Implication of X17 boson to D meson, Charmonium and ϕ meson decays

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Collaborators: Guey-Lin Lin and Fei-Fan Lee

ICHEP, 2024/07/19

NATIONAL YANG MING CHIAO TUNG UNIVERSITY

Outline

1. Introduction
2. X17 hypothesis (vector case) from anomalous ^{8}Be, ^{4}He, and ^{12}C decays
3. Strengths of X17 couplings to light and heavy quarks – determined by fittings to D meson, Charmonium and ϕ meson decays
4. Conclusions

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What is X17 boson?

PRL **116,** 042501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JANUARY 2016

Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

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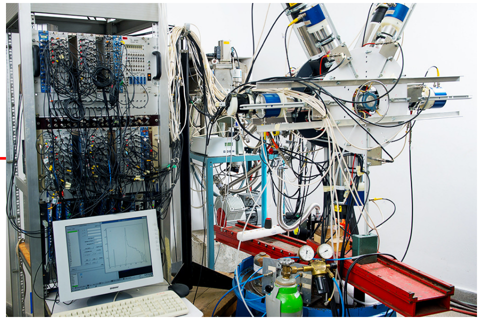
(Received 7 April 2015; published 26 January 2016)

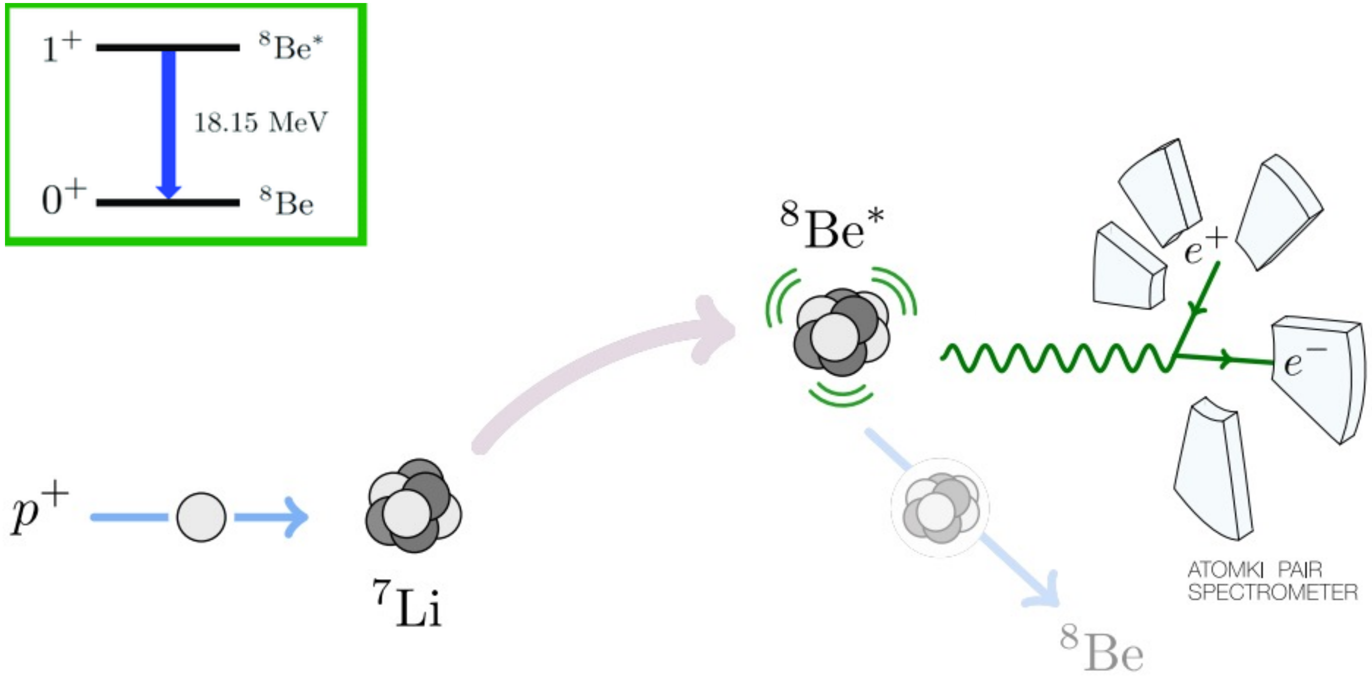
Electron-positron angular correlations were measured for the isovector magnetic dipole 17.6 MeV ($J^{\pi} = 1^{+}$, $T = 1$) state → ground state ($J^{\pi} = 0^{+}$, $T = 0$) and the isoscalar magnetic dipole 18.15 MeV ($J^{\pi} = 1^{+}$, $T = 0$) state → ground state transitions in ^{8}Be. Significant enhancement relative to the internal pair creation was observed at large angles in the angular correlation for the isoscalar transition with a confidence level of $> 5\sigma$. This observation could possibly be due to nuclear reaction interference effects or might indicate that, in an intermediate step, a neutral isoscalar particle with a mass of $16.70 \pm 0.35(\text{stat}) \pm 0.5(\text{syst})$ MeV/c^2 and $J^{\pi} = 1^{+}$ was created.



The Atomki experiment
[Quanta Magazine]

~400 citations, ^{8}Be anomaly, a new light neutral boson

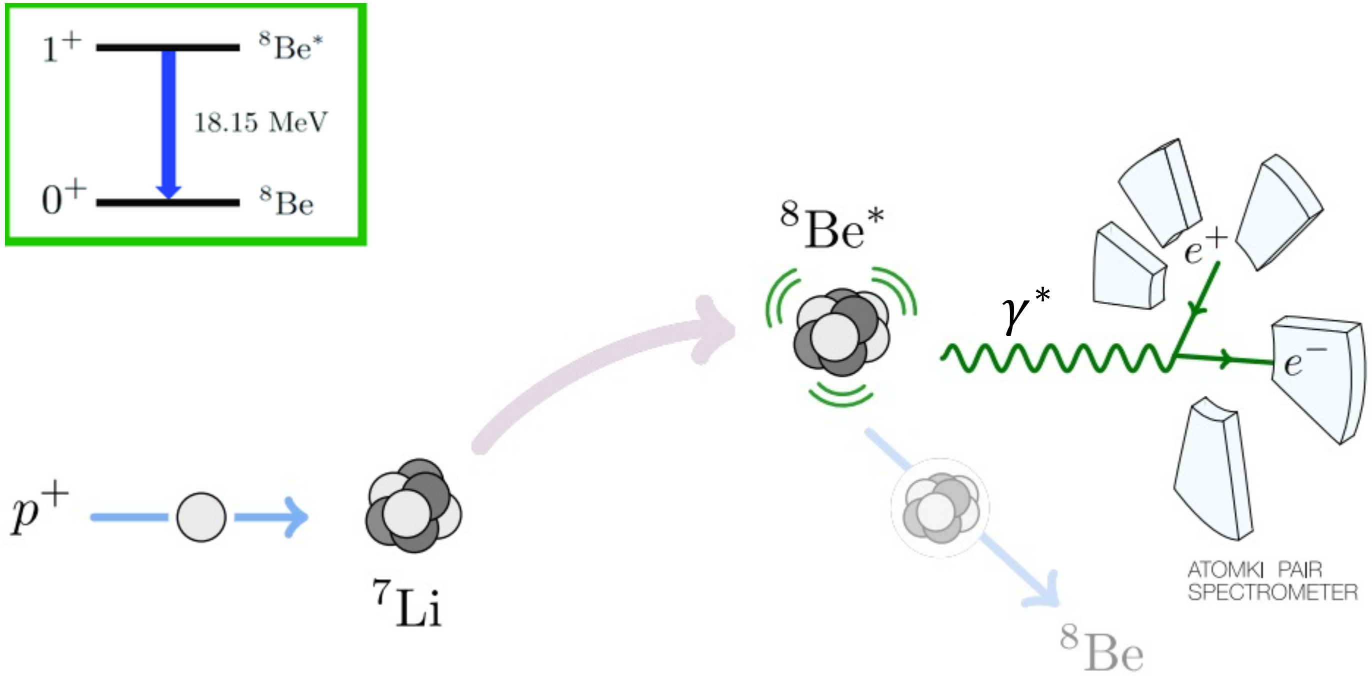
The Atomki experiment



arXiv:1608.03591v2

FIG. 1.1. The proton beam collides the target lithium nuclear to produce the $^8Be^*$ state, which subsequently decays into the ^8Be ground state. This further breaks down into an electron-positron pair whose opening angle and invariant mass are measured.

The Atomki experiment



arXiv:1608.03591v2

FIG. 1.1. The proton beam collides the target lithium nuclear to produce the $^8Be^*$ state, which subsequently decays into the ^8Be ground state. This further breaks down into an electron-positron pair whose opening angle and invariant mass are measured.

Standard Model

Internal Pair Creation Correlation (IPCC), where the nuclear emits a virtual photon which then decays to an e^+e^- pair.

- Hadronic decay $(BR \sim 1)$

$$^8Be^* \to {}^7Li + p$$

- Electromagnetic decay $(BR \sim 1.5\times10^{-5})$

$$^8Be^* \to {}^8Be + \gamma$$

- Internal pair creation $(BR \sim 5.5\times10^{-8})$

$$^8Be^* \to {}^8Be + \gamma^* \to {}^8Be + e^+e^-$$

M. E. Rose, Phys. Rev. 76 (1949).
P. Schlüter, G. Soff, and W. Greiner, Physics Reports 75 no. 6, (1981).
D. R. Tilley *et al.*, Nucl. Phys. A745 (2004).

