

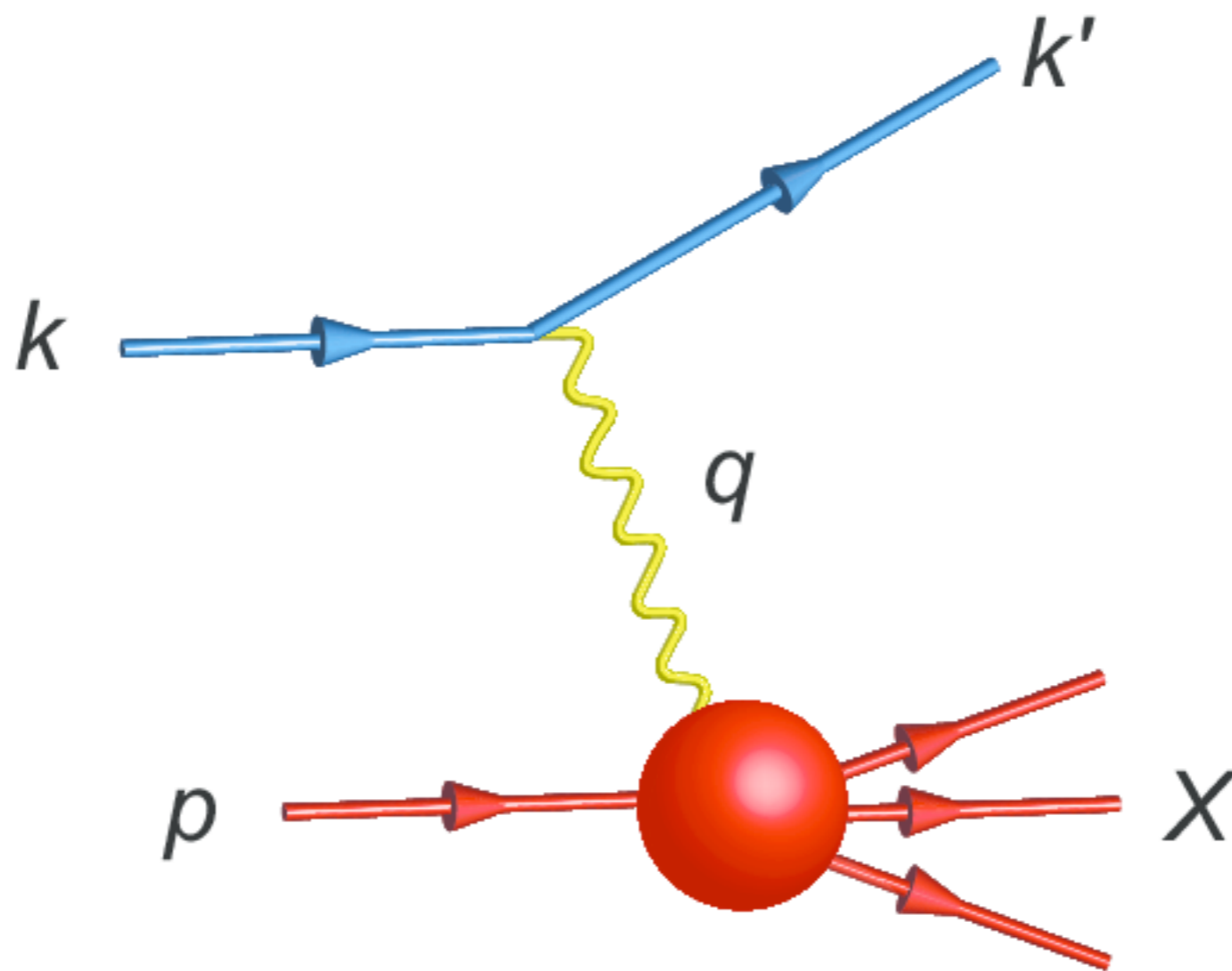
# Deep Inelastic Scattering

# DIS

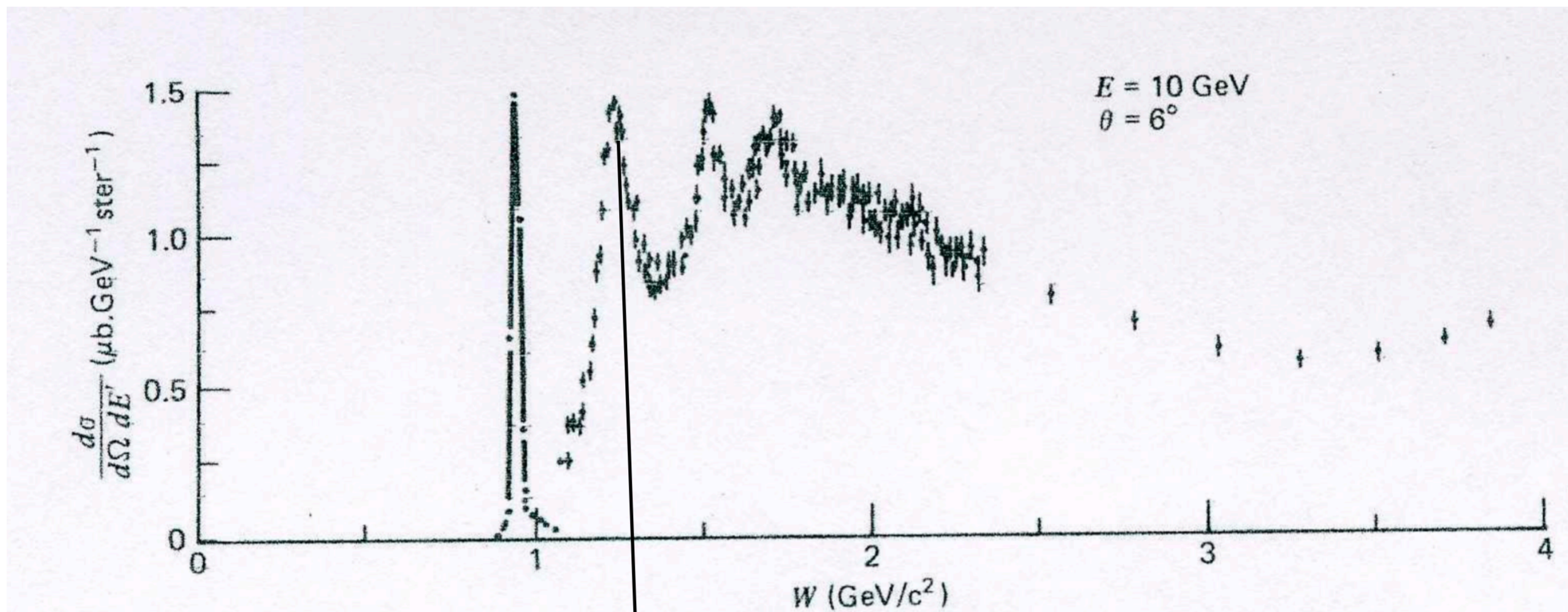
Particle Physics  
Fabrice Couderc / Eli BenHaim

