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Isospin violation in the decays of vector charmonia into $\Lambda\overline{\Sigma}^0 + c.c.$

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Regular Article - Theoretical Physics

The cross section of $e^+e^- \to \Lambda\overline{\Sigma}^0 + $ c.c. as a litmus test of isospin violation in the decays of vector charmonia into $\Lambda\overline{\Sigma}^0 + $ c.c.

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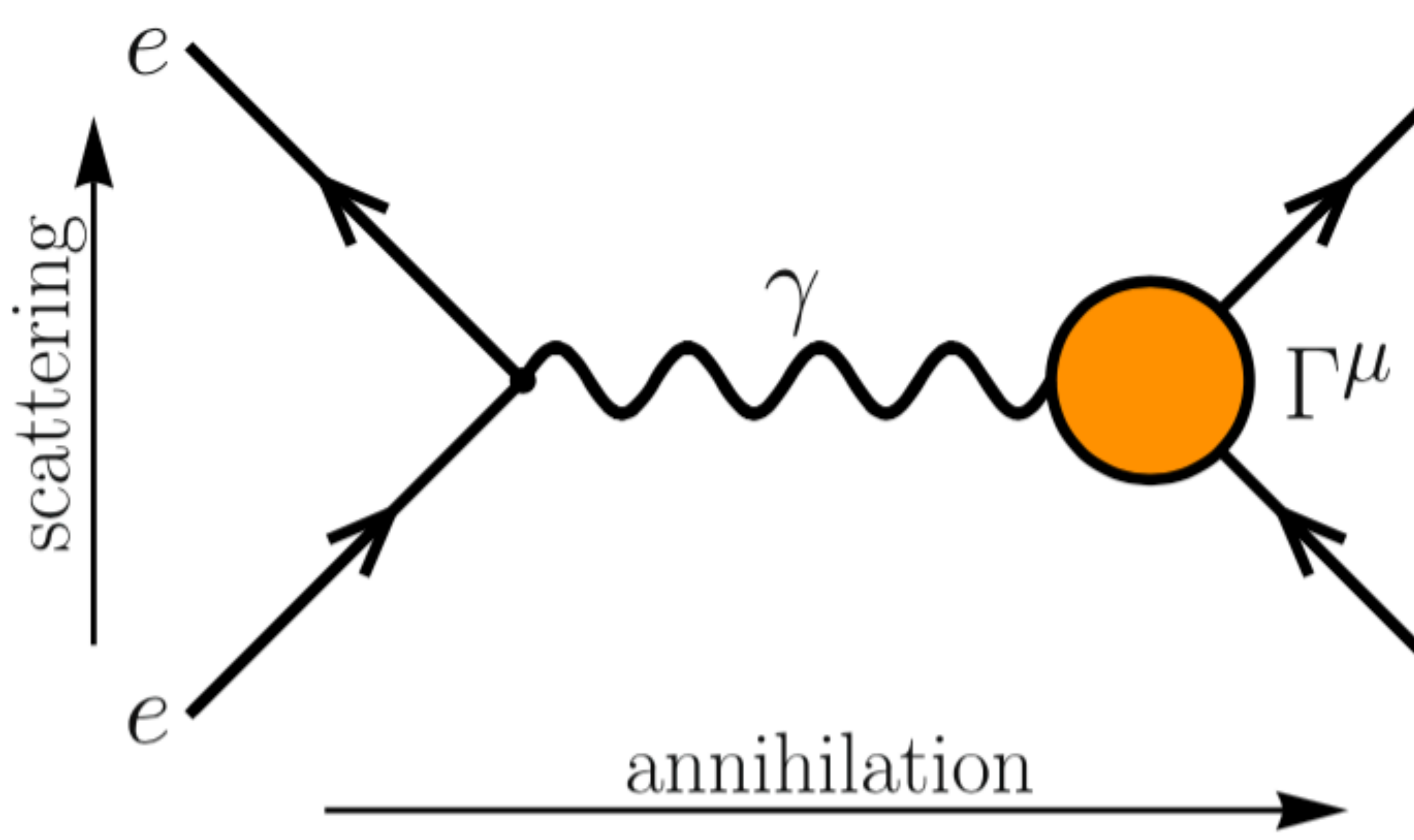
e^+e^- annihilation into baryon-antibaryon

