Large Hadron Collider Physics: The Next Generation

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Fermilab & LPTENS

Why Hadron Colliders?

Discovery machines

$W^{\pm}$, Z^0, t, H, ...

Precision instruments

M_W, m_t, M_H, B_s oscillation frequency, ...

Large energy reach · High event rate

Why Hadron Colliders?

Explore a rich diversity of elementary processes
at the highest accessible energies:

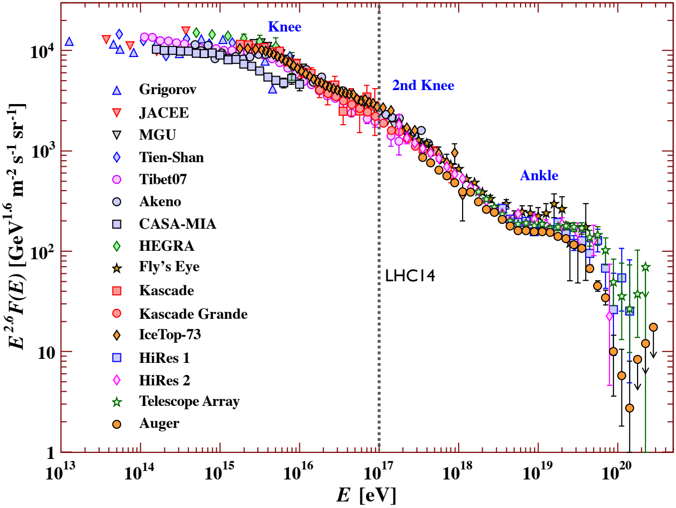
$$(q_i, \bar{q}_i, g, \ldots) \otimes (q_i, \bar{q}_i, g, \ldots)$$

Example: quark-quark collisions at $\sqrt{s} = 1$ TeV

If 3 quarks share half the proton's momentum ($\langle x \rangle = \frac{1}{6}$),
require *pp* collisions at $\sqrt{s} = 6$ TeV

$\rightsquigarrow$ Fixed-target machine with beam momentum
$p \approx 2 \times 10^4$ TeV $= 2 \times 10^{16}$ eV (*cf.* cosmic rays).

Cosmic-ray Spectrum



$$\frac{dI}{dE}(2 \times 10^{16}\ \text{eV}) = (3\ \text{-}\ 5) \times 10^{-16}\ \text{m}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\ \text{eV}^{-1}$$

How to achieve?

Fixed-target, $p \approx 2 \times 10^4$ TeV
Ring radius is

$$r = \frac{10}{3} \cdot \left(\frac{p}{1\ \text{TeV}}\right) \Big/ \left(\frac{B}{1\ \text{tesla}}\right)\ \text{km}.$$

Conventional copper magnets ($B = 2$ teslas) $\rightsquigarrow$

$$r \approx \tfrac{1}{3} \times 10^5\ \text{km}.$$

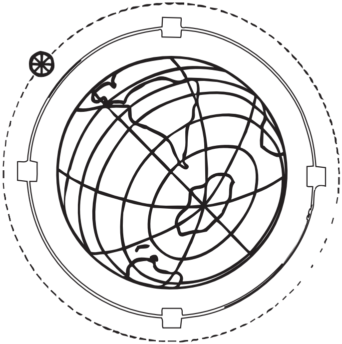
$$\approx \tfrac{1}{12}\ \text{size of Moon's orbit}$$

10-tesla field reduces the accelerator to mere Earth size ($R_\oplus = 6.4 \times 10^3$ km).

Fermi's Dream Machine (1954)

5000-TeV protons to reach $\sqrt{s} \approx 3$ TeV

2-tesla magnets at radius 8000 km



Projected operation 1994, cost \$170 billion

(inflation assumptions not preserved)

Key Advances in Accelerator Technology

- Alternating-gradient ("strong") focusing, invented by Christofilos, Courant, Livingston, and Snyder.

  Before and After ...

Synchrotron	Beam Tube	Magnet Size
Bevatron (6.2 GeV)	1 ft $\times$ 4 ft	$9\frac{1}{2}$ ft $\times$ $20\frac{1}{2}$ ft
FNAL Main Ring (400 GeV)	$\sim$ 2 in $\times$ 4 in	14 in $\times$ 25 in
LHC ($\rightarrow$ 7 TeV)	56 mm	(SC)

- The idea of colliding beams.
- Superconducting accelerator magnets based on "type-II" superconductors, including NbTi and Nb_3Sn.

Key Advances . . .

- Active optics to achieve real-time corrections of the orbits makes possible reliable, highly tuned accelerators using small-aperture magnets. Also "cooling," or phase-space compaction of stored antiprotons.
- The evolution of vacuum technology. Beams stored for approximately 20 hours travel $\sim 2 \times 10^{10}$ km, about 150 times the Earth–Sun distance, without encountering a stray air molecule.
- The development of large-scale cryogenic technology, to maintain many km of magnets at a few kelvins.

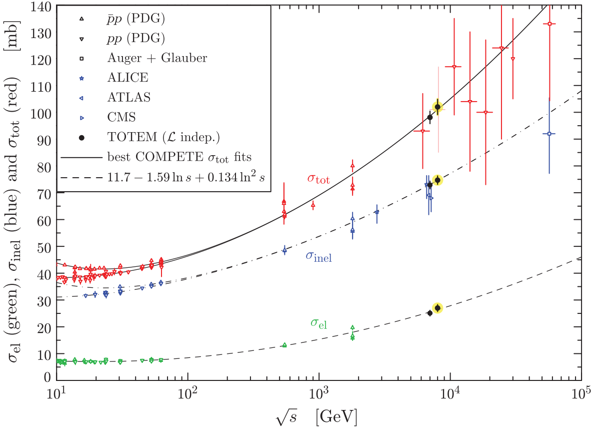
Hadron Colliders through the Ages

- CERN Intersecting Storage Rings: pp collider at $\sqrt{s} \to 63$ GeV. Two rings of conventional magnets.
- S$\bar{p}p$S Collider at CERN: $\bar{p}p$ collisions at $\sqrt{s} = 630(\to 900)$ GeV in conventional-magnet SPS.
- Fermilab Tevatron Collider: $\bar{p}p$ collisions at $\sqrt{s} \approx 2$ TeV with 4-T SC magnets in a 2π-km tunnel.
- Brookhaven Relativistic Heavy-Ion Collider: 3.45-T dipoles in 3.8-km tunnel. Polarized pp, $\sqrt{s} \to 0.5$ TeV
- Large Hadron Collider at CERN: 14-TeV pp collider in the 27-km LEP tunnel, using 9-T magnets at 1.8 K.

High-energy collider parameters, 2014 *Review of Particle Properties* §30

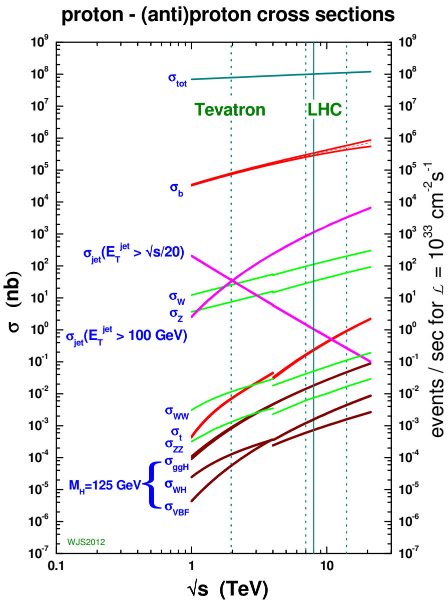
Large Hadron Collider at CERN

$\sqrt{s} = 8$ TeV Interaction Rates

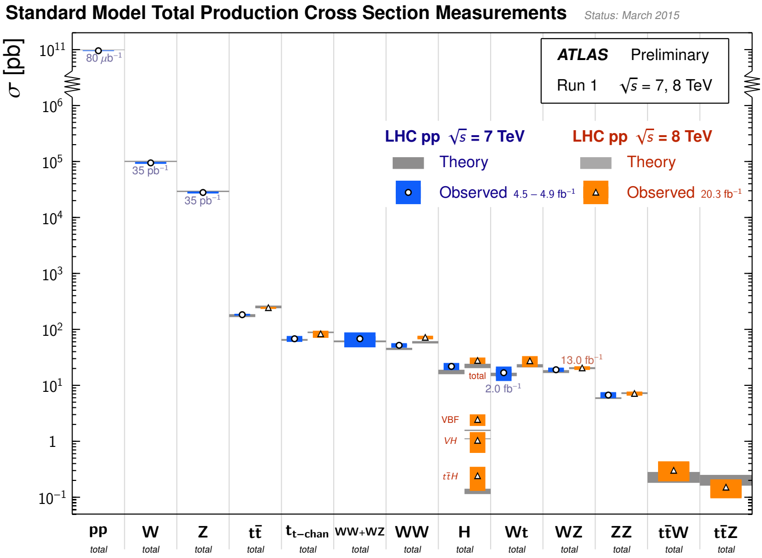


$\sigma_{\rm tot}$	(101.7 ± 2.9) mb
$\sigma_{\rm inel}$	(74.7 ± 1.7) mb
$\sigma_{\rm el}$	(27.1 ± 1.4) mb

Collider Cross Sections



Standard-model Cross Sections



$\sigma_{\text{tot}} \approx 10^{11}$ pb

CMS plots

Luminosity

Number N of events of interest

$$N = \sigma \int dt\, \mathcal{L}(t)$$

$\mathcal{L}(t)$: instantaneous luminosity [in $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$]

Bunches of n_1 and n_2 particles collide head-on at frequency f:

$$\mathcal{L}(t) = f\,\frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

$\sigma_{x,y}$: Gaussian rms $\perp$ beam sizes

Syphers & Zimmermann, 2014 *Review of Particle Physics*, §29

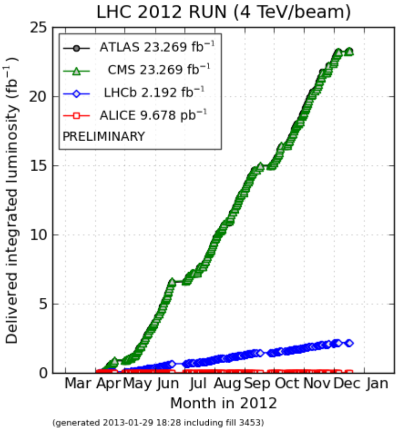
LHC lumi calculator   Zimmermann, "LHC: The Machine," SSI 2012

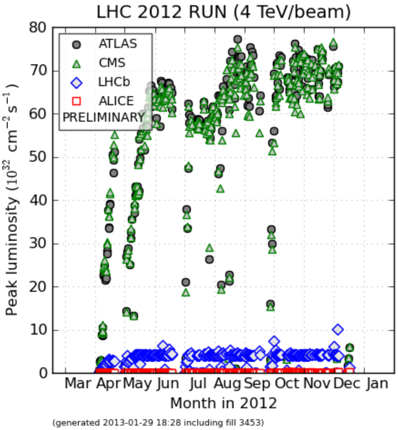
Exercise 1

(a) Estimate the integrated luminosity required to make a convincing observation of each of the standard-model final states shown in the ATLAS plot above. Take into account the gauge-boson branching fractions given in the 2014 *Review of Particle Physics.*

(b) Taking a nominal year of operation as 10^7 s, translate your results into the required average luminosity.

