$\pi^0\pi^0$ production and form factors for $f_0(980)$ and $f_2(1270)$ in single-tag two-photon process

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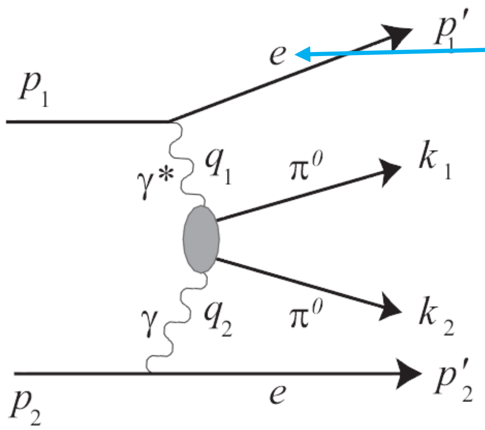
Motivation

- Single-tag two-photon production of hadronic system, $\gamma{*}\gamma \to M$ in $e^+e^- \to e^{\pm}\gamma{*}\gamma$ (plus undetected $e^{\mp}$), is interesting to

  - study strong interaction in low energy region, where pQCD can't be applied;
  - measure Q^2 dependence of Transition Form Factor (TFF);
  - test QCD-based theoretical predictions;
  - provide input for a data-driven estimate of the hadronic light-by-light contribution **[1]** significant for the problem of muon $g-2$.

Ref: [1] G. Colangelo, M. Hofenrichter, B. Cubis, M. Procula and P. Stoffer, Phys. Lett. B 738, 6 (2014).

Selection criteria



e^+: p-tag
e^-: e-tag

Topology: 1-track (e) and 4-Gammas ($\pi 0 \pi 0$)

1. A tagging lepton(e^+/e^-), $E/p > 0.8$ and $p>1.0$ GeV/c.

2. One π_0(π1) : $E_\gamma > 0.1$ GeV (selected by the energetic order, rather high energy) and $0.115 < M(\gamma\gamma) < 0.150$ GeV .

3. The other π_0 (π2) : (rather low energy), mass-constraint fit for other two photons $\chi_2<16$ and no more other π_0 candidates.

4. Right-sign for e-tag charge : $q_{tag} \times (p^*_{z,e} + p^*_{z,\pi 1} + p^*_{z,\pi 2}) < 0$, in e^+e^- c.m. frame.

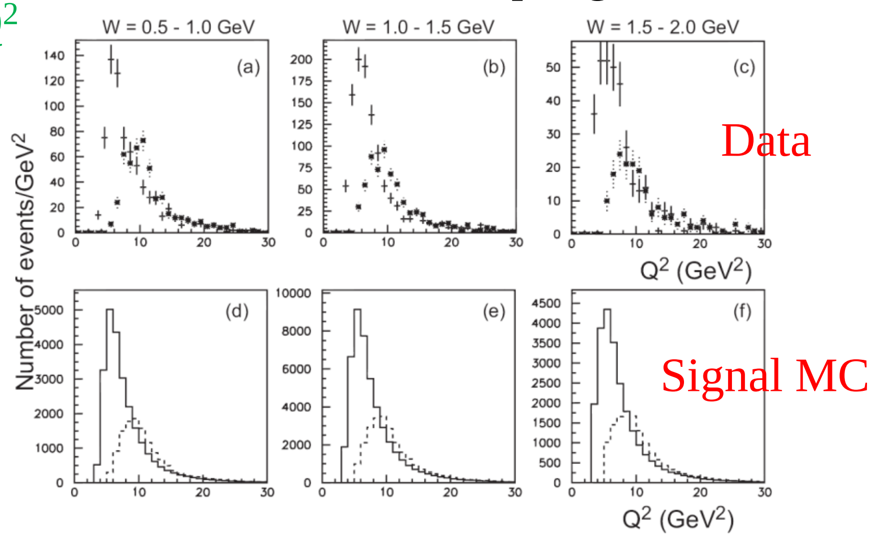
5. 3-body kinematics (4-momentum conservation): for (e) e R, R ≡ $\pi^0\pi^0$ system
$0.85 < E_{ratio} < 1.1$, where $E_{ratio} = E^*_{\pi 0\pi 0,measured}/E^*_{\pi 0\pi 0,expected}$, $E^*_{\pi 0\pi 0,measured}$ ($E^*_{\pi 0\pi 0,expected}$) is the e+e- c.m. energy of the $\pi^0\pi^0$ system measured directly (expected by kinematics without radiation).

6. p_t-balance: $|\Sigma\, \mathbf{p}_t^*|$ (for e and two π^0s) < 0.2 GeV/c.

