Z-Factory & Heavy Hadron Physics

Based on a report by Chinese Z-factory working group

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Outline

- Introduction
- Precision tests of SM
- Rare processes for new physics
- τ-lepton physics
- QCD

  Fragmentation & hadronization
- Hadron physics

  Heavy flavor physics

  Doubly heavy physics

  Exotics (Spectroscopy)
- Conclusion

Introduction

The Z-Factories (CEPC,ILC,Fcc_ee):

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

Resonance effects for all kinds of fermions (except t-quark) in SM!

The old ones

LEP-I（circular）： $\mathcal{L}_0 = 2.4 \cdot 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Scan 88GeV~94GeV

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

Detectors: Aleph, Delphi, L3, Opal.

SLC（linear）： $\mathcal{L}_0 = 0.6 \cdot 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

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

(Especially electron polarization beam: 70%)

Detector: SLD

Introduction

Based on modern techniques:

- Luminosity $\mathcal{L}$ of an e^+e^- collider can be $\mathcal{L}=10^{4\sim5}\mathcal{L}_0=10^{35\sim36}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ even higher
- Runs at the energy as m_Z for a long period
- It can be called as a Super Z-factory (SZF)

The characteristic & significant physics:

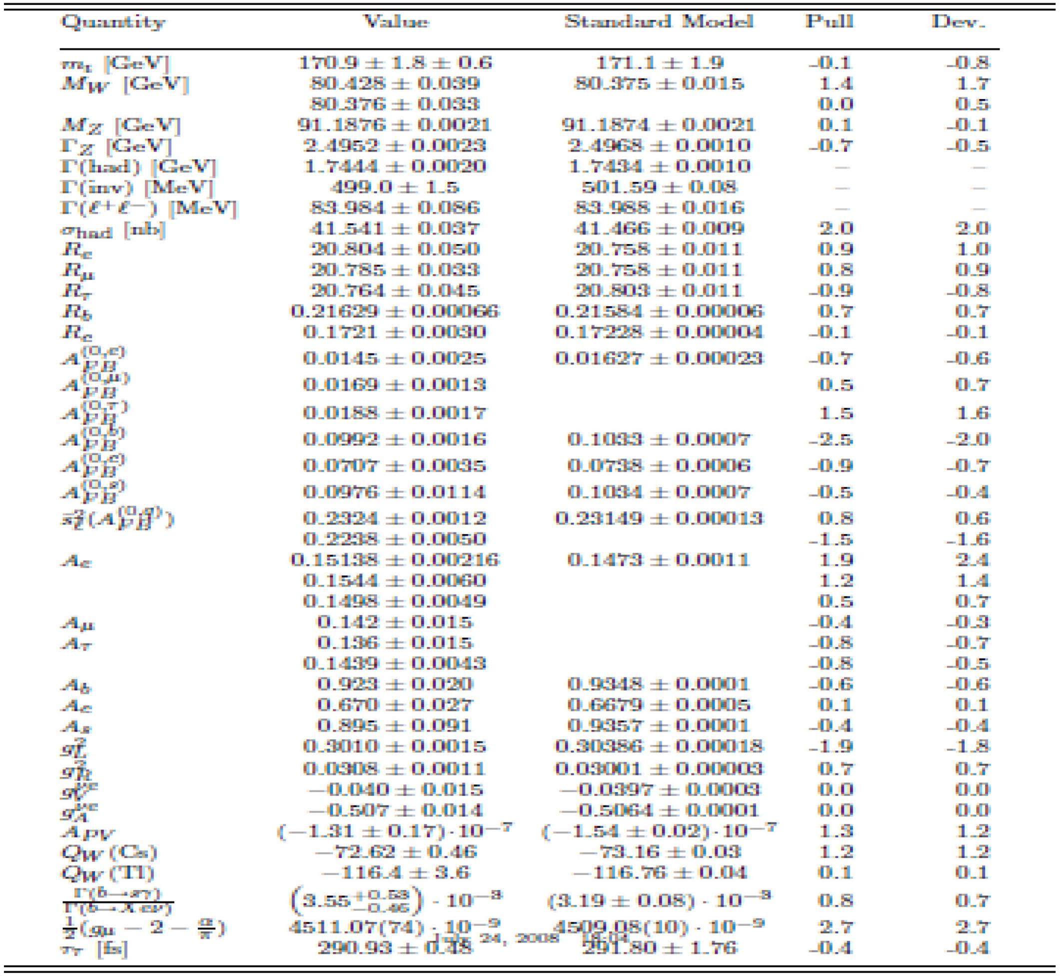
Precision tests of SM; Rare processes; τ-lepton physics; QCD (Fragmentation & hadronization); Hadron physics (Heavy flavor physics, Doubly heavy physics); Dark matter physics etc

No where can be competed in these 'physics' !

The precision tests of SM

- **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(Cs)	-72.62 ± 0.46	-73.16 ± 0.03	1.2	1.2
Q_W(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!

