LHC Physics

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Outline

Lecture I:

- Some motivation.
- Calculating LHC cross sections (Xsection).
- Parton distribution functions, parton luminosities.

Lecture II:

- Example, top-pair Xsection calculation.
- Kinematics & jets.

Lecture I:

Some motivation (SM problems, naturalness);

How to calculate Xsections @ the LHC;

Parton distribution functions (PDFs) parton luminosities.

Why the LHC? What are the problems of the Standard Model* (SM), before the LHC started?

WW/unitarity, masses	fine tuning, naturalness	neutrino masses	flavor puzzle
		dark matter	(strong CP)
		baryogenesis	unification, charge quantisation

* Let's set quantum gravity aside for simplicity …

Why the LHC? What are the problems of the Standard Model* (SM), before the LHC started?

data driven, clear scale	conceptual vague scale	data driven, no clear reachable scale	conceptual
WW/unitarity, masses	fine tuning, naturalness	neutrino masses	flavor puzzle
		dark matter	(strong CP)
		baryogenesis	unification, charge quantisation

* Let's set quantum gravity aside for simplicity …

Why the LHC? (2 subjective reasons)

- Higgs & unitarity, suggests physics < TeV.
- Given the Higgs, the fine tuning problem requires new physics at a scale, generically, within the reach of the LHC.

The SM Higgsless Unitarity Problem

$$\mathcal{L}_{mass} = M_W^2\, W^+_\mu W^{-\,\mu} + \frac{1}{2} M_Z^2\, Z^\mu Z_\mu$$
$$- \sum_{i,j} \left\{ \bar{u}_L^{(i)} M^u_{ij} u_R^{(j)} + \bar{d}_L^{(i)} M^d_{ij} d_R^{(j)} + \bar{e}_L^{(i)} M^e_{ij} e_R^{(j)} + \bar{\nu}_L^{(i)} M^\nu_{ij} \nu_R^{(j)} + h.c. \right\}$$

Mass terms are not invariant under the local $SU(2)_L x U(1)_Y$ symmetry

The optical theorem

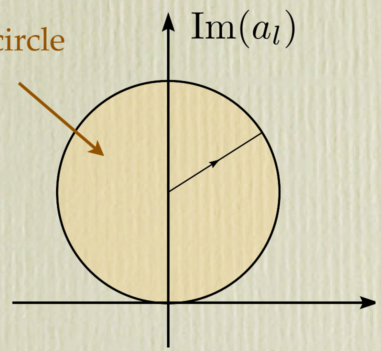
$$\frac{E}{p}\frac{1}{s}\,\mathrm{Im}\,(A(\theta=0)) = \sigma_{tot}(WW \to \text{anything})$$

requires for each partial wave:

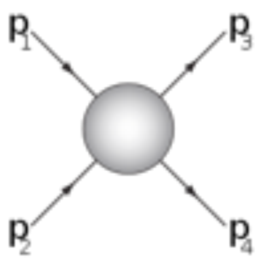
$$\mathrm{Im}(a_l(s)) = |a_l(s)|^2 + |a_l^{in}(s)|^2$$

$$\mathrm{Re}(a_l(s)) \leq \frac{1}{2}$$

physical amplitudes bound within the unitarity circle



The SM Higgsless Unitarity Problem



$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$
$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$
$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$

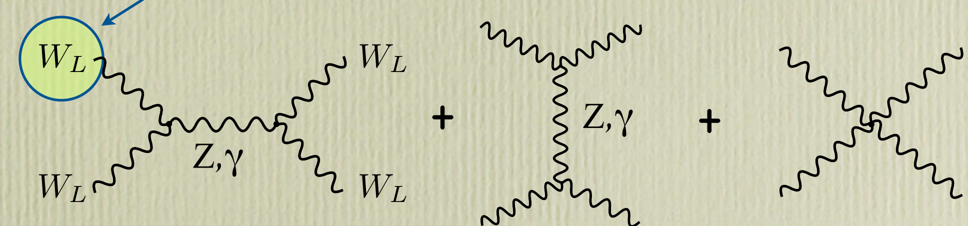
Mandelstam variables

The amplitude for scattering of longitudinal W's and Z's grows with the energy and eventually violates the unitarity bound:

Ex: $$A(W_L^+ W_L^- \to W_L^+ W_L^-) = \frac{g_2^2}{4M_W^2}(s+t)$$

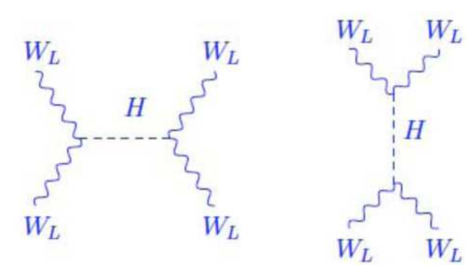
each longitudinal polarization gives a factor E

$$\epsilon_L^\mu = \frac{p^\mu}{M_W} + O\left(\frac{E}{M_W}\right)$$



Unitarity is violated at $\sqrt{s} \simeq \Lambda = 1.2\,\mathrm{TeV}$

Unitarity is restored by adding diagrams with intermediate Higgs in them as long as m_h <. 800 GeV .



