粲 偶 素 与 类 粲 偶 素

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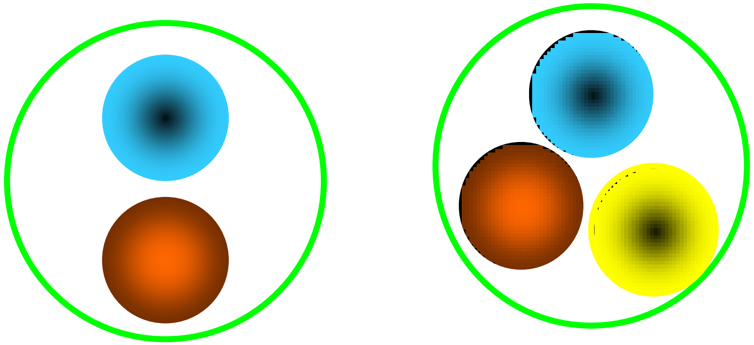
Hadrons: normal & exotic

- Hadrons are composed from 2 (meson) or 3 (baryon) quarks

Quark model



- QCD allows hadrons with $N_{quarks} \neq 2, 3$
  - glueball : $N_{quarks} = 0$ (gg, ggg, …)
  - hybrid : $N_{quarks} = 2$ or more + excited gluon
  - Multiquark state : $N_{quarks} > 3$
  - molecule : bound state of more than 2 hadrons

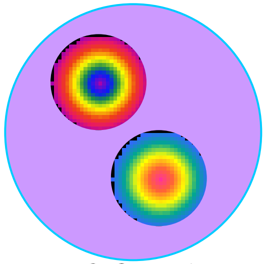
A bit of history on exotics hunting

- "The absence of exotics is one of the most obvious features of QCD" – R. L. Jaffe, 2005
- Deuteron ➔ H state, $\Omega^{-}\Omega^{-}$ bound state, …
- No solid signature of glueballs
- A pentaquark state appeared and disappeared

  ("The story of pentaquark shows how poorly we understand QCD" – F. Wilczek, 2005)
- Do we still have hope? — many XYZ states!