LHC Luminosity, 2012





$\mathcal{L}_{\text{peak}} \approx 7.7 \times 10^{33}\ \text{cm}^{-2}\ \text{s}^{-1}$ ATLAS & CMS

Collider kinematics

Because of its properties under Lorentz boosts, rapidity,

$$y \equiv \tfrac{1}{2} \ln \left| \frac{E + p_z}{E - p_z} \right|,$$

is a highly convenient longitudinal variable for an individual particle or a jet. *Pseudorapidity,*

$$\eta \equiv -\ln \tan(\theta^{\star}/2),$$

is a close approximation to y in the setting of collider detectors, and can be measured, even when the mass of the outgoing object is unknown.

Exercise 2

(a) Expand the definition

$$y \equiv \tfrac{1}{2} \ln \left| \frac{E + p_z}{E - p_z} \right|$$

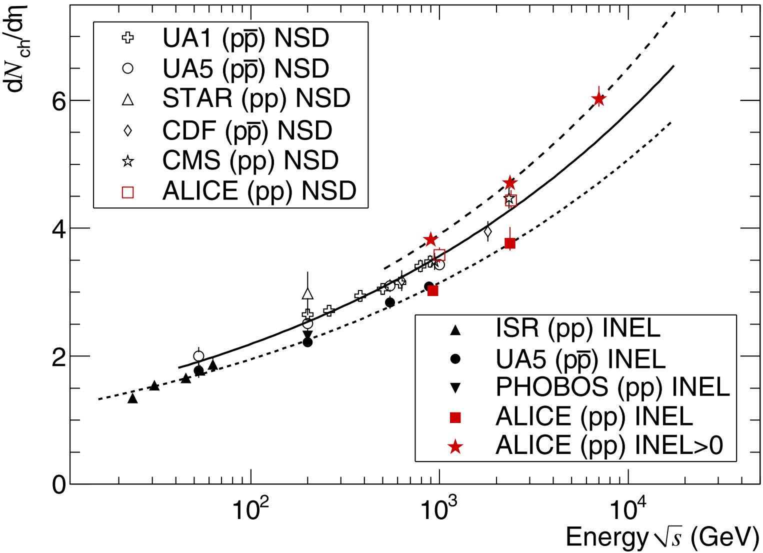
of rapidity for an object with mass m, under the assumption that $p \gg m$, to show that as $m/p \to 0$,

$$y \to \eta \equiv - \ln \tan(\theta^{\star}/2).$$

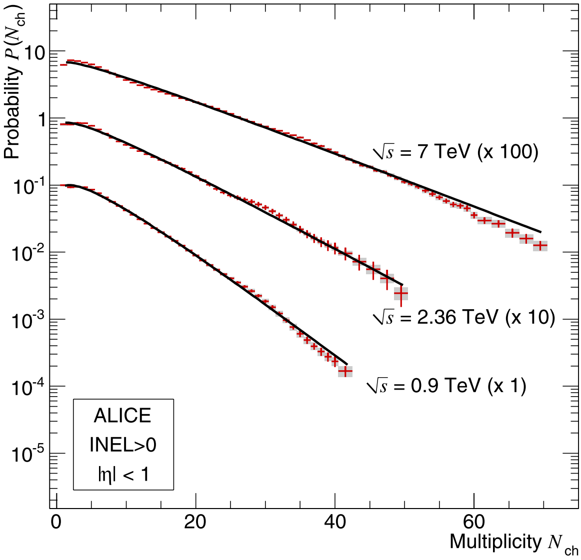
cf. 2014 *Review of Particle Physics* §46.5.2

(b) For pion production, compute the maximum c.m. rapidity at $\sqrt{s} = (8, 14)$ TeV and deduce the angular coverage required to observe the full range.

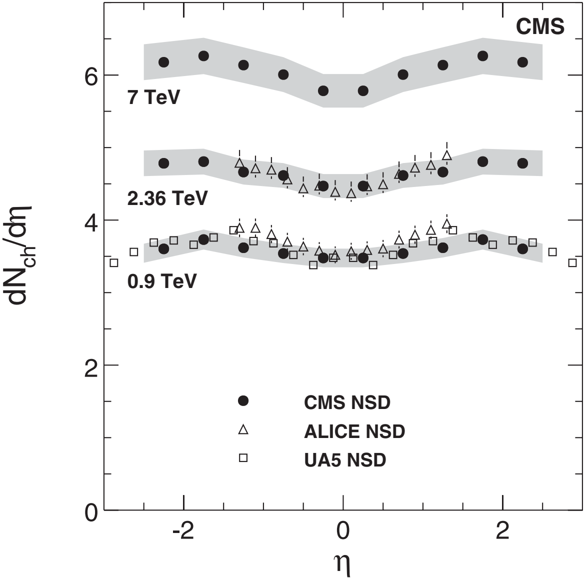
Charged-particle density, $\eta \approx 0$



Charged-particle multiplicity, $|\eta| < 1$



Charged-particle spectra

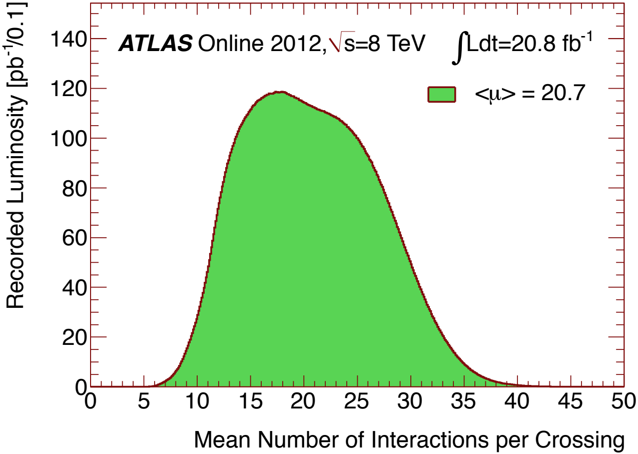


Pileup

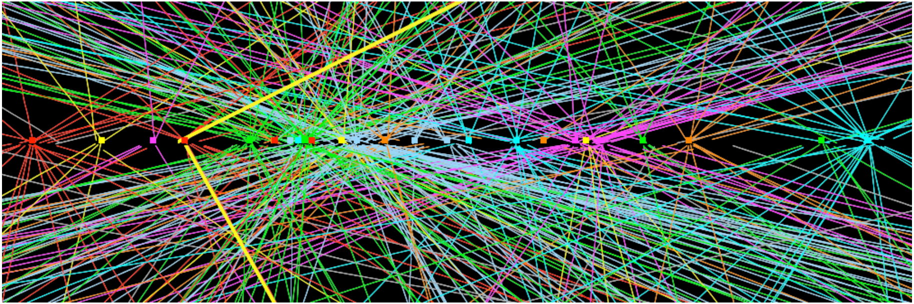
Typical LHC operation: 1.5×10^{11} protons / bunch

bunch separation 50 ns

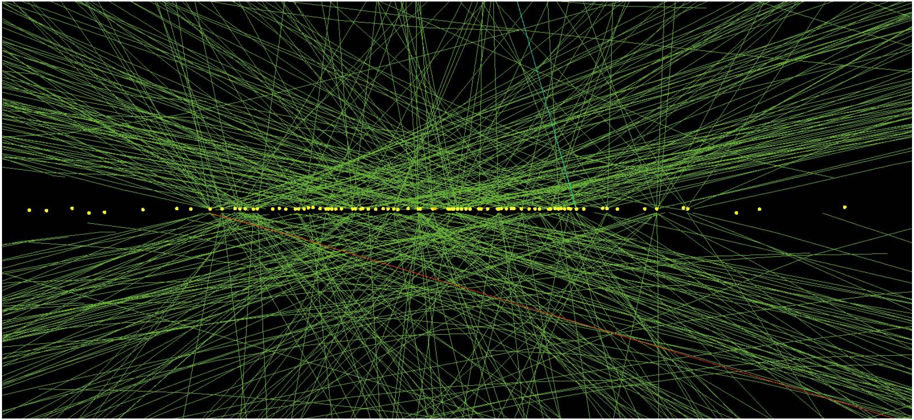
$\rightsquigarrow$ multiple interactions / crossing



