Lineshape of $e^+e^- \to \phi\eta$ around the J/ψ peak and phase angle between strong and EM amplitudes of J/ψ decay

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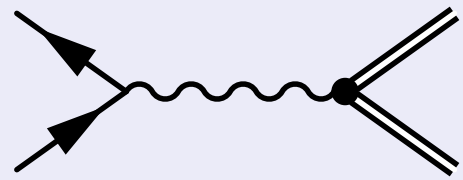
Motivation

- The energy shape of cross-section in the region close to J/ψ production is determined by interference between:
  - non-resonant production:
    $e^+e^- \to \gamma \to hadrons$
  - resonant production:
    $e^+e^- \to J/\psi \to \gamma \to hadrons$
    $e^+e^- \to J/\psi \to 3gluons \to hadrons$

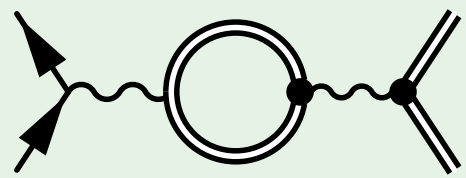
  Our goal is to study the phase between strong and electromagnetic (EM) amplitudes in J/ψ decays

- Meanwhile there are no precise data on the measurement of cross-sections of process $e^+e^- \to \phi\eta$ in the region of energy $\sim 3\text{GeV}/c$

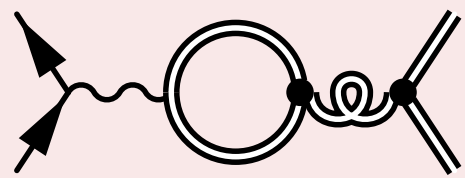
$e^+e^- \to \gamma \to hadrons$



$e^+e^- \to J/\psi \to \gamma \to hh$



$e^+e^- \to J/\psi \to 3g \to hh$



Data Sets

Requested Energy (MeV)	List of runs	BEMS (MeV)	Int.Lum. (pb^{-1})
3050.0	28312 - 28346	3050.213±0.026	14.919±0.161
3060.0	28347 - 28381	3059.257±0.028	15.060±0.161
3080.0	28241 - 28266	3080.195±0.023	17.393±0.193
3083.0	28382-28387; 28466-28469	3083.060±0.043	4.769±0.055
3090.0	28388-28416; 28472-28475	3089.418±0.022	15.558±0.165
3093.0	28417-28453; 28476-28478	3092.324±0.025	14.910±0.160
3094.3	28479 - 28482	3095.261±0.084	2.143±0.025
3095.2	28487 - 28489	3095.994±0.081	1.816±0.021
3095.8	28490 - 28492	3096.390±0.075	2.135±0.025
3096.9	28493 - 28495	3097.777±0.076	2.069±0.026
3098.2	28496 - 28498	3098.904±0.075	2.203±0.026
3099.0	28499 - 28501	3099.606±0.093	0.756±0.011
3101.5	28504 - 28505	3101.923±0.106	1.612±0.021
3105.5	28506 - 28509	3106.144±0.090	2.106±0.025
3112.0	28510 - 28511	3112.615±0.093	1.720±0.021
3120.0	28512 - 28513	3120.442±0.115	1.264±0.016
3080.0	39355 - 39618	—	126.210±0.896

Data

Data Sets:

- We use DST for J/ψ-scan 2012 reconstructed using BOSS 6.6.4
- for R-scan 2015 – BOSS 6.6.5

BEMS – beam energy measurement system:

- We used the measurements of BEMS as described in `http://docbes3.ihep.ac.cn/DocDB/0002/000249/003/RelPhase_Energy_03.pdf`
- There are no BEMS measurements for R-scan data 3080MeV and we used $\mathbf{3080 \pm 1MeV}$
- The energy values were further shifted by -0.55 ± 0.03MeV; *see "Measurement of J/ψ resonance parameters through scan data" (BAM-00268) and "Phase between strong and EM amplitudes in the lineshape of J/ψ resonance" (BAM-00128)*

Data

Integrated Luminosity Measurements:

- We used luminosity from BAM-00157: "Measurement of luminosity for R scan", $e^+e^- \to \gamma\gamma$ process
- Luminosity for R-scan data (2015) are taken from `http://docbes3.ihep.ac.cn/cgi-bin/DocDB/ShowDocument?docid=653`

Monte Carlo

- Monte-Carlo are simulated and reconstructed under BOSS 6.6.4

Signal

We used modified version of MCGPJ (Monte-Carlo Generator of Photon Jets - Eur.Phys.J.C 46,2006,p.689)

- The program allows to take into account ISR photons with an accuracy better than 1%
- We changed MCGPJ by adding the studied processes and the possibility of describing the interference between strong and EM amplitudes
- 150K events in each energy point

Background

- Inclusive MC for J/ψ-decays (3097MeV)
- KKMC generation for energy 3080MeV

Event Selection: $e^+e^- \to \phi\eta$ ($\phi \to K^+K^-$; $\eta \to \gamma\gamma$)

Two opposite charged tracks:

- $|R_{xy}| \leq 1$ cm; $|R_z| \leq 10$ cm
- $cos(\Theta) \leq 0.93$
- PID: $Prob(K) > Prob(\pi)||Prob(proton)$; $Prob(K) > 0.001$

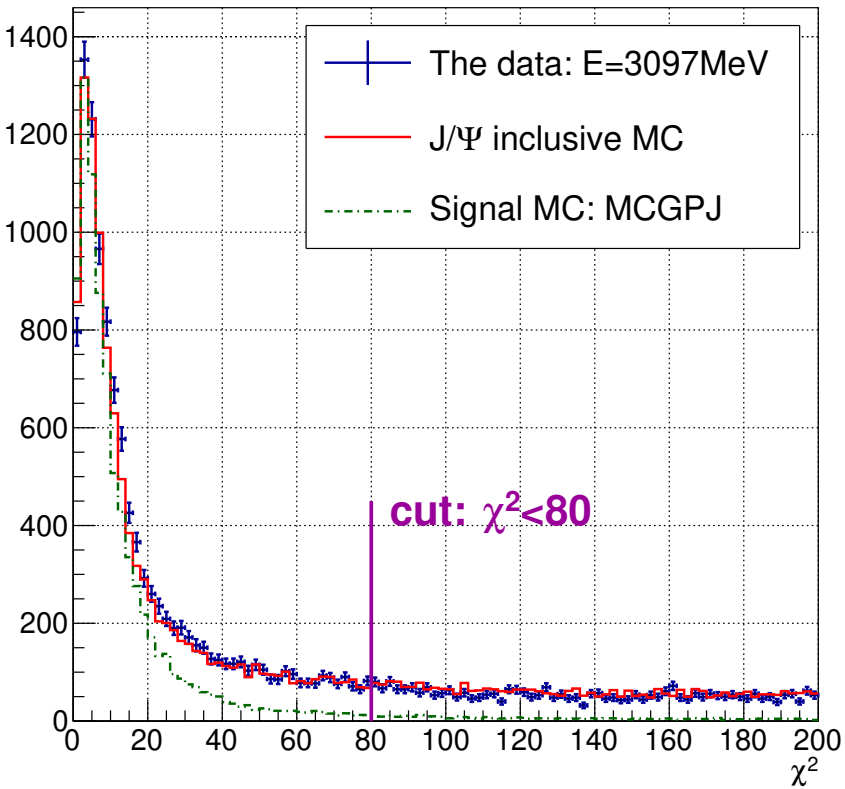
At least two photons:

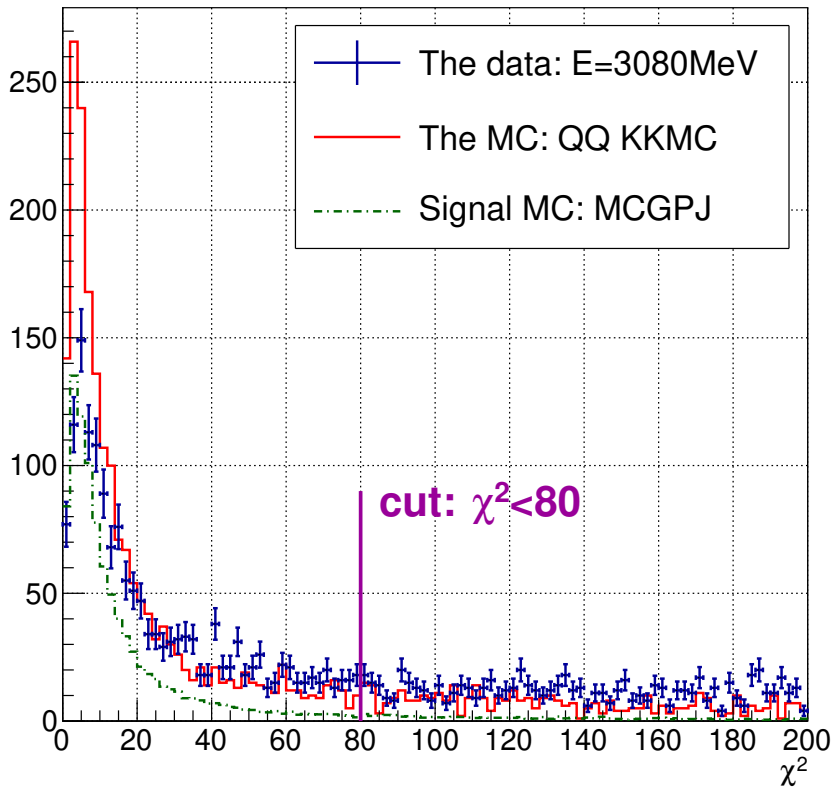
- $E_\gamma > 25$ MeV (barrel EMC) or $E_\gamma > 50$ MeV (end-cap EMC)
- $\alpha_\gamma > 10°$- the angle relative to the nearest charged track

4C kinematic fit under $K^+K^-\gamma\gamma$ hypothesis:

- Choosing the best two photons with the smallest $\chi^2(4C)$
- $\chi^2(4C) < 80$

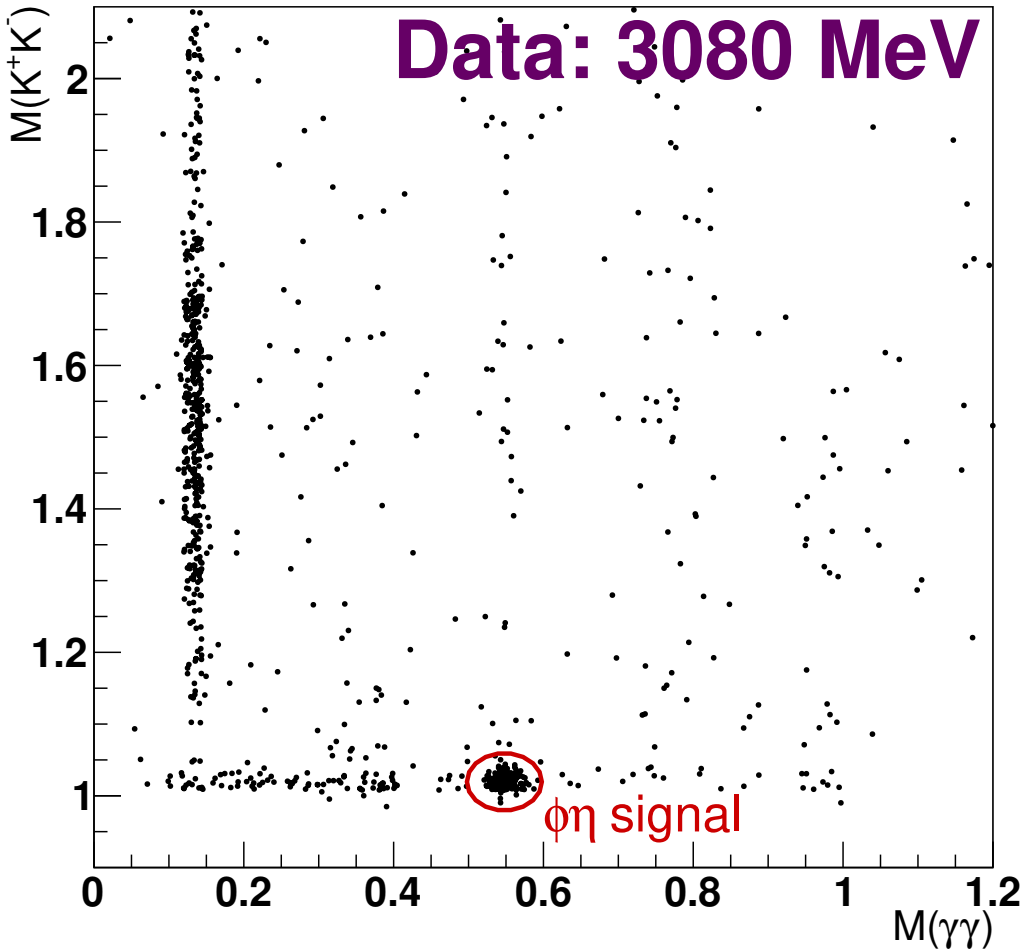
4C – Kinematic fit: χ^2 Data vs MC





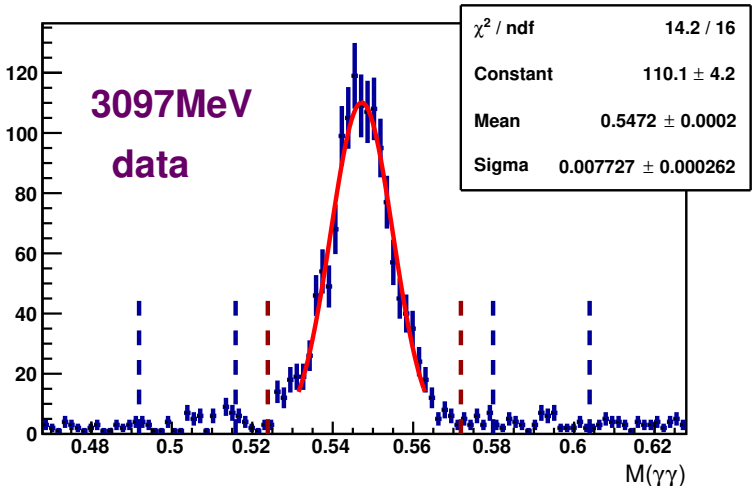
- Good agreement between data and inclusive MC for 3097MeV
- Signal MC shows that cut $\chi^2 < 80$ removes the background tail