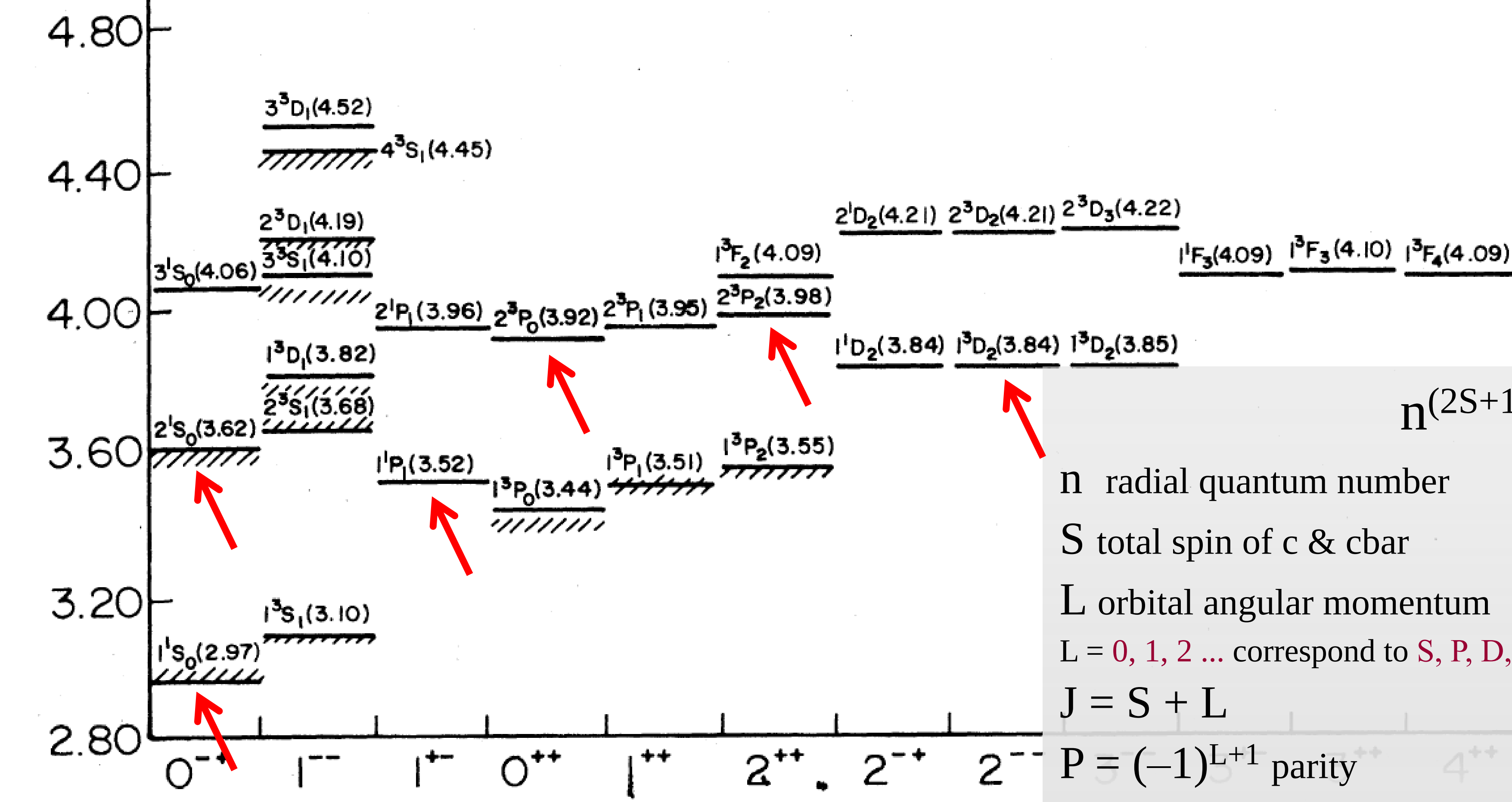
Outline

- Charmonium & XYZ states
- What BESIII/BelleII can do and cannot do
- What STCF can do
- Summary



Charmonium spectroscopy

States below charm threshold are all observed now,
still many missing states above charm threshold.



Godfrey & Isgur, PRD32, 189 (1985)

$$n^{(2S+1)}L_J$$

- n radial quantum number
- S total spin of c & cbar
- L orbital angular momentum
- L = 0, 1, 2 ... correspond to S, P, D, …
- $J = S + L$
- $P = (-1)^{L+1}$ parity
- $C = (-1)^{L+S}$ charge conj.

Where are these states?

- $^1D_2$ (2^{-+}): mass ~ 3830 MeV should be narrow
  $^3D_2$ (2^{--}): only evidence in $\gamma\chi_{c1}$ at 3823 MeV, narrow
  [no $\bar{D}D$, below $\bar{D}D^*$ threshold]
- Where are the 2P, 3P spin-triplet states?
- Where are the 3S, 2P, 3P spin-singlets?
- Can we identify F-wave states?

- P-wave spin-triplets from S-wave E1 transition
- P-wave spin-singlets from S-wave hadronic transition
- $^1D_2$ may be produced in $h_c(2P)$ E1 transition

