The hc hadronproduction

---at the LHC

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The h_c

- **It is a recently found p-wave charmonium state, with a mass below open charm threshold**

- Its J^{pc} is 1^{+-} and L=1 , S=0

- Its mass is about $\mathrm{m} = 3525.93 \pm 0.27\mathrm{MeV}$, total width $\Gamma_{tot} < 1MeV$

(CLEO, E835, BESIII)

The dominant decay modes of h_c include:

$$h_c \to J/\psi + \pi^0$$

- **Theoretical estimate gave a branching ratio of 0.5% (Kuang. et al, Phys. Rev. D 37 (1988) 1210)**
- **It was observed by E760 Collab. (E760 Collaboration, Phys. Rev. D 52 (1995) 4839)**
- **However it was not confirmed by its successor, the E835**

$h_c \to \eta_c + \gamma$

- Theoretical estimate gave a branching ratio of 50％ (Y. P. Kuang. et al, Phys. Rev. D 37 (1988) 1210 ; S. Godfrey. et al, Phys. Rev. D 66 (2002) 014012 ; P. Ko. Phys. Rev D 52 (1995) 1710)

- It was observed by E835 Coll. (E835 Coll., Phys. Rev. D 72 (2005) 092004)

- **In recently, CLEO observed the h_c via $\psi(2S) \to \pi^0 + h_c \to \pi^0 + \eta_c + \gamma$ at CESR**

(CLEO Collaboration, Phys. Rev. L 95 (2005) 102003 , Phys. Rev. D 72 (2005) 092004 , Phys. Rev. L 101 (2008) 182003)

- **BELLE tried to find the h_c in the process of $B^{\pm} \to K^{\pm} + h_c$, but no evidence**

(Belle Collaboration, Phys. Rev. D 74 (2006) 012007）

- **According to the QCD-based potential model prediction, to leading order of the spin–spin interaction the hyperfine splitting should be zero, i.e.,**

$$\Delta M_{hf}(M(^1P_1) - M(^3P_J)) \approx 0$$

- **The spin-weighted average mass of P-wave triplet states**

$$M(^3P_J) = (M(^3P_0) + 3M(^3P_1) + 5M(^3P_2))/9 = 3525.30 \pm 0.04\,\text{MeV}$$

- And higher order corrections to the hyperfine splitting should be less than 1 MeV

T. Appelquiat, R.M. Barnett, K.D. Lane, Annu. Rev. Nucl. Part. Sci. 28 (1978) 387.
S. Godfrey, J.L. Rosner, Phys. Rev. D 66 (2002) 014012.
D.N. Joffe, Ph.D thesis, Northwestern University, 2004;
D.N. Joffe, hep-ex/0505007.

- To obtain more knowledge of h_c , a key point is to get enough data

The leading order calculation for hc Hadroproduction

- **It is found that the LHC will produce copious h_c data, and enables people to perform precise study on its nature**

In hadron-hadron collision, dominant processes for h_c production include

1) $g + g \to h_c({}^1S_0^{[8]}) + g$

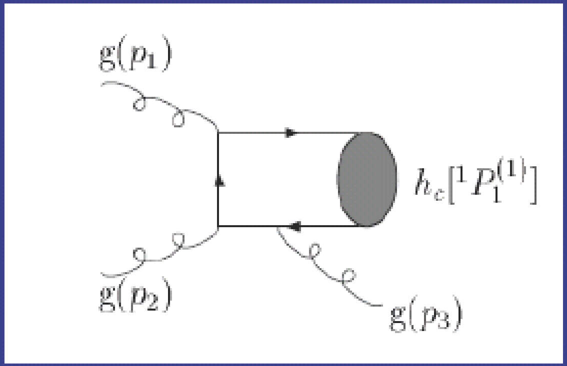
2) $g + q(\overline{q}) \to h_c({}^1S_0^{[8]}) + q(\overline{q})$

