Lecture 1:
Introduction and Basics

Eva Halkiadakis
Rutgers University

TASI Summer School 2009
Boulder, CO

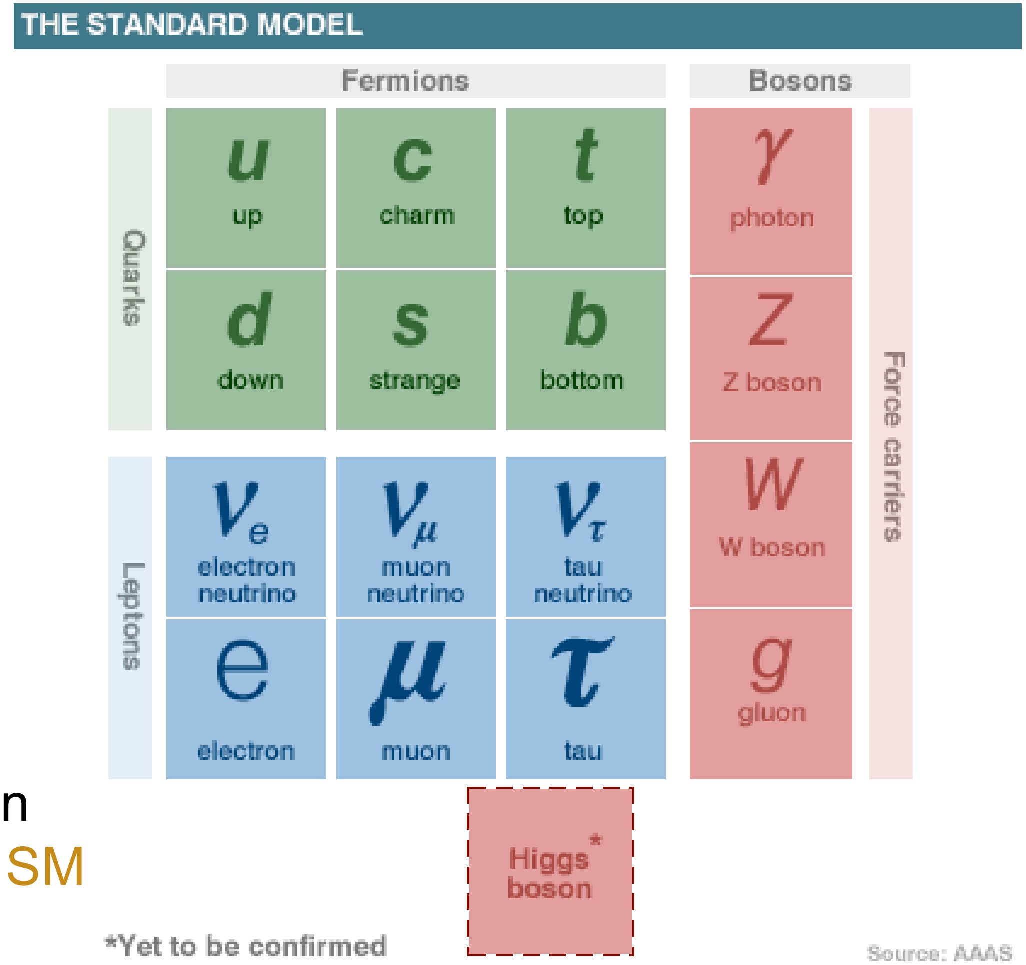
Opening Remarks

- During these lectures, I encourage you to interrupt me to ask me questions!
- I hope by the end of these lectures you will have a better understanding of what experimentalists think (worry) about
- And I hope they will help you in having more fruitful discussions with your experimental colleagues!
- Although I am giving you a basic introduction to the LHC experiments, I will often use many general examples from the (still running) Fermilab Tevatron

The Standard Model

The Standard Model is a good “**theory**”

- Matter: is made out of fermions
- Forces: are mediated by bosons
- Higgs boson: breaks the electroweak symmetry and gives mass to fermions and weak gauge bosons



