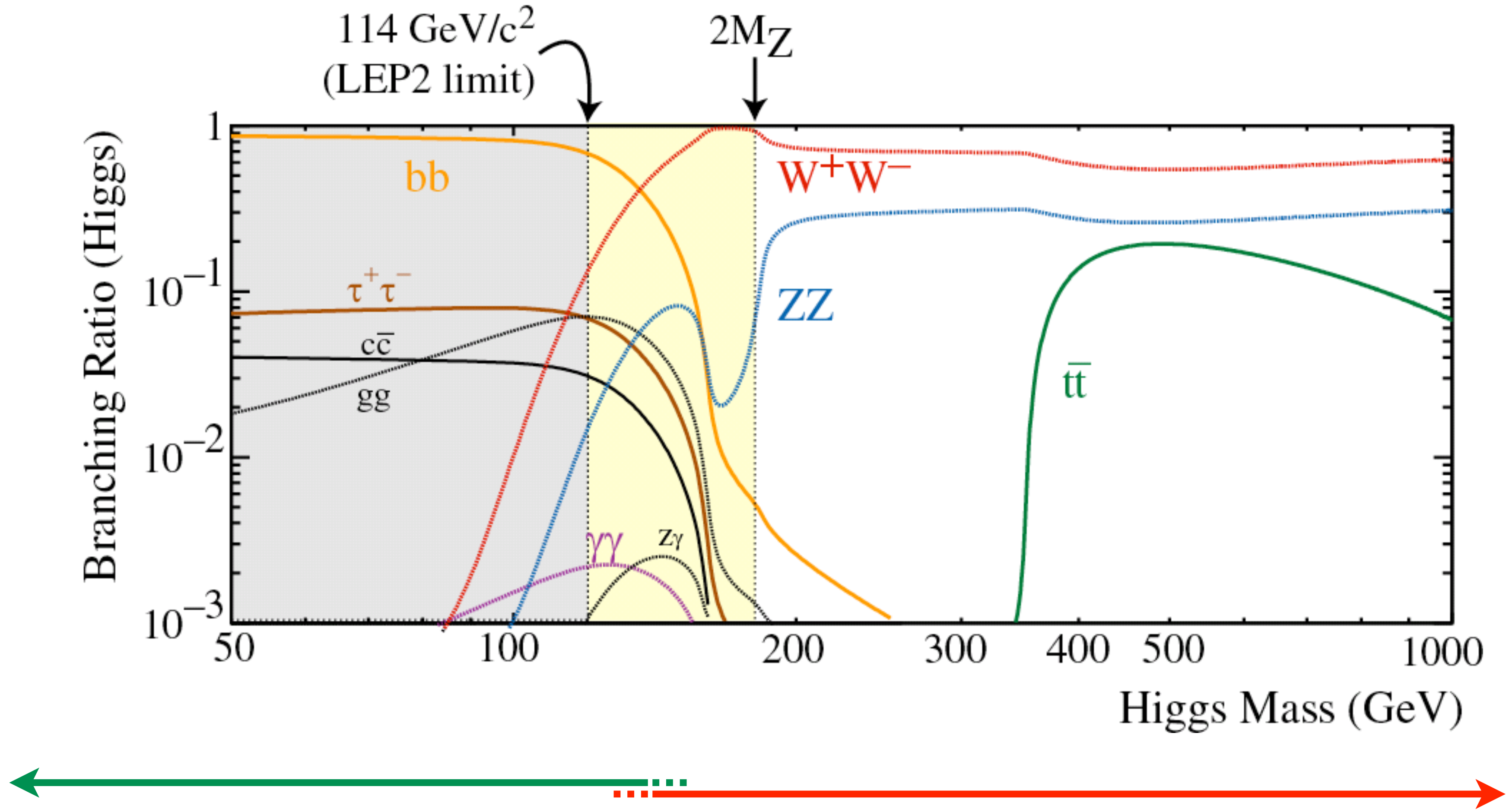
Producing Higgses

- 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

$H \rightarrow bb, \tau\tau, \gamma\gamma$

High Mass

$H \rightarrow WW, ZZ$

$\mu+\tau$

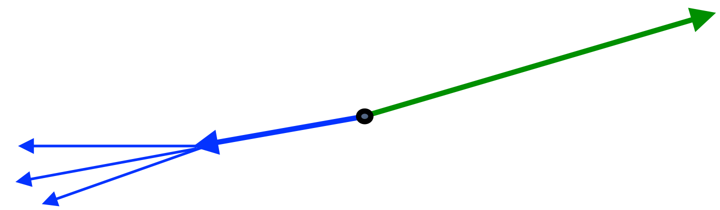
- Indirect constraints fairly weak (as opposed to e.g. $e+\mu$)
  - Indirect: $BR(\mu\tau) < \sim 10\%$; $BR(e\mu) < \sim 10^{-8}$
- Lepton Flavor remains a mystery
  - Observing LFV crucial in understanding origin
  - Know it exists in the neutrino sector
- Experimentally:
  - With 400k Higgses produced, 1% BR yields 4000 signal events (x efficiency)
  - Two leptons ⇒ small to moderate background at hadron collider
    - But τ's don't always decay to e/μ

Tau decays

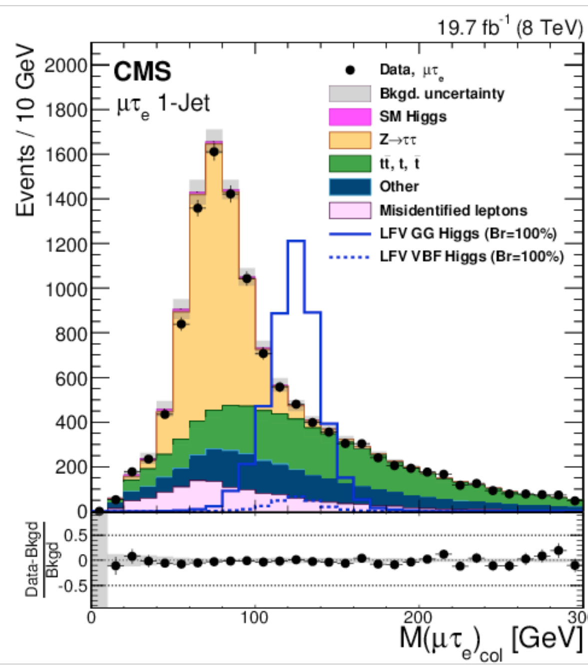
- Exploit two channels:
  - $\tau \rightarrow e\nu\nu$: BR = 18%
  - $\tau \rightarrow h\nu$: BR = 49% (one charged particle) + 15% (three charged particles)
  - Avoid $Z \rightarrow \mu\mu$ background
- Final states are $\mu\tau_e$ and $\mu\tau_h$
  - Irreducible background is $Z \rightarrow \tau\tau$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

Collinear Mass

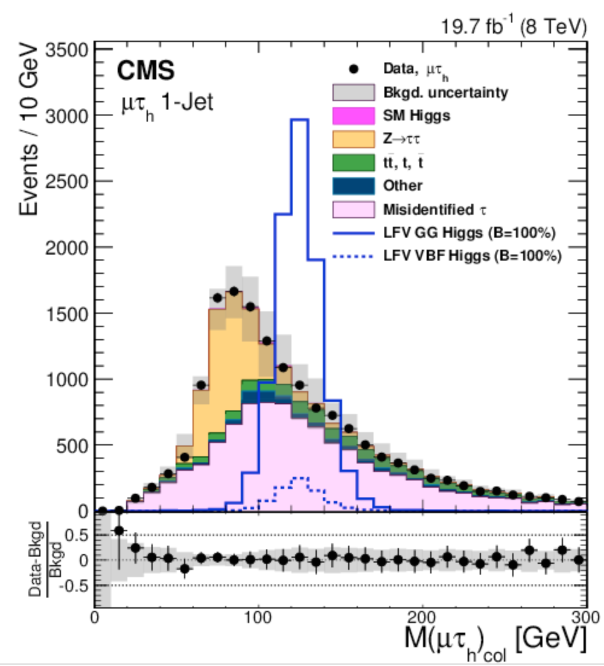
- ❖ m(H) = 125 GeV, m(τ) = 1.8 GeV
  - ➡ Tau is heavily boosted
  - ➡ Tau decay products are collinear with tau
- ❖ Under that assumption, know neutrino direction
  - From direction and missing transverse momentum infer neutrino longitudinal momentum



CMS: arXiv:1502.07400

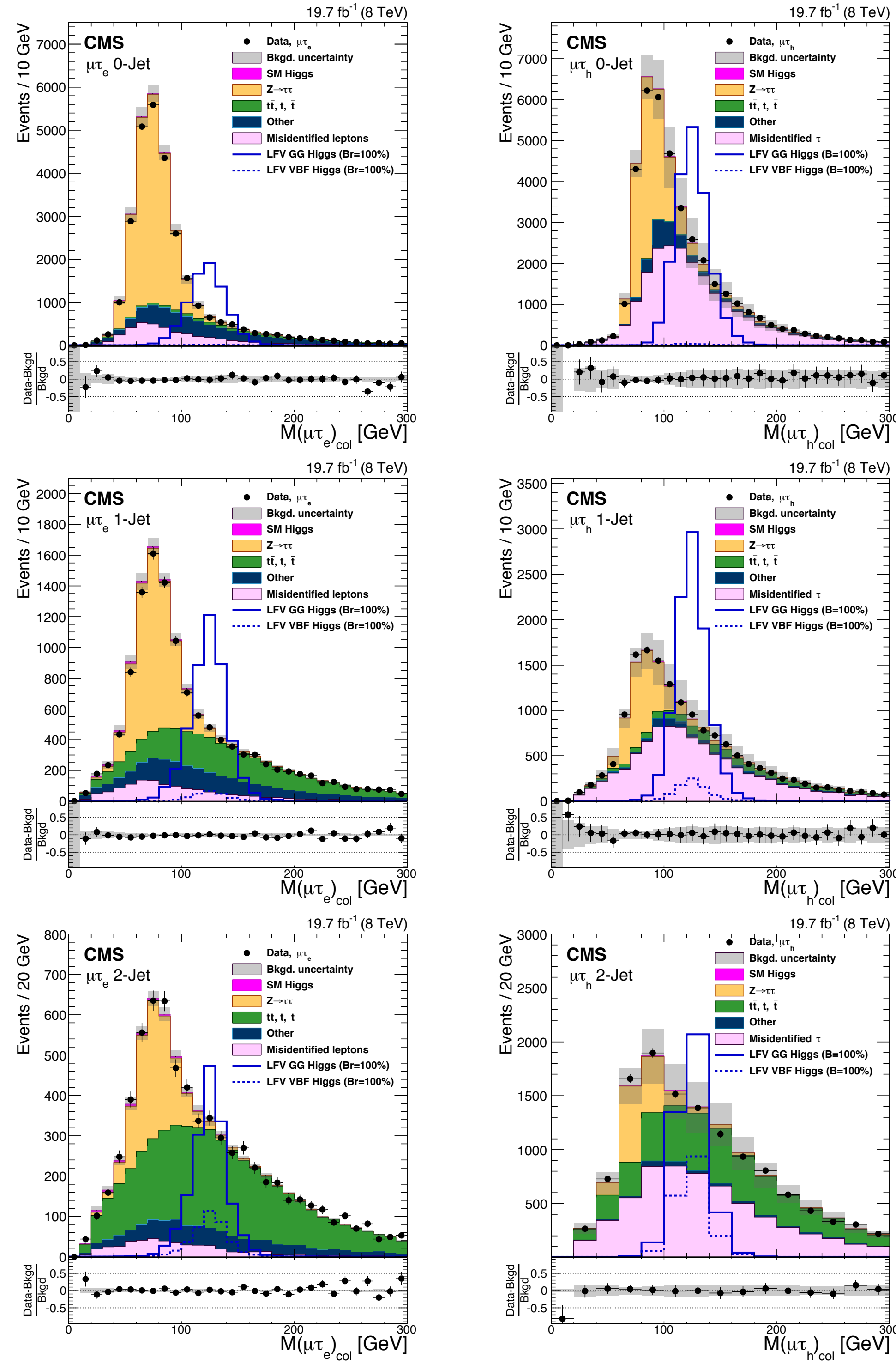


Preselection



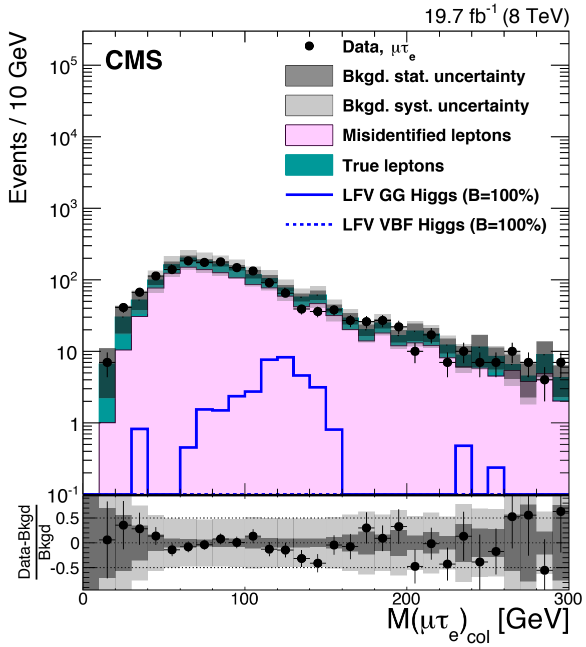
Categorize!

