FERMILAB-CERN
HADRON COLLIDER PHYSICS
Summer School 2014

The Standard Model:

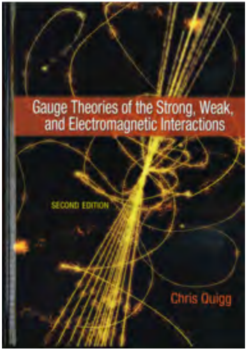
Current Status & Open Questions

Chris Quigg

Fermilab

Tentative Outline

1. Why Hadron Colliders? What Is a Proton?
2. Constructing the Electroweak Theory
3. Validating the Electroweak Theory
4. The Higgs Boson and Beyond



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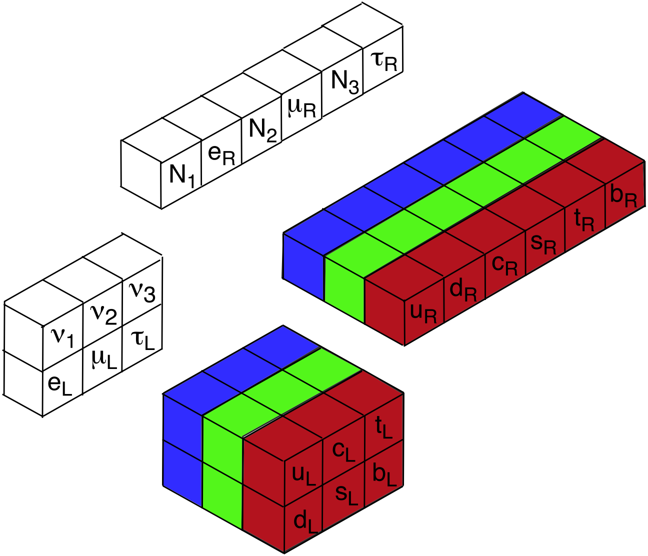
Our Conception of Matter—the Nanoworld

If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis that all things are made of atoms — little particles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another. In that one sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied.

— R. P. Feynman, *The Feynman Lectures on Physics*

Our Conception of Matter—the Nanonanoworld



Our Conception of Matter—the Attoworld

Pointlike constituents ($r < 10^{-18}$ m)

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$$

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

Few fundamental forces, derived from gauge symmetries

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$$

Electroweak symmetry breaking: Higgs mechanism?

Problem 1

In the spirit of Feynman's characterization of the atomic hypothesis, compose a sentence that expresses the "enormous amount of information about the world" captured in the standard model of particle physics, "if just a little imagination and thinking are applied."

Why Hadron Colliders? $\rightsquigarrow$ Eric Prebys Lectures

Discovery machines

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

Precision instruments

M_W, m_t, 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:

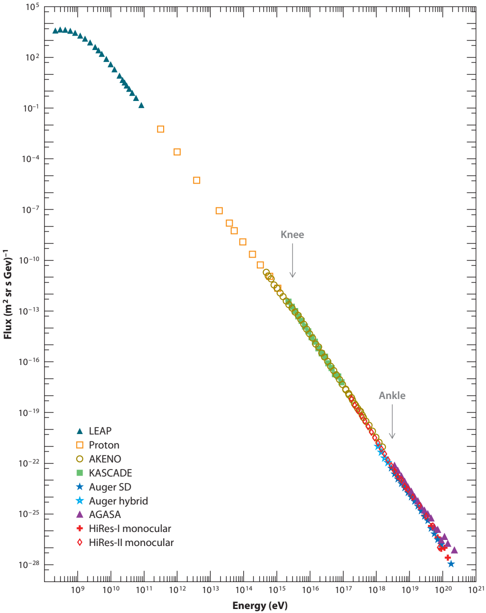
$$(q_i, \bar{q}_i, g, \gamma, W^\pm, Z, \ldots) \otimes (q_j, \bar{q}_j, g, \gamma, W^\pm, Z, \ldots)$$

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

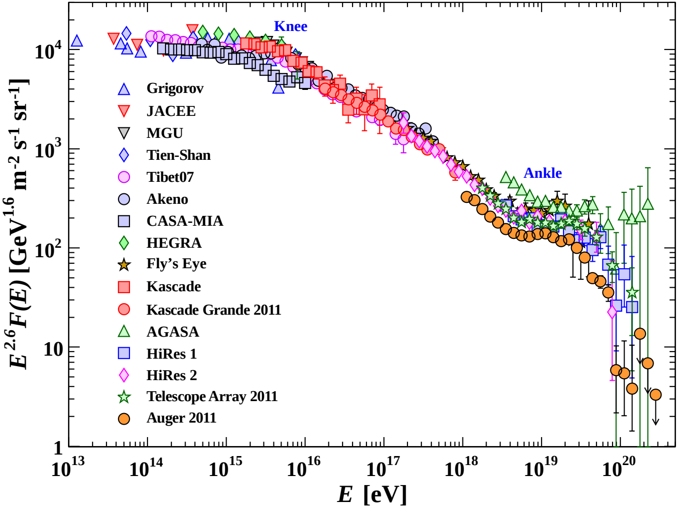
If 3 quarks share half the proton's momentum ($\langle x \rangle = \frac{1}{6}$),
require pp collisions at $\sqrt{s} = 6$ TeV

