Z-Factory Physics

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Outline

- **Introduction**

  The working group (on precision frontier)

  The modernized (Super) Z-factories

- **Characteristic physics @ Super Z-factory**

  (beyond and within SM)

  Precision & rare physics for Z-boson

  Flavor physics & QCD physics etc

- **Summary**

Introduction

The working group (40 and more members) founded in 2009 (volunteered)

due to realizing a modern factory is accessible in technique and considering future for CHEP:

LEP-I: $\mathcal{L}_0 = 2.4 \bullet 10^{31} cm^{-2} s^{-1}$

SLC: $\mathcal{L}_0 = 0.6 \bullet 10^{31} cm^{-2} s^{-1}$

a modern one: $\mathcal{L} = 10^{3\sim5} \mathcal{L}_0$ **even higher**

Z-boson events $\sim 10^{10\sim12}$ /year (more than Giga-Z)

Focus on the characteristic physics @ the factory and its significance

Indeed some progress is made. A special issue

Sci. China. Phys. Mach. & Astron. 53 (2010), 2031-2036.

Introduction

The Z-Factories:

An e^+e^- collider running at the Z resonance (properly apply the resonance effect)

A factory for all kinds of fermions, except t-quark, in SM owing to the resonance effect!

The old ones

LEP-I: $\mathcal{L}_0 = 2.4 \bullet 10^{31} cm^{-2}s^{-1}$

Scan 88GeV～94GeV

$1.55 \cdot 10^7$ hadronic events; $1.7 \cdot 10^6$ leptonic events.

Detectors: Aleph, Delphi, L3, Opal.

SLC: $\mathcal{L}_0 = 0.6 \bullet 10^{31} cm^{-2}s^{-1}$

@Z-peak $0.6 \cdot 10^6$ events

(Especially electron polarization beam: 70％)

Detector: SLD

Introduction

The Z-Factories (cont'd):

A modern ones:

$\mathcal{L} = 10^{3\sim5}\mathcal{L}_0$ even higher

Events: $10^{10\sim12}$ Z/year and all kinds of fermions, except t-quark, in SM produced by Z decay

Well-designed Detector(s)

Note: Considering the requested luminosity and the costs for running, a circle one is better than a linear one.

Characteristic Physics

- **Precision & rare physics for Z-boson:**

  Exp. measurements (LEP-I, SLC) vs Theor. prediction (SM)

Quantity	Value	Standard Model	Pull	Dev.
m_t [GeV]	$170.9 \pm 1.8 \pm 0.6$	171.1 ± 1.9	-0.1	-0.8
M_W [GeV]	80.428 ± 0.039	80.375 ± 0.015	1.4	1.7
	80.376 ± 0.033		0.0	0.5
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1	-0.1
Γ_Z [GeV]	2.4952 ± 0.0023	2.4968 ± 0.0010	-0.7	-0.5
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7434 ± 0.0010	–	–
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.59 ± 0.08	–	–
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	83.988 ± 0.016	–	–
σ_{had} [nb]	41.541 ± 0.037	41.466 ± 0.009	2.0	2.0
R_e	20.804 ± 0.050	20.758 ± 0.011	0.9	1.0
R_μ	20.785 ± 0.033	20.758 ± 0.011	0.8	0.9
R_τ	20.764 ± 0.045	20.803 ± 0.011	-0.9	-0.8
R_b	0.21629 ± 0.00066	0.21584 ± 0.00006	0.7	0.7
R_c	0.1721 ± 0.0030	0.17228 ± 0.00004	-0.1	-0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01627 ± 0.00023	-0.7	-0.6
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.5	0.7
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5	1.6
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1033 ± 0.0007	-2.5	-2.0
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0738 ± 0.0006	-0.9	-0.7
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1034 ± 0.0007	-0.5	-0.4
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23149 ± 0.00013	0.8	0.6
	0.2238 ± 0.0050		-1.5	-1.6
A_e	0.15138 ± 0.00216	0.1473 ± 0.0011	1.9	2.4
	0.1544 ± 0.0060		1.2	1.4
	0.1498 ± 0.0049		0.5	0.7
A_μ	0.142 ± 0.015		-0.4	-0.3
A_τ	0.136 ± 0.015		-0.8	-0.7
	0.1439 ± 0.0043		-0.8	-0.5
A_b	0.923 ± 0.020	0.9348 ± 0.0001	-0.6	-0.6
A_c	0.670 ± 0.027	0.6679 ± 0.0005	0.1	0.1
A_s	0.895 ± 0.091	0.9357 ± 0.0001	-0.4	-0.4
g_L^2	0.3010 ± 0.0015	0.30386 ± 0.00018	-1.9	-1.8
g_R^2	0.0308 ± 0.0011	0.03001 ± 0.00003	0.7	0.7
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0397 ± 0.0003	0.0	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0	0.0
A_{PV}	$(-1.31 \pm 0.17) \cdot 10^{-7}$	$(-1.54 \pm 0.02) \cdot 10^{-7}$	1.3	1.2
$Q_W(\text{Cs})$	-72.62 ± 0.46	-73.16 ± 0.03	1.2	1.2
$Q_W(\text{Tl})$	-116.4 ± 3.6	-116.76 ± 0.04	0.1	0.1
$\frac{\Gamma(b \to s\gamma)}{\Gamma(b \to X e\nu)}$	$\left(3.55^{+0.53}_{-0.46}\right) \cdot 10^{-3}$	$(3.19 \pm 0.08) \cdot 10^{-3}$	0.8	0.7
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	$4511.07(74) \cdot 10^{-9}$	$4509.08(10) \cdot 10^{-9}$	2.7	2.7
τ_τ [fs]	290.93 ± 0.48	291.80 ± 1.76	-0.4	-0.4

