Production of 1++ States at Electron Positron Colliders

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SFB Seminar KPH Mainz 2014

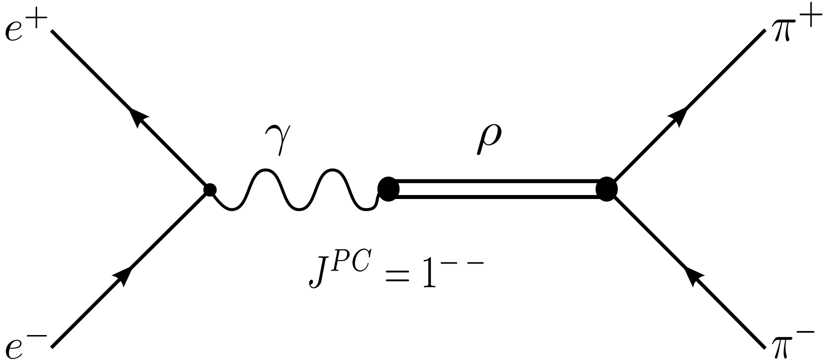
Dec. 15, 2014

Outline

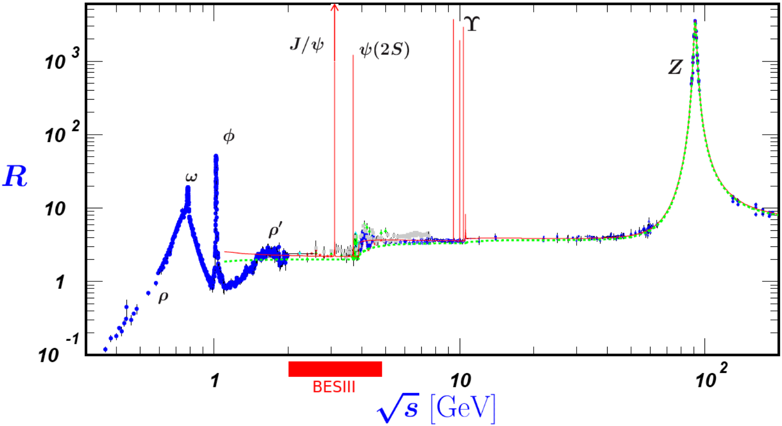
1. Introduction
2. Search for the X(3872) in e^+e^- annihilation
3. Search for the χ_{c1} in e^+e^- annihilation
4. Summary

Electron Positron Colliders

- Which quantum numbers can be produced in an e^+e^- - annihilation?
- Direct production in e^+e^- - collision:
  - $C|e^+e^- >= |e^-e^+ >= -|e^+e^- >$ (similar for parity)
  - Spin: $\frac{1}{2} \otimes \frac{1}{2} = 0 \oplus 1$
- Accessible J^{PC} quantum numbers in direct annihilation:
  - Singlet: 0^{--} no gauge boson coupling available
  - Triplet: $1^{--} \longrightarrow$ virtual photon / vector meson dominance



The R-Ratio

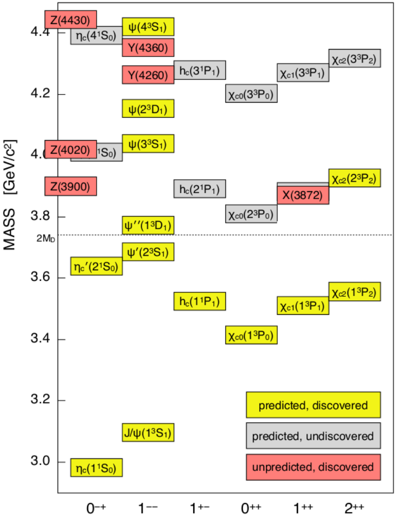


- $R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} = 3\sum_q e_q^2$
- Many 1^{--} states can be produced in e^+e^- annihilation
- Only vector states seen here!