*Yet to be confirmed

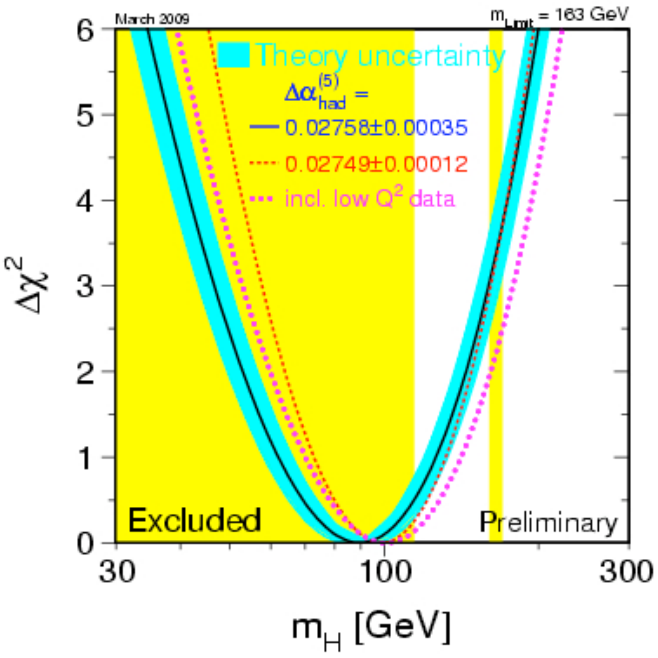
Source: AAAS

Experimentally verified its predictions to incredible precision

Almost all particles predicted by SM have been found

But it does not explain everything…

Unsolved Mysteries

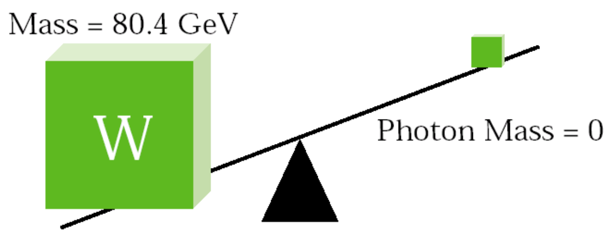


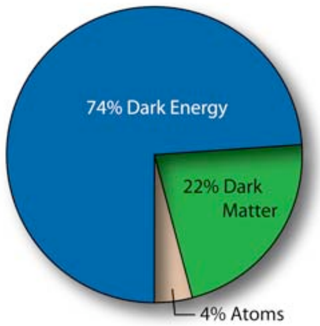
Higgs not yet observed

It is required by the Standard Model

Riddle of masses

Why is there a hierarchy of masses?





What is dark matter?

Why is there almost no anti-matter in the universe?

How does gravity fit into all of this?

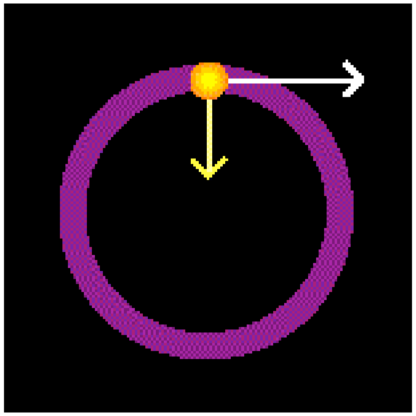
And so on…….

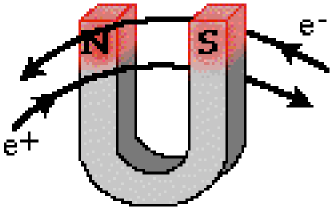
Beyond Standard Model

- Standard Model can not explain many of these mysteries.
- How can we search for new physics beyond the SM?
  - SUSY?
  - Extra space dimensions? (Gravitons)
  - Extra gauge groups? (Z', W')
  - New/excited fermions? (more generations, compositeness)
  - Leptoquarks?
  - Any thing else????
- We need experiments to figure out which theory best describes nature.
- By the end of these lectures I hope you will get a glimpse of how experimentalists plan to search for new physics at the LHC.

Particle Accelerators

- Accelerators are shaped in one of two ways:
  - Linac (e.g. SLAC, Future ILC):
    - Charged particles accelerated through a tube by applying RF voltage to separated sections so that the particles feel an accelerating electric field when they pass the gap.
    - Arranged so that particles arrive at the next gap at the right phase of the RF voltage, so they are accelerated again.
  - Circular/synchrotron (e.g. LEP, Tevatron, LHC):
    - Large circular devices where charged particles travel in evacuated pipes under the influence of magnets positioned around circumference of the circle.
    - Acceleration is achieved by applying RF electric fields at RF cavities along the circumference of ring.
    - Magnetic fields increased synchronously with the acceleration to keep the particles on the constant radius path.





Linac vs. Circular

- 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

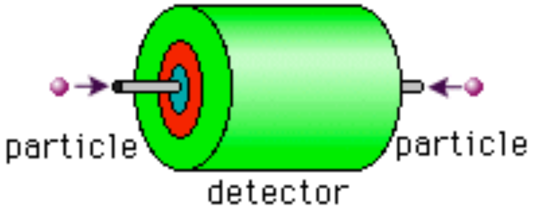
Particle Collisions

- Accelerators can be arranged to provide collisions of two types:
  - Fixed target: Shoot a particle at a fixed target.

$$E_{cm} = \sqrt{2E_{beam} m_{target}}$$

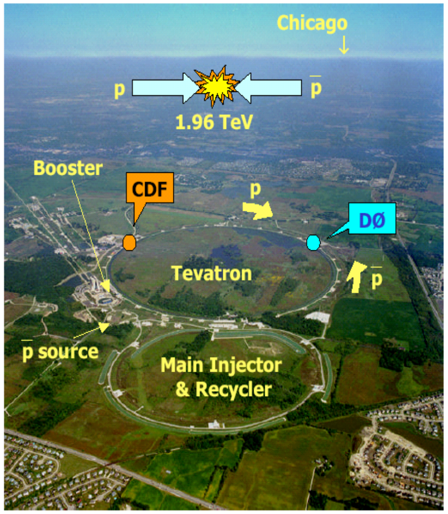
  - Colliding beams: Two beams of particles are made to cross each other.

