Study of K_S^0 pair and $\eta_c(1S)$, $\eta_c(2S)$ and non-resonant $\eta'\pi\pi$ production in two-photon collisions at Belle

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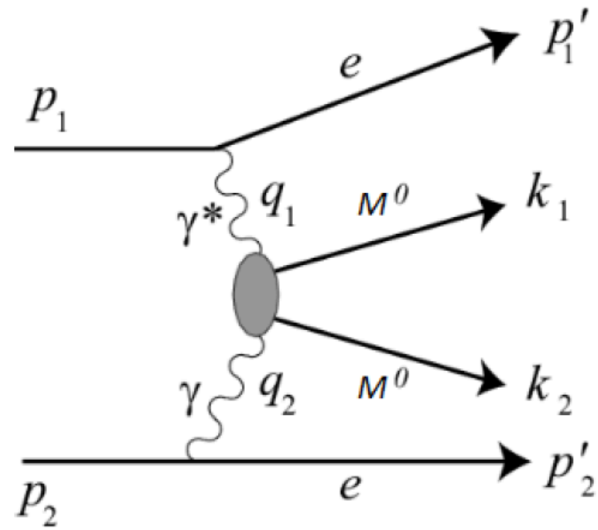
On behalf of the Belle collaboration
IHEP & UCAS, Beijing

ICHEP 2018
4-11 July 2018, Seoul

Motivation of single-tag two-photon process

Reaction:

$e^+e^- \rightarrow e^{\pm}$(undected $e^{\mp}$) hadrons



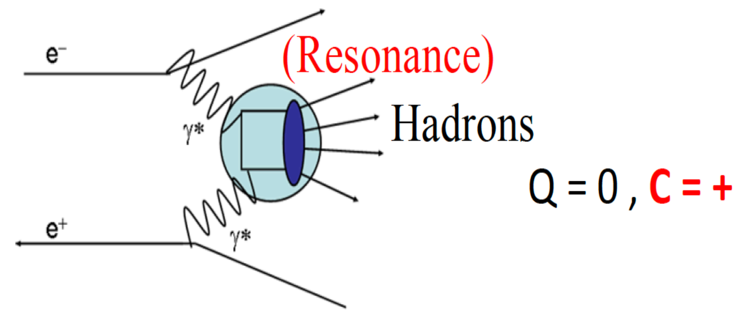
- Study strong interaction in low energy region, where pQCD can't be applied;

- Measure Q^2dependence of Transition Form Factor (TFF);

- Provide input for a data-driven estimate of the hadronic light-by-light contribution significant for the problem of muon g-2.

Motivation of no-tag two-photon process

- Lowest heavy-quakonium $\eta_c(1S)$, plus J/psi, η_b (1S) and $\Upsilon(1S)$, as benchmarks for the fine tuning of input parameters in QCD calculation.
- Attempt to measure $\Gamma_{\gamma\gamma}$ for $\eta_c(2S)$ and to address the discrepancy between data and QCD predictions.



- Improved precision in both data and QCD predictions at higher W mass would provide more sensitive comparisons.
- pseudo-scalar meson pairs were measured by Belle [1]

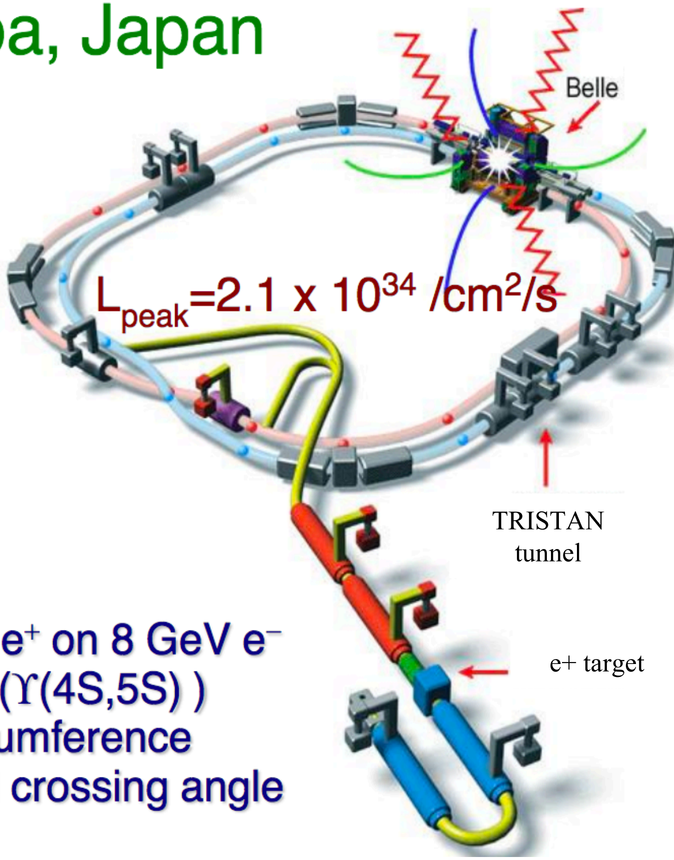
  Charged-meson pairs： $\pi^+\pi^-$, K^+K^-. Neutral-meson pairs: $K^0_SK^0_S$， $\pi^0\pi^0$， $\eta\pi^0$， $\eta\eta$.

- pseudo-scalar tensor pair $\eta' f_2(1270)$ and three-body final state $\eta'\pi\pi$ would provide new information to validate QCD models.

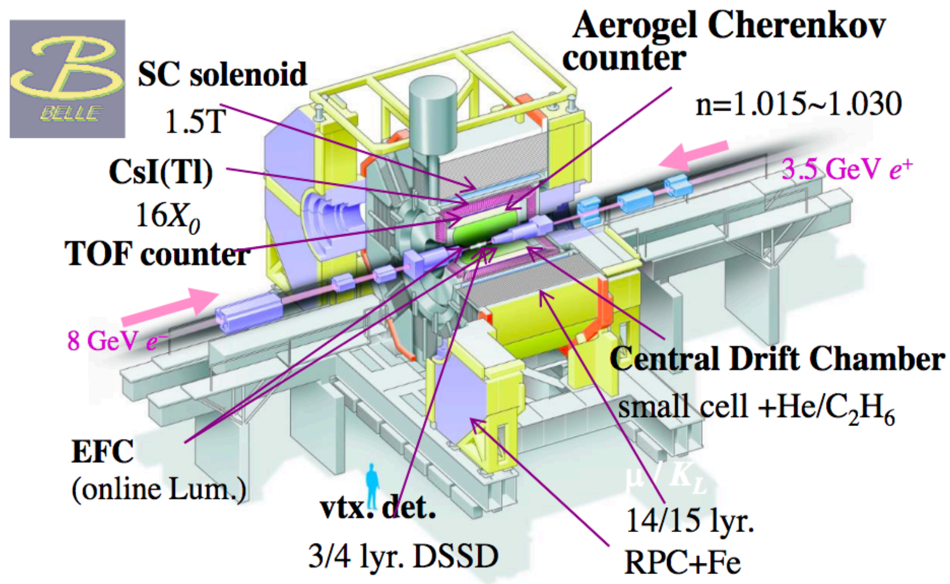
[1] Belle, Euro.Phys.Jour.C (2014) 74:3026