(look for evidences beyond SM)

The effective coupling Z-ff' (in tree and loops & especially when f, f' are leptons) constraints for new physics!

(Taken from PDG)

SM works well so far, but the pulls are 'dominant' by experimental errors.

Characteristic Physics

- **Precision & rare physics for Z-boson:**

  Exp. measurements (LEP-I, SLC) vs Theor. prediction (SM)

	Measurement with Total Error	Systematic Error	Standard Model fit	Pull
$\Delta\alpha^{(5)}_{had}(m_Z^2)$ [82]	0.02758 ± 0.00035	0.00034	0.02768	−0.3
a) LEP-I				
line-shape and lepton asymmetries:				
m_Z [GeV]	91.1875 ± 0.0021	(a)0.0017	91.1874	0.0
Γ_Z [GeV]	2.4952 ± 0.0023	(a)0.0012	2.4959	−0.3
σ^0_{had} [nb]	41.540 ± 0.037	(b)0.028	41.478	1.7
R^0_ℓ	20.767 ± 0.025	(b)0.007	20.742	1.0
$A^{0,\ell}_{FB}$	0.0171 ± 0.0010	(b)0.0003	0.0164	0.7
+ correlation matrix [1]				
τ polarisation:				
$\mathcal{A}_\ell$ ($\mathcal{P}_\tau$)	0.1465 ± 0.0033	0.0016	0.1481	−0.5
$q\overline{q}$ charge asymmetry:				
$\sin^2\theta^{lept}_{eff}(Q^{had}_{FB})$	0.2324 ± 0.0012	0.0010	0.23139	0.8
b) SLD				
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.0010	0.1481	1.6
c) LEP-I/SLD Heavy Flavour				
R^0_b	0.21629 ± 0.00066	0.00050	0.21579	0.8
R^0_c	0.1721 ± 0.0030	0.0019	0.1723	−0.1
$A^{0,b}_{FB}$	0.0992 ± 0.0016	0.0007	0.1038	−2.9
$A^{0,c}_{FB}$	0.0707 ± 0.0035	0.0017	0.0742	−1.0
$\mathcal{A}_b$	0.923 ± 0.020	0.013	0.935	−0.6
$\mathcal{A}_c$	0.670 ± 0.027	0.015	0.668	0.1
+ correlation matrix [1]				
d) LEP-II and Tevatron				
m_W [GeV] (LEP-II, Tevatron)	80.399 ± 0.023		80.379	0.9
Γ_W [GeV] (LEP-II, Tevatron)	2.085 ± 0.042		2.092	0.2
m_t [GeV] (Tevatron [43])	173.3 ± 1.1	0.9	173.4	−0.1

(Taken from arXiv:1012.2367)

SM works well so far, but the pulls are 'dominant' by experimental errors.

It is very difficult to suppress the expt. errors, but with better designed detectors and much higher statistics of events it is possible to confirm some hences @ super Z-factory.

Polarization beam is helpful !

