σ and κ Mesons Observed through J/ψ Decays in BES

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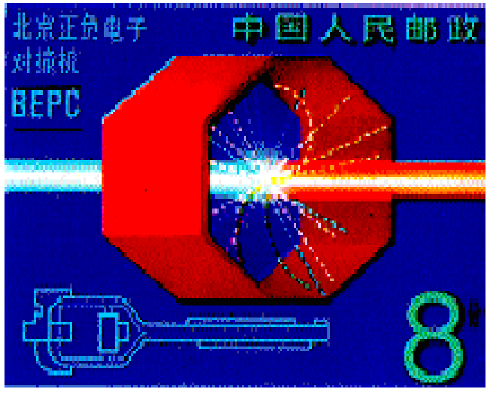


Part I: Introduction

♡ Motivation:

The early analysis of $\pi\pi$ and πK scattering data shows no pole at the lower mass region. For a long time, the existence of σ and κ as resonant particles has not been widely accepted. However, recent re-analysis of the $\pi\pi$ and πK scattering data shows an evidence for existence of the σ and κ particles with comparatively light mass. The important thing is that, if there exists light σ and κ particles, they can not be filled into quark model for ordinary $q\bar{q}$ mesons, so they must be something new.

It is important to search for σ and κ in production process. The advantages of the study on σ and κ particles in $J\psi$ decay are that the background is very low and signal is very clear. Our analysis is based on 58M BESII J/ψ data.

Part II: σ meson production in $J/\psi \to \omega\pi^+\pi^-$

♡ π^0 **signal** After initial cut conditions and some of final cut conditions, we can see very clear π^0 signal.

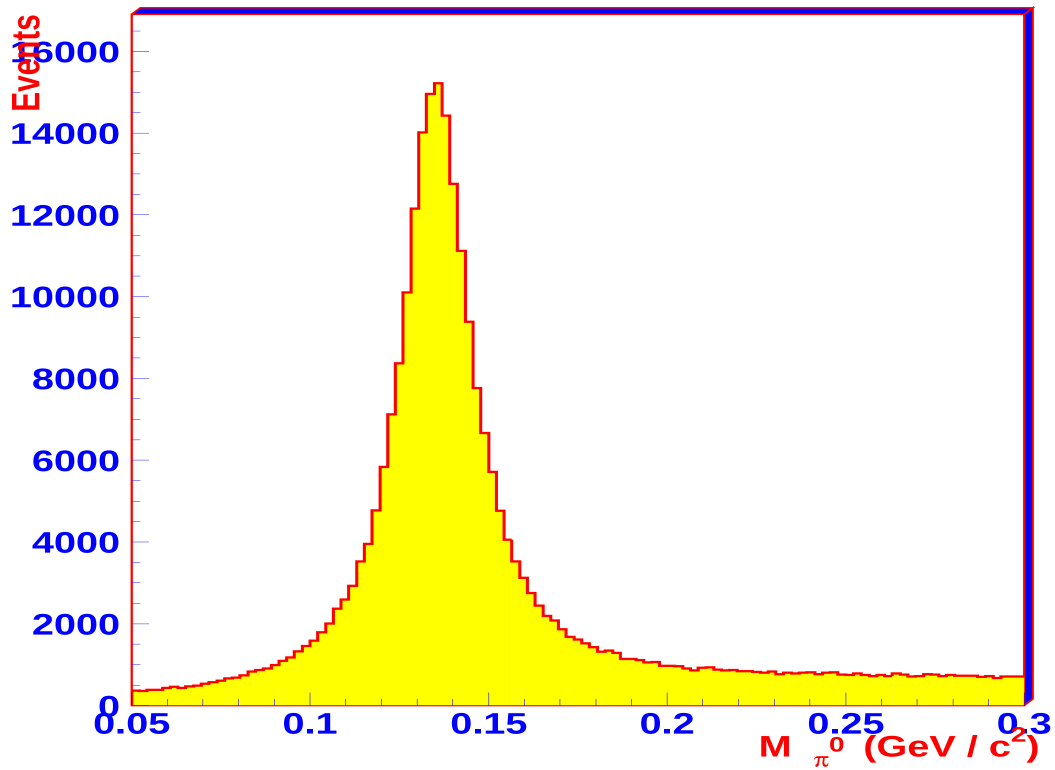


Figure 1: π^0 signal

♡ ω **signal** After initial cut conditions and some of final cut conditions, we can also see clear ω signal.

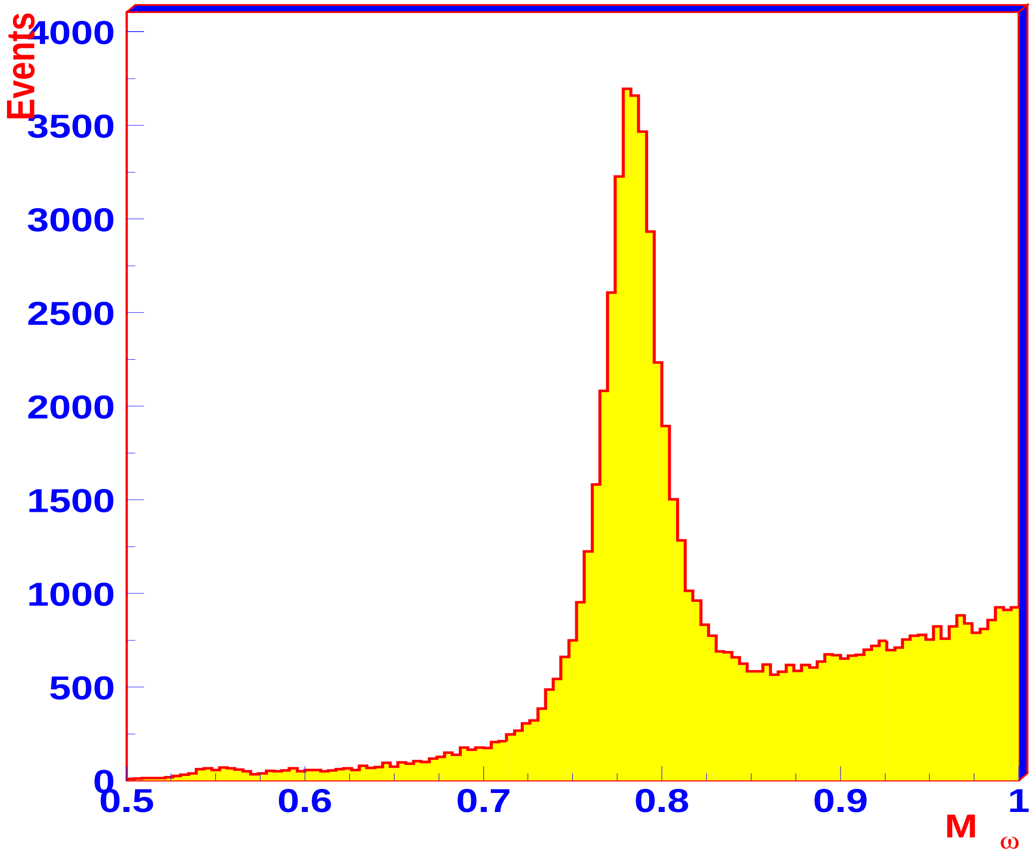


Figure 2: ω signal

♡ $\pi^+\pi^-$ **Mass spectrum:** It is found that there is a low mass enhancement in the $\pi^+\pi^-$ invariant mass spectrum in $J/\psi \to \omega\pi\pi$.

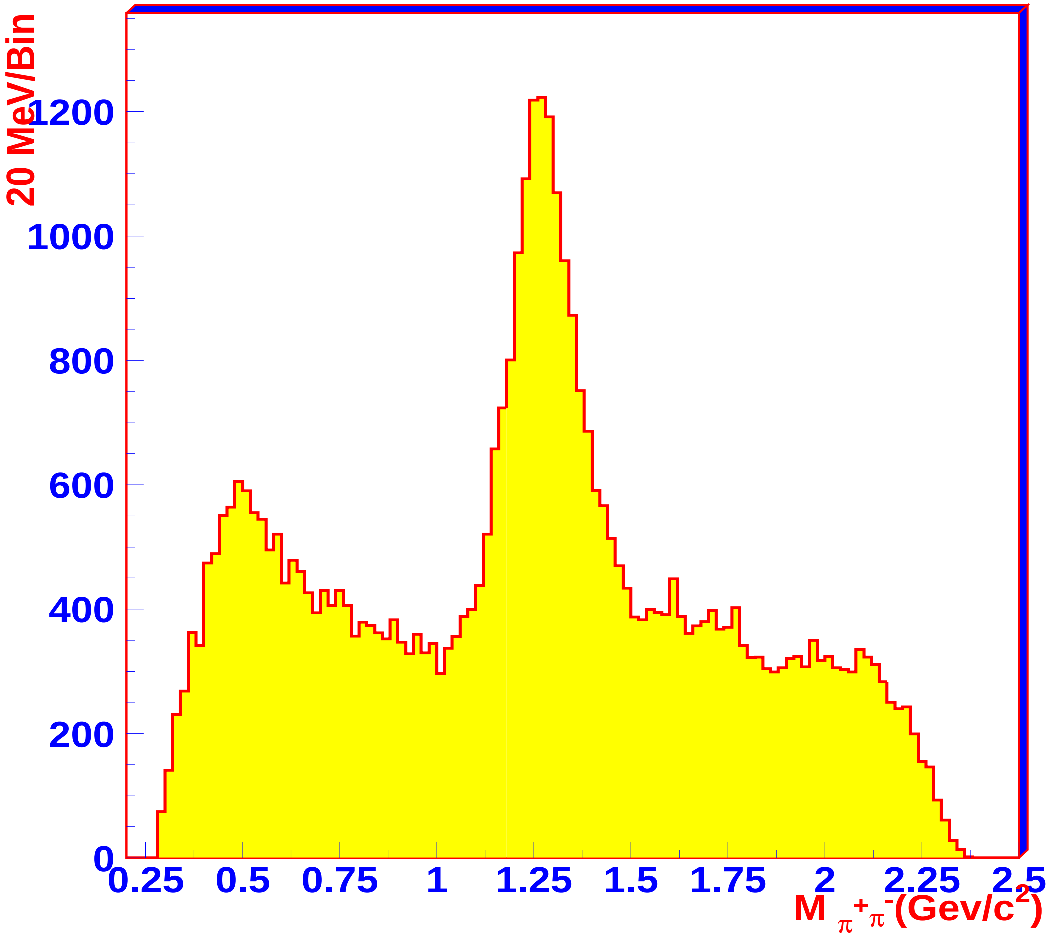


Figure 3: The invariant mass spectrum of $\pi^+\pi^-$

♡ **Daliz plot:** We could see four clear bands in the Daliz plot.

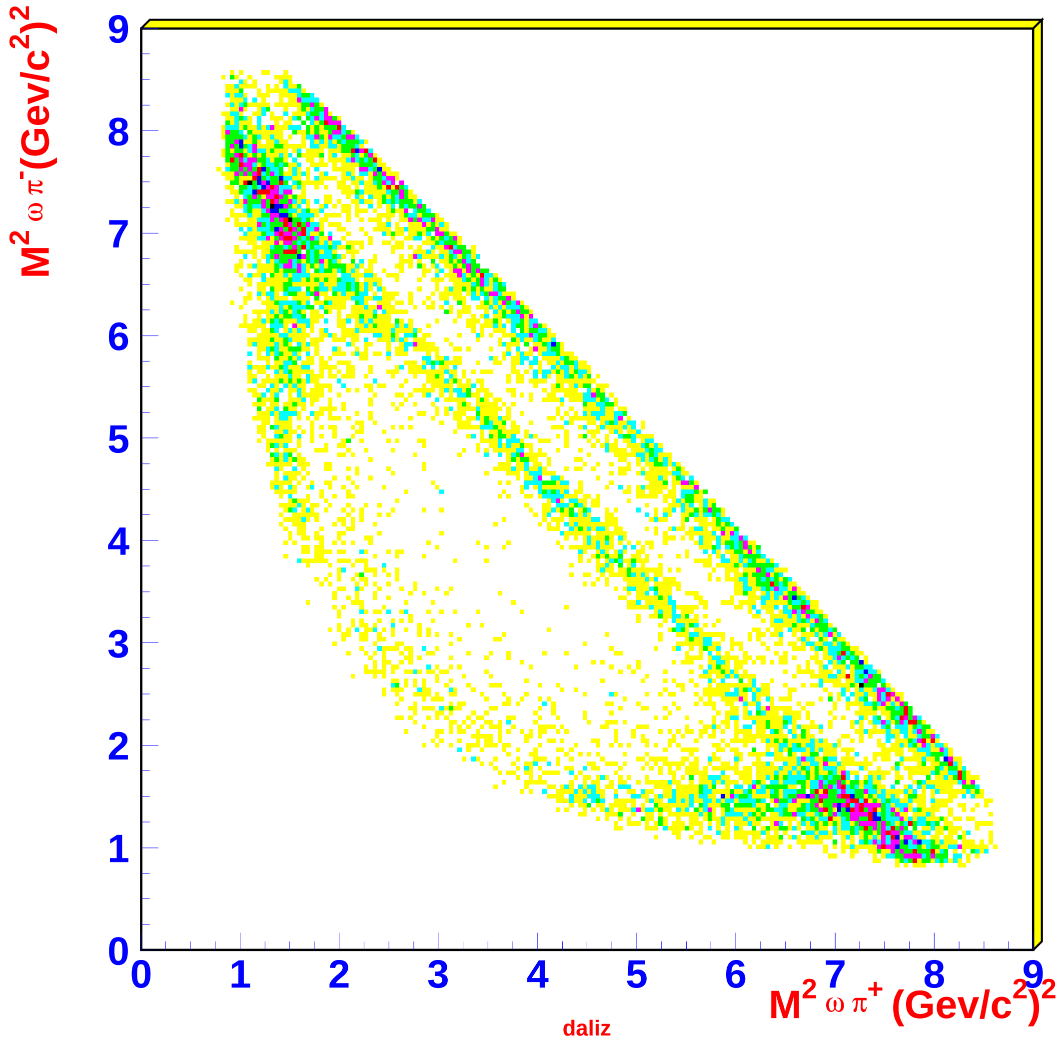


Figure 4: Daliz plot

♡ Possible Origination of the Low Mass Enhancement:

There are several possibilities for the origination of the low mass enhancement:

- From Backgrounds;
- Phase space effects;
- Threshold effects;
- Resonance.

We will study these possibilities one by one.

♡ **Side-band backgrounds:** There are some backgrounds in the above data sample (such as $J/\psi \to \rho 3\pi$, $\cdots$). Some of them can be seen in the ω side-band.

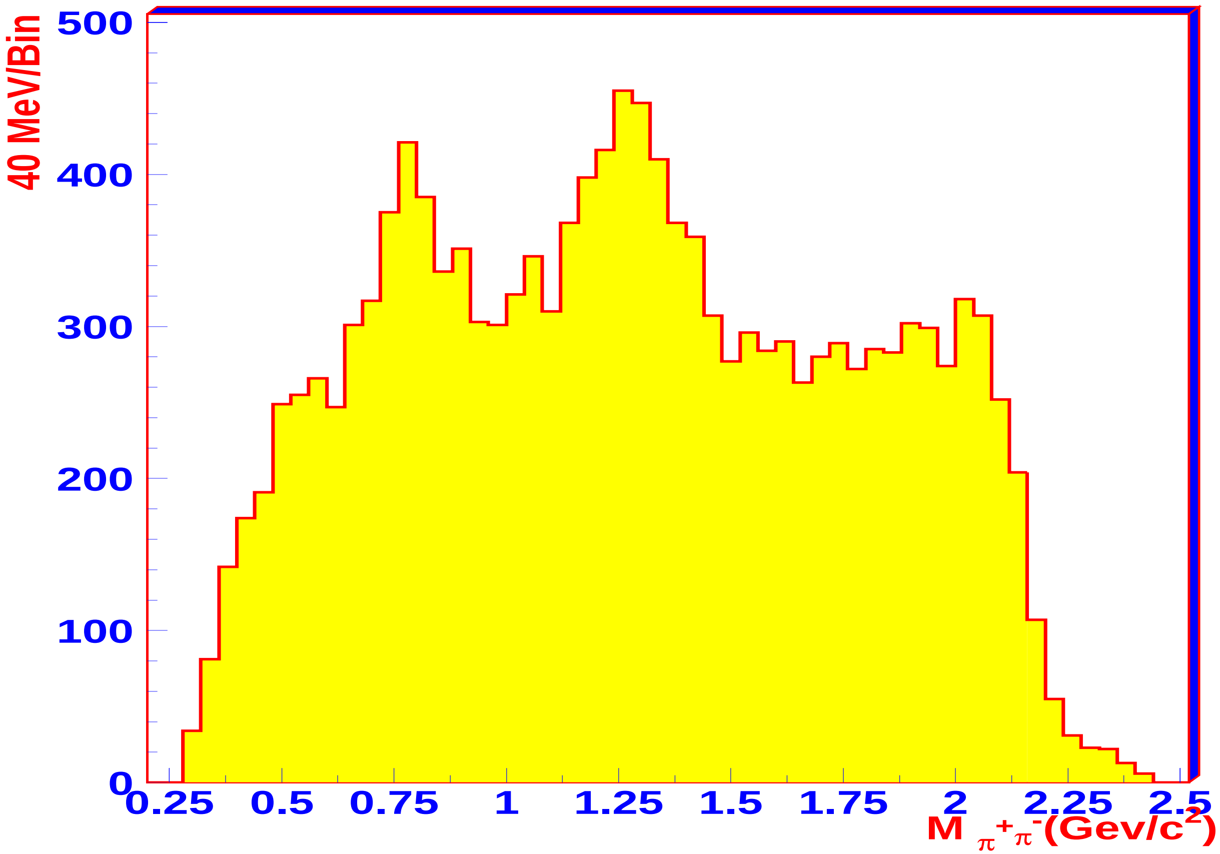


Figure 5: $\pi^+\pi^-$ invariant mass spectrum of ω side-band.

The yellow histogram is the data and violate histogram is ω side-band.

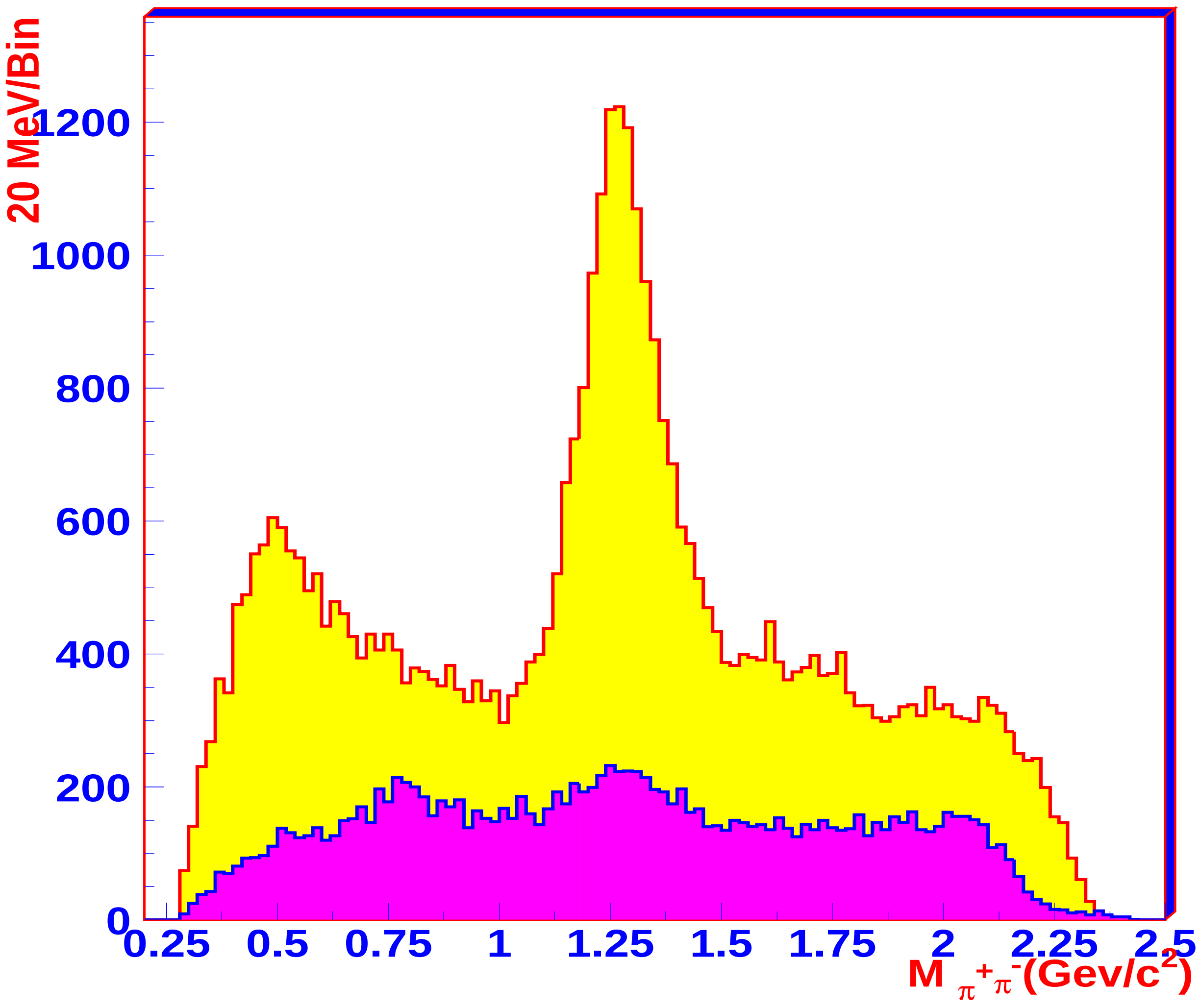


Figure 6: $\pi^+\pi^-$ invariant mass spectrum of ω side-band.

