Experimental Particle Physics PHYS6011

Putting it all together

Lecture 4

Data Analysis

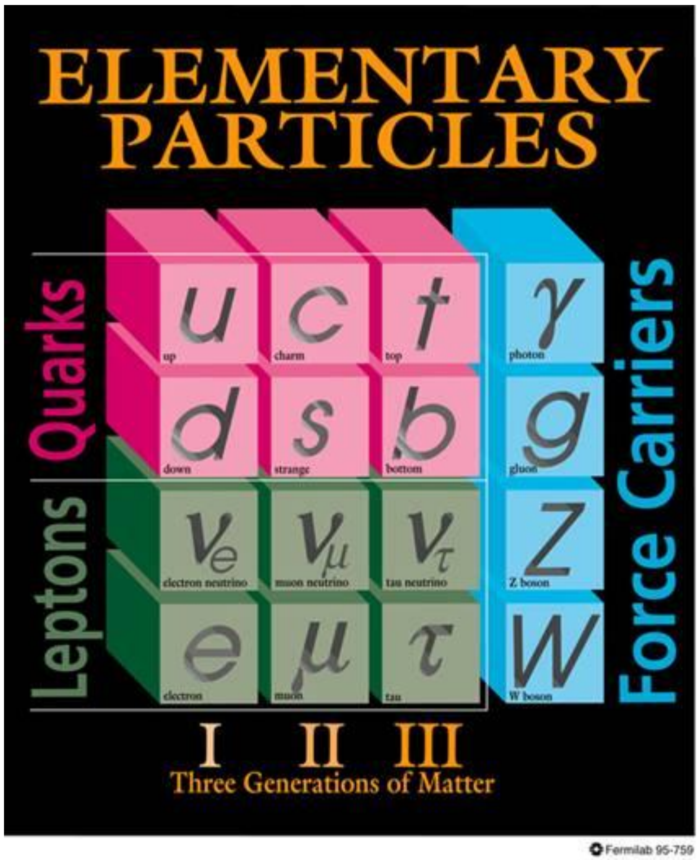
Extract physics from data

- Measure a quantity
- Search for new particles

1. Basic concepts
2. Monte Carlo methods
3. Signal
4. Backgrounds
5. Errors
6. Statistics

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

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

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

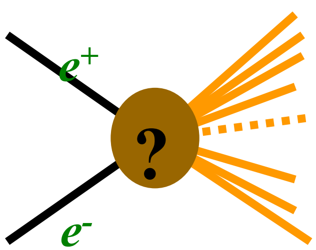
- Properties
  - Mass
    - Measure momentum and energy: $E^2 = p^2 + m^2$
  - Mass width → Lifetime
    - Measure momentum and energy or:
    - How many particles exist after t seconds
  - Branching Fraction
    - Reconstruct the decays and see how many there are.
  - Charge
    - Direction in a magnetic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

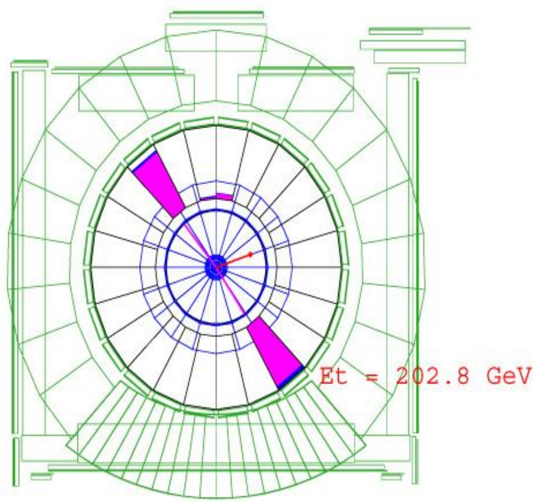
Data Flow

High Signal:Background

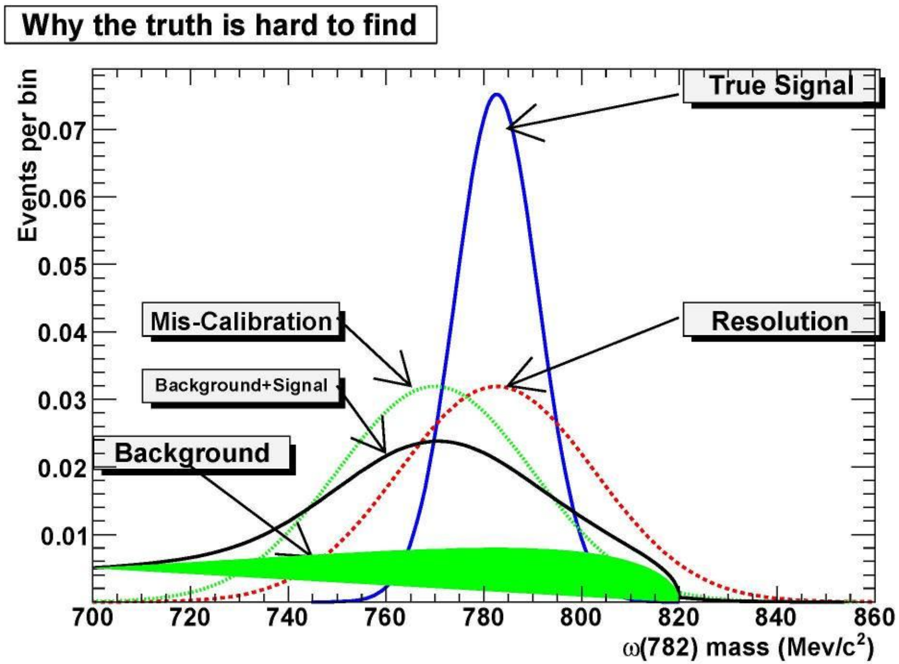
Low Signal:Background

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





Elements of Analysis



Not only *Data* but...

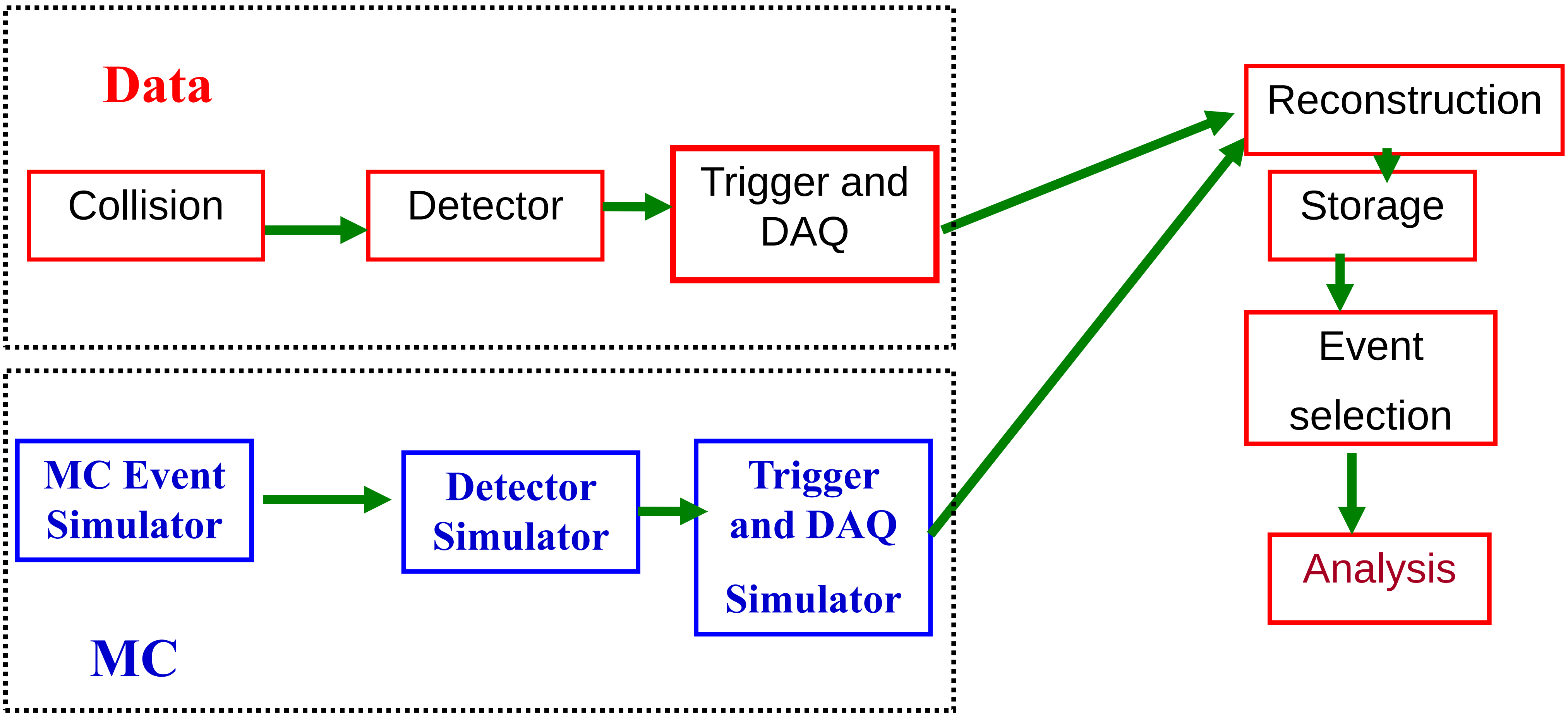
- Detector response to signal
- Background estimates
- Errors
    - statistical
    - systematic
- How to solve?
    - Try and evaluate from data
    - Sometimes need more...
        - Monte Carlo

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*

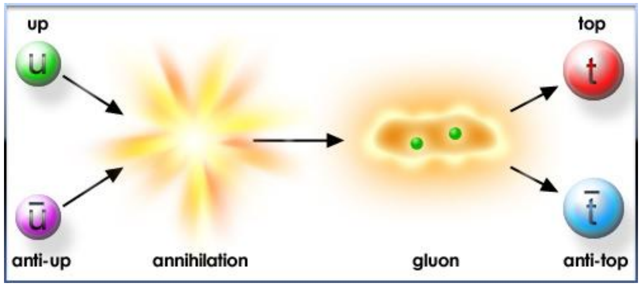
- Computer intensive
- Must be carefully tuned and checked

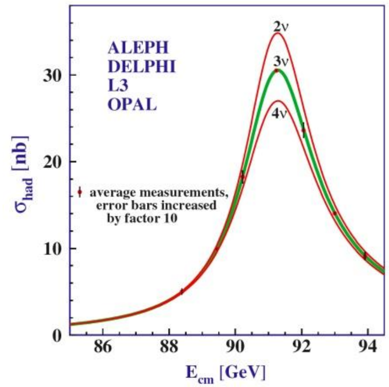
Data and Monte Carlo



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:
  - 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:
  - 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.





