Charmonium production and decays: new results and perspectives

Spin-singlet Quarkonia at the LHC

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Brief introduction

◆Although LHC was designed mainly for the study of electroweak breaking and new physics, the hadron physics capabilities of the ATLAS, CMS, and LHCb detectors are also great

◆At present, there are many open questions in hadron physics, which might be answered in LHC experiment

◆ One of the key issues concerned in hadron physics is about the applicability of QCD to the description of hadrons, their production, decay nature, etc.

◆ A wealth of return may be obtained in hadron physics study to the investigation of effective theory, new phenomena and QCD

h_c (CLEO, E760, E835, BESIII)

h_c, the recently found p-wave spin singlet charmonium state, with a mass below open charm threshold

Its $J^{pc} = 1^{+-}$

Its mass $m = 3525.93 \pm 0.27 \mathrm{MeV}$

Its total decay width $\Gamma_{tot} < 1\ MeV$

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,1988)
- **It was observed by E760 Collab, but was not confirmed by its successor, the E835 (E760 1995)**

The dominant decay modes of h_c include:

$$h_c \rightarrow \eta_c + \gamma$$

- **Theoretical estimate gave a branching ratio of 50% (Kuang, et al.1988; Godfrey. et al, 2002; Ko, 1995)**

- **It was observed by E835 Coll. (E835, 2005), and recently confirmed by CLEO and BES Colls. through (CLEO, 2005, 2008; BES, 2010)**

$$\psi(2S) \rightarrow \pi^0 + h_c \rightarrow \pi^0 + \eta_c + \gamma$$

◆**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**

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

◆Theoretically, higher order corrections to the hyperfine splitting should be less than 1 MeV
(Appelquiat, et al, 1978; Godfrey et al, 2002; Joffe 2005)

◆To have more knowledge of h_c , a key point is to get enough data

η_c

It is widely accepted that η_c is the lowest lying state in charmonium family, and it was observed in the early age of charm physics

Its $J^{pc} = 0^{-+}$

Its mass $m = 2981.0 \pm 1.1$ MeV

Its total decay width $\Gamma = 29.7 \pm 1.0$ MeV

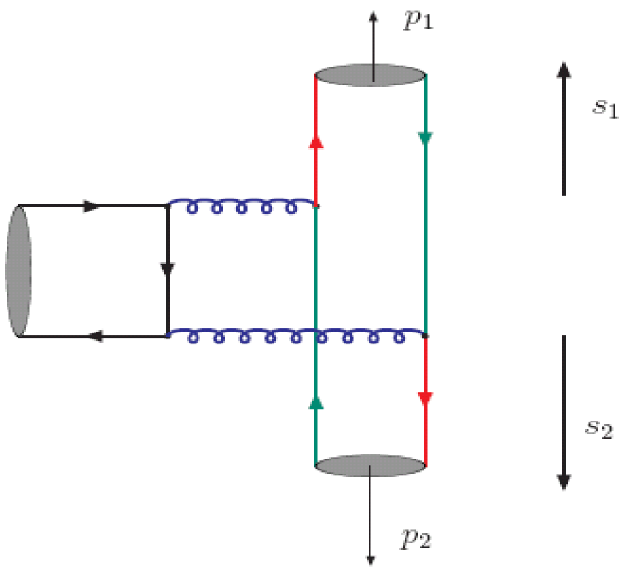
- For η_c, we expect there will be copious data produced at the LHC.
- Although η_c has been observed for many years, there are still many open questions about its nature.
- The most chanllenging one for me is about its exclusive decay to light vector meson pairs:

$$\eta_c \to VV$$

- Perturbatively, $\eta_c \to VV$ process should be helicity suppressed ,

- HSR prediction: $\lambda_1 + \lambda_2 = 0$;
- Parity conservation $\Rightarrow \mathcal{M} \sim \mathcal{A}\epsilon_{\mu\nu\rho\sigma}\varepsilon_1^\mu \varepsilon_2^\nu p_1^\rho p_2^\sigma$

$\varepsilon_L = ap_1 + bp_2$ $\Rightarrow$ No longitudinal polarization!



$P \longrightarrow VV$ decay:

$L = 1,\ S = 1$

$\Downarrow$

$\lambda_1 + \lambda_2 = \pm 2$

$\Downarrow$

$\eta_c \longrightarrow VV$ decays should be suppressed!

