Dispersion relations for $\gamma\gamma \to 2\pi$ and $\gamma\gamma^* \to 2\pi$

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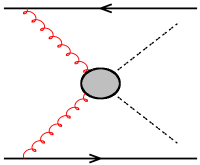
Introduction

- $\gamma\gamma \to hadrons$ at e^+e^- colliders:

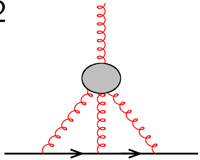
$$\sigma \sim \alpha^4 \ln^4 \frac{E}{m_e} \ln \frac{E}{m_\pi}$$

[Brodsky, Kinoshita, Terazawa (1970)]

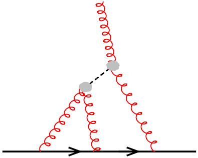


- 2γ couplings of hadrons ($J^{PC} = 0^{++}, 0^{-+}, 2^{++}, 2^{-+}, 3^{++}, \cdots$)
  - → π^0, $\eta \to 2\gamma$: measurement via Primakov [Browman (1974)] was not correct !
  - → σ, $f_0(980)$, $a_0(980) \to 2\gamma$
    Analyticity based extraction:[Mennessier, Z.Phys. C16 (1983) 241]

- LBL hadronic contributions to muon $g-2$



→ Largest contribution: one-pion pole



→ Large N_c approach, next largest: η, σ, $f_0, \cdots$ poles

- More general Bern dispersive approach:

Ingredients:

$$\sum_J [\gamma\gamma^* \to \pi\pi]_J \times [\gamma^*\gamma^* \to \pi\pi]_J$$

$\gamma\gamma \to \pi\pi$: **analyticity**

Independent amplitudes

- Amplitude $\gamma^{(*)}(q_1)\gamma^{(*)}(q_2) \to \pi(p_1)\pi(p_2)$ derived from the matrix element

$$e^2 W_{\mu\nu}(q_i, p_i) = i \int d^4x e^{-iq_1 x} \langle \pi(p_1)\pi(p_2)| T\left(j_\mu(x) j_\nu(0)\right)|0\rangle$$

Ward identities: $q_1^\mu W_{\mu\nu} = q_2^\nu W_{\mu\nu} = 0$.

- Expand on basis $T^n_{\mu\nu}(q_i, p_i)$, $n = 1 \cdots 5$

$$W_{\mu\nu} = A(s,t,q_i^2)\, T^1_{\mu\nu} + B(s,t,q_i^2)\, T^2_{\mu\nu} + C(s,t,q_i^2)\, T^3_{\mu\nu} + \cdots$$

- Helicity amplitudes: $H_{++}(s,\theta)$, $H_{+-}(s,\theta)$, $H_{+0}(s,\theta)$

Analyticity of scattering amplitudes

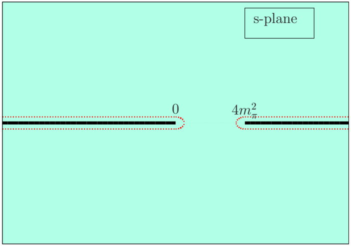
- Starting point: Mandelstam analyticity conjecture[PR 112 (1958) 1344]

$$A(s,t,u) = \int\int_{D_{st}} ds'dt' \frac{\rho_{st}(s',t')}{(s'-s)(t'-t)} + \int\int_{D_{tu}} dt'du' \frac{\rho_{su}(t',u')}{(t'-t)(u'-u)} + \int\int_{D_{us}} du'ds' \frac{\rho_{su}(u',s')}{(u'-u)(s'-s)}$$

→ Partial-wave amplitudes are analytic functions of s

→ $\gamma\gamma \to \pi\pi$:

$$h^I_J(s) = h^I_{J,L}(s) + h^I_{J,R}(s)$$



- Discontinuity across RHC (in elastic region $4m_\pi^2 \leqslant s \leqslant s_{in}$)

$$\frac{1}{2i}\mathrm{disc}[h^I_J(s)] = \mathrm{Im}\,[h^I_J(s)] = \sigma_\pi(s)\underbrace{\left(t^I_J(s)\right)^*}_{\pi\pi \text{ amplitude}} h^I_J(s)$$

