Sizing the double pole resonant enhancement in $e^+e^- \to \pi^0\pi^0\gamma$ and $\tau^- \to \pi^-\pi^0\nu_\tau\gamma$

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Based on
hep-ph: 2308.02766
and PRD 107 056006 (2023)

Gustavo Ávalos, Leonardo Esparza, Antonio Rojas, Marxil Sánchez and GT

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Motivation

- **The importance of two resonant states in:**
- **$e^+e^- \to \pi^0\pi^0\gamma$ cross section**
- **muon g-2 ISB from $\tau^- \to \pi^-\pi^0\nu_\tau\gamma$**

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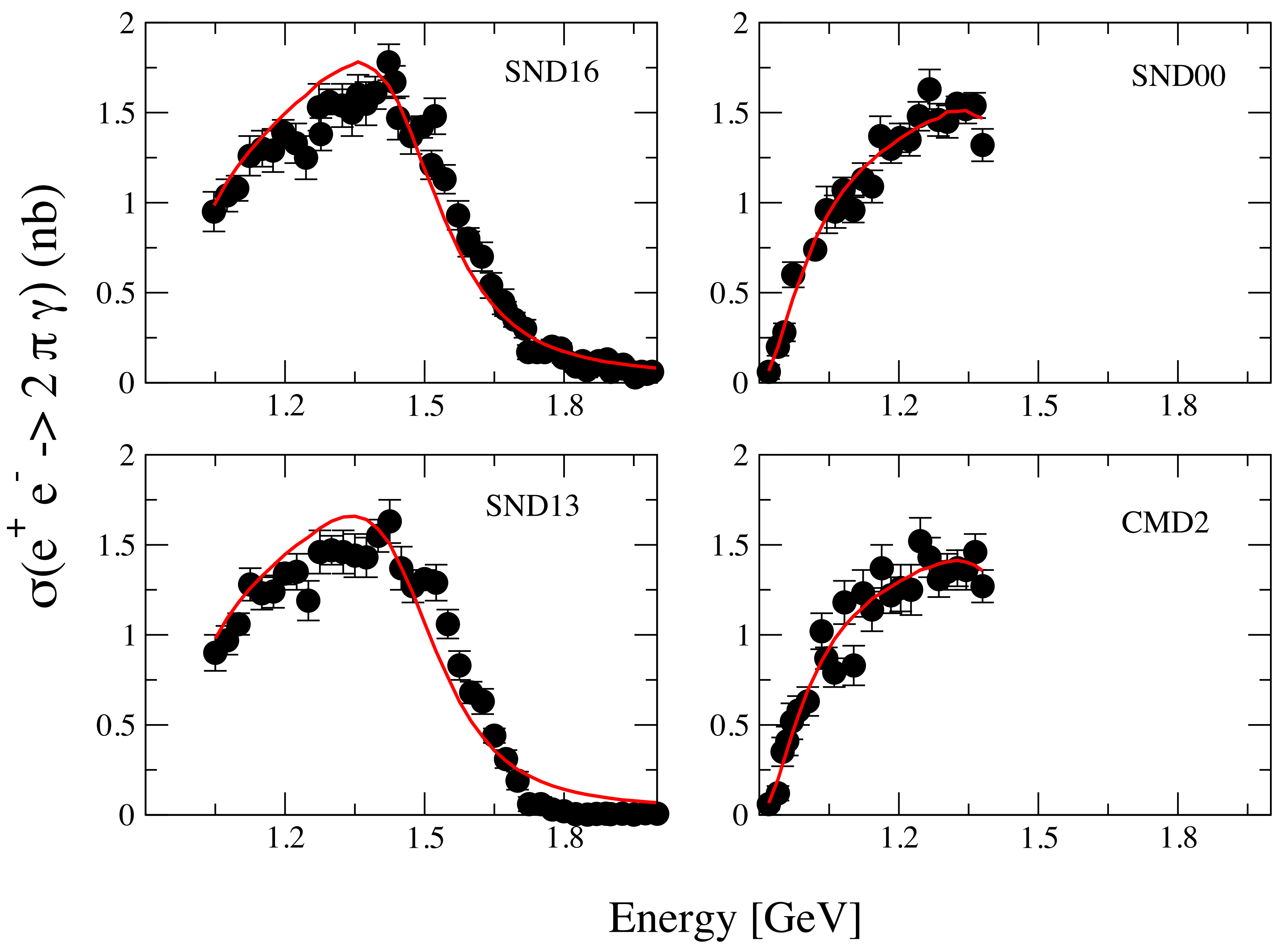
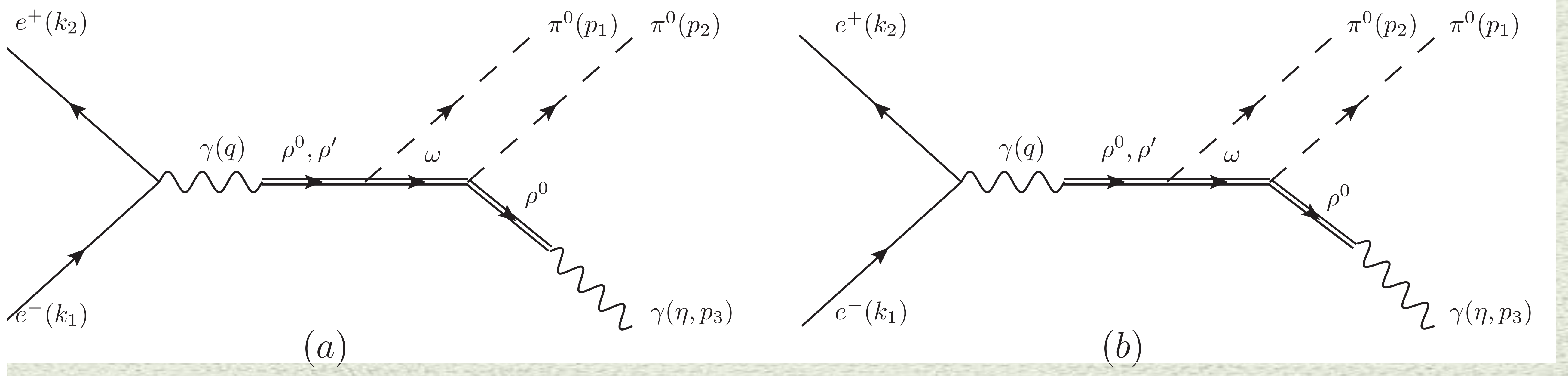
Motivation

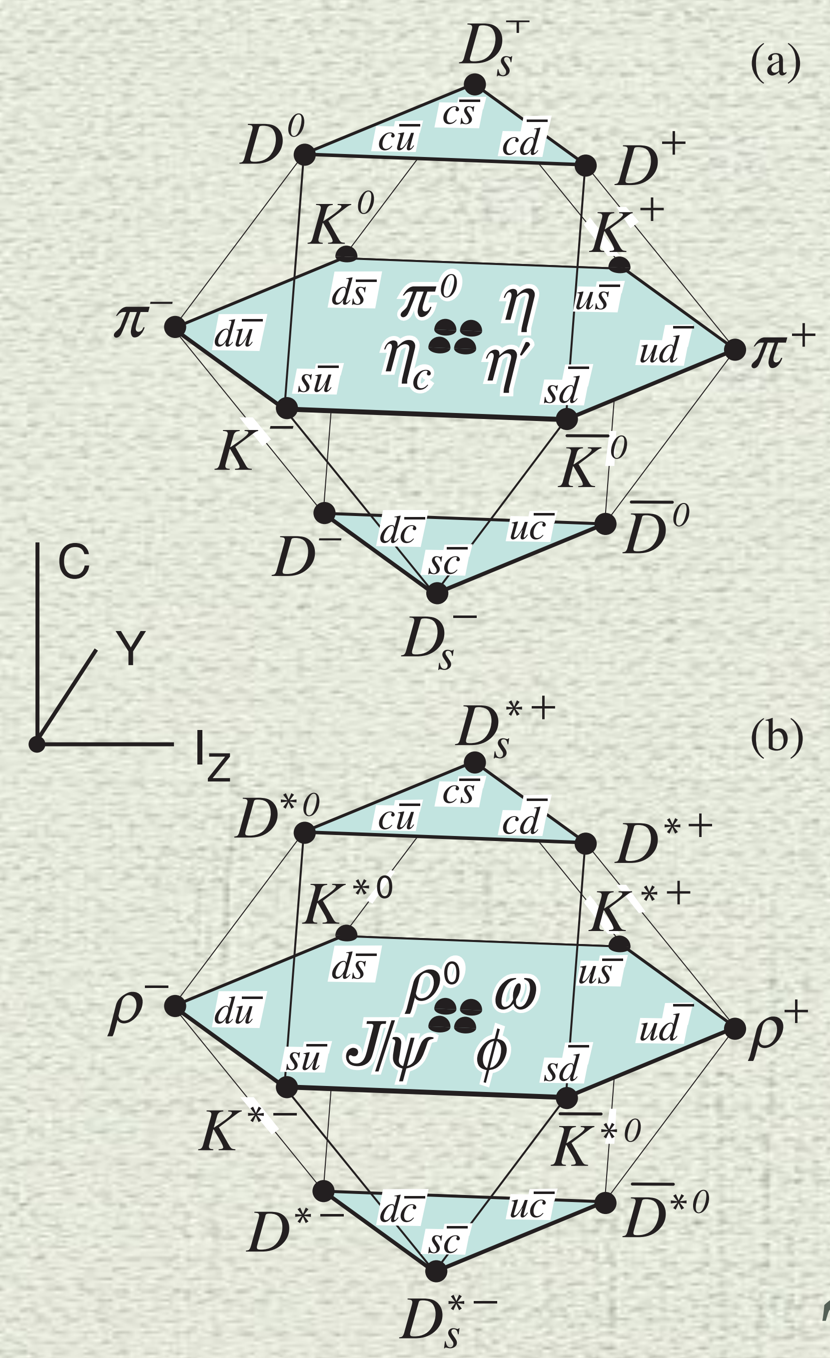
The importance of resonant states in $e^+e^- \to \pi^0\pi^0\gamma$ cross section





The expected combined resonant enhancement takes place not at the CM energy close to their masses

Although rho and omega are close in mass, in this case they carry different momentum.