Electromagnetic amplitude for the electron-positron annihilation into baryon-antibaryon

$$e^-(p_1)e^+(p_2) \to \gamma^*(q) \to B(k_1)\overline{B}(k_2)$$



$$\mathcal{M}^{\gamma}_{B\overline{B}} = -\frac{ie^2}{q^2}\,\overline{v}(p_2)\gamma_\mu u(p_1)\,\overline{u}(k_1)\Gamma^\mu v(k_2)$$

Electromagnetic cross section in Born approximation

$$\beta_{M_B}(q^2) = \sqrt{1 - \frac{4M_B^2}{q^2}}$$

$$\sigma_{B\overline{B}}(q^2) = \frac{4\pi\alpha^2\beta_{M_B}(q^2)}{3q^2}\left(\frac{2M_B^2}{q^2}\,|G_E^B(q^2)|^2 + |G_M^B(q^2)|^2\right)$$

e^+e^- annihilation into baryon-antibaryon

By introducing an effective FF

$$|\mathscr{A}^{\gamma}_{B\overline{B}}(q^2)| = \sqrt{|G_M^B(q^2)|^2 + \frac{2M_B^2}{q^2}|G_E^B(q^2)|^2}$$

The electromagnetic cross section becomes

$$\sigma_{B\overline{B}}(q^2) = \frac{4\pi\alpha^2\beta_{M_B}(q^2)}{3q^2}|\mathscr{A}^{\gamma}_{B\overline{B}}(q^2)|^2$$

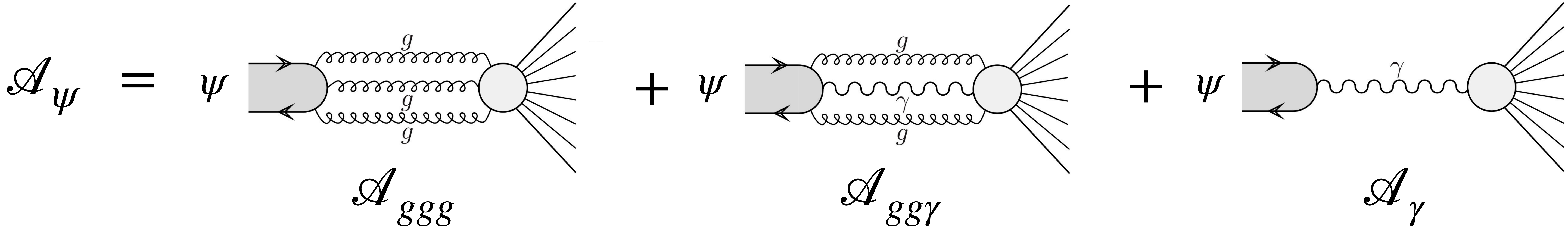
We consider the decays of an SU(3) singlet meson ψ into pairs of spin-1/2 baryon-antibaryon $B\overline{B}$, belonging to the SU(3) octet

$$B = \begin{pmatrix} \Lambda/\sqrt{6}+\Sigma^0/\sqrt{2} & \Sigma^+ & p \\ \Sigma^- & \Lambda/\sqrt{6}-\Sigma^0/\sqrt{2} & n \\ \Xi^- & \Xi^0 & -2\Lambda/\sqrt{6} \end{pmatrix}$$

$$\psi \in \{J/\psi, \psi(2S)\}$$

J/ψ decay amplitude

The amplitude for the process $\psi \to B\bar{B}$ can be parameterized as follows



Consider the pure electromagnetic decay

$$\psi \to \gamma^* \to B\bar{B}$$

$$\mathrm{BR}^{\gamma}_{B\bar{B}} = \frac{|g^{\psi}_{\gamma}|^2 \beta_{M_B}(M^2_\psi)}{16\pi M_\psi \Gamma_\psi} |\mathcal{A}^{\gamma}_{B\bar{B}}(M^2_\psi)|^2$$

$$\mathrm{BR}^{\gamma}_{\mu^+\mu^-} = \frac{|g^{\psi}_{\gamma}|^2}{16\pi M_\psi \Gamma_\psi}$$

$$\sigma^0_{\mu^+\mu^-}(q^2) = \frac{4\pi\alpha^2}{3q^2}$$

$$\sigma_{B\bar{B}}(M^2_\psi) = \frac{\sigma^0_{\mu^+\mu^-}(M^2_\psi)}{\mathrm{BR}^{\gamma}_{\mu^+\mu^+}} \mathrm{BR}^{\gamma}_{B\bar{B}}$$

