Lecture 2:
Particle Interactions with Matter (Part I)

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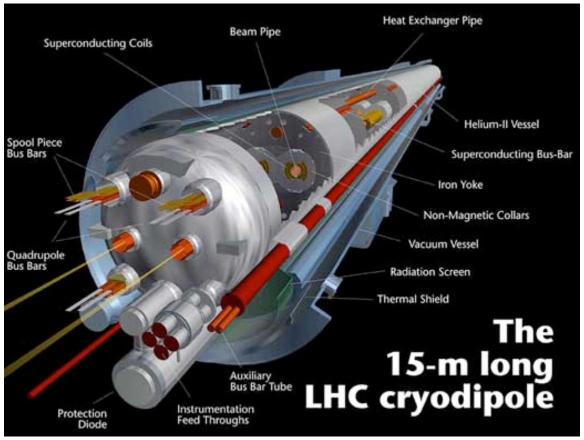
Boulder, CO

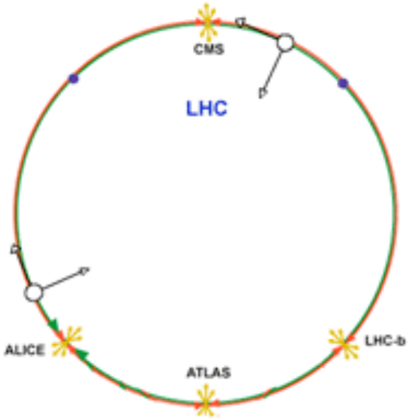
Some review from last time

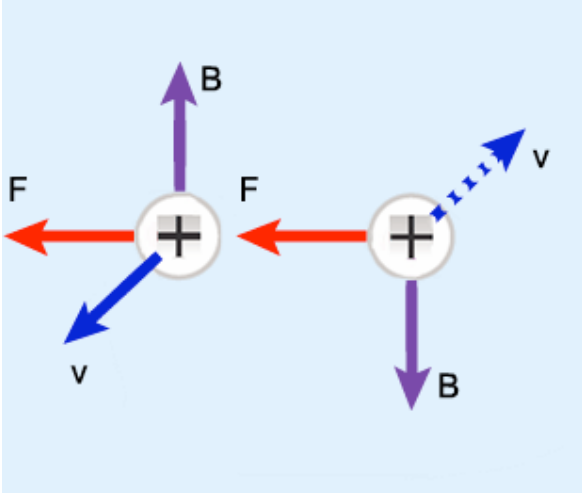
- Linac and circular colliders
  - Linac
    - Examples:
      - SLAC, Future ILC
        - These examples are $e^+ e^-$ colliders
        - Precision measurements
  - Circular:
    - Higher energy than Linac
    - Examples:
      - LEP:
        - e+ e- (synchrotron radiation an issue)
        - Precision measurements
      - Tevatron, LHC:
        - Hadron colliders
        - Very high energies - make discoveries

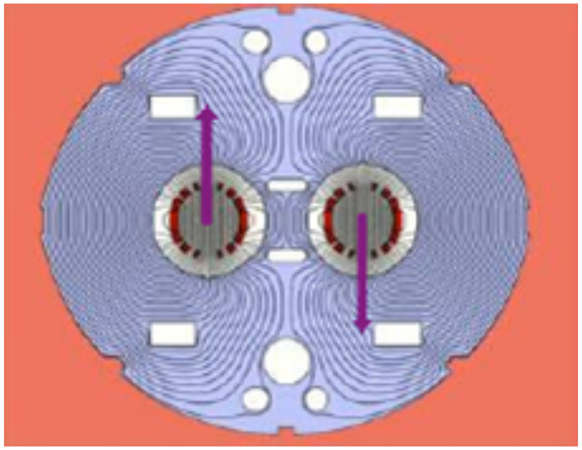
Question about LHC Dipole Magnets

- Ingenious design
  - B field points in opposite directions in each pipe



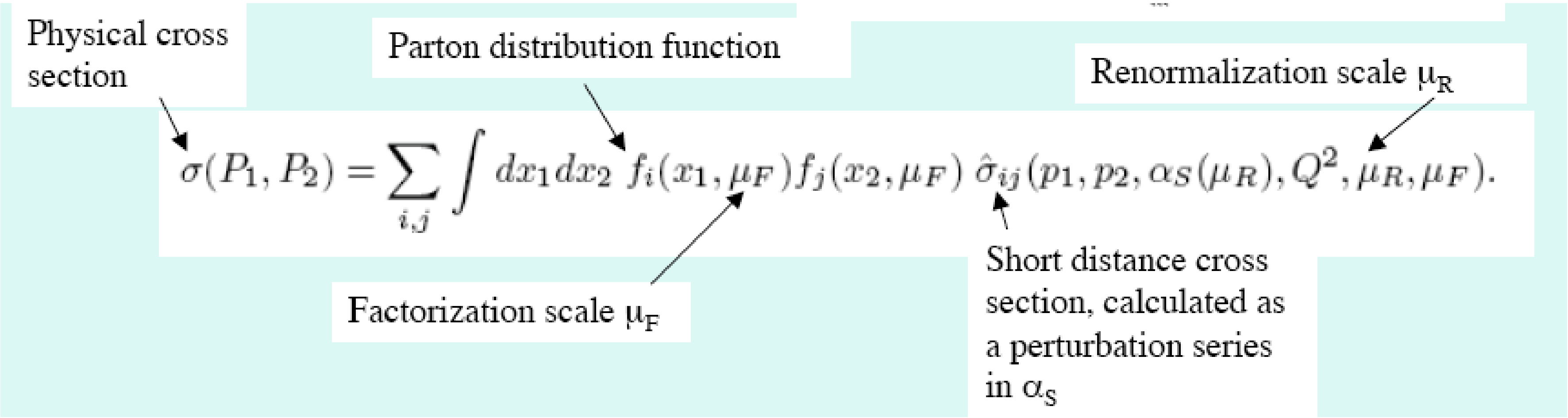






A theorist’s view of a hadron collision

A cross section is convolution of Matrix Element and PDFs



Physical cross section

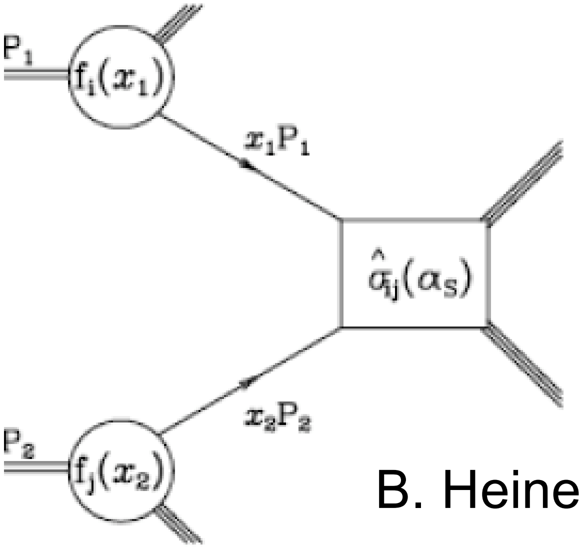
Parton distribution function

Renormalization scale μ_R

$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2\; f_i(x_1, \mu_F) f_j(x_2, \mu_F)\; \hat{\sigma}_{ij}(p_1, p_2, \alpha_S(\mu_R), Q^2, \mu_R, \mu_F).$$

Factorization scale μ_F

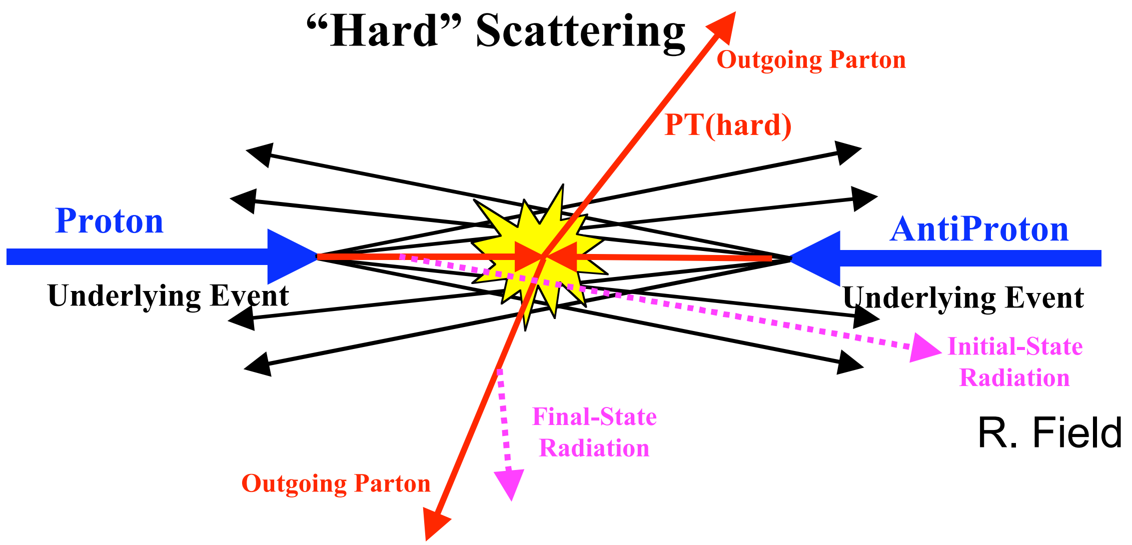
Short distance cross section, calculated as a perturbation series in α_S



B. Heinemann

- Calculations are done in perturbative QCD
  - Possible due to factorization of hard ME and PDF’s
    - Can be treated independently
  - Strong coupling (α_s) is large
    - Higher orders needed
    - Calculations complicated

