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

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On behalf of the Belle collaboration

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Motivation for $\eta_c(1S)$, $\eta_c(2S)$

- Playing an important role in QCD test **[1]**

  - ✓ Precise two-photon decay widths of $\eta_c(1S)$ and $\eta_c(2S)$ give sensitive tests for QCD models **[2]**.
  - ✓ As lowest heavy-quarkonium state, η_c (1S), as well as J/ψ, $\eta_b(1S)$ and $\Upsilon(1S)$, provide a benchmark for fine tuning of input parameters in QCD calculations.

- Poor knowledge available even for $\eta_c(2S)$ hadronic decays, such as $\eta'\pi\pi$.
- $\eta_c(1S)$ and $\eta_c(2S)$ were measured by BESIII in $\Psi(2S)$ radiative decay, by BELLE and CLEO in B decay and two-photon production.
- First measurement of two-photon decay width of $\eta_c(2S)$ via $K^0_S K^+\pi^-$ is given and an upper limit for $\eta_c(2S) \to \eta'\pi^+\pi^-$ signal is set by CLEO [3].
- X(1835) is observed by BESII [4] and confirmed by BESIII [5] with $\eta'\pi^+\pi^-$ final states. And is seen in two-photon collision by Belle [6].

[1] N. Brambilla et al., Eur. Phys. C 71, 1534 (2011).
[2] J. P. Lansberg and T. N. Pham, Phys. Rev. D 74, 034001 (2006).
[3] D.M. Asner, et al.,(CLEO Collaboration) , Phys. Rev. Lett. 92, 142001 (2004).
[4] M. Ablikim, et al., (BESII Collaboration) , Phys. Rev. Lett. 95, 262001 (2005).
[5] M. Ablikim, et al., (BESIII Collaboration) , Phys. Rev. Lett. 106, 072002 (2011).
[6] C.C. Zhang et al. Belle Collaboratin,Phys. Rev D86, 052002 (2012).

Motivation for cross section

- Test QCD calculations
  - Cross sections for two-photon production of pseudo-scalar meson pairs were measured by Belle [1].
    - Charged-meson pairs： $\pi^+\pi^-$， K^+K^-
    - Neutral-meson pairs： $K^0_S K^0_S$， $\pi^0\pi^0$， $\eta\pi^0$， $\eta\eta$
  - Leading term QCD [2] predicts $1/(W^6 \sin^4\theta)$ dependence for charged-meson pair and $1/W^{10}$ and model-dependent angular distribution for neutral-meson pair.
  - Handbag model [3] gives transition amplitude for energy dependence and predicts $1/\sin^4\theta$ dependence both for charged- and neutral-meson pairs.
  - Improved study both in experiment and QCD prediction at higher W mass would provide sensitive test in QCD calculations.
- Cross section measurements for productions of pseudo-scalar tensor pair $\eta' f_2(1270)$ and three-body final state $\eta'\pi\pi$ would provide new data for the QCD test.

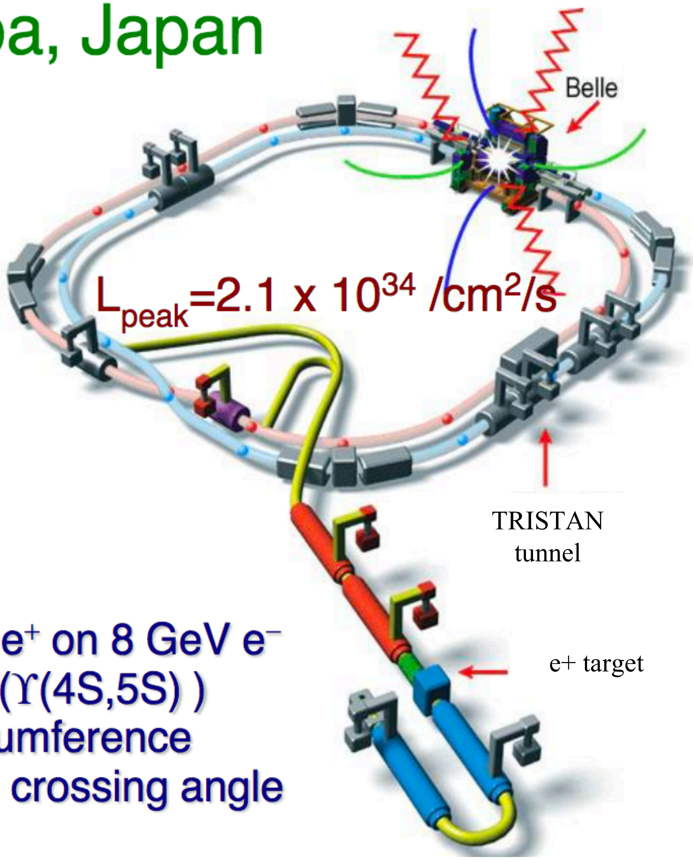
[1] Ed. A.J. Bevan, B. Golob, Th. Mannel, S. Prell, and B.D. Yabsley, Euro.Phys.Jour.C (2014) 74:3026.

[2] M. Benayoun and V. L. Chernyak., *Nucl.Phys.* B329, 285 (1990).

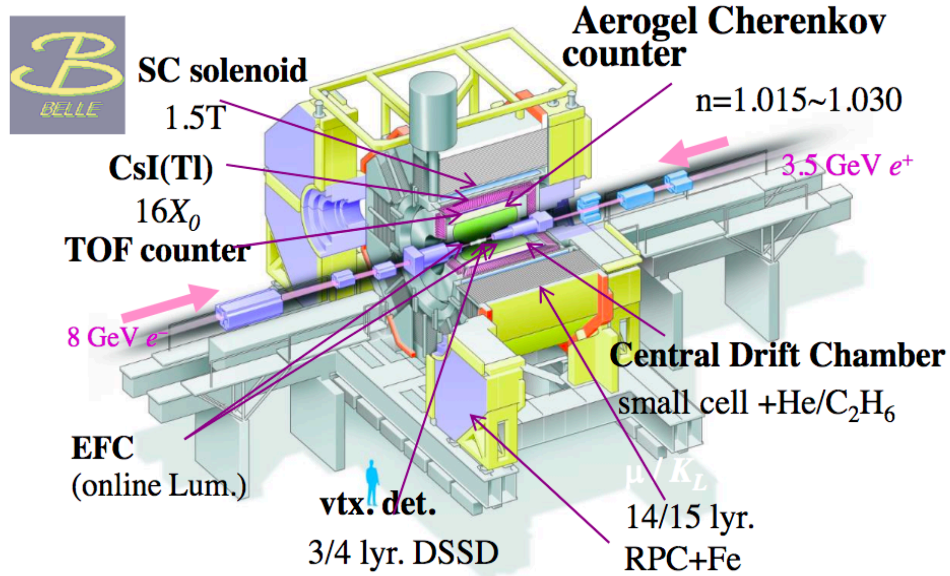
[3] M. Diehl, P. Kroll, and C. Vogt., *Phys. Lett.* B532, 99–110 (2002).

