Elementary Particle Physics

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Elementary particles and fundamental interactions

Matter — fermions $s = 1/2$, $\psi(x)$

$$\begin{cases} \text{leptons} & \begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \\ \text{quarks} & \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \end{cases}$$

Interactions — bosons $s = 1$, B^μ

$$\begin{cases} \text{photon } \gamma & \text{EM} \\ W^\pm, Z^0 & \text{WK} \\ \text{gluons } G^a \ (a = 1, \dots 8) & \text{SG} \end{cases}$$

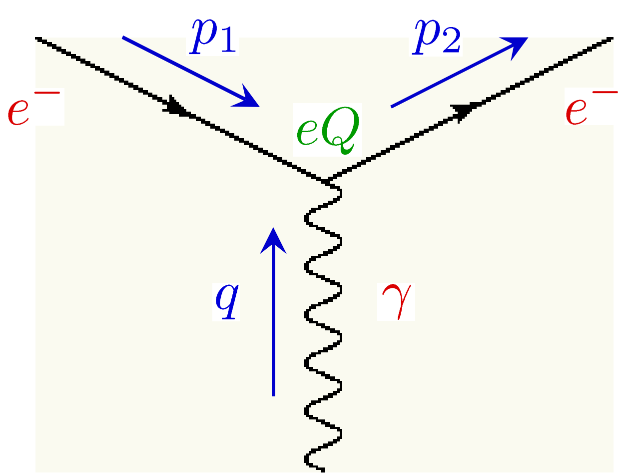
Electromagnetic interaction

$$\mathcal{L}_{\rm EM} = e J_\alpha^{\rm EM} A^\alpha$$

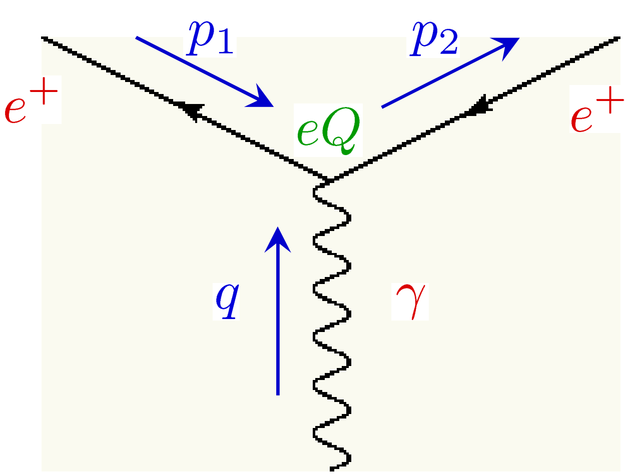
$$J_\alpha^{\rm EM} = Q_i \bar{\psi}_i \gamma_\alpha \psi_i$$

A^α photon field

ψ_i fermion (lepton or quark) field



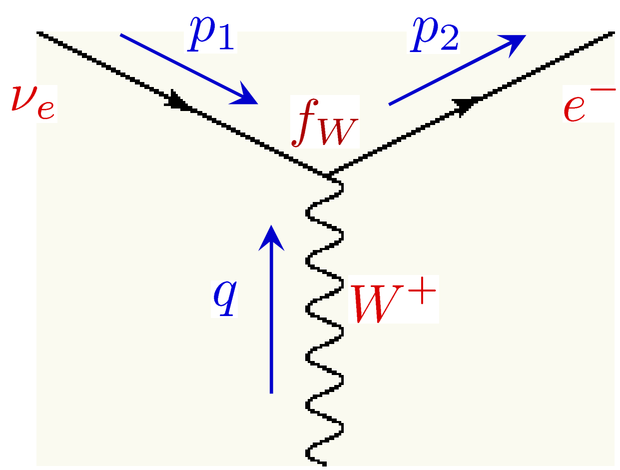
$$q = p_2 - p_1$$



Weak charged current

$$\mathcal{L}_W = f_W (j_\alpha^W + J_\alpha^W) W^\alpha + \text{h.c.}$$

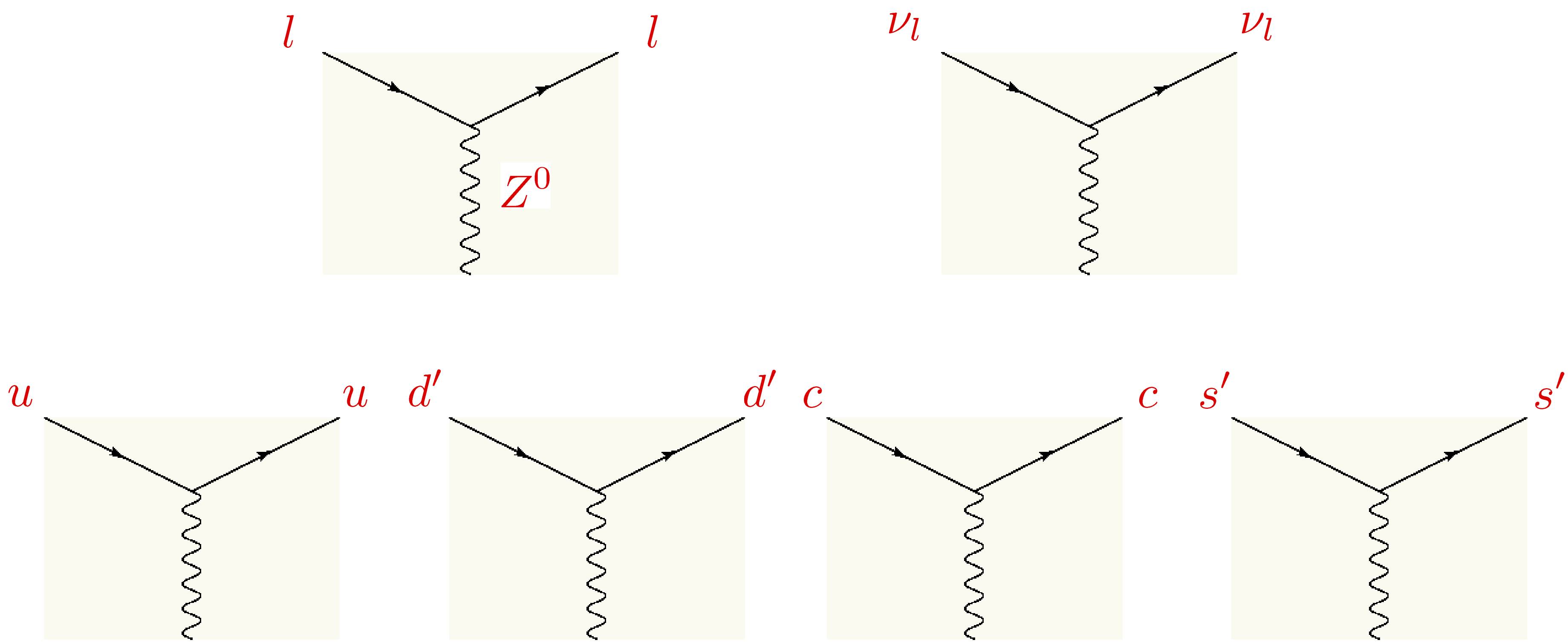
$$j_\alpha^{\text{W}} = \bar{\psi}_e \gamma_\alpha (1-\gamma_5)\psi_{\nu_e} + \bar{\psi}_\mu \gamma_\alpha (1-\gamma_5)\psi_{\nu_\mu} + \bar{\psi}_\tau \gamma_\alpha (1-\gamma_5)\psi_{\nu_\tau}$$



$$q = p_2 - p_1$$

$$J_\alpha^W = \sum_{j=1,2,3} \bar{\psi}_{u_i} \gamma_\alpha (1-\gamma_5) V_{ij} \psi_{d_j}$$

Weak neutral currents



$$\mathcal{L}_Z = f_Z J^Z_\alpha Z^\alpha$$

$J^Z_\alpha = \bar{\psi}_i \mathcal{O}_\alpha \psi_i$ $\quad$ $\mathcal{O}_\alpha$ operator which contains some combination of $\gamma_\alpha, \gamma_\alpha\gamma_5$

Observed:

$$\nu_\mu + \mathcal{N} \longrightarrow \nu_\mu + X$$

$$\bar{\nu}_\mu + \mathcal{N} \longrightarrow \bar{\nu}_\mu + X$$

$$\frac{\sigma(\nu_\mu + \mathcal{N} \to \nu_\mu + X)}{\sigma(\nu_\mu + \mathcal{N} \to \mu^- + X')} \simeq 0.25$$

$$\frac{\sigma(\bar{\nu}_\mu + \mathcal{N} \to \bar{\nu}_\mu + X)}{\sigma(\bar{\nu}_\mu + \mathcal{N} \to \mu^+ + X')} \simeq 0.45$$

Absence of neutral currents with $\Delta S = 1$

Notice that:

$$\begin{aligned} d' &= d\ \cos\theta_C + s\ \sin\theta_C \\ s' &= -d\ \sin\theta_C + s\ \cos\theta_C \end{aligned}$$

$$(\bar{d}'d') \equiv (\bar{\psi}_{d'}\mathcal{O}_\alpha\psi_{d'}) = \cos^2\theta_C(\bar{d}d) + \sin^2\theta_C(\bar{s}s) + \sin\theta_C\cos\theta_C[(\bar{d}s) + (\bar{s}d)]$$

$$(\bar{s}'s') \equiv (\bar{\psi}_{s'}\mathcal{O}_\alpha\psi_{s'}) = \cos^2\theta_C(\bar{s}s) + \sin^2\theta_C(\bar{d}d) - \sin\theta_C\cos\theta_C[(\bar{d}s) + (\bar{s}d)]$$

$$(\bar{d}'d') + (\bar{s}'s') = (\bar{d}d) + (\bar{s}s)$$

Weak neutral current do not lead to S violating processes

This requires the presence of the c quark

Glashow-Iliopoulos-Maiani (GIM) mechanism

In order to properly write the structure of the weak neutral current we have to develop the Standard Model as a gauge theory for weak + electromagnetic interactions

unified view

Glashow-Weinberg-Salam Model

$$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$$ doublet of weak isospin T

$$T_3(\nu_{eL}) = +1/2$$

$$T_3(e_L) = -1/2$$

e_R singlet of weak isospin

Right-handed leptons do not occur in weak interactions, but they are present in electromagnetic ones