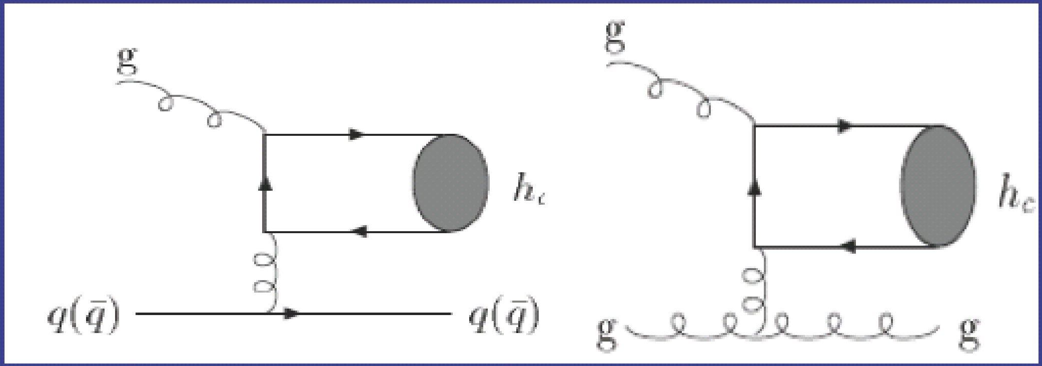
3) $q + \overline{q} \to h_c({}^1S_0^{[8]}) + g$

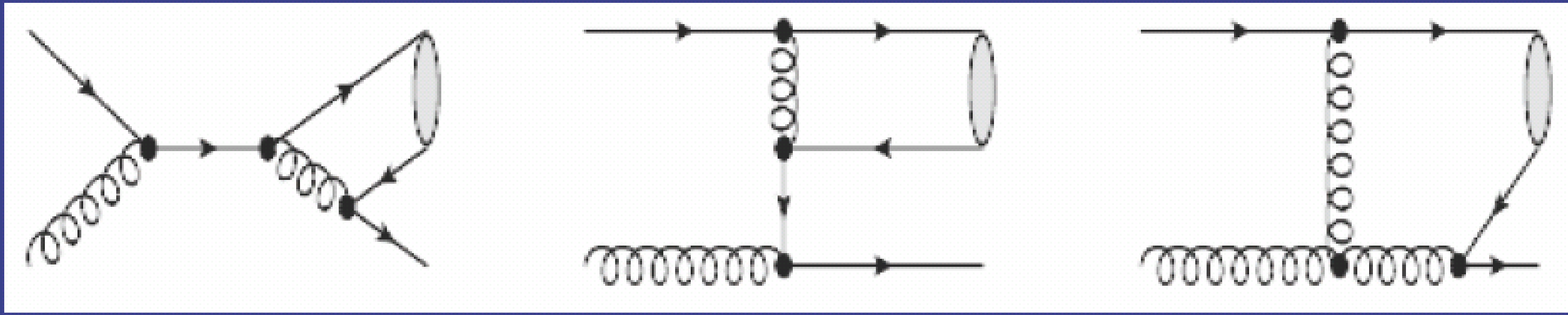
4) $g + g \to h_c({}^1P_1^{[1]}) + g$

5) $g + c(\overline{c}) \to h_c({}^1P_1^{[1]}) + c(\overline{c})$

The typical Feynman diagrams







The differential cross section for h_c hadroproduction is formulated in a standard way,

$$\frac{d\sigma}{dp_T}(pp \to h_c + X) = \sum_{a,b} \int dx_a\, dy\, f_{a/p}(x_a) f_{b/p}(x_b) \frac{4 p_T x_a x_b}{2x_a - \bar{x}_T e^y} \times \frac{d\hat{\sigma}}{dt}(a + b \to h_c + X), \quad (1)$$

where $f_{a/p}$ and $f_{b/p}$ denote the parton densities; s, t, and u are Mandelstam variables at the parton level; y stands for the rapidity of produced h_c; $\bar{x}_T \equiv \frac{2m_T}{\sqrt{S}}$ with $m_T = \sqrt{M^2 + p_T^2}$; and the capital $\sqrt{S}$ and M denote the total energy of incident beam and the mass of h_c, respectively.

