Collider Physics - Introduction
A.A. 2021 - 2022

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AA 21-22

last mod. 22-Sep-21

Contents

- The static quark model
- Hadron structure
- Heavy flavors – e^+e^- low energy
- Weak interactions
- K^0 mesons - CKM matrix
- The Standard Model
- High energy ν interactions

1. Hadron Colliders : pp – $\bar{p}$p
2. The Sp$\bar{p}$S – $W^\pm$ and Z discovery
3. LEP – e^+e^- precision physics
4. Searches and limits
5. LHC – Higgs discovery
6. Physics bSM – the future

since AA 2019-20 the old "Particle Physics" (12 CFU) has been split:

1st part : 1st year, 2nd semester

2nd part : 2nd year, 1st semester (**NOW**).

— Nostro figlio sta cambiando una lampadina... E' meraviglioso quello che insegnano all'università, al giorno d'oggi...

"Our son is changing a light bulb... What they teach at university nowadays is wonderful..."

Collider Physics

How to present the material ? why "collider physics" (*) or "astro-particle physics" instead of "weak interactions" or "strong interactions" ?

i.e. present the results in order of time (history) and technology instead of similar theoretical background ?

In my opinion, the latter approach is correct for old results, which rely on methods now obsolete, and for people who do not want to join the research.

(*) I keep saying "Collider Physics" instead of the official name "Collider Particle Physics" [*sorry*].

(Future) researchers should be aware of the tight connections between experimental methods and theory. The discussion of past results is useful as an example of future activity.

The importance of the technology (detector construction, data taking and manipulation) is such that nowadays a group of physicists extracts all types of information from a data sample, which is both precious and difficult to manage.

These lectures are devoted to "Collider Physics", i.e. the results that in the last years have been obtained with colliding beams, both e^+e^-, $\bar{p}p$ and pp (*in future also* $\mu^+\mu^-$ *might join*).

slides / textbooks / original

- These slides have many sources (lectures in our + other Department(s), textbooks, seminars, …); many thanks to everybody, but all the mistakes are my own responsibility
- download from http://www.roma1.infn.it/people/bagnaia
- comments and criticism to paolo.bagnaia@roma1.infn.it (**please !**)
- they are only meant to help you follow the lectures (and remember the items);
- i.e. NOT enough for the exam; students are also required to study on textbook(s) / original papers (see references);
- the original literature is always quoted; sometimes those papers offer a beautiful example of clarity; however, particularly in recent years, their technical level is difficult, probably more at PhD level;
- students are strongly encouraged to attack the real stuff: these lectures are NOT meant for *amateurs* or interested public (which are welcome), but for future professionals !
- the lectures are delivered in English;
- during the lecture, questions and comments in the language as you like: if necessary, I will translate into English.
- between this course and that of "Particle Physics" there is no formal prerequisite; however, the topics discussed there will be considered known [*few slides shown at the end of this chapter*].

References

[BJ] **W. E. Burcham - M. Jobes – Nuclear and Particle Physics** – Wiley – 768 pag. [*clear, well-organized, old*];

[YN] **Yorikiyo Nagashima – Elementary Particle Physics** – Wiley VCH – 3 vol. [*clear, modern, complete, very expensive*];

[Bettini] **A.Bettini - Introduction to Elementary Particle Physics** [*another textbook*];

[MS] **B.R.Martin, G.Shaw – Particle Physics** [*ditto*];

[Perkins] **D.Perkins - Introduction to High Energy Physics**, 4th ed. [*ditto*];

[Povh] **Povh, Rith, Scholz, Zetsche - Particles and Nuclei** [*ditto, simpler*];

[Thoms] **M. Thomson – Modern Particle Physics** [*ditto*];

[CG] **R.Cahn, G.Goldhaber – The experimental foundation of particle physics** [*a collection of original papers + explanation, the main source for experiments*];

[FNSN1] **C.Dionisi, E.Longo - Fisica Nucleare e Subnucleare 1** – Dispense del corso [*in Italian, download it from our web – you are requested to know them*];

[MQR] **L.Maiani - O.Benhar – Meccanica Quantistica Relativistica** [*in Italian, the theory lectures of the previous year*];

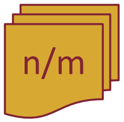
[IE] **L.Maiani – Interazioni elettrodeboli** [*ditto*];

[PDG] **The Review of Particle Physics –** latest: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018) [*the bible; everything there, but more a reference, than a textbook, i.e. hard for newcomers*];

[original] **Original papers** are quoted in the slides [*try to read (some of) them* → help by [CG]].

quoted as [book, chapter] or [book, page];
e.g. [BJ, § 4] *: Burcham-Jobes, § 4*.

Symbols



(in the upper left corner) this is page *n* of a total of *m* pages : read them all together;

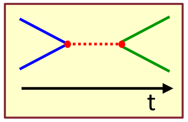
(in the upper right corner) optional material;

(in the upper right corner) tool, used also in other chapters;

summary;

animation (ppt/pptx only);

reference to a paper / textbook;
[if textbook, you are requested to read it; if paper, try (at least some of) them];



in Feynman diagrams, time goes always left to right;

- "QM" : Quantum Mechanics;
- "SM" : Standard Model; here and there, the name and the history behind is explained;
- "bSM" : beyond Standard Model, i.e. the (until now unsuccessful) attempts to extend it, e.g. SUSY;
- ($\hbar$ = c = 1) whenever possible; i.e. mass, momentum and energy in MeV or GeV.
- m : scalar, E : component of a vector;
- $\mathbb{P}$: operator;
- $\vec{v}$: 3-vector, $\vec{v} = (x, y, z)$;
- p : 4-vector, $p = (E, p_x, p_y, p_z) = (E, \vec{p})$;
- if worth, the module is indicated $p = (E, p_x, p_y, p_z; m) = (E, \vec{p}; m)$;
- if irrelevant, the last component of a 3- or 4-vector is skipped : $p = (E, p_x, p_y) = (E, p_x, p_y; m)$.

room, time, services

Lecture time – aula 8 N.E.

- tue (mar) 14 - 16
- wed (mer) 13 - 15
- thu (gio) 8 - 10

[*not perfect but acceptable*]

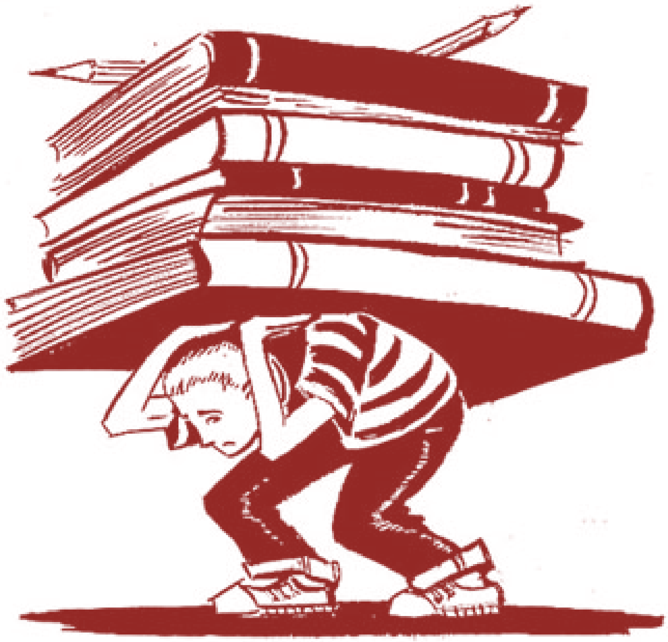
- The lecture system is explained in: https://www.phys.uniroma1.it/fisica/didattica/orario-delle-lezioni
- following the thread, you'll get the timetable, the rules, the link to follow in remote mode, etc etc. (English translation available);
- please be particularly strict on the rules, e.g. greenpass and masks : they have been designed to minimize the risks;
- **play nice with yourselves, your friends, and even with me**.

Faculty referents:

- physical and learning disabilities: prof. Varone (laura.varone@uniroma1.it);
- students' Ombudsperson: prof. Dalla Cort (garantesmfn@uniroma1.it).

exam

- the exam will be in Italian or English, at **<u>your</u>** choice.
- questions [by me] and answers [*possibly by you*];
- 1st question known few days in advance by email [*I'll choose randomly, with a little bias*];
- if theoretician or experimentalist, you may [or may not] tell me [*I'll use it*];
- let me also know curriculum type (e.g. phenomenology, electronics, medical physics) [*I'll apply a stronger bias*];
- other rules after discussion and experiment [*I'm an experimentalist*].



