Particle production in two-photon collisions at Belle

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Belle Collaboration

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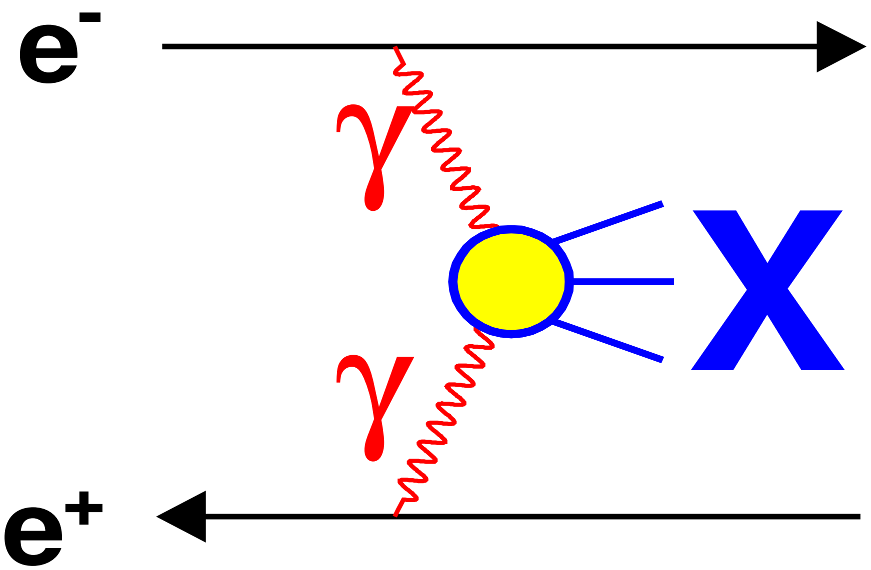
1. **Two-Photon process at Belle**
2. $\gamma\gamma \to \eta\eta$
3. $\gamma\gamma \to \eta_c(2S) \to$ 6prong
4. Summary

Two-photon processes at Belle



- No-tag method
  - Event where beam particles escape to beam pipes with small scattering angle
  - Apply tight transverse momentum cut to select exclusive two-photon events
  - Small virtuality, almost real photons → Measurement of $\Gamma_{\gamma\gamma}$
  - $\gamma\gamma$ axis ≈ e^+e^- axis

Derivation of physics parameters

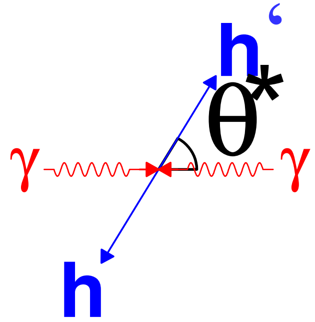
- **Differential cross section and invariant mass spectrum for $\gamma\gamma \to \eta\eta$**

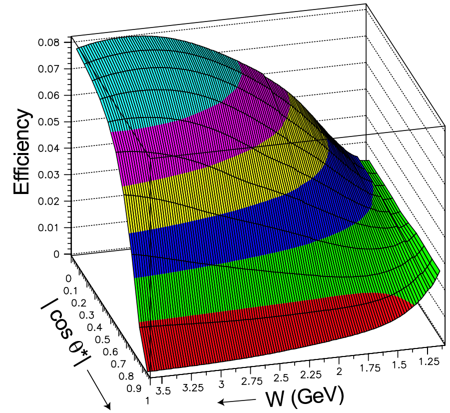
$$\frac{d\sigma}{d|\cos\theta^*|} = \frac{\Delta Y - \Delta B}{\Delta W \Delta|\cos\theta^*|\,\varepsilon \frac{dL_{\gamma\gamma}}{dW}\int L dt}$$

$$\sigma(W) = \Sigma \frac{d\sigma}{d|\cos\theta^*|}\Delta|\cos\theta^*|$$

W=M(γγ)=M(final state)

ε : Efficiency from signal MC





- **Amplitude for resonance with two-photon decay width $\Gamma_{\gamma\gamma}$**

$$A_R^J(W) = \sqrt{\frac{8\pi(2J+1)m_R}{W}}\frac{\sqrt{\Gamma(W)\Gamma_{\gamma\gamma}(W)Br(R\to\eta\eta)}}{m_R^2 - W^2 - im_R\Gamma(W)}$$

Luminosity function

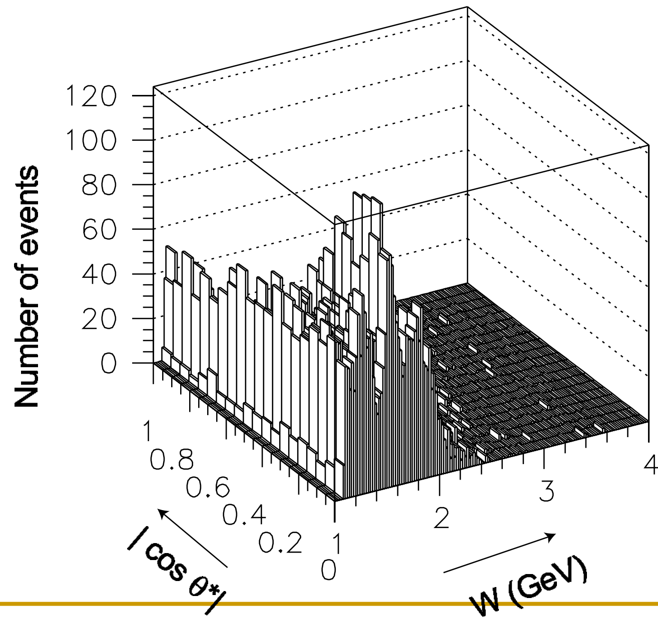
$$\sigma(e^+e^- \to e^+e^- X) = \int \sigma_{\gamma\gamma\to X}(W)\frac{dL_{\gamma\gamma}}{dW}dW$$

