Some issues

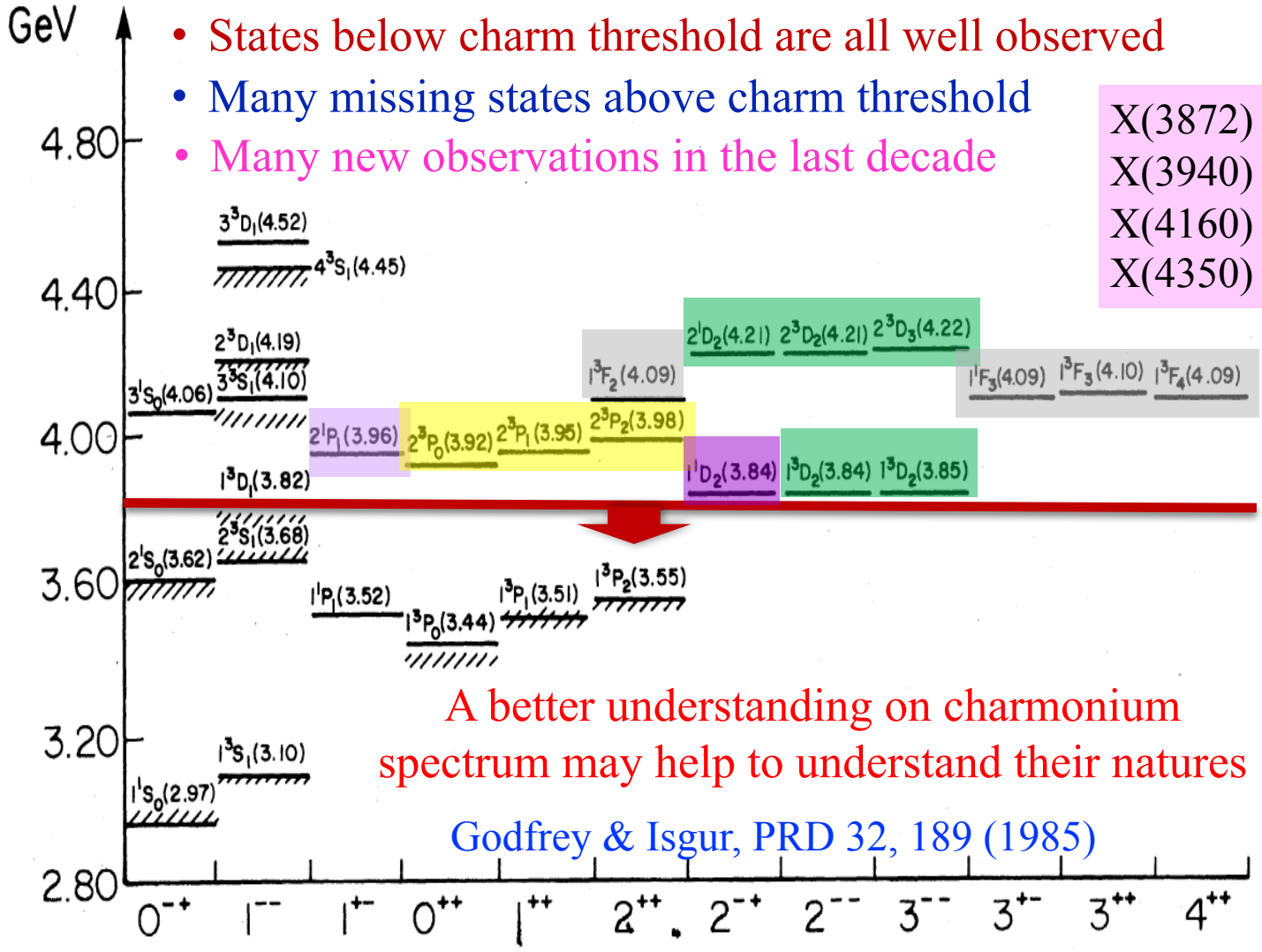
Xiao-Rui Lyu（吕晓睿）

中国科学院大学

Charmonium-(like) spectroscopy

Key Science question : Is there any exotic hadron exist

- States below charm threshold are all well observed
- Many missing states above charm threshold
- Many new observations in the last decade



X(3872)
X(3940)
X(4160)
X(4350)

Y(3940)
Y(4008)
Y(4220)
Y(4360)
Y(4660)

Z(3900)
Z(4020)
Z(4050)
Z(4200)
Z(4250)
Z(4430)

Nature unclear

- Charmonium?
- Hybrid?
- Tetraquark?
- Molecule?
- Non-resonance?