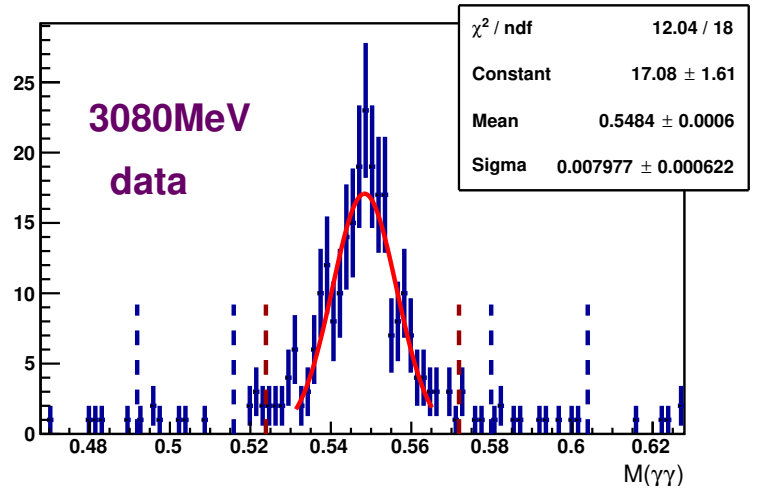
Invariant masses of η and ϕ

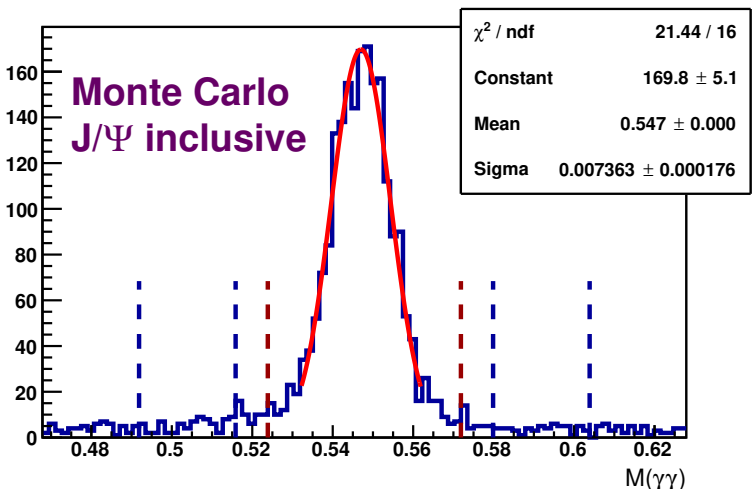


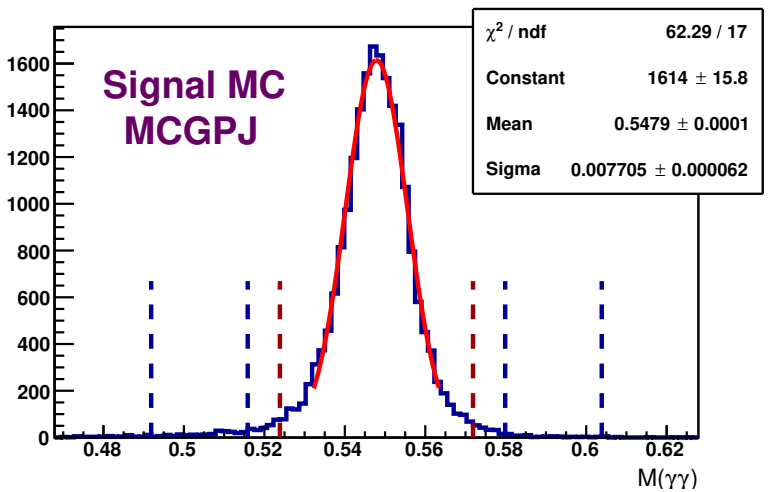
- We see $\phi\eta$ signal after $\chi^2 < 80$ cut

Invariant mass of $\eta \to \gamma\gamma$



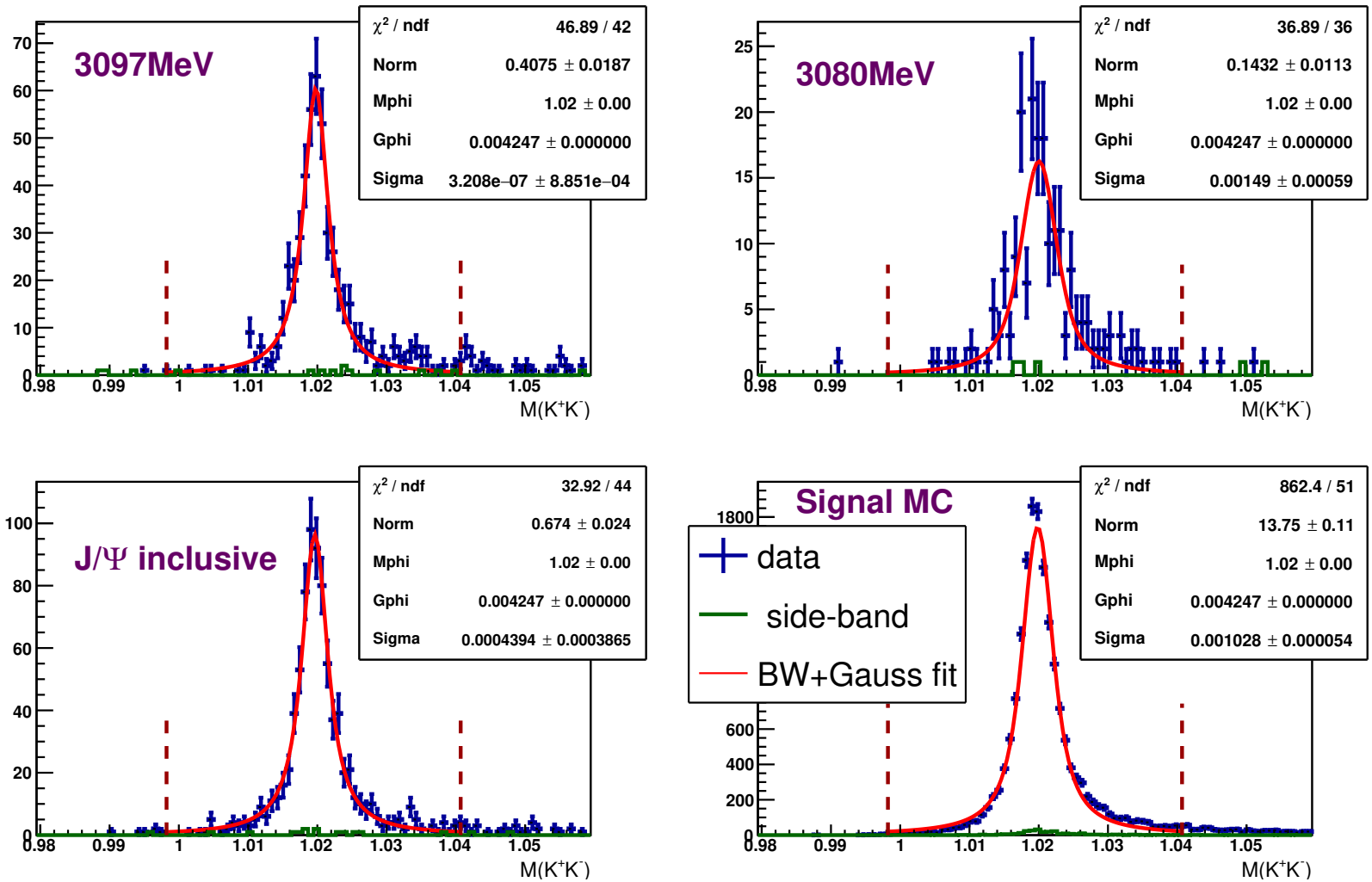






- The distributions fit with Gauss: $\sigma(\eta) \sim 8$ MeV independent of the beam energy
- The dashed lines show the selection window and side bands

Invariant mass of $\phi \to K^+K^-$



- The distributions fit with Breit-Wigner convoluted with Gauss
- The side-band events (green) show there is no peaking background
- The dashed lines show the selection window

Event Selection (continue)

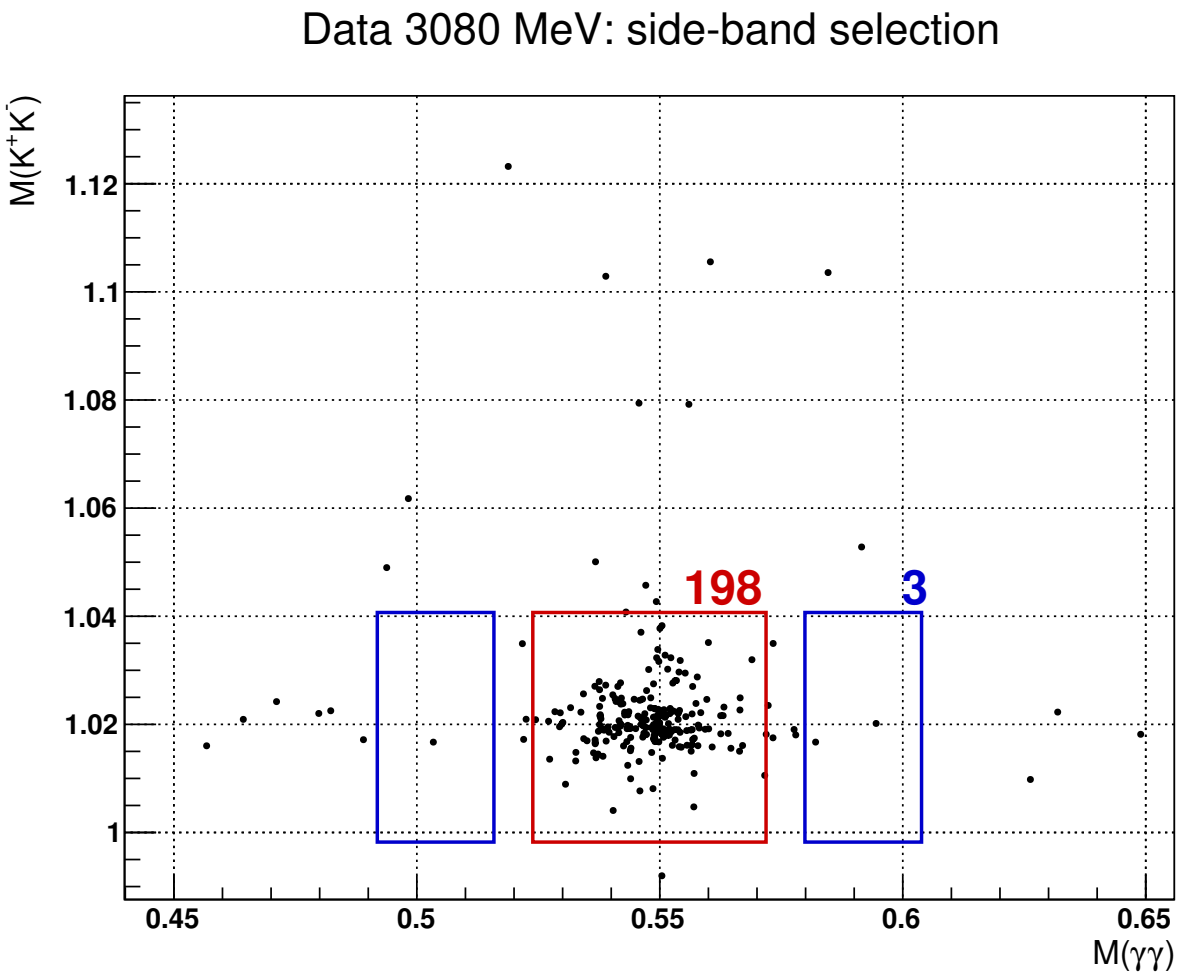
Side-band subtraction for $M(\gamma\gamma)$

- The central part is
$$|M(\gamma\gamma) - M_\eta)| < 3\sigma(\eta)$$
- The background is estimated as the sum of the side band regions:
$$4\sigma(\eta) < |M(\gamma\gamma) - M_\eta)| < 7\sigma(\eta)$$
- $\sigma(\eta) = 8$ MeV

Selection of $M(K^+K^-)$

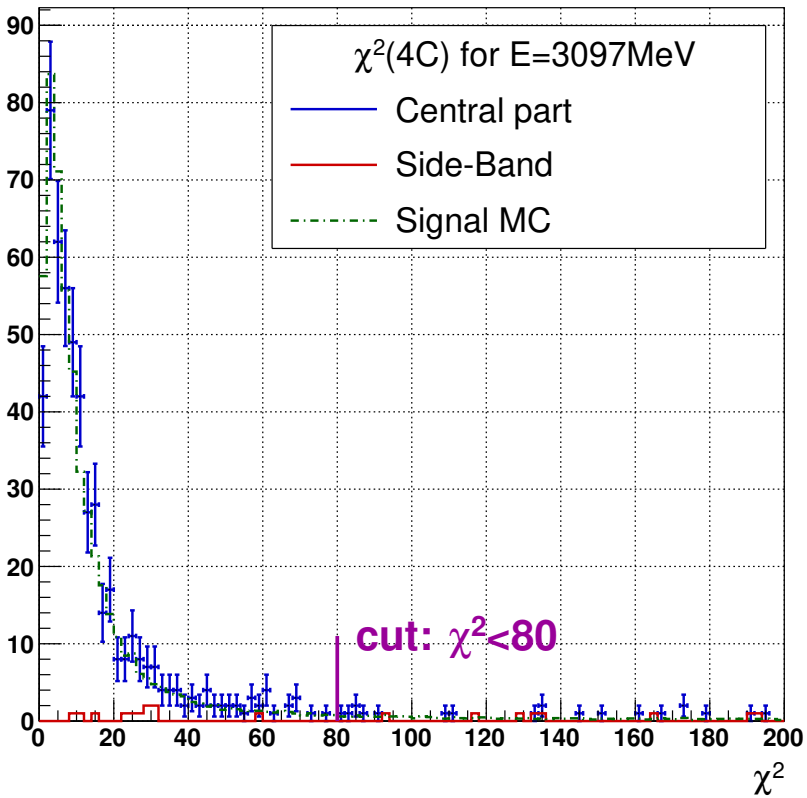
- We use loose selection criteria:
$$|M(K^+K^-) - M_\phi)| < 5 \times \Gamma_\phi$$
- $\Gamma_\phi = 4.247$ MeV

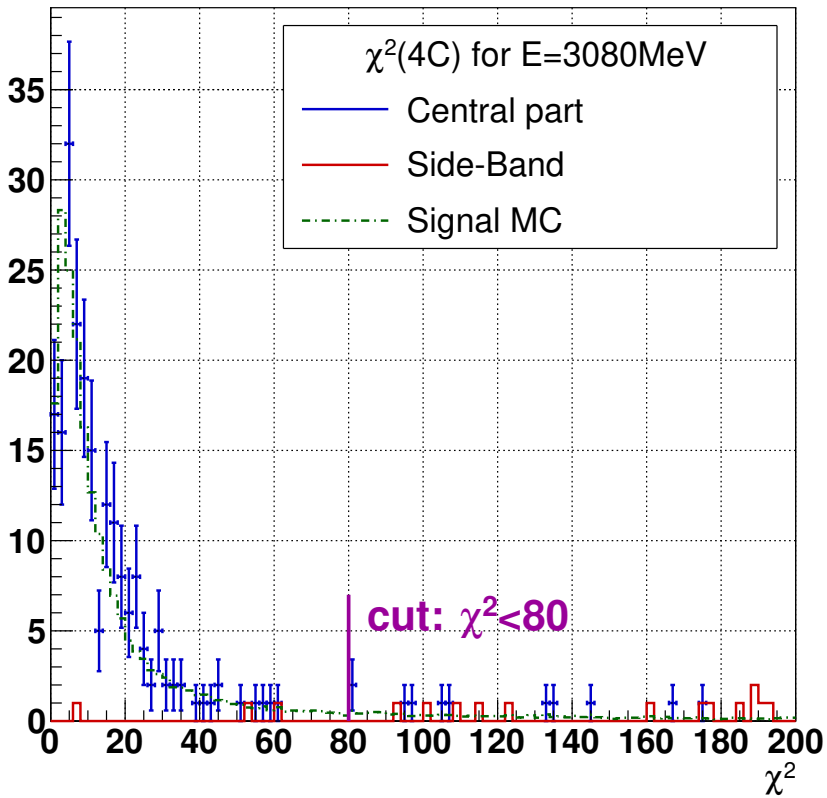
Example of side-band for data



- The red rectangle is the central part and the blue rectangles are the side-band region