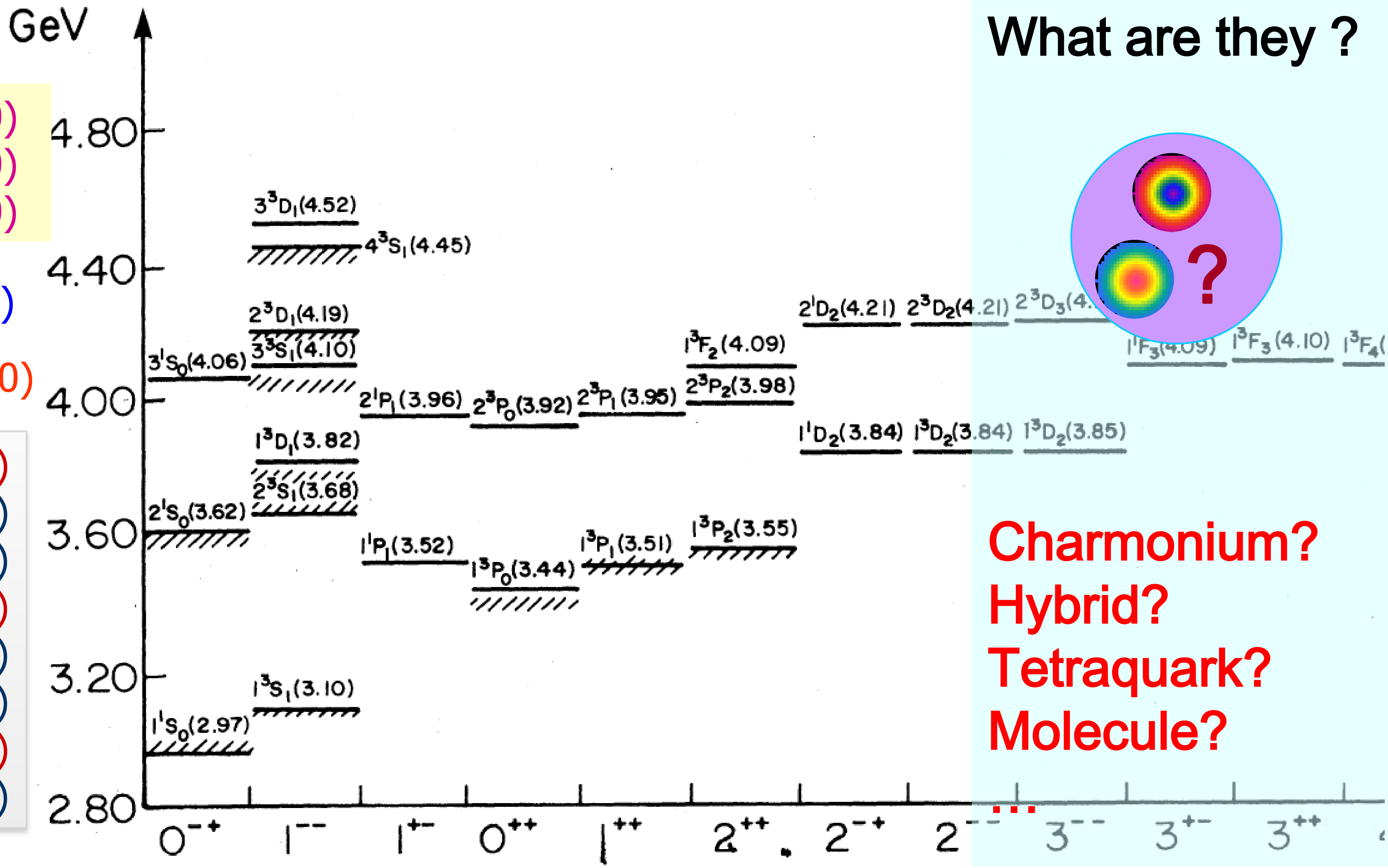
The XYZ states

Z(4430)
Z(4250)
Z(4050)

X(3872)

XYZ(3940)

X(3915)
X(4160)
Y(4008)
Y(4140)
Y(4260)
Y(4360)
X(4350)
Y(4660)



What are they ?

Charmonium?
Hybrid?
Tetraquark?
Molecule?
...

Not all XYZ states are charmonia!

XYZ states

neutral X and Y

Name	J^{PC}	Γ(MeV)	Decay modes	Experiments	interpretation
X(3872)	$1^{++}/2^{-+}$	<1.2	$\pi\pi J/\psi$, $\gamma J/\psi$, DD^*, …	Belle/CDF/D0/BaBar/ LHCb	$\bar{D}D^*$ molecule?
X(3940)	$0^{?+}$	~37	DD^* (not DD, $\omega J/\psi$)	Belle	η_c''(?)
Y(3940)	$?^{?+}$	~30	$\omega J/\psi$ (not DD^*)	Belle/BaBar	
Y(4140)	$?^{?+}$	~11	$\phi J/\psi$	CDF & CMS (not Belle/LHCb)	$c\bar{c}s\bar{s}$?
X(4160)	$0^{?+}$	~140	D^*D^* (not DD, DD^*)	Belle	η_c''(?)
Y(4008)	1^{--}	~220	$\pi\pi J/\psi$	Belle (not Babar)	$\psi(4040)$?
Y(4260)	1^{--}	~80	$\pi\pi J/\psi$	BaBar/CLEO/Belle	$c\bar{c}g$ hybrid?
X(4350)	$?^{?+}$	~13	$\gamma\gamma$, $\phi J/\psi$	Belle	$c\bar{c}s\bar{s}$?
Y(4360)	1^{--}	~75	$\pi\pi\psi(2S)$	BaBar/Belle	
Y(4660)	1^{--}	~50	$\pi\pi\psi(2S)$, $\Lambda_c\Lambda_c$ (?)	Belle/BaBar	

charged Z

$Z^{\pm}(4430)$	$?^{??}$	~100	$\psi(2S)\pi^{\pm}$	Belle (not Babar)	4-quark?
$Z^{\pm}(4050)$	$?^{??}$	~80	$\chi_{c1}\pi^{\pm}$	Belle (not Babar)	4-quark?
$Z^{\pm}(4250)$	$?^{??}$	~180	$\chi_{c1}\pi^{\pm}$	Belle (not Babar)	4-quark?

