

Two-Photon Collisions at Belle

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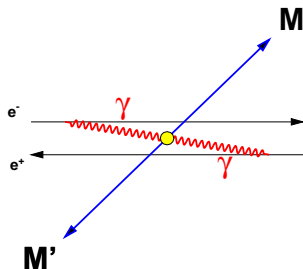
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Two-Photon Collisions at Belle

- $\gamma\gamma \rightarrow \omega\omega, \omega\phi, \phi\phi$
 - PRL108, 232001 (2012)
 - 870 fb^{-1}
 - Resonance Search, Charmonium and Cross Section measurement
- $\gamma\gamma \rightarrow \eta' \pi^+ \pi^-$
 - arXiv:1206.5087, submitted to PRD
 - 673 fb^{-1}
 - Resonance Search, η_c measurement
- $\gamma^* \gamma \rightarrow \pi^0$
 - arXiv:1205.3249, submitted to PRD
 - 759 fb^{-1}
 - Transition Form Factor measurement

No-tag Method at Belle

- e^+e^- escape down beam pipe at small recoil angles.
- Reactions involve small virtuality photons with $|\sum_i \vec{p}_t(M_i)| \sim 0$.
- $\frac{d\sigma}{d|\cos\theta^*|} = \frac{\Delta N}{\Delta W \Delta|\cos\theta^*| \frac{dL_{\gamma\gamma}}{dW} \text{effi} \int \mathcal{L} dt}$,
 $\frac{dL_{\gamma\gamma}}{dW}$: Luminosity Function
- For a resonance R , two-photon decay width $\Gamma_{\gamma\gamma}$ is measured from
$$\sigma(W) = 8\pi(2J+1) \frac{\Gamma_{\gamma\gamma}(R)\Gamma_R \mathcal{B}(R \rightarrow \text{final states})}{(W^2 - M_R^2)^2 + M_R^2 \Gamma_R^2}$$
- Applied to $\gamma\gamma \rightarrow VV$ and $\gamma\gamma \rightarrow \eta' \pi^+ \pi^-$ modes.

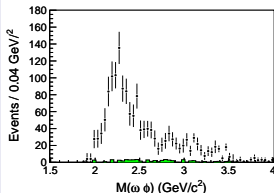


$$W = M(\gamma\gamma) = M(\text{Mesons})$$

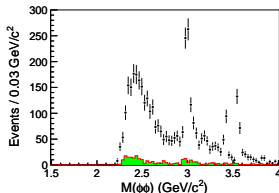
$\gamma\gamma \rightarrow \omega\omega, \omega\phi, \phi\phi$

- $\gamma\gamma \rightarrow \rho^0\rho^0$ [TASSO], $\phi\rho^0$ [ARGUS], $\rho^+\rho^-$ [CELLO, ARGUS], $\omega\phi$ [ARGUS], $\omega\omega$ [ARGUS], all with $< 1\text{fb}^{-1}$. $\phi\phi$ not measured.
- $\gamma\gamma \rightarrow VV$ generally peaks not far above threshold except $\gamma\gamma \rightarrow \rho^+\rho^-$. [PRD70, 034028 (2004) for review]
- First high statistics measurement with 870fb^{-1} .
- Signal by fitting $|\vec{p}_t(V) + \vec{p}_t(V')|$ for each invariant mass bin.
- $|\cos\theta^*| < 0.8$ for $\omega\phi$ and $\phi\phi$, full range for $\omega\omega$.
- non- ω and non- ϕ background from their sideband studies.

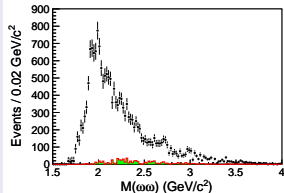
$\gamma\gamma \rightarrow \omega\phi$



$\gamma\gamma \rightarrow \phi\phi$



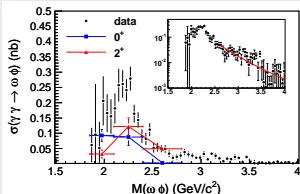
$\gamma\gamma \rightarrow \omega\omega$



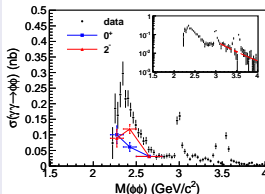
$\gamma\gamma \rightarrow \omega\omega, \omega\phi, \phi\phi$:

Structures in the lower energy region $M(VV) < 3$ GeV.

