

## 2B. Investigate new states with BESIII

**BESIII**  
( $e^+e^-$  collisions in the charmonium region)

*location:* Beijing, China

*accelerator:* BEPC-II

*dates:* 2008 – ?

future and  
ongoing  
experiments

“beyond”  
quark  
model  
states

quark  
model  
states

Belle II

$Y_b(10890)$

$Y(bb)$

**BESIII**

$Y(4260)$

PANDA

$X(3872)$

$\psi(cc)$

$Y_s(2175)$

$\pi_1(1600)$

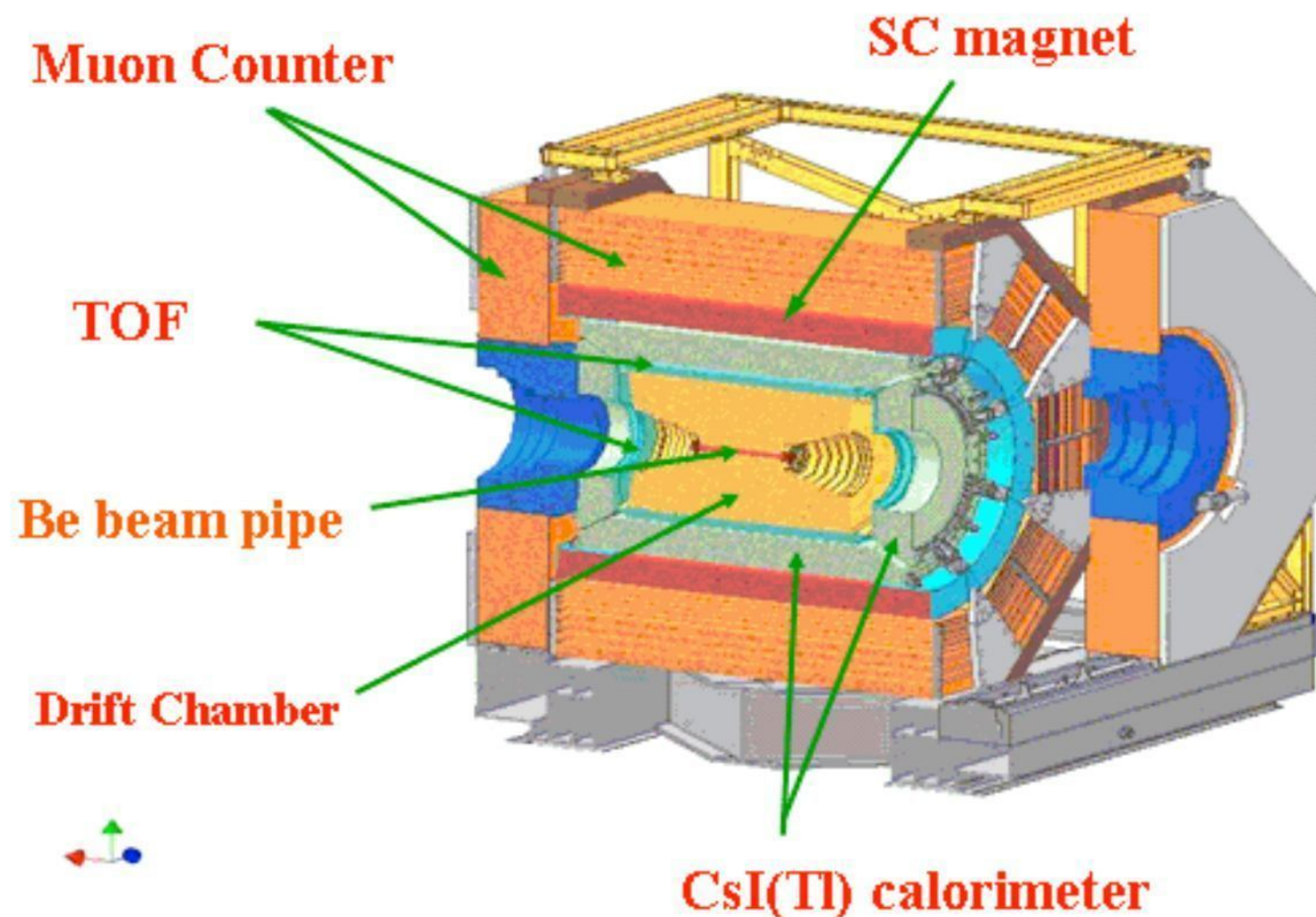
GlueX

$\phi(ss)$

$\omega(nn)$

$\rho(nn)$

## 2B. Investigate new states with BESIII



$e^+e^-$  collisions in the charmonium region

future and ongoing experiments

“beyond” quark model states

quark model states

Belle II

$Y_b(10890)$

$Y(bb)$

**BESIII**

$Y(4260)$

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GlueX

$\phi(ss)$

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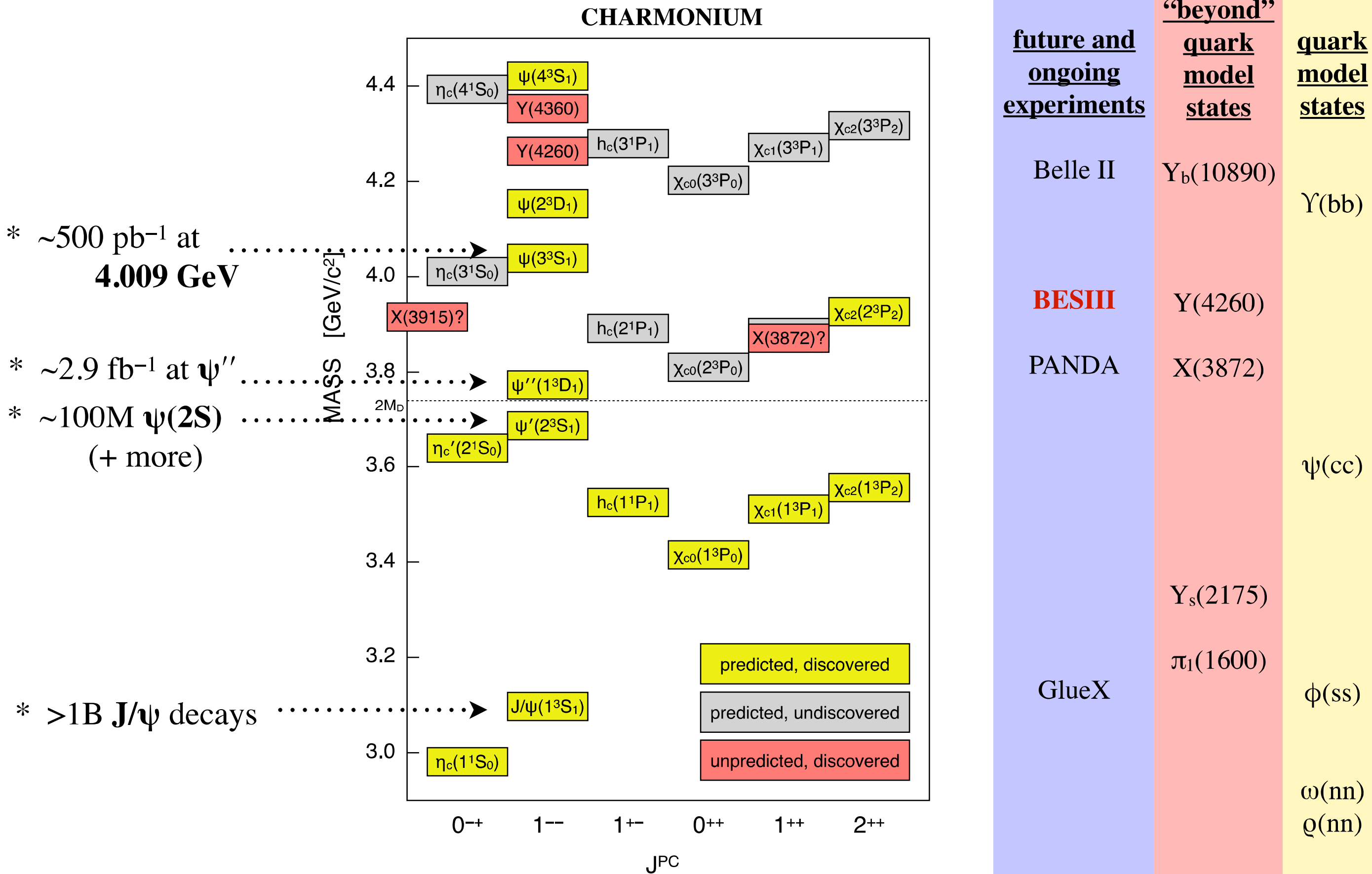
$\rho(nn)$

## 2B. Investigate new states with BESIII



<u>future and ongoing experiments</u>	<u>“beyond” quark model states</u>	<u>quark model states</u>
Belle II	$Y_b(10890)$	$Y(bb)$
<b>BESIII</b>	$Y(4260)$	
PANDA	$X(3872)$	$\psi(cc)$
	$Y_s(2175)$	
GlueX	$\pi_1(1600)$	$\phi(ss)$
		$\omega(nn)$ $\rho(nn)$

# 2B. Investigate new states with BESIII



# 2B. Investigate new states with BESIII

**NEW!**

\*  $\sim 500 \text{ pb}^{-1}$  at **Y(4360)**

\*  $> 500 \text{ pb}^{-1}$  at **Y(4260)**

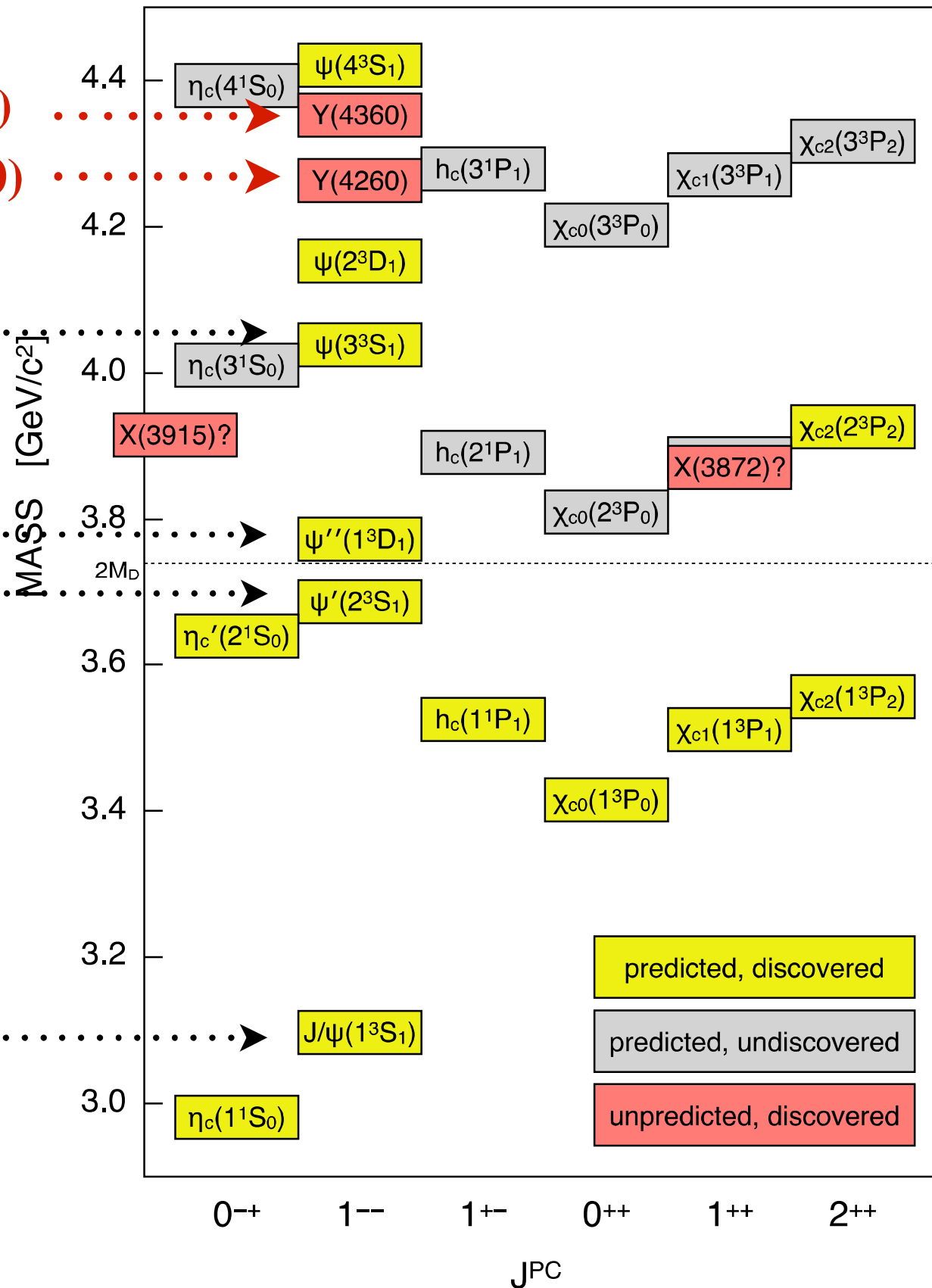
\*  $\sim 500 \text{ pb}^{-1}$  at **4.009 GeV**

\*  $\sim 2.9 \text{ fb}^{-1}$  at  $\psi''$

\*  $\sim 100\text{M } \psi(2\text{S})$   
(+ more)

\*  $> 1\text{B } \text{J}/\psi$  decays

## CHARMONIUM



**future and ongoing experiments**

Belle II

**BESIII**

PANDA

GlueX

**“beyond” quark model states**

$Y_b(10890)$

**Y(4260)**

X(3872)