The Higgs & the fine tuning/naturalness problem

't Hooft definition of technical naturalness:
a parameter is natural if when it's set to 0 there's an enhanced symmetry.

Additive renormaliztion (unnatural parameters): $d\lambda/dln\mu \propto \lambda g(\mu) + f(\mu)$
Multiplicative renormalization (natural parameters): $d\lambda/dln\mu \propto \lambda g(\mu)$

The Higgs mass parameter is subject to additive renormalisation.
Thus, it is sensitive to microscopic new physics dynamics.

Naturalness might give a hint: Higgs mass is additive, sensitive to microscopic scales. Within the SM it translates to UV sensitivity: $\frac{d\,m_H^2}{d\,\ln\mu} = \frac{3m_H^2}{8\pi^2}\left(2\lambda + y_t^2 - \frac{3g_2^2}{4} - \frac{3g_1^2}{20}\right).$

See: Giudice (13)

Beyond the SM: any scale that couples to the Higgs (or even to tops, gauge ...) will induce a large shift to the Higgs mass, $\delta m_H^2 \approx \frac{\alpha}{4\pi} M^2.$ Farina, Pappadopulo & Strumia (13)

Tunning vs. fine tuning/naturalness problem

Flavor puzzle: the parameters' are small and hierarchical.

Is the flavor sector fine tuned? $m_u/m_t \sim 10^{-5}$.

Massless fermions theory: $\mathcal{L}_{\mathrm{fermions}} \in \bar{\psi}_L \partial_\mu \gamma_\mu \psi_L + \bar{\psi}_R \partial_\mu \gamma_\mu \psi_R$

Two separate U(1)'s: $\psi_{L,R} \to e^{\theta_{L,R}} \psi_{L,R}$

Sym' is indeed enhanced when the mass vanishes. (modulo anomalies)

Mass term breaks it to a single U(1): $\bar{\psi}_L m \psi_R$

Only invariant under transformation with $\theta_L = \theta_R = \theta$

Flavor (including neutrinos) parameters are natural

Flavor parameters are natural, subject to tuning & then radiatively stable, no UV sensitivity.

Within the SM the only exception is the Higgs mass. (& the QCD angle & the cosmological constant)

(A simple way to understand this is to realise that a massless fermion requires 2 degrees of freedom (dof) while a massive 4.
A massless vector boson requires 2 and a massive 3.
Thus, there is discontinuity in the massless to massive limit.
This does not happen for a massive scalar.)

LHC physics

Why LHC?

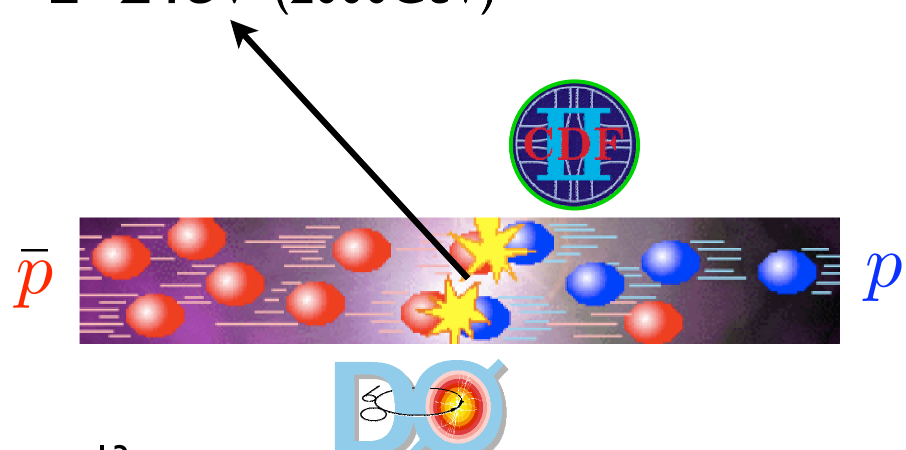
Need more E!