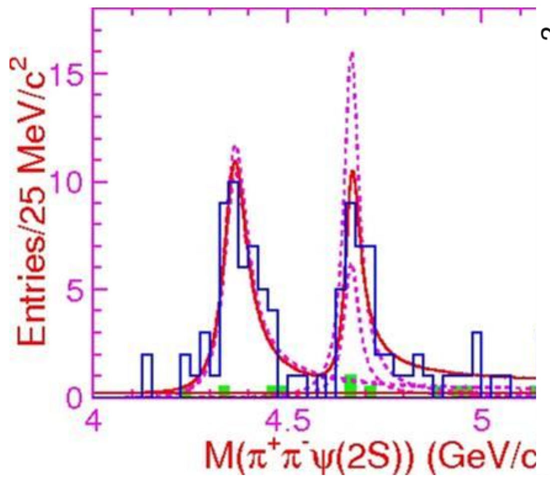
粲偶素与XYZ粒子研究前景

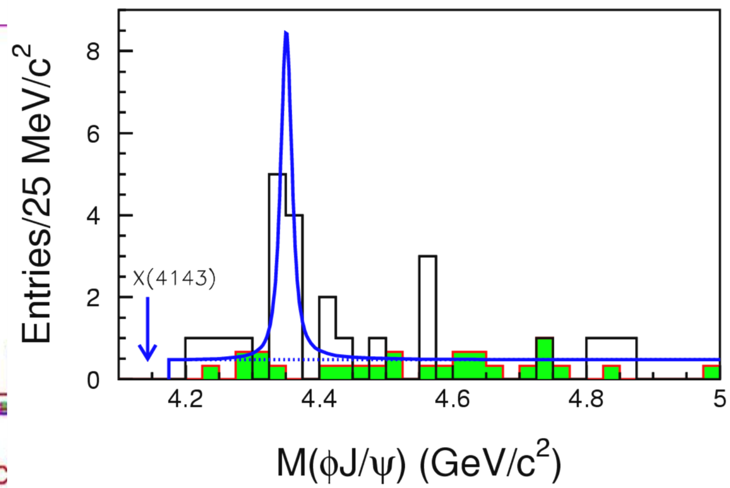
- CLEOc已停，合作组已不复存在，无足够数据进行相关研究；
- BaBar和Belle已停止运行，利用全部数据更新进行中，精度不会有显著改善；
- PANDA(Germany)遥遥无期，5(10?)年内不可能开始运行； Tau-C-factory (Russia) 干打雷不下雨；
- LHC实验（ATLAS, CMS, LHCb）背景复杂，仅能对非常少的过程进行测量。
- BESIII是近5年唯一可以系统研究 $c\bar{c}$ +XYZ的实验!
- BelleII 2016年采集数据，在2018年前不会有足够数据,但2018开始将再次主导该领域($c\bar{c}$ + XYZ!)!
- BelleII 50 ab^{-1}=50xBelle data by 2020!
- STCF 是本领域的未来。