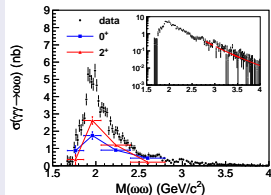
$\gamma\gamma \rightarrow \omega\phi$



$\gamma\gamma \rightarrow \phi\phi$



$\gamma\gamma \rightarrow \omega\omega$



- Structures are seen in lower invariant mass region

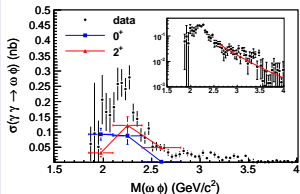
mode	peak [GeV/c ²]	nb
$\omega\phi$	~ 2.2	0.27 ± 0.05
$\phi\phi$	~ 2.35	0.30 ± 0.04
$\omega\omega$	~ 1.91	5.30 ± 0.42

- Theoretical predictions (tetraquark, t -channel factorization and one-pion-exchange models) disagree with our measurements.

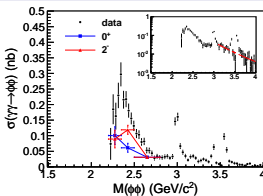
$\gamma\gamma \rightarrow \omega\omega, \omega\phi, \phi\phi$:

Structures in the lower energy region $M(VV) < 3$ GeV.

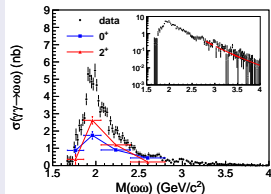
$\gamma\gamma \rightarrow \omega\phi$



$\gamma\gamma \rightarrow \phi\phi$



$\gamma\gamma \rightarrow \omega\omega$

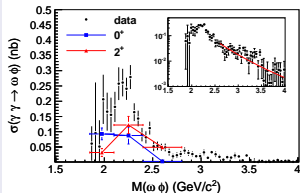


- Angular analysis for the observed structures

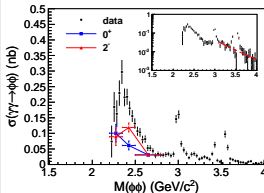
mode	$J^P (L)$	χ^2/NDF
$\omega\phi$	$0^+ (S \text{ wave})$	1.1
	$2^+ (S \text{ wave})$	1.2
	$0^+ (S \text{ wave})$ and $2^+ (S \text{ wave})$	0.9
$\phi\phi$	$0^+ (S \text{ wave})$ and $2^- (P \text{ wave})$	1.3

$\gamma\gamma \rightarrow \omega\omega, \omega\phi, \phi\phi$: W^{-n} dependence in higher energy region

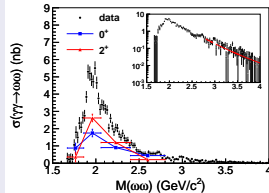
$\gamma\gamma \rightarrow \omega\phi$



$\gamma\gamma \rightarrow \phi\phi$



$\gamma\gamma \rightarrow \omega\omega$



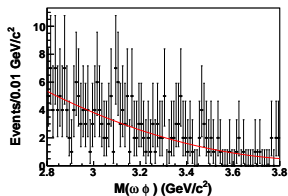
- $\sigma \propto W^{-n}$ in higher invariant mass region

mode	n	region [GeV/c^2]
$\omega\phi$	7.2 ± 0.6	> 3.2
$\phi\phi$	8.4 ± 1.1	> 3.1
$\omega\omega$	9.1 ± 0.6	> 2.8

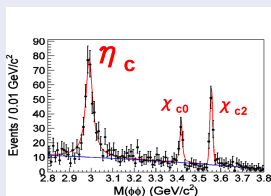
Consistent with (perturbative) QCD prediction, 6 - 10.

