Z-Factory & Heavy Hadron Physics

Based on a report by Chinese Z-factory working group

Chao-Hsi Chang (Zhao-Xi Zhang)

Institute of Theoretical Physics
Chinese Academy of Sciences, Beijing
(ITP, CAS)

The physics

- **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 decays may reach to up-to 10^{-10} level (even higher) !

- **Neutrino physics:**

The invisible width of Z-boson ⇨ 3 (2.984 $\pm$ 0.008)

Types of light neutrinos and how big a room left for the light neutrinos mixing with the sterile ones and else.

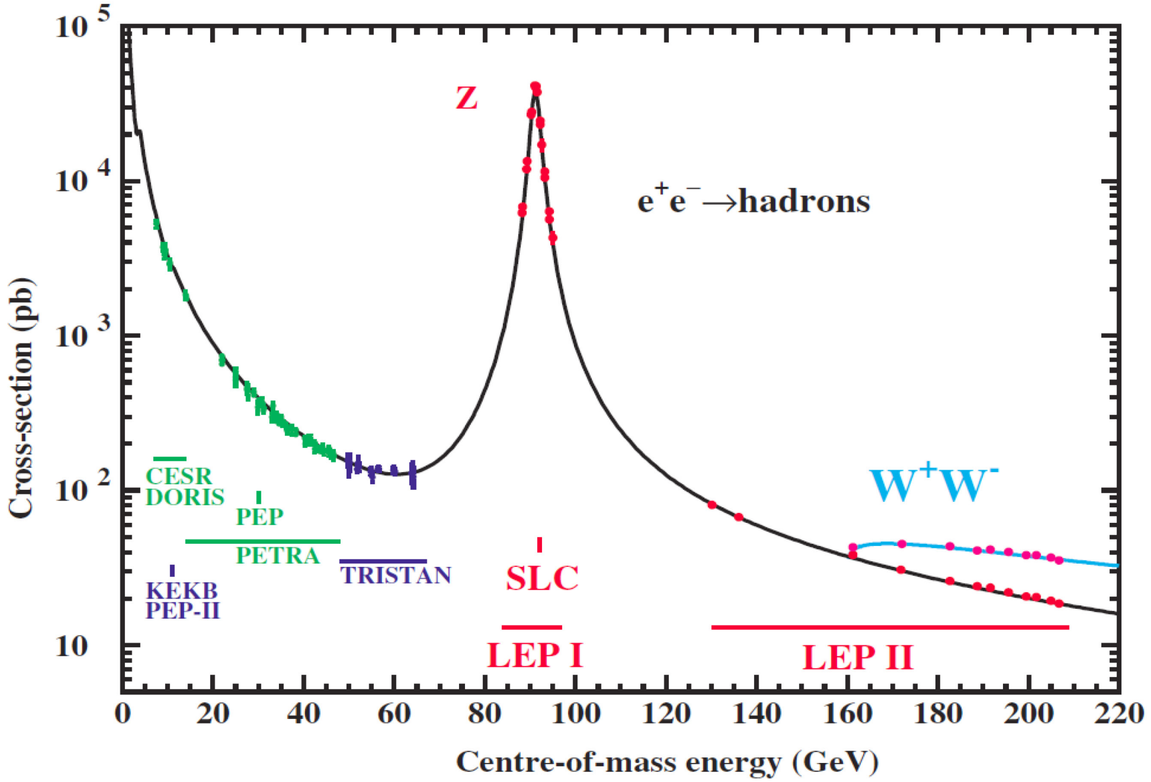
The physics

- **Flavor physics & QCD physics etc**

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

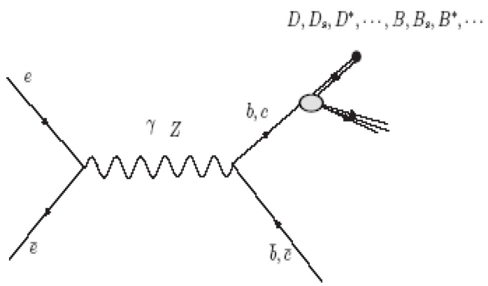
  c, b-hadron physics (especially open bottom)