Pileup: $Z \to \mu^+\mu^-$ in 25 interactions in ATLAS



Pileup: 78 interactions in CMS



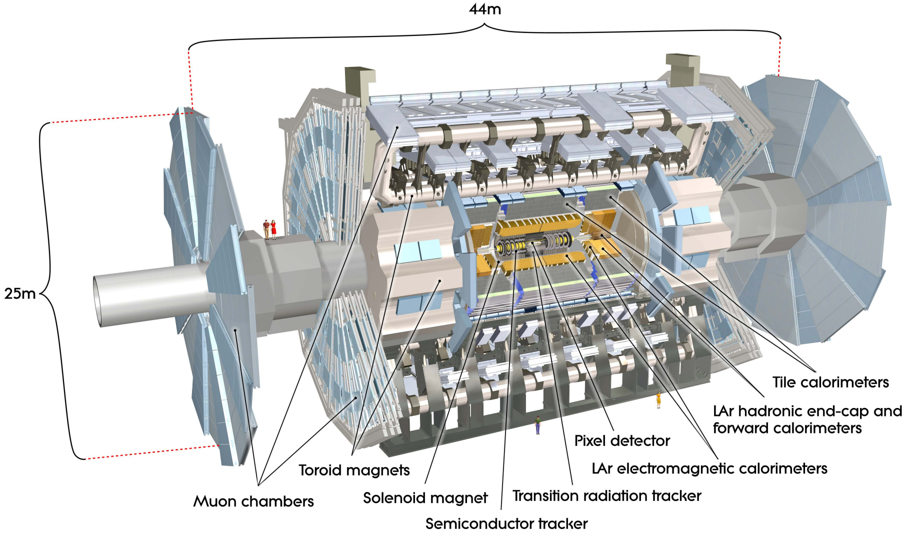
Exercise 3

Consider the reaction $p^{\pm}p \rightarrow \text{jet}_1 + \text{jet}_2 + \text{anything}$ at c.m. energy $\sqrt{s}$. Denote the rapidity of the dijet system as $y_{\text{boost}} \equiv \frac{1}{2}(y_1 + y_2)$ and the individual jet rapidity in the dijet rest frame as $y^* \equiv \frac{1}{2}(y_1 - y_2)$.

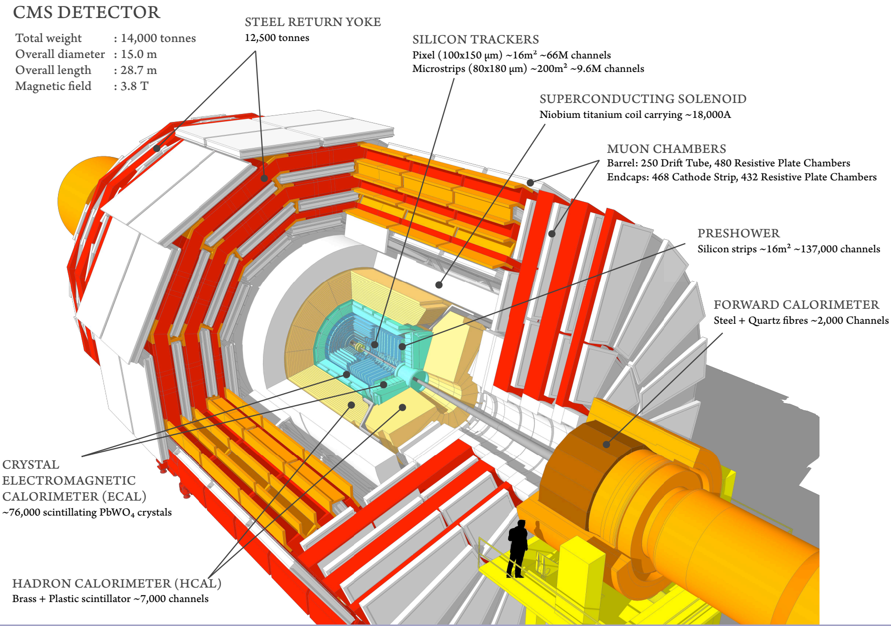
(a) Neglecting the invariant masses of the individual jets with respect to $p_\perp$, show that the invariant mass of the dijet system, and thus of the colliding partons, is $\sqrt{\hat{s}} = 2p_\perp \cosh y^*$.

(b) Deduce the momentum fractions carried by the two colliding partons. Show that $x_{a,b} = \sqrt{\tau} e^{\pm y_{\text{boost}}}$, where $\tau \equiv \hat{s}/s$.

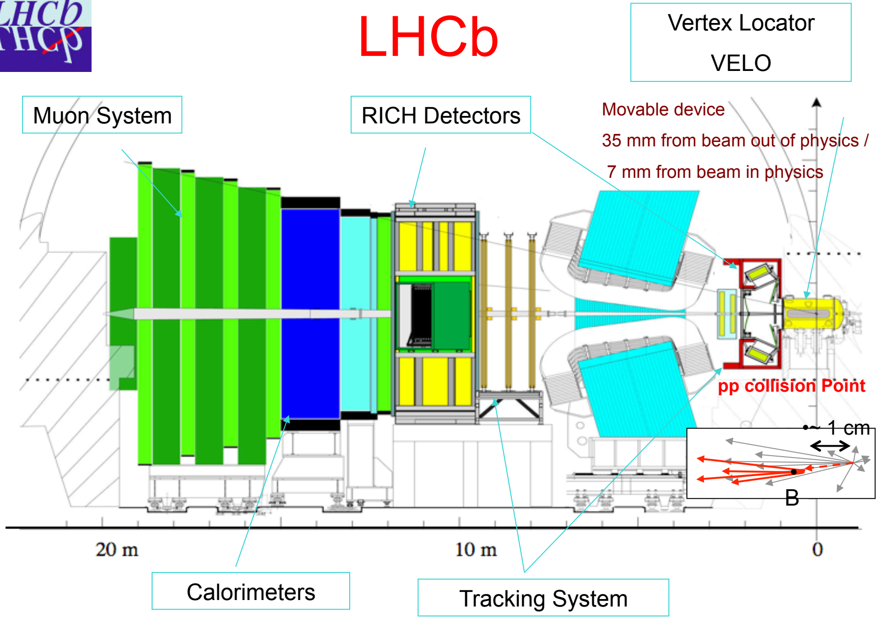
ATLAS


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

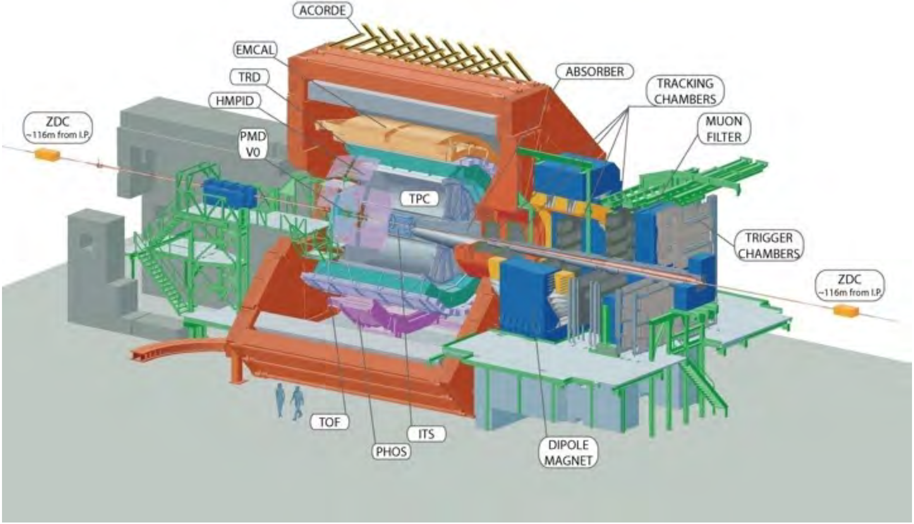
CMS (Compact Muon Solenoid)



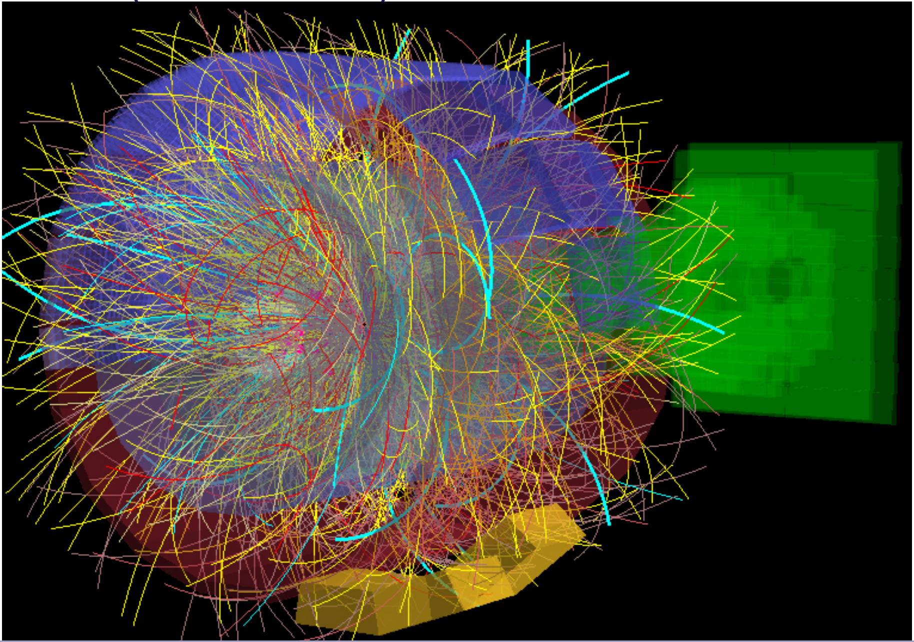
LHC*b*


LHCb
Vertex Locator
VELO
Muon System
RICH Detectors
Movable device
35 mm from beam out of physics /
7 mm from beam in physics
pp collision Point
~ 1 cm
B
20 m
10 m
0
Calorimeters
Tracking System

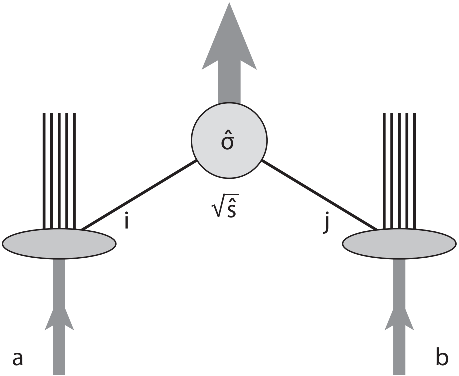
ALICE


ACORDE
EMCAL
TRD
HMPID
ZDC
~116m from I.P.
PMD
V0
ABSORBER
TRACKING
CHAMBERS
MUON
FILTER
TPC
TRIGGER
CHAMBERS
ZDC
~116m from I.P.
TOF
ITS
PHOS
DIPOLE
MAGNET

ALICE (Pb–Pb event)



Computing Cross Sections: *factorization*



$$\frac{d\sigma}{dy_1\,dy_2\,dp_\perp} = \sum_{i\,j} \frac{2\pi p_\perp}{(1+\delta_{ij})s}\left[f_i^{(a)}(x_a,\hat{s})f_j^{(b)}(x_b,\hat{s})\hat{\sigma}_{ij}(\hat{s},\hat{t},\hat{u}) + (i \leftrightarrow j)\right]$$

$\ldots +$ fragmentation (partons $\rightarrow$ particles)

What Is a Proton?