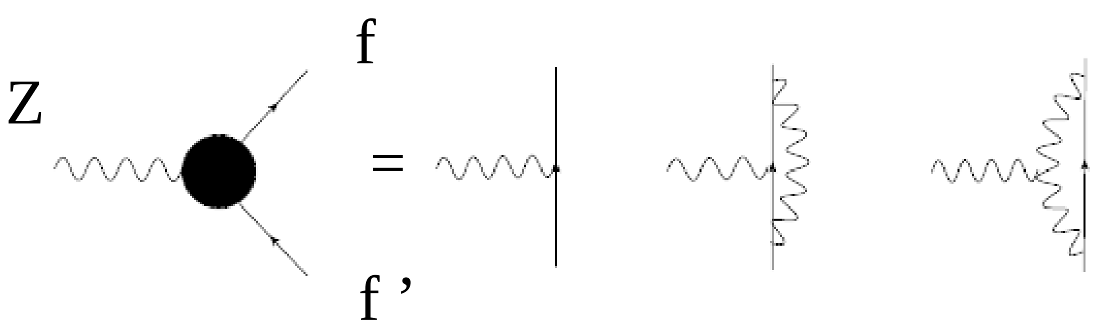
Characteristic Physics

arXiv:1310.6708

Quantity	Current theory error	Leading missing terms	Est. future theory error
$\sin^2\theta^{\ell}_{\rm eff}$	4.5×10^{-5}	$\mathcal{O}(\alpha^2\alpha_s)$, $\mathcal{O}(N_f^{\geq 2}\alpha^3)$	$1...1.5\times10^{-5}$
R_b	$\sim 2\times10^{-4}$	$\mathcal{O}(\alpha^2)$, $\mathcal{O}(N_f^{\geq 2}\alpha^3)$	$\sim 1\times10^{-4}$
Γ_Z	few MeV	$\mathcal{O}(\alpha^2)$, $\mathcal{O}(N_f^{\geq 2}\alpha^3)$	<1 MeV
M_W	4 MeV	$\mathcal{O}(\alpha^2\alpha_s)$, $\mathcal{O}(N_f^{\geq 2}\alpha^3)$	$\lesssim 1$ MeV

Table 1-1. *Some of the most important precision observables for Z-boson production and decay and the W mass (first column), their present-day estimated theory error (second column), the dominant missing higher-order corrections (third column), and the estimated improvement when these corrections are available (fourth column). In many cases, the leading parts in a large-mass expansion are already known, in which case the third column refers to the remaining pieces at the given order. The numbers in the last column are rough order-of-magnitude guesses.*

The rare (tiny) physics relevant to Z boson directly



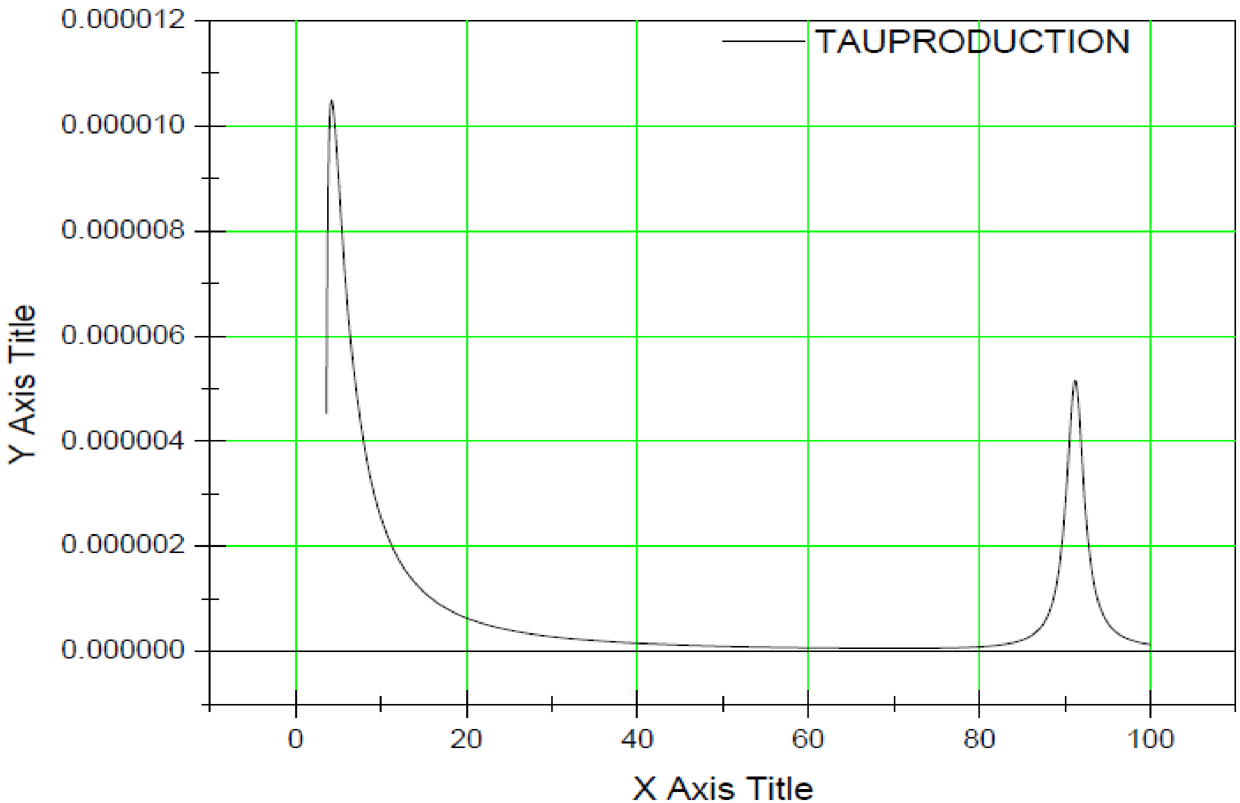
Lepton number violation & FCNC processes; CPV; d_f^Z etc.