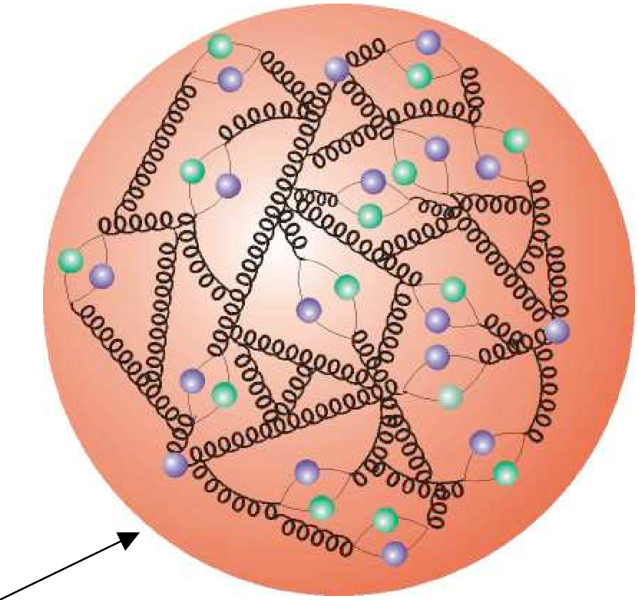
An experimentalist's view of a hadron collision



- Proton collisions are messy!
  - Hard scattering of partons (PDFs)
  - Initial state radiation (ISR)
  - Final state radiation (FSR)
  - Underlying event (I'll define this in a moment)
- We don't know:
  - Which partons hit each other
  - What their momentum is
  - What the other partons do

Proton Composition

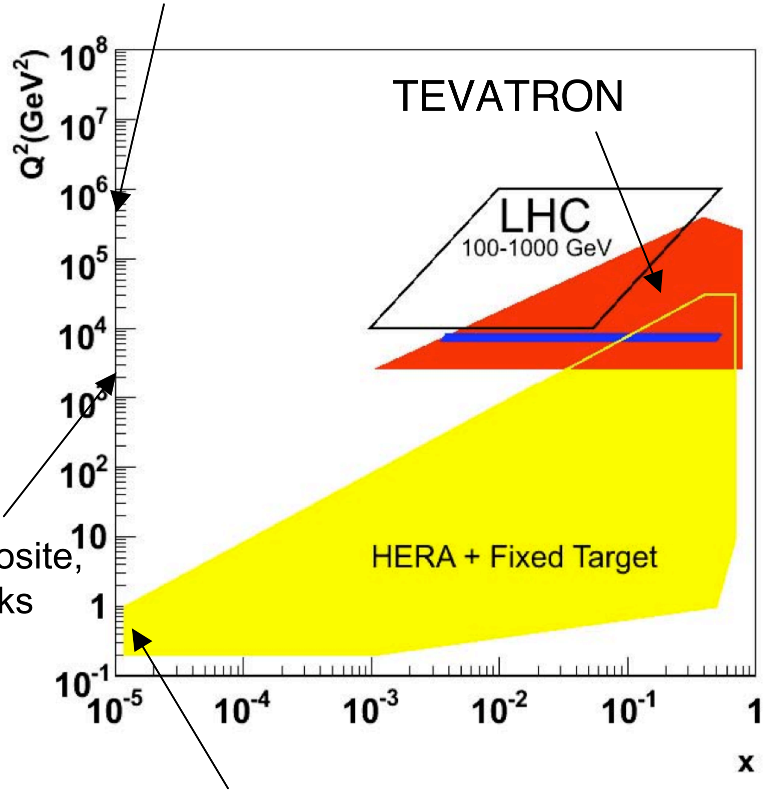
- What is a proton?
  - There are three quarks in a proton
    - False!
  - Each quark carries on average 1/3 the momentum of the proton.
    - False!
  - There are only u and d quarks in a proton (not s, c, b, t)
    - False!
  - The quarks are confined inside the proton and can never escape it.
    - False!
- Answer:
  - It's complicated!
    - Valence quarks, Gluons, Sea quarks
  - Exact mixture depends on:
    - Q^2: ~$(M^2+p_T^2)$
    - Björken-x = fraction or proton momentum carried by parton



Parton Distribution Functions (I)

- PDFs describe ***quark*** and ***gluon*** content of the proton.
- PDFs are essential input to perturbative calculations at hadron colliders
    - Important for signal and background processes
    - Uncertainties can be large
- Measured in many experiments
    - mostly come from DIS data (yellow in the plot)

Gluon and sea quark PDFs dominate

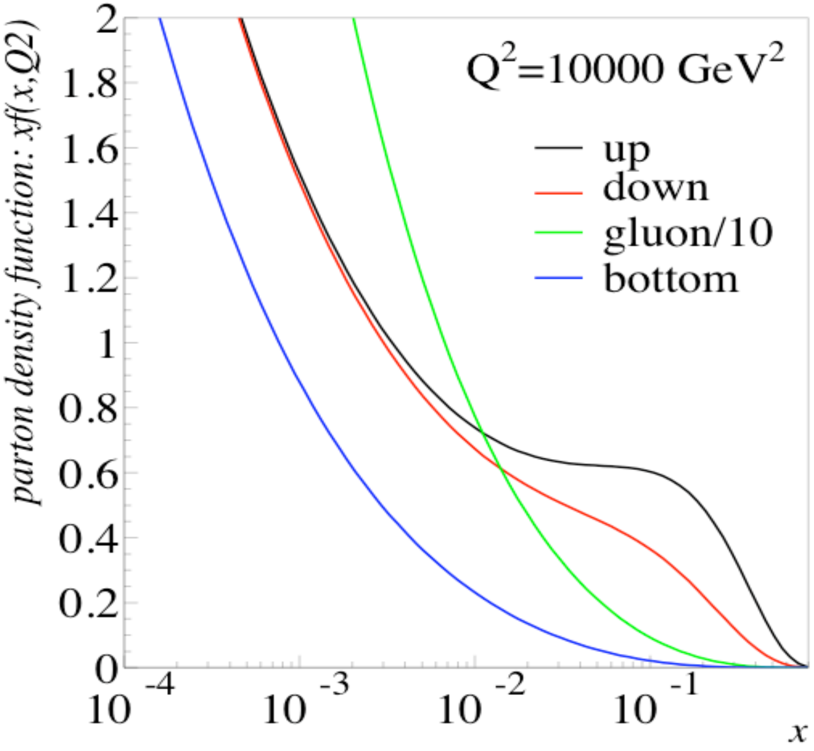


Proton composite, valence quarks dominate

Proton interacts as a single particle

Parton Distribution Functions (II)

- Parton densities rise dramatically towards low x
  - gluons dominate at x < 0.1
  - u, d quarks dominate at x > 0.1
- Example:
  - Higgs: M~100 GeV
    - TeV: <x>=100/2000≈0.05
    - LHC: <x>=100/14000≈0.007
  - Results in larger cross sections a the LHC, e.g. at 14TeV
    - factor ~100 for t-tbar
    - factor ~40 for Higgs
    - factor ~10 for W's

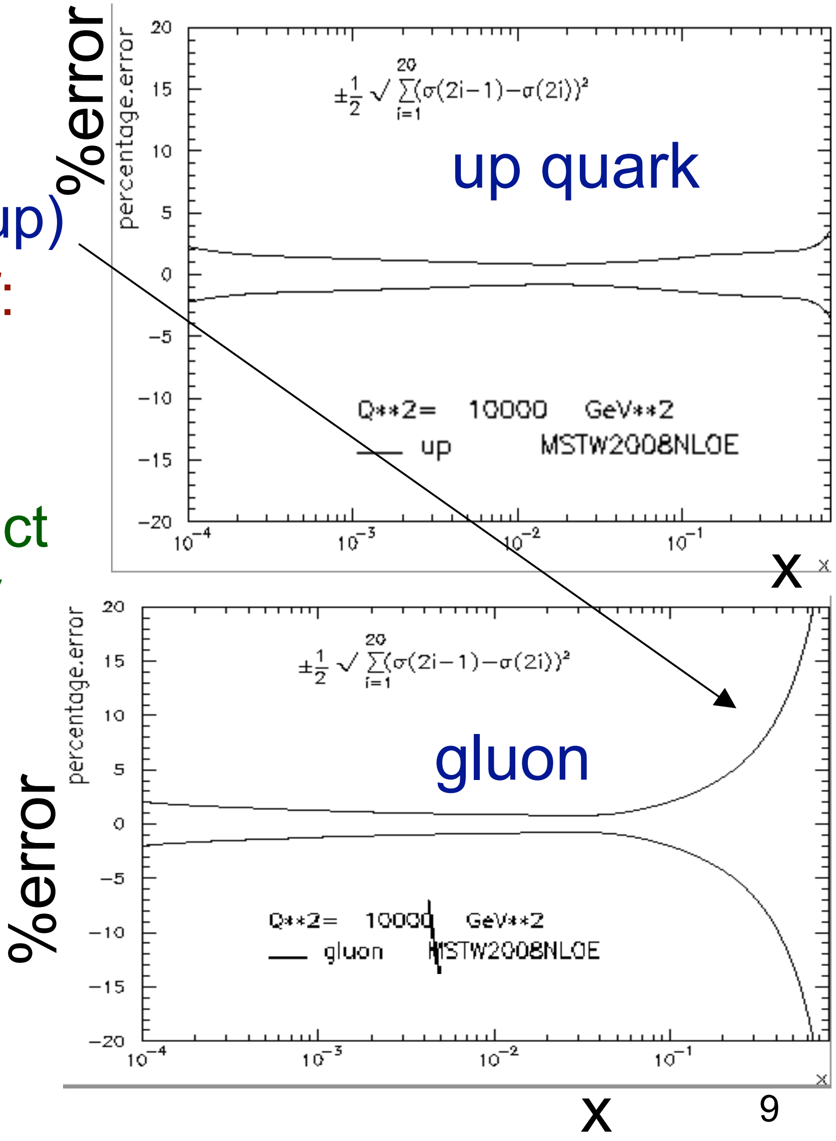


[http://durpdg.dur.ac.uk/hepdata/pdf3.html]

PDF fitting groups:
CTEQ and MRST
(now MSTW)