- The processes 1)--4) were numerically calculated

[Sridhar, PLB674, 36(2009); Qiao and Yuan, PRD63,014007(2001), Qiao, Ren and Sun, PLB680, 159(2009)]

- And, it was found that the intrinsic charm process 5) is very important in the hc production at the LHC

[QIAO, Ren and Sun, PLB680, (2009)159]

The differential cross-section for process 5) is:

$$
\begin{aligned}
\frac{d\hat{\sigma}}{dt} = \frac{16\alpha_s^3\pi|R'(0)|^2}{27m_c(s-m_c^2)^2}\Bigg(&\frac{9t}{(s-m_c^2)^2m_c^2}+\frac{96(3m_c^2-5s)m_c^4}{(s-m_c^2)(t-m_c^2)^4}\\
&+\frac{32(39m_c^4-16sm_c^2-6s^2)m_c^2}{(s-m_c^2)^2(t-m_c^2)^3}\\
&-\frac{6(57m_c^4+14sm_c^2-7s^2)m_c^2}{(s+t-2m_c^2)(s-m_c^2)^4}\\
&+\frac{880m_c^8-631sm_c^6+119s^2m_c^4-201s^3m_c^2+25s^4}{(s-m_c^2)^4(t-m_c^2)m_c^2}\\
&+\frac{1177m_c^8-856sm_c^6-82s^2m_c^4-88s^3m_c^2+9s^4}{(s-m_c^2)^3(t-m_c^2)^2m_c^2}\\
&+\frac{2}{(s+t-2m_c^2)^2}-\frac{256m_c^6}{(t-m_c^2)^5}\\
&+\frac{118m_c^8-379sm_c^6+141s^2m_c^4-161s^3m_c^2+25s^4}{(s-m_c^2)^5m_c^2}\\
&-\frac{8m_c^2}{(s+t-2m_c^2)^3}\Bigg).
\end{aligned}
$$

With the inputs of:

$$\sqrt{S} = 14\ \text{TeV},\ m_c = M/2 = 1.78\ \text{GeV}$$

$$|\eta(h_c)| < 2.2$$

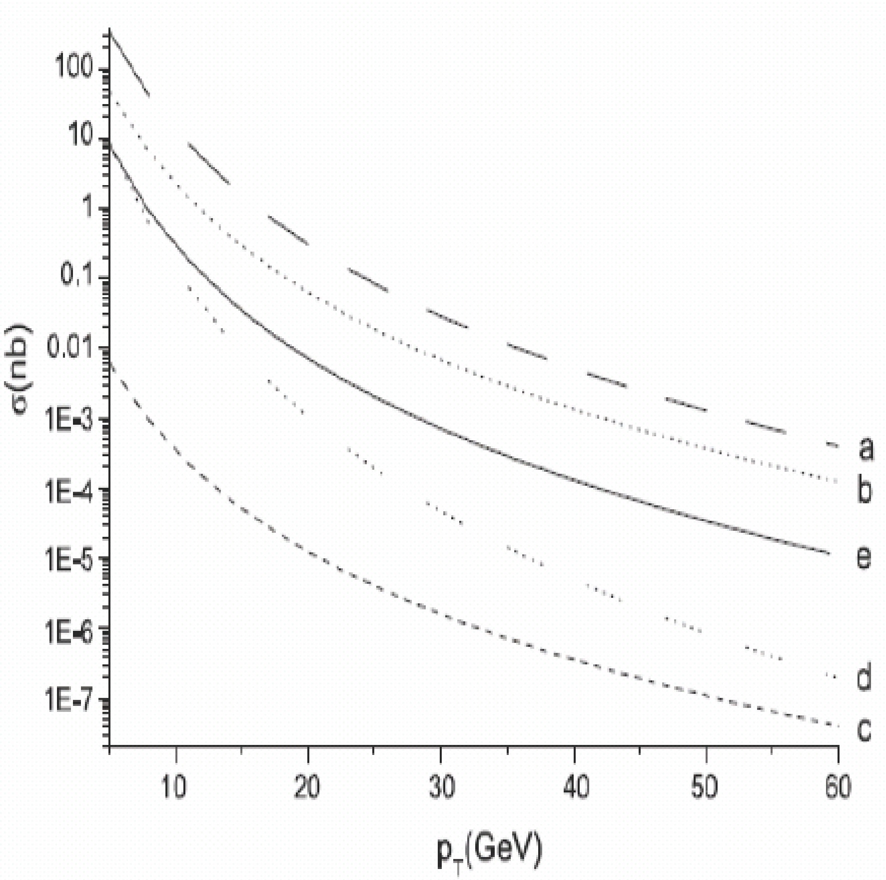
$$|R'(0)| = \sqrt{\frac{2\pi}{27}\langle 0|\mathcal{O}_1^{h_c}(^1P_1)|0\rangle}$$