Sync' radiation,
problem for circular e-collider:

$$\frac{dW}{dt}\Big|_e \approx \left(\frac{e}{r}\right)^2 \left(\frac{E}{m_e}\right)^4 \sim 10^4\,\mathrm{GeV\,s^{-1}} \;\Rightarrow\; \times 10^{12} e \sim \textbf{MWs radiation!}$$

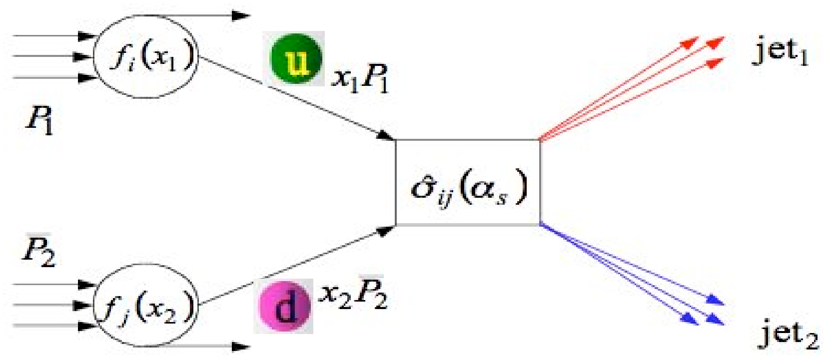
10^{13} improvement when e <=> proton

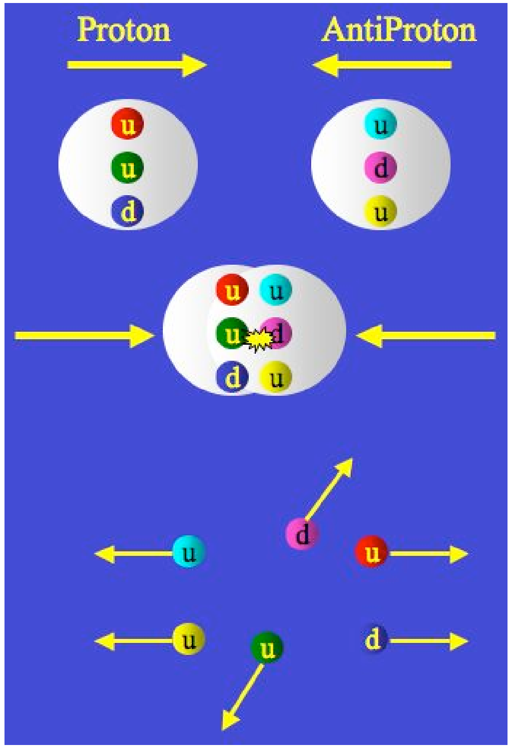
E~2TeV (2000GeV)



Nothing's free - QCD dust

- Expect $m_t = 130\text{-}200\,\text{GeV}$, who needs 2TeV?
- Proton anti-proton are composite:
- Typical E's much smaller: $E^2_{\text{event}} = x_1 x_2 E^2_{p\bar{p}}$





- We don't know what is E_{CM}.
- We don't know which particles interacted.
- And ...

Calculating Xsections at the LHC: Parton Distribution Functions (PDFs)

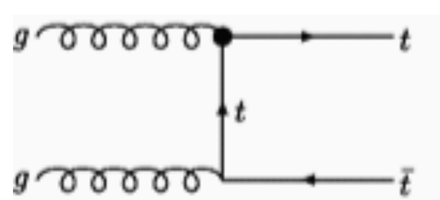
(assuming no p-rapidity or pt cuts)

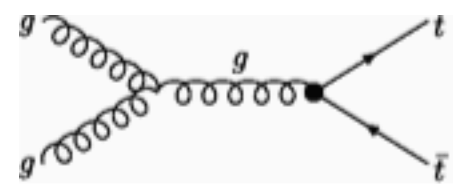
$$\frac{d\sigma(pp \to f)}{d\hat{s}} = \sum_{ij} \hat{\sigma}_{ij}(\hat{s}) \int_0^1 \int_0^1 dx_i dx_j f_i(x_i) f_j(x_j) \delta(\hat{s} - x_i x_j s)$$

$\hat{\sigma}(\hat{s})$ Corresponds to the hard/local/short distance Xsection that we would like to calculate/measure.

