

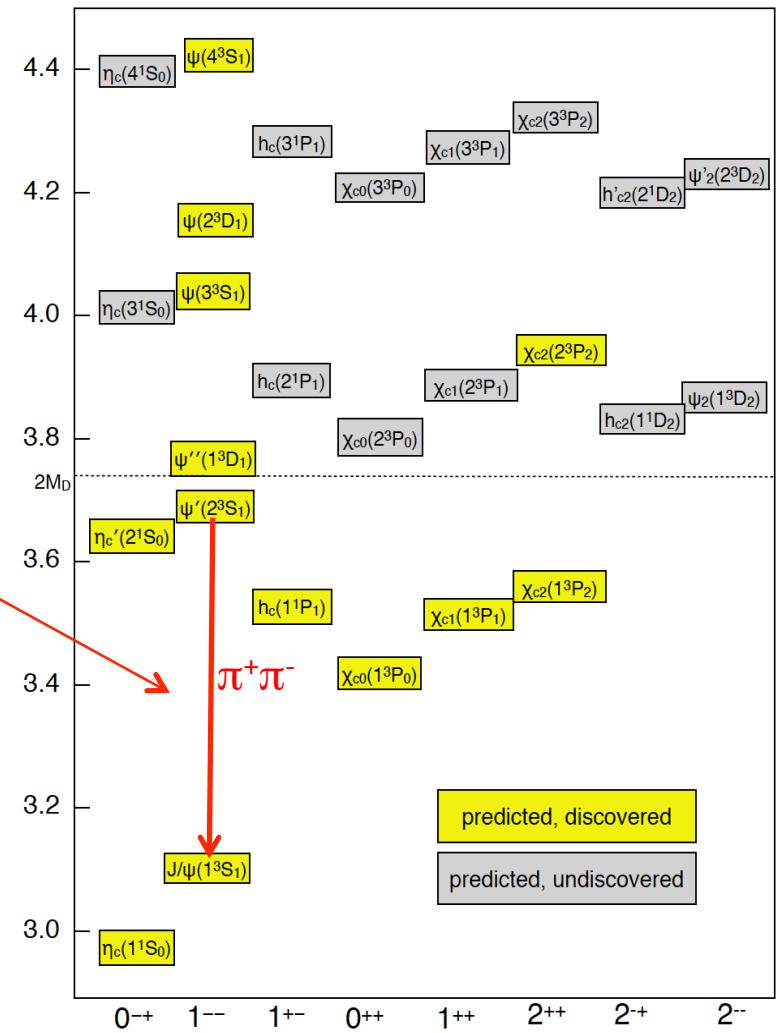
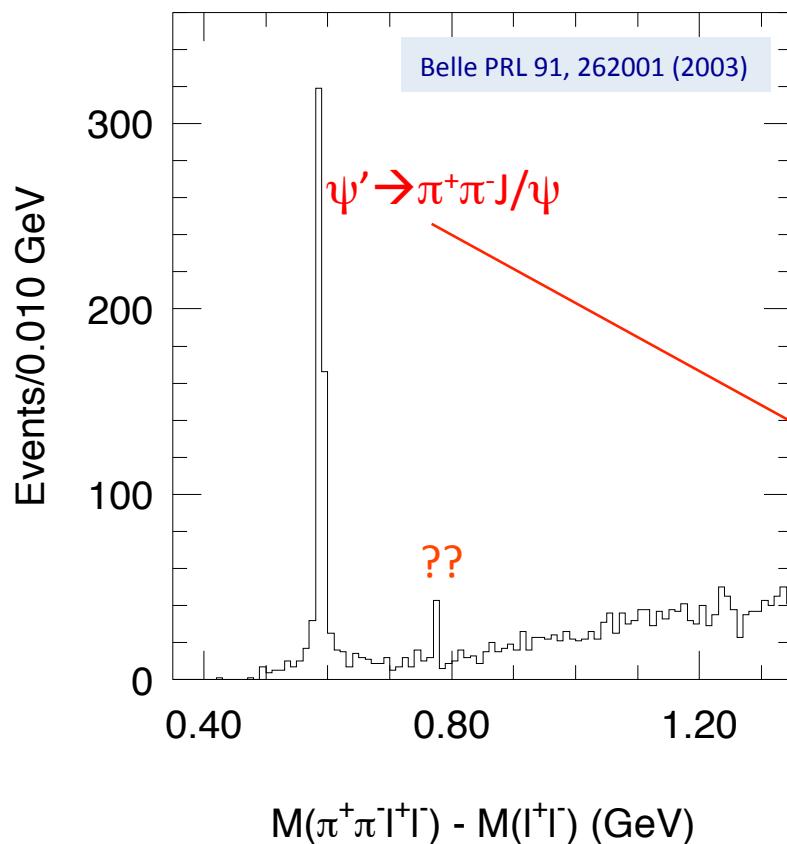
# Interesting things that happen at thresholds



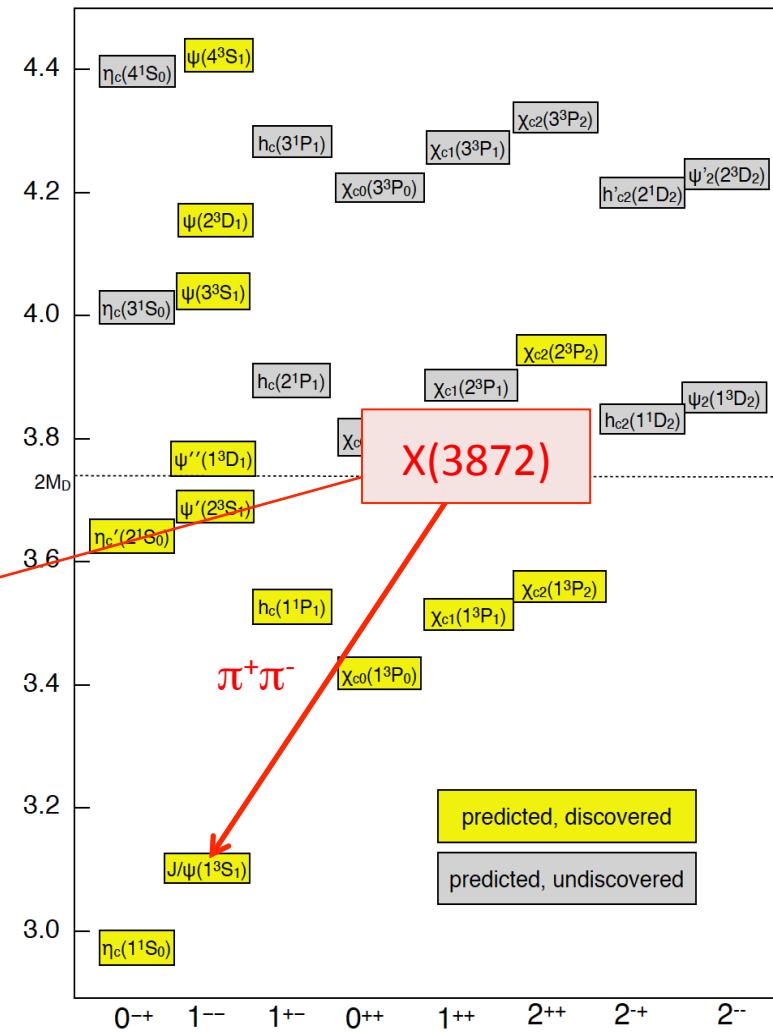
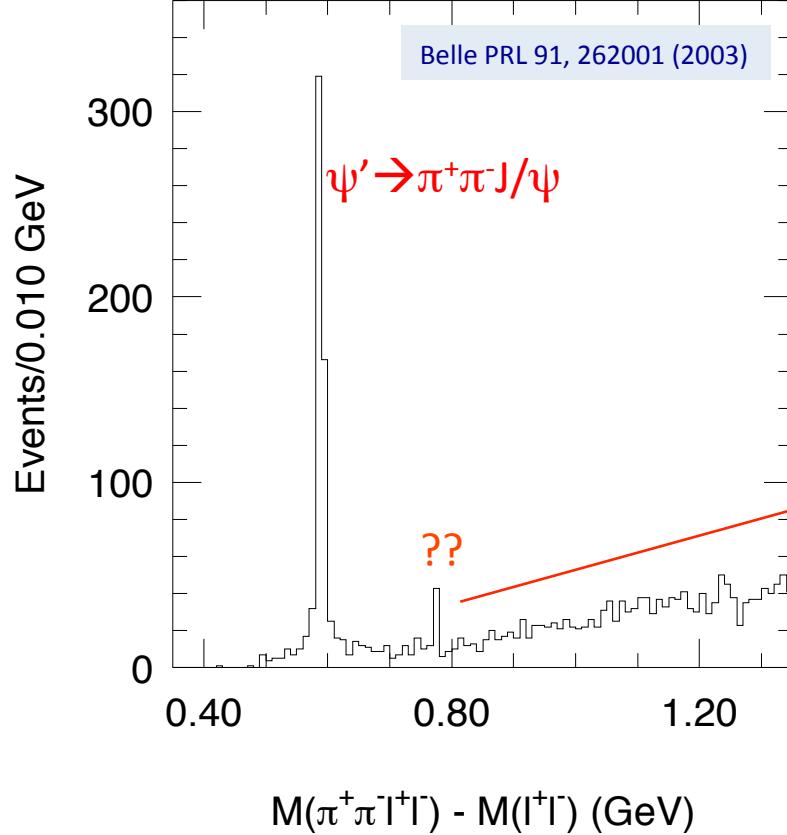
Stephen Lars Olsen **ibs** Institute for Basic Science Daejeon, KOREA

32nd Reimei WS on Hadron Physics in Extreme Conditions  
Inha University, Incheon, KOREA, Oct. 24– 26, 2016

