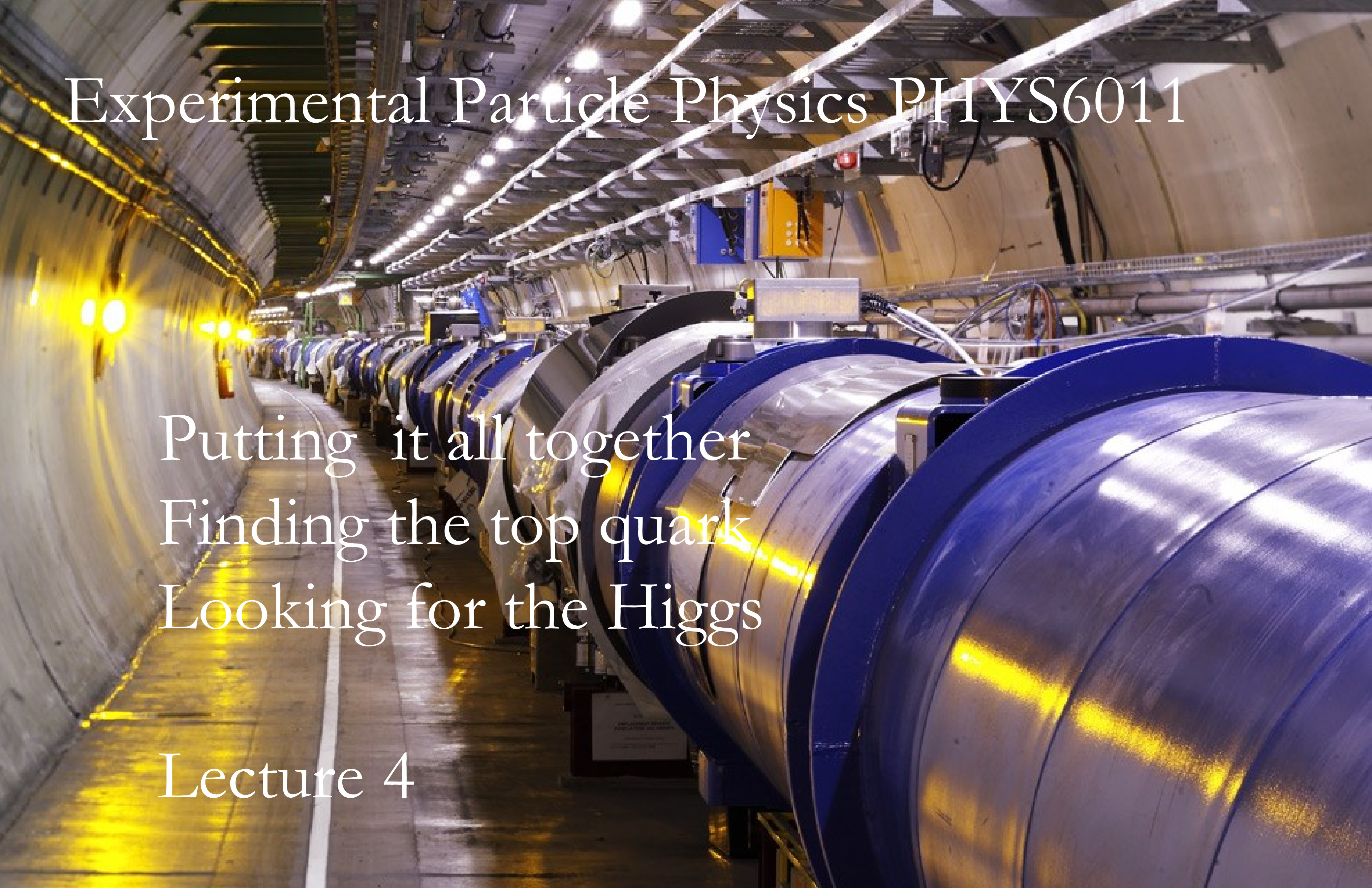
Experimental Particle Physics PHYS6011

Putting it all together
Finding the top quark
Looking for the Higgs

Lecture 4

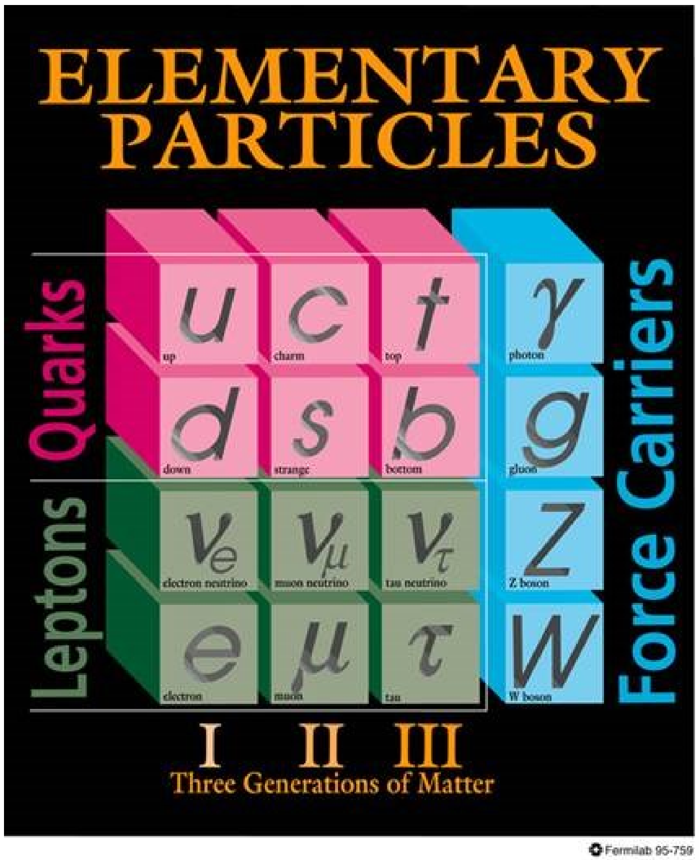


Practical questions

- What do we want to do?
  - Measure a known property e.g. mass of the top quark?
  - Look for new particles e.g. Higgs?
- How to do it?
  - How do you get the information out of the detector?
  - How well is our detector is performing?
  - How do you identify the “true signal”?
  - How do you eliminate the “fake signal”?
  - How confident are you that you really have measured something?

What do we measure?

In principle:



But in reality:

LIGHT UNFLAVORED MESONS
$(S = C = B = 0)$

For $I = 1$ (π, b, ρ, a): $u\bar{d}$, $(u\bar{u} - d\bar{d})/\sqrt{2}$, $d\bar{u}$;
for $I = 0$ (η, η', h, h', ω, ϕ, f, f'): $c_1(u\bar{u} + d\bar{d}) + c_2(s\bar{s})$

Quark content

$\pi^{\pm}$ $\qquad I^G(J^P) = 1^-(0^-)$

Spin

Mass

Lifetime

Mass $m = 139.57018 \pm 0.00035$ MeV (S = 1.2)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)
$c\tau = 7.8045$ m

$\pi^{\pm} \to \ell^{\pm} \nu \gamma$ form factors [a]

$F_V = 0.017 \pm 0.008$
$F_A = 0.0115 \pm 0.0005$ (S = 1.2)
$R = 0.059^{+0.009}_{-0.008}$

Form factor

π^- modes are charge conjugates of the modes below.

For decay limits to particles which are not established, see the appropriate Search sections (Massive Neutrino Peak Search Test, A^0 (axion), and Other Light Boson (X^0) Searches, etc.).

Decay Modes

Branching Fraction

π^+ DECAY MODES			Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\mu^+ \nu_\mu$		[b]	(99.98770 ± 0.00004) %		30
$\mu^+ \nu_\mu \gamma$		[c]	$(2.00 \pm 0.25) \times 10^{-4}$		30
$e^+ \nu_e$		[b]	$(1.230 \pm 0.004) \times 10^{-4}$		70
$e^+ \nu_e \gamma$		[c]	$(1.61 \pm 0.23) \times 10^{-7}$		70
$e^+ \nu_e \pi^0$			$(1.036 \pm 0.006) \times 10^{-8}$		4
$e^+ \nu_e e^+ e^-$			$(3.2 \pm 0.5) \times 10^{-9}$		70
$e^+ \nu_e \nu \bar{\nu}$			$< 5 \times 10^{-6}$	90%	70
Lepton Family number (*LF*) or Lepton number (*L*) violating modes					
$\mu^+ \bar{\nu}_e$	L	[d]	$< 1.5 \times 10^{-3}$	90%	30
$\mu^+ \nu_e$	LF	[d]	$< 8.0 \times 10^{-3}$	90%	30
$\mu^- e^+ e^+ \nu$	LF		$< 1.6 \times 10^{-6}$	90%	30

Particle Properties

- Mass
  - Measure momentum and energy: $E^2 = p^2 + m^2$
- Mass width → Lifetime
  - Measure momentum and energy or
  - How many particles exist after t seconds
- Branching Fraction
  - Reconstruct the decays and see how many there are.
- Charge
  - Direction in a magnetic field
- Spin
  - Angular distribution of decays
- Structure e.g. Proton/Neutron/Nucleus
  - Scatter particles off the proton and look at distribution

$$\Delta M = \frac{\Gamma}{2} = \frac{\hbar}{2\tau}$$

e.g. top mass width $\Delta \mathrm{M} = 2GeV$

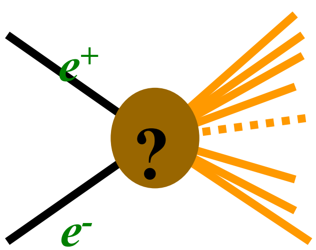
$$\Rightarrow \tau \approx 3x10^{-25}s$$