$\gamma\gamma \rightarrow \omega\omega, \omega\phi, \phi\phi$: Resonances in higher energy region

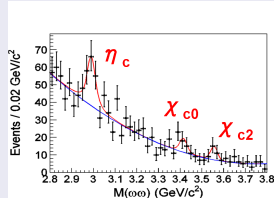
$\gamma\gamma \rightarrow \omega\phi$



$\gamma\gamma \rightarrow \phi\phi$



$\gamma\gamma \rightarrow \omega\omega$



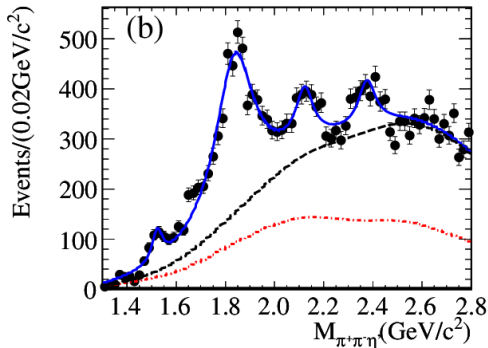
- No exotics.
- $\eta_c, \chi_{c0}, \chi_{c2}$ in $\phi\phi$, η_c in $\omega\omega$ seen.

mode	$\Gamma_{\gamma\gamma}\mathcal{B}$ [eV]	events
$\eta_c \rightarrow \phi\phi$	$7.75 \pm 0.66 \pm 0.62$	386 ± 31
$\chi_{c0} \rightarrow \phi\phi$	$1.72 \pm 0.33 \pm 0.14$	56 ± 11
$\chi_{c2} \rightarrow \phi\phi$	$0.62 \pm 0.07 \pm 0.05$	89 ± 11
$\eta_c \rightarrow \omega\omega$	$8.67 \pm 2.86 \pm 0.96$	85 ± 29

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

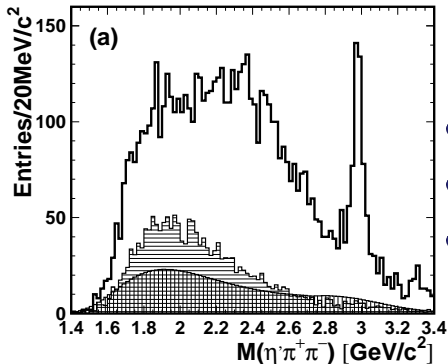
BESIII [PRL106, 072002 (2011)]

$X(1835)$, $X(2120)$, $X(2370)$



- BESII [PRL95, 262001 (2005)] and BESIII [PRL106, 072002 (2011)] observed $X(1835)$, $X(2120)$ and $X(2370)$ in $J/\psi \rightarrow \gamma[\eta' \pi^+ \pi^-]_X$.
- First measurement of $\gamma\gamma \rightarrow \eta' \pi^+ \pi^-$ mode.

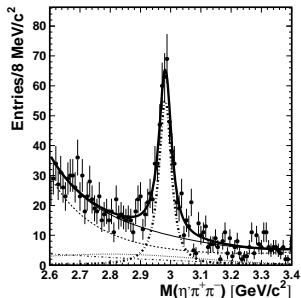
$\gamma\gamma \rightarrow \eta' \pi^+ \pi^-$



- $\eta' \rightarrow \eta \pi^+ \pi^-$, $\eta \rightarrow \gamma\gamma$
- $|\sum \vec{p}_t^*| < 0.9 \text{ GeV}/c$
- Clear η_c peak seen.

- Two background sources in $M(\eta' \pi^+ \pi^-)$ distribution.
 - non- η' : estimate from $M(\eta \pi^+ \pi^-)$ sideband
 - $|\sum \vec{p}_t^*|$ unbalanced background
 - \rightarrow Unbinned maximum likelihood fit
- Enhanced shoulder seen in lower region.

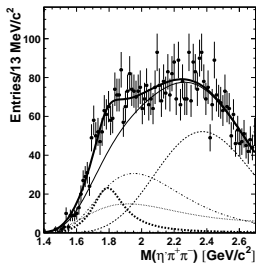
$\gamma\gamma \rightarrow \eta' \pi^+ \pi^-$: $\eta_c(1S)$ Measurement