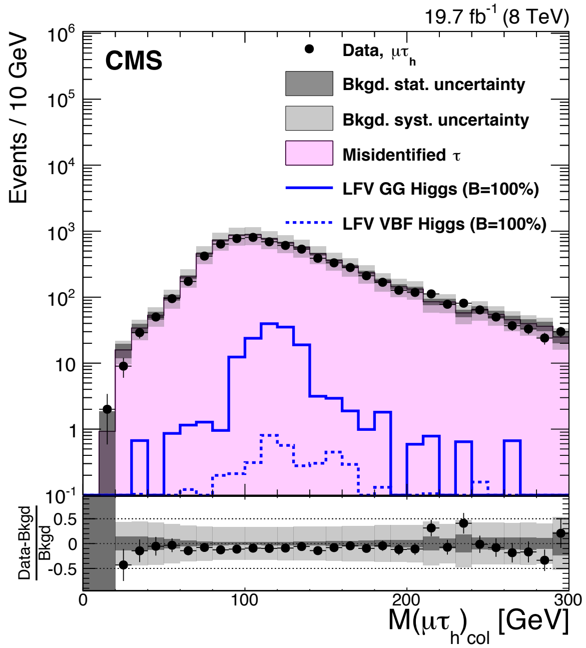
- Different production mechanism (gluon fusion vs. vector boson fusion) lead to different topologies
  - In practice number of jets
- Different decay channels have different reducible backgrounds
  - Hadronic tau decays are low multiplicity jets
- Categorize to exploit different S/B!
  - Assign corresponding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



Backgrounds

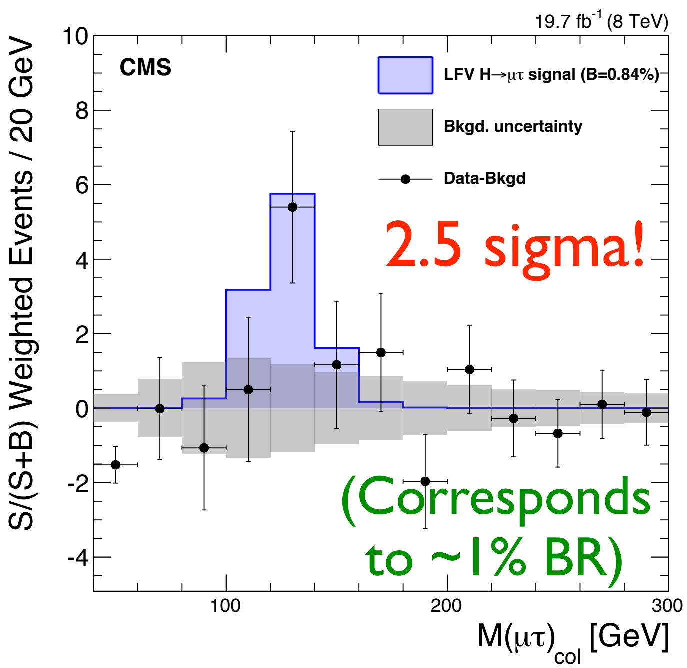
- ❖ Small signal ⇒ need very accurate background estimate
  - Use data where possible
- ❖ In this case:
  - Z → ττ (irreducible): take Z → μμ events from data, replace one muon with simulated tau
  - Misidentified leptons: independently measure probability to fake e or τ_h, check in control region rich in "fakes"
  - Rest: simulation





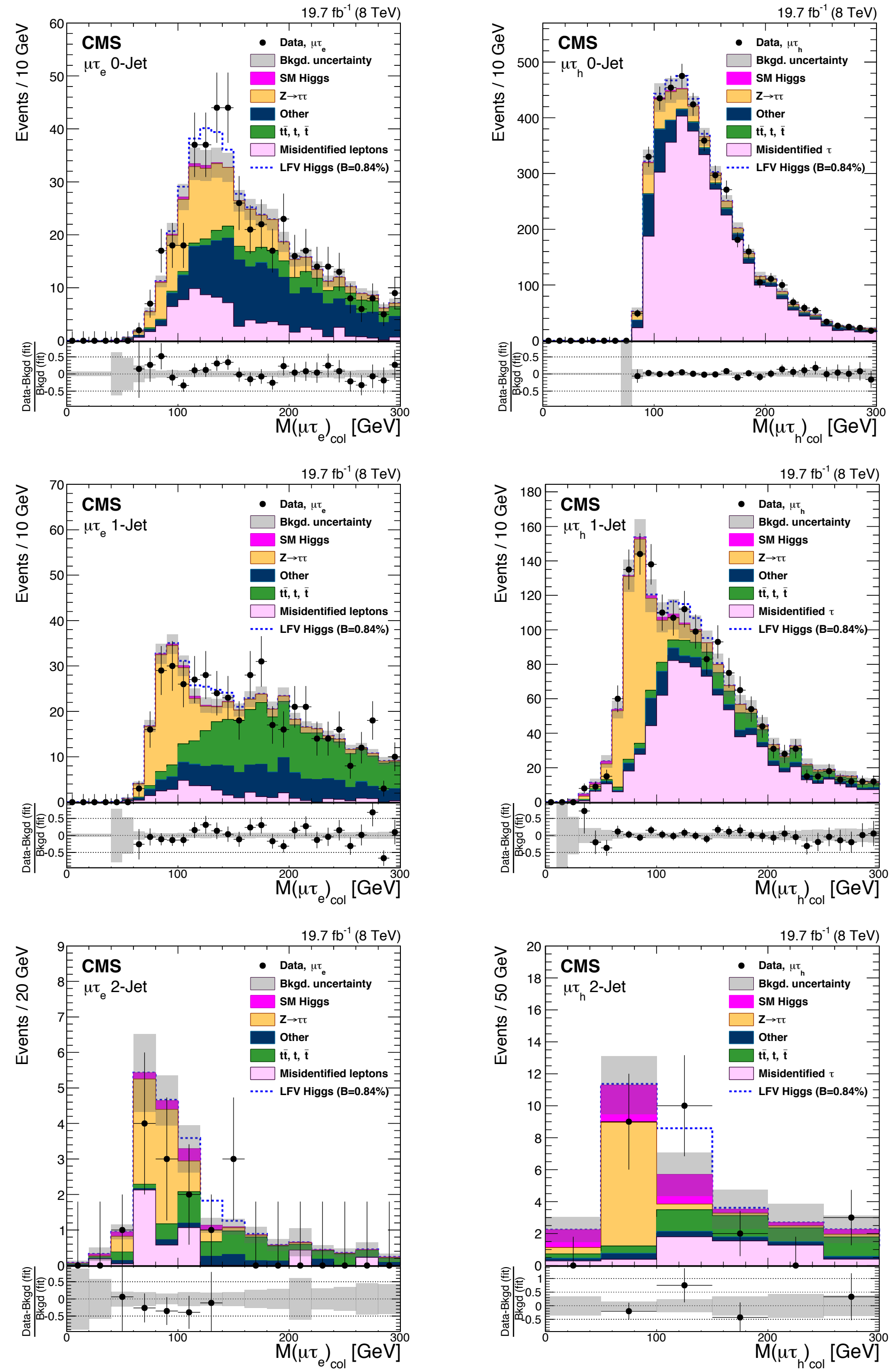
Finally

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



2.5 sigma!

(Corresponds to ~1% BR)



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

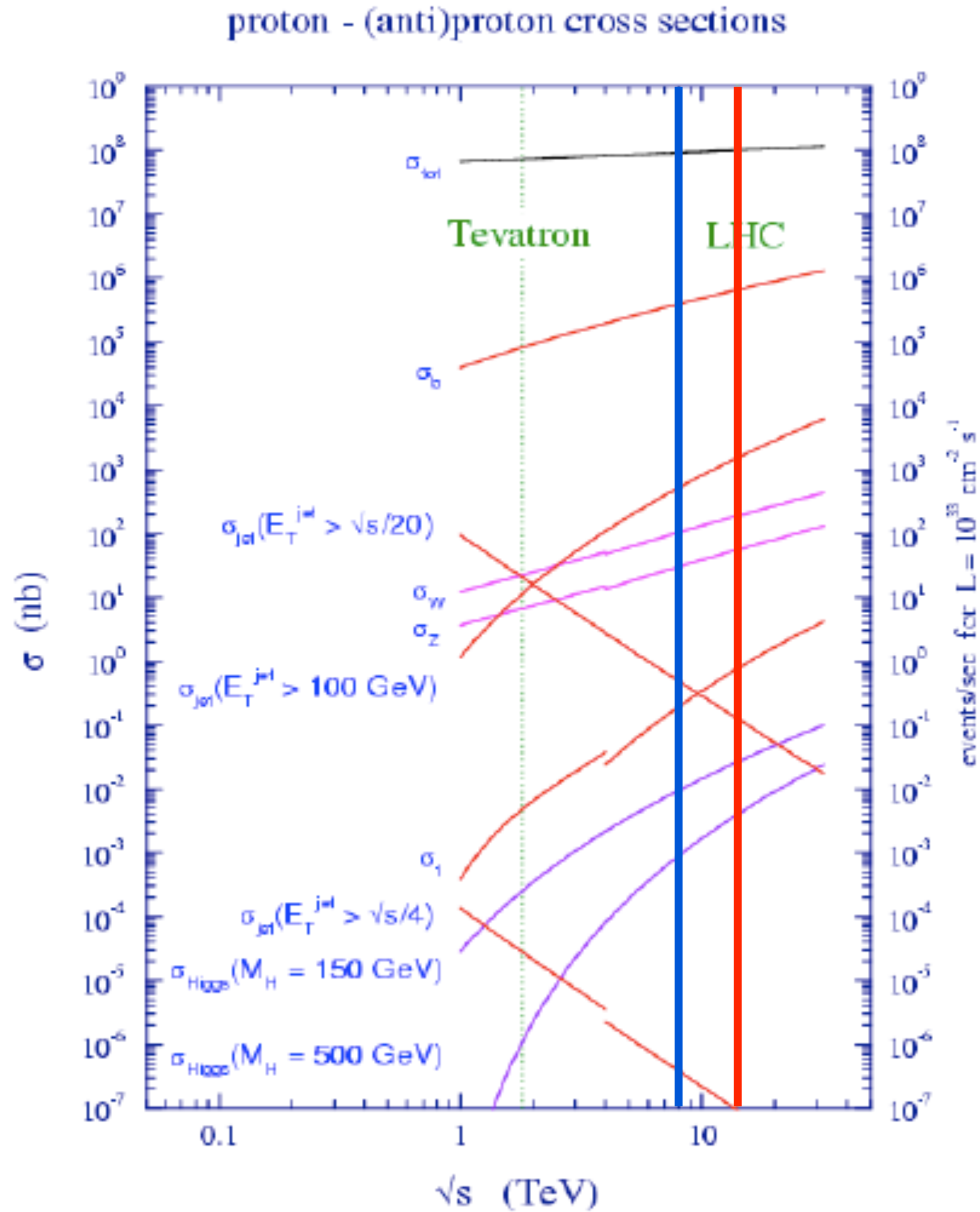
Theory

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?