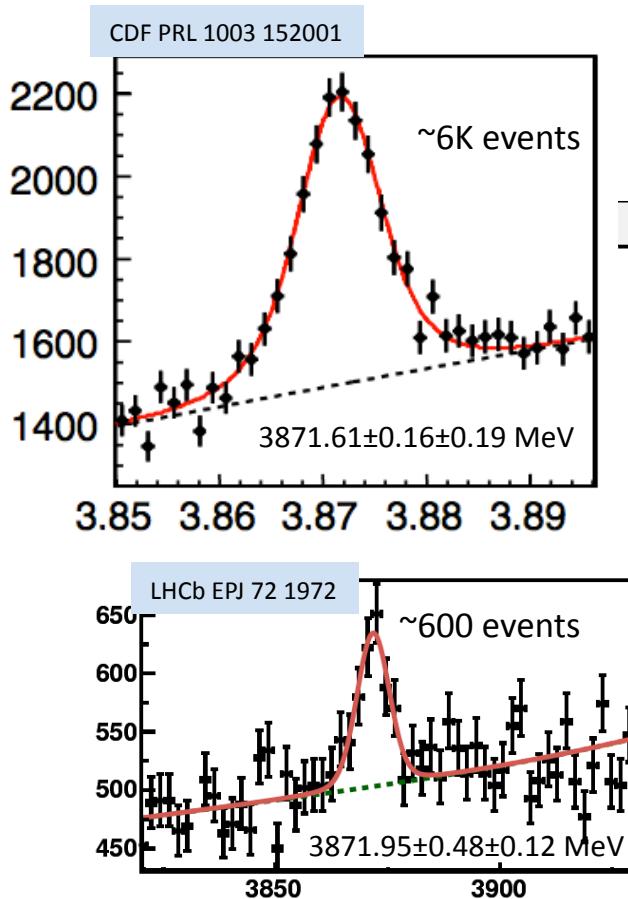
# $M(\pi^+\pi^-J/\psi)$



# $M(\pi^+\pi^-J/\psi)$

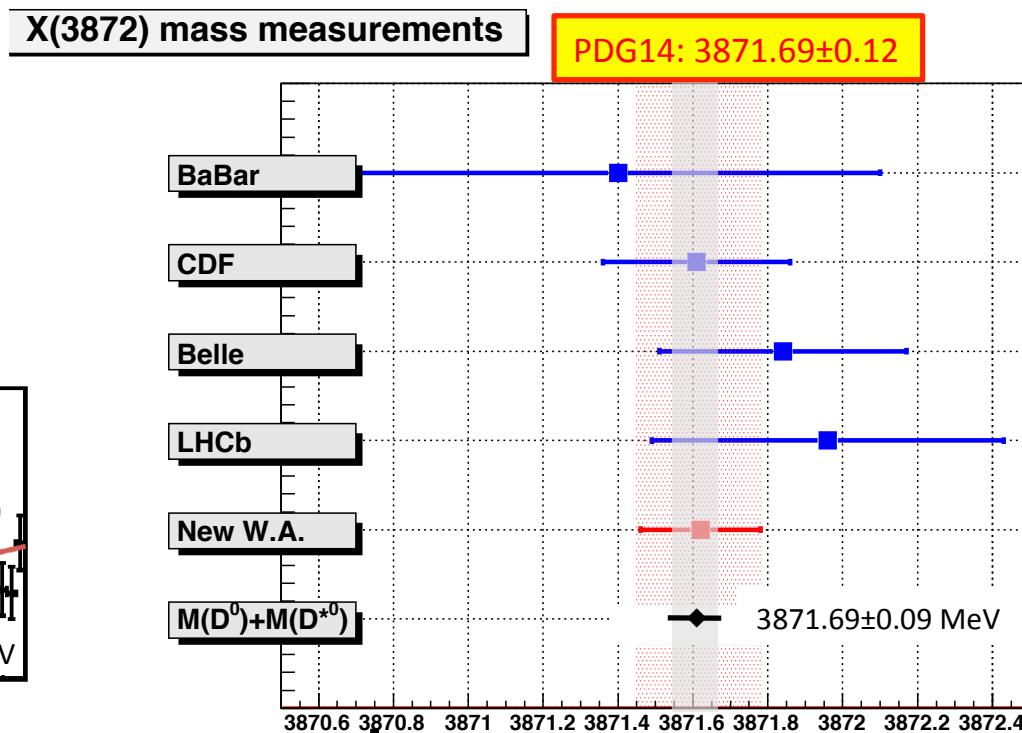


# X(3872) Mass

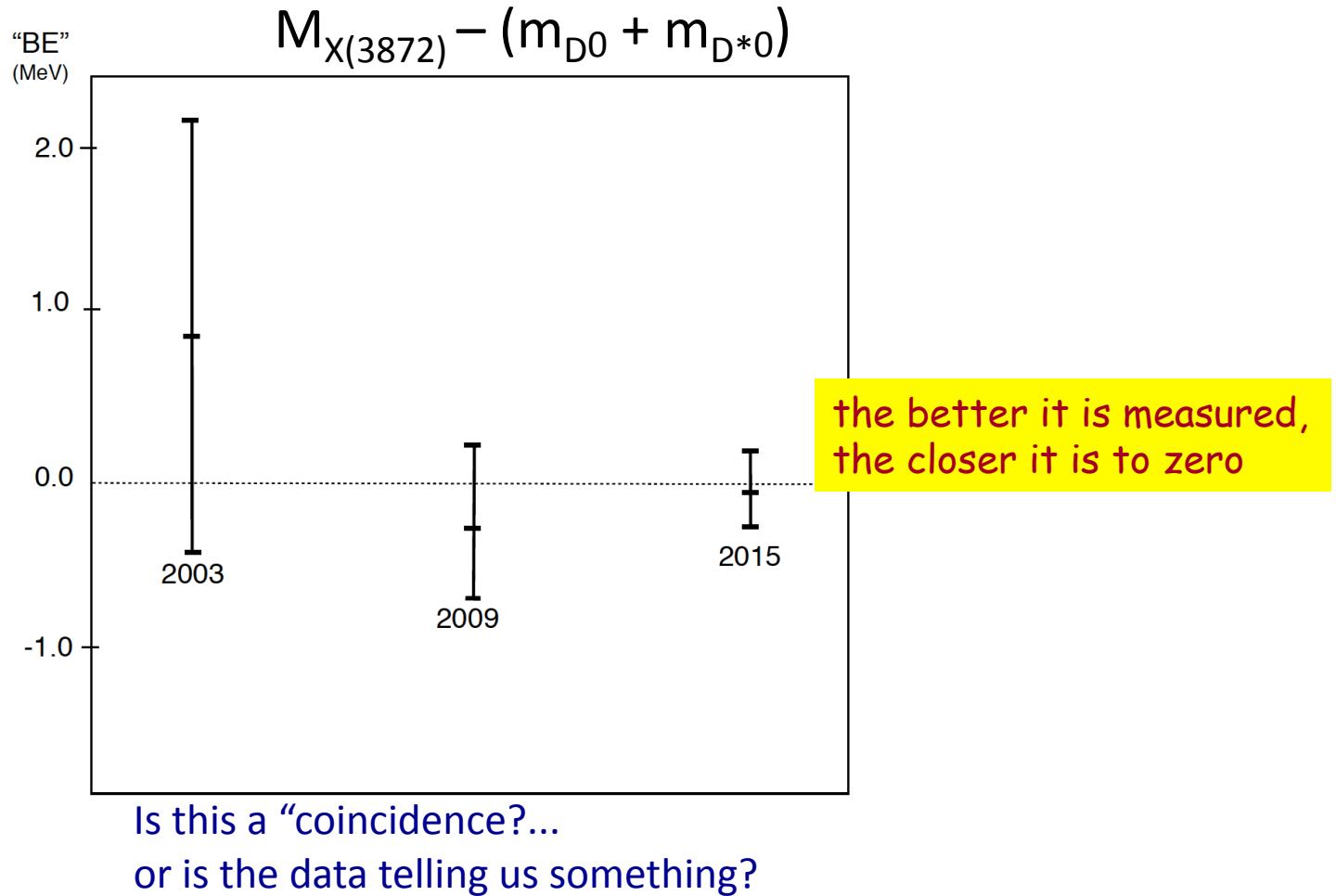


$M_{X(3872)}$  is indistinguishable from  $m_{D^0} + m_{D^{*0}}$

"B.E." =  $3 \pm 193$  keV



# X(3872) “Binding Energy”



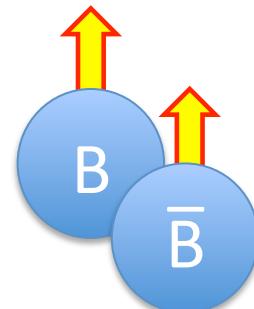
# Thresholds may be interesting



# Look at light baryon thresholds

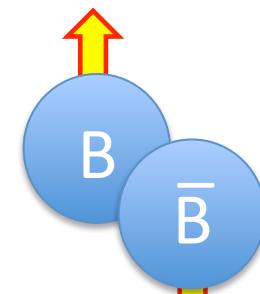
baryon-antibaryon:

2 S-wave threshold states:



$$J^{PC}=1^{--}$$

$$e^+e^- \rightarrow B\bar{B}$$

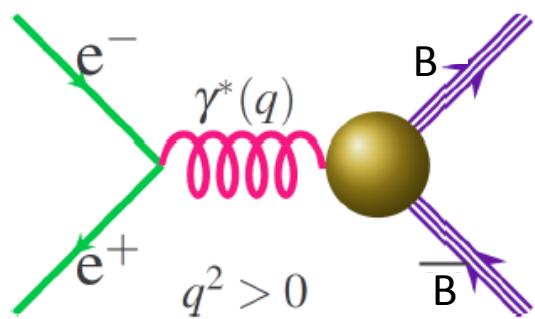


$$J^{PC}=0^{-+}$$

$$J/\psi (\psi') \rightarrow \gamma B\bar{B}$$

# $e^+e^- \rightarrow p\bar{p}, n\bar{n} (\Lambda\bar{\Lambda})$ near threshold

$$e^+e^- \leftrightarrow N\bar{N}, \Lambda\bar{\Lambda}, \dots$$



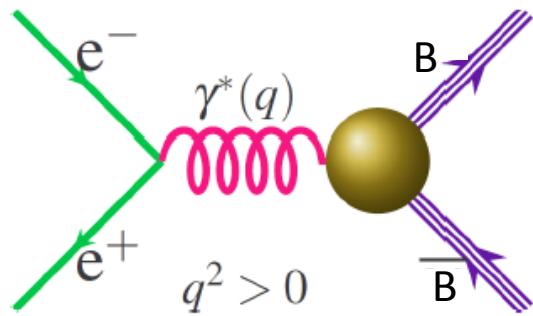
time-like form-factors

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4m_{B\bar{B}}^2} \left[ (1 + \cos^2 \theta) |G_M(m_{B\bar{B}})|^2 + \frac{1}{\tau} \sin^2 \theta |G_E(m_{B\bar{B}})|^2 \right]$$

$$\tau = \frac{m_{p\bar{p}}^2}{4m_B^2} \quad \beta = \sqrt{1 - \frac{1}{\tau}}$$

# $e^+e^- \rightarrow p\bar{p}, n\bar{n} (\Lambda\bar{\Lambda})$ near threshold

$$e^+e^- \leftrightarrow N\bar{N}, \Lambda\bar{\Lambda}, \dots$$



time-like form-factors

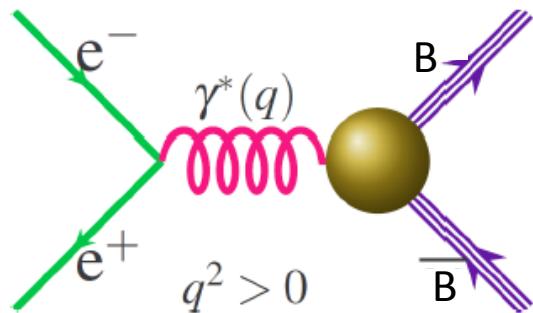
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4m_{B\bar{B}}^2} \left[ (1 + \cos^2 \theta) |G_M(m_{B\bar{B}})|^2 + \frac{1}{\tau} \sin^2 \theta |G_E(m_{B\bar{B}})|^2 \right]$$

$$\tau = \frac{m_{p\bar{p}}^2}{4m_B^2} \quad \beta = \sqrt{1 - \frac{1}{\tau}}$$

$C$  = Coulomb correction

# $e^+e^- \rightarrow p\bar{p}, n\bar{n} (\Lambda\bar{\Lambda})$ near threshold

$$e^+e^- \leftrightarrow N\bar{N}, \Lambda\bar{\Lambda}, \dots$$



time-like form-factors

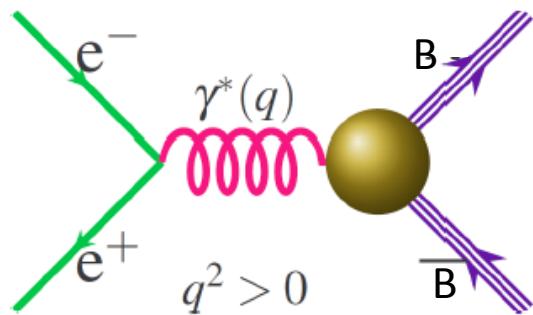
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4m_{B\bar{B}}^2} \left[ (1 + \cos^2 \theta) |G_M(m_{B\bar{B}})|^2 + \frac{1}{\tau} \sin^2 \theta |G_E(m_{B\bar{B}})|^2 \right]$$

$$\tau = \frac{m_{p\bar{p}}^2}{4m_B^2} \quad \beta = \sqrt{1 - \frac{1}{\tau}}$$

for  $p\bar{p}$ :  $C = \frac{\pi\alpha/\beta}{1 - \exp(-\pi\alpha/\beta)} \rightarrow \frac{\pi\alpha}{\beta}$   
 for  $n\bar{n}$  ( $\Lambda\bar{\Lambda}$ ):  $C = 1$   
 in point-like approx

# $e^+e^- \rightarrow p\bar{p}, n\bar{n} (\Lambda\bar{\Lambda})$ near threshold

$$e^+e^- \leftrightarrow N\bar{N}, \Lambda\bar{\Lambda}, \dots$$



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4m_{B\bar{B}}^2} \left[ (1 + \cos^2 \theta) |G_M(m_{B\bar{B}})|^2 + \frac{1}{\tau} \sin^2 \theta |G_E(m_{B\bar{B}})|^2 \right]$$

time-like form-factors

$$\tau = \frac{m_{p\bar{p}}^2}{4m_B^2} \quad \beta = \sqrt{1 - \frac{1}{\tau}}$$

for  $p\bar{p}$ :  $C = \frac{\pi\alpha/\beta}{1 - \exp(-\pi\alpha/\beta)} \rightarrow \frac{\pi\alpha}{\beta}$

for  $n\bar{n}$  ( $\Lambda\bar{\Lambda}$ ):  $C = 1$

in point-like approx

If the form-factors are analytic: as  $\tau \rightarrow 1$   $|G_M| \rightarrow |G_E|$  and  $\frac{d\sigma}{d\Omega} \rightarrow$  isotropic

Integrated cross section:

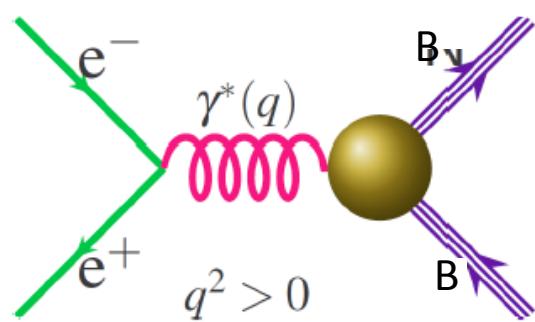
$$\sigma_{B\bar{B}}(m_{B\bar{B}}) = \frac{4\pi\alpha^2\beta C}{3m^2} \left[ |G_M(m_{B\bar{B}})|^2 + \frac{1}{2\tau} |G_E(m_{B\bar{B}})|^2 \right] = \frac{4\pi\alpha^2\beta C}{3m^2} |G_{eff}(m_{B\bar{B}})|^2 \left( 1 + 1/2\tau \right)$$

“effective” form-factor

# $e^+e^- \rightarrow p\bar{p}, n\bar{n} (\Lambda\bar{\Lambda})$ near threshold

Integrated cross section

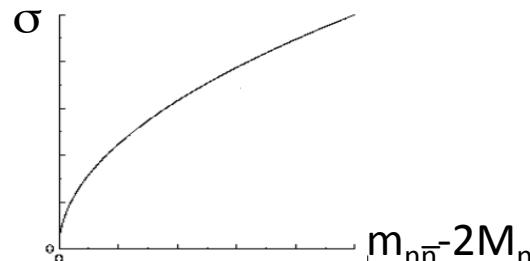
$$e^+e^- \leftrightarrow N\bar{N}, \Lambda\bar{\Lambda}, \dots$$



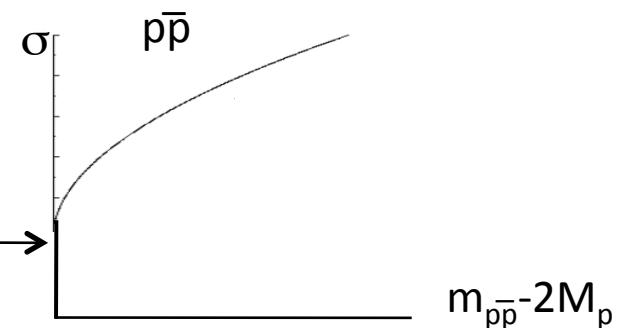
for  $n\bar{n}$  ( $\Lambda\bar{\Lambda}$ ):  $C=1$

$$\sigma_{B\bar{B}} = \frac{4\pi\alpha^2\beta C}{3m^2} \left| G_{eff}(m_{B\bar{B}}) \right|^2 \left( 1 + 1/2\tau \right)$$

$$\text{for } p\bar{p}: C = \frac{\pi\alpha/\beta}{1 - \exp(-\pi\alpha/\beta)} \rightarrow \frac{\pi\alpha}{\beta}$$

