國立陽明交通大學
NATIONAL YANG MING CHIAO TUNG UNIVERSITY
Institute of Physics

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

Speaker: Lam Thi Thuc Uyen

Collaborators: Guey-Lin Lin and Fei-Fan Lee

NYCU, 2024/06/04

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. Conclusion

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What is X17 boson?

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

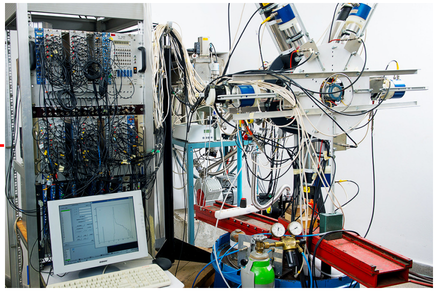
Observation of Anomalous Internal Pair Creation in ^{8}Be: A Possible Indication of a Light, Neutral Boson

A. J. Krasznahorkay,* M. Csatlós, L. Csige, Z. Gácsi, J. Gulyás, M. Hunyadi, I. Kuti, B. M. Nyakó, L. Stuhl, J. Timár, T. G. Tornyi, and Zs. Vajta
Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary

T. J. Ketel
Nikhef National Institute for Subatomic Physics, Science Park 105, 1098 XG Amsterdam, Netherlands

A. Krasznahorkay
CERN, CH-1211 Geneva 23, Switzerland and Institute for Nuclear Research, Hungarian Academy of Sciences (MTA Atomki), P.O. Box 51, H-4001 Debrecen, Hungary
(Received 7 April 2015; published 26 January 2016)

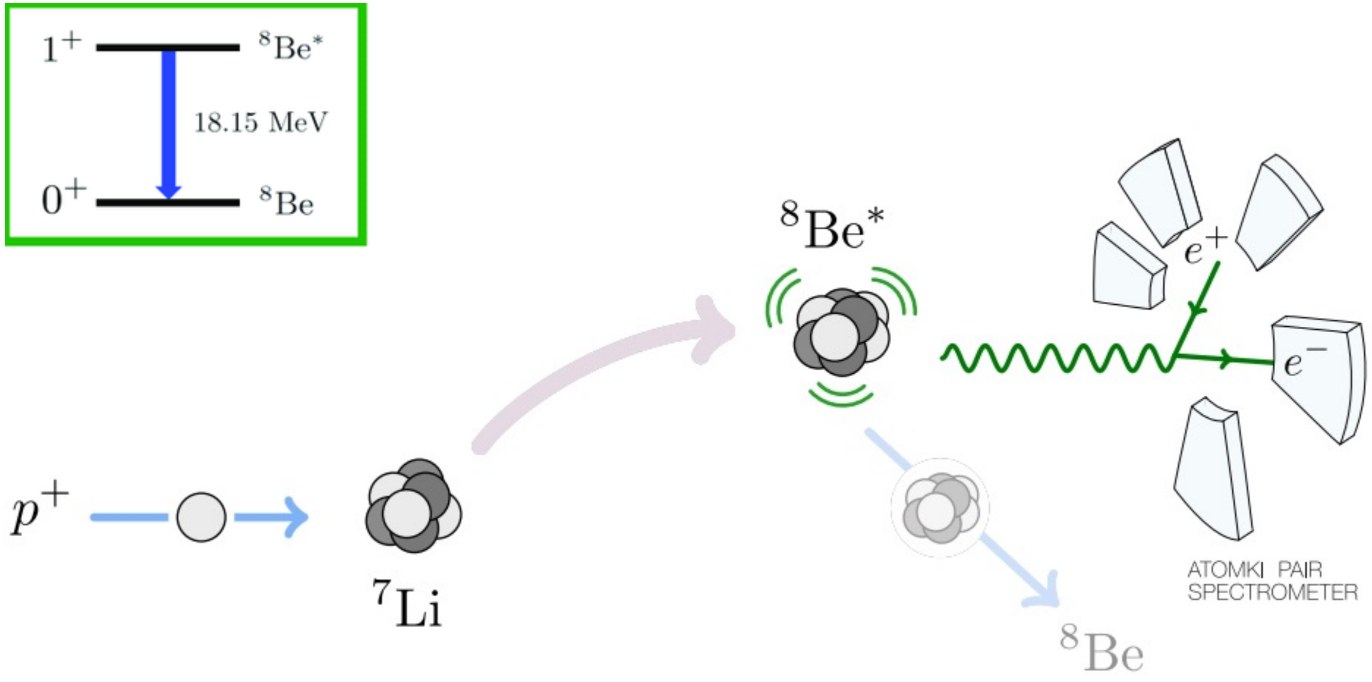
Electron-positron angular correlations were measured for the isovector magnetic dipole 17.6 MeV ($J^\pi = 1^+$, $T = 1$) state → ground state ($J^\pi = 0^+$, $T = 0$) and the isoscalar magnetic dipole 18.15 MeV ($J^\pi = 1^+$, $T = 0$) state → ground state transitions in ^{8}Be. Significant enhancement 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, ^8Be anomaly, X17 boson

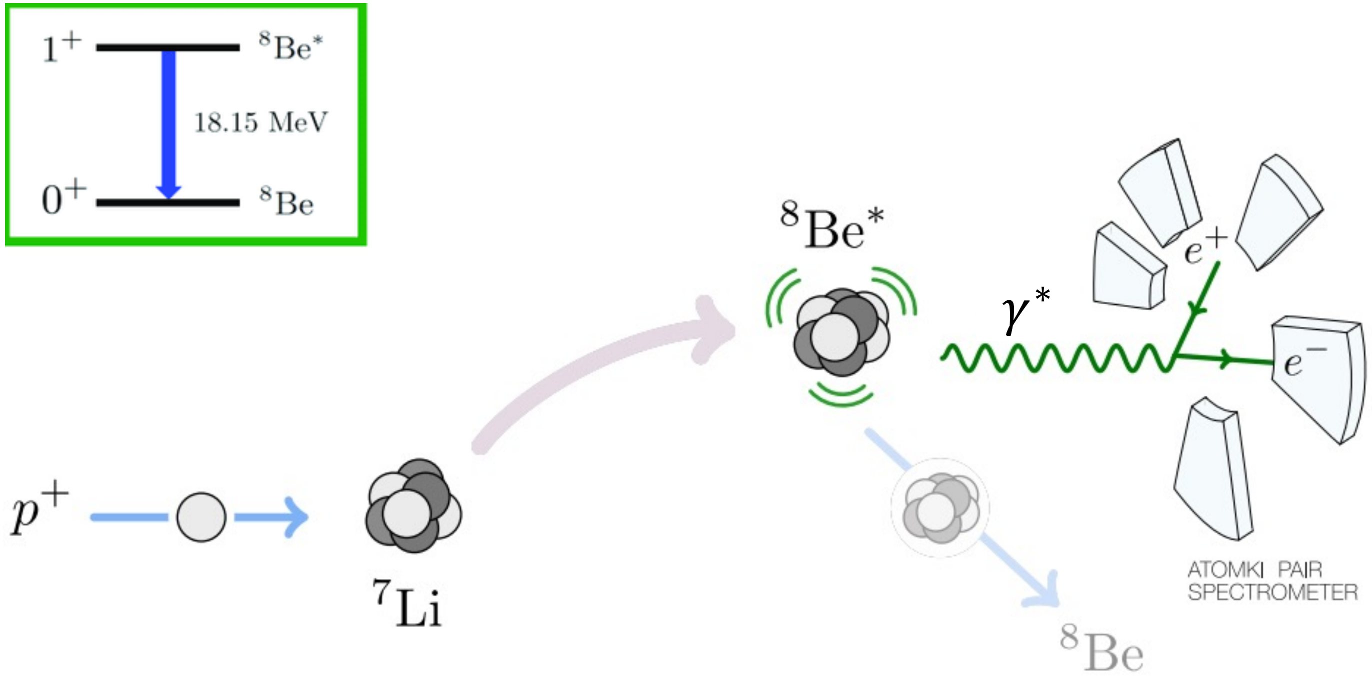
The Atomki experiment



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 $^{8}Be^{*}$ state, which subsequently decays into the ^{8}Be 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 $(BR \sim 1)$

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

- Electromagnetic decay $(BR \sim 1.5{\times}10^{-5})$

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

- Internal pair creation $(BR \sim 5.5{\times}10^{-8})$

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

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).

