Physics at Hadron Colliders

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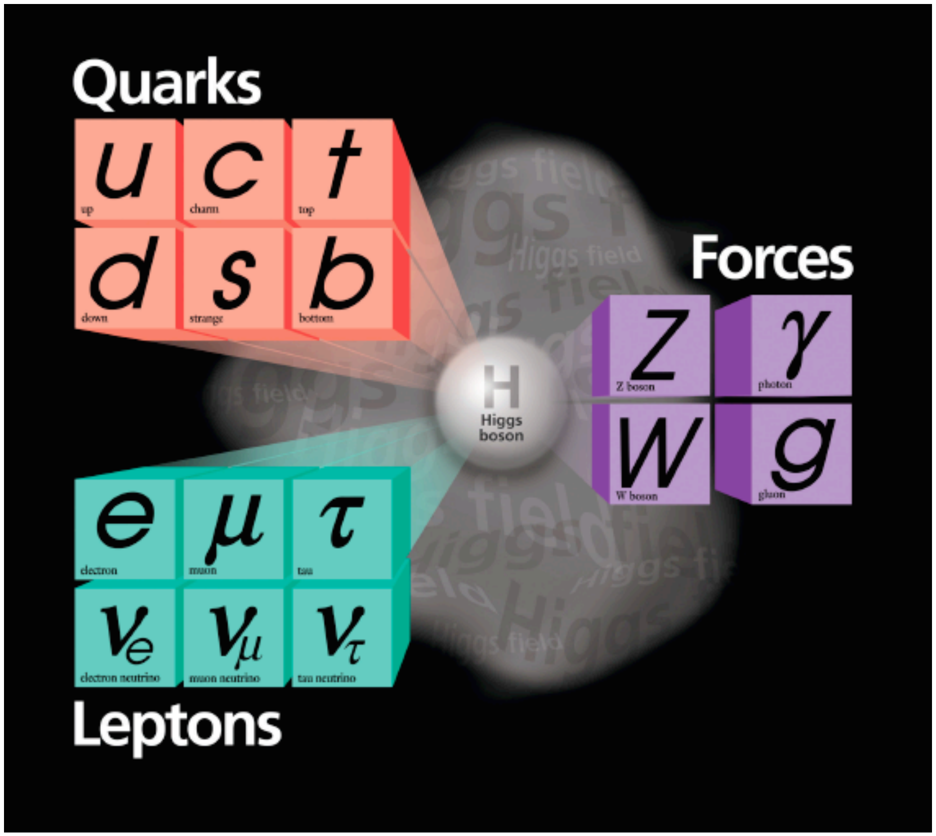
Outline

- **Lecture I: Introduction**
  - Outstanding problems in particle physics
    - and the role of hadron colliders
  - Current colliders: Tevatron and LHC
  - Hadron-hadron collisions
- **Lecture II: Standard Model Measurements**
  - Tests of QCD
  - Precision measurements in electroweak sector
- **Lecture III: Searches for the Higgs Boson**
  - Standard Model Higgs Boson
  - Higgs Bosons beyond the Standard Model
- **Lecture IV: Searches for New Physics**
  - Supersymmetry
  - High Mass Resonances (Extra Dimensions etc.)

Outstanding Problems in Particle Physics

and the role of Hadron Colliders

Fundamental Particles and Forces



- **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

Amazingly successful in describing precisely data from all collider experiments

The Standard Model Lagrangian

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}D\psi$$
$$+ \psi_i\lambda_{ij}\psi_j h + \text{h.c.}$$
$$+ |D_\mu h|^2 - V(h)$$
$$+ \frac{1}{M}L_i\lambda^\nu_{ij}L_j h^2 \text{ or } L_i\lambda^\nu_{ij}N_j$$

- gauge sector ✓
- flavour sector ✓
- EWSB sector ✓
- ν mass sector

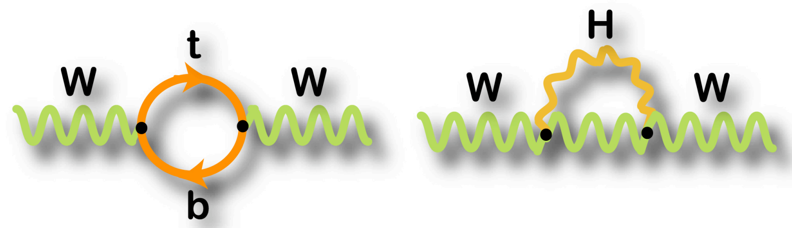
… and beyond?

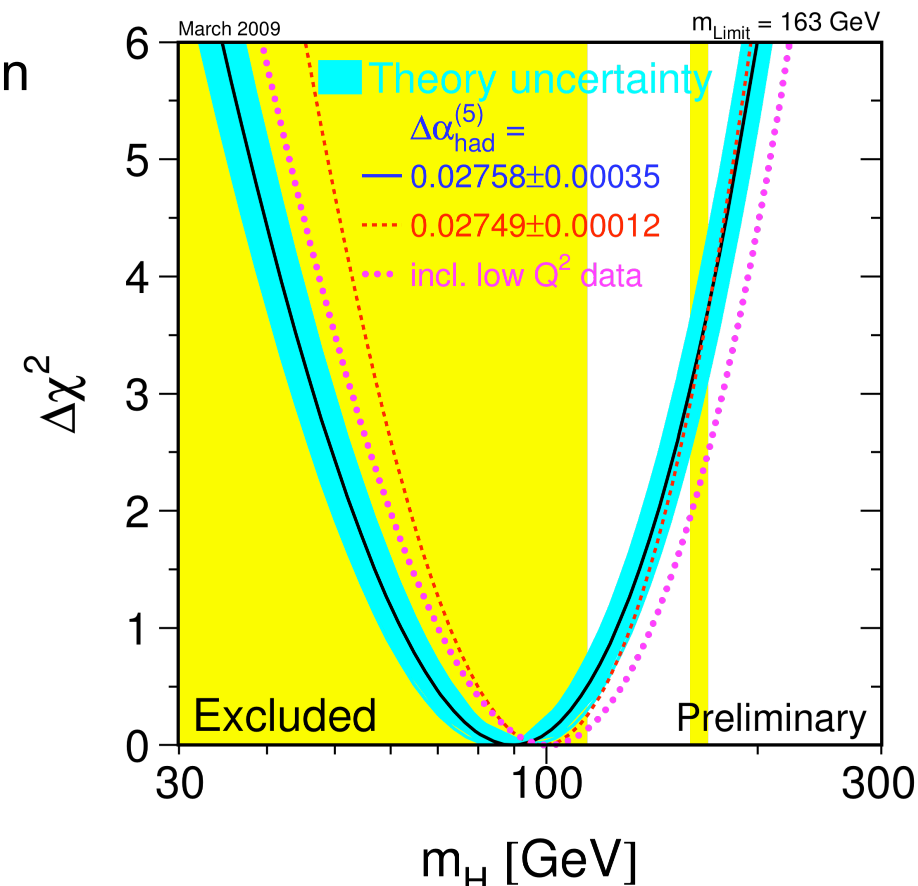
- supersymmetry (many variants)
- extra spacetime dimensions ✓
- compositeness
- strong electroweak symmetry breaking
- …
- something new?!

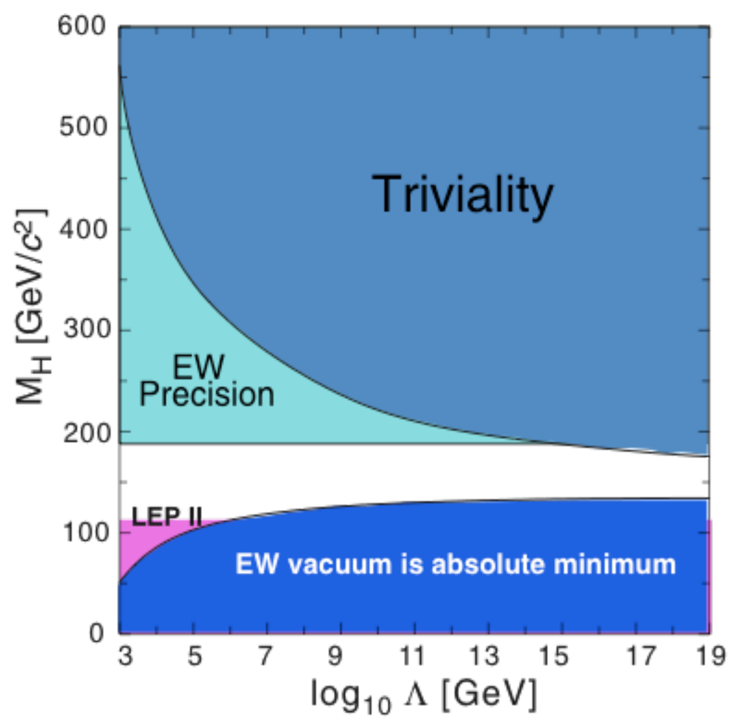
[W. J. Stirling]

Problem I: Where is the Higgs boson?

- Precision measurements of
  - M_W =80.399 ± 0.023 GeV/c^2
  - M_{top}=173.1 ± 1.2 GeV/c^2
  - Precision measurements on Z pole
- Prediction of higgs boson mass within SM due to loop corrections
  - Most likely value: 90^{+36}_{-27} GeV
- Direct limit (LEP): m_h>114.4 GeV

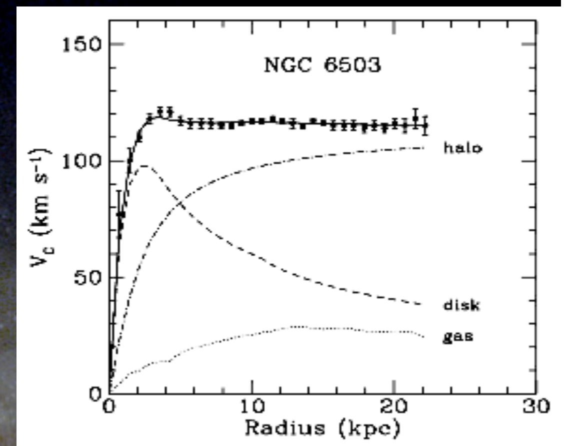






- m_H<163 GeV @95%CL

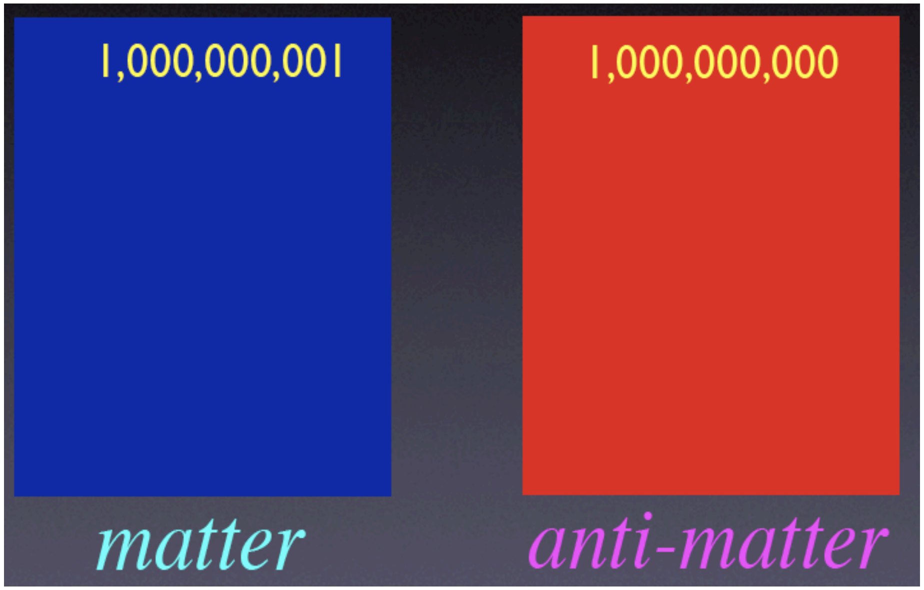
Problem II: What is the Dark Matter?

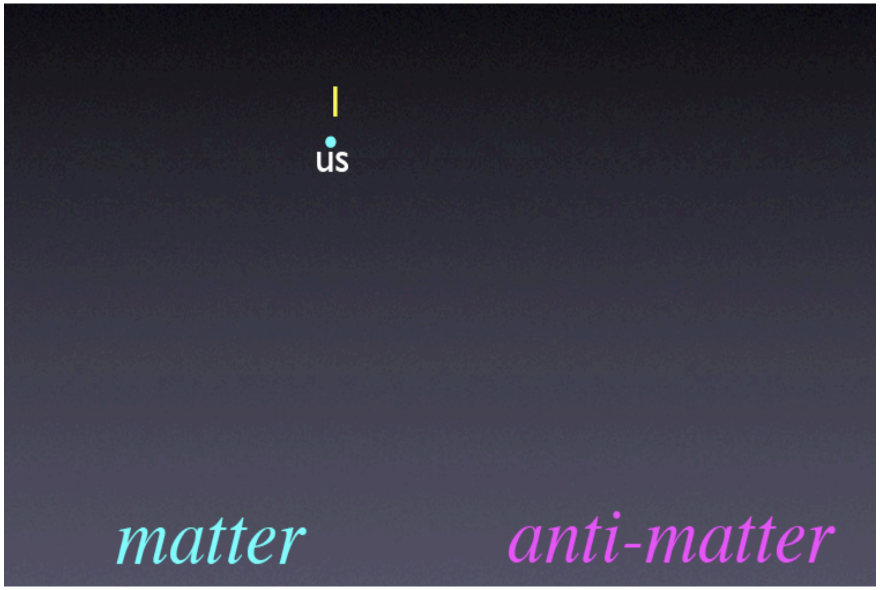


Standard Model only accounts for 20% of the matter of the Universe

$$\frac{\text{matter}}{\text{all atoms}} = 5.70^{+0.39}_{-0.61}$$

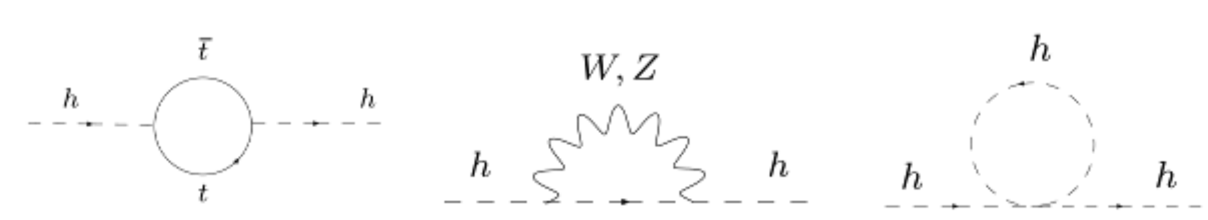
Problem III:
Where did all the Antimatter go?