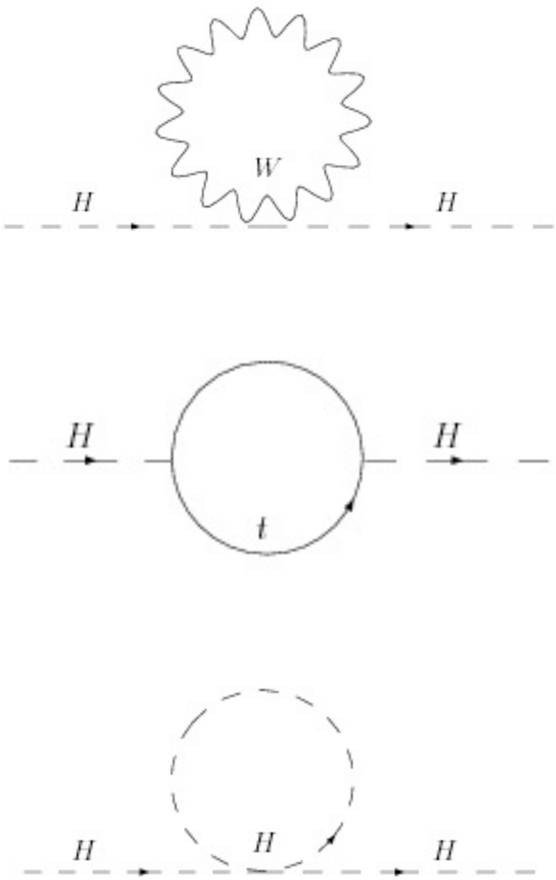


Experimental Searches

- 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



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

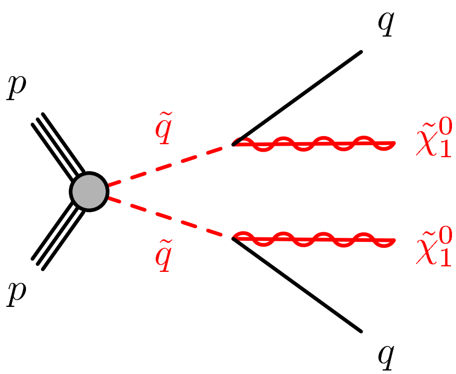
$$\frac{3}{16\pi^2} y_t^2 E^2$$

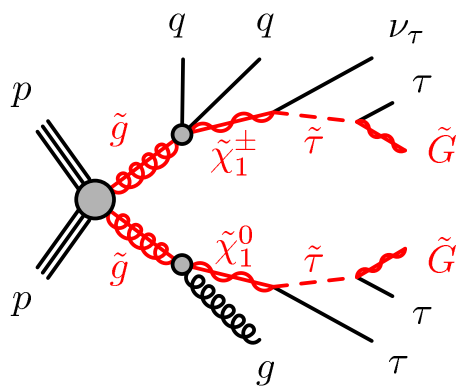
$$\frac{1}{16\pi^2} \lambda E^2$$

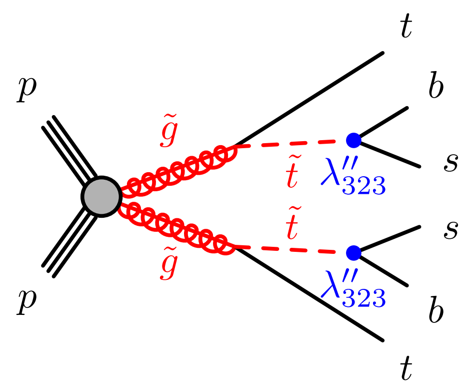
- If for every fermion there is a partner boson and vice-versa
  - Loops cancel each other
- Symmetry cannot be exact (no bosonic electron observed)
  - Symmetry breaking leads to “residual” Higgs mass
- This is supersymmetry

