XYZ mesons
+ some other stuff

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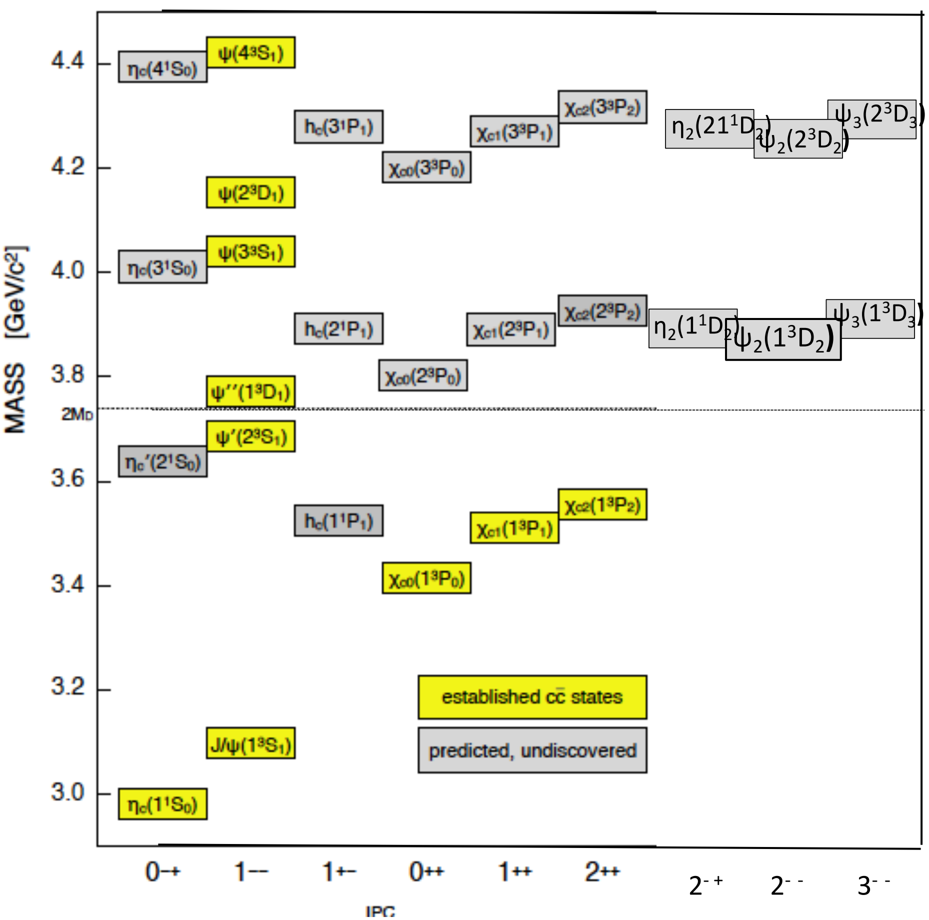
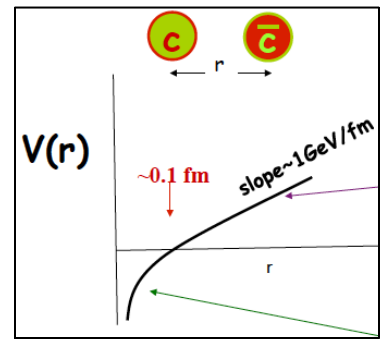
"Hints for New Physics in Heavy Flavors," KMI, Nagoya, Nov. 16-18, 2018

charmonium: pre B-factory

forty-plus years of work

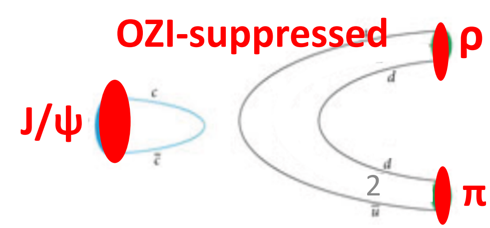


potential model works well

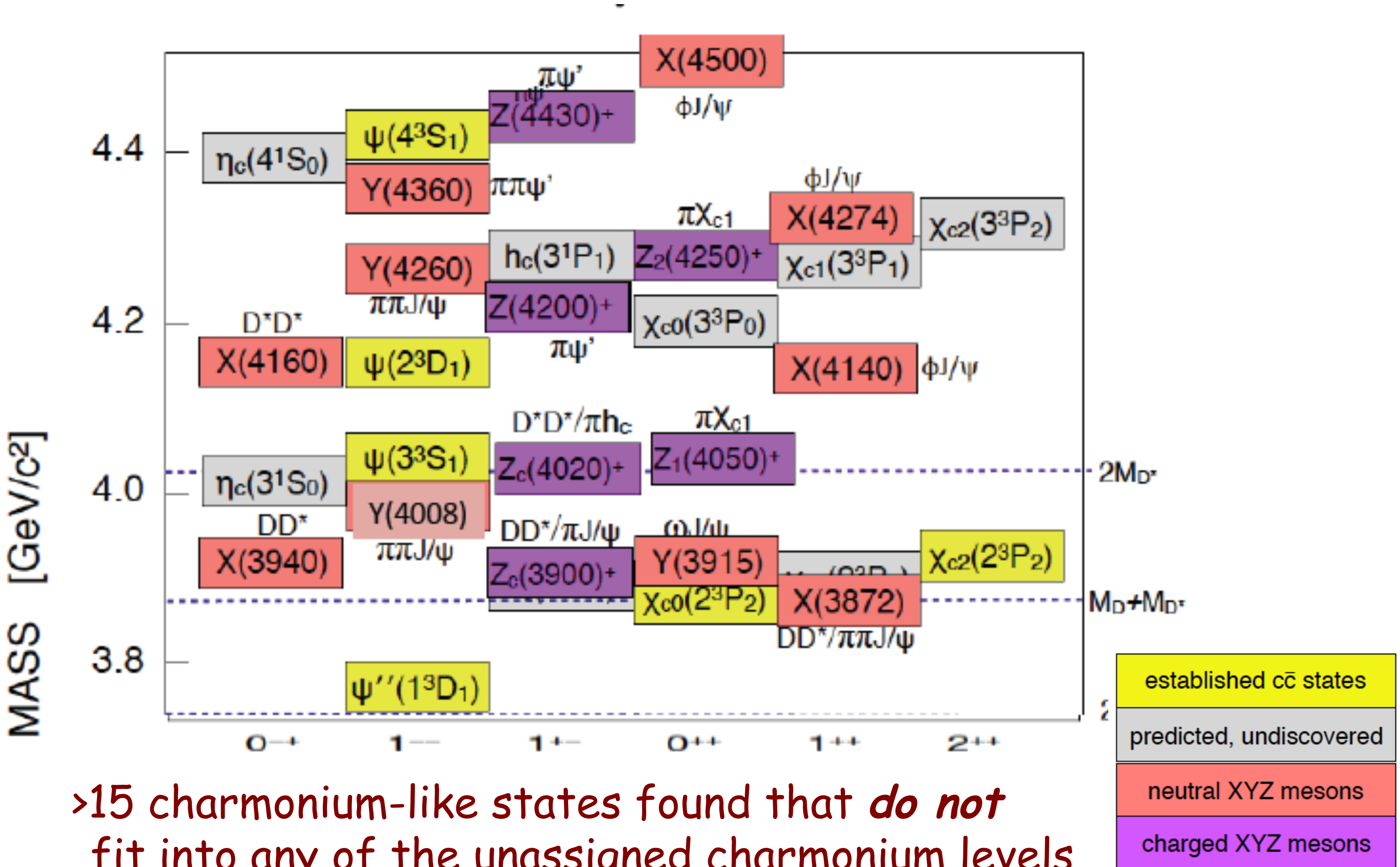


measured &
predicted masses agree

OZI-rule applies
no exceptions



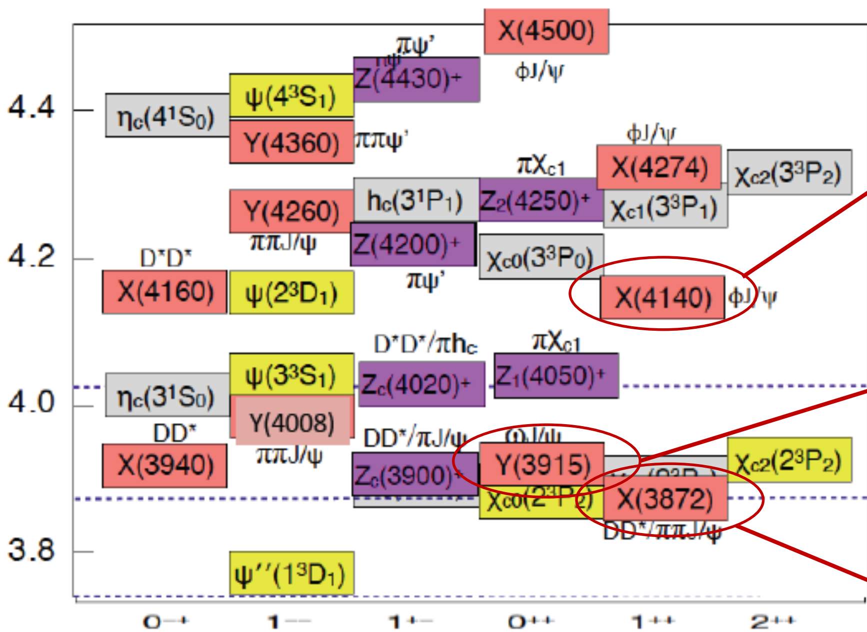
charmonium: post B-factory



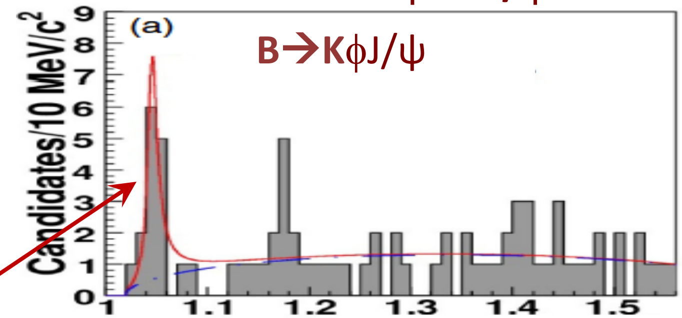
>15 charmonium-like states found that ***do not*** fit into any of the unassigned charmonium levels

Are there patterns to the new particles?

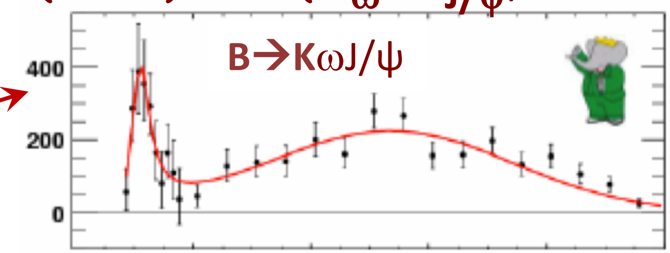
For example:



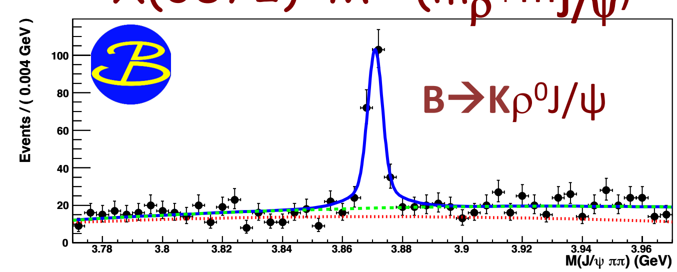
X(4140): $M \approx (m_{\phi}+m_{J/\psi})$+ ~20 MeV



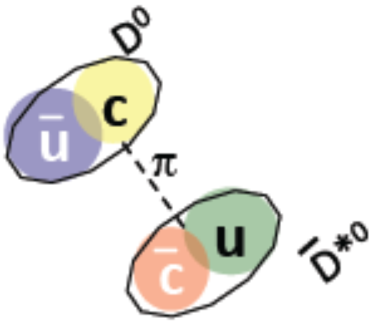
X(3915): $M \approx (m_{\omega}+m_{J/\psi})$+~20 MeV



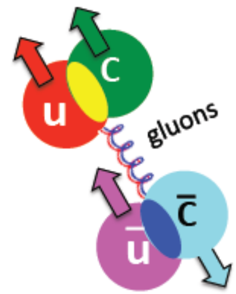
X(3872): $M \approx (m_{\rho}+m_{J/\psi})$



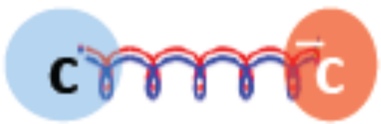
what are they?
-- "standard slide" --



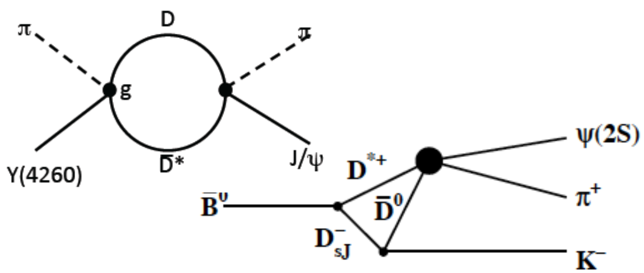
molecules?



QCD tetraquarks?

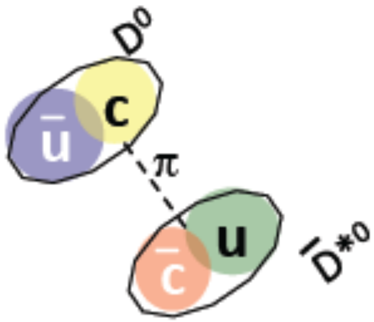


QCD hybrids?

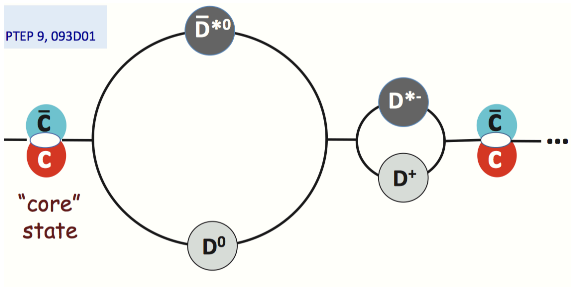


threshold effects?

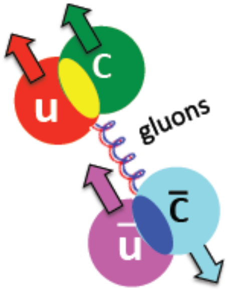
what are they?
-- add one more possibility --



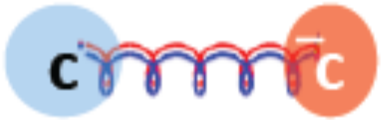
molecules?



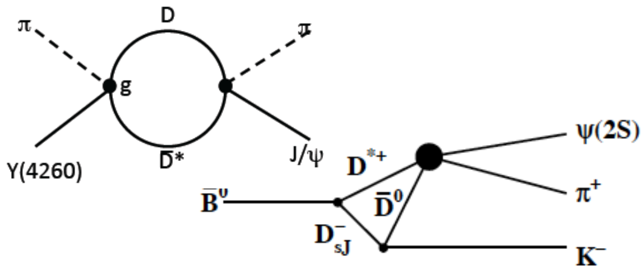
coupled channel system?



QCD tetraquarks?

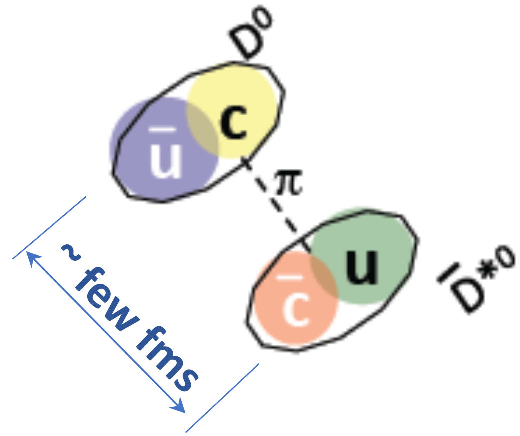


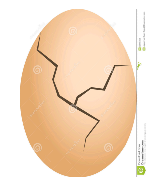
QCD hybrids?



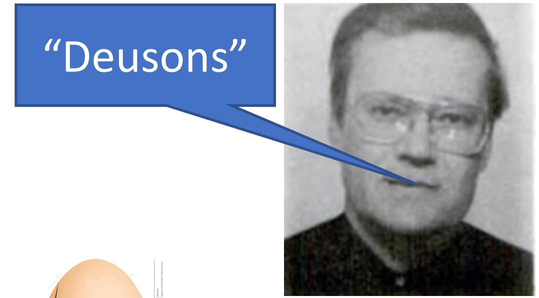
threshold effects?

deuteron-like molecules





egg-like



Nils A. Tornqvist

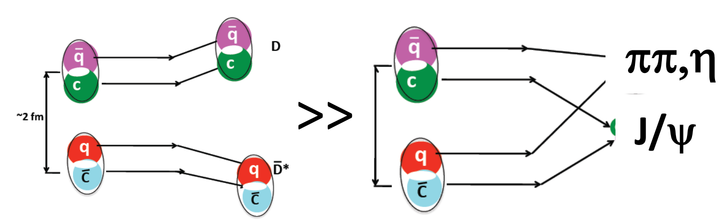
Karliner & Skwarnicki (PDG 2016):

masses near thresholds $d_{rms}^{-1} \approx a^{-1} = \sqrt{2\mu|BE|} < m_\pi \Rightarrow BE < \frac{m_\pi^2}{2\mu} \approx 10 \text{ MeV (for } 2\mu = m_D)$

Constituent mesons should be narrower than the molecule

J^{PC} consistent with S-wave *e.g.*, $J^{PC} = 1^{++}$ for $D\bar{D}^*$; $=1^{--}$ for $D\bar{D}_1^{**}$

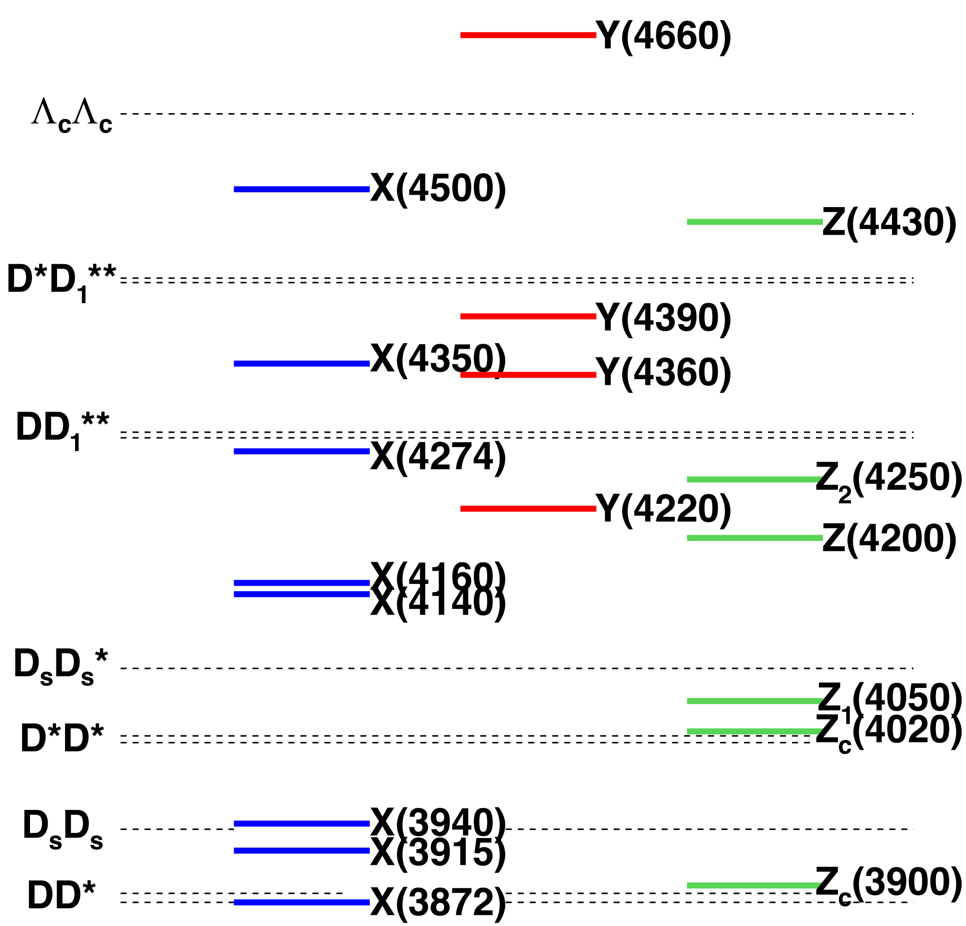
fall-apart decays >> hidden charm modes



no $0^- \oplus 0^-$ molecules (one π-exchange forbidden)

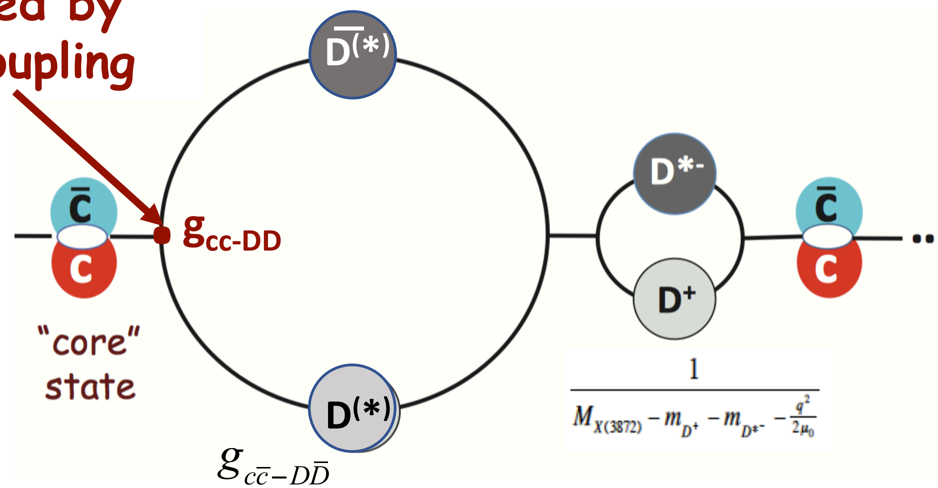
XYZ mesons *vs* open-charm thresholds

-- aside from the X(3872), no apparent correlation --



coupled-channel system

mass affected by
$c\bar{c}$-$D^{(*)}\bar{D}^{(*)}$ coupling



$$\frac{1}{M_{X(3872)} - m_{D^+} - m_{D^{*-}} - \frac{q^2}{2\mu_0}}$$

$$\frac{g_{c\bar{c}-D\bar{D}}}{M_X - m_{D^{(*)}} - m_{\bar{D}^{(*)}} - \frac{q^2}{2\mu}}$$