(For hard scattering) a broad-band, unselected beam of quarks, antiquarks, gluons, & perhaps other constituents, characterized by parton densities

$$f_i^{(a)}(x_a, Q^2),$$

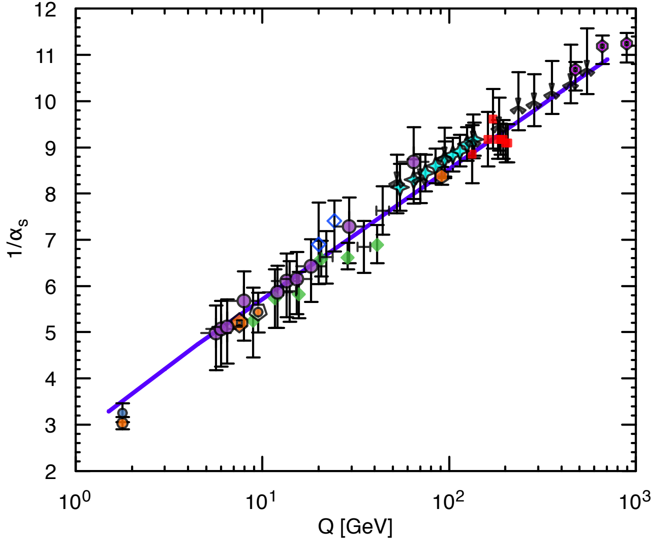
…number density of species i with momentum fraction x_a of hadron a seen by probe with resolving power Q^2.

Q^2 evolution given by QCD perturbation theory

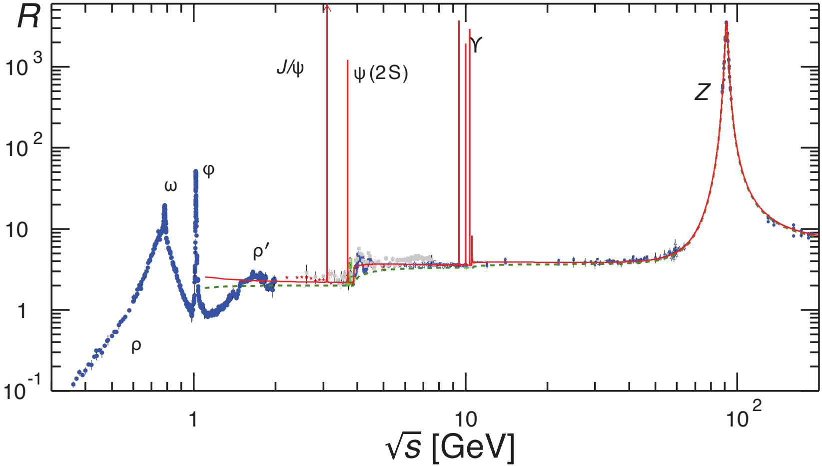
$f_i^{(a)}(x_a, Q_0^2)$: nonperturbative

Asymptotic Freedom

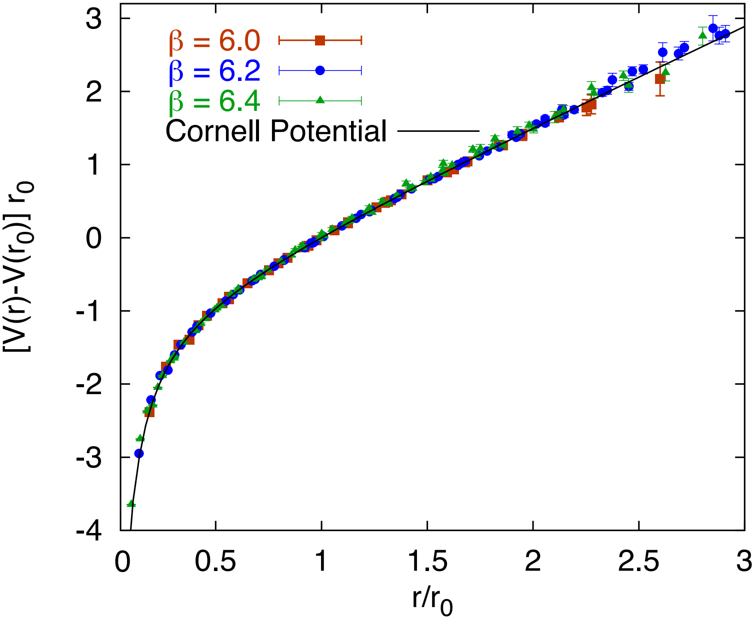
$$\frac{1}{\alpha_s(Q)} = \frac{1}{\alpha_s(\mu)} + \frac{(33 - 2n_f)}{6\pi} \ln\left(\frac{Q}{\mu}\right)$$



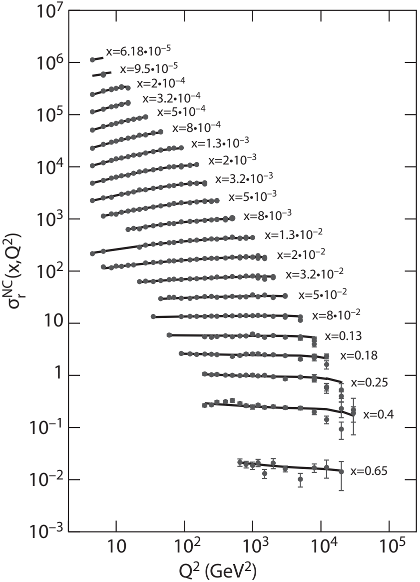
QCD Tests: $e^+e^- \to$ hadrons

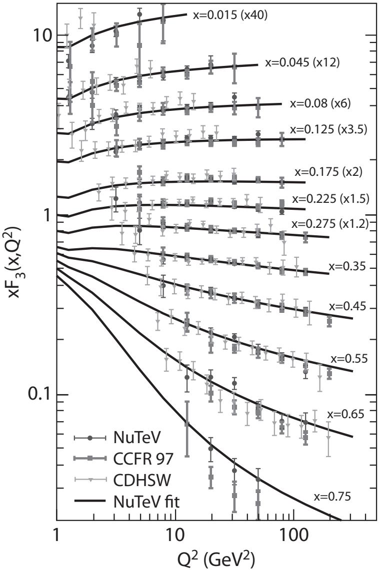


QCD Tests: Quark Confinement

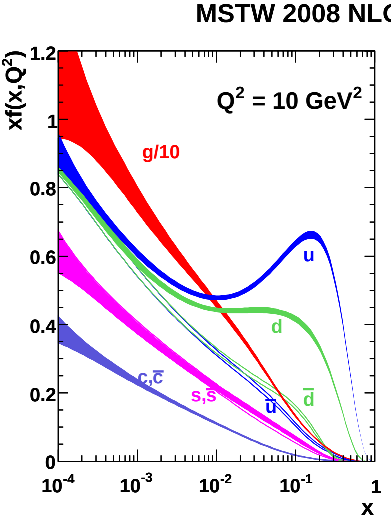


Deeply Inelastic Scattering $\rightsquigarrow f_i^{(a)}(x_a, Q_0^2)$



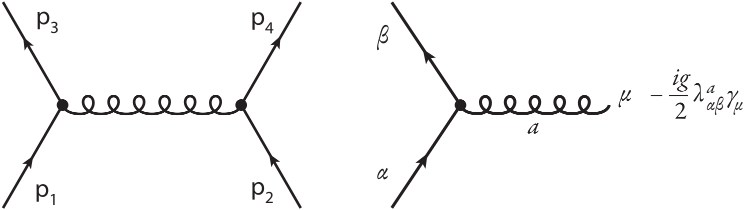


Parton Distribution Functions $f_i(x, Q^2)$



APFEL: A PDF Evolution Library

Example reaction: quark–quark scattering



$$\hat{\sigma}(ud \to ud) = \frac{4\pi\alpha_s^2}{9\hat{s}^2} \cdot \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}$$

$$\hat{s} = (p_1 + p_2)^2 \quad \hat{t} = (p_1 - p_3)^2 \quad \hat{u} = (p_1 - p_4)^2$$

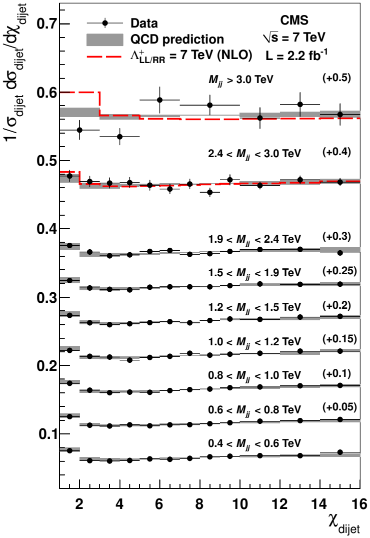
$$\rightsquigarrow d\sigma/d\Omega^* \propto 1/\sin^4(\theta^*/2)$$

Exercise 4

(a) Express the $ud \to ud$ cross section in terms of c.m. angular variables, and verify that the angular distribution is reminiscent of that for Rutherford scattering.