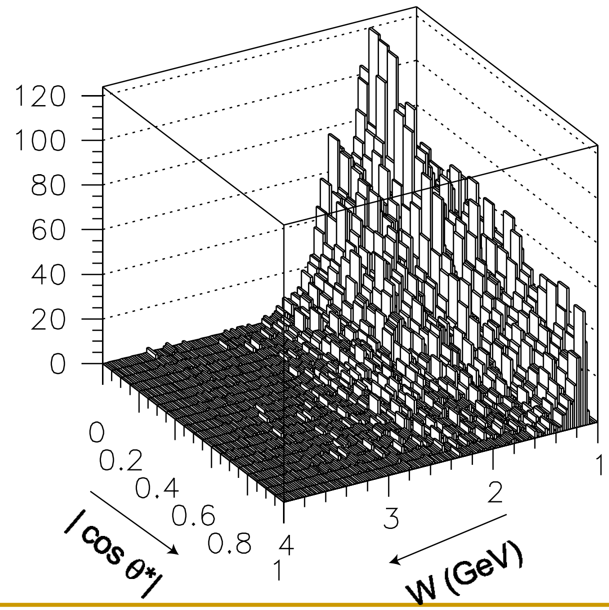
- $\gamma\gamma \rightarrow \eta\eta$
  - 393/fb
  - First measurement

Event Selection

- All neutral final state ($\eta \to \gamma\gamma$ mode only)
- Triggered by Energy sum (>1.15GeV) and cluster counting (>110 MeV for each) information from Electromagnetic Calorimeter
- Just 4 γ's with E_γ>100MeV
  - 2 combinations with 0.52 GeV< $M(\gamma\gamma)$ <0.57 GeV
- π^0 –veto, charged (p_t>0.1GeV/c)-veto
- Scale E_γ with factor $m_\eta/M(\gamma\gamma)$
- $|\Sigma p_t^*| < 50$ MeV/c