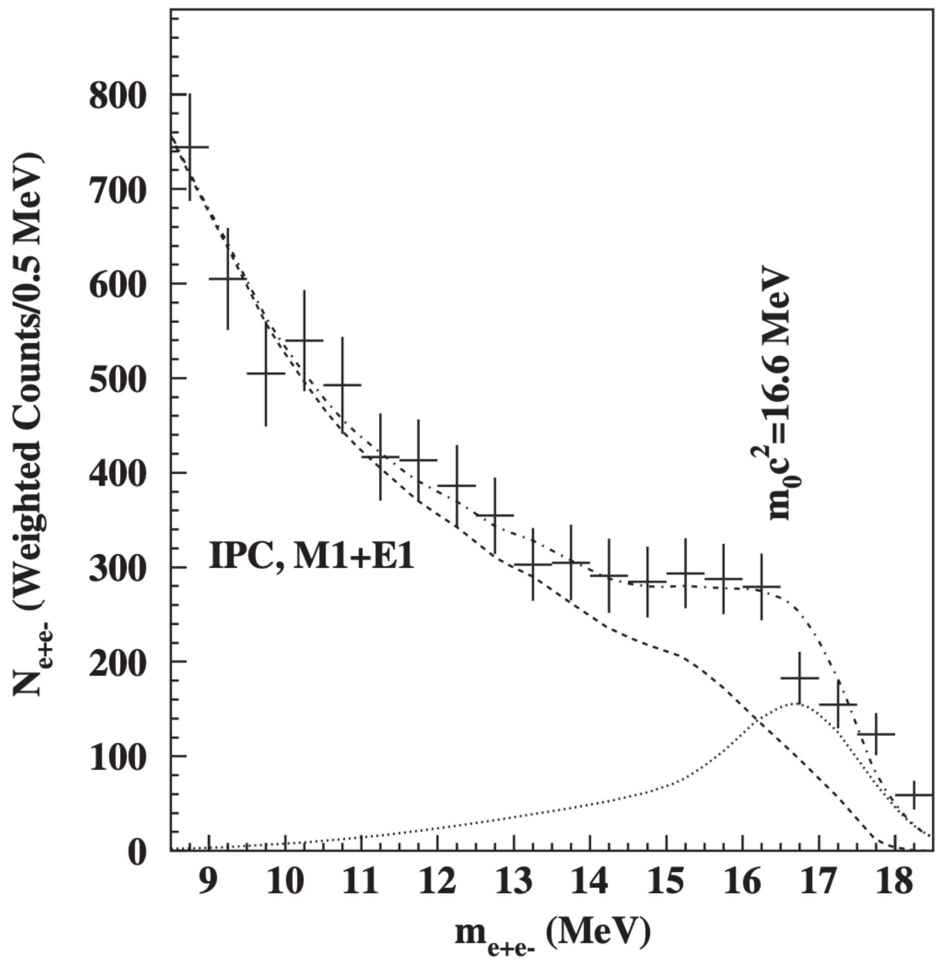


FIG. 1.3. Invariant mass distribution derived for the 18.15MeV transition in ^{8}Be.