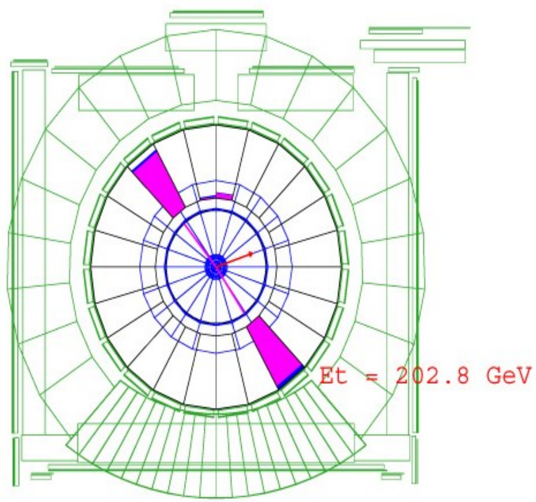
Data Flow

Low Signal: High Background → High Signal: Low Background

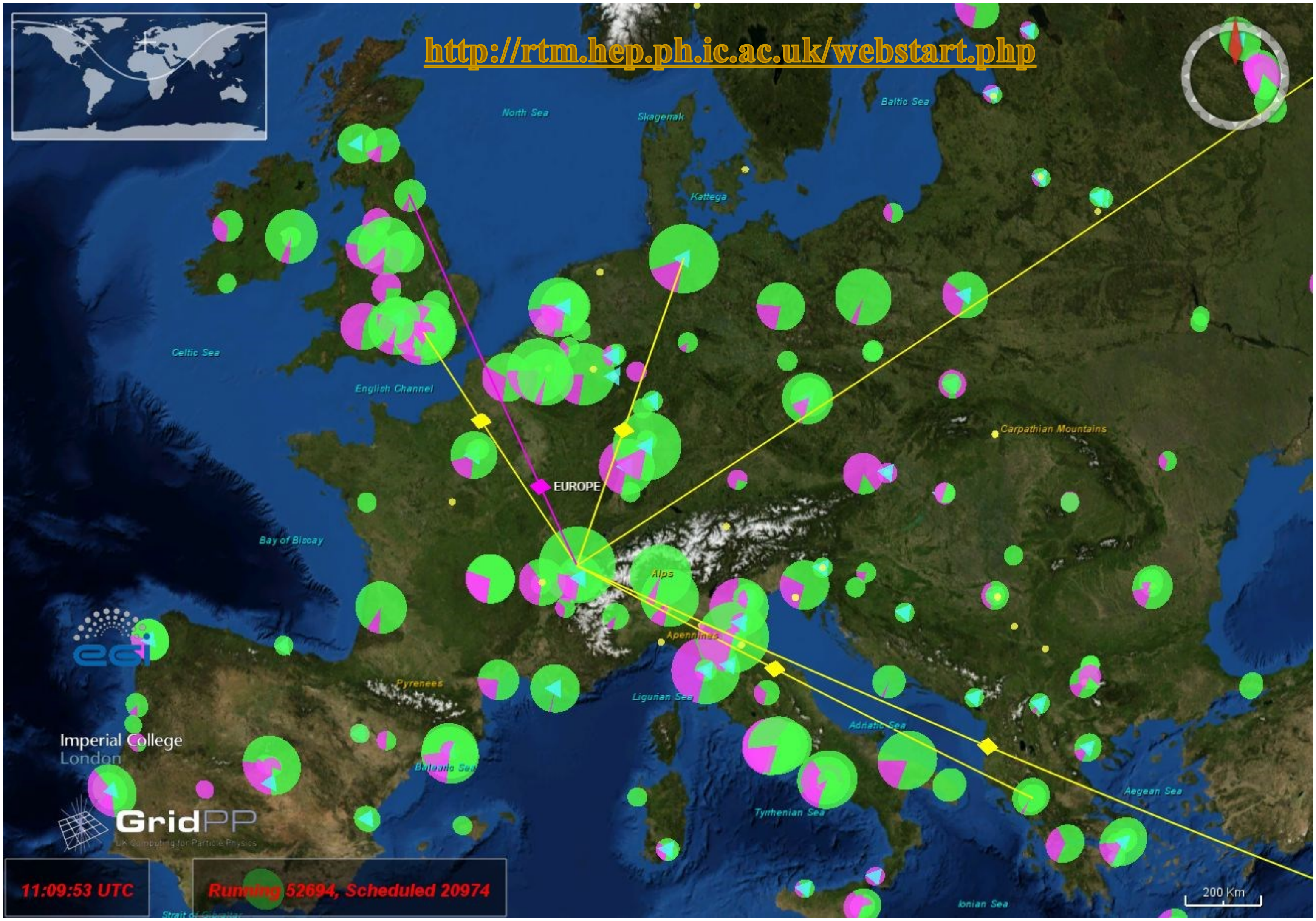
- Collision (10^9 Hz, 800 Tbytes/sec)
- Detector
- Trigger and DAQ
- Storage (200Hz, 2 Gbytes/sec)
- Event Selection
- Storage again
- Analysis

(numbers from an LHC experiment)



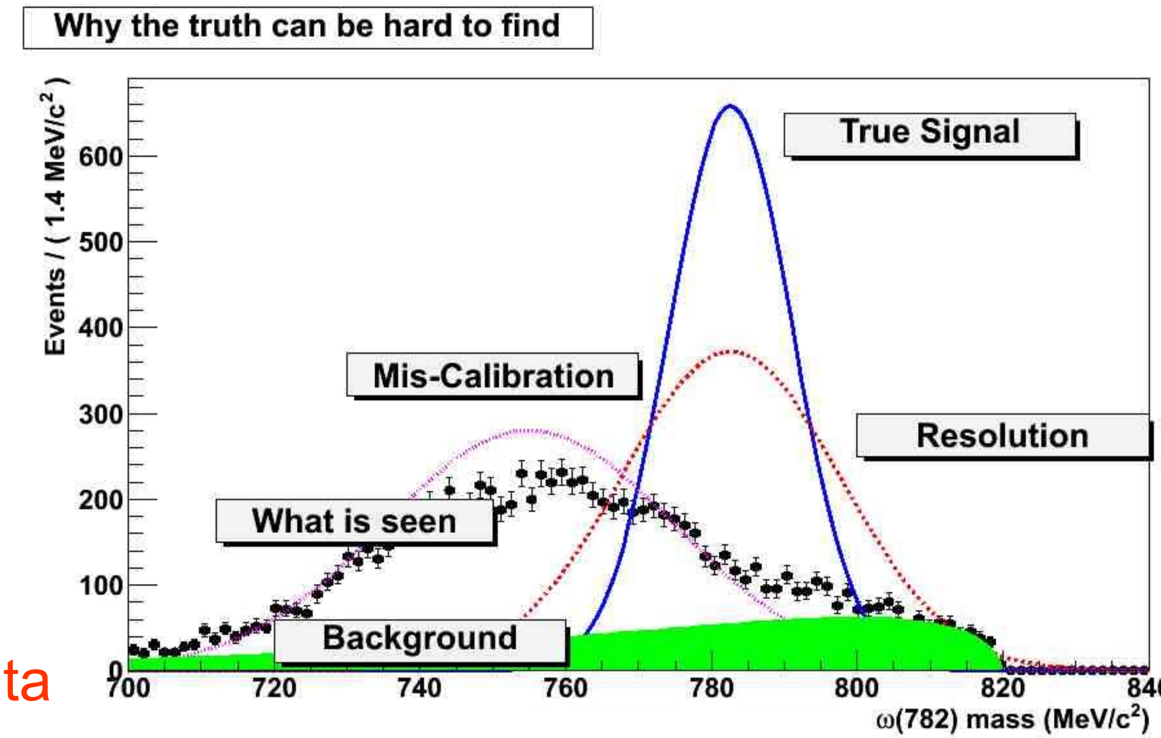


Where is all the LHC data going?



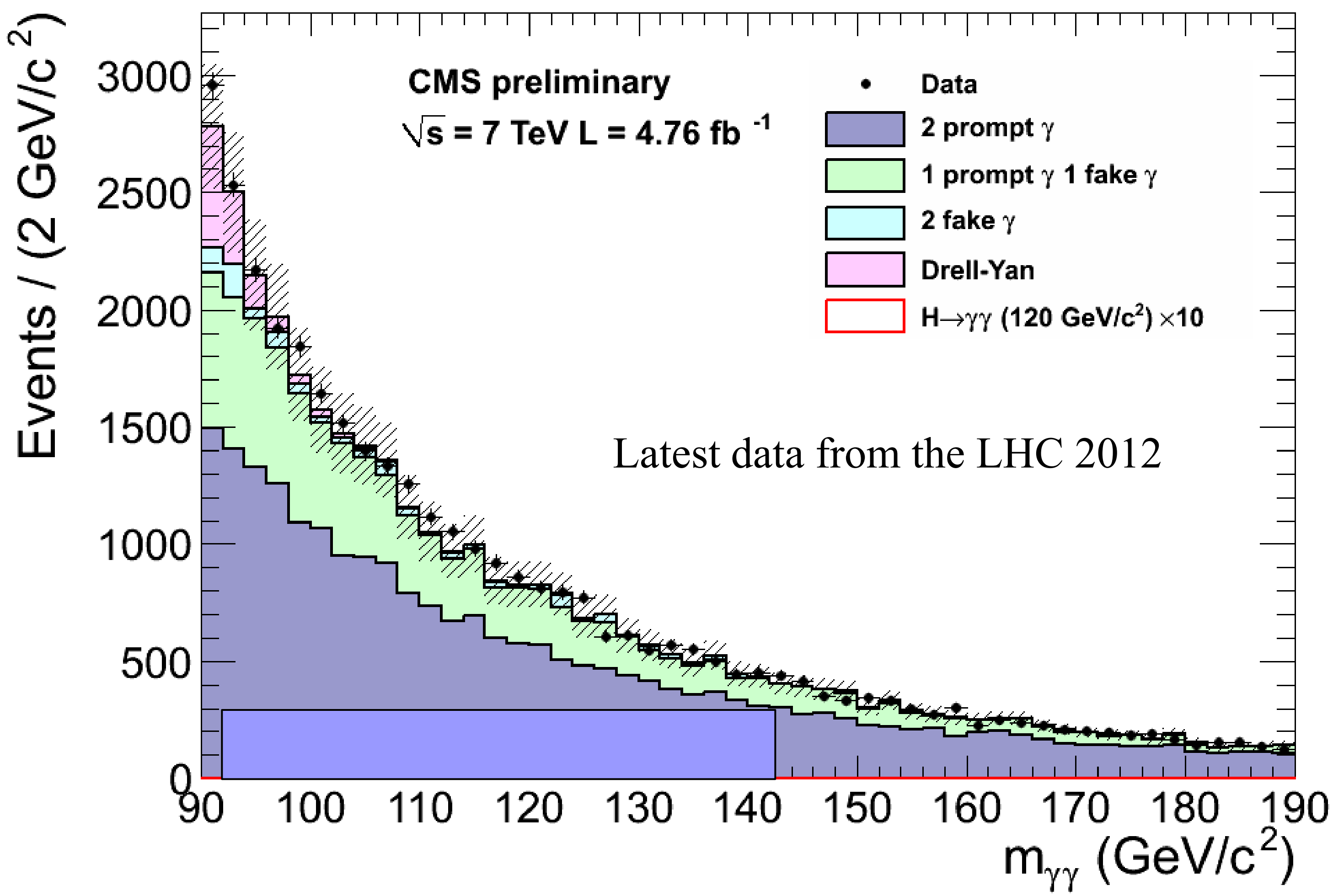
Elements of Analysis

- What you actually measure can be affected by
  - Acceptance (how many events actually enter your detector)
  - Detector Response (not a perfect device)
    - Can smear the distribution
    - Can shift the distribution
  - Errors
    - Statistical
    - Systematic
- How to find the truth?
  - Try and evaluate from the data
  - Create a simulation of your experiment (Monte Carlo)



Can you see the Higgs?

The signal is often much smaller than the background

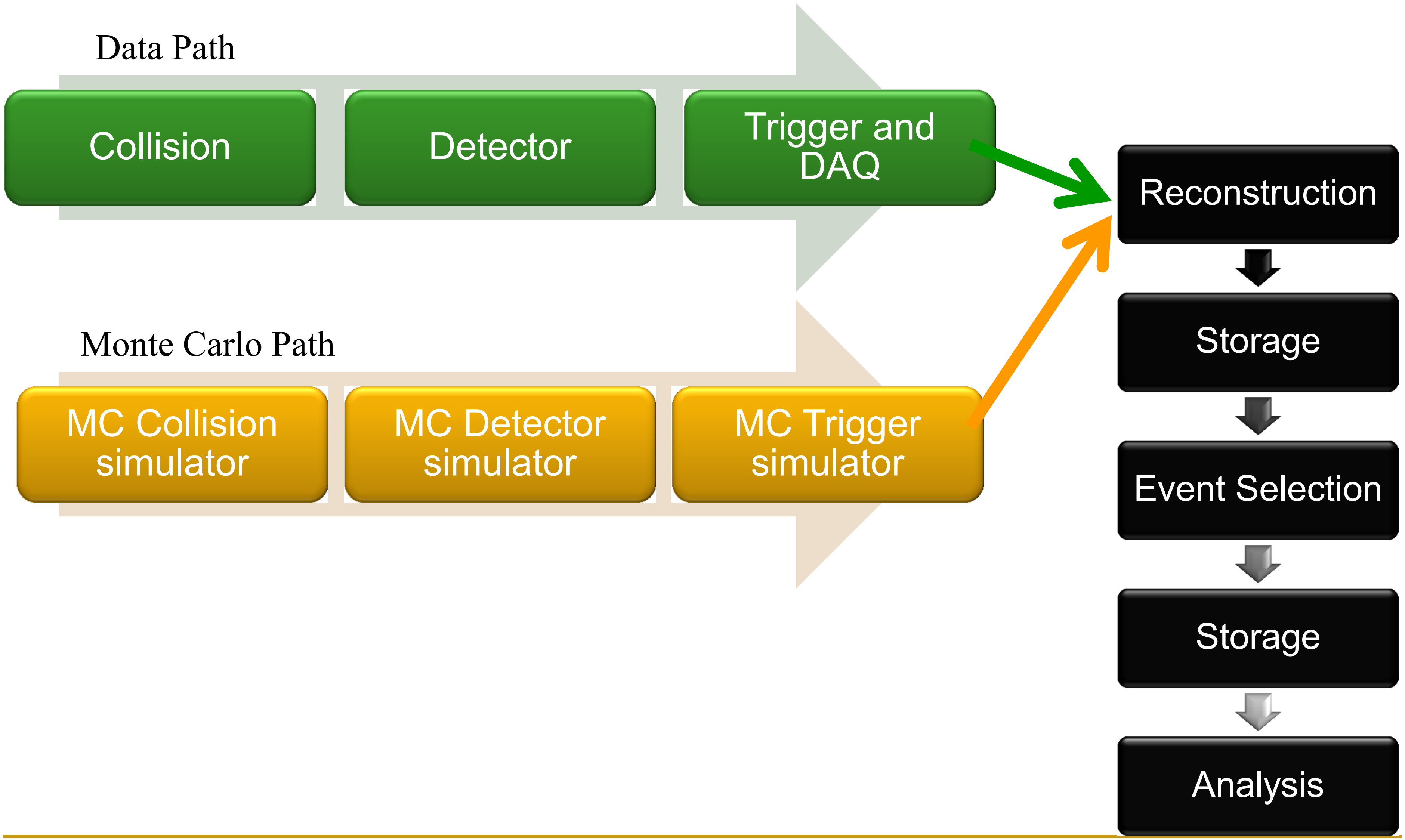


Monte Carlo

- Generate artificial data
- Simulate every component of your detector (from the ~atomic level)
- Analyse the simulated data as though it were real data
  - Response to a known input can be calculated
  - Invert the response to calculate what the input should look like for a given output
- Also used to design the detector
- Very computer intensive