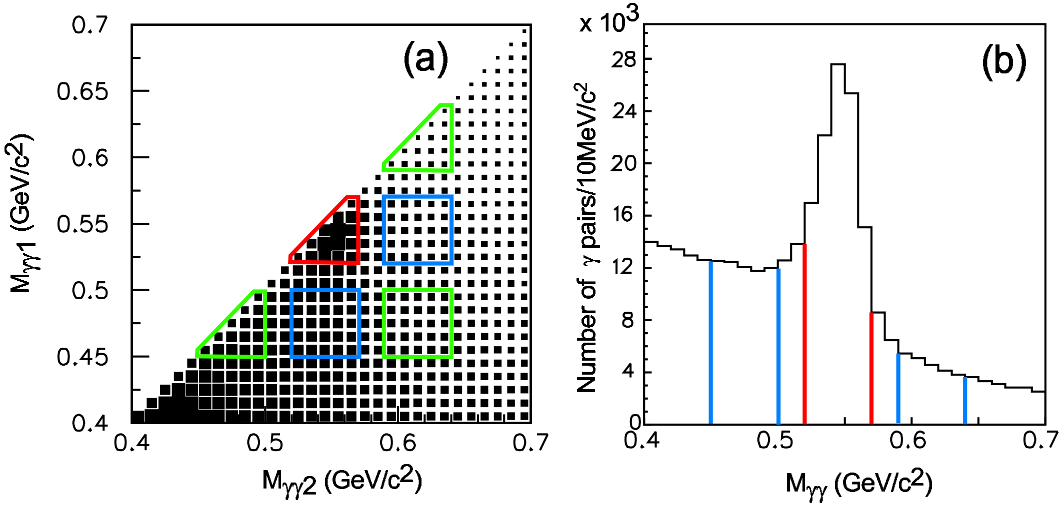
31655 candidates
in W<4.0GeV

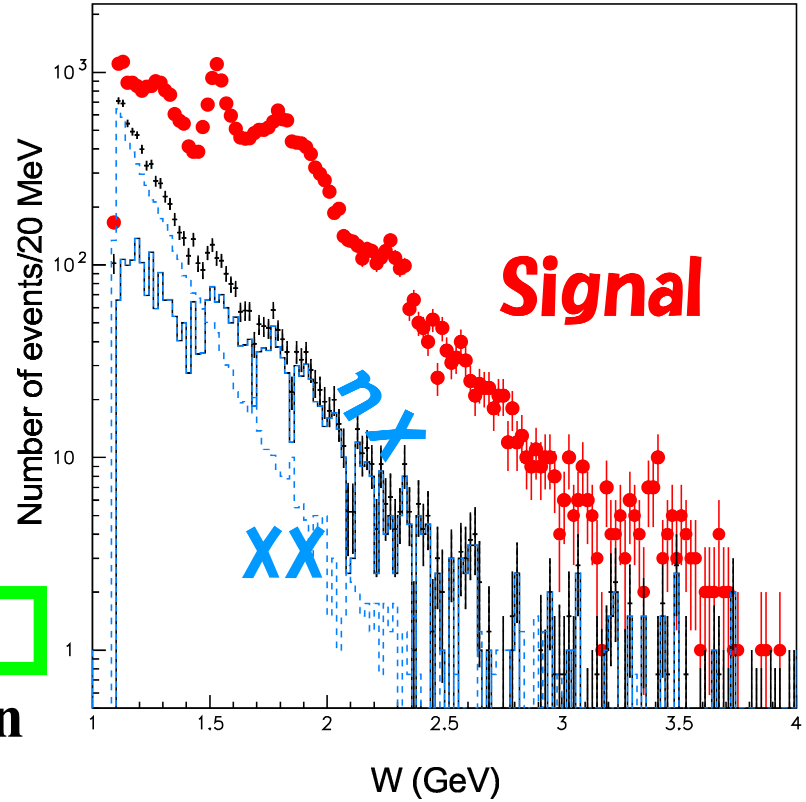




Background subtraction

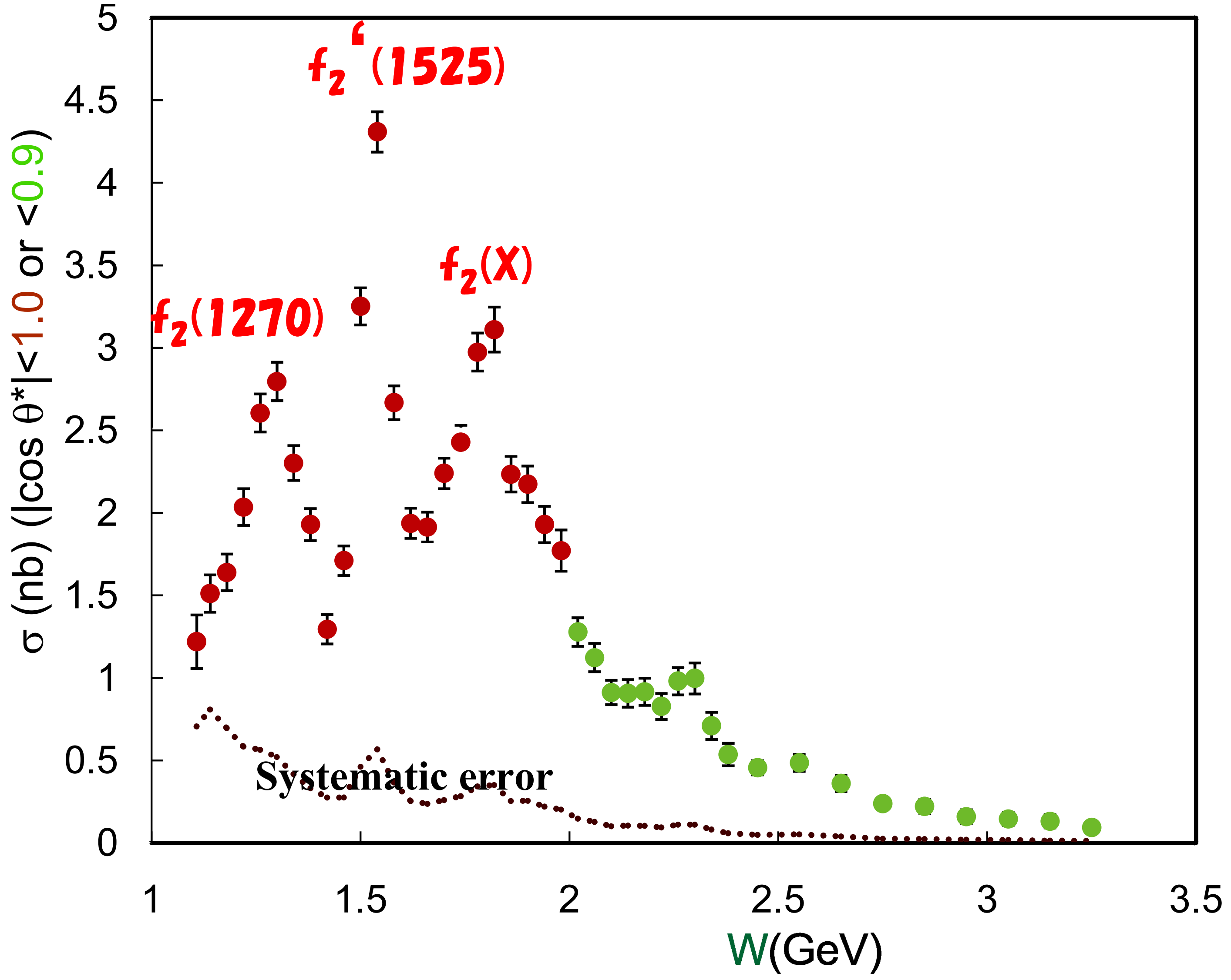
- Background from $\eta\eta$X where X is missed is small
- Estimate ηX and XX ($\eta \neq$X) background using M($\gamma\gamma$) sideband.





- Total Background = 0.5* - 0.25*
- Subtract in each ΔW-Δ|cosθ*| bin

Cross Section for $\gamma\gamma \rightarrow \eta\eta$

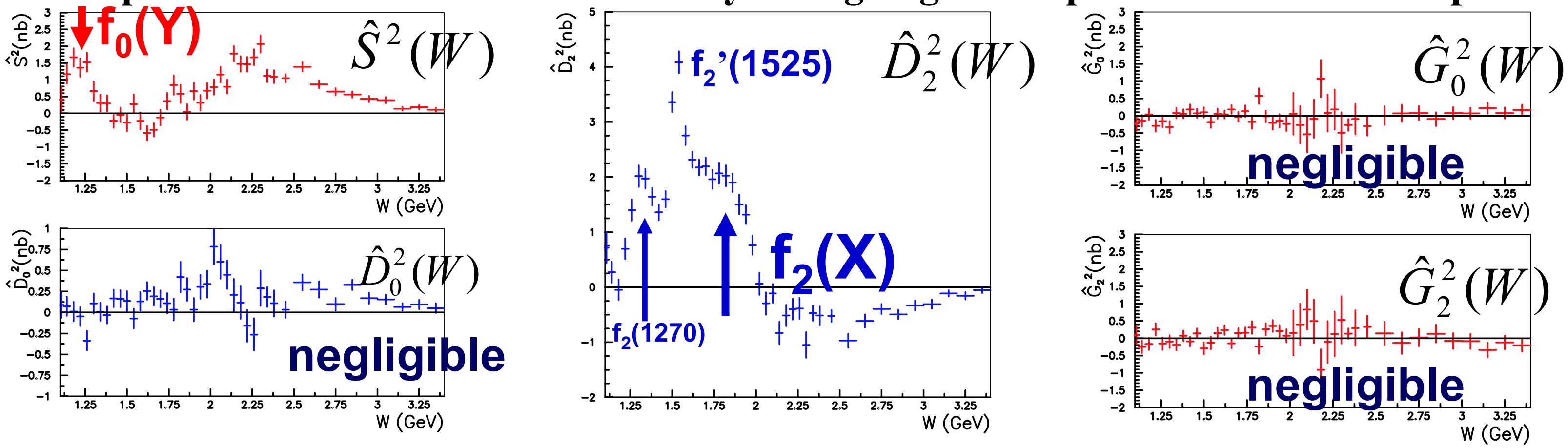


Partial Wave Analysis and Resonant Substructure in $\eta\ \eta$

$$\frac{d\sigma}{4\pi d|\cos\theta *|} = |SY_0^0 + D_0Y_2^0 + G_0Y_4^0|^2 + |D_2Y_2^2 + G_2Y_4^2|^2$$