- FSI theory [Omnès (1958)]:

$$\Omega^I_J(s) = \exp\left[\frac{s}{\pi}\int_{4m_\pi^2}^{\infty}\frac{ds'}{s'(s'-s)}\phi^I_J(s')\right]$$

with:

$$\begin{aligned}\phi^I_J(s') &= \delta^I_J(s'),\ s' \leqslant s_{in}\ \text{(Fermi-Watson)}\\ &= Phase[h^I_J(s')],\ s' > s_{in}\end{aligned}$$

Application to $2\gamma \to 2\pi$: [Gourdin,Martin Nuov.Com.17 (1960) 224]

- Omnès function removes right-hand cut

$$\mathrm{Im}\left[\frac{h^I_J(s)}{\Omega^I_J(s)}\right] = 0, \quad s > 4m_\pi^2$$

- General representation:

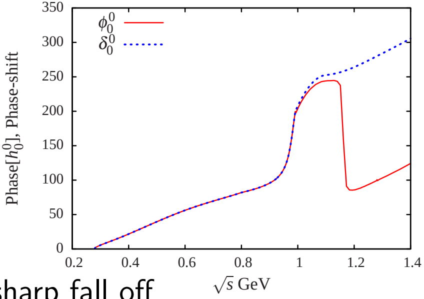
$$h^I_J(s) = h^I_{J,L}(s) + \Omega^I_J(s)\left[P_{n-1}(s) + \frac{s^n}{\pi}\int_{4m_\pi^2}^{\infty} ds' \frac{h^I_{J,L}(s')\sin(\phi^I_J(s'))}{(s')^n(s'-s)|\Omega^I_J(s')|}\right]$$

→ Exact, but needs HE information

→ In practice: in finite energy region efficient approximation, few parameters,

→ Fix (partly) from chiral constraints

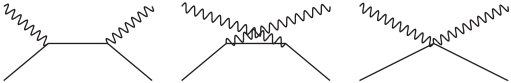
- Phase ϕ^I_J in **inelastic** region ?
  - → $\pi\pi_{J=0,I=0}$: main contrib. to inelasticity from $K\overline{K}$
  - → Coupled channel extension: Ω^I_J is 2×2 matrix: must be computed numerically from $\pi\pi$, $K\overline{K}$ 2×2 T-matrix
- Prediction for $\phi^0_0 = \text{Phase}[h^0_0]$



  - → Phase$[h^0_0]$ displays sharp fall off

Left-hand cut

- Leading contribution at small s: from pion pole in $\gamma\pi^+ \to \gamma\pi^+$, computed from sQED Lagrangian



called Born term

- Soft photon theorem[F. Low, PR 110(1958)974]

$$h_J^I(s) \to h_J^{I,Born}(s) + O(s)$$

$\Rightarrow \ P_{n-1}(0) = 0.$

- Beyond pion pole: two options

  1) Start from Mandelstam based DR's (e.g. family with $(t-a)(u-a)=b$)[Hoferichter et al. EPJ C71 (2011)1743]. Then, project on PW's:

     $\longrightarrow h_{J,L}(s)$ in terms of $\mathrm{Im}\,[\gamma\pi\to\gamma\pi]_J$ (but no detailed exp. inputs)

  2) Less rigorous (large N_c): resonance contributions to $\gamma\pi\to\gamma\pi$, from Lagrangian : ρ, ω, a_1, b_1, a_2 ...

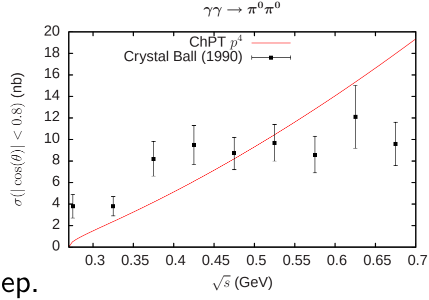
     → Extension to γ^* rather simple

Chiral expansion results and constraints

- Historically: $\gamma\gamma \to \pi^0\pi^0$:[Bijnens, Cornet NP B296 (1988) 557, Donoghue, Holstein,Lin PR D37 (1988)2423]. One-loop calc. in ChPT: finite, no LEC's

$$H^n_{++}(s) = \frac{m_\pi^2 - s}{8\pi^2 F_\pi^2}\left(1 + \frac{m_\pi^2}{s}\log^2\frac{\sigma_\pi(s)-1}{\sigma_\pi(s)+1}\right)$$

- Measured at DESY[Crystal Ball, PR D41 (1990) 3324]



- Two-loop calc.[Bellucci et al.(1990)] improves energy dep.