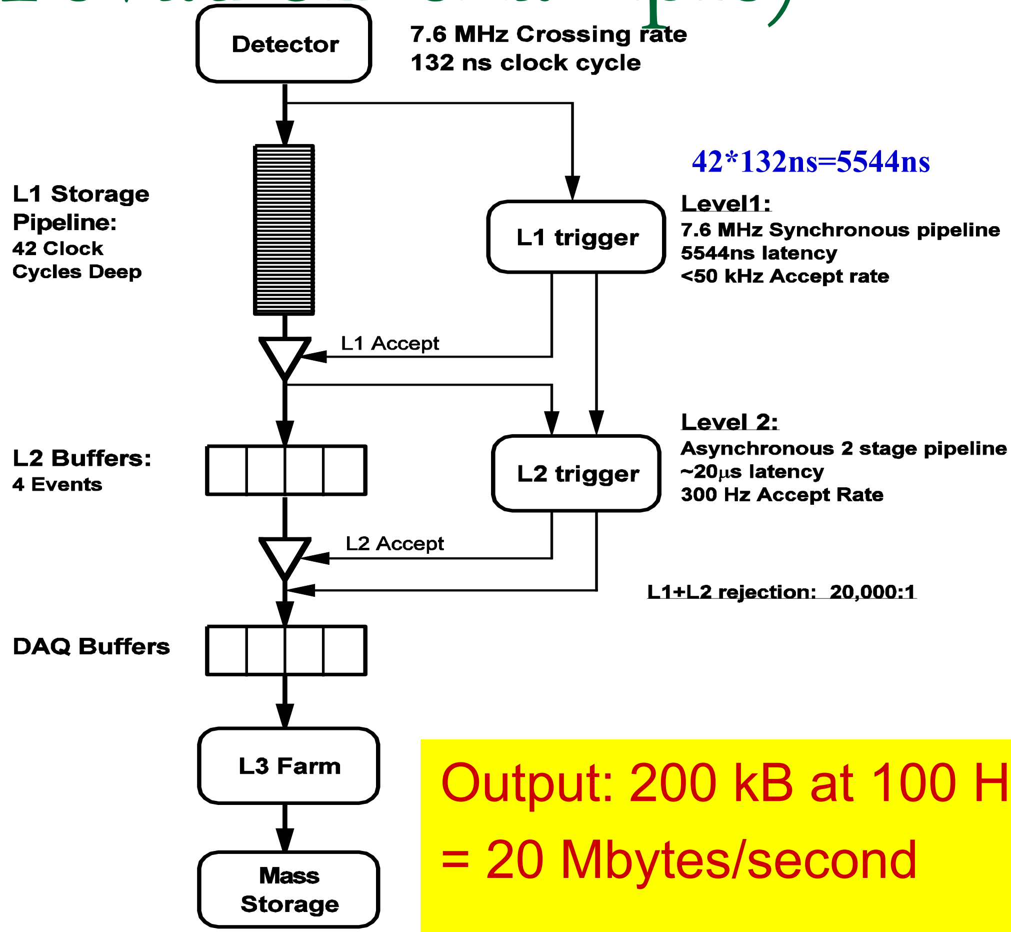
- One LHC event takes 20 minutes to simulate.
- In 20 minutes, LHC creates 250,000 real events.
- So need 250,000 computers to keep up.

Data and Monte Carlo Comparison



Trigger and DAQ (Tevatron example)

Input: a million channels at 2.5 MHz
= 10 Tbytes/second



DAQ

- Data AcQuisition
- Processing
- Storage

Keywords:

- **Pipeline**
- **Latency**
- **Buffer**
- **Trigger Rate**

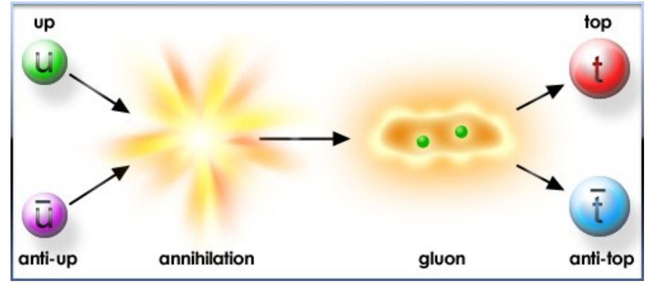
Trigger Inputs:

- **Number of tracks**
- **Energy Clusters**
- **Particle Type**

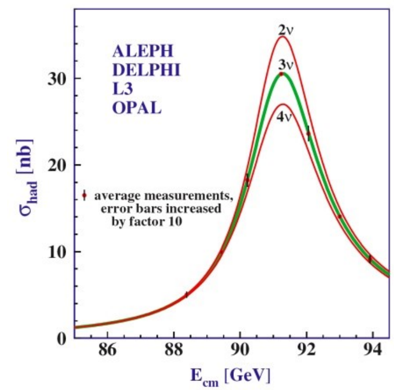
Output: 200 kB at 100 Hz
= 20 Mbytes/second

"The trigger does not tell what is right but what is left."

What should we collide?



- Generally want to collide particles and anti-particles:
  - They annihilate into energy
  - But anti-particles can be expensive to produce.
- Electron / Positron colliders (e.g. LEP):
  - Point-like with well-known initial energy.
  - All the energy goes into the collision.
  - All decays have roughly the same cross-section so there are no large backgrounds.
  - Lose lots of synchrotron radiation in circular colliders.
  - Need to have good idea of the mass of the particles you want to produce e.g. e+e- $\rightarrow Z^0$
- Proton / Anti-proton colliders (e.g. Tevatron):
  - Composite particles so initial energy not known
  - Not all the energy goes into the collision so need to accelerate to higher energies
  - Large cross-sections but large QCD backgrounds
  - Heavy so do not lose lots of energy via synchrotron radiation
  - Useful if you don't know the mass of the particles you want to produce e.g. gg$\rightarrow$H



- Proton / Proton colliders (e.g. LHC)
  - At high energies, most interactions involve gluons and sea-quarks so little difference in proton/proton and proton/anti-proton cross-section.
- Neutrino / Nucleon colliders (e.g. T2K)
  - Need a lot of mass to stop neutrinos
- Electron / Proton (e.g. ZEUS and H1 at DESY)
  - A giant electron microscope to probe the structure of the proton.

Looking for the top quark and the Higgs

Looking for the top quark and the Higgs

- We will consider two collider facilities

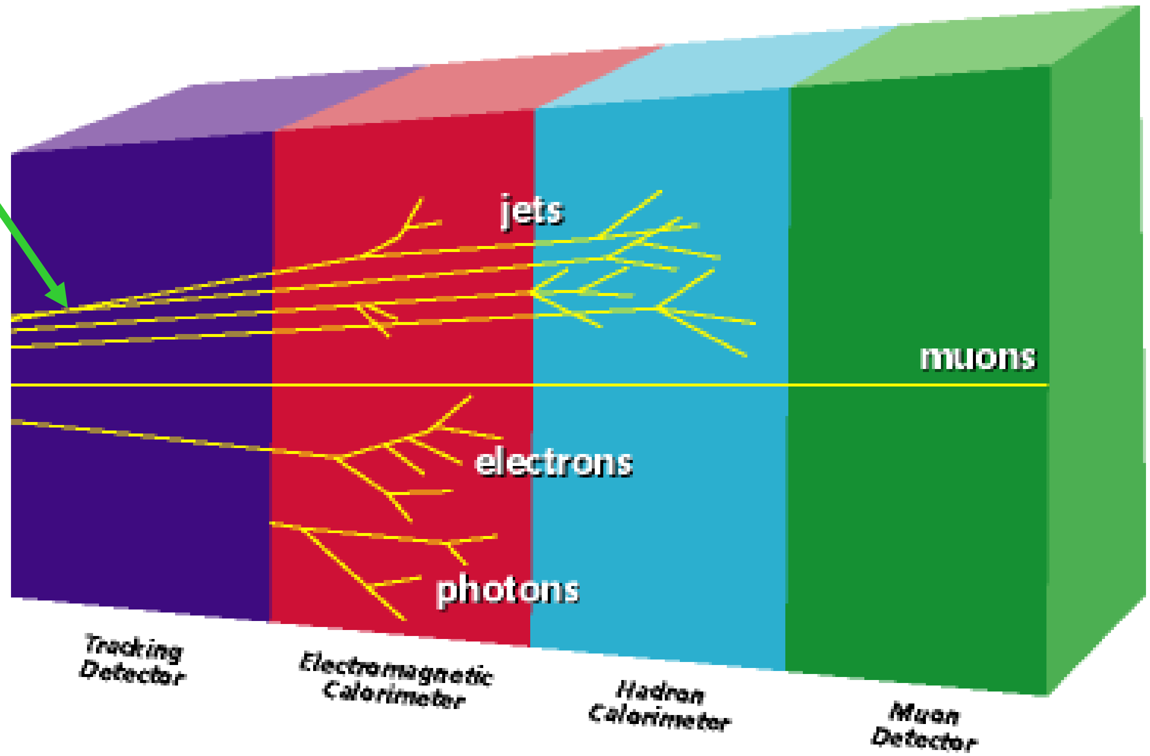
Current parameters	Tevatron	Large Hadron Collider
Location	Illinois, USA	Geneva, Switzerland
Particles	Proton on anti-proton	Proton on proton
Duration	2001-2011	Nov 2009-
Energy (TeV)	0.98	4.0 (7.0 design)
Luminosity ($cm^{-2}s^{-1}$)	4×10^{32}	2×10^{32}
Integrated Luminosity (fb^{-1})	12	~6
Interactions per crossing	3	20

- Consider two types of searches
  - Looking for the top quark
  - Looking for the Higgs