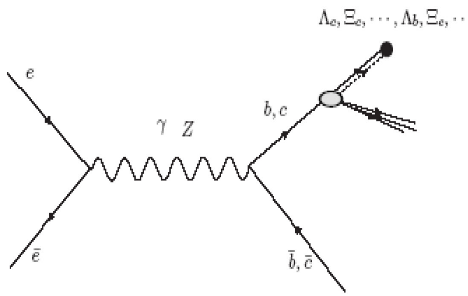
The production of hadrons @ e^+e^- -collider



The physics

- **QCD physics:**
  - **Directly measure $\alpha_s(m^2_Z)$ etc**
  - **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 understand QCD & models etc.**

The FF for b or c-quark to ground, excited B or D meson and to bottom or charm baryon etc.

Also polarized fragmentation functions:

◆ The Polarized fragmentation functions:

For example: b to Λ_b^0

$$e^+ + e^- \to b + \bar{b}$$

$$b \to \Lambda_b^0 + \cdots$$ **Frag. Func.**

$$\Lambda_b^0 \to \Lambda_c^+ + \pi^-$$ **To measure polarization**

◆Non-perturbative fragmentation models:

LUND , Webber Cluster, Quark Combination (ShangDong) Model. It is the best place to test the models.

The physics

- **Flavor & hadron physics**

  Light flavors & hadrons (contain light quarks only)

  $m_{u,}\ m_{d,}\ m_s < \Lambda_{QCD,}$

  Heavy flavors & hadrons (contain heavy quarks)

  $m_b > m_c > \Lambda_{QCD,}$ **(without t-quark)**

We need to understand both kinds of the hadrons and advantages to understand the heavy hadrons:

- **pQCD applicable due the 'heaviness' ;**
- **Effective theories: Heavy flavor effective theory, NRQCD etc;**
- **Mass hierarchy of b, c quarks (small, mixing);**
- **Lifetime for heavy component 'matches' the detectors;**
- **etc**

The physics

- c, b-flavor physics (especially 'Lorentz boost')

  D-meson: $D^0 - \overline{D}^0$ 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.

The physics

◆c, b-hadron physics

$$Br(Z \to b\bar{b}) = (15.12 \pm 0.05)\% , \quad Br(Z \to c\bar{c}) = (12.03 \pm 0.21)\% ,$$

Heavy flavored hadrons: mesons and baryons

CKM elements, mixing, CPV, rare processes

$$Br(Z \to B + X) = (6.08 \pm 0.13)\% , \quad Br(Z \to B_s + X) = (1.59 \pm 0.13)\%$$

$$Br(Z \to \Lambda_c + X) = (1.54 \pm 0.33)\% , \quad Br(Z \to \Xi_c + X) = seen ,$$

$$Br(Z \to \Xi_b + X) = seen ,$$

$$\Lambda_b \ \ (???) , \quad Br(Z \to b - baryon + X) = (1.38 \pm 0.22)\%$$

Many baryon states need to be confirmed!

The physics

- **Double heavy hadrons :**

$$Br(Z \to b\bar{b}b\bar{b}) = (3.6 \pm 1.3) \times 10^{-4}$$

$$Br(Z \to b\bar{b}c\bar{c}) \sim 10^{-3}, \quad Br(Z \to c\bar{c}c\bar{c}) \sim 10^{-3}$$

$H_{QQ'}$:

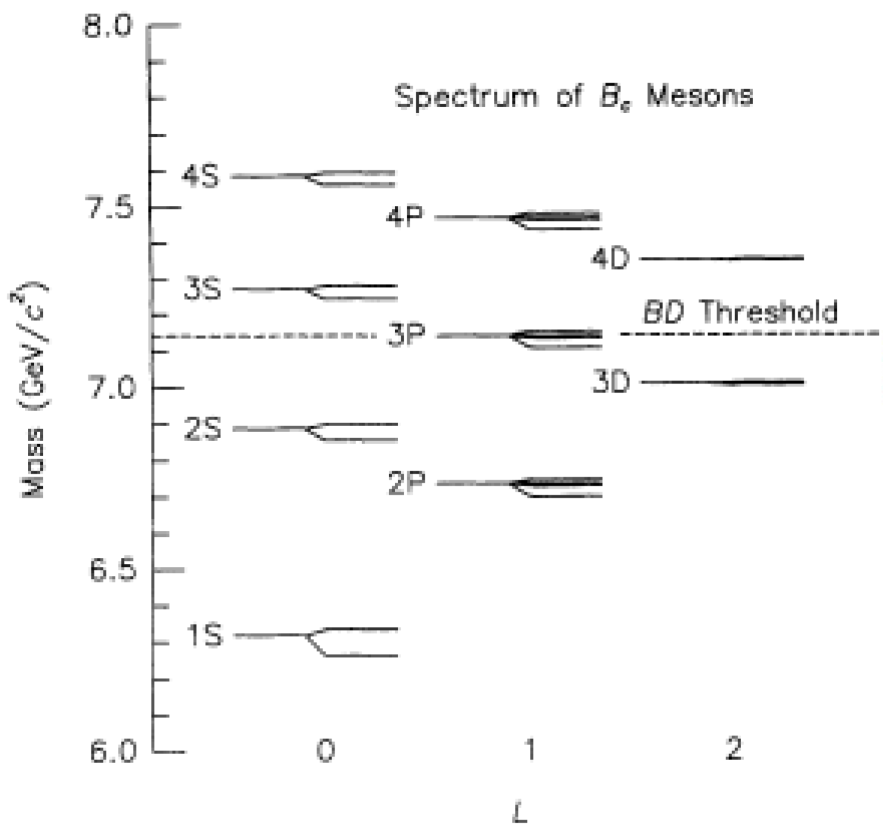
B_c meson, ……, Ξ_{cc}, Ω_{cc}, Ξ_{bc}, Ω_{bc}, Ξ_{bb}, and their excited states:

- **Their production can be estimated by pQCD reliable;**
- **The ground states decay 'weakly' that they have a comparatively long lifetime (1.0~0.1ps) and one can trace the vertices in vertex detector from production to decay (with the Lorentz boost).**

The physics

Take example B_c meson & its excited states to illustrate :

The spectroscopy:



$(c\bar{b})$: $B_c\,, B'_c\,, \cdots\,; B^*_c\,, B^{*\prime}_c\,, \cdots\,;\ \chi^J_{B_c}\,, \cdots\,;\ h_{B_c}\,, \cdots$

Bc: $(c\bar{b})$ ground state $({}^1S_0,\quad J^P=0^-)$

Bc: $(c\bar{b})$ ground state $({}^1S_0,\quad J^P=0^-)$

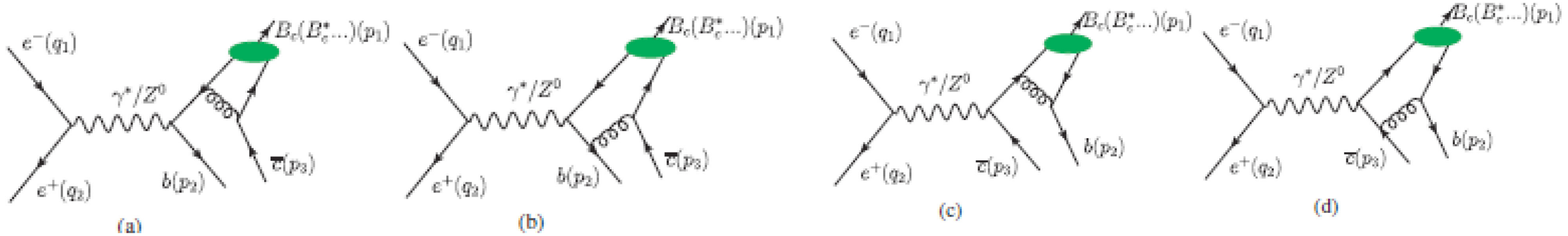
B*c: $(c\bar{b})$ 1^{st} excited state $({}^3S_1,\quad J^P=1^-)$