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

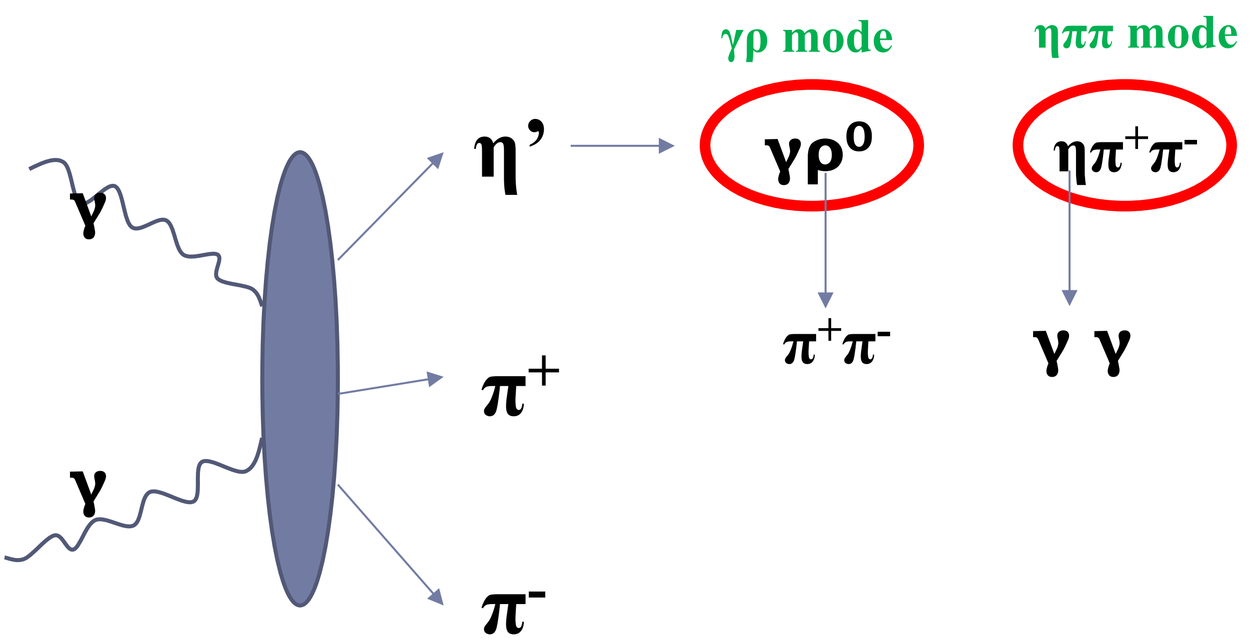


Belle $\gamma\gamma \to \eta'\pi\pi$ analysis

Data sample:

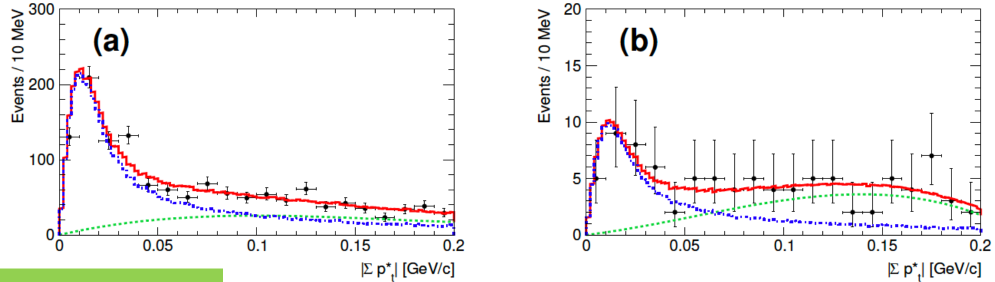
792 fb^{-1} at $\sqrt{s}$=10.58 GeV (Υ(4S)) and 60 MeV below it.

149 fb^{-1} at $\sqrt{s}$=10.88 GeV (Υ(5S)) and scan data around this energy point.

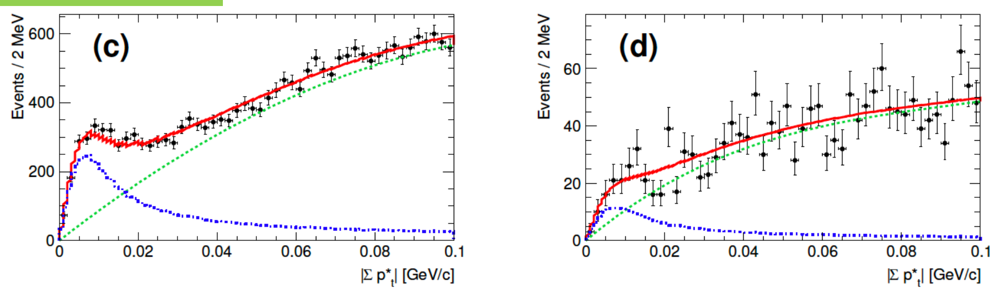


|ΣP*t| and M(η'ππ) distributions

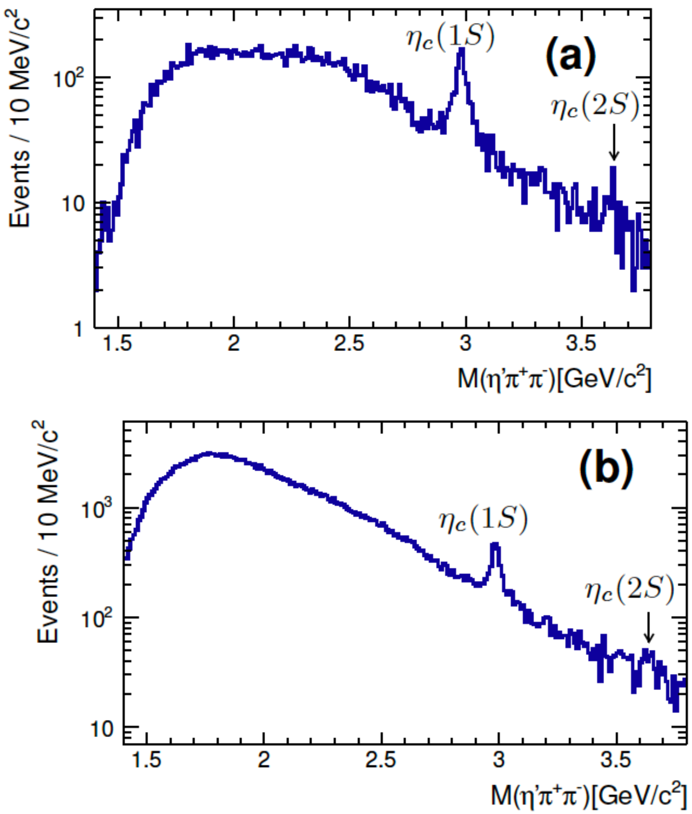
ηππ mode



γρ mode



in η_c(1s) signal region　　in η_c(2s) signal region



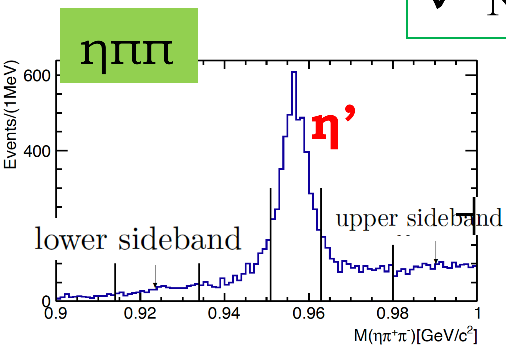
- Untagged two-photon process tend to carry small transverse momentum.
- A |ΣP*t| requirement allows significant background reduction.