A. J. Krasznahorkay *et al.* [Atomki] (2016)

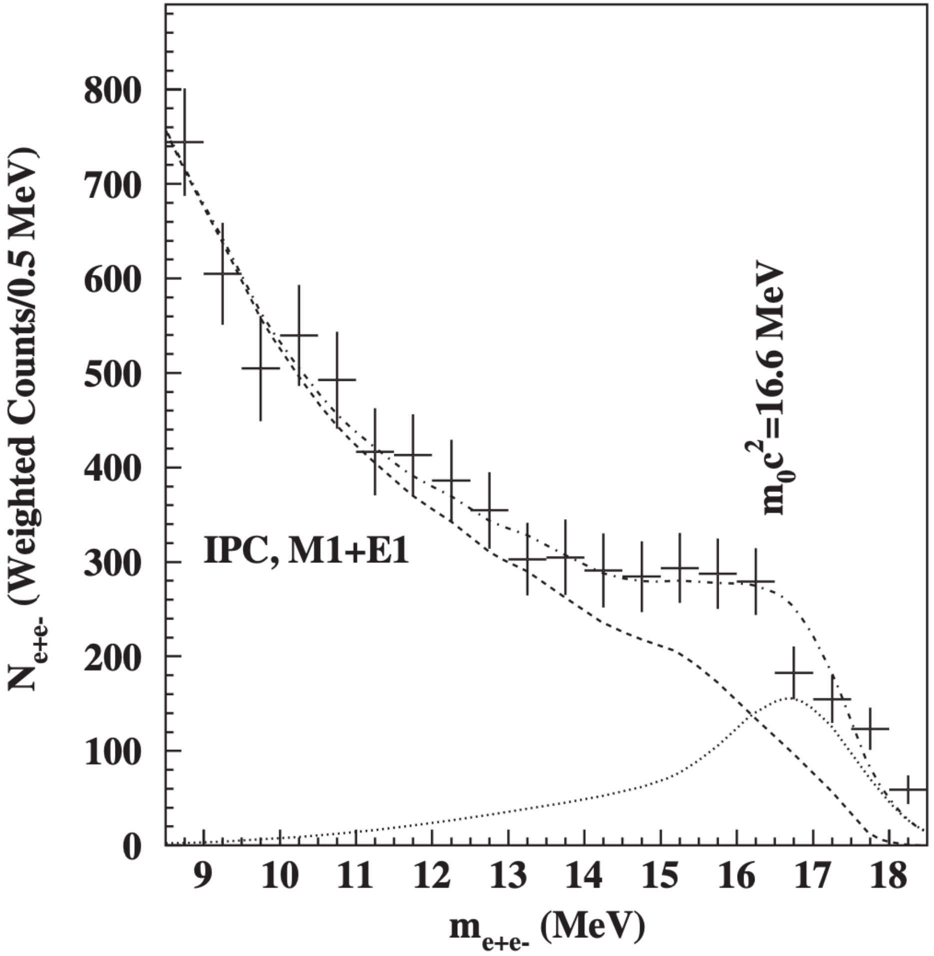


FIG. 1.3. Invariant mass distribution derived for the 18.15MeV transition in ^{8}Be.

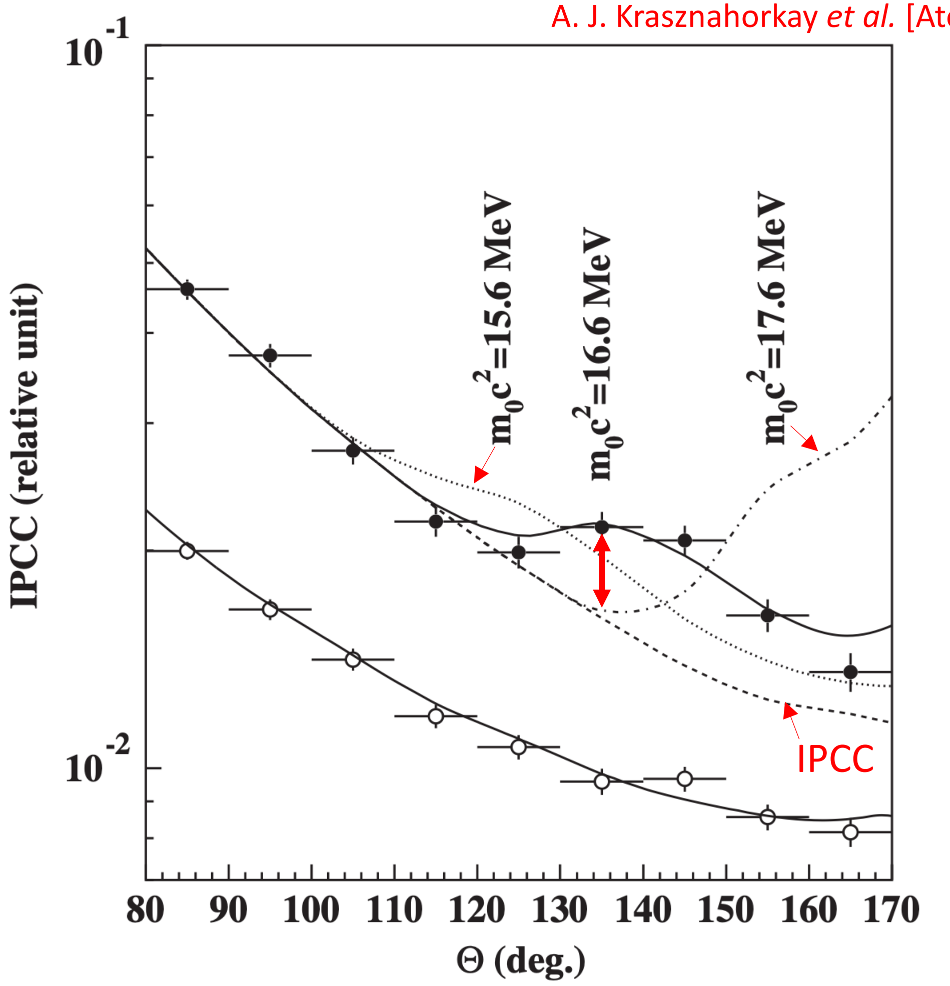
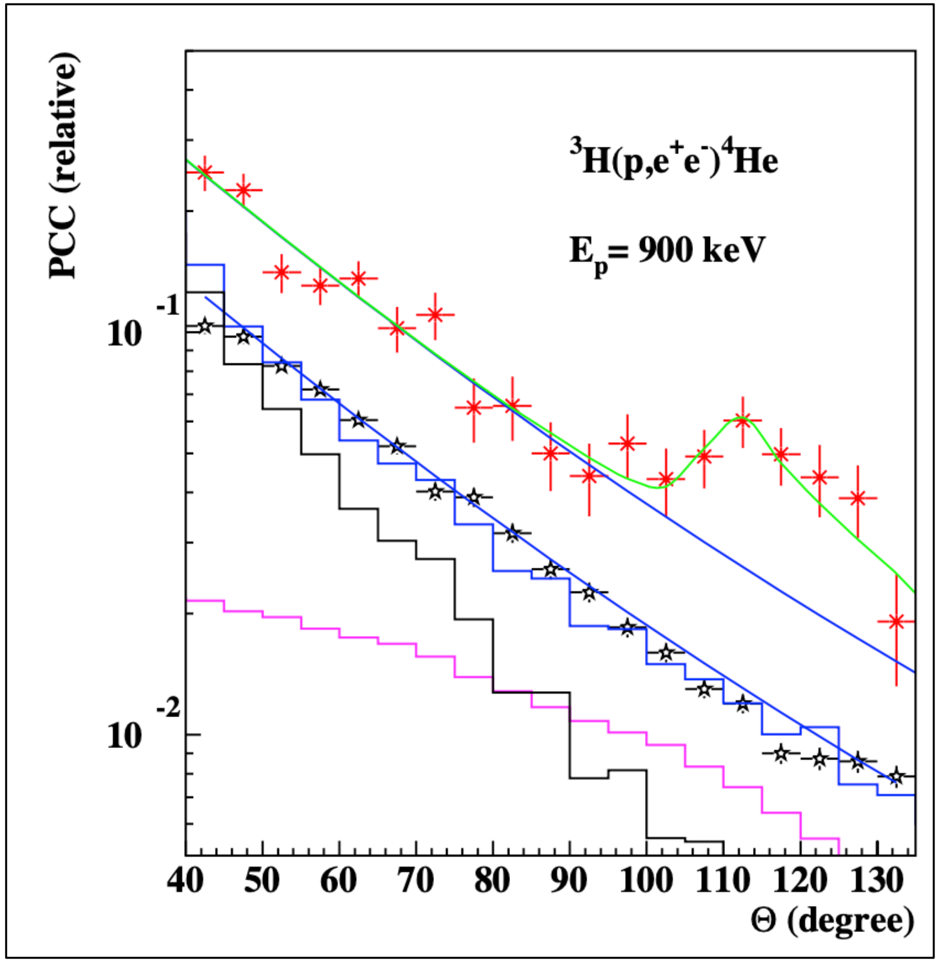


FIG. 1.2. Experimental angular e^+e^-pair correlations measured in the $^7Li(p, e^+e^-)$ reaction at $E_p = 1.10MeV$

$m_X = 16.7 \pm 0.35$ (stat) ± 0.5 (sys) MeV

$$\frac{BR(^8Be^* \to X + {}^8Be)}{BR(^8Be^* \to \gamma + {}^8Be)} \times BR(X \to e^+e^-) = (6 \pm 1) \times 10^{-6}$$

