Issues in Hadron Spectroscopy

-- puzzling near-threshold anomalies --

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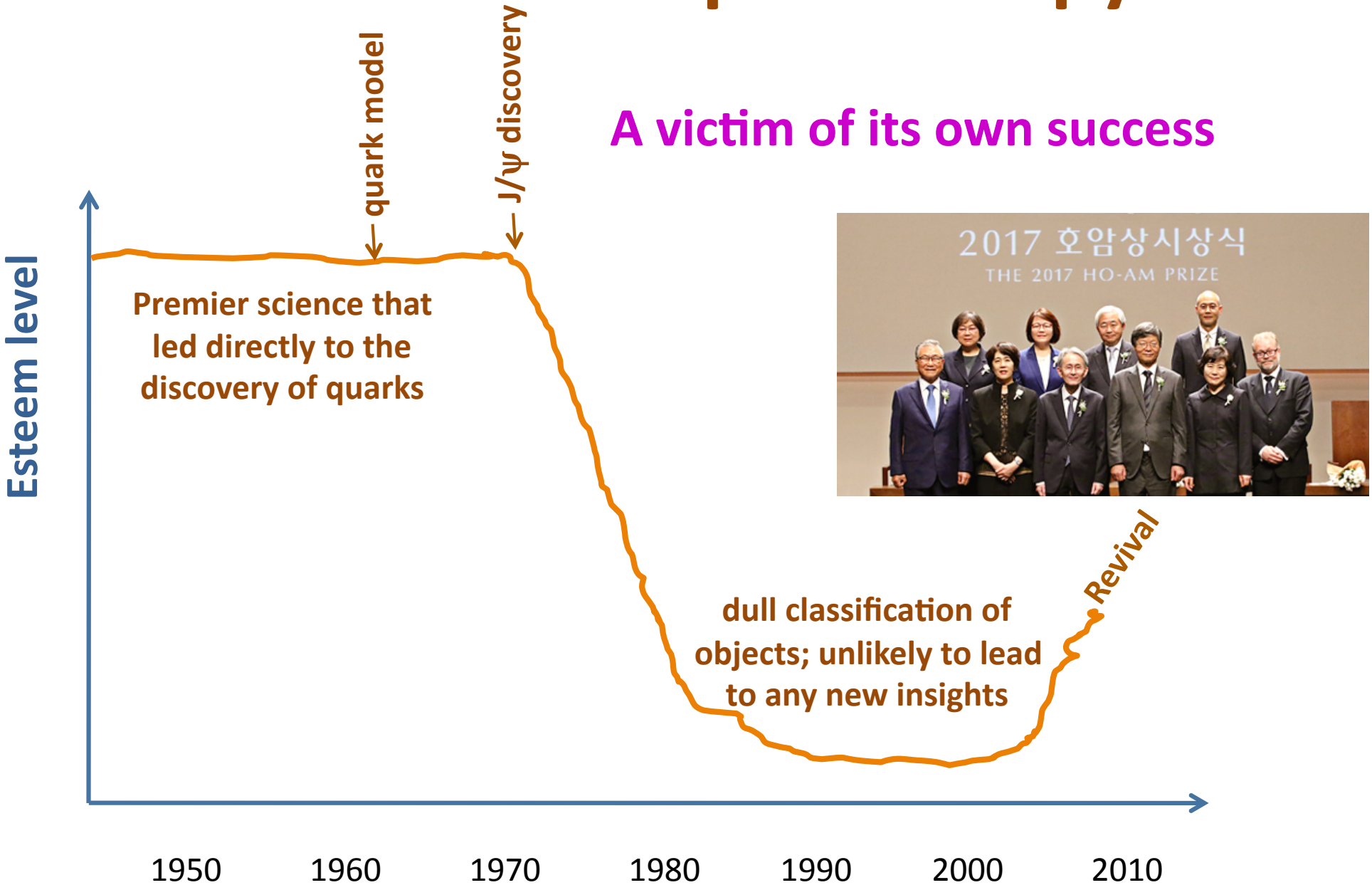
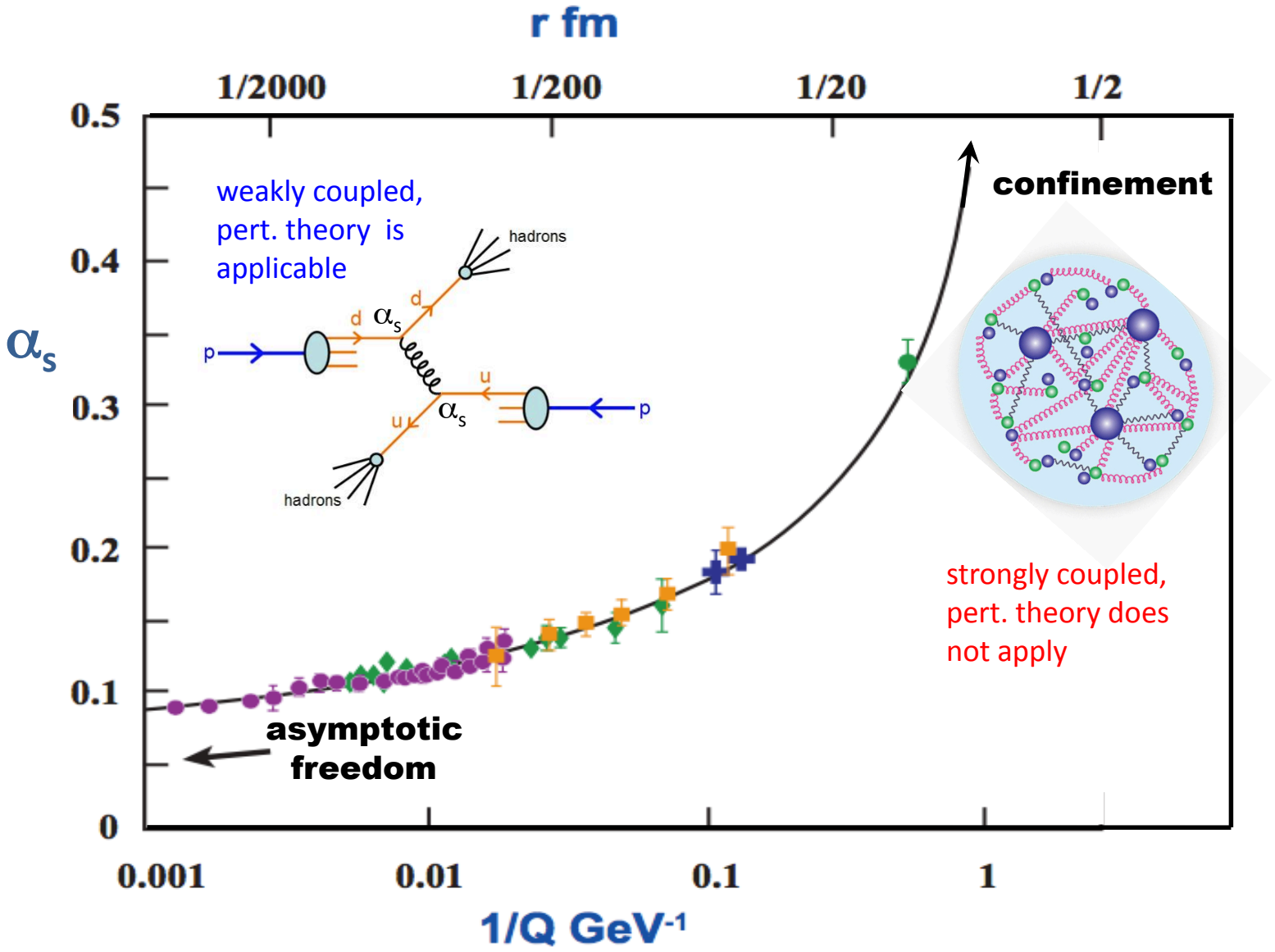
Joint Symposium on Nuclear, Particle & Field, and Astrophysics (SYNPA2017)
Chonnam University, Gwangju, KOREA, Nov. 17-18, 2016

Status of hadron spectroscopy:



QCD dilemma

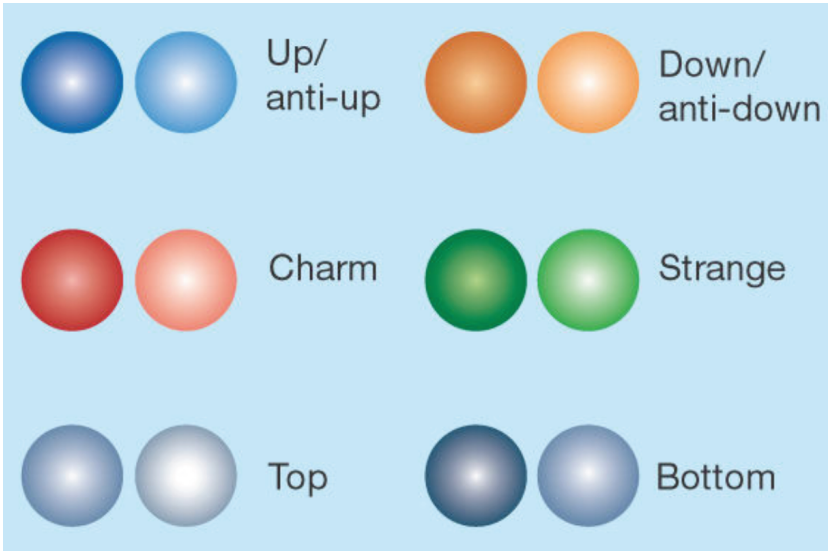

r fm
1/2000
1/200
1/20
1/2
0.5
0.4
0.3
0.2
0.1
0
α_s
weakly coupled, pert. theory is applicable
hadrons
d
α_s
p
u
hadrons
confinement
strongly coupled, pert. theory does not apply
asymptotic freedom
0.001
0.01
0.1
1
1/Q GeV^{-1}

“psychological” problem

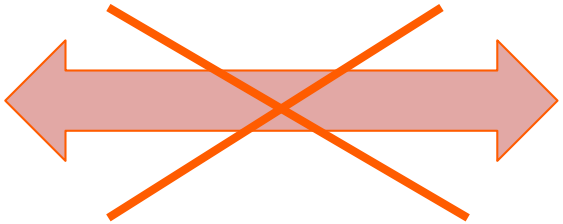
-- theory is divorced from reality --

strongly interacting particles
of the Standard Model

quarks

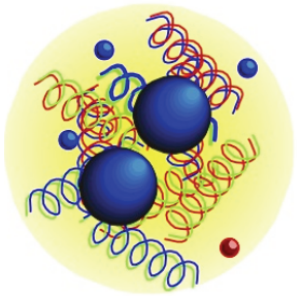


gluons

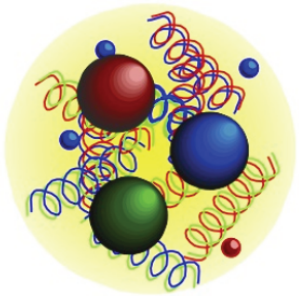


no useful 1st-principle
relation connects these

strongly interacting particles
in Nature



mesons



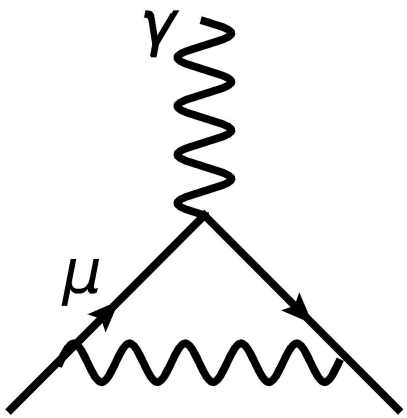
baryons

"practical" problem

– long-distance QCD effects limits on new physics searches –

$(g-2)_\mu /2$: experimental precision $\delta_{exp} = \pm 6.3 \times 10^{-10}$

a)

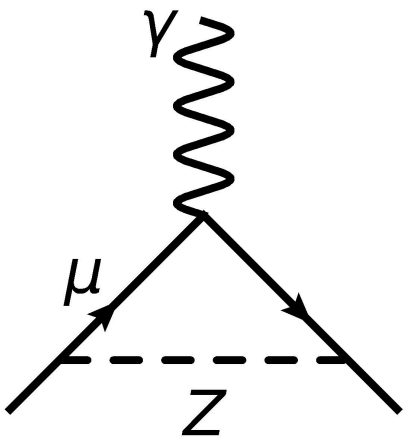


QED: 11658472×10^{-10}
(1.2×10^{-3})

$\delta_{QED} = \pm 0.02 \times 10^{-10}$

12,672 diagrams!

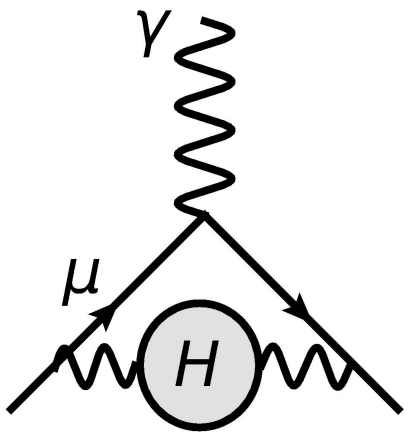
b)



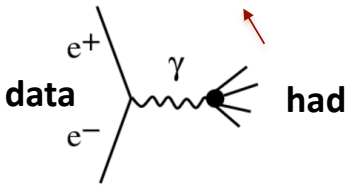
EW: 15.4×10^{-10}

$\delta_{EW} = \pm 0.2 \times 10^{-10}$

c)



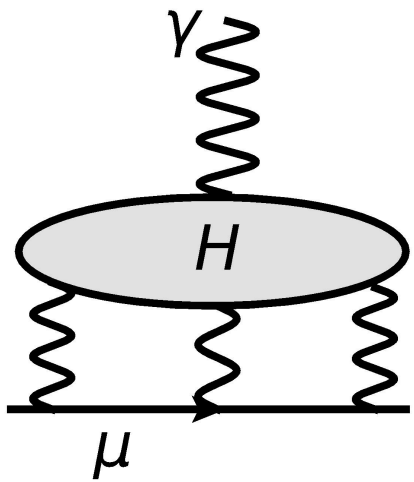
LO+NLO had: 682×10^{-10}



+ dispersion relns

$\delta_{NLO} = \pm 4.6 \times 10^{-10}$

d)



ℓ-by-ℓ 14×10^{-10}

$\delta_{\ell\text{-by-}\ell} \approx \pm 3 \times 10^{-10}$

"practical" problem

– long-distance QCD effects limits on new physics searches –

$(g-2)_\mu/2$: experimental precision $\delta_{exp} = \pm 6.3 \times 10^{-10}$

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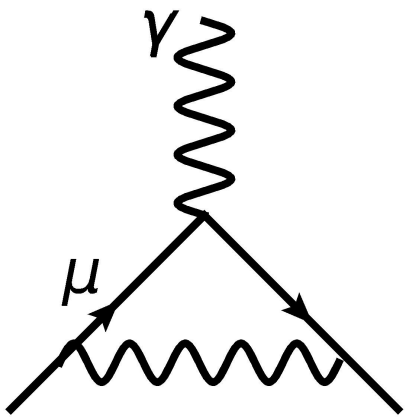

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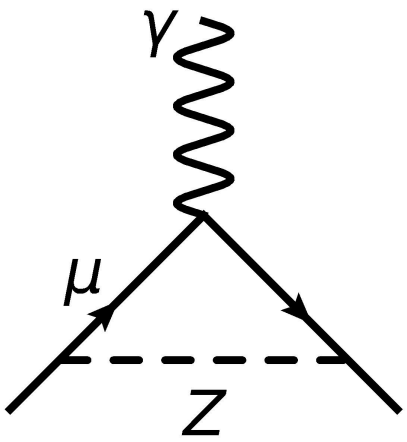

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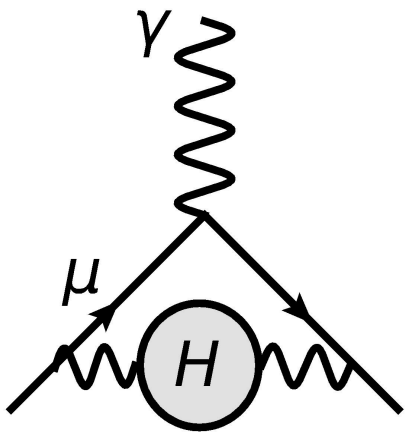

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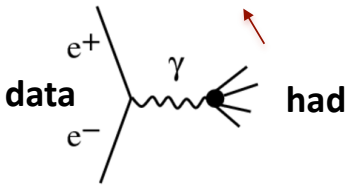

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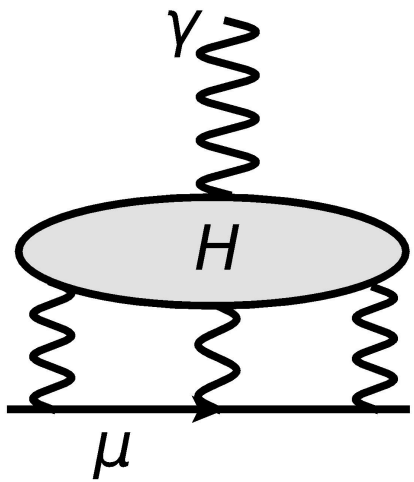


ℓ-by-ℓ 14×10^{-10}

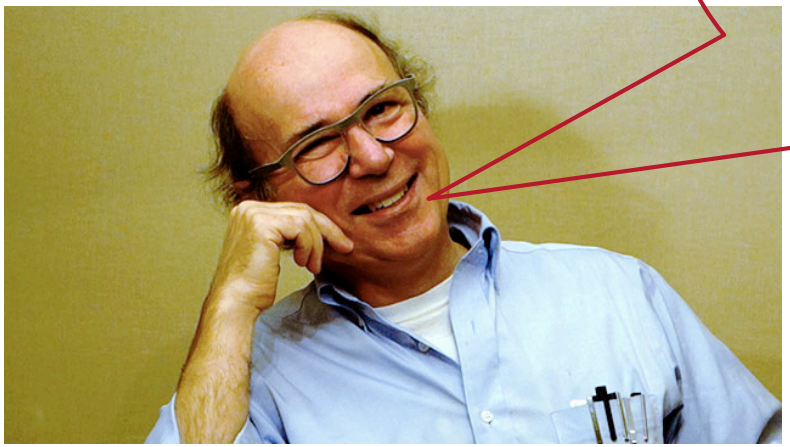
$\delta_{\ell\text{-by-}\ell} \approx \pm 3 \times 10^{-10}$

this will ultimately be the dominant SM error and larger than δ_{exp}

A better understanding of long-distance QCD is essential

We have something called a standard model, but its foundations are kind of ***scandalous***. We have not known how to define an important part of it mathematically rigorously, …

Frank Wilczek



http://www.edge.org/conversation/frank wilczek-power-over-nature

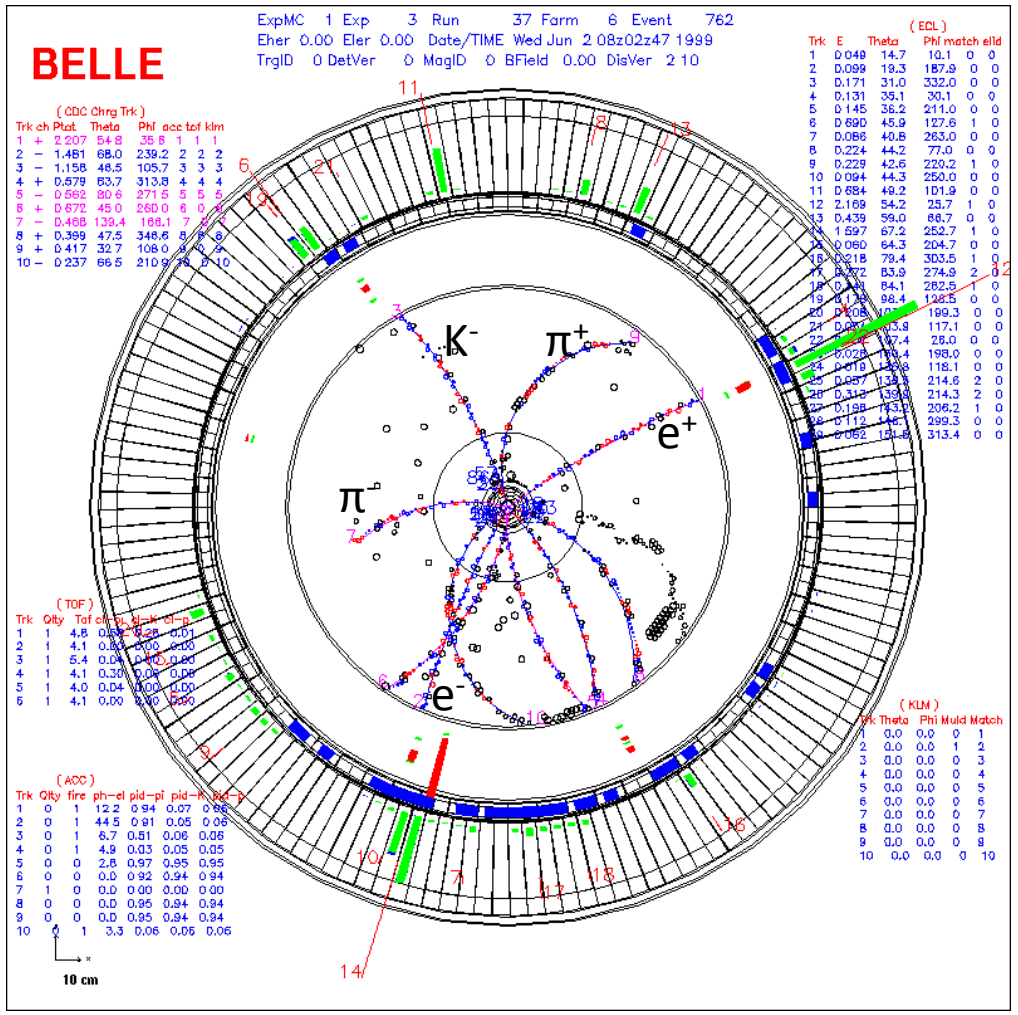
Possible strategies for dealing with the "scandalous" situation

