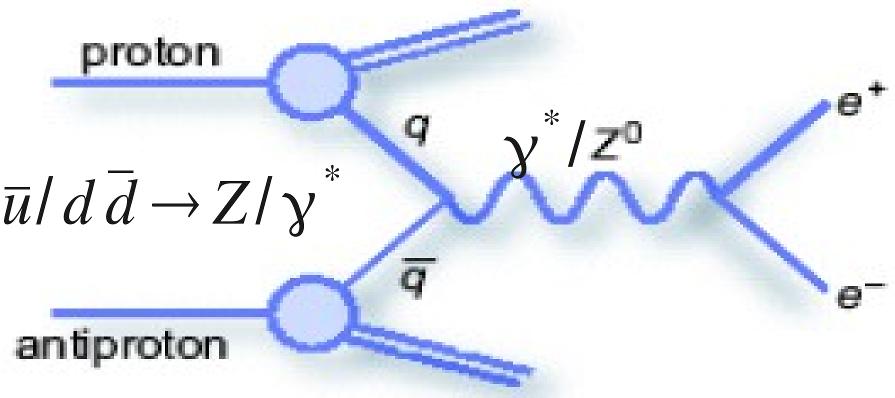
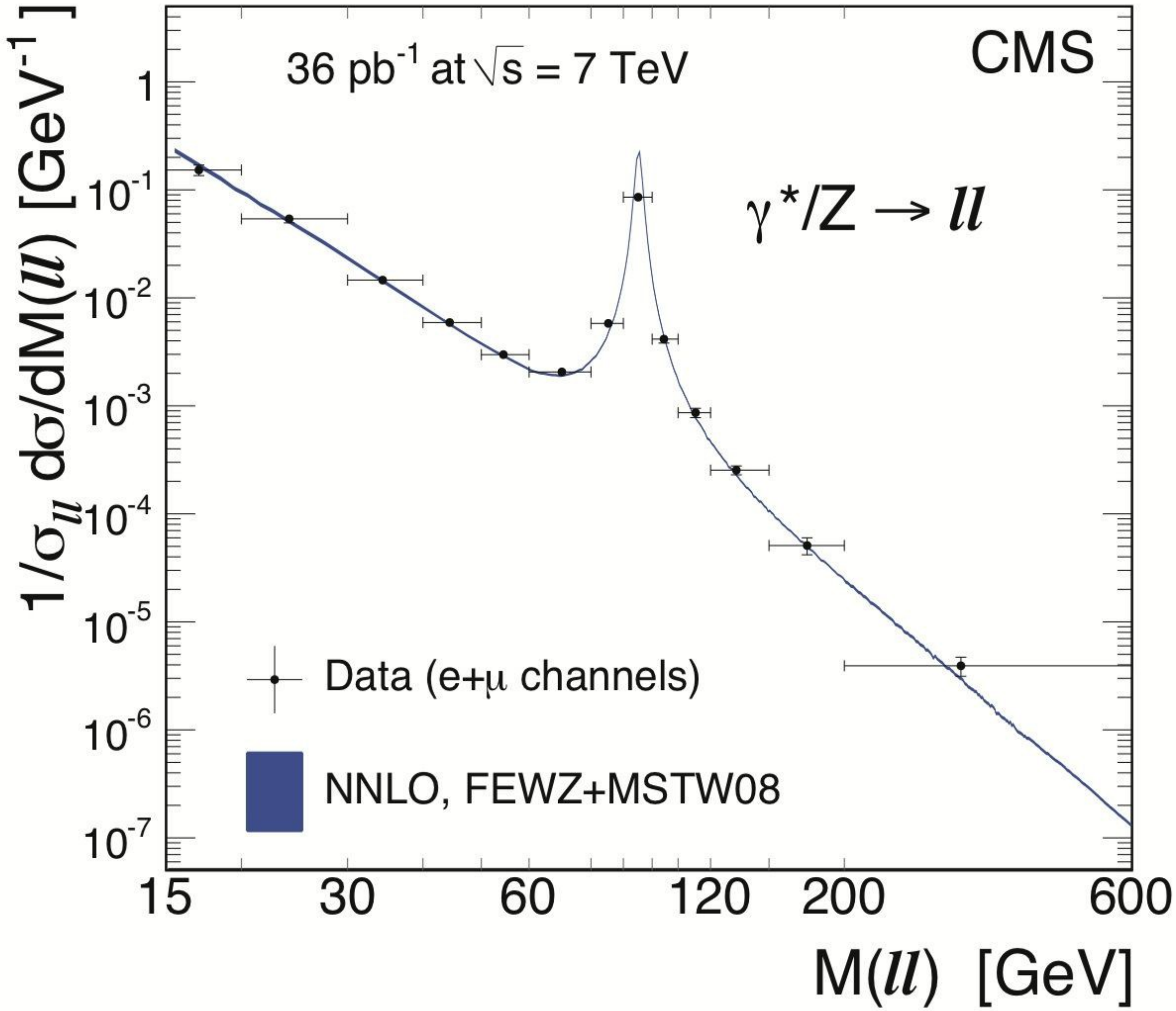
Drell-Yan production at the Large Hadron Collider (LHC)