$$= \hat{S}^2|Y_0^0|^2 + \hat{D}_0^2|Y_2^0|^2 + \hat{D}_2^2|Y_2^2|^2 + \hat{G}_0^2|Y_4^0|^2 + \hat{G}_2^2|Y_4^2|^2$$

- **W dependence of each wave obtained by fitting angular dependence for each W point**



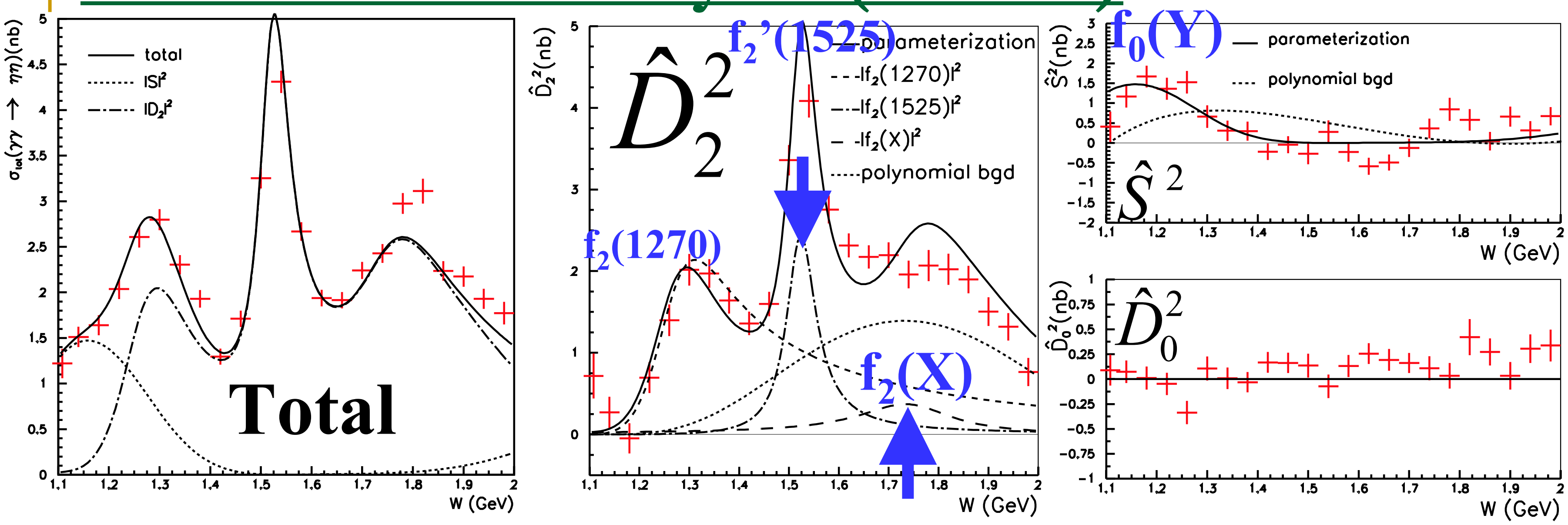
- **Based on information above, perform 2D fit for 1.12 < W < 2.0 GeV with**

$$S(W) = A_{f_0(Y)}e^{i\phi_Y} + B_S$$

$$D_2(W) = A_{f_2(1270)}e^{i\phi_2} + A_{f_2'(1525)}e^{i\phi_5} + A_{f_2(X)}e^{i\phi_X} + B_{D_2}$$

A: Breit-Wigner Resonance
B: Coherent Background

Partial Wave Analysis (results)

