Physics @ Hyper Z-Factory (HZF)

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Outline

- Introduction
  1. The working group
  2. The Modernized Z-Factories (HZF)
- The Physics @ HZF
  (Beyond and within SM)
  1. Precision tests of SM & clue for BSM
  2. □-physics (even □-physics)
  3. Flavor physics & QCD physics etc
- Our working plan

Introduction

1. The working group was founded in 2009 (volunteered) due to realizing a modern factory is accessible in technique.

   The old ones:

   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∼ a few $10^{10\sim12}$ /year (more than Giga-Z)

   Focus on the physics @ the factory and its significance

Indeed some progress is made. A special issue Sci. China. Phys. Mach. & Astron. 53 (2010), 2031-2036.

Introduction

HZF (also a factory for all flavors) :

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

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

The old ones

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

Scan 88GeV~94GeV

$15.5 \cdot 10^6$ hadronic events; $1.7 \cdot 10^6$ leptonic events accumulated by the 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 accumulated by the detector: SLD (especially, electron beam: 70% polarization)

Introduction

The Hyper Z-Factories:

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

Events: $10^{10\sim12}$ Z/year and more

Production (via Z-decay) of all flavors (except t)

Decays of the flavors

(with well-designed detectors)

Note: **Circle or linear both are OK, but the requested luminosity by physics and the costs for constructing and running must be considered.**

Physics @ HZF

1. 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
$\Gamma(\mathrm{had})$ [GeV]	1.7444 ± 0.0020	1.7434 ± 0.0010	—	—
$\Gamma(\mathrm{inv})$ [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
$Q_W(\mathrm{Cs})$	-72.62 ± 0.46	-73.16 ± 0.03	1.2	1.2
$Q_W(\mathrm{Tl})$	-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

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

(look for evidences BSM)

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

Taken from PDG based on LEP-I

Physics @ HZF

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)

It is difficult to suppress the expt. errors, but with better designed detectors and much higher statistics it is possible to improve the errors. At HZF it is expected.

Polarization beam is helpful !

Physics @ HZF

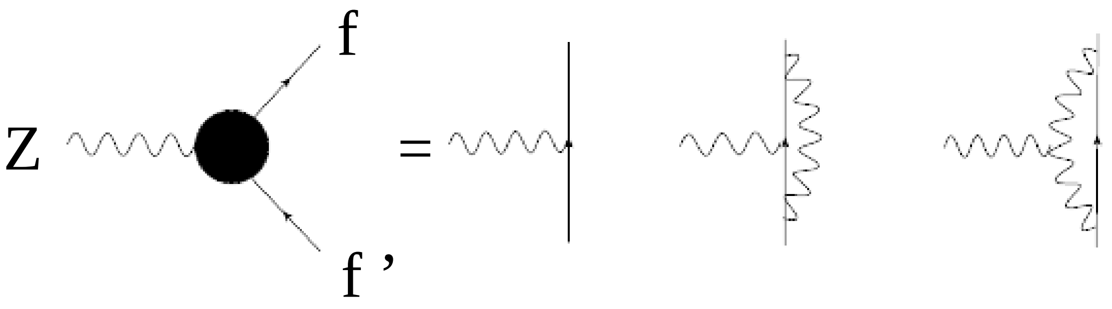
arXiv:1310.6708

Quantity	Current theory error	Leading missing terms	Est. future theory error
$\sin^2\theta^\ell_{\rm eff}$	4.5×10^{-5}	$\mathcal{O}(\alpha^2\alpha_s)$, $\mathcal{O}(N_f^{\geq2}\alpha^3)$	$1...1.5\times10^{-5}$
R_b	$\sim2\times10^{-4}$	$\mathcal{O}(\alpha^2)$, $\mathcal{O}(N_f^{\geq2}\alpha^3)$	$\sim1\times10^{-4}$
Γ_Z	few MeV	$\mathcal{O}(\alpha^2)$, $\mathcal{O}(N_f^{\geq2}\alpha^3)$	<1 MeV
M_W	4 MeV	$\mathcal{O}(\alpha^2\alpha_s)$, $\mathcal{O}(N_f^{\geq2}\alpha^3)$	$\lesssim1$ 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.*

Physics @ HZF

The rare physics directly relating to Z-boson:



FCNC (lepton number violation) processes;
CP violation processes (CPV);
Weak dipole momentum: d_f^Z etc.

