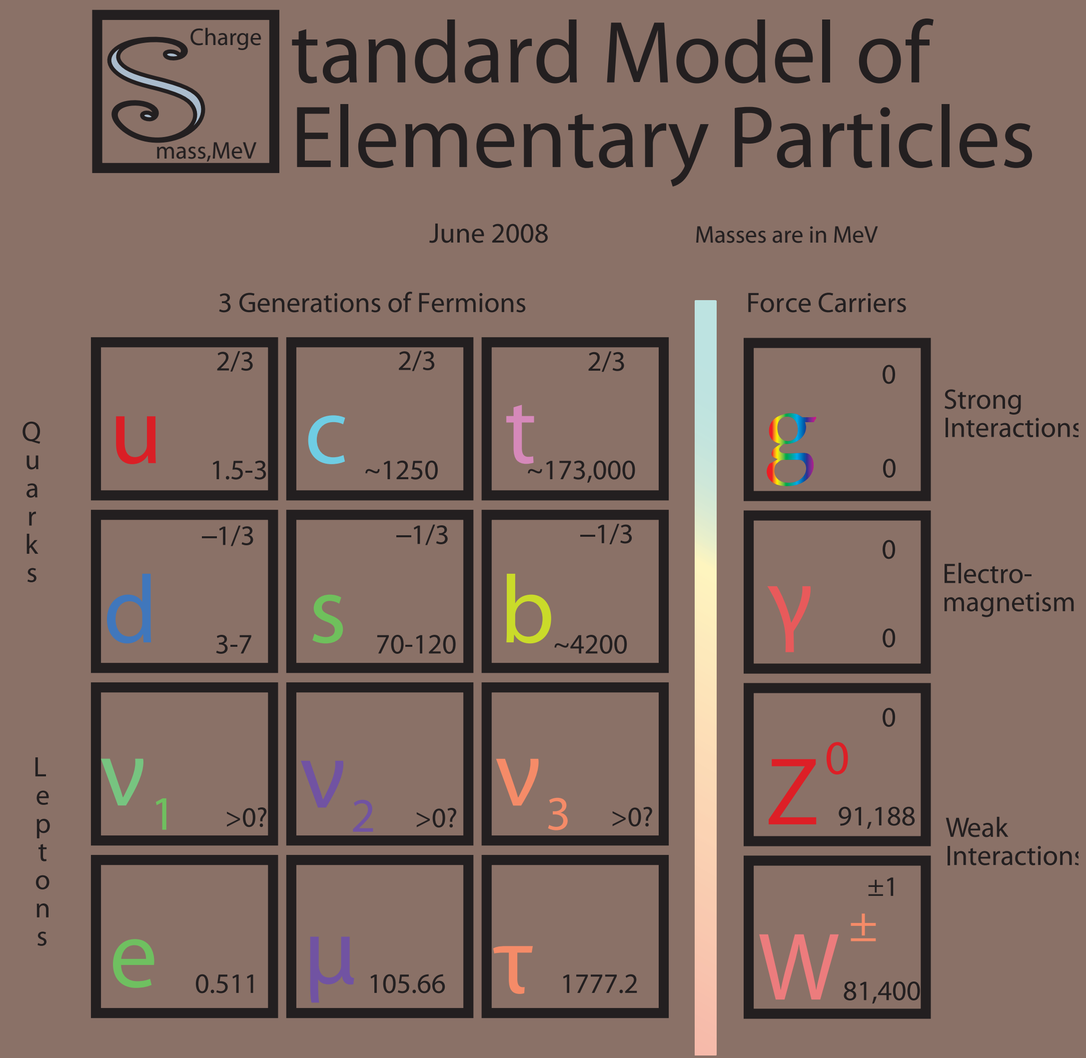


DATA REDUCTION

In these lectures

- Use an example, Z production at D0 to show how a data analysis is actually done.
- Theory has been covered by Pavel Nadolsky
- Lecture by W. Smith next week will say more about triggers/measurements at the LHC
- Neutrinos and DIS in the discussion

Warning!

- Plots are mixed and matched between
  - Z→ μμ Gavin Hesketh and Andrew Kobach
  - Z→ ee - Lei Wang, Hang Yin and Junjie Zhu
  - Jets – Levan Babukhadia and Mikko Voutilainen

HEP Units

Energy is measured in eV, the energy picked up by an electron in going through 1V potential.

1 GeV is 10^9 electron volts or

1 GeV = 1.602×10^{-10} Joules

Momentum is measured in GeV/c

Mass is measured in GeV/c^2

so $M^2c^4 = E^2 - c^2p^2$ can be calculated

with 'c=1'

M(proton) = 938 MeV/c^2

M(electron) = 0.511 MeV/c^2

γ = 959 for a 900 GeV Proton

β = 0.9999994

Example: The proton energy in the Tevatron is 960 GeV

There are 10^{12} protons in the machine.

E_{beam} = 960 GeV*10^{12} = 1.7×10^5 J

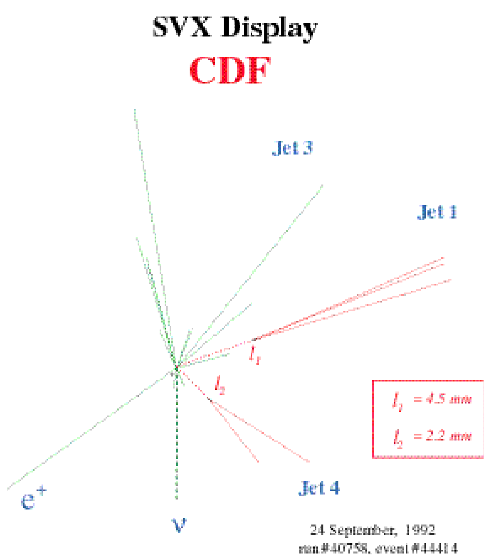
More on Units

The speed of light is

3×10^{8} m/sec

For a particle travelling at 'c'

1 nsec ~ 1 foot.



Example:

B meson as a lifetime in rest frame of τ

$= 1.5 \times 10^{-12}$ sec

and mass of ~ 5 GeV/c^2

$N(t) = N_0 e^{-t/\tau}$ in rest frame

a 50 GeV B meson has $\gamma = 10$

and time-dilated lifetime of

$t = \gamma\tau \sim 1.5 \times 10^{-11}$ sec

It will travel ~4.5 mm on average.

Even more on Units

Quantum mechanics gives particles wavelengths related to their energy

$\lambda = hc/E$

A particle needs E > hc/r to probe size scale r.

hbar = 197 MeV - fm

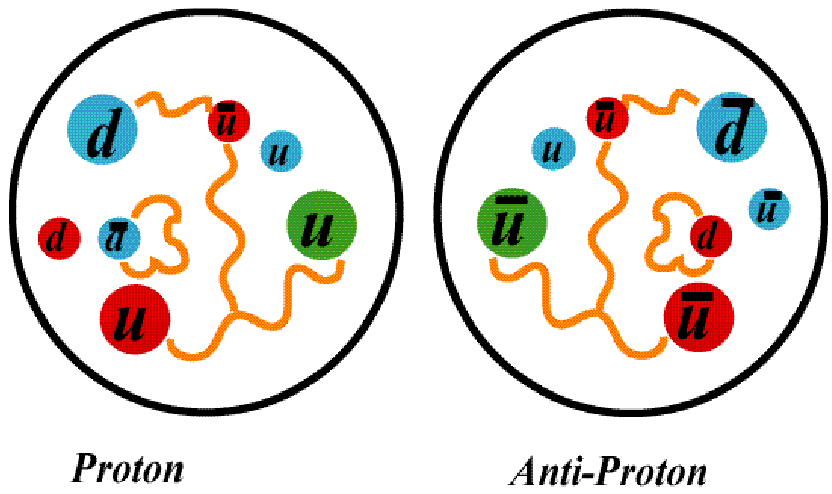
- 1 fm = 10^{-15} m
- Nucleii are 1-10 fm in size. This is the range of the strong force.
- Particles of E > 200 MeV can probe nuclear scales
- 900 GeV proton can probe

  r ≅ 197 MeV - fm /900 GeV

  ~ 2 x 10^{-19} m

Protons and Anti-protons

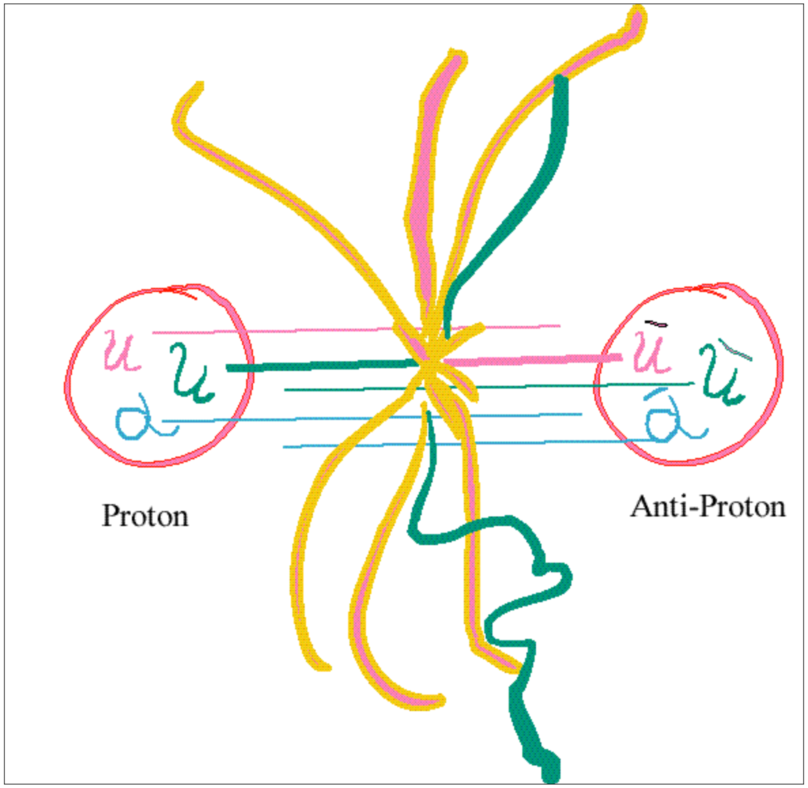
- All physics at hadron colliders starts with the collision of a proton with an antiproton (at the Tevatron) or another proton at the LHC.
- Protons are made up of quarks, anti-quarks and gluons collectively called Partons



Proton-AntiProton Collisions

- Collide a 980 GeV proton with a 980 GeV antiproton going in the opposite direction

$$E_{tot} = E_p + E_{pbar} = 1960\,GeV$$
$$\vec{P}_{tot} = \vec{P}_p + \vec{P}_{pbar} = 0$$
$$Q_{tot} = 0$$
$$Mc^2 = \sqrt{s} = \sqrt{E_{tot}^{\ 2} - |c\vec{P}_{tot}|^2} = 1960\,GeV$$