Longitudinal component of Z-boson couple to a pair of fermions m_f

Characteristic Physics

-lepton is special (the heaviest lepton)

Very good place of τ-lepton physics (@ Z-factory):



Based on SM: m_Z, $Sin^2\theta_W$, α, Γ_Z, etc

σ(cross-section) @ Z-peak ~ 0.5 σ @ the highest one (threshold) ~ 2.3 σ @ B-factory

3 10[10] **pairs/year**

is the heaviest lepton in SM!

An important factor is the Lorentz boost effects !

Characteristic Physics

The most important is the Lorentz boost effects:

-lepton lifetime :

τ= 0.2906· 10^{-12} s (comparatively small), $c\tau \simeq$ 87.11 μm

Lorentz boost @ Z-factory: γ_{Z-fac}= 25.66, $c\tau\gamma \simeq$ 2235.2 μm

For comparison:

B^+-meson:	τ= 1.638 · 10^{-12} s	$c\tau \simeq$ 491.1 μm
B^0-meson:	τ= 1.525 · 10^{-12} s	$c\tau \simeq$ 457.2 μm
B_s-meson:	τ= 1.472 · 10^{-12} s	$c\tau \simeq$ 441 μm
D^+-meson:	τ= 1.040 · 10^{-12} s	$c\tau \simeq$ 311.8 μm
D^0-meson:	τ= 0.4101· 10-12 s	$c\tau \simeq$ 122.9 μm
D_s-meson:	τ= 0.500· 10^{-12} s	$c\tau \simeq$ 149.9 μm

With vertex detector the momentum-energy of the produced τ-lepton may be well measured@ Z-factory, because γ is quite great indeed.

Characteristic Physics

LEP-I example:

the data samples recorded between 1991 and 1995 with OPAL

69778 τ-pair events

CPV of $V_{Z\tau\tau}$:

(weak dipole)

$$\mathrm{Re}(d_\tau^w) = (0.72 \pm 2.46 \pm 0.24) \times 10^{-18}\, e\ \mathrm{cm}$$

$$\mathrm{Im}(d_\tau^w) = (0.35 \pm 0.57 \pm 0.08) \times 10^{-17}\, e\ \mathrm{cm}$$

If we define: $\epsilon_\tau \equiv \frac{\Delta\Gamma_{Z^0\to\tau^+\tau^-}}{\Gamma_{Z^0\to\tau^+\tau^-}}$, where $\Delta\Gamma_{Z^0\to\tau^+\tau^-} = \frac{|d_\tau^w|^2}{24\pi} m_Z^3 \left(1 - \frac{4m_\tau^2}{m_Z^2}\right)^{3/2}$

The limit means:

$\epsilon_\tau < 7.2 \times 10^{-3}$ using $|d_\tau^w|$ and

$\epsilon_\tau < 8.9 \times 10^{-4}$ assuming $\mathrm{Im}(d_\tau^w) = 0$

$\Gamma_{Z^0\to\tau^+\tau^-} = (83.88 \pm 0.39)$ MeV

precision of the test of $\mathcal{CP}$ invariance

a level of one in thousand

Statistics errors quite large, so there are rooms to improve the measurement(s) !

New result: It is greatly helpful that the direction of produced is measured.