There are no R neutrinos since they are neutral and do not have EM interactions

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$$\psi_L = \frac{1}{2}(1 - \gamma_5)\psi \qquad \psi_R = \frac{1}{2}(1 + \gamma_5)\psi$$

Leptons

	Q	T_3	Y
ν_{eL}	0	$+1/2$	-1
e_L	-1	$-1/2$	-1
e_R	-1	0	-2

Weak hypercharge $$Q = T_3 + \frac{1}{2}Y$$

QED

$U(1)$ Local gauge symmetry

Q Charge: conserved quantum number

A_α Photon: gauge boson

$$\mathcal{L} = \bar{\psi}(i\gamma^\alpha \partial_\alpha - m)\psi \xrightarrow[i\partial_\alpha \to i\partial_\alpha + \underbrace{eQA_\alpha}]{} \mathcal{L}_{\rm int} = -eJ_\alpha^{\rm EM} A^\alpha$$

$$J_\alpha^{\rm EM} = \bar{\psi}\gamma_\alpha \psi$$

This fixes the interaction between charged fermions and the photon

e Coupling constant

GSM

$$SU(2)_T \times U(1)_Y$$

T weak isospin

Y weak hypercharge

g $\quad SU(2) \longrightarrow A_\alpha^{(1)}, A_\alpha^{(2)}, A_\alpha^{(3)}$ 3 gauge bosons

g' $\quad U(1) \longrightarrow B_\alpha$ 1 gauge boson

$$i\partial_\alpha \rightarrow i\partial_\alpha + g t^a A_\alpha^{(a)} - \frac{1}{2} g' Y B_\alpha$$

The interaction lagrangian has a fixed form and may be written as:

$$\mathcal{L} = \frac{g}{2\sqrt{2}} \left[j_\alpha^W W^\alpha + \text{h.c.} \right] +$$
$$\frac{g}{2} j_\alpha^{(3)} A^{(3)\alpha} + g' \left(\frac{1}{2} j_\alpha^{(3)} - j_\alpha^{(\text{EM})} \right) B^\alpha$$

where:

$$W_\alpha = W_\alpha^{(+)} = \frac{1}{\sqrt{2}} (A_\alpha^{(1)} - i A_\alpha^{(2)})$$
$$W_\alpha^\dagger = W_\alpha^{(-)} = \frac{1}{\sqrt{2}} (A_\alpha^{(1)} + i A_\alpha^{(2)})$$

The EM current and the photon are recovered by means of the rotation:

$$\begin{aligned} Z_\alpha &= A_\alpha^{(3)} \cos\theta_W + B_\alpha \sin\theta_W \\ A_\alpha &= -A_\alpha^{(3)} \sin\theta_W + B_\alpha \cos\theta_W \end{aligned}$$

θ_W Weinberg angle

experimentally: $\sin^2\theta_W = 0.23$

The interaction lagrangian has a fixed form and may be written as:

$$\mathcal{L} = \frac{g}{2\sqrt{2}} \left[j_\alpha^W W^\alpha + \text{h.c.} \right] +$$

$$e j_\alpha^{\text{EM}} A^\alpha + \frac{1}{2} \frac{g}{\cos\theta_W} j_\alpha^Z Z^\alpha$$

where:

$$g' \cos\theta_W = g \sin\theta_W = e$$

Weak neutral current: Leptons

$$j_\alpha^Z = j_\alpha^{(3)} - 2\sin^2\theta_W j_\alpha^{\rm EM}$$

$$j_\alpha^Z = \bar\psi_{\nu_e}\gamma_\alpha(1-\gamma_5)\psi_{\nu_e} + g_L\bar\psi_e\gamma_\alpha(1-\gamma_5)\psi_e + g_R\bar\psi_e\gamma_\alpha(1+\gamma_5)\psi_e +$$

$$= \bar\psi_{\nu_e}\gamma_\alpha(1-\gamma_5)\psi_{\nu_e} + \bar\psi_e\gamma_\alpha(g_V - g_A\gamma_5)\psi_e$$

T_3 $-Q$

↓ ↓

$$g_L = -\frac{1}{2} + \sin^2\theta_W \qquad g_V = g_L + g_R = -\frac{1}{2} + 2\sin^2\theta_W$$

$$g_R = \sin^2\theta_W \qquad g_A = g_L - g_R = -\frac{1}{2}$$

Quark sector

$$\begin{pmatrix} u_L \\ d'_L \end{pmatrix}$$

doublet of weak isospin T

$$T_3(u_L) = +1/2$$

$$T_3(d'_L) = -1/2$$

u_R, d_R singlets of weak isospin

Quarks

	Q	T_3	Y
u_L	$2/3$	$+1/2$	$1/3$
d'_L	$-1/3$	$-1/2$	$1/3$
u_R	$2/3$	0	$4/3$
d'_R	$-1/3$	0	$-2/3$

Weak neutral current: Quarks

$$J_\alpha^Z = J_\alpha^{(3)} - 2\sin^2\theta_W J_\alpha^{\mathrm{EM}}$$

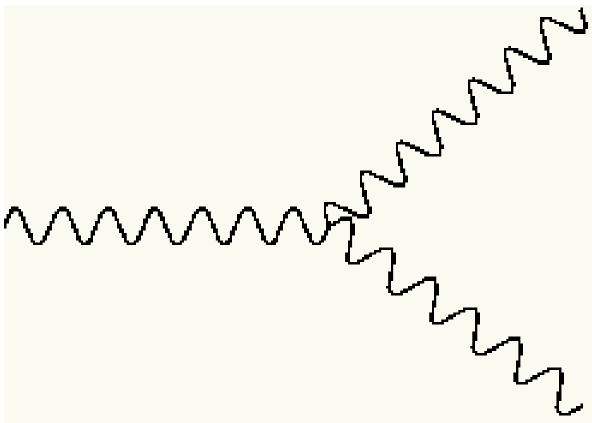
$$\begin{aligned} J_\alpha^Z = \; & U_L[\bar\psi_u\gamma_\alpha(1-\gamma_5)\psi_u + \bar\psi_c\gamma_\alpha(1-\gamma_5)\psi_c] + \\ & U_R[\bar\psi_u\gamma_\alpha(1+\gamma_5)\psi_u + \bar\psi_c\gamma_\alpha(1+\gamma_5)\psi_c] + \\ & D_L[\bar\psi_d\gamma_\alpha(1-\gamma_5)\psi_d + \bar\psi_s\gamma_\alpha(1-\gamma_5)\psi_s] + \\ & D_R[\bar\psi_d\gamma_\alpha(1+\gamma_5)\psi_d + \bar\psi_s\gamma_\alpha(1+\gamma_5)\psi_s] \end{aligned}$$

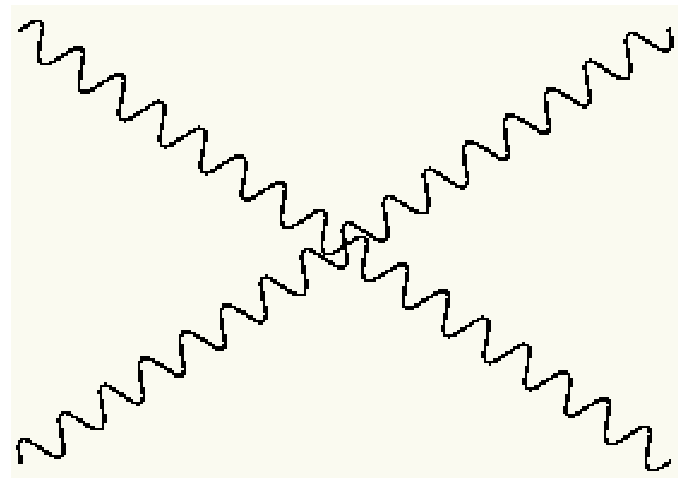
T_3 $\quad -Q$

$$U_L = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W \qquad U_R = -\frac{2}{3}\sin^2\theta_W$$

$$D_L = -\frac{1}{2} + \frac{1}{3}\sin^2\theta_W \qquad D_R = \frac{1}{3}\sin^2\theta_W$$