Events are almost even scattered in the phase space. We could not see the low mass enhancement in this Daliz plot.

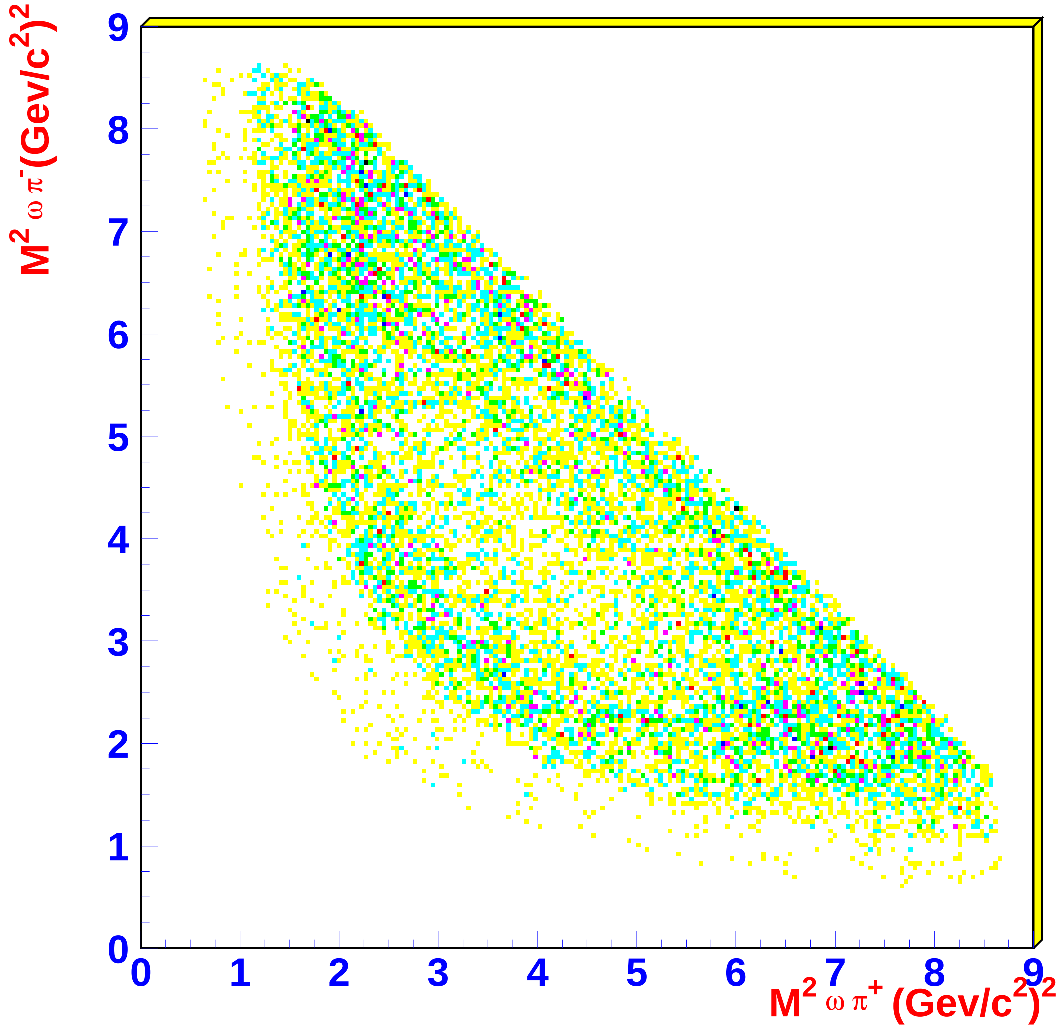


Figure 7: Daliz plot for ω side-band.

The low mass enhancment can be clearly seen in the $\pi^+\pi^-$ invariant mass spectrum after ω side-band subtraction, which means that it does not come from backgrounds that do not contain ω in the final states.

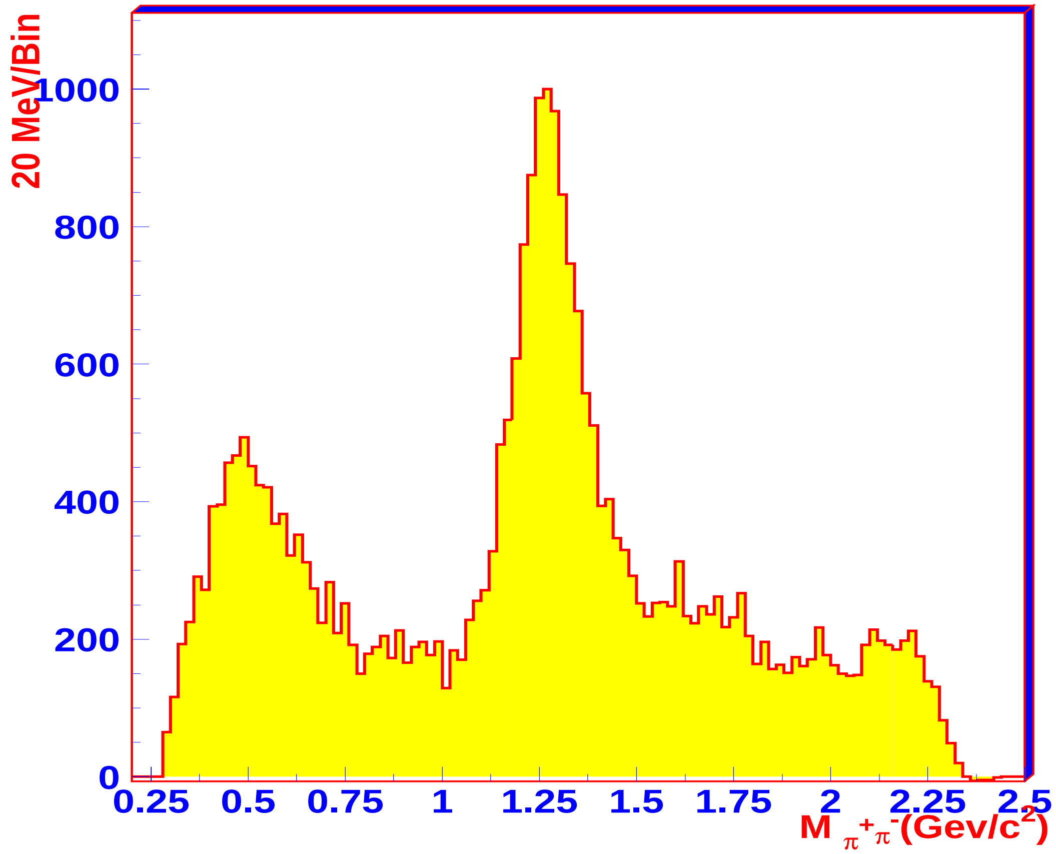


Figure 8: $\pi^+\pi^-$ invariant mass spectrum (after ω side-band subtraction).

♡ **Monte Carlo Simulation:** Events from other J/ψ decay channels are very small.

Decay channels	Total MC events	Event number after cut	Selection efficiency
$\omega\pi^+\pi^-$	500000	49445	9.89 %
ωK^+K^-	100000	9	0.009 %
$\pi^0\pi^+\pi^-\pi^+\pi^-$	100000	130	0.13 %
$\rho^0\pi^+\pi^-\pi^0$	100000	109	0.11 %
$\omega\pi^+\pi^-\pi^+\pi^-$	100000	0	0 %
$\omega\pi^+\pi^-K^+K^-$	100000	0	0 %

Table 1: Monte Carlo simulation for background study.

♡ **Phase space effect:** Some backgrounds can be removed through side-band subtraction. It does not originate from phase space effect.

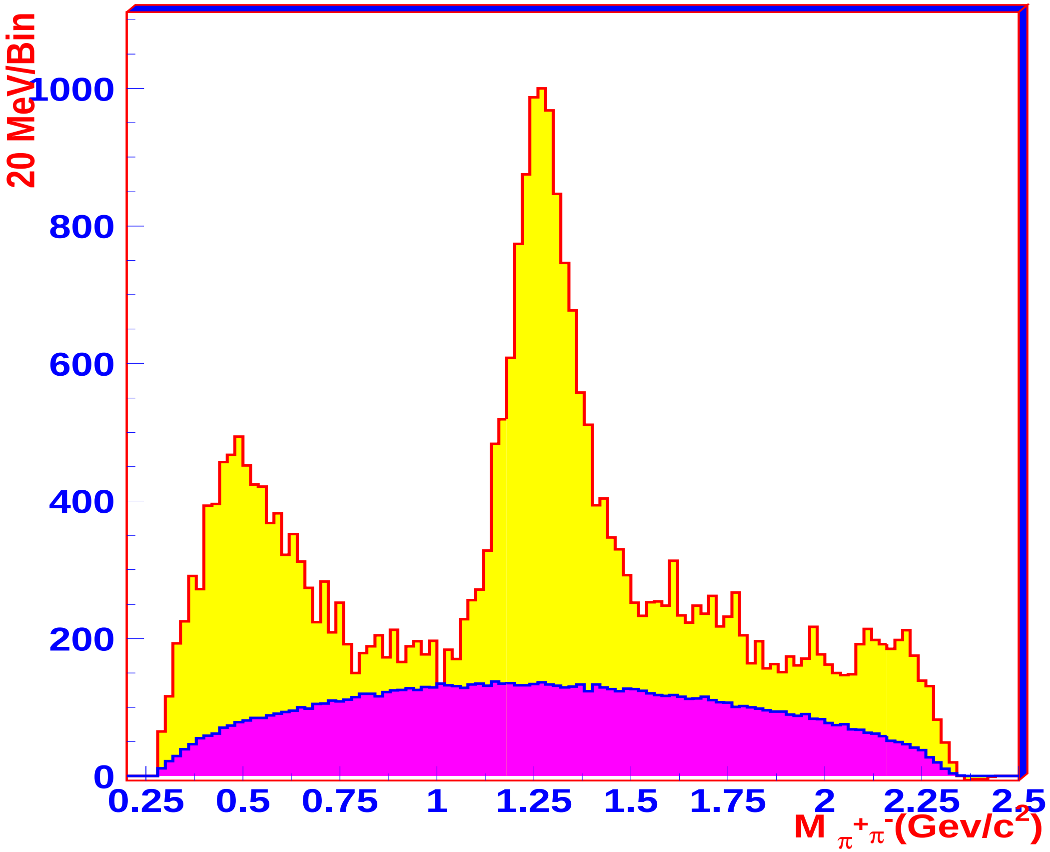


Figure 9: Phase space effect. The violet area is the phase space effect and the yellow histogram is real data after side-band subtraction.

♡ **S-matrix squared :** Both threshold effect and σ particle can be seen in the S-matrix squared. Threshold effect is a $1/p$ factor in the s-matrix squared.

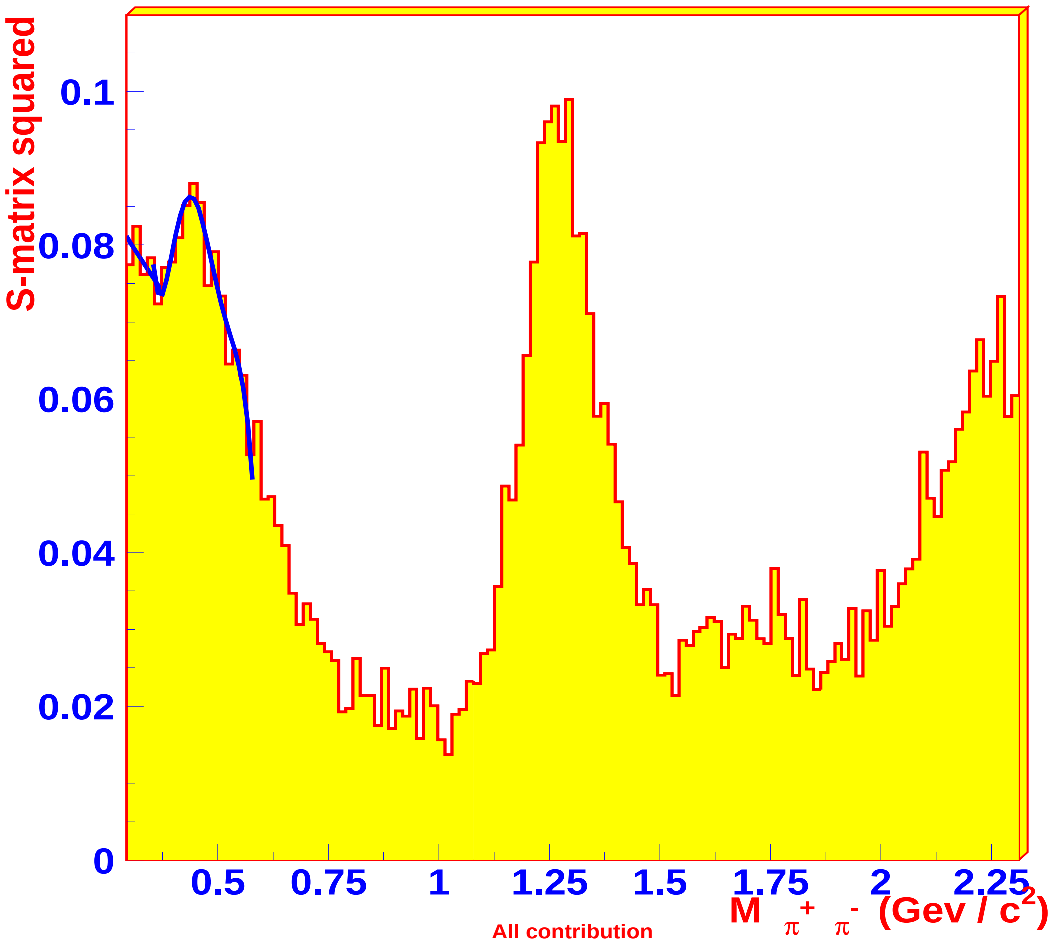


Figure 10: S-matrix squared.

♡ **Monte Carlo Study (1):** We generate 50M J/ψ Monte Carlo data which contains all known J/ψ decay channels. In Monte Carlo simulation, there is no structure at low mass region.

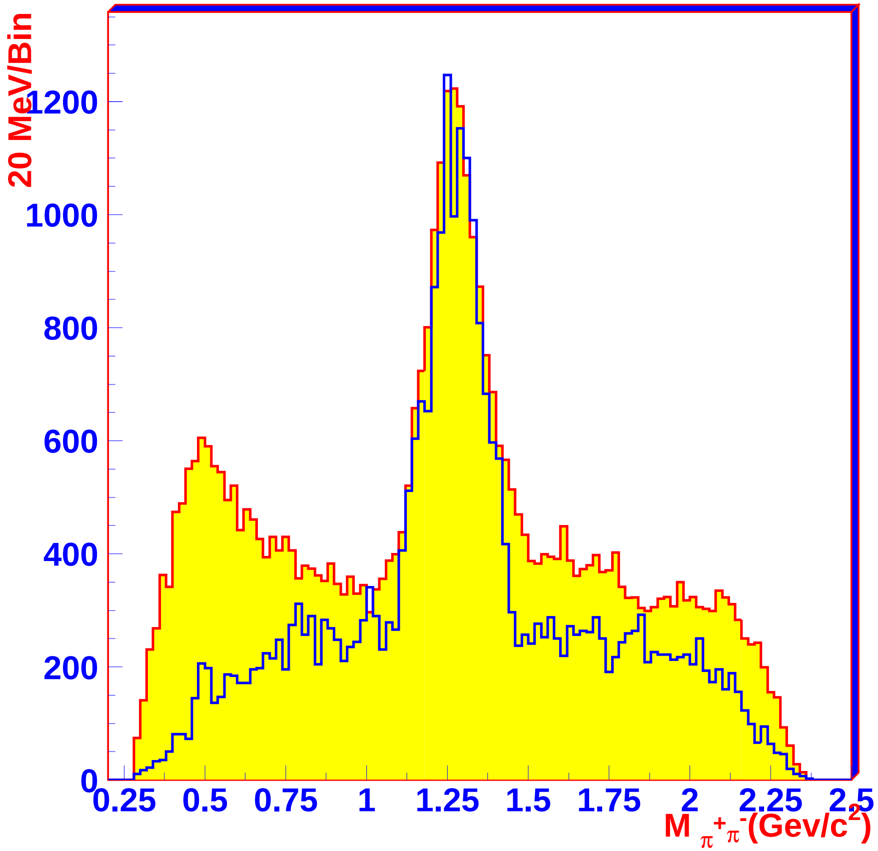


Figure 11: Invariant mass spectrum of $\pi^-\pi^-$ of Monte Carlo simulation

♡ Monte Carlo Study (2):

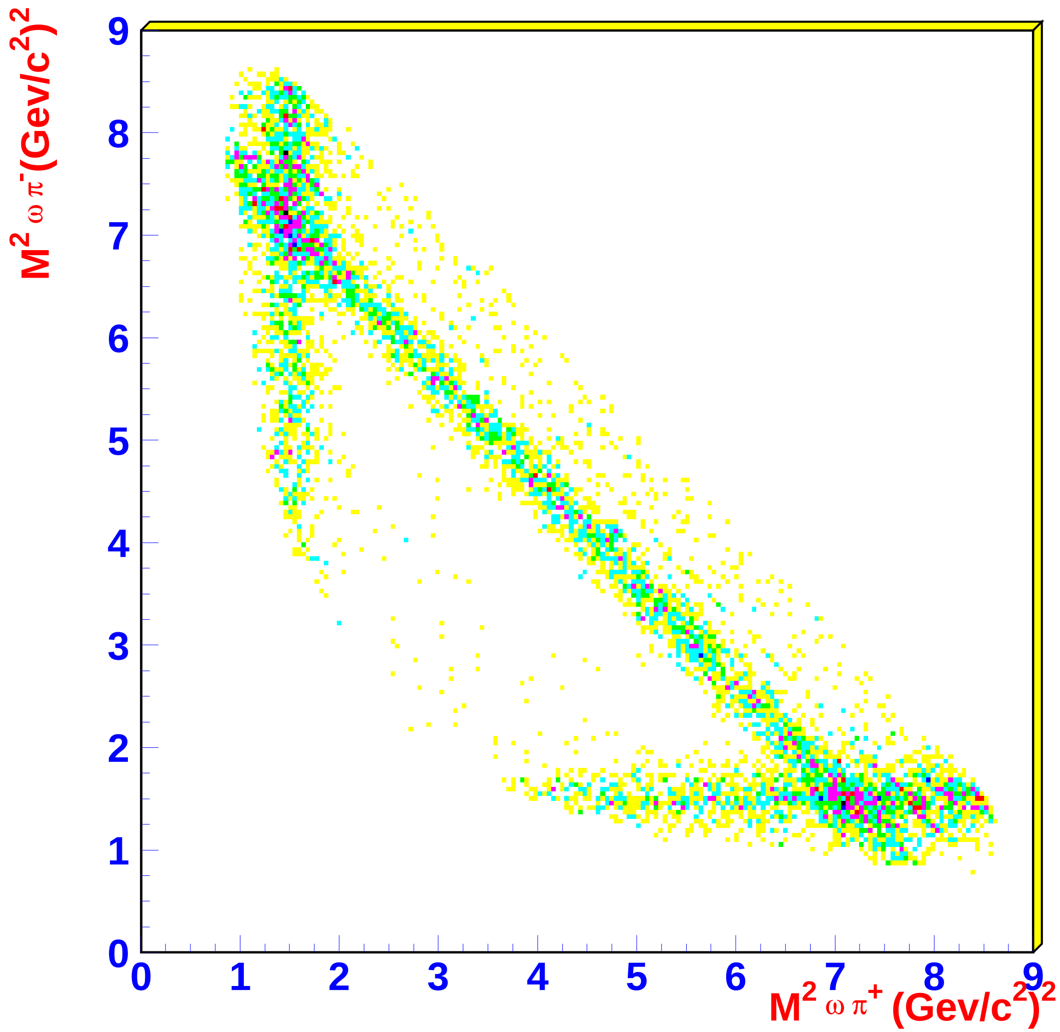
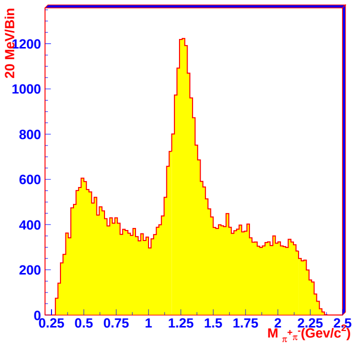


Figure 12: Daliz plot of Monte Carlo simulation

♡ **Summary:** According to the above study, we have some preliminary results on the first peak.