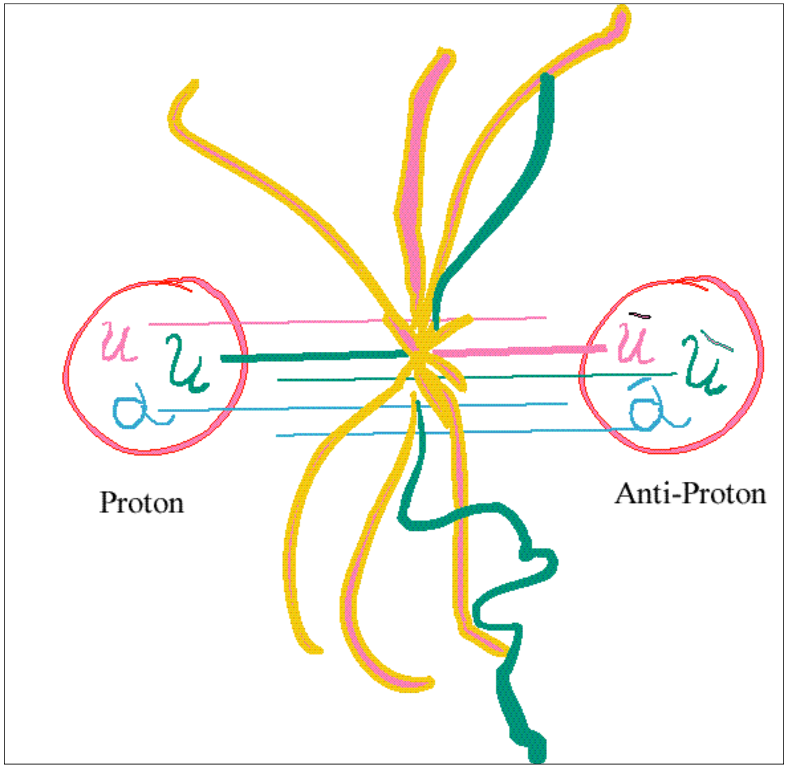


But the partons that collide only carry part of the proton momentum

Proton Anti-Proton Collisions

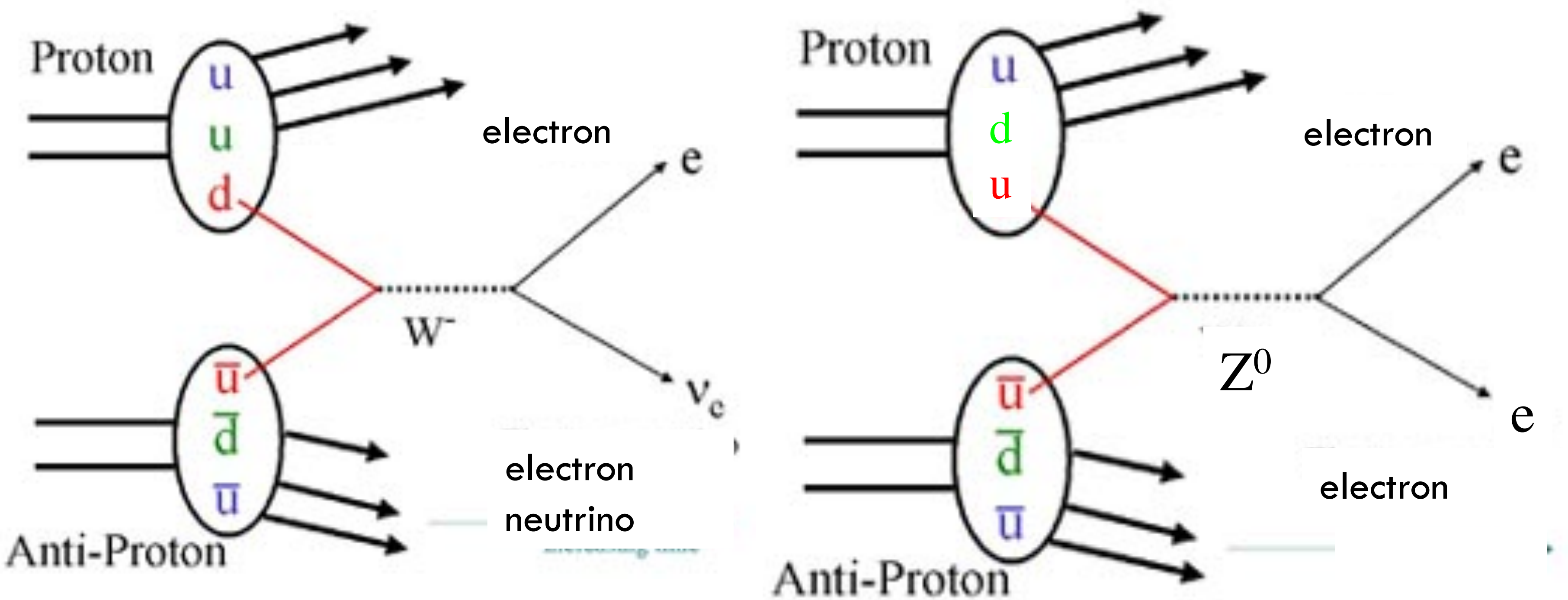
- When a proton and anti-proton collide, the hard part of the collision is actually two partons, which carry fractions x_1 and x_2 of the proton/antiproton momenta

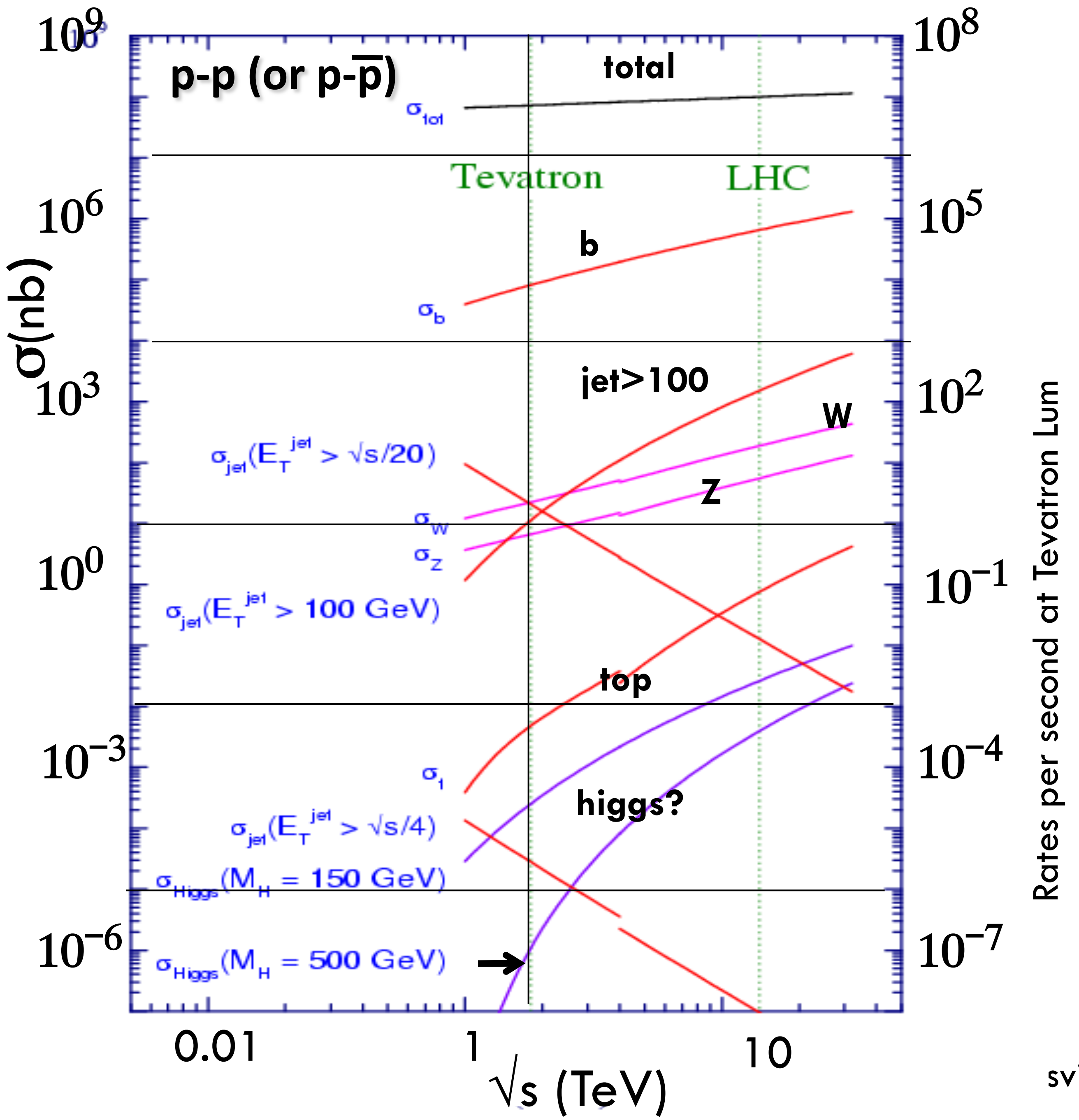
$$E_{hard} = x_1 E_p + x_2 E_{\overline{p}} = (x_1 + x_2) E_{beam}$$
$$\vec{P}_{hard} = \vec{P}_p + \vec{P}_{\overline{p}} = (0, 0, x_1 - x_2) E_{beam}$$
$$M^2_{hard} = E^2_{hard} - |\vec{P}_{hard}|^2 = 4 x_1 x_2 E^2_{beam}$$



Can get anything between 0 -1800 GeV/c^2

W and Z production





p-p (or p-p̄)
total
σ_{tot}
Tevatron
LHC
b
σ_b
jet>100
W
Z
$\sigma_{jet}(E_T^{jet} > \sqrt{s}/20)$
σ_W
σ_Z
$\sigma_{jet}(E_T^{jet} > 100\ GeV)$
top
σ_t
higgs?
$\sigma_{jet}(E_T^{jet} > \sqrt{s}/4)$
$\sigma_{Higgs}(M_H = 150\ GeV)$
$\sigma_{Higgs}(M_H = 500\ GeV)$
σ(nb)
10^9
10^6
10^3
10^0
10^{-3}
10^{-6}
10^8
10^5
10^2
10^{-1}
10^{-4}
10^{-7}
Rates per second at Tevatron Lum
0.01
1
10
$\sqrt{s}$ (TeV)

sville

Parts of a cross section measurement

Cross Section

Detector

$$N_{observed} = \Delta t \times \mathrm{L} \times \varepsilon \times \mathrm{A} \times \sigma + \mathrm{B}$$

$ Machine Background

Physical Cross Section

L is the Luminosity
$\varepsilon \times$ A is the efficiency X acceptance
B is the Background

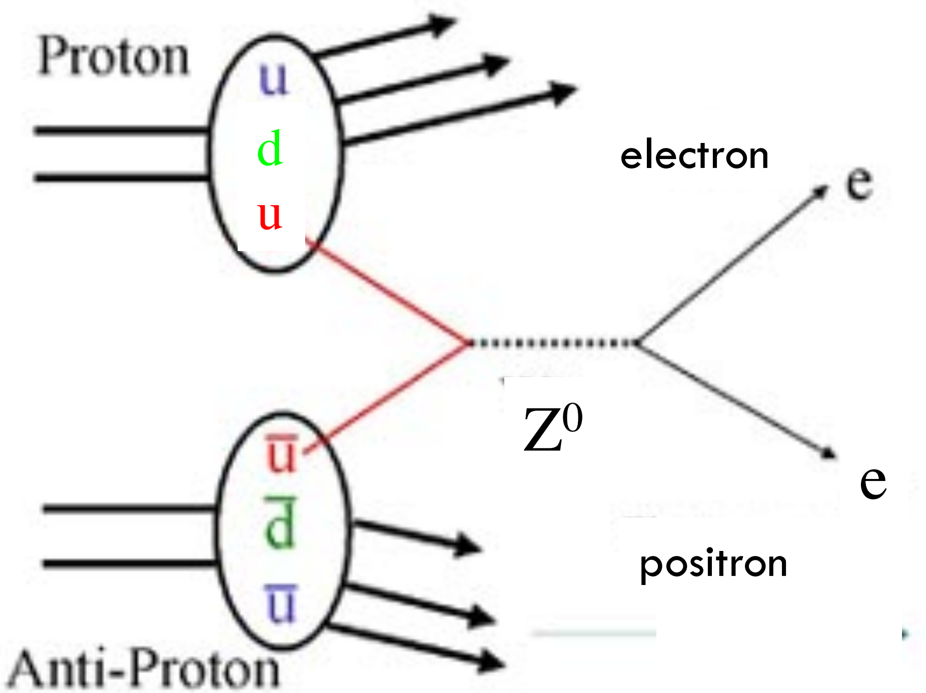
σ is the cross section

The Cross Section will be the same for
any experiment with the same physical conditions

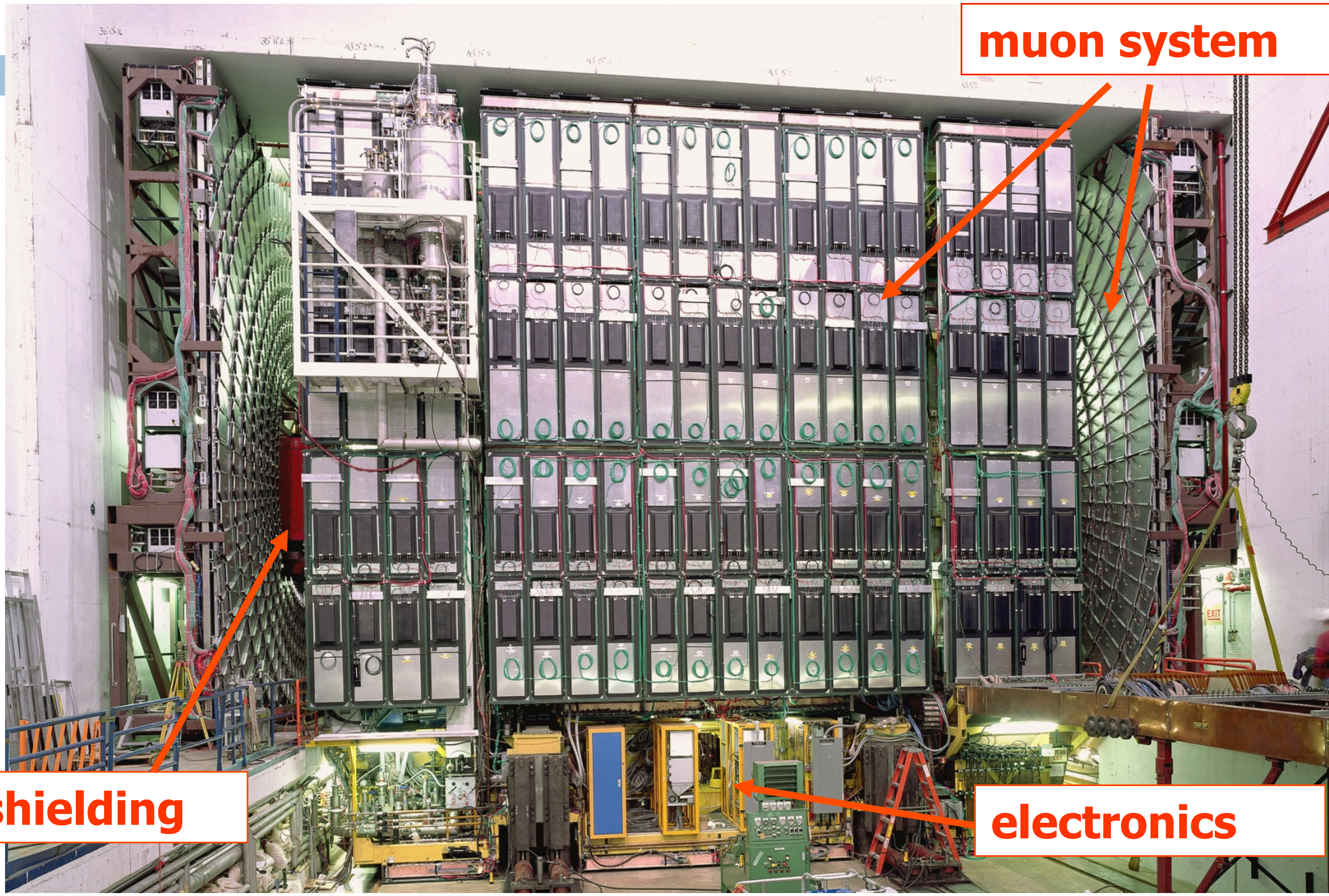
Unit of Cross Section is area
essentially the effective scattering size for the process