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

Cosmic-ray Spectrum

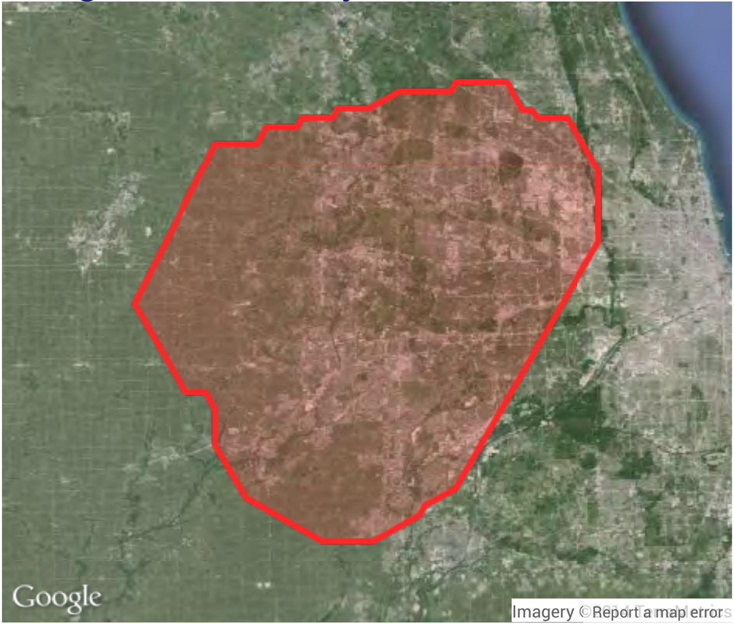


Cosmic-ray Spectrum



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

Pierre Auger Observatory over Fermilab



Some Great Cosmic-Ray Observatories

$$E > 10^{19}\ \text{eV: } 1\ \text{km}^{-2}\ \text{century}^{-1}$$

Pierre Auger Observatory (Mendoza, Argentina):
~ 3000 km^2 array of 1600 shower detectors plus 4 atmospheric fluorescence detectors

Telescope Array (Utah, USA):
~ 750 km^2 array of 500 scintillation detectors plus 3 atmospheric fluorescence telescopes

Problem 2

Plot the correspondence between c.m. energy, $\sqrt{s}$, and fixed-target beam momentum, p_{lab}, for pp collisions over the range $10\ \mathrm{GeV} \le \sqrt{s} \le 100\ \mathrm{TeV}$. Note in particular the values of p_{lab} that correspond to $\sqrt{s} = 8, 14, 100$ TeV.

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) $\rightsquigarrow$

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

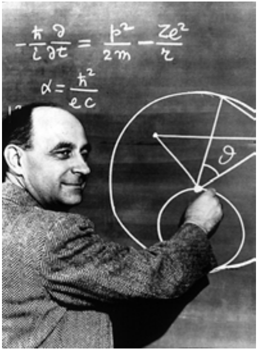
$$\approx \tfrac{1}{12}\ \text{size of Moon's orbit}$$

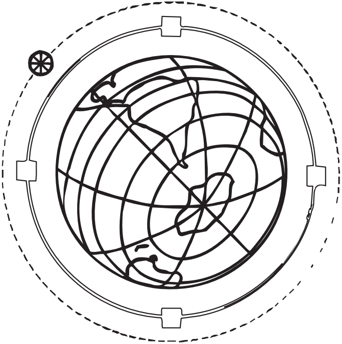
10-tesla field reduces the accelerator to mere Earth size ($R_\oplus = 6.4 \times 10^3$ km).

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 (anti)protons.
- 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.
- An Even Bigger Collider?

High-energy collider parameters, 2012 *Review of Particle Properties* §28

Tevatron: $\bar{p}p$ at $\sqrt{s} = 1.96$ TeV

Large Hadron Collider at CERN

Competing technologies?

- None for quark–gluon interactions
- None for highest energies (derate composite protons)
- Lepton–lepton collisions: LEP ($\sqrt{s} \approx 0.2$ TeV) was the last great electron synchrotron?

  Synchrotron radiation $\Rightarrow$ linear colliders for higher $\sqrt{s}$
  $\rightsquigarrow$ International Linear Collider

  - Challenge to reach 1 TeV; $\mathcal{L}$ *a great challenge*
  - Can we surpass 1 TeV? CLIC, . . .

Competing technologies?

- Lepton–hadron collisions: HERA ($e^{\pm}p$) as example; energy intermediate between e^+e^-, pp

  $e^{\pm}(u, d)$ leptoquark channel, proton structure, γp

  High $\mathcal{L}$ a challenge: beam profiles don't match

  (Far) future: $\mu^{\pm}p$ collider?

- Heavy-ion collisions: RHIC the prototype; LHC (relatively) modest energy per nucleon; quark-gluon plasma; new phases of matter

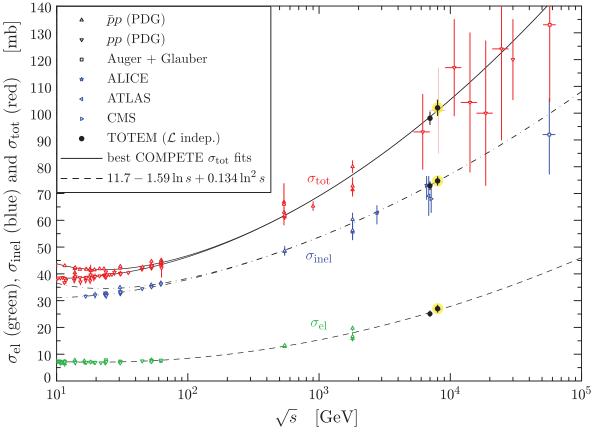
Unorthodox projectiles?

- $\gamma\gamma$ Collider: Backscattered laser beams; enhancement of linear collider capabilities
- $\mu^+\mu^-$ collider: Advantage of elementary particle, disadvantage of muon decay (2.2μs).