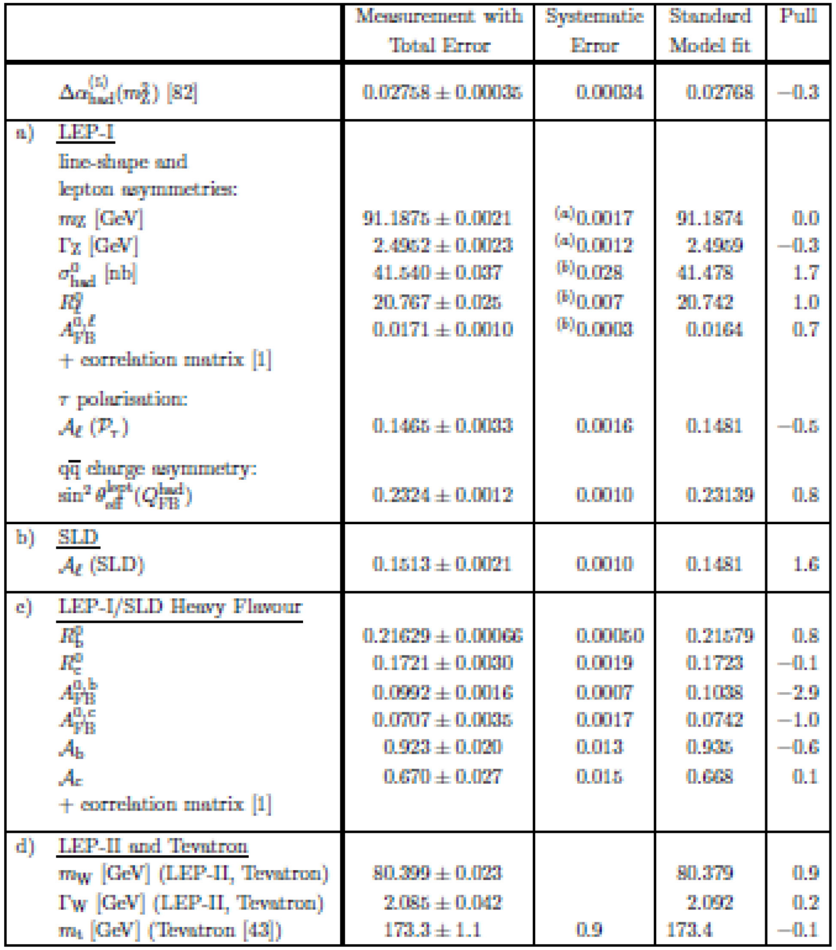
(Taken from PDG)

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

The precision tests of SM

- ## 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
$\Delta\alpha_{\mathrm{had}}^{(5)}(m_Z^2)$ [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_{had}^0 [nb]	41.540 ± 0.037	$^{(b)}0.028$	41.478	1.7
R_ℓ^0	20.767 ± 0.025	$^{(b)}0.007$	20.742	1.0
$A_{\mathrm{FB}}^{0,\ell}$	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:				
$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}(Q_{\mathrm{FB}}^{\mathrm{had}})$	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_b^0	0.21629 ± 0.00066	0.00050	0.21579	0.8
R_c^0	0.1721 ± 0.0030	0.0019	0.1723	−0.1
$A_{\mathrm{FB}}^{0,b}$	0.0992 ± 0.0016	0.0007	0.1038	−2.9
$A_{\mathrm{FB}}^{0,c}$	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.

Theoretical loop calculations have been made progresses steadily recently

Polarization beam is helpful !

Situation after Higgs was discovered (m_H=125GeV)

The Higgs mechanism: the boson masses:

$2m_W = g_2 v$, $2m_Z = (g_1^2+g_2^2)^{0.5} v$

v =247GeV

$$L = g_{hff} \bar{f} H f + \frac{g_{hhh}}{6} H^3 + \frac{g_{hhhh}}{24} H^4 + \eta_v V_\mu V^\mu \left(g_{hvv} H + \frac{g_{hhvv}}{2} H^2 \right)$$