1. It does not come from backgrounds;
2. it does not come from threshold effect;
3. it does not come from phase space effect;
4. It is a s-channel resonance.

We have performed Partial Wave Analysis(PWA) on the $\pi^+\pi^-$ invariant mass spectrum to study the structure of the first peak. There are three independent analysis in this channel, only two of them are reported in this talk, another is reported by Dr. Komada.



♡ **Final Data Sample for PWA Analysis:** In order to avoid possible ambiguity and complexity on the higher mass region, we only perform PWA analysis on the $\pi^+\pi^-$ invariant mass spectrum below 1.5 GeV.

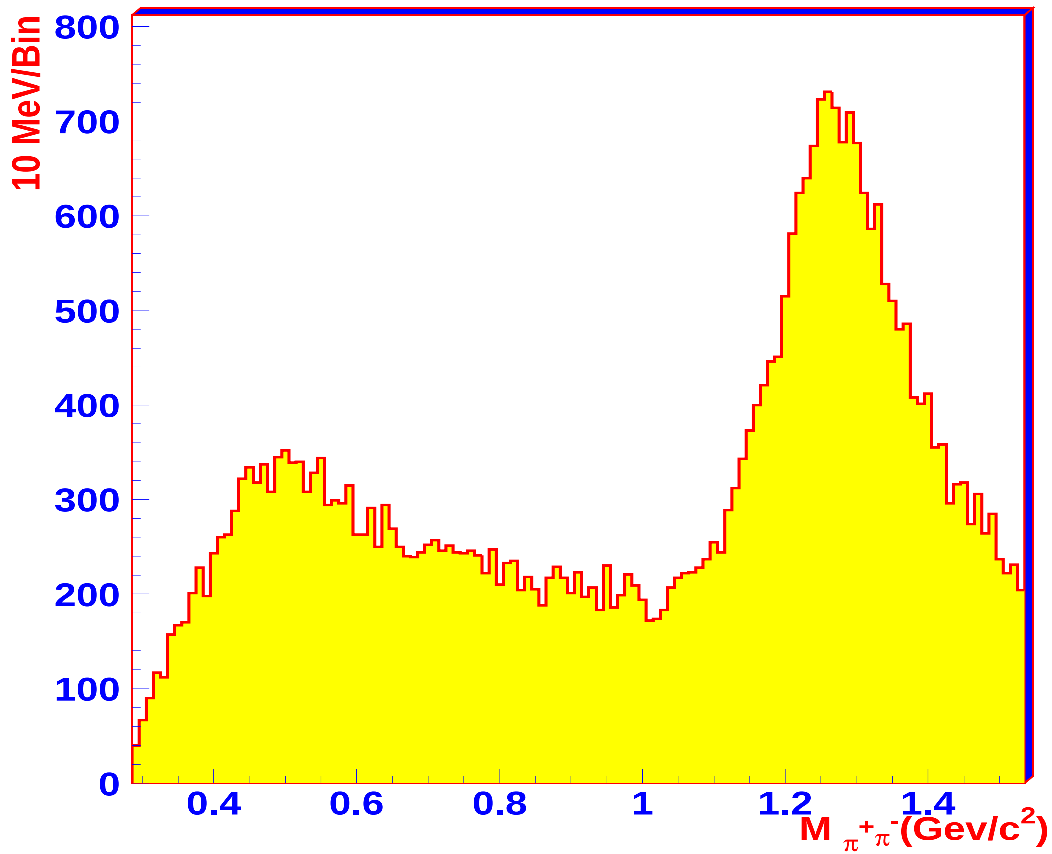


Figure 13: Invariant mass spectrum of $\pi^+\pi^-$ with $M_{\pi\pi}$ below 1.5 GeV.

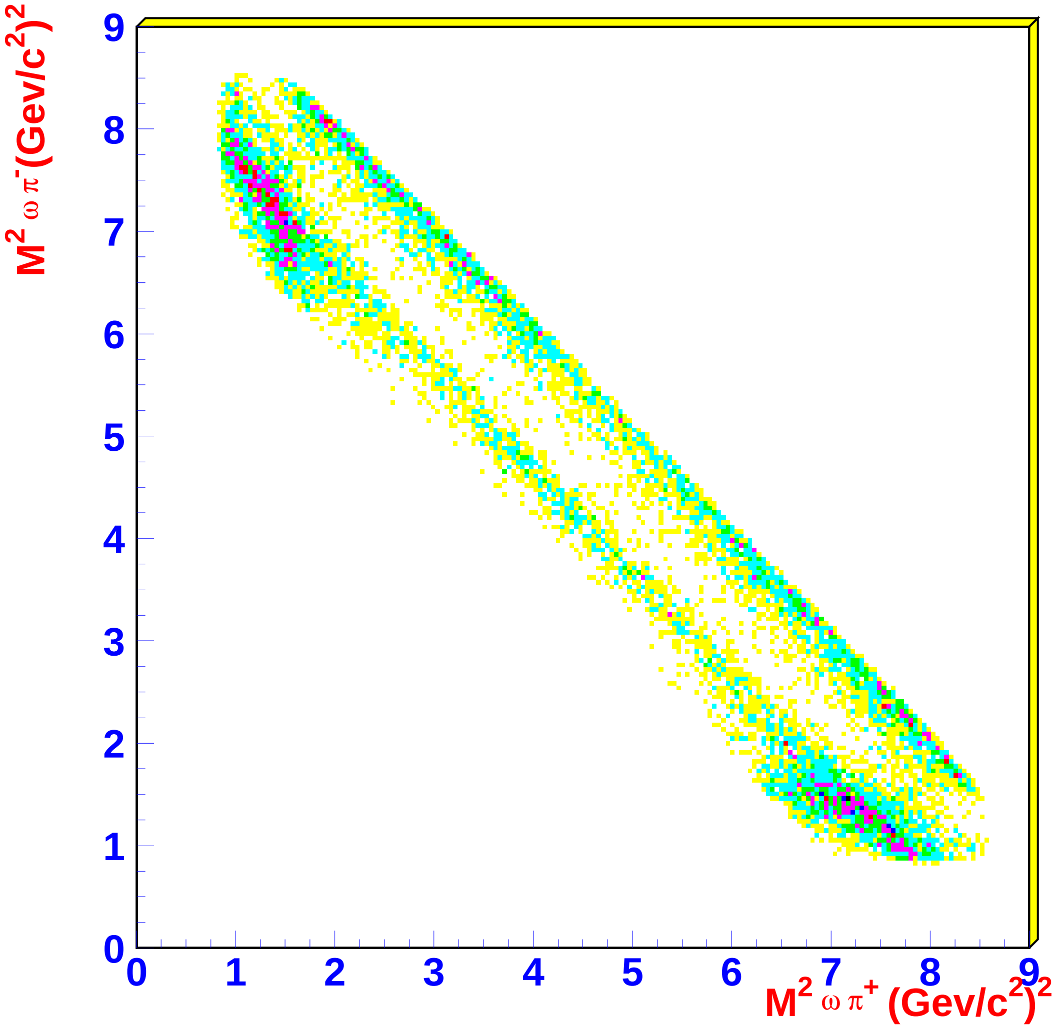


Figure 14: Daliz plot with $M_{\pi\pi}$ below 1.5 GeV.

♡ **Angular Distributions in the sigma maas region:** It is almost flat, which looks like a spin-0 resonance.

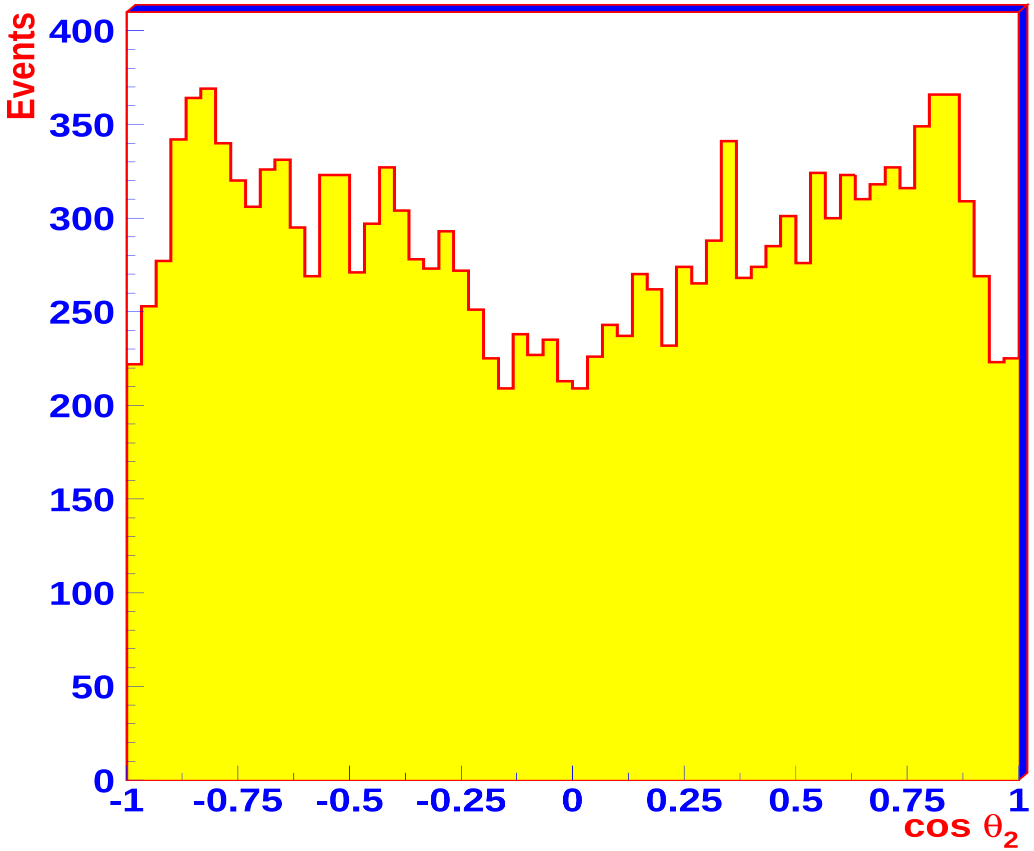


Figure 15: Angular distribution of low mass enhancement (in the mass region 0.0 – 1.0 Gev) (The polar angle of π^+ in $\pi^+\pi^-$ center of mass system).

♡ **Spin-parity and statistical significance:** We first use a 0^{++} to fit the first peak. We have tested its statistical significance and spin-parity. Its spin-parity is 0^{++}.

Spin-parity	LF	Change	Significance
0^{++}	-6231	—	—
$omit$	-3612	2619	$\gg$ 20 σ
2^{++}	-5776	455	$\gg$ 20 σ
4^{++}	-5054	1103	$\gg$ 20 σ

Table 2: Spin-parity and statistical significance of σ. (LF means Likelihood Function)

♡ **Mass and width scan:** We determine its mass and width through mass and width scan.

$$M_\sigma = 487 \pm 68 \quad MeV,$$
$$\Gamma_\sigma = 363 \pm 131 \quad MeV.$$

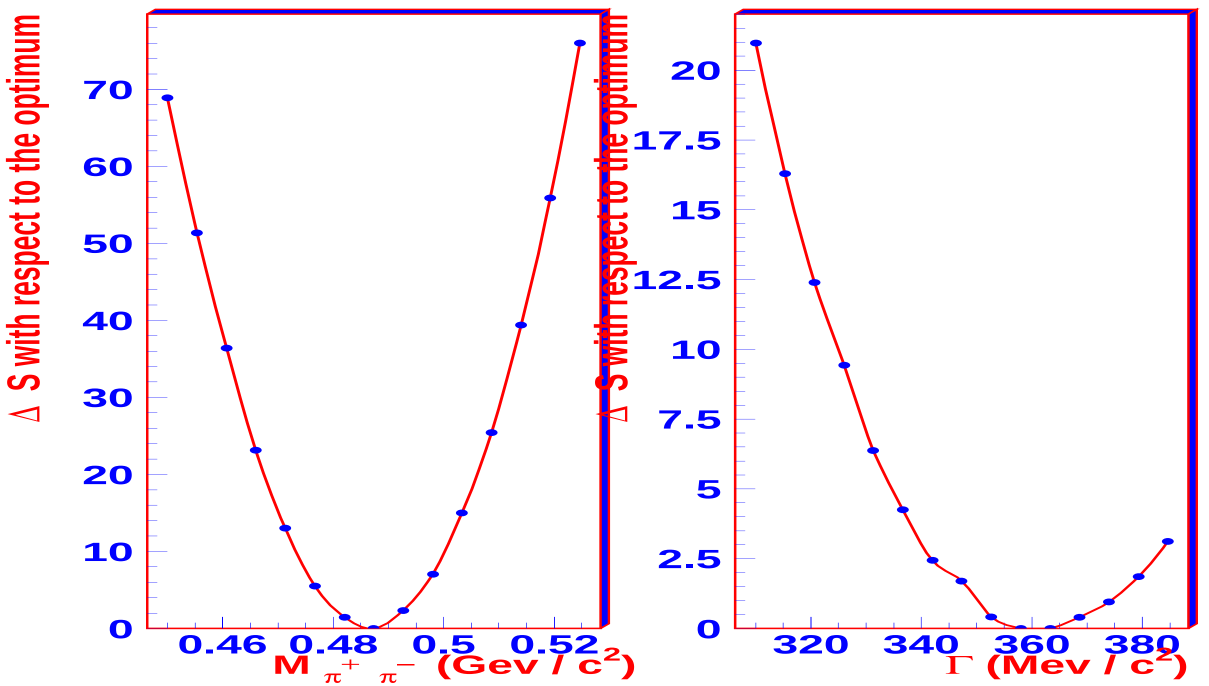


Figure 16: Mass and width scan on σ.

♡ **S-Matrix square:** We could see a peak at about 430 MeV which corresponds to sigma particle.

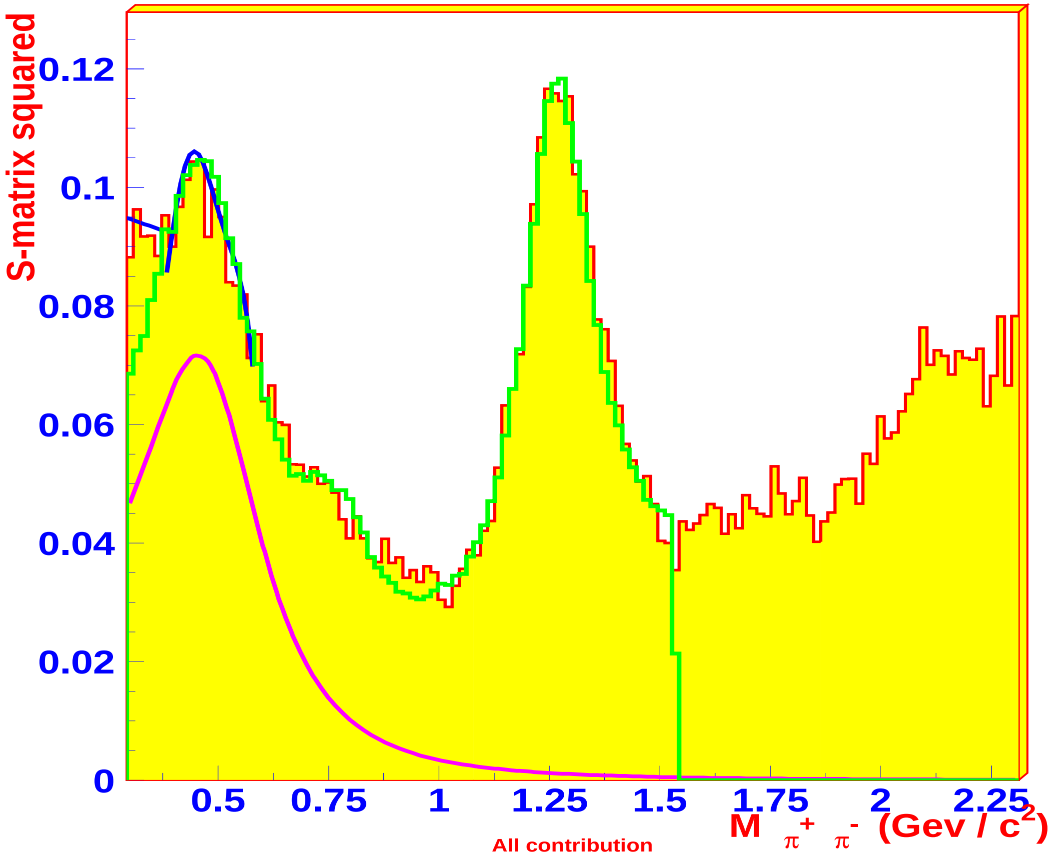


Figure 17: Mass and width scan on σ.

♡ Fitting on angular distributions of σ mass region:

Our final fit on the angular distributions of σ mass region ($M_{\pi^+\pi^-} < 0.9$ GeV) is quite good.