Matching DR's and ChPT

- Pion polarisabilities electric (α_i) and magnetic (β_i)

$$\frac{e^2}{2\pi m_\pi} H_{++}(s, t = m_\pi^2) = s\,(\alpha_1 - \beta_1) + \frac{s^2}{12}\,(\alpha_2 - \beta_2) + \cdots$$
$$\frac{-e^2}{2\pi m_\pi} H_{+-}(s, t = m_\pi^2) = s\,(\alpha_1 + \beta_1) + \frac{s^2}{12}\,(\alpha_2 + \beta_2) + \cdots$$

- Polarisabilities in ChPT [Gasser, Ivanov, Sainio NP B728 (2005) 31,B745(2006)84]

π^0	$(\alpha - \beta)$ $[10^{-4}\ \mathrm{fm}^3]$	p^4, p^6 Couplings
one-loop	-1.0	None
two-loops	$-(1.9 \pm 0.2)$	$c_{29}, c_{30}, c_{31}, c_{32}, c_{33}, c_{34}$
π^+		
one-loop	6.0 ± 0.6	$\bar{l}_5 - \bar{l}_6$
two-loops	5.7 ± 1.0	$\cdots + c_6, c_{35}, c_{44}, c_{46}, c_{47}, c_{50}, c_{51}$

Compass(2014): $(\alpha - \beta)^{\pi^+} = (4.0 \pm 1.2 \pm 1.4) \cdot 10^{-4}\ \mathrm{fm}^3$

- Use four constraints from ChPT:

1) For π^+: [Gasser et al., NP B745 (2006)84]
$(\alpha_1 - \beta_1) = \boxed{[4.7 - 5.7]\, 10^{-4}\ \text{fm}^3}$

2) For π^0: relation between dipole and quadrupole polarisabilities in terms of one p^6 coupling

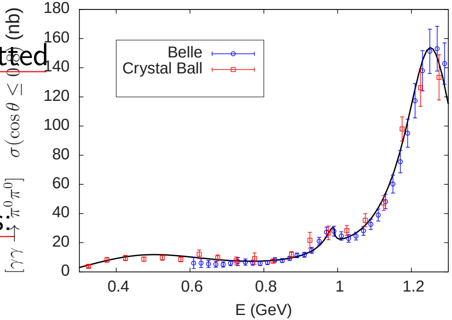
$$\boxed{6(\alpha_1 - \beta_1)^{\pi^0} + m_\pi^2(\alpha_2 - \beta_2)^{\pi^0} = (6.20 + 10^5 c_{34}^r)10^{-4}\text{fm}^3}$$

c_{34}^r can be estimated from sum rule: (τ decays inputs)

$10^5\, c_{34}^r = (1.18 \pm 0.31)$: [Dürr,Kambor PR D61 (2000)]
$10^5\, c_{34}^r = (1.37 \pm 0.16)$:[Golterman et al.,PR D89 (2014)]

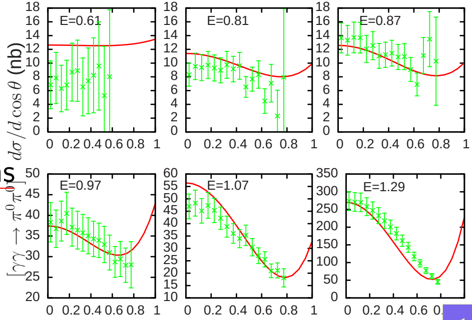
3) For K^+, K^0: ChPT p^4
$(\alpha_1 - \beta_1)^{K^0} = 0,\ (\alpha_1 - \beta_1)^{K^+} = \dfrac{2e^2}{\pi m_K F_K^2}(L_9^r + L_{10}^r)$