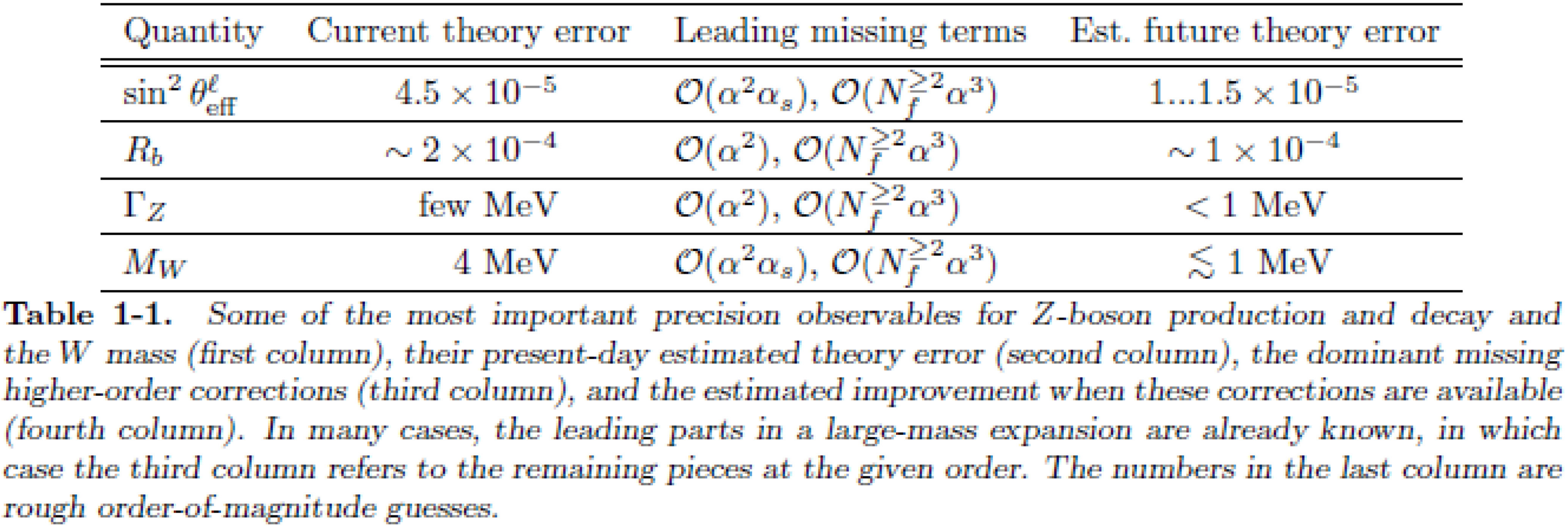
$$g_{hff} = \frac{m_f}{v}\,, \quad g_{hvv} = \frac{m_v^2}{v}\,, \quad g_{hhvv} = \frac{2m_V^2}{v^2}\,, \quad g_{hhh} = \frac{3m_H^2}{v}\,, \quad g_{hhhh} = \frac{3m_H^2}{v^2}$$

$$V = W^\pm \; or \; Z\,; \quad \eta_v = 1 \; for \; V = W\,, \quad \eta_v = 0.5 \; for \; V = Z.$$

To measure (constrain) the deviation from SM though loop process for the parameters !

The precision tests of SM

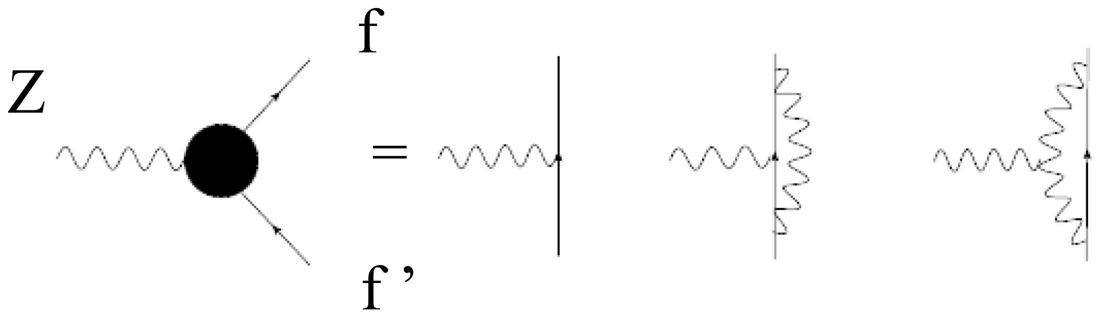
arXiv:1310.6708



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



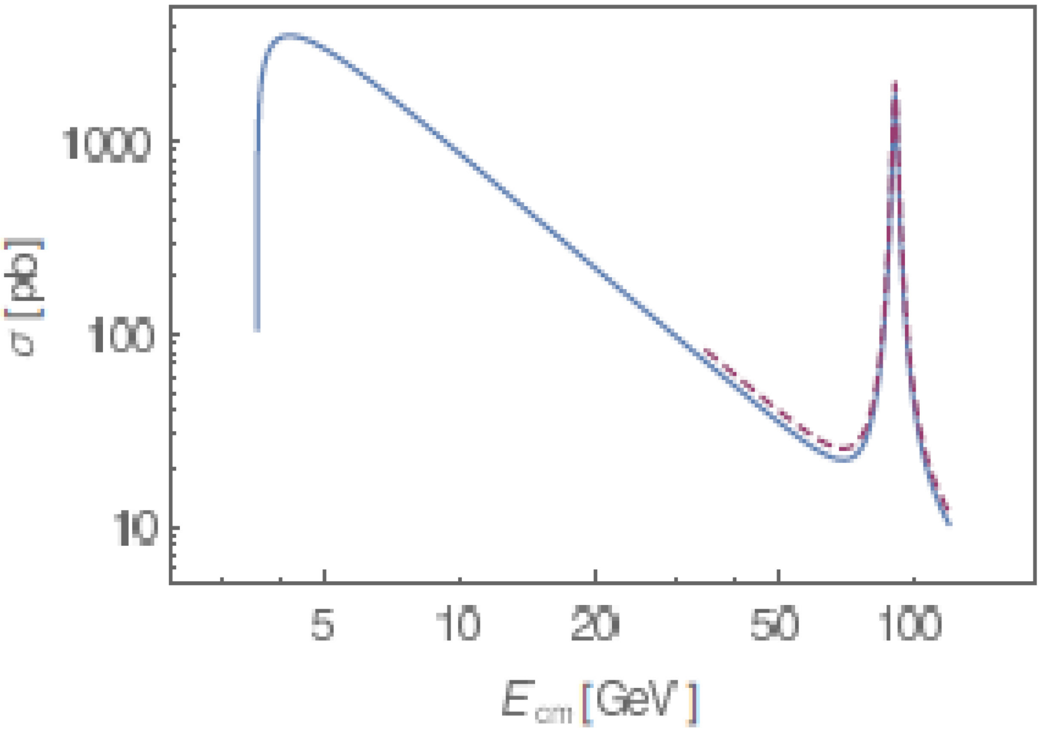
Lepton number violation & FCNC processes; CPV; d_f^Z etc.