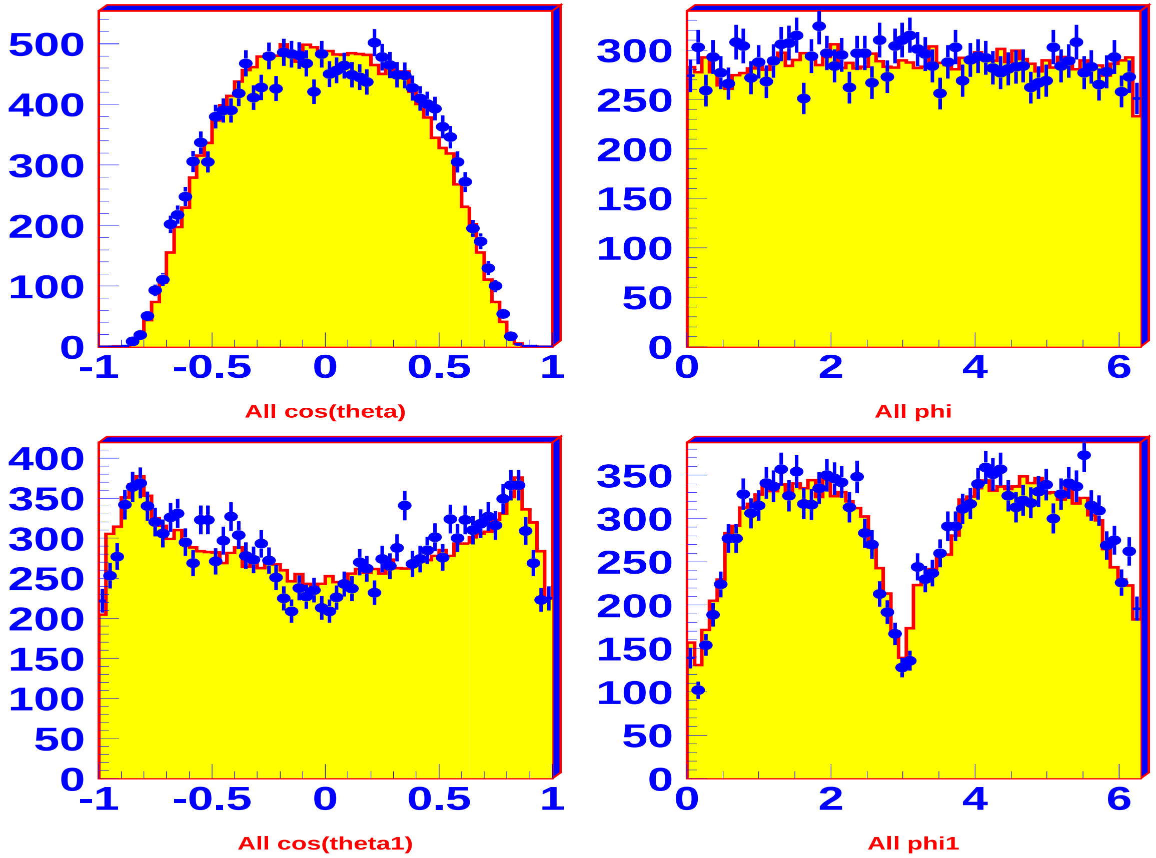


Figure 18: Final fit on the angular distributions of σ mass region. Error bar is the data and histogram is our final fit.

♡ σ **contribution :** The σ-particle is needed in our final fit on the first peak.

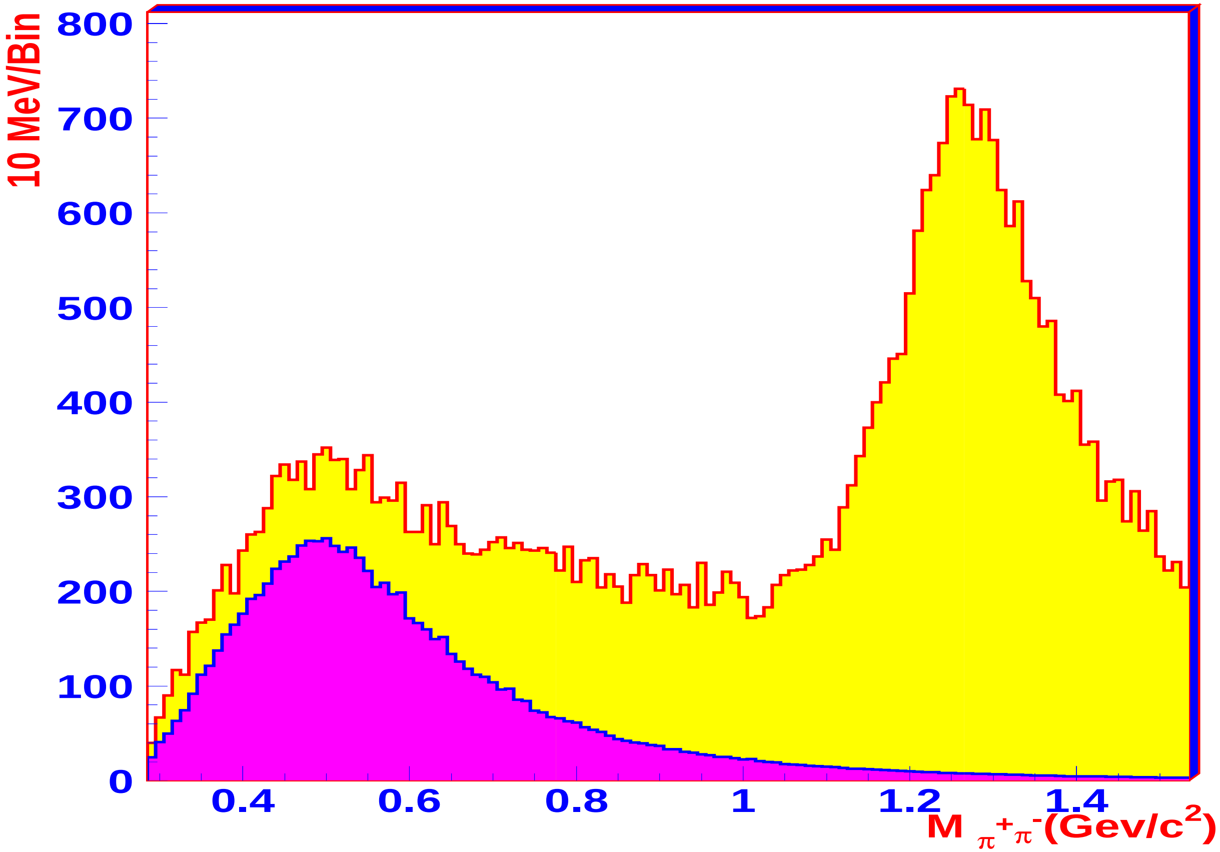


Figure 19: σ-particle contribution. The yellow histogram is the real data and the blue histogram is the contribution from σ-particle.

♡ Global fit: Final global fit on the whole mass spectrum

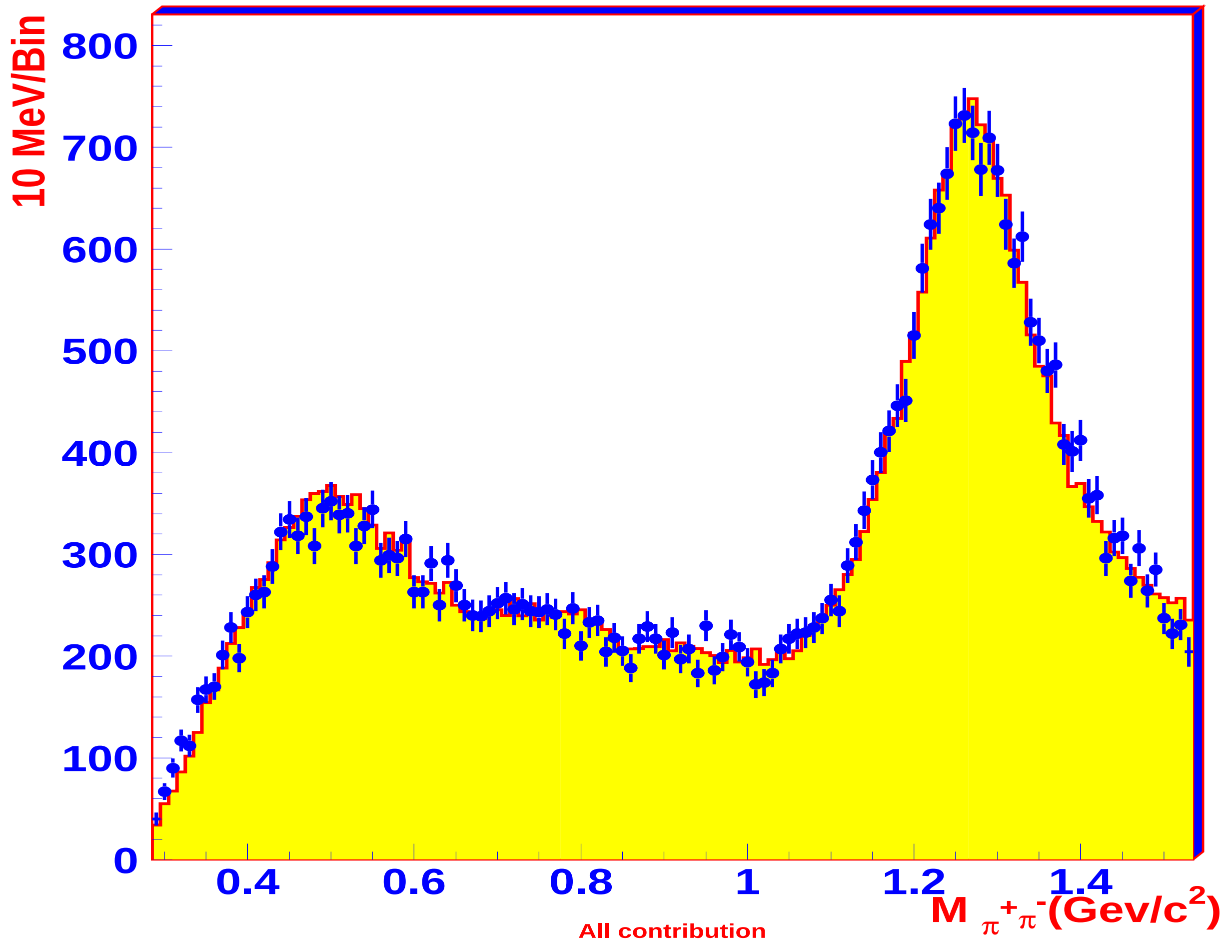
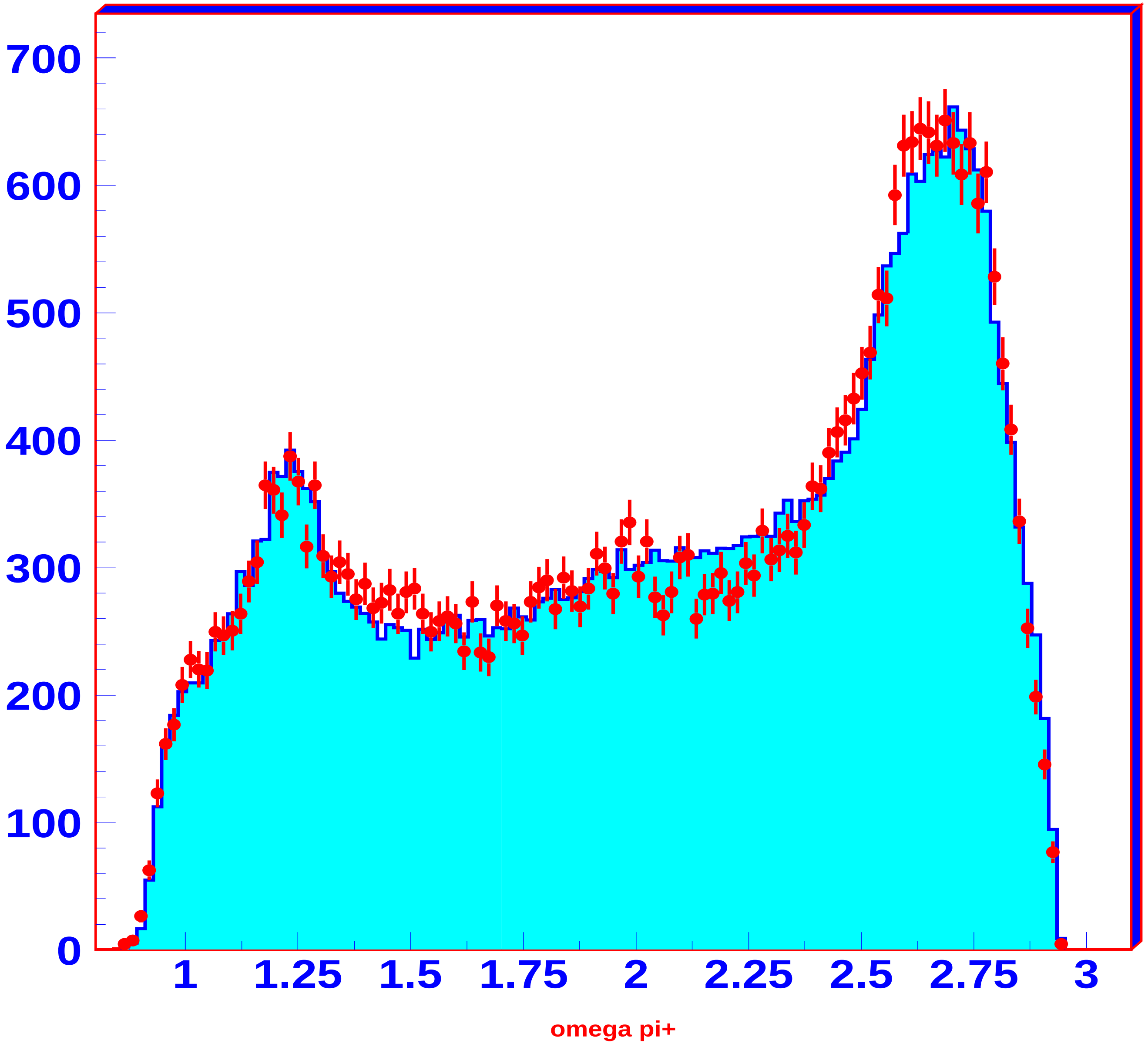
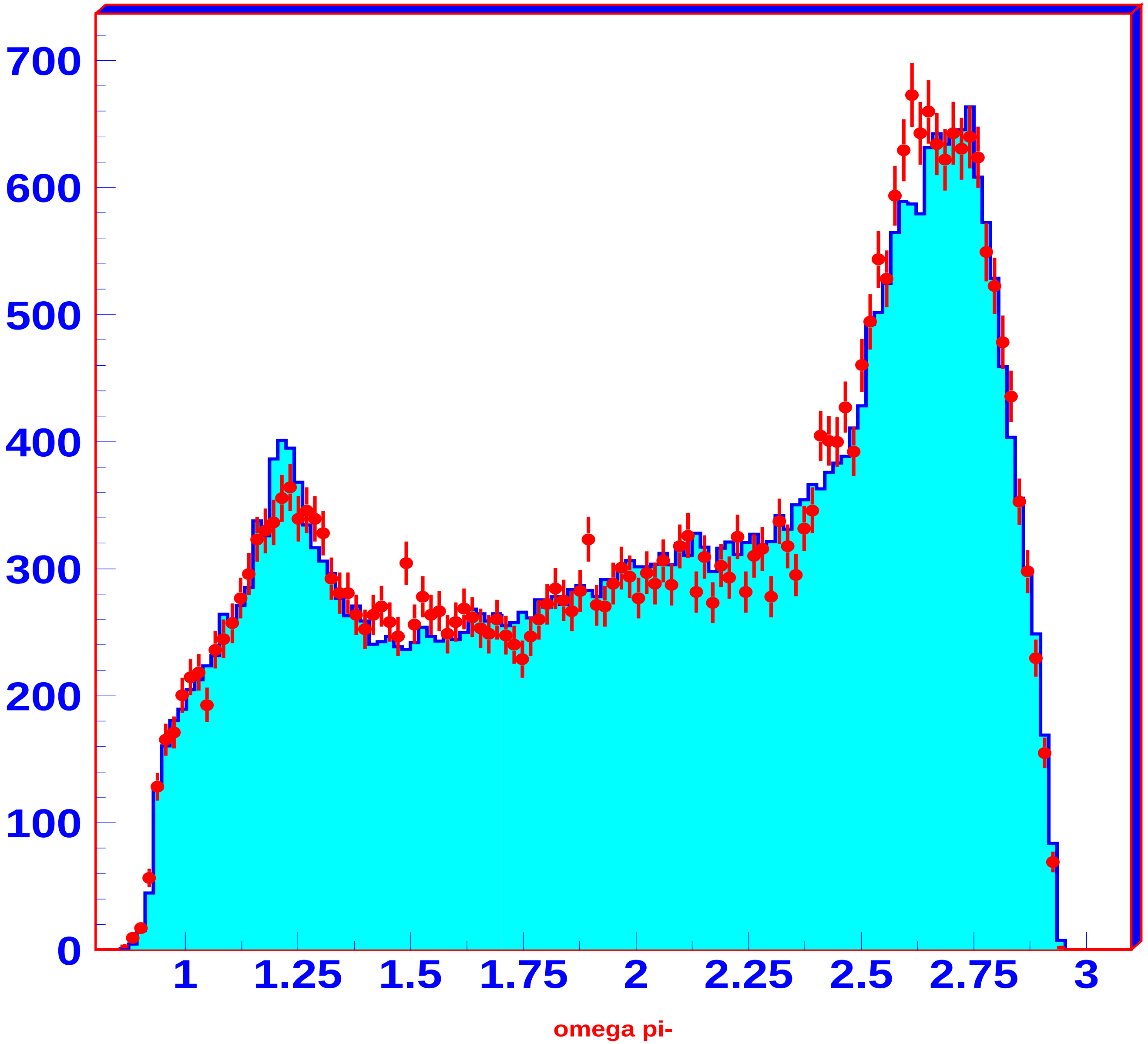


Figure 20: Final global fit on invariant mass spectrum.