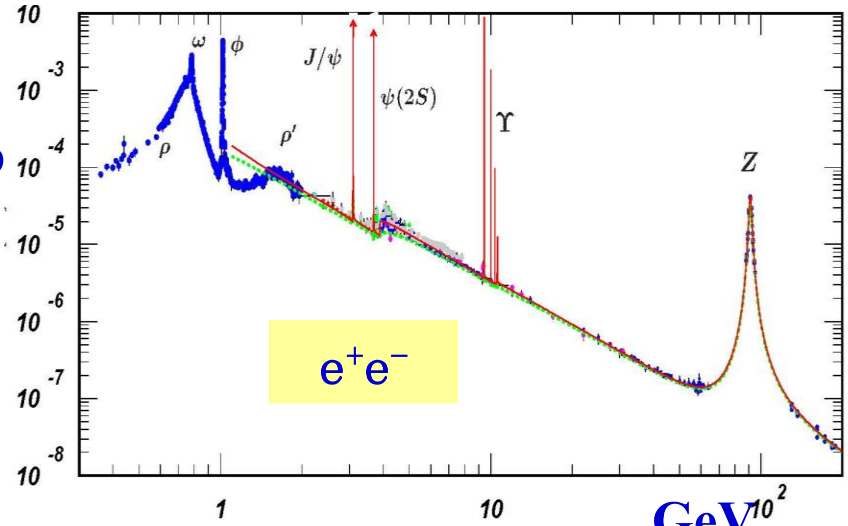
A Collider Experiment

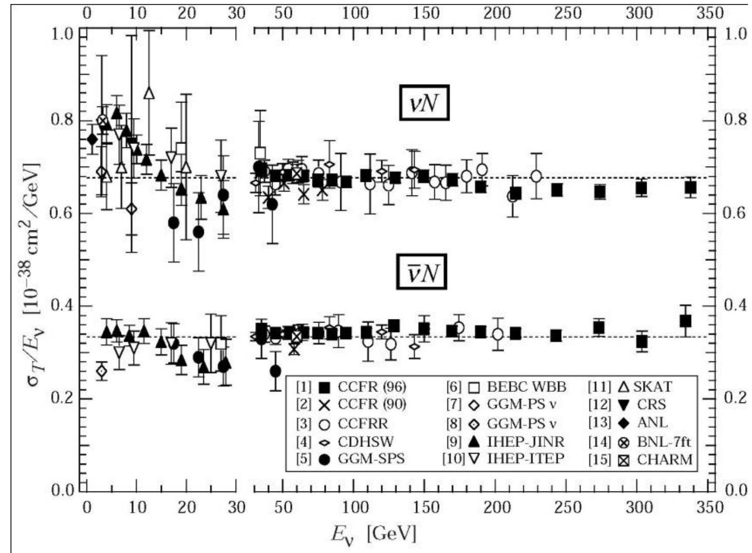
- So far:
  - Accelerators and colliders
  - Particle interactions
  - Types of detectors
- *Combine them to do physics…*
- Example: CDF at the Tevatron
  1. Proton-antiproton collisions
  2. Fermilab and the Tevatron
  3. CDF and DØ
  4. Identifying particles
  5. Identifying physics processes
     - Top production
     - Higgs Production