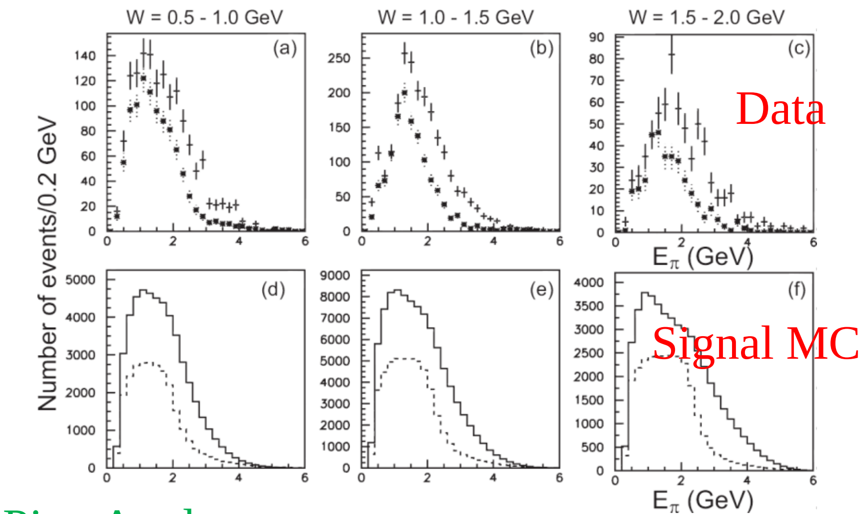
Signal MC and comparison of distributions for selected signal candidates

+ or solid histo : e-tag
* or dashed hiso : p-tag

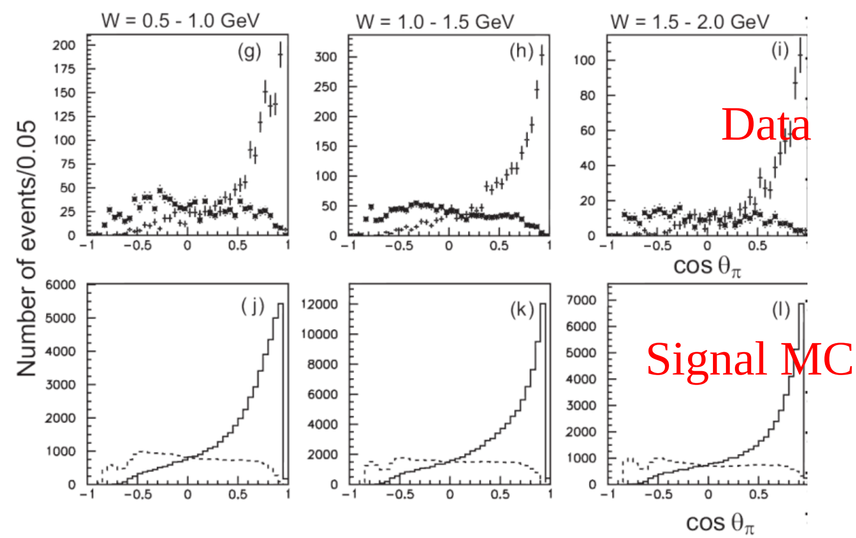
Q^2



Pion Energy



Pion Angle



- MC generator TREPSBSS
- Uniform angular distribution for signal MC.
- No large discrepancy between data and signal MC.
- The background in data is not very large.

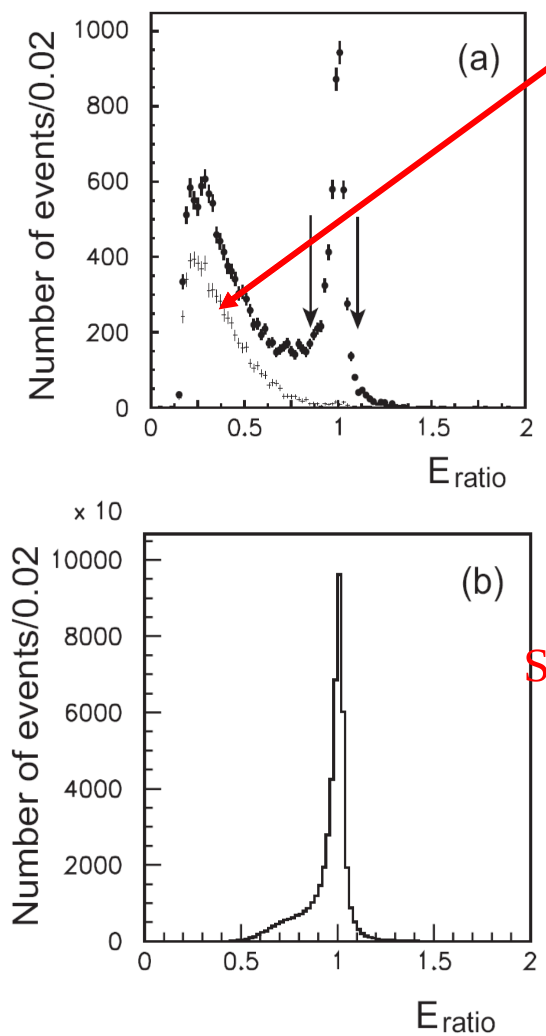
- Q^2, is calculated in the e^+e^- c.m. fram as

$$\begin{aligned} Q^2_{\rm rec} &= -(p_{\rm beam} - p_e)^2 \\ &= 2E^*_{\rm beam}E^*_e(1 + q_{\rm tag}\cos\theta^*_e) \end{aligned}$$

Kinematical distributions, E_{ratio} and P_t-balance

The wrong-sign events, that the tagged $e^+(e^-)$ have wrong charge sign.

