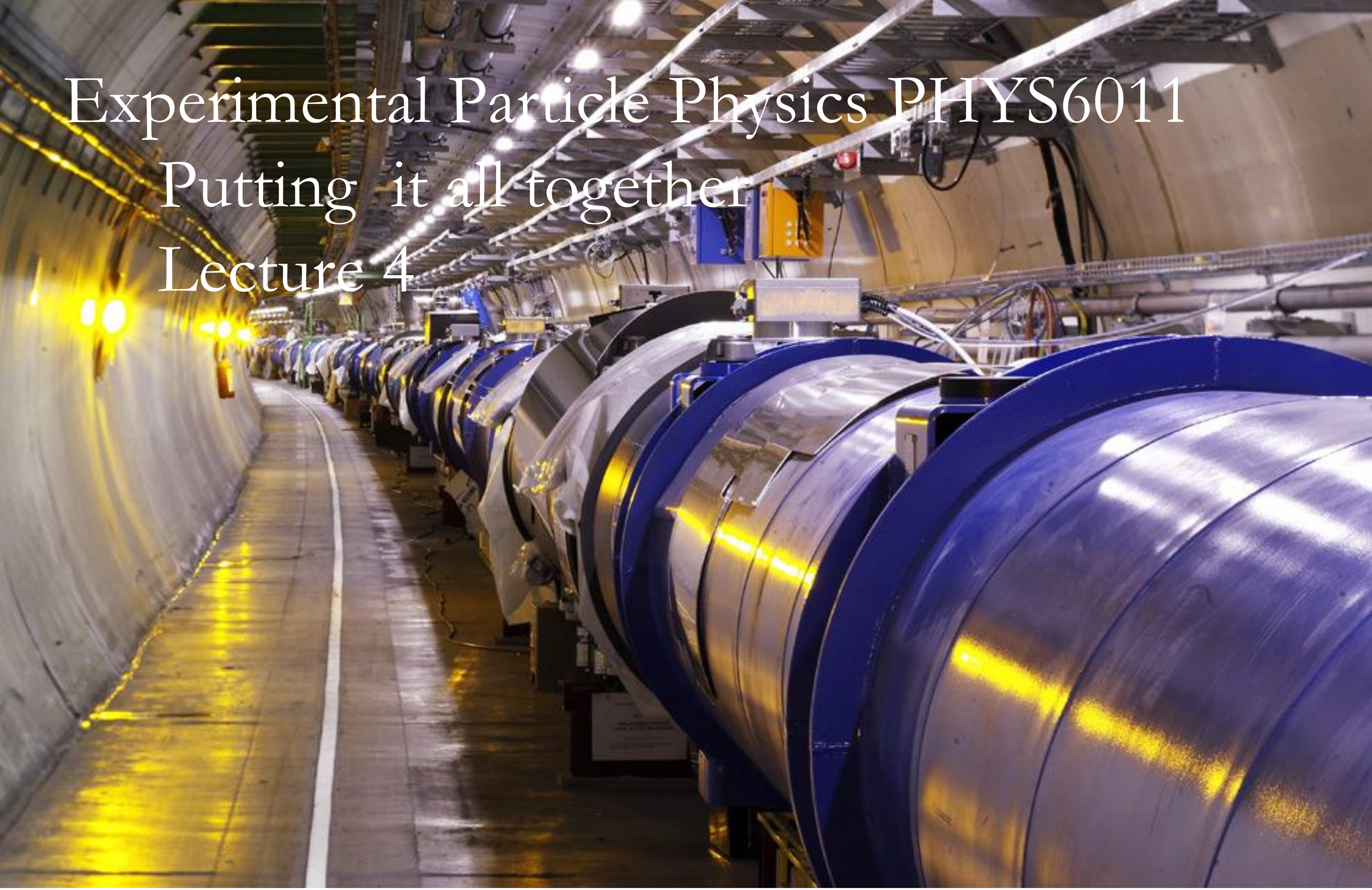
Experimental Particle Physics PHYS6011

Putting it all together

Lecture 4

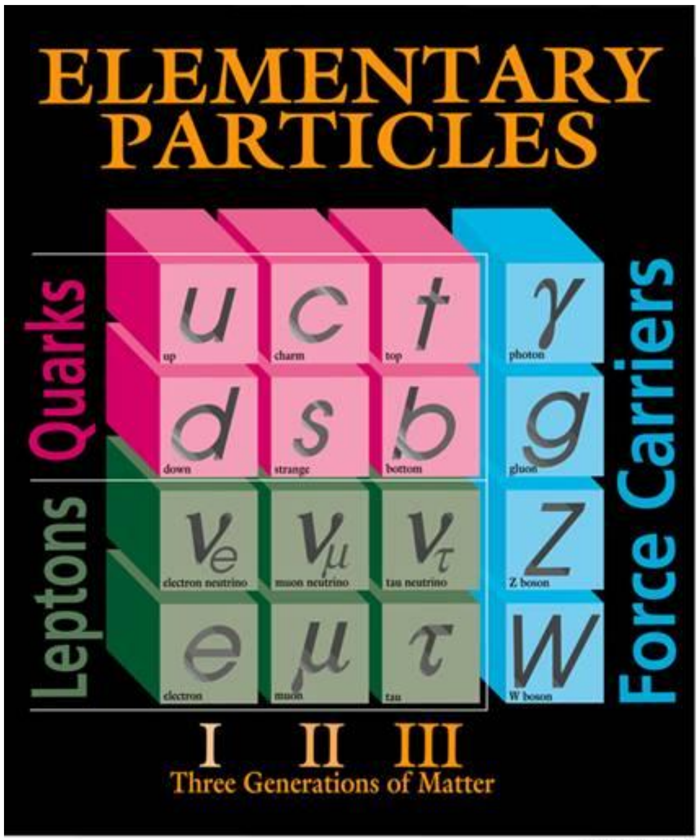


Practical questions

- 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:



Fermilab 95-759

But in reality:

Quark content

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

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

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

Mass Mass $m = 139.57018 \pm 0.00035$ MeV (S = 1.2)

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

$\pi^{\pm} \rightarrow \ell^{\pm}\nu\gamma$ 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]	$(2.00 \pm0.25) \times 10^{-4}$		30
$e^+\nu_e$		[b]	$(1.230 \pm0.004) \times 10^{-4}$		70
$e^+\nu_e\gamma$		[c]	$(1.61 \pm0.23) \times 10^{-7}$		70
$e^+\nu_e\pi^0$			$(1.036 \pm0.006) \times 10^{-8}$		4
$e^+\nu_e e^+ e^-$			$(3.2 \pm0.5) \times 10^{-9}$		70
$e^+\nu_e\nu\overline{\nu}$			$< 5 \times 10^{-6}$	90%	70
Lepton Family number (*LF*) or Lepton number (*L*) violating modes					
$\mu^+\overline{\nu}_e$	*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

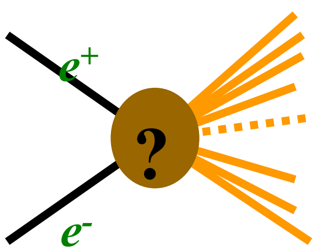
Particle Properties

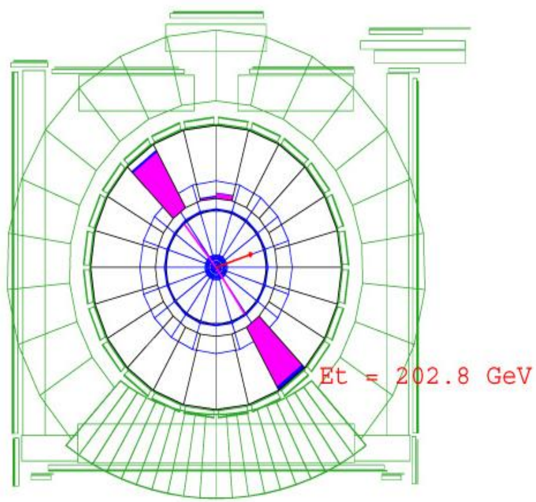
- Mass
  - Measure momentum and energy: $E^2 = p^2 + m^2$
- Mass width → Lifetime
  - Measure momentum and energy or:
  - How many particles exist after t seconds
- Branching Fraction
  - Reconstruct the decays and see how many there are.
- Charge
  - Direction in a magnetic field
- Spin
  - Angular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

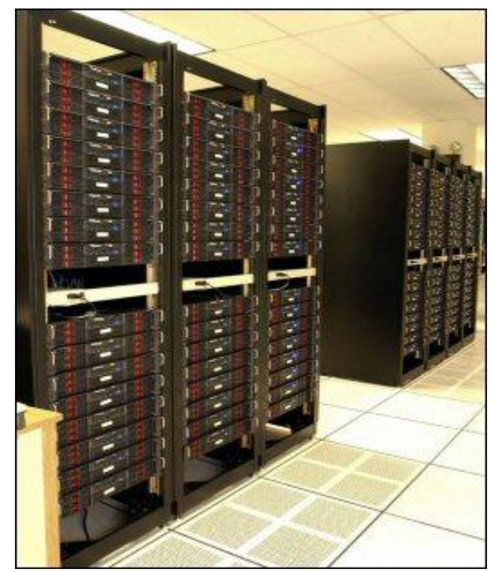
Data Flow

Low Signal: High Background → **High Signal: Low Background**

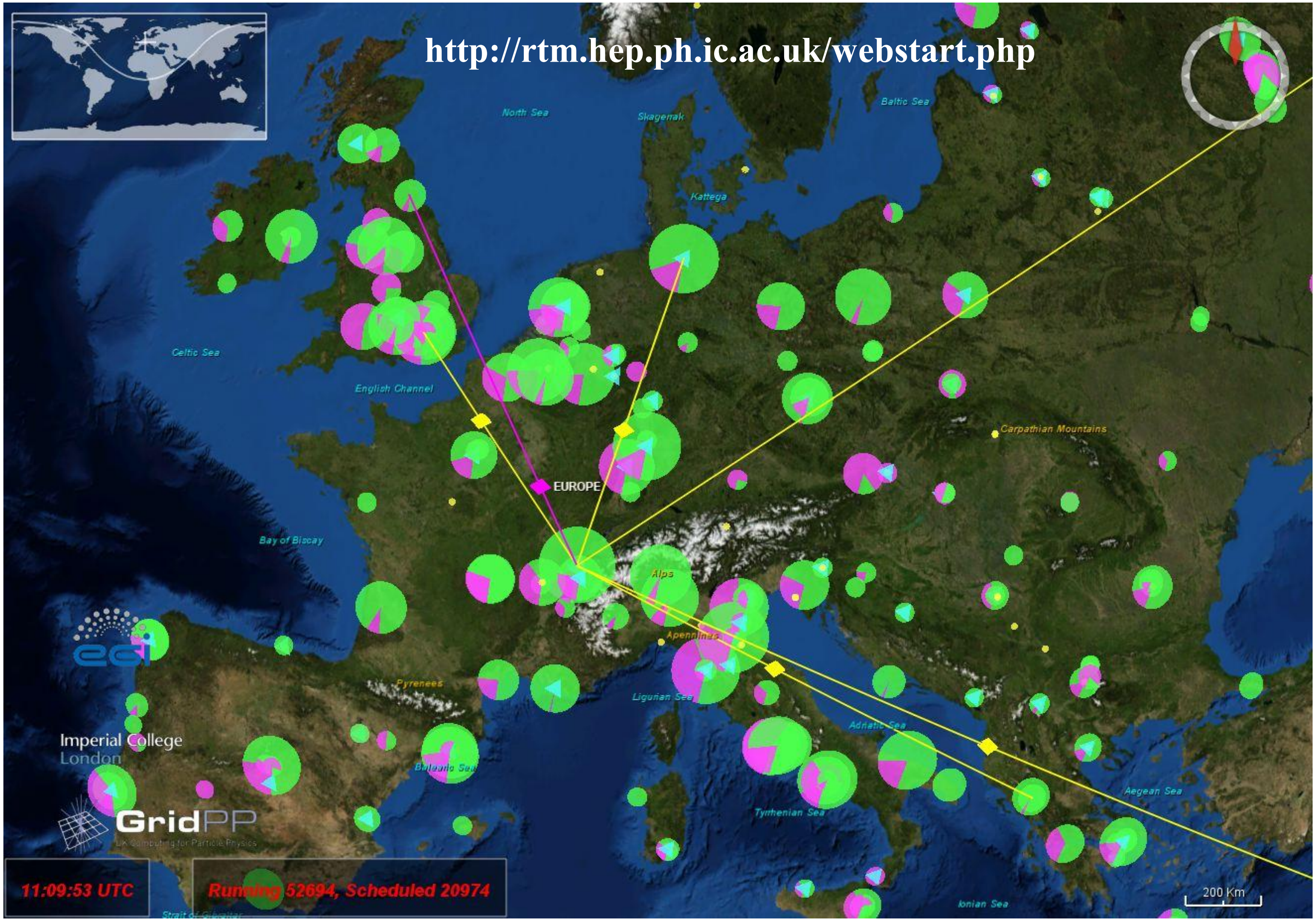
Collision → Detector → Trigger and DAQ → Storage → Event selection → Analysis