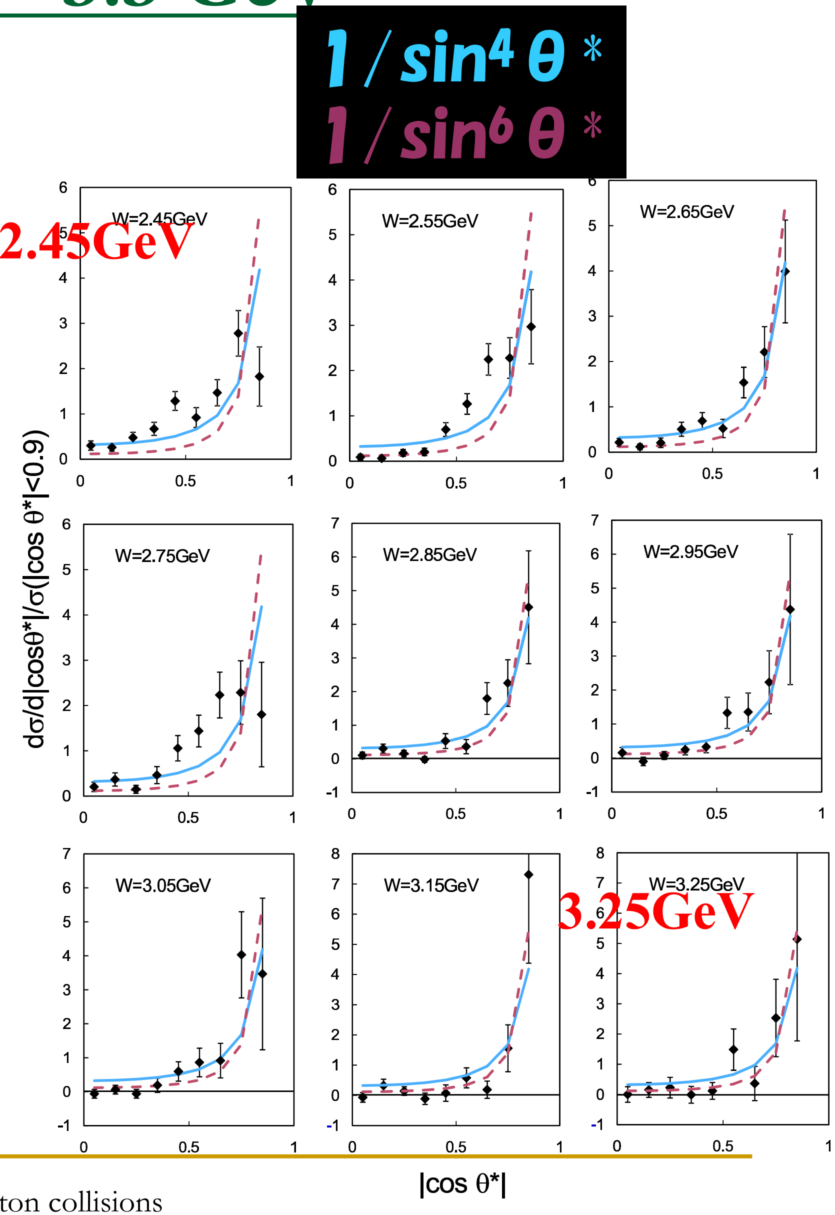


M (f_2(X))	$1742 \pm 9\ ^{+198}_{-65}$ MeV/c²
Γ (f_2(X))	$228\ ^{+21}_{-20}\ ^{+234}_{-153}$ MeV
$\Gamma_{\gamma\gamma}$(f_2(X)) B(η η)	$5.2\ ^{+0.9}_{-0.8}\ ^{+37.3}_{-4.5}$ eV
M (f_0(Y))	$1262\ ^{+51}_{-78}\ ^{+82}_{-103}$ MeV/c²
Γ (f_0(Y))	$484\ ^{+246}_{-170}\ ^{+246}_{-263}$ MeV
$\Gamma_{\gamma\gamma}$(f_0(Y)) B(η η)	$121\ ^{+133}_{-53}\ ^{+169}_{-106}$ eV
$\Gamma_{\gamma\gamma}$(f_2(1270)) B(η η)	$11.5\ ^{+1.8}_{-2.0}\ ^{+4.5}_{-3.7}$ eV

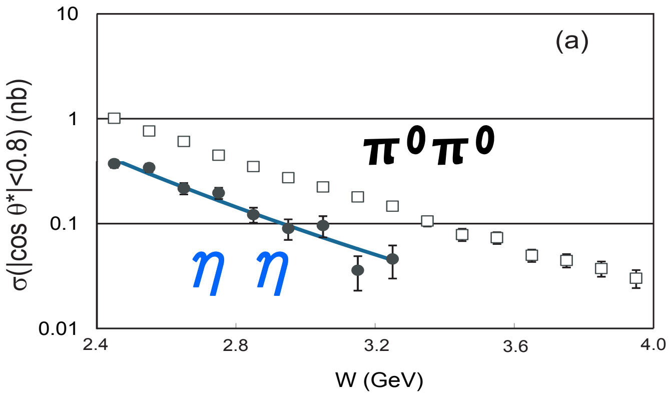
Angular dependence in 2.4 – 3.3 GeV

- $1/\sin^4\theta^*$ poor agreement with $\eta\eta$, though agrees with $\pi^0\pi^0$ and other modes for W>3.1GeV.
- $\eta\eta$ close to $1/\sin^6\theta^*$ for W>3.0 GeV

→ May imply different production mechanism from $\pi^0\pi^0$ and other modes



Cross Section: Comparison with (p)QCD in 2.4 – 3.3 GeV

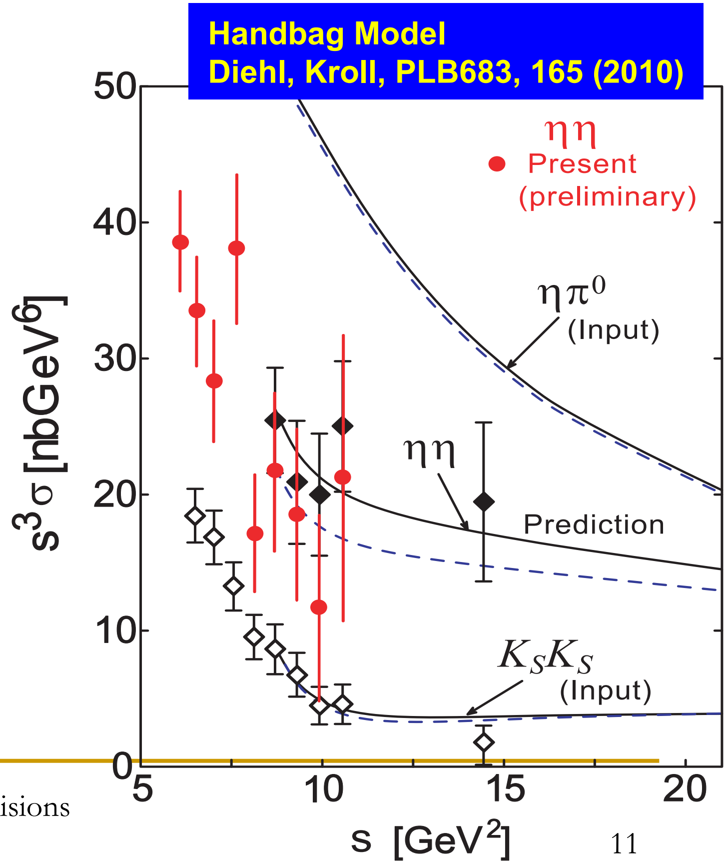


- $\sigma(W) \sim W^{-n}$
  - n=7.8 ±0.6±0.4 ($\eta\eta$)
  - n=8.0±0.5±0.4 ($\pi^0\pi^0$: PRD79, 052009(2009))
- Handbag model
  - SU(3) flavor symmetry and charge counting
  - Agrees well with the present study