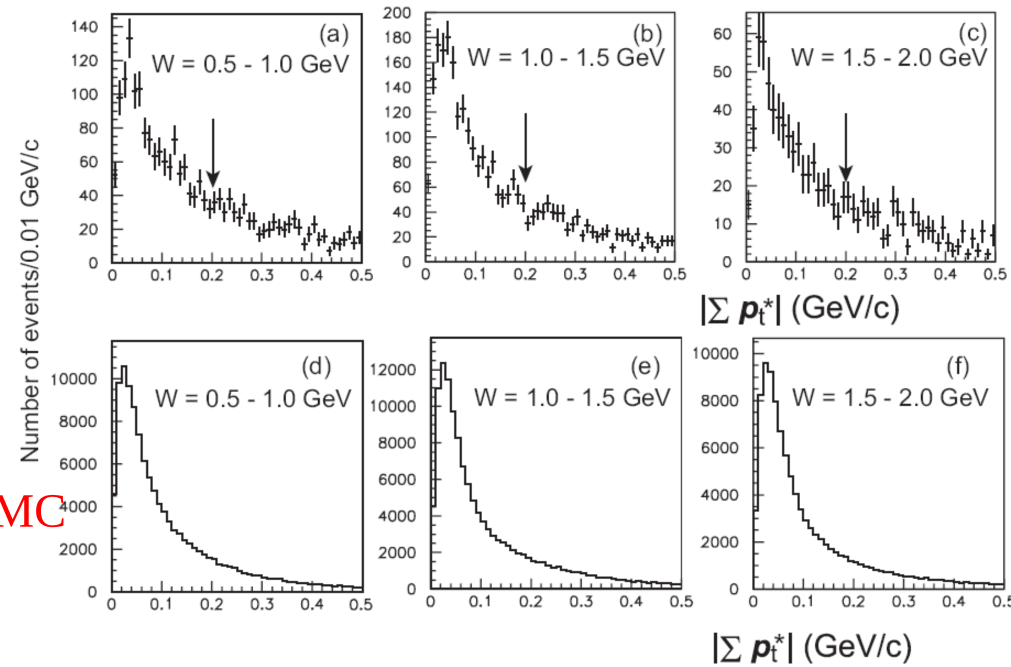
E_{ratio}



Data

Signal MC

P_t

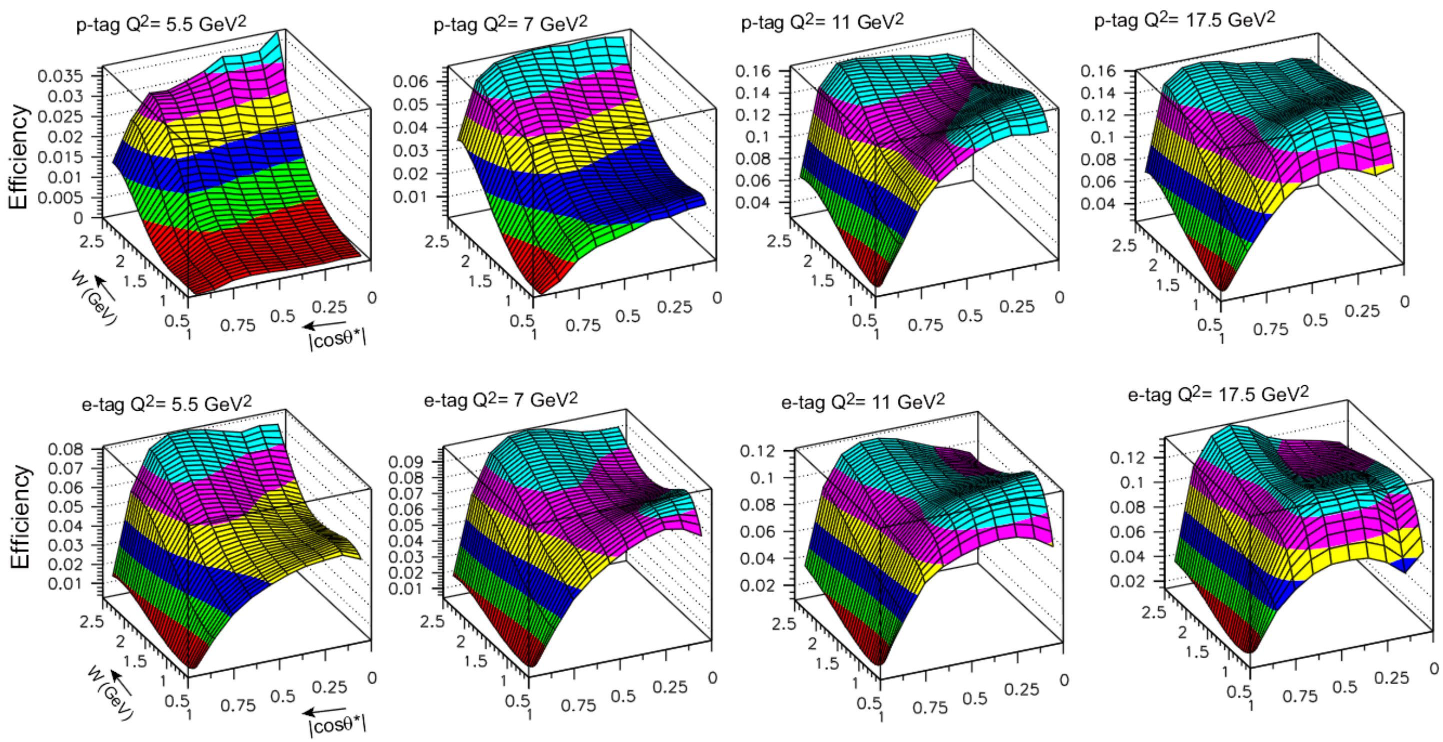


Efficiency estimated from signal-MC

W- and |cosθ *|- dependent efficiencies for 4 selected Q^2 bins

p-tag

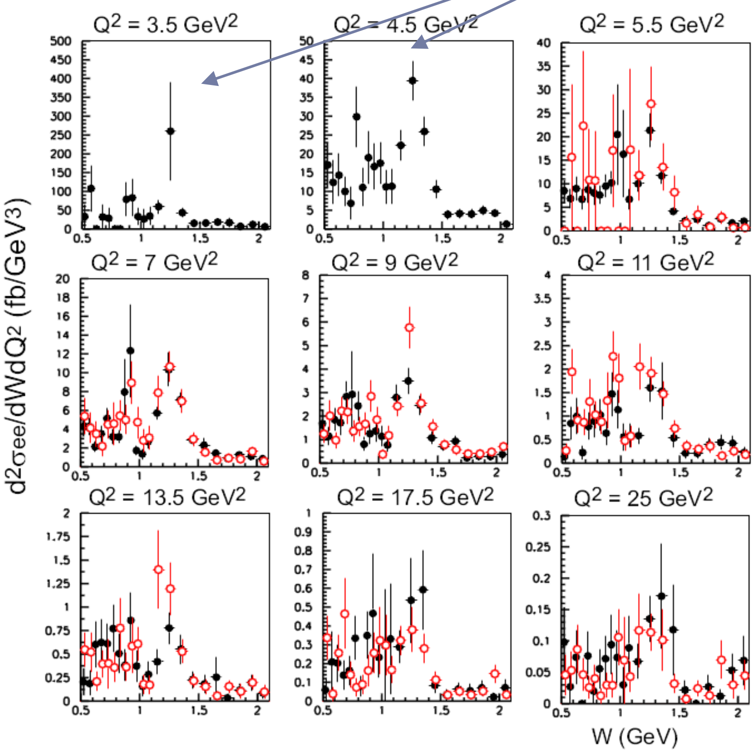
e-tag



e+e- based Cross Section

W dependencies

