LAL Cours d'automne 2009

Potential Discoveries at the Large Hadron Collider

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Fermilab

Lecture 2: Exploring the New Landscape

- More on the Electroweak Theory
- Early Running
- Physics Potential *vs.* Energy

Stability bounds

Quantum corrections to $V(\varphi^\dagger\varphi) = \mu^2(\varphi^\dagger\varphi) + |\lambda|\,(\varphi^\dagger\varphi)^2$

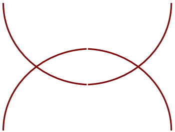
Triviality of scalar field theory bounds M_H from above

- Only *noninteracting* scalar field theories make sense on all energy scales
- Quantum field theory vacuum is a dielectric medium that screens charge
- $\Rightarrow$ *effective charge* is a function of the distance or, equivalently, of the energy scale

running coupling constant

Bounding M_H from above ...

In $\lambda\phi^4$ theory, calculate variation of coupling constant λ in perturbation theory by summing bubble graphs



$\lambda(\mu)$ is related to a higher scale Λ by

$$\frac{1}{\lambda(\mu)} = \frac{1}{\lambda(\Lambda)} + \frac{3}{2\pi^2}\log\left(\Lambda/\mu\right)$$

(Perturbation theory reliable only when λ is small, lattice field theory treats strong-coupling regime)

Bounding M_H from above . . .

For stable Higgs potential (*i.e.*, for vacuum energy not to race off to $-\infty$), *require* $\lambda(\Lambda) \geq 0$

Rewrite RGE as an inequality

$$\frac{1}{\lambda(\mu)} \geq \frac{3}{2\pi^2} \log\left(\Lambda/\mu\right)$$

. . . implies an *upper bound*

$$\boxed{\lambda(\mu) \leq 2\pi^2/3 \log\left(\Lambda/\mu\right)}$$

Bounding M_H from above . . .

If we require the theory to make sense to arbitrarily high energies—or short distances—then we must take the limit $\Lambda \to \infty$ while holding μ fixed at some reasonable physical scale. In this limit, the bound forces $\lambda(\mu)$ to zero.

$\longrightarrow$ free field theory "trivial"

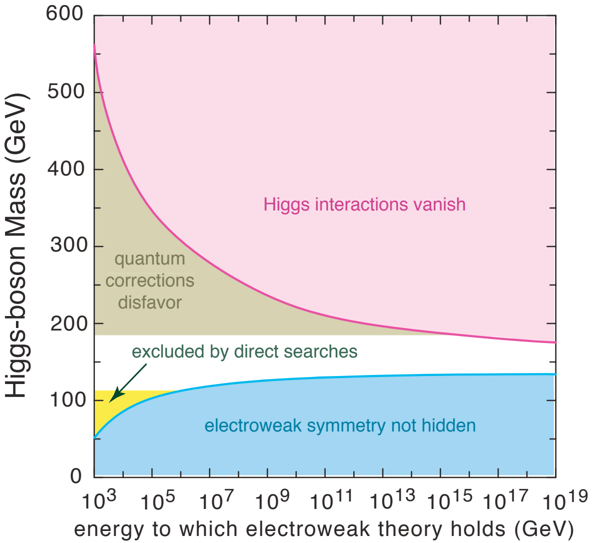
Rewrite as bound on M_H:

$$\Lambda \leq \mu \exp\left(\frac{2\pi^2}{3\lambda(\mu)}\right)$$

Choose $\mu = M_H$, and recall $M_H^2 = 2\lambda(M_H)v^2$

$$\boxed{\Lambda \leq M_H \exp\left(4\pi^2 v^2 / 3M_H^2\right)}$$

Bounding M_H from above . . .



Bounding M_H from above . . .

Moral: For any M_H, there is a *maximum energy scale* $\Lambda^\star$ at which the theory ceases to make sense.

The description of the Higgs boson as an elementary scalar is at best an effective theory, valid over a finite range of energies

Perturbative analysis breaks down when $M_H \to 1\ \text{TeV}/c^2$ and interactions become strong

Lattice analyses $\Longrightarrow$ $M_H \lesssim 710 \pm 60$ GeV if theory describes physics to a few percent up to a few TeV