Nota Bene

Between this course and "Particle Physics" there is no formal prerequisite; however, the topics discussed there will be considered known.

In the following, I enclose some slides, useful as a reference. Neither a part of the program, nor for the exam, but you better remember.

Resonance parameterizations [PP § 0]

Many more parameterizations used in literature (semi-empirical or *theory inspired*), e.g.:

$$\sigma_0 = \left[\frac{16\pi}{(2p)^2}\right]\left[\frac{(2J_R+1)}{(2S_a+1)(2S_b+1)}\right]\left[\frac{\Gamma_{ab}}{\Gamma_R}\right]\left[\frac{\Gamma_{final}}{\Gamma_R}\right]\left[\frac{\Gamma_R^2/4}{\left(\sqrt{s}-M_R\right)^2+\Gamma_R^2/4}\right]$$

original, non-relativistic

$$\sigma_1 = \left[\frac{16\pi}{s}\right]\left[\frac{(2J_R+1)}{(2S_a+1)(2S_b+1)}\right]\left[\frac{\Gamma_{ab}}{\Gamma_R}\right]\left[\frac{\Gamma_{final}}{\Gamma_R}\right]\left[\frac{\Gamma_R^2/4}{\left(\sqrt{s}-M_R\right)^2+\Gamma_R^2/4}\right]$$

m_a, m_b << p

$$\sigma_2 = \left[\frac{16\pi}{M_R^2}\right]\left[\frac{(2J_R+1)}{(2S_a+1)(2S_b+1)}\right]\left[\frac{\Gamma_{ab}}{\Gamma_R}\right]\left[\frac{\Gamma_{final}}{\Gamma_R}\right]\left[\frac{\Gamma_R^2/4}{\left(\sqrt{s}-M_R\right)^2+\Gamma_R^2/4}\right]$$

if $M_R \gg \Gamma_R$, neglect s-dependence

$$\sigma_3 = \left[\frac{16\pi}{M_Z^2}\right]\left[\frac{3}{4}\right]\left[\frac{\Gamma_{ee}}{\Gamma_Z}\right]\left[\frac{\Gamma_{f\bar{f}}}{\Gamma_Z}\right]\left[\frac{M_Z^2\Gamma_Z^2}{\left(s-M_Z^2\right)^2+M_Z^2\Gamma_Z^2}\right]$$

relativistic BW for $e^+e^- \to Z \to f\bar{f}$

$$\sigma_4 = \left[\frac{16\pi}{M_Z^2}\right]\left[\frac{3}{4}\right]\left[\frac{\Gamma_{ee}}{\Gamma_Z}\right]\left[\frac{\Gamma_{f\bar{f}}}{\Gamma_Z}\right]\left[\frac{s\Gamma_Z^2}{\left(s-M_Z^2\right)^2+s^2\Gamma_Z^2/M_Z^2}\right]$$

"s-dependent Γ_Z" (used at LEP for the Z lineshape)

Hypothesis test [PP § 0]

Given a measurement x with an expected value μ and an error σ, the value

$$F(x) = \int_x^{+\infty} G(t\,|\,\mu,\sigma)dt$$

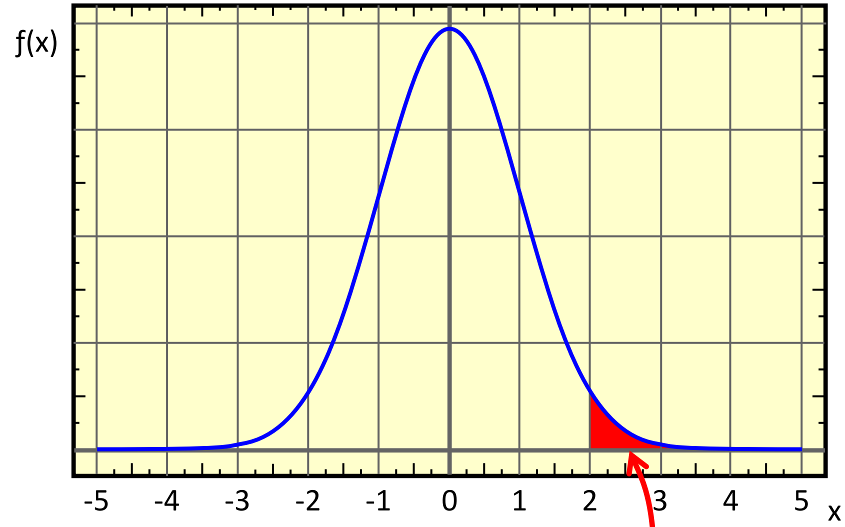
is often used as a "hypothesis test" of the expectation.

E.g. (see the ◣ plot): if the observation is at 2σ from the expectation, one speaks of a "2σ fluctuation" (not dramatic, it happens once every 44 trials – or 22 trials if both sides are considered).

The value of "5σ" (*) has assumed a special value in modern HEP [*see later*].

———————————————

(*) in popular language, the term "5σ" means a fluctuation with probability $\leq$ 2.87 E-7, even in the non-gauss case (strictly speaking a mistake, but everybody says so).



x	G(x|0,1)	F(x)	$=1/n_{trial}$
0	3.989 E-01	5.000 E-01	2
1	2.420 E-01	1.587 E-01	6.3
2	5.399 E-02	**2.275 E-02**	44.0
3	4.432 E-03	1.350 E-03	741
4	1.338 E-04	3.167 E-05	31,500
5	**1.487 E-06**	**2.867 E-07**	**3.5 E+06**
6	6.076 E-09	9.866 E-10	1.0 E+09
7	9.135 E-12	1.280 E-12	7.8 E+11

Kinematical variables of DIS [PP § 2]

$\begin{cases} e^-_{init} & p\ (E, \vec{p}; m_\ell); \\ N_{init} & P\ (M, \vec{0}; M); \end{cases}$ $\begin{cases} e^-_{fin} & p'\ (E', \vec{p}'; m_\ell); \\ N_{fin} & p_H\ (E_H, \vec{p}_H; W); \end{cases}$

p, p', P, P_H, q, Q^2, M, ν, x, y, W^2 Lorentz invariant;

E,E', … Lab sys (= P at rest).

$$q = p - p' = (E - E', \vec{p} - \vec{p}');$$

m << M (safe approx);

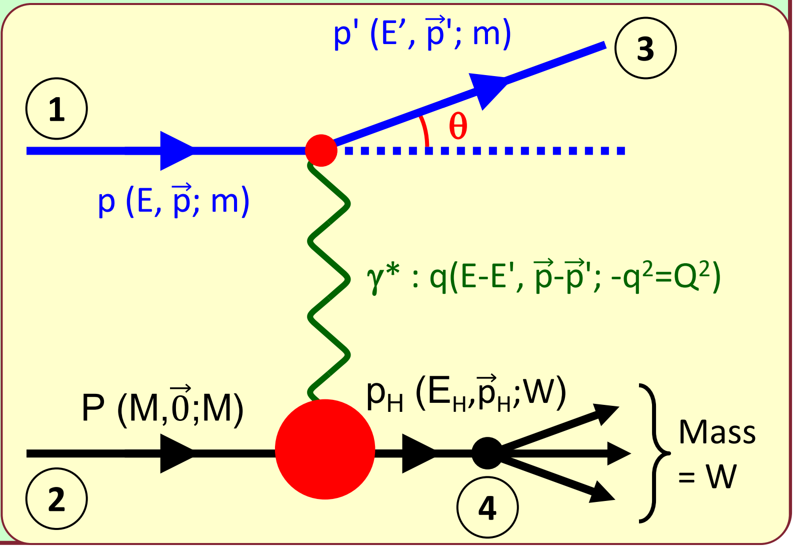
$$q^2 = m^2 + m^2 - 2EE' + 2pp'\cos\theta \approx -2EE'(1 - \cos\theta) = -4EE'\sin^2\left(\frac{\theta}{2}\right) \equiv -Q^2;$$

$$\nu \equiv \frac{q \cdot P}{M} = \frac{(E - E')M}{M} = (E - E');$$

warning: x_B is very interesting, *see later*

$$x \equiv \frac{Q^2}{2M\nu}; \qquad y \equiv \frac{q \cdot P}{p \cdot P} = \frac{(E - E')M}{EM} = \frac{E - E'}{E} = \frac{\nu}{E};$$

