P-P PHYSICS AT LHC

Inelastic scattering at LHC

Lecture 1

DIPARTIMENTO DI FISICA

SAPIENZA
UNIVERSITÀ DI ROMA

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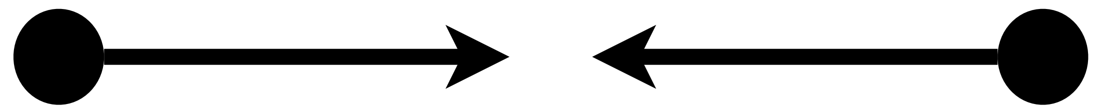
KINEMATICS

$$E = 3.5\text{TeV} \qquad E = 3.5\text{TeV}$$



$$m = 1\text{GeV} \qquad m = 1\text{GeV}$$

$$\sqrt{s} = 7\,\text{TeV}$$

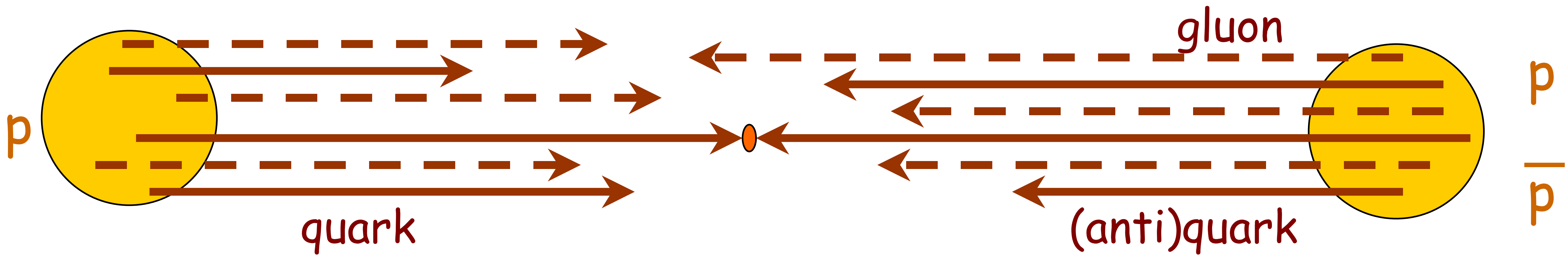
$$s = [(E_1, \overrightarrow{p_1}) + (E_2, \overrightarrow{p_2})]^2$$

$$= [(2E, \vec{0})]^2$$

$$= 4E^2$$

- Much higher beam energy needed to achieve same $\sqrt{s}$ with fixed target
- Electron-positron collisions much better with linear colliders. Why?

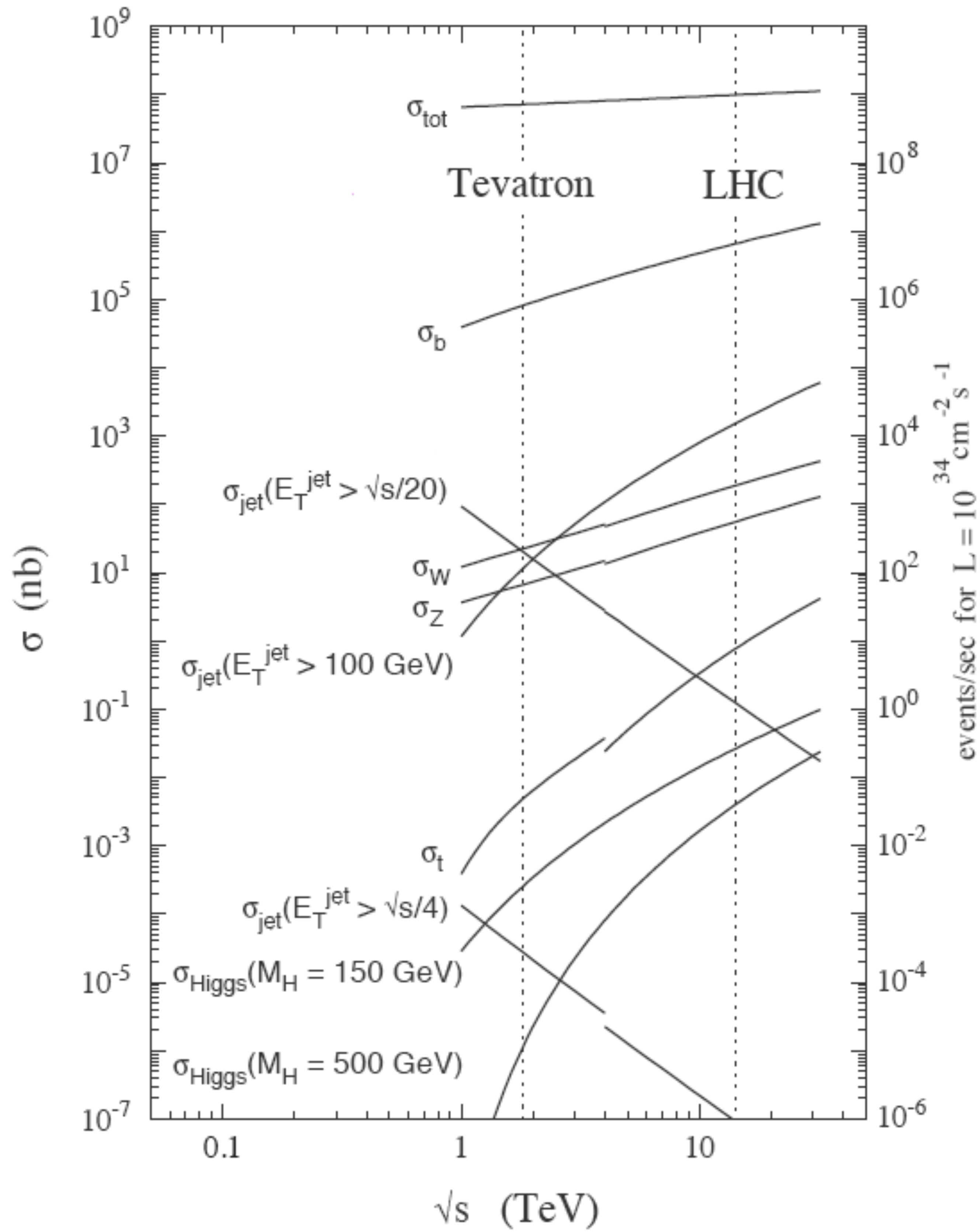
PROTON VS. ANTI-PROTON



- Low energy: valence quark are dominate ➞ $pp \neq p\bar{p}$
- High energy: gluons and sea quarks become dominant ➞ $pp \simeq p\bar{p}$

