Exotic hadrons at e^+e^- machines

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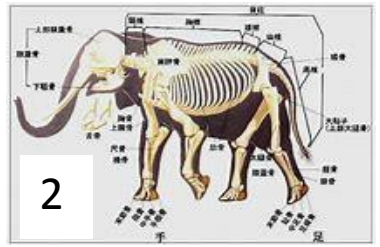
FPCP 2021, June 07 - 11, Shanghai

Outline



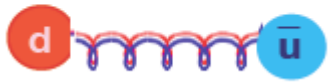
?

- Brief review
- Recent results
  1. Production modes
  2. Final state combinations
  3. Relations between XYZ
- Future

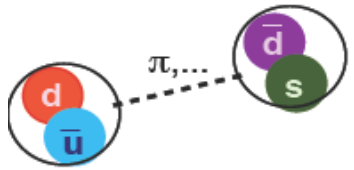
From meson/baryon to exotic hadrons

Glueball

Hybrid



Molecule



Pentaquark

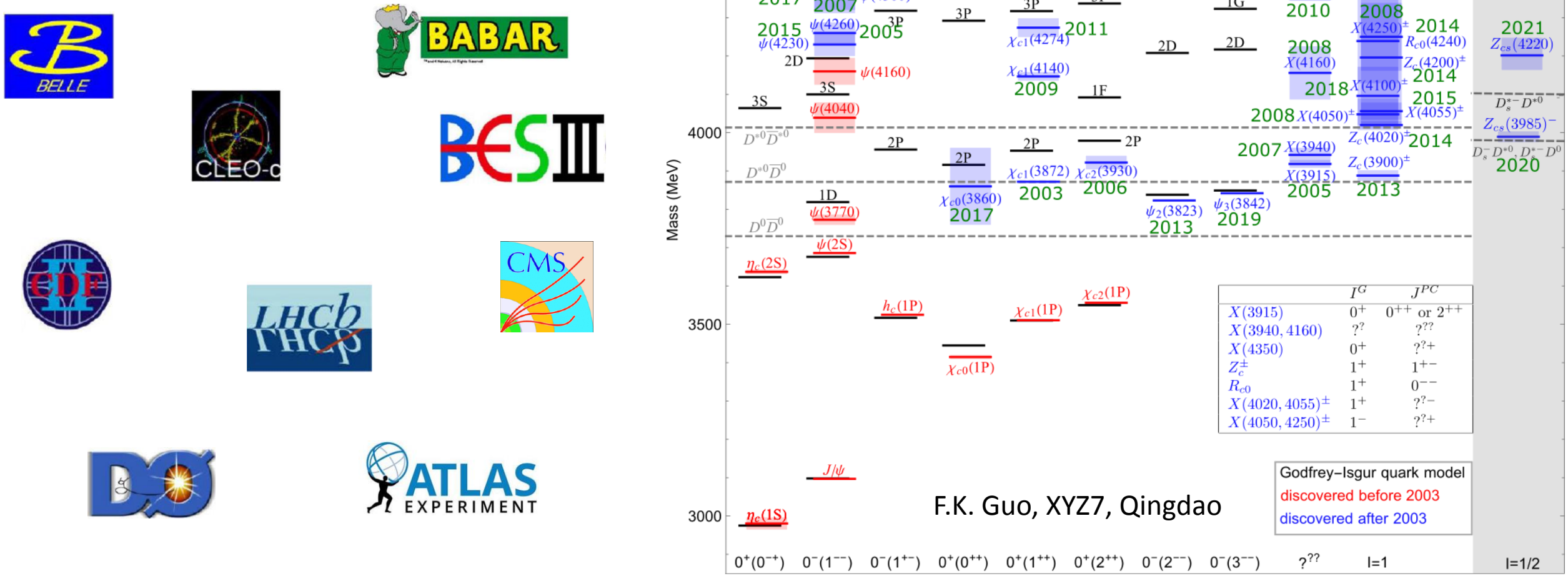
H-dibaryon

Tetraquark

All allowed by QCD

figures from arXiv:1403.1254, S. Olsen

Charmonium-like states Beyond potential model

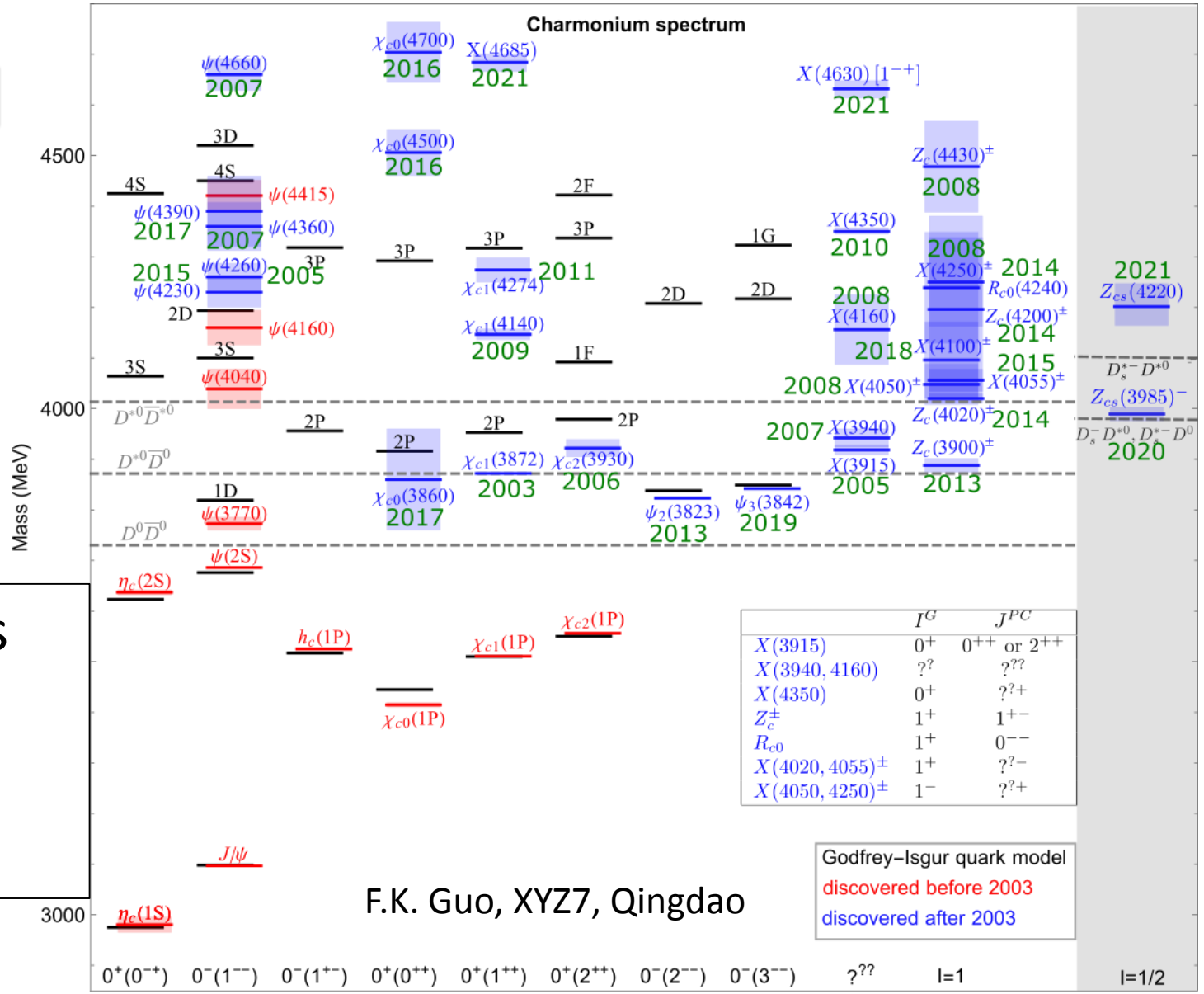


F.K. Guo, XYZ7, Qingdao

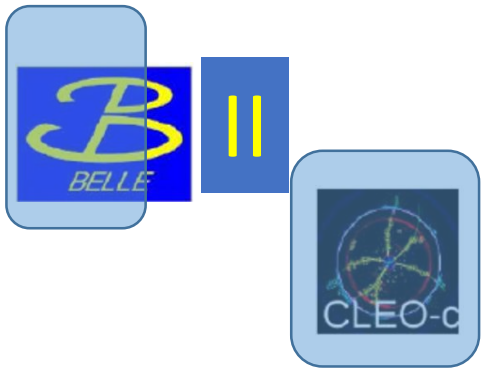
Charmonium-like states Beyond potential model

Specifications from e^+e^- machines

- Prologue: discovery of X(3872)
- Natural J^{PC} indicator: vector
- Smoking gun: charged Z_c



Charmonium-like states Beyond potential model



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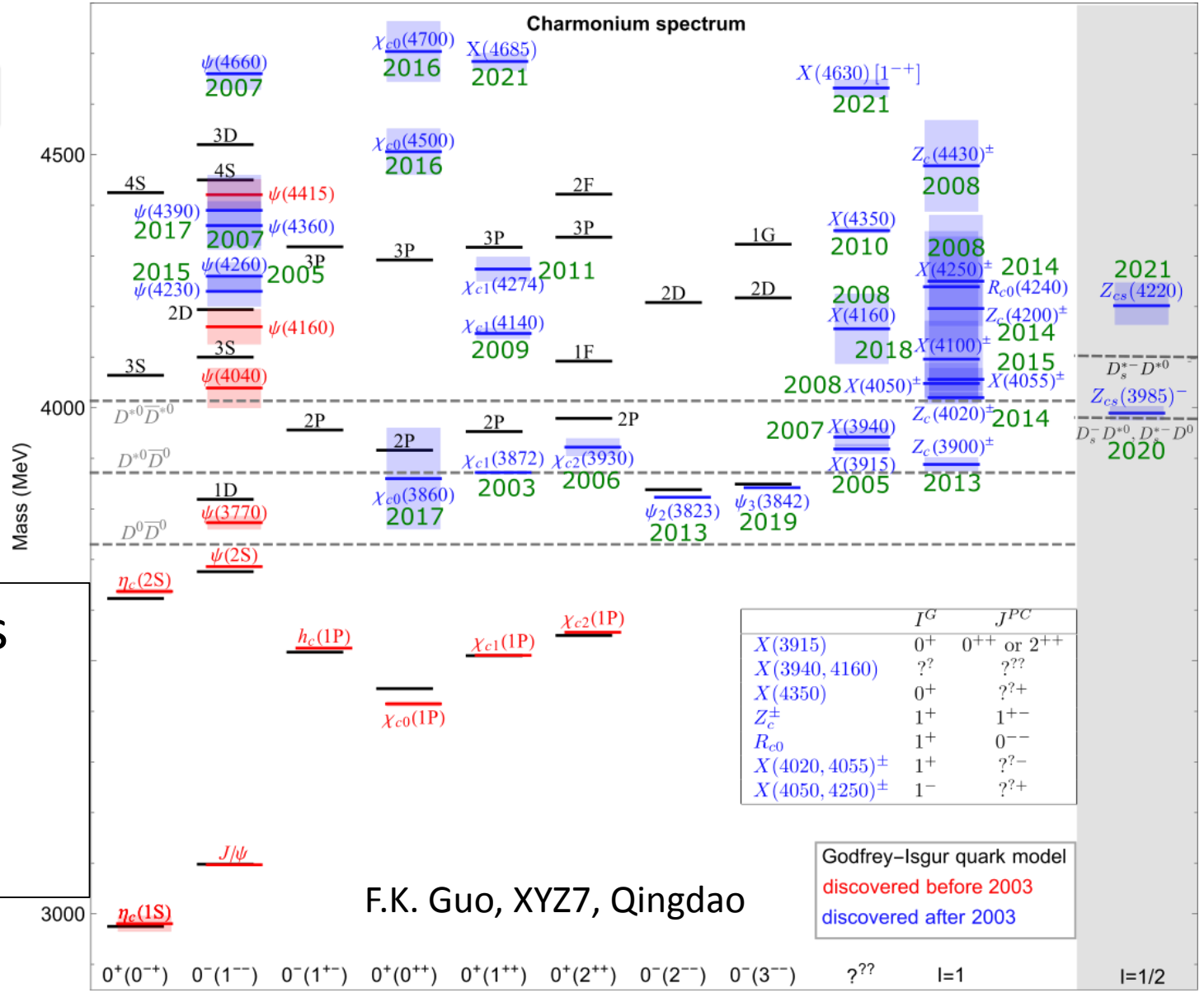
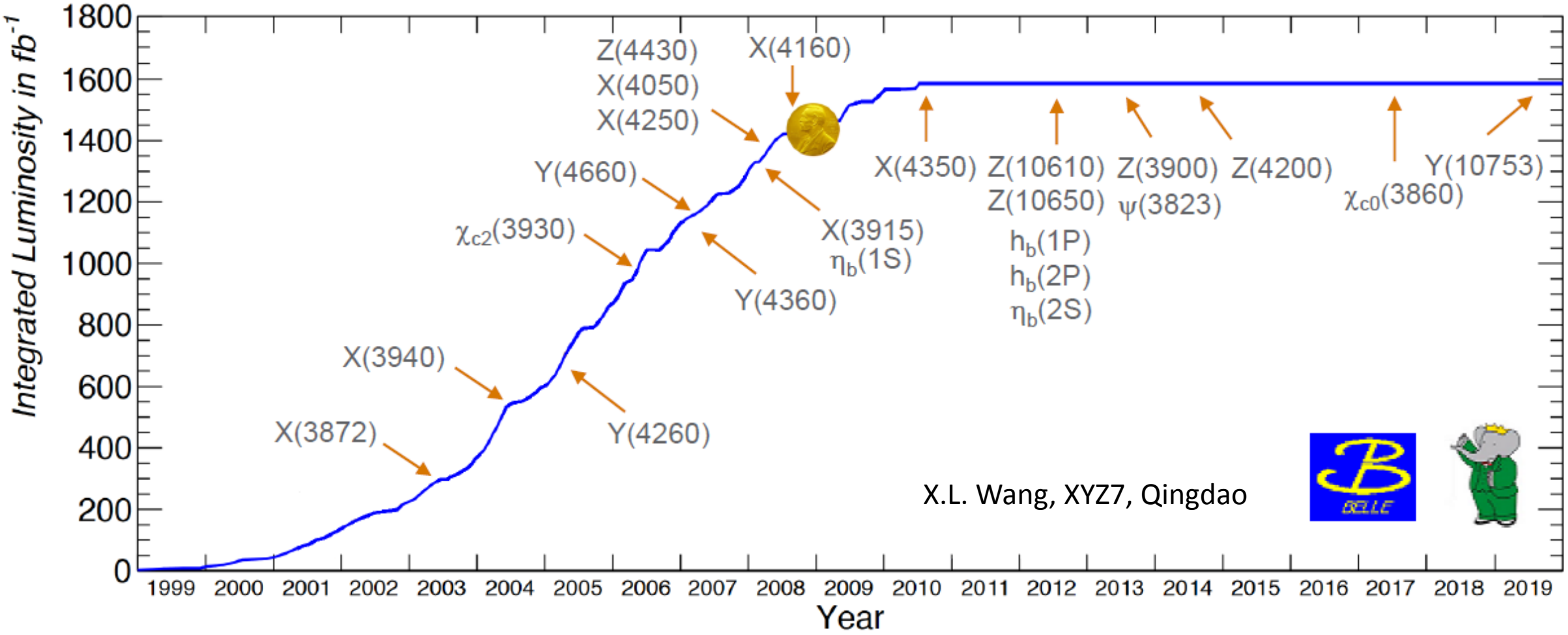
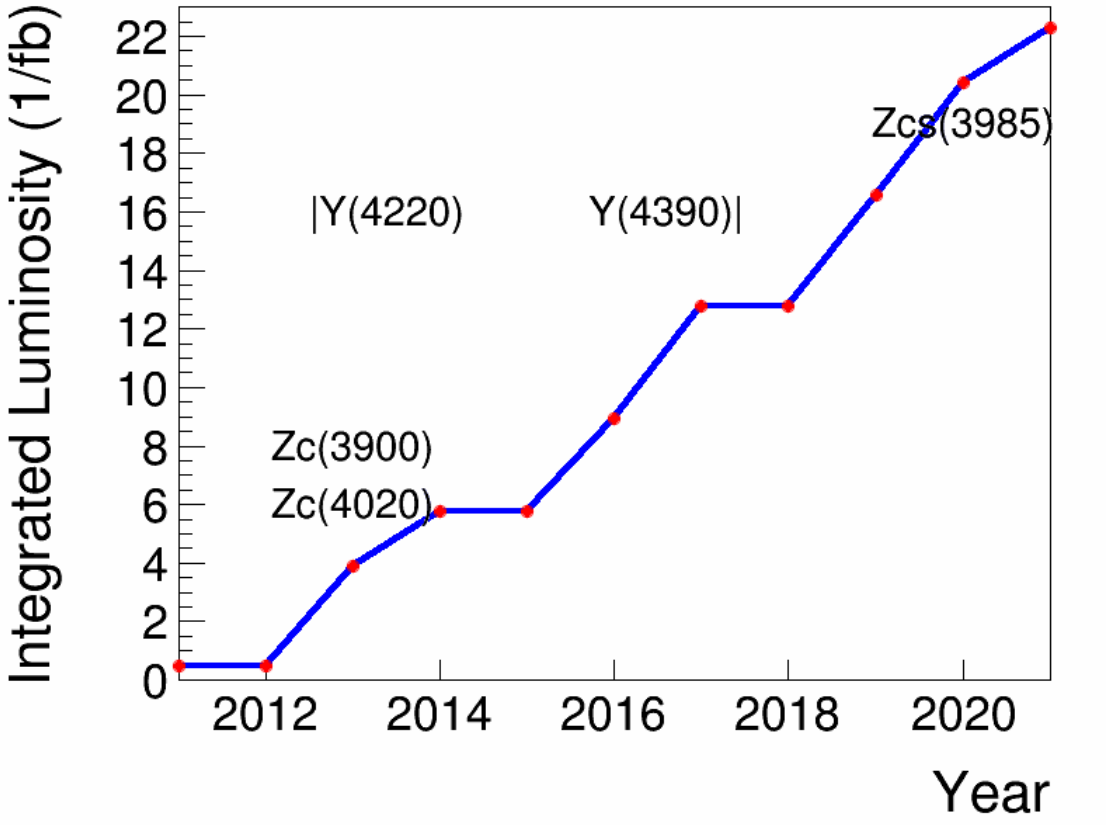