BEPCII

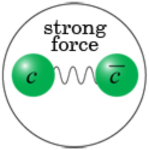
- Operating at BEPCII (Beijing)
- $\sqrt{s} = 2 - 4.6$ GeV
- $\mathcal{L} = 8.04 \times 10^{-32}$ ($\approx 85\%$ of the design Luminosity)

Charmonium Spectroscopy



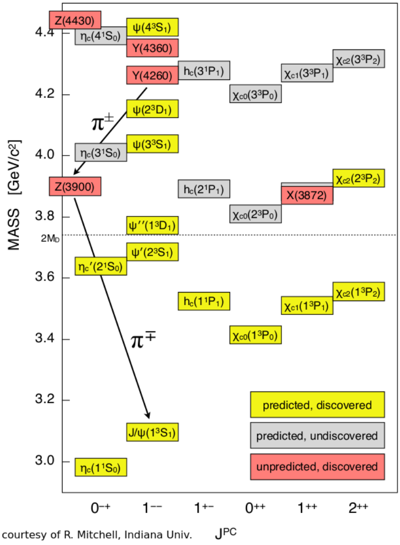
courtesy of R. Mitchell, Indiana Univ.

- Similar to hydrogen/positronium spectroscopy!



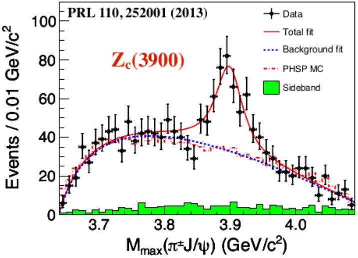
- Spectrum of charmonium states
- unexpected states "XYZ"
- Great hunt for charmonium states at **LHCb**, **Babar**, **Belle**, **CLEO** and **BESIII**

Recently Discovered



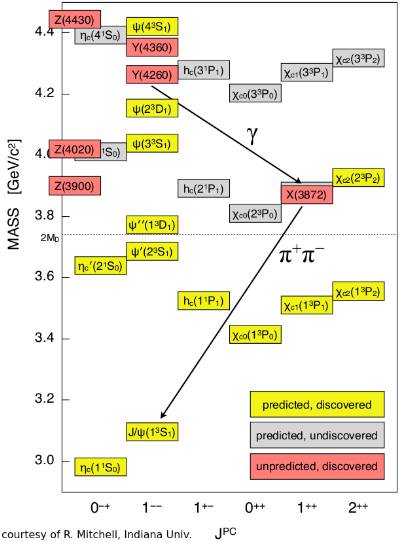
courtesy of R. Mitchell, Indiana Univ.

e^+e^- (at 4260 MeV) $\to \pi^+\pi^- J/\psi$ at BESIII



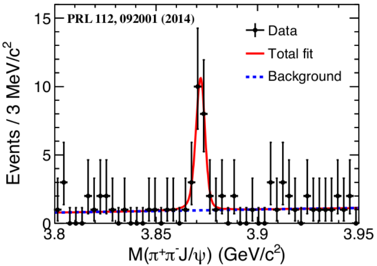
- $Z_C(3900)$ is Charged!
- Also neutral partner observed
- Can not be pure $c\bar{c}$ state
- Mass: $3899.0 \pm 3.6 \pm 4.9$ MeV
- Width: $46 \pm 10 \pm 20$ MeV
- Many other similar states found

The exotic X(3872) I



courtesy of R. Mitchell, Indiana Univ.

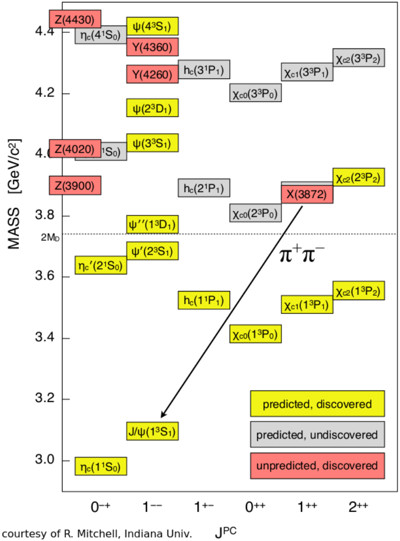
$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$ at BESIII



$$Y(4260) \to \gamma_{rad} X(3872)$$
$$\to \gamma_{rad} \pi^+\pi^- J/\psi$$

- X(3872) observed at BESIII
- radiative decay
- connection between XYZ

The exotic X(3872) II



courtesy of R. Mitchell, Indiana Univ.

