# Deep Inelastic Scattering
# DIS

Particle Physics
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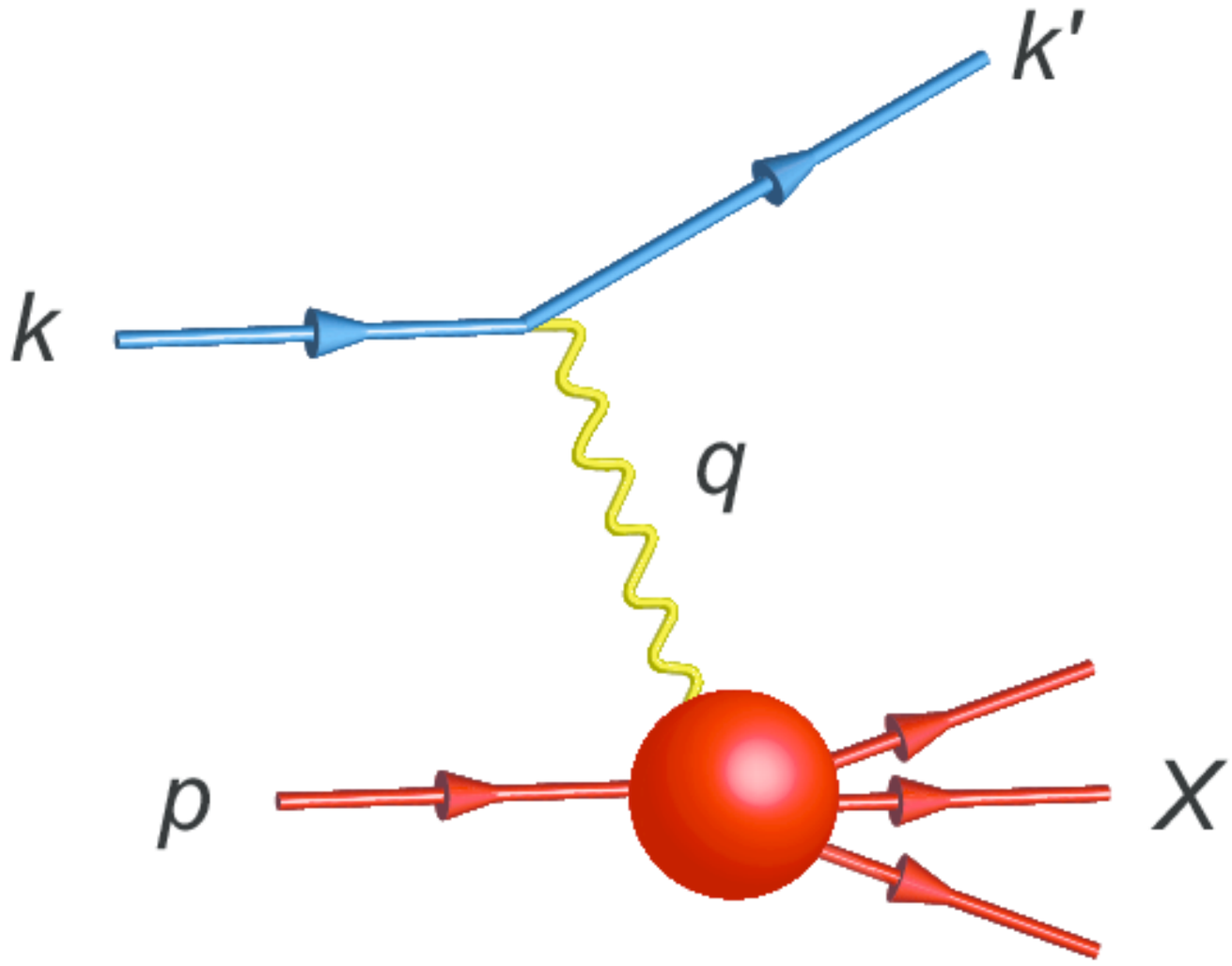
**NPAC 2023/2024**

# Overview

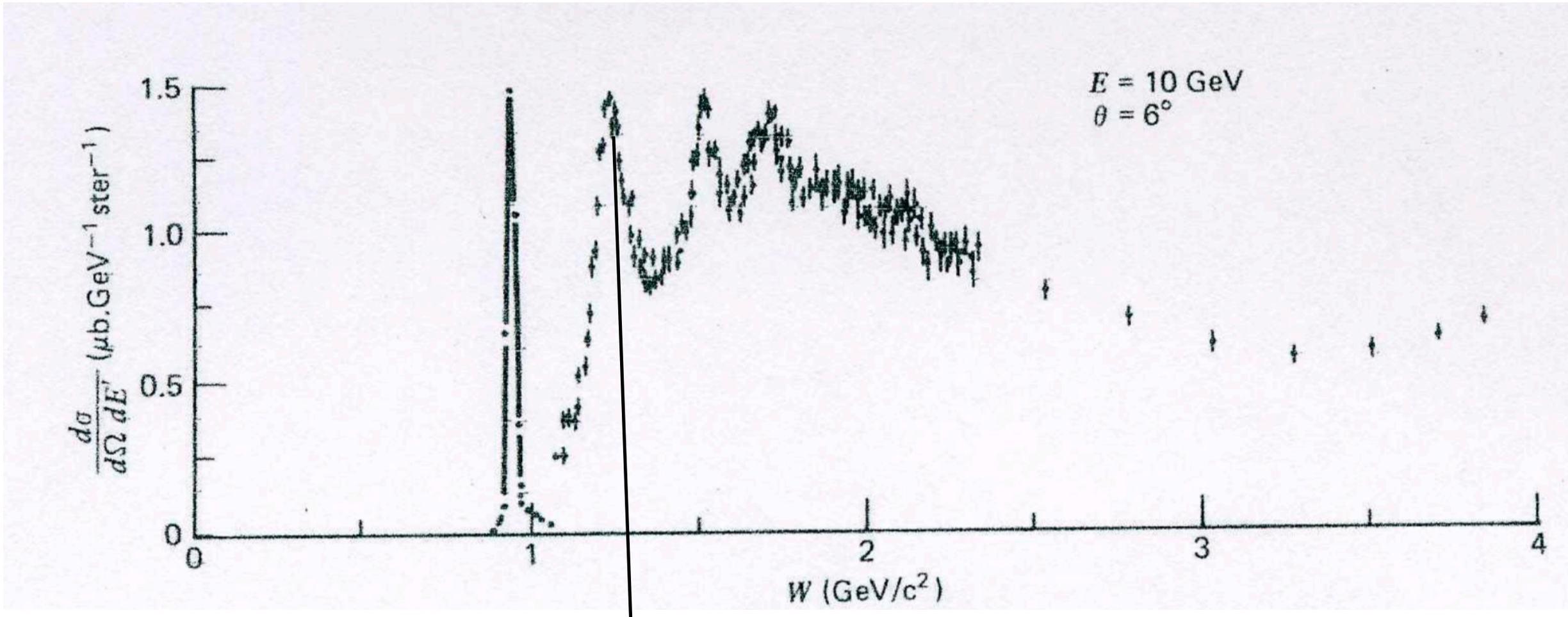
- Introduction to Deep Inelastic Scattering
  - ✓ Kinematics
  - ✓ Electron-proton scattering formalism
    - ✦ The Hadronic tensor
  - ✓ Elastic scattering
    - ✦ Point like particle
    - ✦ e p → e p
- Parton model and Bjorken Scaling invariance
  - ✓ Structure functions (brief reminder)
  - ✓ Spin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