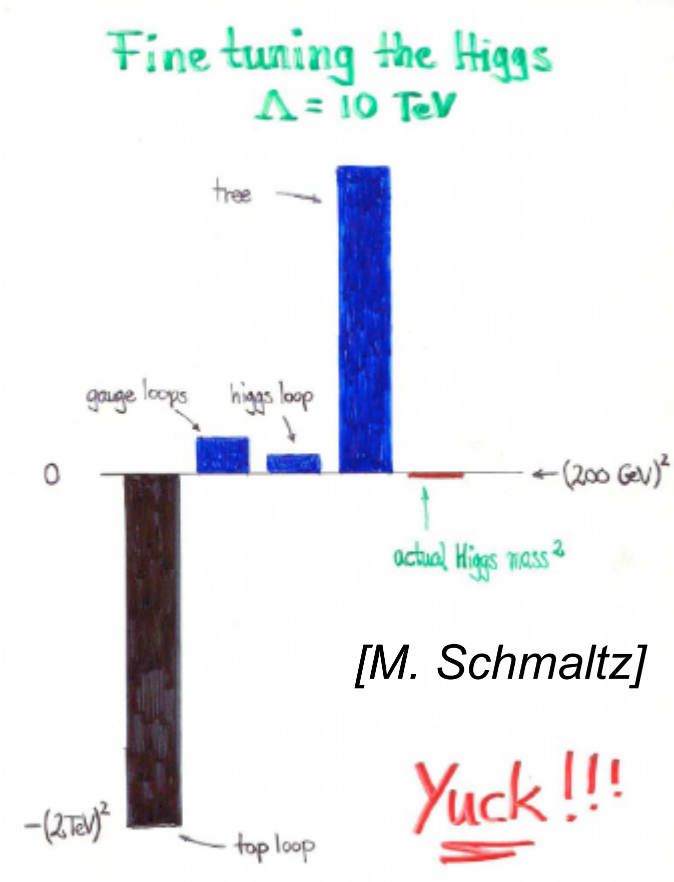
- **Not explained by Standard Model**

Problem IV: Hierarchy Problem



$$m^2_H \approx (200\text{ GeV})^2 = m^{2\,\text{tree}}_H + \delta m^{2\,\text{top}}_H + \delta m^{2\,\text{gauge}}_H + \delta m^{2\,\text{higgs}}_H$$

- **Why is gravity so weak?**
  - M_W/M_{Planck} ~10^{16} or G_F/G_N~10^{32}!
  - Free parameter $m^{2\,\text{tree}}_H$ needs to be "finetuned" to cancel huge corrections
- Can be solved by presence of **new particles at M ~1 TeV**
  - Already really bad for M~10 TeV

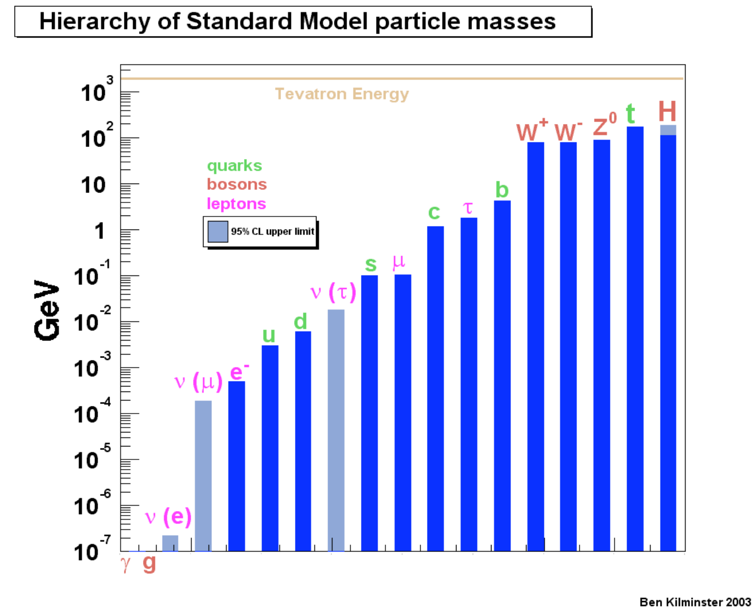


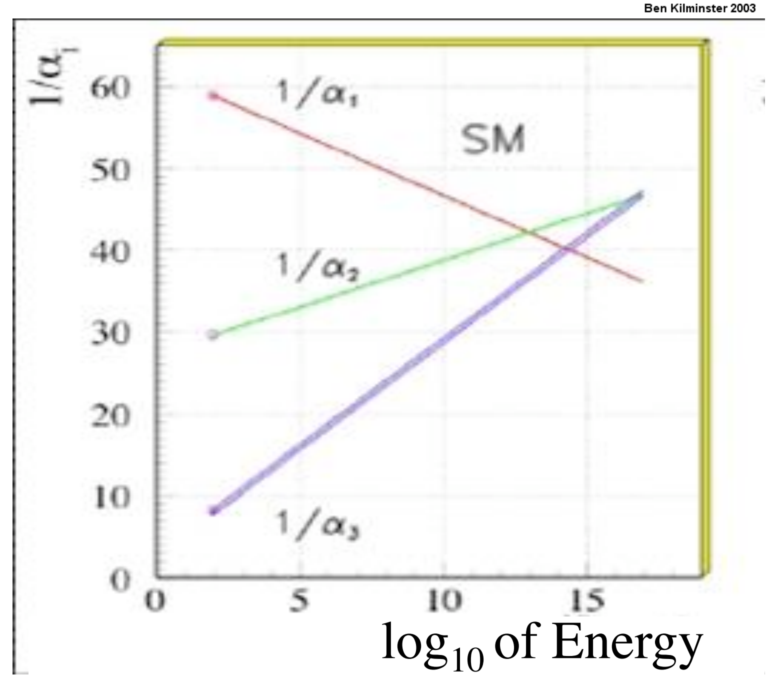
[M. Schmaltz]

(Some) More Problems …

- **Matter:**
  - SM cannot explain **number of fermion generations**
  - or their **large mass hierarchy**
    - m_{top}/m_{up}~100,000
- **Gauge forces:**
  - electroweak and strong **interactions do not unify** in SM
  - SM has no concept of **gravity**
- **What is Dark Energy?**

"Supersymmetry" (SUSY) can solve some of these problems

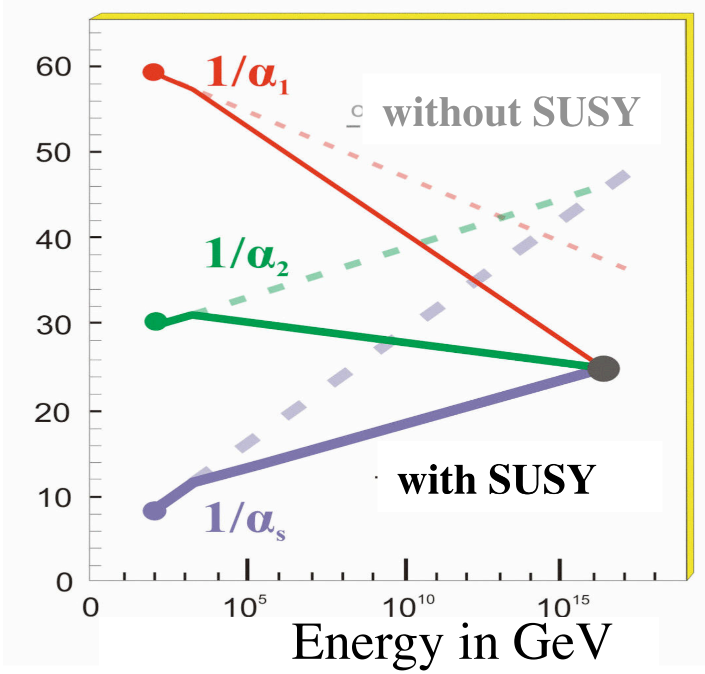


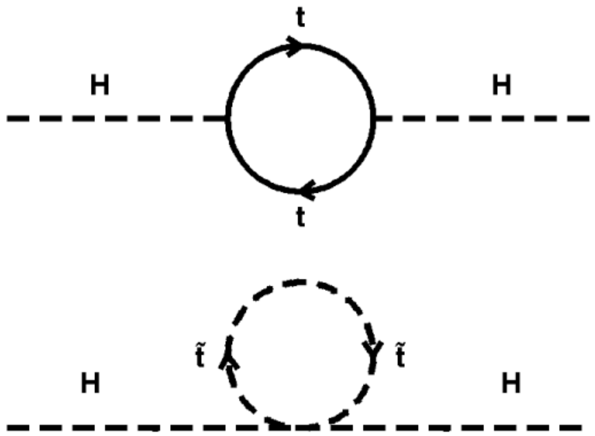


SUSY can solve some problems

- Supersymmetry (SUSY)
  - Each SM particle gets a partner differing in spin by 1/2
- Unifications of forces possible
  - SUSY changes running of couplings
- Dark matter candidate exists:
  - The lightest neutral partner of the gauge bosons
- No (or little) fine-tuning required
  - Radiative corrections to Higgs acquire SUSY corrections
    - Cancellation of fermion and sfermion loops

Mass of supersymmetric particles must not be too high (~TeV)

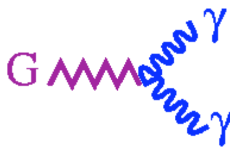




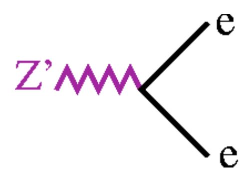
Beyond Supersymmetry

- **Strong theoretical prejudices for SUSY being true**
  - But so far there is a lack of SUSY observation….

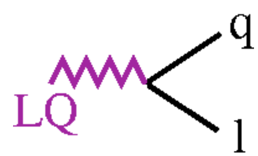
- **Need to keep an open eye for e.g.:**
  - **Extra spatial dimensions:**
    - Addresses hierarchy problem: make gravity strong at TeV scale



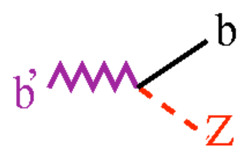
  - **Extra gauge groups: Z’, W’**
    - Occur naturally in GUT scale theories



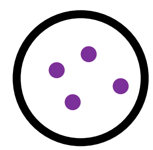
  - **Leptoquarks:**
    - Would combine naturally the quark and lepton sector



  - **New/excited fermions**
    - More generations? Compositeness?



  - **Preons:**
    - atom⇒nucleus ⇒ proton/neutron ⇒ quarks ⇒ preons?



  - **… ????**: something nobody has thought of yet

Confusion among Theorists?

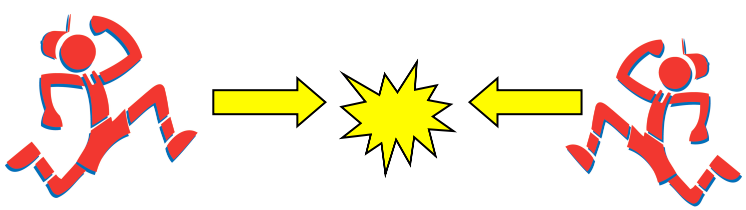
[Hitoshi Murayama]

Need experiments to figure out which (if any) represents Nature

Why a Hadron Collider?

- Disadvantages:
  - Hadrons are complex objects
    - High multiplicity of other stuff
    - Energy and type of colliding parton (quark, gluon) unknown
      - Kinematics of events not fully constrained
- Advantage:
  - Can access higher energies

Lepton Collider
(collision of two point-like particles)



Hadron collider
(collision of ~50 point-like particles)

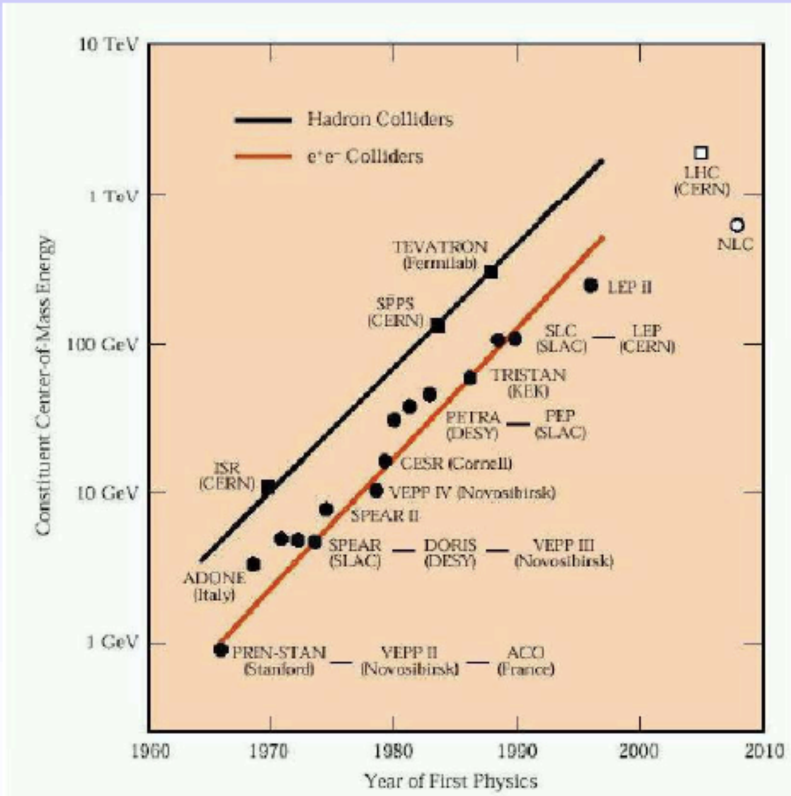
[Karl Jakobs]

e^+e^- vs Hadron Colliders

- Circular colliders:
  - Pro:
    - Reuse their power on each turn
  - Con:
    - Synchrotron radiation reduces energy of particles
      - Problem worsens with m^4
- Linear colliders:
  - Particle sees each component just once
  - Now more cost-effective for electrons than circular collider => proposal of *ILC* (=International Linear Collider)