If $M_H \to 1$ TeV EW theory lives on brink of instability

Requiring $V(v) < V(0)$ gives *lower* bound on M_H

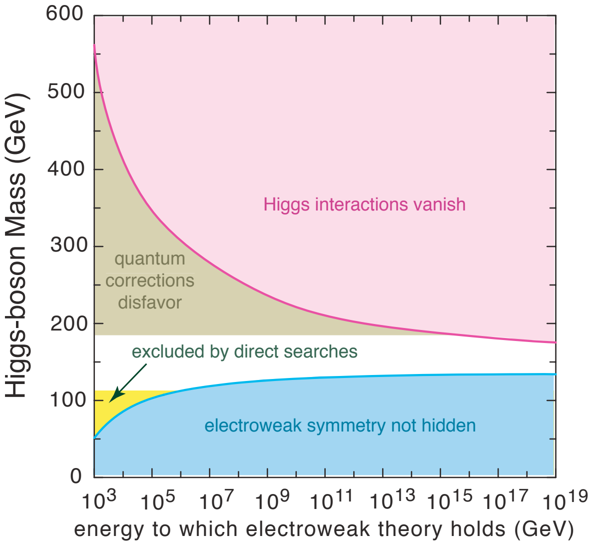
Requiring that $\langle\phi\rangle_0 \neq 0$ be an absolute minimum of the one-loop potential up to a scale Λ yields the vacuum-stability condition . . . (for $m_t \lesssim M_W$)

$$M_H^2 > \frac{3G_F\sqrt{2}}{8\pi^2}(2M_W^4 + M_Z^4 - 4m_t^4)\log(\Lambda^2/v^2)$$

(No illuminating analytic form for heavy m_t)

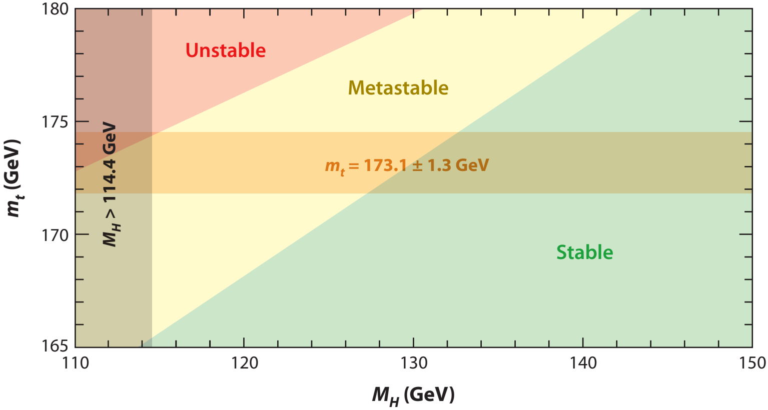
If Higgs boson is relatively light (which would require explanation) then theory can be self-consistent up to very high energies

Consistent to M_{Planck} if 134 GeV $\lesssim M_H \lesssim$ 177 GeV



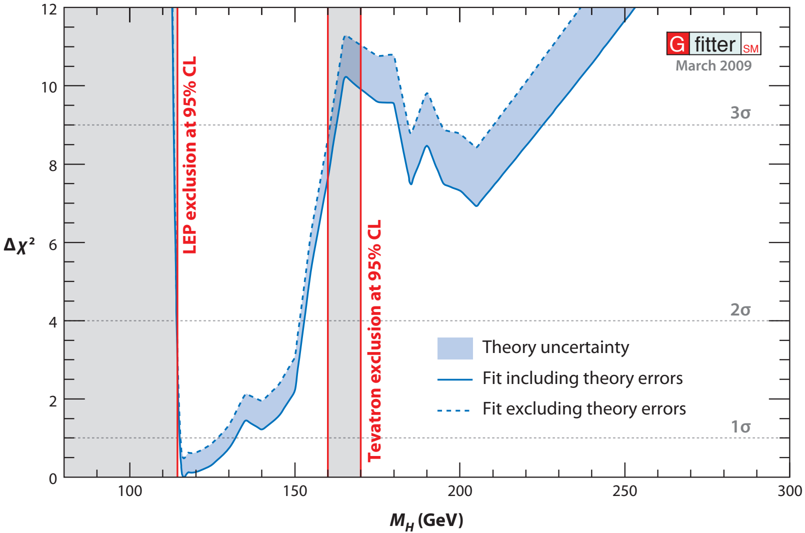
Living on the Edge?