A better understanding on charmonium spectrum may help to understand their natures

Godfrey & Isgur, PRD 32, 189 (1985)

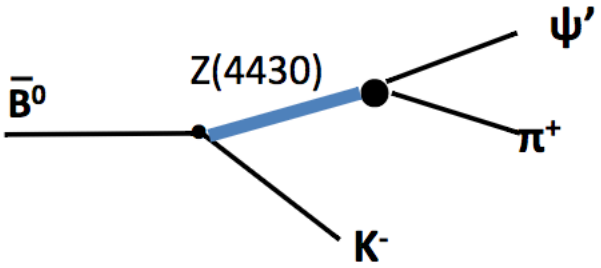
Exotics found in different channels

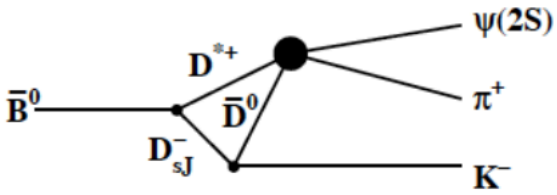
Process	Production	Decay	Particle
B and Λ_b Decays	$B \to K + X$	$X \to \pi^+\pi^- J/\psi$ [4, 109, 110, 111, 112, 113, 114] $X \to D^{*0}\bar{D}^0$ [115, 116, 117] $X \to \gamma J/\psi$ [118, 119, 120, 121] $X \to \gamma\psi(2S)$ [118, 120]	$X(3872)$
		$X \to \omega J/\psi$ [106, 122, 123]	$X(3872)$ $Y(3940)$
		$X \to \gamma\chi_{c1}$ [124]	$X(3823)$
		$X \to \phi J/\psi$ [125, 126, 127, 128, 129, 130, 131, 132]	$Y(4140)$ $Y(4274)$ $X(4500)$ $X(4700)$
	$B \to K + Z$	$Z \to \pi^\pm\chi_{c1}$ [133, 134]	$Z_1(4050)$ $Z_2(4250)$
		$Z \to \pi^\pm J/\psi$ [46, 135]	$Z_c(4200)$ $Z_c(4430)$
		$Z \to \pi^\pm\psi(2S)$ [30, 135, 136, 137, 138, 139]	$Z_c(4240)$ $Z_c(4430)$
	$B \to K\pi + X$	$X \to \pi^+\pi^- J/\psi$ [140]	$X(3872)$
	$\Lambda_b \to K + P_c$	$P_c \to pJ/\psi$ [35]	$P_c(4380)$ $P_c(4450)$
e^+e^- Annihilation	$e^+e^- \to Y$	$Y \to \pi\pi J/\psi$ [23, 29, 141, 142, 143, 144, 145]	$Y(4008)$ $Y(4260)$
		$Y \to \pi\pi\psi(2S)$ [108, 146, 147, 148]	$Y(4360)$ $Y(4660)$
		$Y \to \omega\chi_{c0}$ [149]	$Y(4230)$
		$Y \to \Lambda_c\bar{\Lambda}_c$ [150]	$X(4630)$
		$Y \to \pi\pi\Upsilon(1S, 2S, 3S)$ [151, 152] $Y \to \pi\pi h_b(1P, 2P)$ [153]	$Y_b(10888)$
	$e^+e^- \to \pi + Z$	$Z \to \pi J/\psi$ [22, 23, 31, 32] $Z \to D^*\bar{D}$ [33, 154, 155]	$Z_c(3900)$
		$Z \to \pi h_c$ [156, 157] $Z \to D^*\bar{D}^*$ [158, 159]	$Z_c(4020)$
		$Z \to \pi^\pm\psi(2S)$ [148]	$Z_c(4055)$
		$Z \to \pi\Upsilon(1S, 2S, 3S)$ [160, 161, 162] $Z \to \pi h_b(1P, 2P)$ [160]	$Z_b(10610)$ $Z_b(10650)$
		$Z \to B\bar{B}^*$ [163]	$Z_b(10610)$
		$Z \to B^*\bar{B}^*$ [163]	$Z_b(10650)$
	$e^+e^- \to \gamma + X$	$X \to \pi^+\pi^- J/\psi$ [52]	$X(3872)$
	$e^+e^- \to \pi^+\pi^- + X$	$X \to \gamma\chi_{c1}$ [164]	$X(3823)$
	$e^+e^- \to J/\psi + X$	$X \to D\bar{D}^*$ [41, 165]	$X(3940)$
		$X \to D^*\bar{D}^*$ [41]	$X(4160)$
$\gamma\gamma$ Collisions	$\gamma\gamma \to X$	$X \to \omega J/\psi$ [166, 167]	$X(3915)$
		$X \to D\bar{D}$ [168, 169]	$Z(3930)$
		$X \to \phi J/\psi$ [170]	$X(4350)$
Hadron Collisions	pp or $p\bar{p} \to X$+ anything	$X \to \pi^+\pi^- J/\psi$ [27, 171, 172, 173]	$X(3872)$
		$X \to \phi J/\psi$ [174]	$Y(4140)$
		$X \to B_s\pi^\pm$ [175]	$X(5568)$

Lebed, Mitchell, Swanson, PPNP93(2017)143

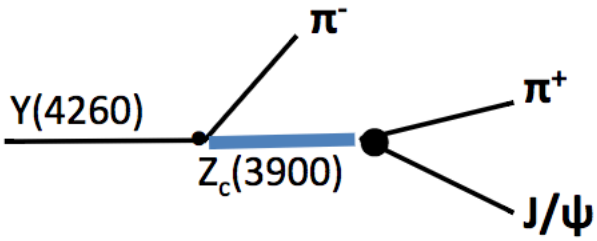
General issue with XYZ mesons

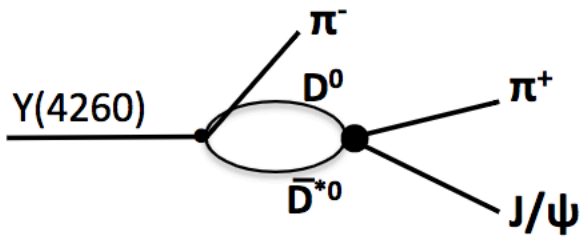
true resonances? ... or kInematical effects?