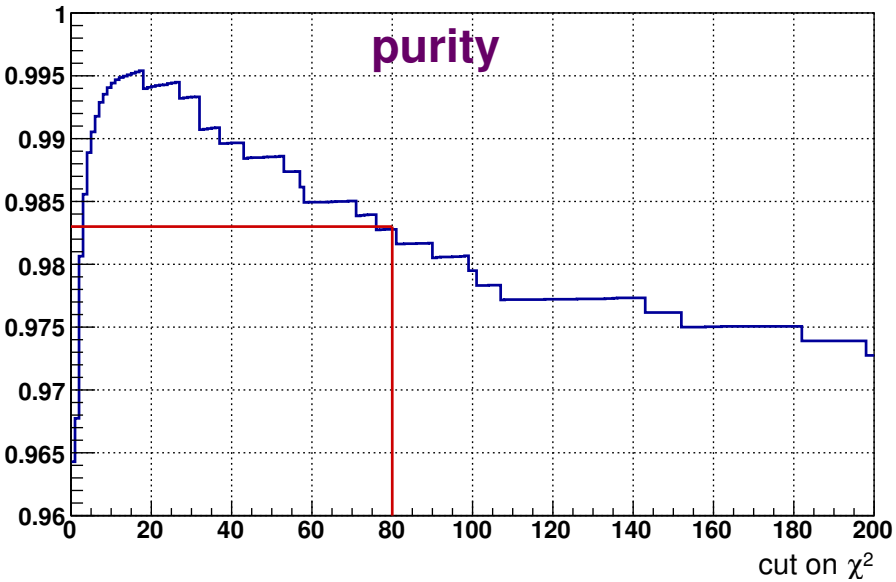
$\chi^2(4C)$ for signal and side-band events

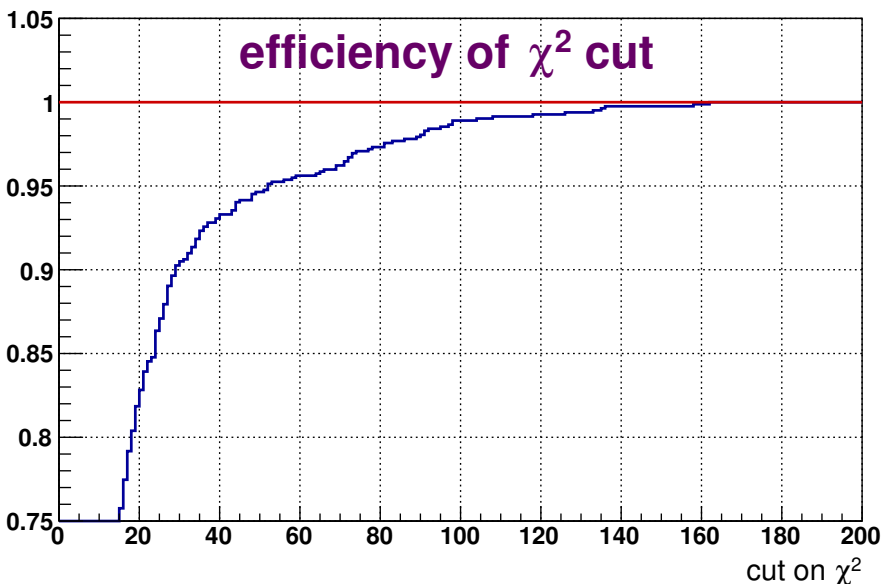




- Good agreement between data and signal MC
- Backgrounds estimated by side-band events are small

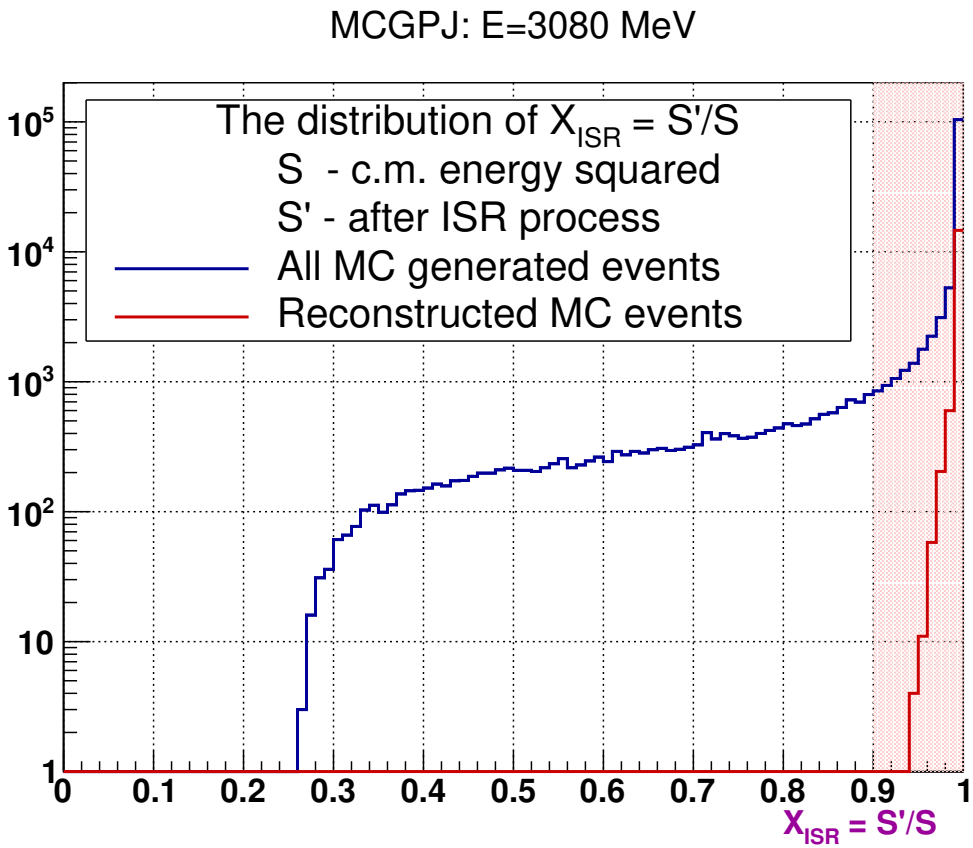
Background study (3097 MeV; inclusive J/ψ MC)





- Cut on $\chi^2(4C)$ is the last cut
- The purity and efficiency shown as a function of $\chi^2(4C)$ cut
- The background is less than 2% for $\chi^2(4C) < 80$

Reconstruction of ISR events



- Only events with $X_{ISR} > 0.9$ pass selection cuts
- If we would report the cross-section for the whole X_{ISR} region, we would completely rely on correction from MCGPJ generator
- To avoid this we choose $X_{ISR} > 0.9$ as a signal definition region

Cross Section of $e^+e^- \to \phi\eta$

Note: efficiency includes $Br(\eta \to 2\gamma) = 39.4\%$

$X_{ISR} > 0.9$; statistical errors only

E(GeV)	Lum.(pb^{-1})	Signal	Eff.(%)	Cross Section(nb)
3.049663	14.919	23 ± 4.8	12.48	0.0253 ± 0.0053
3.058707	15.06	26 ± 5.1	12.57	0.0281 ± 0.0055
3.079645	17.393	35 ± 5.9	12.65	0.0325 ± 0.0055
3.082510	4.769	5 ± 2.6	12.75	0.0168 ± 0.0089
3.088868	15.558	30 ± 5.8	12.96	0.0304 ± 0.0059
3.091774	14.91	39 ± 6.2	13.10	0.0408 ± 0.0065
3.094711	2.143	32 ± 5.7	13.63	0.2240 ± 0.0396
3.095444	1.816	93 ± 9.8	13.89	0.7540 ± 0.0799
3.095840	2.135	320 ± 18.4	13.74	2.2314 ± 0.1286
3.097227	2.069	503 ± 22.9	13.85	3.5886 ± 0.1635
3.098354	2.203	255 ± 16.2	13.71	1.7272 ± 0.1094
3.099056	0.756	23 ± 4.8	13.74	0.4528 ± 0.0944
3.101373	1.612	12 ± 4.0	13.76	0.1107 ± 0.0369
3.105594	2.106	9 ± 3.3	13.50	0.0647 ± 0.0239
3.112065	1.72	10 ± 3.2	13.22	0.0899 ± 0.0284
3.119892	1.264	3 ± 1.7	11.96	0.0406 ± 0.0234
3.080000	126.21	195 ± 14.2	12.65	0.0250 ± 0.0018

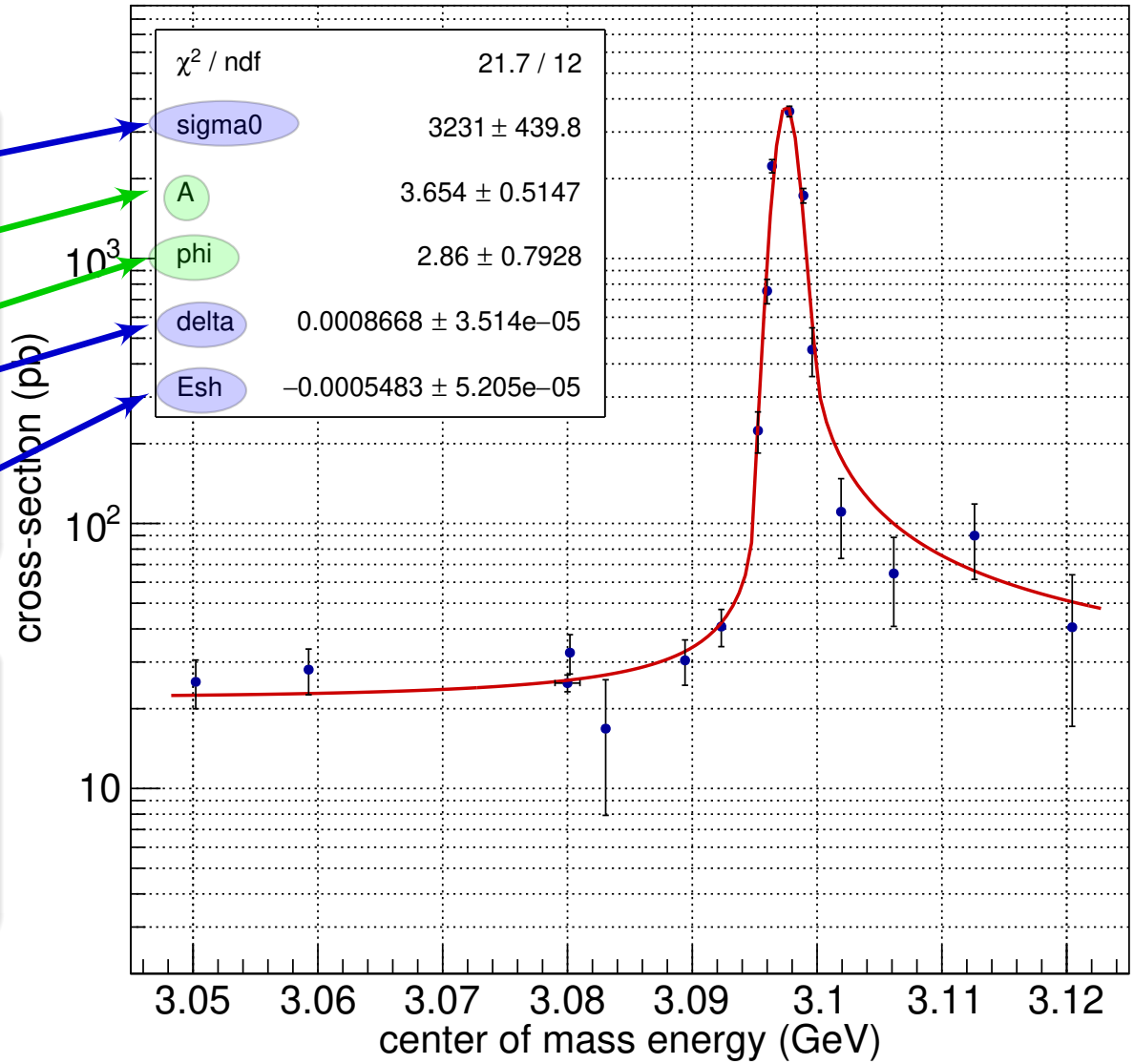
Cross Section of $e^+e^- \to \phi\eta$

Notations:

σ_0 – normalization
A – relative magnitude of strong interaction
φ – phase angle
δ – energy spread
ΔE – overall energy shift

$\Delta E = -0.55 \pm 0.05 \text{MeV}$

- Our fit confirms the shift in the beam energy



Systematic uncertainties I

- **Luminosity (BAM-00157):**
  - is mainly defined by systematic uncertainties of luminosity measurement $\sim 1\%$;
    we consider these values to be uncorrelated between the energies
- **Track reconstruction efficiency:**
  - independent of energy: $2 \times 1\%$
- **Photon reconstruction efficiency:**
  - independent of energy: $2 \times 1\%$
- **Branching fractions (PDG):**
  - independent of energy: $\delta Br(\phi \to K^+K^-) \oplus \delta Br(\eta \to 2\gamma) = 1.1\%$

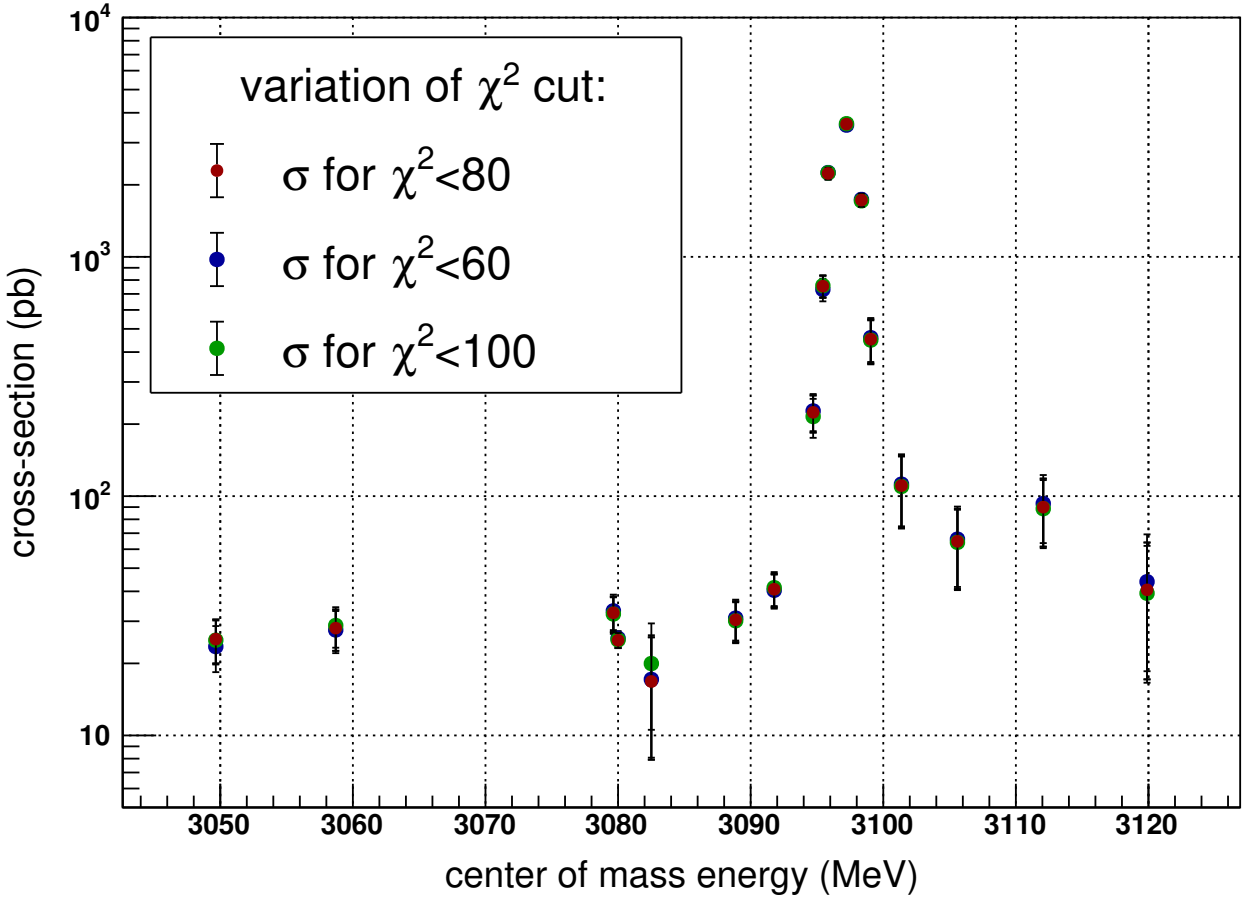
Systematic uncertainties II

- **Selection:**
  We have changed the different selection criteria and see how the cross section has changed:
  - varying χ^2 cut
  - varying side-band criteria
  - varying window for invariant mass of K^+K^-