Require cosmological tunneling time, not absolute stability

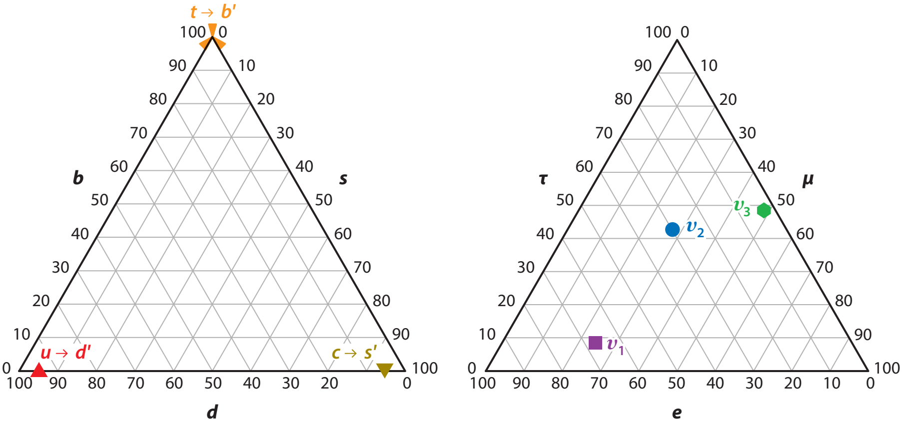


Isidori, et al., hep-ph/0104016

Electroweak theory projection
Global fit + exclusions



The Problem of Identity
Quark and Lepton Mixing



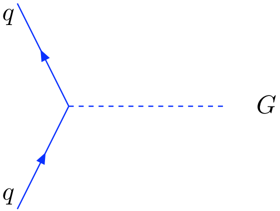
What makes a top quark a top quark, . . . ?

Why is empty space so nearly massless?

Natural to neglect gravity in particle physics . . .

Gravitational *ep* interaction $\approx 10^{-41} \times$ EM

$$G_{\text{Newton}}\ \textit{small} \iff M_{\text{Planck}} = \left(\frac{\hbar c}{G_{\text{Newton}}}\right)^{\frac{1}{2}} \approx 1.22 \times 10^{19}\ \text{GeV}\ \textit{large}$$



$$\sim \frac{E}{M_{\text{Planck}}}$$

$$\text{Estimate } B(K \to \pi G) \sim \left(\frac{M_K}{M_{\text{Planck}}}\right)^2 \sim 10^{-38}$$

But gravity is not always negligible . . .

The vacuum energy problem

$$\text{Higgs potential } V(\varphi^\dagger\varphi) = \mu^2(\varphi^\dagger\varphi) + |\lambda|\,(\varphi^\dagger\varphi)^2$$

At the minimum,

$$V(\langle\varphi^\dagger\varphi\rangle_0) = \frac{\mu^2 v^2}{4} = -\frac{|\lambda|\,v^4}{4} < 0.$$

$$\text{Identify } M_H^2 = -2\mu^2$$

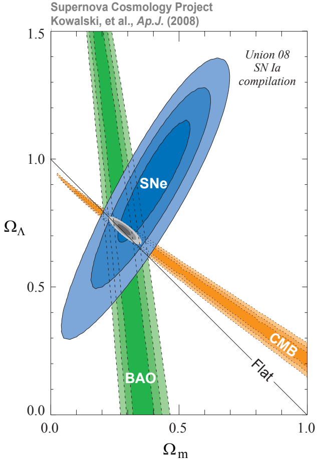
$V \neq 0$ contributes position-independent vacuum energy density

$$\boxed{\varrho_H \equiv \frac{M_H^2 v^2}{8} \geq 10^8\ \text{GeV}^4} \quad \approx 10^{24}\ \text{g cm}^{-3}$$

Adding vacuum energy density $\varrho_{\text{vac}} \Leftrightarrow$ adding cosmological constant Λ to Einstein's equation

$$R_{\mu\nu} - \tfrac{1}{2}Rg_{\mu\nu} = \frac{8\pi G_{\text{N}}}{c^4}T_{\mu\nu} + \Lambda g_{\mu\nu} \qquad \Lambda = \frac{8\pi G_{\text{N}}}{c^4}\varrho_{\text{vac}}$$

Observed $\varrho_{\text{vac}} \lesssim 10^{-46}\ \text{GeV}^4$



$\varrho_H \gtrsim 10^8\ \text{GeV}^4$: mismatch by 10^{54}

A chronic dull headache for thirty years . . .

Lecture 2: Exploring the New Landscape
Early Running

CLNS-131
November 1970
September 1973

(<u>Preliminary Version</u>)

Some Experiments on Multiple Production*

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Ithaca, New York 14850

A program of experiments is described mainly on secondary particle spectra to test scaling hypotheses derived from the multiperipheral model. It is assumed that diffraction dissociation and multiperipheral processes are distinct effects, and the consequences of this for the scaling laws are explained. Feynman's analogy linking multiple production to the statistical mechanical distribution functions of a gas is outlined, and based on this analogy it is suggested that one look for a correlation length in the two particle spectrum of secondaries.