First find you signal

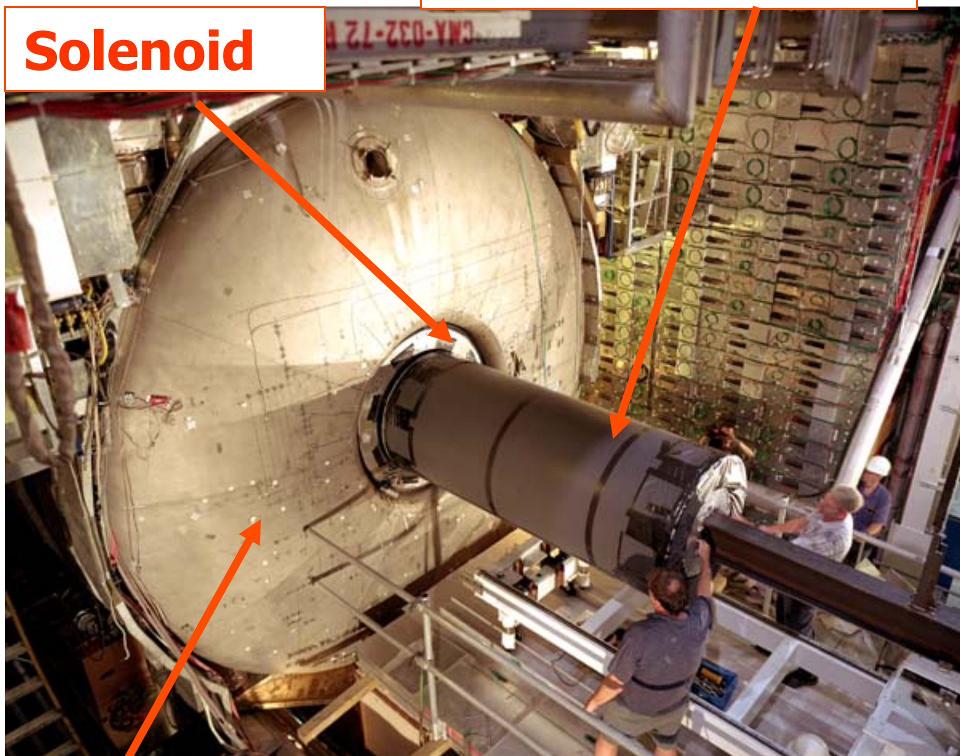
- Easiest way to find a Z boson is to look for:
- Two leptons opposite sign leptons.
  - Tau's are hard
  - Neutrinos are harder
  - B mesons are harder
  - Light quarks are really hard