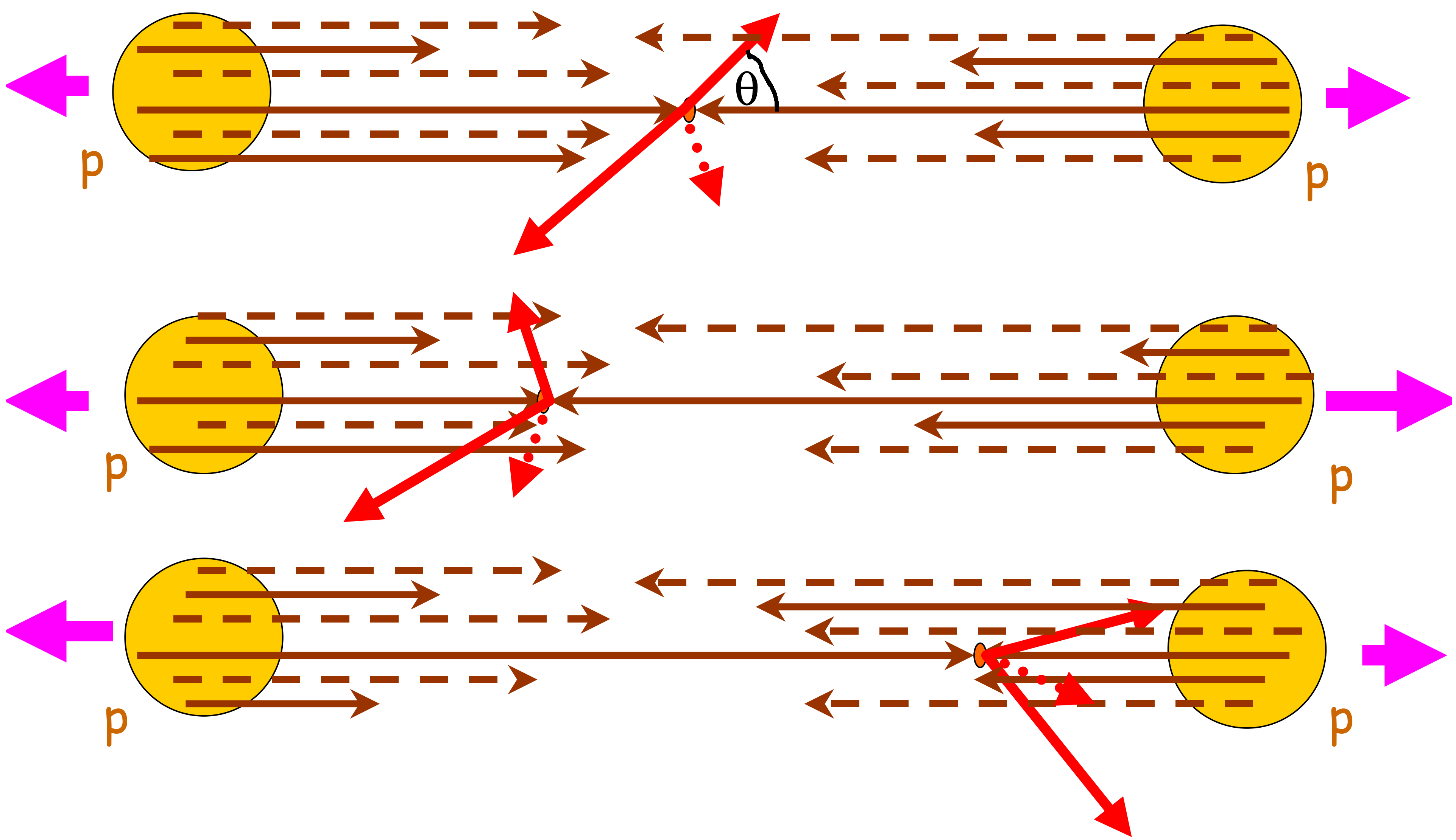
Cross Section at Hadron Colliders

- QCD dominates the total cross section
  - Not surprising since these are hadron colliders and strong interaction dominates over EW and QED
- Interesting processes are order of magnitudes smaller
  - background rejection is the most critical ingredient of all analysis
- Background discrimination
  - reducible background: processes mimic signal because of mis-reconstructed objects
    - γ+jet → γ+γ
  - irreducible background: processes with same content in final states as signal
    - QCD di-photon production