Wilson's Experiments in Multiple Production

- Topological cross sections: multiplicity distributions diffractive + multiperipheral production?
- Feynman scaling: $\rho(k_z/E, k_\perp, E)$ independent of E?
- Factorization: $\rho(k_z/E, k_\perp, E)$ same for $(\pi, p)p$ in proton hemisphere?
- Flat rapidity plateau in central region?
- Double Pomeron exchange?
- Correlation length experiment: $\propto \exp(-\left|y_1 - y_2\right|/L)$?
- Factorization test with central trigger (to eliminate diffraction)

QCD could be complete, up to ultrahigh energies

Doesn't mean it must be!

No structural deficiencies à la electroweak theory

(but strong CP problem remains)

Perhaps . . .

- new kinds of colored matter beyond quarks gluons (and maybe their superpartners)
- quarks might be composite in an unexpected manner
- $SU(3)_c$ gauge symmetry might be vestige of a larger, spontaneously broken, color symmetry.

My speculation . . .

Event structure not a simple extrapolation of Tevatron

LHC's first surprise in this area: not a crack in the foundations, but something perhaps buried within QCD that we have not been clever enough to anticipate.

Some unusual structure in a few percent of events? High-multiplicity hedgehog events? Sporadic event structures? Dozens of small jets or other manifestations of multiple parton collisions?

Soft collisions + underlying events
$\rightsquigarrow$ *understanding multiple production, parton showers*

Lecture 2: Exploring the New Landscape
Physics Potential versus Energy

arXiv:0908.3660v2 [hep-ph] 8 Sep 2009

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.

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/PartonLum

LHC experiments begin soon . . .

The Large Hadron Collider will run for the first part of the 2009-2010 run at 3.5 TeV per beam, with the energy rising later in the run.

- How is the physics potential compromised by running below 14 TeV?
- At what point will the LHC begin to explore virgin territory and surpass the discovery reach of the Tevatron experiments CDF and D0?

Parton Luminosities + Prior Knowledge = Answers

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

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

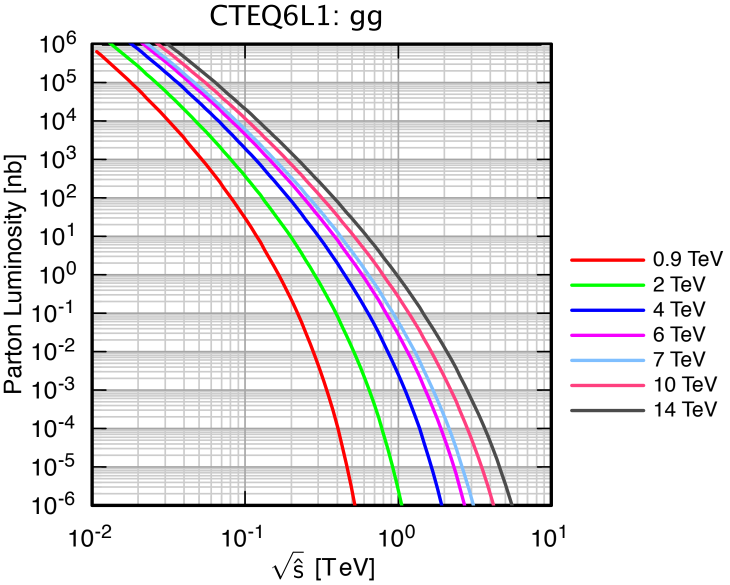
is a convenient measure of parton *ij* luminosity.