If $M_X \rightarrow D^{(*)}\bar{D}^{(*)}$ threshold, propagator→ divergent
and the coupling is amplified

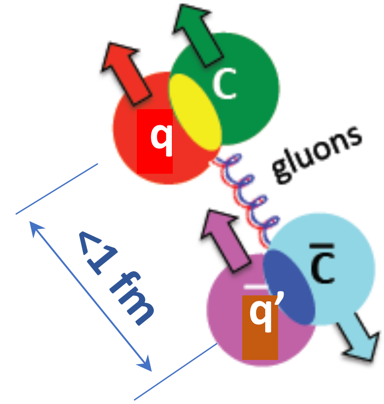
Specific model by
Takizawa & Takeuchi, PTEP 9, 093D01

$$|X(3872)\rangle = 0.94|D^0\bar{D}^{*0}\rangle + 0.23|D^+D^{*-}\rangle - 0.24|c\bar{c}\rangle$$

need a core $c\bar{c}$ state strongly coupled to an S-wave $D^{(*)}\bar{D}^{(*)}$ system

close to a $D^{(*)}\bar{D}^{(*)}$ mass threshold

QCD tetraquarks



ball bearing-like

Maiani et al.,, PRD 71, 014028 (2005)

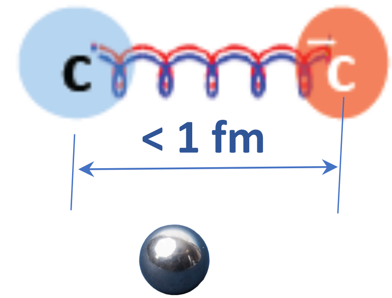
compact & tightly bound by the color force: BE = "∞"

since spin force ~ 1/m_Q, "bad" diquarks are not so bad

most masses and J^{PC} values are accessible for [cq][$\bar{c}\bar{q}$']

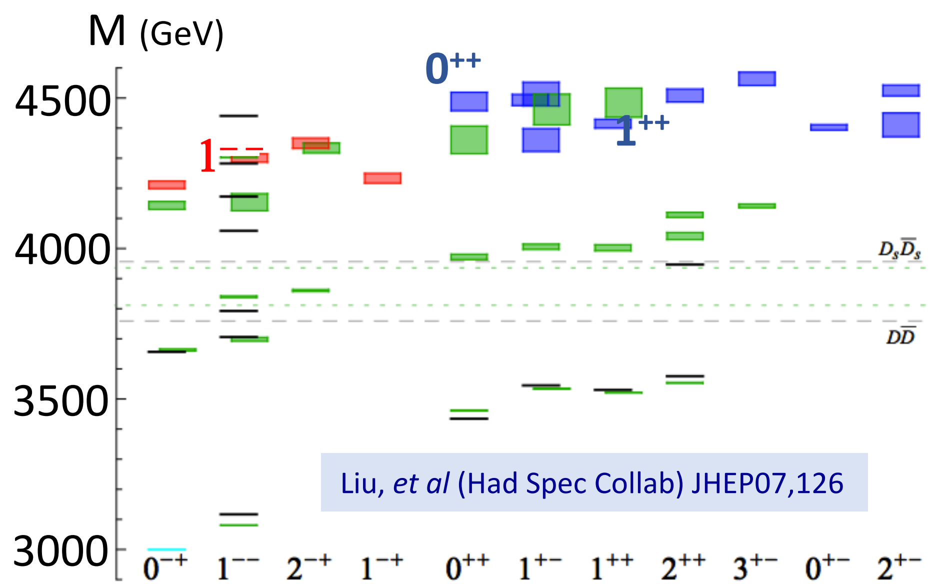
QCD is flavor blind (q=u,d,s) ∴ tetraquark states should come in octets

charmonium hybrids



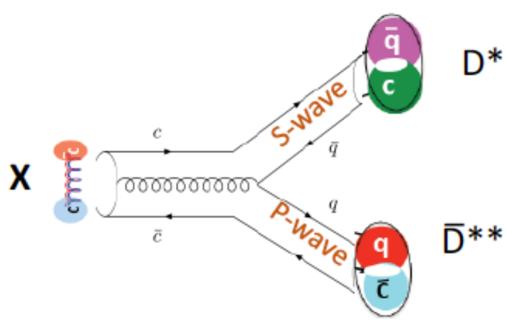
ball bearing-like

LQCD (m_π=400 MeV) predicts high masses
(e.g.: 1^{--}≈4.3 GeV; 0^{++}≈4.5 GeV; 1^{++}≈4.4 GeV)



no charged states

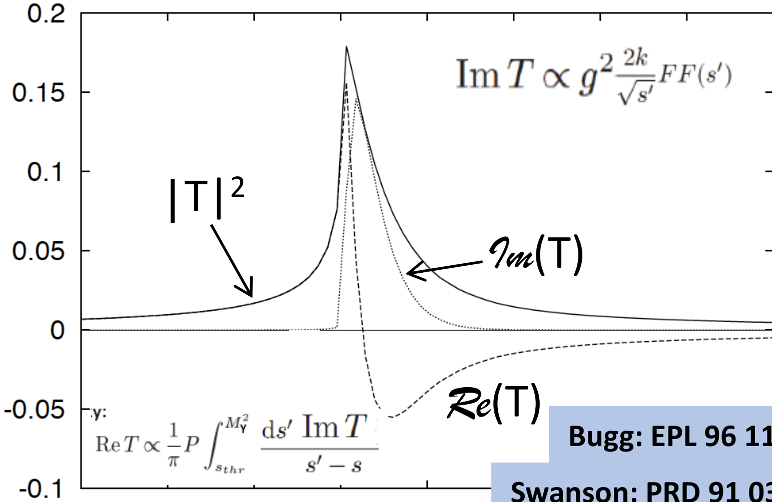
decays to S-wave ⊕ P-wave preferred



Page, Swanson, Szczepaniak, PRD 59, 034016 (1999)

Threshold effects

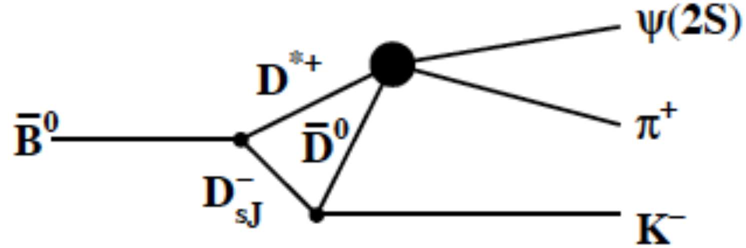
cusps



Bugg: EPL 96 11002 (2011)

Swanson: PRD 91 034009 (2015)

rescattering



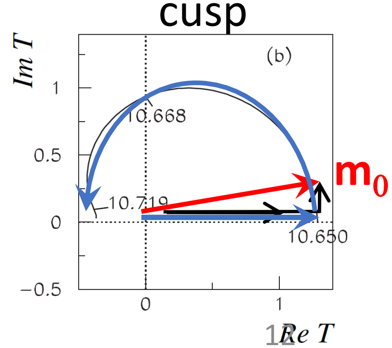
Landau: singular when loop particles are on the mass shell

Pakhlov & Uglov, PLB748,183 (2015)

peaks just above threshold: $a^{-1} = \sqrt{2\mu\delta E} < m_\pi \Rightarrow \delta E < \frac{m_\pi^2}{2\mu} \approx 10\ \mathrm{MeV}\ (\text{for } 2\mu = m_D)$

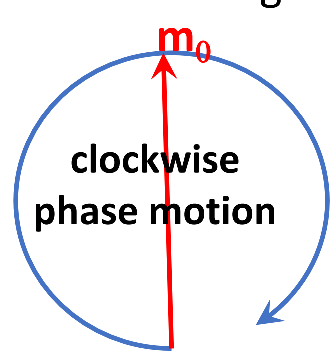
distinctive phase motion:

cusp

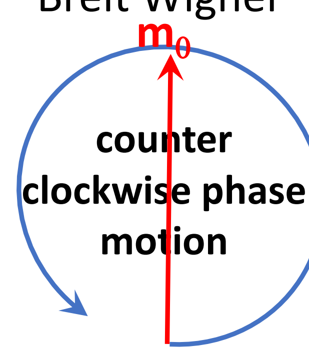


semi-circle

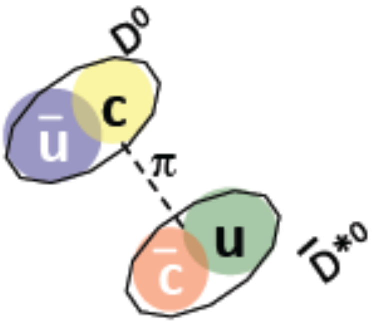
rescattering



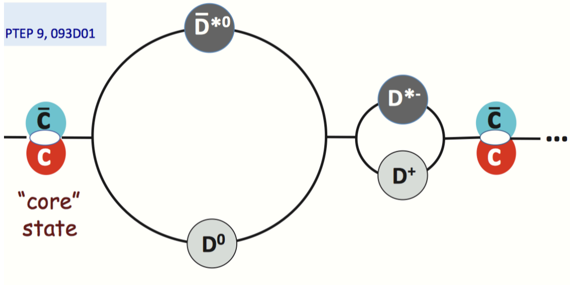
Breit Wigner



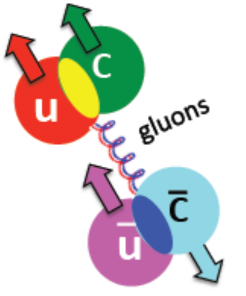
what are they?



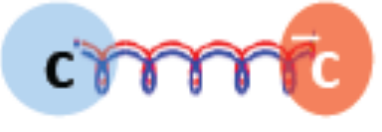
molecules?



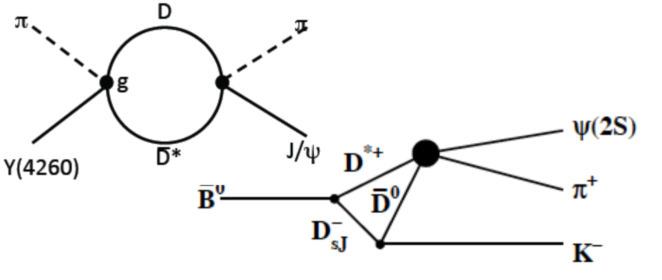
coupled channel system?



QCD tetraquarks?



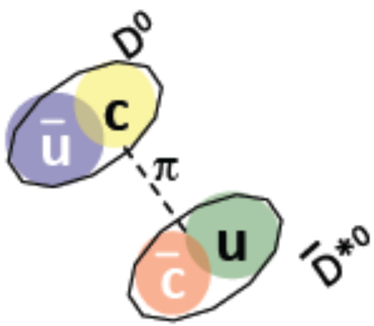
QCD hybrids?



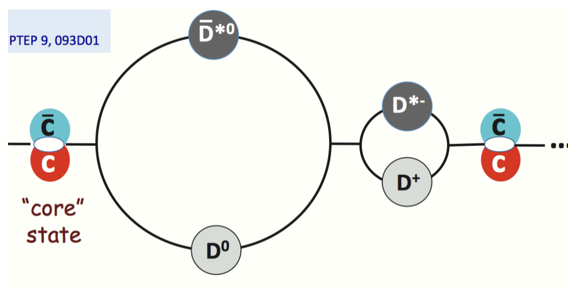
threshold effects?

~~what are they~~?

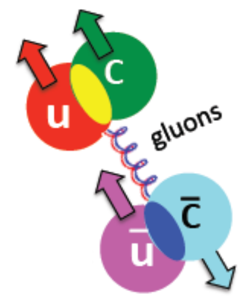
What aren't they?



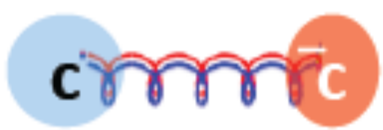
molecules?



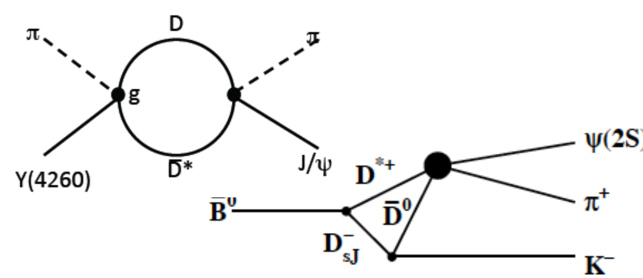
coupled channel system?



QCD tetraquarks?

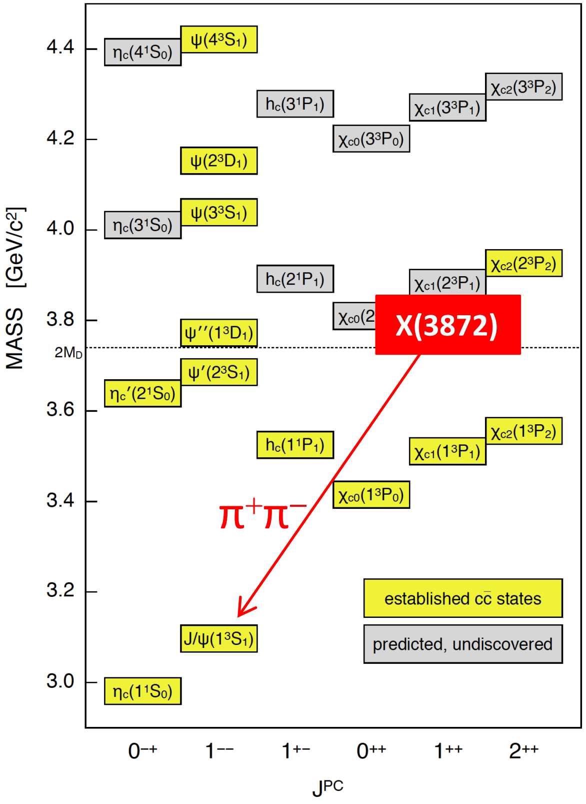


QCD hybrids?



threshold effects?

X(3872)

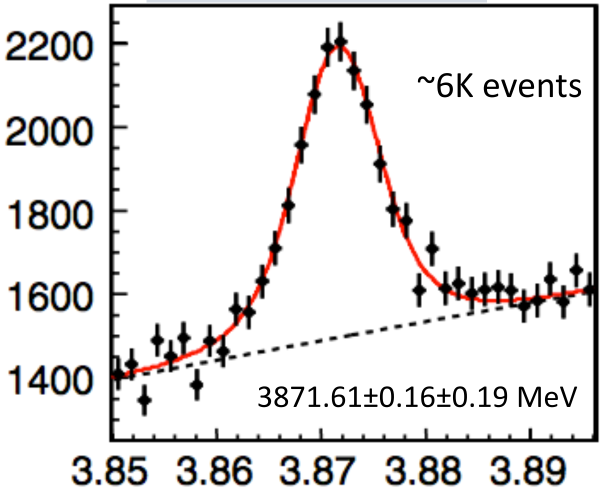


MASS [GeV/c²]
4.4
4.2
4.0
3.8
2MD
3.6
3.4
3.2
3.0
ηc(4¹S0)
ψ(4³S1)
hc(3¹P1)
χc1(3³P1)
χc2(3³P2)
χc0(3³P0)
ψ(2³D1)
ηc(3¹S0)
ψ(3³S1)
hc(2¹P1)
χc1(2³P1)
χc2(2³P2)
χc0(2
X(3872)
ψ''(1³D1)
ψ'(2³S1)
ηc'(2¹S0)
hc(1¹P1)
χc1(1³P1)
χc2(1³P2)
χc0(1³P0)
π⁺π⁻
established cc̄ states
predicted, undiscovered
J/ψ(1³S1)
ηc(1¹S0)
0⁻⁺
1⁻⁻
1⁺⁻
0⁺⁺
1⁺⁺
2⁺⁺
JPC

X(3872) properties

X(3872) & $m_{D^0}+m_{D^{*0}}$ are indistinguishable

CDF PRL 103 152001 (2009)

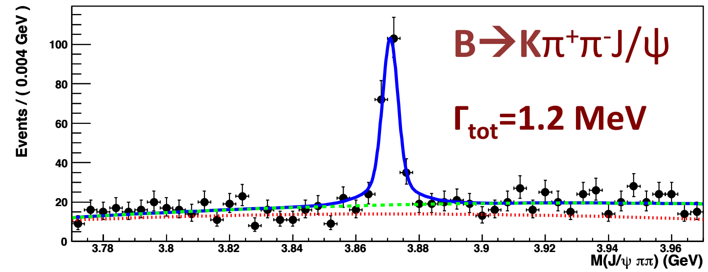


PDG17: $M_{X3872} = 3871.69 \pm 0.17$

$m_{D^0}+m_{D^{*0}} = 3871.85 \pm 0.11$

$$"BE" = (m_{D^0} + m_{D^{*0}}) - M_{X3872} = 0.16 \pm 0.20$$

narrow width: $\Gamma_{X(3872)} \lesssim \Gamma_{\chi c1}$

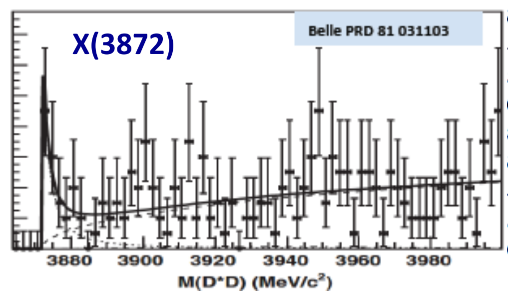


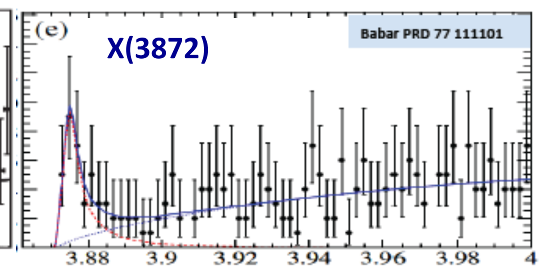
$M(\pi^+\pi^- J/\psi)$

Belle PRD 84 052004 (2011)

Strongly coupled to $D^0\bar{D}^{*0}$

$B \rightarrow K\, D^0\bar{D}^{*0}$



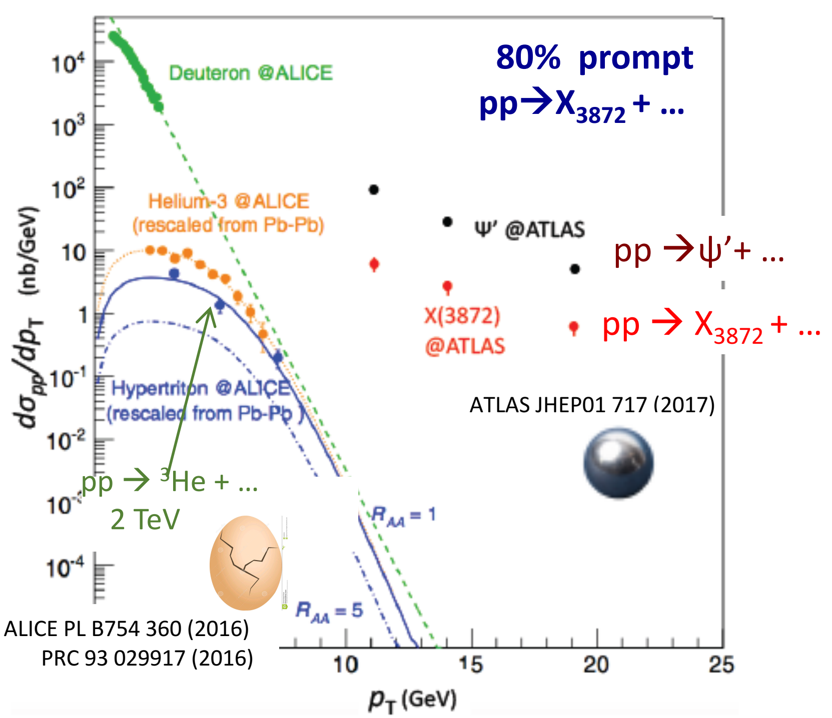


LHCb: $J^{PC} = 1^{++}$

LHCb PRD 92 011102

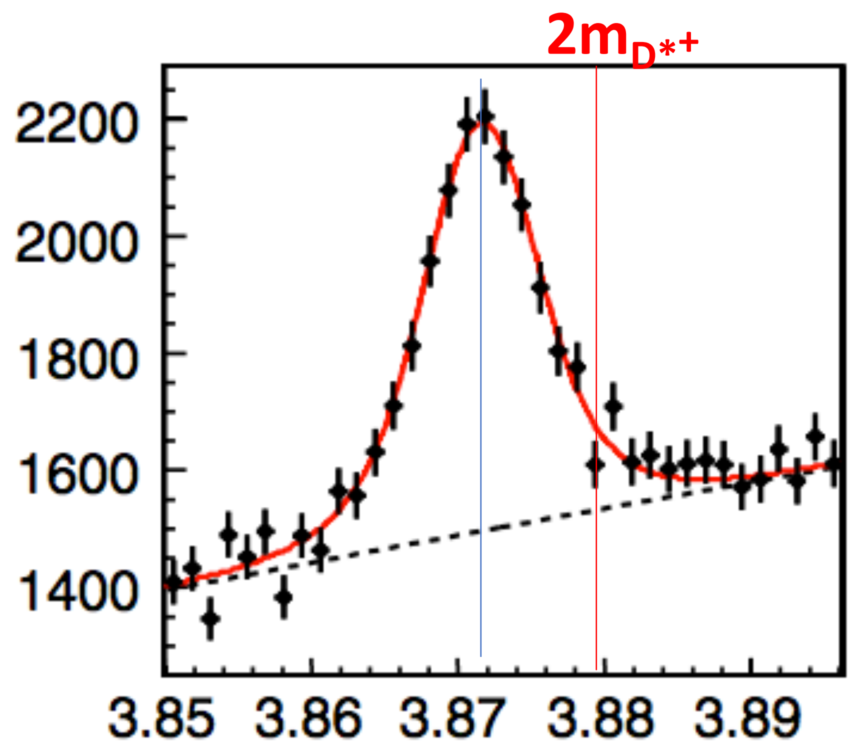
X(3872) = deuteron-like $D^0\bar{D}^{*0}$ molecule?

produced promptly in 7 TeV pp collisions



See Esposito et al., PRD 92 034028 (2015)

no sign of it in D^0/D^{*-} or D^+D^{*-}

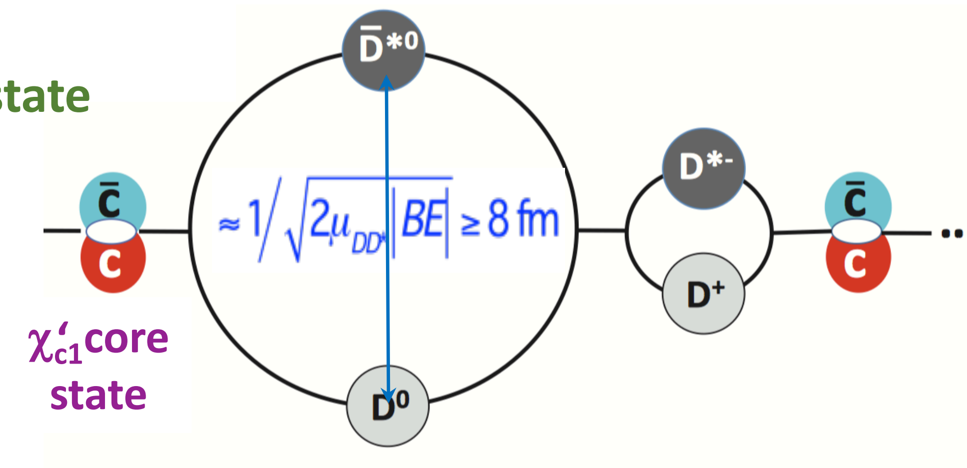


CDF PRL 103 152001 (2009)

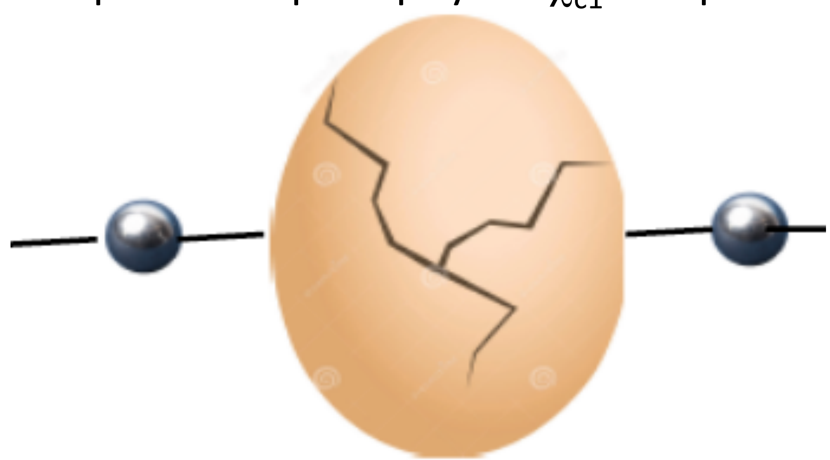
X(3872)=coupled channel state?