# Scattering kinematics



# e-p inelastic scattering

- SLAC experiments 1967-

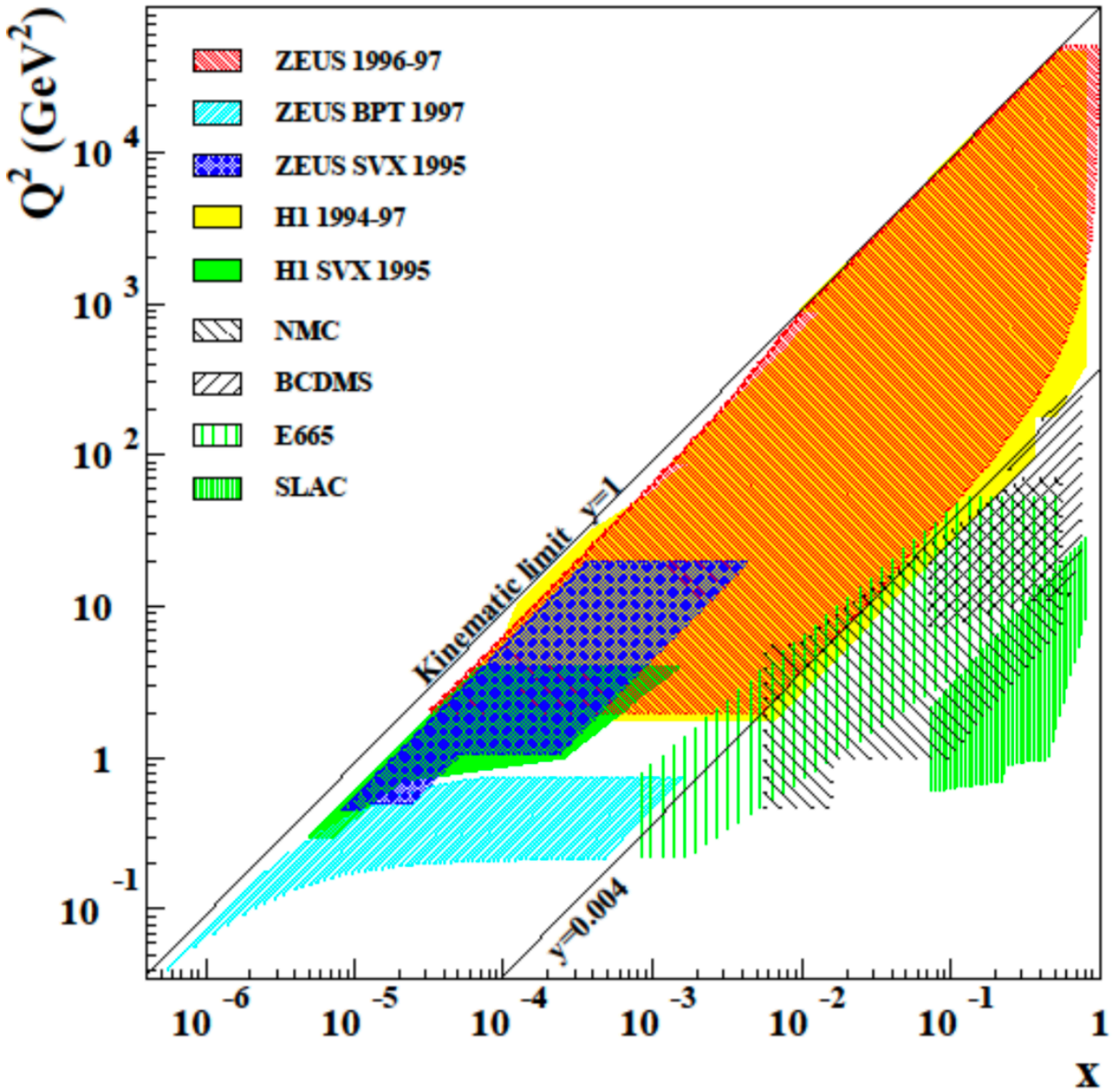


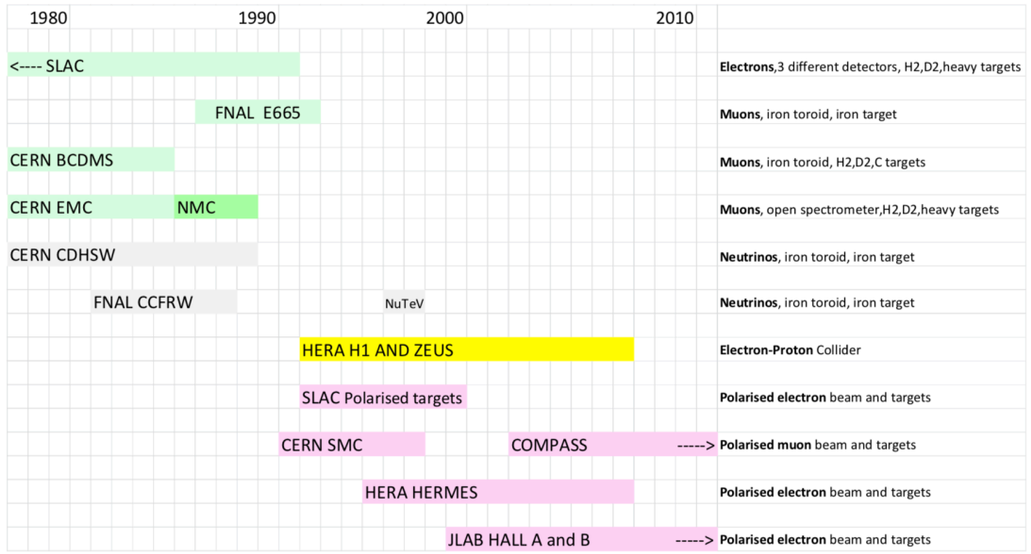

