Progress in Z-Factory Suggestion (Hadronic Physics and Heavy Flavors)

Chao-Hsi Chang (Zhao-Xi Zhang)

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

The 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.

The 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
$\Delta\alpha^{(5)}_{\rm had}(m_Z^2)$ [82]	0.02758 ± 0.00035	0.00034	0.02768	−0.3
a) <u>LEP-I</u>				
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
$\sigma^0_{\rm had}$ [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
$A^{0,\ell}_{\rm FB}$	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
$q\bar{q}$ charge asymmetry:				
$\sin^2\theta^{\rm lept}_{\rm eff}(Q^{\rm had}_{\rm FB})$	0.2324 ± 0.0012	0.0010	0.23139	0.8
b) <u>SLD</u>				
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.0010	0.1481	1.6
c) <u>LEP-I/SLD Heavy Flavour</u>				
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
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	0.0007	0.1038	−2.9
$A^{0,c}_{\rm FB}$	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) <u>LEP-II and Tevatron</u>				
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.

Theoretical loop calculations have been made progresses steadily recently

Polarization beam is helpful !

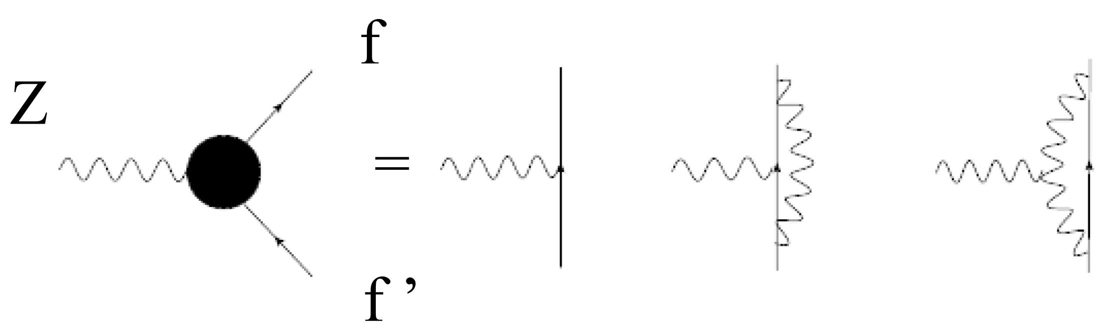
The Physics

arXiv:1310.6708

Quantity	Current theory error	Leading missing terms	Est. future theory error
$\sin^2\theta^{\ell}_{\rm eff}$	4.5×10^{-5}	$\mathcal{O}(\alpha^2\alpha_s)$, $\mathcal{O}(N_f^{\geq2}\alpha^3)$	$1...1.5\times10^{-5}$
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.*

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

The 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

The 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: $Z\tau\bar{\tau}\,,\ Z\mu\bar{\tau}\,,\ Z\tau\bar{\mu}\,,\ Ze\bar{\tau}\,,\ Z\tau\bar{e}$