$D\bar{D}^* \oplus \chi_{c1}'$ coupled channel state

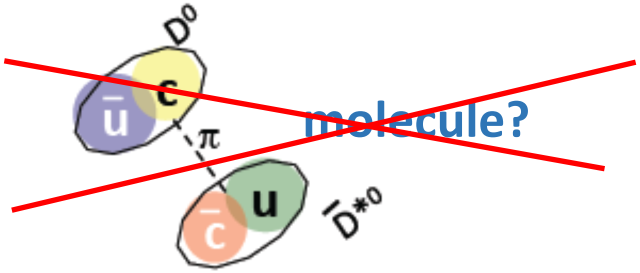
Specific model by
Takizawa & Takeuchi, PTEP 9, 093D01



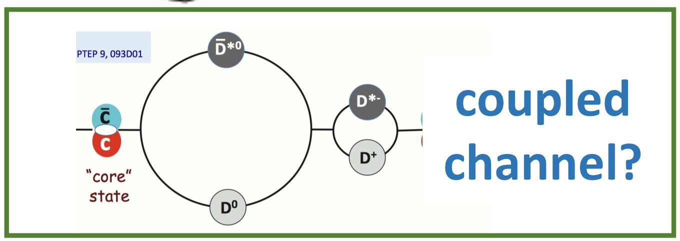
produced promptly via χ_{c1}' component



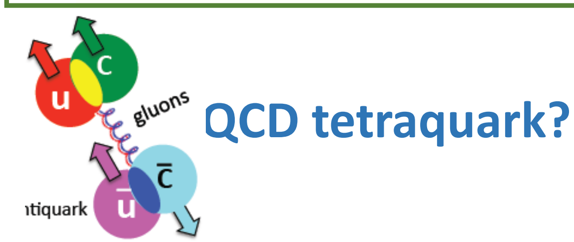
X(3872)



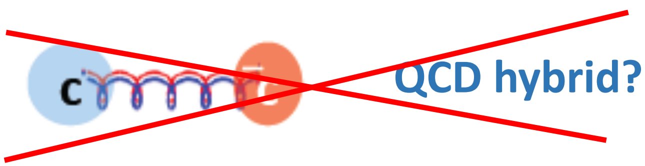
Produced promptly in HE pp collisions
no isopspin-related states are seen



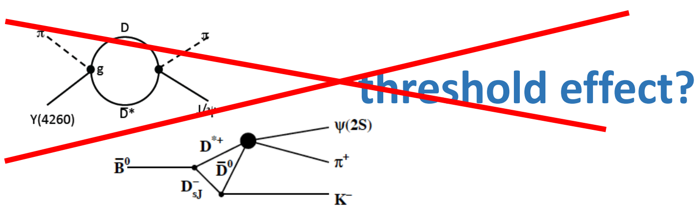
good description   PTEP 9, 093D01 (2013)



PRD 71 014028 (2005)
no 1^{++} partner states seen

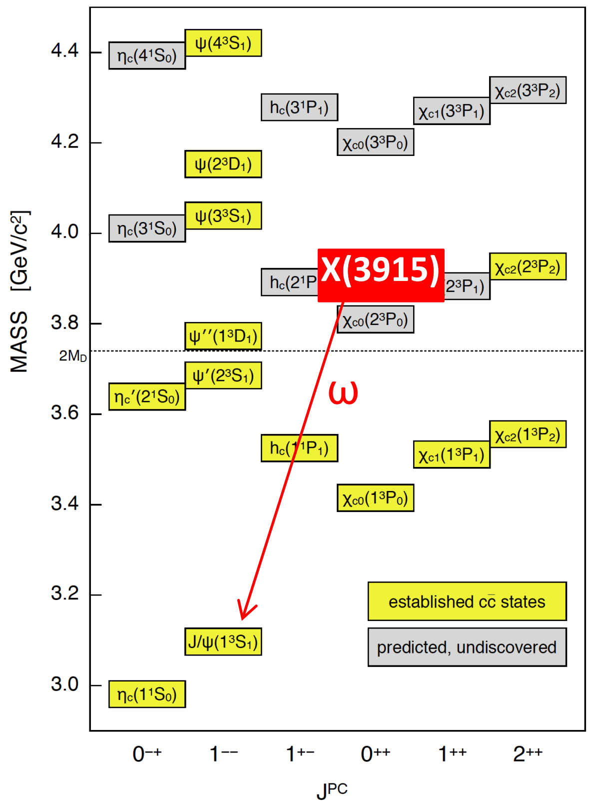


mass is 500 MeV below
LQCD's lightest 1^{++} hybrid



width is too narrow; mass
too close to threshold

X(3915)



4.4
4.2
4.0
3.8
2M$_D$
3.6
3.4
3.2
3.0
MASS [GeV/c^2]
$\eta_c(4^1S_0)$
$\psi(4^3S_1)$
$h_c(3^1P_1)$
$\chi_{c1}(3^3P_1)$
$\chi_{c2}(3^3P_2)$
$\chi_{c0}(3^3P_0)$
$\psi(2^3D_1)$
$\eta_c(3^1S_0)$
$\psi(3^3S_1)$
X(3915)
$h_c(2^1P$
$2^3P_1)$
$\chi_{c2}(2^3P_2)$
$\chi_{c0}(2^3P_0)$
$\psi''(1^3D_1)$
$\psi'(2^3S_1)$
$\eta_c'(2^1S_0)$
ω
$h_c(1^1P_1)$
$\chi_{c1}(1^3P_1)$
$\chi_{c2}(1^3P_2)$
$\chi_{c0}(1^3P_0)$
established $c\bar{c}$ states
predicted, undiscovered
$J/\psi(1^3S_1)$
$\eta_c(1^1S_0)$
0^{-+}
1^{--}
1^{+-}
0^{++}
1^{++}
2^{++}
J^{PC}

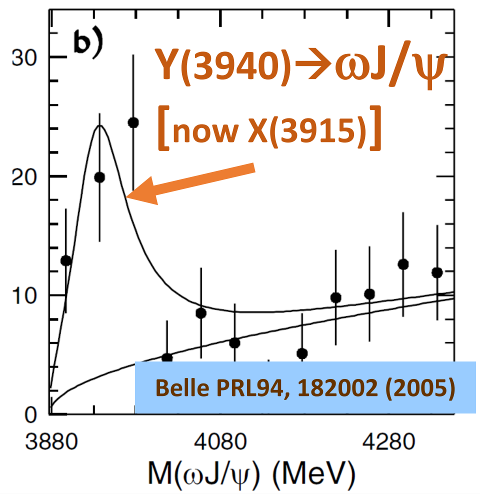
X(3915) -- seen in 2 production channels by 2 experiments --

PDG 2018: $M_{X(3915)} = 3918 \pm 2$ MeV

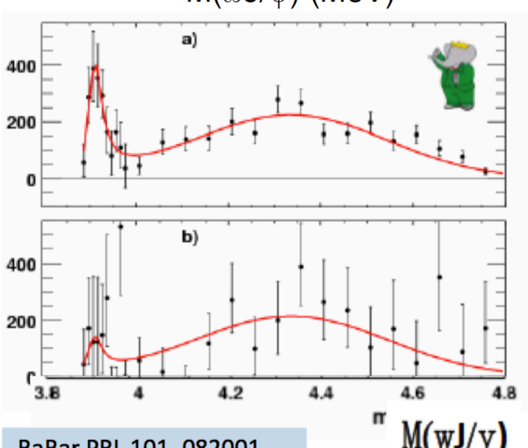
$\Gamma_{X(3915)} = 20 \pm 5$ MeV

$M_{X(3915)} = 2m_{D_s} - 18$ MeV

B→KωJ/ψ



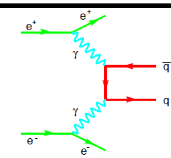
Belle PRL94, 182002 (2005)



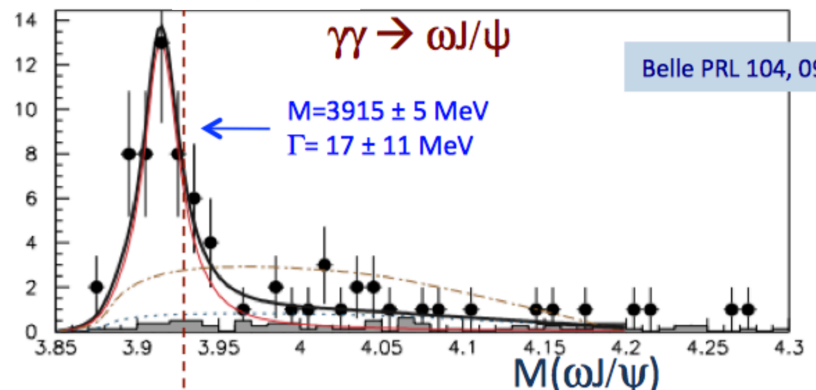
BaBar PRL 101, 082001

$B^{\pm}$→$K^{\pm}$ωJ/ψ

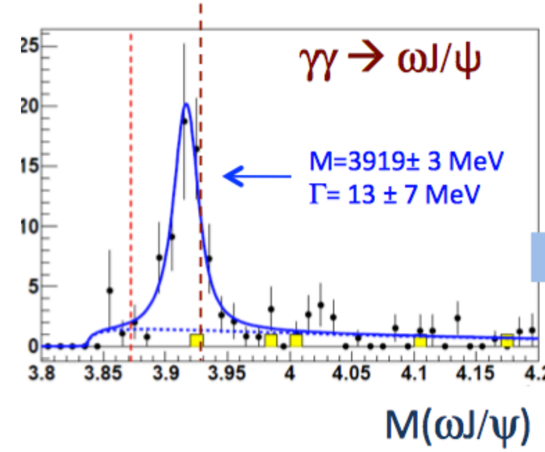
B^0→K_SωJ/ψ



γγ→ωJ/ψ

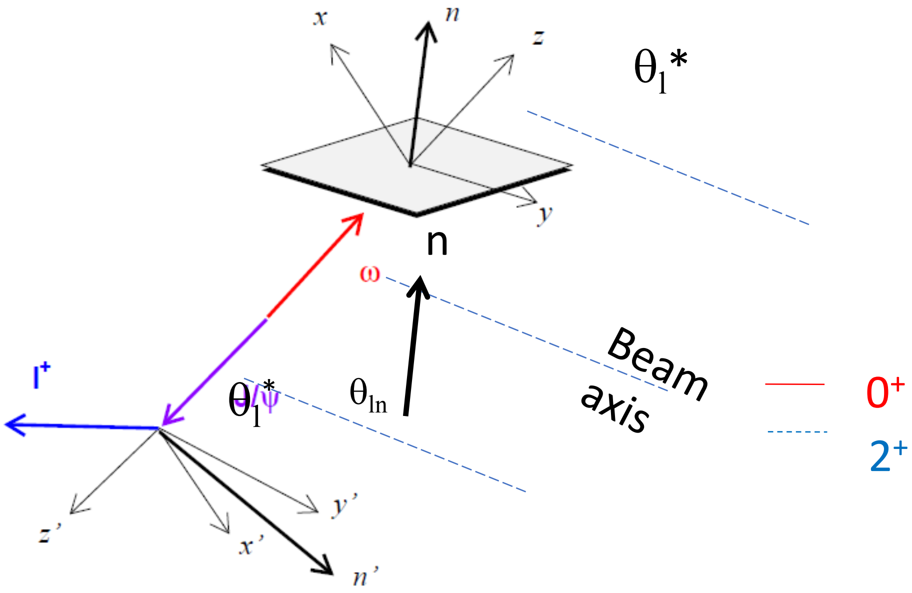


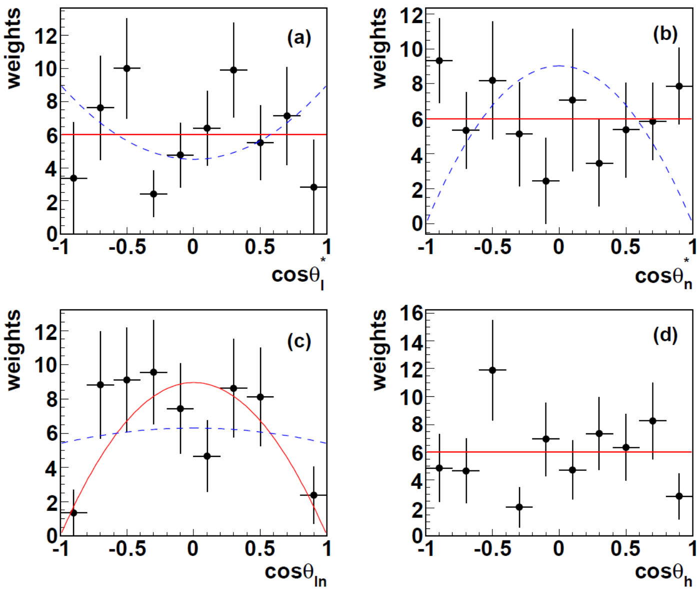
Belle PRL 104, 092001 (2010)



BaBar PRD 86, 072002 (2012)

BaBar measurements prefer $J^{PC}=0^{++}$



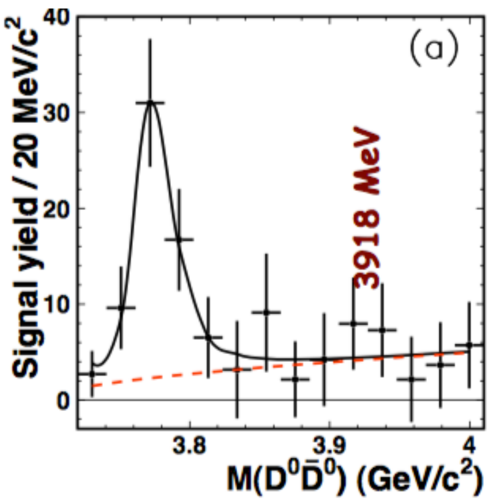


BaBar PRD 86, 072002 (2012)

no sign of X(3915)→ $D\bar{D}$

-- in either $B \to K D\bar{D}$ or $\gamma\gamma \to D\bar{D}$ --

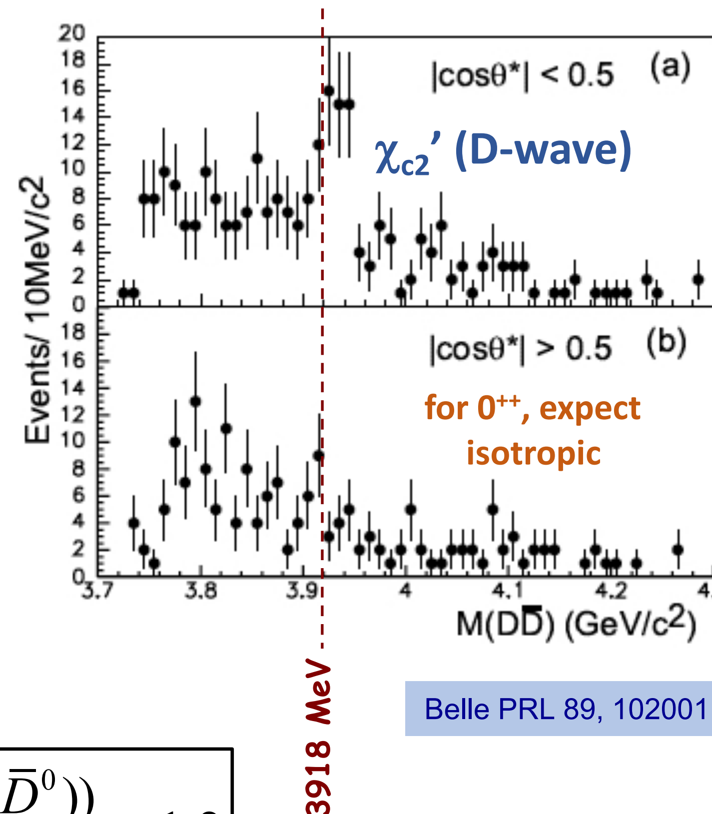
$B \to K D\bar{D}$ (Belle)



⇨ **$\Gamma(X_{3915}) \to D\bar{D}) < 1$ MeV**

J. Brodzicka et al. (Belle) PRD 100, 092001

$\gamma\gamma \to K D\bar{D}$ (Belle)



Belle PRL 89, 102001 (2002)

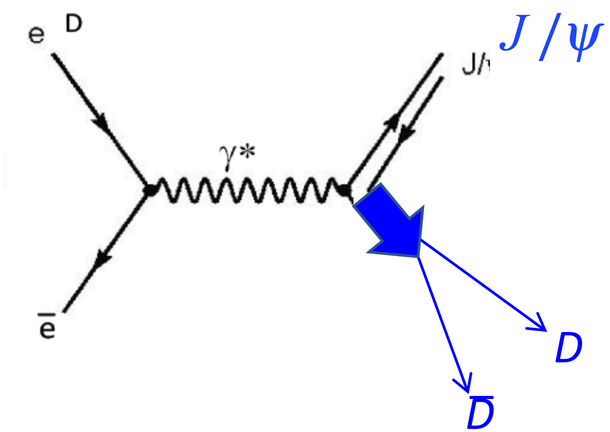
$$\frac{Bf(X(3915) \to D^0 \bar{D}^0))}{Bf(X(3915) \to \omega J/\psi))} < 1.2$$

SLO PRD91, 057501 (2015)

X(3915)→ωJψ/ is OZI-rule violating for a $c\bar{c}$ meson

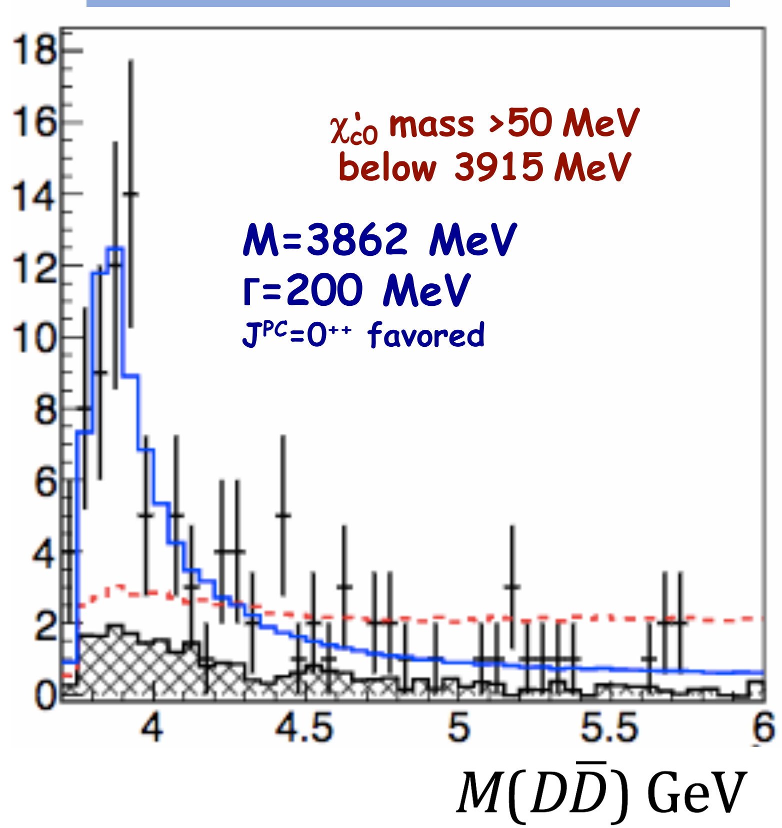
& it isn't the χ'_{c0} charmonium state

Belle found the "real" χ'_{c0} last year

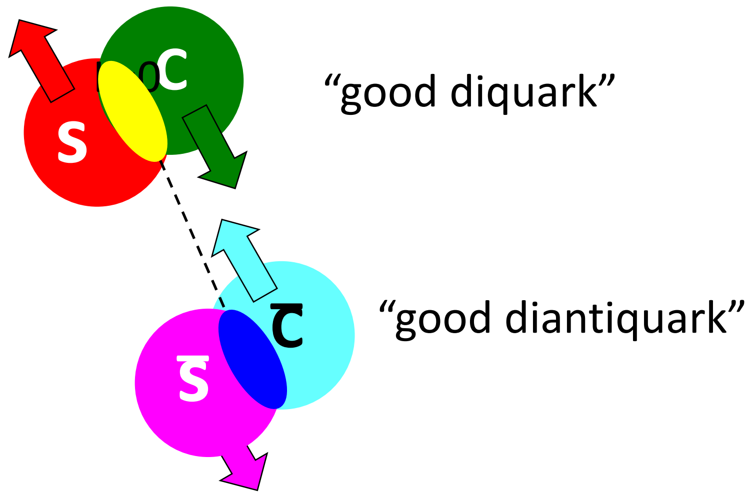


$$e^+e^- \to J/\psi\ \chi'_{c0}$$
$$\hookrightarrow D\bar{D}$$

K. Chilikin et al. (Belle) PRD 95, 092003c(2017)

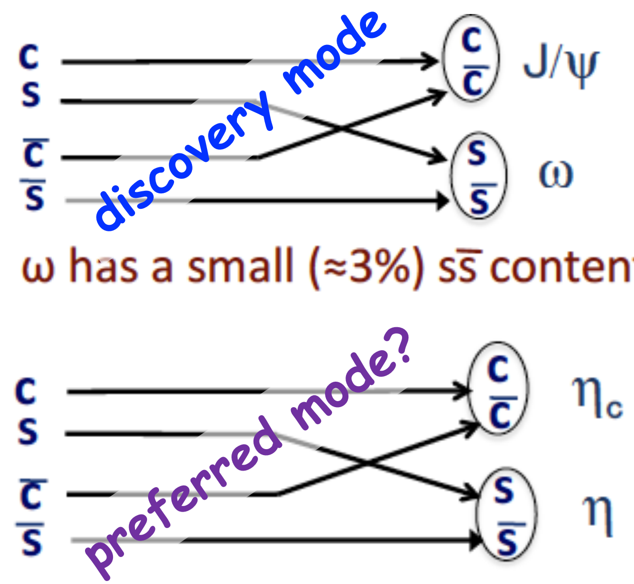


a $J^{PC}=0^{++}$ $cs\bar{c}\bar{s}$ tetraquark?