(b) In the search for new interactions, the angular distribution for quark-quark scattering, inferred from dijet production in $p^{\pm}p$ collisions, is a sensitive diagnostic. Show that when re-expressed in terms of the variable $\chi = (1 + \cos\theta^*)/(1 - \cos\theta^*)$, the angular distribution for ud scattering is $d\sigma/d\chi \propto$ constant.

Compositeness search in CMS ($|y_{\text{boost}}| < 1.11$)



$$\chi_{\text{dijet}} = e^{|y_1 - y_2|}$$

Parton Luminosity

Hard scattering: $\hat{\sigma} \propto 1/\hat{s}$; Resonance: $\hat{\sigma} \propto \tau$; form

$$\frac{\tau}{\hat{s}} \frac{d\mathcal{L}}{d\tau} \equiv \frac{\tau/\hat{s}}{1+\delta_{ij}} \int_\tau^1 \frac{dx}{x} [f_i^{(a)}(x) f_j^{(b)}(\tau/x) + f_j^{(a)}(x) f_i^{(b)}(\tau/x)]$$

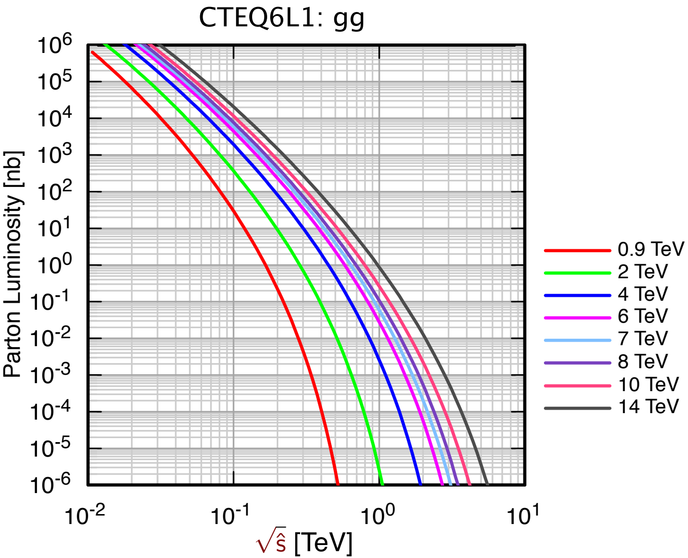
[dimensions σ] measures parton ij luminosity ($\tau = \hat{s}/s$)

$$\sigma(s) = \sum_{i\,j} \int_{\tau_0}^1 \frac{d\tau}{\tau} \cdot \frac{\tau}{\hat{s}} \frac{d\mathcal{L}_{ij}}{d\tau} \cdot [\hat{s}\hat{\sigma}_{ij}(\hat{s})]$$

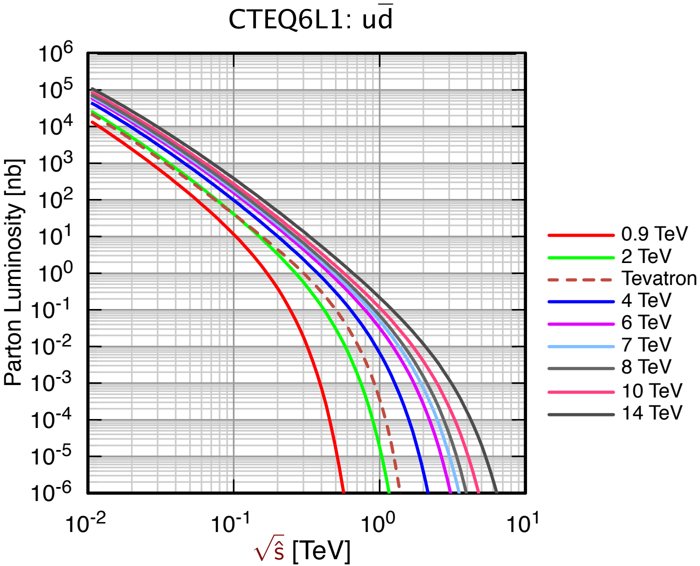
Dmensionless factor $[\cdots] \approx$ determined by couplings.
Logarithmic integral typically gives a factor of order unity.

My luminosity page   Stirling luminosities

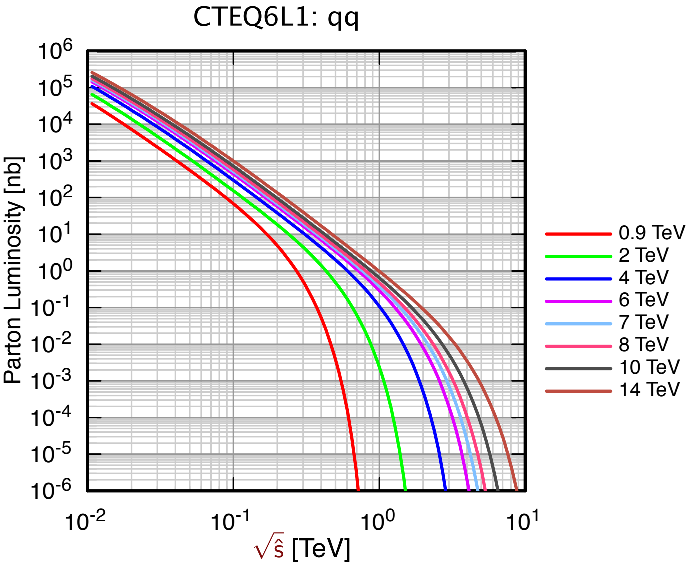
Parton Luminosity: *gg*



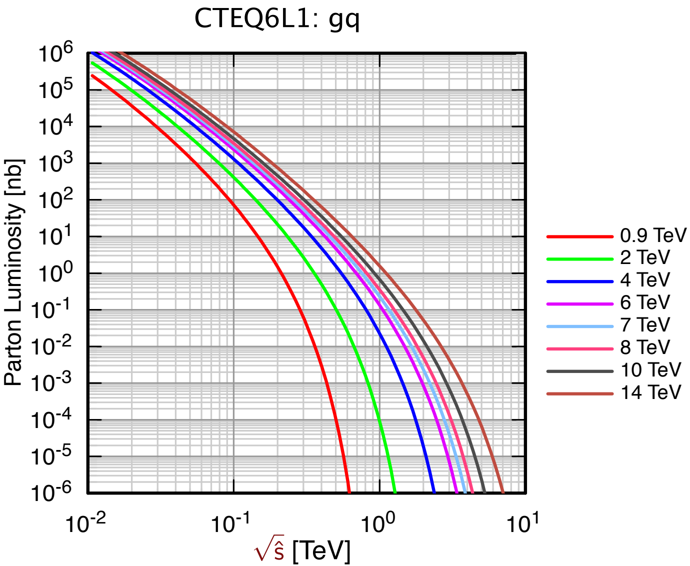
Parton Luminosity: $u\bar{d}$



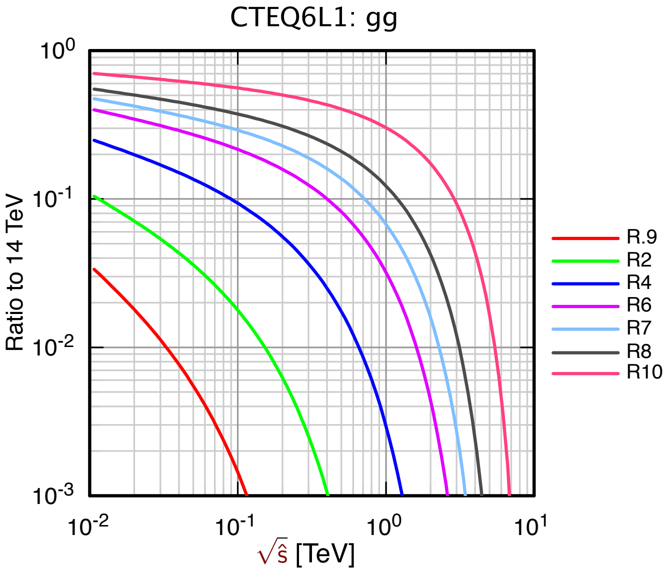
Parton Luminosity (light quarks)