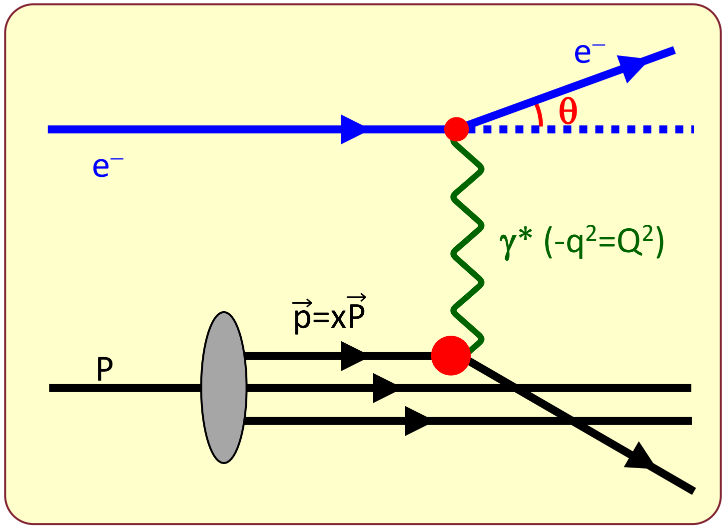
$$W^2 = p_H^2 = (P + q)^2 = M^2 - Q^2 + 2M\nu.$$



The parton model in DIS [PP § 2]

A summary of the model, with final formulæ (shown below and in the next slide):

- at high Q^2, a hadron (p/n) behaves as a mixture of small components, the partons.
- partons are pointlike, spin ½;
- each parton in each interaction is described by its fraction x_i of the 4-momentum of the hadron;



- the x_i are qm variables, described by their distribution functions $f_i^p(x)$ [called "***PDF***"];
- in principle the PDF are different for each parton and each hadron;
- $\sum_j \int dx\, x\, f_j^p(x) \leq 1$;
- parton spin = ½ → Callan-Gross $2xF_1(x) = F_2(x)$.

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2}{Q^4}\left[W_2\left(Q^2,\nu\right)\cos^2\frac{\theta}{2} + 2W_1\left(Q^2,\nu\right)\sin^2\frac{\theta}{2}\right];$$

$$\frac{d^2\sigma}{dxdy} = \frac{4\pi\alpha^2 s}{Q^4}\left[xy^2F_1\left(x,Q^2\right) + (1-y)F_2\left(x,Q^2\right)\right];$$

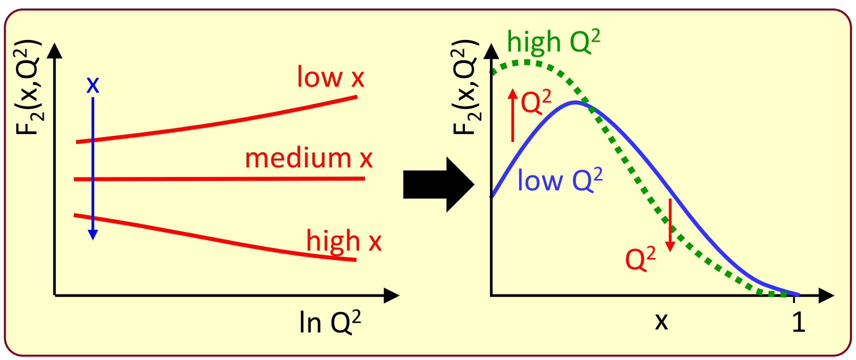
$$F_1\left(x,Q^2\right) = MW_1(Q^2,\nu) = \frac{1}{2}\sum_j e_j^2 f_j(x);$$

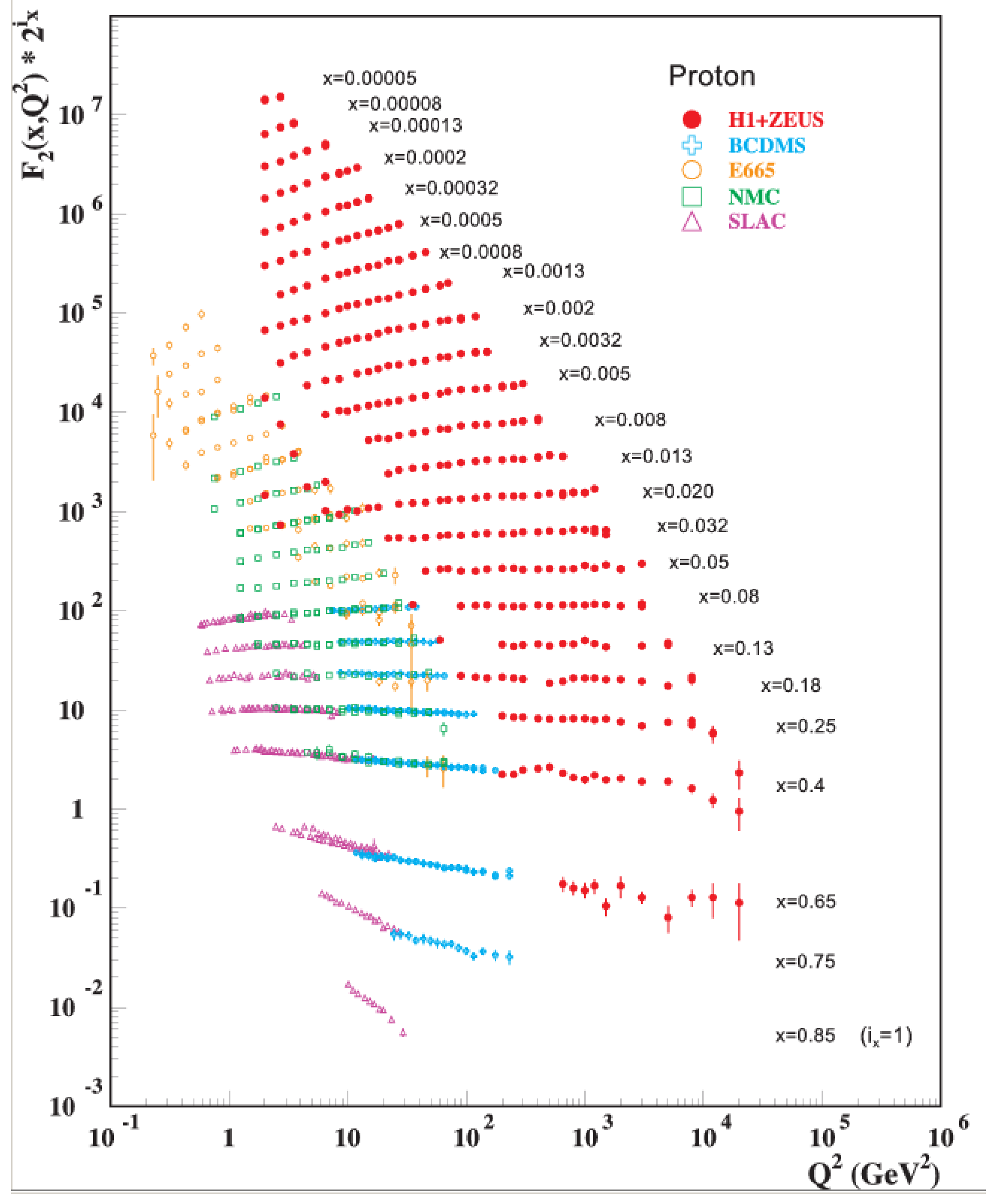
$$F_2\left(x,Q^2\right) = \nu W_2(Q^2,\nu) = x\sum_j e_j^2 f_j(x).$$

$F_2(x,Q^2)$: Scaling violations [PP § 2]

Modern experiments have probed the nucleon to very high values of Q^2. Now electrons are often replaced with muons, which have the advantage of intense beams of higher momenta. Or, even better, the experiments are carried out at e^-p Colliders (HERA).

