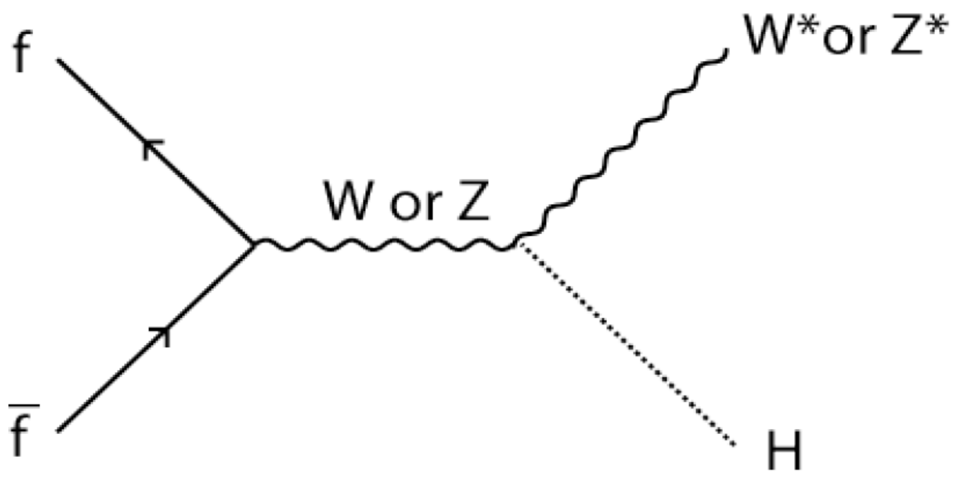
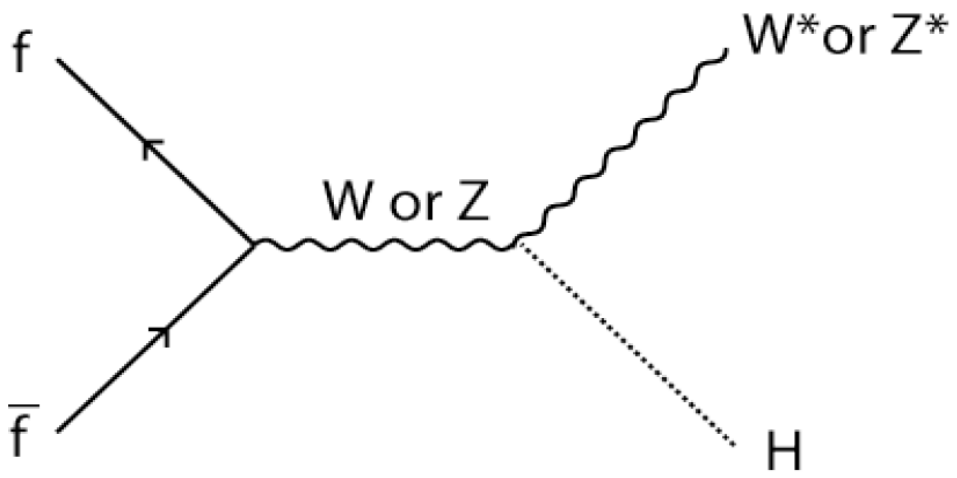
Why Collider Physics ?



W, Z decay to electrons, muons and/or neutrinos

- First order of business from Uncertainty Principle:
  - To probe small-distance phenomena we must scatter particles at high energy
  - What is the center-of-mass energy of a fixed target collision?
    - $(P_{beam} + P_{target})^2 = [\ (p,0,0,p) + (M,0,0,0)\ ]^2 = p^2 + 2pM + M^2 - p^2 \sim 2pM$
    - => collision energy in center-of-mass frame = $\sqrt{(2pM)}$
    - Where p is the energy of the beam and M is the mass of the target
    - To obtain 1 TeV of COM frame energy, and proton target (~1 GeV), need 500 TeV beam energy

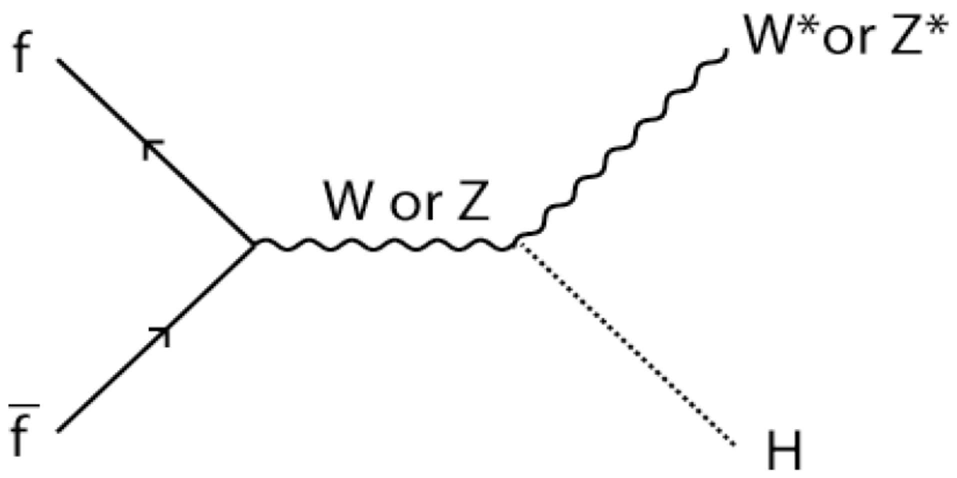
Why Collider Physics ?



W, Z decay to electrons, muons and/or neutrinos

- First order of business from Uncertainty Principle:
  - To probe small-distance phenomena we must scatter particles at high energy
  - What is the center-of-mass energy of a collider configuration?
    - $(P_{beam1} + P_{beam2})^2 = [\, (p_1,0,0,p_1) + (p_2,0,0,-p_2)\,]^2 = (p_1+ p_2)^2 - (p_1-p_2)^2 \sim (2p)^2$
    - => collision energy in COM-frame is $2p$, where $p_1 = p_2 = p$
    - To obtain 1 TeV of COM frame energy, need 500 GeV beams

Why Collider Physics ?



W, Z decay to electrons, muons and/or neutrinos

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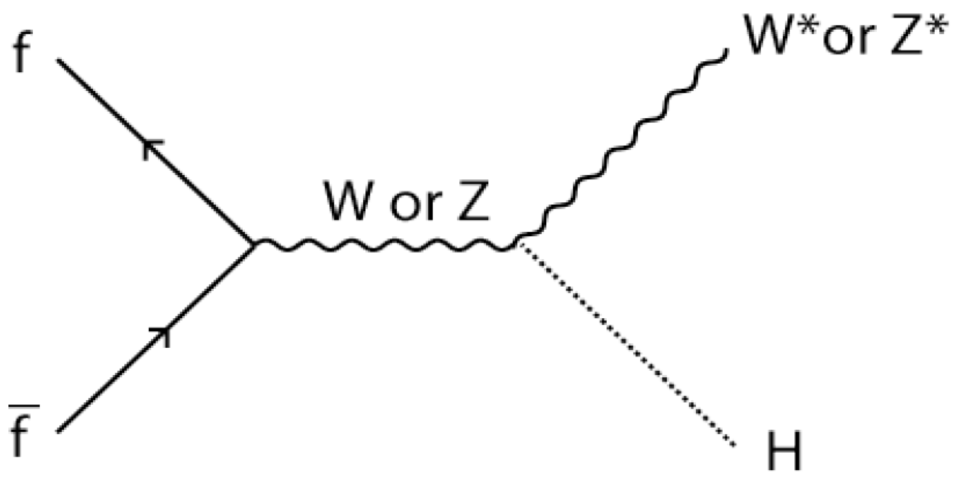
What happens to the rest of the energy of the 500 TeV fixed-target beam?

Why Collider Physics ?



W, Z decay to electrons,
muons and/or neutrinos

- If it takes 500 GeV beams in collider configuration and 500 TeV beam in fixed-target configuration to achieve a 1 TeV collision energy in the COM frame...

What happens to the rest of the energy of the 500 TeV fixed-target beam?

- It is “wasted” as kinetic energy of the collision products !

- Sometimes a certain amount of kinetic energy for the decay products is beneficial e.g. the asymmetric electron-positron *b*-factories at BABAR (at SLAC) and
  - BELLE (at KEK) experiments

Electron-Positron Colliders

A number of electron-positron colliders have been built, including:

- SPEAR at SLAC (>3 GeV COM energy) where the bound charmonium state J/ψ was co-discovered (later understood as a bound state of charm and anti-charm quarks)

- DORIS at DESY and CESR at Cornell (10 GeV COM energy) for b-physics using the Upsilon bound state of bottom and anti-bottom quarks

- BEPC at IHEP Beijing (2.6 GeV COM energy) for τ lepton and charm quark studies

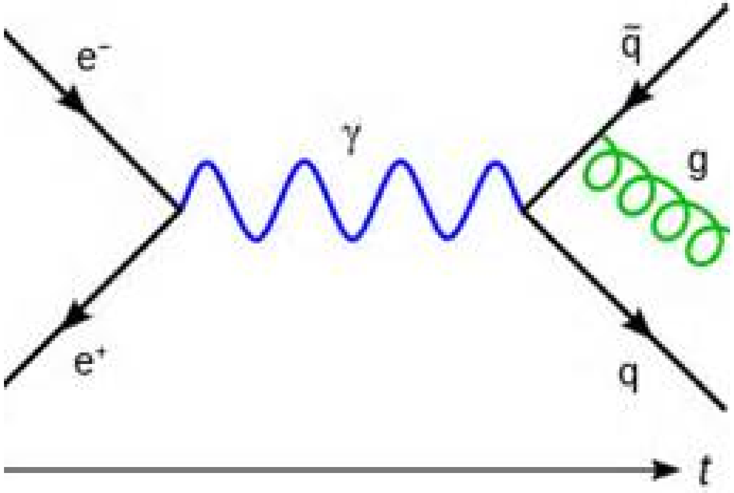
- PETRA at DESY (38 GeV COM energy) and PEP at SLAC (30 GeV COM energy) – PETRA is credited with gluon discovery via 3-jet events

- TRISTAN at KEK (64 GeV COM energy) showed the Q^2-dependence (running) of the electromagnetic coupling constant
- LEP at CERN (91 → 209 GeV) and SLC at SLAC (91 GeV) made precise measurements of SM parameters

Advantage of Electron-Positron Colliders

1) Electrons and positrons are point-like particles, with no (known) sub-structure

=> the entire energy of the beam particles is available for producing new particles