no "fall-apart" decays to $D\bar{D}$

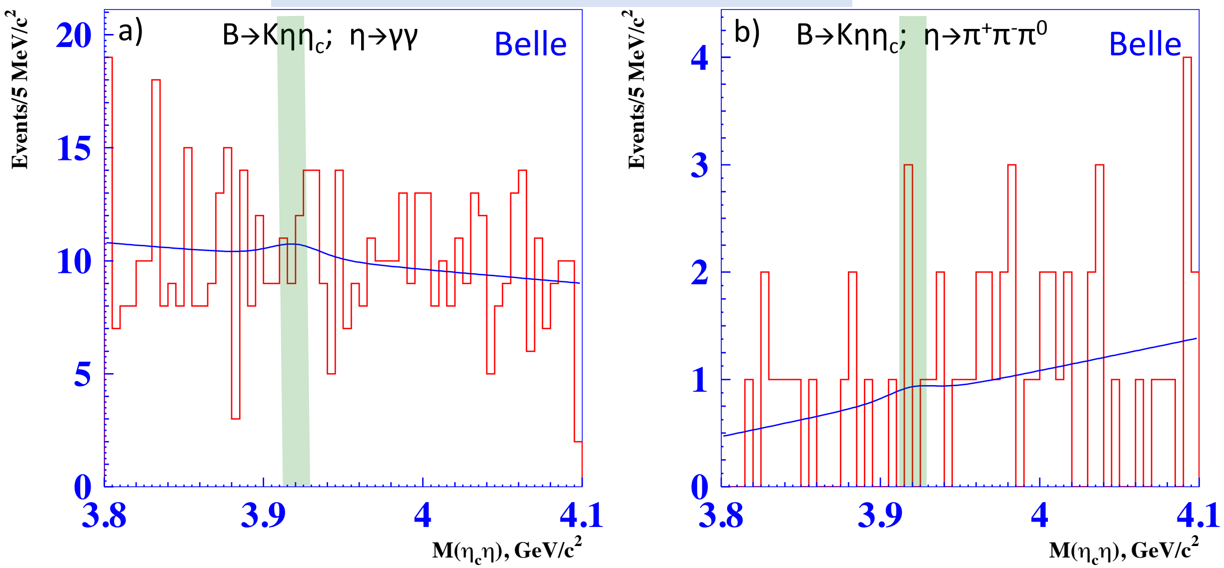
OZI-allowed decay processes:



Expect: $\frac{Bf(X(3915))\to\eta\eta_c}{Bf(X(S915))\to\omega J/\psi}\gg 1$

No sign of X(3915)→$\eta_c\eta$

Vinokurova *et al* (Belle) JHEP06,132 ← plus erratum



$$\mathcal{B}(B^+ \to K^+X(3915)) \times \mathcal{B}(X \to \eta\eta_c) < 4.7 \times 10^{-5}$$

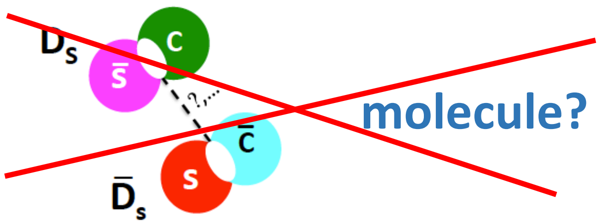
$$\mathcal{B}(B^+ \to K^+X(3915)) \times \mathcal{B}(X \to \omega J/\psi) = 3.0^{+0.9}_{-0.7} \times 10^{-5}$$

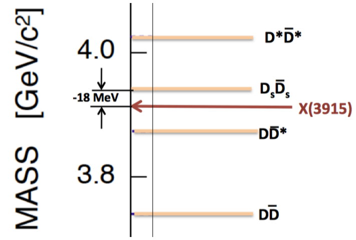
⇨

$$\frac{Bf(X \to \eta_c\eta)}{Bf(X \to J/\psi\ \omega)} < 2$$

not good for a tetraquark interpretation

X(3915)



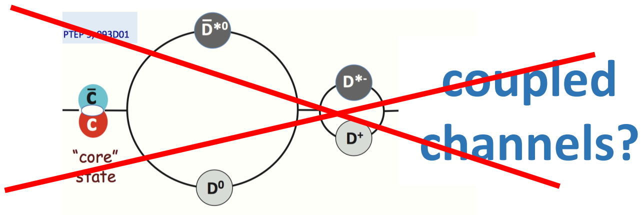


$D_s\bar{D}_s$ B.E. (≈18 MeV) large

$D^*\bar{D}^*$ B.E. (≈100 MeV) *very* large

π-exchange forbidden for $D_s\bar{D}_s$

but see: PRD91 114014 (2015)

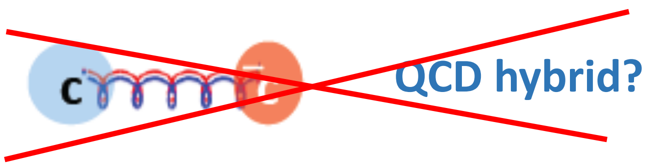


no nearby $D\bar{D}$ threshold

no candidate $c\bar{c}$ core state

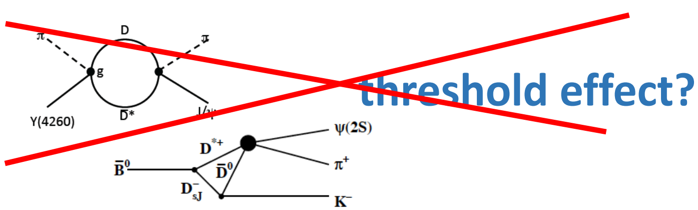
possible $[cs][\bar{c}\bar{s}]$ tetraquark PRD93, 094024 (2016)

-- no sign of X(3915)→$\eta\eta_c$ or partner states



mass is 500 MeV below

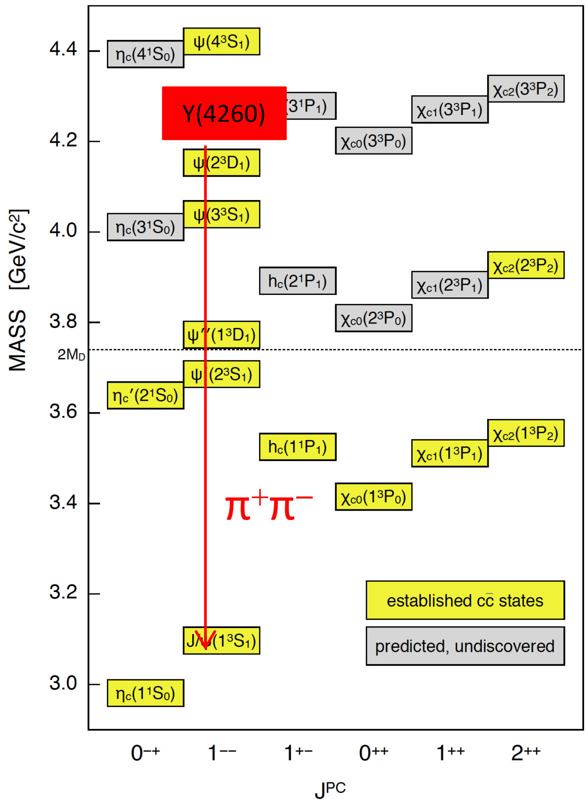
LQCD's lightest 0^{++} hybrid



mass is *below* the only

nearby threshold

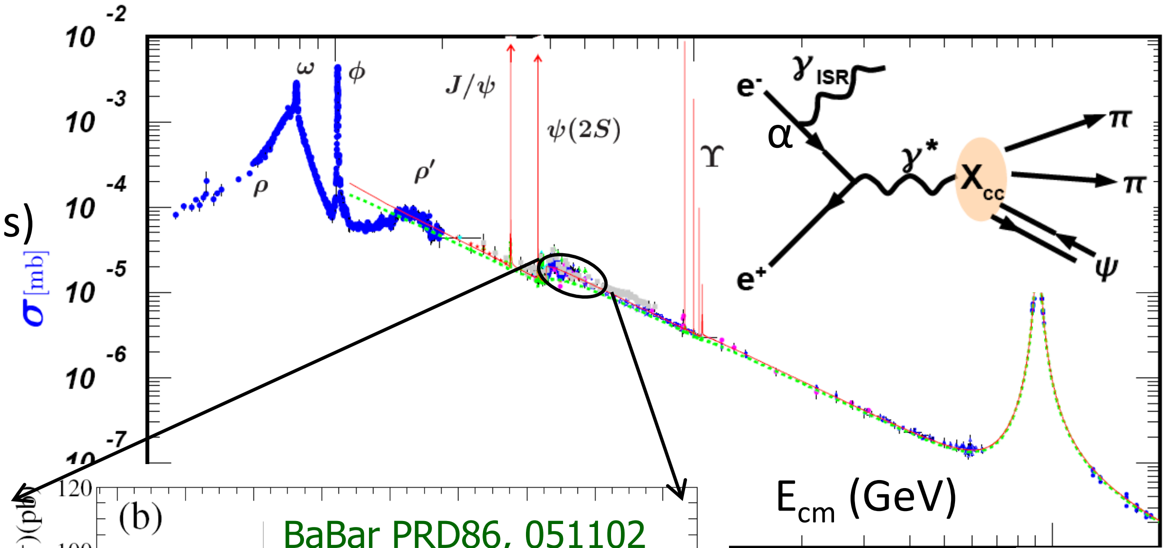
Y(4260)



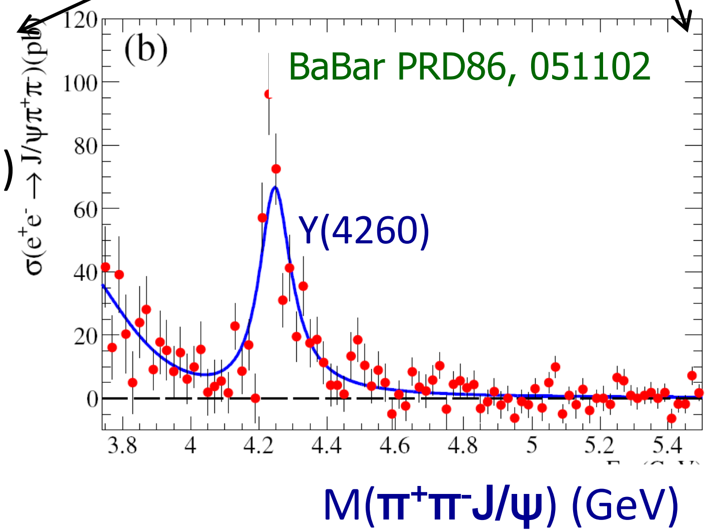
4.4
4.2
4.0
3.8
3.6
3.4
3.2
3.0
MASS [GeV/c²]
2M_D
ηc(4¹S₀)
ψ(4³S₁)
Y(4260)
(3¹P₁)
χc2(3³P₂)
χc1(3³P₁)
χc0(3³P₀)
ψ(2³D₁)
ηc(3¹S₀)
ψ(3³S₁)
hc(2¹P₁)
χc2(2³P₂)
χc1(2³P₁)
χc0(2³P₀)
ψ″(1³D₁)
ψ′(2³S₁)
ηc′(2¹S₀)
hc(1¹P₁)
χc2(1³P₂)
χc1(1³P₁)
χc0(1³P₀)
π⁺π⁻
J/ψ(1³S₁)
ηc(1¹S₀)
established cc̄ states
predicted, undiscovered
0⁻⁺
1⁻⁻
1⁺⁻
0⁺⁺
1⁺⁺
2⁺⁺
J^PC

found by BaBar in $e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi$

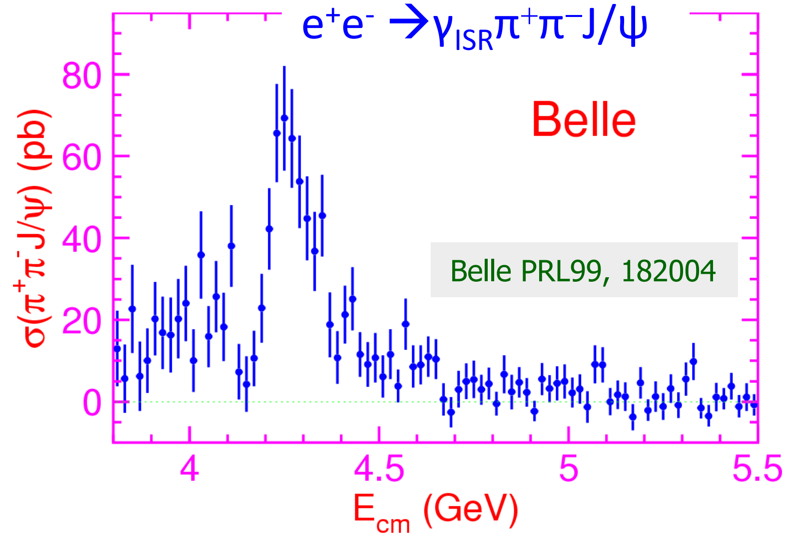
σ(e⁺e⁻ → hadrons)



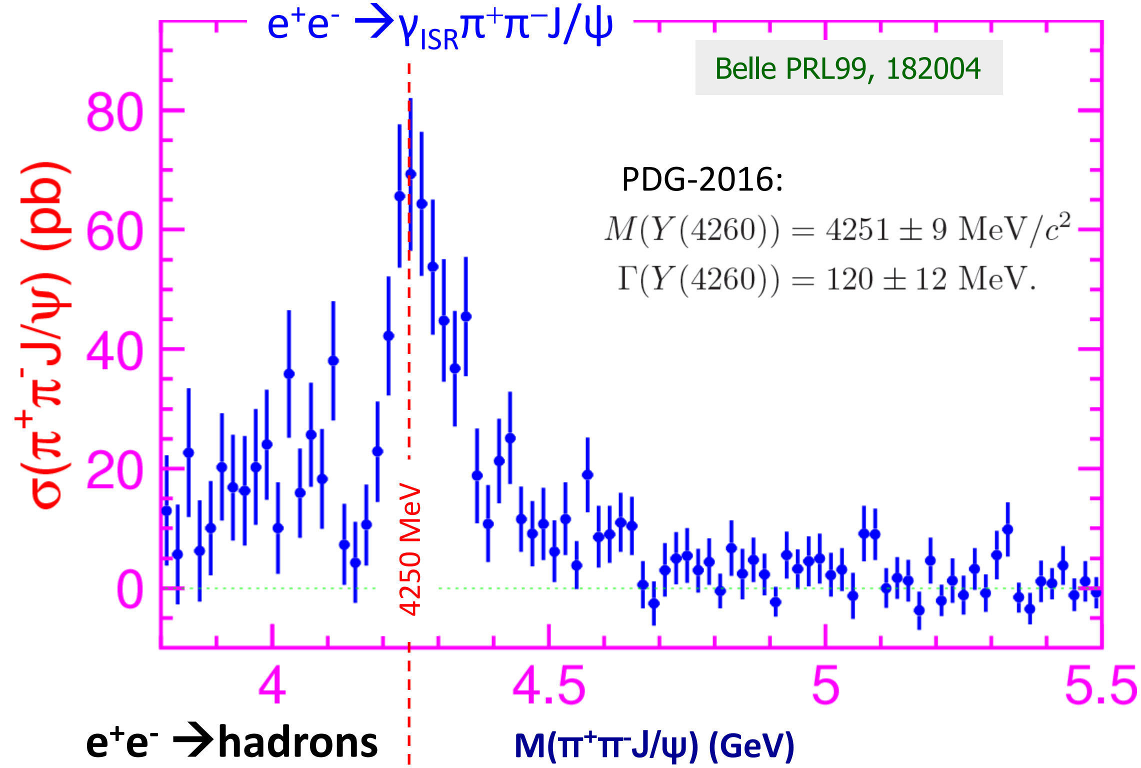
σ(e⁺e⁻ → **π⁺π⁻J/ψ**)

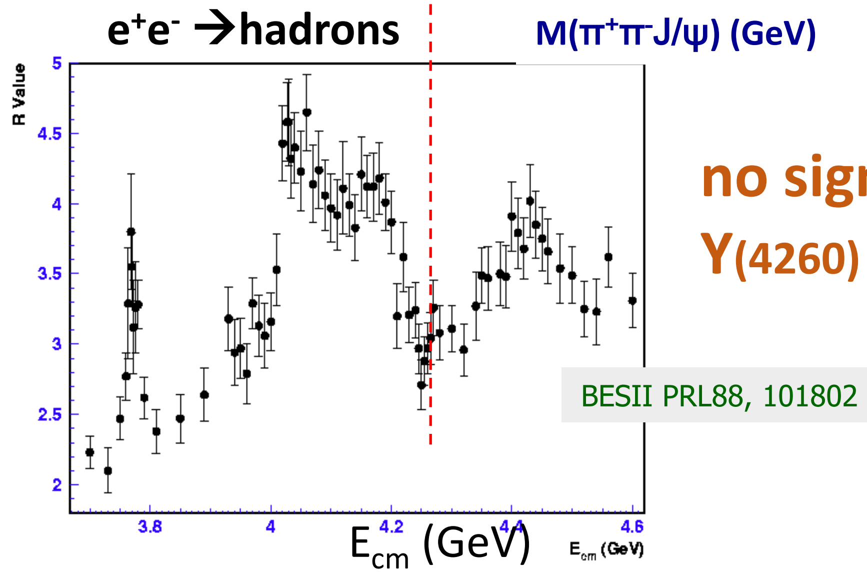


confirmed by Belle
$e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi$



peculiar fact 1: $\pi\pi J/\psi$ peak at a dip in R_{had}





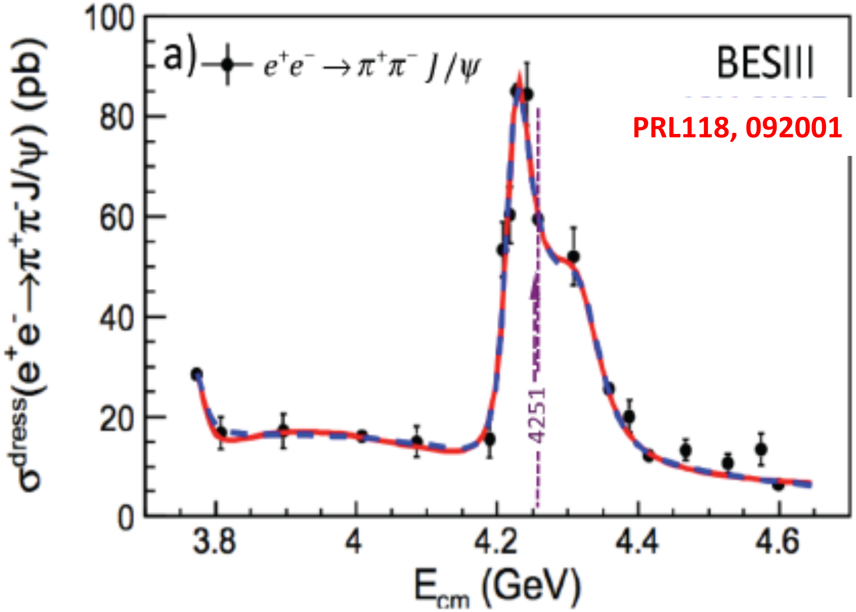
$\Gamma(\pi^+\pi^- J/\psi)$ is large, but
should be OZI suppressed if $c\bar{c}$

no sign of
$Y(4260) \to D^{(*)}\bar{D}^{(*)}$

peculiar fact 2: Y(4260)→ππJ/ψ is 2 peaks

-- one at ≈4220 MeV & one at ≈4320 MeV --

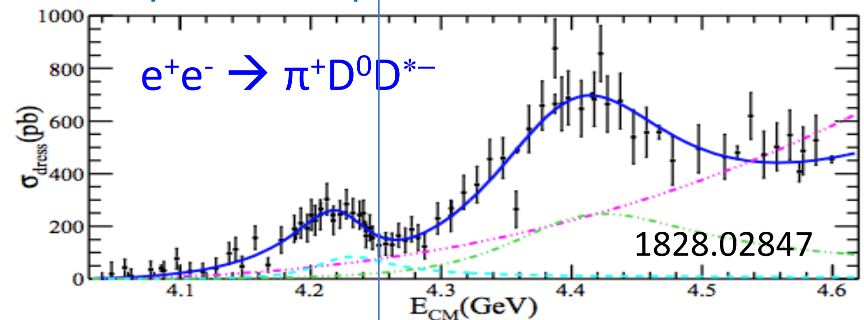
2 peaks in $e^+e^- \to \pi^+\pi^-J/\psi$

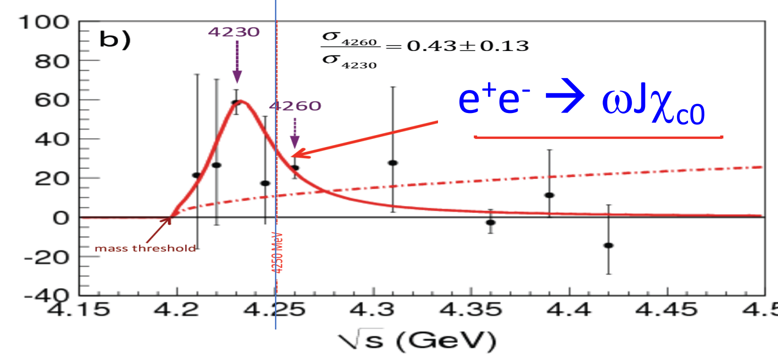


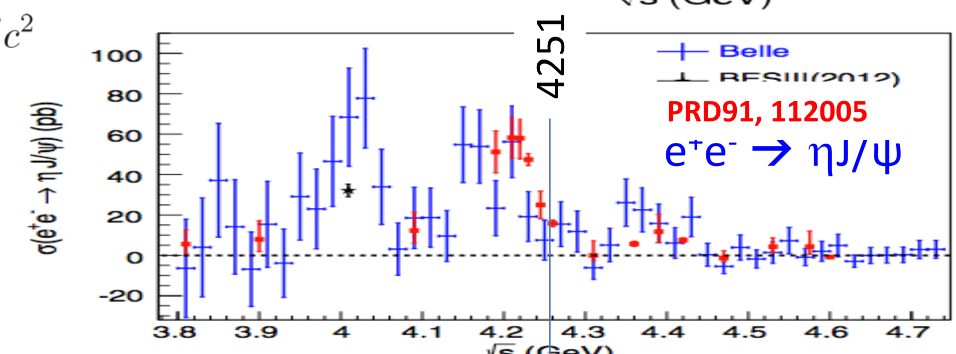
$M_1 = 4220 \pm 4\ \mathrm{MeV}/c^2$ $M_2 = 4320 \pm 13\ \mathrm{MeV}/c^2$

$\Gamma_1 = 44 \pm 5\ \mathrm{MeV}$ $\Gamma_2 = 101^{+27}_{-22}\ \mathrm{MeV}$

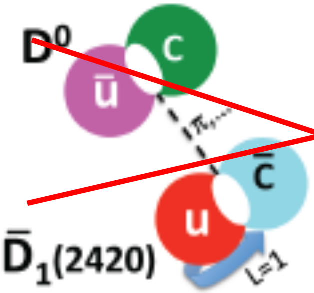
only the lower peak seen in other channels





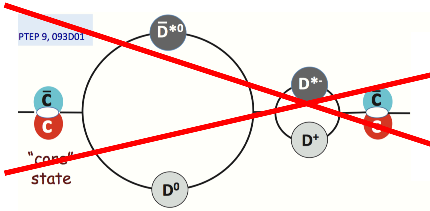


Y(4260)



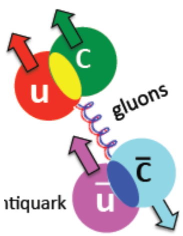
molecule?