- Clear η_c (1S) signal in the two decay modes.
- A heavy combinational background by the low energy photons for γρ mode .

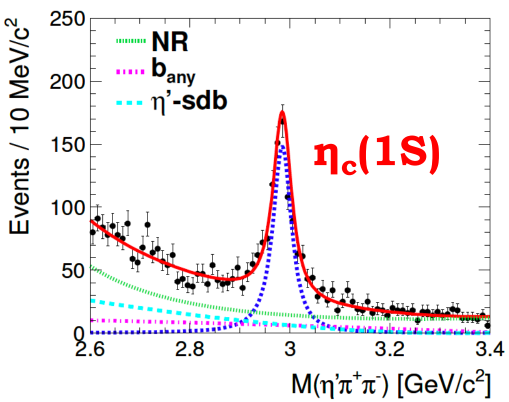
Background in fit to η’ππ mass spectrum

Background for M(η’ππ) spectrum dominant by :

- ✓ Background in η’ signal region(η’ -sdb).
- ✓ η’ππ+any (b_any).
- ✓ Non resonance (NR): e+e- →e+e- η’$\pi^+\pi^-$.



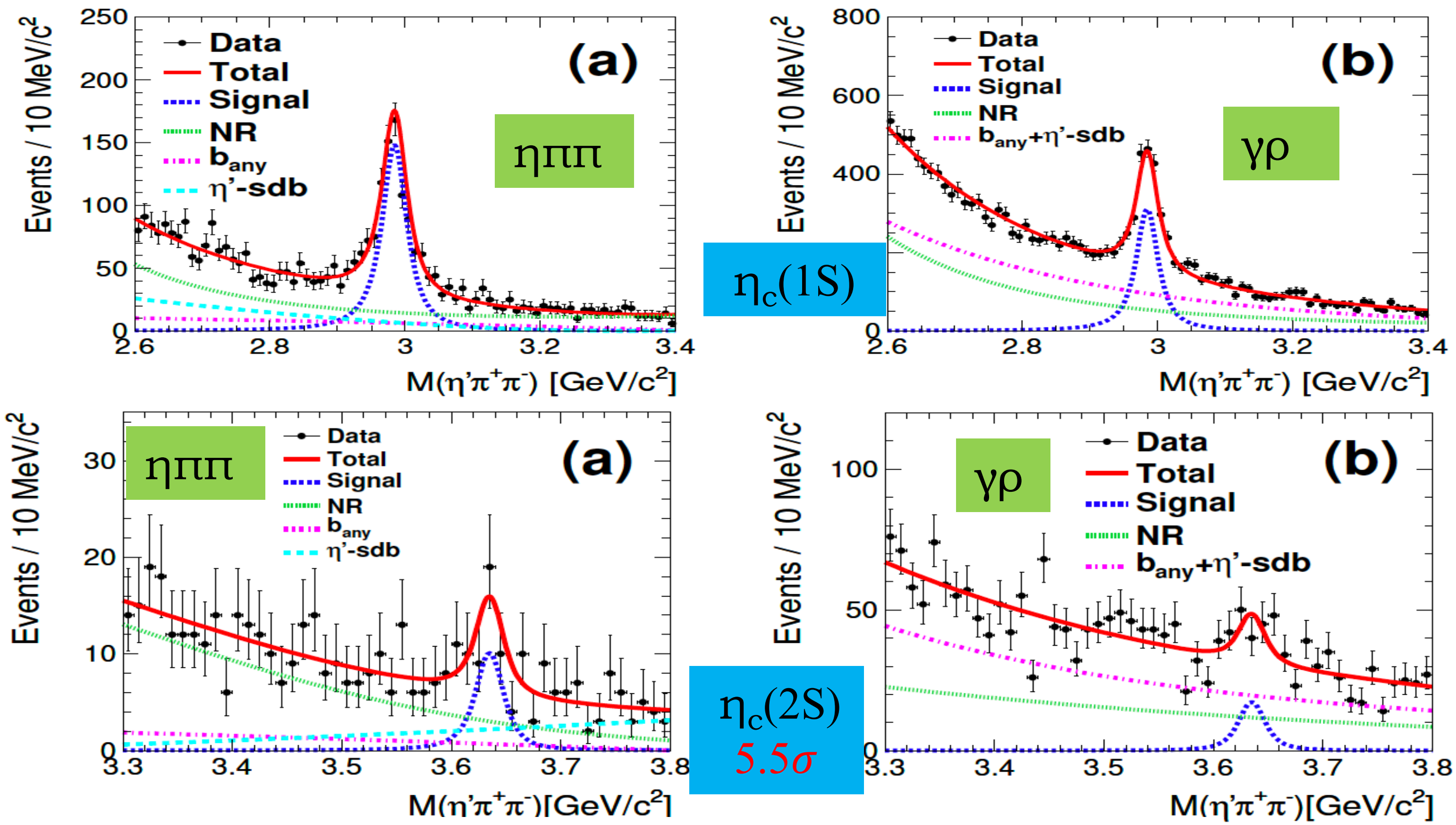
- ✓ Low smooth background.
- ✓ η’-sdb determined by events in the η’ sideband region
- ✓ b_any described by events in region of 0.17< |ΣP*$_t$| <0.2GeV.



- ✓ Heavy background (including a peaking component due to η’ mass constraint fit.).
- ✓ η’ -sdb + b_any determined by events in a region 0.15< |ΣP*$_t$| <0.2GeV.

- ✓ NR described by a 3rd exponential polynomial in fit for γρ and ηππ.

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,

	Belle ($\eta'\pi\pi$)	BaBar($K\bar{K}\pi$)[1]	CLEO ($K_sK\pi$)[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.