Landau singularity?





Threshold cusp?

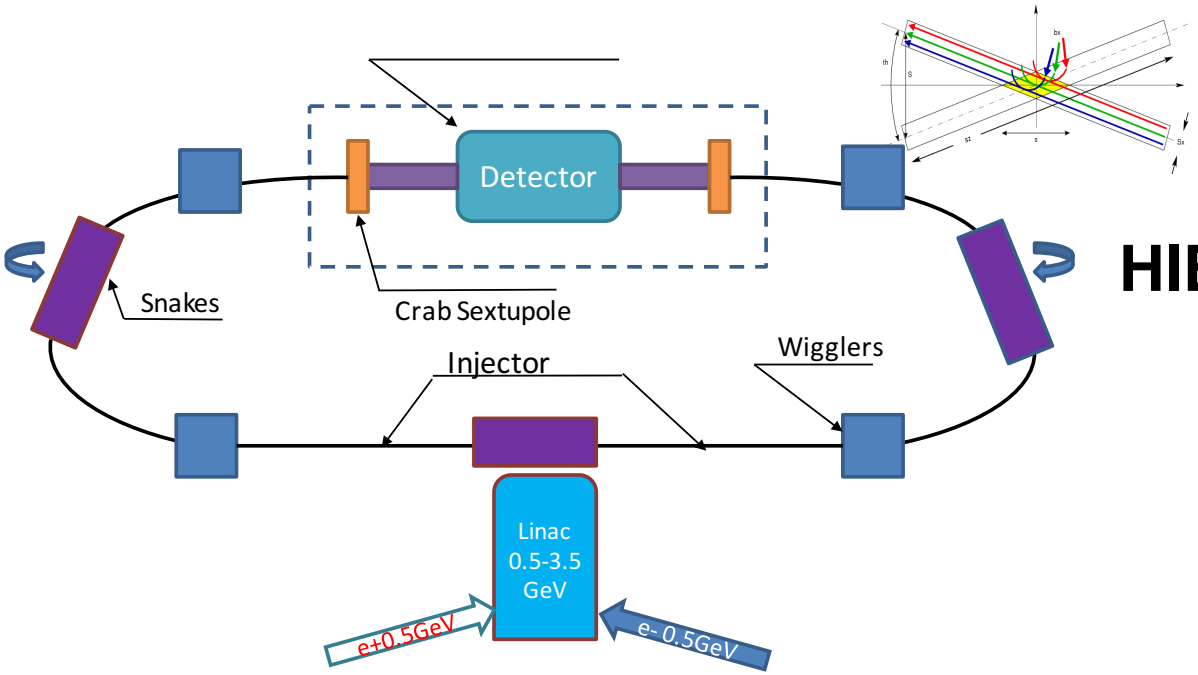
Two observations:

- 1^{--} Y's are not yet seen in b-hadron decays
- Zc seen in b decays are not seen in Y decays; vice versa

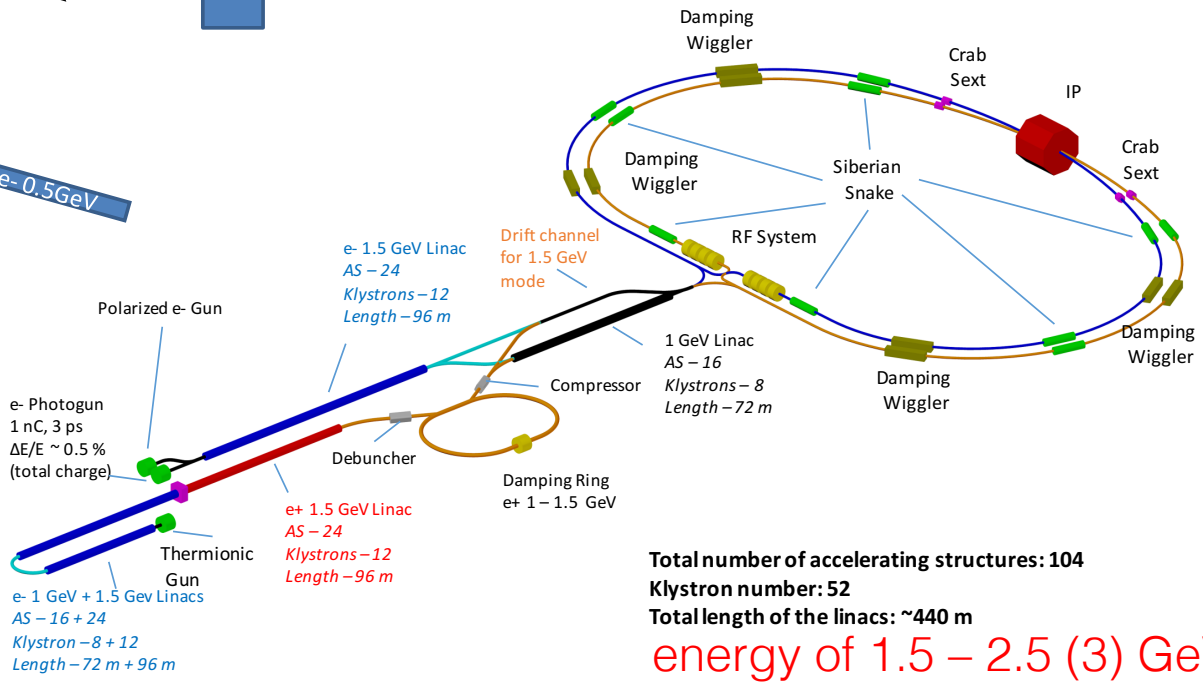
Question(s):

- Resonance? Particle?
- Well-defined pole position?