Theorists: abandon old ideas, try to dream up new ones

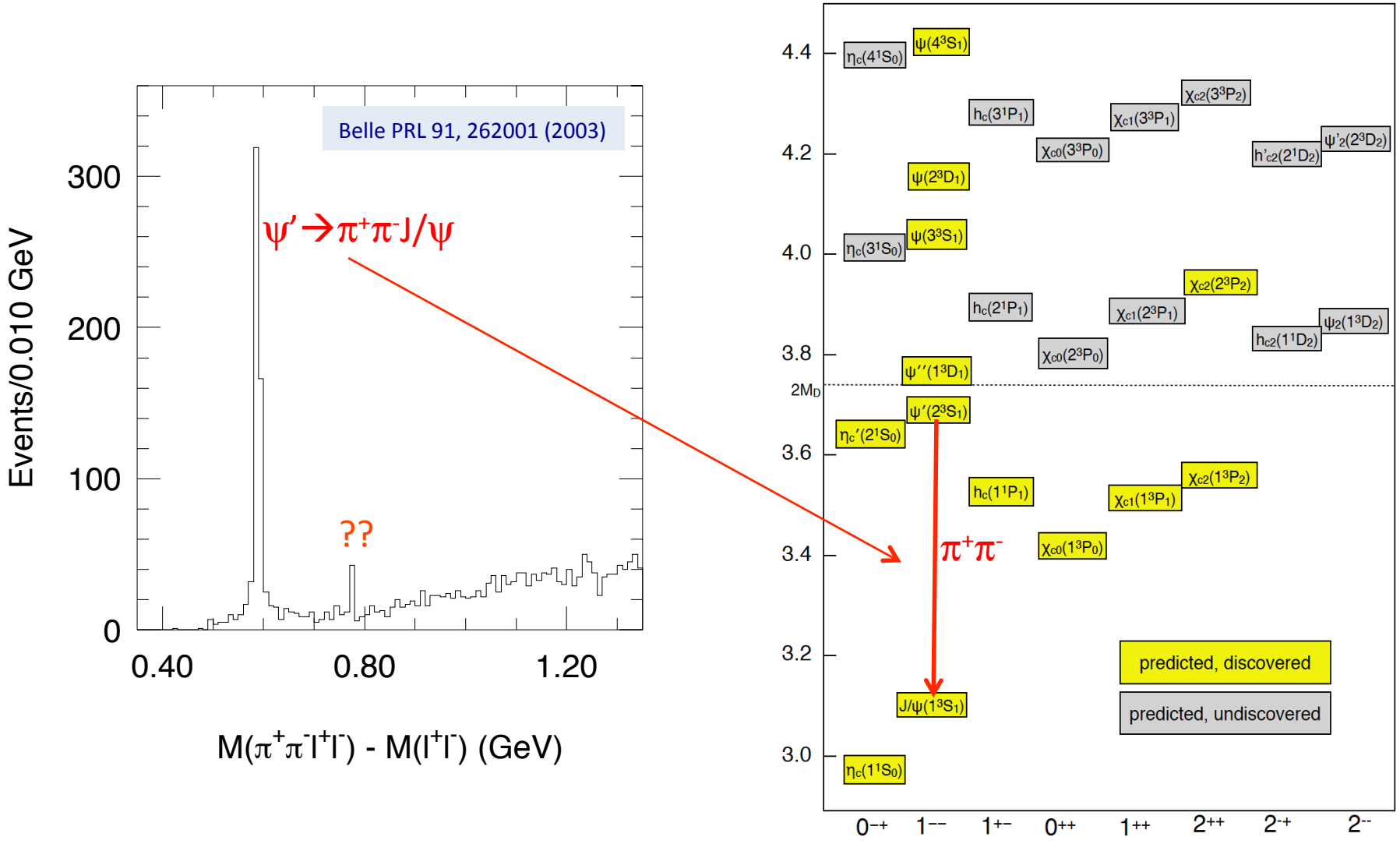
Experimenters: try to identify previously unrecognized patterns in the data

$B^- \to K^- \pi^+ \pi^- J/\psi$ event in Belle

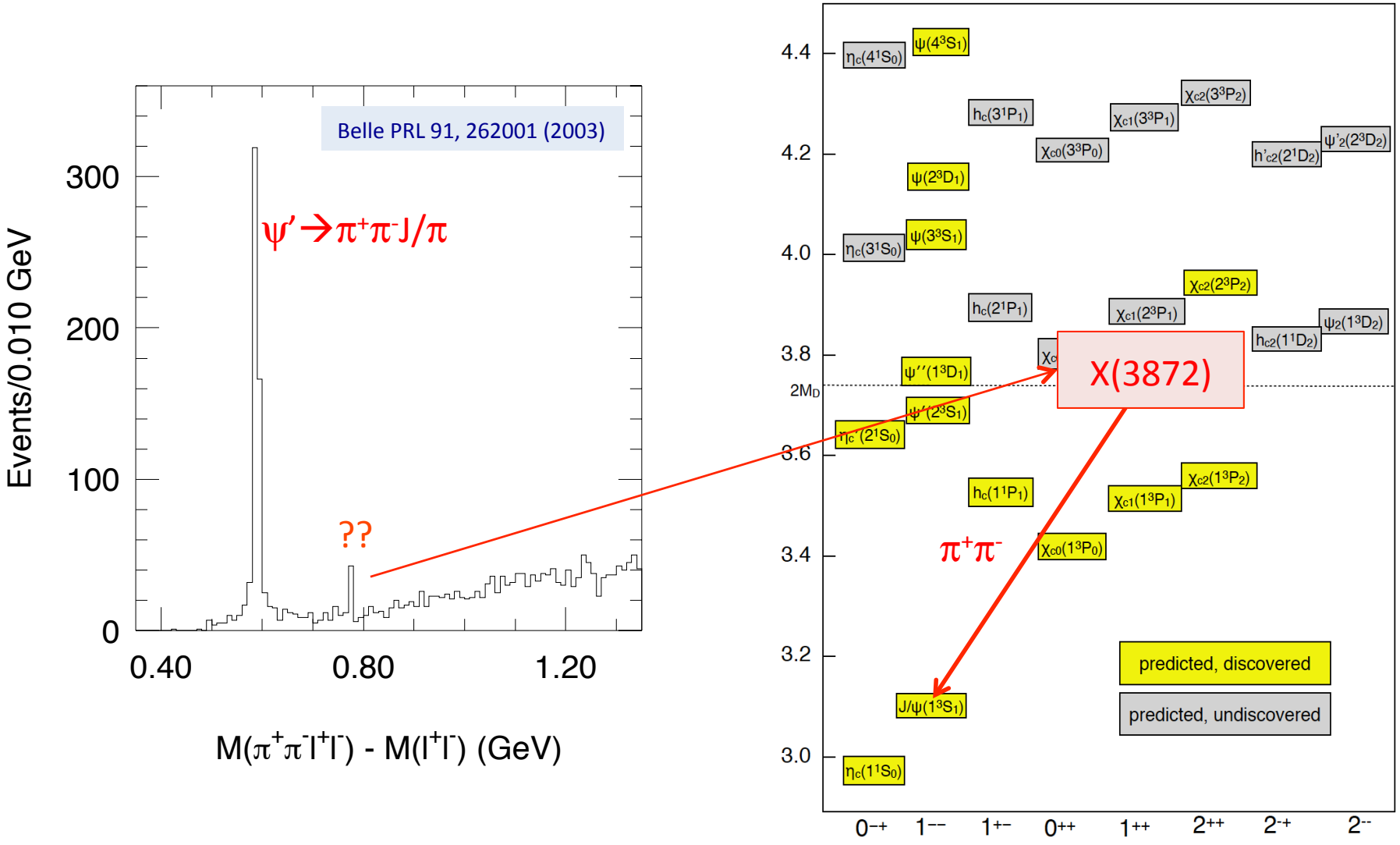
↳ $e^+ e^-$



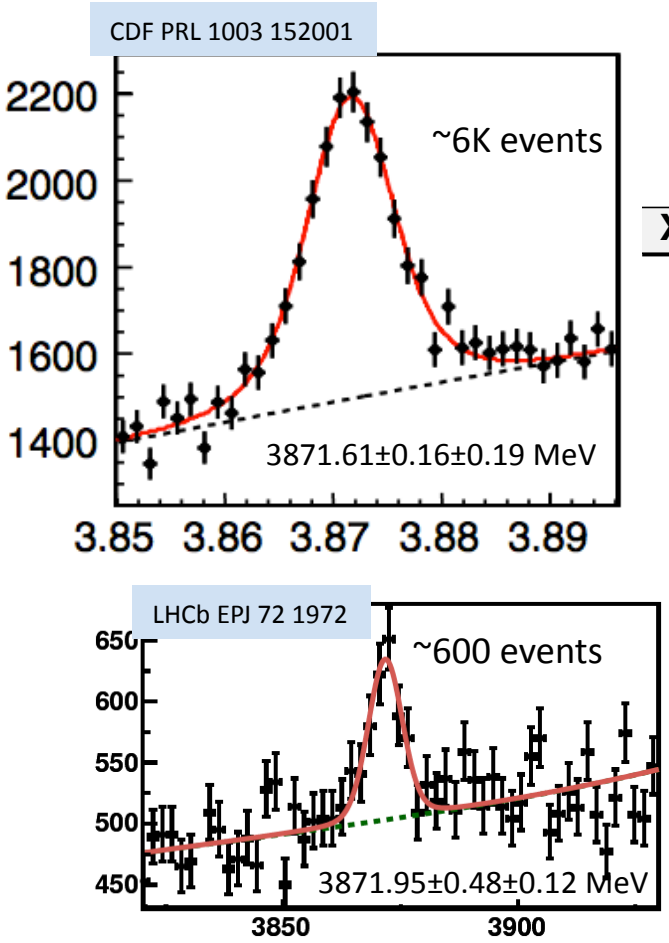
$M(\pi^+\pi^- J/\psi)$


Belle PRL 91, 262001 (2003)
ψ′→π⁺π⁻J/ψ
??
Events/0.010 GeV
300
200
100
0
0.40
0.80
1.20
M(π⁺π⁻l⁺l⁻) - M(l⁺l⁻) (GeV)
4.4
4.2
4.0
3.8
2M_D
3.6
3.4
3.2
3.0
ηc(4¹S0)
ψ(4³S1)
hc(3¹P1)
χc2(3³P2)
χc1(3³P1)
χc0(3³P0)
h′c2(2¹D2)
ψ′2(2³D2)
ψ(2³D1)
ηc(3¹S0)
ψ(3³S1)
χc2(2³P2)
hc(2¹P1)
χc1(2³P1)
ψ2(1³D2)
hc2(1¹D2)
χc0(2³P0)
ψ′′(1³D1)
ψ′(2³S1)
ηc′(2¹S0)
hc(1¹P1)
χc2(1³P2)
χc1(1³P1)
π⁺π⁻
χc0(1³P0)
J/ψ(1³S1)
ηc(1¹S0)
predicted, discovered
predicted, undiscovered
0⁻⁺
1⁻⁻
1⁺⁻
0⁺⁺
1⁺⁺
2⁺⁺
2⁻⁺
2⁻⁻

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

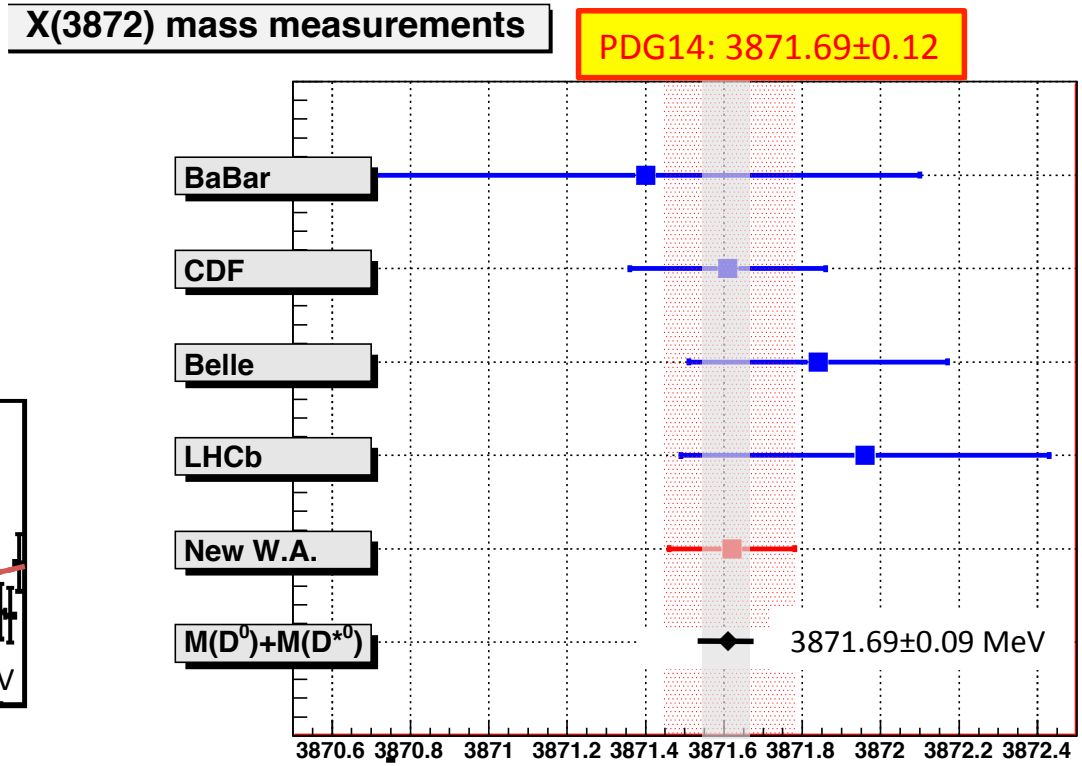

Belle PRL 91, 262001 (2003)
ψ′→π⁺π⁻J/π
??
Events/0.010 GeV
300
200
100
0
0.40
0.80
1.20
M(π⁺π⁻l⁺l⁻) - M(l⁺l⁻) (GeV)
X(3872)
π⁺π⁻
2M_D
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
ηc(4¹S0)
ψ(4³S1)
hc(3¹P1)
χc2(3³P2)
χc1(3³P1)
χc0(3³P0)
h′c2(2¹D2)
ψ′2(2³D2)
ψ(2³D1)
ηc(3¹S0)
ψ(3³S1)
χc2(2³P2)
hc(2¹P1)
χc1(2³P1)
ψ2(1³D2)
hc2(1¹D2)
ψ′′(1³D1)
ψ′(2³S1)
ηc′(2¹S0)
hc(1¹P1)
χc2(1³P2)
χc1(1³P1)
χc0(1³P0)
J/ψ(1³S1)
ηc(1¹S0)
predicted, discovered
predicted, undiscovered
0⁻⁺
1⁻⁻
1⁺⁻
0⁺⁺
1⁺⁺
2⁺⁺
2⁻⁺
2⁻⁻

X(3872) Mass

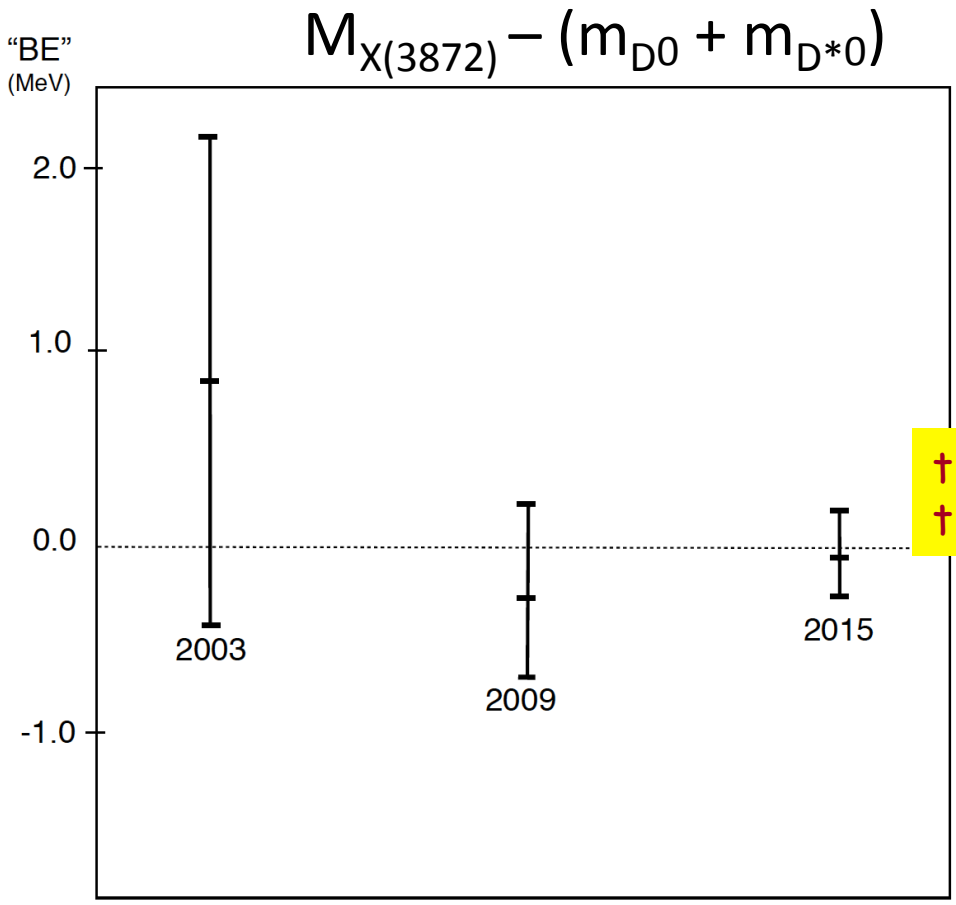


$M_{X(3872)}$ is indistinguishable from $m_{D^0} + m_{D^{*0}}$

"B.E."=3 ± 193 keV



X(3872) “Binding Energy”



the better it is measured,
the closer it is to zero

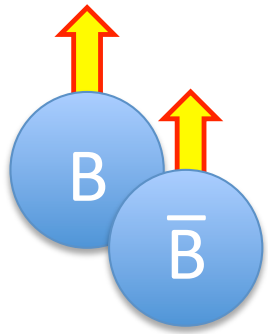
Is this a “coincidence?...
or is the data telling us something?