**Elastic peak**

**DIS continuum**

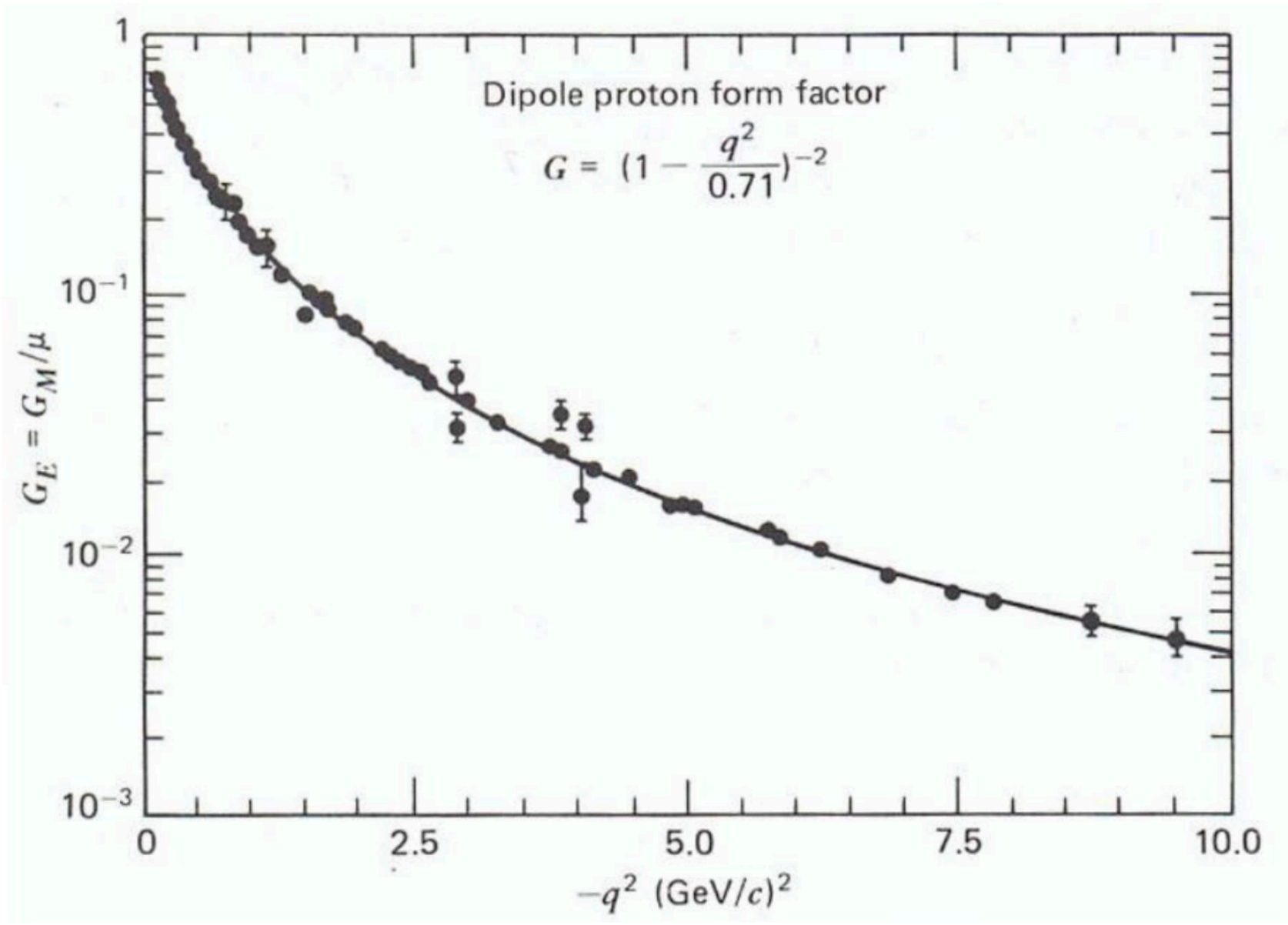
**Resonances**
**ep → eΔ**

# Kinematic 2D space



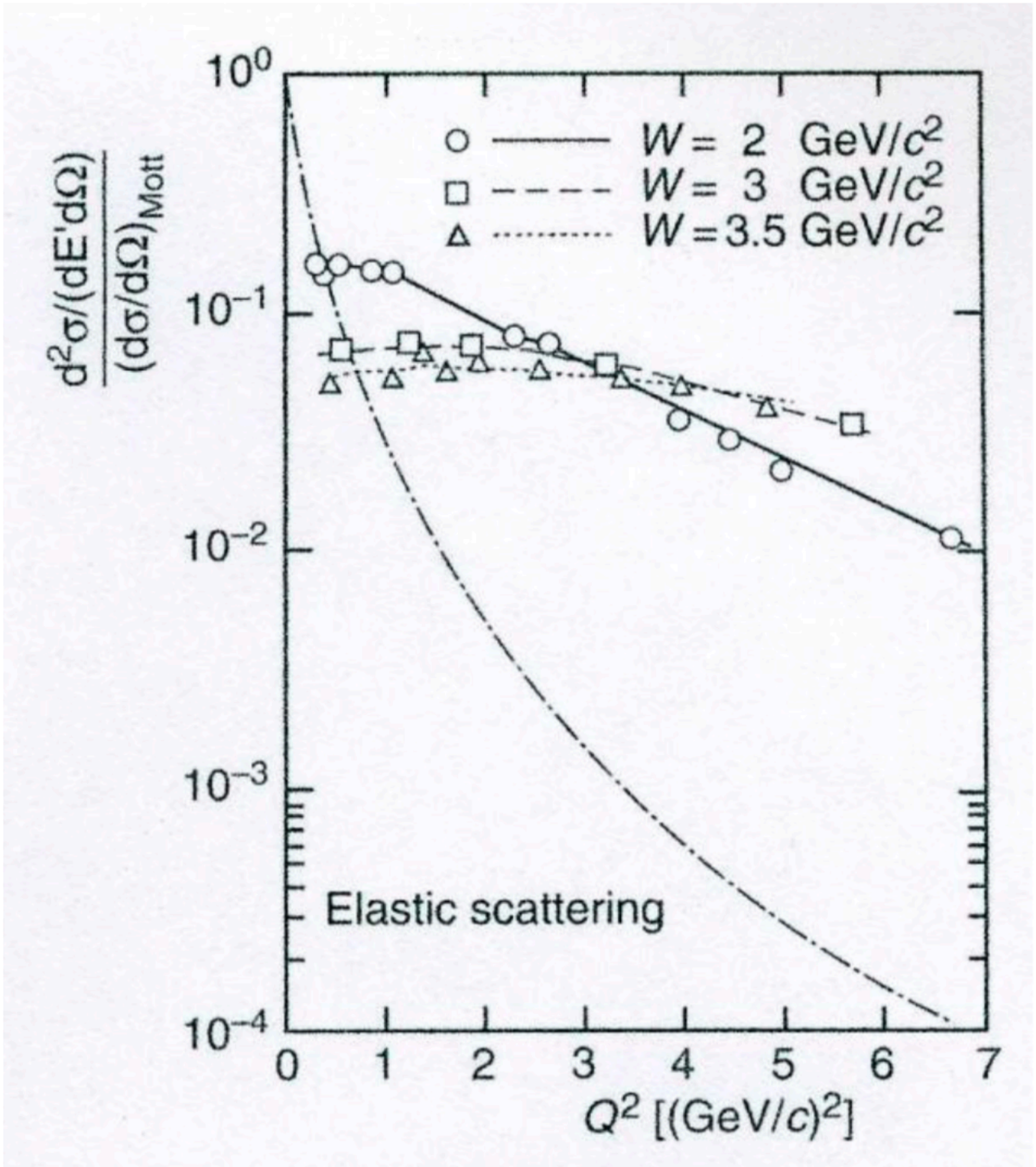
# e-p Elastic scattering




**W = $M_p$**

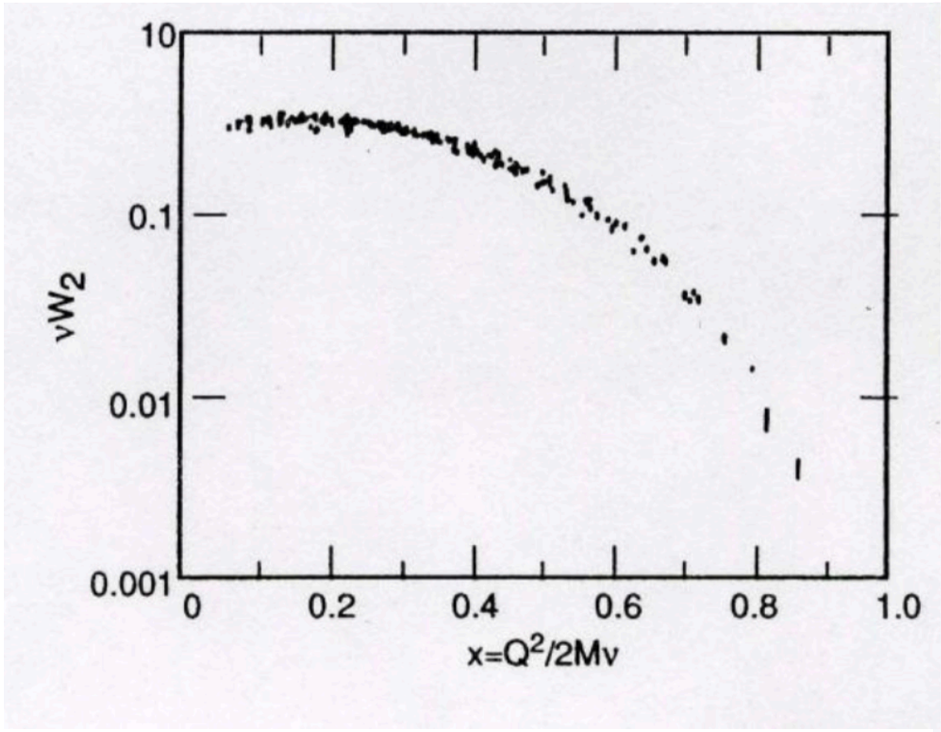
# e-p inelastic scattering

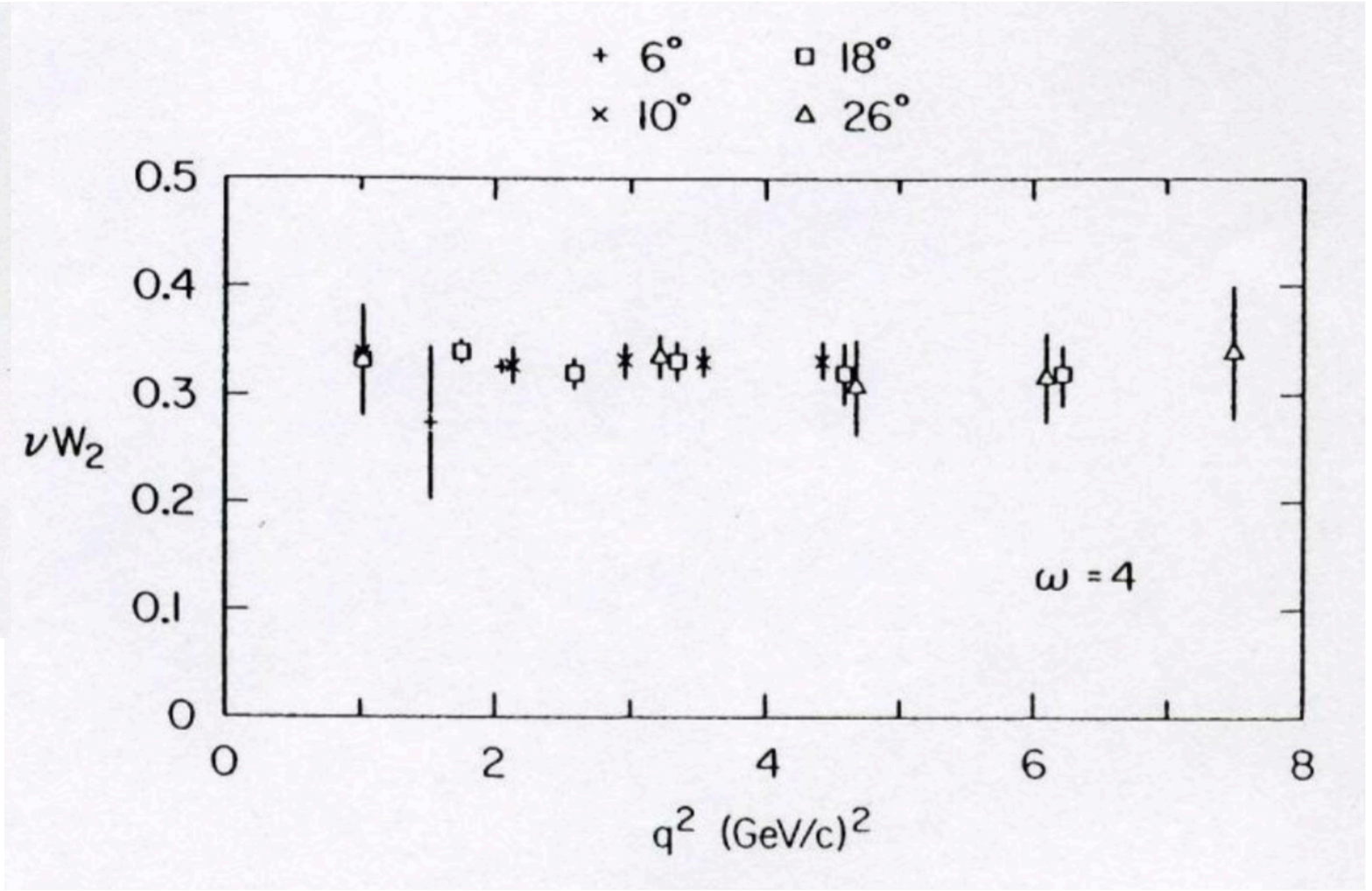
- Reminder: point-like particle in the parton! (valence quarks)