However, in reality:

- BES Collaboration, Phys.Rev.D72:072005,2005.

Final state	Branching ratio(Br)	Br/κ_{12}^3
$\rho^0\rho^0$	4.15×10^{-3}	6.6×10^{-3}
$K^{*0}\overline{K}^{*0}$	5.2×10^{-3}	5.0×10^{-3}
$\phi\phi$	2.5×10^{-3}	6.0×10^{-3}
$\omega\omega$	$< 4 \times 10^{-3}$	$< 6.4 \times 10^{-3}$
$\omega\phi$	$< 7.1 \times 10^{-3}$	$< 6.8 \times 10^{-3}$

K_{12} is a kinematic factor

η_b

The lowest energy state in Υ family, the η_b , is very elusive. The existence of the η_b is a solid prediction of the quark model

Its $J^{pc} = 0^{-+}$

Its mass $m \approx 11\ \text{MeV}$ (BELLE Collaboration, 2013)

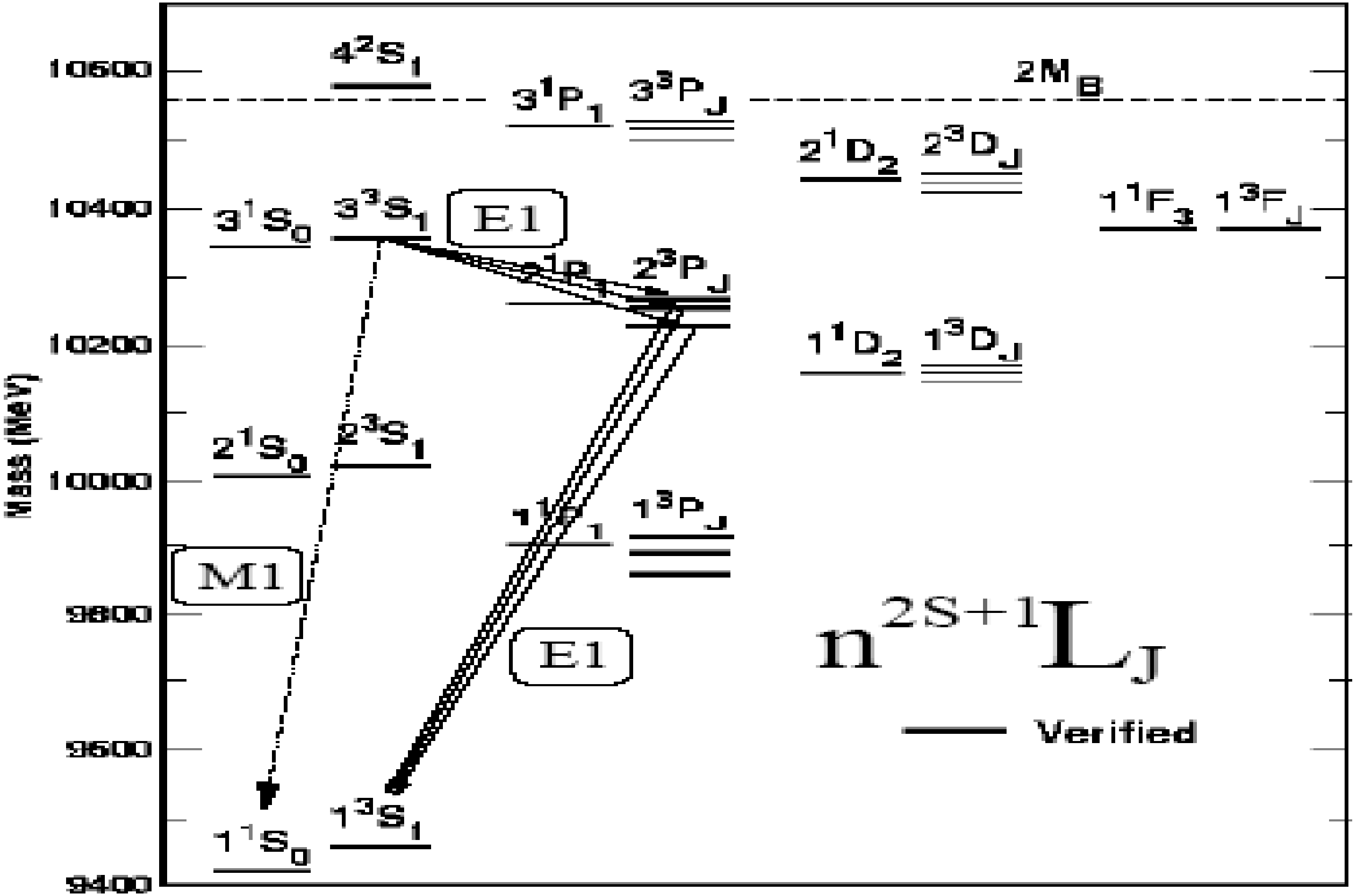
Its total decay width $\Gamma = ??\ \text{MeV}$