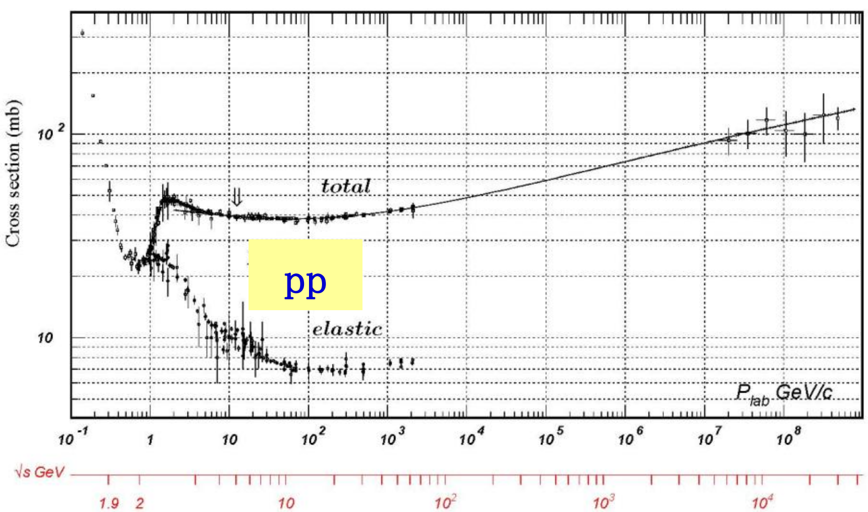
Cross-Sections

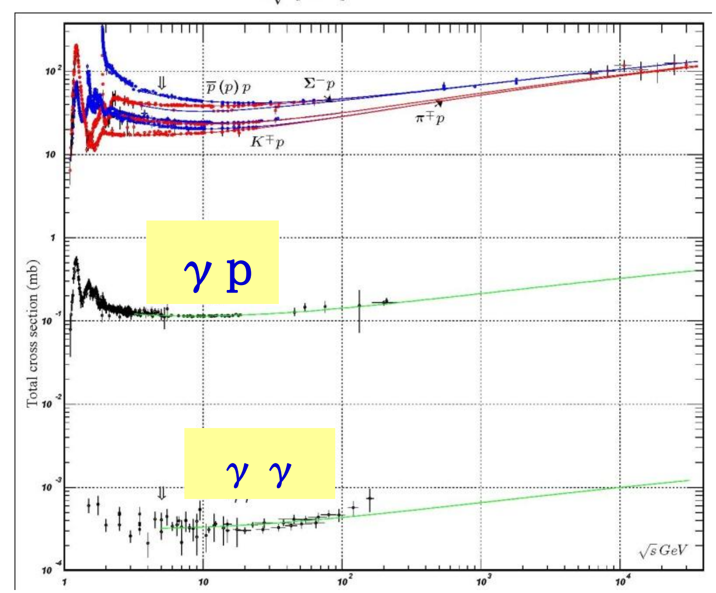
1 mb = 10^{-27} cm^2

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



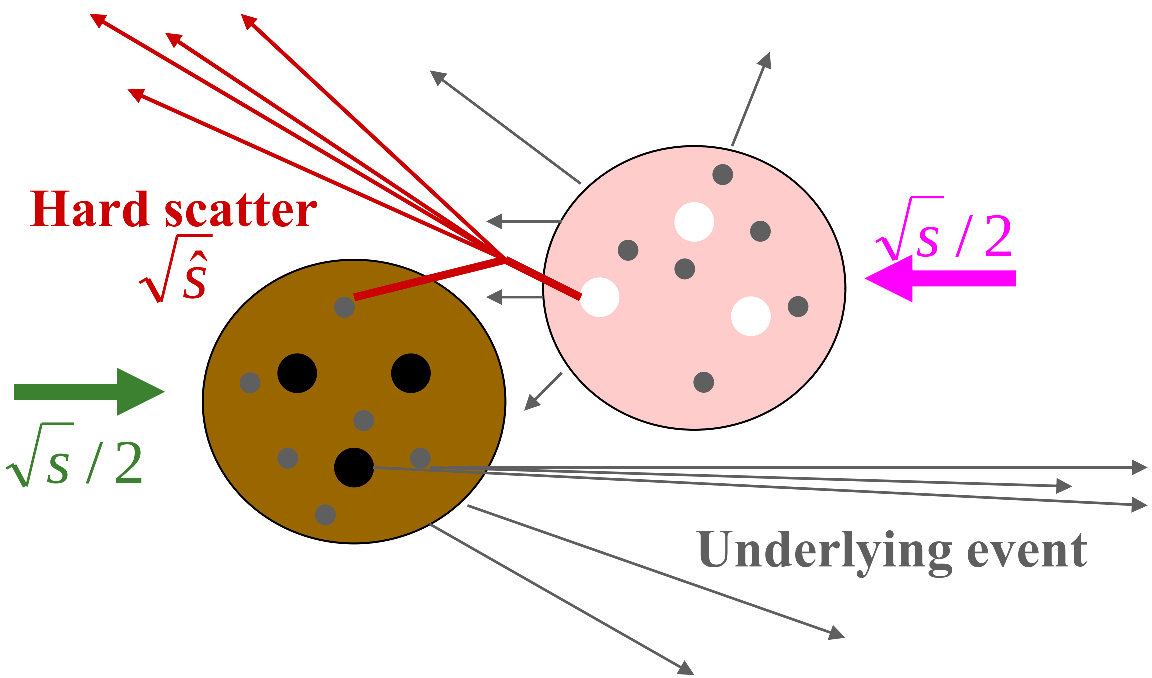






Proton-Antiproton Collisions

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

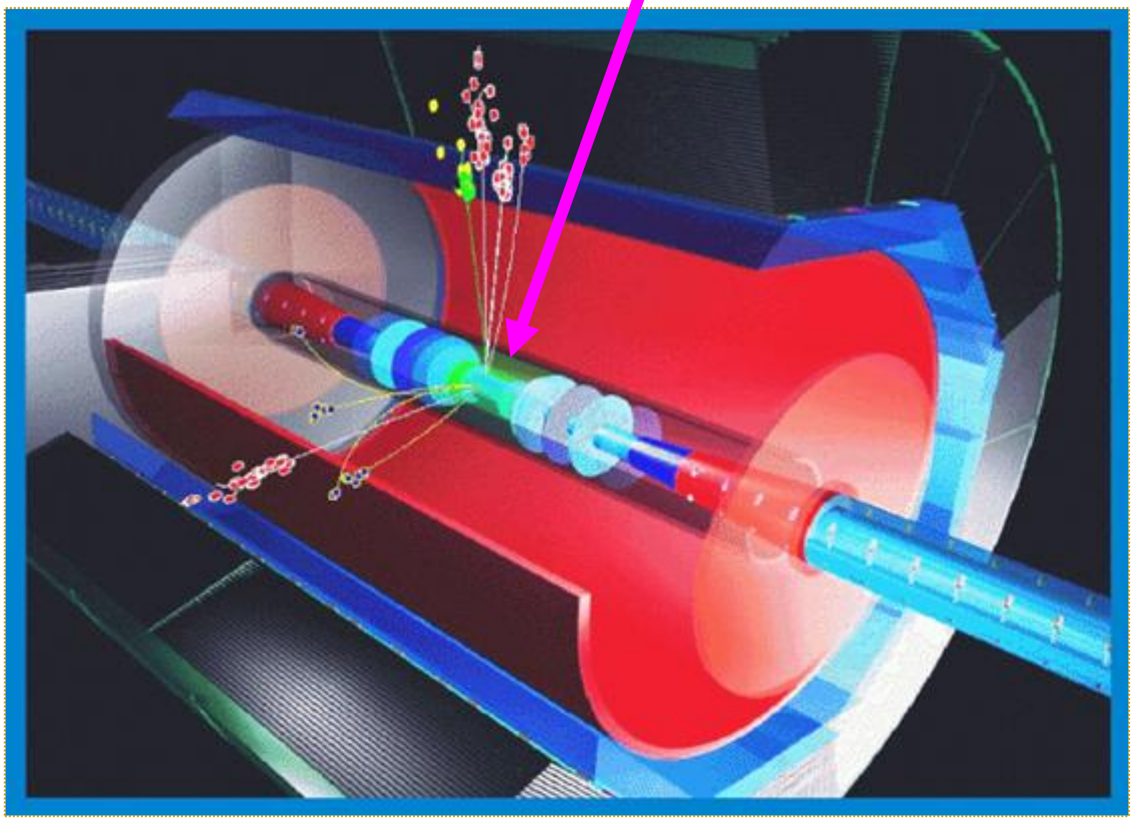


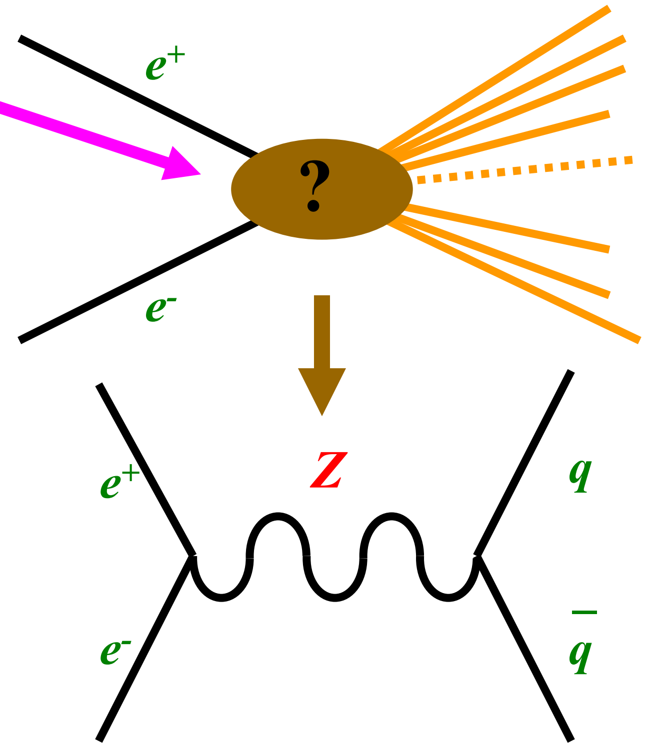
- Underlying event:
  - Most lost at low angles
  - Some in detector
- p_z unknown
- Extra detector hits
- Initial partons unknown
- Huge total cross section *(10s of mb)*

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

Reconstructing Collisions

What happened here?





or something more exotic.....