Gauge bosons interaction





$\gamma W^+ W^-$

$Z^0 W^+ W^-$

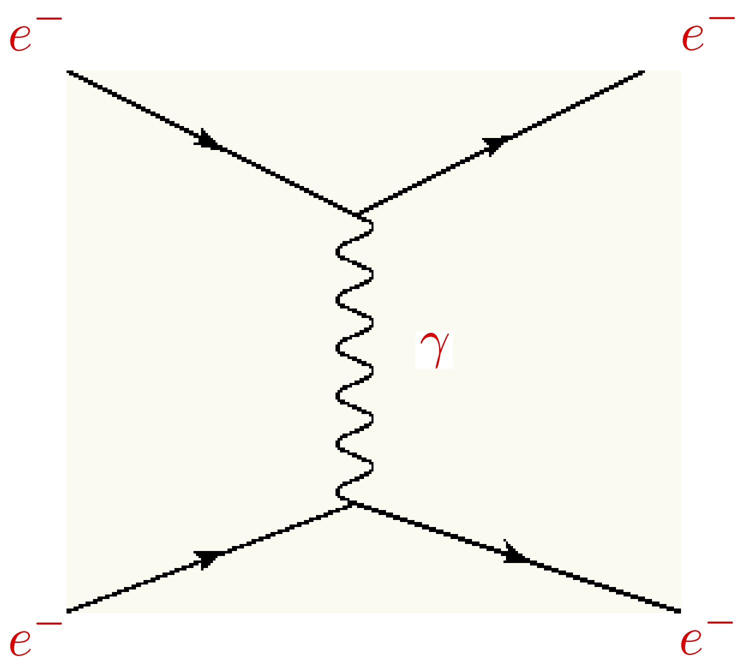
$W^+ W^- W^+ W^-$

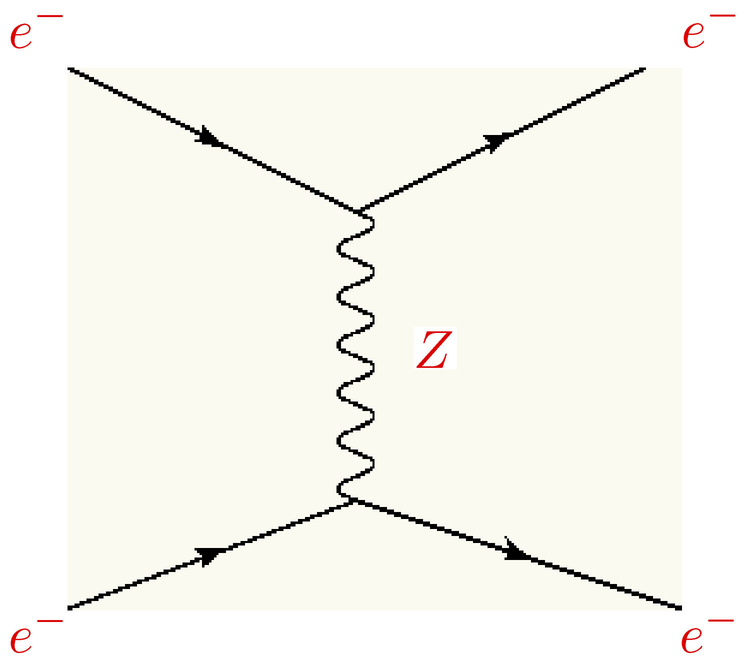
$W^+ W^- Z^0 Z^0$

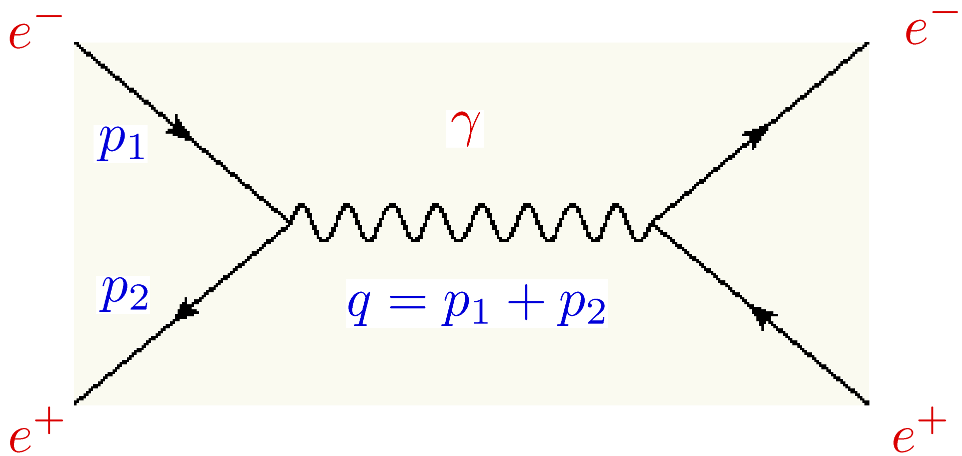
$W^+ W^- \gamma\gamma$

$W^+ W^- Z^0 \gamma$

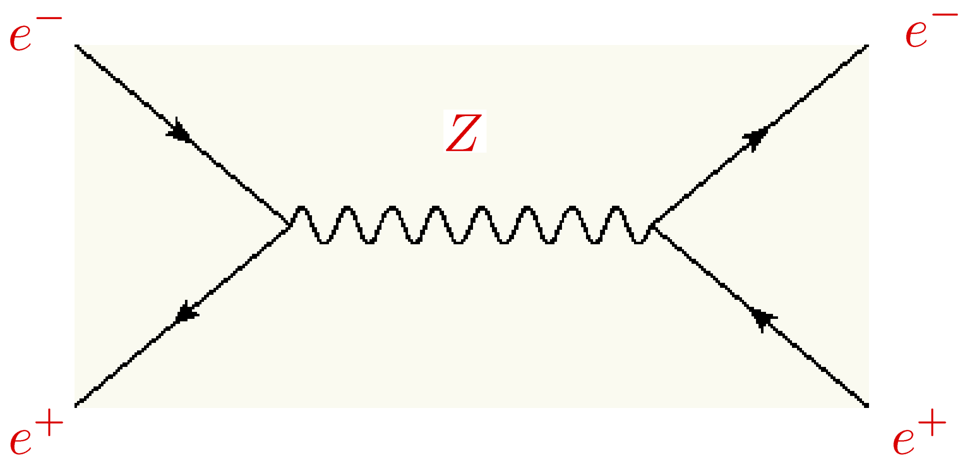
EW contributions at high energies



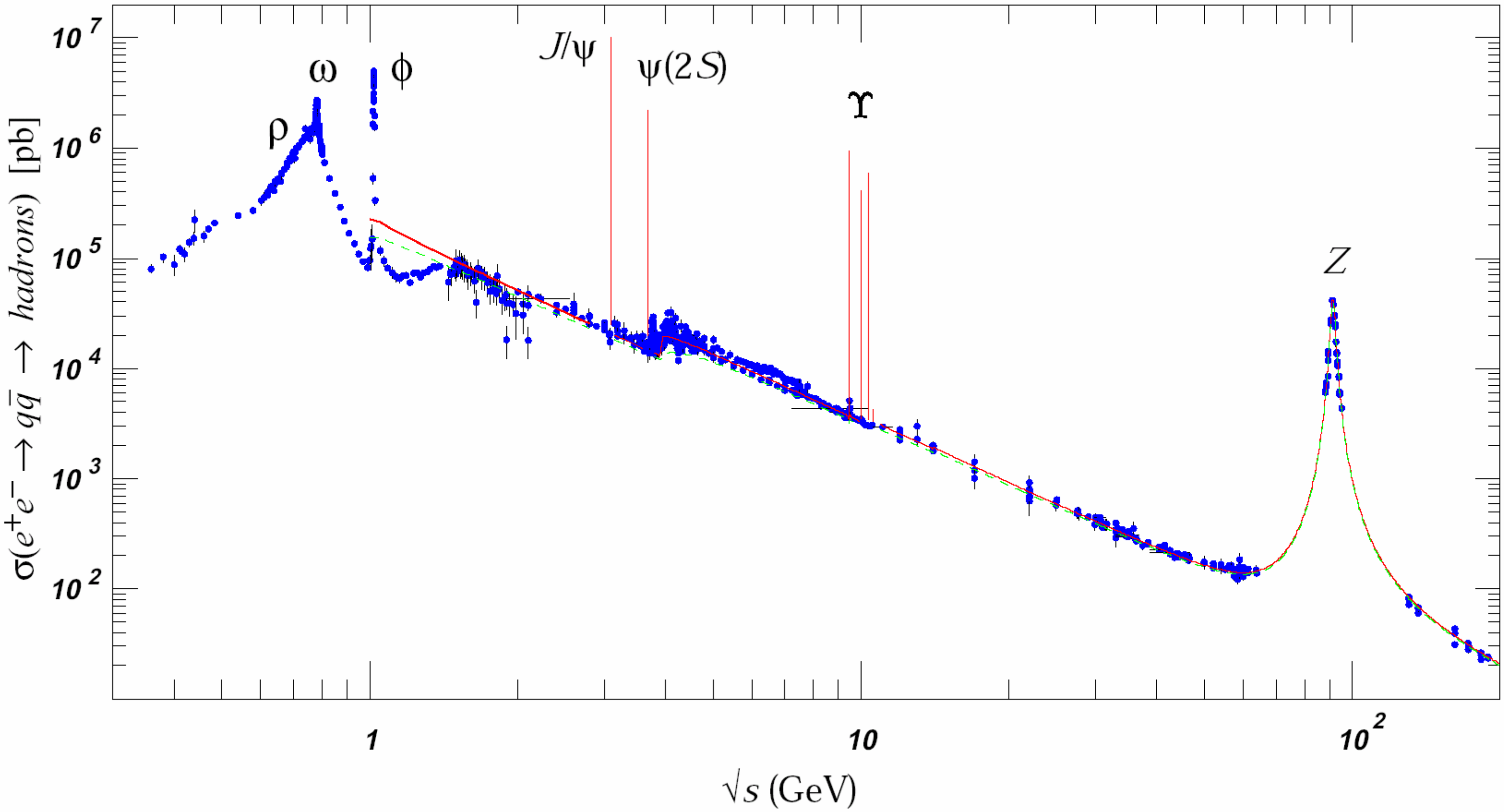




$$\mathcal{P}_\gamma \sim \frac{1}{q^2}$$



$$\mathcal{P}_Z \sim \frac{1}{q^2 - M_Z^2}$$



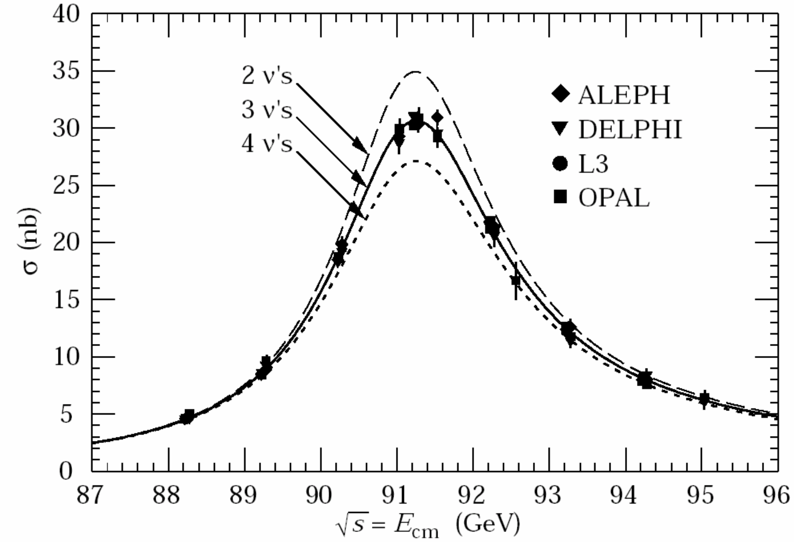
$\sigma(e^+e^- \to q\bar{q} \to hadrons)$ [pb]
10^7
10^6
10^5
10^4
10^3
10^2
ρ
ω
φ
J/ψ
$\psi(2S)$
Υ
Z
1
10
10^2
$\sqrt{s}$ (GeV)