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

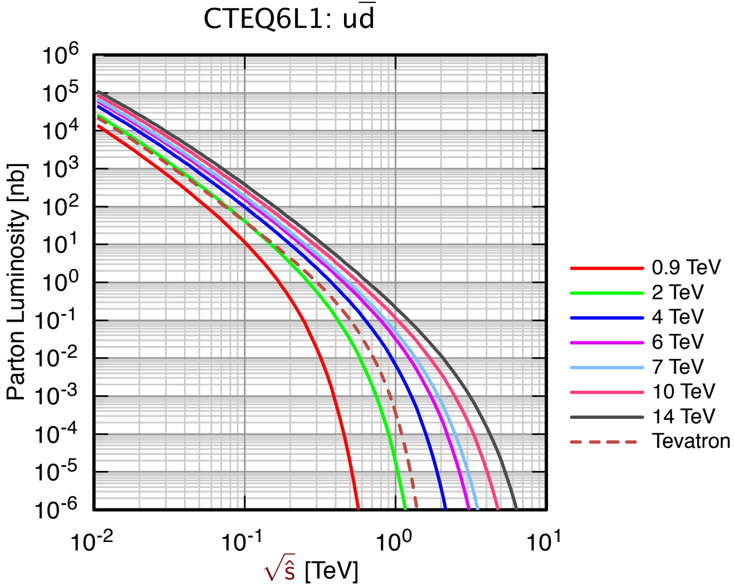
$$\sigma(s) = \sum_{\{ij\}}\int_{\tau_0}^1 \frac{d\tau}{\tau}\cdot\frac{\tau}{\hat{s}}\frac{d\mathcal{L}_{ij}}{d\tau}\cdot[\hat{s}\hat{\sigma}_{ij}(\hat{s})]$$

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

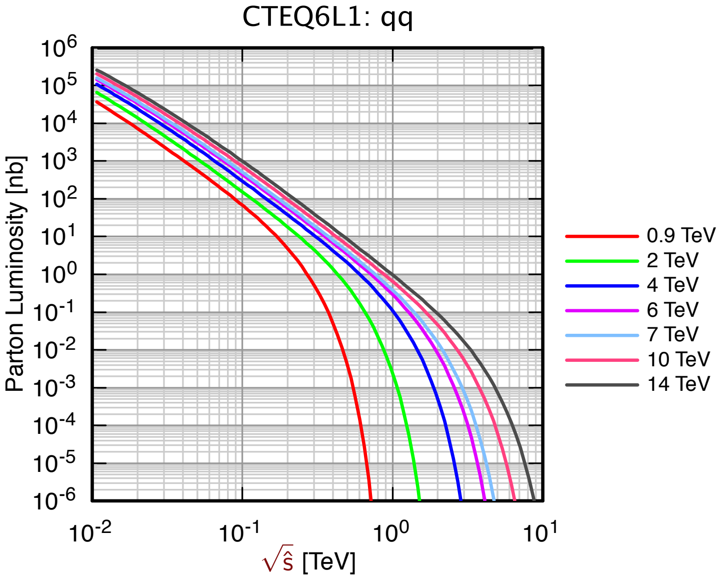
Parton Luminosity



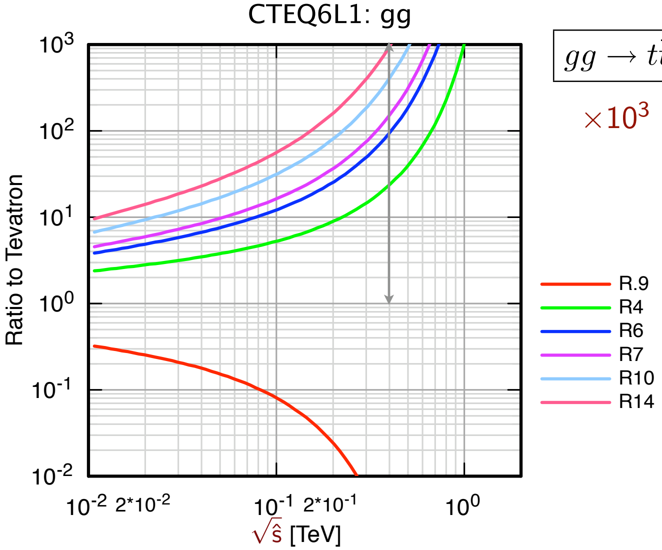
Parton Luminosity



Parton Luminosity (light quarks)