Parametrization of the electromagnetic amplitudes

$$\mathscr{L} = \mathscr{L}_{\Sigma^0\Lambda} + \mathscr{L}_p + \mathscr{L}_n + \mathscr{L}_{\Sigma^+} + \mathscr{L}_{\Sigma^-} + \mathscr{L}_{\Xi^0} + \mathscr{L}_{\Xi^-}$$

$\propto \mathrm{Tr}[B\overline{B}]$ + SU(3) breaking symmetry corrections

$B\overline{B}$	$A_{B\overline{B}} = A^{ggg}_{B\overline{B}} + A^{gg\gamma}_{B\overline{B}} + A^{\gamma}_{B\overline{B}}$
$\Sigma^0\overline{\Sigma}^0$	$(G_0 + 2D_m)e^{i\varphi} + D_e$
$\Lambda\overline{\Lambda}$	$(G_0 - 2D_m)e^{i\varphi} - D_e$
$\Lambda\overline{\Sigma}^0$+ c.c.	$\sqrt{3}\,D_e$
$p\overline{p}$	$(G_0 - D_m + F_m)(1 + R)e^{i\varphi} + D_e + F_e$
$n\overline{n}$	$(G_0 - D_m + F_m)e^{i\varphi} - 2\,D_e$
$\Sigma^+\overline{\Sigma}^-$	$(G_0 + 2D_m)(1 + R)e^{i\varphi} + D_e + F_e$
$\Sigma^-\overline{\Sigma}^+$	$(G_0 + 2D_m)(1 + R)e^{i\varphi} + D_e - F_e$
$\Xi^0\overline{\Xi}^0$	$(G_0 - D_m - F_m)e^{i\varphi} - 2\,D_e$
$\Xi^-\overline{\Xi}^+$	$(G_0 - D_m - F_m)(1 + R)e^{i\varphi} + D_e - F_e$

[Baldini, Mangoni, Pacetti, Zhu, Phys.Lett. B799 (2019) 135041]

EM amplitudes →

$B\overline{B}$	$\lvert\mathcal{A}^{\gamma}_{B\overline{B}}\rvert$
$\Sigma^0\overline{\Sigma}^0$	$\lvert D_e\rvert$
$\Lambda\overline{\Lambda}$	$\lvert D_e\rvert$
$\Lambda\overline{\Sigma}^0$+ c.c.	$\sqrt{3}\,\lvert D_e\rvert$
$p\overline{p}$	$\lvert D_e + F_e\rvert$
$n\overline{n}$	$2\,\lvert D_e\rvert$
$\Sigma^+\overline{\Sigma}^-$	$\lvert D_e + F_e\rvert$
$\Sigma^-\overline{\Sigma}^+$	$\lvert D_e - F_e\rvert$
$\Xi^-\overline{\Xi}^+$	$\lvert D_e - F_e\rvert$
$\Xi^0\overline{\Xi}^0$	$2\,\lvert D_e\rvert$

The D_e parameter

The decay amplitude for the decay $\psi \to \Lambda\overline{\Sigma}^0$ + c.c. **is purely EM** (assuming isospin conservation)

Decay process	Branching ratio	Error (%)
$J/\psi \to \Lambda\overline{\Sigma}^0 + \text{c.c.}$	$(2.83 \pm 0.23) \times 10^{-5}$	8.13
$\psi(2S) \to \Lambda\overline{\Sigma}^0 + \text{c.c.}$	$(1.23 \pm 0.24) \times 10^{-5}$	19.5
$J/\psi \to \mu^+\mu^-$	$(5.961 \pm 0.033) \times 10^{-2}$	0.55
$\psi(2S) \to \mu^+\mu^-$	$(8.0 \pm 0.8) \times 10^{-3}$	10