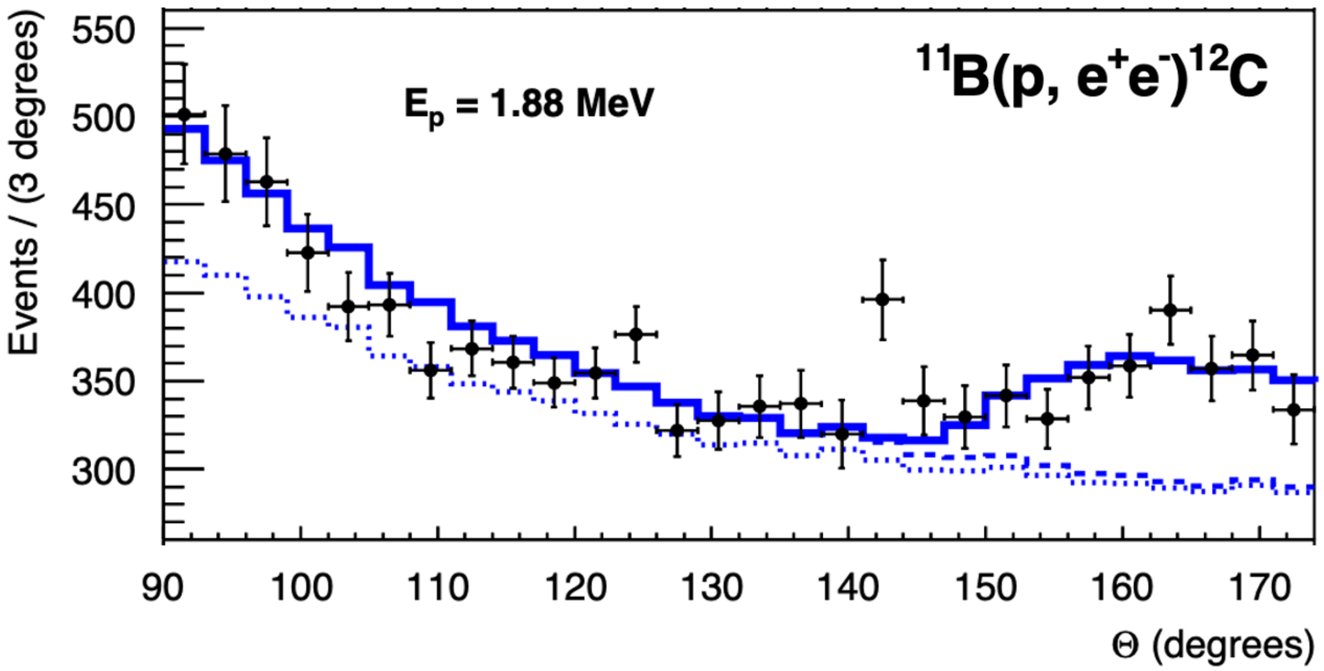
A. J. Krasznahorkay *et al.* [Atomki] (Oct 2019)



^{4}He **anomaly**, X17 boson

$$p + {}^{3}H \rightarrow {}^{4}He^{*} \rightarrow {}^{4}He_0 + e^{+}e^{-}$$

A. J. Krasznahorkay *et al.* [Atomki] (Nov 2022)



^{12}C **anomaly**, X17 boson

$$p + {}^{11}B \rightarrow {}^{12}C^{*} \rightarrow {}^{12}C_0 + e^{+}e^{-}$$

1. Introduction

The decay: $H^* \to He^+e^-$ *here,* H^* *is vector mesons with spin−parity* 1^-

H *is pseudoscalar mesons with spin−parity* 0^-

Meson name	H^*	H	Quark content	m_{H^*} [MeV]	m_H [MeV]
D mesons	D^{*0} →	D^0	$c\bar{u}$	2006.85 ± 0.05	1864.84 ± 0.05
	D^{*+} →	D^+	$c\bar{d}$	2010.26 ± 0.05	1869.66 ± 0.05
	D_s^{*+} →	D_s^+	$c\bar{s}$	2112.2 ± 0.4	1968.35 ± 0.07
Charmonium	$\psi(2S)$ →	$\eta_c(1S)$	$c\bar{c}$	3686.097 ± 0.011	2984.1 ± 0.4
ϕ meson	$\phi(1020)$ →	η	$\phi(s\bar{s})$ and $\eta\left(\frac{u\bar{u}+d\bar{d}-2s\bar{s}}{\sqrt{6}}\right)$	1019.461 ± 0.016	547.862 ± 0.017

PDG *(S. Navas et al., Phys. Rev. D 110, 030001 (2024))*

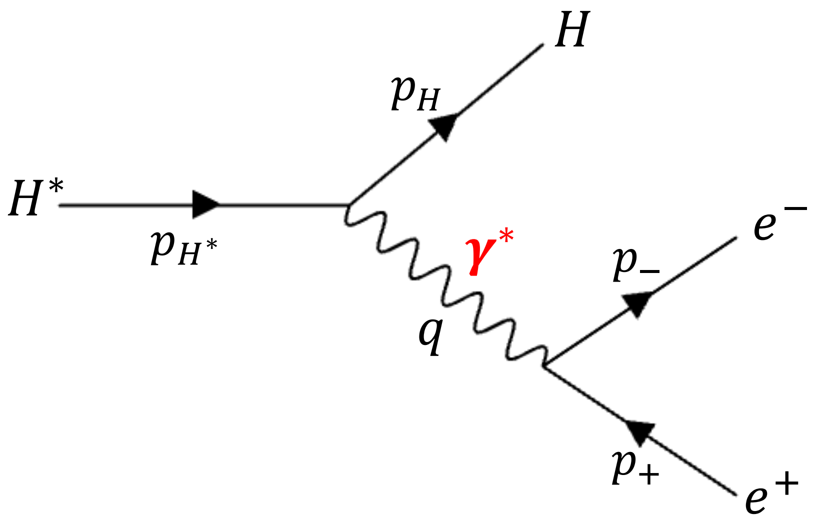


FIG.1.1: Feynman diagram for intermediate photon

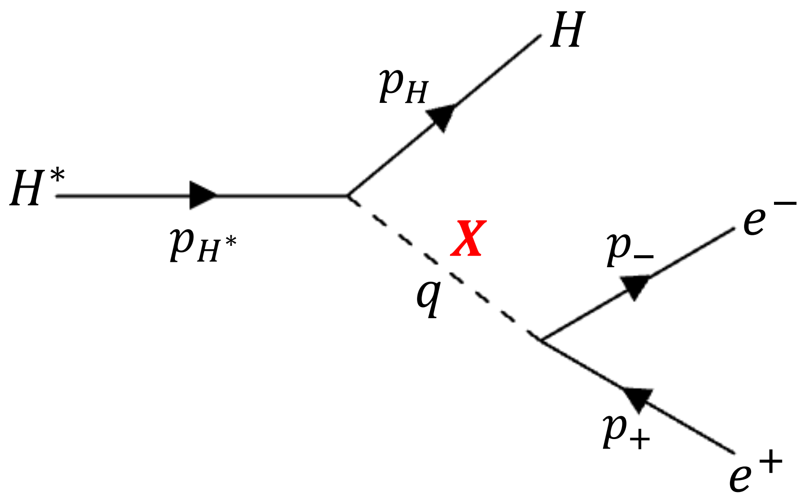


FIG.1.2: Feynman diagram for intermediate X boson

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Quark Coupling Constants $\boldsymbol{\varepsilon_Q}, \boldsymbol{\varepsilon_q}$

$$\mathcal{L}_{X(Q,q)} = \boldsymbol{\varepsilon_Q} X_\mu (\bar{Q}\gamma^\mu Q) + \boldsymbol{\varepsilon_q} X_\mu (\bar{q}\gamma^\mu q)$$

2016

Based on data of ^8Be anomaly,

a "protophobic".

$$\varepsilon_u \backsimeq \pm 3.7\times 10^{-3}$$
$$\varepsilon_d \backsimeq \mp 7.4\times 10^{-3}$$

J.L.Feng *et al.* Phys. Rev. Lett. 071803 (2016)
$\boldsymbol{m_X} =$ **17 MeV**

2023

- Based on data of ^8Be, ^4He and ^{12}C anomalies.
- ^8Be scattering : no isospin effects, isospin mixing, isospin mixing & breaking.

ε_u and ε_d have different signs:

$$|\varepsilon_u| \simeq (0.5 - 0.9)\times 10^{-3}$$
$$|\varepsilon_d| \simeq (2.5 - 2.9)\times 10^{-3}$$

P.B.Denton, J.Gehrlein, Phys. Rev. D 015009 (2023)
$\boldsymbol{m_X} =$ **16.85 ± 0.04 MeV**

2. X17 hypothesis (vector case)

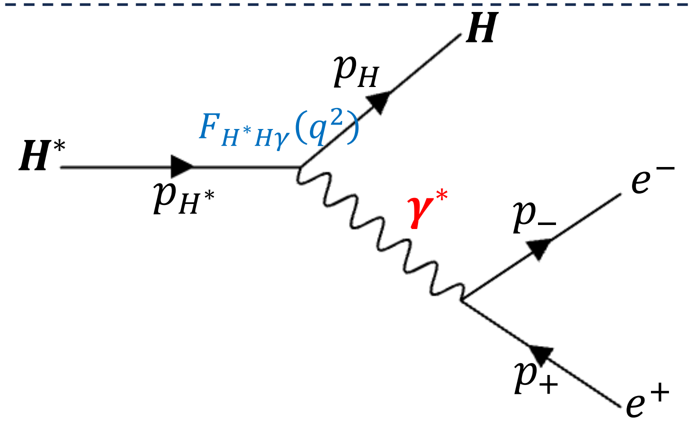

FIG.2.1: Feynman diagram for photon intermediate

$$q^2 G_{H^*H\gamma}(q^2) = F_{H^*H\gamma}(q^2)$$

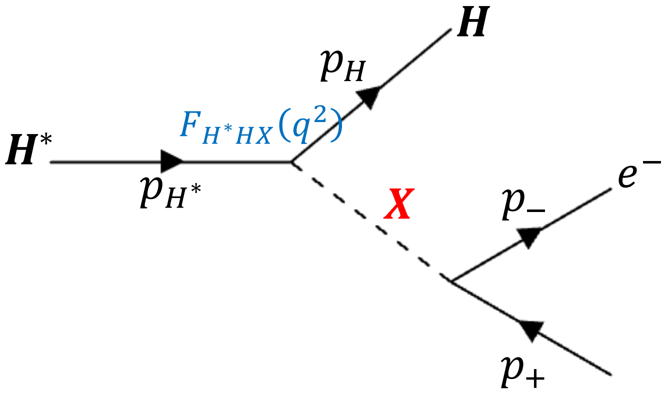

FIG.2.2: Feynman diagram for X boson intermediate

$$(q^2 - m_X^2 + i m_X \Gamma_X) G_{H^*HX}(q^2) = \varepsilon_e F_{H^*HX}(q^2)$$

$$\mathcal{M}(H^* \to H e^+ e^-) = e^2 G_{H^*HV}(q^2) \epsilon_{\mu\nu\sigma\rho} l^\mu \epsilon_{H^*}^\nu p_{H^*}^\sigma p_H^\rho$$