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

The physics

τ-lepton is special (the heaviest lepton)

Unique 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 !

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:

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

The limit means:

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

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

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

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.

The precision tests of SM

τ-lepton:

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.

Asymmetries ($\sin^2\Theta_W$):

$$A_{FB}^{0,f} \equiv \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4} A_e A_f$$

$$A_f \equiv 2\frac{\bar{g}_V^f/\bar{g}_A^f}{1+(\bar{g}_V^f/\bar{g}_A^f)^2} = \frac{1-4|Q_f|\sin^2\theta_{eff}^f}{1-4\sin^2\theta_{eff}^f+8(\sin^2\theta_{eff}^f)^2}$$

$$A_{LR}^e = \sqrt{\frac{(\sigma_{++}+\sigma_{+-}-\sigma_{-+}-\sigma_{--})(-\sigma_{++}+\sigma_{+-}-\sigma_{-+}+\sigma_{--})}{(\sigma_{++}+\sigma_{+-}+\sigma_{-+}+\sigma_{--})(-\sigma_{++}+\sigma_{+-}+\sigma_{-+}-\sigma_{--})}}\ .$$

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) !

The precision tests of SM

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

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

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

R_b & R_c

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

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

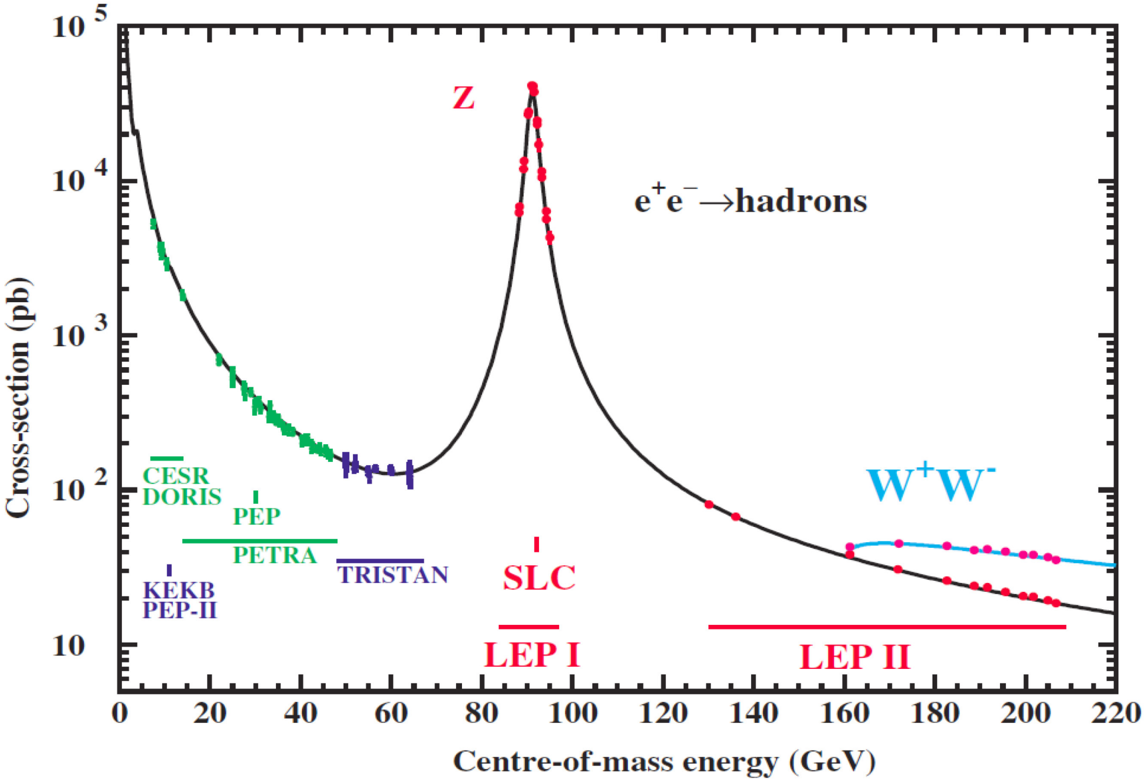
Difficulties are in identifying the flavor