Characteristic Physics

New Physics:

SUSY Models, Multi-Higgs Model, Little Higgs Model, RPV SUSY, Extra Z-boson Model etc

The effective couplings $Zf'\bar{f}$

For leptons: $Z\tau\bar{\tau}\,,\quad Z\mu\bar{\tau}\,,\quad Z\tau\bar{\mu}\,,\quad Ze\bar{\tau}\,,\quad Z\tau\bar{e}$

It is expeced that Z-factory will offer the most precise constraint on them.

When f=f', the fermion, is b-quark or c-quark or a light quarks

R_b & R_c

$$A_{\rm FB} \equiv \frac{\sigma(\cos\theta>0)-\sigma(\cos\theta<0)}{\sigma(\cos\theta>0)+\sigma(\cos\theta<0)} = \mathcal{R}_{\rm FB}\,\frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

$$A_{\rm LR} \equiv \frac{\sigma(\mathcal{P}_e>0)-\sigma(\mathcal{P}_e<0)}{\sigma(\mathcal{P}_e>0)+\sigma(\mathcal{P}_e<0)} = \mathcal{A}_e.$$

Difficulties are in identifying the flavor

Characteristic Physics

- **Flavor physics & QCD physics etc**

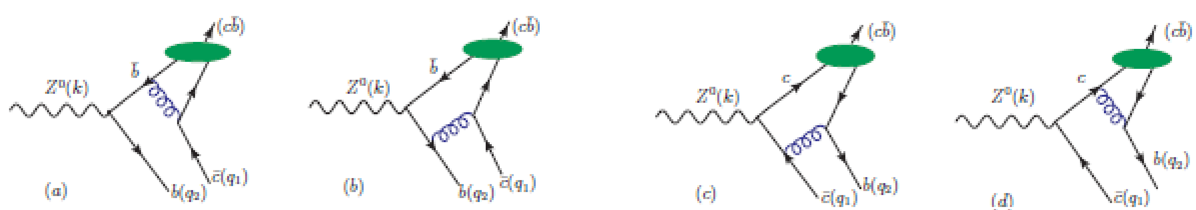
Z-factory vs super B-factory & τ-charm factory

c, b-hadron physics (especially open bottom)

- **Double heavy hadrons $H_{QQ'}$:**

B_c meson, ……, Ξ_{cc}, Ω_{cc}, Ξ_{bc}, , Ω_{bc} , Ξ_{bb}, etc

& their excited states (easier to treat bg. than @LHCb)

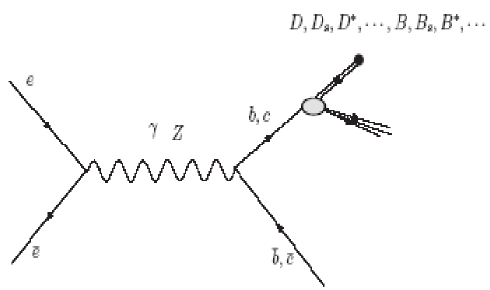


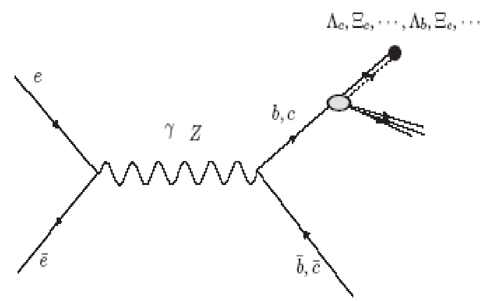
Roughly theo. estimate Br($Z \to H_{QQ'}$+……) ~ 10^{-5} (more 10^6 samples)

The events produced in the factory are sufficient for thorough study of the hadrons themselves (mechanism for production and decays etc) and the flavors in hadrons.

Characteristic Physics

- **Flavor physics & QCD physics etc (cont'd)**
  - **D-meson:** $D^0 - \bar{D}^0$ **mixing:**
    Due the Lorentz boost and the lifetime of D meson, at Z-factory the CP violation in the mixing can be observed, whereas it is impossible at B-factory & τ- Charm factory.
  - **Fragmentation functions (FFs):**





For example:
FF of a (heavy) hadron from a quark c or b or a light quark or a gluon etc

Significance: **experimentally to use them for flavor tag in hadron collisions etc. ; theoretically to test QCD & models etc.**