General comments

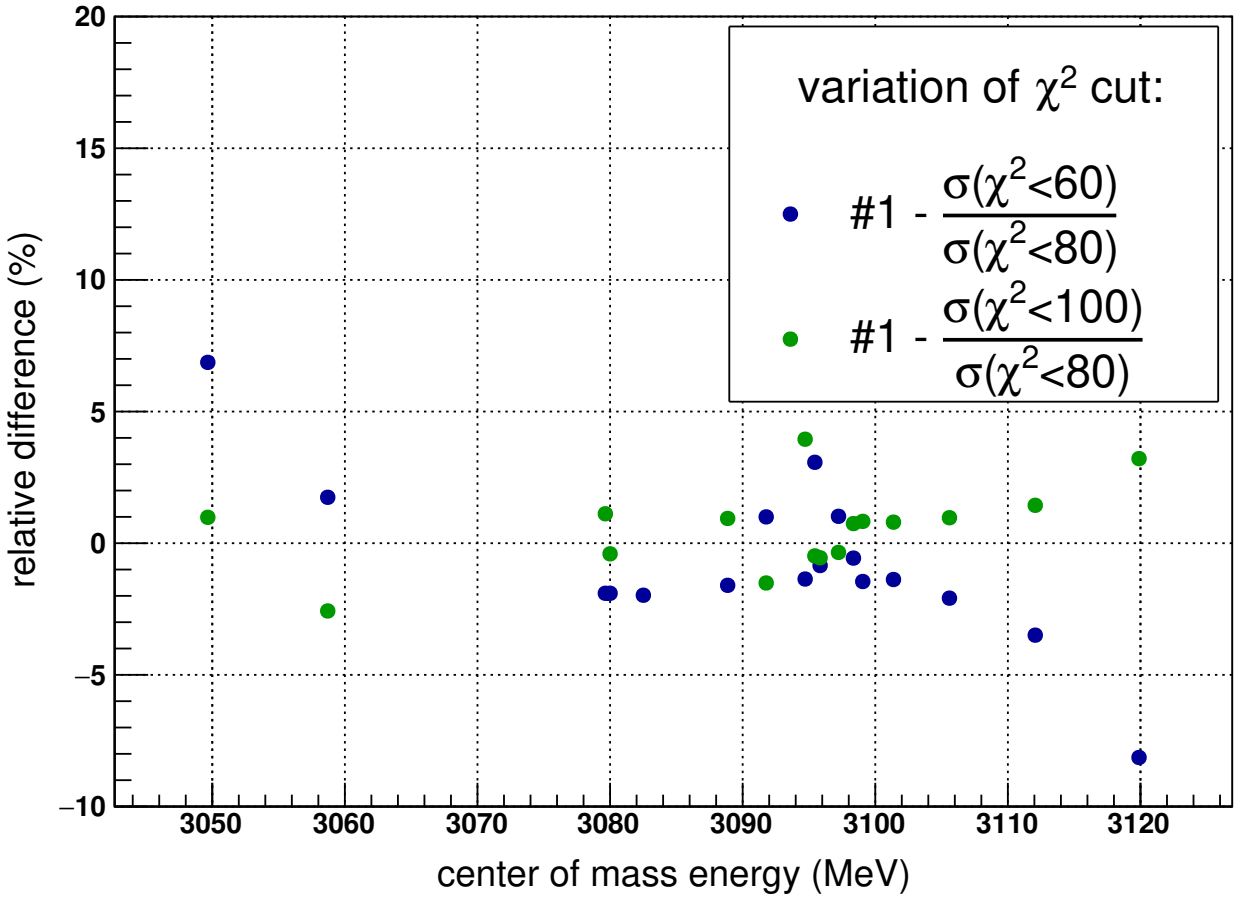
- ✓ There is no obvious dependence on energy
- ✓ Therefore, we used the values at the points with the maximum statistics (3080 MeV and 3097 MeV) to evaluate the systematic uncertainty and consider it to be energy independent

Varying χ^2 cut: cross section



- The cross-section changes within the statistical errors

Varying χ^2 cut: relative errors



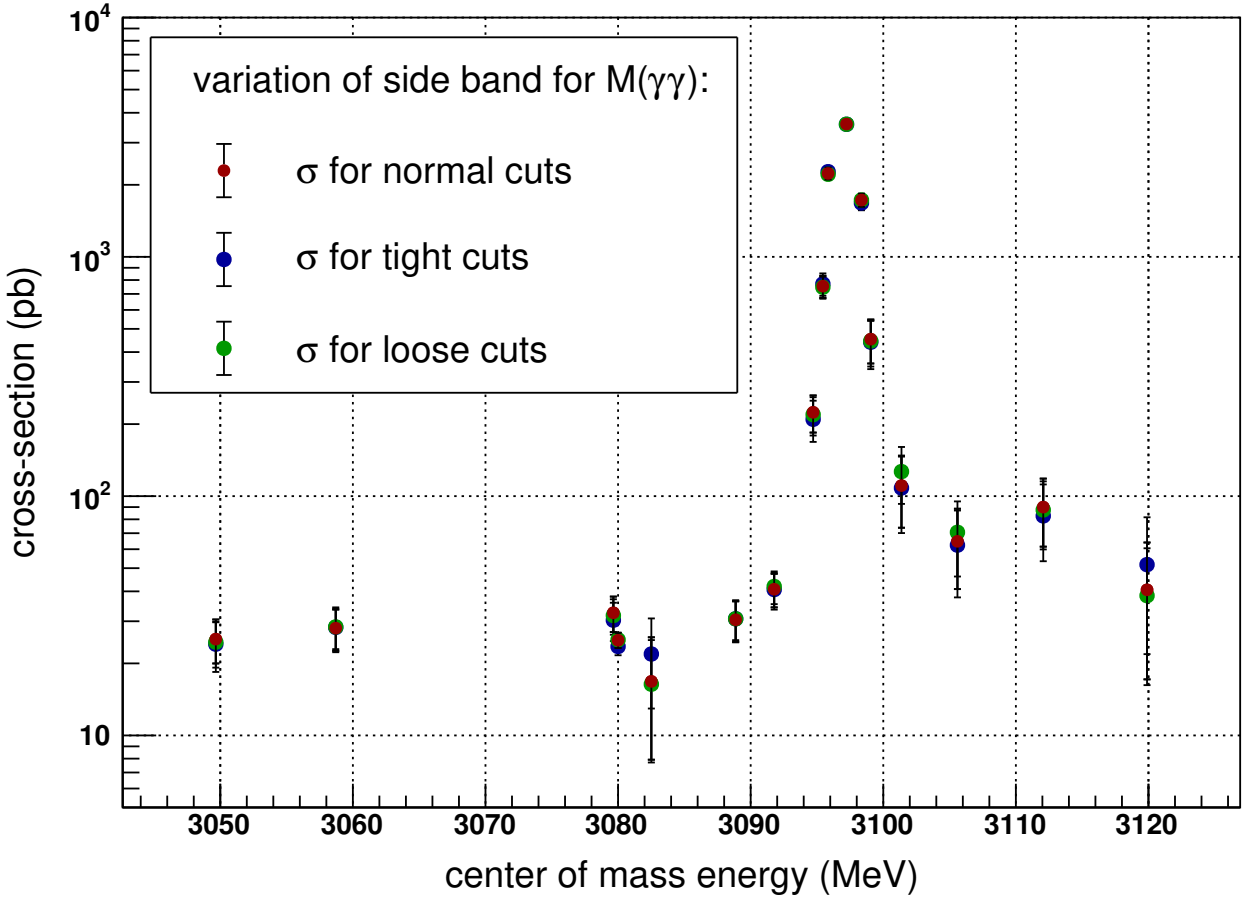
- There is no obvious dependence of the relative error on energy
- We used the value of maximum deviation for energy 3080 MeV as the uncertainty: 1.9%

Varying side-band criteria

Side-band subtraction for $M(\gamma\gamma)$

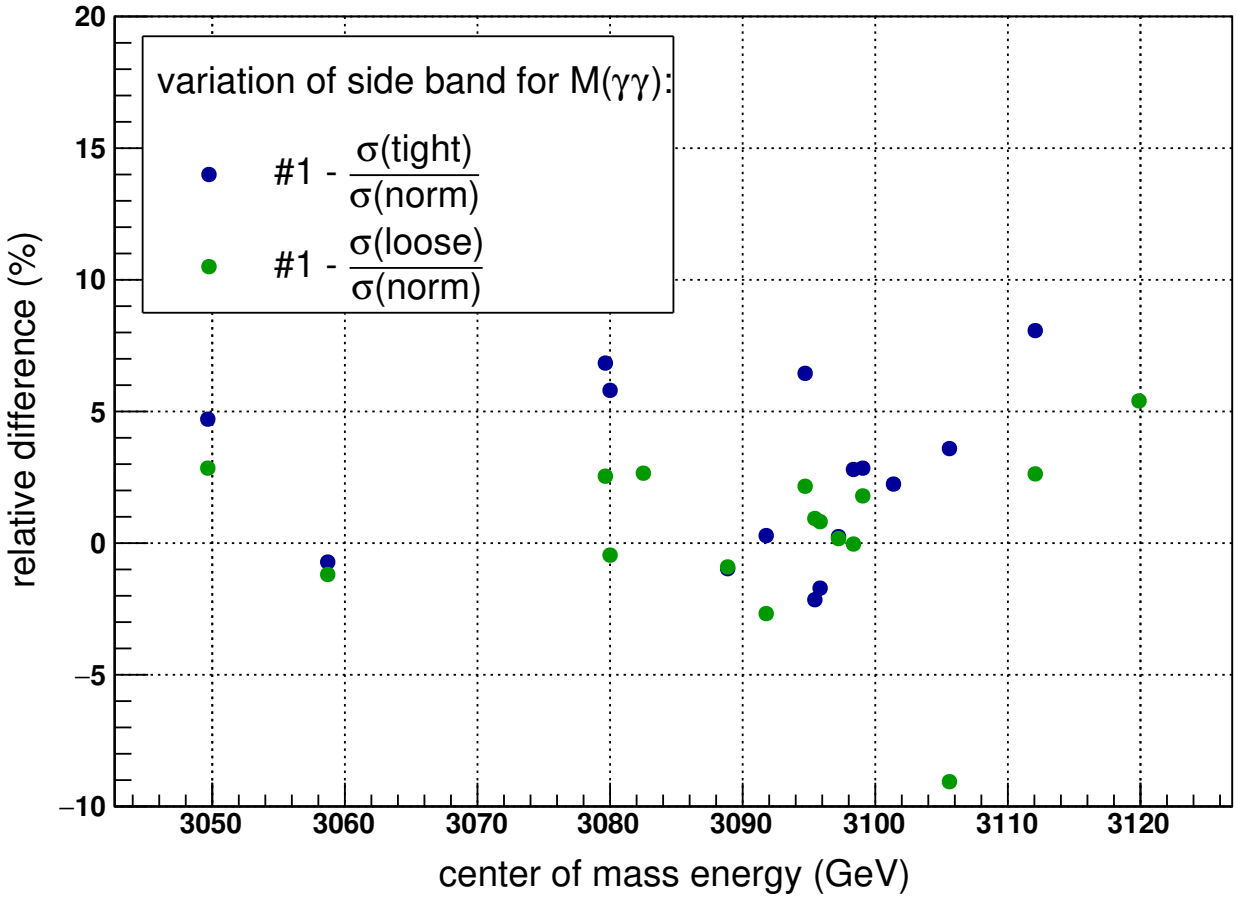
- central part: $|M(\gamma\gamma) - M_\eta)| < N \cdot \sigma(\eta)$
  side band regions: $(N+1) \cdot \sigma(\eta) < |M(\gamma\gamma) - M_\eta)| < (2N+1) \cdot \sigma(\eta)$
- we denote:
  $N = 3$ – is the normal cuts
  $N = 2$ – is the tight cuts
  $N = 4$ – is the loose cuts

Varying side-band criteria: cross section



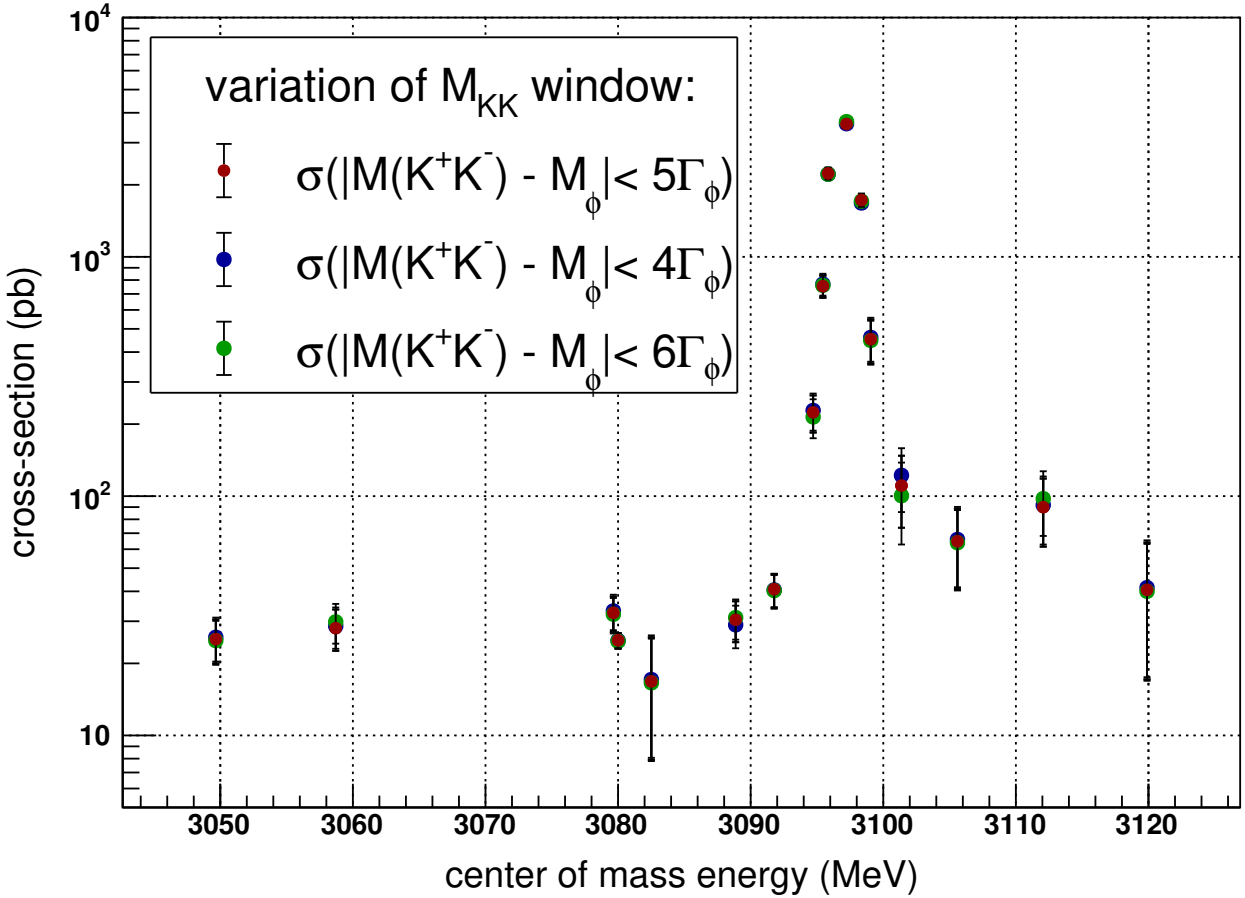
- The cross-section changes within the statistical errors