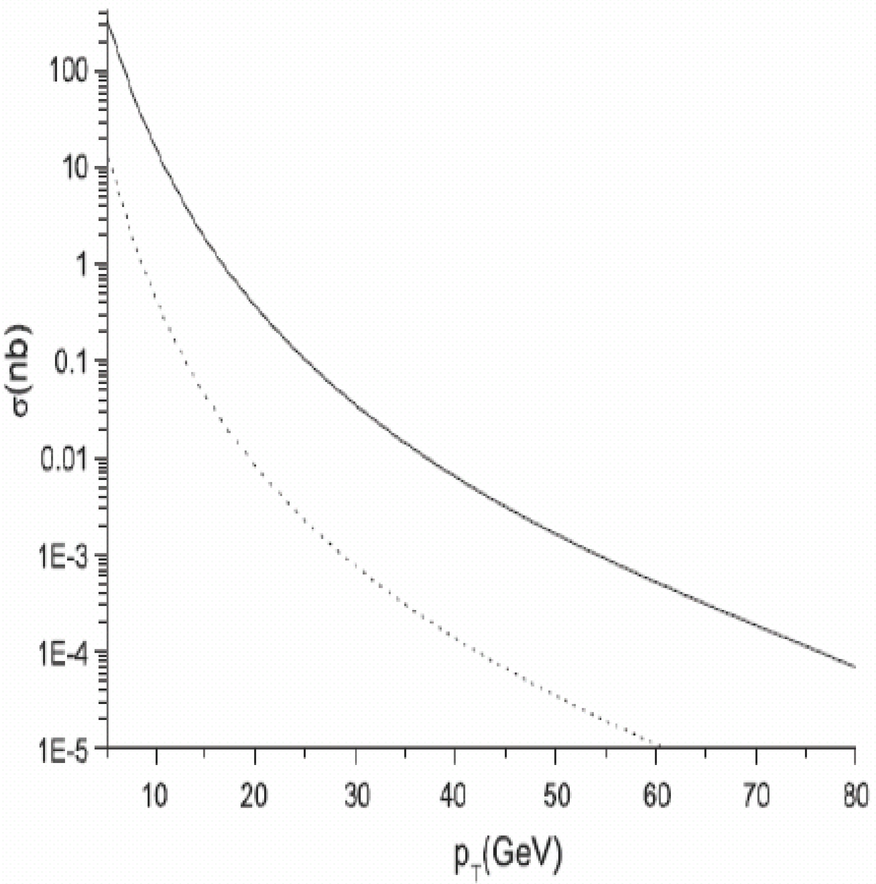
$$\langle 0|\mathcal{O}_1^{h_c}(^1P_1)|0\rangle = 0.32\ \text{GeV}^5$$

$$\langle 0|\mathcal{O}_8^{h_c}(^1S_0)|0\rangle = 9.8\times 10^{-3}\ \text{GeV}^3$$

P.L. Cho, A.K. Leibovich, Phys. Rev. D 53 (1996) 150;
P.L. Cho, A.K. Leibovich, Phys. Rev. D 53 (1996) 53.

We obtain(a-e for process 1-5 on the left; solid for CO and dashed line for CS)





The result shows:

- The color-octet process contributes more to hc hadroprodution at the LHC
- In color-singlet mechanism, the intrinsic charm quark induced process dominates over the other one

From PDG and theoretical calculation

$$(A)\ h_c \to J/\psi + \pi^0 \to \mu^+\mu^- + \gamma\gamma$$

$$(B)\ h_c \to \eta_c + \gamma \to p\bar{p} + \gamma$$

$$(C)\ h_c \to \eta_c + \gamma \to \gamma\gamma + \gamma$$

- Br[A] = 0. 5% × 5.9% × 100% = 2.95×10^{-4}
- Br[B] = 50% × 0.13% = 6.5×10^{-4}
- Br[C] = 50% × 0.024% = 1.2×10^{-4}

That means:

	Color-singlet event			
P_{Tcut}	5GeV	10GeV	20GeV	30GeV
Total	1.65×10^{8}	4.32×10^{6}	8.14×10^{4}	7.57×10^{3}
Chain [A]	4.49×10^{4}	1.30×10^{3}	2.44×10	2.27
Chain [B]	1.07×10^{5}	2.81×10^{3}	5.29×10	4.92
Chain [C]	1.97×10^{4}	5.19×10^{2}	9.76	0.91

	Color-octet event			
P_{Tcut}	5GeV	10GeV	20GeV	30GeV
Total	3.78×10^{9}	1.56×10^{8}	3.67×10^{6}	3.54×10^{5}
Chain [A]	1.13×10^{6}	4.68×10^{4}	1.10×10^{3}	1.06×10^{2}
Chain [B]	2.45×10^{6}	1.01×10^{5}	2.38×10^{3}	2.30×10^{2}
Chain [C]	4.53×10^{5}	1.87×10^{4}	4.40×10^{2}	4.42×10

hc production through fragmentation

$$d\sigma_H(p) = \sum_i \int_0^1 dz \, d\hat{\sigma}_i(p/z) \, D_{i\to H}(z)$$

Cross section for **parton** production

Fragmentation Function: How **parton i** fragments into **hadron H**

Fragmentation function for heavy quarkonium

- Generally, fragmentation function for heavy quarkonium has factorized formation

$$D_{i\to H}(z) = \sum_n d_n(z)\langle \mathcal{O}_n^H \rangle$$

n: quantum number

Color, spin…

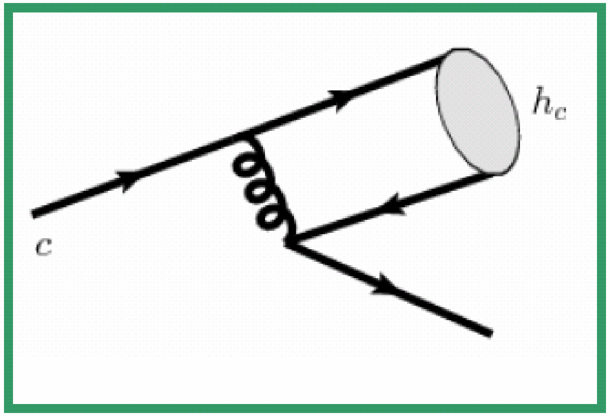
• Production of quark pair **in n state**

•pQCD calculable due to large mass of heavy quark

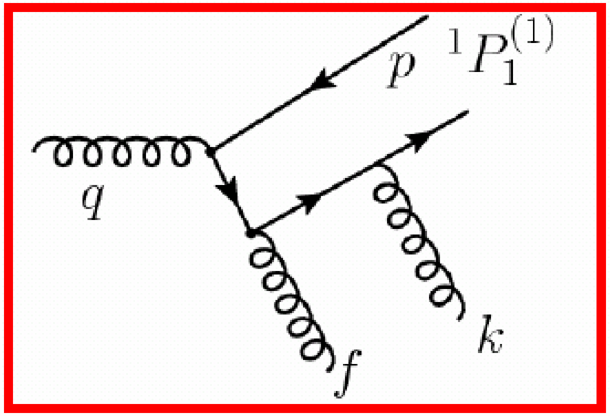
• NRQCD operator
• Quark pair hadronization into heavy quarkonium
• non-perturbative quantity

Fragmentation function for hc

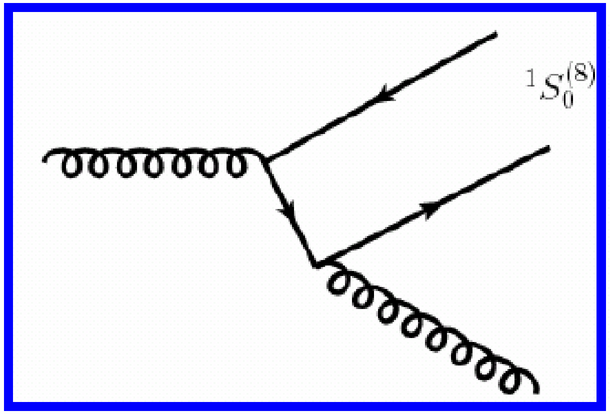
- Charm quark fragmentation



- Gluon fragmentation



Color Singlet



Color Octet

Gluon fragmentation function for hc

G.Hao & C.F.Q, Y.B.Zuo, arXiv:0911.5539

- At LO of α_s and NLO of v

$$D_{g\to h_c}(z) = d_1(z,\Lambda)\langle \mathcal{O}^{h_c}({}^1P_1^{(1)})\rangle + d_8(z)\langle \mathcal{O}^{h_c}({}^1S_0^{(8)})\rangle(\Lambda)$$