- About thirty year after it spin triplet partner being found, recently it was observed for the first time by Babar through Υ (3s) --> $\eta_b \gamma$
  (Aubert, et al., Babar Collaboration, 2008)

- In recent years, the search for η_b has been conducted at CLEO, LEP, and CDF, B-factories, using both inclusive and exclusive methods

- It is worth noting that both Babar and CLEO-c measurements are indirect ones.

- For further study on η_b physics, direct measurements on its decay products are necessary


10600
10400
10200
10000
9800
9600
9400
Mass (MeV)
4²S₁
3¹P₁
3³P_J
2M_B
2¹D₂
2³D_J
3¹S₀
3³S₁
E1
1¹F₃
1³F_J
2¹P₁
2³P_J
1¹D₂
1³D_J
2¹S₀
2³S₁
1¹P₁
1³P_J
M1
E1
n^{2S+1}L_J
Verified
1¹S₀
1³S₁

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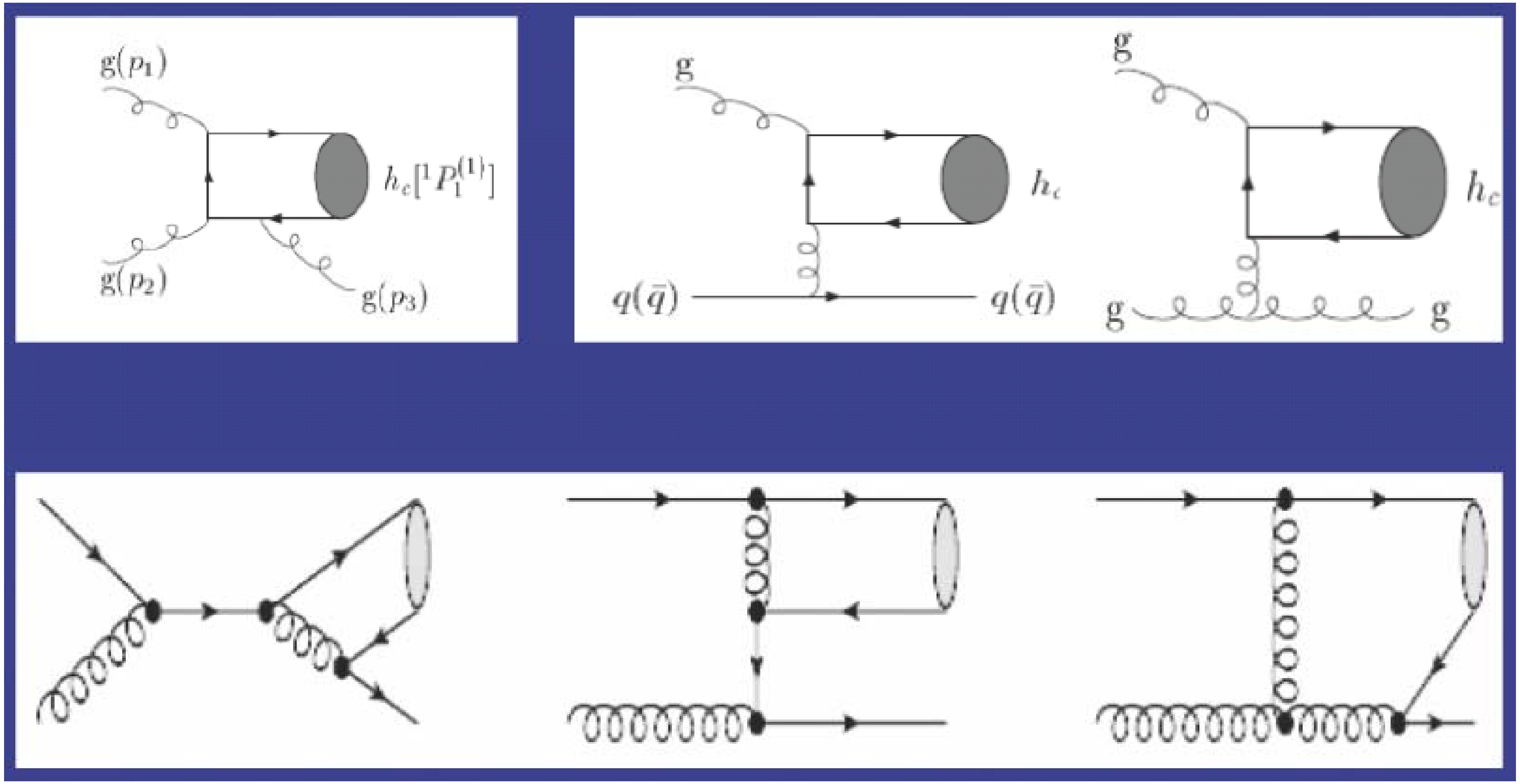
➢It is found that the LHC will produce a huge number of h_c , which enables people to perform precise study on its nature