For instance $gg \to t\bar{t}$

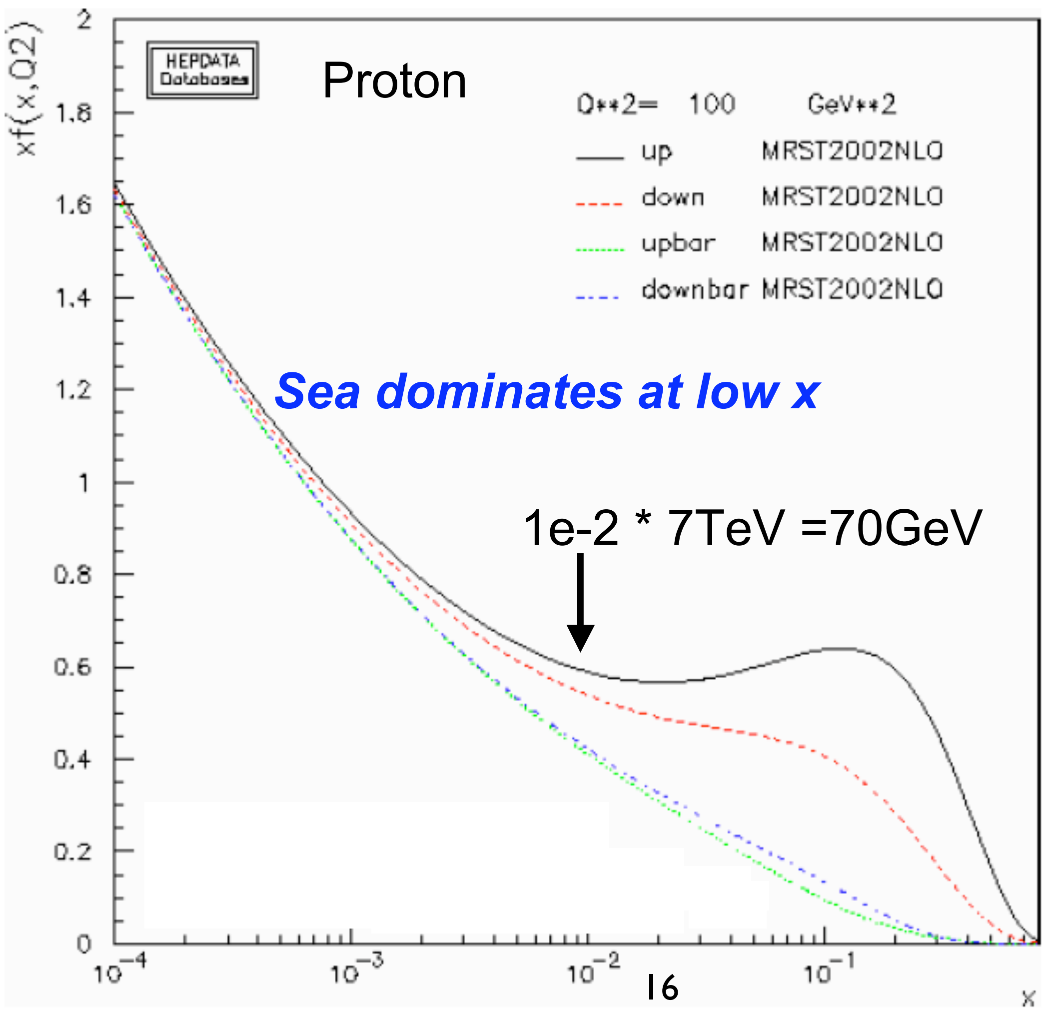
$\hat{s} = (p_t + p_{\bar{t}})^2 = (p_g + p_{g'})^2$



