

# The Road to Discovery

Searching for BSM Physics at Hadron Colliders

Gustaaf Brooijmans



# Goals

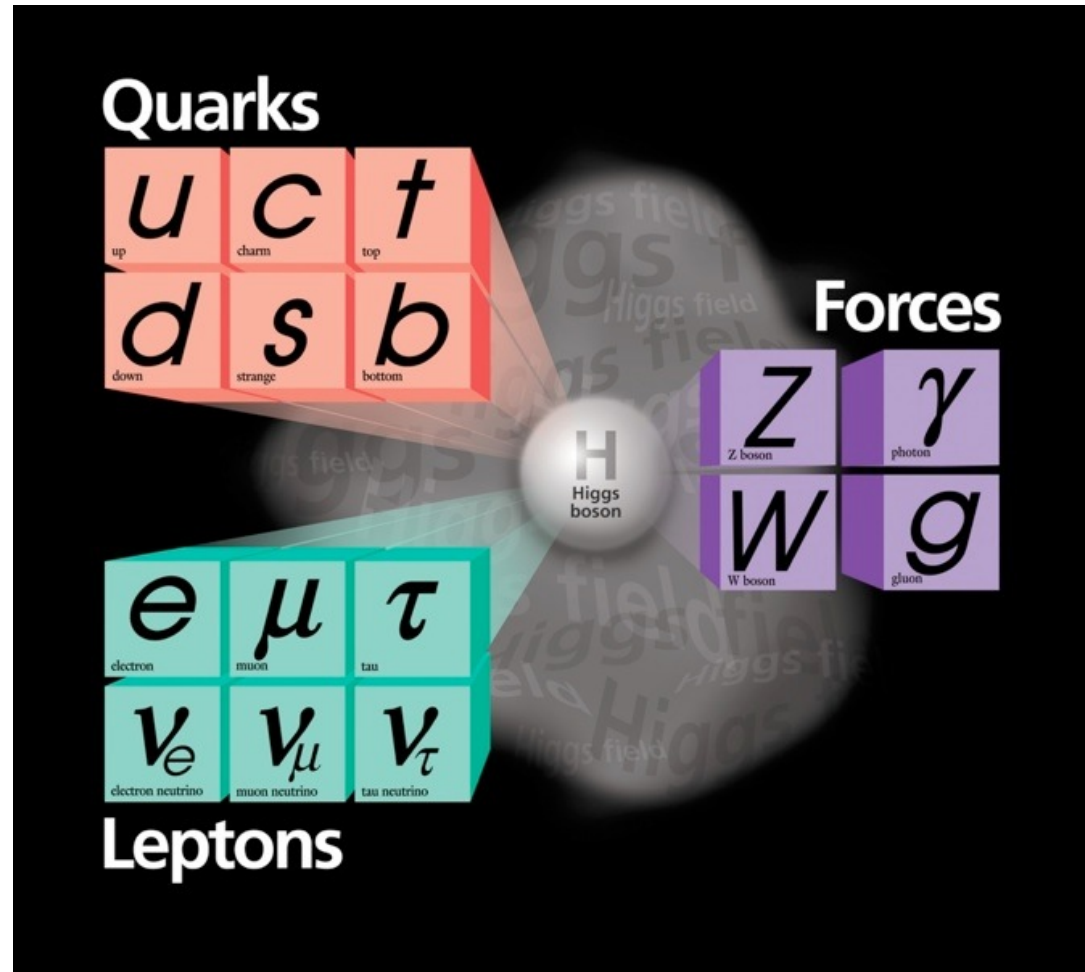
## ❖ Searches span very wide spectrum

- Overview of many types of searches, with focus on experimental aspects
  - Challenges posed at hadron colliders
  - Ease of generating false positives
  - Techniques to deal with limited knowledges
- But far from exhaustive!

## ❖ Thread in results

- Including some that may be hints

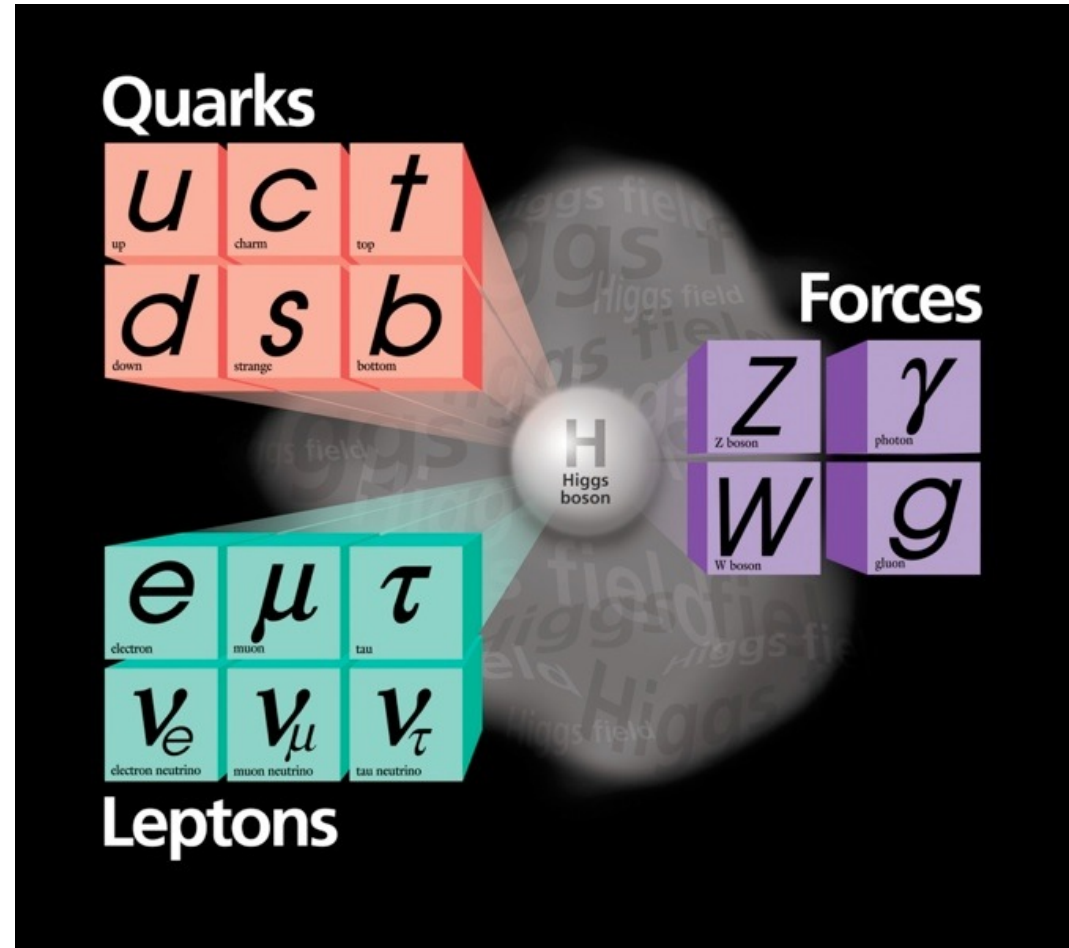
# Standard Model Today



**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

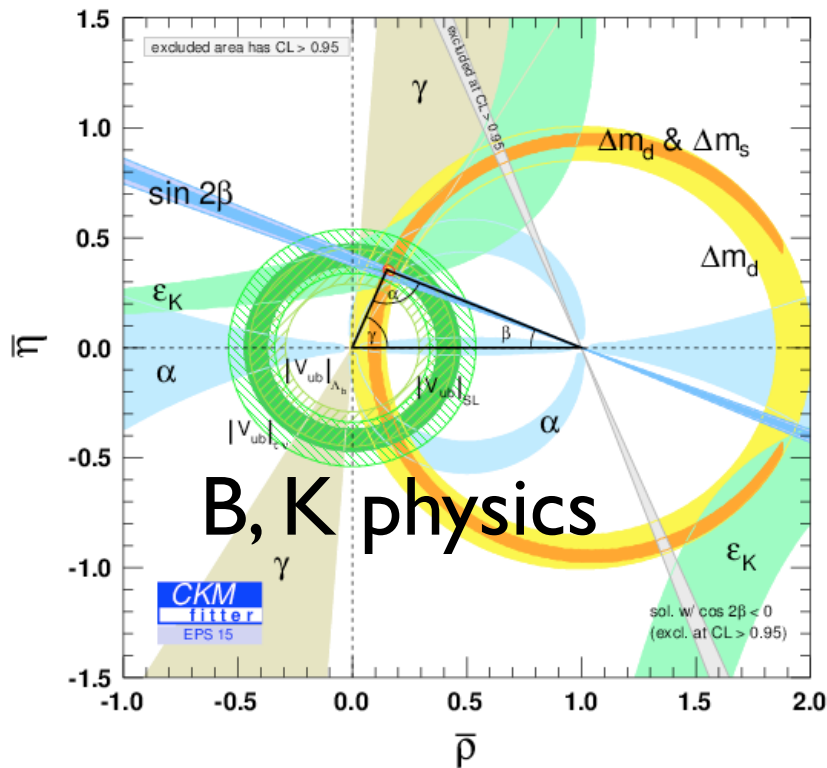
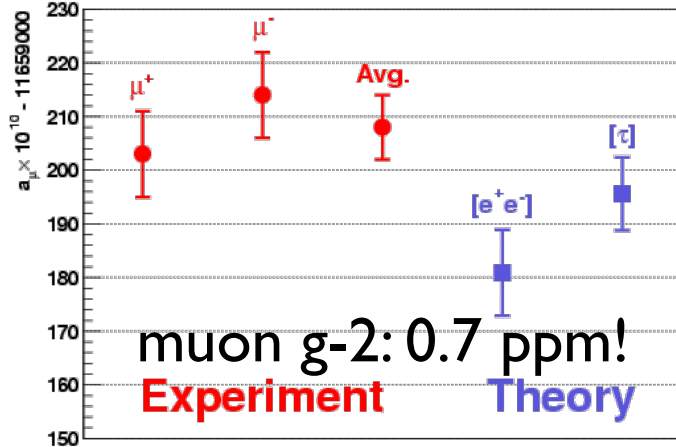
## ❖ It's a theory of interactions:

- 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

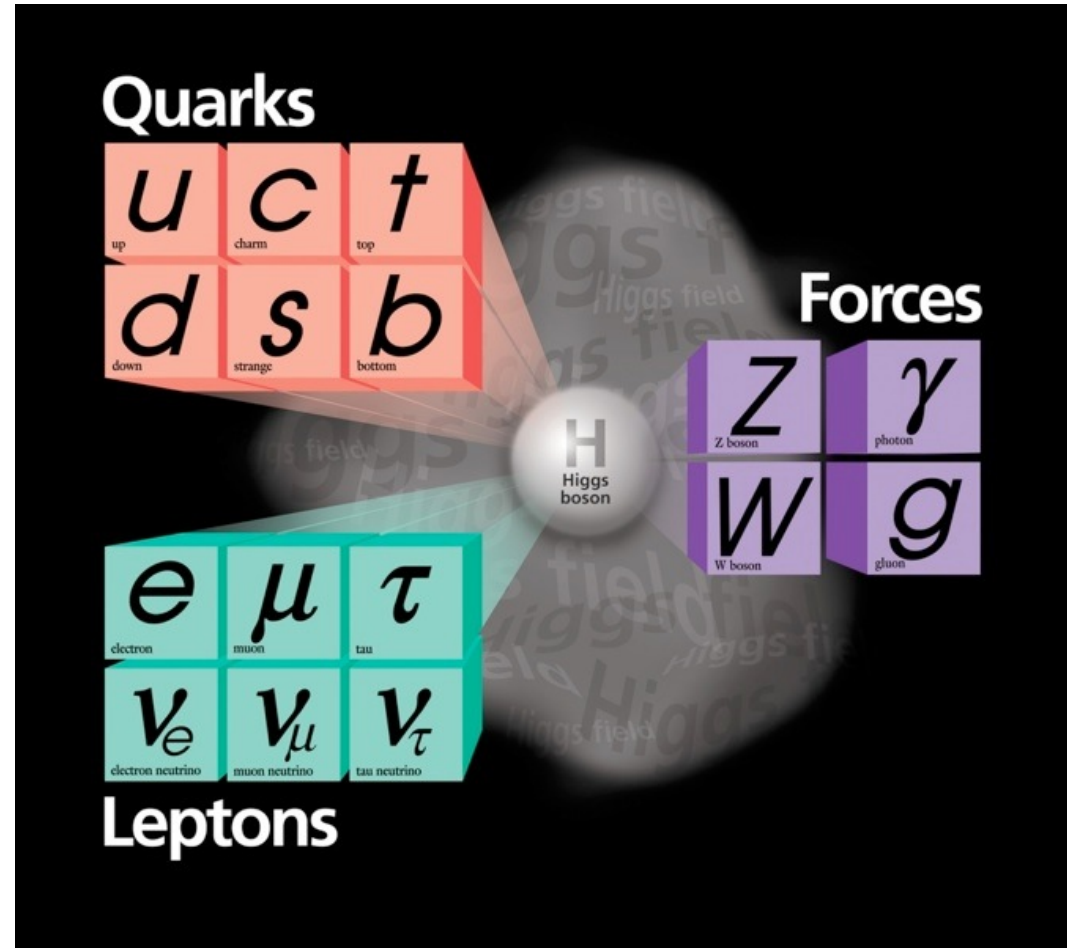


	Measurement	Fit	$ O^{\text{meas}} - O^{\text{fit}}  / \sigma^{\text{meas}}$
$\Delta\alpha_{\text{had}}^{(5)}(m_Z)$	$0.02758 \pm 0.00035$	0.02768	0.3
$m_Z$ [GeV]	$91.1875 \pm 0.0021$	91.1875	0.0
$\Gamma_Z$ [GeV]	$2.4952 \pm 0.0023$	2.4957	0.2
$\sigma_{\text{had}}^0$ [nb]	$41.540 \pm 0.037$	41.477	1.7
$R_l$	$20.767 \pm 0.025$	20.744	0.9
$A_{\text{fb}}^{0,l}$	$0.01714 \pm 0.00095$	0.01645	0.7
$A_l(P_\tau)$	$0.1465 \pm 0.0032$	0.1481	0.5
$R_b$	$0.21629 \pm 0.00066$	0.21586	0.7
$R_c$	$0.1721 \pm 0.0030$	0.1722	0.0
$A_{\text{fb}}^{0,b}$	$0.0992 \pm 0.0016$	0.1038	2.8
$A_{\text{fb}}^{0,c}$	$0.0707 \pm 0.0035$	0.0742	1.0
$A_b$	$0.923 \pm 0.020$	0.935	0.6
$A_c$	$0.670 \pm 0.027$	0.668	0.0
$A_l(\text{SLD})$	$0.1513 \pm 0.0021$	0.1481	1.6
$\sin^2 \theta_{\text{eff}}^{\text{lept}}(Q_{\text{fb}})$	$0.2324 \pm 0.0012$	0.2314	0.8
$m_W$ [GeV]	$80.398 \pm 0.025$	80.374	0.9
$\Gamma_W$ [GeV]	$2.140 \pm 0.060$	2.091	0.8
$m_t$ [GeV]	$170.9 \pm 1.8$	171.3	0.2

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
    - $q(\text{down}) = q(e)/N_c$
  - 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

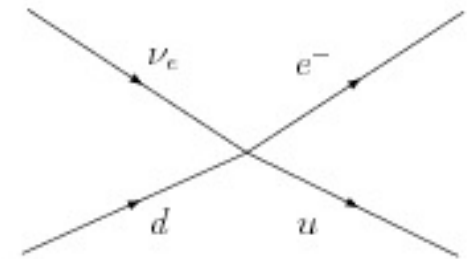
- ❖ What exactly *is* spin? Or color? Or electric charge? Why are they quantized?
- ❖ Are there only 3 generations? If so, why?
- ❖ Why are there e.g. no neutral, colored fermions?
- ❖ What is mass? Why are particles so light?
- ❖ Is there a link between particle and nucleon masses?
- ❖ How does all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

# Particles Solve Problems

(Problems Predict Particles)

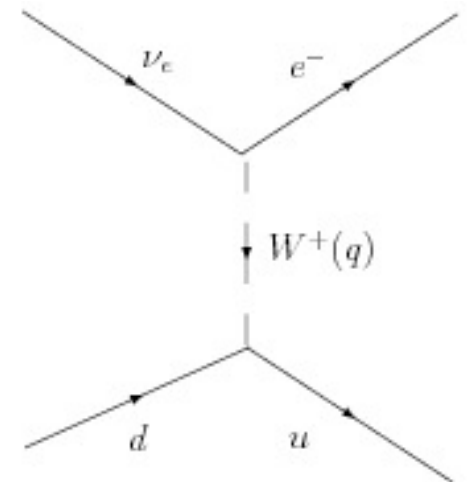
# Vector Boson Scattering

- 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  $q^2 \ll (M_W)^2$ , looks like a “contact interaction”, and cross-section grows with center of mass energy:  $\sigma \sim s$



# 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  $q^2 \ll (M_W)^2$ , looks like a “contact interaction”, and cross-section grows with center of mass energy:  $\sigma \sim s$
  - But when  $q^2 \approx (M_W)^2$ , W-boson propagation becomes visible, and “cures” this problem



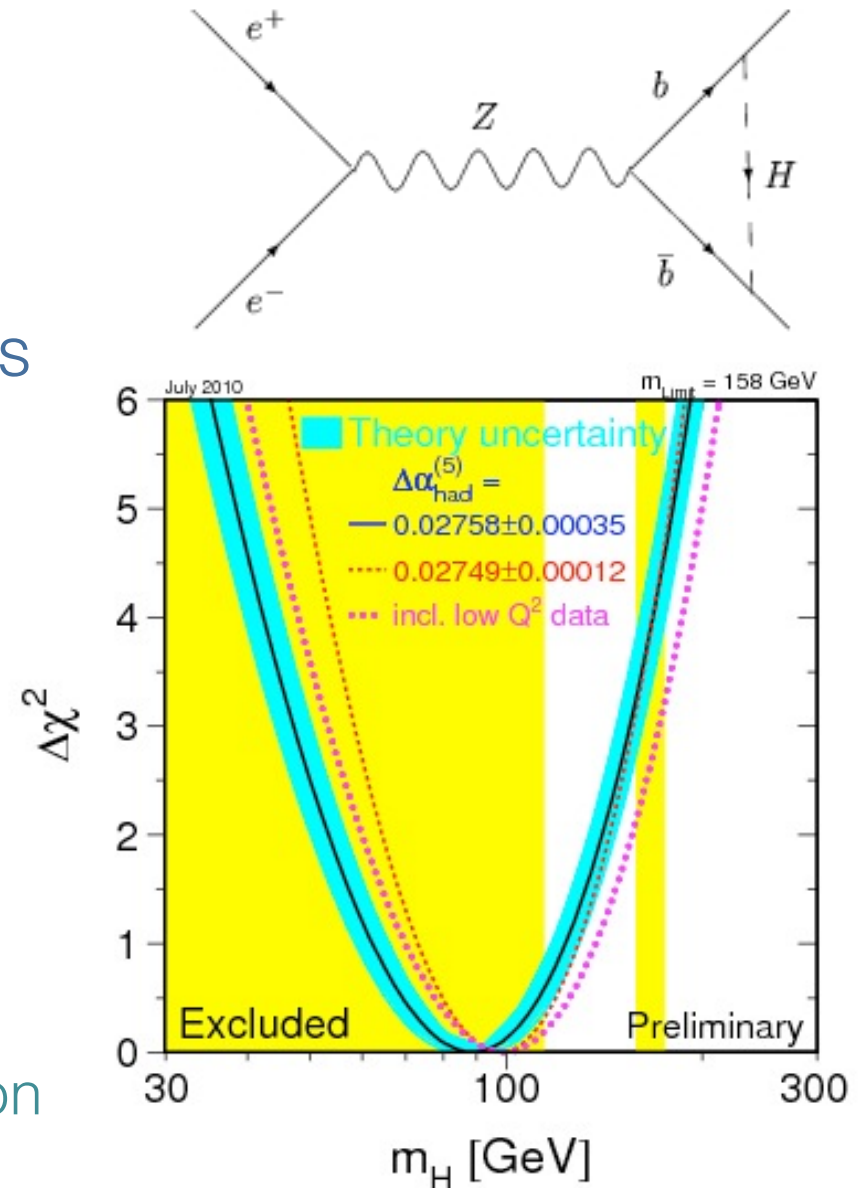
# The Higgs Boson

- ❖ One way to solve WW, is to introduce a massive, spinless particle (of mass  $< \sim 1 \text{ TeV}$ )
  - 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”



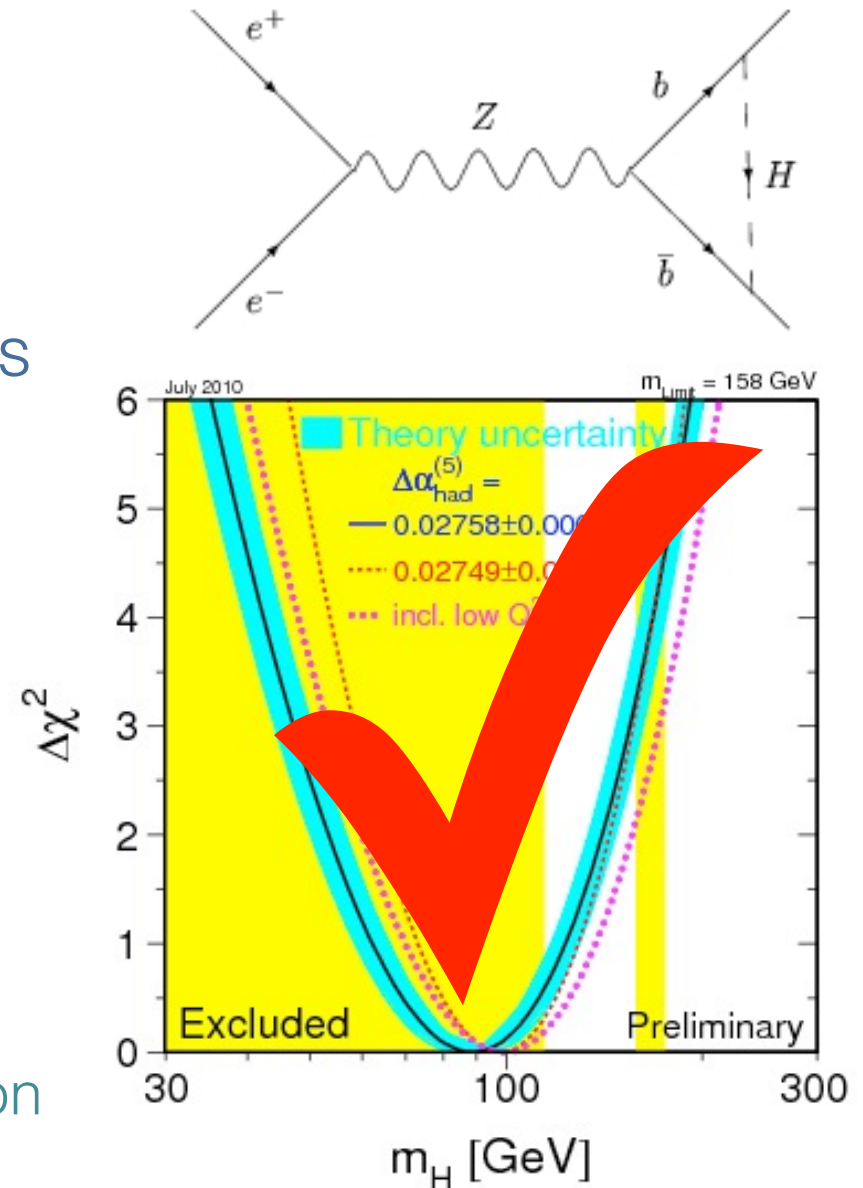
# Precision Measurements

- ❖ In fact, we were able to say something about the standard model Higgs mass
  - If the fermions get their masses from the Higgs, we know all couplings and can infer the Higgs mass from precision measurements
  - Result is very sensitive to measured top quark, W boson masses
  - Really wants a “light” Higgs boson