PDG

$$\mathrm{BR}^{\gamma}_{\Lambda\overline{\Sigma}^0} = \frac{3\,|D_e|^2\,\beta_{M_{\Lambda\overline{\Sigma}^0}}(M_\psi^2)}{16\pi M_\psi \Gamma_\psi}$$

$$M_{\Lambda\overline{\Sigma}^0}(q^2) = \sqrt{\frac{1}{2}(M_{\Sigma^0}^2 + M_\Lambda^2) - \frac{1}{q^2}(M_{\Sigma^0}^2 - M_\Lambda^2)^2}$$

$J/\psi \to \quad |D_e| = (4.52 \pm 0.18) \times 10^{-4}$ GeV

$\psi(2S) \to |D_e| = (5.35 \pm 0.52) \times 10^{-4}$ GeV

Electromagnetic cross sections

$B\overline{B}$	$\vert\mathcal{A}^{\gamma}_{B\overline{B}}\vert$
$\Sigma^0\overline{\Sigma}^0$	$\vert D_e\vert$
$\Lambda\overline{\Lambda}$	$\vert D_e\vert$
$\Lambda\overline{\Sigma}^0 +$ c.c.	$\sqrt{3}\,\vert D_e\vert$
$p\overline{p}$	$\vert D_e + F_e\vert$
$n\overline{n}$	$2\,\vert D_e\vert$
$\Sigma^+\overline{\Sigma}^-$	$\vert D_e + F_e\vert$
$\Sigma^-\overline{\Sigma}^+$	$\vert D_e - F_e\vert$
$\Xi^-\overline{\Xi}^+$	$\vert D_e - F_e\vert$
$\Xi^0\overline{\Xi}^0$	$2\,\vert D_e\vert$

$$\sigma_{B^0\bar{B}^0}(M_\psi^2) = \frac{N^2_{B^0\bar{B}^0}\,\beta_{M_{B^0}}(M_\psi^2)}{\beta_{M_{\Lambda\bar{\Sigma}^0}}(M_\psi^2)}\,\frac{\sigma^0_{\mu^+\mu^-}(M_\psi^2)}{\mathrm{BR}^\gamma_{\mu^+\mu^-}}\,\mathrm{BR}^\gamma_{\Lambda\bar{\Sigma}^0}$$

$$B^0\bar{B}^0 \in \{\Lambda\bar{\Sigma}^0 + \mathrm{c.c.}, n\bar{n}, \Lambda\bar{\Lambda}, \Sigma^0\bar{\Sigma}^0, \Xi^0\bar{\Xi}^0\}$$

The EM amplitudes for the neutral final states depend on the only EM coupling D_e

$$N_{B^0\bar{B}^0} = \begin{cases} 1 & \text{if } B^0\bar{B}^0 = \Lambda\bar{\Sigma}^0 + \mathrm{c.c.} \\ -2/\sqrt{3} & \text{if } B^0 = n \\ -1/\sqrt{3} & \text{if } B^0 = \Lambda \\ 1/\sqrt{3} & \text{if } B^0 = \Sigma^0 \\ -2/\sqrt{3} & \text{if } B^0 = \Xi^0 \end{cases}$$

Electromagnetic cross sections

We define a "scaled cross section" $\tilde{\sigma}$

$$\tilde{\sigma}(q^2) \equiv \frac{\sigma_{B^0\bar{B}^0}(q^2)}{N^2_{B^0\bar{B}^0}\,\beta_{M_{B^0}}(q^2)}$$

$$N_{B^0\bar{B}^0} = \begin{cases} 1 & \text{if } B^0\bar{B}^0 = \Lambda\bar{\Sigma}^0 + \mathrm{c.c.} \\ -2/\sqrt{3} & \text{if } B^0 = n \\ -1/\sqrt{3} & \text{if } B^0 = \Lambda \\ 1/\sqrt{3} & \text{if } B^0 = \Sigma^0 \\ -2/\sqrt{3} & \text{if } B^0 = \Xi^0 \end{cases}$$

↓

We can compare the data on the $B^0\bar{B}^0$ cross section from BESIII and BABAR to obtain the value of D_e at $q^2 = M_\psi^2$

$$\tilde{\sigma}(M_\psi^2) = \frac{\alpha^2 |D_e|^2}{4M_\psi^3\Gamma_\psi \mathrm{BR}^\psi_{\mu^+\mu^-}}$$

Electromagnetic cross sections

EM cross section data from BESIII and BABAR

BABAR [Phys. Rev. D 76 (2007), 092006]

for $B\overline{B} = \Lambda\overline{\Lambda}$

for $B\overline{B} = \Sigma^0\overline{\Sigma}^0$

for $B\overline{B} = \Lambda\overline{\Sigma}^0$ + c.c.