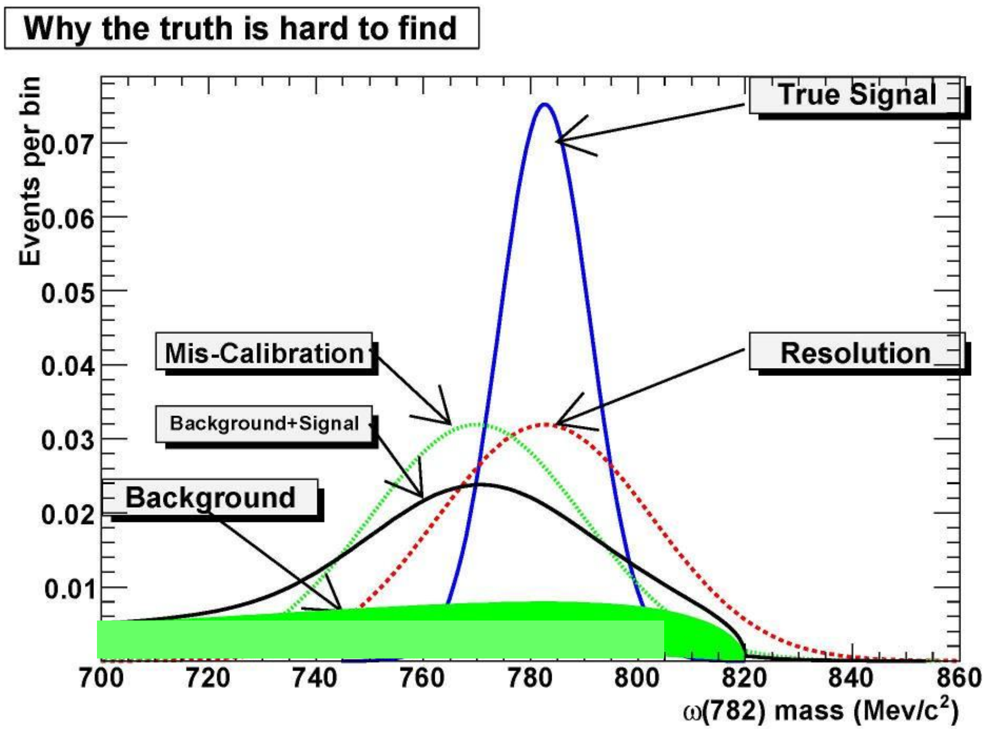




Where is all the LHC data going?



Elements of Analysis



Not only *Data* but...

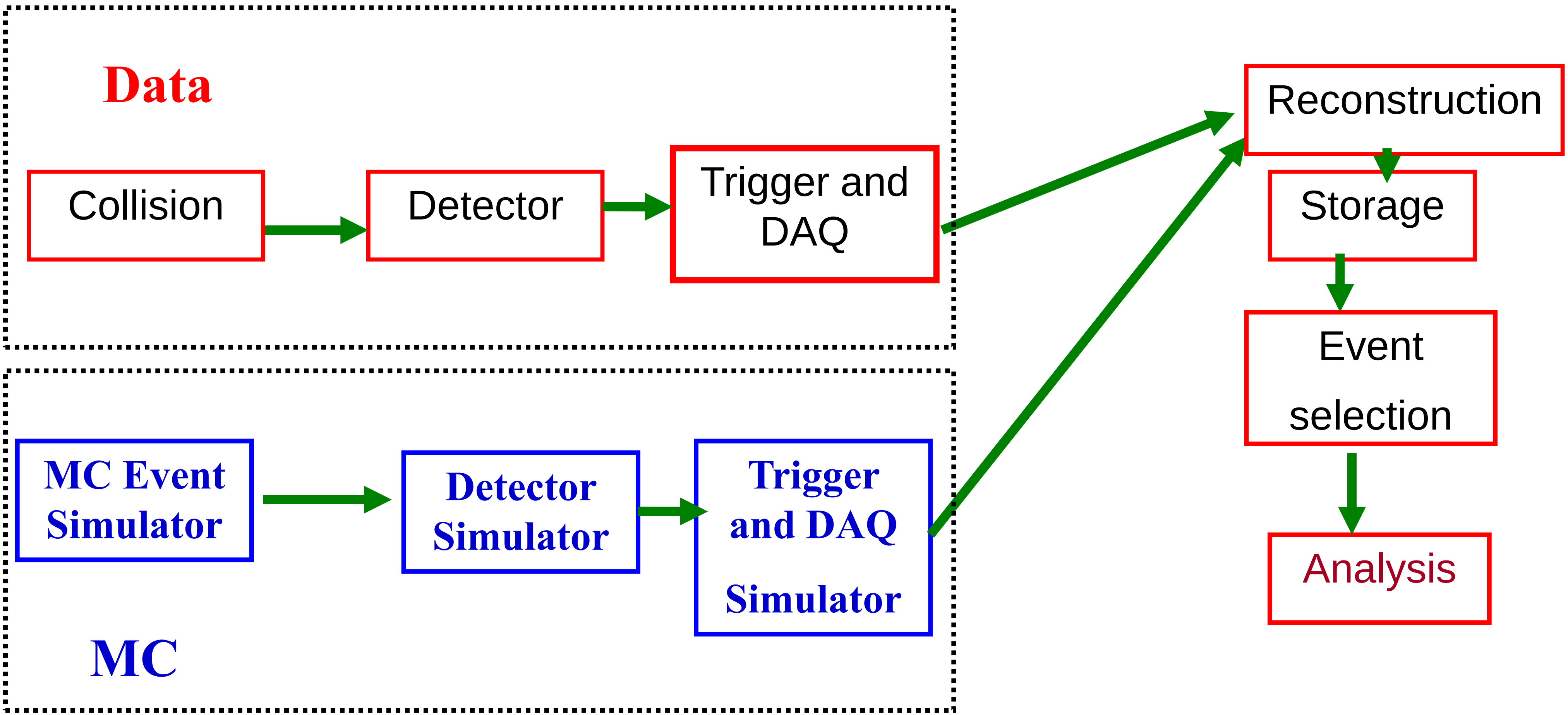
- Detector response to signal
- Background estimates
- Errors
  - statistical
  - systematic
- How to solve?
  - Try and evaluate from data
  - Sometimes need more...
    - Monte Carlo

Monte Carlo

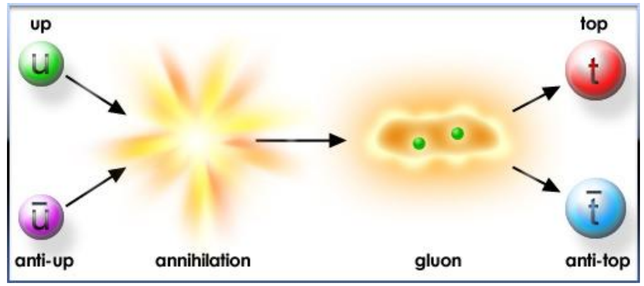
1. Generate artificial data
2. Simulate detector response
3. Analyse simulated data as if it were real
   - Response to known input can be calculated
   - *Also used in detector design*

- Computer intensive
- Must be carefully tuned and checked

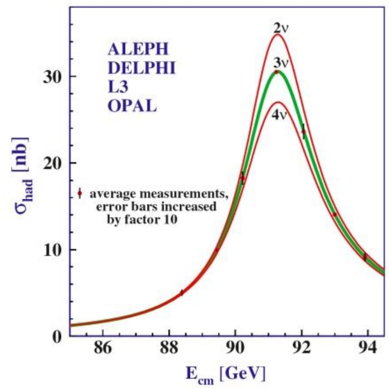
Data and Monte Carlo



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.

A Collider Experiment

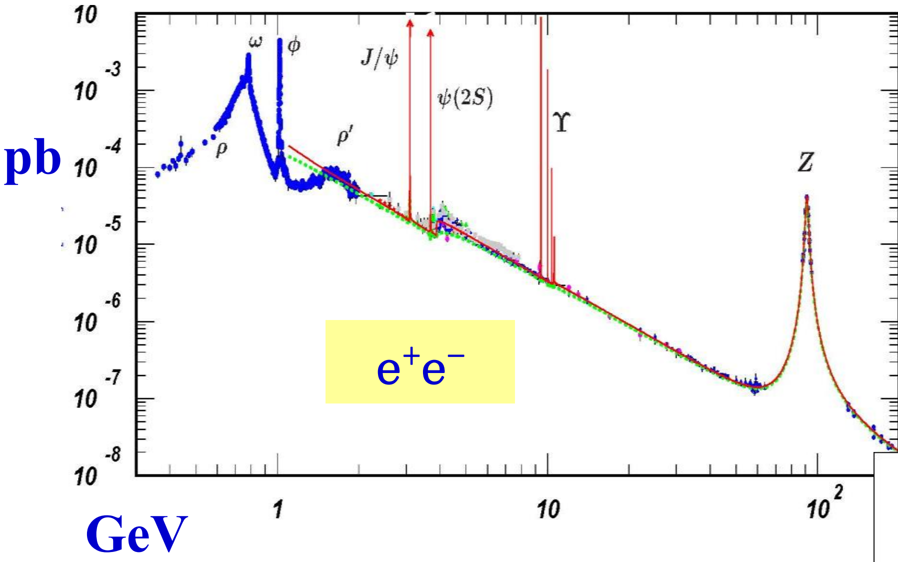
- So far:
  - Accelerators and colliders
  - Particle interactions
  - Types of detectors