$$E_{cm} = 2E_{beam}$$

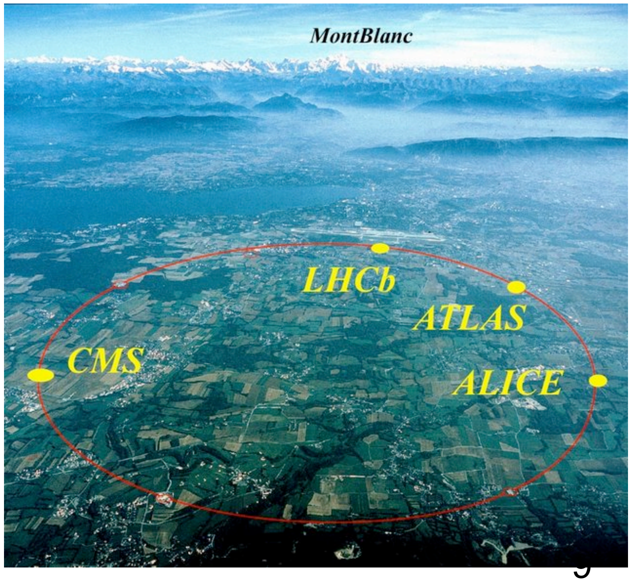


Hadron Colliders

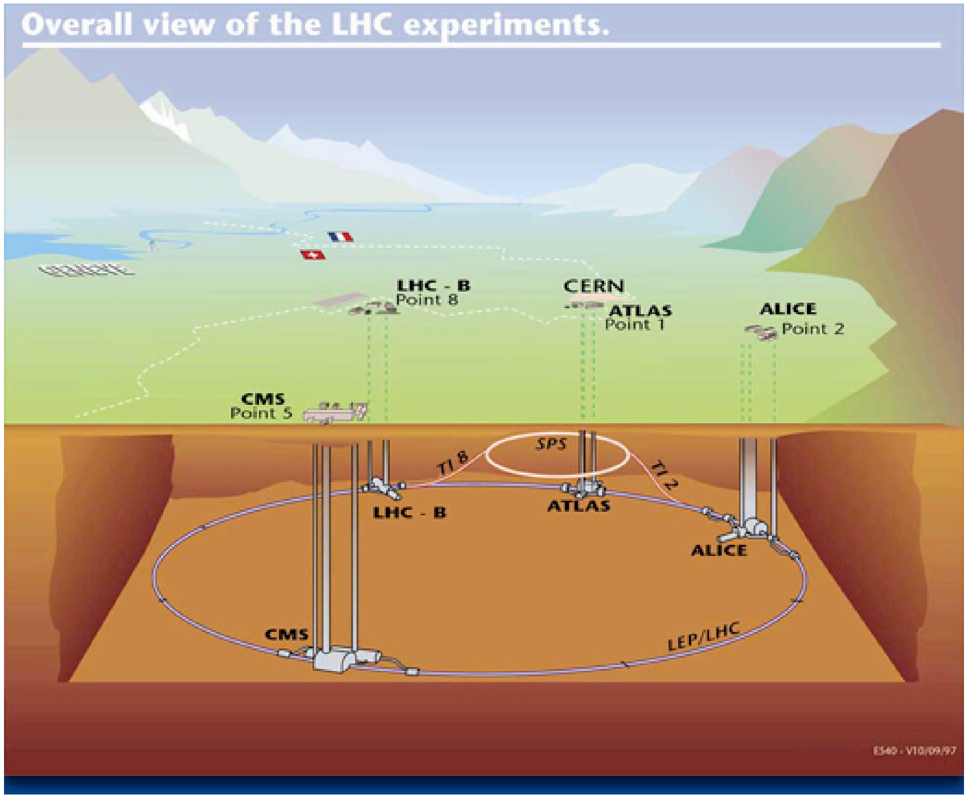
- Tevatron at Fermilab
  - Proton- anti-proton collisions
  - 6.5 km circumference
  - E_{beam} ~ 980 GeV, E_{cm} ~ 2 TeV
  - Run II since 2001-present



- Large Hadron Collider at CERN
  - Proton-proton collisions
  - 27 km circumference
  - E_{beam}=5 TeV, E_{cm} = 10TeV initially
  - E_{beam}=7 TeV, E_{cm} = 14TeV design
  - Also heavy Ion collisions (Pb-Pb)
    - Shorter running periods (~1month/year)
    - E_{cm}= 2.76 TeV per nucleon
  - First collisions expected this fall