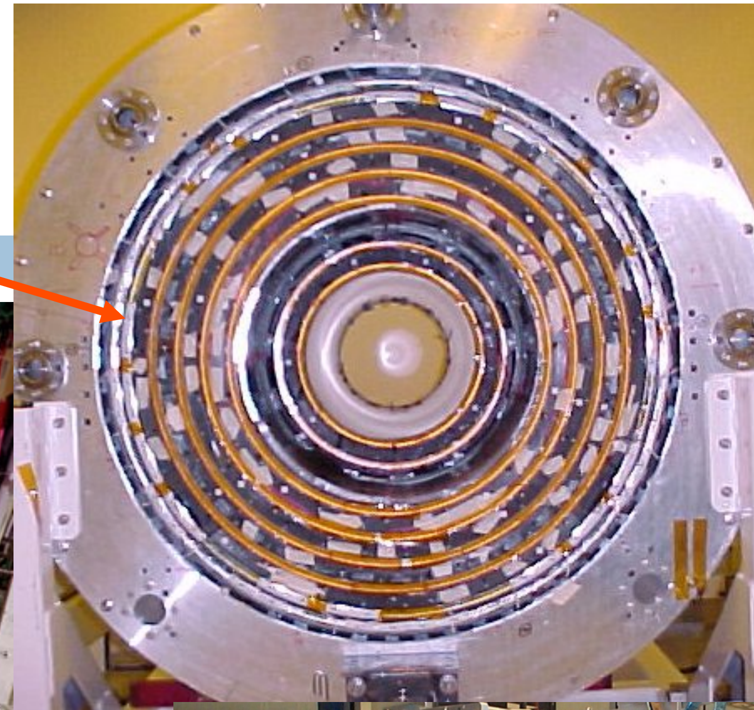


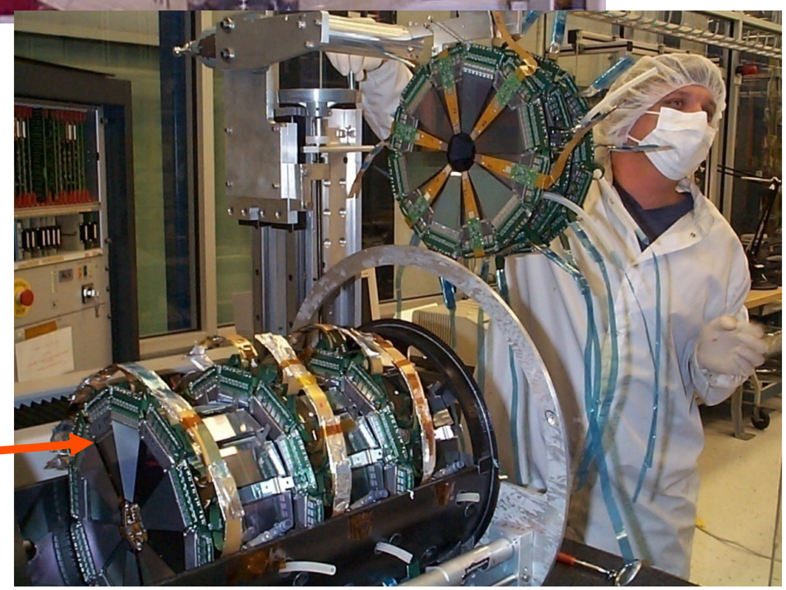
First build a detector



DØ Detector







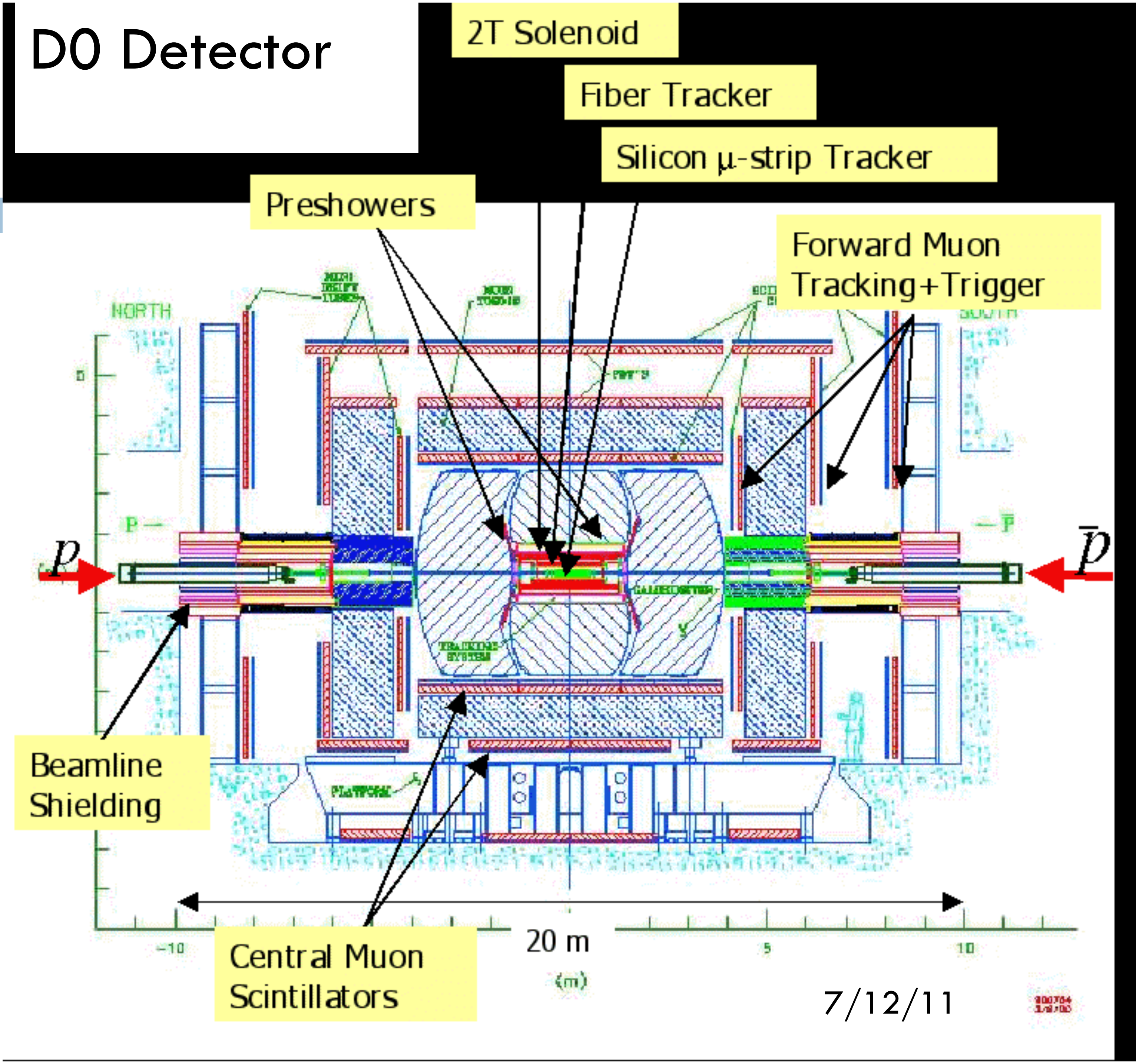
Fiber Tracker

Solenoid

Central Calorimeter

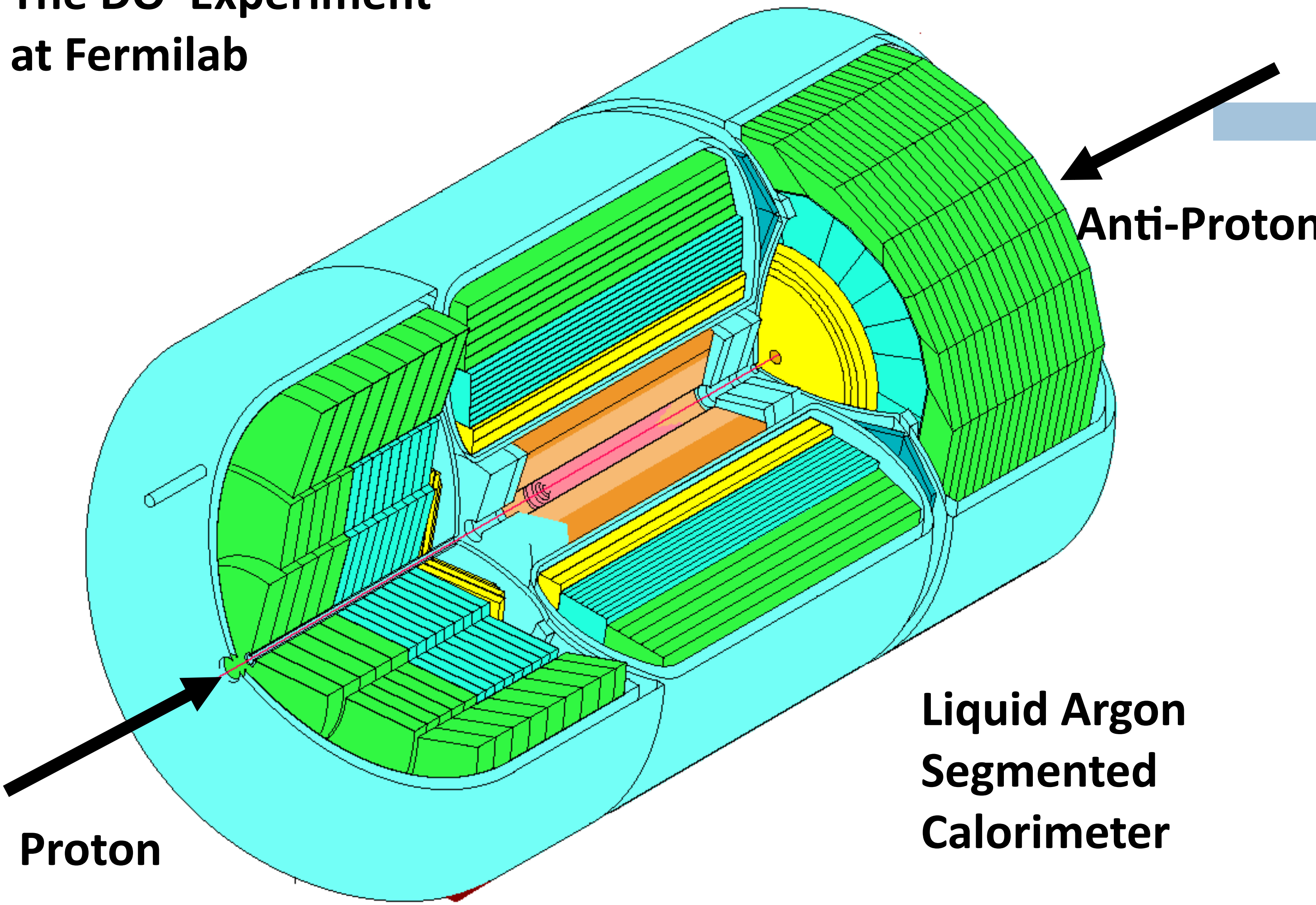
Silicon

D0 Detector

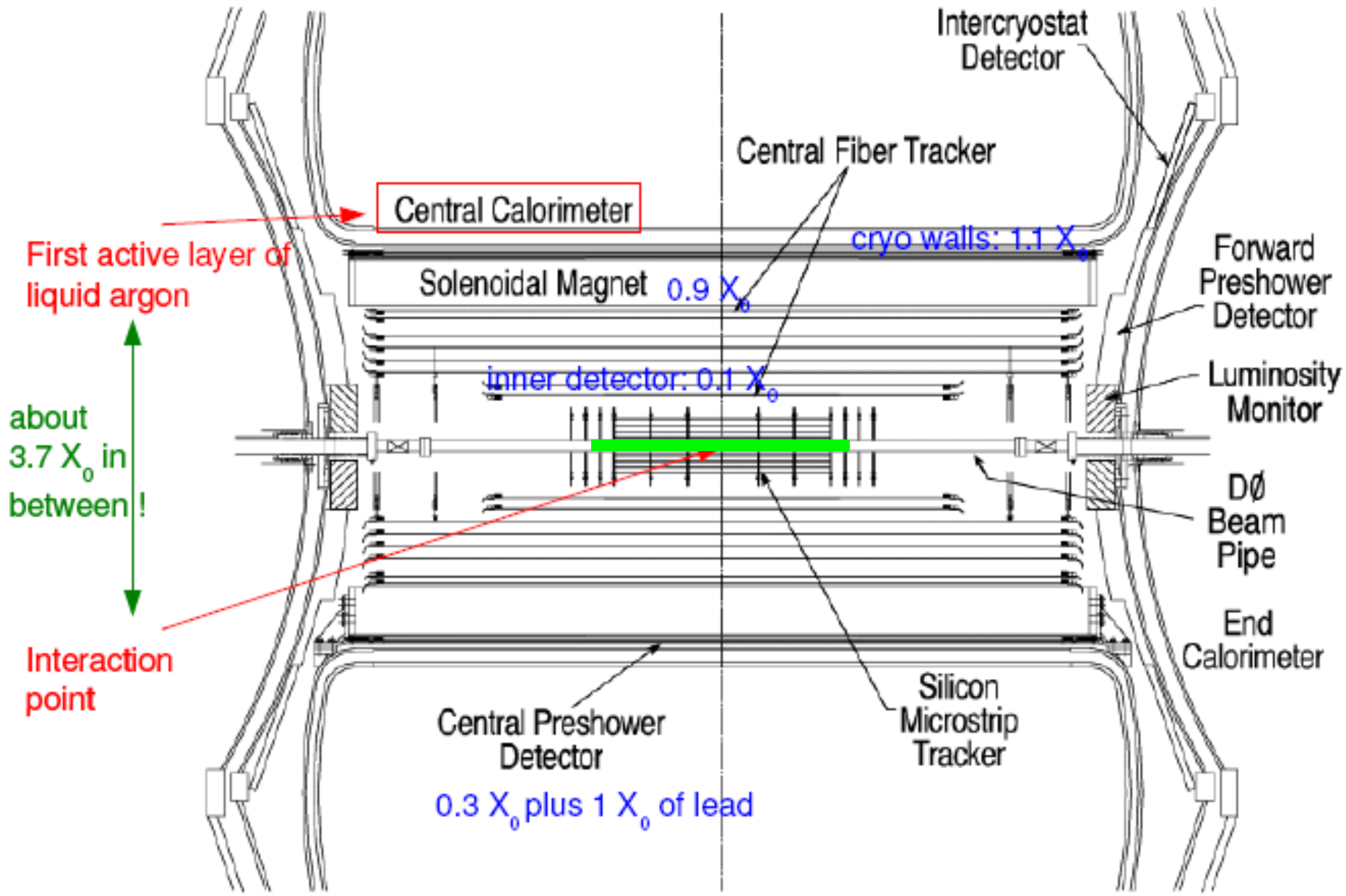


2T Solenoid
Fiber Tracker
Silicon μ-strip Tracker
Preshowers
Forward Muon Tracking+Trigger
NORTH
p
$\bar{p}$
Beamline Shielding
Central Muon Scintillators
20 m
−10
5
10
(m)

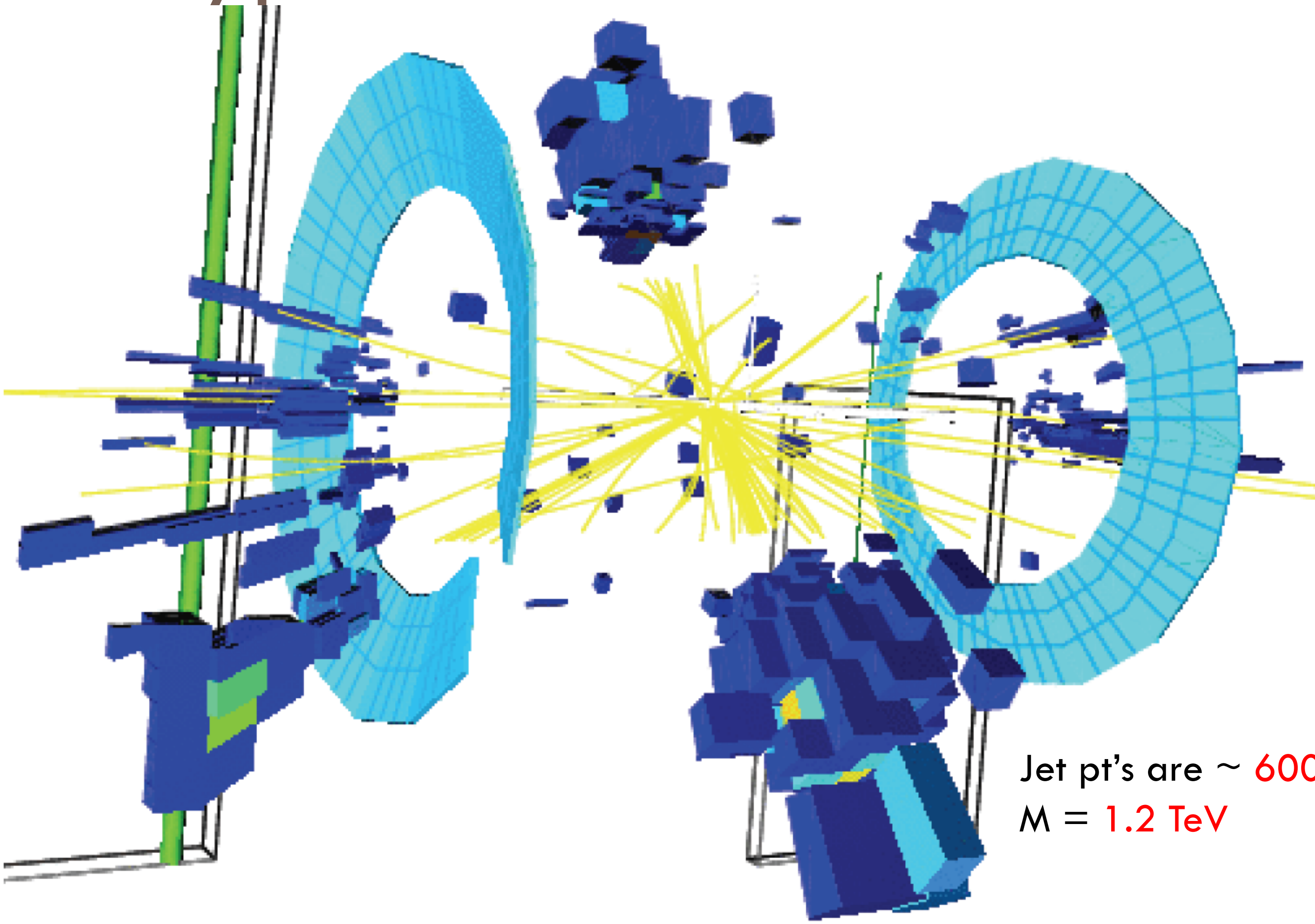
The DO Experiment
at Fermilab



Side view of the D0 tracker/calorimeter



“Typical” event at D0



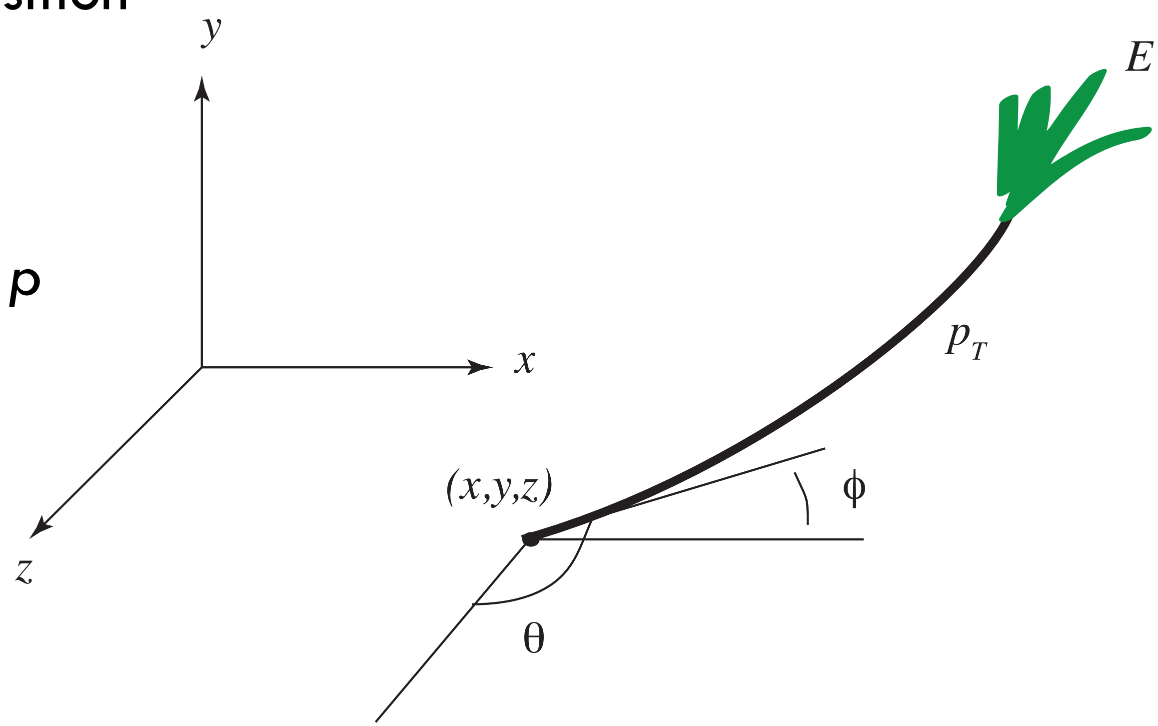
Jet pt’s are ~ 600 GeV
M = 1.2 TeV

How do we detect particles?

- Single charged particles
- Electrons and Photons
- Quarks and Gluons
- Neutrinos

Particle parameters

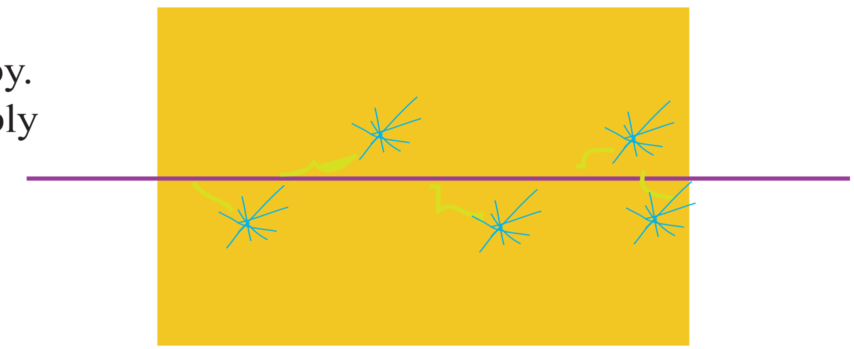
- A trajectory has 6 parameters
- *x,y,z* of starting position
- Polar angle θ
- Azimuthal angle ϕ
- Particle momentum *p*



Charged particle detection

Detection of charged particles

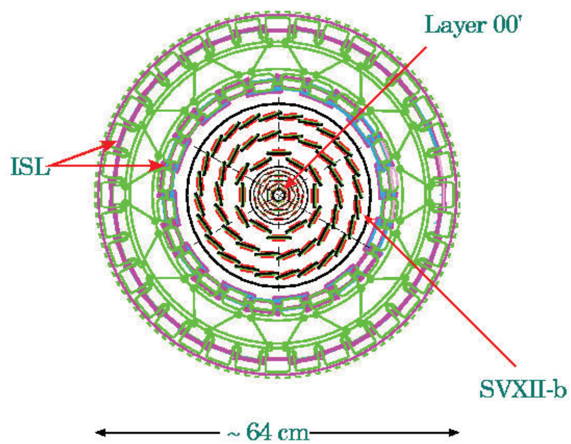
When a relativistic charged particle passes through matter, it knocks electron out of atoms as it passes by. This is what we call 'Energy Loss' and it is reasonably independent of the particle or material type.

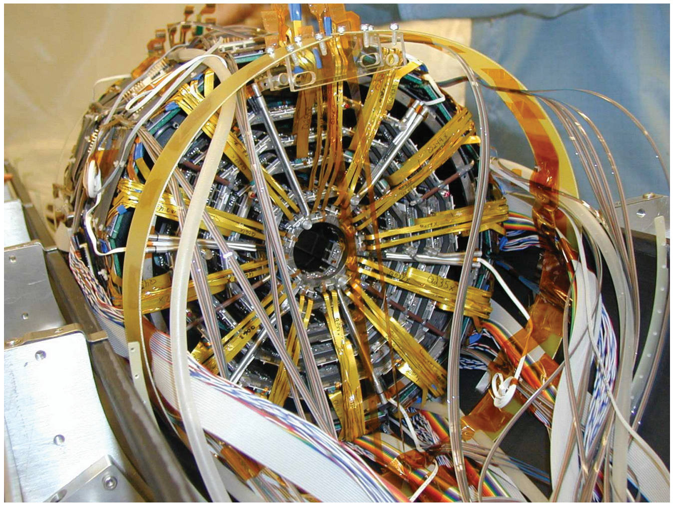


$$dE/dx \sim 2 \text{ MeV/cm x } \rho \text{ [gr/cm}^3\text{]}$$

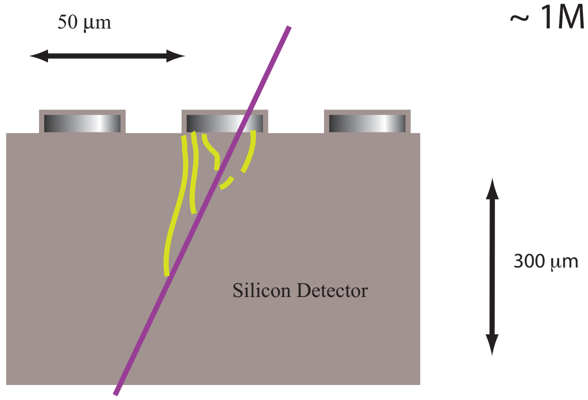
this energy shows up as low energy electrons and photons and can be detected optically or electronically.