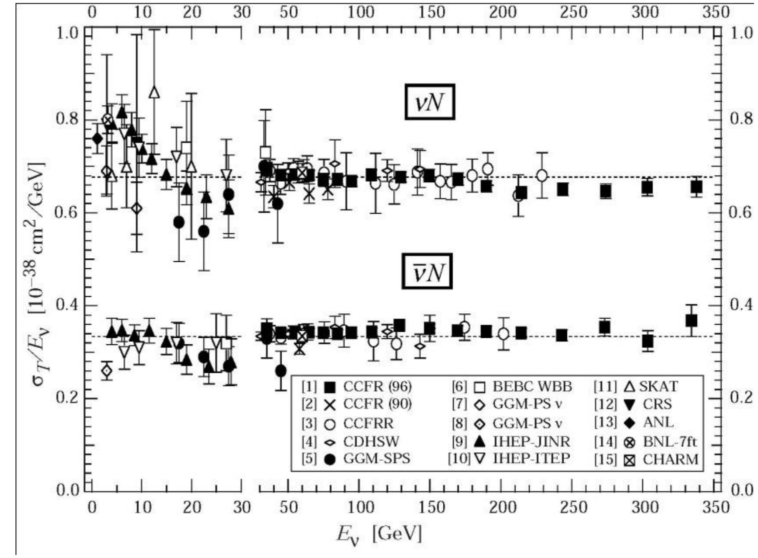
- *Combine them to do physics…*
- Example: CDF at the Tevatron
  1. Proton-antiproton collisions
  2. Fermilab and the Tevatron
  3. CDF and DØ
  4. Identifying particles
  5. Identifying physics processes
     - Top production
     - Higgs Production

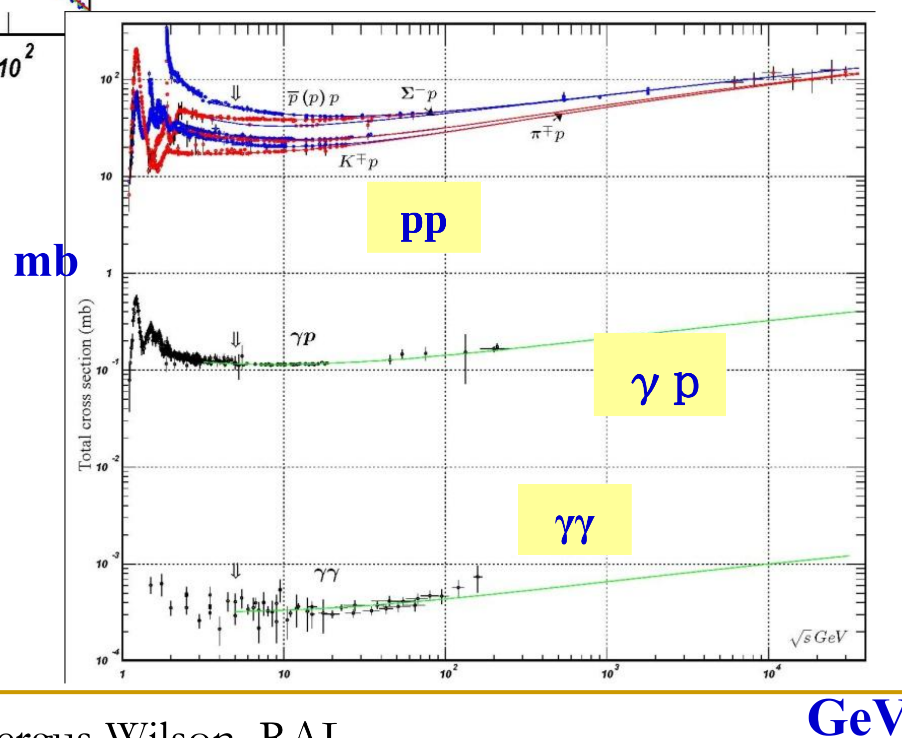
Cross-Sections

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

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

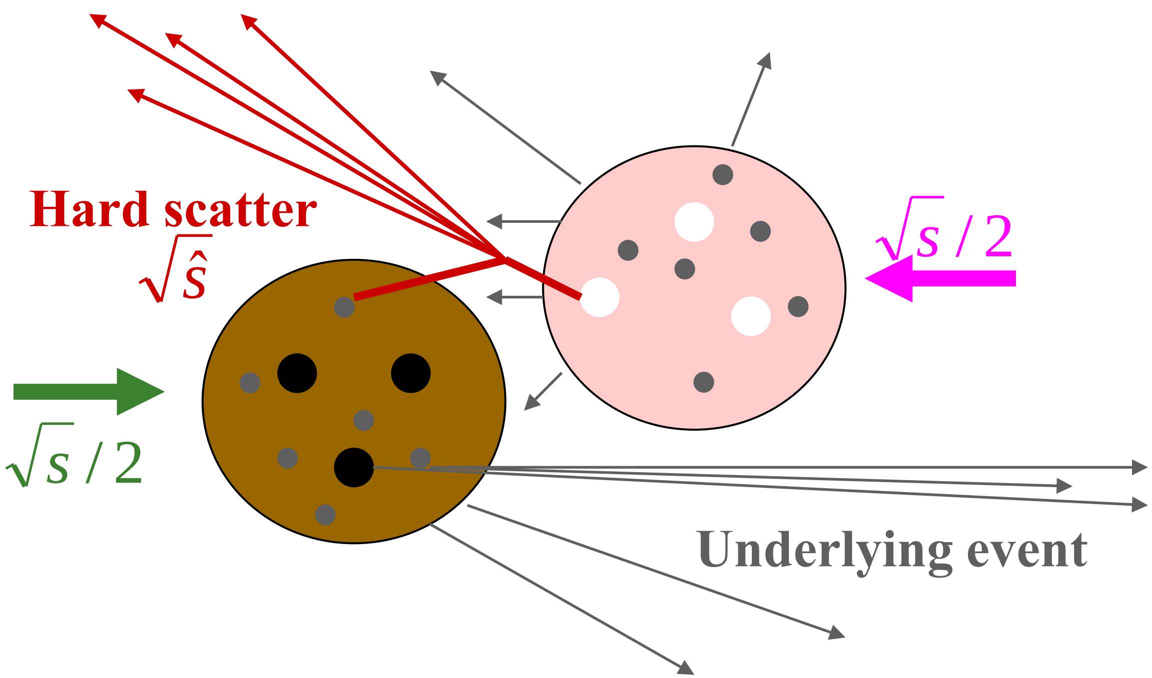






Proton-Antiproton Collisions

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

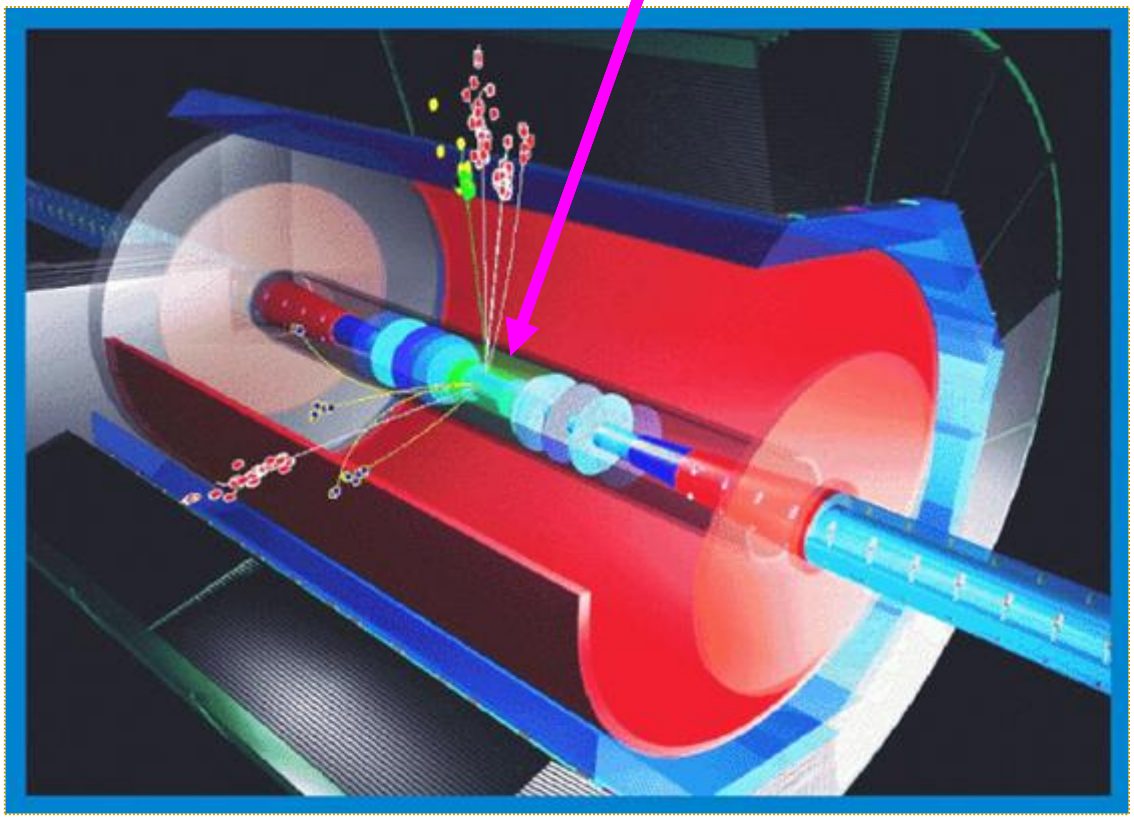


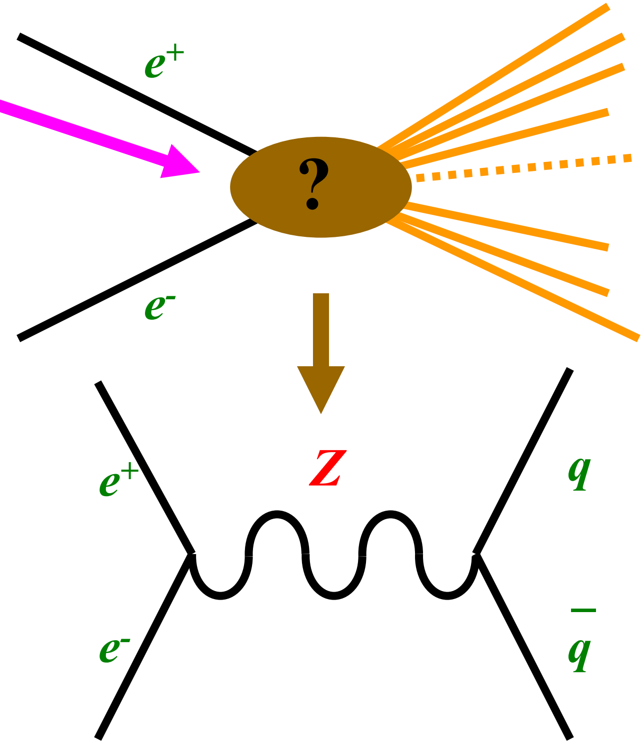
- Underlying event:
  - Most lost at low angles
  - Some in detector
- p_z unknown
- Extra detector hits
- Initial partons unknown
- Huge total cross section *(10s of mb)*

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

Reconstructing Collisions

What happened here?





or something more exotic.....