Thresholds may be interesting

Look at light baryon thresholds

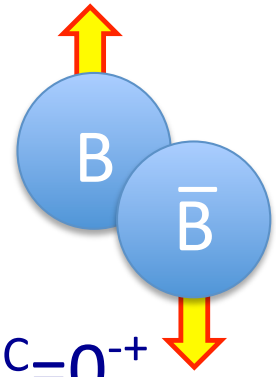
baryon-antibaryon:

2 S-wave threshold states:



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

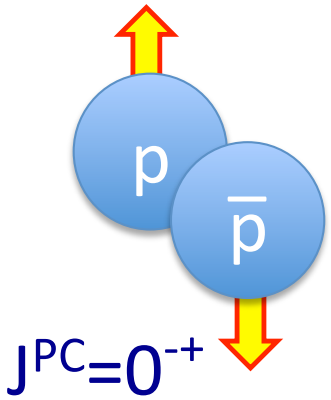
$e^+e^- \rightarrow B\bar{B}$



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

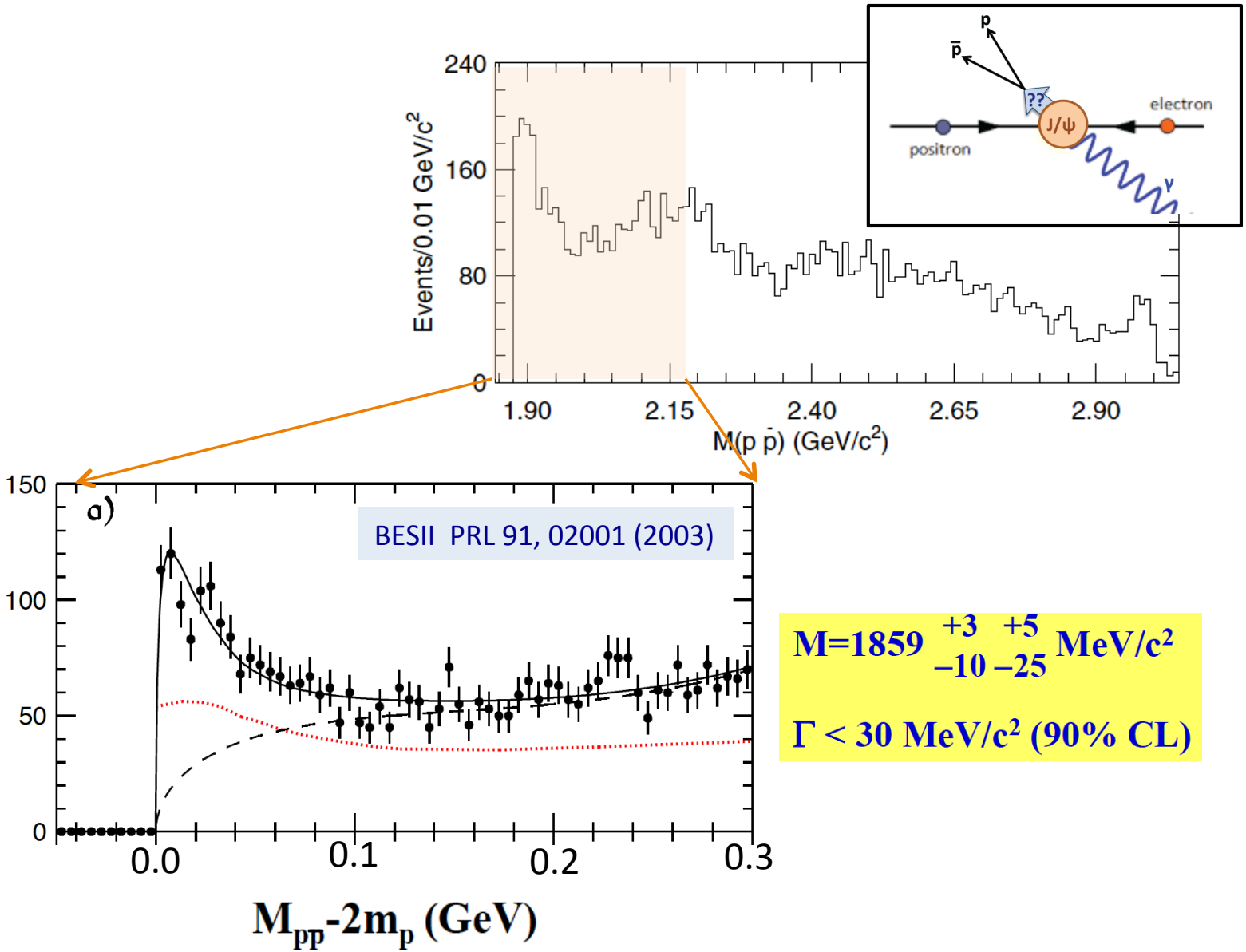
$J/\psi\ (\psi') \rightarrow \gamma B\bar{B}$

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



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

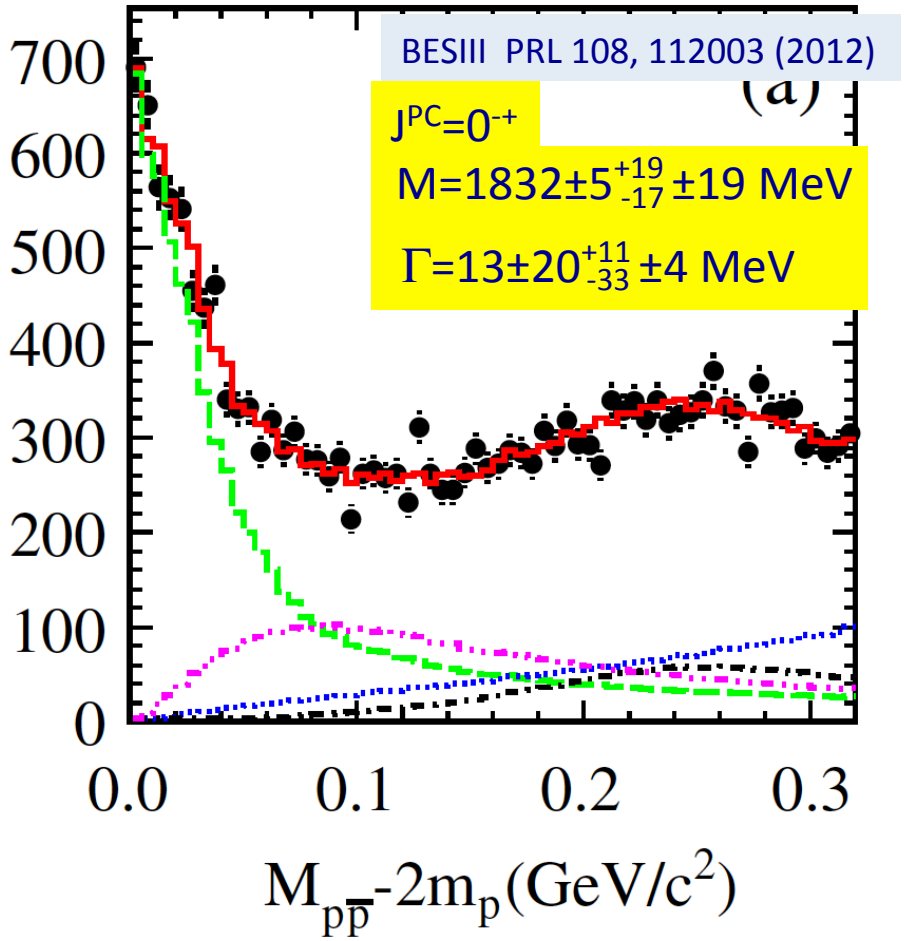
$J/\psi \rightarrow \gamma p\bar{p}$ at BESII



$M = 1859\ ^{+3}_{-10}\ ^{+5}_{-25}\ MeV/c^2$

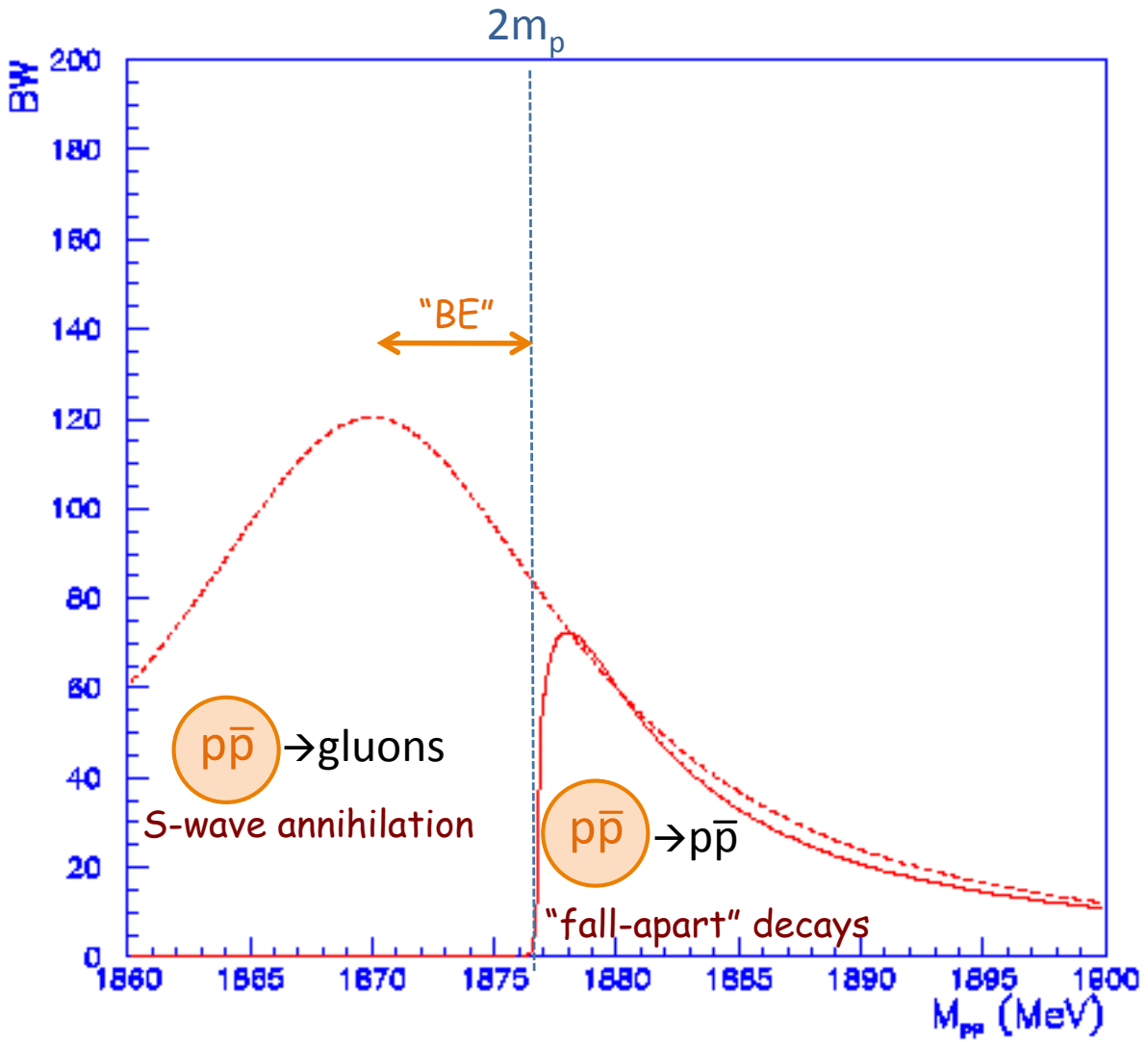
$\Gamma < 30\ MeV/c^2$ (90% CL)

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



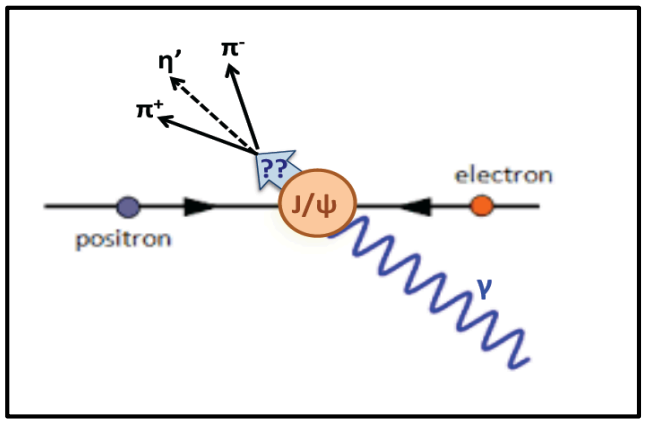
FSI included: A. Sibirtsev et al, PRD71, 054010 (2005)

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



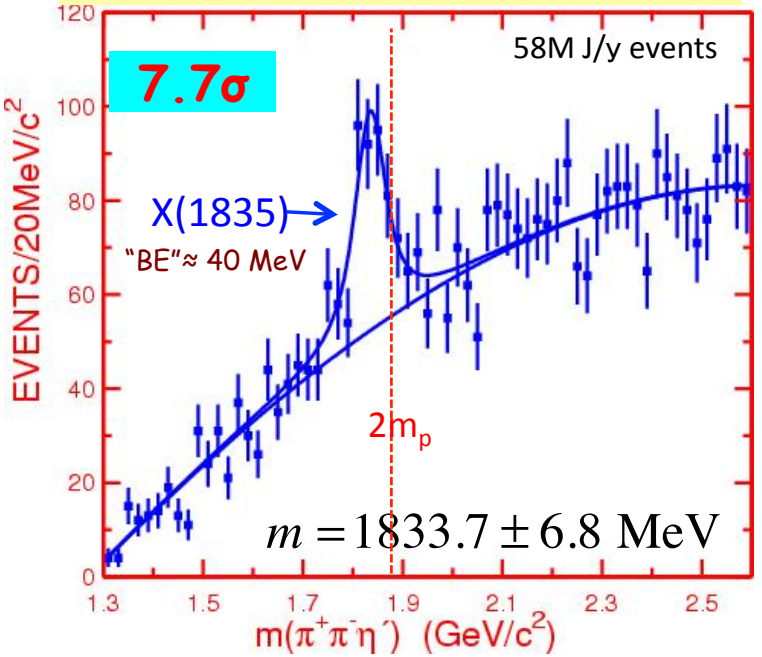
G.J. Ding & M.L. Yan Phys. Rev. C 72, 015208

X(1835)→$\pi^+\pi^-\eta'$ with 58M J/ψ decays (BESII)



BESII observation of X(1835) in

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

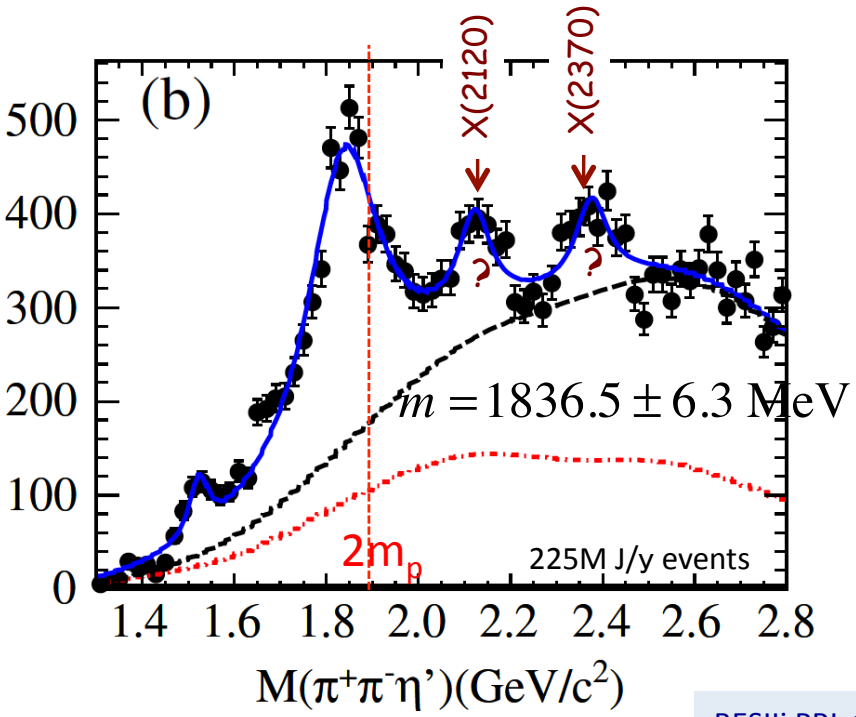


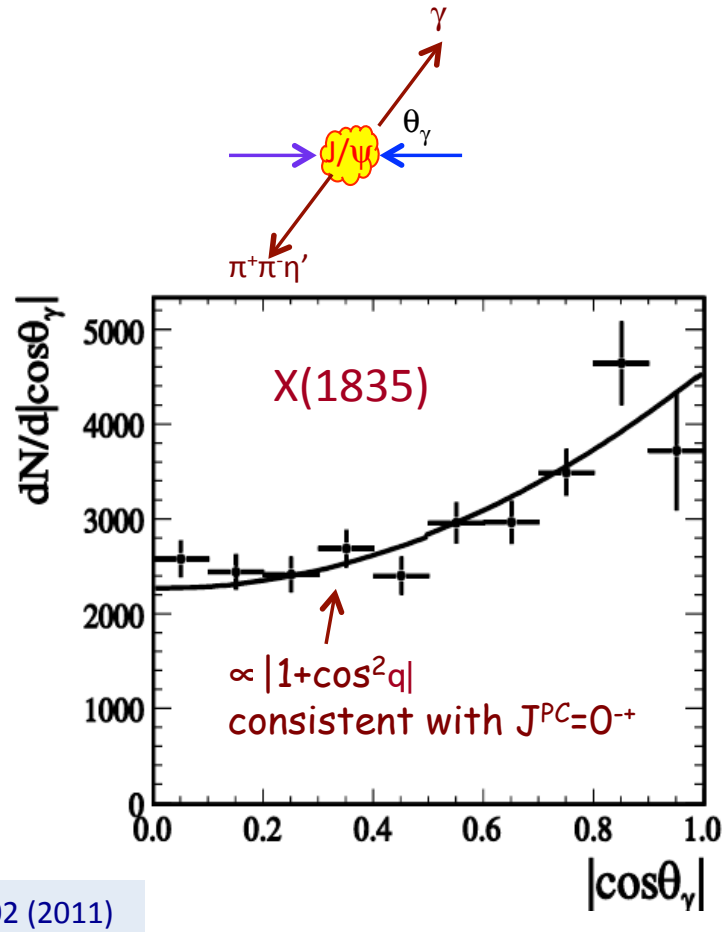
BESII PRL 95, 262001 (2005)

X(1835)→$\pi^+\pi^-\eta'$ with 225M J/ψ decays (BESIII)

BESIII observation of X(1835) in

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

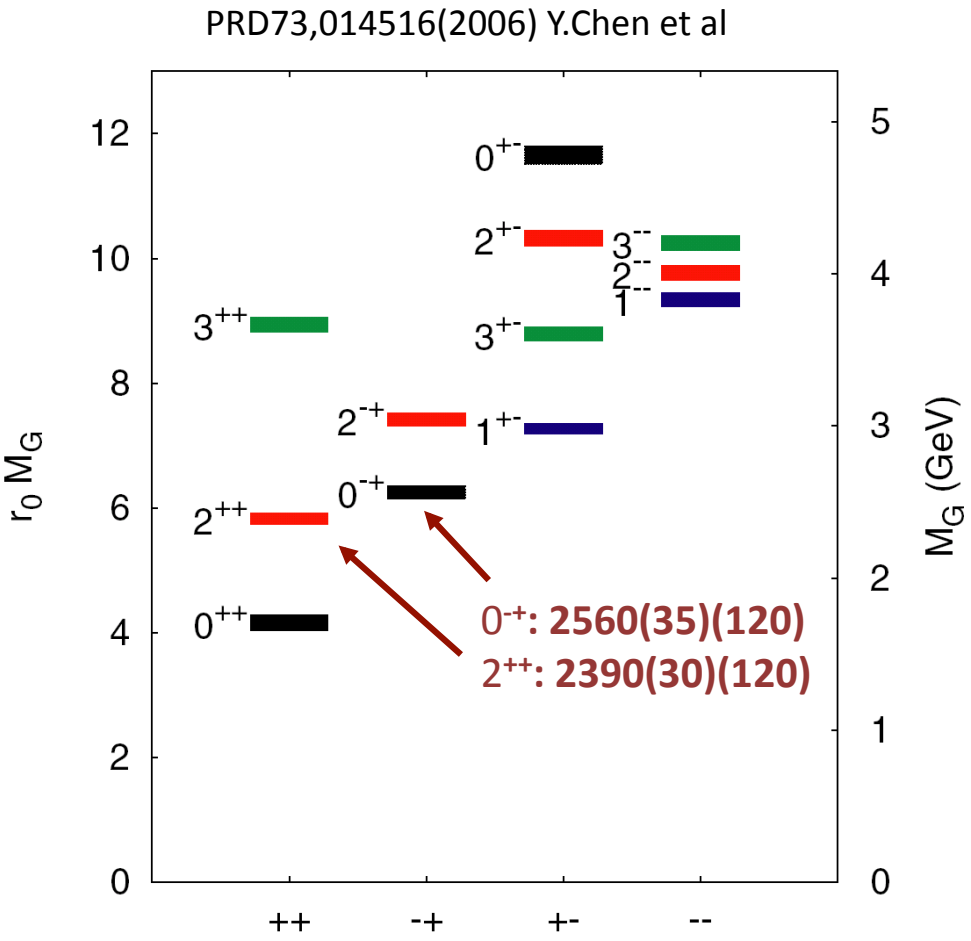




BESIIi PRL 106, 072002 (2011)

What are the new structures?

way above threshold, but narrow (Γ≈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:

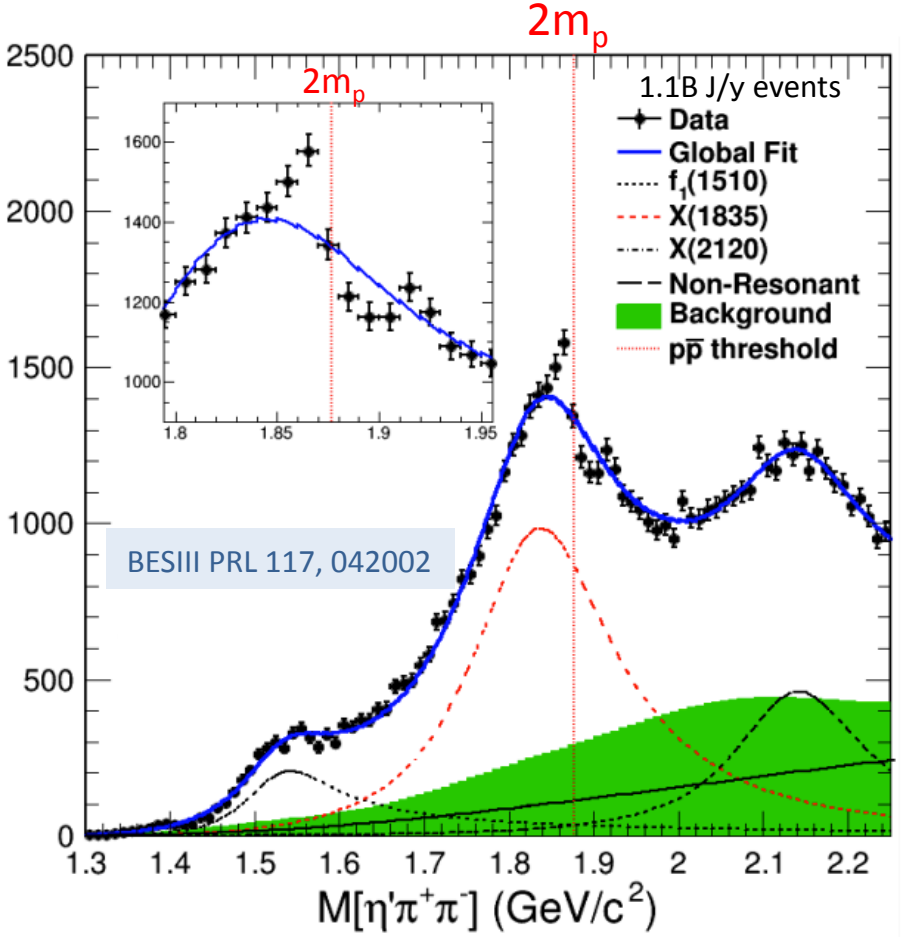
-pseudoscalar glueball ?