$Y_s(2175)$

$\pi_1(1600)$

**quark model states**

$\Upsilon(bb)$

$\psi(cc)$

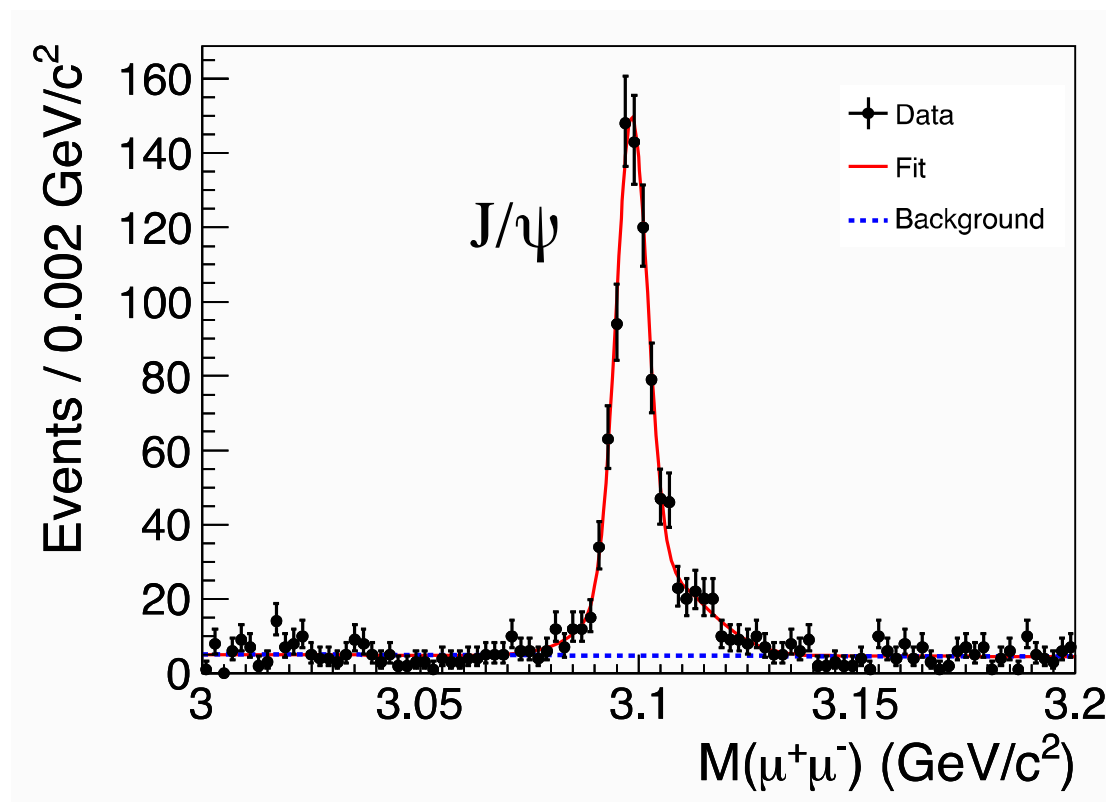
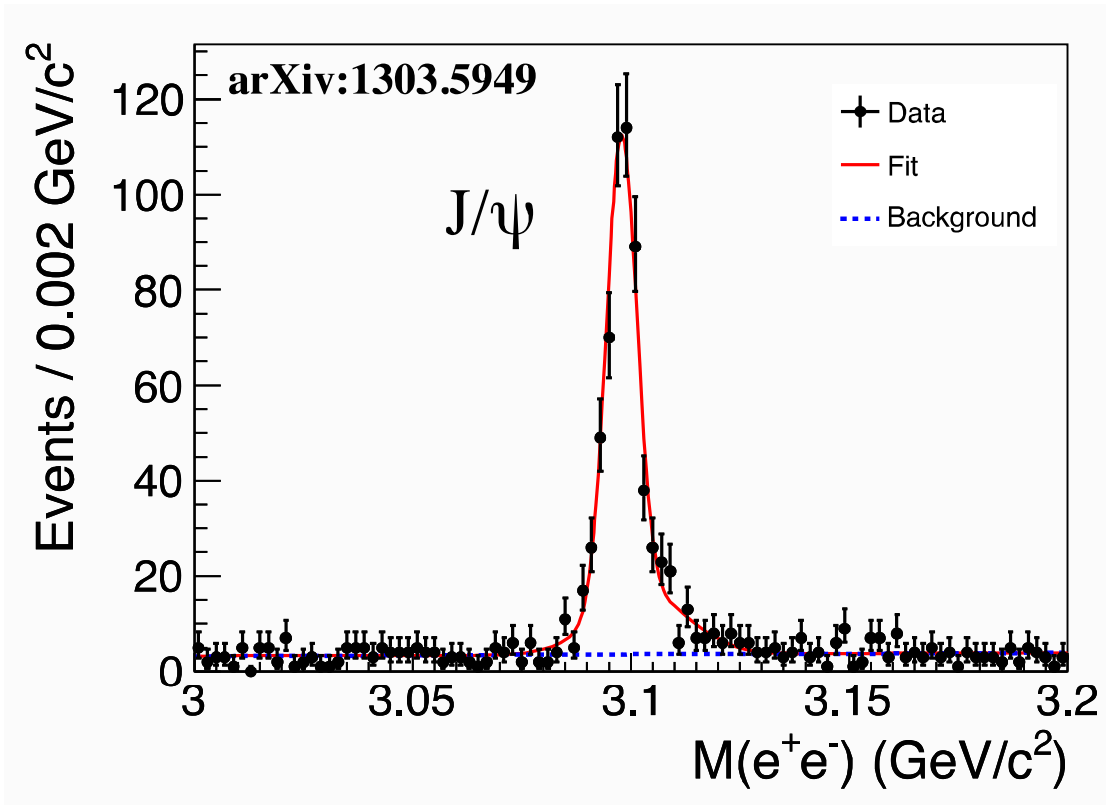
$\phi(ss)$

$\omega(nn)$

$\rho(nn)$

# 2B. Investigate new states with BESIII

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



future and ongoing experiments

“beyond” quark model states

quark model states

Belle II

$Y_b(10890)$

$Y(bb)$

**BESIII**

**$Y(4260)$**

PANDA

$X(3872)$

$\psi(cc)$

GlueX

$Y_s(2175)$

$\pi_1(1600)$

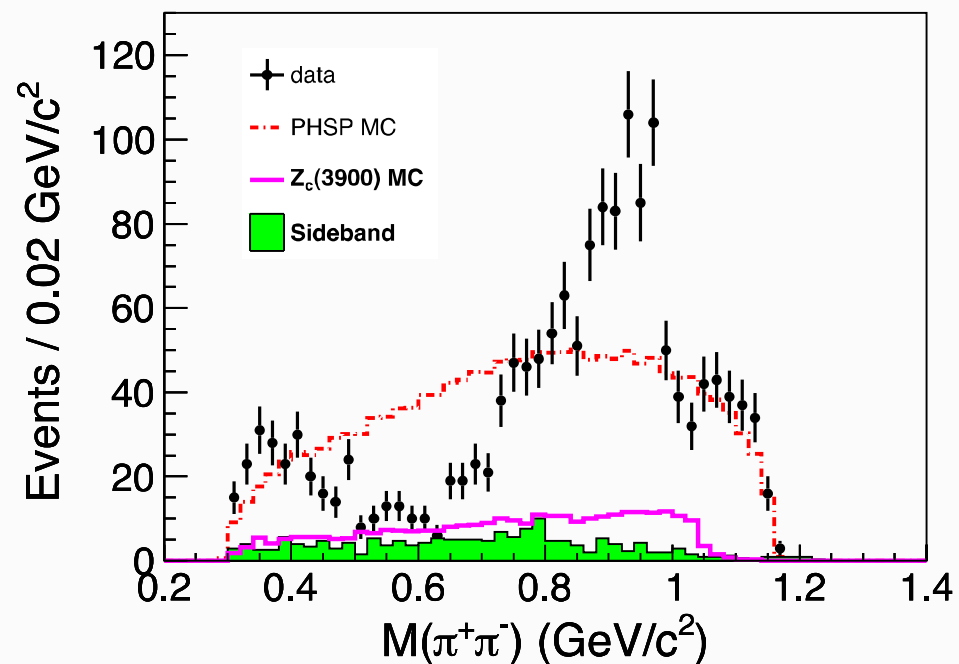
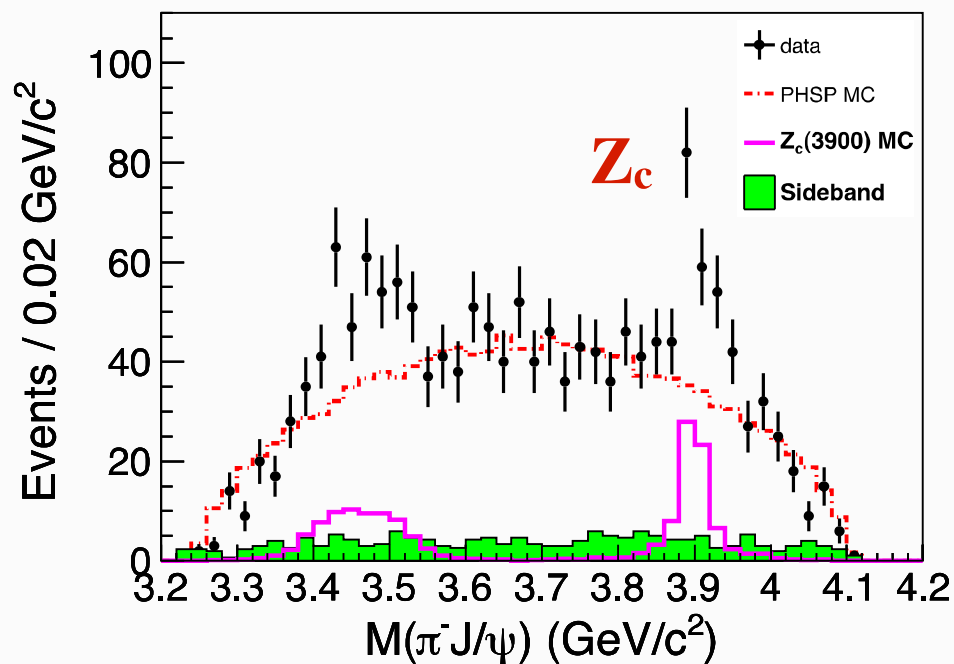
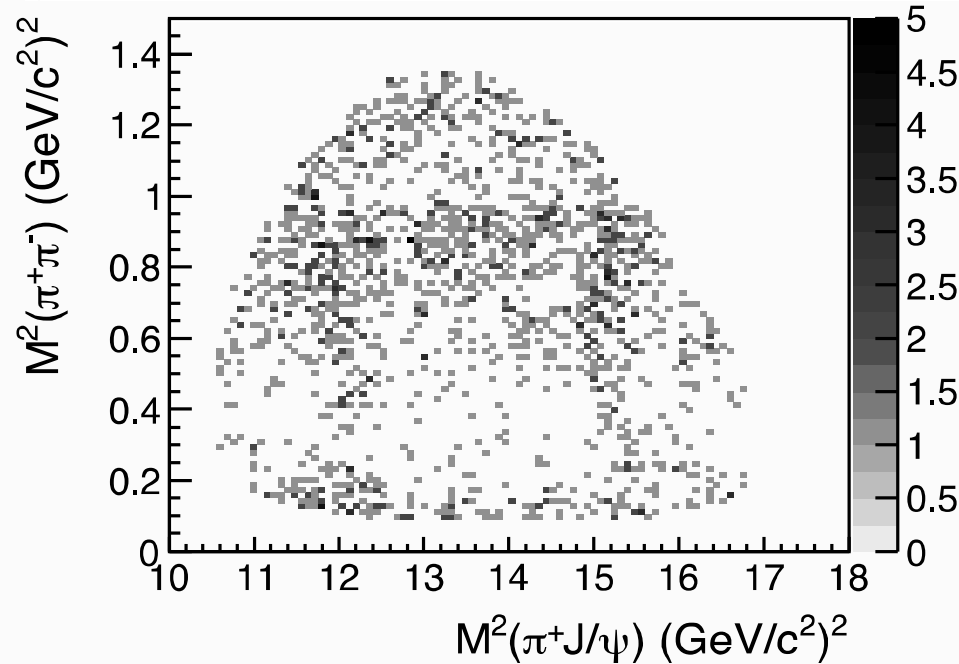
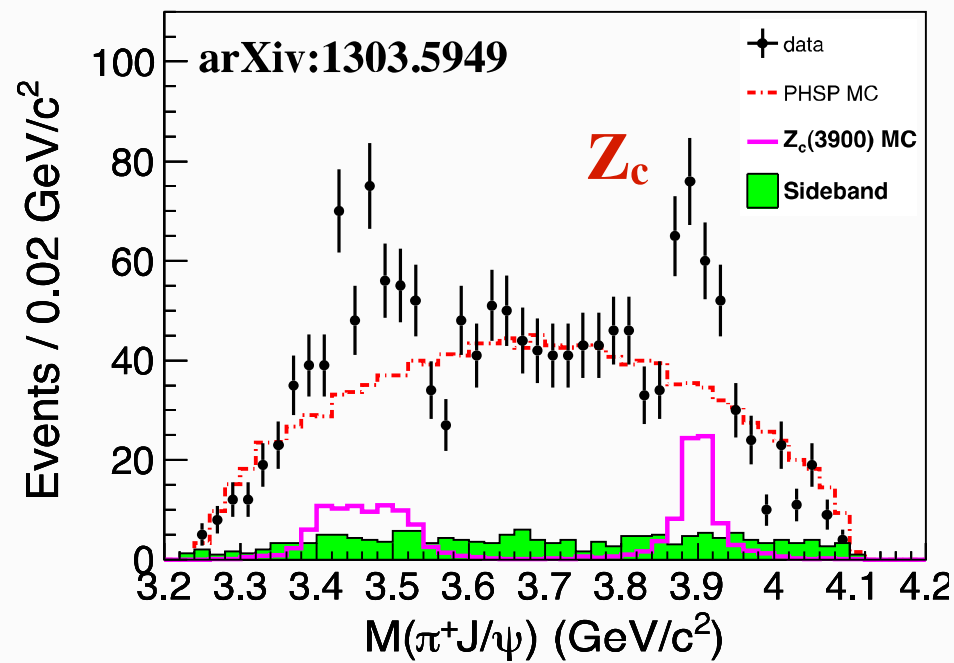
$\phi(ss)$

$\omega(nn)$

$\rho(nn)$

# 2B. Investigate new states with BESIII

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



*Observation of a  $Z_c(3900)$  state.*

future and ongoing experiments

“beyond” quark model states

quark model states

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$Y(bb)$

**BESIII**

**$Y(4260)$**

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$\psi(cc)$

$Y_s(2175)$

$\pi_1(1600)$

GlueX

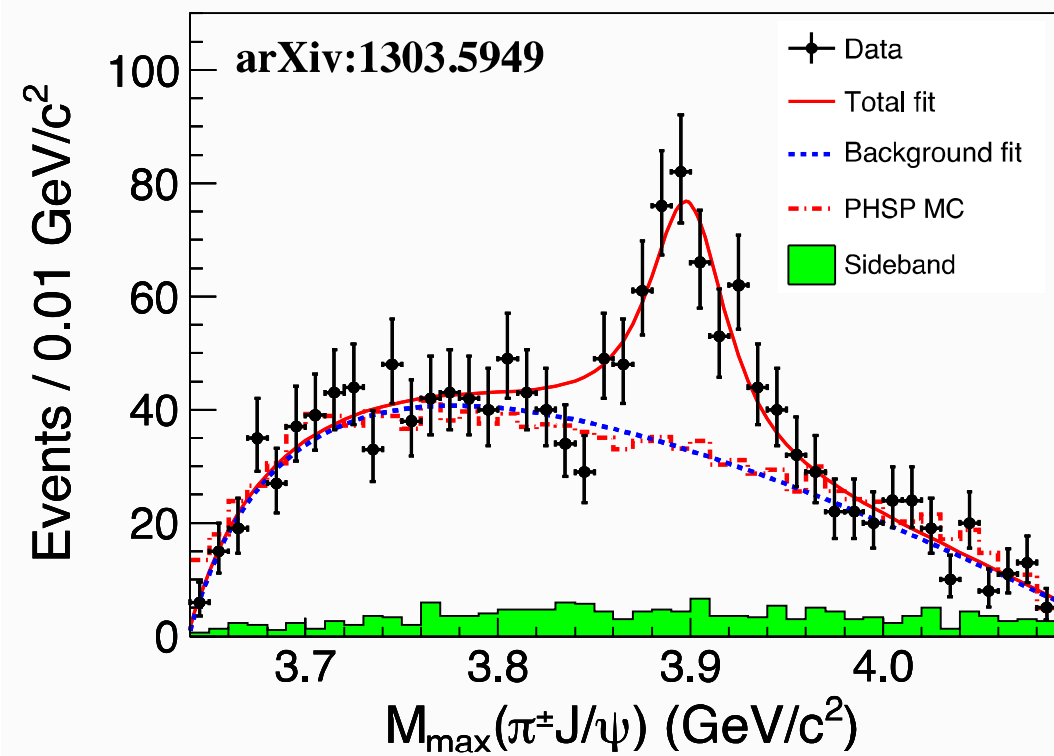
$\phi(ss)$

$\omega(nn)$

$\rho(nn)$

# 2B. Investigate new states with BESIII

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



$$M = 3899.0 \pm 3.6 \pm 4.9 \text{ MeV}$$

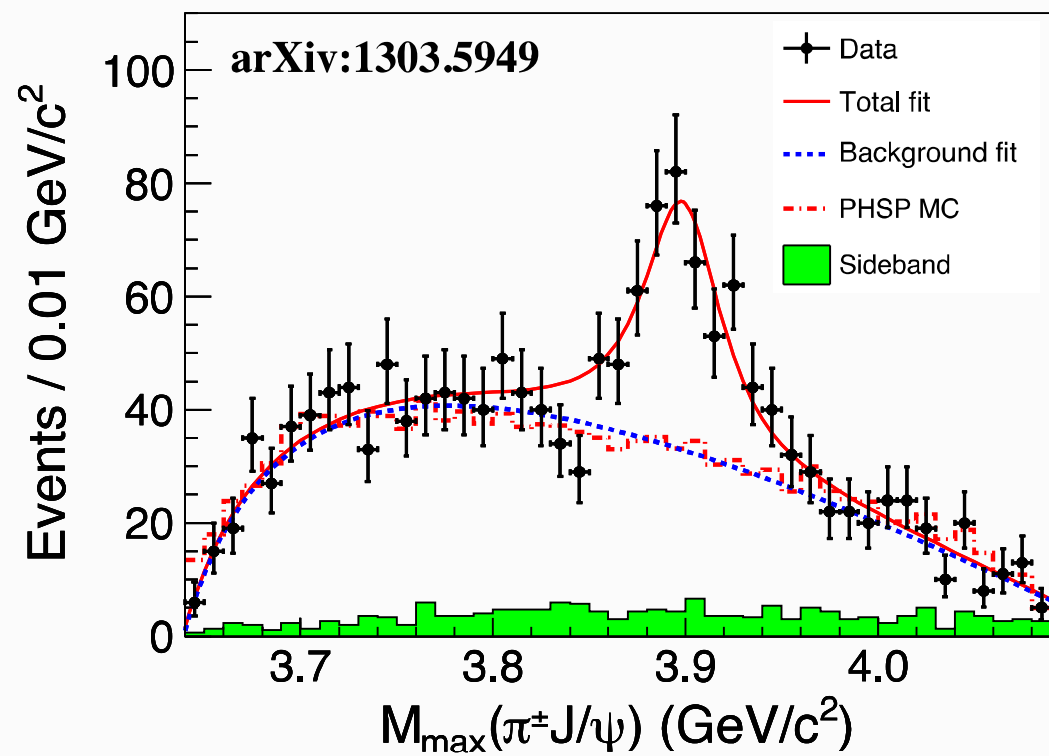
$$\Gamma = 46 \pm 10 \pm 20 \text{ MeV}$$