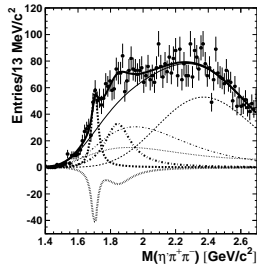
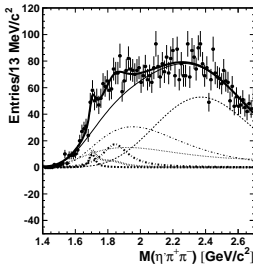
Parameters	This work	PDG
Yield	$486^{+40}_{-39} \pm 53$	
M , MeV/c^2	$2982.7 \pm 1.8 \pm 2.2$	2980.3 ± 1.2
Γ , MeV/c^2	$37.8^{+5.8}_{-5.3} \pm 2.8$	26.7 ± 3
$\Gamma_{\gamma\gamma} \mathcal{B}$, eV/c^2	$50.5^{+4.2}_{-4.1} \pm 5.6$	194 ± 97
\mathcal{B} , %	0.87 ± 0.20	2.7 ± 1.1

$\gamma\gamma \rightarrow \eta' \pi^+ \pi^-$: UML for lower energy region

One resonance



Two resonances with interference

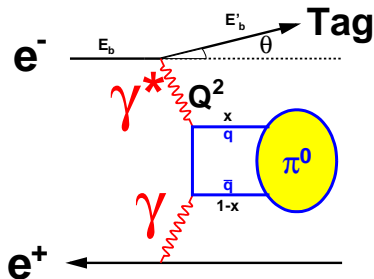


- Breit-Wigner for resonance peak.
- Two background and one non-resonant functions as the most conservative configuration among six different ones.
- Fit with one resonance or two coherent resonances.
 - Peak in one resonance fit consistent with $\eta(1760)$.
 - For fit with two resonances, peaks consistent with $\eta(1760)$ and $X(1835)$. Constructive and destructive solutions found.

$\gamma\gamma \rightarrow \eta' \pi^+ \pi^-$: Fit results for $\eta(1760)$ and $X(1835)$

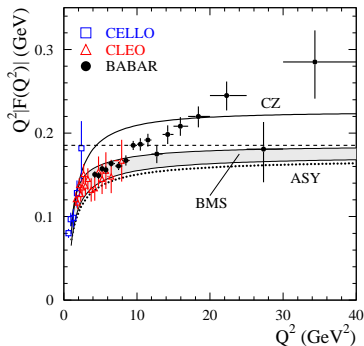
Parameter	One resonance	Two interfering resonances		Reference
		Solution I	Solution II	
$X(1835)$				
$M, \text{MeV}/c^2$		1836.5 (fixed)		$1836.5 \pm 3.0^{+5.6}_{-2.1}$ [BES]
$\Gamma, \text{MeV}/c^2$		190 (fixed)		$190 \pm 9^{+38}_{-36}$ [BES]
Yield		$332^{+140}_{-122} \pm 73$	$632^{+224}_{-231} \pm 139$	
Y_{90}		< 650	< 1490	
$\Gamma_{\gamma\gamma} \mathcal{B}, \text{eV}/c^2$		$18.2^{+7.7}_{-6.7} \pm 4.0$	$35^{+12}_{-13} \pm 8$	
$(\Gamma_{\gamma\gamma} \mathcal{B})_{90} \text{eV}/c^2$		< 35.6	< 83	
Significance, σ		2.8 (including syst.)		
$\eta(1760)$				
$M, \text{MeV}/c^2$	$1768^{+24}_{-25} \pm 10$	$1703^{+12}_{-11} \pm 1.8$		1756 ± 9 [PDG]
$\Gamma, \text{MeV}/c^2$	$224^{+62}_{-56} \pm 25$	$42^{+36}_{-22} \pm 15$		96 ± 70 [PDG]
Yield	$465^{+131}_{-124} \pm 60$	$52^{+35}_{-20} \pm 15$	$315^{+223}_{-165} \pm 88$	
$\Gamma_{\gamma\gamma} \mathcal{B}, \text{eV}/c^2$	$28.2^{+7.9}_{-7.5} \pm 3.7$	$3.0^{+2.0}_{-1.2} \pm 0.8$	$18^{+13}_{-10} \pm 5$	
Significance, σ	4.7	4.1		
ϕ		$(287^{+42}_{-51})^\circ$	$(139^{+19}_{-9})^\circ$	

Single-tag Method at Belle



- Reactions involve a virtual photon and a small virtuality photon with $|\vec{p}_t(\pi^0) + \vec{p}_t(e^\pm \text{tag})| \sim 0$
- Q^2 from tagged e^\pm , $Q^2 = 4E_b E'_b \sin^2 \frac{\theta}{2}$

