ELEMENTARY PARTICLE PHYSICS
Laurea Magistrale in Fisica, curriculum Fisica Nucleare e Subnucleare
Lecture 3
(1^{st} part)

Simonetta Gentile*

* Università Sapienza,Roma,Italia.

October 14, 2018

Preliminaries

Simonetta Gentile
terzo piano Dipartimento di Fisica *Gugliemo Marconi*
Tel. 0649914405
e-mail: simonetta.gentile@roma1.infn.it
pagina
web:`http://www.roma1.infn.it/people/gentile/simo.html`

Bibliography

♠ Bibliography

- K.A. Olive et al. (Particle Data Group), *The Review of Particle Physics*, Chin. Phys. C, 38, 090001 (2014)(PDG) update 2015, http://pdg.lbl.gov/
- F. Halzen and A. Martin, *Quarks and Leptons: An introductory course in Modern Particle Physics* , Wiley and Sons, USA(1984).

♠ Other basic bibliography:

- A.Das and T.Ferbel, *Introduction to Nuclear Particle Physics* World Scientific,Singapore, 2^{nd} Edition(2009)(DF).
- D. Griffiths, *Introduction to Elementary Particles* Wiley-VCH,Weinheim, 2^{nd} Edition(2008),(DG)
- B.Povh *et al.*, *Particles and Nuclei* Springer Verlag, DE, 2^{nd} Edition(2004).(BP)
- D.H. Perkins,*Introduction to High Energy Physics* Cambridge University Press, UK, 2^{nd} Edition(2000).
- Y.Kirsh & Y. Ne'eman, *The Particle Hunters*

♠ Particle Detectors bibliography:

- William R. Leo *Techniques for Nuclear and Particle Physics Experiments*,
  Springer Verlag (1994)(LEO)
- C. Grupen, B. Shawartz *Particle Detectors*,
  Cambridge University Press (2008)(CS)
- *The Particle Detector Brief Book*,(BB)
  http://physics.web.cern.ch/Physics/ParticleDetector/Briefbook/

Specific bibliography is given in each lecture

Lecture Contents - 1 part

1. Introduction. Lep Legacy
2. Proton Structure
3. Hard interactions of quarks and gluons: Introduction to LHC Physics
4. Collider phenomenolgy
5. The machine LHC
6. Inelastic cros section pp
7. W and Z Physics at LHC
8. Top Physics: Inclusive and Differential cross section $t\bar{t}$ W, $t\bar{t}$ Z
9. Top Physics: quark top mass, single top production
10. Dark matter
    - Indirect searches
    - Direct searches

Specific Bibliography

♠ Bibliography of this Lecture

- J.M. Campbell, J.W. Huston, W.J. Stirling,*Hard Interactions of Quarks and Gluons: a Primer for LHC Physics*, Rept.Prog.Phys.70:89,2007,arXiv:hep-ph/0611148 (CHS)
- A.Martin,*Proton structure, Partons, QCD, DGLAP and beyond*Acta Phys.Polon.B39:2025-2062,2008,arXiv:0802.0161v1
- C.Quigg,*LHC Potential vs. energy* https://arxiv.org/pdf/0908.3660
- C.Quigg,*LHC Potential vs. energy:Consideration for2011Run*https://arxiv.org/pdf/1101.3201

Contents

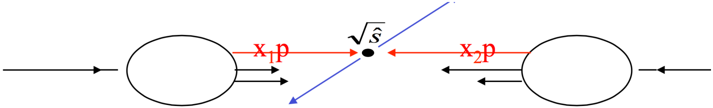
Introduction

- **Scattering processes** at high energy hadron colliders can be classified as either **hard** or **soft**. [1]
- Quantum Chromodynamics (QCD) is the underlying theory, but the approach and level of understanding is very different for the two cases.
- For **hard processes**, (e.g. Higgs boson or high pT jet production), the rates and event properties can be **predicted with good precision using perturbation theory**.
- For **soft processes**, (e.g. the total cross section, the underlying event etc.), the **rates and properties are dominated by non-perturbative QCD effects**, which are **less well understood**.
- In the following we'll limit our discussion to the hard processes.

[1] CHS

Hard scattering

Monochromatic proton beam can be seen as **beam of quarks and gluons with a wide band of energy**.Occasionally hard scattering (head on) between constituents of incoming protons occurs.



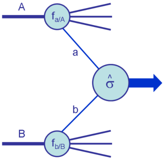
- Leading order processes (LO).
- **Factorization Theorem**. Drell and Yan suggested that parton model ideas developed for deep inelastic scattering could be extended to certain processes in hadron-hadron collisions.
- The paradigm process was the **production of a massive lepton pair by quark-antiquark annihilation**(the Drell-Yan process).
- It was postulated that **the hadronic cross section** $\boldsymbol{\sigma(AB \to \mu^+\mu^- + X)}$ could be obtained by **weighting the subprocess cross section** $\boldsymbol{(\hat{\sigma}(q\bar{q}) \to \mu^+\mu^-)}$ with the **parton distribution functions** (pdfs) $f_{q/A}(x)$ extracted from deep inelastic scattering.