Rho(1450) may play a similar game with omega

Motivation

The importance of resonant states in muon g-2 ISB from $\tau^- \to \pi^- \pi^0 \nu_\tau \gamma$

Table 1 Contributions to $a_\mu^{\rm had,LO}[\pi\pi,\tau]$ ($\times 10^{-10}$) from the isospin-breaking corrections discussed in Sect. 3. Corrections shown in two separate columns correspond to the Gounaris–Sakurai (GS) and Kühn–Santamaria (KS) parametrisations, respectively

Source	$\Delta a_\mu^{\rm had,LO}[\pi\pi,\tau]$ (10^{-10}) GS model	KS model
$S_{\rm EW}$	-12.21 ± 0.15	
$G_{\rm EM}$	-1.92 ± 0.90	
FSR	$+4.67 \pm 0.47$	
ρ–ω interference	$+2.80 \pm 0.19$	$+2.80 \pm 0.15$
$m_{\pi^\pm} - m_{\pi^0}$ effect on σ	-7.88	
$m_{\pi^\pm} - m_{\pi^0}$ effect on Γ_ρ	$+4.09$	$+4.02$
$m_{\rho^\pm} - m_{\rho^0_{\rm bare}}$	$+0.20^{+0.27}_{-0.19}$	$+0.11^{+0.19}_{-0.11}$
$\pi\pi\gamma$, electrom. decays	-5.91 ± 0.59	-6.39 ± 0.64
Total	-16.07 ± 1.22	-16.70 ± 1.23
	-16.07 ± 1.85	

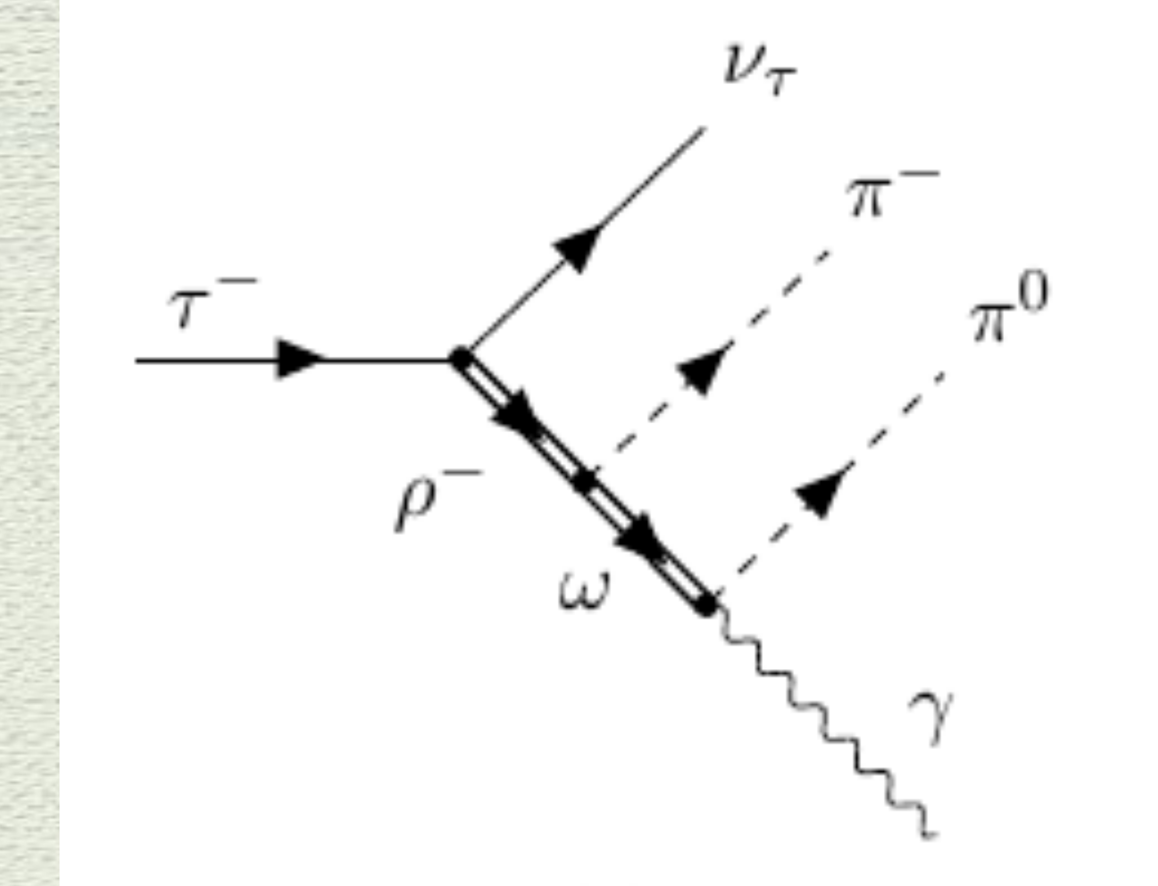
M. Davier, et al, Eur. Phys. J. C 66, 127-136 (2010)

Uncertainties quoted to incorporate the deviation from

V. Cirigliano, G. Ecker and H. Neufeld, JHEP. 08 (2002) 002

	ChPT $\mathcal{O}(p^4)$	$R_\chi T\ \mathcal{O}(p^4)$	$R_\chi T\ \mathcal{O}(p^6)$
$\Delta a_\mu^{\rm HVP\ LO}\vert_{G_{EM}(t)}$ ($\times 10^{-11}$)	-10	$-15.9^{+5.7}_{-16.0}$	-76 ± 46

J. A. Miranda and P. Roig, Phys. Rev. D 102, 114017 (2020)



In VMD this model dependent (MD) channel found to be the main responsible for the deviation from purely SI result

VMD approach

A. Flores-Tlalpa, G. Lopez Castro and GT, Phys. Rev. D 72, 113003 (2005)
F. Flores-Baez, A. Flores-Tlalpa, G. Lopez Castro and GT, Phys. Rev. D 74, 071301 (2006)
Flores-Tlalpa, F. Flores-Baez, G. Lopez Castro and GT, Nucl. Phys. B Proc. Suppl. 169, 250-254 (2007)
G. Lopez Castro, P. Roig and GT, Nucl. Part. Phys. Proc. 260, 70-74 (2015)

Not considered in estimates using BELLE data (removed but its interference)

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In this work

- General description of the two poles carrying different energy
- Explore the $e^+e^- \to \pi^0\pi^0\gamma$ differential cross section, to identify the double pole resonant enhancement features
- Perform an analysis of the parameters involved, in base of experimental data available, to identify their robustness
- Perform an analysis of the $\tau^- \to \pi^-\pi^0\nu_\tau\gamma$ omega channel, to exhibit the analogies to the previous case
- Analyse the muon g-2 ISB correction from $\tau^- \to \pi^-\pi^0\nu_\tau\gamma$
- Conclusions

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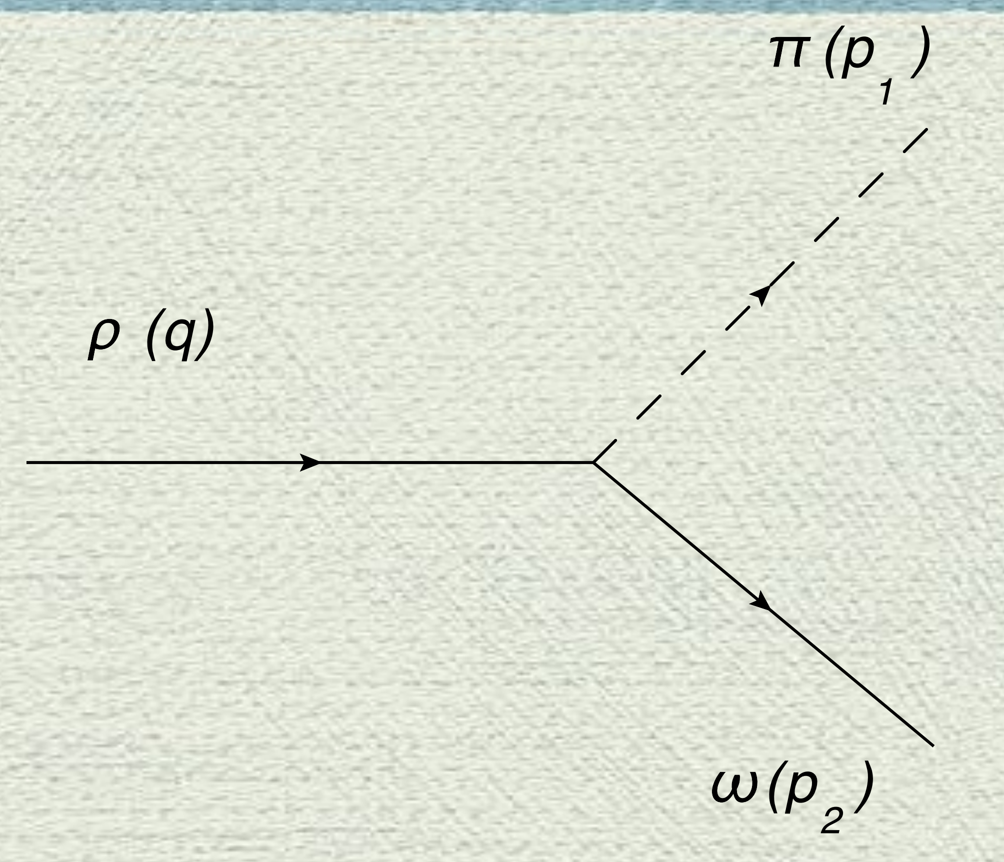
Two poles carrying different energy

L. Esparza-Arellano, Antonio Rojas and GT hep-ph: 2308.02766



At least one of them off-shell

$$s \equiv (p_1 + p_2)^2$$

$$s_2 \equiv p_2^2$$

corresponding form factors

$$f_\rho[s] \equiv \frac{m_\rho^2}{m_\rho^2 - s + i m_\rho \Gamma_\rho} \qquad f_\omega[s_2] \equiv \frac{m_\omega^2}{m_\omega^2 - s_2 + i m_\omega \Gamma_\omega};$$

$$s_2 = s + m_\pi^2 - 2\sqrt{s}\, E_\pi .$$

minimal energy for omega on-shell

$$\sqrt{s} = m_\omega + m_\pi = 0.92 \text{ GeV} \qquad m_\rho + \Gamma_\rho .$$

$\pi^\pm$ $\quad I^G(J^P) = 1^-(0^-)$

Mass $m = 139.57039 \pm 0.00018$ MeV (S = 1.8)
Mean life $\tau = (2.6033 \pm 0.0005) \times 10^{-8}$ s (S = 1.2)

$\rho(770)$ $\quad I^G(J^{PC}) = 1^+(1^{--})$

See the review on "Spectroscopy of Light Meson Resonances."
T-Matrix Pole $\sqrt{s} = (761\text{–}765) - i\,(71\text{–}74)$ MeV
Mass (Breit-Wigner) $= 775.26 \pm 0.23$ MeV
Full width (Breit-Wigner) $= 149.1 \pm 0.8$ MeV

$\omega(782)$ $\quad I^G(J^{PC}) = 0^-(1^{--})$

Mass $m = 782.66 \pm 0.13$ MeV (S = 2.0)
Full width $\Gamma = 8.68 \pm 0.13$ MeV

Can we characterize when the maximum enhancement takes place, in terms of the resonance properties, in a particular process?

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Description of low energy processes

Vector meson dominance approach and effective interactions

$$\mathcal{L} = \sum_{V=\rho,\,\rho'} g_{V\pi\pi}\,\epsilon_{abc}\,V^a_\mu\,\pi^b\,\partial^\mu\,\pi^c + \sum_{V=\rho,\,\rho'} g_{\omega V\pi}\,\delta_{ab}\,\epsilon^{\mu\nu\lambda\sigma}\,\partial_\mu\,\omega_\nu\,\partial_\lambda\,V^a_\sigma\,\pi^b$$
$$+\; g_{3\pi}\,\epsilon_{abc}\,\epsilon^{\mu\nu\lambda\sigma}\,\omega_\mu\,\partial_\nu\,\pi^a\,\partial_\lambda\,\pi^b\,\partial_\sigma\,\pi^c + \sum_{V=\rho,\,\rho',\,\omega} \frac{e\,m_V^2}{g_V}\,V_\mu\,A^\mu.$$

Consider hadrons as the relevant degrees of freedom at low energies.
Couplings are free parameters to be determined from experiment.