Properties of X(3872)

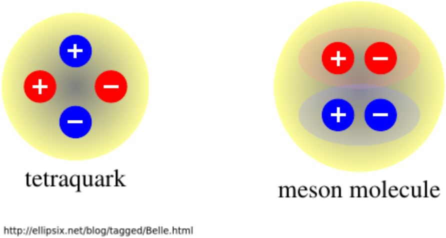
- First observed by **Belle** in 2003
- Confirmed by many other exp.
- Very narrow ($<$ 1.2 MeV)
- $J^{PC} = 1^{++}$ (**LHCb**)
- Mass close to $D\overline{D}^*$
- Important decay channels:

$D^0\overline{D}^*\pi^0$	$>$ 32%
$\gamma\psi(2S)$	$>$ 3.0%
$\rho J/\psi$	$>$ 2.6%
$\omega J/\psi$	$>$ 1.9%

- No charged partners!
- Exotic?

Physical Motivation

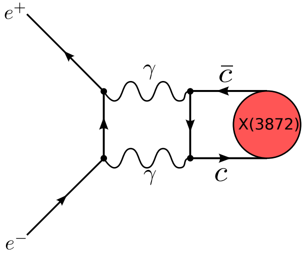
- What is the substructure of X(3872)?



- Electronic width: $\Gamma_{ee} \sim \sigma(e^+e^- \leftrightarrow X(3872)) \sim |\psi(0)|^2$
- Electronic width of X(3872) strongly depending on its substructure
- Theoretical predictions under construction
- More precise value of electronic width may rule out some models for structure

Technique of Analysis I

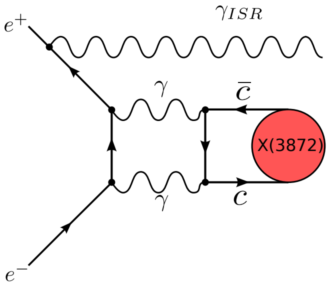
- $X(3872)$ is not a vector resonance, it has $J^{PC} = 1^{++}$
- **Problem:** $X(3872)$ can not be produced in an e^+e^- annihilation
- **Trick:** production via box diagram (Highly suppressed)

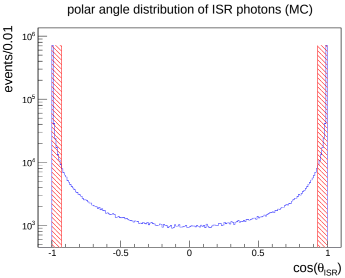


- Never observed 1^{++} state in e^+e^- collision
- $\mathcal{L}_{int} \approx 3\,\text{fb}^{-1}$ data in total at 4.009 GeV, 4.23 GeV, 4.26 GeV and 4.36 GeV
- **Problem:** No data at 3.872 GeV
- **Solution:** Initial State Radiation

ISR Technique I

- e^- or e^+ can radiate a photon before collision

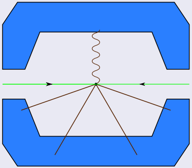




- Emission of ISR photons is suppressed by α/π
- Center of mass energy for collision reduced
- Acceptance of BESIII calorimeter: $|\cos\theta| \leq 0.93$
- Two analysis modes: ISR tagged, ISR untagged

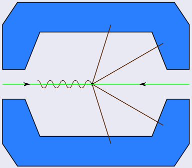
ISR Technique II

Tagged Analysis



- $J/\psi\pi^+\pi^-$ reconstructed
- ISR photon measured
  $\Rightarrow$ All particles detected

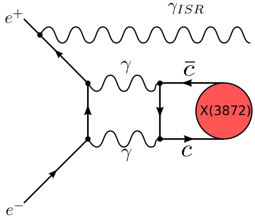
Untagged Analysis



- only $J/\psi\pi^+\pi^-$ reconstructed
- predict 4-momentum of ISR photon by demanding 4-momentum conservation

ISR untagged mode to avoid background from radiative decay
$e^+e^- \to Y(4260) \to \gamma X(3872)$

Technique of Analysis II



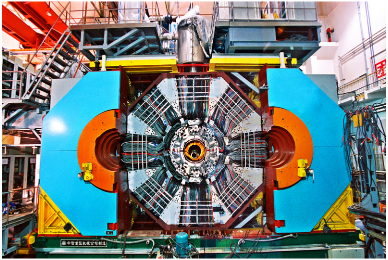
- Decay mode:

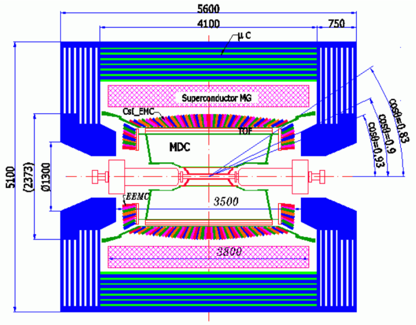
$$e^+e^- \longrightarrow X(3872)\gamma_{ISR} \longrightarrow \pi^+\pi^- J/\psi\gamma_{ISR}$$
$$\longrightarrow \pi^+\pi^-\ell^+\ell^-\gamma_{ISR} \quad , \qquad \ell = \mu, e$$

- Relation between radiative cross section and non radiative cross section

$$\frac{d\sigma_{X\gamma}}{dm} = \frac{2m}{s} W(s,m)\sigma_X(m)$$

The BESIII Detector



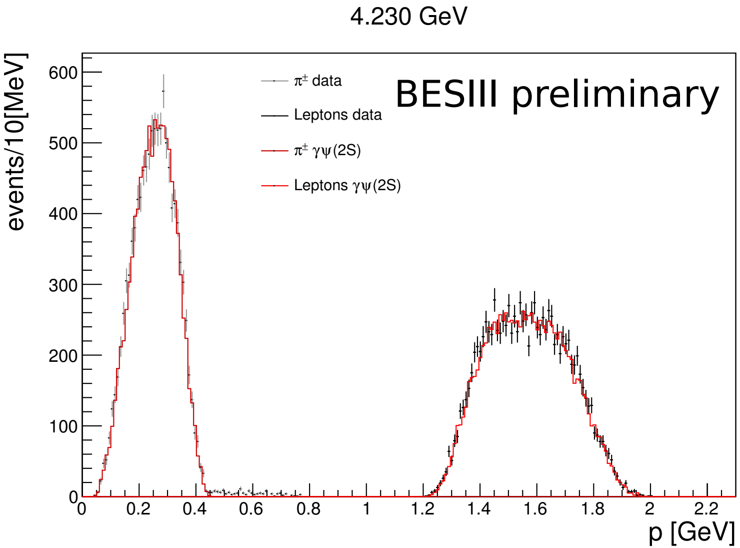


- Superconducting solenoid
- Drift chamber
- Time of flight detector
- Calorimeter
- Muon chamber