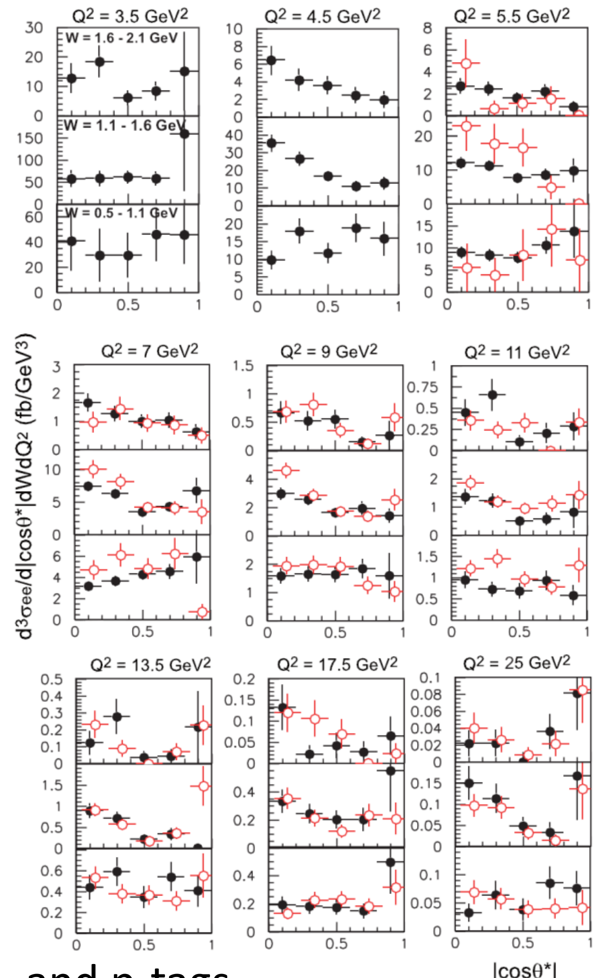
Low statistics for p-tag data



9 Q^2 bins

Red : p-tag
Black: e-tag

$|\cos\theta^*|$ dependences



- Detector acceptance is much different between e- and p-tags.
- The cross-sections measurement are consistent.
- Validation check for systematic effects (trigger, acceptance, selection) is satisfied.