From Bjorken scaling to hard processes

The Bjorken scaling behavior discussed in the previous lecture generalize to all high energy hard processes.In the modern QCD perspective, this generalization can be exemplified by a typical high energy hadron-hadron scattering process, such as the production of a lepton-pair with high invariant mass $Q = M^2_{\ell^+\ell^-}$, $AB \to \ell^+\ell^- + X$.The dimensionless ratio of the physical cross section to the corresponding one for point-like scattering particles (analogous σ_{Mott}):

$$\sigma_{AB}(s,\tau)/\sigma_0(s) \;=\; f_a \otimes \hat{\sigma}_{ab} \otimes f_b \;=$$

$$\iint \mathrm{d}x_a \mathrm{d}x_b \sum_{a,b} f_{a/A}(x_a, Q) f_{b/B}(x_b, Q) \hat{\sigma}_{ab \to X}(x_a, x_b Q^2/s, \alpha_s(Q))$$



If the parton distributions f_a, f_b and the QCD coupling α_s were **not Q-dependent** , $\sigma(\tau, s)/\sigma_0$ is a function of the scaling variable $\tau = \frac{Q^2}{s}$ is **independent** from s the equivalent of Bjorken scaling in its original form.

Hard scattering

Simpler writing:

$$\sigma_{AB} = \int \mathrm{d}x_a \mathrm{d}x_b \boldsymbol{f_{a/A}(x_a) f_{b/B}(x_b) \hat{\sigma}_{ab \to X}}$$

the Drell-Yan process: $X = \ell^+\ell^-$, $ab = q\bar{q}, \bar{q}q$. Validity is the asymptotic *scaling limit*[2]: $M_X \equiv M^2_{\ell^+\ell^-}, s \to \infty, \tau = M^2_{\ell^+\ell^-}/s$ fixed.

- good agreement between theoretical predictions and the measured cross sections $\Longrightarrow$ studies were extended to other *hard scattering* processes.
- Problem: Large logarithms terms from gluons emitted collinear with the incoming quarks. As in deep inelastic scattering these could be absorbed, via the DGLAP equations, in the definition of the parton distributions.
- All logarithms appearing in the Drell-Yan corrections, depending fon momentum scale Q^2 of the process could be factored into renormalized parton distributions.
- Taking into account the leading logarithm corrections $\Longrightarrow$ next

[2] analogous Bjorken scaling

Factorization theorem

Taking into account the leading logarithm corrections $\Longrightarrow$ Leading logarithm cross section :

$$\sigma_{AB} = \int \mathrm{d}x_a \mathrm{d}x_b f_{a/A}(x_a, \boldsymbol{Q^2}) f_{b/B}(x_b, \boldsymbol{Q^2}) \hat{\sigma}_{ab\rightarrow\ X}$$

$\hat{\sigma}_{ab\rightarrow\ X}$ hard scattering cross section, $\boldsymbol{f_{a/A}, f_{b/B}}$ parton distribution functions, depending from $\boldsymbol{Q^2}$ is a large momentum scale that characterizes the hard scattering, $e.g. M^2_{\ell^+\ell^-}, p_T^2$(from which depend the correction)

• Reminder: The DGLAP equations determine the Q^2 dependence of the pdfs. The x dependence, on the other hand, has to be obtained from fitting deep inelastic and other hard-scattering

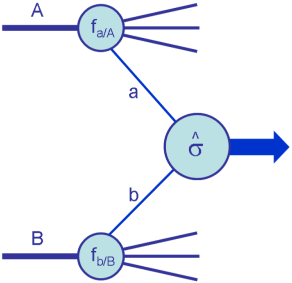


Figure : Diagrammatic Structure of a generic hard scattering process

Final step

After the logarithms had been factored, there are not universal **corrections**had to be **calculated separately for each process**, giving rise to perturbative $\mathcal{O}(\alpha_S^n)$ corrections to the leading logarithm cross section.

$$\sigma_{AB} = \int dx_a dx_b f_{a/A}(x_a, \boldsymbol{\mu_F^2}) f_{b/B}(x_b, \boldsymbol{\mu_F^2}) \times \left[\hat{\sigma}_0 + \alpha_S(\mu_R^2)\hat{\sigma}_1 + \dots\right]_{ab-}$$

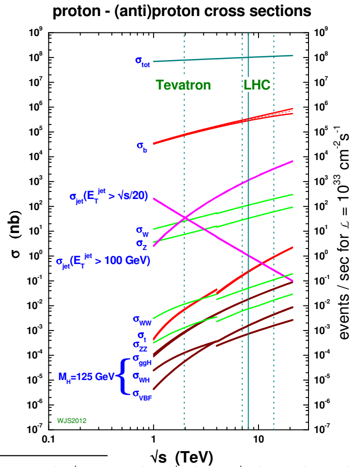
μ_F^2 is the factorization scale, which can be thought of as the scale that separates the long- and short-distance physics,μ_R^2 is the renormalization scale for the QCD running coupling. The cross section calculated to all orders in perturbation, is invariant under changes in these parameters, the μ_F^2 and μ_R^2 dependence of the coefficients, *e.g.* σ^1, exactly compensating the explicit scale dependence of the parton distributions and the coupling constant.

This compensation becomes **more exact as more terms are included in the perturbation series**.

A standard choice is $\mu_F^2 = \mu_R^2 = M$, the mass of the lepton pair.

Prediction for SM process cross section

Predictions for Standard Model cross sections[3] at $p\bar{p}$ and pp colliders, calculated at next-to-leading order in perturbation theory, i.e. including also the σ^1.



[3] http://www.hep.ph.ic.ac.uk/ wstirlin/plots/plots.html

Drell-Yan process

The Drell-Yan process is the production of a lepton pair $\ell^+\ell^-$ of large invariant mass M, at Tevatron & LHC even W and Z, in hadron-hadron collisions by the mechanism of quark- antiquark annihilation($q\bar{q} \to \gamma^* \ \to \ \ell^+\ell^-$). From QED:

$$\hat{\sigma}(q\bar{q} \to e^+e^-) \ = \ \frac{4\pi\alpha^2}{3\hat{s}}\frac{1}{N}Q_q^2$$

$Q_q^2 = +2/3, 1/3$ is the quark charge, $\frac{1}{N} = \frac{1}{3}$ indicates only when the colour of the quark matches with the colour of the antiquark can annihilation into a colour-singlet final state take place.