Canonical SUSY

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

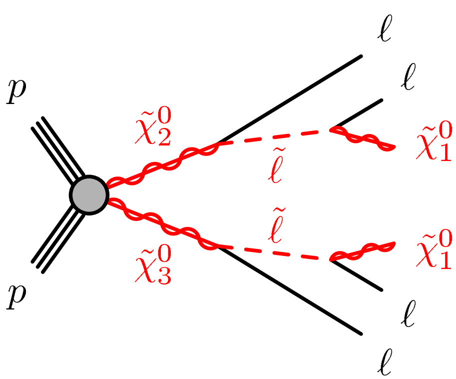


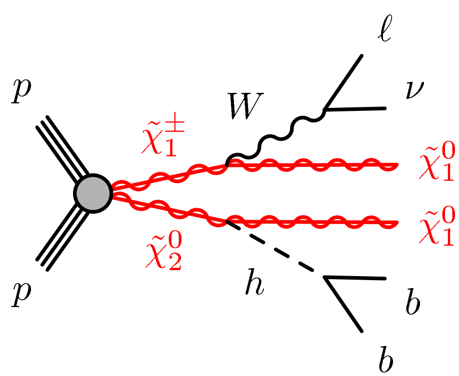


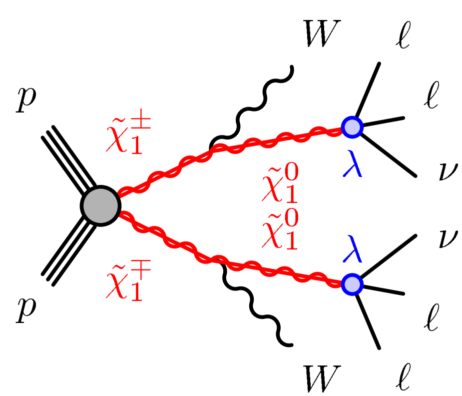


  - … or weak production

RPV



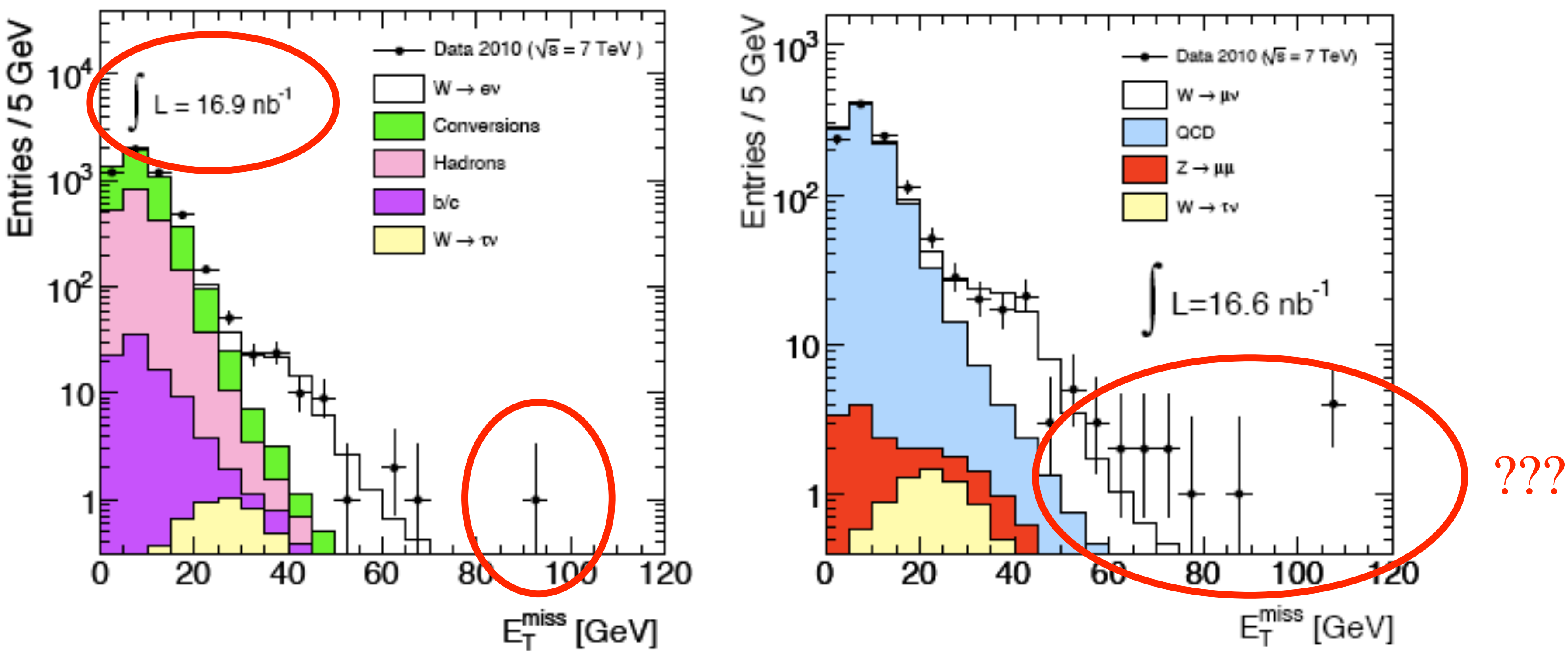


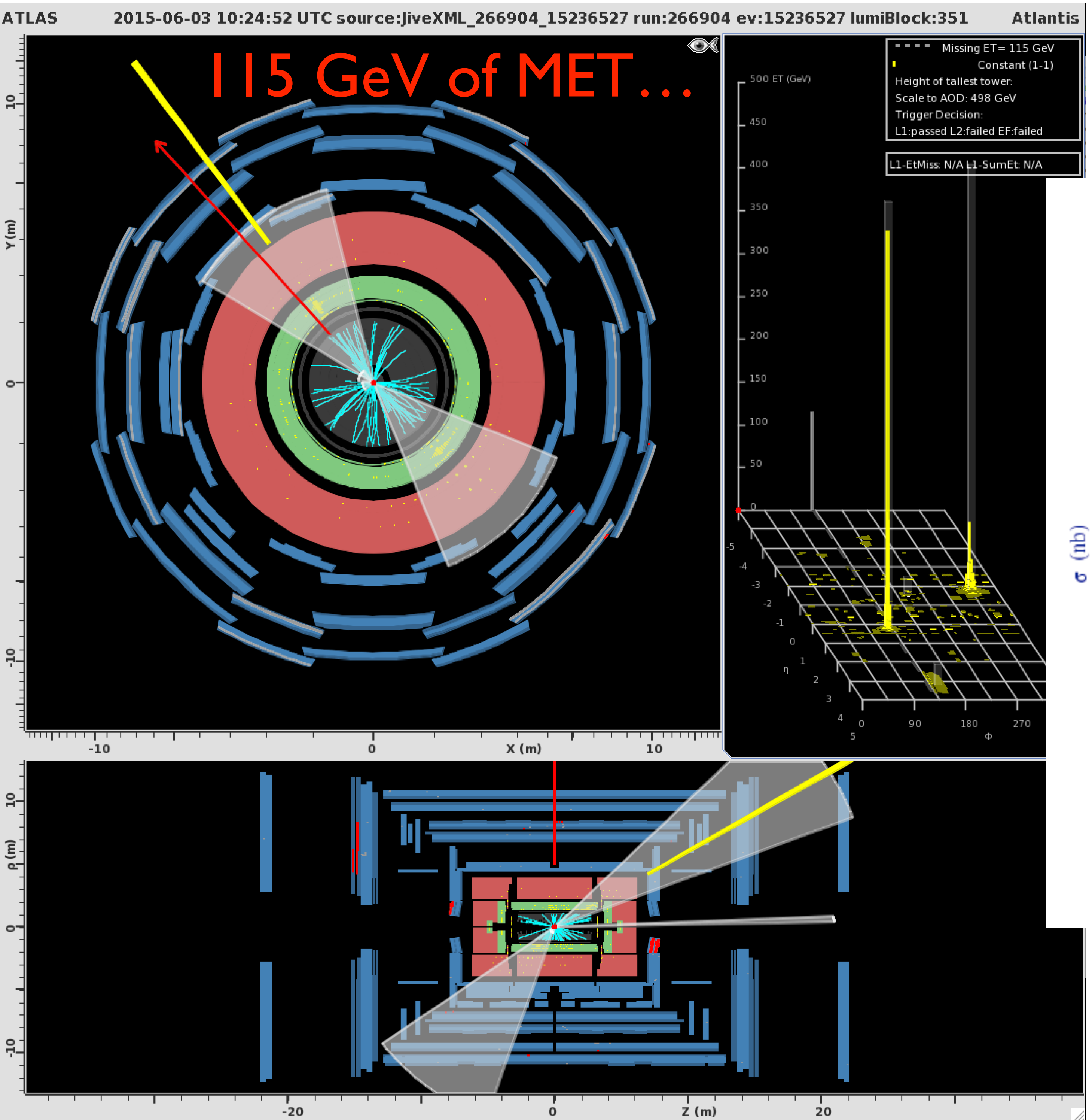


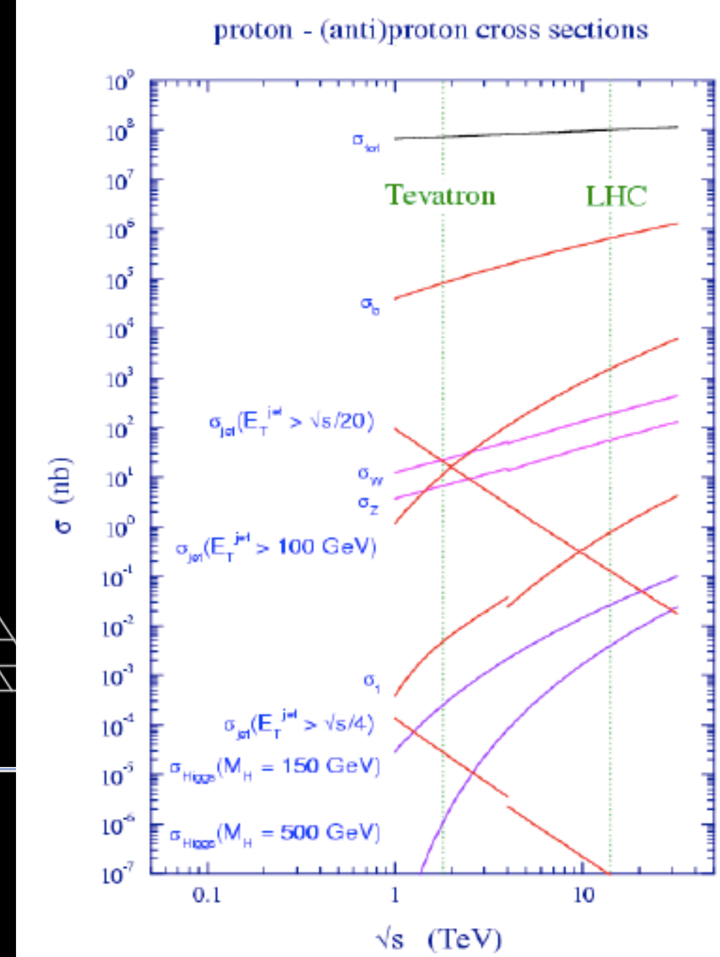
Missing ET

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

Early 2010

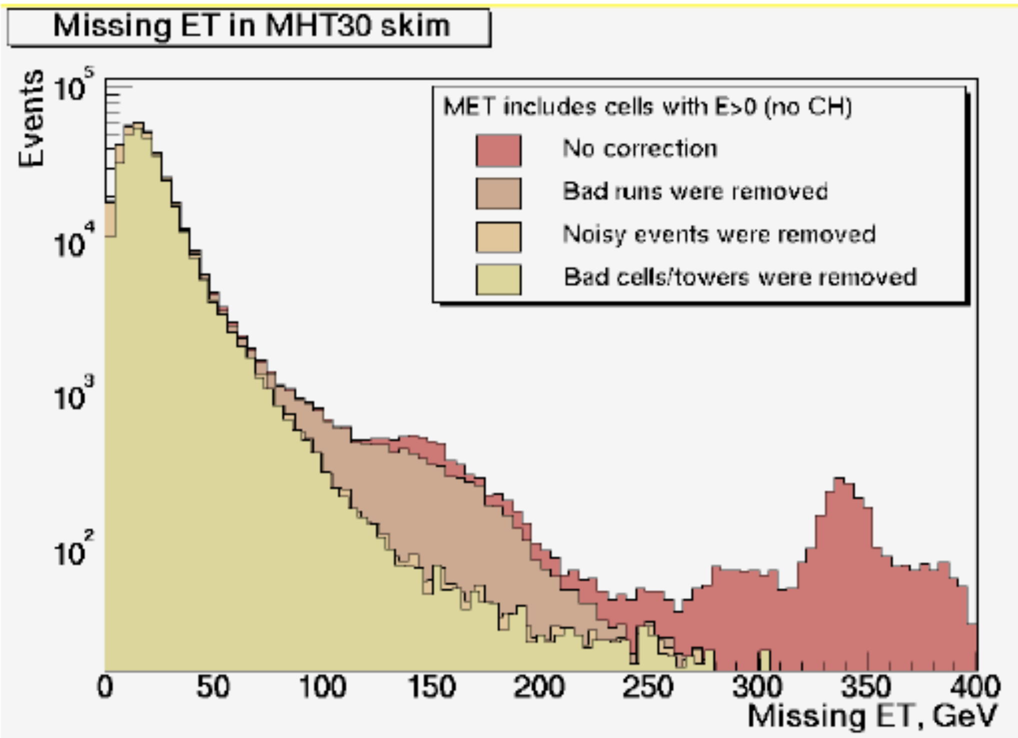



ATLAS
2015-06-03 10:24:52 UTC source:JiveXML_266904_15236527 run:266904 ev:15236527 lumiBlock:351
Atlantis
115 GeV of MET…
Missing ET= 115 GeV
Constant (1-1)
Height of tallest tower:
Scale to AOD: 498 GeV
Trigger Decision:
L1:passed L2:failed EF:failed
L1-EtMiss: N/A L1-SumEt: N/A
500 ET (GeV)
Y (m)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

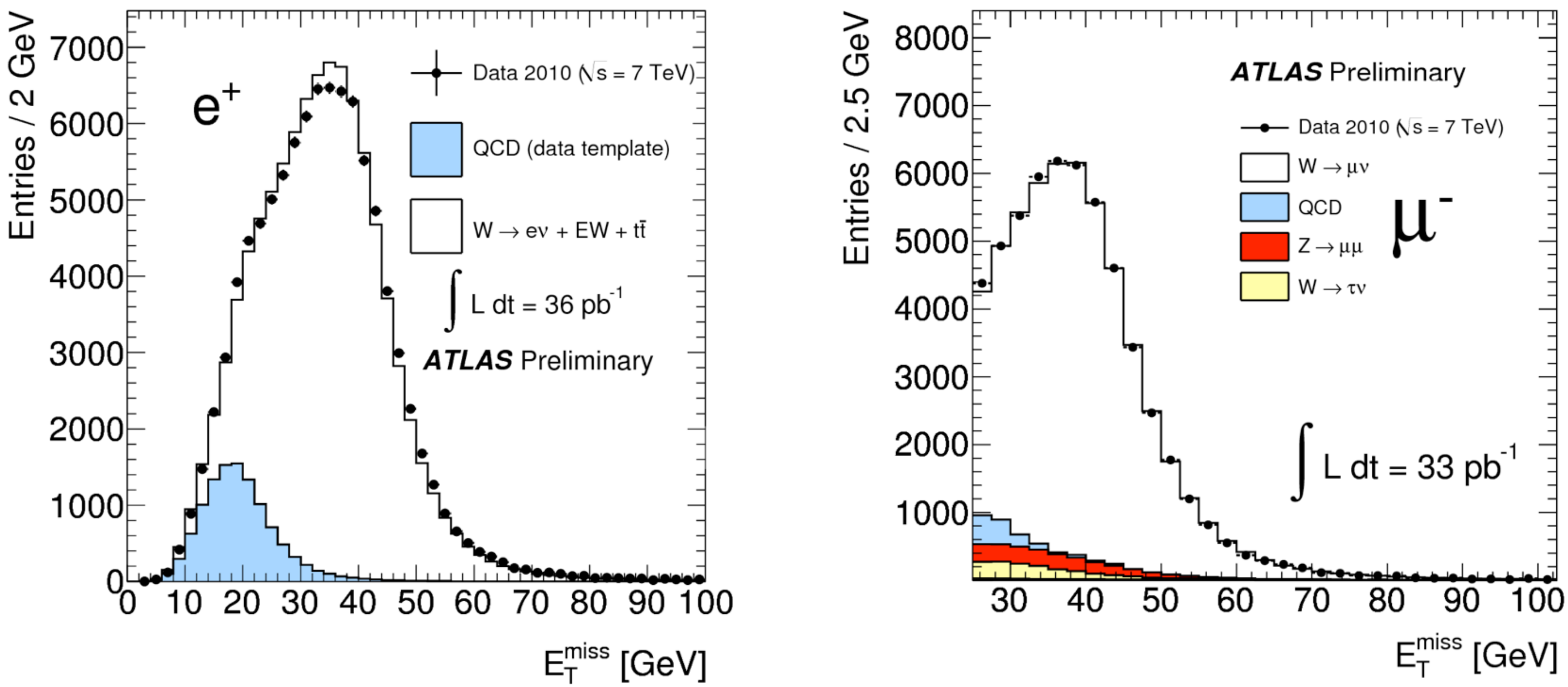

proton - (anti)proton cross sections
Tevatron
LHC
σ (nb)
√s (TeV)
σ_tot
σ_b
σ_jet(E_T^jet > √s/20)
σ_W
σ_Z
σ_jet(E_T^jet > 100 GeV)
σ_t
σ_jet(E_T^jet > √s/4)
σ_Higgs(M_H = 150 GeV)
σ_Higgs(M_H = 500 GeV)

❖ Analyses using MET are particularly sensitive

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

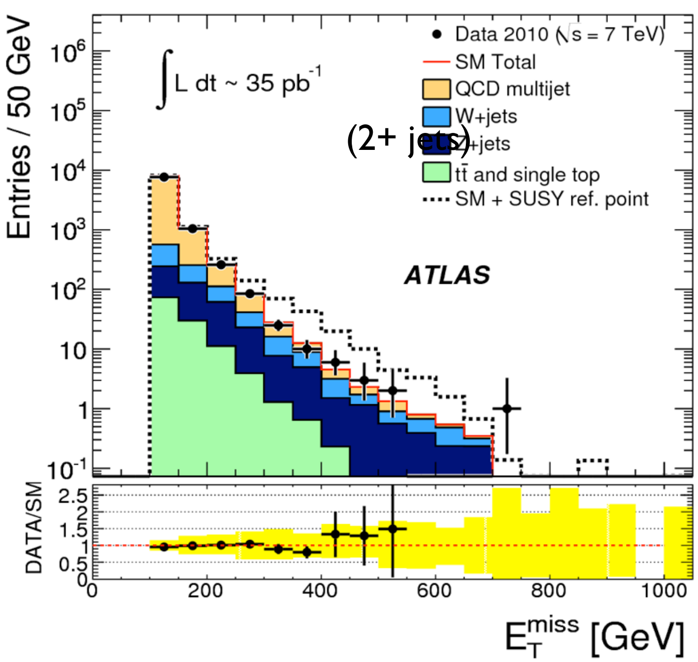


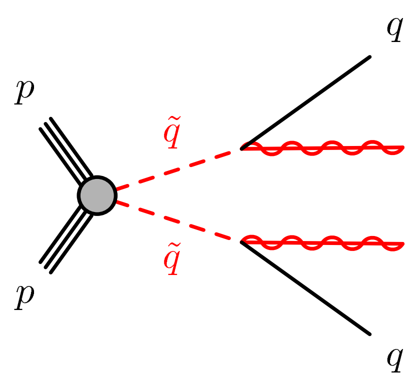
❖ Already ~200k clean $W \rightarrow \ell\nu$ events in 2010