There are data up to $Q^2 \approx 10^5$ GeV^2: when plotting F_2 as function of Q^2 at fixed x, some Q^2-dependence appears, incompatible with Bjorken scaling [*see plot and sketch, and the next slides*].





$F_2(x,Q^2)$: Q^2 evolution [PP § 2]

However, this effect (*scaling violations*), is NOT attributed to sub-structures or other novel physics, but to a dynamical change in F_2, well understood in QCD.

$$\begin{cases} \sum_{\text{partons}} \int_0^1 x f_j(x) dx < 1; \\ \sum_{\text{partons}} \int_0^1 f_j(x) dx = \text{undefined (but large).} \end{cases}$$

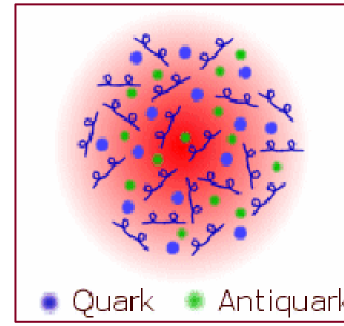
In QCD :

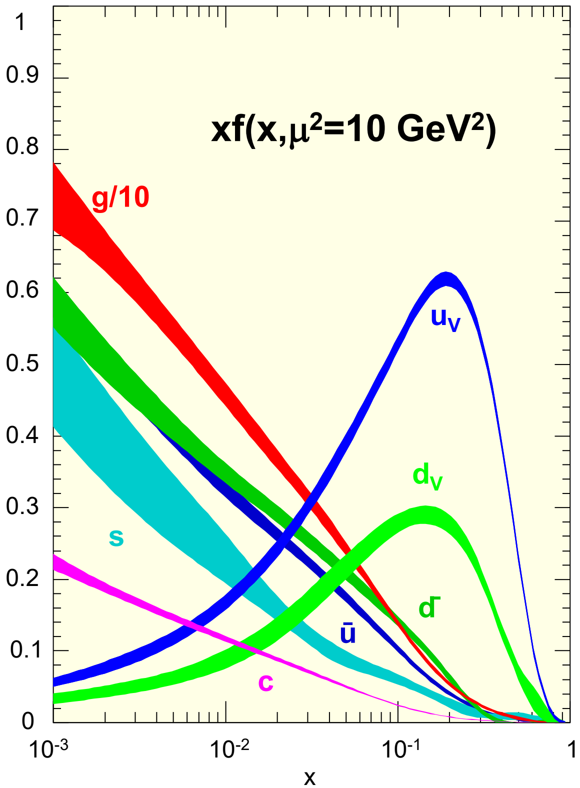
- higher Q^2

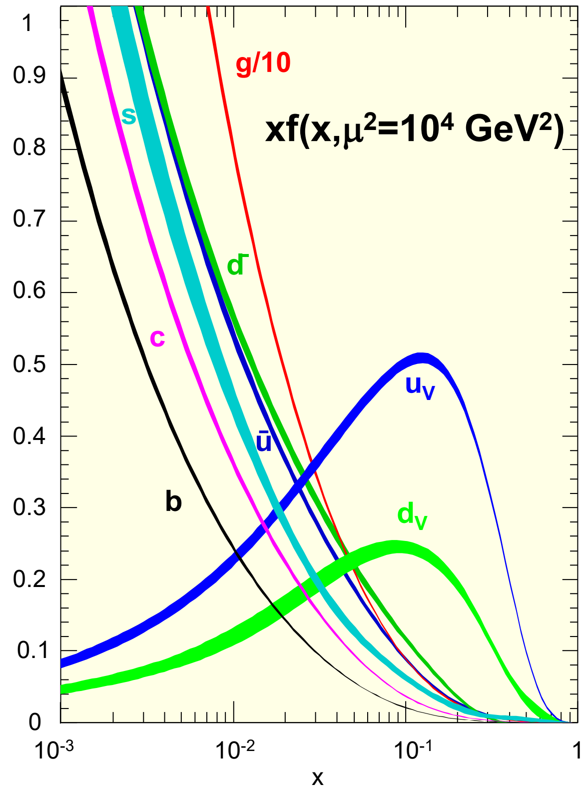
$\rightarrow$ smaller size probed

$\rightarrow$ more $q\bar{q}$ and gluons

$\rightarrow$ less valence quarks.



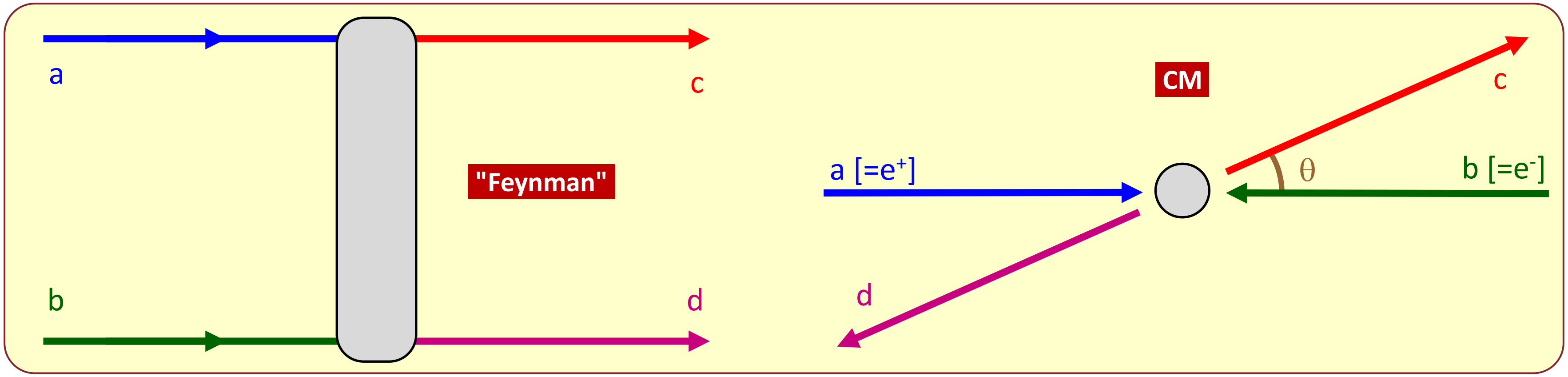




a modern parameterization of the PDF [*NNPDF3.0- (NNLO)*] shows clearly the difference in the PDF when $Q^2 = 10 \div 10^4$ GeV^2:

- u_V, d_V $\rightarrow$ down;
- $\bar{u}$, $\bar{d}$, [= u_S, d_S,] g $\rightarrow$ up;
- s, c, b $\rightarrow$ up (more phase space).

Mandelstam variables [PP § 3]



The Mandelstam variables **s, t, u**:

CM system:

- $p_a = [E, \quad p, \quad 0, \quad 0];$
- $p_b = [E, \quad -p, \quad 0, \quad 0];$
- $p_c = [E, p\cos\theta, p\sin\theta, \quad 0];$
- $p_d = [E, -p\cos\theta, -p\sin\theta, 0];$

s,t,u L-invariant:

- $s \equiv (p_a + p_b)^2 = (p_c + p_d)^2 = 4E^2;$
- $t \equiv (p_a - p_c)^2 = (p_b - p_d)^2 \approx -½\, s\, (1 - \cos\theta) = -s \sin^2(\theta/2);$
- $u \equiv (p_a - p_d)^2 = (p_b - p_c)^2 \approx -½\, s\, (1 + \cos\theta) = -s \cos^2(\theta/2);$
- $s + t + u = 0$ (→ 1+1 independent variables, e.g. [E,θ], [s, t], [√s,θ]).

Lorentz-invariant variables for 2→2 processes.

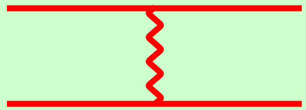
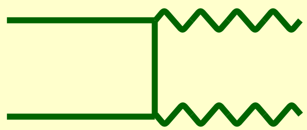
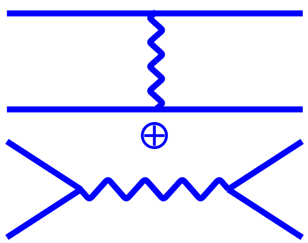
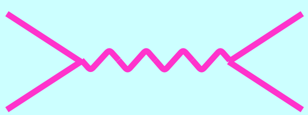
Assume $E \gg m_i$, for the masses of all 4 bodies (otherwise, look for the formulæ in [PDG]).