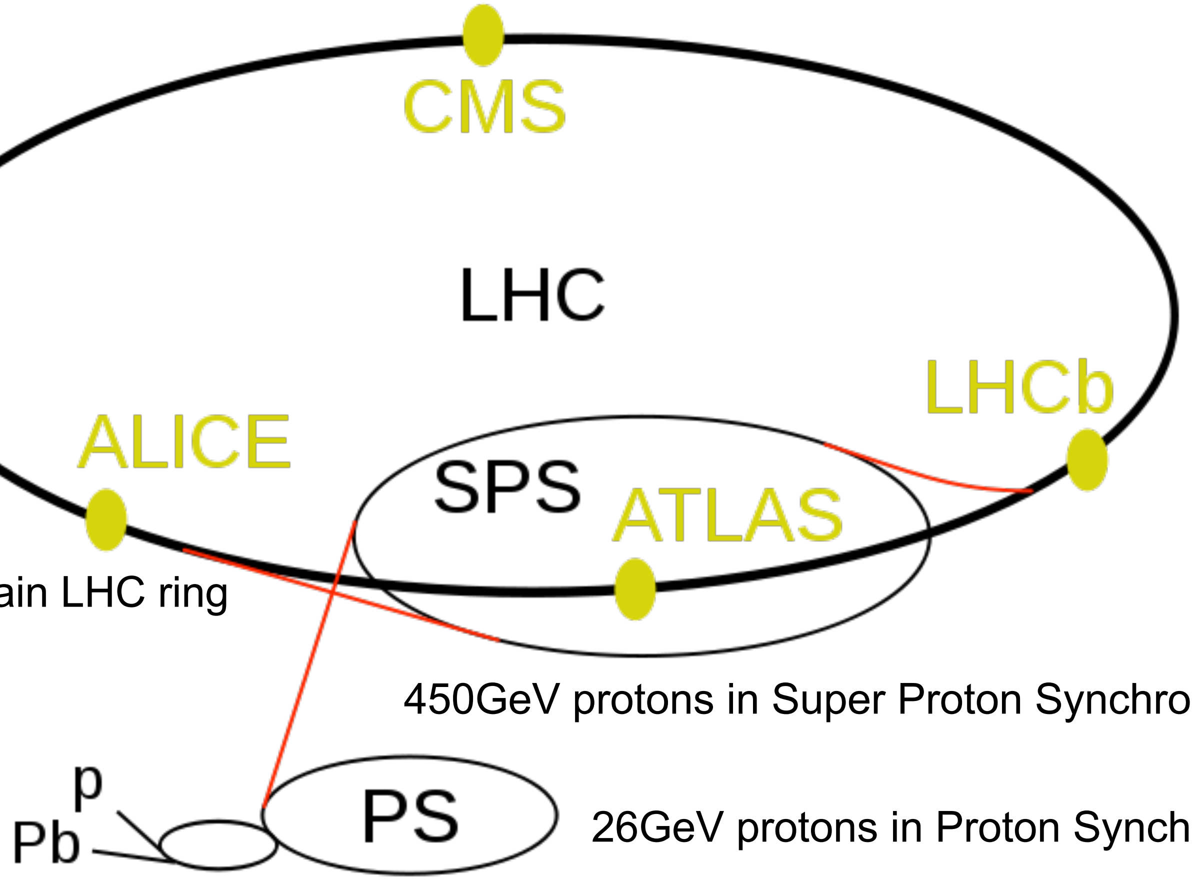


The LHC



- Circular tunnel 27 km in circumference.
- The tunnel is buried around 100m underground
- The beams move around the LHC ring inside a continuous vacuum guided by superconducting magnets.
- The beams will be stored at high energy for hours. During this time collisions take place inside the four main LHC experiments.
  - CMS } Large “general purpose” experiments.
  - ATLAS } I will focus primarily on these.
  - LHCb → b physics (CP violation, rare decays)
  - ALICE → Heavy Ion experiment (quark-gluon plasma)