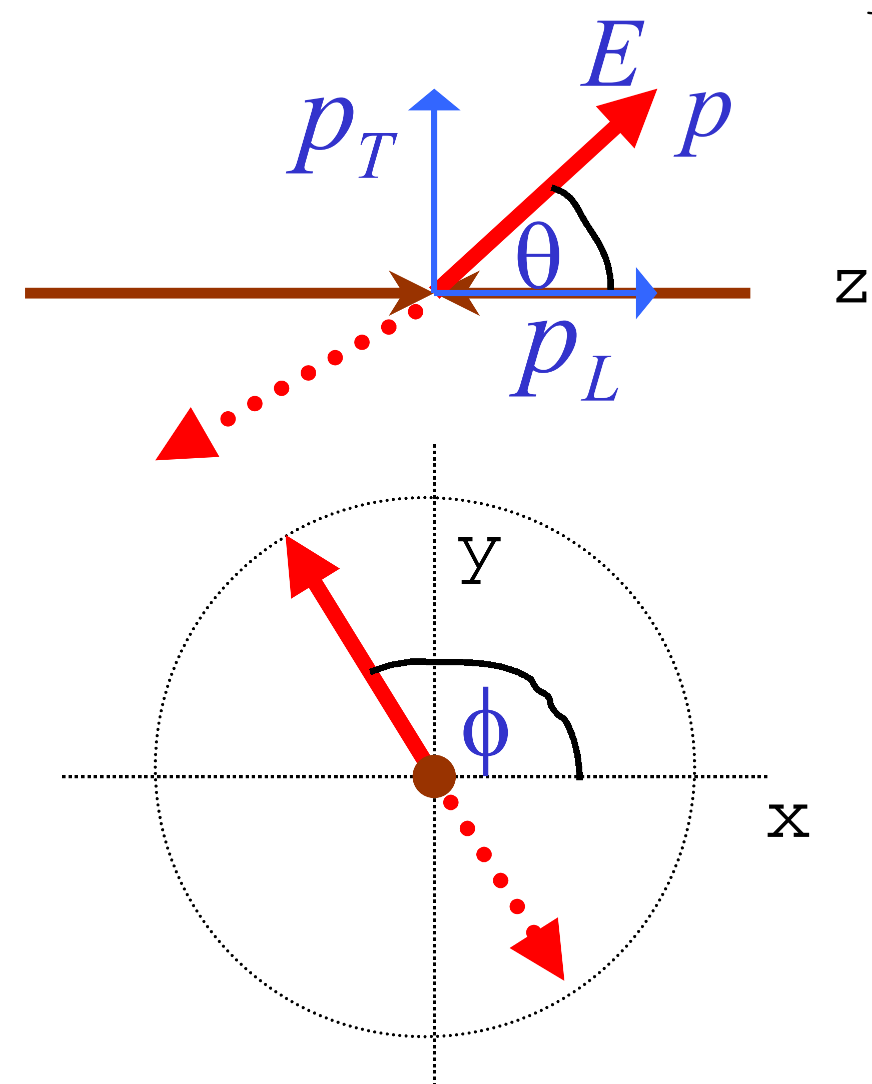
Boost of Center of Mass

$$p_1 = x_1 \cdot E_{beam} \qquad p_2 = x_2 \cdot E_{beam}$$



- No a-priori knowledge of the boost: x_i different and unknown
- Cannot determine boost unless ALL particles in final states reconstructed
  - Not feasible

KINEMATIC VARIABLES



- azimuthal angle ϕ
- polar angle θ
- energy E
- momentum p
- transverse momentum p_T
- longitudinal momentum p_L

- rapidity $$y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L}$$
- pseudorapidity $$\eta = -\ln \tan \frac{\theta}{2}$$

$m << E, p_L$

LORENTZ INVARIANT OBSERVABLES

- Differential cross sections are typically studied as a function of momentum, energy and polar angle
  - for known boost change of reference frame trivial

- Problems arise with unknown boost
  - Need variables not sensitive to boost
    - pseudo-rapidity intervals
  - Variables unchanged under longitudinal boost
    - transverse momentum

Rapidity for High Energy Particles

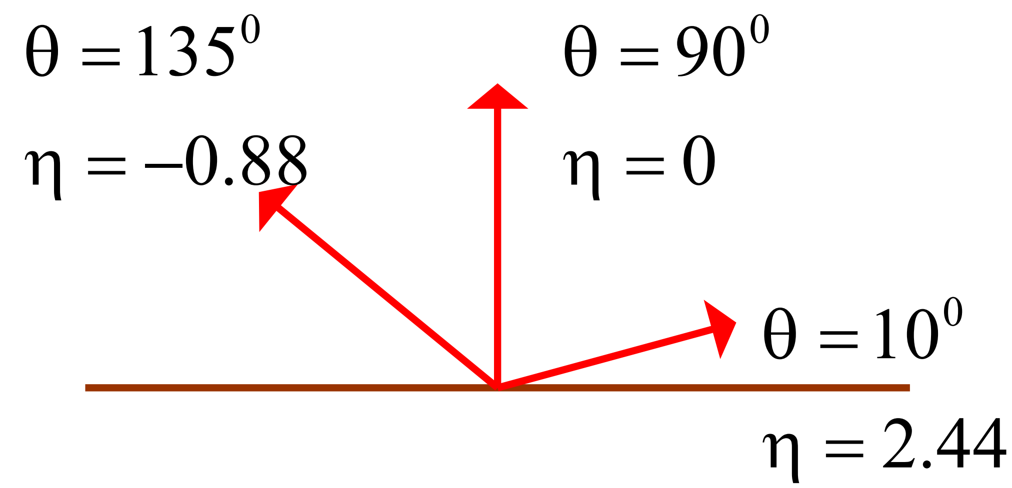
$$y = \ln \frac{E + p_L}{\sqrt{p_T^2 + m^2}}$$