Particles Signatures

- Electron, photons, muons and jets

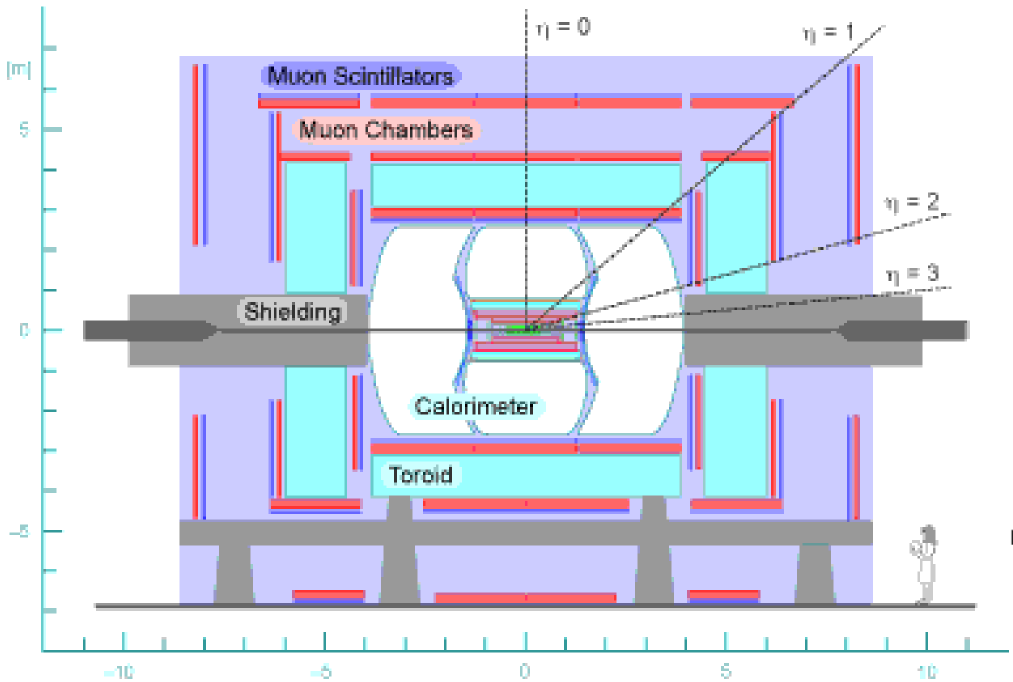
$\pi^{\pm}$, $K^{\pm}$, p



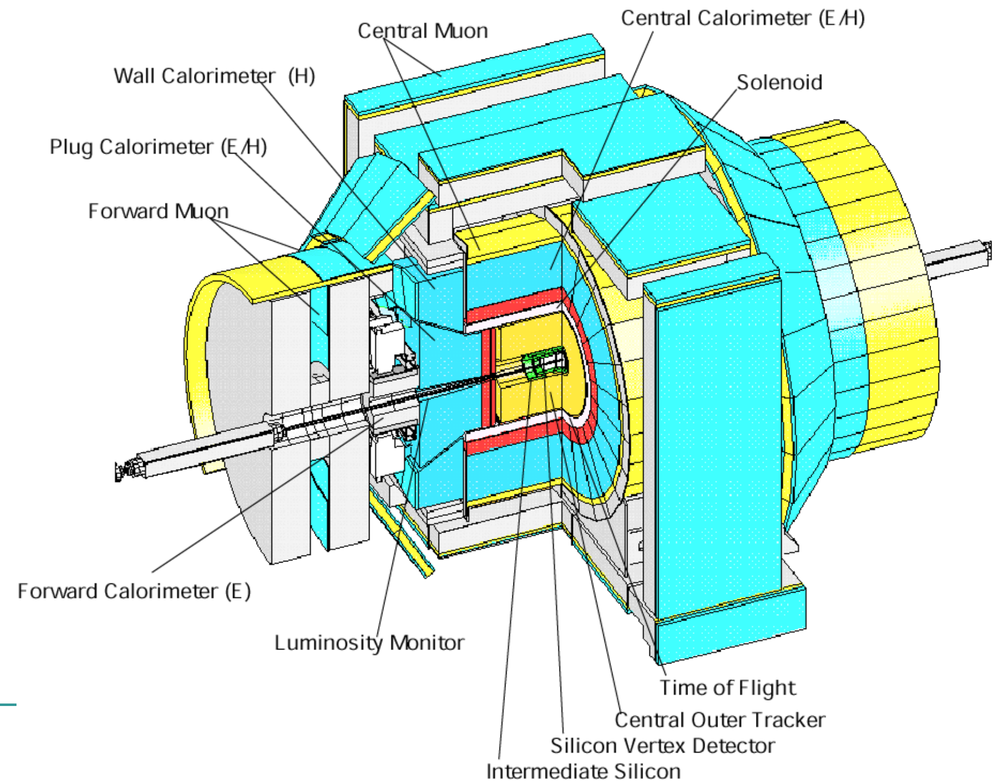
- Tau lepton identification depends on decay mode

The Tevatron Experiments

DØ - optimised for calorimetry



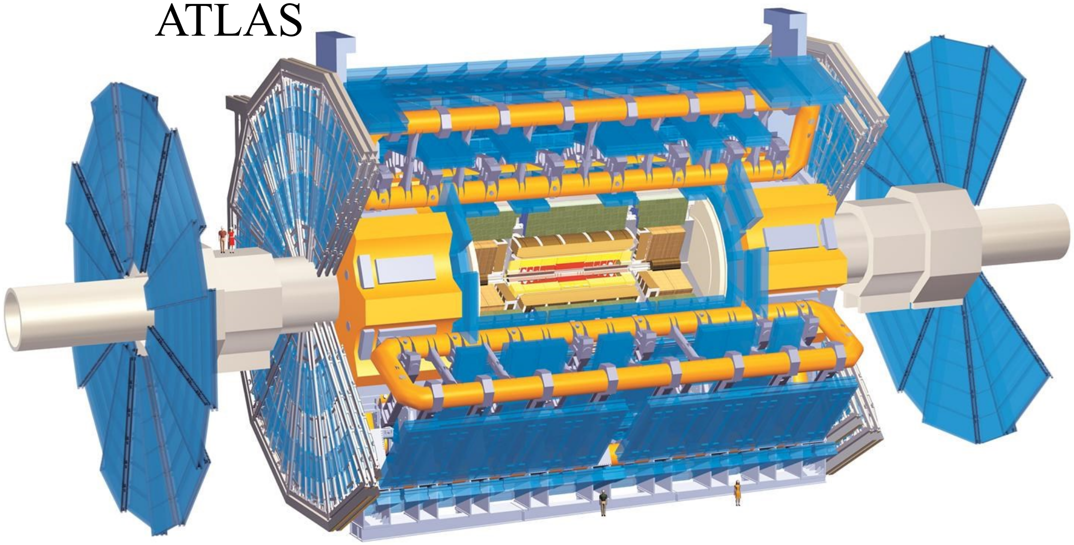
CDF - optimised for tracking



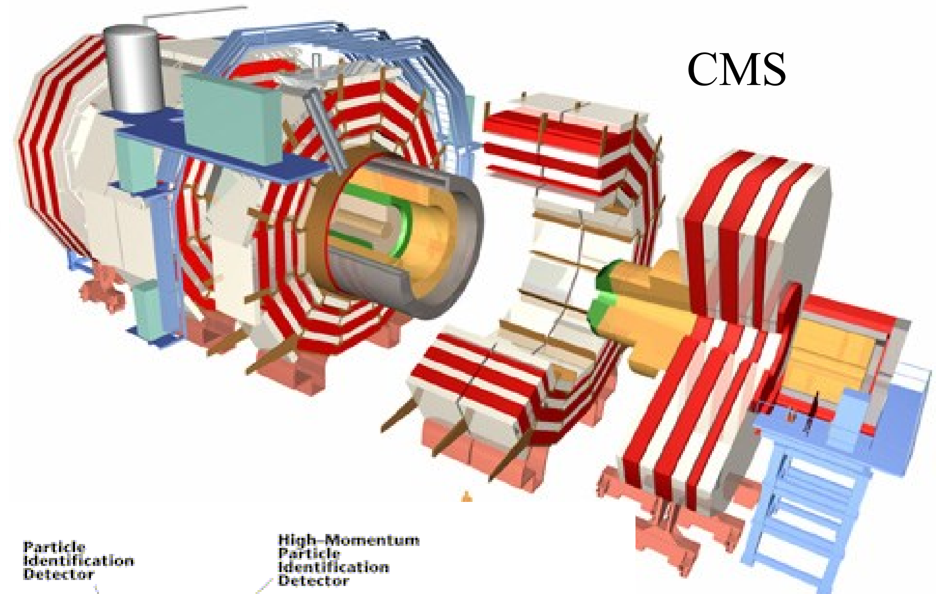
http://www.fnal.gov/pub/tevatron/index.html