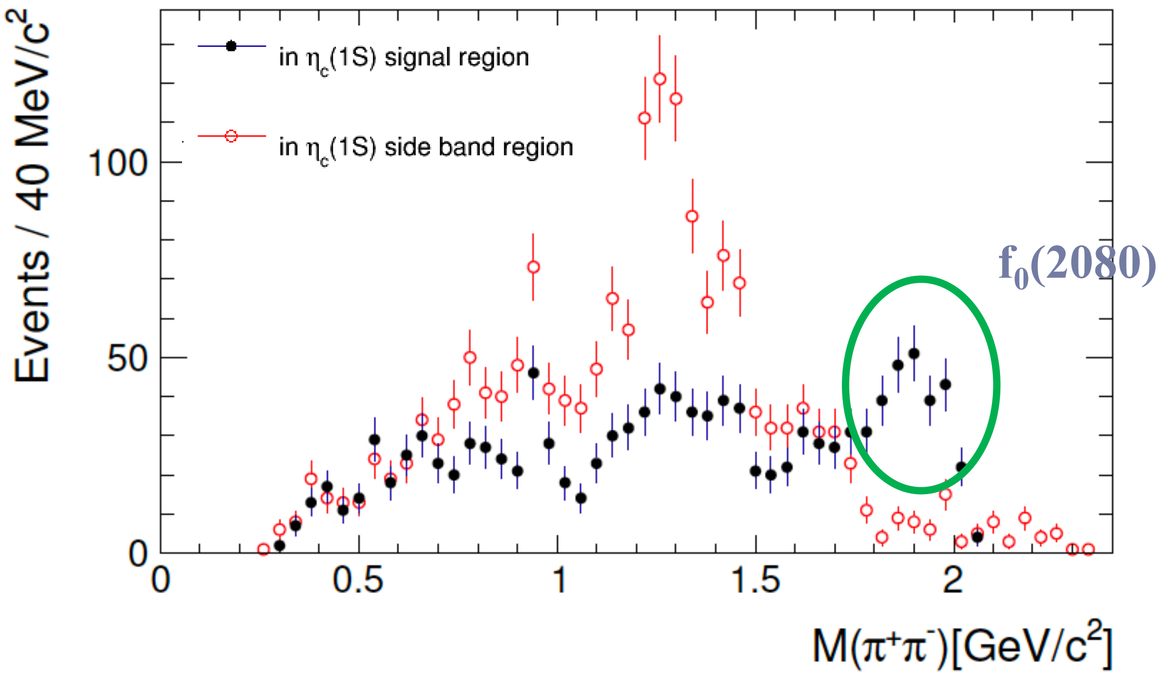
- Assuming $R_B \cong 1$ and
  using the world average value $\Gamma_{\gamma\gamma}(\eta_c(1S)) = 5.1 \pm 0.4$ keV,
  we obtain $\Gamma_{\gamma\gamma}(\eta_C(2S))$ = **0.44 ± 0.13** keV for Belle ($\eta'\pi\pi$) and
  0.54 ± 0.11 keV for BaBar($K\bar{K}\pi$) [1].
  Both $\Gamma_{\gamma\gamma}(\eta_C(2S))$ values by Belle are lower than
  0.92 ± 0.28 keV for CLEO($K_sK\pi$) [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 [3,4].
- It is essential to have **precise measurement** of either $B(\eta_c(2S) \to K_sK\pi)$ 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.

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



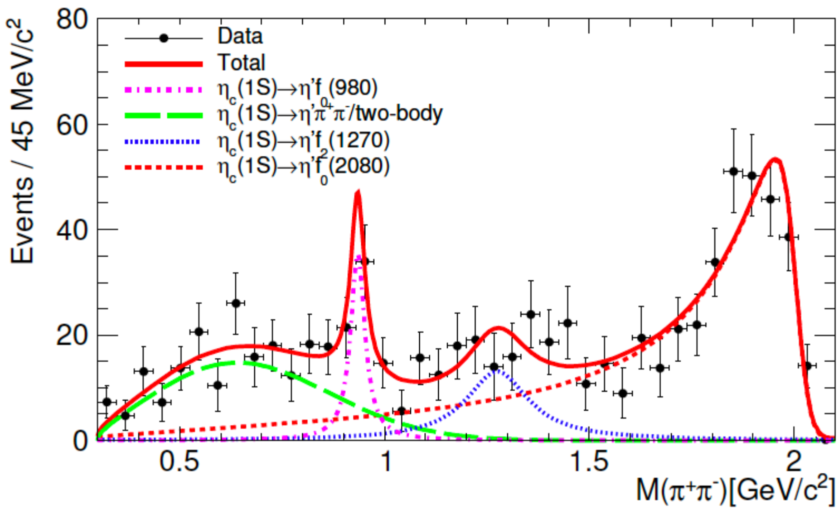
Black dots and red circles for events selected in $\eta_c(1S)$ **signal** and sideband regions.

Fitting $f_0(2080) \to \pi^+\pi^-$ with sample in $\eta_c(1S)$ signal region

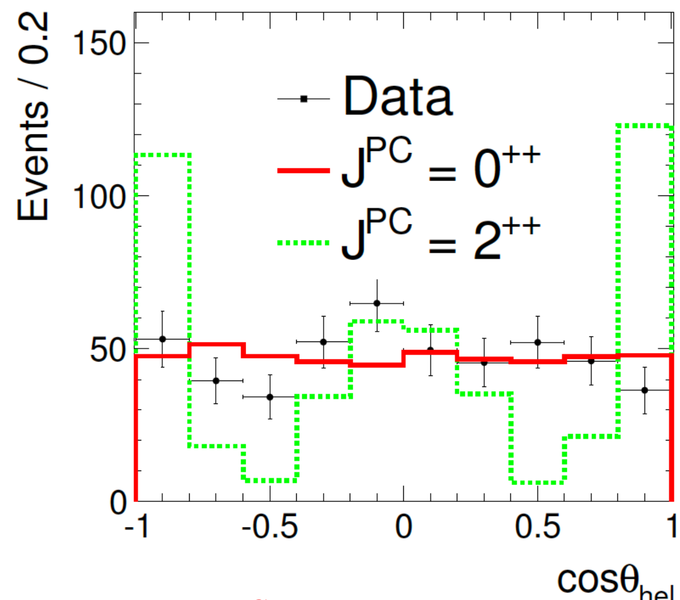
Blatt-Weisskopf Breit-Wigner function for the signal:

$$f_s(m) = n_s(f_{BW}(m; M, \Gamma)p(m)\epsilon(m)\int_{m_d}^{m_u} q(m, m_{\eta_c})f_{BW}(m_{\eta_c})\frac{dL_{\gamma^*\gamma^*}}{dm_{\eta_c}}dm_{\eta_c})\otimes g_{res}(m)$$

- ✓ $\varepsilon(m)$: detection efficiency.
- ✓ $p(m)$: π momentum in $f_0(2080)$ rest frame.
- ✓ $q(m, m_{\eta c})$: $f_0(2080)$ momentum in γ γ rest frame.
- ✓ $\frac{dL_{\gamma\gamma}}{dm_{\eta_c}}$: two-photon luminosity function.
- ✓ $g_{res}(m)$: resolution of mass m.
- ✓ (m_d, m_u) = (2.9, 3.06)GeV if m<2.9 – 0.958 (η' mass)
  (m_d, m_u) = (m+0.958, 3.06)GeV if m>2.9 – 0.958