$\gamma^*\gamma$ based Cross Section

Combine the measurement of p- and e-tag :

$$\frac{d^3\sigma_{ee}}{dW\,d|\cos\theta^*|dQ^2} = \frac{Y(W,|\cos\theta^*|,Q^2)(1-b(W,|\cos\theta^*|,Q^2))}{\varepsilon\prime(W,|\cos\theta^*|,Q^2)\Delta W\Delta|\cos\theta^*|\Delta Q^2\int\mathcal{L}dt}$$

$Y = Y_{p\text{-tag}} + Y_{e\text{-tag}}$

$\varepsilon' = (\varepsilon'_{p\text{-tag}} + \varepsilon'_{e\text{-tag}})/2$

b is the background fraction combined for p- and e-tag.

$\gamma^*\gamma$ based Cross Section:

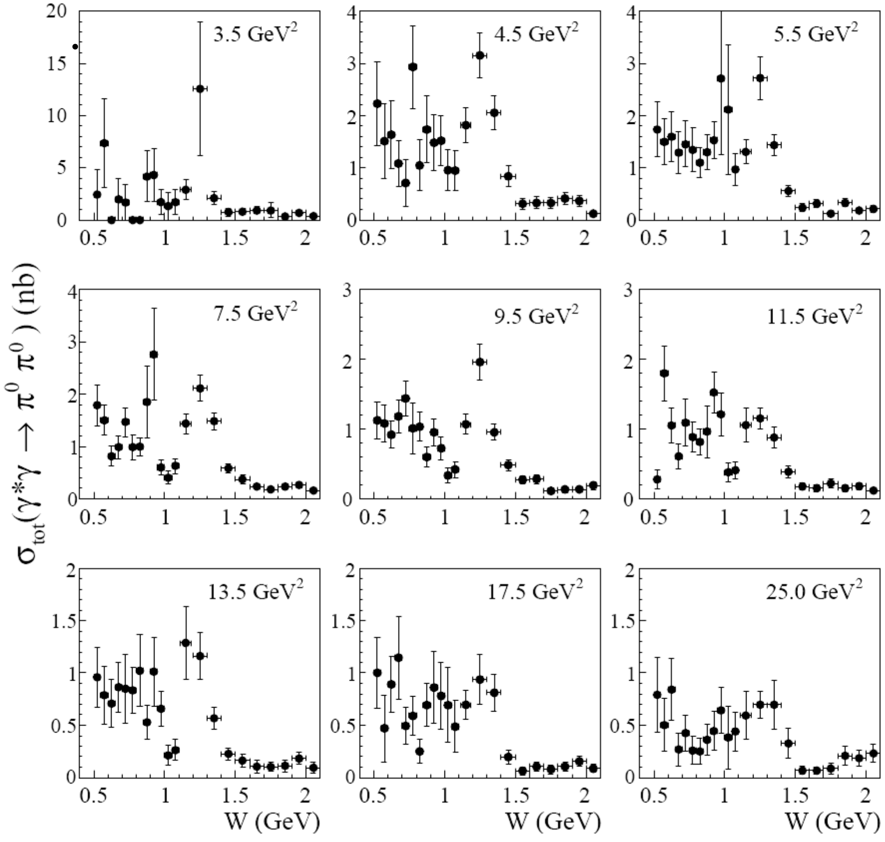
$$\frac{d\sigma_{\gamma^*\gamma}}{d|\cos\theta^*|} = \frac{d^3\sigma_{ee}}{dW\,d|\cos\theta^*|dQ^2}\frac{f}{2\frac{d^2L_{\gamma^*\gamma}}{dW\,dQ^2}(1+\delta)(\varepsilon/\varepsilon')\varepsilon'}$$

δ: radiative correction.

ε: efficiency corrected for φ* dependence.

f: unfolding effect for Q^2.

Integrated cross section as a function of W in nine Q^2 bins



Peaks corresponding to the $f_2(1270)$ and $f_0(980)$ are evident.

Cross section formalism

Waves: S, D_0, D_1, and D_2, contribute (W<1.5GeV)
Differential cross section for $\gamma^*\gamma \to \pi^0\pi^0$ is given by **[3]**.