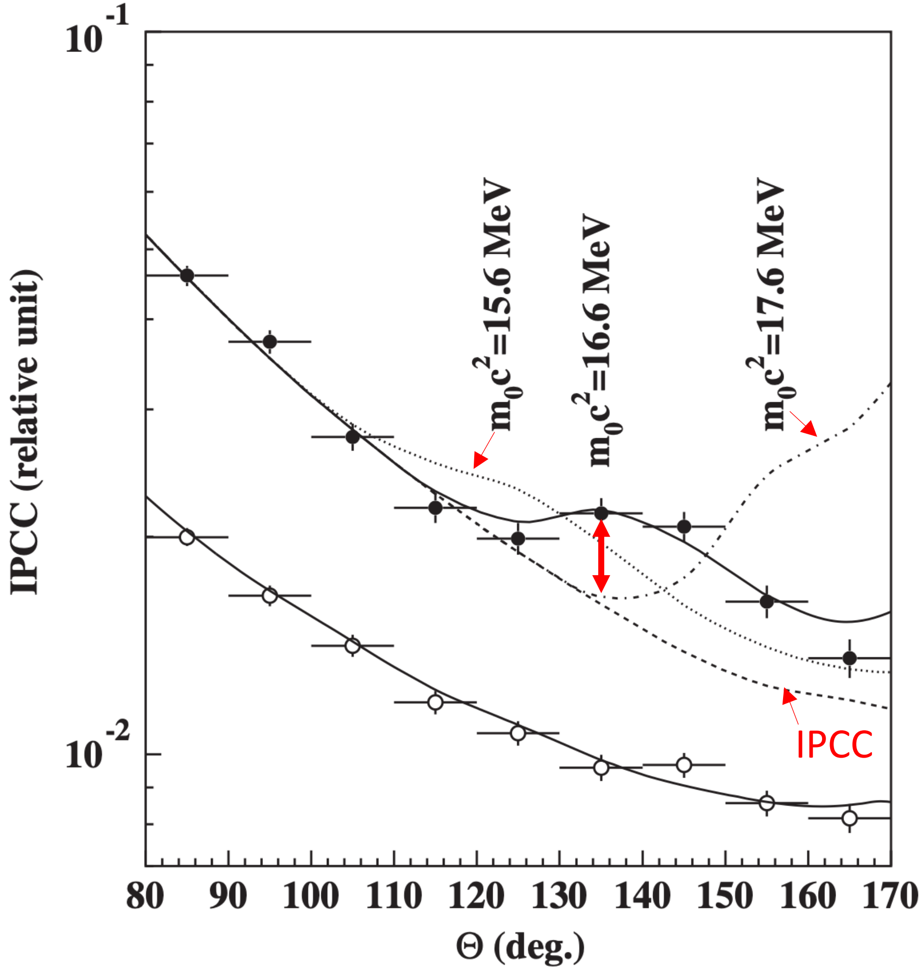


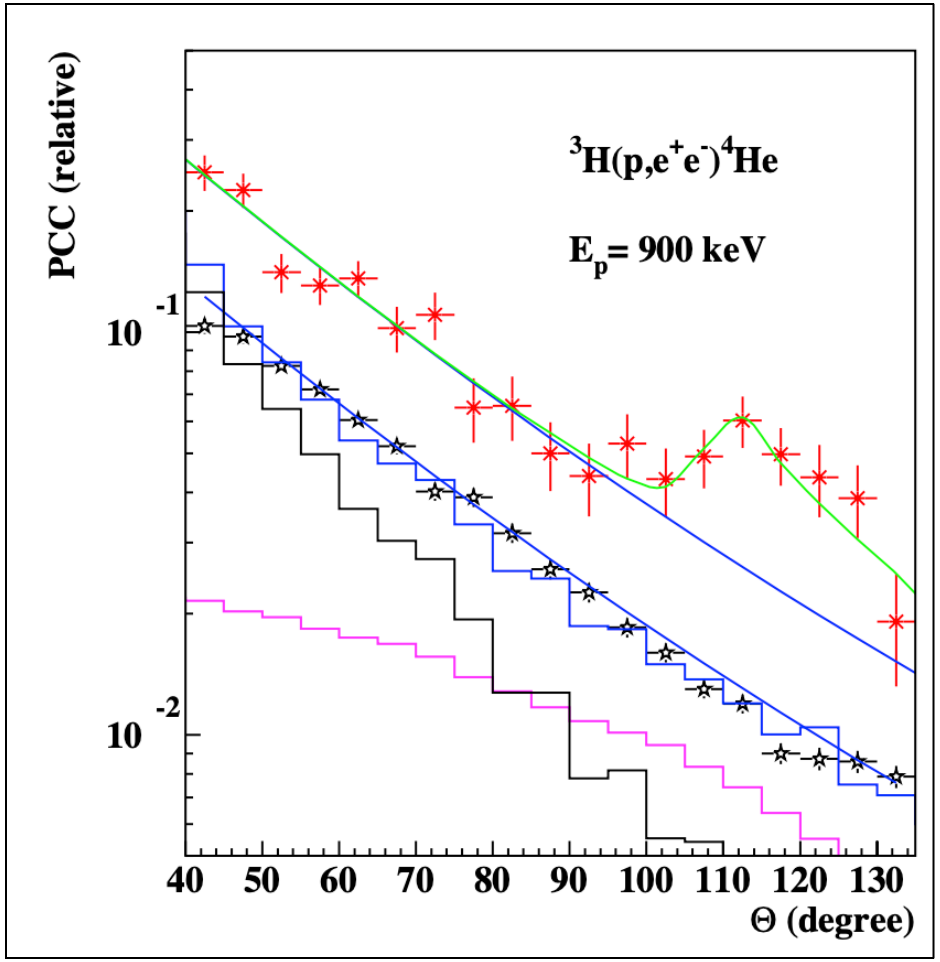
FIG. 1.2. Experimental angular e^+e^-pair correlations measured in the $^7Li(p,e^+e^-)$ reaction at $E_p = 1.10MeV$

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

$$m_X = 16.7 \pm 0.35\ \text{(stat)} \pm 0.5\ \text{(sys) MeV}$$

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

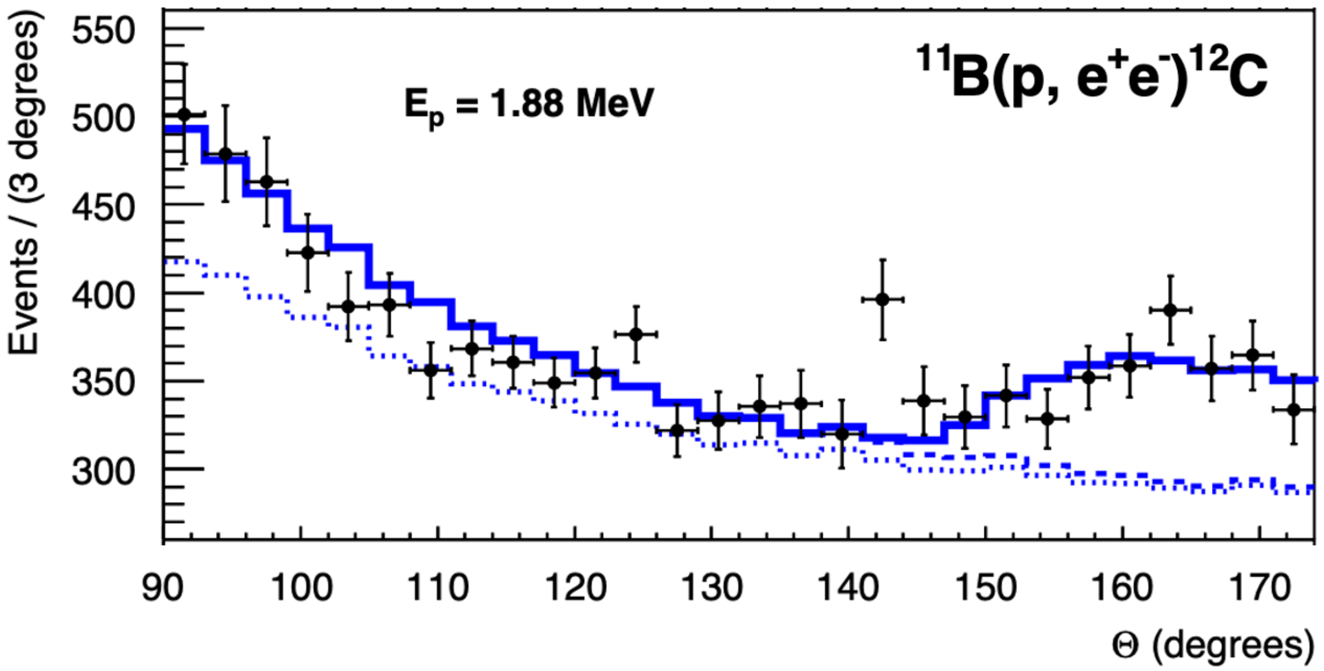
A. J. Krasznahorkay *et al.* [Atomki] (Oct 2019)



~ 100 citations, ^4He **anomaly**, X17 boson

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

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



> 30 citations, ^{12}C **anomaly**, X17 boson

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

1. Introduction

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

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

Meson name	H^*	H	Quark content
D mesons	D^{*0} →	D^0	$c\bar{u}$
	D^{*+} →	D^+	$c\bar{d}$
	D_s^{*+} →	D_s^+	$c\bar{s}$
Charmonium	$\psi(2S)$ →	$\eta_c(1S)$	$c\bar{c}$
ϕ meson	$\phi(1020)$ →	η	$\phi(s\bar{s})$ and $\eta\left(\frac{u\bar{u}+d\bar{d}-2s\bar{s}}{\sqrt{6}}\right)$

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

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Charmonium	$\psi(2S)$ →	$\eta_c(1S)$	$c\bar{c}$
ϕ meson	$\phi(1020)$ →	η	$\phi(s\bar{s})$ and $\eta\left(\frac{u\bar{u}+d\bar{d}-2s\bar{s}}{\sqrt{6}}\right)$

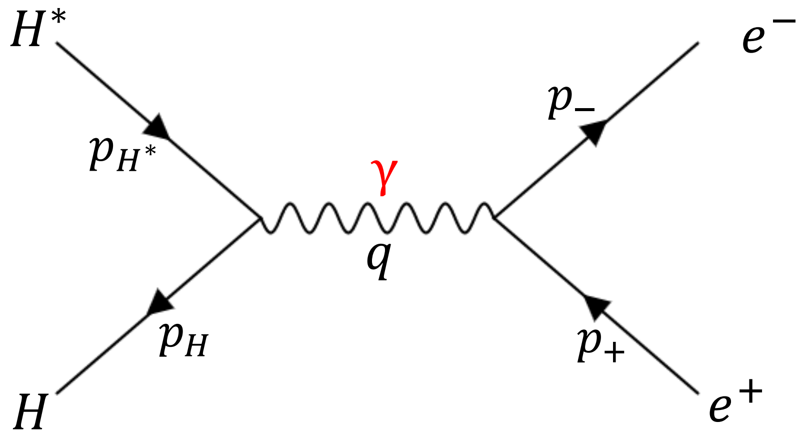

FIG.1.1: Feynman diagram for photon intermediate

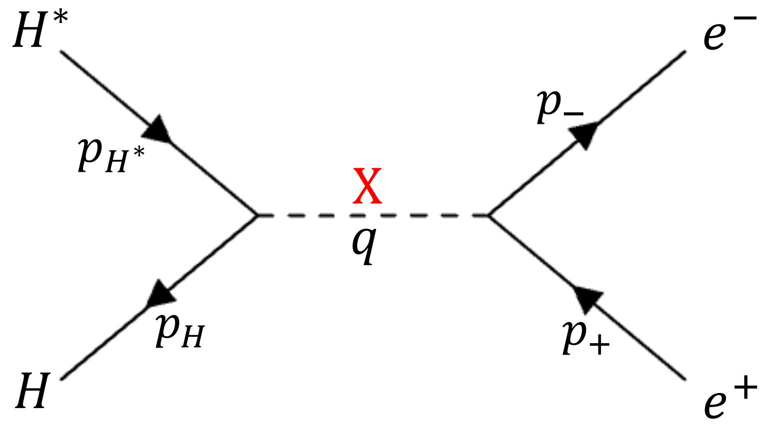

FIG.1.2: Feynman diagram for X boson intermediate

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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