- **pQCD prediction for σ ratio by Brodsky, Lepage (PRD24, 1808 (1981))**

η in SU(3)	$\sigma(\eta\pi^0)/\sigma(\pi^0\pi^0)$	$\sigma(\eta\eta)/\sigma(\pi^0\pi^0)$
Octet	0.24 R_f	0.36 R_f^2
θ_P= - 18°	0.46 R_f	0.62 R_f^2
Measure-ment	0.48±0.05±0.04 (PRD80, 032001(2009))	0.37±0.02±0.03
	3.1 < W < 4.0 GeV	2.4 < W < 3.3 GeV

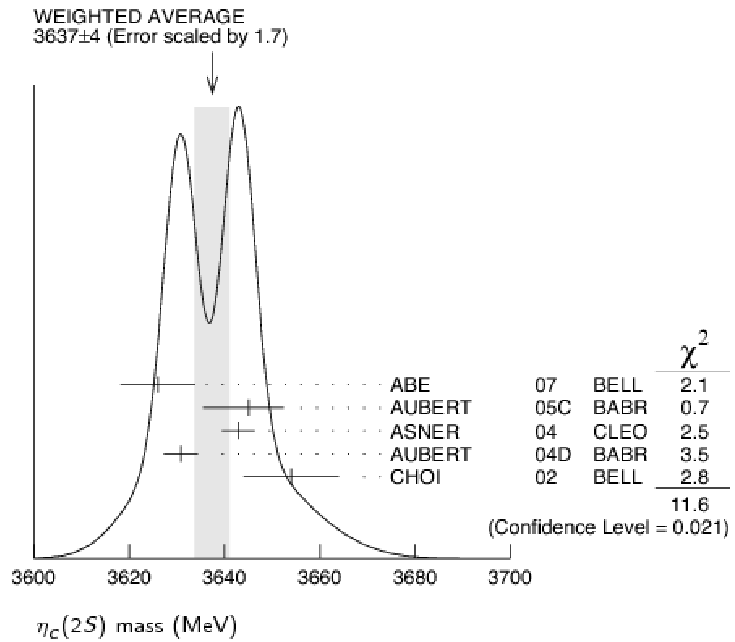
$R_f=(f_\eta/f_\pi)^2$



- $\gamma\gamma \to \eta_c(2S) \to$ 6-prong
  - 923/fb
  - First measurement of $\eta_c(2S)$ decay to 6-prong

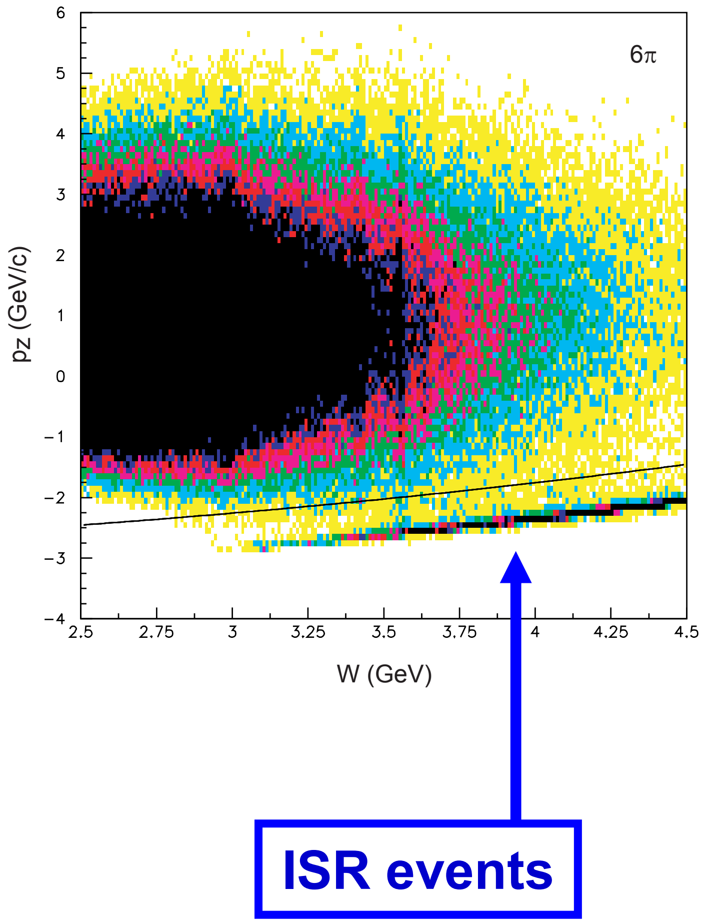
Current situation of $\eta_c(2S)$

- Only one exclusive decay mode, $K\bar{K}\pi$
- Not seen in 4-meson final state (Belle EPJC53, 1 (2008))
- World average
  - M=3637±4 MeV/c^2
    - Not quite consistent
  - Γ=14±7 MeV
    - Large error