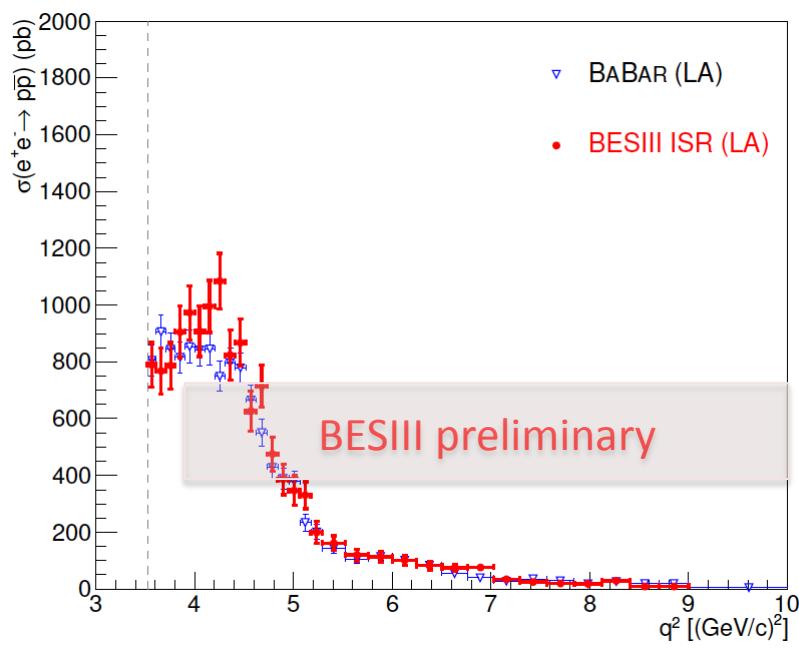


$$\begin{aligned} \sigma_0 &= \frac{\pi^2\alpha^3}{2M_p^2} \left| G_M(2M_p) \right|^2 \\ &\approx 0.85 \text{ nb} \left| G_M(2M_p) \right|^2 \end{aligned}$$

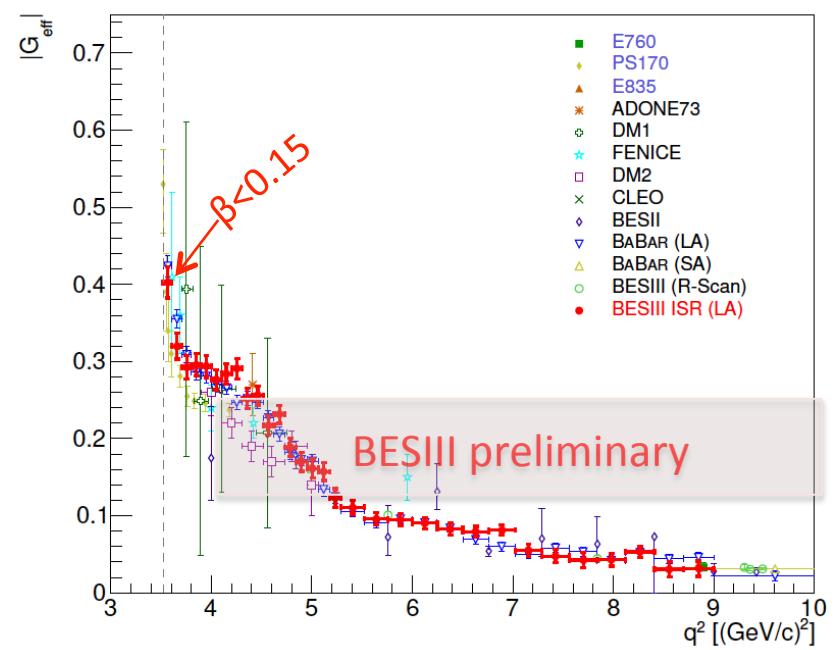


# $\sigma(e^+e^- \rightarrow p\bar{p})$ threshold data

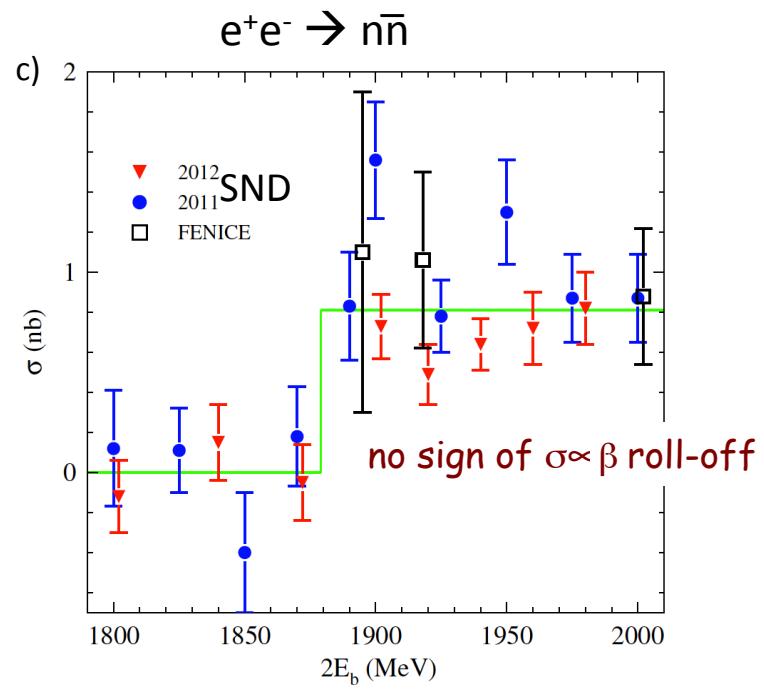
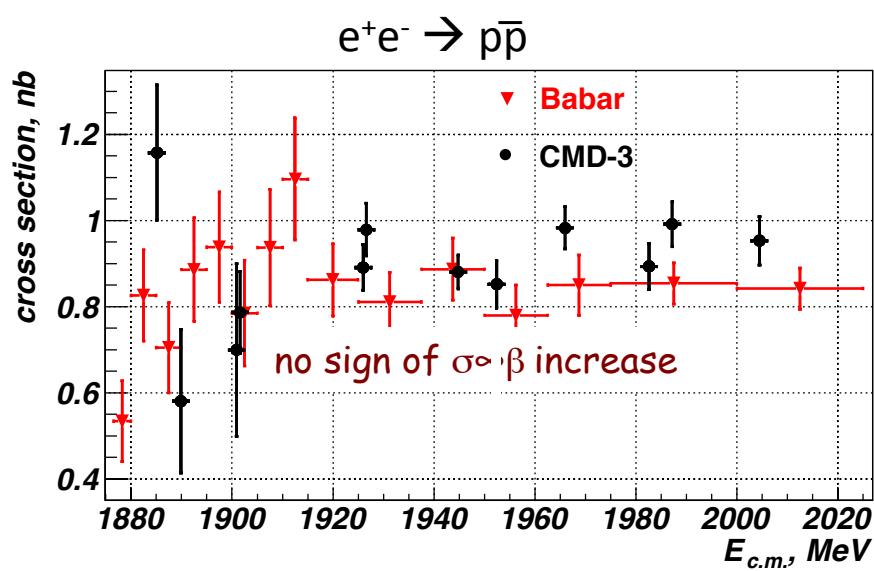
$\sigma(e^+e^- \rightarrow p\bar{p})$



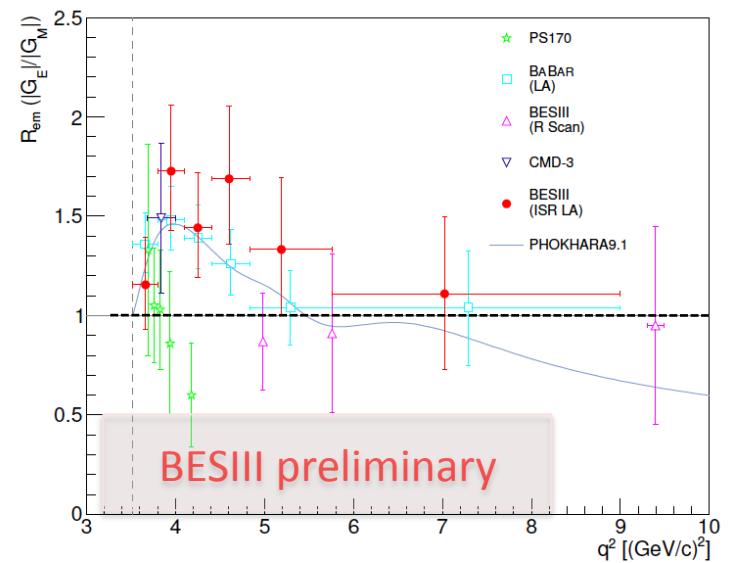
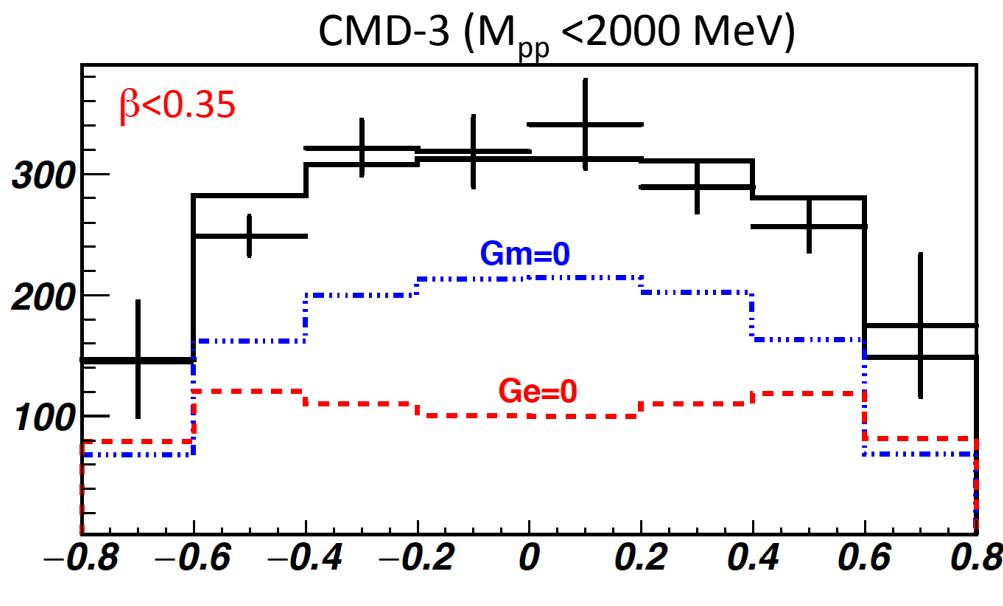
$|G_{\text{eff}}|$



# $\sigma(e^+e^- \rightarrow p\bar{p}, n\bar{n})$ threshold data



$\frac{d\sigma}{d\Omega}(e^+e^- \rightarrow p\bar{p}) \rightarrow$  isotropic??  
 $(|G_M(0)|/|G_E(0)| \rightarrow 1 ??)$



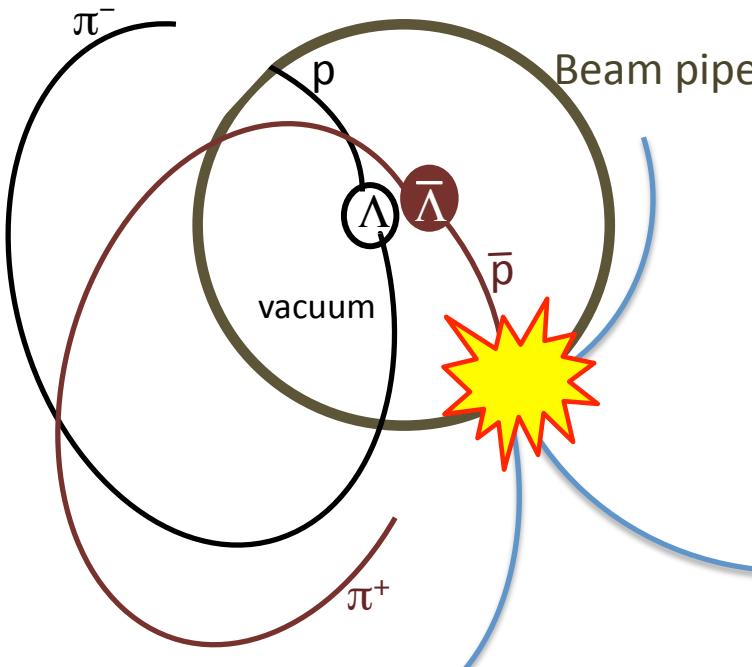
$e^+e^- \rightarrow \gamma^* \rightarrow \Lambda\bar{\Lambda}$  at threshold

# a $\Lambda\bar{\Lambda}$ threshold event in BESIII

for:  $\Lambda \rightarrow p\pi^-$  and  $\bar{\Lambda} \rightarrow \bar{p}\pi^+$