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

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

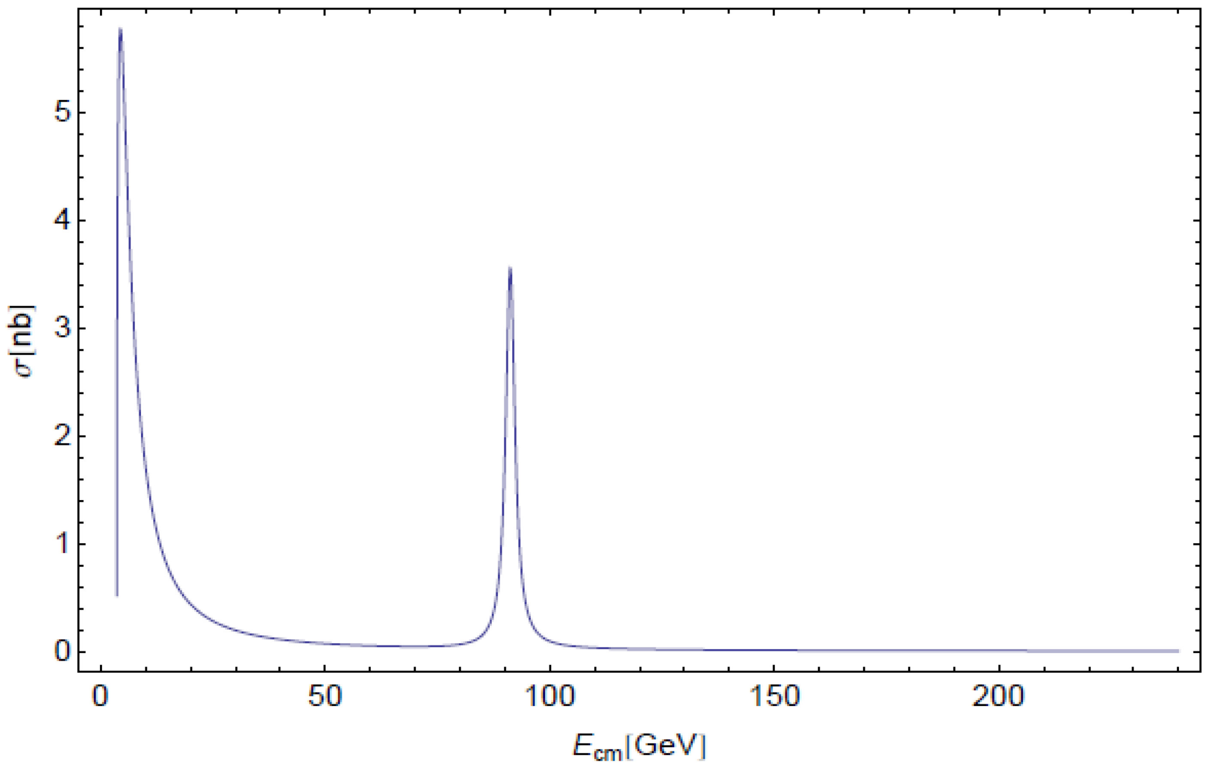
$$A_{\rm LR} \equiv \frac{\sigma(\mathcal{P}_e > 0) - \sigma(\mathcal{P}_e < 0)}{\sigma(\mathcal{P}_e > 0) + \sigma(\mathcal{P}_e < 0)} = \mathcal{A}_e.$$

Difficulties are in identifying the flavor

The physics

τ-lepton is special (the heaviest lepton)

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



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

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

3×10^{10} **τ pairs/year**

τ 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**

The Physics

- **τ-lepton physics:**

  about 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 ± 0.008)