In general, the incoming quark and antiquark will have a spectrum of centre-of-mass energies $\sqrt{\hat{s}}$:

$$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}M^2} \ = \ \frac{\hat{s}_0}{N}Q_q^2\delta(\hat{s} \ - \ M^2), \quad \hat{\sigma}_0 \ = \ \frac{4\pi\alpha^2}{3M^2}$$

M = mass of $\ell^+\ell^-$ or the produced particle.

In c.m.s of two hadrons the incoming parton momenta:

$$p_1^\mu = \frac{\sqrt(s)}{2}(x_1, 0, 0, x_1) \qquad p_2^\mu = \frac{\sqrt(s)}{2}(x_2, 0, 0, x_2)$$

square of parton c.m.s energy: $\hat{s} = x_1 x_2 s$. Folding in the pdfs for the initial state quarks and antiquarks in the colliding beams gives the hadronic cross section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M^2} = \frac{\hat{\sigma}_0}{N} \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2\ \delta(x_1 x_2 s - M^2)$$
$$\times \Big[\sum_k Q_k^2 (q_k(x_1, M^2) \bar{q}_k(x_2, M^2) + [1 \leftrightarrow 2]) \Big]$$

$q_k(x_1, M^2), \bar{q}_k(x_2, M^2)$ quarks antiquarks parton distribution. Rapidity and square mass of the produced lepton pair :

$$y = \frac{1}{2} \log \frac{x_1}{x_2} \qquad x_1 x_2 s = M^2$$
$$x_1 = \frac{M}{\sqrt{s}} e^{y} \qquad x_2 = \frac{M}{\sqrt{s}} e^{-y}$$

$$\frac{d\sigma}{dM^2 dy} = \frac{\hat{\sigma}_0}{Ns} \times \Big[\sum_k Q_k^2 (q_k(x_1, M^2) \bar{q}_k(x_2, M^2) \; + \; [1 \; \leftrightarrow \; 2]) \Big]$$

$$x_1 = \frac{M}{\sqrt{s}} e^{y} \qquad x_2 = \frac{M}{\sqrt{s}} e^{-y}$$

- Thus different values of M and y probe different values of the parton x of the colliding beams. The formulae relating x_1 and x_2 to M and y of course also apply to the production of any final state with this mass and rapidity.
- Assuming the factorization scale (Q) is equal to M, the mass of the final state, the relationship between the parton (x, Q^2) values and the kinematic variables M and y can be illustrated .

The double differential cross section:

$$\frac{d\sigma}{dM^2 dy} = \frac{\hat{\sigma}_0}{N}\left[\sum_k Q_k^2 (q_k(x_1, M^2)\bar{q}_k(x_2, M^2) \; + \; [1 \; \leftrightarrow \; 2])\right]$$

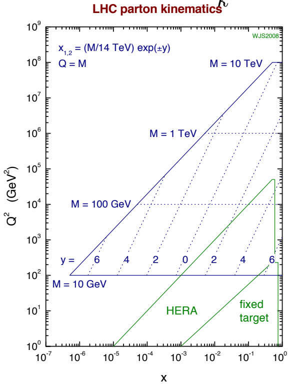
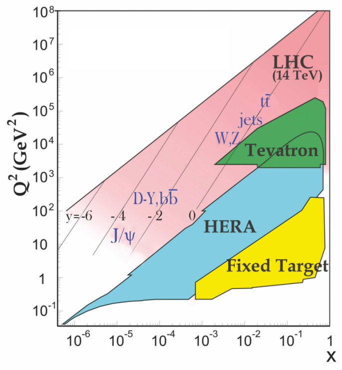


Figure : Relationship between parton (x, Q^2) variables and the kinematic variables M and y corresponding to a final state of mass M produced, the factorization scale (Q) = M, at $\sqrt{s}$ = 14 TeV.

- $x_{1,2} = \frac{M}{\sqrt{s}} e^{\pm y}$
- $y = \frac{1}{2} \log \frac{x_1}{x_2}$ Producing particles at large rapidity implies very different x for incoming partons
- It can apply to the production of any final state with this mass and rapidity.
- Different values of M and y probe different values of the parton x of the colliding beam.
- At $y = 0, x_1, x_2 = M/\sqrt{s}$
- A mass M= 100 GeV and y=4 is produced with 2 partons with $x = 0.00015$ and 0.35

The double differential cross section:

$$\frac{d\sigma}{dM^2 dy} = \frac{\hat{\sigma}_0}{N}\Big[\sum_k Q_k^2 (q_k(x_1, M^2)\bar{q}_k(x_2, M^2) \; + \; [1 \; \leftrightarrow \; 2])\Big]$$



- Kinematic domains in x and Q^2 probed by fixed-target and collider experiments.
- The incoming partons have $x_{1,2} = (M/14 \text{ TeV})e^{\pm y}$ with Q $=$ M where M is the mass of the state shown in blue in the figure.
- For example, exclusive J/Ψ production at high $|y|$ at the LHC may probe the gluon PDF down to $x \sim 10^{-5}$.

- **New heavy particles need relatively large values of x .**
- Producing particles at large rapidity (y $\approx$ 2 or more) implies very different x for incoming partons.