- Five polyn.parameters fitted



$\pi^0\pi^0$ data :

Integrated cross sections:
agreement is fair

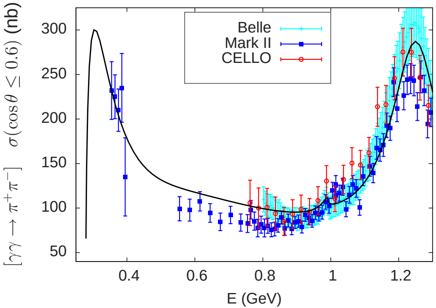


Differential cross sections
larger angular coverage
needed

■ $\pi^+\pi^-$ data

Integrated cross sections:

some tension w. Mark II

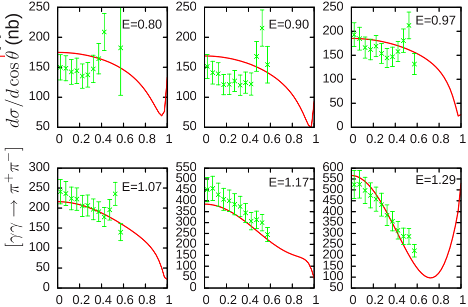


Differential cross sections:

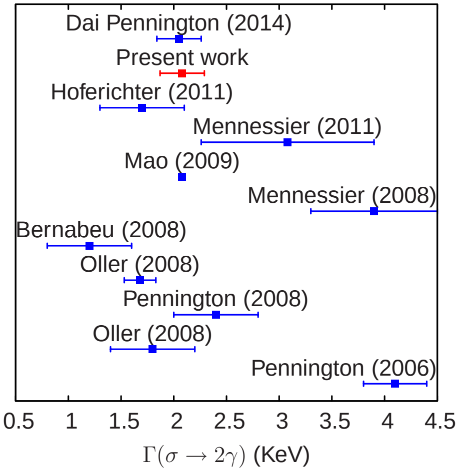
Needed:

→ Better precision

→ Larger angular coverage



$\sigma \to 2\gamma$ couplings



From $\gamma\gamma$ to $\gamma\gamma^*(q^2)$

- Goal is to extend the same formalism to $\gamma\gamma^*(q^2) \longrightarrow \pi\pi$ (not seemed to have been considered previously)

- Two physically accessible situations:

$$e^- e^+ \longrightarrow \gamma\pi\pi \qquad (q^2 > 4m_\pi^2)$$
$$e^-\gamma \longrightarrow e^-\pi\pi \qquad (q^2 < 0)$$

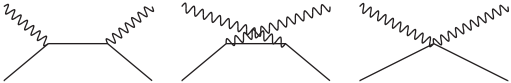
- Issues to address

  1) "left-hand" cut $(q^2 > 4m_\pi^2)$

  2) Form factors

Left-hand cut when $q^2 \neq 0$

- Definition of Born term: compute diagrams with sQED and $q^2 \neq 0$



- Influence of pion form factor

$$\langle \pi^+(p)|j_\mu(0)|\pi^+(p')\rangle = (p+p')_\mu \, F_\pi^v((p-p')^2)$$

→ First two diagrams mult. by $F_\pi^v(q^2)$

→ Gauge invariance: $\Rightarrow$ mult. also third diagram

- Consider $\boxed{J=0}$ partial wave projection

$$h_0^{Born}(s,q^2) = \frac{F_\pi^v(q^2)}{s-q^2}\left(\frac{4m_\pi^2}{\sigma_\pi(s)}\log\frac{1+\sigma_\pi(s)}{1-\sigma_\pi(s)} - 2q^2\right)$$

with $\sigma_\pi(s) = \sqrt{1-4m_\pi^2/s}$

→ Cut is on the negative real axis

→ But: if $q^2 > 4m_\pi^2$ pole at $s=q^2$ in the physical region

→ Note: $s=q^2$ corresponds to soft photon

→ Omnès dispersive integral:

$$I(s,q^2) = \frac{1}{\pi}\int_{4m_\pi^2}^{\infty} \frac{ds'\ \sin\delta(s')\,(4m_\pi^2 L_\pi(s') - 2q^2)}{(s'-s)(s'-q^2)\,|\Omega(s')|}$$