BelleII —利用多种机制研究

粲偶素或类粲偶素粒子有多种产生机制：

1. 初态辐射产生
2. B介子衰变
3. 双光子产生
4. 双粲偶素产生
5. 粲偶素衰变
6. ϒ(1S)、ϒ(2S)衰变
7. 连续产生

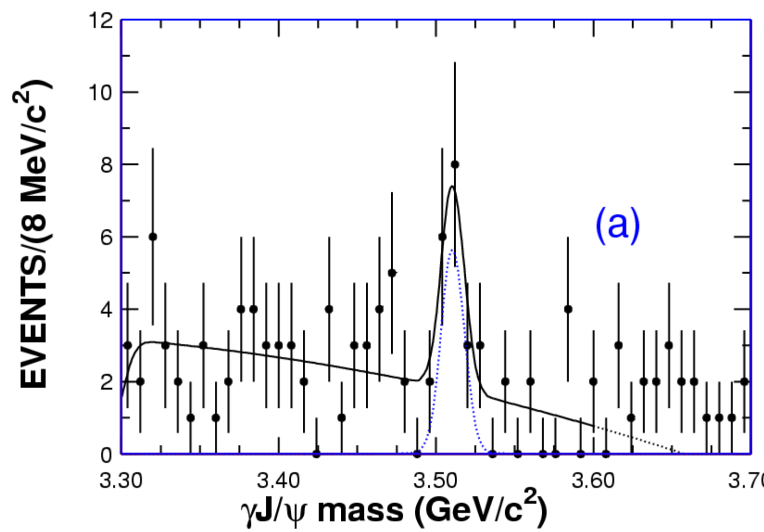




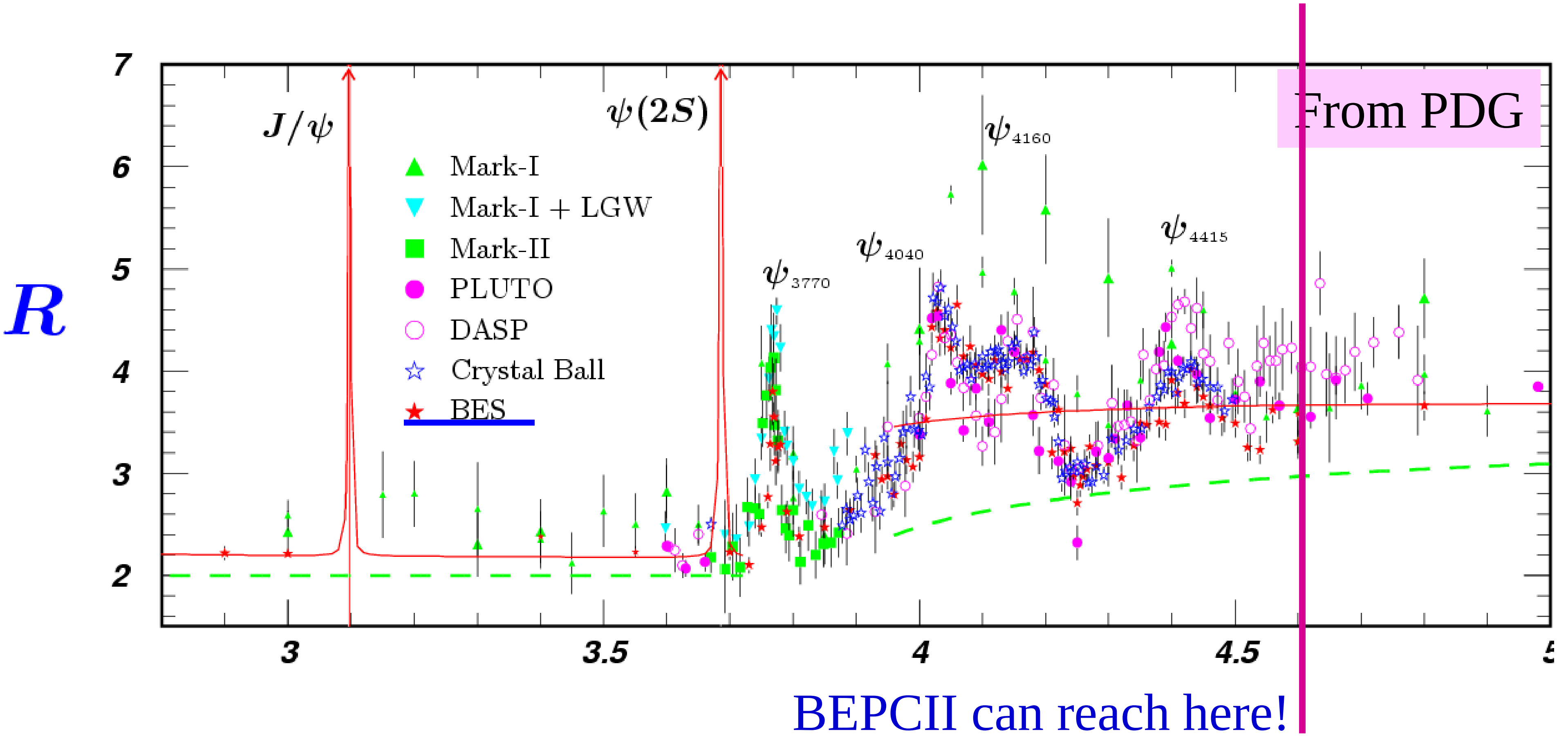
(类)底偶素产生：

- ϒ(5S)、ϒ(6S)衰变

  [SuperKEKB can reach 12 GeV]