Proposals of the Super Tau-Charm Factory (STCF)



HIEPA in China



Super-CT Project in Russia

Total number of accelerating structures: 104
Klystron number: 52
Total length of the linacs: ~440 m

energy of 1.5 – 2.5 (3) GeV

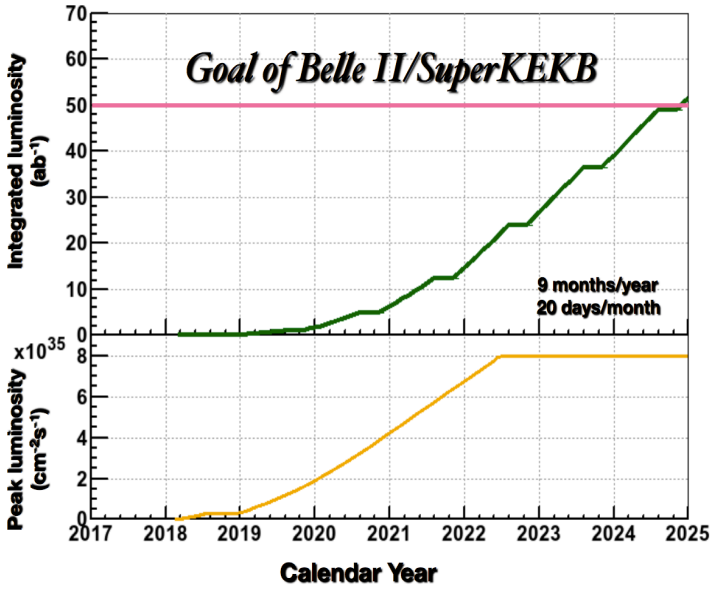
Integral Luminosity of STCF

- No Synchrotron radiation mode, assume running time 9 months/year
- Assume data taking efficiency 90%

$$10^{35}\text{cm}^{-2}\text{s}^{-1} \times 86400\text{s} \times 270\text{days} \times 90\% \sim \mathbf{2.0ab^{-1}/year}$$

10 years data taking, total 20 ab^{-1} conservatively

Excellent opportunities for the τ-charm physics



BELLEII each 1 ab^{-1} dataset provides

- $\sim 1.1 \times 10^9$ $B\bar{B} \Rightarrow$ a B-factory;
- $\sim 1.3 \times 10^9$ $c\bar{c} \Rightarrow$ a charm factory;
- $\sim 0.9 \times 10^9$ $\tau^+\tau^- \Rightarrow$ a τ factory;
- wide $E_{CM}^{eff.}$=[0.5-10] GeV via ISR.

Native question: competition between STCF and BELLE-II ?

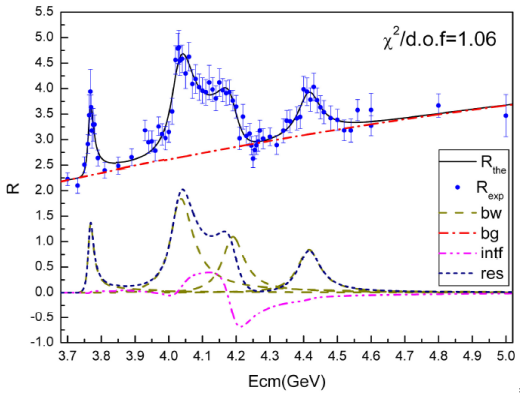
Charmonium(-like) states @ STCF

- ψ/Y/hybrid(ccg) (1^{--}) produced in the e^+e^- collision
  - To determine the resonance parameters for the excited ψ or Y state
  - Precisely measure the x-sec of inclusive/exclusive final states at different energy points
- Charge parity c=+1 states produced via radiative transition from vector ψ/Y/hybrid(ccg)
  - The decay rate ψ(nS/nD)→γX(3872), X(3940)…
  - Search for $\chi_{cJ}(2P)$、$\chi_{cJ}(3P)$、$\eta_c(3S)$、 $\eta_c(4S)$、 …

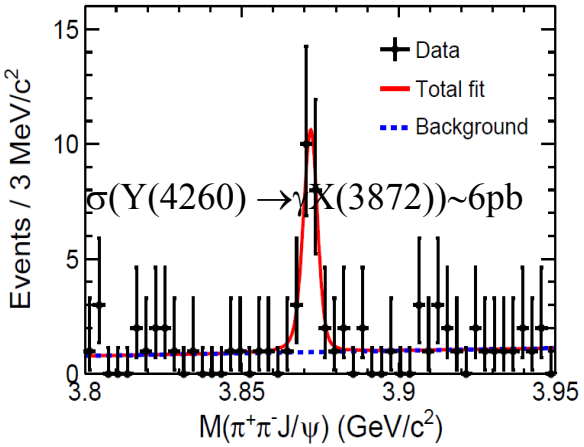
    $B(\psi(3S)\to\gamma\chi'_{cJ}) = (7, 3, 1) \times 10^{-4}$ for J=2,1,0

    [Rev. Mod. Phys. 80, 1161 (2008)]
- Search for new states from hadronic transition
  - To search for Zc, Zcs, hc(2P) ….