<u>future and ongoing experiments</u>	<u>“beyond” quark model states</u>	<u>quark model states</u>
Belle II	$Y_b(10890)$	$Y(bb)$
<b>BESIII</b>	<b><math>Y(4260)</math></b>	
PANDA	$X(3872)$	
		$\psi(cc)$
	$Y_s(2175)$	
	$\pi_1(1600)$	
GlueX		$\phi(ss)$
		$\omega(nn)$ $\rho(nn)$



# 2B. Investigate new states with BESIII

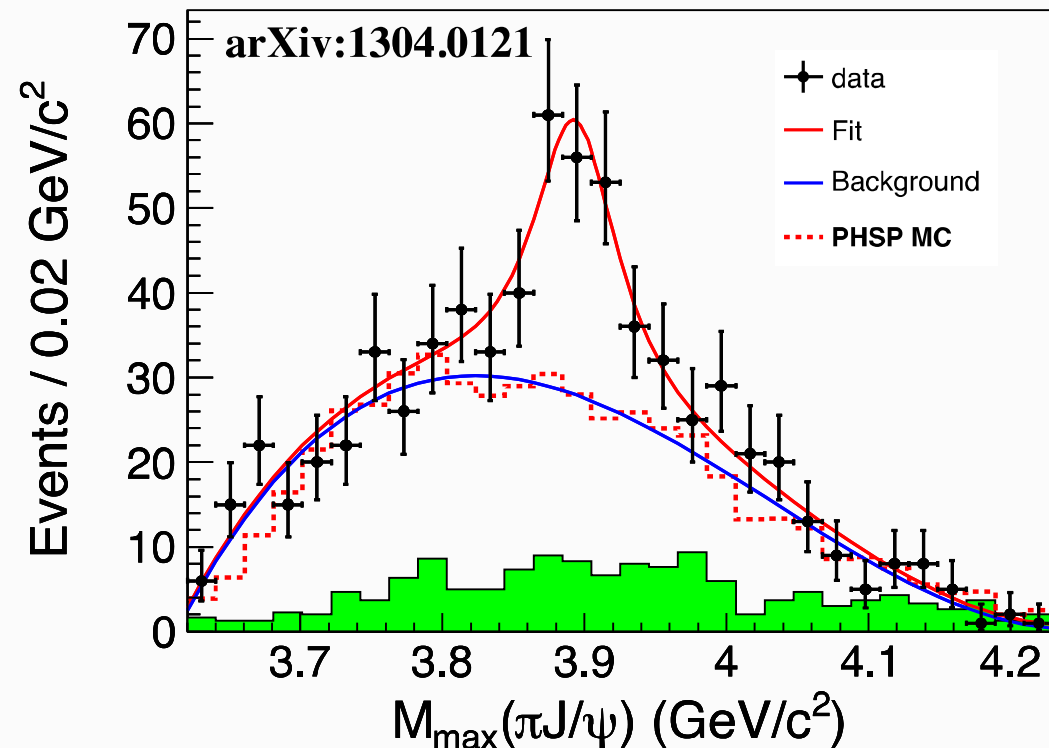
$e^+e^-$  (at 4260 MeV)  $\rightarrow \pi^+\pi^-J/\psi$  at BESIII



$$M = 3899.0 \pm 3.6 \pm 4.9 \text{ MeV}$$

$$\Gamma = 46 \pm 10 \pm 20 \text{ MeV}$$

$e^+e^-(\gamma_{\text{ISR}}) \rightarrow \pi^+\pi^-J/\psi$  at Belle



$$M = 3894.5 \pm 6.6 \pm 4.5 \text{ MeV}$$

$$\Gamma = 63 \pm 24 \pm 26 \text{ MeV}$$

future and ongoing experiments

“beyond” quark model states

quark model states

Belle II

$Y_b(10890)$

$Y(bb)$

**BESIII**

**$Y(4260)$**

PANDA

$X(3872)$

$\psi(cc)$

GlueX

$Y_s(2175)$

$\pi_1(1600)$

$\phi(ss)$

$\omega(nn)$

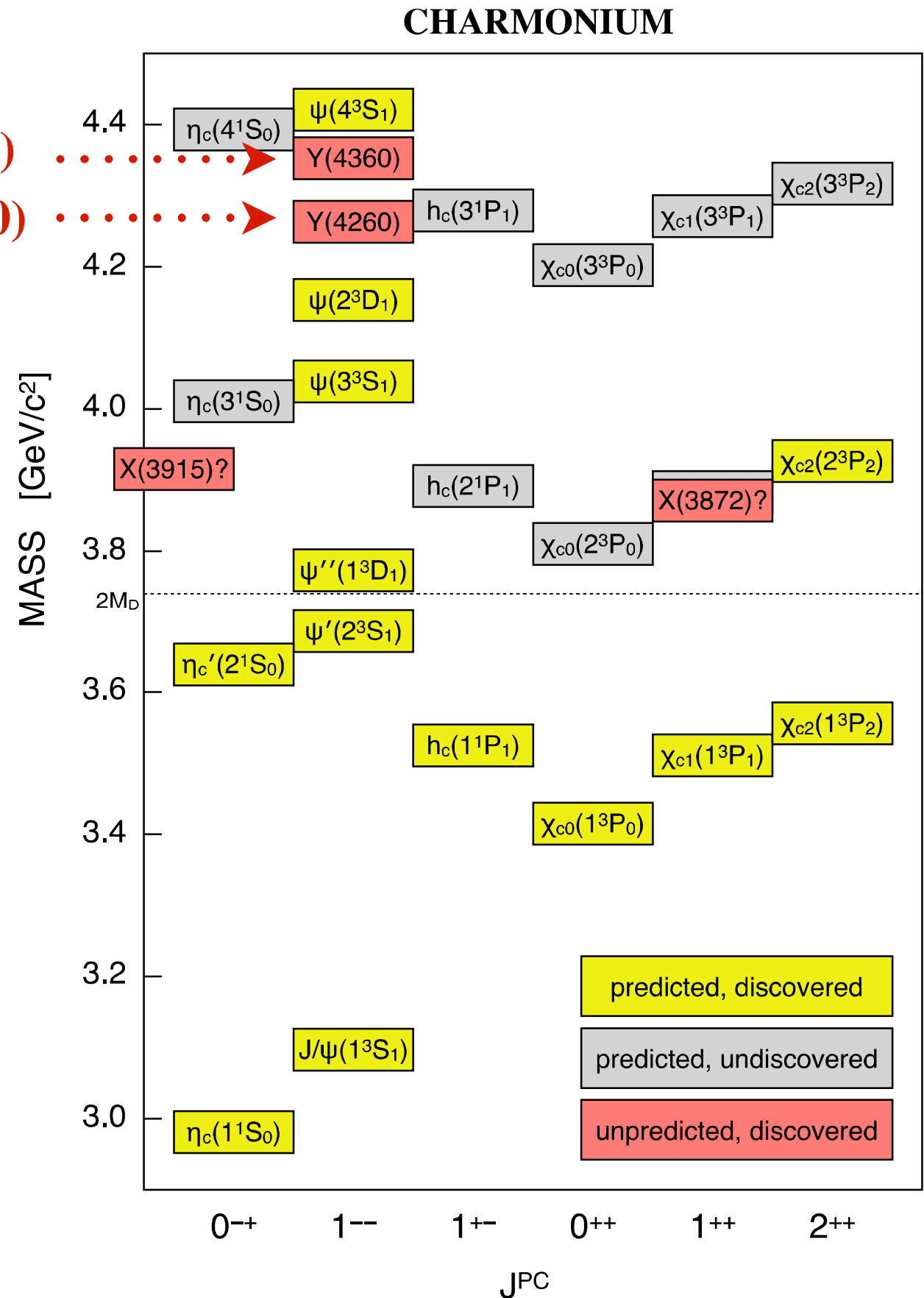
$\rho(nn)$

# 2B. Investigate new states with BESIII

**NEW!**

\*  $\sim 500 \text{ pb}^{-1}$  at **Y(4360)**

\*  $> 500 \text{ pb}^{-1}$  at **Y(4260)**



This data is less than two months old...

Expect many new results soon!

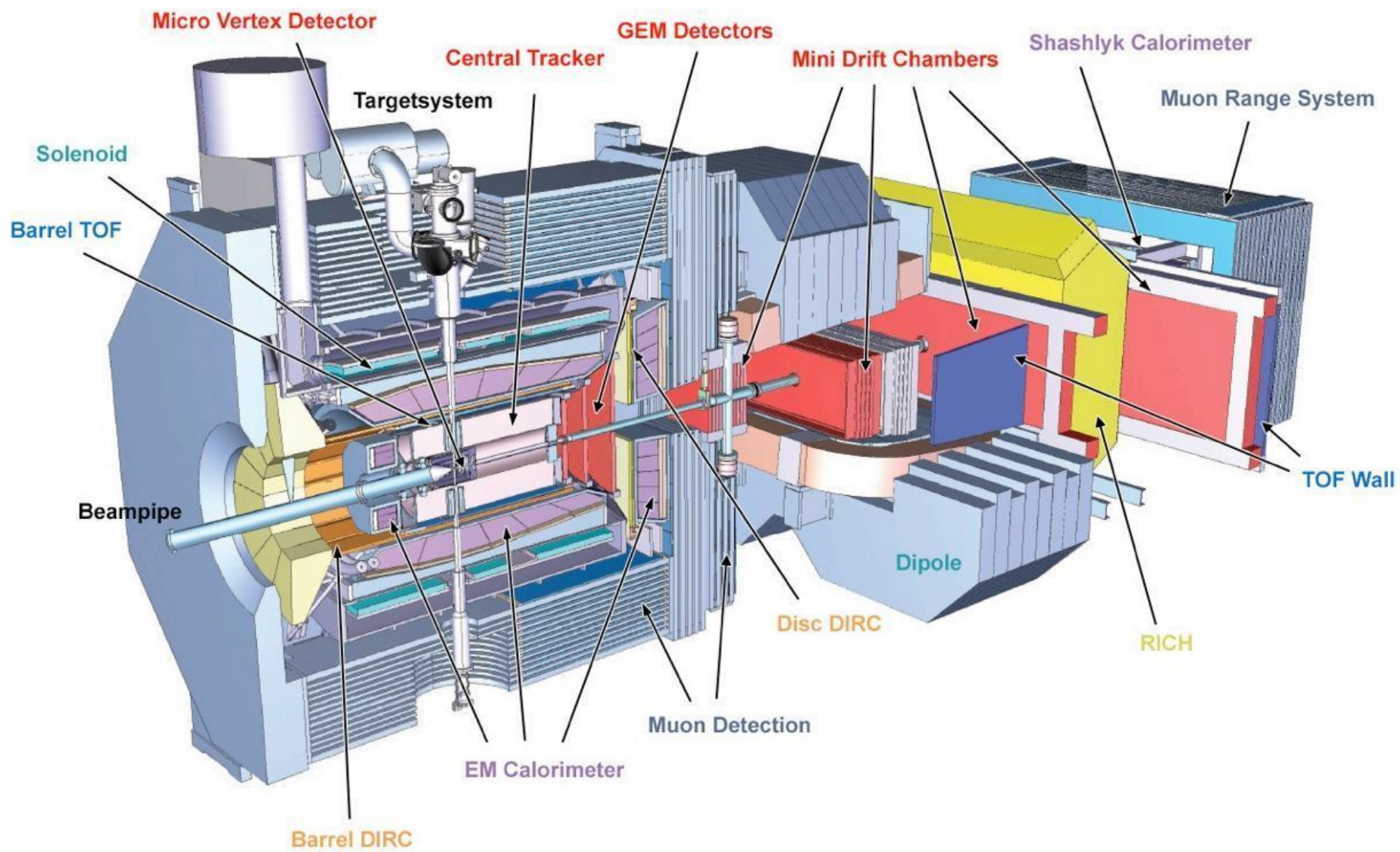
<u>future and ongoing experiments</u>	<u>“beyond” quark model states</u>	<u>quark model states</u>
Belle II	Y <sub>b</sub> (10890)	Υ(bb)
<b>BESIII</b>	<b>Y(4260)</b>	
PANDA	X(3872)	
		ψ(cc)
	Y <sub>s</sub> (2175)	
GlueX	π <sub>1</sub> (1600)	φ(ss)
		ω(nn) ρ(nn)

## 2C. Investigate new states with PANDA

**PANDA**  
 ( $p\bar{p}$  collisions in the charmonium region)  
  
*location:* Darmstadt, Germany  
*accelerator:* HESR at FAIR  
*dates:* ~2018 – ?

<u>future and ongoing experiments</u>	<u>“beyond” quark model states</u>	<u>quark model states</u>
Belle II	$Y_b(10890)$	$Y(bb)$
BESIII	$Y(4260)$	
<b>PANDA</b>	$X(3872)$	$\psi(cc)$
	$Y_s(2175)$	
GlueX	$\pi_1(1600)$	$\phi(ss)$
		$\omega(nn)$ $\rho(nn)$

# 2C. Investigate new states with PANDA



$\bar{p}$  beam on a fixed p target

future and ongoing experiments

“beyond” quark model states

quark model states

Belle II

$Y_b(10890)$

$Y(bb)$

BESIII

$Y(4260)$

**PANDA**

$X(3872)$

$\psi(cc)$

$Y_s(2175)$

$\pi_1(1600)$

GlueX

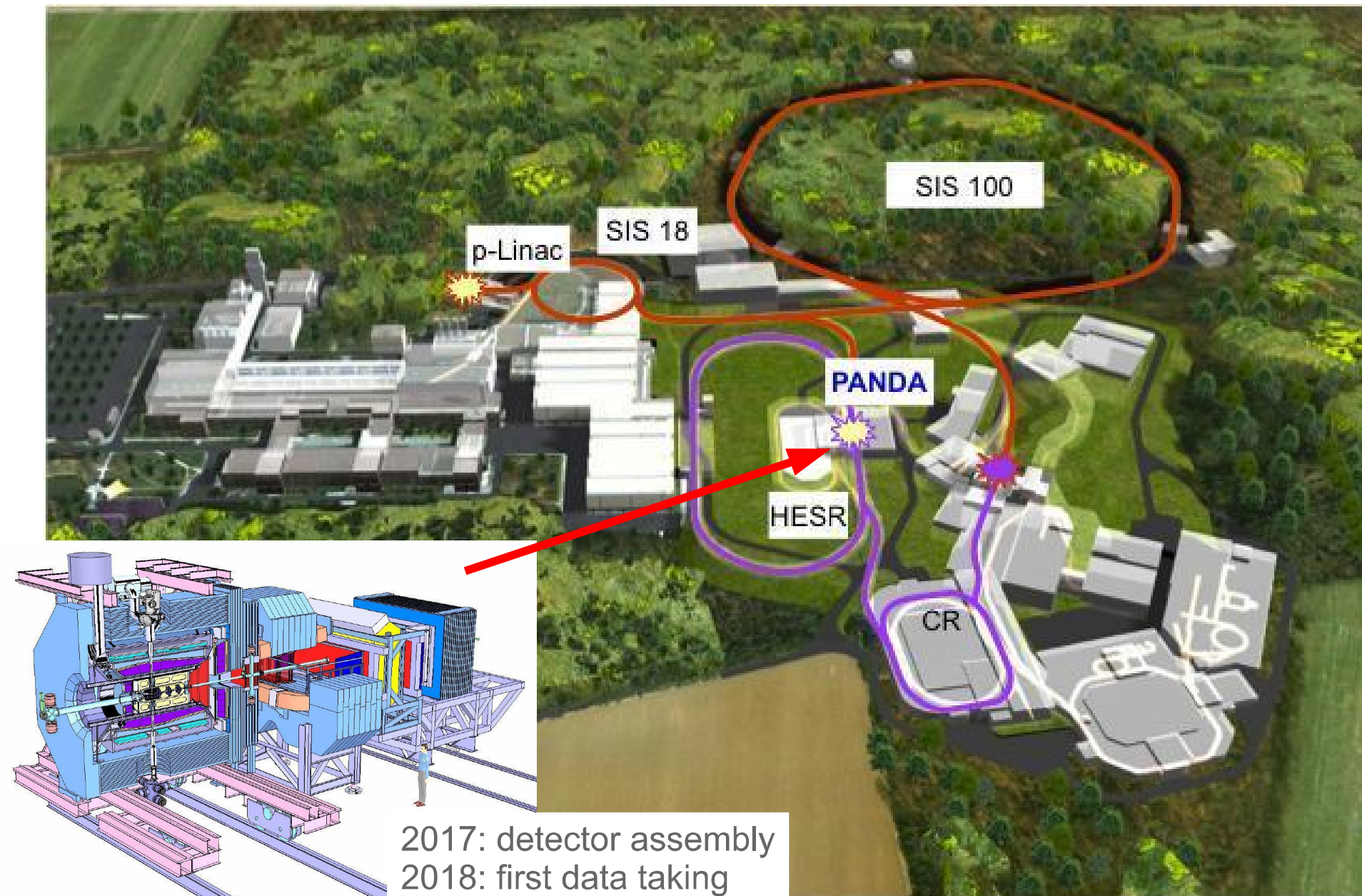
$\phi(ss)$

$\omega(nn)$

$\rho(nn)$

# 2C. Investigate new states with PANDA

## PANDA at FAIR



M. Pelizäus, Charm 2012

antiprotons with momenta **1.5 to 15 GeV/c** and  $\delta p/p < 4 \times 10^{-5}$

