The production mechanisms for double heavy hadrons

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Outline

- Double Heavy Flavor Hadrons
- Mechanisms for Double Heavy Hadron Production
  - Non-perturbative Mechanism
  - Perturbative Mechanism
- The Production @ Tevatron & LHC
- The Production @ Z-factory
- Summary & outlook

Double Heavy Flavor Hadrons

Double Heavy Flavor Mesons $(c\bar{b})$:

$B_c\,, \cdots\cdots$

Double Heavy Flavor Baryons:

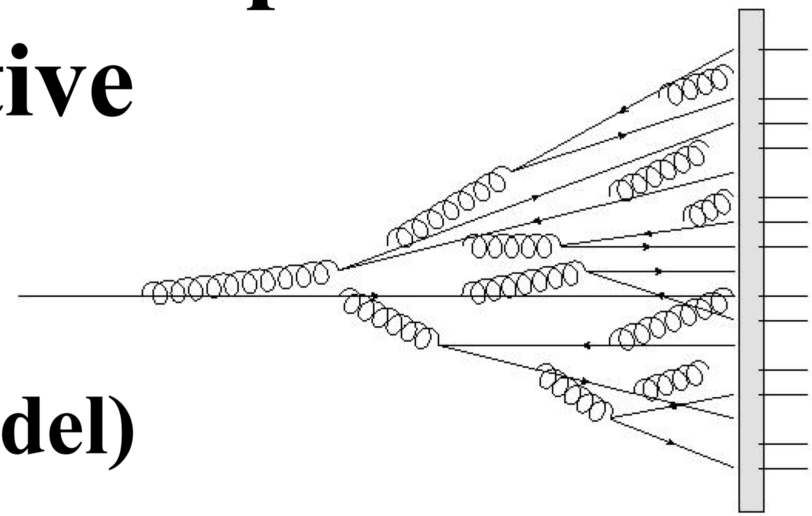
Baryons (ccu):	Baryons (bcu):	Baryons (bbu):
$\Xi_{cc}^{++}\,, \cdots\cdots$	$\Xi_{bcu}^{+}\,, \cdots\cdots$	$\Xi_{bb}^{0}\,, \cdots\cdots$
Baryons (ccd):	Baryons (bcd):	Baryons (bbd):
$\Xi_{cc}^{+}\,, \cdots\cdots$	$\Xi_{bc}^{0}\,, \cdots\cdots$	$\Xi_{bb}^{-}\,, \cdots\cdots$
Baryons (ccs):	Baryons (bcs):	Baryons (bbs):
$\Omega_{cc}^{+}\,, \cdots\cdots$	$\Omega_{bc}^{0}\,, \cdots\cdots$	$\Omega_{bb}^{-}\,, \cdots\cdots$

Doubly heavy hadrons play a special role in study of hadron physics !

The Mechanisms for Production

The production is the first problem

- **The non-perturbative mechanisms:**



- **String Model (Lund Model)**
- **Webber Cluster Model**
- **SDQC Model**

u : d : s : c ≈ 1.0 : 1.0 : 0.3~0.4 : 10^{-10}~10^{-11} @ ~ 0^{o}K

The non-perturbative production

The non-perturbative production for doubly heavy hadrons is ignorable unless QGP @ very high temperature:

$$T >> m_c$$

(Even when $T > m_c$, the chemical potential still should be considered.)

Therefore, the non-perturbative mechanism does not work at low temperature for the production!

The Mechanisms for Production

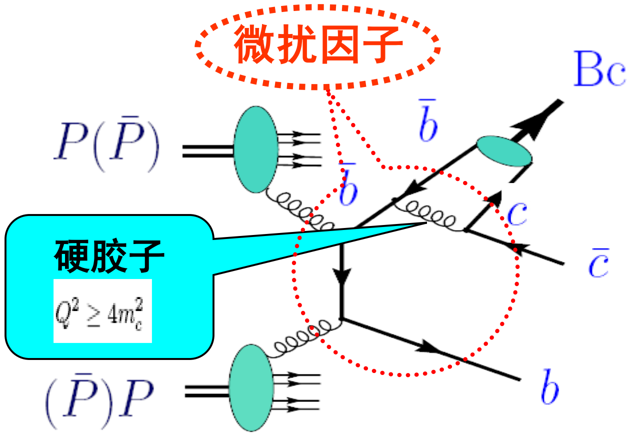
- **The perturbative ones: Dominant mechanism**
  - **To produce heavy quark pairs @HEP**
  - **To combine into hadron 'immediately'**

    Production @ Tevatron & LHC

    Production @ Z-factory (LEP-I)

To take Bc production as example below:

Production of Bc @Tevatron & LHC



Gluon-gluon fusion mechanism dominant

Subprocess: $gg \rightarrow B_c + c + \bar{b}$

36 Feynman diagrams for complete calculations

The information about the accompany quark-jets interests experimentalists

QCD factorization:

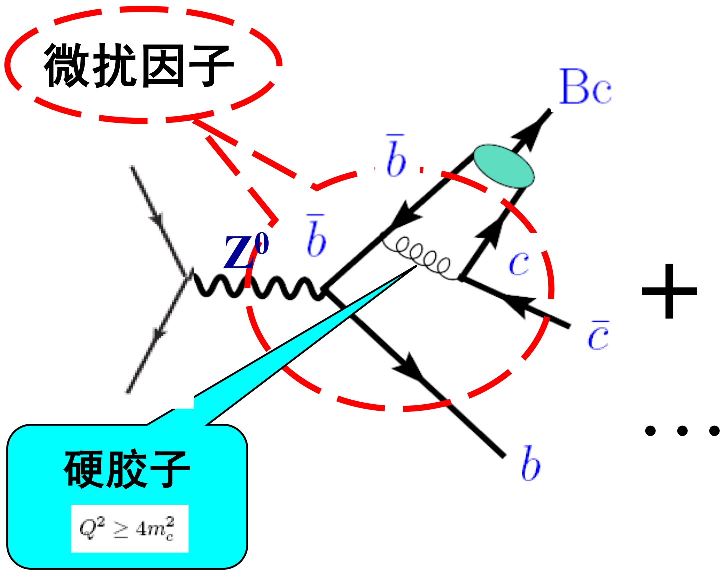
$$d\sigma = \sum_{ij} \int dx_1 \int dx_2 F^i_{H_1(P_1)}(x_1, \mu_F^2) \times F^j_{H_2(P_2)}(x_2, \mu_F^2) d\hat{\sigma}_{ij\to B_c b\bar{c}}(P_1, P_2, x_1, x_2, \mu_F^2)$$

$$\simeq \sum_{ij} \int dx_1 \int dx_2 F^i_{H_1(P_1)}(x_1, \mu_F^2, \mu_R^2) \times F^j_{H_2(P_2)}(x_2, \mu_F^2, \mu_R^2) \cdot \sum_{m=4}^{n} \left\{ d\hat{\sigma}^{(m)}_{ij\to B_c b\bar{c}}(P_1, P_2, x_1, x_2, \alpha_s, Q^2, \mu_F^2, \mu_R^2) \right\}$$

$F^i_{H_1(P_1)}(x_1, \mu_F^2)$, $F^j_{H_2(P_2)}(x_2, \mu_F^2)$: structure functions

μ_R, μ_F, Q^2: renormalization, factorization, characteristic energy scales

Production of Bc et al at Z–factory



The key point is the hard gluon & it can be QCD factorized as indicated by the figure.

PRD**46**, (1992) 3845; PLB**284**, (1992) 127; PRD**93** (2016) 034019

The result is that at Z^0 peak for LEP-I several thousands of Bc may be produced per year ! Considering the detecting efficiency, to observe Bc at LEP-I is on the margin.

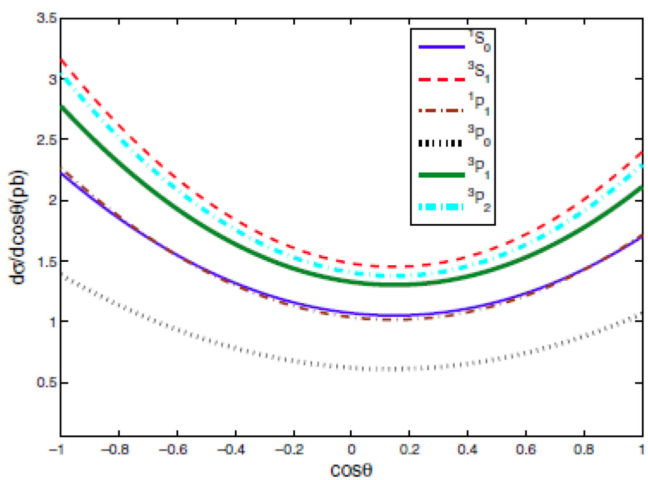
Whereas @ Super Z-factory, there are many interesting aspects when the luminocity very and can collect a lot events !