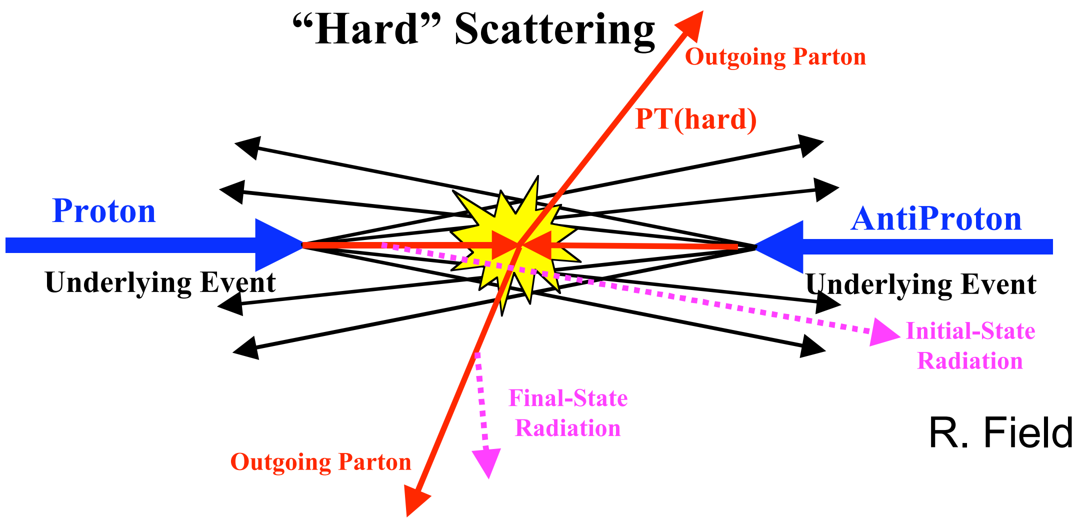
PDF Uncertainties

- PDF uncertainties of 2-30% or more (e.g. gluon PDF uncertainties blow up)
- This quantifies our understanding of:
  - The parton content of the proton
  - The cross sections of processes
- Uncertainties mean we cannot predict well-understood processes perfectly
- Extrapolation to LHC cross section calculations can vary a lot



[http://durpdg.dur.ac.uk/hepdata/pdf3.html]

The Underlying Event

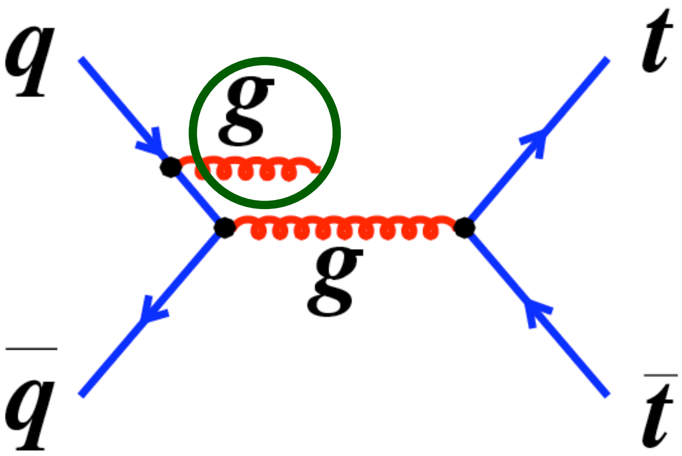


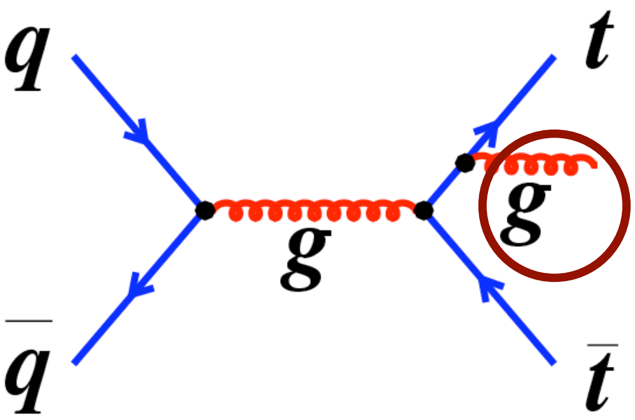
R. Field

- Everything except the hard scatter is called the **underlying event**
- It includes
  - initial state, final state radiation
  - Interactions of other partons in proton (remnants of the beam particles)
- **Additional pp interactions do occur!!**
  - On average 20 at design luminosity of LHC
  - Currently ~8 at the Tevatron (@ ~3x10^{32})

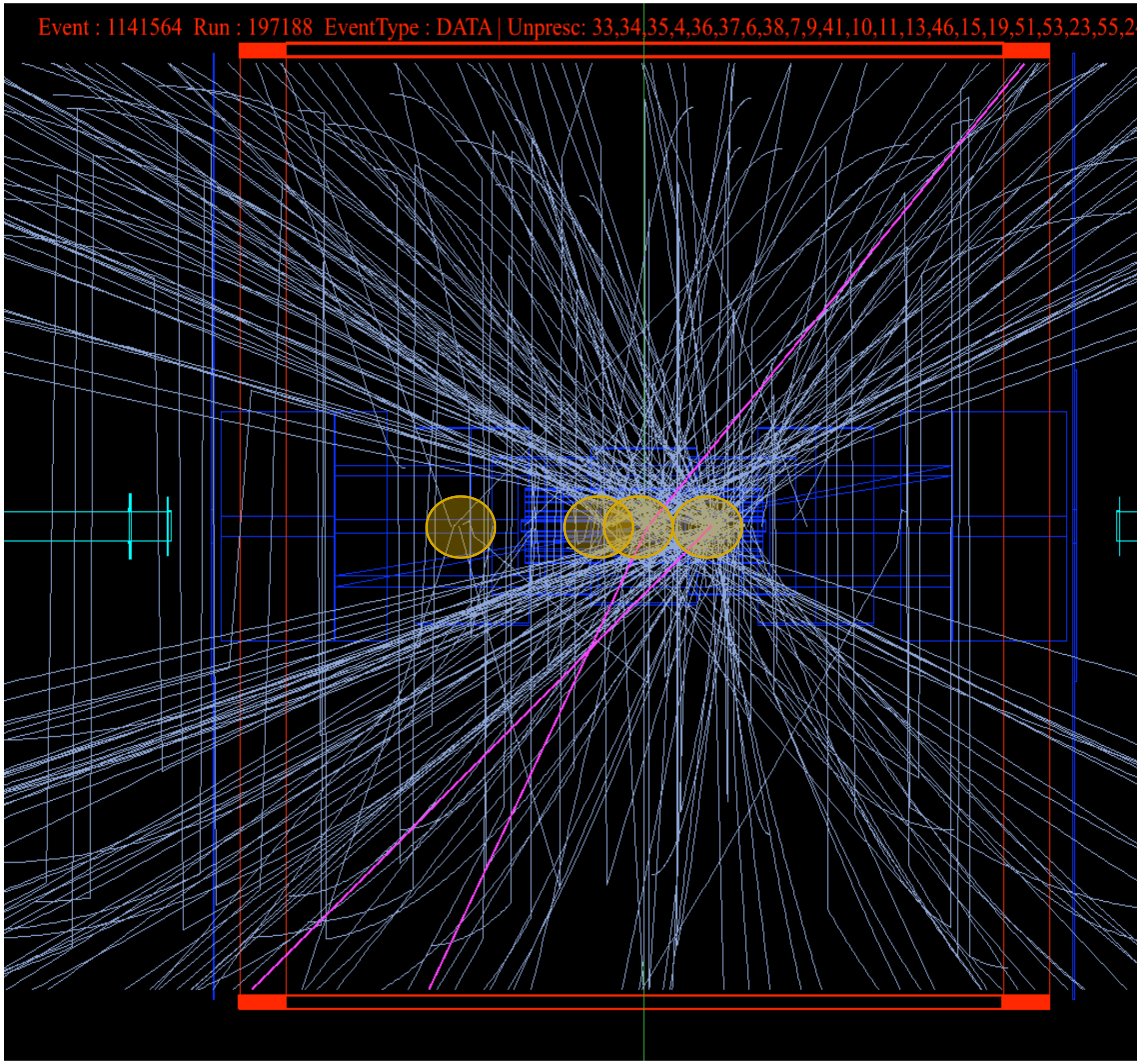
ISR/FSR

- Initial state and final state radiation can be very important even for the (apparently) simplest of processes:





The Reality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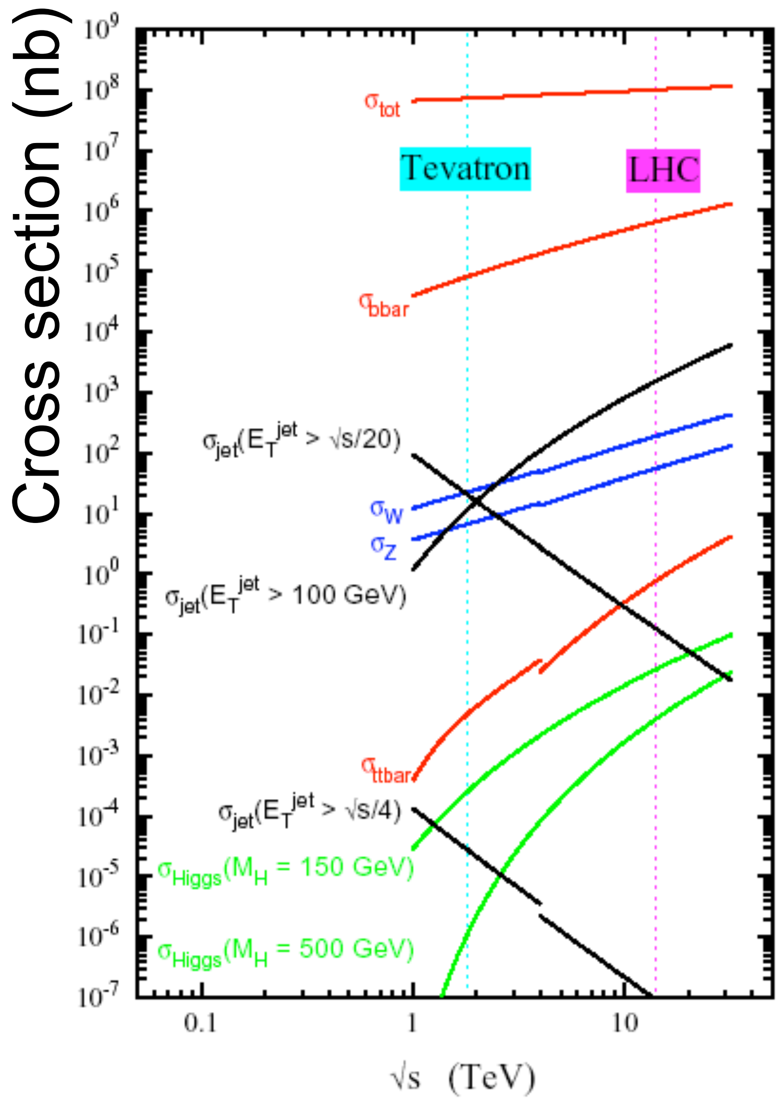
Cross Sections at Tevatron and LHC