LHC Accelerator Chain



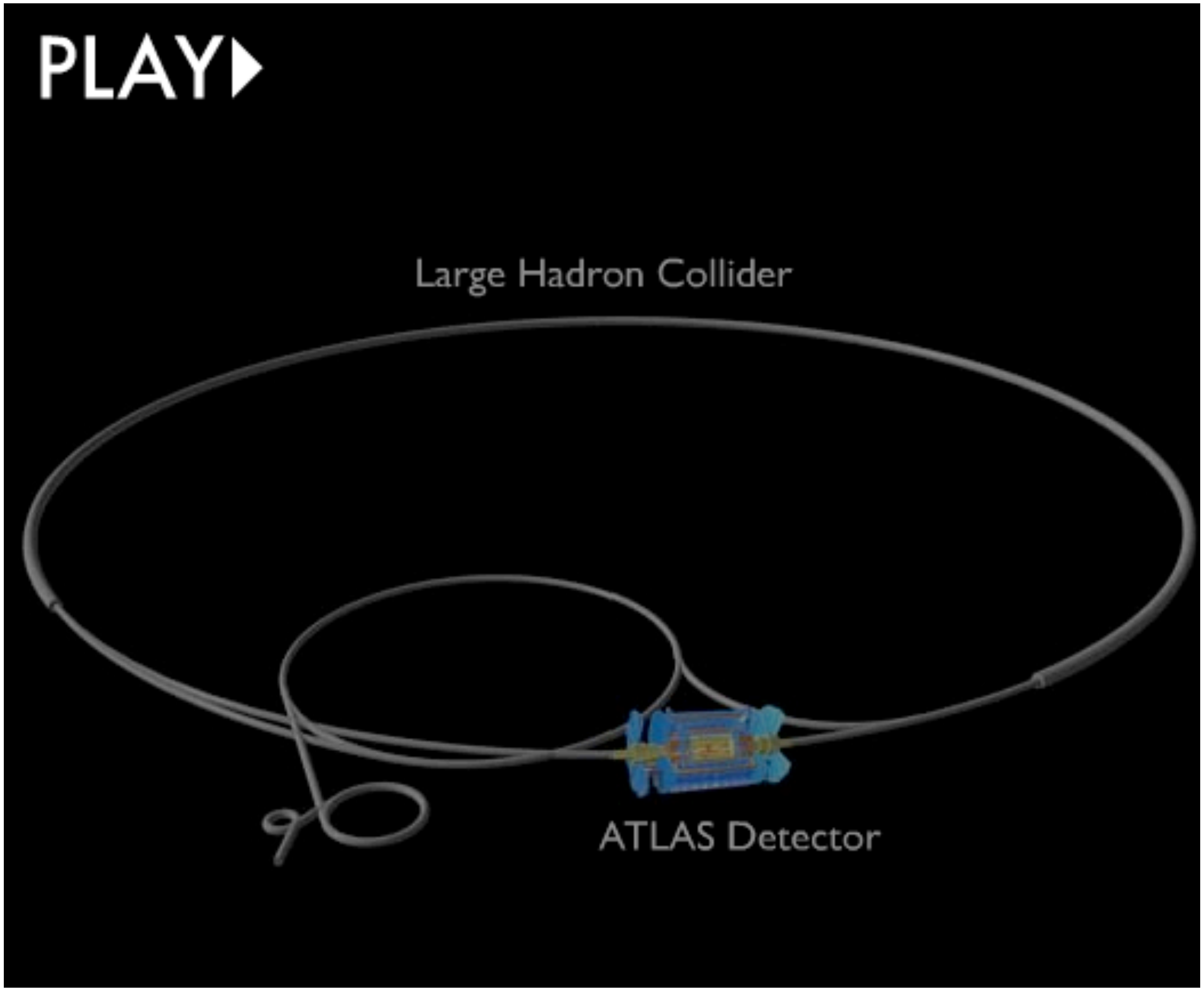
7 TeV protons in main LHC ring

450GeV protons in Super Proton Synchrotron (SPS)

26GeV protons in Proton Synchrotron (PS)

50MeV-1.4GeV protons in LINAC/Booster

Let’s see this in action …

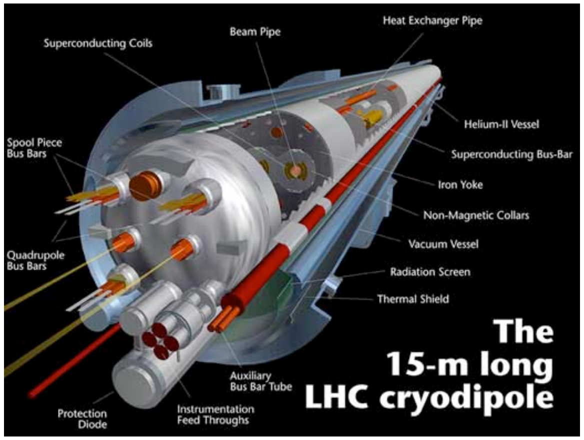


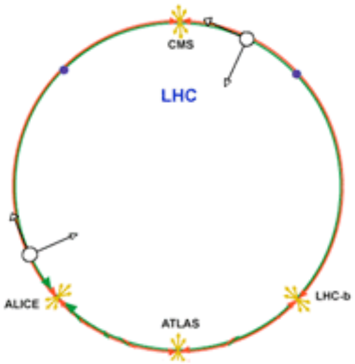
LHC Dipole Magnets

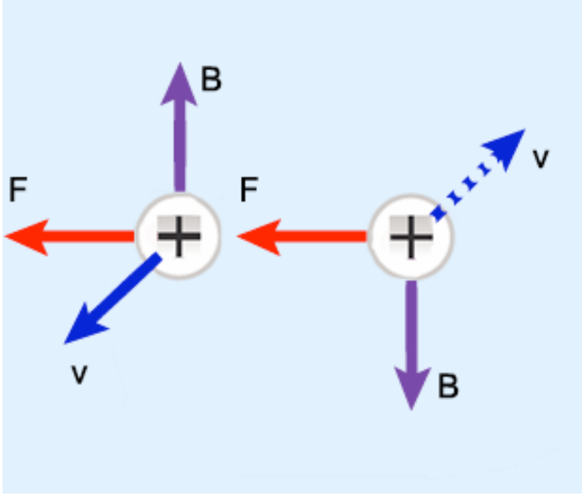
- 1232 15-m long, 35 ton dipole magnets positioned around the 27-km circumference of the collider.
- Use niobium-titanium (NbTi) cables, which become superconducting below a temperature of 10 K (–263.2°C).
- In fact, the LHC will operate at the still lower temperature of 1.9 K (–271.3°C), reached by pumping superfluid helium into the magnet systems.
- A current of 11,700 A flows in the dipoles, to create the high magnetic field of 8.3 T, required to bend the 7 TeV beams around the ring.