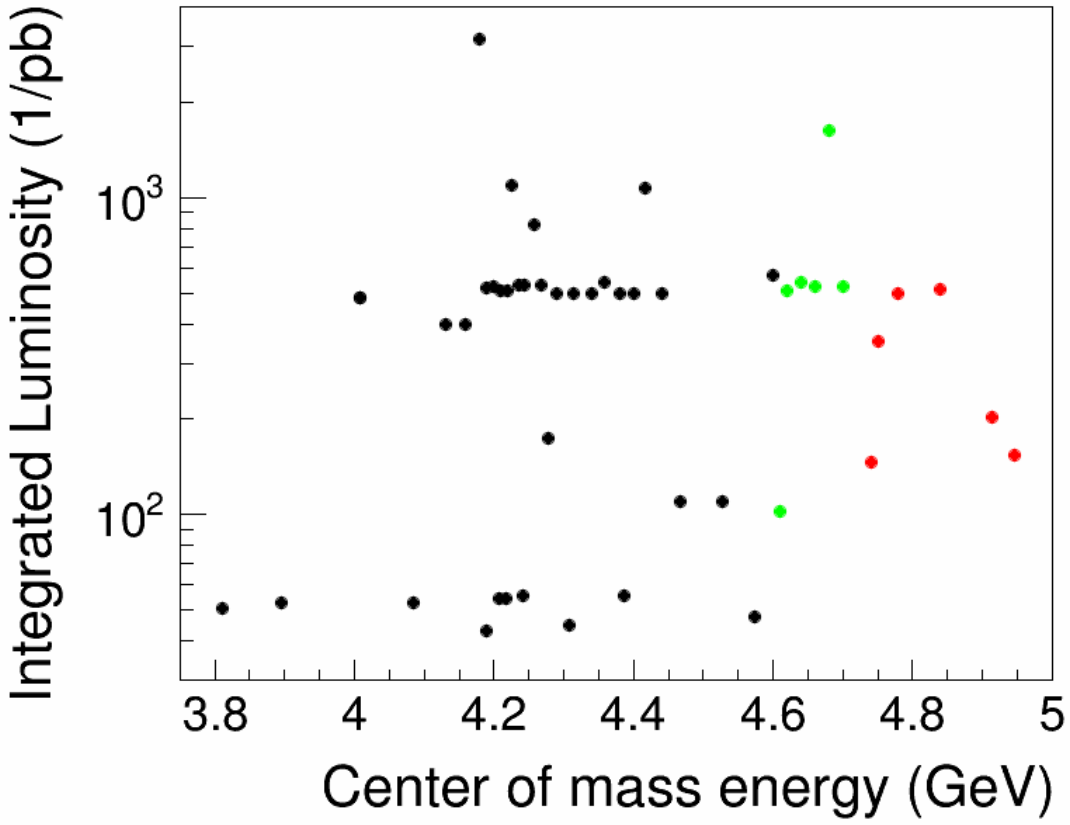
Belle/BaBar data samples

Both started in 1999, 20 years ago.



BESIII scan data samples

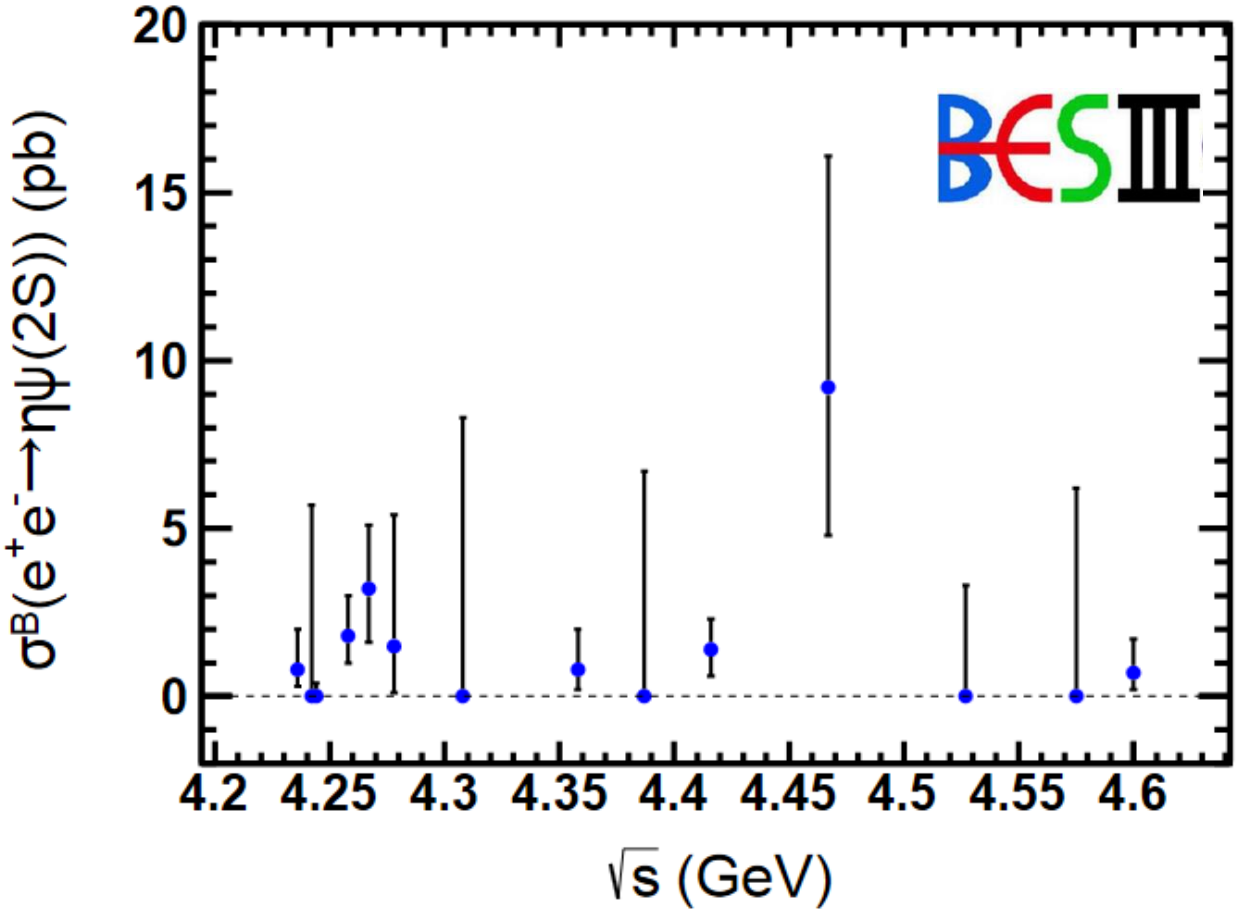




Production modes @ e^+e^- machines

- e^+e^- direct annihilation
- B decay
- ISR
- $\gamma\gamma$
- Charmonium/Bottomonium(-like) decay

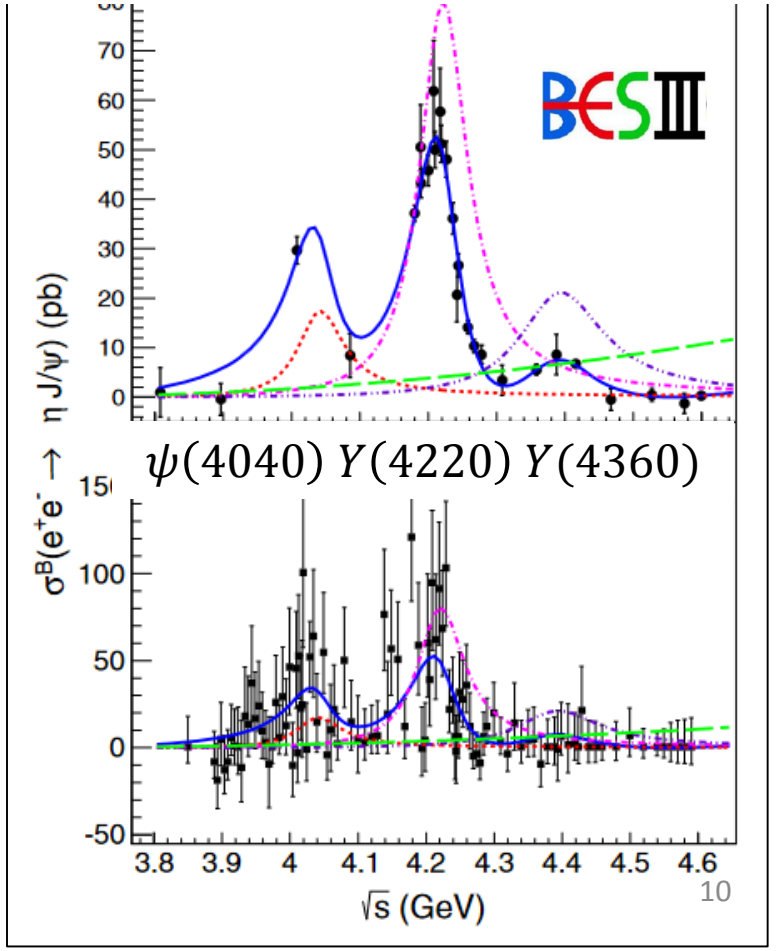
Observation of $e^+e^- \to \eta\psi(2S)$ at center-of-mass energies from 4.236 to 4.600 GeV arXiv:2103.01480



- The process of $e^+e^- \to \eta\psi(2S)$ is observed for the first time with 5σ significance.

