ELEKTROSLABE OPSERVABLE

MJERENJA ASIMETRIJA NA LEPu i SLCu

- W i Z BOZONI U SMu
- Anihilacija na Z-rezonanci
- Mjerenje kuta slabog miješanja

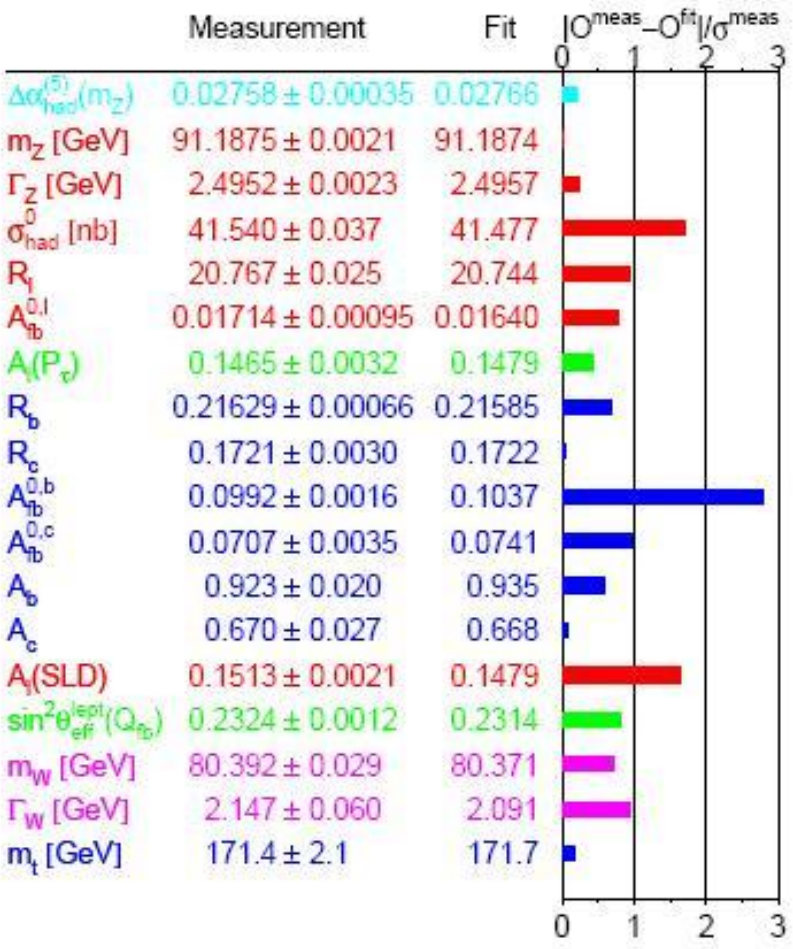
4 POKUSA NA LEPu:

ALEPH
DELPHI
L3
OPAL

Global fit to ew precision data

χ^2/dof=17.8/13 (16.6%)

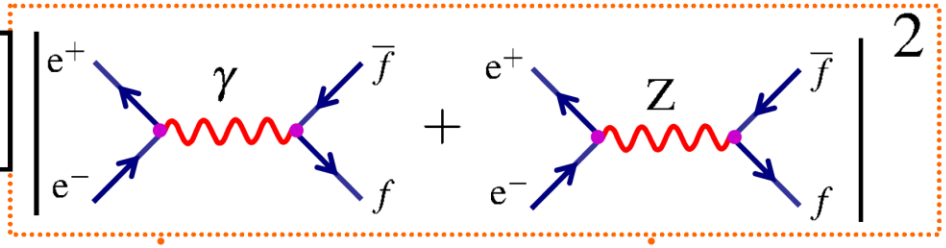
Largest pull is from LEP b-quark forward/backward asymmetry.

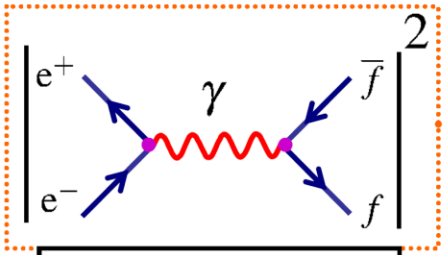


PROCESI ELEKTRON-POZITRON ANIHILACIJE

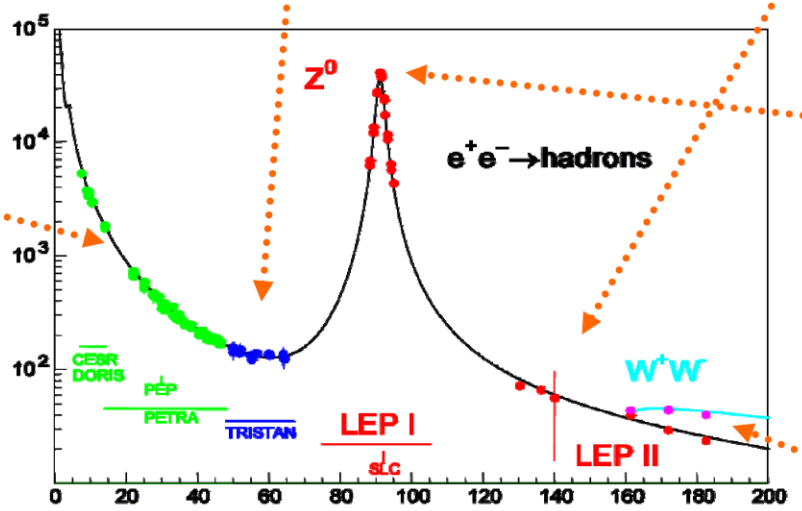
e^+e^- Annihilation in Feynman Diagrams

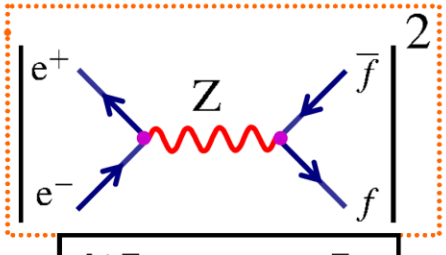
In general e^+e^- annihilation involves both photon and Z exchange : + interference