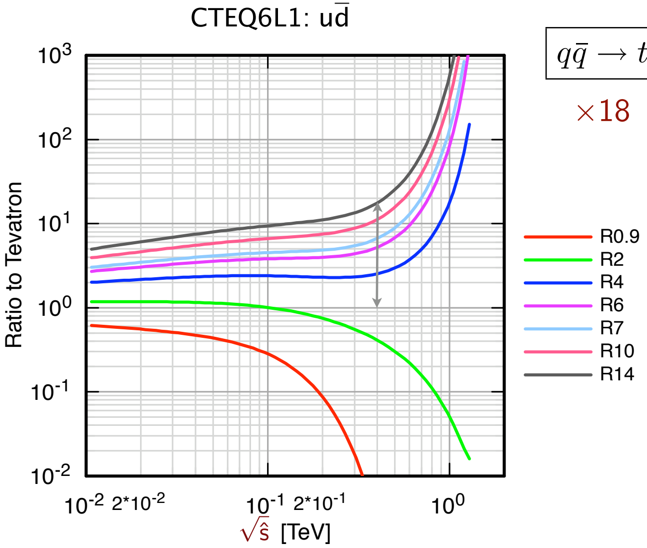
Luminosity Ratios



$gg \to t\bar{t}$

$\times 10^3$

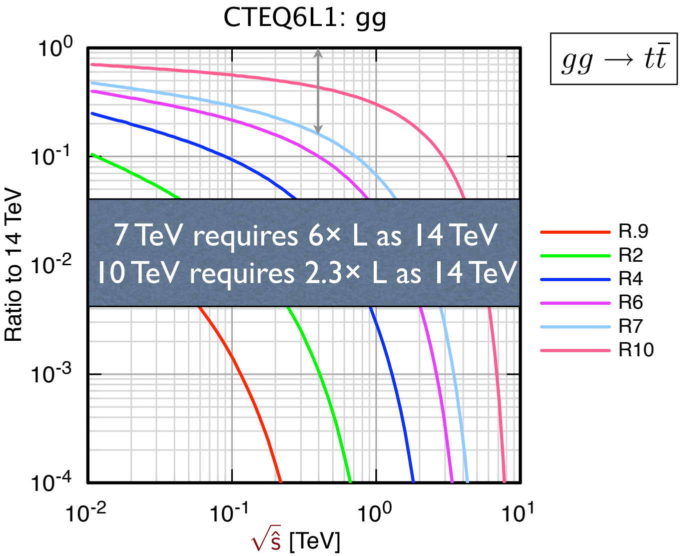
Luminosity Ratios



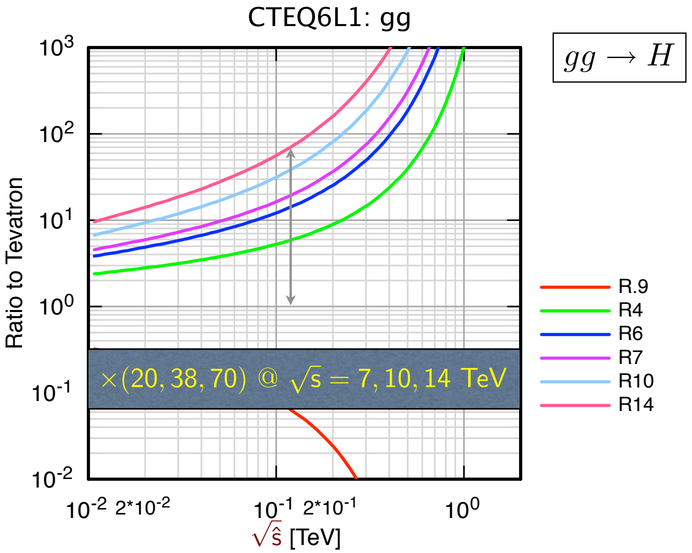
$q\bar{q} \to t\bar{t}$