Next-to-leading order calculation

- Lowest order (LO) calculations can in general describe broad features of a particular process and provide the first estimate of its cross section, in many cases this approximation is insufficient.
- *Virtual and real radiation* A next-to-leading order(NLO) QCD calculation requires the consideration of all diagrams that contribute an additional strong coupling factor, α_s. These diagrams are obtained from the lowest order ones by **adding additional quarks and gluons**and they can be divided into two categories, **virtual (or loop)** contributions and the **real** radiation component.

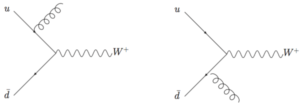


Figure : LO order for W production at hadron collider

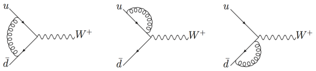


Figure : Virtual diagram included in NLO order corrections to Drell-Yan W production at hadron collider

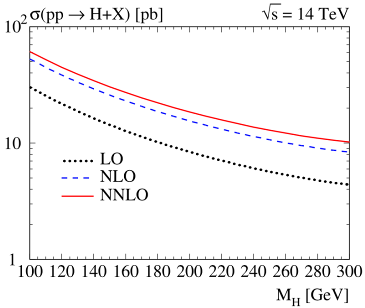
NLO k-factor

- The **K-factor** for a given process is a useful shorthand which encapsulates the strength of the **NLO corrections**to the lowest order cross section. It is calculated by simply taking the ratio of the NLO to the LO cross section.
- K-factor may be very different for various kinematic regions of the same process.
- The K-factor often varies slowly and may be approximated as the**one number**.
- The **PDF should at same order of cross section**.
  Standard practice to use a NLO pdf (for instance, the CTEQ6M set) in evaluating the NLO cross section and a LO pdf (such as CTEQ6L) in the lowest order calculation.
- The **K-factor** can depend quite strongly on the region of **phase space**that is being studied (*e.g.*analysis cuts) .

$$k = \frac{\sigma_{\mathrm{NLO}}(PDF\ NLO)}{\sigma_{\mathrm{LO}}(PDF\ LO)}$$

NLO k-factor

	Typical scales		Tevatron K-factor			LHC K-factor		
Process	μ_0	μ_1	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$	$\mathcal{K}(\mu_0)$	$\mathcal{K}(\mu_1)$	$\mathcal{K}'(\mu_0)$
W	m_W	$2m_W$	1.33	1.31	1.21	1.15	1.05	1.15
$W + 1$ jet	m_W	$\langle p_T^{\rm jet}\rangle$	1.42	1.20	1.43	1.21	1.32	1.42
$W + 2$ jets	m_W	$\langle p_T^{\rm jet}\rangle$	1.16	0.91	1.29	0.89	0.88	1.10
$t\bar{t}$	m_t	$2m_t$	1.08	1.31	1.24	1.40	1.59	1.48
$b\bar{b}$	m_b	$2m_b$	1.20	1.21	2.10	0.98	0.84	2.51
Higgs via WBF	m_H	$\langle p_T^{\rm jet}\rangle$	1.07	0.97	1.07	1.23	1.34	1.09

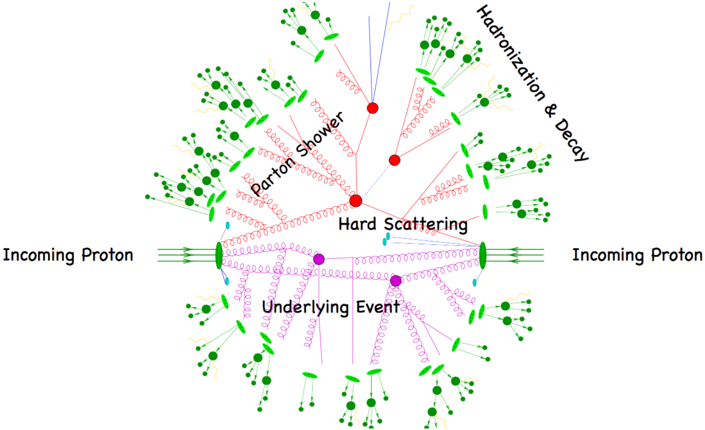


- This approach use calculation at LO and K factor was largely used from LHC Collaboration until few years ago.

All order approaches

• Nowdays: rather than systematically calculating to higher and higher orders in the perturbative expansion of a given observable alternative methods *all-orders* approaches are also commonly used to describe the phenomena observed at high-energy colliders. The merging of such a description with fixed-order calculations, in order to offer the best of both worlds, is of course highly desirable. One example:

• **Parton shower**. It is a **numerical approach**(program PYTHYA, HERWIG,SHERPA).By the use of the parton showering process, a few partons produced in a hard interaction at a high energy scale can be related to partons at a lower energy scale, where, a universal non-perturbative model can then be used to provide the transition from partons to the hadrons that are observed experimentally.This is possible because the parton showering allows for the evolution, using the DGLAP formalism, of the parton fragmentation function.