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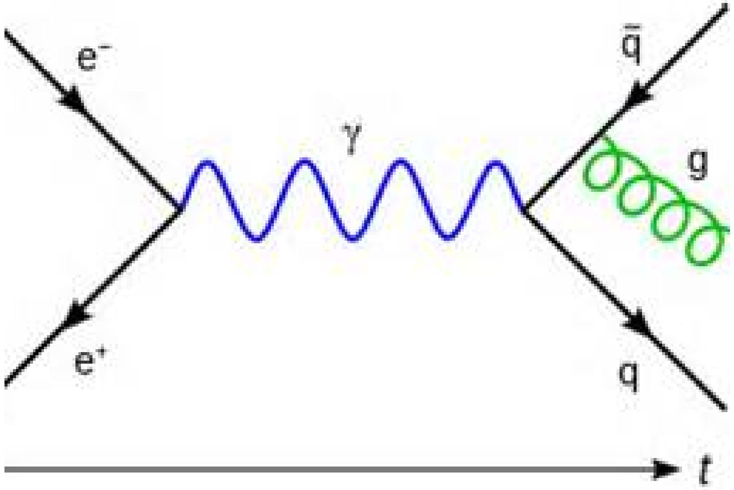

2) Total incoming 4-momentum is known, therefore total out-going 4-momentum is known => powerful constraint for reconstructing the properties of the final state

Especially if there is a neutrino or other undetectable particle in the final state, its 3-momentum can be fully deduced (4-momentum requires knowledge of its mass)

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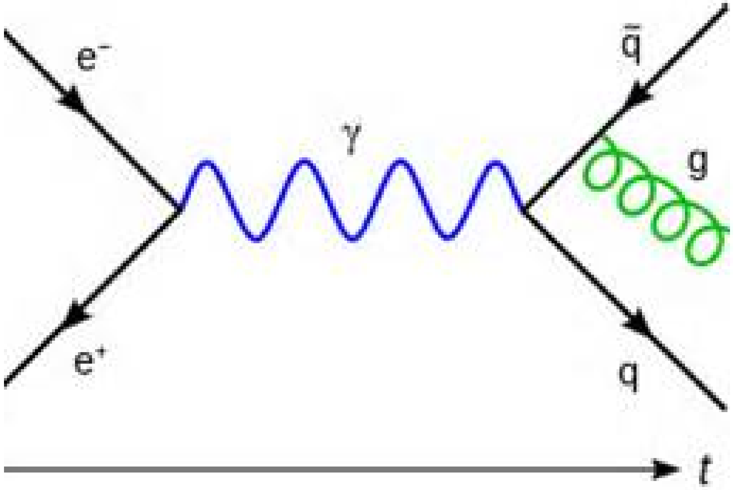

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3) Electrons and positrons interact via the electroweak interaction => energetic interactions of more than one electron (from one beam) and one positron (from the other beam) is rare

=> there are no particles from "underlying event" and "pileup" (to be defined for hadron colliders) contaminating the collision event: all detected particles originate from the energetic collision of one electron and one positron

Hadron Colliders

- Intersecting Storage Rings at CERN (proton-proton and later proton-antiproton collider) with maximum COM energy of 62 GeV: the first pp and p-pbar collider
  - Studied charged and neutral particle production
  - Development of “stochastic cooling” to reduce both the transverse size of the beam and reduce the energy spread (Nobel Prize for Simon Van der Meer): critical for future proton-antiproton colliders

- Super Proton Synchrotron (maximum beam energy of 450 GeV) at CERN, was also used as a proton-antiproton collider at COM energy of 630 GeV
  - Discovery of W and Z bosons via direct production and decay into leptons

- Tevatron at Fermilab (1.8 → 1.96 TeV proton-antiproton collider)
  - Discovery of top quark

- Large Hadron Collider at CERN (7 → 8 → 13 TeV proton-proton collider)
  - Discovery of Higgs boson

Advantage of Hadron Colliders

- Circular accelerators can exploit multi-turn acceleration compared to linear accelerators: therefore can be smaller (=> cheaper) for the same final energy
  - BUT the big issue for circular accelerators is synchrotron radiation
  - Charged particle bent in a circular orbit by magnetic field => accelerated charge radiates
  - For relativistic particles. radiated power P $\propto e^2 \gamma^4 / r^2$
    - For particle charge *e,* Lorentz boost γ and ring radius r
  - *For the same particle energy,* relativistic electrons radiate a factor of 10^{13} more power than protons

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- Therefore, circular electron accelerators have to be VERY big (i.e. large *r*) or their beam energy is limited by synchrotron energy loss
  - Large energy loss causes technical difficulties for beam pipe
  - $$$ cost of total power loss
  - e.g. LEP was 27 km in circumference and could not exceed ~104 GeV in beam energy

Advantage of Hadron Colliders

- Proton collider energy not limited by synchrotron energy loss – therefore, a smaller ring can be used for achieving a higher beam energy
  - e.g. Tevatron: 1 TeV beam energy with 6.3 km circumference
  - LHC: 7 TeV beams with 27 km circumference

- What limits the highest energy achievable with a circular proton collider ?
  - The strength of the magnetic field in the magnets used to bend the beam
    - Beam momentum $p \propto Br$ where B is the magnetic field
    - e.g. LHC needs ~1200 magnets, each of 8.4 T strength requiring ~12,000 A of current (=> superconducting at 1.9 K)
    - Cost of each magnet: 0.5M CHF
    - ~2000 such dipole magnets in LHC
    - High p requires high B and/or high r

Disadvantage of Hadron Colliders

- Protons are not point-like particles !
    - At low energy, a proton is a complicated bound state of quarks and gluons
    - Theoretically, this is the regime of
        - non-perturbative QCD calculations
        - Confinement of QCD-colored constituents

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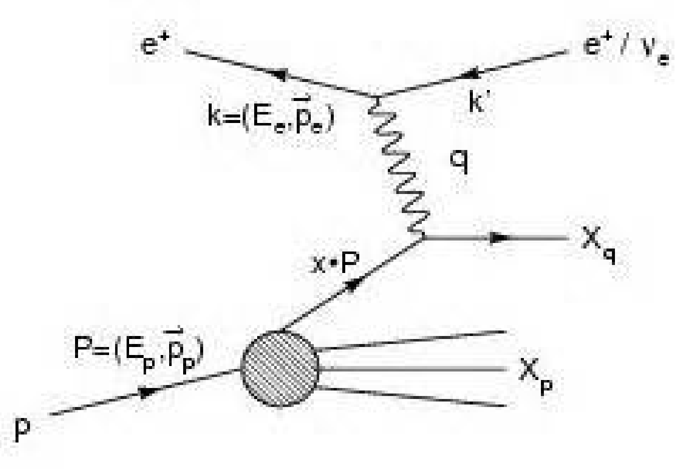
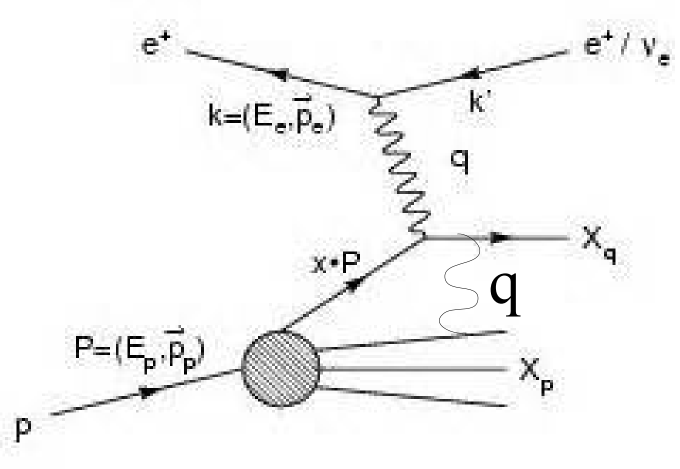
  - Theoretically, this is the regime of
    - non-perturbative QCD calculations
    - Confinement of QCD-colored constituents
- However, for scattering at high energy, a number of important theoretical insights simplify the picture
    - Bjorken's "scaling" regime: scattering amplitude is dominated by scattering between point-like constituents
    - Bound-state effects between multiple constituents are suppressed by powers of momentum-transfer in the scattering process





Proton Scattering

- Gell-Mann and Zwieg had postulated quarks with SU(3)-symmetric flavor quantum numbers to explain the static properties of baryons and mesons
  - Baryon = bound state of 3 quarks
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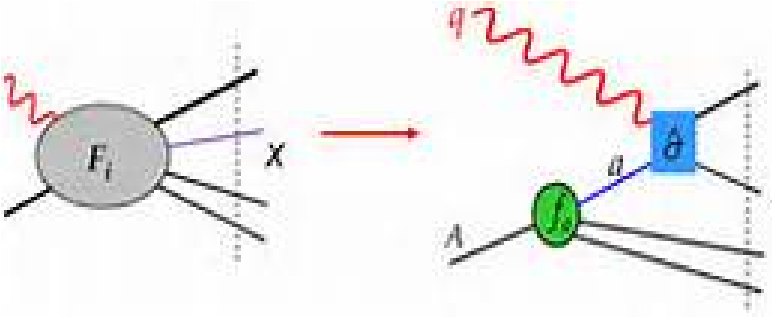
- Finally, QCD as a non-abelian gauge theory of the strong interactions came into the fore when
  - It was shown by t'Hooft (with Veltman) that such theories were “renormalizable” i.e. infinities in quantum loops could be re-absorbed into the definitions of the theory's parameters
  - It was shown by Politzer and by Gross and Wilczek that QCD is “asympotically free”, i.e. the QCD coupling constant decreases as the scattering energy increases

Proton Scattering

- The combination of these ideas and formal developments in quantum field theory led to the “Factorization Theorem” of Collins, Soper and Sterman
  - Total probability for the “probe” boson with 4-momentum *q* to scatter off hadron A “factorizes” into two parts:
  - “hard” part *i.e.* the high-p_T scattering part σ which describes the cross section for the probe to scatter off parton “a” in the hadron at high-p_T
  - “soft” part describing the probability of finding parton “a” in the hadron, carrying a certain momentum fraction of the hadron



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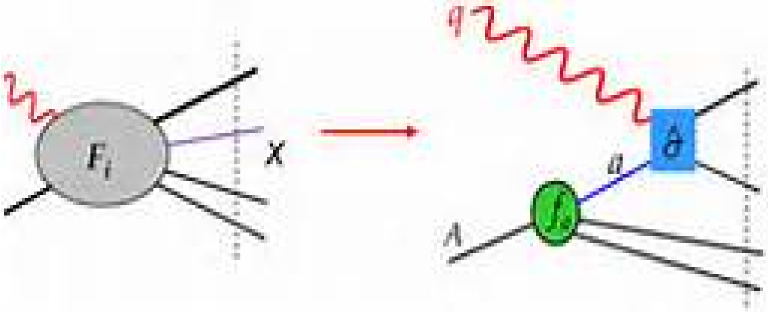