KEKB and Belle Detector

Tsukuba, Japan



3.5 GeV e^+ on 8 GeV e^-
W_{CM} = M(ϒ(4S,5S))
3km circumference
~11mrad crossing angle

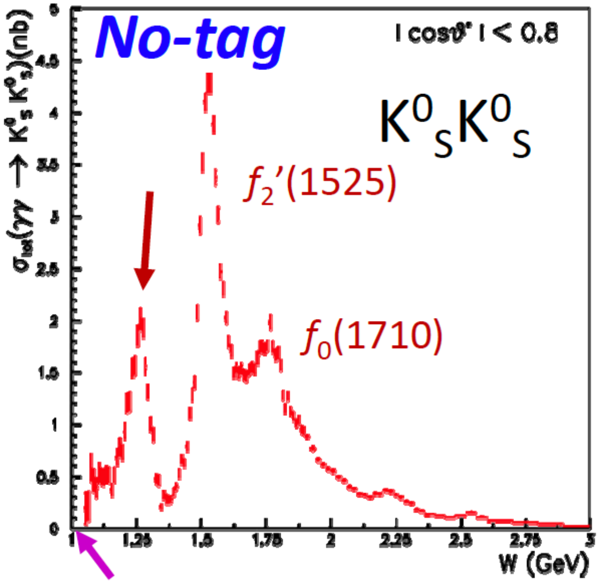


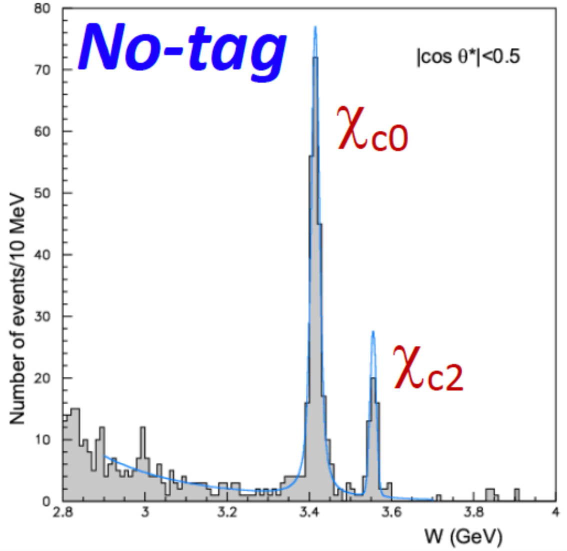
$\gamma^*\gamma \to K_S^0 K_S^0$

Dataset: 759 fb^{-1}

PRD 97, 052003 (2018)

No-tag results for $K_S^0 K_S^0$ process





PTEP 2013, 123C01 (2013)

Maximum at the $f_2'(1525)$ peak

$f_2(1270)/a_2(1320)$ destructive interference

Two-photon coupling of $f_0(1710)$

No data near the $K^0_S K^0_S$ mass threshold

χ_{cJ} Yield

Interference	$N_{\chi c0}$	$N_{\chi c2}$	$-2\ln\mathcal{L}/ndf$
not included	$248.3^{+17.9}_{-17.2}$	$53.0^{+8.1}_{-7.4}$	57.34/73
included	266 ± 53	53^{+14}_{-12}	57.22/71

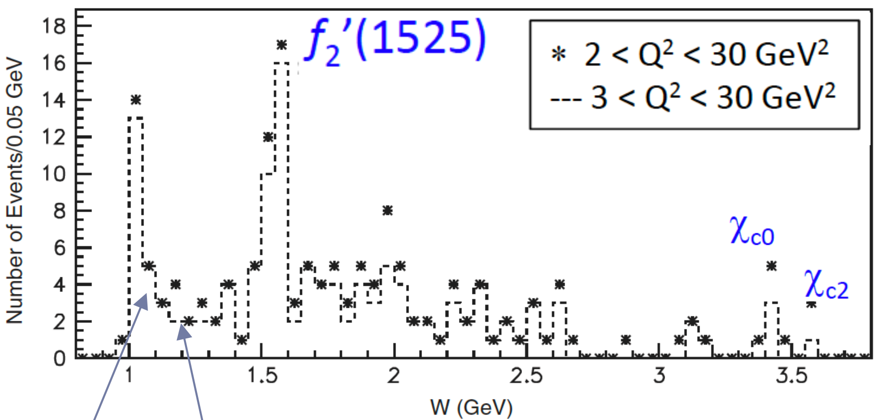
Two-photon decay width × $B(K^0_S K^0_S)$

Interference	$\Gamma_{\gamma\gamma}\mathcal{B}(\chi_{c0})$ (eV)	$\Gamma_{\gamma\gamma}\mathcal{B}(\chi_{c2})$ (eV)
not included	$8.09 \pm 0.58 \pm 0.83$	$0.268^{+0.041}_{-0.037} \pm 0.028$
included	$8.7 \pm 1.7 \pm 0.9$	$0.27^{+0.07}_{-0.06} \pm 0.03$
Belle 2007	$7.00 \pm 0.65 \pm 0.71$	$0.31 \pm 0.05 \pm 0.03$
PDG 2012	7.3 ± 0.5	0.297 ± 0.026

$\gamma^*\gamma \to K_S^0 K_S^0$

W dependence and $\gamma^*\gamma$ cross section at Q^2 bins

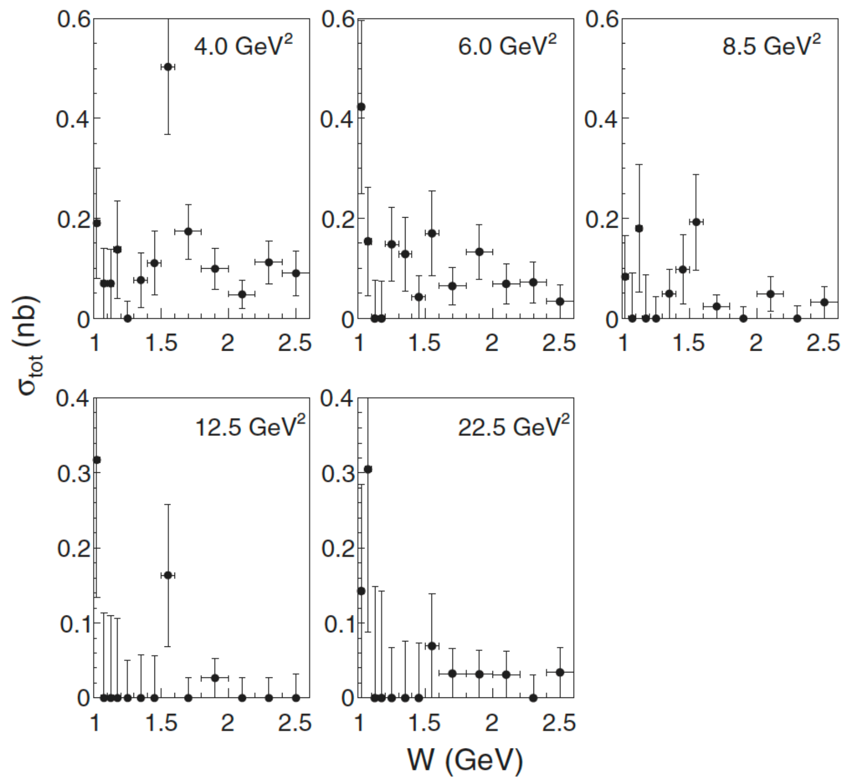
W distributions includes background



No $f_2(1270)/a_2(1320)$ is seen

Threshold enhancement,
may be associated with $f_0(980)/a_0(980)$.