$\chi^J_{B_c}$: $(c\bar{b})$ P-wave excited states $({}^3P_J\,,\ J^P=0^+\,,1^+\,,2^+)$

h_{B_c}: $(c\bar{b})$ P-wave excited state $({}^1P_1,\quad J^P=1^+)$

The physics

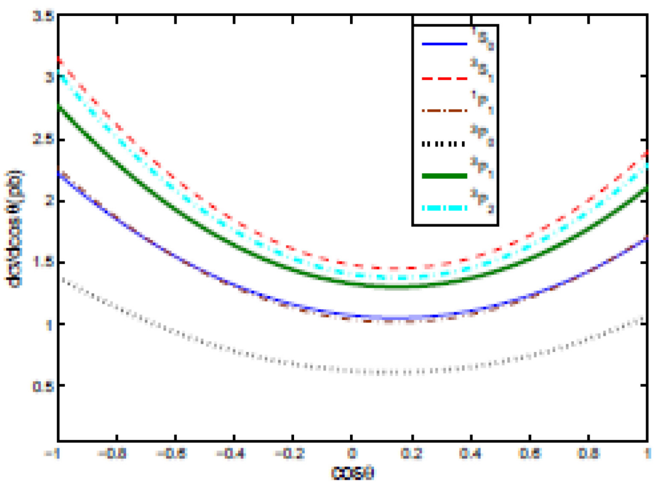
Production (estimated reliably by NRQCD):



contribution	total	$\bar{b}$-frag.	c-frag.	interference
$\sigma(B_c,\ ^1S_0)$	2.734	2.613	5.20×10^{-2}	6.90×10^{-2}
$\sigma(B_c^*,\ ^3S_1)$	3.823	3.722	4.45×10^{-2}	5.65×10^{-2}
$\sigma(B_c^{**},\ ^1P_1)$	0.271	0.269	3.01×10^{-3}	-1.01×10^{-3}
$\sigma(B_c^{**},\ ^3P_0)$	0.164	0.157	8.13×10^{-3}	-1.13×10^{-3}
$\sigma(B_c^{**},\ ^3P_1)$	0.340	0.331	5.77×10^{-3}	3.23×10^{-3}
$\sigma(B_c^{**},\ ^3P_2)$	0.365	0.366	3.87×10^{-4}	-1.39×10^{-3}

The cross sections in *pb*.

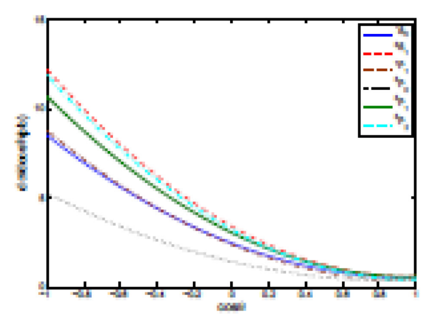
The physics

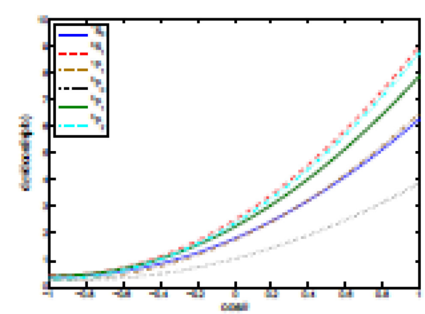


Differential cross sections for various states.