Gauge bosons decay

$Z^0 \longrightarrow l\bar{l}$ 3.4% each

$Z^0 \longrightarrow q\bar{q}$ 12% each

$Z^0 \longrightarrow \nu\bar{\nu}$ 20% invisible



$W^+ \longrightarrow c\bar{s}$ (etc) 31%

$W^+ \longrightarrow l^+\nu_l$ 11% each

Mass generation in the GWS Model

- If the gauge symmetry SU(2)xU(1) is an exact symmetry, all the gauge bosons must be massless

- We have in total 4 gauge bosons (W^+, W^-, Z and photon): we need to give mass to three of them

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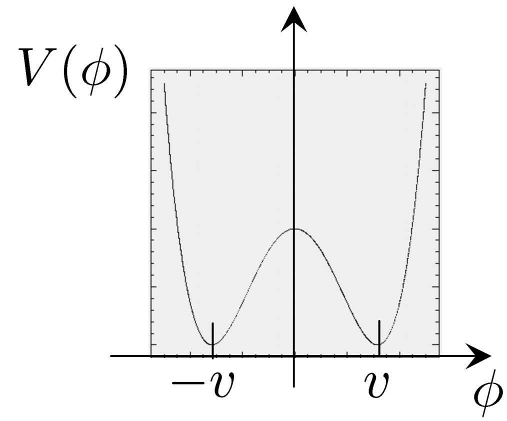
Spontaneous symmetry breaking through the Higgs mechanism

- A scalar field is introduced with a potential of the type:

$$V(\phi) = -\mu^2\phi^2 + \lambda\phi^4$$



$$\phi \to -\phi$$

- The lagrangian is symmetric but the minimum of the potential does not share the same symmetry

- When the scalar field stays in one of the minima of the potential, the symmetry is spontaneously broken

$\langle 0|\phi|0\rangle = v$ is not symmetric

$$\Phi = \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix}$$

charged scalar doublet under weak isospin

- 4 scalar fields

3 enter as longitudinal polarizations of the W and Z bosons
therefore they become massive

1 remains as a physical particle

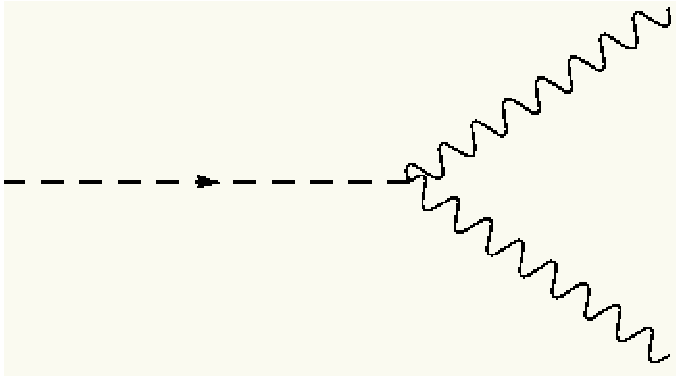
H Higgs boson

$$s = 0$$

$$m_H = ? \quad (m_H > 114 \text{ GeV})$$

Prediction

$$m_W = m_Z \cos\theta_W$$ experimentally verified



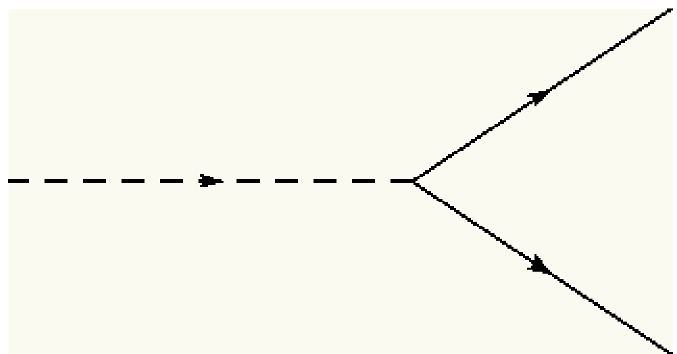
$$g_{HWW} = \frac{2}{v} m_W^2$$

$$g_{HZZ} = \frac{2}{v} m_Z^2$$

$$\langle 0 | \phi^{(0)} | 0 \rangle = v$$ scale of symmetry breaking

Coupling of Higgs to fermions gives:

- Mass to fermions (again after symmetry breaking)
- Higgs-fermion interaction



$$g_{Hff} = \frac{m_f}{v}$$

Strong interaction: QCD

$$\begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix}$$

Color triplet

$SU(3)_C$

8 gauge bosons: gluons G^a_α

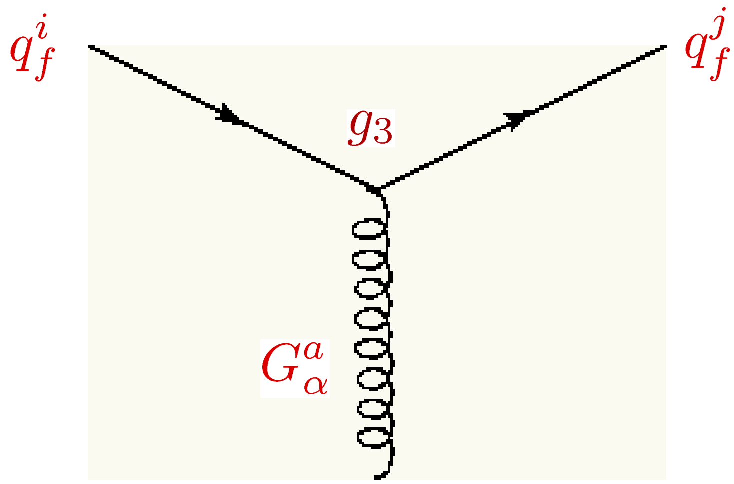
$$i\partial_\alpha \rightarrow i\partial_\alpha + g_3 T^a G^a_\alpha$$

g_3 → strong coupling constant

Quark-gluon interaction

$$\mathcal{L}_G = g_3 J^a_\alpha G^{a,\alpha}$$

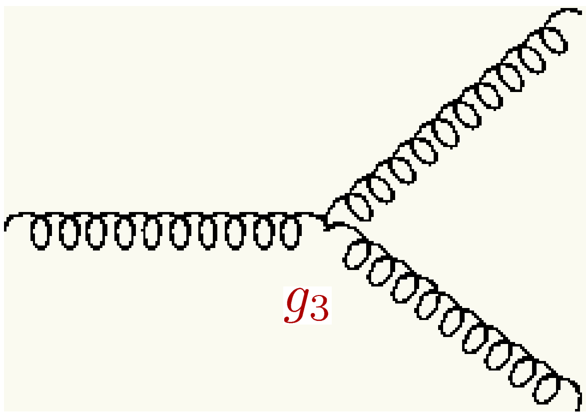
$$J^a_\alpha = g_3 \bar{\psi}^i \gamma_\alpha (T^a)_{ij} \psi^j$$

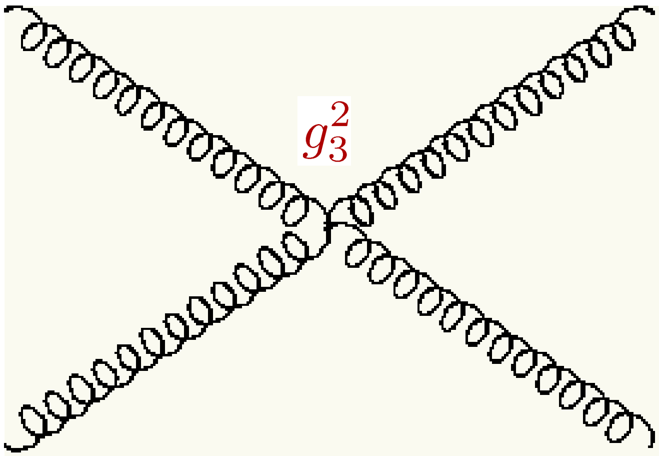


$i \longrightarrow j$ color

$f \longrightarrow f$ flavour diagonal

Gluon-gluon interaction

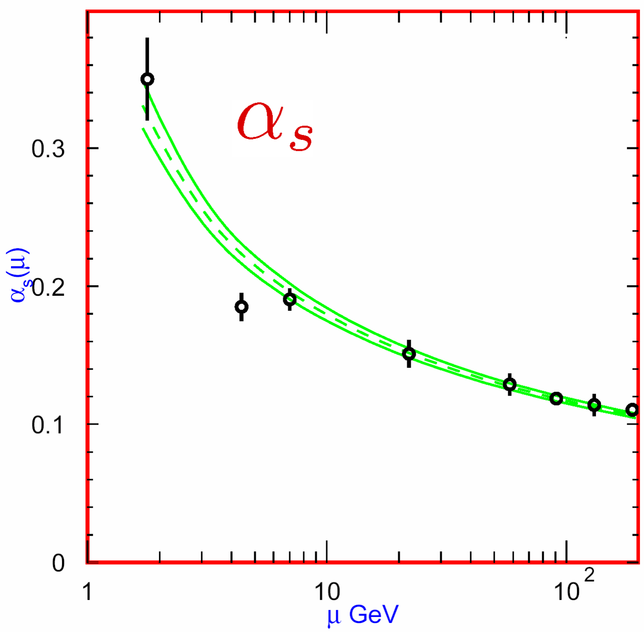




Running of coupling constants

$$\alpha_s \equiv \frac{g_3^2}{4\pi}$$

$$\boxed{\frac{d\alpha_s(\mu)}{dt} = \beta(\alpha_s)} \qquad t = \ln(\mu^2/\mu_0^2)$$