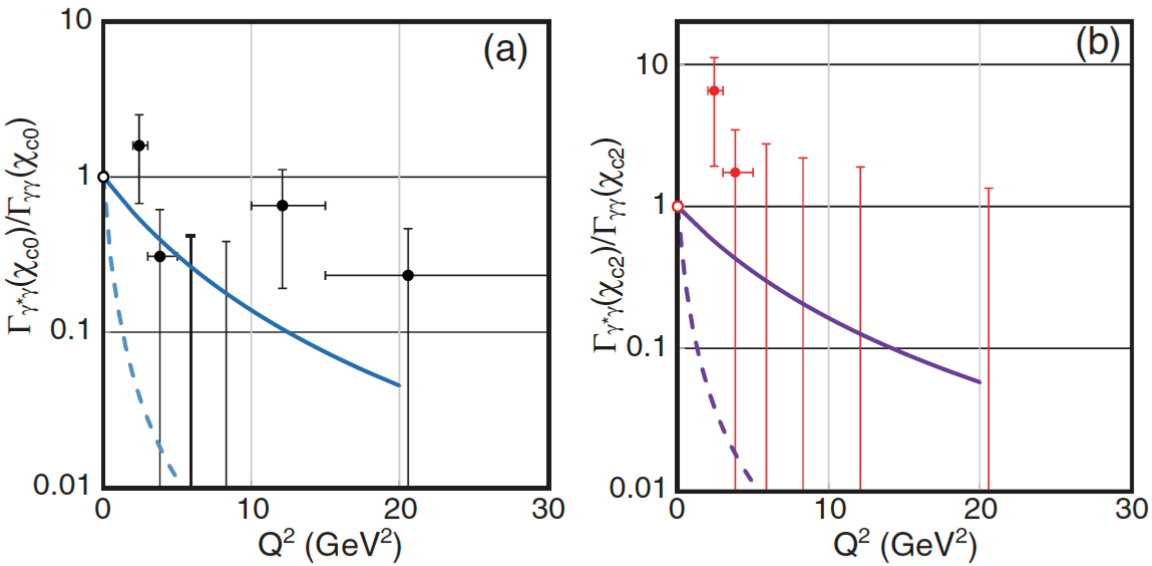
$$\sigma_{\rm tot}(\gamma^*\gamma \to K_S^0 K_S^0) = \frac{1}{2\frac{d^2L_{\gamma^*\gamma}}{dW\,dQ^2}} \frac{Y(W,Q^2)}{(1+\delta)\varepsilon(W,Q^2)\Delta W \Delta Q^2 \int \mathcal{L}dt\mathcal{B}^2}$$



Partial decay width of χ_{cJ} mesons

Assume that in total 7 events (3 events) peaking near the χ_{c0} (χ_{c2}) mass are purely from the charmonium (backgrounds are estimated <1 event in total)

Q^2 dependence $\Gamma_{\gamma^*\gamma}/\Gamma_{\gamma\gamma}$



The first measurement of χ_{cJ} production in high-Q^2 single-tag two-photon collisions.

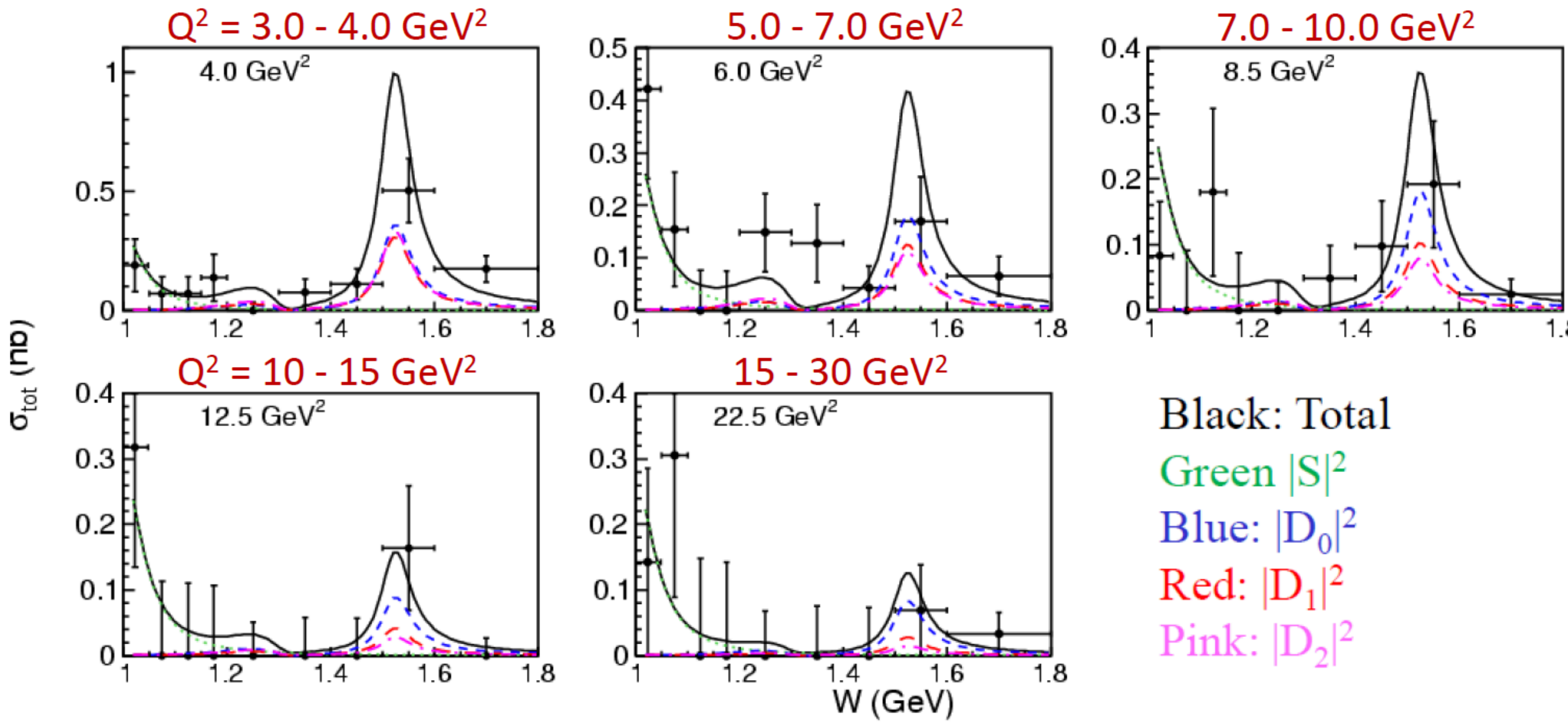
Solid curve: SBG [1] with the charmonium-mass scale (much favored).

Dashed curve: With the ρ-mass scale (VDM like)

[1] Schuler, Berends, and van Gulik, Nucl. Phys. B523, 423 (1998).

$\gamma^*\gamma \rightarrow K_S^0 K_S^0$

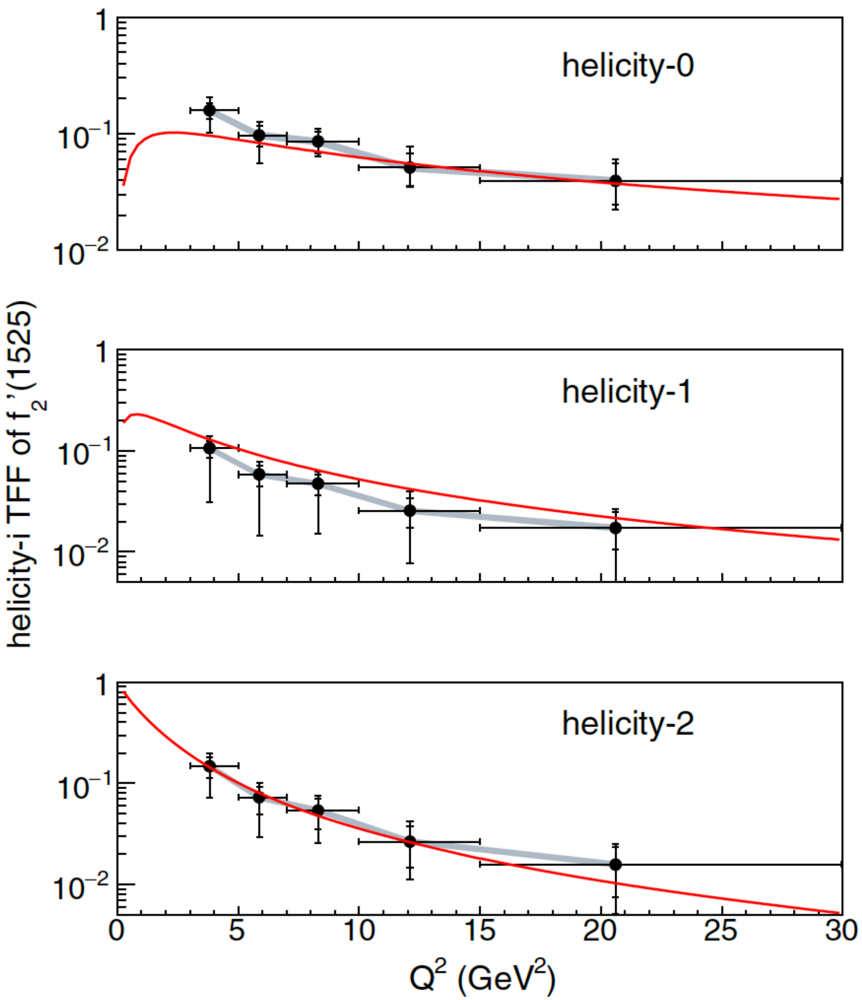
PWA results in W dependence at Q^2 bins



- Non-zero D_0 and D_1 components in the $f_2'(1525)$.
- No $f_2(1270)/a_2(1320)$ is seen.
- An enhancement near the threshold (0.995 GeV).