PLB 660, 315 (2008)



PRL 112, 092001 (2014)



Search for $\eta_{c2}(1^1D_2)$

Naïve estimations @ STCF
$L_{peak} = 10^{35}cm^{-1}s^{-1}$, 1 year running ~ 2 ab^{-1}
a BESIII-like detector

$\eta_{c2}(1^1D_2)$

- $\sigma(e^+e^-\to\pi^+\pi^-h_c(2P)) \sim 20$ pb @ Ecm=??GeV
- $B(h_c(2P)\to\gamma\eta_{c2}) \sim 3\times10^{-4}$ [E1 trans., Barnes′ 05]
- $B(\eta_{c2}\to\gamma h_c) \sim (44–54)\%$ [E1 trans., Fan′ 09]
- $B(h_c\to\gamma\eta_c) \sim 54\%$ [E1 trans., BESIII′10]
- $\varepsilon B(\eta_c\to\text{hadrons}) \sim 1.5\%$ at BESIII
- $N^{obs}=2\times10^{-5}\times L$ (L is int. lumi. in pb^{-1})
- $N^{obs}=40$ events /year,
- Bkg is low for narrow h_c and η_c

$\eta_{c2}(1^1D_2)$

- $pp \to \eta_{c2}X, \eta_{c2} \to \mu^+\mu^- h_c, h_c \to \bar{p}p\pi^+\pi^-$
- $\eta_{c2} \to \gamma h_c$ (future upgrade ECAL?)
- In addition, search for $h_c \to \pi^+\pi^- J/\psi$

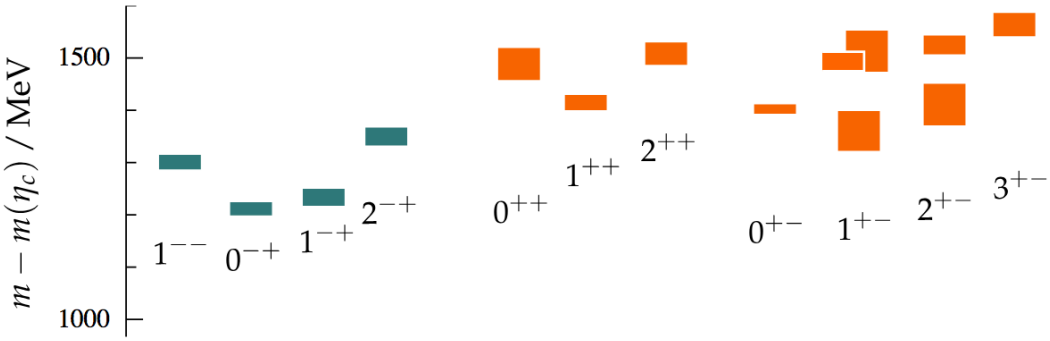
at LHCb

Search for 1^{--} hybrid $H_{ccg} \to \gamma\eta_c$ & $\gamma\chi_{c0}$

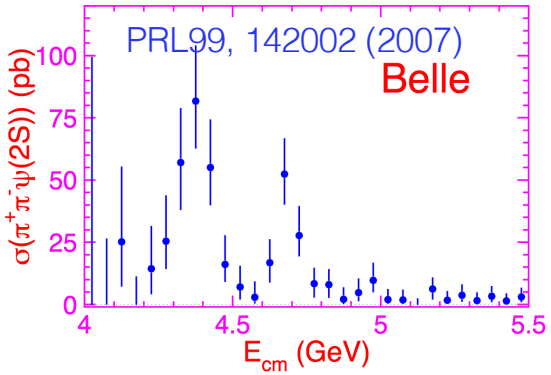
- 1^{--} Hybrid may produce directly in e^+e^- collision, and radiative decay to spin-zero charmonium states [in Hybrid, cc in spin-singlet, LQCD by Dudek'09]
  - Assume $\sigma(e^+e^- \to H_{ccg})$ ~ O(10–100) pb [???]
  - $B(H_{ccg} \to \gamma\eta_c) \sim 2 \times B(\eta_{c2} \to \gamma\chi_{c0}) \sim 4 \times 10^{-4}$
- Scan between 4-5 GeV for 1 year ($2ab^{-1}$), search for exotic structure in process $e^+e^- \to \gamma\eta_c$ and $\gamma\chi_{c0}$
  - Assume εB ~ 10% for $\gamma\eta_c$ and $\gamma\chi_{c0}$ decay to γ+hadrons
- With 100 energy points between 4-5 GeV
  - $N^{obs}(\gamma\eta_c)$=O(8-80) events/point/year at peak
  - $N^{obs}(\gamma\chi_{c0})$=O(4-40) events/point/year at peak