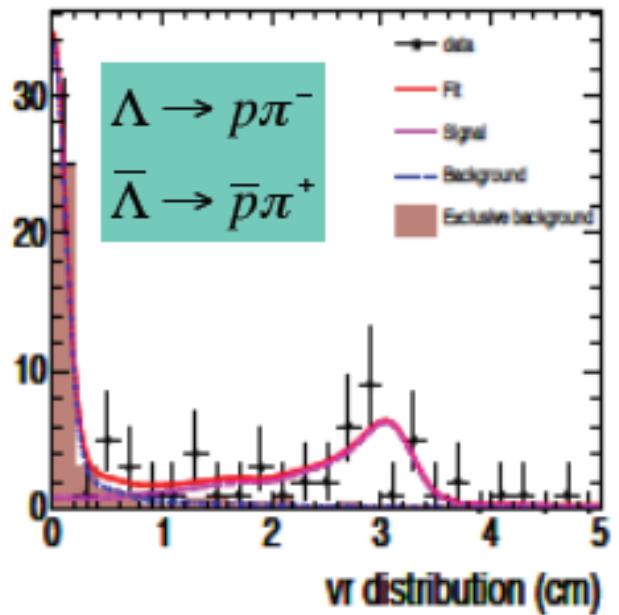
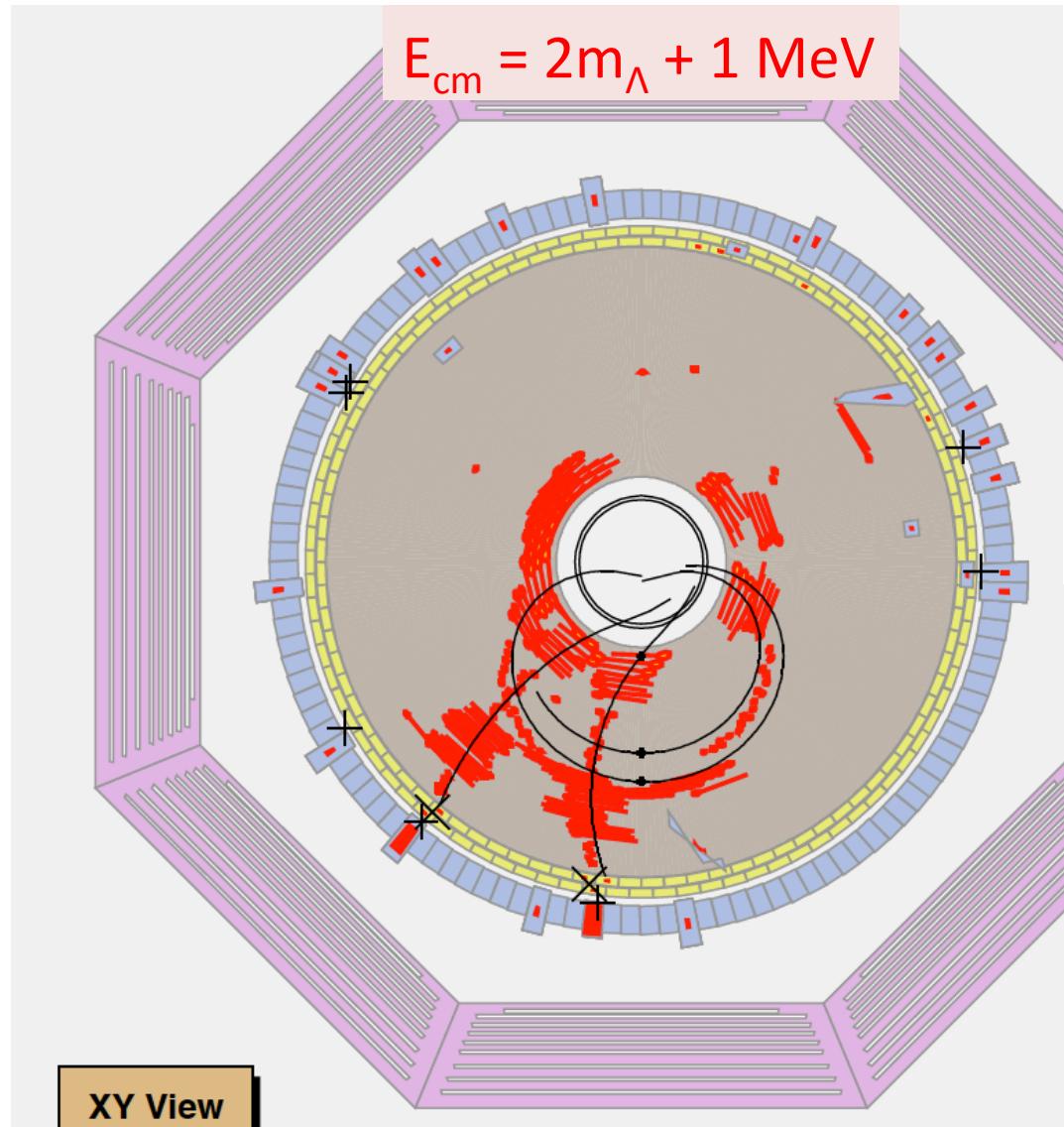
Tracking volume

$KE_p \approx 6 \text{ MeV}$

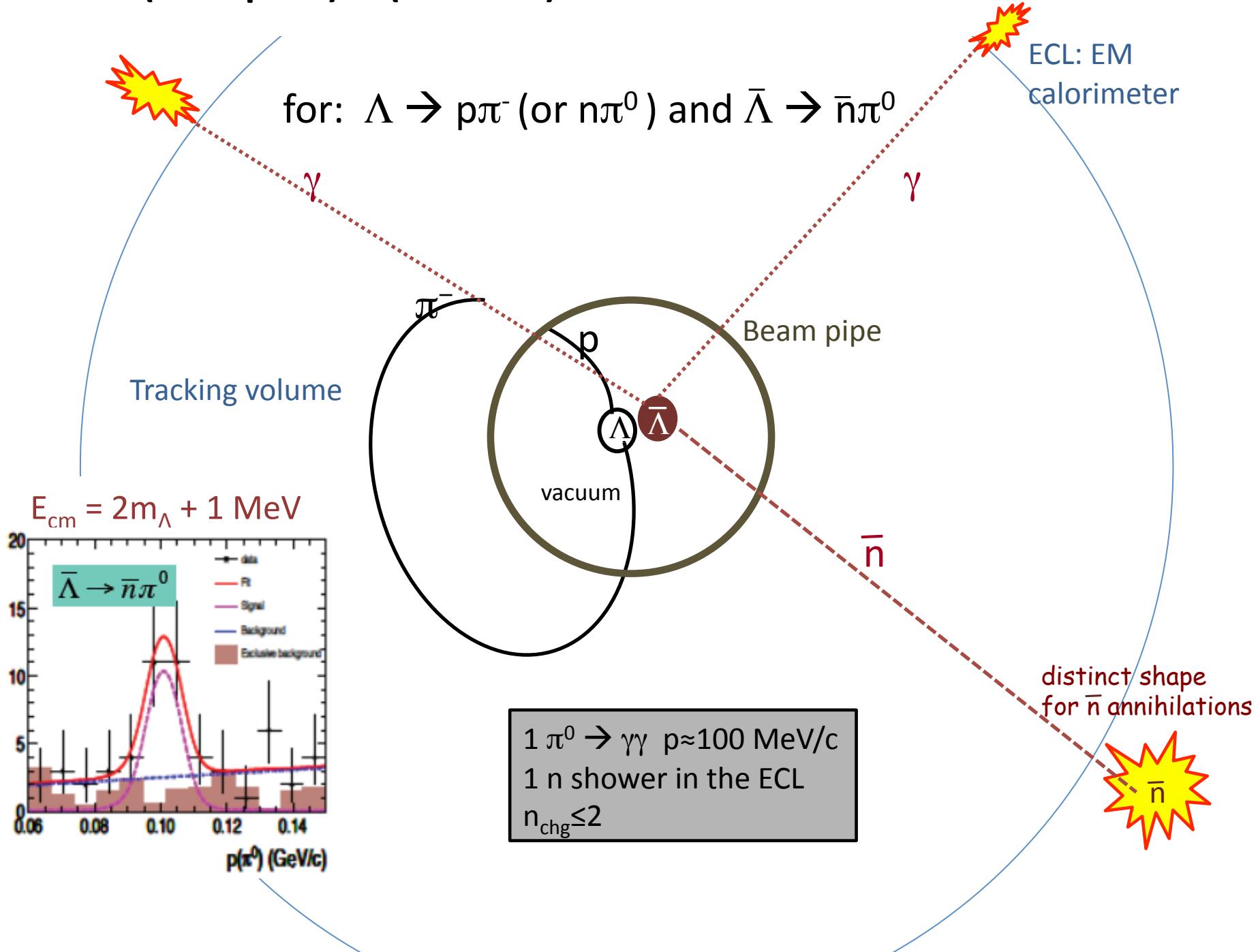


1  $\pi^+$  && 1  $\pi^-$  with  $p \approx 100 \text{ MeV}/c$   
at least 1 track from  $r \approx 3 \text{ cm}$

# BESIII sees events like this

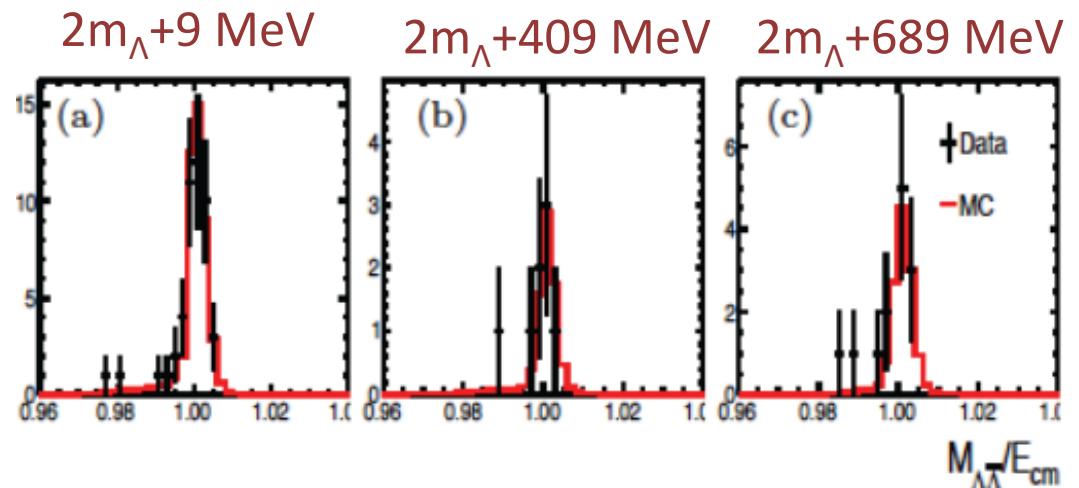
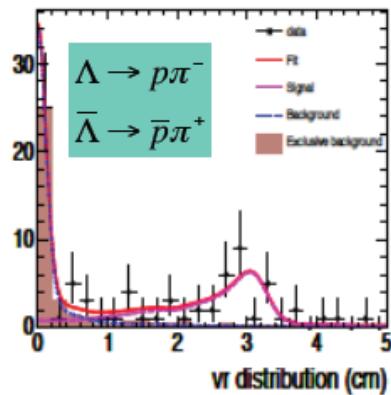


# a $(\Lambda \rightarrow p\pi^-)\bar{\Lambda}(\rightarrow \bar{n}\pi^0)$ threshold event in BESIII



# BESIII $e^+e^- \rightarrow \Lambda\bar{\Lambda}$ measurements

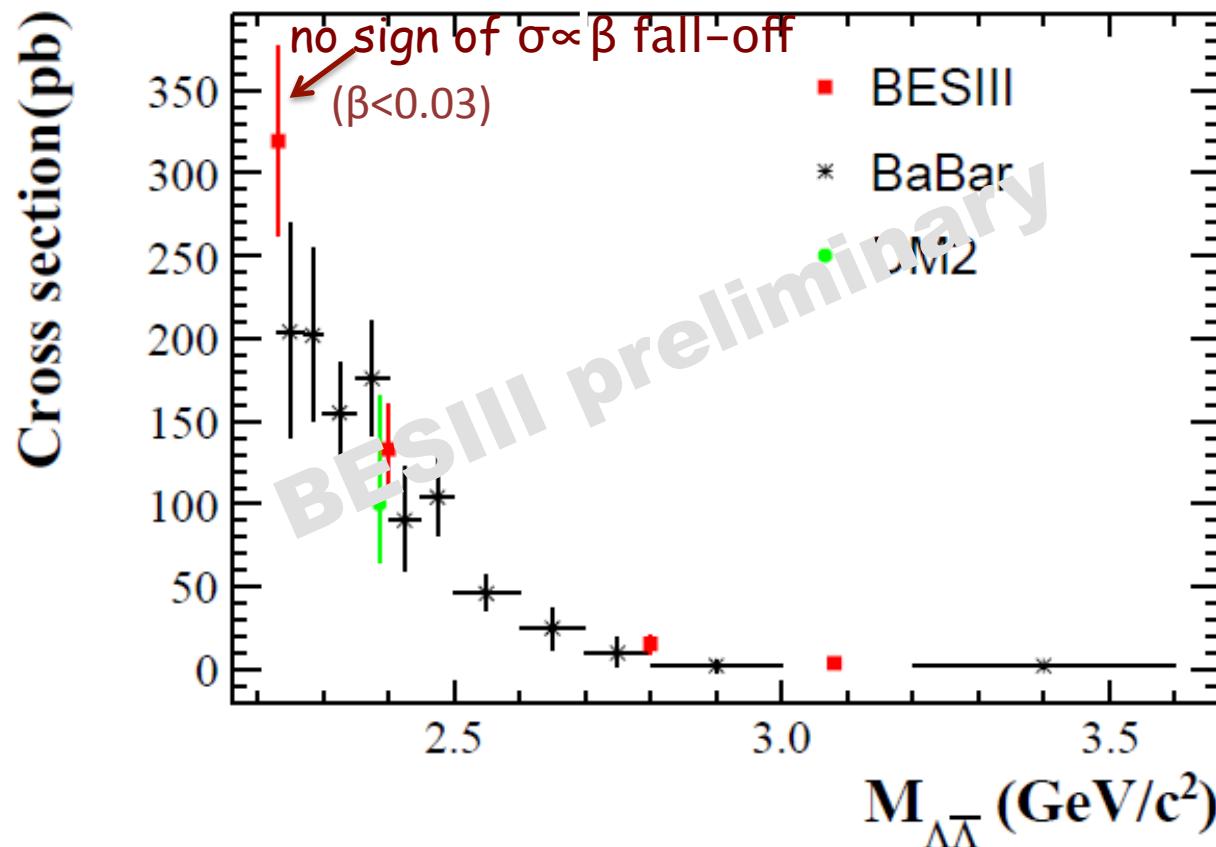
$$E_{cm} = 2m_\Lambda + 1 \text{ MeV}$$



$\sqrt{s}$ (MeV)	Reconstruction	$\sigma_{Born}$ (pb)	$ G  (\times 10^{-2})$
2232.4	$\Lambda \rightarrow p\pi^-$ , $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ $\bar{\Lambda} \rightarrow \bar{n}\pi^0$ combined	$325 \pm 53 \pm 46$ $(3.0 \pm 1.0 \pm 0.4) \times 10^2$ $320 \pm 58$	$63.4 \pm 5.7$
conventional analyses at higher energies	{ 2400.0 2800.0 3080.0	$133 \pm 20 \pm 19$ $15.3 \pm 5.4 \pm 2.0$ $3.9 \pm 1.1 \pm 0.5$	$12.93 \pm 0.97 \pm 0.92$ $4.16 \pm 0.73 \pm 0.27$ $2.21 \pm 0.31 \pm 0.14$