  Small ring to reach very high effective energies?

  Muon storage ring (neutrino factory) would turn bug into feature!

$p^{\pm}p$ Interaction Rates

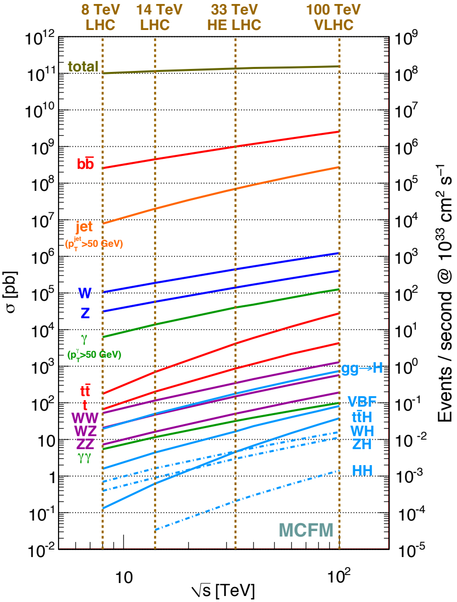


σ_{tot}	(101.7 ± 2.9) mb
σ_{inel}	(74.7 ± 1.7) mb
σ_{el}	(27.1 ± 1.4) mb

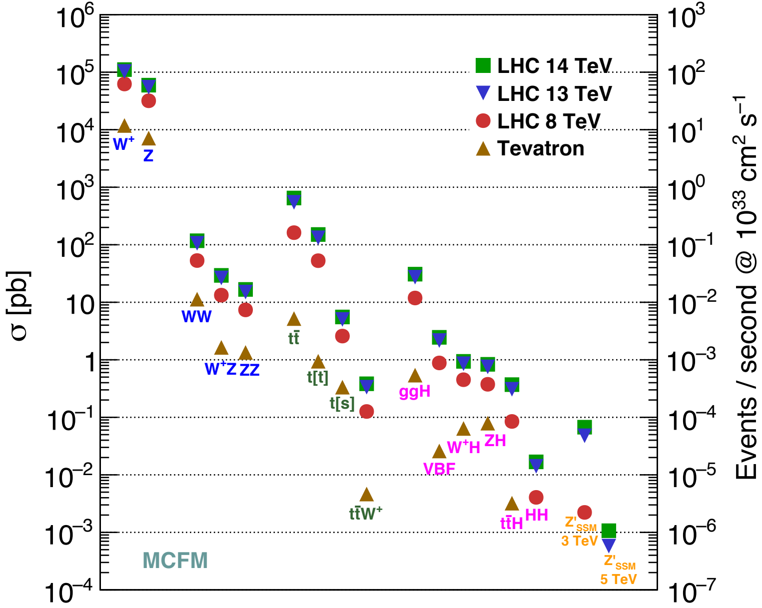
$\sigma_{\text{tot}} \approx 10^{11}$ pb

TOTEM

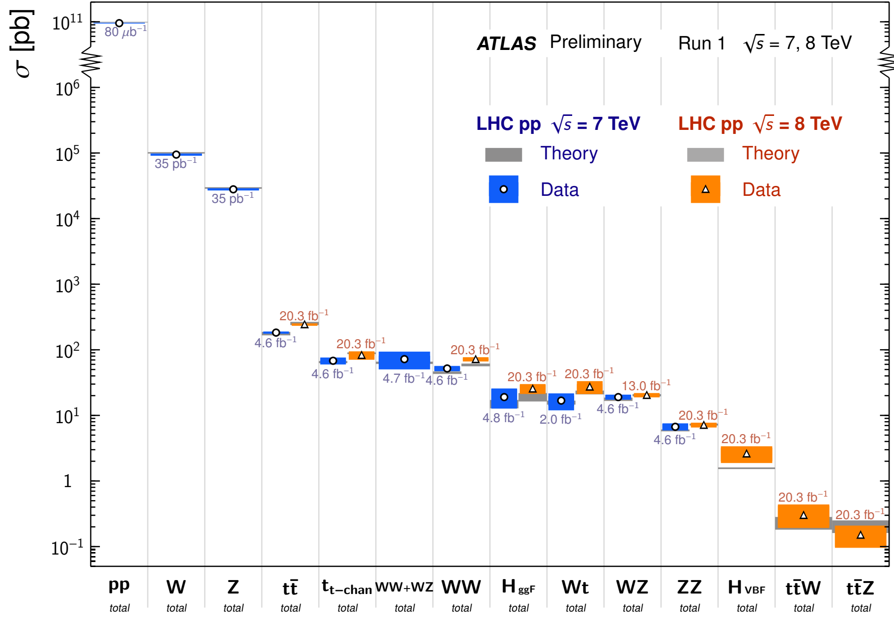
Collider Cross Sections



Standard-model Cross Sections



Standard-model Cross Sections



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:

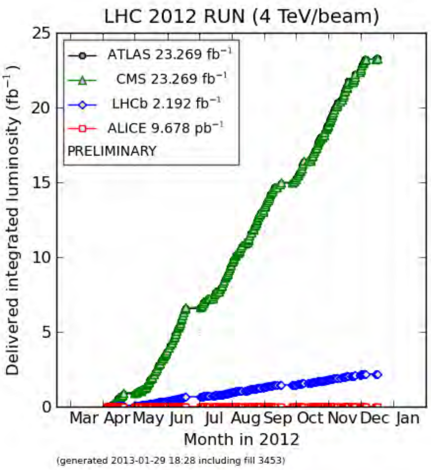
$$\mathcal{L}(t) = f\,\frac{n_1 n_2}{4\pi\sigma_x\sigma_y}$$