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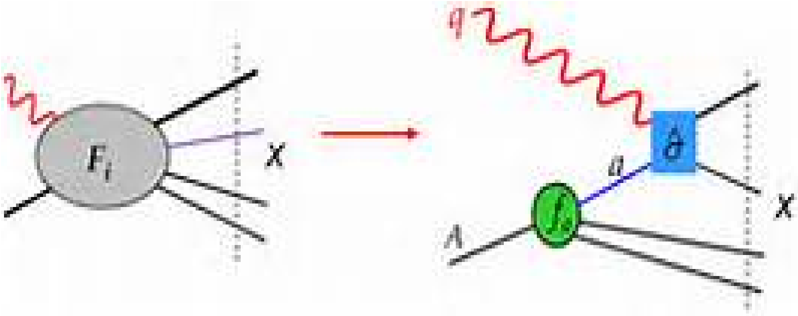
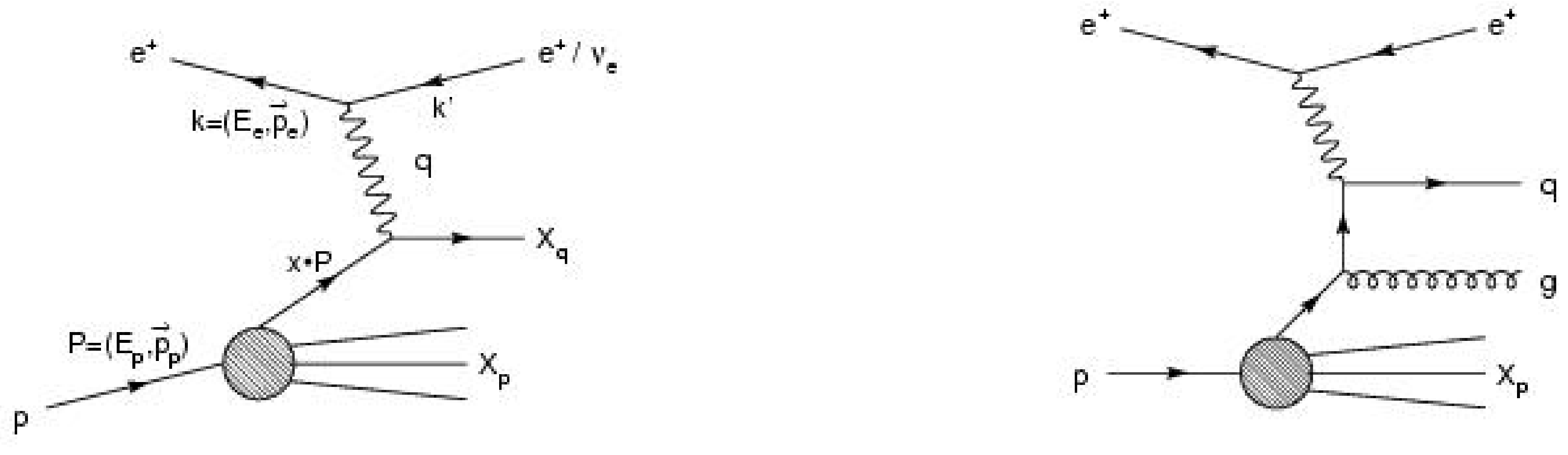
- The "soft" part is parameterized by "parton distribution functions"
  - It depends on the parton type
  - It contains the non-perturbative physics
  - not calculable
  - But it is universal !!



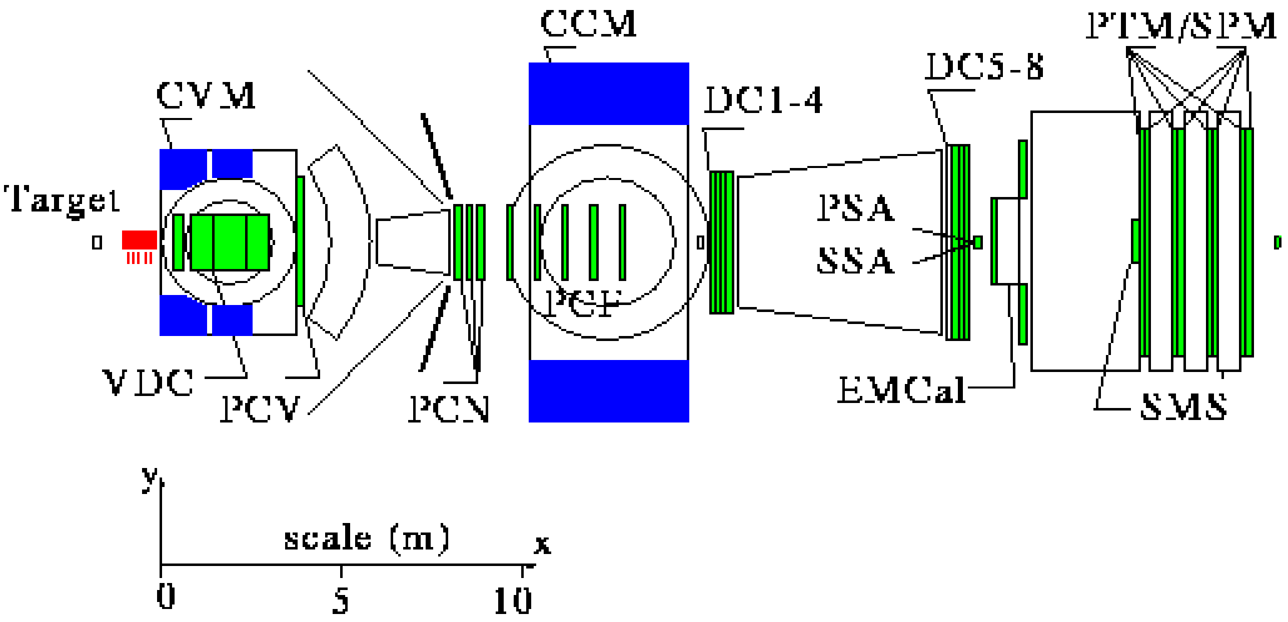
Measuring the Parton Distribution Functions

- Deep inelastic scattering (DIS) is the process of scattering leptons off hadrons at high energy and high p_T
- In this lepton kinematic regime, the lepton transfers a lot of energy to the target hadron, and it scatters at a large angle with respect to the incoming beam direction
  - Ensures that the exchanged boson (photon, *W* or Z) is highly virtual, $|q^2| >> 0$
  - Ensures that the boson-parton scattering process is a short-distance process, *i.e.* “hard” process calculable in perturbative QFT



Measuring the Parton Distribution Functions

- A number of DIS experiments using fixed targets
  - Neutrino beam: e.g. CDHS (CERN) CCFR & NuTeV (FNAL)
  - Muon beam: e.g. BCDMS, EMC & NMC (CERN), E665 (FNAL)
  - Electron beam: SLAC, Jefferson Lab experiments
  - E665 (my PhD Thesis experiment) had the highest energy mean (470 GeV muons)



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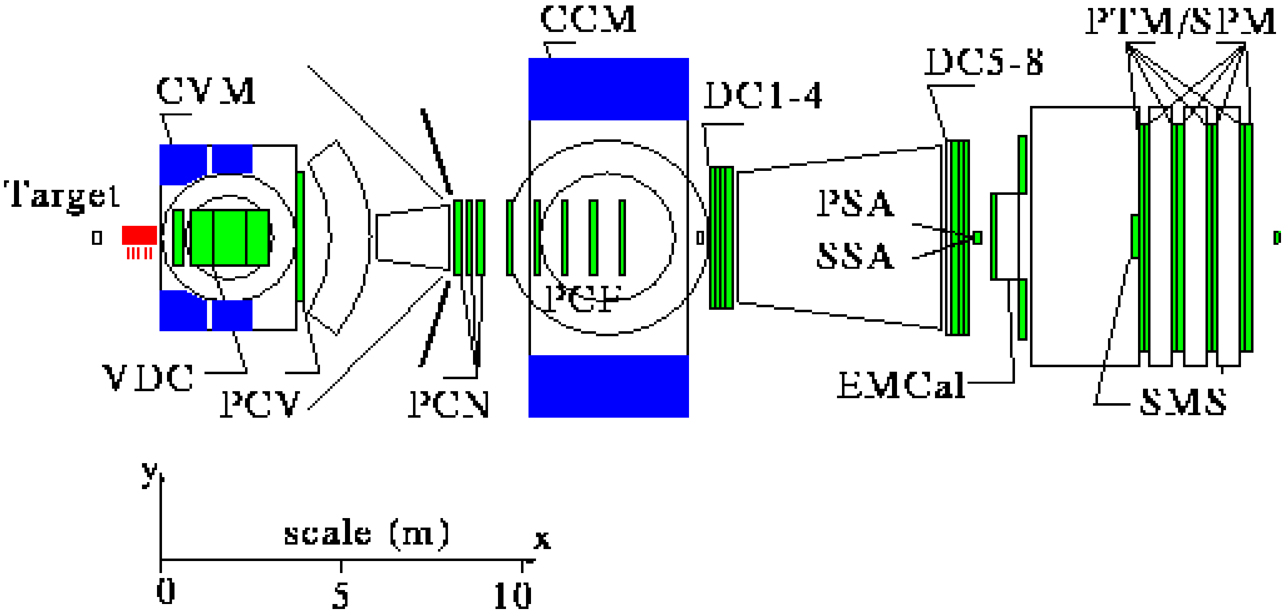
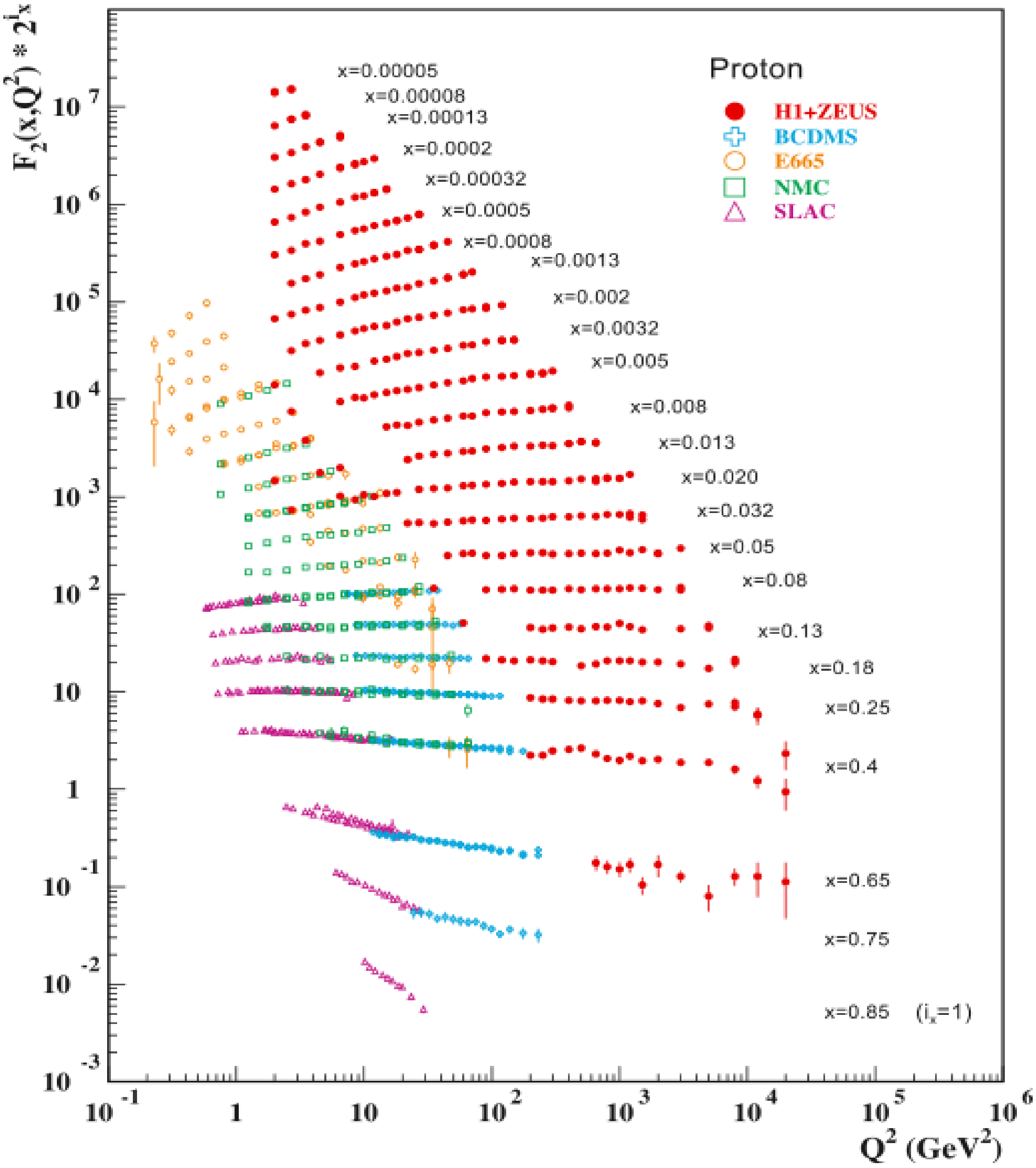