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

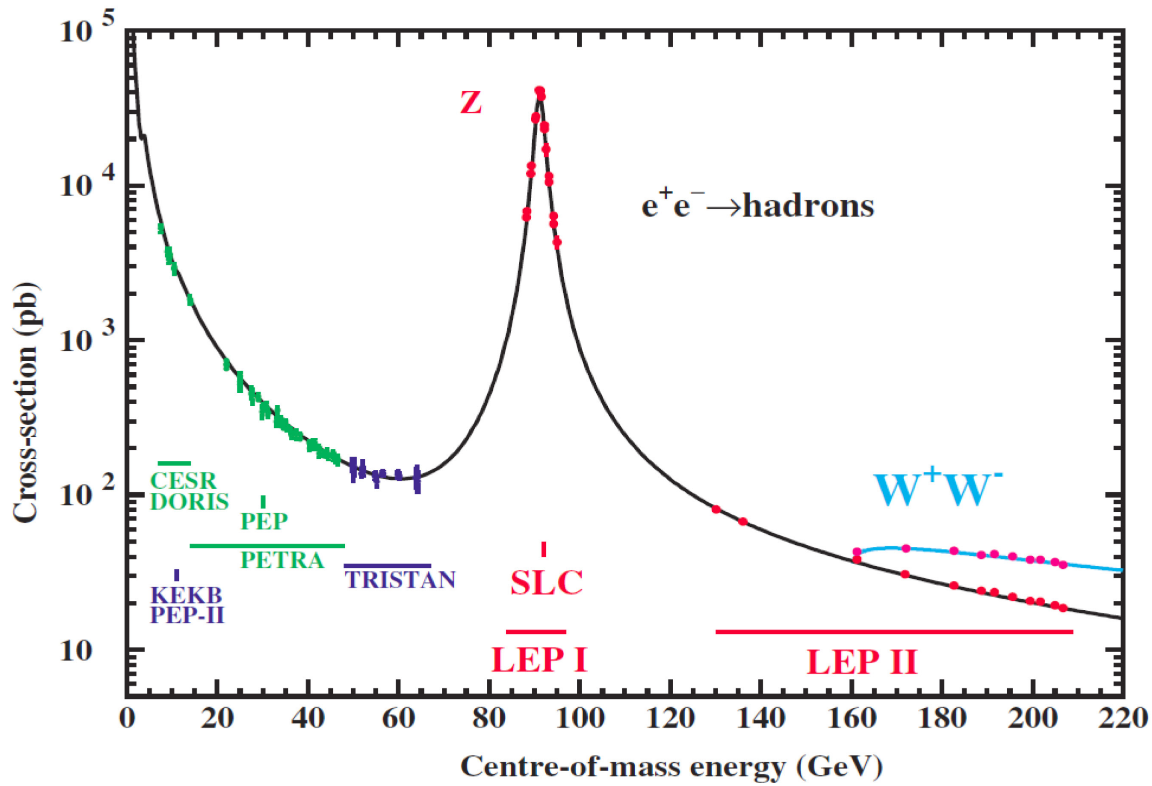
The Hadronic Physics

- **Flavor physics & QCD physics etc**

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

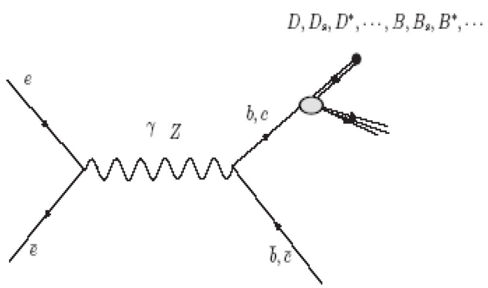
  c, b-hadron physics (especially open bottom)

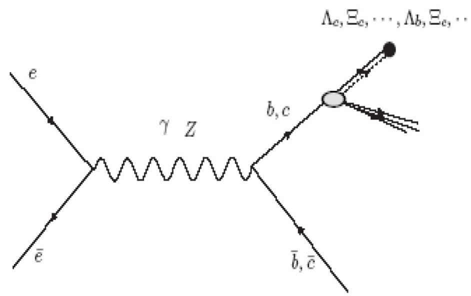
The production of hadrons @ e^+e^- -collider



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.

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: $D^0-\bar{D}^0$ **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.

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 :**

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

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

$H_{QQ'}$: Explicitly Doubly Heavy Flavored Hadrons

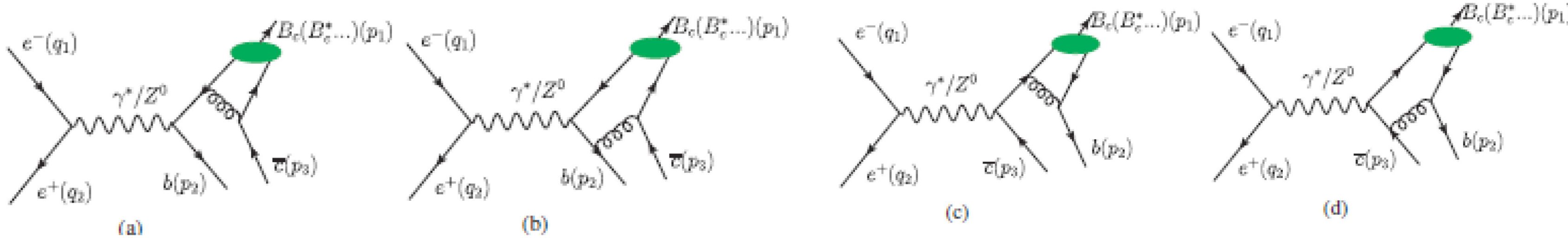
Meson B_c, Excited states

Baryons Ξ_{cc}, Ω_{cc}, Ξ_{bc}, Ω_{bc}, Ξ_{bb}, Ω_{bb} , 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);**
- **Very important for heavy flavor physics**

The Physics

Production (estimated reliably by NRQCD):