-η/η' 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)→$\pi^+\pi^-\eta'$ with 1.1B J/ψ events (BESIII)

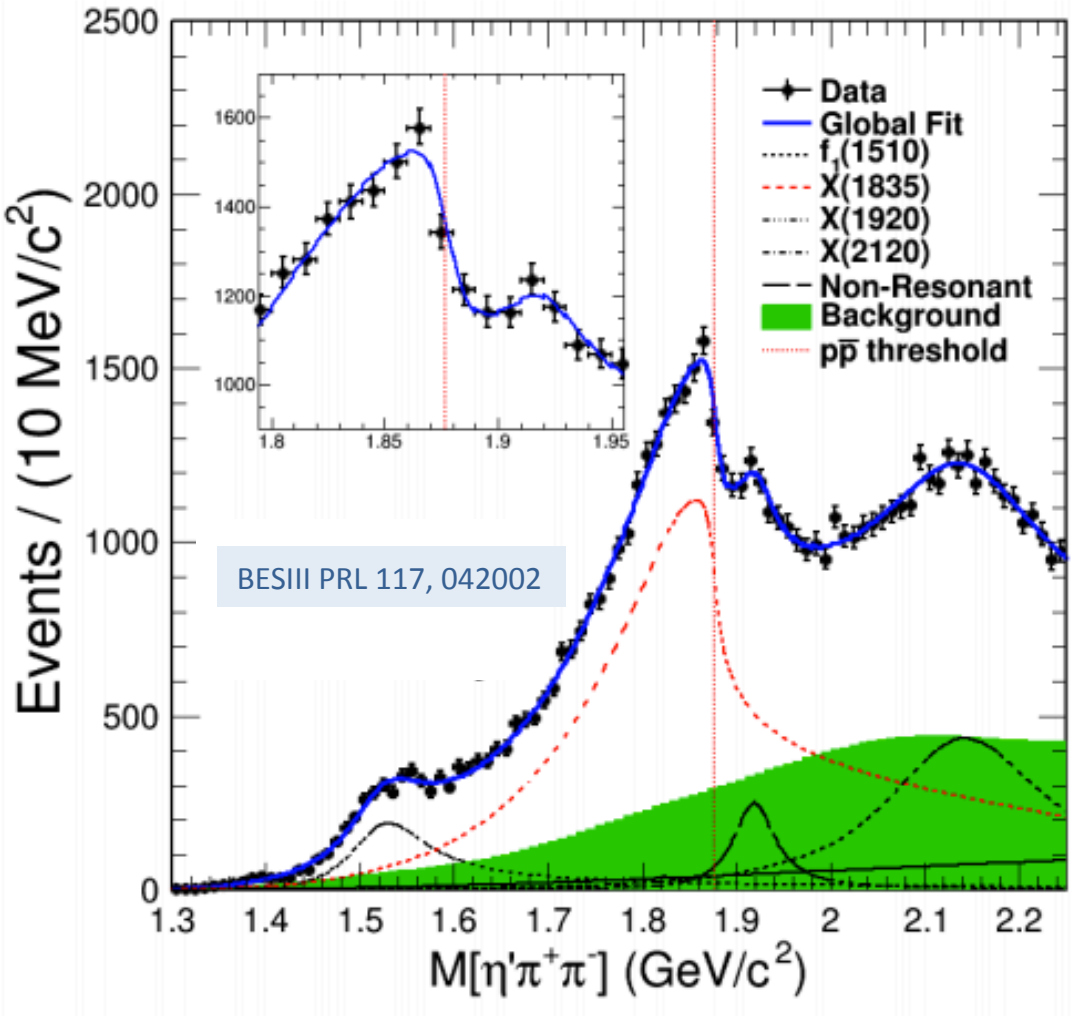
$$J/\psi \to \gamma \pi^+ \pi^- \eta'$$



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. Flatte PLB 63, 224 (1976)



Fit results:

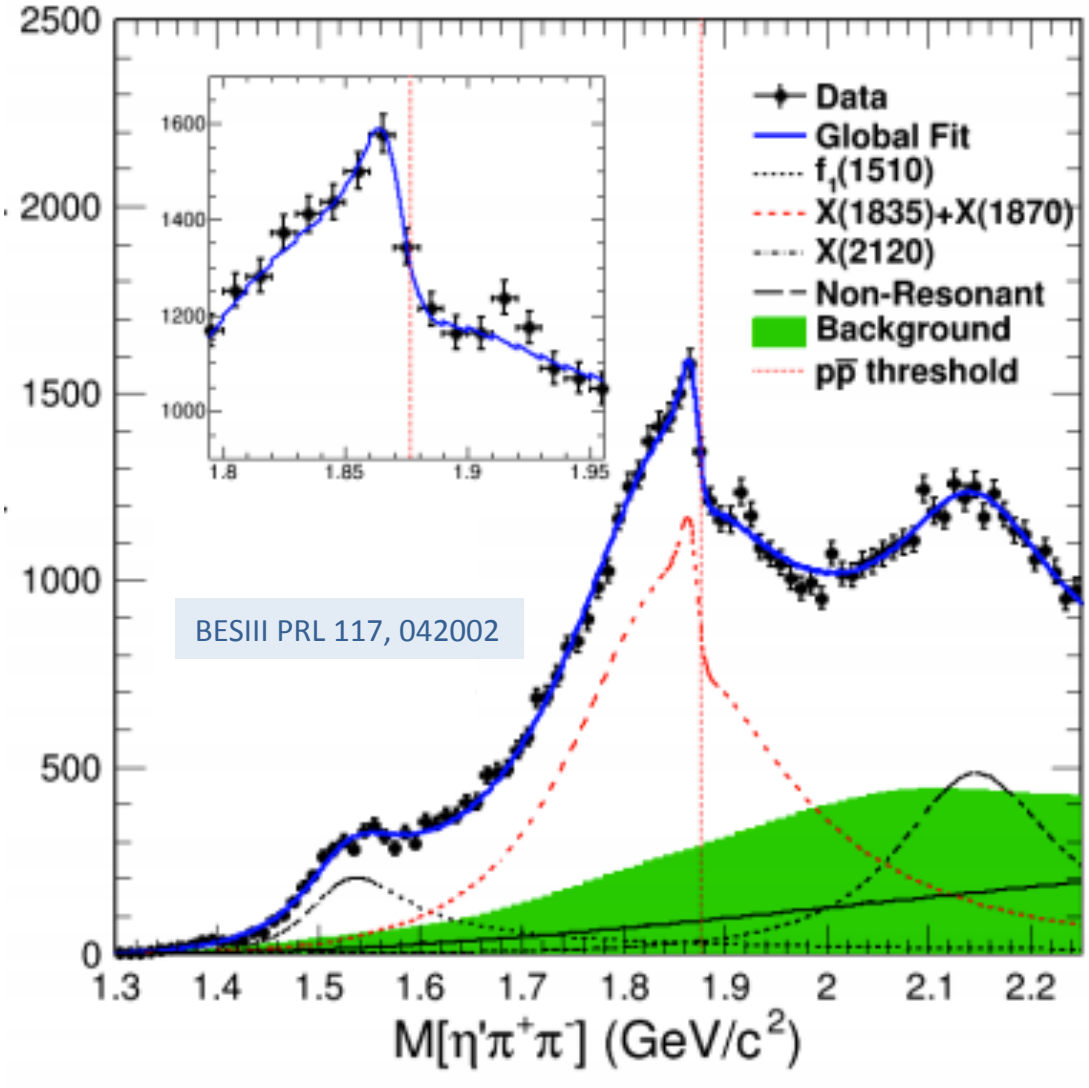
$$\frac{g_{p\bar{p}}^2}{g_0^2} = 2.31 \pm 0.37$$

X coupling to $p\bar{p}$

X coupling to everything else

Two-resonance fit

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

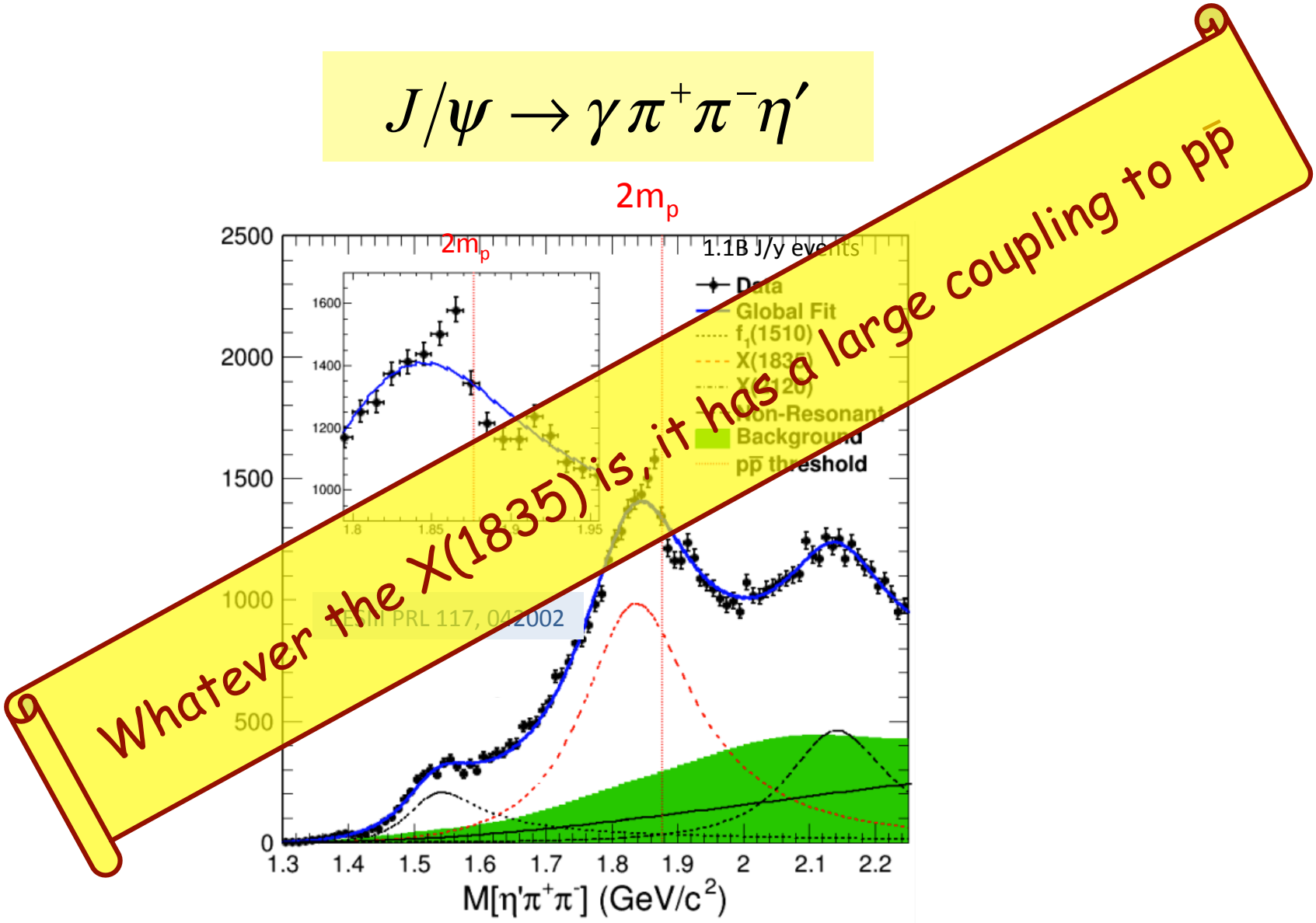


1st resonance (X(1835)):
M_1= 1825.3 ±2.4$^{+17.3}_{-2.4}$ MeV
Γ_1 = 245 ±16 MeV

2nd resonance (X(1870)):
M_2= 2m_p - 6.3±3.2 MeV
Γ_2 = 13.0 ±6.7 MeV

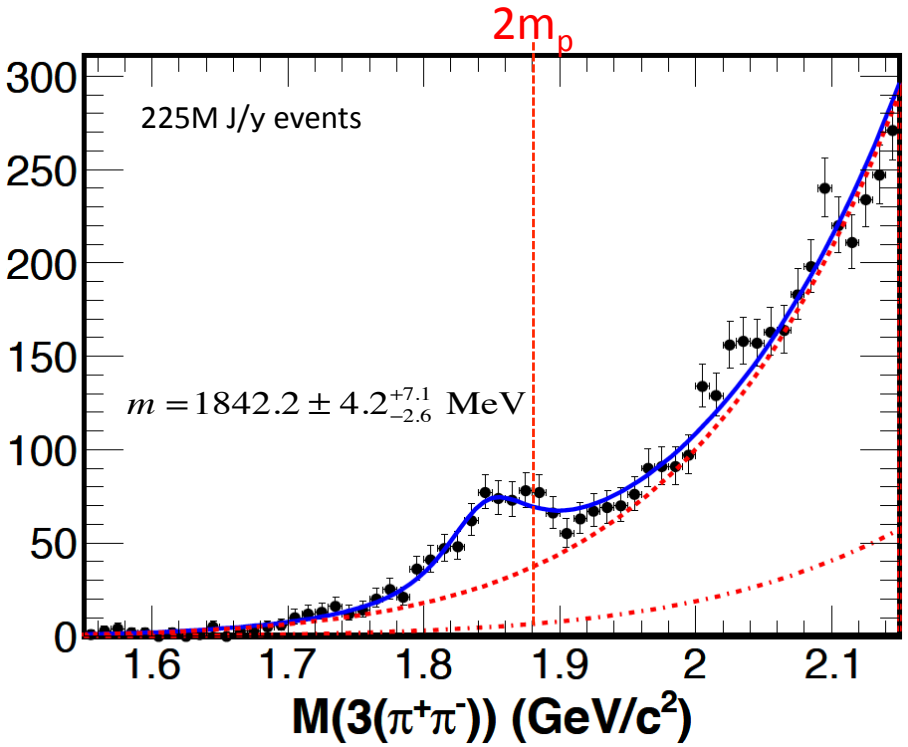
X(1835)→$\pi^+\pi^-\eta'$ with 1.1B J/ψ events

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



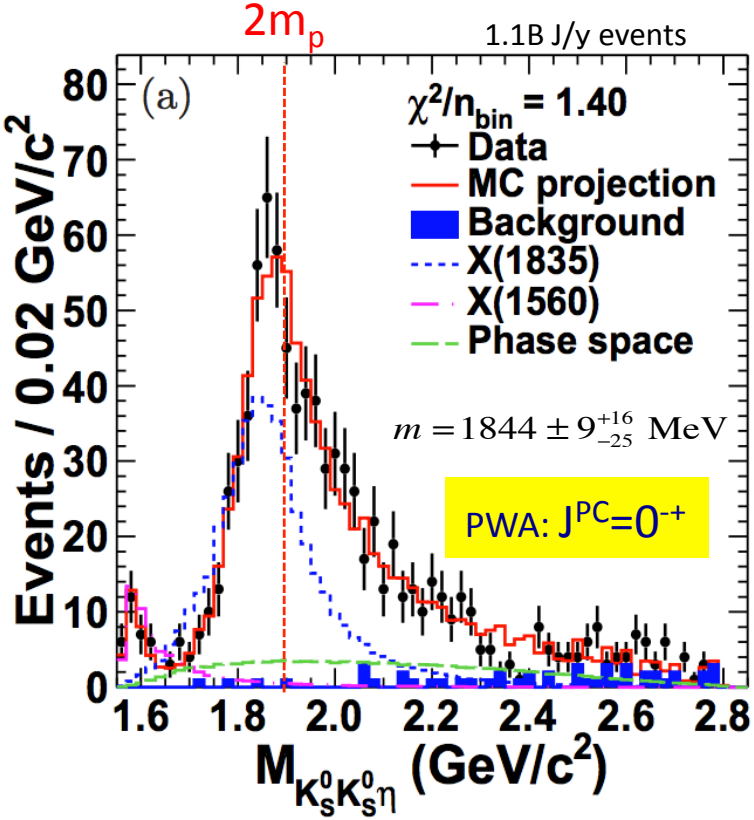
X(1835) in other channels (BESIII)

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



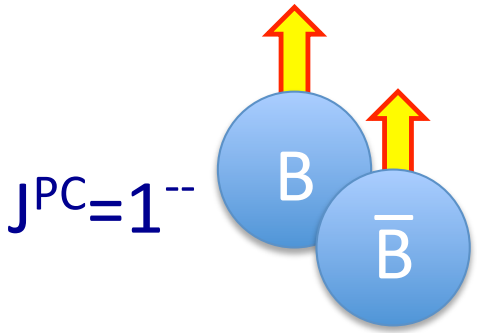
BESIII PRD 88, 091502 (2013)

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

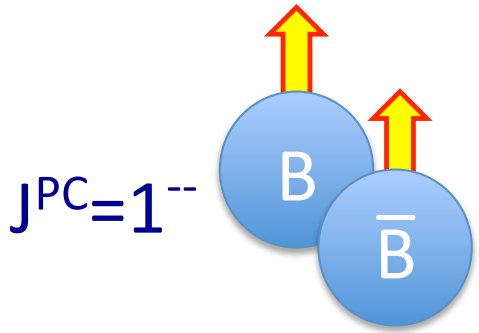


BESIII PRL 115, 091803 (2015)

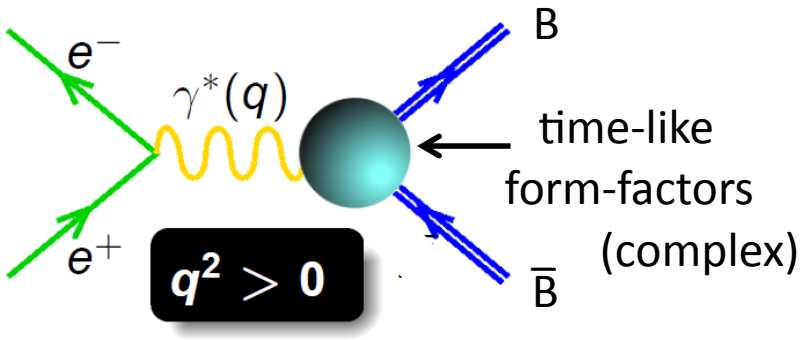
1^{--} baryon-antibaryon systems



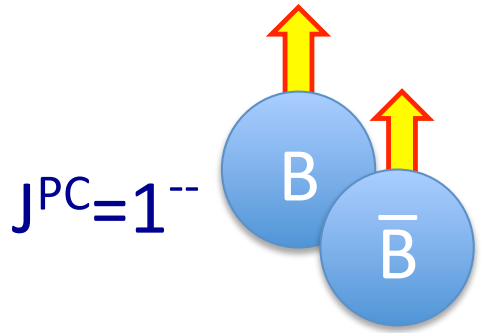
1^{--} baryon-antibaryon systems



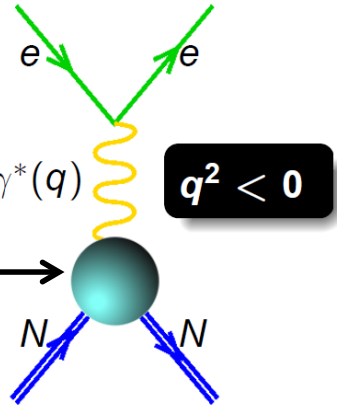
$e^+e^- \rightarrow B\overline{B}$



1^{--} baryon-antibaryon systems

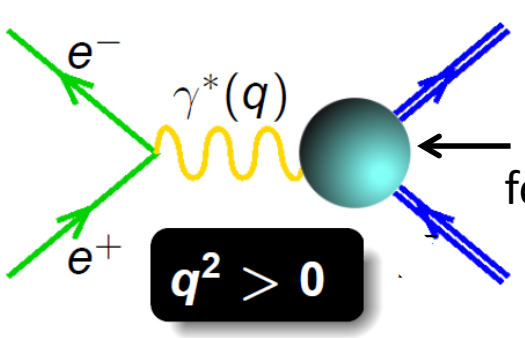


$e^{\pm}N \rightarrow e^{\pm}N$
elastic scattering

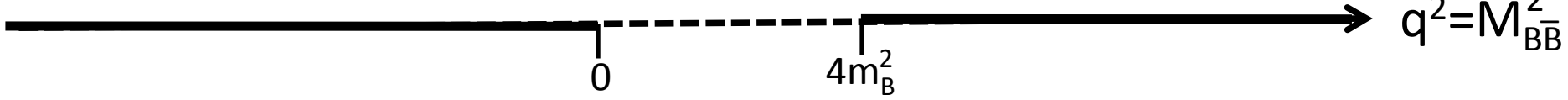


space-like
form factors
(real)

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

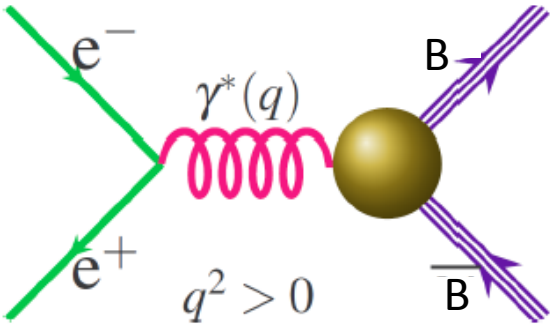


time-like
form-factors
(complex)