**NPAC 2022**

- Introduction to Deep Inelastic Scattering
  - ✓ Kinematics
  - ✓ Electron-proton scattering formalism
    - ◆ The Hadronic tensor
  - ✓ Elastic scattering
    - ◆ Point like particle
    - ◆  $e p \rightarrow e p$
- Parton model and Bjorken Scaling invariance
  - ✓ Structure functions (brief reminder)
  - ✓ Spin of quarks
  - ✓ Sea quarks
  - ✓ Evolution of the different models
- Scaling violation and DGLAP equations
  - ✓ Invitation
  - ✓ From low to high  $Q^2$ , why ?
  - ✓ DGLAP
  - ✓ Recap



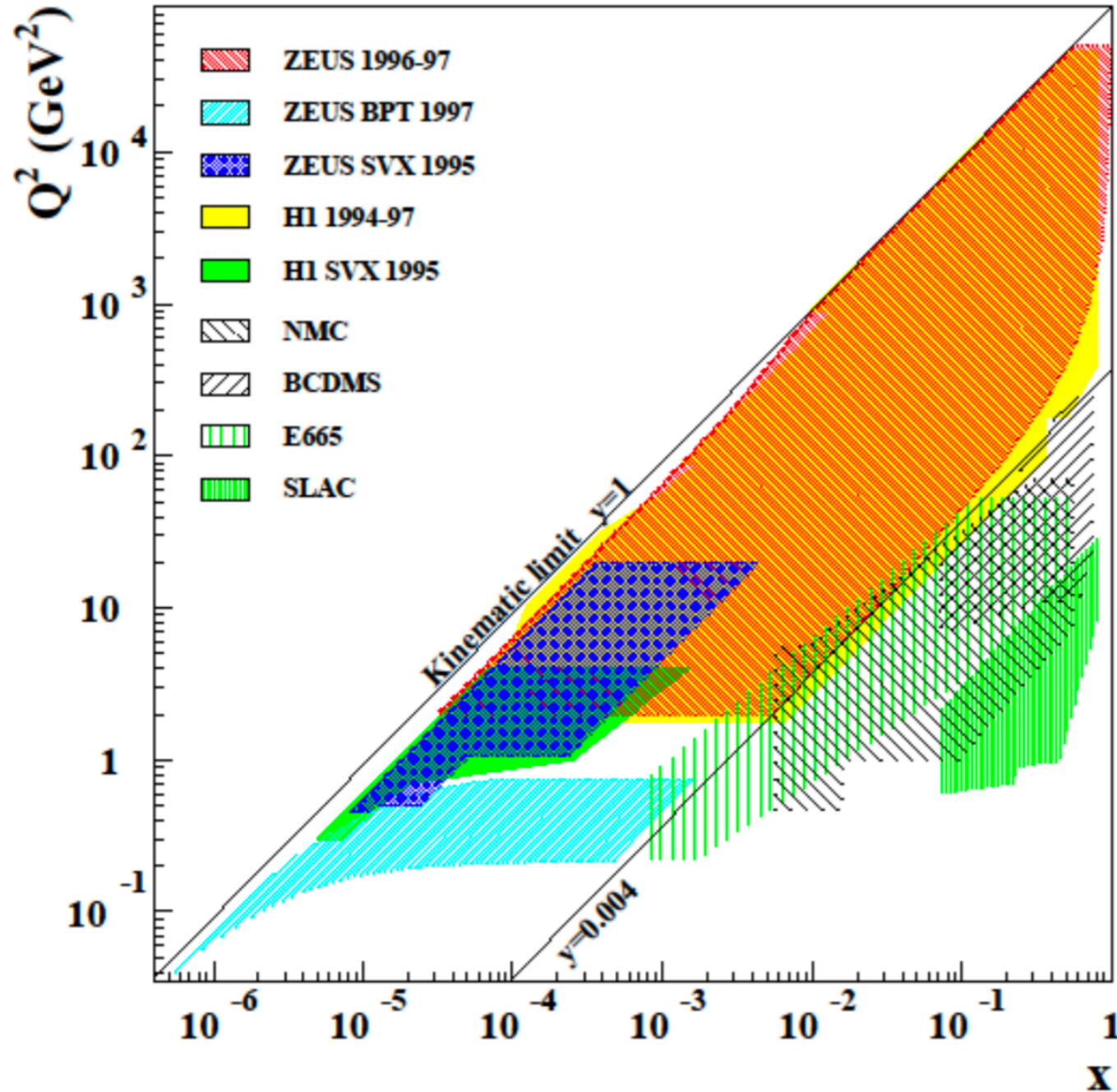
- SLAC experiments 1967-



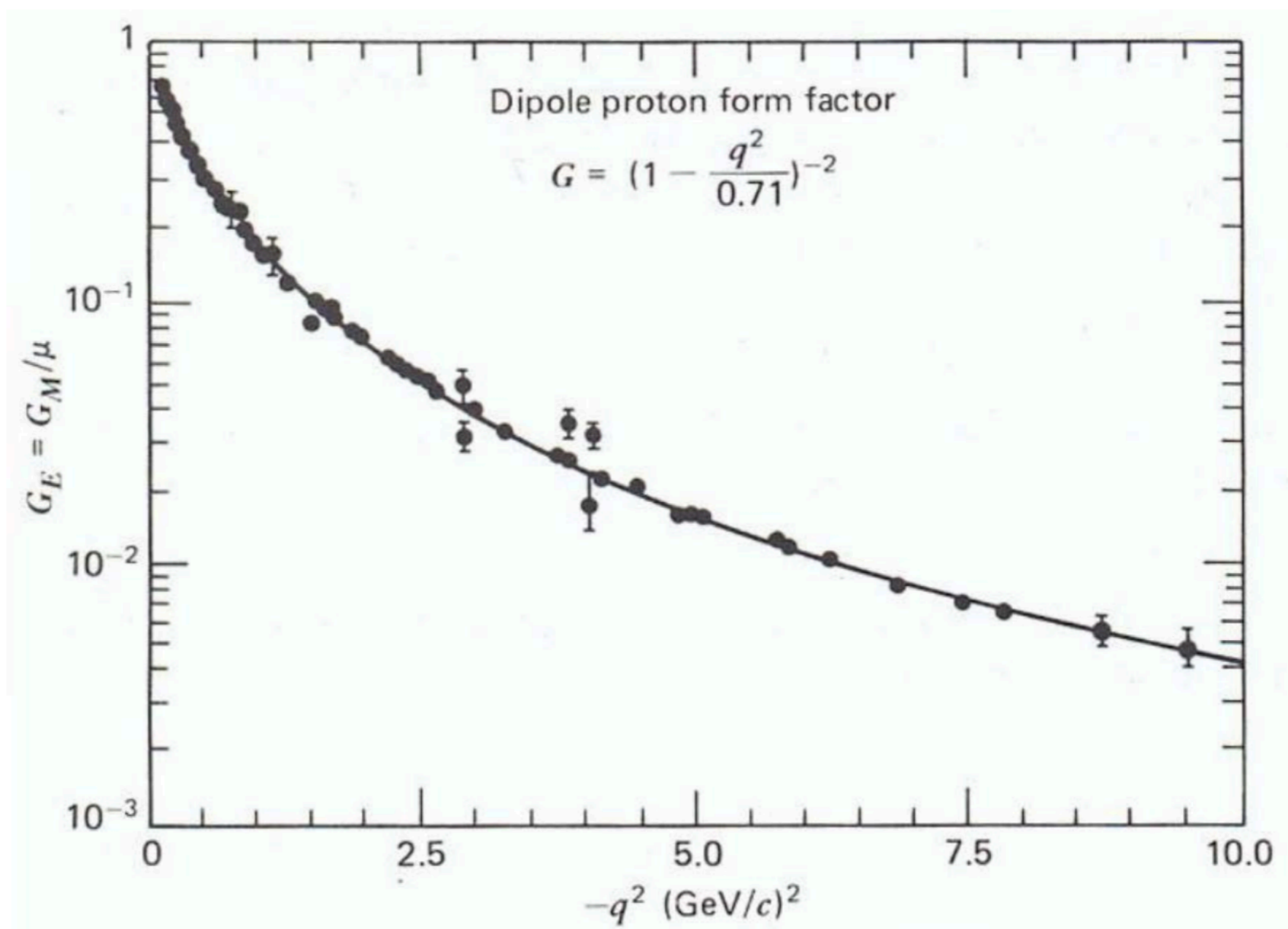
**Elastic peak**

**DIS continuum**

**Resonances**  
 $ep \rightarrow e\Delta$