- Operating at BEPCII (Beijing)
- $\sqrt{s} = 2 - 4.6$ GeV

J/ψ Reconstruction

- Pions and leptons are well separated by momentum
- Cut: pions $p < 0.6$ GeV



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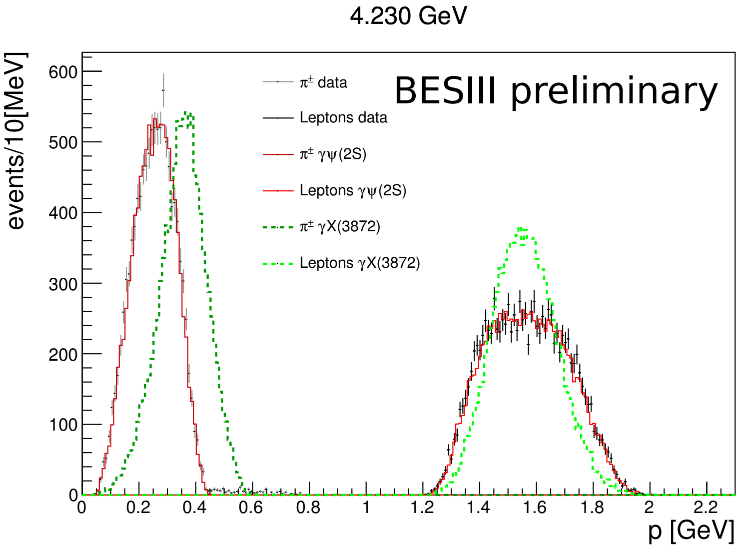
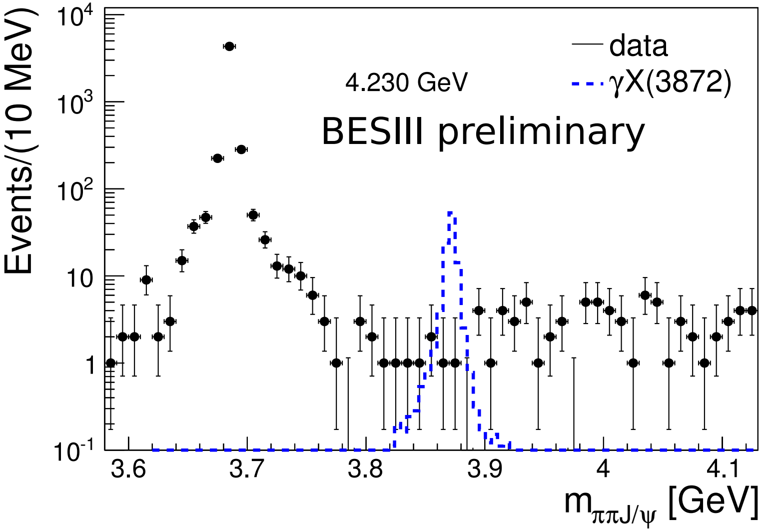
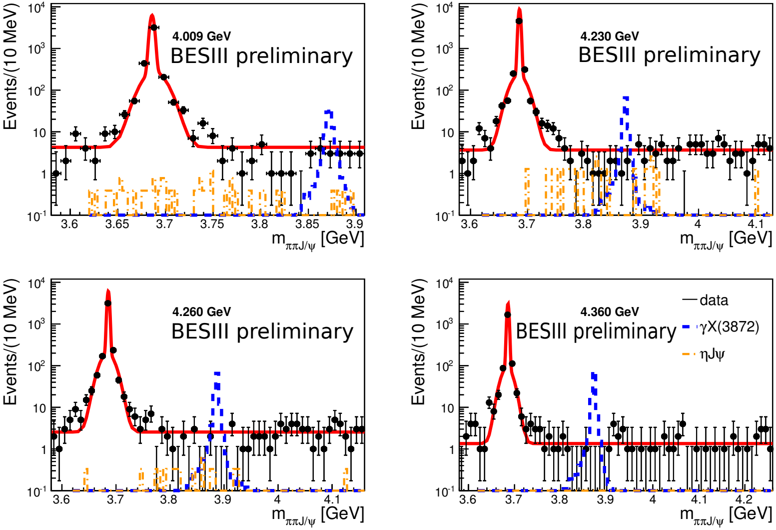


Mass Spectrum at Small Angles (Untagged Mode) I



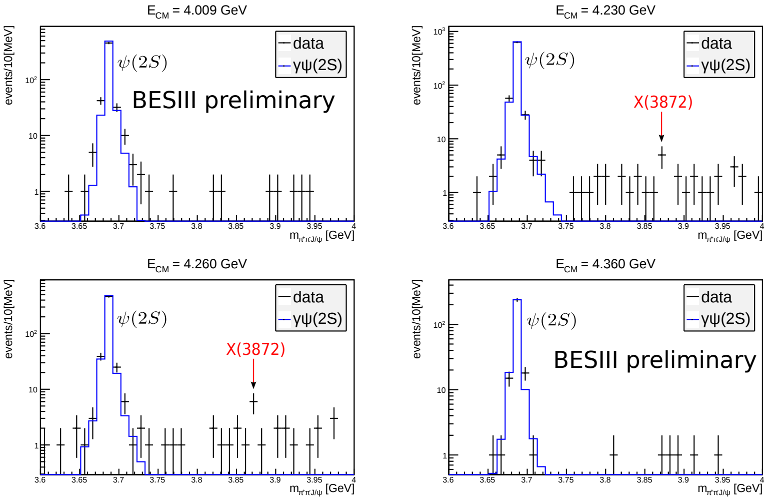
- $|\cos\theta_\gamma| > 0.95$
- No X(3872) peak observed

Mass Spectrum at Small Angles (Untagged Mode)II



- Fit: double Gaussian for $\psi(2S)$ + Gaussian for X(3872) + linear for background

Cross check at Large Angles (Tagged Mode)



- These are no ISR events, but $Y(4260) \to \gamma X(3872)$ events
- 19 ± 0.9 $X(3872)$ events observed by direct count
- In agreement with $e^+e^- \to \gamma X(3872)$ measurement from BESIII, PRL 112, 092001