- And the HERA electron-proton collider at DESY
  - 30 GeV electrons and 820 GeV protons
  - Very high COM energy

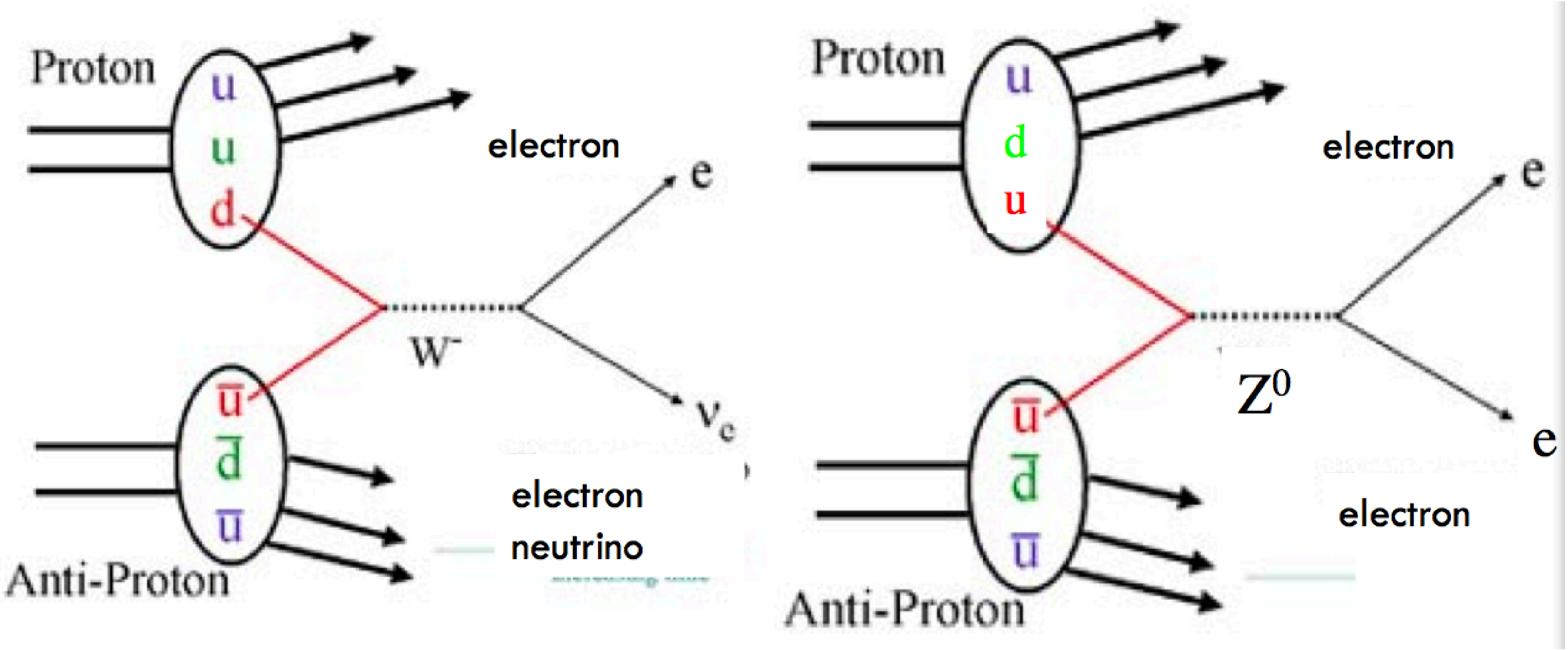
Measuring the Parton Distribution Functions

In the quark-parton model, $F_2(x,Q^2)$ is simply related to the momentum density of quarks carrying fraction x of the proton's momentum

Logarithmic Q^2-dependence (scaling violation) was predicted by QCD radiation of gluons



Cross Sections at Hadron Colliders

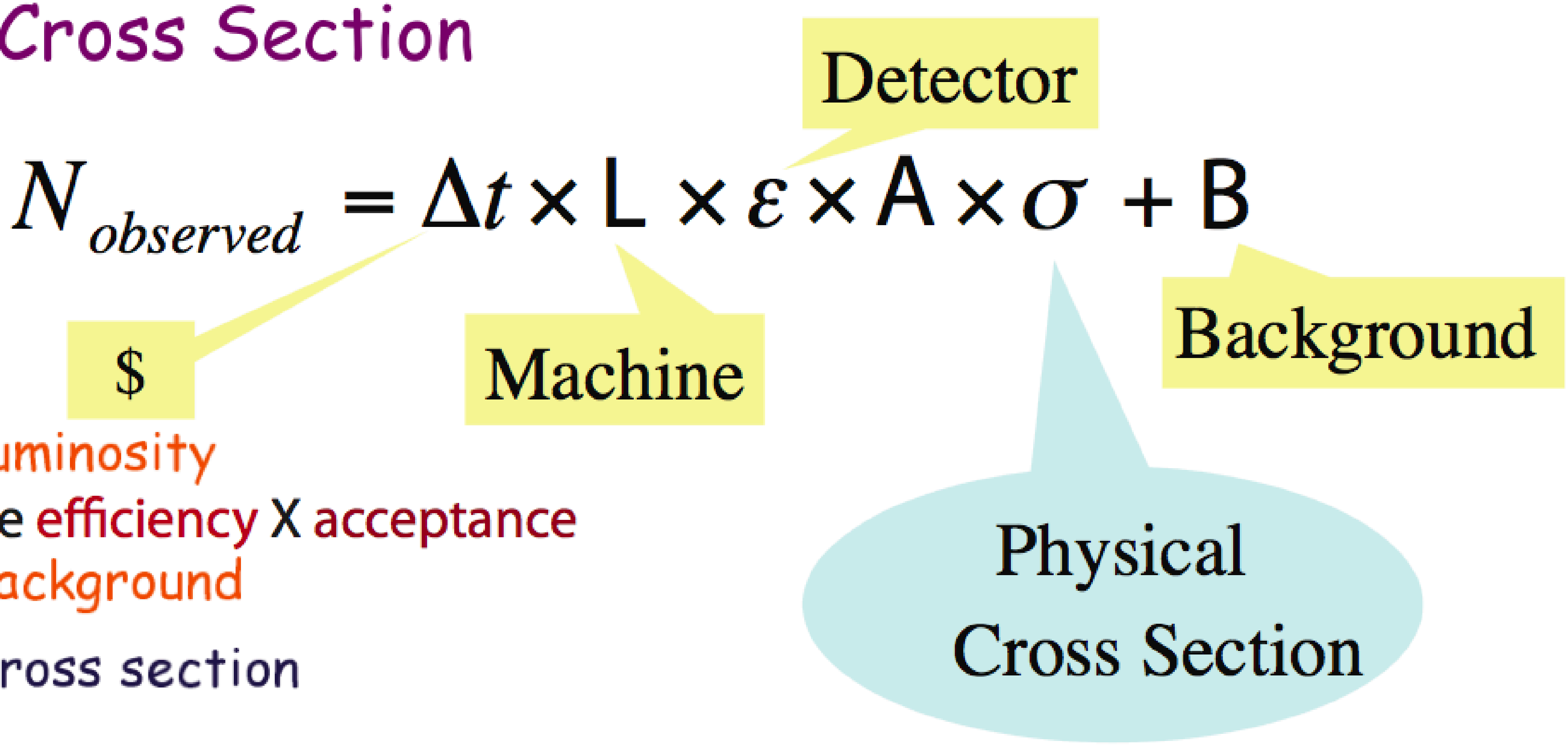


$$\frac{d\sigma_{AB}}{dy\,dp_T^2} = \int dx\, f_{a/A}(x,\mu) \int dx'\, f_{b/B}(x',\mu)\, \frac{d\hat{\sigma}_{ab}(\alpha_s(\mu))}{dy\,dp_T^2}$$

$$+ \text{ frag contribution} + \mathcal{O}\left(\frac{1}{p_T^n}\right)$$

Hard part: $\hat{\sigma}_{ab}(\alpha_s(\mu)) = \hat{\sigma}^0_{ab}\alpha_s^m(\mu) + \hat{\sigma}^1_{ab}(\log(\mu))\alpha_s^{m+1}(\mu) + \ldots$

Cross Section



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

Detector

$

Machine

Background

Physical Cross Section

L is the Luminosity

$\varepsilon \times \mathrm{A}$ 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