700
600
500
400
300
200
100
0
1
1.25
1.5
1.75
2
2.25
2.5
2.75
3
omega pi+


700
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1.75
2
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2.75
3
omega pi-

Final global fit on the angular distributions

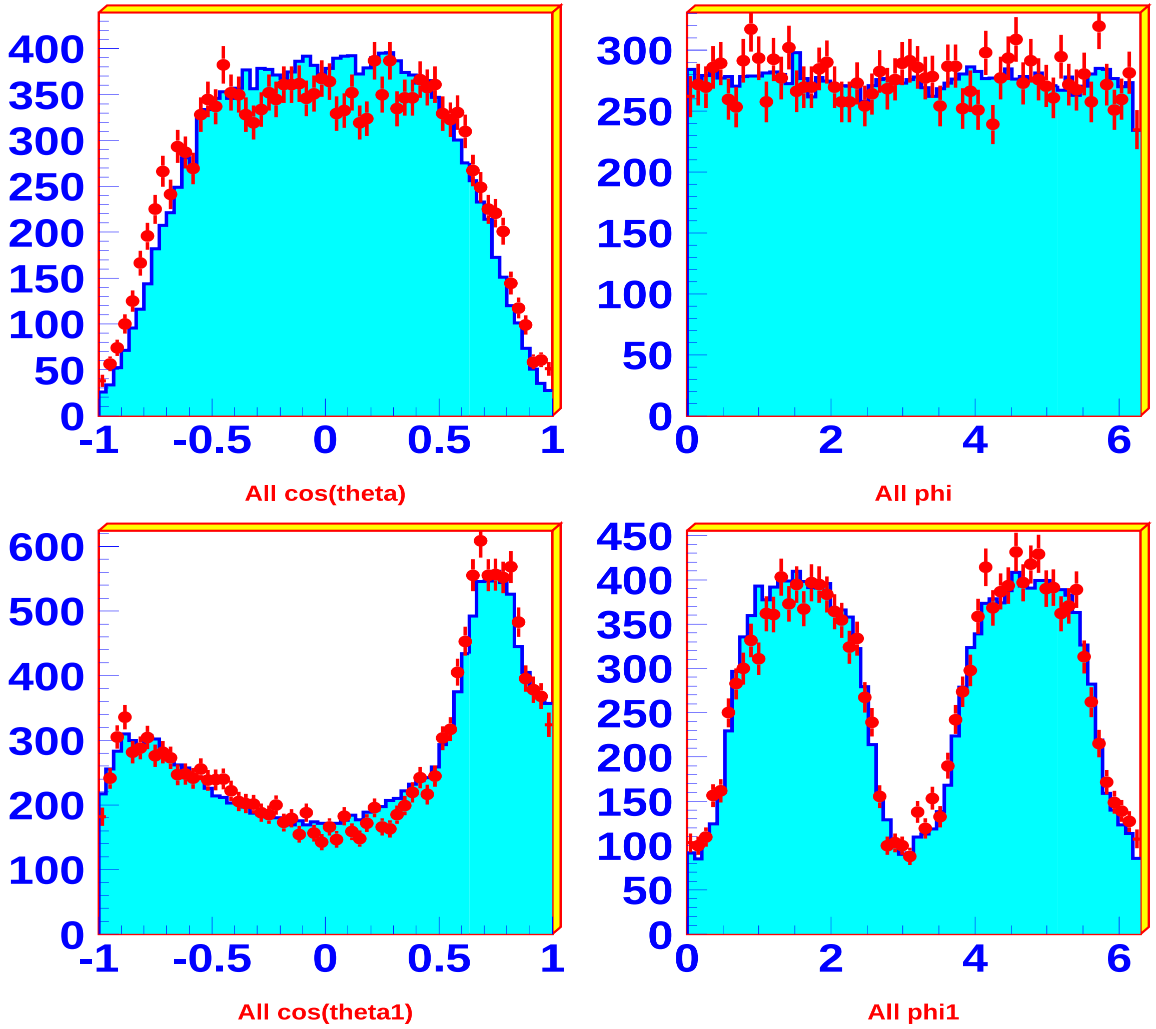
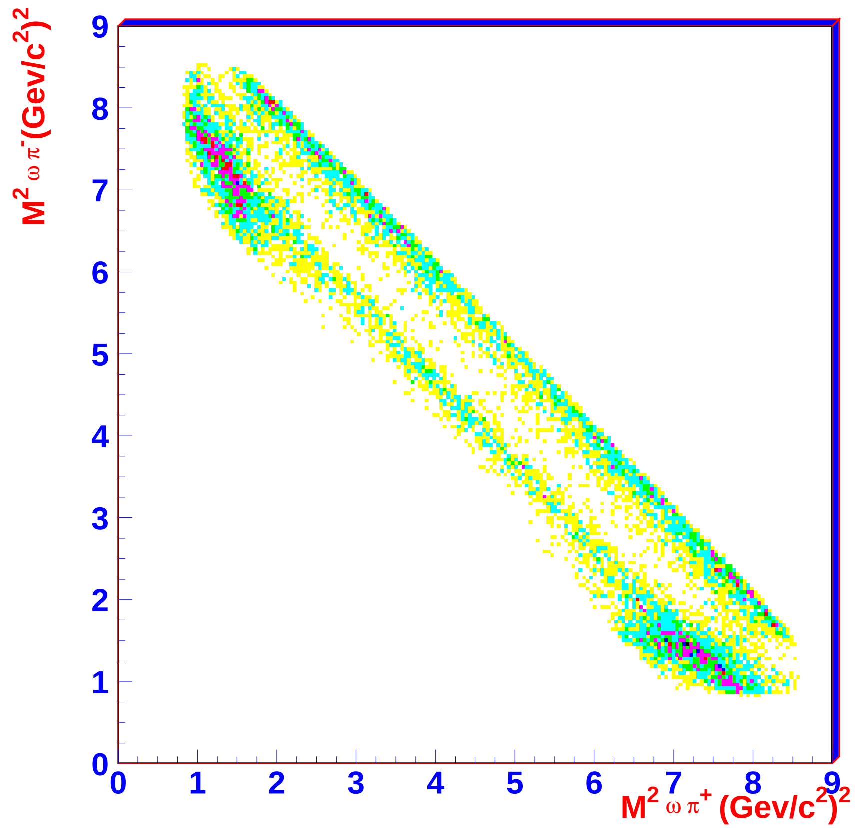


Figure 23: Final global fit on angular distributions.



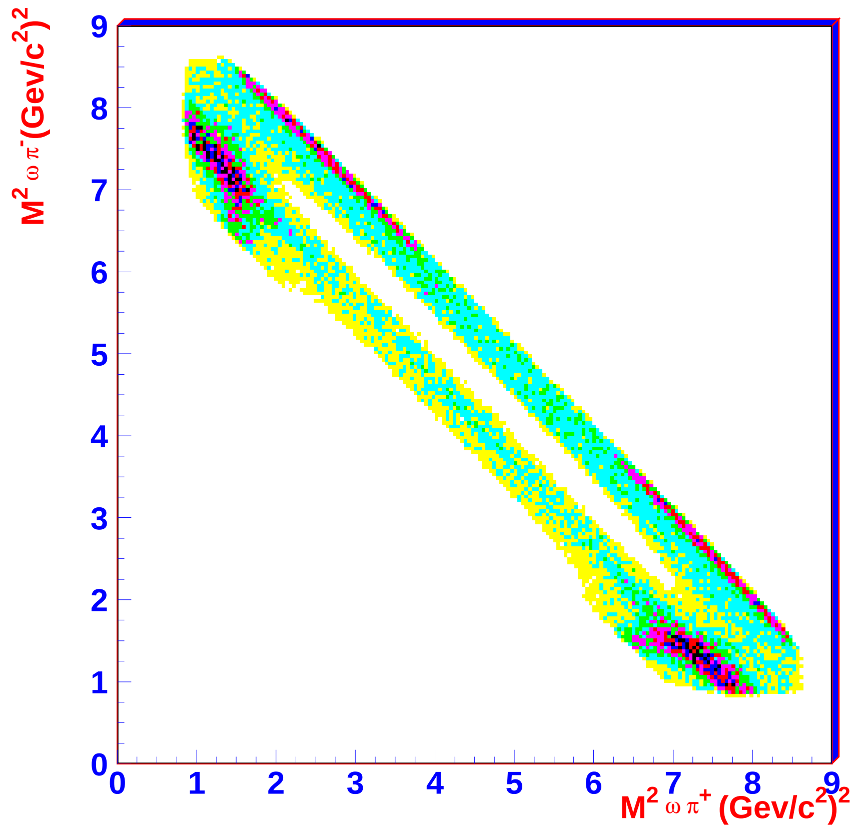
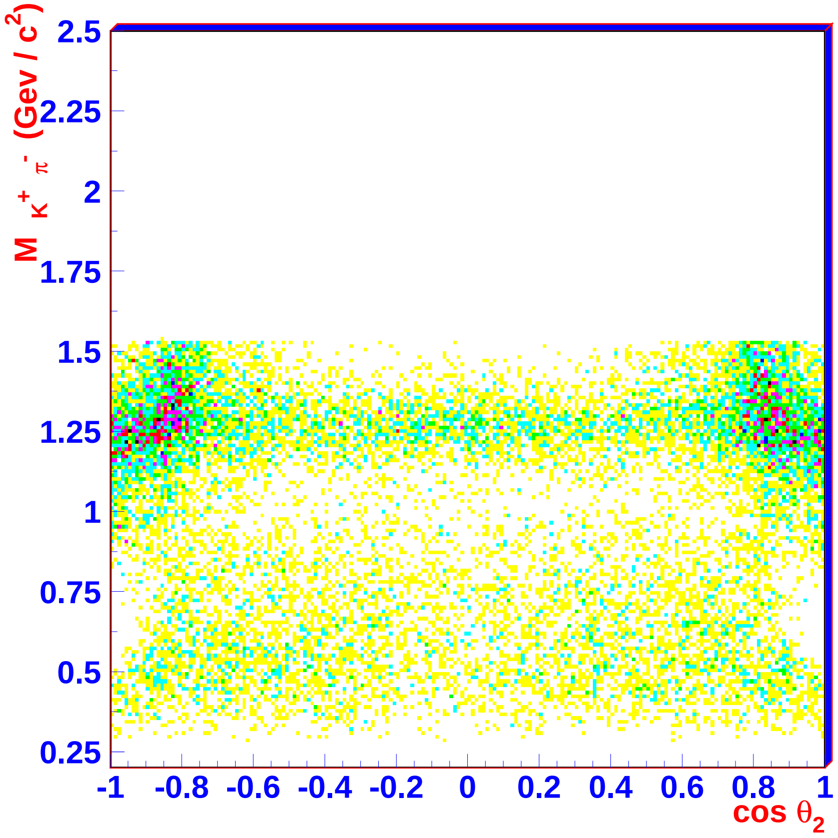


Figure 24: LEFT: data, RIGHT: fit



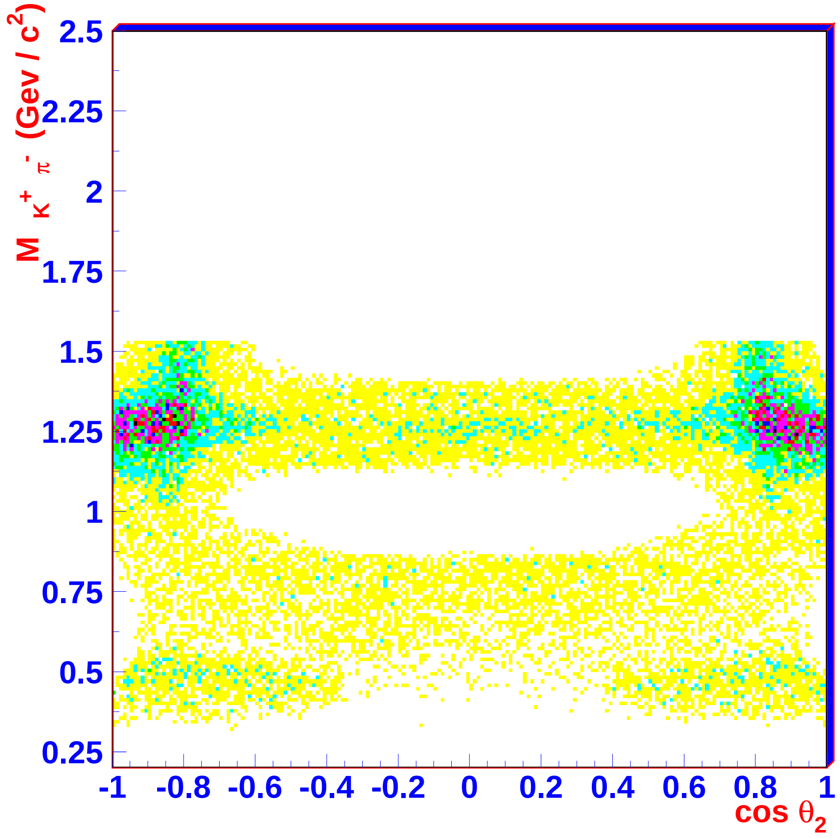


Figure 25: LEFT: data, RIGHT: fit

♡ Radiative decay: σ is not found in the $J/\psi \to \gamma\pi^+\pi^-$

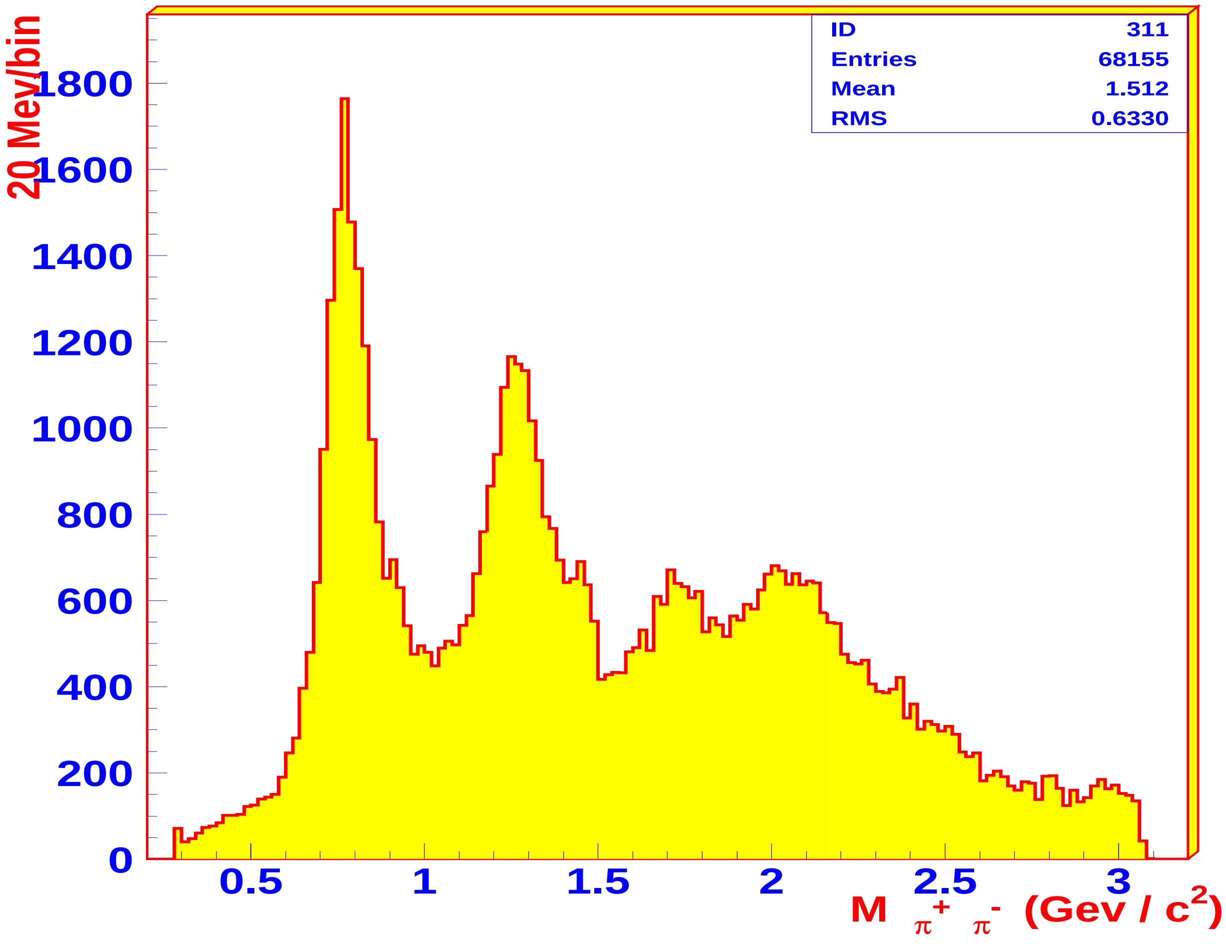


Figure 26: The invariant mass spectrum of $\pi^+\pi^-$ in $J/\psi \to \gamma\pi^+\pi^-$.

♡ Discussions

1. We find a 0^{++} resonance in the $J/\psi \to \omega\pi^+\pi^-$. It is a Iso-scalar scalar particle. It is considered to be the σ-particle.

2. Final results are highly model dependent. Different parameterization gives out different results on its mass and width.

3. We didn't find σ in $J/\psi \to \gamma\pi^+\pi^-$. It means that it does not look like a scalar glueball.

4. Mass and width(Preliminary):

$$BW_\sigma = \frac{1}{m_\sigma^2 - s - i\sqrt{s}\Gamma_\sigma(s)}, \qquad \Gamma_\sigma(s) = \frac{g_\sigma^2 p_1(s)}{8\pi s},$$

$$M_\sigma \;=\; 487 \pm 68 \quad MeV,$$
$$\Gamma_\sigma(M_\sigma) \;=\; 363 \pm 131 \quad MeV.$$

Another independent fit:

$$BW_\sigma = \frac{1}{m_\sigma^2 - s - iM_\sigma\Gamma_\sigma(s)}, \qquad \Gamma_\sigma(s) = g_1\rho_{\pi\pi}(s) + g_2\frac{\rho_{4\pi}(s)}{\rho_{4\pi}(M_\sigma^2)}$$

$$g_1 = M_\sigma f(s)\frac{s - m_\pi^2/2}{M_\sigma^2 - m_\pi^2/2}e^{-(s-M_\sigma^2)/a}, \quad f(s) = 0.5843 + 1.663s, \quad M_\sigma = 0.9264$$

$$Pole: \;(M, \Gamma) = \;(\,534 \pm 25\;\;,\;494 \pm 50)MeV$$

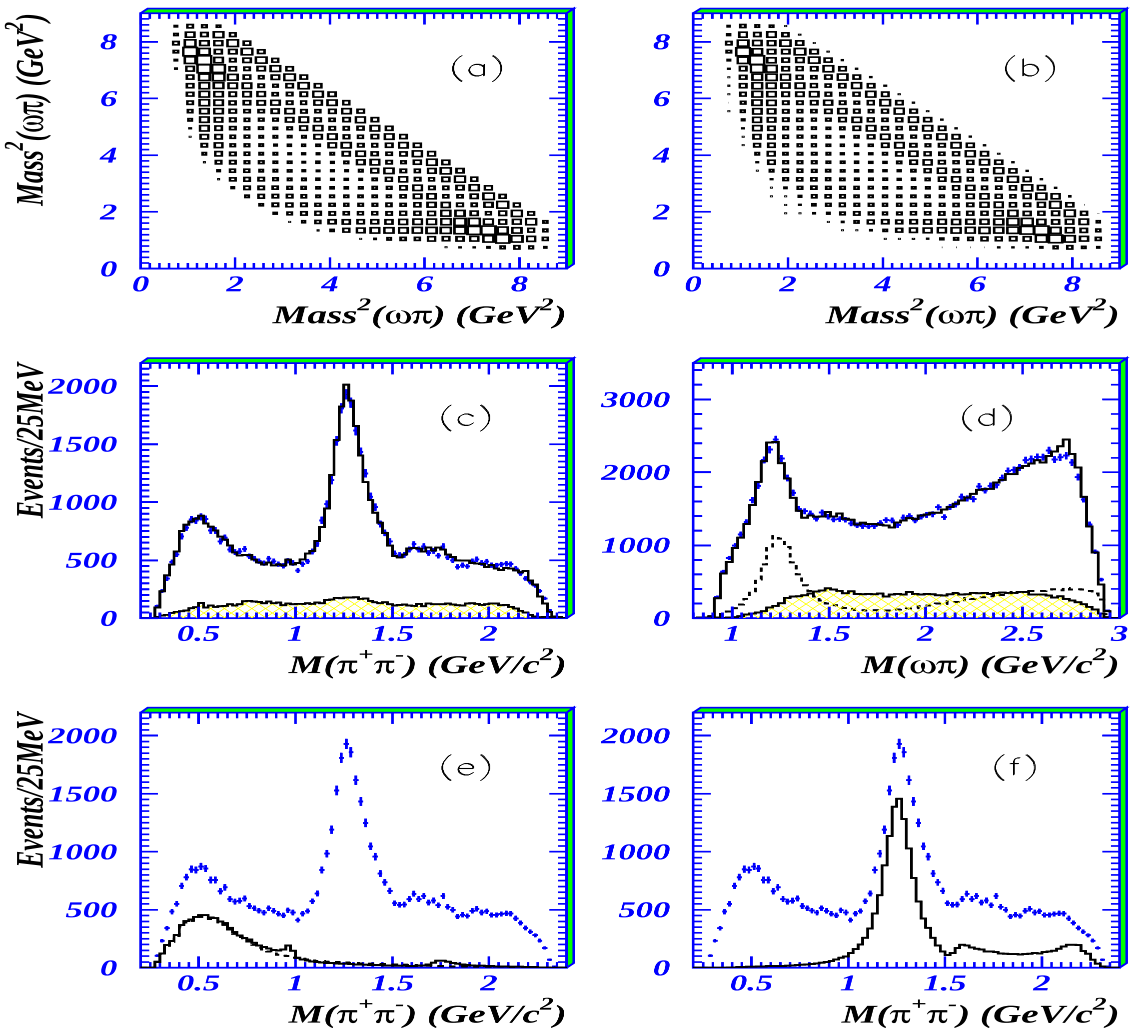


Figure 27: Fit on mass spectrum of whole mass region by another independent fit.

Part III: κ meson production in $J/\psi \to \bar{K}^*(892)^0 K^+\pi^-$

♡ **$\bar{K}^*(892)^0$ signal** After initial cut conditions and some of final cut conditions, we can see very clear $\bar{K}^*(892)^0$ signal.