$DD_1(2460)$ BE (≈65 MeV) is very large
-- but see PRD 90, 074039



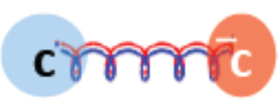
coupled channels?

no candidate $c\bar{c}$ state or nearby $D\bar{D}$ threshold
-- but see PRD 94, 054035



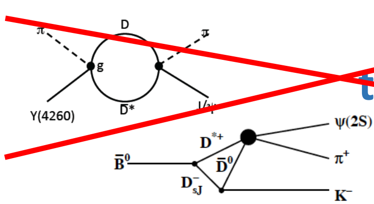
QCD tetraquark?

$[cq][\bar{c}\bar{q}]$ tetraquark
-- but no partner states have been identified



QCD hybrid?

PLB 631 164 (2005)
≈80 MeV below LQCD's lightest 1^{--} hybrid



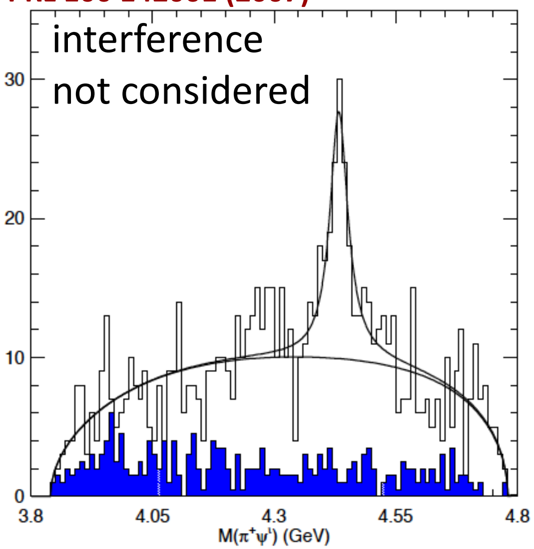
threshold effect?

mass is *below* the only relevant threshold

What about the charged Z states?

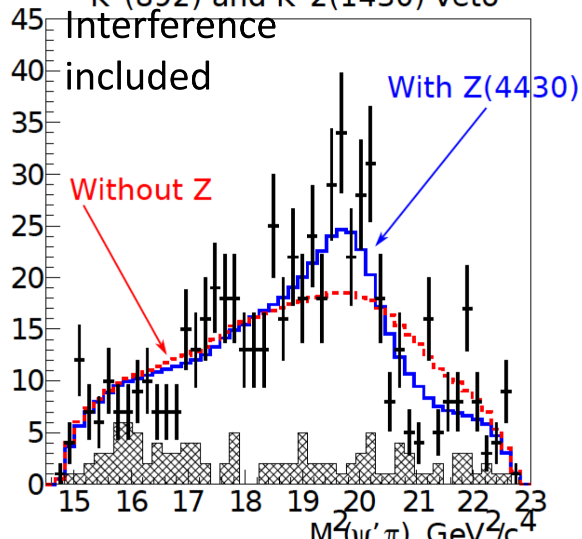
Z(4430) found by Belle; confirmed by LHCb

Belle: PRL 100 142001 (2007)



Belle: PRD 88 074026 (2013)

K*(892) and K*2(1430) veto



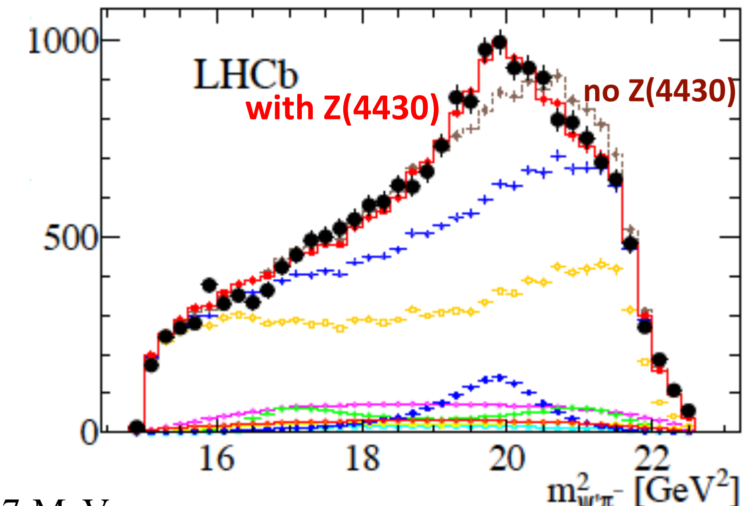
PDG 2018 average

$$M(Z(4430)) = 4478 \pm 17 \text{ MeV}$$

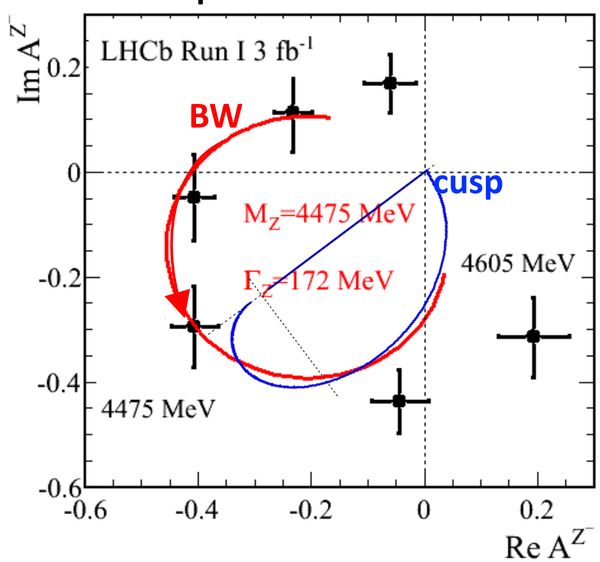
$$\Gamma(Z(4430)) = 181 \pm 31 \text{ MeV}$$

LHCb: PRL 112 222002 (2014)

no K* vetoes



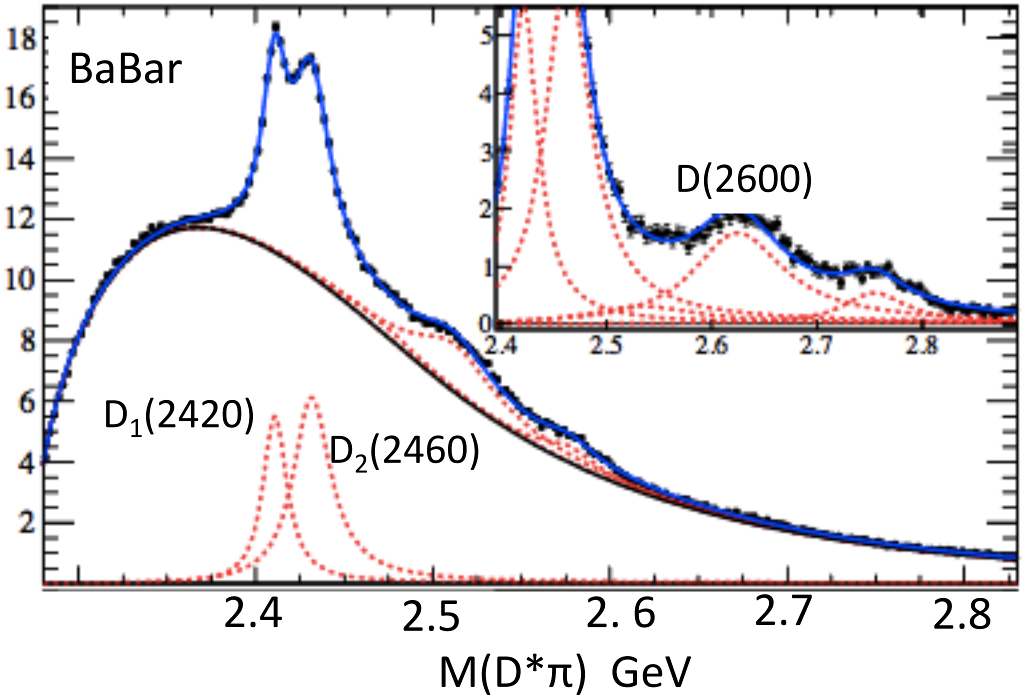
BW-like phase motion confirmed

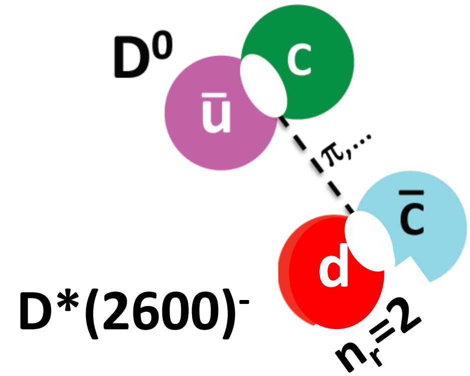


$D\bar{D}^*(2S)$ molecule

-- ($D^*(2S)$=radially excited D^*?) --

BaBar: Phys. Rev. D82, 111101



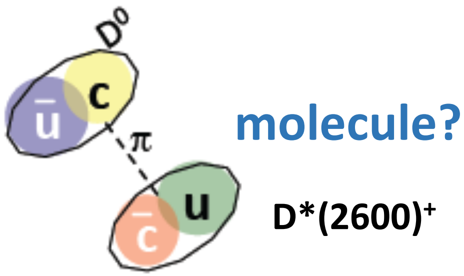


$$M(D(2600)) = 2609 \pm 4 \text{ MeV}$$

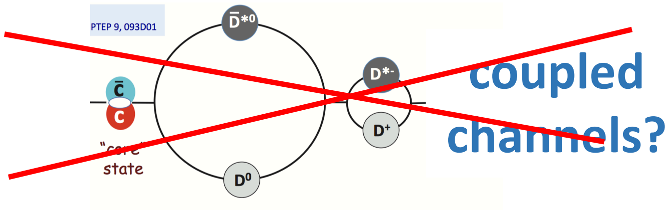
$$\Gamma(D(2600)) = 93 \pm 15 \text{ MeV}$$

"B.E."= $(m_{D^+} + m_{D^*(2S)}) - M_{Z(4430)} \approx 0 \pm 18 \text{ MeV}$

Z(4430)

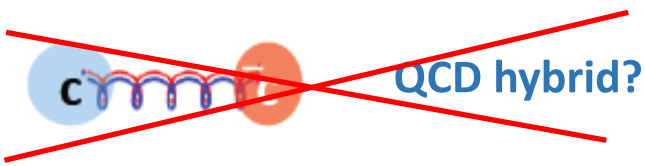


Γ(Z(4430)≈180 MeV & Γ(D*(2600)) ≈100 MeV too short-lived for a molecule?

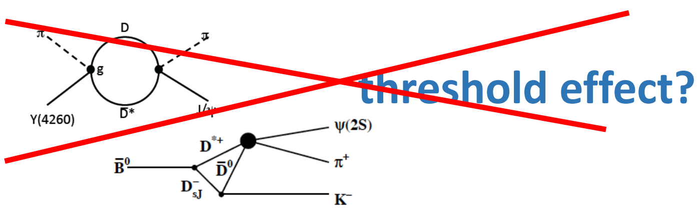


no charged cc core states

PRD 89 114010 (2012) / PRL 113, 112001 (2014)
no partner states seen



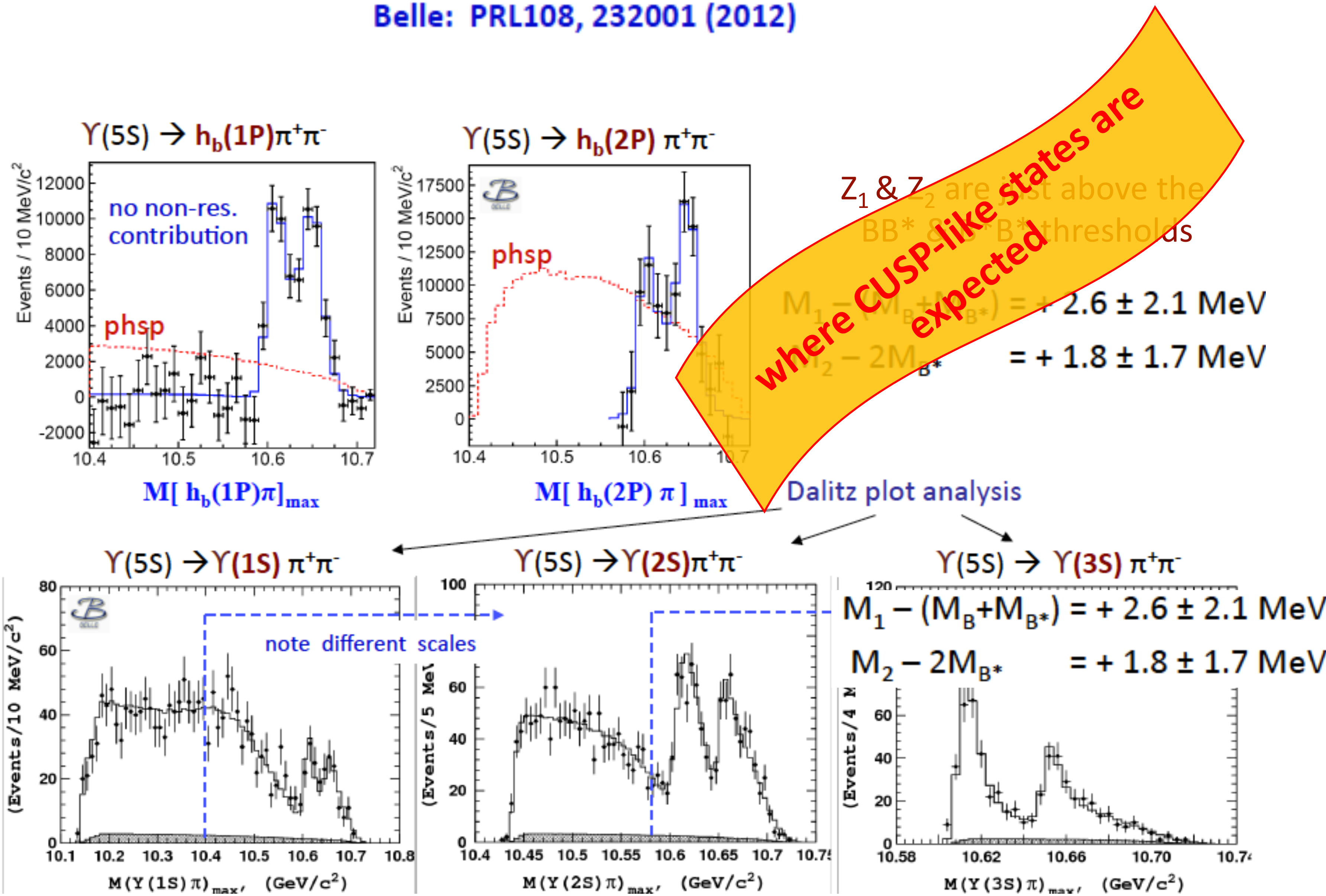
no charged cc-gluon states



Argand plot favors BW-like phase motion

Z_b states discovered by Belle

Belle: PRL108, 232001 (2012)

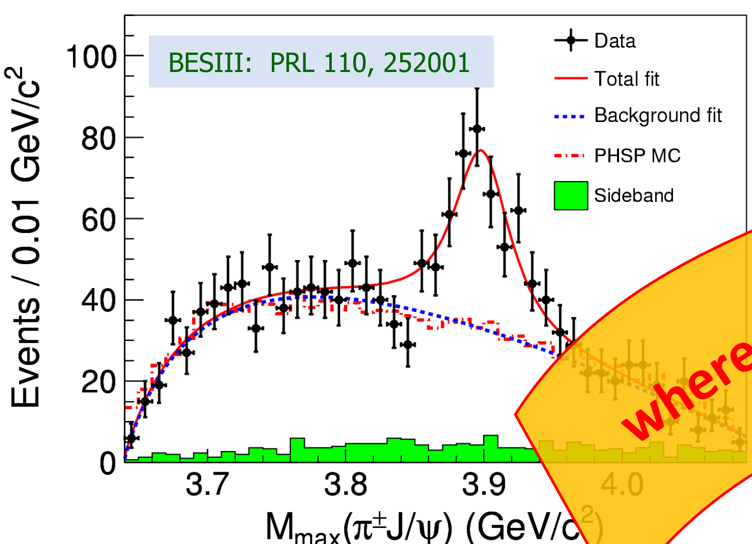


$M_1 - (M_B + M_{B^*}) = +2.6 \pm 2.1$ MeV

$M_2 - 2M_{B^*} = +1.8 \pm 1.7$ MeV

Z_c states discovered by BESIII & Belle

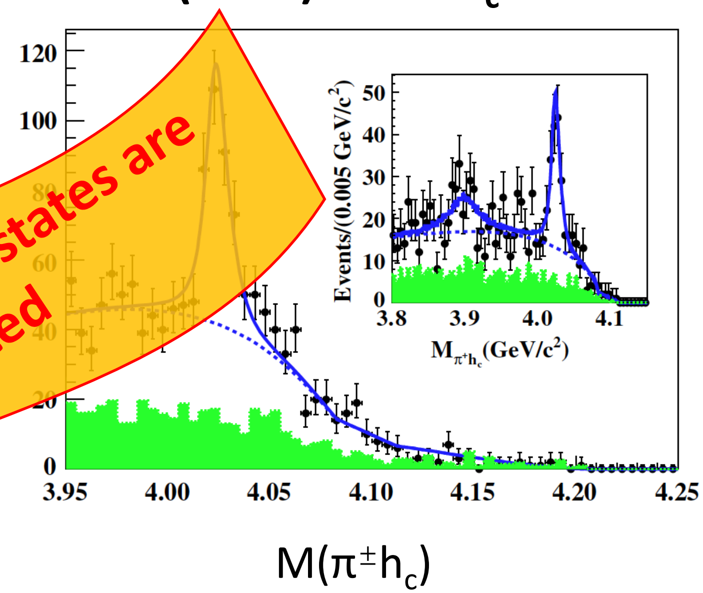
$Y(4260) \to \pi^+\pi^- J/\psi$



12 ± 3 MeV above D^0D^{*-} thresh.

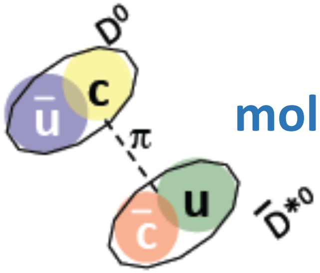
Also seen by Belle:
BESIII: PRL110, 252002

$Y(4260) \to \pi^+\pi^- h_c$



5.6 ± 2.8 MeV above $D^{*0}D^{*-}$ thresh.

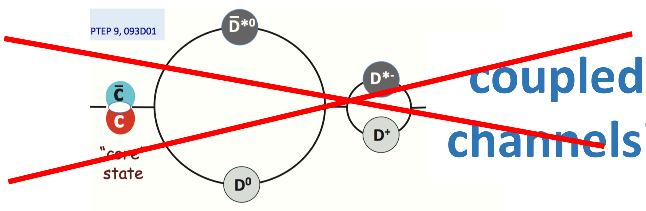
Z_c(3900/Z_c(4020) & Z_1(10610)/Z_2(10650)



molecules?

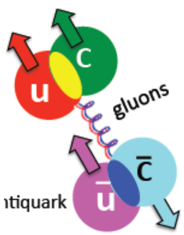
just above DD*/D*D* (BB*/B*B*) thresholds

-- but no phase motion measurements



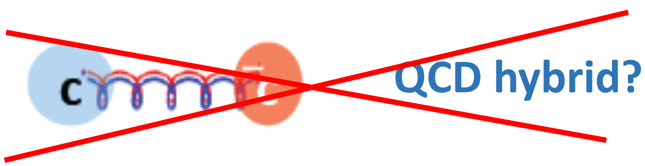
coupled channels?

no charged cc core states



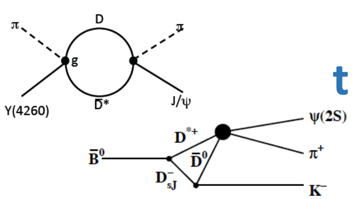
QCD tetraquark?