Q. : what about φ (the azimuth) ?
A. : if nothing in the dynamics is φ-dependent (e.g. the spin direction), then the cross-section must be φ-symmetric.

(*) **NOT** specific of h.f. or e^+e^-; here just for convenience.

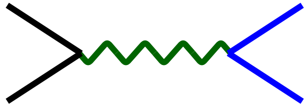
Collisions e^+e^- : QED cross sections [PP § 3]

Consider some QED processes in lowest order [$\sqrt{s} \ll m_Z$, only γ^* exchange] :

➢ $e^\pm e^\pm \to e^\pm e^\pm$		$\frac{d\sigma(e^\pm e^\pm \to e^\pm e^\pm)}{d\cos\theta} = \frac{2\pi\alpha^2}{s} \times \left(\frac{3+\cos^2\theta}{1-\cos^2\theta}\right)^2;$
➢ $e^+e^- \to$ □		$\frac{d\sigma(e^+e^- \to \gamma\gamma)}{d\cos\theta} = \frac{2\pi\alpha^2}{s} \times \frac{1+\cos^2\theta}{1-\cos^2\theta};$
➢ $e^+e^- \to e^+e^-$		$\frac{d\sigma(e^+e^- \to e^+e^-)}{d\cos\theta} = \frac{\pi\alpha^2}{2s} \times \left(\frac{3+\cos^2\theta}{1-\cos\theta}\right)^2;$
➢ $e^+e^- \to \mu^+\mu^-$		$\frac{d\sigma(e^+e^- \to \mu^+\mu^-)}{d\cos\theta} = \frac{\pi\alpha^2}{2s} \times \left(1+\cos^2\theta\right);$

Collisions e^+e^- : $\sigma(e^+e^- \to \mu^+\mu^-, q\bar{q})$ [PP § 3]

- $e^+e^- \to \mu^+\mu^-$



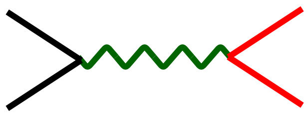
$$\sigma_{\mu\mu} = \int_{-1}^{1} d\cos\theta \left[\frac{d\sigma_{\mu\mu}}{d\cos\theta}\right] = \frac{\pi\alpha^2}{2s}\int_{-1}^{1} d\cos\theta\left(1+\cos^2\theta\right) =$$

$$= \frac{4\pi\alpha^2}{3s} = \frac{86.8 \text{ nb}}{s[\text{GeV}^2]} = \frac{21.7 \text{ nb}}{E^2_{beam}[\text{GeV}^2]}.$$

$[1+\cos^2\theta] = P_1^{Legendre}(\cos\theta)$

[spin 1 $\to$ 2 spin ½]

- $e^+e^- \to q\bar{q}$



$$\frac{d\sigma_{q\bar{q}}}{d\cos\theta} = \frac{d\sigma_{\mu\mu}}{d\cos\theta} \times c_f e_f^2 = \frac{\pi\alpha^2}{2s} c_f e_f^2 \left(1+\cos^2\theta\right); \quad c_f = \begin{cases} 3 & \text{quarks} \\ 1 & \text{leptons} \end{cases} \quad \text{[color]}$$

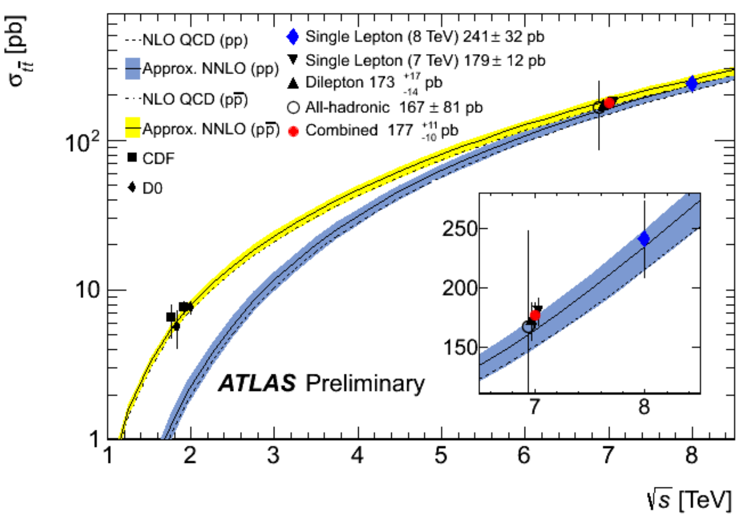
$$\sigma_{q\bar{q}} = \sigma_{\mu\mu} c_f e_f^2 = \frac{4\pi\alpha^2}{3s} c_f e_f^2; \quad e_f = \begin{cases} 1 & \text{leptons} \\ 2/3 & u\ c\ t \\ -1/3 & d\ s\ b \end{cases} \quad \text{[charge].}$$

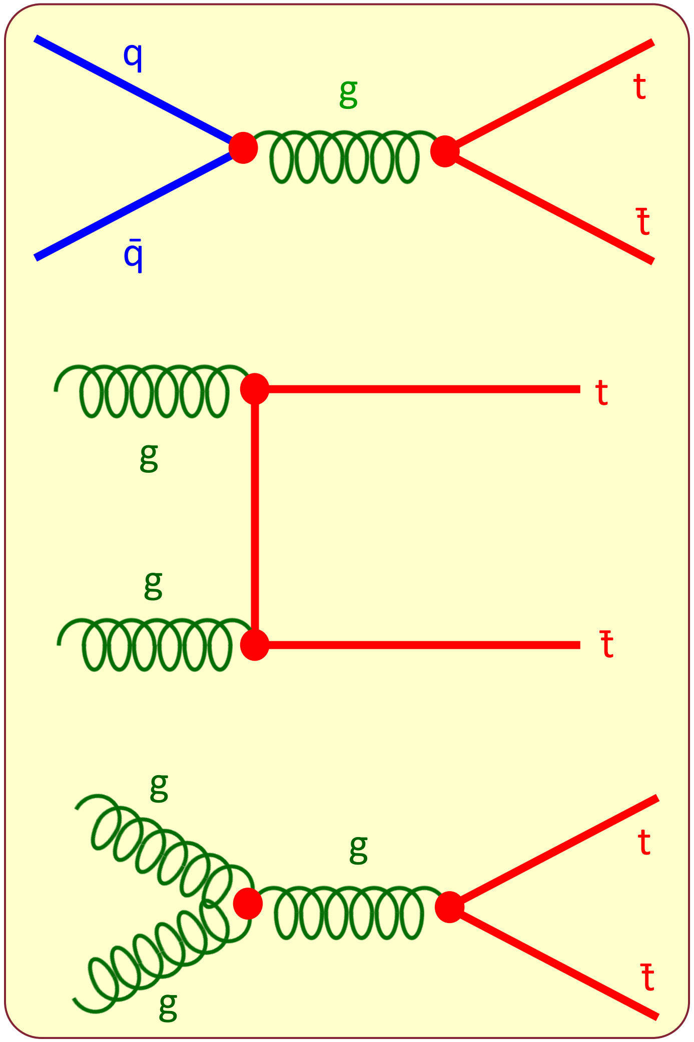
heavy quarks ($e^+e^- \to f\bar{f}$):

$$\beta_f = \sqrt{1 - \frac{4m_f^2}{s}} \qquad \frac{d\sigma_{f\bar{f}}}{d\cos\theta} = \frac{\pi\alpha^2 c_f e_f^2}{2s}\beta_f\left[\left(1+\cos^2\theta\right) + \left(1-\beta_f^2\right)\sin^2\theta\right] \qquad \sigma_{f\bar{f}} = \boxed{\frac{4\pi\alpha^2}{3s}}\ \beta_f \frac{3-\beta_f^2}{2} = \boxed{\sigma_0}\ \beta_f \frac{3-\beta_f^2}{2}.$$