$e^+e^- \to \eta J/\psi$

PRD(RC) 102, 031101 (2020)



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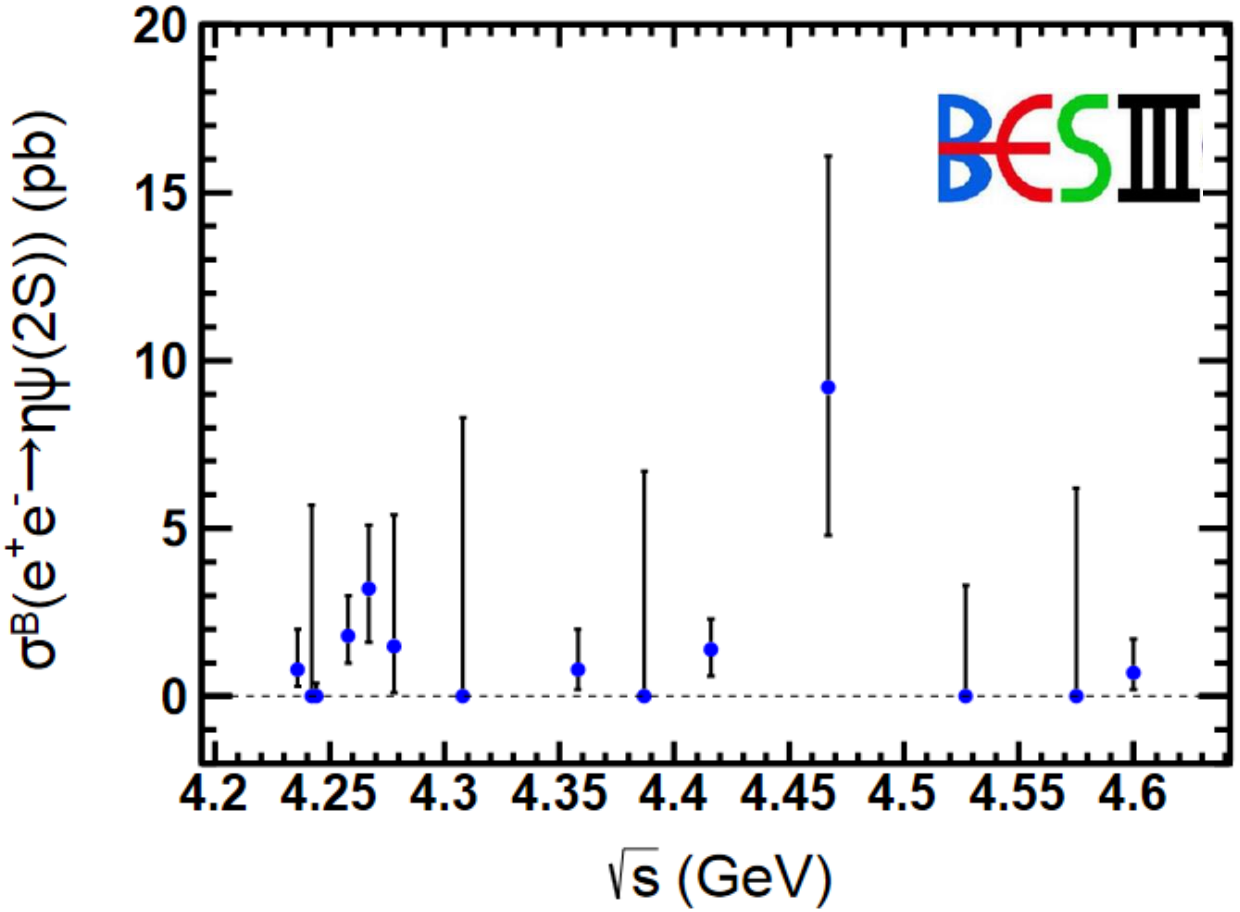
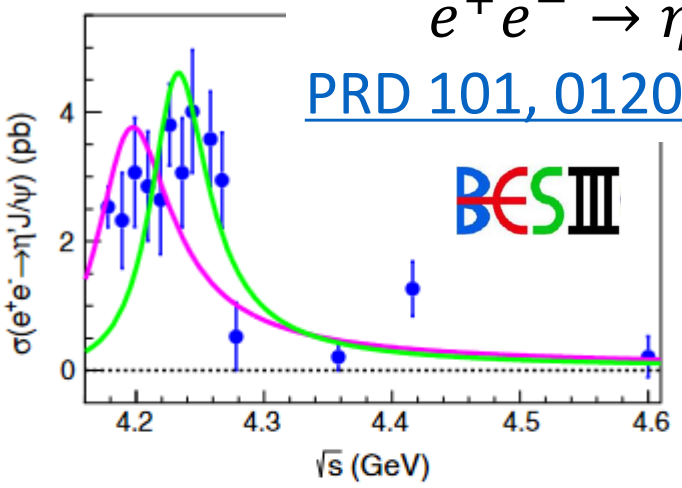
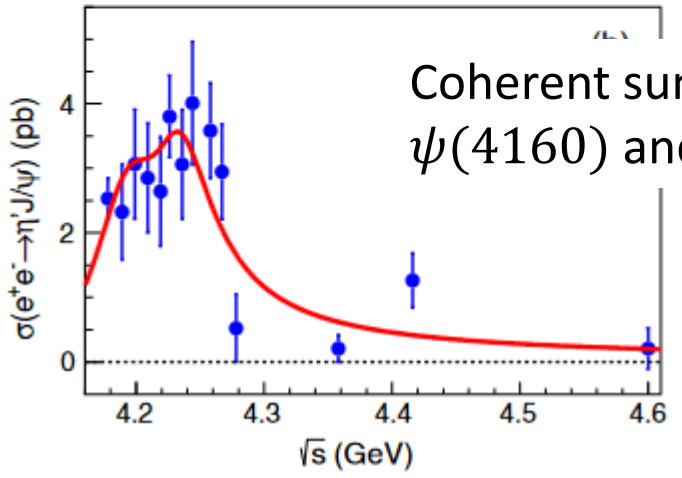


- The process of $e^+e^- \to \eta\psi(2S)$ is observed for the first time with 5σ significance.

$e^+e^- \to \eta' J/\psi$

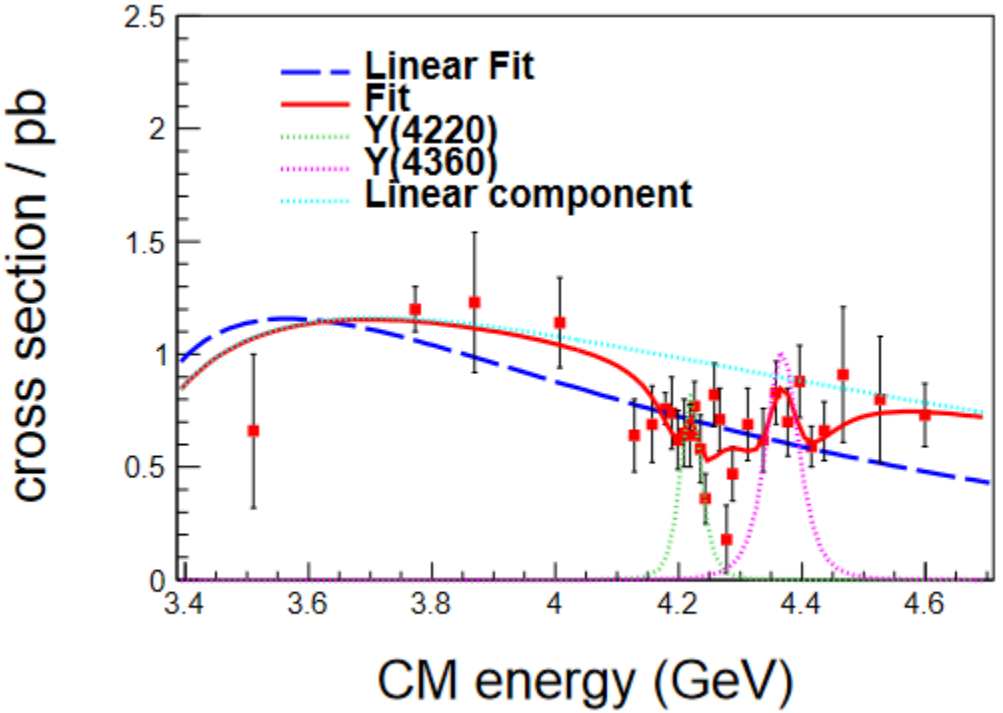
PRD 101, 012008 (2020)

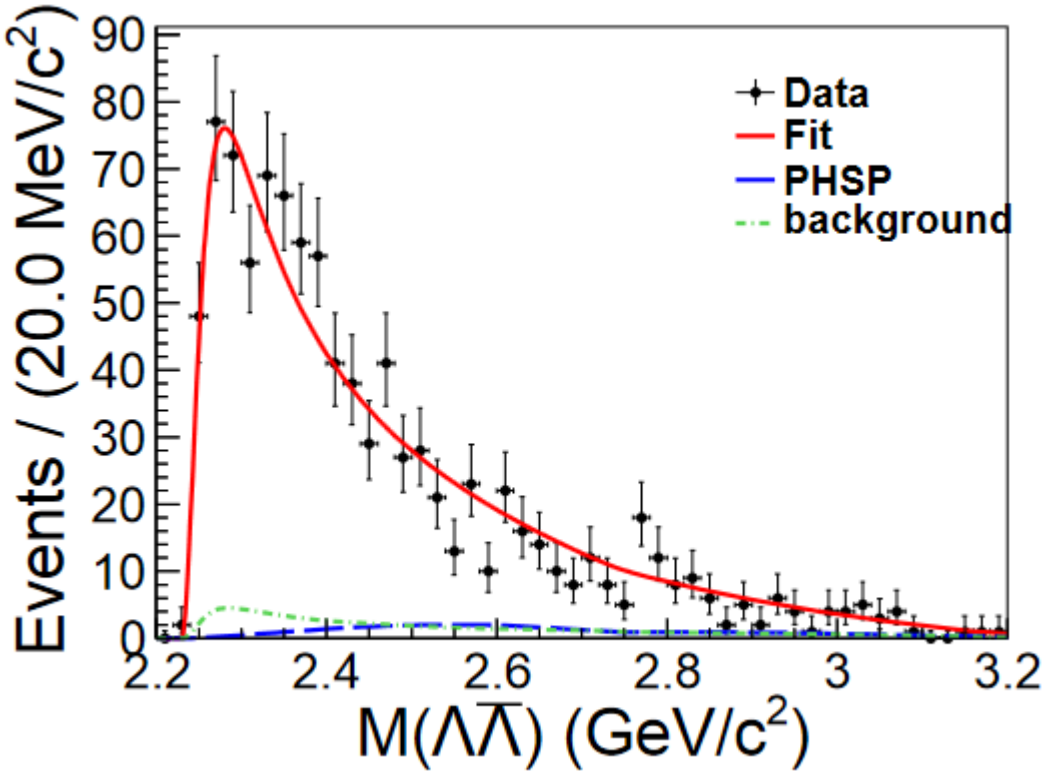




Coherent sum of $\psi(4160)$ and $\psi(4260)$

$e^+e^- \to \phi\Lambda\bar{\Lambda}$, 3.51 to 4.60 GeV arXiv:2104.08754



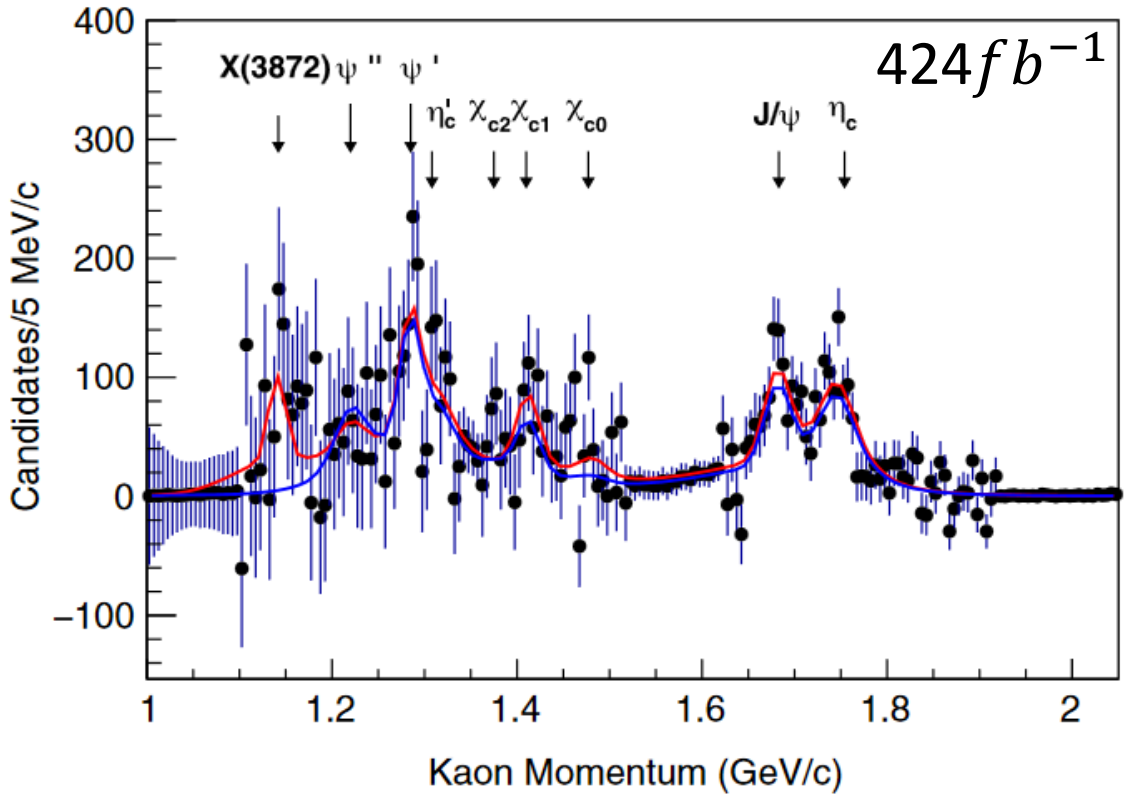


Peaking structures at 4.23 and 4.36 GeV with significance 4.2σ and 3.1σ

$M = 2262 \pm 4 \pm 28\,, \Gamma = 72 \pm 5 \pm 43$ MeV
Not match any known resonance

Measurements of the Absolute Branching Fractions of $B^{\pm} \to K^{\pm} X_{cc}$

PRL 124, 152001 (2020)



After background subtraction

$$\mathcal{B}[B^+ \to X(3872)K^+] = [2.1 \pm 0.6(\text{stat}) \pm 0.3(\text{syst}) \pm 0.1(\text{ref})] \times 10^{-4}$$

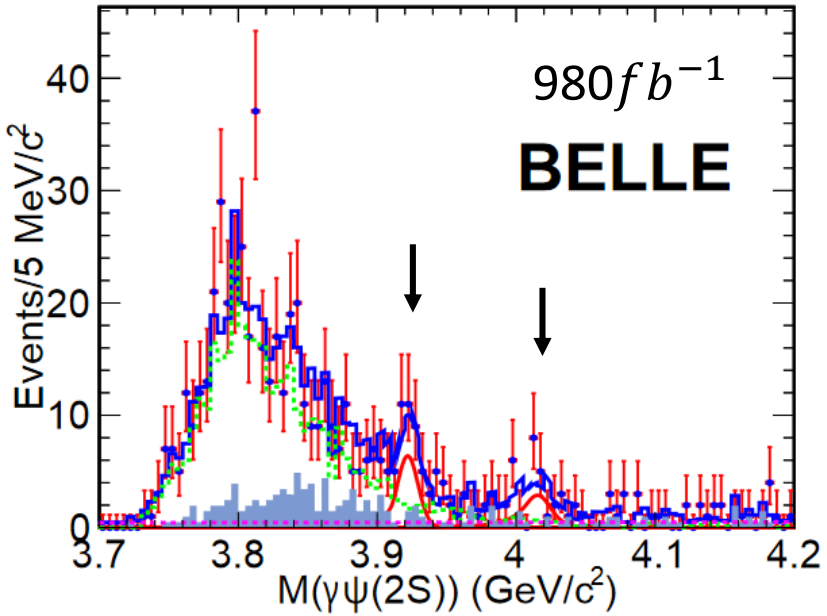
First measurement, 3σ

$$\mathcal{B}[X(3872) \to J/\psi\pi^+\pi^-] = (4.1 \pm 1.3)\%$$

Suggest X(3872) has significant molecular component.