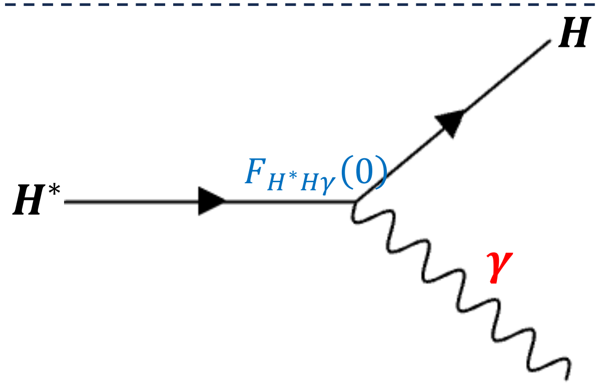

FIG.2.3: Feynman diagram for a real photon

$$\Gamma(H^* \to H\gamma) = \frac{\alpha_{EM}}{3} F_{H^*H\gamma}^2(0)\, p_\gamma^3$$

$$R_{ee}^{V=\gamma,X} = \frac{\Gamma^V(H^* \to H e^+ e^-)}{\Gamma(H^* \to H\gamma)}$$

Meson name	H^*	H	Quark content	m_{H^*} [MeV]	m_H [MeV]
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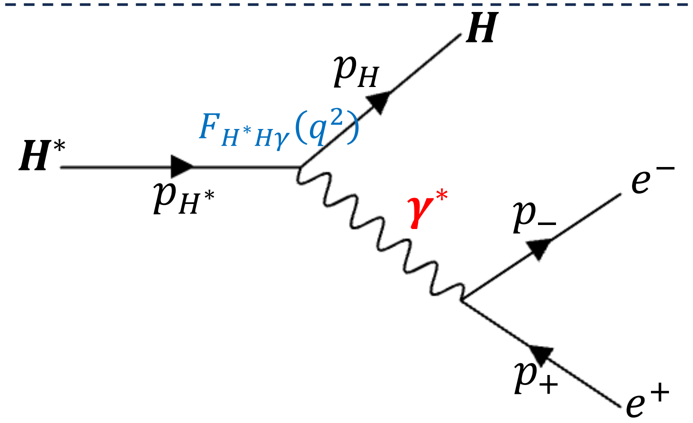


FIG.2.1: Feynman diagram for photon intermediate

$$q^2 G_{H^*H\gamma}(q^2) = F_{H^*H\gamma}(q^2)$$

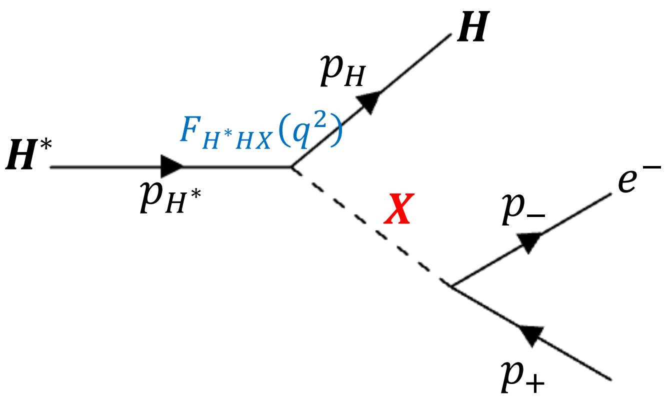


FIG.2.2: Feynman diagram for X boson intermediate

$$(q^2 - m_X^2 + i m_X \Gamma_X) G_{H^*HX}(q^2) = \varepsilon_e F_{H^*HX}(q^2)$$

$$\mathcal{M}(H^* \to He^+e^-) = e^2 G_{H^*HV}(q^2)\epsilon_{\mu\nu\sigma\rho} l^\mu \epsilon^\nu_{H^*} p^\sigma_{H^*} p^\rho_H$$

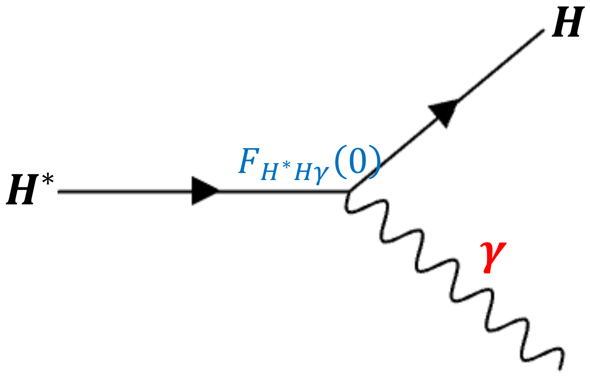


FIG.2.3: Feynman diagram for a real photon

$$\Gamma(H^* \to H\gamma) = \frac{\alpha_{EM}}{3} F^2_{H^*H\gamma}(0)\, p_\gamma^3$$

$$R_{ee}^{V=\gamma,X} = \frac{\Gamma^V(H^* \to He^+e^-)}{\Gamma(H^* \to H\gamma)} = \int_{q^2_{min}}^{q^2_{max}} \mathcal{F}_V(q^2) \times |\mathcal{R}(q^2)|^2\, dq^2$$

with $\mathcal{F}_\gamma(q^2) = \frac{\alpha_{EM}}{3\pi}\frac{1}{q^2}\left(1 + \frac{2m_e^2}{q^2}\right)\sqrt{1 - \frac{4m_e^2}{q^2}}\,\frac{\lambda^{3/2}(m^2_{H^*}, m^2_H, q^2)}{(m^2_{H^*} - m^2_H)^3}$, where $\lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz$

$$\mathcal{F}_X(q^2) = \frac{\alpha_{EM}}{3\pi}\frac{\varepsilon_e^2 q^2}{(q^2 - m_X^2)^2 + m_X^2 \Gamma_{XV}^2}\left(1 + \frac{2m_e^2}{q^2}\right)\sqrt{1 - \frac{4m_e^2}{q^2}}\,\frac{\lambda^{3/2}(m^2_{H^*}, m^2_H, q^2)}{(m^2_{H^*} - m^2_H)^3},$$

$\mathcal{R}(q^2) = \frac{F_{H^*HV}(q^2)}{F_{H^*H\gamma}(0)}$: Transition Form Factor (TFF) ⬅ **Vector Meson Dominance (VMD)**

P.Colangelo, F.De Fazio, G.Nardulli Phys.Lett. B316 (1993)

HQET

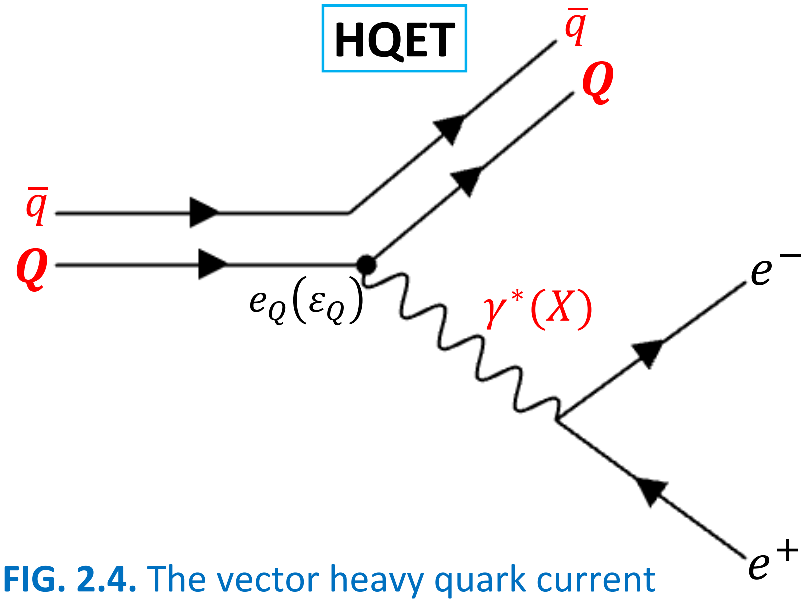


FIG. 2.4. The vector heavy quark current

$$\mathcal{J}^{\mu}_{Q} = \langle D(p_D)|\bar{Q}\gamma^{\mu}Q|D^*(p_{D^*},\epsilon_{D^*})\rangle$$

$$= i\sqrt{m_{D^*}m_D}\,\xi(v_{D^*}\cdot v_D)\,\epsilon^{\mu\nu\alpha\beta}\epsilon_{D^*\nu}v_{D^*\alpha}v_{D\beta}$$

D meson decays:

- $D^{*0}(c\bar{u}) \to D^0 e^+e^-$
- $D^{*+}(c\bar{d}) \to D^+ e^+e^-$
- $D_s^{*+}(c\bar{s}) \to D_s^+ e^+e^-$

$$\mathcal{J}^{\mu}_{\gamma} = e\left(e_Q\mathcal{J}^{\mu}_{Q} + e_q\mathcal{J}^{\mu}_{q}\right)$$

$$\mathcal{J}^{\mu}_{X} = e\left(\varepsilon_Q\mathcal{J}^{\mu}_{Q} + \varepsilon_q\mathcal{J}^{\mu}_{q}\right)$$