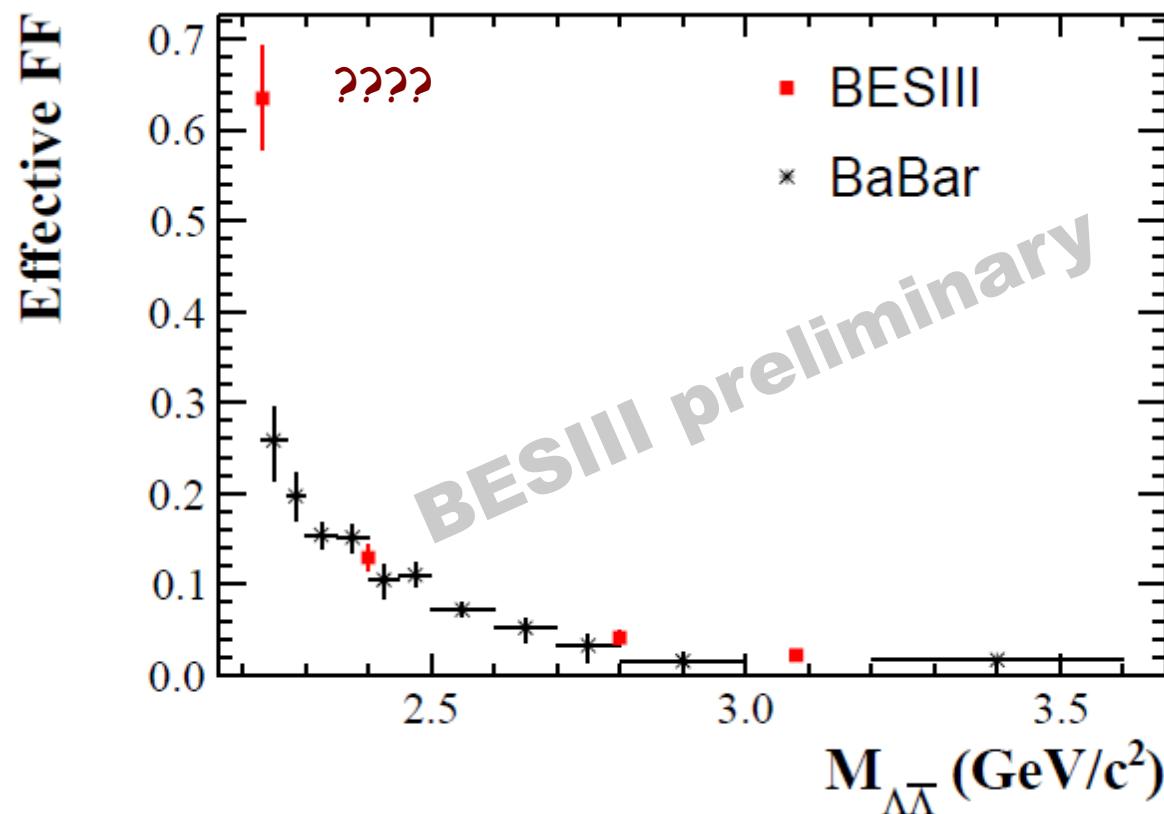
# Cross section: $e^+e^- \rightarrow \gamma^* \rightarrow \Lambda\bar{\Lambda}$

$$\sigma_{\Lambda\bar{\Lambda}}(m) = \frac{4\pi\alpha^2\beta}{3m^2} \left[ |G_M(m)|^2 + \frac{1}{2\tau} |G_E(m)|^2 \right] = \frac{4\pi\alpha^2\beta}{3m^2} |G_{eff}(m)|^2 (1 + 1/2\tau)$$



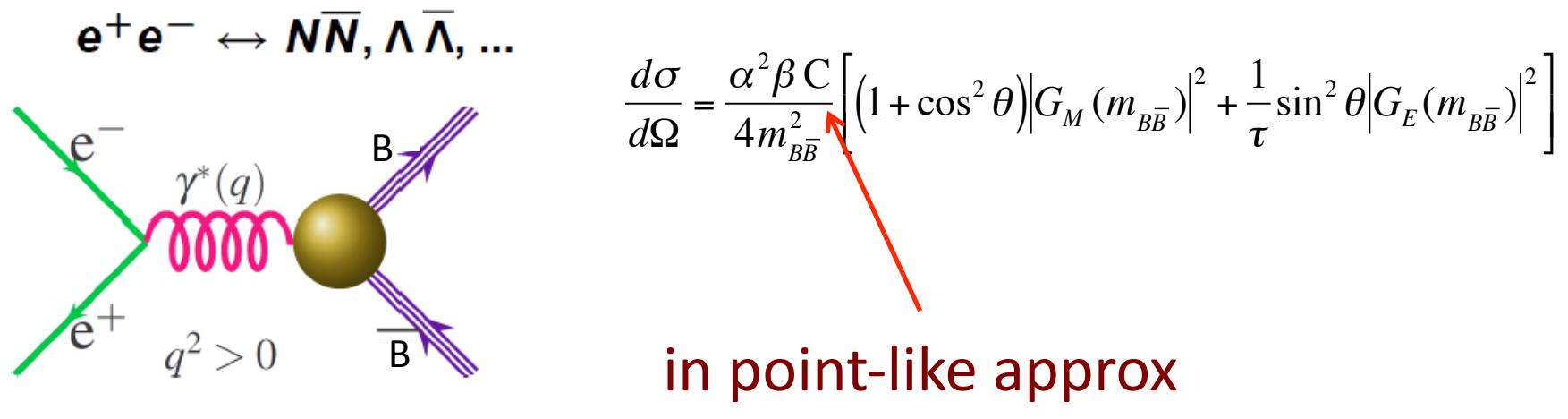
# Effective time-like form-factor of the $\Lambda$

$$|G_{eff}(m)| = \sqrt{\frac{3m^2\sigma_{\Lambda\bar{\Lambda}}}{4\pi\alpha^2\beta(1+1/2\tau)}}$$



# Is the Coulomb factor reliable?

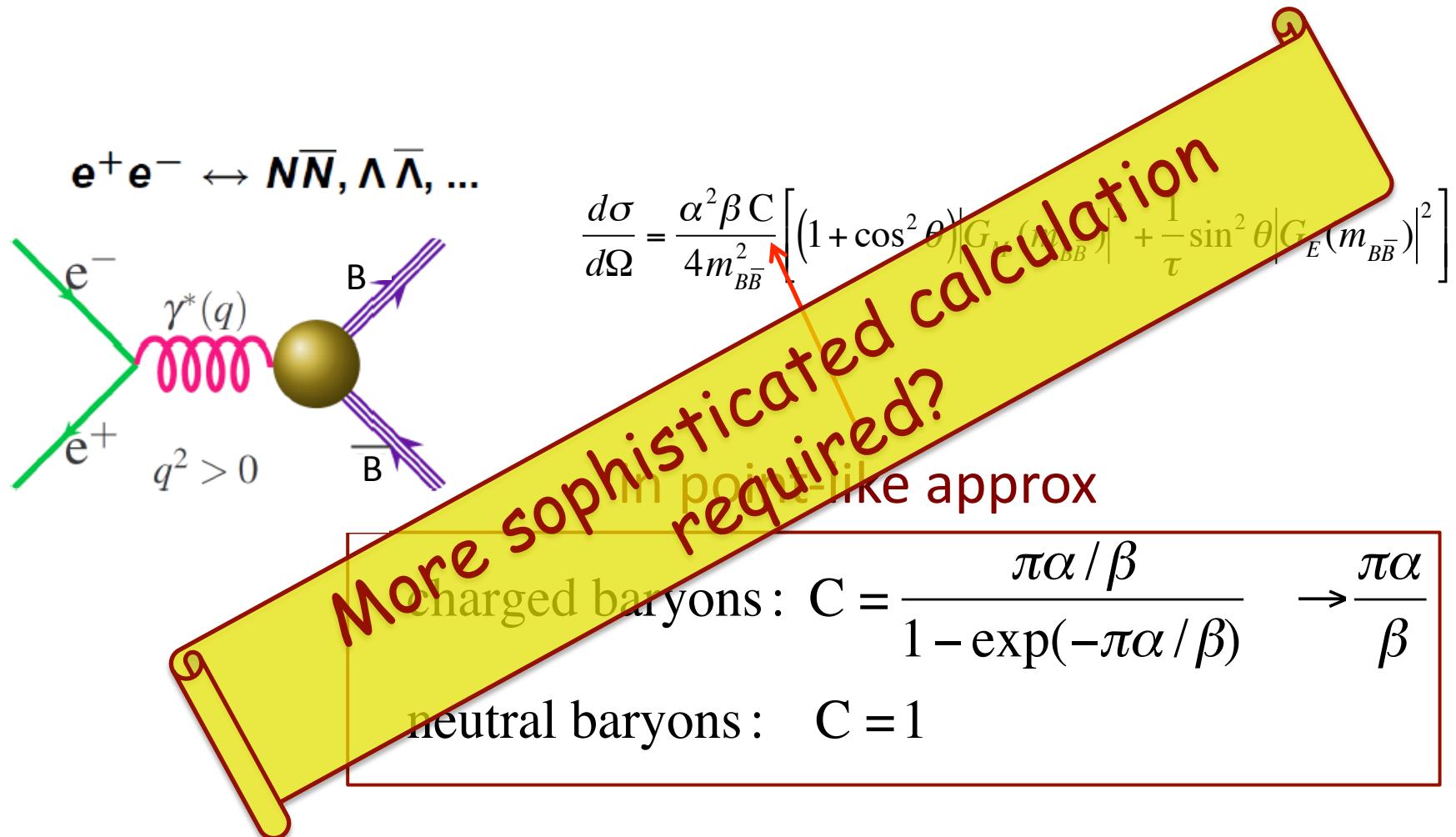
# Is the Coulomb factor reliable?



charged baryons :  $C = \frac{\pi\alpha/\beta}{1 - \exp(-\pi\alpha/\beta)} \rightarrow \frac{\pi\alpha}{\beta}$

neutral baryons :  $C = 1$

# Is the Coulomb factor reliable?



# BB threshold measurement prospects

Data “in the can”

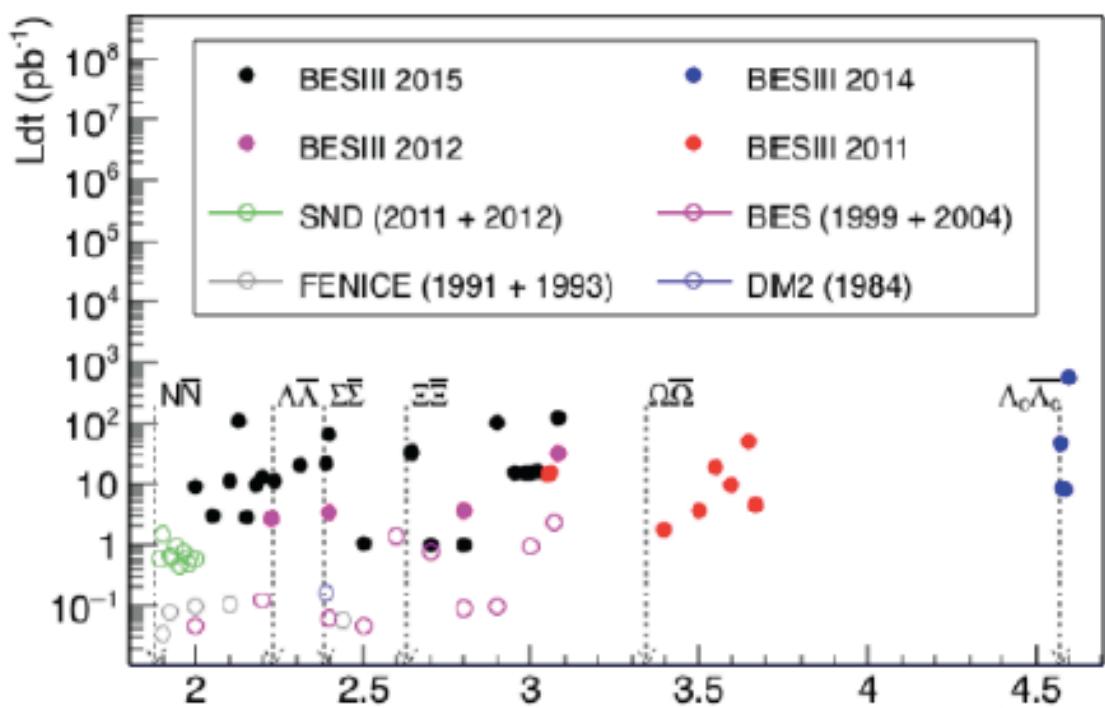
- under analysis -

Scan data 2015 between 2 and 3.08 GeV ( $552 \text{ pb}^{-1}$ )

$e^+e^- \rightarrow \Lambda\bar{\Sigma}^0, \bar{\Sigma}^0\Sigma^0$  measured  
by BaBar: no extraction of R

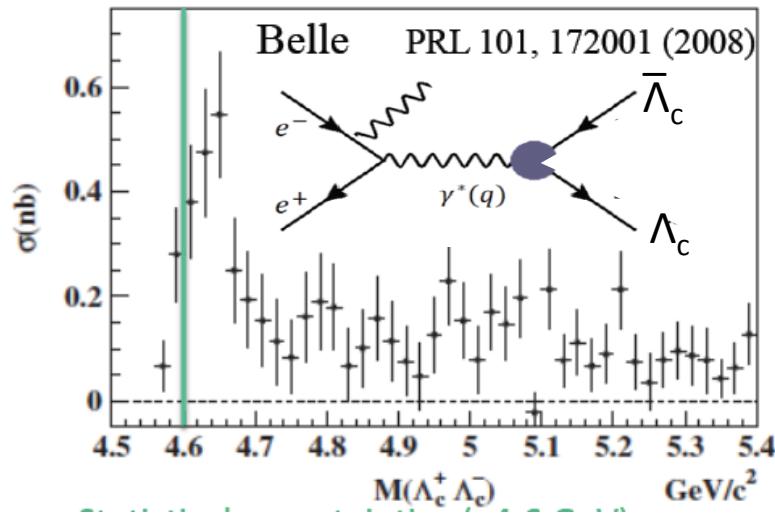


$e^+e^- \rightarrow \Lambda\bar{\Sigma}^0, \bar{\Sigma}^0\Sigma^0, \bar{\Sigma}^-\Sigma^+, \bar{\Sigma}^+\Sigma^-,$   
 $\bar{\Xi}^0\Xi^0, \bar{\Xi}^+\Xi^-, \bar{\Omega}^+\Omega^-$



# $e^+e^- \rightarrow \Lambda_c \bar{\Lambda}_c$ analysis near completion

- Large Q-values in (e.g.  $\Lambda_c \rightarrow pK\pi$ :  $Q \sim 700$  MeV) facilitate threshold measurements  
angular distribution measurements are feasible
- Belle saw large threshold enhancement  
in  $e^+e^- \rightarrow \gamma_{\text{ISR}} \Lambda_c \bar{\Lambda}_c$  measurements