The (4 out of 6) LHC Experiments

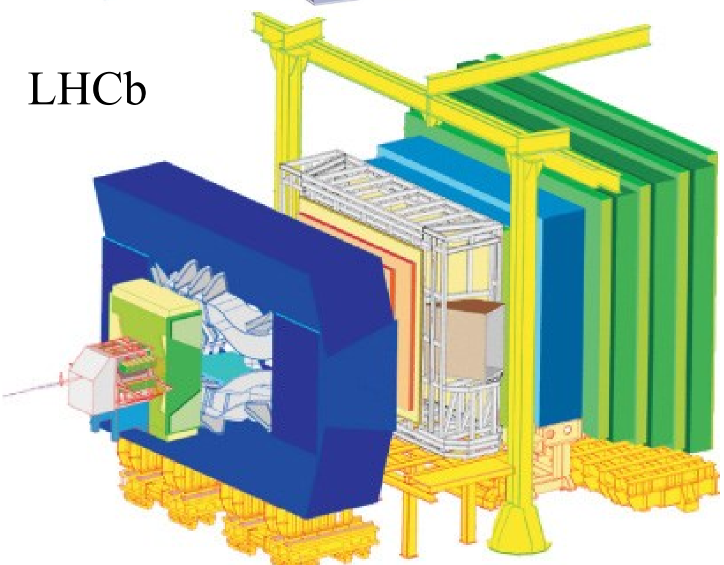
ATLAS

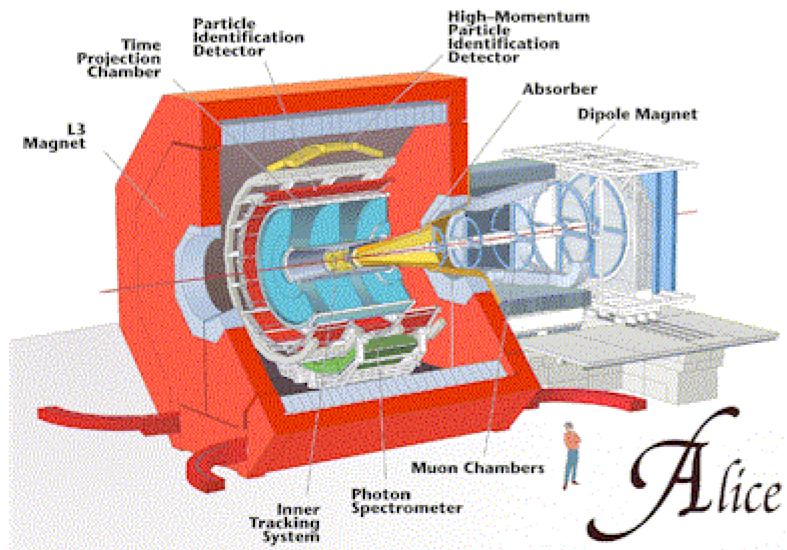


CMS



LHCb

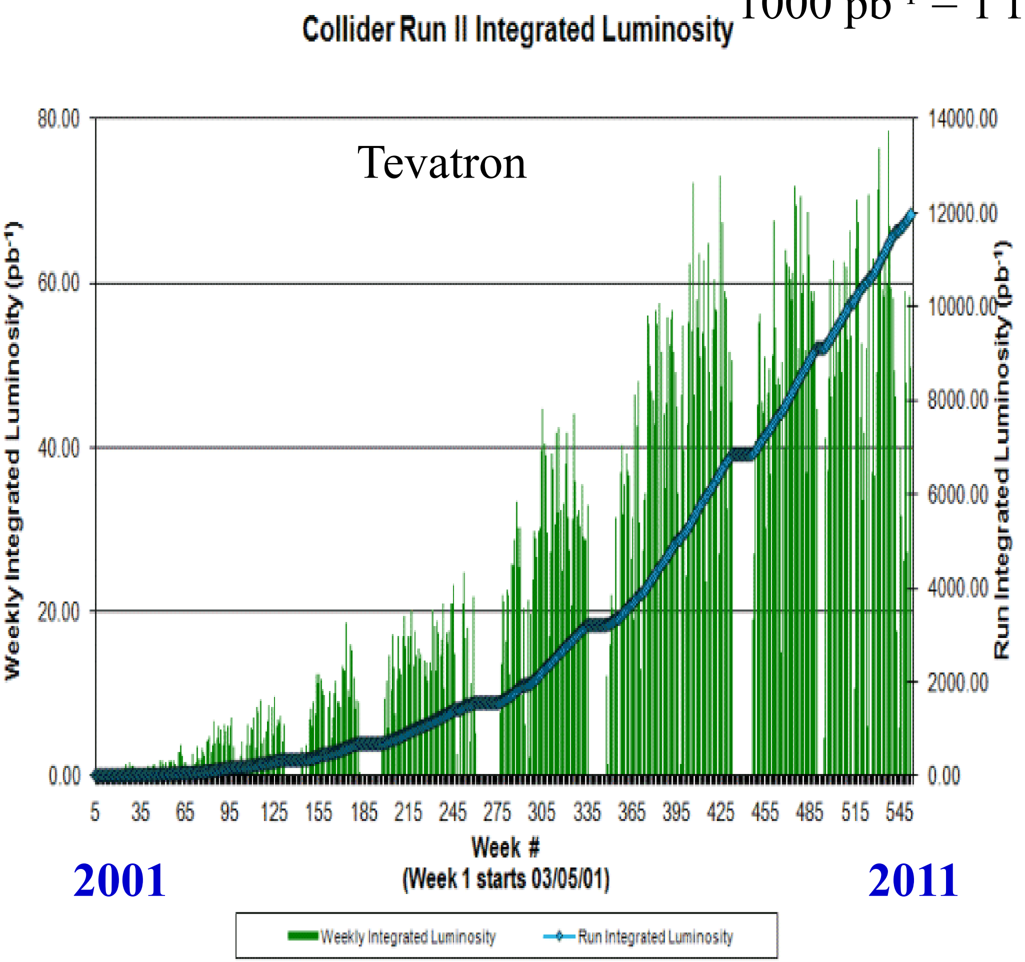


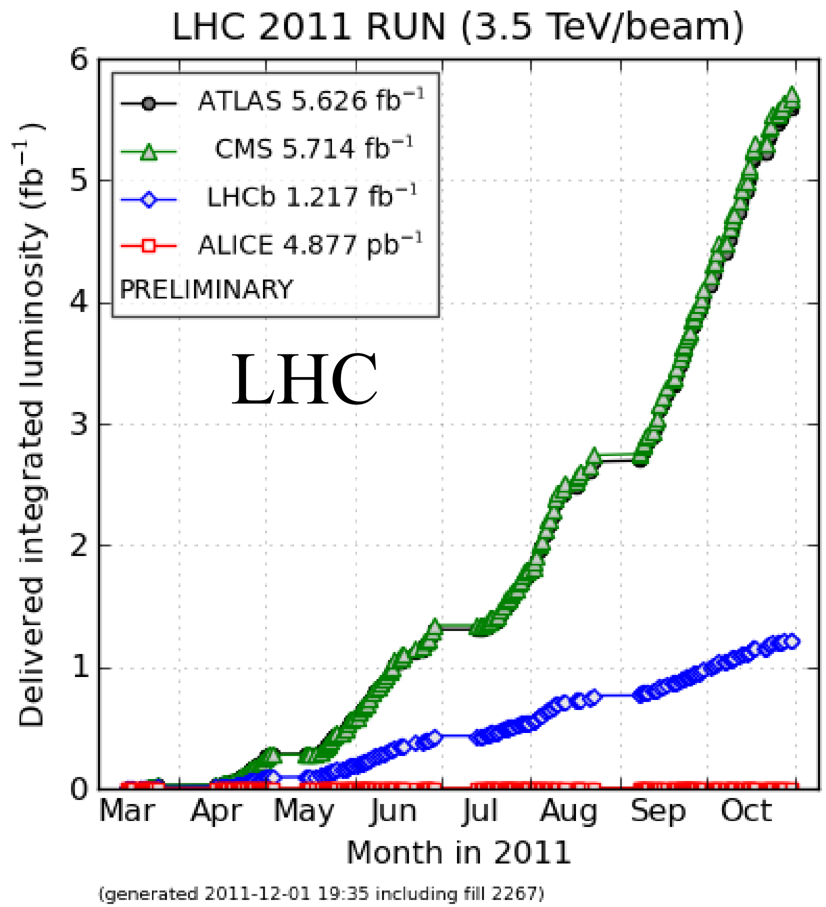


Integrated Luminosity Comparison

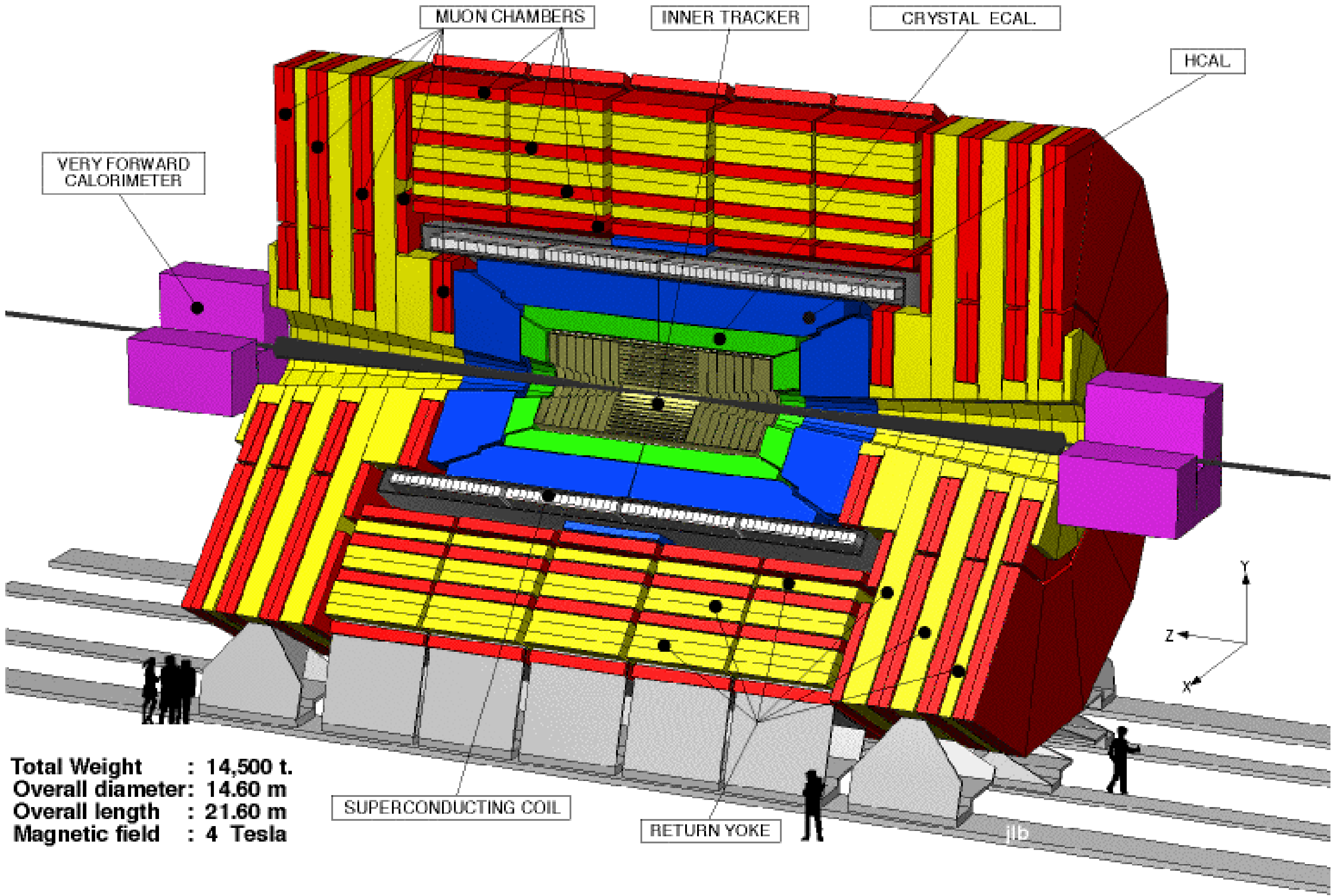
$1 fb^{-1} = 10^{-39} cm^{-2}$

$1000 pb^{-1} = 1 fb^{-1}$





The CMS detector

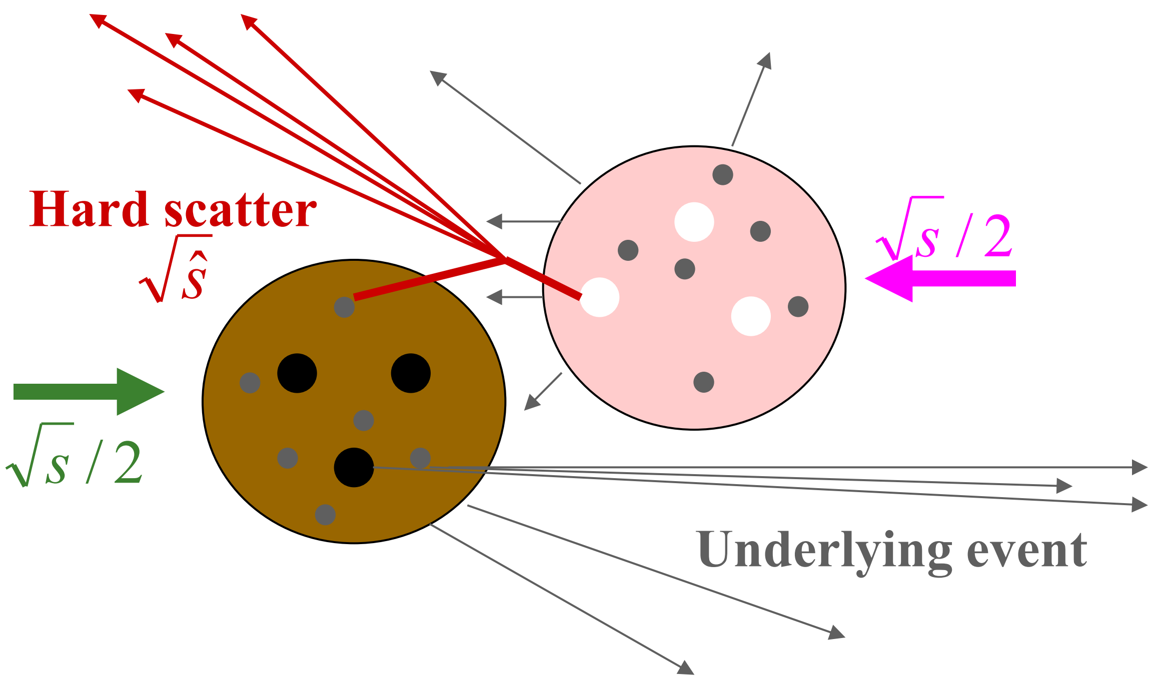


Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

Building the ATLAS detector

Proton-Antiproton Collisions

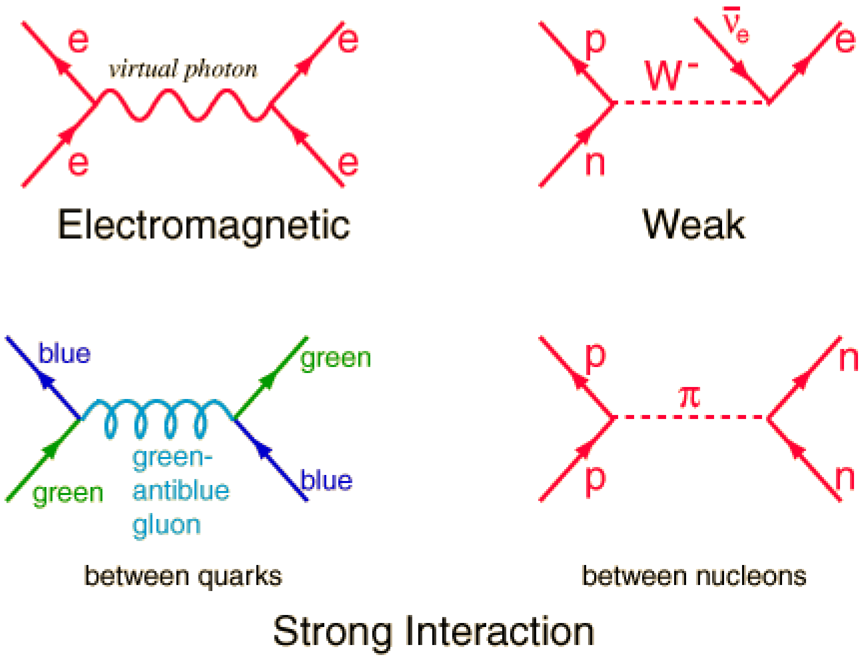
- Protons are composite objects: valence & sea quarks; gluons
- Really *parton-parton* collisions
- Proton – proton collisions similar