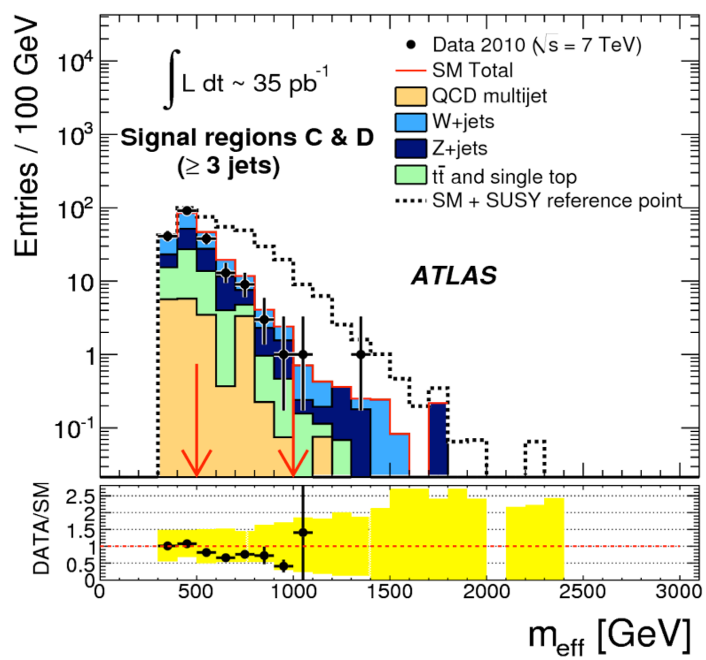
- Almost a billion now

SUSY as a Benchmark

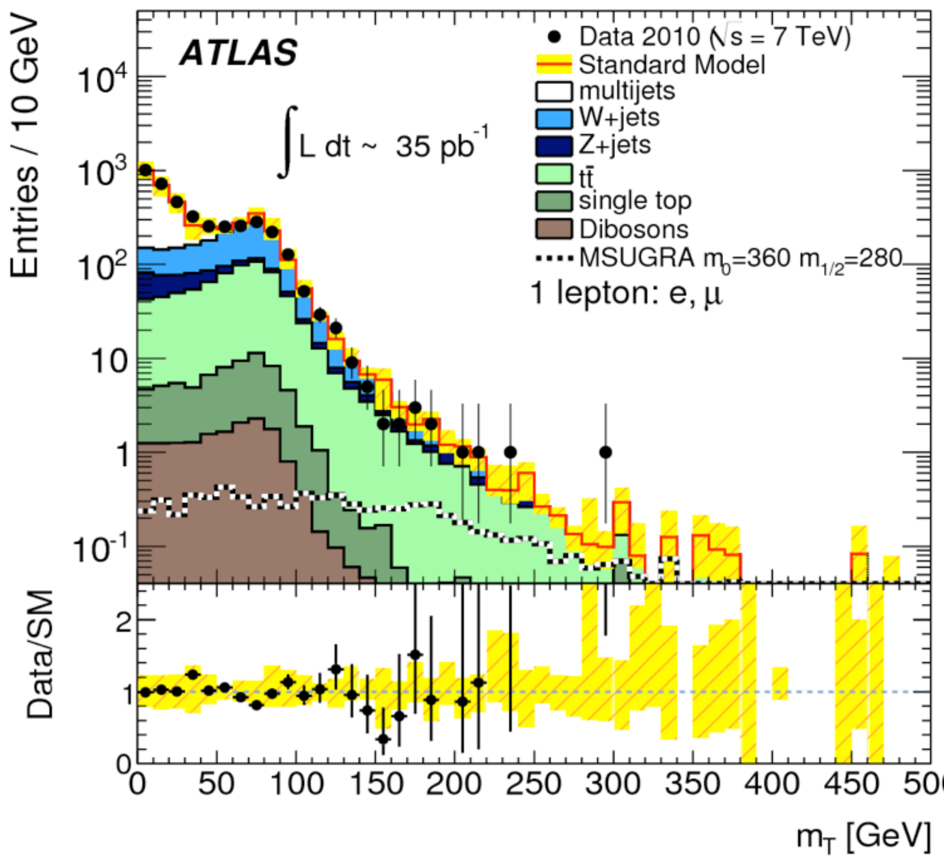
- Hadron collider ⇒ produce squarks and gluinos decaying to jets + MET
  - Optimize jet p_T & MET cuts for different scenarios, since gluinos produce more jets than squarks
    - Use M_{eff} to discriminate, measure of event Q^2

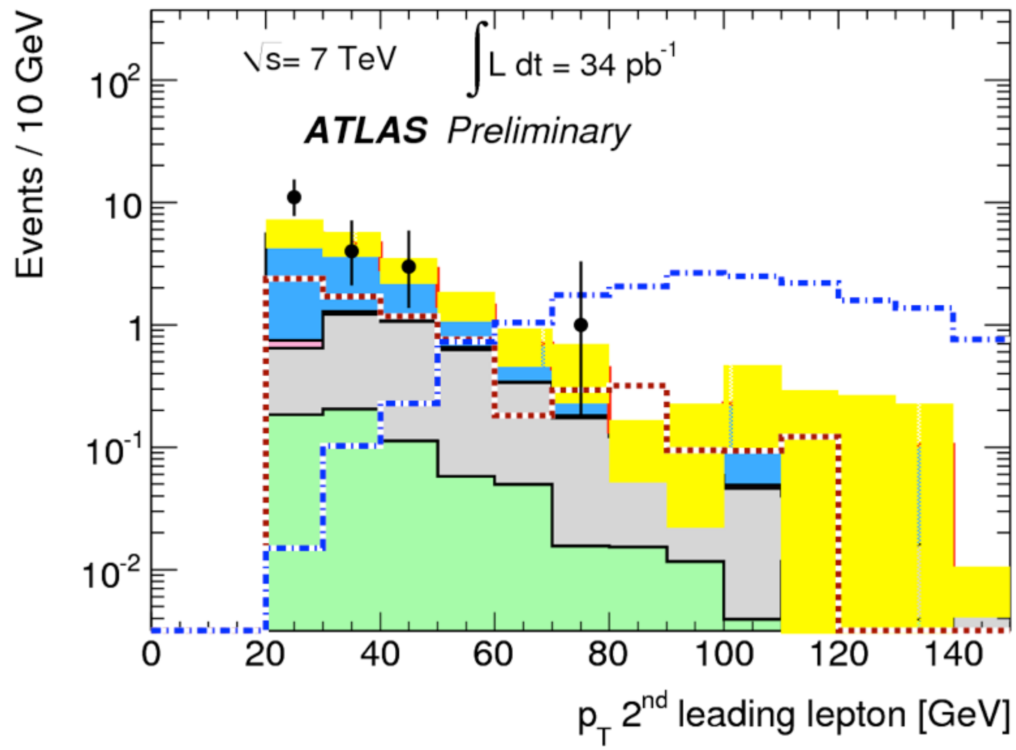




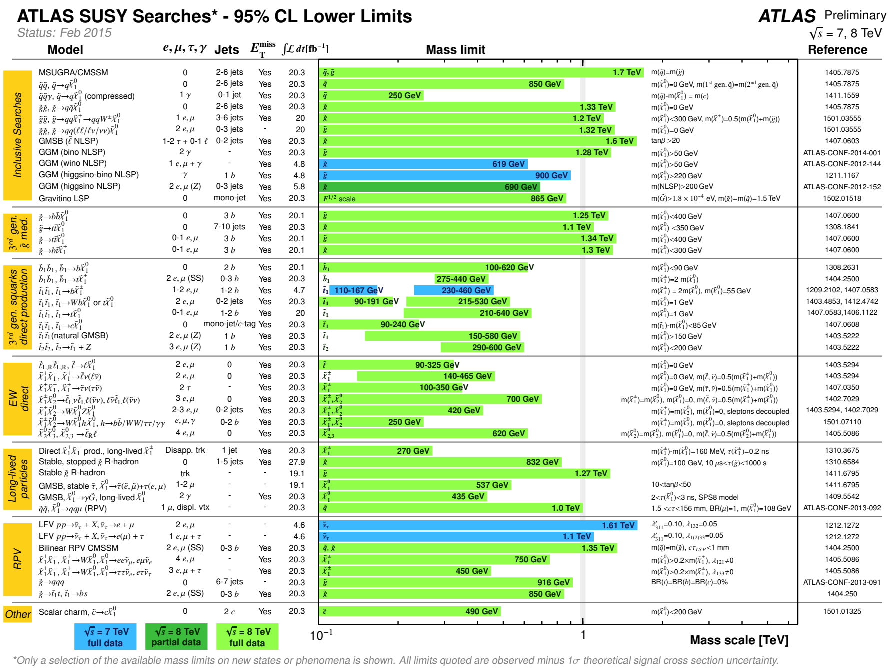


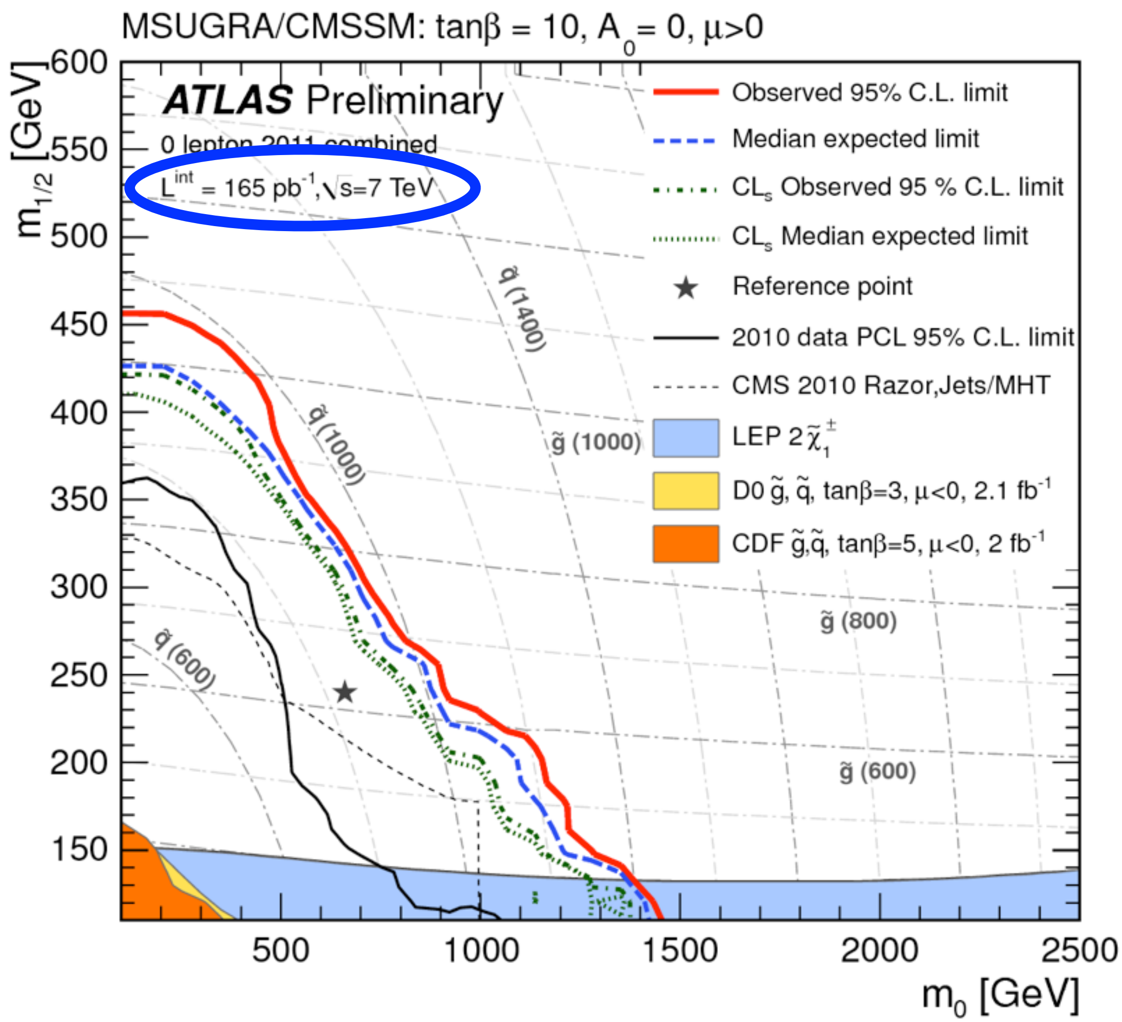
❖ Leptons in decay chains....





All Praise COM Energy!

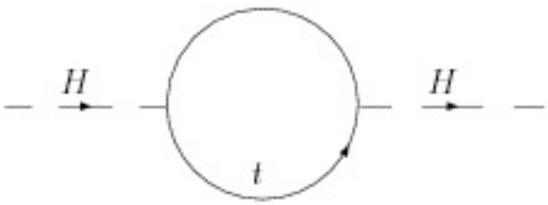




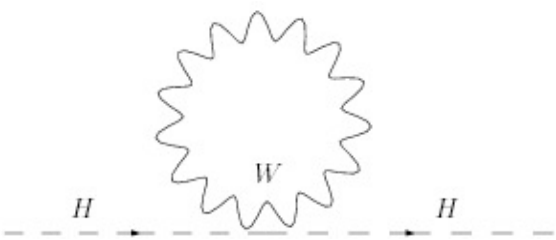
Tevatron blown away.... 8 (2016) hours of LHC data

But…

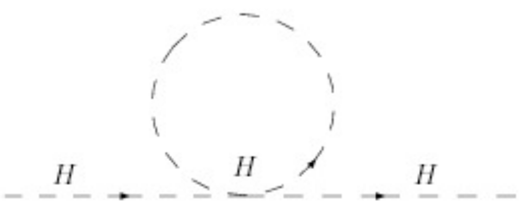
We’ve Found a Higgs!