Production of Bc et al at Z–factory

The cross-sections of the production (around Z-pole, in pb):

$(\sqrt{s}-m_Z)$ (GeV)	-5	-2.5	-1.5	-0.8	-0.4	-0.2	0	0.2	0.4	0.8	1.5	2.5	5
$\sigma(B_c, {}^1S_0)$	0.15	0.53	1.09	1.91	2.46	2.65	2.73	2.68	2.50	1.97	1.15	0.56	0.17
$\sigma(B_c^*, {}^3S_1)$	0.21	0.74	1.52	2.67	3.44	3.71	3.82	3.74	3.50	2.75	1.60	0.79	0.24
$\sigma(B_c^{**}, {}^1P_1)$	0.01	0.05	0.11	0.19	0.24	0.26	0.27	0.27	0.25	0.19	0.11	0.06	0.02
$\sigma(B_c^{**}, {}^3P_0)$	0.01	0.03	0.07	0.11	0.15	0.16	0.16	0.16	0.15	0.12	0.07	0.03	0.01
$\sigma(B_c^{**}, {}^3P_1)$	0.02	0.07	0.14	0.24	0.31	0.33	0.34	0.33	0.31	0.24	0.14	0.07	0.02
$\sigma(B_c^{**}, {}^3P_2)$	0.02	0.07	0.15	0.25	0.33	0.35	0.37	0.36	0.33	0.26	0.15	0.08	0.02

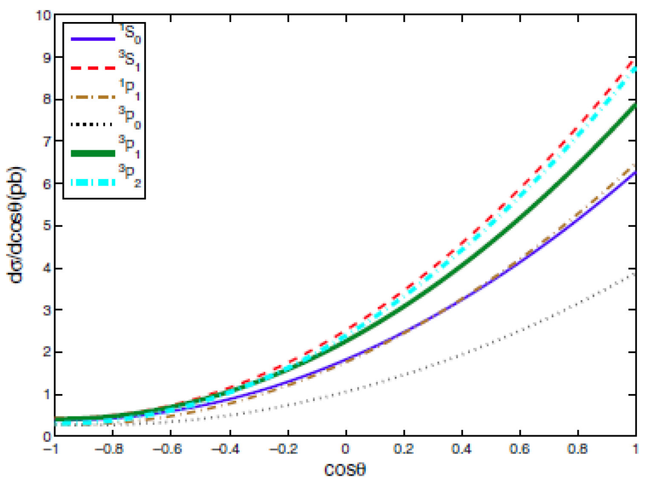
The differential cross-sections of the production @ Z-pole:



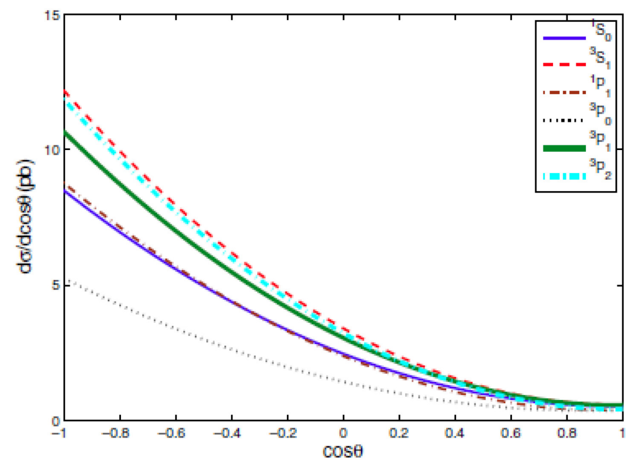
The asymmetry is due to the vector and axial vector couplings of Z-boson to fermions !

Production of Bc et al at Z–factory

With polarized e^+, e^- beams the asymmetry:



$$e_L^+ e_R^- \to B_c(B_c^*, \ldots) + b + \bar{c}$$

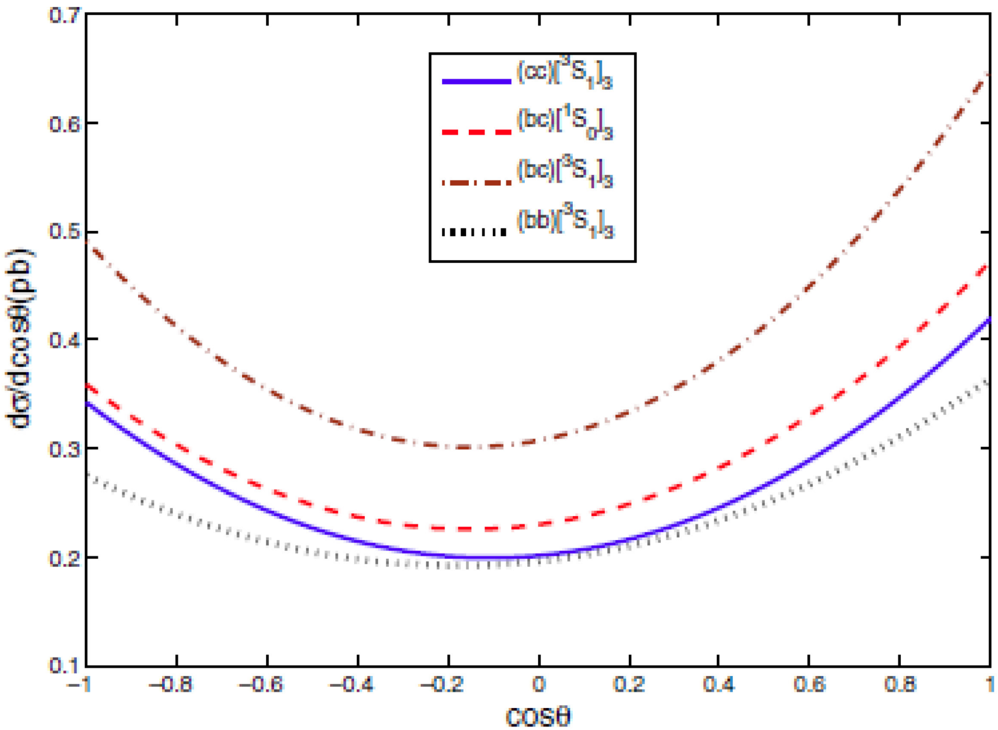


$$e_R^+ e_L^- \to B_c(B_c^*, \ldots) + b + \bar{c}$$

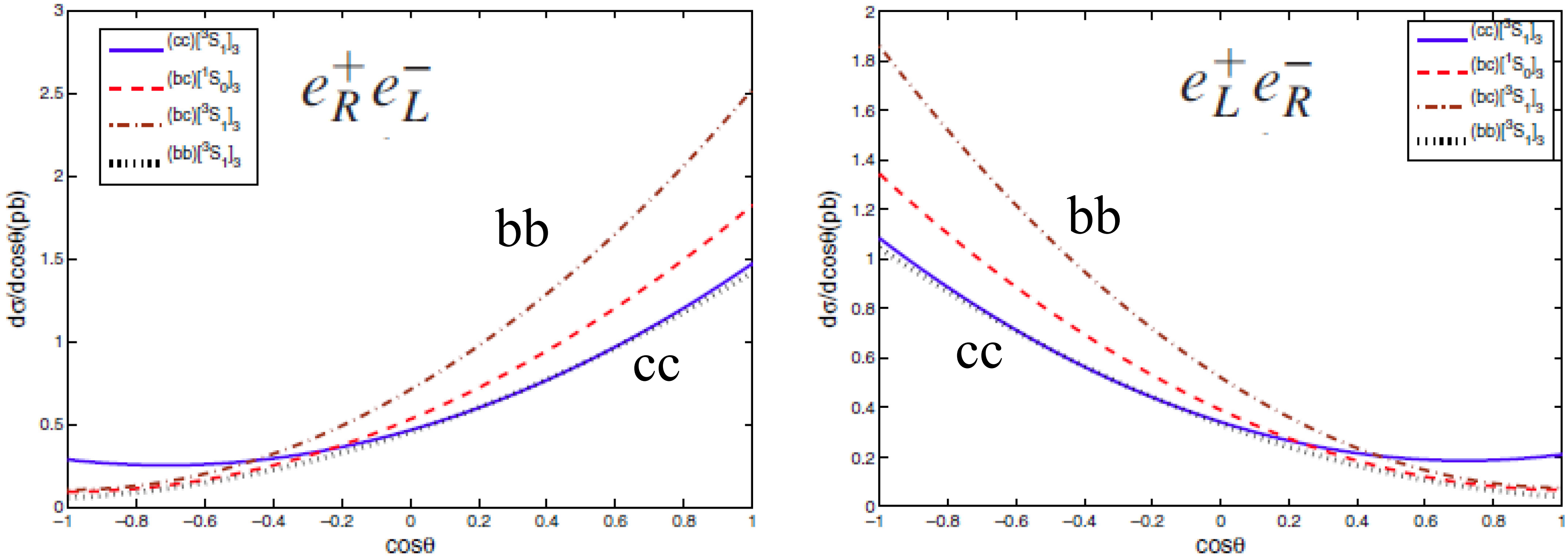
The asymmetry depends on the $\sin\theta_W$ directly and enhanced by polarized beams.

Production of Bc et al at Z–factory

The situation for double heavy baryons (the heavy diquarks) is similar:
The asymmetry:



Production of Bc et al at Z–factory



Therefore now we are calculating the production up-to NLO of QCD!

arXiv: 1701.04561

Summary & outlook

- **To study production mechanisms itself is important physics so is an interesting topic, and it can tell us where enough events can be produced for observation.**
- **The doubly heavy hadron production is comparatively simple than that of heavy quarkonium production.**
- **Doubly heavy hadron production @ hadronic colliders**
  HLCb : Bc, Ξcc, ……
  The excited states, ……
- **Double heavy hadron production @ e^+e^- colliders**
  The chances for Super Z-factory only: to produce enough doubly heavy hadrons for experimental study and tests of SM etc.

向C. Rubbia说明Bc介子产生的困难,需要LHC（1992）

Thanks for attention !