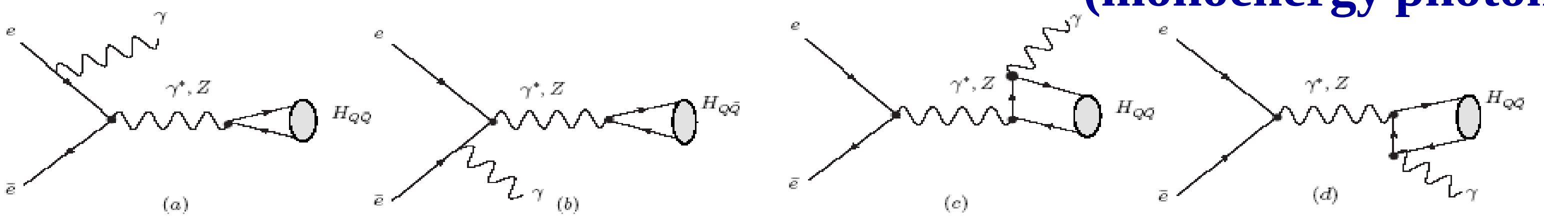
Characteristic Physics

- **Flavor physics & QCD physics etc (cont'd)**
  - **Spectroscopy for heavy hadrons (especially open bottom)**

    For example:

$$e^+(p_1) + e^-(p_2) \to \gamma(p_3) + H_{Q\bar{Q}}(P)$$

Two body final state! (monoenergy photon)



Here $H_{Q\bar{Q}}$: $\eta_c,\ J/\psi,\ \cdots\ \eta_b,\ \Upsilon,\ \cdots\ X_{c\bar{c}},\ \cdots\ X_{b\bar{b}},\ \cdots$

	$^3S_1$	$^1S_0$	$^3P_0$	$^3P_1$	$^3P_2$	$^1P_1$
$\sigma_{(c\bar{c})}(pb)$	0.934	0.662×10^{-3}	0.328×10^{-4}	0.197×10^{-3}	0.661×10^{-4}	0.615×10^{-3}
$\sigma_{(b\bar{b})}(pb)$	0.565×10^{-1}	0.475×10^{-2}	0.128×10^{-4}	0.838×10^{-4}	0.930×10^{-4}	0.833×10^{-4}

Characteristic Physics

- **Flavor physics & QCD physics etc (cont'd)**
  - **Spectroscopy for heavy hadrons (cont'd)**

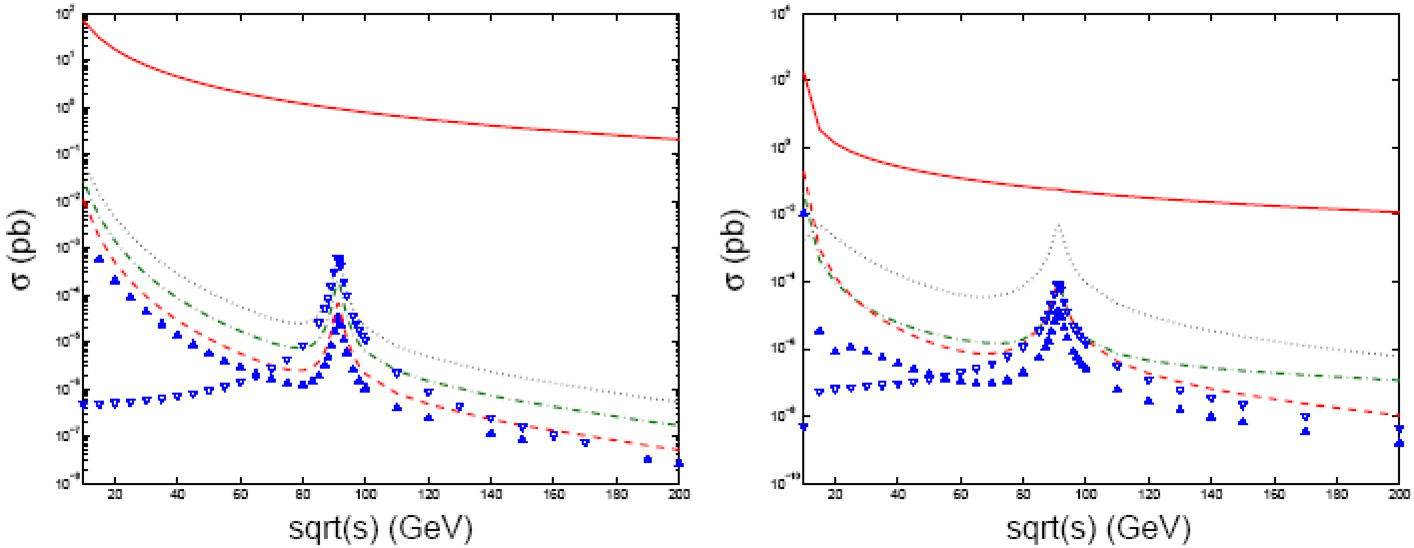


FIG. 2: (color online) Total cross sections for the processes $e^- + e^+ \to \gamma + H_{Q\bar{Q}}$ versus the collision energy. The red solid, the black dotted, the blue up-solid-triangle, the green dash-dotted, the red dashed and the down-hollow-triangle lines stand for $Q\bar{Q}$ in ${}^3S_1$, ${}^1S_0$, ${}^3P_0$, ${}^3P_1$, ${}^3P_2$, ${}^1P_1$ respectively. The left figure is for charmonium and the right one is for bottomonium.