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

- $g + g \to h_c({}^1S_0^{[8]}) + g$
- $g + q(\bar{q}) \to h_c({}^1S_0^{[8]}) + q(\bar{q})$
- $q + \bar{q} \to h_c({}^1S_0^{[8]}) + g$
- $g + g \to h_c({}^1P_1^{[1]}) + g$
- $g + c(\bar{c}) \to h_c({}^1P_1^{[1]}) + c(\bar{c})$

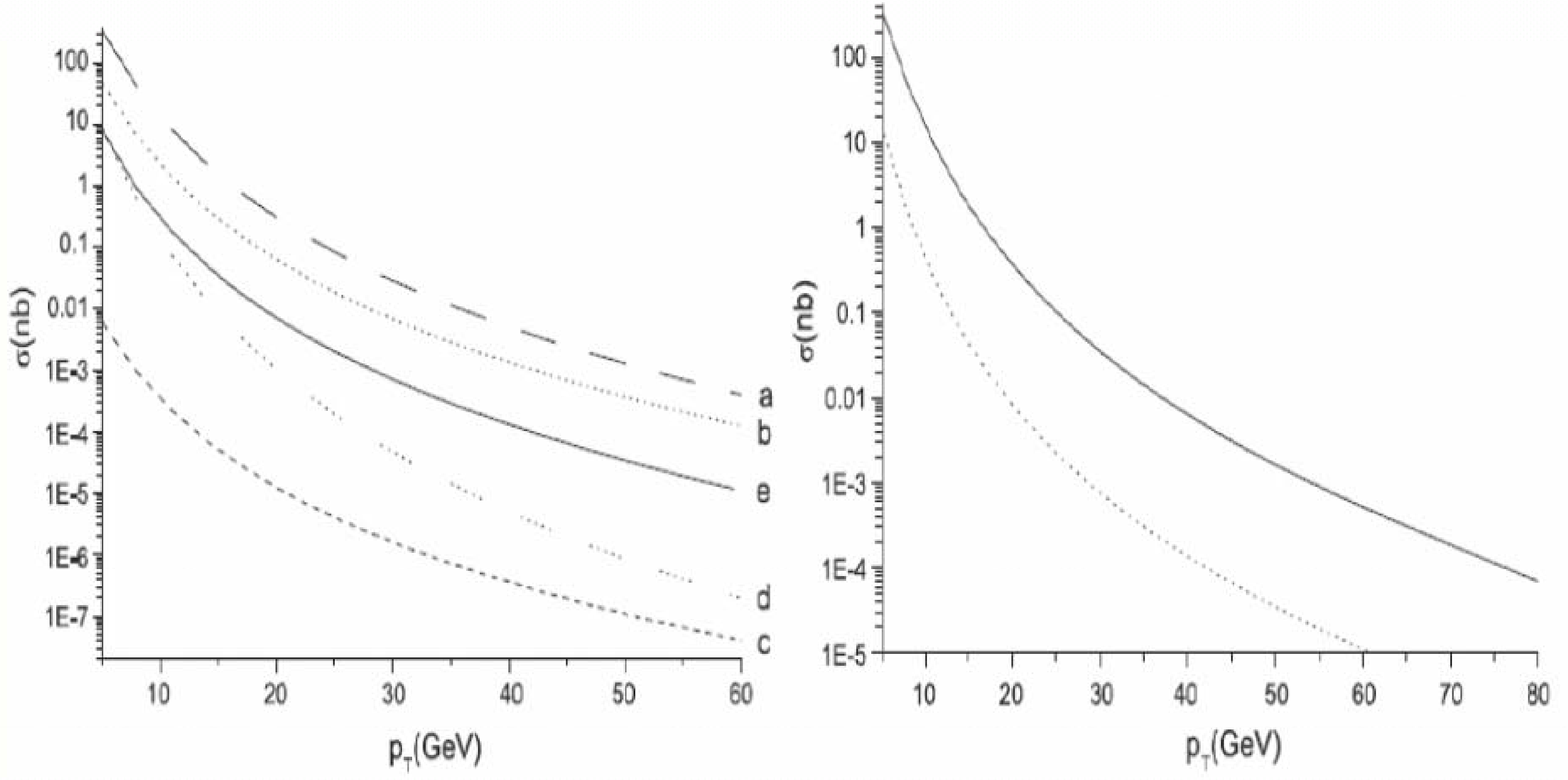
The typical Feynman diagrams



- The processes (1)-(4) were numerically calculated
  [Sridhar, 2009; Qiao and Yuan, 2001; Qiao, et al., 2009]

- It was found that the intrinsic charm process (5) is very important in the h_c production at the LHC
  [QIAO, et al., 2009]

We obtain(a-e for process 1-5 on the left; on right, 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

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

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

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

- 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 tells:

	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

That tells:

	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