Calculation of Γ_{ee}

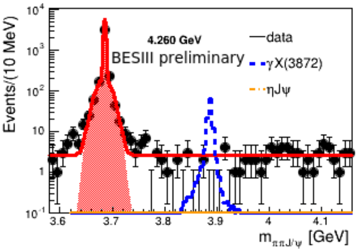
Number of observed $X(3872)$ given by:

$$\frac{dN_A^{\text{obs}}}{dx} = \mathcal{L}\varepsilon_A W(s,x)\sigma^A(m(s,x))\mathcal{B}(A \to f)$$
$$\Rightarrow N_A^{\text{obs}} = \varepsilon_A \mathcal{L}\Gamma_{ee}^A \mathcal{B}(A \to f) I_A$$

- for $A = X(3872)$, $\psi(2S)$.
- ε_A is the reconstruction efficiency
- $I_A = \int b_A(m(s,x))W(s,x)dx \quad , \quad x = 1 - m^2/s$
- $W(s,x)$ is the radiator function
- $b_A(m)$ is the relativistic Breit-Wigner function over Γ_{ee}^A

$$\Gamma_{ee}^A = \frac{N_A^{\text{obs}}}{\mathcal{L}\varepsilon_A I_A \mathcal{B}(A \to \pi^+\pi^- J/\psi)\mathcal{B}(J/\psi \to \ell^+\ell^-)}$$

Electronic Width of the $\psi(2S)$



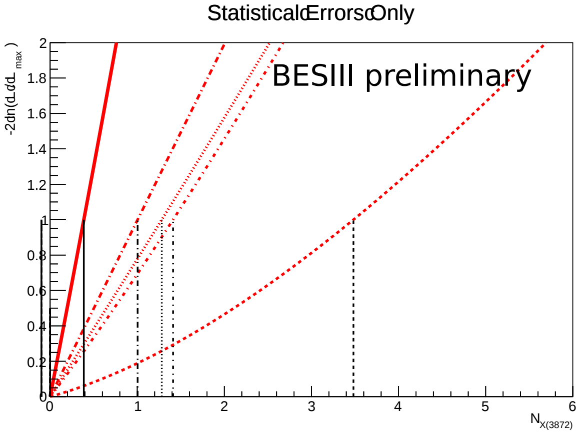
- $\Gamma_{ee}^{\psi(2S)} = \frac{N^{obs}_{\psi(2S)}}{\mathcal{L}\,\varepsilon\, I\, \mathcal{B}(\psi(2S)\to\pi^+\pi^-\ell^+\ell^-)}$
- Number of events under double Gaussian
- Branching fractions for $\psi(2S)$ from PDG
- $\mathcal{L}$ is Luminosity of data at each energy point

E_{CM}[GeV]	$N^{obs}_{\psi(2S)}$	$I_{\psi(2S)}$ [pb/keV]	$\varepsilon_{\psi(2S)}$	$\Gamma_{ee}^{\psi(2S)}$[eV]
4.009	4108 ± 45	310.48	0.308	2273 ± 28
4.230	4982 ± 82	172.37	0.291	2317 ± 41
4.260	3512 ± 35	161.46	0.291	2304 ± 26
4.360	1828 ± 51	133.23	0.289	2237 ± 65

Luminosity weighted average

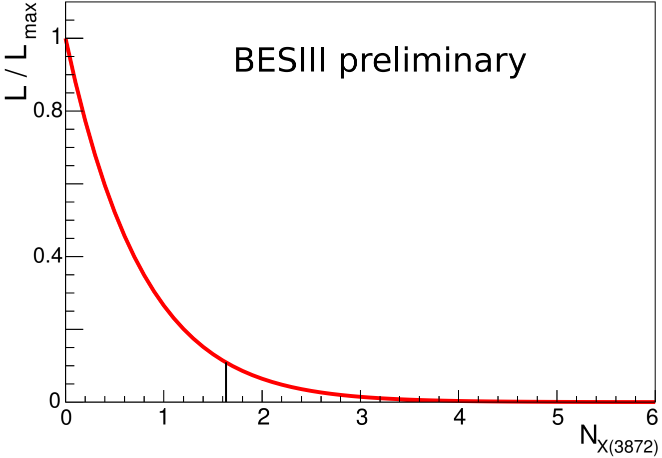
$\Gamma_{ee}^{\psi(2S)} = 2291 \pm 25(\text{stat}) \pm 101(\text{sys})\,\text{eV}$, PDG: 2350 ± 40 eV

Log Likelihood Scan for 90 % C.L.