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



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

Cross section for $\gamma\gamma\to\eta'\pi\pi$, $\eta' f_2(1270)$

- The differential cross section in a W and |cosθ*| two-dimensional bin is estimated by :

$$\frac{d\sigma_{\gamma\gamma\to\eta'\pi^+\pi^-}(W_{\gamma\gamma}, cos\theta^*)}{d|cos\theta^*|} = \frac{\Delta N(W_{\gamma\gamma}, cos\theta^*)/\epsilon(W_{\gamma\gamma}, cos\theta^*)}{L_{int}\cdot\frac{dL_{\gamma\gamma}(W_{\gamma\gamma})}{dW_{\gamma\gamma}}\cdot\Delta W_{\gamma\gamma}\cdot\Delta|cos\theta^*|} \quad (1)$$

- The W-dependent cross section of $\gamma\gamma\to\eta'\pi^+\pi^-$ obtained by a summation over Δ |cosθ*| bins:

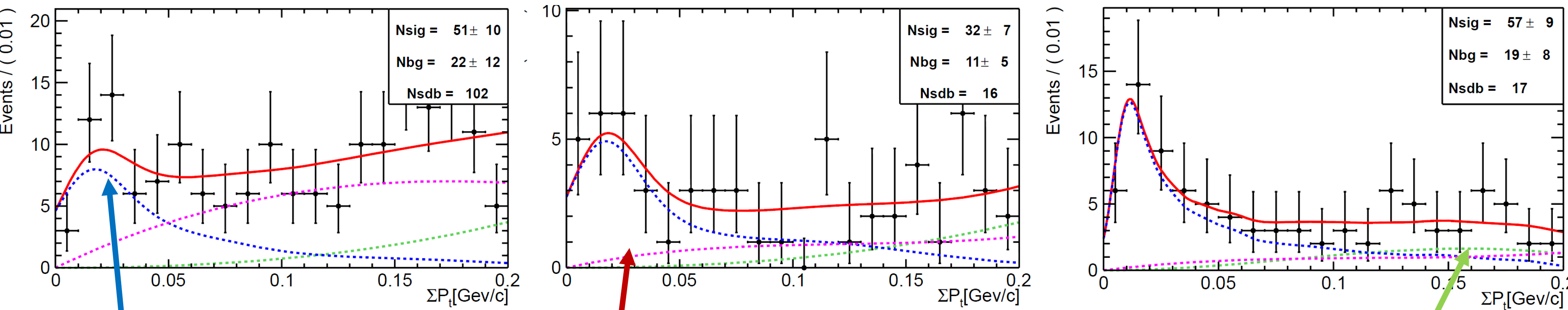
$$\sigma_{\gamma\gamma\to\eta'\pi^+\pi^-}(W_{\gamma\gamma}) = \sum_{\Delta_i|cos\theta^*|}\frac{d\sigma_{\gamma\gamma\to\eta'\pi^+\pi^-}(W_{\gamma\gamma}, cos\theta^*)}{d|cos\theta^*|}\Delta_i|cos\theta^*| \quad (2)$$

- The differential cross section in |cosθ*| averaged over W bins within a certain W region:

$$\sigma_{\gamma\gamma\to\eta'\pi^+\pi^-}(\cos\theta^*) = \frac{\Sigma\left(\frac{\mathrm{d}\sigma_{\gamma\gamma\to\eta'\pi^+\pi^-}(\mathrm{W}_{\gamma\gamma},\cos\theta^*)}{\mathrm{d}|\cos\theta^*|}\Delta\mathrm{W}_{\gamma\gamma}\right)}{\Sigma\Delta\mathrm{W}_{\gamma\gamma}} \quad (3)$$

$\sigma(\gamma\gamma\to\eta'\pi\pi)$: fitting $|\Sigma P^*t|$

Two-photon signal yield is extracted by fitting $|\Sigma P^*t|$ distribution in data for each 2-dimension bin.



$1.66<W<1.74$
$0.4<|\cos\theta^*|<0.5$

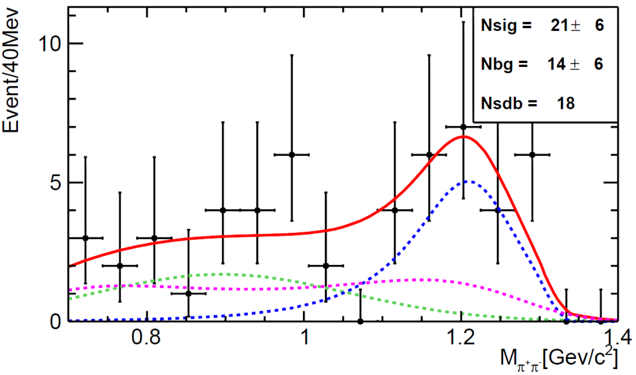
$2.50<W<2.54$
$0.4<|\cos\theta^*|<0.5$

$3.08<W<3.24$
$0.4<|\cos\theta^*|<0.6$

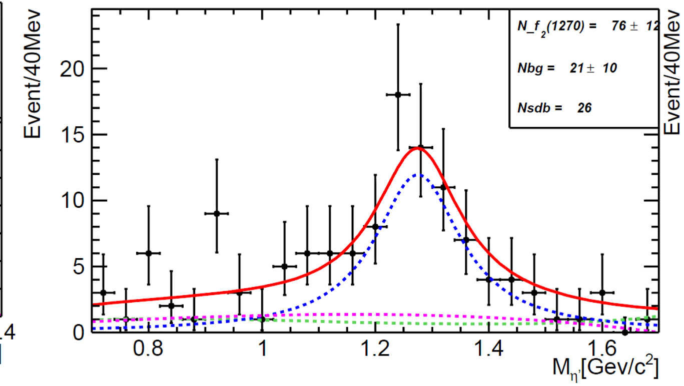
signal shape in MC is fixed, η'-sdb in data is normalized and fixed, and b_any is described by a 3rd order polynomial.

σ(γγ→η'f_2(1270)) : fitting M(ππ)

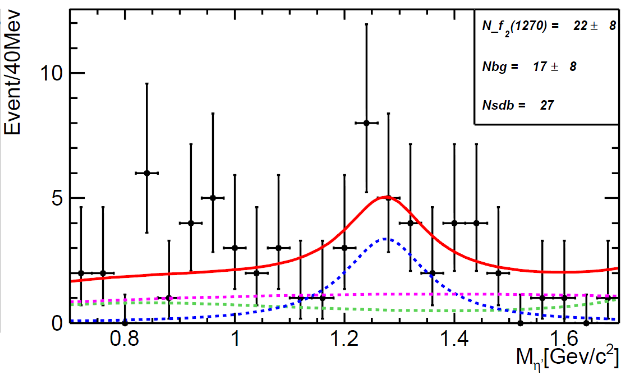
f_2(1270) yield is extracted from fitting $M(\pi^+\pi^-)$ distribution in data for each 2-dimensional bin.