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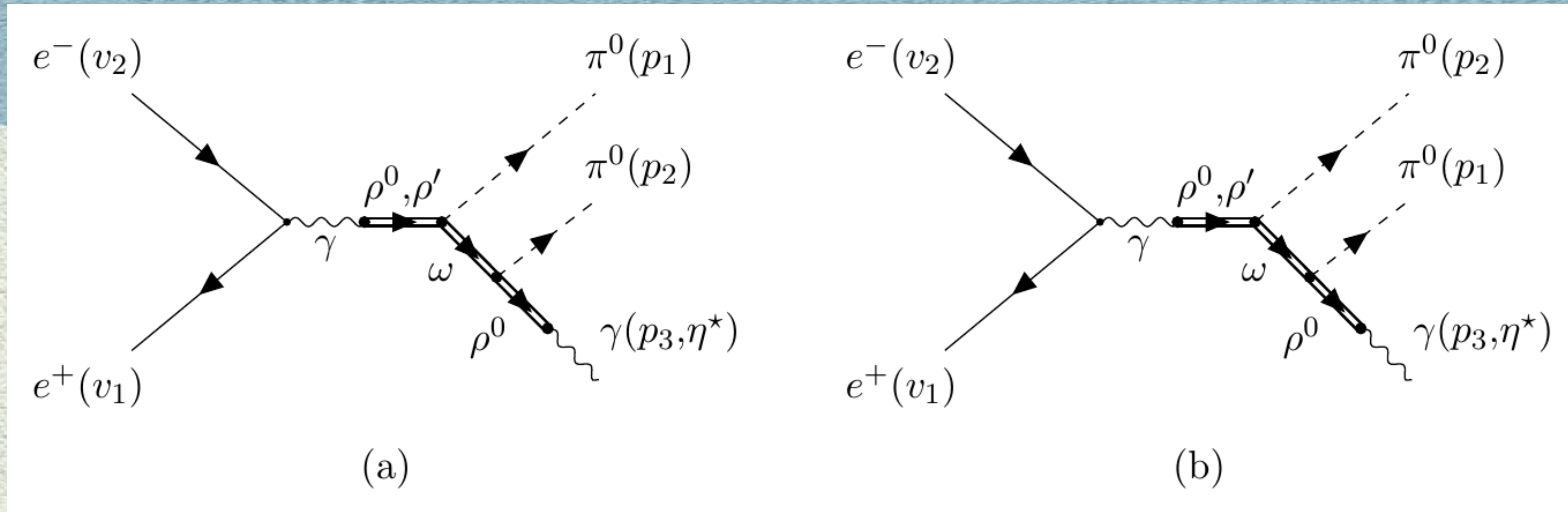
$e^+e^- \to \pi^0\pi^0\gamma$ differential cross section



Amplitude

$$\mathcal{M}_{(a)} = \frac{e^2}{q^2}\left(C_{\rho^0} + e^{i\theta} C_{\rho'}\right) D_\omega(q-p_1)\, \epsilon_{\mu\sigma\epsilon\lambda}\, q^\sigma\, (q-p_1)^\epsilon\, \epsilon_{\alpha\lambda\beta\nu}\, (q-p_1)^\alpha\, {p_3}^\beta\, \eta^{*\nu}\, l^\mu,$$

$$C_\rho = \left(\frac{g_{\omega\rho\pi}}{g_\rho m_\omega}\right)^2 f_\rho[s] f_\omega[s_1], \qquad C_{\rho'} = \frac{g_{\omega\rho'\pi}\, g_{\omega\rho\pi}}{g_\rho\, g_{\rho'} m_\omega^2} f_{\rho'}[s] f_\omega[s_1], \qquad l^\mu = -ie\bar{v}(v_1)\gamma^\mu u(v_2),$$

The differential cross section for a given angle of one of the pions emission wrt the collision axis

$$\frac{d\sigma(e^+e^- \to 2\pi^0\gamma)}{d\zeta} = \int \frac{|\bar{\mathcal{M}}|^2}{4(2\pi)^5 |\boldsymbol{v}_1||\boldsymbol{v}_2|} \cdot \frac{\pi|(s_{1+}-s_{1-})(u_{1+}-u_{1+})(t_{1+}-t_{1+})|}{4s\,\lambda(s, m_\pi^2, u_1)\sqrt{(1-\xi_1^2)(1-\eta_1^2)(1-\zeta_1^2)}},$$

$$\zeta = \cos\theta = \boldsymbol{p}_1 \cdot \boldsymbol{v}_1 / |\boldsymbol{p}_1||\boldsymbol{v}_1|$$

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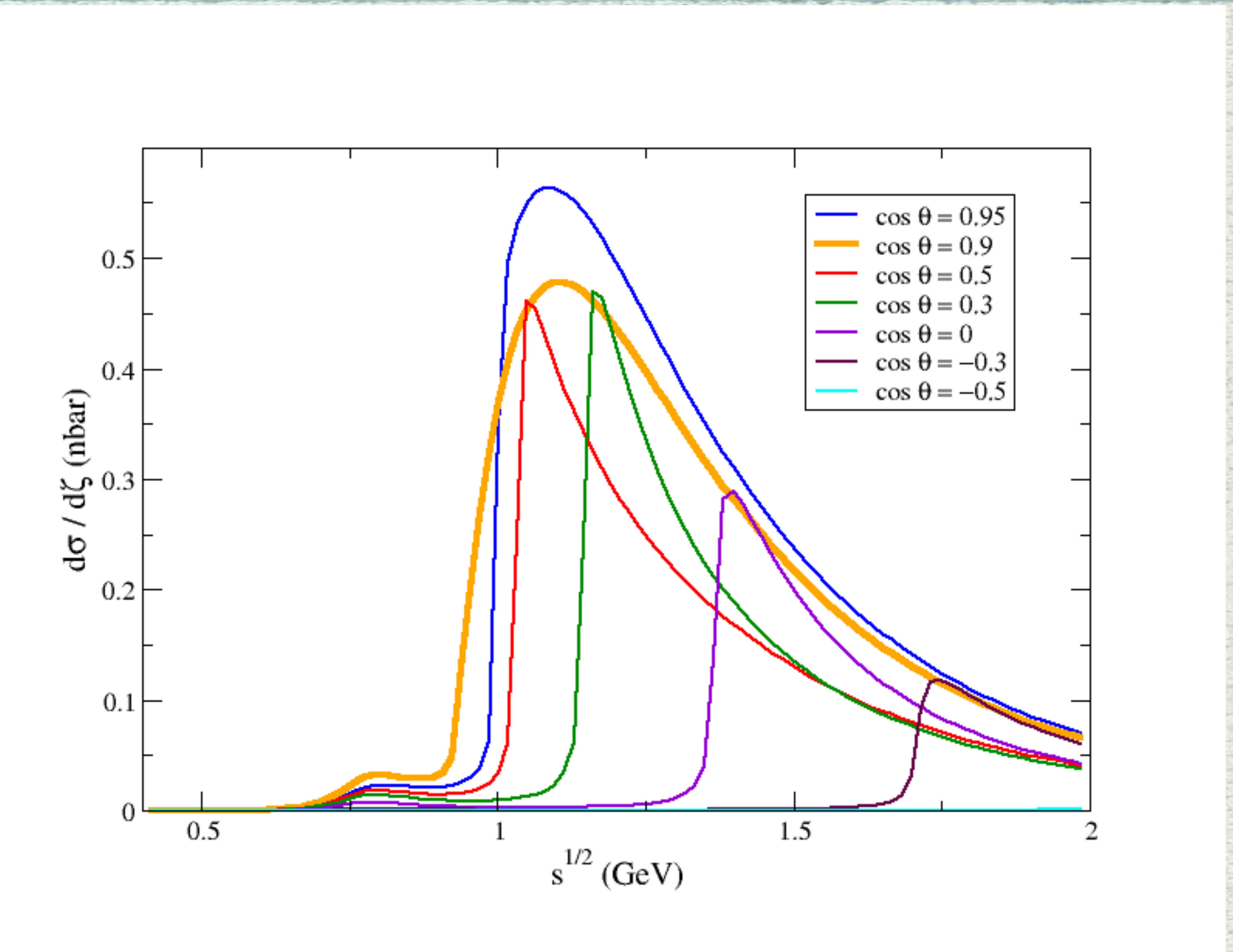
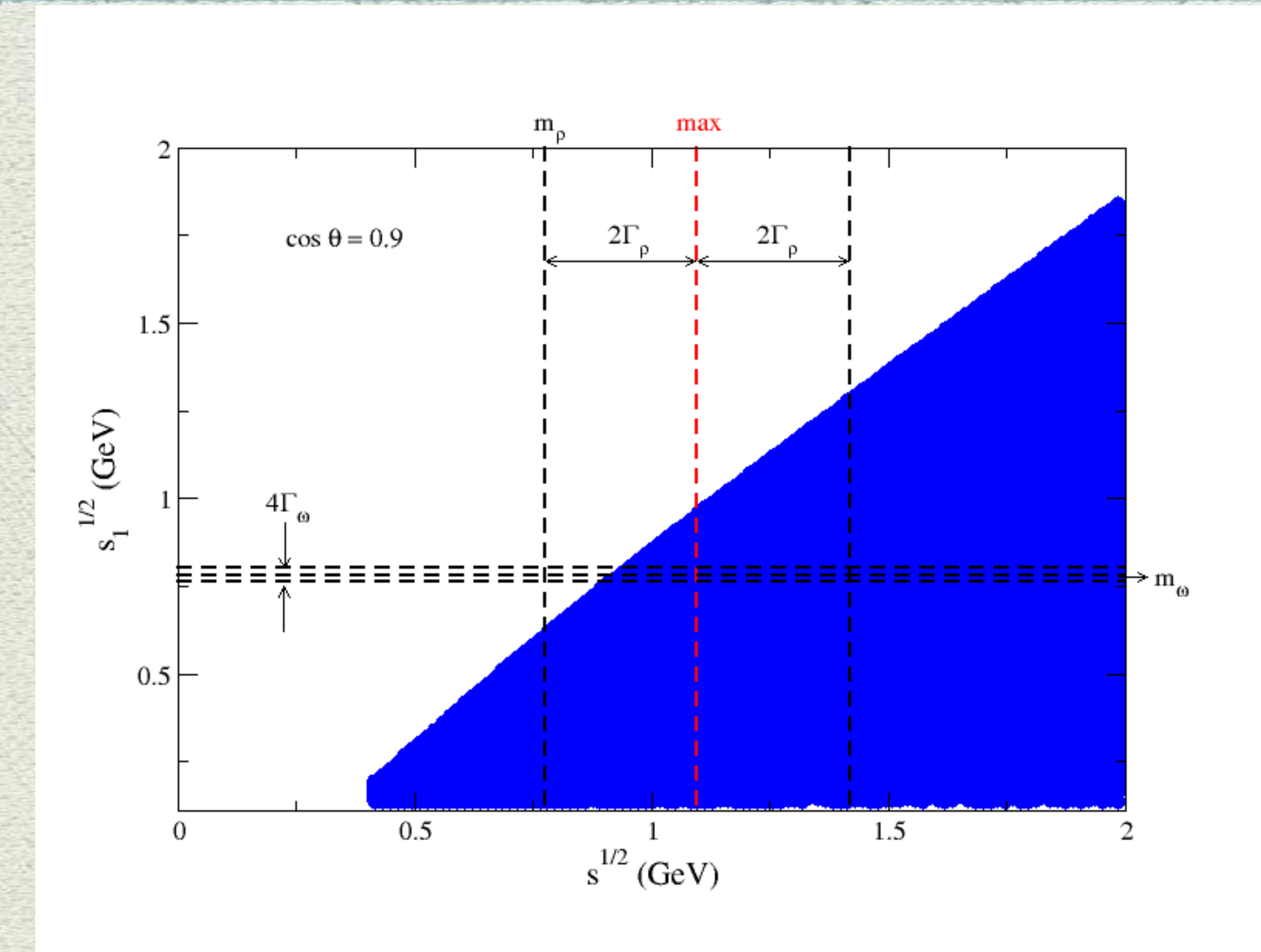
$e^+e^-\to\pi^0\pi^0\gamma$ differential cross section

Including only ρ and the ω resonant features



e+e- -> pi pi gamma differential cross section

both ϱ and ω particles resonant features combine to give a maximal enhancement



Dalitz region

The resonances around the maximum are twice their corresponding decay width away from its pole mass value