$\gamma\gamma \to \gamma\psi(2S)$

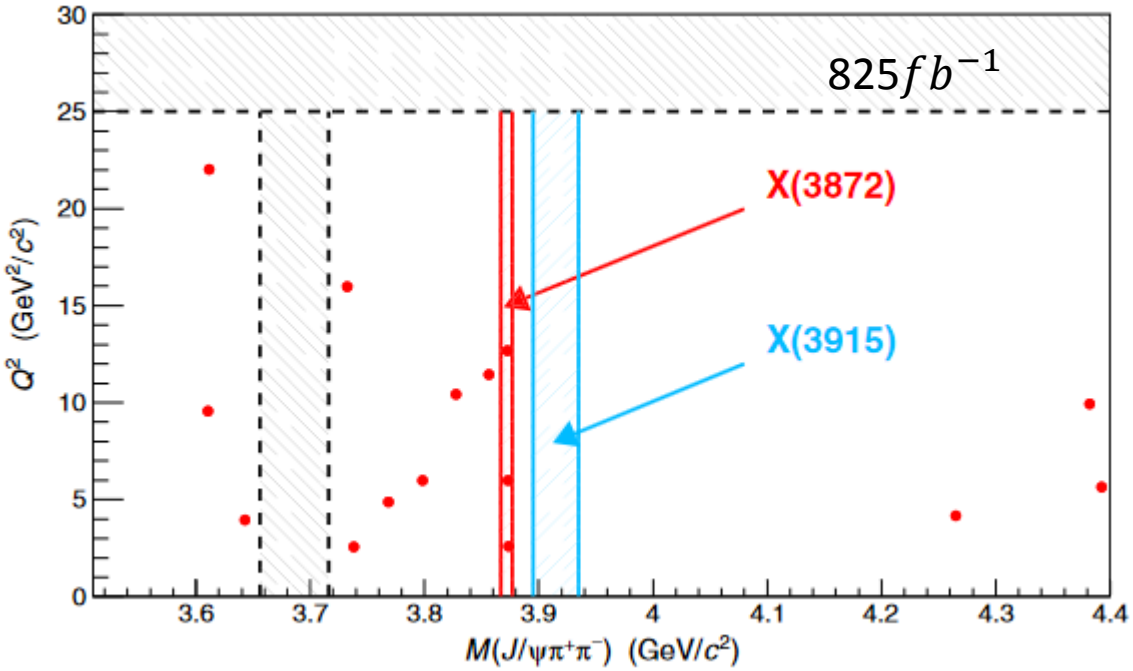
arxiv:2105.06605



- Two narrow structures at 3921 and 4014 MeV with local significance 4.0σ and 3.0σ
- Maybe $\chi_{c0}(2P)$ and $\chi_{c2}(2P)$

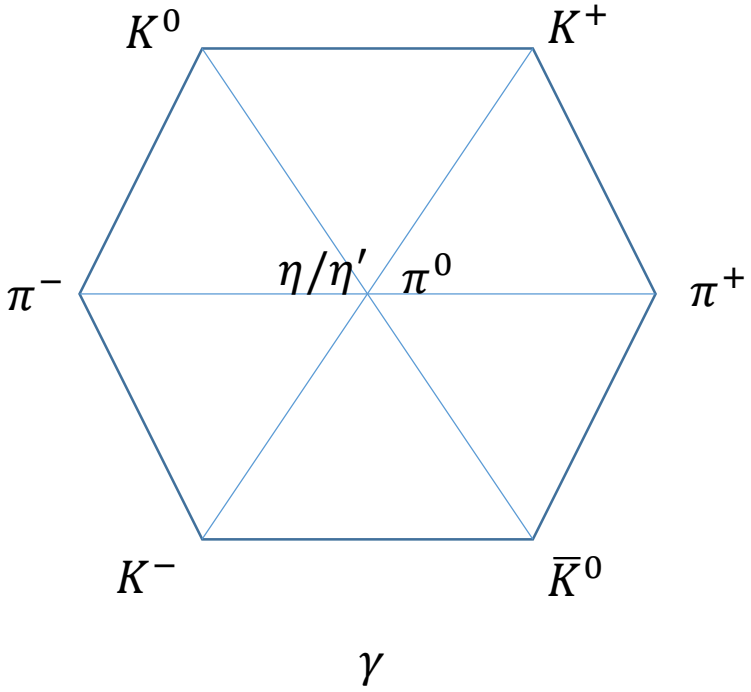
$\gamma\gamma \to X(3872)$

PRL 126, 122001 (2021)



Three X(3872) candidates are observed with significance 3.0σ

Eightyfold way



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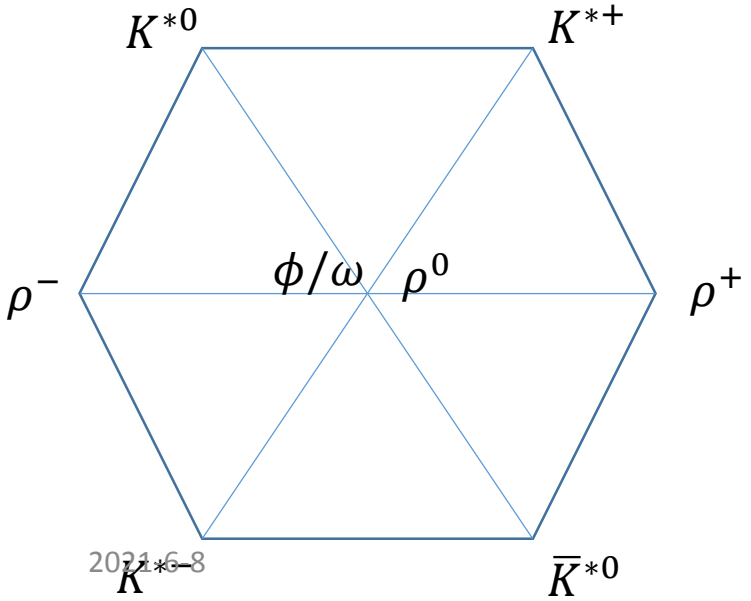

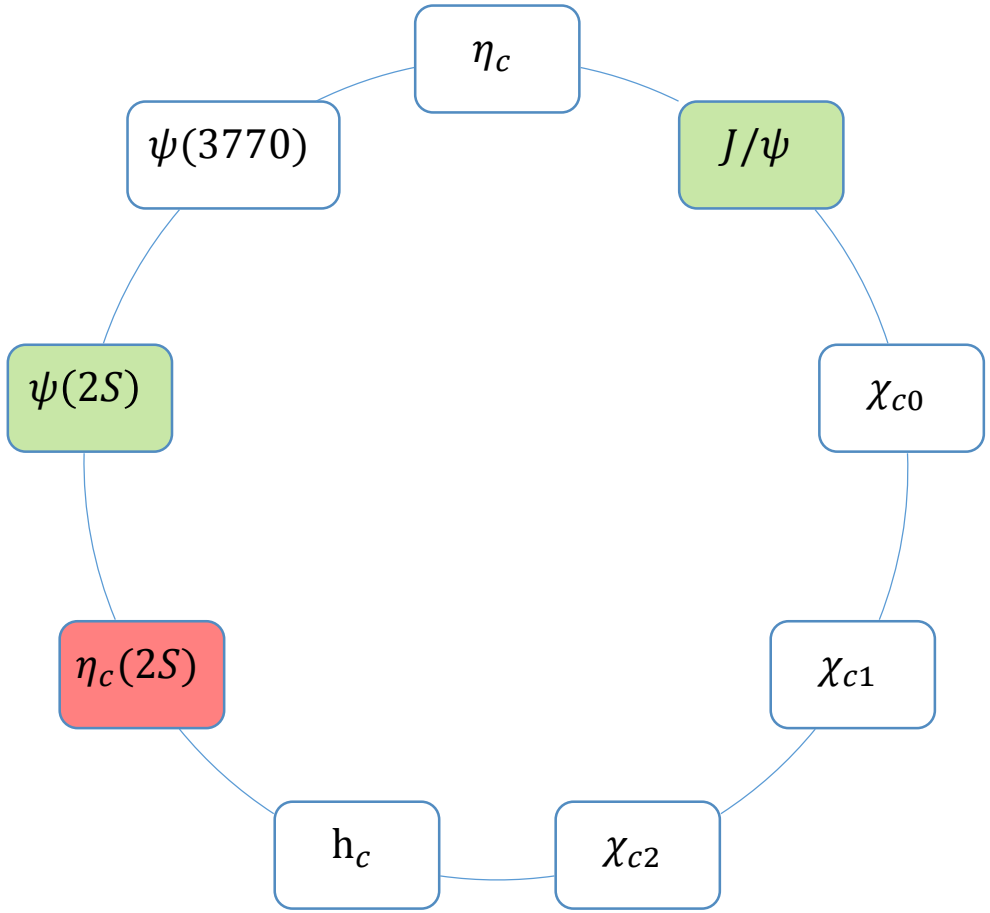

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Different combinations in final states

BESIII recent results with η_c and χ_{cJ}

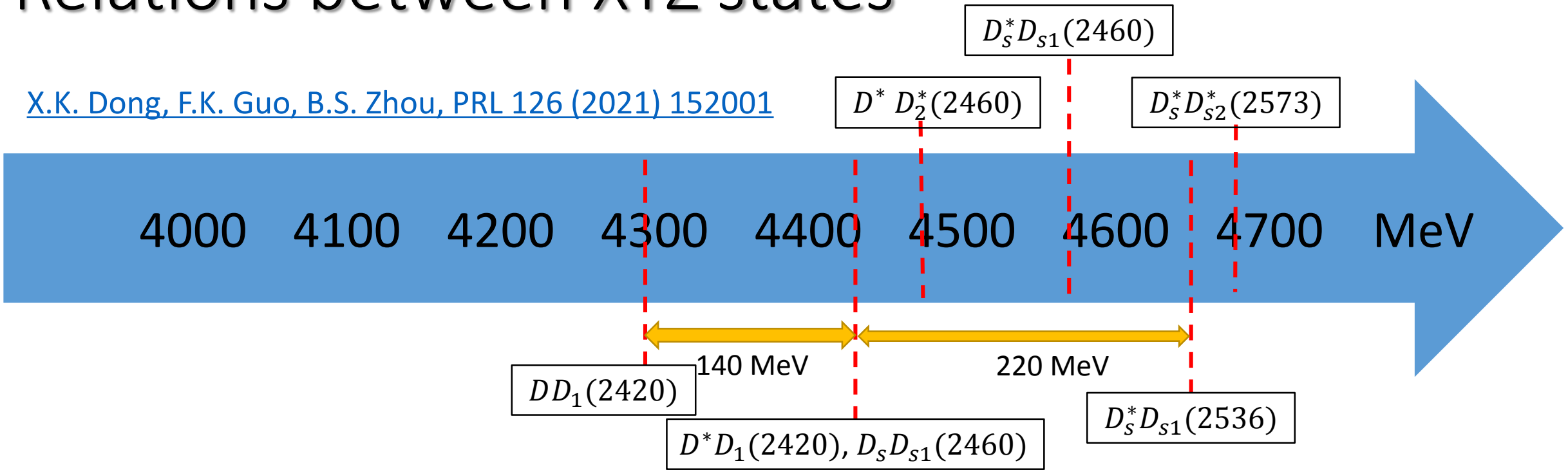
Details in Xuhong Li's and Ruiting Ma's talks (both Wed AM)

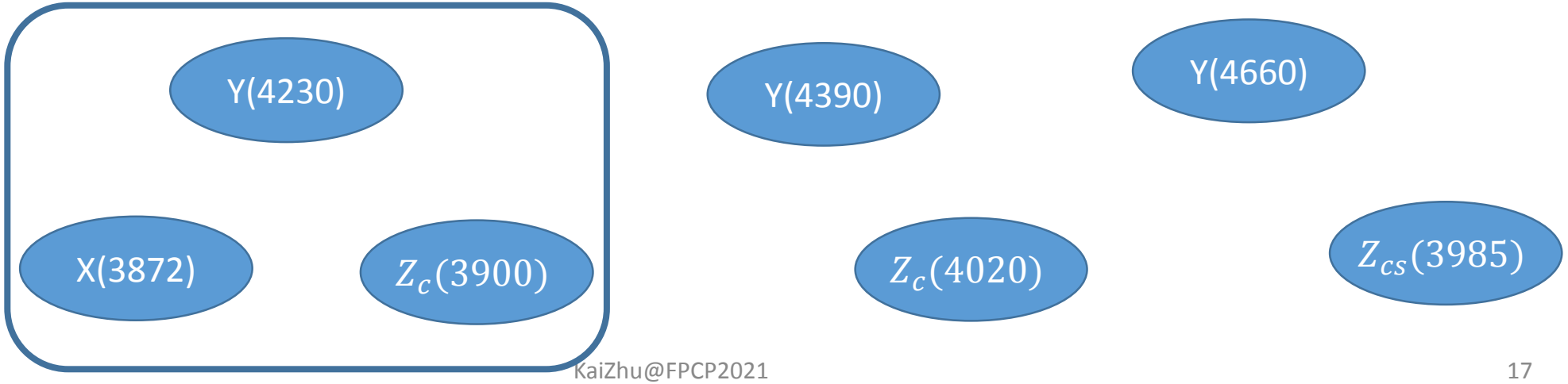
- Search for the reaction $e^+e^- \to \chi_{cJ}\,\pi^+\pi^-$ and a charmonium-like structure decaying to $\chi_{cJ}\pi^{\pm}$ between 4.18 and 4.60 GeV, Phys. Rev. D 103, 052010 (2021)
- Search for the reaction channel $e^+e^- \to \eta_c\,\eta\,\pi^+\pi^-$ at center-of-mass energies from 4.23 to 4.60 GeV, Phys. Rev. D 103, 032004 (2021)
- Measurements of $e^+e^- \to \eta_c\pi^+\pi^-\pi^0$, $\eta_c\pi^+\pi^-$ and $\eta_c\pi^0\gamma$ at $\sqrt{s}$ from 4.18 to 4.60 GeV, and search for a Z_c state close to the DDbar threshold at 4.23 GeV decaying to $\eta_c\pi$, Phys. Rev. D 103, 032006 (2021)

Upper limit is matter!