$\gamma^*\gamma \to K_s^0 K_s^0$

$f_2'(1525)$ TFF results



The obtained helicity-0, -1, and -2 TFF of the $f_2'(1525)$ meson as a function of Q^2.

Shorter error bars: statistical
Longer error bars: statistical and systematic
Shaded areas: overall systematic on $\Gamma_{\gamma\gamma}$.

— Schuler, Berends, van Glick (SBG) Nucl. Phys. B 523, 423, (1998).

helicity-0 and -2 agree well with SBG.
helicity-1 -- slightly smaller, but not inconsistent.

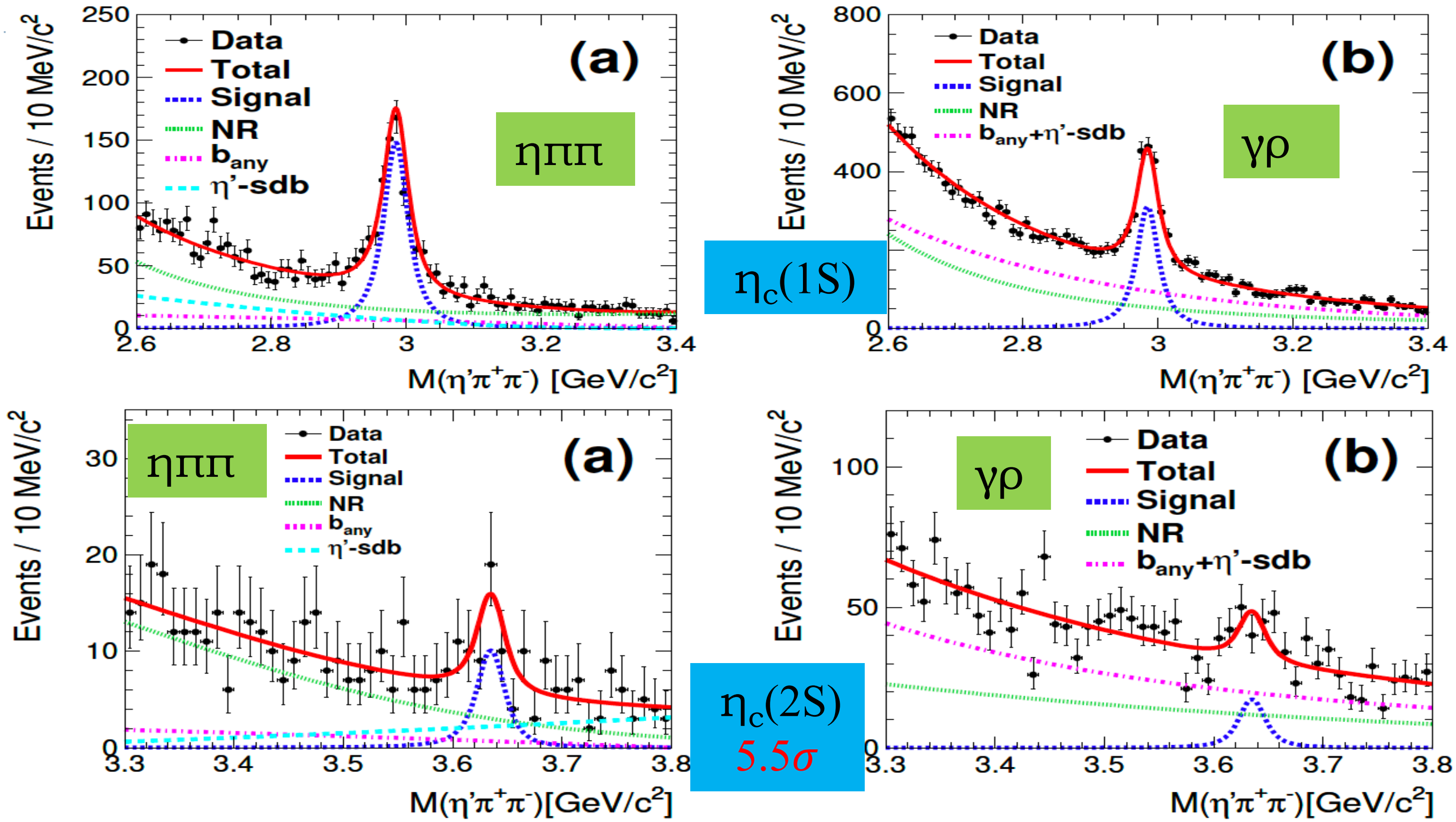
$$\gamma\gamma \rightarrow \eta'\pi^+\pi^-$$

Dataset: 941 fb^{-1}

arXiv: 1805.03044
Submitted to PRD

$\gamma\gamma \to \eta'\pi^+\pi^-$

Simultaneous Fit for $\eta_c(1s)$ and $\eta_c(2s)$



	$\eta_c(1S)$		$\eta_c(2S)$	
	$\gamma\rho$	$\eta\pi^+\pi^-$	$\gamma\rho$	$\eta\pi^+\pi^-$
n_s	1728^{+69}_{-68}	945^{+38}_{-37}	65^{+14}_{-13}	41^{+9}_{-8}
M (MeV/c^2)	$2984.6 \pm 0.7 \pm 2.2$		$3635.1 \pm 3.7 \pm 2.9$	
Γ (MeV)	$30.8^{+2.3}_{-2.2} \pm 2.5$		11.3[fixed]	
$\Gamma_{\gamma\gamma}\mathcal{B}$ (eV)	$65.4 \pm 2.6 \pm 6.9$		$5.6^{+1.2}_{-1.1} \pm 1.1$	

Discussion on $\Gamma_{\gamma\gamma}$ of $\eta_c(2S)$

- Defining the ratio R = $\frac{\Gamma_{\gamma\gamma}(\eta_c(2S))B(\eta_c(2S))}{\Gamma_{\gamma\gamma}(\eta_c(1S))B(\eta_c(1S))}$, which is directly measured,

	This work	BaBar($K\bar{K}\pi$)[1]	CLEO[2]
R	$(8.6 \pm 2.6)\cdot 10^{-2}$	$(10.6 \pm 2.0)\cdot 10^{-2}$	$(18 \pm 5 \pm 2)\cdot 10^{-2}$

Consistent

so, we have $R_B = \frac{B(\eta_c(2S)\to\eta'\pi\pi)}{B(\eta_c(1S)\to\eta'\pi\pi)} \cong \frac{B(\eta_c(2S)\to K\bar{K}\pi)}{B(\eta_c(1S)\to K\bar{K}\pi)}$ within error.