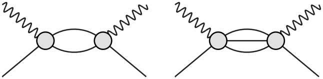
→ well defined: both s, q^2 energy variables, $I(s,q^2)$ defined with $\lim_{\epsilon\to 0}\ s+i\epsilon,\ q^2+i\epsilon$

→ Note: Fermi-Watson breaks down[Creutz, Einhorn PR D1 (1970) 2537]

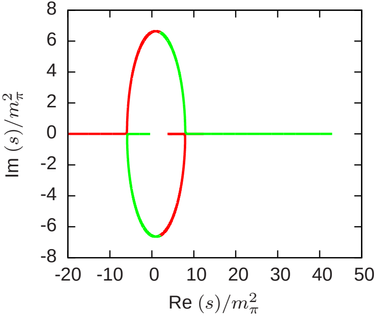
→ Unitarity: $\mathrm{Im}\,\langle\gamma\gamma^*|\pi\pi\rangle$

$$= \langle\gamma\gamma^*|\pi\pi\rangle\langle\pi\pi|\pi\pi\rangle + \langle\gamma^*|\pi\pi\rangle\langle\gamma\pi\pi|\pi\pi\rangle$$

- Further contributions to left-hand cut



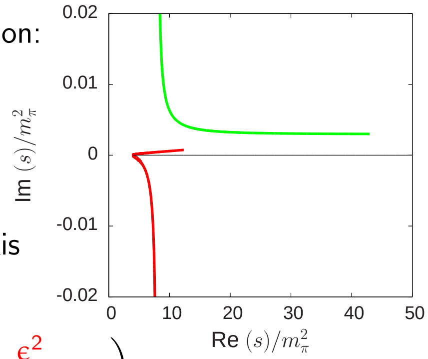
- Cut :



→ Overlaps with positive real axis

→ Problem with Omnès ?

- Using $q^2 + i\epsilon$ prescription:



→ Cut crosses real axis at $s_c < 4m_\pi^2$:

$$s_c = 4m_\pi^2 \left(1 - \frac{\epsilon^2}{(q^2 - 4m_\pi^2)^2}\right)$$

→ Cuts are well separated, Omnès integrals well defined

→ Absence of anomalous threshold. No longer true in case of two virtual photons[Hoferichter et al., arXiv:1309.6877]

Low-energy constraints and Omnès dispersive formula

1) Soft photon limit: $s \to q^2$

$$H^n_{\lambda\lambda'} = O(s - q^2), \quad H^c_{\lambda\lambda'} = H^{Born}_{\lambda\lambda'} + O(s - q^2)$$

2) Soft pion theorem for $\gamma\gamma^* \to \pi^0\pi^0$

$$A(s,t,q^2) + 2q^2\left(B(s,t,q^2) - C(s,t,q^2)\right)\Big|_{m_\pi=0,t=0,s=0} = 0$$

(for any q^2)

$\Rightarrow$ Physical helicity amplitude H_{++} whith $t = m_\pi^2$ has an Adler zero i.e. $H^n_{++}(s=0, t=m_\pi^2) = O(m_\pi^2)$

- Twice subtracted representation (at $s = 0$) which generalises the $q^2 = 0$ one

$$
\begin{aligned}
&H^I_{++}(s, q^2, \theta) = \\
&\quad F^v_\pi(q^2)\, \bar{H}^{I,Born}_{++}(s, q^2, \theta) + \sum_{\rho,\omega} F_{V\pi}(q^2)\, \bar{H}^{I,V}_{++}(s, q^2, \theta) \\
&+\Omega^I_0(s)\Big\{ s\, F^v_\pi(q^2) \left[\frac{s[J^{I,\pi}(s,q^2) - J^{I,\pi}(q^2,q^2)]}{s-q^2} - q^2\, \hat{J}^{I,\pi}(q^2) \right] \\
&\qquad + s \sum_{\rho,\omega} F_{V\pi}(q^2) \left[s\, J^{I,V}(s, q^2) - q^2 J^{I,V}(q^2, q^2) \right] \\
&\qquad + (s - q^2)\, b^I(q^2) \Big\} + (J \geqslant 2)
\end{aligned}
$$