φ*-dependent

$$\frac{d\sigma}{d\Omega} = \sum_{n=0}^{2} t_n \cos n\varphi^*$$

$$t_0 = |SY_0^0 + D_0 Y_2^0|^2 + |D_2 Y_2^2|^2 + 2\varepsilon_0 |D_1 Y_2^1|^2$$

$$t_1 = 2\varepsilon_1 \mathrm{Re}\left((D_2 |Y_2^2| - SY_0^0 - D_0 Y_2^0) D_1^* |Y_2^1|\right)$$

$$t_2 = -2\varepsilon_1 \mathrm{Re}\left(D_1^* |Y_2^1| (SY_0^0 + D_0 Y_2^0)\right)$$

$\varepsilon_0, \varepsilon_1$ are variables that depend on $x = \dfrac{q_1 \cdot q_2}{p_1 \cdot p_2}$

Spherical Harmonics

$$\begin{aligned} Y_0^0 &= \sqrt{\frac{1}{4\pi}}, \\ Y_2^0 &= \sqrt{\frac{5}{16\pi}}(3\cos^2\theta^* - 1), \\ |Y_2^1| &= \sqrt{\frac{15}{8\pi}} \sin\theta^* \cos\theta^*, \\ |Y_2^2| &= \sqrt{\frac{15}{32\pi}} \sin^2\theta^*. \end{aligned}$$

φ*-integrated

$$\frac{d\sigma}{4\pi d|\cos\vartheta^*|} = |SY_0^0 + D_0 Y_2^0|^2 + |D_2 Y_2^2|^2 + 2\varepsilon_0 |D_1 Y_2^1|^2$$

[3] I.F. Ginzburg, A. Shiller and V.G. Serbo, Eur. Phys. J, C 18, 731-746 (2001); and private communication with V.G. Serbo.

Parameterization of amplitudes

S and D_i amplitudes:

$$\begin{aligned} S &= A_{f_0(980)} e^{i\phi_{f0}} + B_S e^{i\phi_{BS}}, \\ D_i &= \sqrt{\boxed{r_i(Q^2)}} A_{f_2(1270)} e^{i\phi_{f2Di}} + B_{Di} e^{i\phi_{BDi}} \end{aligned}$$

Where $r_i(Q^2)$ is fraction of $f_2(1270)$ contribution in Di wave

$$\boxed{\sum_{i=0}^{2} r_1 = 1}$$

Transition Form Factors

$$A_{f_0(980)} = \boxed{F_{f0}(Q^2)} \sqrt{1 + \frac{Q^2}{M_{f_0}^2}} \frac{\sqrt{8\pi\beta_\pi}}{W} \frac{g_{f_0\gamma\gamma} g_{f_0\pi\pi}}{16\sqrt{3}\pi} \frac{1}{D_{f_0}}$$

$$A_R^J(W) = \boxed{F_R(Q^2)} \sqrt{1 + \frac{Q^2}{M_R^2}} \sqrt{\frac{8\pi(2J+1)m_R}{W}} \times \frac{\sqrt{\Gamma_{\mathrm{tot}}(W)\Gamma_{\gamma\gamma}(W)\mathcal{B}(\pi^0\pi^0)}}{m_R^2 - W^2 - i m_R \Gamma_{\mathrm{tot}}(W)}$$

Parameterizations of the f0(980) and f2(1270) is given.

Fit strategy for TFFS

Fundamental limitation:

φ*-integrated differential cross section,
So, only 3 out of S, D_0, D_1, and D_2 are independent.

Procedure (due to limited statistics) :

1st fit φ*-dependent cross section(but integrated over Q^2) to extract $r_1(\overline{Q^2})$ with $\overline{Q^2}$ =9.6GeV^2 as

- $r_1(\overline{Q^2})$ = 0.15+0.05-0.03.

2nd fit φ*-integrated cross section with $r_1(\overline{Q^2})$.

Fit φ*-integrated cross section

- To extract Q^2 dependence of TFFs:
  - Float $F_{f0(980)}(Q^2)$, $F_{f2(1270)}(Q^2)$, and $r_0(Q^2)$ in each Q^2 bin.

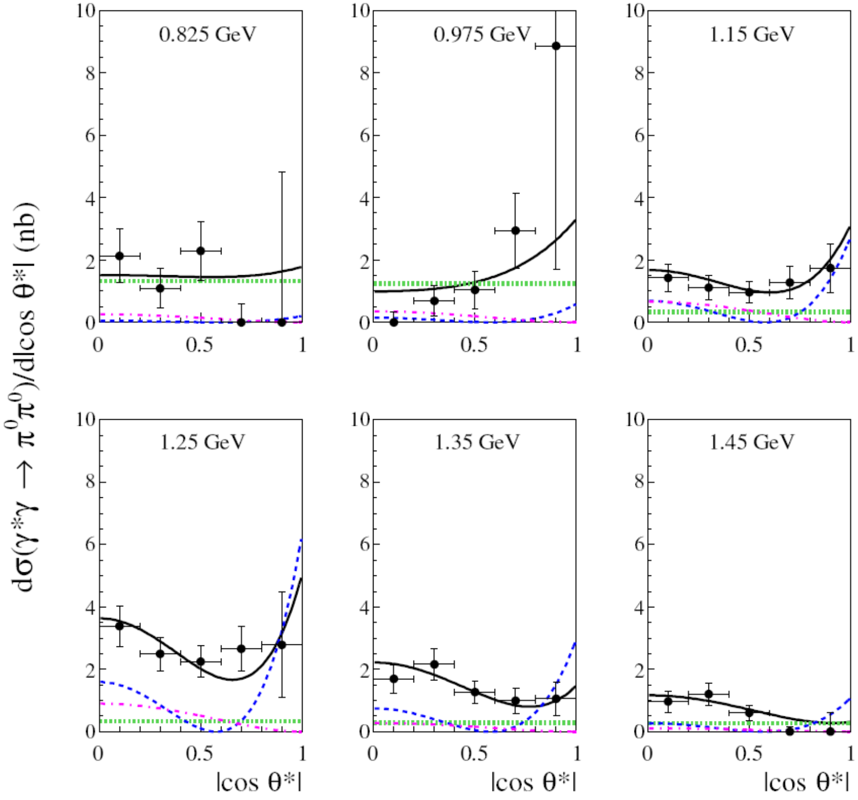
- Assume $r_1(Q^2) = r_{1ave}(Q^2/Q_{ave}{}^2)^d = 0.15*(Q^2/9.6)^d$