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

J.L.Feng *et al.* Phys. Rev. Lett. 071803 (2016)

…

2023

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

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

P.B.Denton, J.Gehrlein, Phys. Rev. D 015009 (2023)

2. X17 hypothesis (vector case)

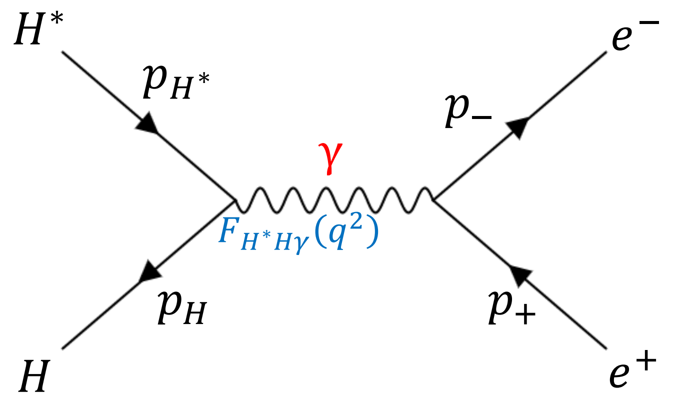


FIG.2.1: Feynman diagram for photon intermediate

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

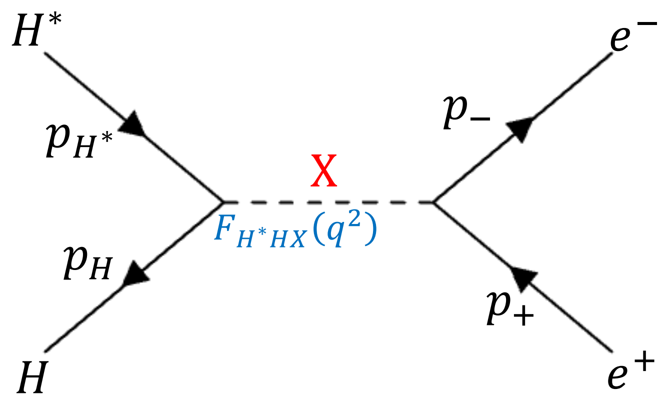


FIG.2.2: Feynman diagram for X boson intermediate

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

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

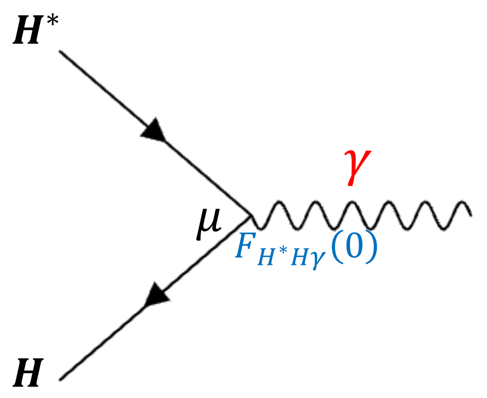


FIG.2.3: Feynman diagram for a real photon

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

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

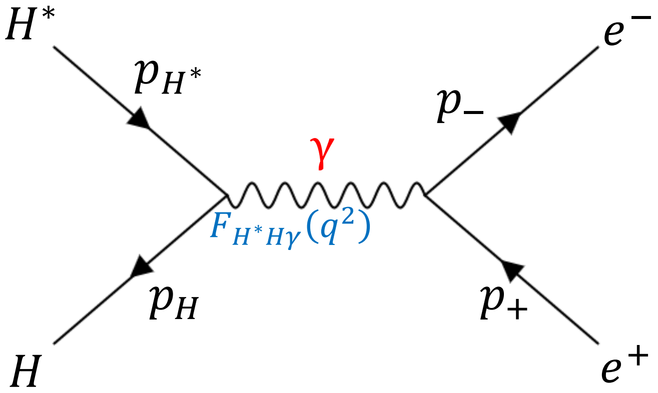


FIG.2.1: Feynman diagram for photon intermediate

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

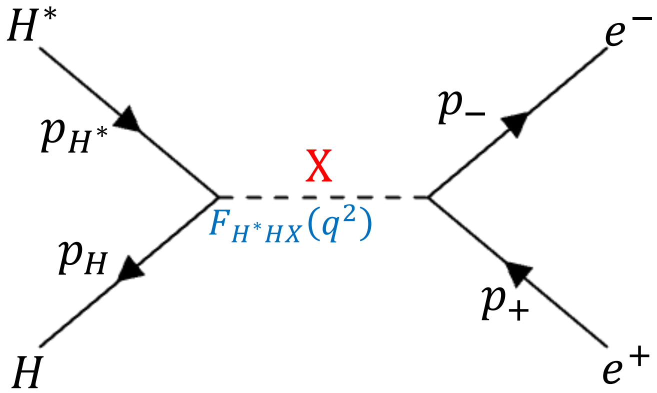


FIG.2.2: Feynman diagram for X boson intermediate

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

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

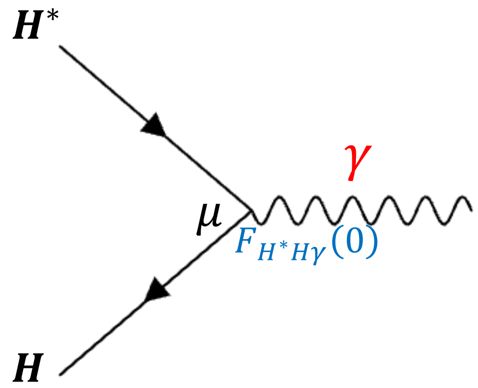


FIG.2.3: Feynman diagram for a real photon

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

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

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) ⬅ **VMD model**

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

D meson decays:

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

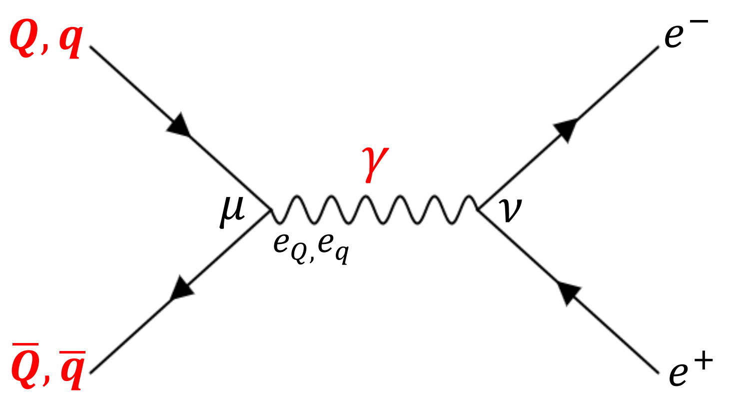


FIG. 2.4. D meson decays in intermediate photon

$$\langle D(p_D)|J^\mu_{em}|D^*(p_{D^*},\epsilon_{D^*})\rangle$$
$$= \langle D(p_D)|e_Q\bar{Q}\gamma^\mu Q + e_q\bar{q}\gamma^\mu q|D^*(p_{D^*},\epsilon_{D^*})\rangle$$