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

# Bjorken scaling

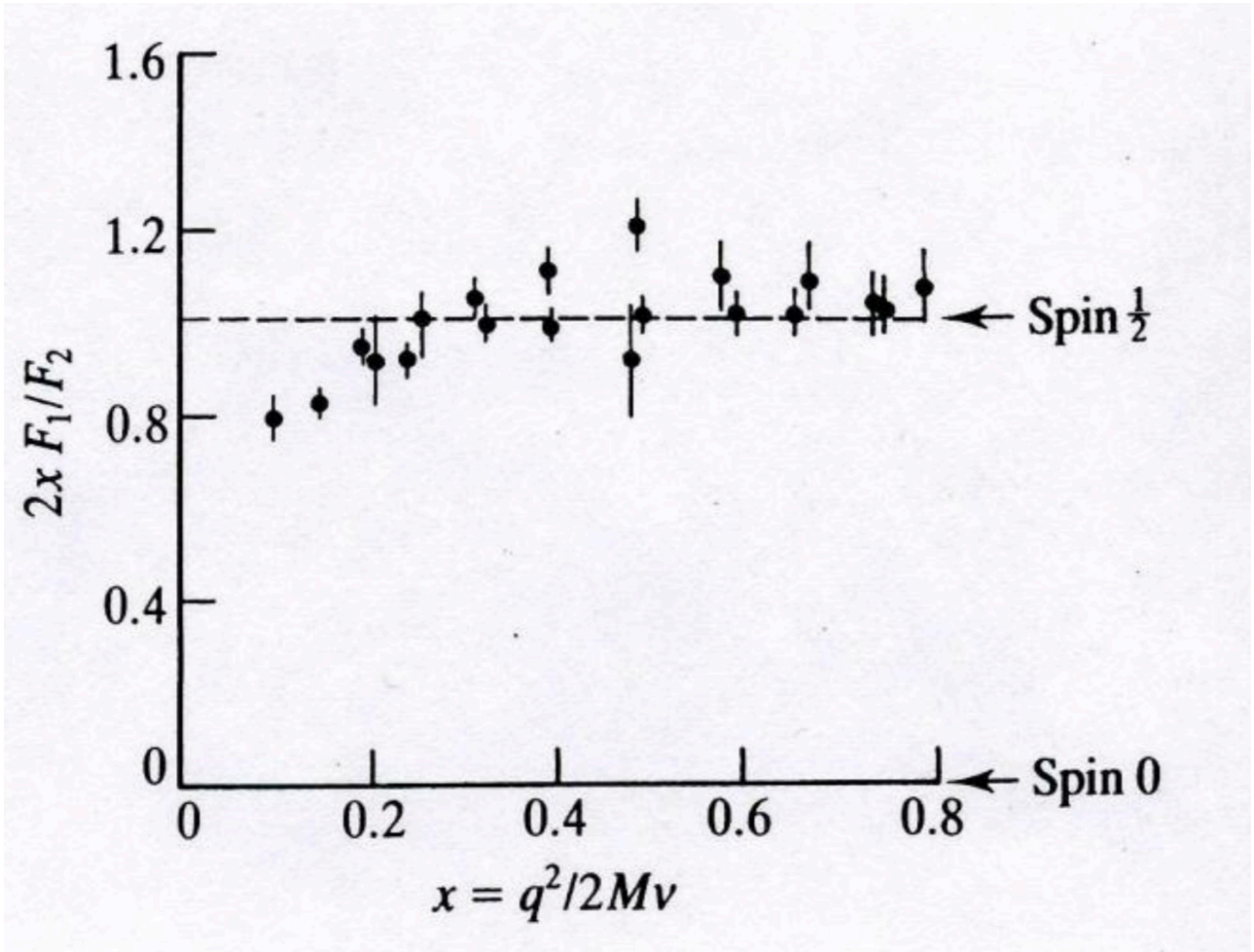



**$\nu W_2$ depends on x**

**$\nu W_2$ does no depends on $Q^2$**

# Quarks: a spin 1/2 particles

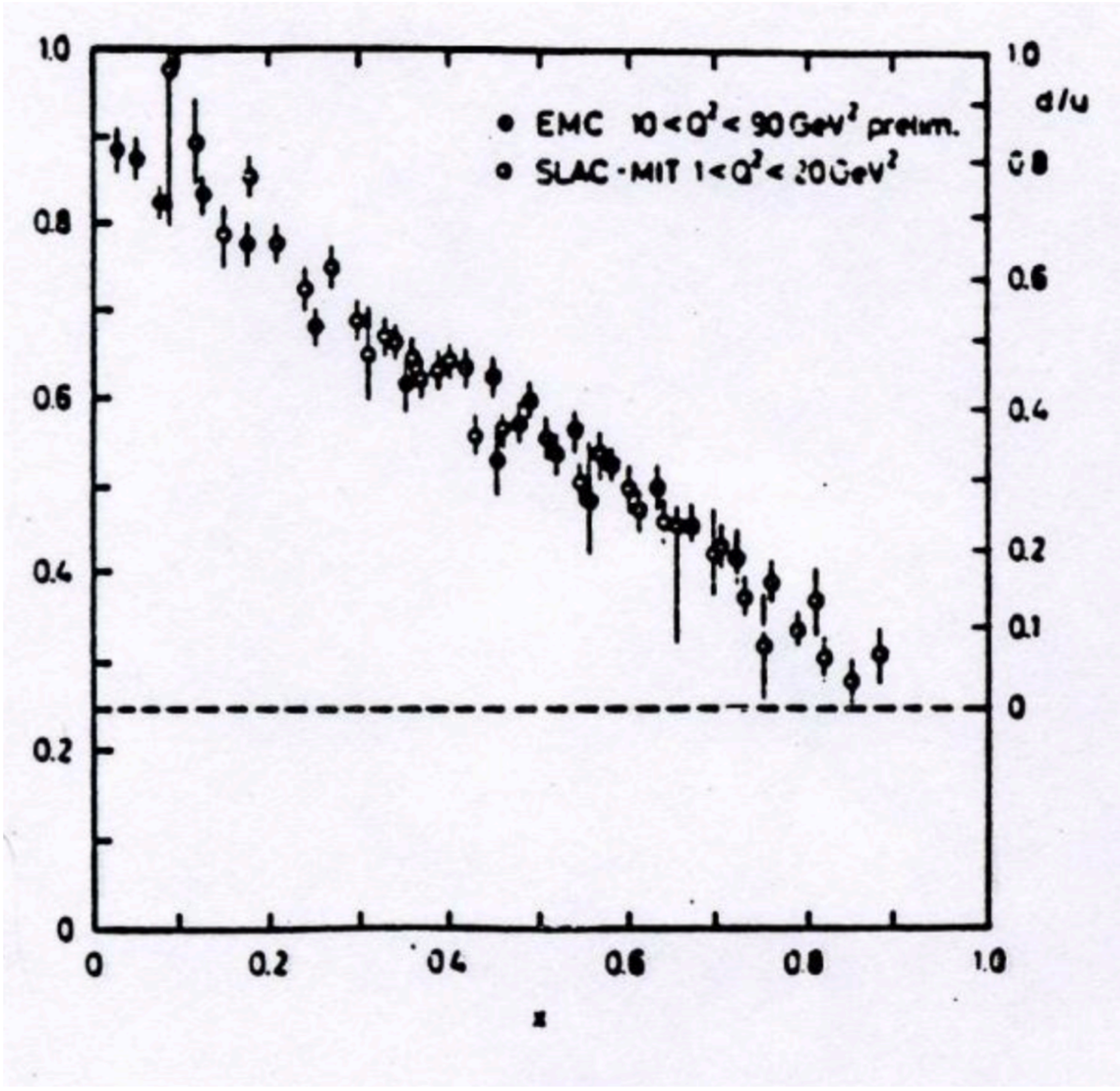