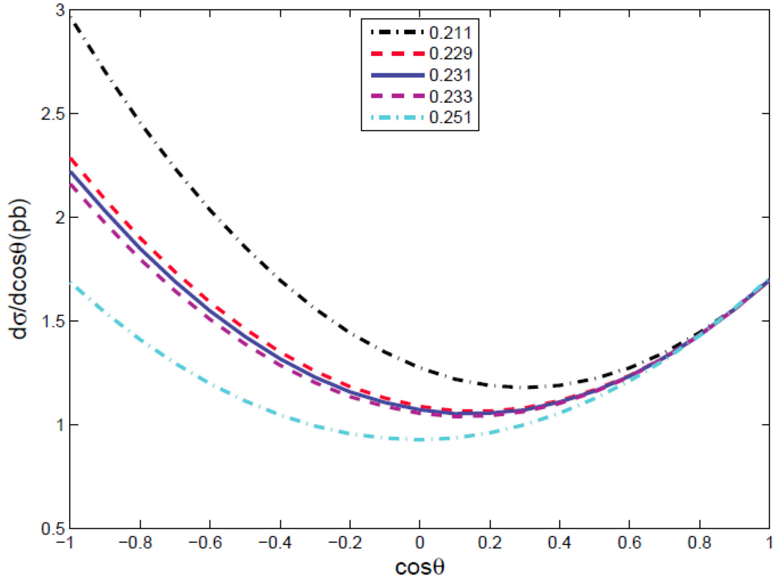
Z couples to fermions in vector and psudo-vector that makes the asymmetry in forward and backward, thus the asymmetry in production may be used to measure $\mathrm{Sin}\Theta_W$!

The polarized e+e- beams make the asymmetry stronger.





The physics



The dependence on the Wenberg angle $\mathbf{Sin}\Theta_W$.

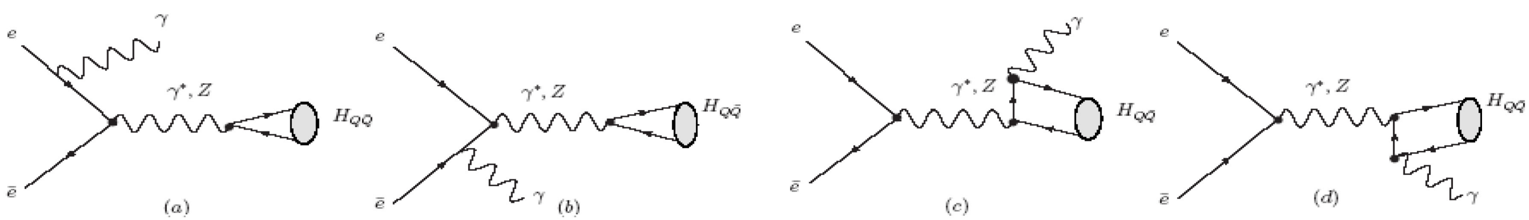
The physics

- **Another example:o measure the spectrum for heavy quarkonia & exatics:**

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

Two body final state! (monoenergy photon)

Here $H_{Q\bar{Q}}$: η_c, J/ψ, $\cdots$ η_b, Υ, $\cdots$ $X_{c\bar{c}}$, $\cdots$ $X_{b\bar{b}}$, $\cdots$