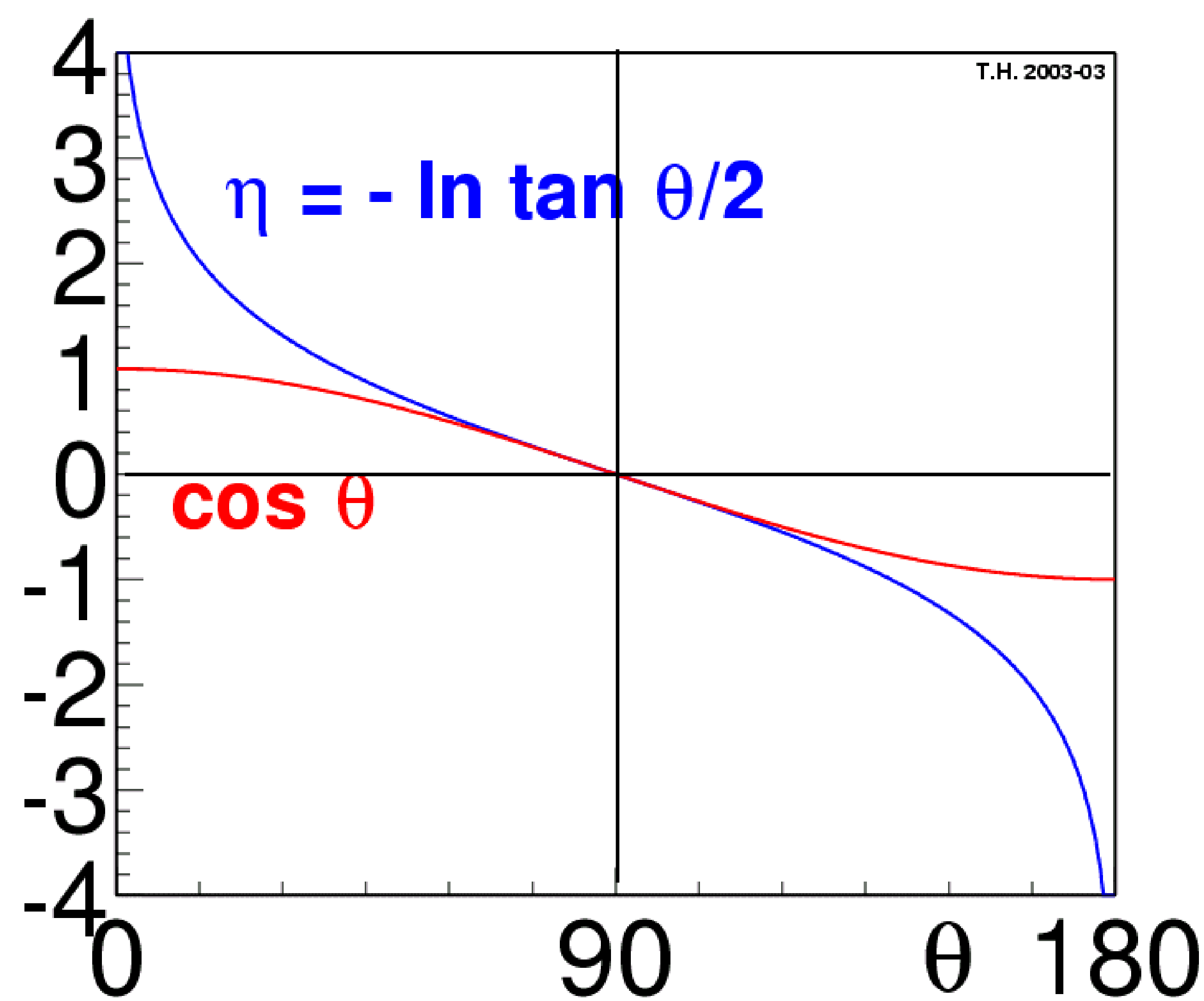
$$m << E, p_L$$

$$\rightarrow \ln \frac{E + E\cos\theta}{E\sin\theta}$$

$$= \ln \frac{2\cos^2\frac{\theta}{2}}{2\sin\frac{\theta}{2}\cos\frac{\theta}{2}}$$

$$= -\ln\tan\frac{\theta}{2} = \eta$$





PSEUDO-RAPIDITY INTERVALS UNDER BOOST

$$y = \frac{1}{2}\ln\frac{E+p_L}{E-p_L} = \ln\frac{\sqrt{E+p_L}}{\sqrt{E-p_L}}\cdot\frac{\sqrt{E+p_L}}{\sqrt{E+p_L}} = \ln\frac{E+p_L}{\sqrt{E^2-p_L^2}}$$

$$= \ln\frac{E+p_L}{\sqrt{p_T^2+m^2}}$$

Boost along z axis:

$$y' = \ln\frac{E'+p'_L}{\sqrt{p_T^2+m^2}} = \ln\frac{\gamma\,(E+\beta\,p_L)+\gamma\,(p_L+\beta\,E)}{\sqrt{p_T^2+m^2}}$$

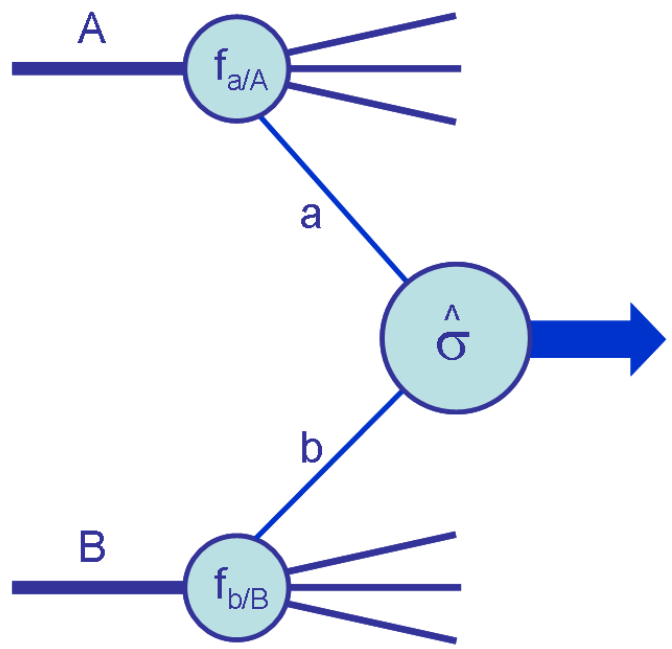
$$= \ln[\gamma\,(1+\beta)\frac{E+p_L}{\sqrt{p_T^2+m^2}}] = y + \ln\gamma\,(1+\beta)$$