VMD

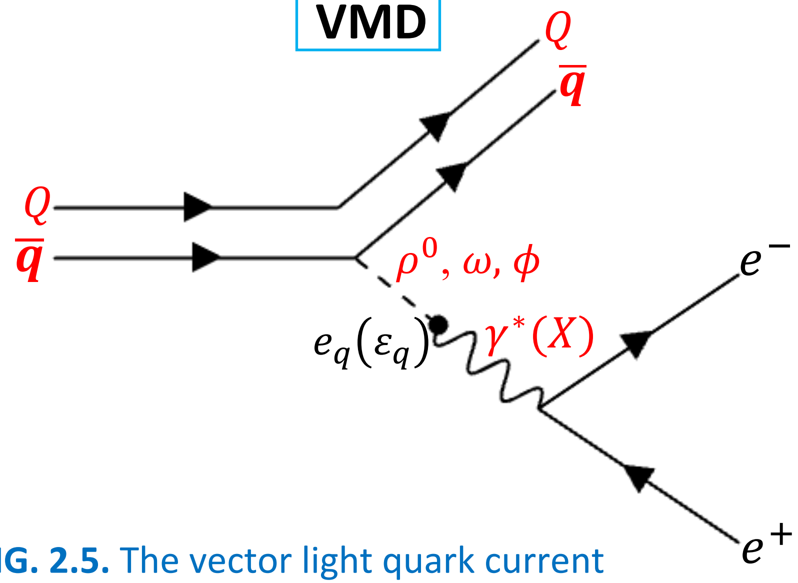
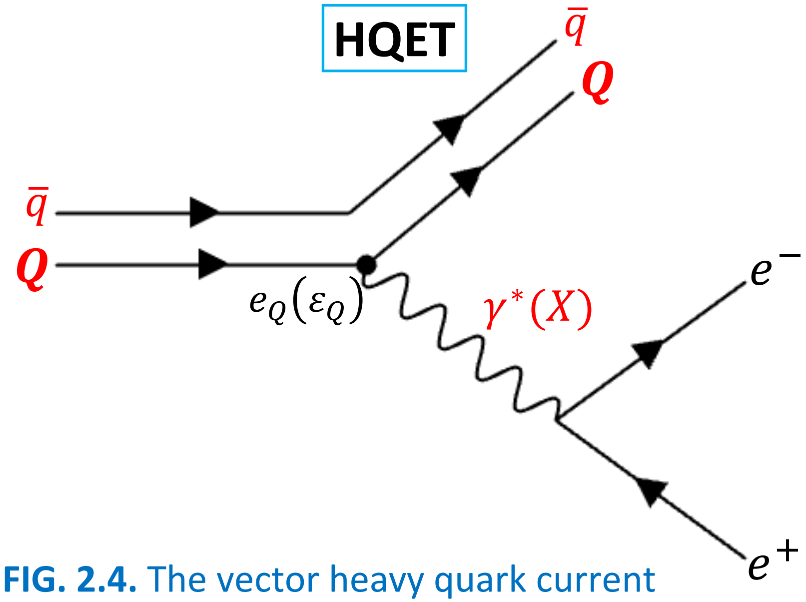


FIG. 2.5. The vector light quark current

$$\mathcal{J}^{\mu}_{q} = \langle D(p_D)|\bar{q}\gamma^{\mu}q|D^*(p_{D^*},\epsilon_{D^*})\rangle$$

$$= \sum_V \langle D(p_D)V(q,\eta)|D^*(p_{D^*},\epsilon_{D^*})\rangle \frac{i}{q^2-m_V^2}\langle 0|\bar{q}\gamma^{\mu}q|V(q,\eta)\rangle$$



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D meson decays:

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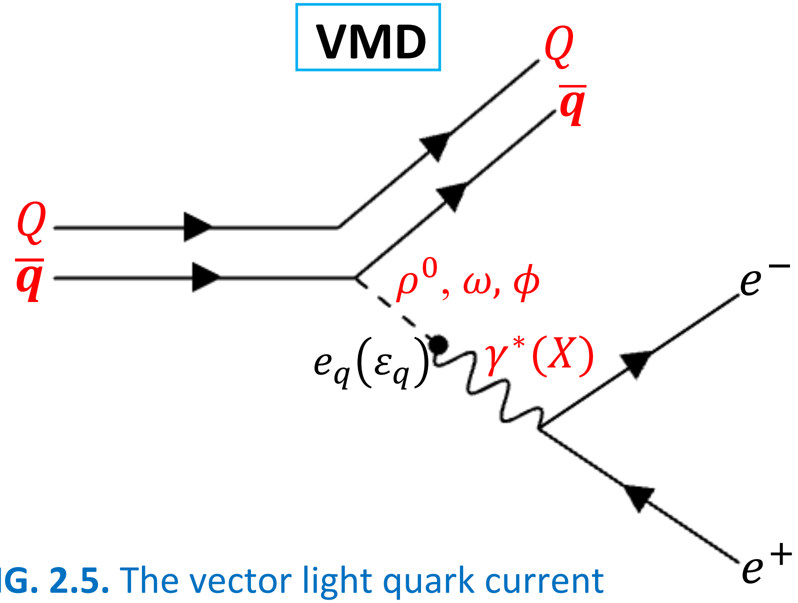
- $D^{*+}(c\bar{d}) \to D^+ e^+e^-$
- $D_s^{*+}(c\bar{s}) \to D_s^+ e^+e^-$

$$\mathcal{J}_\gamma^\mu = e\left(e_Q\mathcal{J}_Q^\mu + e_q\mathcal{J}_q^\mu\right)$$
$$\mathcal{J}_X^\mu = e\left(\varepsilon_Q\mathcal{J}_Q^\mu + \varepsilon_q\mathcal{J}_q^\mu\right)$$



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$$= \sum_V \langle D(p_D)V(q,\eta)|D^*(p_{D^*},\epsilon_{D^*})\rangle \frac{i}{q^2-m_V^2}\langle 0|\bar{q}\gamma^\mu q|V(q,\eta)\rangle$$

G.L.Castro, N.Quintero, Phys. Rev. D 093002 (2021)

- **VMD** is based on the assumption of ideal mixing for vector mesons resonances : $\rho^0\left(\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}\right), \omega\left(\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}\right), \phi(s\bar{s})$.
- The universality assumption of the X17 boson to quarks: $\boldsymbol{\varepsilon_u = \varepsilon_c}$ and $\boldsymbol{\varepsilon_d = \varepsilon_s = \varepsilon_b}$.
- $\boldsymbol{F_{D^*D\gamma}(q^2)} = \sqrt{\frac{m_{D^*}}{m_D}}\left[\frac{e_Q}{m_{D^*}} + \frac{e_q}{m_q(q^2)}\right]$ and $\boldsymbol{F_{D^*DX}(q^2)} = \sqrt{\frac{m_{D^*}}{m_D}}\left[\frac{\varepsilon_Q}{m_{D^*}} + \frac{\varepsilon_q}{m_q(q^2)}\right]$ with $\boldsymbol{m_q(q^2)} = -\sum_V\left(2\sqrt{2}g_V\lambda\frac{f_V}{m_V^2}\right)\left(1-\frac{q^2}{m_V^2}\right)$.

- **Charmonium decay:** $\psi(2S)(c\bar{c}) \to \eta_c e^+ e^-$

$$\mathcal{R}_{\psi'\eta_c X}(q^2) = \frac{F_{\psi'\eta_c X}(q^2)}{F_{\psi'\eta_c\gamma}(0)} = \boldsymbol{\varepsilon_c} \times \frac{F_{\psi'\eta_c\gamma}(q^2)}{F_{\psi'\eta_c\gamma}(0)} = \frac{\boldsymbol{\varepsilon_c}}{1 - q^2/\boldsymbol{\Lambda^2_{\psi'\eta_c}}}$$

➡ The VMD is used to explain the TFF $\mathcal{R}_{\psi'\eta_c\gamma}(q^2)$, where the virtual photon effectively couples to the vector meson resonance.

➡ The pole mass of the vector meson resonance $\Lambda_{\psi'\eta_c}$ nears the energy scale of the decaying particle $\psi(2S)$:

$$\boldsymbol{\Lambda_{\psi'\eta_c} = m_{\psi(3S)} = 3773.7 \pm 0.4\ \mathrm{MeV}/c^2}.$$

- **ϕ meson decay:** $\phi(1S)(s\bar{s}) \to e^+ e^- \eta\left(\frac{u\bar{u} + d\bar{d} - 2s\bar{s}}{\sqrt{6}}\right)$

$$\mathcal{R}_{\phi\eta X}(q^2) = \frac{F_{\phi\eta X}(q^2)}{F_{\phi\eta\gamma}(0)} = \frac{\mathbf{2}}{\sqrt{\mathbf{6}}}\boldsymbol{\varepsilon_s} \times \frac{F_{\phi\eta\gamma}(q^2)}{F_{\phi\eta\gamma}(0)} = \frac{\mathbf{2}}{\sqrt{\mathbf{6}}} \frac{\boldsymbol{\varepsilon_s}}{1 - q^2/\boldsymbol{\Lambda^2_{\phi\eta}}}$$

with $\boldsymbol{\Lambda_{\phi\eta} = m_{\phi(2S)} = 1680 \pm 20\ \mathrm{MeV}/c^2}$.