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

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



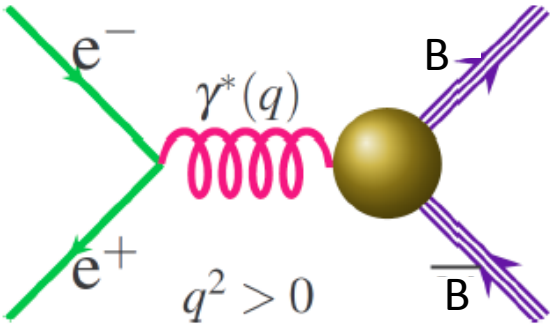
time-like form-factors

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

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

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

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



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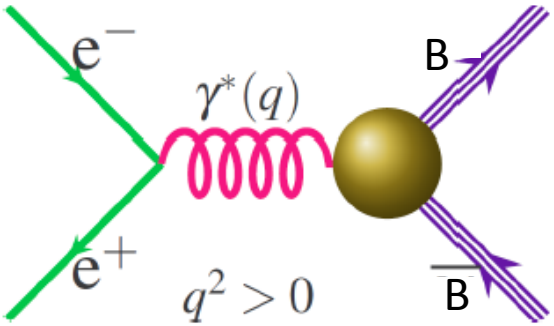
$$\tau = \frac{m_{B\bar{B}}^2}{4m_B^2} \qquad \beta = \sqrt{1-\frac{1}{\tau}}$$

C = Coulomb correction

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

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



time-like form-factors

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

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

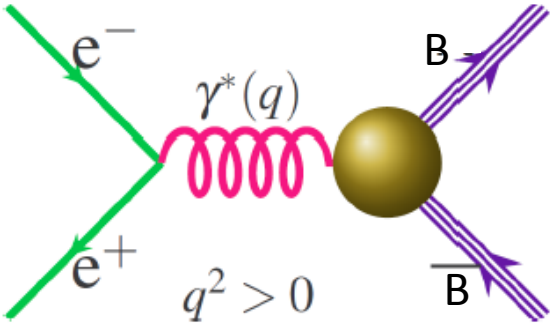
for $p\bar{p}$: $C = \dfrac{\pi\alpha/\beta}{1-\exp(-\pi\alpha/\beta)} \to \dfrac{\pi\alpha}{\beta}$

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

in point-like approx

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

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



time-like form-factors

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

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

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

in point-like approx

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

Integrated cross section:

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

"effective" form-factor

effective form factor

$$\left|G_{eff}\right| = \sqrt{\frac{2\tau\left|G_M\right|^2 + \left|G_E{}^2\right|}{2\tau+1}}$$

numerology

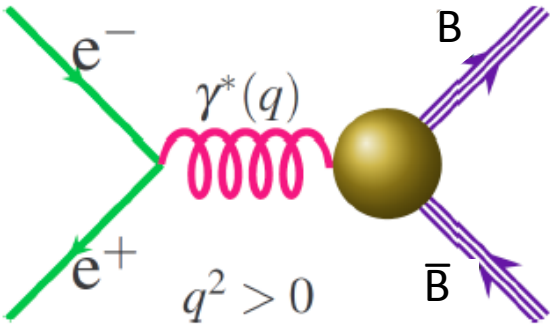
$$\sigma_{B\bar{B}}\left(m_{B\bar{B}}\right) = \frac{4\pi\alpha^2\beta C}{3m_{B\bar{B}}{}^2}\left|G_{eff}(m_{B\bar{B}})\right|^2\left(1+1/2\tau\right) = 98.6\text{ nb}\frac{\beta C}{m_{B\bar{B}}^2/m_p^2}\left|G_{eff}(m_{B\bar{B}})\right|^2\left(1+1/2\tau\right)$$

$$\frac{4\pi\alpha^2}{3m_p} = 98.6\,\text{nb};$$

at threshold: $\tau \to 1$, $m_{B\bar{B}} \to 2m_B$, $\left|G_{eff}\right| \to \left|G_M\right|$

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

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



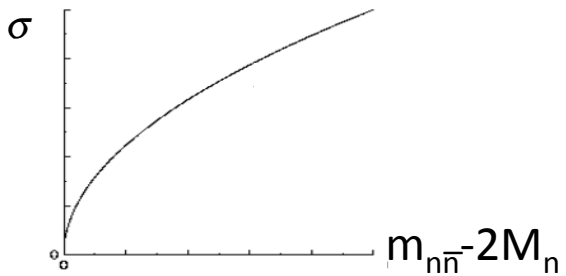
Integrated cross section

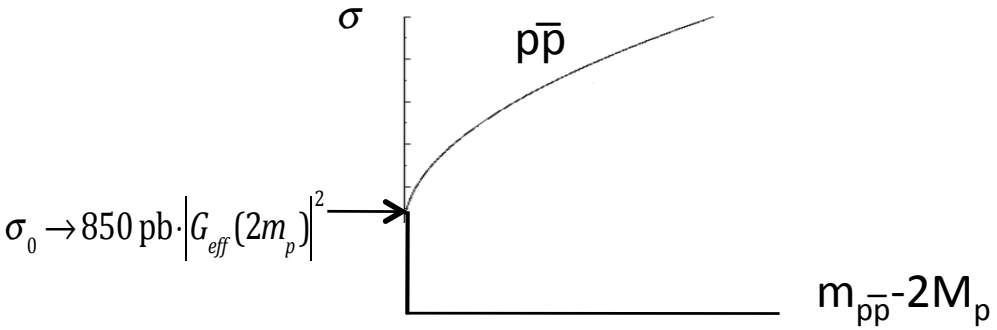
$$\sigma_{B\bar{B}}\left(m_{B\bar{B}}\right) = 98.6\ \text{nb}\frac{\beta C}{m^2_{B\bar{B}}/m^2_p}\left|G_{eff}(m_{B\bar{B}}\right|^2\left(1+1/2\tau\right)$$

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

$$\sigma_{p\bar{p}}\left(m_{p\bar{p}} \to 2m_p\right) \to 0.85\ \text{nb}\left|G_{eff}(2m_p)\right|^2$$

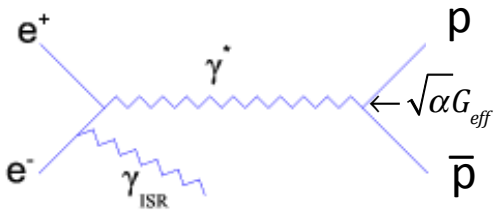
for $n\bar{n}$ ($\Lambda\bar{\Lambda}$): C=1



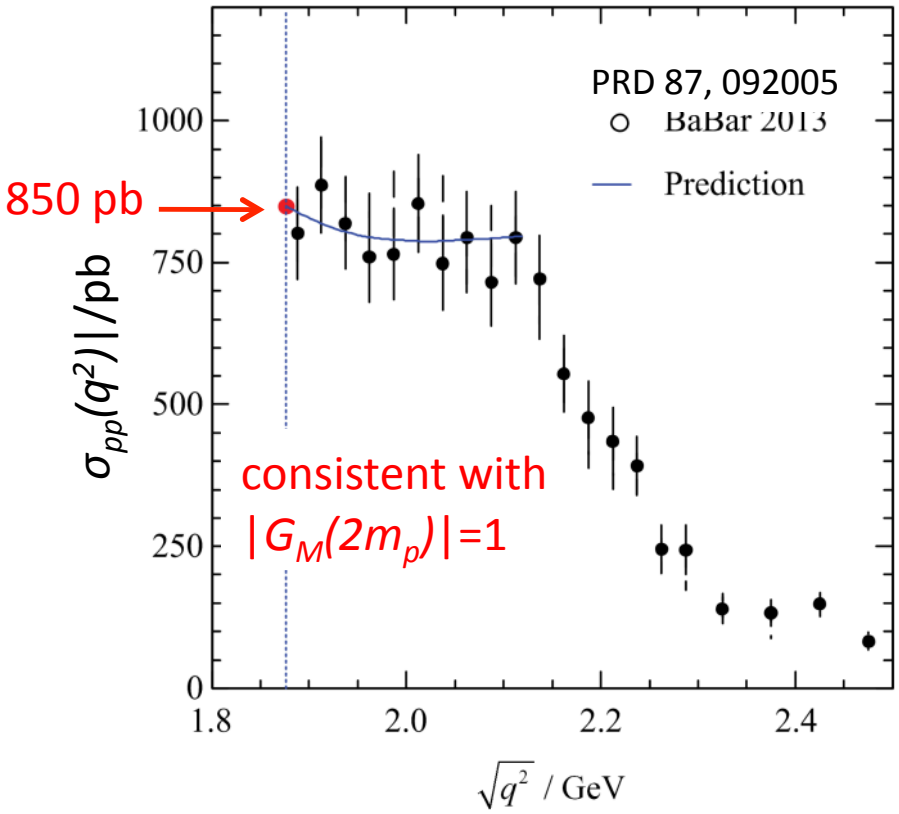


$\sigma(e^+e^- \rightarrow p\bar{p})$ threshold data

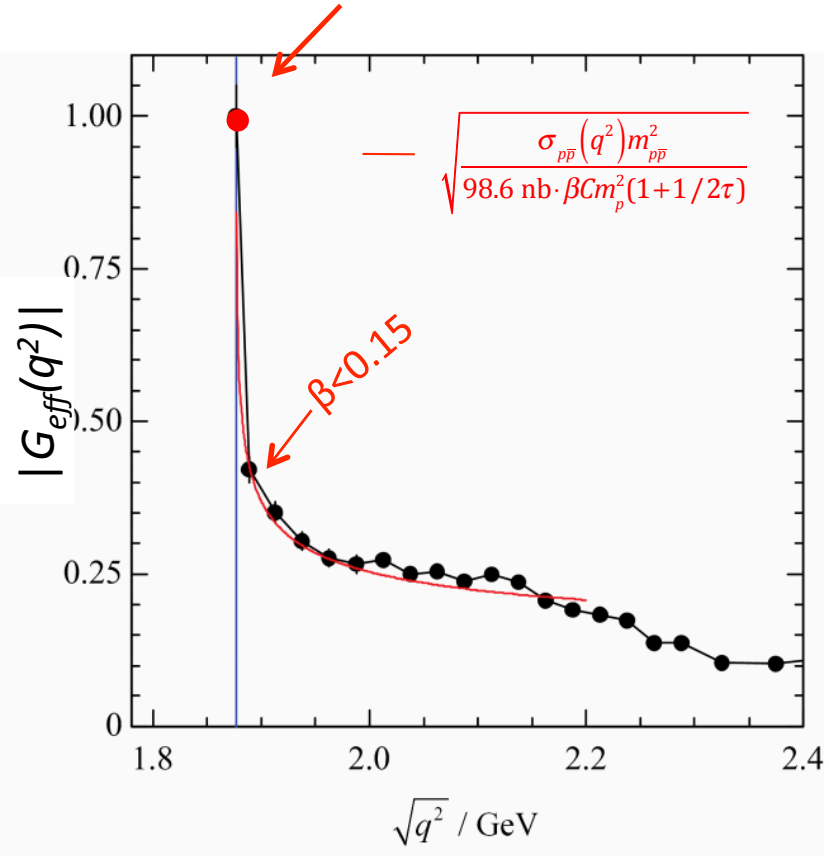
--from BaBar, using initial-state-radiation--



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

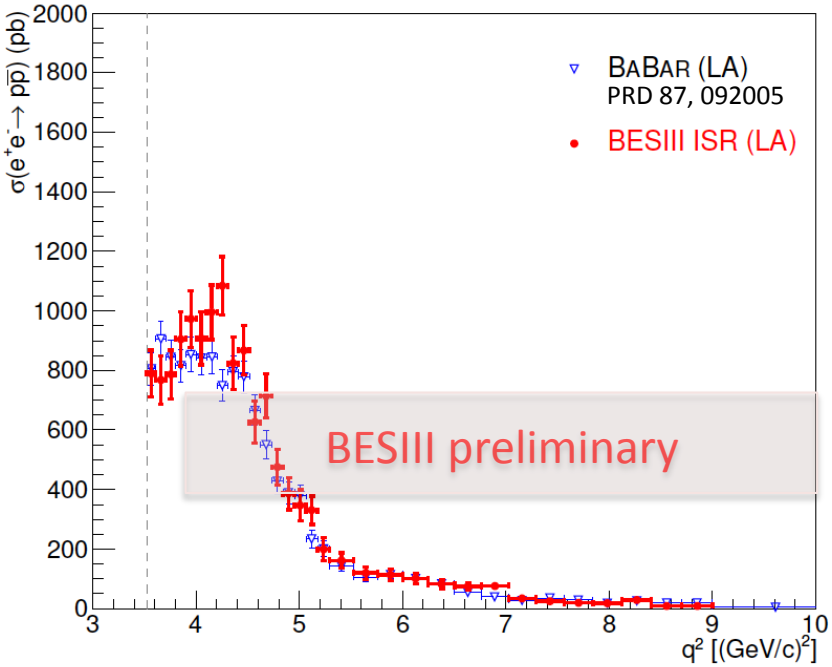


not directly measured

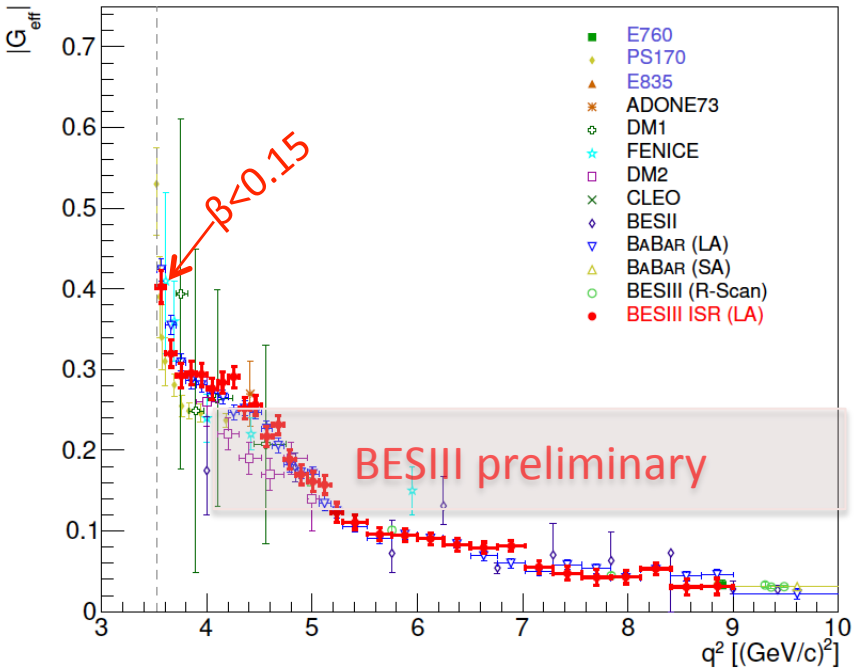


PreliminaryBESIII data confirms BaBar

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

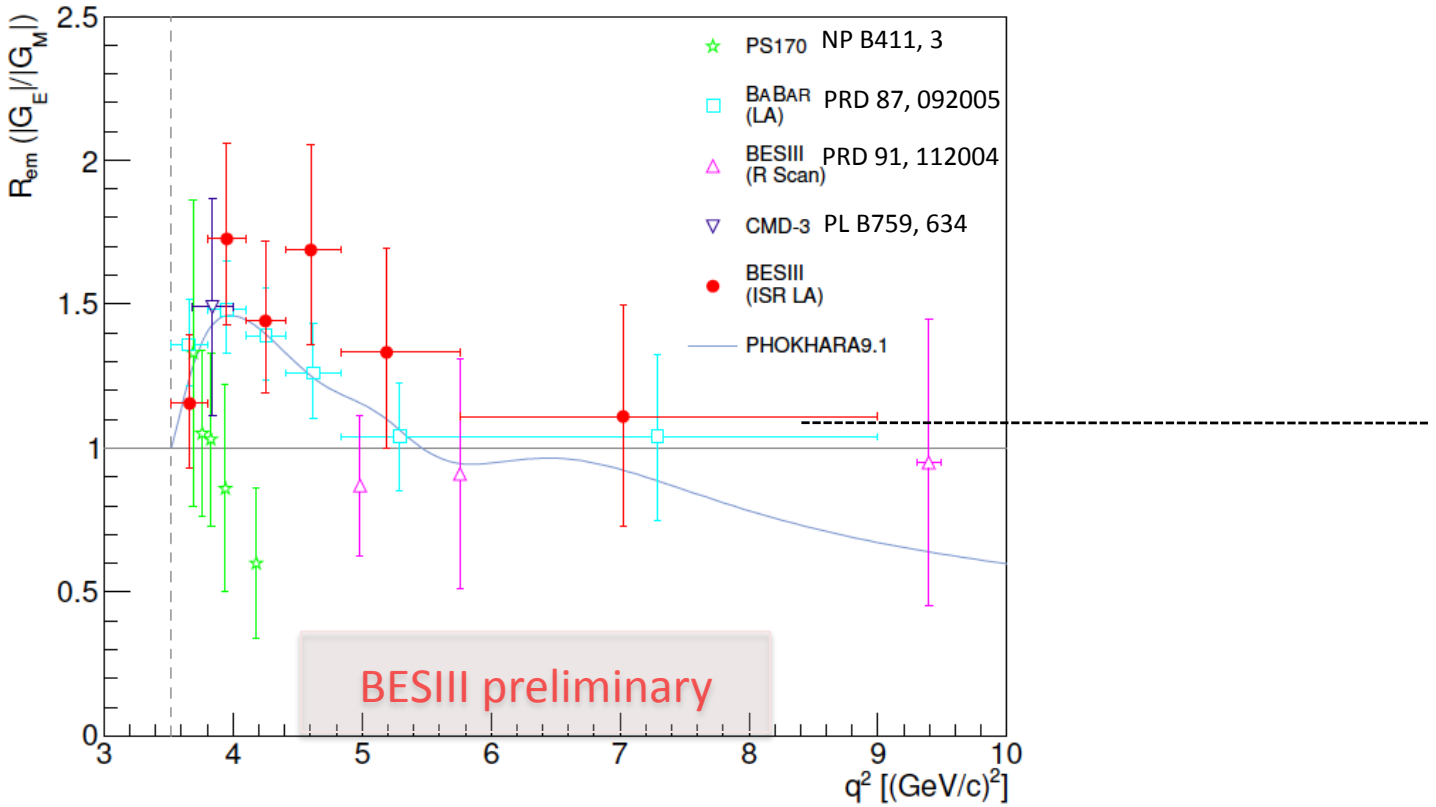


$|G_{eff}|$



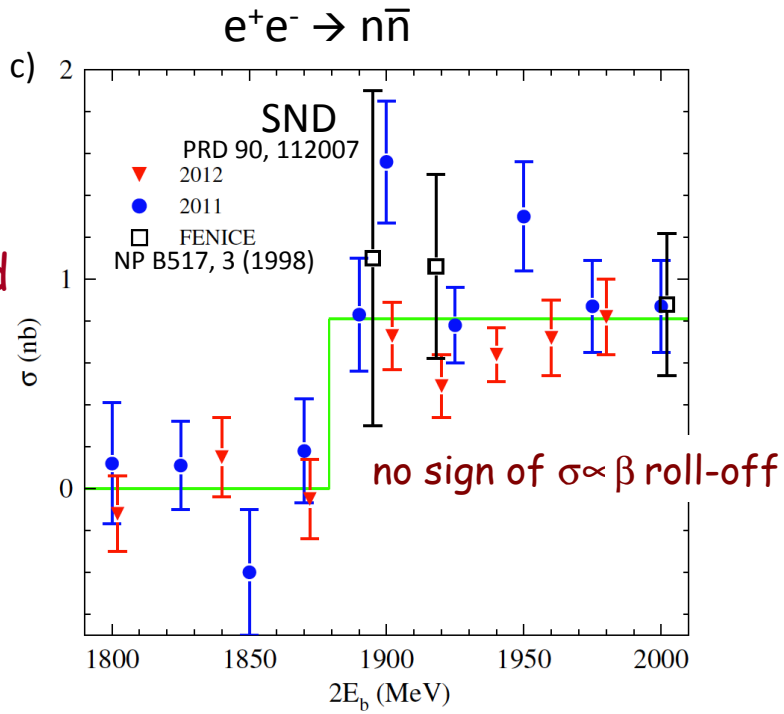
$|G_E(2m_p)|/|G_M(2m_p)| \to 1$

$\sigma(e^+e^- \to \gamma_{isr}\, p\bar{p})$

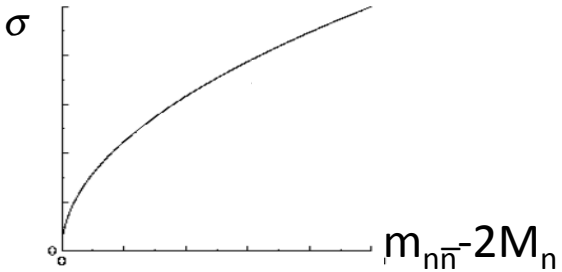


$\sigma(e^+e^- \to n\bar{n})$ near threshold

~ same size threshold jump as seen for $p\bar{p}$

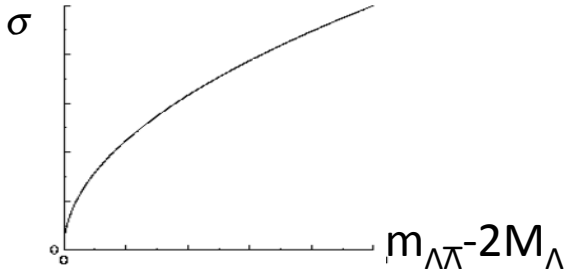


for $n\bar{n}$, C=1; $\sigma \propto \beta$



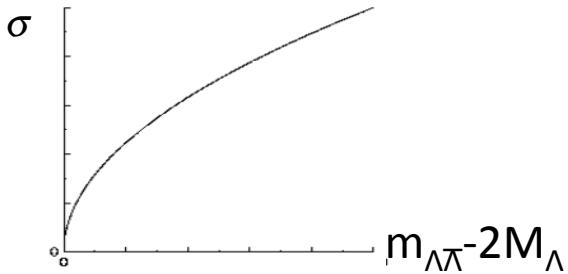
$e^+e^- \rightarrow \gamma^* \rightarrow \Lambda\bar{\Lambda}$ at threshold