BESIII: 粲偶素、类粲偶素的产生



ψ/Y 粒子可以直接产生（出现在上图中）

电荷共轭宇称为正的粒子可以通过辐射跃迁产生

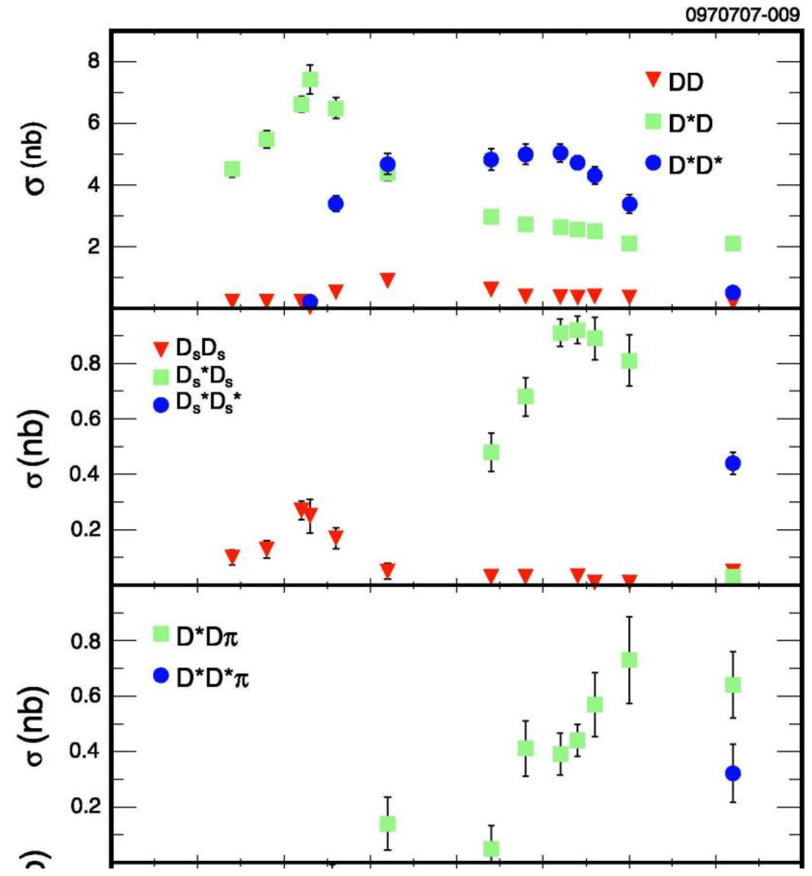
通过R值扫描研究矢量态

- 目标：确定ψ激发态和Υ态的共振参数和衰变特性
- 方法：精确测量不同能量点各主要过程截面
- 利用耦合道信息拟合数据

$$|A_{res}|^2 = \sum_f \left| \sum_r A_r^f(W) \right|^2$$

$$A_r^f(W) = \frac{M_r\sqrt{\Gamma_r^{ee}\Gamma_r^f}}{W^2 - M_r^2 + iM_r\Gamma_r} e^{i\delta_r}$$

$$\Gamma_r^{had}(W) = \frac{2M_r}{M_r + W} \sum_f \Gamma_r^f(W)$$



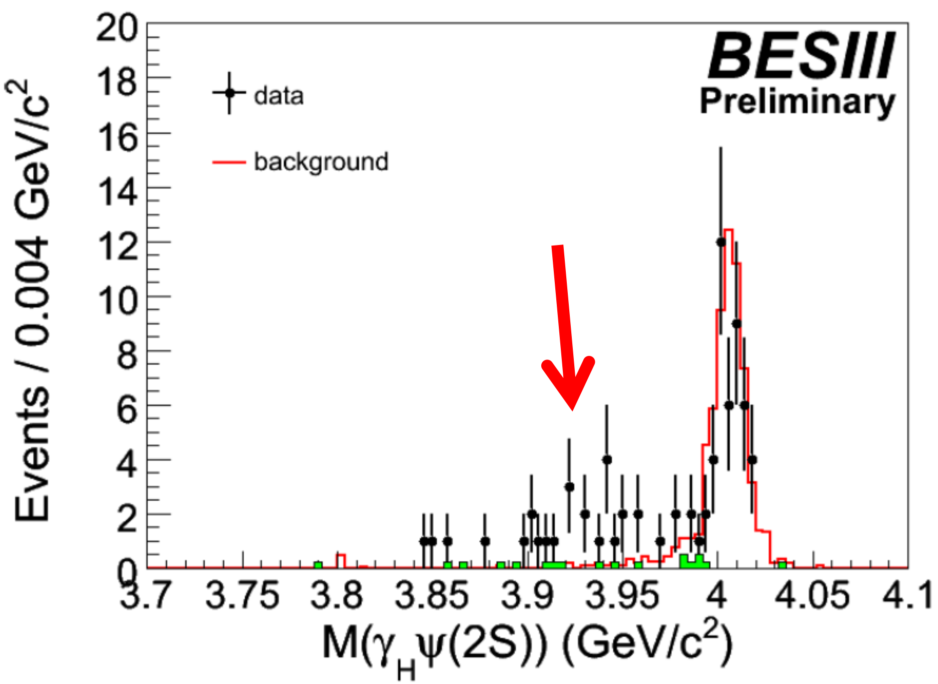
通过矢量态辐射跃迁研究C=+的态

- ψ(nS/nD)→γ+XYZ [X(3872), XYZ(3940)等]
  - 跃迁几率没有理论预期
- 寻找χ_{cJ}(2P)、χ_{cJ}(3P)、η_c(3S)、 η_c(4S)、 …
  - B(ψ(3S)→$\gamma\chi'_{cJ}$)=(7, 3, 1)x10^{-4} for J=2,1,0