Varying side-band criteria: relative errors



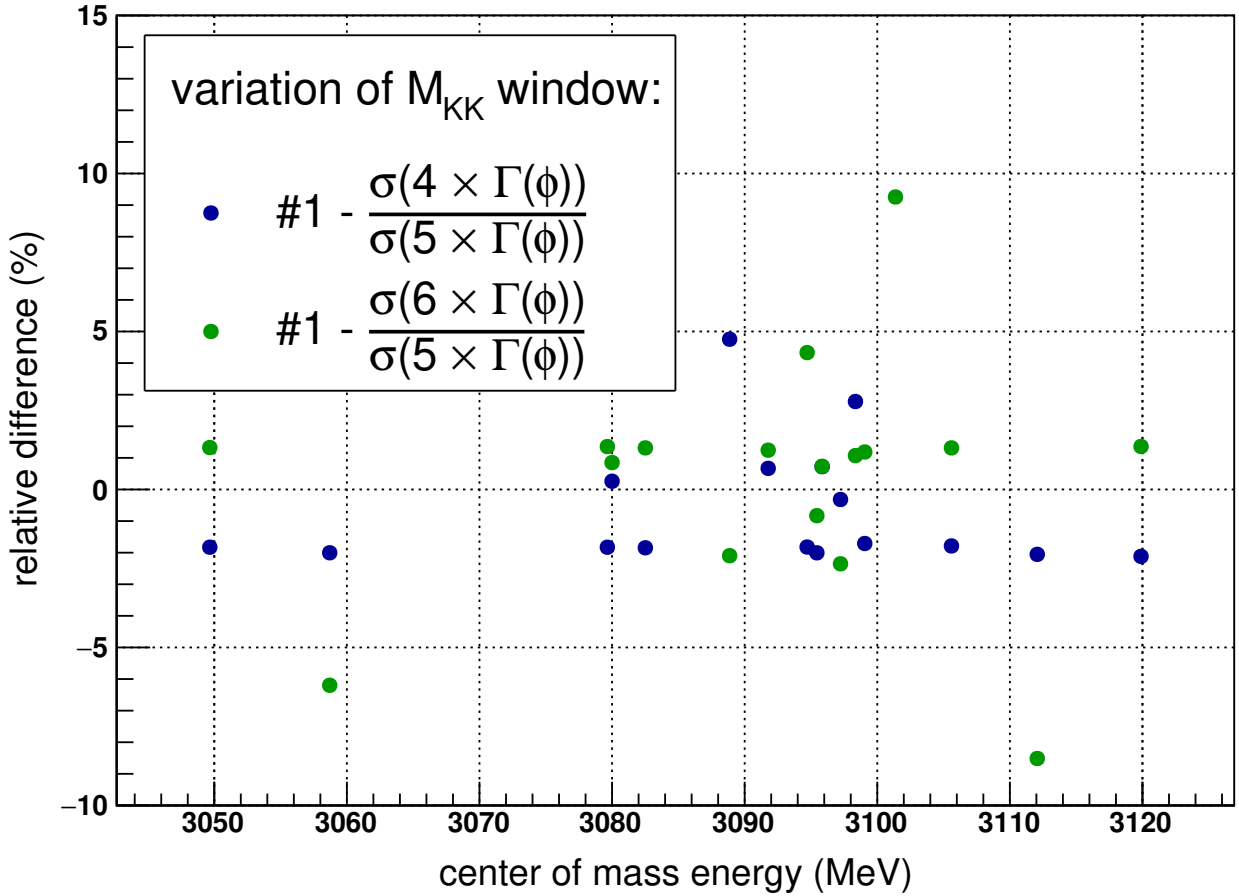
- We used the maximum deviation value for energy 3080 MeV as the uncertainty: 5.8%

Varying window for $M(K^+K^-)$: cross section



- The cross-section changes within the statistical errors

Varying window for $M(K^+K^-)$: relative errors



- We used the maximum deviation value for energy 3097 MeV as the uncertainty: 2.4%

Systematic uncertainties III

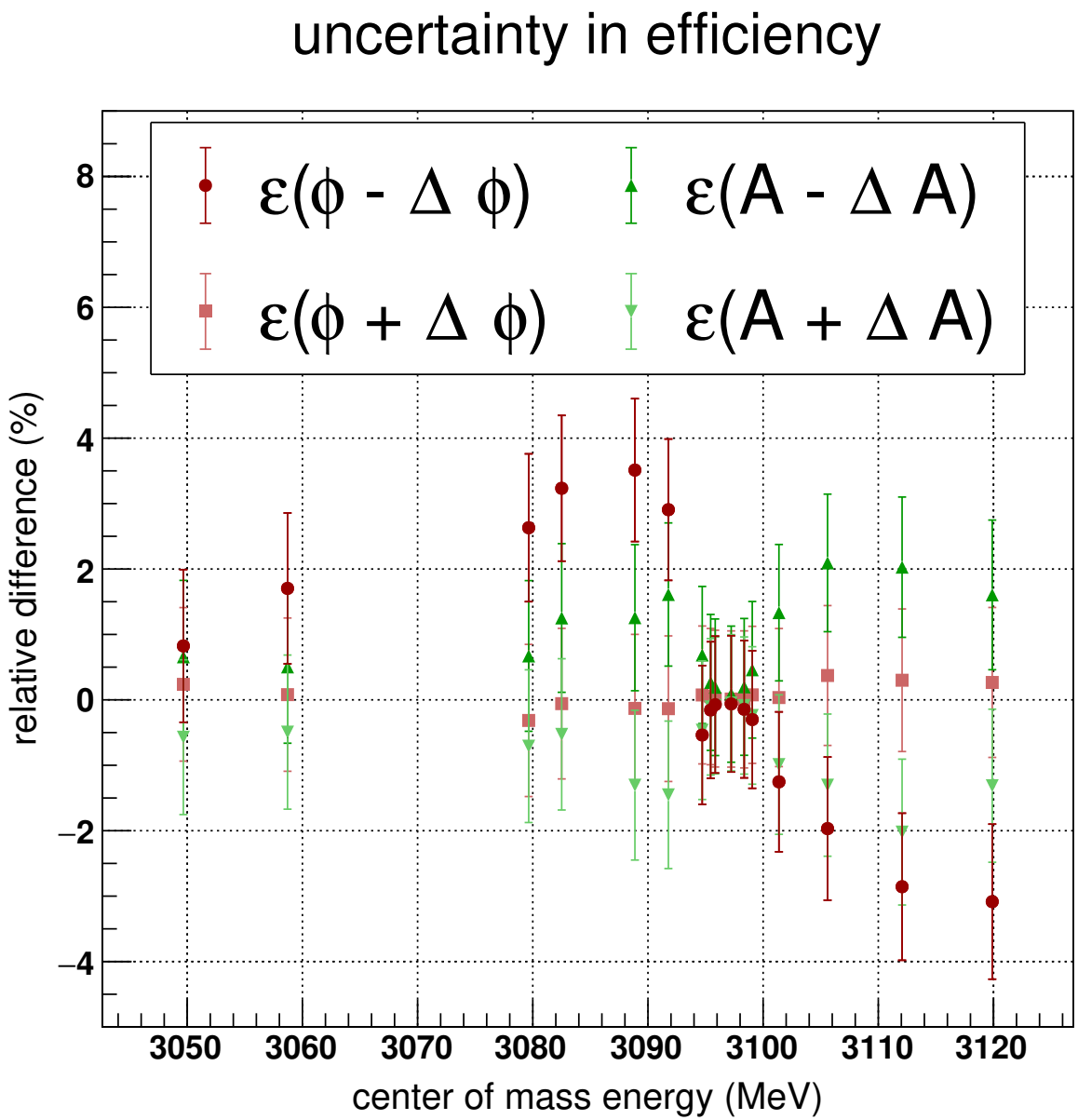
- **Parameters of MCGPJ generator:**
  - MC generator used measured cross section of $e^+e^- \to \phi\eta$ as input
  - There are two main parameters determining the cross section shape; the fit [18] gives values: $A = 3.7 \pm 0.5$ and $\phi = 2.9 \pm 0.8$
  - We generated 4 MC samples with parameter values corresponding to one sigma deviation from the obtained values:
    1. $A = 3.2 \quad \phi = 2.9$
    2. $A = 4.2 \quad \phi = 2.9$
    3. $A = 3.7 \quad \phi = 2.1$
    4. $A = 3.7 \quad \phi = 3.14$
  - The difference in the efficiency of selection for each set from the nominal efficiency is used to estimate the systematic uncertainty

The maximum deviation was obtained for the parameters

$$A = 3.7 \quad \phi = 2.1$$

we use them as energy dependant systematic uncertainty

Varying parameters of MCGPJ



Summary of systematic uncertainties

Source	Value	Energy dependence
Luminosity	$\sim 1\%$	Yes
Track reconstruction	2%	No
Photon reconstruction	2%	No
Branchings	1.1%	No
Cut on χ^2	1.9%	No
Mass window of ϕ	2.4%	No
Side-band for η	5.8%	No
Parameters of MCGPJ	$0.1 - 3.5\%$	Yes
Total	$7.0 - 7.9\%$	

Cross Section of $e^+e^- \to \phi\eta$ with systematics

$X_{ISR} > 0.9$

E(GeV)	Cross Section(nb)
3.049663	$0.025 \pm 0.005 \pm 0.002$
3.058707	$0.028 \pm 0.006 \pm 0.002$
3.079645	$0.033 \pm 0.006 \pm 0.002$
3.082510	$0.017 \pm 0.009 \pm 0.001$
3.088868	$0.030 \pm 0.006 \pm 0.002$
3.091774	$0.041 \pm 0.007 \pm 0.003$
3.094711	$0.224 \pm 0.040 \pm 0.016$
3.095444	$0.754 \pm 0.080 \pm 0.053$
3.095840	$2.231 \pm 0.129 \pm 0.157$
3.097227	$3.589 \pm 0.163 \pm 0.253$
3.098354	$1.727 \pm 0.109 \pm 0.122$
3.099056	$0.453 \pm 0.094 \pm 0.032$
3.101373	$0.111 \pm 0.037 \pm 0.008$
3.105594	$0.065 \pm 0.024 \pm 0.005$
3.112065	$0.090 \pm 0.028 \pm 0.007$
3.119892	$0.041 \pm 0.023 \pm 0.003$
3.080000	$0.025 \pm 0.002 \pm 0.002$

Formulas of cross section for lineshape fit

Born cross section

$$\sigma_{\mathrm{born}}(s) = |\mathcal{A}_{cont.} + \mathcal{A}_{\gamma} + \mathcal{A}_{3g}|^2$$
$$= \frac{\sigma_0}{s^3}\left|1 + \frac{3/\alpha\sqrt{s\,\Gamma_e\Gamma_\mu}}{(s - M^2) + i\sqrt{s}\,\Gamma} \cdot (1 + Ae^{i\varphi})\right|^2$$

s – is the centre of mass energy squared

M and Γ are the mass and total width of J/ψ

Fit parameters

σ_0 – is the normalization constant

A – is the relative magnitude of strong interaction to EM

φ – is the phase angle between strong and EM amplitudes

Formulas of cross section for lineshape fit

Observable cross section

Taking into account the ISR corrections and beam energy spread:

$$\sigma(E) = \int_{E-5\delta}^{E+5\delta} dE' \int_{0}^{1-X_{ISR}} dx \quad G(E'-E,\delta)\cdot F_{ISR}(x,s)\cdot \sigma_{\mathrm{born}}(s(1-x))$$

F_{ISR} – is the ISR-function by Kuraev and Fadin

X_{ISR} – is the minimal value for $\frac{s'}{s}$ ratio ($X_{ISR} = 0.9$ in our analysis)

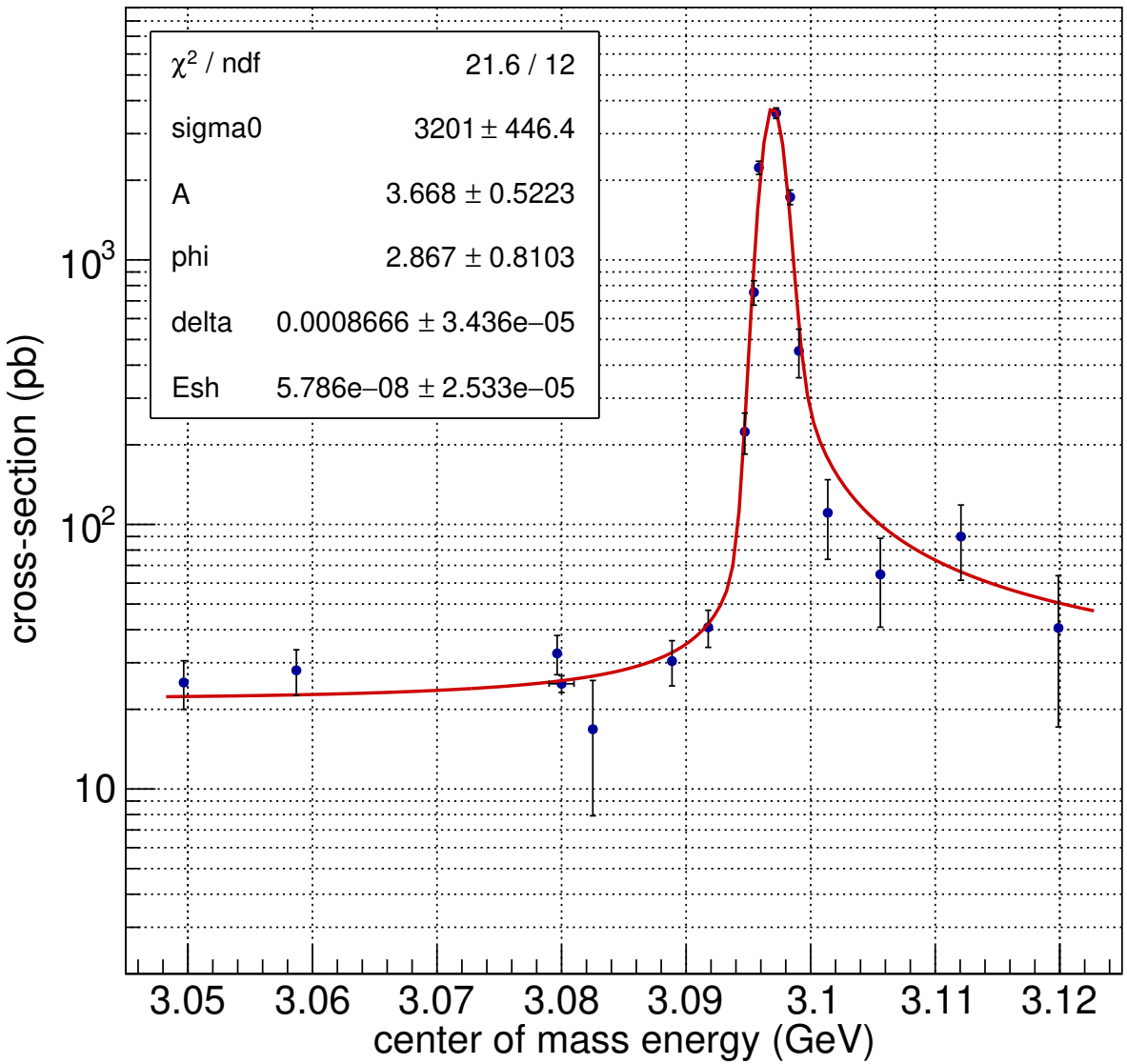
G – is the Gaussian function

δ – is the energy spread; this is the parameter of our fit

- double integration is performed numerically
- fit is performed by ROOT minimization