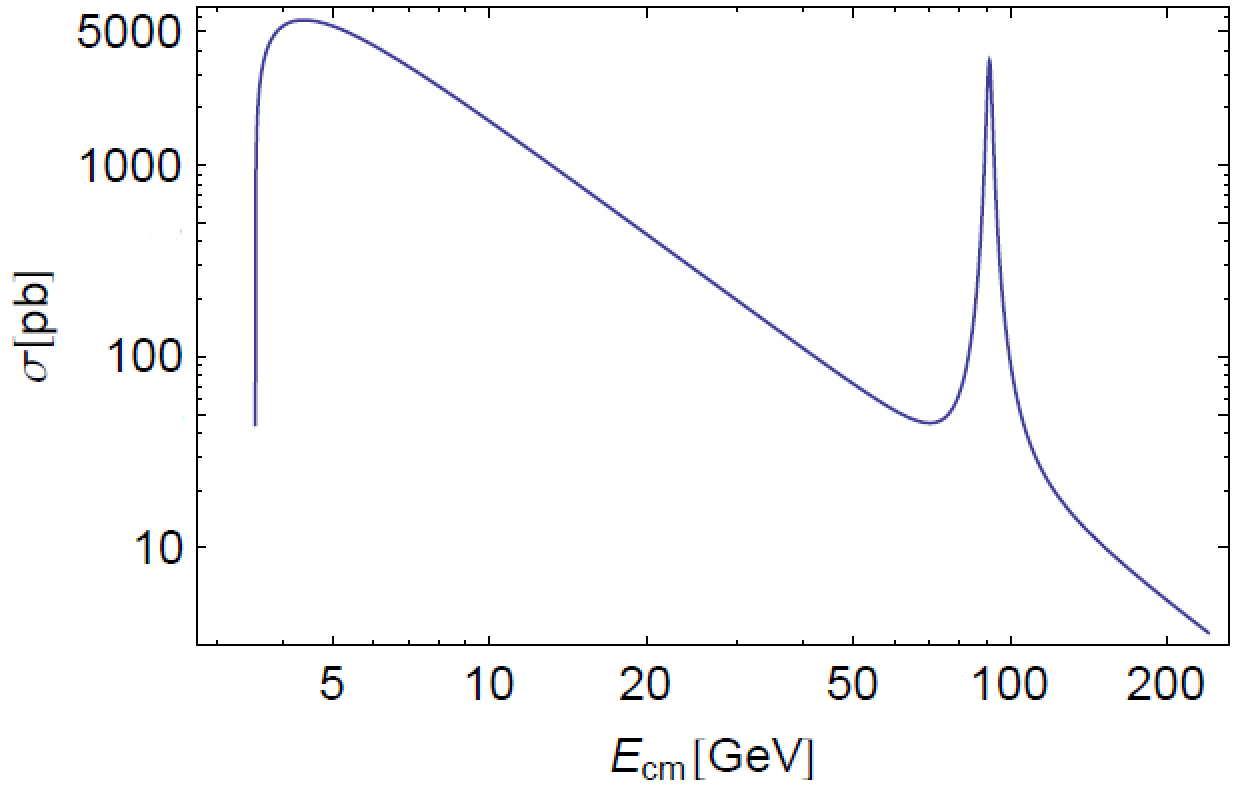
Note: the couplings for the longitudinal component of Z-boson to a pair of fermions are proportional to the mass of the fermion ($\propto m_f$) !