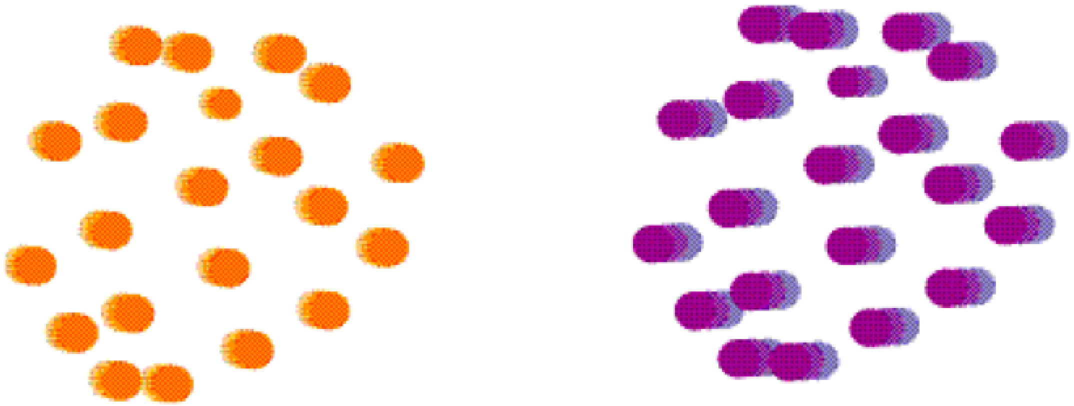
Unit of Cross Section is area essentially the effective scattering size for the process

Thanks to H. Schellman

Collider Luminosity

Luminosity is a measure of how often protons/antiprotons get close enough to interact

$$L = f\,\frac{n_1 n_2}{4\pi\, s_x s_y}$$



50 ns → 25 ns at LHC

f= beam crossing frequency

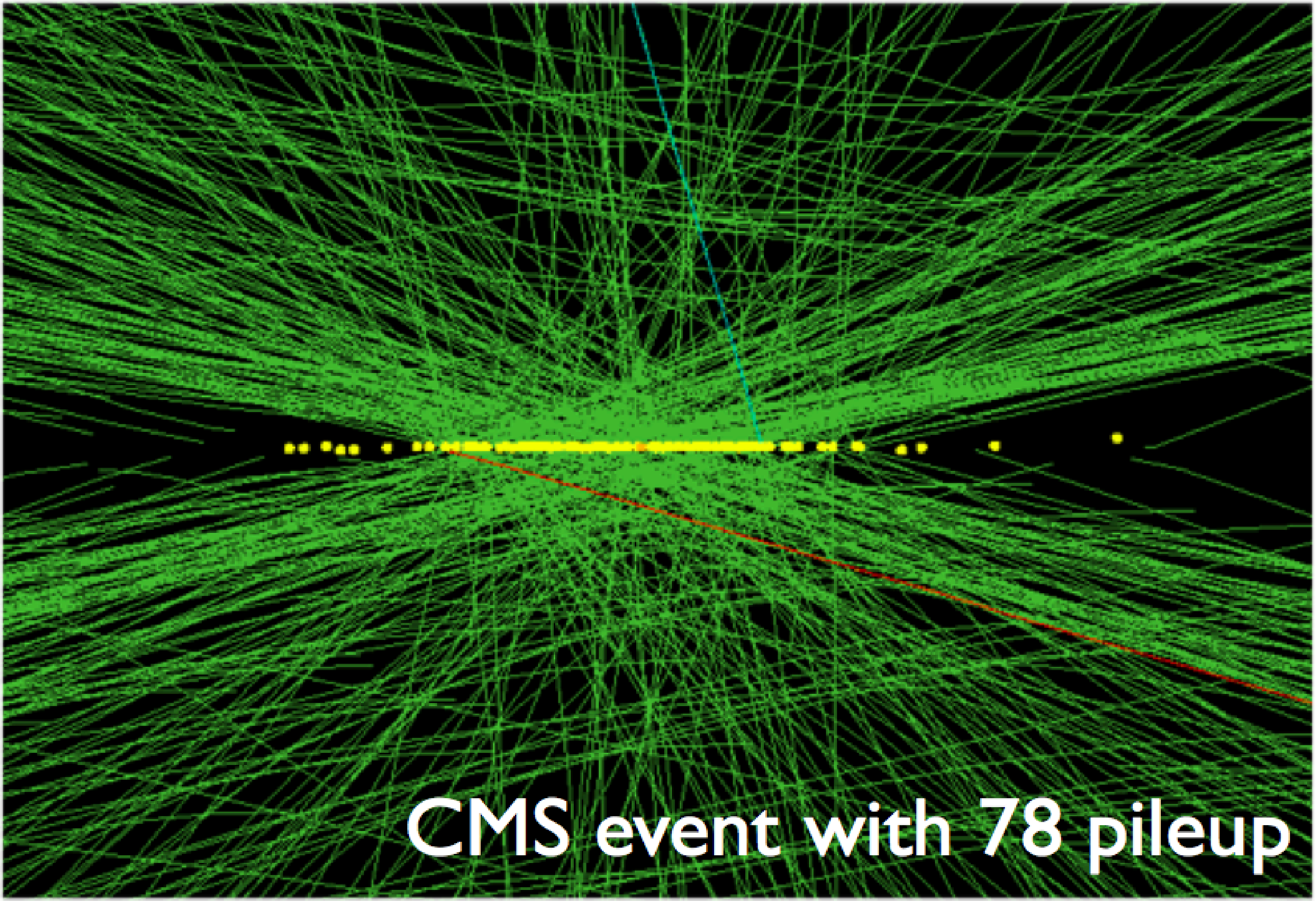
n= protons/bunch

s = transverse beam size

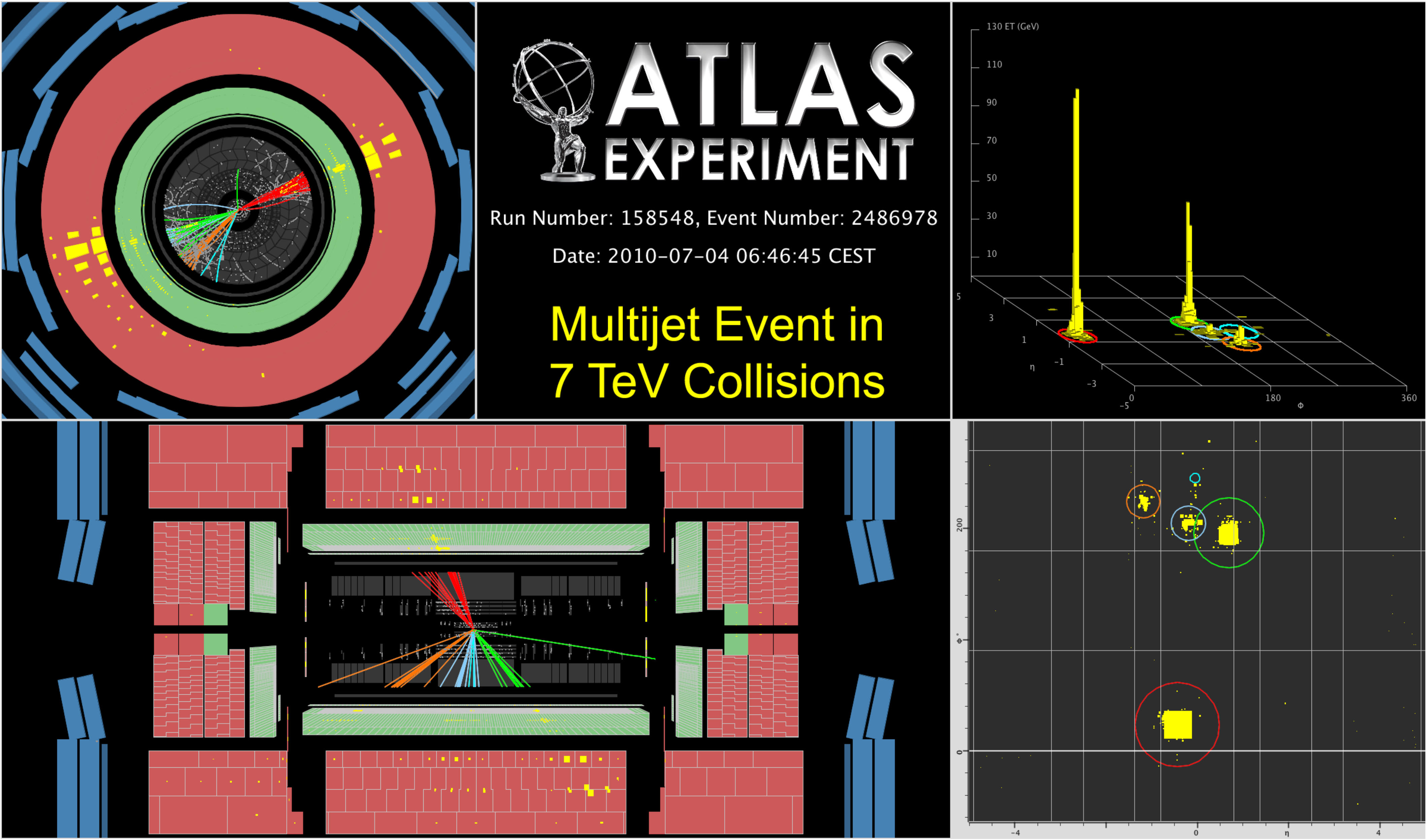
L ~ 10^{34} crossings/cm^2/sec

Thanks to H. Schellman

Multiple pp Interactions (pileup)