$\gamma\gamma^* \rightarrow \pi^0$: π^0 Transition form factor

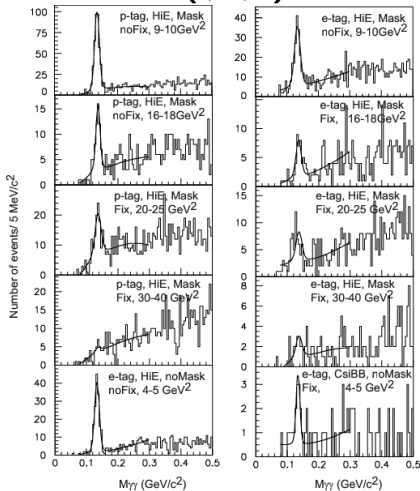


- π^0 transition form factor (TFF), coupling of π^0 with two-photons.
- Good test for QCD in high Q^2 region.
- $F(Q^2) = \frac{\sqrt{2}f_\pi}{3} \int T_H(x, Q^2, \mu) \phi_\pi(x, \mu) dx$.
- Measured with single-tag method in two-photon process.
- BaBar [PRD80, 052002, (2009)] with 442 fb^{-1} .
- Consistent with CLEO in $Q^2 < 8 \text{ GeV}^2$.
- **Larger than the asymptotic pQCD prediction in $Q^2 > 10 \text{ GeV}^2$.**
- BaBar's TFFs for η and η' consistent with pQCD.

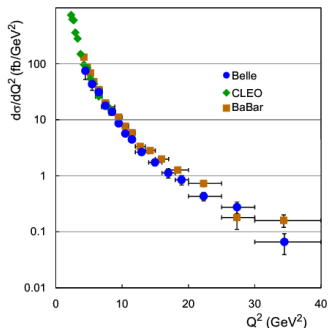
$\gamma\gamma^* \rightarrow \pi^0$: Signal Extraction

- Using 759 fb^{-1} , measure π^0 TFF in $4.0 \lesssim Q^2 \lesssim 40 \text{ GeV}^2$.
- Require final state of e^\pm , 2γ and no additional tracks or showers.
- Measure e^- (e-tag) or e^+ (p-tag) modes separately.
- $|\vec{p}_t(e^\pm) + \vec{p}_t(\gamma\gamma)| < 0.2 \text{ GeV}/c$.
- Signal yield is determined by fitting $M_{\gamma\gamma}$ for each Q^2 region.

$M(\gamma\gamma)$



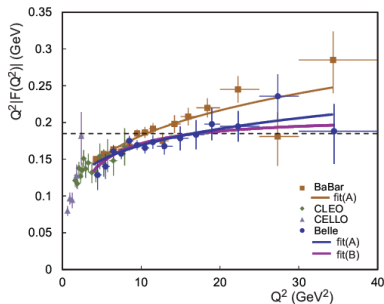
$\gamma\gamma^* \rightarrow \pi^0: d\sigma/dQ^2$



- $$\frac{d\sigma}{dQ^2} = \frac{N(1-r_b)}{\int L dt \epsilon \mathcal{B}(\pi^0 \rightarrow \gamma\gamma)(1+\delta)\Delta Q^2}$$

ϵ efficiency
 r_b background fraction
 δ radiative correction, +2%
- e-tag and p-tag results are consistent and hence are combined for the final measurement.

$\gamma\gamma^* \rightarrow \pi^0: Q^2|F(Q^2)|$



- $Q^2|F(Q^2)| = \frac{Q^2 \sqrt{(d\sigma/dQ^2)/(2A(Q^2))}}$
- $2A(Q^2)$ from QED [PRD4, 1532 (1971)]

- Growth in $Q^2 > 9 \text{ GeV}^2$ not seen, approaches to $0.209 \pm 0.016 \text{ GeV}$. Consistent with QCD value of 0.185 GeV (dashed line).

- fit(A): $Q^2|F(Q^2)| = BQ^2/(Q^2 + C)$

- fit(B): function by BaBar, $Q^2|F(Q^2)| = A(Q^2/10 \text{ GeV}^2)^\beta$

	A GeV	β
BaBar	$0.182 \pm 0.002 \pm 0.004$	0.25 ± 0.02
Belle	0.169 ± 0.006	0.18 ± 0.05

$\sim 1.5\sigma$ difference.