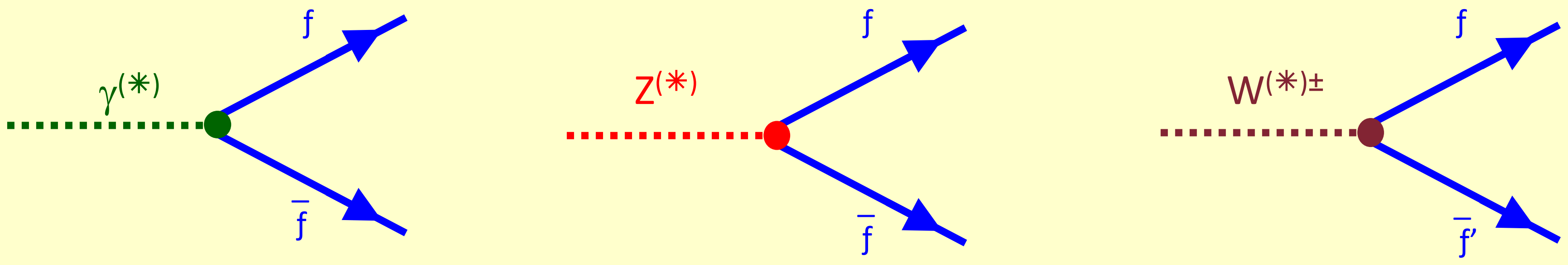
The t quark production [PP § 3]

- in a hadronic collider [*see Coll.Phys.*], the top is produced in pairs, via hadronic interactions;
- in pp and p̄p the PDF of initial state partons are different (valence / sea): the qq̄ channel decreases from 90% (p̄p at Tevatron, √s=1.8 TeV) to 5% (pp at LHC, √s=14 TeV) [*qualitatively understandable*];
- in the same range, the total cross section increases from 5 to 600 pb [*also quite understandable*].





e.m., NC, CC [PP § 4]



photon (γ)
(electromagnetism)

$$\mathcal{L}_F = -e J^{\mu}_{e.m.} A_{\mu};$$
$$J^{\mu}_{e.m.} = Q_f \overline{\Psi}_f \gamma^{\mu} \Psi.$$

[V]

neutral IVB (Z)
(neutral current)

$$\mathcal{L}_F = \frac{-e}{\sin\theta_W \cos\theta_W} J^{\mu}_{nc} Z_{\mu};$$
$$J^{\mu}_{nc} = \overline{\Psi}_f \gamma^{\mu} \frac{g^f_V - g^f_A \gamma^5}{2} \Psi_f.$$

[combination g^f_V V + g^f_A A]

charged IVB (W±)
(charged current)

$$\mathcal{L}_F = \frac{-e}{\sqrt{2}\sin\theta_W} J^{\mu}_{cc} \tau^{\pm} W^{\pm}_{\mu};$$
$$J^{\mu}_{cc} = \overline{\Psi}_f \gamma^{\mu} \frac{1-\gamma^5}{2} \Psi_f.$$

[V - A]

CKM matrix [PP § 5]

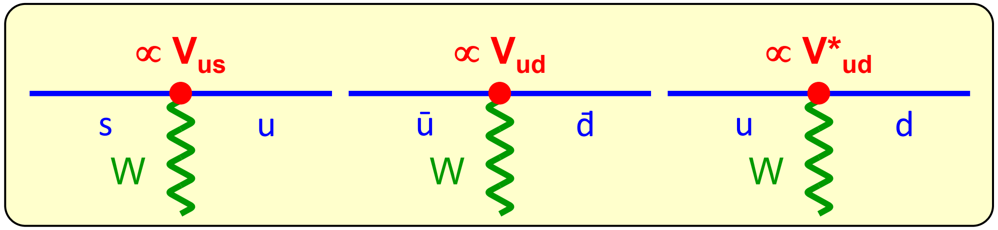
Reinterpret the ℂℙ violation using the CKM matrix [§ 4]:

NB **V_{CKM}** is a fundamental ingredient of the SM; the actual values V_{ij} are observable (→ measurable, see later), but not predictable inside the SM (like fermion masses, number of families, ...)

- the weak charged current for quarks [d,s,b are down-quark spinors and ū,c̄,t̄ are the adjoint spinors for up-quarks]

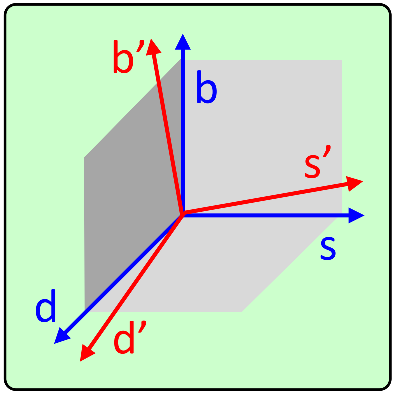
$$j^{\mu}_{qq} = -i\frac{g}{\sqrt{2}}(\bar{u},\ \bar{c},\ \bar{t})\gamma^{\mu}\frac{1}{2}\left(1-\gamma^{5}\right)V_{CKM}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- therefore, e.g. [notice the "*"; the definition is "V_{ij} when bds is a spinor and ūc̄t̄ the adjoint spinor" and "V^*_{ij} when uct is a spinor and b̄d̄s̄ the adjoint spinor".]



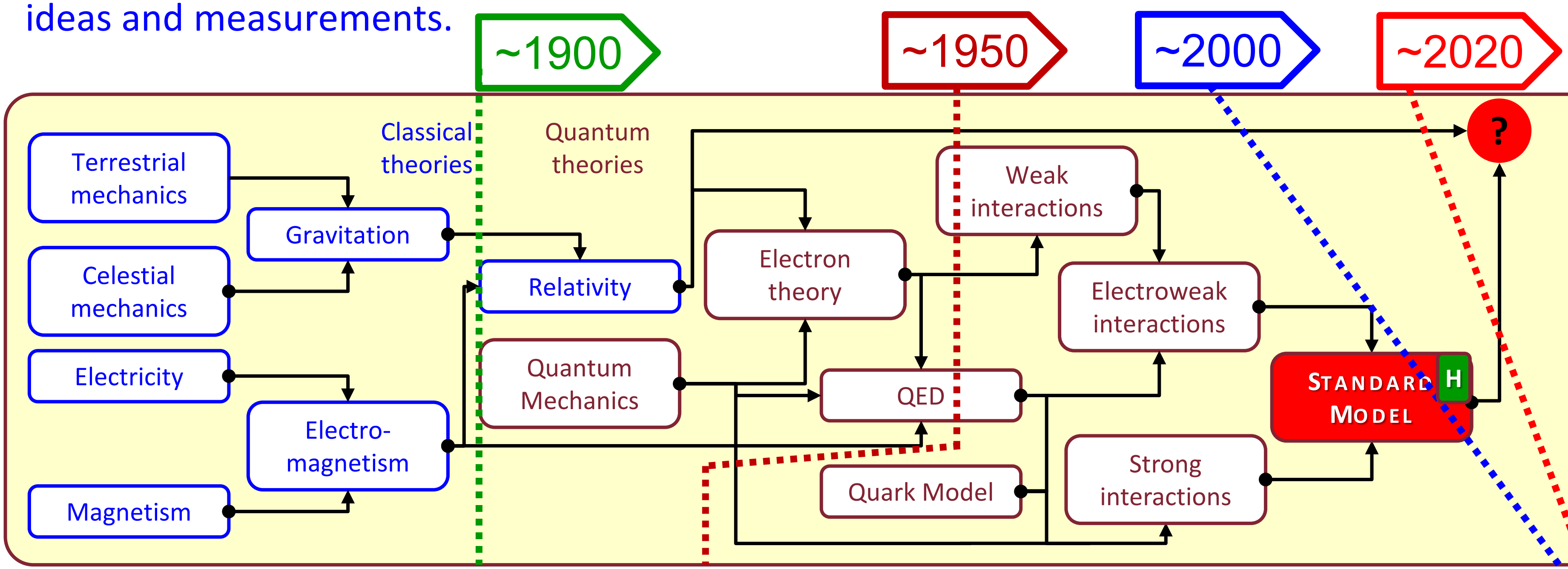
- the V_{CKM} matrix represents the rotation, i.e. the amount of mixing among rotated quarks.