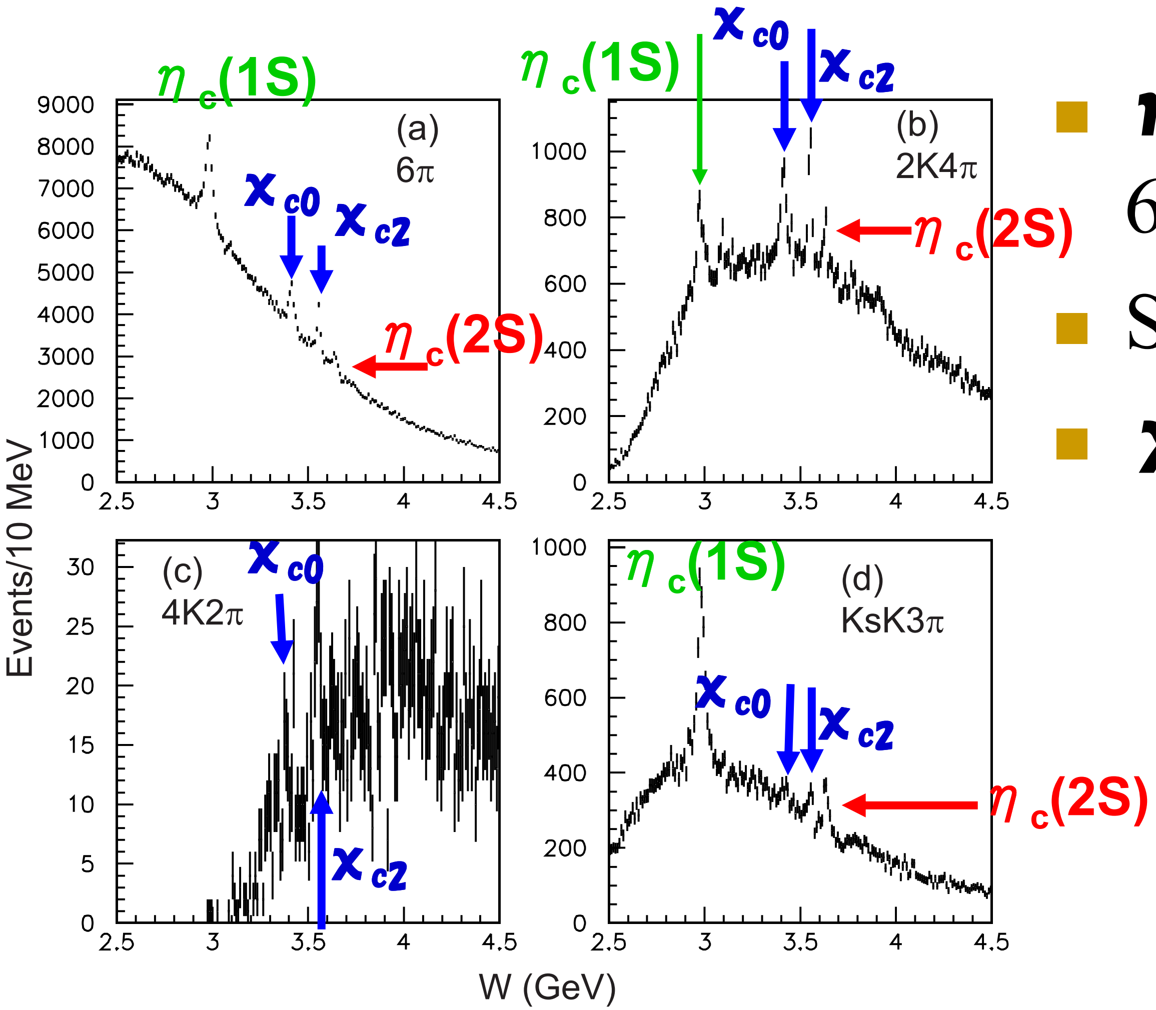


Event Selection

- 4 modes – all charged final states
  - 6π (π+π-π+π-π+π-),
  - 2K4π (K+K-π+π-π+π-),
  - 4K2π (K+K-K+K-π+π-),
  - K_SK3π (K_SK+π-π+π-)
- ISR events are rejected with Σ p_z
- |Σ p_t^*| < 100 MeV/c

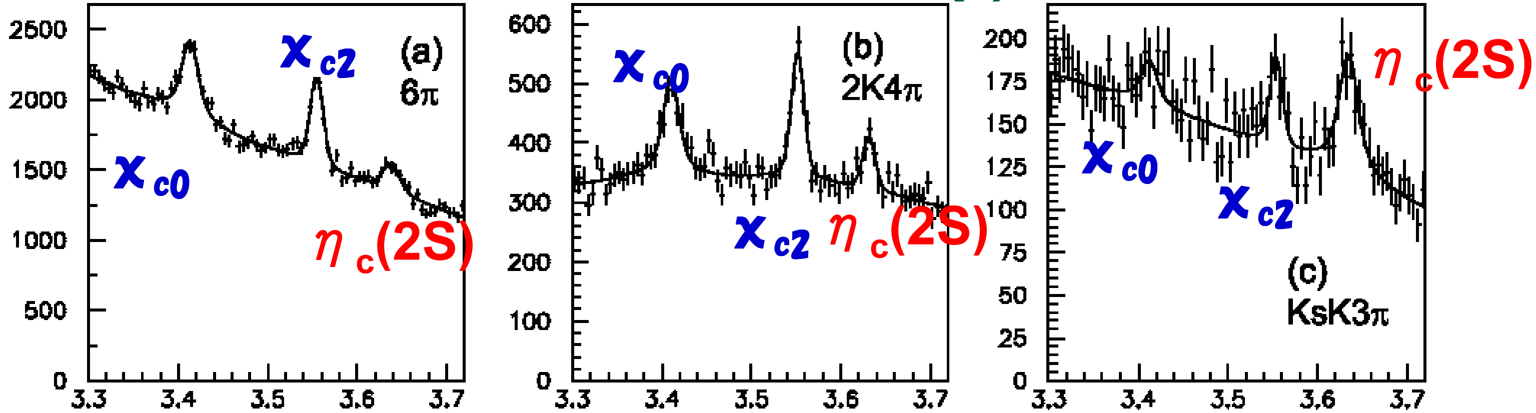


Raw mass spectra



- η_c(2S) seen in 6π,2K4π,K_SK3π
- So is η_c(1S)
- χ_{c0}, χ_{c2} seen in all 4 modes

Fits to the charmonia region



- Interference not taken into account
- Relativistic Breit-Wigner with double-Gaussian smearing, plus 2nd polynomial
- χ_{c0}, χ_{c2} with χ_{c2} masses floated as reference