- **extract maximum information from outgoing particles**

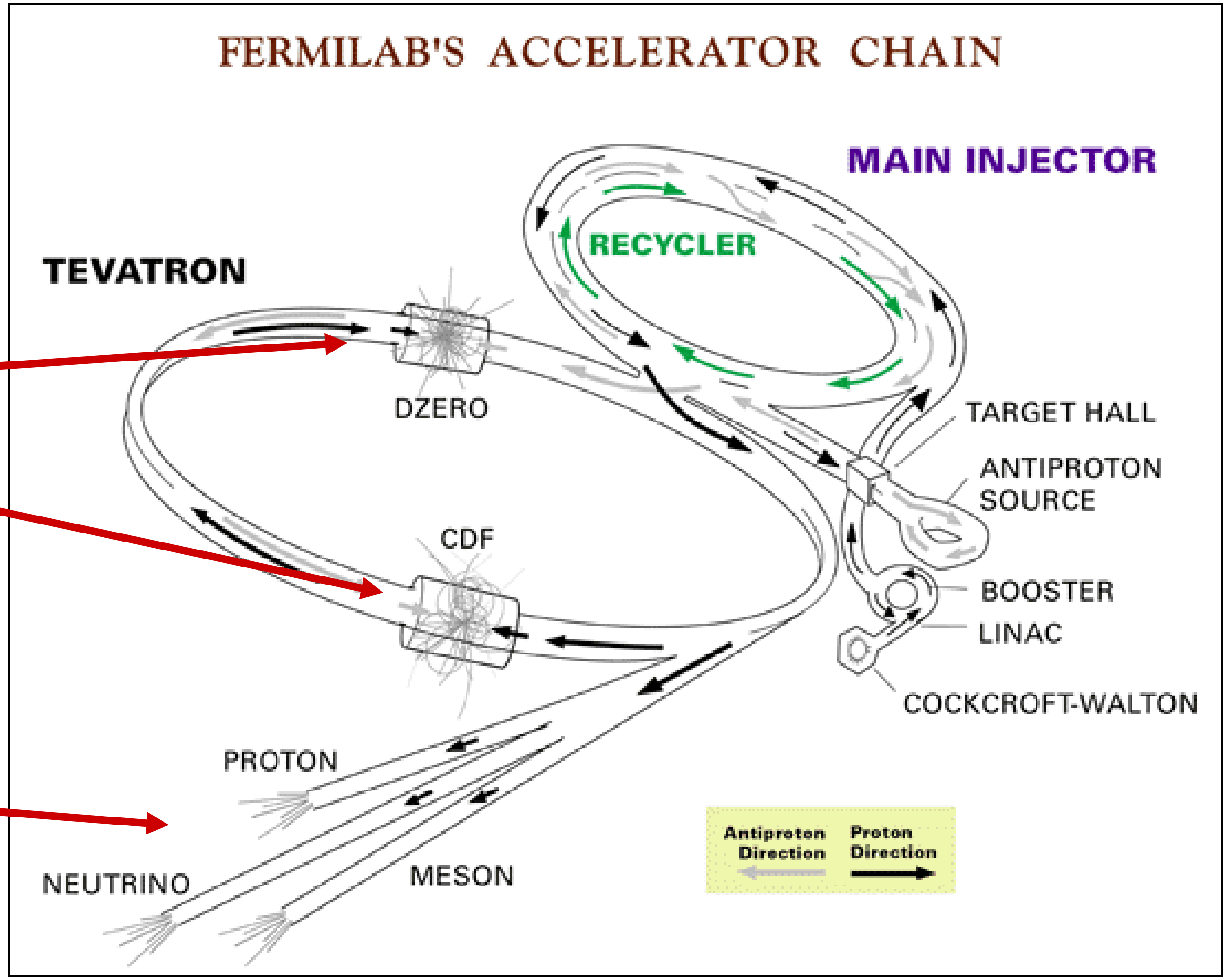
Fermilab

- 30 miles west of Chicago
- 10 square miles
- Started operating in 1972
- Major discoveries
  - 1977 Bottom quark
  - 1995 Top quark
  - 1999 Direct CP Violation
  - 2000 Tau Neutrino
  - 2006 B_s Oscillation
  - 2009 Higgs Exclusion Limits
  - 2011 April Higgs found?

Fermilab Accelerators

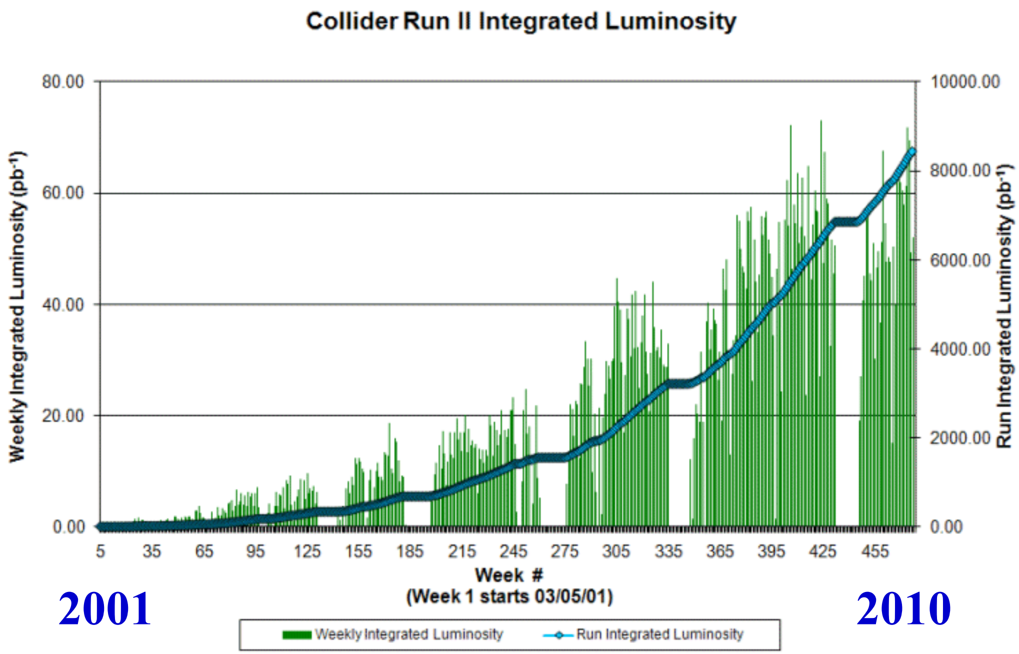
Collider Experiments

Fixed target beams



The Tevatron Run II

- Upgraded in 2001
- $\sqrt{s}$ = 1.96 TeV
- proton-antiproton collisions

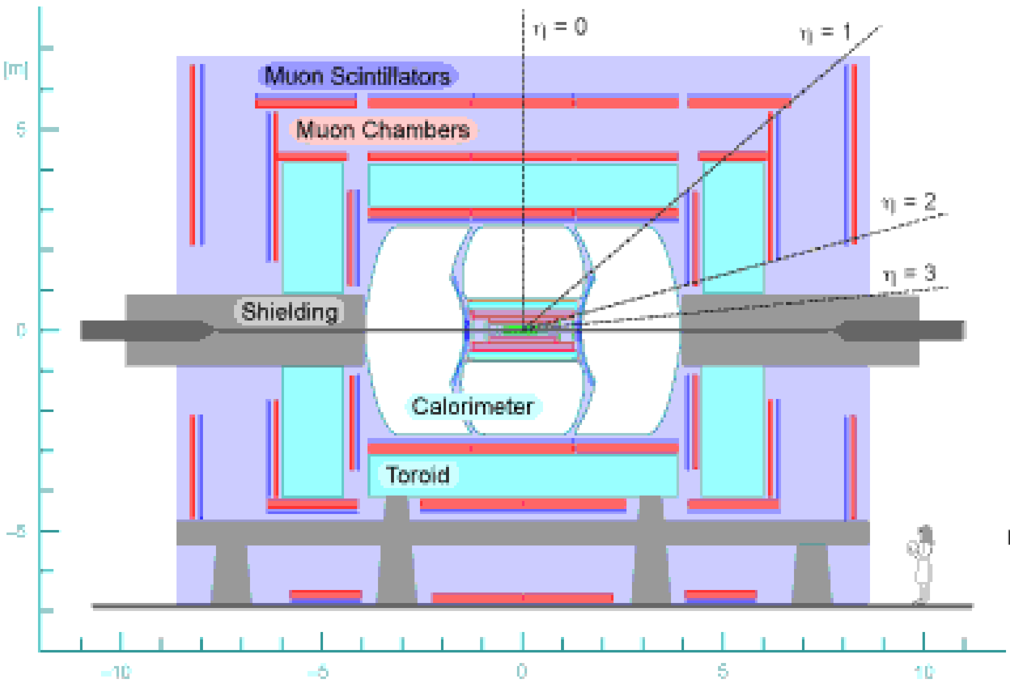


2001 **2010**

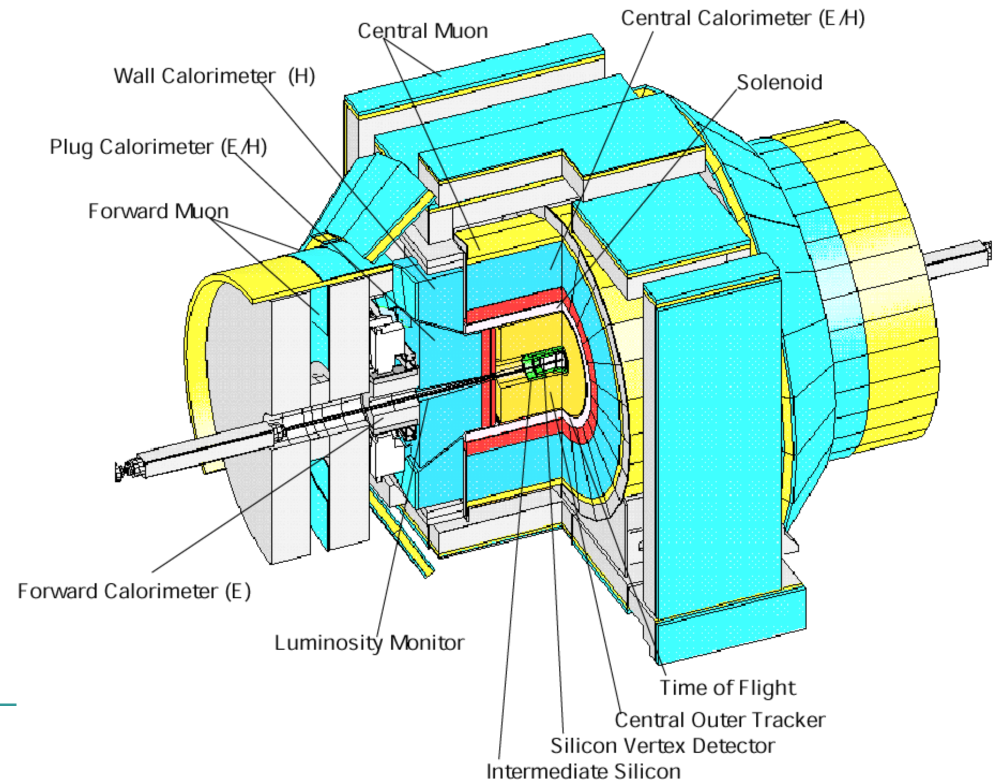
- 36 bunches
- 396 ns bunch crossing
- L ~ 10^{32} $cm^{-2}s^{-1}$
  - *3 interactions per crossing*