Hadronization & Decay
Parton Shower
Hard Scattering
Incoming Proton
Incoming Proton
Underlying Event

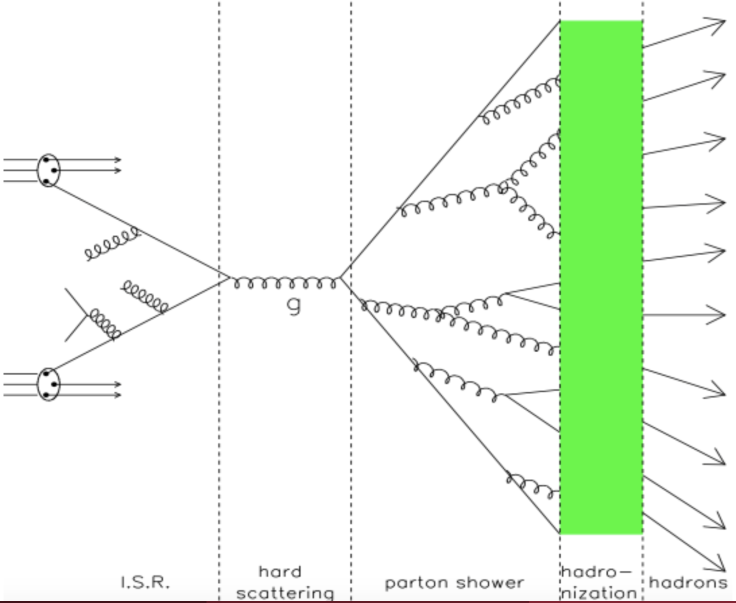
Pythia

- **PYTHIA** irradiates initial and final partons .
- PYTHIA generates as well high p_T partons.
- Generally parton shower rusums low p_T partons and NLO calculation take care of high p_T partons.
- In this sense PYTHIA overlies both fields.
- PYTHIA does take care of **hadronization**, dress the partons to detactable hadrons.

A combination of **NLO calculations with parton shower Monte Carlos** leads to the best of both worlds.

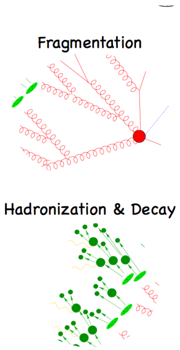
- The **NLO** aspect leads to a correct prediction for the **rate of the process** and also improves the description of the **first hard parton emission**.
- The **parton shower** aspect provides a sensible description of **multiple/soft collinear emissions**with a final state consisting of hadrons, which can then be input to a detector simulation.

Hadron collision



From Parton to Jets

- Steps **from partons** produced in hard subprocess **to** color neutral **hadrons**:
    - **Fragmentation**: partons can split into other partons (*parton shower*) → QCD: resummation of leading logarithmic contributions
    - **Hadronization**: parton shower forms hadrons → non-perturbative, only models
    - **Decay** of unstable **hadrons**→ pert. QCD, electroweak theory
- In practice: all of the above handled by Monte Carlo (MC) simulations



Parton luminosity

- Scattering at the LHC is not simply rescaled scattering at the Tevatron.
- For many of the key processes the typical **momentum fractions x are small**; thus, there is a **dominance of sea quark and gluon**scattering as compared to valence quark scattering at the Tevatron.
- There is a large phase space for **gluon emission** and thus intensive QCD backgrounds for many of the signatures of new physics.
- Useful to define the differential **parton-parton luminosity** $\frac{\mathrm{dLij}}{\mathrm{d\hat{s}dy}}$ and its integral $\frac{\mathrm{dLij}}{\mathrm{d\hat{s}}}$[4]

[4]rapidity: $y = \frac{1}{2} \log \frac{x_1}{x_2}$, parton centre-of-mass energy $\hat{s} = x_1 x_2 s$,$\longrightarrow$ partonic cross section decrease with $\frac{1}{\hat{s}}$

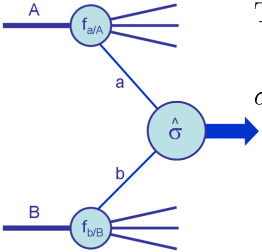
Parton luminosity

$$\frac{\mathrm{dLij}}{\mathrm{d\hat{s}dy}} = \frac{1}{s}\frac{1}{1 + \delta_{ij}}\left[f_i(x_1,\mu)f_j(x_2,\mu) + 1 \leftrightarrow 2\right]$$

s = centre-of-mass energy, μ is the it factorization scale, which can be thought as separation between long- and short- distance physics, Factor with Kronecker delta avoids double-counting when partons are identical(δ_{ij}).

Parton luminosity

$$\frac{\mathrm{dL_{ij}}}{\mathrm{d\hat{s}dy}} = \frac{1}{s}\frac{1}{1 + \delta_{ij}}\left[f_i(x_1,\mu)f_j(x_2,\mu) + 1 \leftrightarrow 2\right]$$



The generic parton-model formula: This

$$\sigma = \sum_{i,j}\int_0^1 \mathrm{d}x_1\mathrm{d}x_2 f_i(x_1,\mu)f_j(x_2,\mu)\hat{\sigma}_{ij}$$

can be written as

$$\sigma = \sum_{i,j}\int\left(\frac{\mathrm{d\hat{s}}}{\hat{s}}\mathrm{dy}\right)\left(\frac{\mathrm{dL_{ij}}}{\mathrm{d\hat{s}\ dy}}\right)(\hat{\mathrm{s}}\hat{\sigma}_{\mathrm{ij}})$$

result is easily derived by defining $\tau \equiv x_1 x_2 = \frac{\hat{s}}{s}$ and observing that the Jacobian $\frac{\partial(\tau,y)}{\partial(x_1,x_2)} = 1$:

Parton luminosity

$$\sigma = \sum_{i,j} \int \mathrm{d}\hat{s}\ \mathrm{d}y \left(\frac{\mathrm{dL_{ij}}}{\mathrm{d}\hat{s}\ \mathrm{d}y} \right) \hat{\sigma}_{\mathrm{ij}}(\hat{s})$$

$$\boldsymbol{\sigma} = \sum_{i,j} \int \mathrm{d}\hat{s} \left(\frac{\mathrm{dL_{ij}}}{\mathrm{d}\hat{s}} \right) \hat{\sigma}_{\mathrm{ij}}(\hat{s})$$

- This can be used to estimate the **production rate for subprocesses at LHC** or other colliders.