Physics @ HZF

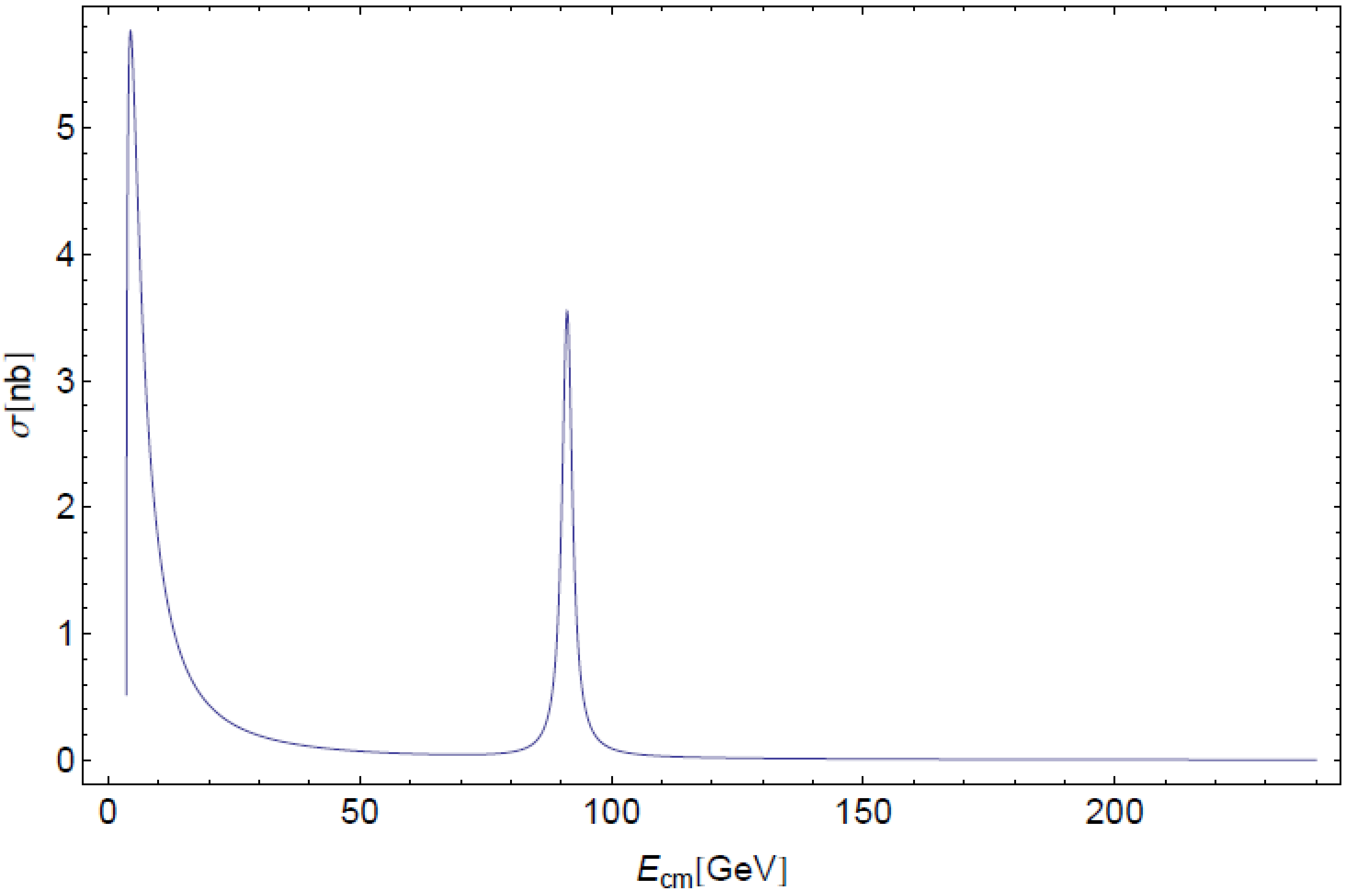
2. -lepton (the heaviest lepton) physics

An excellence place to study the -lepton:

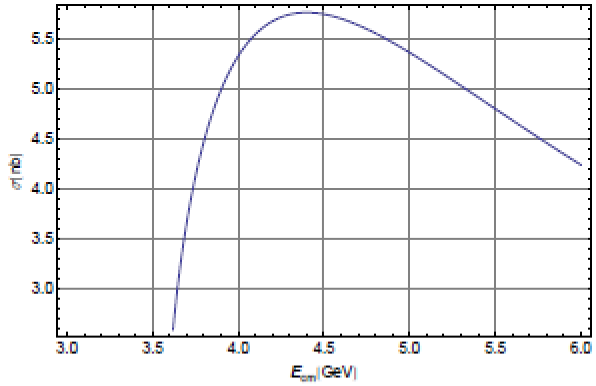
Based on SM: $m_{Z,}$ $Sin^2\theta_W$, α,Γ_Z, etc, the production rate (cross-section):