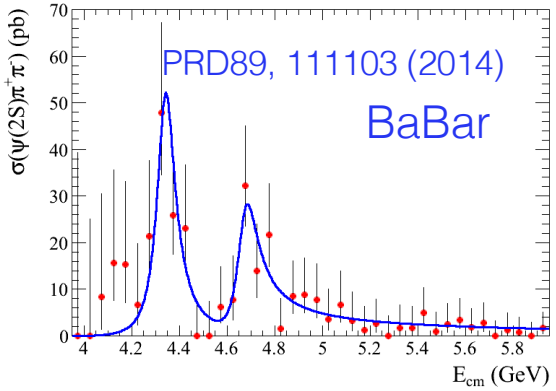
Question: production and decay rate

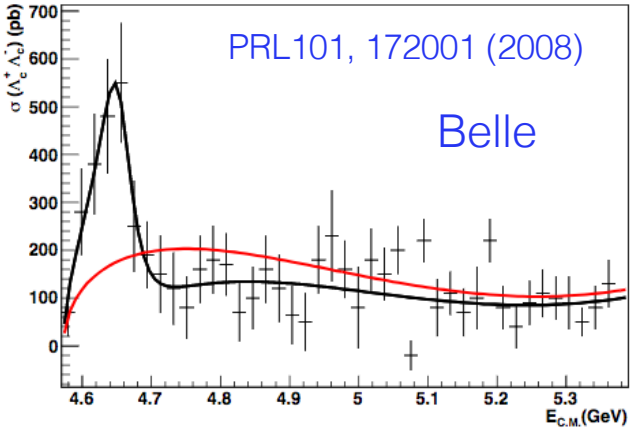
- Important to provide quantitative argument in the proposal
- Essential input for experiment design (CDR&TDR)
- Example search case:
  - Pc in $e^+e^- \to \bar{p}pJ/\psi$ (useful from $e^+e^- \to \bar{p}p\phi$?)
  - 0^{--} glueball in $e^+e^- \to h(1^+)\, G^{--}$ (predicted two states of 3.81 and 4.33GeV) *Phys.Rev.Lett. 113 (2014) 221601*
  - $H_{c\bar{c}g}$: production in e^+e^- and decay from $c\bar{c}$

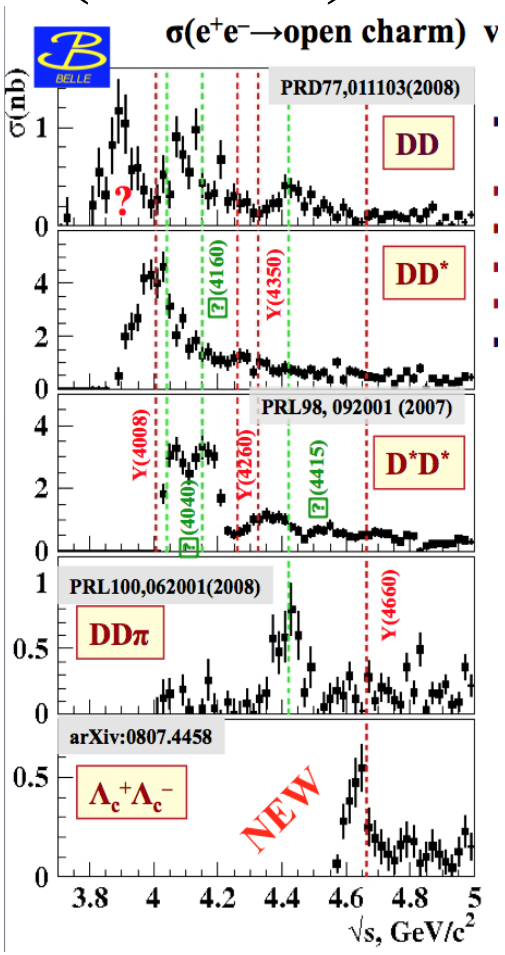


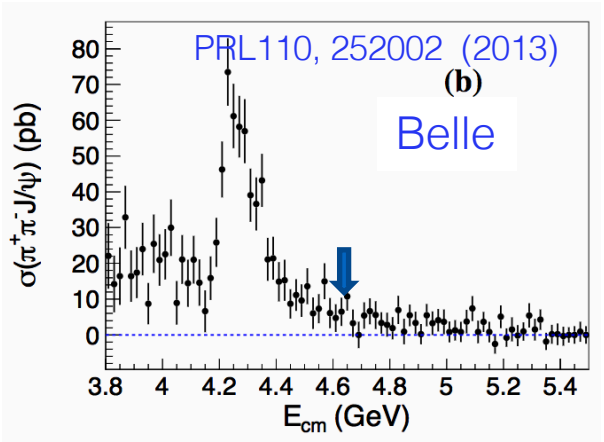
The Y(4630)/Y(4660)











$$\frac{\mathcal{B}(Y_B \to \Lambda_c \bar{\Lambda}_c)}{\mathcal{B}(Y_B \to \psi(2S)\pi^+\pi^-)} = 25 \pm 7,$$