Energy loss per turn: $$-\Delta E \approx \frac{4\,\pi\,e^2}{3\,R}\left(\frac{E}{mc^2}\right)^4$$

Energy loss: e vs p $$\frac{\Delta E(e)}{\Delta E(p)} = \left(\frac{m_p}{m_e}\right)^4 \sim 10^{13}$$



Current Hadron Colliders:
Tevatron and LHC
(and the experiments)

Luminosity

- Single most important quantity
  - Drives our ability to detect new processes

$$L = \frac{f_{rev}\, n_{bunch}\, N_p^{\,2}}{4\,\pi\,\sigma_x\,\sigma_y}$$

revolving frequency: f_{rev}=11245.5/s
#bunches: n_{bunch}=2808
#protons / bunch: N_p= 1.15 x 10^{11}
Area of beams: $4\pi\sigma_x\sigma_y$~40 μm

  - Rate of physics processes per unit time directly related:

$$N_{obs} = \int L dt \cdot \varepsilon \cdot \sigma$$

Efficiency: optimized by experimentalist

Cross section σ: Given by Nature (calc. by theorists)

Ability to observe something depends on N_{obs}

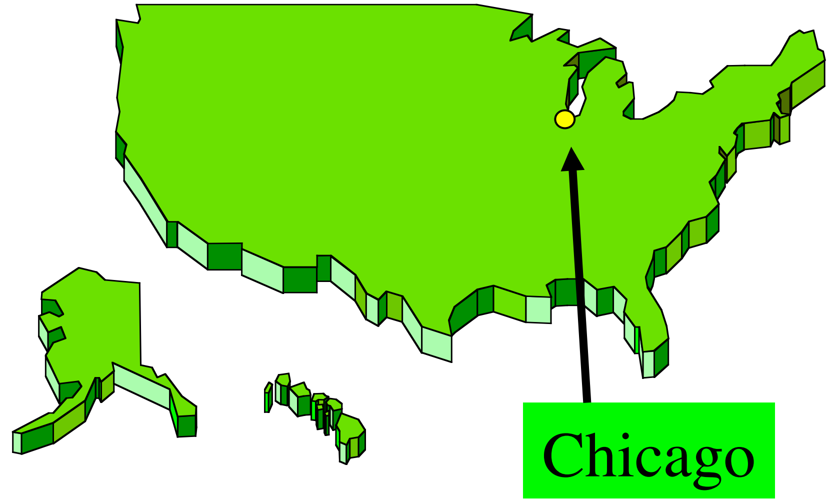
LHC and Tevatron Machine Parameters

	LHC (today)	LHC (design)	Tevatron (achieved)
Centre-of-mass energy	7 TeV	14 TeV	1.96 TeV
Number of coll. bunches	8	2808	36
Energy stored in beam	0.6 MJ	360 MJ	1 MJ
Peak Luminosity (10^{30} $cm^{-2}s^{-1}$)	1.6	10000	400
Integrated Luminosity: $\int L dt$	0.35 pb^{-1}	>100 fb^{-1}	~9 fb^{-1}

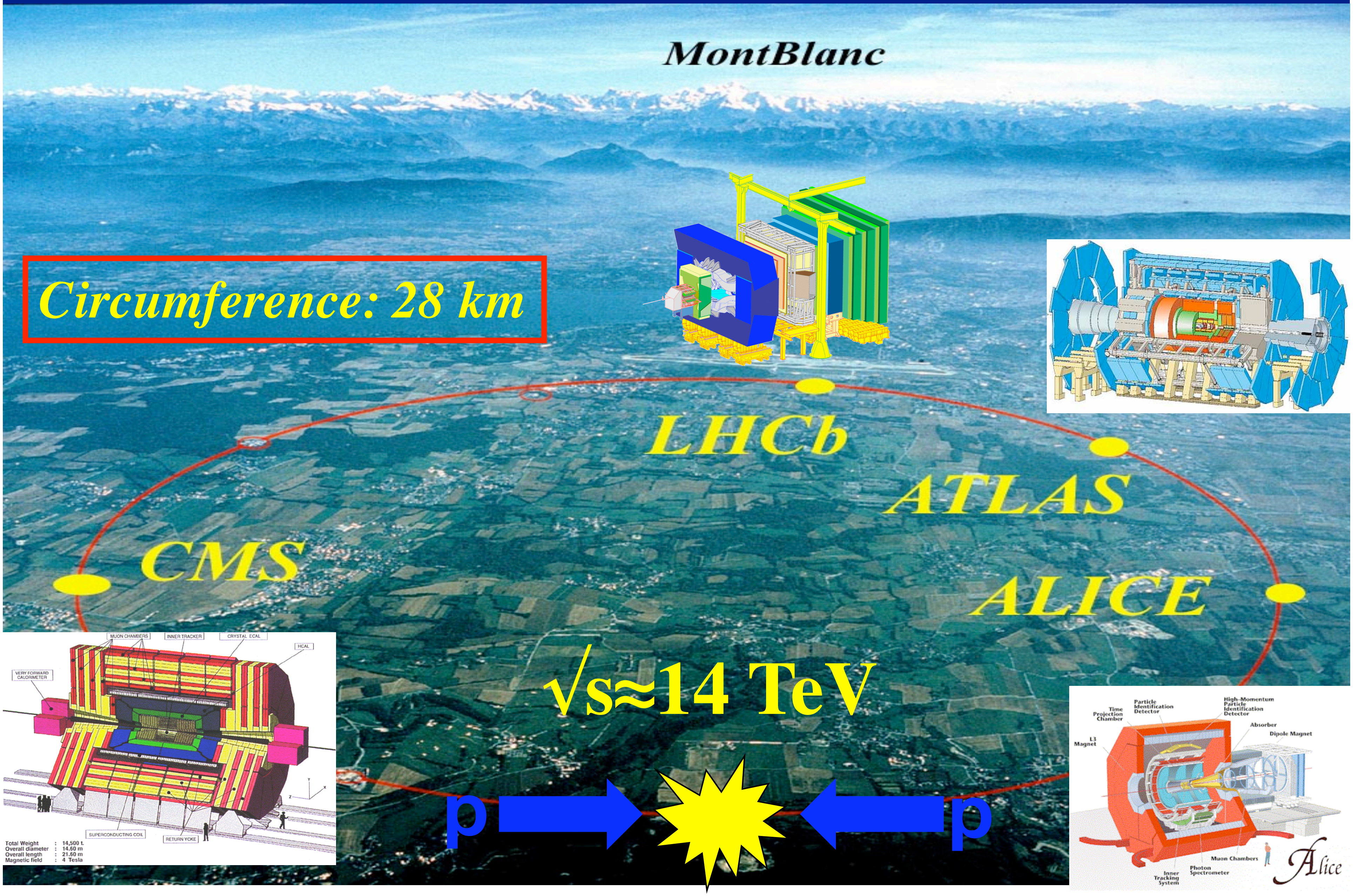
- LHC today
  - Delivers less data than Tevatron
  - But runs at 3.5 time higher energy
- Depends on process which is more powerful

The Tevatron

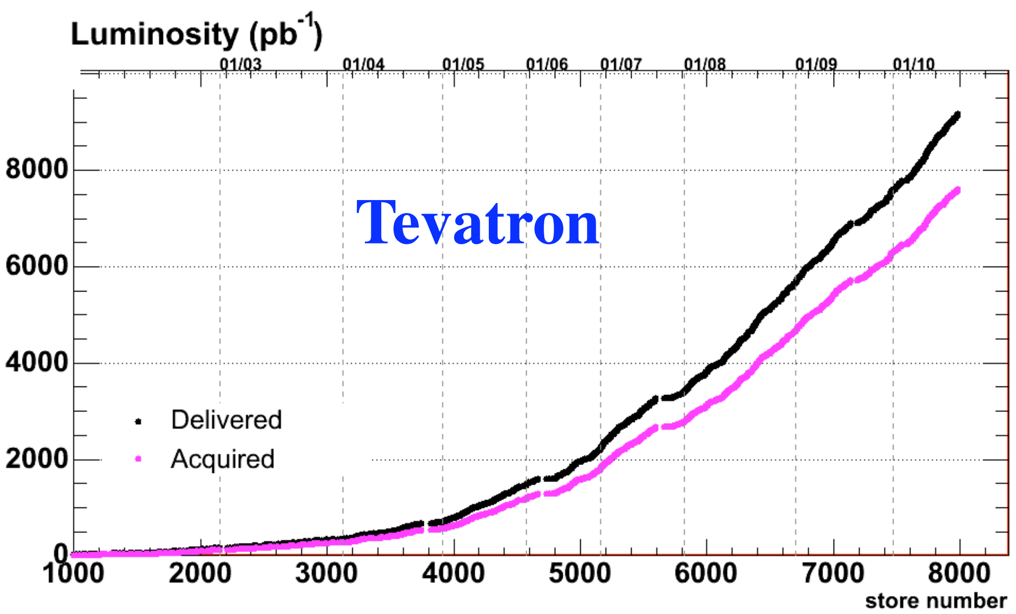
- $p\bar{p}$ collider:
  - 6.5 km circumference
  - Beam energy: 980 GeV
    - $\sqrt{s}$=1.96 TeV
  - 36 bunches:
    - Time between bunches: Δt=396 ns
- Main challenges:
  - Anti-proton production and storage
  - Irregular failures:
    - Quenches
- CDF and DØ experiments:
  - 700 physicists/experiment

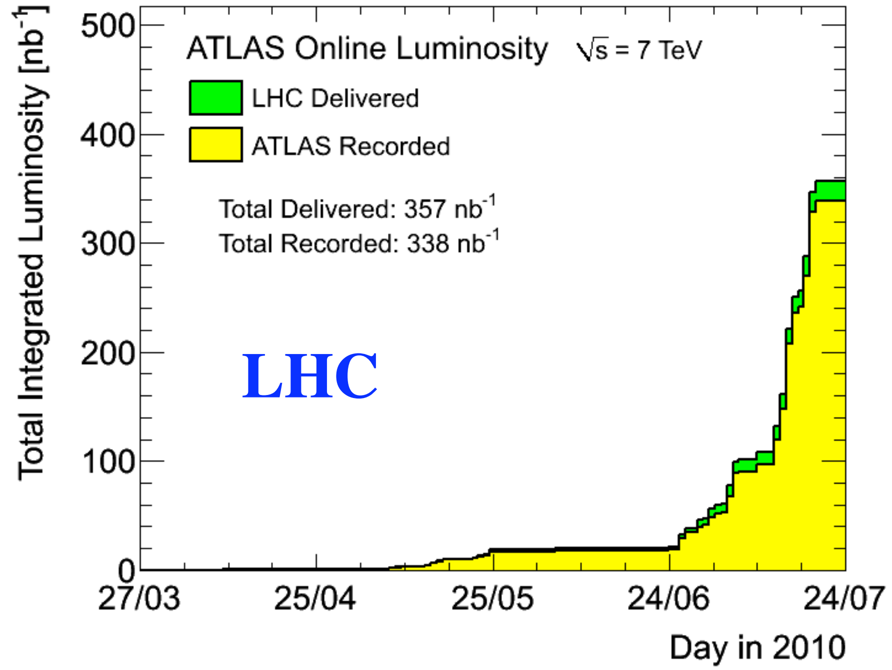


The Large Hadron Collider (LHC)



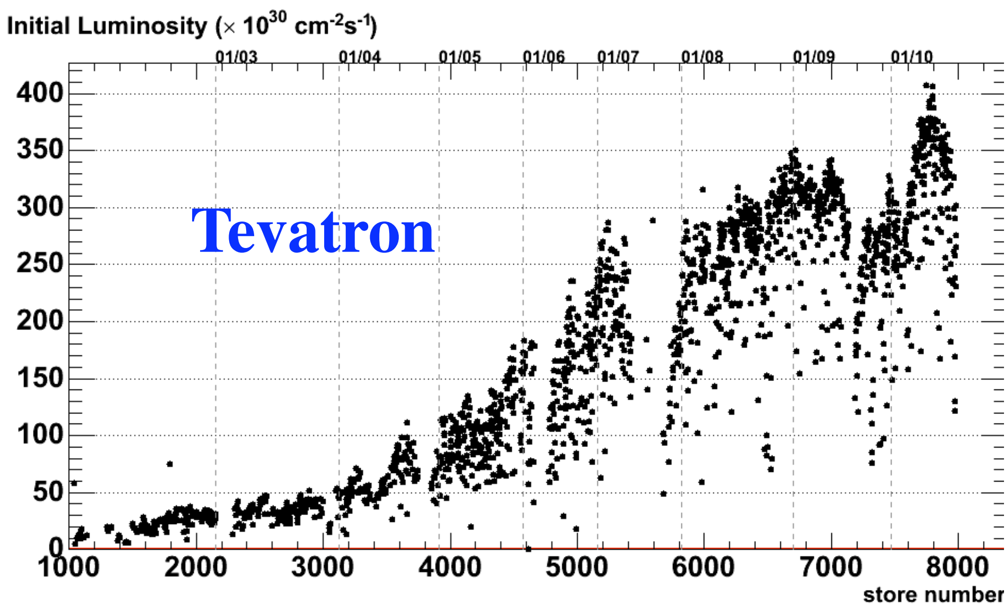
Integrated Luminosity

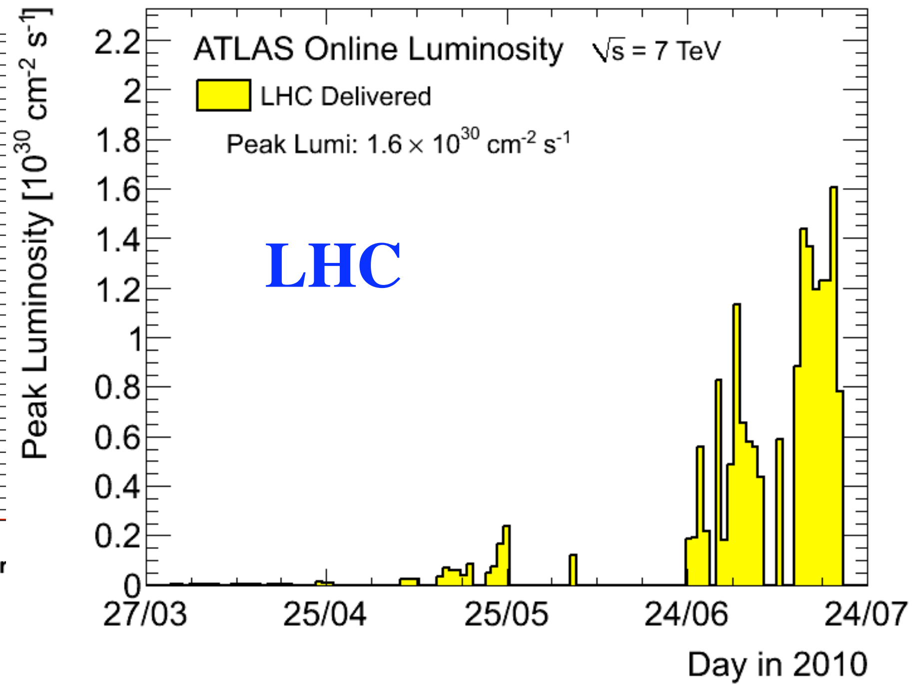




- Tevatron: 9 fb^{-1} delivered
- LHC: 0.36 pb^{-1} delivered
  - Very steeply rising due to progress in accelerator commissioning