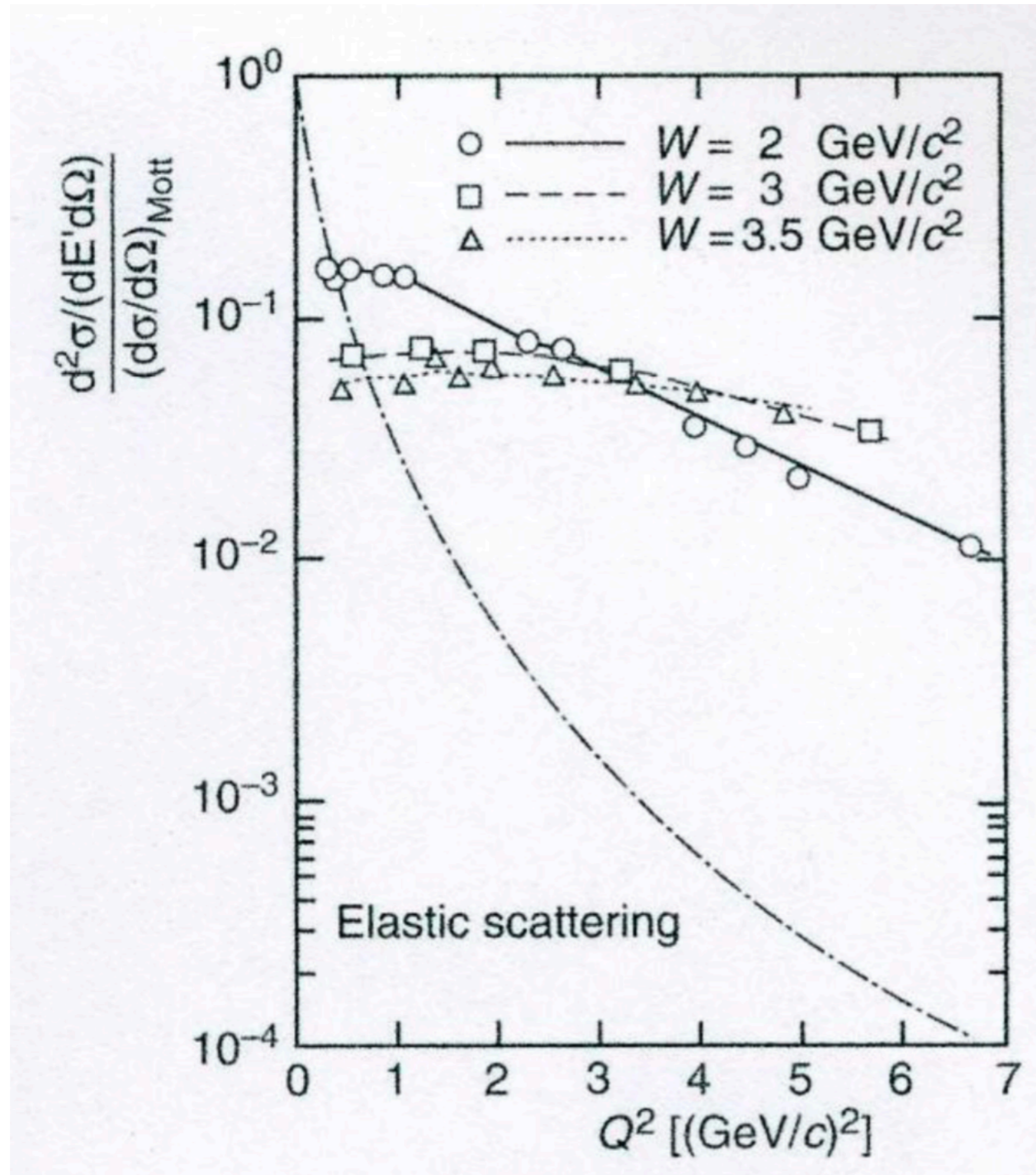


1980	1990	2000	2010
<--- SLAC			Electrons, 3 different detectors, H2, D2, heavy targets
	FNAL E665		Muons, iron toroid, iron target
	CERN BCDMS		Muons, iron toroid, H2, D2, C targets
	CERN EMC	NMC	Muons, open spectrometer, H2, D2, heavy targets
	CERN CDHSW		Neutrinos, iron toroid, iron target
	FNAL CCFRW	NuTeV	Neutrinos, iron toroid, iron target
		HERA H1 AND ZEUS	Electron-Proton Collider
		SLAC Polarised targets	Polarised electron beam and targets
	CERN SMC	COMPASS	Polarised muon beam and targets
		HERA HERMES	Polarised electron beam and targets
		JLAB HALL A and B	Polarised electron beam and targets