Particle Detection



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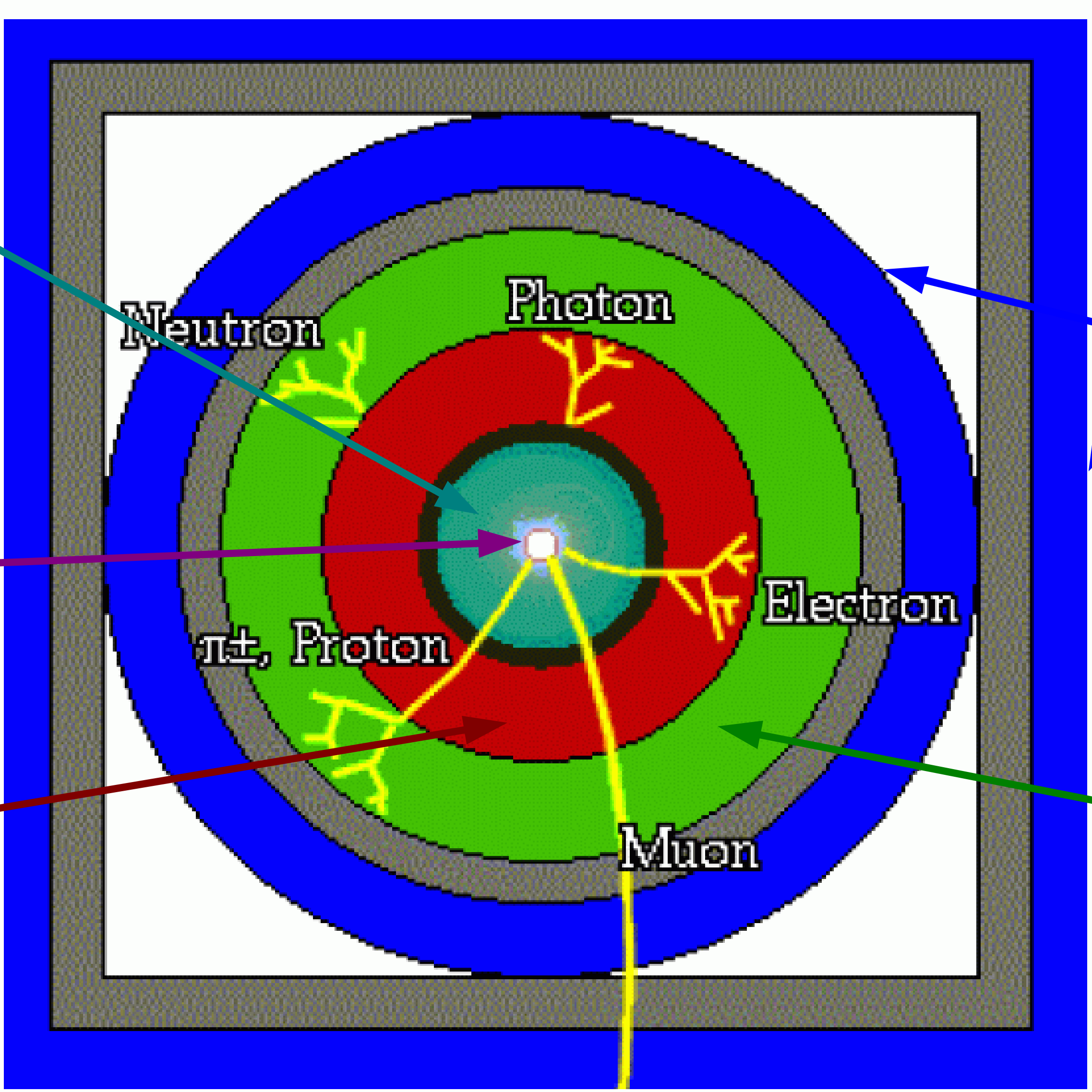


Drift chamber:
reconstuct particle
trajectory by sensing
ionization in gas
on high voltage wires

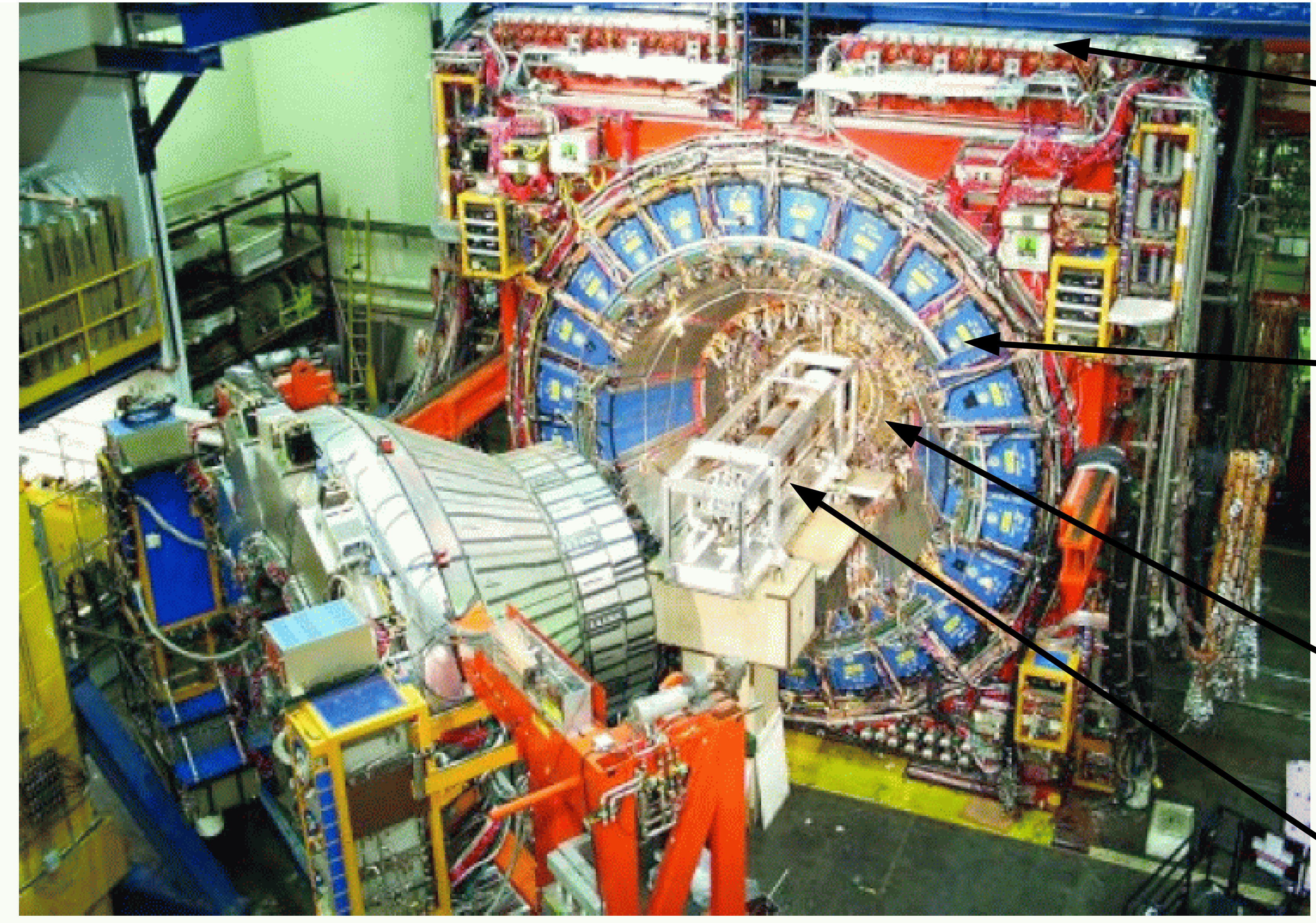
Silicon detector:
reconstuct particle
trajectory by sensing
ionization in planar
silicon sensors
(diodes)

Electromagnetic
(EM) calorimeter:
metal sheets cause
e/γ shower, sense
light or charge

Muon chambers:
detect penetrating
particles behind
shielding

Hadronic
calorimeter:
metal sheets
cause hadronic
showers, sense
scintillator light
or charge

Collider Detector at Fermilab (CDF)