- rapidity intervals are invariant under longitudinal boost

$$y_1 - y_2 \to y_1' - y_2' = y_1 - y_2$$

$$\frac{\partial\sigma}{\partial y'} = \frac{\partial\sigma}{\partial y}$$

Cross Section Calculation



$$\sigma_{AB} = \sum_{a,b=q,g} \left[\hat{\sigma}_{ab}^{\mathrm{LO}} + \alpha_S(Q^2)\hat{\sigma}_{ab}^{\mathrm{NLO}} + \ldots\right] \otimes f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2)$$

$$\sigma_X = \sum_{a,b} \int_0^1 dx_a dx_b f(x_a, flav_a, Q^2) f(x_b, flav_b, Q^2) \cdot \sigma_{ab\to X}(x_a, x_b, Q^2).$$

Sum over initial partonic states a,b

Parton Density Function

hard scattering cross-section

PARTON DENSITY FUNCTIONS

$$f_i(x,Q^2) \begin{cases} i = u_v,\ d_v,\ g \text{ and sea} \\ x = p_{parton} / E_{beam} \quad \textbf{parton momentum fraction} \\ Q^2 = \textbf{momentum transfer} \end{cases}$$

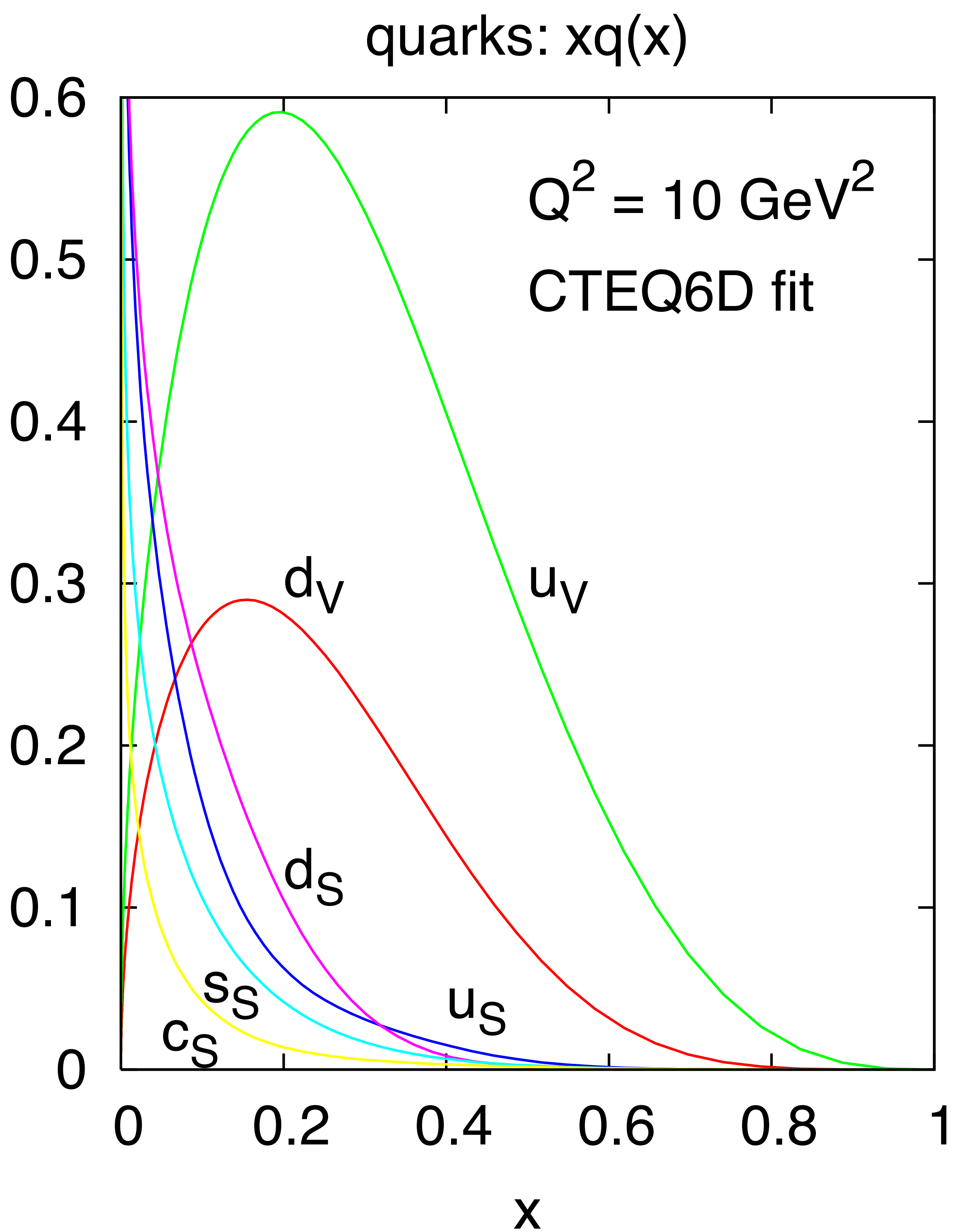
How are PDF's determined?