- Dramatic increase of some cross sections from Tevatron to LHC (figure shows line for 14TeV)
  - Improved discovery potential at LHC

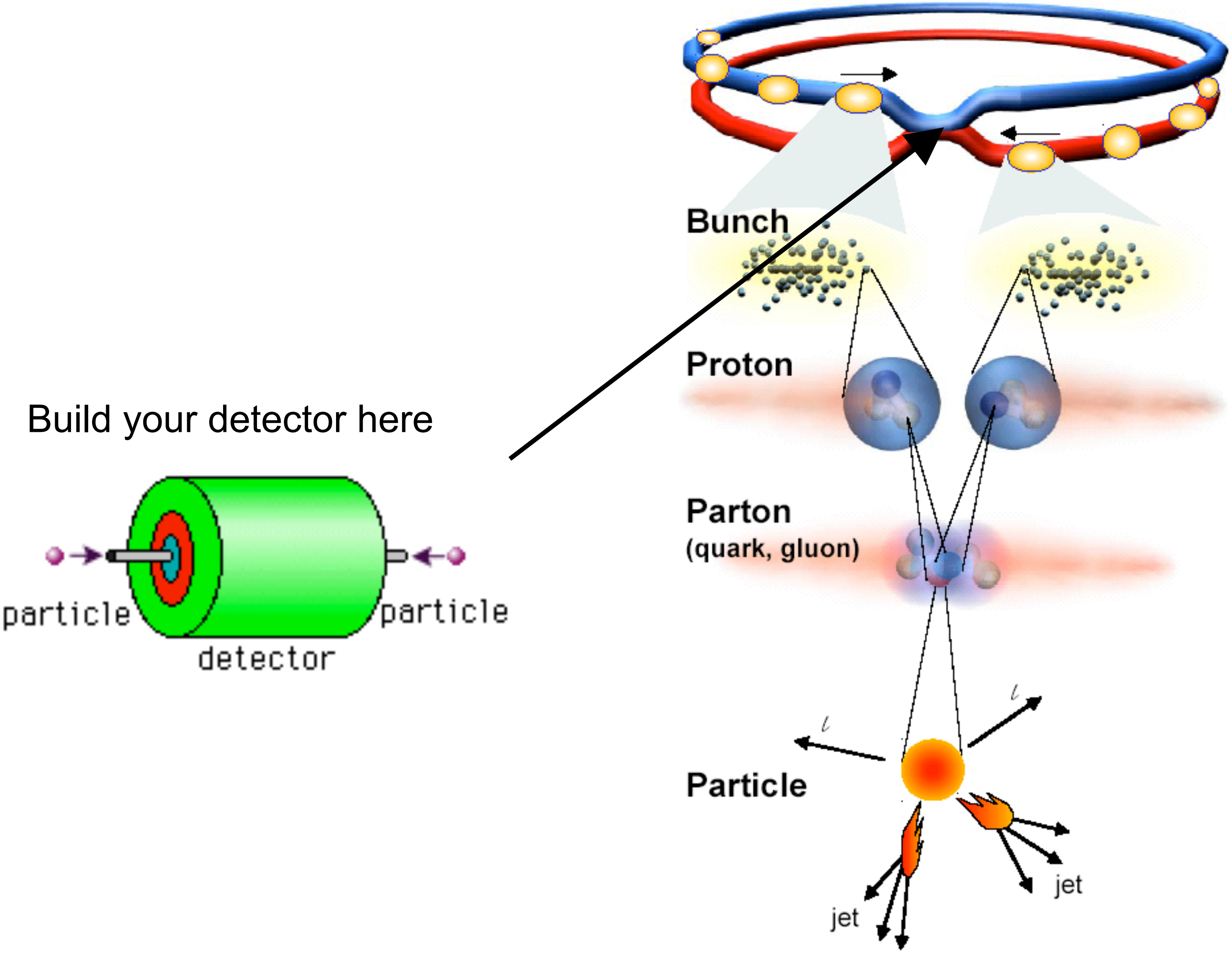
- A lot more “uninteresting” than “interesting” processes at design luminosity ($L=10^{34}$ $cm^{-2}s^{-1}$) at 14TeV
  - Any event: 10^9 / second
  - W boson: 150 / second
  - Top quark: 8 / second
  - Higgs (150 GeV): 0.2 / second

- This is a needle-in-haystack type of science
  - The next lectures focus on how we overcome these challenges

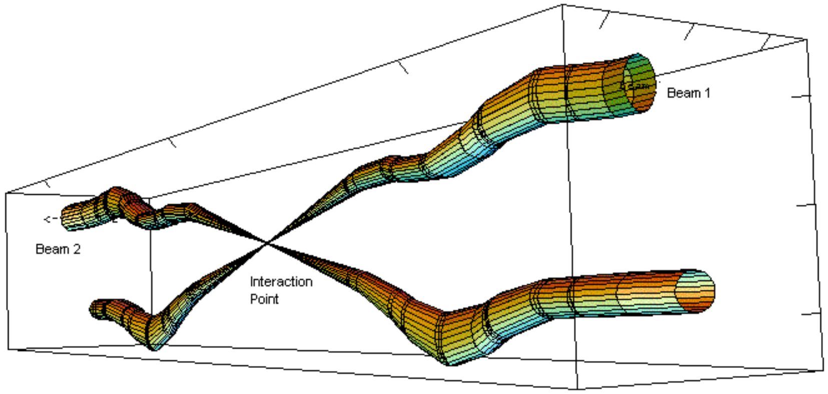


Colliding Beams

Build your detector here



Collisions



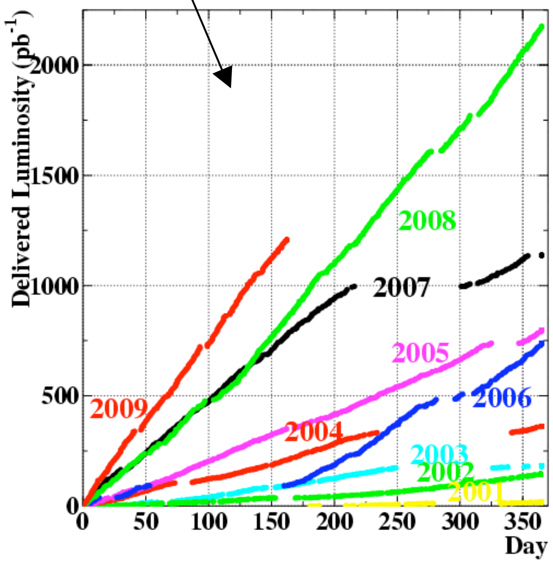
Relative beam sizes around IP1 (Atlas) in collision

- 2808 bunches of protons per beam.
- 100 billion protons per bunch and will be about a few cm. long
- Squeeze the beam size down as much as possible at the collision point to increase the chances of a collision.
    - squeeze down to *tens* of microns (about the width of a human hair) at the interaction point
    - around 20 collisions per crossing!
- The bunches cross every 25 nanoseconds
- Around 600 million collisions per second
- Most protons miss each other and continue around the ring. The beams will keep circulating for hours.

The LHC vs. The Tevatron

	LHC (design)	Tevatron (achieved)
Center-of-mass energy	**14 TeV**	1.96 TeV
Number of bunches	**2808**	36
Bunch spacing	**25 ns**	396 ns
Energy stored in beam	**360 MJ**	1 MJ
Peak Luminosity	**10^{33}-10^{34} $cm^{-2}s^{-1}$**	3.5 x 10^{32} $cm^{-2}s^{-1}$
Integrated Luminosity / year	**10-100 fb^{-1}**	>2 fb^{-1} in 2008

- Factor of ~1000 more powerful than Tevatron
  - 7 times more energy
  - Factor 3-30 times more luminosity
  - Physics cross sections factor 10-1000 larger (we saw this in the figure at the end of last lecture!)
- First collisions expected Fall 2009 at √s=10 TeV



Luminosity Revisited

- Recall, that the event rate in a collider is:

$$R = \mathcal{L}\sigma$$

- If two bunches containing n_1 and n_2 particles collide with frequency f , the luminosity is

$$\mathcal{L} = f\frac{n_1 n_2}{4\pi\sigma_x\sigma_y} \approx f\frac{n_b N_p{}^2}{4\pi\sigma_x\sigma_y}$$

- where σ_x and σ_y characterize the size of transverse beam (RMS assuming Gaussian spot size)
- n_b is the number of bunches
- And N_p is the number of particles (protons) per bunch

Example

$$\mathcal{L} \approx f \frac{n_b N_p^{\;2}}{4\pi\sigma_x\sigma_y}$$

- What size beam spot is needed for $\mathcal{L}$=1x10^{34}cm^{-2}sec^{-1}?
  - LHC machine frequency f = c/27km = 11kHz
  - n_b=2808 bunches
  - N_p=1x10^{11} protons per bunch

$$\sigma_{x,y} \approx \sqrt{11kHz \frac{2808(10^{11})^2}{4\pi(10^{34}\,cm^{-2}\,\sec^{-1})}} = 1.5\times10^{-3}\,cm = 15\mu m$$

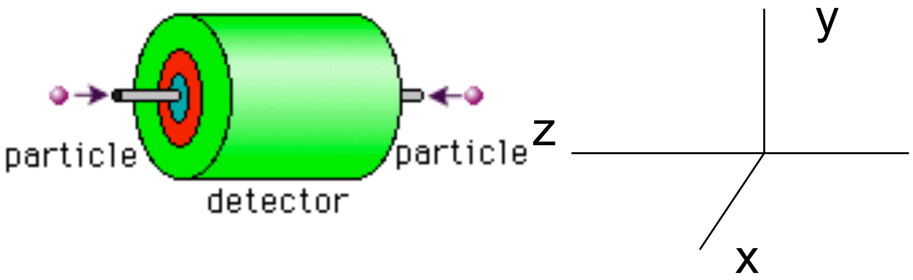
- So we will need approximately 15micron beam size
- For comparison, the Tevatron beam size is ~35μm