- **extract maximum information from outgoing particles**

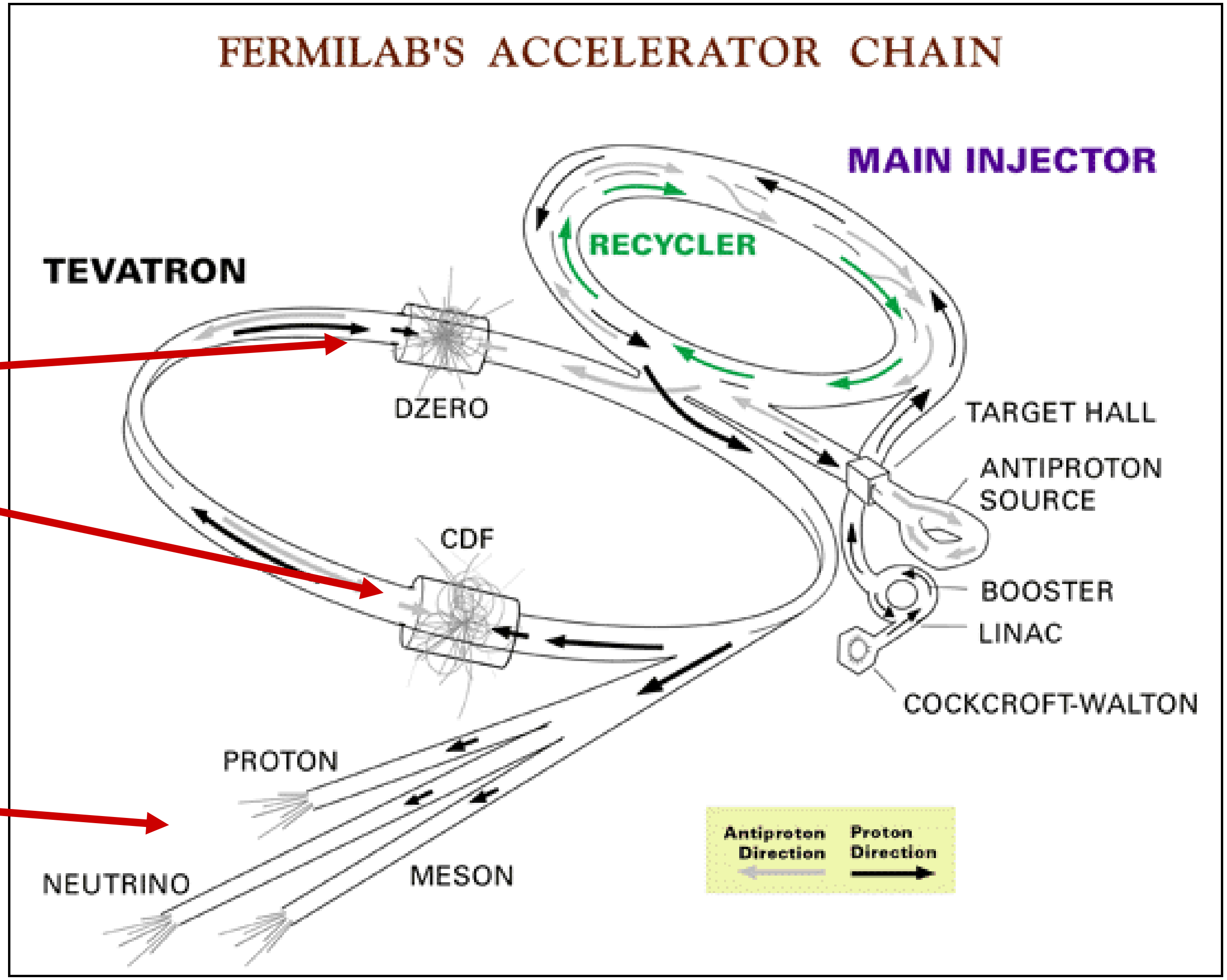
Fermilab

- 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

Fermilab Accelerators

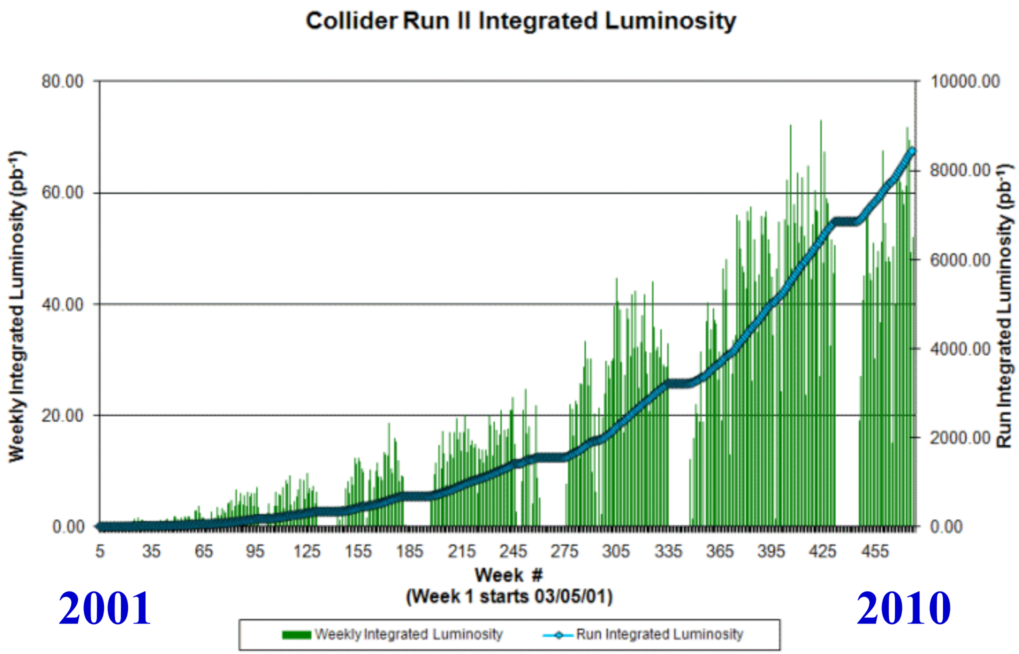
Collider Experiments

Fixed target beams



The Tevatron Run II

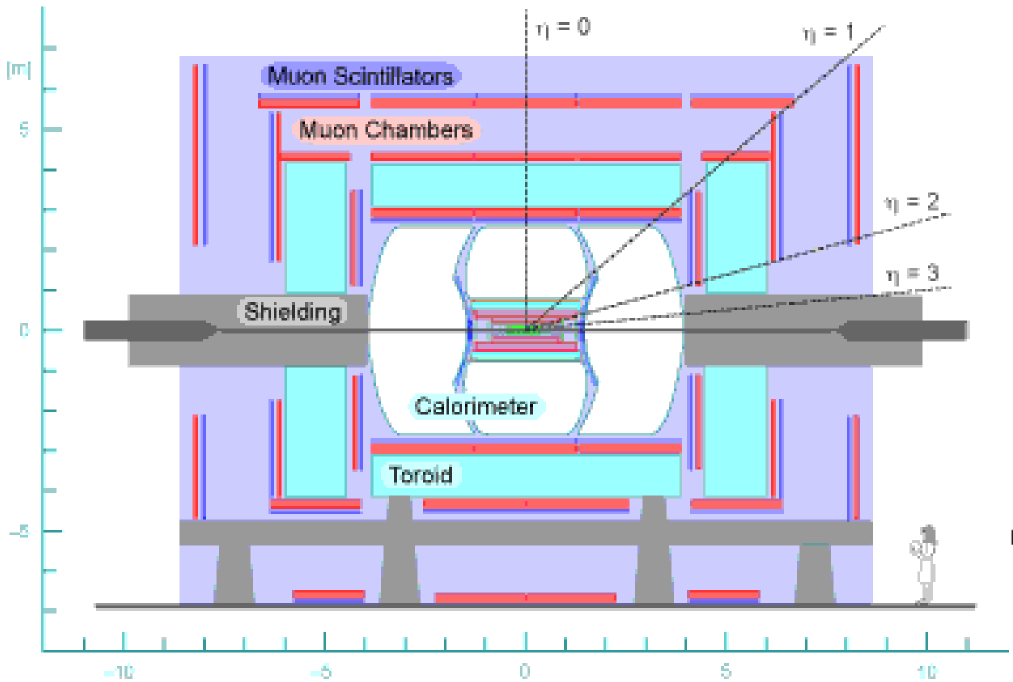
- Upgraded in 2001
- $\sqrt{s}$ = 1.96 TeV
- proton-antiproton collisions



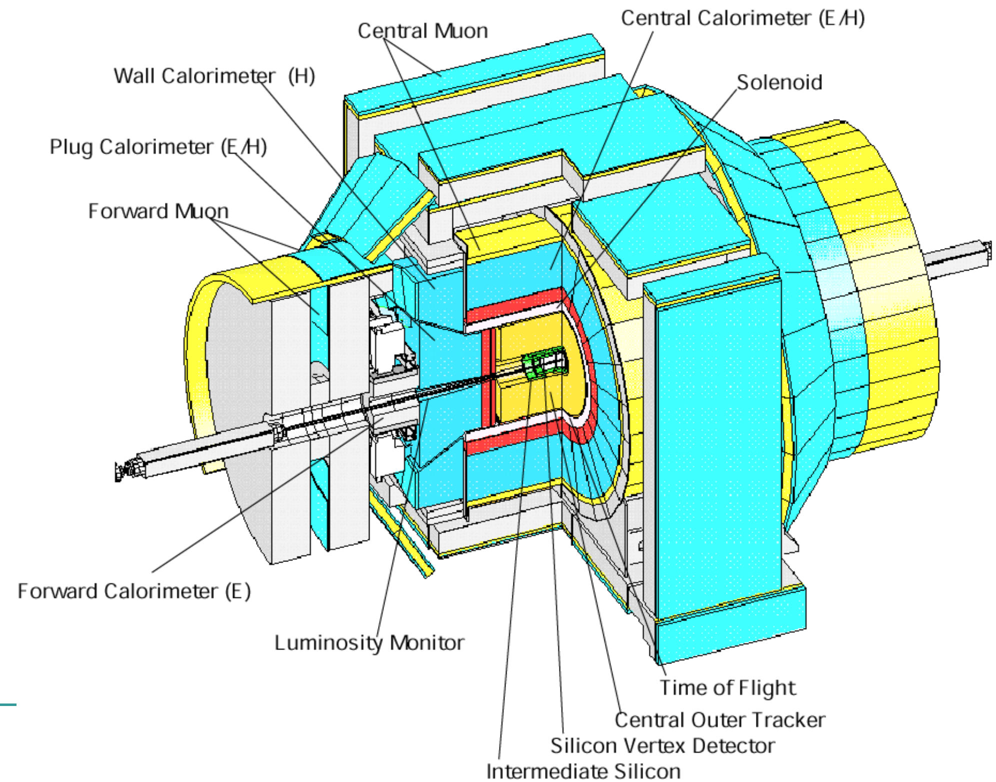
- 36 bunches
- 396 ns bunch crossing
- L ~ 10^{32} $cm^{-2}s^{-1}$
  - *3 interactions per crossing*