Silicon detectors find (x,y,z)





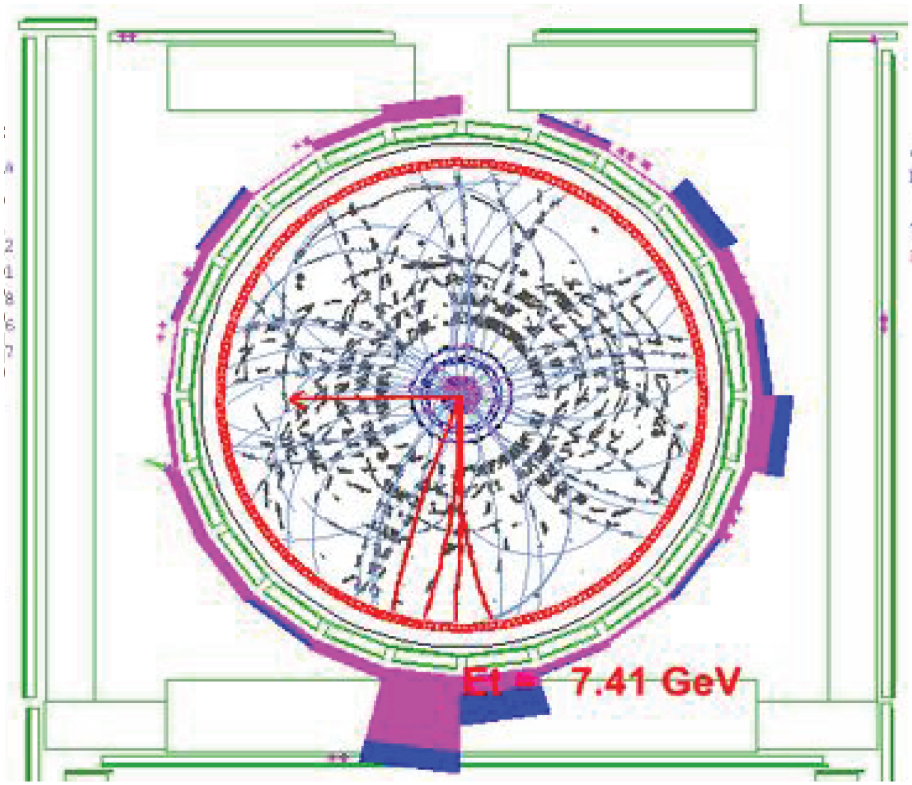
Silicon detectors - CDF SVXIIb
~ 1M channels



Detect ~2000 e in a 350 μm thick detector

Can measure x,y, z to 10-20 μm

Magnetic Tracking



Measure transverse momentum, p_T, θ, ϕ

Magnetic tracking measures the curvature of a track.

The curvature is related to the momentum perpendicular to the field B in Tesla

$$k = 0.3Q \times B/p_T$$

and has approximately Gaussian distributed errors.

$$\delta k \approx \frac{\sigma}{L^2}\sqrt{720/(N+4)}$$

$\frac{\delta p_T}{p_T}$ scales as

$$p_T \times \frac{1}{Q} \times \frac{\sigma}{L^2} \times \frac{1}{B} \times \frac{1}{\sqrt{N}}$$

and is not Gaussian.

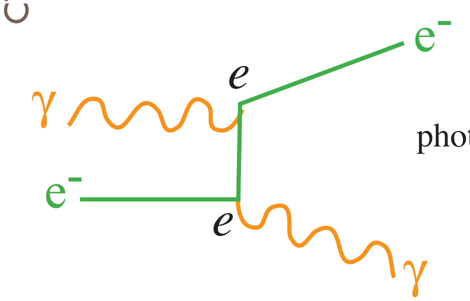
Electron and photon detection

γ

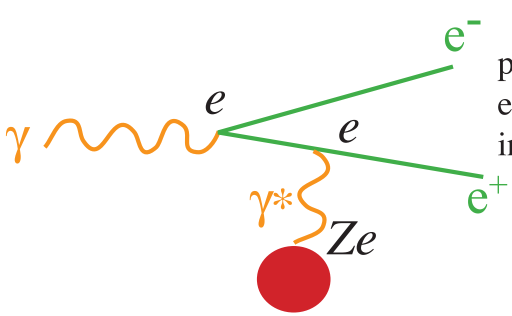
m = 0

Q=0

couples to charge
force carrier for Electro-Magnetism
no strong or weak interaction



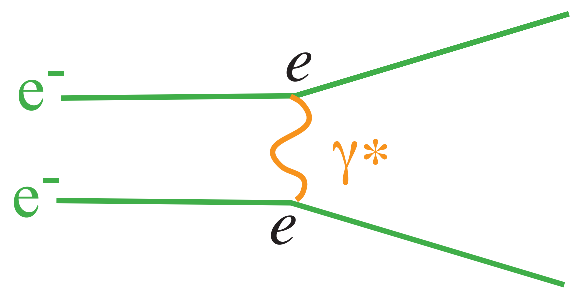
photon-electron scatter

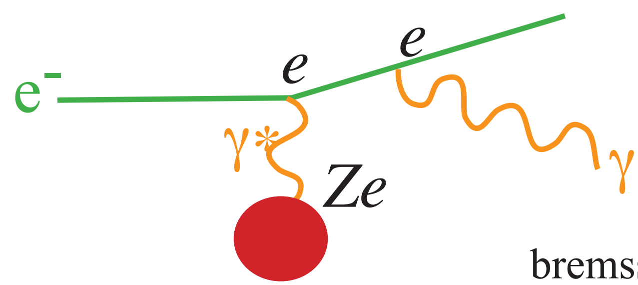


pair-production of
electron/positron
in field of a nucleus

e electron

Q = -e
m = 0.511 MeV/c^2
stable
couples to γ, W, Z

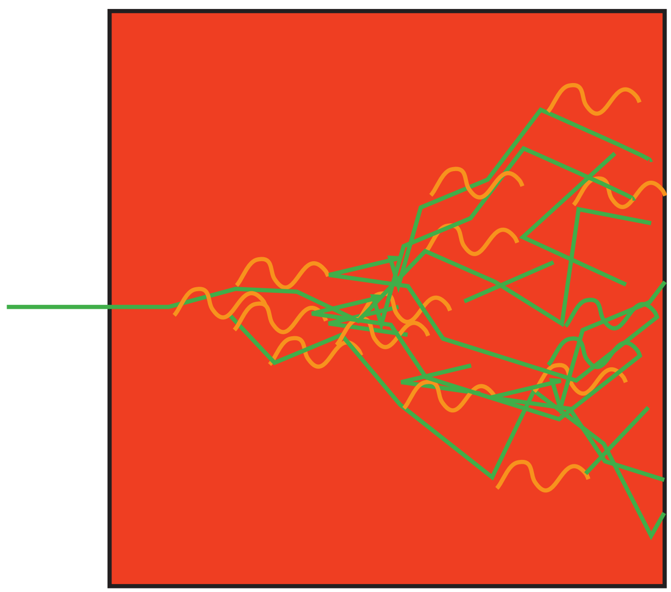




bremsstrahlung

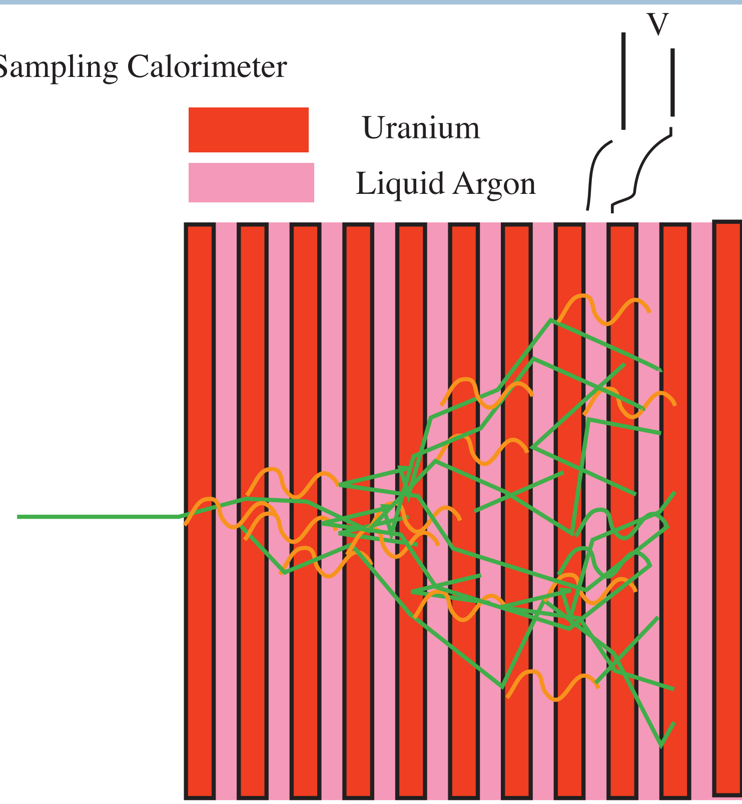
Electromagnetic calorimetry

Electron detection



electron bremsstrahlungs,
photon pair-produces, electrons radiate, products do the same. Length scale for one interaction is
X0 ~ 0.3 cm in lead, 9 cm in silicon
Shower length ~ X0 log(ZE)

Sampling Calorimeter



Electrons knocked loose in the Argon are detected

$$\frac{\delta E}{E} \approx 0.15 \frac{1}{\sqrt{(E, GeV)}}$$

Combine calorimetry and tracking

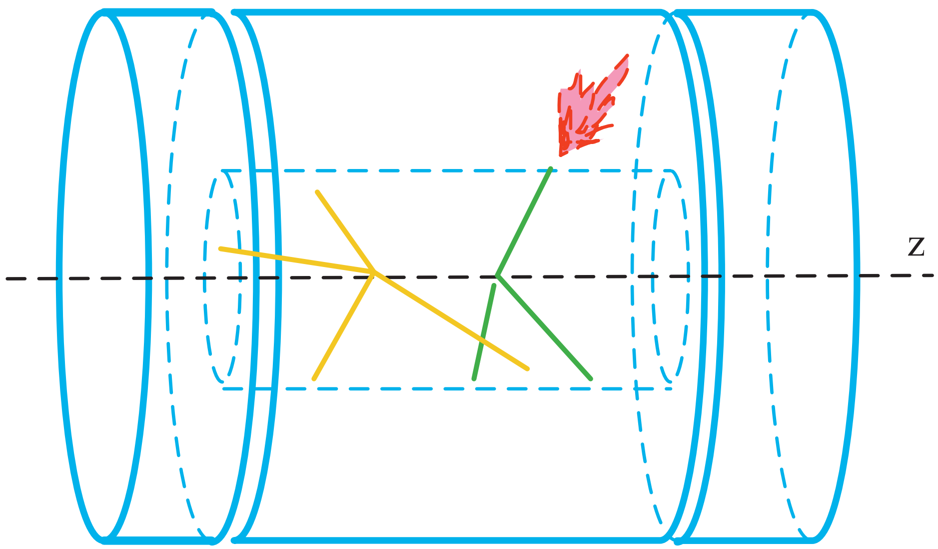
Measure :

Energy and z-ϕ of shower

P_T and θ,ϕ of track

x-y-z of vertex

Know radius R of calorimeter



Derive:

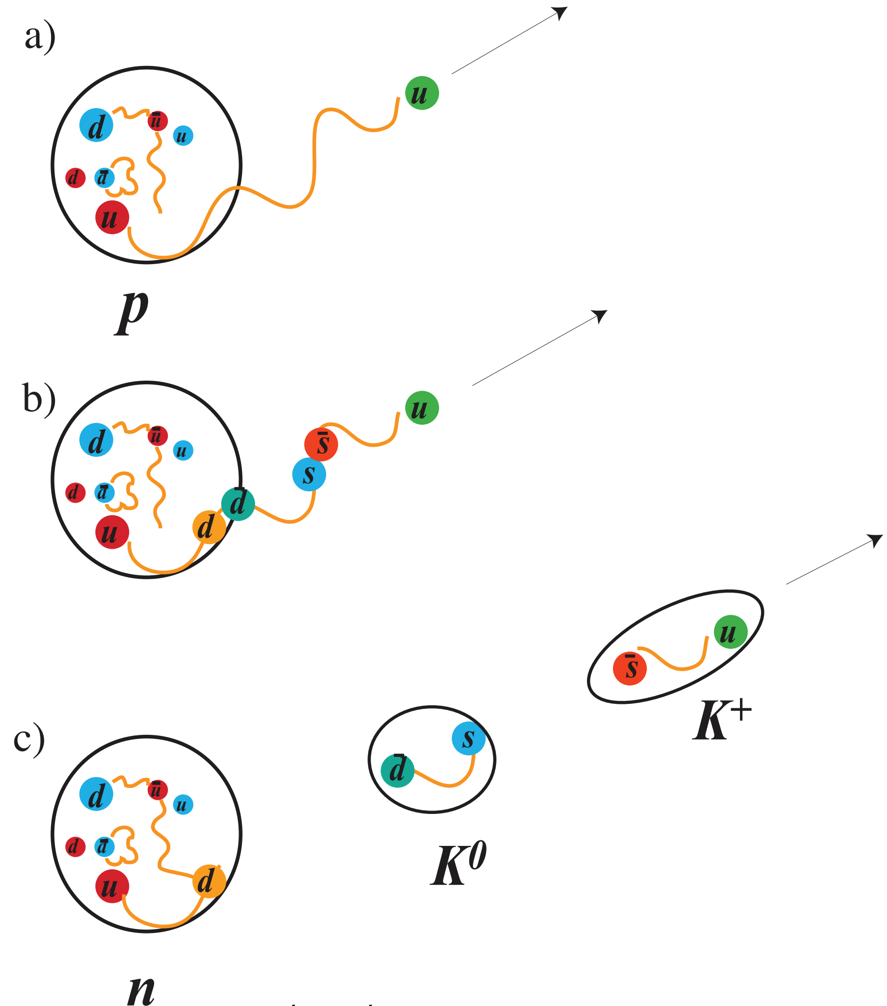
angle θ of shower = $\tan^{-1} R/\Delta z$