- Underlying event:
  - Most lost at low angles
  - Some in detector
- p_z unknown
- Extra detector hits
- Initial partons unknown
- Huge total cross section *(10s of mb)*

1 mb = 10^{-27} cm^2

What is happening at the Feynman level



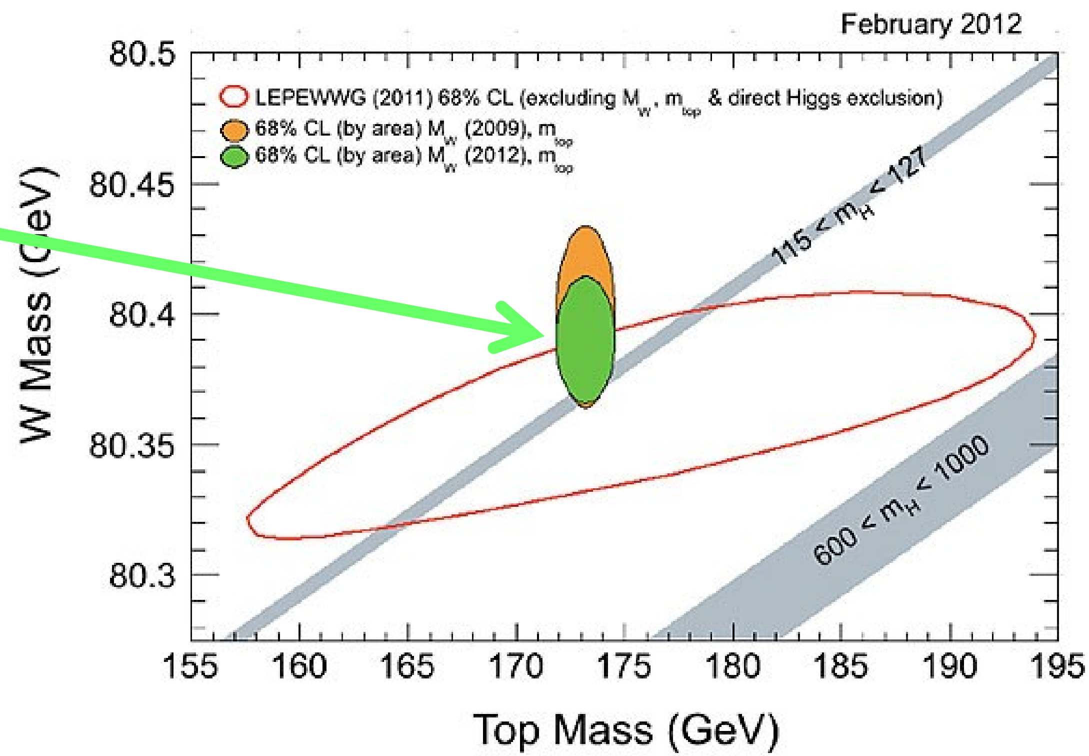
- **Can directly observe outgoing particles**
  - Long-lived (picosecond)
  - Interacts with detector
  - Not confined e.g. not a quark
- **If not:**
  - Reconstruct from decay products
  - Reconstruct from missing transverse momentum
  - Produces jets

Why look for the top quark?

- The top quark and W boson are very heavy
- Their mass is influenced by the Higgs mass
- If we measure both we can “predict” Higgs mass

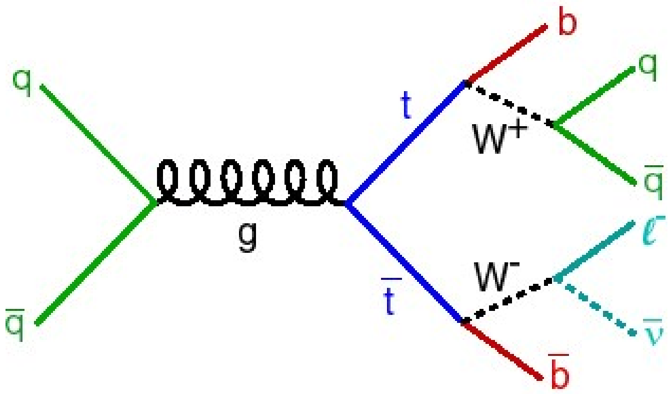
Top mass : 172.6 ± 1.4 GeV

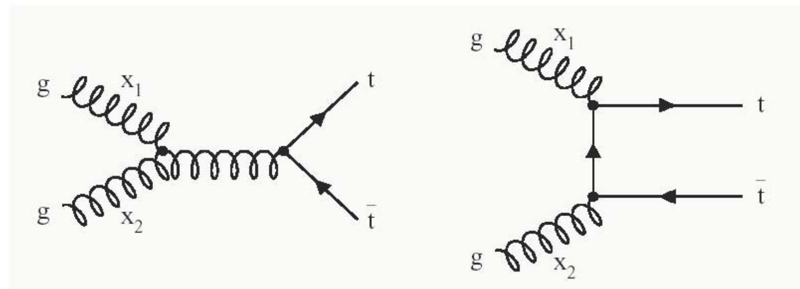
W mass : 80.385 ± 0.0021 GeV



Top Pair Production and decay

- Tevatron
- LHC

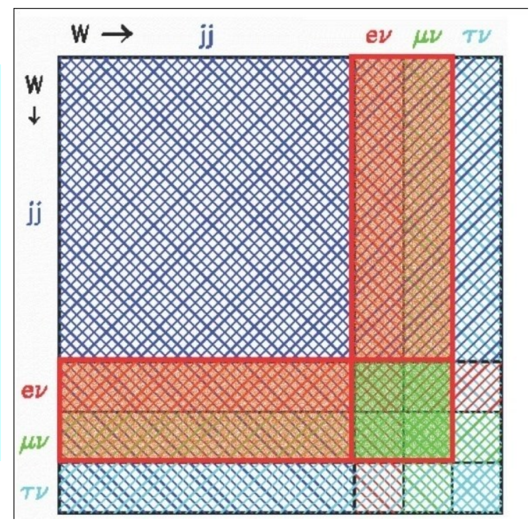




$$t \to W^+ b \quad (100\%)$$
$$W^+ \to q\bar{q} \quad (70\%)$$
$$W^+ \to l^+ \nu \quad (10\% \text{ per lepton})$$

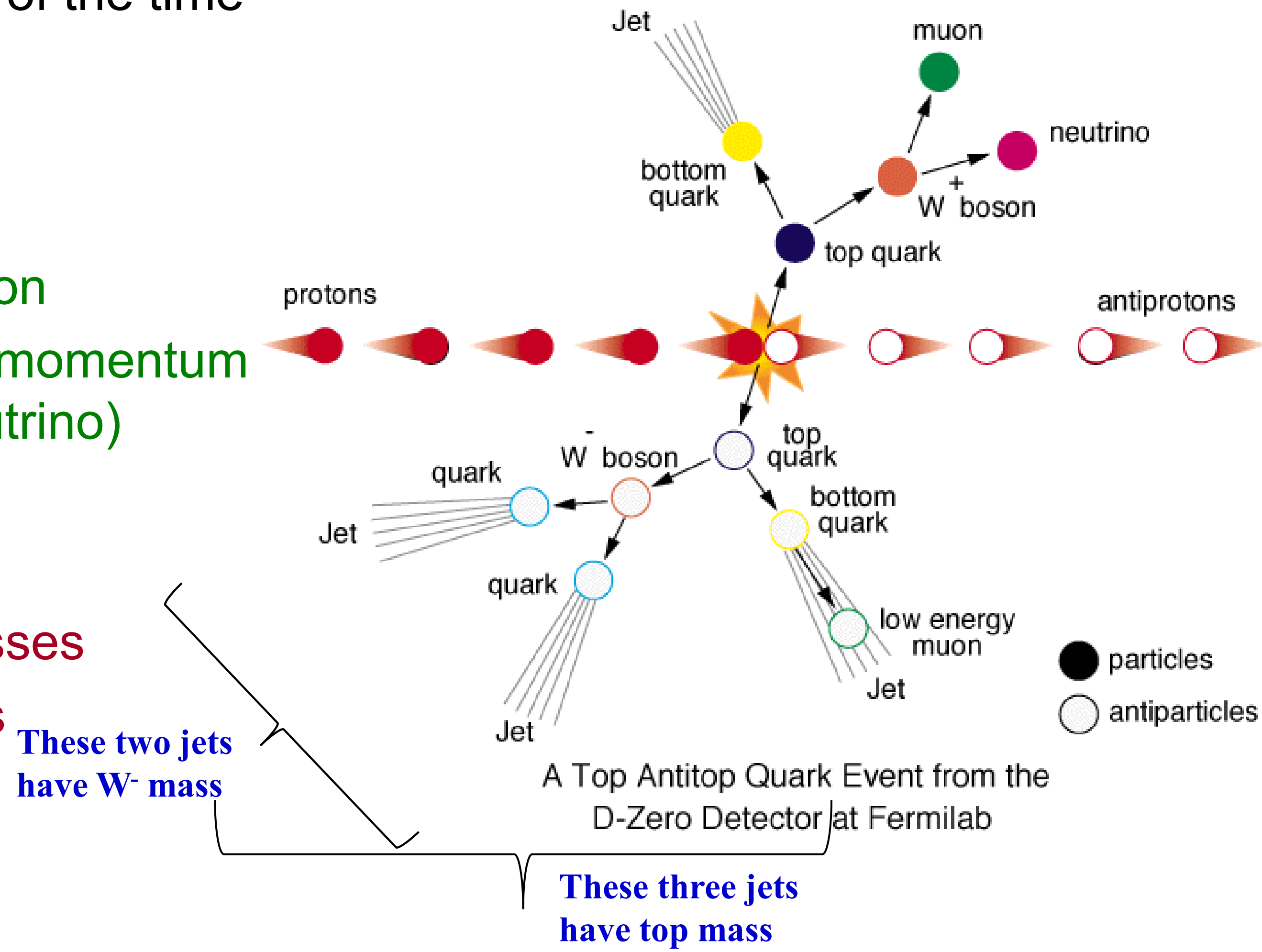
Semi-leptonic ($l^+\upsilon$) channel is best

- $l^+$is an electron or muon
- $l^+$is easy to identify
- *O*nly one neutrino
- Each b quark decays into a jet
- Each q quark decay into another 2 jets



Best decay channel to look for

- Semi-leptonic mode (lepton+neutrino)
- Electron or muon 20% of the time
- Signature:
  - 2 light quark jets
  - 2 bottom jets
  - One electron or muon
  - Missing transverse momentum (because of the neutrino)
- Extras:
  - Underlying event
  - Higher order processes
  - Multiple interactions