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



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



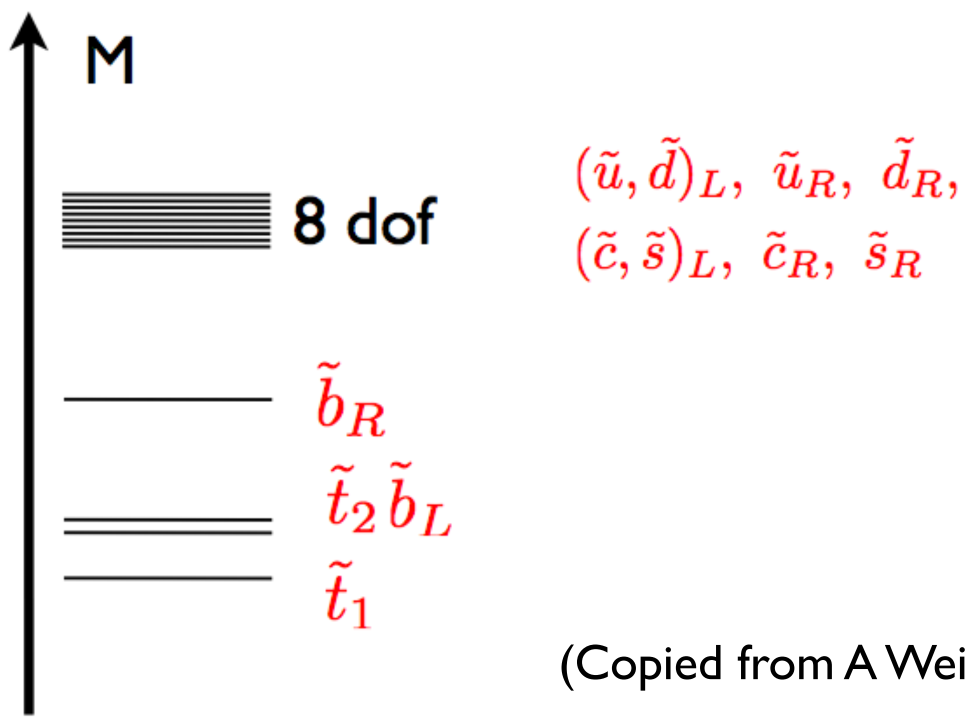
$$\rightarrow \frac{1}{16\pi^2} \lambda E^2$$

- 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**

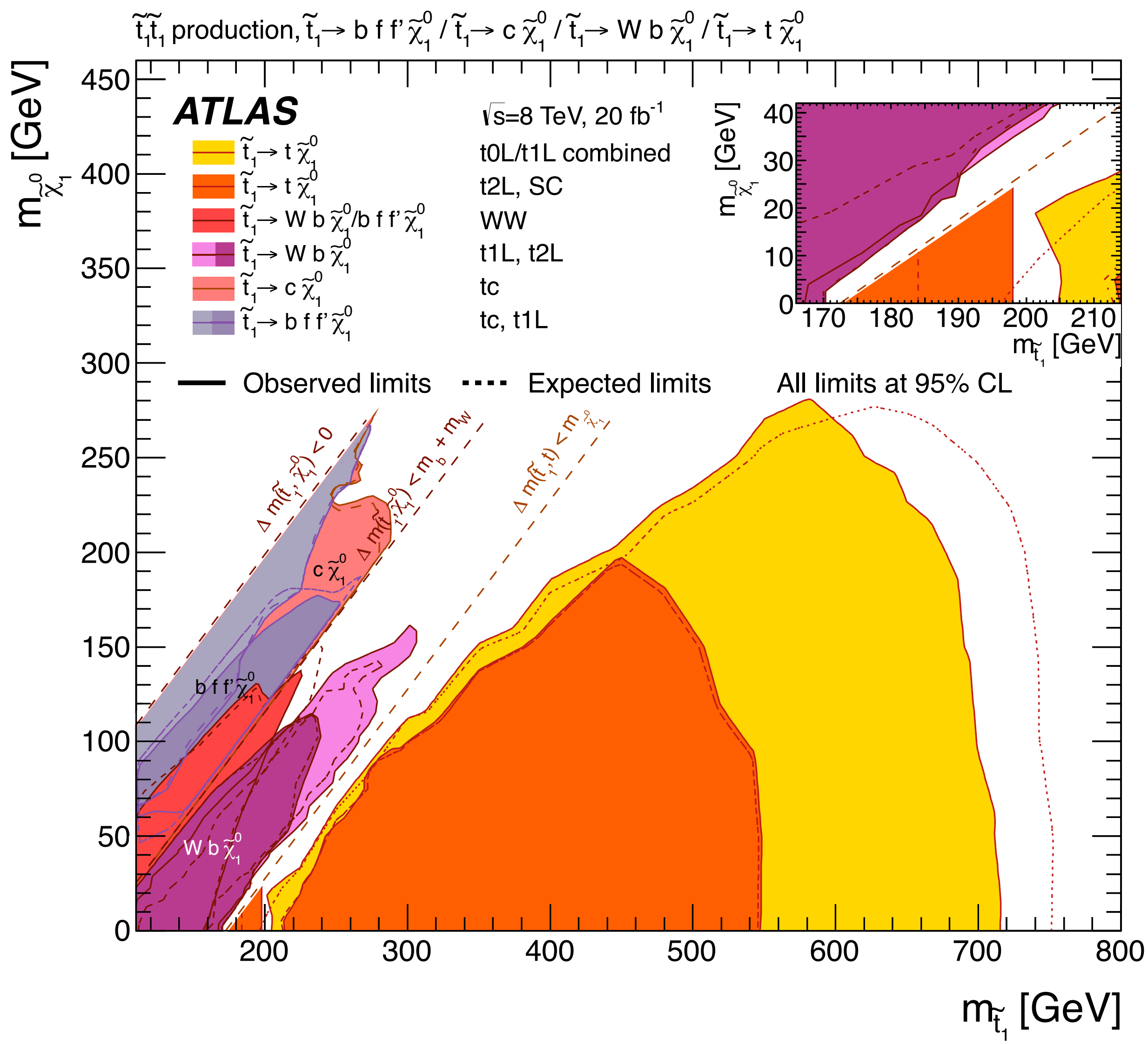
SUSY and the Higgs

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

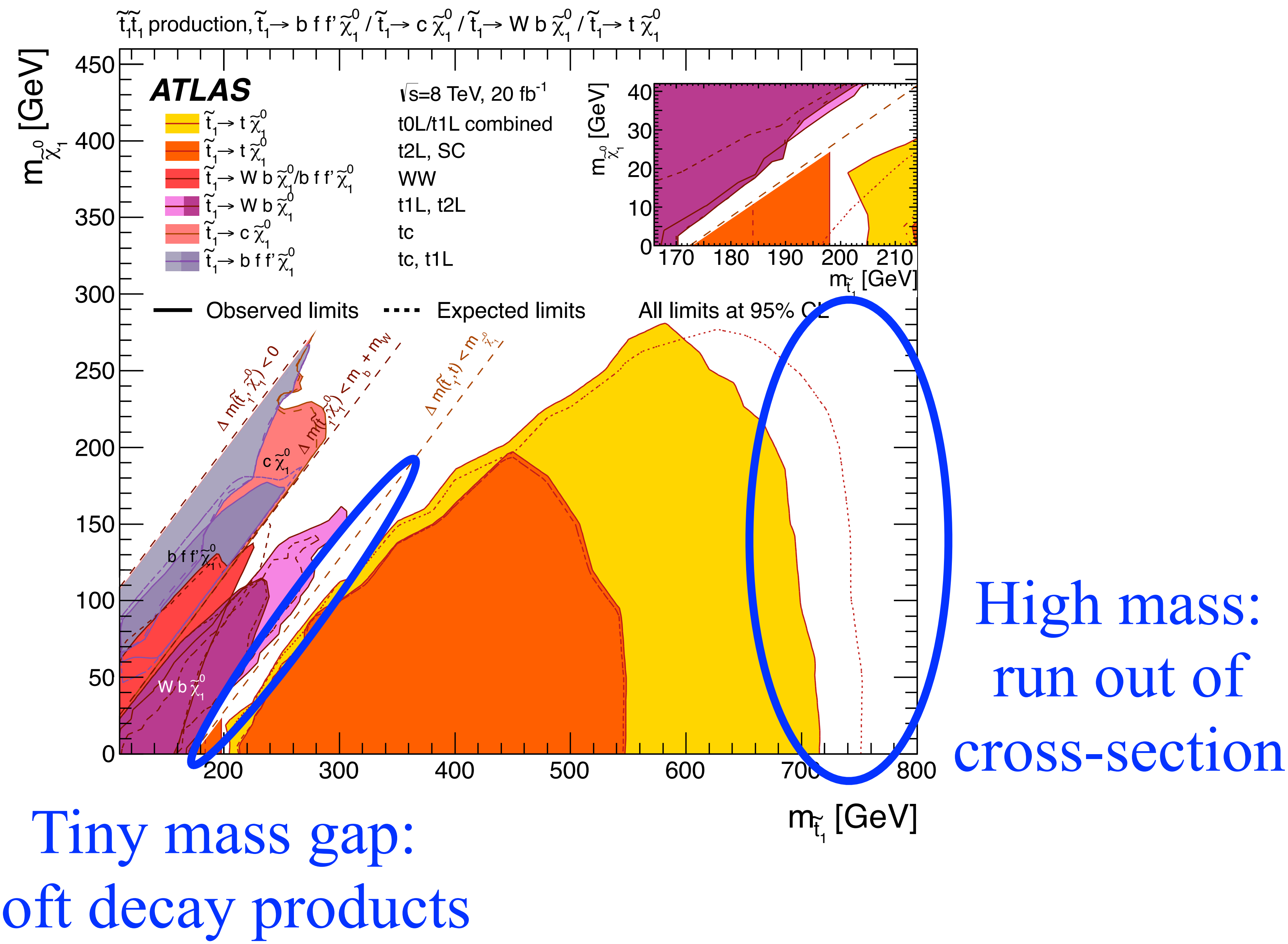


(Copied from A Weiler)