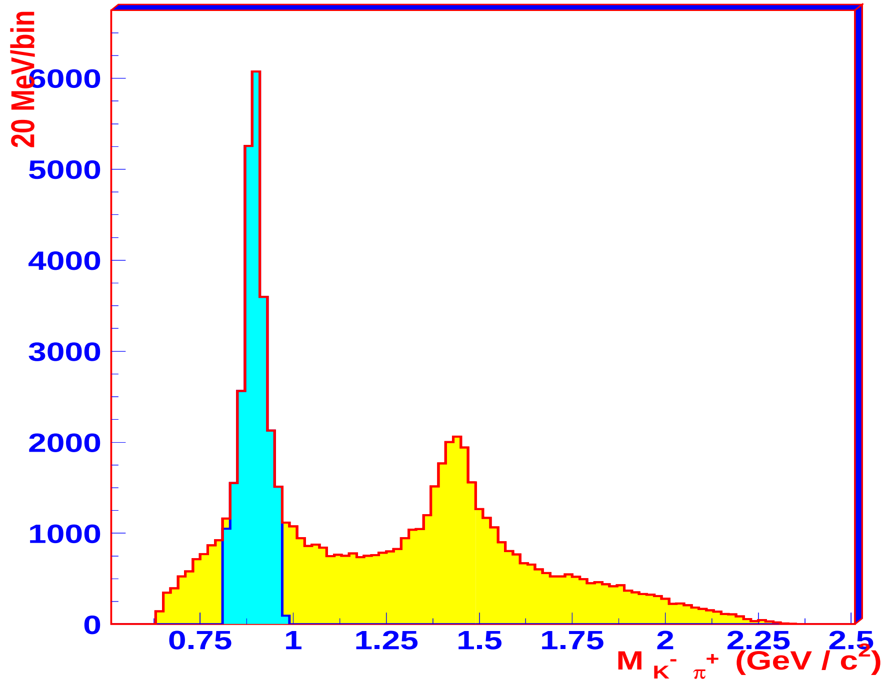


Figure 28: $\bar{K}^*(892)^0$ signal

♡ **Scatter plot of $M_{K^+\pi^-}$ vs. $M_{K^-\pi^+}$** From Daliz plot, we can see two clear bands which corresponds to $J/\psi \to \bar{K}^*(892)^0 K^+\pi^-$ and $J/\psi \to K^*(892)^0 K^-\pi^+$.

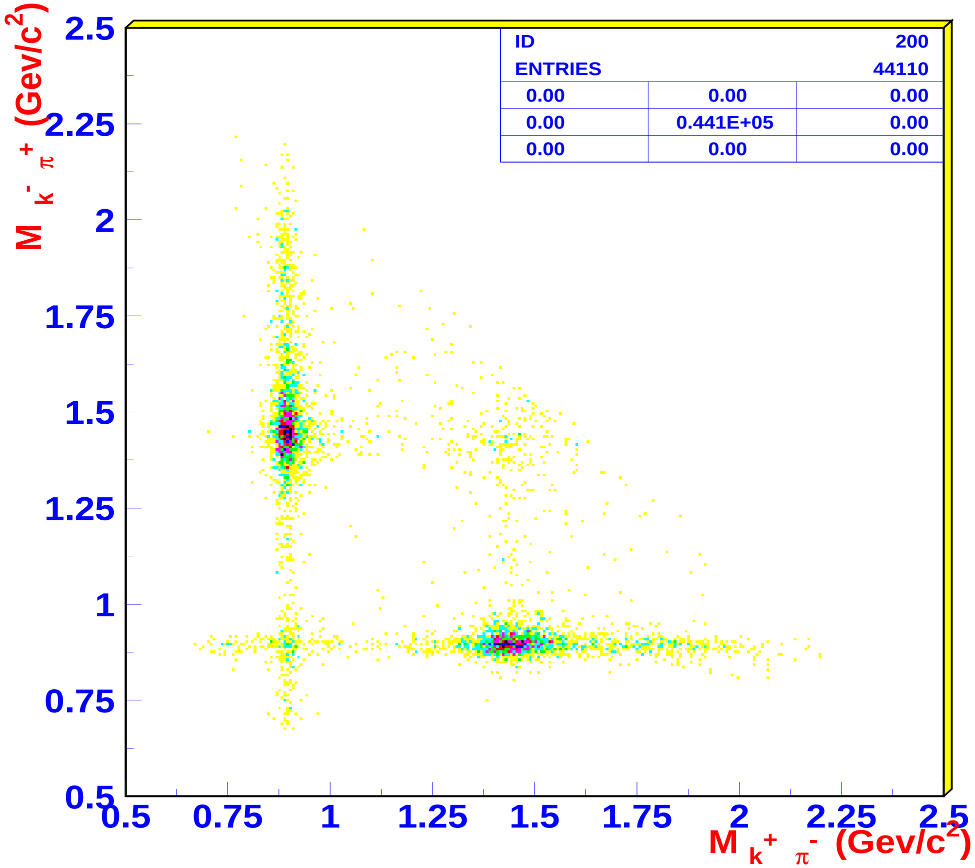


Figure 29: Scatter plot of $M_{K^+\pi^-}$ vs. $M_{K^-\pi^+}$ (BESII data)

♡ **Invariant mass spectrum of $K^+\pi^-$** We can see a peak at 1430 MeV, $K^*(892)^0$ and a low mass enhancement.

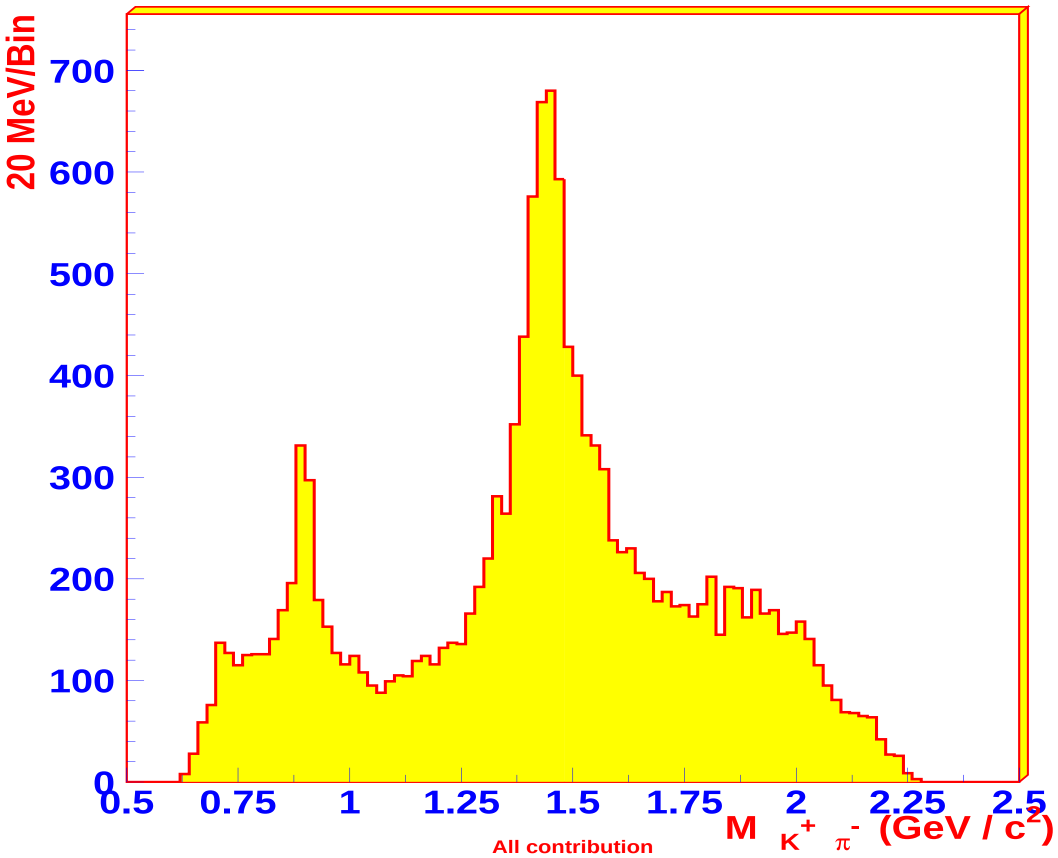


Figure 30: Invariant mass spectrum of $K^+\pi^-$ (BESII data)

♡ Daliz Plot

We can see three clear bands at Daliz plot.

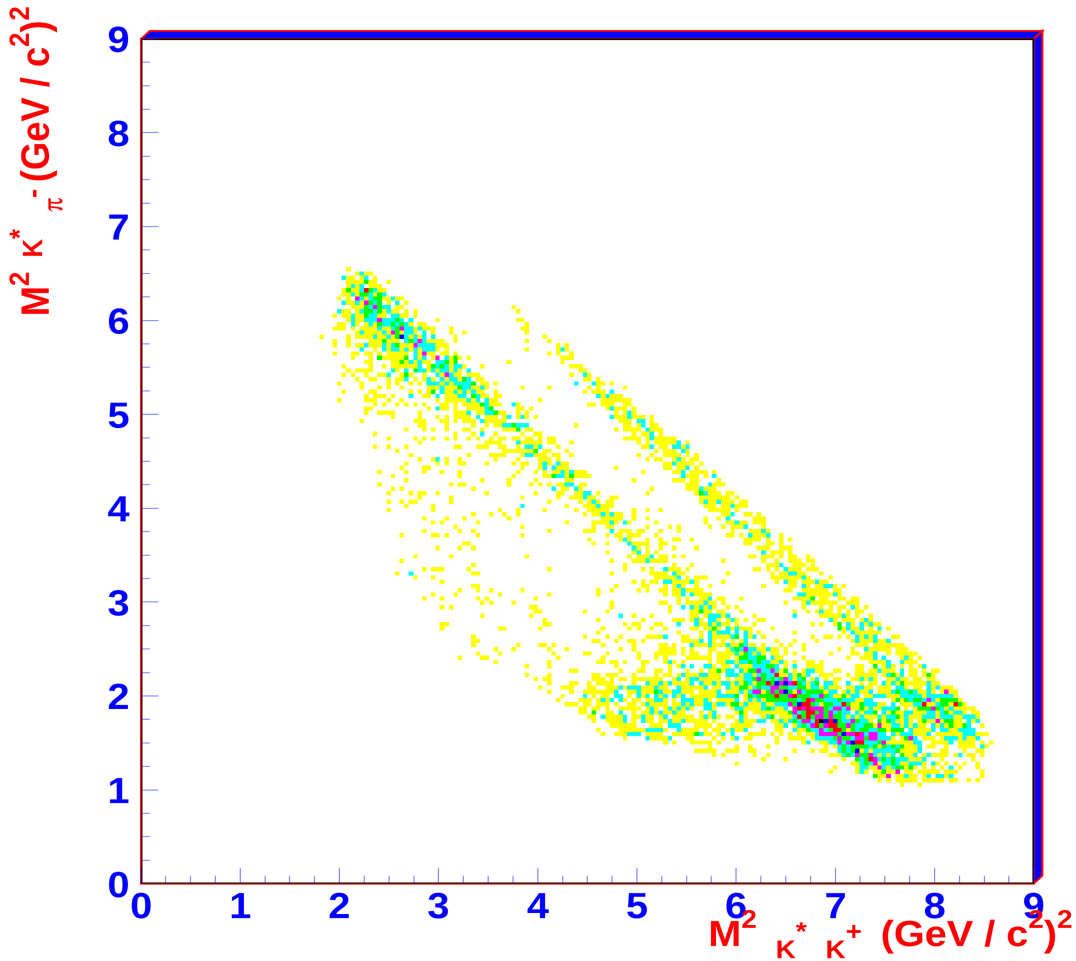


Figure 31: Daliz Plot (BESII data)

♡ Possible Origination of the Low Mass Enhancement:

There are several possibilities for the origination of the low mass enhancement:

- From Backgrounds;
- Phase space effects;
- Resonance.

We will study these possibilities one by one.

♡ Side-band structure

We can see clear $K^*(892)^0$ signal.

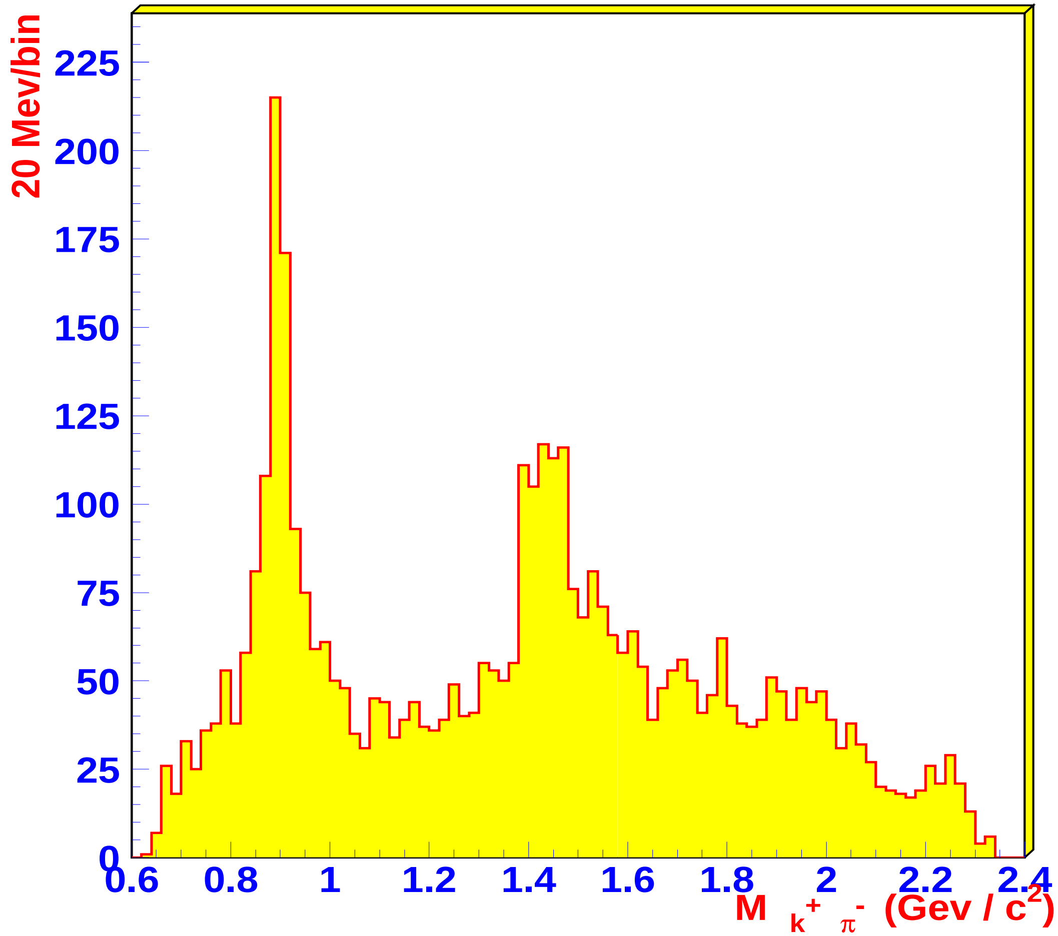


Figure 32: $\bar{K}^*(892)^0$ side-band structure (BESII data)

♡ **Invariant mass spectrum of $K^+\pi^-$** Invariant mass spectrum of $K^+\pi^-$ after side-band subtraction. $K^*(892)^0$ peak disappears. Low mass enhancement does not disappear.

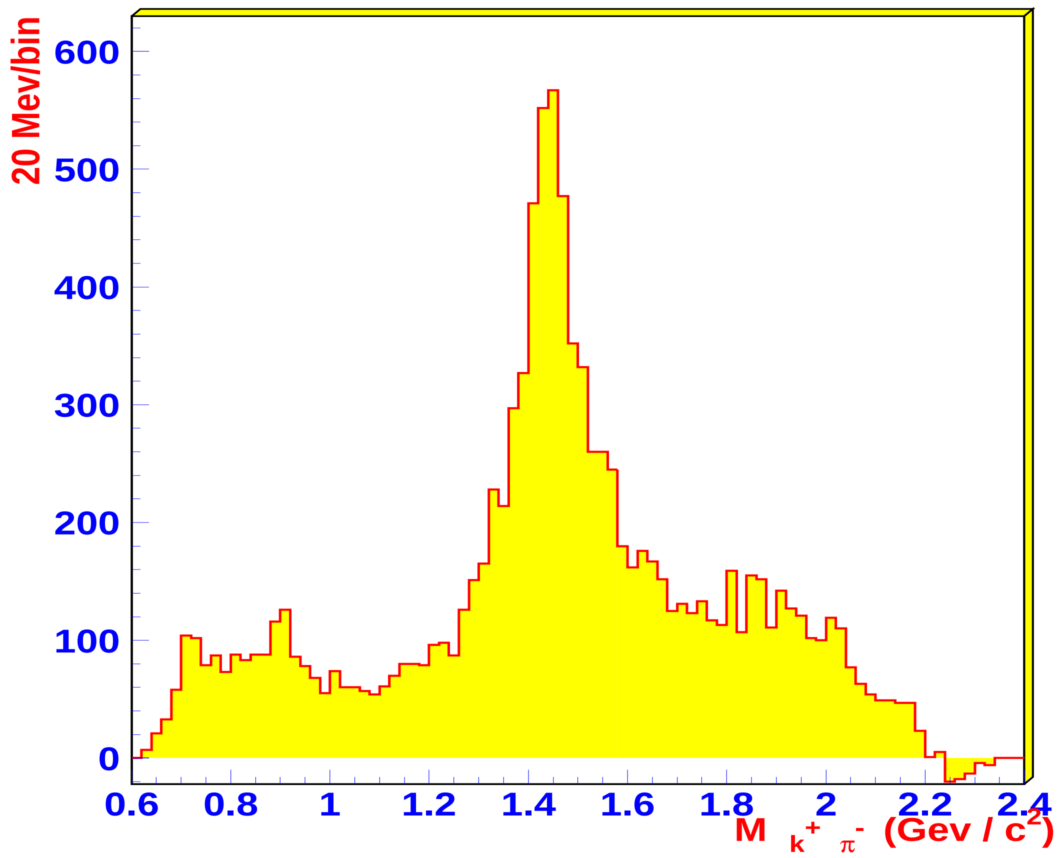


Figure 33: Invariant mass spectrum of $K^+\pi^-$ (BESII data)

Decay channels	Total MC events	Event number after cut	Selection efficiency
$K^+K^-\pi^+\pi^-$	100000	29219	29.2 %
$\pi^+\pi^-\pi^+\pi^-$	10000	10	0.1 %
$K^+K^-K^+K^-$	10000	0	0 %
$\gamma K^+K^-\pi^+\pi^-$	10000	19	0.19 %
$\gamma\pi^+\pi^-\pi^+\pi^-$	10000	2	0.02 %
$\gamma K^+K^-K^+K^-$	10000	0	0 %

Table 3: Monte Carlo simulation for background study.

♡ **Monte Carlo simulation(1)** We generate 50M Monte Carlo J/ψ events.