$\beta(\alpha_s) < 0$ QCD

$\beta(\alpha) > 0$ QED

Confinement
non pQCD
$\Lambda_{\rm QCD} \sim 200$ MeV

Asymptotic freedom
pQCD

- At small distancies, i.e. large energies, quarks are almost free

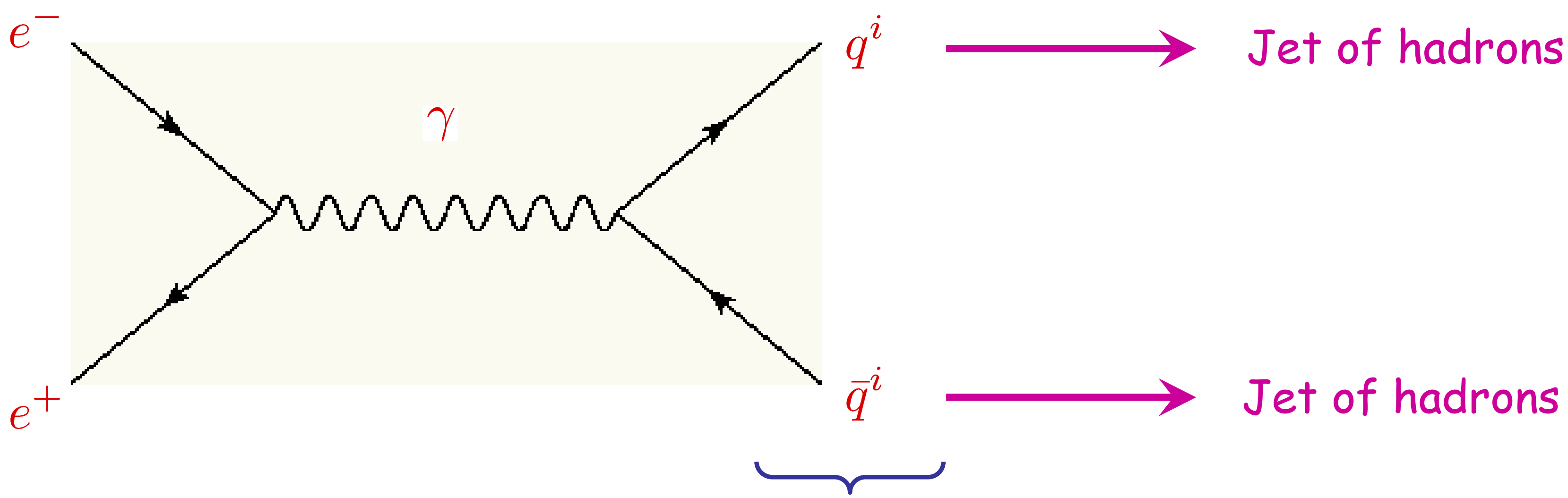
asymptotic freedom

- At large distancies, i.e. small energies, quarks are strongly interacting and confined into hadrons

confinement

Elementary processes in pQCD - I

$$e^- + e^+ \to \text{hadrons}$$



At large energies asymptotic freedom allows us to assume the process at the parton level

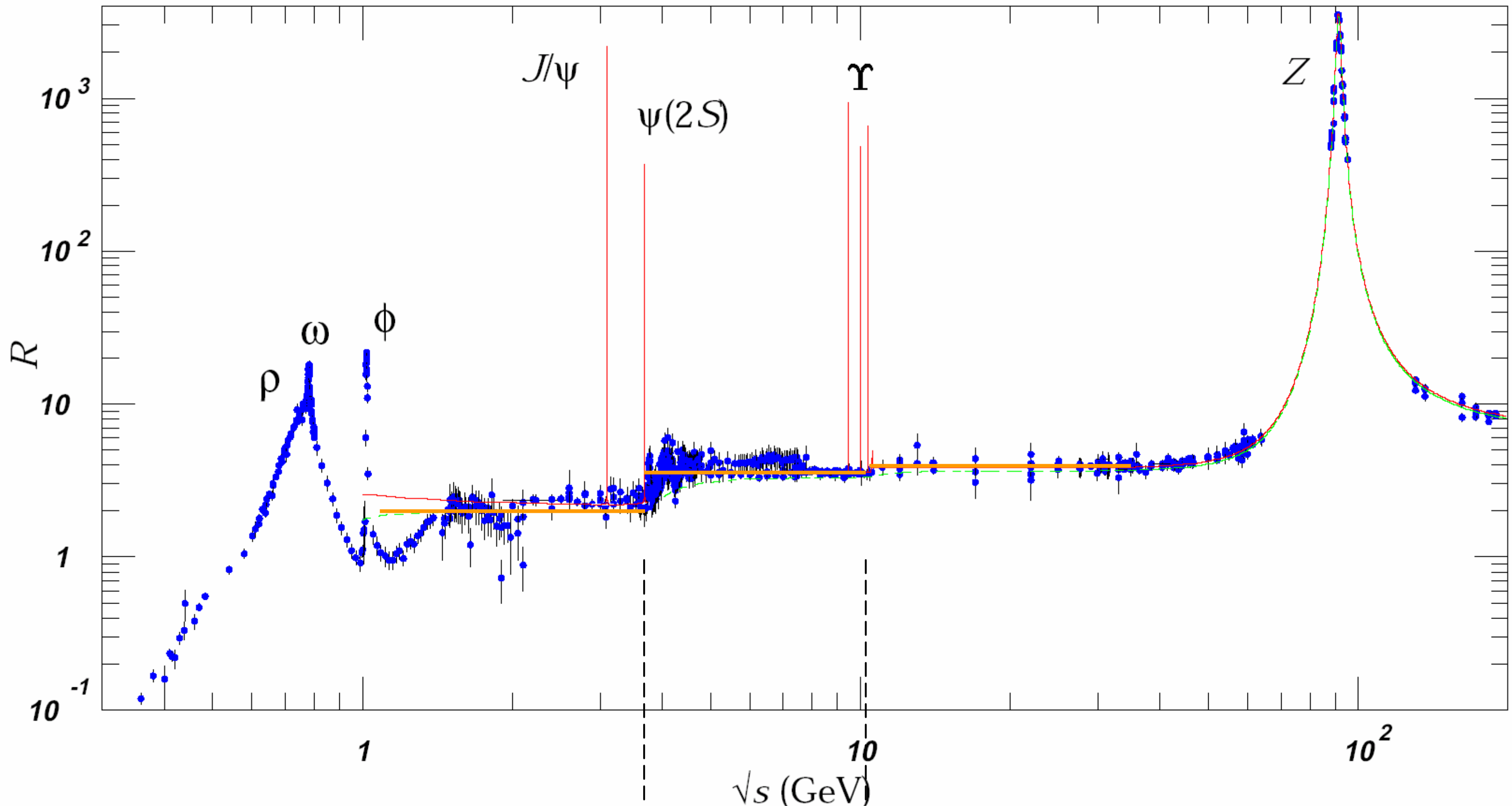
$$e^- + e^+ \longrightarrow \underbrace{q^i \bar{q}^i} \xrightarrow{\hspace{5cm}} j_1 + j_2$$

$(q, \bar{q})$ Cannot remain as free particles, they must form colorless states

Hadronization

$$\sigma[e^- e^+ \to \text{hadrons}] \longrightarrow \sigma[e^- e^+ \to q\bar{q}]$$

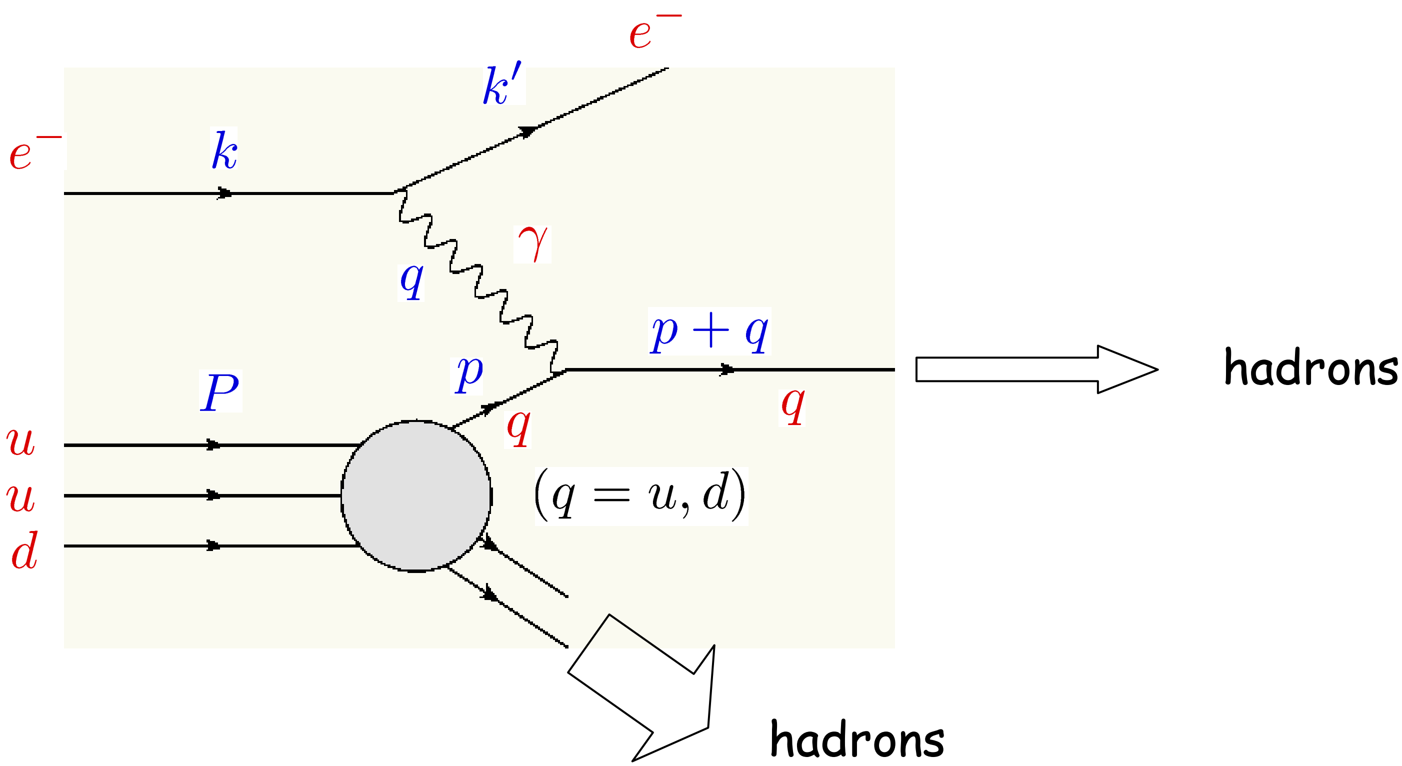
$$R = \frac{\sigma[e^- e^+ \to \text{hadrons}]}{\sigma[e^- e^+ \to \mu^- \mu^+]} \longrightarrow \sum_q 3 Q_q^2$$