2.26<W<2.30
0.4< |cosθ*|<0.5



2.62<W<2.66
0.4< |cosθ*|<0.6

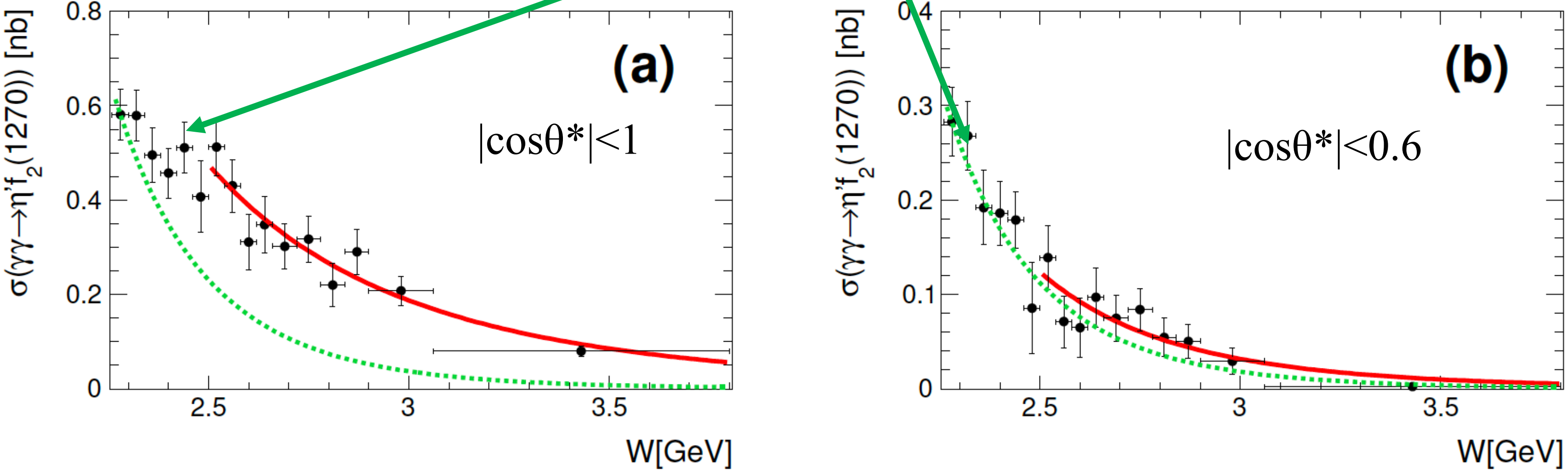


2.72<W<2.78
0.4< |cosθ*|<0.6

- Signal shape is described by a Breit-Wigner with Γ and M fixed.
- Normalized η'-sdb in data is fixed.
- b_any is described by a 4th order exponential polynomial.

Result of σ(γγ→η'f_2(1270))

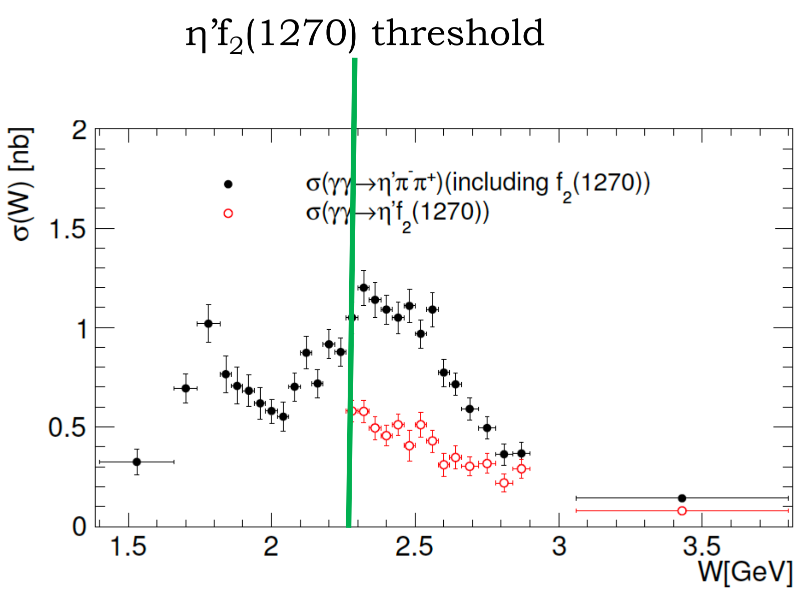
Solid points are the measured cross section in data

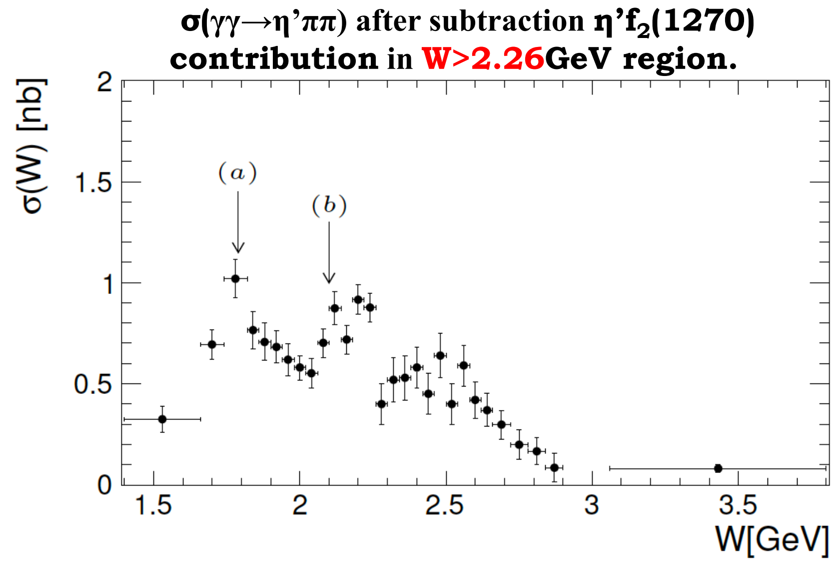


- Green dashed is the leading term QCD predictions for neutral meson pairs $\sim 1/W^{10}$ [1].
- No prediction for γγ→ η'f_2(1270) .
- Assuming $\sigma \sim 1/w^n$.
- We get the fitted value of $n = 5.1 \pm 1.0$ for $|\cos\theta^*|<1$ and $n = 7.5 \pm 2.0$ for $|\cos\theta^*|<0.6$.

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

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





(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 $\gamma\gamma \to I(2100) \to \eta' f_0(980)$.