$\times 18$

Luminosity Ratios



Luminosity Ratios



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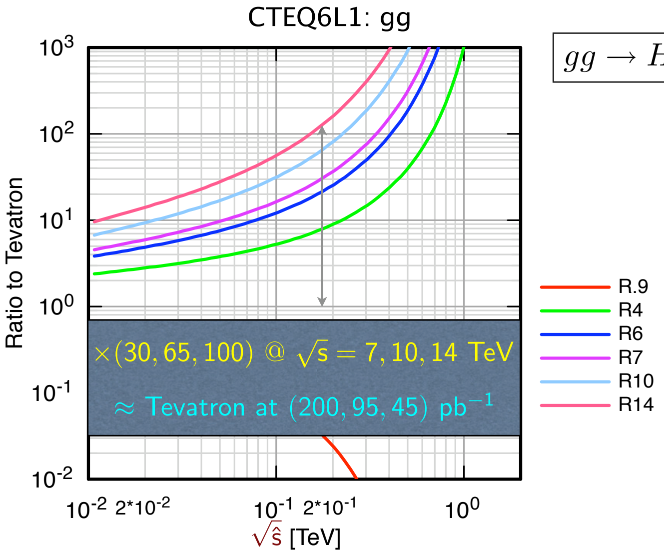
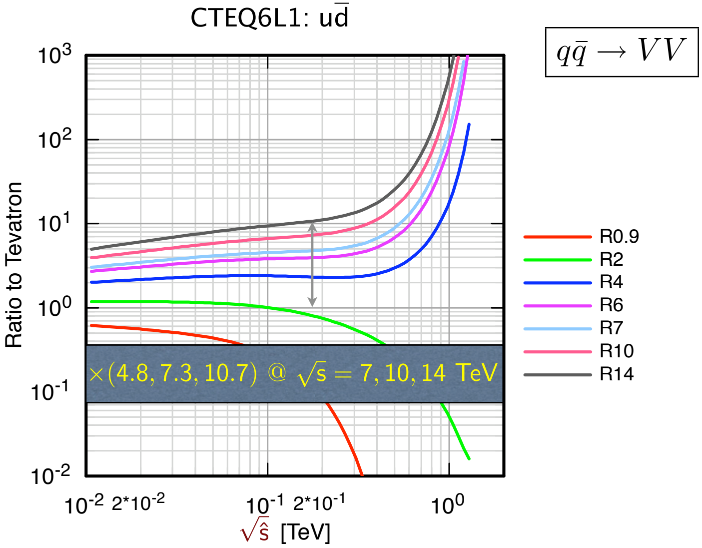
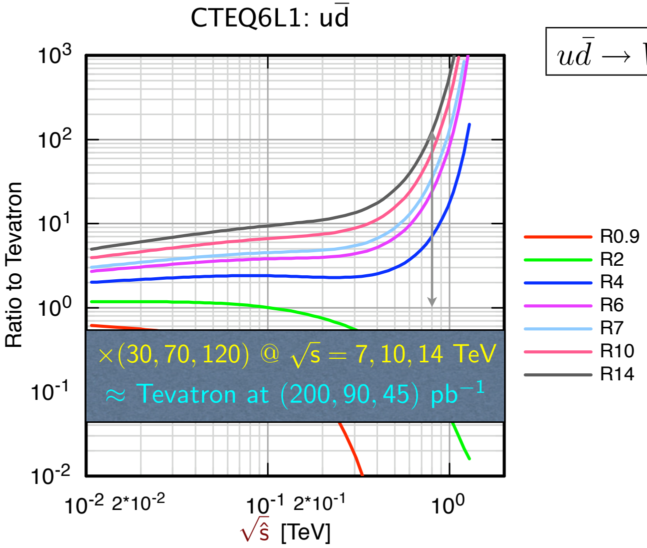