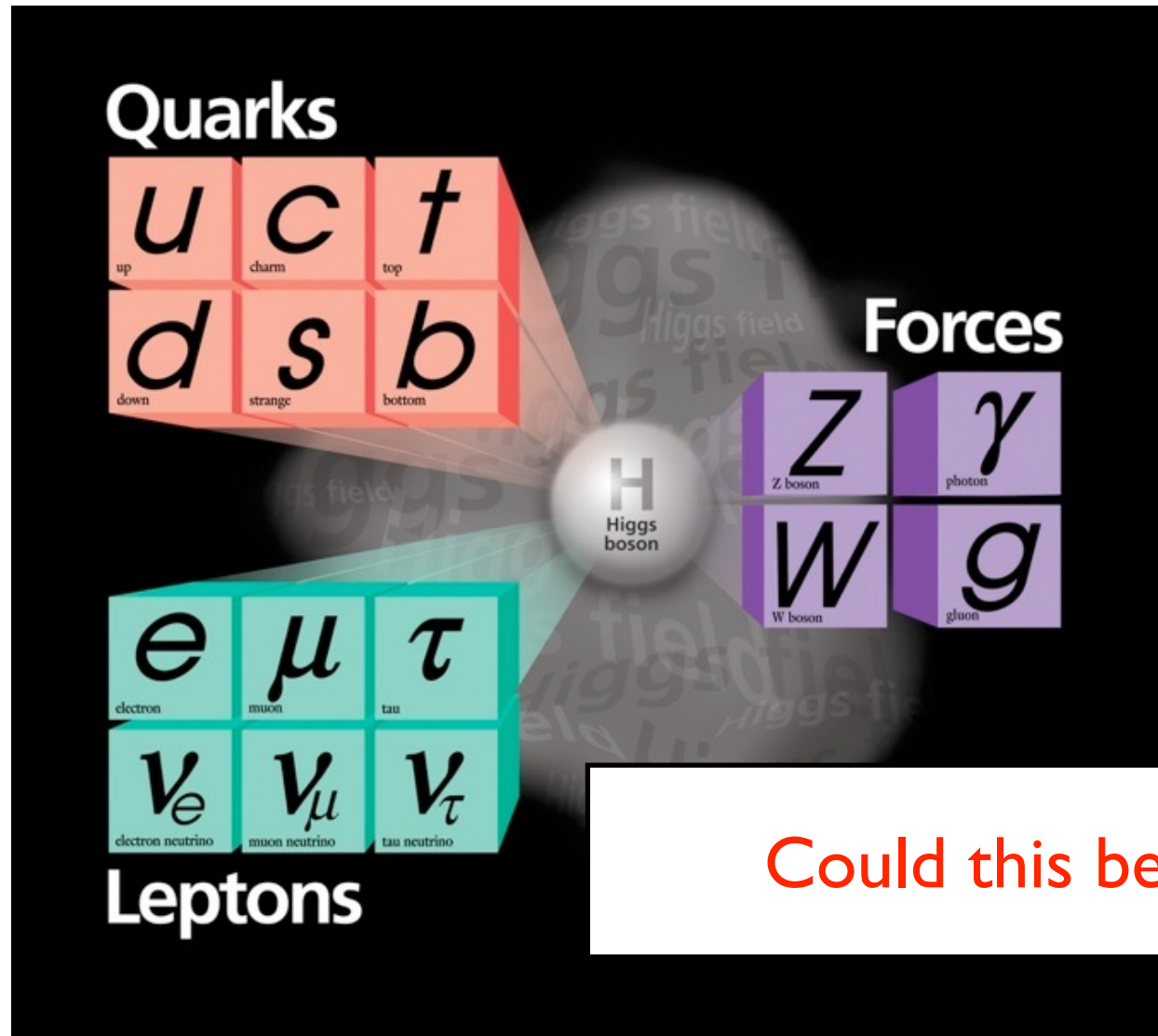
# Precision Measurements

- ❖ In fact, we were able to say something about the standard model Higgs mass
  - If the fermions get their masses from the Higgs, we know all couplings and can infer the Higgs mass from precision measurements
  - Result is very sensitive to measured top quark, W boson masses
  - Really wants a “light” Higgs boson

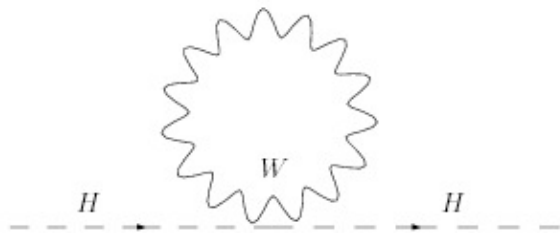


# The Plot Thickens

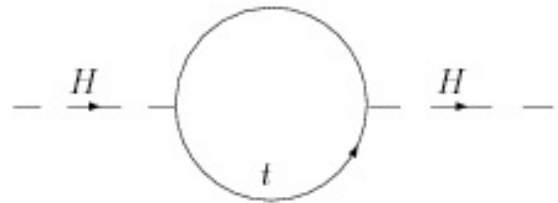
# New Physics?



# Higgs Mass



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



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



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

- ❖ 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?

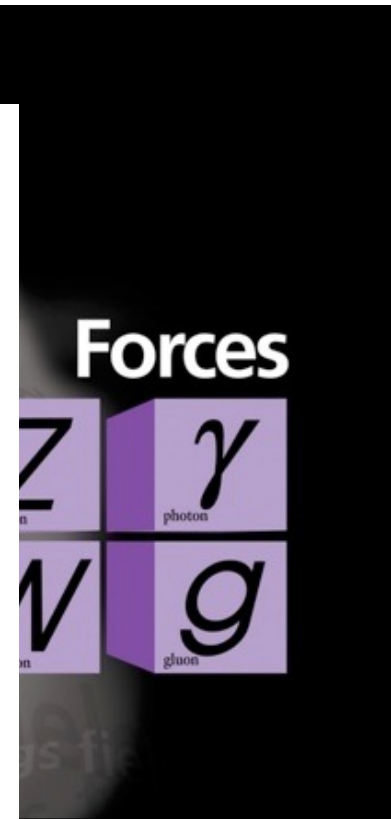
## The hierarchy problem of the electroweak Standard Model revisited

FRED JEGERLEHNER,

Humboldt-Universität zu Berlin, Institut für Physik,  
Newtonstrasse 15, D-12489 Berlin, Germany  
Deutsches Elektronen-Synchrotron (DESY),  
Platanenallee 6, D-15738 Zeuthen, Germany

### 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.



Could this be it?

# New Physics?



The hierarchy problem  
Mo

FREI

Humboldt-Universität  
Newtonstrasse  
Deutsches Elek  
Platanenallee 6

A careful renormalization group  
that **there is no hierarchy problem**  
out to be natural as it is self-protects  
that the scalar Higgs needs not be  
symmetry, in order not to be muc  
protected by gauge- or chiral-symm  
in the SM cannot motivate the nee  
in contrast plays an important role  
in shaping the Higgs potential in th  
observation.

## Natural Tuning: Towards A Proof of Concept

Sergei Dubovsky, Victor Gorbenko, and Mehrdad Mirbabayi

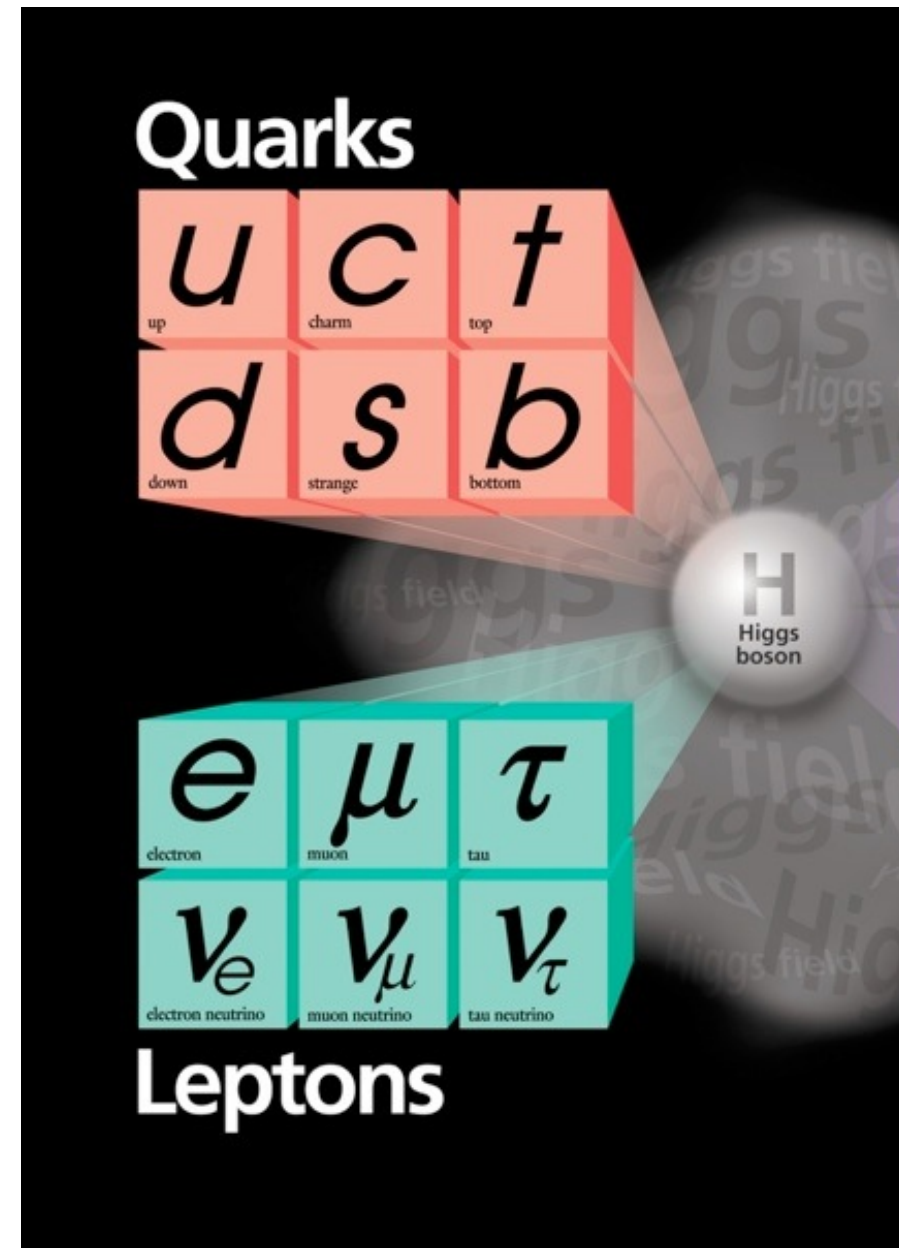
*Center for Cosmology and Particle Physics,  
Department of Physics, New York University  
New York, NY, 10003, USA*

### 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

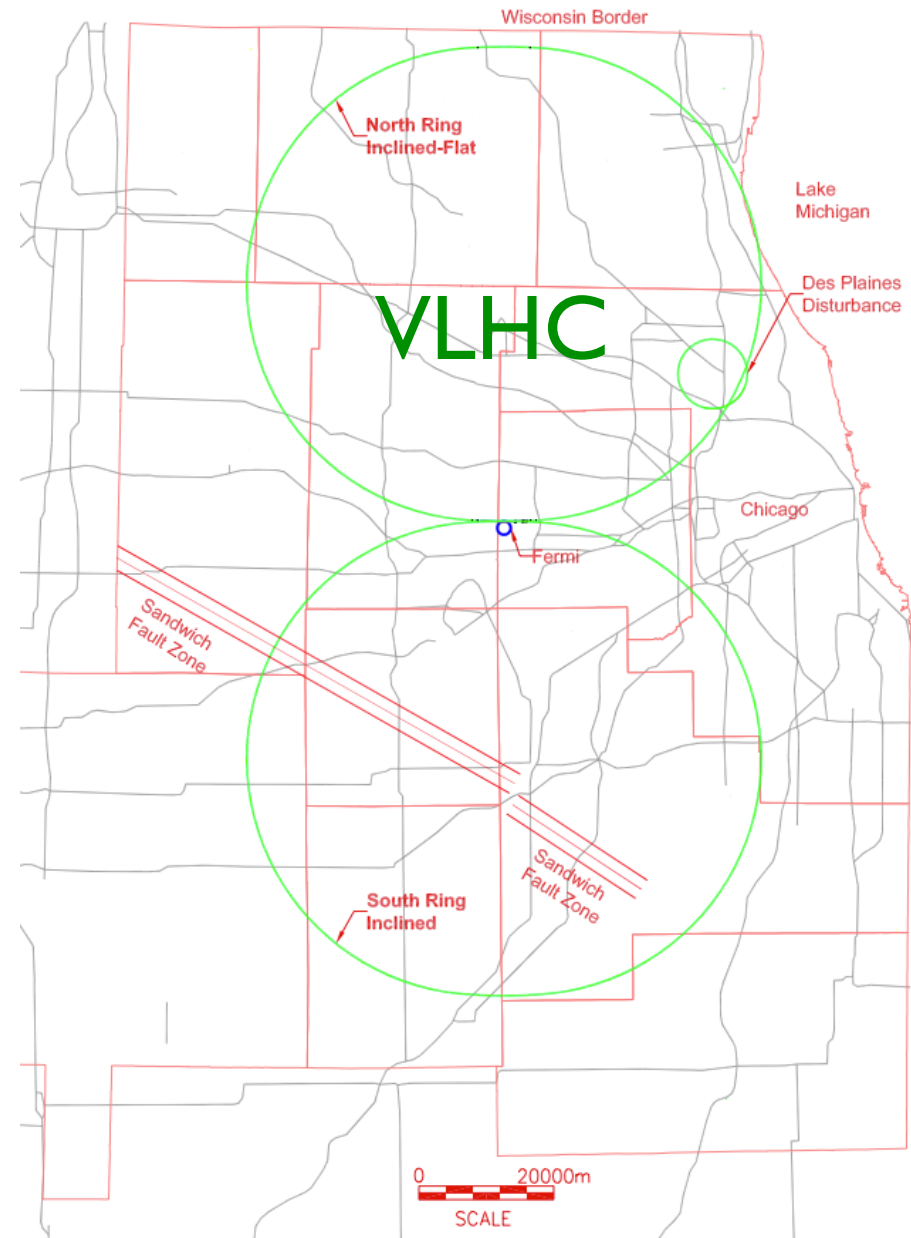
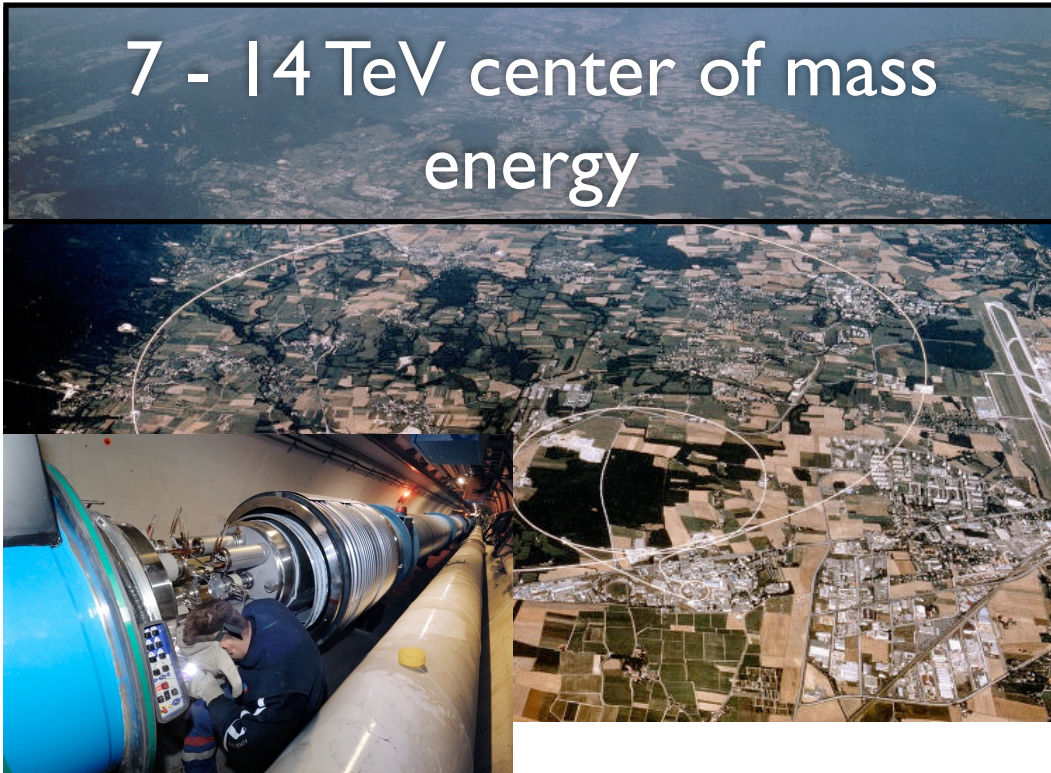
# Energy Frontier