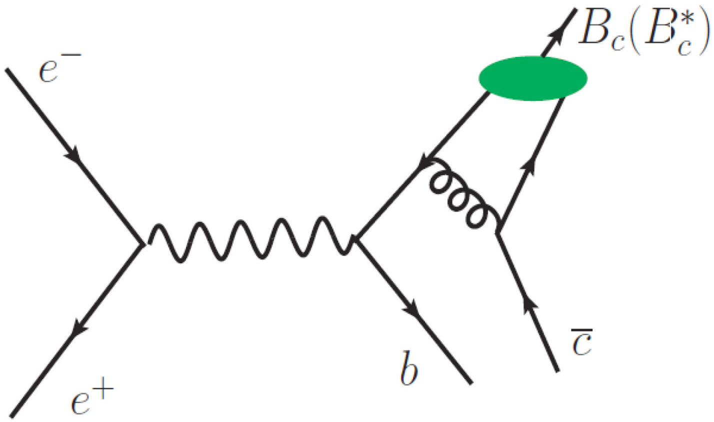


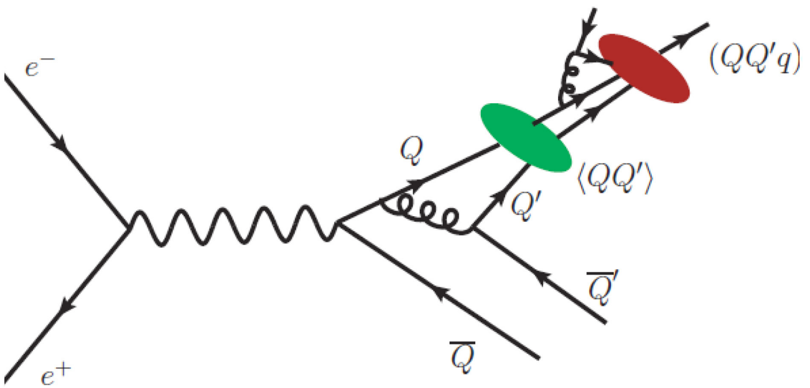
contribution	total	$\bar{b}$-frag.	c-frag.	interference
$\sigma(B_c,\ ^1S_0)$	2.734	2.613	5.20×10^{-2}	6.90×10^{-2}
$\sigma(B_c^*,\ ^3S_1)$	3.823	3.722	4.45×10^{-2}	5.65×10^{-2}
$\sigma(B_c^{**},\ ^1P_1)$	0.271	0.269	3.01×10^{-3}	-1.01×10^{-3}
$\sigma(B_c^{**},\ ^3P_0)$	0.164	0.157	8.13×10^{-3}	-1.13×10^{-3}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

Production of Doubly Heavy Flavor Baryons Similar to that of Bc





$$\begin{aligned} & d\sigma\left(e^+e^- \to (\gamma/Z) \to \langle QQ'\rangle + \bar{Q} + \bar{Q}'\right) \\ = & \textstyle\sum_n d\hat{\sigma}\left(e^+e^- \to (\gamma/Z) \to (QQ')[n] + \bar{Q} + \bar{Q}'\right) \\ & \cdot \langle \mathcal{O}^{\langle QQ'\rangle}(n)\rangle, \end{aligned}$$

$$D^H_{\langle QQ'\rangle}(z) = \frac{N^H_{\langle QQ'\rangle}}{z[1 - 1/z - \epsilon_H/(1-z)]^2}$$

$$\frac{d\sigma(H(z))}{dz} = \int_z^1 \frac{dy}{y} \frac{d\sigma(e^+e^- \to \langle QQ'\rangle(y) + \bar{Q} + \bar{Q}')}{dy} \cdot D^H_{\langle QQ'\rangle}(z/y) \,.$$

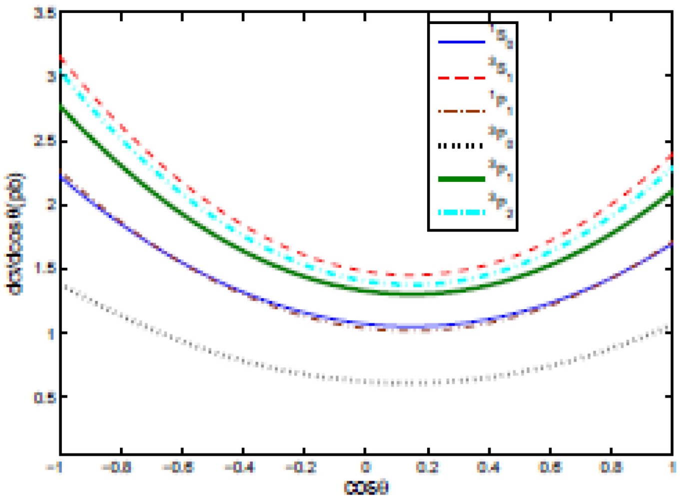
$$\epsilon_H \approx m_q^2 / m^2_{\langle QQ'\rangle}$$