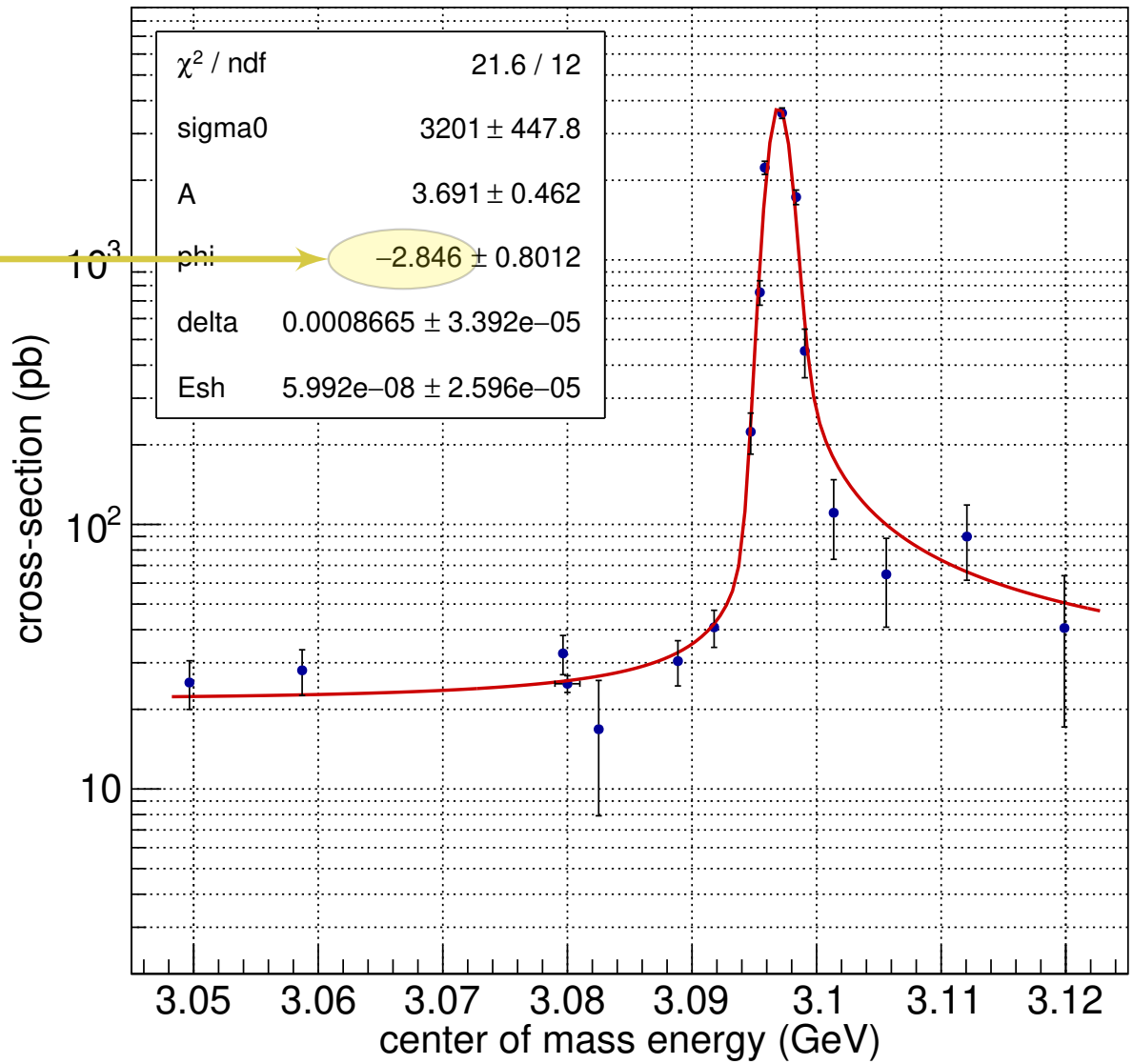
Fit result: statistical errors only

Here and below we shifted the energy on -0.55 MeV and used 0.03 MeV from BAM-00268 as error on this value in minimization



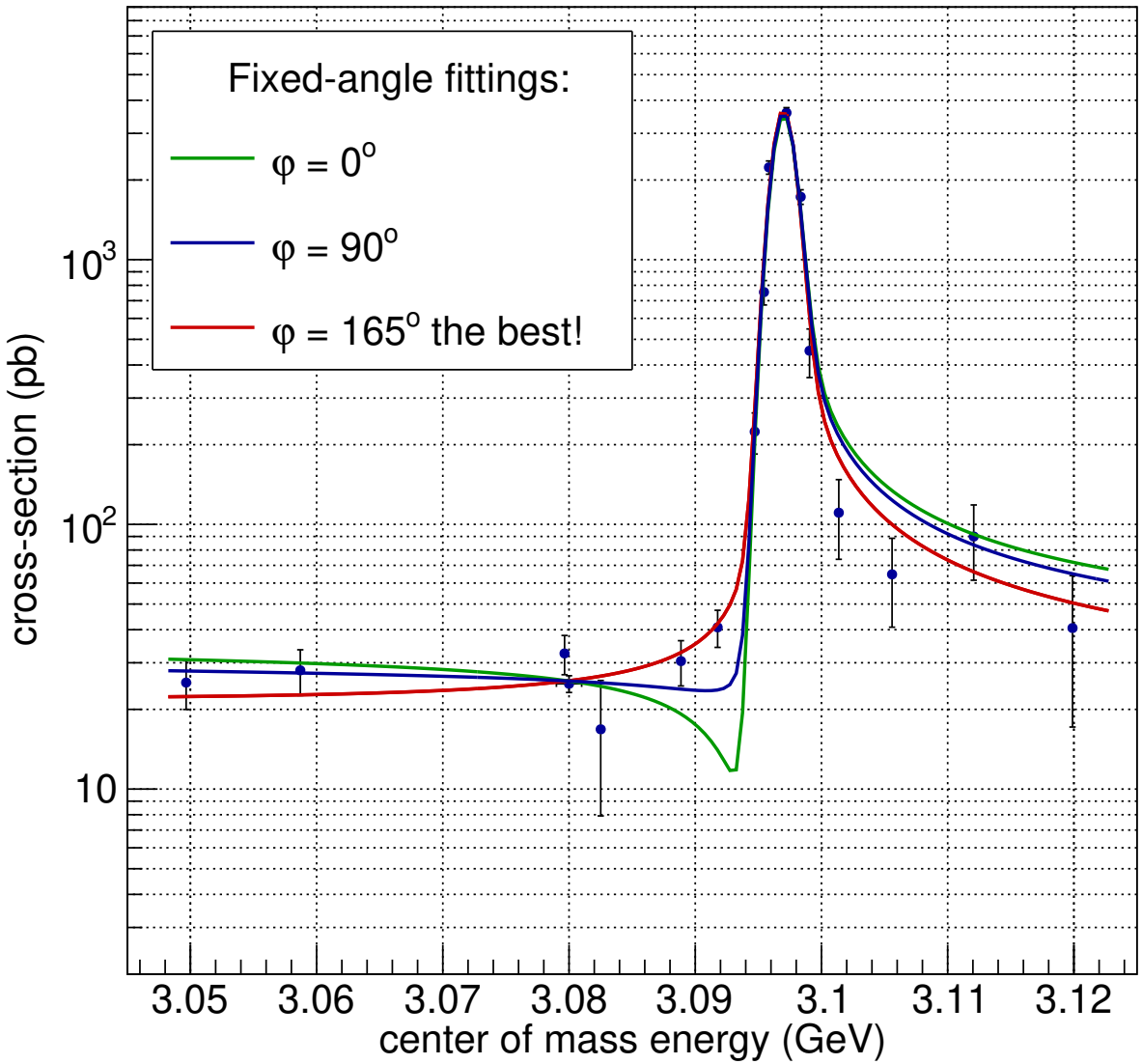
Fit result: the second solution

- there is always a second solution
- the sign of φ is opposite
- the remaining parameters almost the same as in the first solution
- below I will show the first positive solution



Fit result: example of fit with fixed angles

- $\varphi = 0° \rightarrow \chi^2 = 59.8$
- $\varphi = 90° \rightarrow \chi^2 = 38.1$
- $\varphi = 165° \rightarrow \chi^2 = 21.6$

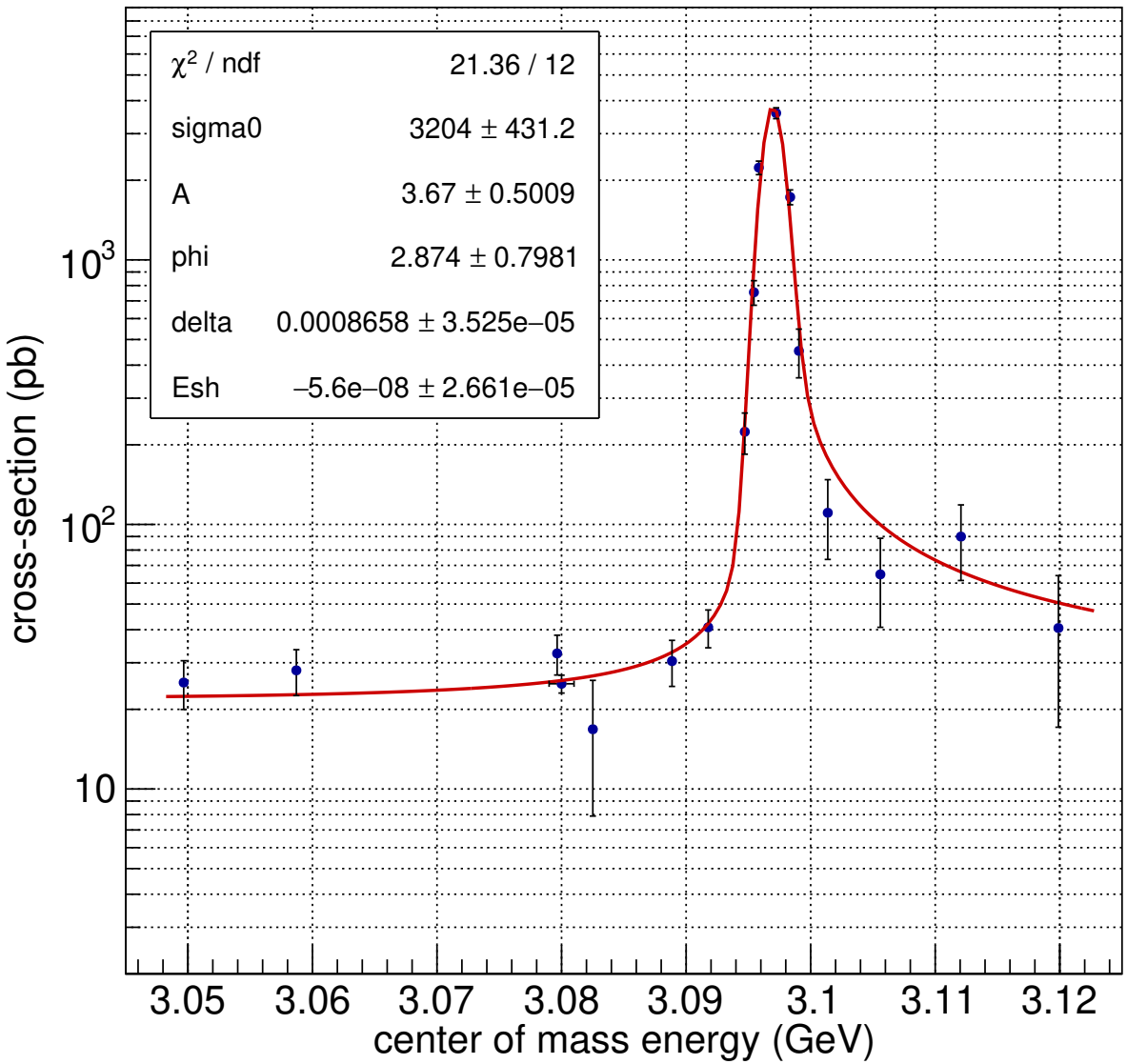


Fit result: systematic uncertainty

The central value

✓ We used only those systematic uncertainties of the cross section that depend on the energy

$$\varphi = 2.87 \pm 0.80$$

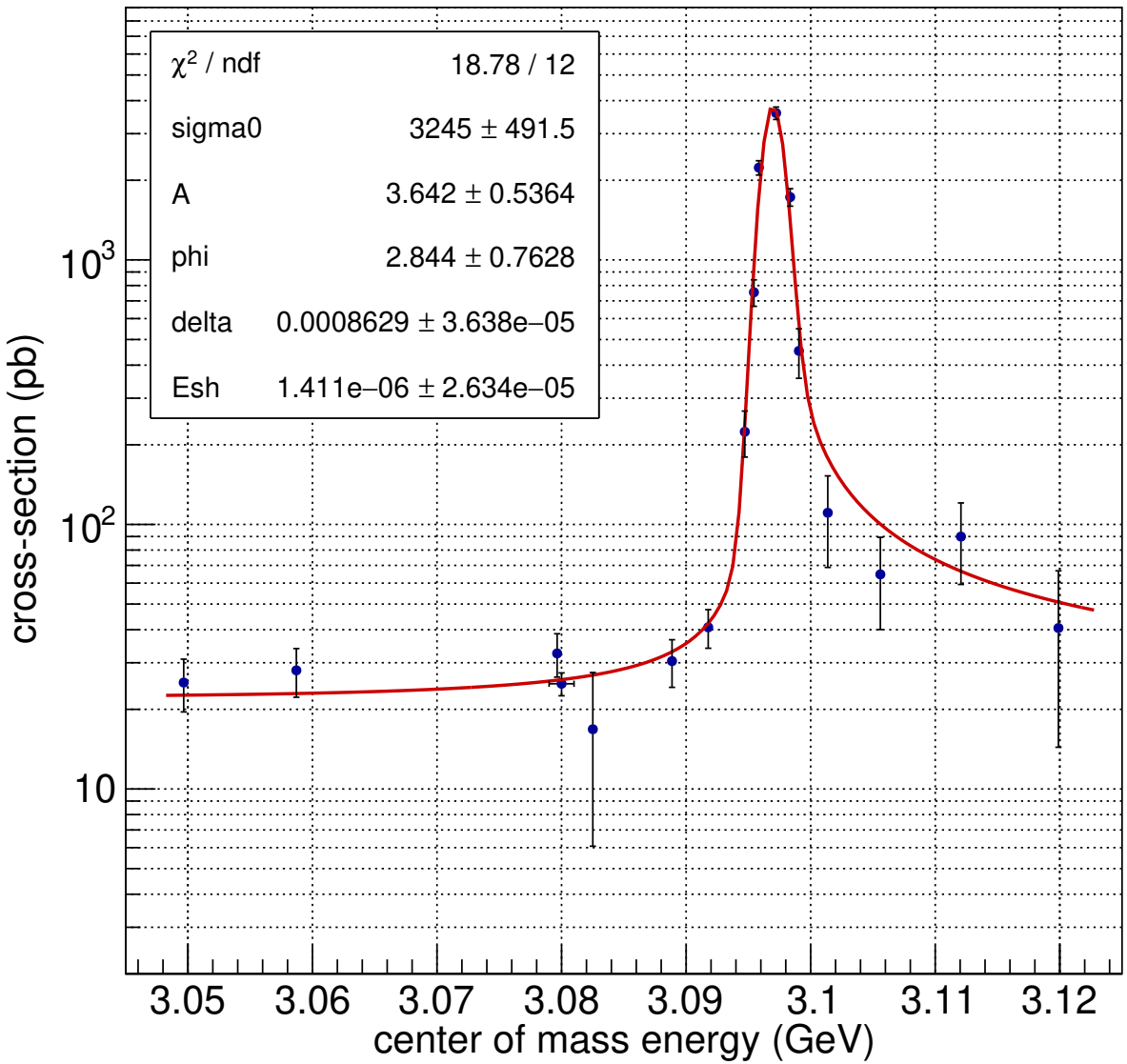


Fit result: systematic uncertainty

Variation 1

Like the central value but we are considering that the uncertainties from the selection criteria also depend on the energy (see slides [22], [25], [27])