Figure shows parton-parton luminosities at $\sqrt{s} = 14$ TeV(integrated on y) for various parton combinations, calculated using the CTEQ6.1 parton distribution functions and scale $\mu = \sqrt{\hat{s}}$ [5].

$$\sigma = \sum_{i,j} \int d\hat{s} \left(\frac{dL_{ij}}{d\hat{s}} \right) \hat{\sigma}_{ij}(\hat{s})$$

- All energy and mass dependence is contained in parton luminosity function.
- Useful combination are $gg, \sum_i (gq_i + g\bar{q}_i + q_i g + \bar{q}_i g), \sum_i q_i\bar{q}_i + \bar{q}_i q_i (q_i = d, u, s, c, d)$
- Widths of curves estimate PDF uncertainties

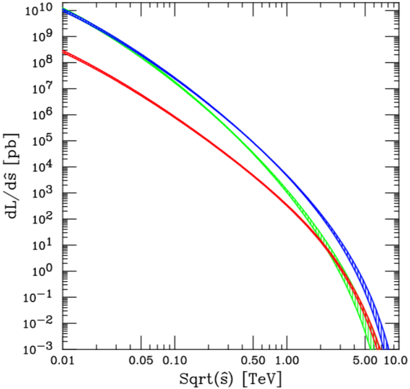


Figure : Green $= gg$, Blue $= \sum_i (gq_i + g\bar{q}_i + q_i g + \bar{q}_i g)$, Red $= \sum_i q_i\bar{q}_i + \bar{q}_i q_i (q_i = d, u, s, c, d)$

Parton luminosity

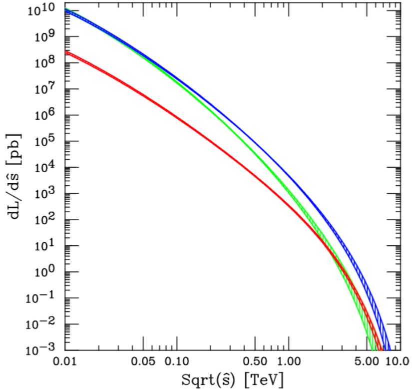


Figure : Green $= gg$, Blue $= \sum_i (gq_i + g\bar{q}_i + q_i g + \bar{q}_i g)$, Red $= \sum_i q_i\bar{q}_i + \bar{q}_i q_i (q_i = d, u, s, c, d)$

- As expected, the gg luminosity is large at low $\sqrt{\hat{s}}$ but falls rapidly with respect to the other parton luminosities.
- The gq luminosity is large large over the entire kinematic region plotted.

Parton luminosity

The precedent expression not integrated in y was:

$$\sigma = \sum_{i,j} \int \left(\frac{\mathrm{d}\hat{s}}{\hat{s}}\mathrm{dy}\right)\left(\frac{\mathrm{dL_{ij}}}{\mathrm{d}\hat{s}\ \mathrm{dy}}\right)(\hat{s}\hat{\sigma}_{\mathrm{ij}})$$

$$\sigma = \sum_{i,j} \int \mathrm{d}\hat{s}\ \mathrm{dy}\left(\frac{\mathrm{dL_{ij}}}{\mathrm{d}\hat{s}\ \mathrm{dy}}\right)\hat{\sigma}_{\mathrm{ij}}(\hat{s})$$

- **Masseles partons in final state**

The second product $\hat{\sigma}_{ij}(\hat{s})$for various $2 \leftrightarrow 2$ partonic processes has been calculated for massive and masseles partons in final state for parton with $p_T > 0.1 \times \sqrt{\hat{s}}$

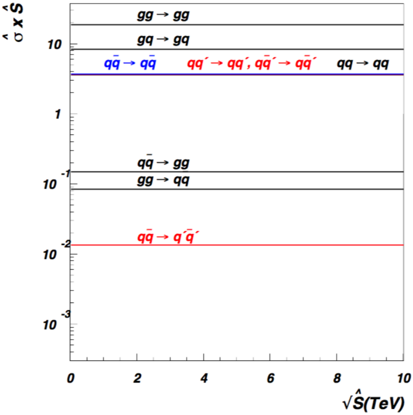


Figure : Parton level cross section $\hat{\sigma}_{ij}(\hat{s})$ involving massless partons final states

Parton luminosity

The precedent expression not integrated in y was:

$$\sigma = \sum_{i,j} \int \left(\frac{d\hat{s}}{\hat{s}} dy\right) \left(\frac{dL_{ij}}{d\hat{s}\ dy}\right) (\hat{s}\hat{\sigma}_{ij})$$

$$\sigma = \sum_{i,j} \int d\hat{s}\ dy \left(\frac{dL_{ij}}{d\hat{s}\ dy}\right) \hat{\sigma}_{ij}(\hat{s})$$

- **Massive partons in final state**
  - There is a threshold behaviour not present with massless partons.
  - The threshold behaviour is different for qq and gg initial states. The gg

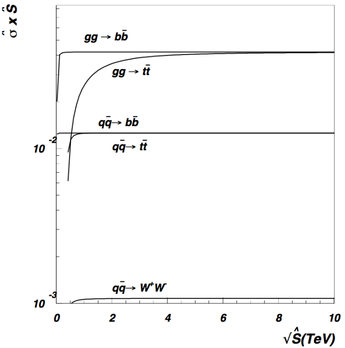


Figure : Parton level cross section $\hat{\sigma}_{ij}(\hat{s})$ involving massive partons final states