QCD predicts the scale dependence of $f_i(x,Q^2)$ through DGLAP evolution equations BUT does not accurately predict the x-dependence which has non perturbative origin

1. the x-dependence is parameterised at a fixed scale Q_0^2:
   - valence quarks: $f \sim x^{\lambda} (1-x)^{\eta} P(x)$
   - sea/gluon: $f \sim x^{-\lambda} (1-x)^{\eta} P(x)$

   different parameterisations and no.of free parameters used
2. $f_i(x,Q^2)$ is evolved from Q_0^2 to any other Q^2 by numerically solving the DGLAP equations to various orders (LO,NLO, NNLO)
3. the free parameters are determined by fit to data from experimental observables **(data from HERA experiments H1, ZEUS ,fixed target DIS experiments ,CDF, D0)**

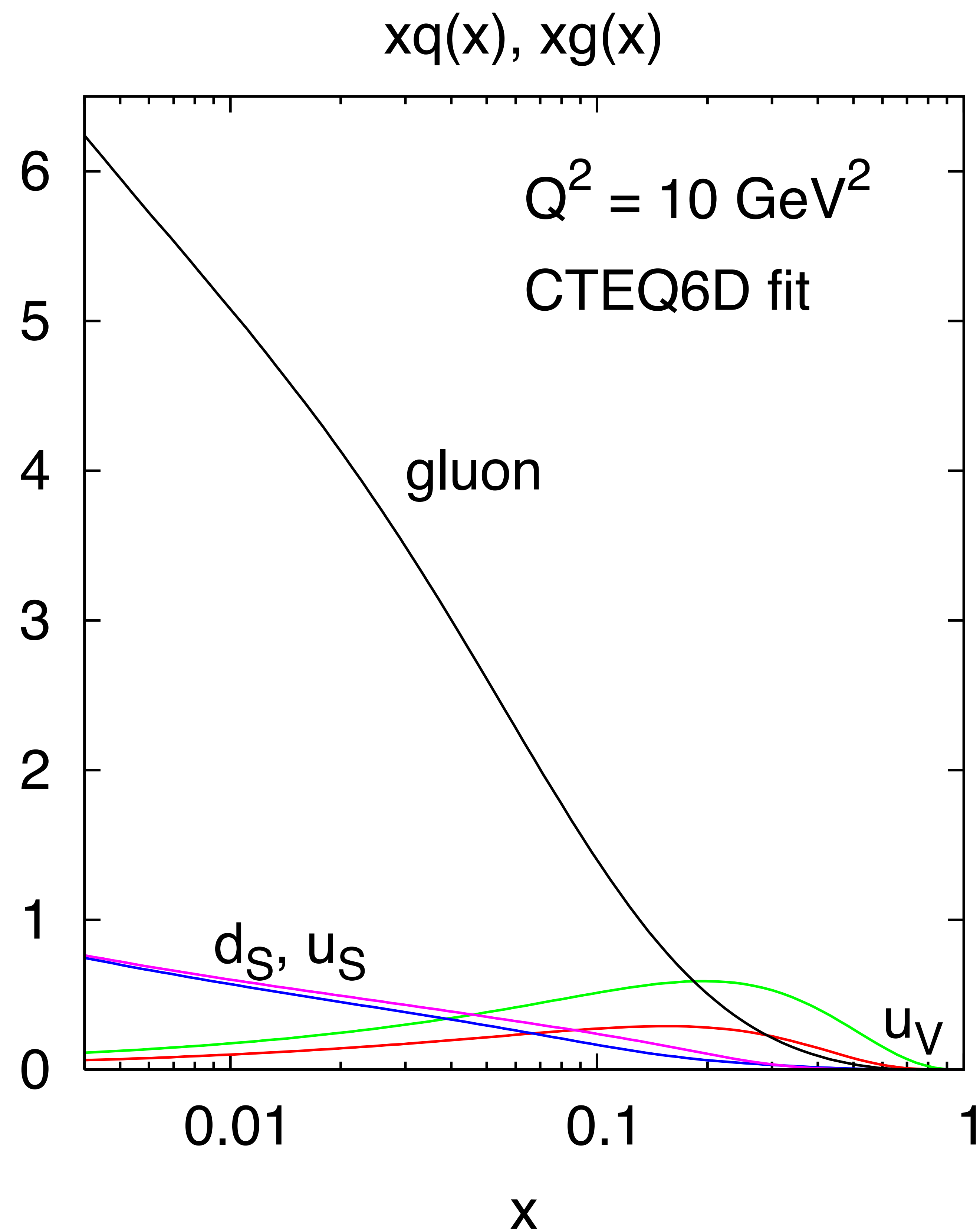
Parton Density Function



- valence quarks ($u_V = u - \bar{u}$) are *hard*
  $x \to 1 : xq_V(x) \sim (1-x)^3$
  quark counting rules
  $x \to 0 : xq_V(x) \sim x^{0.5}$
  Regge theory
- sea quarks ($u_S = 2\bar{u}, \ldots$) fairly *soft* (low-momentum)
  $x \to 1 : xq_S(x) \sim (1-x)^7$
  $x \to 0 : xq_S(x) \sim x^{-0.2}$

GLUON DENSITY FUNCTION

- Gluons dominate by far at low x
- LHC dominated mainly by gluon-gluon fusion (hard scattering of 2 gluons) at low x
- Different experimental signatures for qq, q-anti-q and qg hard scattering
  - also very different cross sections



PDF Sum Rules

- PDF for partons and anti-partons related through CP symmetry

$$f_q^{\bar{p}}(x) = f_{\bar{q}}(x) \qquad f_{\bar{q}}^{\bar{p}}(x) = f_q(x) \qquad f_g^{\bar{p}}(x) = f_g(x)$$