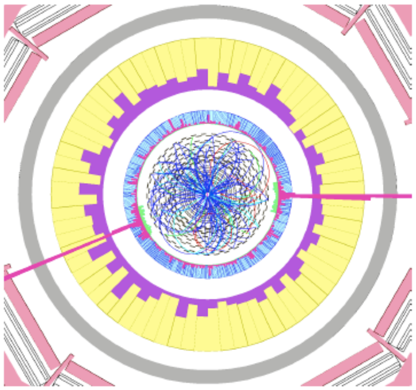
Instantaneous Luminosity



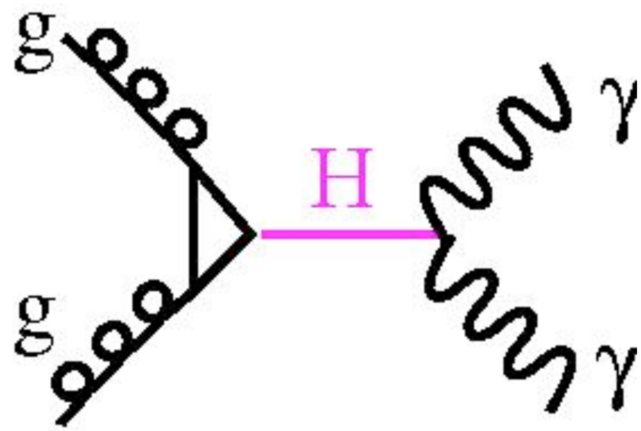


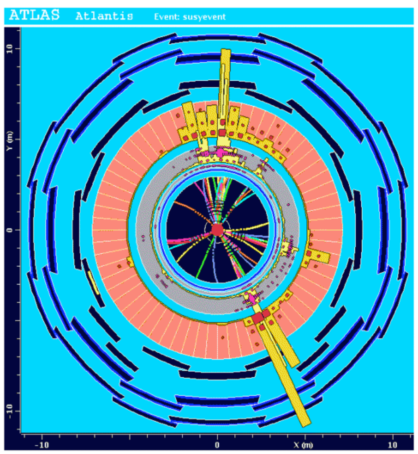
- **Tevatron: 4.0×10^{32} cm^{-2} s^{-1}**
- **LHC: 1.6×10^{30} cm^{-2} s^{-1}**
  - **Goal: reach 1×10^{32} cm^{-2} s^{-1} by the end of this year**
  - **At 1×10^{32} cm^{-2} s^{-1} it takes about 24h to get 10 pb^{-1}**

The Experimental Challenge

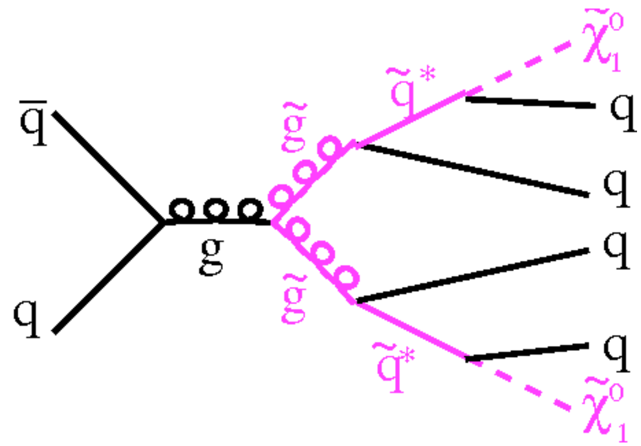


Higgs





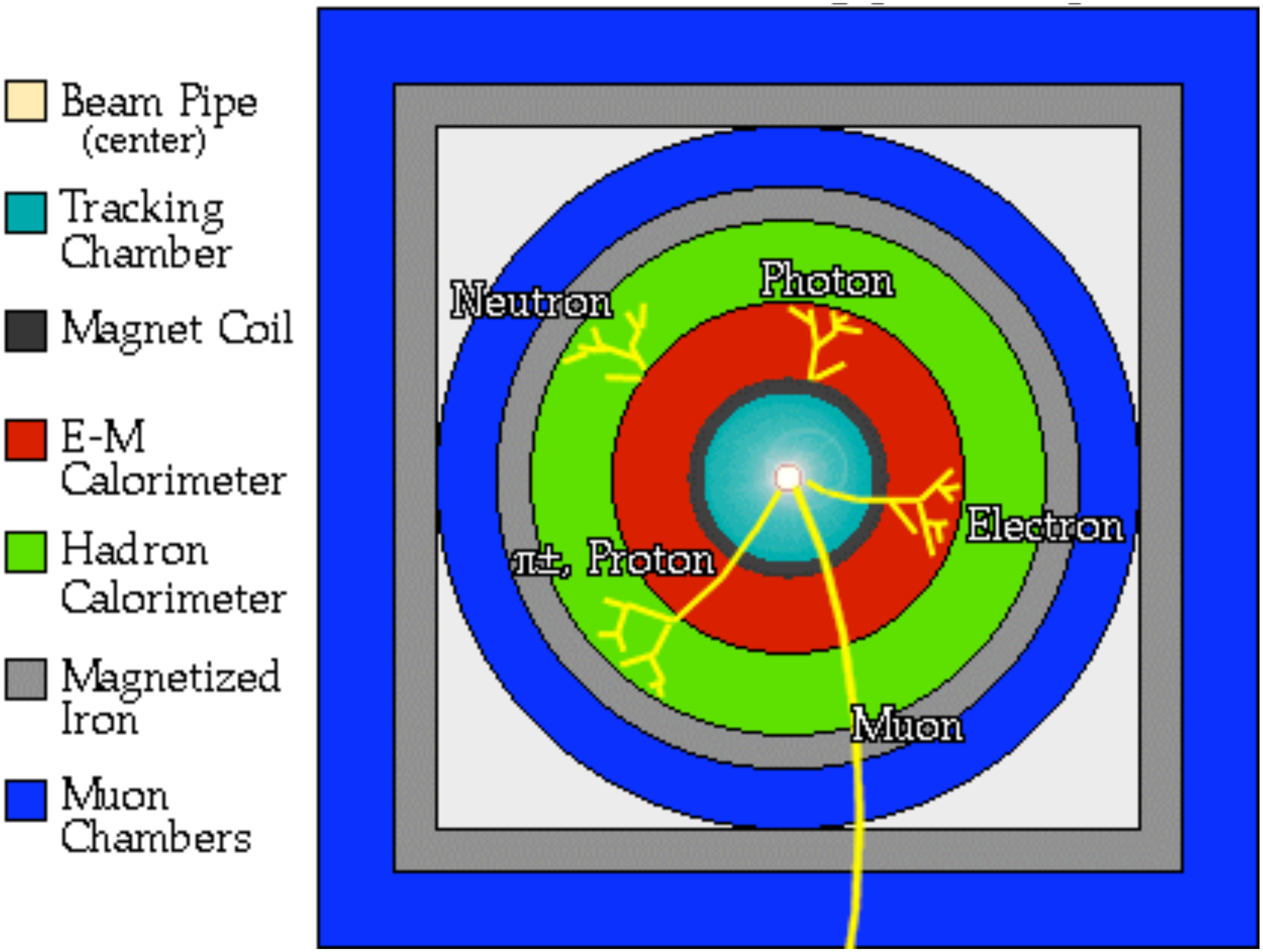
Supersymmetry



- Measured hits in detector
- => use hits to reconstruct particle paths and energies
- => estimate background processes
- => understand the underlying physics

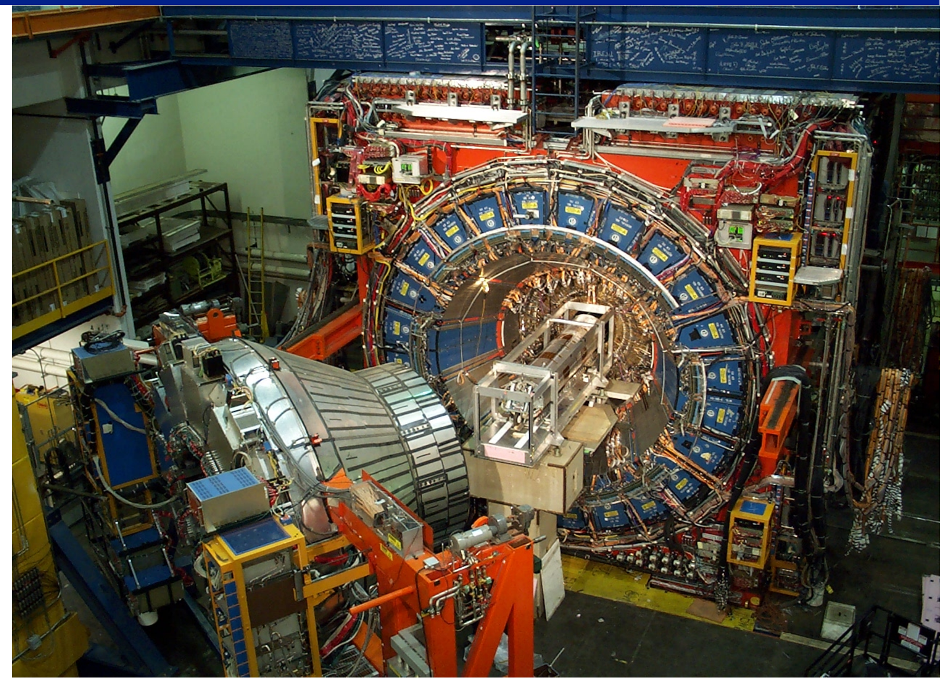
Particle Identification

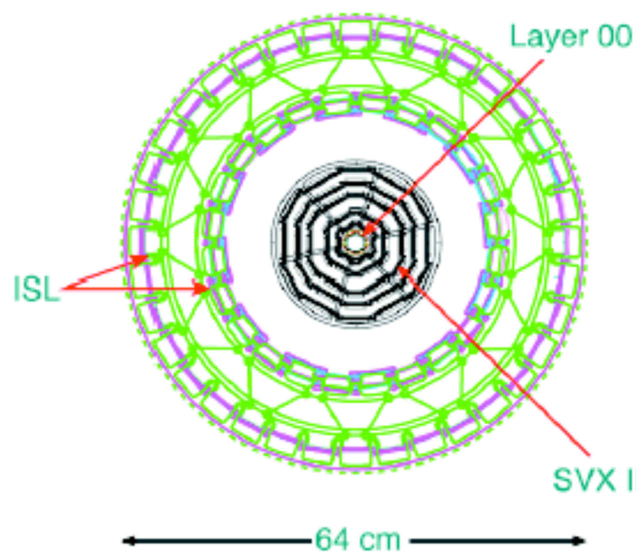
Detector designed to separate electrons, photons, muons, neutral and charged hadrons



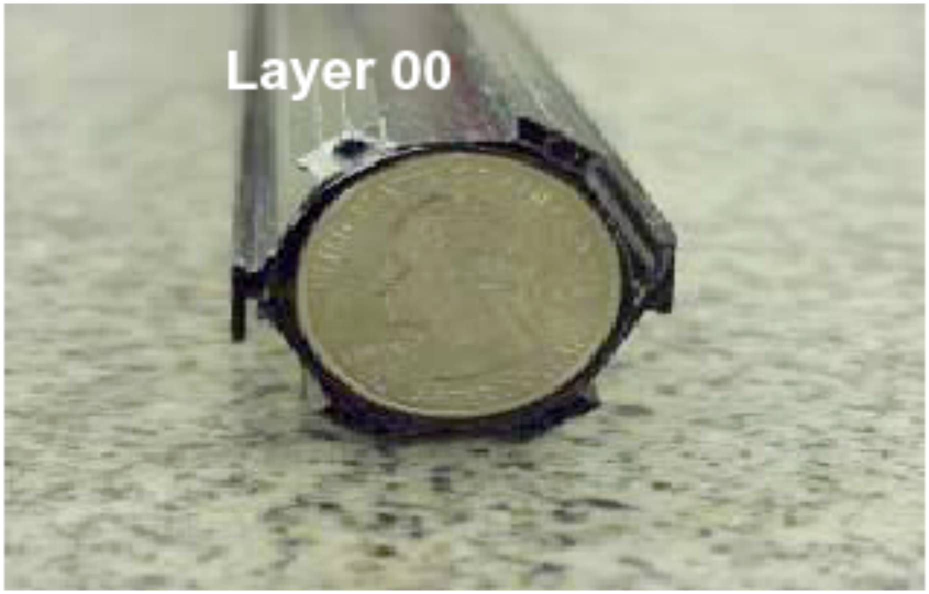
CDF

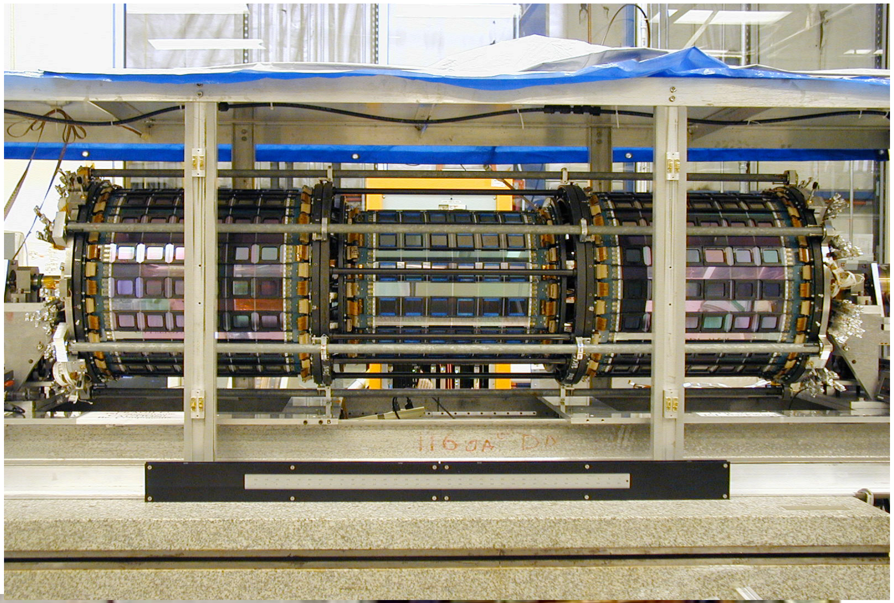
- Core detector operates since 1985:
  - Central Calorimeters
  - Central muon chambers
- Major upgrades for Run II:
  - Drift chamber: COT
  - Silicon: SVX, ISL, L00
    - 8 layers
    - 700k readout channels
    - 6 m^2
    - material:15% X_0
  - Forward calorimeters
  - Forward muon system
    - Improved central too
  - Time-of-flight
  - Preshower detector
  - Timing in EM calorimeter
  - Trigger and DAQ