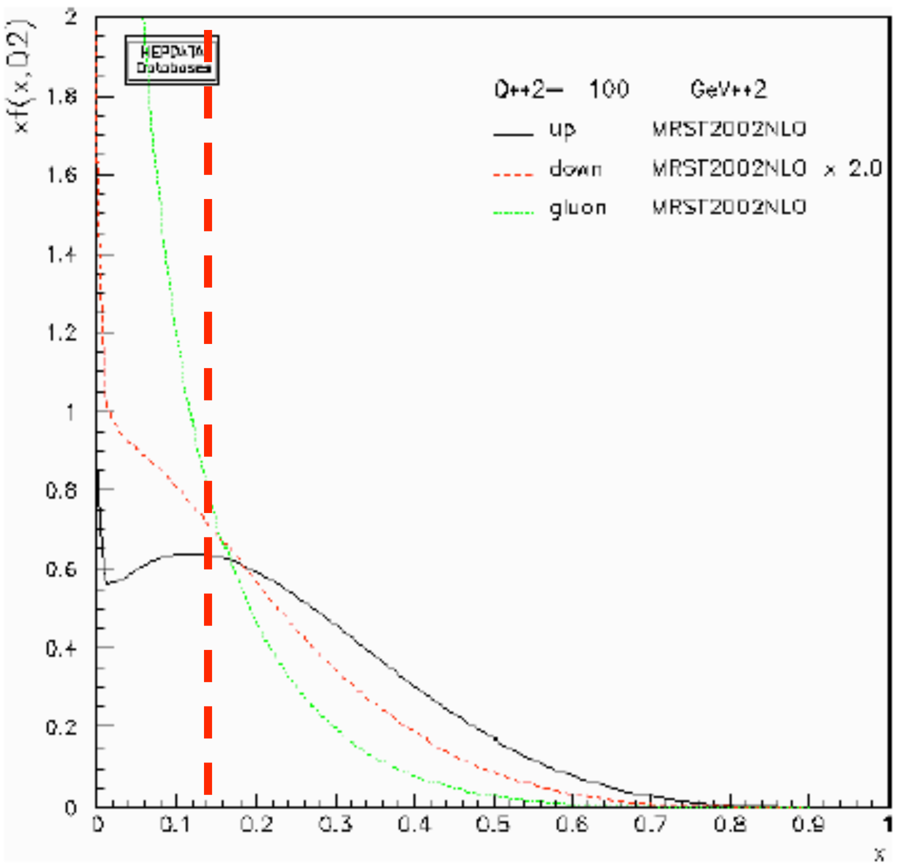


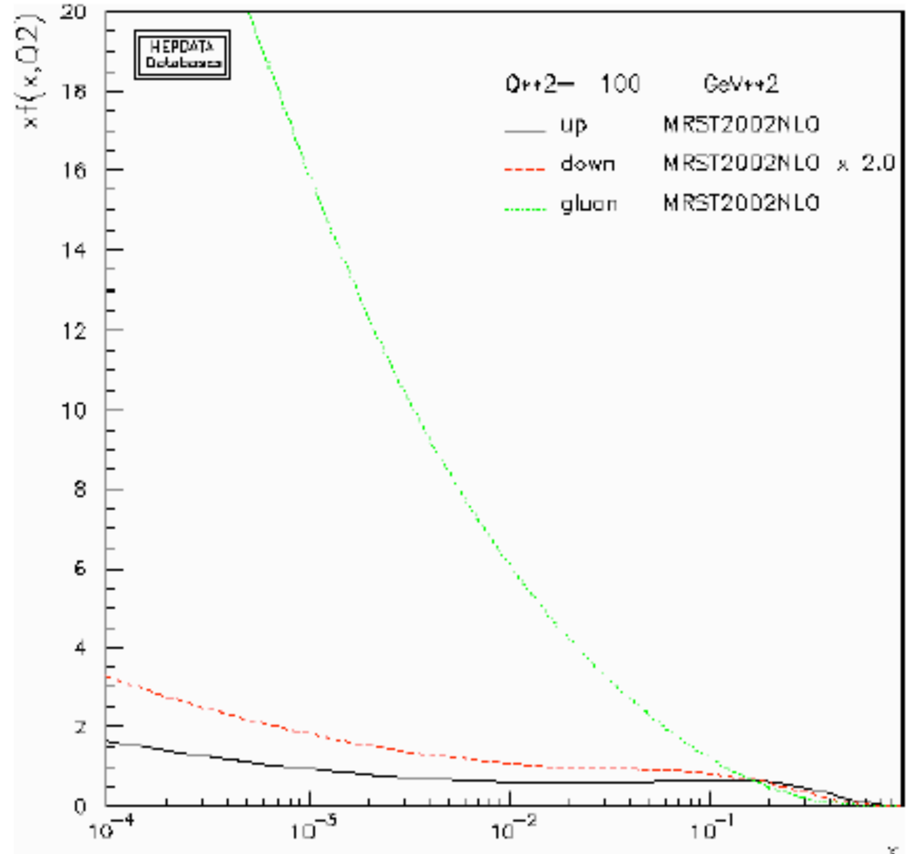
PDFs (What are they?)

Probability of finding a constituent f with a longitudinal momentum fraction of $x \Rightarrow f_f(x)dx$



PDFs at the LHC





Gluons dominate at low x .

To set the scale, x = 0.14 at LHC is 0.14 * 7TeV = 1TeV

=> The LHC is a gluon collider !!!

Physically only pairs of PDF are important

(assuming no p-rapidity or pt cuts)

$$\frac{d\sigma\left(pp \to f\right)}{d\hat{s}} = \sum_{ij} \hat{\sigma}_{ij}\left(\hat{s}\right) \int_0^1 \int_0^1 dx_i dx_j f_i(x_i) f_j(x_j) \delta\left(\hat{s} - x_i x_j s\right)$$

$$= \sum_{ij} \frac{\hat{\sigma}_{ij}\left(\hat{s}\right)}{\hat{s}} \int_0^1 \int_0^1 dx_i dx_j f_i(x_i) f_j(x_j) \delta\left(1 - x_i x_j \frac{s}{\hat{s}}\right)$$

$$\tau = \frac{\hat{s}}{s}$$

$$\frac{d\sigma\left(pp \to f\right)}{d\tau} = \sum_{ij} \frac{\hat{\sigma}_{ij}\left(\hat{s}\right)}{\tau} \int_0^1 \int_0^1 dx_i dx_j f_i(x_i) f_j(x_j) \delta\left(1 - \frac{x_i x_j}{\tau}\right)$$