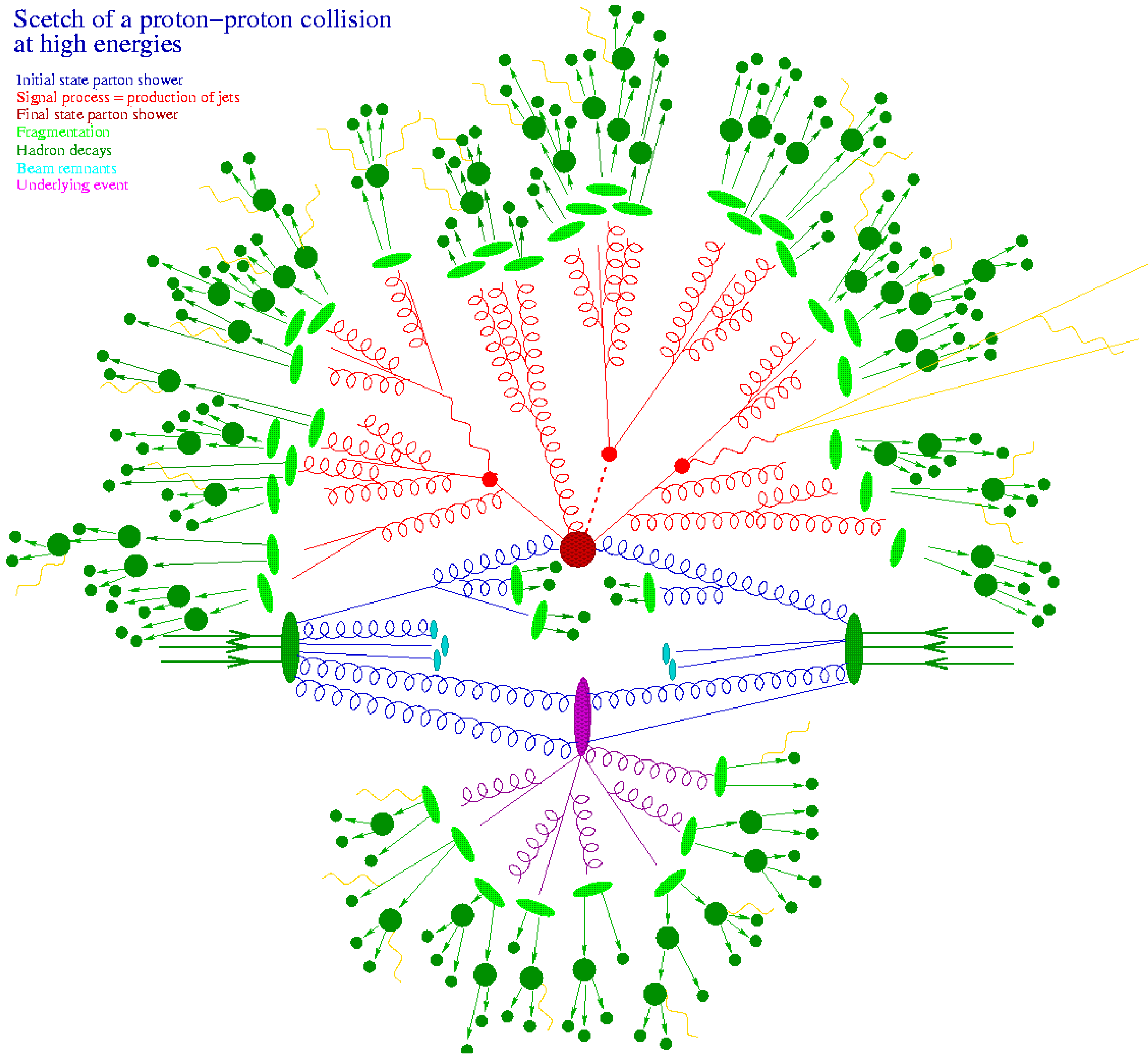
- Number of quarks and momentum of proton also provides constraints on different PDF functions
- 3 valence quarks in proton

$$\langle N_u \rangle = \int_0^1 dx \ \left(f_u(x) - f_{\bar{u}}(x)\right) = 2 \qquad \langle N_d \rangle = \int_0^1 dx \ \left(f_d(x) - f_{\bar{d}}(x)\right) = 1$$

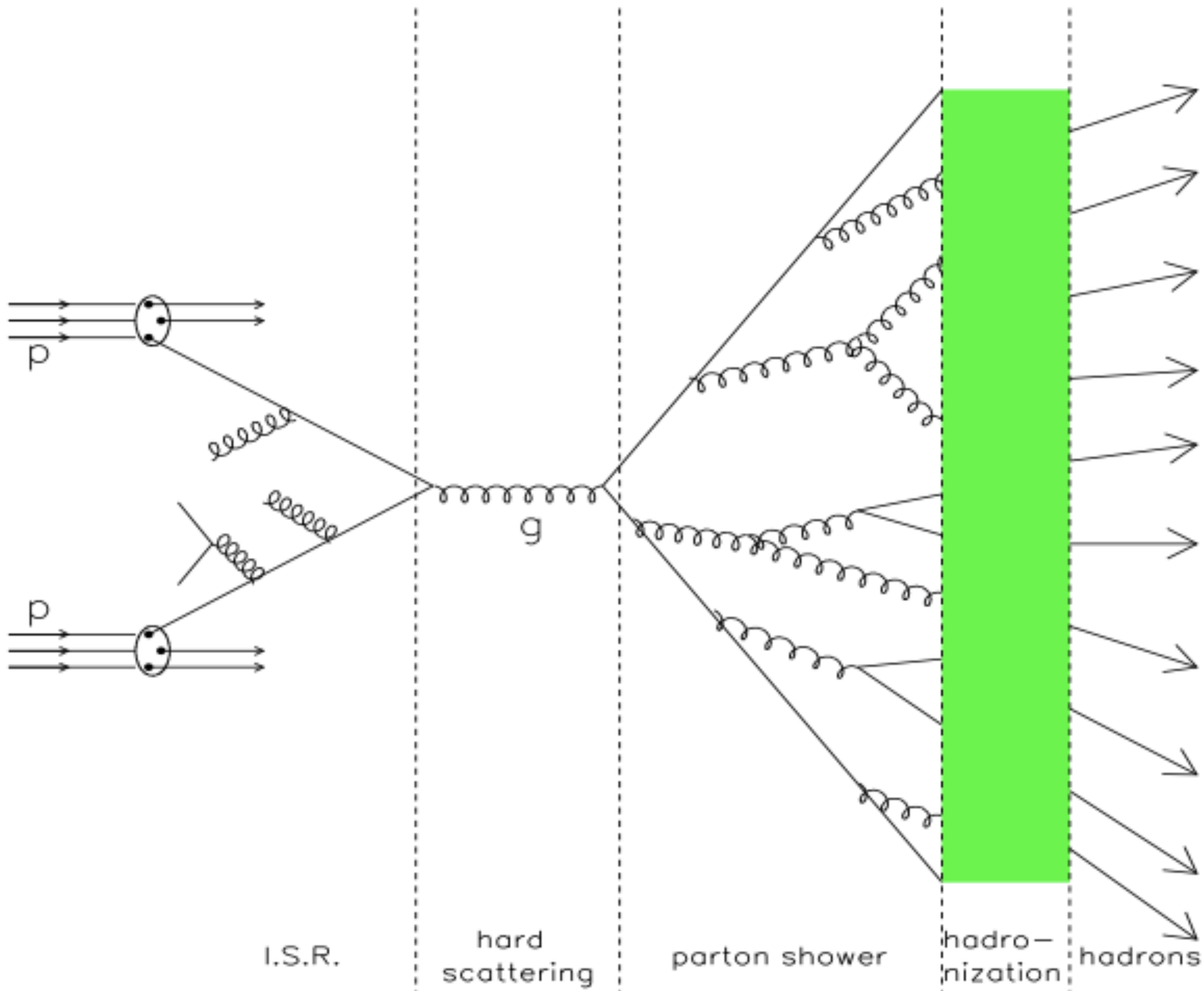
- sum of all parton momenta must add up to proton momentum