→ Soft photon condition determines one subtr. function, one remains: $b^I(q^2)$

- Remark: $\hat{J}^{I,\pi}$ function involves derivative

$$\hat{J}^{I,\pi}(s,q^2) = \frac{1}{\pi}\int_{4m_\pi^2}^{\infty} \frac{ds'}{s'-s}\frac{d}{ds'}\left[\frac{\sin\delta_0^I(s')(4m_\pi^2 L_\pi(s') - 2q^2)}{|\Omega_0^I(s')|\,(s')^2}\right]$$

→ Phase-shift has a cusp at $K\overline{K}$ threshold: principal-value integration diverges (when $s \geqslant 4m_K^2$)

- Two-channel expression has no problem :

$$\mathrm{Im}\,\mathbf{\Omega}^{-1} = -\mathbf{\Omega}^{-1}\times\mathbf{T}\times\begin{pmatrix}\sigma_\pi(s')\theta(s'-4m_\pi^2) & 0\\ 0 & \sigma_K(s')\theta(s'-4m_K^2)\end{pmatrix}$$

and
$(\mathbf{\Omega}^{-1}\times\mathbf{T})_{ij}$ has no cusp

Form factors and Subtraction functions

- $F^V_{\pi\pi}$ well known. Similar parametrisations used for $F^V_{\omega\pi}$, $F^V_{\rho\pi}$
- Functions $b^I(q^2)$ expected to have cuts $q^2 = 4m_\pi^2,\ 9m_\pi^2, \ldots$, strong q^2 dep. induced by vector resonances
- Representation w. four parameters (only $\pi^0\pi^0$ data is available)

$$b^n(q^2) = b^n(0)\frac{\chi(q^2)}{\chi(0)} + \beta_\rho(GS_\rho(q^2) - 1) + \beta_\omega(BW_\omega(q^2) - 1)$$
$$b^c(q^2) = b^c(0) + \beta_\rho(GS_\rho(q^2) - 1) + \beta_\omega(BW_\omega(q^2) - 1)$$

- where b^c, b^n are linear combinations

$$b^c = -(\sqrt{2}\,b^0 + b^2)/\sqrt{6}, \quad b^n = -(b^0 - \sqrt{2}\,b^2)/\sqrt{3}$$

- Function $\chi(q^2)$ from $O(p^4)$ $\pi^0\pi^0$ amplitude at $s=0$

$$\chi(q^2) = \frac{-2m_\pi^2(\bar{G}_\pi(q^2) - \bar{J}_\pi(q^2))}{F_\pi^2\, q^2}$$

Note:

$\chi(q^2)$ is $O(m_\pi^2)$ if $q^2 \neq 0$

$\chi(0) = -1/(96\pi^2 F_\pi^2)$ is $O(1)$.

- $q^2 = 0$: $b^n(0)$, $b^c(0)$ constrained from polarisabilities

$$(\alpha_1 - \beta_1)^{\pi^0} = \frac{2\alpha}{m_\pi}\left[b^n(0) - 4m_\pi^2 \tilde{C}_{\rho^0}\widetilde{BW}_\rho(m_\pi^2) - \frac{4m_\pi^2\tilde{C}_\omega}{m_\omega^2 - m_\pi^2}\right]$$

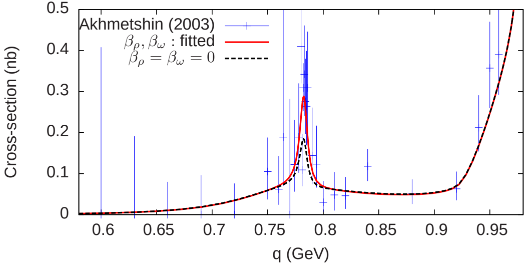
$$(\alpha_1 - \beta_1)^{\pi^+} = \frac{2\alpha}{m_\pi}\left[b^c(0) - 4m_\pi^2 \tilde{C}_{\rho^+}\widetilde{BW}_\rho(m_\pi^2)\right]$$