❖ Currently, hadron colliders:

- High energy implies probing of short distances, and production of other, massive particles

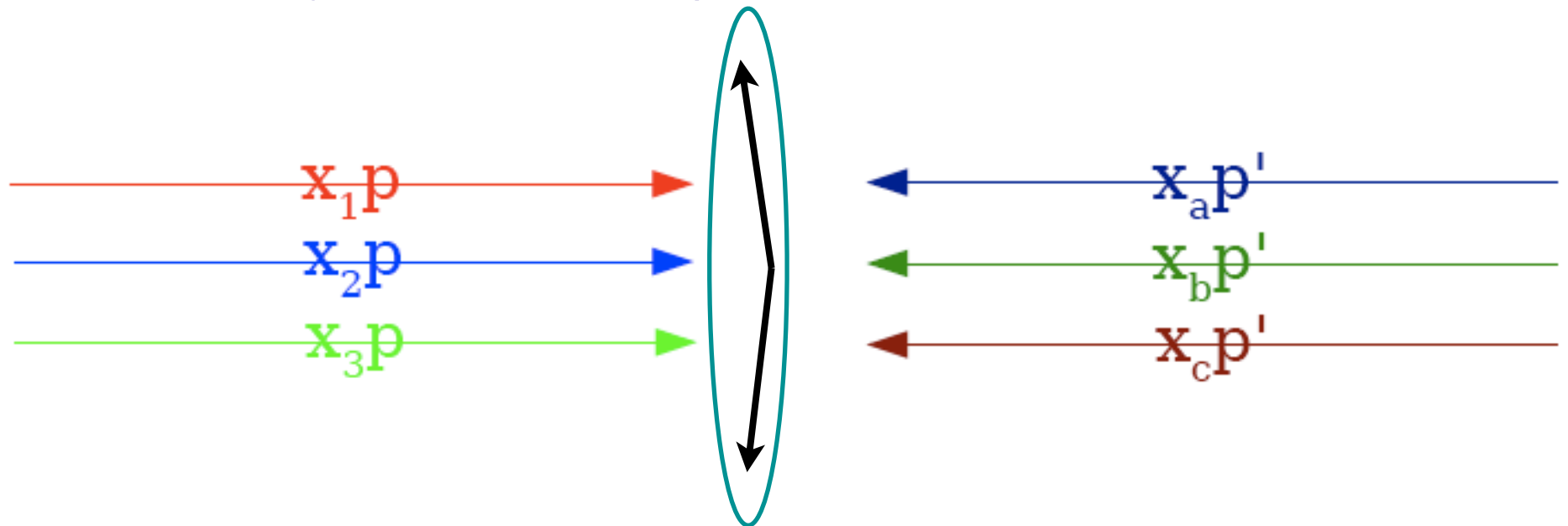
LHC

7 - 14 TeV center of mass energy



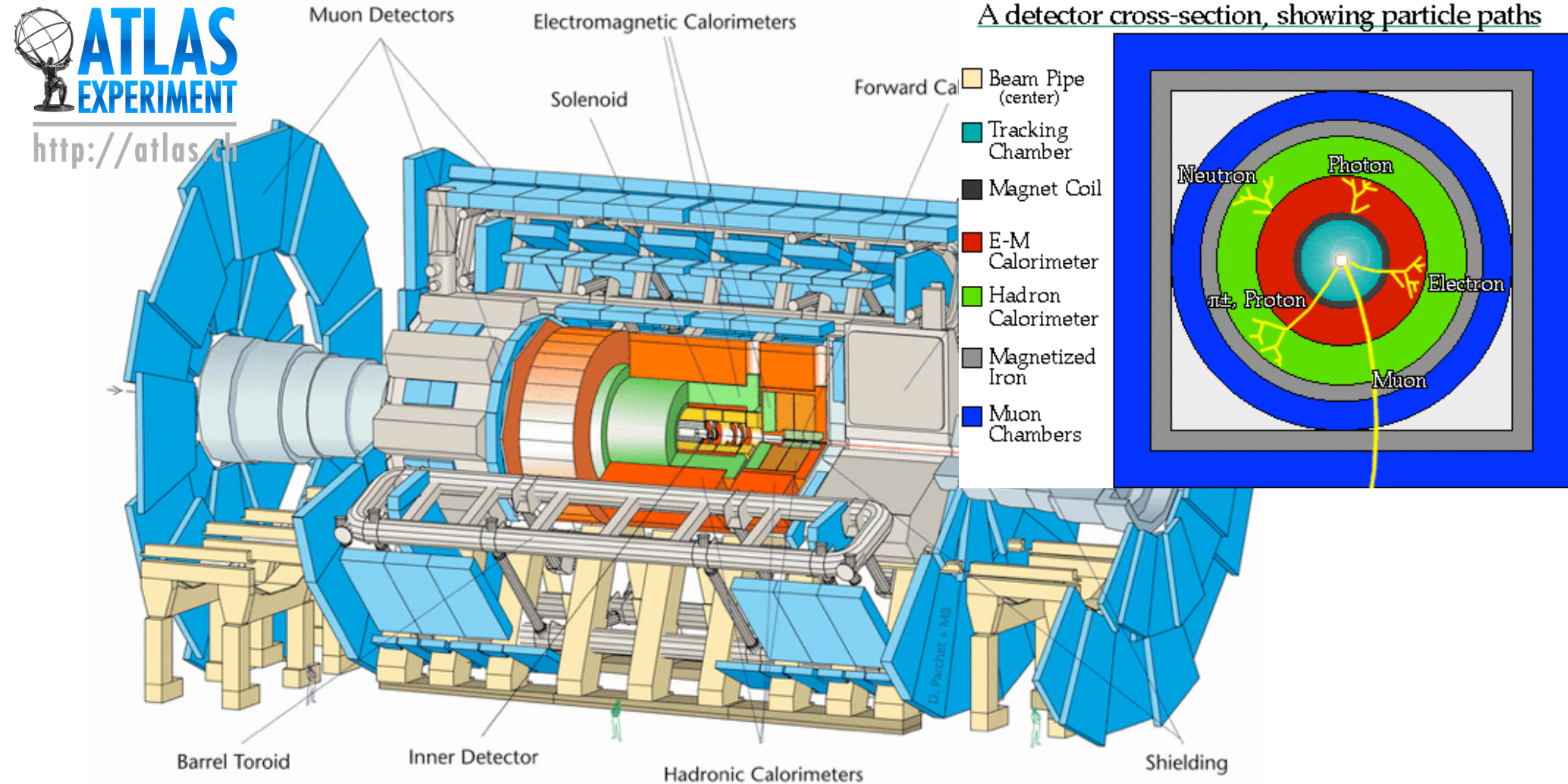
# Hadron Colliders

- ❖ 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



# Detectors

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



# CMS

Total weight 14000 t  
Overall diameter 15 m  
Overall length 28.7 m

# CMS

MUON ENDCAPS

473 Cathode Strip Chambers (CSC)  
432 Resistive Plate Chambers (RPC)

ECAL 76k scintillating  
PbWO<sub>4</sub> crystals

HCAL Scintillator/brass  
Interleaved ~7k ch

3.8T Solenoid

IRON YOKE

Preshower  
Si Strips ~16 m<sup>2</sup>  
~137k ch

Forward Cal  
Steel + quartz  
Fibers ~2~k ch

YBO

YB1-2

YE1-3

Pixel  
Tracker  
ECAL  
HCAL  
Muons  
Solenoid coil

Pixels & Tracker

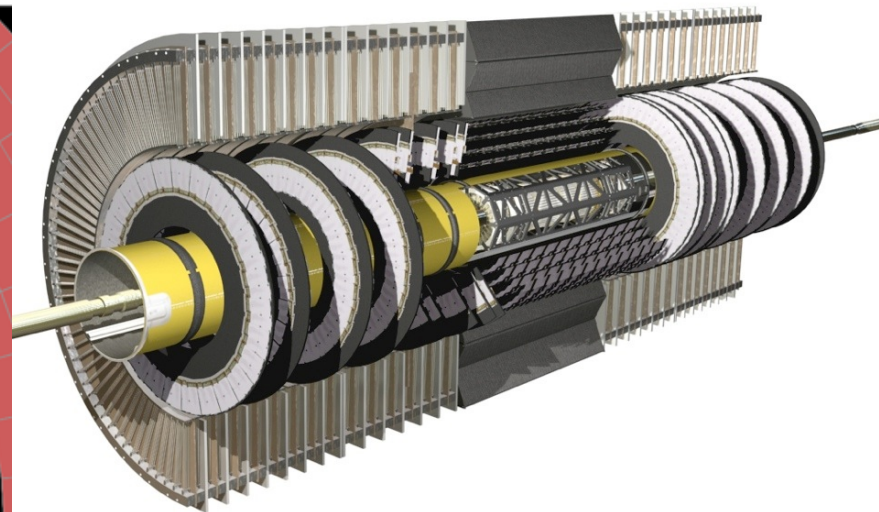
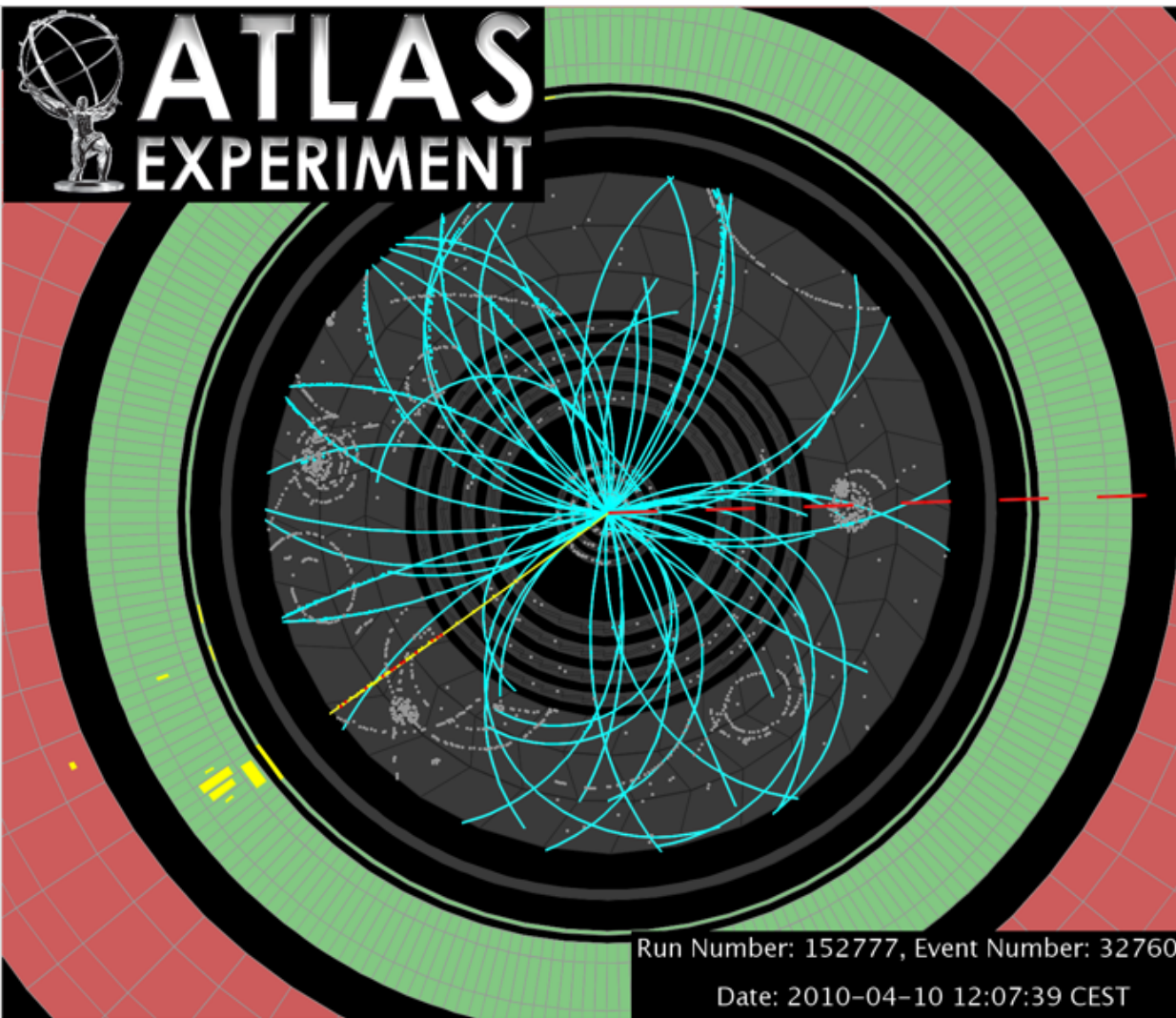
- Pixels (100x150  $\mu\text{m}^2$ )  
~ 1 m<sup>2</sup> ~66M ch
- Si Strips (80-180  $\mu\text{m}$ )  
~200 m<sup>2</sup> ~9.6M ch