$$u\,\bar{u} / d\,\bar{d} \rightarrow Z / \gamma^*$$





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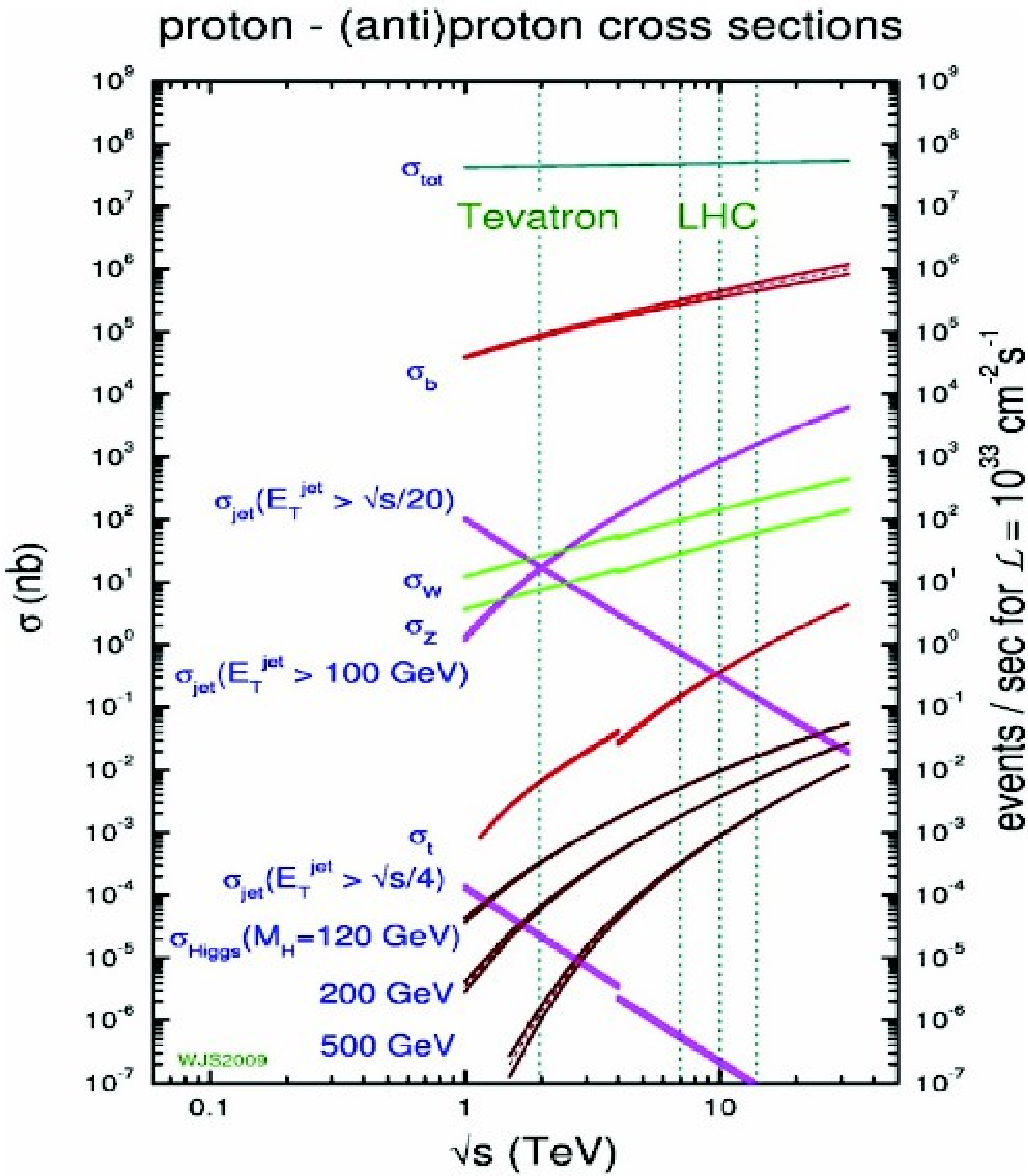


$$\dot{N}_{reac} = L \cdot \sigma$$
$$N_{reac} = \sigma \int L\,dt = \sigma \cdot L_{\text{int}}$$