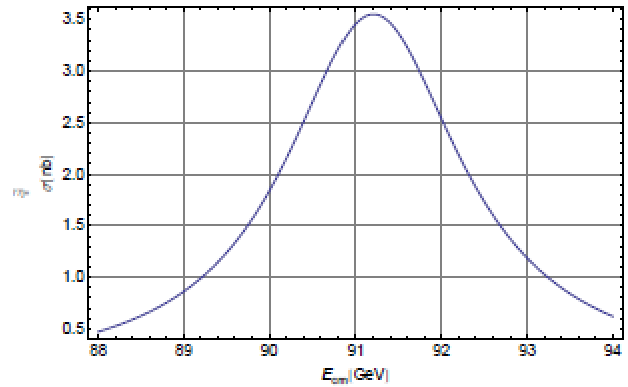
Physics @ HZF



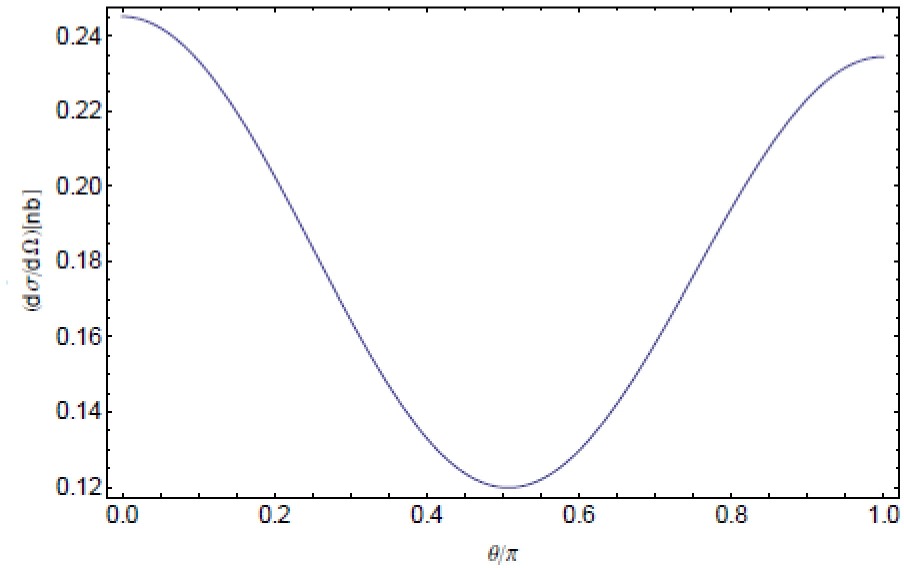
Physics @ HZF



The cross-section around the threshold



The cross-section around Z-peak



The differential cross-section

σ(cross-section) @ Z-peak

~0.62 σ @ the highest one (above the threshold)

~2.1 σ @ B-factory !

The cross-section @ Z-peak is greater than that @ B-factory !

Physics @ HZF

The Lorentz boost effects for exp. -physics is important:

-lepton lifetime : $\tau = 0.2906 \cdot 10^{-12}$ s

$c\tau \simeq 87.11\ \mu m$ (comparatively small);

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

For comparison:

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

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

Physics @ HZF

-lepton couples to Z-boson directly:

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.

Physics @ HZF

Physics BSM:

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' is b-quark or c-quark or a light quarks