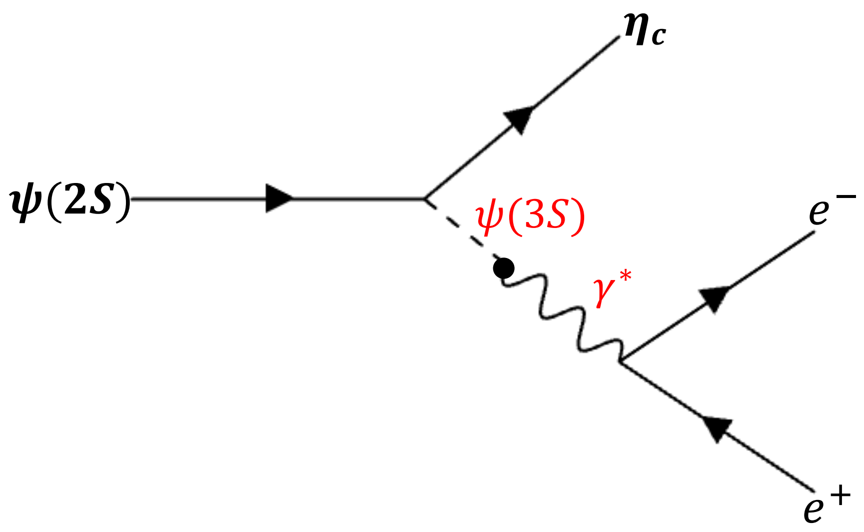

FIG.2.6: The VMD assumption for $\psi(2S) \to \eta_c e^+ e^-$

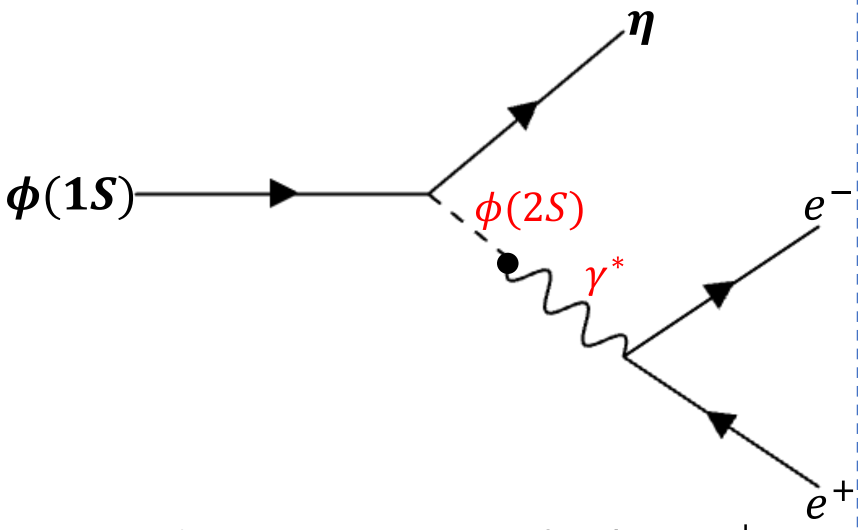

FIG.2.7: The VMD assumption for $\phi \to \eta e^+ e^-$

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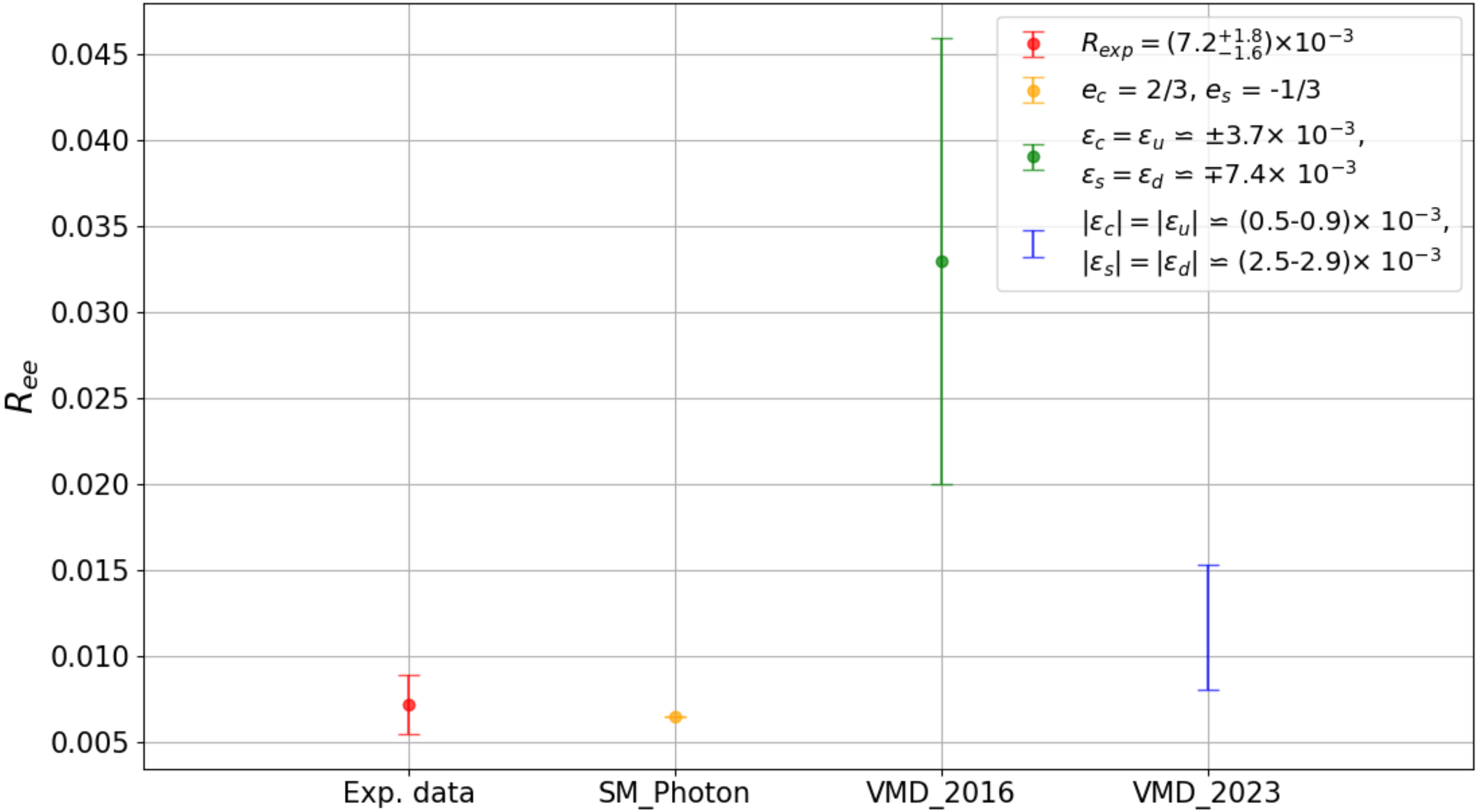
3. Strengths of X17 couplings to light and heavy quarks

$R_{ee} = R_{ee}^X + R_{ee}^{\gamma}$

D meson decays: $D_s^{*+} \to D_s^+ e^+ e^- (c\bar{s})$

D. Cronin-Hennessy, et al. [CLEO Collaboration] (2012)



- The photon mediated contribution is in good agreement with $R_{exp} = (7.2^{+1.8}_{-1.6}) \times 10^{-3}$.
- R_{ee} in label "VMD_2016" is completely inconsistent with the data R_{exp}.
- The reults from "VMD_2023" still somewhat consistent with the data in the decays $D_s^{*+} \to D_s^+ e^+ e^-$.

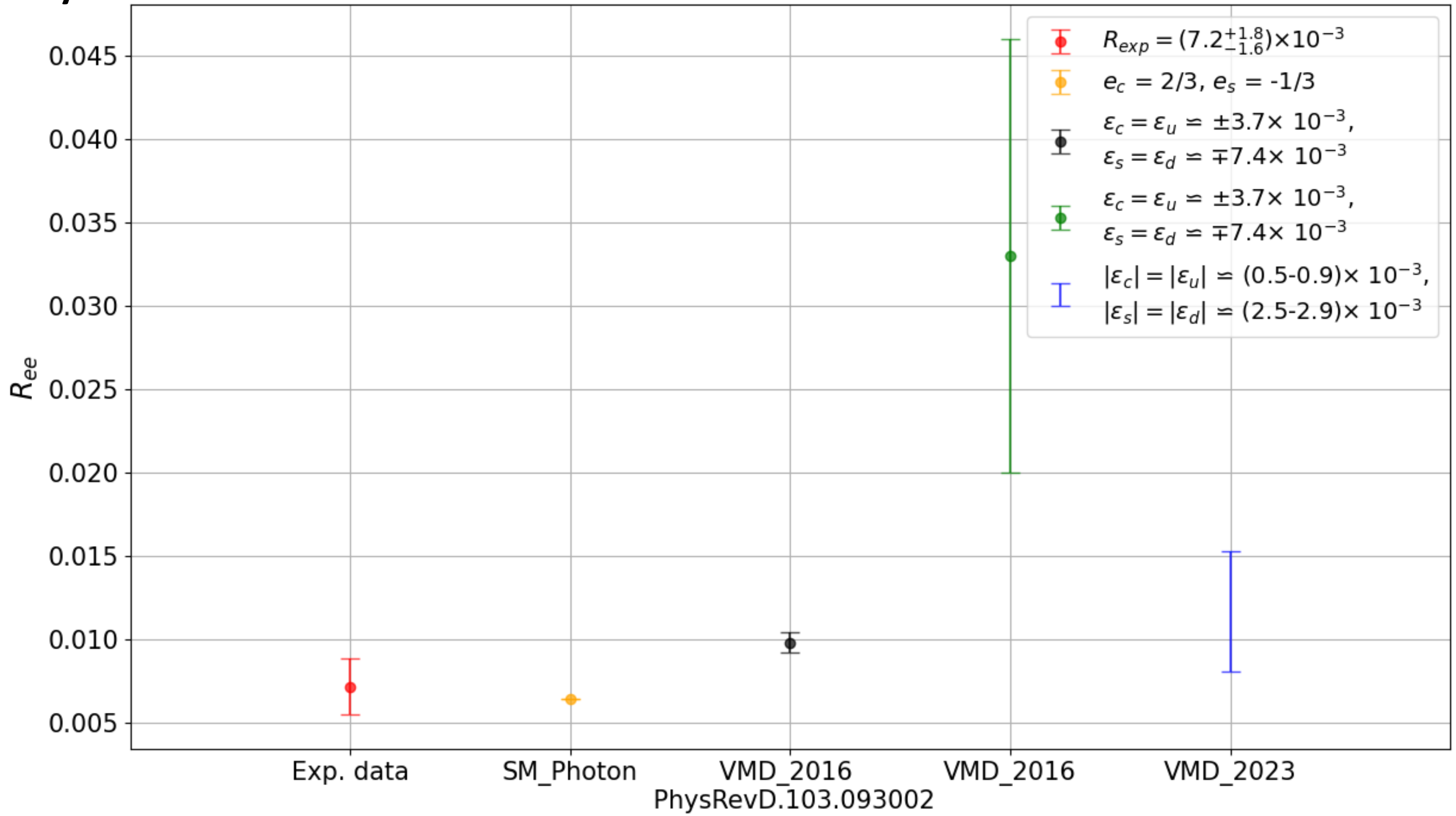
3. Strengths of X17 couplings to light and heavy quarks