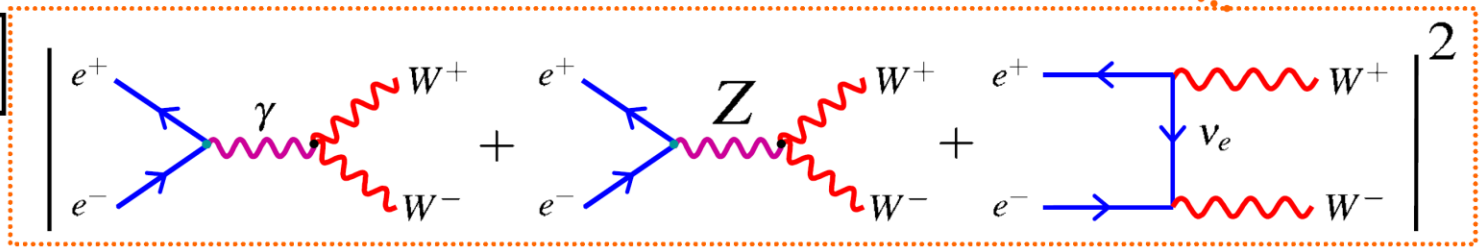
Well below Z: photon exchange dominant



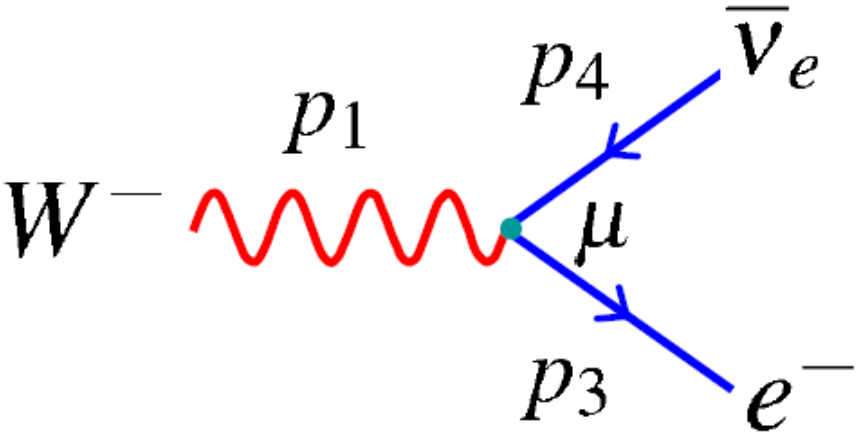


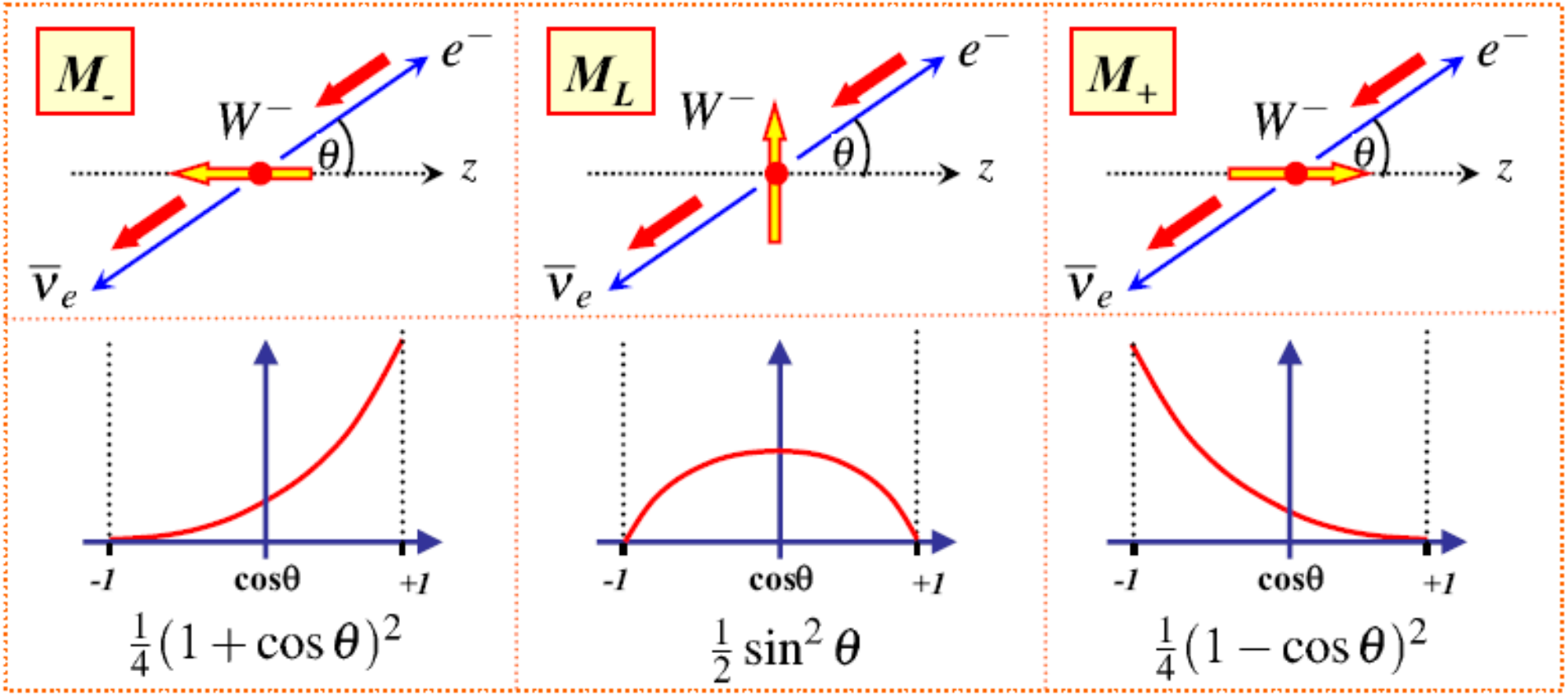
At Z resonance: Z exchange dominant

High energies: WW production

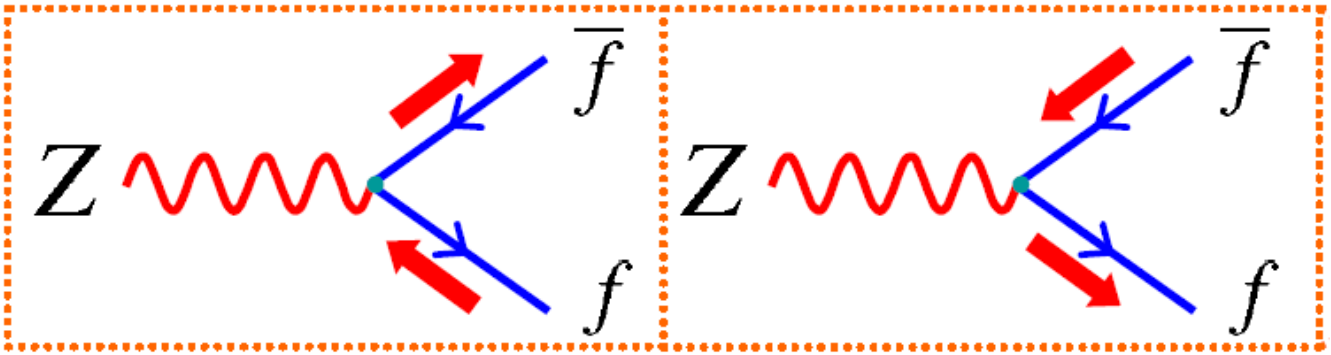


W-BOZON U SM-u


p_1
p_4
$\overline{\nu}_e$
W^-
μ
p_3
e^-

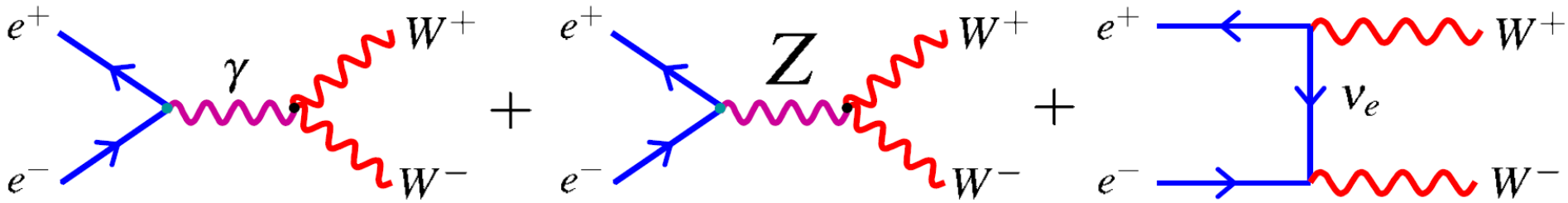

M_-
W^-
e^-
θ
z
$\overline{\nu}_e$
M_L
W^-
e^-
θ
z
$\overline{\nu}_e$
M_+
W^-
e^-
θ
z
$\overline{\nu}_e$
-1
cosθ
+1
$\frac{1}{4}(1+\cos\theta)^2$
-1
cosθ
+1
$\frac{1}{2}\sin^2\theta$
-1
cosθ
+1
$\frac{1}{4}(1-\cos\theta)^2$

Z-BOZON U SM-u

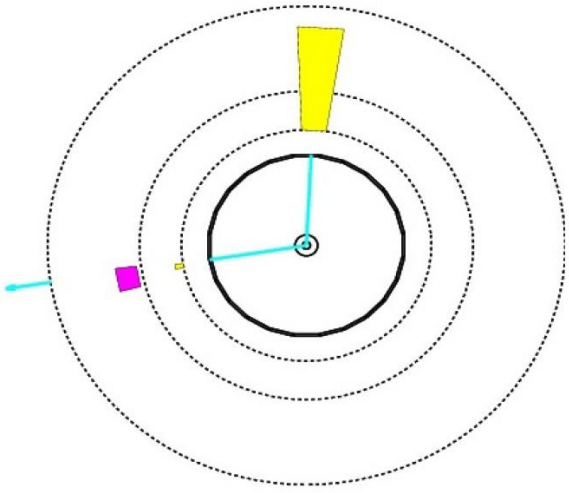


Fermion	Q	I_W^3	c_L	c_R	c_V	c_A
ν_e, ν_μ, ν_τ	0	$+\frac{1}{2}$	$+\frac{1}{2}$	0	$+\frac{1}{2}$	$+\frac{1}{2}$
e^-, μ^-, τ^-	-1	$-\frac{1}{2}$	-0.27	0.23	-0.04	$-\frac{1}{2}$
u, c, t	$+\frac{2}{3}$	$+\frac{1}{2}$	0.35	-0.15	$+0.19$	$+\frac{1}{2}$
d, s, b	$-\frac{1}{3}$	$-\frac{1}{2}$	-0.42	0.08	-0.35	$-\frac{1}{2}$

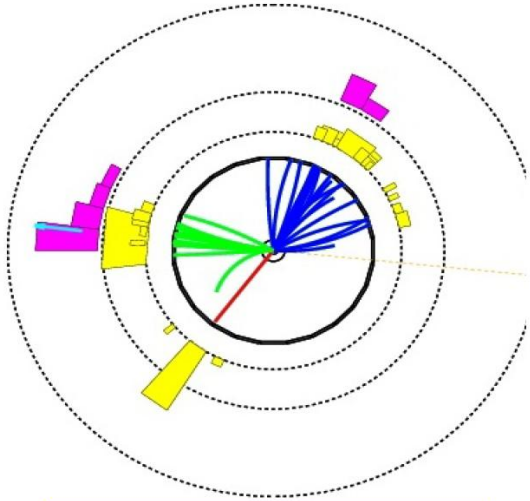
LEP-II: IZNAD PRAGA PRODUKCIJE PARA W-BOZONA



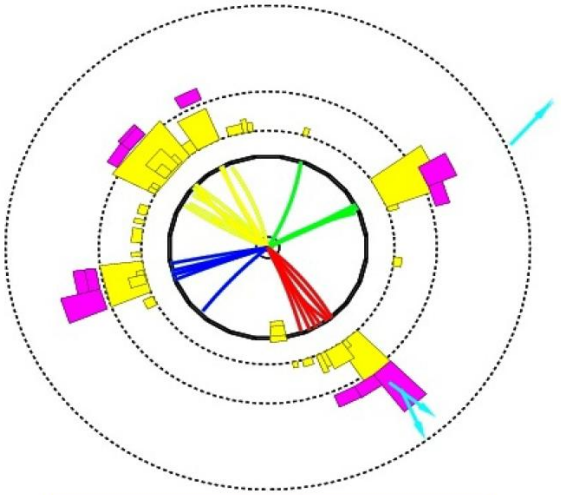
- TRI RAZLIČITE TOPOLOGIJE:



$W^+W^- \to \ell^+\nu\ell^-\overline{\nu}$

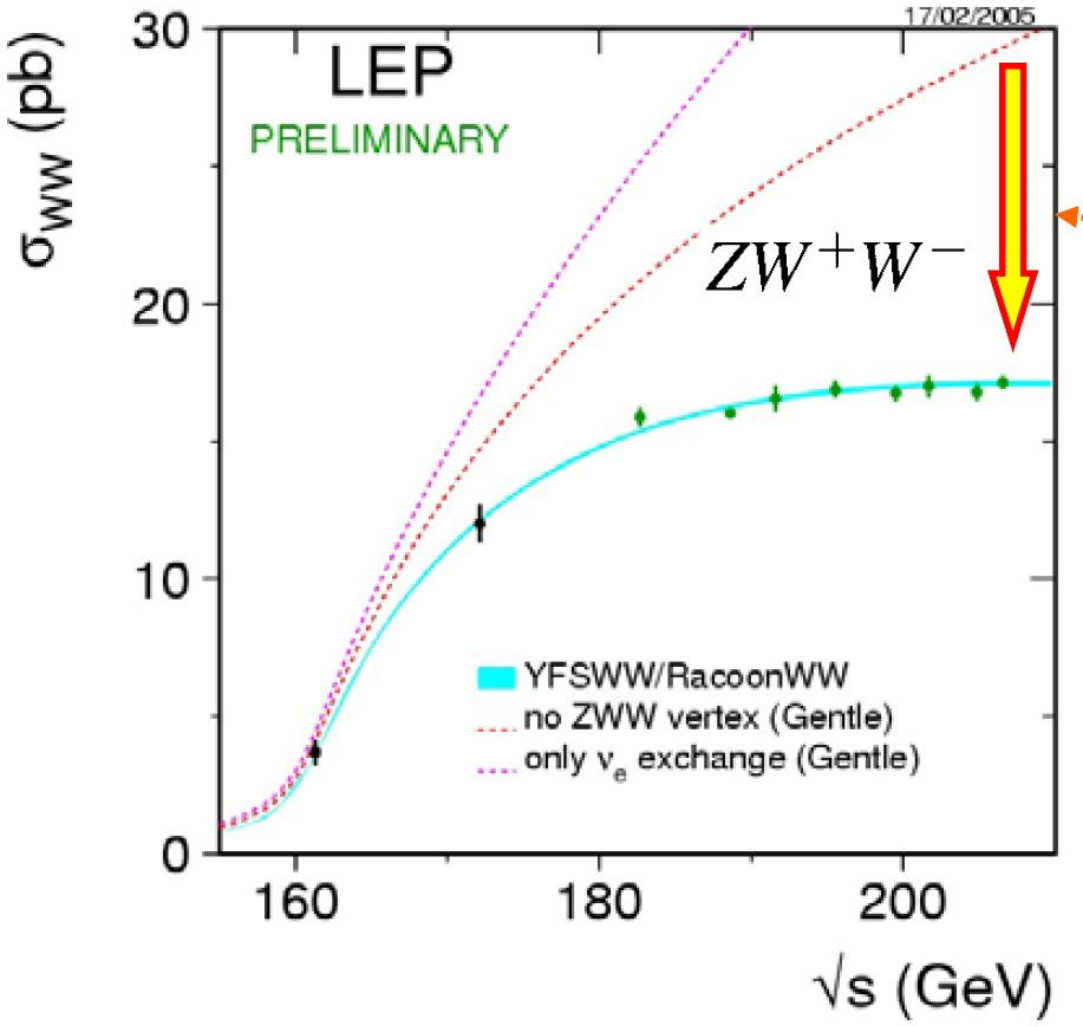


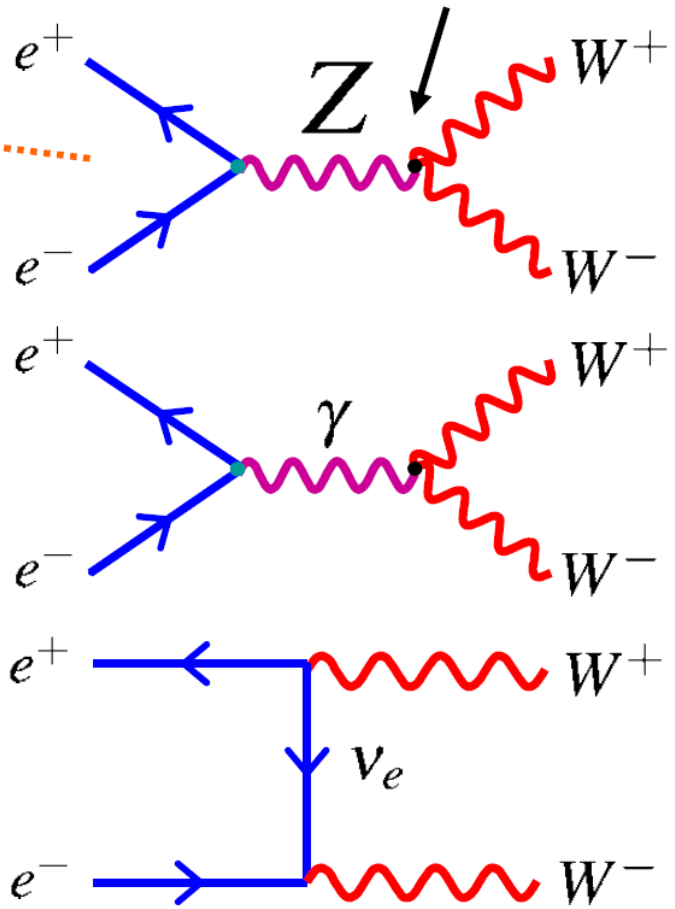
$W^+W^- \to q\bar{q}\ell\nu$



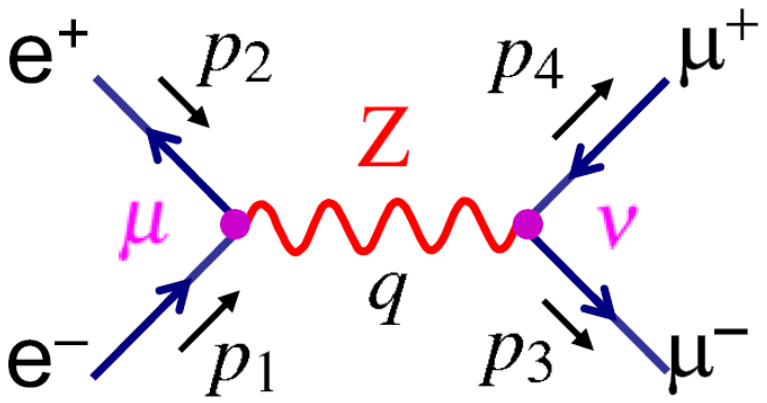
$W^+W^- \to q\bar{q}q\bar{q}$

IZRAVNI TEST VRHA ZWW

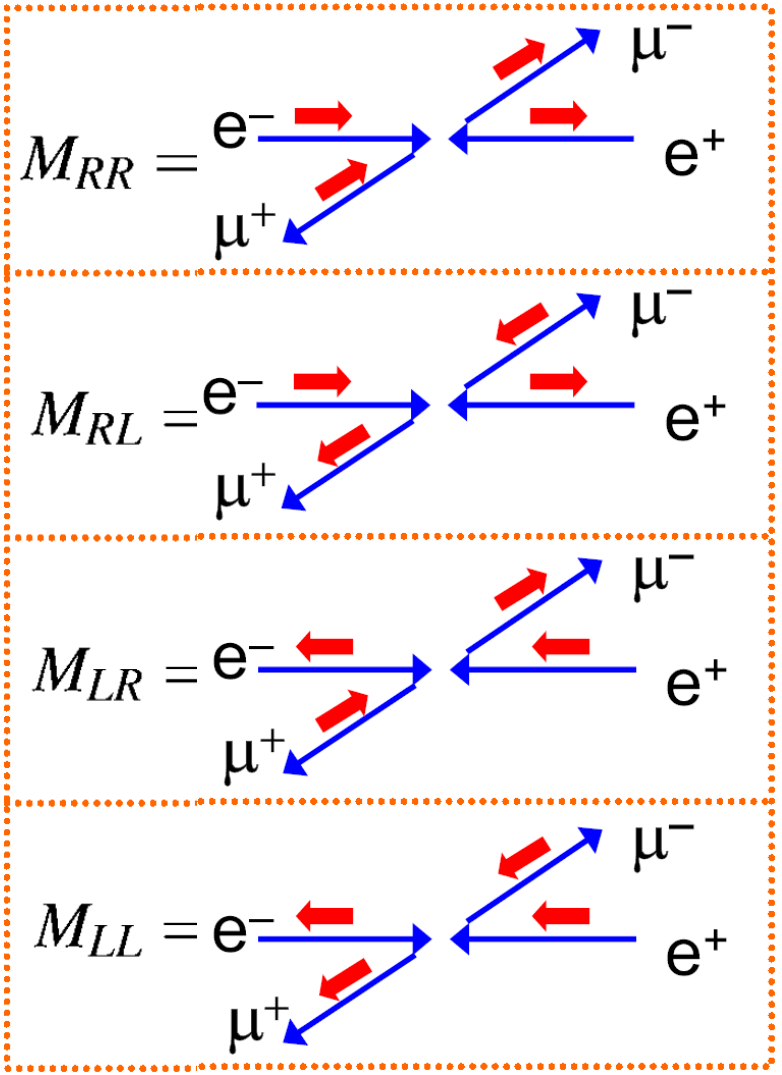




ANIHILACIJA IZMJENOM Z-BOZONA



- POOPĆENJE ANIHILACIJE PUTEM FOTONA



$$M_{fi} = M_{RR} + M_{RL} + M_{LR} + M_{LL}$$

$$|M_{RR}|^2 = s^2 \left| \frac{g_Z^2}{s - m_Z^2} \right|^2 (c_R^e)^2 (c_R^\mu)^2 (1 + \cos\theta)^2$$