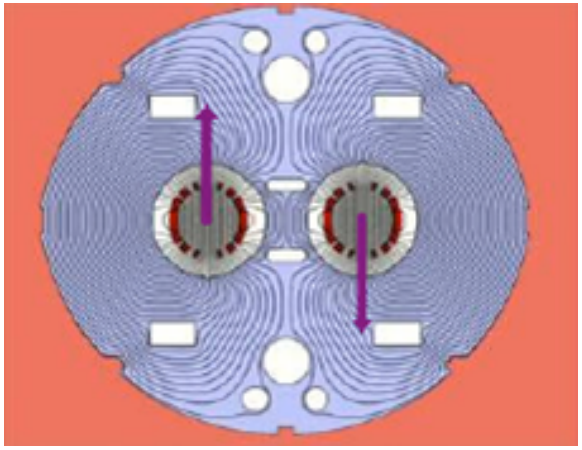
LHC Dipole Magnets

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









Luminosity

- Important parameters in colliders are
  - the energy of the beams (previous slide)
  - the rate of collisions or the luminosity

Number of events / second

$$\boxed{R} = \frac{dN}{dt} = \mathscr{L}\sigma$$

Cross section:
Given by nature/Calculated by theorists

Integrated luminosity:
Given by accelerator

Number of events over a period of time

$$\boxed{N}_{\text{events }\underline{\text{produced}}} = \boxed{\sigma}\times\boxed{\int \mathscr{L}dt}$$

$$\boxed{N}_{\text{events }\underline{\text{observed}}} = \sigma\times\int \mathscr{L}dt\times\boxed{\varepsilon}$$

Detector efficiency:
Evaluated by experimentalists

Units of Cross Section and Luminosity

- Units of cross section
  - [cross section]=

    [area]

    cm^2

    or

    1 barn = 10^{-24} cm^2

    or

    mb, μb, nb, pb, fb, …

- Units of luminosity:
  - [instantaneous $\mathscr{L}$]=

    1/(cross section x time)=

    $1/cm^2$ 1/s
  - [integrated $\mathscr{L}$] =

    unit of 1/cross section =

    $1/cm^2$

    or

    pb^{-1} or fb^{-1}…

Example 1

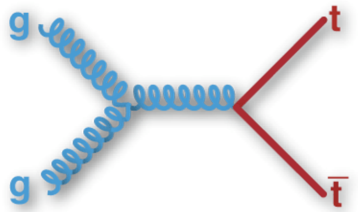
- If a hadron collider, like the LHC or the Tevatron, runs for 1 year with an **instantaneous luminosity of 10^{31}cm^{-2}sec^{-1}**, how much **integrated luminosity** will be delivered to the experiments?
  - A year is $3\text{x}10^{7}$ sec, but no accelerator runs every day. Let's assume a good year of running is 10^{7} sec. This is a rough estimate.

$$\int \mathscr{L} dt = 10^{31} cm^{-2} \sec^{-1} \times 10^{7} \sec$$

$$= 10^{38} cm^{-2} = 10^{14} barns = 100\, pb^{-1}$$

Example 2

- In $100pb^{-1}$ of data, how many top+anti-top quark pairs (pp→t tbar) will be produced at the LHC at 10TeV?



  - The t-tbar pair production cross section @10 TeV is roughly 400 pb

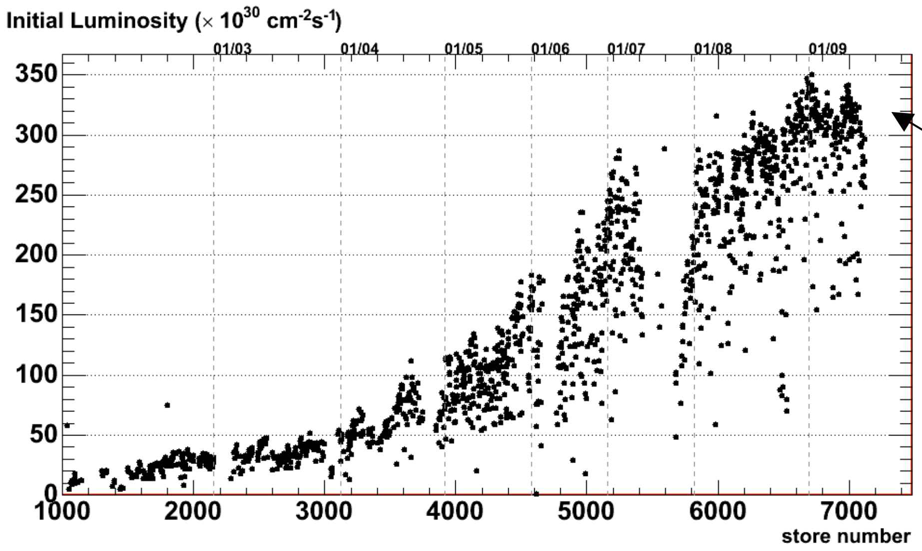
$$N_{\text{events produced}} = \sigma \times \int \mathcal{L} dt$$