A Top Antitop Quark Event from the D-Zero Detector at Fermilab

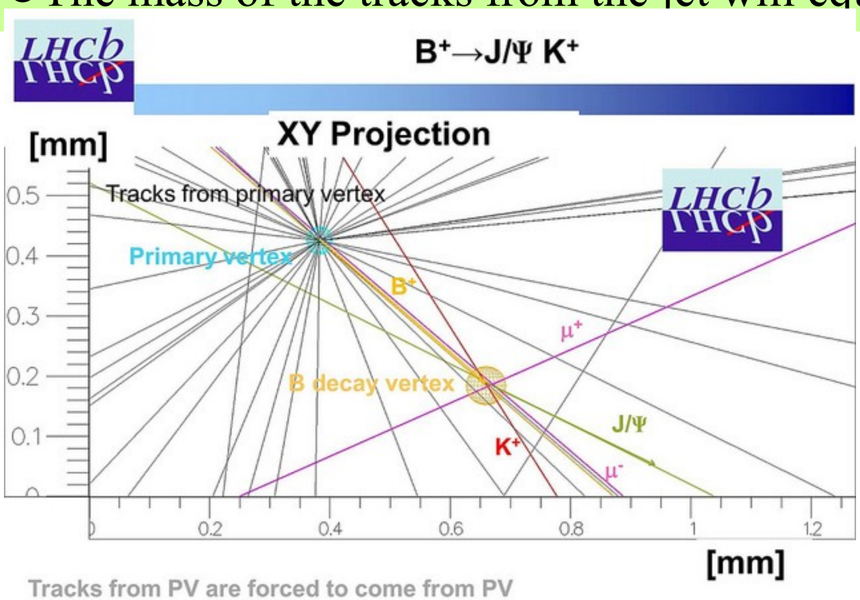
What is the difference between a b and q

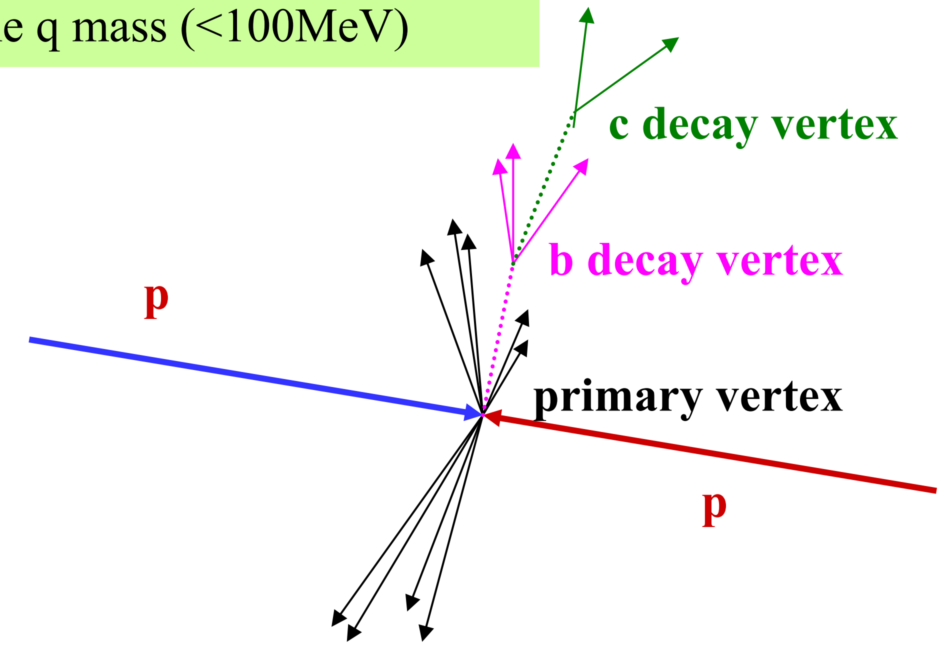
b quark

- It will travel a short distance (mm) before decaying into a jet
- The mass of the tracks from the jet will equal the b quark mass (~5GeV)

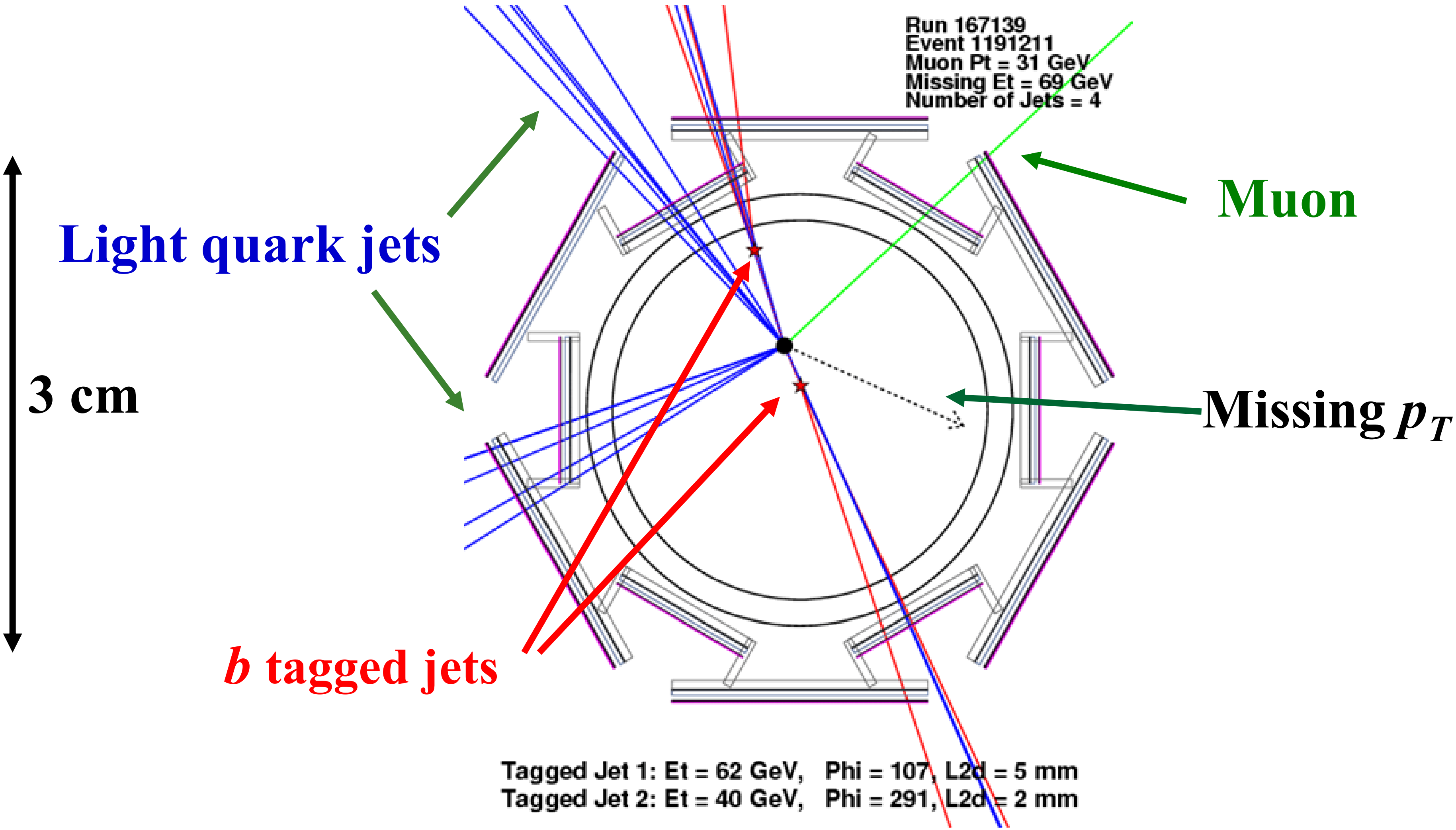
q quark

- It will decay immediately into a jet
- The mass of the tracks from the jet will equal the q mass (<100MeV)



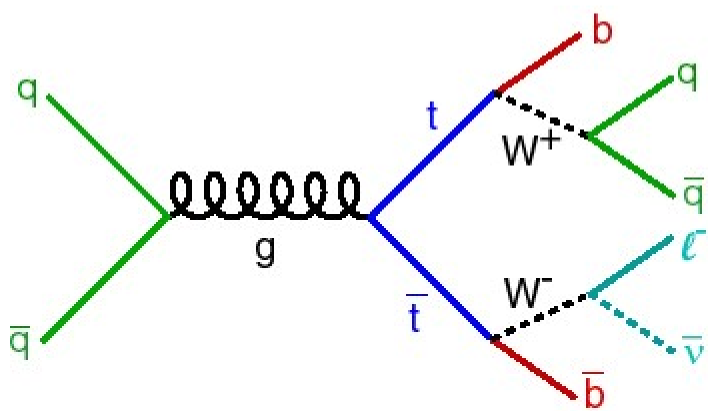


Top Event


Run 167139
Event 1191211
Muon Pt = 31 GeV
Missing Et = 69 GeV
Number of Jets = 4
Light quark jets
Muon
3 cm
Missing p_T
b tagged jets
Tagged Jet 1: Et = 62 GeV, Phi = 107, L2d = 5 mm
Tagged Jet 2: Et = 40 GeV, Phi = 291, L2d = 2 mm