- Assuming $R_B \cong 1$ [3] and
using the world average value $\Gamma_{\gamma\gamma}(\eta_c(1S)) = 5.1 \pm 0.4$ keV,
we obtain $\Gamma_{\gamma\gamma}(\eta_C(2S))$ = **0.44 ± 0.13** keV for $\eta'\pi\pi$ (this) and
0.54 ± 0.11 keV for BaBar($K\bar{K}\pi$) [1].
Both $\Gamma_{\gamma\gamma}(\eta_C(2S))$ values by Belle and BaBar are lower than
0.92 ± 0.28 keV from CLEO [2]

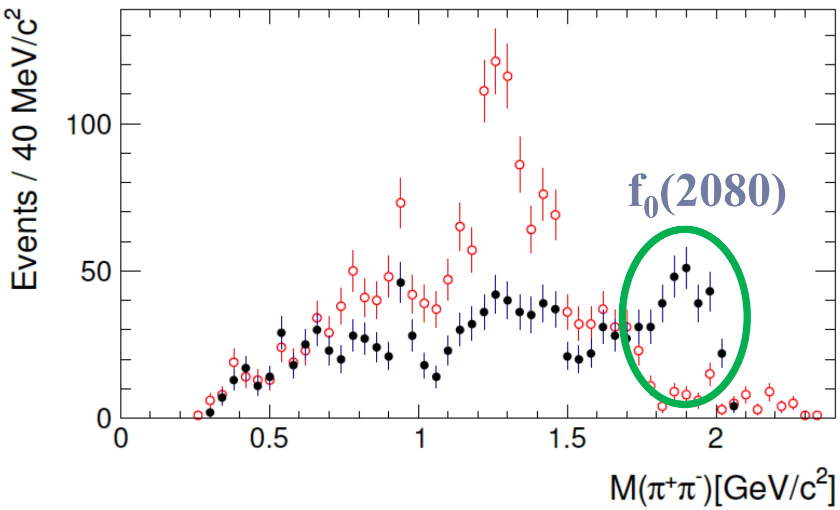
Discrepancy between data and QCD values

- QCD predictions for two-photon decay width of $\eta_c(2S)$ are ranged from 1.4 to 5.7.
- It is essential to have **precise measurement** of either $B(\eta_c(2S) \to K_s K\pi)$ or $B(B\to K\eta_c(2S))$

[1] del Amo Sanchez. P. et al. (BaBar Collaboration) Phys.Rev. D84 (2011) 012004.
[2] D. M. Asner *et al.* CLEO Collaboration, Phys. Rev.Lett. **92** (2004) 142001.
[3] T. Barnes, T. E. Browder, and S. F. Tuan, Phys. Lett. B **385**, 391 (1996).
[4] J.P. Lansberg, T.N. Pham, AIP Conf. Proc. 1038 (2008) 259.

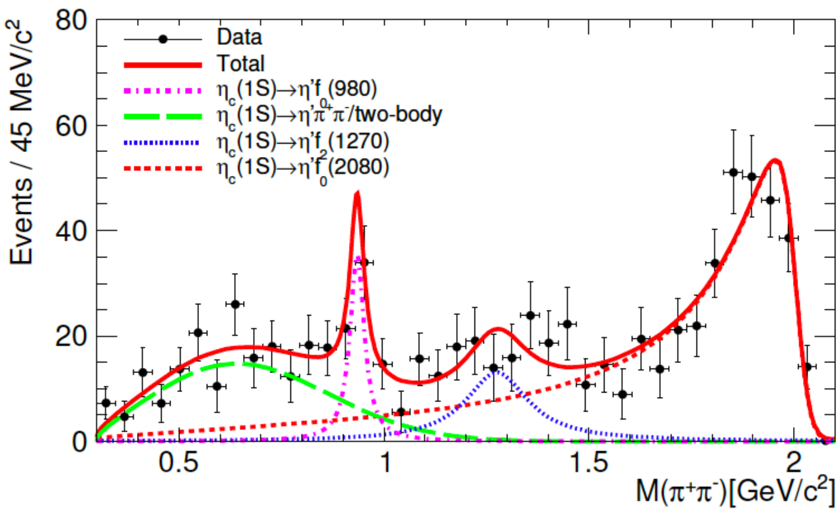
$\gamma\gamma \to \eta'\pi^+\pi^-$

Study of $\eta_c(1S) \to \eta' f_0(2080)$ decay with $f_0(2080) \to \pi^+\pi^-$

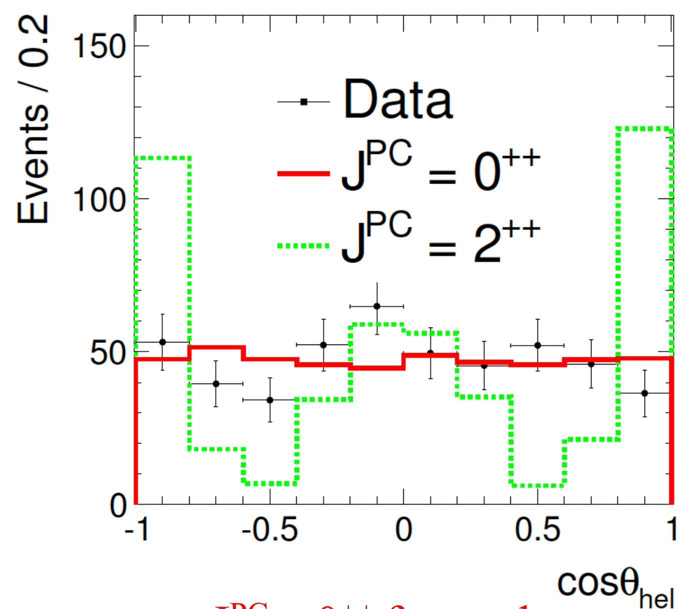


Black dots and red circles for events selected in $\eta_c(1S)$ **signal** and sideband regions.

No enhanced structure is seen in the Dalitz distributions for the $\eta_c(1S) \to a_2^{\pm}\pi^{\mp}$ with $a_2^{\pm} \to \eta'\pi^{\pm}$