future and ongoing experiments

“beyond” quark model states

quark model states

Belle II

$Y_b(10890)$

$Y(bb)$

BESIII

$Y(4260)$

**PANDA**

$X(3872)$

$\psi(cc)$

$Y_s(2175)$

$\pi_1(1600)$

GlueX

$\phi(ss)$

$\omega(nn)$

$\rho(nn)$

## 2C. Investigate new states with PANDA

preparation of the construction site,  
March 2012

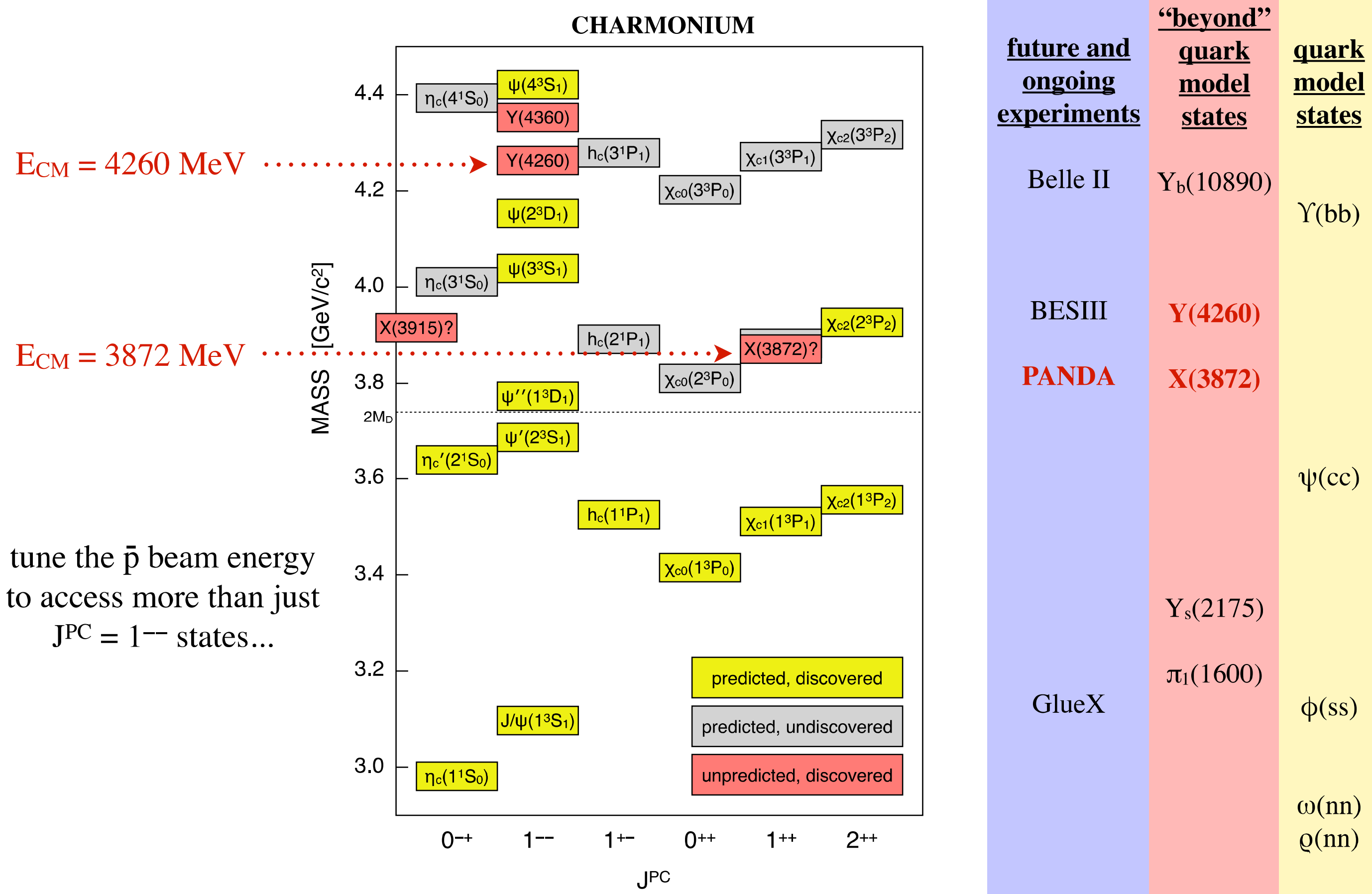


M. Pelizäus, Charm 2012

antiprotons with momenta **1.5 to 15 GeV/c** and  $\delta p/p < 4 \times 10^{-5}$

<u>future and ongoing experiments</u>	<u>“beyond” quark model states</u>	<u>quark model states</u>
Belle II	$Y_b(10890)$	$Y(bb)$
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GlueX	$\pi_1(1600)$	$\phi(ss)$
		$\omega(nn)$ $\rho(nn)$

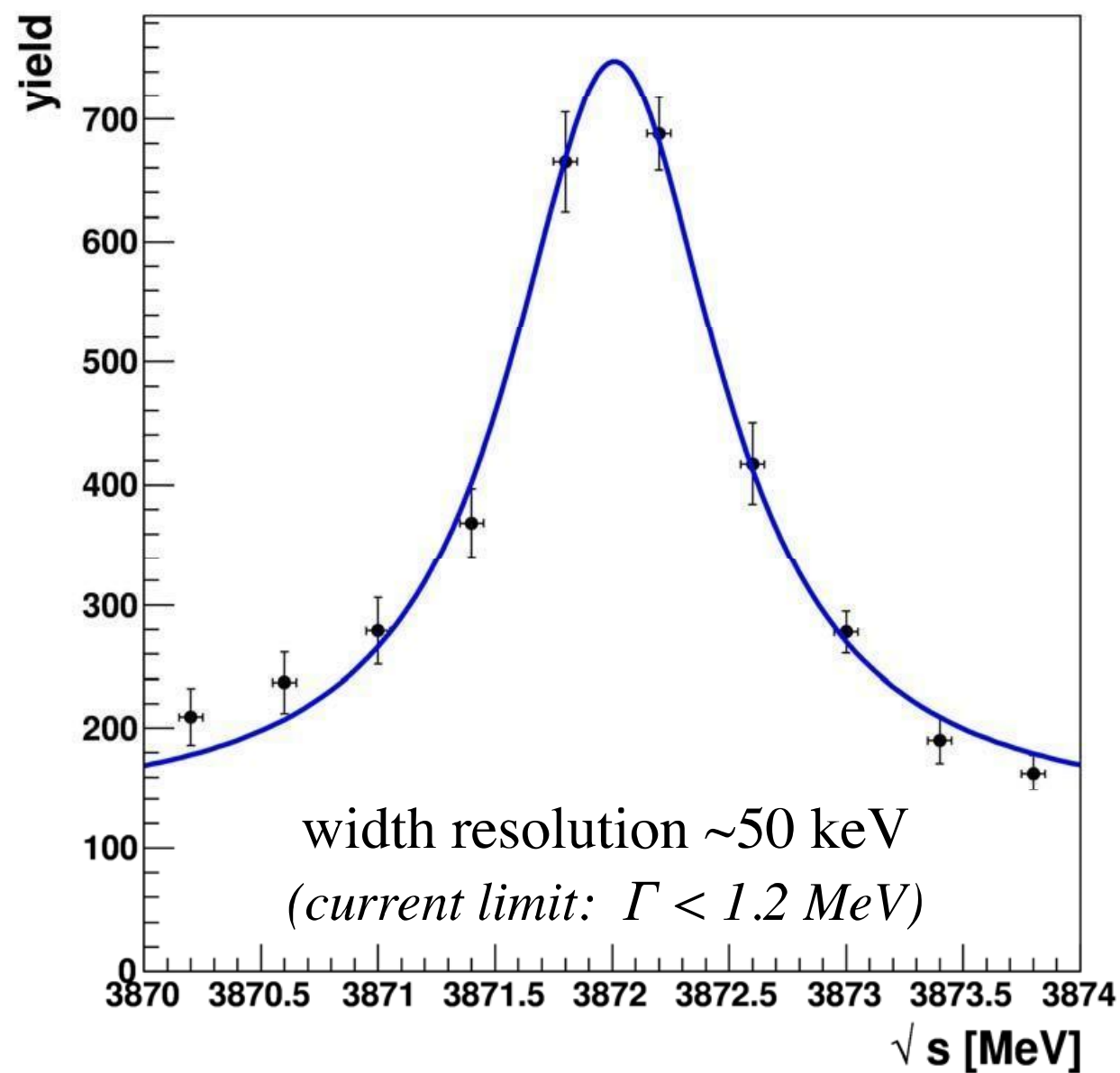
# 2C. Investigate new states with PANDA



# 2C. Investigate new states with PANDA

PANDA MC study of the X(3872)

$\Gamma_{\text{input}} = 1 \text{ MeV}$



M. Fritsch, Trento 2011

future and ongoing experiments

“beyond” quark model states

quark model states

Belle II

$Y_b(10890)$

$Y(bb)$

BESIII

$Y(4260)$

**PANDA**

**X(3872)**

$\psi(cc)$

$Y_s(2175)$

$\pi_1(1600)$

GlueX

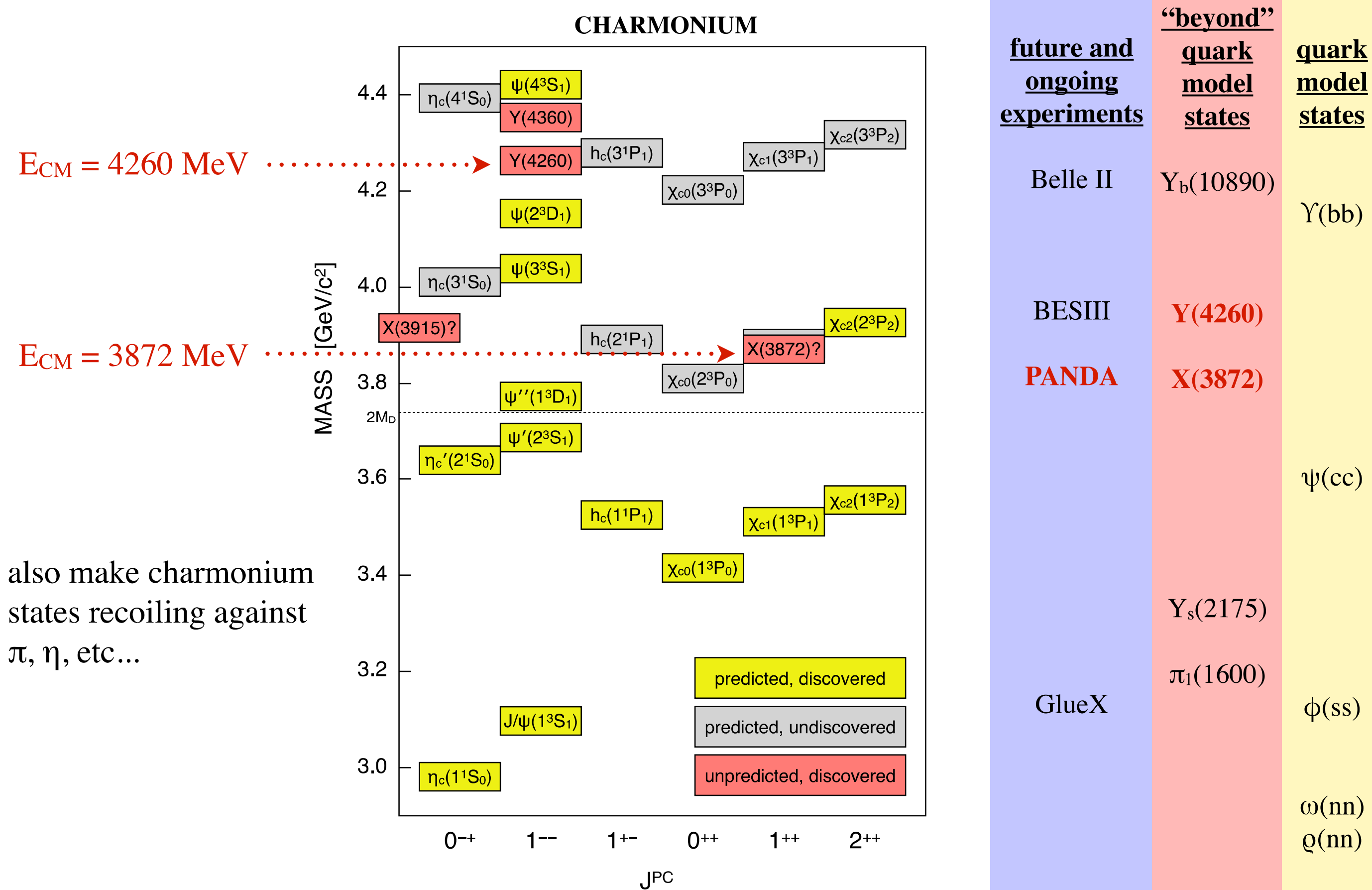
$\phi(ss)$

$\omega(nn)$

$\rho(nn)$



# 2C. Investigate new states with PANDA

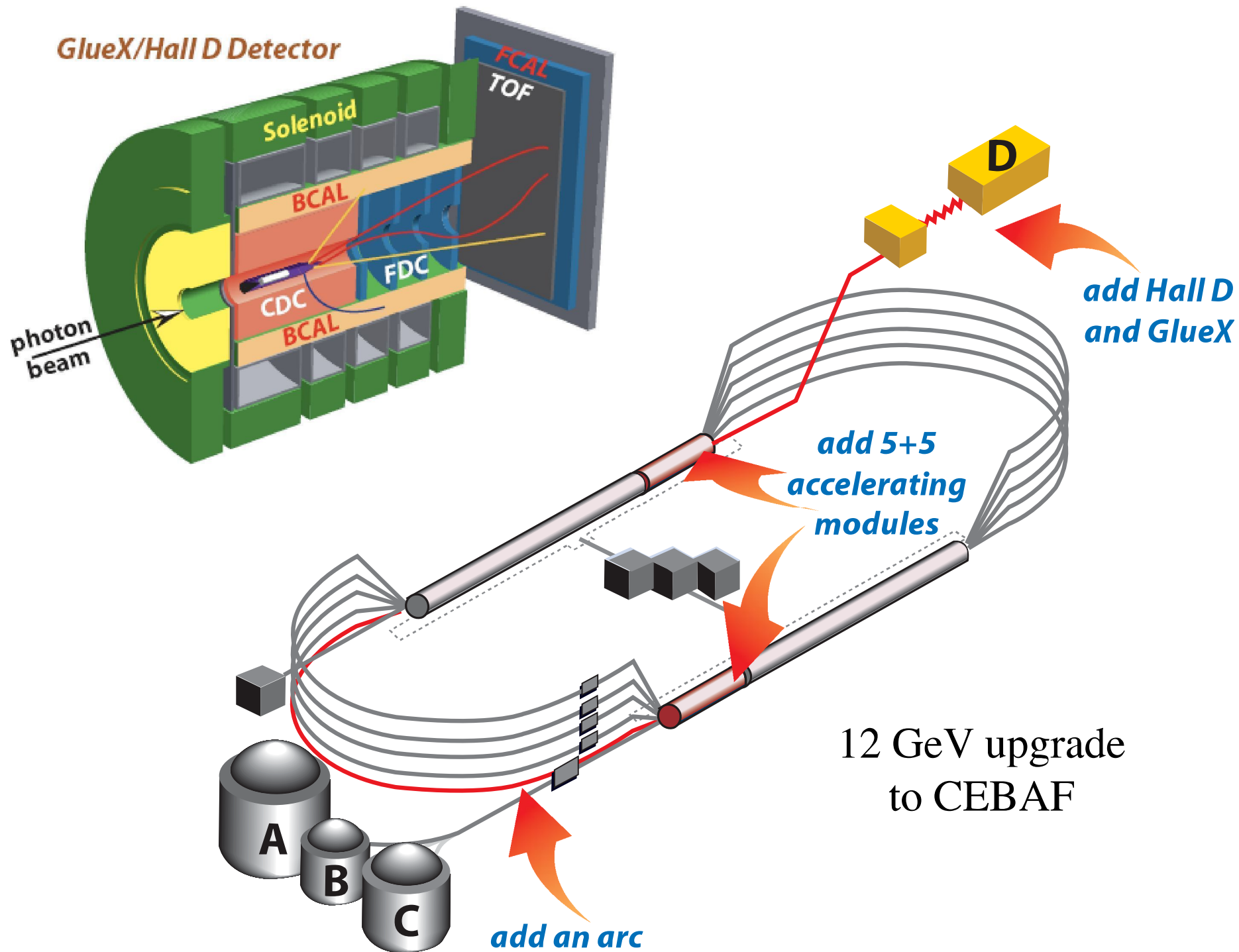


# 2D. Investigate new states with GlueX

**GlueX**  
 (9 GeV photoproduction)  
  
*location:* Newport News, VA  
*accelerator:* upgraded CEBAF  
*dates:* ~2014 – ?