P_T of shower relative to beam = $E \sin\theta$

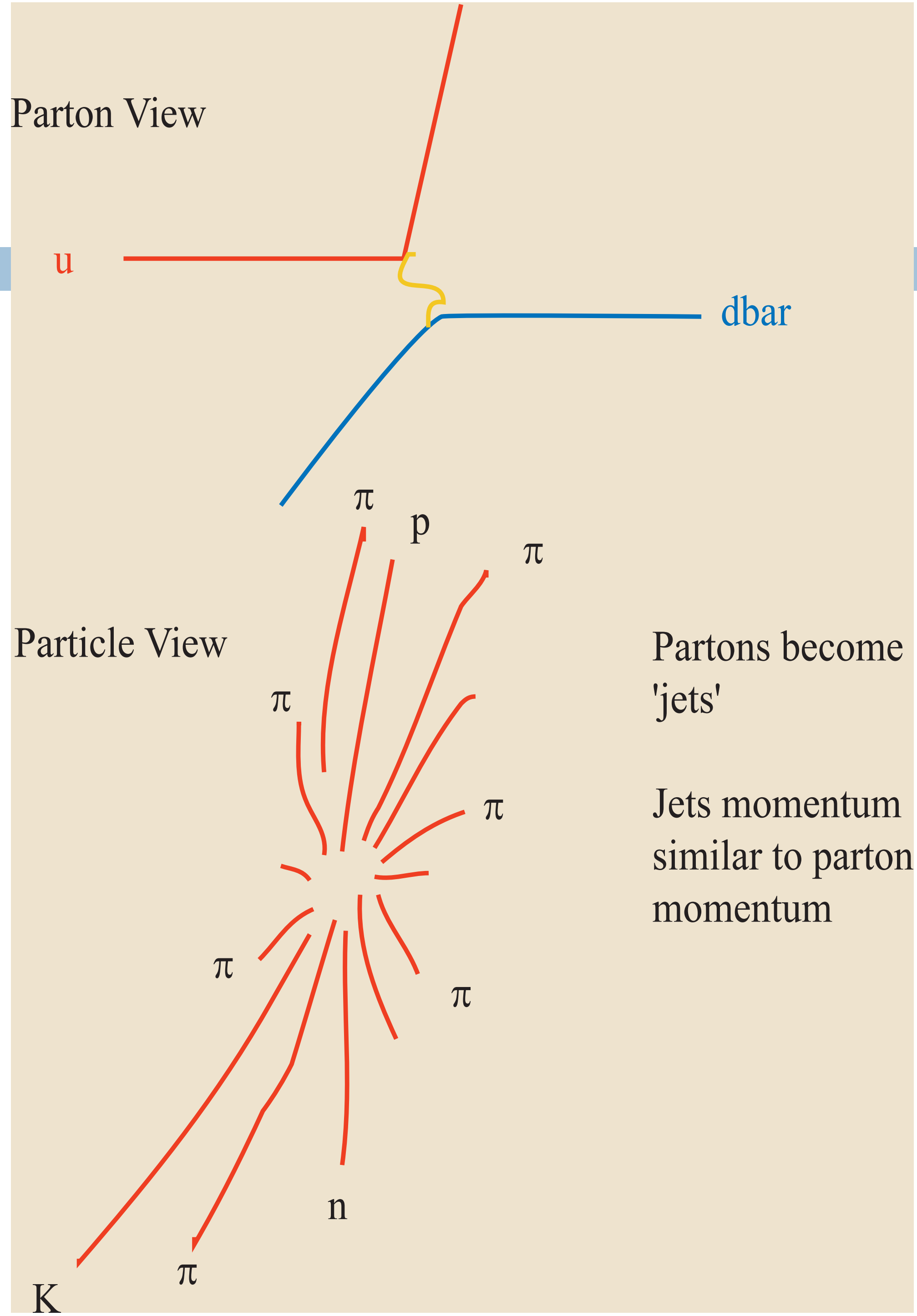
$\eta = -\ln \tan \theta/2$

Quark and Gluon detection

- Quarks and gluons are confined.
- Energetically easier to make new quarks than to separate them.
- If you try to knock one out of a proton
- You get a "jet" of particles