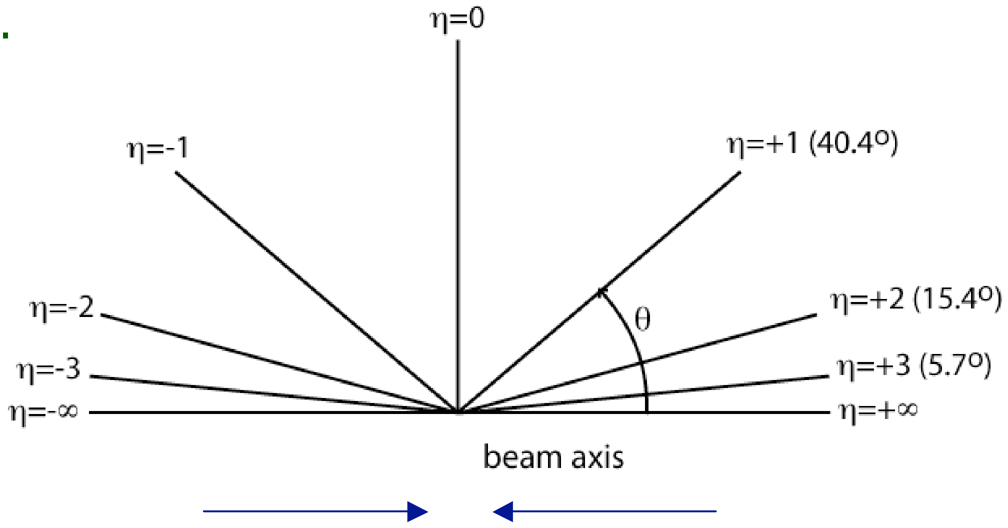
Definitions

- Now some definitions that every HEP physicist should know
  - Both theorists and experimentalists

Kinematical Definitions: η

- Natural coordinates are cylindrical around the beampipe
  - θ polar angle, ϕ azimuthal angle
- Polar angle θ is not Lorentz-invariant
- **Pseudorapidity is a function of polar angle**
  - $\boxed{\eta \equiv -\log\tan(\theta/2)}$
    - θ = 0 (η ≥ 1) forward
    - θ = π (η ≤ -1) backward
    - θ = π/2 (η =0) central





Interaction point

Kinematical Definitions: y

- **Rapidity** is a function of E, p_z

$$\boxed{y = \frac{1}{2}\log\frac{E + p_z}{E - p_z} = \tanh^{-1}(\frac{p_z}{E})}$$

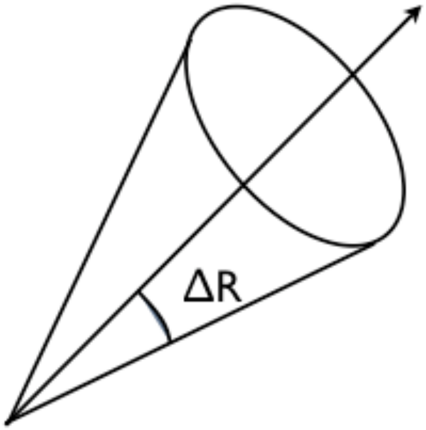
  - Δy is Lorentz-invariant under boosts along the beam direction
  - For a massless (or nearly massless particles where p>>m) particle y=η
  - Note: we can calculate η without knowing the mass of the particle!

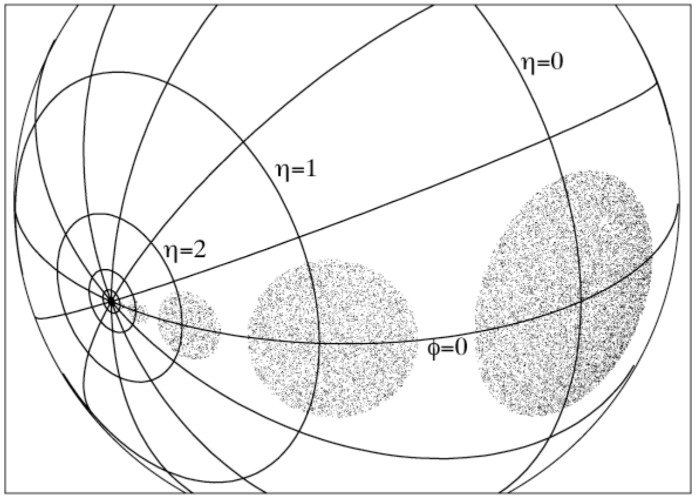
Kinematical Definitions: ΔR

- Experimentalists use ΔR as a measure of “distance”:

$$\boxed{\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}}$$

- We use it to determine separation in direction between particles
- We use “cones” of ΔR to group particles with each other in “jet” reconstruction (more on this on Wed.)

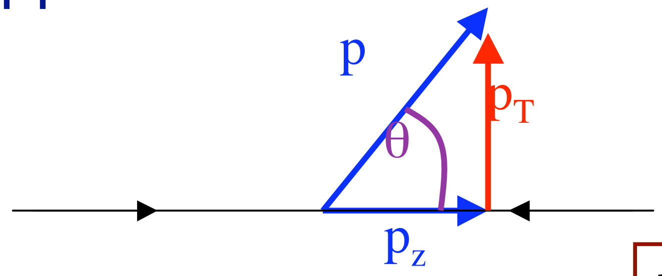




J. Conway

Transverse Quantities I

- Experimentalists focus on the transverse plane
  - opposite of “forward”



- Transverse Momentum $\boxed{p_T = p \sin\theta}$
  - Invariant under z-boosts
  - Particles that escape detection (forward) have $p_T \approx 0$
  - “Visible” transverse momentum conserved
- Transverse Energy $\boxed{E_T = E \sin\theta}$
- Transverse Mass $\boxed{m_T^2 = \sqrt{E_T^2 - p_T^2}}$
- etc…

Transverse Quantities II

- Missing transverse energy, or MET, is defined as

$$\boxed{\not{E}_T \equiv -\sum_i E_T^i \hat{n}_i = -\sum_{\textit{all}\ \mathrm{visible}} \vec{\mathrm{E}}_\mathrm{T}}$$

  - where nhat$_i$ is the component in the transverse plane of a unit vector that points from the interaction point to the ith calorimeter detector tower (this will become clearer later)
  - It's an event-wide z-boost-invariant quantity
  - **It's one of the most interesting and most difficult quantities for experimentalists!**
- It is also interesting to look at the measure of the scale of the visible p$_T$

$$\boxed{H_T \equiv \sum_{i=objects} \left|\vec{p}_{i,T}\right|}$$

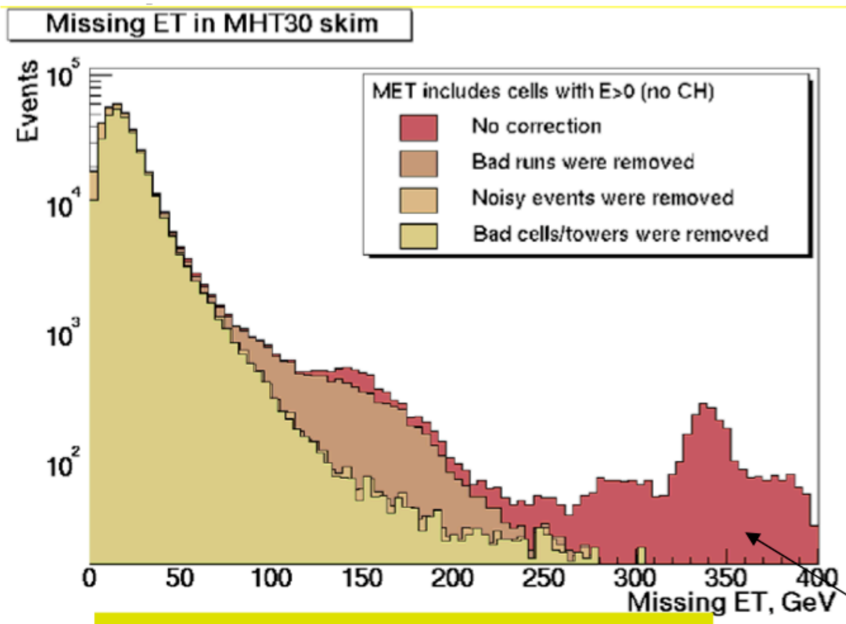
  - Definition varies: which objects (leptons, jets, MET) to include in the sum
  - Also an event-wide z-boost-invariant quantity

Why the transverse plane?

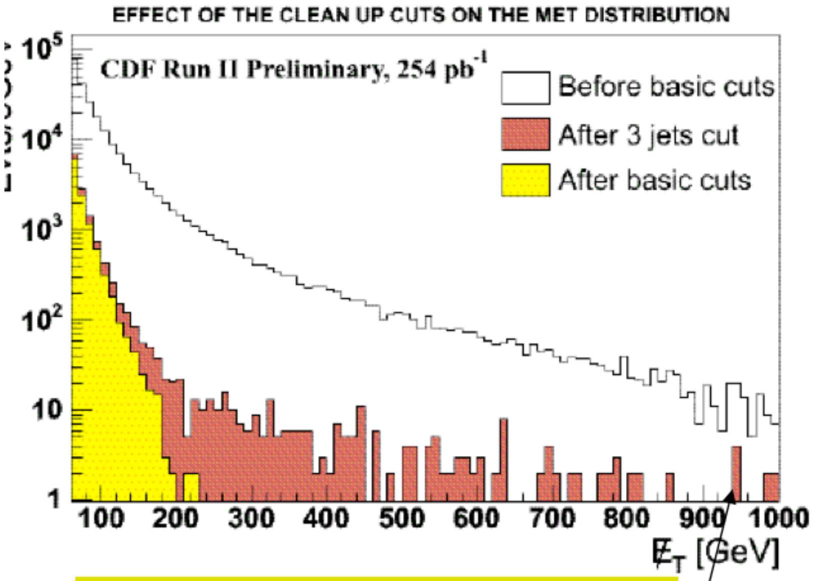
- Question: why don't we look for missing p_z or missing E?
  - In hadron collisions you don't know the initial state
    - Remember, the proton is not what scatters!
  - Particles that scatter (underlying event) and escape detection have large p_z
  - Visible p_z is not conserved and is therefore not a useful variable
  - So, to good a approximation $\sum_i p_T^i \approx 0$
    - We have momentum conservation in transverse plane