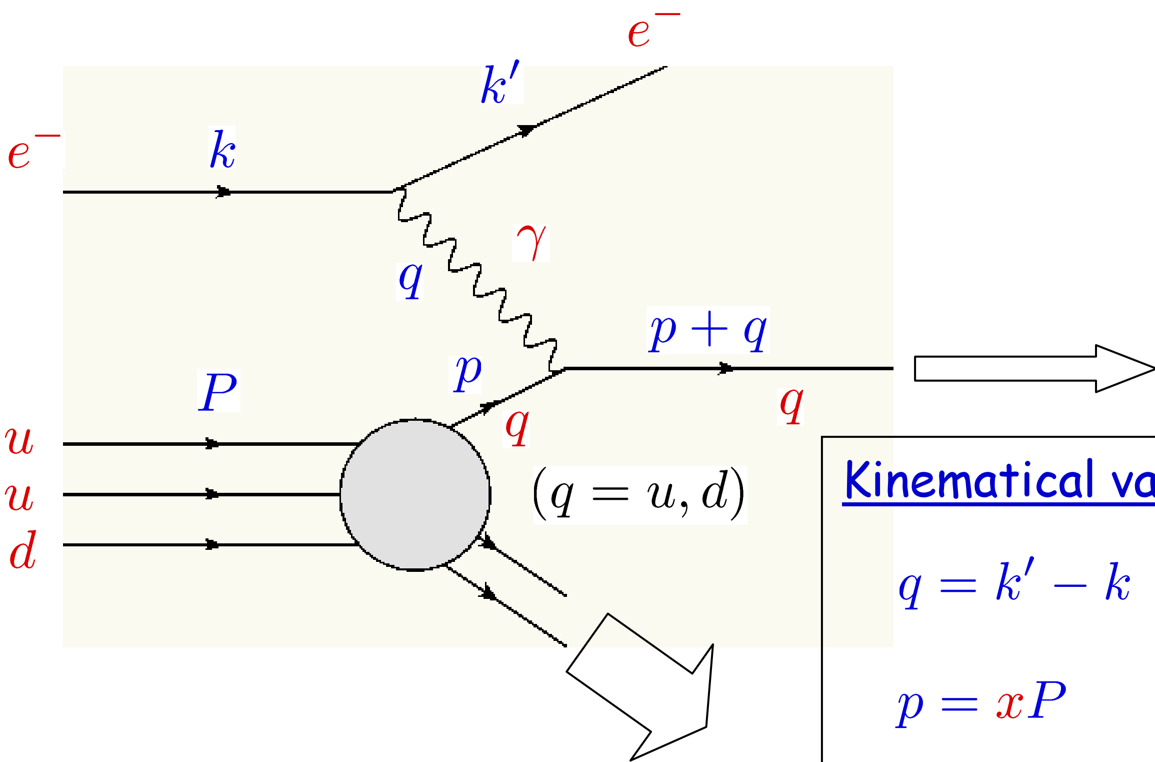
u, d, s	u, d, s, c	u, d, s, c, b
$R = 2$	$R = 10/3$	$R = 11/3$

Elementary processes - II: Deep Inelastic Scattering

$$e^- + p \to e^- + X$$



At large energies (above tens of GeV) we resolve the partons inside the hadron



Kinematical variables

$$q = k' - k \qquad Q^2 = -q^2$$

$$p = xP \qquad x = \frac{Q^2}{2(P \cdot q)}$$

Q^2, x are determined in terms of electrons energy and momentum

x longitudinal momentum fraction of the parton

$f_i(x)$ momenta distribution inside the hadron

$f_i(x)dx$ gives the probability of finding a parton q_i with momentum in the range $(x, x+dx)P$

$$p \; = \; [uud]_V \; + \; (q\bar{q})_S \; + \; \text{gluons}_S$$

$f_u^{[\mathrm{p}]}(x) \quad f_d^{[p]}(x) \quad f_s^{[p]}(x)$ etc.

$f_{\bar{u}}^{[\mathrm{p}]}(x) \quad f_{\bar{d}}^{[p]}(x) \quad f_{\bar{s}}^{[p]}(x)$ etc.

$$\int_0^1 dx [f_u^{[\mathrm{p}]}(x) - f_{\bar{u}}^{[\mathrm{p}]}(x)] = 2$$

$$\int_0^1 dx [f_d^{[\mathrm{p}]}(x) - f_{\bar{d}}^{[\mathrm{p}]}(x)] = 1$$

$$\int_0^1 dx \sum_i x \; f_i^{[\mathrm{p}]}(x) = 1$$

$$\int_0^1 dx \sum_{i=\mathrm{q},\bar{\mathrm{q}}} x \; f_i^{[\mathrm{p}]}(x) \sim 0.5$$ observ.

$$n \; = \; [udd]_V \; + \; (q\bar{q})_S \; + \; \text{gluons}_S$$

$$f_u^{[\mathrm{n}]}(x) = f_d^{[\mathrm{p}]}(x)$$
$$f_d^{[\mathrm{n}]}(x) = f_d^{[\mathrm{p}]}(x)$$

by isospin symmetry

etc.

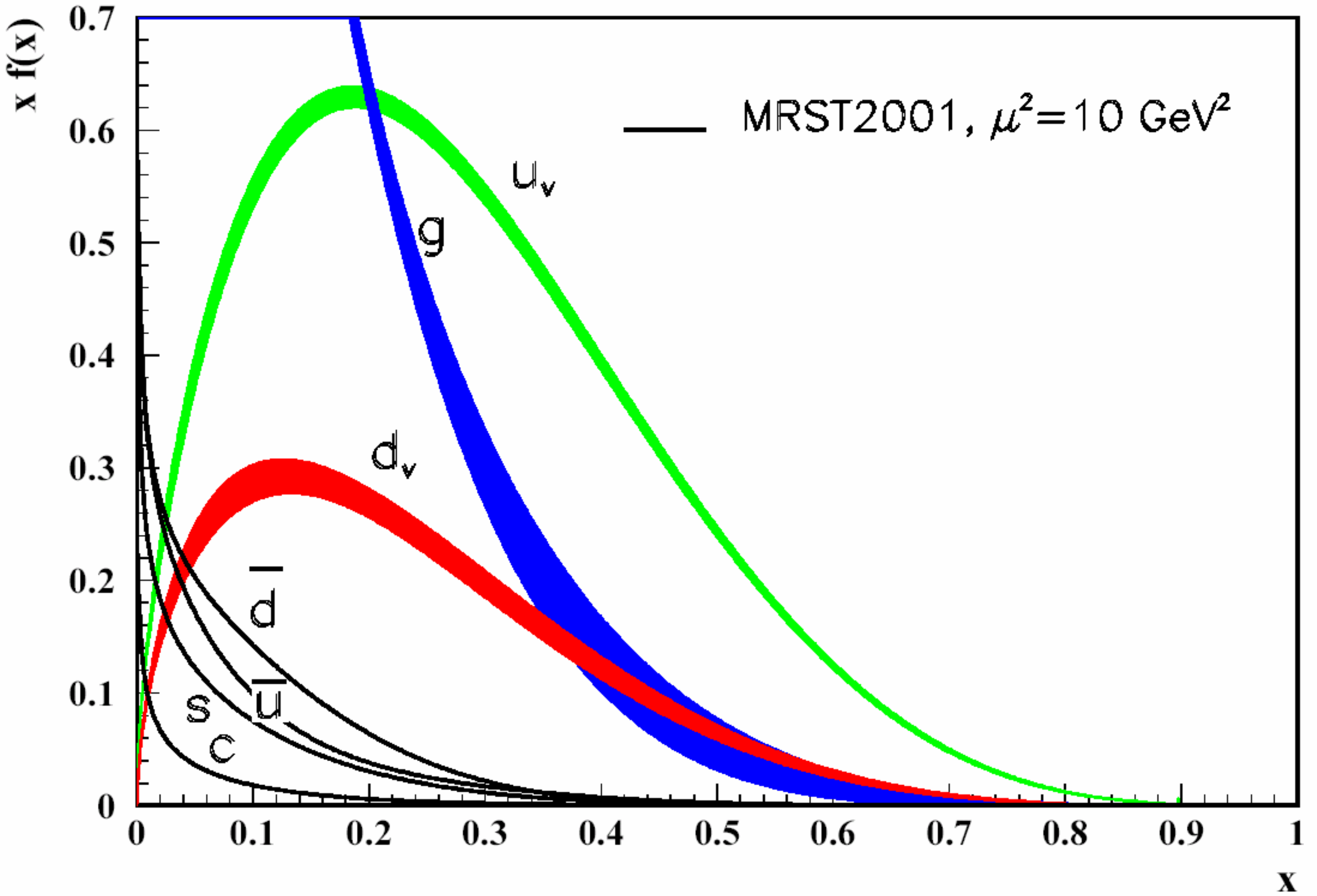
$$\sigma[e^-(k)p(P) \to e^-(k')X] = \int_0^1 dx \sum_i f_i(x)\sigma[e^-(k)q_i(xP) \to e^-(k')q_i(p')]$$

sum over all partons

depend only on x, not on Q^2 (at leading order)