$$\varphi = 2.84 \pm 0.76$$

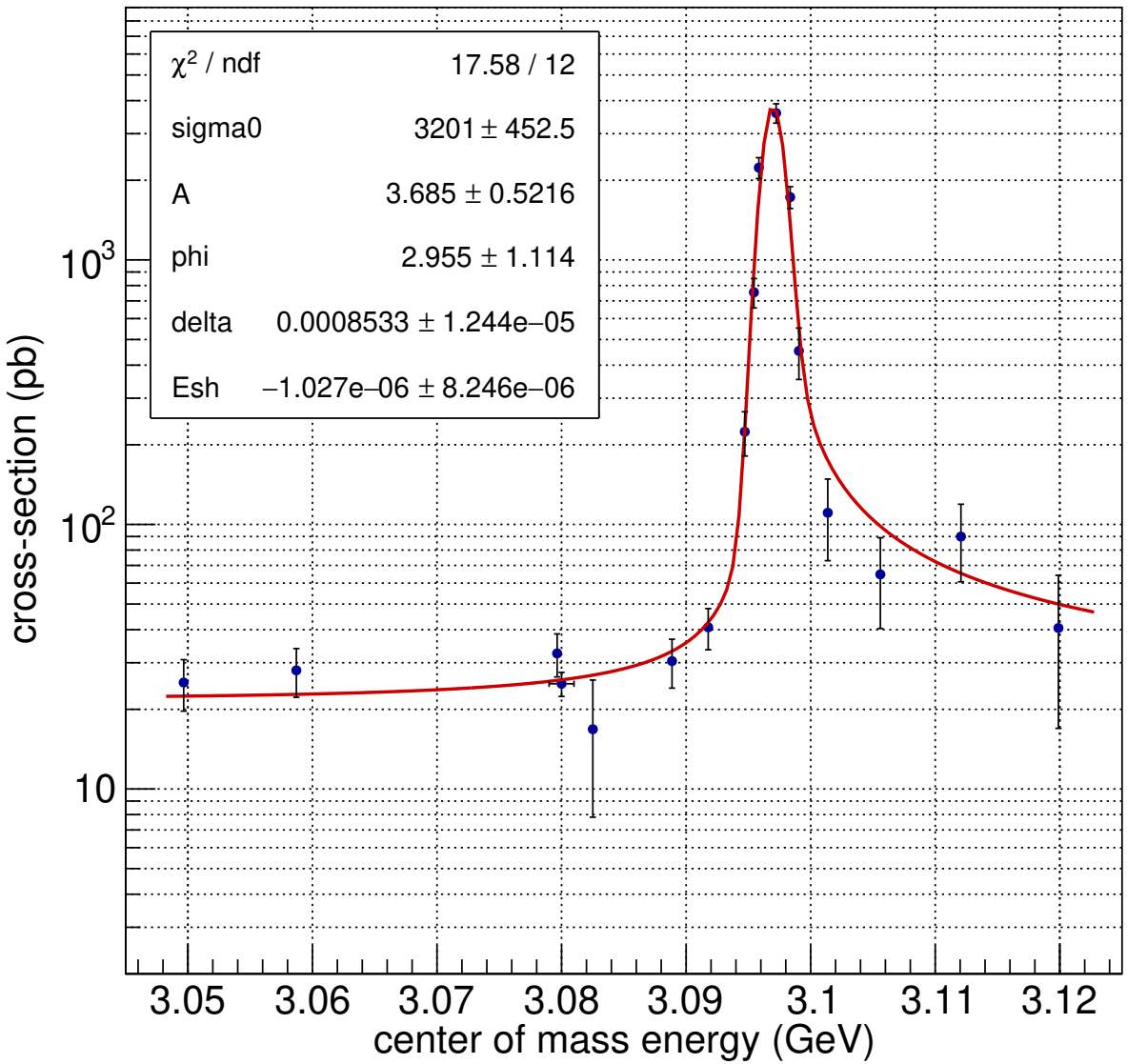


Fit result: systematic uncertainty

Variation 2

Total systematic uncertainties of the cross section ignoring correlation for different energies

$$\varphi = 2.96 \pm 1.11$$



Summary of fit result

- The main interest for us is the line shape of cross section so we consider the central value as the main result of the fit:
$$\varphi = 2.87 \pm 0.80$$
- We tested several other strategies for using systematic uncertainties and found that the maximum deviation is achieved if we consider them uncorrelated:
$$\varphi(var.2) = 2.96 \pm 1.11$$
- We use this deviation as estimation of systematic uncertainty of the phase angle:
$$\varphi = 2.87 \pm 0.80 \pm 0.09$$

Conclusion

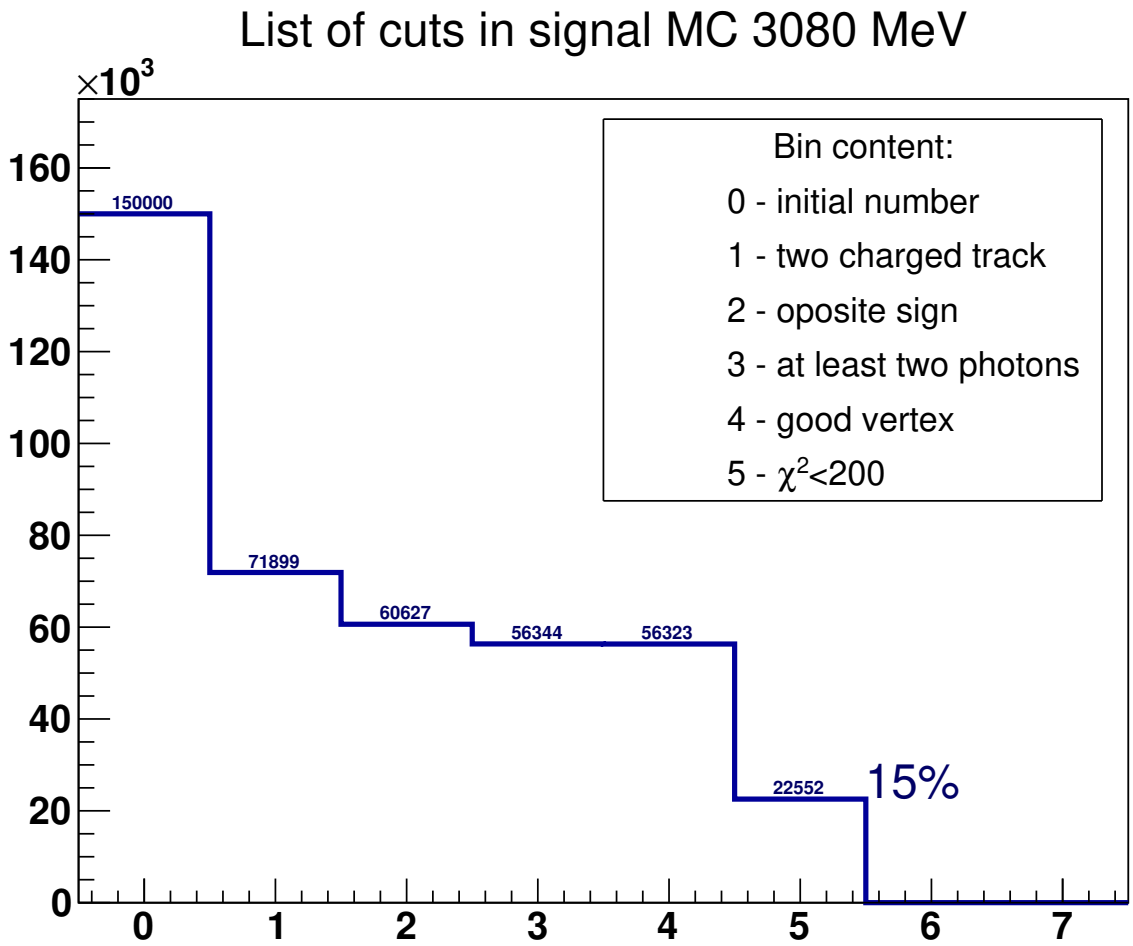
- We measured the cross sections line shape of $e^+e^- \to \phi\eta$ in the region of energies around J/ψ
- We estimated the phase angle between strong and electromagnetic amplitudes in decays $J/\psi \to \phi\eta$:

$$\varphi = 2.87 \pm 0.80 \pm 0.09$$
$$164^\circ \pm 46^\circ \pm 5^\circ$$

- Memo in the process of preparation
- We are ready to present our analysis at the collaboration meeting

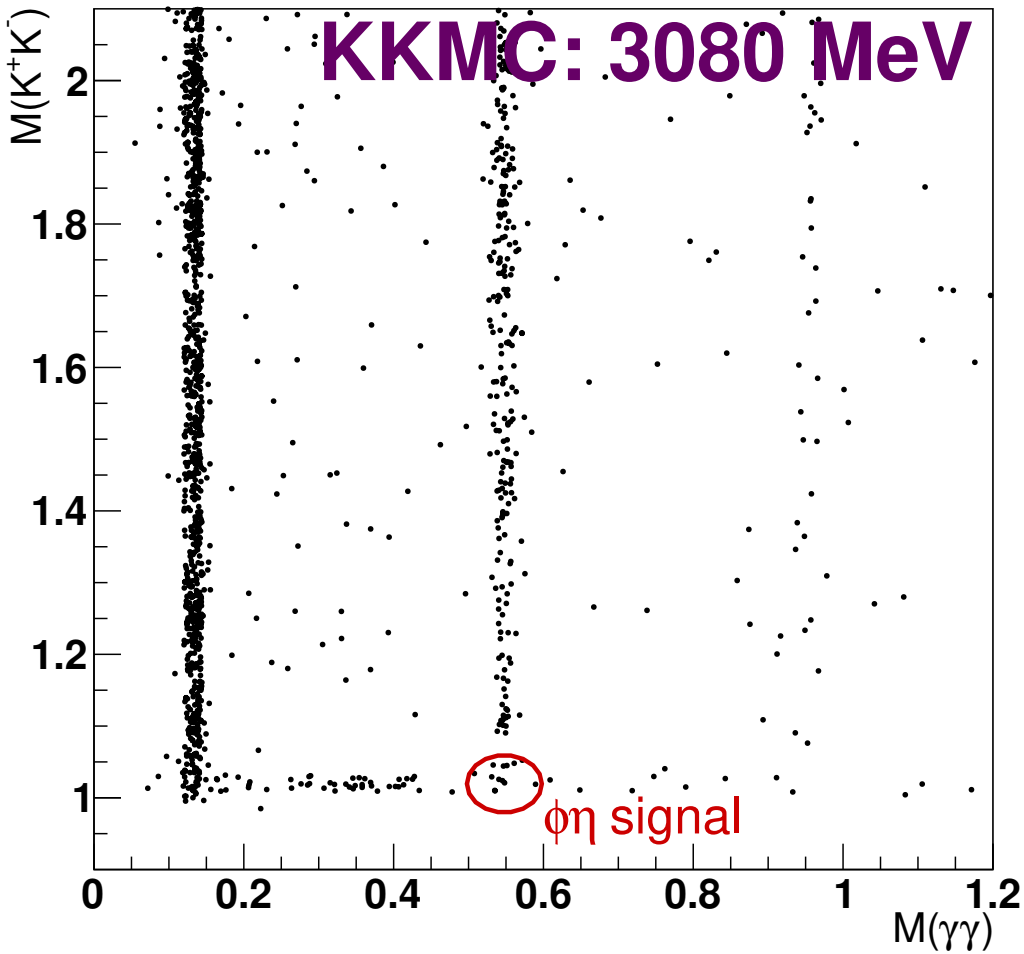
Backup slides

Preselection cuts in signal MC 3080 MeV



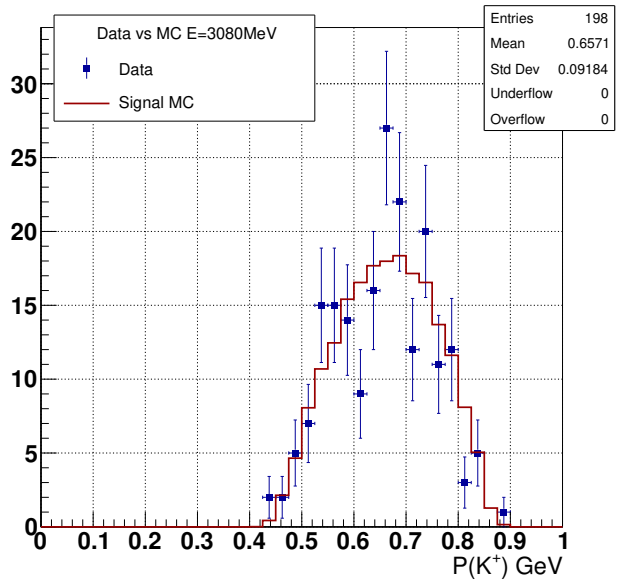
- In signal MC η decays in all possible ways
  $Br(\eta \to 2\gamma) = 39.41 \pm 0.20\%$