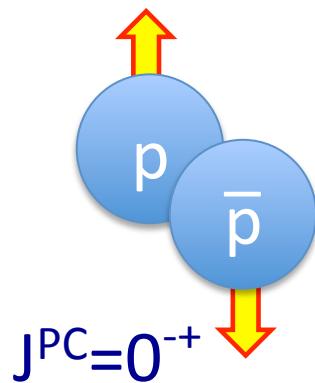
$2m_{\Lambda_c} + 1$  MeV  $\rightarrow$

BESIII $e^+e^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$ data	
$\sqrt{s}$ (GeV)	Luminosity (pb <sup>-1</sup> )
4.5745	47.67
4.580	8.545
4.590	8.162
4.5995	566.9

# $0^-$ p $\bar{p}$ system



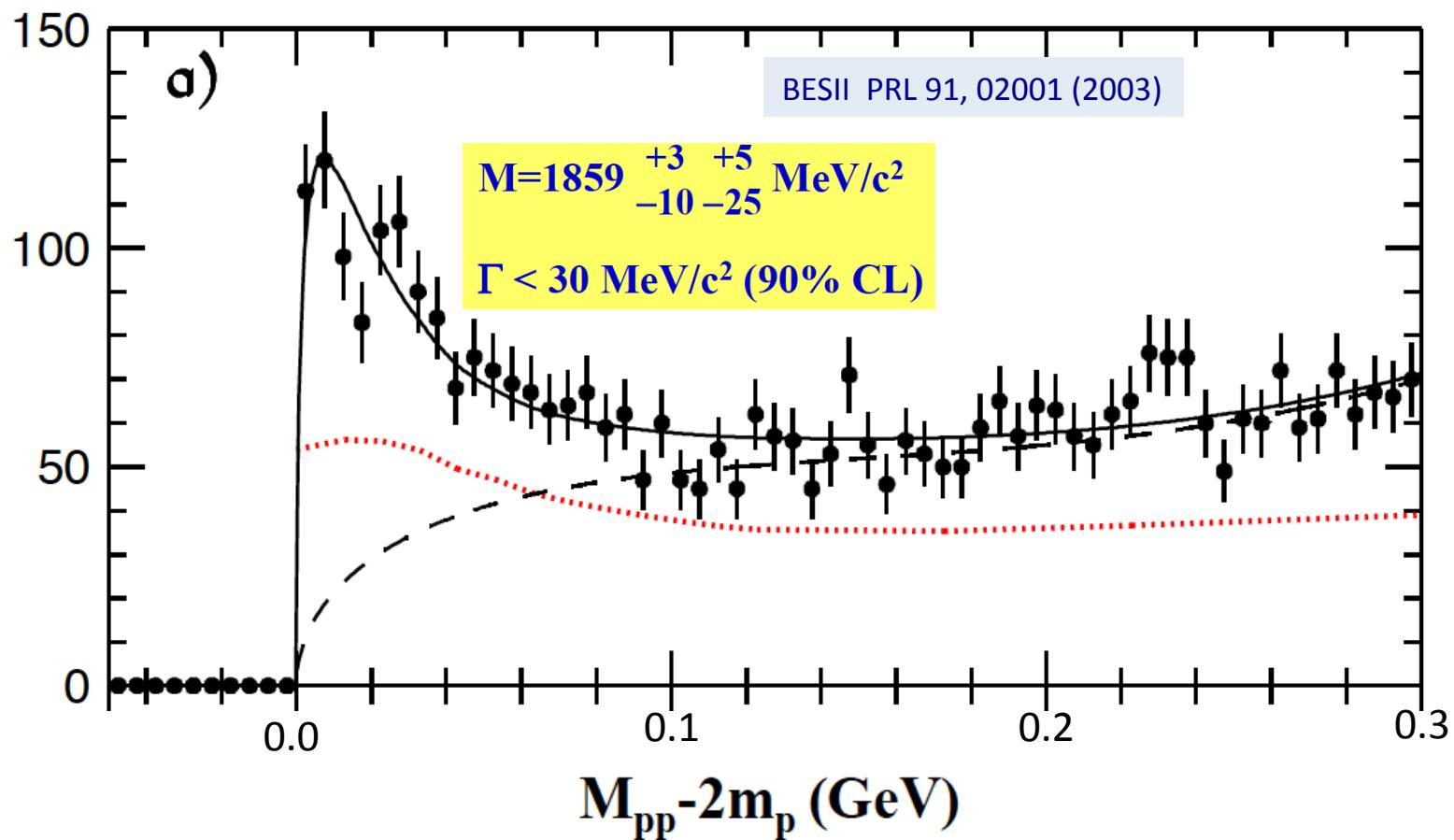
# $0^{-+}$ $p\bar{p}$ system



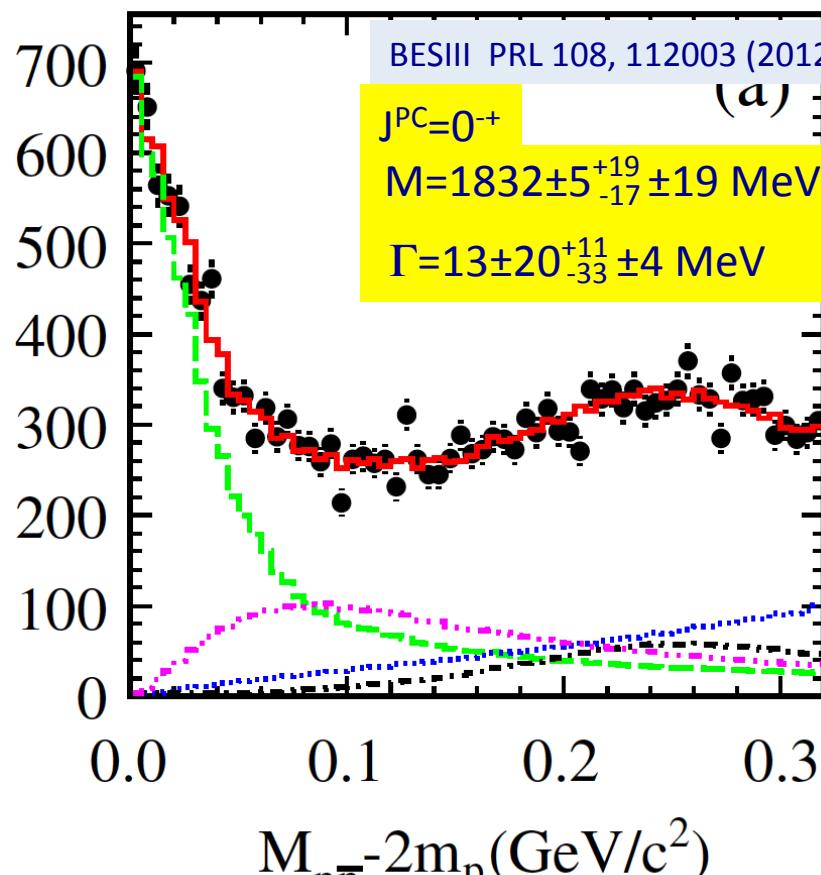
$$J/\psi (\psi') \rightarrow \gamma B\bar{B}$$

Discussed yesterday in Tianjue Min's talk

# $J/\psi \rightarrow \gamma p\bar{p}$ at BESII

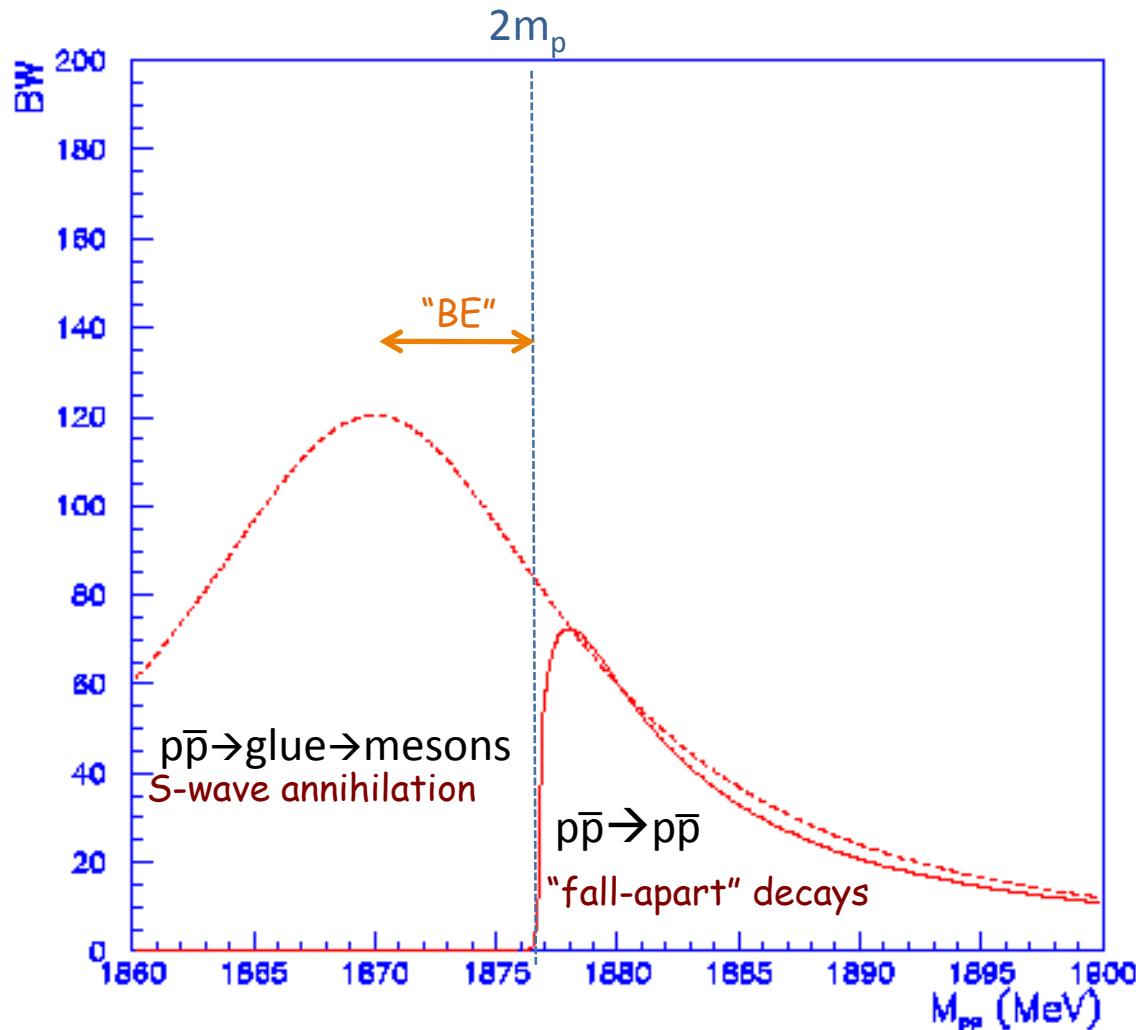


# $J/\psi \rightarrow \gamma p\bar{p}$ at BESIII (PWA)



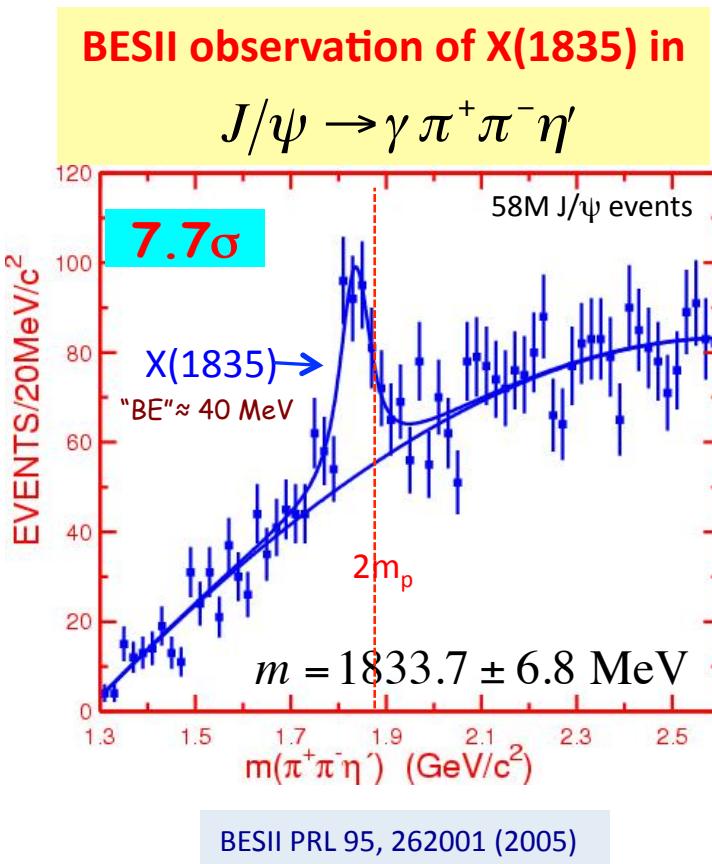
FSI included: A. Sibirtsev et al, PRD71, 054010 (2005)