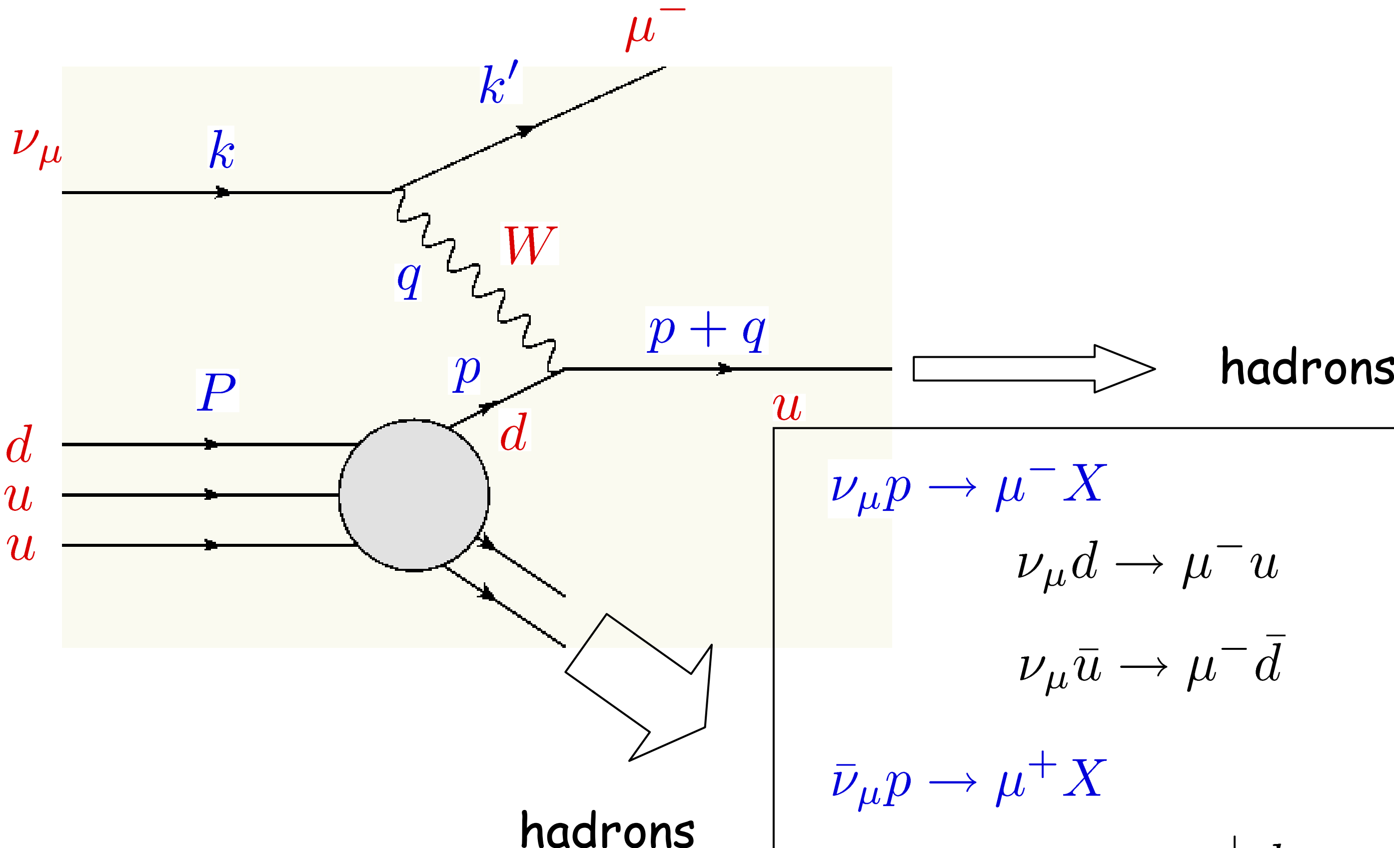
Bjorken scaling

Unpolarized parton distributions for the proton



Deep Inelastic Scattering with neutrinos

$$\nu_\mu + p \to \mu^- + X$$



$$\nu_\mu p \to \mu^- X$$

$$\nu_\mu d \to \mu^- u \qquad f_d^{[p]}(x)$$

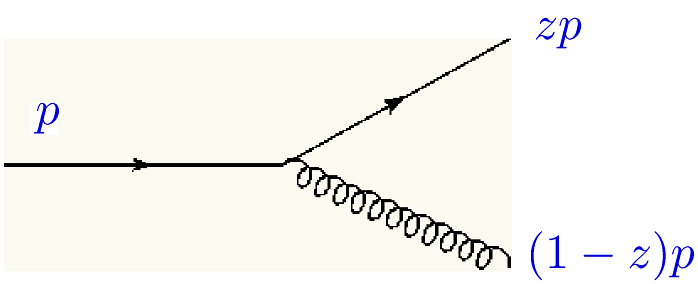
$$\nu_\mu \bar{u} \to \mu^- \bar{d} \qquad f_{\bar{u}}^{[p]}(x)$$

$$\bar{\nu}_\mu p \to \mu^+ X$$

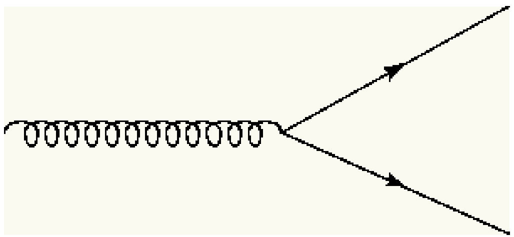
$$\bar{\nu}_\mu u \to \mu^+ d \qquad f_u^{[p]}(x)$$

$$\bar{\nu}_\mu \bar{d} \to \mu^+ \bar{u} \qquad f_{\bar{d}}^{[p]}(x)$$

Higher order QCD effects: scaling violation



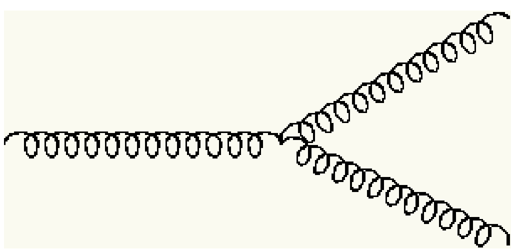
$\mathcal{P}_{q \to q}(z)$ Probability for a parton to radiate a hard gluon with z fraction of momentum