[E. Eichten et al., Rev. Mod. Phys. 80, 1161 (2008)]

- 完善粲偶素能谱

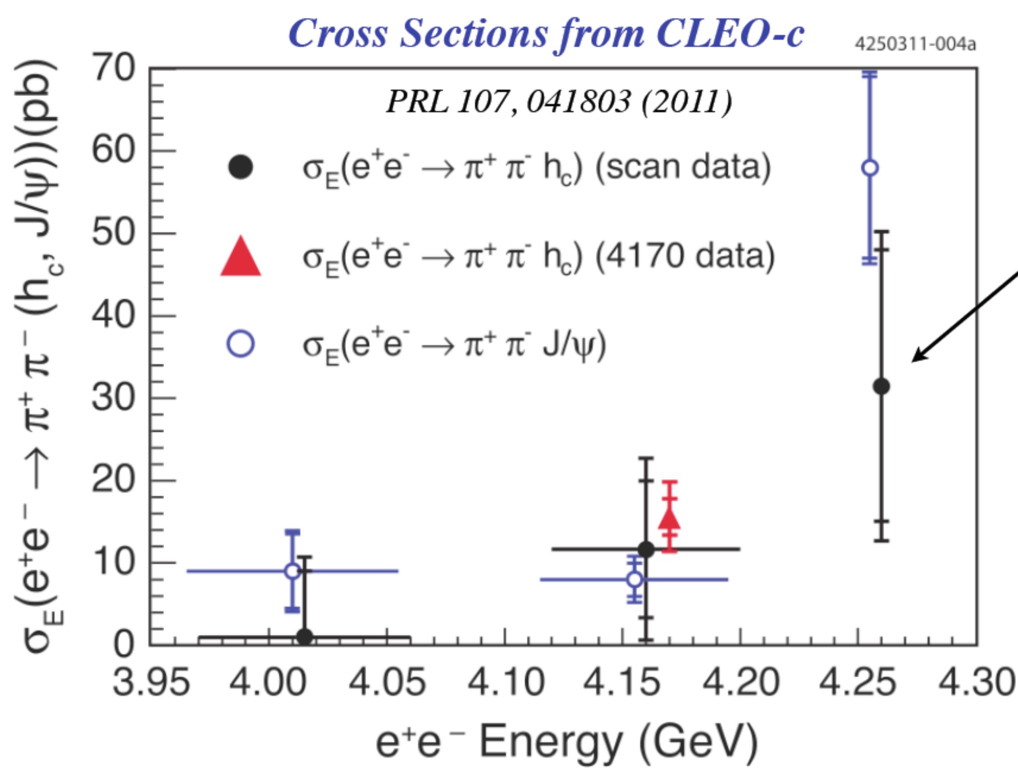
  确认奇特态粒子



寻找矢量态强子跃迁中的共振结构

- 目标：寻找Z_c态，寻找$h_c(2P)$态
- 方法：分析$Y(4260) \rightarrow \pi\pi J/\psi$、$\pi\pi h_c(1P)$中的中间态

  分析$Y(4360) \rightarrow \pi\pi\psi'$、$\pi\pi h_c(2P)$中的中间态



CLEO-c results are "suggestive" but far from definitive

(based on only 13.1 pb^{-1} of data at 4260 MeV)

This can be definitively studied at BESIII…

STCF topics

- $\eta_{c2}(^1D_2)$ production and decays
- Where is $\chi_{c1}(2P)$?
- Can we see X(3872)?
- $Z_c \rightarrow \pi J/\psi$, πh_c, $\pi\chi_c$
- Identify $\bar{c}cg$ hybrid state via e+e- $\rightarrow \gamma\eta_c$ and $\gamma\chi_{c0}$ cross section scan
- Other charmonium+XYZ topics

If $\eta_{c2}(1^1D_2) \neq X(3872)$, find it!

- $\sigma(e+e- \rightarrow \pi^+\pi^- h_c(2P))$ ~ 20 pb @Ecm=?? GeV
- $B(h_c(2P) \rightarrow \gamma\eta_{c2})$ ~ $3\text{x}10^{-4}$ [E1 trans., Barnes'05]
- $B(\eta_{c2} \rightarrow \gamma h_c)$ ~ (44-54)% [E1 trans., Fan'09]
- $B(h_c \rightarrow \gamma\eta_c)$ ~ 54% [E1 trans., BESIII'10]
- $\varepsilon B(\eta_c \rightarrow \text{hadrons})$ ~ 2% at BESIII [Yuping Guo'12]
- $N^{obs}=3\text{x}10^{-5}\text{x}L$ (L is integrated luminosity in pb^{-1})
- $L_{peak}=10^{36}/cm^2/s$, 1 year running = $10^7 pb^{-1}=10 ab^{-1}$
- N^{obs}=300/year; bkg is low for narrow h_c & η_{c2}
- A BESIII-like detector OK; simulations needed

If $\chi_{c1}(2^3P_1) \neq X(3872)$, find it!