Characteristic Physics

- **Flavor physics & QCD physics etc (cont'd)**
  - **Spectroscopy for heavy hadrons (cont'd)**

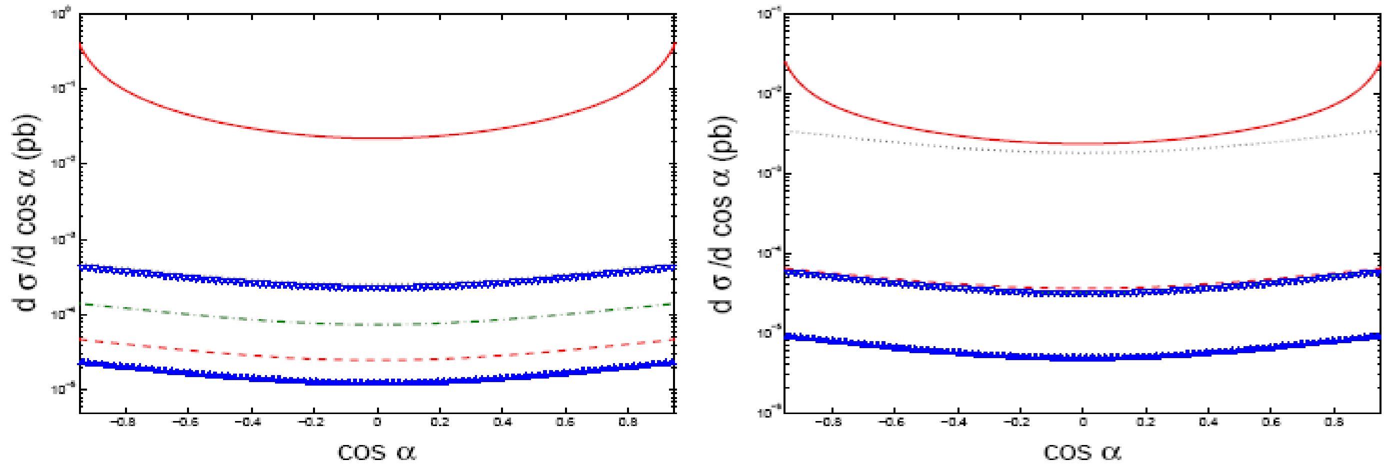


FIG. 3: (color online) Differential cross sections for the processes $e^- + e^+ \to \gamma + H_{Q\bar{Q}}$ versus $\cos\alpha$ at a C.M.S. energy as Z-mass. The red solid, the black dotted, the blue up-solid-triangle, the green dash-dotted, the red dashed and the blue down-hollow-triangle lines stand for $Q\bar{Q}$ in $^3S_1$, $^1S_0$, $^3P_0$, $^3P_1$, $^3P_2$, $^1P_1$ respectively. The left figure is for charmonium (the dotted line and the blue down-hollow-triangle almost emerge together almost) and the right one is for bottomonium (the red dashed line, the green dash-dotted line and the blue down-hollow-triangle emerge together almost).

Characteristic Physics

- **Flavor physics & QCD physics etc (continued)**

- **τ-lepton physics:**

  If 10^{12} Z-bosons/year or higher, then 10^{10} τ-lepton pairs (more)/year with quite great Lorentz boost effects may be produced @ Super Z-factory.

  Therefore, the rare decays

  $\tau \to e\gamma,\ \tau \to \mu\gamma,\ \tau \to \bar{\mu}\mu\mu,\ \tau \to \mu\bar{e}e,\ \tau \to \bar{e}ee,$ **etc**

  and/or CPV in decay may reach to 10^{-10} level (even higher) !

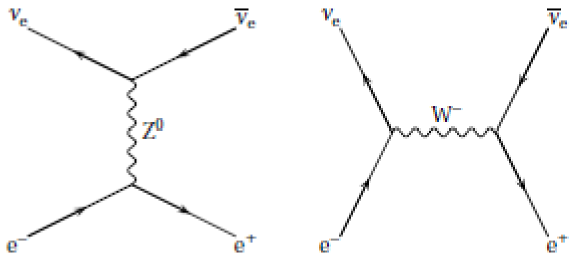
- **Neutrino physics:**

  The invisible width of Z-boson ≈ 3 (2.984±0.008) types of light neutrinos.