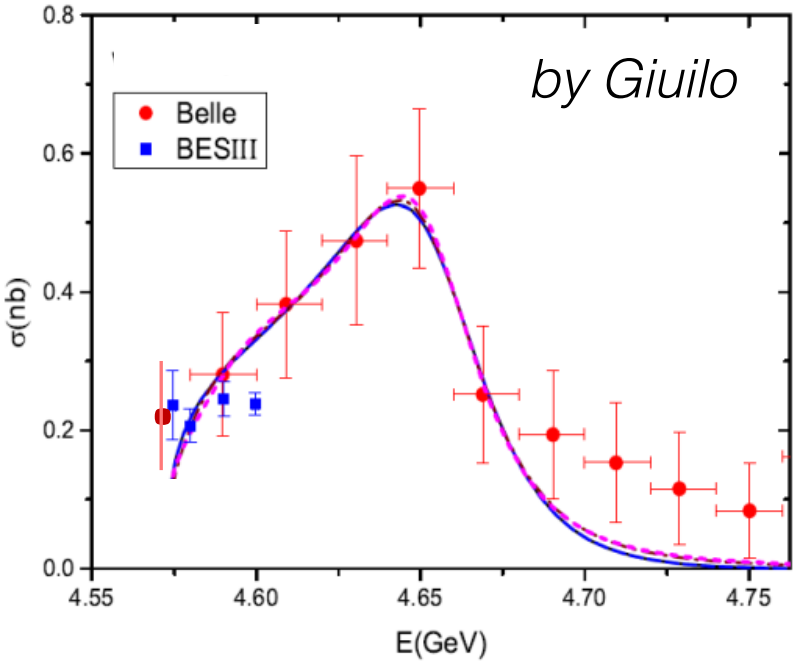
Phys.Rev.Lett. 104 (2010) 132005

$$\frac{B(Y_B \to D^0 D^{*-}\pi^+)}{B(Y_B \to \psi(2S)\pi^+\pi^-)} < 10$$

PDG

- Y(4660) baryonic coupling $\geq$ 10 mesonic coupling (unexpected!)
- Another missing large mesonic decay? Or Y(4660) is a charmed baryonium?

Lineshape of $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$



Belle: PRL101, 172001 (2008)
BESIII: PRL120,132001(2018)

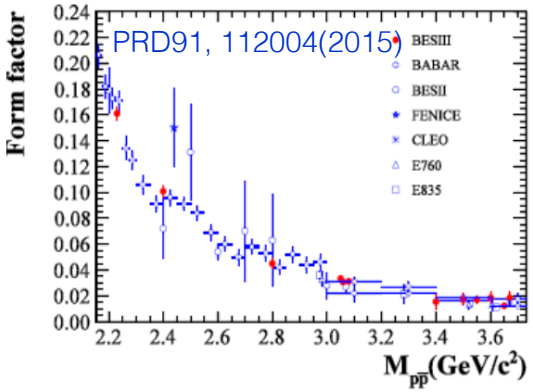
- Some tension between BELLE and BESIII data on $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$
- BESIII future data above 4.6 GeV will follow a sharp rise of the Y(4660) or a flat cross section near threshold?

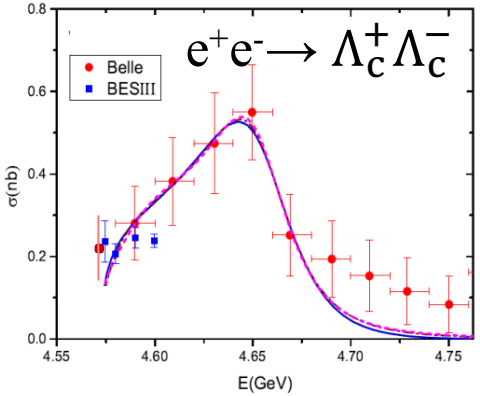
The threshold production of baryon pair

The Born cross section of the reaction $e^+e^- \to \gamma^* \to B\bar{B}$ can be parameterized in terms of electromagnetic form factors:

$$\sigma_{B\bar{B}}(q) = \frac{4\pi\alpha^2 C\beta}{3q^2}[|G_M(q)|^2 + \frac{1}{2\tau}|G_E(q)|^2]$$

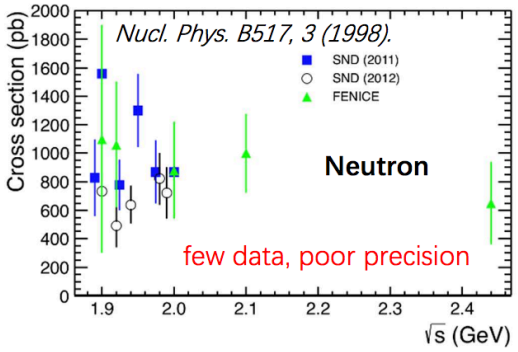
- Baryon velocity $\beta = \sqrt{1 - 4m_B^2c^4/q^2}$, $\tau = q^2/(4m_B^2c^4)$
- For charged B, the Coulomb factor C will results in a non-zero cross section at threshold

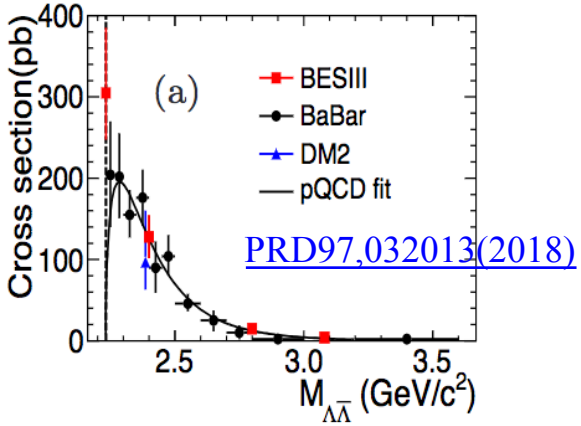


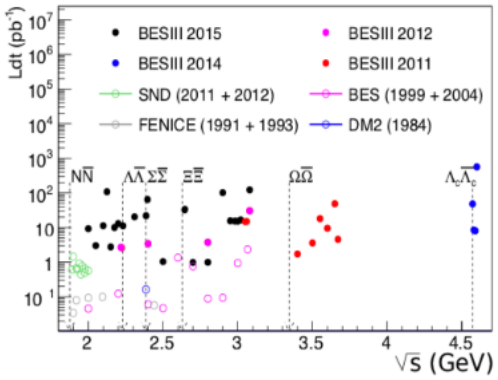


Form factor reflects spatial distributions of electric charge and current inside the nucleon