MUON BARREL

250 Drift Tubes (DT) and  
480 Resistive Plate Chambers (RPC)

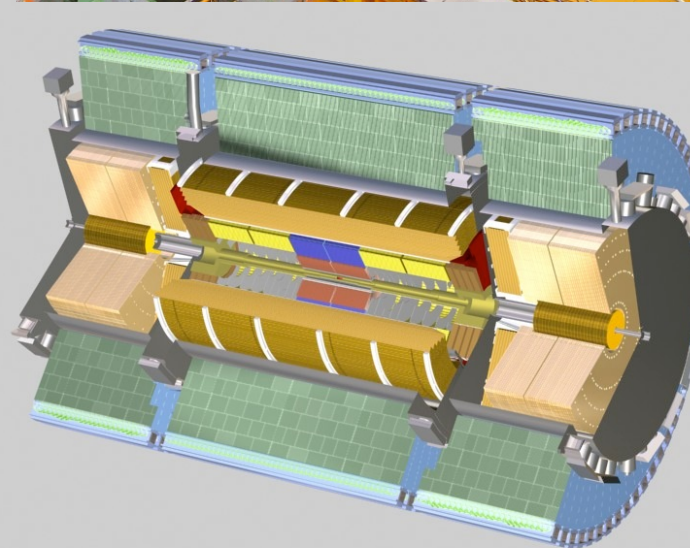
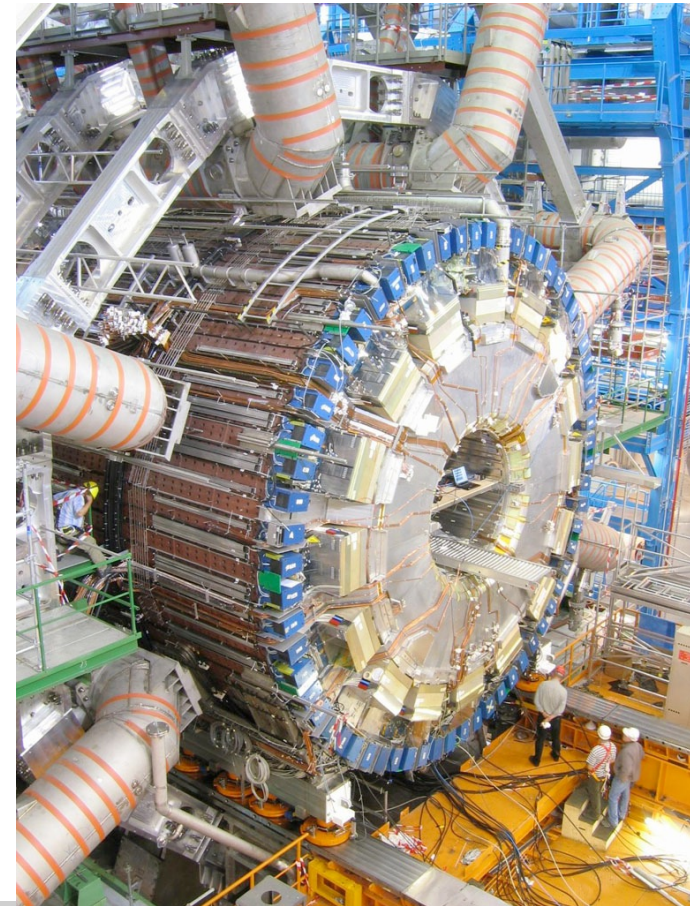
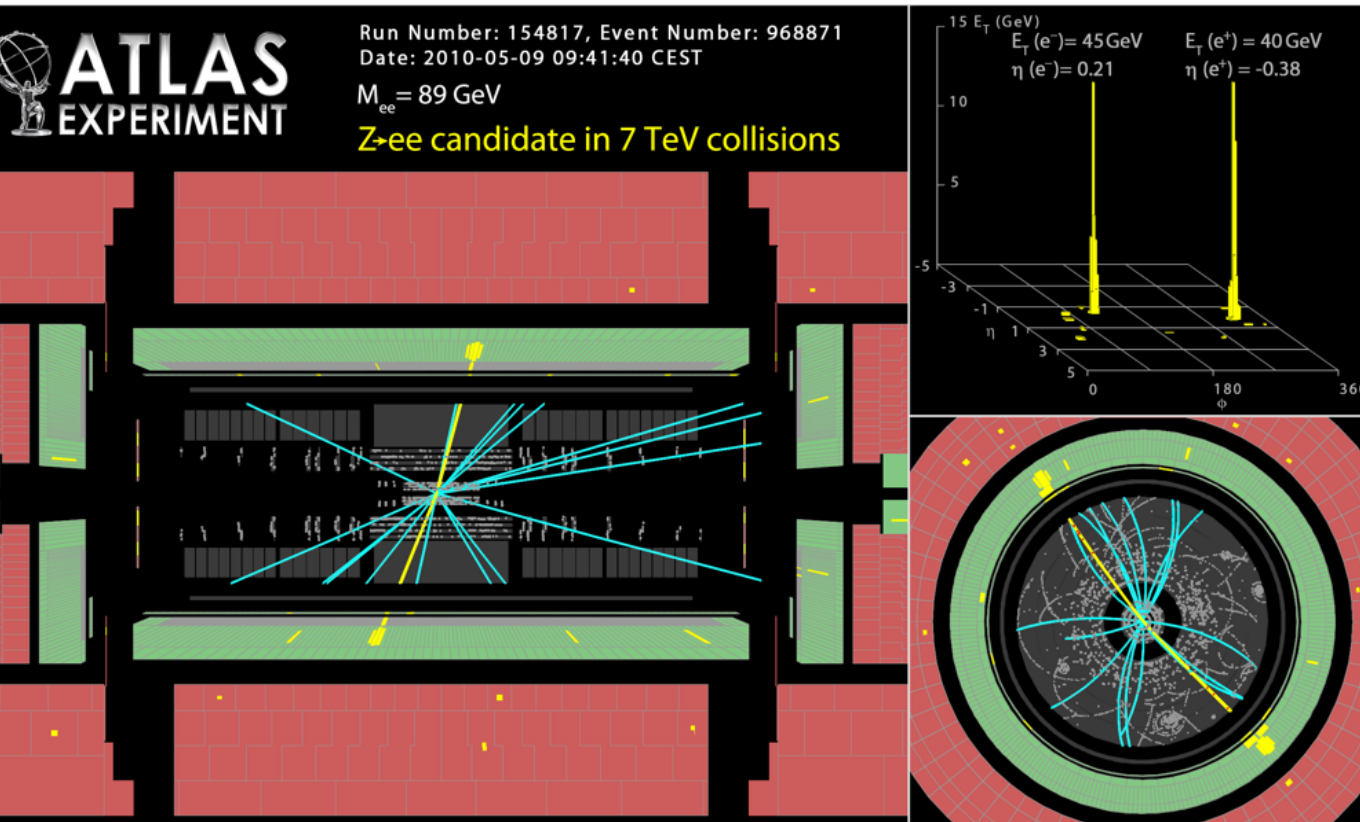
# Charged Particles

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



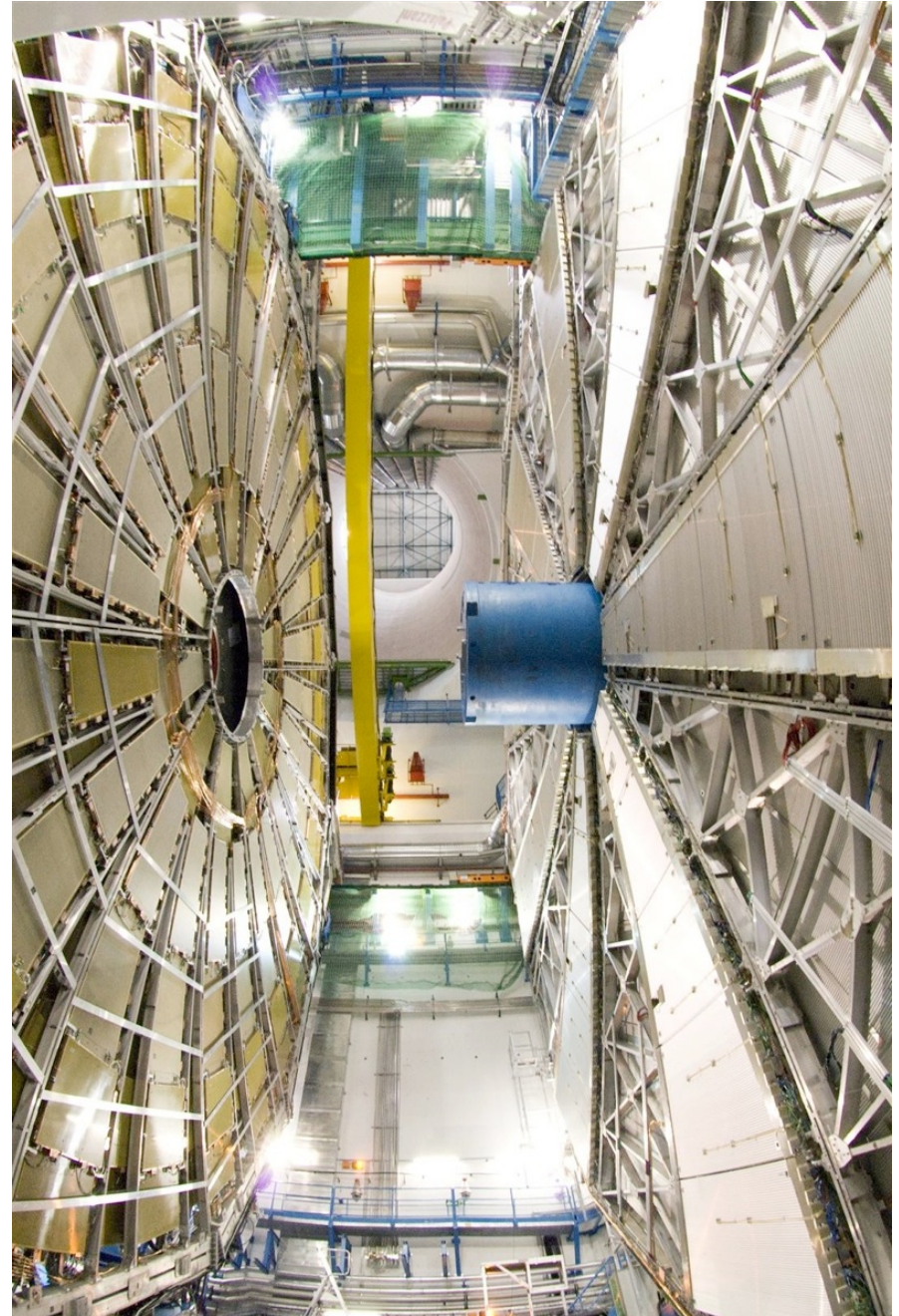
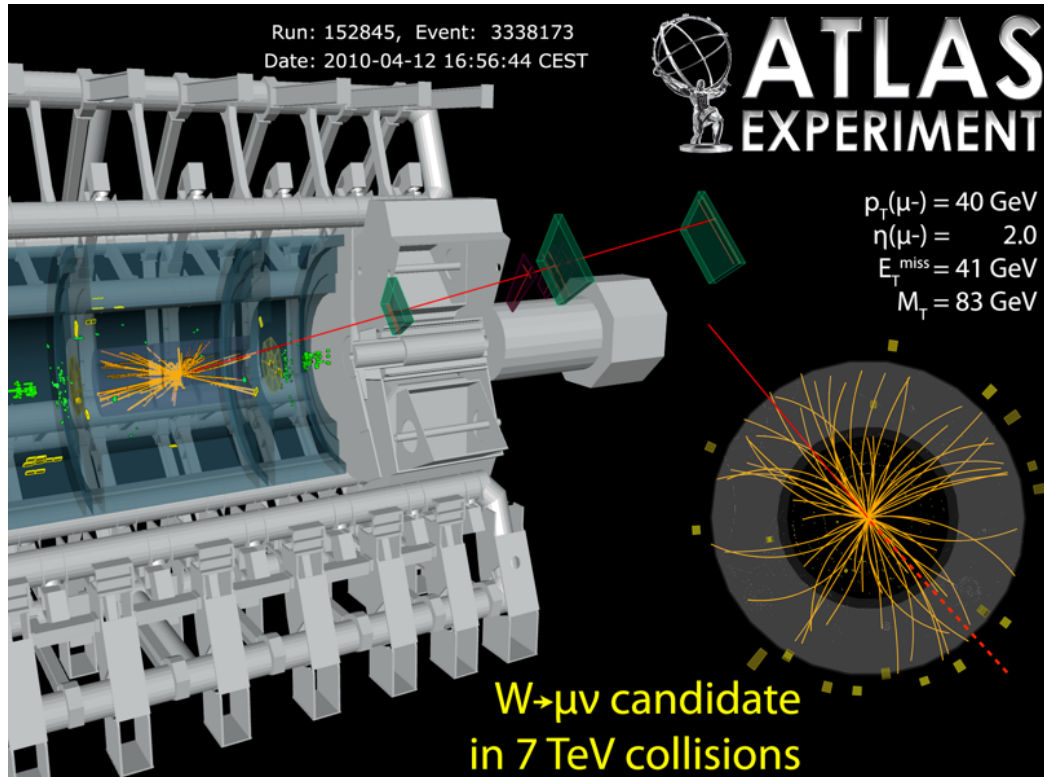
# Calorimetry