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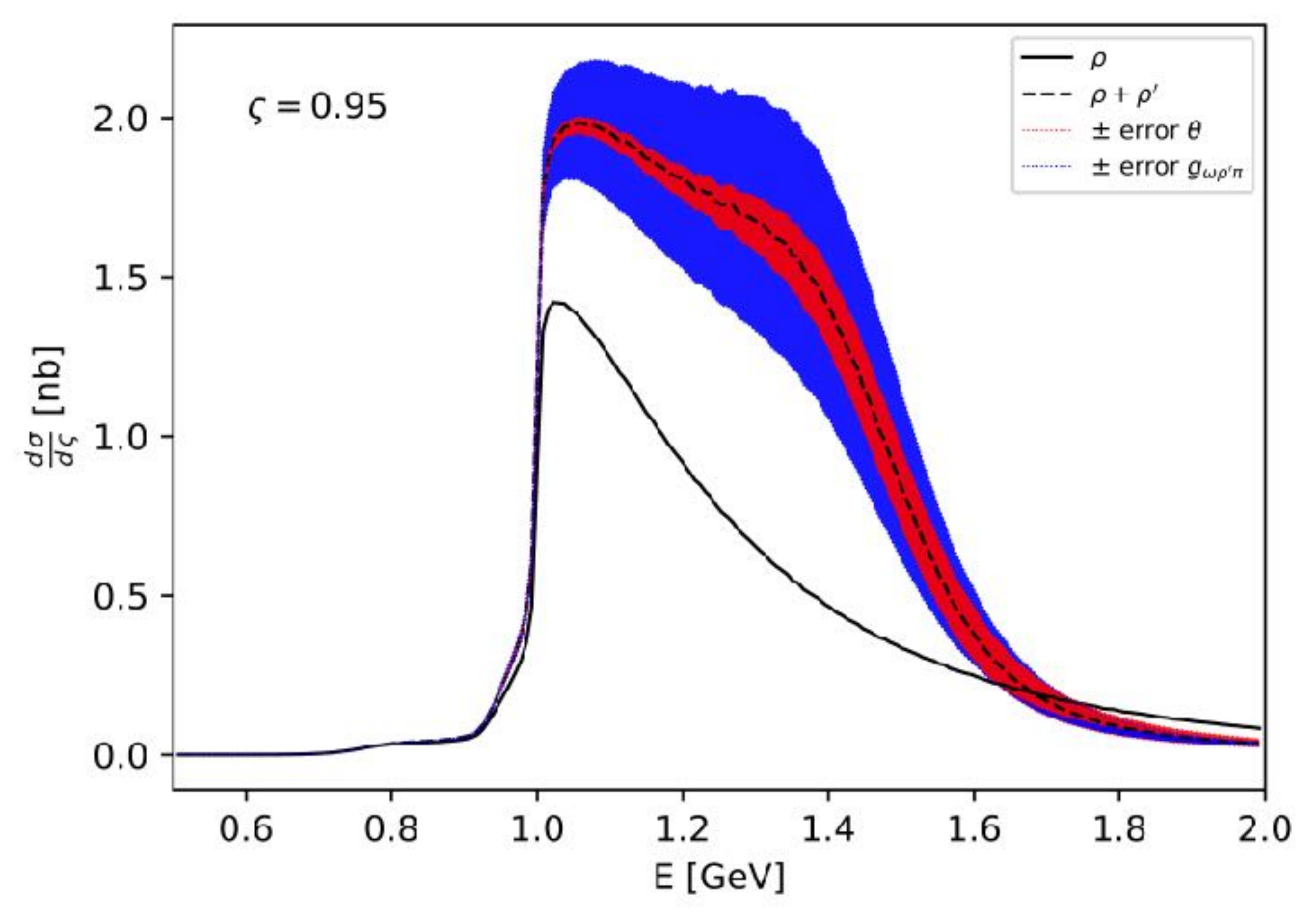
$e^+e^- \to \pi^0\pi^0\gamma$ differential cross section

Including both ϱ and ϱ′ with the ω resonant features



Including only ϱ has small uncertainty (as we show later)

Observable strongly dependent on the ϱ′ parameters

Measurement of this differential cross section can shed light on the ϱ′ effect

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Parameters analysis. From decay modes to cross section data

G. Avalos, A. Rojas, M Sanchez, GT
Phys Rev D 107 056006 (2023)

We minimize the function

$$\chi^2(\theta) = \sum_{i=1}^{N} \frac{(y_i - \mu(x_i;\theta))^2}{E_i^2},$$

considering the couplings as free parameters, for the following data:

(a) 10 decay modes: $\rho \to \pi\pi$ $\rho^0 \to e^+e^-, \mu^+\mu^-$ $\omega \to e^+e^-, \mu^+\mu^-$ $\rho \to \pi\gamma$ $\omega \to \pi^0\gamma.$ $\pi^0 \to \gamma\gamma.$

11 decay modes: (a) + $\omega \to 3\pi$

(b)11 decay modes + $e^+e^- \to \pi^0\pi^0\gamma$ SND (00), (13), (16), CMD2

(c)11 decay modes + $e^+e^- \to 3\pi$ SND, BABAR, CMD2, BES 3

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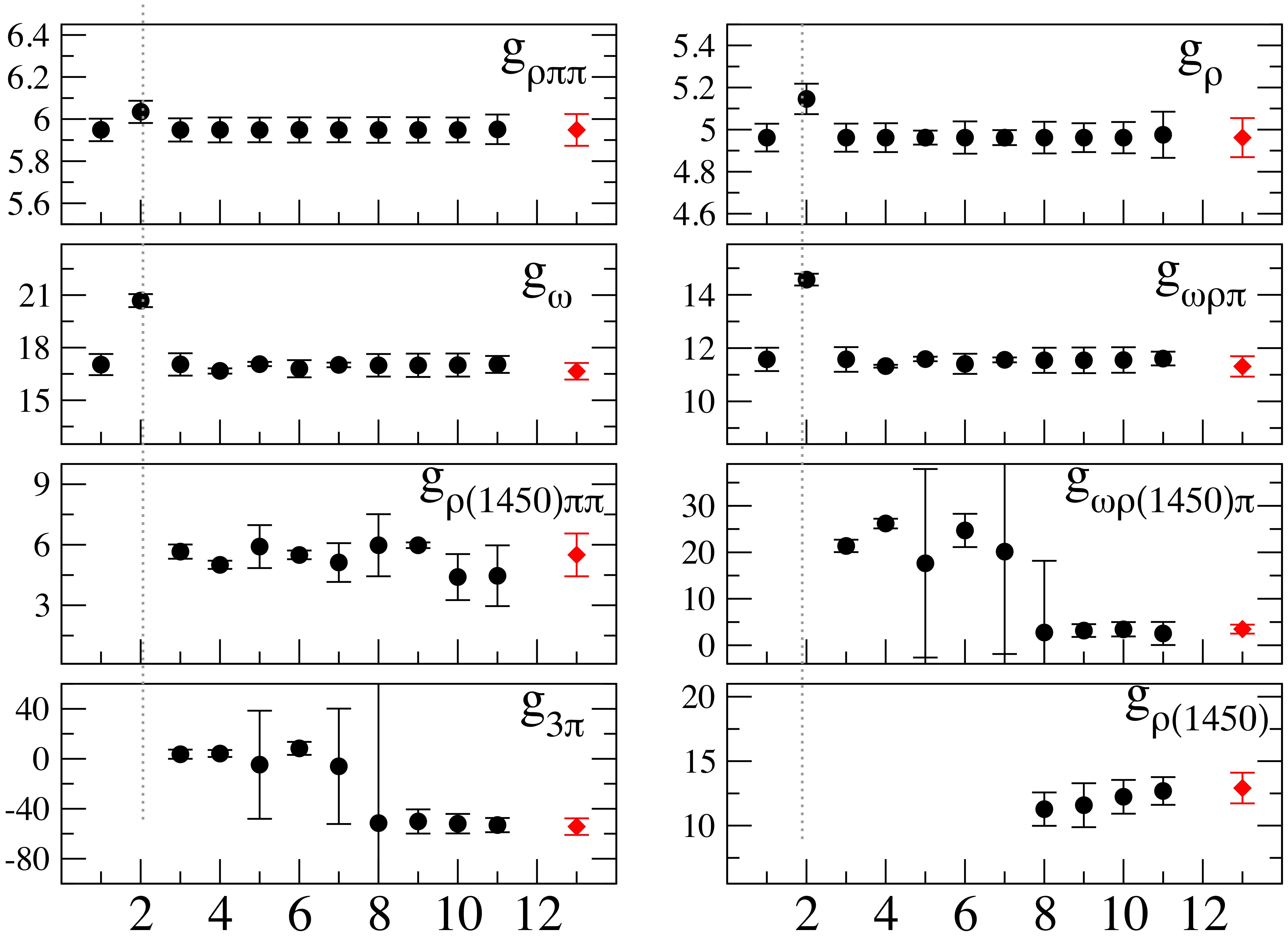
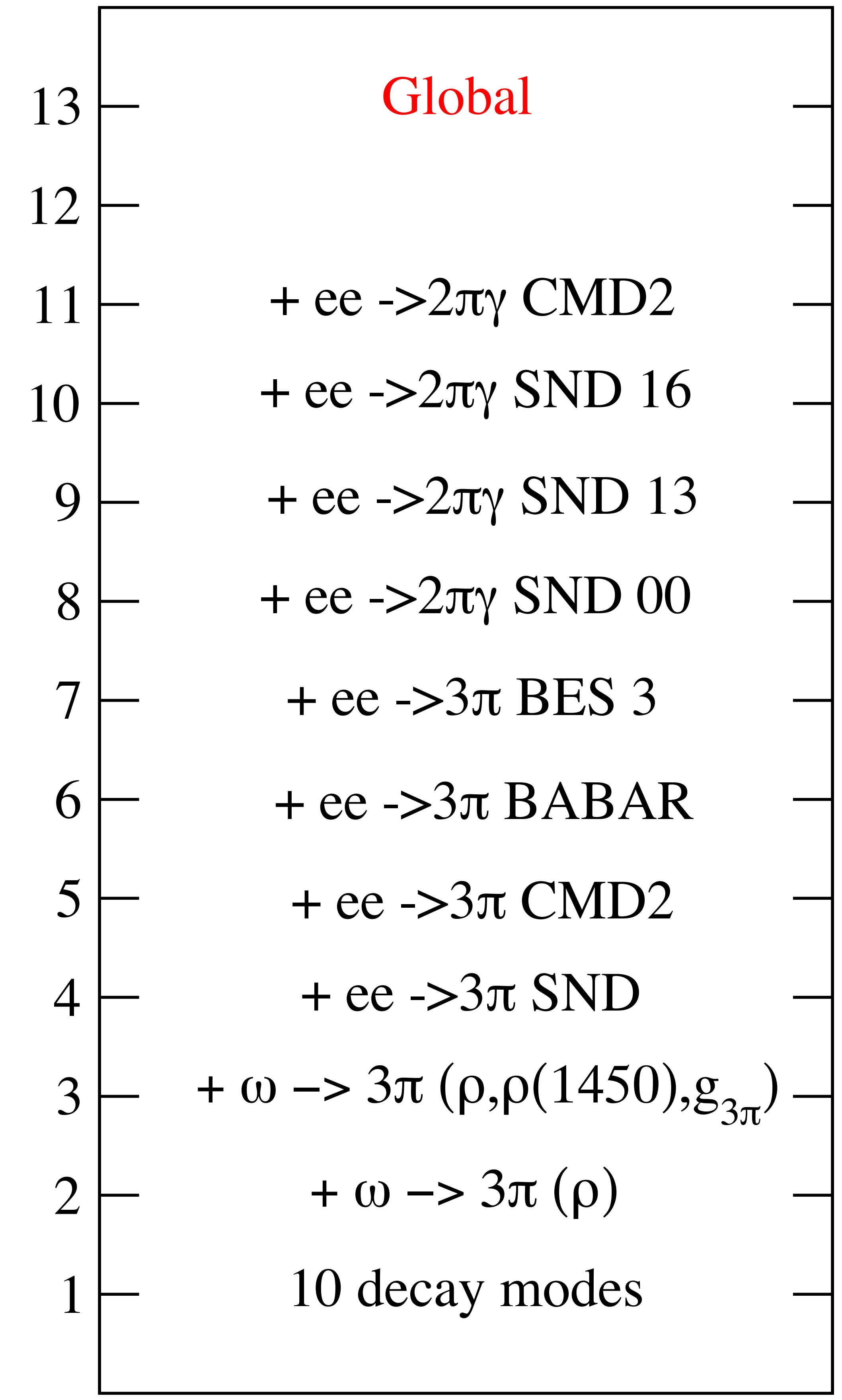
Couplings behavior for individual data