PRD87 111102 (2013)
no partner states seen



QCD hybrid?

no charged cc-gluon states



threshold effect?

similar to expectations for cusps
EPL 96 11002 (2011) / PRD 91 034009 (2015)

-- Argand plots are needed

Scorecard

state	Molecule?	Coupled-channel	Tetraquark?	Hybrid?	Threshold effect?
X(3872)	problem with pp production	Yes	partners not seen	m≈500 MeV too low	narrow/ at threshold
X(3915)	no 1-π exchange allowed	no $c\bar{c}$ core or $D\bar{D}$ thresh.	partners not seen	m≈500 MeV too low	below threshold
Y(4260) (Y(4220))?	$D \oplus \bar{D}_1(2420)$? B.E.≈65 MeV	no $c\bar{c}$ core or $D\bar{D}$ thresh.	partner not seen	m≈65 MeV too low	no nearby threshold
Z(4430)	$D \oplus \bar{D}^*(2S)$? short lifetimes	no $c\bar{c}$ core state	partner not seen	electrically charged	below threshold
$Z_c(3900)$ $Z_c(4020)$	≈7 MeV *above* DD* (D*D*) threshold	no $c\bar{c}$ core state	partner not seen	electrically charged	need Argand plot
$Z_1(10610)$ $Z_2(10650)$	≈2MeV *above* BB* (B*B*) threshold	no $c\bar{c}$ core state	partner not seen	electrically charged	need Argand plot

only the X(3872) has a clear assignment

Comments:

the X(3872) seems unique & not closely related to the other XYZ states

QCD-tetraquark model can account for everything & predict nothing

A "deuson-like" bound molecule has not yet been seen

Y(4220) is the only XYZ hybrid possibility, but this assignment is not compelling

Comments:

the X(3872) seems unique & not closely related to the other XYZ states

QCD-tetraquark model can account for everything & predict nothing

A “deuson’-like bound molecule has not yet been seen

Y(4220) is the only XYZ hybrid possibility, but this assignment is not compelling

to do list for experimenters:

are X(3915) seen in B→KωJ/ψ & X(3915) seen in γγ→ωJ/ψ the same state?
-- need separate J^{PC} measurements

is *Bf*(X(3915)→$\eta\eta_c$) < *Bf*(X(3915)→ωJ/ψ)?
-- If so, it's bad for the QCD-tetraquark model

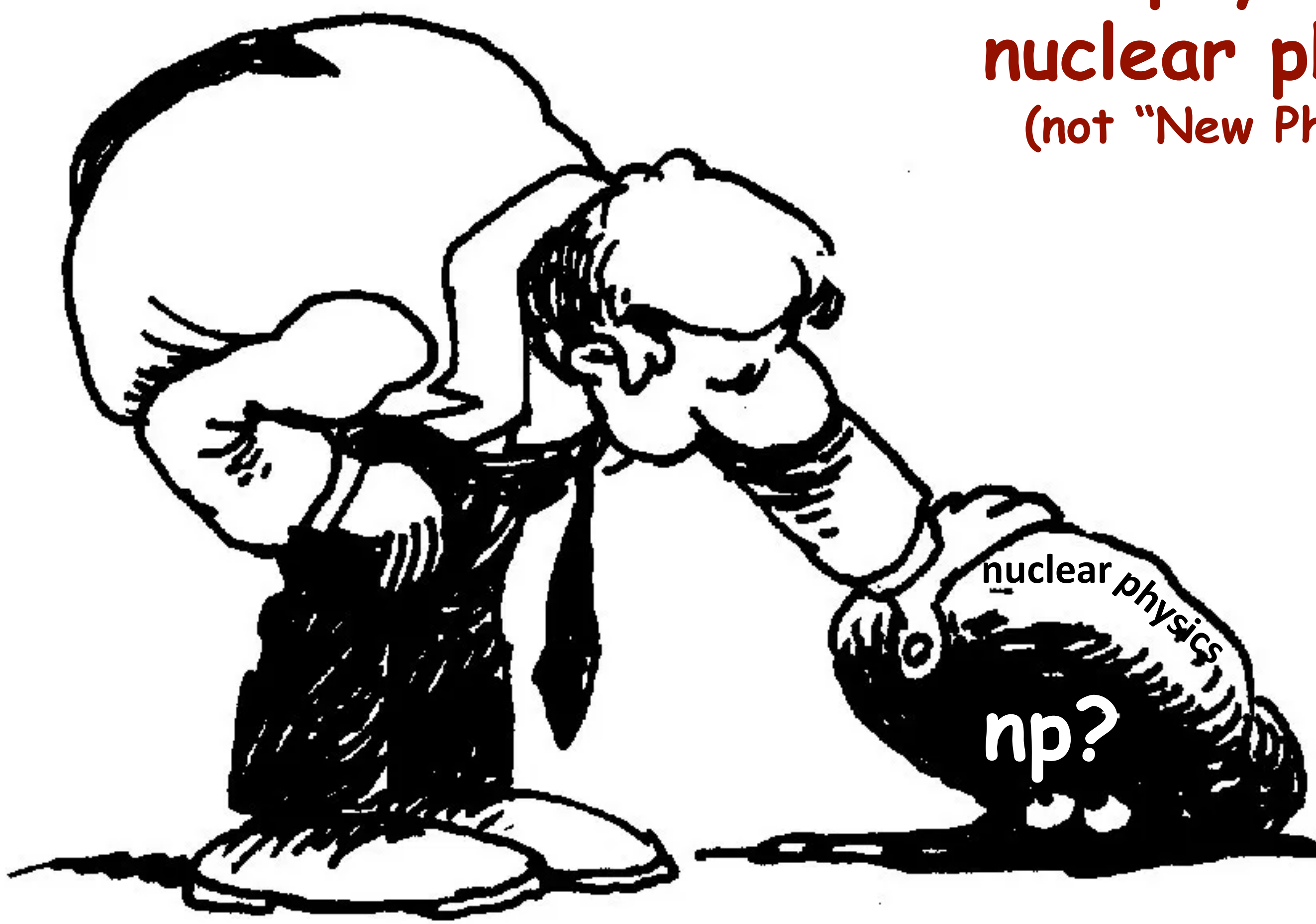
Argand plots for the Z_c ($Z_{1,2}$) states are desperately needed

***Bf*(B→KZ_c(3900/4020))=? ; *Bf*(B→KY(4220))=?**

time-like baryon form-factors from BaBar, CMD3 and BESIII

time-like baryon form-factors from BaBar, CMD3 and BESIII

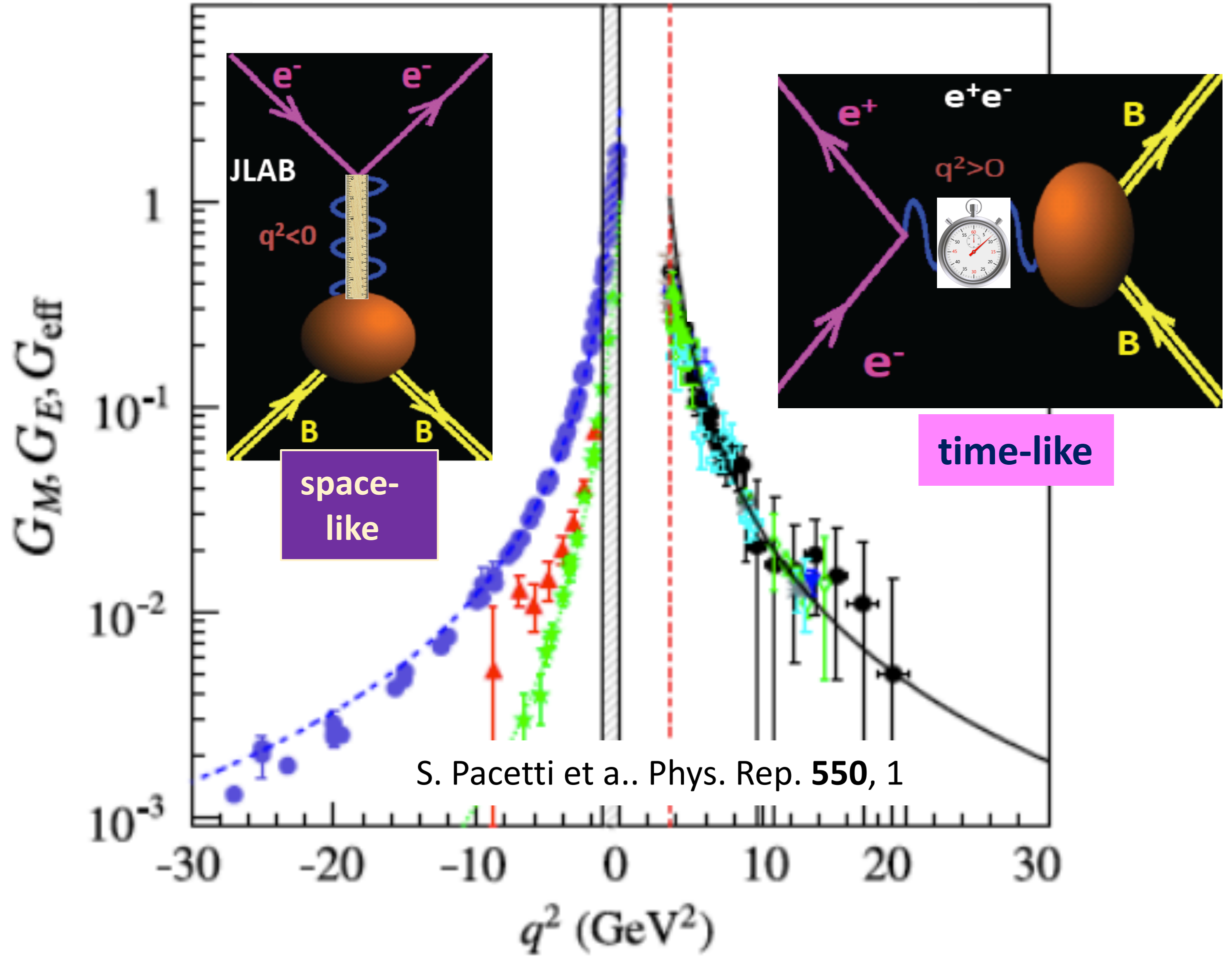
new physics in nuclear physics?
(not "New Physics")



Time-like & space-like form-factors

Crossing symmetry:

$$\langle N(p')|j^{\mu}|N(p)\rangle \rightarrow \langle \overline{N}(p')N(p)|j^{\mu}|0\rangle$$



S. Pacetti et a.. Phys. Rep. **550**, 1

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

-- formulae & definitions --

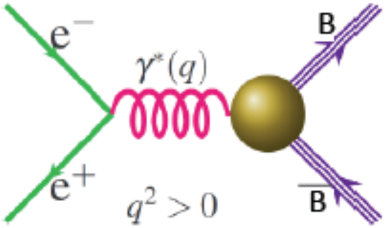
Sachs form factors

$$G_E = F_1 + \frac{q^2}{4M^2} F_2$$
$$G_M = F_1 + F_2$$

$G_E(0) = Q_N$
$G_M(0) = \mu_N$

Born cross section:

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



time-like "Sachs" form-factors

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

$$\tau = \frac{m^2_{B\bar{B}}}{4M^2_B} \qquad \beta = \sqrt{1-\frac{1}{\tau}}$$

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

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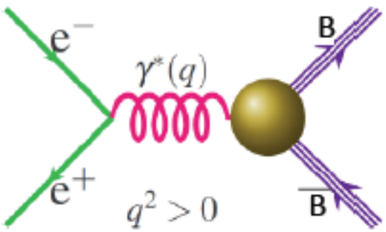

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*C*oulomb enhancement factor

$$C_{\text{charged}} = \frac{\pi\alpha/\beta}{1-\exp(-\pi\alpha/\beta)} \xrightarrow{(\beta\to 0)} \pi\alpha/\beta$$

$$C_{\text{neutral}} = 1$$

in point-like approx

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

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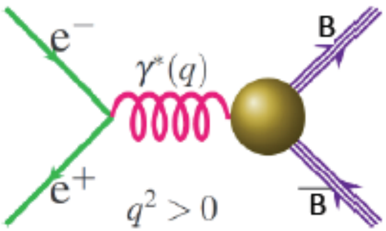

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integrated cross section:

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

"effective" form factor

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

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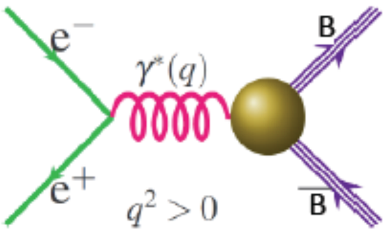

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effective form factor:

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

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

-- formulae & definitions --

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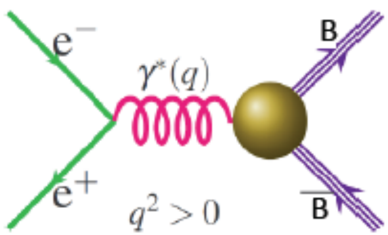

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in point-like approx

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effective form factor:

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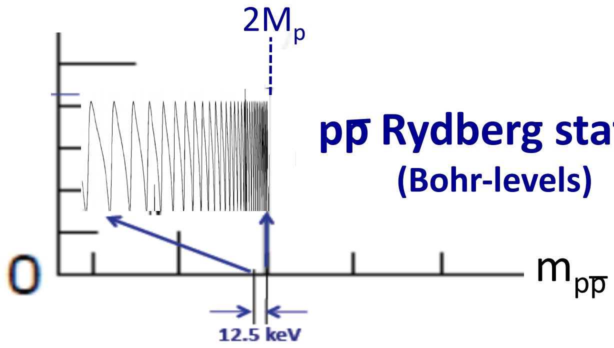
analyticity:

$$G_M(4M_B^2) = G_E(4M_B^2) \;\Rightarrow\; G_{eff}(4M_B^2) = G_M(4M_B^2)$$

$e^+e^- \rightarrow p\bar{p}$ at threshold

Integrated cross section:

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



$p\bar{p}$ Rydberg states

(Bohr-levels)

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

Sommerfeld resummation factor

$e^+e^- \rightarrow p\bar{p}$ at threshold

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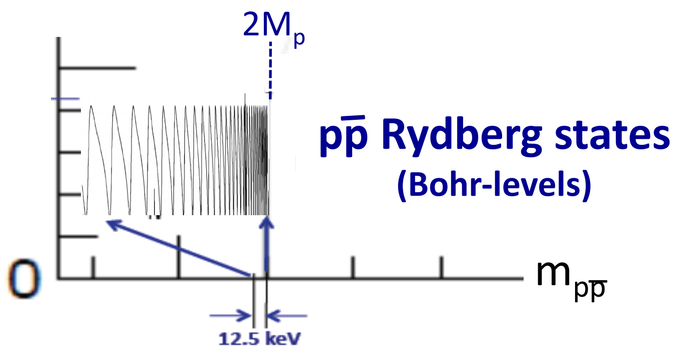

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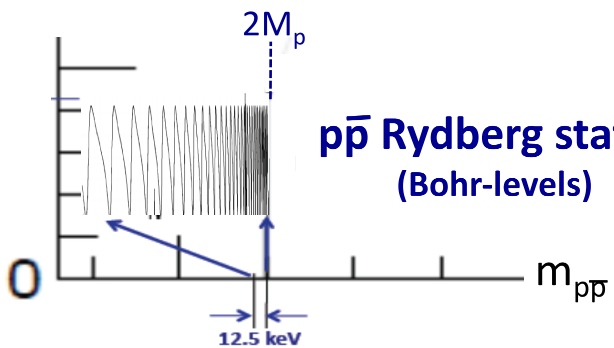


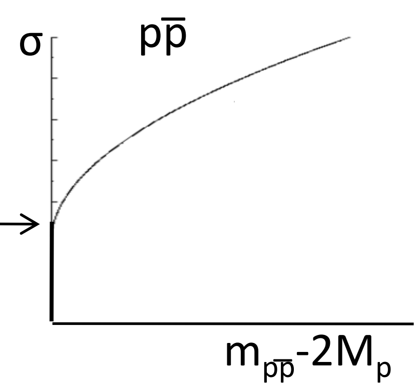
$$\text{for } p\bar{p}\text{: } C = \frac{\pi\alpha/\beta}{1-\exp(-\pi\alpha/\beta)} \rightarrow \frac{\pi\alpha}{\beta}$$

Sommerfeld resummation factor

in point-like approx:

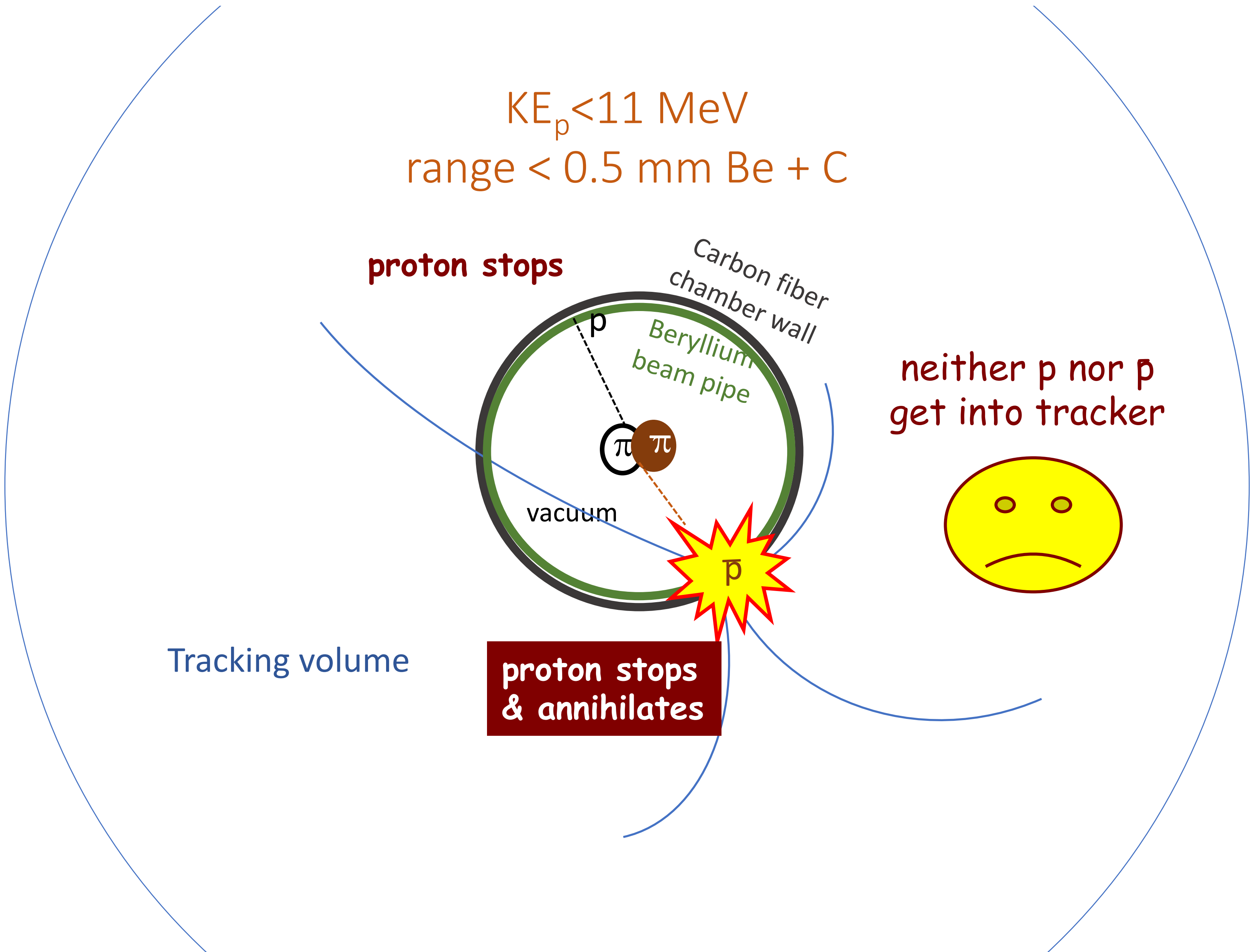
$$\sigma_0 = \frac{\pi^2\alpha^3}{2M_p^2}\left|G_{eff}(2M_p)\right|^2$$

$$\approx 0.85\text{nb}\left|G_{eff}(2M_p)\right|^2 \longrightarrow$$



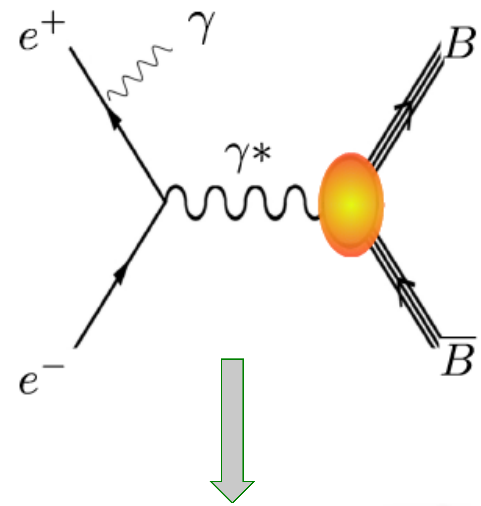
$e^+e^- \rightarrow p\bar{p}$ near threshold for E_{cm}<1.9 GeV

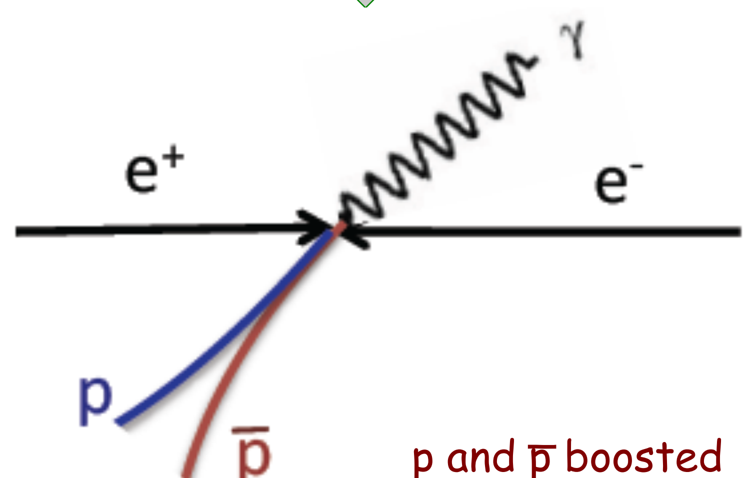
-- experimental issues --



BaBar: produce boosted p$\bar{p}$ pairs via isr

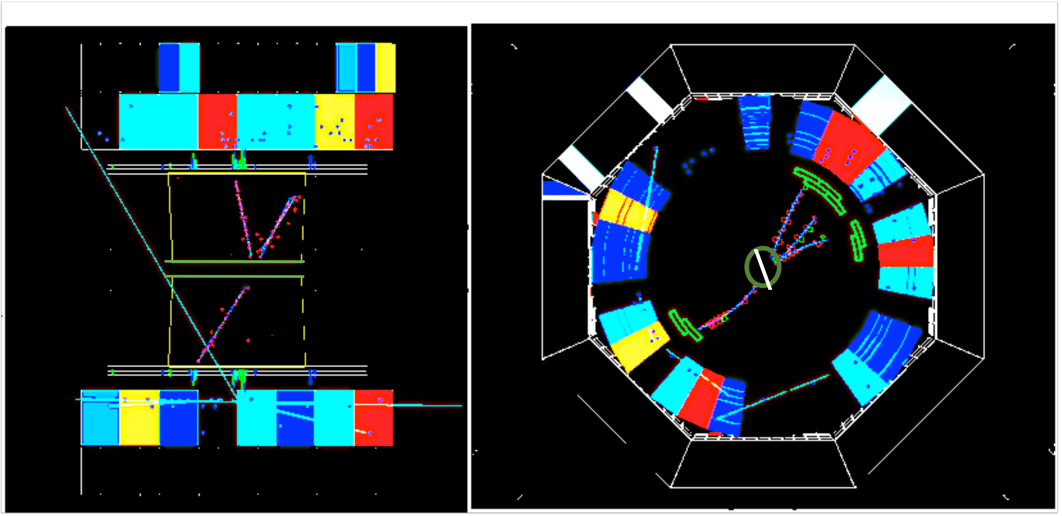
large angle initial state radiation (isr):