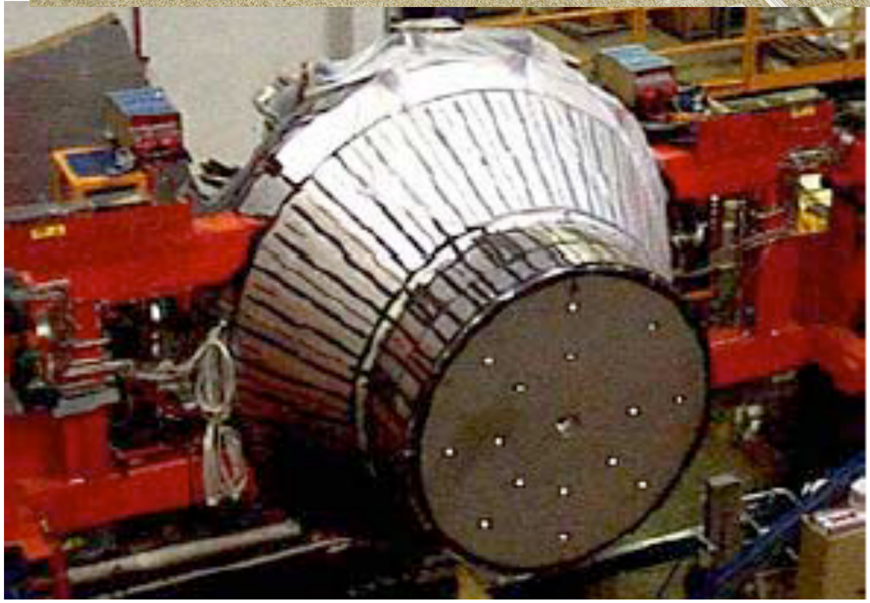




Some CDF Subdetectors



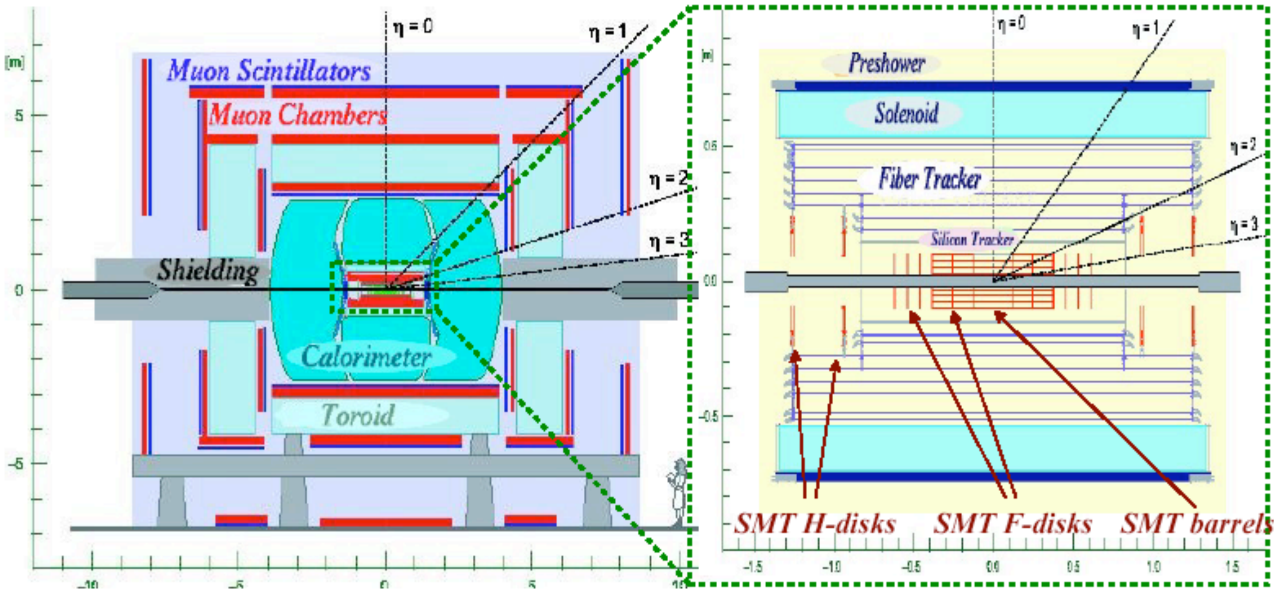


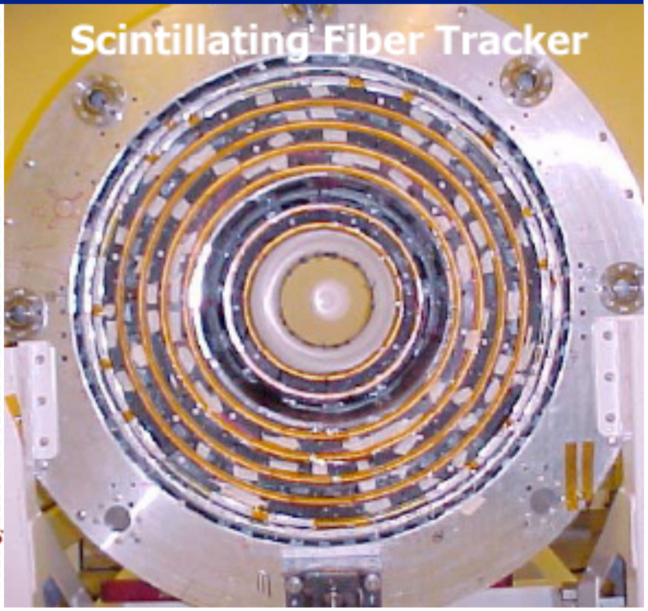


DØ Detector

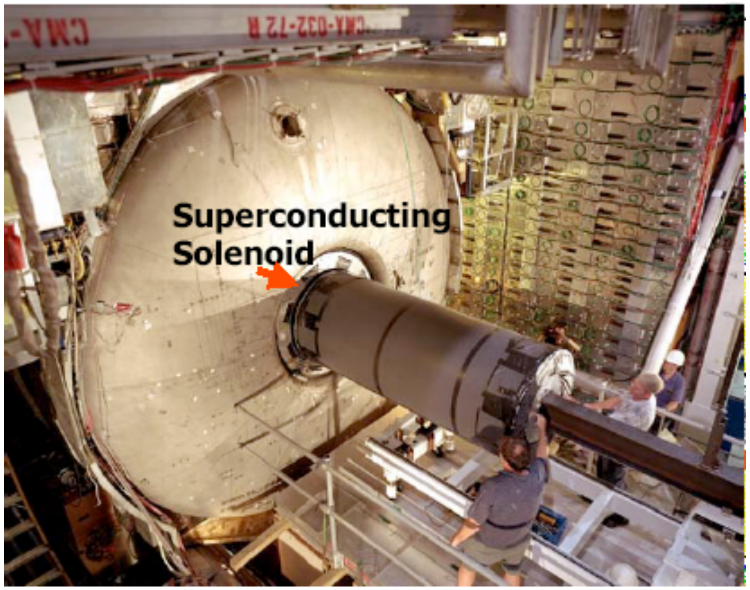
- Retained from Run I
  - Excellent muon coverage
  - Compact high granularity LAr calorimeter
- New for run 2:
  - 2 Tesla magnet
  - Silicon detector
  - Fiber tracker
  - Trigger and Readout
  - Forward roman pots

DØ Detector

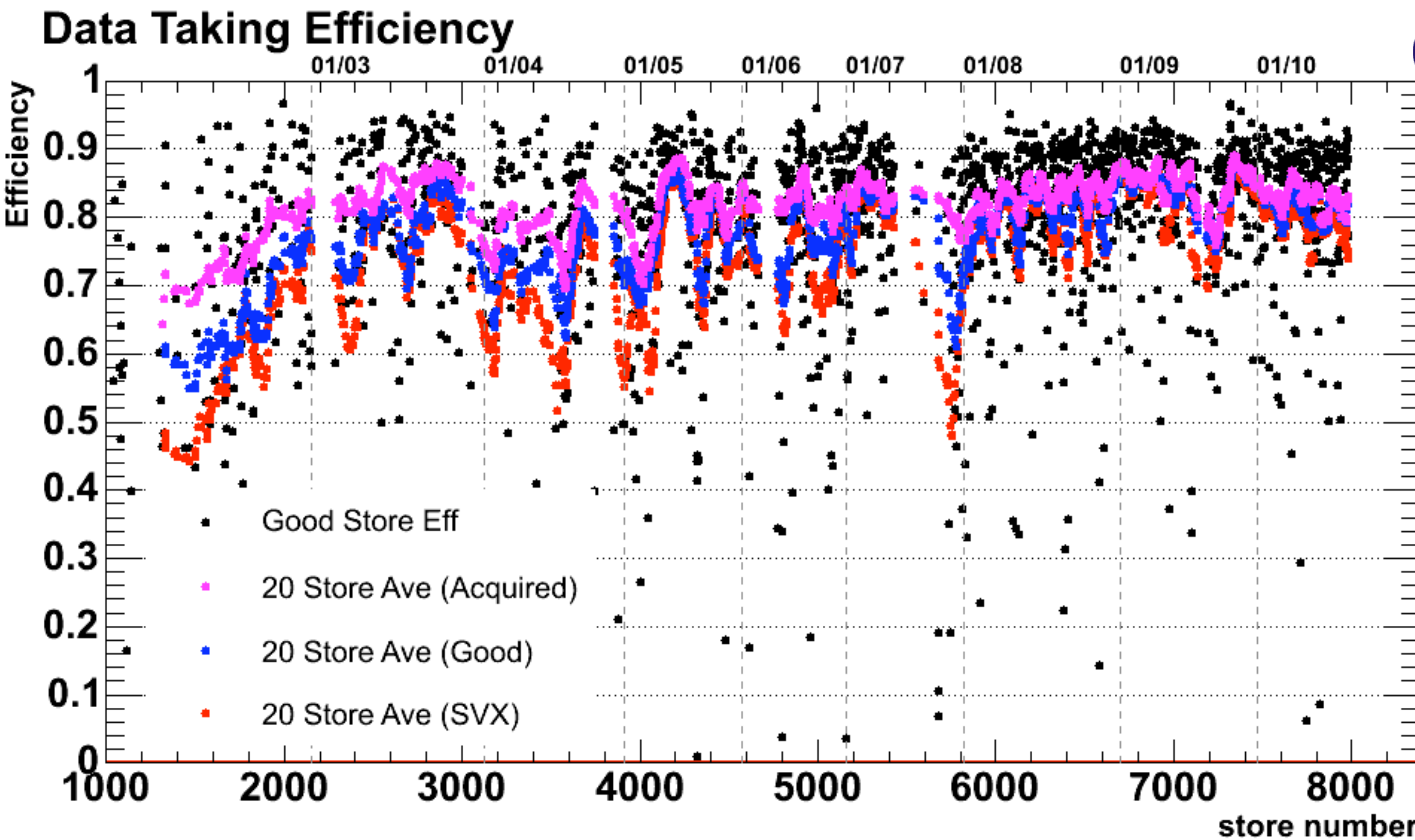

η = 0
η = 1
η = 2
η = 3
Muon Scintillators
Muon Chambers
Shielding
Calorimeter
Toroid
Preshower
Solenoid
Fiber Tracker
Silicon Tracker
SMT H-disks
SMT F-disks
SMT barrels