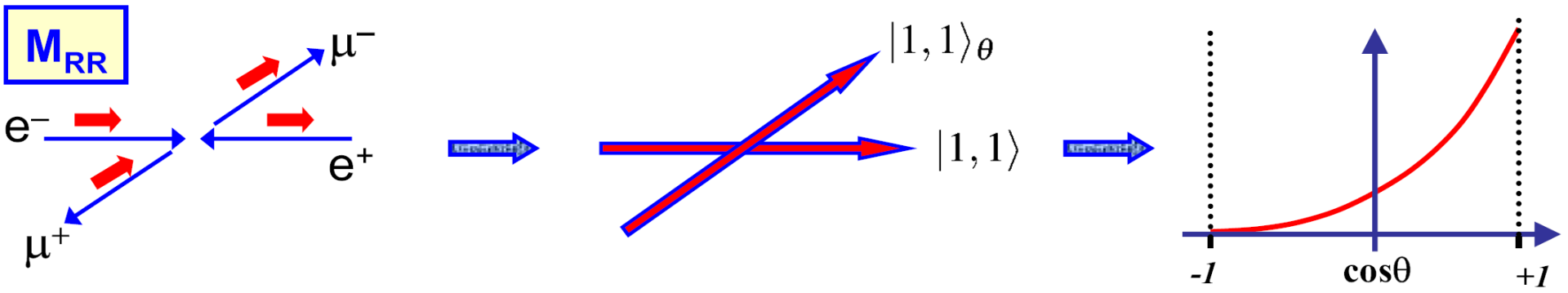
$$|M_{RL}|^2 = s^2 \left| \frac{g_Z^2}{s - m_Z^2} \right|^2 (c_R^e)^2 (c_L^\mu)^2 (1 - \cos\theta)^2$$

$$|M_{LR}|^2 = s^2 \left| \frac{g_Z^2}{s - m_Z^2} \right|^2 (c_L^e)^2 (c_R^\mu)^2 (1 - \cos\theta)^2$$

$$|M_{LR}|^2 = s^2 \left| \frac{g_Z^2}{s - m_Z^2} \right|^2 (c_L^e)^2 (c_L^\mu)^2 (1 + \cos\theta)^2$$

$$\frac{g_Z^2}{q^2 - m_Z^2} c^e c^\mu$$

$$q^2 = s = 4E_e^2$$



ANIHILACIJA NA Z-REZONANCI

- VREMENSKI DIO VAL-F-JE NESTABILNE Č.:

$$\psi \sim e^{-imt} e^{-\Gamma t/2}$$

- VJEROJ. OPADA EKSPONENCIJALNO:

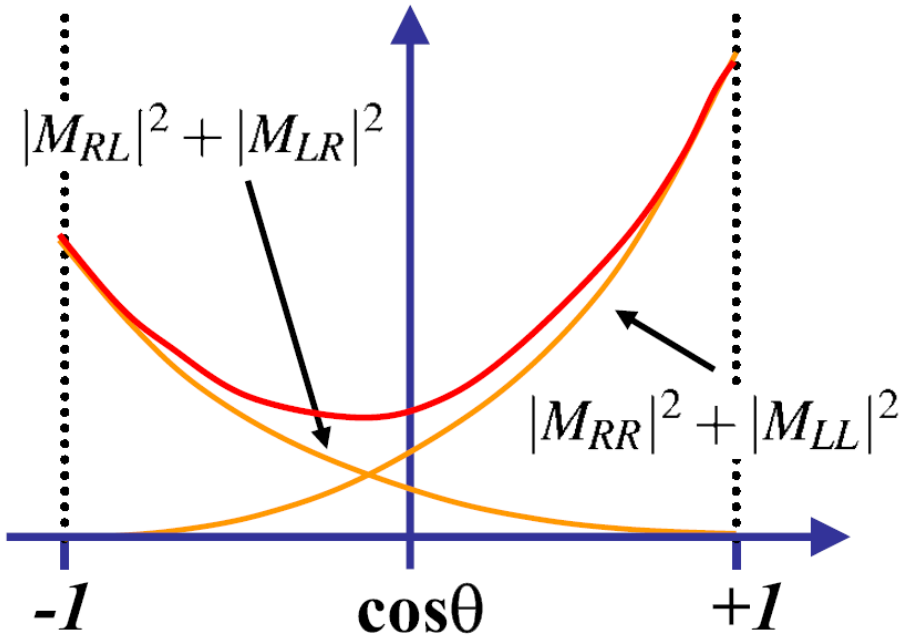
$$\psi^* \psi \sim e^{-\Gamma t} = e^{-t/\tau}$$

- EKVIV. SUPSTITUCIJI U PROPAGATORU:

$$m_Z \to m_Z - i\Gamma_Z/2$$

$$\left| \frac{1}{s - m_Z^2} \right|^2 \to \left| \frac{1}{s - m_Z^2 + i m_Z \Gamma_Z} \right|^2 = \frac{1}{(s - m_Z^2)^2 + m_Z^2 \Gamma_Z^2}$$

UKUPNI DIFERENC. UD. PRESJEK JE ASIMETRIČAN



$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}|M_{fi}|^2$$

$$\frac{d\sigma_{RR}}{d\Omega} = \frac{1}{64\pi^2}\frac{g_Z^4 s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}(c_R^e)^2(c_R^\mu)^2(1+\cos\theta)^2$$

$$\frac{d\sigma_{LL}}{d\Omega} = \frac{1}{64\pi^2}\frac{g_Z^4 s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}(c_L^e)^2(c_L^\mu)^2(1+\cos\theta)^2$$

$$\frac{d\sigma_{LR}}{d\Omega} = \frac{1}{64\pi^2}\frac{g_Z^4 s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}(c_L^e)^2(c_R^\mu)^2(1-\cos\theta)^2$$

$$\frac{d\sigma_{RL}}{d\Omega} = \frac{1}{64\pi^2}\frac{g_Z^4 s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}(c_L^e)^2(c_R^\mu)^2(1-\cos\theta)^2$$

NEPOLARIZIRANI UD. PRESJEK & Breit-Wignerova formula

$$\langle |M_{fi}|^2 \rangle = \frac{1}{2}\cdot\frac{1}{2}\cdot(|M_{RR}|^2 + |M_{LL}|^2 + |M_{LR}|^2 + |M_{RL}|^2)$$

$$= \tfrac{1}{2}\cdot\tfrac{1}{2}\,\frac{g_Z^4 s^2}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2} \times \{[(c_R^e)^2(c_R^\mu)^2 + (c_L^e)^2(c_L^2)^2](1+\cos\theta)^2$$
$$+[(c_L^e)^2(c_R^\mu)^2 + (c_R^e)^2(c_L^2)^2](1-\cos\theta)^2\}$$

$$\{\ldots\} = \frac{1}{4}[(c_V^e)^2 + (c_A^e)^2][(c_V^\mu)^2 + (c_A^\mu)^2](1+\cos^2\theta) + 2c_V^e c_A^e c_V^\mu c_A^\mu \cos\theta$$

$$\int_{-1}^{+1}(1+\cos^2\theta)\mathrm{d}(\cos\theta) = \int_{-1}^{+1}(1+x^2)dx = \tfrac{8}{3}$$

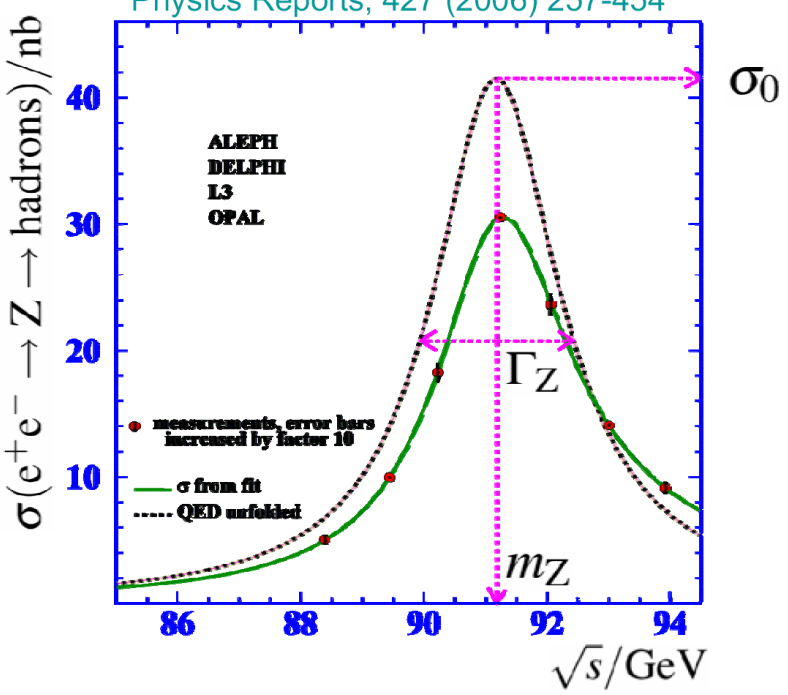
$$\sigma_{e^+e^-\to Z\to\mu^+\mu^-} = \frac{1}{192\pi}\,\frac{g_Z^4 s}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2}\,[(c_V^e)^2 + (c_A^e)^2][(c_V^\mu)^2 + (c_A^\mu)^2]]$$

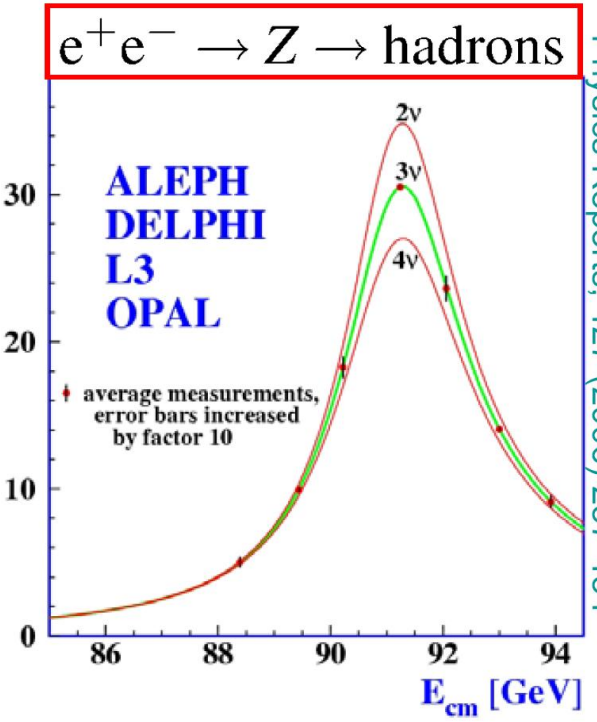
$$\Gamma(Z\to e^+e^-) = \frac{g_Z^2 m_Z}{48\pi}[(c_V^e)^2 + (c_A^e)^2]$$

$$\sigma(e^+e^-\to Z\to f\bar{f}) = \frac{12\pi}{m_Z^2}\,\frac{s}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2}\,\Gamma_e\Gamma_f$$