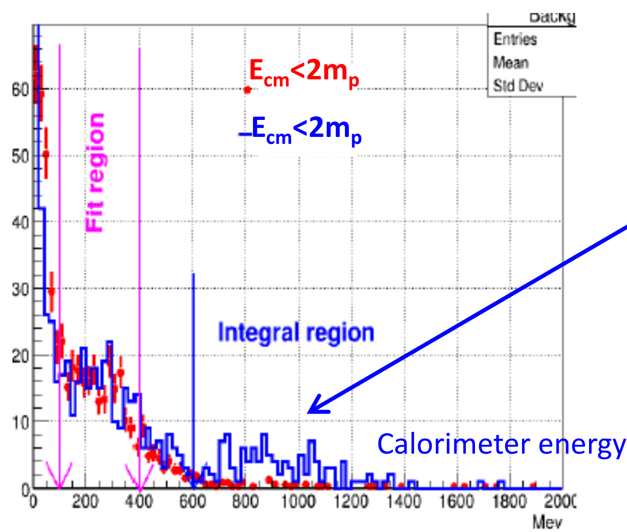


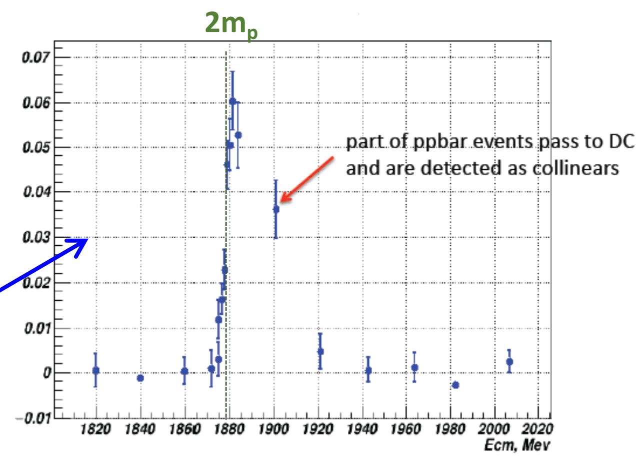
p and $\bar{p}$ boosted
into the detector

CMD3: Detect $\bar{p}$ annihilations in beam pipe



Solodov talk at Bad Honnef 2018

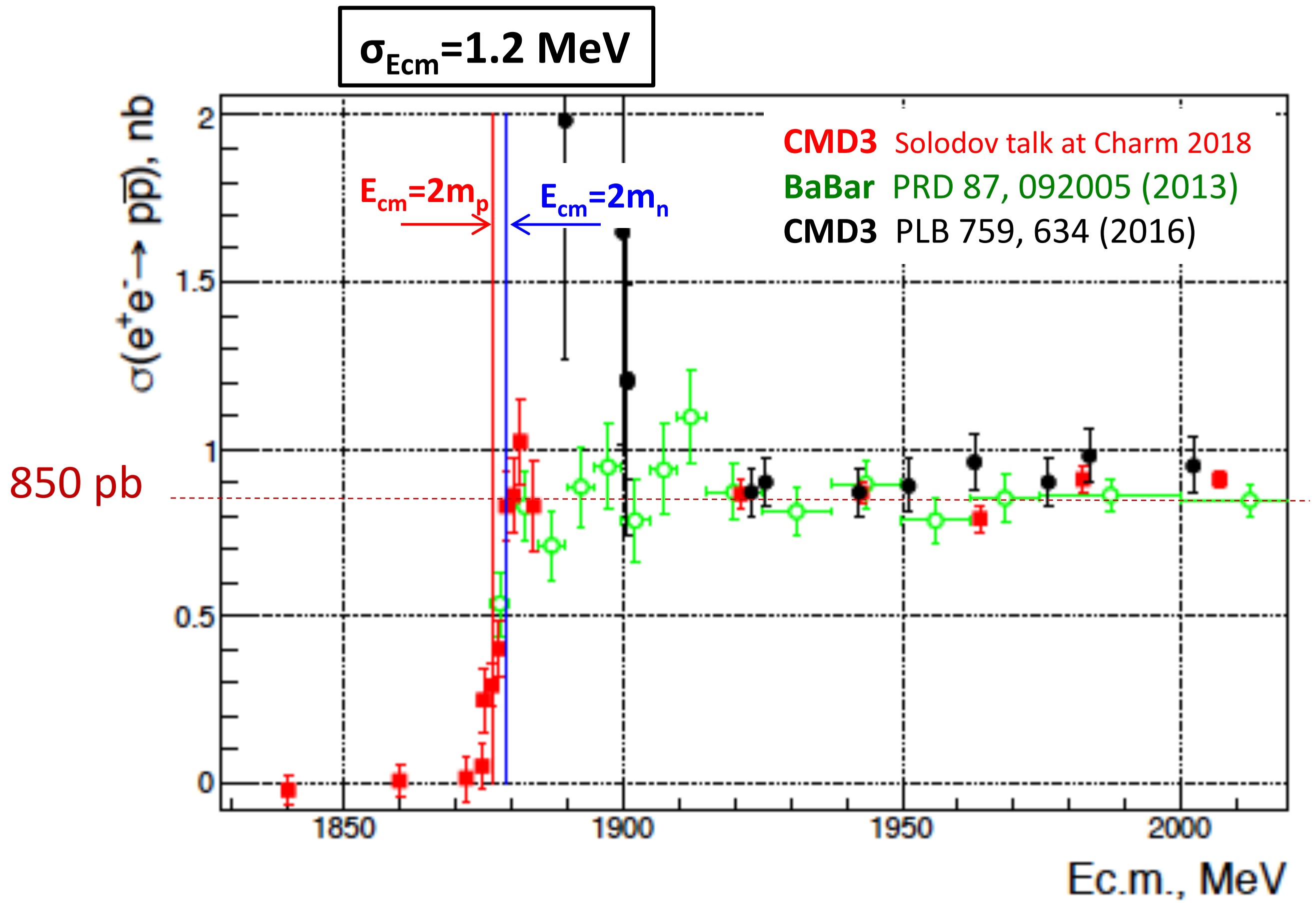




490 events have been found

$e^+e^- \to p\bar{p}$ at $E_{cm}=2m_p$ threshold

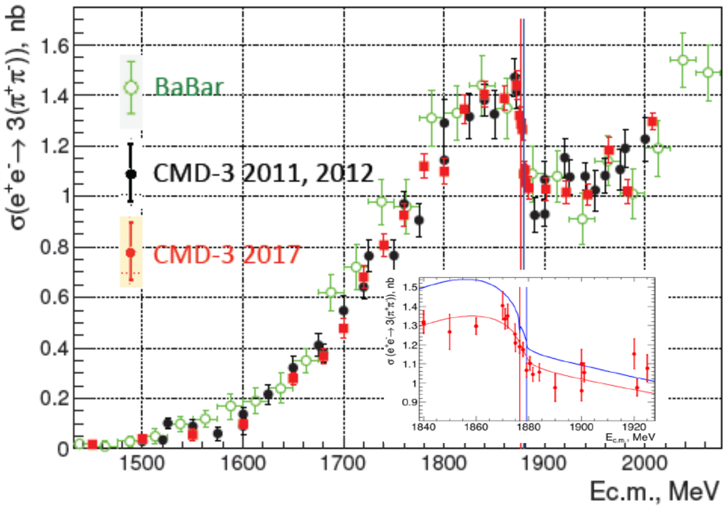
-- fast ($\delta E_{cm} \lesssim 1$ MeV) cross section jump at threshold --



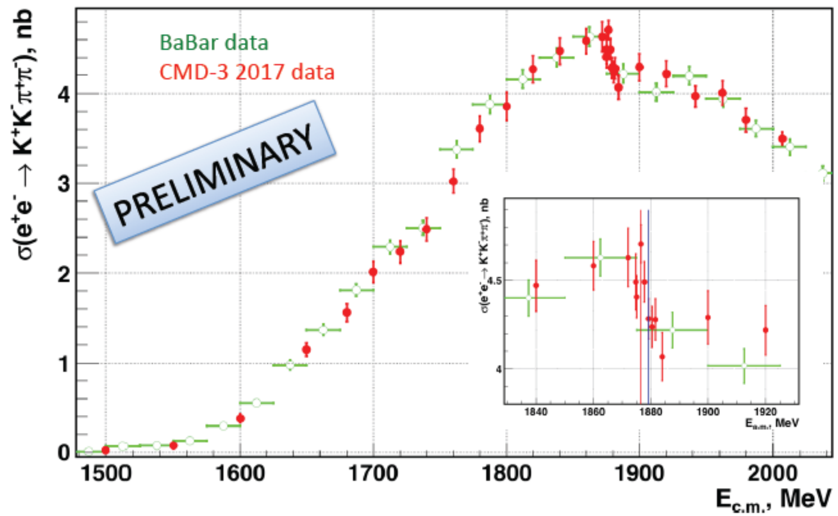
point-like approx. works well

look at other channels

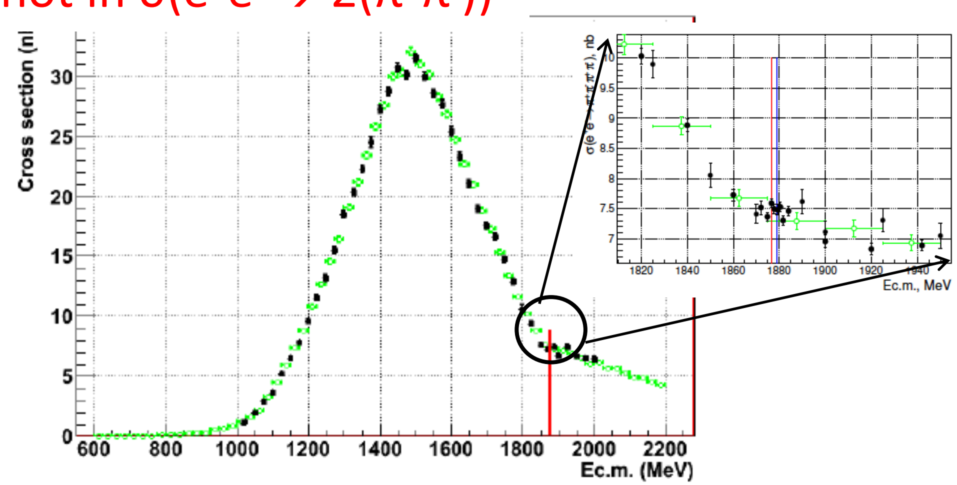
rapid dips in $\sigma(e^+e^- \to 3(\pi^+\pi^-))$



and $\sigma(e^+e^- \to K^+K^-\pi^+\pi^-)$

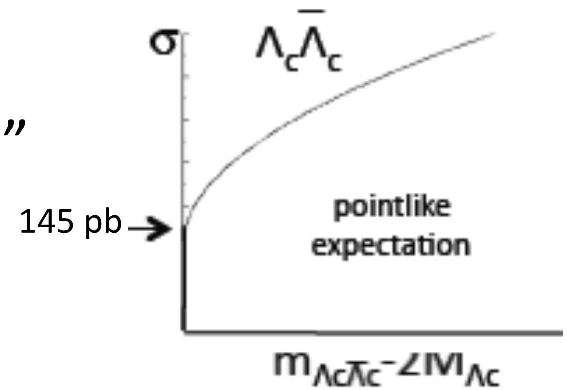


but not in $\sigma(e^+e^- \to 2(\pi^+\pi^-))$



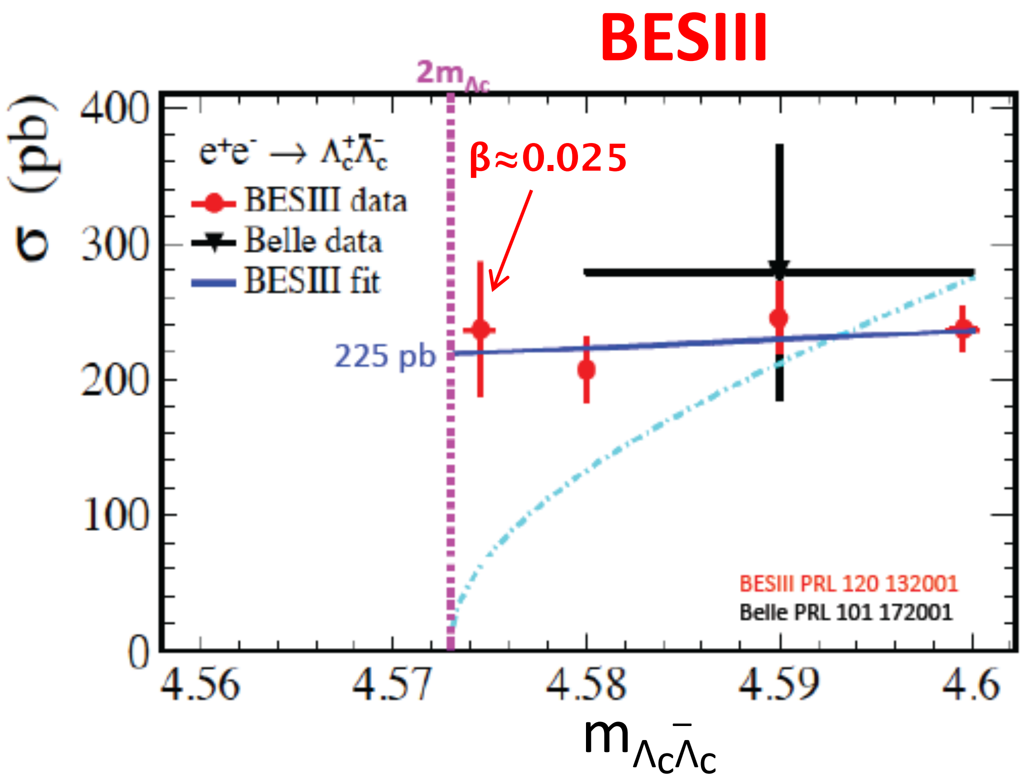
$e^+e^- \rightarrow \Lambda_c^+\Lambda_c^-$

Λ_c is charged, expect ≈145pb "jump"
in point-like approximation



Λ_c is an Isospin singlet, no π-exchange
no Λ_c-Λ_c moleculelike states expected

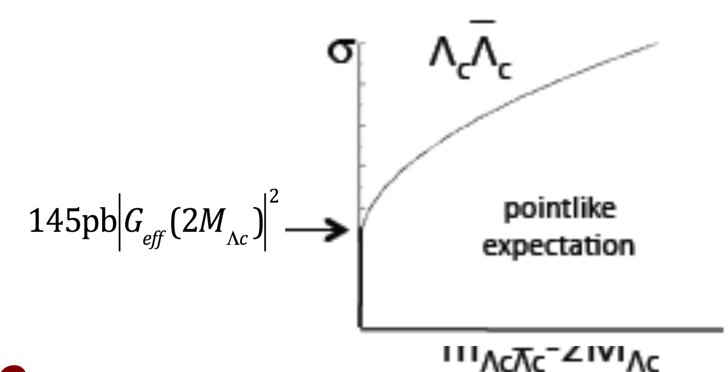
$\sigma(e^+e^- \to \Lambda_c^+\Lambda_c^-)$ @ threshold



≈225 pb "jump" at threshold

≈consistent with δσ ≈ 145 pb
$|G_{eff}|=1$ pointlike jump

but ≈flat after that (like pp)



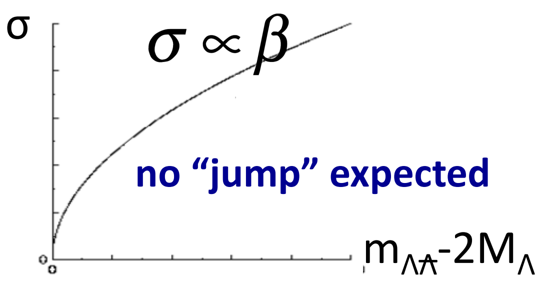
point-like approx. works here too

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

in point-like approx:

Electrically neutral → no Ryberg states

- no Coulomb enhancement

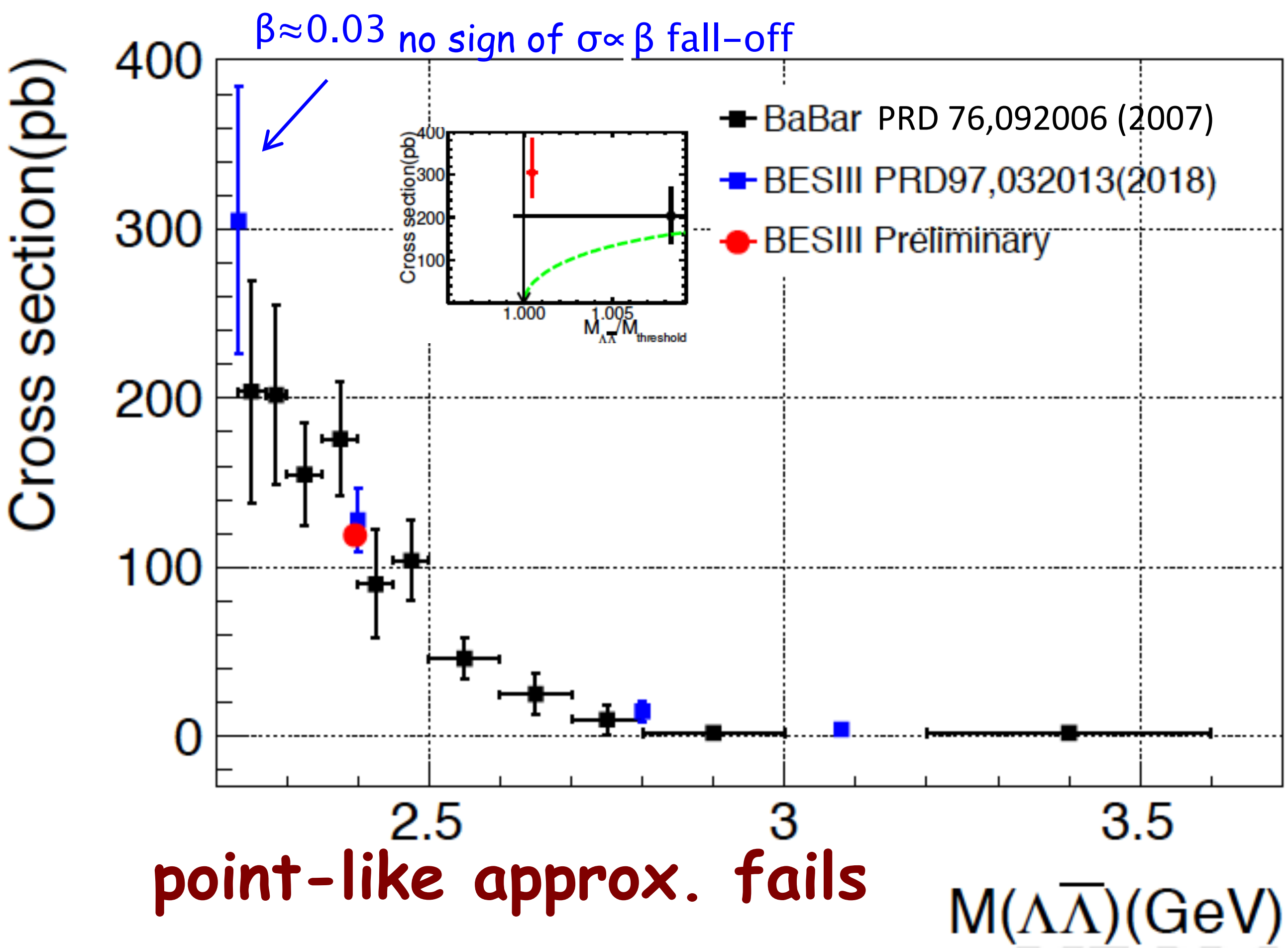


Isospin singlet, π-exchange not allowed

- Λ-$\bar{\Lambda}$ molecule is unlikely

$\sigma(e^+e^- \to \Lambda\bar{\Lambda})$ at $E_{cm} \approx 2m_\Lambda$ threshold

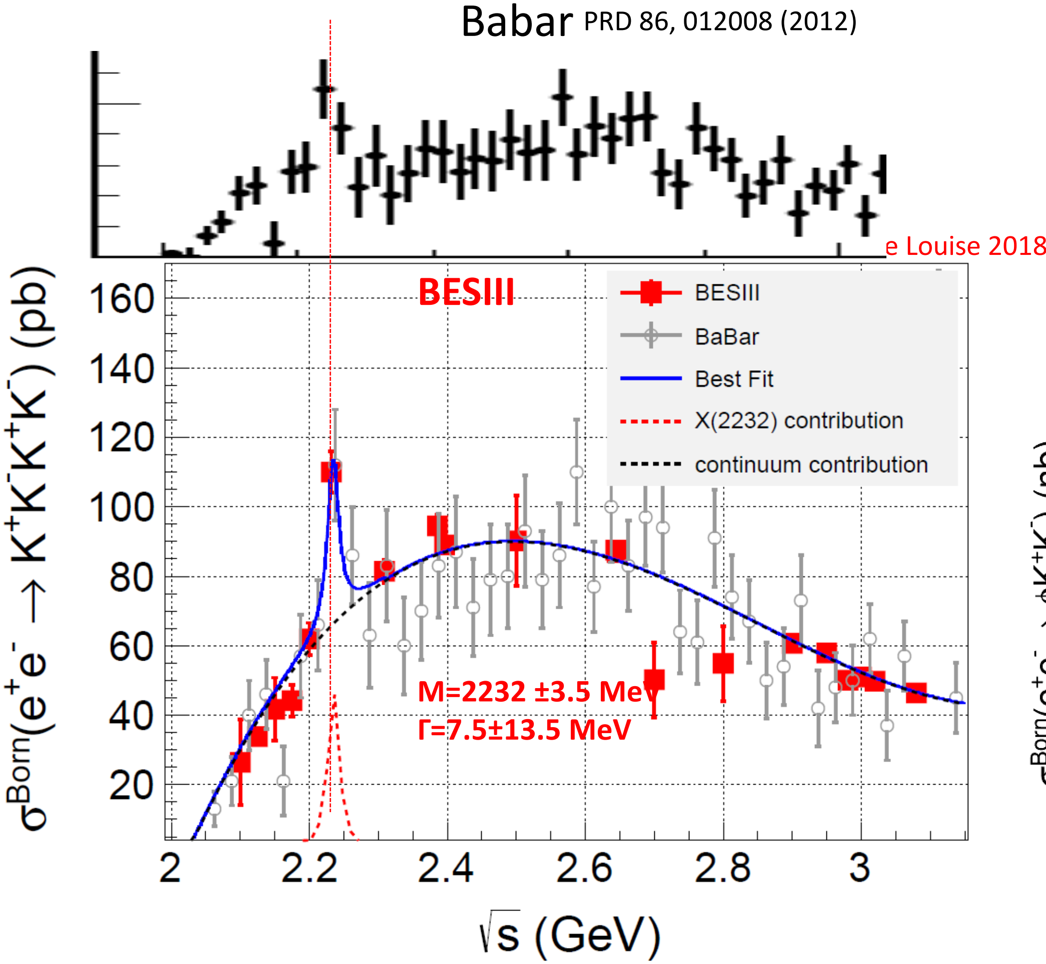
$$\sigma_{\Lambda\bar{\Lambda}}(m) = \frac{4\pi\alpha^2\beta}{3m^2}\left|G_{eff}(m)\right|^2\left(1+1/2\tau\right)$$



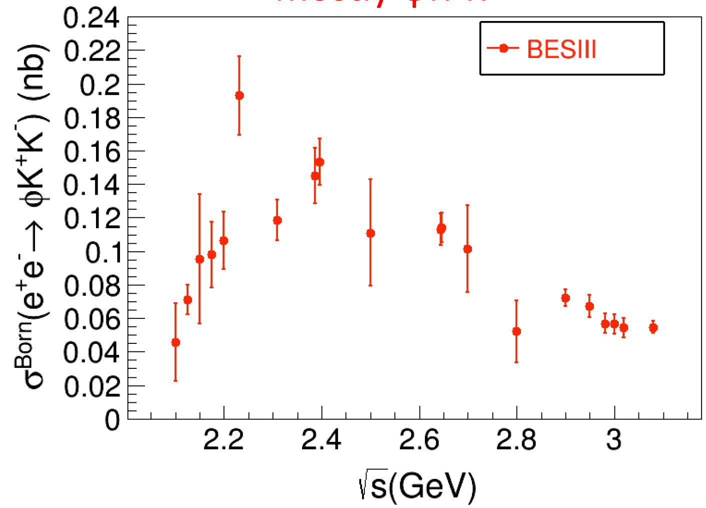
σ($e^+e^- \to K^+K^- K^+K^-$) peak @ $2m_\Lambda$?