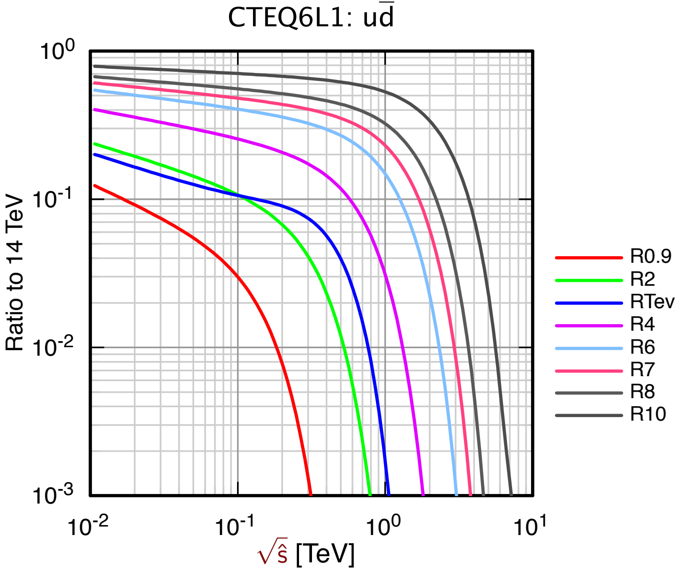
Parton Luminosity: *gq*



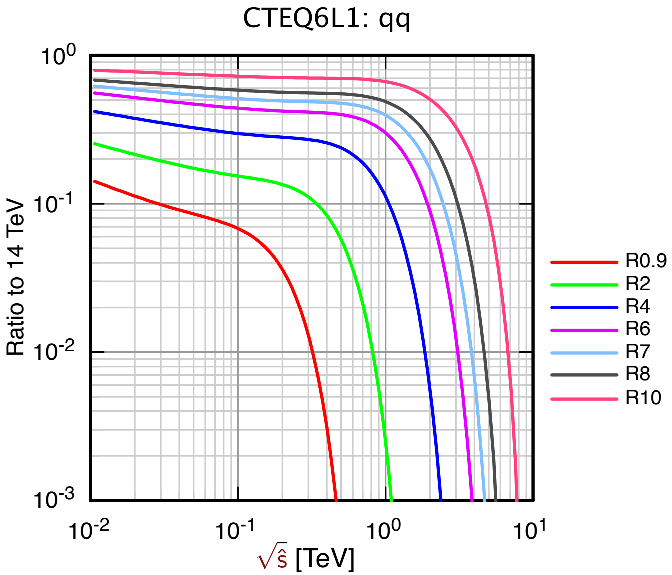
Luminosity Ratios: *gg*



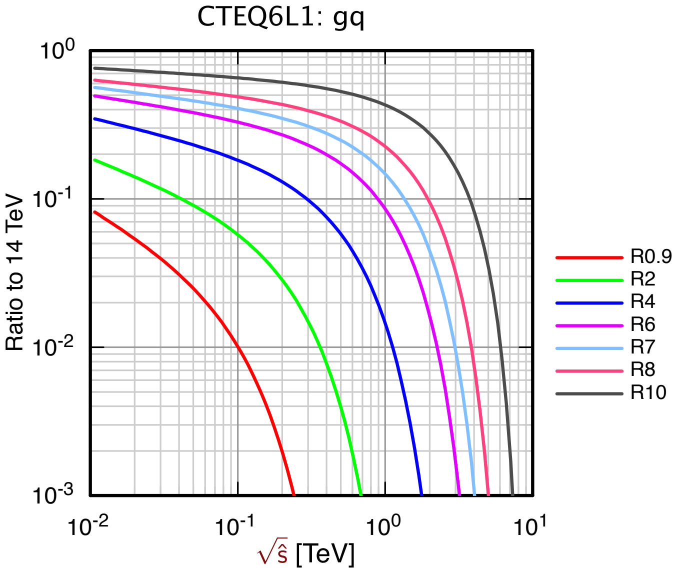
Luminosity Ratios: $u\bar{d}$



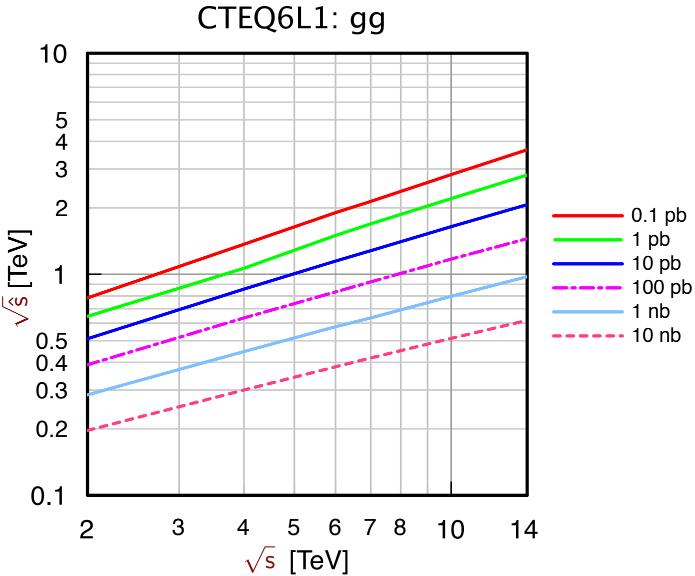
Luminosity Ratios (light quarks)



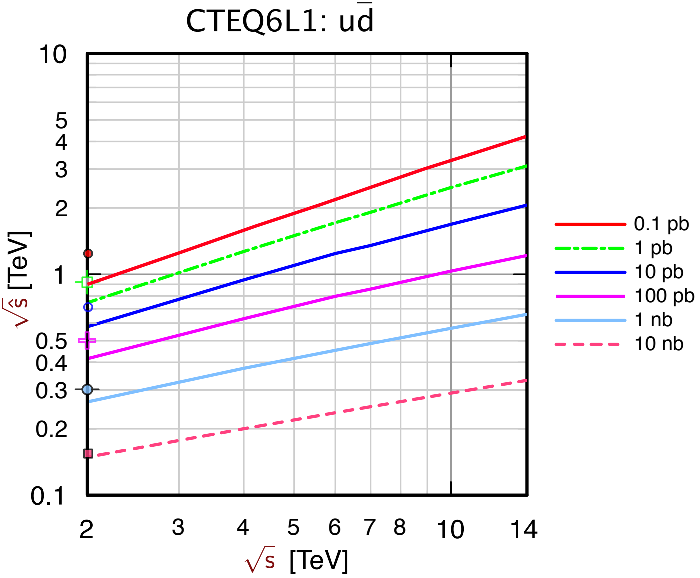
Luminosity Ratios: *gq*



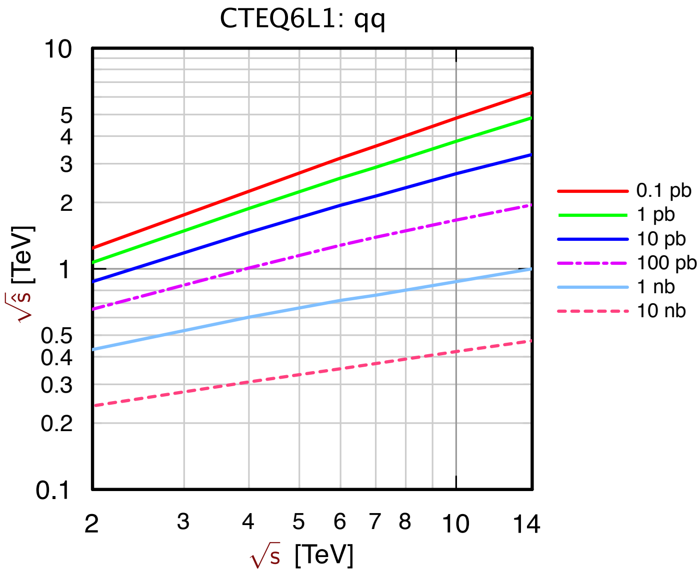
Luminosity Contours: *gg*



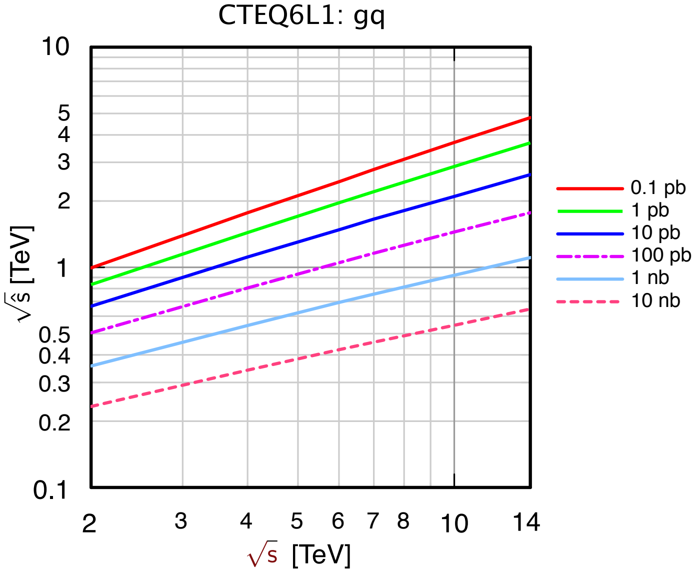
Luminosity Contours: $u\bar{d}$



Luminosity Contours (light quarks)



Luminosity Contours: *gq*



Venerable Overview

Supercollider physics

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Eichten *et al.* summarize the motivation for exploring the 1-TeV ($=10^{12}$ eV) energy scale in elementary particle interactions and explore the capabilities of proton-(anti)proton colliders with beam energies between 1 and 50 TeV. The authors calculate the production rates and characteristics for a number of conventional processes, and discuss their intrinsic physics interest as well as their role as backgrounds to more exotic phenomena. The authors review the theoretical motivation and expected signatures for several new phenomena which may occur on the 1-TeV scale. Their results provide a reference point for the choice of machine parameters and for experiment design.

CONTENTS

I. INTRODUCTION

The physics of elementary particles has undergone a remarkable development during the past decade. A host of new experimental results made accessible by a new generation of particle accelerators and the accompanying rapid convergence of theoretical ideas have brought to the subject a new coherence. Our current outlook has been shaped by the identification of quarks and leptons as fundamental constituents of matter and by the gauge theory synthesis of the fundamental interactions.[1] These developments represent an important simplification of

[1]For expositions of the current paradigm, see the textbooks by Okun (1981), Perkins (1982), Aitchison and Hey (1982), Leader and Predazzi (1982), Quigg (1983), and Halzen and Martin (1984) and the summer school proceedings edited by Gaillard and Stora (1983).

Reviews of Modern Physics, Vol. 56, No. 4, October 1984

Anticipating the LHC . . .