The Experiments

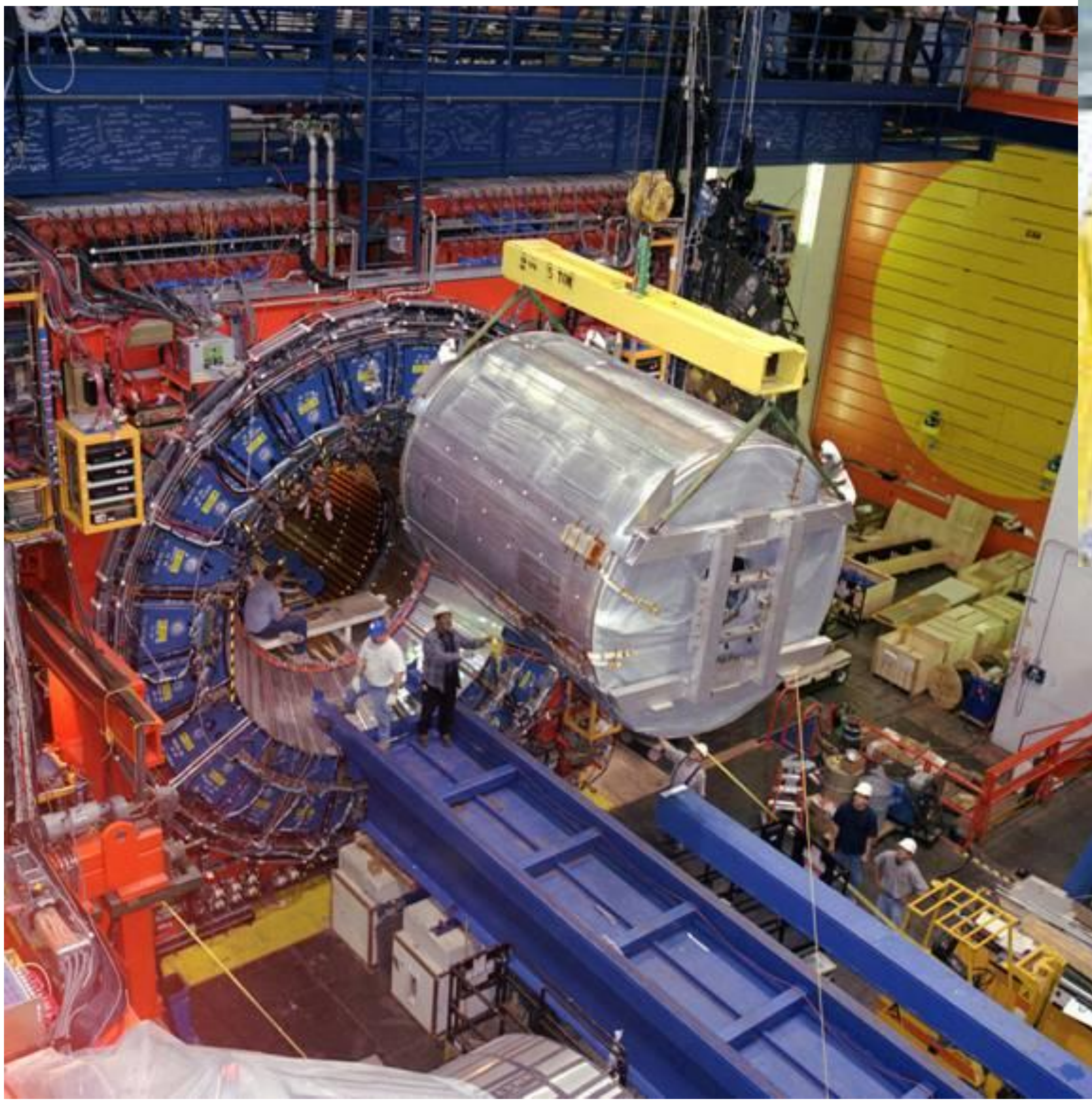
DØ - optimised for calorimetry



CDF - optimised for tracking

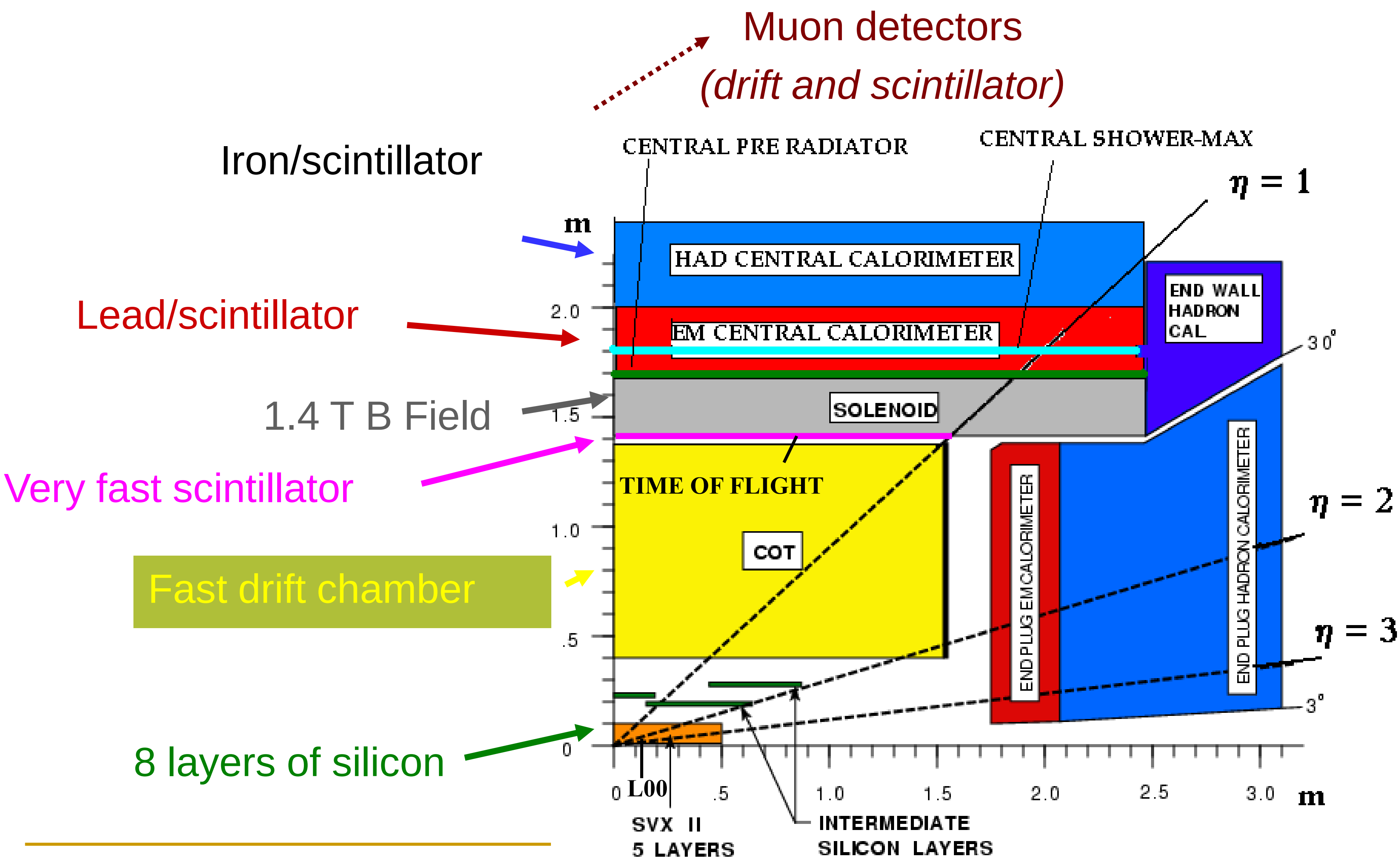


CDF



- 2001Upgrade
  - Higher luminosity
  - Newer technology

CDF Components

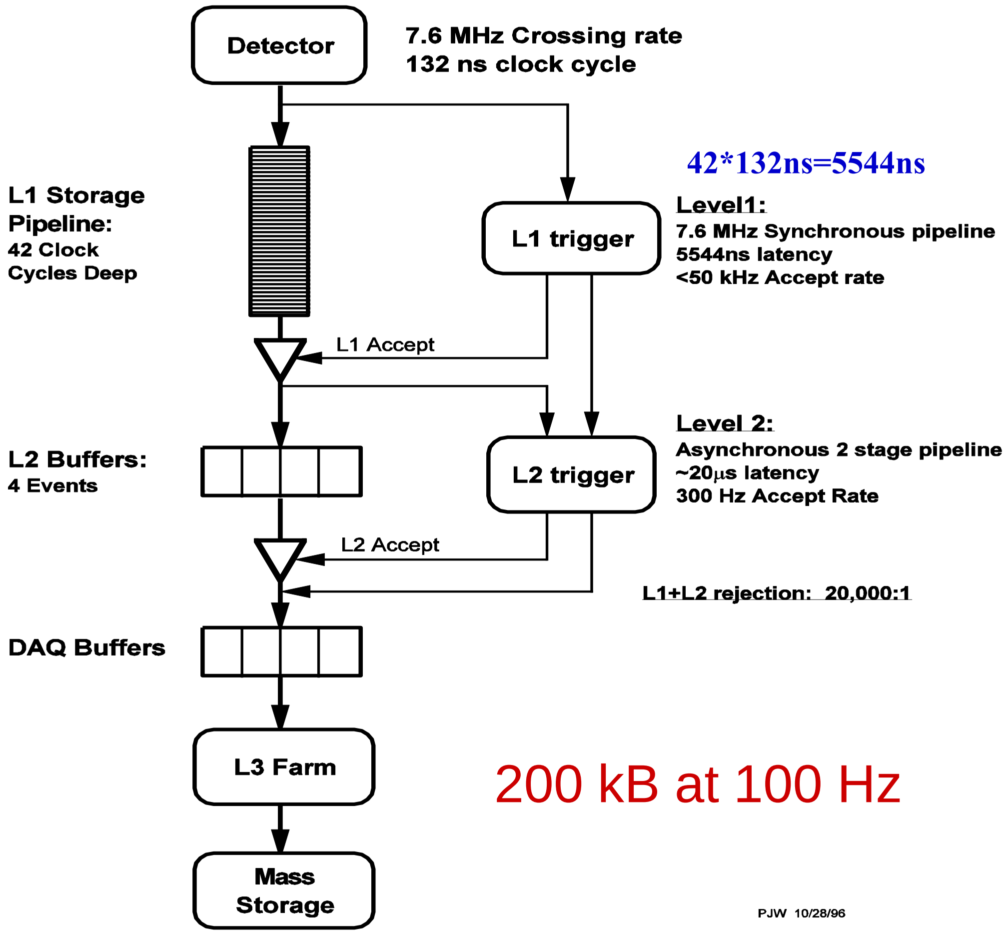


Trigger and DAQ

A million channels at 2.5 MHz

DAQ

- Data AcQuisition
- Processing
- Storage



200 kB at 100 Hz

Keywords:

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

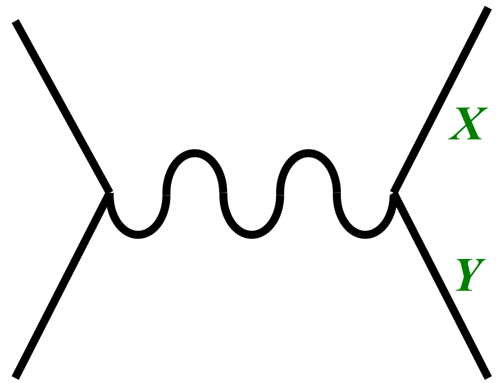
Trigger Inputs:

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

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

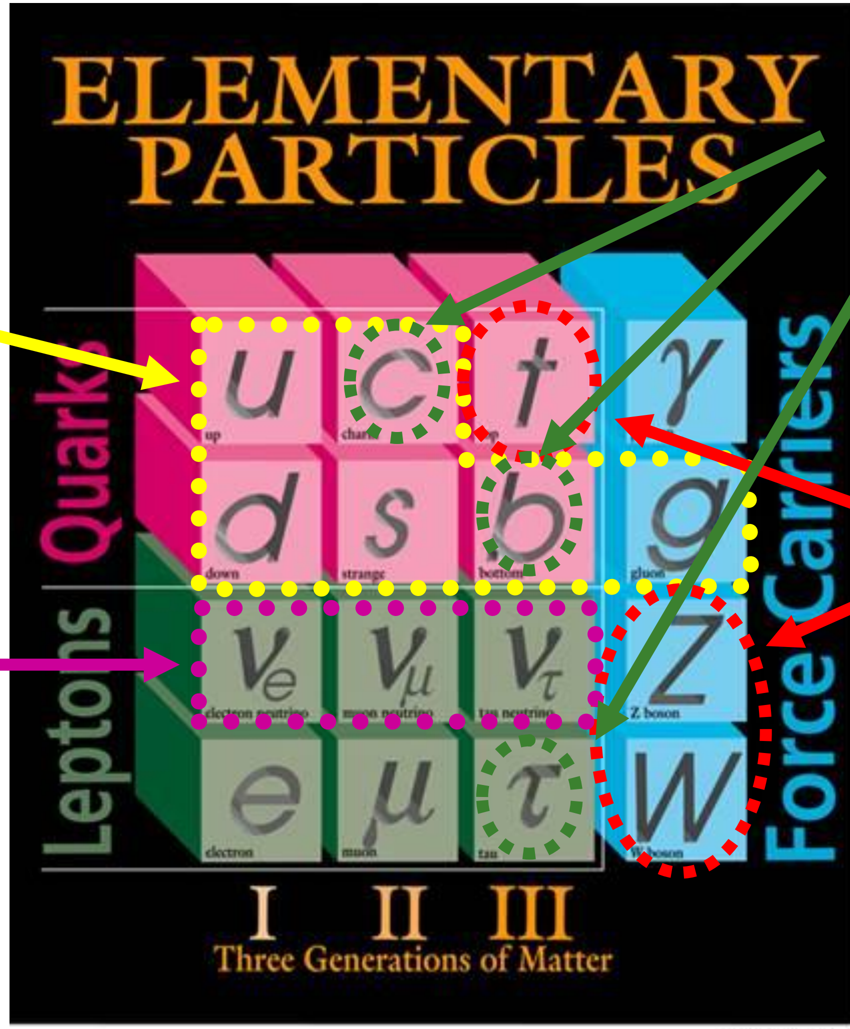
Feynman Level

- 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



Fermilab 95-759

Confined

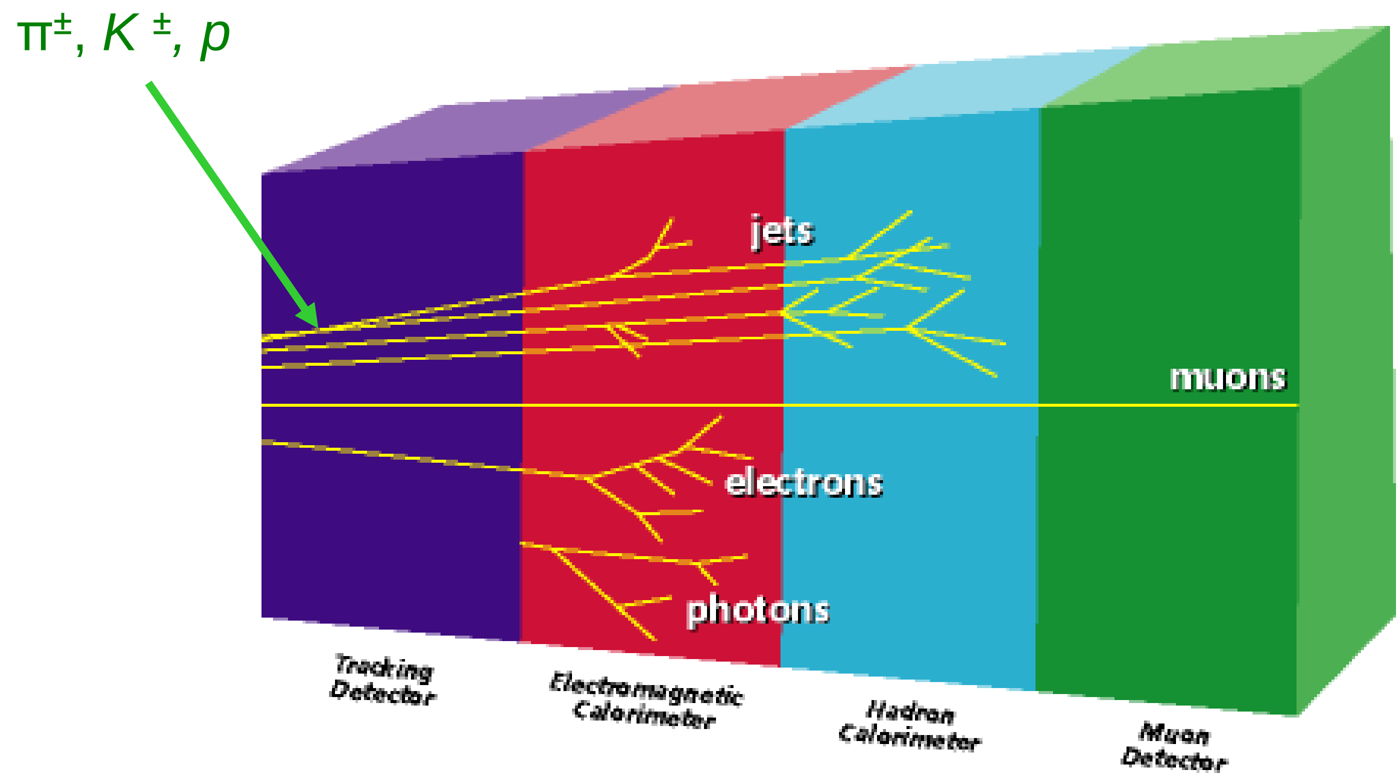
Lifetime ~ ps

Short lived

Non interacting

Particles Signatures

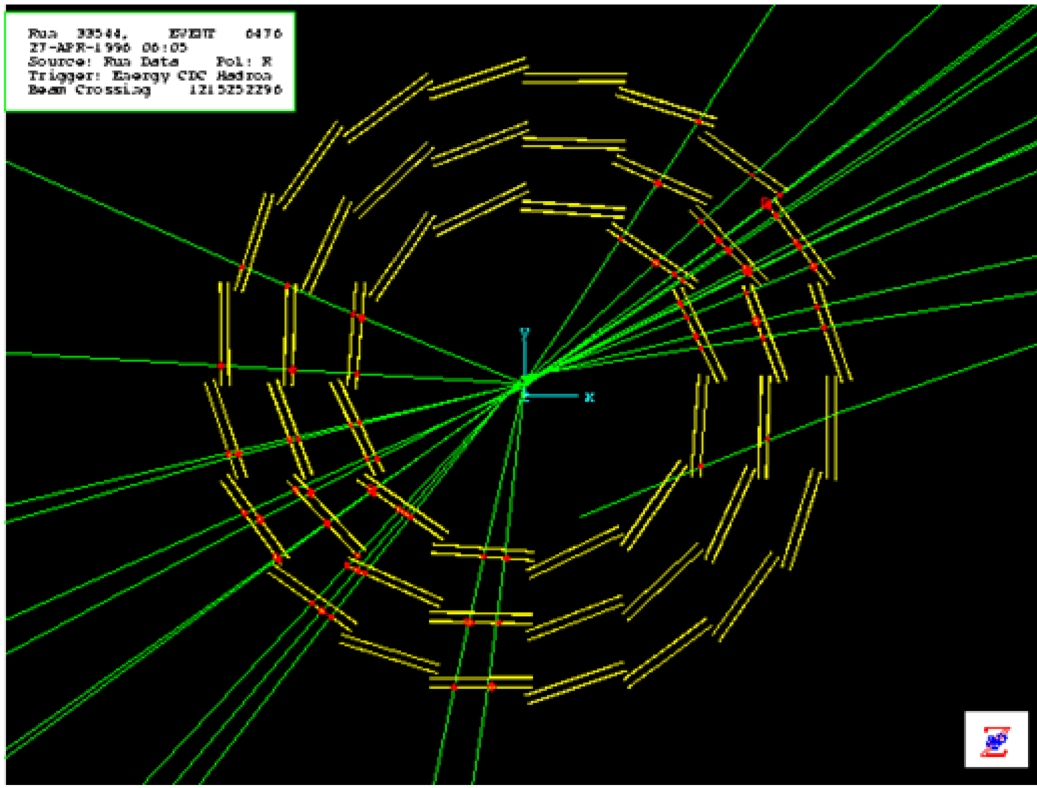
- Electron, photons, muons and jets

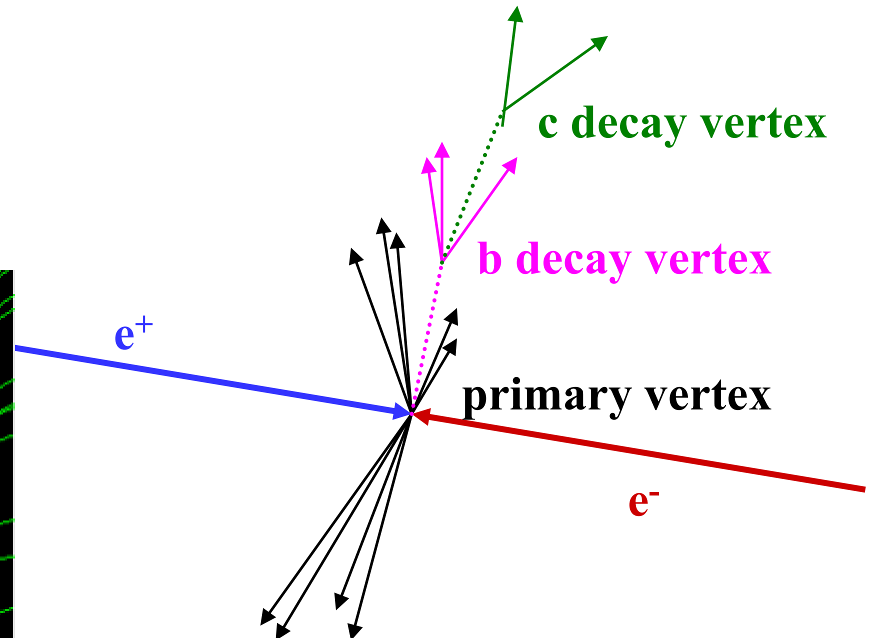


- Tau lepton identification depends on decay mode

Vertex Tagging

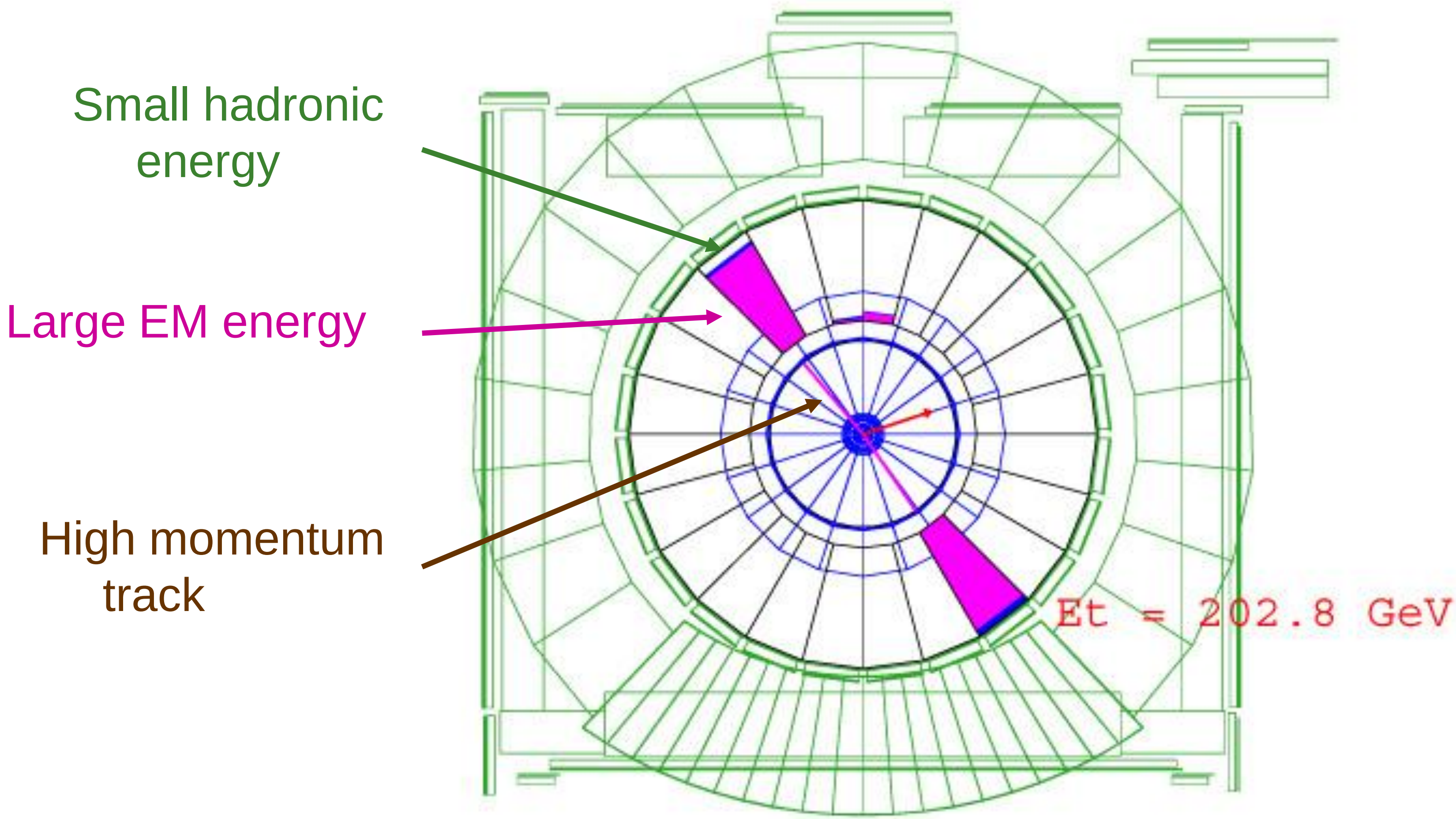
- *b-quark, c-quark,* τ-lepton will travel a few mm then decay