  then $D_1 = \sqrt{0.15\left(\frac{Q^2}{9.6}\right)^d}\, A_{f2(1270)} \exp(i\Phi_{f2D1})$, denoted as r_1 fit.

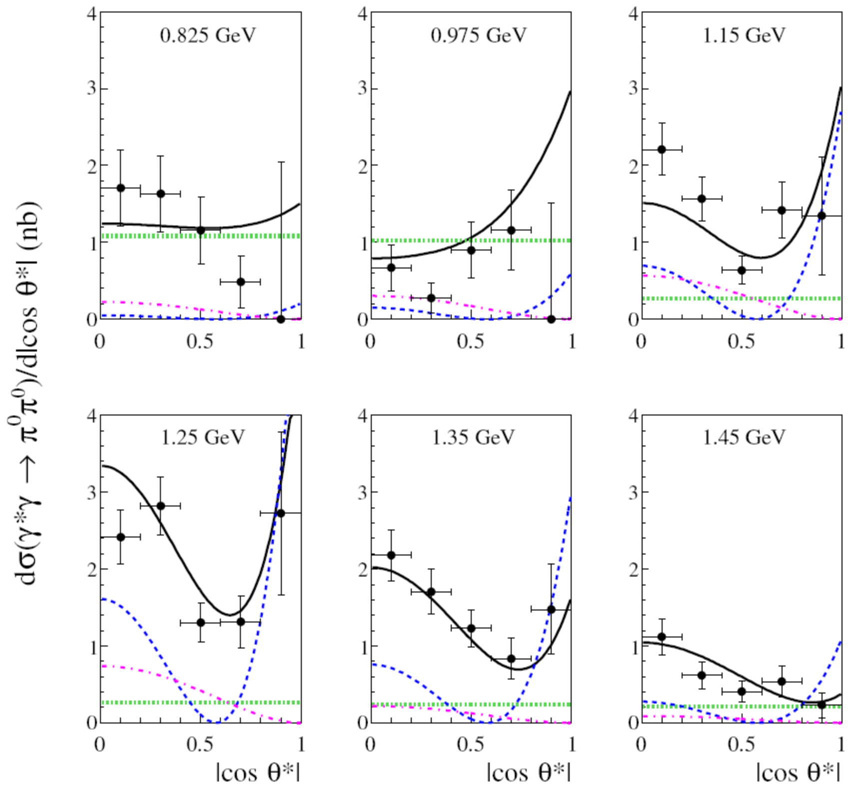
Fitted results on angular distributions

Angular dependence of the cross section in the indicated W bin and its results of r1 fit at Q^2=5.5 and 7.0 GeV^2. (example)