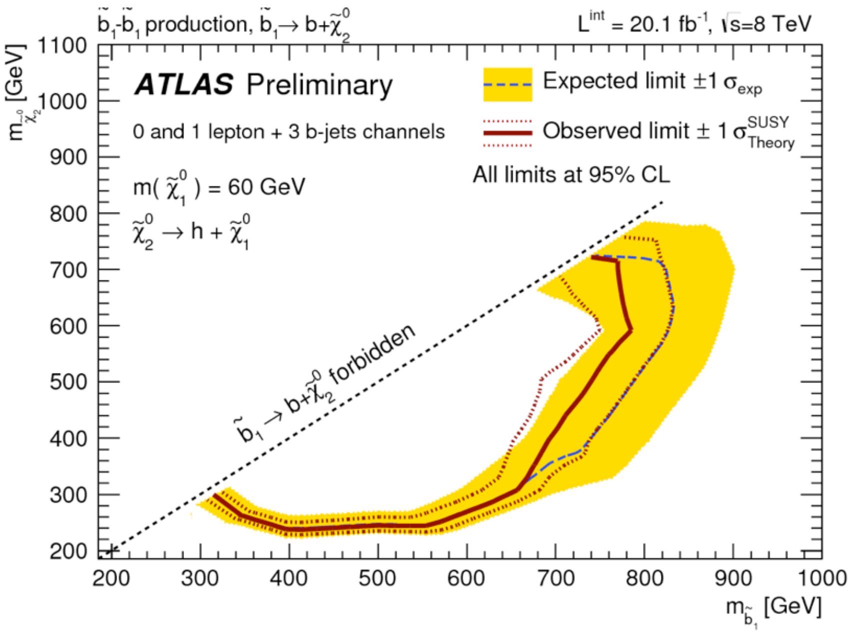
Stop Searching Anatomy

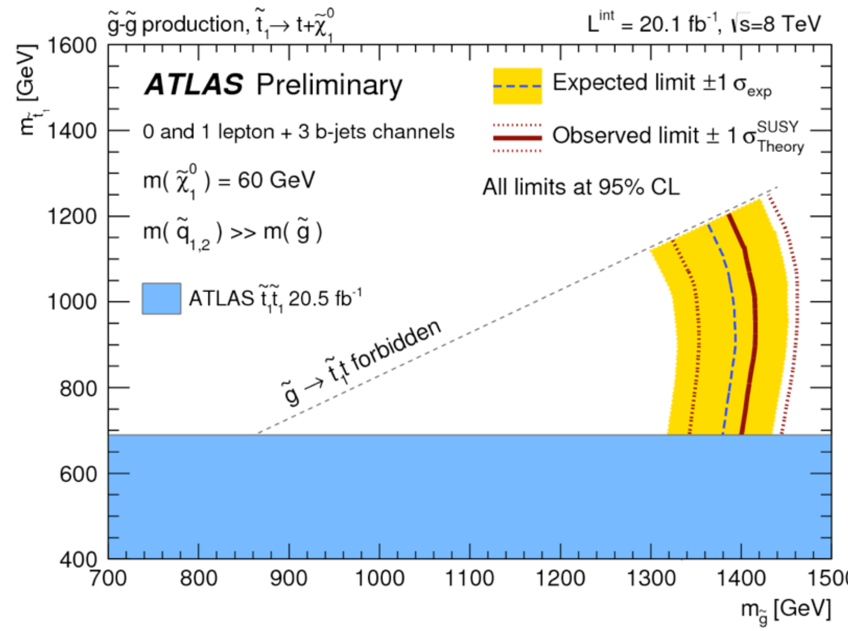


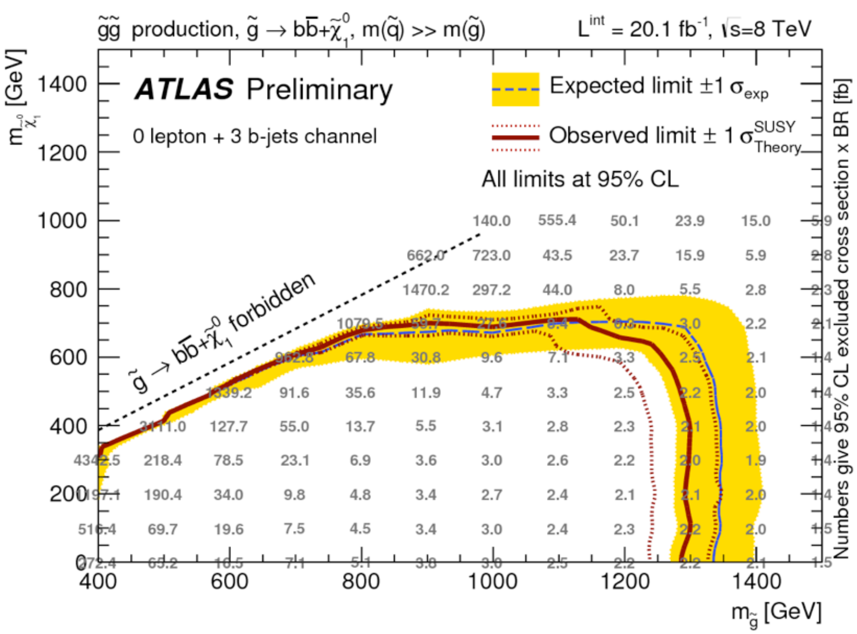
Stop Searching Anatomy

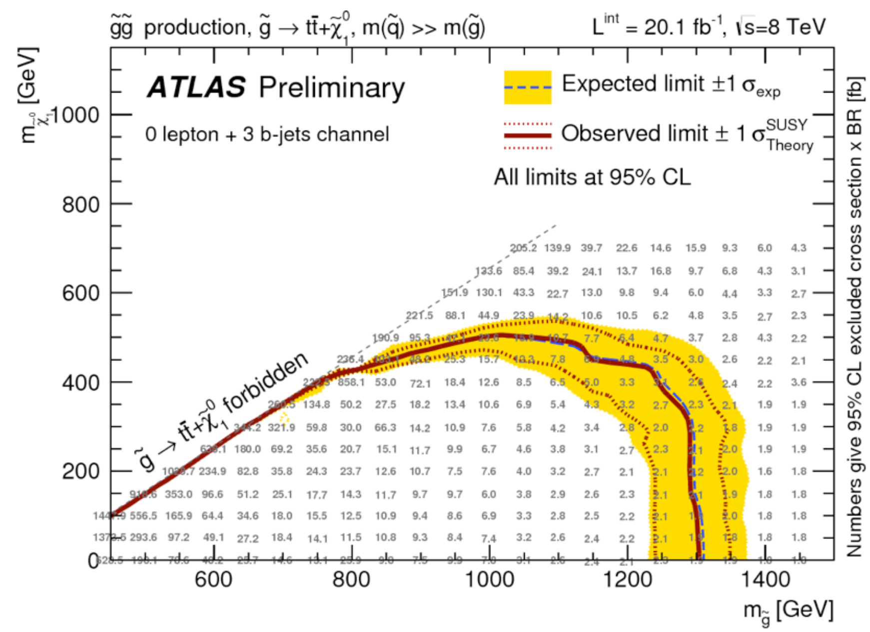


Many Many Limits… Sigh



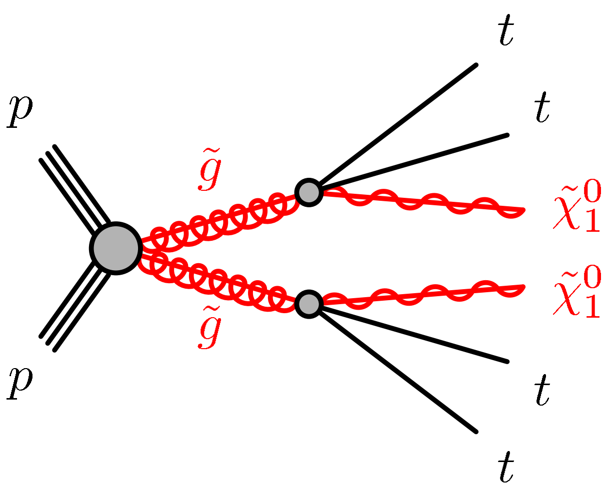


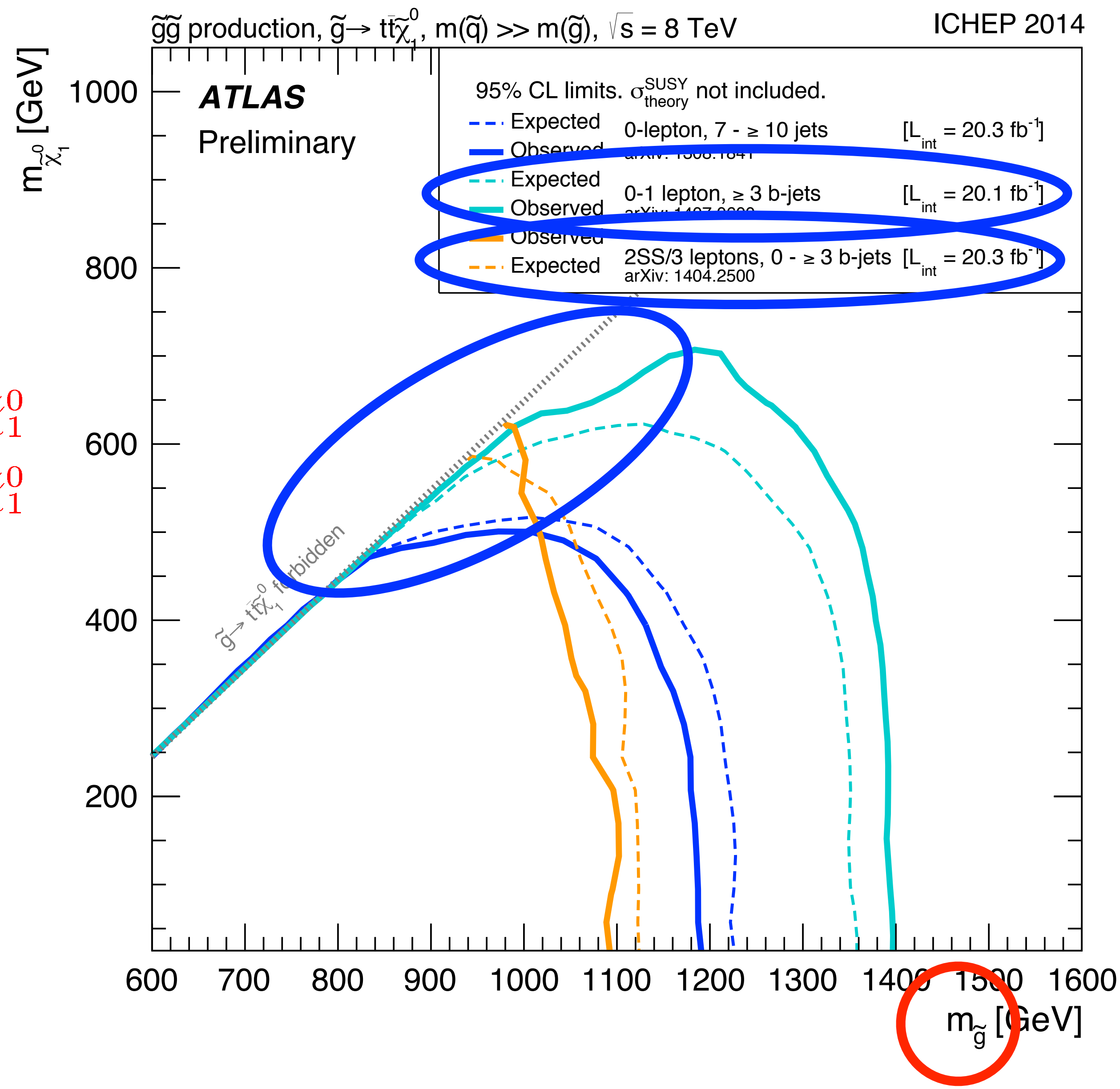




Stop Searching Anatomy

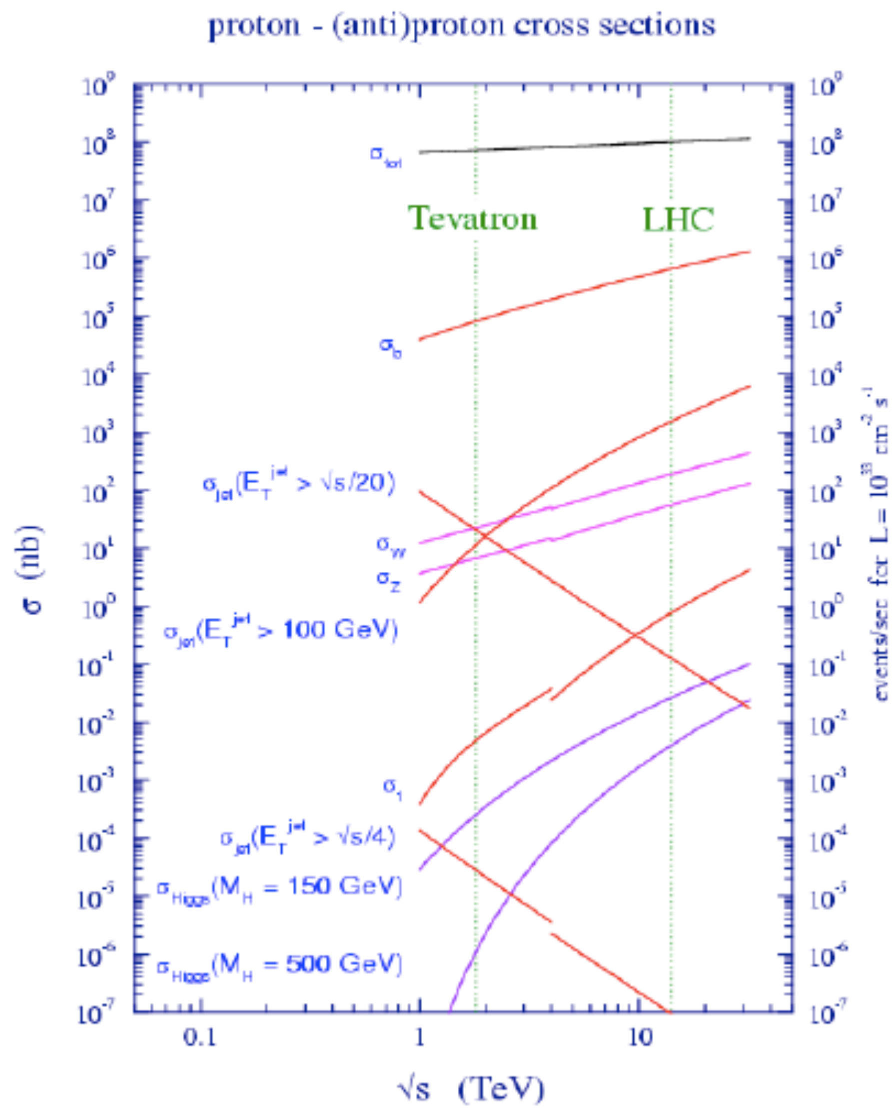
(Off-shell intermediate stop)