X axis labels



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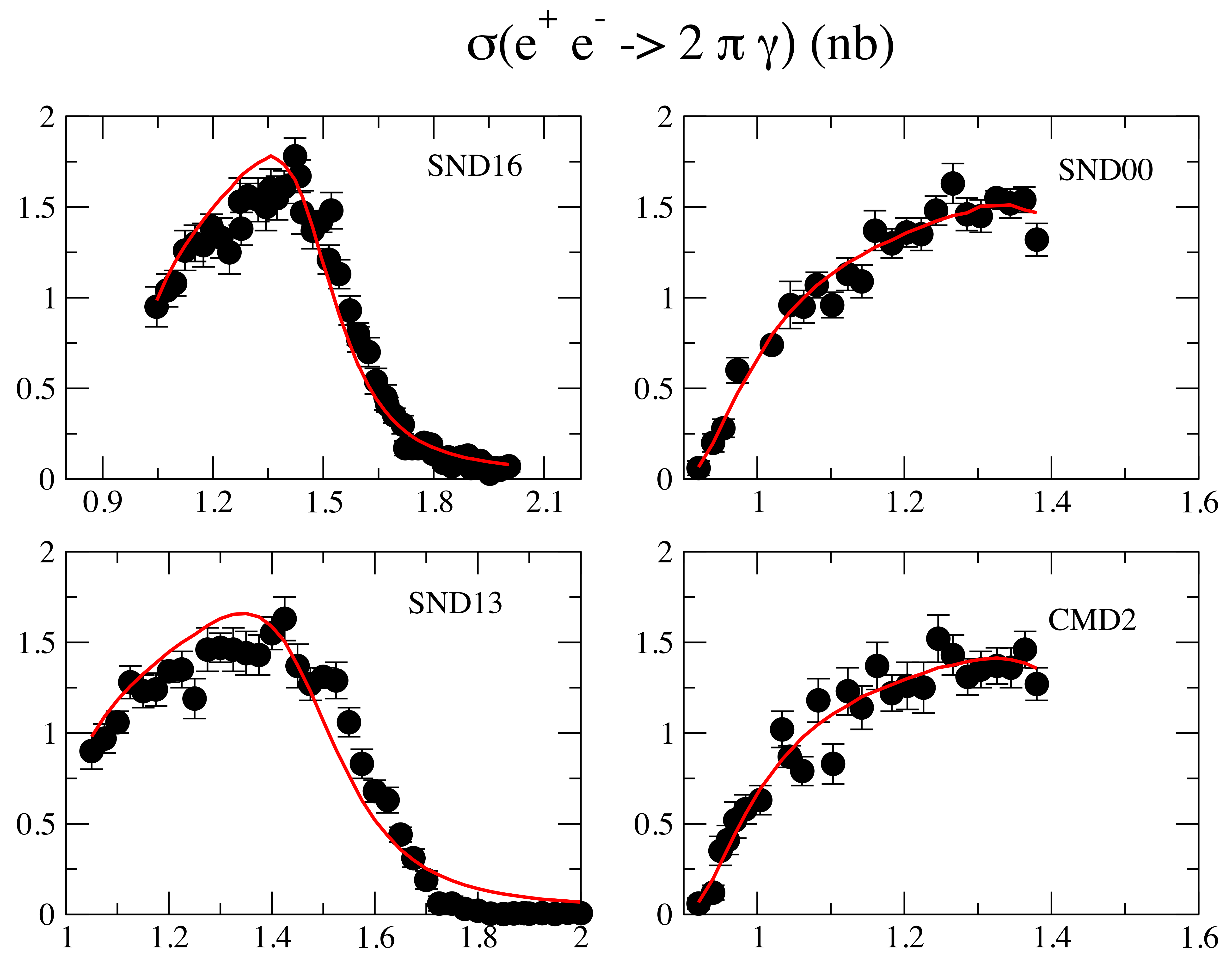
Cross section description $e^+e^- \to \pi^0\pi^0\gamma$



- M. N. Achasov, et al.,
- Phys. Rev. D 94, 112001 (2016).

- M. N. Achasov, et al.,
- Phys. Lett. B 486, 29 (2000).

- M. N. Achasov, et al.,
- Phys. Rev. D 88, 054013 (2013).

- R. R. Akhmetshin et al. (CMD-2 Collaboration),
- Phys. Lett. B 562, 173 (2003).

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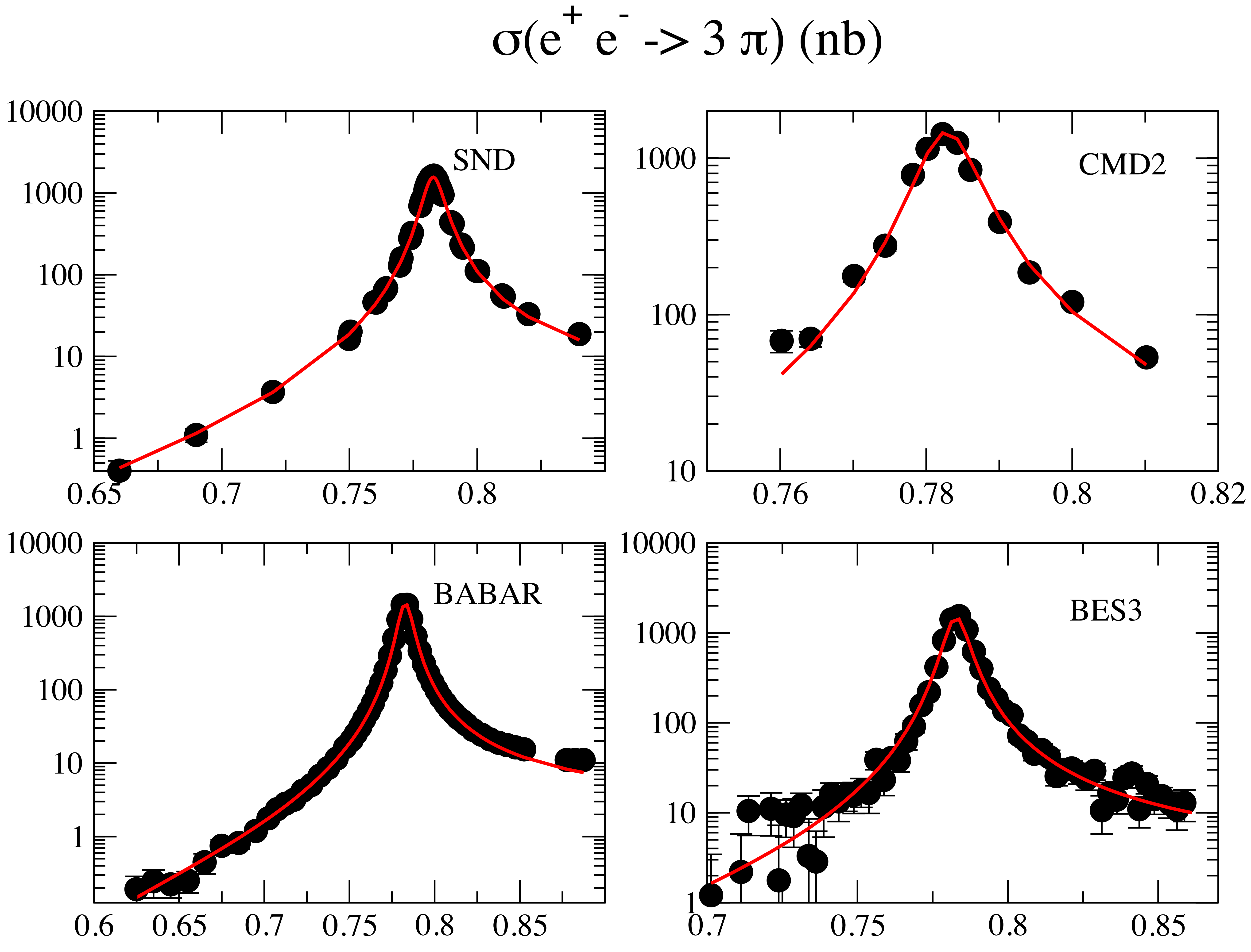
Cross section description

$e^+e^- \to 3\pi$



- M. N. Achasov, et al.,
- Phys. Rev. D 68, 052006 (2003).

- R. R. Akhmetshin et al. (CMD-2 Collaboration),
- Phys. Lett. B 578, 285 (2004).

- J. P. Lees et al. (BABAR Collaboration),
- Phys. Rev. D 104, 112003 (2021).

- M. Ablikim et al. (BESIII Collaboration),
- arXiv:1912.11208.

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$\tau^- \to \pi^- \pi^0 \nu_\tau \gamma$
General description

The general structure of the amplitude

$$\mathcal{M}_T = eG_F V_{ud}^* \epsilon^{*\mu} \Big[F_\nu \bar{u}(q)\gamma^\nu(1-\gamma_5)(m_\tau + \not{p} - \not{k})\gamma_\mu u(p) + (V_{\mu\nu} - A_{\mu\nu})\bar{u}(q)\gamma^\nu(1-\gamma_5)u(p) \Big],$$

where

$$V_{\mu\nu} = -f_+[t'] \frac{p_{-\mu}}{p_- \cdot k}(\bar{Q}-k)_\nu - f_+[t'] g_{\mu\nu} + \frac{f_+[t'] - f_+[t]}{k \cdot k_-} k_{-\mu} \bar{Q}_\nu + \hat{V}_{\mu\nu},$$

$$\hat{V}_{\mu\nu} \equiv v_1\, p_- \cdot k\, F_{\mu\nu}(p_-) + v_2\, p_0 \cdot k\, F_{\mu\nu}(p_0) + v_3\, p_0 \cdot k\, p_- \cdot k\, L_\mu(p_-, p_0)\, p_{-\nu} + v_4\, p_0 \cdot k\, p_- \cdot k L_\mu(p_-, p_0) k_{+\nu},$$