# “protononium:” a $p\bar{p}$ bound state?



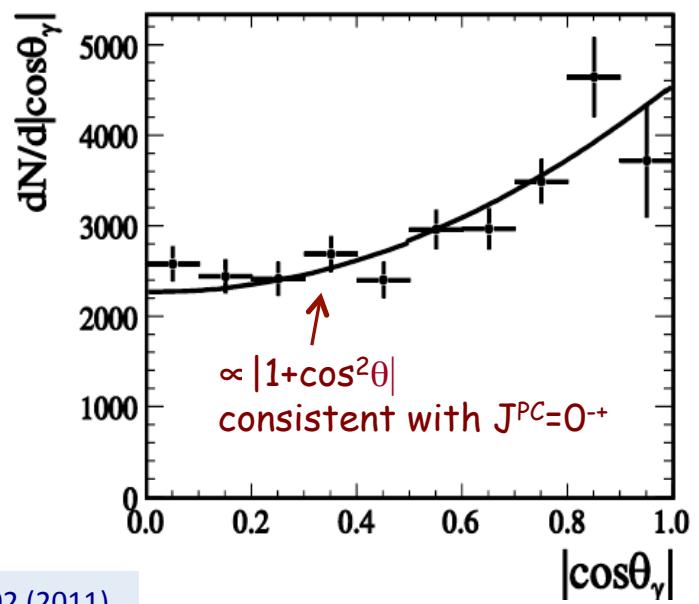
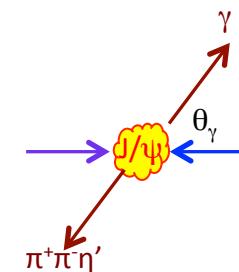
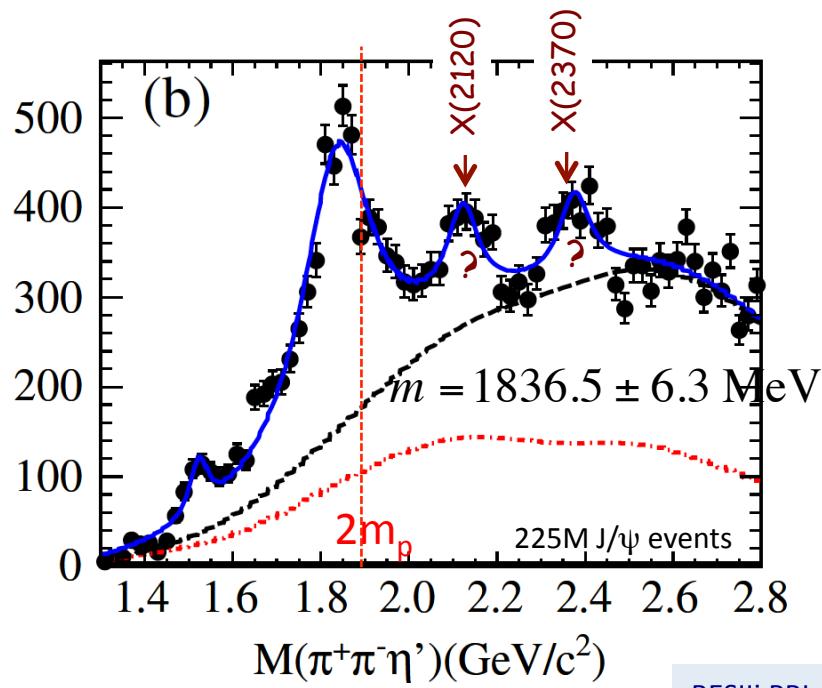
G.J. Ding & M.L. Yan Phys. Rev. C 72, 015208

# $X(1835) \rightarrow \pi^+ \pi^- \eta'$ with 58M $J/\psi$ decays (BESII)



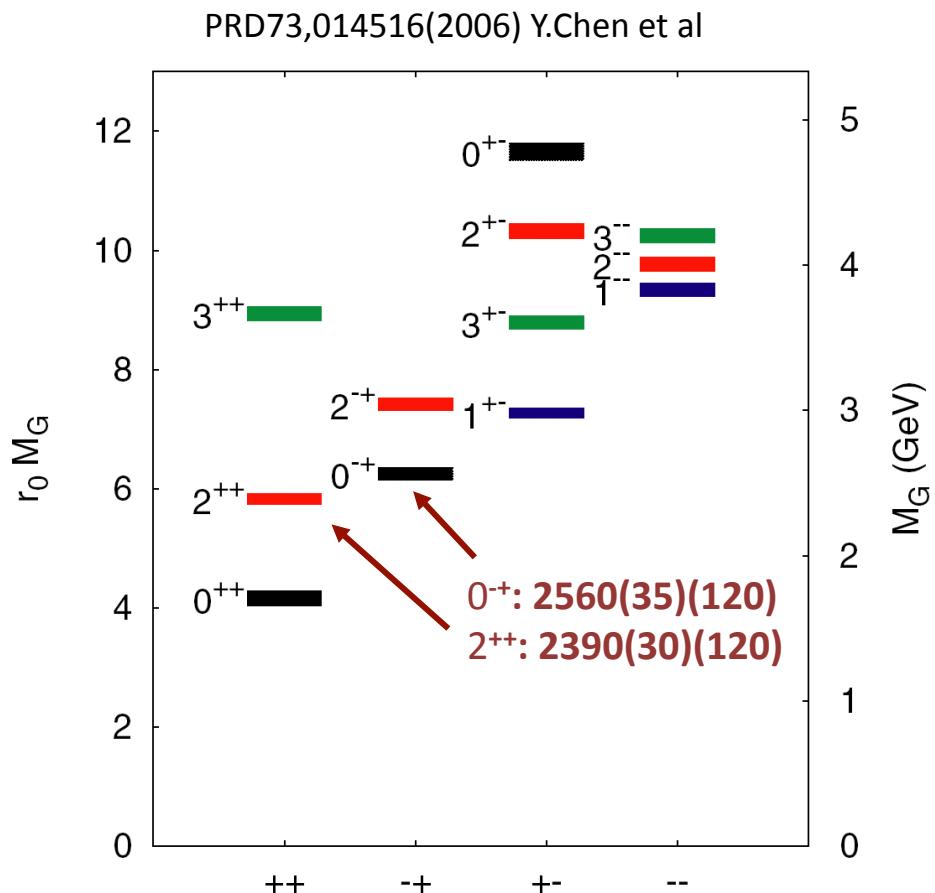
# $X(1835) \rightarrow \pi^+ \pi^- \eta'$ with 225M $J/\psi$ decays

BESIII observation of  $X(1835)$  in  
 $J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'$



# What are the new structures?

way above threshold, but narrow ( $\Gamma \approx 80$  MeV)!!

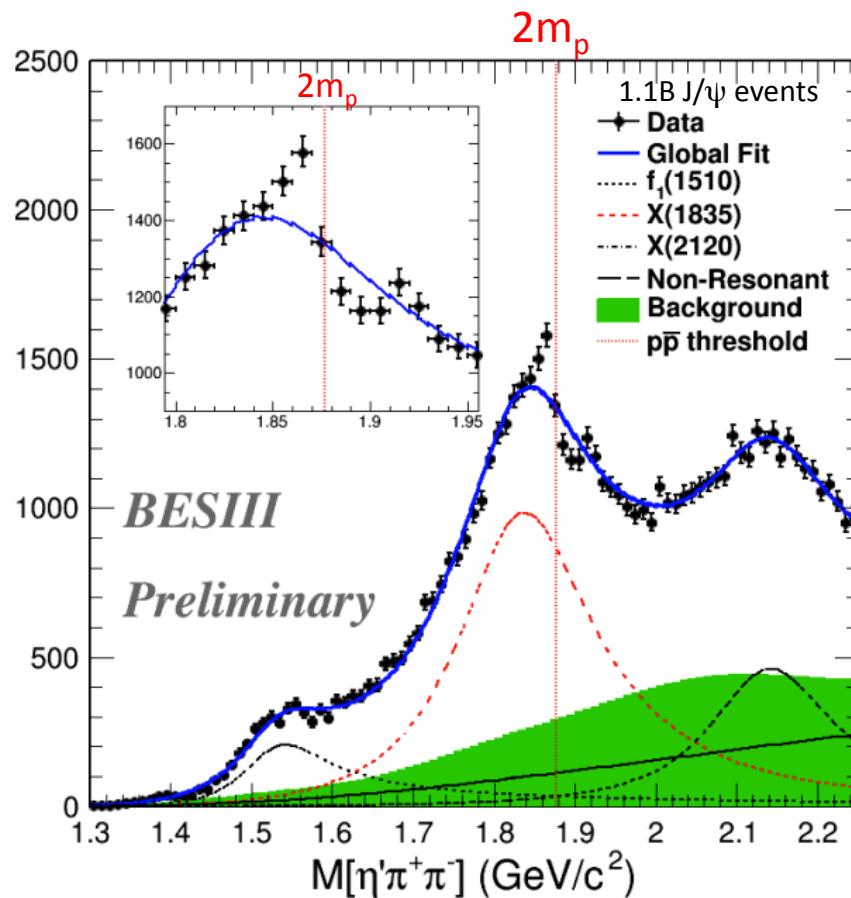


- ✓ first resonant structures observed in the 2.3 GeV region:
  - LQCD predicts that the lowest –lying pseudoscalar glueball: around 2.3 GeV
  - $J/\psi \rightarrow \eta' \pi^+ \pi^-$  is a good decay channel for finding  $0^+$  glueballs.
- ✓ X(2120)/X(2370) possibilities:
  - pseudoscalar glueball ?
  - $\eta/\eta'$  radial excitations?

PRD82,074026,2010 J.F. Liu, G.J. Ding and M.L.Yan  
PRD83:114007,2011 (J.S. Yu, Z.-F. Sun, X. Liu, Q. Zhao)

# $X(1835) \rightarrow \pi^+ \pi^- \eta'$ with 1.1B $J/\psi$ events (BESIII)

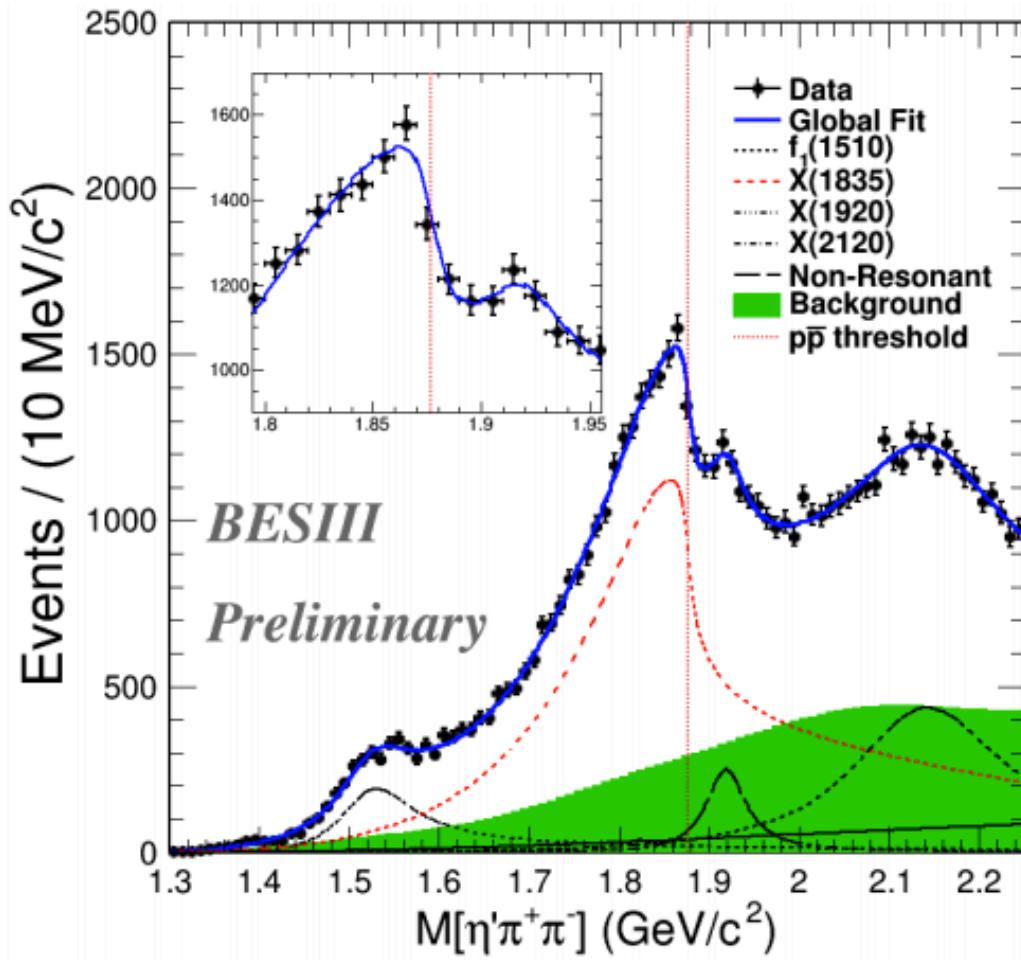
$$J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'$$



# Flatté formula fit:

$$T = \frac{\sqrt{\rho_{out}}}{\mathcal{M}^2 - s - i \sum_k g_k^2 \rho_k}, \sum_k g_k^2 \rho_k \simeq g_0^2 (\rho_0 + \frac{g_{p\bar{p}}^2}{g_0^2} \rho_{p\bar{p}})$$

S.M. Flatté PLB 63, 224 (1976)