R_b & R_c

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

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

Physics @ HZF

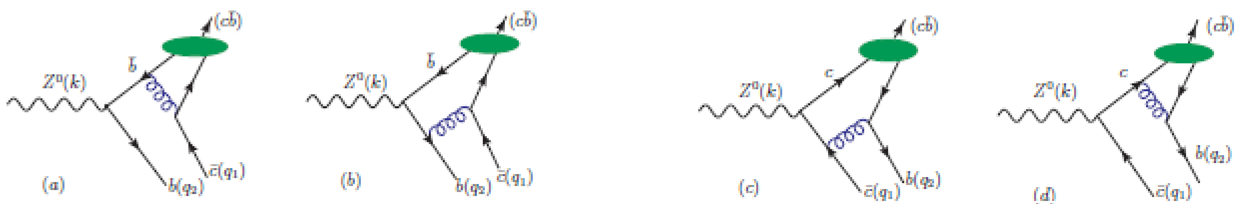
3. Flavor physics & QCD physics etc

- **HZF complementary to super B-factory & τ-charm factory: c, b-hadron physics (especially open bottom, baryons, excited states, X_b, Y_b, Z_b, etc)**

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

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

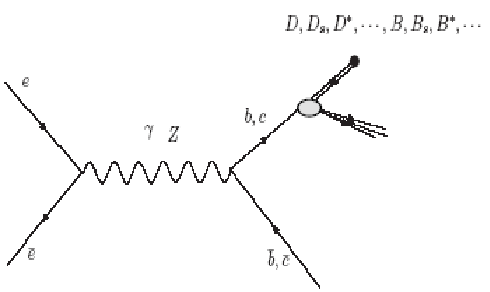
& their excited states (easier to treat bg. than @LHCb)

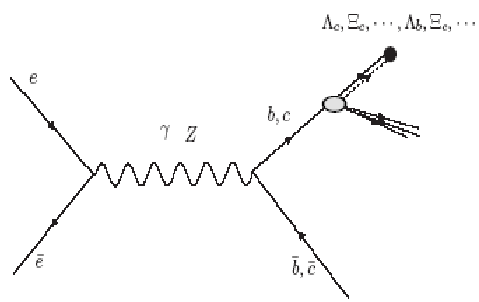


Roughly theo. estimate $Br(Z \to H_{QQ'} + \ldots\ldots) \sim 10^{-5}$ (more 10^6 samples) thus to study them at HZF is OK, but at LEP-I is not !

Physics @ HZF

- **D-meson:** $D^0 - \bar{D}^0$ **mixing:**
  Due the Lorentz boost and the lifetime of D meson, at HZF the CP violation in the mixing can be observed, whereas it is impossible at B-factory & □- Charm factory.
- **Fragmentation functions (FFs):**





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

Significance: Experimentally to use them for improving flavor tag in hadron collisions exp. etc. ; theoretically to test QCD & models etc.