E_{CM} [GeV]	σ_{N_3}	$\Delta\Gamma_{ee,1}\mathcal{B}$ [eV]	$\Delta\Gamma_{ee,2}\mathcal{B}$ [eV]
4.009	3.48	0.290	0.299
4.230	1.28	0.123	0.125
4.260	1.41	0.197	0.201
4.360	1.00	0.273	0.287

Combining the Four Measurements



- Summing up the single log likelihoods and take exponential
- $N_3^{\text{tot}} = 1.63$ at 90% of the integral
- $\Gamma_{ee}^{X}\mathcal{B} = \dfrac{N_3^{\text{tot}}}{\mathcal{B}(X(3872)\to f)\sum_i \varepsilon_i^{X(3872)}\mathcal{L}_i I_i^{X(3872)}} = 0.101\,\text{eV}$

Systematic Errors

source	$\sigma_{sys}^{X(3872)}$ [%]	$\sigma_{sys}^{\psi(2S)}$ [%]
Luminosity	1.0	1.0
Tracking	4.0	4.0
J/ψ mass window	0.2	0.2
Branching ratios	1.4	1.4
Background model	0.027	0.027
X(3872) width	2.7	-
ISR simulation	3.4	0.5
$\psi(2S)$ fit model	0.69	-
Total	6.2	4.2

$$\Delta\Gamma_{ee}^{\psi(2S)} = 101\,\text{eV}\,,$$
$$\Delta\Gamma_{ee}^{X(3872)} = 0.005\,\text{eV}\,,$$

Final Result for X(3872)

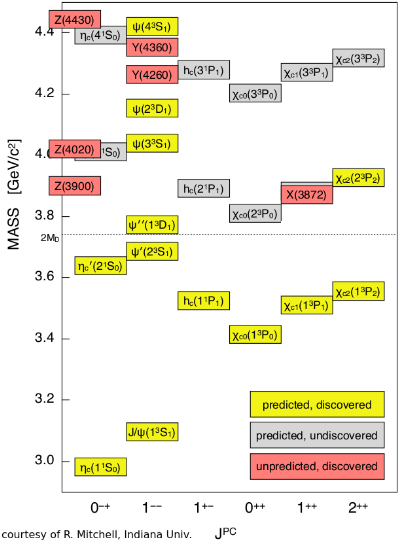
Preliminary Results

$$\Gamma_{ee}^{X(3872)}\Gamma_{\pi^+\pi^- J/\psi}^{X(3872)}/\Gamma_{tot} < 0.106\,\text{eV} \qquad \text{at} \quad 90\%\,\text{C.L.}$$

$$\Gamma_{ee}^{\psi(2S)} = 2291 \pm 25(\text{stat}) \pm 101(\text{sys})\,\text{eV}$$

- PDG: $\Gamma_{ee} < 280\,eV$ Yuan , $\Gamma_{ee}\Gamma_{\pi^+\pi^- J/\psi}/\Gamma_{tot} < 6.2\,eV$ Aubert
- Assuming $\mathcal{B}(X(3872) \to \pi^+\pi^- J/\psi) < 6.6\%$ yields $\Gamma_{ee,1}^{X(3872)} < 1.61\,\text{eV}$ at 90% C.L.
- **Improvement by 2 orders of magnitude**
- Theoretical calculation predicts: $\Gamma_{ee}^{X(3872)} \approx 0.03\,\text{eV}$
  A. Denig, F. -K. Guo, C. Hanhart, A. V. Nefediev
  Phys. Lett. B **736** (2014) 221
- Waiting for more theoretical calculations

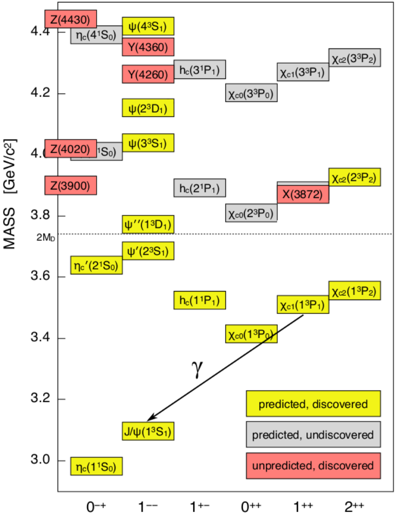
Let's Try Again!



courtesy of R. Mitchell, Indiana Univ.