Scintillating Fiber Tracker


Silicon Microstrip Tracker

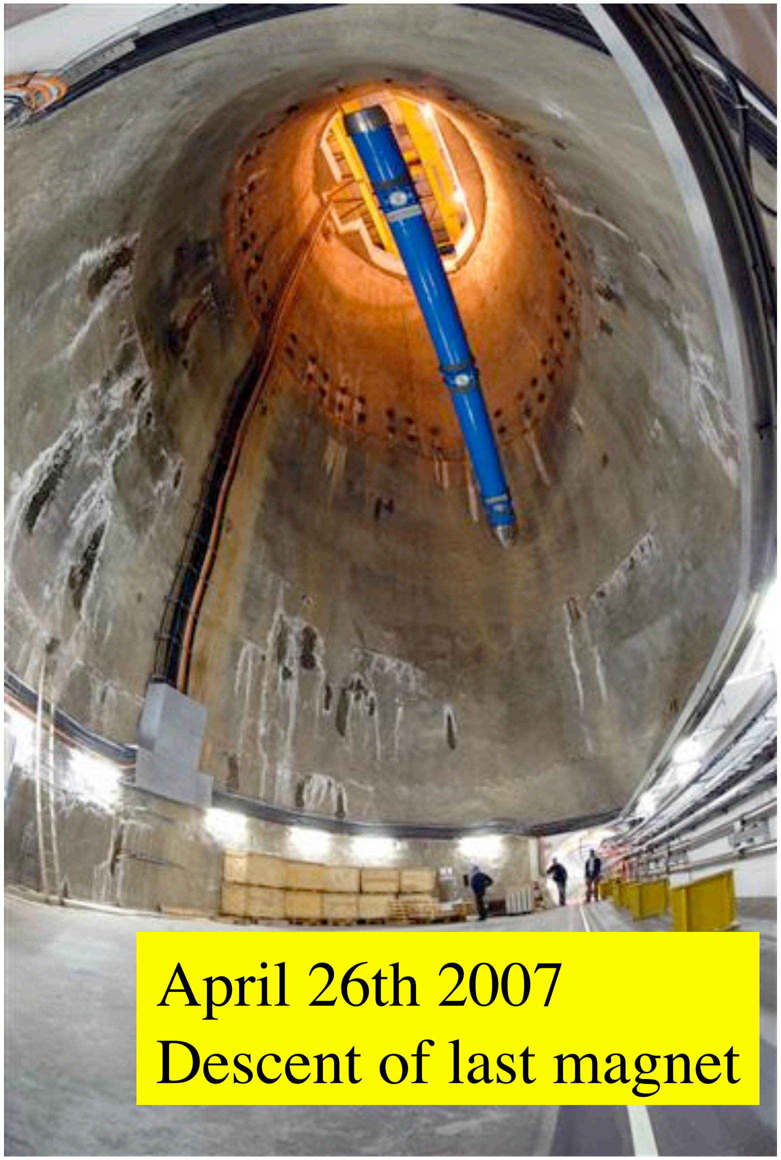

Superconducting
Solenoid

Detector Operation



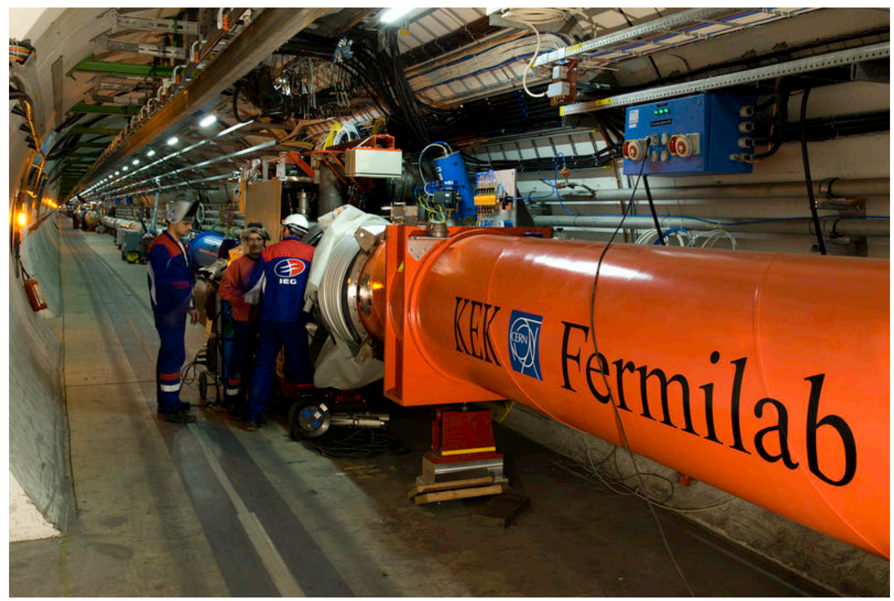
- Data taking efficiency about 80-85%
  - Depending on which components are needed for analysis