for $\Lambda\bar{\Lambda}$, C=1; $\sigma \propto \beta$



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

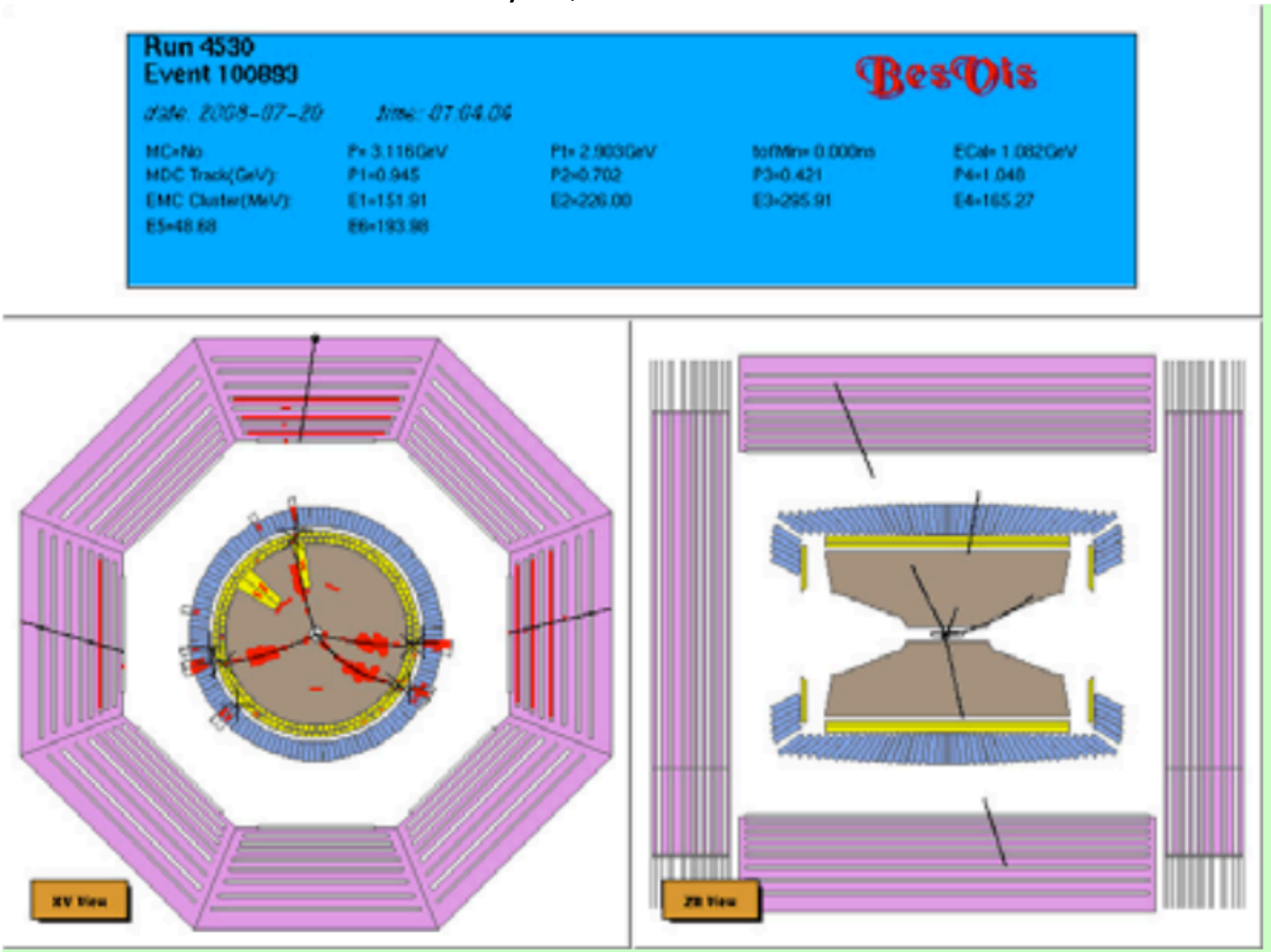
for $\Lambda\bar{\Lambda}$, C=1; $\sigma \propto \beta$



but 1st some experimental physics

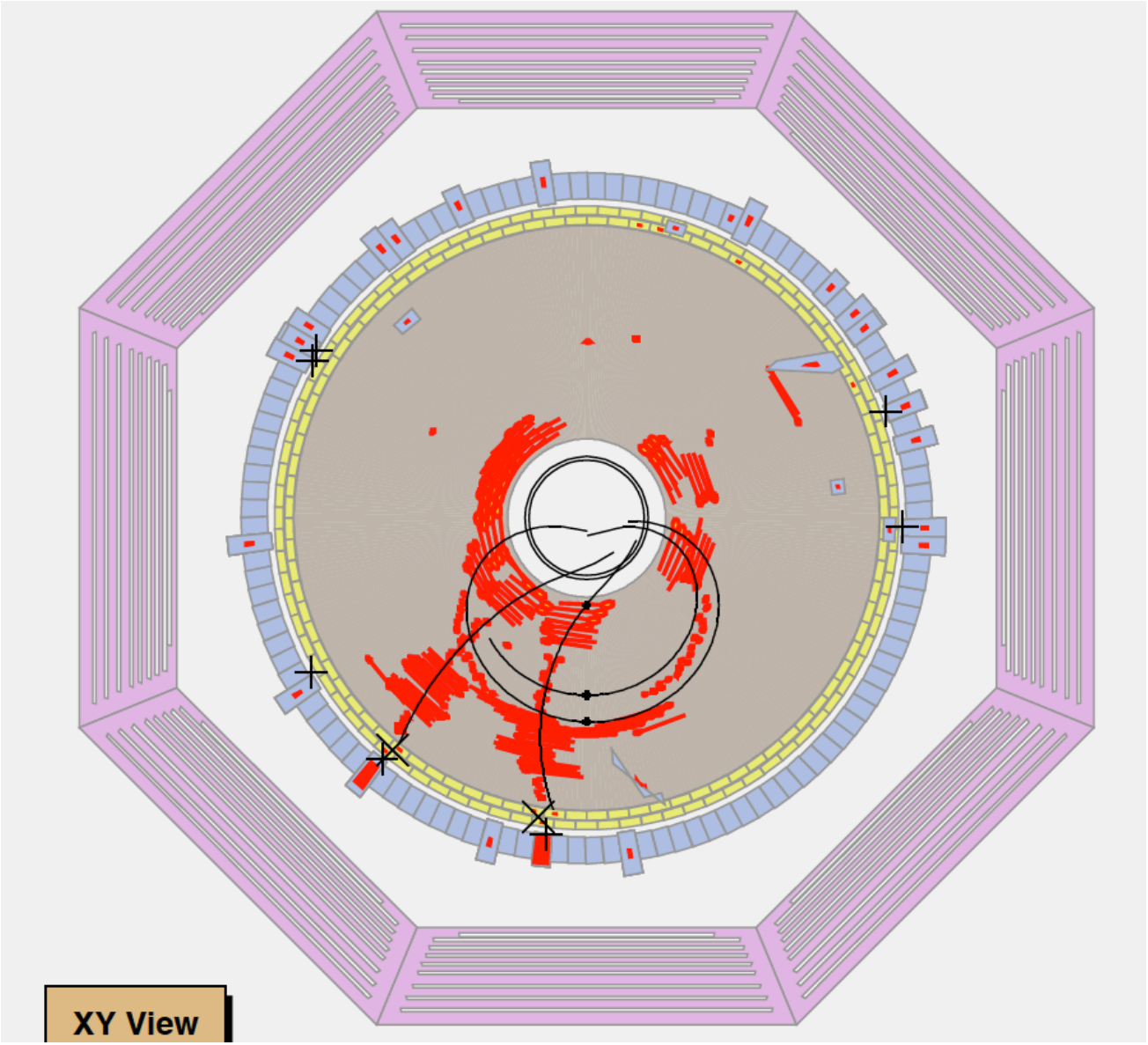
First event in BESIII

July 20, 2007

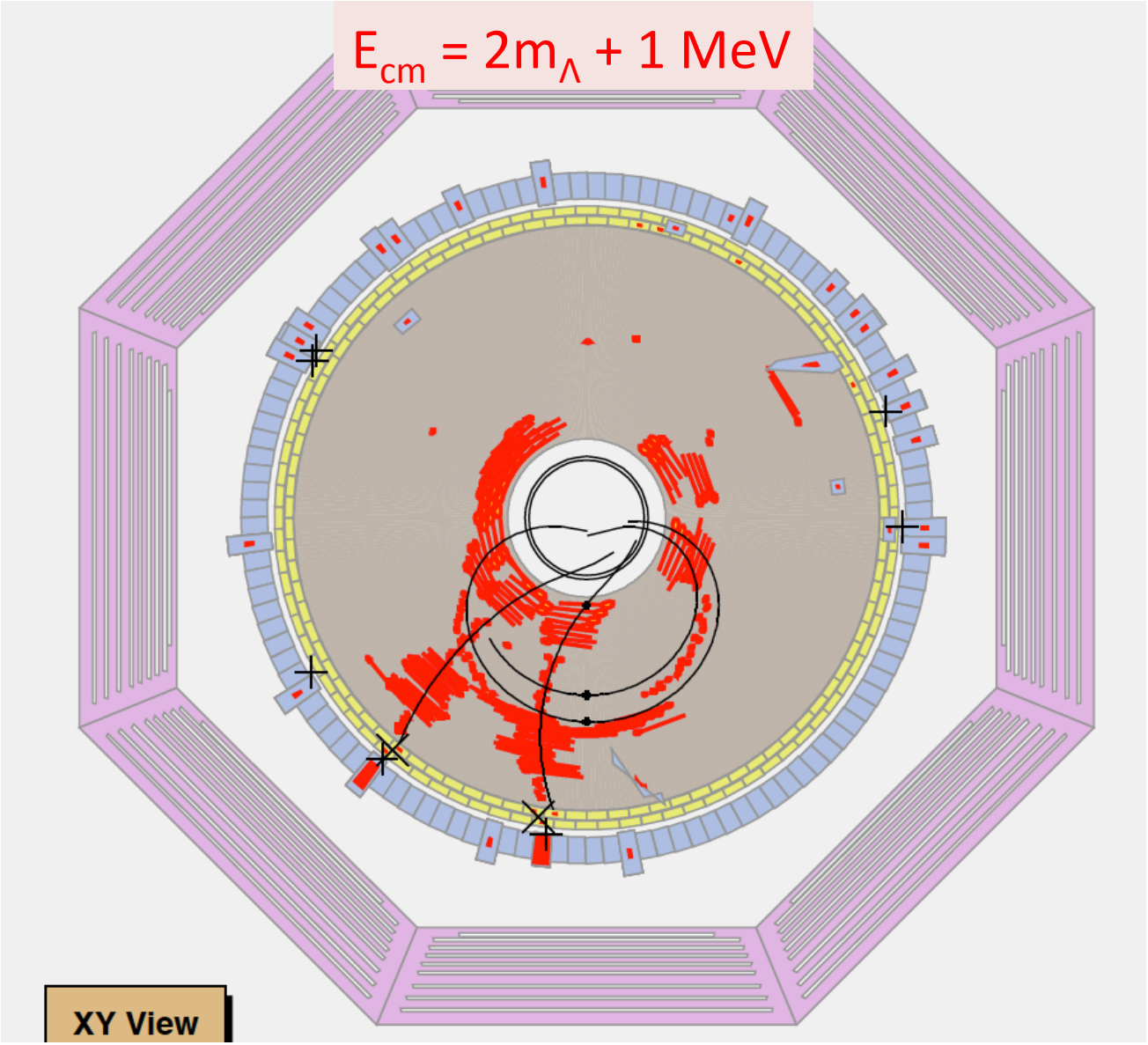


First collision event

events we don’t usually show in public



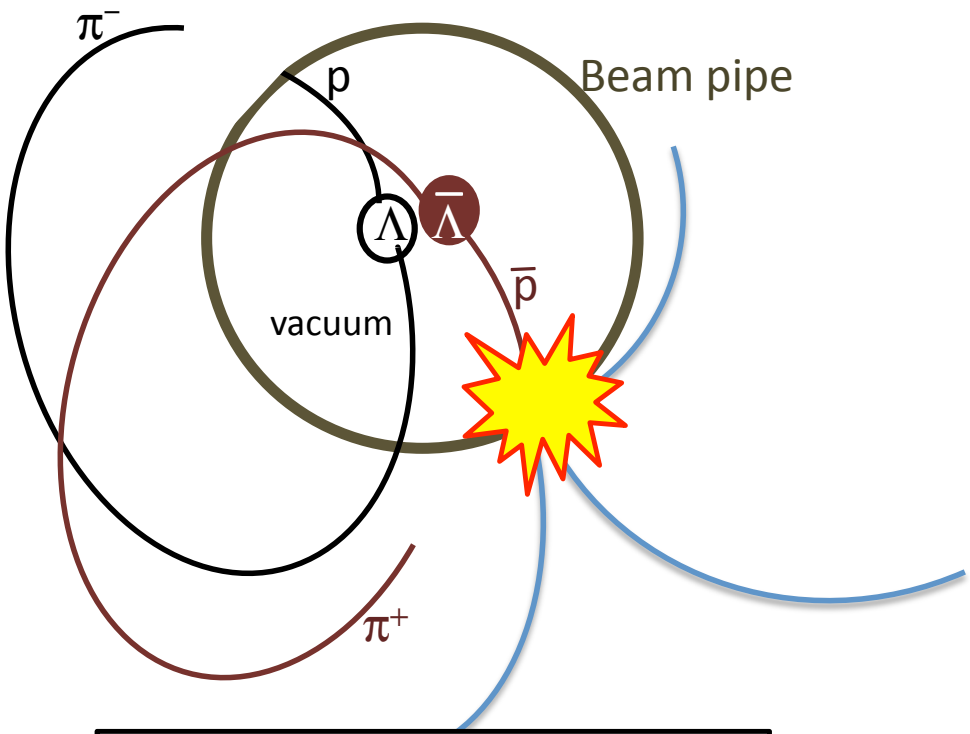
events we don’t usually show in public



What would a $\Lambda\bar{\Lambda}$ at rest look like in BESIII

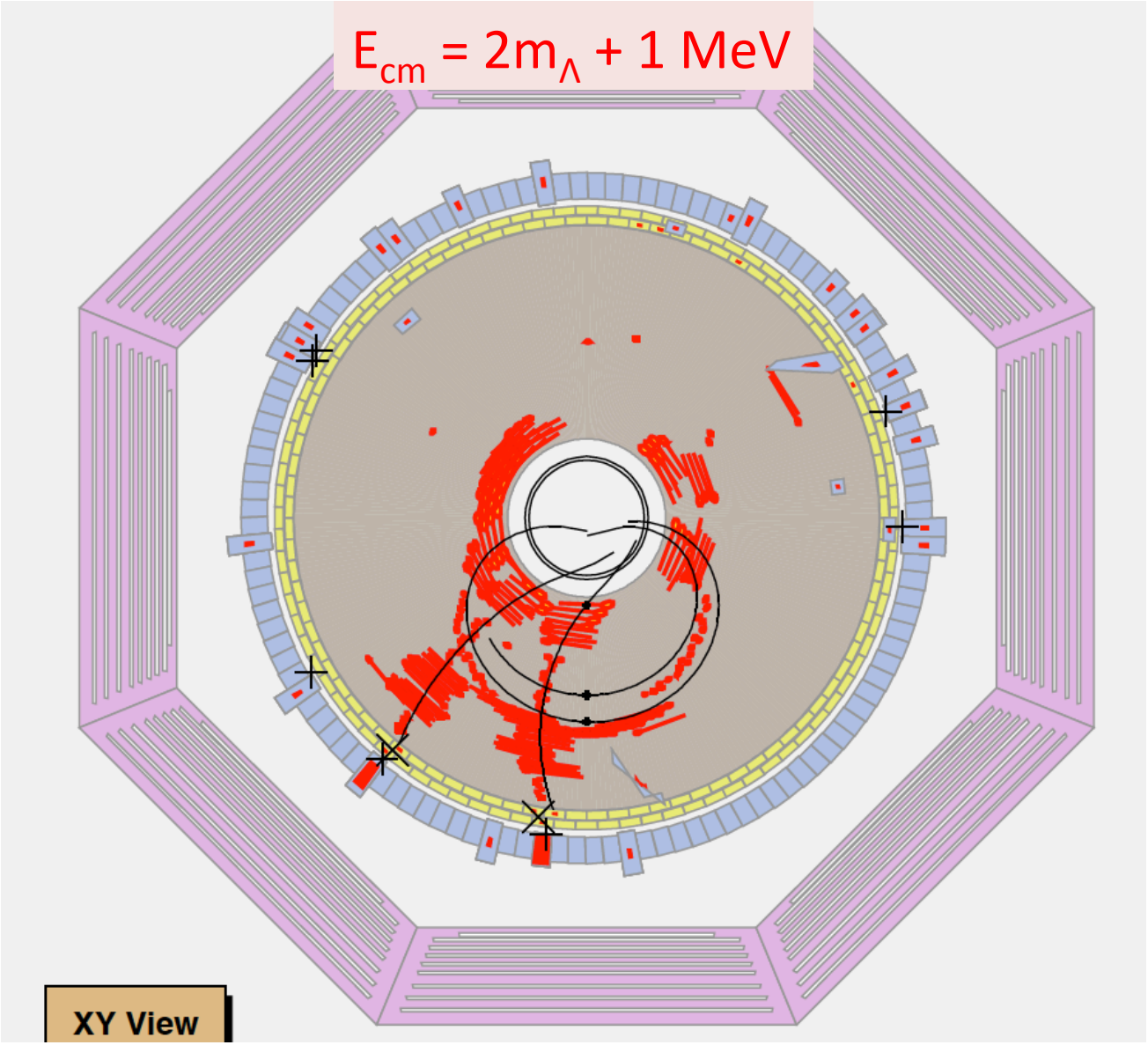
For $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$