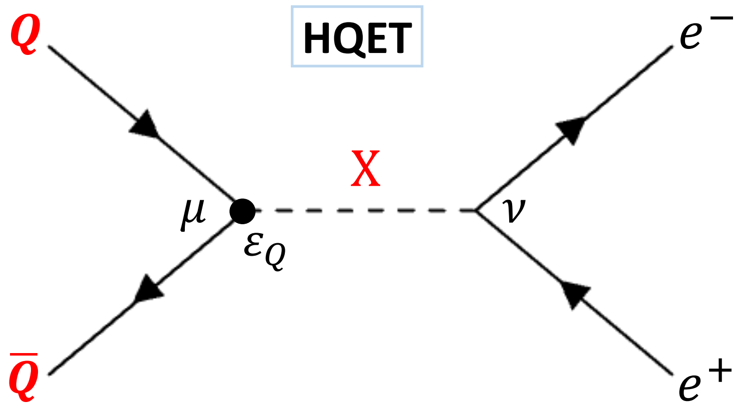


FIG. 2.5. The vector heavy quark current

$$\varepsilon_Q\,\langle D(p_D)|\bar{Q}\gamma^\mu Q|D^*(p_{D^*},\epsilon_{D^*})\rangle$$
$$= i\varepsilon_Q\sqrt{m_{D^*}m_D}\,\xi(v_{D^*}\cdot v_D)\epsilon^{\mu\nu\alpha\beta}\epsilon_{D^*\nu}v_{D^*\alpha}v_{D\beta}$$

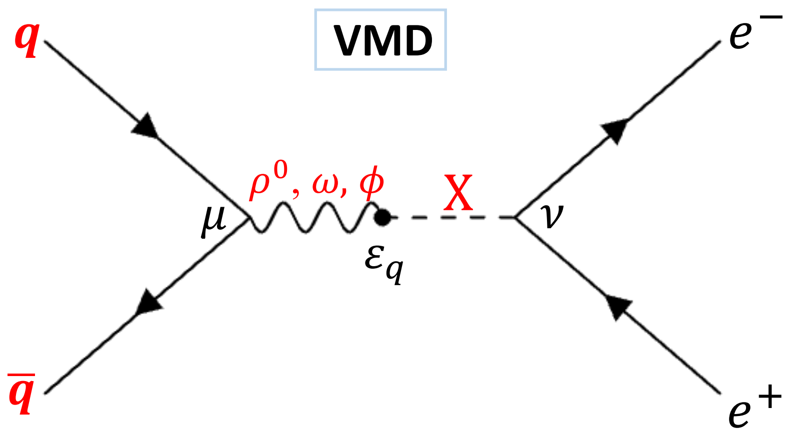


FIG. 2.6. The vector light quark current

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

D meson decays:

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

***H^*H*-vector vertices** ➡ $H^*(Q\bar{q})$

→ *the heavy quark effective theory: HQET*

→ *the vector meson dominance model : VMD*

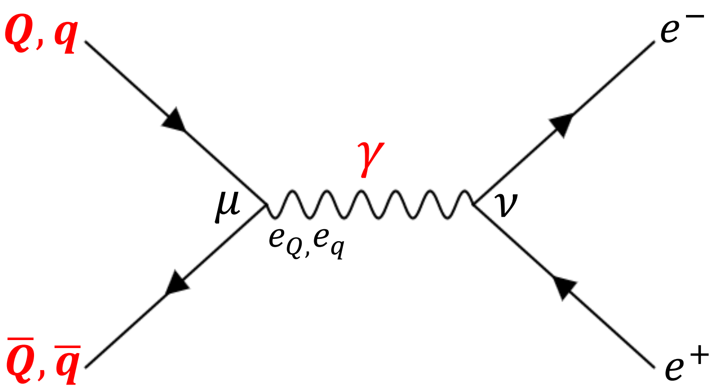


FIG. 2.4. D meson decays in intermediate photon

$$\langle D(p_D)|J^\mu_{em}|D^*(p_{D^*},\epsilon_{D^*})\rangle$$
$$= \langle D(p_D)|e_Q\bar{Q}\gamma^\mu Q + e_q\bar{q}\gamma^\mu q|D^*(p_{D^*},\epsilon_{D^*})\rangle$$

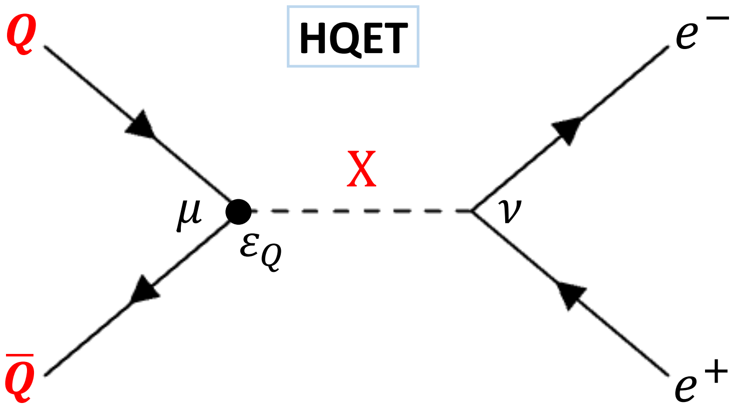


FIG. 2.5. The vector heavy quark current

$$\varepsilon_Q\,\langle D(p_D)|\bar{Q}\gamma^\mu Q|D^*(p_{D^*},\epsilon_{D^*})\rangle$$
$$= i\varepsilon_Q\sqrt{m_{D^*}m_D}\,\xi(v_{D^*}\cdot v_D)\epsilon^{\mu\nu\alpha\beta}\epsilon_{D^*\nu}v_{D^*\alpha}v_{D\beta}$$

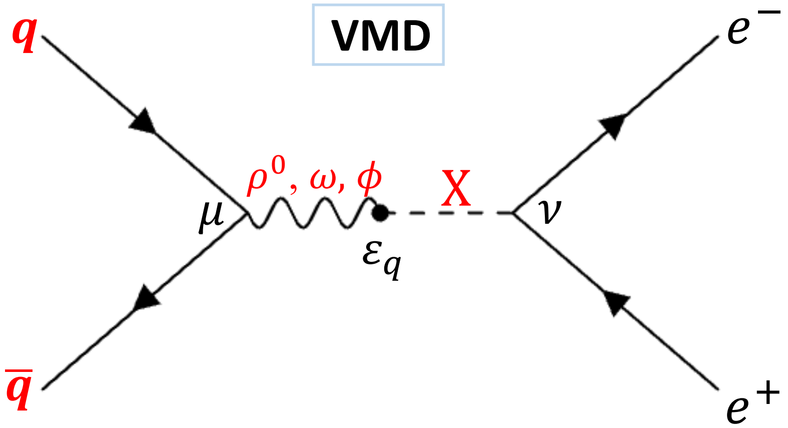


FIG. 2.6. The vector light quark current

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

- **VMD** is based on the assumption of ideal mixing for vector mesons resonances : $\rho^0\left(\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}\right)$, $\omega\left(\frac{u\bar{u}+d\bar{d}}{\sqrt{2}}\right)$, $\phi(s\bar{s})$
- $F_{D^*D\gamma}(q^2) = \sqrt{\frac{m_{D^*}}{m_D}}\left[\frac{e_Q}{m_{D^*}} + \frac{e_q}{m_q(q^2)}\right]$ and $F_{D^*DX}(q^2) = \sqrt{\frac{m_{D^*}}{m_D}}\left[\frac{\varepsilon_Q}{m_{D^*}} + \frac{\varepsilon_q}{m_q(q^2)}\right]$ with $m_q(q^2) = -\sum_{\mathcal{V}}\left(2\sqrt{2}g_{\mathcal{V}}\lambda\frac{f_{\mathcal{V}}}{m_{\mathcal{V}}^2}\right)\left(1-\frac{q^2}{m_{\mathcal{V}}^2}\right)$.