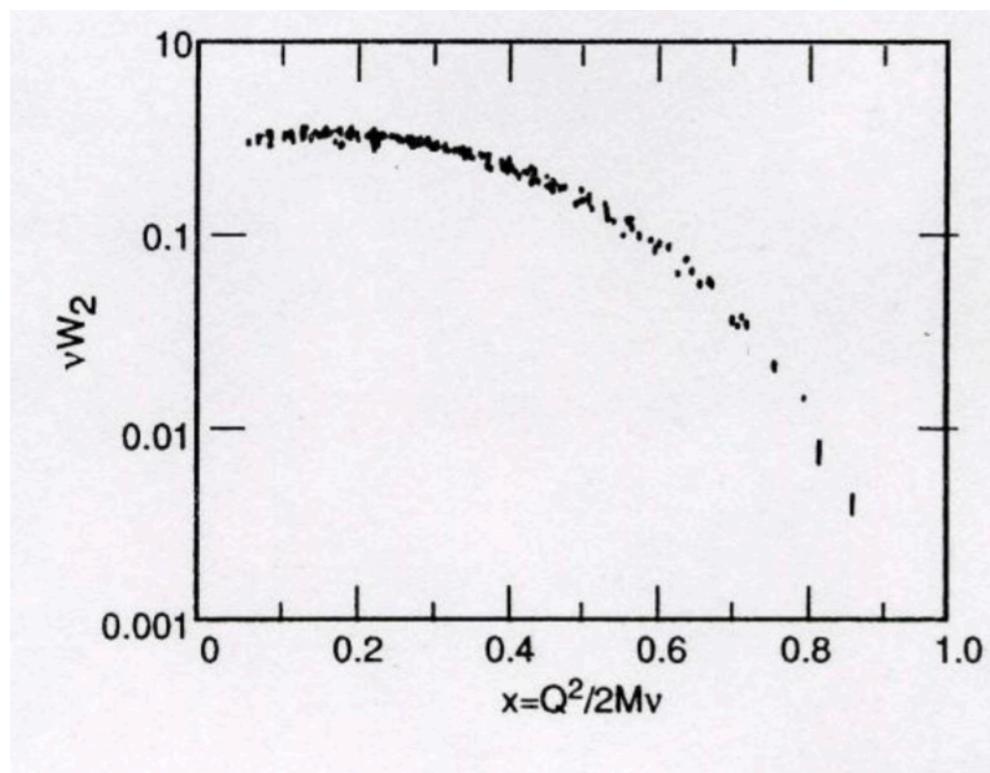


$$\mathbf{W} = \mathbf{M}_p$$

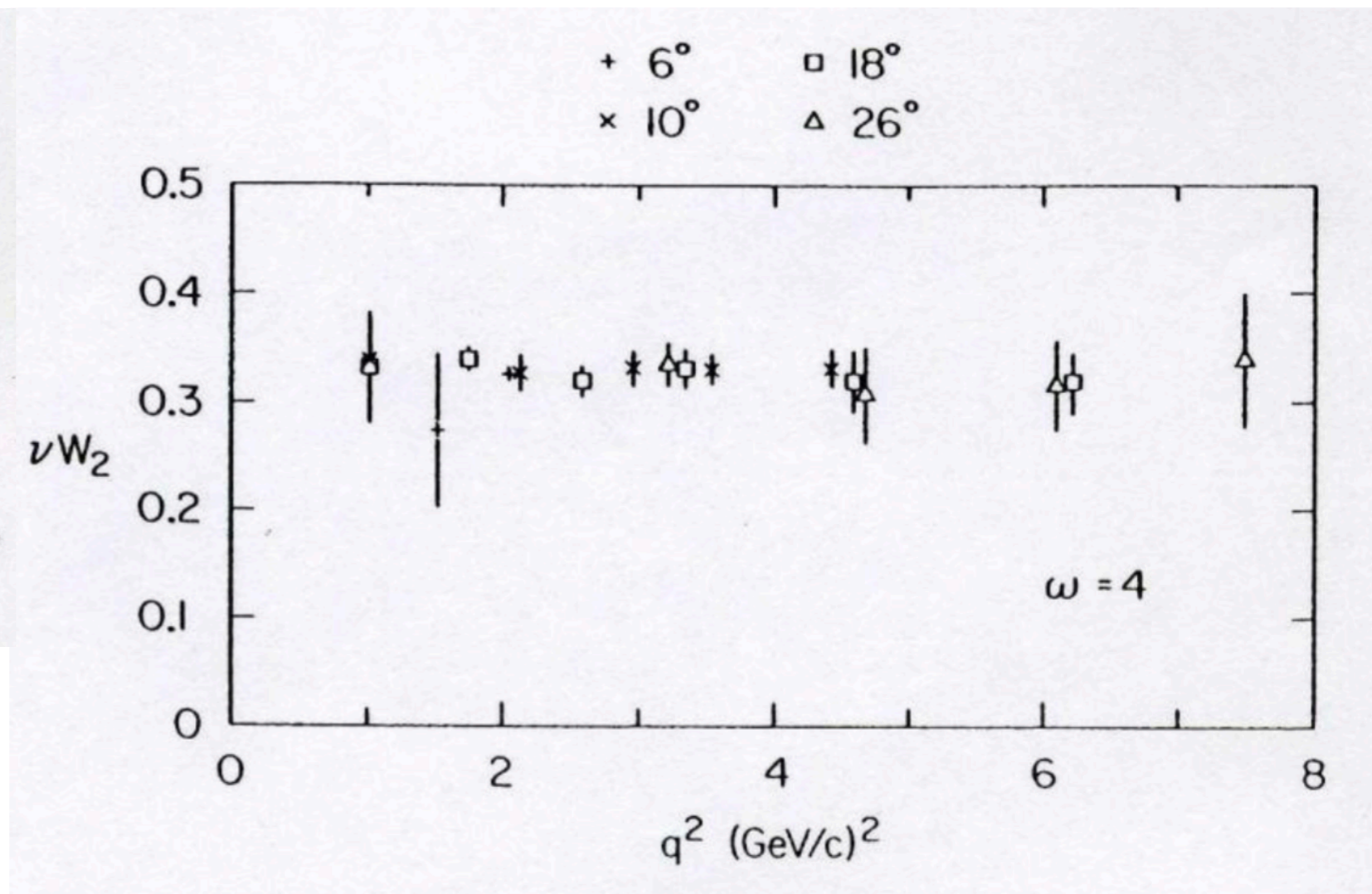
- Reminder: point-like particle in the parton! (valence quarks)