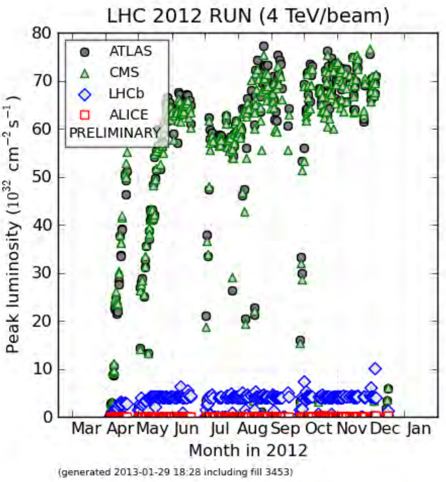
$\sigma_{x,y}$: Gaussian rms $\perp$ beam sizes

Edwards & Syphers, 2012 *Review of Particle Physics*, §27

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

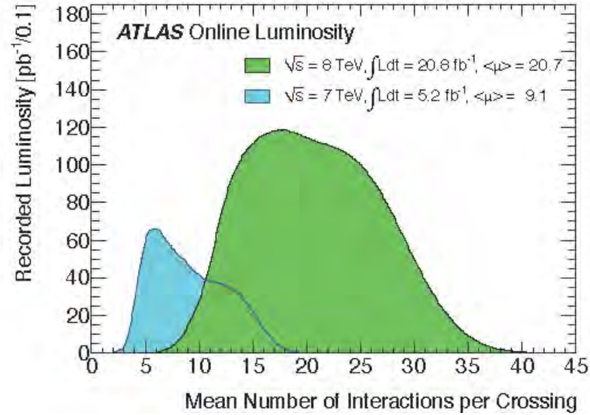
LHC Luminosity Growth





$1400 \otimes 1400$ bunches cross every 50 ns (25 ns in future?)

High Luminosity and Pileup



Problem 3

(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 *Review of Particle Physics.*

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

$$\text{Hard scattering } \sigma \propto 1/\hat{s} \rightsquigarrow \mathcal{L} \propto \hat{s}$$

What Is a Proton?

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

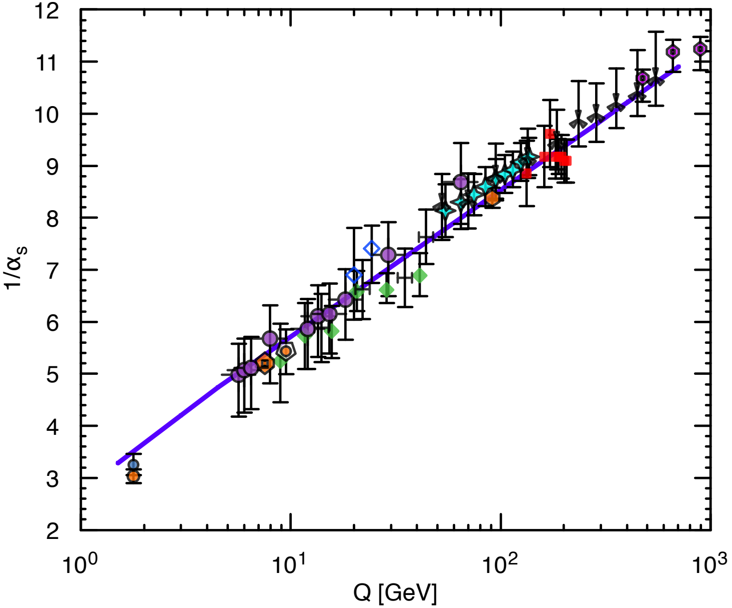
$$f_i^{(a)}(x_a, Q^2),$$

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

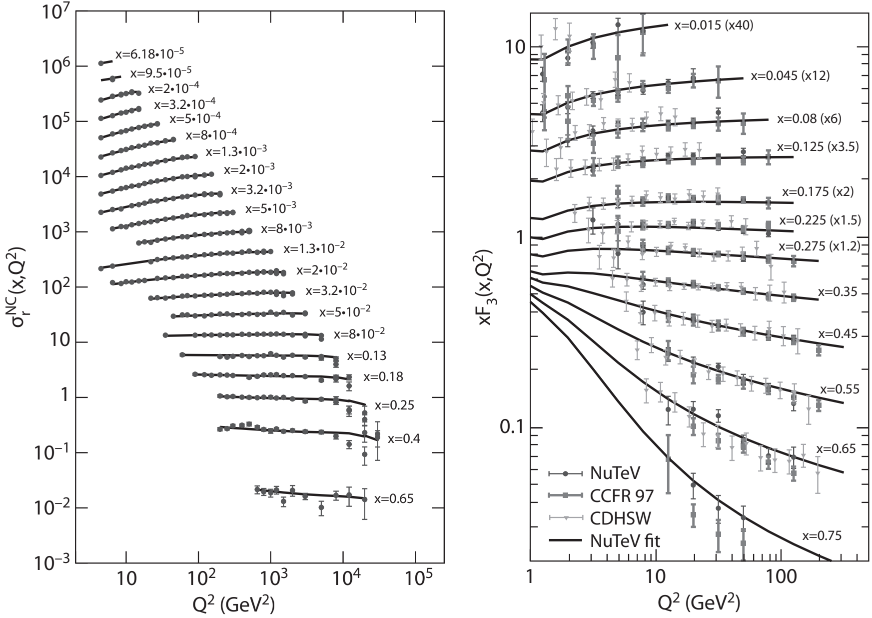
Q^2 evolution given by QCD perturbation theory