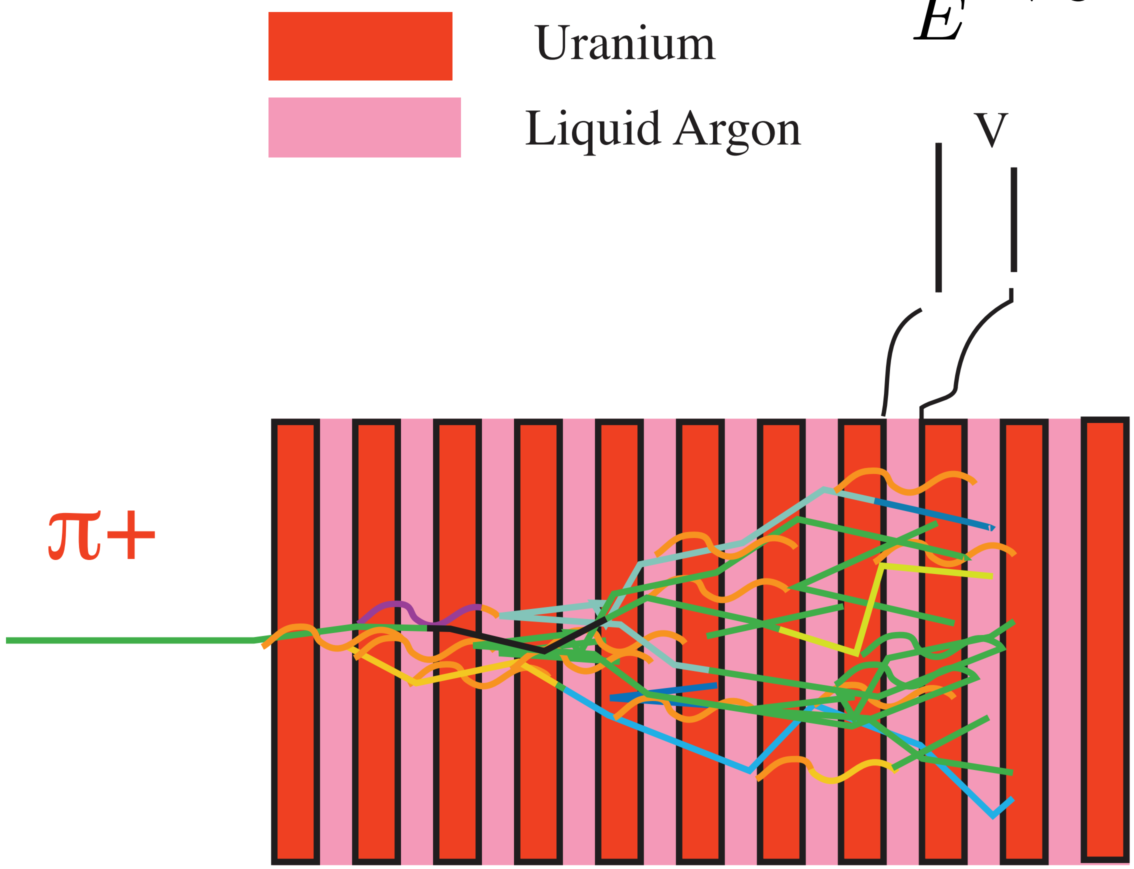
Parton and Particle view



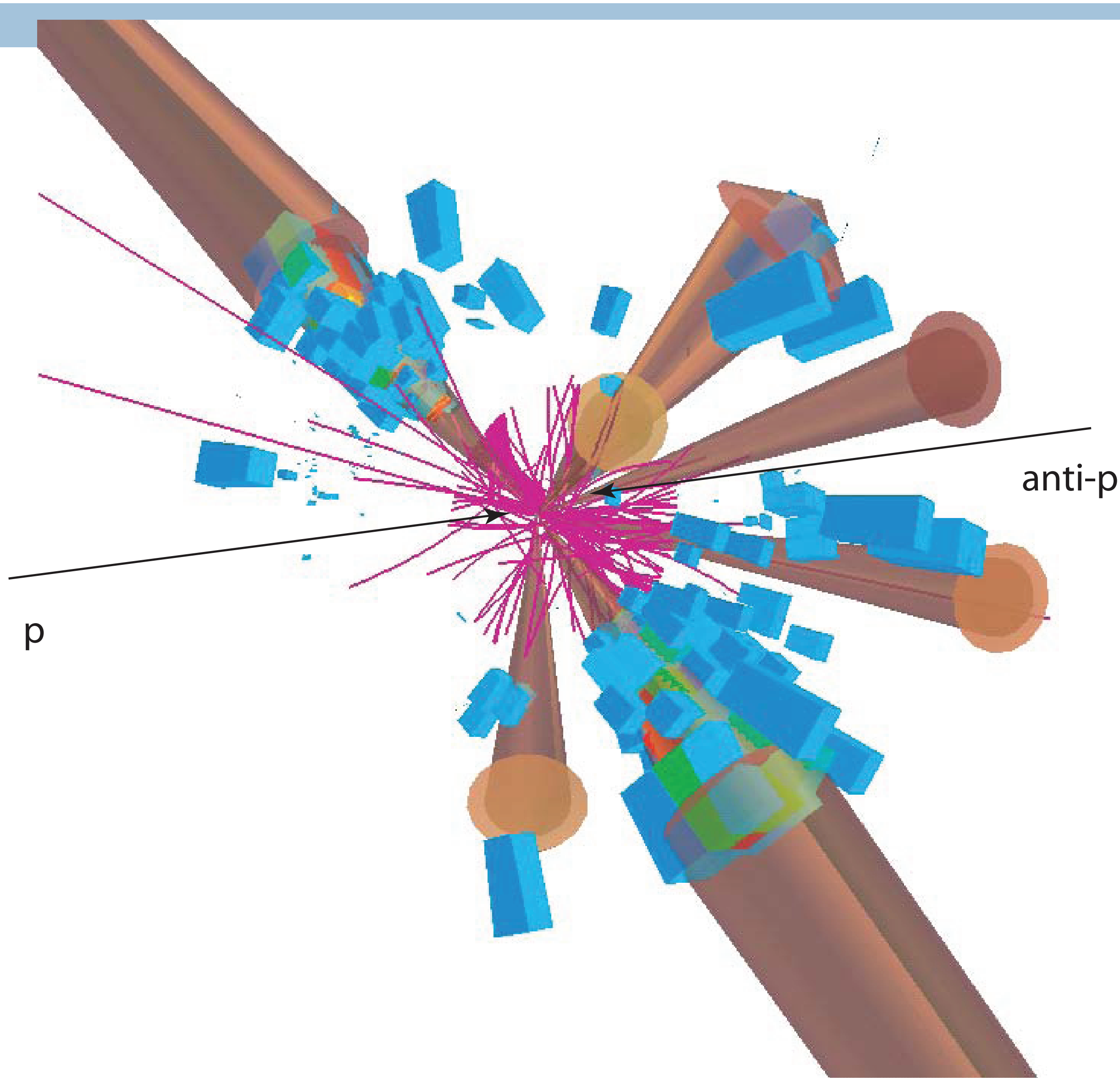
Hadron calorimetry

Sampling Calorimeter

$$\frac{\delta E}{E} \approx 0.50 \frac{1}{\sqrt{(E, GeV)}}$$



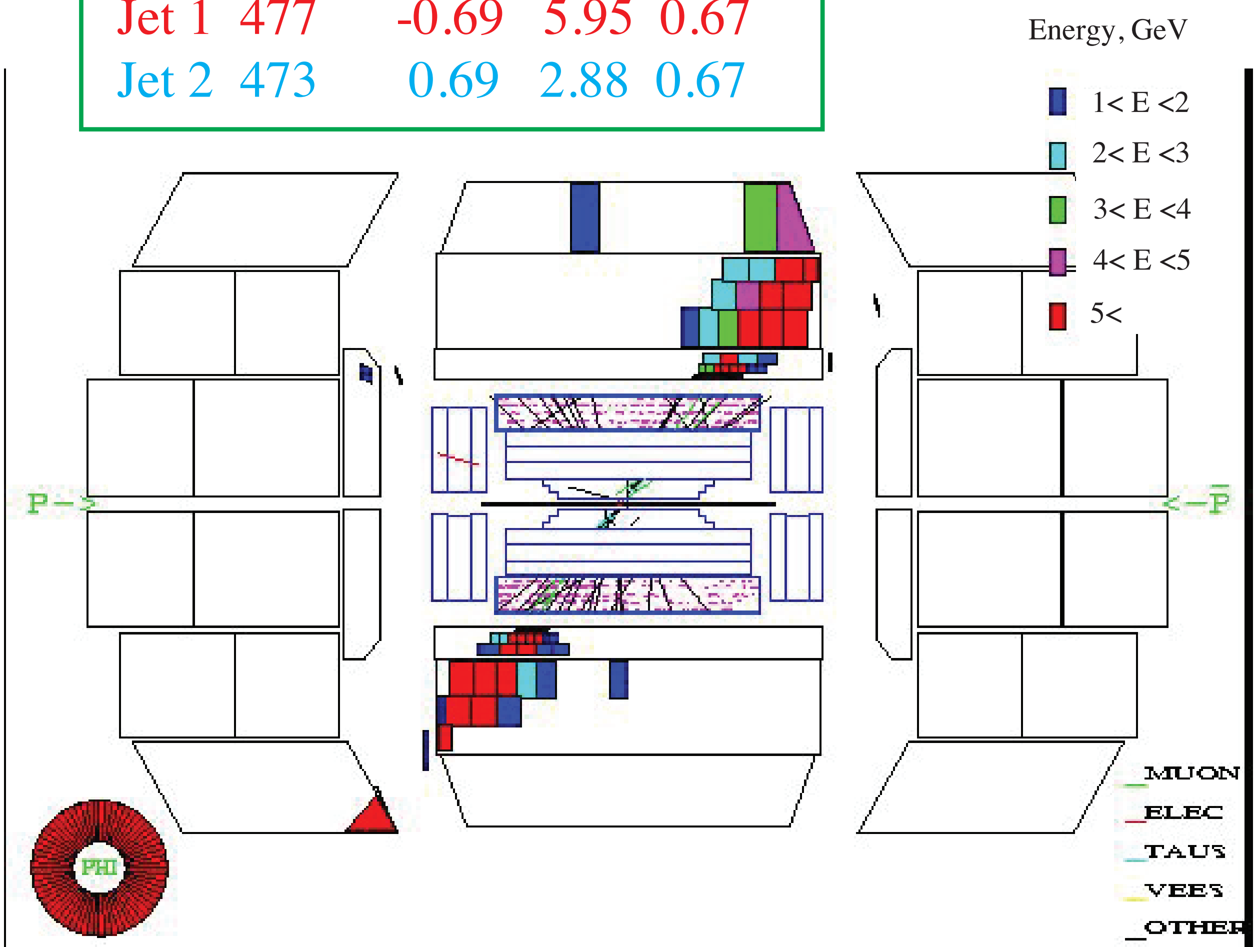
Calorimeter cells and jets



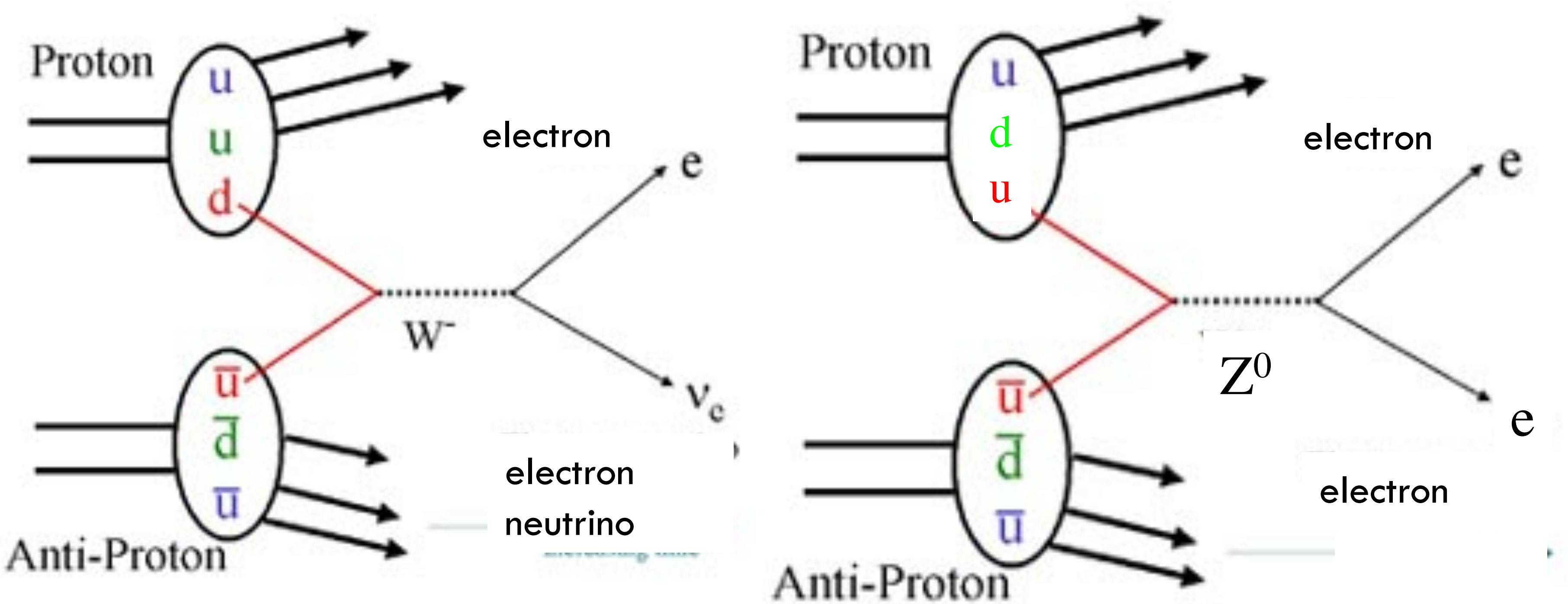
`Typical' Event in the D0 Detector

Missing ET 8.4 GeV $\hat{s}$ = 1187 GeV

	E_T ,GeV	η	ϕ	x_{parton}
Jet 1	477	-0.69	5.95	0.67
Jet 2	473	0.69	2.88	0.67



W and Z production

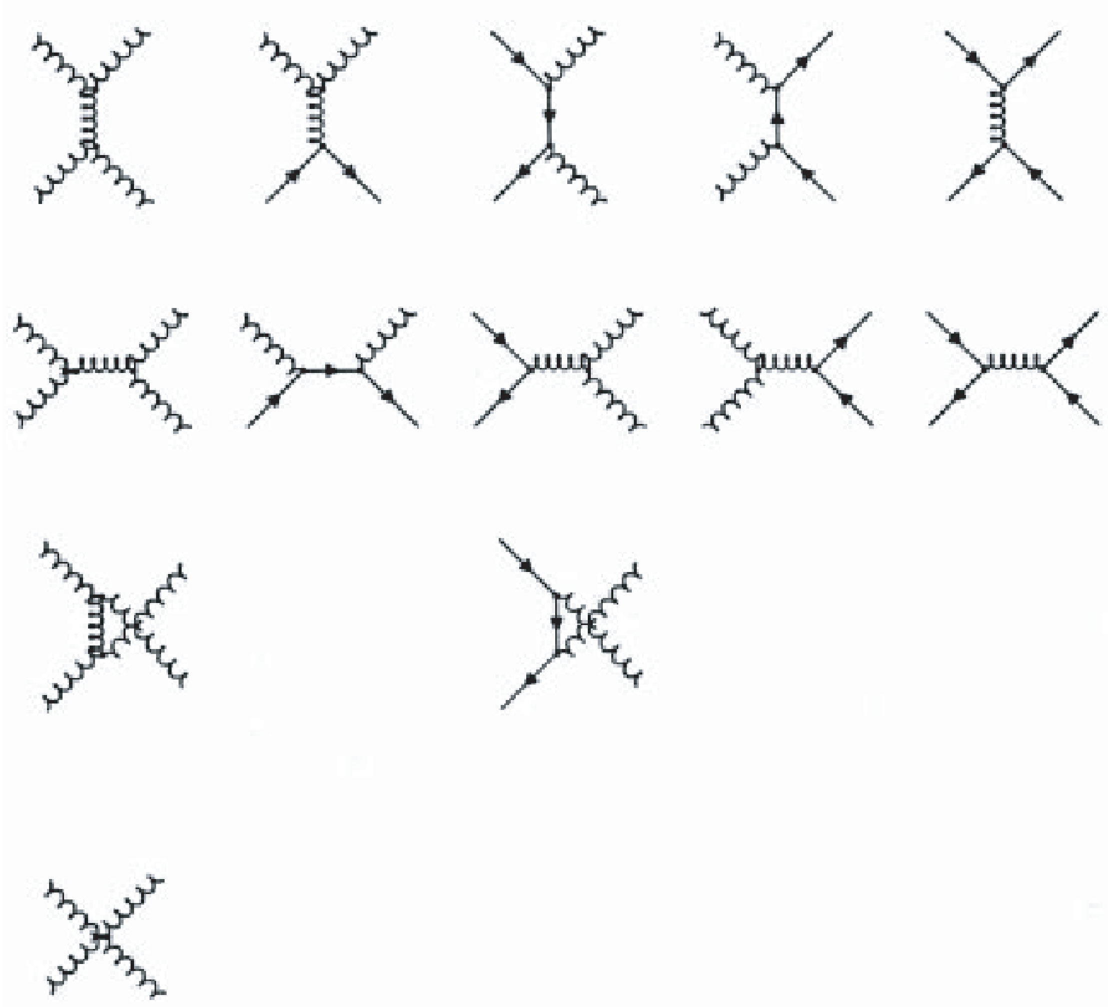


QCD processes at hadron colliders

t channel

s channel

u channel



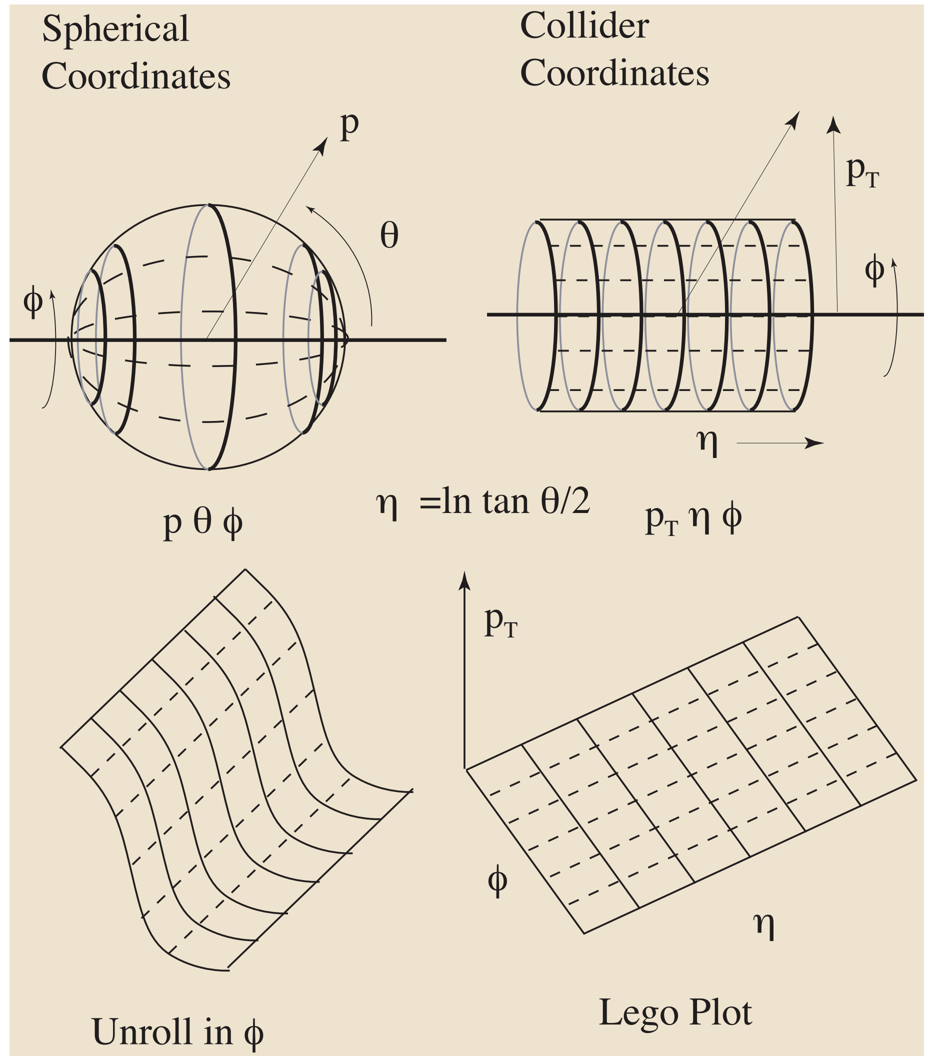
Collider kinematics

CTEQ2011 Schellman

- The initial state is made up of colliding partons.
- The initial state has unknown momentum in the z direction
- Differences in rapidity, y, are invariant under boosts along z.

$$R = \sqrt{\Delta y^2 + \Delta\phi^2}$$

- Defines an invariant distance between particle



Rapidity continued

$$y \equiv \frac{1}{2}\left(\frac{E+p_{\|}}{E-p_{\|}}\right)$$

$$E = \frac{1}{2}e^{y}\sqrt{m^2+p_T^2}$$

Lorentz Invariant Phase Space can be written as

$$\frac{d^3p}{2E} = d\phi\; d\cos\theta\; p^2 dp = d\phi dy dp_T^2 = 2\pi dy dp_T^2$$