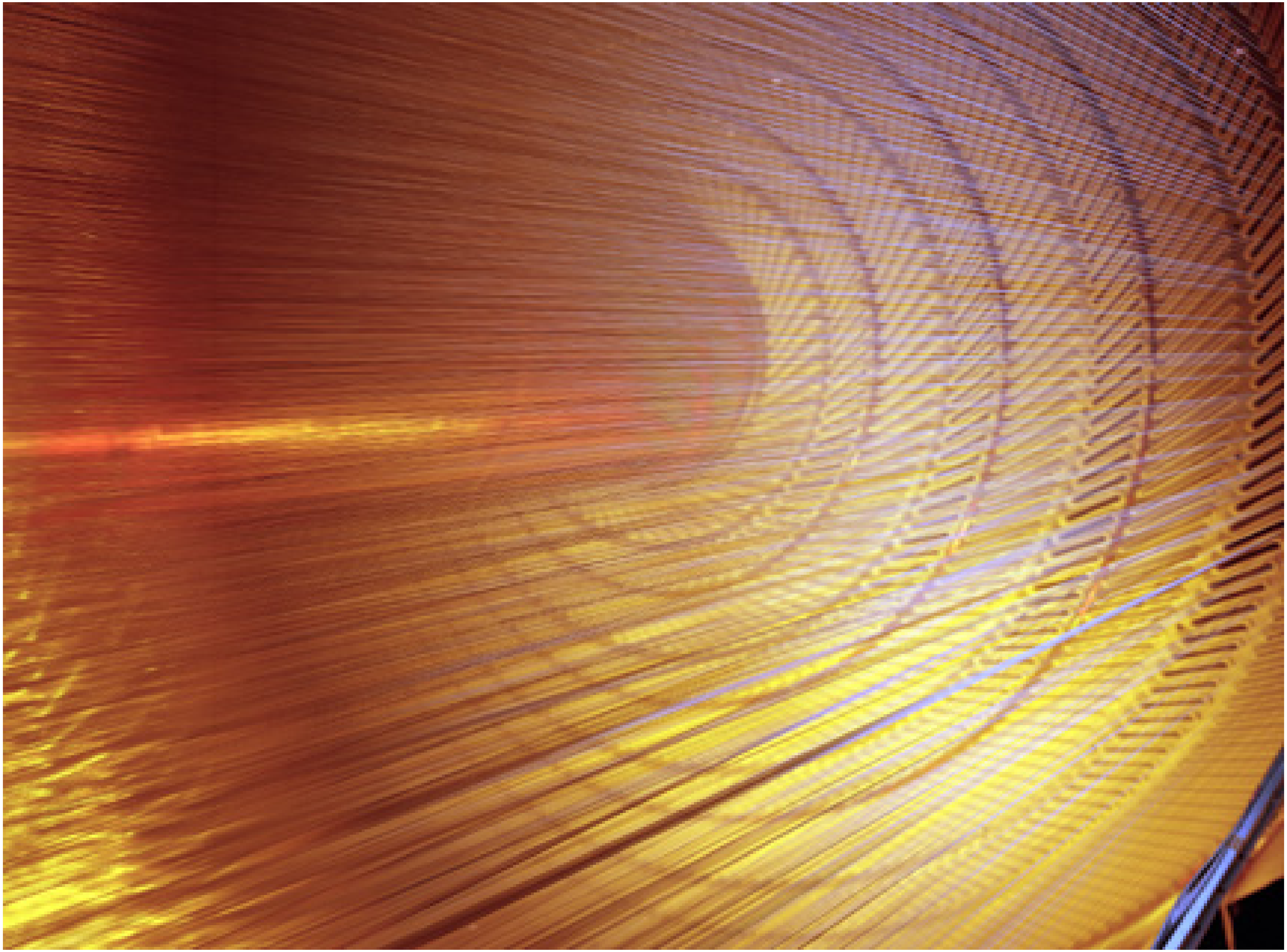
Muon detector

Central hadronic calorimeter

central drift chamber

Silicon detector

CDF Tracking Chamber



Sensing Ionization Energy Loss

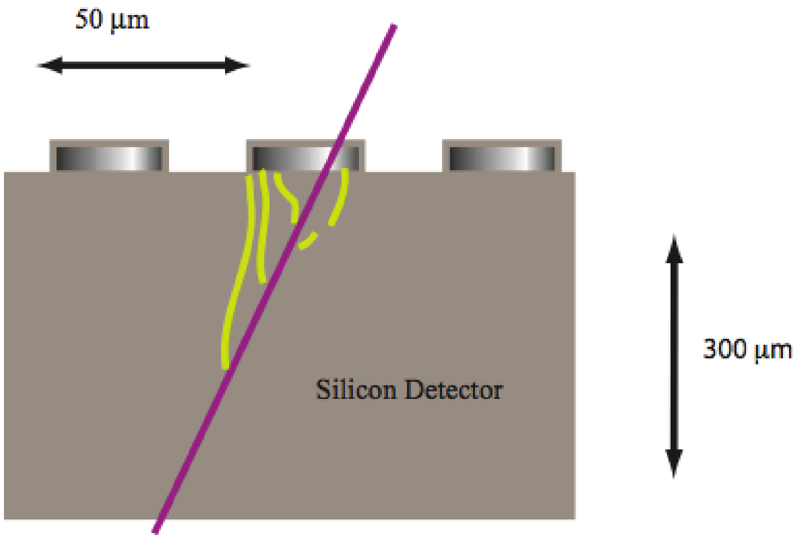
Detection of charged particles

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.

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

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

ATLAS Silicon Tracker

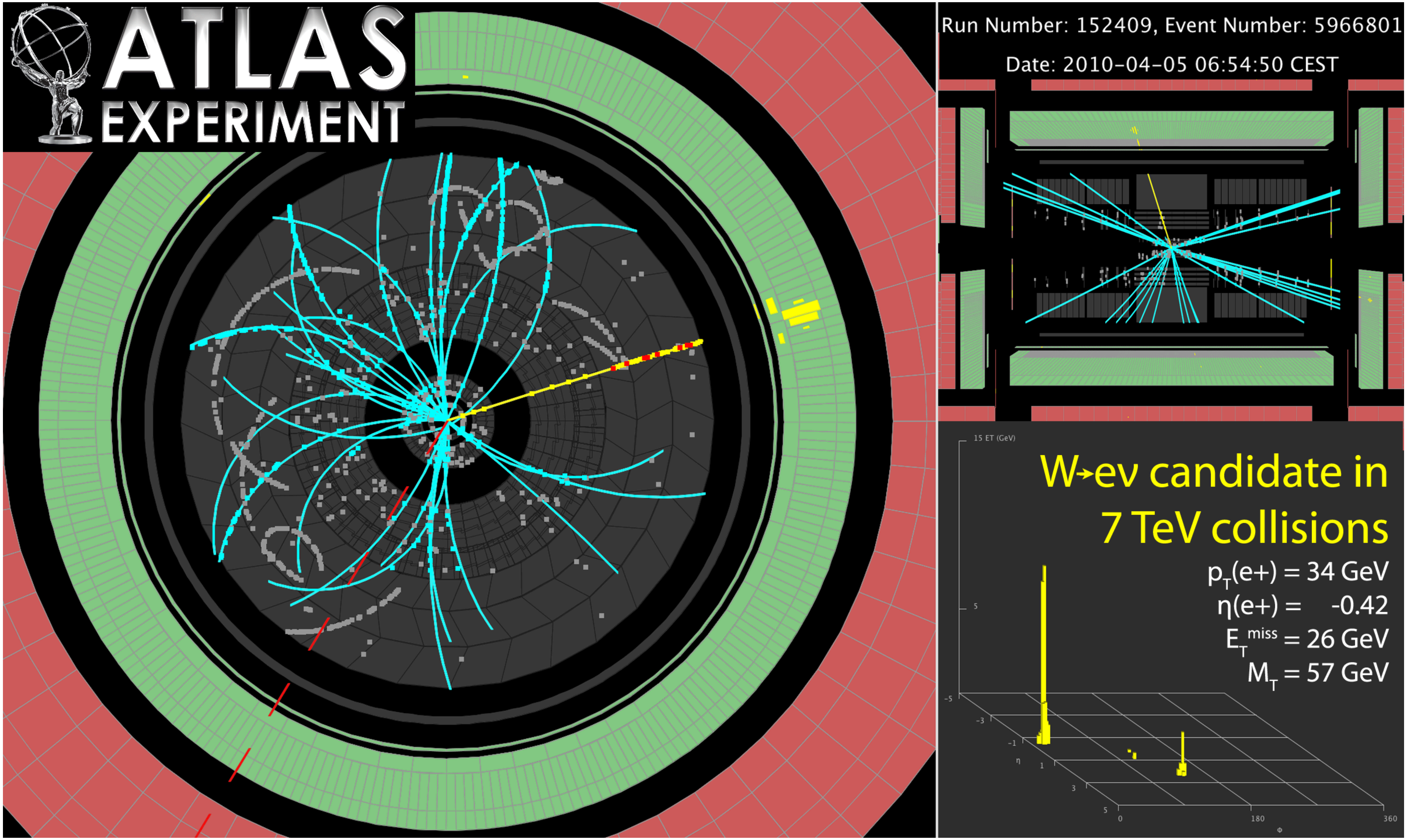


Detect ~2000 e in a 350 µm thick detector

Can measure x,y, z to 10-20 µm

Magnetic Tracking

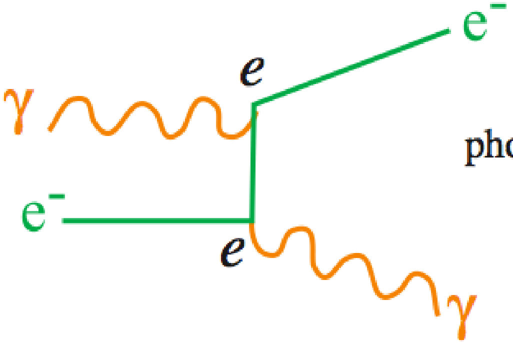
B field →



Fit the helical trajectory in the longitudinal magnetic field

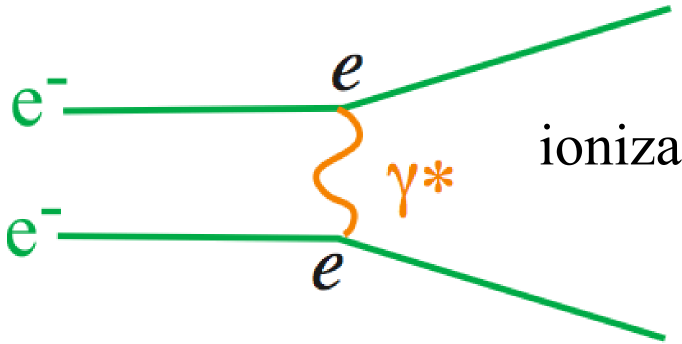
=> Extract position, direction and momentum of charged particles