The Physics

Hadrons	σ(pb)
B_c	2.69
B_c^*	3.76
$\Xi_{cc}[(cc)_{[^3S_1]\bar{\mathbf{3}}}]$	0.45
$\Omega_{cc}[(cc)_{[^3S_1]\bar{\mathbf{3}}}]$	0.068
$\Xi_{bc}[(bc)_{[^1S_0]\bar{\mathbf{3}}}]$	0.50
$\Omega_{bc}[(bc)_{[^1S_0]\bar{\mathbf{3}}}]$	0.074
$\Xi_{bc}[(bc)_{[^3S_1]\bar{\mathbf{3}}}]$	0.68
$\Omega_{bc}[(bc)_{[^3S_1]\bar{\mathbf{3}}}]$	0.101
$\Xi_{bb}[(bb)_{[^3S_1]\bar{\mathbf{3}}}]$	0.043
$\Omega_{bb}[(bb)_{[^3S_1]\bar{\mathbf{3}}}]$	0.0065

The cross-sections of doubly heavy flavor hadrons @Z-factory: High luminosity is crucial !

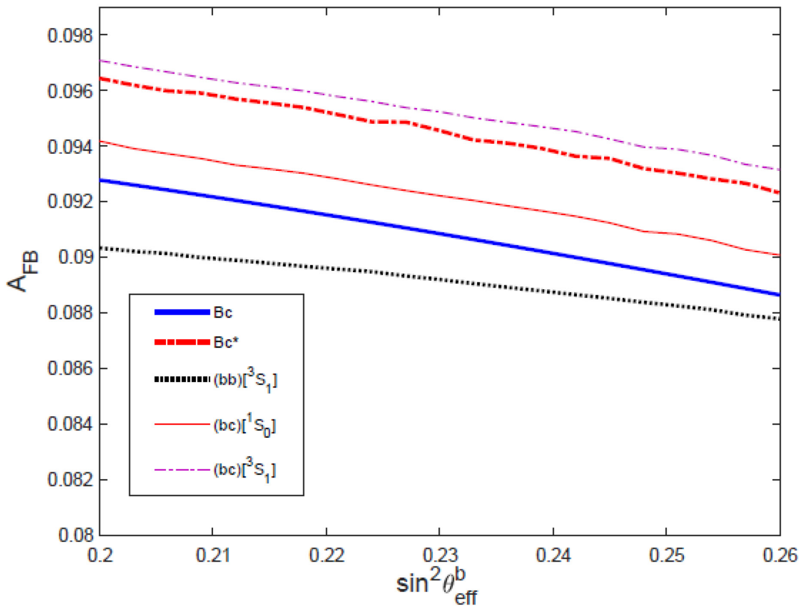
The Physics



Differential cross sections for various states (asymmetry).

Z couples to fermion currents in vector and axial vector that makes the asymmetry in forward and backward, thus the asymmetry in production may be used to measure $\sin\Theta_W$!