MJERENJE OBLIKA REZONANCE & BROJA NEUTRINA

Physics Reports, 427 (2006) 257-454





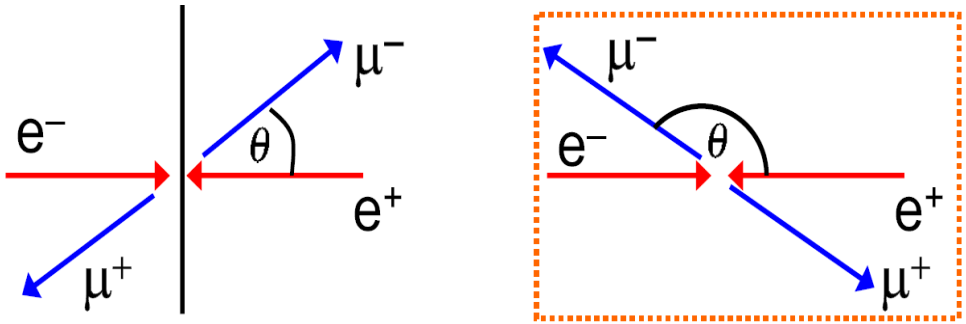
Physics Reports, 427 (2006) 257-454

$$m_Z = 91.1875 \pm 0.0021\,\text{GeV}$$

$$\Gamma_Z = 2.4952 \pm 0.0023\,\text{GeV}$$

$$N_\nu = 2.9840 \pm 0.0082$$

ASIMETRIJA NAPRIJED-NATRAG (Forward-Backward)

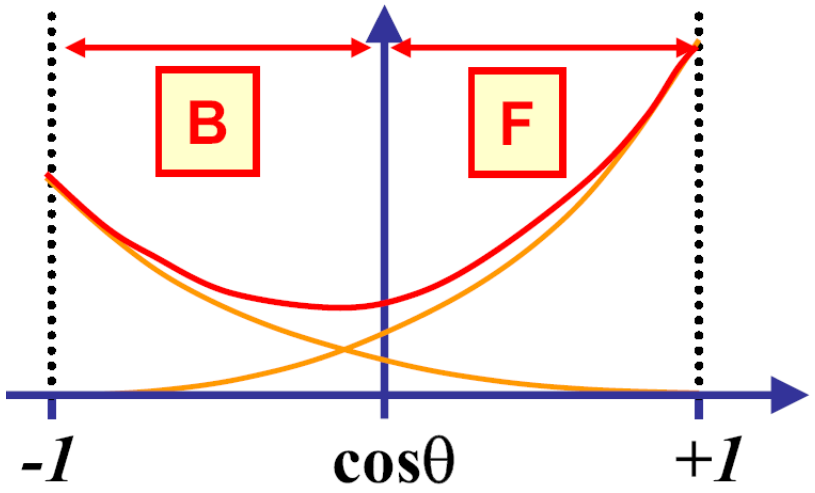


$$\frac{d\sigma}{d\Omega} = \kappa \times [A(1+\cos^2\theta) + B\cos\theta]$$

$$\begin{cases} A = [(c_L^e)^2 + (c_R^e)^2][(c_L^\mu)^2 + (c_R^\mu)^2] \\ B = [(c_L^e)^2 - (c_R^e)^2][(c_L^\mu)^2 - (c_R^\mu)^2] \end{cases}$$

$$\sigma_F \equiv \int_0^1 \frac{d\sigma}{d\cos\theta} d\cos\theta$$

$$\sigma_B \equiv \int_{-1}^0 \frac{d\sigma}{d\cos\theta} d\cos\theta$$



ASIMETRIJA NAPRIJED-NATRAG

$$A_{\mathrm{FB}} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$$\sigma_F = \kappa \int_0^1 [A(1+\cos^2\theta) + B\cos\theta]\,\mathrm{d}\cos\theta = \kappa \int_0^1 [A(1+x^2) + Bx]\,\mathrm{d}x = \kappa\left(\frac{4}{3}A + \frac{1}{2}B\right)$$

$$\sigma_B = \kappa \int_{-1}^0 [A(1+\cos^2\theta) + B\cos\theta]\,\mathrm{d}\cos\theta = \kappa \int_0^1 [A(1+x^2) + Bx]\,\mathrm{d}x = \kappa\left(\frac{4}{3}A - \frac{1}{2}B\right)$$

$$A_{\mathrm{FB}} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{B}{(8/3)A} = \frac{3}{4}\left[\frac{(c_L^e)^2 - (c_R^e)^2}{(c_L^e)^2 + (c_R^e)^2}\right] \cdot \left[\frac{(c_L^\mu)^2 - (c_R^\mu)^2}{(c_L^\mu)^2 + (c_R^\mu)^2}\right]$$

$$A_{\mathrm{FB}} = \frac{3}{4} A_e A_\mu$$

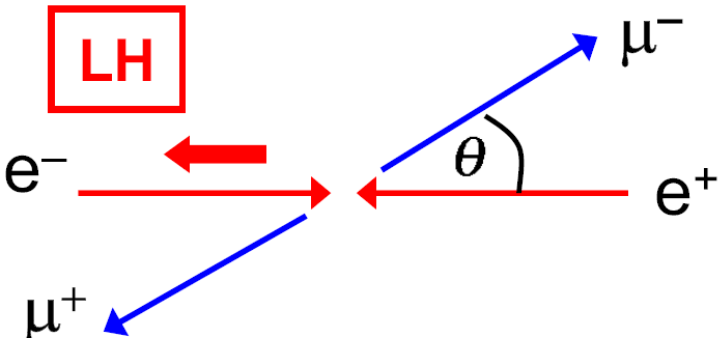
$$A_f \equiv \frac{(c_L^e)^2 - (c_R^e)^2}{(c_L^e)^2 + (c_R^e)^2} = \frac{2 c_V^f c_A^f}{(c_V^f)^2 + (c_A^f)^2}$$

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

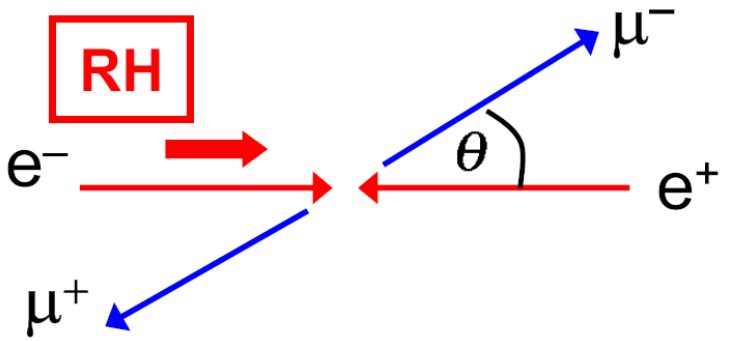
$$A_{LR} = \frac{(c_L^e)^2 - (c_R^e)^2}{(c_L^e)^2 + (c_R^e)^2} = A_e$$

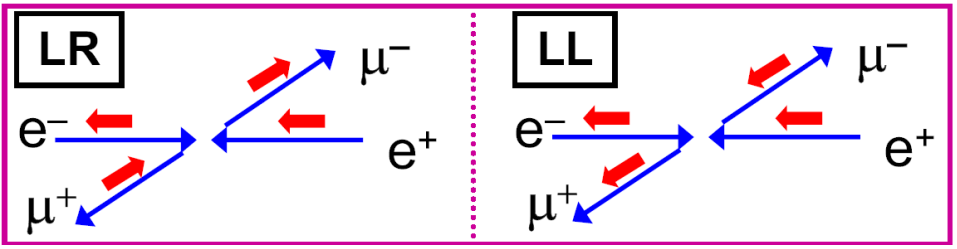
ASIM. LIJEVO-DESNO mjerenje dva procesa (SLC):

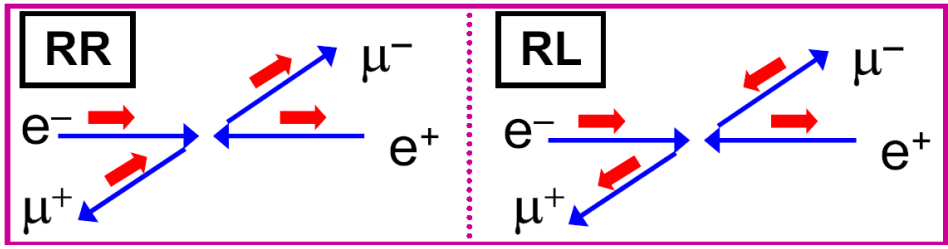
$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$



vs.