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

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

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

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

➡ The pole mass $\Lambda_{\psi'\eta_c}$ should be the mass of the vector resonances near the energy scale of the decaying particle.

$$\boldsymbol{\Lambda_{\psi'\eta_c} = m_{\psi(3770)} = 3773.7 \pm 0.4\ \mathrm{MeV}/c^2}$$

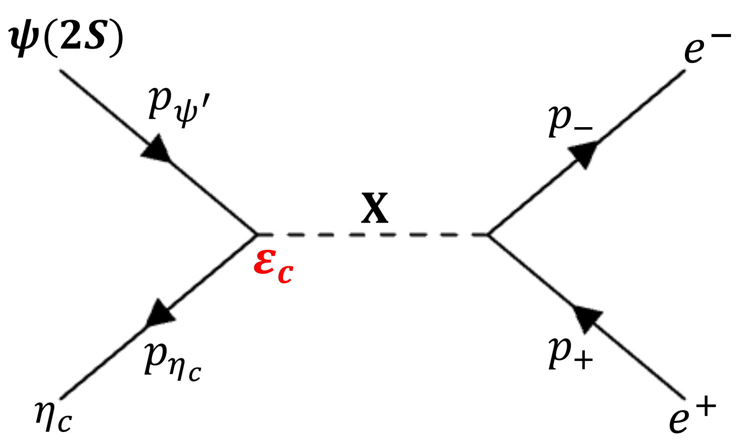


FIG.2.7: $\psi(2S) \to \eta_c e^+ e^-$ for X boson intermediate

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

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

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

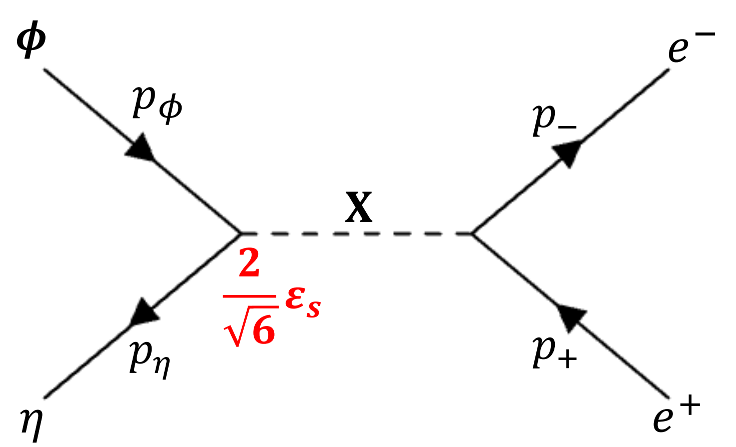


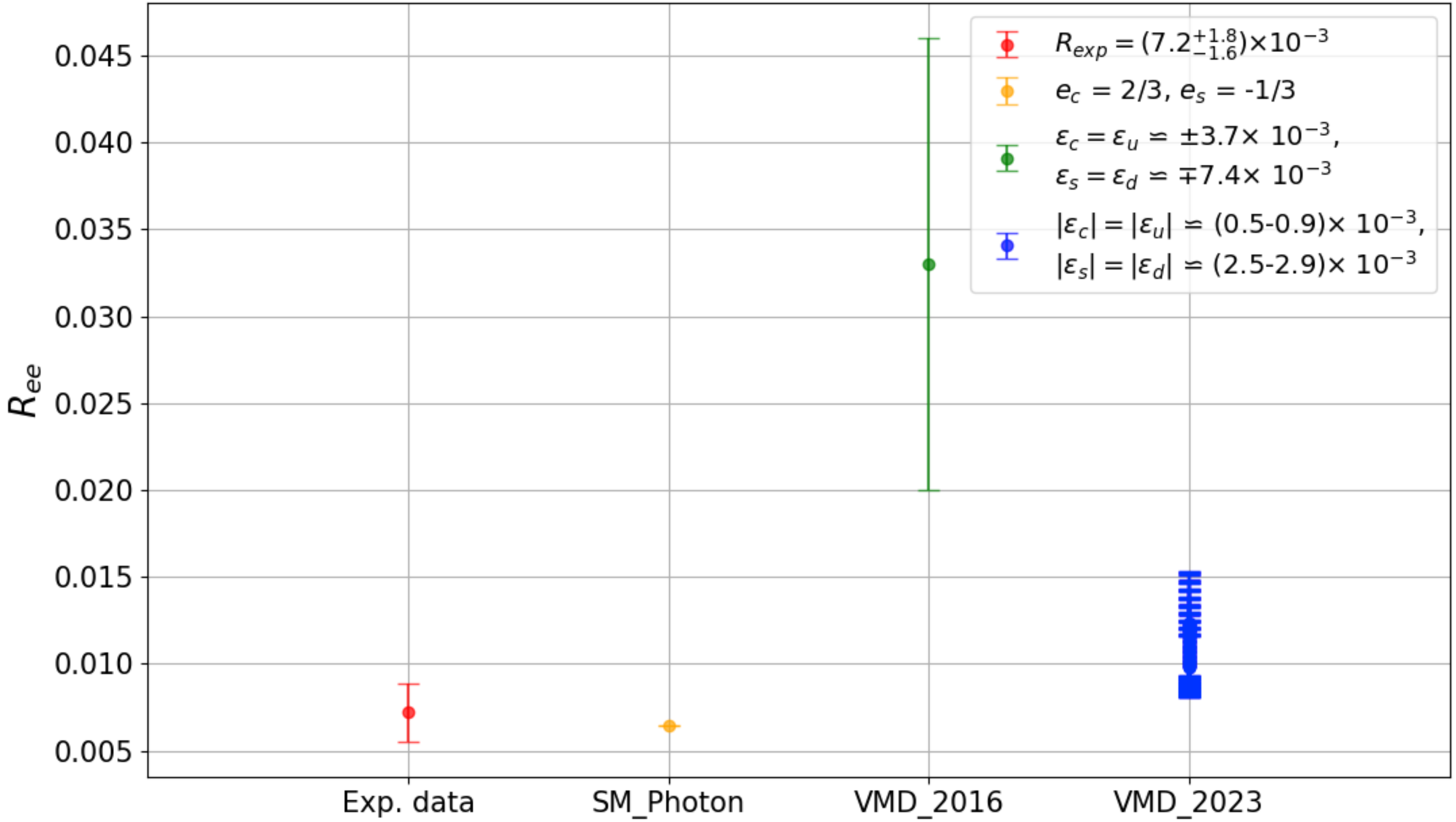
FIG.2.8: $\phi \to \eta e^+ e^-$ for X boson intermediate