LHC Construction

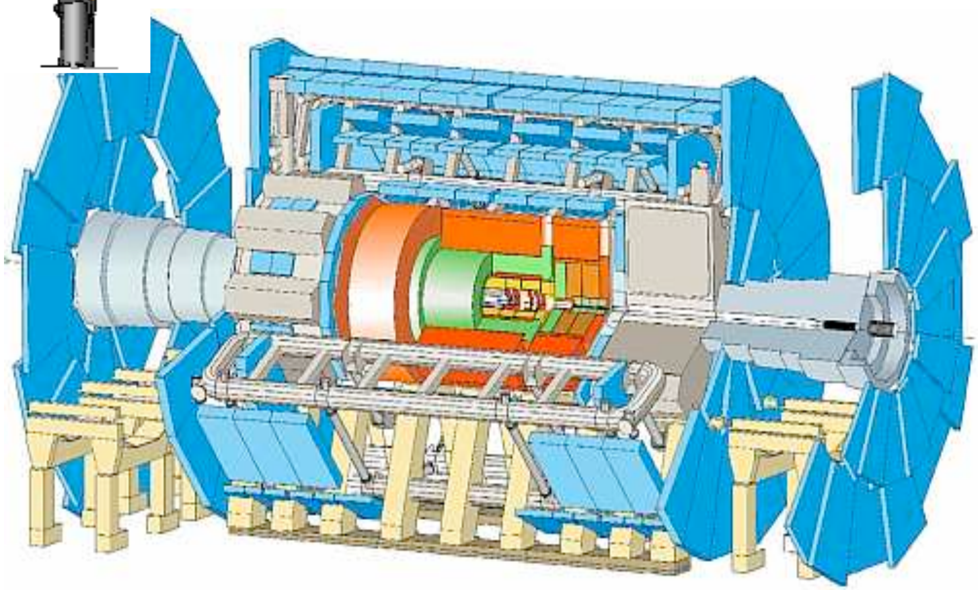


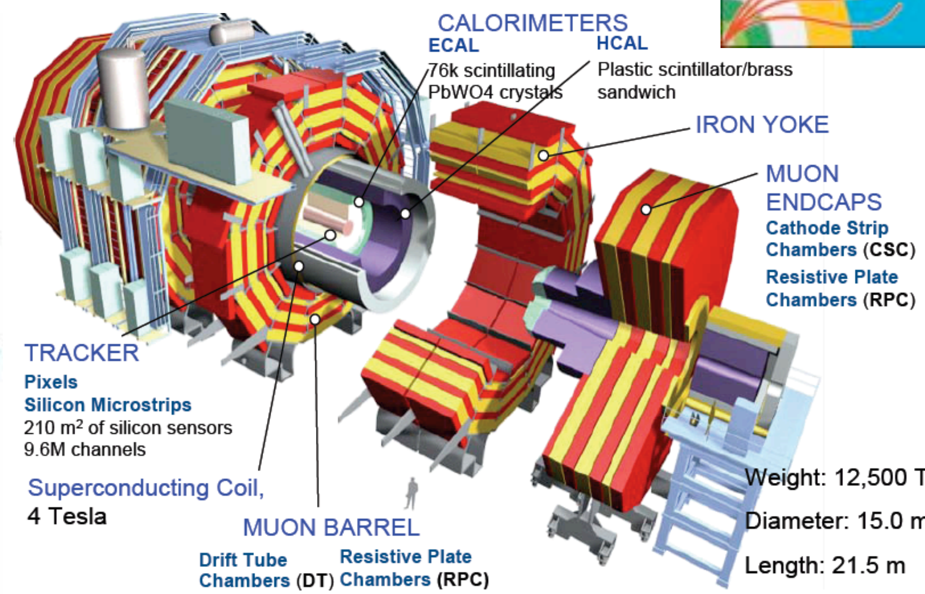
April 26th 2007
Descent of last magnet

Cryostating	425 FTE.years
Cold tests	640 FTE.years



ATLAS and CMS Detectors

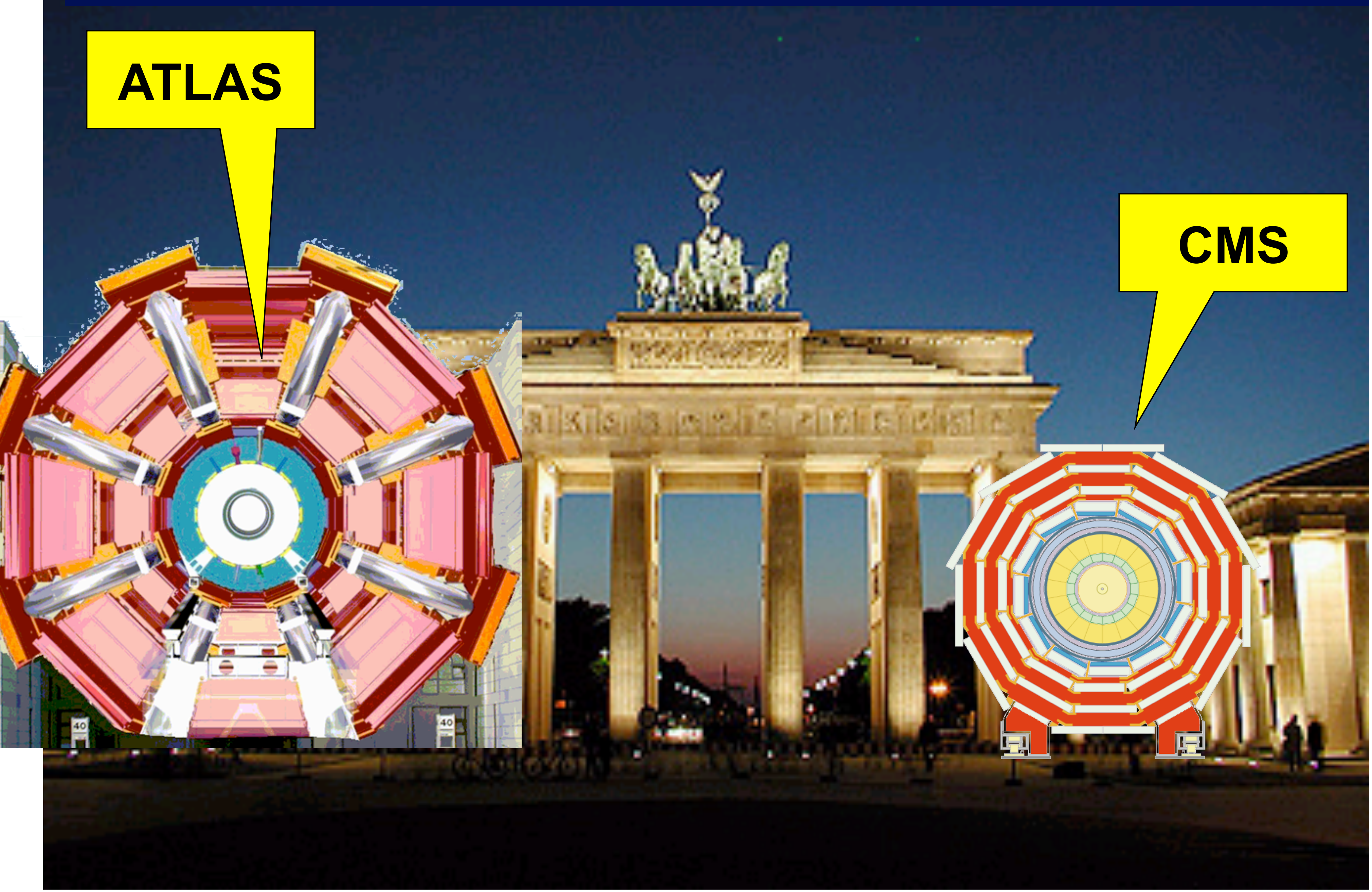




	Weight (tons)	Length (m)	Height (m)
ATLAS	7,000	42	22
CMS	12,500	21	15

~2000 Scientists per experiment
+ many engineers and technicians

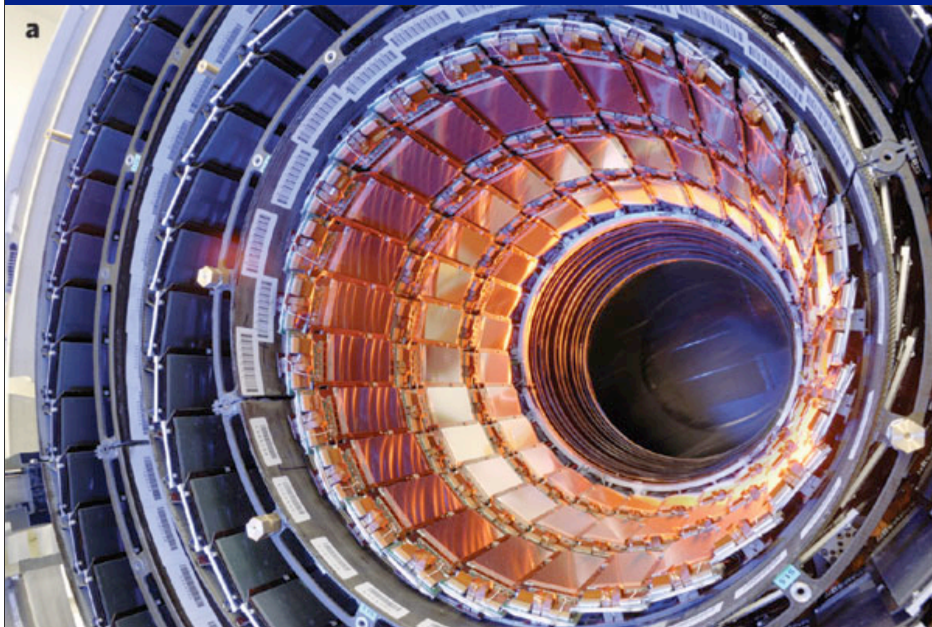
ATLAS and CMS in Berlin

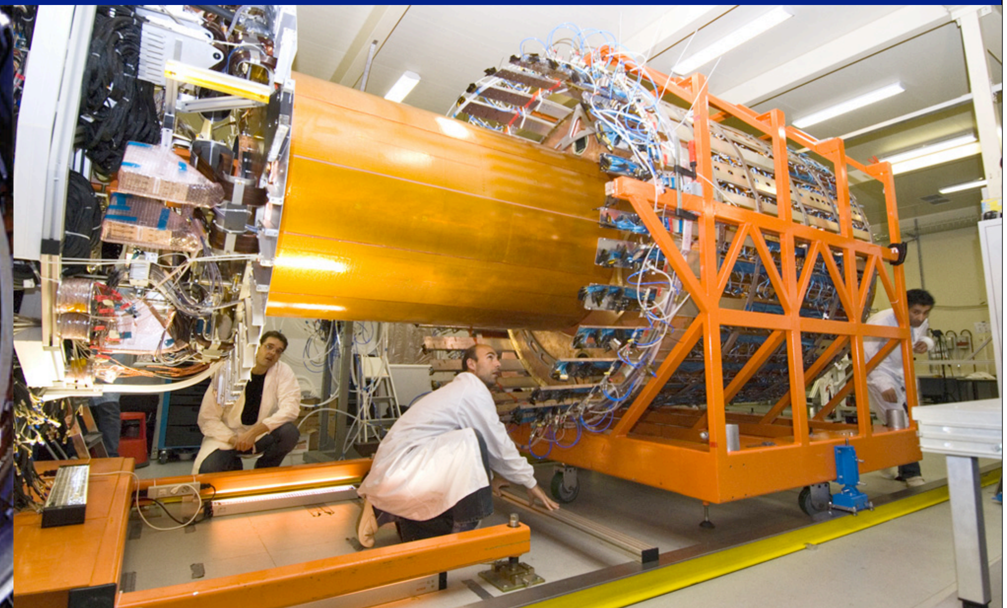


Detector Mass in Perspective

CMS is 30% heavier than the Eiffel tower

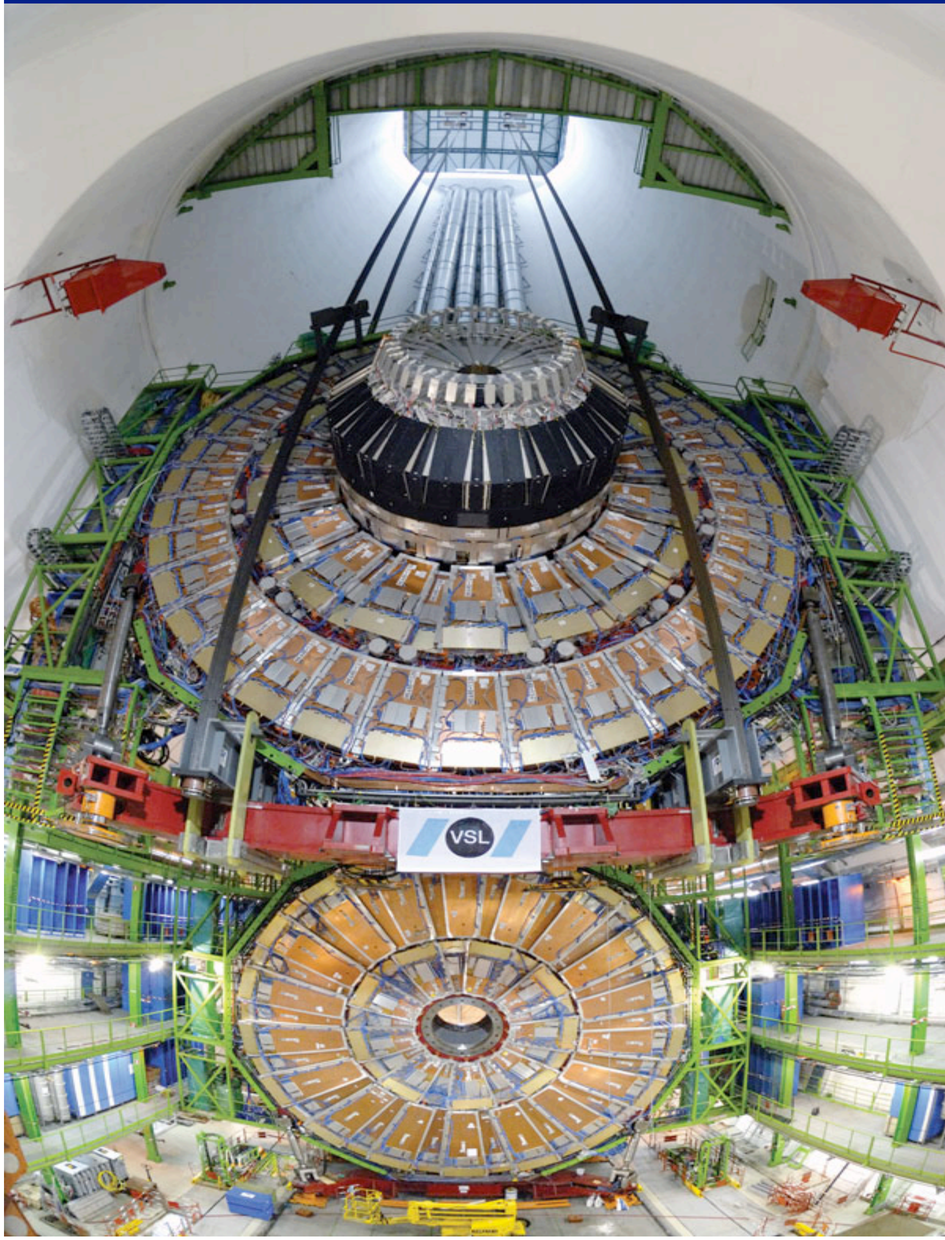
Silicon Tracking Detectors

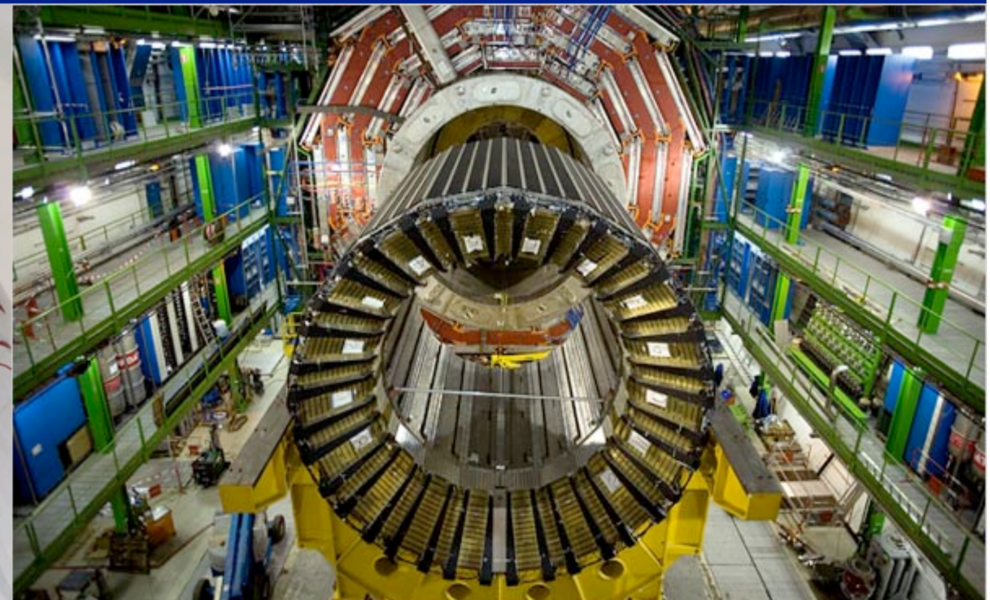


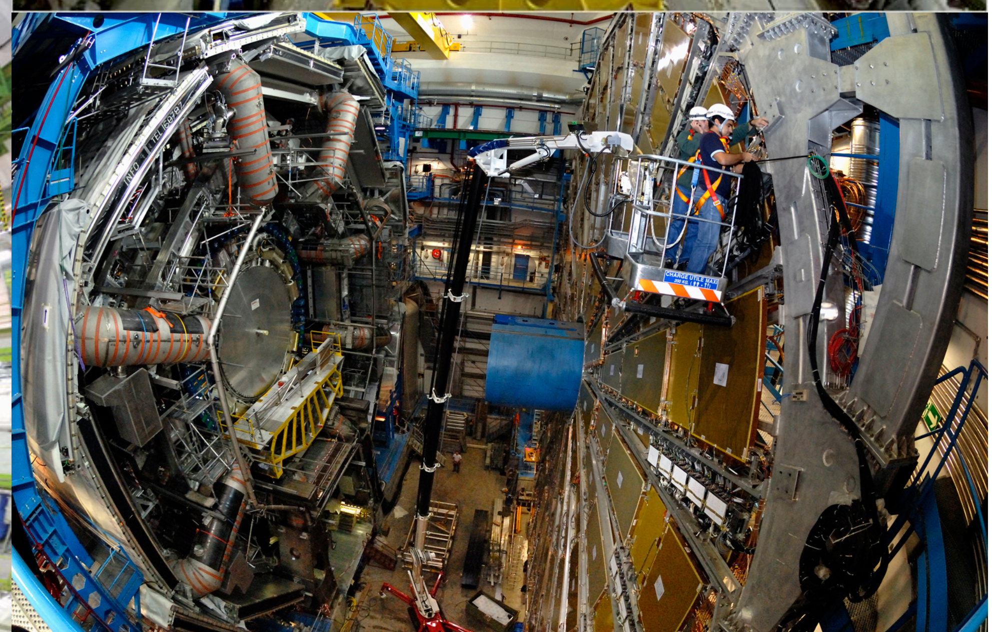


- Silicon strip and pixel detectors
  - Pixels used for first time at hadron colliders
  - Huge!
    - area of CMS silicon ~200 m^2
    - Like a football field!

Muon Systems and Calorimeters







Celebrating 7 TeV Collisions in ATLAS

See Lectures from T. LeCompte

Hadron-Hadron Collisions

Calculating a Cross Section

- Cross section is convolution of pdf's and Matrix Element

Physical cross section

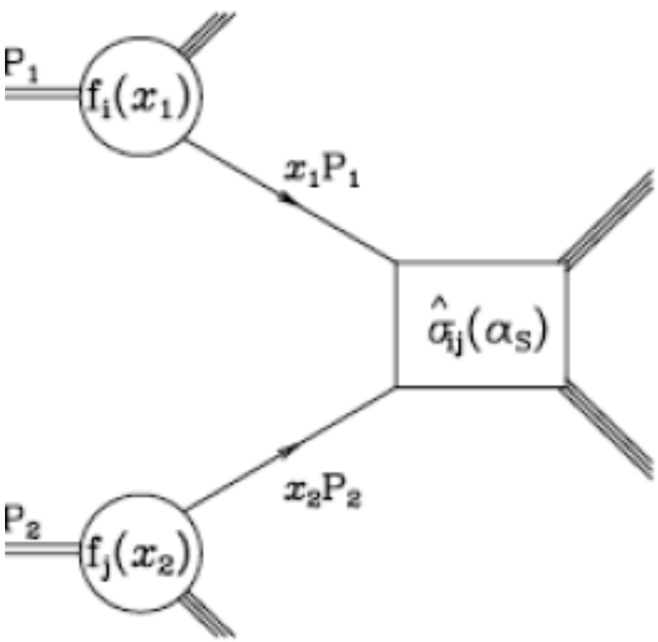
Parton distribution function

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

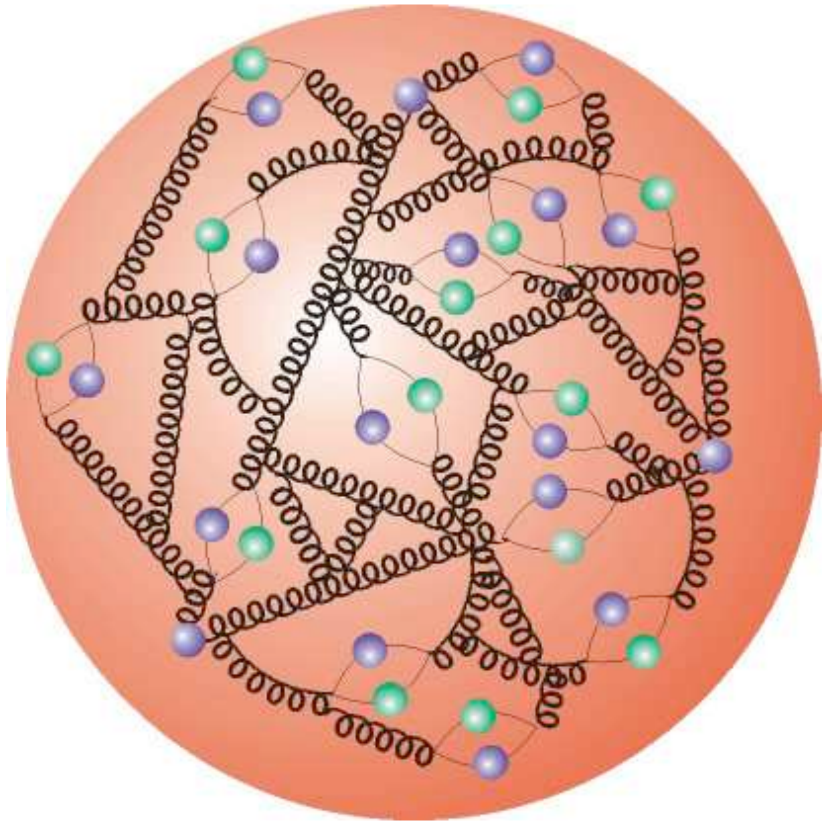
Short distance cross section, calculated as a perturbation series in α_S