More on MET

- A lot of careful work needed to understand MET
- Anything going wrong produces MET! (more on Wed.)
- Lessons learned at the Tevatron:



MET, before corrections (Do)



MET, after corrections (CDF)

This is where new physics may sit

CMS and ATLAS Detectors

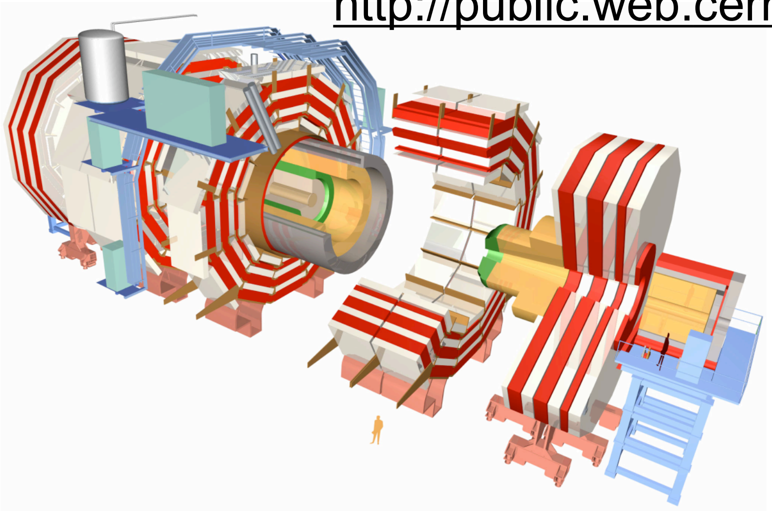
Compact Muon Solenid (CMS)

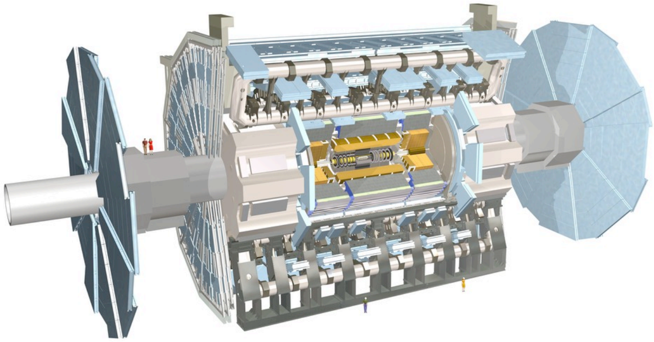
- Size: 21 m long, 15 high m and 15 m wide.
- Weight: 12 500 tons!
- Location: Cessy, France

A Toroidal LHC ApparatuS (ATLAS)

- Size: 46 m long, 25 m high and 25 m wide
- Weight: 7000 tons!
- Location: Meyrin, Switzerland.

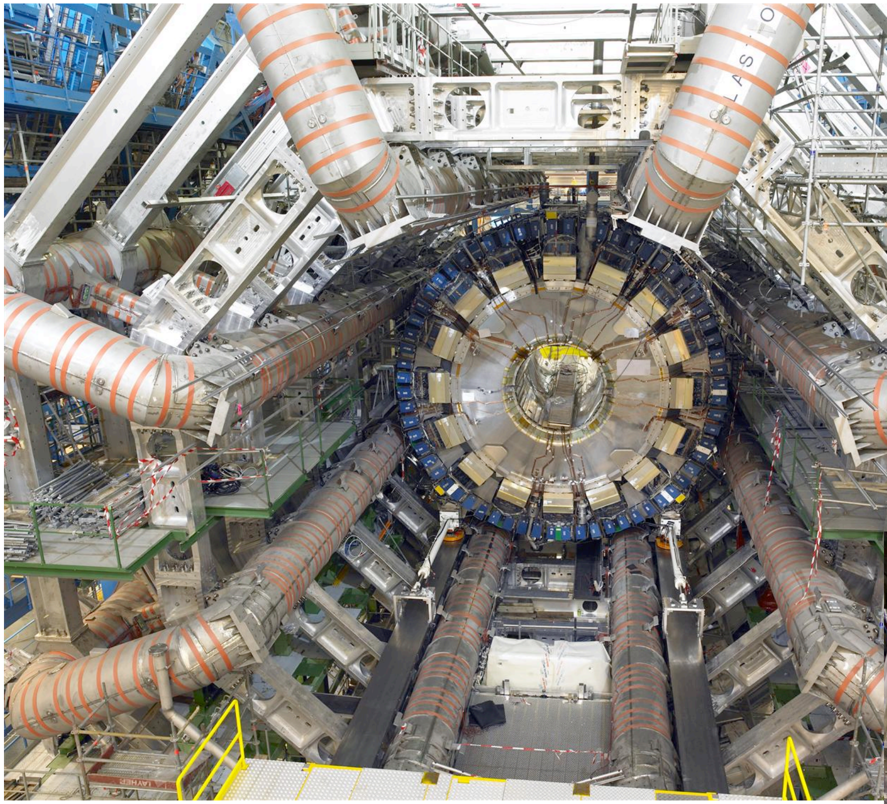
Fun facts and figures:
http://public.web.cern.ch/public/en/LHC/Facts-en.html



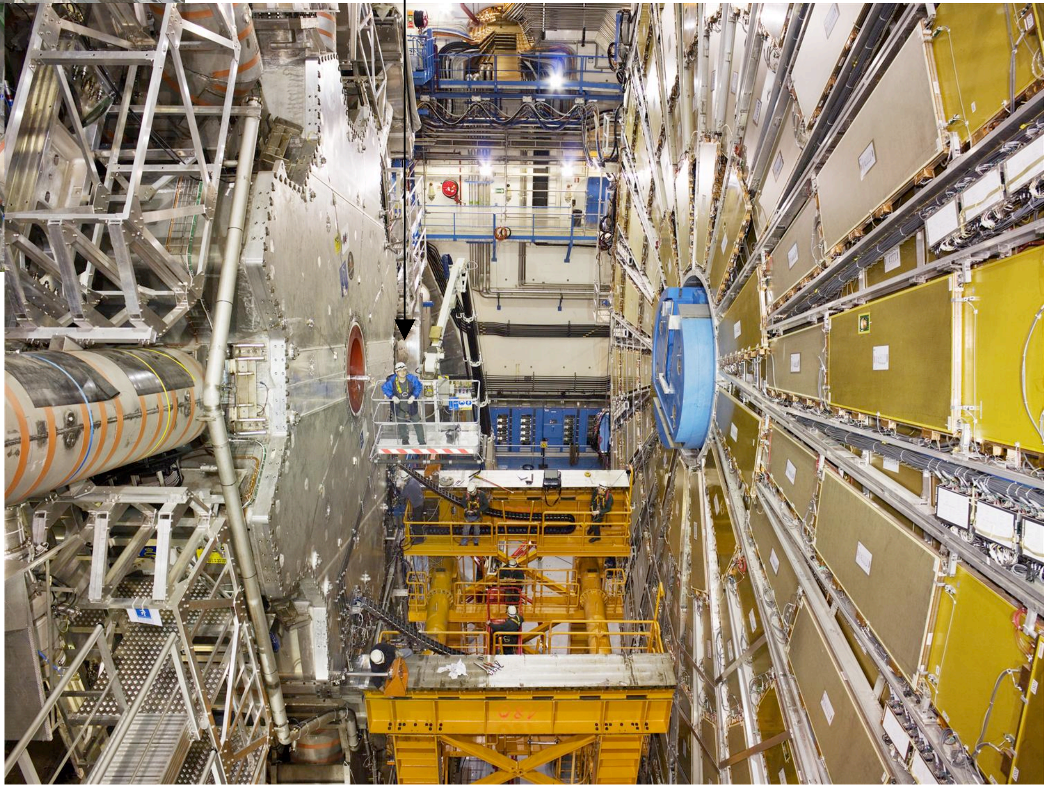


These are large (~2K people) international (~40 countries) collaborations!

ATLAS



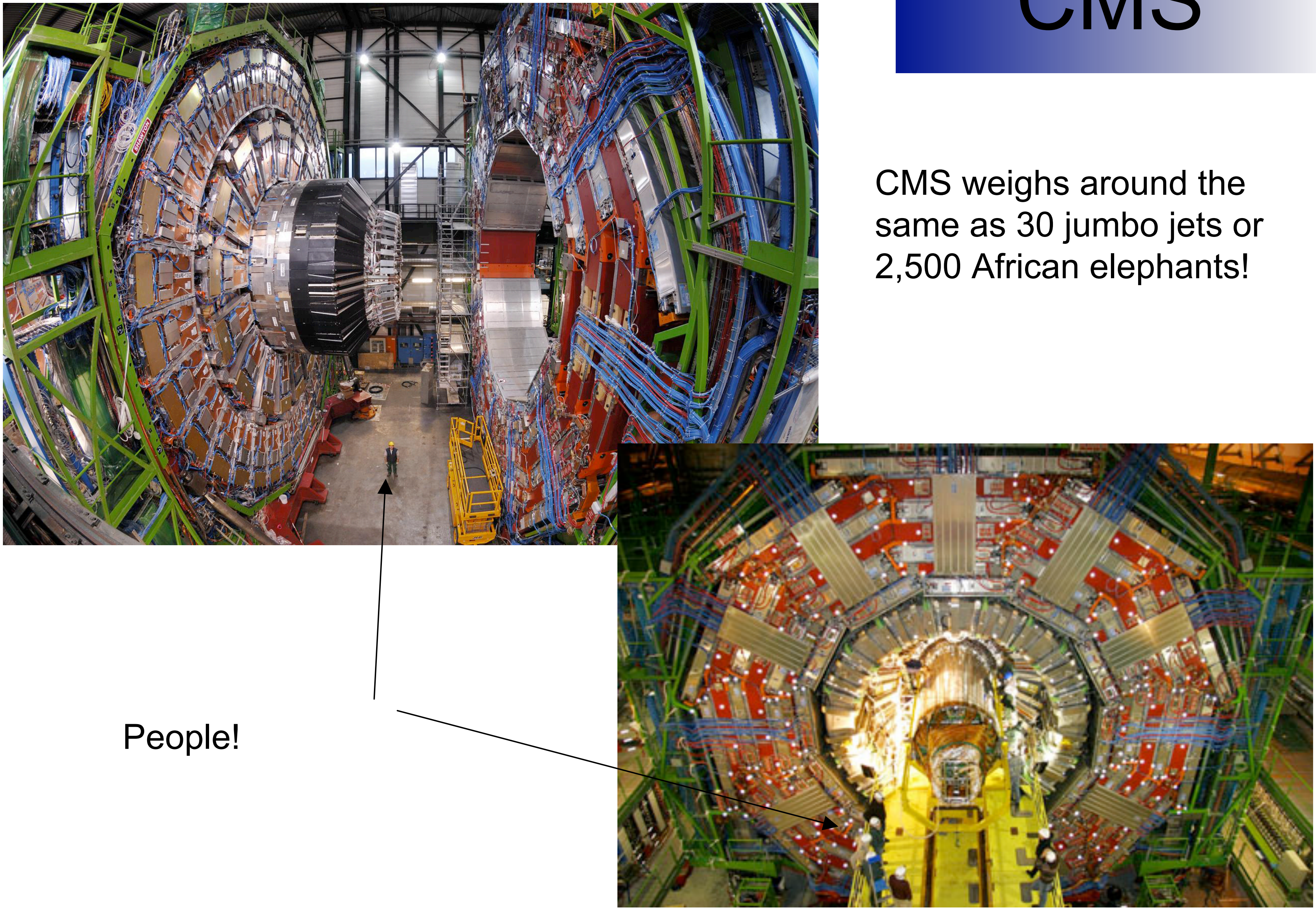
The ATLAS cavern could hold the nave of Notre Dam cathedral!