PDG *(Prog. Theor. Exp. Phys. 2022, 083C01 (2022) and 2023 update)*

Outline

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

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

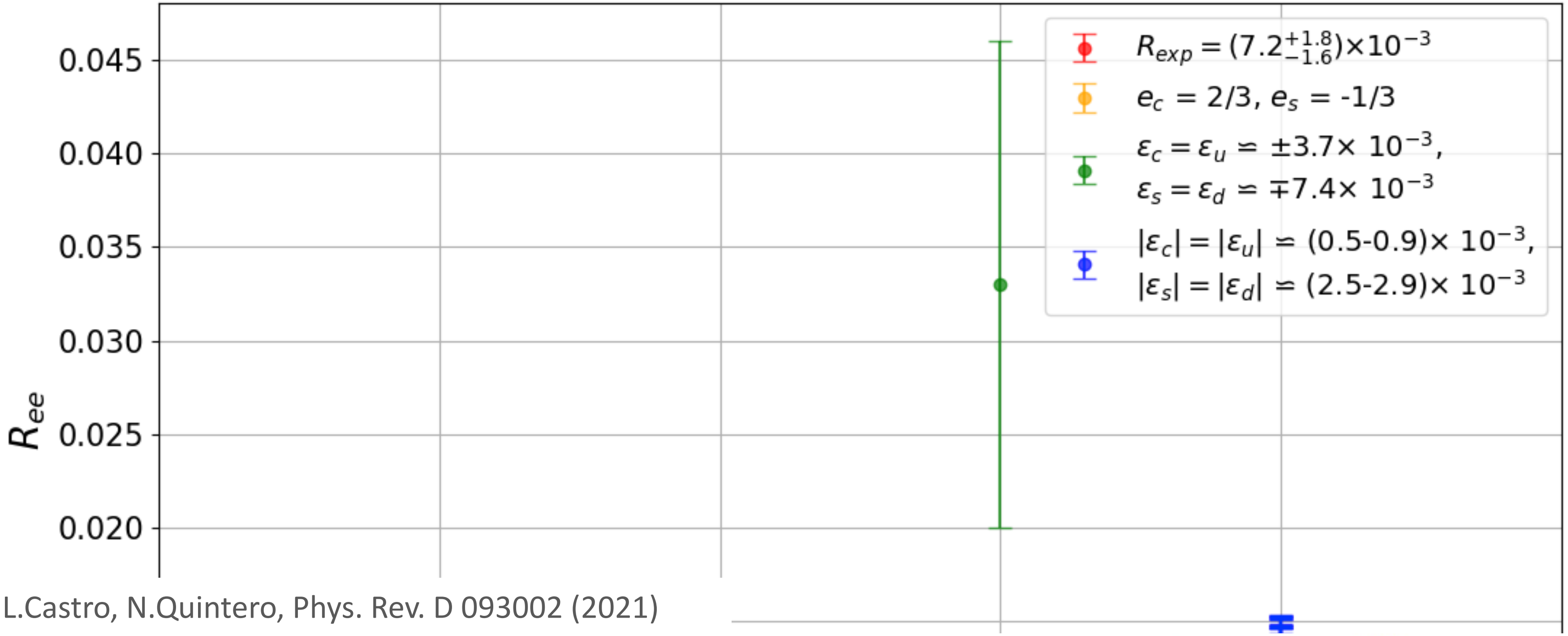


- The photon mediated contribution is in good agreement with $R_{exp} = (7.2^{+1.8}_{-1.6}) \times 10^{-3}$.
- The reults from "VMD_2023" still somewhat consistent with the data in the decays $D_s^{*+} \to D_s^{+} e^{+} e^{-}$.
- R_{ee} in label "VMD_2016" is completely inconsistent with the data R_{exp}.

D. Cronin-Hennessy, *et al.* [CLEO Collaboration] (2011)

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

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



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

TABLE III. Photon and $X17$ boson exchange contributions to the ratio of decay rates defined in Eq. (10). We assume universal couplings of the hypothetical $X17$ boson to down-type quarks [$\varepsilon_b = \varepsilon_s = \varepsilon_d = \mp 7.4 \times 10^{-3}$] and up-type quarks [$\varepsilon_c = \varepsilon_u = \pm 3.7 \times 10^{-3}$] (see end of Sec. II). Unless explicitly indicated, theoretical uncertainties are at least 3 orders of magnitude smaller than the corresponding central values.

Channel	$R_{ee}^{\gamma}(H^*)$	$R_{ee}^{X}(H^*)$	Total	Experiment
$D^{*+} \to D^{+} e^{+} e^{-}$	6.67×10^{-3} ✓	$(1.05 \pm 0.07) \times 10^{-3}$ ✓	$(7.72 \pm 0.07) \times 10^{-3}$ ✓	...
$D^{*0} \to D^{0} e^{+} e^{-}$	6.67×10^{-3} ✓	3.02×10^{-5} ✓	6.70×10^{-3} ✓	...
$D_s^{*+} \to D_s^{+} e^{+} e^{-}$	6.72×10^{-3} ✓	$(3.10 \pm 0.60) \times 10^{-3}$	$(9.82 \pm 0.60) \times 10^{-3}$	$(7.2^{+1.8}_{-1.6}) \times 10^{-3}$ [26]
		$(2.62 \pm 1.3) \times 10^{-2}$	$(3.3 \pm 1.3) \times 10^{-2}$	

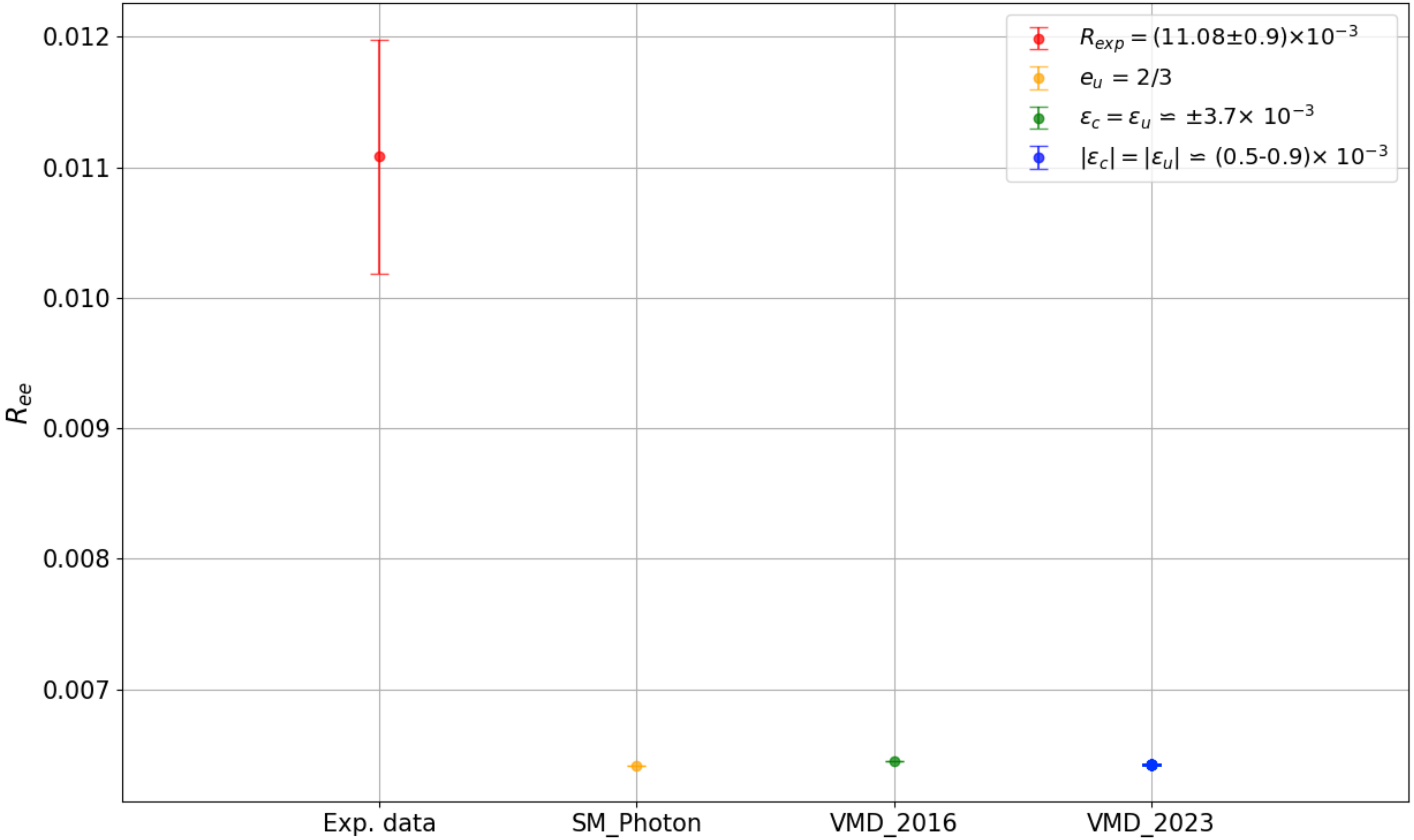
The red numbers recalculated and revised

D. Cronin-Hennessy, *et al.* [CLEO Collaboration] (2011)

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

D meson decays:

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



- 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 $|\varepsilon_d| = |\varepsilon_s|$.