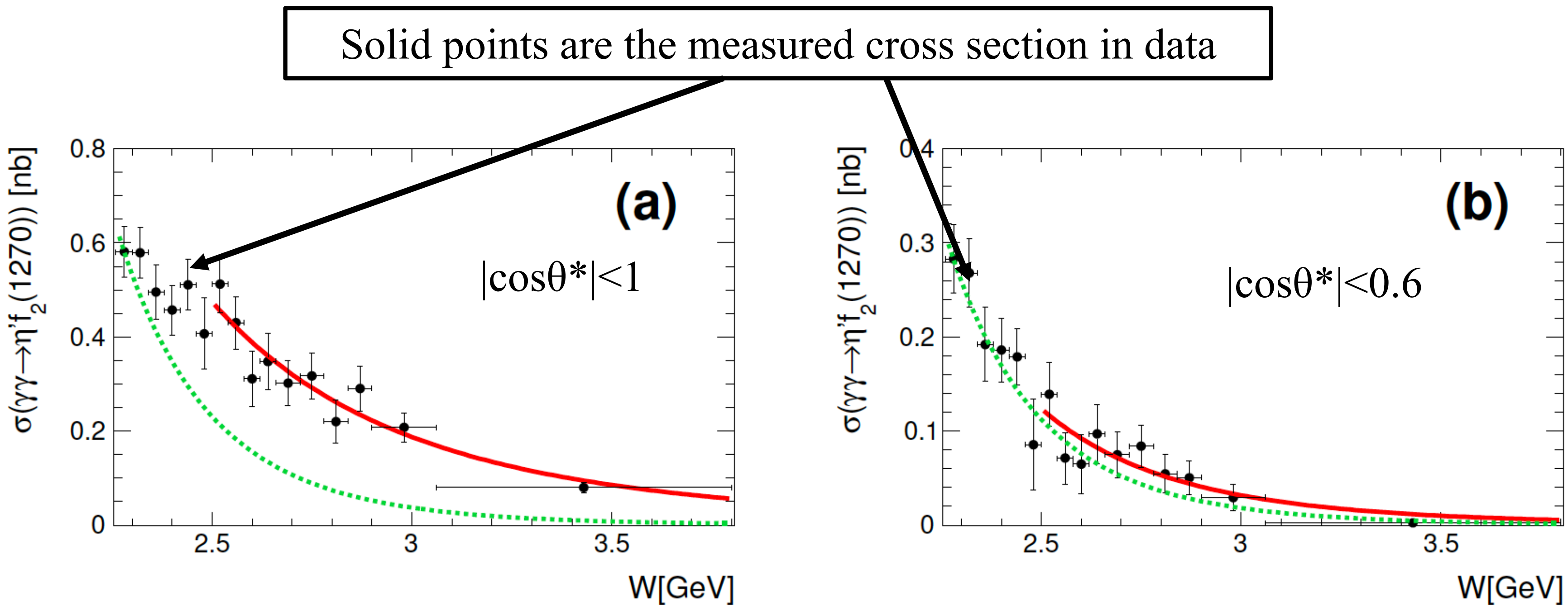


$M = 2083^{+63}_{-66} \pm 32\ \text{MeV},\ \ \Gamma = 178^{+60}_{-178} \pm 55\ \text{MeV}$



$J^{PC} = 0^{++}$ favored

Result of $\sigma(\gamma\gamma \to \eta' f_2(1270))$

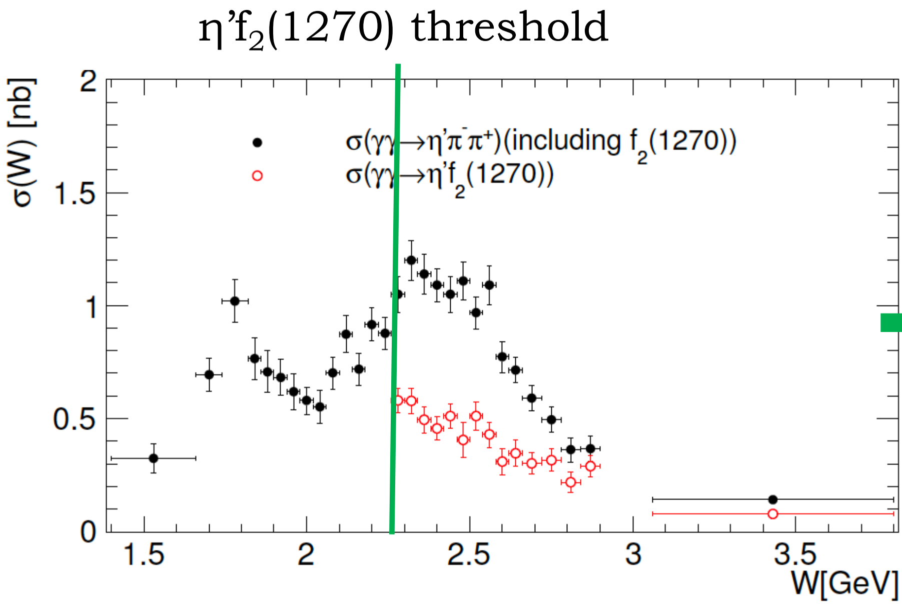


- Green dashed is the leading term QCD predictions for neutral meson pairs $\sim 1/W^{10}$ [1]
- No prediction for for $\gamma\gamma \to \eta' f_2(1270)$.
- Assuming $\sigma \sim 1/w^n$.
- The red solid line is the fitted value of $n = 5.1 \pm 1.0$ for $|\cos\theta^*|<1$ and $n = 7.5 \pm 2.0$ for $|\cos\theta^*|<0.6$.

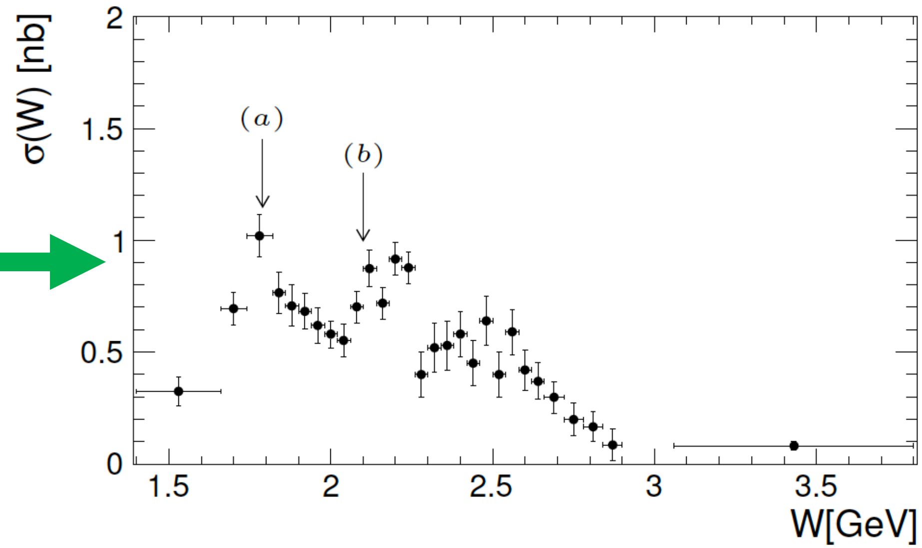
[1] Ed. A.J. Bevan, B. Golob, Th. Mannel, S. Prell, and B.D. Yabsley, Euro.Phys.Jour.C (2014) 74:3026.

$\gamma\gamma \rightarrow \eta'\pi^+\pi^-$

Result of $\sigma(\gamma\gamma \rightarrow \eta'\pi\pi)$



σ(γγ→η'ππ) after subtraction η'f$_2$(1270) contribution in W>2.26GeV region.



(a).Structure near 1.8 GeV/c^2 is contributed from X(1835) or η(1760) [1].

(b) Enhancement at 2.1GeV/c^2 is possible contribution from γγ→I(2100) → η'f_0(980).

[1]C.C. Zhang et al. Belle Collaboratin,Phys. Rev D86, 052002 (2012).