Tracking volume

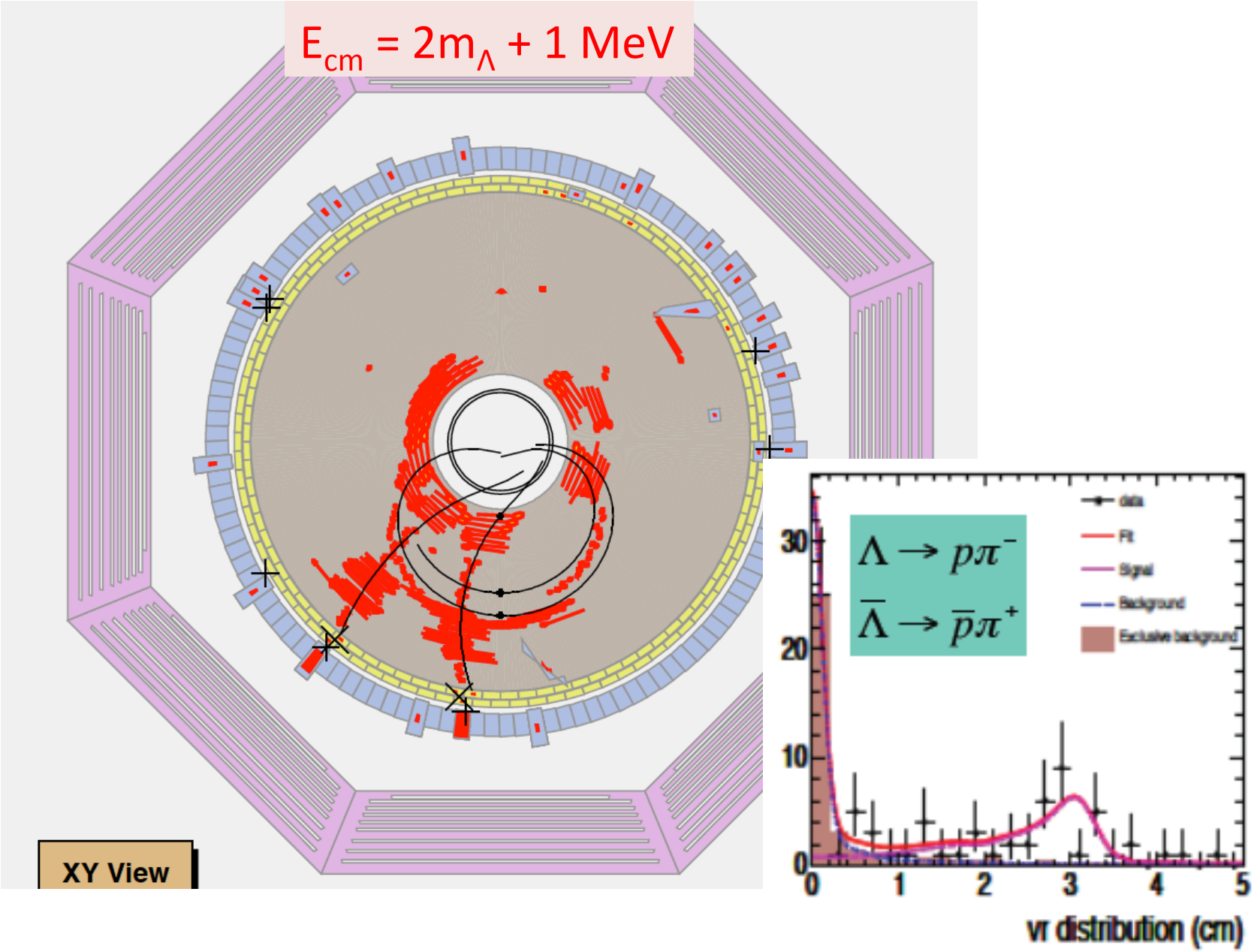


1 π^+ && 1 π^- with p≈100 MeV/c
at least 1 track from r≈3cm

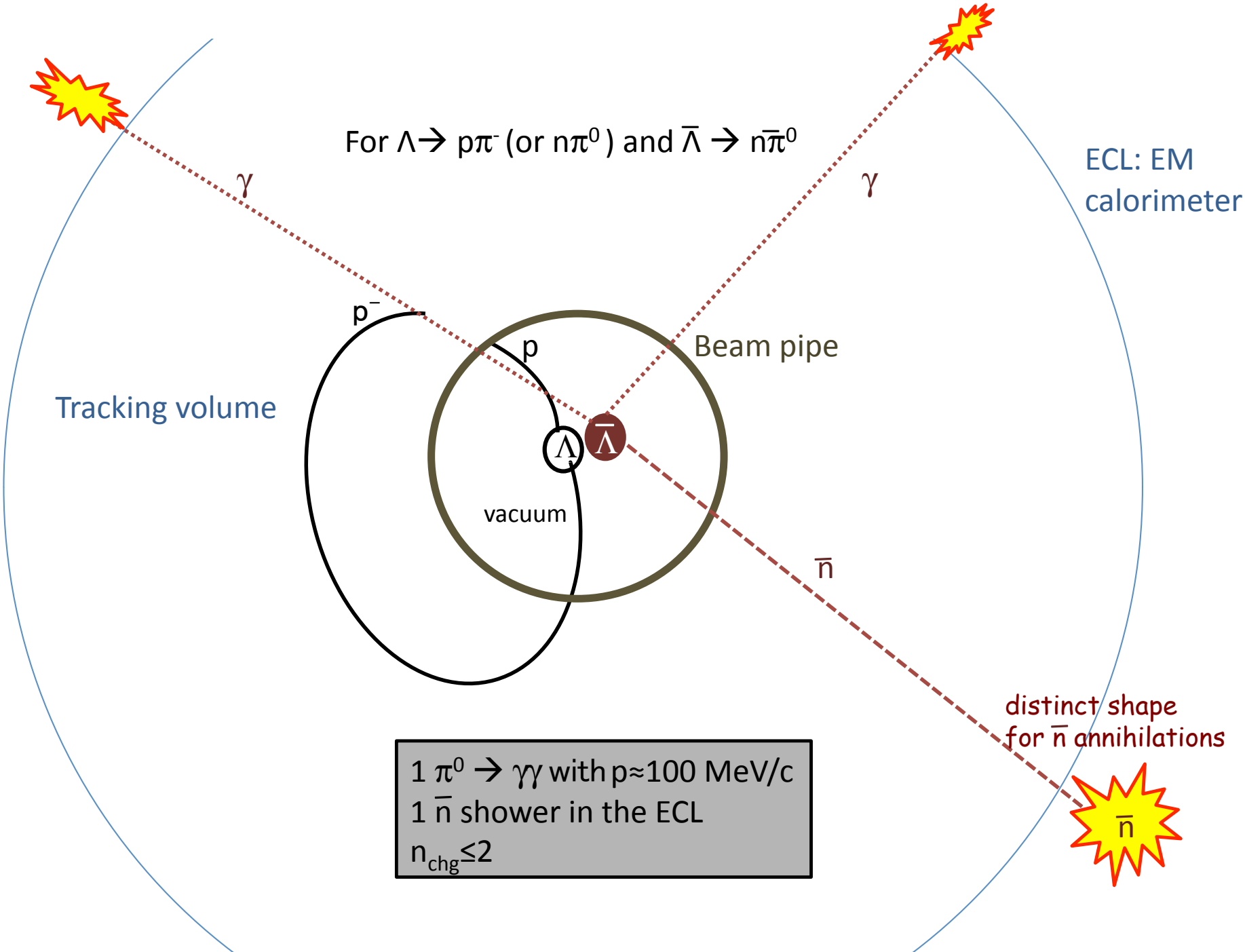
about like this



about like this



What would a $\Lambda\bar{\Lambda}$ at rest look like in BESIII



What would a $\Lambda\bar{\Lambda}$ at rest look like in BESIII

For $\Lambda \rightarrow p\pi^-$ (or $n\pi^0$) and $\bar{\Lambda} \rightarrow \bar{n}\pi^0$

ECL: EM calorimeter

γ

γ

p^-

p

Beam pipe

Tracking volume

Λ

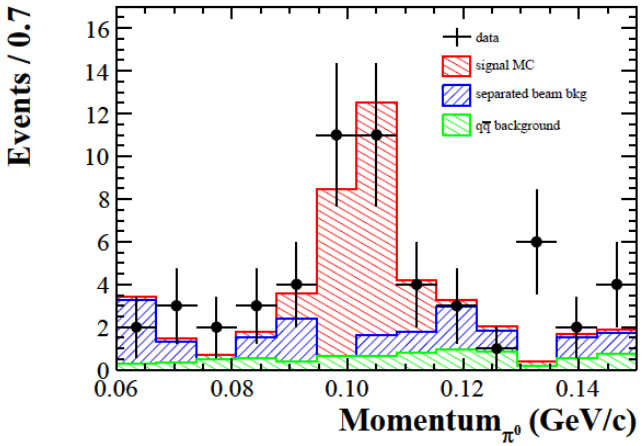
$\bar{\Lambda}$

vacuum

$\bar{n}$

distinct shape for $\bar{n}$ annihilations

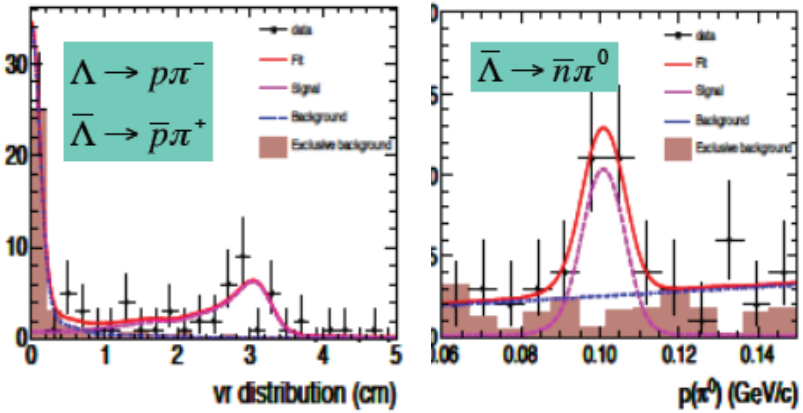
$\bar{n}$



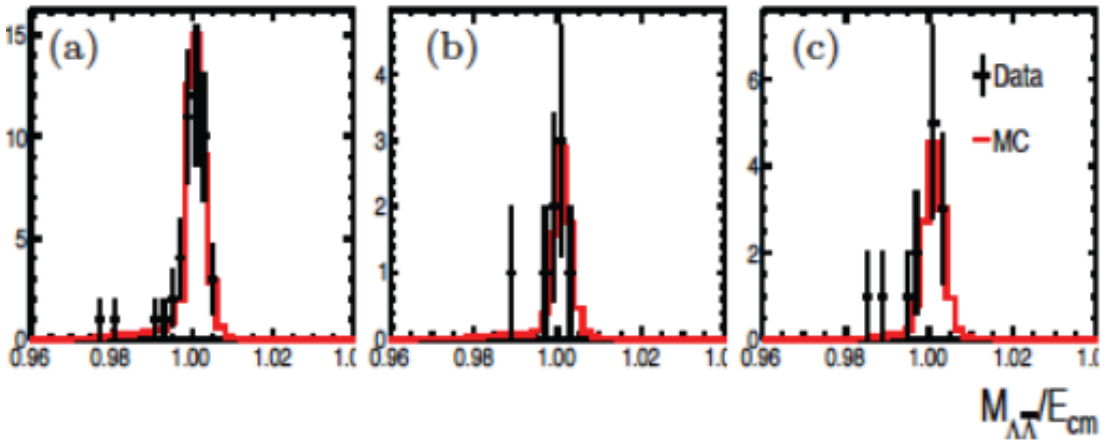
1 $\pi^0 \rightarrow \gamma\gamma$ with p≈100 MeV/c
1 $\bar{n}$ shower in the ECL
$n_{chg} \leq 2$

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

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



$2m_\Lambda$+9 MeV $2m_\Lambda$+409 MeV $2m_\Lambda$+689 MeV



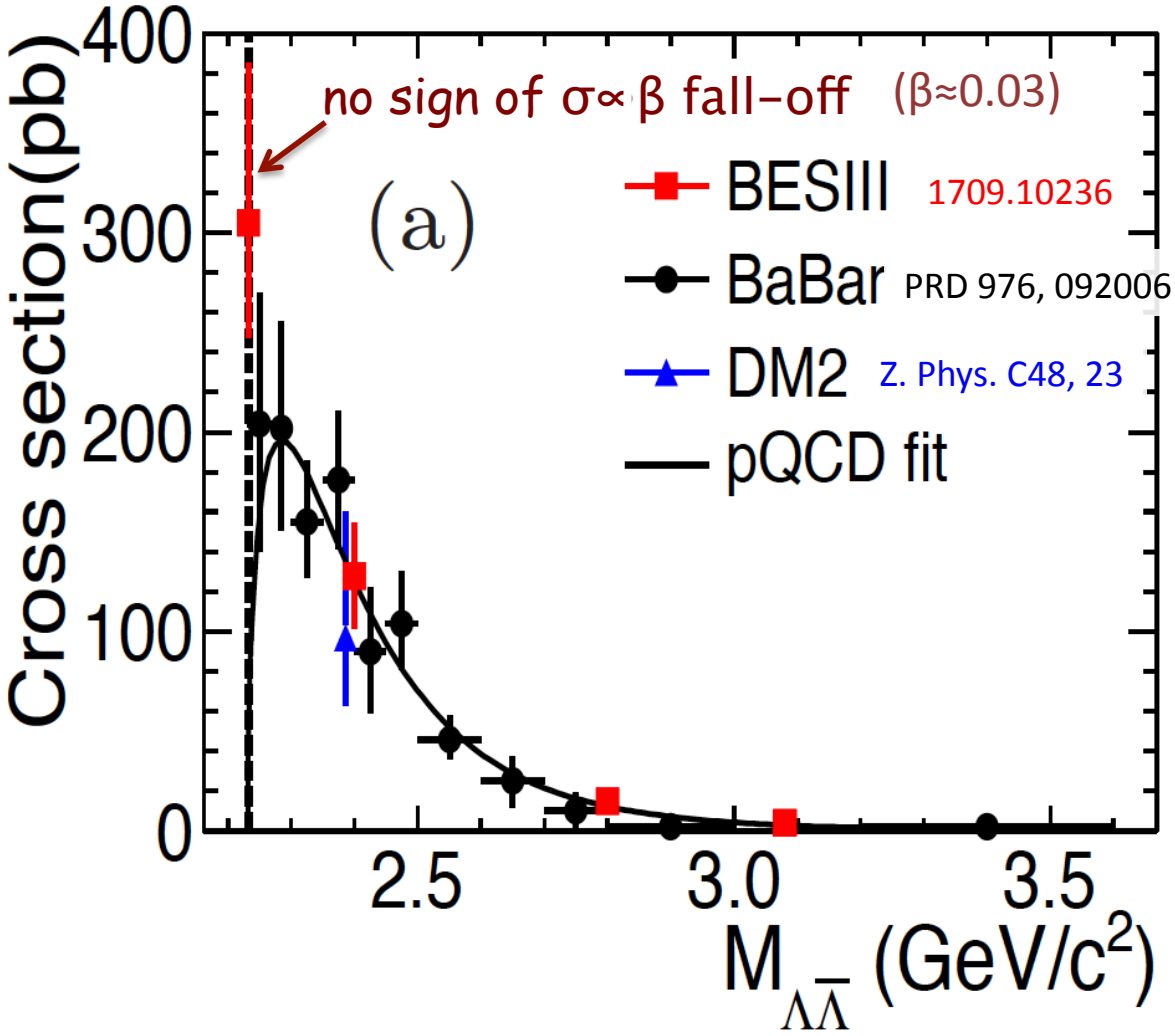
$\sqrt{s}$ (GeV)	$\mathcal{L}_{\rm int}$ (pb^{-1})	$N_{\rm obs}$	$\epsilon(1+\delta)$ (%)	$\sigma^{\rm B}$ (pb)	$\lvert G\rvert$ ($\times 10^{-2}$)
2.2324_1	2.63	43 ± 7	12.9	$312 \pm 51^{+72}_{-45}$	two methods are consistent
2.2324_2	2.63	22 ± 6	8.25	$288 \pm 96^{+64}_{-36}$	
2.2324_c				$305 \pm 45^{+66}_{-36}$	$61.9 \pm 4.6^{+11.6}_{-9.0}$
2.400	3.42	45 ± 7	25.3	$128 \pm 19 \pm 18$	$12.7 \pm 0.9 \pm 0.9$
2.800	3.75	8 ± 3	36.1	$14.8 \pm 5.2 \pm 1.9$	$4.10 \pm 0.72 \pm 0.26$
3.080	30.73	13 ± 4	24.5	$4.2 \pm 1.2 \pm 0.5$	$2.29 \pm 0.33 \pm 0.14$

conventional analyses at higher energies

BESIII 709.10236

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

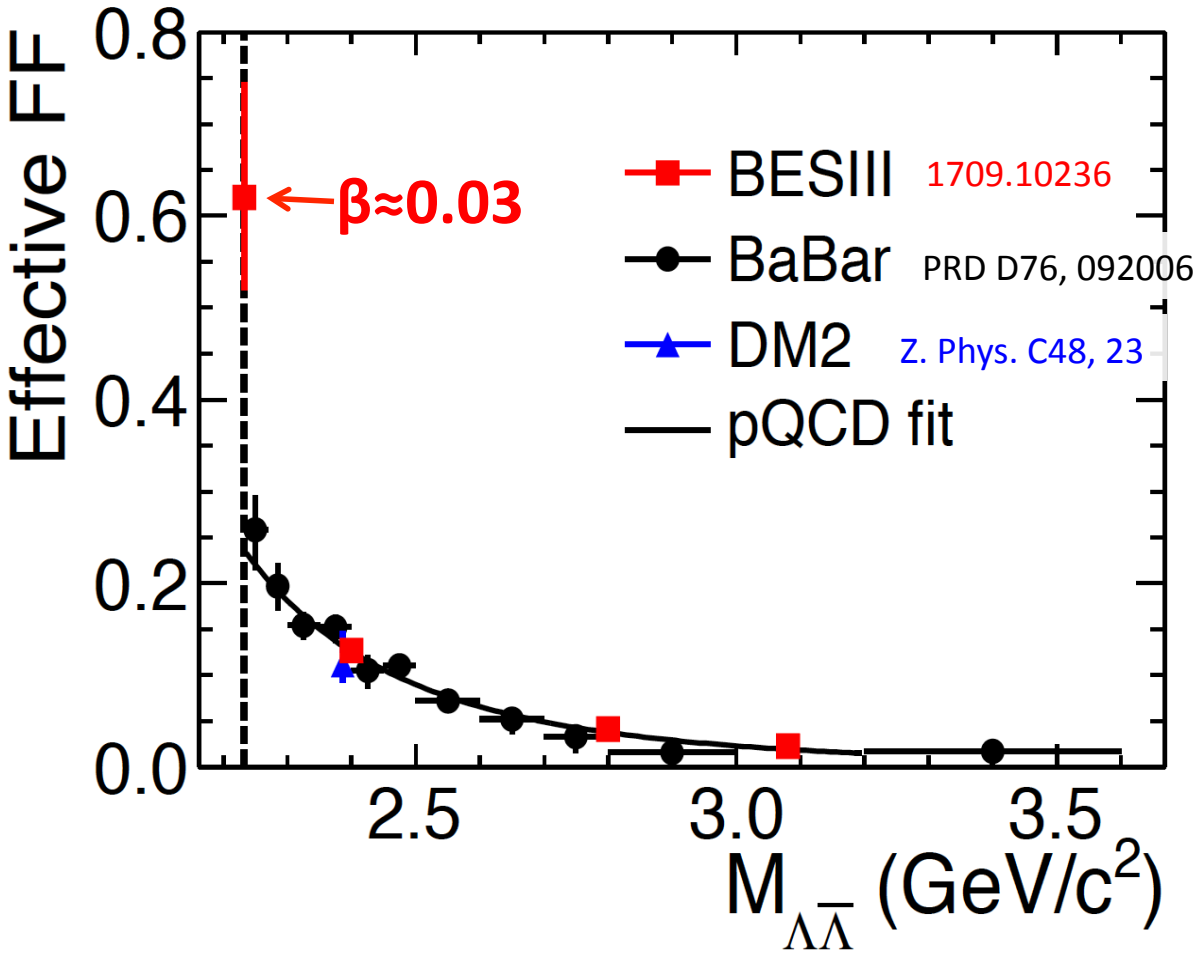
$$\sigma_{\Lambda\bar{\Lambda}}(m) = \frac{4\pi\alpha^2\beta}{3m^2}\left[\left|G_M(m)\right|^2 + \frac{1}{2\tau}\left|G_E(m)\right|^2\right] = \frac{4\pi\alpha^2\beta}{3m^2}\left|G_{eff}(m)\right|^2\left(1+1/2\tau\right)$$



Effective time-like form-factor of the Λ

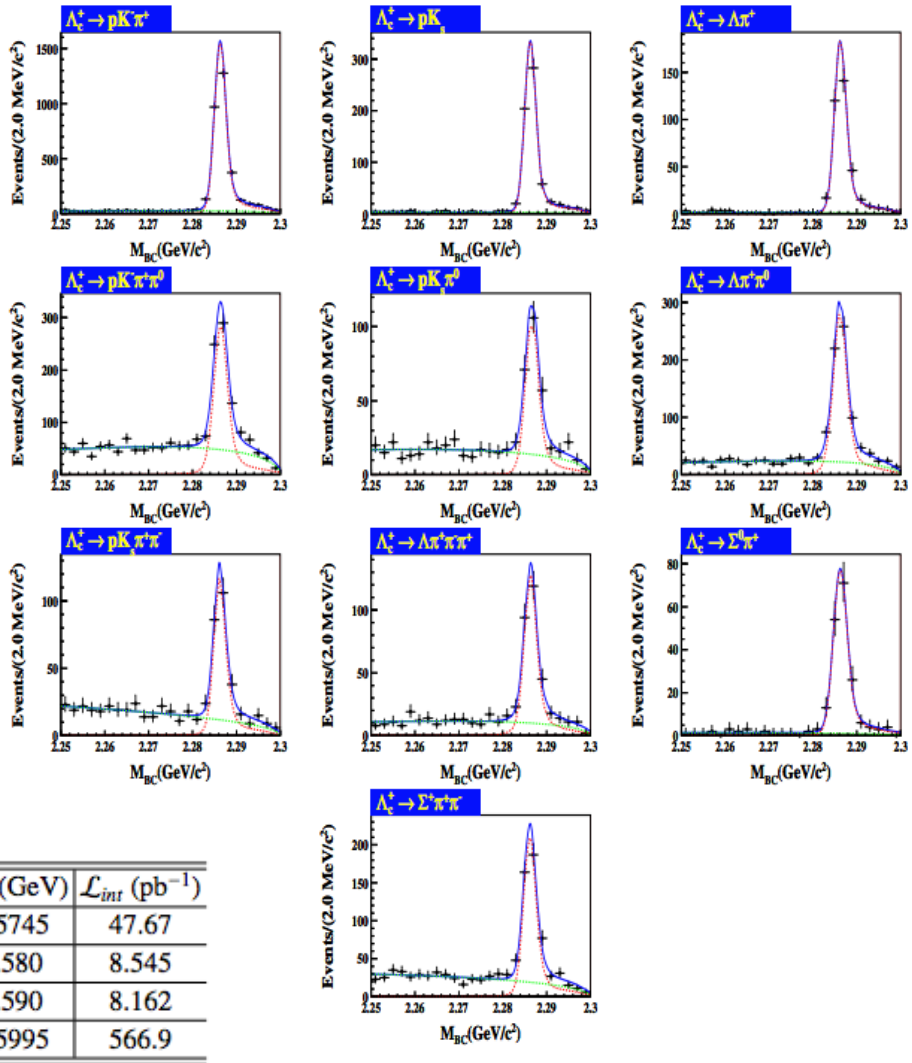
$$\left|G_{eff}(m_{\Lambda\bar{\Lambda}})\right| = \sqrt{\frac{3m^2_{\Lambda\bar{\Lambda}}\sigma_{\Lambda\bar{\Lambda}}}{4\pi\alpha^2\beta\left(1+1/2\tau\right)}}$$

diverging?