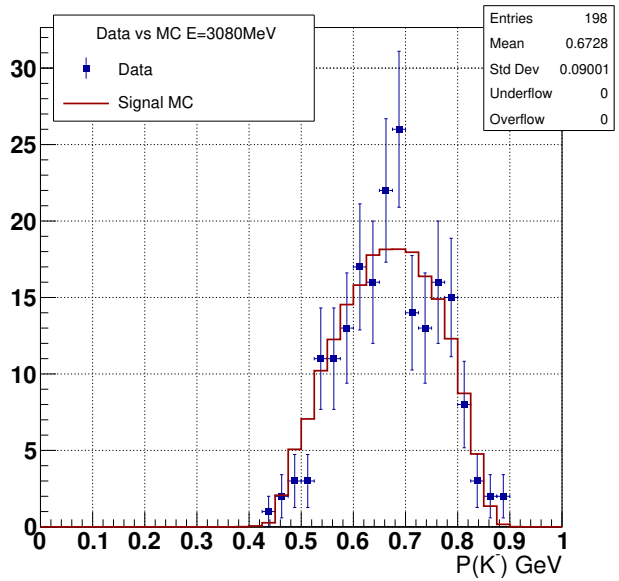
Invariant masses of η and ϕ

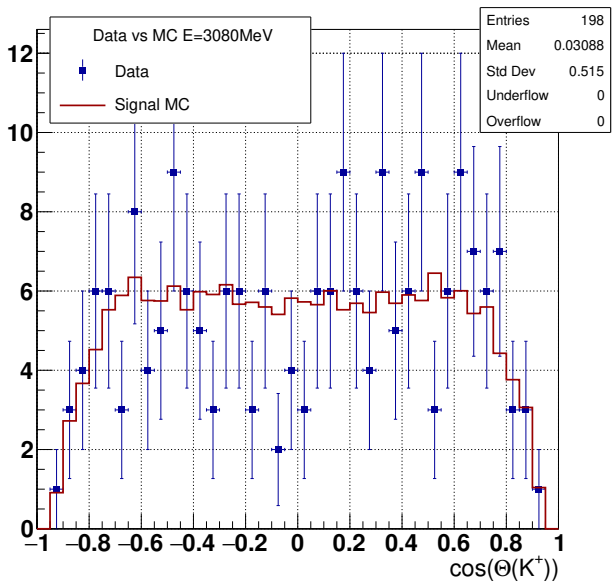


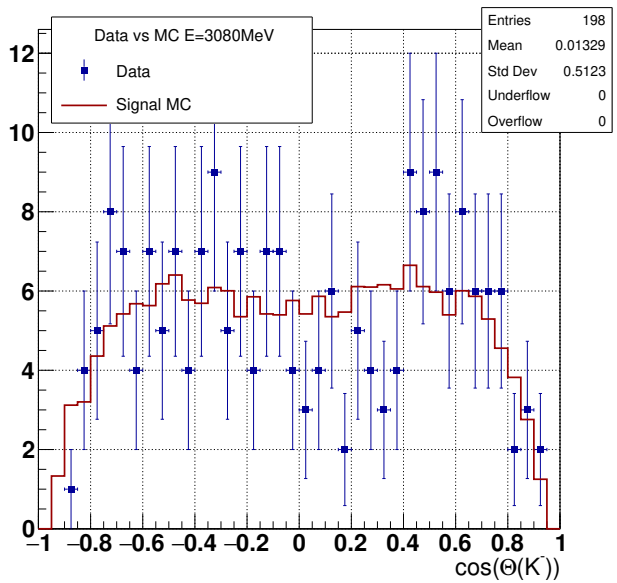
- after $\chi^2 < 80$ cut

Data vs MC: 3080 MeV

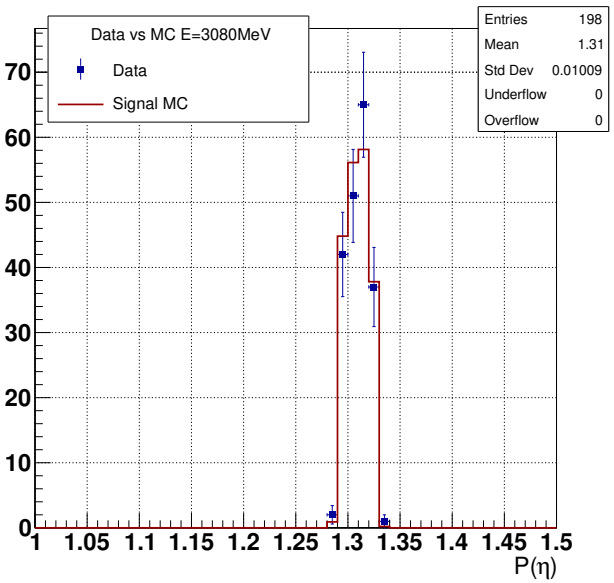


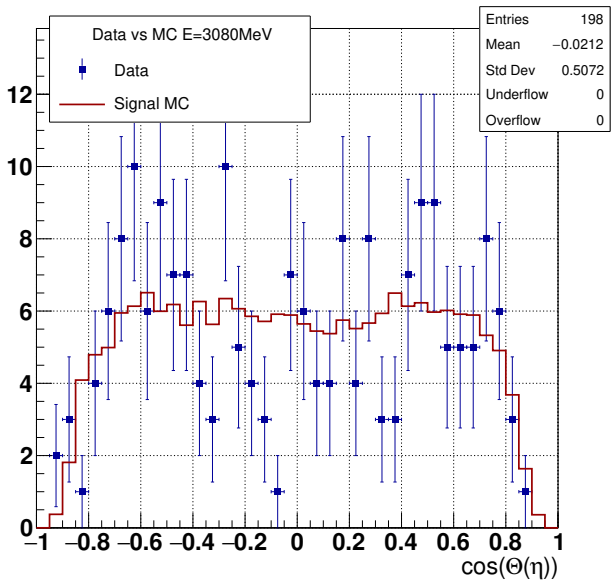




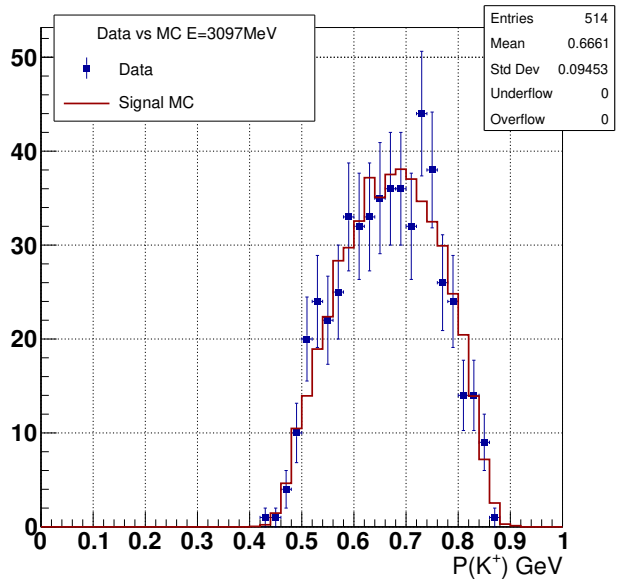


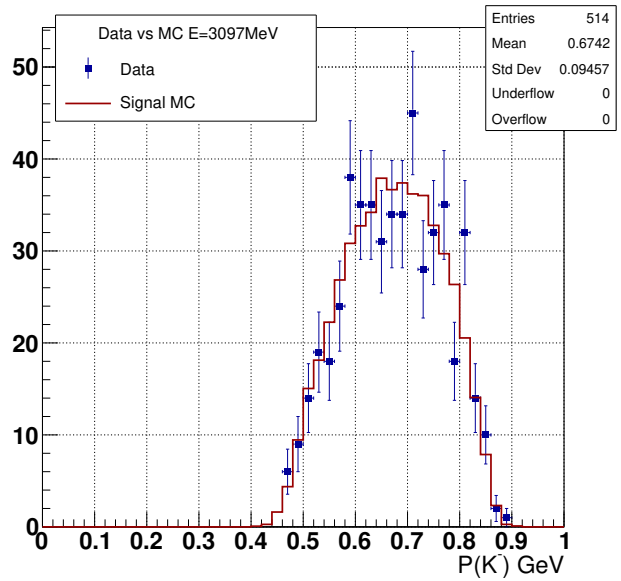
Data vs MC: 3080 MeV

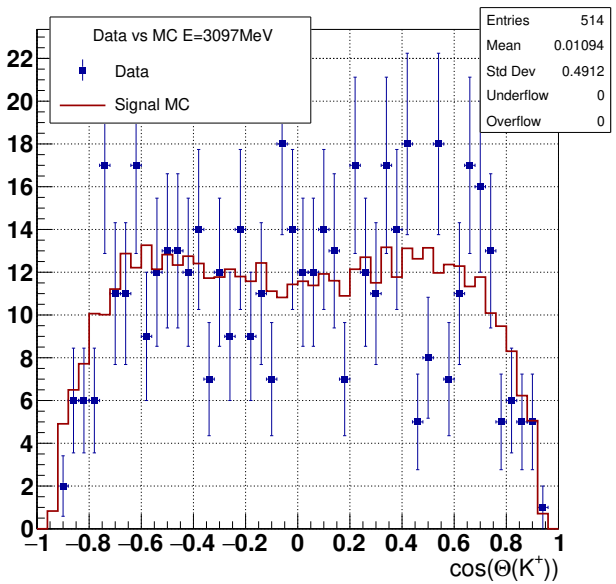


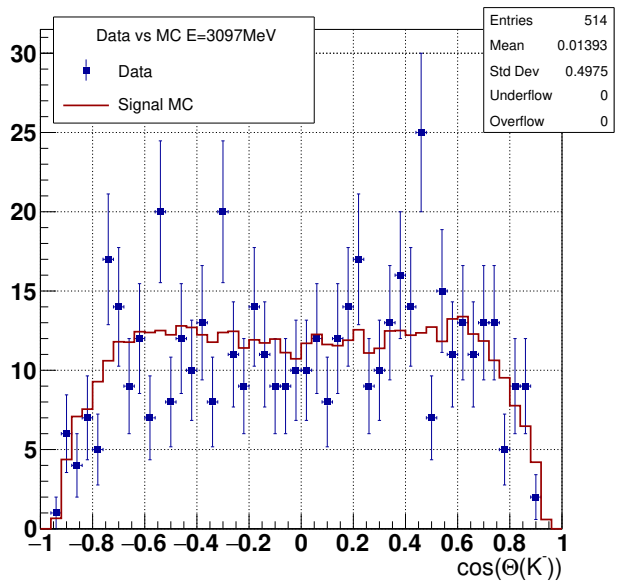


Data vs MC: 3097 MeV

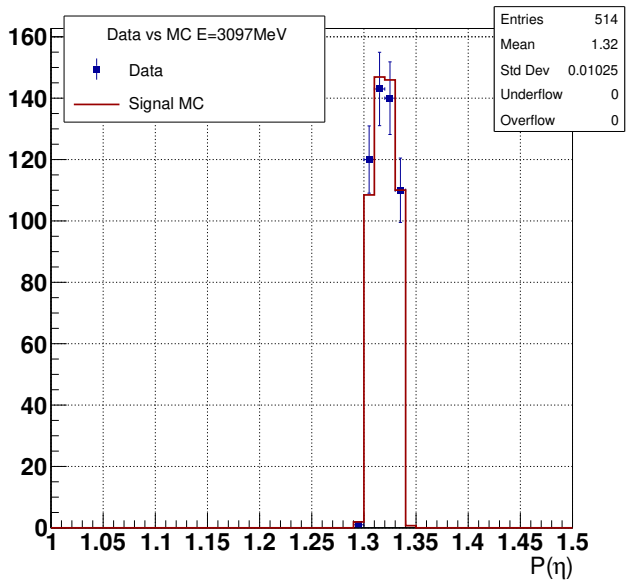


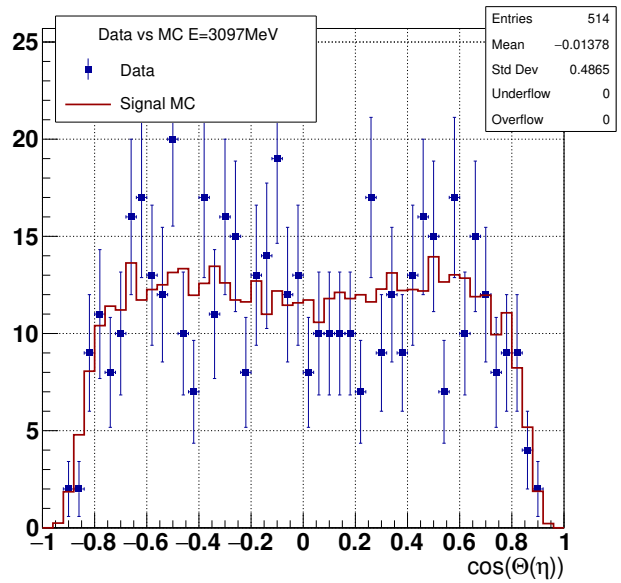




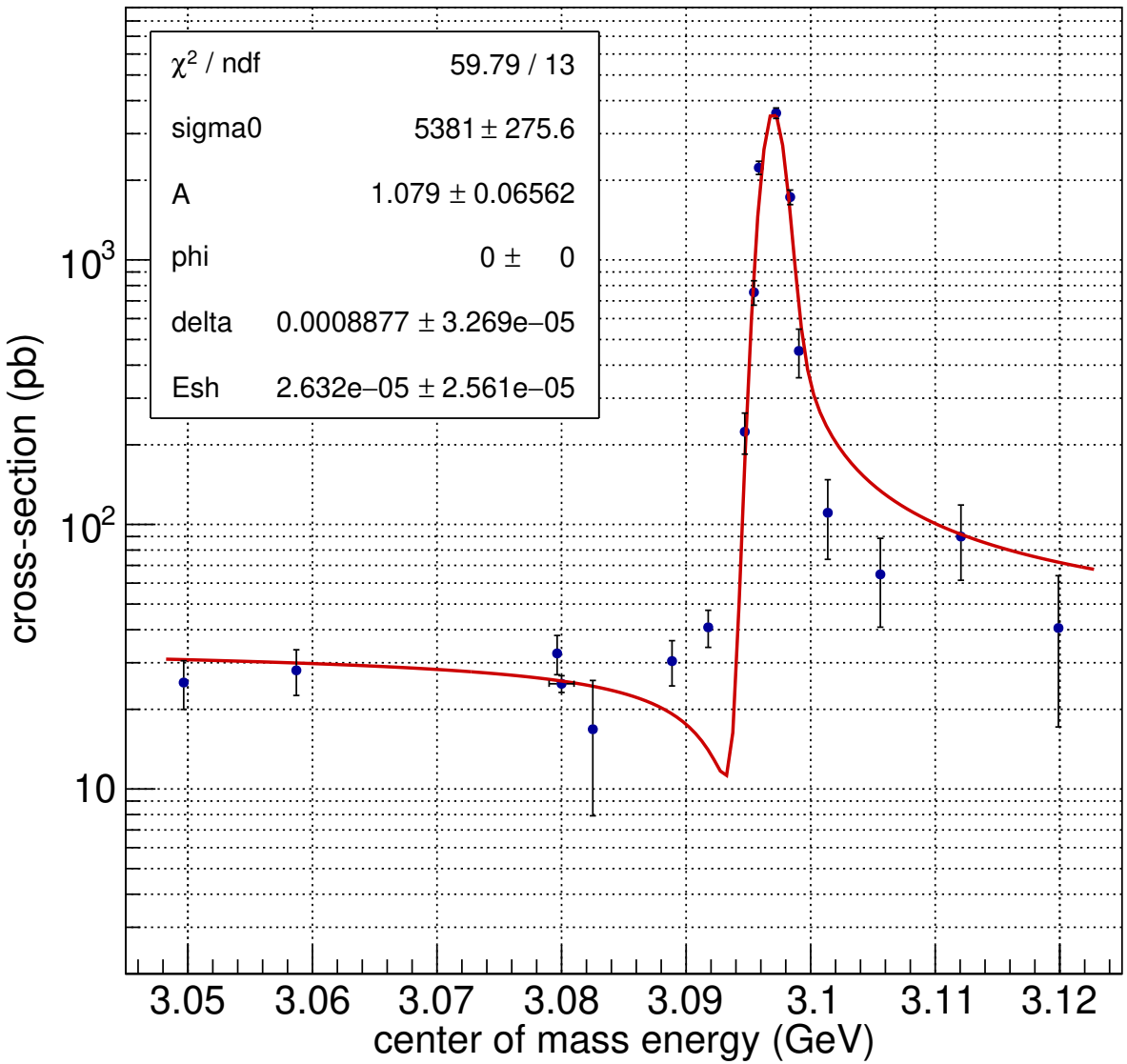


Data vs MC: 3097 MeV





Fixed-angle fitting $\varphi = 0°$



Fixed-angle fitting $\varphi = 90°$