$$L_\mu(a,b) \equiv \frac{a_\mu}{a \cdot k} - \frac{b_\mu}{b \cdot k},$$

$$L(a,b) = L_\mu(a,b)\epsilon^\mu,$$

$$F_{\mu\nu}(a) \equiv g_{\mu\nu} - \frac{a_\mu k_\nu}{a \cdot k}.$$

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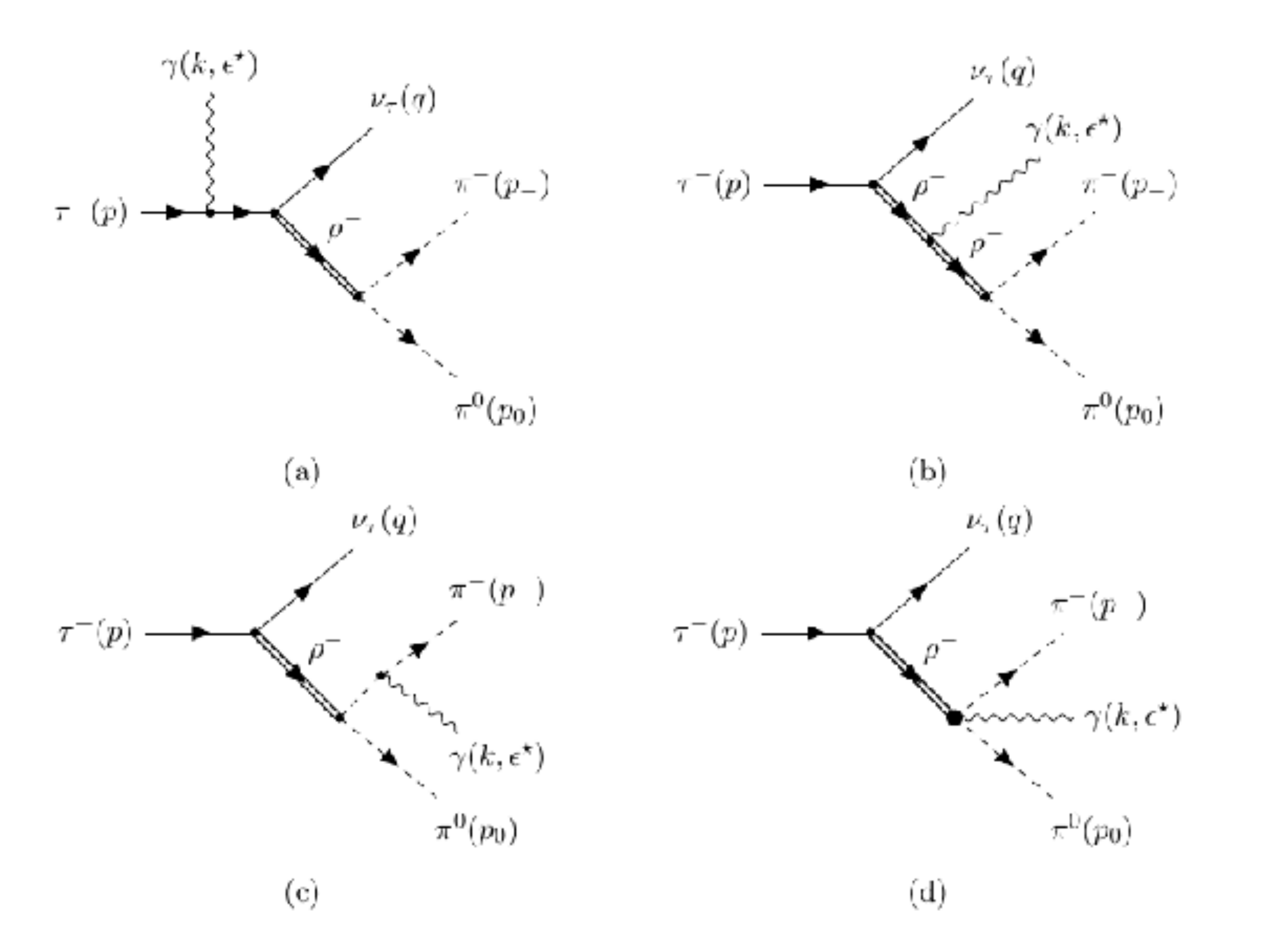
The $\tau^- \to \pi^- \pi^0 \nu_\tau \gamma$ soft photon approximation



Diagrams SI

Model independent amplitude (MI) (up to O(k^0))

$$
\begin{aligned}
\mathcal{M}_{Low} &= eG_F V_{ud}^* \Big\{ f_+[t]\, L(p,p_-)\bar{Q}_\nu + 2\,p_0\cdot k\, L(p_0,p_-)\,\frac{df_+[t]}{dt}\,\bar{Q}_\nu \\
&\quad - \frac{f_+[t]}{2\,p\cdot k}\,\epsilon^\mu \Big[F_{\mu\nu}(\bar{Q})\bar{Q}\cdot k + i\bar{Q}^\alpha k^\beta \epsilon_{\nu\alpha\beta\mu}\Big] \\
&\quad - f_+[t]\,\epsilon^\mu\, F_{\mu\nu}(p_-)\Big\}\, l^\nu,
\end{aligned}
$$

The ϱ MDM fig. (b) introduces model dependent terms

$$
\begin{aligned}
v_1 &= -v_2 = \beta_0 \frac{[f_+(t') - f_+(t)]}{2\,k_-\cdot k}, \\
v_3 &= 0, \\
v_4 &= 2\left(\frac{\beta_0}{2} - 1\right)\frac{(1+i\gamma)}{m_\rho^2}\,\frac{[f_+(t') - f_+(t)]}{k_-\cdot k}.
\end{aligned}
$$

Adding these two contributions is known as the structure independent amplitude (SI)

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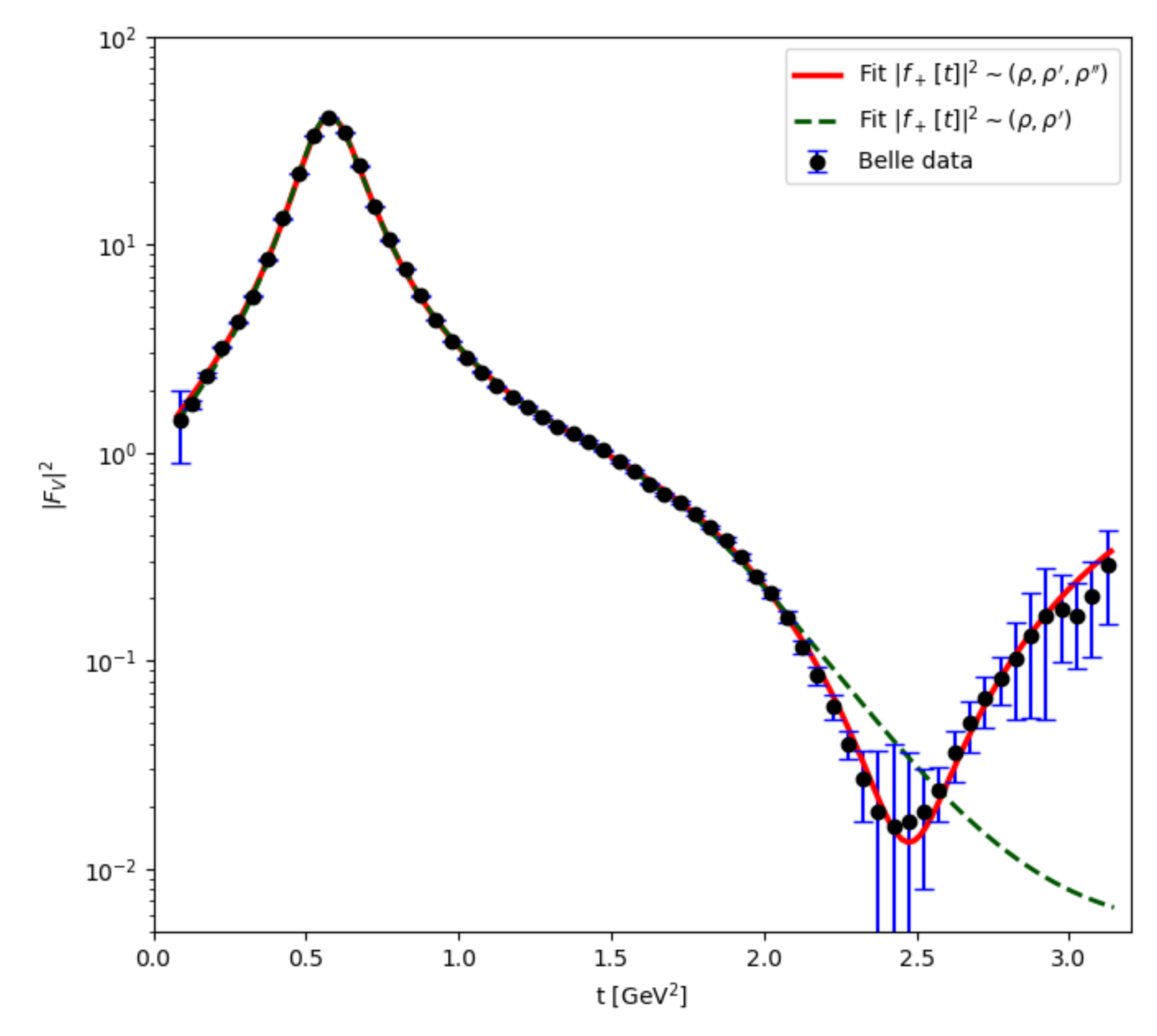
The vector form factor



Fit to Belle data

$$f_+[t] = \frac{1}{1+\beta+\gamma}\left\{f_\rho[t] + \beta\, f_{\rho'}[t] + \gamma\, f_{\rho''}[t]\right\},$$

Parameter	Value	Parameter	Value
m_ρ	0.7747 GeV	Γ_ρ	0.14612 GeV
$m_{\rho'}$	1.3832 GeV	$\Gamma_{\rho'}$	0.5653 GeV
$m_{\rho''}$	1.868 GeV	$\Gamma_{\rho''}$	0.3941 GeV
B_0	-0.4028	f_b	1.1321
G_0	-0.1725	f_g	4.3756×10^{-8}

TABLE II: Parameters obtained from a fit to the Belle data form factor $f_+[t]$.

Phys.Rev.D 78 (2008) 072006

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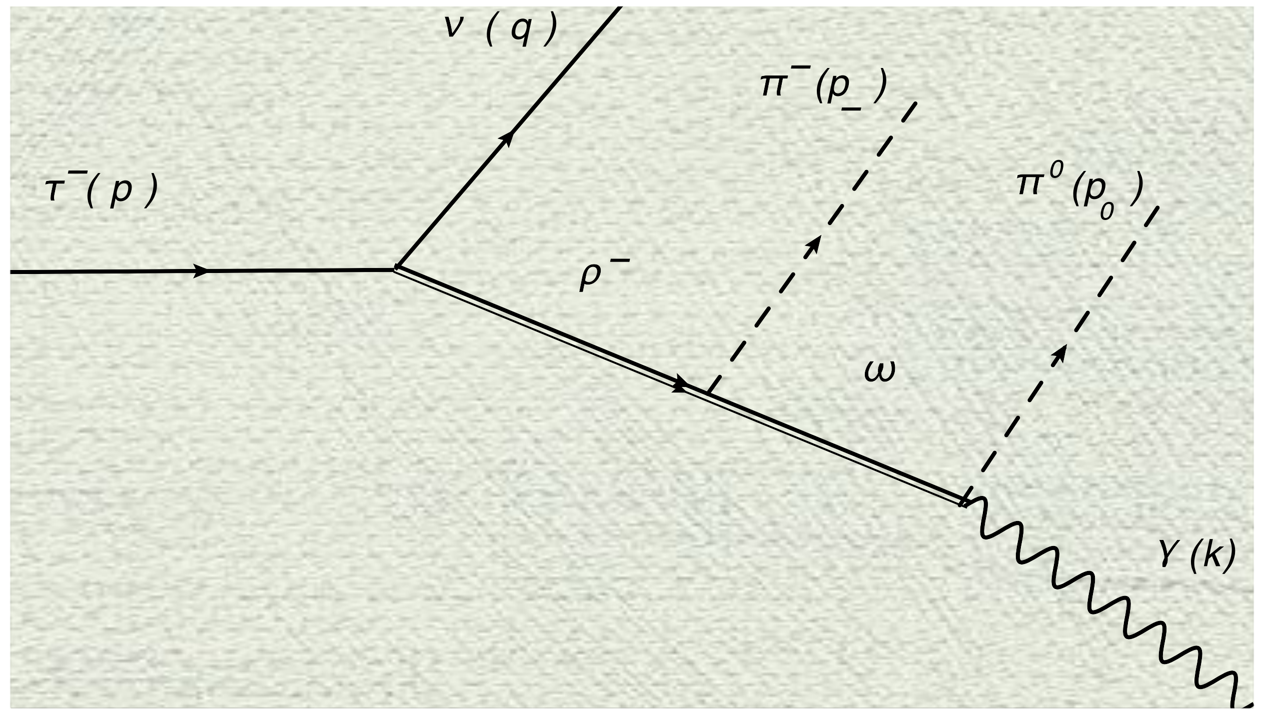
The $\tau^- \to \pi^- \pi^0 \nu_\tau \gamma$ omega channel