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Direct Measurement of η_b at the LHC

- LHC can produce 10^8~10^9 η_b per year, η_c is about the same order

- Recently, the $\eta_b \rightarrow J/\psi\ J/\psi$ process was calculated at the next-to-leading order accuracy and find the NLO correction many enhance the branching fraction to the same level of relativistic correction

[Bin Gong, Yu Jia, and J.X.Wang, PLB, 2009; Braguta & Kartvelishvili, PRD, 2010; Sun, Hao, Qiao, PLB, 2010]

The typical Feynman diagrams

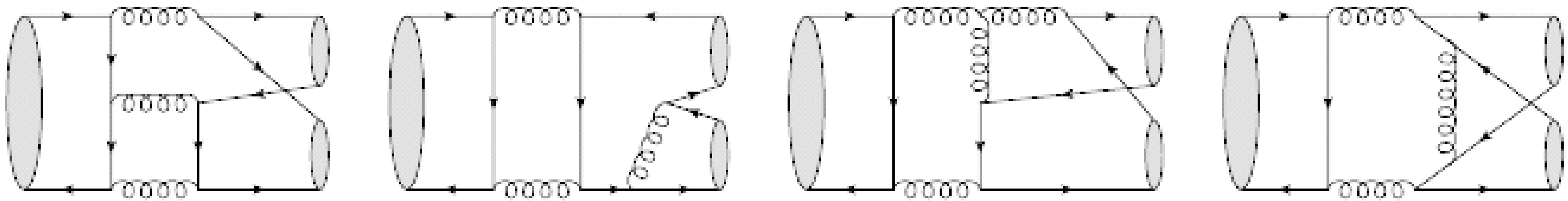

FIG. 1: Typical Feynman diagrams of the exclusive process $\eta_b(P_{\eta_b}) \to J/\psi(P_{J/\psi_1}) + J/\psi(P_{J/\psi_2})$ at the one-loop level.

Because of parity and Lorentz invariance, the decay amplitude possesses the following unique tensor structure

$$\mathcal{M}(\lambda_1, \lambda_2) = \mathcal{A}\, \varepsilon_{\mu\nu\rho\sigma} \varepsilon^{*\mu}_{J/\psi_1}(\lambda_1) \varepsilon^{*\nu}_{J/\psi_2}(\lambda_2) P^{\rho}_{J/\psi_1} P^{\sigma}_{J/\psi_1} .$$