The Experiments

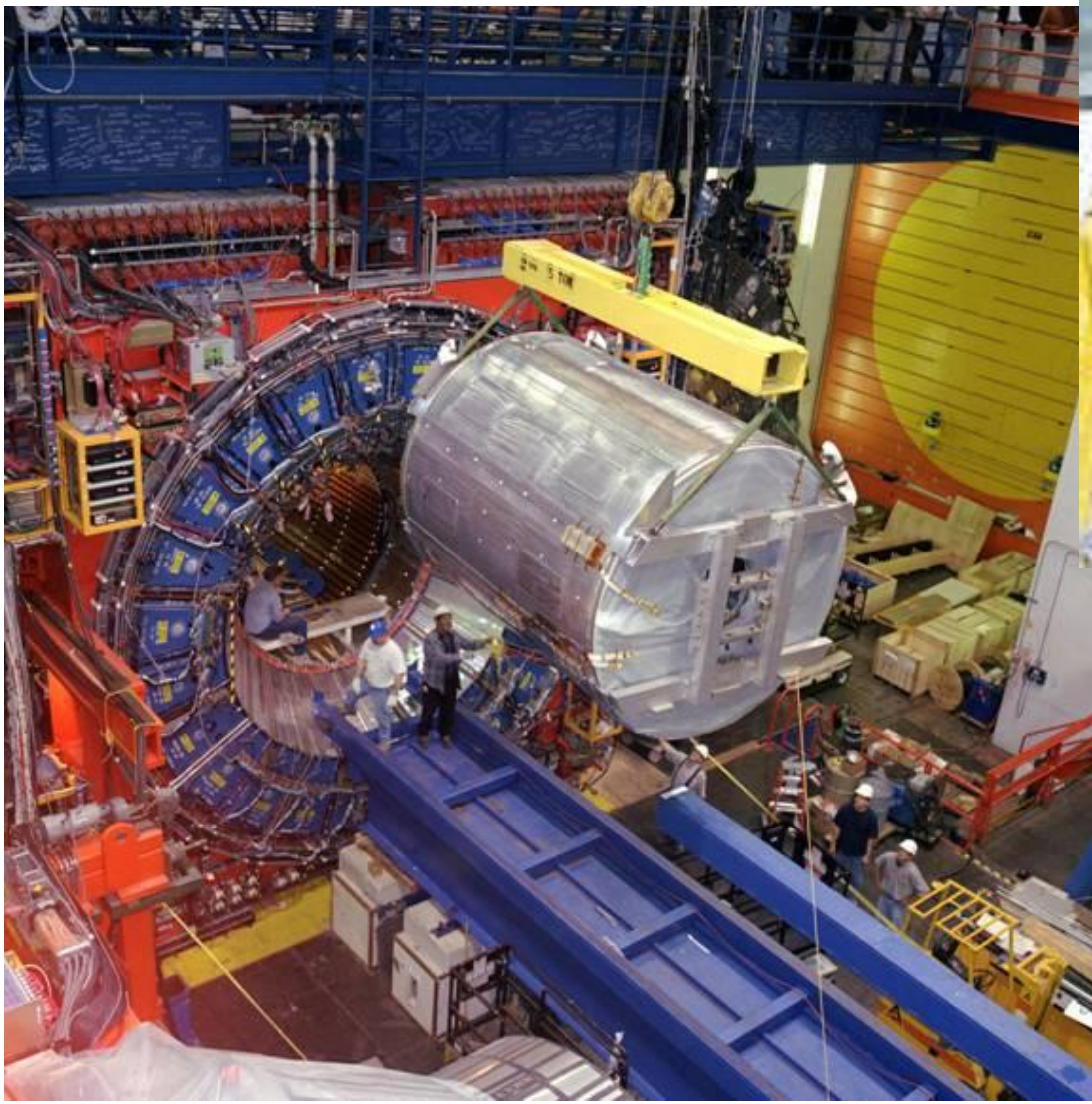
DØ - optimised for calorimetry



CDF - optimised for tracking

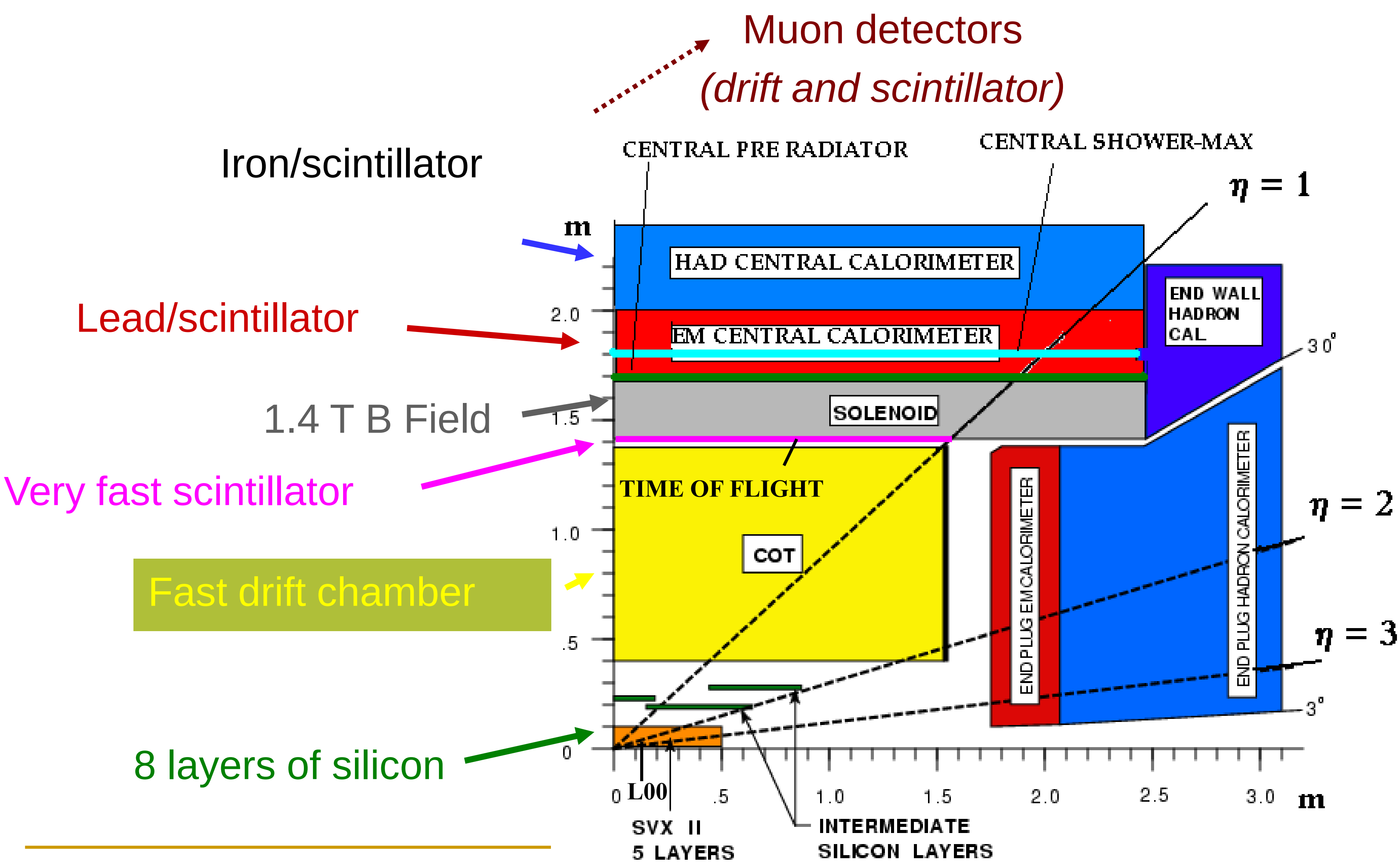


CDF



- 2001Upgrade
  - Higher luminosity
  - Newer technology

CDF Components



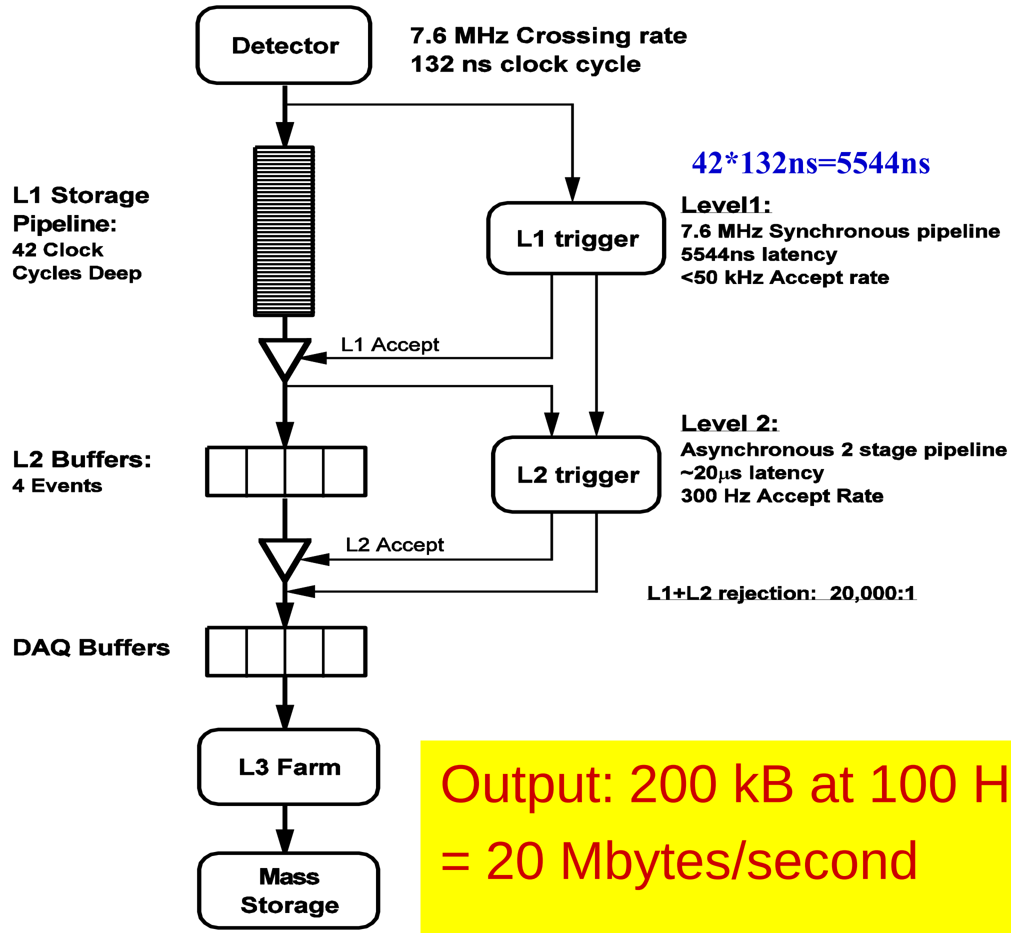
Trigger and DAQ

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**

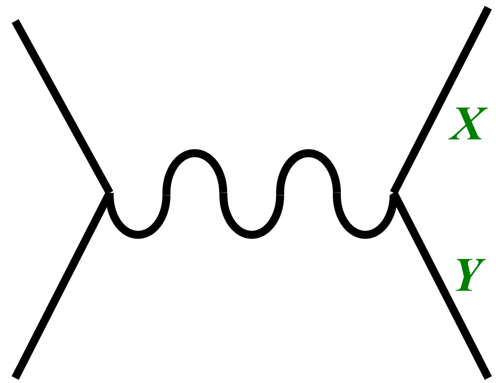
Output: 200 kB at 100 Hz

= 20 Mbytes/second

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

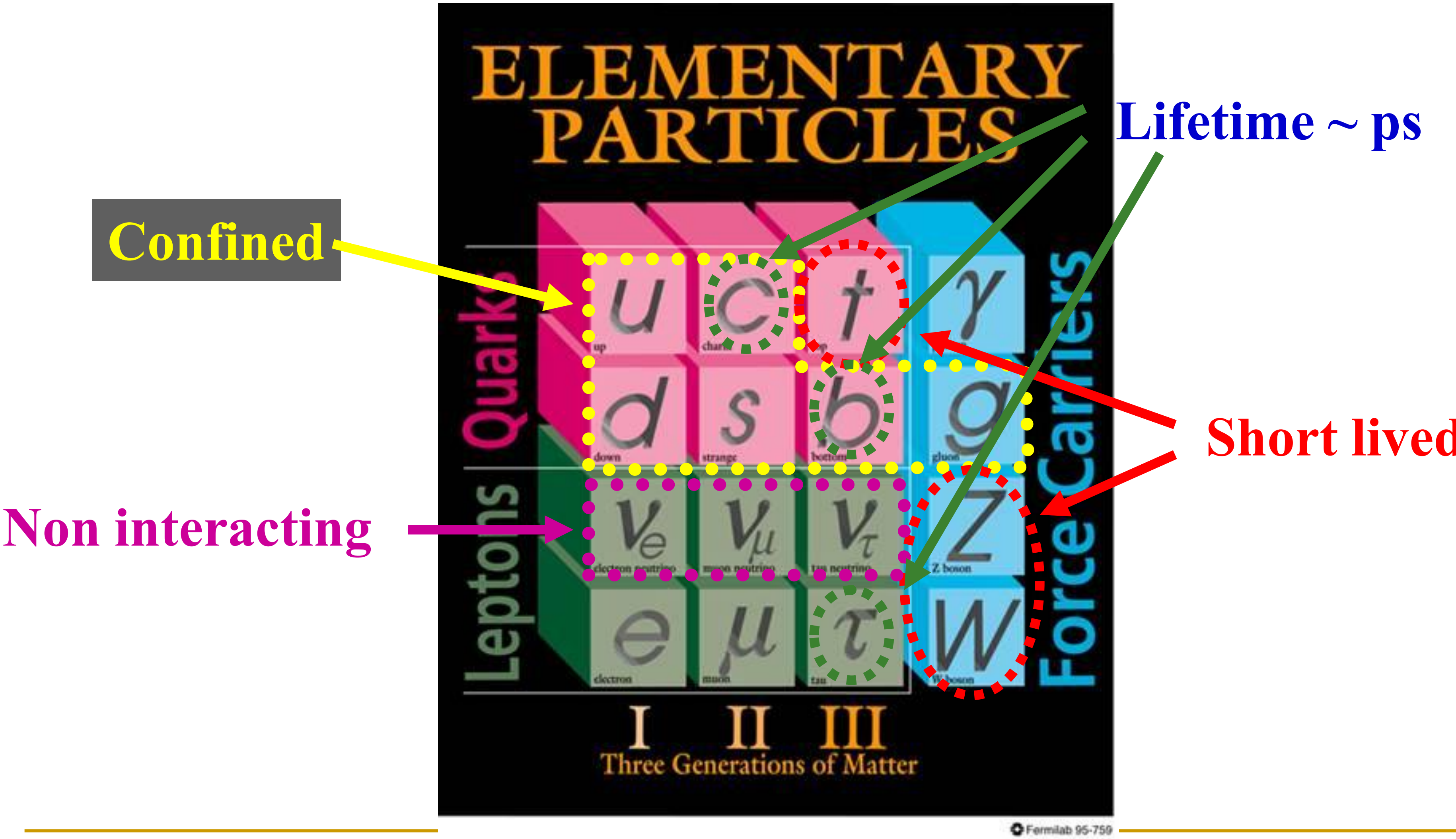
Feynman Level

- Hard process with final state X and Y



Directly observe X and Y if:		If not:
Long-lived (>picosecond)	➡	Reconstruct from decay products
Interact with detectors	➡	Reconstructed from "missing" transverse momentum p_T
Not confined (e.g. not a quark)	➡	Produce jets