Model dependent amplitude O(k)

$$\mathcal{M}_\omega = eG_F V_{ud}^* \frac{G_\rho}{\sqrt{2}} \frac{g^2_{\omega\rho\pi}}{g_\rho m_\rho^2 m_\omega^2} f_\omega[(p_0+k)^2] f_o[t'] \epsilon_{\alpha\sigma\mu}{}^{\lambda} \epsilon_{\phi\lambda\chi}{}^{\nu} k^\sigma p_0^\alpha (p_0+k)^\phi p_-^\chi \epsilon^{*\mu} \ell^\nu ,$$

Including both ϱ and ϱ′ coupled to the ω

$$f_o[t'] \equiv \frac{1}{1+B_1 e^{i\theta}} \left\{ f_\rho[t'] + B_1 e^{i\theta} f_{\rho'}[t'] \right\} .$$

The amplitude set in the general structure form

$$\mathcal{M}_\omega = eG_F V_{ud}^* \epsilon^{*\mu} \hat{V}^{(\omega)}_{\mu\nu} \ell^\nu ,$$

with

$$\begin{aligned} v_1^\omega &= -C_\omega f_\omega[(p_0+k)^2] f_o[t'](p_0+2k)\cdot p_0, \\ v_2^\omega &= C_\omega f_\omega[(p_0+k)^2] f_o[t'](p_0+k)\cdot p_-, \\ v_3^\omega &= C_\omega f_\omega[(p_0+k)^2] f_o[t'], \\ v_4^\omega &= -C_\omega f_\omega[(p_0+k)^2] f_o[t'], \end{aligned}$$

$$C_\omega = \frac{g^2_{\omega\rho\pi}}{m_\omega^2 g_\rho g_{\rho\pi\pi}} .$$

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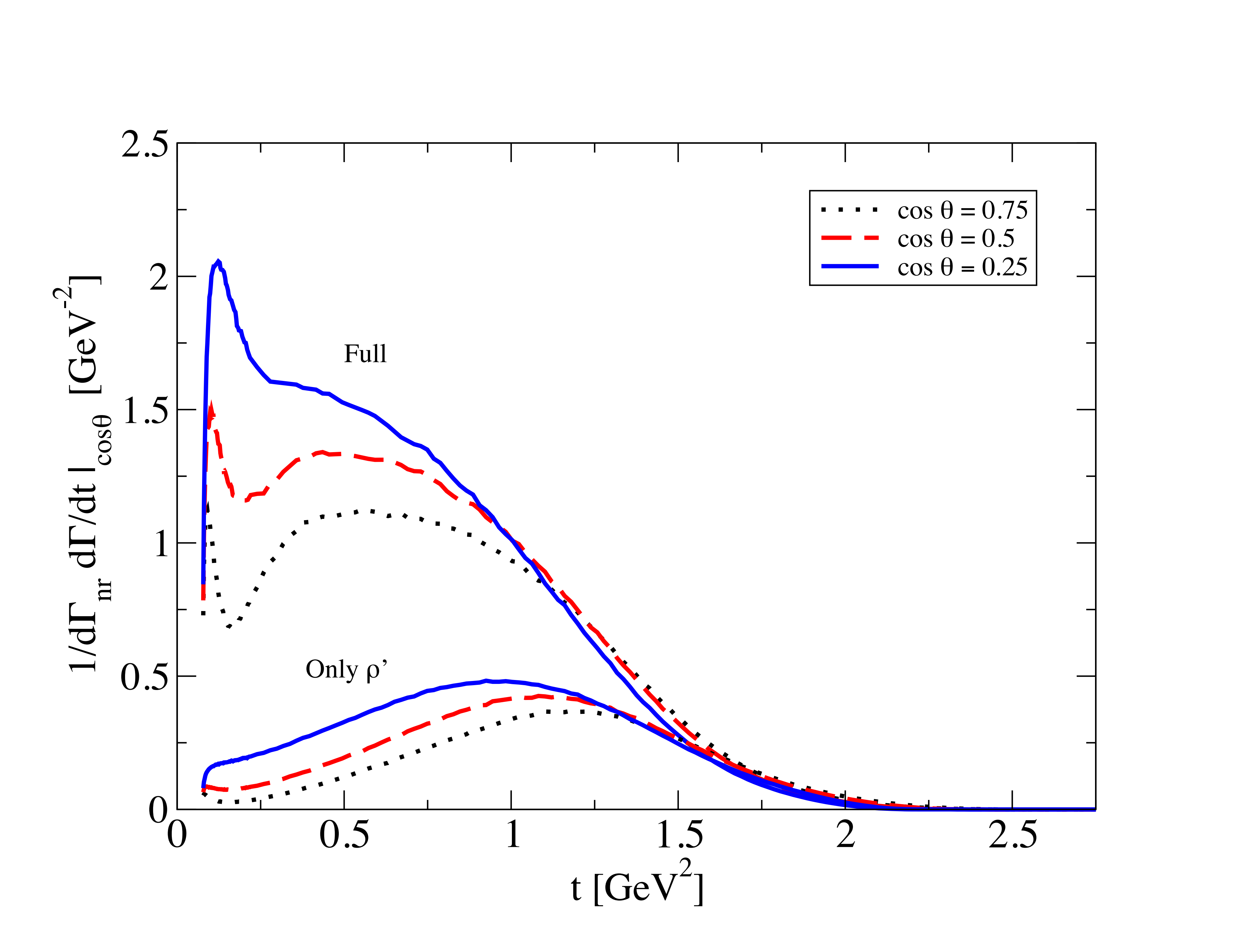
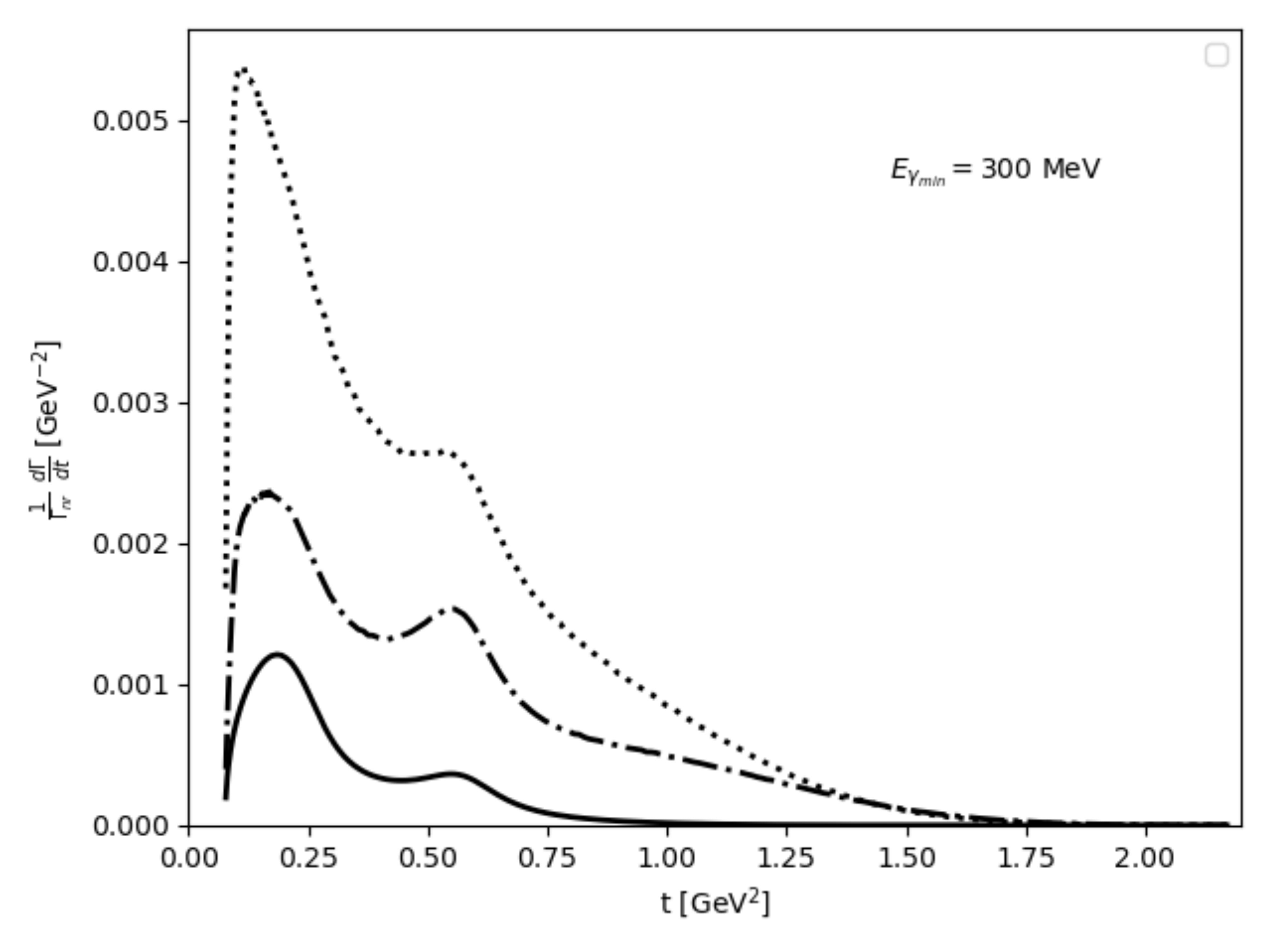
The $\tau^- \to \pi^- \pi^0 \nu_\tau \gamma$ omega channel



Dipion invariant mass distribution due to the ω channel, normalized to the non-radiative decay width (Γnr) for several angles of the charged pion emission wrt dipion momentum



Dipion invariant mass distribution. The doted line corresponds to the total, the dot-dashed line is the contribution excluding the ϱ′ in the omega channel, and the solid line is the SI contribution