$R_{ee} = R_{ee}^X + R_{ee}^\gamma$

D. Cronin-Hennessy, et al. [CLEO Collaboration] (2012)

D meson decays:

$D_s^{*+} \to D_s^+ e^+ e^- (c\bar{s})$



G.L.Castro, N.Quintero, PhysRevD.103.093002 (2021)

Channel	$R_{ee}^\gamma(H^*)$	$R_{ee}^X(H^*)$	Total	Experiment
$D^{*+} \to D^+e^+e^-$	6.67×10^{-3} ✓	$(1.05\pm0.07)\times10^{-3}$ ✓	$(7.72\pm0.07)\times10^{-3}$ ✓	...
$D^{*0} \to D^0e^+e^-$	6.67×10^{-3} ✓	3.02×10^{-5} ✓	6.70×10^{-3} ✓	...
$D_s^{*+} \to D_s^+e^+e^-$	6.72×10^{-3} ✓	$(3.10\pm0.60)\times10^{-3}$	$(9.82\pm0.60)\times10^{-3}$	$(7.2^{+1.8}_{-1.6})\times10^{-3}$ [26]
		$(2.62\pm1.3)\times10^{-2}$	$(3.3\pm1.3)\times10^{-2}$	

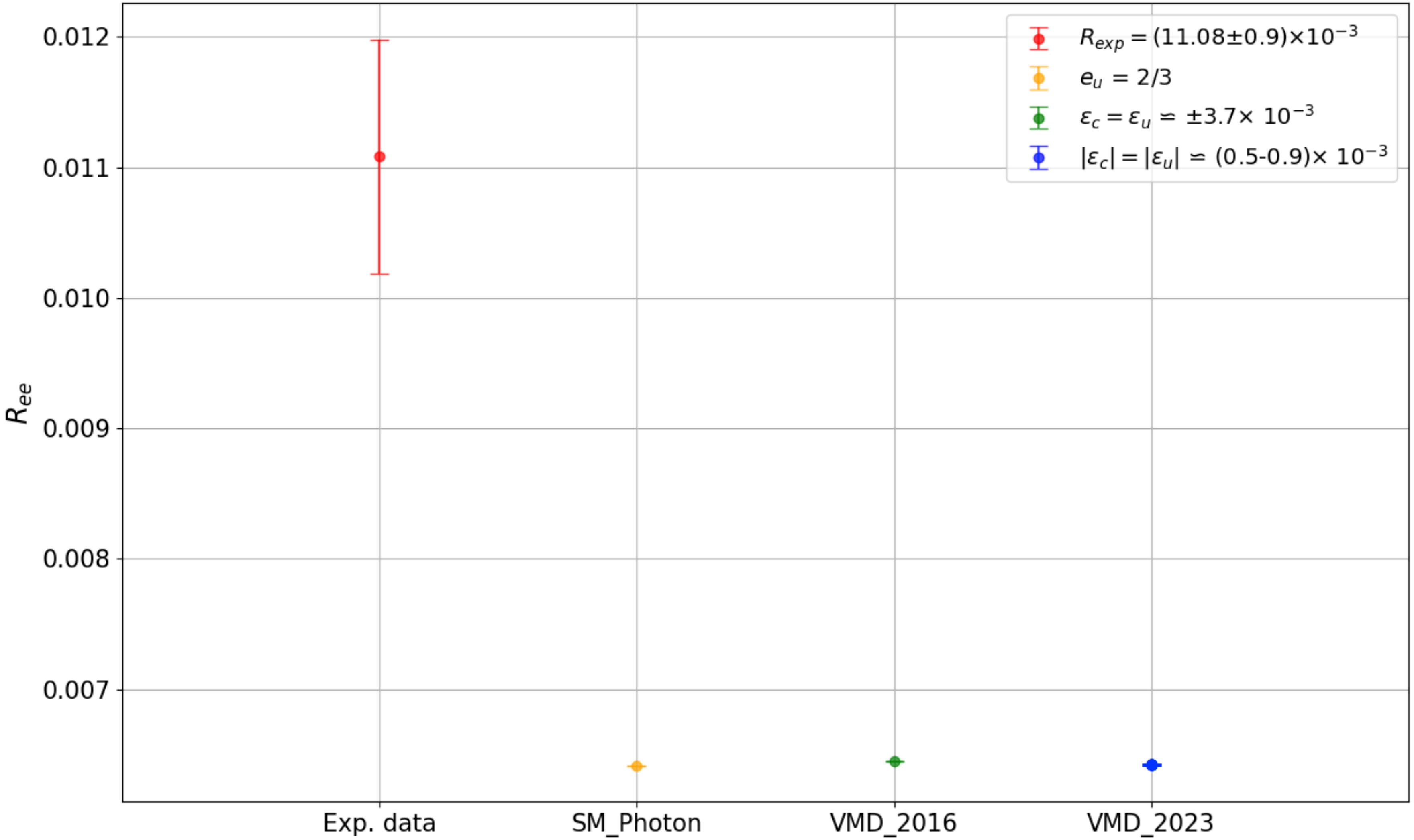
The red numbers recalculated and revised

3. Strengths of X17 couplings to light and heavy quarks

$R_{ee} = R_{ee}^{X} + R_{ee}^{\gamma}$

D meson decays: $D^{*0} \to D^0 e^+ e^- (c\bar{u})$

M. Ablikim, et al. [BESIII Collaboration] (2021)



- A significant difference exists between the experimental data and theoretical models in the decays $D^{*0} \to D^0 e^+ e^-$.
- To resolve this situation, we need to change the value of ε_c ➧ remove the assumption of $\varepsilon_u = \varepsilon_c$ and $\varepsilon_d = \varepsilon_s$.

3. Strengths of X17 couplings to light and heavy quarks

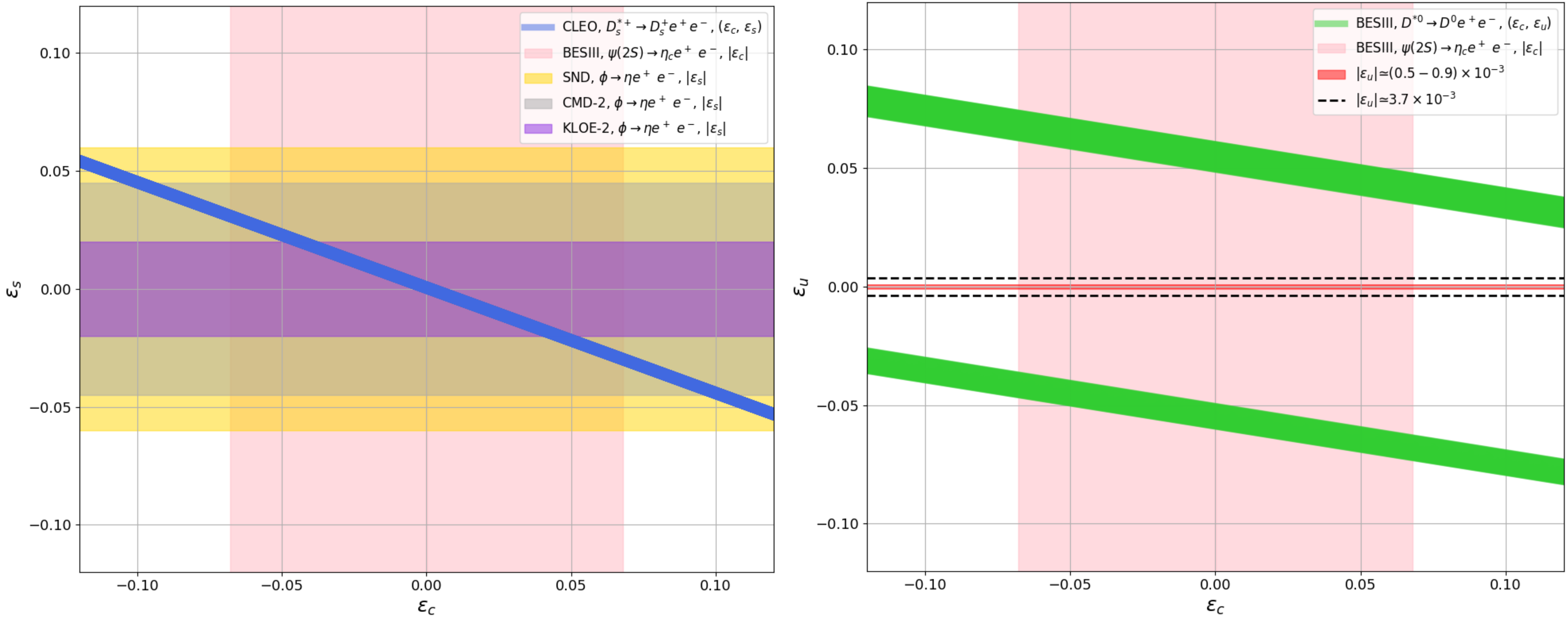


Fig. 3.3. $(\varepsilon_c, \varepsilon_s)$ and $(\varepsilon_c, \varepsilon_u)$ are extracted from the data of D meson, Charmonium and ϕ meson decays.