- ❖ 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

3 Generations of Fermions			Force Carriers	
Q u a r k s	<div> <math>\frac{2}{3}</math>  <u>u</u> ✓  <math>\sim 5</math> </div>	<div> <math>\frac{2}{3}</math>  <u>c</u> ✓  <math>\sim 1350</math> </div>	<div> <math>\frac{2}{3}</math>  <u>t</u> ✓  <math>175000</math> </div>	<div> <math>0</math>  <u>g</u> ✓  <math>0</math> </div> <div>Strong Interactions</div>
	<div> <math>-\frac{1}{3}</math>  <u>d</u> ✓  <math>\sim 9</math> </div>	<div> <math>-\frac{1}{3}</math>  <u>s</u> ✓  <math>\sim 175</math> </div>	<div> <math>-\frac{1}{3}</math>  <u>b</u> ✓  <math>\sim 4500</math> </div>	<div> <math>0</math>  <u><math>\gamma</math></u> ✓  <math>0</math> </div> <div>Electro-magnetism</div>
L e p t o n s	<div> <u><math>\nu_e</math></u> ✓  <math>0?</math> </div>	<div> <u><math>\nu_\mu</math></u> ✓  <math>0?</math> </div>	<div> <u><math>\nu_\tau</math></u> ✓  <math>0?</math> </div>	<div> <math>0</math>  <u><math>Z^0</math></u> ✓  <math>91187</math> </div> <div>Weak Interactions</div>
	<div> <u>e</u> ✓  <math>0.511</math> </div>	<div> <u><math>\mu</math></u> ✓  <math>105.66</math> </div>	<div> <u><math>\tau</math></u> ✓  <math>1777.2</math> </div>	<div> <math>\pm 1</math>  <u><math>W^\pm</math></u> ✓  <math>81400</math> </div>
<div> <u>H</u> ✓  <math>125500</math> </div>				<div> <math>0</math>  <u>H</u> ✓  <math>125500</math> </div>

Masses are in MeV

✓ : Detect with high efficiency

✓ : Detect by missing  
transverse energy

✓ : Detect through decays:  $t \rightarrow Wb, W/Z \rightarrow \text{leptons}, \dots$

# The Work

# Steps in a Physics Analysis

- ❖ Choose a topic (often theory-motivated)
- ❖ What is the final state?  $\Rightarrow$  “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  $1000 \text{ Hz} \times 1+ \text{ MB/event} = 1+ \text{ GB/s}$
    - “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  $\int \mathcal{L}$

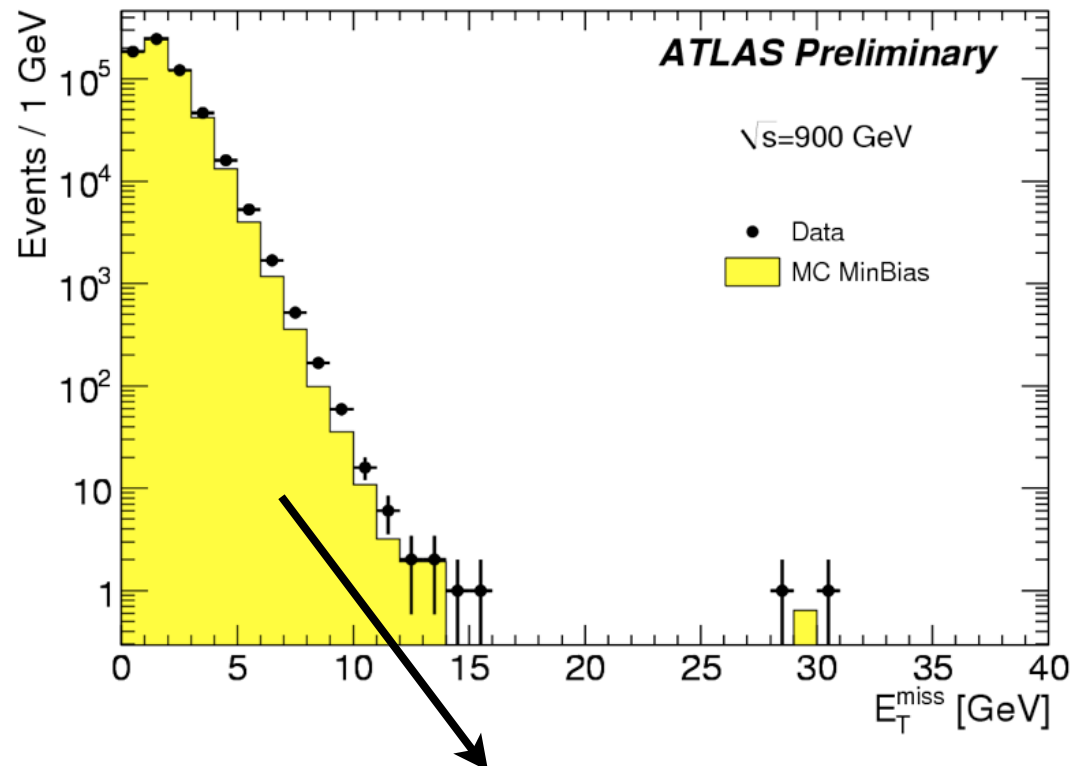
# Steps (II)

## ❖ 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)

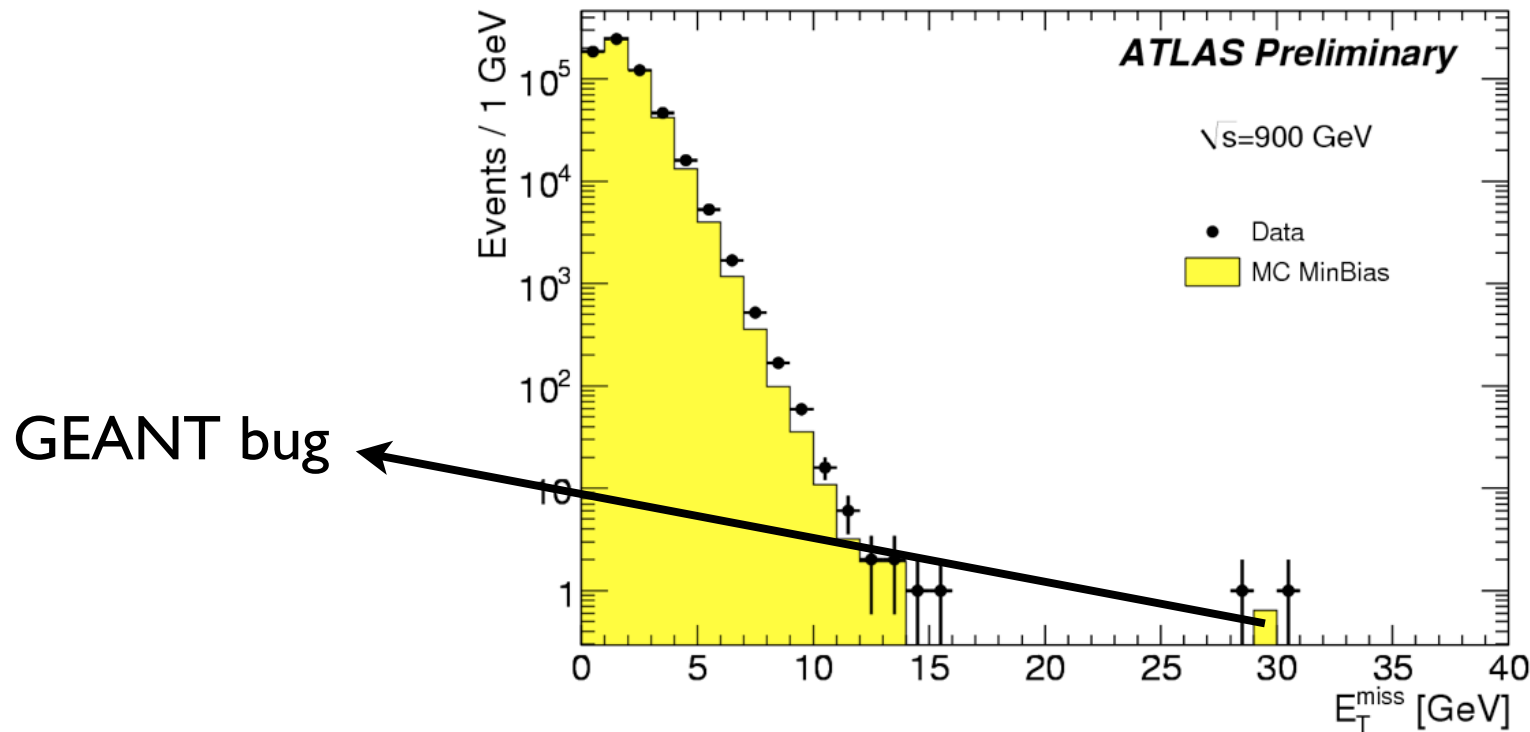
- ❖ Everybody wants experimenters to produce results fast
  - Lots of pressure in the early days of LHC...