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



[PP § 6]

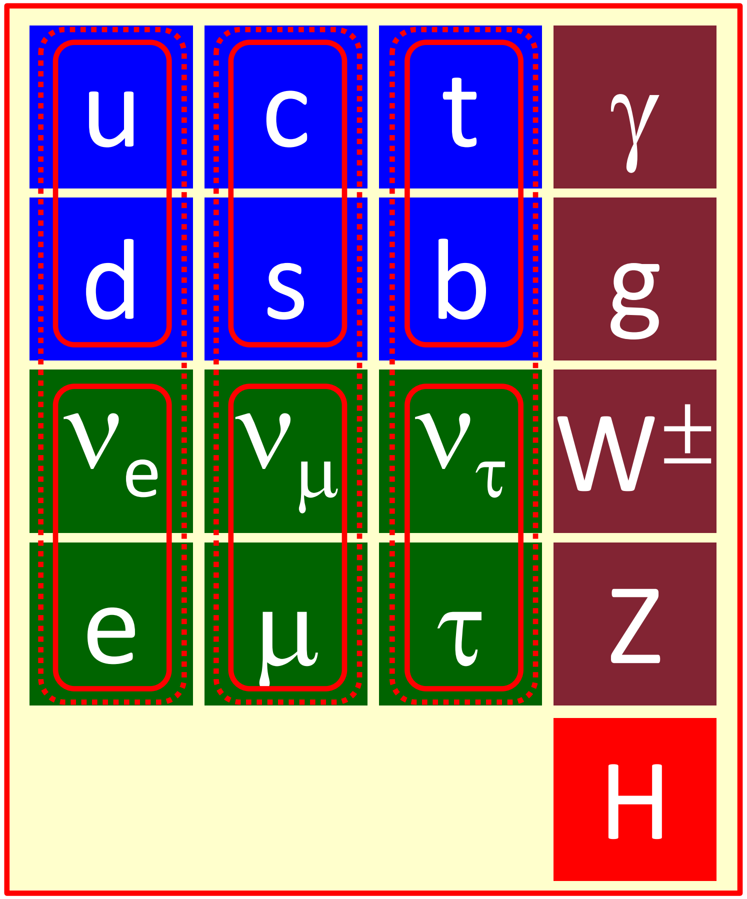
- The name **SM** (not a fancy name) designates the theory of the Electromagnetic, Weak and Strong interactions.
- The theory has grown in time, the name went together.
- The development of the SM is a complicated interplay between new ideas and measurements.
- Many theoreticians have contributed : since the G-S-W model is at the core of the SM, it is common to quote them as the main authors.
- The little scheme [BJ] of its time evolution may help (missing connections, approximations, …).



Particle classification [PP § 6]

The present understanding of our world, in terms of its constituents and interactions, is much advanced:

- **fermions** (quarks/leptons) = matter:
  - "families" of doublets + antiparticles;
  - spin ½;
  - massive (large differences in mass);
  - charge ±⅔, ±⅓, 0, ±1;
- **bosons** = forces:
  - spin 1;
  - massless (γ, g) or massive ($W^{\pm}$, Z);
  - charged ($W^{\pm}$) or neutral (γ, g, Z);
  - some self-coupled;
- the mysterious **Higgs boson** carries the particle masses.



Summary of e.w. formulæ [PP § 6]

- The Z coupling is "universal": it only depends on the electric charge and weak isospin:

$$g_z \equiv \frac{g}{\cos\theta_w}\left[I_{w_z} - Q\sin^2\theta_w\right] =$$

$$= \frac{\sqrt{4\pi\alpha}}{\sin\theta_w \cos\theta_w}\left[I_{w_z} - Q\sin^2\theta_w\right].$$

warning: these formulæ (and all those of this chapter) are simple and elegant, but only valid at 1st order; *the devil lies in the details* (= higher order corrections).

Summary :

$$m_w^2 = \frac{\sqrt{2}g^2}{8G_F} = \frac{\pi\alpha}{\sqrt{2}G_F \sin^2\theta_w} = \left(\frac{37.3}{\sin\theta_w}\ \text{GeV}\right)^2$$

$$G_F = \frac{\sqrt{2}g^2}{8m_w^2}$$

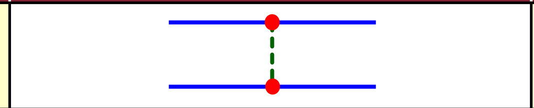
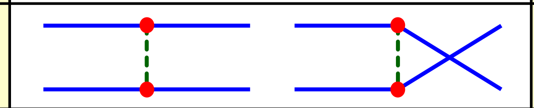
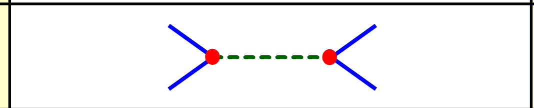
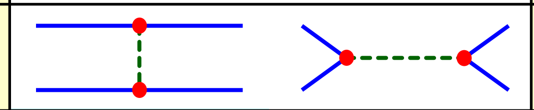
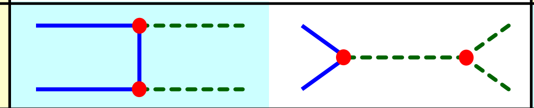
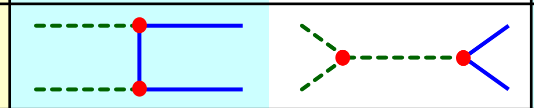
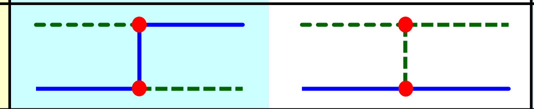
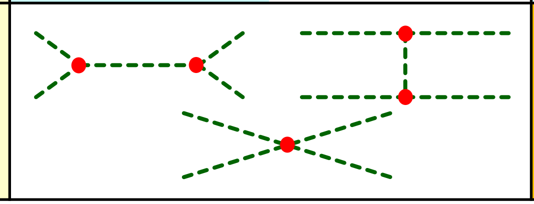
$$\tan\theta_w = \frac{g'}{g}$$

$$g\sin\theta_w = q_e = \sqrt{4\pi\alpha}$$

$$\frac{1}{\alpha} = \frac{4\pi}{g^2} + \frac{4\pi}{g'^2}$$

$$m_w = m_z\cos\theta_w$$

Strong interactions: 2→2 processes [PP § 6]

process	$[\frac{d\sigma}{d\Omega} = \alpha_s^2 f(s,t,u)/(9s)]$ f(s,t,u)	f(θ=90°) [t=u=−s/2]	diagram(s)	QED equivalent
$qq' \to qq'$ $\bar{q}q' \to \bar{q}q'$	$(s^2+u^2)/t^2$	5		$e^-\mu^- \to e^-\mu^-$ $e^+\mu^- \to e^+\mu^-$
$qq \to qq$ $\bar{q}\bar{q} \to \bar{q}\bar{q}$	$(s^2+t^2)/u^2+(s^2+u^2)/t^2-2s^2/(3ut)$	7+⅓= 7.3		$e^-e^- \to e^-e^-$ $e^+e^+ \to e^+e^+$
$q\bar{q} \to q'\bar{q}'$	$(t^2+u^2)/s^2$	½= 0.5		$e^+e^- \to \mu^+\mu^-$
$q\bar{q} \to q\bar{q}$	$(t^2+u^2)/s^2+(s^2+u^2)/t^2-2u^2/(3st)$	5+⅚= 5.8		$e^+e^- \to e^+e^-$
$q\bar{q} \to gg$	$8/3(t^2+u^2)[1/(tu) -9/(4s^2)]$	2+⅓= 2.3		$e^+e^- \to \gamma\gamma$
$gg \to q\bar{q}$	$3/8(t^2+u^2)\ [1/(tu) -9/(4s^2)]$	$^{21}/_{64}$= 0.3		$\gamma\gamma \to e^+e^-$
$gq \to gq$ $g\bar{q} \to g\bar{q}$	$(s^2+u^2)[9/(4t^2)-1/(su)]$	13+¾= 13.8		$\gamma e^- \to \gamma e^-$ $\gamma e^+ \to \gamma e^+$
$gg \to gg$	$81/8[3-ut/s^2-su/t^2-st/u^2]$	68+$^{11}/_{32}$= 68.3		$[\gamma\gamma \to \gamma\gamma]$

The **lowest order processes** of **the strong interactions in QCD:**

- s,t,u,θ at parton level ($\hat{s}$, $\hat{t}$, $\hat{u}$);
- q' : q' ≠ q.