- 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

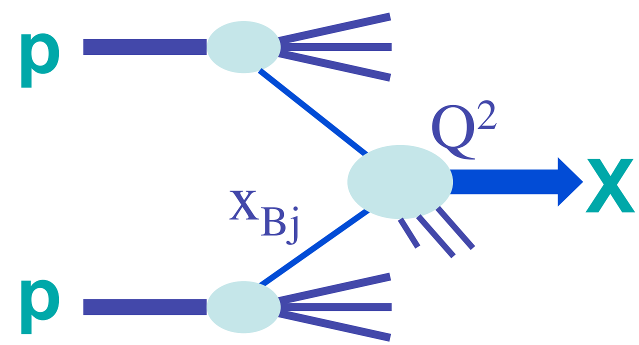
The Proton Composition

- 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
- Energy of parton collision:



$$\hat{s} = x_p \cdot x_{\bar{p}} \cdot s$$

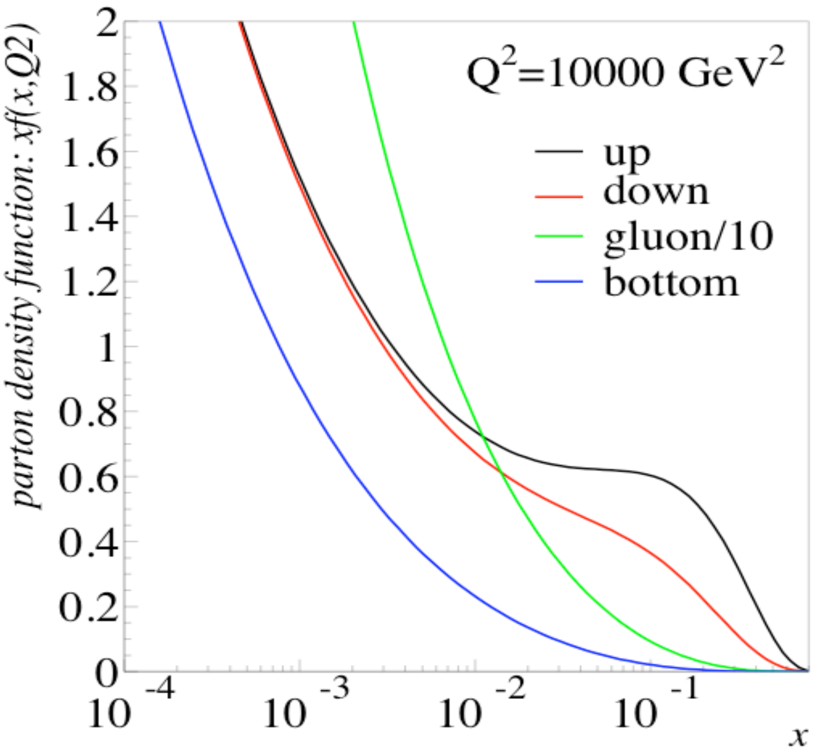
$$M_X = \sqrt{\hat{s}}$$



Parton Kinematics

- Examples:
  - Higgs: M~100 GeV/c^2
    - LHC: $<x_p>=100/14000\approx0.007$
    - TeV: $<x_p>=100/2000\approx0.05$
  - Gluino: M~1000 GeV/c^2
    - LHC: $<x_p>=1000/14000\approx0.07$
    - TeV: $<x_p>=1000/2000\approx0.5$

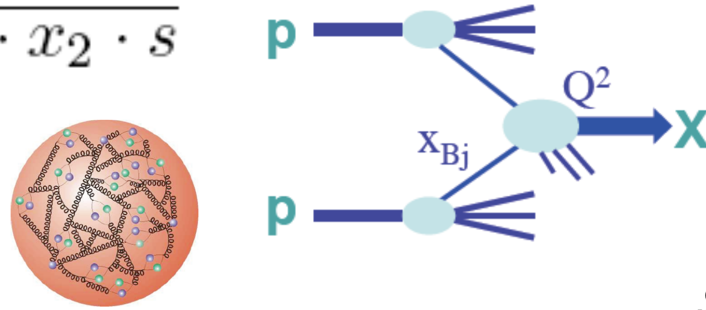
pdf's measured in deep-inelastic scattering



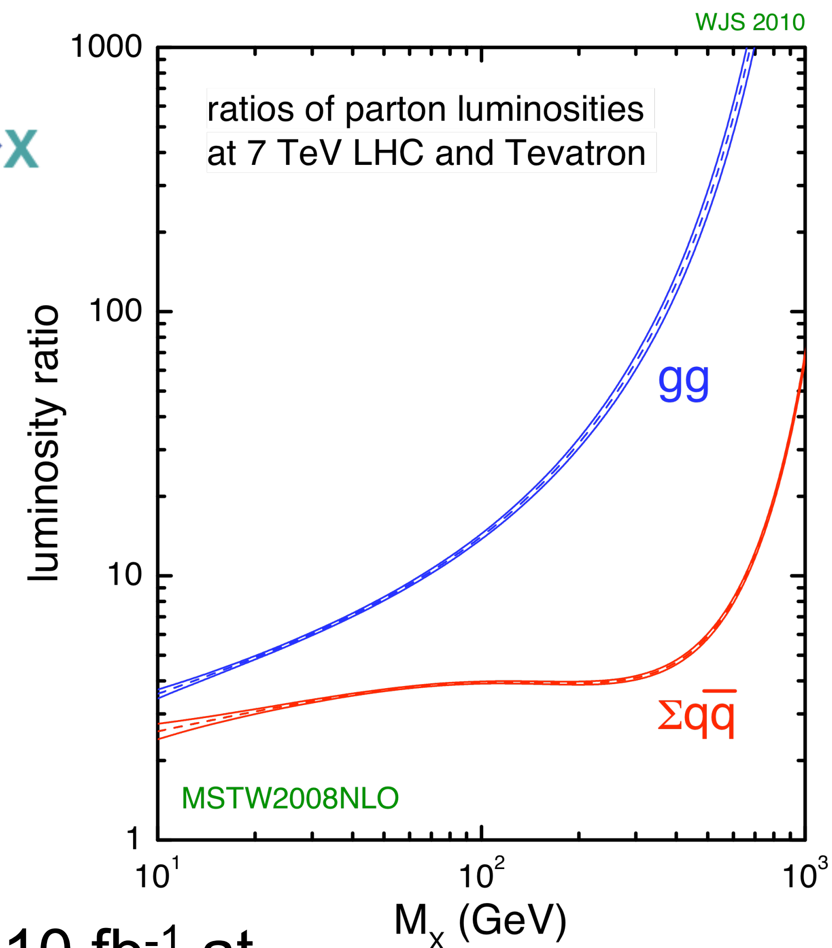
- Parton densities rise dramatically towards low x
  - Results in larger cross sections for LHC

Physics Cross Sections

$$M_X = \sqrt{x_1 \cdot x_2 \cdot s}$$



Process	M_X	$\frac{\sigma(\text{LHC @ 7 TeV})}{\sigma(\text{Tevatron})}$
$q\bar{q} \to W$	80 GeV	3
$q\bar{q} \to Z'_{SM}$	1 TeV	50
$gg \to H$	120 GeV	20
$q\bar{q}/gg \to t\bar{t}$	2x173 GeV	15
$gg \to \tilde{g}\tilde{g}$	2x400 GeV	1000

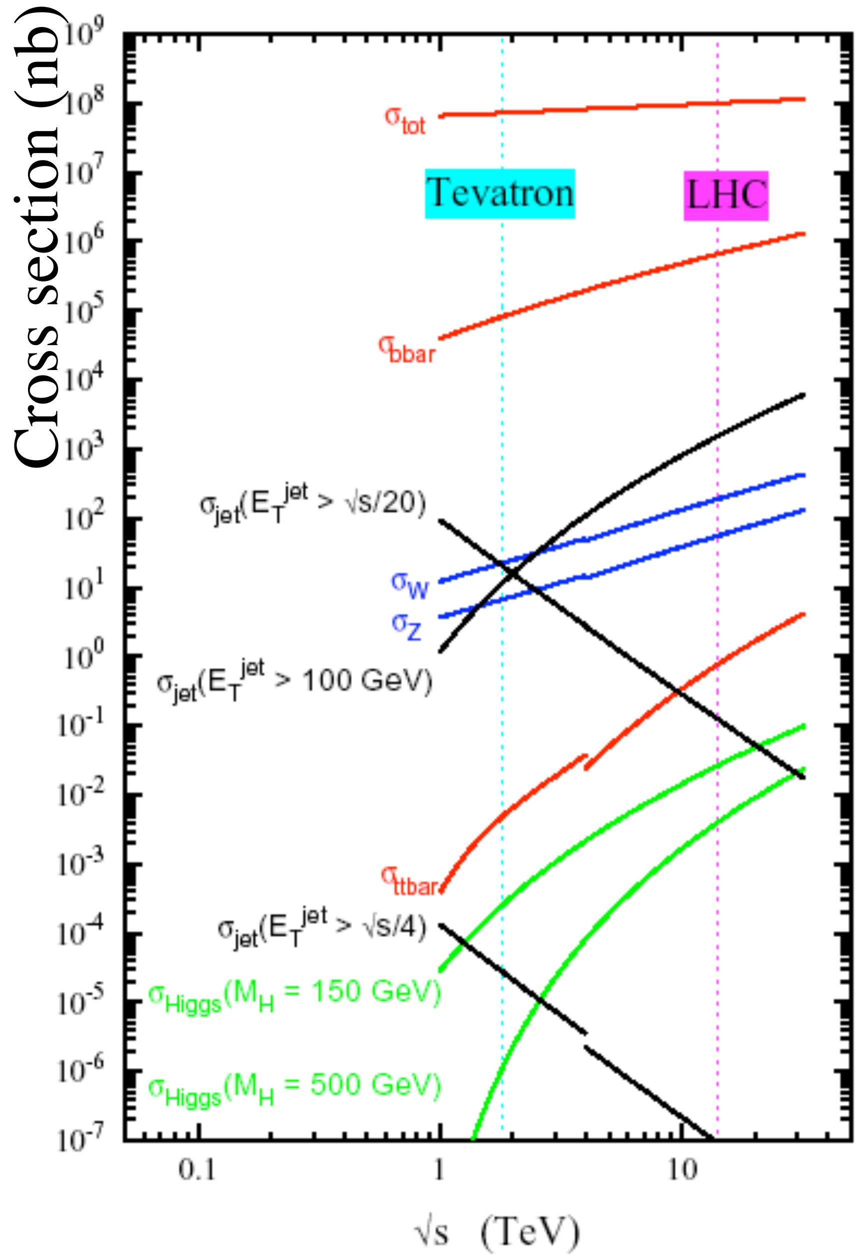


- $\int L dt = 1\ fb^{-1}$ at LHC competitive with $10\ fb^{-1}$ at Tevatron for high mass processes
- $\int L dt = 100\ pb^{-1}$ already interesting in some cases

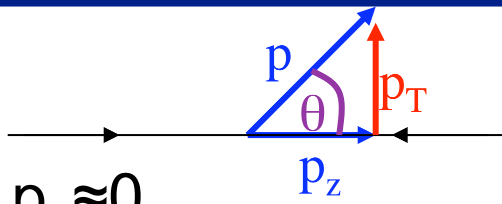
Cross Sections at Tevatron and LHC

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

- Interesting events gets selected
  - By trigger:
    - Online selection mechanism to find events which contain hard jets, leptons etc.
  - By physics analysis
    - Offline selection designed to suppress the background compared to the signal



Kinematic Constraints and Variables



- **Transverse momentum, p_T**
  - Particles that escape detection ($\theta<3^o$) have $p_T \approx 0$
  - Visible transverse momentum conserved $\sum_i p_T^i \approx 0$
    - **Very useful variable!**
- **Longitudinal momentum and energy, p_z and E**
  - Particles that escape detection have large p_z
  - Visible p_z is not conserved
    - **Not a useful variable**
- **Polar angle θ**
  - Polar angle θ is not Lorentz invariant
  - Rapidity: y
  - Pseudorapidity: η

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

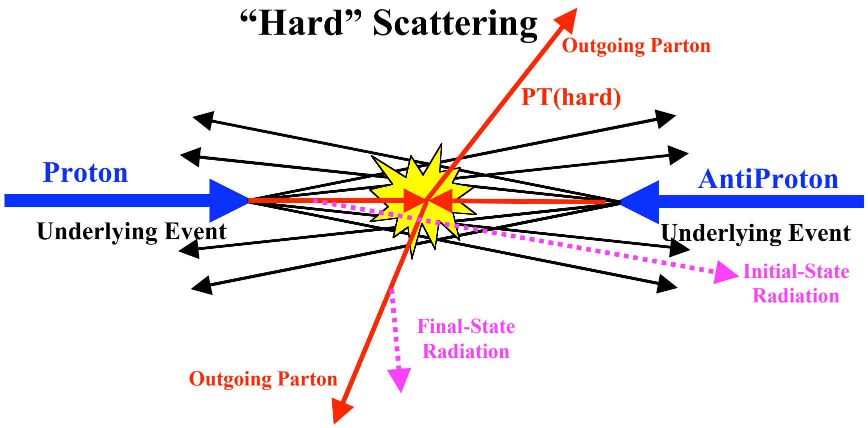
For M=0

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

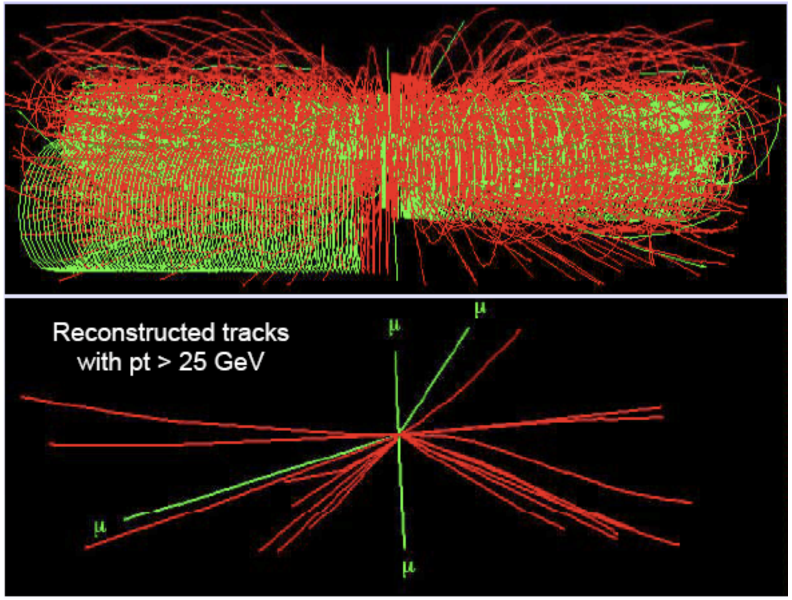
Conclusion of 1st Lecture

- Hadron Colliders
  - can address many of the problems with the Standard Model
    - Higgs boson
    - Physics beyond the Standard Model (e.g. Supersymmetry)
  - access higher energies than lepton colliders
    - Thus higher mass particles
  - are experimentally challenging
    - Many uninteresting background processes
    - The collisions themselves are complex
- Current colliders:
  - Tevatron is running since 2001
    - Has about 9 fb^{-1} collected
  - LHC is now running as the world's highest energy collider
    - Luminosity continues to increase: goal 1 fb^{-1} by end of 2011
    - Will then be competitive with LHC in most areas

Every Event is Complicated



$H \rightarrow ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-)$



- "Underlying event":
  - Initial state radiation
  - Interactions of other partons in proton
- Additional pp interactions
  - LHC: ~1.5 (~23 at design values)
  - Tevatron: ~10
- Many forward particles escape detection
  - Transverse momentum ~0
  - Longitudinal momentum >>0