# Valence and sea quarks

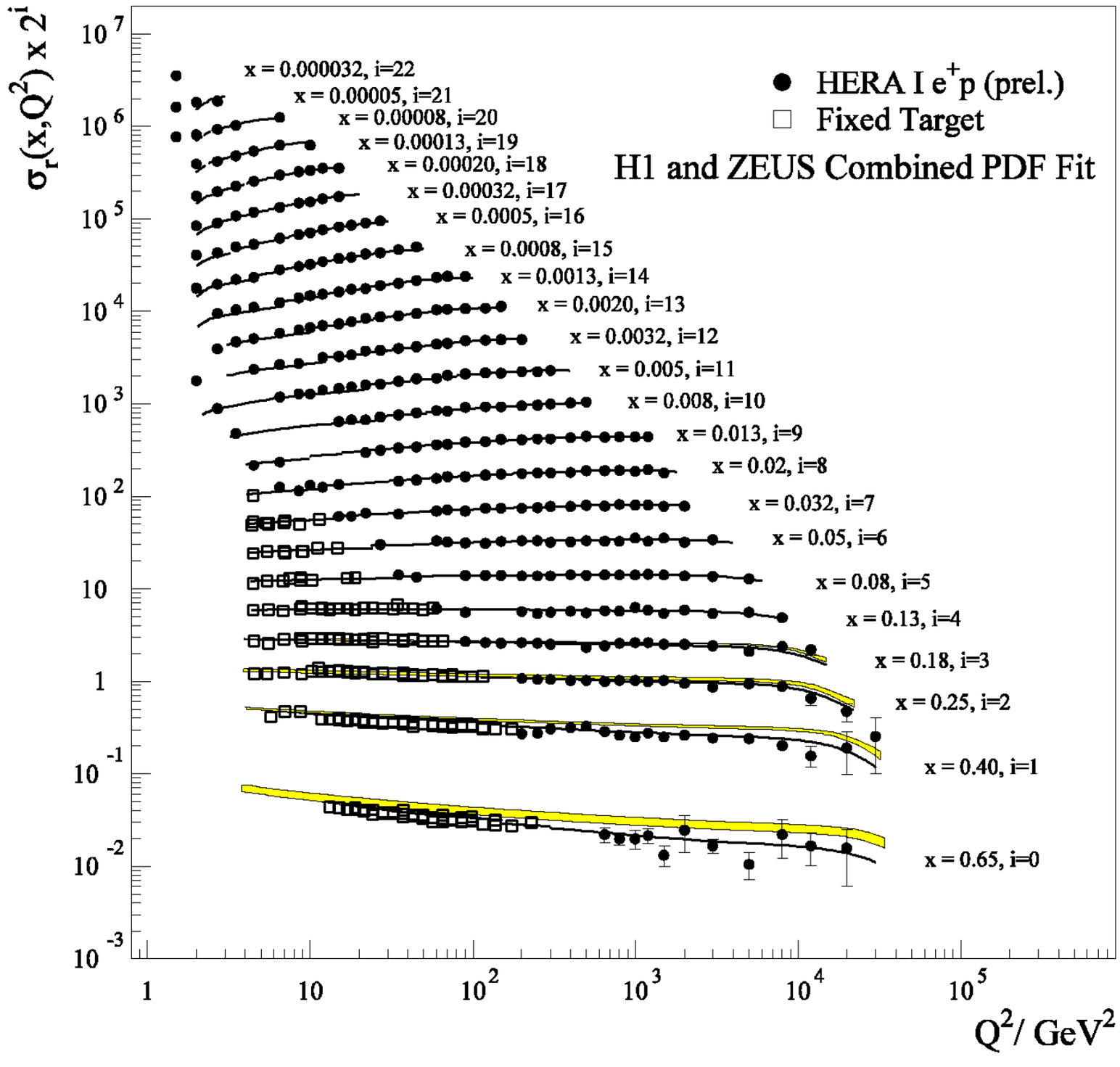
$R_2 = F_2^{en} / F_2^{ep}$

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

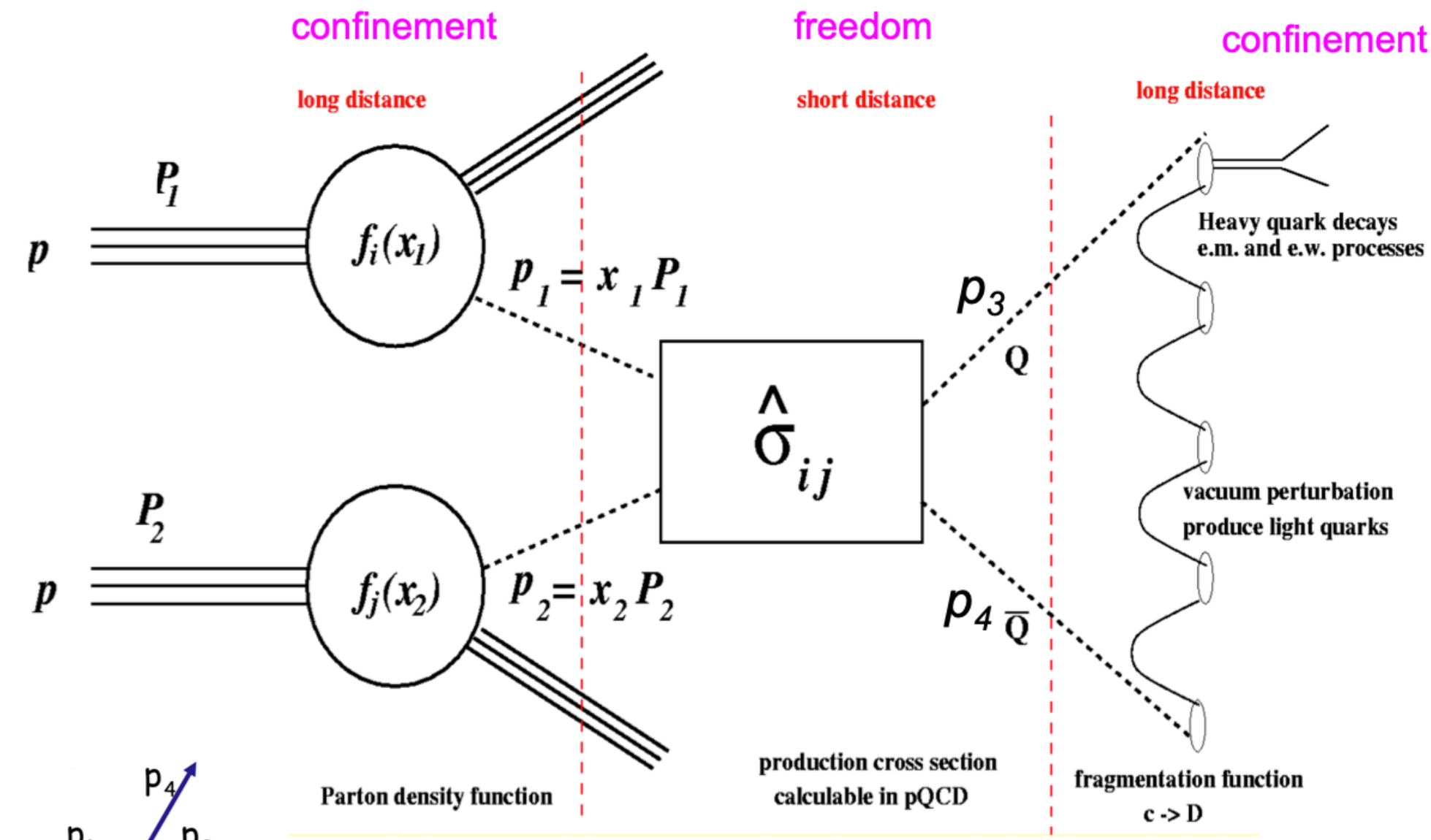
demonstrates:
$d_v(x) / u_v(x) \sim 1-x$