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

QCD & hadron physics

- **Z-factory vs super B-factory & τ-charm factory**
  c, b-hadron physics (especially open bottom)

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



QCD & hadron physics

QCD:

To measure $\alpha_S(m^2{}_Z)$:

via τ-lepton decay

$$R_\tau \equiv \frac{\Gamma[\tau^- \to v_\tau hadrons(\gamma)]}{\Gamma[\tau^- \to v_\tau e^- \bar{v}_e(\gamma)]}$$

$$\alpha_s(m_\tau^2) = 0.331 \pm 0.013$$

Via Jet shape

directly measure $\alpha_s(m_Z^2)$

etc

QCD & hadron physics

Flavors & hadron physics

Light flavors & hadrons (contains light quarks only)

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

Light flavers: u, d, s

Heavy flavors & hadrons (contain heavy quarks)

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

Heavy flavers: c, b, (t)

We need to understand both kinds of the hadrons !

Advantages to understand the heavy and doubly 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

Heavy flavor physics @SZF

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

- c, b-flavored hadron weak decay mechanisms
- CP-violation for c, b-flavored hadrons

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 frag. Func. for light hadrons：

The hadrons relevant to light quarks:

The non-perturbative effects taken into account by models:

The hadronization models:

LUND

Webber Cluster

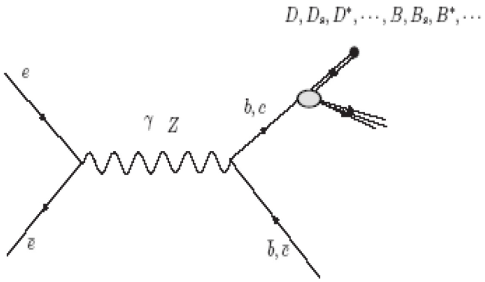
Quark Combination (ShangDong) Model

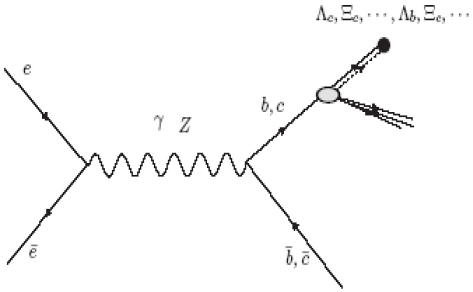
etc

SZF also is the best facility to test these models (no interference from initial state).

QCD & hadron physics

QCD: 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.

Based on factorization theorem of QCD, the FF can be obtained by:

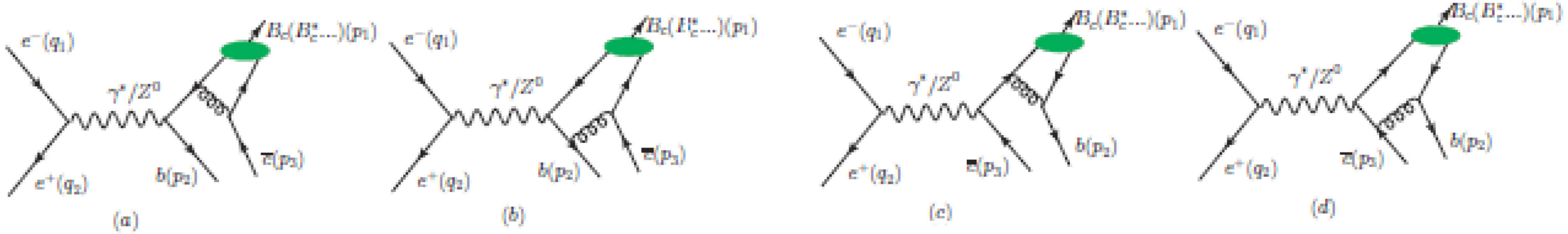
$$D_{q\to h}(z,\mu_0) = \frac{1}{\sigma^{LO}(e^+e^- \to q\bar{q})} \frac{d\sigma(e^+e^- \to \cdots + q \to h + X)}{dz}\Big|_{\mu_0}$$

If the hadron (h) is a light one or a heavy one, the cross-section $d\sigma(e^+e^- \to \cdots + q \to h + X)$ is obtained by measurements.

QCD & hadron physics

If the hadron (h) is a doubly heavy one, the cross-section $d\sigma(e^+e^- \to \cdots + q \to h + X)$ is calculable via NRQCD!