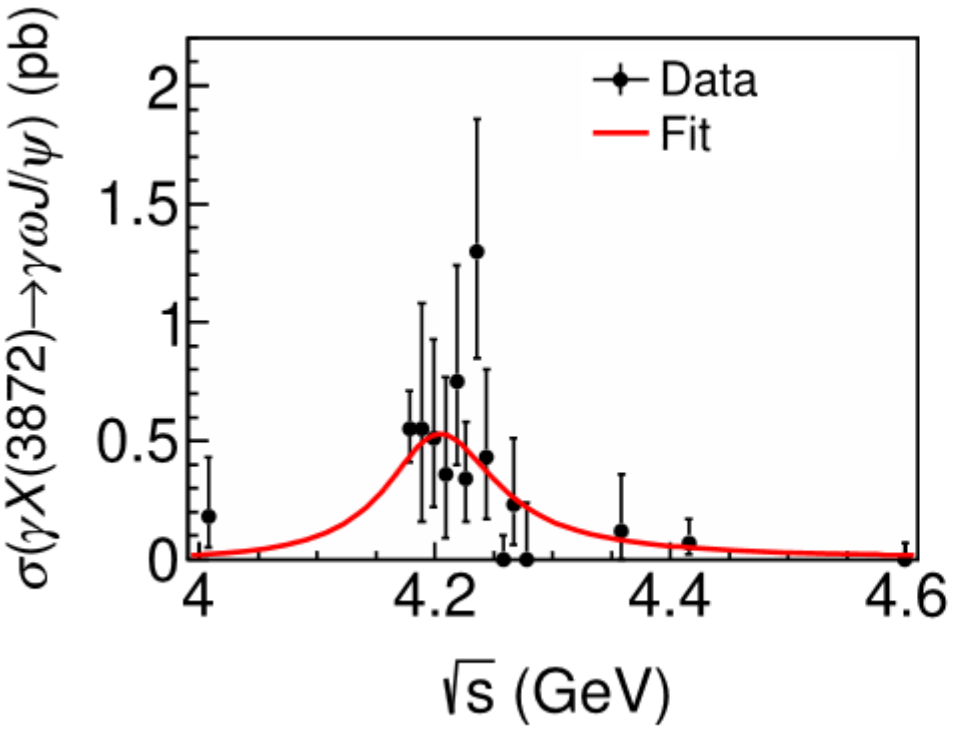
Relations between XYZ states

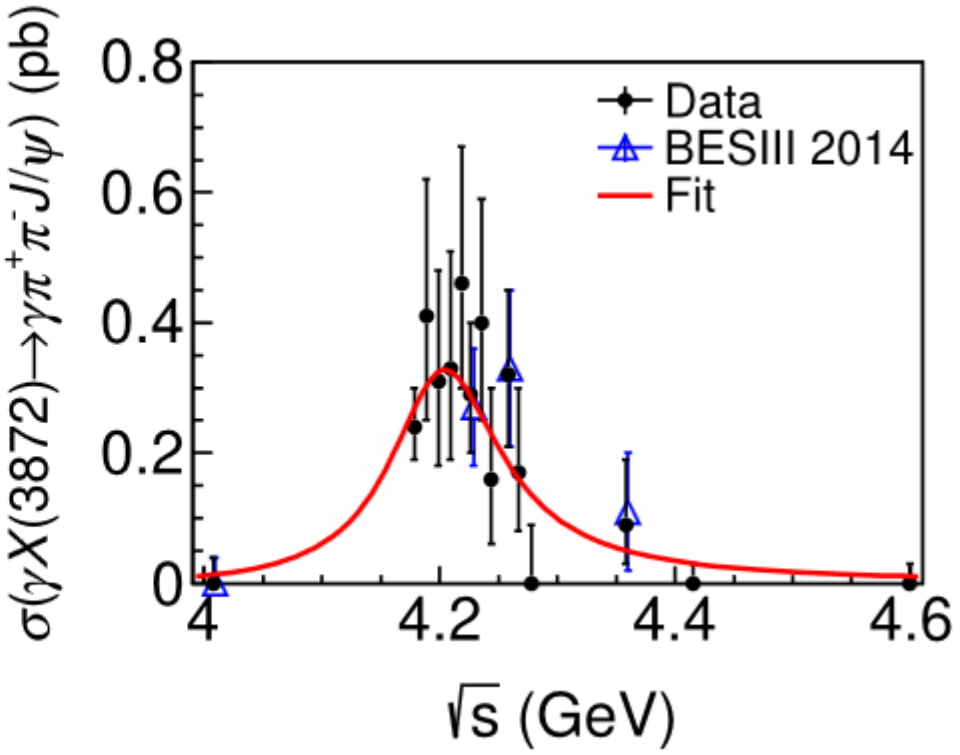
X.K. Dong, F.K. Guo, B.S. Zhou, PRL 126 (2021) 152001





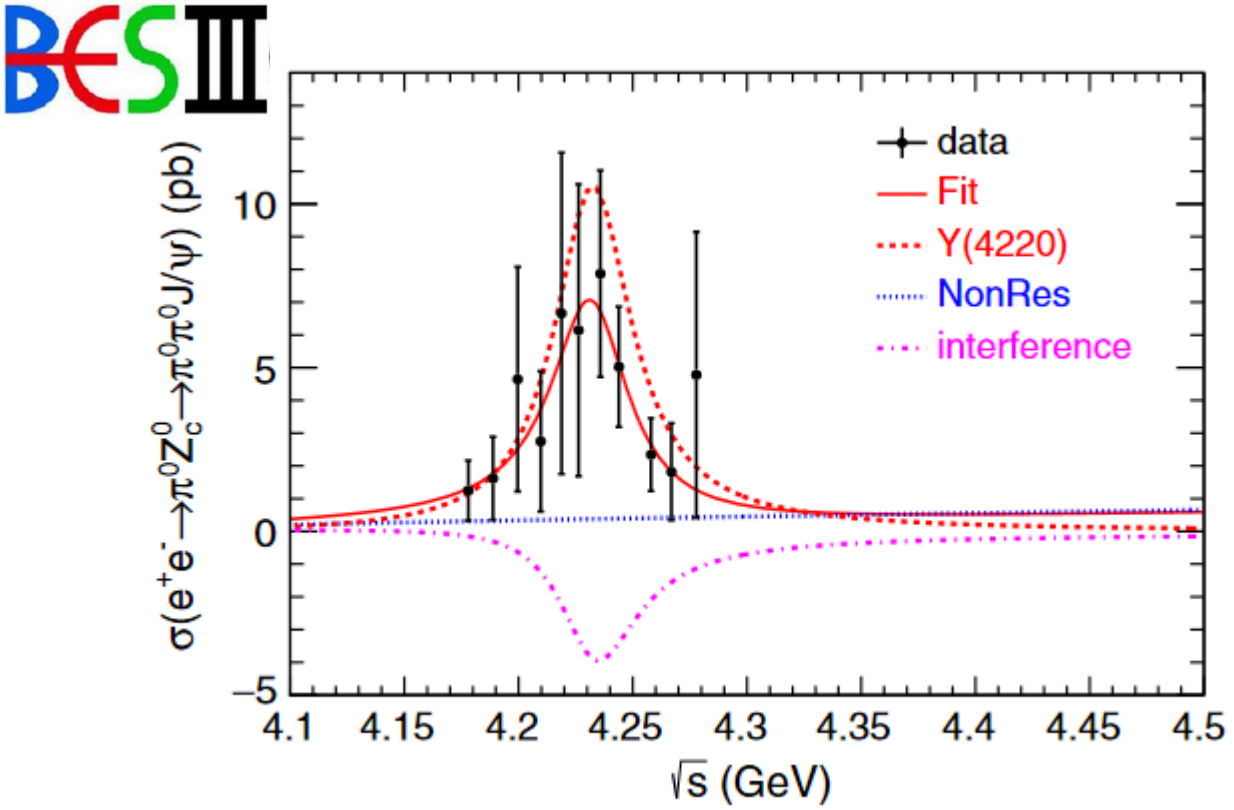
$Y(4230) \to \gamma X(3872)$ PRL 122, 232002 (2019)





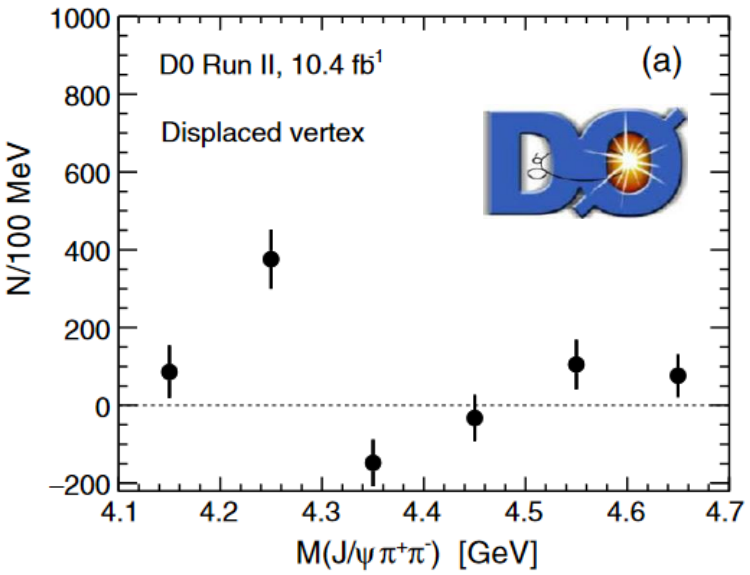
- A simultaneous fit with a single BW resonance.
- $M = 4200.6^{+7.9}_{-13.3} \pm 3.0$ MeV, $\Gamma = 115^{+38}_{-26} \pm 12$ MeV

$\Upsilon(4230) \to \pi^0 Z_c(3900)^0$ PRD 102, 012009 (2020)



Details in Ruiting and Xuhong's talks

Consistent with charged mode
PRD 100, 012005 (2019)



$Z_c(3900)$ signal yield

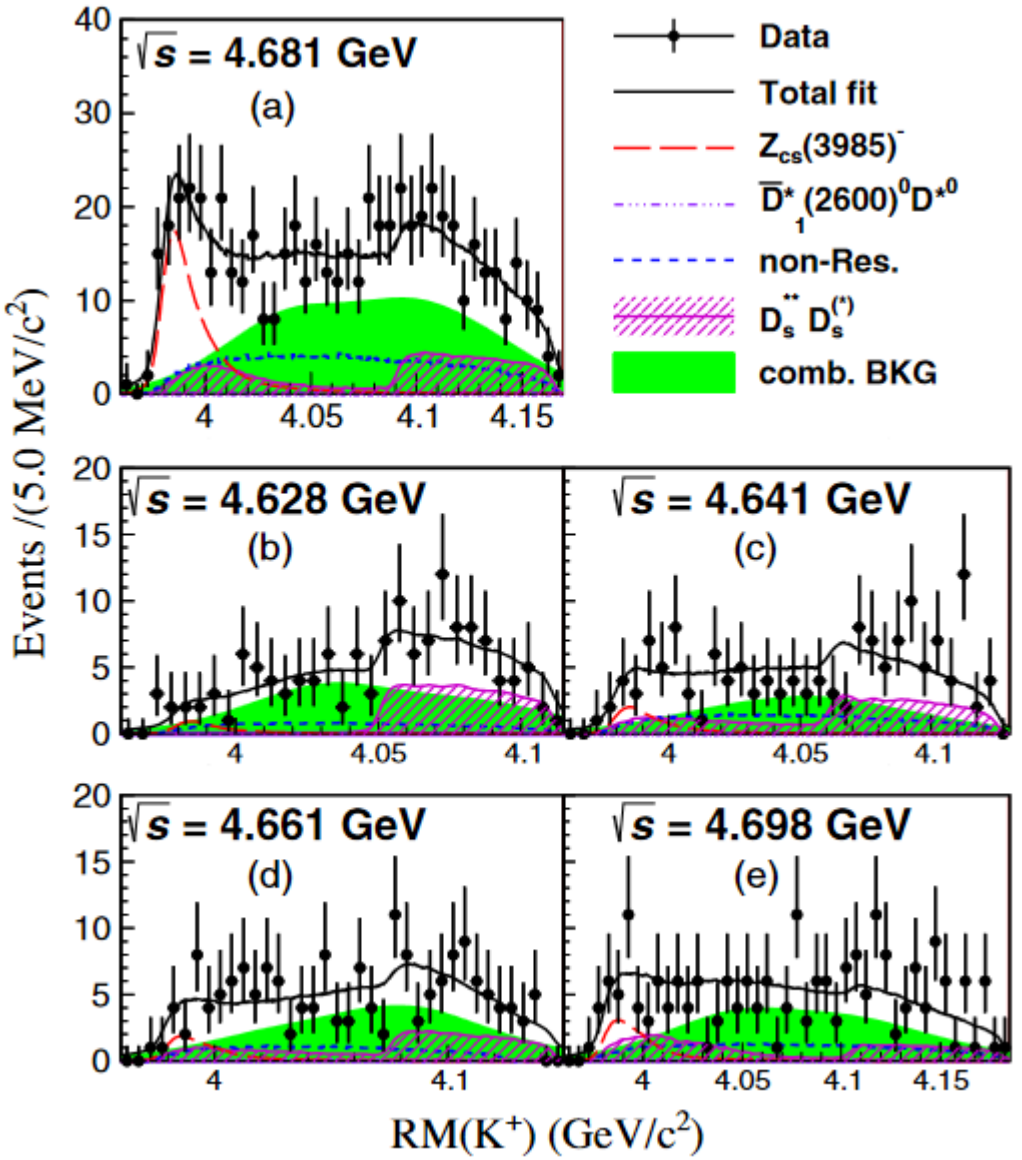
$Y(4660) \to K^+ Z_{cs}^-(3985)$?