BESIII [Samer Ahmed, 30-10-2019, Cyprus]

for $B\overline{B} = n\overline{n}$

We fit the $\tilde{\sigma}(q^2)$ data with the function

$$\tilde{\sigma}_{\rm fit}(q^2) = \frac{A}{(q^2)^5\left(\pi^2 + \ln^2(q^2/\Lambda^2_{\rm QCD})\right)^2}$$

$$\Lambda_{\rm QCD} = 0.35\ {\rm GeV}$$

A is a free parameter to be determined by a χ^2 minimization procedure

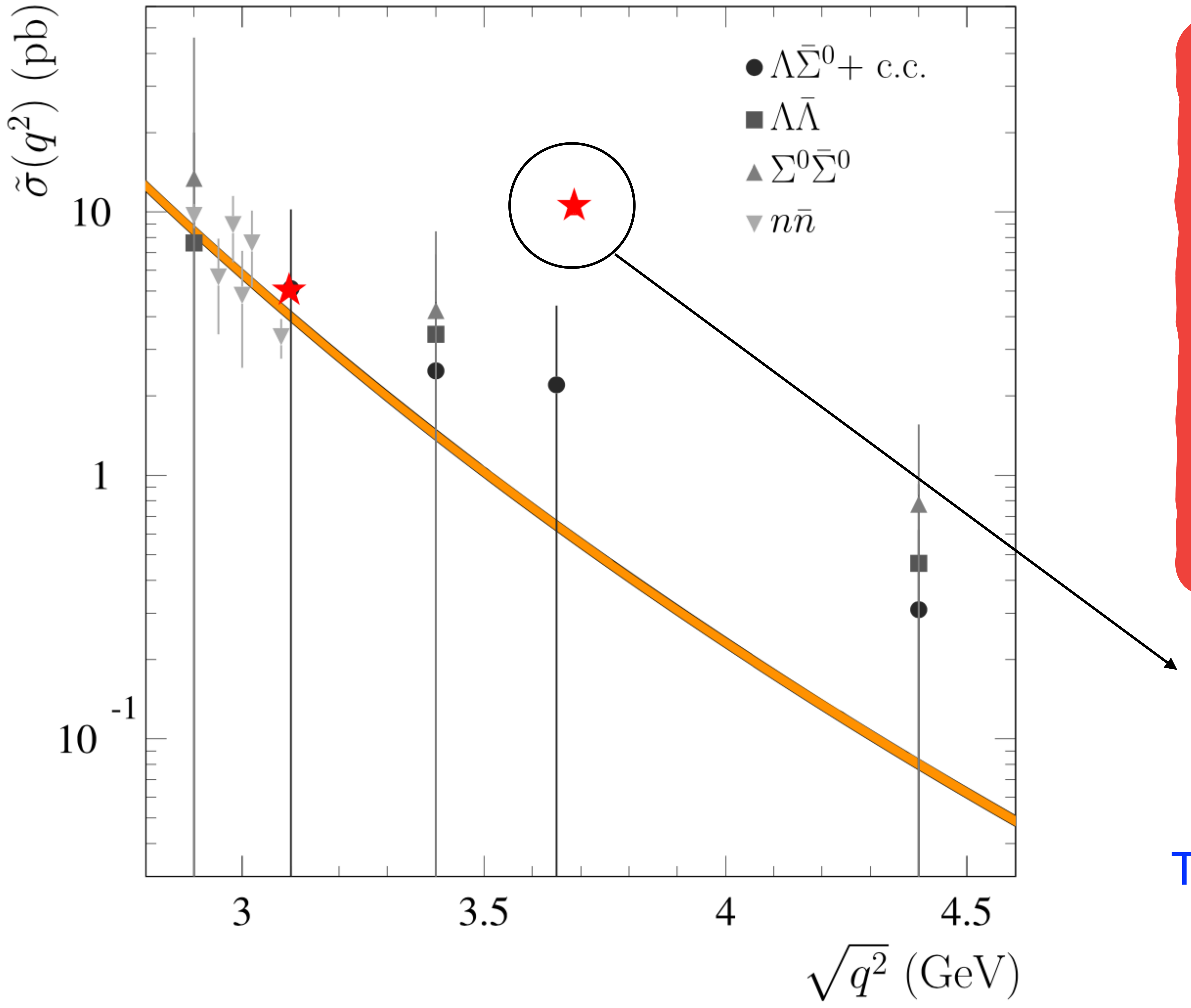
We scale the cross sections data by the factor