After a lengthy calculation in NRQCD formalism, we get

$$Br[\eta_b \to J/\psi J/\psi] = 5.93 \times 10^{-8} \sim 2.58 \times 10^{-7}$$

with the following inputs

$$\psi_{J/\psi}(0) = 0.263\ \mathrm{GeV}^{3/2},\ m_c = 1.5\ \mathrm{GeV},\ m_b = 4.7\ \mathrm{GeV},\ \alpha_s = 0.18 \sim 0.26$$

which is unreachable in LHC experiment

However, in light-cone formalism, after taking the NLO twist contribution into account, we find

$$Br[\eta_b \to J/\psi J/\psi] = (1.1 \sim 2.3) \times 10^{-6} \,.$$

It is marginal in LHC experiment

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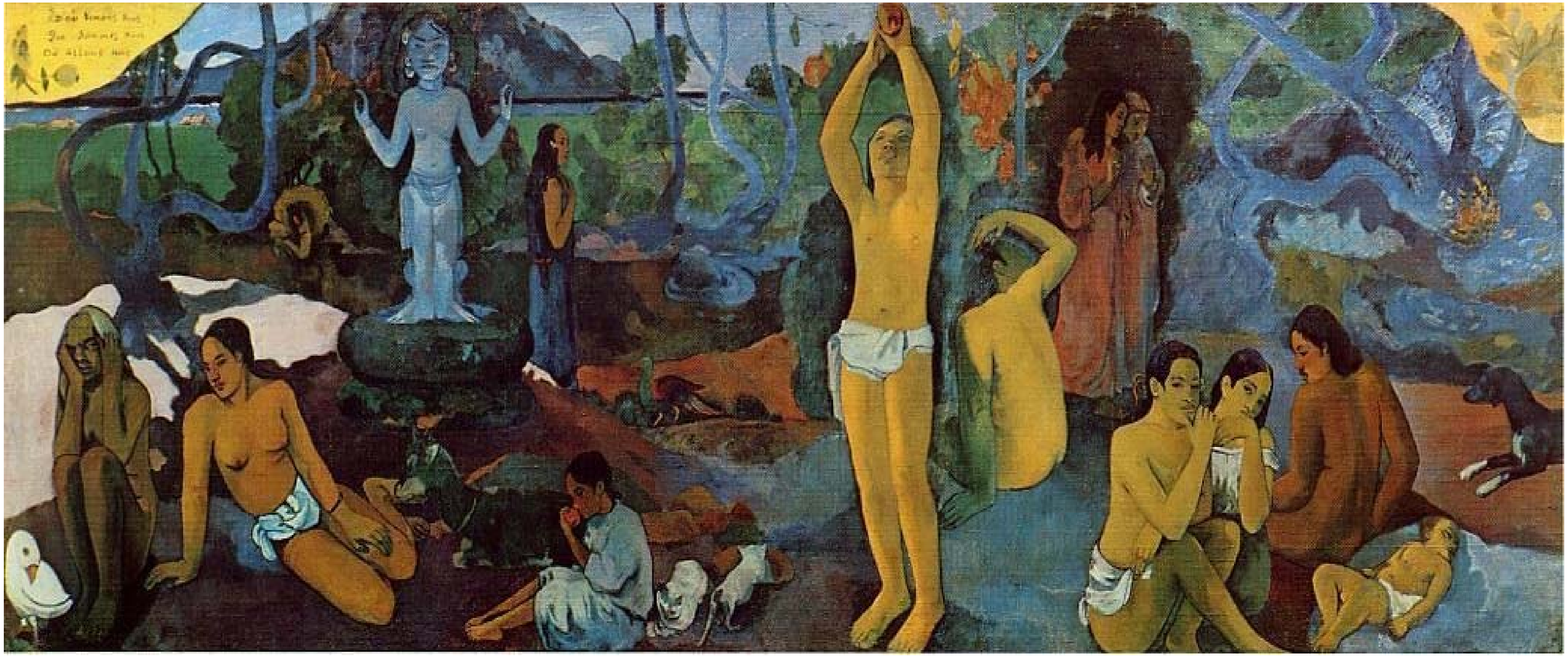
Summary

- The LHC produces a huge number of η_c 、 η_b and h_c, which enable people to make precise measurements on them

- Besides these states, $\eta_c^{`}$ 、$\eta_b^{`}$ and h_b also deserve to pay attention to

Thanks for your attention!



Where Do We Come From? What Are We?
Where Are We Going? ---Paul Gauguin