[PRL 126, 102001 (2021)]

Details of Z_{cs} in Ruiting's talk

$$m_{\text{pole}}[Z_{cs}(3985)^-] = (3982.5^{+1.8}_{-2.6} \pm 2.1)\ \text{MeV}/c^2,$$
$$\Gamma_{\text{pole}}[Z_{cs}(3985)^-] = (12.8^{+5.3}_{-4.4} \pm 3.0)\ \text{MeV}.$$

- Main contribution seems from 4.681 GeV, due to Y(4660)?
- Related analyses such as the searching Z_{cs} in neutral mode, KJ/ψ mode, excited states are on-going at BESIII



Study of $e^+e^- \to \pi^0 X(3872)\gamma$ and search for $Z_c(4020)^0 \to X(3872)\gamma$

arXiv:2102.00644

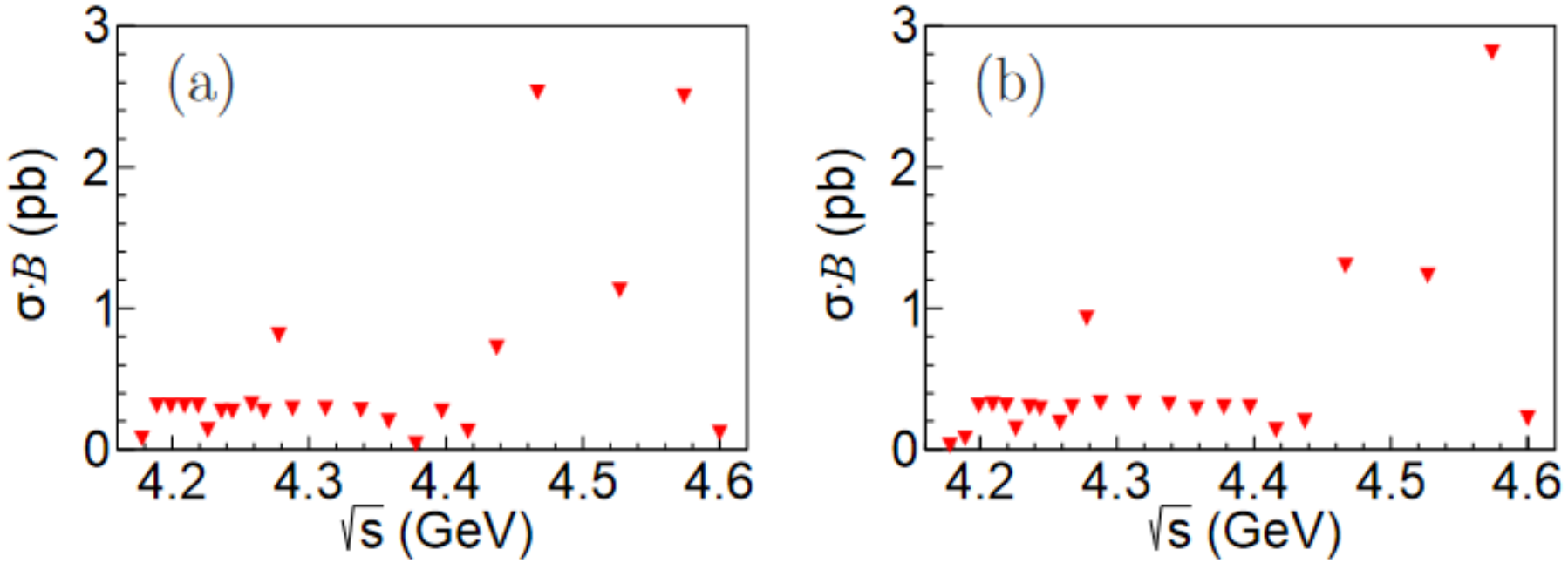


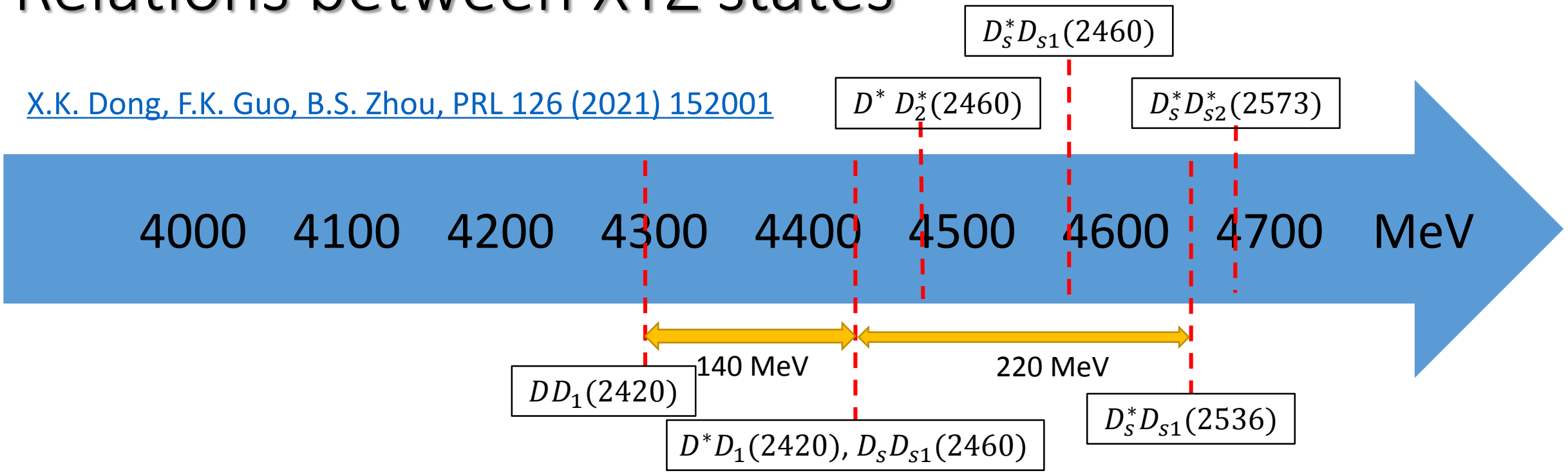
FIG. 2. The upper limits at the 90% C.L. on $\sigma(e^+e^- \to \pi^0 X(3872)\gamma) \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ (a) and $\sigma(e^+e^- \to \pi^0 Z_c(4020)^0) \cdot \mathcal{B}(Z_c(4020)^0 \to X(3872)\gamma) \cdot \mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi)$ (b) for each energy point.

No obvious signal

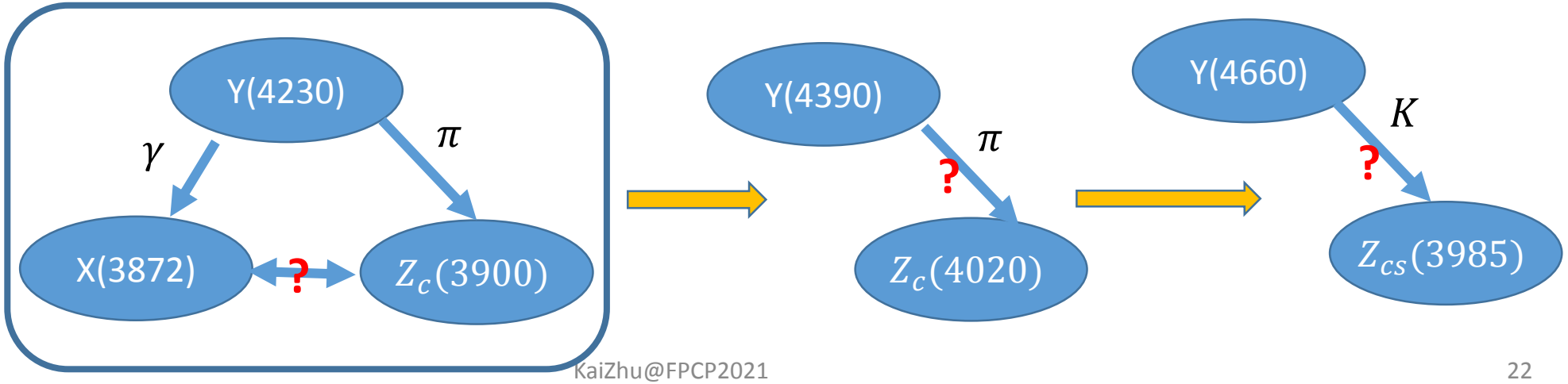
Relations between XYZ states

K. Zhu arxiv:2101.10622

X.K. Dong, F.K. Guo, B.S. Zhou, PRL 126 (2021) 152001



Information is still very limited.



Near future

Same strategy applied to enhance luminosity:
squeeze beam size & **boom beam current**

- Upgrade on **BEPC II** (details in Yuan Zhang's talk in Friday AM)
  - Luminosity: 3 times @ 4.7 GeV
  - Energy: maximum from 4.94 to 5.6 GeV
- **SuperKEKB** and **BELLE II** (details in Minakshi NAYAK's talk in Friday PM)
  - Luminosity: KEKB x 40!
  - Detectors: vertex, tracking, PID, high event rate, etc
  - Plan:
    - Peak luminosity: $\sim 6 \times 10^{35}\ cm^{-2}s^{-1}$ in ~2028;
    - Integrated luminosity: $50\ ab^{-1}$ in ~2030 ($40\ ab^{-1}$in ~2029)
  - Has started collected data since 2019 Mar., some preliminary XYZ results already

Summary

- Lots of contributions from e^+e^- machines
  - Many discoveries and precision measurements
  - Improved knowledge on various aspects
- Still many unknown about these exotic states
  - Mass and width (especially important near thresholds)
  - Quantum numbers
  - Transitions between them
  - New/Undiscovered states
  - Absolute/Relative decay rates
  - Production modes
  - …
- BESIII and BELLE II will continue be active in the next 15~20 years

Thanks, and wish you good health!

backup

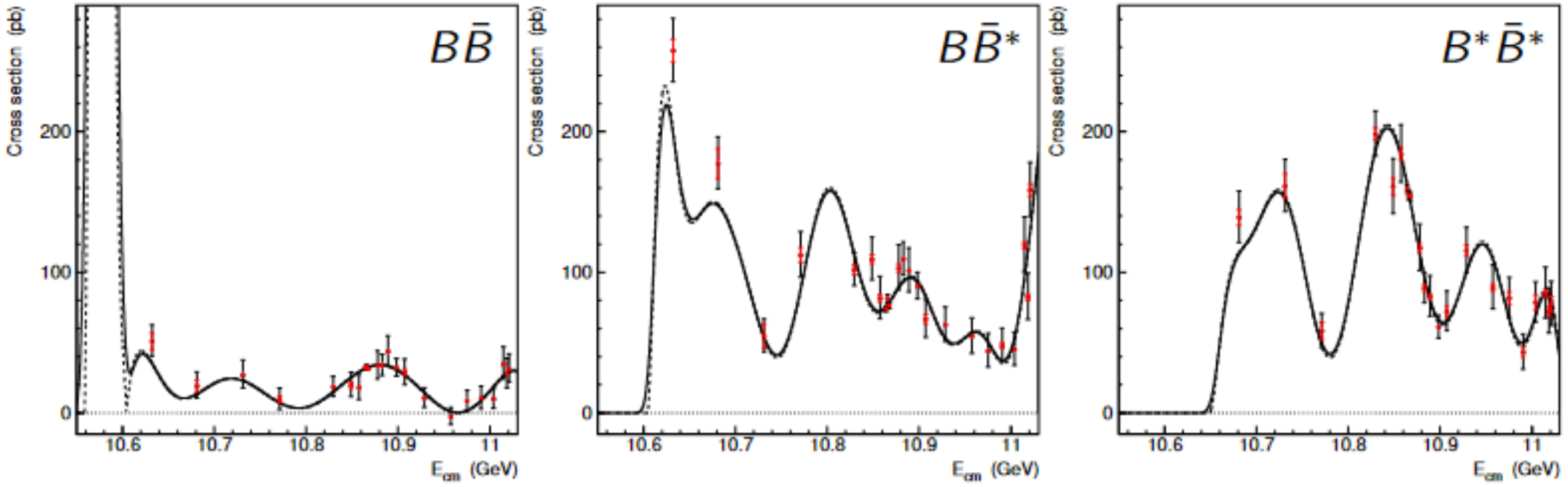
$e^+e^- \to B^{(*)}\bar{B}^{(*)}$

R. Mizuk, QWG2021

Dressed cross sections

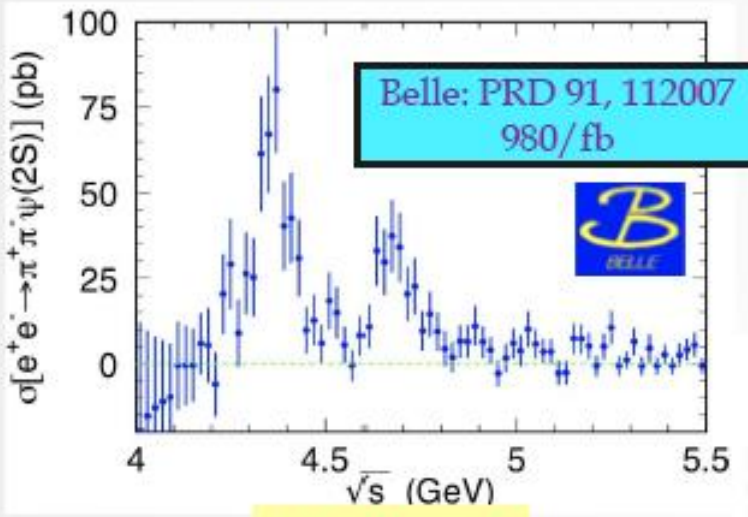
$$\sigma^{\text{dressed}} = \frac{N}{L\,\varepsilon\,(1+\delta_{\text{ISR}})}$$

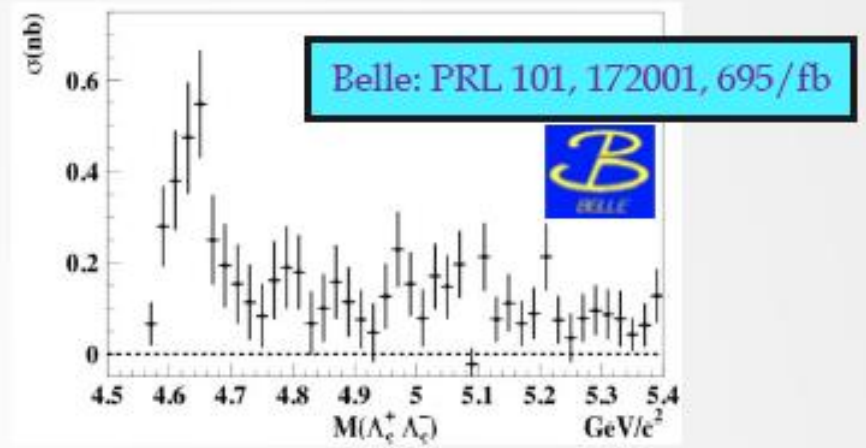
stat., uncorrelated syst. errors



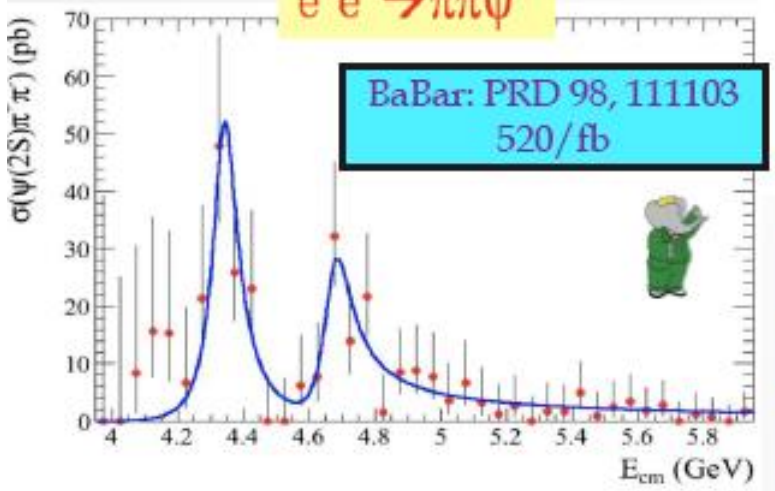
- First exclusive cross sections in the range 10.63 and 11.02 GeV
- Oscillatory behavior and no obvious signal of $\Upsilon(5S)$

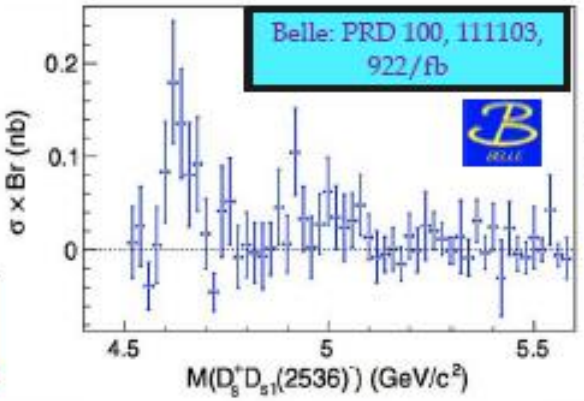
Y(4630) = Y(4660)?