D. Cronin-Hennessy et al. [CLEO Collaboration] (2012)
D. Babusci et al. (KLEO-2 Collaboration) (2015)
M. N. Achasov et al. [SND collaboration] (2001)
R. R. Akhmetshin et al. [CMD-2 collaboration] (2001)
M. Ablikim, et al. [BESIII Collaboration] (2021)
M. Ablikim, et al. [BESIII Collaboration] (2022)

3. Strengths of X17 couplings to light and heavy quarks

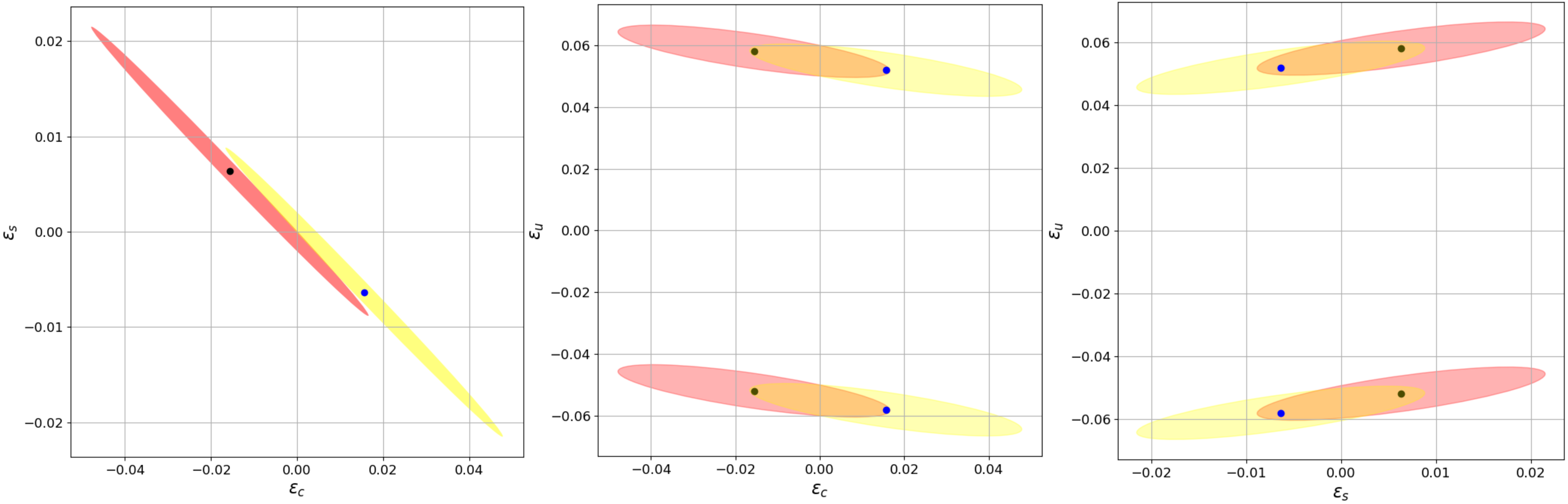


FIG. 3.4. χ^2 method for three parameters $\varepsilon_c, \varepsilon_s$ and ε_u estimated at 1σ using four measurements from D meson, Charmonium and ϕ meson decays.

$$\chi^2 = \sum_{i=1}^{4} \frac{\left(R_i^{th}(\varepsilon_c, \varepsilon_s, \varepsilon_u) - R_i^{ob}\right)^2}{\sigma_i^2}$$

- $|\varepsilon_c| = 0.016$, $|\varepsilon_s| = 0.0063$, ε_c and ε_s have opposite signs.
- $|\varepsilon_u| = 0.052$ or 0.058, $\varepsilon_u \propto 10^{-2}$ (larger than ε_u determined from Atomki measurements).

3. Strengths of X17 couplings to light and heavy quarks

The decay: $H^* \to He^+e^-$ *here,* H^* *is vector mesons with spin–parity* 1^-

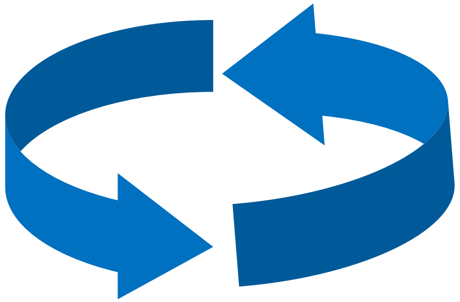
H *is pseudoscalar mesons with spin–parity* 0^-

Meson name	H^*	H	Quark content	m_{H^*} [MeV]	m_H [MeV]
D mesons	D^{*0} →	D^0	$c\bar{u}$	2006.85 ± 0.05	1864.84 ± 0.05
	D^{*+} →	D^+	$c\bar{d}$	2010.26 ± 0.05	1869.66 ± 0.05
	D_s^{*+} →	D_s^+	$c\bar{s}$	2112.2 ± 0.4	1968.35 ± 0.07
Charmonium	$\psi(2S)$ →	$\eta_c(1S)$	$c\bar{c}$	3686.097 ± 0.011	2984.1 ± 0.4
ϕ meson	$\phi(1020)$ →	η	$\phi(s\bar{s})$ and $\eta\left(\frac{u\bar{u}+d\bar{d}-2s\bar{s}}{\sqrt{6}}\right)$	1019.461 ± 0.016	547.862 ± 0.017

Atomki mesurements

$\boldsymbol{\varepsilon_u, \varepsilon_d}$

$\varepsilon_u \propto (10^{-4} - 10^{-3})$



D meson, Charmonium, and ϕ meson decays

$\boldsymbol{\varepsilon_u, \varepsilon_s, \varepsilon_c}$

$\varepsilon_u \propto 10^{-2}$

Outline

1. Introduction
2. X17 hypothesis (vector case) from anomalous ^{8}Be, ^{4}He, and ^{12}C decays
3. Strengths of X17 couplings to light and heavy quarks – determined by fittings to D meson, Charmonium and ϕ meson decays
4. Conclusions

Conclusions

- The effects of the X17 boson in interactions with D meson, Charmonium, and ϕ meson decays are analyzed using the Vector Meson Dominance for calculating the transition form factors.

- Building upon the assumptions of generation universality $|\varepsilon_u| = |\varepsilon_c|$ and $|\varepsilon_d| = |\varepsilon_s|$, we have examined the decay process $D^{*0} \to D^0 e^+ e^-$, which is mediated by the X17 boson. Surprisingly, this decay process does not significantly enhance R_{ee} to align with the data. However, a more promising fit is observed in the decay $D_s^{*+} \to D_s^+ e^+ e^-$. This intriguing result suggests that merely knowing the couplings of the X17 boson with the up and down quarks is insufficient.

- Combined fittings to data from D meson, Charmonium, and ϕ meson decays opens up various possibilities regarding the magnitude and sign of ε_q and ε_Q. The best-fit values are $|\varepsilon_c| = 0.016$ and $|\varepsilon_s| = 0.0063$, while $|\varepsilon_u| = 0.052$ or 0.058. An ε_u with an absolute value about few times of 10^{-2} is not compatible with the data of anomalous $^8Be,\ ^4He, and\ ^{12}C$ decays. The mode $D^{*0} \to D^0 e^+ e^-$ at BESIII is responsible for this serious tension.

BACKUP

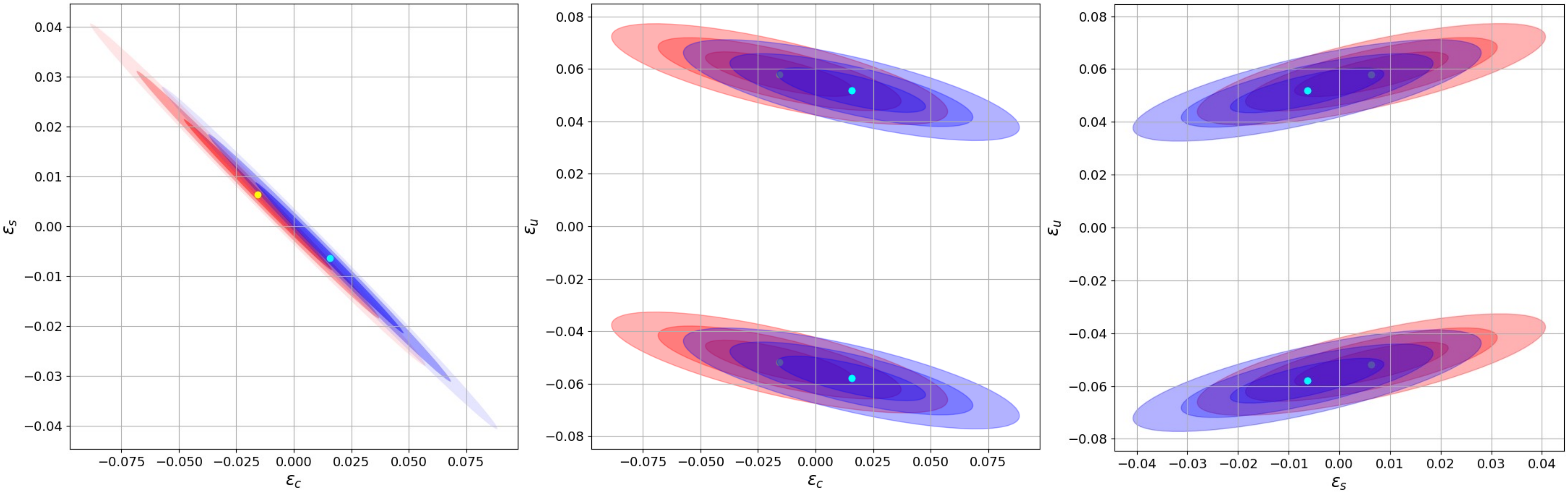


FIG. 3.5. χ^2 method for three parameters $\varepsilon_c, \varepsilon_s$ and ε_u estimated at 1,2,3σ using four measurements from D meson, Charmonium and ϕ meson decays.

$$\chi^2 = \sum_{i=1}^{4} \frac{\left(R_i^{th}(\varepsilon_c, \varepsilon_s, \varepsilon_u) - R_i^{ob}\right)^2}{\sigma_i^2}$$