$gg \to H$

Luminosity Ratios



Luminosity Ratios

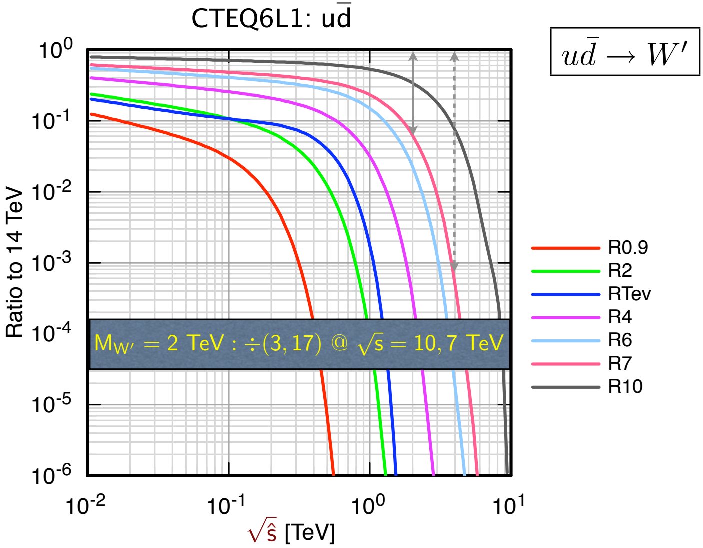


$u\bar{d} \to W'$

$\times(30, 70, 120)$ @ $\sqrt{s} = 7, 10, 14$ TeV

$\approx$ Tevatron at $(200, 90, 45)$ pb^{-1}

Luminosity Ratios



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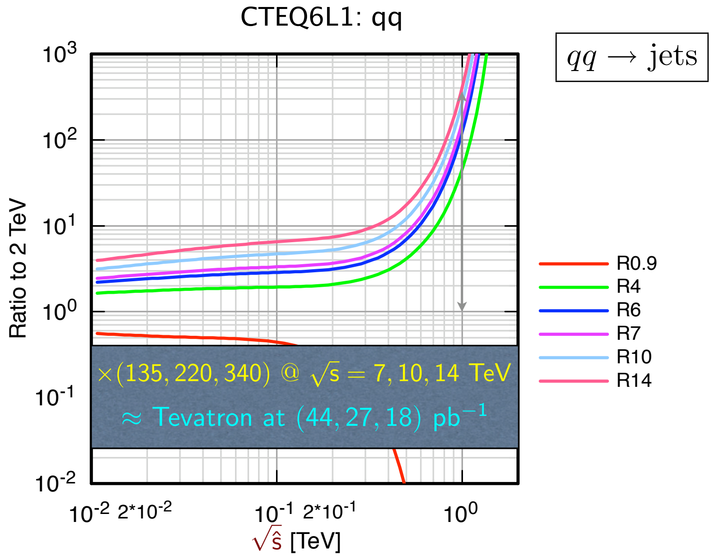

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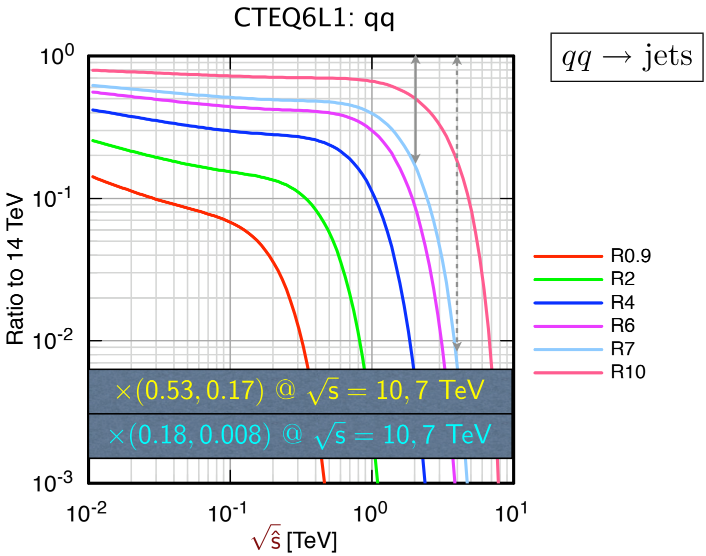

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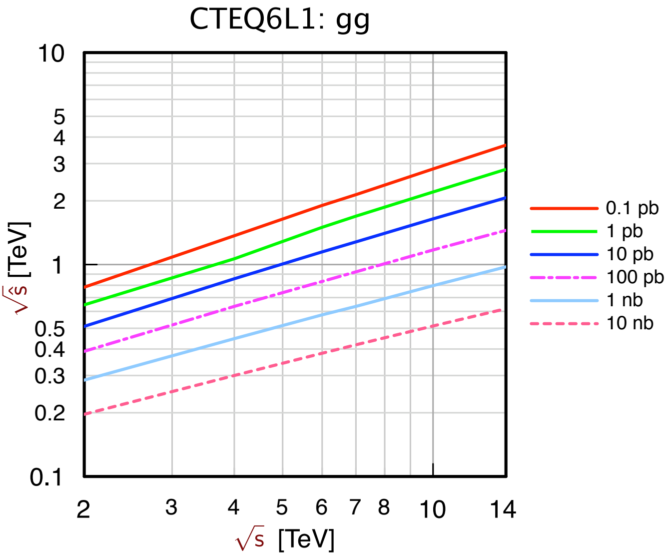

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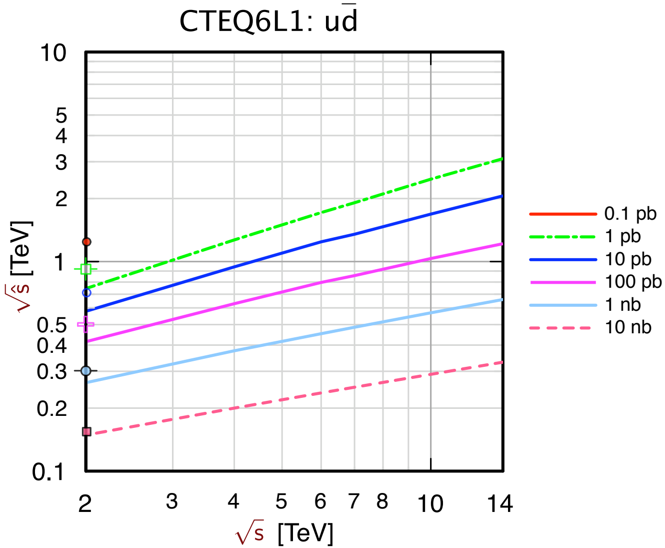

Luminosity Ratios