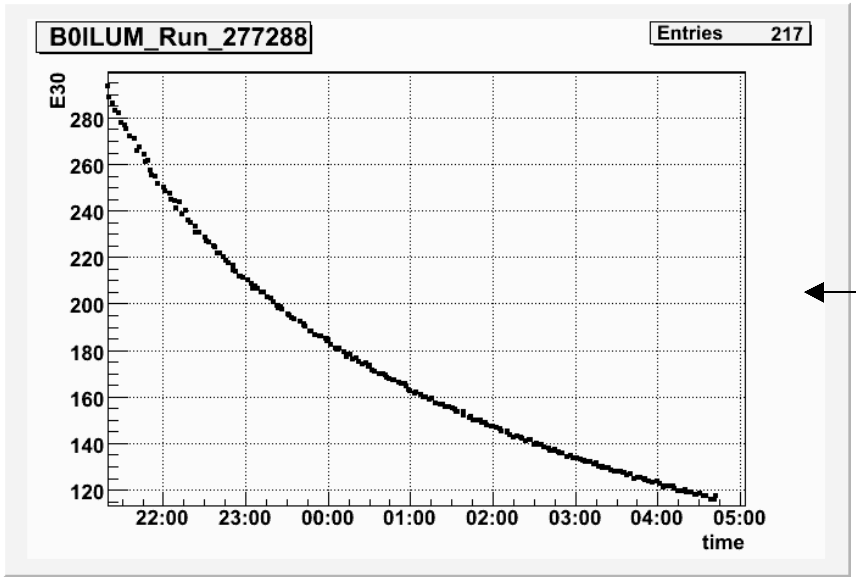
$$= 400\,pb \times 100\,pb^{-1}$$

$$= 40{,}000\ \mathrm{t\bar{t}}\ \text{pairs}$$

How many we observe, depends on our efficiency of observing them in our detector. More on this in lecture 4.

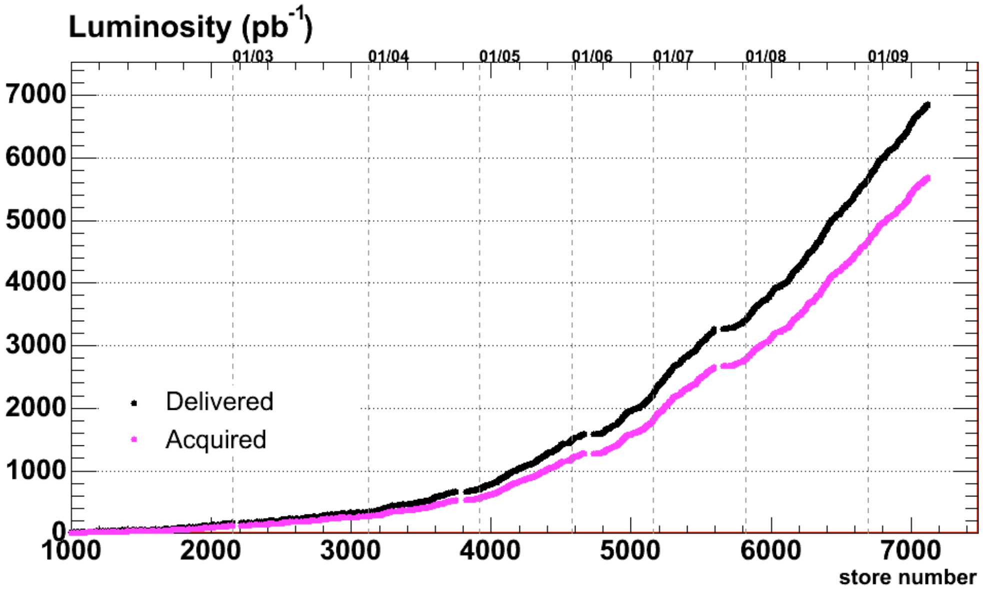
Tevatron Instantaneous $\mathcal{L}$





- Peak initial instantaneous luminosity of 3.5×10^{32} cm^{-2} s^{-1}
  - Also, when LHC starts you will see this kind of plot shown at conferences
- Instantaneous luminosity drops as protons (in this case p-pbar) collide