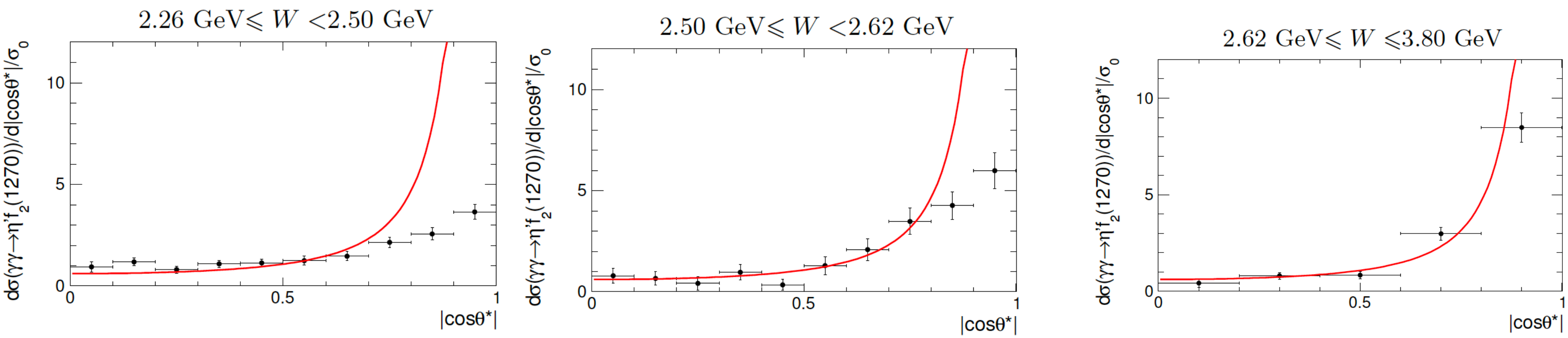
$\gamma\gamma \to \eta'\pi^+\pi^-$

Cross Section in |cosθ*|

- Black dots with error bar are the |cosθ*| dependent cross sections in data

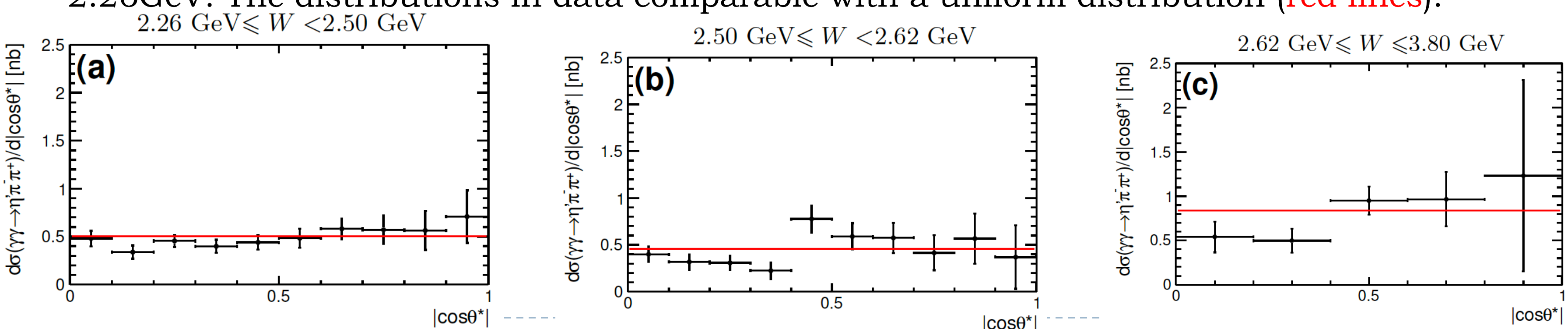
$\gamma\gamma \to \eta' f_2(1270)$

Red lines , normalized to the data, follows a $1/\sin^4\theta$ behavior.



$\gamma\gamma \to \eta'\pi\pi$

Measured cross section after subtracting the $\gamma\gamma \to \eta' f_2(1270)$ contribution in W region above 2.26GeV. The distributions in data comparable with a uniform distribution (red lines).



Summary

Single-tag two-photon results

- Cross section for $\gamma^*\gamma \to K_S^0 K_S^0$ has been measured for $2M(K_S^0) < W < 2.6$ GeV, 3 GeV^2 < Q^2 < 30 GeV^2
- Q^2 dependence of $\Gamma_{\gamma^*\gamma}$ of χ_{c0} and χ_{c2} has been measured.
- Q^2 dependence of $f_2'(1525)$ TFF has been measured.

No-tag two-photon results

- First observation of $\eta_C(2S) \to \eta'\pi\pi$ with a significance 5.5σ including systematic error.
- First observation of $\eta_c(1S) \to \eta' f_0(2080)$ decay with $f_0(2080) \to \pi^+\pi^-$ with a significance 20σ
- Measurements of pseudo-scalar tensor pair $\eta' f_2(1270)$ production, as well as that of $\eta'\pi\pi$, are made for the first time.

Thanks for your attention!

Backup

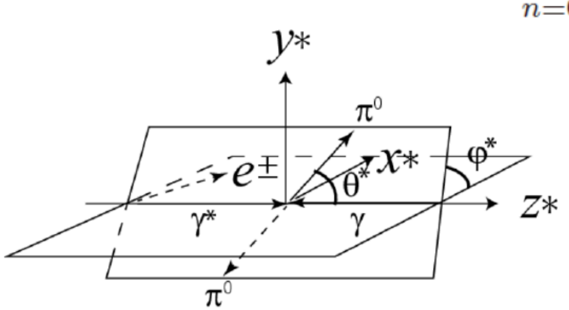
From Uehara-san's DIS 2018 report

Partial Wave Analysis for TFF of $f'_2(1525)$

Applied for W<1.8 GeV. We take into account partial waves up to J=2. J=1 does not couple with $K^0_S K^0_S$ ($\rightarrow J^P = 0^+$ and 2^+)

PRD 97, 052003 (2018)

$$\frac{d\sigma(\gamma^*\gamma \to K^0_S K^0_S)}{d\Omega} = \sum_{n=0}^{2} t_n \cos(n\varphi^*),$$



γ*γ c.m. frame
z^* axis // γ^*
x^*z^*plane includes tag-e

Resonance amplitude for f'_2, etc.

$$A^J_R(W) = F_R(Q^2)\sqrt{1+\frac{Q^2}{m_R^2}}\sqrt{\frac{8\pi(2J+1)m_R}{W}} \times \frac{\sqrt{\Gamma_{\rm tot}(W)\Gamma_{\gamma\gamma}(W)\mathcal{B}(K^0_S K^0_S)}}{m_R^2 - W^2 - im_R\Gamma_{\rm tot}(W)}$$

$$\begin{aligned}
t_0 &= |SY_0^0 + D_0Y_2^0|^2 + |D_2Y_2^2|^2 + 2\epsilon_0|D_1Y_2^1|^2, \\
t_1 &= 2\epsilon_1\Re\left[(D_2^*|Y_2^2| - S^*Y_0^0 - D_0^*Y_2^0)D_1|Y_2^1|\right], \\
t_2 &= -2\epsilon_0\Re\left[D_2^*|Y_2^2|(SY_0^0 + D_0Y_2^0)\right].
\end{aligned}$$

TFF of f'_2 for helicity $i = \lambda$

$$\sqrt{r_{ifp}}F_{f2p}\ (i = 0,\,1,\,2)$$

$$r_{0fp} + r_{1fp} + r_{2fp} = 1$$

S, D_0, etc. --- Partial-wave amplitudes
ε_0, ε_1 --- Spin-dependent flux factor ratios for the virtual photon
Y_j^m --- Spherical harmonics

From Uehara-san's DIS 2018 report

Formalism of PWA and parametrizations

Problems: Low statistics

Only 3 out of *S*, D_0, D_1 and D_2 are independent

Non-unique solution (multiple solutions for resonances)

→ Parametrization of the amplitudes with modelled W and Q^2 dependences

$$
\begin{aligned}
S &= A_{BW} e^{i\phi_{BW}} + B_S e^{i\phi_{BS}}, \\
D_i &= \sqrt{r_{ifa}(Q^2)}(A_{f_2(1270)} - A_{a_2(1320)}) e^{i\phi_{faDi}} \\
&+ \sqrt{r_{ifp}(Q^2)} A_{f_2'(1525)} e^{i\phi_{fpDi}} \\
&+ B_{Di} e^{i\phi_{BDi}},
\end{aligned}
$$

$$
\begin{aligned}
B_S &= \frac{\beta a_S (W_0/W)^{b_S}}{(Q^2/m_0^2+1)^{c_S}}, \\
B_{D0} &= \frac{\beta^5 a_{D0} (W_0/W)^{b_{D0}}}{(Q^2/m_0^2+1)^{c_{D0}}}, \\
B_{D1} &= \frac{\beta^5 Q^2 a_{D1} (W_0/W)^{b_{D1}}}{(Q^2/m_0^2+1)^{c_{D1}}}, \\
B_{D2} &= \frac{\beta^5 a_{D2} (W_0/W)^{b_{D2}}}{(Q^2/m_0^2+1)^{c_{D2}}},
\end{aligned}
$$

$$
\beta = \sqrt{1 - 4m_{K_S^0}^2/W^2} \text{ is the } K_S^0 \text{ velocity}
$$

$$
A_{BW}(W) = \sqrt{\frac{8\pi m_S}{W}} \frac{f_S}{m_S^2 - W^2 - i m_S g_S} \times \frac{1}{(Q^2/m_0^2+1)^{p_S}},
$$