<u>future and ongoing experiments</u>	<u>“beyond” quark model states</u>	<u>quark model states</u>
Belle II	$Y_b(10890)$	$Y(bb)$
BESIII	$Y(4260)$	
PANDA	$X(3872)$	$\psi(cc)$
	$Y_s(2175)$	
<b>GlueX</b>	$\pi_1(1600)$	$\phi(ss)$
		$\omega(nn)$ $\rho(nn)$

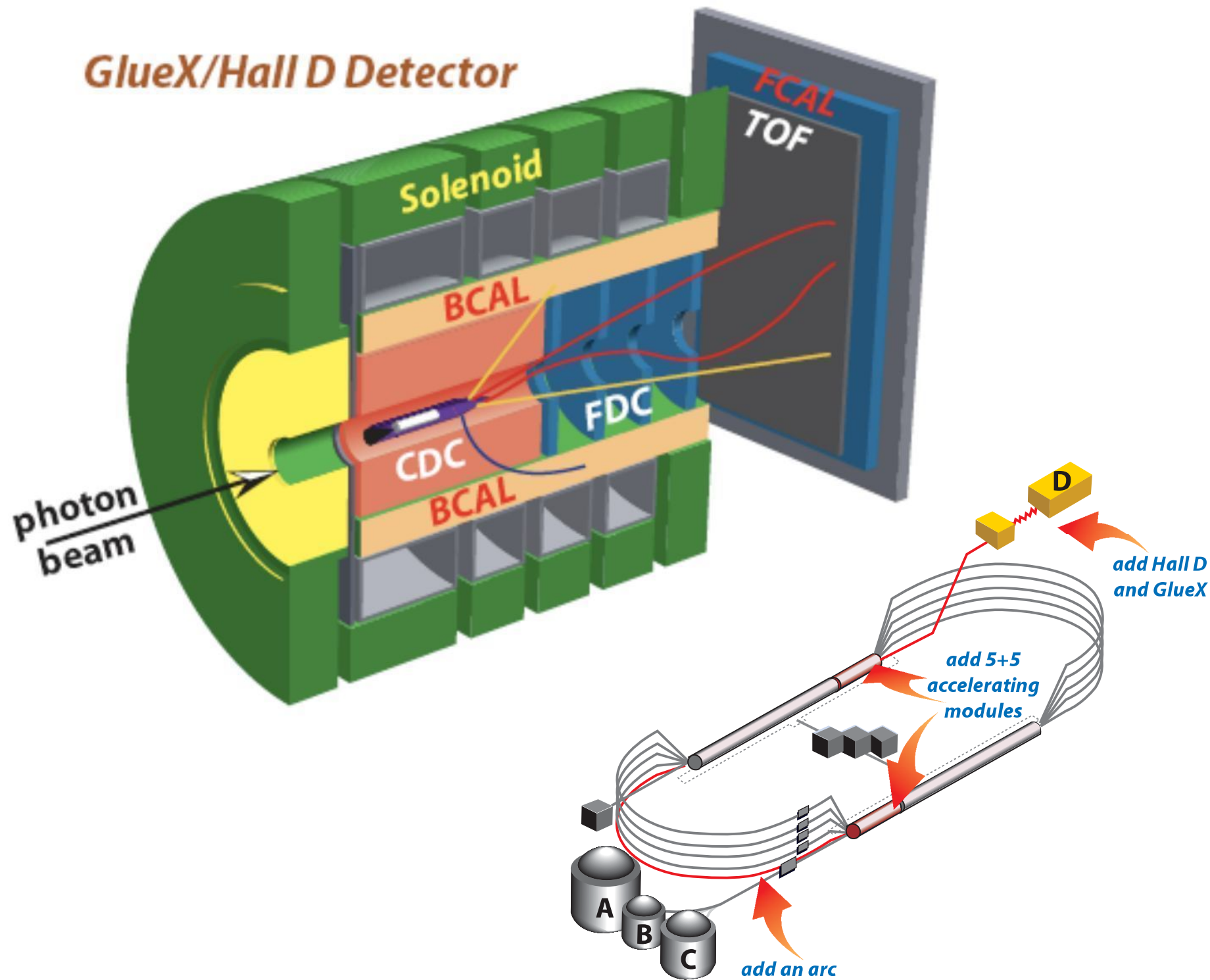
# 2D. Investigate new states with GlueX



9 GeV polarized photons on a proton target

<u>future and ongoing experiments</u>	<u>“beyond” quark model states</u>	<u>quark model states</u>
Belle II	$Y_b(10890)$	$Y(bb)$
BESIII	$Y(4260)$	
PANDA	$X(3872)$	$\psi(cc)$
<b>GlueX</b>	$Y_s(2175)$ $\pi_1(1600)$	$\phi(ss)$ $\omega(nn)$ $\rho(nn)$

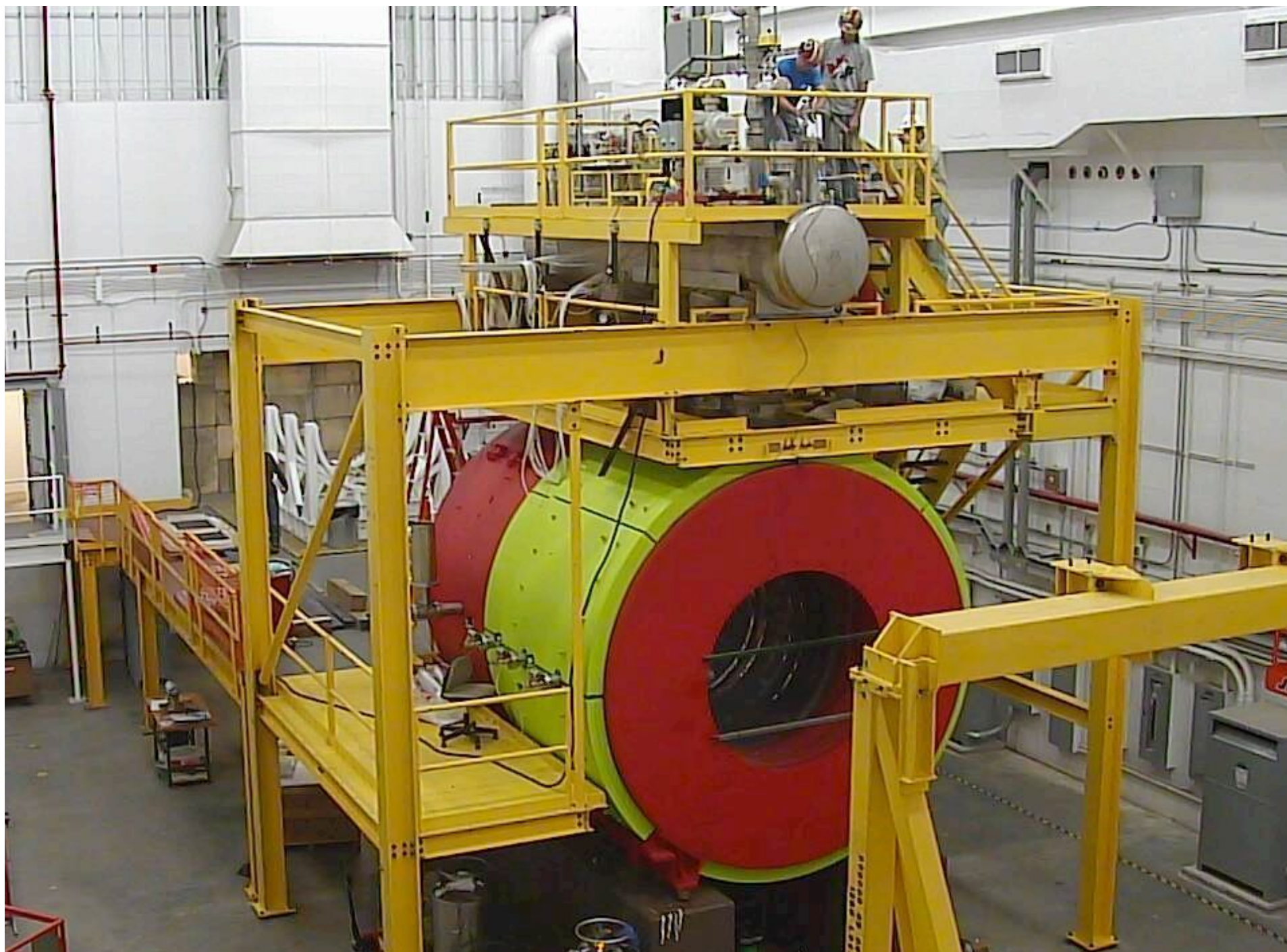
# 2D. Investigate new states with GlueX



9 GeV polarized photons on a proton target

<u>future and ongoing experiments</u>	<u>“beyond” quark model states</u>	<u>quark model states</u>
Belle II	$Y_b(10890)$	$Y(bb)$
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PANDA	$X(3872)$	
		$\psi(cc)$
	$Y_s(2175)$	
	$\pi_1(1600)$	
<b>GlueX</b>		$\phi(ss)$
		$\omega(nn)$ $\rho(nn)$

# 2D. Investigate new states with GlueX



9 GeV polarized photons on a proton target

<u>future and ongoing experiments</u>	<u>“beyond” quark model states</u>	<u>quark model states</u>
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BESIII	$Y(4260)$	
PANDA	$X(3872)$	$\psi(cc)$
	$Y_s(2175)$	
	$\pi_1(1600)$	$\phi(ss)$
<b>GlueX</b>		$\omega(nn)$ $\rho(nn)$

## 2D. Investigate new states with GlueX



9 GeV polarized photons on a proton target

future and ongoing experiments

“beyond” quark model states

quark model states

Belle II

$Y_b(10890)$

$Y(bb)$

BESIII

$Y(4260)$

PANDA

$X(3872)$

$\psi(cc)$

$Y_s(2175)$

$\pi_1(1600)$

**GlueX**

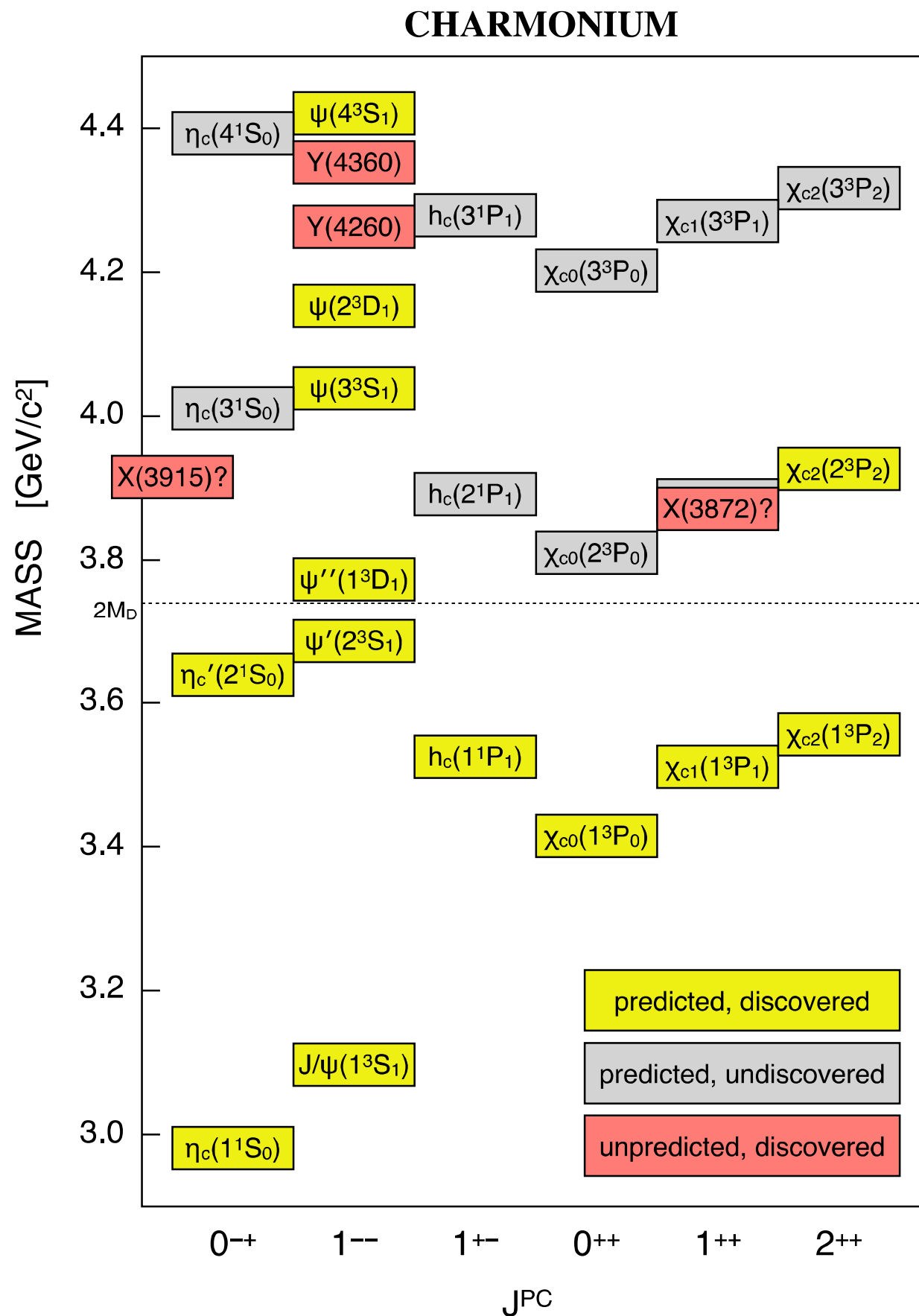
$\phi(ss)$

$\omega(nn)$

$\rho(nn)$

# 2D. Investigate new states with GlueX

**a problem:**  
the XYZ states  
of charmonium have  
conventional  $J^{PC}$



future and ongoing experiments

Belle II

BESIII

PANDA

**GlueX**

“beyond” quark model states

$Y_b(10890)$

$Y(4260)$

$X(3872)$

$Y_s(2175)$

$\pi_1(1600)$

quark model states

$Y(bb)$

$\psi(cc)$

$\phi(ss)$

$\omega(nn)$

$\rho(nn)$

## 2D. Investigate new states with GlueX

**a solution:** produce light quark states with exotic  $J^{PC}$ ...

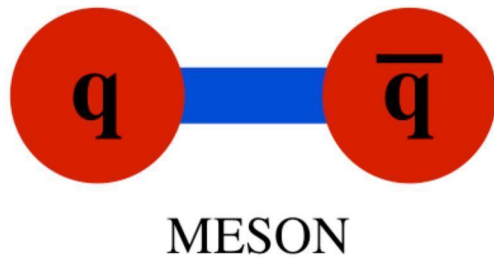
<u>future and ongoing experiments</u>	<u>“beyond” quark model states</u>	<u>quark model states</u>
Belle II	$Y_b(10890)$	$Y(bb)$
BESIII	$Y(4260)$	
PANDA	$X(3872)$	$\psi(cc)$
	$Y_s(2175)$	
<b>GlueX</b>	<b><math>\pi_1(1600)</math></b>	$\phi(ss)$
		$\omega(nn)$ $\rho(nn)$



# 2D. Investigate new states with GlueX

a solution: produce light quark states with exotic  $J^{PC}$ ...

a “Quark Model” meson... has “conventional” quantum numbers:



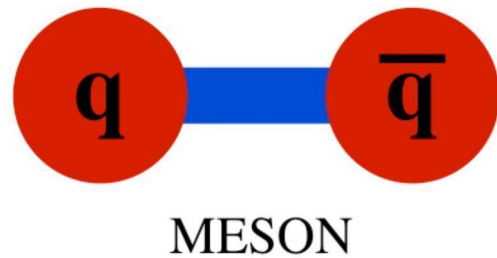
$J^{PC} = 0^{-+} (\eta, \pi) [S = 0; L = 0; J = 0]$   
 $0^{++} (f_0, a_0) [S = 1; L = 1; J = 0]$   
 $1^{++} (f_1, a_1) [S = 1; L = 1; J = 1]$   
 $1^{+-} (h_1, b_1) [S = 0; L = 1; J = 1]$   
 $1^{-} (\omega, \rho) [S = 1; L = 0; J = 1]$   
 etc.