Take h=Bc meson as an example: **(C.-H. Chang et al. PRD 46, 3845; PRD 93, 034019)**



$$\frac{1}{\sigma_0}\frac{d^2\sigma}{dx\ dz} = \frac{128\alpha_s^2(4m_c^2)|\Psi'_P(0)|^2}{27k^2M^3r_1^4(1-r_2z)^4}\left[\frac{w_0(z)}{(1-x)^2} + \frac{d\ w_1(z)}{(1-x)^3} + \frac{d^2\ w_2(z)}{(1-x)^4} + \frac{d^3\ w_3(z)}{(1-x)^5} + \frac{d^4\ w_4(z)}{(1-x)^5}\right]$$

$$D_{\bar{b}\to B^*_{c,J(P)}}(z,\mu_0) = \frac{128\alpha_s^2(4m_c^2)|\Psi'_P(0)|^2}{27m_c^4M(1-r_2z)^4}\left[\delta w_0(z) + \frac{\delta^2}{2}w_1(z) + \frac{\delta^3}{3}w_2(z) + \frac{\delta^4}{4}w_3(z) + \frac{\delta^5}{5}w_4(z)\right]$$

The situation for FF of doubly heavy baryons is similar!

QCD & hadron physics

The Polarized fragmentation functions:

For example: b to Λ_b^0

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

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

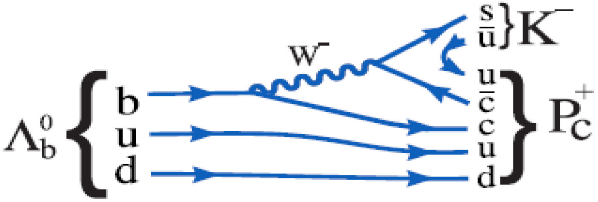
The polarization by measuring $\Lambda_b^0 \to \Lambda_c^+ + \pi^-$

Exotic hadrons (all are doubly heavy):

X,Y,Z particles ;

Recently (Aug. 2015) :

P_c^+

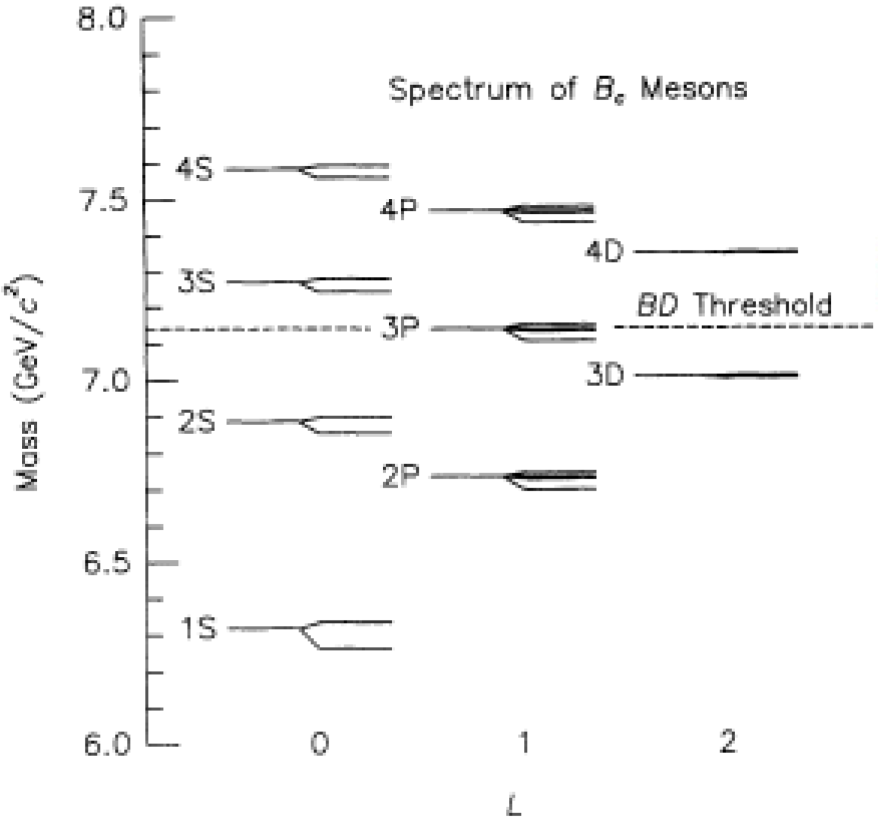


'Doubly heavy'

QCD & hadron physics (spectroscopy)

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 $(^3S_1,\quad J^P=1^-)$

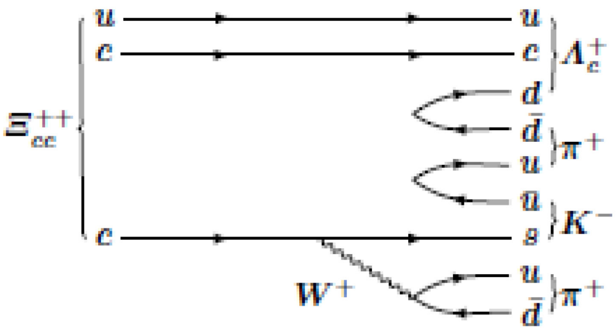
$\chi^J_{B_c}$: $(c\bar{b})$ P-wave excited states $(^3P_J\,,\ J^P=0^+\,,1^+\,,2^+)$