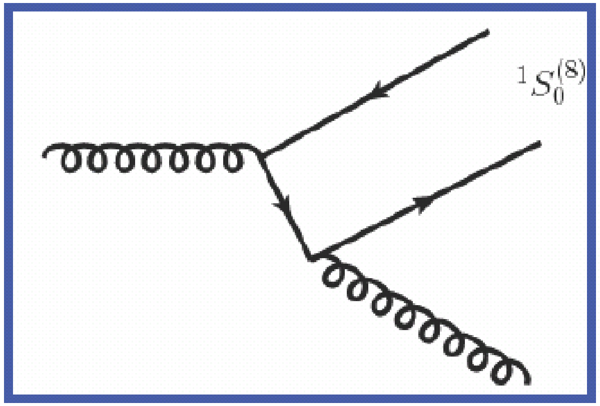
- Λ is factorization scale.
- Only $d_1(z)$ and Matrix element of octet operator depends on Λ:

$$\Lambda \frac{d}{d\Lambda}\langle 0|\mathcal{O}_8^{h_c}({}^1S_0)|0\rangle = \frac{4C_F\alpha_s(\Lambda)}{3N_c\pi m_c^2}\langle 0|\mathcal{O}_1^{h_c}({}^1P_1)|0\rangle.$$

Braaten and Yuan PRD50,3176,1994

Calculation of d_8

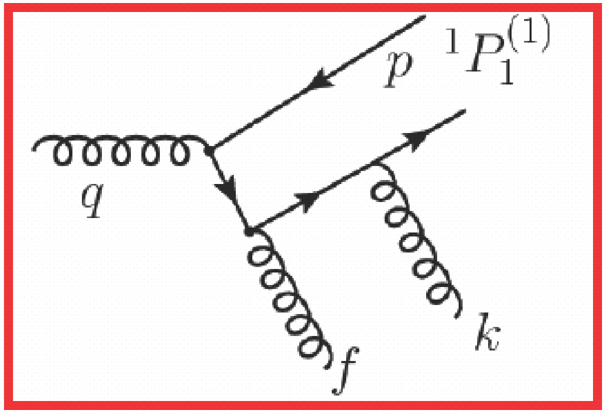
- Calculation of $d_8(z)$ is easy



$$d_8(z) = \frac{5}{24}\frac{\alpha_s^2}{m_c^3}[3z - 2z^2 + 2(1-z)\ln(1-z)]$$

Calculation of d_1

- Infrared divergence in color-singlet process
  - set a cutoff Λ for gluon's energy
  - $d_1(z)$ depends on Λ



$$d_1(z,\Lambda) = f(z) - \frac{10\alpha_s^3}{81\pi m_c^5}[3z - 2z^2 + 2(1-z)\ln(1-z)]\ln\frac{\Lambda}{m_c}$$

- f(z) has no Λ dependence, but very complicated expression.

Fragmentation function for hc

- To avoid large logarithms, we choose

$$\Lambda = m_c$$

- Gluon fragmentation function is

$$D_{g\to h_c}(z) = f(z)\langle \mathcal{O}^{h_c}(^1P_1^{(1)})\rangle + d_8(z)\langle \mathcal{O}^{h_c}(^1S_0^{(8)})\rangle(m_c)$$

- Probability of gluon fragmentation into hc

$$P_{g\to h_c} = \int_0^1 dz D_{g\to h_c}(z)$$

- c -> hc probability is about 10^-5
- g -> hc probability is about 10^-7
- Therefore, for near future experiment, the hc fragmentation production is negligible

Summary

- The LHC may be suitable for the precise hc study

- If so, by the study of hc production, the charmonium production mechanism may also be elucidated in some sense

- To fully consider the hc large transverse momentum production, the fragmentation mechanism should be taken into account

Thank you for your attention