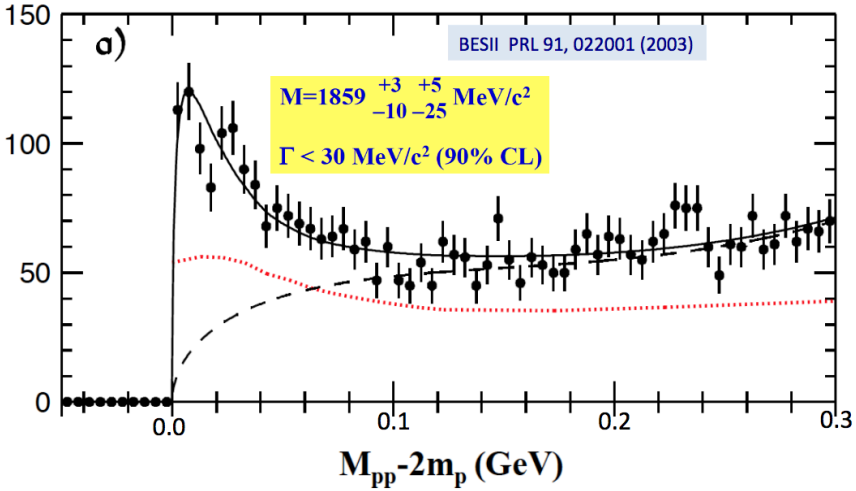
How to understand this?



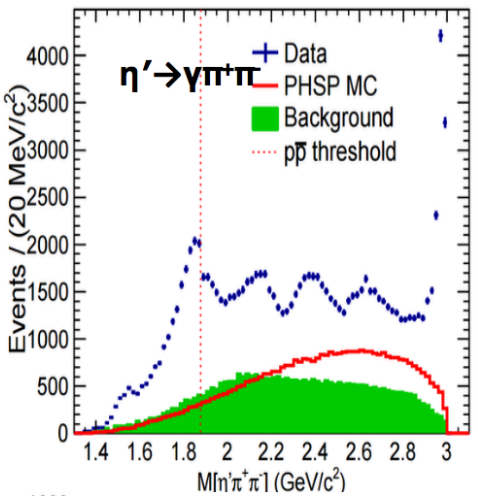




Baryonium state?

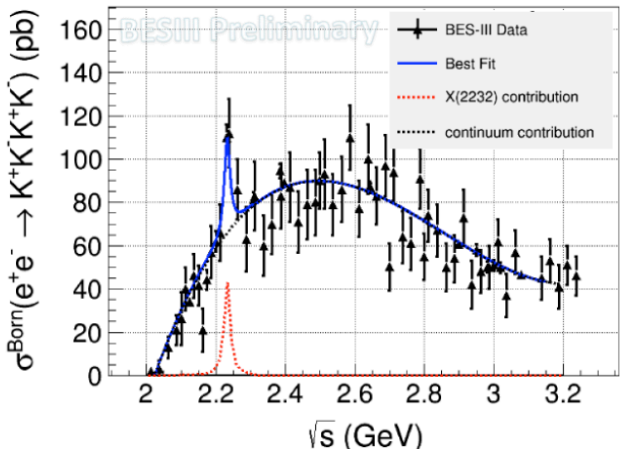


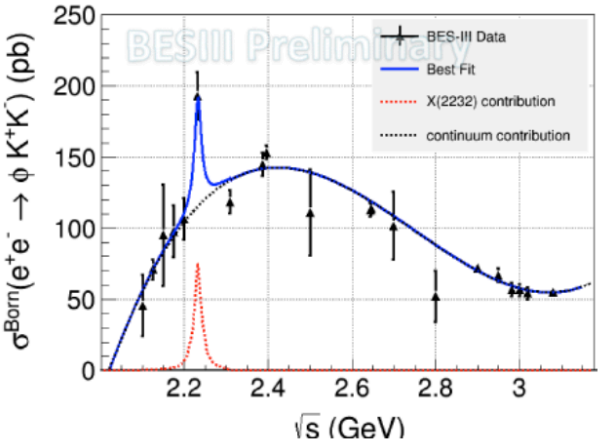
PRL 117, 042002 (2016)



M=2.232 ±3.5 MeV (2m$_\Lambda$=2.2314 MeV)

0^{+-} $p\bar{p}$ molecule??





1^{--} $\Lambda\bar{\Lambda}$ molecule??

Th-Ex Collaboration

- In the future, multidimensional, coupled-channel amplitude analyses for many final states will become necessary to fully map out all the findings.
- How to improve parameterizations of the dynamics
  - Breit-Wigner, K-matrix approach
  - Phenomenological parameterization of the amplitude for resonances and kinematic effects
- Need close collaboration to analyze data together
  - But how?
- Another way?

  a public database for archiving full experimental data and relevant efficiency tables, along with paper publication. So outside people can perform complicated fit