Preliminary results

First observations

	$M(\eta_c(2S))$ MeV/c²	$\Gamma(\eta_c(2S))$ MeV	Ev($\eta_c(2S)$)	Signi.	$\Gamma_{\gamma\gamma}B(\eta_c(2S))$ eV
6π	3638.9±1.6±2.3	10.7±4.9	1485±274	8.5 σ	20.1±3.7±3.2
$2K4\pi$	3634.7±1.6±2.8	$1.4^{+6.3}_{-1.4}$, <13 (90%C.L.)	407±91	6.2 σ	10.2±2.3±3.4
$K_SK3\pi$	3636.5±1.8±2.4	15.9±5.7	563±71	8.7 σ	30.7±3.9±3.7
Average	3636.9±1.1±2.5±5.0	9.9±3.2±2.6±2.0			

Uncertainty from possible interference

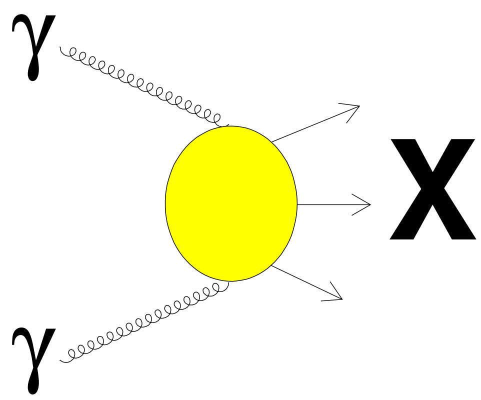
Good agreement of $M(\chi_{c2})$ among 3 modes and PDG

Summary

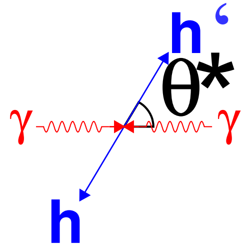
- Differential Cross Section for $\gamma\gamma \to \eta\eta$ measured for the first time
  - f_J mesons have been studied using Partial Wave Analysis
    - $f_0(Y)$, $f_2(X)$ were required
  - Comparison of $\sigma(\eta\eta)$, $\sigma(\eta\eta)/\sigma(\pi^0\pi^0)$ with (p)QCD for $2.4 < W < 3.3$ GeV
- New decay modes $\eta_c(2S)$ to $3(\pi^+\pi^-)$, $K^+K^-2(\pi^+\pi^-)$, $K_SK^+\pi^-\pi^+\pi^-$ observed in two-photon collision
  - Probably $\Gamma(\eta c(2S)) < \Gamma(\eta c(1S))$.
  - $\eta c(1S) \to K_SK3\pi$,
    $\chi_{c0} \to 2K4\pi$, $KsK3\pi$,
    $\chi_{c2} \to 2K4\pi$, $4K2\pi$, $KsK3\pi$
    clearly seen for the first time

Two-photon Process

- Process with almost real photons
- (Differential) Cross section at $W \gtrsim 2.4$ GeV
  - pQCD leading-order calculation for hadron pair production
    - $\sigma(\gamma\gamma \to h\,h') \sim W^{-n}$ $(W \to \infty)$
      - n = 6 for charged meson pair
      - n = 10 for baryon pair
    - $d\sigma / d|\cos\theta^*| \sim \sin^{-4}\theta^*$ for charged meson pair
      - Consistent with $\gamma\gamma \to \pi^+\pi^-$, K^+K^- for W>3.1 GeV
      - Handbag model (non pQCD) ~ $\sin^{-4}\theta^*$ also for neutral pair
- Resonance study
  - C=even (↔ C=odd for X in $e^+e^- \to X$), $J \neq 1$
  - Comparison with calculations for $\Gamma_{\gamma\gamma}$
  - $W \leq 3.0$GeV
    - Light meson study by Partial Wave Analysis
      - Provides information to solve light scalar meson puzzle
  - $W \geq 3.0$GeV
    - Charmonium study, XYZ search



$W = M(\gamma\gamma) = M(X)$



$\gamma\gamma \to \eta\eta$: Systematic Errors (%)

Trigger efficiency	4
eta-pair reconstruction efficiency	6
Pt-balance cut	3
Sideband background subtraction	2-27 (W>1.2GeV)
	28-60(W<1.2GeV)
Pt-unbalanced background subtraction	2
Luminosity function and integrated Luminosity	4-5
Overlapping hits from beam background etc.	3-4
Without unfolding	4-7
Other efficiency errors	4
Overall	11-29 (W>1.2GeV)
	30-61 (W<1.2GeV)

Partial Wave Analysis (formalism)

$$\frac{d\sigma}{4\pi d|\cos\theta*|} = |SY_0^0|^2 + |D_2Y_2^2|^2 = \hat{S}^2|Y_0^0|^2 + \hat{D}_2^2|Y_2^2|^2$$

$$S(W) = A_{f_0(Y)}e^{i\phi_Y} + B_S e^{i\phi_S}$$

$$D_2(W) = A_{f_2(1270)}e^{i\phi_2} + A_{f_2'(1525)}e^{i\phi_5} + B_{D_2} + A_{f_2(X)}$$

- **Y_J^λ(|cos θ *|) : Spherical Harmonics with spin J, helicity λ**
- **B_L(W) coherent background with 2nd-polynomial of W* β ^(2J+1)**
- **From pre-study**
    - **Contributions from G-waves (J=4) and $\hat{D}_0^2(W)$ are small**
    - **Introduce f_0(Y) for structure found in lower energy region in $\hat{S}^2(W)$**
    - **Introduce f_2(X) for structure found around 1.8GeV in $\hat{D}_2^2(W)$**
- **Fit**
    - **At first, fit 1.12 GeV < W < 1.64 GeV (below f_2(X) region)**
        - **Fixing f_2(1270) and f_2'(1525) parameters to nominal values, except $\Gamma_{\gamma\gamma}$(f_2(1270)) B (η η)**
    - **Then, fit 1.16 GeV < W < 2.0 GeV (up to f_2(X) region)**
        - **Fixing parameters to values obtained from the first step**