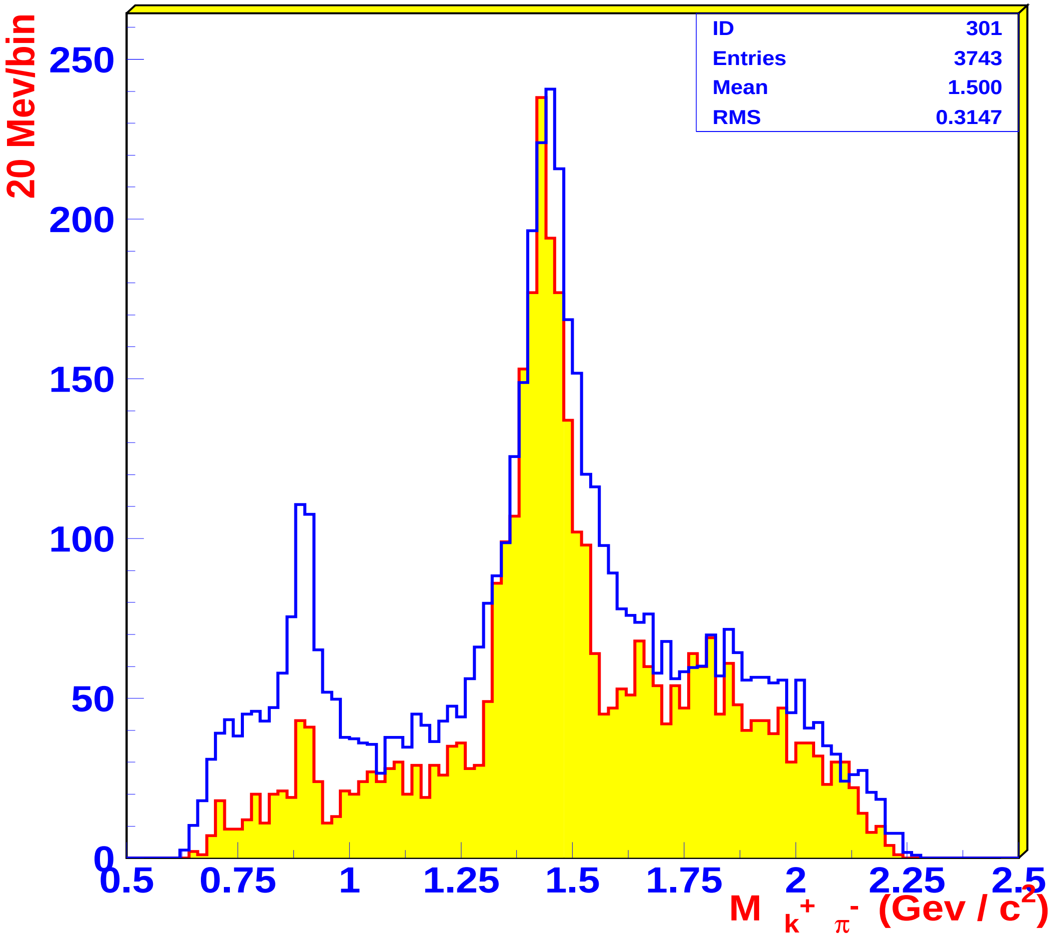


Figure 34: Monte Carlo simulation(1)

♡ **Monte Carlo simulation(2)** Scatter plot of $M_{K^+\pi^-}$ vs. $M_{K^-\pi^+}$ of 50M Monte Carlo J/ψ events.

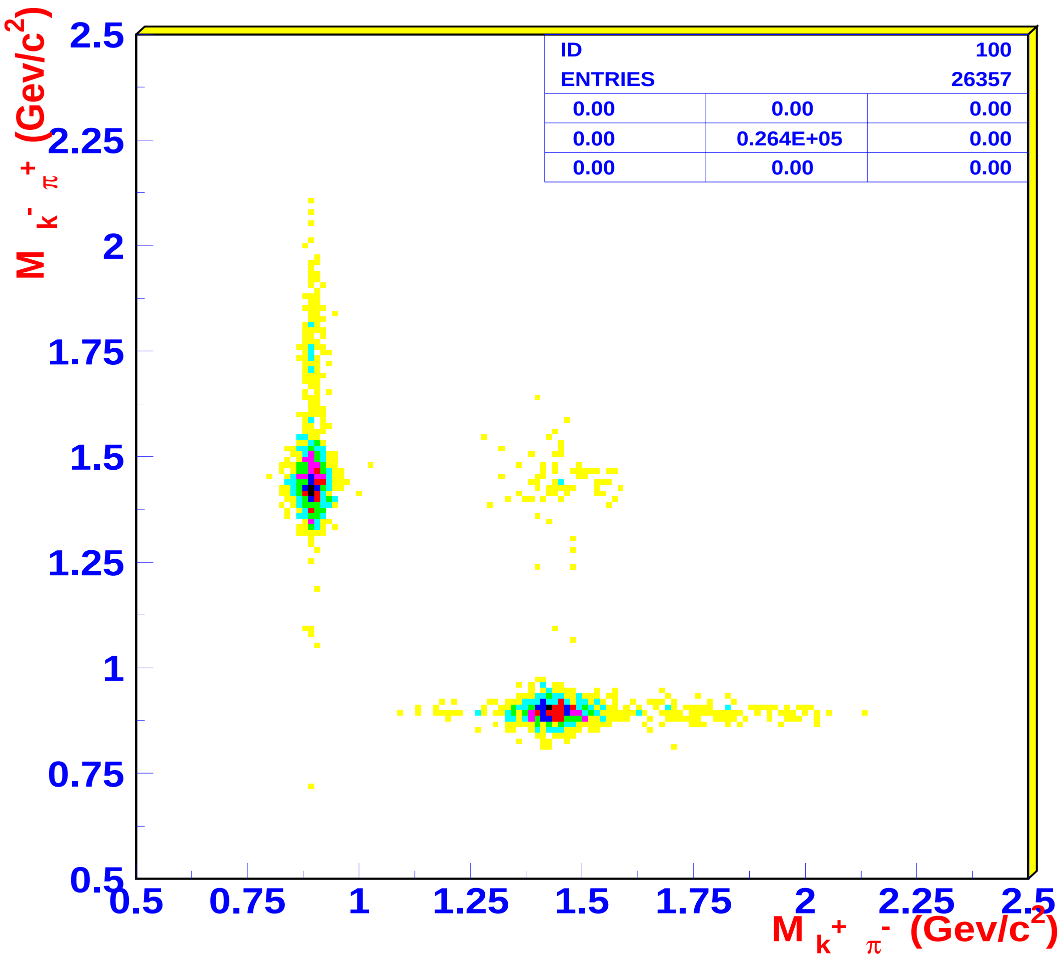


Figure 35: Monte Carlo simulation(2)

♡ Scatter plot of $M_{K^+\pi^-}$ vs. $M_{K^-\pi^+}$ BESII data.

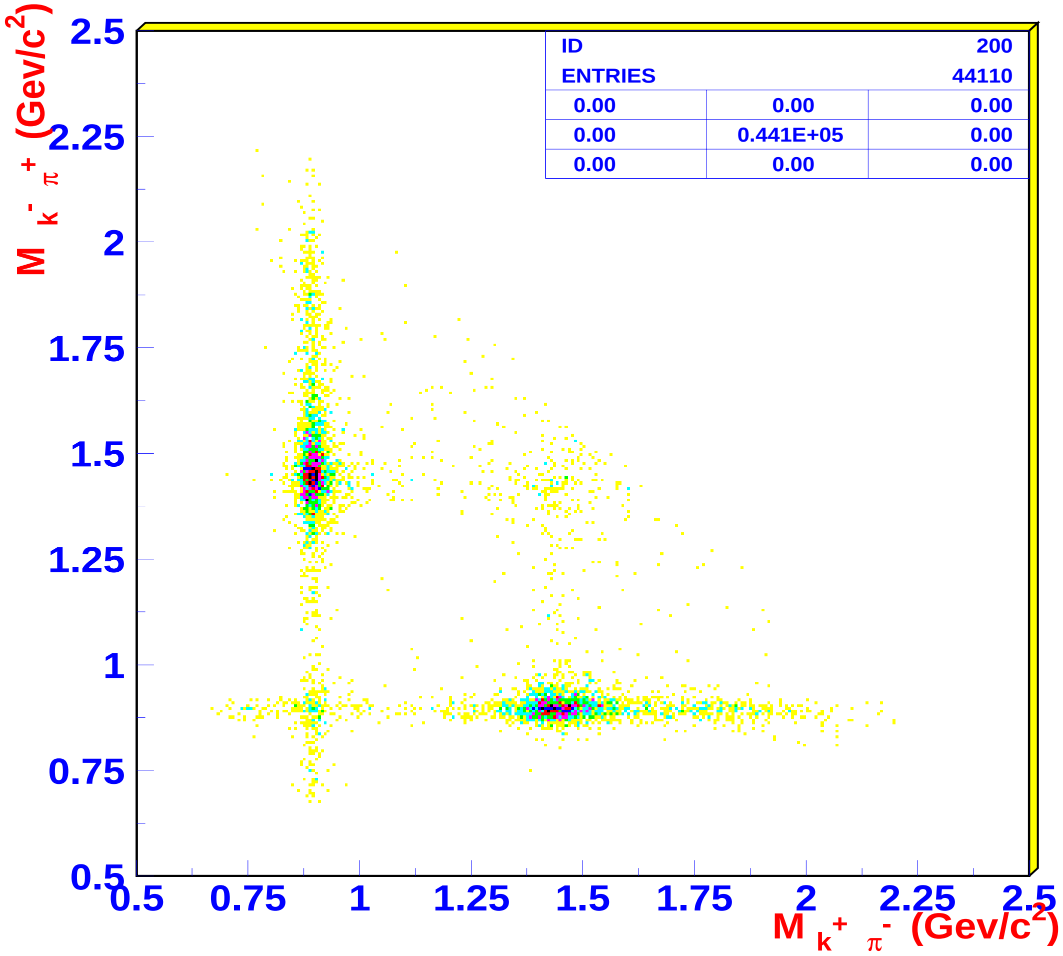


Figure 36: Daliz plot of $M_{K^+\pi^-}$ vs. $M_{K^-\pi^+}$ (BESII data)

♡ Monte Carlo simulation(3)

Daliz plot of 50M Monte Carlo J/ψ events.

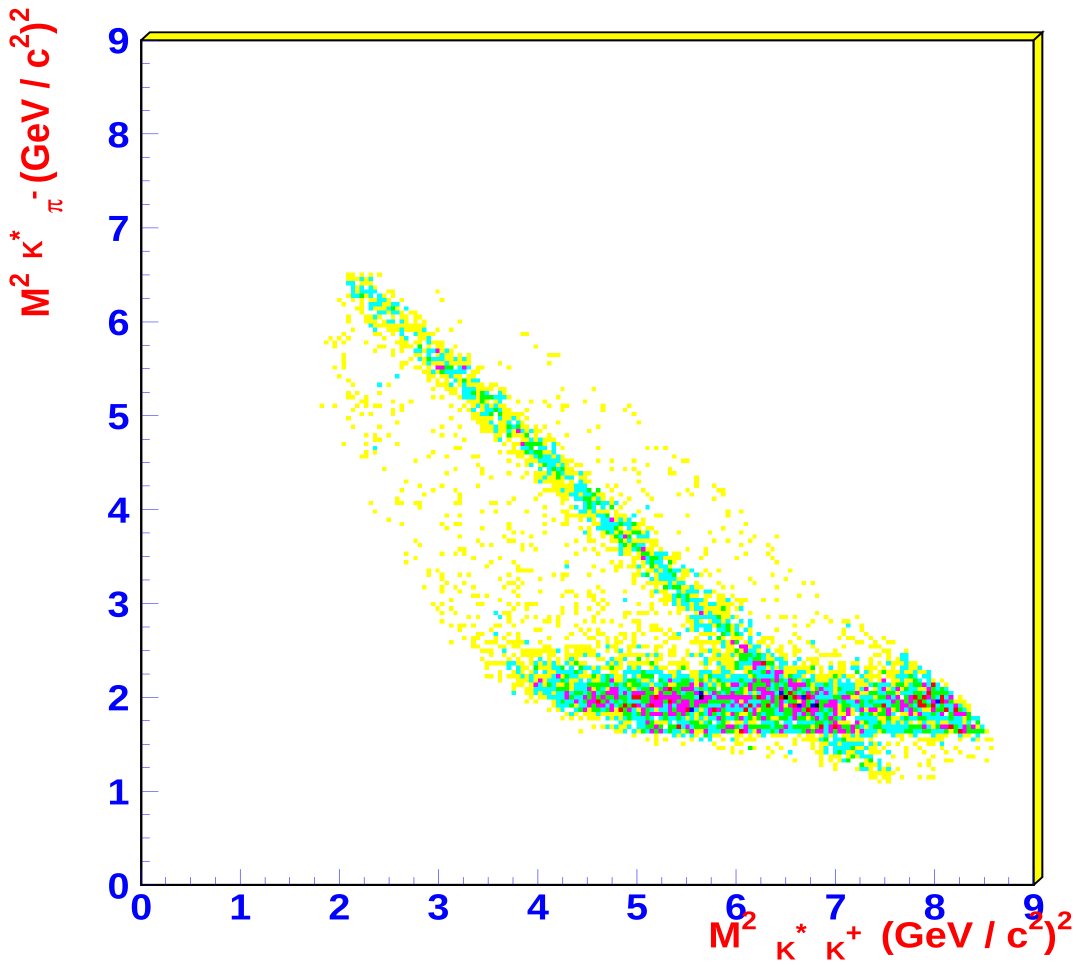


Figure 37: Monte Carlo simulation(3): Daliz Plot.

♡ Daliz Plot

Daliz plot of BESII data.

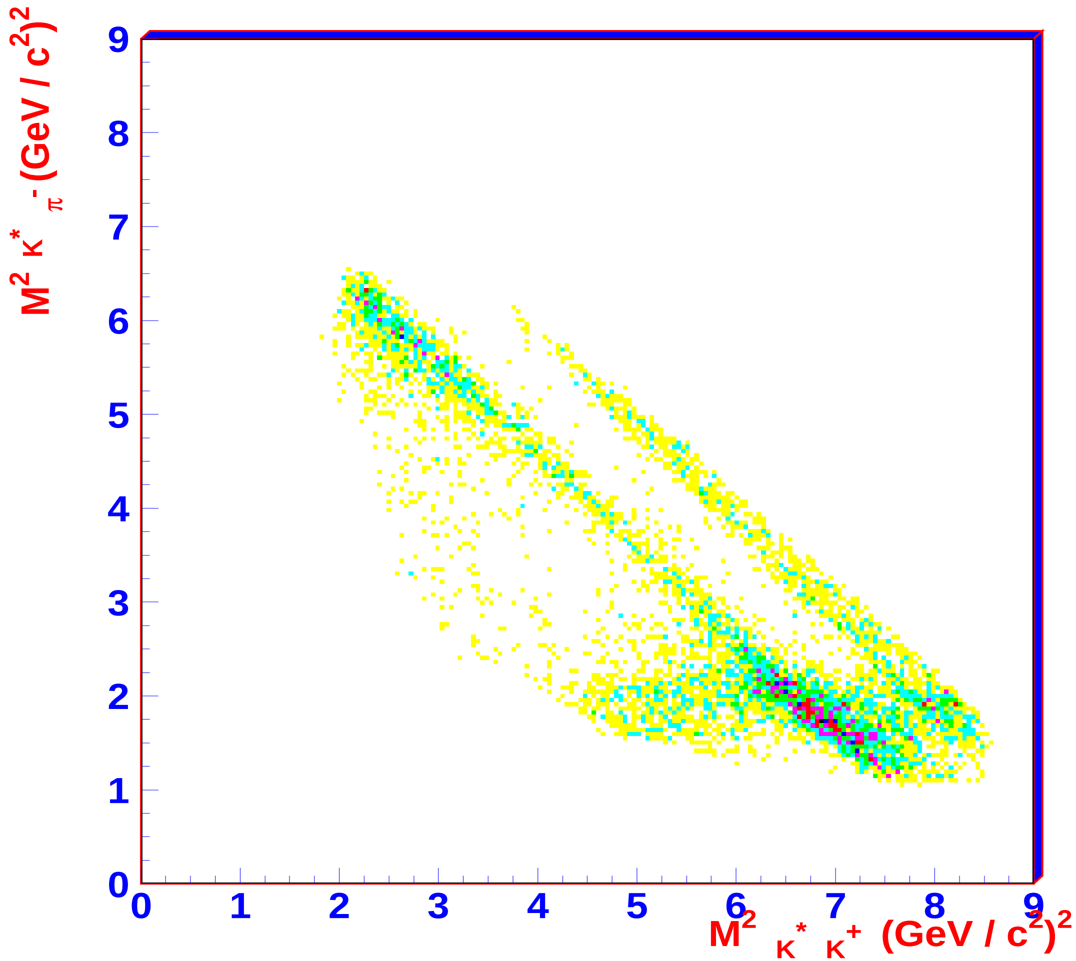


Figure 38: Daliz Plot (BESII data)

♡ Phase space: It does not come from phase space effect.

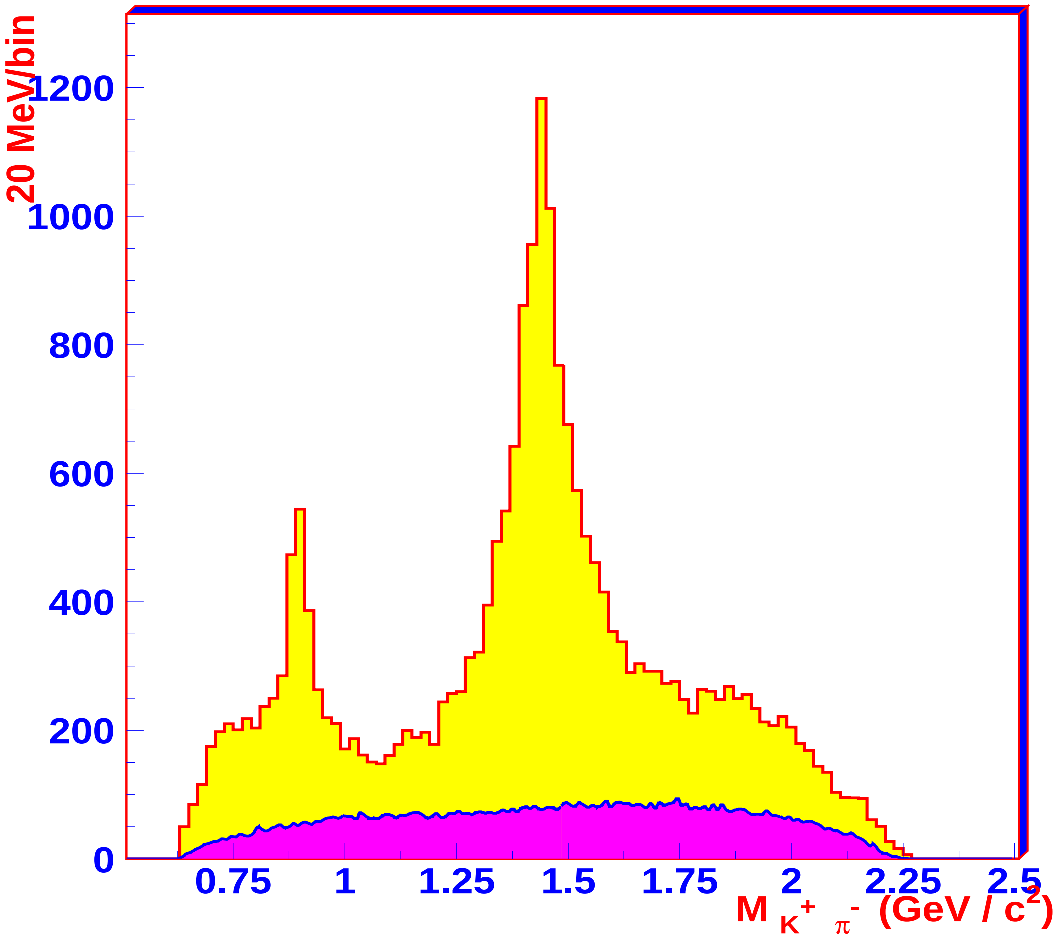


Figure 39: The shape of phase space.

♡ **Recoil particle against κ:** The recoil particle against κ is $\bar{K}^*(892)^0$.