Parton luminosity

- Estimation of the QCD production cross sections for a given $\Delta\hat{s}$ and interval and a particular cut on $\frac{p_T}{\hat{s}}$

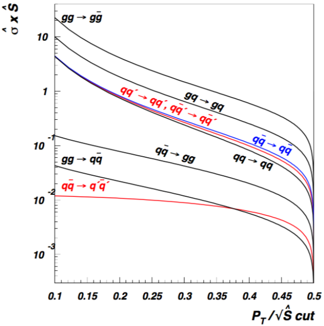


Figure : Parton level cross sections $\hat{\sigma}_{ij}(\hat{s})$ involving massless partons final states vs $\frac{p_T}{\hat{s}}$

$$\sigma \;=\; \frac{\Delta\hat{s}}{\hat{s}}\left(\frac{\mathrm{dL_{ij}}}{\mathrm{d\hat{s}}}\right)(\hat{\sigma}_{ij}(\hat{s}))$$

♣ example: **gluon-gluon pair production rate $gg \to gg$ at $\hat{s} = 1$ TeV, $\Delta\hat{s} = 0.01\hat{s}$**

- $\frac{\Delta\hat{s}}{\hat{s}}$
- $\left(\frac{\mathrm{dL_{ij}}}{\mathrm{d\hat{s}}}\right) \simeq 10^3\mathrm{pb}$
- $(\hat{\sigma}_{ij}(s\hat{_{gg}}\hat{s})\cdot) \simeq 20$

$\Longrightarrow \simeq 200$ pb$(p_T > 0.1 \times \sqrt{\hat{s}})$

Parton luminosity

One can further specify the parton-parton luminosity for a specific rapidity y and $\hat{s}$ and $\left(\frac{\mathrm{dL_{ij}}}{\mathrm{d\hat{s}\ dy}}\right)$

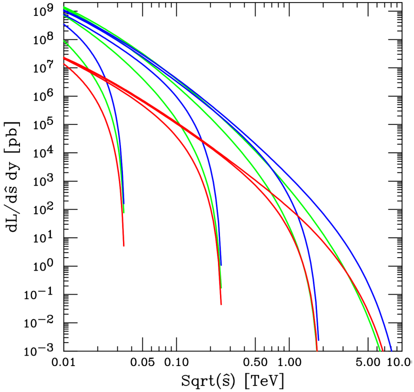


Figure : $\left(\frac{\mathrm{dL_{ij}}}{\mathrm{d\hat{s}\ dy}}\right)$ at rapidity (right to left) y = 0, 2, 4, 6. Green = gg , Blue = $\sum_i (gq_i + g\bar{q}_i + q_i g + \bar{q}_i g)$, Red = $\sum_i q_i\bar{q}_i + \bar{q}_i q_i (q_i = d, u, s, c, d)$

- **LHC vs Tevatron**

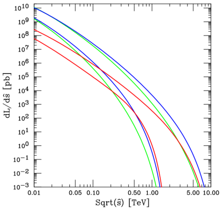


Figure : The parton-parton luminosity $\left(\frac{\mathrm{dL_{ij}}}{\mathrm{d\hat{s}}}\right)$ in pb integrated over y. Green $= gg$, Blue $= \sum_i (gq_i + g\bar{q}_i + q_i g + \bar{q}_i g)$, Red $= \sum_i q_i\bar{q}_i + \bar{q}_i q_i (q_i = d, u, s, c, b)$.The top family of curves are for the LHC and the bottom for the Tevatron.

The increase in pdf luminosity at the LHC comes from gg initial states, followed by gq initial states and then $q\bar{q}$ initial states. The latter ratio is smallest because of the availability of valence antiquarks at the Tevatron at moderate to large x.

Parton luminosity- advantages

- Hard process cross section calculation independent from particle accelerator or center of mass - except for kinematic phase space factors and requirements
- Parton luminosity allows to compare cross sections at different energies and between proton-proton vs proton-antiproton
- If event rates for signal and backgrounds are known, by calculation or by measurement,for some point $(\sqrt{s}, \sqrt{\hat{s}})$, the parton luminosities can be used to estimate the rates at other points, at an accuracy satisfactory for orientation for past (Tevatron) present(LHC) future accelerators.

Gluon-Gluon Fusion [6]

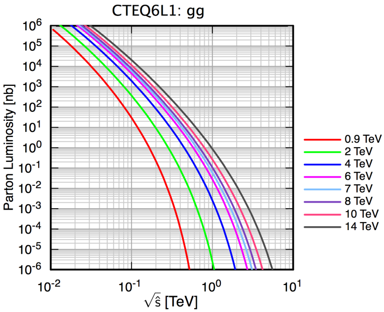


Figure : Parton luminosity gg interactions

- loss of magnitude running $\sqrt{s}$= 14 TeV or 7 TeV
- reduction in cross section implies longer data taking period to accumulate same number of events needed for discovery or exclusion $N = \mathcal{L} \cdot \sigma$
- identical for pp and $p\bar{p}$
- gluon-gluon fusion critical for Higgs discovery at LHC

[6] http://www.hep.ph.ic.ac.uk/ wstirlin/plots/plots.html, C.Quigg,LHC Potential vs. energy:Consideration for2011Run https://arxiv.org/pdf/1101.3201