The Physics

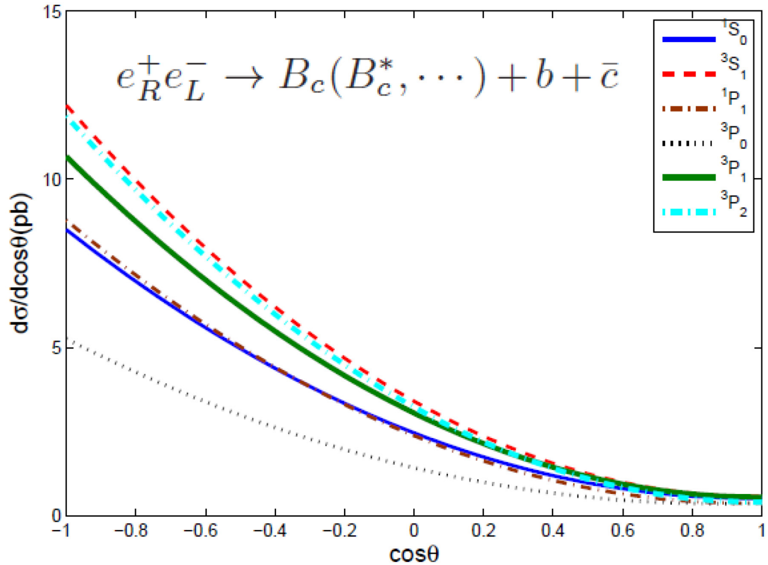


The distribution can be used to measure the Wenberg angle $Sin\Theta_W$

The A_{FB} on the Wenberg angle $Sin\Theta_W$.

The Physics

Polarized beam production of Bc:



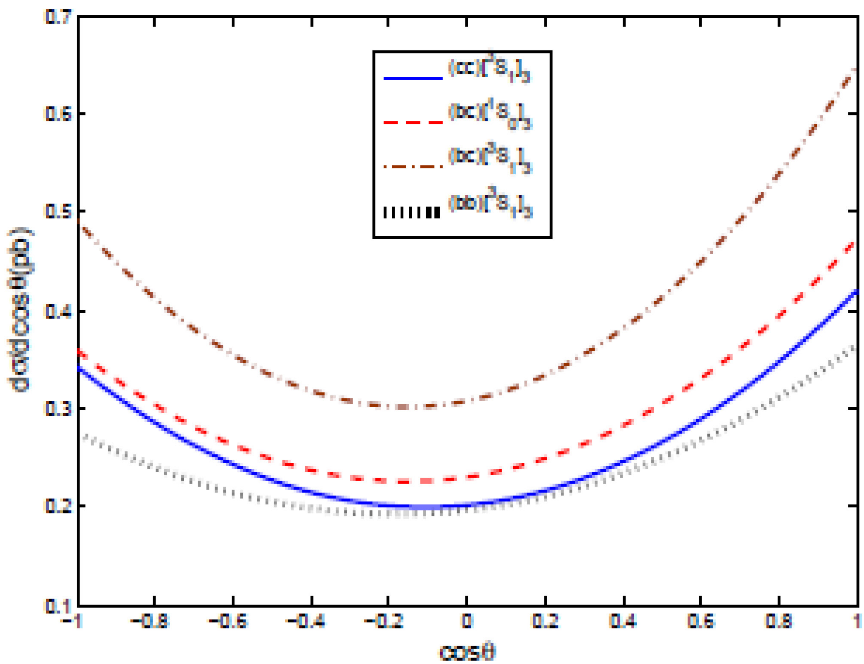
The distribution can be used to measure the Wenberg angle $\sin\Theta_W$

The dependence on the Wenberg angle $\sin\Theta_W$.

The Physics

One more example:

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

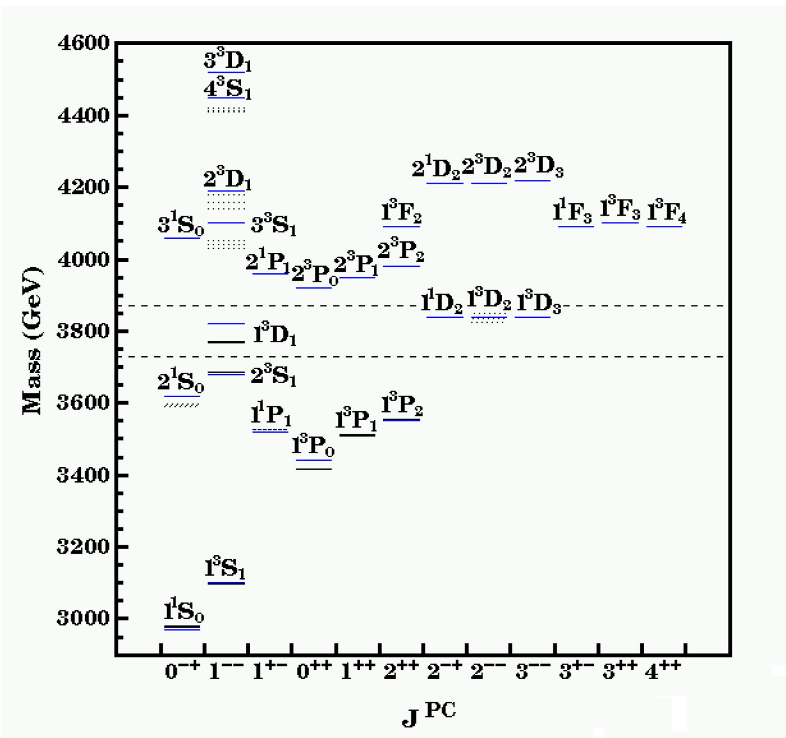


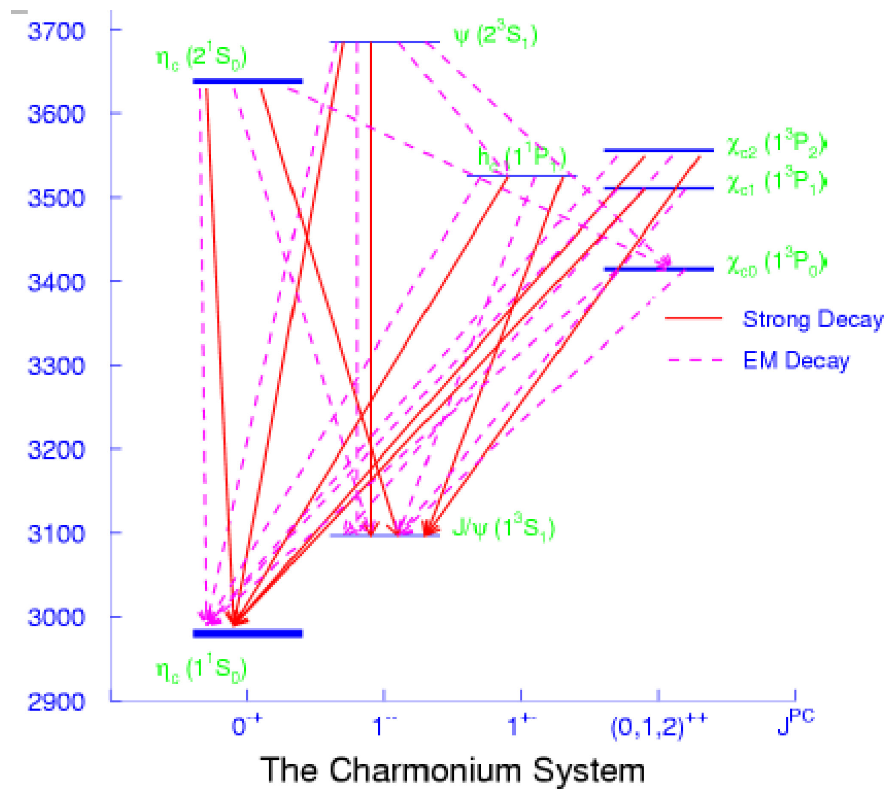
（其中Ξ_{bb}的截面乘了因子10！）

The distribution can be used to measure the Wenberg angle $\sin\Theta_W$

‘粲耦素’系统的质谱（位势模型）

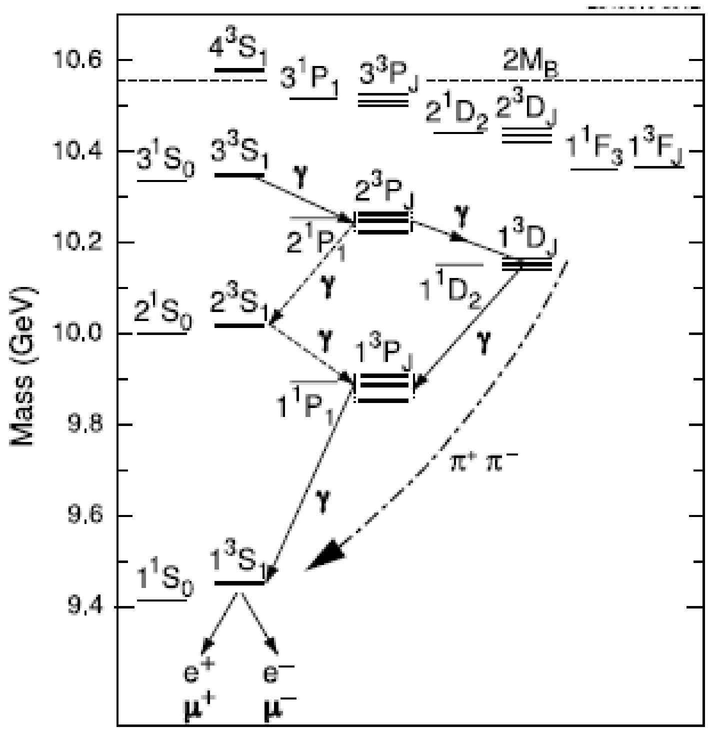
质谱的研究可对（二体）束缚的相互作用，束缚的情况等的理解



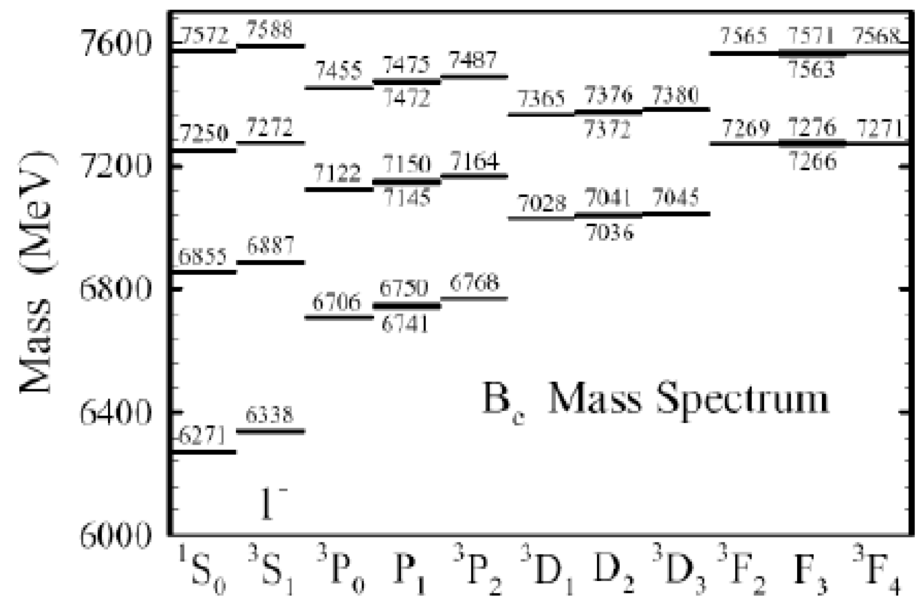


- BEPC+BES在研究粲耦素的质谱上做出重要贡献。
- B-工厂通过‘初态辐射’也对粲耦素质谱研究做出贡献并有新发现。

‘底耦素’和（$\bar{c}b$）系统的质谱（位势模型）