$\mathcal{P}_{G \to q}(z)$

$\mathcal{P}_{q \to G}(z)$

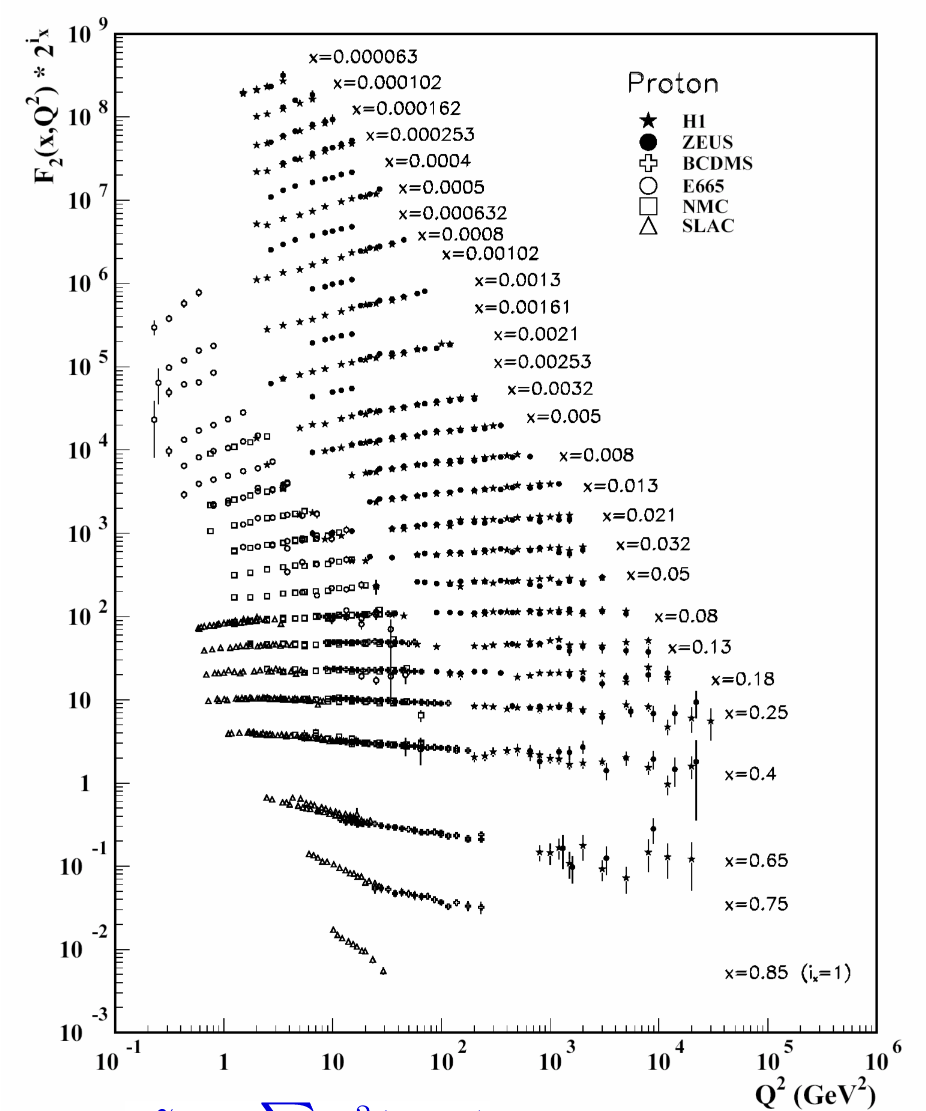
$\mathcal{P}_{G \to G}(z)$

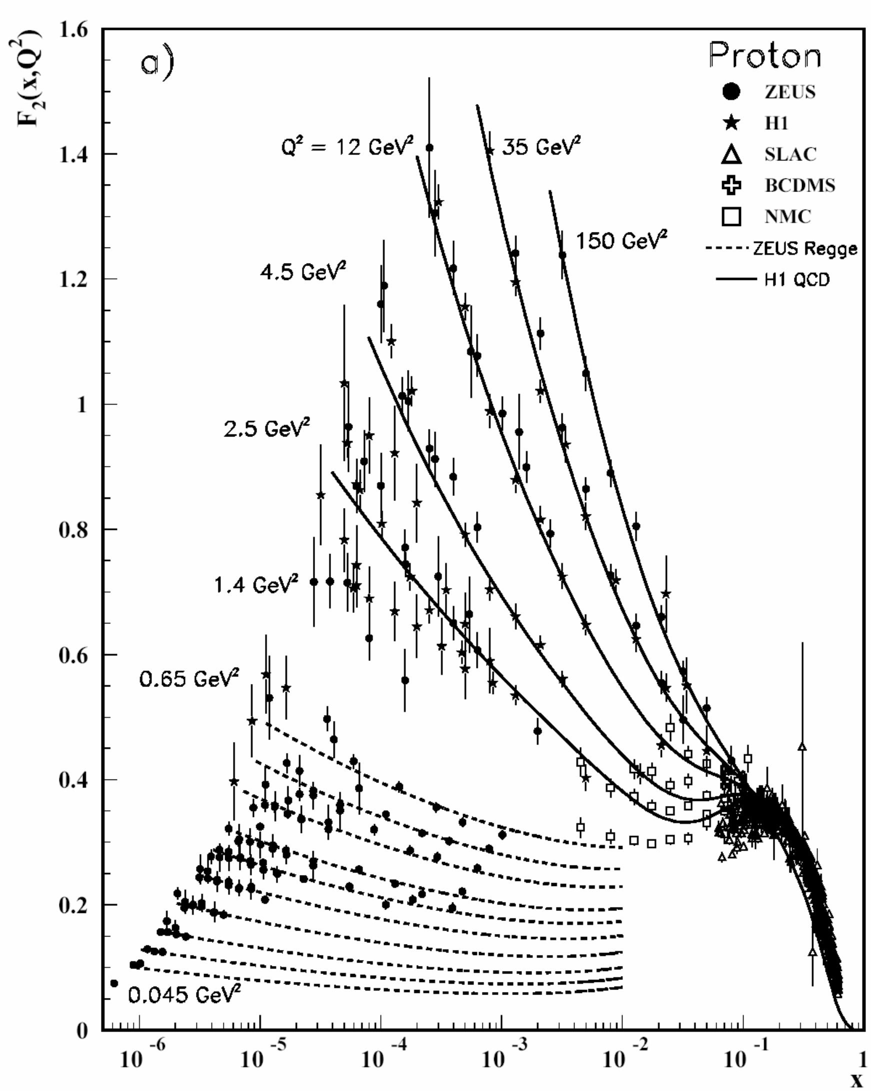


DGLAP

$f_i(x) \longrightarrow f_i(x, Q^2)$ scaling violation (log evolution with energy scale)

Structure function of proton from electron and muon EM scattering





$$F_2^\gamma = x \sum_q Q_q^2 (q + \bar{q})$$

Elementary processes - III: hadron scattering

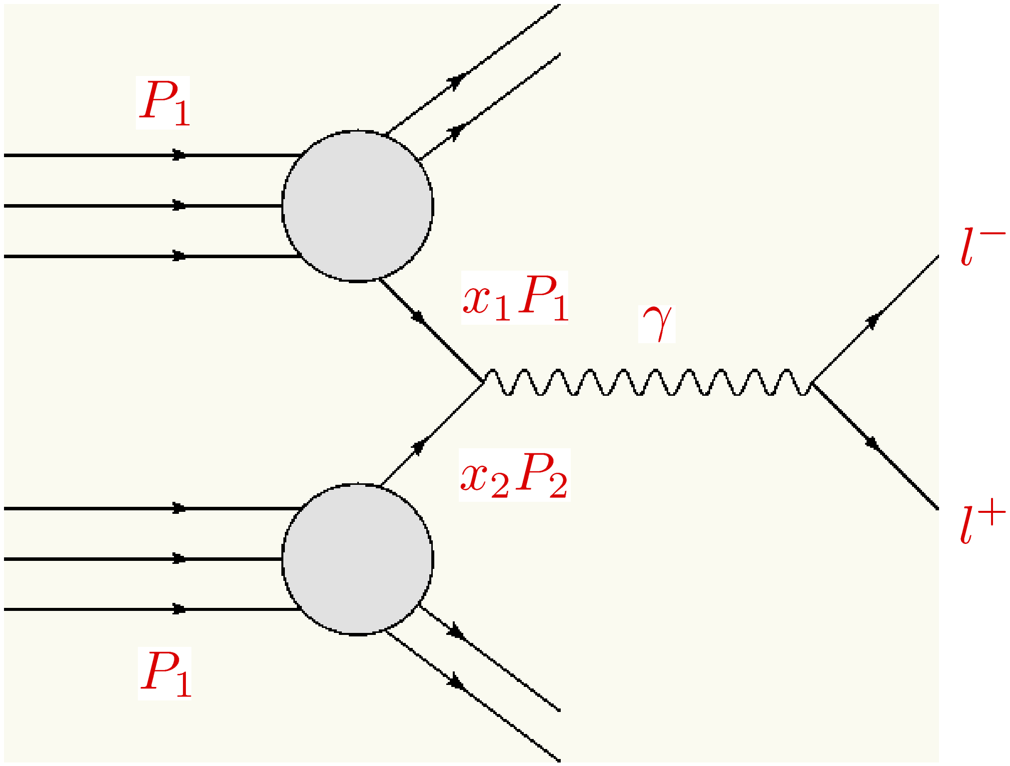
$$\boxed{p + p \longrightarrow \text{hadrons}}$$

$$q_i \bar{q}_j \longrightarrow q q' \longrightarrow j_1 + j_2$$

$$\sigma[p(P_1)p(P_2) \to X + Y] =$$
$$\int_0^1 dx_1 \int_0^1 dx_2 \sum_{ij} f_i(x_1) f_j(x_2) \sigma[q_i(x_1) q_j(x_2) \to q q']$$

Drell-Yan

$$p + p \longrightarrow l^+ + l^-$$



at the parton level: $q_i \bar{q}_i \longrightarrow l^+ l^-$ EM

Jet production

$$\text{hadron} + \text{hadron} \longrightarrow j_1 + j_2$$

$$qq \longrightarrow qq$$

$$q\bar{q} \longrightarrow q\bar{q}$$

$$q\bar{q} \longrightarrow GG$$

$$qG \longrightarrow qG$$

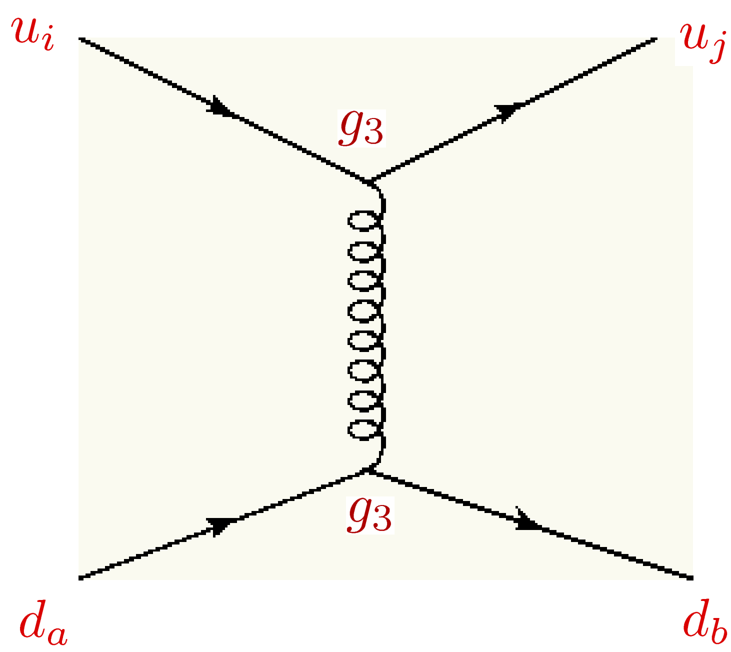
$$GG \longrightarrow q\bar{q}$$

$$GG \longrightarrow GG$$

Partons of the initial state hadrons | Partons of the final state hadrons

Example

$$u + d \longrightarrow u + d$$



$$\text{hadron} + \text{hadron} \longrightarrow j_1 + j_2$$

Standard Model

Matter fermions $s = 1/2$ $\psi(x)$

- leptons $\begin{pmatrix} \nu_e \\ e \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$
- quarks $\begin{pmatrix} u_i \\ d_i \end{pmatrix} \begin{pmatrix} c_i \\ s_i \end{pmatrix} \begin{pmatrix} t_i \\ b_i \end{pmatrix}$

$$SU(3)_c \times SU(2)_T \times U(1)_Y$$

Interactions bosons $s = 1$ B^μ

- photon γ EM
- $W^\pm, Z^0$ WK
- gluons G^a $(a = 1, \ldots 8)$ SG