$u\bar{d}$

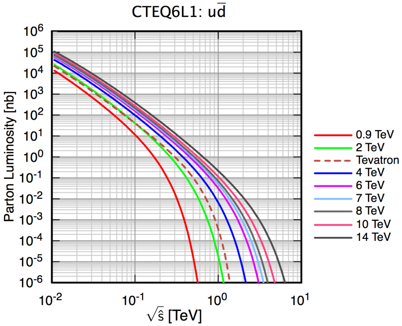


Figure : Parton luminosity $u\bar{d}$ interactions

- In pp collisions $u\bar{d}$ is a valence-sea combination.
- in $p\bar{p}$ collisions $u\bar{d}$ is valence-valence
- The difference is reflected in the excess of the Tevatron luminosities over the proton-proton luminosities at $\sqrt{s} = 2$ TeV.
- Smaller gain for higher center of mass energy at LHC

lightquark-lightquark

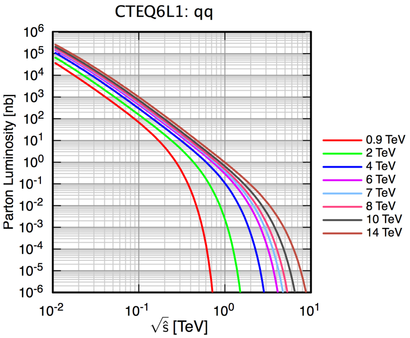


Figure : Parton luminosity light quarks interactions

- The parton luminosities for light-quark-light-quark interactions in pp collisions
- examples of valence-valence interactions leading to final states such as two jets:
- Combination of $(u + d)^{(1)} \otimes (u + d)^{(2)}$ for pp
- Combination of $(u + d)^{(p)} \otimes (\bar{u} + \bar{d})^{(\bar{p})}$ for $p\bar{p}$(2TeV Tevatron interpretation)
- Moderate but not huge gain at LHC even at 14 TeV

gluon-lightquark

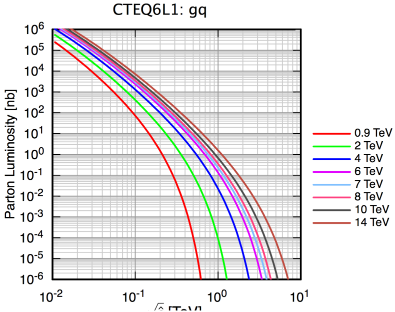


Figure : Parton luminosity light quarks gluon interactions

- Displayed $(u + d)^{(1)} \otimes g^{(2)}$
- For pp the gq luminosity is is twice what is shown in Figure $(u + d)^{(1)} \otimes g^{(2)} + (u + d)^{(2)} \otimes g^{(1)}$
- For $p\bar{p}$ $(u + d)^{(p)} \otimes g^{(\bar{p})}$ (gq collisions) or $q^{(p)} \otimes (\bar{u} + \bar{d})^{(\bar{p})}$ ($g\bar{q}$ collisions) (2TeV Tevatron interpretation)

Parton luminosity-Ratio

Ratios of parton luminosities are especially useful for addressing what is gained or lost by running at one energy instead of another.

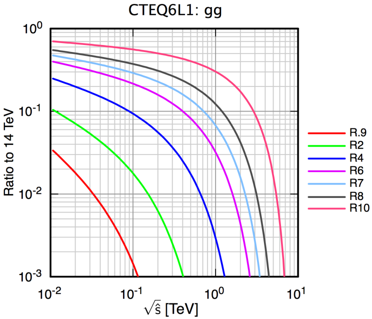


Figure : Comparison of parton luminosity for gg interactions at specified energies at 14 TeV

- At $\sqrt{\hat{s}} \approx 0.4$ TeV ($t\bar{t}$ production) the gg luminosity rises by three orders of magnitude from the 2-TeV Tevatron to the 14-TeV LHC.
- This rise is the source of the computed increase in $gg \to t\bar{t}$ cross section from Tevatron to LHC.
- The $gg \to t\bar{t}$ yield drops by a bit more than a factor of 6 between 14 TeV and 7

Higgs

To first approximation, accumulating a $t\bar{t}$ sample of specified size at $\sqrt{s} = 7$ TeV will require about $6\times$ the integrated luminosity that would have been needed at $\sqrt{s} = 14$ TeV.

The dominant mechanism for light Higgs-boson production at both the Tevatron and the LHC is $gg \to$ top-quark loop $\to H$, so the rates are determined by gg luminosity,

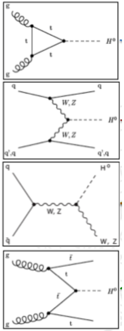


Figure : Production diagramms

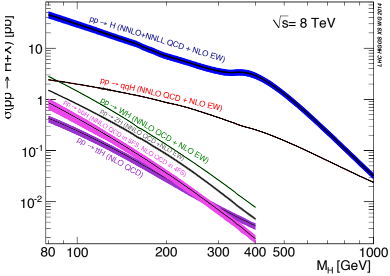


Figure : SM Higgs production cross section at 8 TeV

Higgs

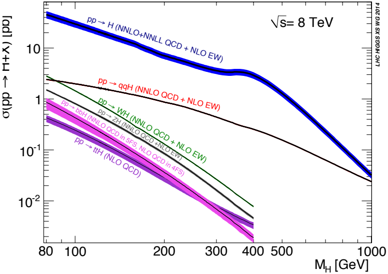


Figure : SM Higgs production cross section at 8 TeV

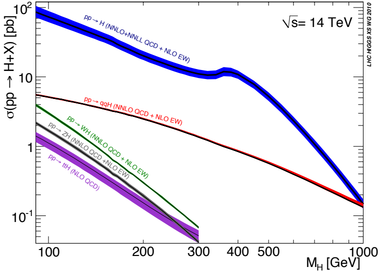


Figure : SM Higgs production cross section at 14 TeV