Nominal fit

Bs = 0

$$
r_{0fp} : r_{1fp} : r_{2fp} = k_0 Q^2 : k_1 \sqrt{Q^2} : 1
$$

-Destructive interference between $f_2(1270)$ and $a_2(1320)$

-$r_i(Q^2)$ and TFF for $f_2(1270)$ and $a_2(1320)$ are the same; use the values obtained in single-tag $\pi^0\pi^0$

Determine each component and the relative phase by a fit

Angular dependence and the PWA fit

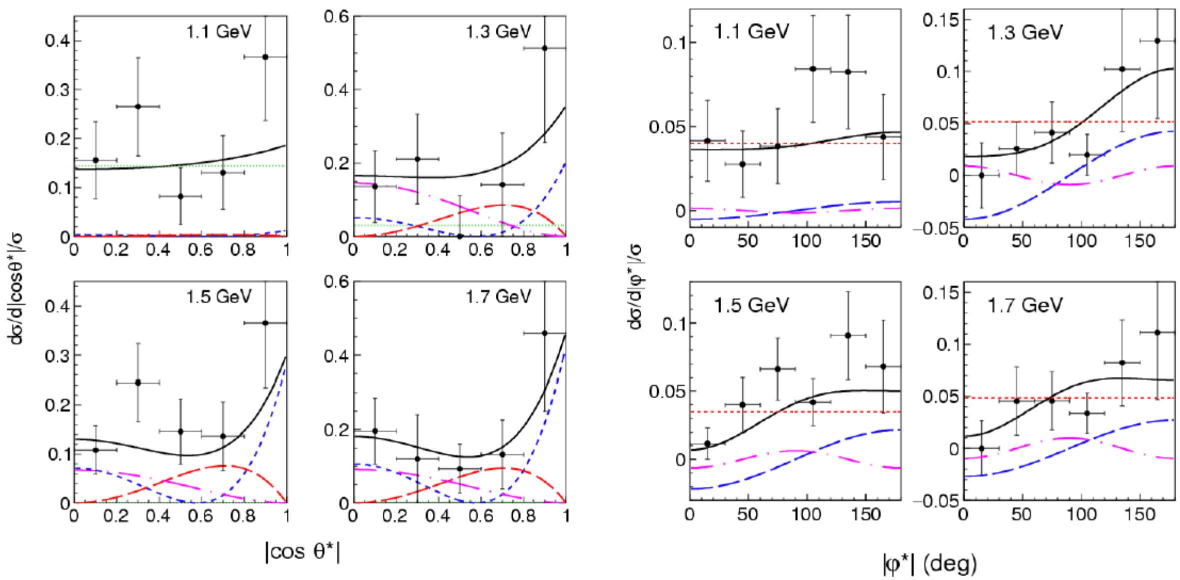
Due to a lack of statistics, we use Q^2-integrated angular differential cross section derived with the following convention (MC generated isotropically)

$$d^2\sigma/d|\cos\theta^*|d|\varphi^*| \propto N_{\rm EXP}(|\cos\theta^*|, |\varphi^*|)/N_{\rm MC}(|\cos\theta^*|, |\varphi^*|)$$

Q^2: integrated over the full range between 3 and 30 GeV^2

W: 4 bins

|cos θ*| dependence (|φ*| integrated) |φ*| dependence (|cos θ*| integrated)



We regard this as the angular dependence at $<Q^2> = 6.5$ GeV^2

Fit:

Black: total

Red: t_0

Blue: $t_1 \cos\varphi^*$

Magenta: $t_2 \cos 2\varphi^*$

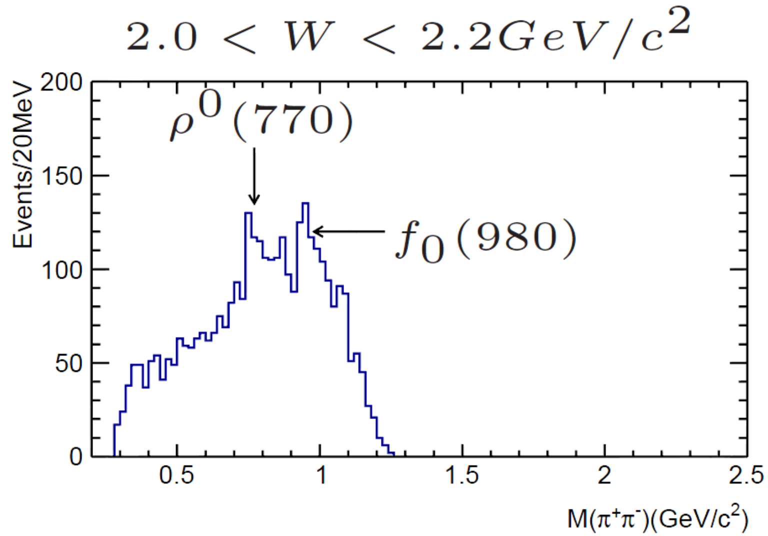
The fit is applied to the two-dimensional angular-dependence data.

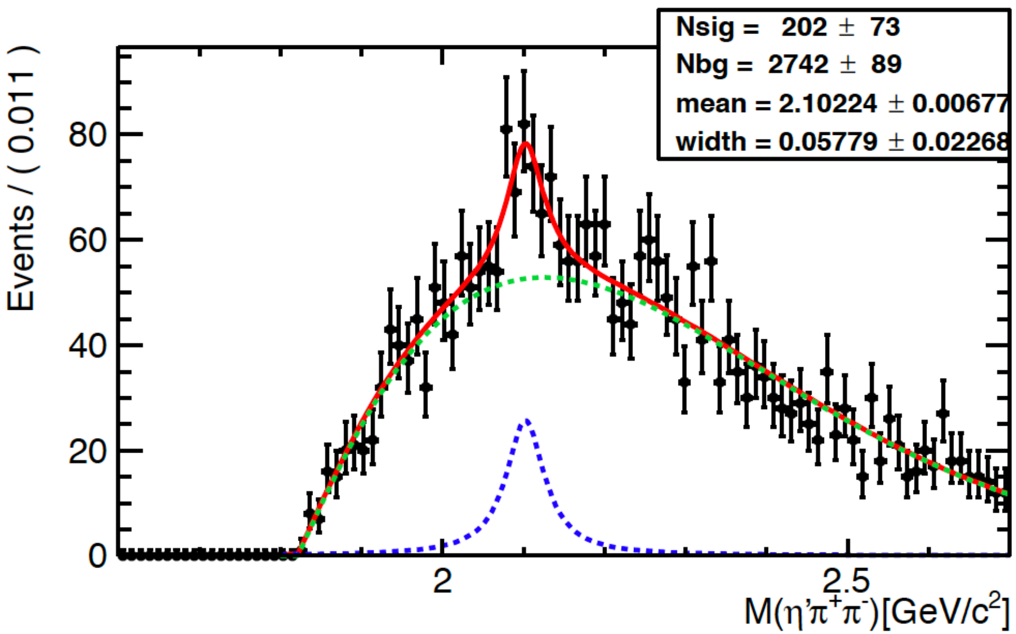
Forward enhancement is from the helicity-0 component.

From PDG 2017

	Branching fraction
$\eta_c(1S) \rightarrow K\bar{K}\pi$	$(7.3 \pm 0.5)\%$
$\eta_c(2S) \rightarrow K\bar{K}\pi$	$(1.9 \pm 1.2)\%$
$B \rightarrow K(\eta_c(1S) \rightarrow K_s K\pi)$	$(2.7 \pm 0.6)\times10^{-5}$
$B \rightarrow K(\eta_c(2S) \rightarrow K_s K\pi)$	$(3.4^{+2.3}_{-16})\times10^{-6}$

Possible intermediate from $\gamma\gamma \rightarrow I(2100) \rightarrow \eta' f_0(980)$





- In $f_0(980)$ signal region $0.86 < M(\pi\pi) < 1.10$ GeV/c^2.
- I(2100) with statistic significance 3.5σ.