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

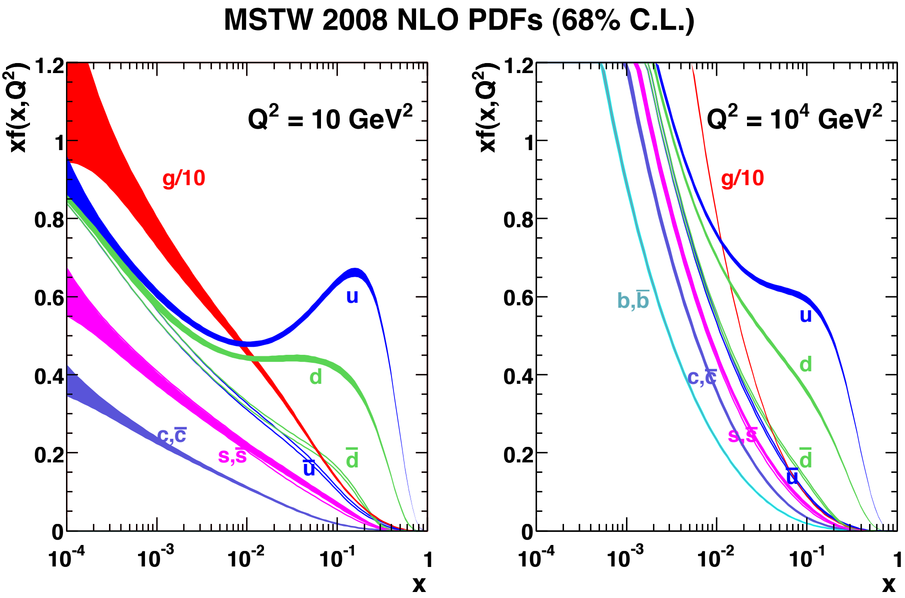
Evolution of the Strong Coupling Constant



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



What Is a Proton?



Parton Distribution Functions Literature

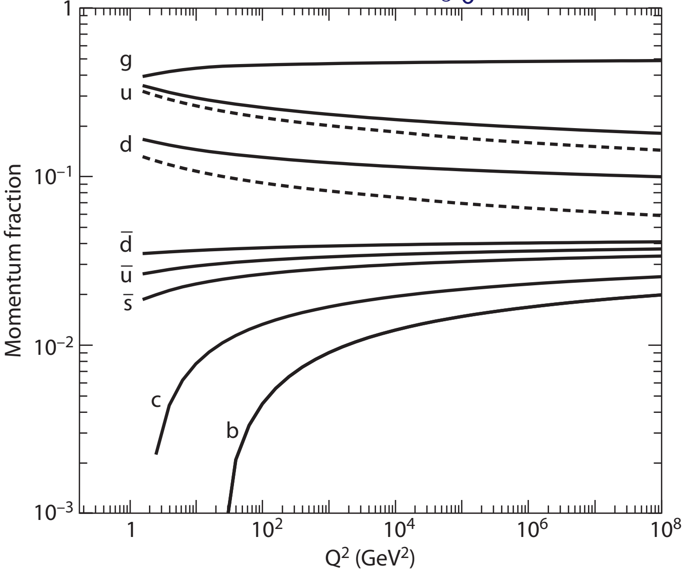
The state of the art is reviewed in A. De Roeck & R. S. Thorne, *Prog. Part. Nucl. Phys.* **66**, 727 (2011).

Recommendations and assessments of uncertainties are given by the PDF4LHC Working Group.

Convenient access to many sets of parton distributions is available through the Durham HEPData Project Online.

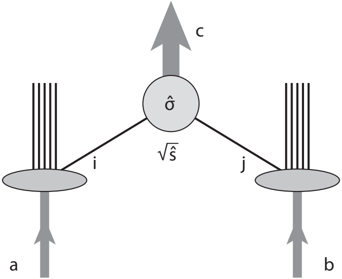
A common interface to many modern sets of PDFs is M. R. Whalley & A. Buckley, "LHAPDF: the Les Houches Accord Parton Distribution Function Interface."

Flavor Content of the Proton: $\int_0^1 dx\, x\, f_i(x, Q^2)$



Asymptotic limit ($Q^2 \to \infty$): $g : \frac{8}{17}$; $q_s : \frac{3}{68}$; $q_v : 0$

Hard-scattering cross sections



$$d\sigma(a+b\to c+X) \;=\; \sum_{ij}\int dx_a dx_b\,\delta(\tau - x_a x_b)\cdot$$

$$f_i^{(a)}(x_a,Q^2)f_j^{(b)}(x_b,Q^2)d\hat{\sigma}(i+j\to c+X),$$

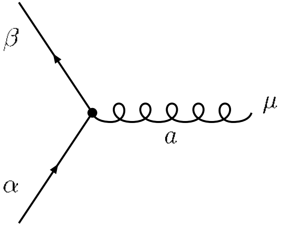
$d\hat{\sigma}$: elementary cross section at energy $\sqrt{\hat{s}} = \sqrt{x_a x_b s}$ $(\tau = \hat{s}/s)$

Example Leading-Order Calculation

Compute the differential cross section $d\sigma/dt$ for the elementary reaction $ud \to ud$, neglecting quark masses. Show that

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

where $\hat{s}, \hat{t}, \hat{u}$ are the usual Mandelstam invariants for the parton-parton collision.