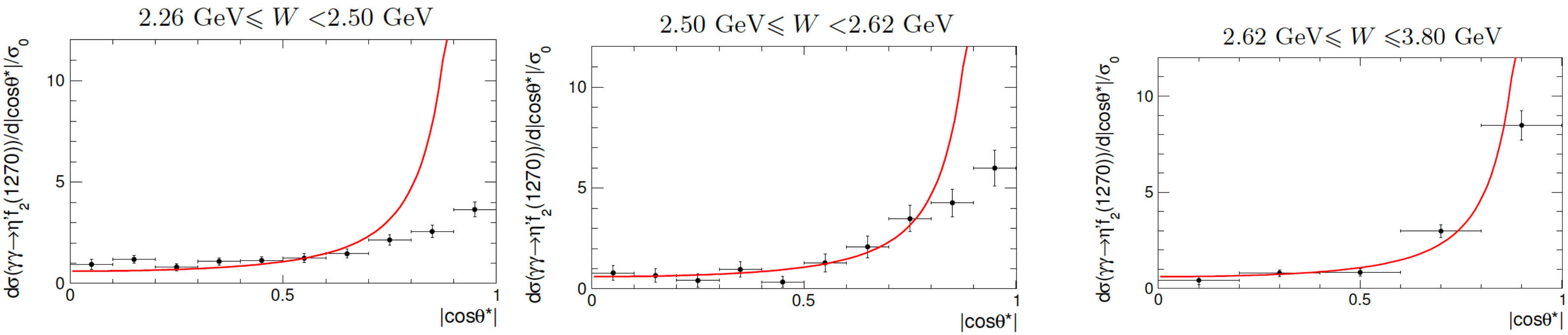
[1]C.C. Zhang et al. Belle Collaboratin,Phys. Rev D86, 052002 (2012).

Cross Section in |cosθ*|

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

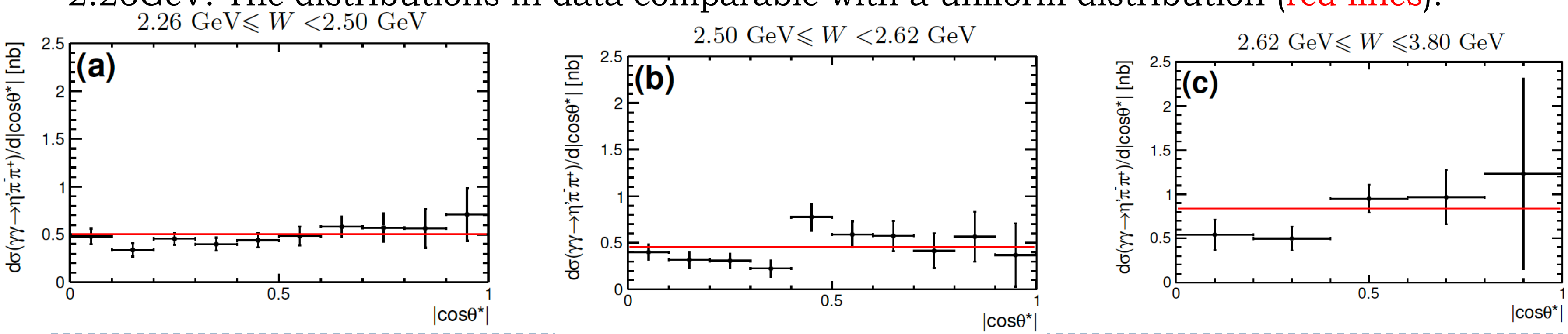
$\gamma\gamma \rightarrow \eta' f_2(1270)$

Red line is QCD predictions for neutral meson pairs ~$1/\sin^4\theta$



$\gamma\gamma \rightarrow \eta'\pi\pi$

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



Summary

- Results on the $\gamma\gamma\to\eta'\pi\pi$ process for both $\eta'\to\eta\pi\pi$ & $\gamma\rho$ decays using 941 fb^{-1} Belle data are presented.

- First observation of $\eta_C(2S)\to\eta'\pi\pi$ with a significance **5.5σ** including systematic error.
  - **Consistent ratio** $R = \frac{\Gamma_{\gamma\gamma}(\eta_c(2S))B(\eta_c(2S))}{\Gamma_{\gamma\gamma}(\eta_c(1S))B(\eta_c(1S))}$ **between** $K\bar{K}\pi$ **(BaBar) and** $\eta'\boldsymbol{\pi\pi}$ **(Belle) decays, is interesting in QCD test.**

- **First observation** of $\boldsymbol{\eta_c(1S)\to\eta' f_0(2080)}$ decay with $f_0(2080)\to\pi^+\pi^-$ with a significance 20σ, and its mass and width is determined to be

  $$\mathbf{M} = 2083^{+63}_{-66} \pm 32\ \mathrm{MeV}/c^2,$$

  $$\mathbf{\Gamma} = 178^{+60}_{-178} \pm 55\ \mathrm{MeV}.$$

- **Measurements of pseudo-scalar tensor pair** $\boldsymbol{\eta' f_2(1270)}$ **production**, as well as that of $\eta'\pi\pi$, are made for the **first time**.

Thanks for your attention!

Backup

Selection criteria

$\gamma\rho$ mode

Variable	cut value
P_{sum}	< 5.5 GeV/c
E_{sum}	< 4.5 GeV
N_{π^+}, N_{π^-}	2,2
N_{charge}	4
$N_{k^+} + N_{k^-}$	< 1
$N_{p^+} + N_{p^-}$	< 1
$N_{e^+} + N_{e^-}$	< 1
k_s-veto	$\notin (0.508, 0.488)[\mathrm{GeV}/c^2]$
$M(\eta')$	$(0.942, 0.974)[\mathrm{GeV}/c^2]$
π^0, η-veto	$\notin (0.115, 0.155), (0.524, 0.572)[\mathrm{GeV}/c^2]$
E_γ	> 100MeV
Σp_t	$< 0.1\mathrm{GeV}/c$