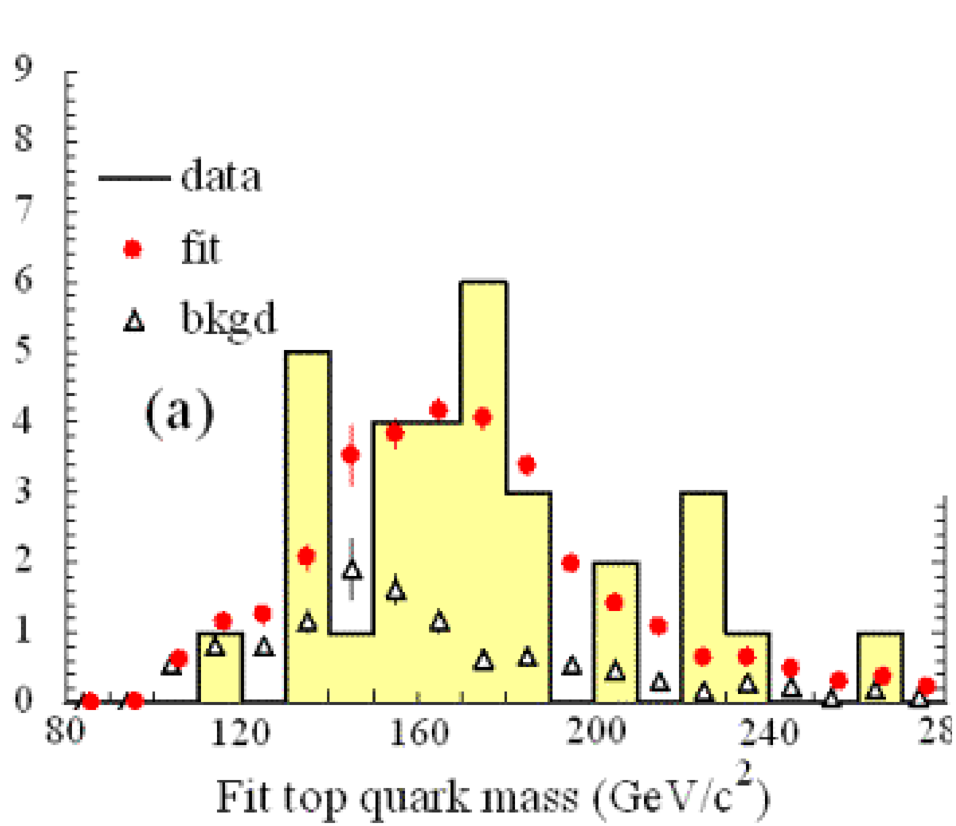
The Top mass

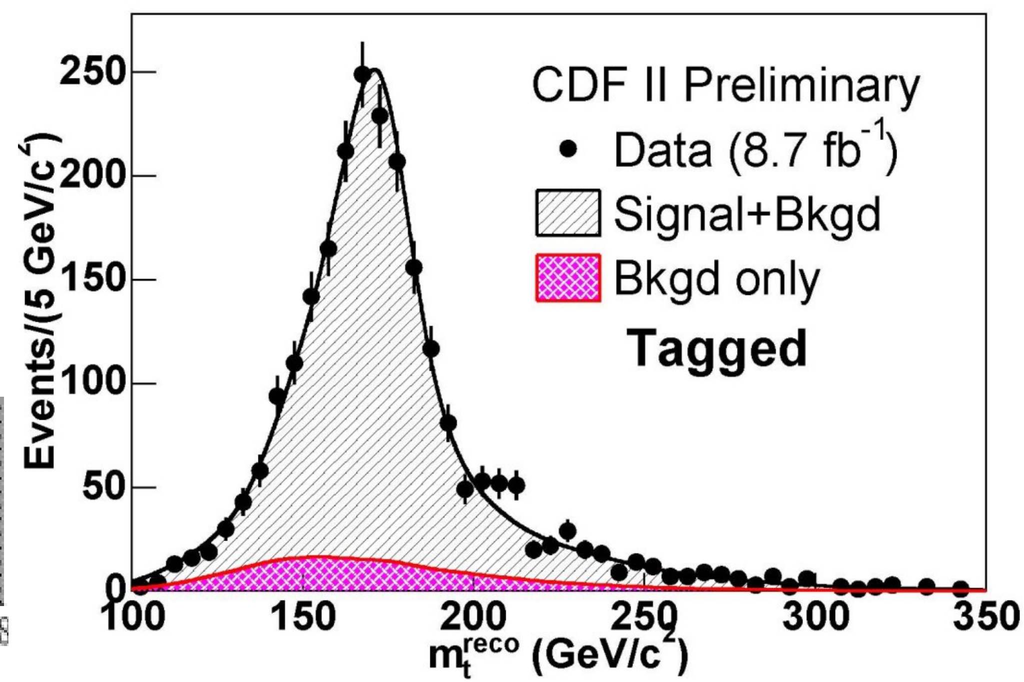
- How do we find the top mass



- Add together the q and q jets to form W^+ mass
- If this is okay, add the b quark jet to get the top mass

An example of the top mass





~1999 **2011**

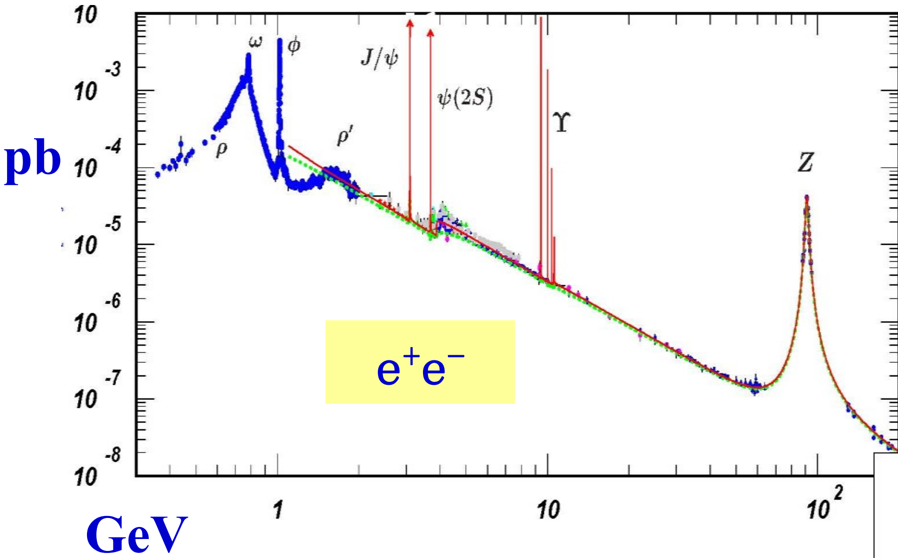
Next Time...

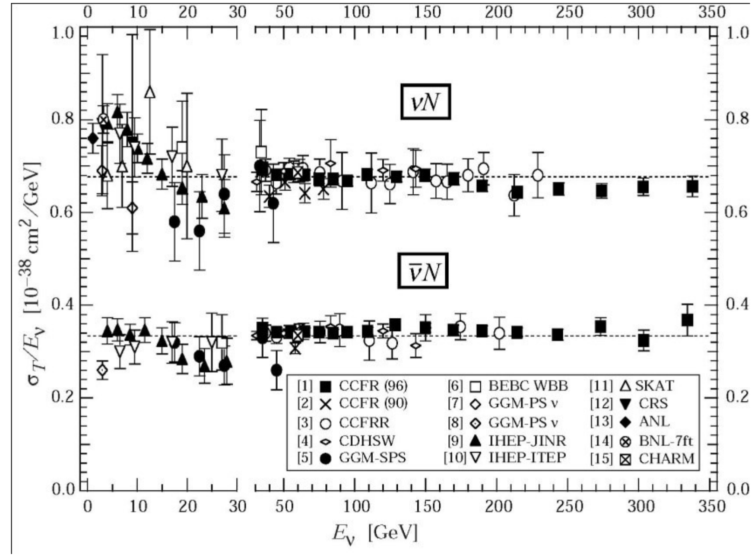
Finding the Higgs and writing your first paper

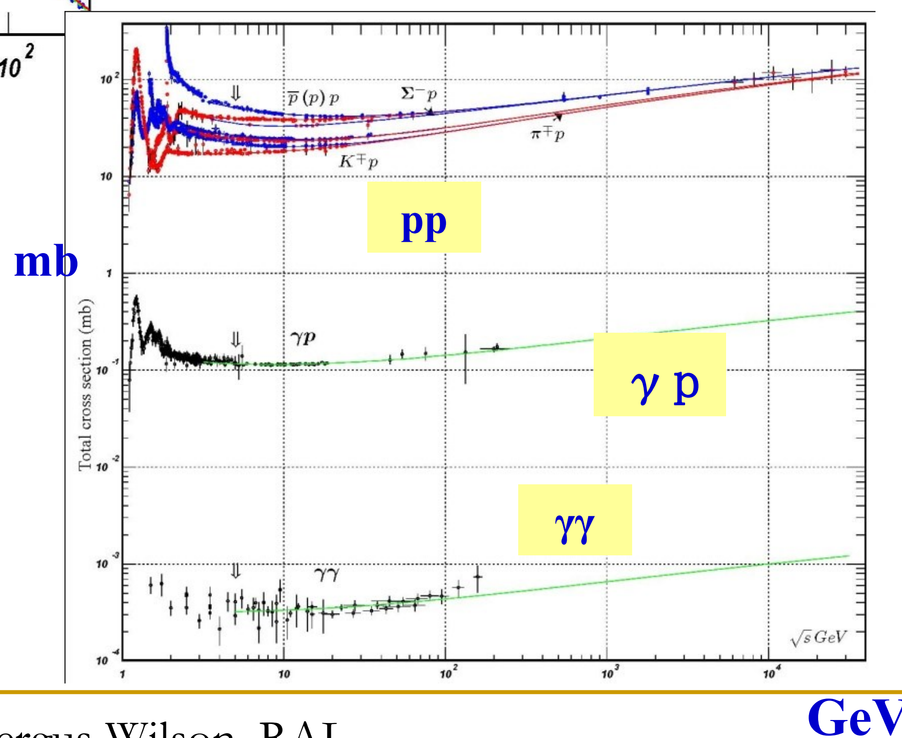
Cross-Sections

1 mb = 10^{-27} cm^2

1 fb = 10^{-39} cm^2

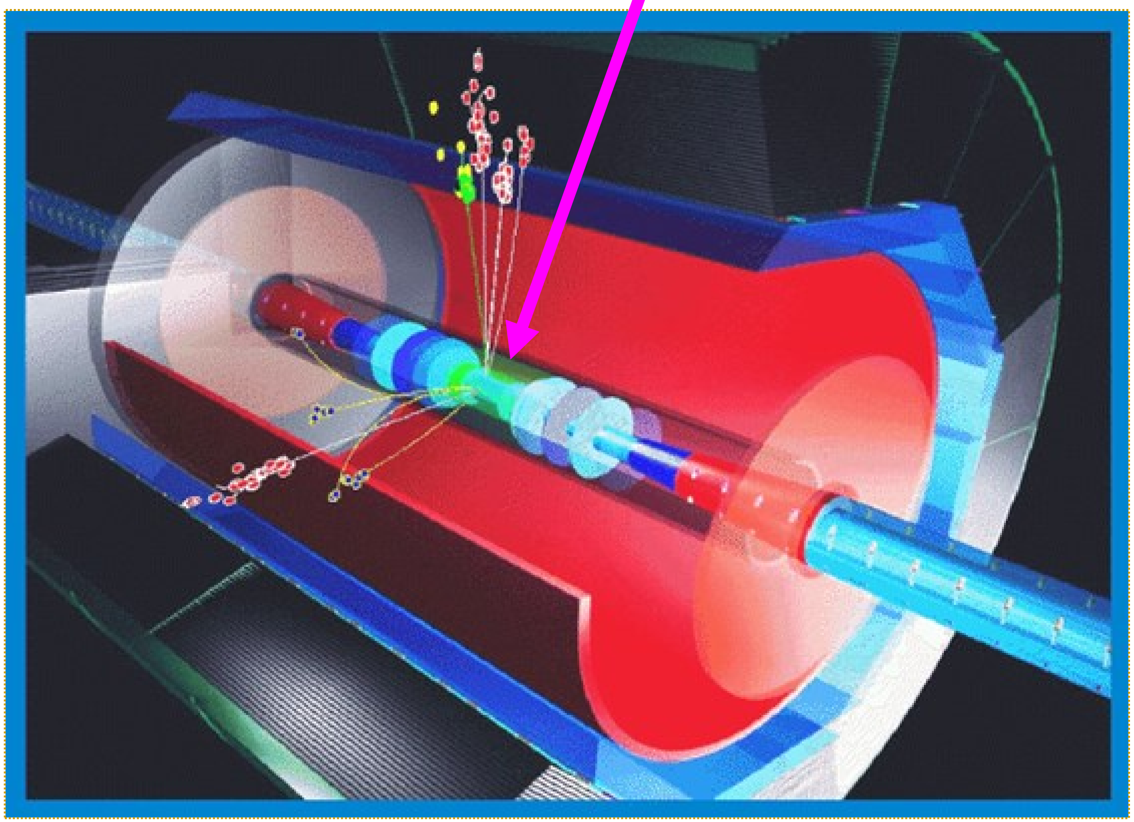


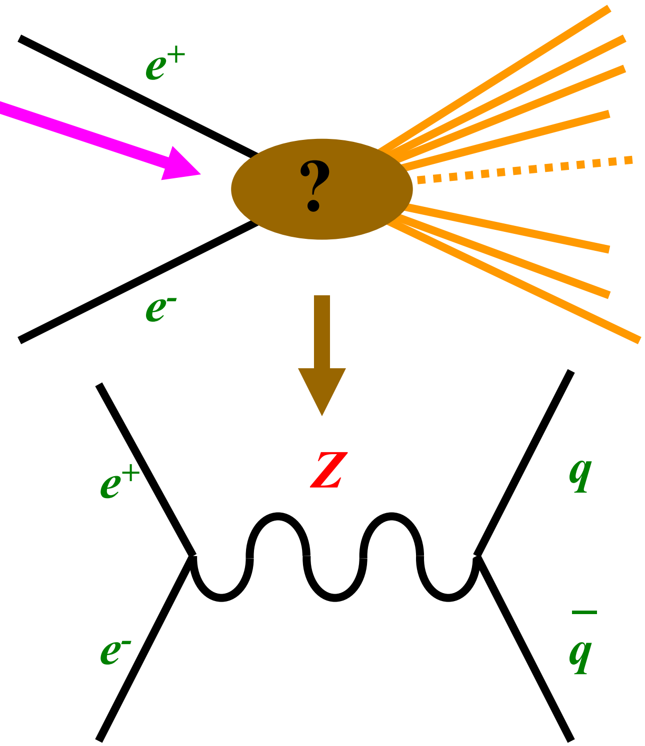




Reconstructing Collisions

What happened here?





or something more exotic.....

- **extract maximum information from outgoing particles**

Standard Model Particles