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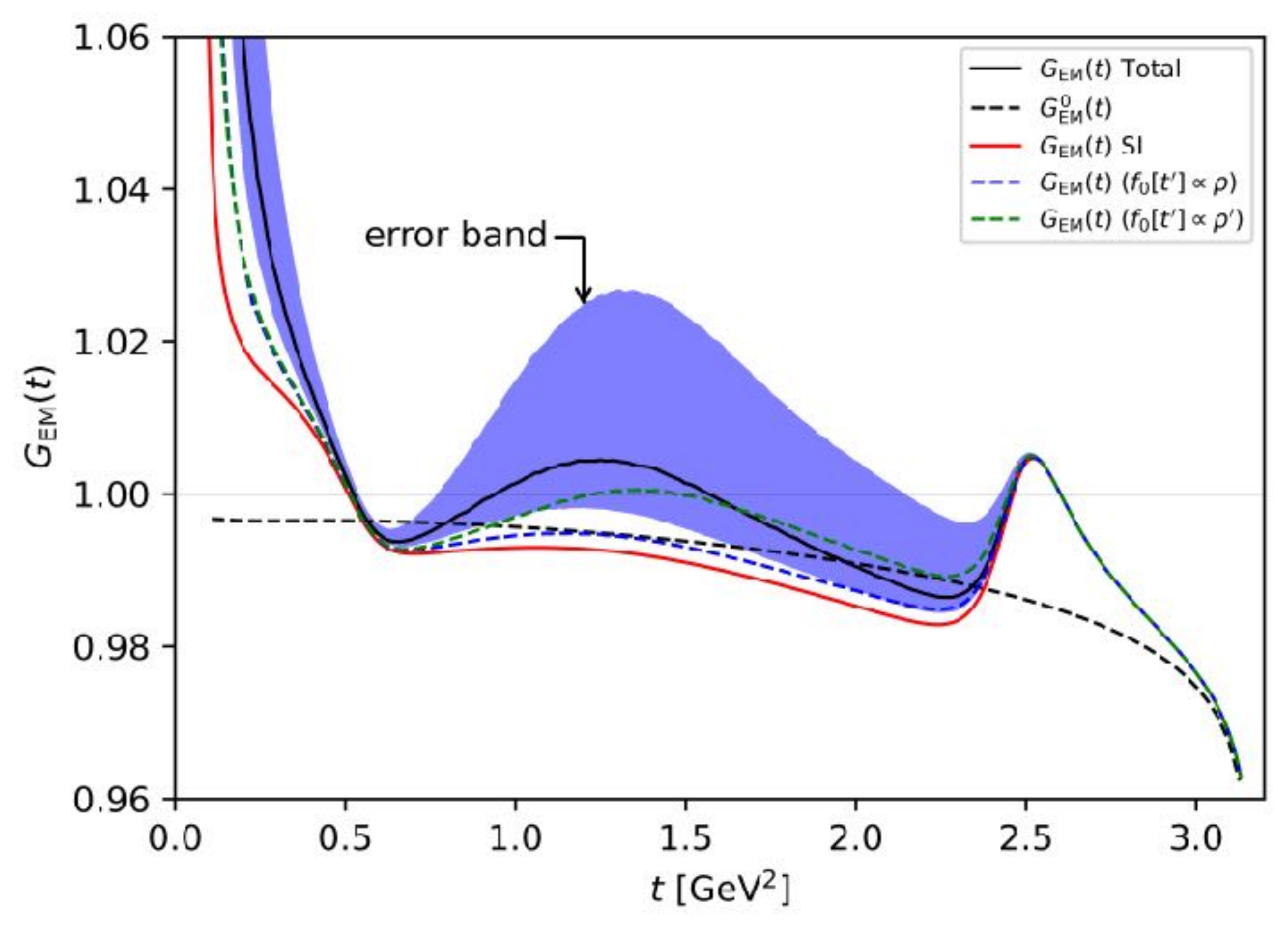
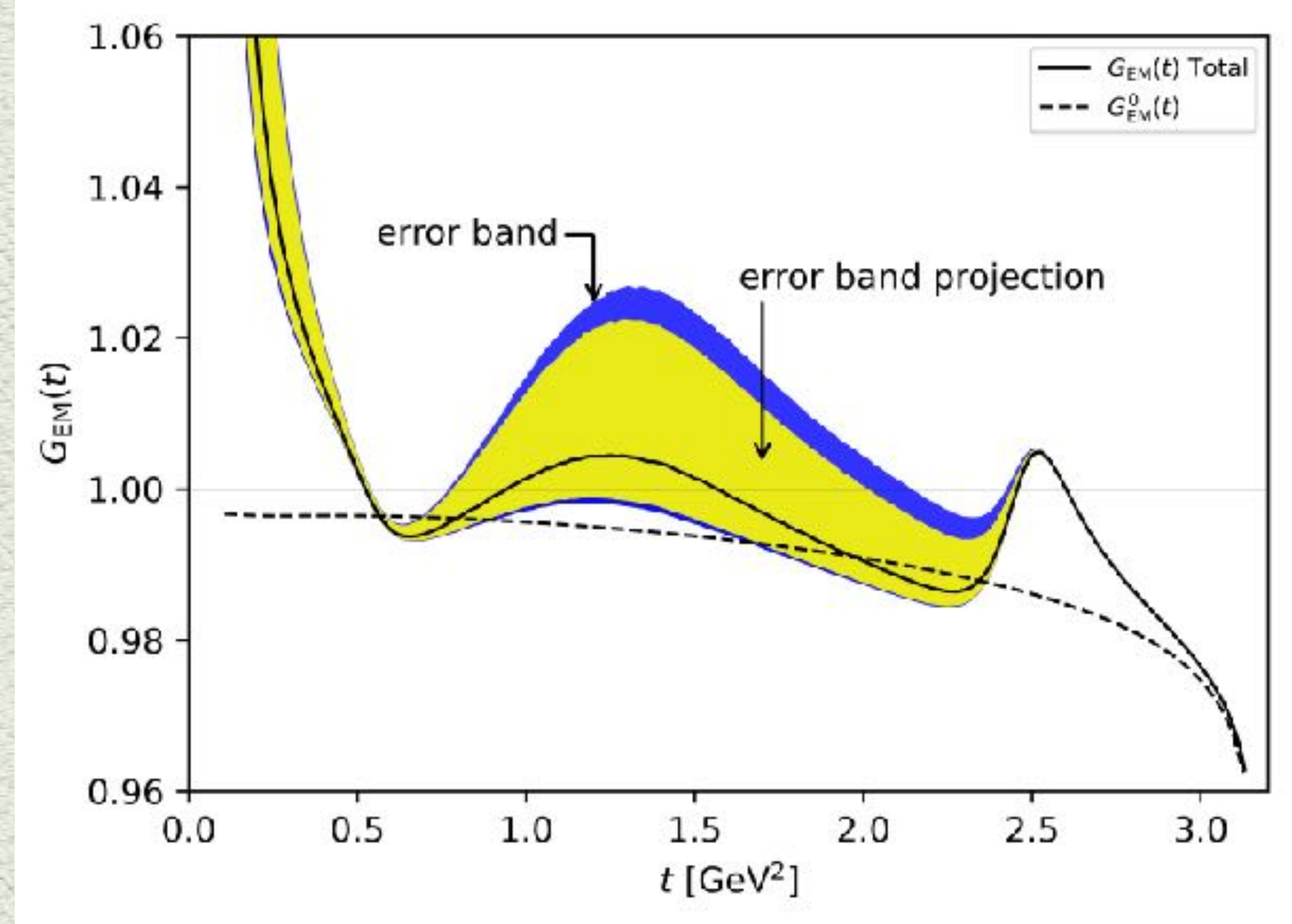
The $\tau^- \to \pi^- \pi^0 \nu_\tau$ radiative correction

Electromagnetic function $$\frac{d\Gamma_{2\pi(\gamma)}}{dt} = \frac{d\Gamma^0_{2\pi}}{dt} G_{EM}(t), \qquad G_{EM}(t) = G^0_{EM}(t) + G^{rest}_{EM}(t),$$

G0 (t) accounts for the virtual and real contribution up to O(k^{-2}),
Grest(t), includes the remaining higher order contributions from the real part



GEM (t) function including several contributions (the error band corresponds to the inclusion of the rho')



Projection on rho(1450)

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muon g-2 ISB correction from $\tau^- \to \pi^- \pi^0 \nu_\tau(\gamma)$

Isospin symmetry breaking correction

$$R_{IB}(t) = \frac{FSR(t)}{G_{EM}(t)} \frac{\beta^3_{\pi^+\pi^-}}{\beta^3_{\pi^+\pi^0}} \left| \frac{F_V(t)}{f_+(t)} \right|^2 .$$

$$\Delta a_\mu^{(HVP,LO)}|_{G_{EM}(t)} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} dt\, K(t) \frac{K_\sigma(t)}{K_\Gamma(t)} \frac{d\Gamma_{2\pi(\gamma)}}{dt} \times \left[\frac{1}{G_{EM}(t)} - 1 \right],$$

$$K_\Gamma(t) = \frac{G_F^2 |V_{ud}|^2 m_\tau^3}{384\pi^3} \left(1 - \frac{t}{m_\tau^2}\right)\left(1 + \frac{2t}{m_\tau^2}\right), \quad K_\sigma = \frac{\pi\alpha^2}{3t},$$

	$G_{EM}(t)$	$\Delta a_\mu^{(HVP,LO)}$ ($\times 10^{-11}$)
(i)	$G^0_{EM}(t)$	18
(ii)	$G_{EM}(t)$(MI)	-12
(iii)	$G_{EM}(t)$(SI)	-15
(iv)	$G_{EM}(t)$ (Full)	$-38.3^{+2.8}_{-3.2}$
(v)	$G_{EM}(t)$ (Full+ρ')	$-94.2^{+32.3}_{-91.9}$
(vi)	$G_{EM}(t)$ (Projection)	$-94.2^{+28.2}_{-66}$

Consistent with previous estimates

Anomalously large

	ChPT $\mathcal{O}(p^4)$	$R_\chi T$ $\mathcal{O}(p^4)$	$R_\chi T$ $\mathcal{O}(p^6)$
$\Delta a_\mu^{\text{HVP LO}}\|_{G_{EM}(t)}$ ($\times 10^{-11}$)	-10	$-15.9^{+5.7}_{-16.0}$	-76 ± 46

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muon g-2 ISB correction from $\tau^- \to \pi^- \pi^0 \nu_\tau(\gamma)$

Table 1 Contributions to $a_\mu^{\text{had,LO}}[\pi\pi,\tau]$ ($\times 10^{-10}$) from the isospin-breaking corrections discussed in Sect. 3. Corrections shown in two separate columns correspond to the Gounaris–Sakurai (GS) and Kühn–Santamaria (KS) parametrisations, respectively

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ρ–ω interference	$+2.80 \pm 0.19$	$+2.80 \pm 0.15$
$m_{\pi^\pm} - m_{\pi^0}$ effect on σ	-7.88	
$m_{\pi^\pm} - m_{\pi^0}$ effect on Γ_ρ	$+4.09$	$+4.02$
$m_{\rho^\pm} - m_{\rho^0_{\text{bare}}}$	$+0.20^{+0.27}_{-0.19}$	$+0.11^{+0.19}_{-0.11}$
$\pi\pi\gamma$, electrom. decays	-5.91 ± 0.59	-6.39 ± 0.64
Total	-16.07 ± 1.22	-16.70 ± 1.23
	-16.07 ± 1.85	

M. Davier, et al, Eur. Phys. J. C 66, 127-136 (2010)

muon g-2 experimental result 2023

$a_\mu = 116\,592\,057(25) \times 10^{-11}$ (0.21 ppm). Combining this result with our previous result from the 2018 data, we obtain $a_\mu(\text{FNAL}) = 116\,592\,055(24) \times 10^{-11}$ (0.20 ppm). The new experimental world average is $a_\mu(\text{Exp}) = 116\,592\,059(22) \times 10^{-11}$ (0.19 ppm), which represents a factor of two improvement in precision.

from $-(16.07 \pm 1.85) \times 10^{-11}$ to $-(17.98 \pm 1.64) \times 10^{-10}$ considering only the ρ in the ω channel, and $-(23.57^{+3.67}_{-9.33}) \times 10^{-10}$ when adding the ρ'.

Conclusions

We explored the $e^+e^- \to \pi^0\pi^0\gamma$ differential cross section, and identified the double pole resonant enhancement features.

Performed an analysis of the parameters involved, in base of experimental data, to identify their robustness. $g_{\rho\omega\pi} = 11.314 \pm 0.383\ \mathrm{GeV}^{-1}$ was found to be consistent with all the relevant observables.

Performed an analysis of the $\tau^- \to \pi^-\pi^0\nu_\tau\gamma$ omega channel, exhibiting the analogies to the previous case

The muon g-2 ISB correction from $\tau^- \to \pi^-\pi^0\nu_{\tau}(\gamma)$ was found to be consistent with previous calculations using the same approach.

Considering only the rho, the uncertainties are well grounded.

The inclusion of rho(1450) calls for revision as the large effects observed may signal departure from soft photon approximation and structure dependence.

The link between the $e^+e^- \to \pi^0\pi^0\gamma$ process and the ω channel of the $\tau^- \to \pi^-\pi^0\nu_\tau\gamma$ decay, can be used to gain further insight into the description of such processes.

THANK YOU
for your attention

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