<u>future and ongoing experiments</u>	<u>“beyond” quark model states</u>	<u>quark model states</u>
Belle II	$Y_b(10890)$	$\Upsilon(bb)$
BESIII	$Y(4260)$	
PANDA	$X(3872)$	
		$\psi(cc)$
	$Y_s(2175)$	
<b>GlueX</b>	<b><math>\pi_1(1600)</math></b>	$\phi(ss)$
		$\omega(nn)$ $\rho(nn)$

# 2D. Investigate new states with GlueX

**a solution:** produce light quark states with exotic  $J^{PC}$ ...

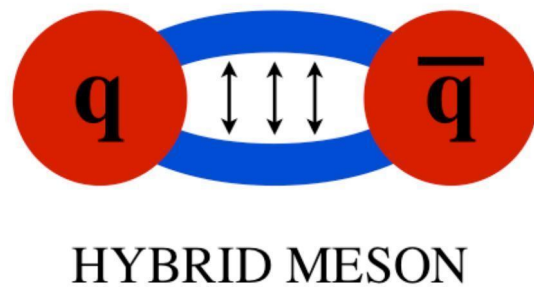
a “Quark Model” meson... has “conventional” quantum numbers:



$J^{PC} = 0^{-+} (\eta, \pi) [S = 0; L = 0; J = 0]$   
 $0^{++} (f_0, a_0) [S = 1; L = 1; J = 0]$   
 $1^{++} (f_1, a_1) [S = 1; L = 1; J = 1]$   
 $1^{+-} (h_1, b_1) [S = 0; L = 1; J = 1]$   
 $1^{-} (\omega, \rho) [S = 1; L = 0; J = 1]$   
 etc.

but hybrid mesons...

can have “exotic” quantum numbers:



$J^{PC} = 1^{-+} (\eta_1, \pi_1)$  (for example)

*⇒ unambiguous signature for a state beyond the quark model!*

future and ongoing experiments

“beyond” quark model states

quark model states

Belle II

$Y_b(10890)$

$Y(bb)$

BESIII

$Y(4260)$

PANDA

$X(3872)$

$\psi(cc)$

$Y_s(2175)$

$\pi_1(1600)$

**GlueX**

$\phi(ss)$

$\omega(nn)$

$\rho(nn)$

## 2D. Investigate new states with GlueX

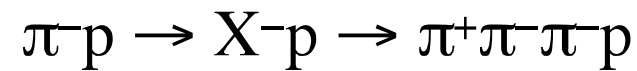
**a cost:** amplitude analyses are required to disentangle  $J^{PC}$ ...

<u>future and ongoing experiments</u>	<u>“beyond” quark model states</u>	<u>quark model states</u>
Belle II	$Y_b(10890)$	$Y(bb)$
BESIII	$Y(4260)$	
PANDA	$X(3872)$	
		$\psi(cc)$
	$Y_s(2175)$	
<b>GlueX</b>	<b><math>\pi_1(1600)</math></b>	$\phi(ss)$
		$\omega(nn)$ $\rho(nn)$

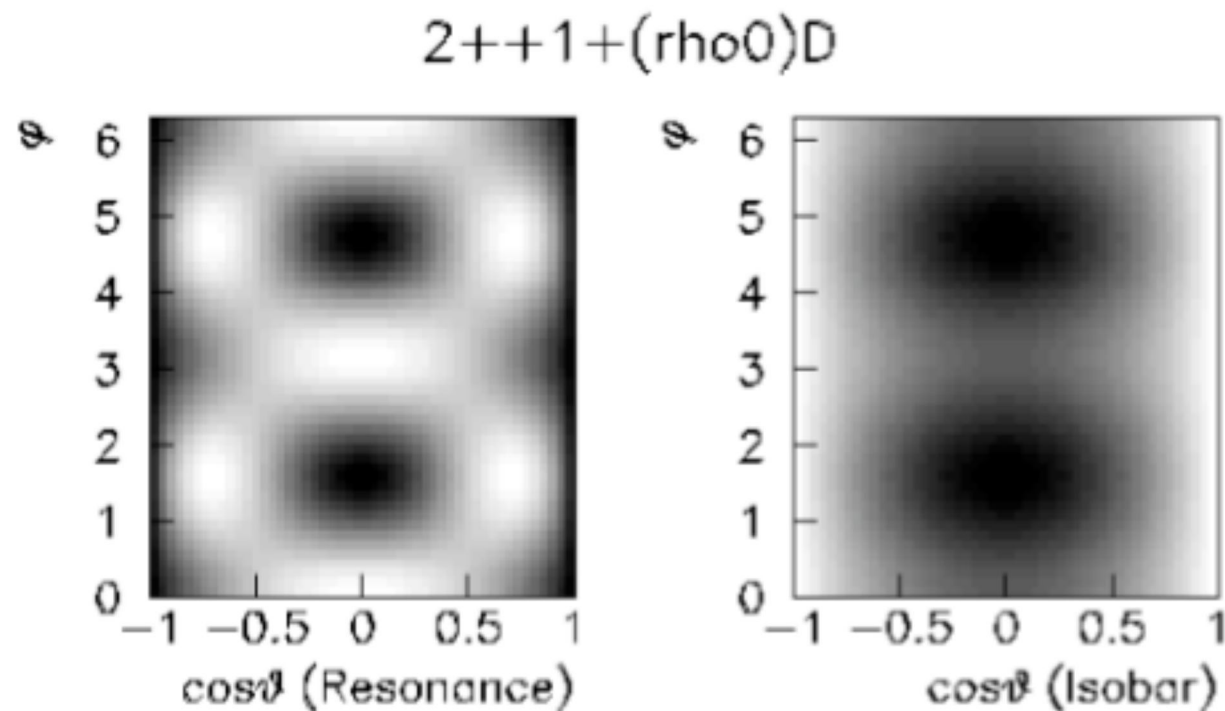
# 2D. Investigate new states with GlueX

*distinguish quantum numbers using angular distributions of decay products*

for example:



if  $X^-$  has  $J^{PC} = 2^{++}$  and decays to  $\rho^0 \pi^-$  in a D-wave, then you expect these angular distributions:



single  $J^{PC}$ ...

future and ongoing experiments

“beyond” quark model states

quark model states

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**GlueX**

$\phi(ss)$

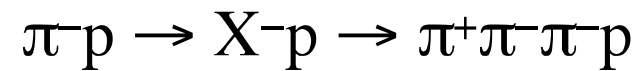
$\omega(nn)$

$\rho(nn)$

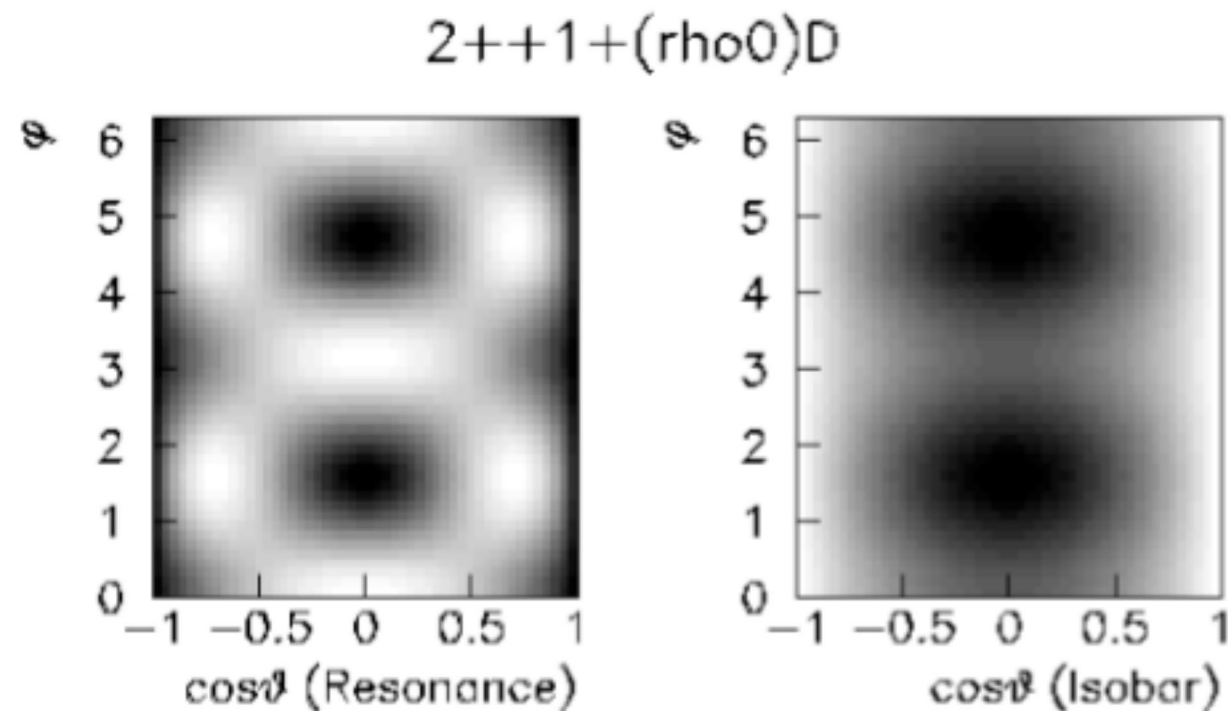
## 2D. Investigate new states with GlueX

*distinguish quantum numbers using angular distributions of decay products*

for example:



if  $X^-$  has  $J^{PC} = 2^{++}$  and decays to  $\rho^0 \pi^-$  in a D-wave, then you expect these angular distributions:



it's called an "*amplitude analysis*" because distributions are added on the amplitude level:

$$I(\Omega) = \sum_{\alpha} \left| \sum_{\beta} V_{\alpha,\beta} A_{\alpha,\beta}(\Omega) \right|^2$$

$A(\Omega)$  = Resonance Angles  
 × Isobar Angles  
 × Isobar Breit Wigner

$V$  are complex fit parameters

**GlueX**

$Y_s(2175)$

$\pi_1(1600)$

$\phi(ss)$

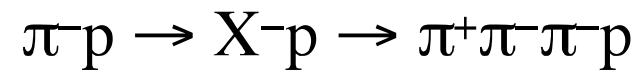
$\omega(nn)$

$\rho(nn)$

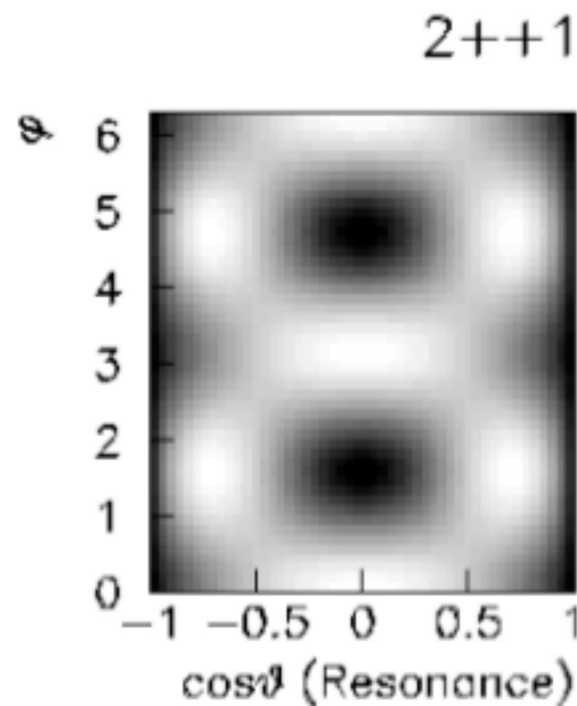
# 2D. Investigate new states with GlueX

*distinguish quantum numbers using angular distributions of decay products*

for example:



if  $X^-$  has  $J^{PC} = 2^{++}$  and decays to  $\pi^+ \pi^- \pi^-$  then you expect these angular distributions

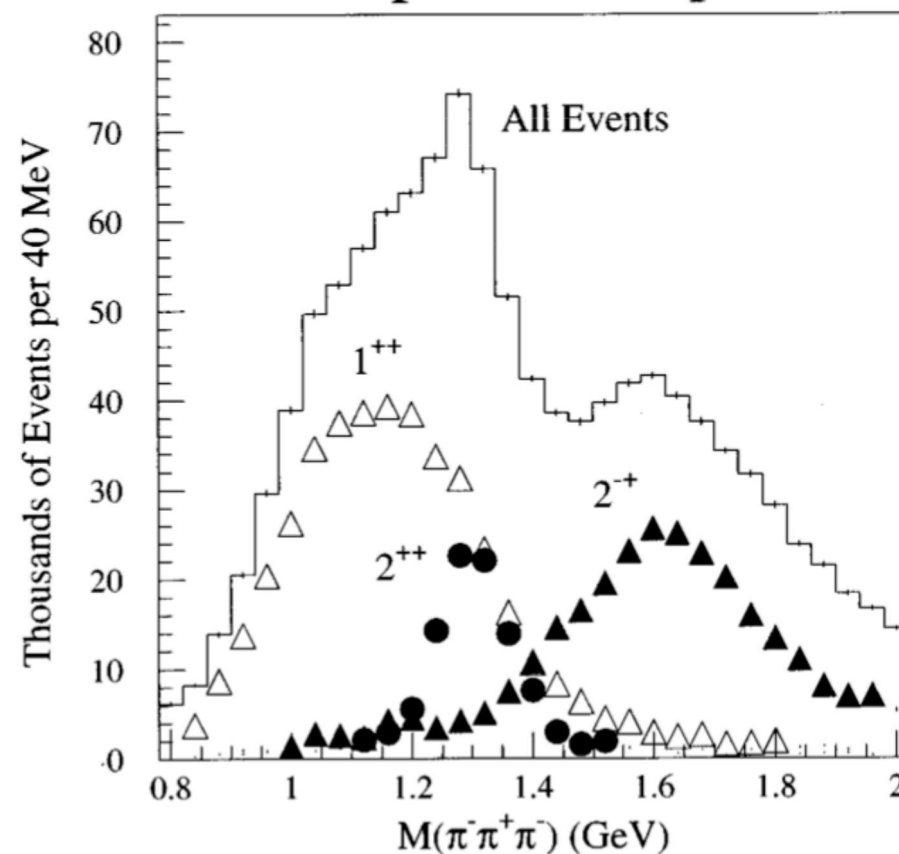
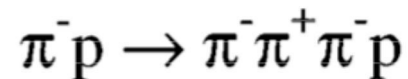


$2^{++} 1^{+}$

it's called an "*amplitude analysis*" because distributions are added on the amplitude level:

$$I(\Omega) = \sum_{\alpha} \left| \sum_{\beta} V_{\alpha,\beta} A_{\alpha,\beta}(\Omega) \right|^2$$

## decomposition of $3\pi$ from E852



- Resonance Angles
- Isobar Angles
- Isobar Breit Wigner
- complex fit parameters