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

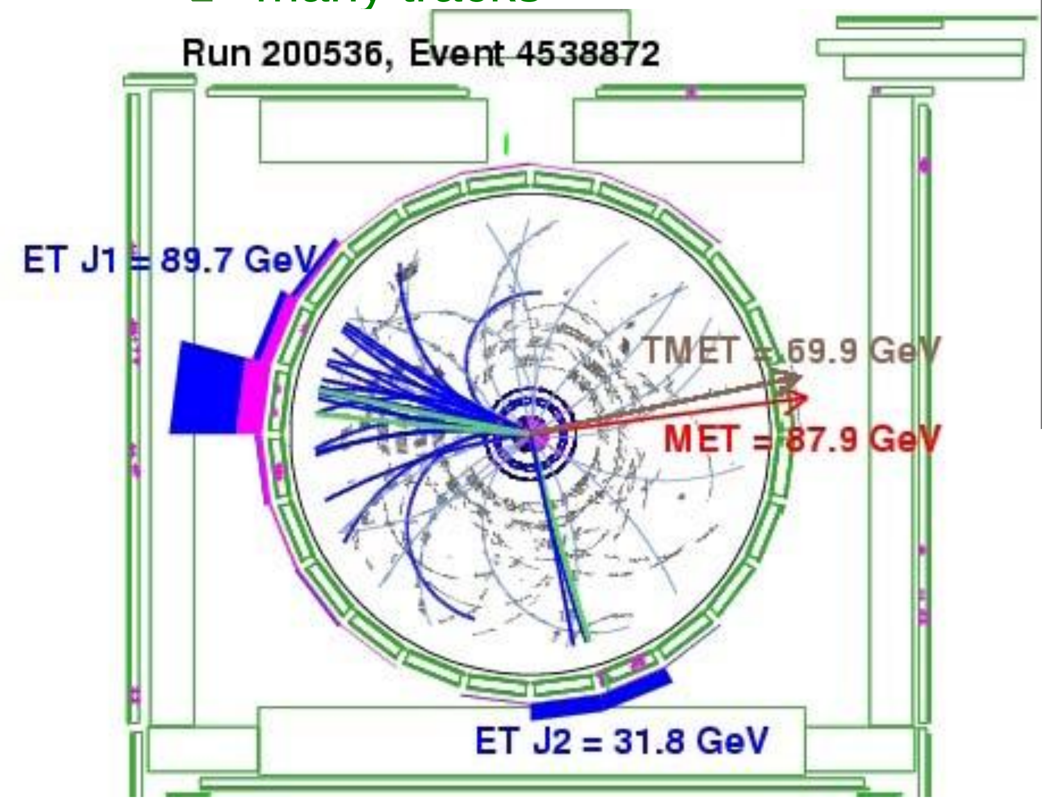
Signatures: Two Electron Event

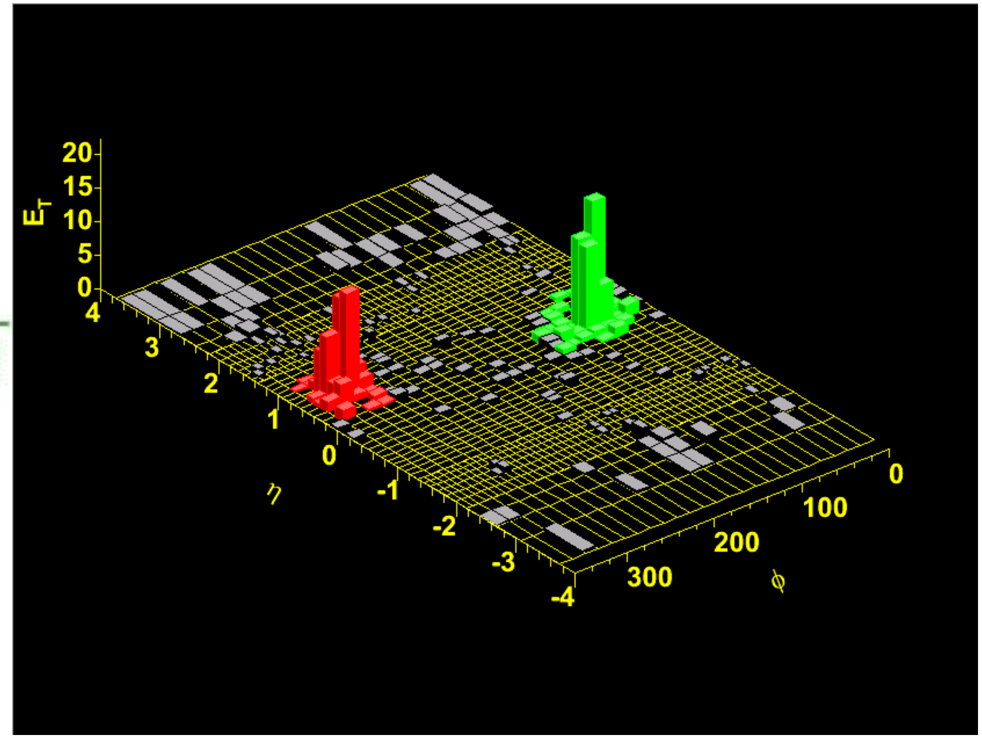


- Tracks and energies below a threshold not shown!

Signatures: Dijet + Missing Energy Trigger

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





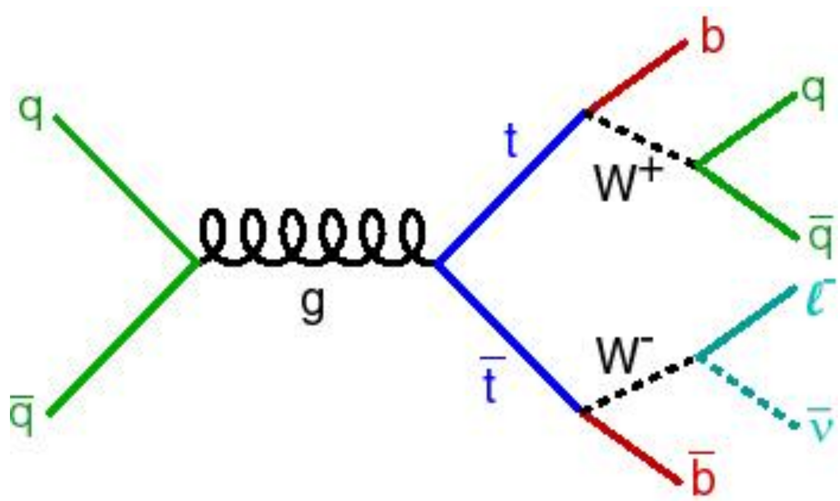
Alternate view of calorimeter

- 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 ($W^+ \rightarrow qq$) ≈ 70%
  - Br ($W^+ \rightarrow l^+ \nu$) ≈ 10% per *lepton*

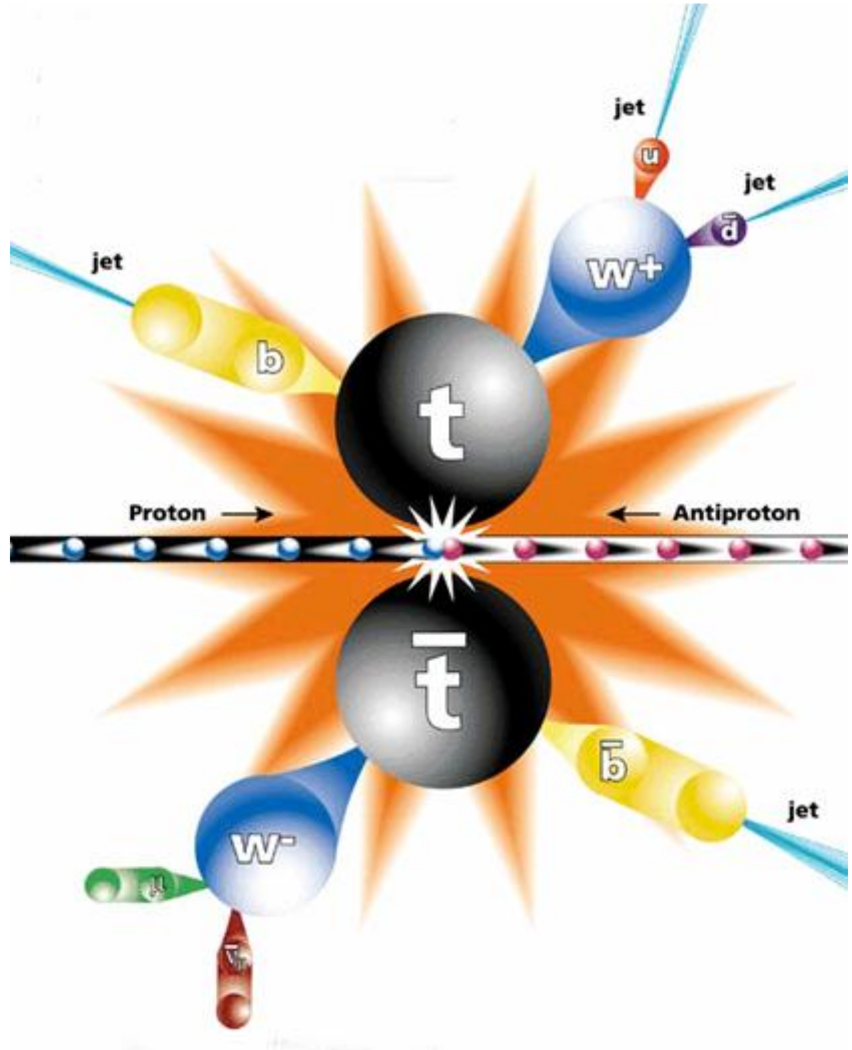


- Semileptonic channel
  - l^- is electron or muon
  - l^- easy to identify
  - only one neutrino
  - q is a “light jet” from a u,d,s quark.