Is there another $J^{PC} = 1^{++}$ state in the charmonium spectrum?

The χ_{c1}



courtesy of R. Mitchell, Indiana Univ.

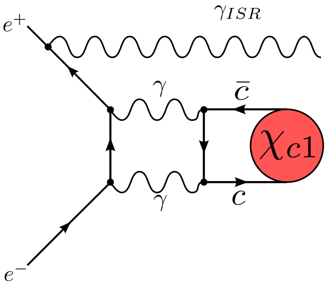
Properties of χ_{c1}

- First observed 1977 by **Biddic et al.**
- Confirmed by many other exp.
- Mass: 3.51 GeV
- Very narrow (0.84 MeV)
- $J^{PC} = 1^{++}$
- Mass close to $D\overline{D}^*$
- Important decay channels:

$$\begin{array}{ll} \gamma J/\psi & 34\% \\ \rho\pi\pi & 1.9\% \end{array}$$

- $\Gamma_{ee} = 0.46\,eV$ (VMD model) J. Kaplan, H.Kühn, PLB78 (1978) 252

Search for $e^+e^- \longrightarrow \chi_{c1}\gamma_{ISR}$ I

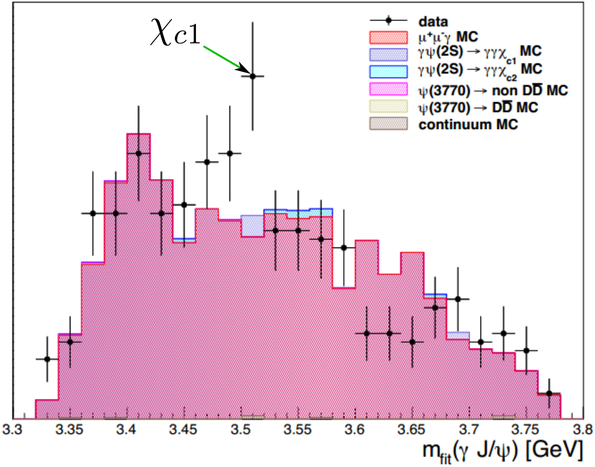


- Analysis similar to X(3872) case
- Decay mode:

$$e^+e^- \longrightarrow \chi_{c1}\gamma_{ISR} \longrightarrow J/\psi\gamma\gamma_{ISR}$$
$$\longrightarrow \mu^+\mu^-\gamma\gamma_{ISR}$$

- Dominating background: $e^+e^- \longrightarrow \mu^+\mu^-\gamma_{ISR}$ (well known!)
- Analysis performed by Benedikt Kloss

Search for $e^+e^- \longrightarrow \chi_{c1}\gamma_{ISR}$ II



- Some indication for χ_{c1} signal!
- Statistics too small

Future χ_{c1} Search

- Proposed to take $\approx 400pb^{-1}$ data in three Energy points on and around χ_{c1} mass
- Directly analyse resonant χ_{c1} production
  $e^+e^- \longrightarrow \chi_{c1} \longrightarrow J/\psi\gamma \longrightarrow \mu\mu\gamma$
- Interference between χ_{c1} and $\mu\mu\gamma$ needs to be considered
- Expected statistical significance of discovery will depend on sign of the interference
- Proposal accepted by the BESIII collaboration
- Data taking in spring next year

Summary

- Only $J^{PC} = 1^{--}$ states can be produced directly produced in e^+e^- annihilations
- $J^{PC} = 1^{++}$ states can be produced via a box diagram
- The ISR method gives access to resonances below the center of mass Energy
- $\Gamma_{ee,1}^{X(3872)} < 1.61\,\text{eV}$ at 90% C.L.
- World's so far best limit improved by 2 orders of magnitude
- Data taking next year to directly see the χ_{c1}
- **We hope to discover a 1++ state produced in e^+e^- annihilation soon!**

Thank you for your attention!