Sp$\bar{p}$S (√s=540 GeV):
L = 5 10^{28} cm^{-2} s^{-1}
L_{int}= 153 nb^{-1}

Z production at a hadron collider like the LHC

Cross section for l^+l^- production in hadron-hadron scattering in the parton model:

$$\sigma = \sum_q \int dx_1\, dx_2\, f_q^{h_1}(x_1)\, f_{\bar{q}}^{h_2}(x_2)\, \hat{\sigma}(q(p_1)\bar{q}(p_2) \to l^+ l^-)$$

Parton Distribuionion Funct. (PDF) **Momentum fraction of parton inside hadron**

$$p_1 = x_1 P_{h_1},\quad p_2 = x_2 P_{h_2}$$

$$\hat{\sigma}(q\bar{q} \xrightarrow{\gamma^*, Z} l^+ l^-) = \frac{4\pi\alpha^2}{3\hat{s}} \frac{1}{N_C}\left(q_f^2 - 2 q_f g_V^q g_V^l \chi_1(\hat{s}) + (g_A^{l\,2} + g_V^{l\,2})(g_A^{q\,2} + g_V^{q\,2})\chi_2(\hat{s})\right)$$

$\hat{s} = (p_1 + p_2)^2$ — Pure γ exchange — Z-γ interference — Pure Z exchange

$$\chi_1(\hat{s}) = \frac{\sqrt{2}\, G_F M_Z^2}{4\pi\alpha} \frac{\hat{s}(\hat{s} - M_Z^2)}{(\hat{s} - M_Z^2)^2 + \Gamma_Z^2 M_Z^2}$$

$$\chi_2(\hat{s}) = \frac{2\, G_F^2 M_Z^4}{4^2\pi^2\alpha^2} \frac{\hat{s}^2}{(\hat{s} - M_Z^2)^2 + \Gamma_Z^2 M_Z^2}$$

$\Gamma_Z << M_Z$ ("Narrow width approximation"):

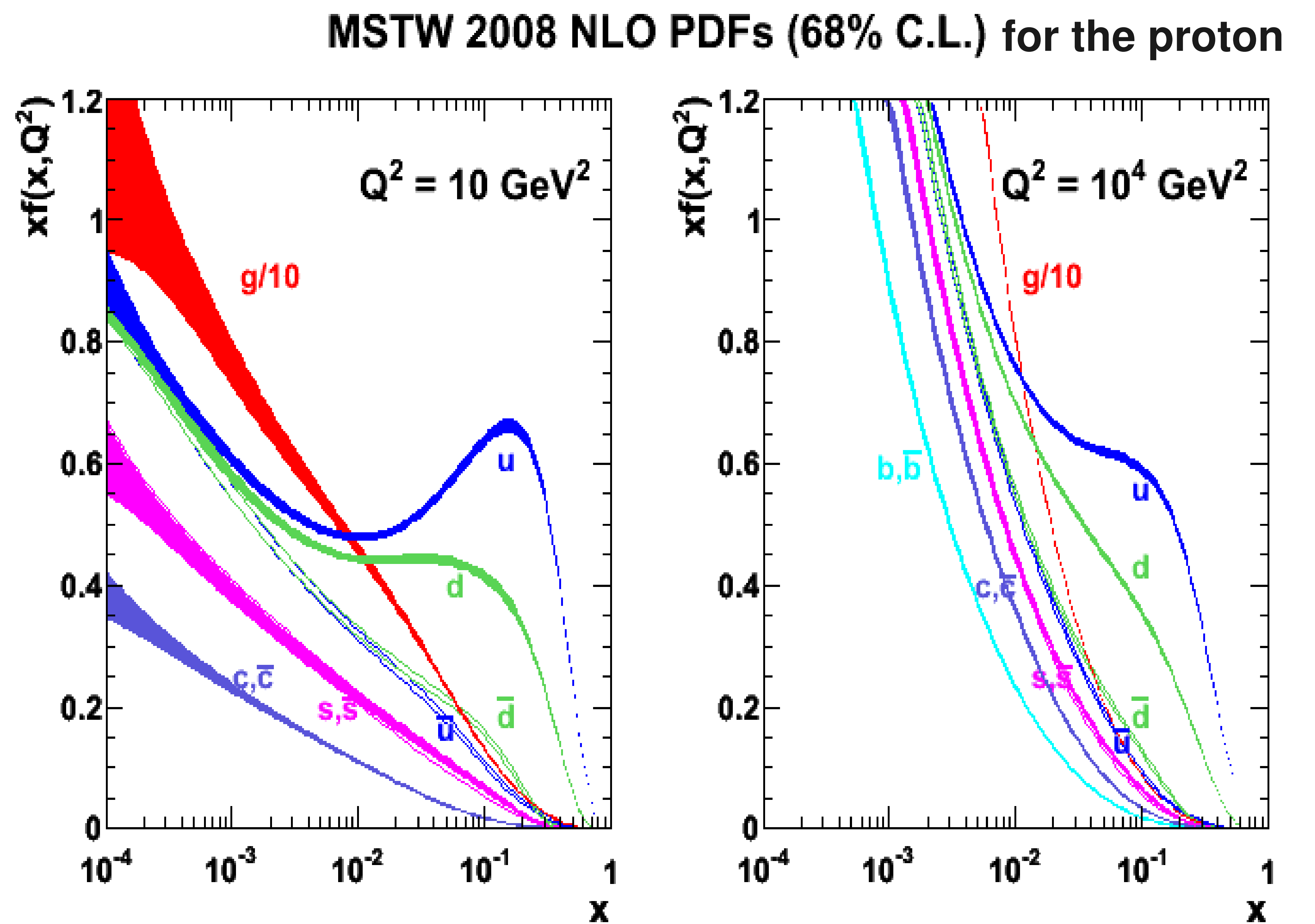
$$\hat{\sigma}(q(p_1)\bar{q}(p_2) \xrightarrow{Z} l^+ l^-) = \hat{\sigma}(q\bar{q} \to Z) \cdot BF(Z \to l^+ l^-)$$