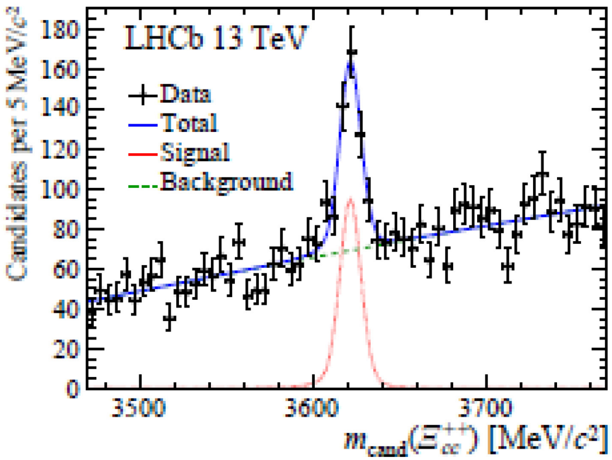
h_{B_c}: $(c\bar{b})$ P-wave excited state $(^1P_1,\quad J^P=1^+)$

QCD & hadron physics

- **Bc meson (ground state) has been observed for years.**
- **Recent the doubly heavy baryon Ξ^{++}_{cc} was observed:**

arXiv1707.01621





$$3621.40\pm0.72\,(\mathrm{stat})\pm0.27\,(\mathrm{syst})\pm0.14\,(\Lambda_c^+)\ \mathrm{MeV}/c^2$$

Quite difficult for experimental observation although comparatively easy to deal with them theoretically!

If we have a super Z-factory, all QCD & hadron physics will enter into a new era especial for doubly heavy ones.

Heavy flavor 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 (even ground states) need to be confirmed!

Heavy flavor physics

Double heavy hadrons :

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

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

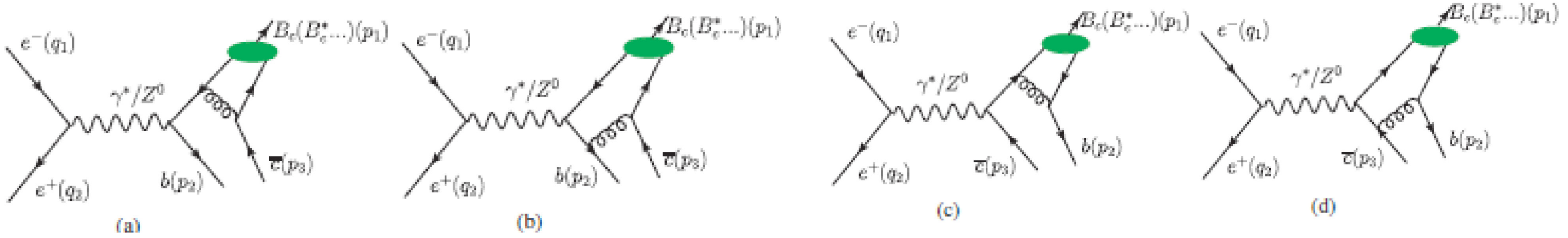
Diquark $H_{QQ'}$:

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 within certain uncertanties;
- 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).

QCD & hadron physics

Production of Bc and its exited states (estimated reliably):

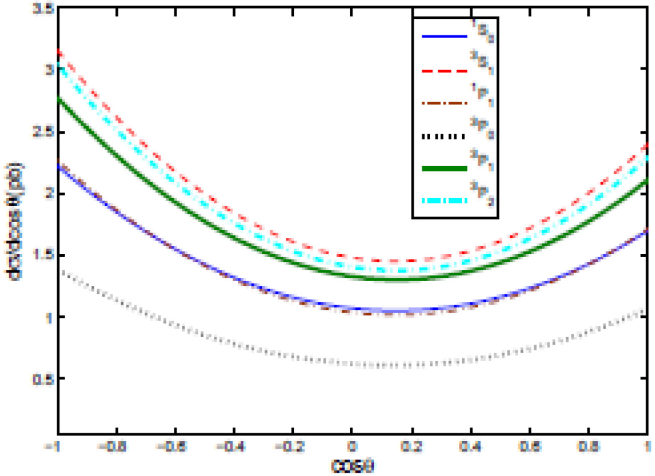


contribution	total	$\bar{b}$-frag.	c-frag.	interference
$\sigma(B_c,\ ^1S_0)$	2.734	2.613	5.20×10^{-2}	6.90×10^{-2}
$\sigma(B_c^*,\ ^3S_1)$	3.823	3.722	4.45×10^{-2}	5.65×10^{-2}
$\sigma(B_c^{**},\ ^1P_1)$	0.271	0.269	3.01×10^{-3}	-1.01×10^{-3}
$\sigma(B_c^{**},\ ^3P_0)$	0.164	0.157	8.13×10^{-3}	-1.13×10^{-3}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