$$N^2_{B^0\overline{B}^0}\,\beta_{M_{B^0}}(q^2) \quad \Rightarrow \quad \tilde{\sigma}(q^2) \equiv \frac{\sigma_{B^0\bar{B}^0}(q^2)}{N^2_{B^0\overline{B}^0}\,\beta_{M_{B^0}}(q^2)}$$

$$\tilde{\sigma}(M^2_\psi) = \frac{\alpha^2|D_e|^2}{4M^3_\psi\Gamma_\psi{\rm BR}^\psi_{\mu^+\mu^-}}$$

independent by the final state baryons

Comparison between fit and data



Solid points: data on $\tilde{\sigma}$ from BESIII and BABAR

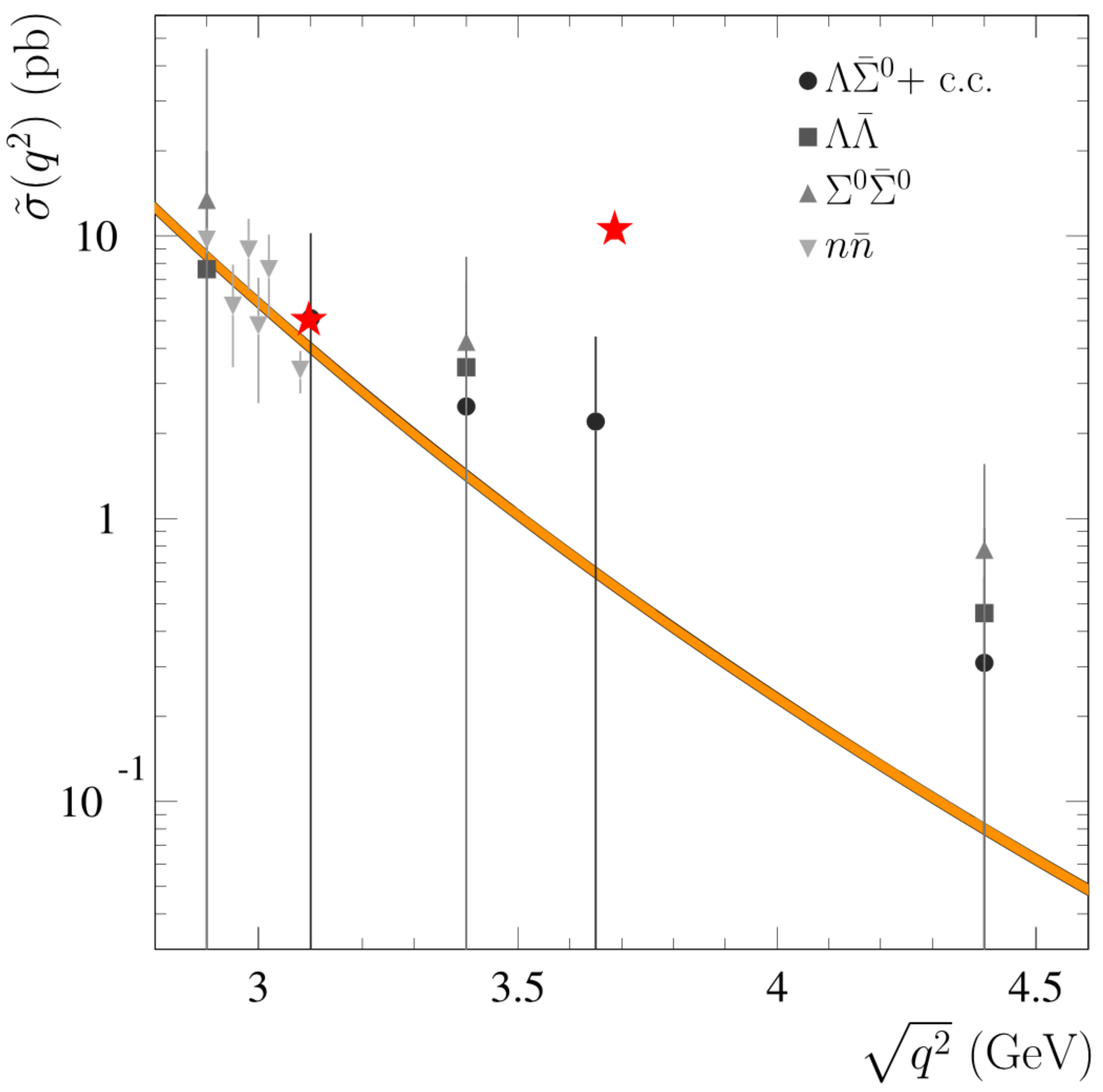
Orange band: fit results including the errors