$$\hat{\sigma}(q\bar{q} \to Z) = \frac{\pi}{3}\sqrt{2}\, G_F M_Z^2 (g_A^{q\,2} + g_V^{q\,2})\, \delta(\hat{s} - M_Z^2)$$

Analogous for W-boson production:

$$\hat{\sigma}(q(p_1)\bar{q}'(p_2) \xrightarrow{W} l\nu) = \hat{\sigma}(q\bar{q}' \to W) \cdot BF(W \to l\nu)$$

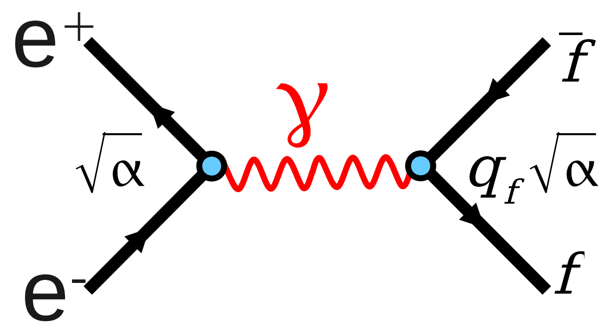
$$\hat{\sigma}(q\bar{q}' \to W) = \frac{\pi}{3}\sqrt{2}\, G_F M_W^2 |V_{qq'}|^2 \delta(\hat{s} - M_W^2)$$


MSTW 2008 NLO PDFs (68% C.L.) for the proton
xf(x,Q²)
Q² = 10 GeV²
g/10
u
d
d̄
ū
s,s̄
c,c̄
x
Q² = 10⁴ GeV²
b,b̄

3.2 Z-resonance in e^+e^- annihilation (LEP, SLC)

3.2.1 Basics

a) e^+e^- at $\sqrt{s} \ll M_Z$: pure QED



CMS: $\sqrt{s} = 2E_e$

(for $E_{e^+} = E_{e^-} = E_e$)

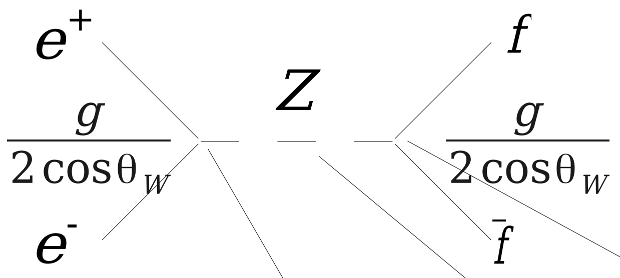
$$f\bar{f}: \quad e^+e^-, \mu^+\mu^-, \tau^+\tau^- \qquad c_f = 1 \qquad \sigma_f = c_f q_f^2 \sigma_0 \qquad \sigma_0 = \frac{4\pi\alpha^2}{3s}$$

$$u\bar{u},\ d\bar{d},\ \ldots \qquad c_f = 3\ (colours)$$

b) Angular distribution due to spin ½ of fermion: $$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 c_f q_f^2}{4s}\left(1+\cos^2\theta\right)$$