Heavy flavor physics

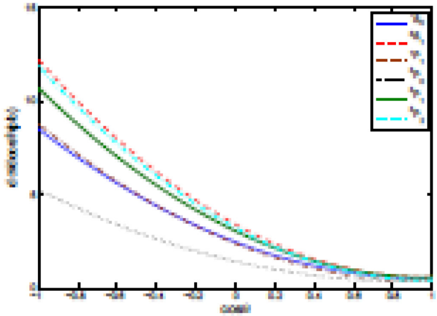
Bc production @ SZF

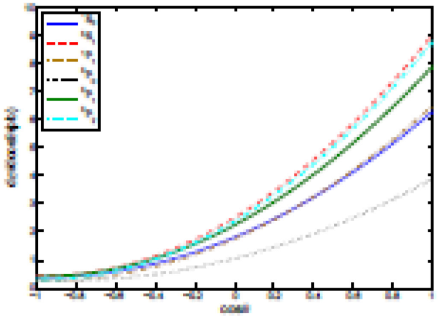


Differential cross sections for various states.

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 SinΘ_W !

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

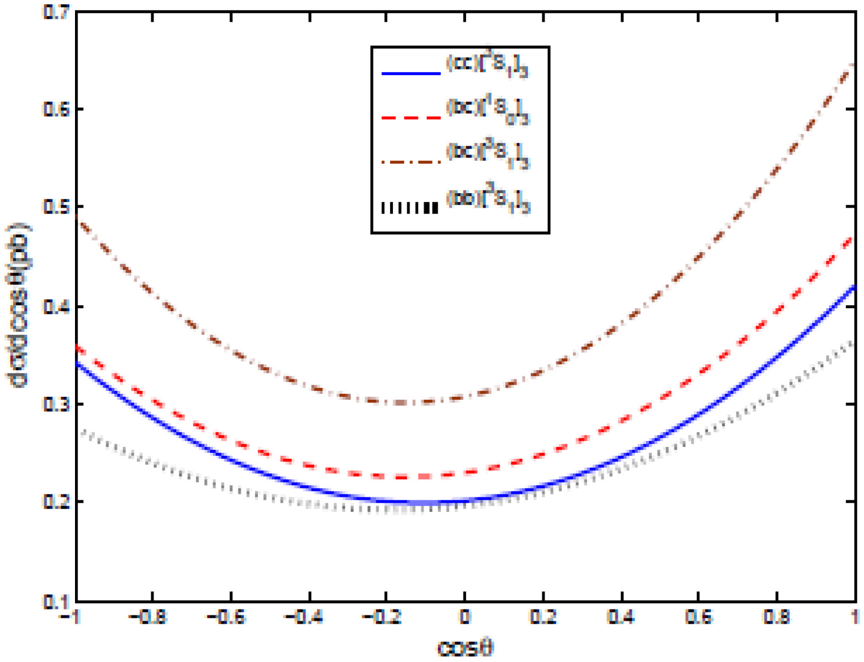




Heavy flavor physics

One more example:

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



(The cross section for Ξ_{bb} is timed by 10!)

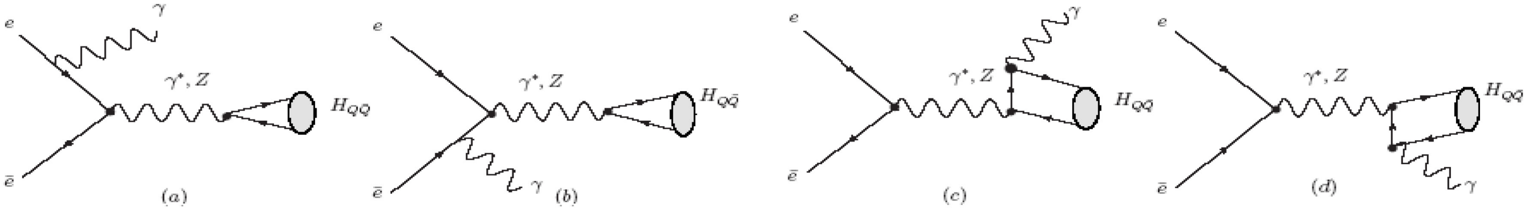
Heavy flavor physics

To measure the heavy quarkonia & exatics @ SZF:

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

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}

Heavy flavor physics

Heavy 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

Conclusion

- Many interesting and important physics
  - Highly precise tests of SM, looking for direct and indirect evidence for new physics
  - QCD, FFs for heavy and double heavy hadrons
  - Heavy flavor physics
  - Heavy and double heavy hadron physics
  - Exotic hadrons X_c, Y_c, Z_c, X_b, Y_b, Z_b & baryons
- 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).
  - For highly precise test of SM and finding 'new physics' the higher luminosity is the better too.

Thanks !

QCD & hadron physics