$$\langle |M_L| \rangle^2 = \tfrac{1}{2}(|M_{LL}|^2 + |M_{LR}|^2)$$

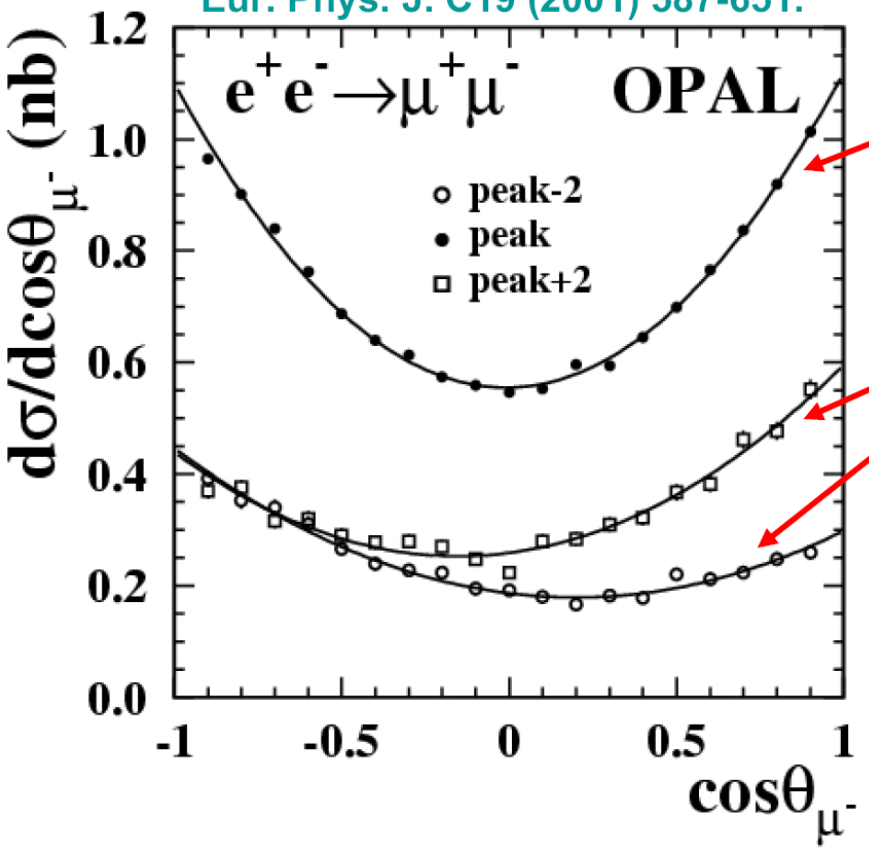
$$\sigma_L = \tfrac{1}{2}(\sigma_{LR} + \sigma_{LL})$$

$$\langle |M_R| \rangle^2 = \tfrac{1}{2}(|M_{RL}|^2 + |M_{RR}|^2)$$

$$\sigma_R = \tfrac{1}{2}(\sigma_{RR} + \sigma_{RL})$$

MJERENJE F-B ASIMETRIJE na Z-rezonanci i interferencijom s γ

OPAL Collaboration,
Eur. Phys. J. C19 (2001) 587-651.



$$e^+e^- \to Z \to \mu^+\mu^-$$

$$e^+e^- \to \gamma \to \mu^+\mu^-$$

★**LEP data combined:**

$$A_{FB}^{0,e} = 0.0145 \pm 0.0025$$

$$A_{FB}^{0,\mu} = 0.0169 \pm 0.0013$$

$$A_{FB}^{0,\tau} = 0.0188 \pm 0.0017$$

MJERENJIMA F-B ASIMETRIJA određuje se kut slabog miješanja:

- MJERENJE LEPa
- MJERENJE SLCa

$$\left.\begin{aligned} A_{FB}^{0,f} &= \tfrac{3}{4} A_e A_f \\ A_{LR} &= A_e \end{aligned}\right\} \quad A_e, A_\mu, A_\tau, \ldots$$

$$A_e = 0.1514 \pm 0.0019$$
$$A_\mu = 0.1456 \pm 0.0091$$
$$A_\tau = 0.1449 \pm 0.0040$$

$$A_f \equiv \frac{2 c_V^f c_A^f}{(c_V^f)^2 + (c_A^f)^2} = 2 \frac{c_V / c_A}{1 + (c_V / c_A)^2}$$

$$\frac{c_V}{c_A} = \frac{I_W^3 - 2Q \sin^2 \theta_W}{I_W^3}$$

$$= 1 - 4|Q| \sin^2 \theta_W$$

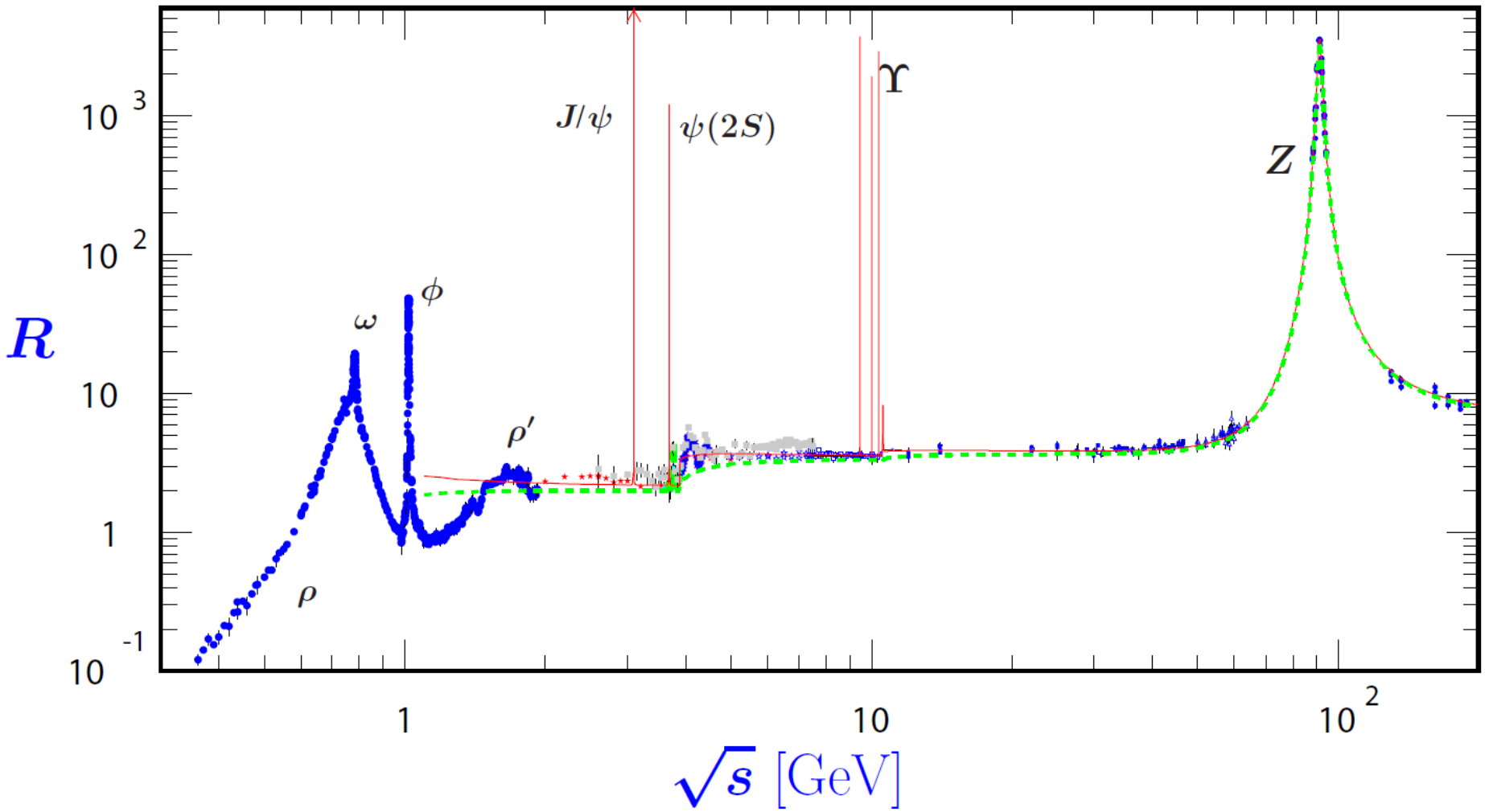
$$\sin^2 \theta_W = 0.23154 \pm 0.00016$$