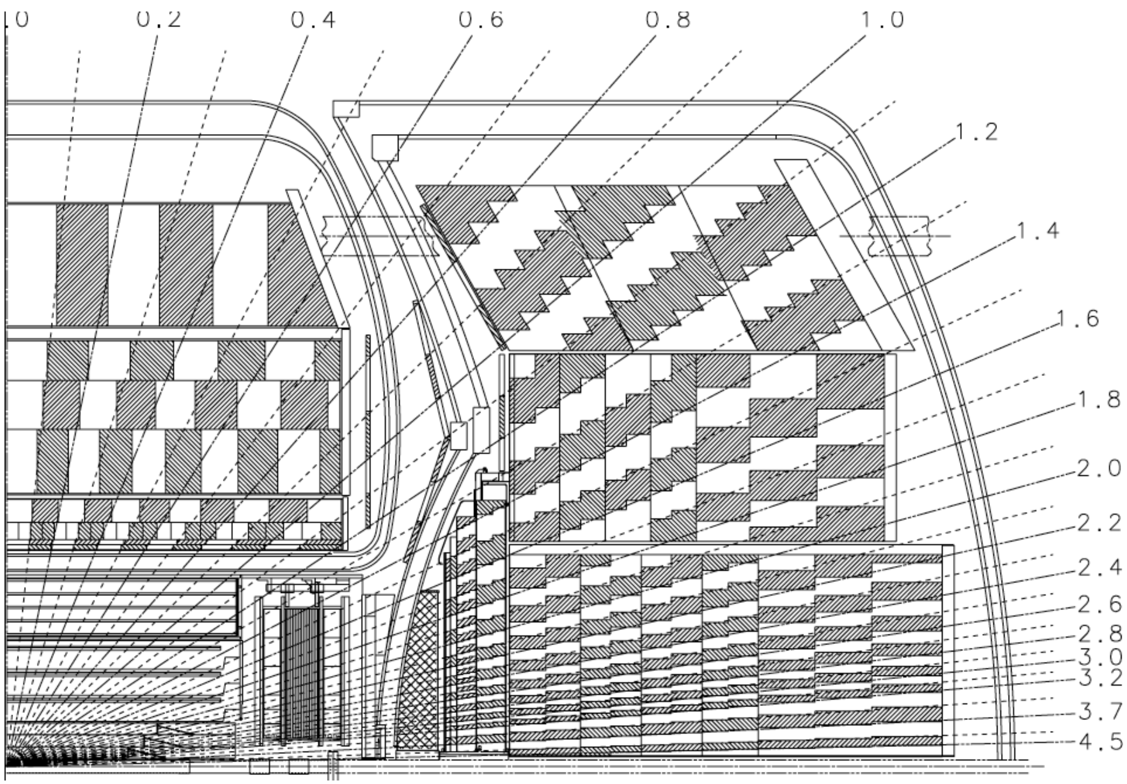
In frame where $p_z = 0$,

$$\delta y \approx \delta\theta + \mathcal{O}(\delta\theta)^3$$

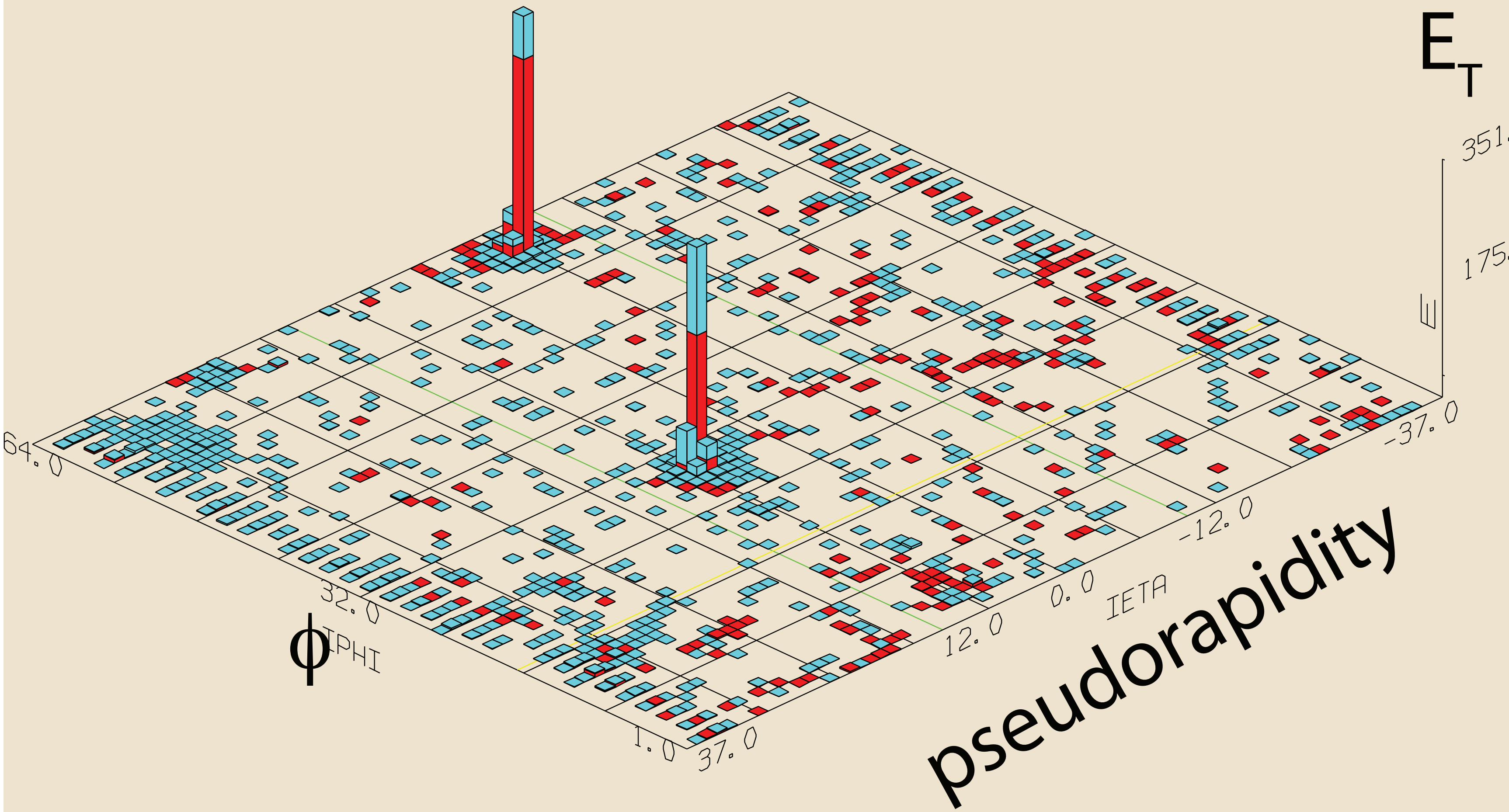
equivalent to small variations in the polar angle θ.

Pseudo-rapidity

For massless particles
the rapidity y reduces to the pseudo-rapidity:

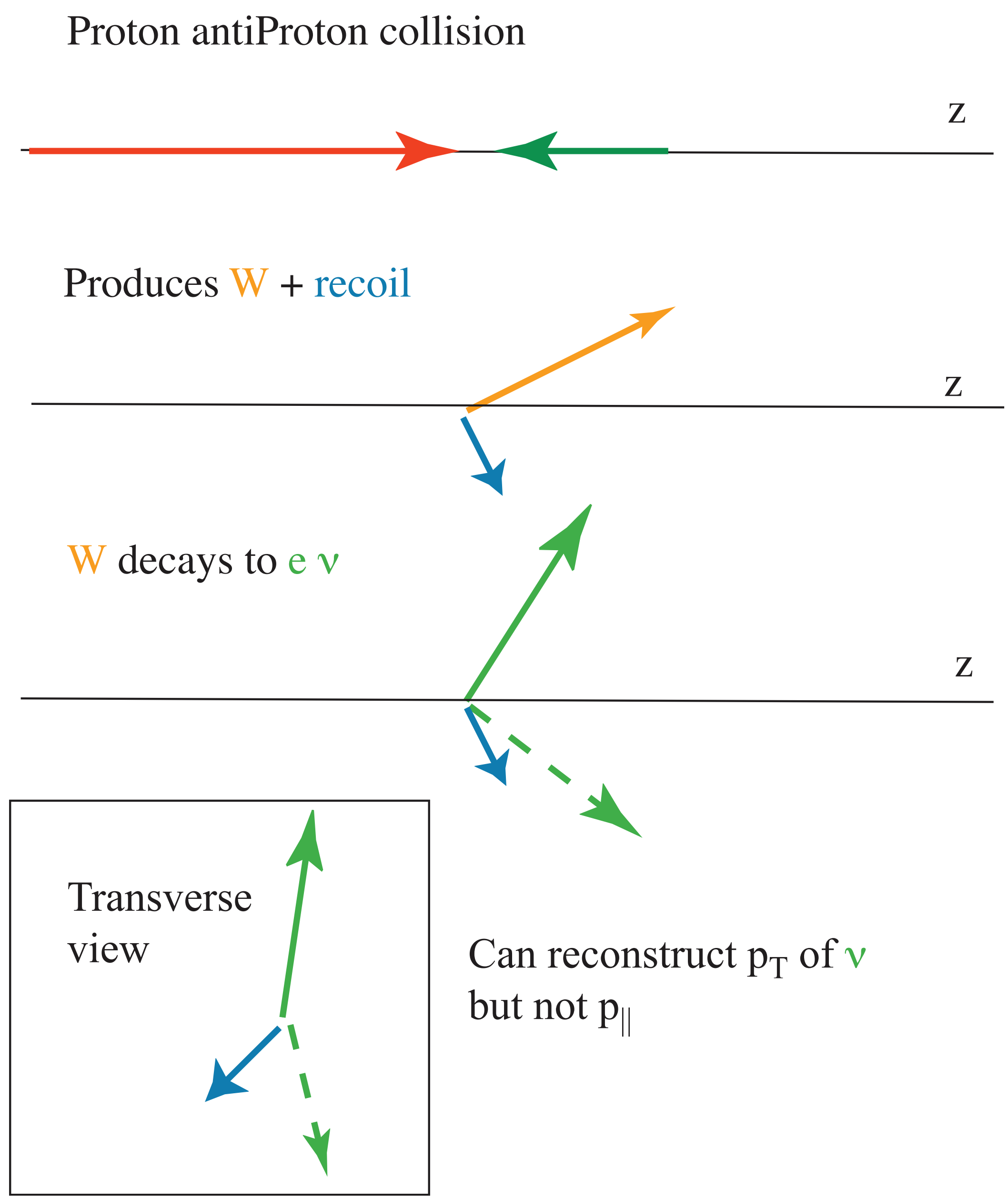


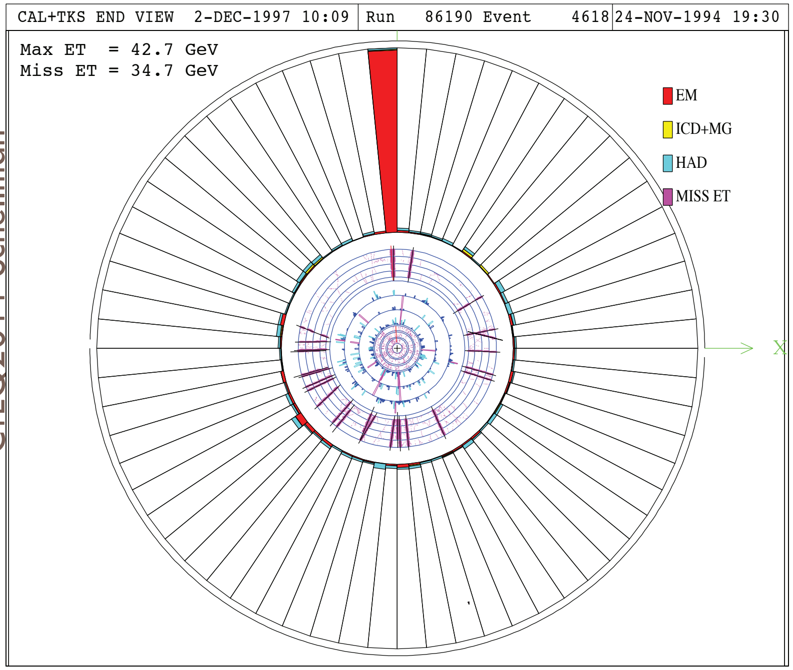
$$\eta = -\log(\tan\frac{\theta}{2})$$

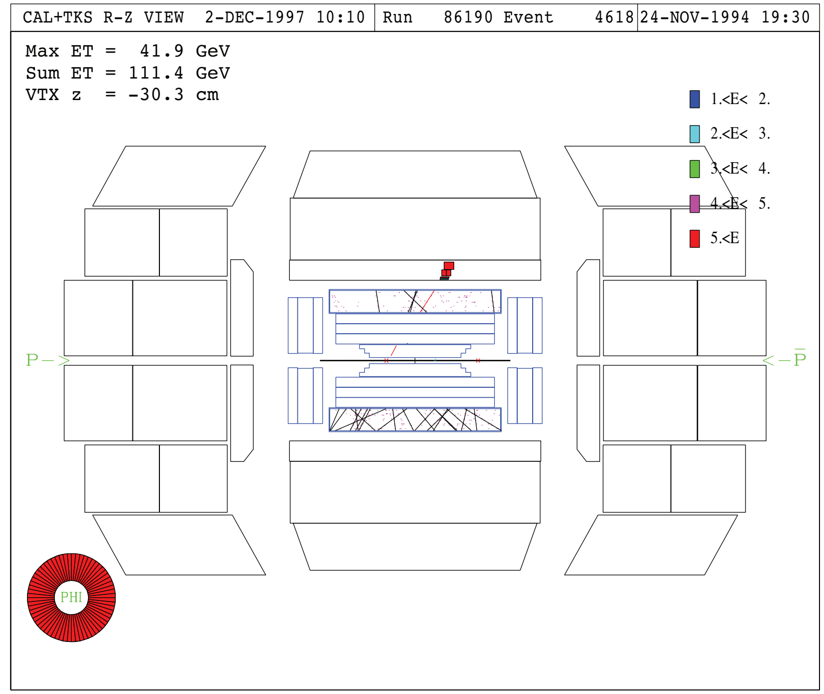

EM E
HAD E
E
T
351.
175.
E
-37.0
-12.0
0.0
IETA
12.0
37.0
64.0
32.0
IPHI
1.0
φ
pseudorapidity

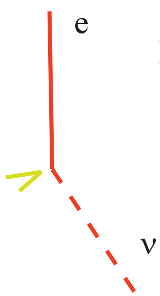
LEGO PLOT

Detecting neutrinos









Infer neutrino direction from momentum balance

Only works perp to beam
PT balance