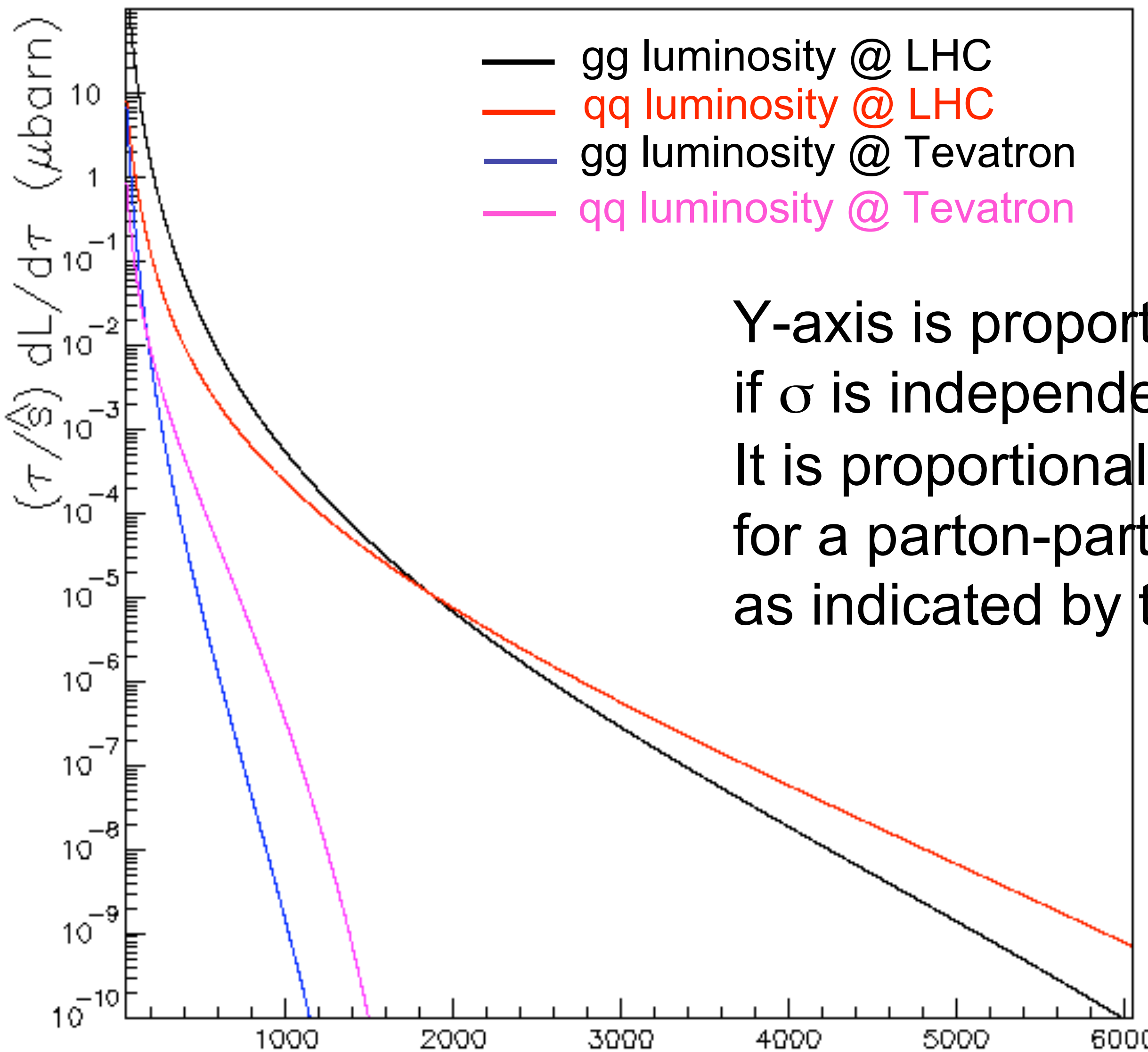
$$\frac{d\sigma\left(pp \to f\right)}{d\tau} = \sum_{ij} \frac{\hat{\sigma}_{ij}\left(\hat{s}\right)}{\tau} \int_\tau^1 dx_i \frac{\tau}{x_i} f_i(x_i) f_j\left(\frac{\tau}{x_i}\right)$$

Parton-parton luminosities

$$\frac{dL_{ij}}{d\tau} = \frac{1}{1+\delta_{ij}} \int_{\tau}^{1} \frac{dx}{x} \left[f_i(x) f_j\left(\frac{\tau}{x}\right) + f_i\left(\frac{\tau}{x}\right) f_j(x) \right]$$