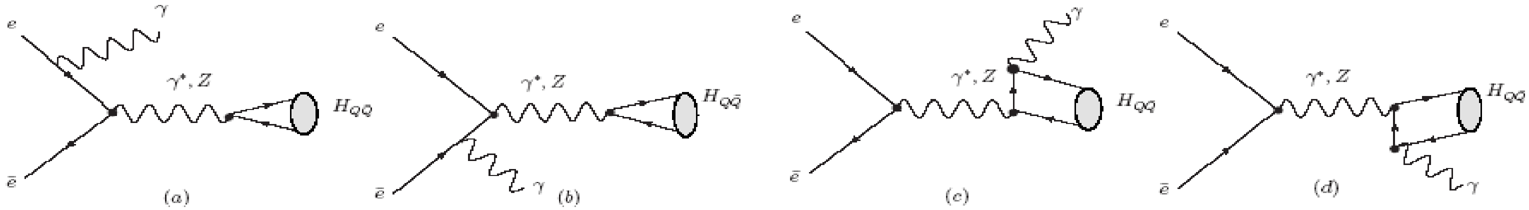
Physics @ HZF

- **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}

Physics @ HZF

- **Spectroscopy for heavy hadrons (cont'd)**

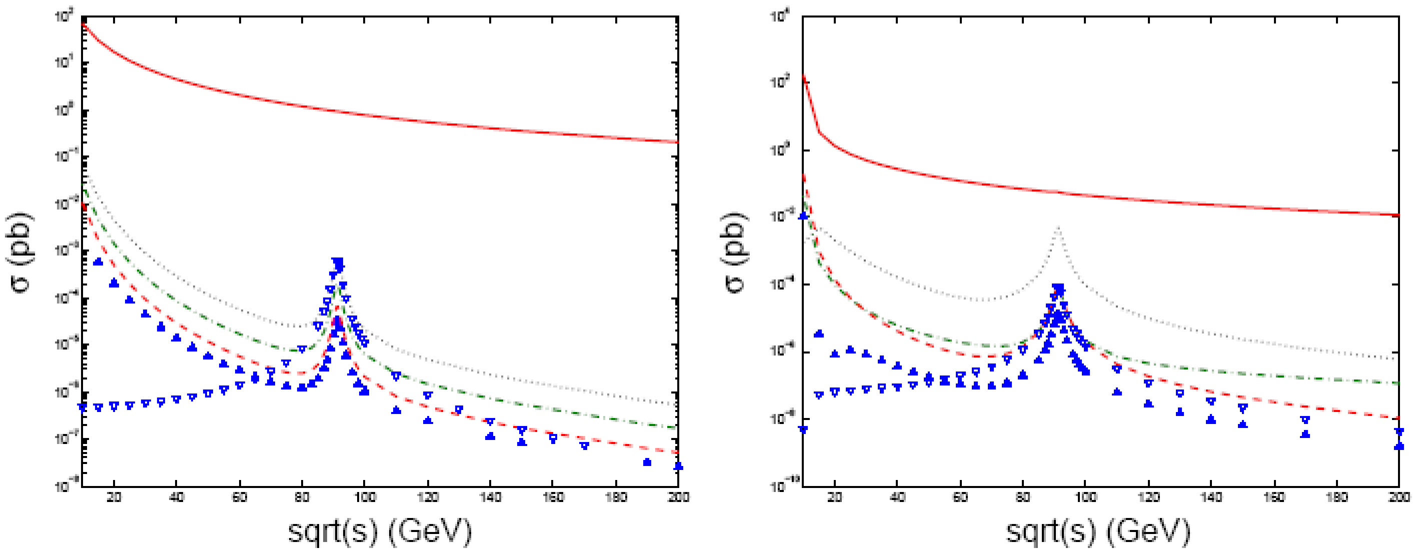


FIG. 2: (color online) Total cross sections for the processes $e^- + e^+ \to \gamma + H_{Q\bar{Q}}$ versus the collision energy. The red solid, the black dotted, the blue up-solid-triangle, the green dash-dotted, the red dashed and the down-hollow-triangle lines stand for $Q\bar{Q}$ in ${}^3S_1$, ${}^1S_0$,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