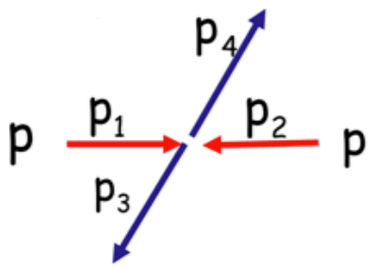


# Bjorken scaling violation



# QCD Factorisation theorem




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

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

# QCD Factorisation theorem

- 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 —> 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

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

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

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

# From HERA to LHC pdfs ?

LO, $p_T[M] = 0$

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

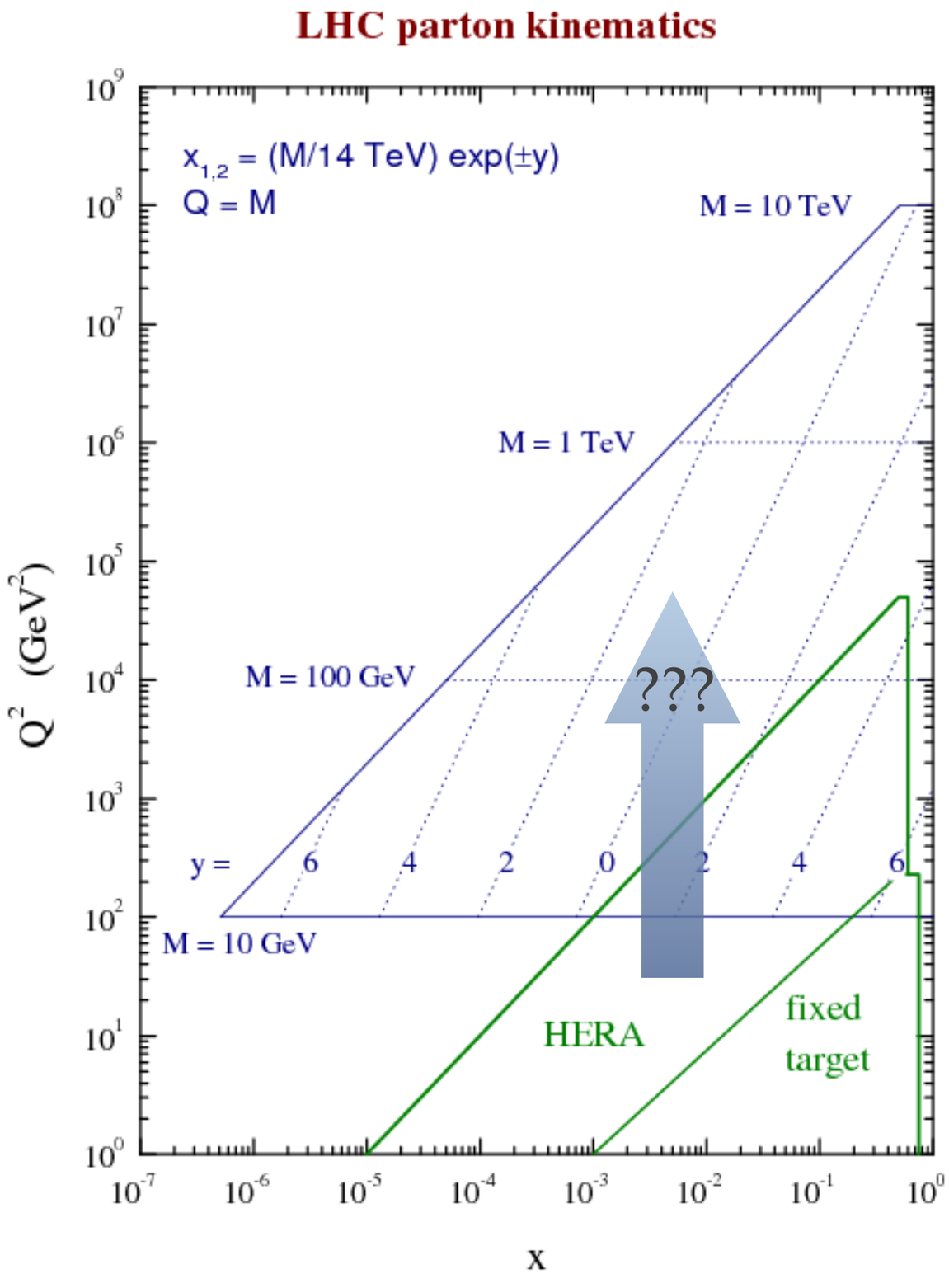
$M^2 = E^2 - p_z^2 = x_1\, x_2\, s$

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

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

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