A person!

CMS

CMS weighs around the same as 30 jumbo jets or 2,500 African elephants!



People!

Detectors and Particle Interactions

- Understanding the LHC detectors (and their differences) requires a basic understanding of the interaction of high energy particles and matter
- Also required for understanding how experimentalists identify particles and make physics measurements/discoveries
- Particles can interact with:
  - atoms/molecules
  - atomic electrons
  - nucleus
- Results in many effects:
  - Ionization (inelastic)
  - Elastic scattering (Coulomb)
  - Energy loss (Bremsstrahlung)
  - Pair-creation
  - etc.

Important to understand interactions of:
- Charged Particles
  - Light: Electrons
  - Heavy: All Others (π, μ, K, etc.)
- Neutral Particles
  - Photons
  - Neutrons

Lot's of sources. Main one used here is the PDG: pdg.lbl.gov

Energy Loss of Charged Heavy Particles

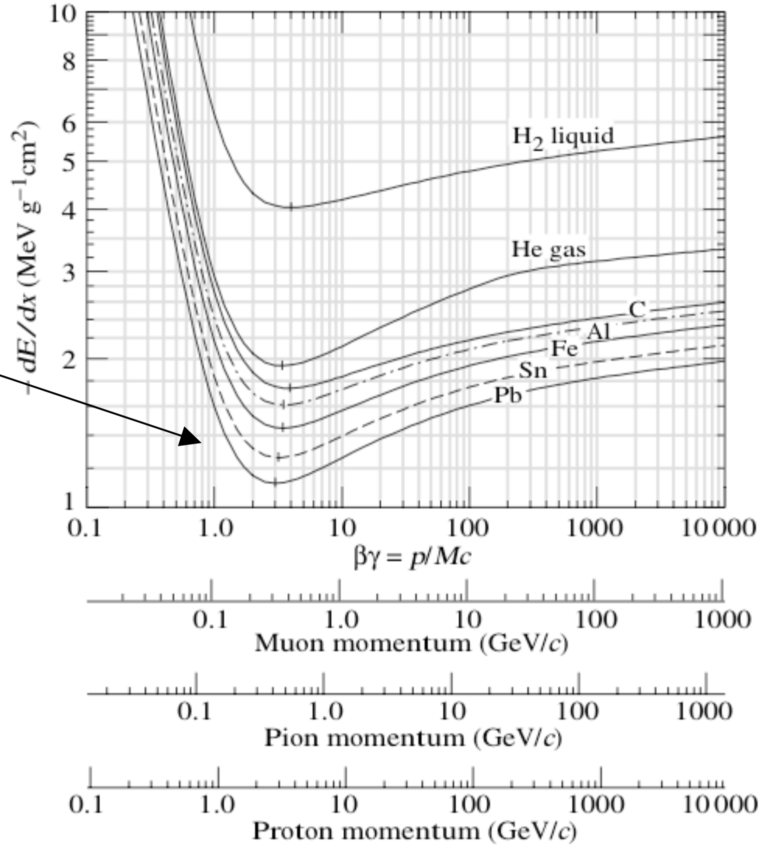
- Moderately relativistic heavy charged particles lose energy in matter primarily by *ionization* and *atomic excitation*.
- Average rate of energy loss is:

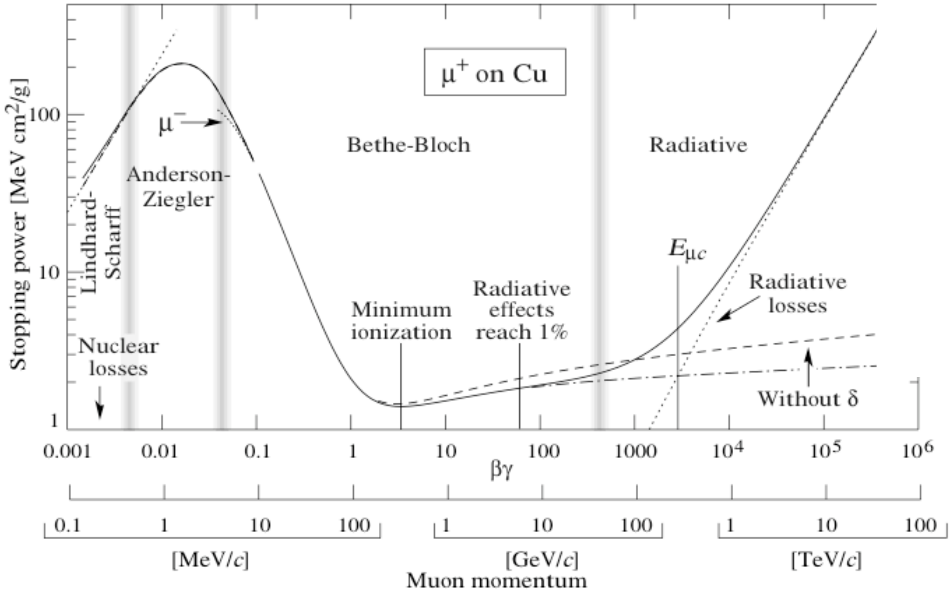
$$-\frac{dE}{dx} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\mathrm{max}}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

- This is known as the Bethe-Bloch equation.
- Also called the “stopping power”

Bethe-Bloch

- Ionization (dE/dx)
  - expressed in terms of MeV/(g/cm^2)
  - depends on material density
- Minimum at $\beta\gamma \sim 3$ independent of target
- Minimum ionizing particles or MIPs





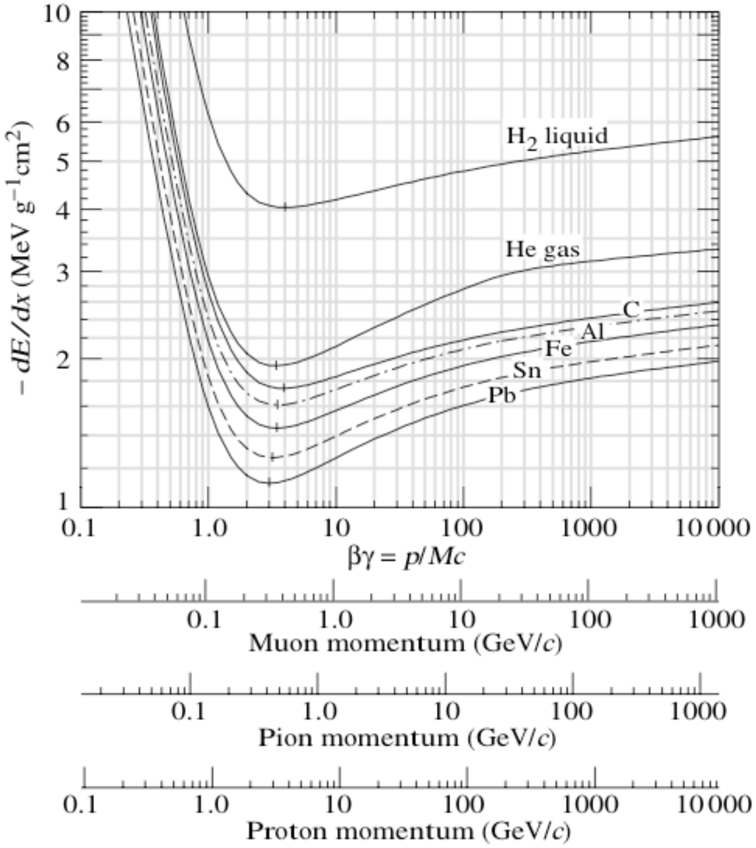
PDG

Example

- How much energy loss for a MIP in silicon?
- dE/dx:

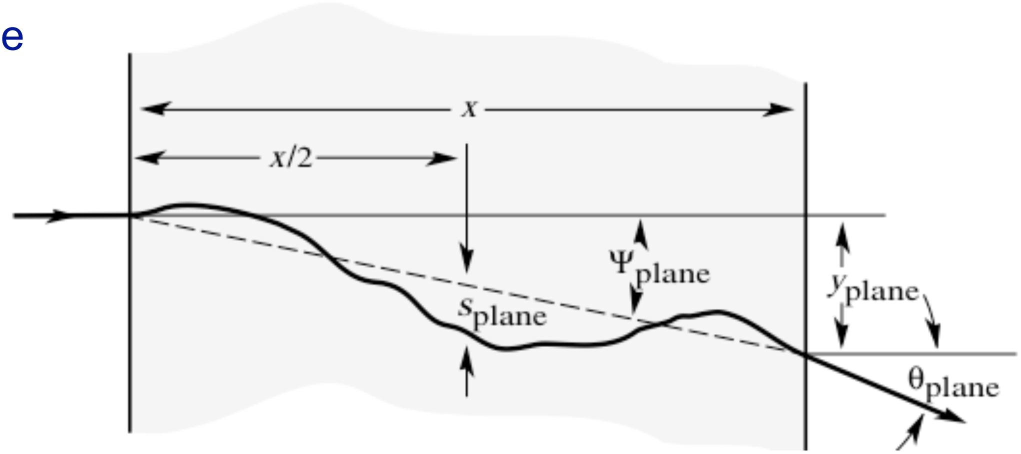
  1.6 MeV/(g/ cm^2) x 2.33 g/cm^3 =

  3.7 MeV/cm
- This is not very much!
  - This value determines the minimal detector thickness
  - We will see later, silicon detectors are very thin