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

3. Strengths of X17 couplings to light and heavy quarks

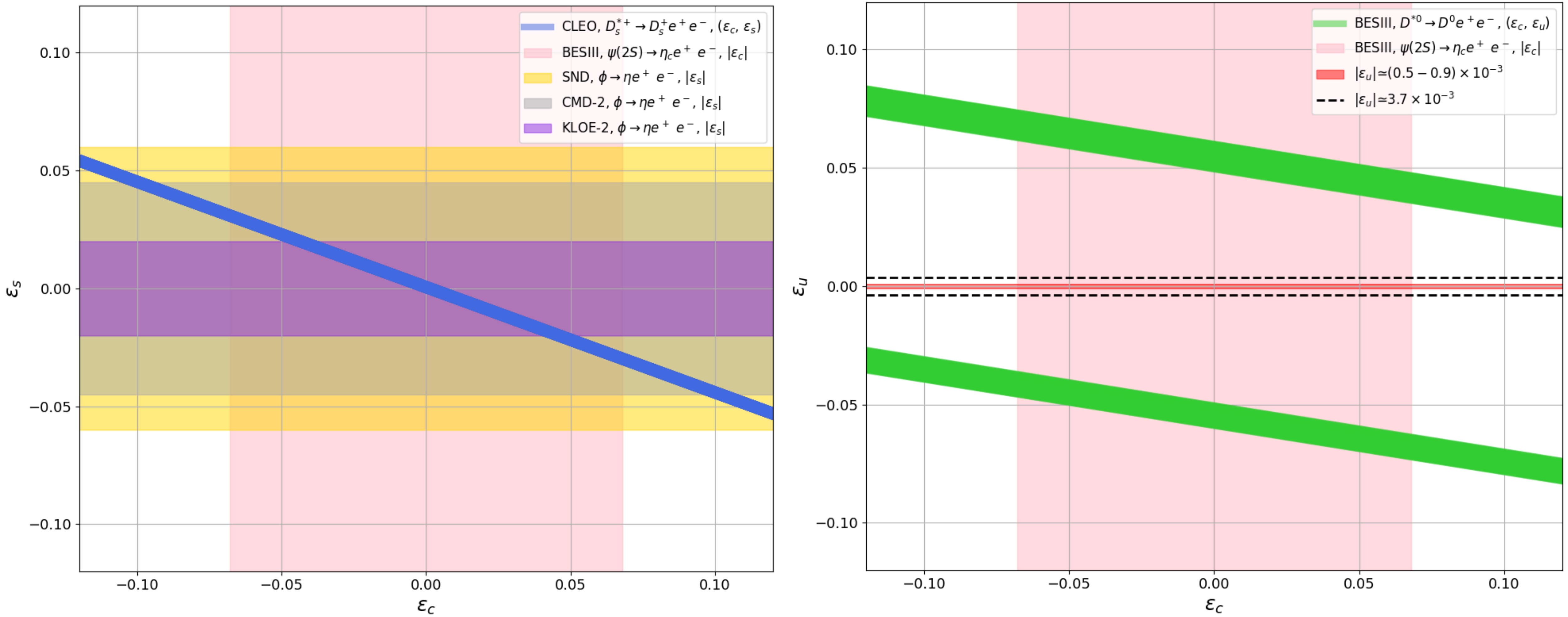


Fig. 3.3. $(\varepsilon_c, \varepsilon_s)$ and $(\varepsilon_c, \varepsilon_u)$ are extracted from the data of D meson, Charmonium and ϕ meson decays.

3. Strengths of X17 couplings to light and heavy quarks

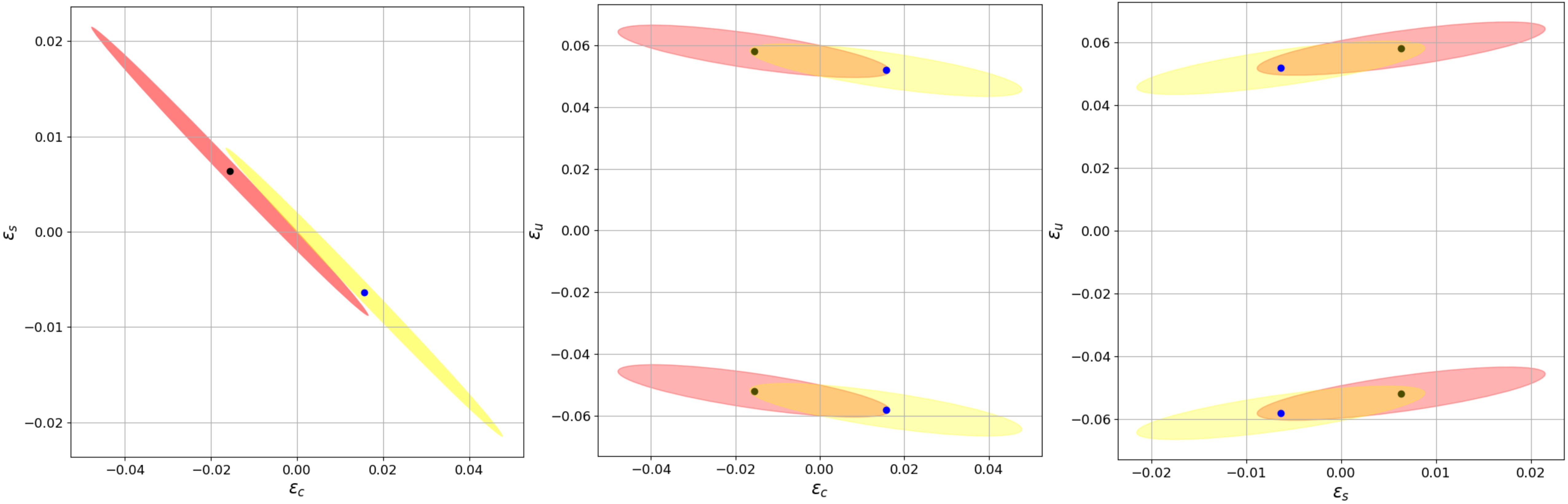


FIG. 3.4. χ^2 method for three parameters $\varepsilon_c, \varepsilon_s$ and ε_u estimated at 1σ using four measurements from D meson, Charmonium and ϕ meson decays.

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

- $|\varepsilon_c| = 0.016$, $|\varepsilon_s| = 0.0063$, ε_c and ε_s have opposite signs.
- For each pair of values ε_c, ε_s, we get two values $\varepsilon_u > 0$ and $\varepsilon_u < 0$, $|\varepsilon_u| \propto 10^{-2}$.

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. Conclusion

Conclusion

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

- To fit the data of $D^{*0} \rightarrow D^0 e^+ e^-$ by BESIII, we have to remove the assumptions of generation universality $|\varepsilon_u| = |\varepsilon_c|$ and $|\varepsilon_d| = |\varepsilon_s|$.

- 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.