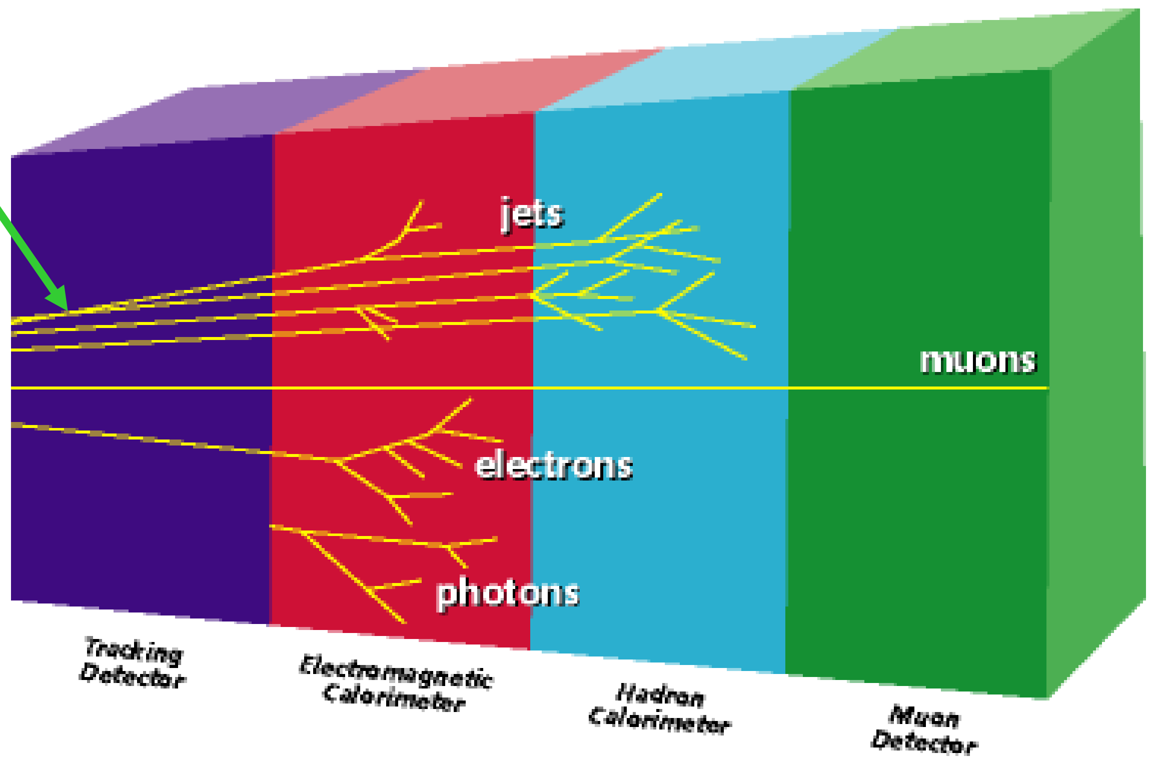
Standard Model Particles



Particles Signatures

- Electron, photons, muons and jets

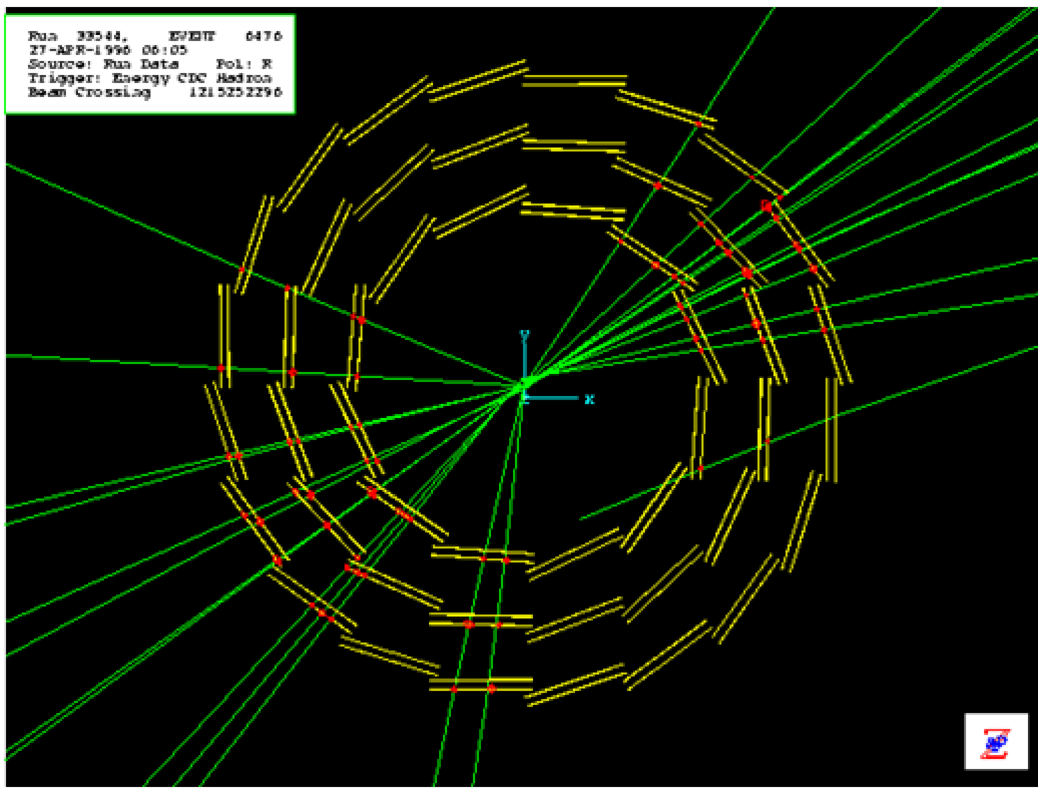
$\pi^{\pm}$, $K^{\pm}$, p

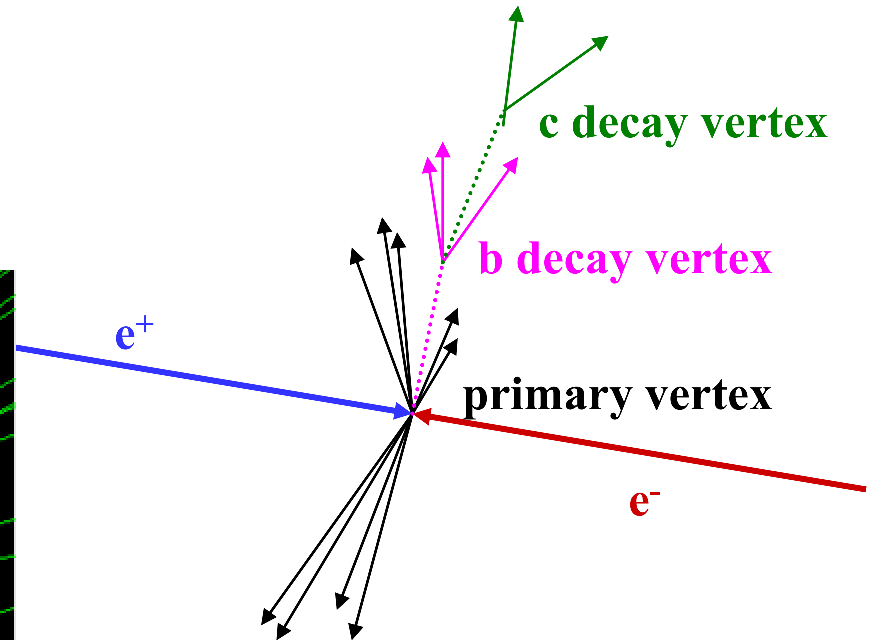


- Tau lepton identification depends on decay mode

Vertex Tagging

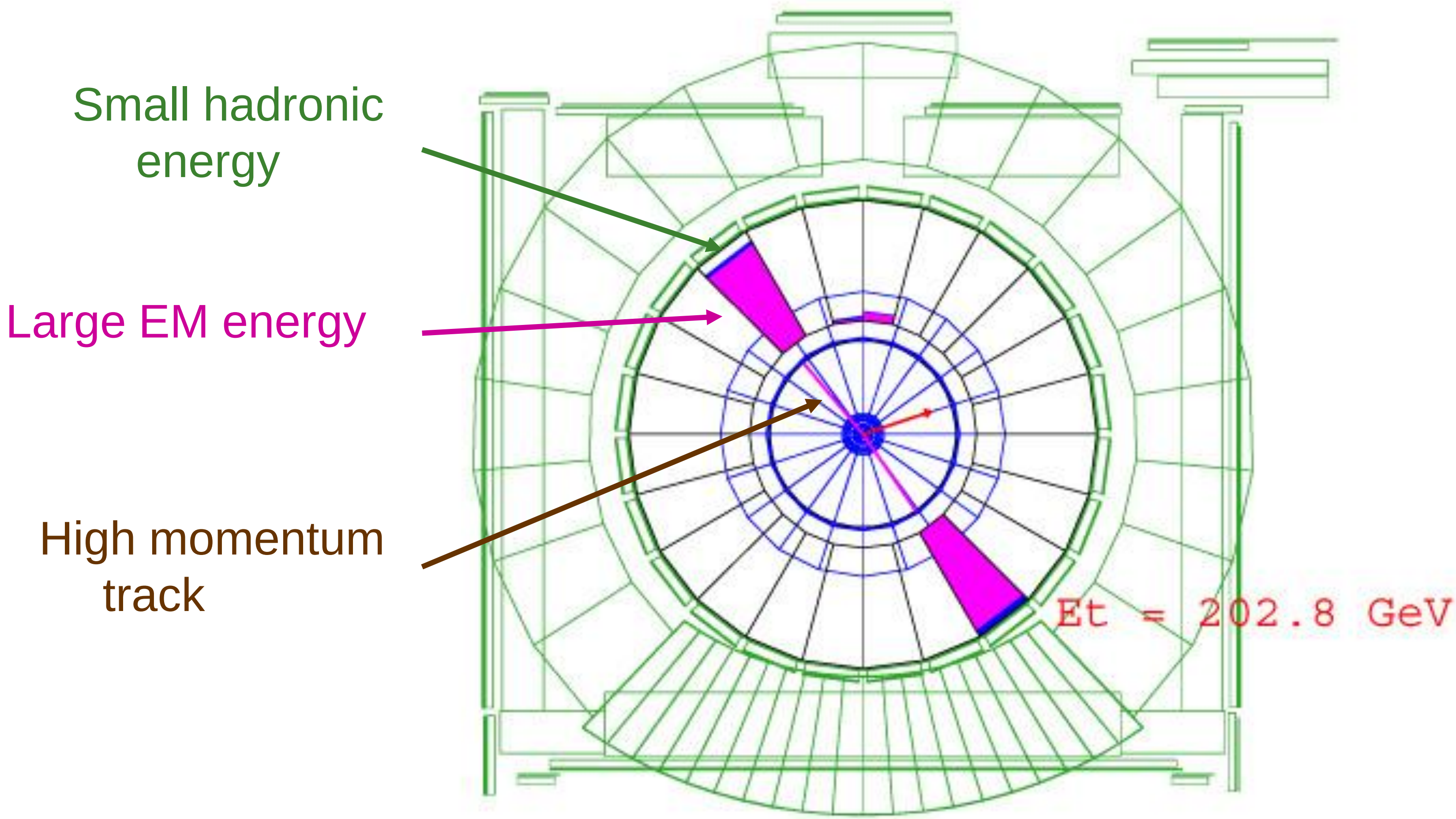
- *b-quark, c-quark,* τ-lepton will travel a few mm then decay





- Precise tracking shows "displaced vertices"
- Easiest for *b* hadrons

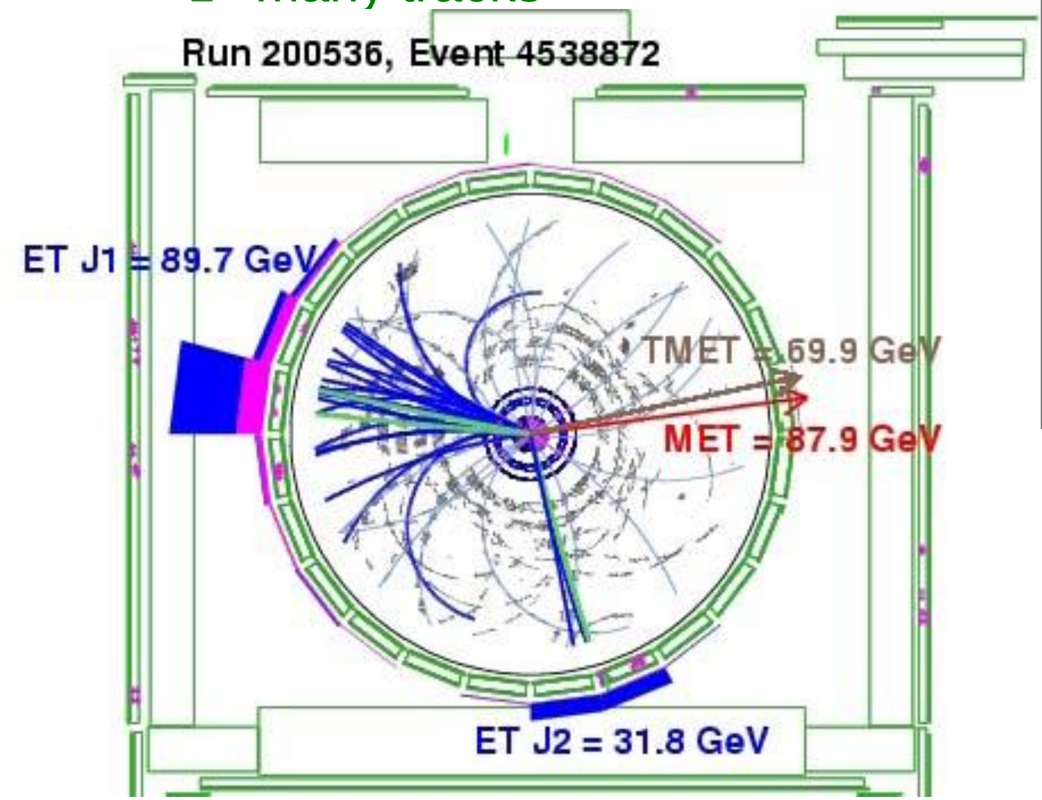