(Consequence of helicity conservation for E >> m)

c) e^+e^- at $\sqrt{s} = M_Z = 91\ GeV$: Z exchange dominant

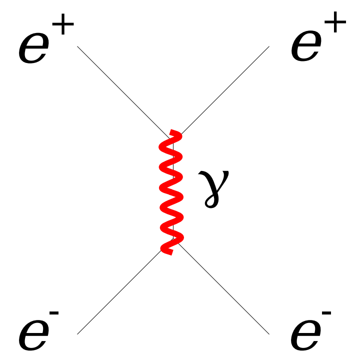


$$\Gamma_Z = \sum_f \Gamma_{Z\to f\bar{f}} = \frac{1}{\tau_Z} \approx 2.5\ GeV$$

$$A = \sqrt{2}\, G_F M_Z^2 \cdot j_\mu^{(e)} \cdot \frac{1}{s - M_Z^2 + i M_Z \Gamma_Z} \cdot j^{(f)\mu} + small\ QED\ contr.$$

$$j^{(f)\mu} = \bar{f}\,[g_V^f \gamma^\mu - g_A^f \gamma^\mu \gamma^5]\, f$$

- **f=e: additional t-channel diagram (Bhabha scattering)**



$$\frac{d\sigma}{d\Omega} \overset{\text{Ruther-}}{\underset{\text{ford}}{\propto}} \frac{1}{\sin^4\frac{\theta}{2}}$$

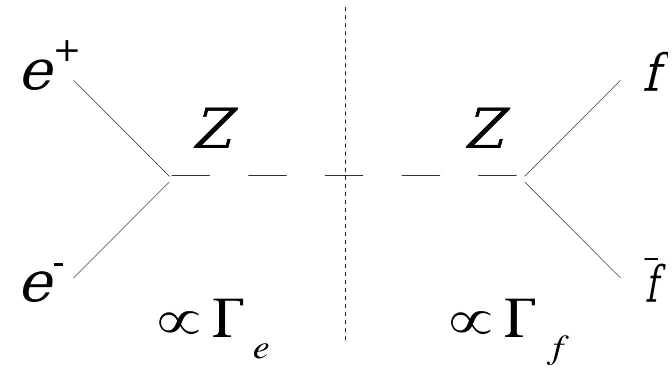
- **Partial widths:** $\Gamma_{Z\to f\bar{f}} = \Gamma_f = \frac{G_F M_Z^3 c_f}{6\pi\sqrt{2}} (g_V^{f\,2} + g_A^{f\,2}) \quad \Rightarrow \quad g_V^{f\,2} + g_A^{f\,2}$

Differential distributions => $g_V^f,\ g_A^f$ individually

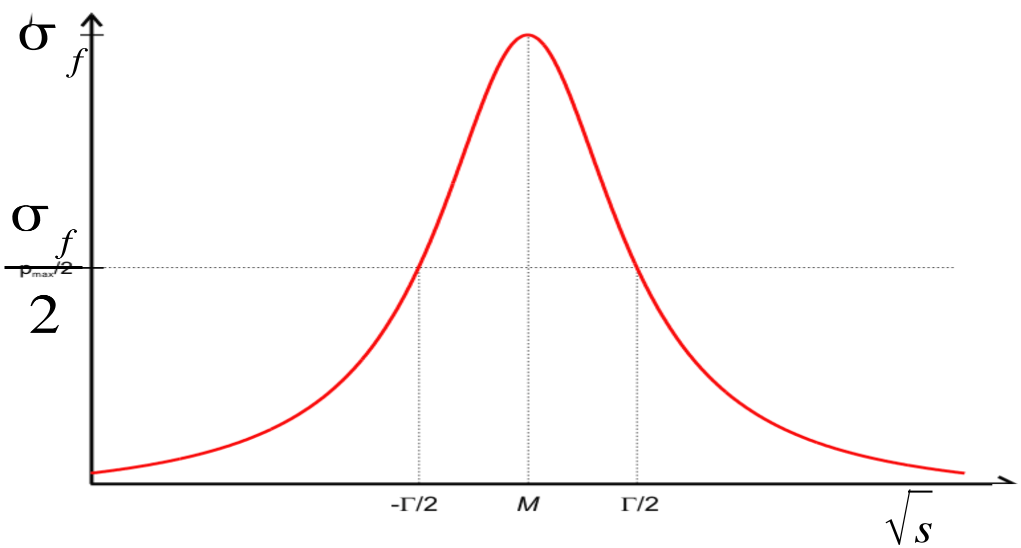
3.2.2 The Z-resonance curve

- **Cross section at $\sqrt{s} \approx M_Z$ (γ-exchange neglected)**

$$\sigma_f = \frac{s}{M_Z^2} \frac{12\pi}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2} \cdot \Gamma_f \cdot \Gamma_e$$