Unanswered Questions in the Electroweak Theory

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Key Words

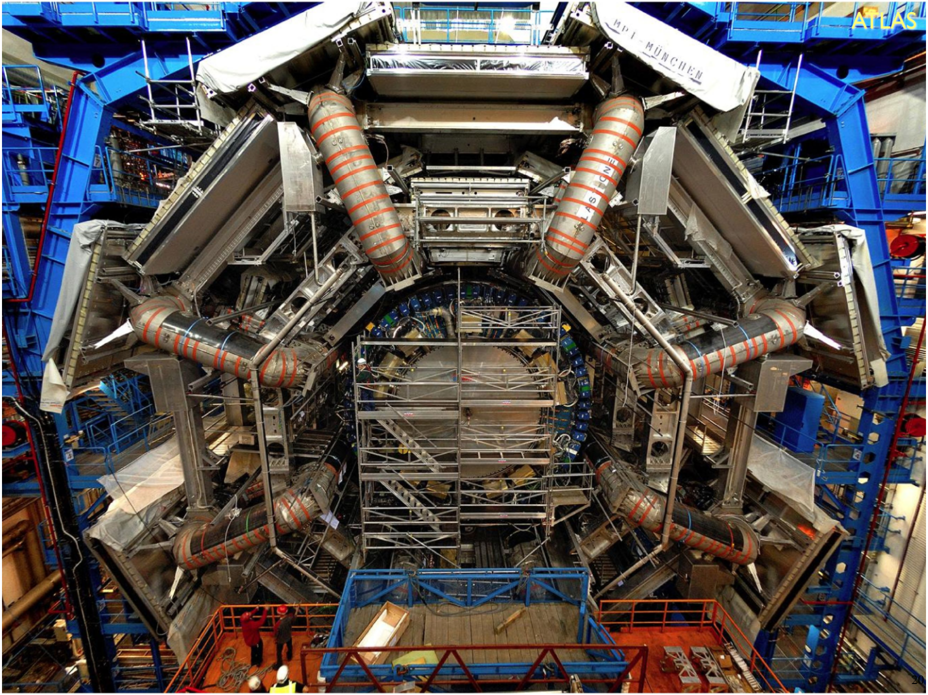
electroweak symmetry breaking, Higgs boson, 1-TeV scale, Large Hadron Collider (LHC), hierarchy problem, extensions to the Standard Model

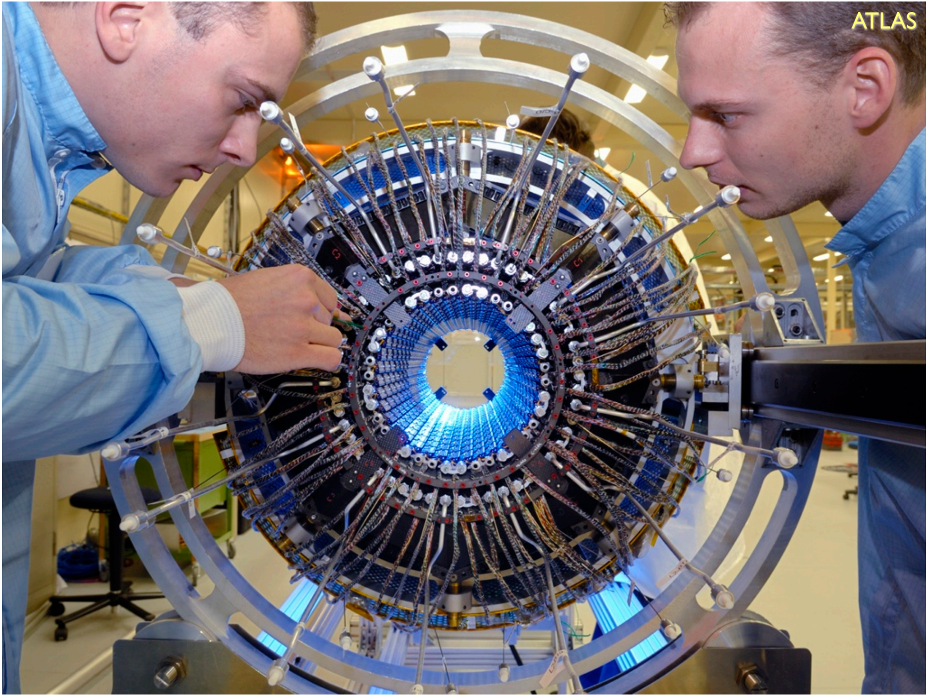
Abstract

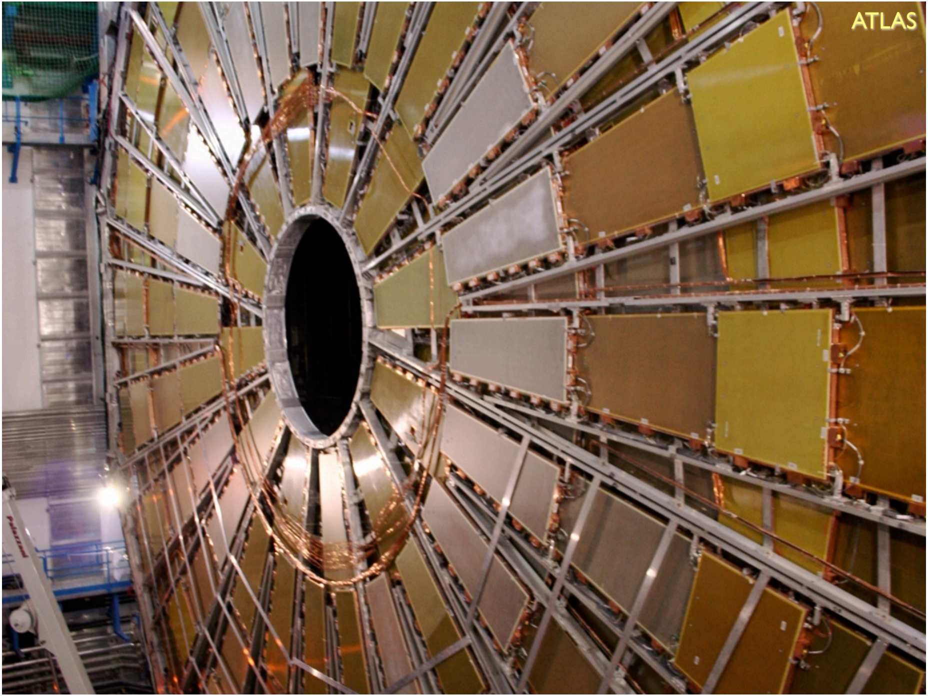
This article is devoted to the status of the electroweak theory on the eve of experimentation at CERN's Large Hadron Collider (LHC). A compact summary of the logic and structure of the electroweak theory precedes an examination of what experimental tests have established so far. The outstanding unconfirmed prediction is the existence of the Higgs boson, a weakly interacting spin-zero agent of electroweak symmetry breaking and the giver of mass to the weak gauge bosons, the quarks, and the leptons. General arguments imply that the Higgs boson or other new physics is required on the 1-TeV energy scale.

Even if a "standard" Higgs boson is found, new physics will be implicated by many questions about the physical world that the Standard Model cannot answer. Some puzzles and possible resolutions are recalled. The LHC moves experiments squarely into the 1-TeV scale, where answers to important outstanding questions will be found.

505


ATLAS
MPI - MÜNCHEN
20


ATLAS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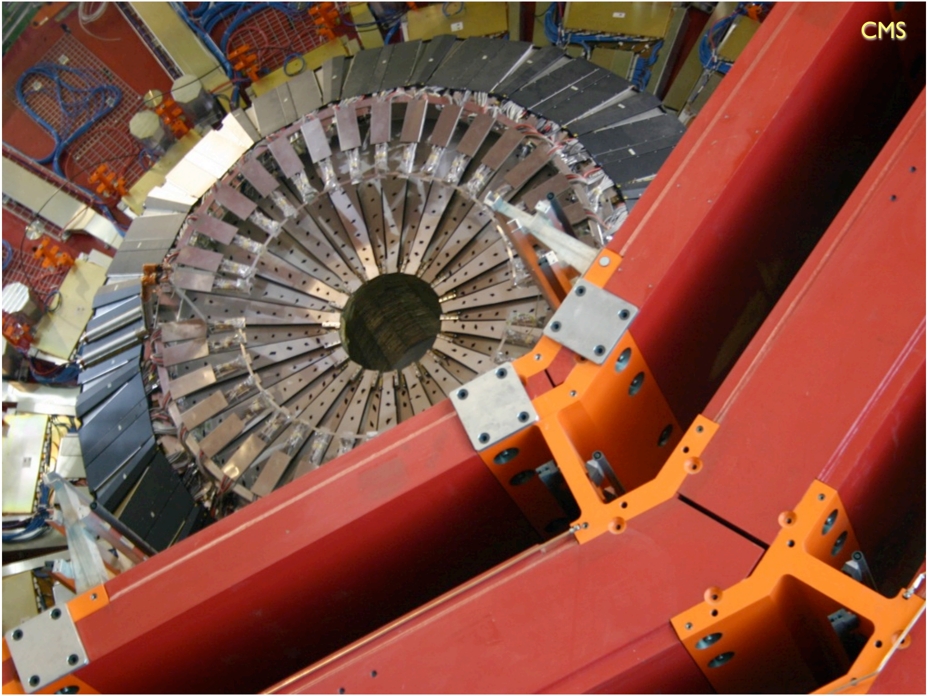
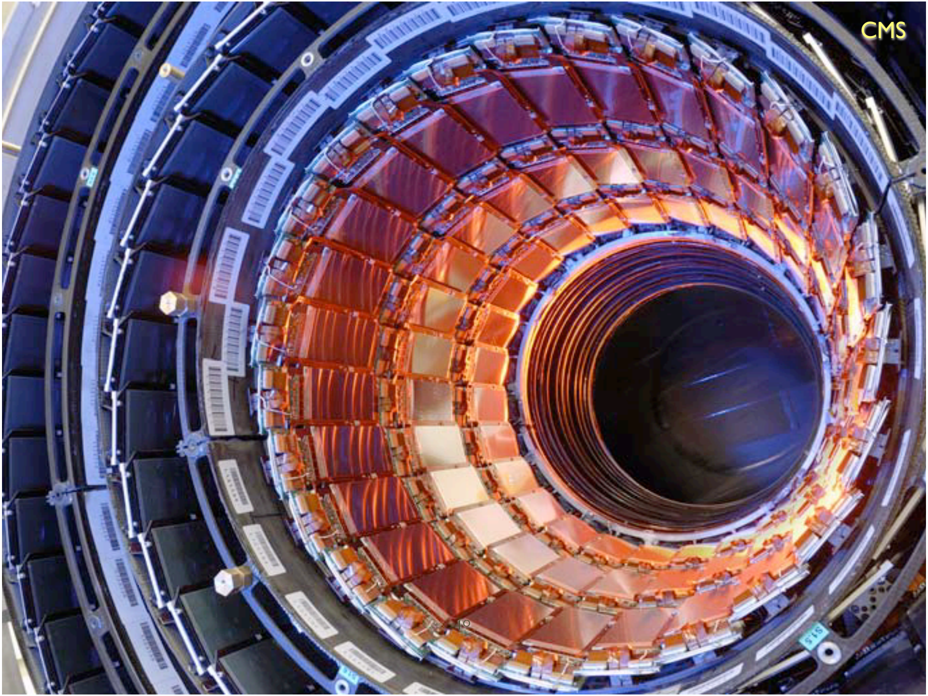