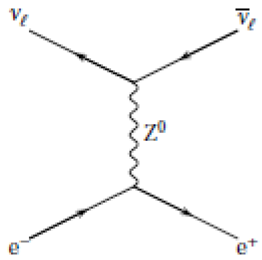
  We think that we should estimate the number more carefully and to see how big a room left for the light neutrinos mixing with the sterile one and else.

Characteristic Physics

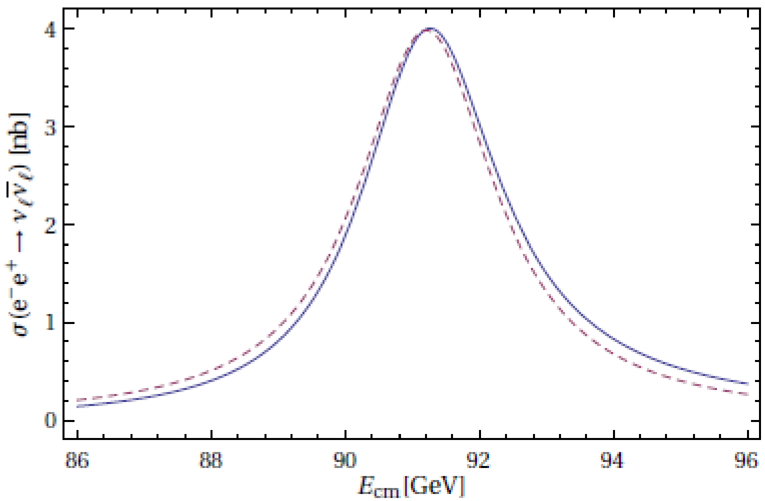
- **Flavor physics & QCD physics etc (cont'd)**
  - **Neutrino physics (cont'd) :**



The Feynman diagrams for the process $e^-e^+ \to \nu_e\bar{\nu}_e$



The Feynman diagram for the process $e^-e^+ \to \nu_l\bar{\nu}_i$ $(l=\nu,\tau)$.

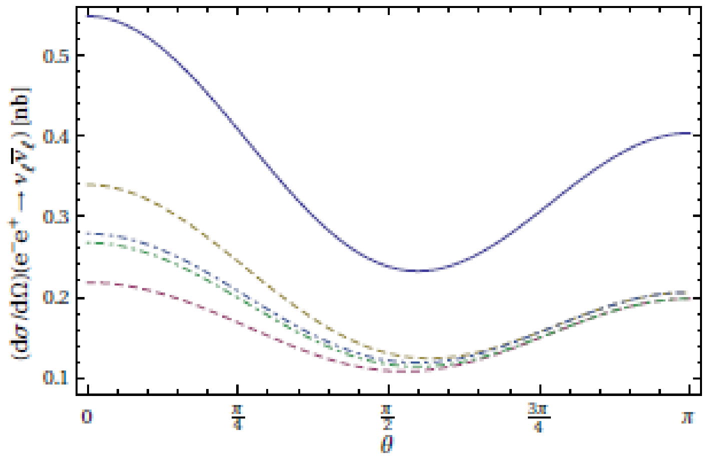


Solid curve is of e-neutrino production; dished curve is of □- or □-neutrino production.

Characteristic Physics

- **Flavor physics & QCD physics etc (cont'd)**
  - **Neutrino physics (cont'd) :**

The differential cross-section:



Q: May be used as a source of monoenergy neutrino ?

A: Depends. Yes, if the luminosity of the factory can reach to that of higher than $10^{36} cm^{-2} s^{-1}$.

- **Non-perturbative fragmentation models: LUND , Webber Cluster, Quark Combination (ShangDong) Model.**

It is the best place to test the models.

In summary

With modern tech., now a Z-factory may reach to such a luminosity so higher than that of LEP-I & SLC by a magnitude of $10^{5\text{-}6}$. Quite a lot of observations of the characteristic physics may be carried out @it , thus we can expect that some hints beyond SM and/or some fresh phenomena within SM may be explored at the factory and such kinds of discoveries will guide us to develop our knowledge further in a right way.

Based on our preliminary studies we suspect that for humankind in the long march to explore the world of particle physics, a Z-factory concerned here would play an irreplaceable role.

Thanks !