"Breit-Wigner"
(from propagator)



Parameters:

Position $\longleftrightarrow$ M_Z

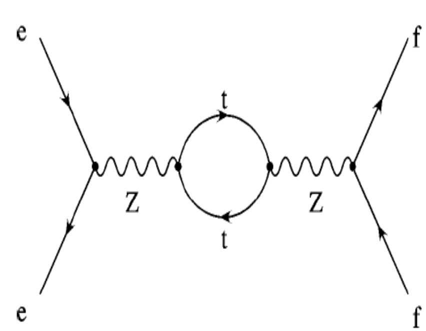
Width $\longleftrightarrow$ Γ_Z

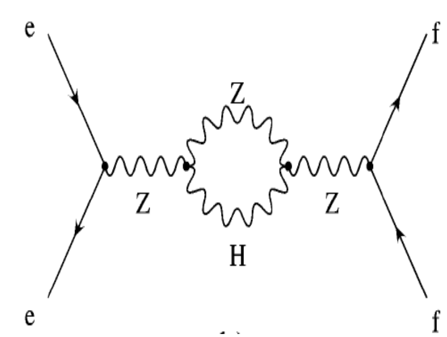
Amplitude $\longleftrightarrow$ $\Gamma_e \cdot \Gamma_f$

sensitive to e.w. corrections:

$\propto m_t^2, \propto \ln M_H,$

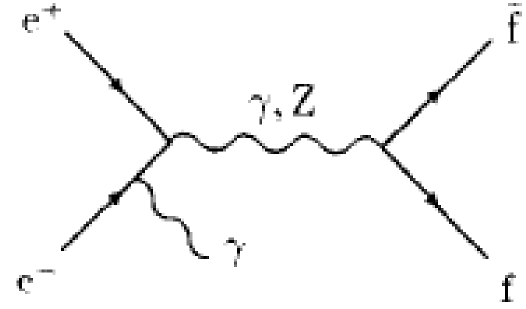
New Physics

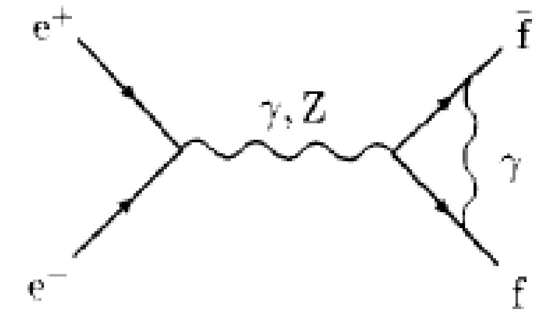


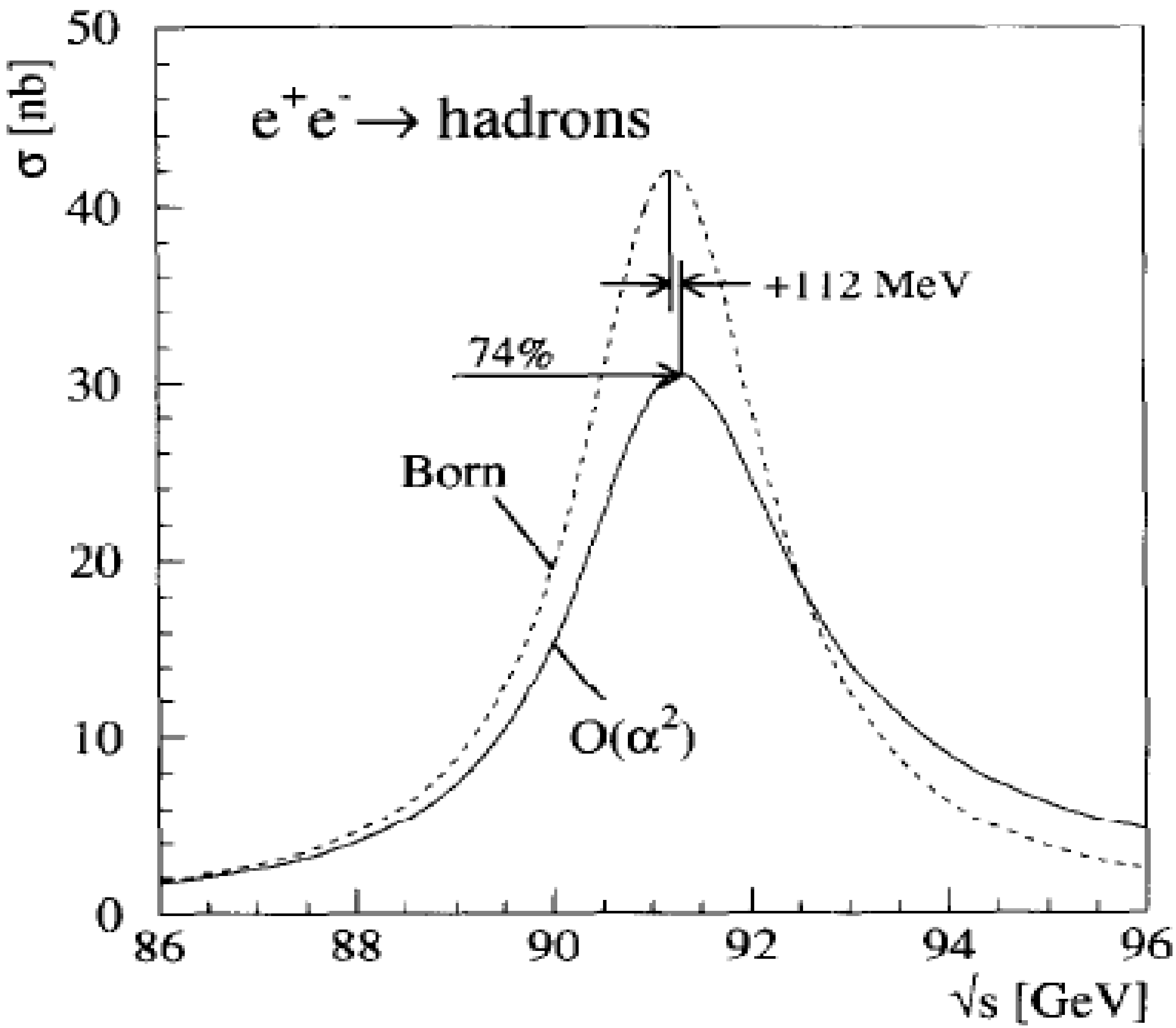


3.2.2 The Z-resonance curve

- QED effects
  (Initial State Radiation,
  vertex correction) large,
  but well-known



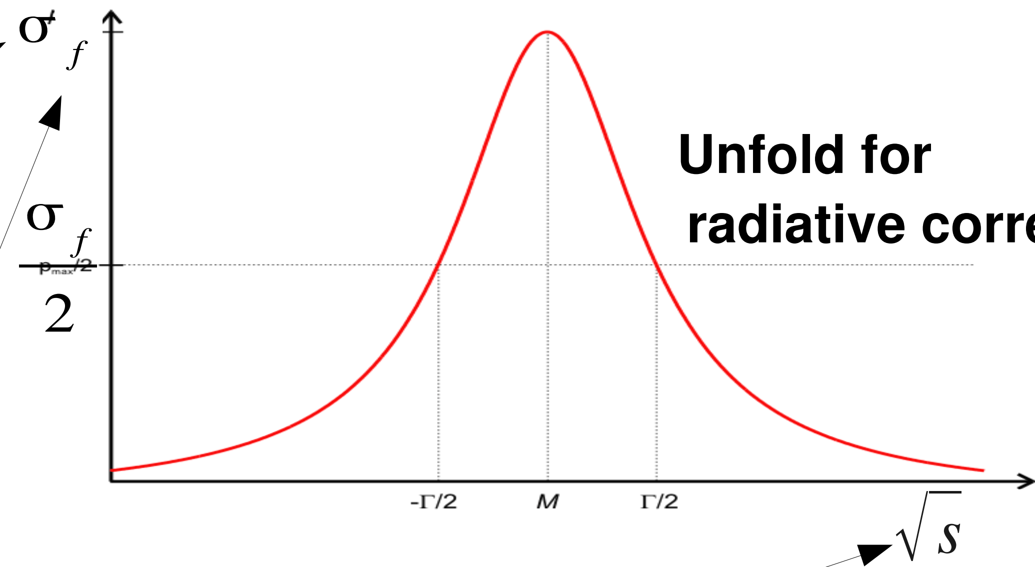




3.2.3 Measurement of the resonance curve

- **Method:**

Measure
a) luminosity
b) event rate for final state f
(selection !)