$$-\frac{ig}{2}(\lambda^a)_{\alpha\beta}\gamma_\mu$$

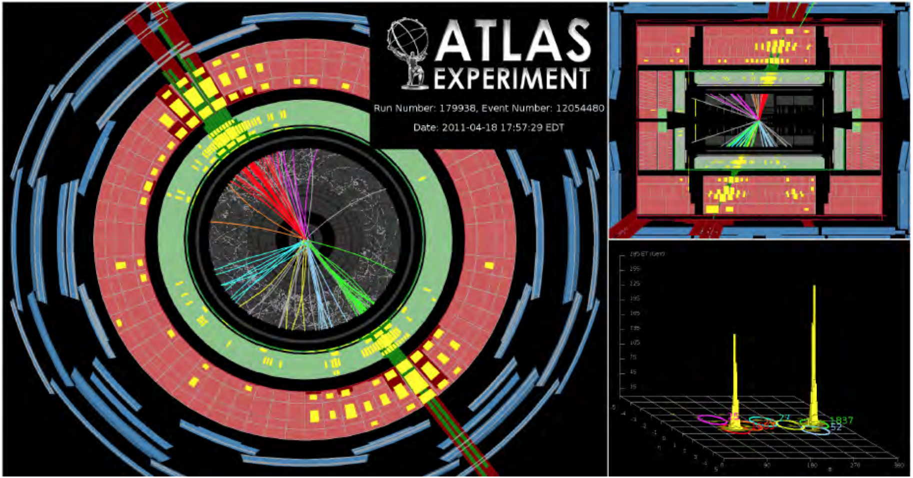
Problem 4

(a) Express the *ud* $\to$ *ud* cross section in terms of c.m. angular variables, and note that the angular distribution is reminiscent of that for Rutherford scattering, $d\sigma/d\Omega^* \propto 1/\sin^4(\theta^*/2)$.

(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.

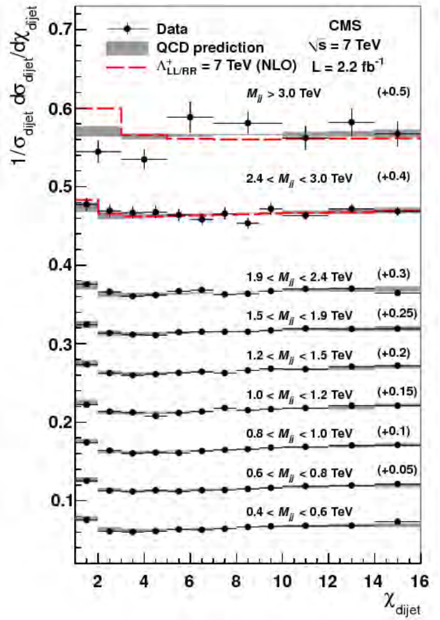
(c) The rapidity variable, $y = \frac{1}{2}\ln[(E+p_z)/(E-p_z)]$, is useful in the study of high-energy collisions because it shifts simply under Lorentz boosts. Show that in the extreme relativistic limit, measuring the jet rapidities in the reaction $p^{\pm}p \to$ jet$_1$ + jet$_2$ leads directly to a determination of the variable χ for parton-parton scattering as $\chi = \exp(y_1 - y_2)$. For early LHC studies, see G. Aad *et al.* [ATLAS Collaboration], *Phys. Lett. B* **694**, 327 (2011); V. Khachatryan *et al.* [CMS Collaboration], *Phys. Rev. Lett.* **106,** 201804 (2011).

Probing Elementarity



$E_{\perp}$: 1.8 TeV + 1.8 TeV · Dijet mass: 4 TeV

Probing Elementarity



Physics Potential versus Energy

LHC Physics Potential *vs.* Energy

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Parton luminosities are convenient for estimating how the physics potential of Large Hadron Collider experiments depends on the energy of the proton beams. I present parton luminosities, ratios of parton luminosities, and contours of fixed parton luminosity for gg, $u\bar{d}$, and qq interactions over the energy range relevant to the Large Hadron Collider, along with example analyses for specific processes.

LHC Physics Potential *vs.* Energy: Considerations for the 2011 Run

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Parton luminosities are convenient for estimating how the physics potential of Large Hadron Collider experiments depends on the energy of the proton beams. I quantify the advantage of increasing the beam energy from 3.5 TeV to 4 TeV. I present parton luminosities, ratios of parton luminosities, and contours of fixed parton luminosity for gg, $u\bar{d}$, qq, and gq interactions over the energy range relevant to the Large Hadron Collider, along with example analyses for specific processes. This note extends the analysis presented in Ref. [1]. Full-size figures are available as pdf files at lutece.fnal.gov/PartonLum11/.

EHLQ, *Rev. Mod. Phys.* **56**, 579 (1984)

Ellis, Stirling, Webber, *QCD & Collider Physics*

MRSW08NLO examples + RKE Lecture 3, SUSSP 2009

Full-page figures: lutece.fnal.gov/PartonLum11

High-energy p: broadband unseparated beam of q, $\bar{q}$, g

Parton Luminosities + Prior Knowledge = Answers

Taking into account $1/\hat{s}$ behavior of hard scattering,

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

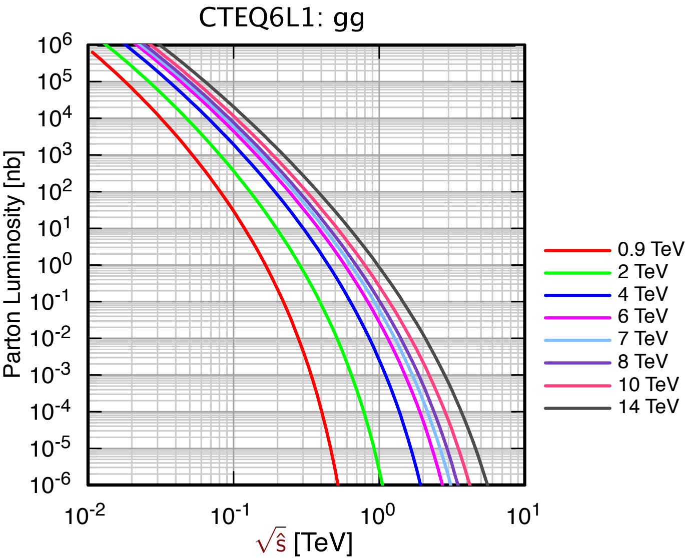
is a convenient measure of parton ij luminosity.