Photon and Electron Detection

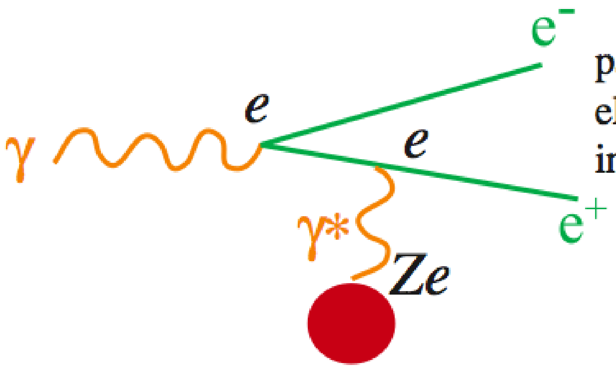


photon-electron scatter

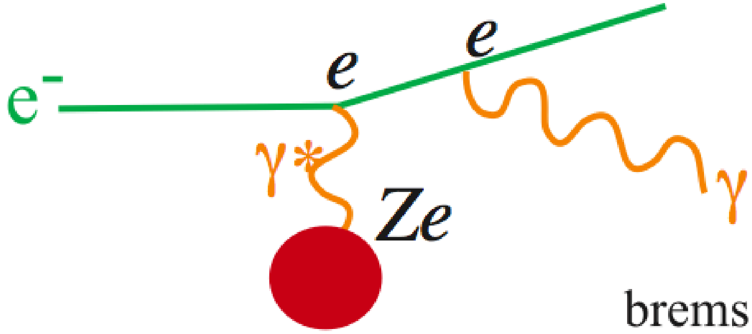
Compton



ionization



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



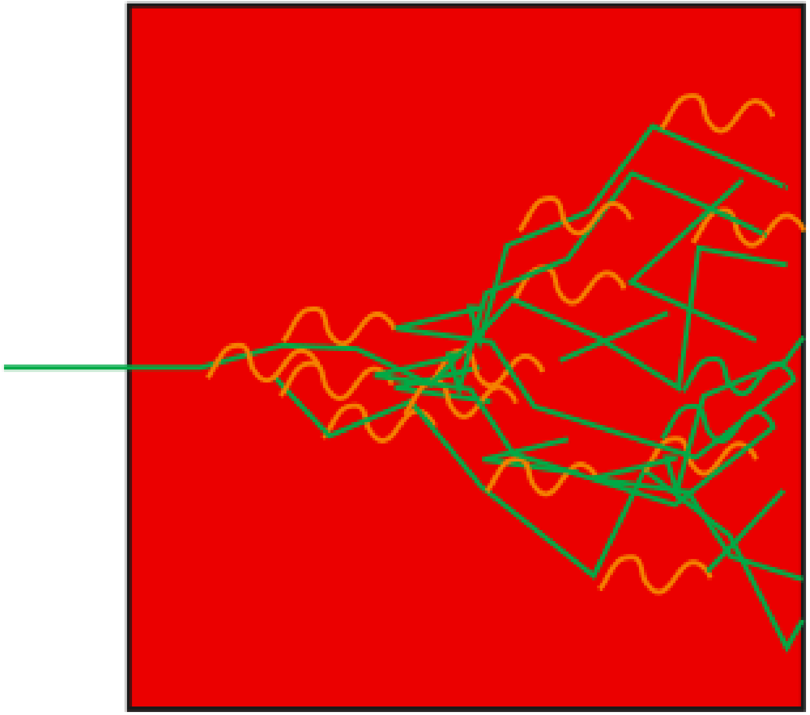
bremsstrahlung

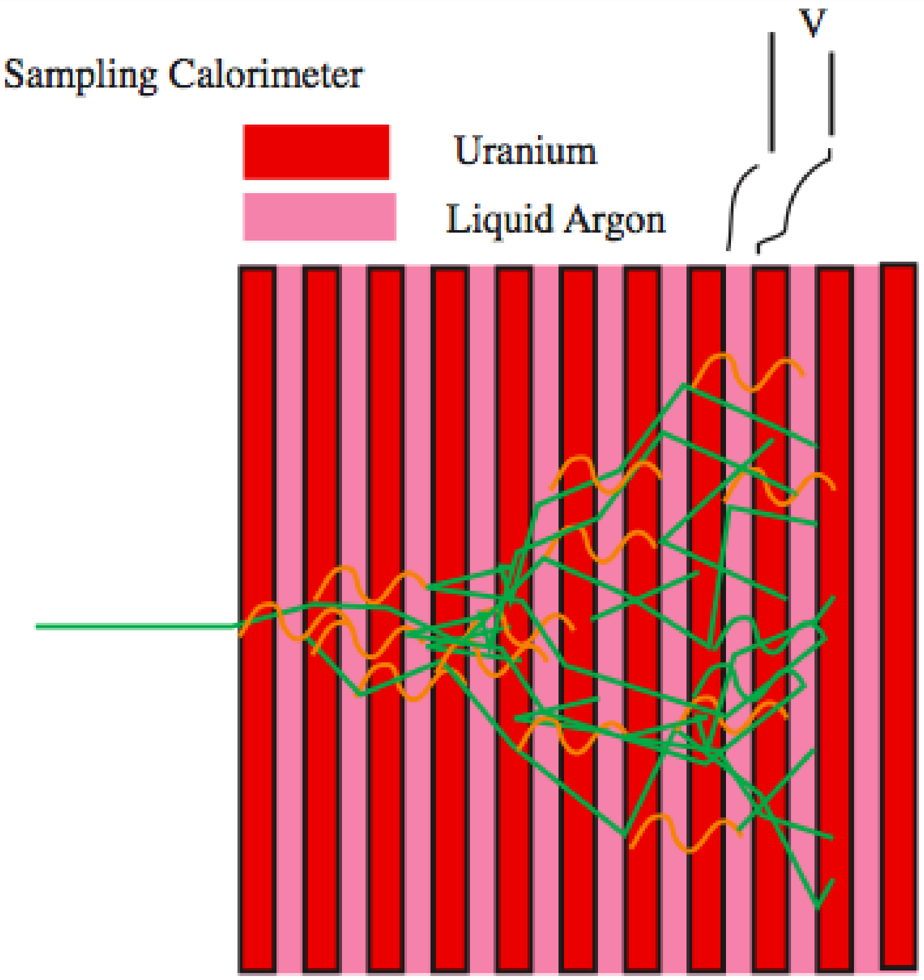
At high energy and for high-*Z* material, energy loss by pair-production and bremsstrahlung dominates.

Cross sections scale as lepton mass^{-2}: bremsstrahlung is small for incident muons

Photon and Electron Detection

Total absorbtion calorimeter
e.g. lead glass, lead tungstate (CMS)

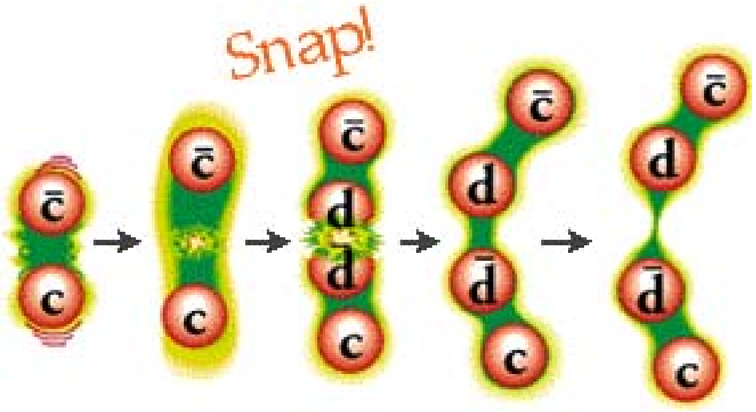




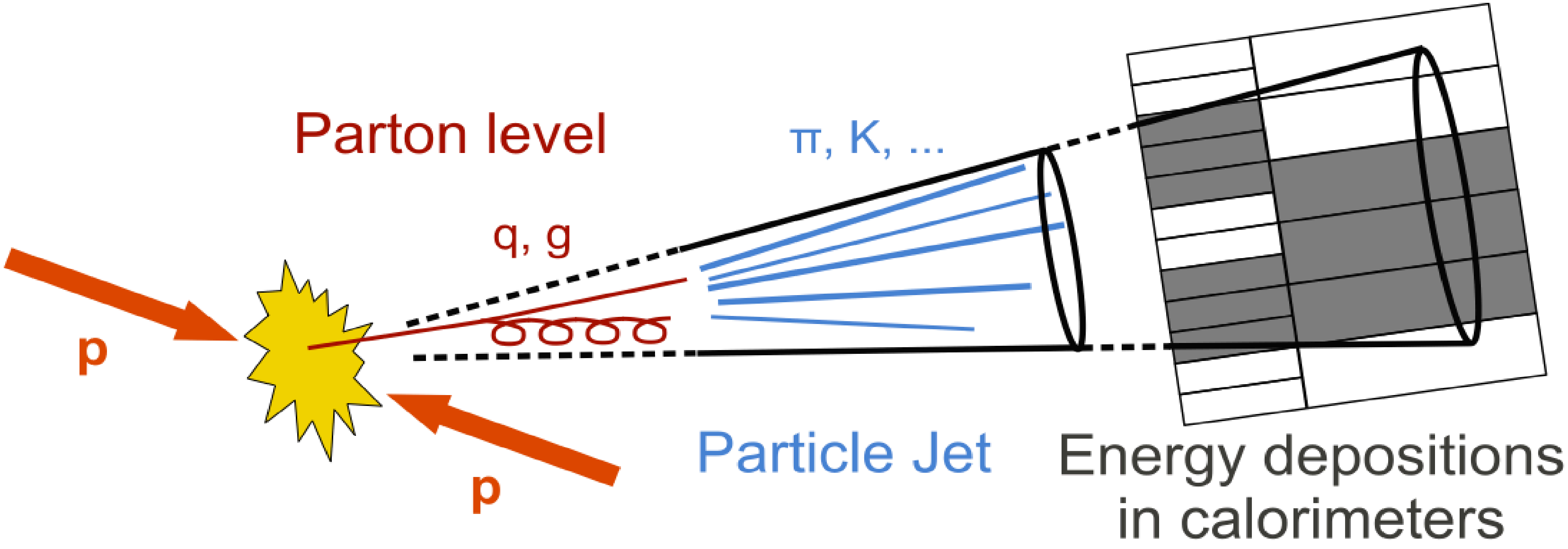
Cascade of electrons and photons due to repeated pair-production and bremsstrahlung

Collect light or electric charge deposited by the shower electrons and photons

Hadronic Shower



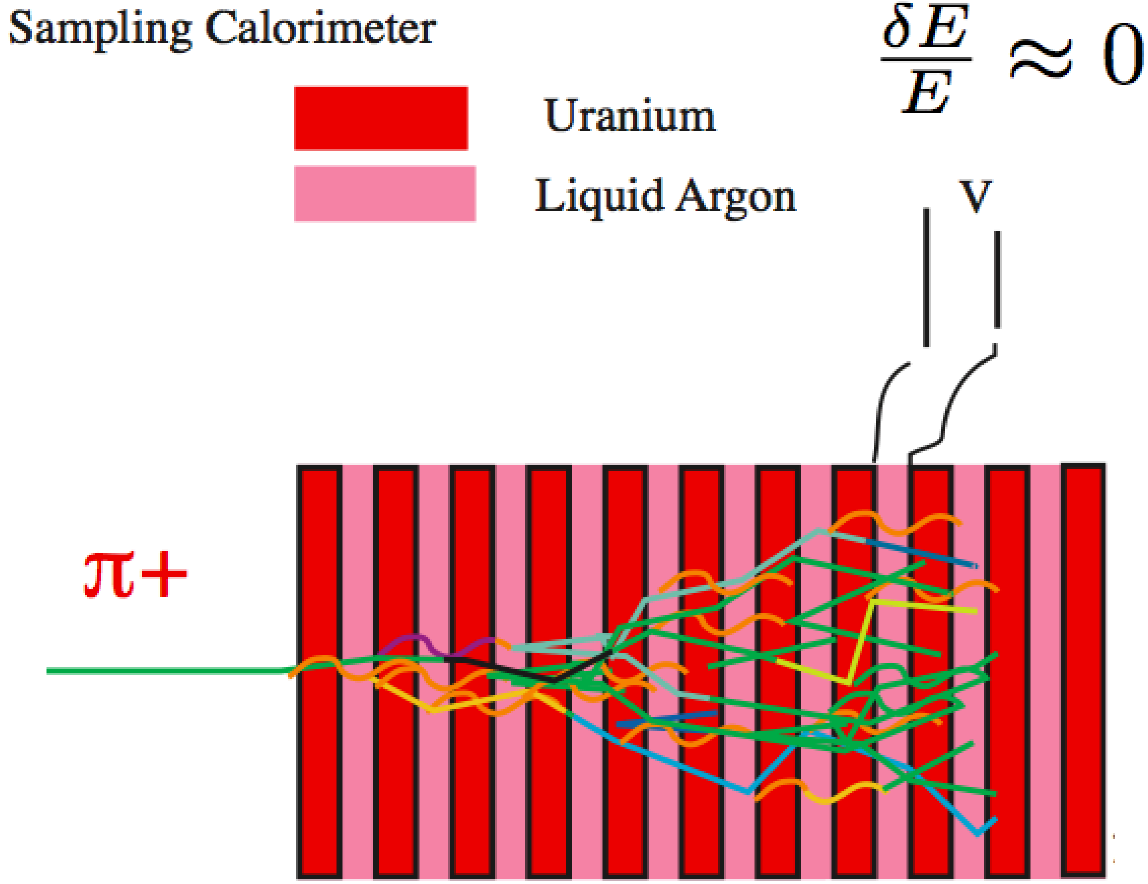
- Due to confining effect of strong force, colored quarks/gluons cannot separate:
  - gluon "string" connecting them generates the confining potential $U \propto distance$
  - String breaks with new quarks/antiquarks created from the vacuum when string energy becomes large enough



Hadronic Calorimeter

- Strong interactions of hadrons with atomic nuclei generates a cascade of particles
  => hadronic shower

- Shower fluctuations are larger than in the electron/photon case: neutrinos, neutrons, nuclear spallation products, hadronic vs electromagnetic ($\pi^0 \rightarrow \gamma\gamma$) fraction ...



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