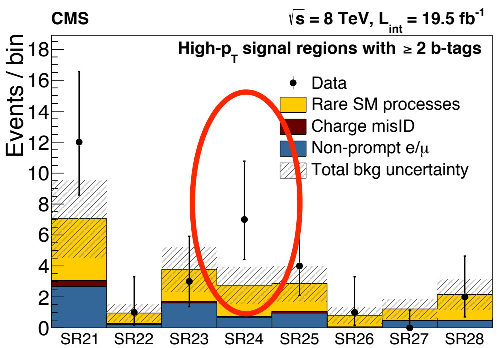


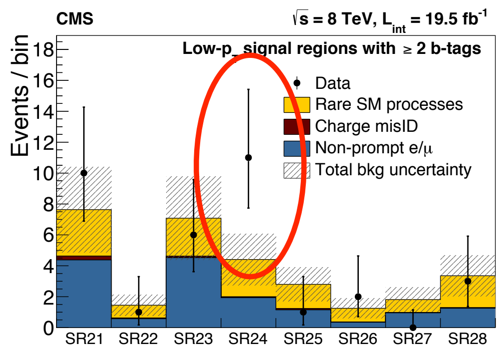
Same-Sign Leptons

- ❖ 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
    - Need to get from data!
  - and wrong charge measurement
- ❖ With lower background, access to smaller cross-sections, smaller mass gaps
  - At the cost of small branching ratio



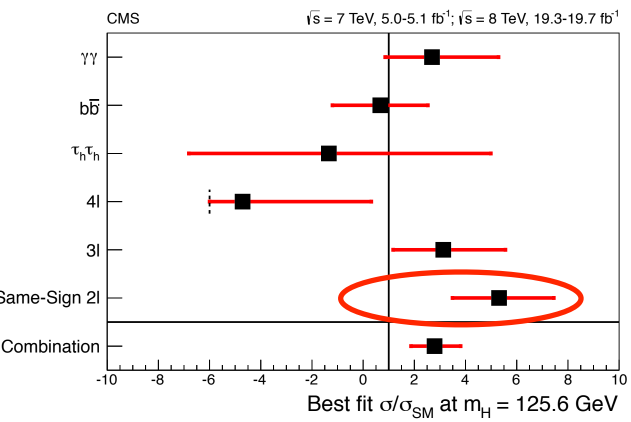
Same Sign Lepton Excesses



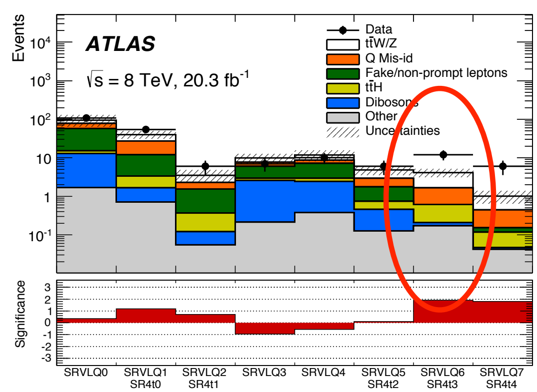


SR1b $_{1bin}$	Total	ee	$e\mu$	$\mu\mu$
Observed events	10	6	4	0
Total expected background events	4.7 ± 2.1	1.4 ± 0.8	2.1 ± 1.1	1.2 ± 0.4
Components of the background				
$t\bar{t}V$, $t\bar{t}H$, tZ and $t\bar{t}t\bar{t}$	2.5 ± 1.7	0.6 ± 0.3	1.2 ± 1.0	0.7 ± 0.3
Dibosons and tribosons	0.9 ± 0.4	0.10 ± 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

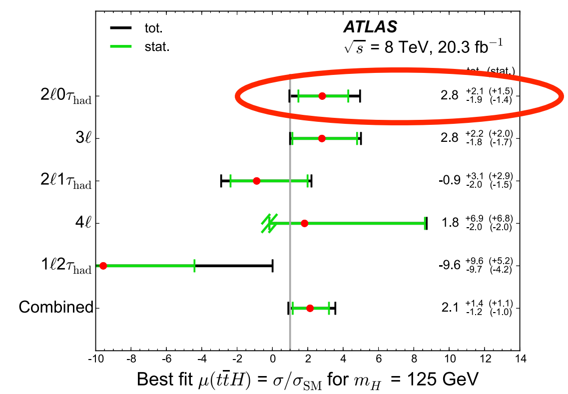
CMS (SUSY), http://arxiv.org/abs/1311.6736 (24 signal regions in paper) ATLAS (SUSY), http://arxiv.org/abs/1404.2500 (5 signal regions in paper)



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



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



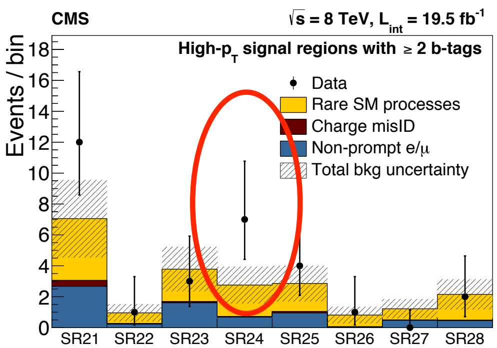
ATLAS (ttH), http://arxiv.org/abs/1506.05988

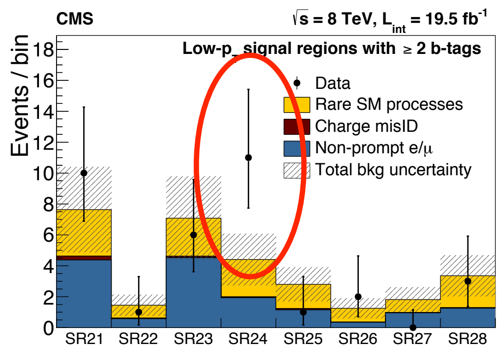
It certainly looks like multiple analyses looking at same sign leptons and b-jets see excesses!

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

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

Same Sign Lepton Excesses





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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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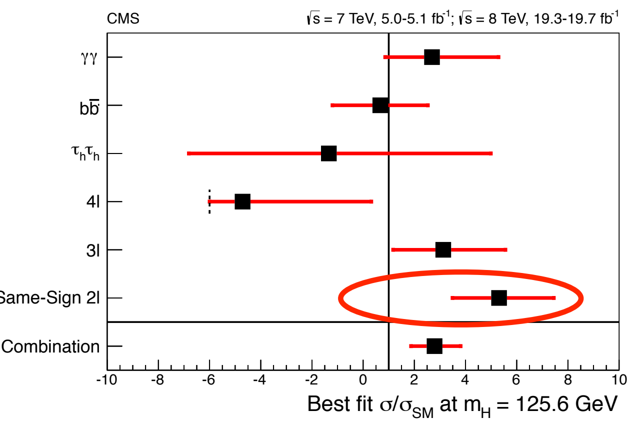
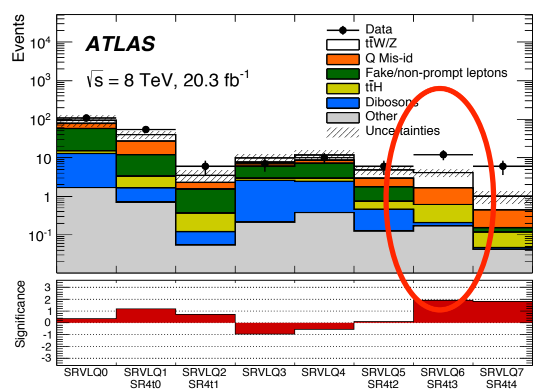
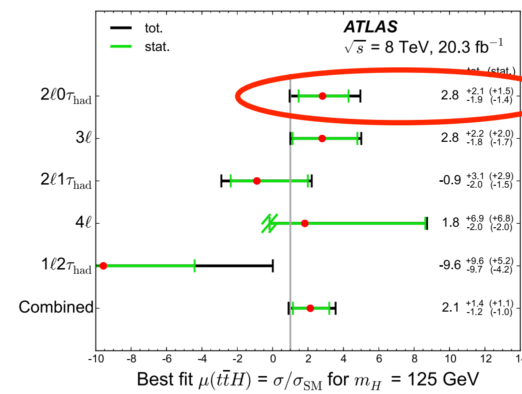






CMS (ttH), http://arxiv.org/abs/1408.1682 ATLAS (TT), http://arxiv.org/abs/1504.04605 ATLAS (ttH), http://arxiv.org/abs/1506.05988

The ATLAS analyses are correlated, and same for CMS

So, ~2 analyses and excesses are < 3 σ

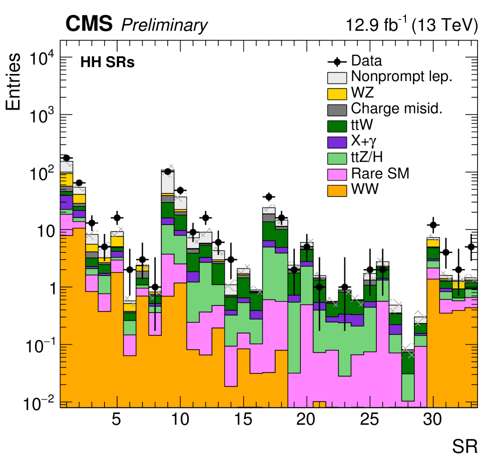
Worth keeping an eye on? Sure.

13 TeV

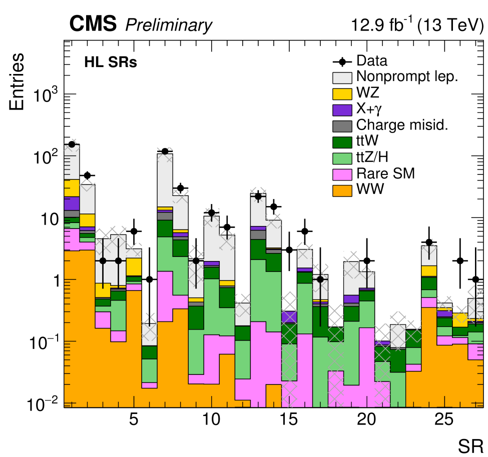
ATLAS-CONF-2016-037

	SR3L1	SR3L2	SR0b1	SR0b2	SR1b
Observed	6	2	5	0	12
Total SM background	6.1 ± 2.2	1.2 ± 0.5	8.8 ± 2.9	1.6 ± 0.8	11.4 ± 2.8
$t\bar{t}Z$	0.69 ± 0.25	0.10 ± 0.04	0.45 ± 0.18	0.10 ± 0.04	1.6 ± 0.6
$t\bar{t}W$	0.09 ± 0.04	0.02 ± 0.01	0.45 ± 0.17	0.13 ± 0.06	2.0 ± 0.7
Diboson	4.2 ± 2.0	0.7 ± 0.4	3.7 ± 1.9	0.7 ± 0.5	0.5 ± 0.4
Rare	0.8 ± 0.4	0.21 ± 0.13	0.8 ± 0.4	0.18 ± 0.12	2.7 ± 0.9
Fake/non-prompt leptons	0.29 ± 0.29	0.15 ± 0.15	2.9 ± 2.0	0.4 ± 0.5	3.3 ± 2.1
Charge-flip	–	–	0.50 ± 0.09	0.08 ± 0.03	1.43 ± 0.19

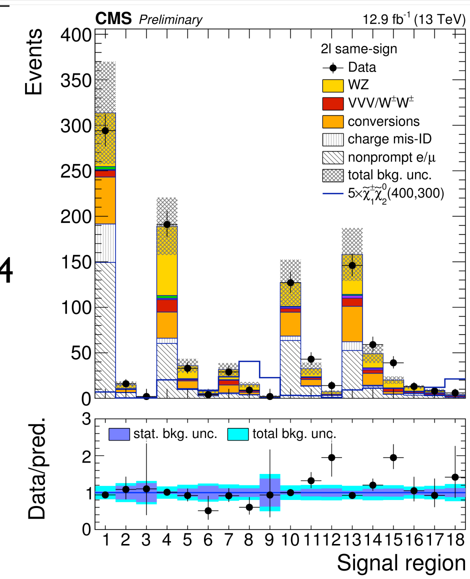
	SR3b	SR1b-GG	SR1b-DD	SR3b-DD
Observed	2	2	12	4
Total SM background	1.6 ± 0.6	1.7 ± 0.5	12.0 ± 2.7	1.9 ± 0.8
$t\bar{t}Z$	0.19 ± 0.07	0.26 ± 0.08	2.8 ± 0.9	0.30 ± 0.10
$t\bar{t}W$	0.17 ± 0.06	0.33 ± 0.11	1.8 ± 0.6	0.18 ± 0.07
Diboson	< 0.1	0.08 ± 0.19	0.6 ± 0.4	< 0.1
Rare	0.89 ± 0.31	0.64 ± 0.34	2.6 ± 1.3	0.8 ± 0.4
Fake/non-prompt leptons	0.2 ± 0.5	0.21 ± 0.33	2.5 ± 1.7	0.5 ± 0.6
Charge-flip	0.14 ± 0.03	0.18 ± 0.07	1.74 ± 0.22	0.14 ± 0.03



CMS-PAS-SUS-16-020



CMS-PAS-SUS-16-024



Not much there….