Tevatron Integrated $\mathscr{L}$



Again, you will see similar plots shown when LHC starts

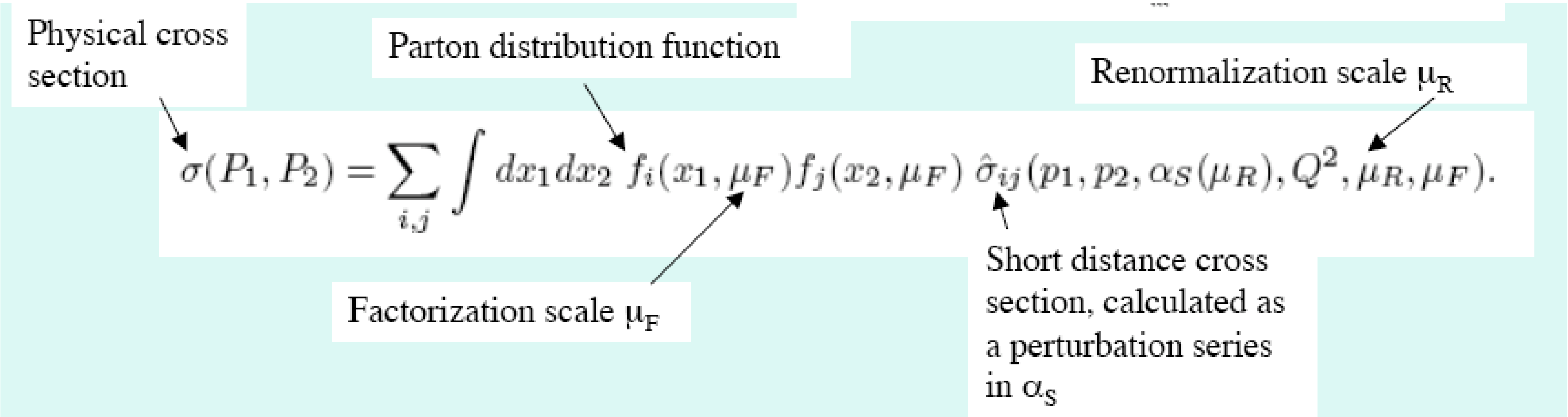
- It's impossible to record every collision at a hadron collider!
  - Trigger - more on this in lecture 3
- The difference between the two curves is how efficiently the experiment (in this case CDF) collects the data (integrated $\mathscr{L}$) that the accelerator delivers
- Remember:

$$N_{\text{events observed}} = \sigma \times \int \mathscr{L} dt \times \varepsilon$$

On Thursday we will find that there are several contributions to this!

A theorist’s view of a hadron collision

A cross section is convolution of Matrix Element and PDFs



Physical cross section

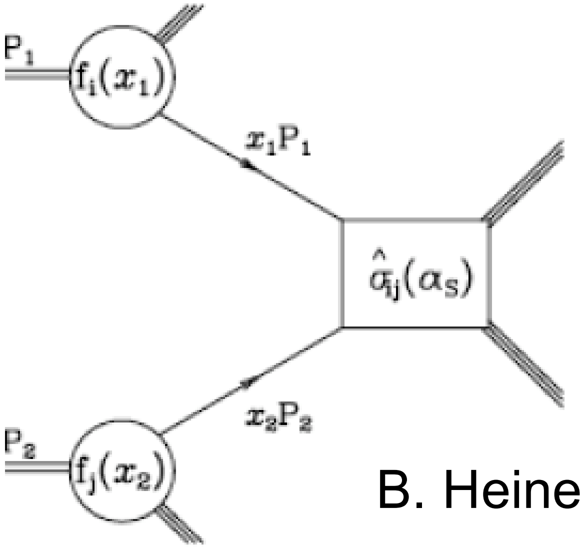
Parton distribution function

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

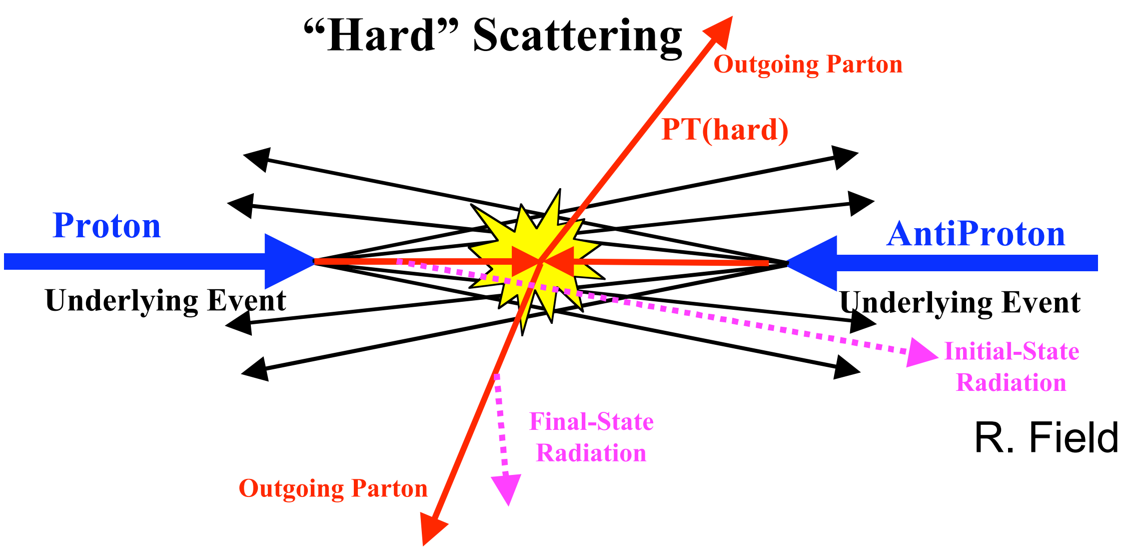
Short distance cross section, calculated as a perturbation series in α_S



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