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



# DGLAP

Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

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

PDFs

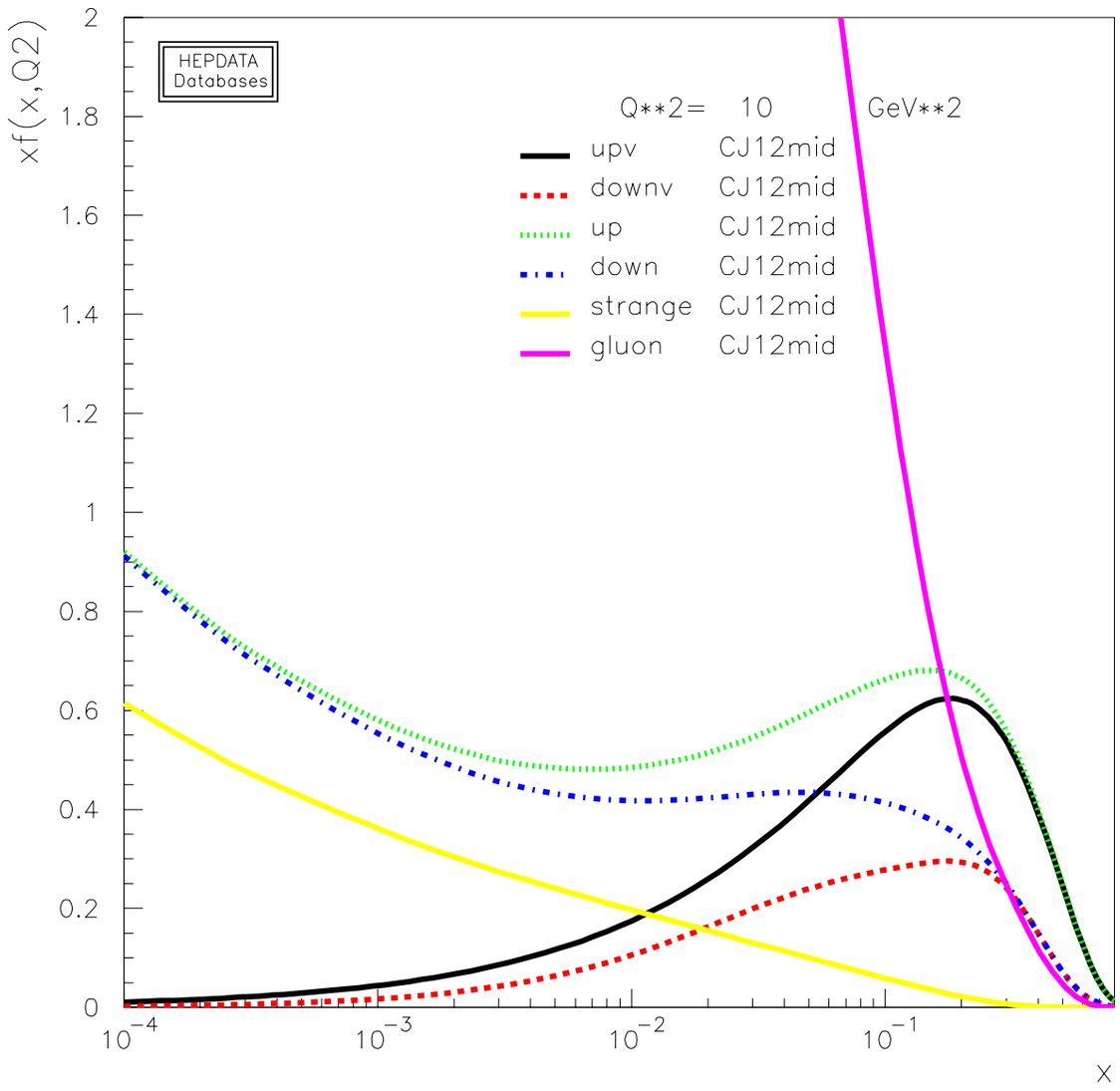
$$\frac{\partial}{\partial \log Q^2}\begin{bmatrix} q(x,Q^2) \\ g(x,Q^2) \end{bmatrix} = \frac{\alpha_s}{2\pi}\begin{bmatrix} P_{q/q}\left[z\right] & P_{q/g}\left[z\right] \\ P_{g/q}\left[z\right] & P_{g/g}\left[z\right] \end{bmatrix} \otimes \begin{bmatrix} q(x,Q^2) \\ g(x,Q^2) \end{bmatrix}$$

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

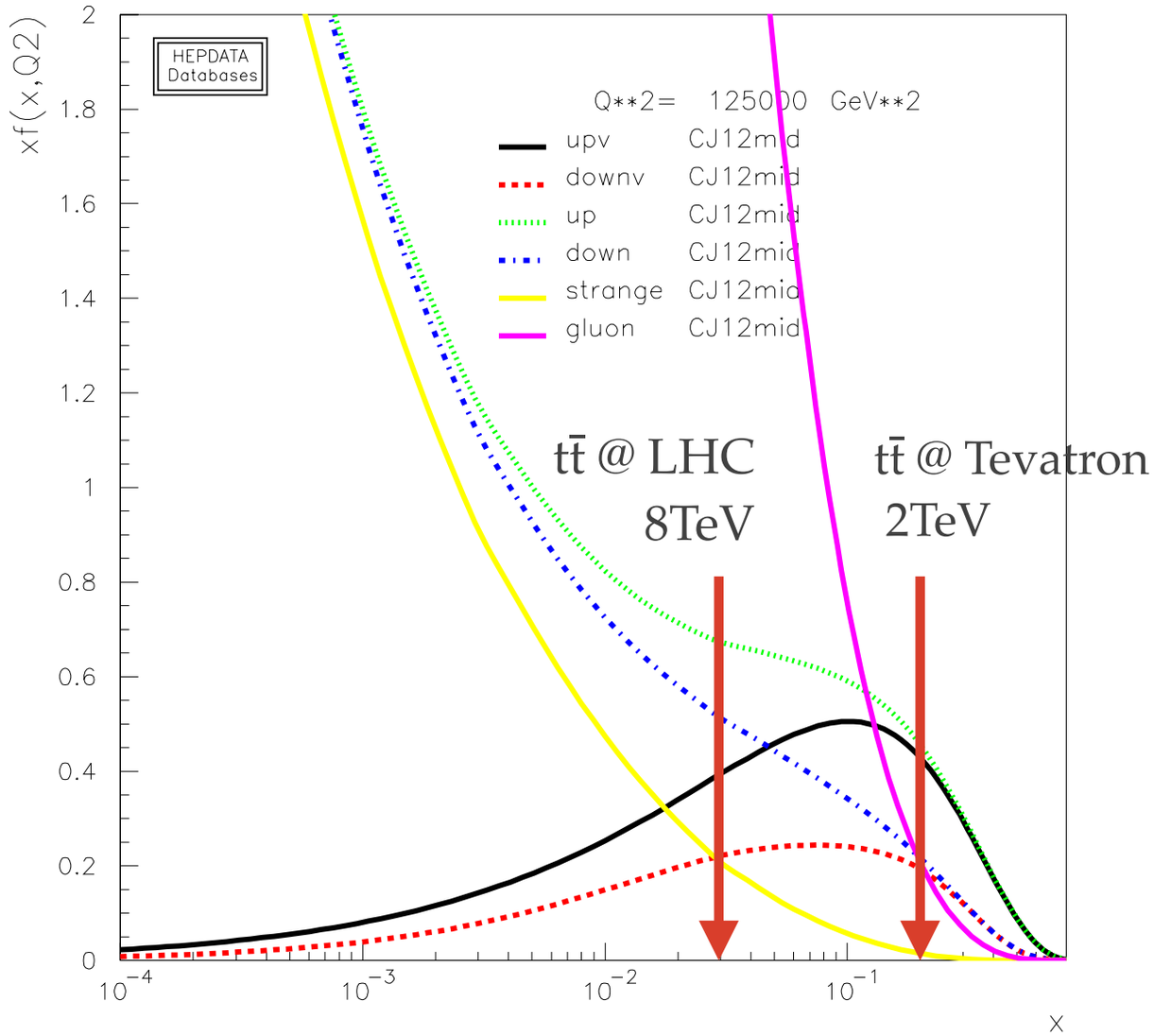
$$\frac{4}{3}\left[\frac{1+(1-z)^2}{z}\right] \qquad 6\left[\frac{z}{1-z}+\frac{1-z}{z}+z(1-z)\right]$$

# Parton density function recap

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




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




**tt production threshold**