Q^2=5.5GeV^2



Q^2=7.0GeV^2

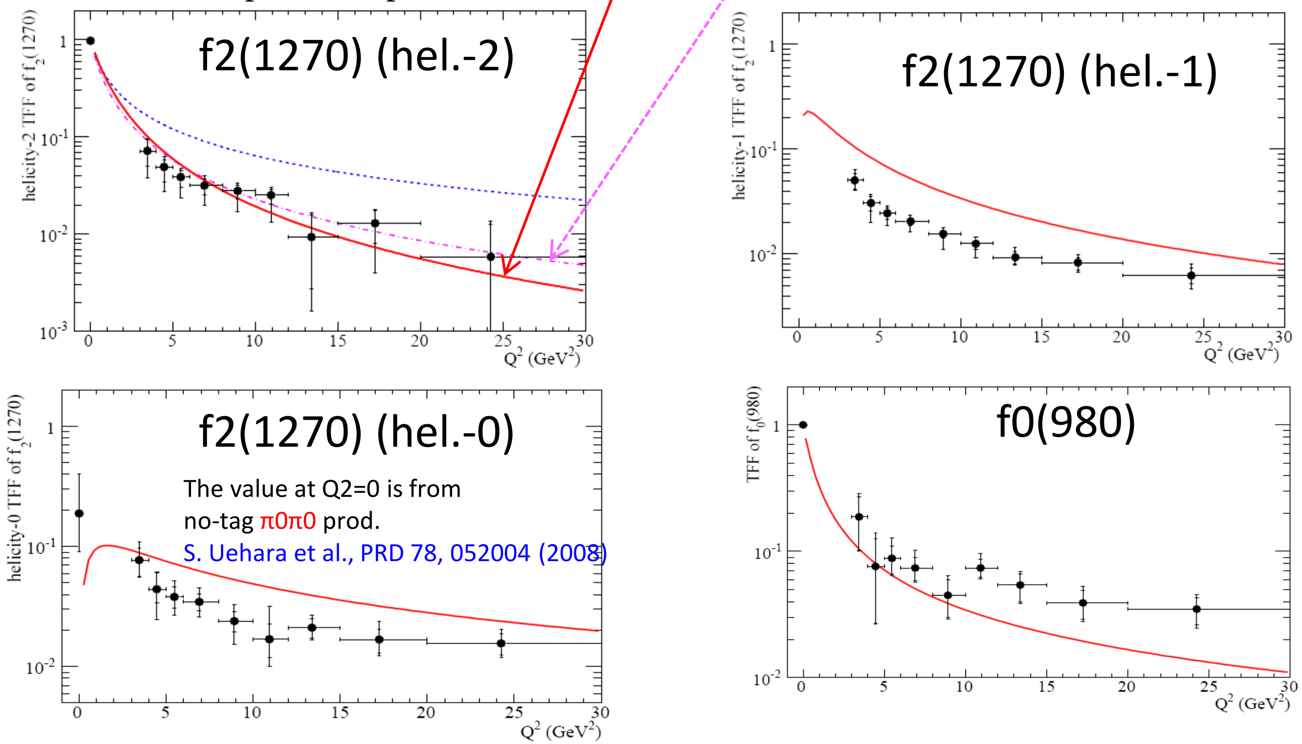


Black: Total, Green $|S|^2$, Blue: $|D_0|^2$, Pink: $|D_2|^2$

TFF Results

- hel.-2 TFF of $f_2(1270)$ agrees with the prediction by Ref.[4] and Ref. [5].
- hel.-0 and 1 TFF, a factor of 1.5 – 2 smaller than the prediction by Ref.[4] .
- TFF of $f_0(980)$: agree well with the prediction by Ref.[4] for Q^2<10GeV^2

  less steeper Q^2 dependence for Q^2>10GeV^2



Ref: **[4] G.A. Schuler, F.A. Berends and R. van Gulik, Nucl. Phys. B 523, 423 (1998).**
Based on application of heavy quark approximation to light quarks
[5] V. Pascalutsa, V. Pauk and M. Vanderhaeghen, Phys. Rev. D 85, 116001 (2012).
Based on sum rules

Systematic uncertainties to cross section and TFFs

Source	Uncertainty (%)
Tracking	1
Electron-ID	1
Pion-pair detection (for two π^0's)	7.2
Kinematical selection	2
Geometrical acceptance	2
Trigger efficiency	3
Background effect for the efficiency	2
φ^* dependence	1 – 16
Background subtraction	1 – 23
Unfolding for Q^2	2
Radiative correction	3
Luminosity function	4
Integrated luminosity	1.4
Total	11 – 26

Uncertainties for cross section:

- The value indicated in rages depending on W, |cosθ*|, and Q^2.
- Uncertainties in total: 11 - 26%

Uncertainty sources to estimate the error size for TFFs

- Overall normalization (Q^2 independent)
  - from Br(γγ) errors: ±15% for $f_2(1270)$; +32%, -30% for $f_0(980)$.
- Individual items (Q^2 dependent)
  - cross section 11-26%
  - Fitting W-range 0.7-1.5GeV to 0.65-1.4GeV or to 0.75-1.6GeV
  - Mass of $f_0(980)$ 980 ±20MeV
  - $g_{f0\pi\pi}$ 1.82±0.03+0.24-0.17(GeV)
  - rR 3.62±0.03$(Gev/c)^{-1}$
  - more with smaller uncertainties

Q^2 dependent error of TFF is shown as error bars in the figures on page 13.

Summary

- First measurement for $\sigma(\gamma^*\gamma \to \pi^0\pi^0)$ with Q^2 up to 30 GeV^2.

- The differential cross section is fitted with partial-wave amplitudes.

- The azimuthal and polar angle dependence shows large (small but non-zero) contribution for the $f_2(1270)$ hel.-0 (hel.-1) component .

- The transition form factors (**TFFs**) of $f_0(980)$ and $f_2(1270)$ are measured for Q^2 up to 30 GeV^2.
  - hel.-2 **TFF** of $f_2(1270)$ agrees well with the prediction of Ref.**[4]** and with one of two predictions of Ref. **[5].**

    That of the hel.-0 and -1 **TFF** are about a factor of 1.5 – 2smaller than the prediction of Ref.**[4]** .
  - The Q^2 dependence for **TFF** of $f_0(980)$ agree well with the prediction of Ref.**[4]** for Q^2<10GeV^2 , but less steeper for Q^2>10GeV^2.

Thank you !