Unfold for radiative corrections

Measure beam energies

a) Beam energy: Resonant depolarisation (Relative uncertainty: O(10^{-5}))

Synchrotron radiation → e-beam transversly polarized (Sokolov-Ternov effect)

Precision of electron spin with: $\nu = \frac{g_e - 2}{2} \frac{E_{beam}}{m_e c^2}$

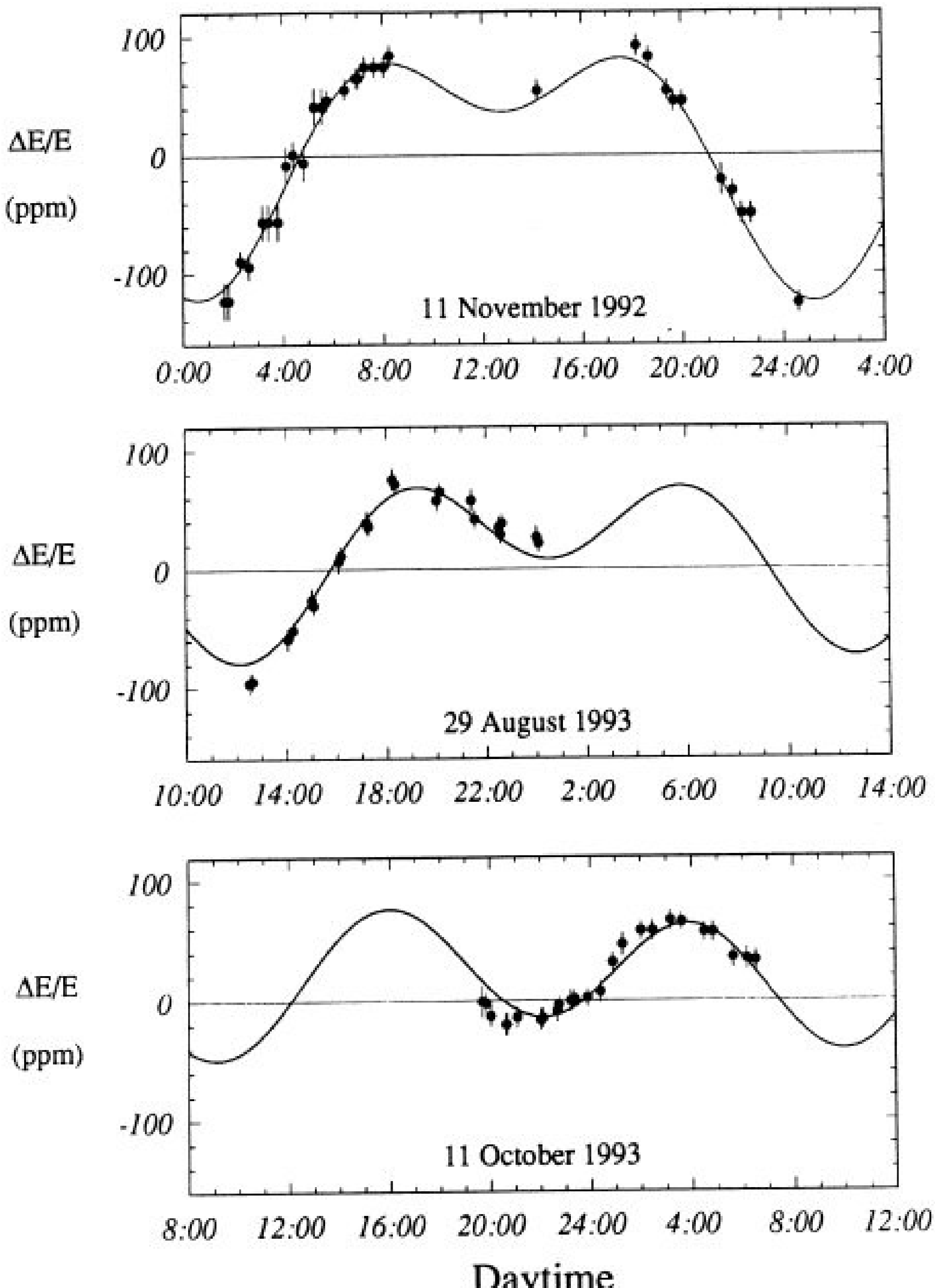
Excite beam with vertical B-field: depolarisation for frequency ν

E_{beam} sensitive to: tides (sun and moon), weather (rain),
time schedule of TGV (Geneva–Paris), ...

b) Luminosity: measurable with 0.2% precision

reference reaction: Bhabha scattering (pure QED)

Tidal effects in LEP beam energy



Full moon

Half moon