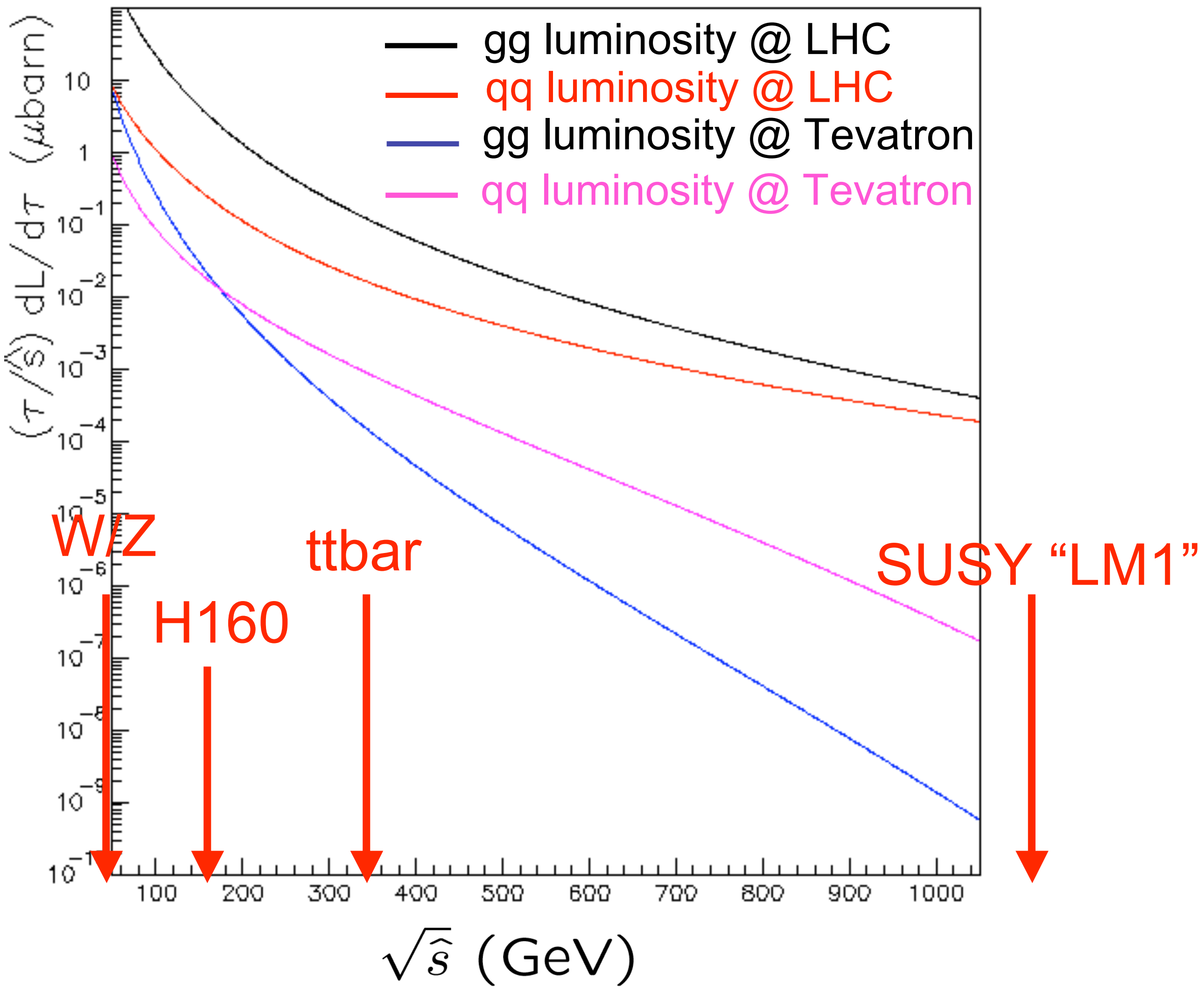
- Function of dimensionless quantity:
  - Scaling => independent of CM energy of proton proton collisions.
- However, $\hat{\sigma}_{ij}(\hat{s}) \equiv \hat{\sigma}_{ij}(E^2)$ depends on E. The collider characteristics only help us understand the energy scale E^2 accessible given an S for proton-proton collisions.

Luminosity functions, adding Xsection scale



Y-axis is proportional to σ
if σ is independent of $\hat{s}$
It is proportional to probability
for a parton-parton collision with $\hat{s}$
as indicated by the x-axis.