$e^+e^- \to \Lambda_c\bar{\Lambda}_c$

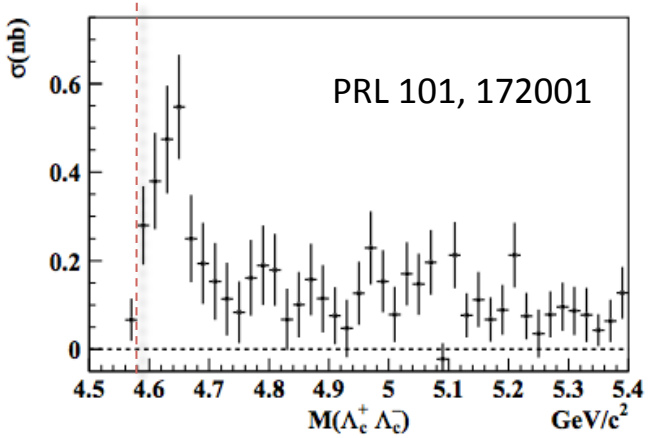
Detect one Λ_c; use 10 different decay modes



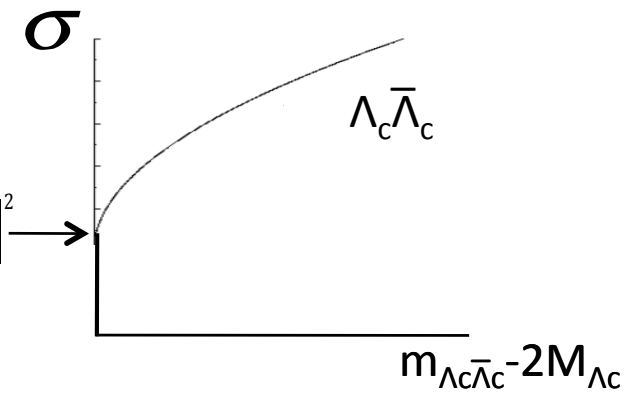
$\sqrt{s}$ (GeV)	$\mathcal{L}_{int}$ (pb^{-1})
4.5745	47.67
4.580	8.545
4.590	8.162
4.5995	566.9

expectations:

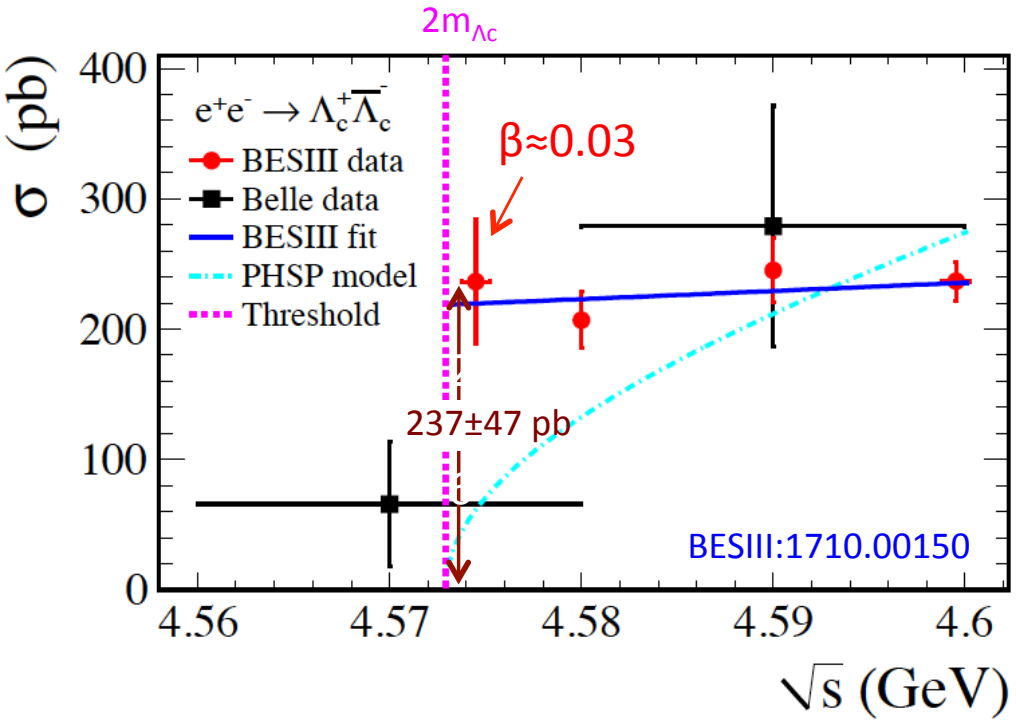
$\sigma(e^+e^- \to \Lambda_c\bar{\Lambda}_c)$ vis isr from Belle



$$\sigma_0 \approx 140\,\text{pb}\cdot\left|G_{eff}(2m_\Lambda)\right|^2$$



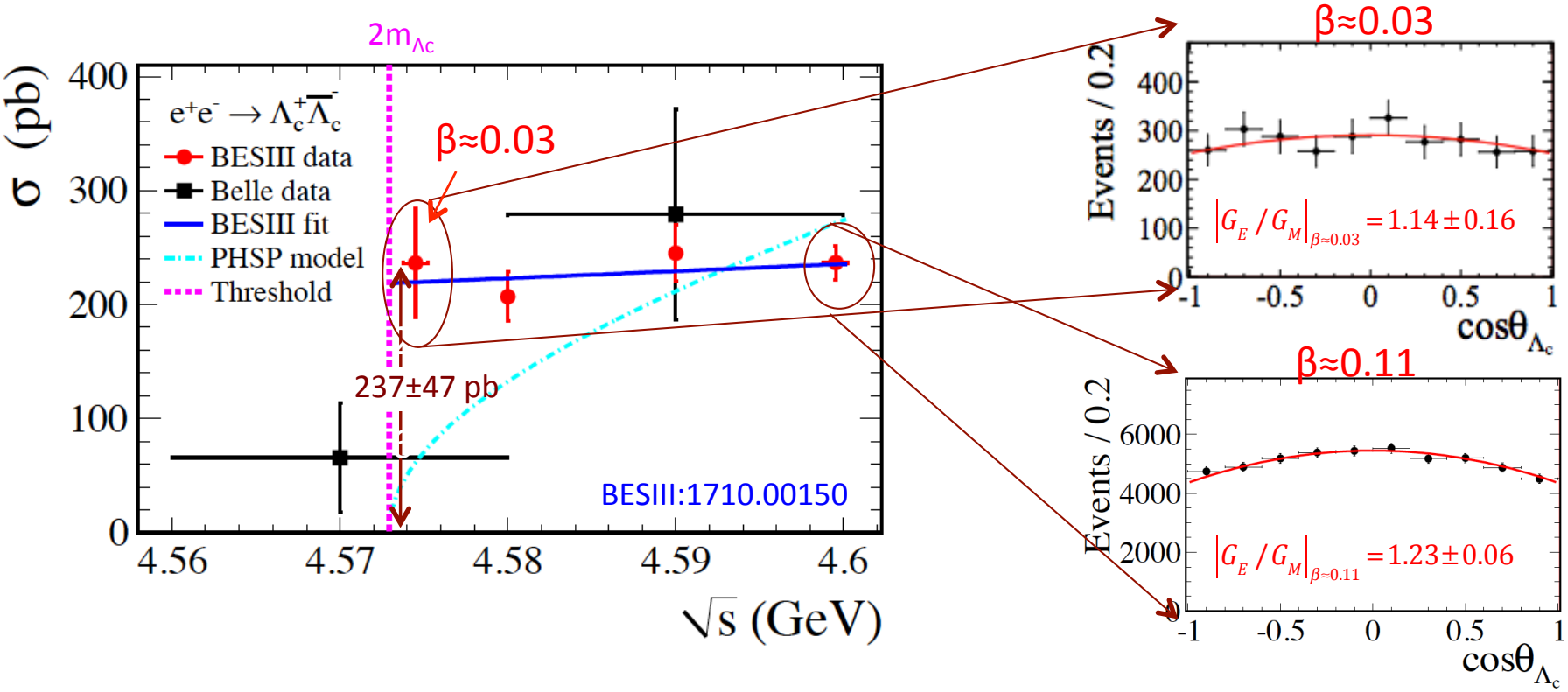
$e^+e^- \to \Lambda_c\bar{\Lambda}_c$ results



$\sqrt{s}$ (MeV)	$\mathcal{L}_{\rm int}$ (pb^{-1})	$f_{\rm ISR}$	σ (pb)
4574.5	47.67	0.45	$236 \pm 11 \pm 46$
4580.0	8.545	0.66	$207 \pm 17 \pm 13$
4590.0	8.162	0.71	$245 \pm 19 \pm 16$
4599.5	566.9	0.74	$237 \pm 3 \pm 15$

$2m_{\Lambda c}$+1.6 MeV

$e^+e^- \to \Lambda_c\bar{\Lambda}_c$ results



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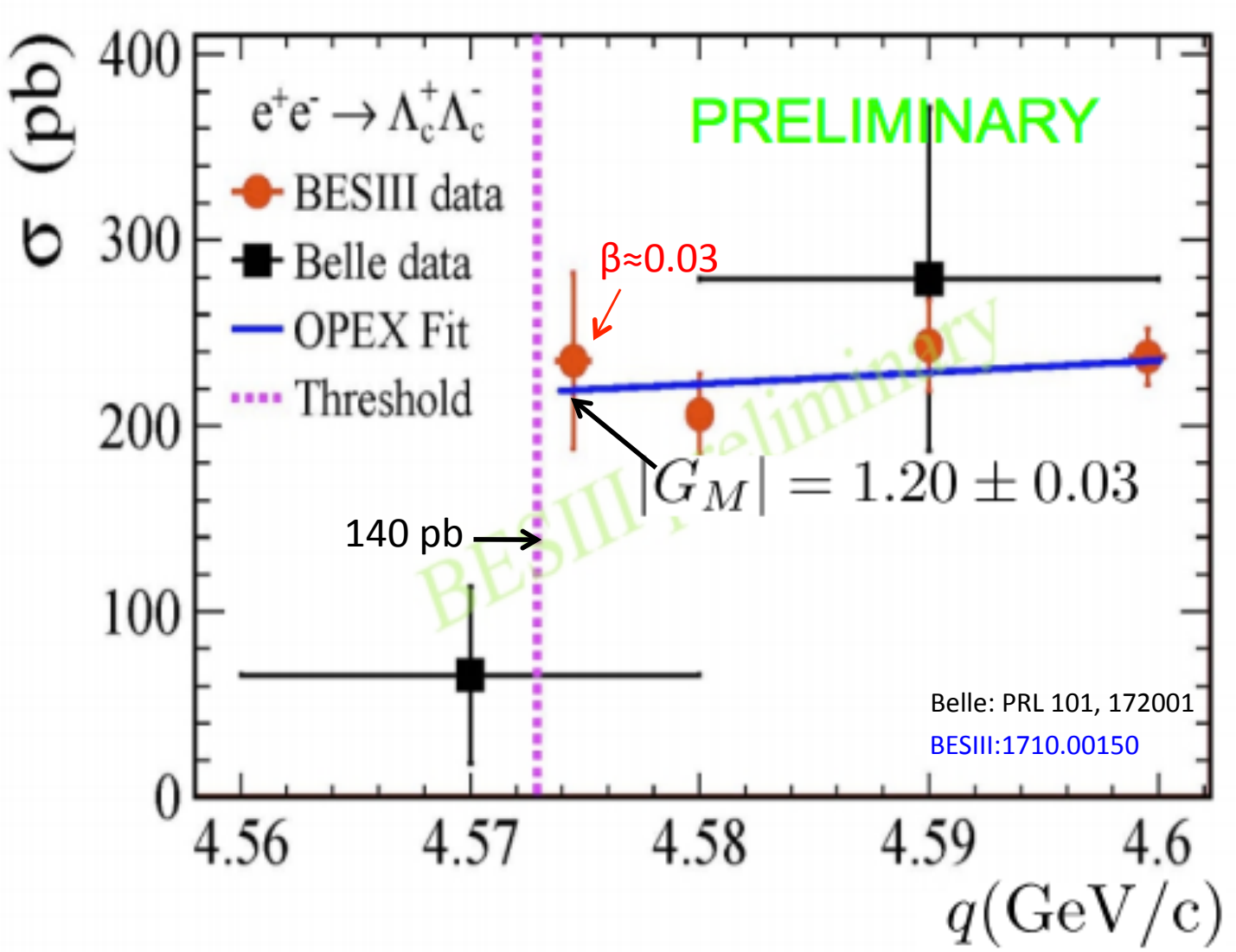
$2m_{\Lambda c}$+1.6 MeV

$|G_M(2m_{\Lambda_c})|>1$!



question to theorists:

Is the Coulomb factor reliable?

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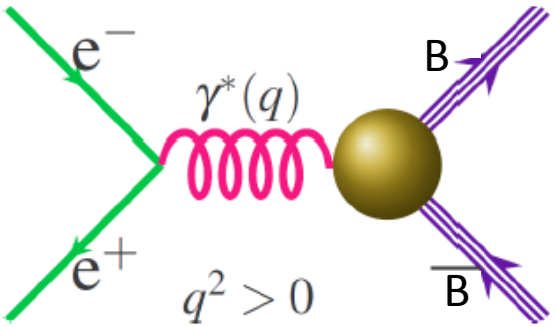
$e^+e^- \leftrightarrow N\bar{N}, \Lambda\bar{\Lambda}, \ldots$



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

in point-like approx

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

$$\text{neutral baryons}: \ \mathrm{C} = 1$$

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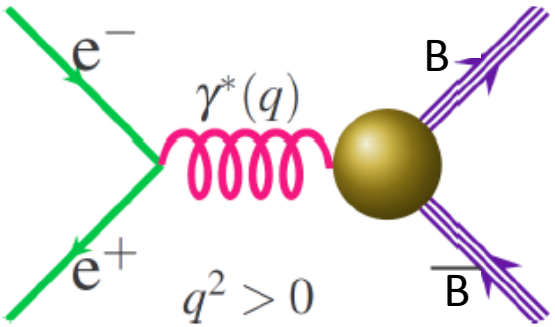

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more sophisticated calculation required?

in point-like approx

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

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$B\bar{B}$ threshold measurement prospects

BESIII data "in the can"

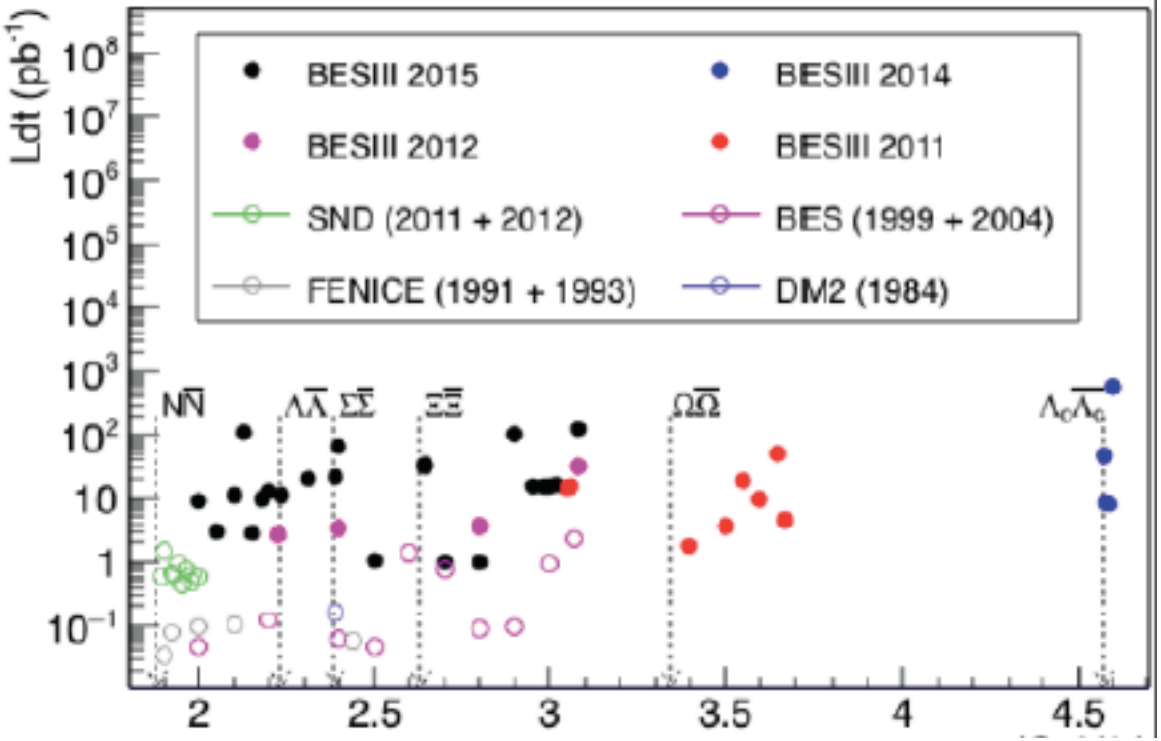
- & under analysis -

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

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

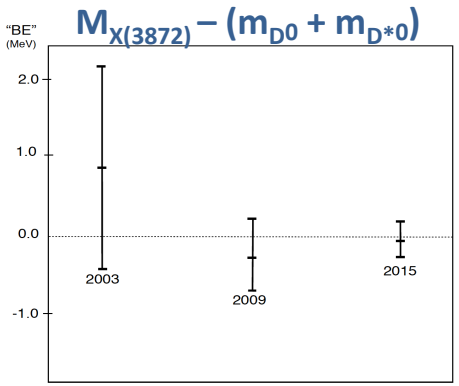
BESIII

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

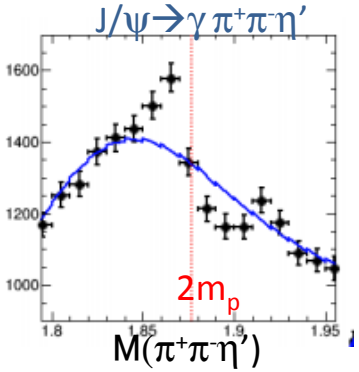


Comments

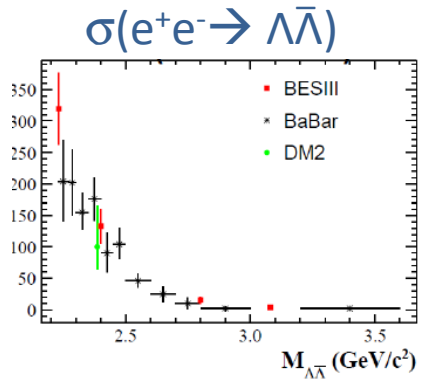
- M(X(3872)) is right at the $D^0\bar{D}^{*0}$ threshold
  - the better it is measured, the closer it gets
  - coincidence or physics?
  - motivates studies of other S-wave thresholds



- a 0^{-+} $p\bar{p}$ bound state?
  - seen in $J/\psi \to \gamma p\bar{p}$ & $\pi^+\pi^-\eta'$
  - needs simultaneous multi-channel analyses



- 1^{--} $n\bar{n}$, $\Lambda\bar{\Lambda}$ & $\Lambda_c\bar{\Lambda}_c$ puzzles @ threshold
  - need more data, closer to thresholds
  - and other channels
  - and theory (especially for Coulomb corrections)
  - $|G_M|$ @ threshold: useful probes of long-distance QCD?



Thresholds *are* interesting

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at least until we understand what is going on

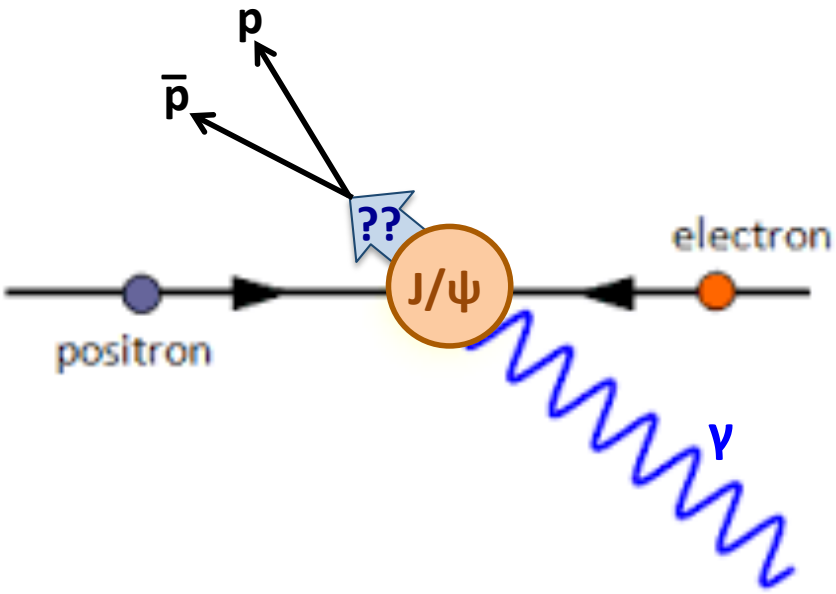
Acknowledgement

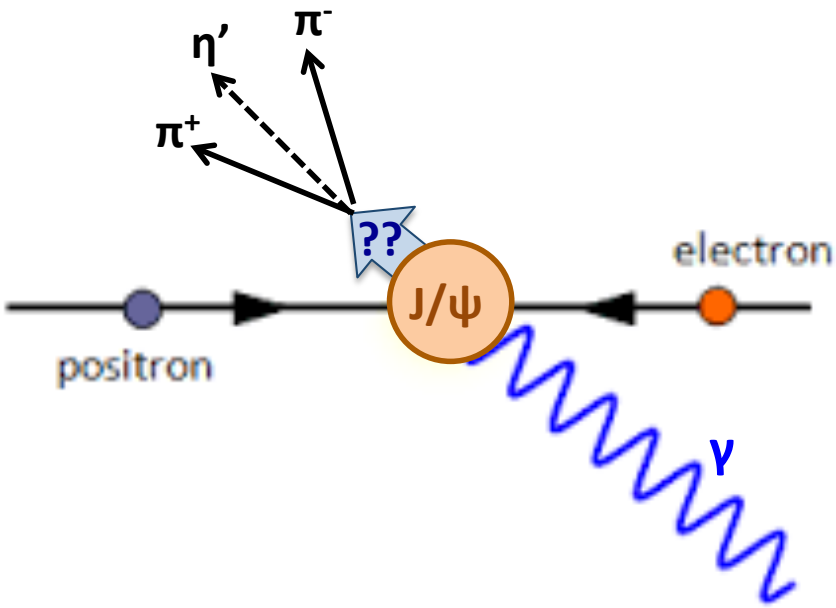
Thanks to my colleague **Rinaldo Baldini** (INFN-Frascati), who taught me all I know about time-like form factors and got me & BESIII colleagues involved in the subject

Thank you

감사합니다

Backup Slides


p
p̄
??
J/ψ
electron
positron
γ


η′
π⁻
π⁺
??
J/ψ
electron
positron
γ