Fit results:

$$\frac{g_{p\bar{p}}^2}{g_0^2} = 2.31 \pm 0.37$$

$\downarrow$

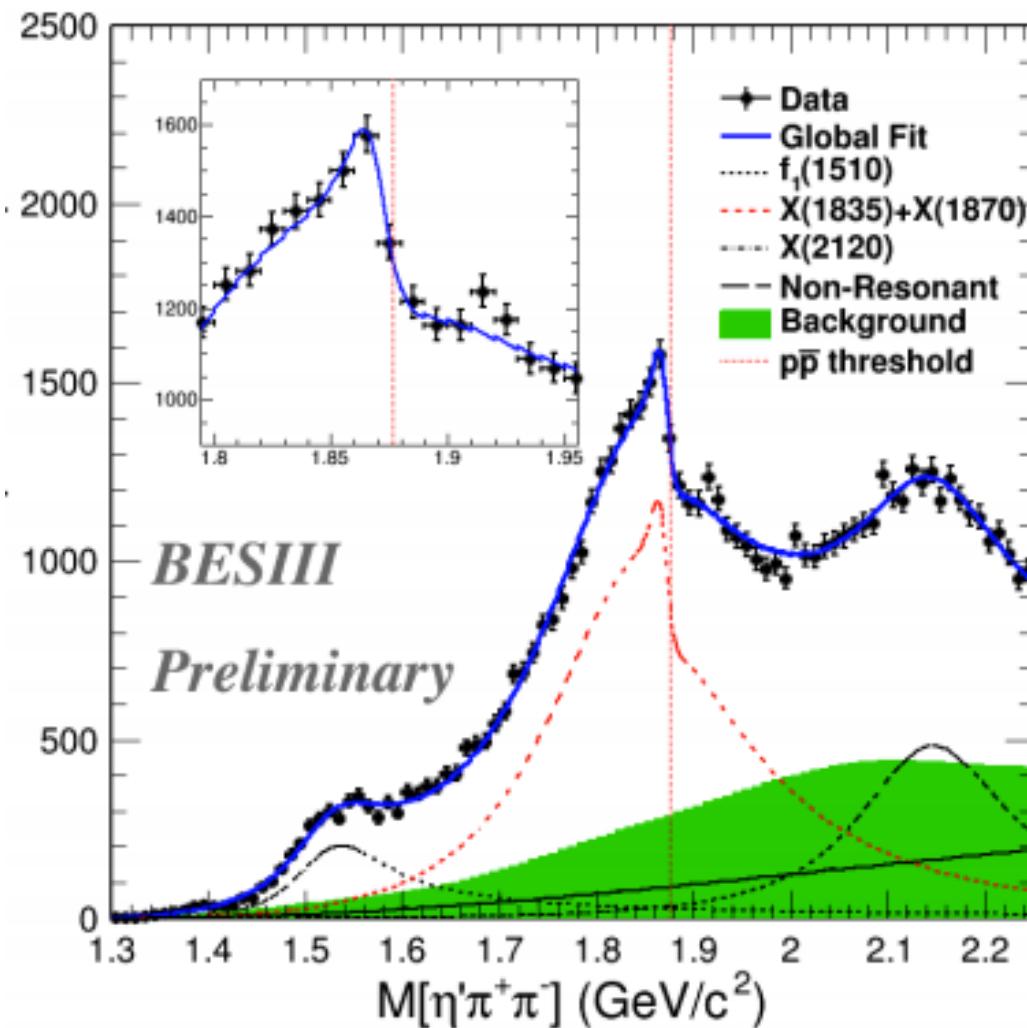
$X$  coupling to  $p\bar{p}$

$\downarrow$

$X$  coupling to everything else

# Two-resonance fit

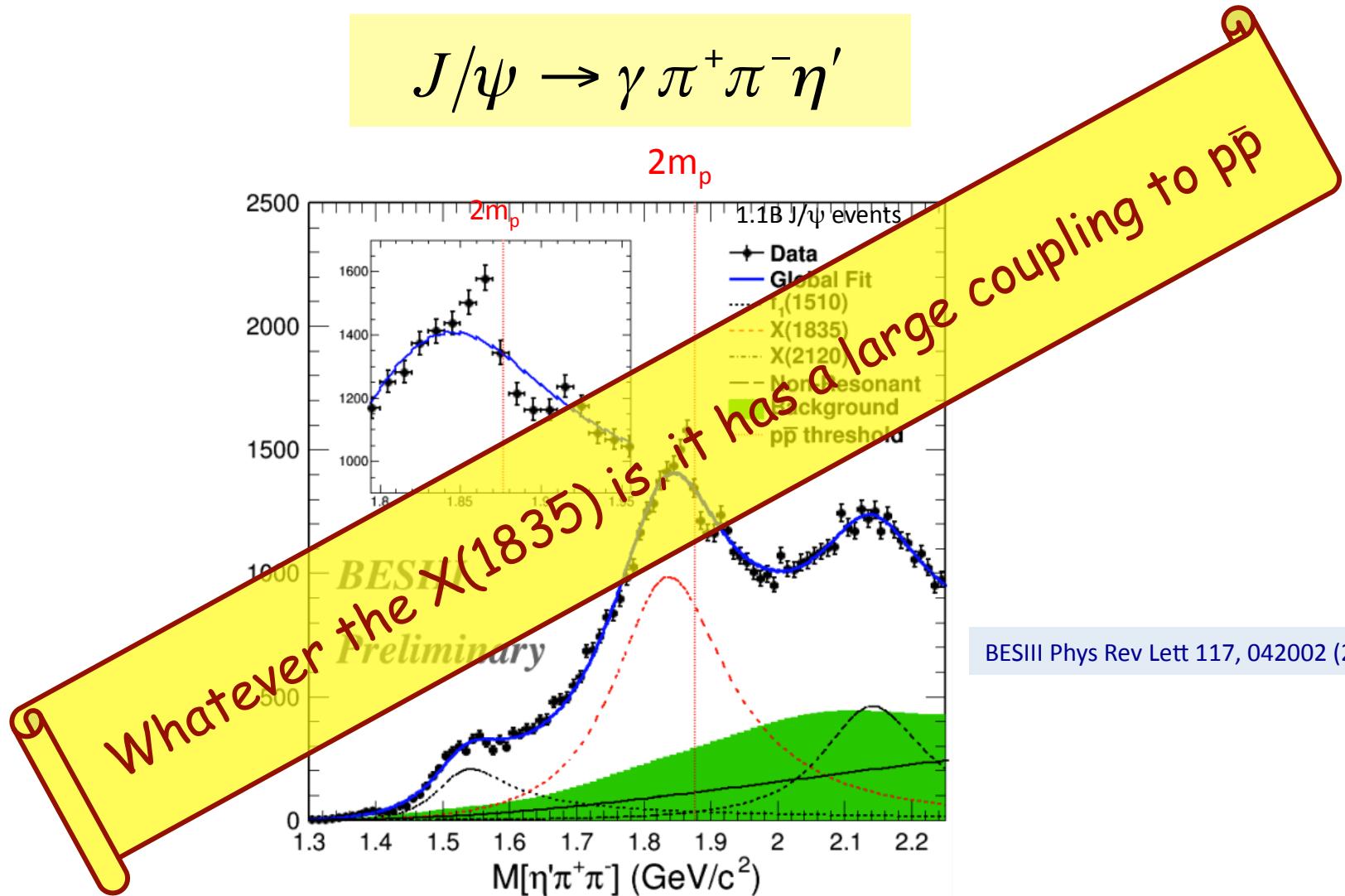
$$T = \frac{\sqrt{\rho_{out}}}{M_1^2 - s - iM_1\Gamma_1} + \frac{\beta \cdot e^{i\theta} \cdot \sqrt{\rho_{out}}}{M_2^2 - s - iM_2\Gamma_2}$$



1<sup>st</sup> resonance ( $X(1835)$ ):  
 $M_1 = 1825.3 \pm 2.4^{+17.3}_{-2.4} \text{ MeV}$   
 $\Gamma_1 = 245 \pm 16 \text{ MeV}$

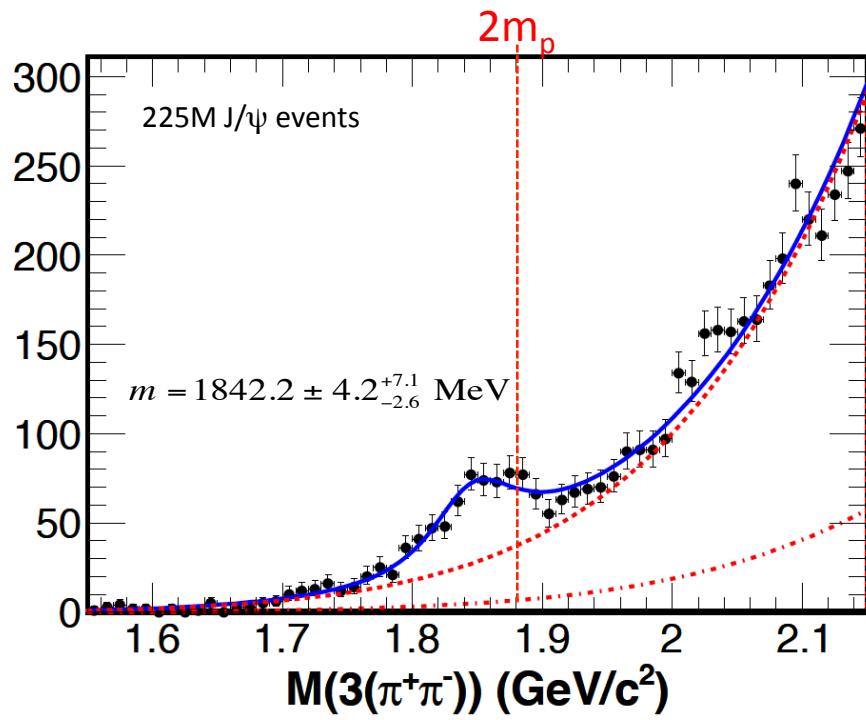
2<sup>nd</sup> resonance ( $X(1870)$ ):  
 $M_2 = 2m_p - 6.3 \pm 3.2 \text{ MeV}$   
 $\Gamma_2 = 13.0 \pm 6.7 \text{ MeV}$

# $X(1835) \rightarrow \pi^+ \pi^- \eta'$ with 1.1B $J/\psi$ events



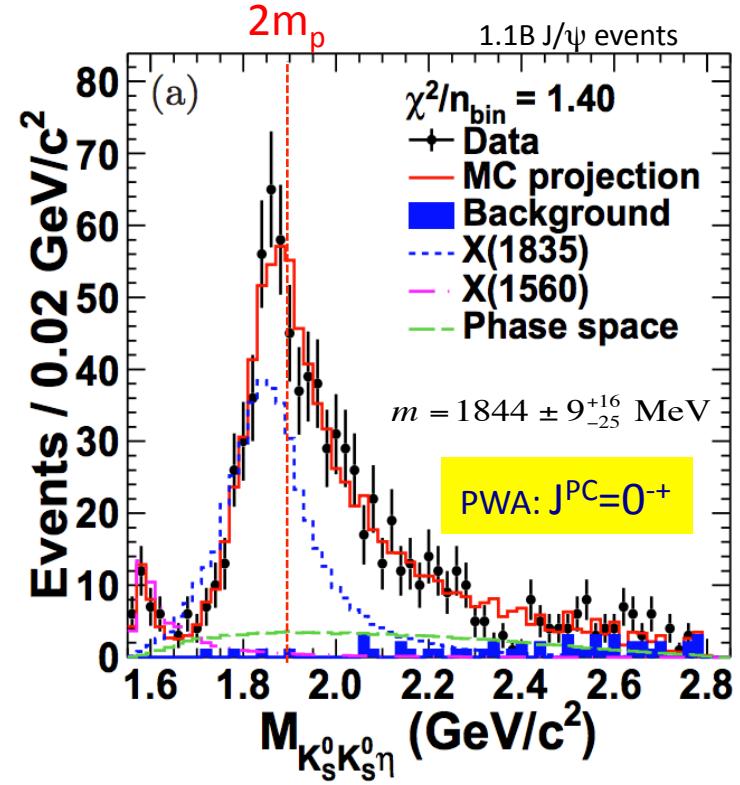
# $X(1835)$ in other channels

$J/\psi \rightarrow \gamma 3(\pi^+ \pi^-)$



BESIII PRD 88, 091502 (2013)

$J/\psi \rightarrow \gamma K_S^0 K_S^0 \eta$

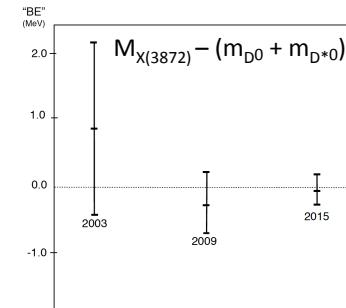


BESIII arXiv:1506.04807 [hep-ex]

# Comments

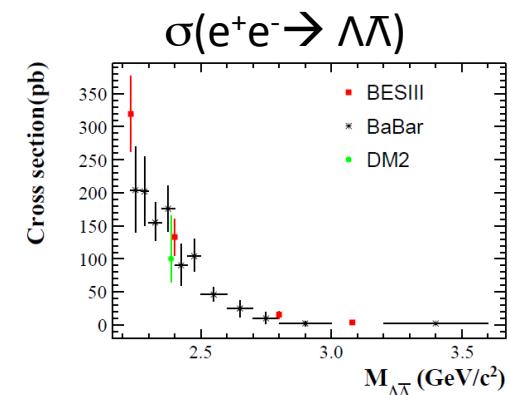
## ◆ The X(3872) mass is right at the $D^0\bar{D}^{*0}$ threshold

- ◆ the better it is measured, the closer it is
- ◆ coincidence or physics?
- ◆ motivates studies of other S-wave thresholds



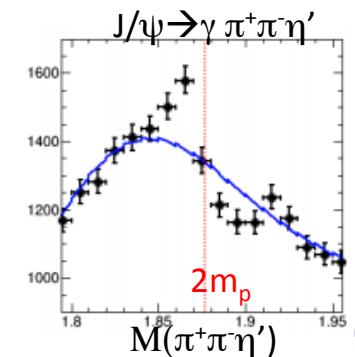
## ◆ Peculiarities in $1^{--} p\bar{p}$ & $\Lambda\bar{\Lambda}$ at threshold

- ◆ need for better data, closer to thresholds
- ◆ and other channels
- ◆ and theory (especially for Coulomb corrections)



## ◆ Strong case for a $0^+$ $p\bar{p}$ bound state in $J/\psi \rightarrow \gamma p\bar{p}$ & $\pi^+\pi^-\eta'$

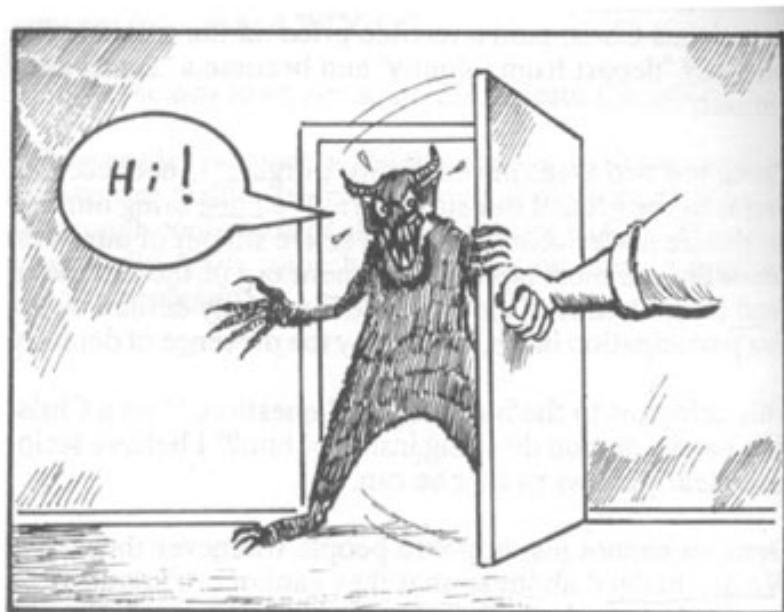
- ◆ need simultaneous multi-channel analysis



# Thresholds may be interesting



...or maybe not!



Thank you

どうも ありがとう

감사합니다

謝謝

# Backup Slides

$\Upsilon(1S,2S) \rightarrow \Lambda\bar{\Lambda} + X$