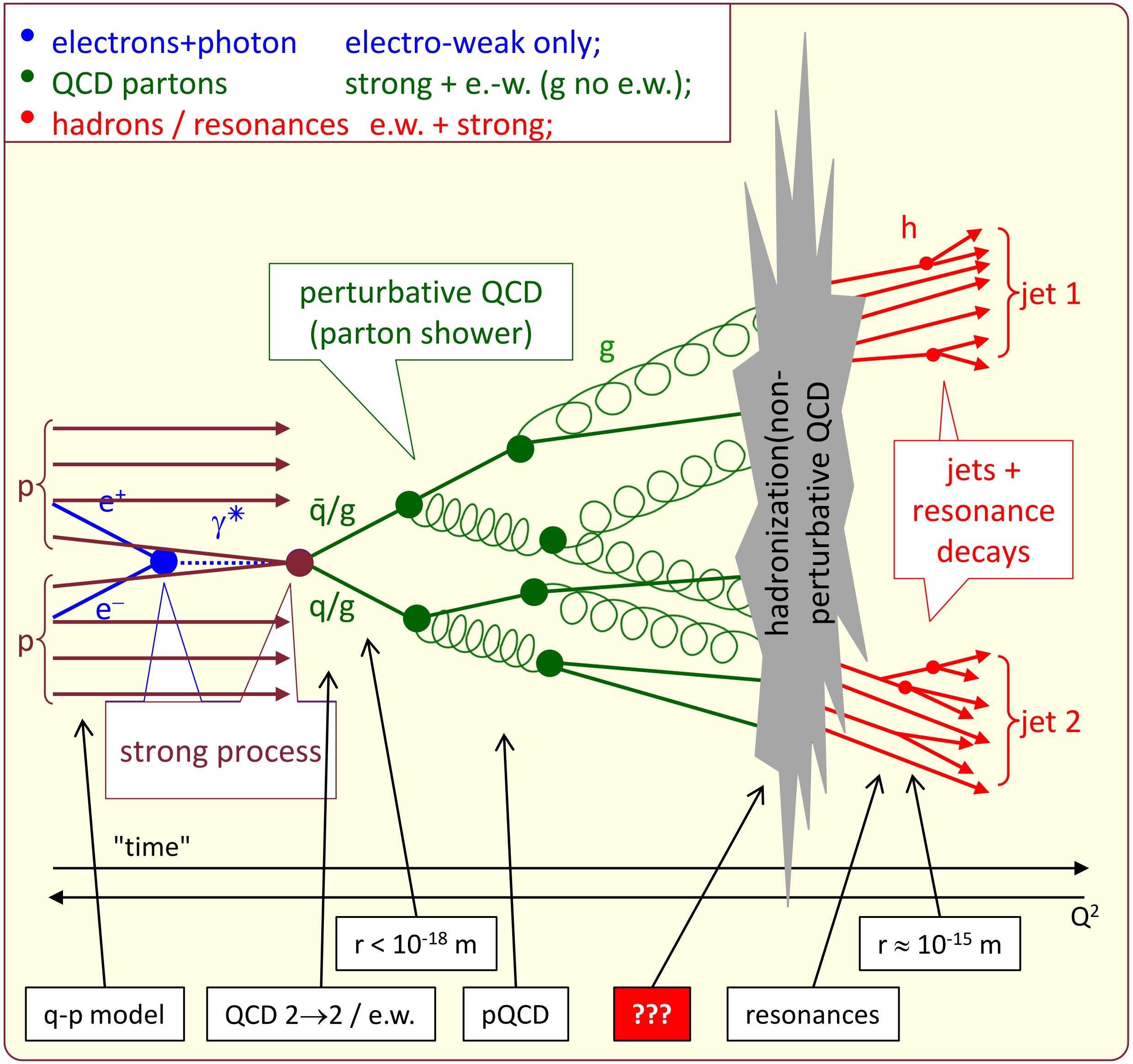
——— q or $\bar{q}$;
- - - - γ_{QED} or g_{QCD}.

Strong interactions: jets [PP § 6]

Three phases after elementary process :

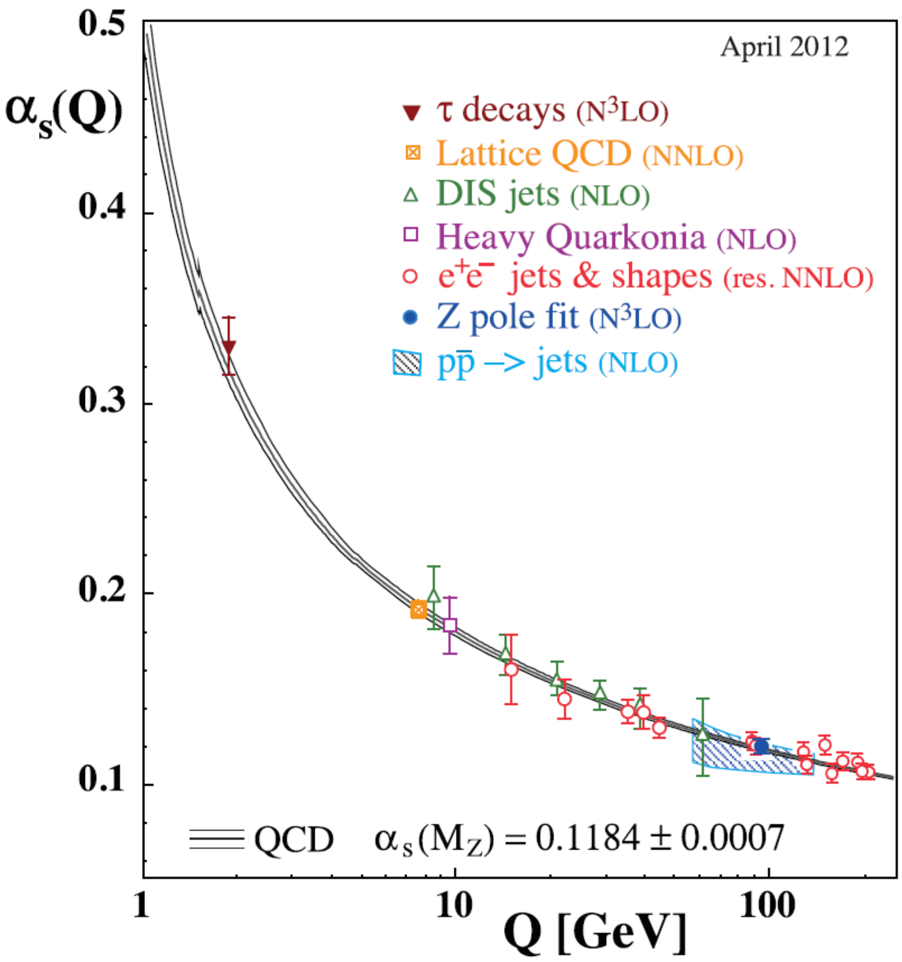
- **parton shower** : perturbative cascade of (q q̄ g); notice the gluon self-coupling (non-abelian);
- **hadronization** : low-Q^2 parton processes, <u>no well-funded calculation</u>;
- **hadrons** : decays of resonances and emergence of jets.

NB Lot of work in parameterizations, fitting, algorithms, speculations …



The running of α_s in QCD [PP § 6]

- Actually the running of $\alpha_s = \alpha_s(Q^2)$ has been shown, by measuring the strength of the coupling at different Q^2.
- The data of the figure show a variation of 100 in $\sqrt{Q^2}$, which ranges from τ decay to jets at LHC energies.
- The measurements are compared with predictions, normalized to the value with smallest error, i.e. at $Q^2 = m^2(Z)$ [only the "running" can be computed in QCD, not the abs. value].
- The funny acronyms (N^3LO, NNLO) refer to the computations : they are performed at a given order of Feynman diagrams : NLO = "next to leading order", NNLO = "next to next …"…
- *What does "Lattice QCD" mean ?*



$$\alpha_s(Q^2) = \alpha_s(Q_0^2) \Big/ \left[1 + \alpha_s(Q_0^2)\frac{11N_c - 2N_f}{12\pi}\ell n\left(\frac{Q^2}{Q_0^2}\right)\right].$$

In addition, a lot about detectors and accelerators (from the Lab. course) and some statistics and data manipulation (= computing); I'll try to be auto-consistent, but clearly more knowledge = better understanding.

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End - Introduction