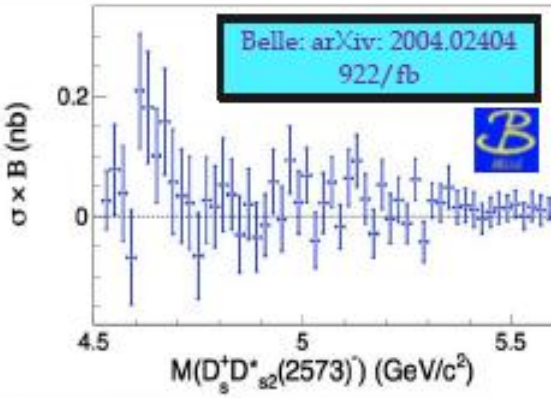




$e^+e^-\to\pi\pi\psi'$



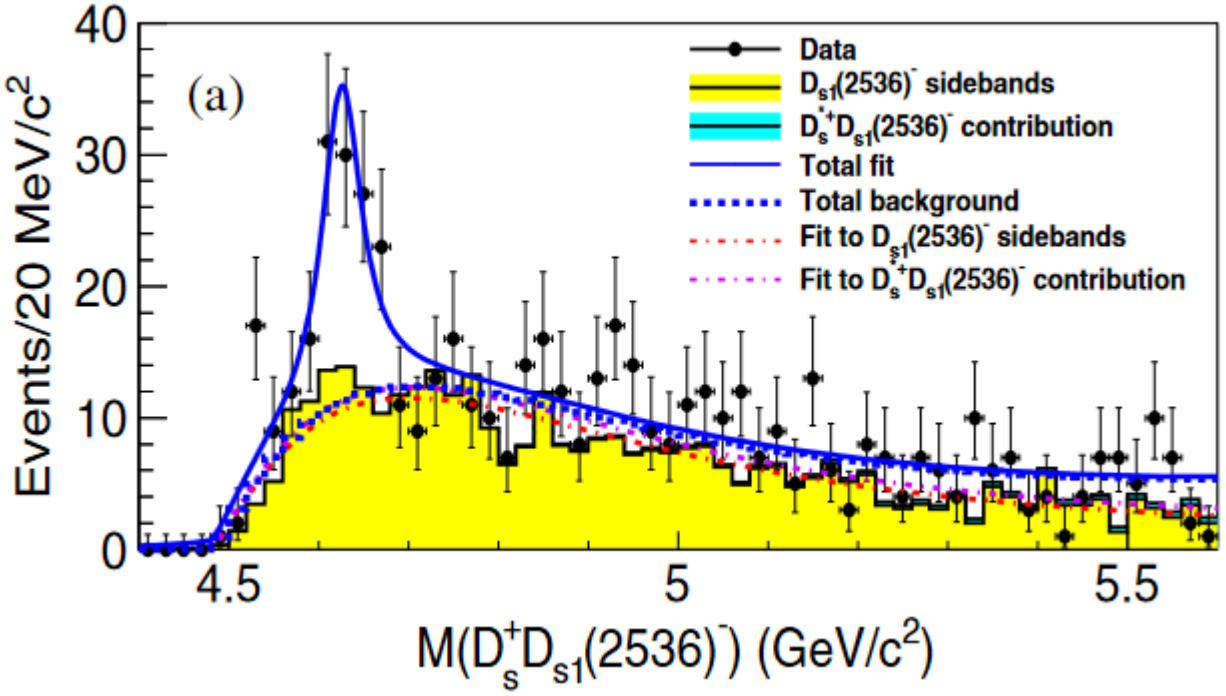


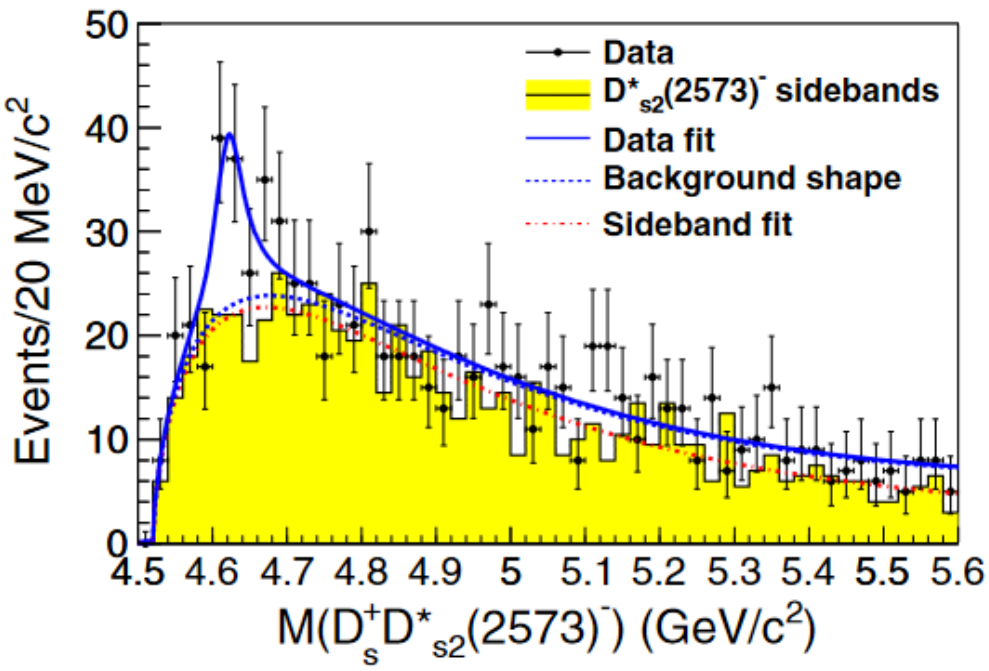


- These states may be the same
- Need improved precision

Experiment	Mass (MeV)	Width (MeV)
Belle, $\Lambda_c^+\Lambda_c^-$	$4634^{+8\,+5}_{-7\,-8}$	$92^{+40\,+10}_{-24\,-21}$
Belle, $\pi^+\pi^-\psi(2S)$	$4652\pm10\pm8$	$68\pm11\pm1$
BaBar, $\pi^+\pi^-\psi(2S)$	$4669\pm21\pm3$	$104\pm48\pm10$
Belle, $D_s^+D_{s1}(2536)^-$	$4626^{+7}_{-7}\pm1$	$49.8^{+14}_{-12}\pm4$
Belle, $D_s^+D^*_{s2}(2573)^-$	$4620^{+9}_{-8}\pm3$	$47.0^{+32}_{-15}\pm5$

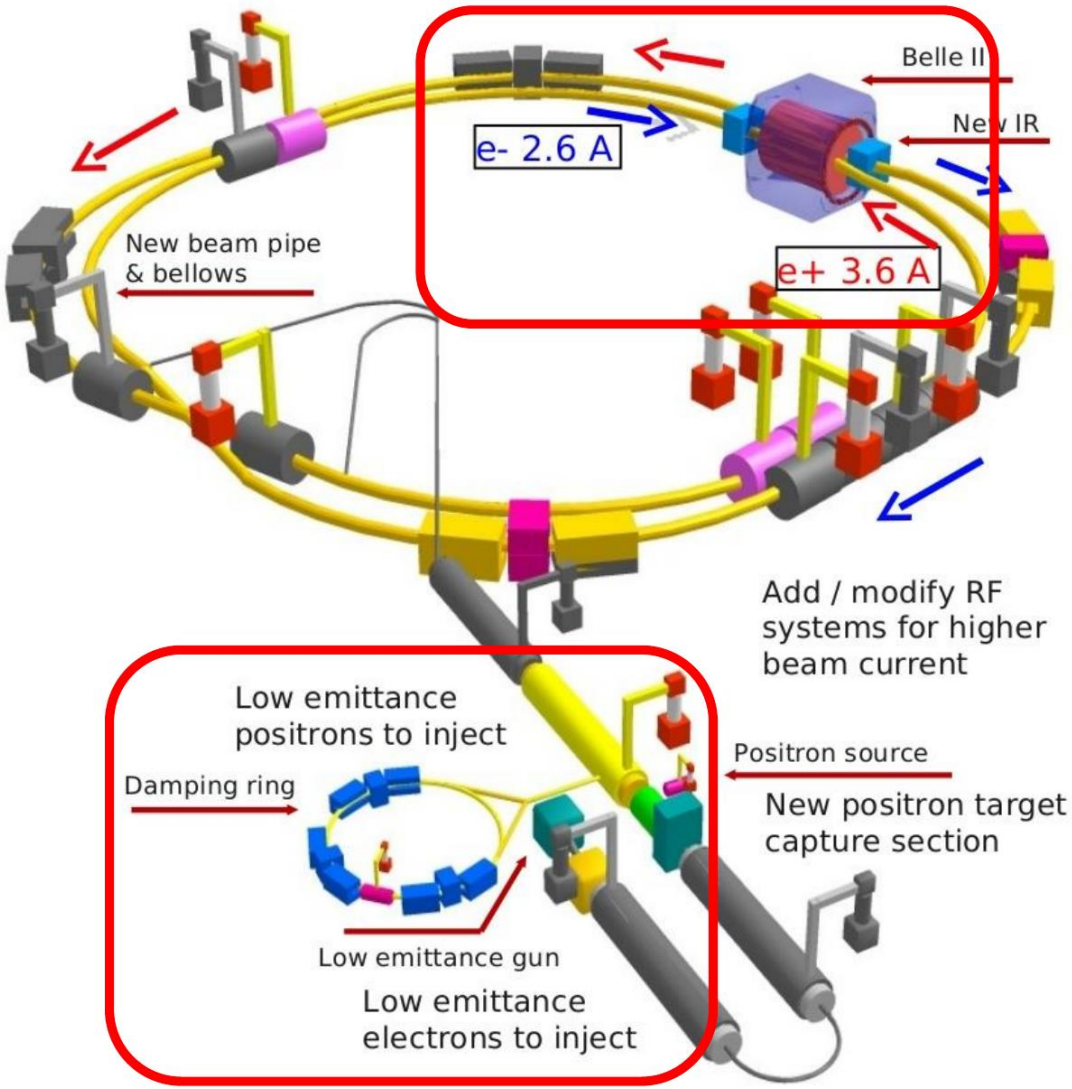
Y(4626): $e^+e^- \to \gamma_{ISR}\, D_s^+ D_{s1}(2536)^-$ PRD 100, 111103(R)
$D_s^+ D_{s2}^*(2537)^-$ PRD 101, 091101(R)

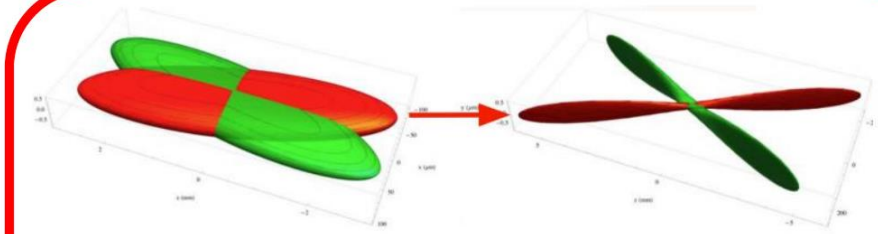




- No obvious signal from $D_s^* D_{sJ}$
- Uncertainty is large, cross check from BESIII is deserved.
- Y(4626) = Y(4660)? Maybe. Need improve precision.