Red stars: values of $\tilde{\sigma}$ derived by the decays BRs from PDG

Very unexpected behavior at $\sqrt{q^2} = M_{\psi(2S)}$ ☐

The predicted value at the J/ψ mass is satisfactory ☑

Comparison between fit and data



$\lvert\tilde{\sigma}\rvert$	Using the BR of $\psi \to \Lambda\bar{\Sigma}^0$ + c.c. from PDG as purely EM	Using the EM cross sections data from BESIII and BABAR
J/ψ	(6.45 ± 0.54) pb	(4.86 ± 0.44) pb
$\psi(2S)$	(12.6 ± 2.6) pb	(0.692 ± 0.096) pb

In the $\psi(2S)$ case the discrepancy is about 4.6 σ

(less than 2.3 σ for the J/ψ)

Conclusions

Possible hypotheses to explain the unnatural trend of the electromagnetic cross section at the $\psi(2S)$ mass

- The PDG value of $\mathrm{BR}(\psi(2S) \to \Lambda\overline{\Sigma}^0 + \mathrm{c.c.})$ is not completely reliable
- The decay $\psi(2S) \to \Lambda\overline{\Sigma}^0 + \mathrm{c.c.}$ is not purely EM
  - Isospin violation contribution?

Conclusions

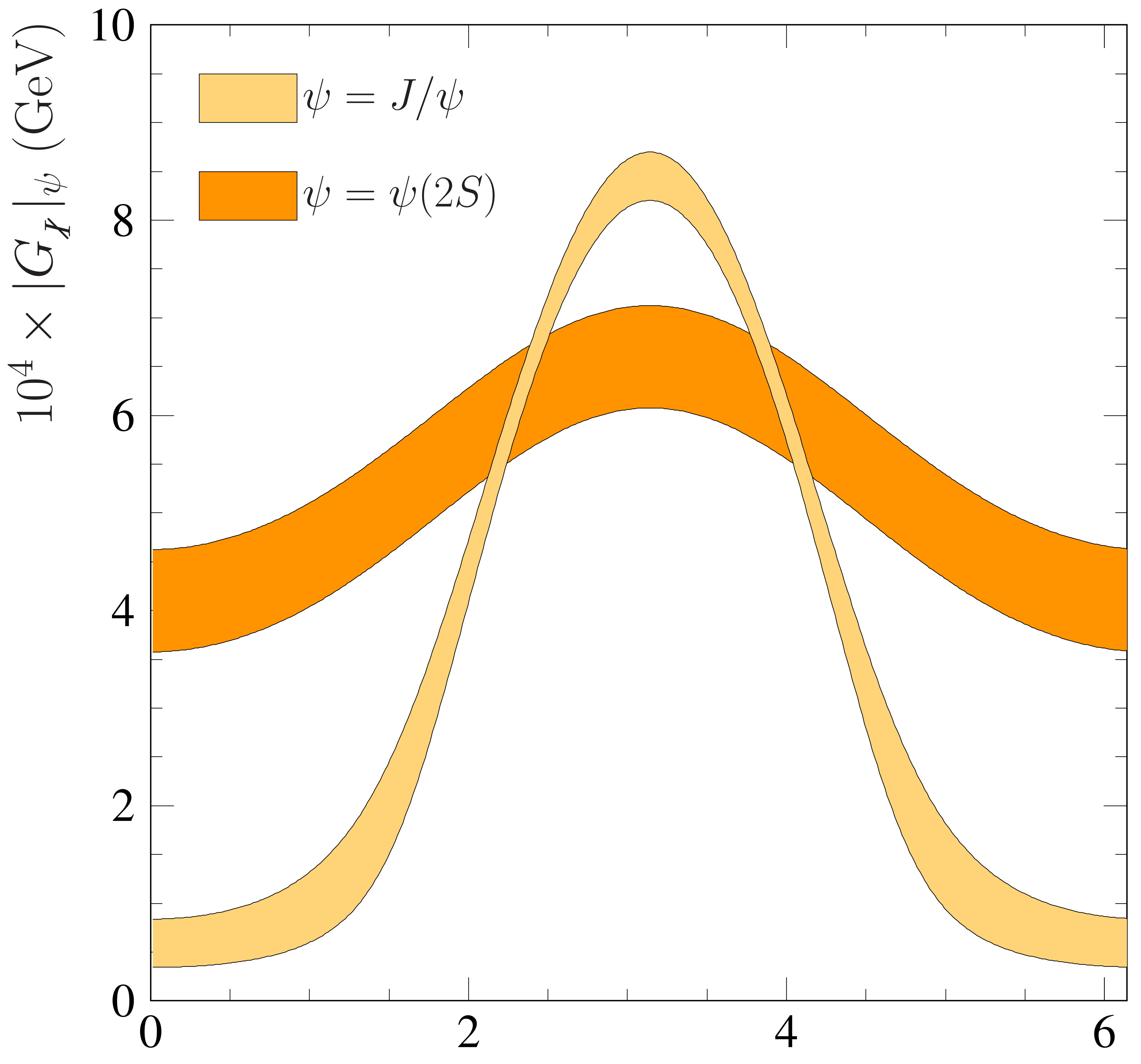
We can introduce an isospin violating term in the amplitude