-- seen by both BaBar and BESIII --

Babar PRD 86, 012008 (2012)

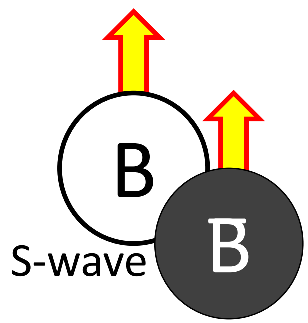


mostly ϕK^+K^-



baryonium?

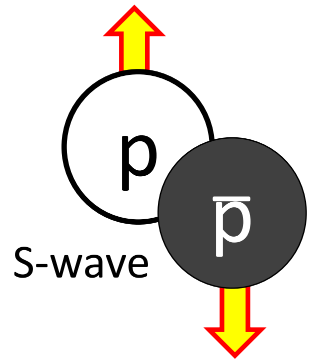
-- sub-threshold $B\bar{B}$ QCD S-wave bound states --



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

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

a 0^{-+} $p\bar{p}$ bound state is well established

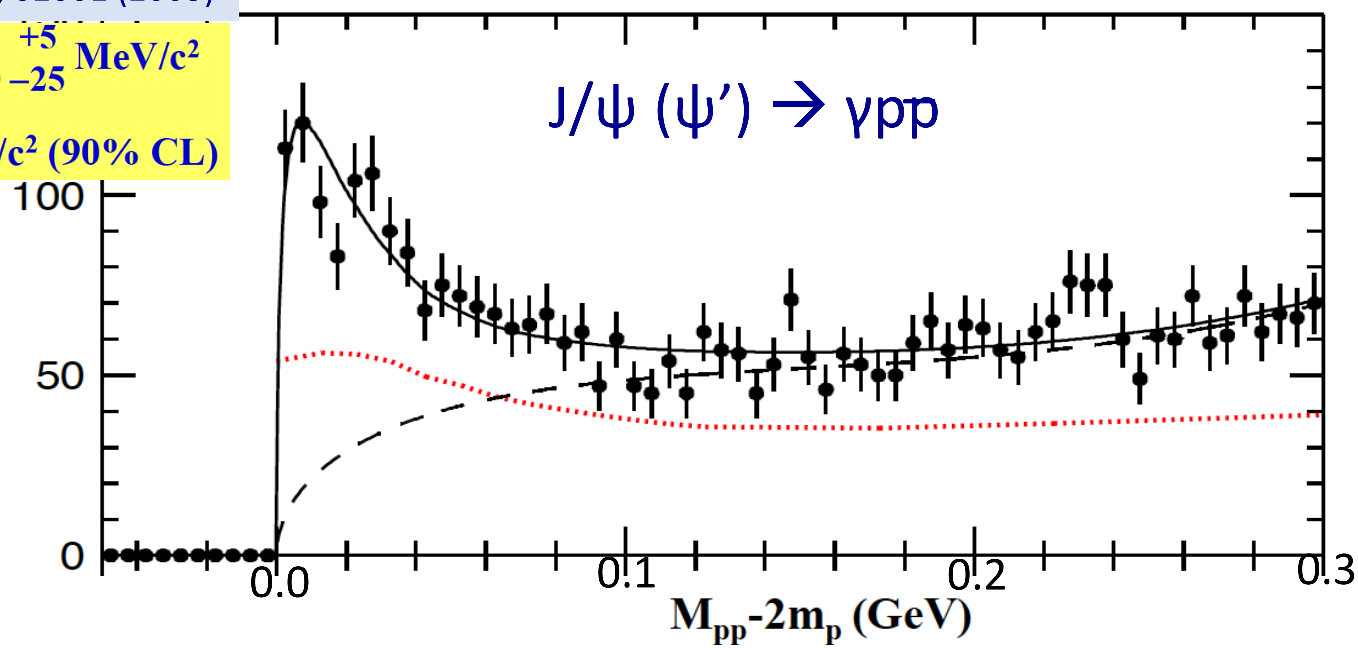


$J^{PC}=0^{-+}$

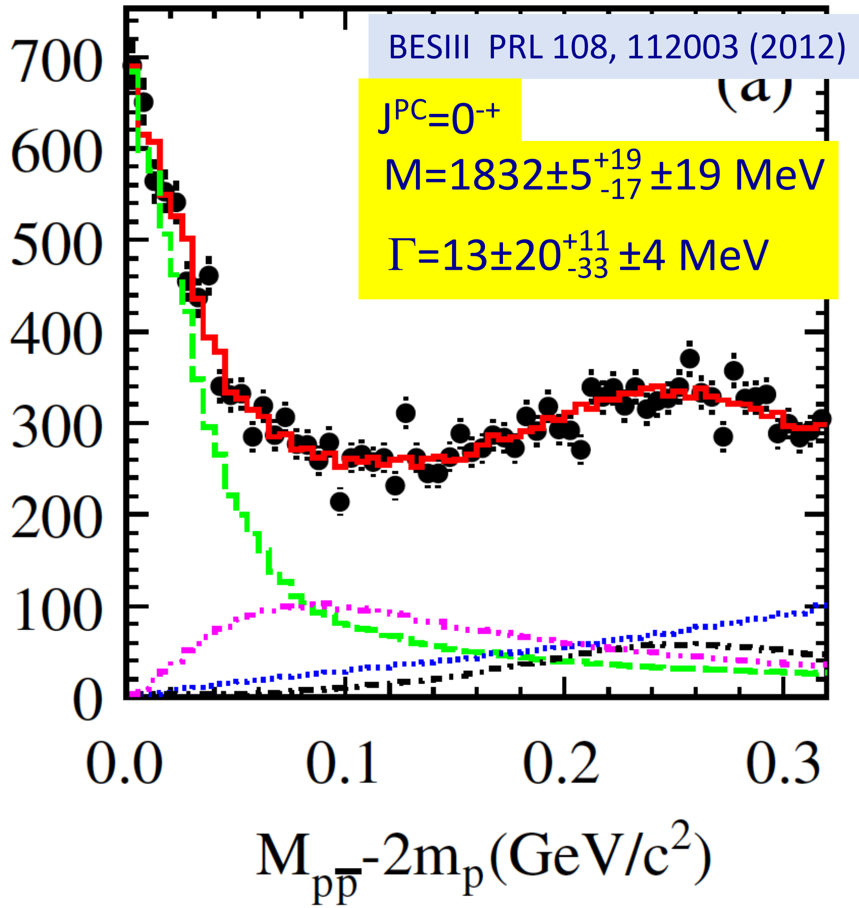
BESII PRL 91, 02001 (2003)

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

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

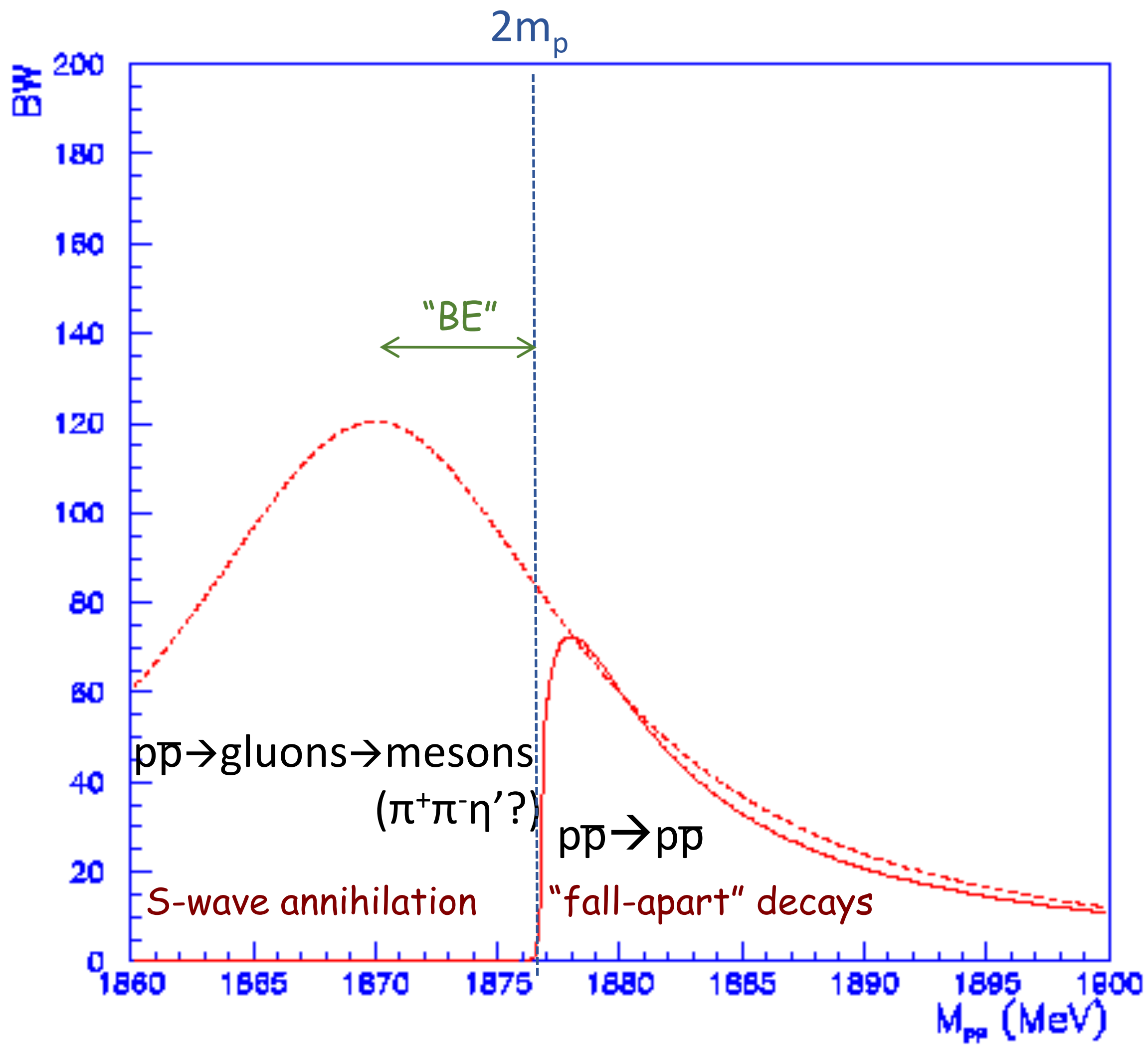


$J/\psi \to \gamma p\bar{p}$ at BESIII (PWA)



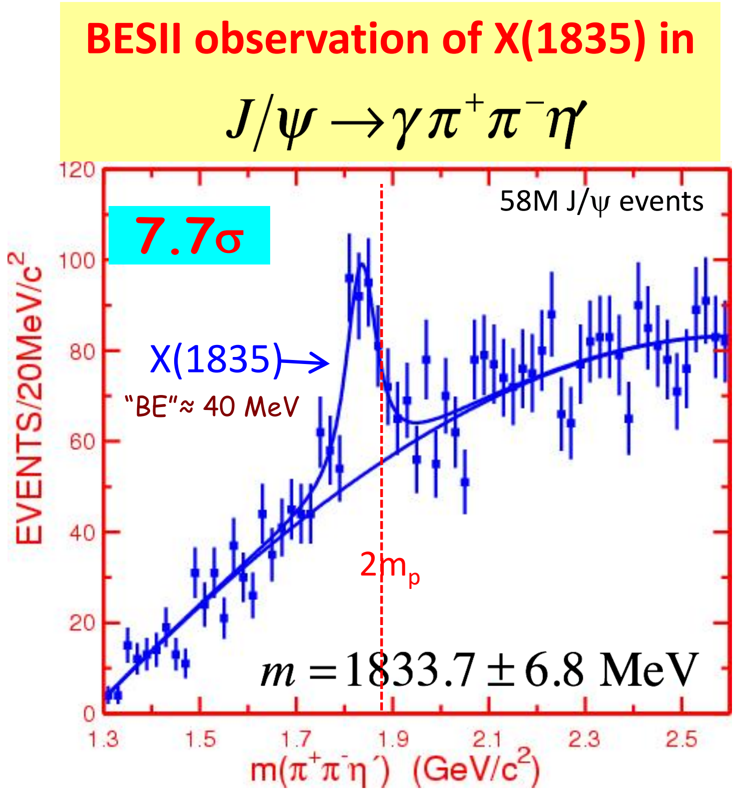
FSI included: A. Sibirtsev et al, PRD71, 054010 (2005)

"protononium:" a p$\bar{p}$ bound state?



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

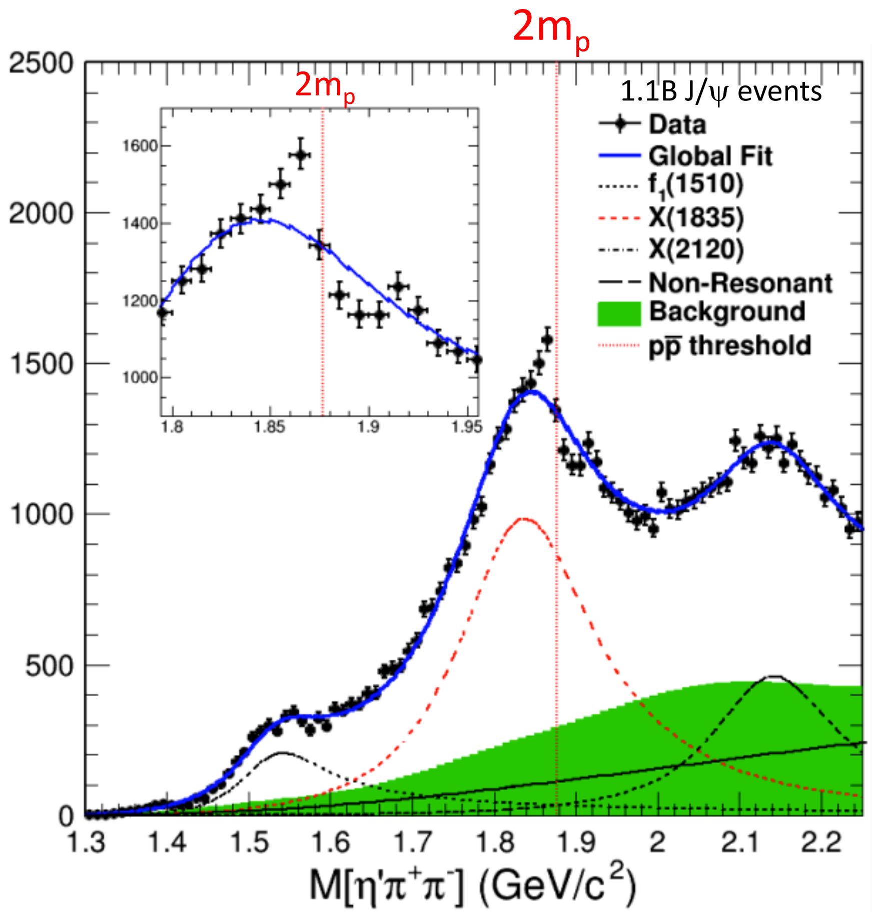
$X(1835) \rightarrow \pi^+\pi^-\eta'$ with 58M J/ψ decays (BESII)



BESII PRL 95, 262001 (2005)

X(1835)→π⁺π⁻η′ with 1.1B J/ψ decays (BESIII)

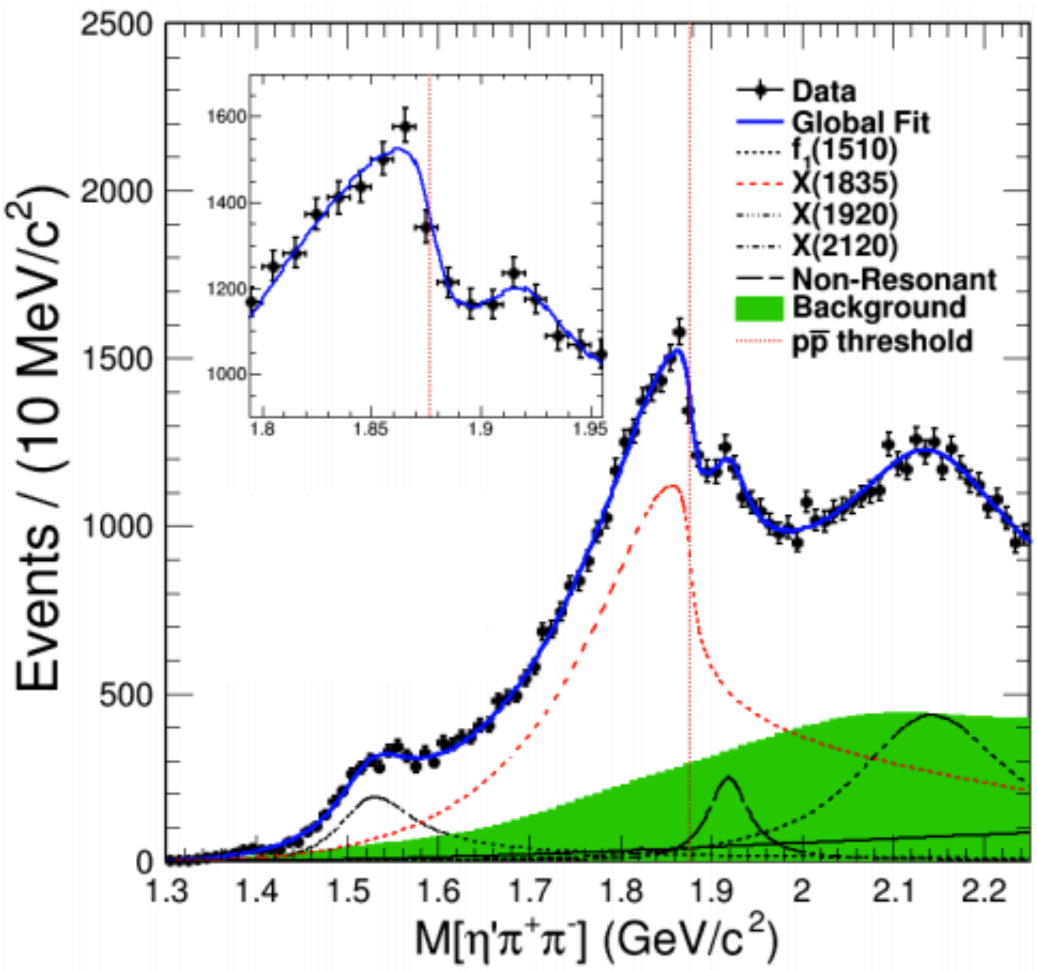
$$J/\psi \rightarrow \gamma \pi^+ \pi^- \eta'$$



Flatté formula fit:

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

S.M. Flatté PLB 63, 224 (1976)



Fit results:

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

X coupling to pp̄

X coupling to everything else

summary

Cross section threshold jumps see for $e^+e^- \rightarrow B\bar{B}$

-- both for charged ($p\bar{p}$ & $\Lambda_c\bar{\Lambda}_c$) and neutral ($n\bar{n}$ & $\Lambda\bar{\Lambda}$) pairs

-- jump times < 1 ns (much faster than phase space)

-- consistent with expectations for pointlike, ***charged*** particles

-- above threshold behavior is decidedly non-pointlike

Accompanying structures seen in other channels

-- dips in $\sigma(e^+e^- \rightarrow 3(\pi^+\pi^-)$ & $K^+K^-\pi^+\pi^-)$ at $E_{cm}=2m_p$ (but not $2(\pi^+\pi^-)$)

-- peak in $e^+e^- \rightarrow \varphi K^+K^-$ at $E_{cm}=2m_\Lambda$

A subthreshold 0^{-+} $p\bar{p}$ state seen in $J/\psi \rightarrow \gamma p\bar{p}$

-- associated structure seen in $e^+e^- \rightarrow \pi^+\pi^-\eta'$

More results expected soon

-- $e^+e^- \rightarrow \Sigma\bar{\Sigma}$ and $\Xi\bar{\Xi}$ at threshold from BESIII

--more $e^+e^- \rightarrow p\bar{p}$ and $n\bar{n}$ from CMDS, SND & BESIII

There is lots still to be learned about the ”well known’’ stable baryons

Thank You

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謝謝

감사합니다