CMS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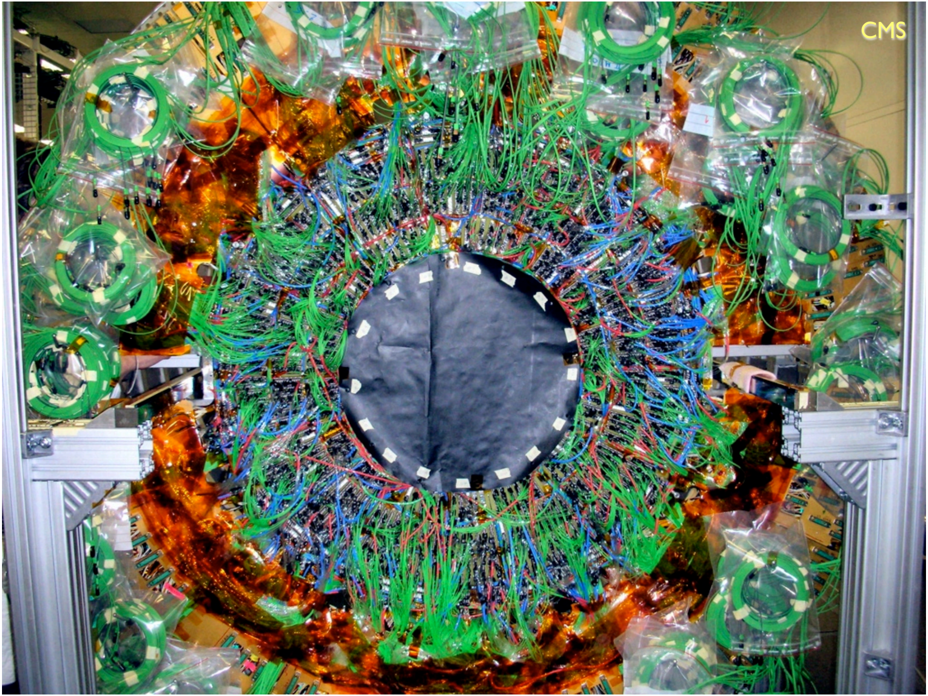
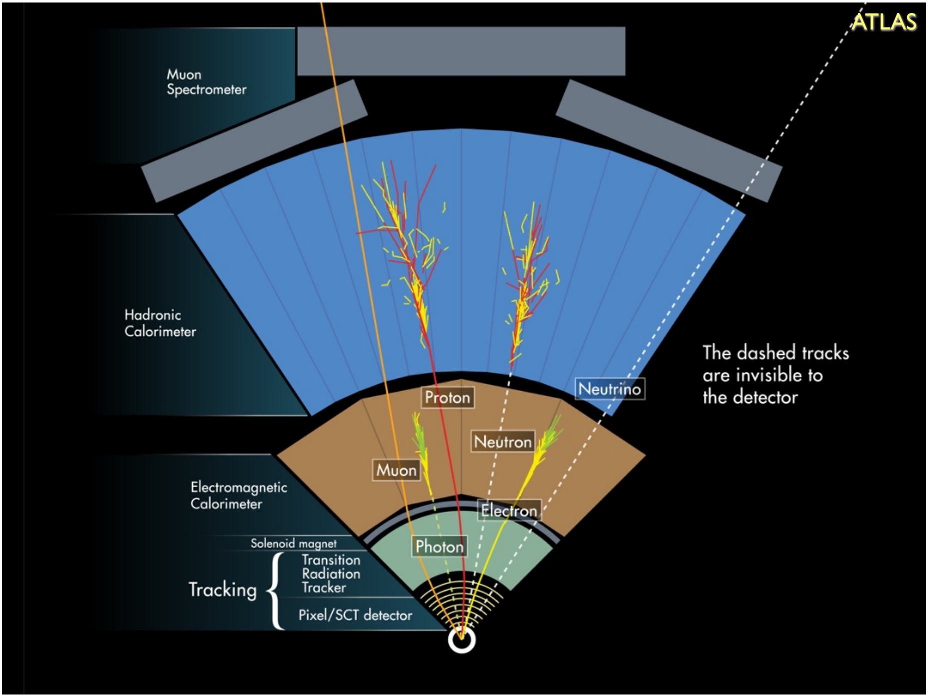

CMS

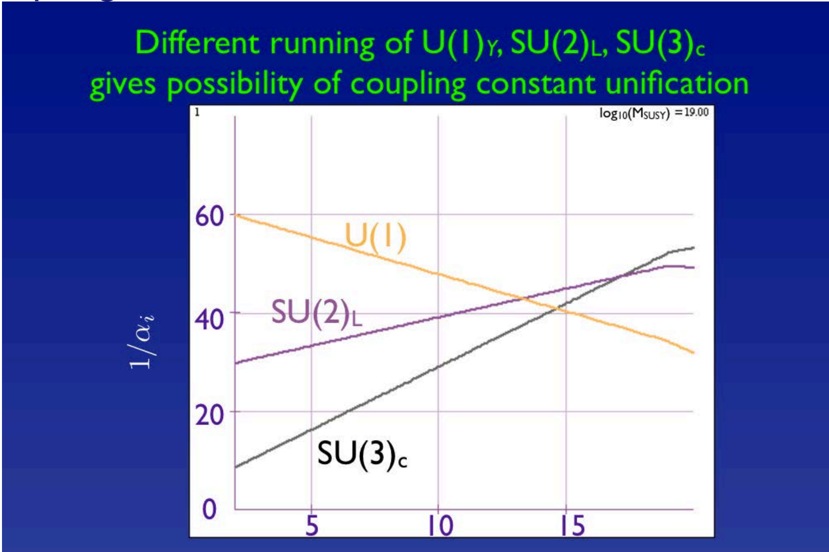

ATLAS
Muon
Spectrometer
Hadronic
Calorimeter
Electromagnetic
Calorimeter
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT detector
Proton
Neutrino
Neutron
Muon
Electron
Photon
The dashed tracks
are invisible to
the detector

Exercise 5

Explain the response of the ATLAS detector to different particle species, as shown in the graphic on the preceding page.

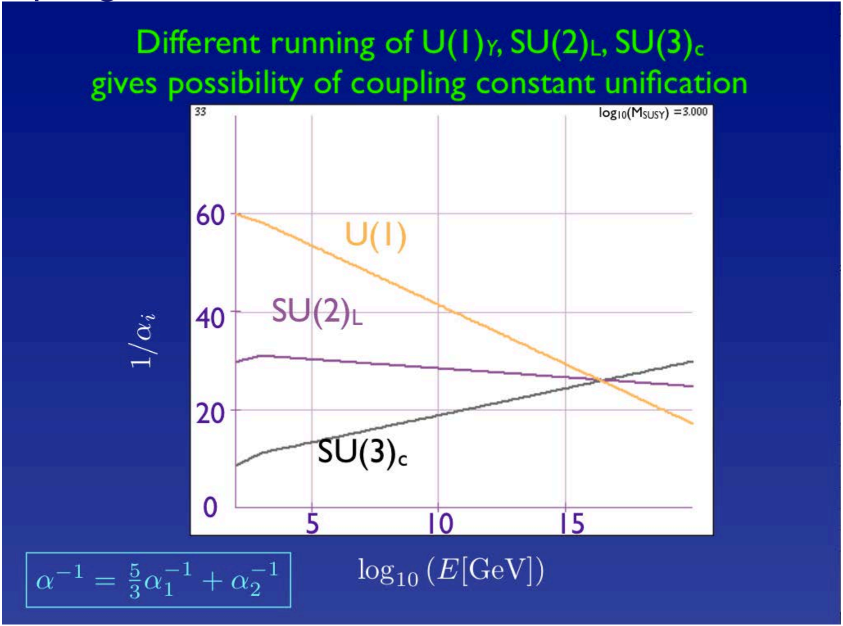
An interactive slice through the CMS detector animates the response to five particle types.

Coupling-constant Unification



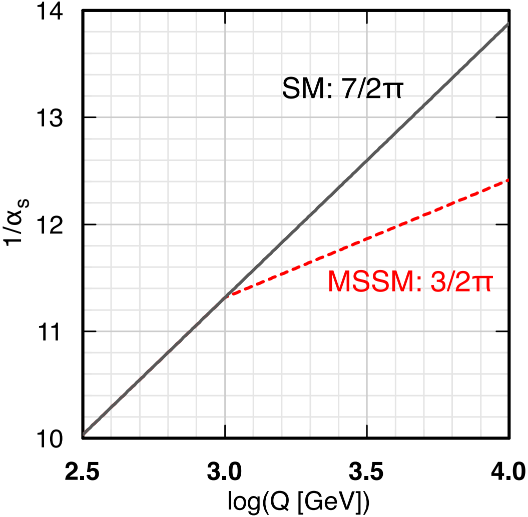
$$\alpha^{-1} = \frac{5}{3}\alpha_1^{-1} + \alpha_2^{-1}$$

Coupling-constant Unification



Can LHC See Change in Evolution?

Sensitive to new colored particles



(sharp threshold illustrated)

. . . also for $\sin^2\theta_W$