**Bjorken scaling  
Invariance vs  $Q^2$**



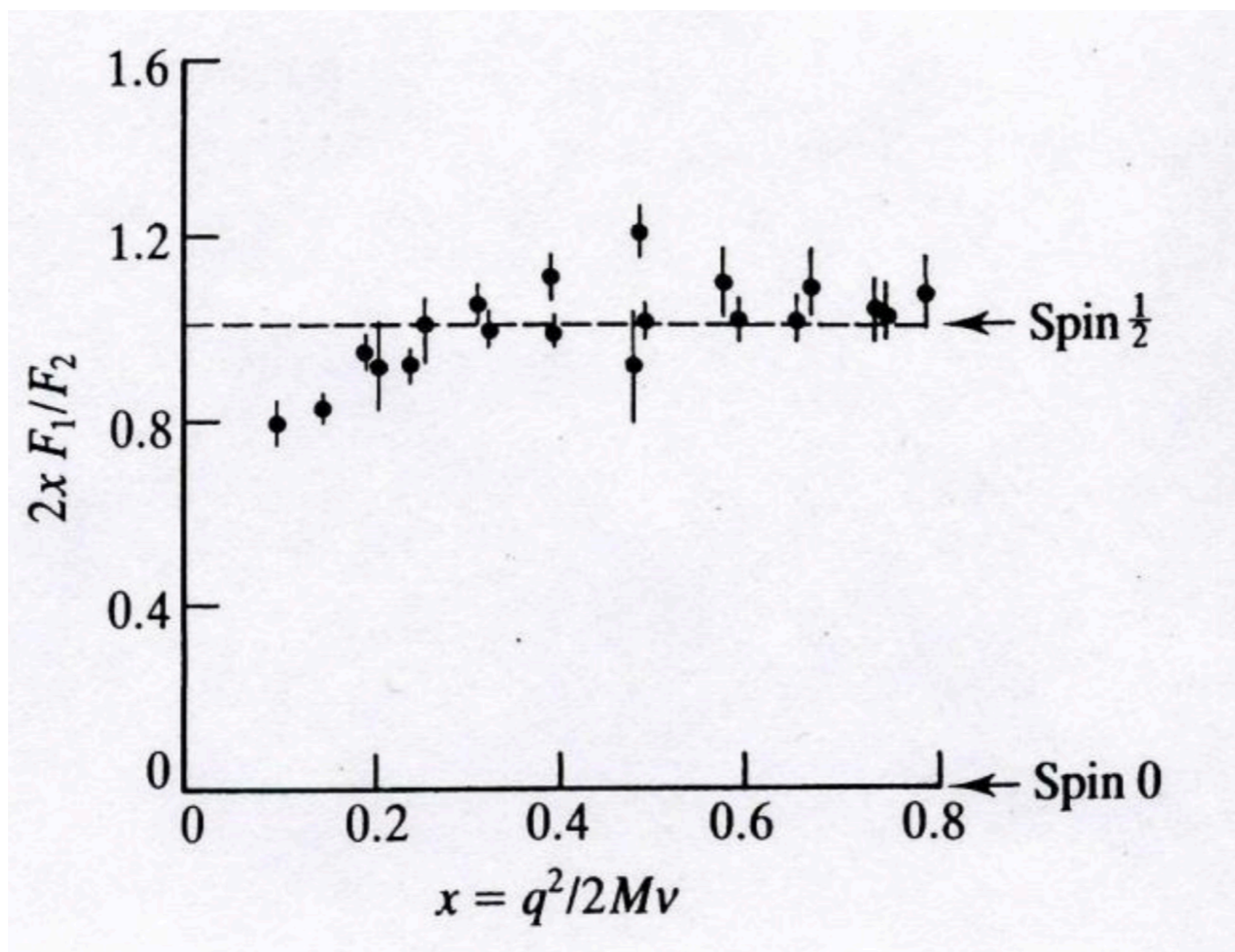
$\nu W_2$  depends on  $x$



$\nu W_2$  does not depend on  $Q^2$



# Quarks: a spin 1/2 particles

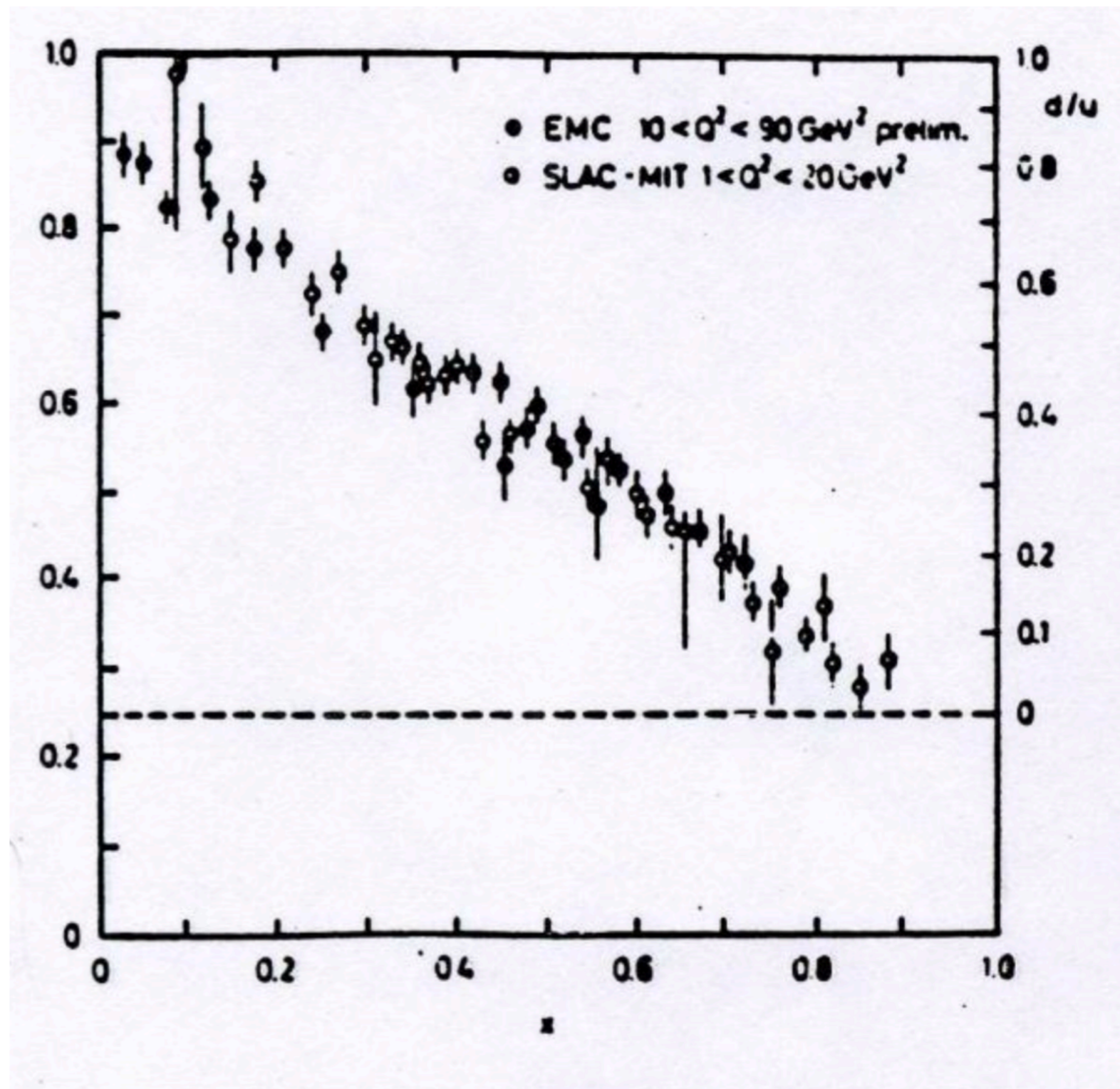


# Valence and sea quarks

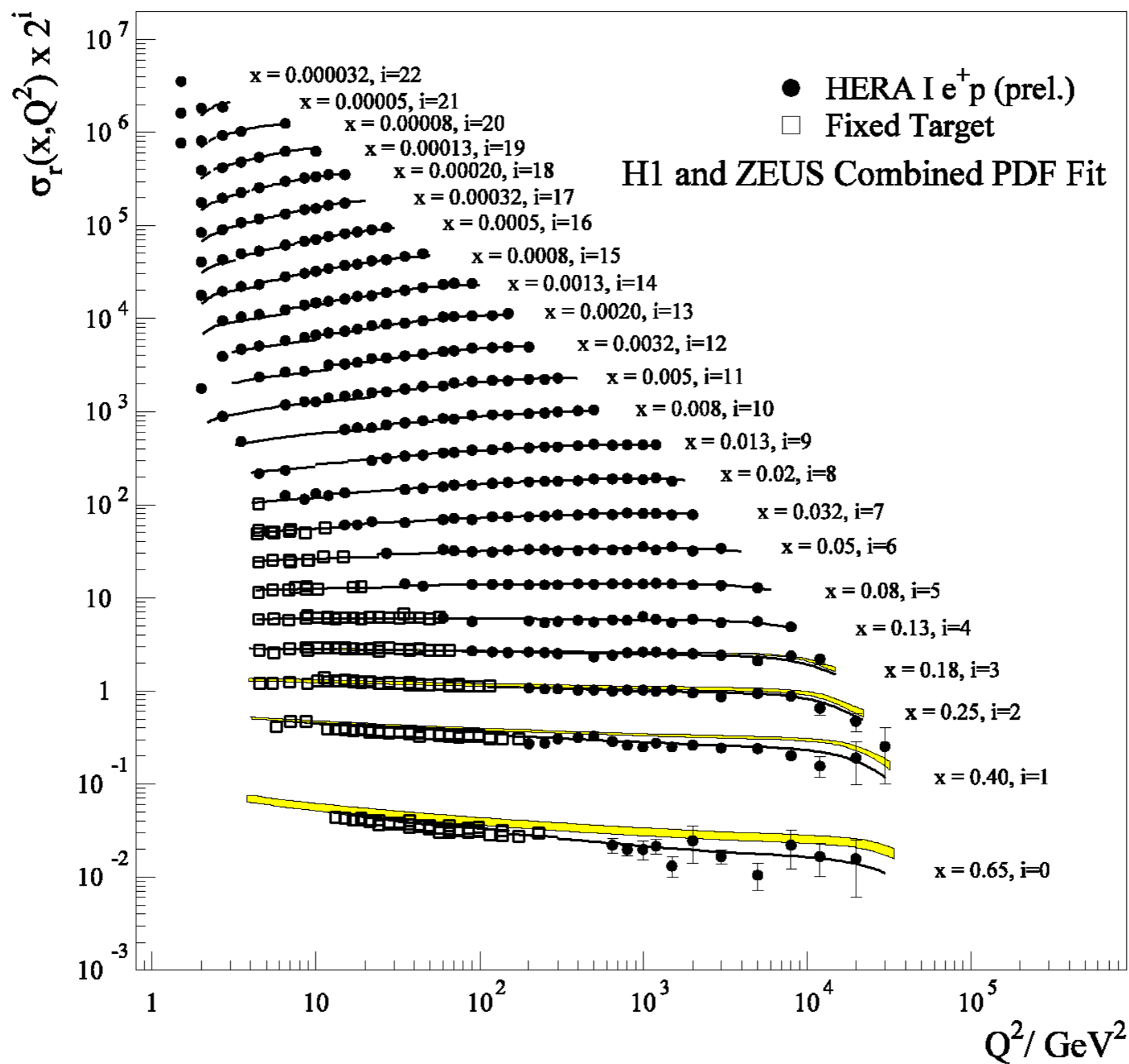
$$R_2 = F_2^{en} / F_2^{ep}$$

- low x: sea dominates  $R_2 = 1$
- High x:  $R_2 = 0.25$

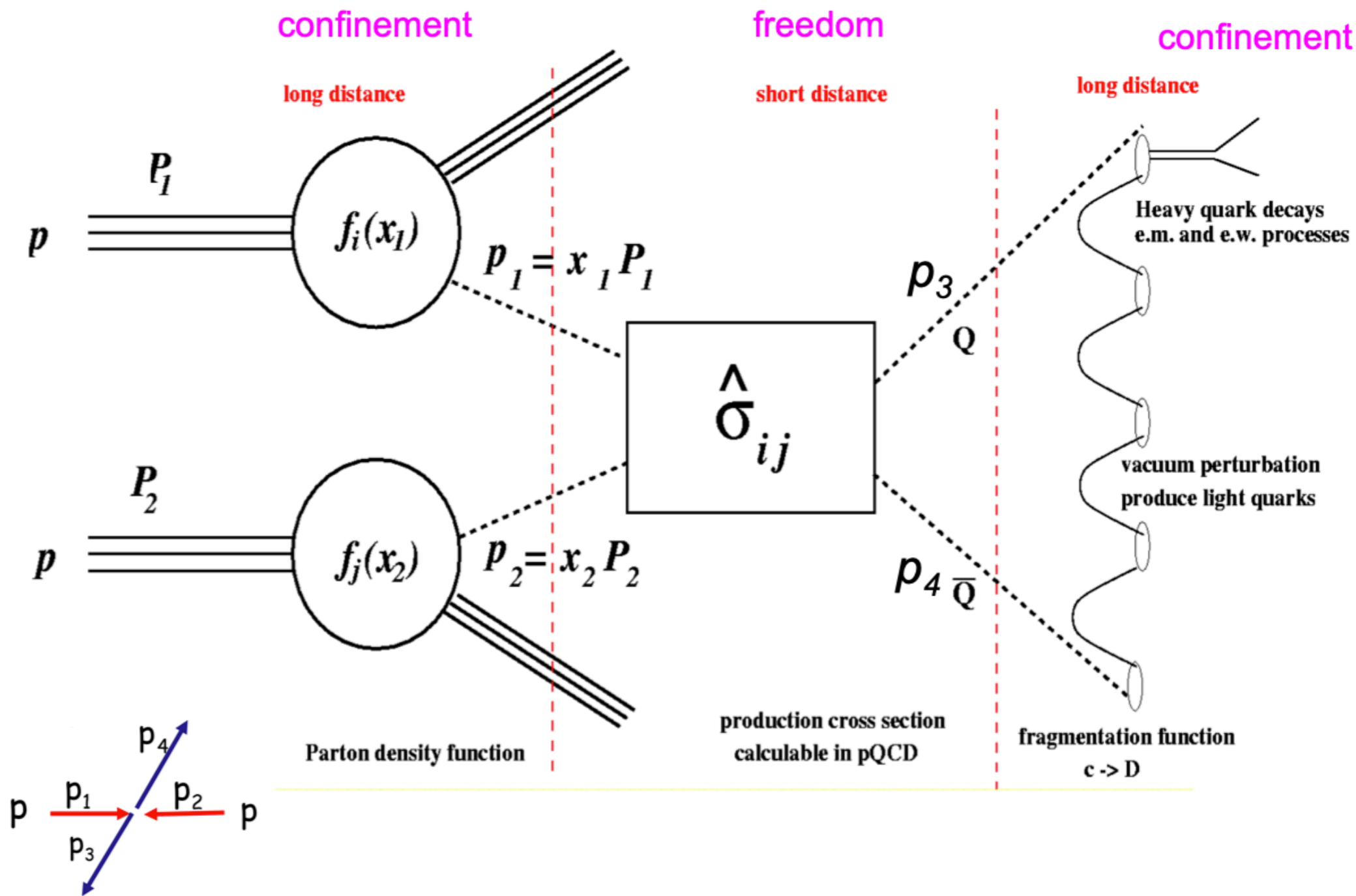
demonstrates:  
 $d_v(x) / u_v(x) \sim 1-x$



# Bjorken scaling violation



# QCD Factorisation theorem



$$\sigma_{2 \rightarrow n} = \sum_{a,b} \int_0^1 dx_a dx_b f_{a/h_1}(x_a, \mu_F) f_{b/h_2}(x_b, \mu_F) \hat{\sigma}_{ab \rightarrow n}(\mu_F, \mu_R)$$

a factorization scale  $\mu_F$      a renormalization scale  $\mu_R$

- According to QCD factorisation theorem
  - ✓ It exists a “factorisation scale” for which we can separate
    - ◆ long distance effects are included in pdfs
    - ◆ hard scatter process ( parton a + parton b  $\rightarrow$  n )
      - Cross section  $d\hat{\sigma}$  computable at a renormalisation scale  $\mu_R$ )  $d\sigma$
  - ✓ The “factorisation scale” is named  $\mu_F$  is not well defined
    - ◆ Taken as the energy scale of the hard process
    - ◆ Varied in the computation of the systematic uncertainties in the cross section prediction

$$\sigma_{2 \rightarrow n} = \sum_{a,b} \int_0^1 dx_a dx_b f_{a/h_1}(x_a, \mu_F) f_{b/h_2}(x_b, \mu_F) \hat{\sigma}_{ab \rightarrow n}(\mu_F, \mu_R)$$

a factorization scale  $\mu_F$      a renormalization scale  $\mu_R$

$f_{a/h_1}$  : pdf of parton a in hadron h1  
 $f_{b/h_2}$  : pdf of parton b in hadron h2