**GlueX**

$Y_s(2175)$

$\pi_1(1600)$

$\phi(ss)$

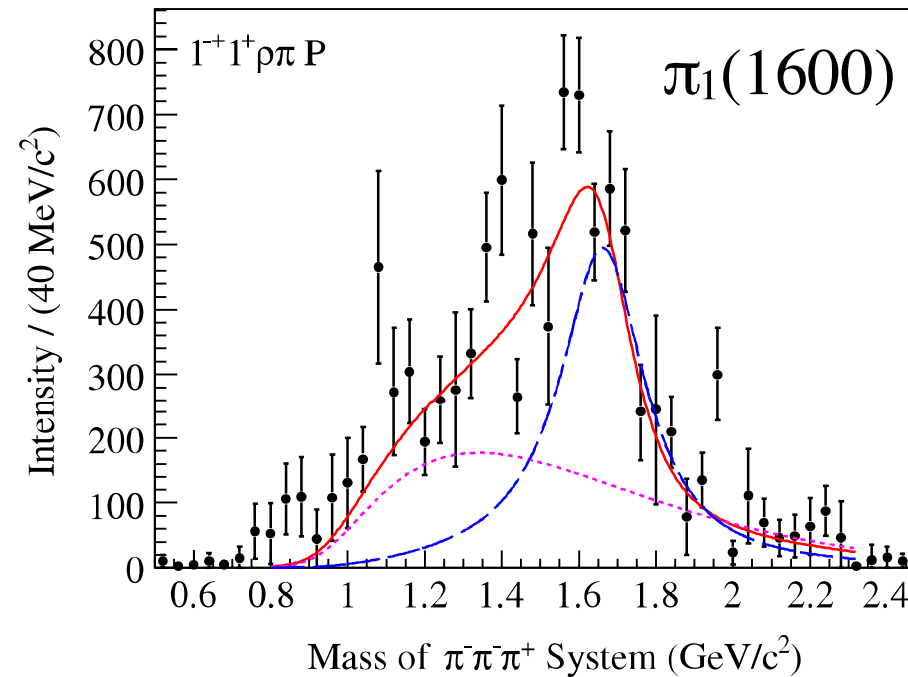
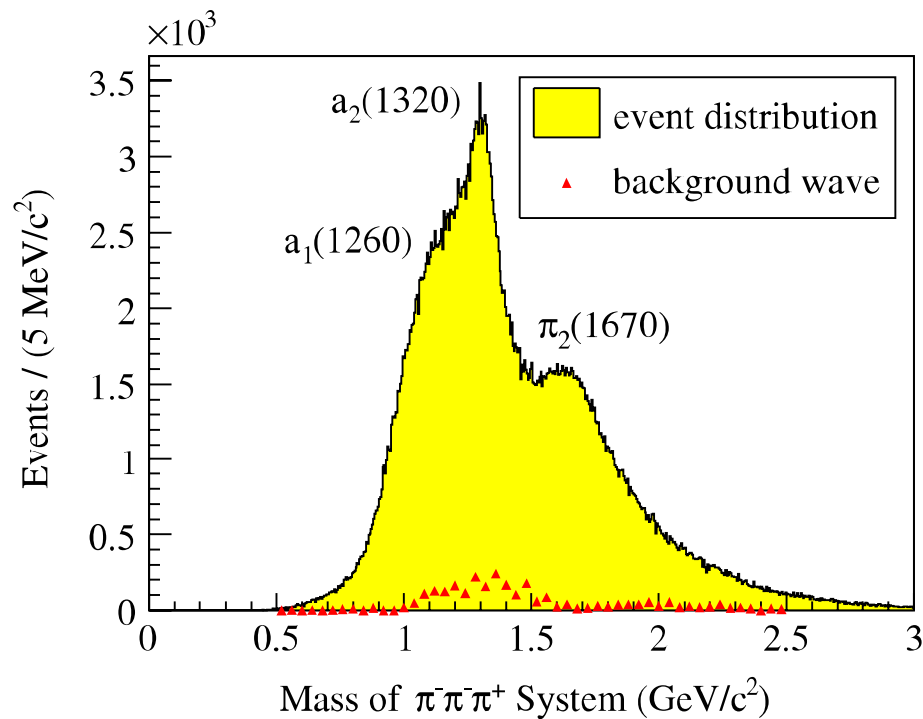
$\omega(nn)$

$\rho(nn)$

# 2D. Investigate new states with GlueX

## Analysis of $\pi^- \text{Pb} \rightarrow \pi^+ \pi^- \pi^- \text{Pb}$ at COMPASS

PRL 104, 241803 (2010)



- indication of an exotic ( $1^{-+}$ ) decaying to  $\rho\pi$  with phase motion
- a factor of  $\sim 11$  smaller than  $a_2(1320)$

future and ongoing experiments

“beyond” quark model states

quark model states

Belle II

$Y_b(10890)$

$Y(bb)$

BESIII

$Y(4260)$

PANDA

$X(3872)$

$\psi(cc)$

$Y_s(2175)$

**GlueX**

**$\pi_1(1600)$**

$\phi(ss)$

$\omega(nn)$

$\rho(nn)$

## 2D. Investigate new states with GlueX

strengths of GlueX:

\* photoproduction

<u>future and ongoing experiments</u>	<u>“beyond” quark model states</u>	<u>quark model states</u>
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<b>GlueX</b>	<b><math>\pi_1(1600)</math></b>	$\phi(ss)$
		$\omega(nn)$ $\rho(nn)$



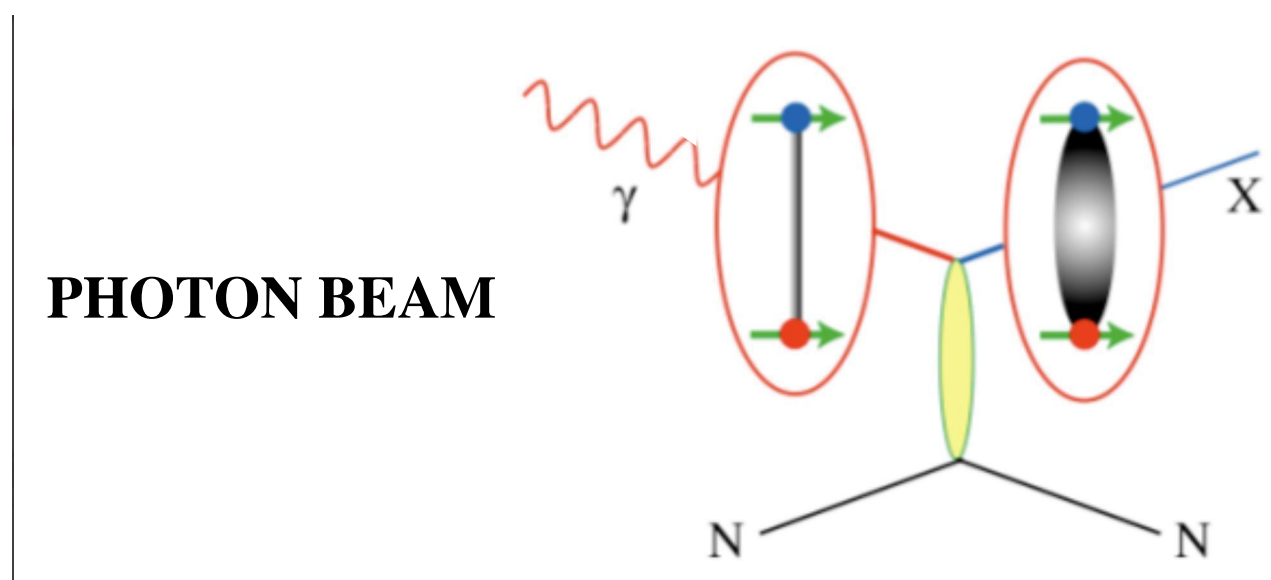
# 2D. Investigate new states with GlueX

strengths of GlueX:

\* **photoproduction**

Argument:

1. it is likely the  $\pi_1(1600)$  has  $S = 1$ ....
2. it is likely to be easier to produce  $S = 1$  states in photoproduction than pion production...



<u>future and ongoing experiments</u>	<u>“beyond” quark model states</u>	<u>quark model states</u>
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## 2D. Investigate new states with GlueX

strengths of GlueX:

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\* **acceptances**

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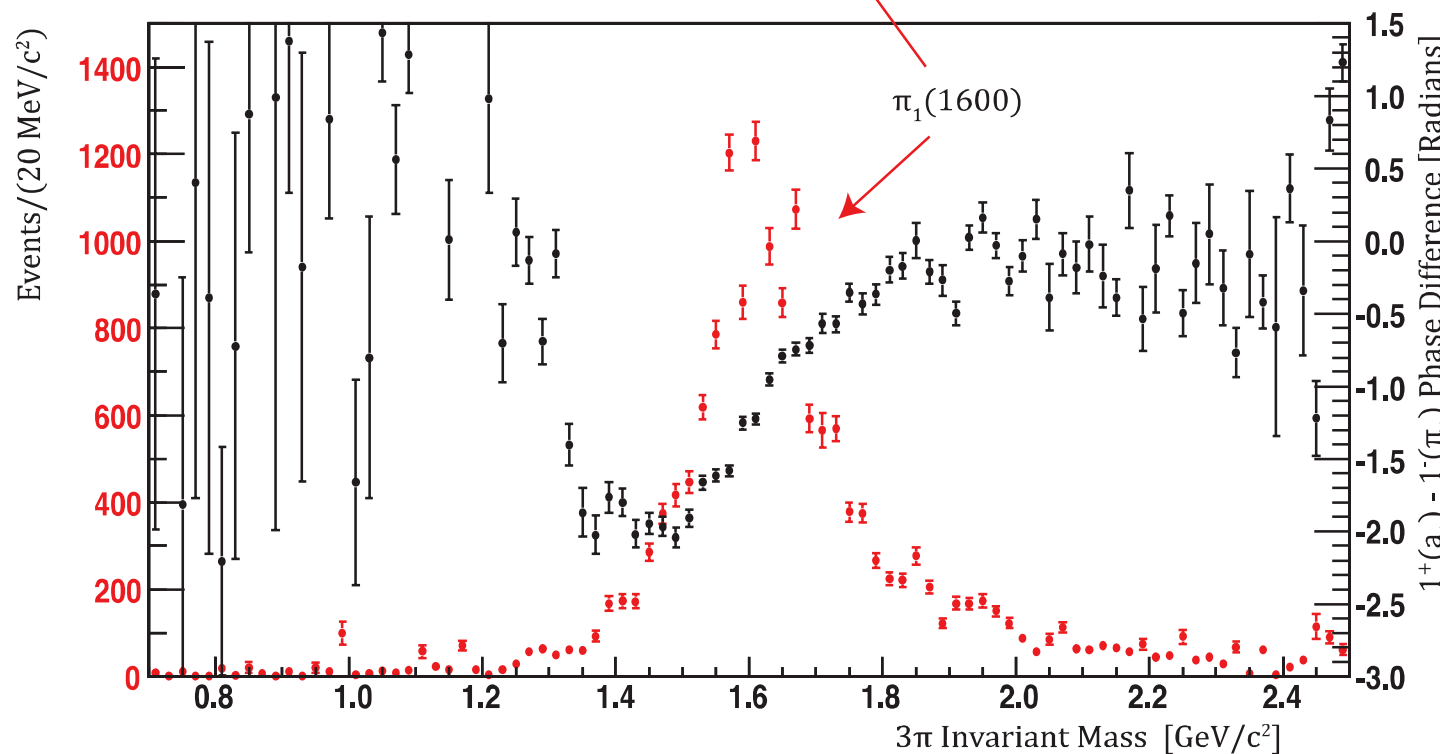
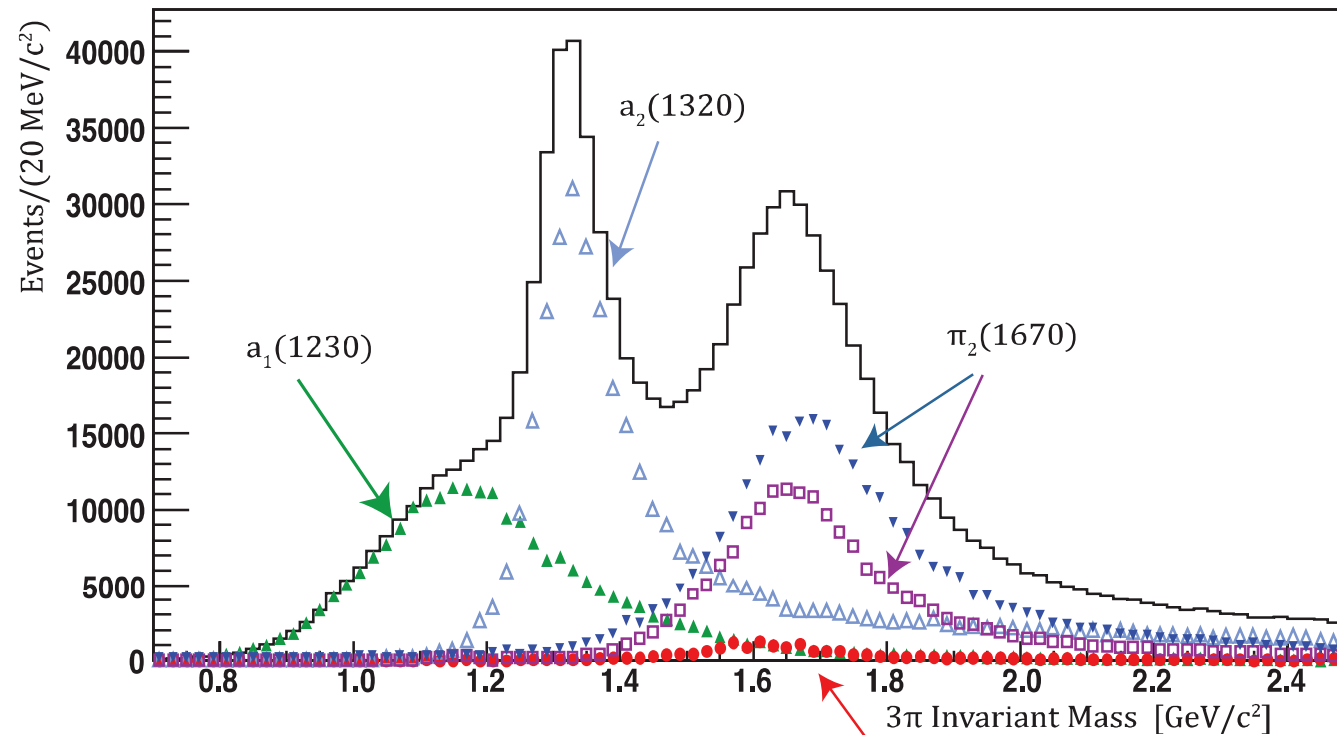
# 2D. Investigate new states with GlueX

strengths of GlueX:

- \* photoproduction
- \* **acceptances**

a simulation of  
3 hours of  
GlueX beam!

MC study of  $\gamma p \rightarrow \pi^+ \pi^+ \pi^- n$



<u>future and ongoing experiments</u>	<u>“beyond” quark model states</u>	<u>quark model states</u>
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# 2D. Investigate new states with GlueX

strengths of GlueX:

- \* photoproduction
- \* acceptances
- \* versatility

<u>future and ongoing experiments</u>	<u>“beyond” quark model states</u>	<u>quark model states</u>
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	<b><math>\pi_1(1600)</math></b>	$\phi(ss)$
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## 2. Investigate new states.

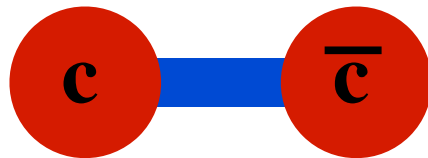
Summary:

- \* experimental results are coming fast and there are more coming...
- \* it is going to take some work to put all of this together into a coherent picture...