Signatures: Two Electron Event

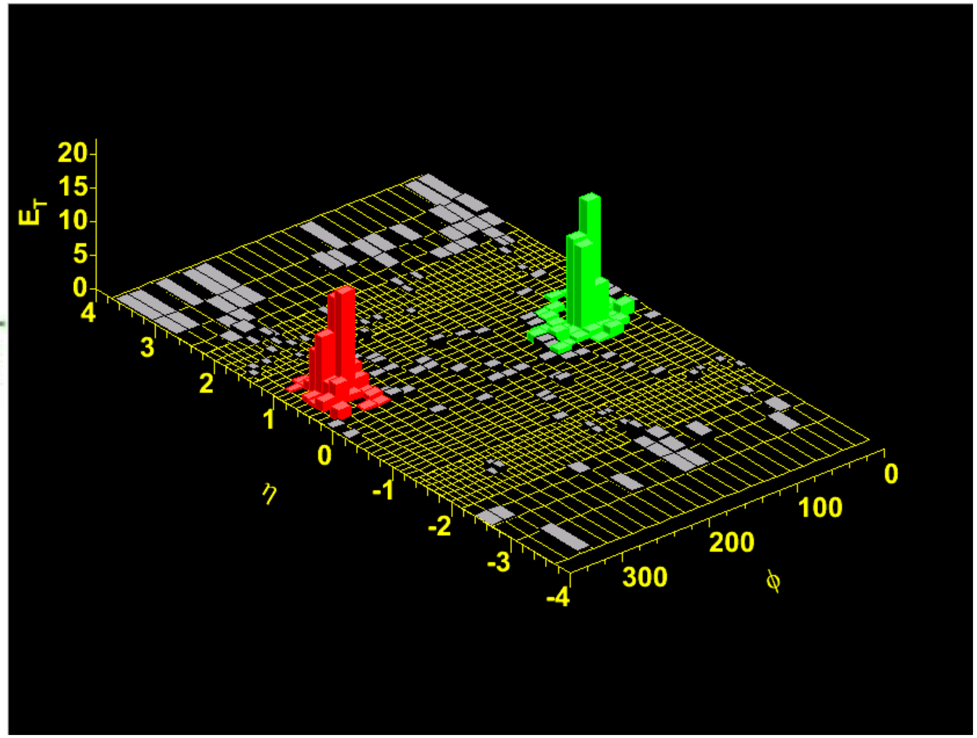


- Tracks and energies below a threshold not shown!

Signatures: Dijet + Missing Energy

- Two jets
  - energy in EM and hadron
  - many tracks





Alternate view of calorimeter

- *Transverse Momentum (p_T)* not balanced
  - *undetected particles*

Finding Top Quarks

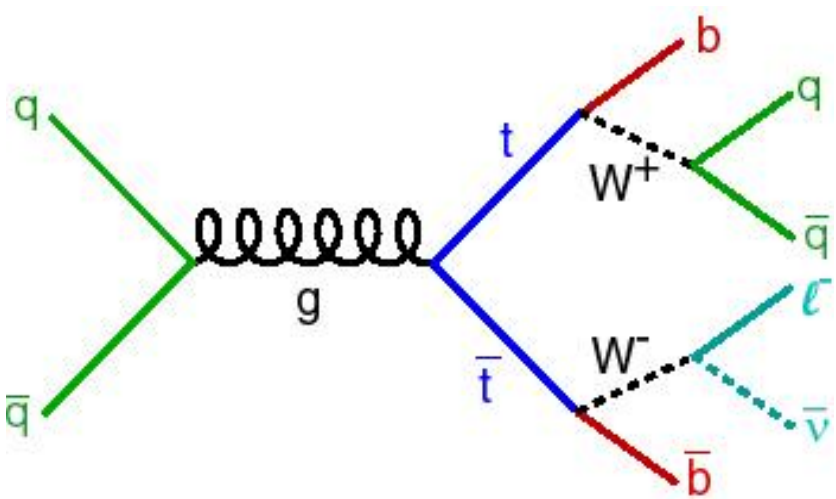
$$p\bar{p} \rightarrow t\bar{t}$$

- Top quark discovered at CDF and DØ in 1995
- Need to identify top pair production:

  Br ($t \rightarrow bW^+$) ≈ 100%

  Br ($W^+ \rightarrow q\bar{q}$) ≈ 70%

  Br ($W^+ \rightarrow l^+ v$) ≈ 10% per *lepton*

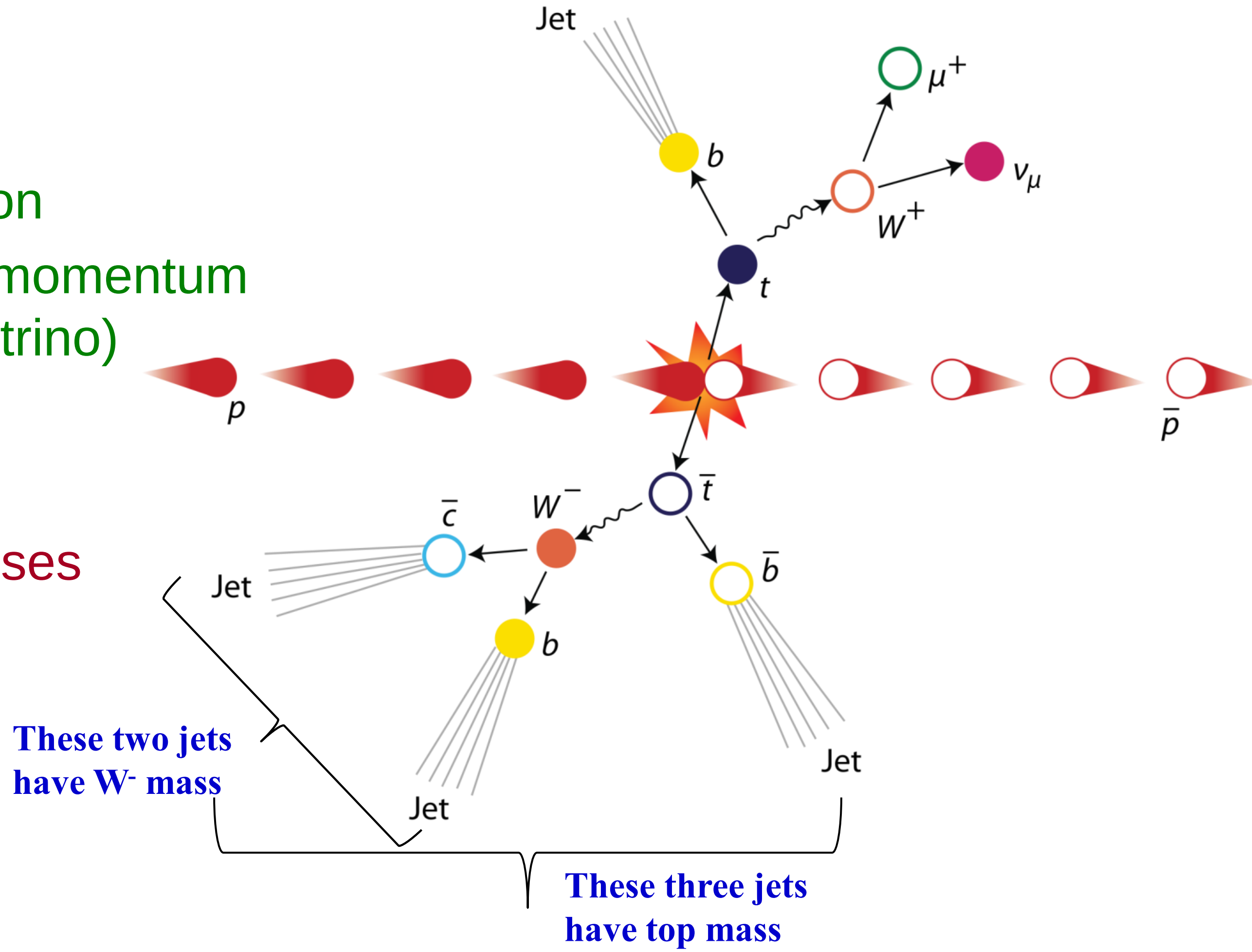


- Semileptonic channel
  - l^- is electron or muon
  - l^- easy to identify
  - only one neutrino
  - q is a “light jet” from a u,d,s quark.

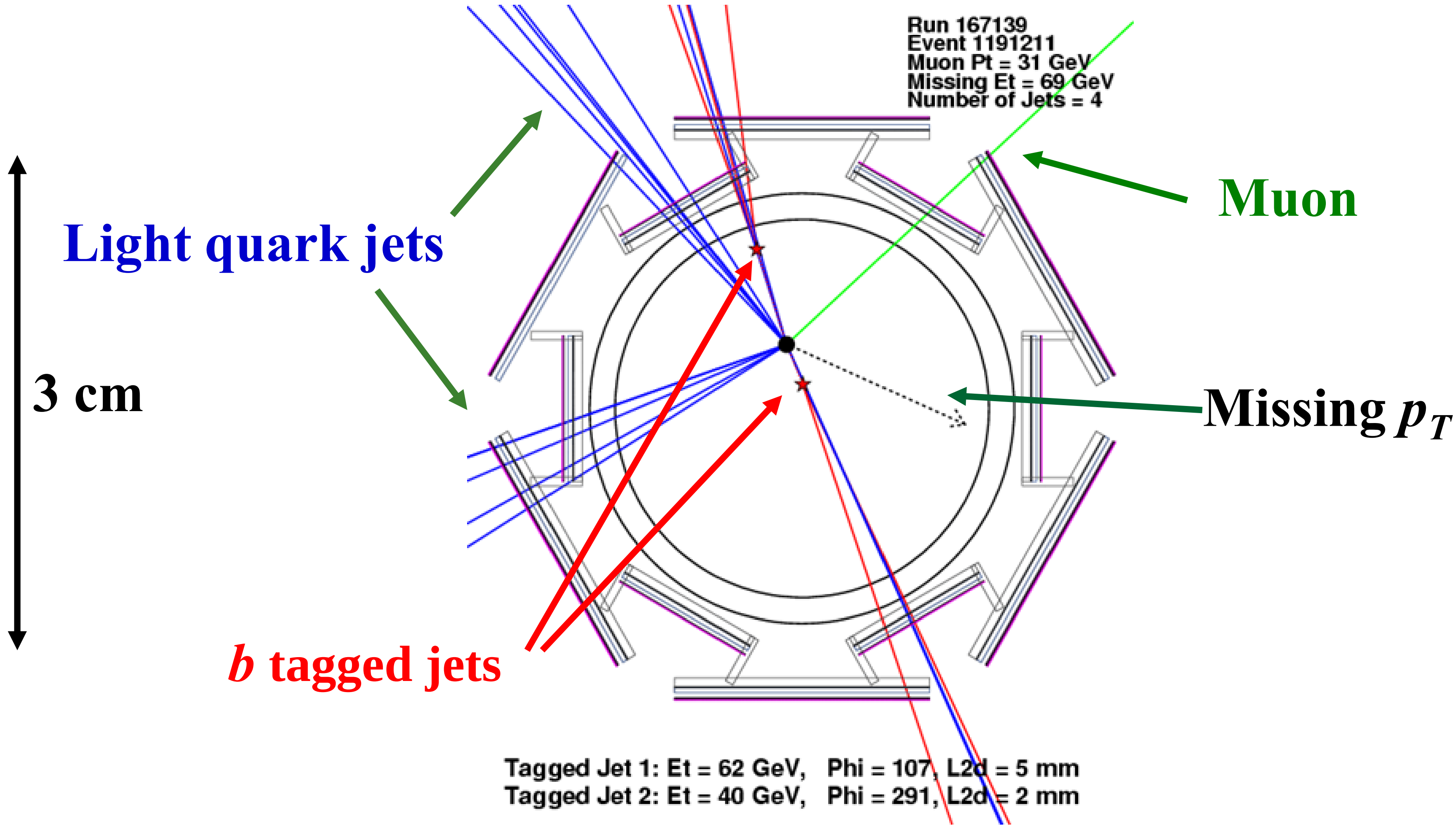
  NB may be higher order effects

Top Pair Production

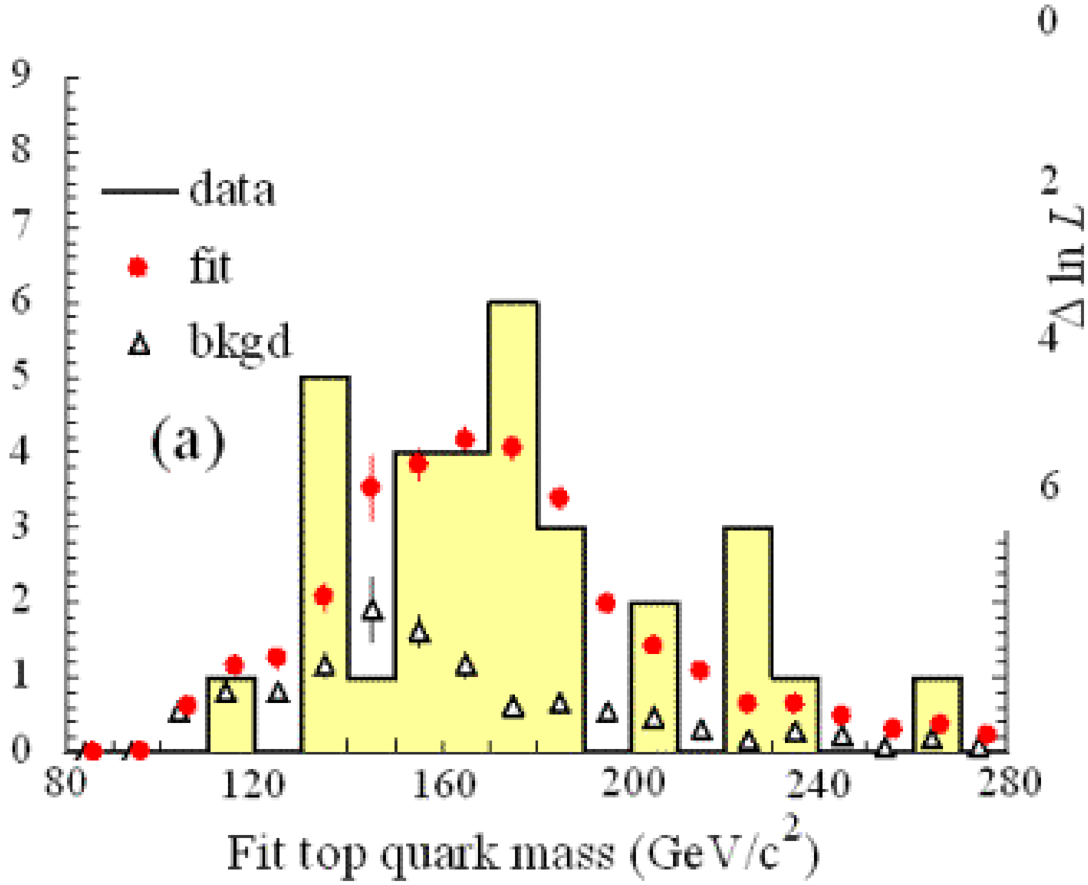
- Electron or muon 20% of the time
- Signature:
  - 2 light quark jets
  - 2 bottom jets
  - One electron or muon
  - Missing transverse momentum (because of the neutrino)
- Extras:
  - Underlying event
  - Higher order processes
  - Multiple interactions



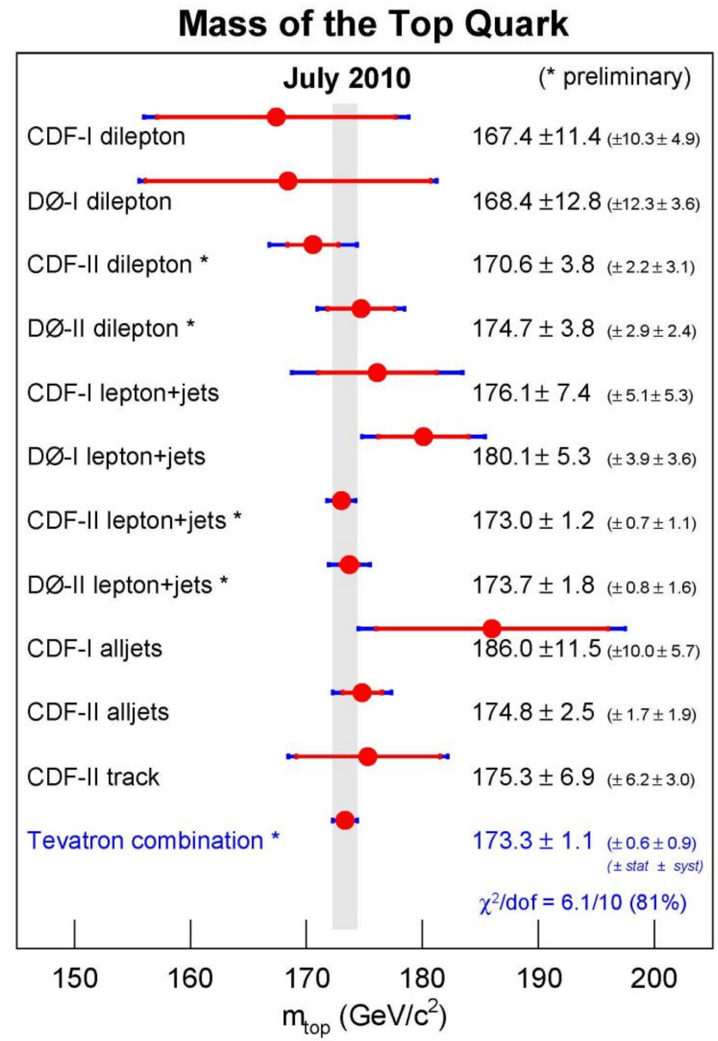
Top Event


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

An example of the top mass



~1999



2010

Next Time...

Finding the Higgs and writing your first paper