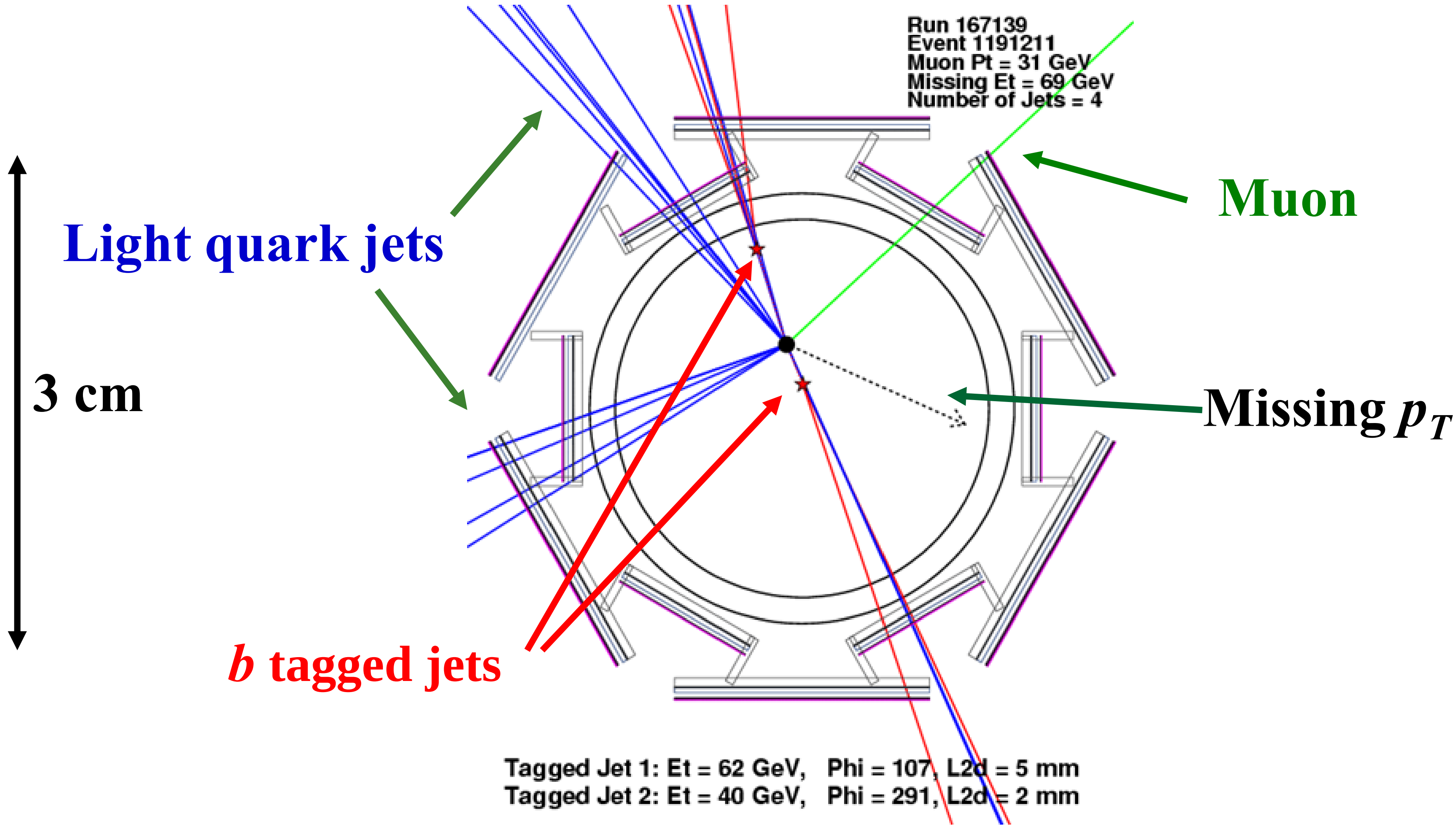
NB may be higher order effects

Top Pair Production

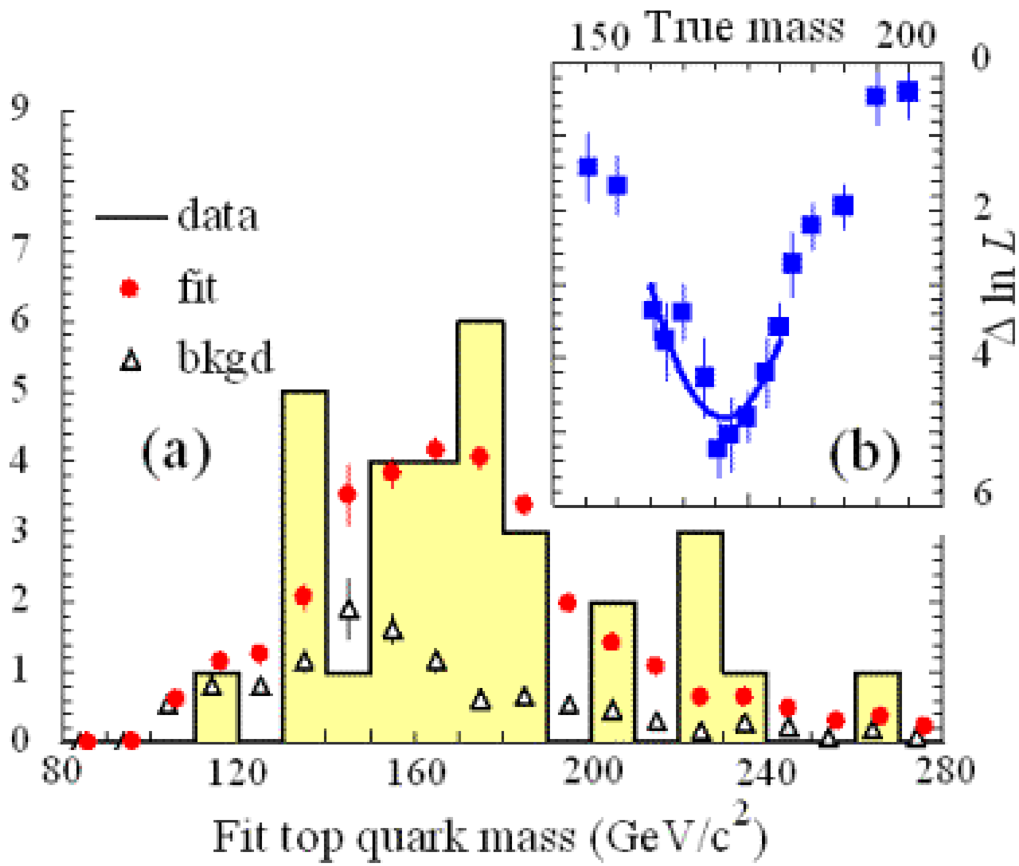
- Electron or muon 20% of the time
- Signature:
  - 2 light quark jets
  - 2 bottom jets
  - One electron or muon
  - Missing transverse momentum (because of the neutrino)
- Extras:
  - Underlying event
  - Higher order processes
  - Multiple interactions



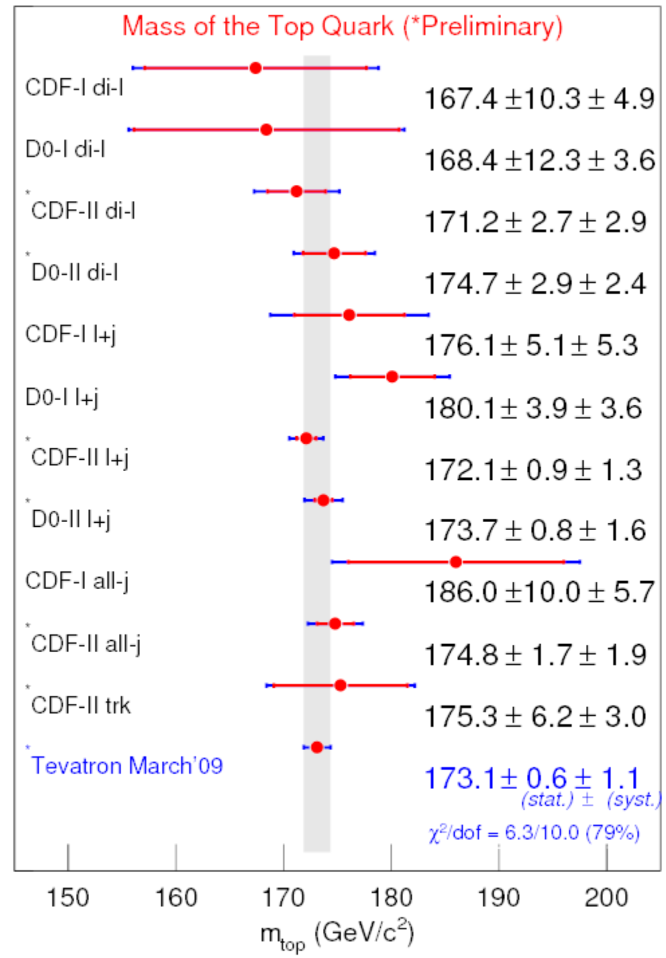
Top Event


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



2009

Next Time...

Finding the Higgs and writing your first paper