# From HERA to LHC pdfs ?

LO,  $p_T[M] = 0$

$\Rightarrow E = (x_1+x_2)\sqrt{s}/2, p_z = (x_1-x_2)\sqrt{s}/2$

$M^2 = E^2 - p_z^2 = x_1 x_2 s$

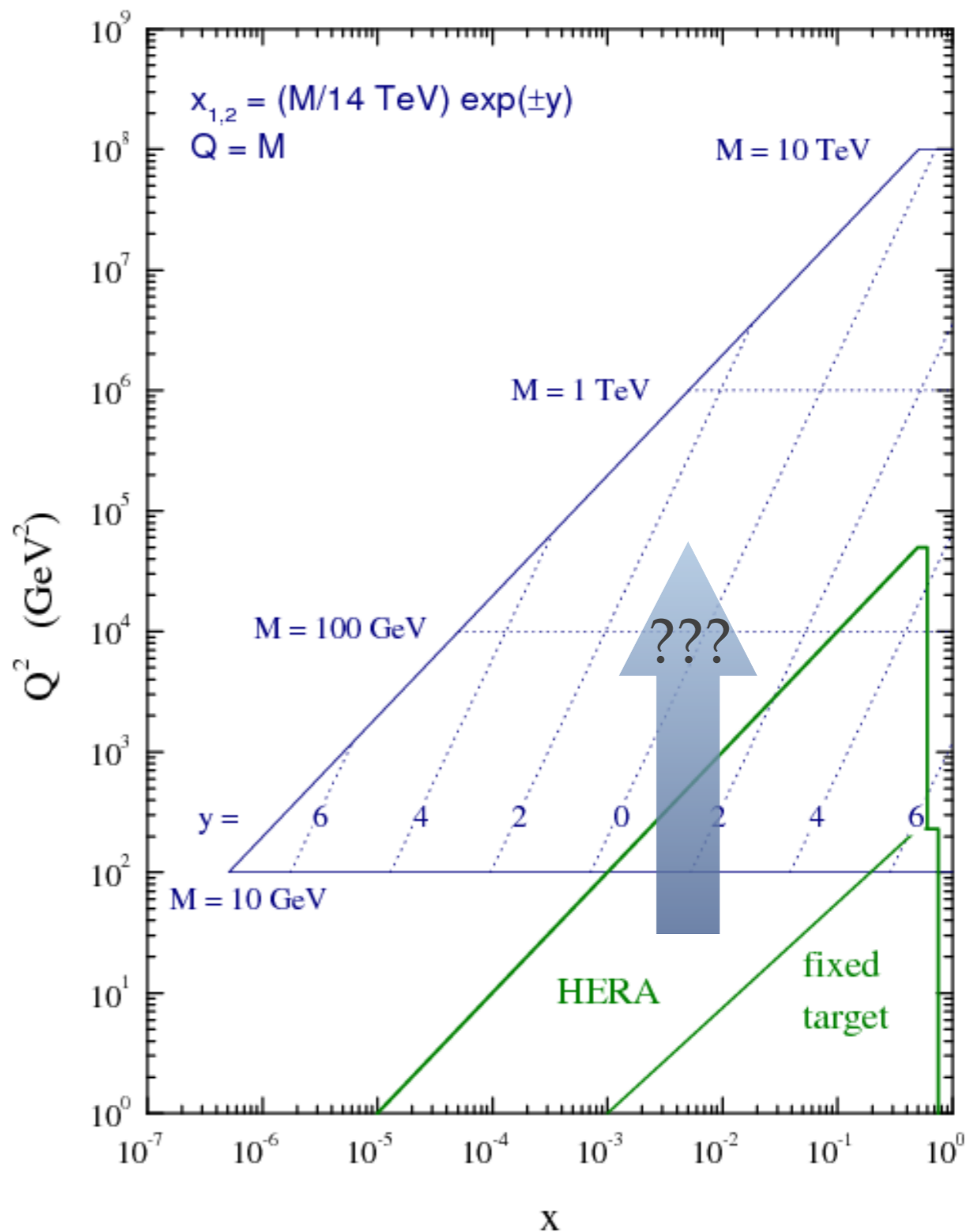
$y = 0.5 \times \ln [ (E+p_z)/(E-p_z) ]$

$y = 0.5 \times \ln [ (E + p_z)^2 / M^2 ]$

$y = 0.5 \times \ln [ x_1^2 s / M^2 ]$

$M^2 = x_1 x_2 s$   
 $x_1 = M / \sqrt{s} e^y$   
 $x_2 = M / \sqrt{s} e^{-y}$

LHC parton kinematics



Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

$$\frac{\partial}{\partial \log Q^2} \begin{bmatrix} q(x, Q^2) \\ g(x, Q^2) \end{bmatrix} = \frac{\alpha_s}{2\pi} \begin{bmatrix} \mathcal{P}_{q/q} \left[ \begin{array}{c} z \\ \text{diagram} \end{array} \right] & \mathcal{P}_{q/g} \left[ \begin{array}{c} z \\ \text{diagram} \end{array} \right] \\ \mathcal{P}_{g/q} \left[ \begin{array}{c} z \\ \text{diagram} \end{array} \right] & \mathcal{P}_{g/g} \left[ \begin{array}{c} z \\ \text{diagram} \end{array} \right] \end{bmatrix} \otimes \begin{bmatrix} q(x, Q^2) \\ g(x, Q^2) \end{bmatrix}$$

PDFs

$$\mathcal{P} \otimes f(x, Q^2) = \int_x^1 \frac{dy}{y} \mathcal{P}(x/y) f(y, Q^2)$$