Only jets, background easy

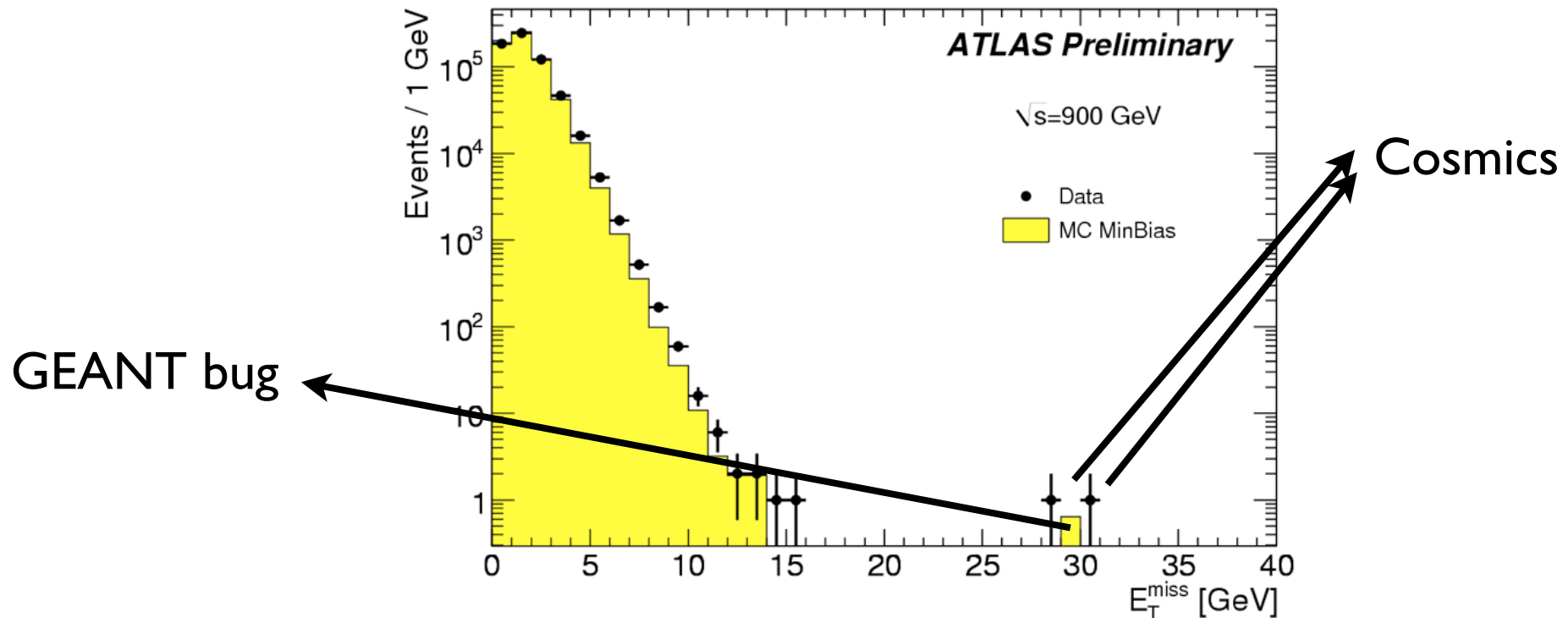
# Anecdotes From the Field (I)

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



# Anecdotes From the Field (I)

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

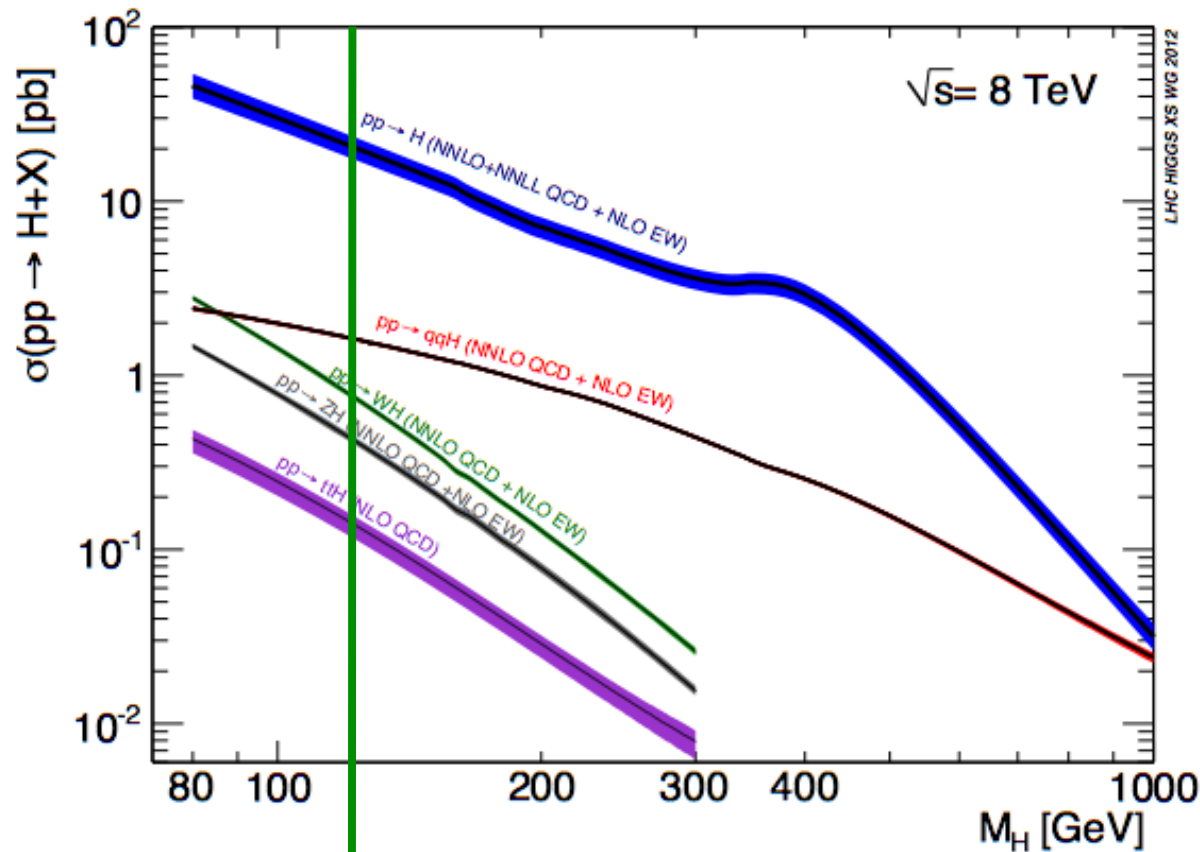


- Sometimes, it's better to take the appropriate time to investigate

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

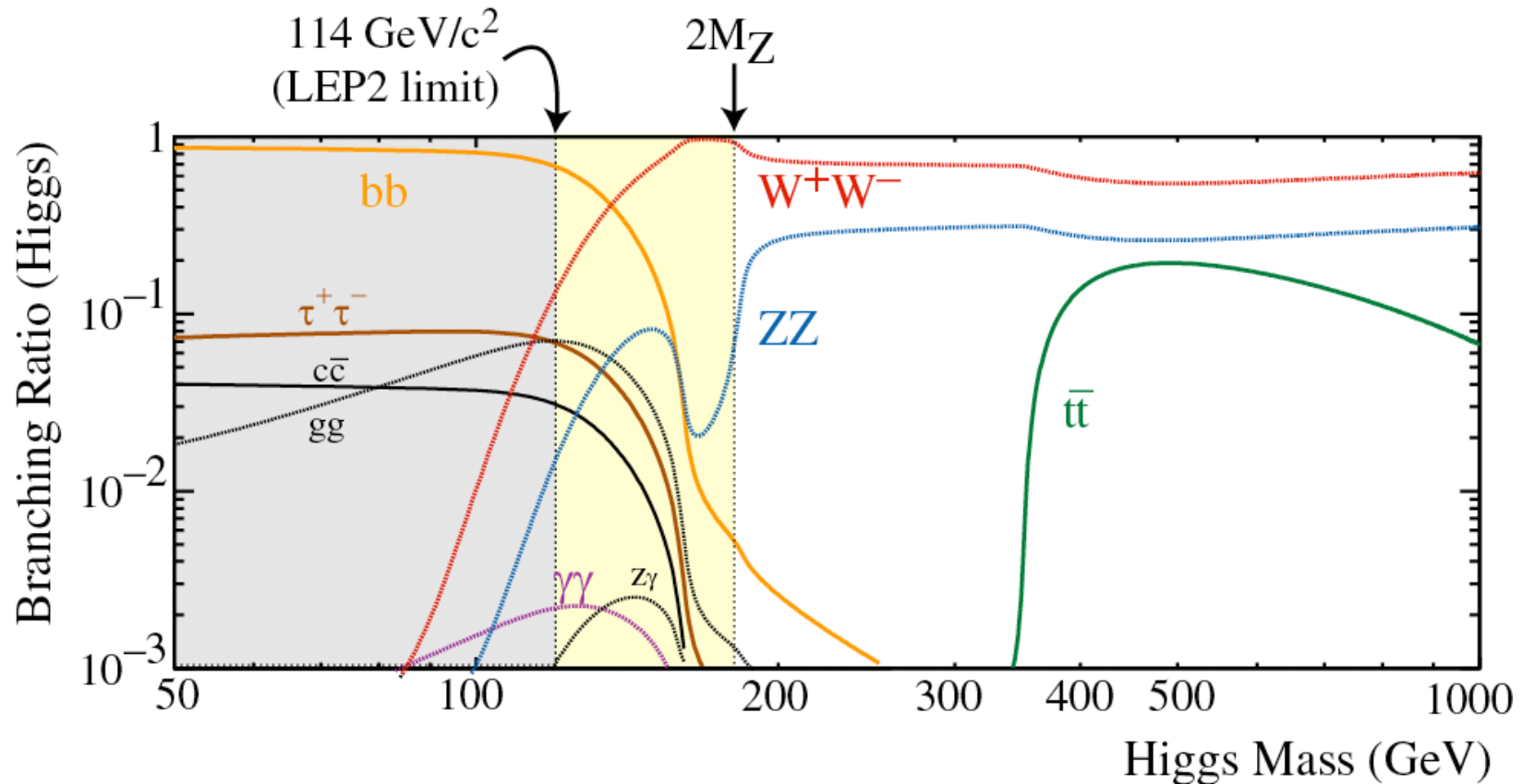
# Producing Higgses

❖ 20 fb<sup>-1</sup> 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  
 $H \rightarrow b\bar{b}, \tau^+\tau^-, \gamma\gamma$

High Mass  
 $H \rightarrow W^+W^-, ZZ$

# $\mu + \tau$

- ❖ Indirect constraints fairly weak (as opposed to e.g.  $e + \mu$ )
  - Indirect:  $\text{BR}(\mu\tau) < \sim 10\%$ ;  $\text{BR}(e\mu) < \sim 10^{-8}$
- ❖ 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  $\Rightarrow$  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  $\mu$ - $\tau$  invariant mass
  - Unfortunately not directly reconstructible: neutrinos escape!

# Collinear Mass

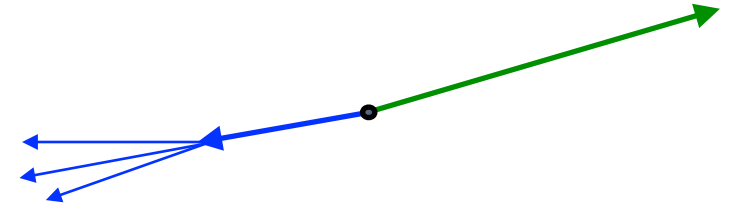
❖  $m(H) = 125 \text{ GeV}$ ,  $m(\tau) = 1.8 \text{ GeV}$

➡ Tau is heavily boosted

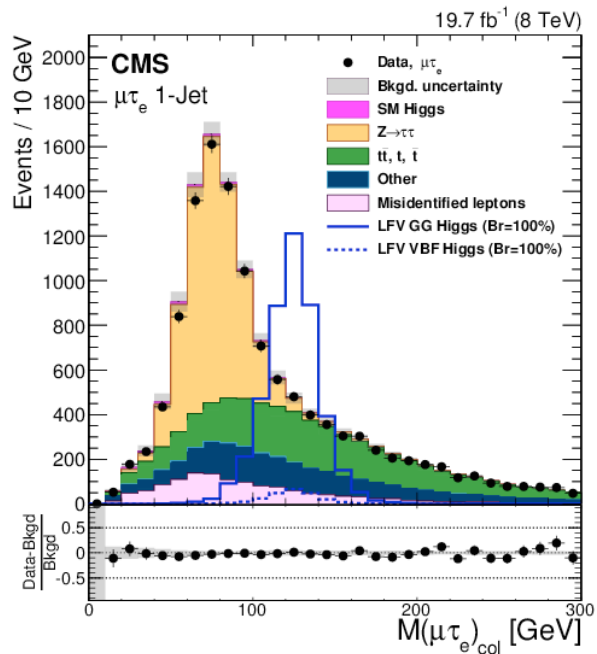
➡ Tau decay products are collinear with tau

❖ Under that assumption, know neutrino direction

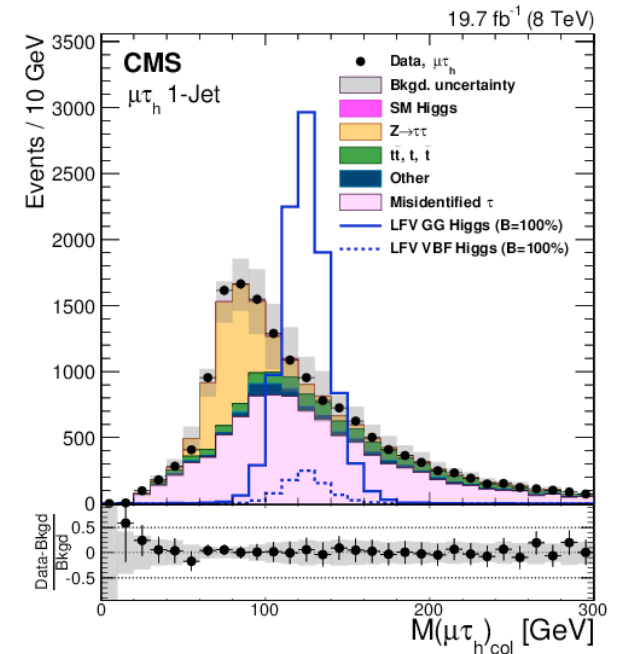
- From direction and missing transverse momentum infer neutrino longitudinal momentum



CMS: [arXiv:1502.07400](https://arxiv.org/abs/1502.07400)