$$\langle \sum x_i \rangle = \int_0^1 dx \ x \left(\sum_q f_q(x) + \sum_{\bar{q}} f_{\bar{q}}(x) + f_g(x) \right) = 1$$

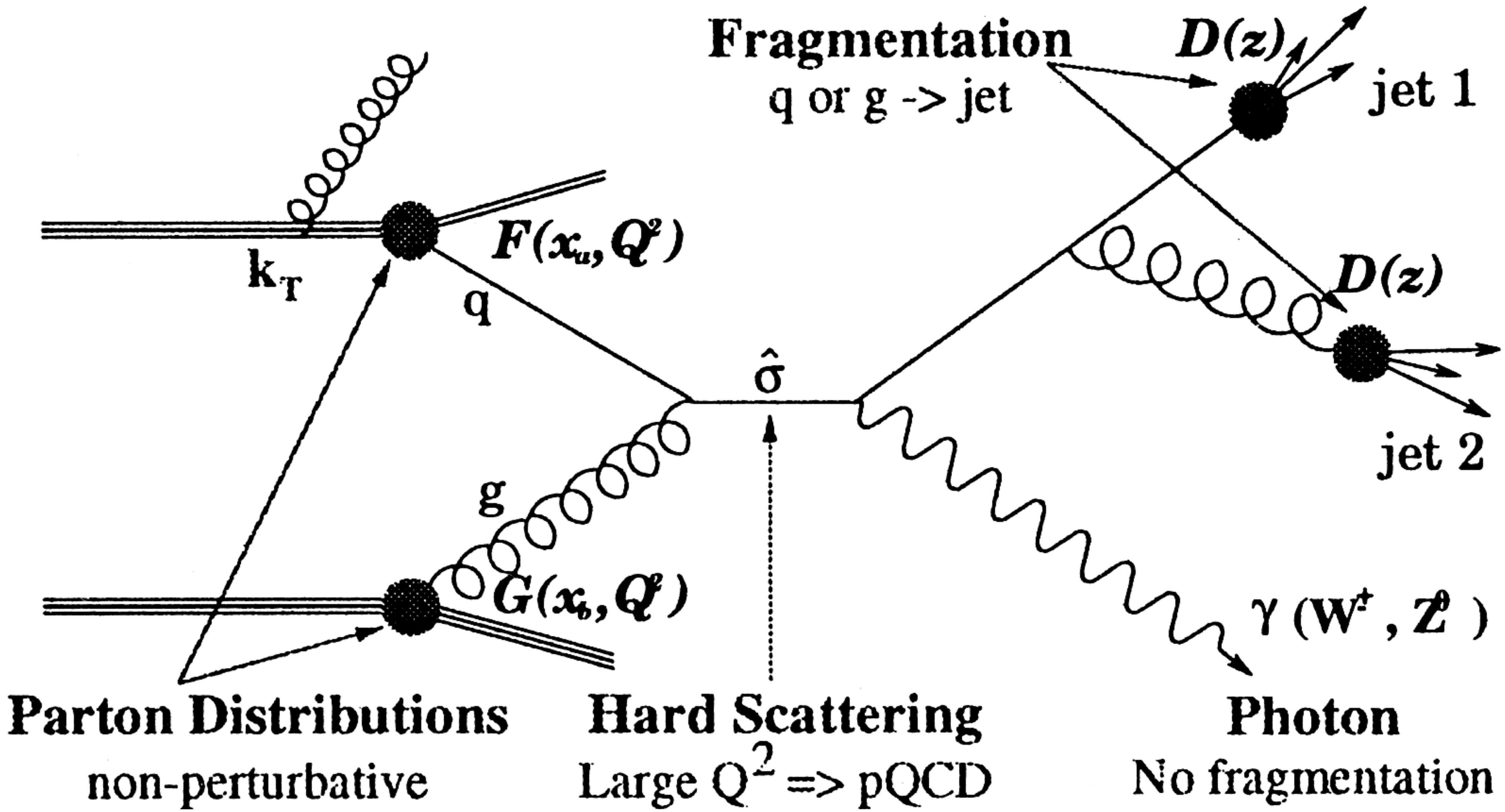
PICTORIAL REPRESENTATION OF P-P COLLISION



Hadron Hadron Collisions



QCD Process



Fragmentation
q or g -> jet
D(z)
jet 1
F(x_a, Q^2)
k_T
q
D(z)
σ̂
jet 2
g
G(x_b, Q^2)
γ (W^±, Z^0)
Parton Distributions
non-perturbative
Hard Scattering
Large Q^2 => pQCD
Photon
No fragmentation