- $\sigma(e^+e^- \rightarrow \psi(nS)/\psi(mD)) \sim$ (3-7) nb for n>2, m>1
- $B(\psi \rightarrow \gamma\chi'_{c1}) \sim 3\text{x}10^{-4}$ [E1 trans., Barnes'05]
- $B(\chi'_{c1} \rightarrow \gamma\psi') \sim 1\text{x}10^{-3}$ [E1 trans., Barnes'05]
- $B(\chi'_{c1} \rightarrow \gamma J/\psi) \sim 1\text{x}10^{-4}$ [E1 trans., Barnes'05]
- $\varepsilon B \sim$ (1-5)% at BESIII [Zhiqing Liu'12]
- $N^{obs}=(1\text{-}10)\text{x}10^{-5}\text{x}L$ (Lum. in pb^{-1})
- $L_{peak}=10^{36}/cm^2/s$, 1 year running = $10^7 pb^{-1}=10 ab^{-1}$
- N^{obs}=(100-500)/year; bkg low for narrow ψ', J/ψ
- A BESIII-like detector OK; simulations needed

Search for X(3872) in ψ decays

- $\sigma(e^+e^- \rightarrow \psi(nS)/\psi(mD)) \sim$ (3-7) nb for n>2, m>1
- $B(\psi \rightarrow \gamma X)$ unknown
- $B(X \rightarrow \pi^+\pi^- J/\psi) \sim 5\%$ [my guess]
- $\varepsilon B \sim 5\%$
- $N^{obs} = (10\sim20) \times B(\psi \rightarrow \gamma X) \times L$ (Lum. in pb^{-1})
- $L_{peak} = 10^{36}/cm^2/s$, 1 year running = $10^7 pb^{-1} = 10 ab^{-1}$
- One year data at a ψ peak will reach a sensitivity of $B(\psi \rightarrow \gamma X) \sim O(10^{-7})$ level
- X(3872) would be extremely exotic if it cannot be produced at 10^{-7} level in charmonium decays!

$Z_c \rightarrow \pi J/\psi$, πh_c, $\pi\chi_c$

- $\sigma(e^+e^- \rightarrow \pi\pi$+charmonium$) \sim O(10)$ pb
- Look for states in π+charmonium
- $\varepsilon B \sim 3\%$ for $\pi\pi h_c \rightarrow \pi\pi\gamma\eta_c$
- $\varepsilon B \sim 5\%$ for $\pi\pi J/\psi$
- $\varepsilon B \sim 2\%$ for $\pi\pi\chi_c \rightarrow \pi\pi\gamma J/\psi$
- $L_{peak}=10^{36}/cm^2/s$, 1 year running = $10^7 pb^{-1}=10 ab^{-1}$
- $N^{obs}=O(10^6)$/year; enough for PWA

- May also measure other charmonia at high energy

$H_{ccg} \rightarrow \gamma\eta_c$ & $\gamma\chi_{c0}$

- $\sigma(e^+e^- \rightarrow H_{ccg}) \sim$ O(10-100) pb [???]
- $B(H_{ccg} \rightarrow \gamma\eta_c) \sim 2x(B(H_{ccg} \rightarrow \gamma\chi_{c0}) \sim 4x10^{-4}$

  [in H, $\bar{c}c$ in spin-singlet! LQCD by Dudek'09]
- Scan e+e-$\rightarrow \gamma\eta_c$ and $\gamma\chi_{c0}$ for exotic structures
- $\varepsilon B \sim 10\%$ for $\gamma\eta_c$ and $\gamma\chi_{c0} \rightarrow \gamma$+hadrons
- $L_{peak}=10^{36}/cm^2/s$, 1 year running = $10^7 pb^{-1}=10ab^{-1}$
- At 100 energy points above DD threshold
- $N^{obs}(\gamma\eta_c)$=O(40~400)/point/year at peak
- $N^{obs}(\gamma\chi_{c0})$=O(20~200)/point/year at peak

Summary

- We still do not quite understand strong interaction at low energy; charmonium can help
- STCF with L_{peak}~$10^{36}/cm^2/s$ is needed for charmonium & charmoniumlike states study
- A detector comparable to BESIII should work for these topics [so not expensive!]
- More MC studies needed to understand the background, and to improve the sensitivity

Thanks a lot!