SuperKEKB accelerator





"nano-beam" scheme
Beam squeezing: x20 smaller at IR

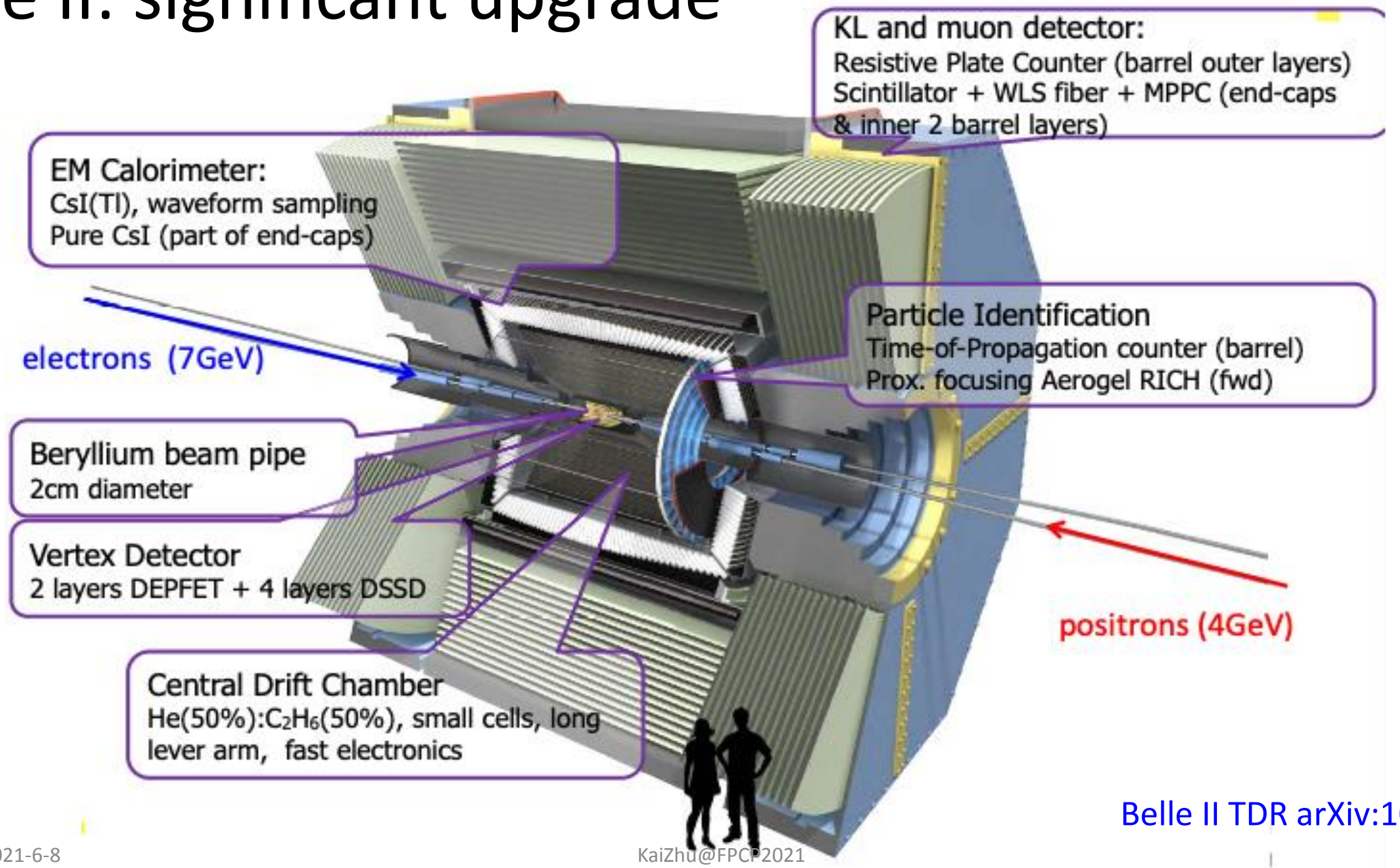
$$\textbf{Luminosity} = \frac{\gamma_{\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_{\pm}\zeta_{\pm y}}{\beta_y^*}\frac{R_L}{R_y}$$

x2

X1/20

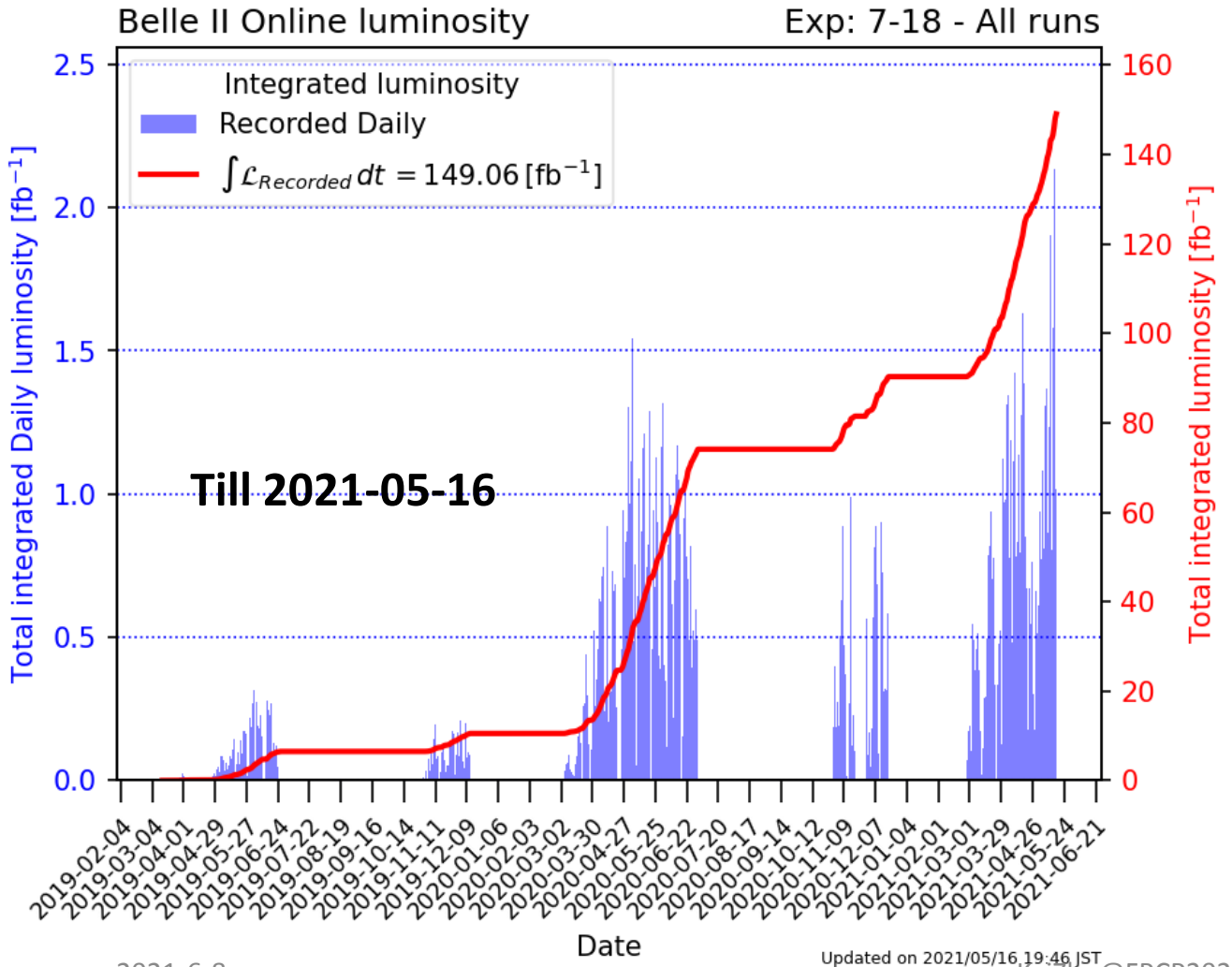
Target luminosity: $8\times10^{35}cm^{-2}s^{-1}$
KEKB x 40!

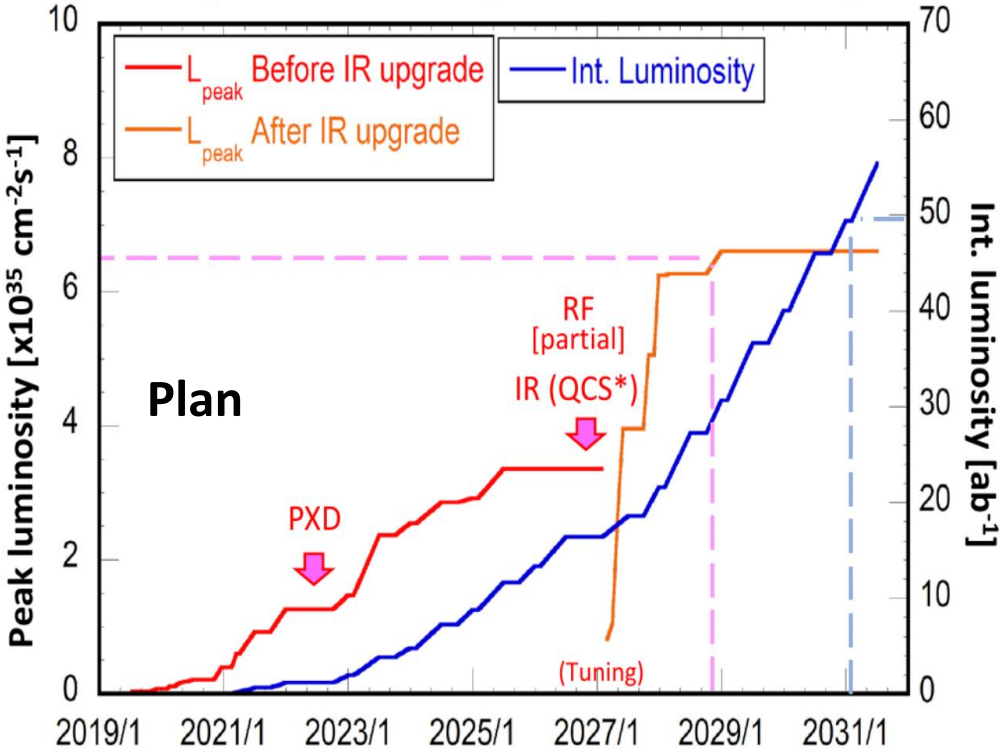
Belle II: significant upgrade



Belle II TDR arXiv:1011.0352

Recent data taking and plan





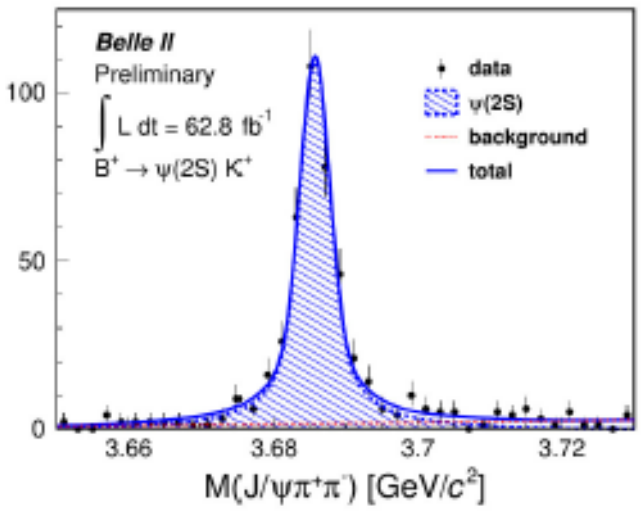
Four steps:

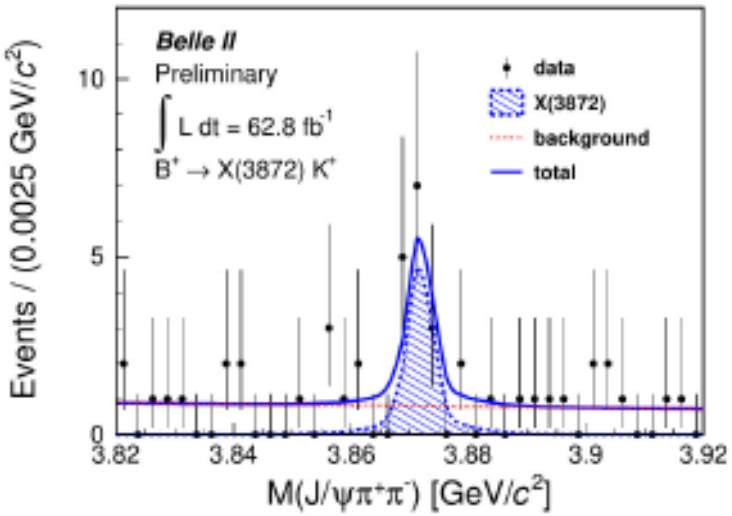
- ✓ *Intermediate luminosity:* (1→3) x 10^{35}/cm^2/sec, 5 ab^{-1}
- ✓ *High Luminosity:* 6 x 10^{35}/cm^2/sec, 50 ab^{-1} with a detector upgrade
- ✓ Beam-polarization upgrade, advanced R&D
- ✓ *Ultra high luminosity:* 4 x 10^{36}/cm^2/sec, 250 ab^{-1}, R&D project

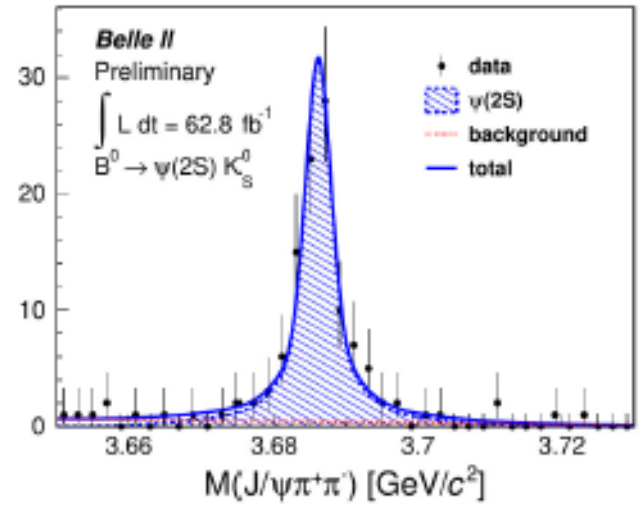
- ➢ Peak luminosity
  $\sim 6 \times 10^{35}\ cm^{-2}s^{-1}$ in ~2028
- ➢ Integrated luminosity
  $50\ ab^{-1}$ in ~2030 (40 in ~2029)

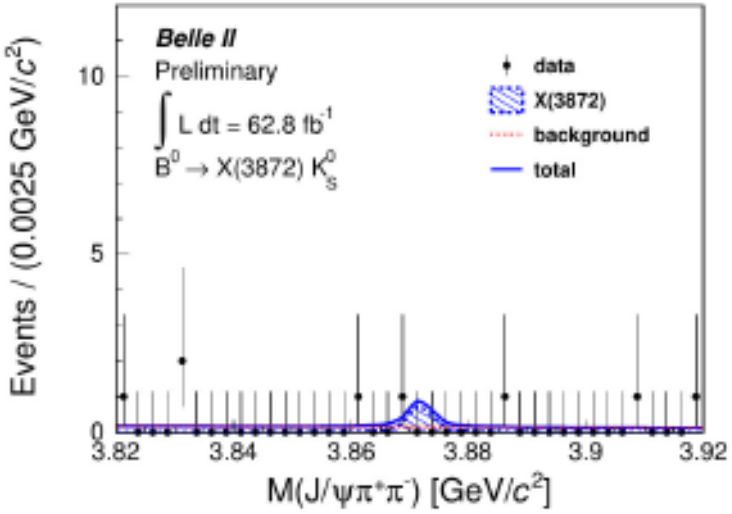
Evidence for the $X(3872)$ in Belle II data

K. Chilikin
XYZ workshop
13 Apr 2021









Using a data sample of 62.8 fb^{-1}, evidence for the $X(3872)$ was found with 4.6σ significance.