‘底耦素’系统质谱



（$c\bar{b}$）系统的质谱

衰变常数f_{Bc}= 480MeV

B-工厂在底耦素在底耦素研究做出贡献。

Tevatron上发现Bc，LHC也观测到Bc。

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

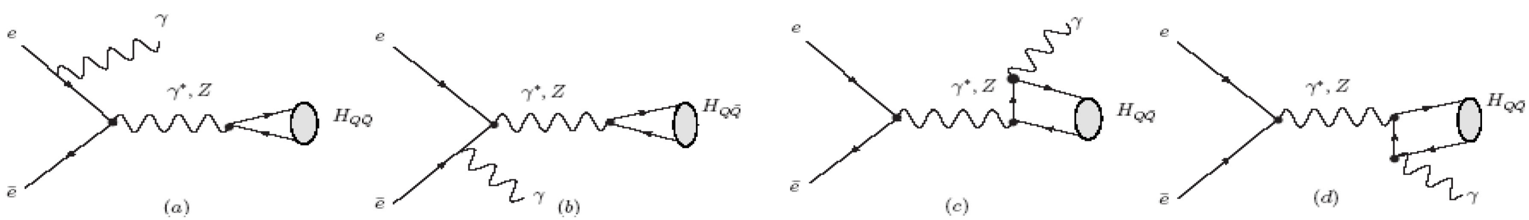
The physics

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



	$^3S_1$	$^1S_0$	$^3P_0$	$^3P_1$	$^3P_2$	$^1P_1$
$\sigma_{(c\bar{c})}(pb)$	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}

Summary

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