$$f_i^{(a)}(x)\text{: pdf;} \quad \tau = \hat{s}/s$$

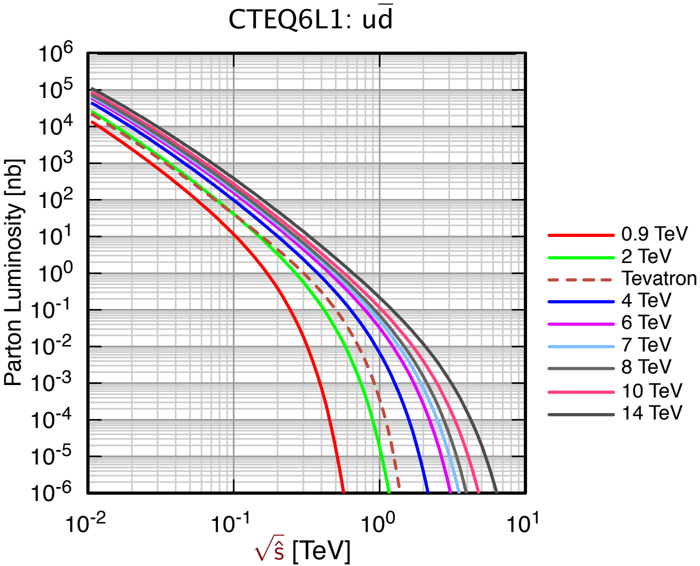
$$\sigma(s) = \sum_{\{ij\}}\int_{\tau_0}^{1}\frac{d\tau}{\tau}\cdot\frac{\tau}{\hat{s}}\frac{d\mathcal{L}_{ij}}{d\tau}\cdot[\hat{s}\hat{\sigma}_{ij}(\hat{s})]$$

EHLQ §2; *QCD & Collider Physics*, §7.3

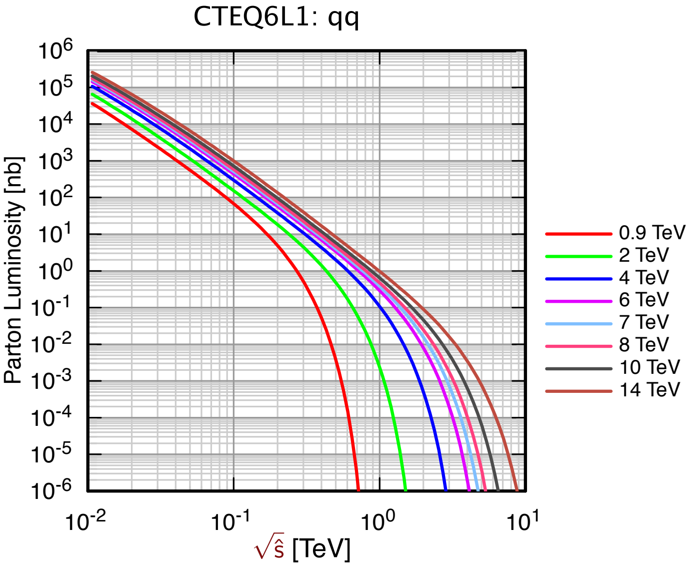
Parton Luminosity



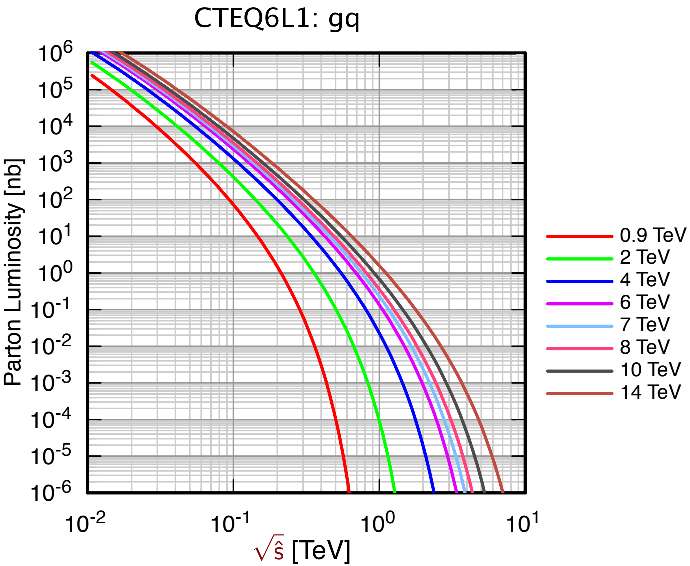
Parton Luminosity



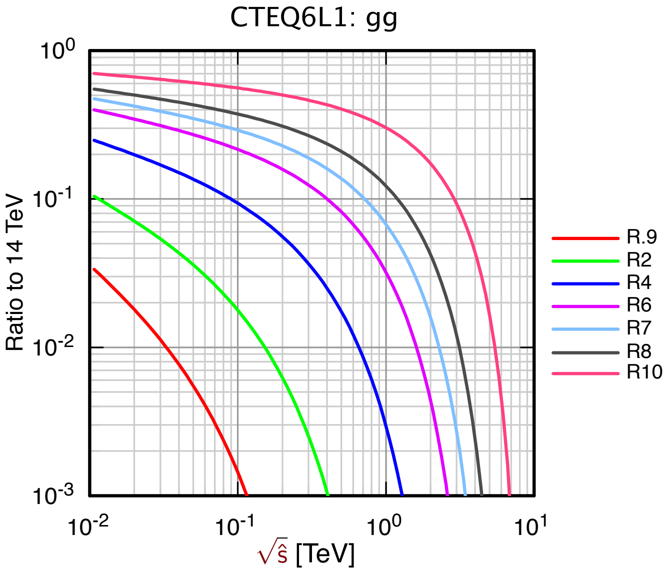
Parton Luminosity (light quarks)