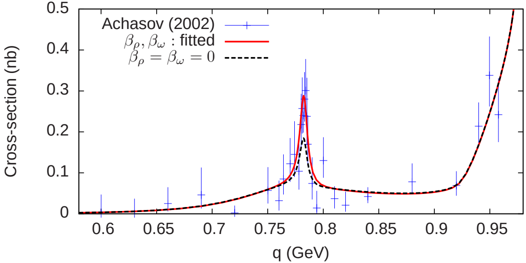
- $q^2 \neq 0$: Data on $e^+e^- \to \gamma^* \to \pi^0\pi^0\gamma$ [Akhmetshin et al.[CMD2], Phys.Lett.B580(2004)119,Achasov et al., [SND], Phys.Lett.B537 (2002) 201]

- Two parameters fit:

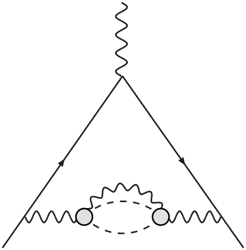
β_ρ	β_ω	χ^2/N_{dof}	ref.
0.14 ± 0.12	$(-0.39 \pm 0.12)\,10^{-1}$	$20.2/27$	SND (2002)
-0.13 ± 0.15	$(-0.31 \pm 0.15)\,10^{-1}$	$15.0/21$	CMD-2 (2003)
0.05 ± 0.09	$(-0.37 \pm 0.09)\,10^{-1}$	$38.1/50$	Combined

- $e^+e^- \to \gamma^* \to \pi^0\pi^0\gamma$ data is well reproduced (but not very precise)





$\gamma\pi\pi$ contribution to a_μ via HVP



- Generic expression
  [Lautrup,de Rafael (1974)]

$$a_\mu^{\pi\pi\gamma}[q_{max}] = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{q^2_{\max}} dq^2\, K_\mu(q^2)\, \sigma_{e^+e^-\to\pi\pi\gamma}(q^2)$$

→ In terms of helicity amplitudes

$$\sigma(q^2) = \frac{\alpha^3}{12(q^2)^3}\int_{4m_\pi^2}^{q^2} ds(q^2-s)\sigma_\pi(s)\int_{-1}^{1} dz \sum |H_{\lambda\lambda'}(s,q^2,\theta)|^2$$

→ For charged pions

$$|H^c_{\lambda\lambda'}|^2 = \underbrace{|H^{Born}_{\lambda\lambda'}|^2}_{} + 2\mathrm{Re}[H^{Born}_{\lambda\lambda'}\hat{H}^*_{\lambda\lambda'}] + |\hat{H}_{\lambda\lambda'}|^2$$

$$\sigma = \sigma^{sQED} + \hat{\sigma}^{Born} + \hat{\sigma}$$

- σ^{sQED}: made finite by adding rad. corr. of $\gamma^*\pi^+\pi^-$ vertex

$$\sigma^{sQED} = \frac{\pi\alpha^3}{3q^2}\sigma_\pi^3(q^2)|F_\pi^v(q^2)|^2 \times \frac{\alpha}{\pi}\eta(s)$$

[Jegerlehner, Nyffeler PRep. 477(2009)1]

- Numerical results $(q^{max} = 0.95\ \text{GeV})$:

channel	cross-section	a_μ
$\gamma\pi^+\pi^-$	σ^{sQED}	41.9×10^{-11}
$\gamma\pi^+\pi^-$	$\hat{\sigma}^{Born}$	$(1.31 \pm 0.30) \times 10^{-11}$
$\gamma\pi^+\pi^-$	$\hat{\sigma}$	$(0.16 \pm 0.05) \times 10^{-11}$
$\gamma\pi^0\pi^0$	$\sigma^{\gamma\pi^0\pi^0}$	$(0.33 \pm 0.05) \times 10^{-11}$

→ For comparison: [Davier et al. (2010)]
$a_\mu^{\pi\pi(\gamma)} = (5078.0 \pm 12.2 \pm 25.0 \pm 5.6) \times 10^{-11}$

Conclusions

$\gamma\gamma \to \pi\pi$:

1) In region $E_{\pi\pi} \lesssim 0.8$ GeV: parameter-free representation, once matching w. ChPT near $s = 0$ (+ phase with a dip in Omnès funct.)
2) In larger region $E_{\pi\pi} \lesssim 1.3$ GeV, with CC unitarity in $J = 0$, 6 params repres. fits the data.
3) Larger angular coverage needed !