Zooming-in on the < 1 TeV region



Cross sections at 1.96TeV versus 14TeV Tevatron vs LHC

	Cross section		Ratio
$Z \rightarrow \mu\mu$	260pb	1750pb	6.7
WW	10pb	100pb	10
H_{160GeV}	0.2pb	25pb	125
$mSugra_{LM1}$	0.0006pb	50pb	80,000

At $10^{32}cm^{-2}s^{-1}$ LHC might accumulate $10pb^{-1}$ in one day!

Boosted jets mass distribution, $E_J > 400\,\mathrm{GeV}$

$$\frac{d\sigma}{dm_J^2} \propto \frac{C_F}{m_J^2}\log\left(\frac{E^2 R^2}{m_J^2}\right) \quad \text{(expect mostly quarks } C_F = 4/3\text{)}$$

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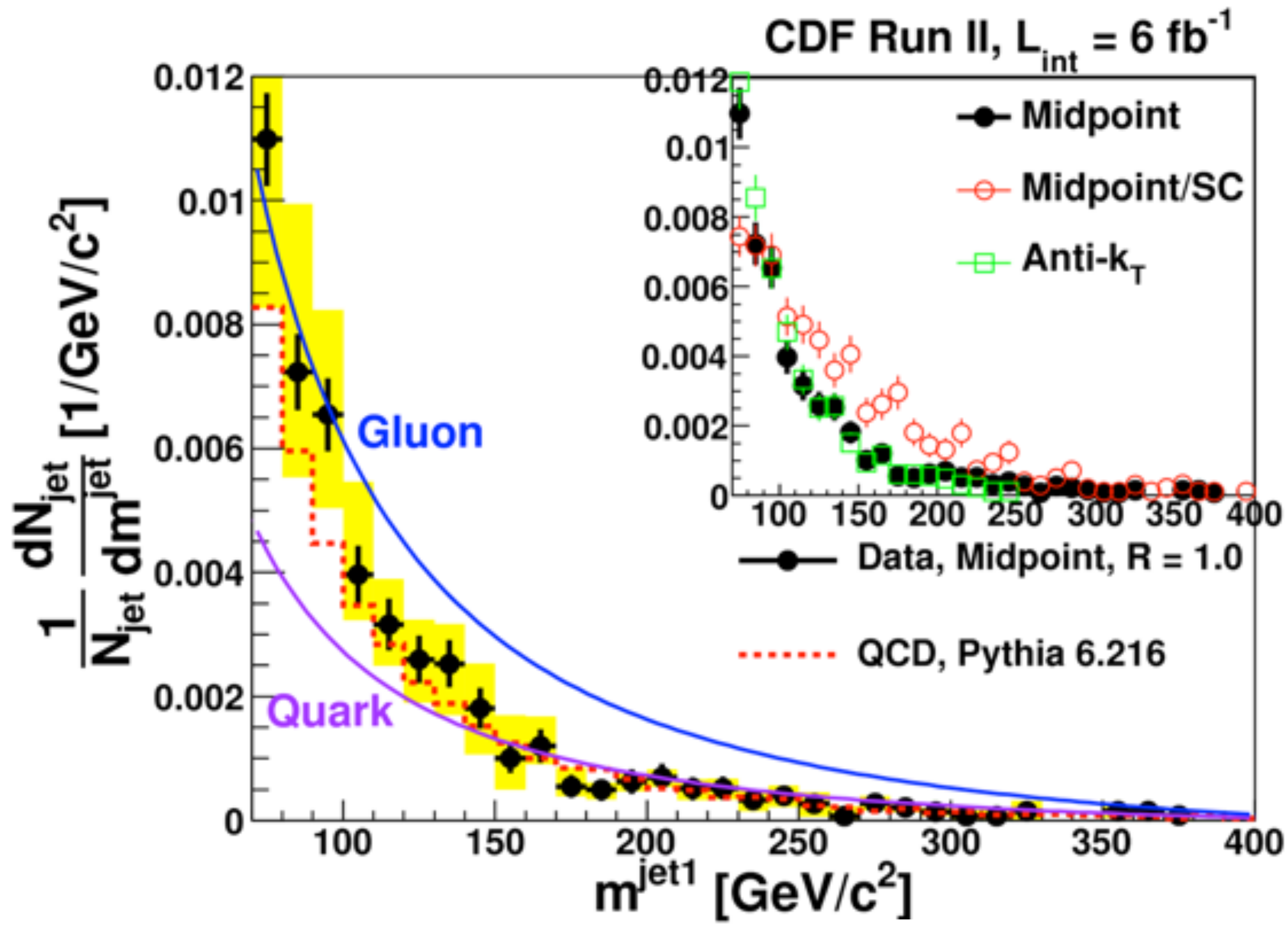

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