$\eta\pi\pi$ mode

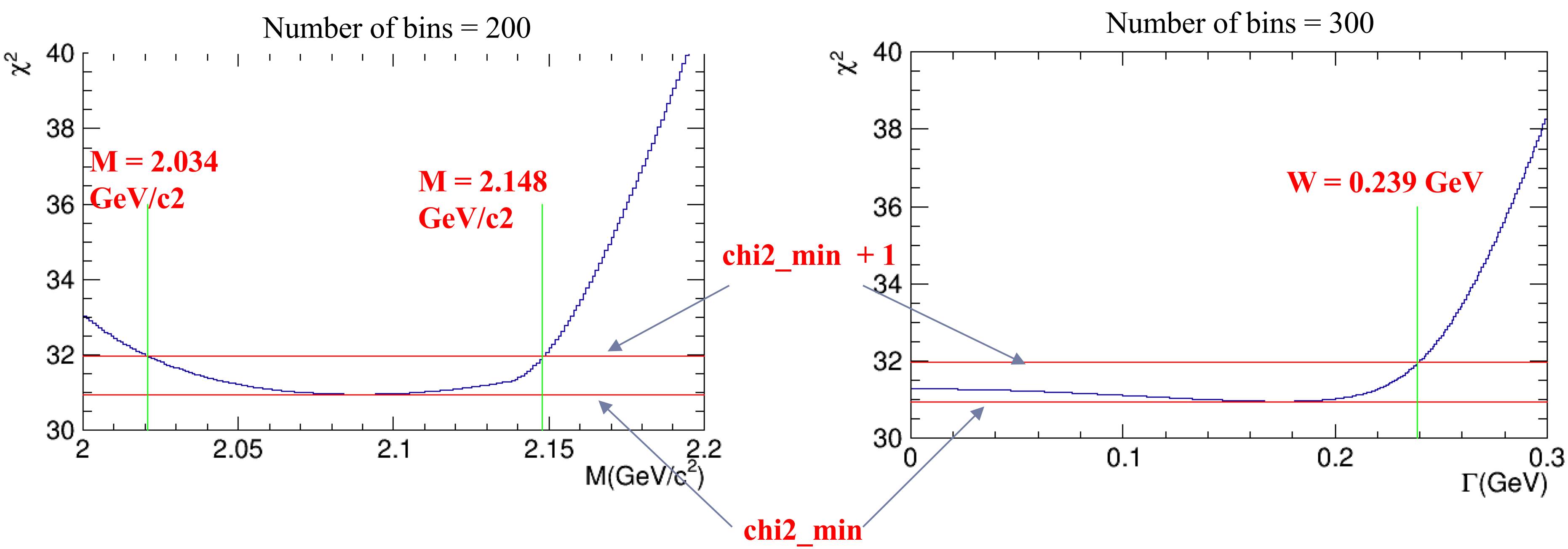
Variable	cut value
P_{sum}	$< 5.5\mathrm{GeV}/c$
E_{sum}	< 4.5GeV
N_{π^+}, N_{π^-}	2,2
N_{charge}	4
$N_{k^+} + N_{k^-}$	< 1
$N_{p^+} + N_{p^-}$	< 1
$N_{e^+} + N_{e^-}$	< 1
$k_s - veto$	$\notin (0.488, 0.508)[\mathrm{GeV}/c^2]$
$E(\gamma)$	> 100MeV
$M(\eta)$	$(0.524, 0.572)[\mathrm{GeV}/c^2]$
$M(\eta')$	$(0.951, 0.963)[\mathrm{GeV}/c^2]$
$\pi^0 - veto$	$\notin (0.115, 0.155)[\mathrm{GeV}/c^2]$
Σp_t	$< 0.15\mathrm{GeV}/c$

$|\Sigma P^*t|$ is optimized with the best $s/\sqrt{s+b}$ in $\eta_c(1s)$ and $\eta_c(2s)$ signal region.

From PDG 2017

	Branching fraction
$\eta_c(1S) \to K\bar{K}\pi$	$(7.3 \pm 0.5)\%$
$\eta_c(2S) \to K\bar{K}\pi$	$(1.9 \pm 1.2)\%$
$B \to K(\eta_c(1S) \to K_s K\pi)$	$(2.7 \pm 0.6)\times 10^{-5}$
$B \to K(\eta_c(2S) \to K_s K\pi)$	$(3.4^{+2.3}_{-16})\times 10^{-6}$

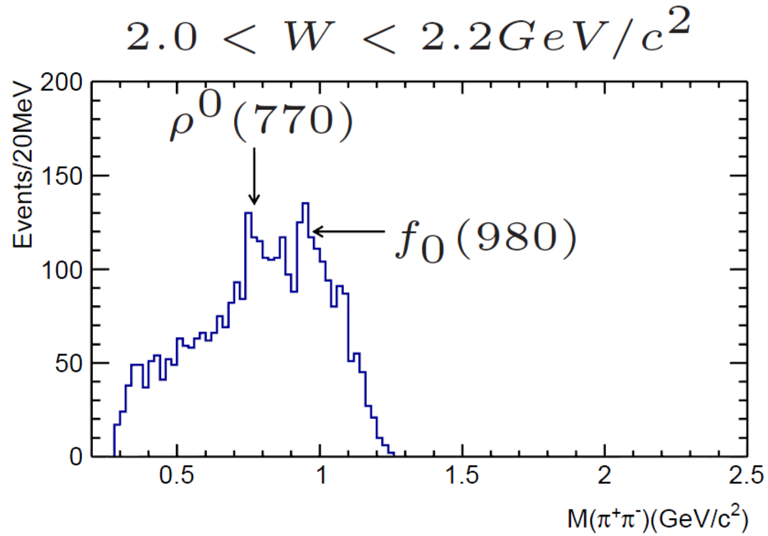
χ^2 scan for $f_0(2080)$ mass and width

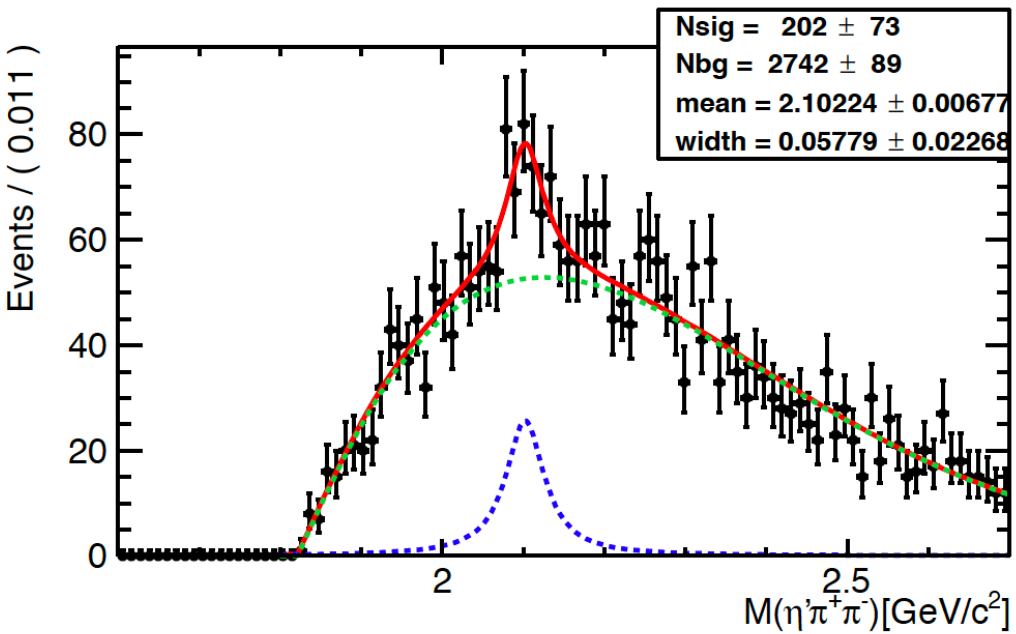


From the chi2 scan we get:
M = 2088 +60 -54 MeV/c2
W = 177 +62 -177 MeV
Which are comparable with the results from MINOS fit.

From MINOS fit:
M = 2083 +63 -67 MeV/c2
W = 178 +60 -178 MeV

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





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