$$\frac{4}{3} \left[ \frac{1+z^2}{1-z} \right]$$

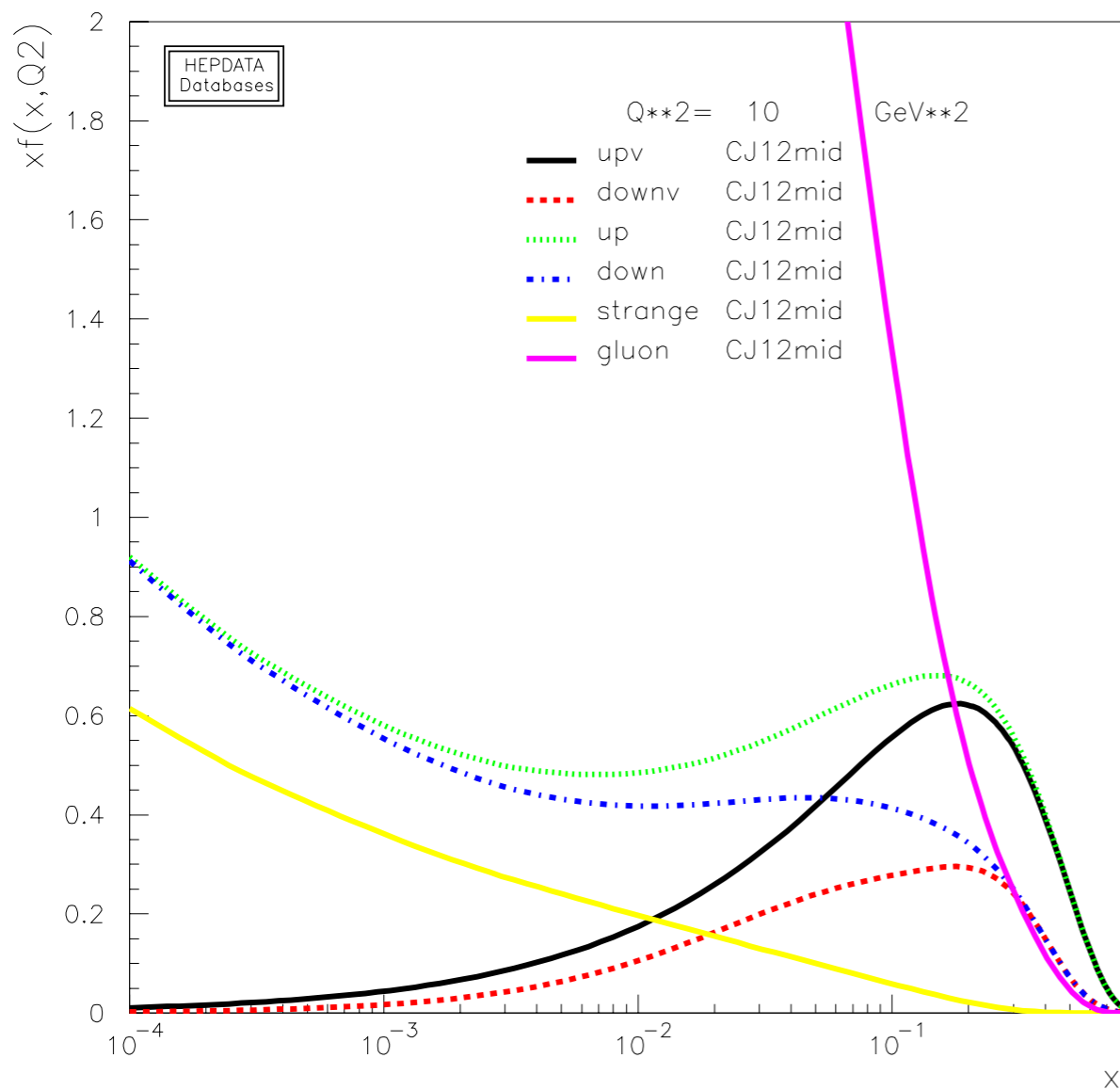
$$\frac{1}{2} [z^2 + (1-z^2)]$$

$$\frac{4}{3} \left[ \frac{1+(1-z)^2}{z} \right]$$

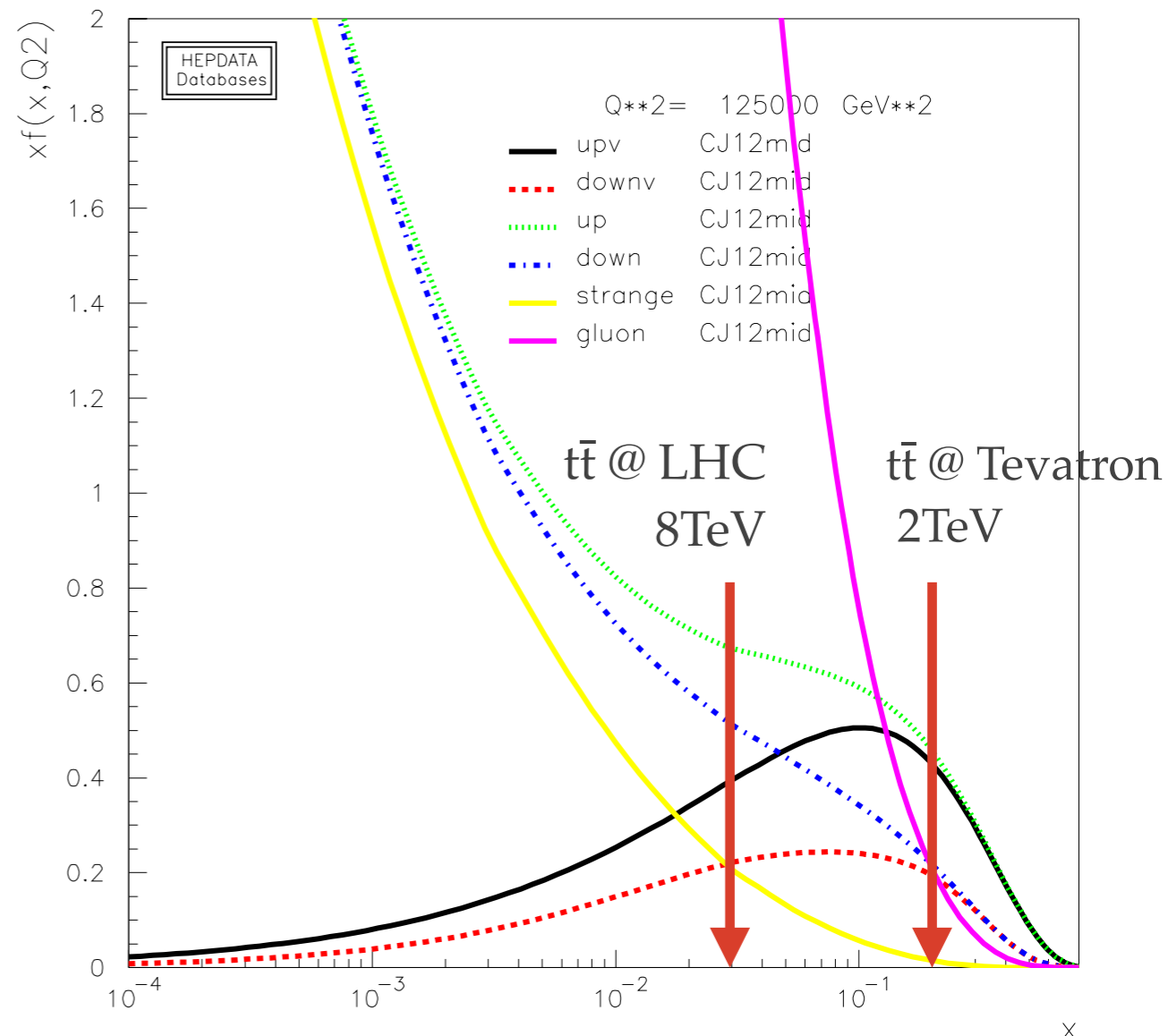
$$6 \left[ \frac{z}{1-z} + \frac{1-z}{z} + z(1-z) \right]$$

# Parton density function recap

$Q^2 = (10 \text{ GeV})^2$



$Q^2 = (350 \text{ GeV})^2$



$t\bar{t}$  production threshold