$\gamma\gamma^* \to \pi\pi$:

1) Extension of one-channel formalism presented: involves two subtractions functions of q^2
2) Available data $e^+e^- \to \gamma\pi^0\pi^0$ (Novosibirsk) reproduced. Data from KLOE at $q^2 \simeq m_\phi^2$ requires CC extension.
3) Application: $\gamma\pi\pi$ contrib. in HVP to muon $g-2$: beyond sQED, very small.

Extra slides

Form factors

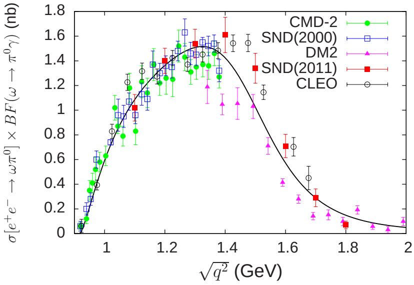
- Pion form factor is well studied experimentally[Babar PR D86(2012)032013, KLOE PL B670(2009)285...]
  → Parametris. with q^2 analyticity and rel. to $\pi\pi$ $J = 1$ phase-shifts[Colangelo, NP B (proc.sup.) 162(2006)256]

- $\omega\pi$ form factor: data also exists
  1) $q^2 > (m_\omega + m_\pi)^2$ (From $e^+e^- \to \omega\pi$)
  2) $q^2 < (m_\omega - m_\pi)^2$ (From $\omega \to l^+l^-\pi$)

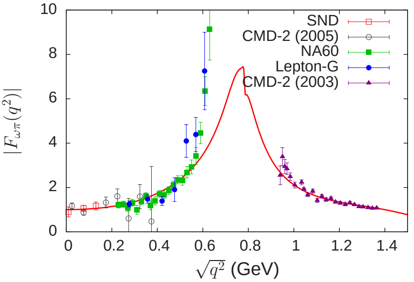
  Use simple representation:

$$F_{\omega\pi}(q^2) = \frac{1}{1+\beta'}\left[GS_\rho(q^2)\left(1+\delta\frac{q^2}{m_\omega^2}BW_\omega(q^2)\right)+\beta' GS_{\rho(1450)}(q^2)\right]$$

- Data in range $q^2 > (m_\omega + m_\pi)^2$ well reproduced



- Also data in range $\sqrt{q^2} < 0.6$ GeV



- Some data points problematic

- $\rho\pi$ form factor: no data exists in this case. Plausible guess: assume three $I = 0$ resonances dominate

$$F_{\rho\pi}(q^2) = \alpha_\omega BW_\omega(q^2) + \alpha_\phi BW_\phi(q^2) + \alpha_{\omega'} BW_{\omega'}(q^2)$$

with $(\alpha_\omega + \alpha_\phi + \alpha_{\omega'} = 1)$. Use relations

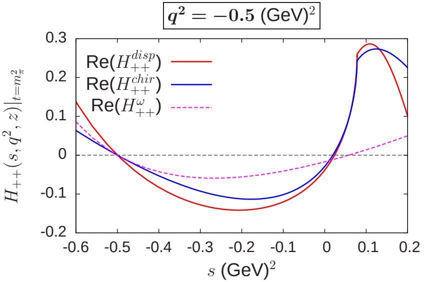
$$\alpha_V = \frac{F_V g_{V\rho\pi}}{2m_V C_\rho}, \quad V = \omega, \phi$$

and phenomenological determinations of $g_{V\rho\pi}$

→ Fortunately: this form factor is much less important numerically than $F_{\omega\pi}$

Comparison of chiral and dispersive H^n_{++}

- $q^2 < 0$
  Adler zero is present



- $q^2 > 0.3$ (GeV^2)
  Adler zero disappears