Preselection



# Categorize!

❖ Different production mechanism (gluon fusion vs. vector boson fusion) lead to different topologies

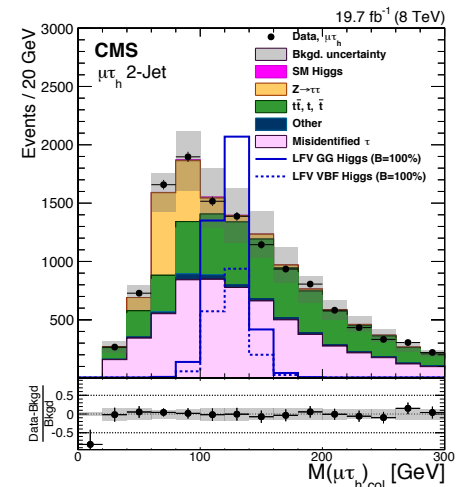
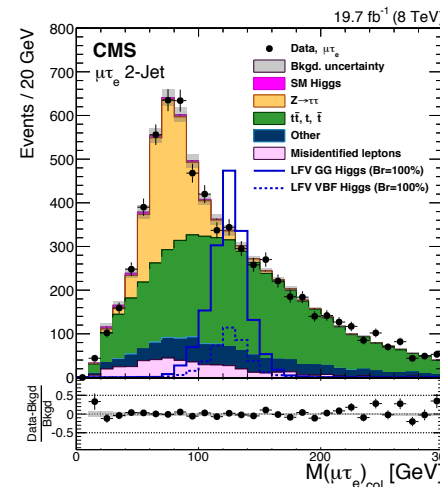
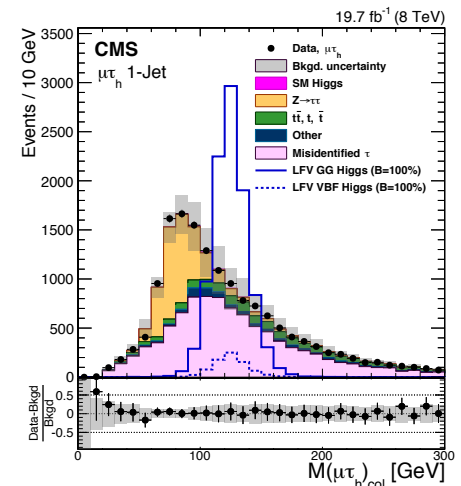
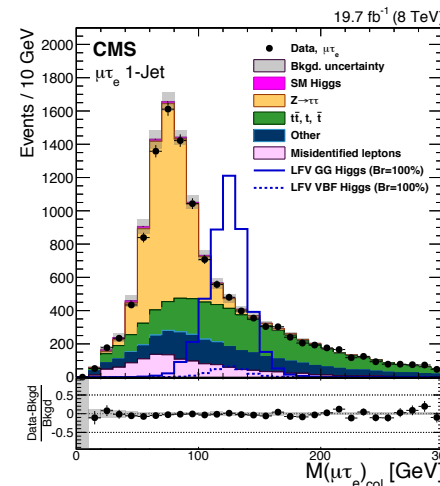
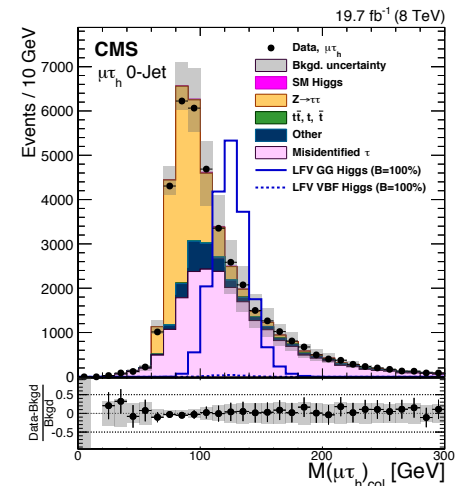
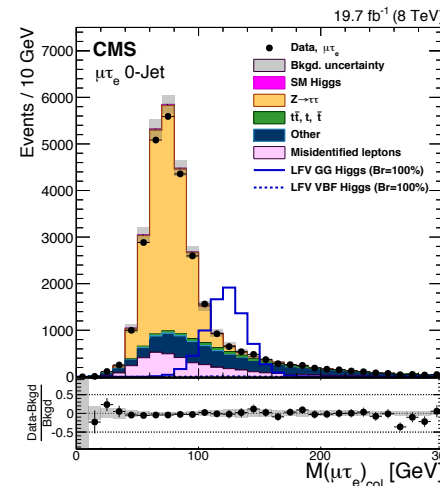
- In practice number of jets

❖ 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



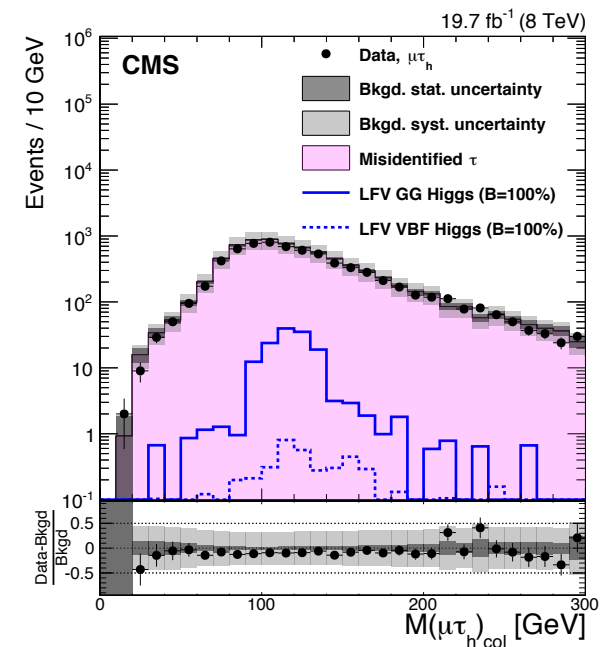
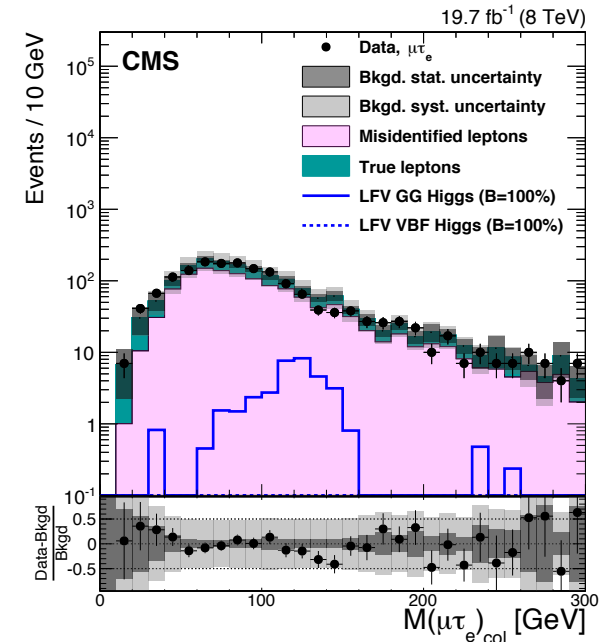
# Backgrounds

❖ Small signal  $\Rightarrow$  need very accurate background estimate

- Use data where possible

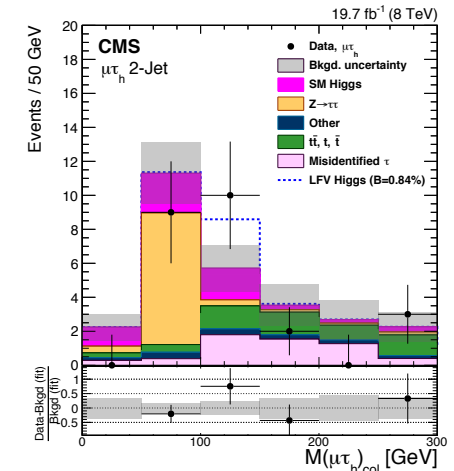
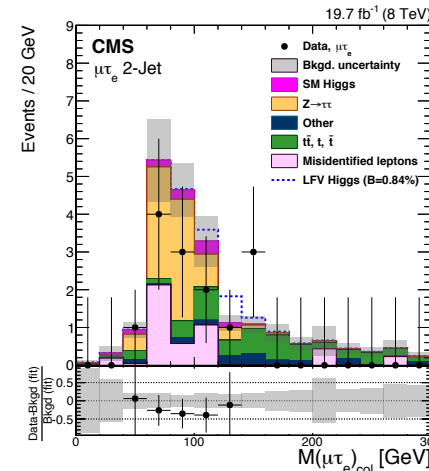
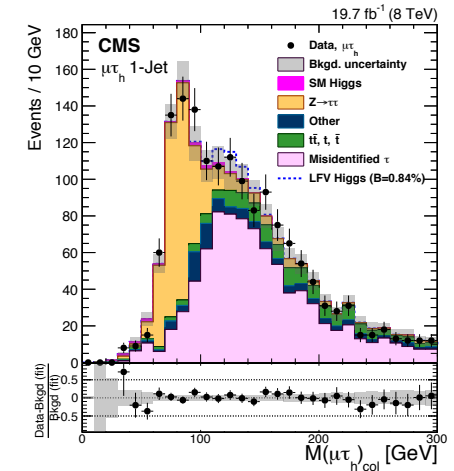
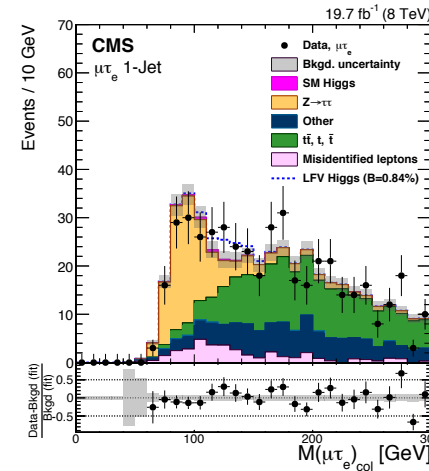
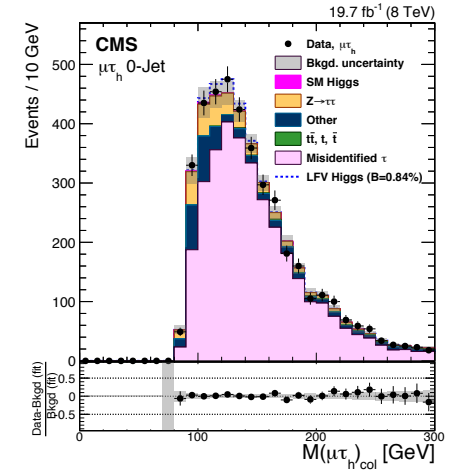
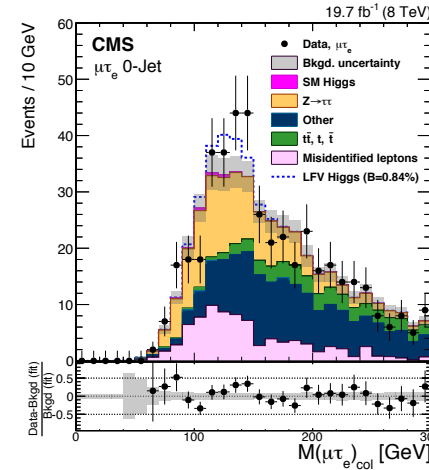
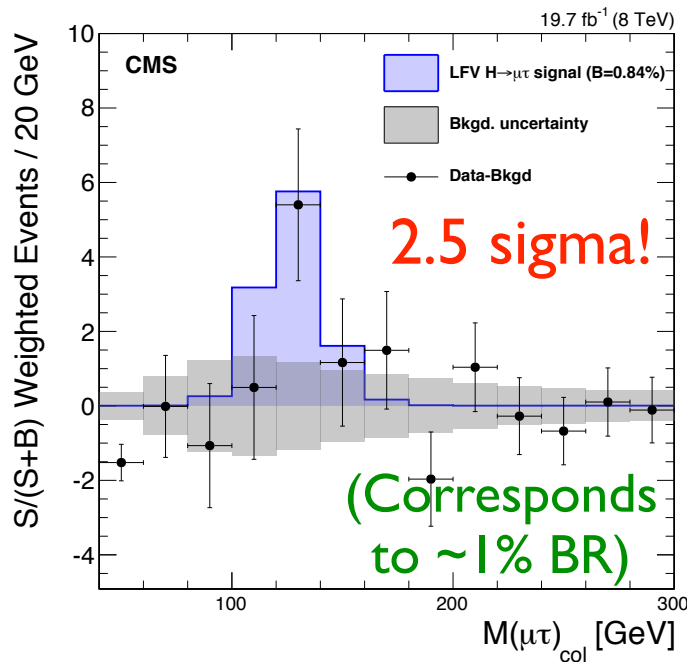
❖ In this case:

- $Z \rightarrow \tau\tau$  (irreducible): take  $Z \rightarrow \mu\mu$  events from data, replace one muon with simulated tau
- Misidentified leptons: get control sample, and independently measure probability to fake e or  $\tau_h$ , 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”



# 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....?