Summary

$$\gamma\gamma \rightarrow VV$$

- Cross sections for $\gamma\gamma \rightarrow \omega\phi$, $\gamma\gamma \rightarrow \omega\omega$ and $\gamma\gamma \rightarrow \phi\phi$ have been measured.
- Structures are seen near threshold in all three modes.
- Chamonia seen.
- No exotics.

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

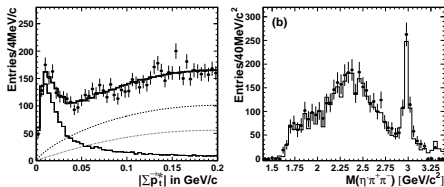
- First study of $\eta(1760)$ and $X(1835)$ in $\gamma\gamma \rightarrow \eta'\pi^+\pi^-$.
- Obtained first evidence for $\eta(1760) \rightarrow \eta'\pi^+\pi^-$
- Signal of $X(1835)$ is marginal, 2.8σ .

$$\gamma\gamma^* \rightarrow \pi^0$$

- π^0 TFF has been measured in $4 \text{ GeV}^2 \lesssim Q^2 \lesssim 40 \text{ GeV}^2$.
- Consistent with QCD asymptotic value.
- Rapid growth seen in $Q^2 > 9 \text{ GeV}^2$ by BaBar is not confirmed.

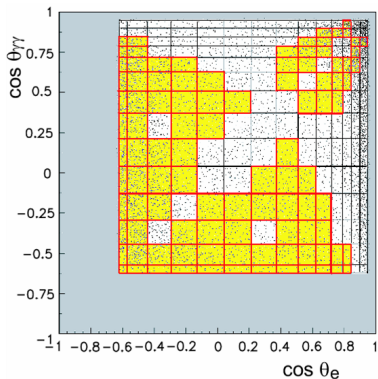
Backup Slides

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



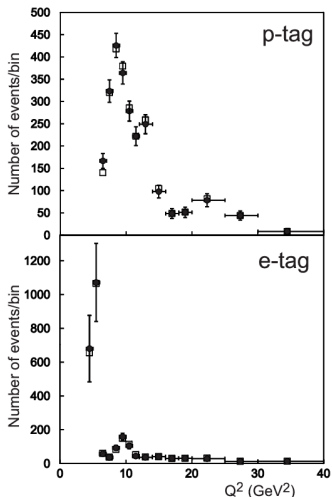
- Check of background estimation
 - Signal yield estimation from fitting $|\sum \vec{p}_t^*|$
- Good agreement.

$\gamma\gamma^* \rightarrow \pi^0$: π^0 Transition form factor measurement



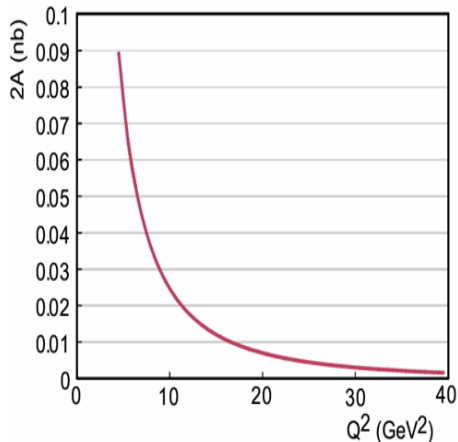
- $|E_{\gamma 1} - E_{\gamma 2}|/E_{\gamma\gamma} < 0.8$ and $E_{\gamma\gamma}|\theta_{\gamma 1} - \theta_{\gamma 2}| > 1.8$ reject large Radiative Bhabha ($(e)e\gamma$) background
- Bhabha-veto trigger causes low efficiency region in $\cos \theta_{\gamma\gamma}$ vs $\cos \theta_{e^\pm}$ plane.
- Select events in yellow region only.

$\gamma\gamma^* \rightarrow \pi^0$: π^0 Transition form factor measurement



- Signal yields. Unfolding applied.
- Efficiency from signal MC
 - Trigger simulator tuning using real data from Virtual Compton process (e) $e\gamma$ $\sim O(1\text{nb})$.
 - Validity check and systematic estimation using Rabhat generator

$\gamma\gamma^* \rightarrow \pi^0: Q^2|F(Q^2)|$



$2A(Q^2)$ from QED [PRD4, 1532 (1971)]