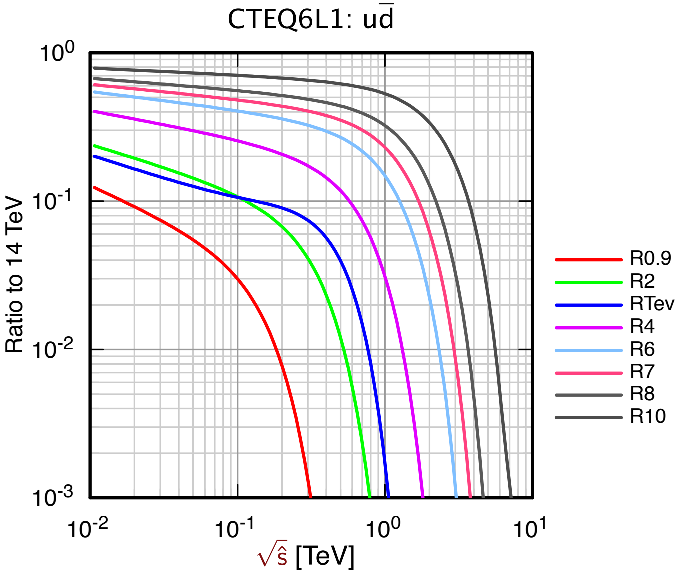
Parton Luminosity (gluon–light quarks)



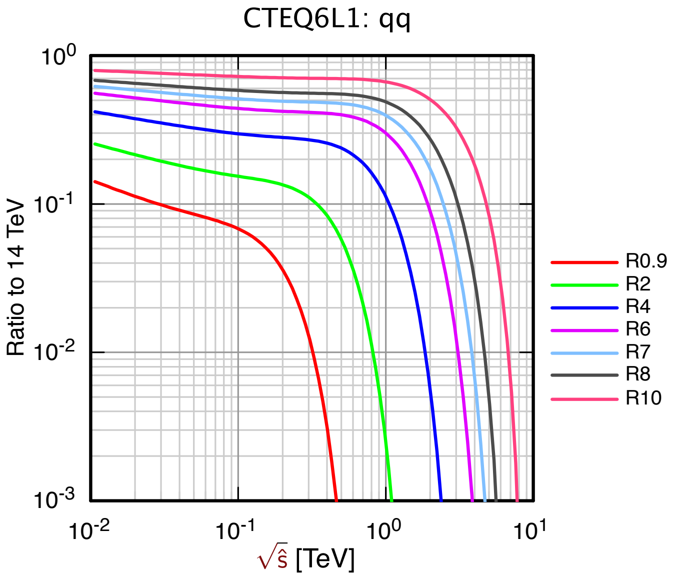
Luminosity Ratios



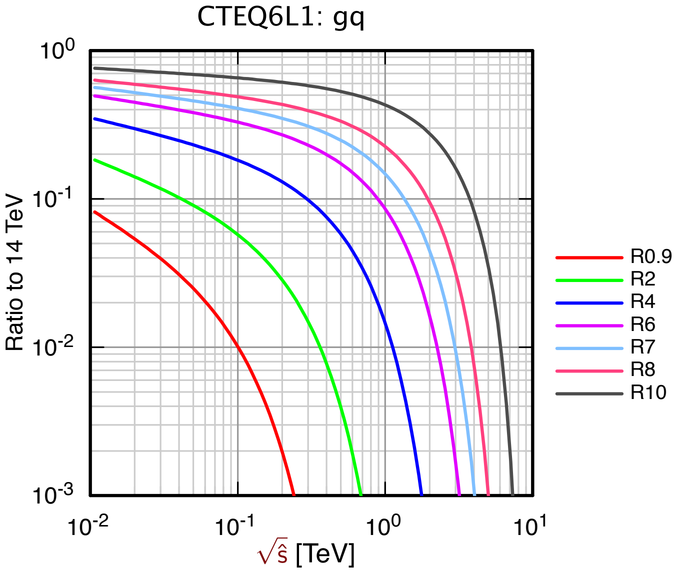
Luminosity Ratios



Luminosity Ratios



Luminosity Ratios



Problem 5

(a) Referring to the gg luminosity ratios, estimate the increased yield of $H(125)$ at 14 TeV compared with 8 TeV.

(b) Referring to the $u\bar{d}$ luminosity ratios, estimate the increased yield of $W'(2\text{ TeV})$ and $W'(4\text{ TeV})$ at 14 TeV compared with 8 TeV.

(c) Referring to the qq luminosity ratios, estimate the increased yield of dijets at $\sqrt{\hat{s}} = 2$ TeV and $\sqrt{\hat{s}} = 4$ TeV at 14 TeV compared with 8 TeV.

(d) Compare your estimates with the explicit Standard-model Cross Sections calculated using MCFM.