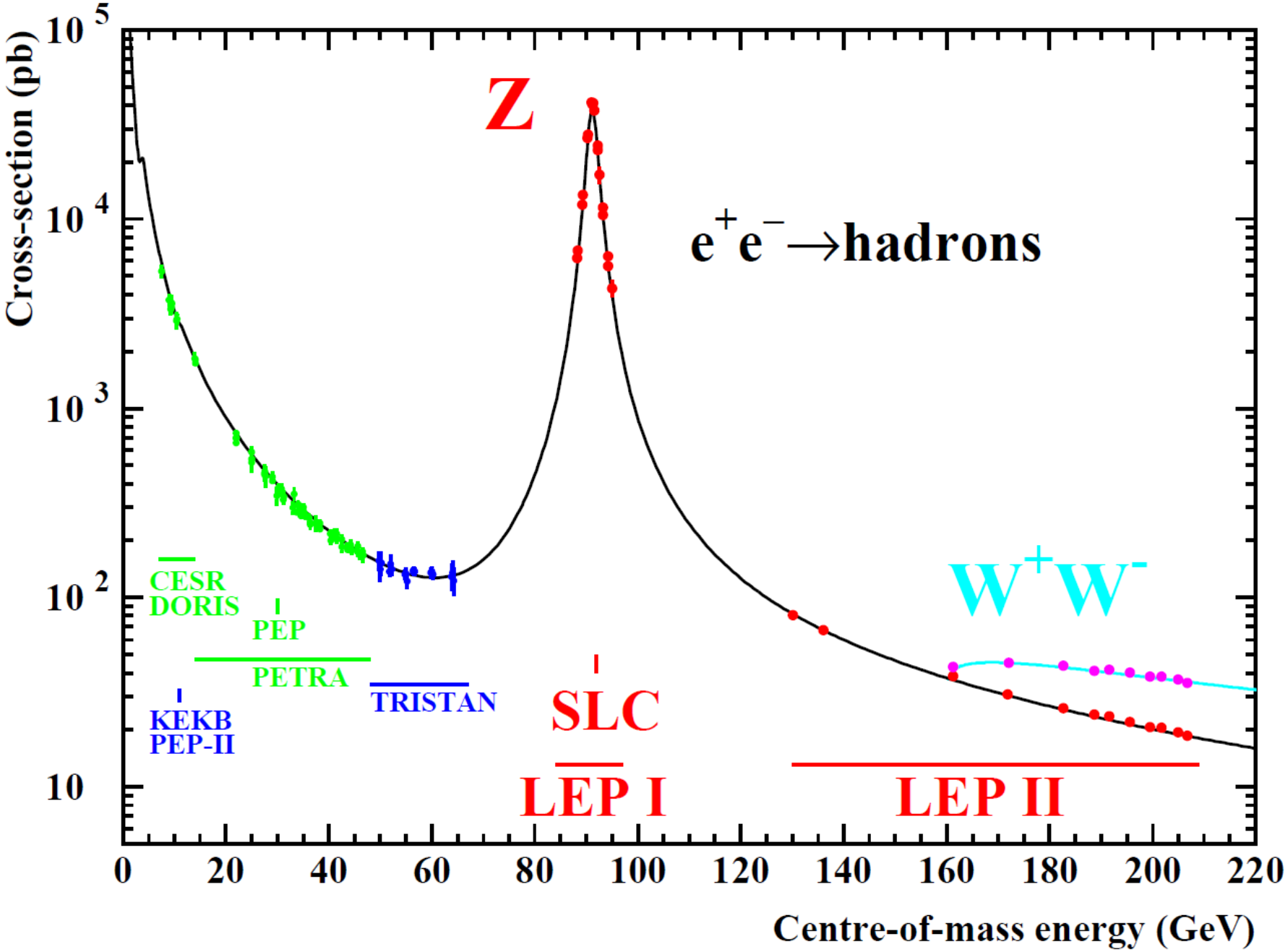
ANIHILACIJA ELEKTRON-POZITRON U HADRONE - na Z-rezonanci

$$-i\mathcal{M} = \left[\bar{u}_1 i\gamma^\mu \left(g_R P_R + g_L P_L\right) v_2\right] \frac{-ig_{\mu\nu} + \dots}{s - M_Z^2} \left[\bar{v}_b i\gamma^\nu \left(g_R P_R + g_L P_L\right) u_a\right]$$

$$\overline{|\mathcal{M}|^2} = \frac{s}{\left(s - M_Z^2\right)^2 + M_Z^2 \Gamma_Z^2} \left\{ \left(g_L^2 + g_R^2\right)^2 \left(1 + \cos^2\theta\right) + 2\left(g_L^2 - g_R^2\right)^2 \cos\theta \right\}$$

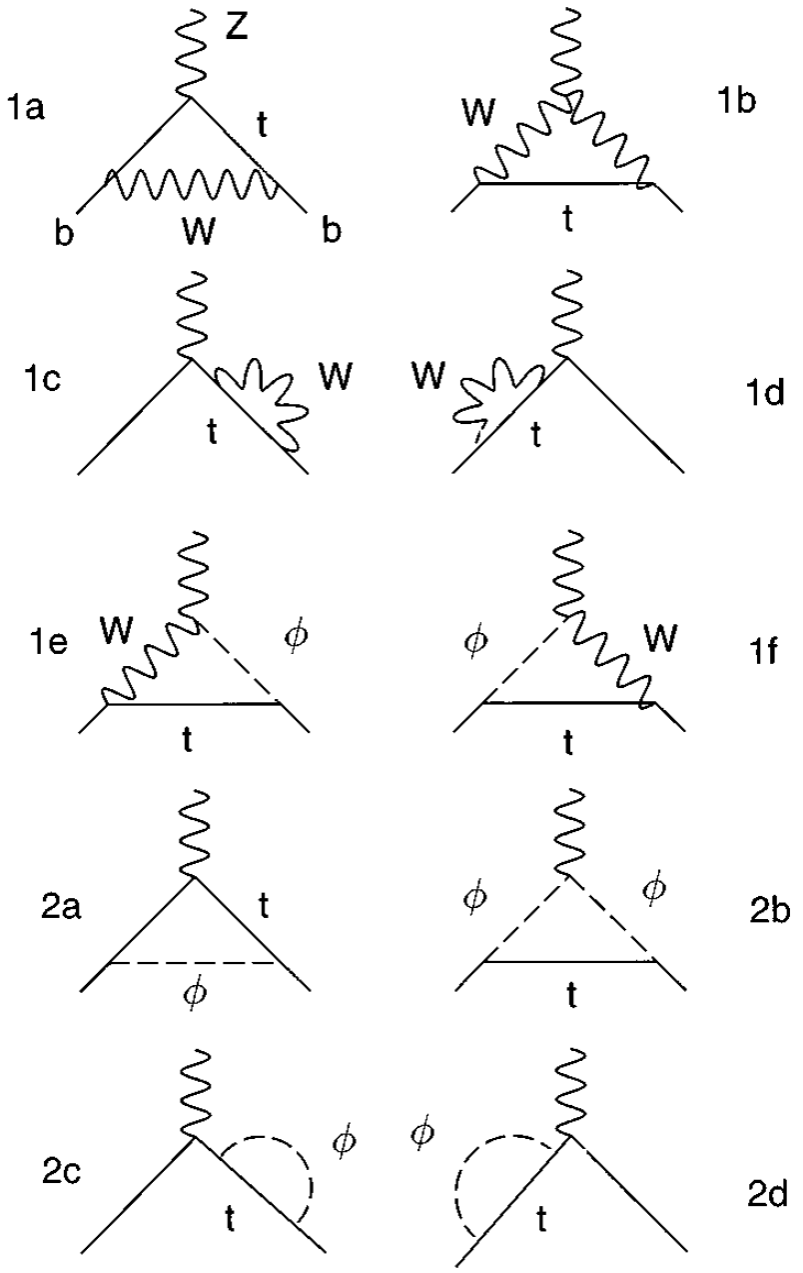
$$R_\mu \equiv \frac{e^+e^- \to Z \to \mu^+\mu^-}{e^+e^- \to Z \to \text{ hadrons}} \qquad R_\mu = \frac{\left(g_L^{\mu\ 2} + g_R^{\mu\ 2}\right)}{\sum_q \left(g_L^{q\ 2} + g_R^{q\ 2}\right)}$$

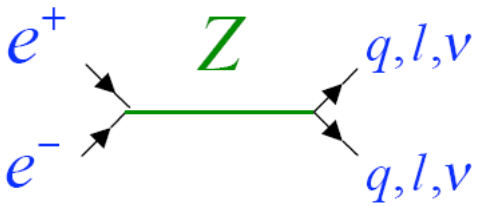

R
10 3
10 2
10
1
10 -1
1
10
10 2
√s [GeV]
ρ
ω
φ
ρ′
J/ψ
ψ(2S)
ϒ
Z

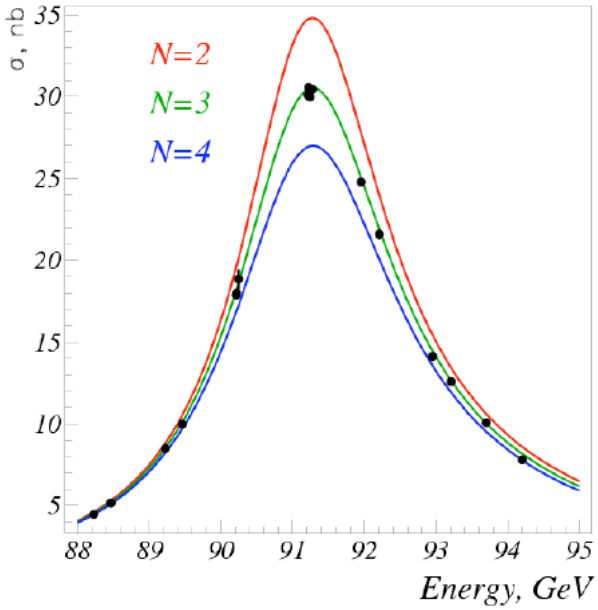

Cross-section (pb)
10 5
10 4
10 3
10 2
10
Z
e+e−→hadrons
W+W-
CESR
DORIS
PEP
PETRA
TRISTAN
KEKB
PEP-II
SLC
LEP I
LEP II
0
20
40
60
80
100
120
140
160
180
200
220
Centre-of-mass energy (GeV)

OPSERVABLE NA Z-REZONANCI

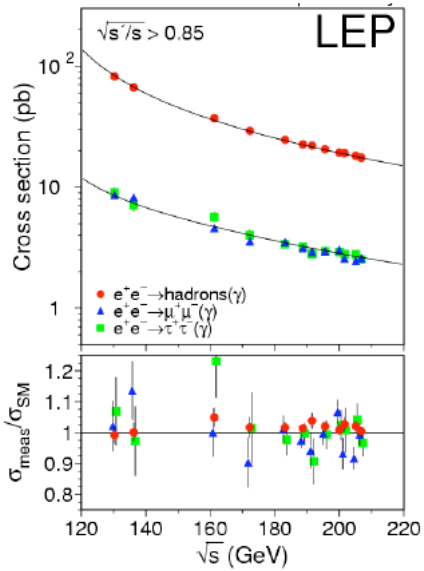
- UKUPNA ŠIRINA
- Z-ASIMETRIJE
- Parametar Rb