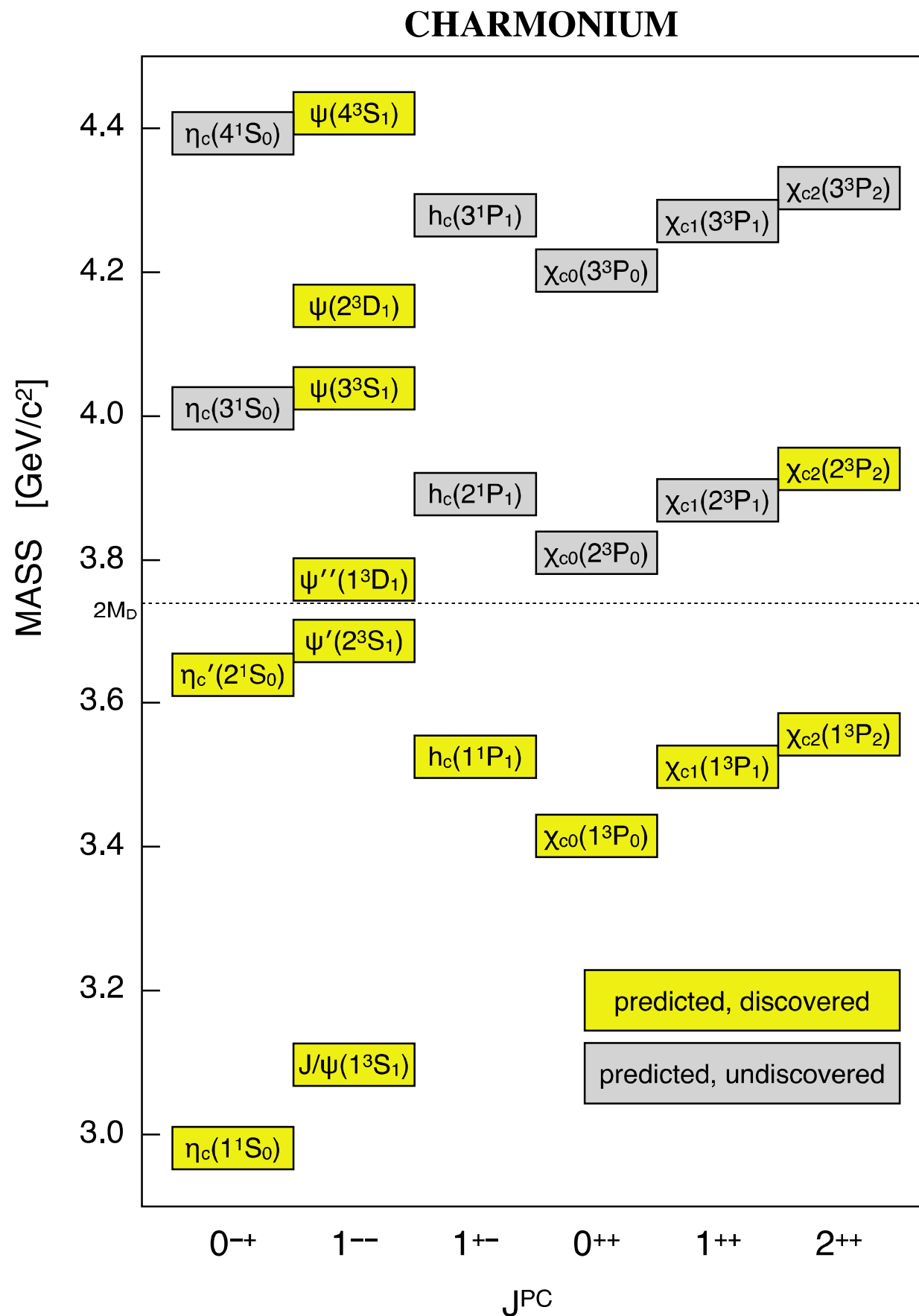
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# Three Goals of Experimental Meson Spectroscopy

## 1. Understand quark model states.



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future and ongoing experiments

“beyond” quark model states

quark model states

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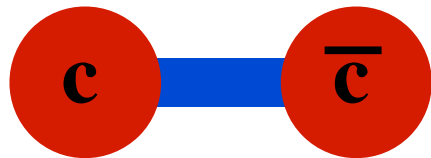
$\phi(ss)$

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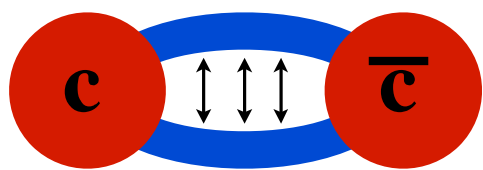
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## 1. Understand quark model states.

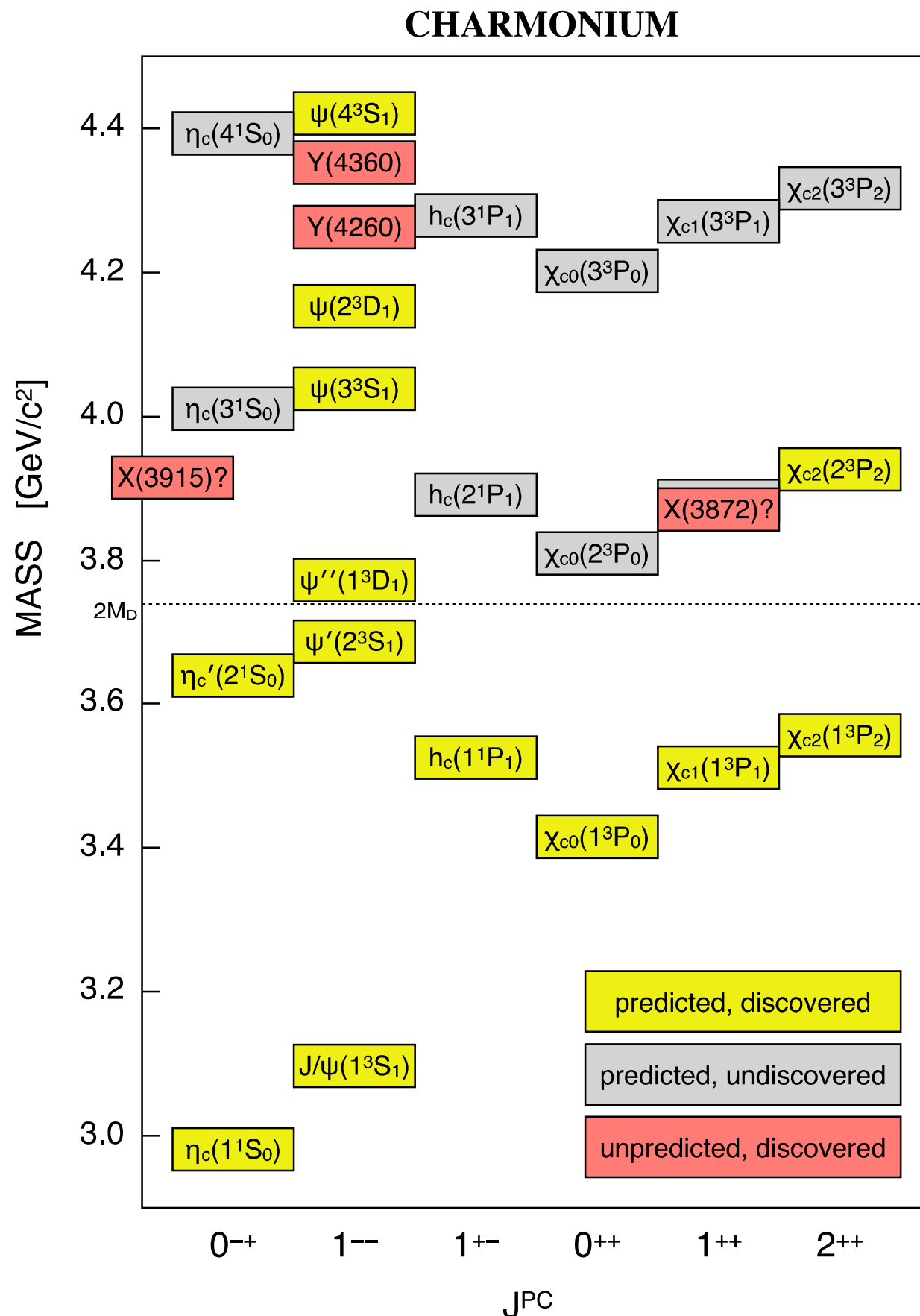


CHARMONIUM

## 2. Investigate new states.



HYBRID CHARMONIUM



**future and ongoing experiments**

**“beyond” quark model states**

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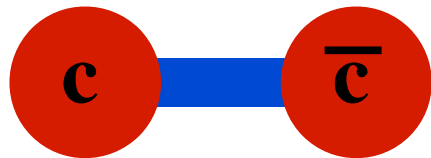
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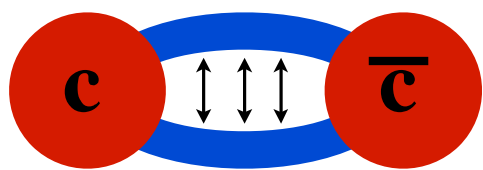
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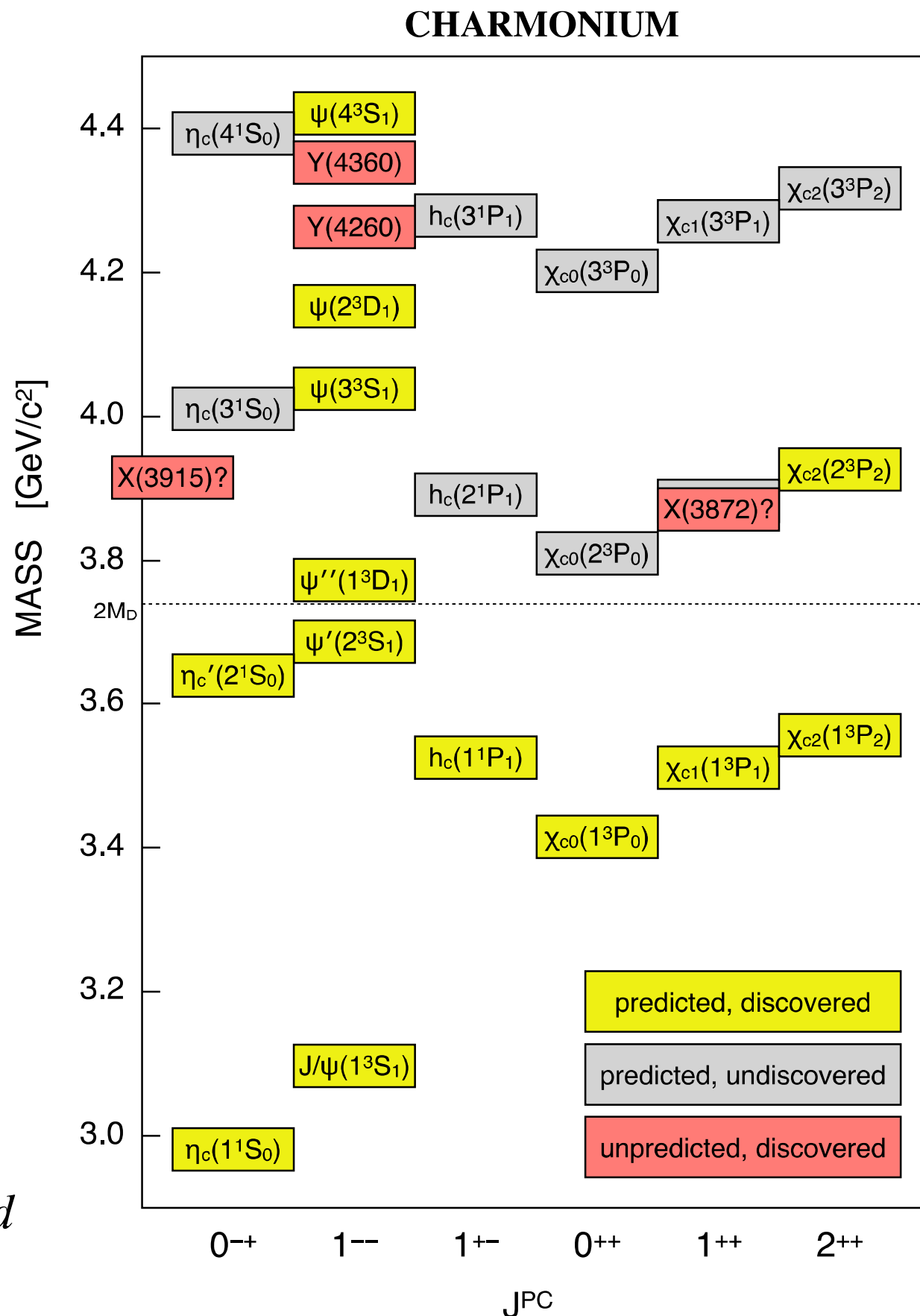
## 2. Investigate new states.



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## 3. Explore.

*Explore the unpredicted and the undiscovered...*



**future and ongoing experiments**

Belle II

BESIII

PANDA

GlueX

**“beyond”  
quark  
model  
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**quark  
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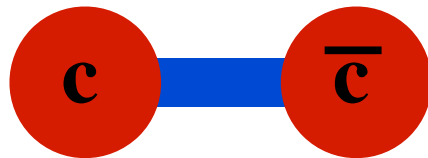
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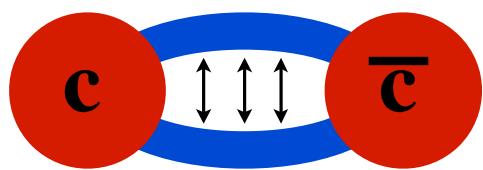
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CHARMONIUM

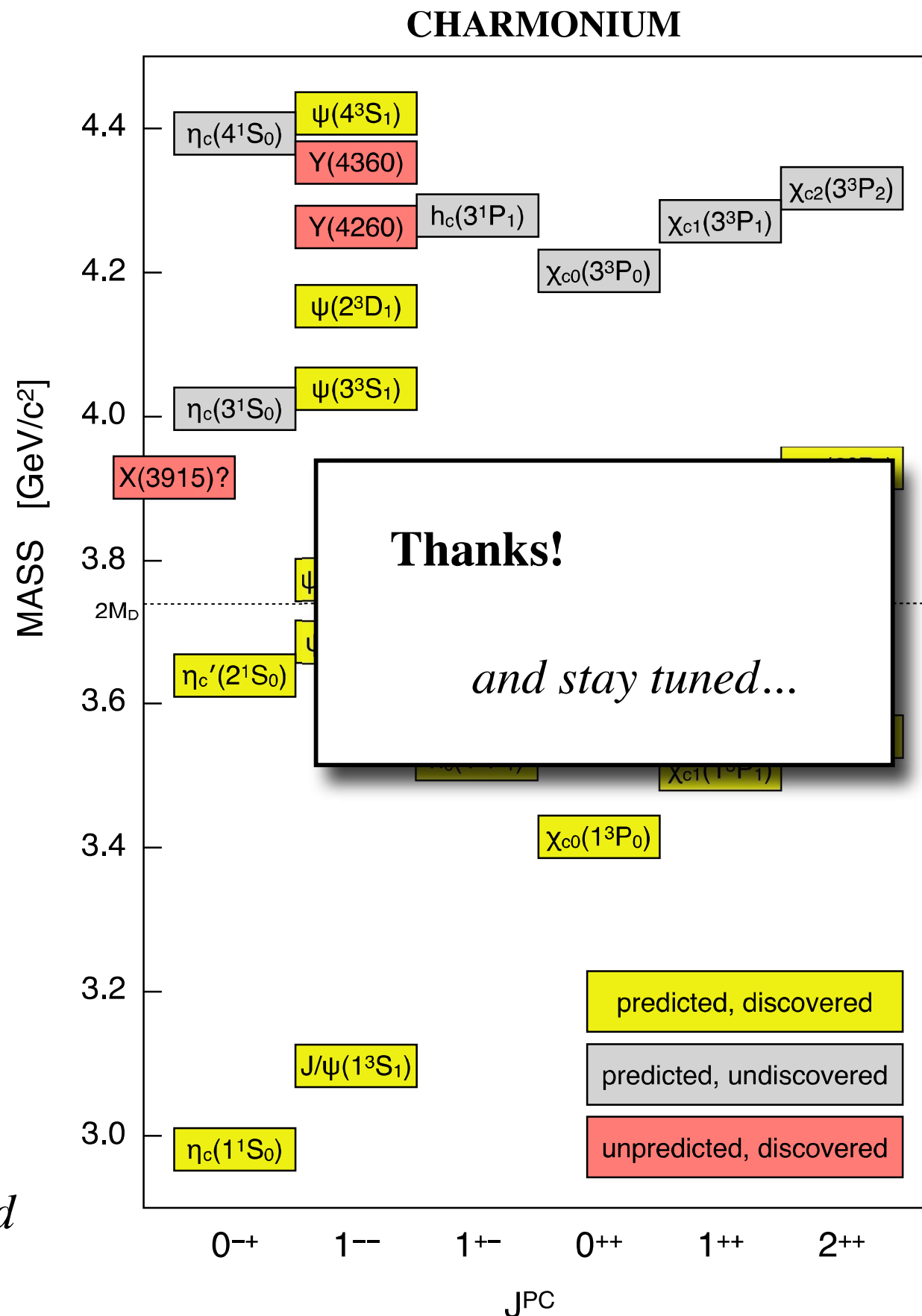
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HYBRID CHARMONIUM

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future and ongoing experiments

“beyond” quark model states

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