Physics @ HZF

- **Spectroscopy for heavy hadrons (cont'd)**

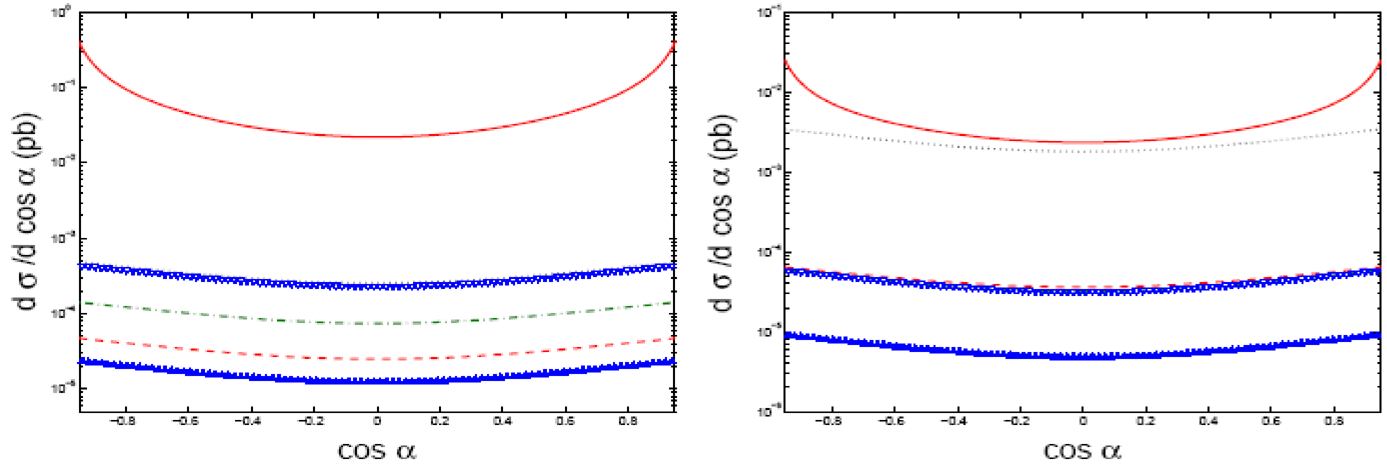


FIG. 3: (color online) Differential cross sections for the processes $e^- + e^+ \to \gamma + H_{Q\bar{Q}}$ versus $\cos\alpha$ at a C.M.S. energy as Z-mass. The red solid, the black dotted, the blue up-solid-triangle, the green dash-dotted, the red dashed and the blue down-hollow-triangle lines stand 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).

Physics @ HZF

- **τ-lepton physics (τ-lepton decays):**
  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 @ HZF.

  Especially, the rare decays

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

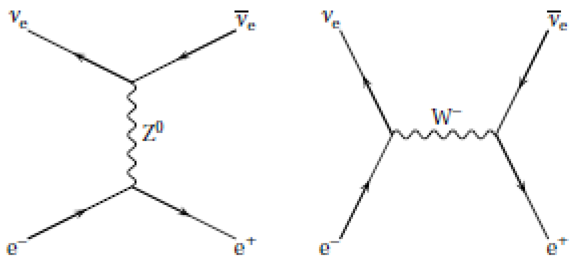
  and/or CPV in decay may reach to 10^{-10} level (even higher) !

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

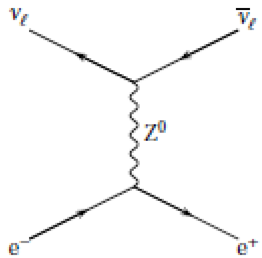
  We think that we should estimate the number more carefully and to see how big a room left for the light neutrinos mixing with the sterile one and else.

Physics @ HZF

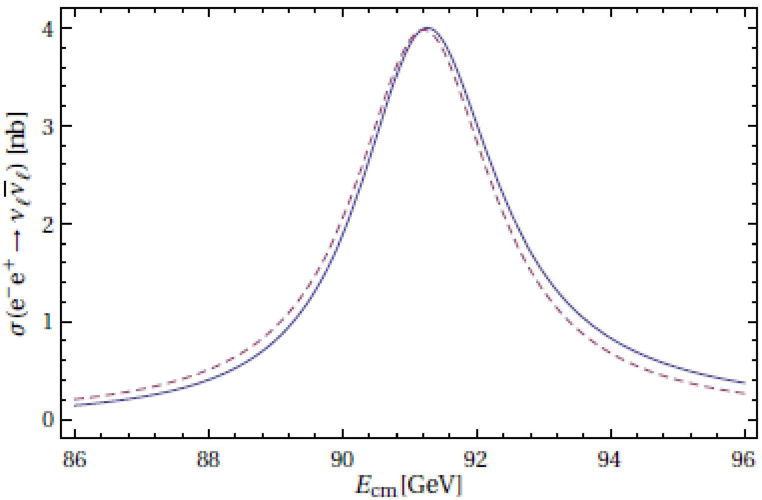
- **Neutrino physics (cont'd) :**



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; dished curve is of □- or □-neutrino.

Q: **May be used as a source of the mono-energy neutrinos ?**

A: **Yes, depends. Only when the luminosity of HZF reaches to higher than $10^{36}cm^{-2}s^{-1}$, the neutrinos can be detectable with a reasonable detector.**

Physics @ HZF

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

It is the best place to determine the parameters and to test the models.

Our working plan

According to the latest group meeting:

- To continue finding and understanding **characteristic and/or interesting physics** at HZF.
- To choose some typical processes to study more guantitatively.
- To write a report and it contents:
  1. Accelerator:
  2. Detector(s):
  3. Physics:
     - Precision test SM
     - New clue BSM & rare processes
     - τ-lepton physics
     - Flavor physics
     - QCD fragmentation functions
     - Spectroscopy for heavy flavor hadrons
     - Hadronization (non-perturbative QCD)
- A draft of the report is wished to complete within a half year.

Thanks !