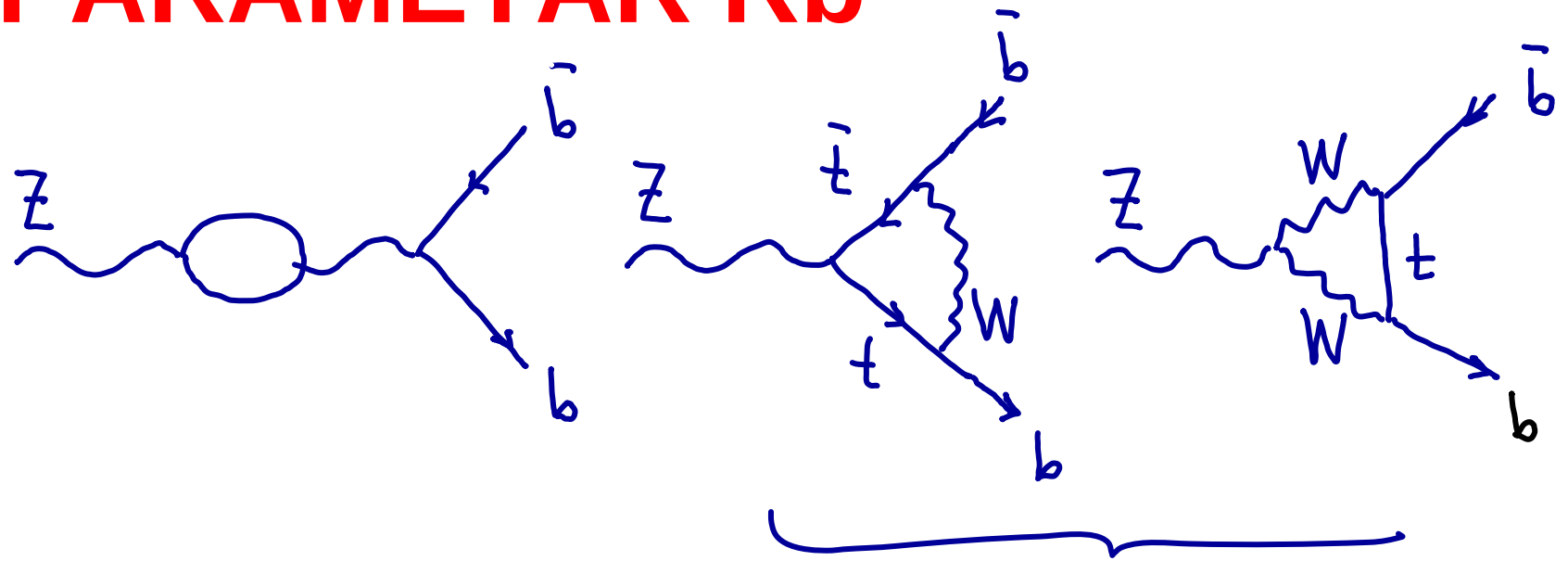
(N is no. of light - wrt M_Z - neutrinos)



$$\sigma(e^+e^- \to hadrons) = \frac{12\pi\,\Gamma(Z \to ee)\Gamma(Z \to hadrons)}{(E^2 - M_Z^2)^2 + M_Z^2\Gamma_Z^2}$$

$$\left|\tilde{\Delta}_F(p)\right|^2 = \left|\frac{1}{p^2 - m^2 + im\Gamma_{tot}}\right|^2$$

PARAMETAR Rb



ne-univerzalne korekcije

daju korekciju naboju $b_L Z$-vezanja

$$Q_{Z_L} = -\left(\frac{1}{2} - \frac{1}{3}s_W^2 - \frac{\alpha}{16\pi s_W^2}\frac{m_t^2}{M_W^2}\right)$$

TEST NEODVEZANIH ST. SLOB.

$R_b^{exp} = 0.21630 \pm 0.00066$

$$\sim \frac{g^2 y_t^2 \langle \phi^+ \phi \rangle Z_\mu b_L \gamma^\mu b_L}{M^2_W}$$

The $O(10^{-3})$ accuracy reached at LEP−I let us to probe the genuine e.w. effects at the 20−30% level

possible NP ↕ contrib.:

$$\frac{\langle \phi^+ \phi \rangle Z_\mu b_L \gamma^\mu b_L}{\Lambda^2}$$

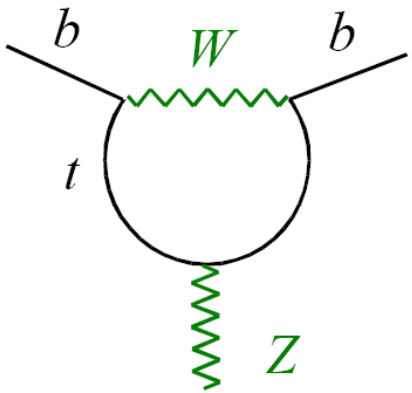
↕

probe scales of new−physics not too far from the TeV

OKUSNO-UNIVERZANE ("oblique") & NEUNIVERZALNE ("decoupling")

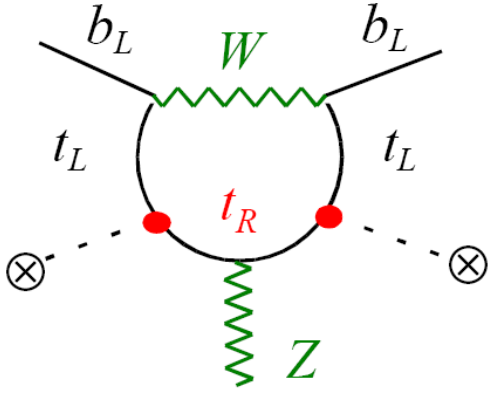
E.g.:

$$R_b = \frac{\Gamma(Z \to bb)}{\Gamma(Z \to had)}$$



leading m_t dep.

driven by



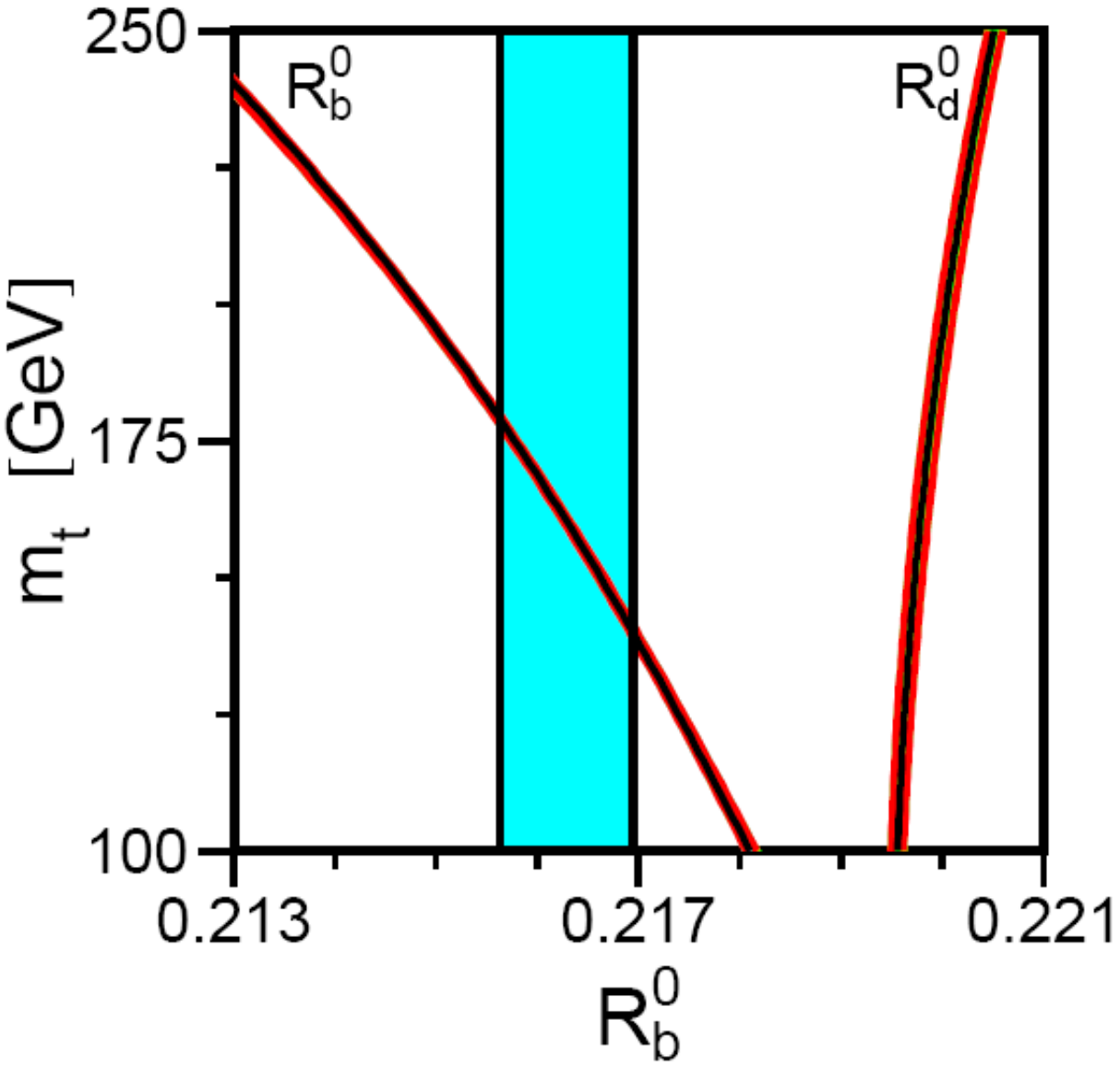
$$R_b = R_0 [\, 1 - G_F m_t^2 / 2\pi^2\sqrt{2} + \ldots \,] \approx 0.2182 - 0.0024$$

$$\sim \frac{g^2 y_t^2 \langle \phi^+ \phi \rangle Z_\mu b_L \gamma^\mu b_L}{M^2_W}$$

tree−level

+ flavour−universal corrections

Mjerenje Rb (LEP,SLD) određuje masu t-kvarka



Usporedba mjerenja i analize SM s globalnom EW-prilagodbom