Multiple Scattering

- As high energy charged particles ionize materials, they change their direction with each interaction
  - Multiple Coulomb scattering off nuclei



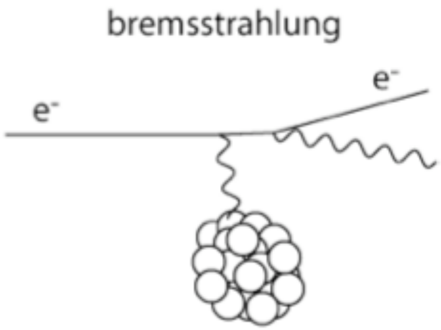
PDG

- Distribution dominated by gaussian of width θ_0

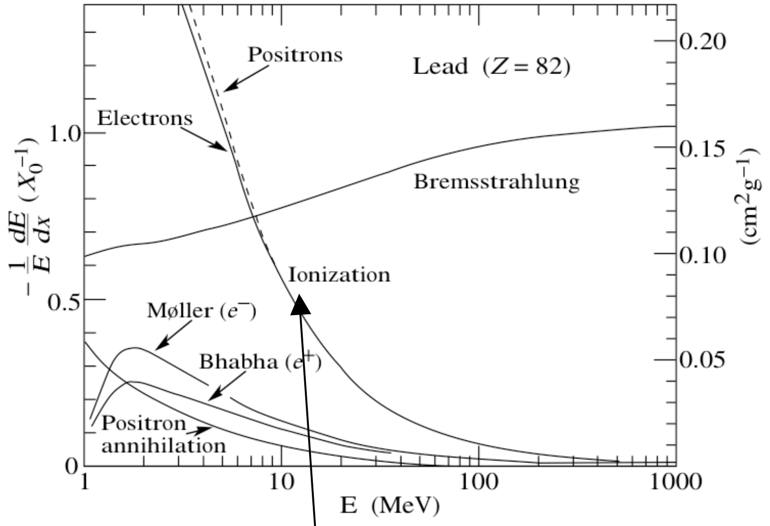
$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]\ .$$

- But large non-gaussian tails from high angle scattering
- Important for relatively low-energy particles (~ few GeV)

Energy Loss of Electrons



J.Conway



PDG

- Electrons loose energy by bremsstrahlung at a rate nearly proportional to its energy (see next slide)
- Ionization loss rate rises logarithmically.
- The critical energy is the energy at which the two loss rates are equal, and depends strongly on the absorbing material (e.g. 9.5 MeV for Pb shown above).

Radiation Length

- The radiation length (X_0) is th characteristic length that describes the energy decay of a beam of electrons:

$$X_0 = \frac{716.4 \text{ g cm}^{-2} A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

- Distance over which the electron energy is reduced by a factor of 1/e due to radiation losses only
- Radiation loss is approx. independent of material when thickness expressed in terms of X_0
- Higher Z materials have shorter radiation length
  - want high-Z material for an EM calorimeter
  - want as little material as possible in front of calorimeter

material	X_0 g/cm^2
H_2	63
Al	24
Fe	13.8
Pb	6.3

- Example:

  lead: ρ = 11.4 g/cm^3 so X_0 = 5.5 mm

- The energy loss by brem is:

$$\boxed{-\frac{dE}{dx} = \frac{E}{X_0}}$$

Backup

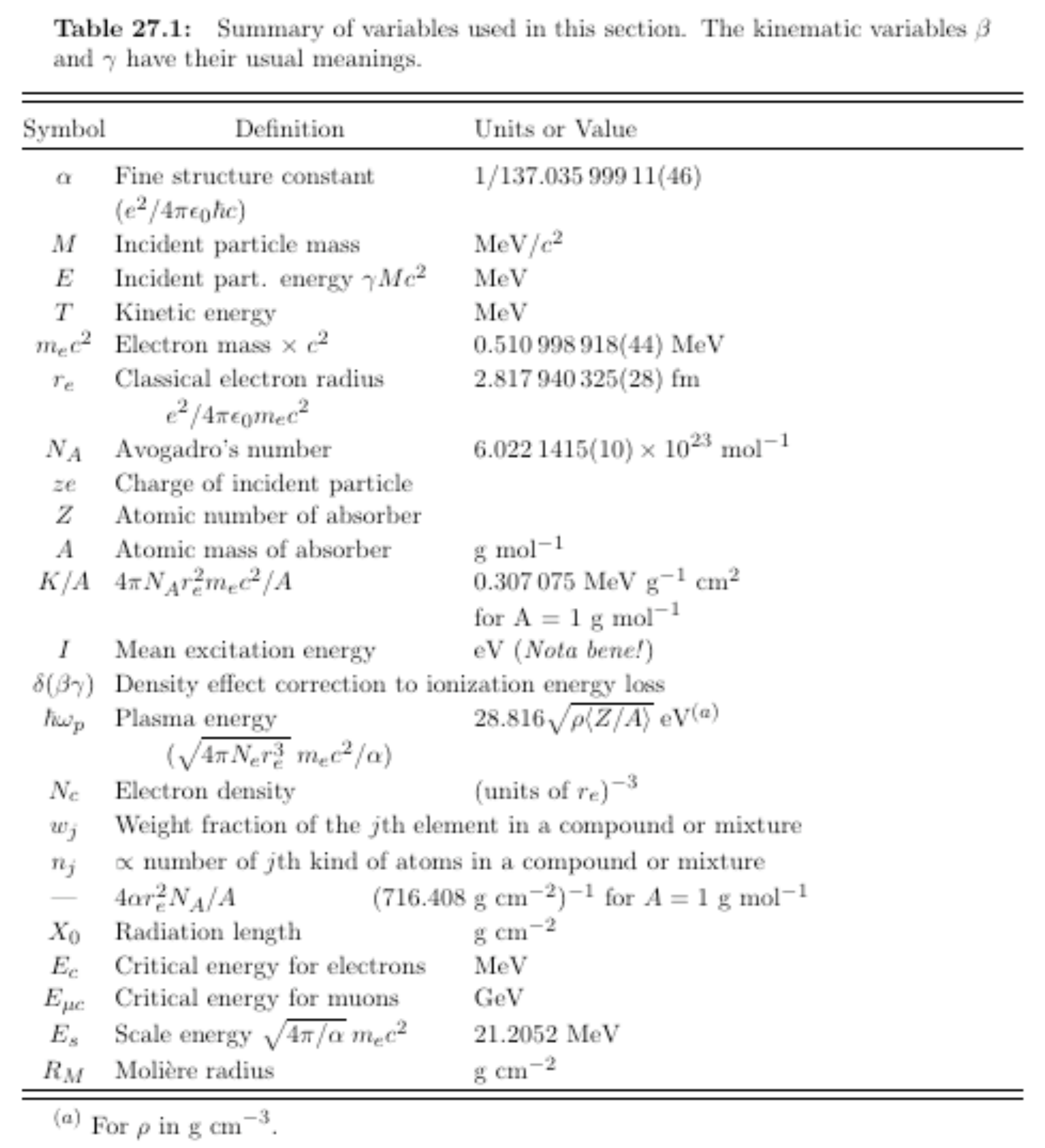


Table 27.1: Summary of variables used in this section. The kinematic variables β and γ have their usual meanings.

Symbol	Definition	Units or Value
α	Fine structure constant $(e^2/4\pi\epsilon_0\hbar c)$	$1/137.035\,999\,11(46)$
M	Incident particle mass	MeV/c^2
E	Incident part. energy γMc^2	MeV
T	Kinetic energy	MeV
m_ec^2	Electron mass $\times\ c^2$	$0.510\,998\,918(44)$ MeV
r_e	Classical electron radius $e^2/4\pi\epsilon_0 m_ec^2$	$2.817\,940\,325(28)$ fm
N_A	Avogadro's number	$6.022\,1415(10)\times 10^{23}\ \mathrm{mol}^{-1}$
ze	Charge of incident particle	
Z	Atomic number of absorber	
A	Atomic mass of absorber	$\mathrm{g\ mol}^{-1}$
K/A	$4\pi N_A r_e^2 m_ec^2/A$	$0.307\,075\ \mathrm{MeV\ g}^{-1}\ \mathrm{cm}^2$ for $A = 1\ \mathrm{g\ mol}^{-1}$
I	Mean excitation energy	eV (*Nota bene!*)
$\delta(\beta\gamma)$	Density effect correction to ionization energy loss	
$\hbar\omega_p$	Plasma energy $(\sqrt{4\pi N_e r_e^3}\ m_ec^2/\alpha)$	$28.816\sqrt{\rho\langle Z/A\rangle}\ \mathrm{eV}^{(a)}$
N_c	Electron density	(units of $r_e)^{-3}$
w_j	Weight fraction of the jth element in a compound or mixture	
n_j	$\propto$ number of jth kind of atoms in a compound or mixture	
—	$4\alpha r_e^2 N_A/A$	$(716.408\ \mathrm{g\ cm}^{-2})^{-1}$ for $A = 1\ \mathrm{g\ mol}^{-1}$
X_0	Radiation length	$\mathrm{g\ cm}^{-2}$
E_c	Critical energy for electrons	MeV
$E_{\mu c}$	Critical energy for muons	GeV
E_s	Scale energy $\sqrt{4\pi/\alpha}\ m_ec^2$	21.2052 MeV
R_M	Molière radius	$\mathrm{g\ cm}^{-2}$

$^{(a)}$ For ρ in $\mathrm{g\ cm}^{-3}$.