$$\mathrm{BR}^{\gamma+\not{I}}_{\Lambda\bar{\Sigma}^0+\mathrm{c.c.}} = \frac{3\,|D_e + G_{\not{I}}|^2\,\beta_{\Lambda\bar{\Sigma}^0+\mathrm{c.c.}}(M_\psi^2)}{16\pi M_\psi \Gamma_\psi}$$

$$|G_{\not{I}}|_\psi = \sqrt{|D_e+G_{\not{I}}|_\psi^2 - |D_e|_\psi^2 \sin^2(\phi_\psi)} - |D_e|_\psi \cos(\phi_\psi)$$

$$(5.9 \pm 2.5)\cdot 10^{-5} < \frac{|G_{\not{I}}|_{J/\psi}}{\mathrm{GeV}} < (8.45 \pm 0.25)\cdot 10^{-4}$$

$$(4.10 \pm 0.52)\cdot 10^{-4} < \frac{|G_{\not{I}}|_{\psi(2S)}}{\mathrm{GeV}} < (6.60 \pm 0.52)\cdot 10^{-4}$$



ϕ_ψ is the relative phase between D_e and $G_{\not{I}}$

Conclusions

- Under the aegis of isospin conservation the branching ratio for the decay $\psi \to \Lambda\overline{\Sigma}^0 + \text{c.c.}$, with $\psi \in \{J/\psi, \psi(2S)\}$, is purely EM
- Using the PDG value of $\mathrm{BR}(\psi \to \Lambda\overline{\Sigma}^0 + \text{c.c.})$ we determine the value of the EM amplitudes for the $\psi \to B\overline{B}$ decays, where B is a neutral spin-1/2 baryon of the SU(3) octet
- For the four pairs of neutral baryon final states, $\Sigma^0\overline{\Sigma}^0$, $\Lambda\overline{\Lambda}$, $n\overline{n}$ and $\Xi^0\overline{\Xi}^0$ we calculate the values of the EM cross sections at $q^2 = M^2_{J/\psi}$ and $q^2 = M^2_{\psi(2S)}$
- At the J/ψ mass the EM cross sections are compatible with the corresponding experimental values from BESIII and BABAR. On the contrary, at the $\psi(2S)$ mass, the predicted values show an unnatural trend, not in agreement with data