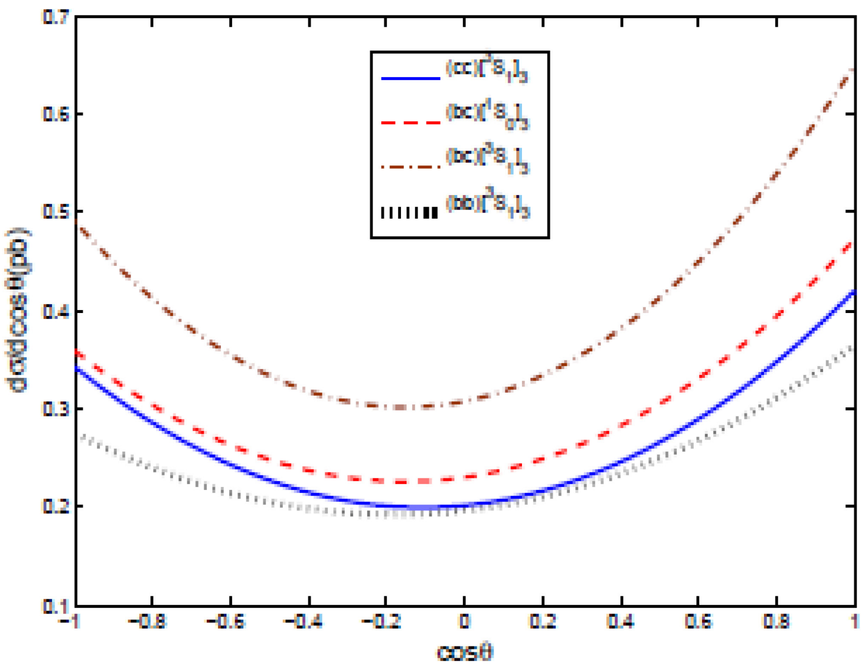


	$^3S_1$	$^1S_0$	$^3P_0$	$^3P_1$	$^3P_2$	$^1P_1$
$\sigma_{(c\bar{c})}(pb)$	0.934	0.662×10^{-3}	0.328×10^{-4}	0.197×10^{-3}	0.661×10^{-4}	0.615×10^{-3}
$\sigma_{(b\bar{b})}(pb)$	0.565×10^{-1}	0.475×10^{-2}	0.128×10^{-4}	0.838×10^{-4}	0.930×10^{-4}	0.833×10^{-4}

The physics

One more example:

The production of baryons $\Xi_{cc,}$ $\Xi_{bc,}$ Ξ_{bb} (in *pb*):



（其中 Ξ_{bb}的截面乘了因子10！）

The physics

Heay flavored exotic hadrons:

Tetraquarks (Z⁺(3900),....):

$$(Q\bar{Q}'q\bar{q}'),(Q\bar{Q}'Q\bar{q}'),(Q\bar{Q}'q\bar{Q}'),(Q\bar{Q}'Q\bar{Q}')\ :\ Q,Q'=c,b;\ \ q,q'=u,d,s$$

Pentaquarks (Pc⁺(4450), Pc⁺(4380),....):

$$(Q\bar{Q}'qq'q''),(Q\bar{Q}'Qqq'),etc\ :\ Q,Q'=c,b;\ \ q,q',q''=u,d,s$$

Hybrads:

$$(Q\bar{Q}'g),etc\ :\ Q,Q'=c,b;\ \ g=gluon$$

Advantages in studying the heavy exotic hadrons:

The ‘mixing’ and ‘interferences’ are simple;

The heavy components decay in the detector;

etc

Summary

- **There are may interesting and important physics:**
  - ◆ **Highly precise tests of SM, looking for direct and indirect evidence for new physics**
  - ◆ **FFs for heavy and double heavy hadrons**
  - ◆ **Heavy flavor physics**
  - ◆ **Heavy and double heavy hadron physics**
- **The luminosity of SZF $\mathcal{L} \geq 10^{35}cm^{-2}s^{-1}$ is crucial for hadron physics**
  - ◆ **For the QCD problems and hadron physics, the luminosity $\mathcal{L} \geq 10^{35}cm^{-2}s^{-1}$ is crucial, as the production in the order of pb (even smaller).**
  - ◆ **There is no 'critical luminosity' for such physics as 'highly precise test of SM, ...'**