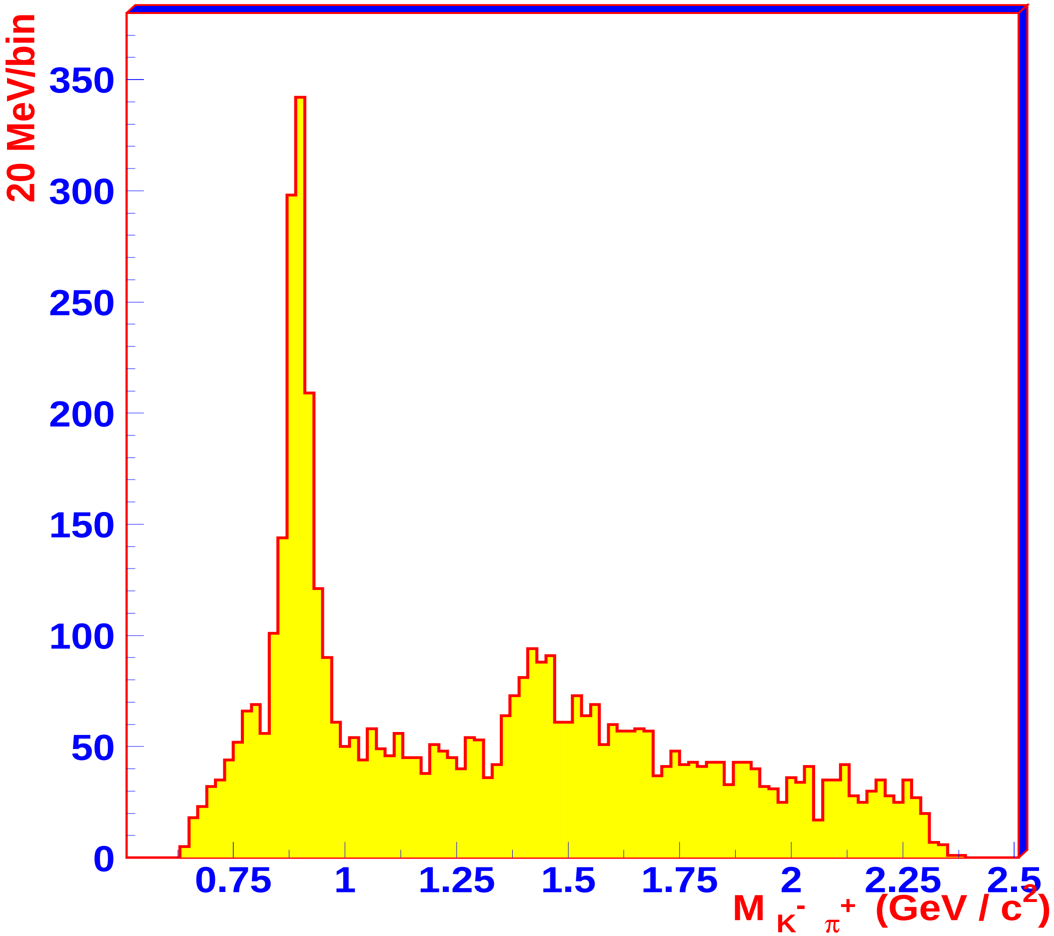


Figure 40: Invariant mass of $K^-\pi^+$ with $M_{K^+\pi^-} < 0.8Gev$.

♡ **Summary:** According to the above study, we have some preliminary results on the first peak.

1. It does not come from backgrounds;
2. it does not come from phase space effect;
3. It is a s-channel resonance.

♡ Spin-parity and statistical significance of κ

It is needed in our fitting, and its spin-parity is 0^+.

Spin-parity	LF	Change	Significance
0^+	-4193	—	—
omit	-4012	181	18.5 σ
1^-	-4109	84	12.2 σ
2^+	-4144	49	9.1 σ
3^-	-4114	79	11.8 σ
4^+	-4138	55	9.7 σ

Table 4: Spin-parity and statistical significance of κ. (LF means Likelihood Function)

♡ Mass and width on κ

$M_\kappa = 877 \pm 85$ MeV
$\Gamma_\kappa = 346 \pm 89$ MeV

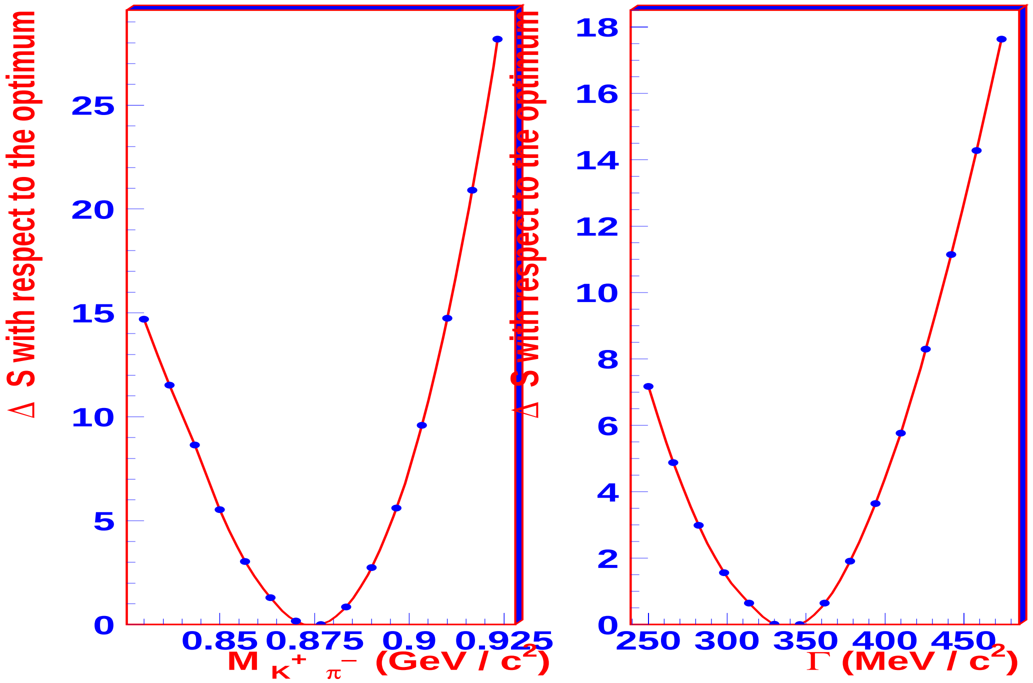


Figure 41: Mass and width on κ

♡ **Fit on angular distribution of κ mass region.** Our fit on this region is ok!

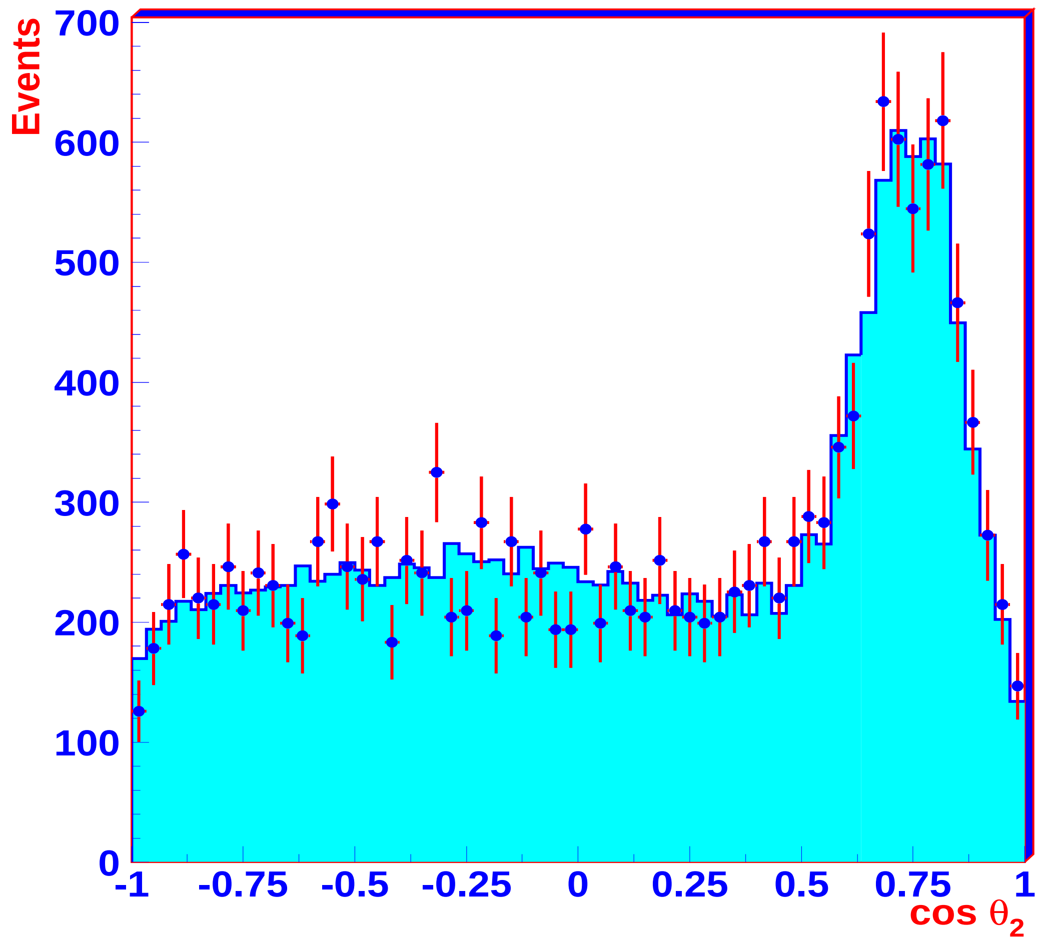


Figure 42: Angular distribution of κ mass region.

♡ **Fit on mass spectrum of whole mass region.** Our fit is ok!

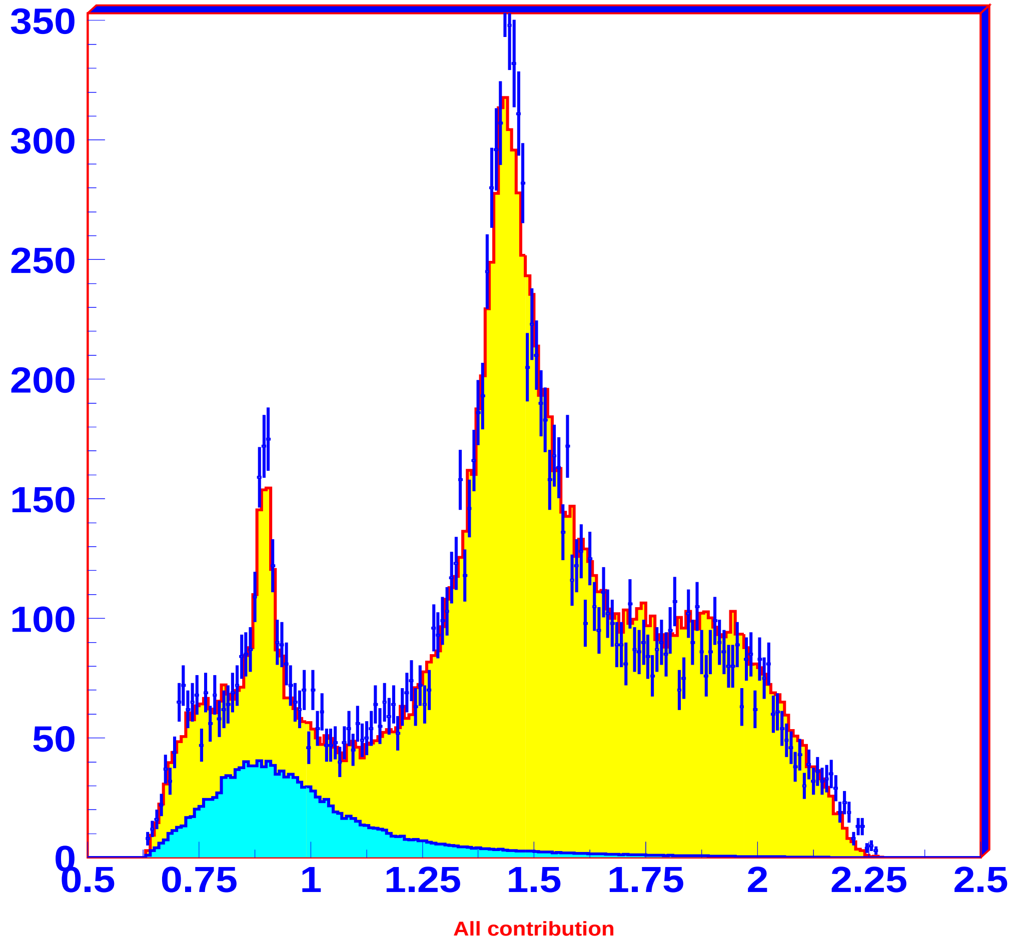


Figure 43: Fit on mass spectrum of whole mass region.

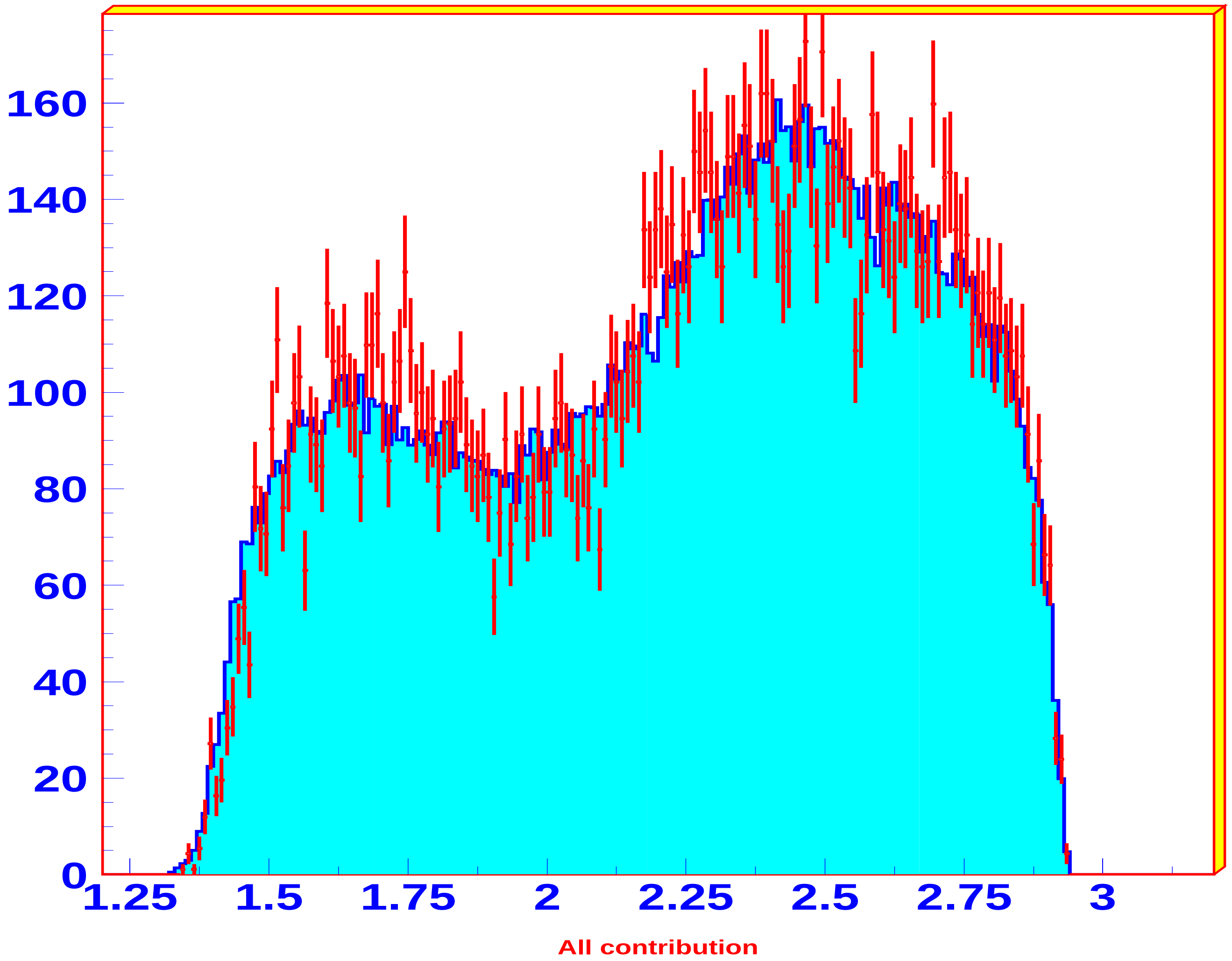


Figure 44: Final global fit on $\bar{K}^*(892)^0\pi^-$ invariant mass spectrum.

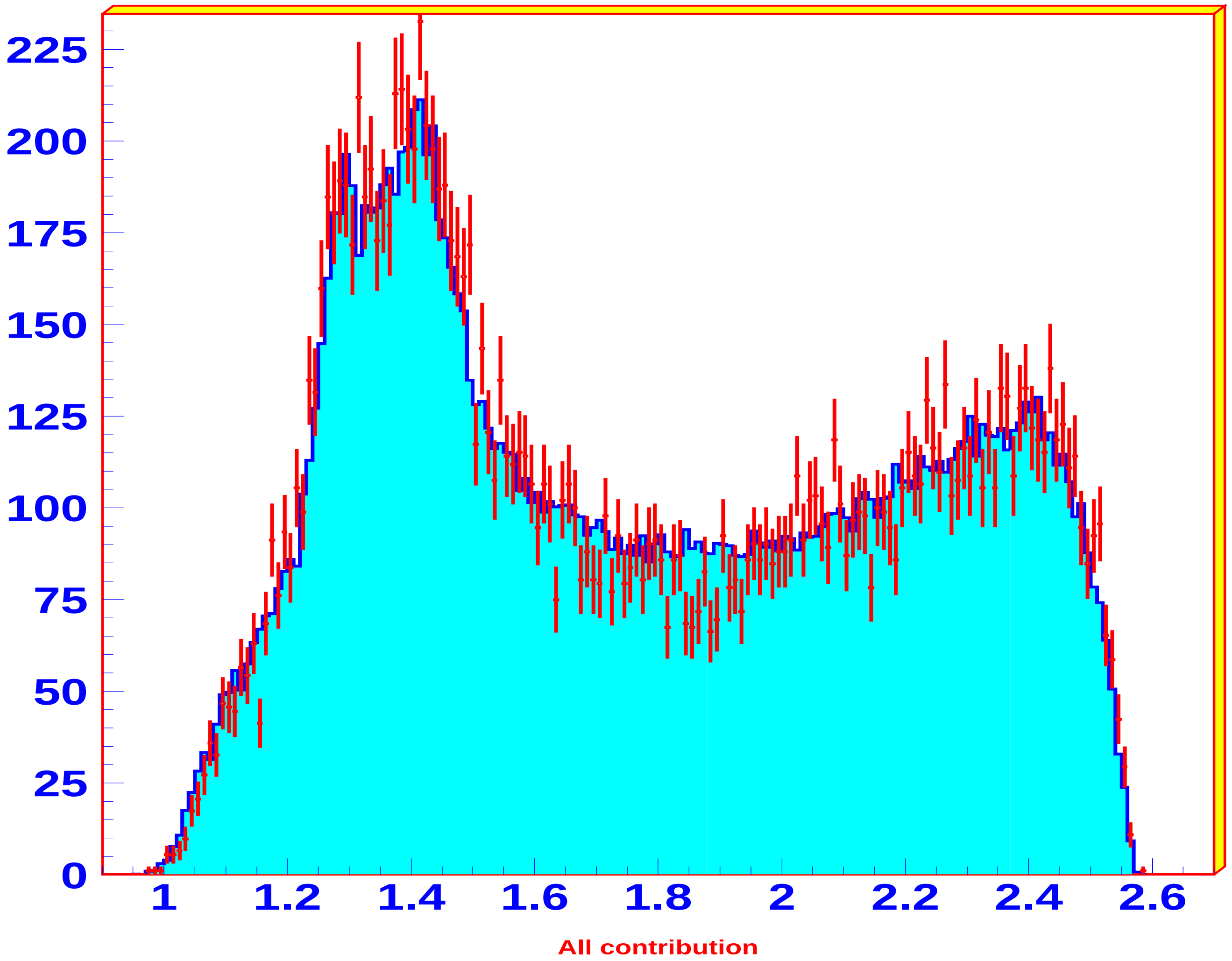


Figure 45: Final global fit on $\bar{K}^*(892)^0K^+$ invariant mass spectrum.

♡ Fit on angular distribution of whole mass region.

Our fit is ok!

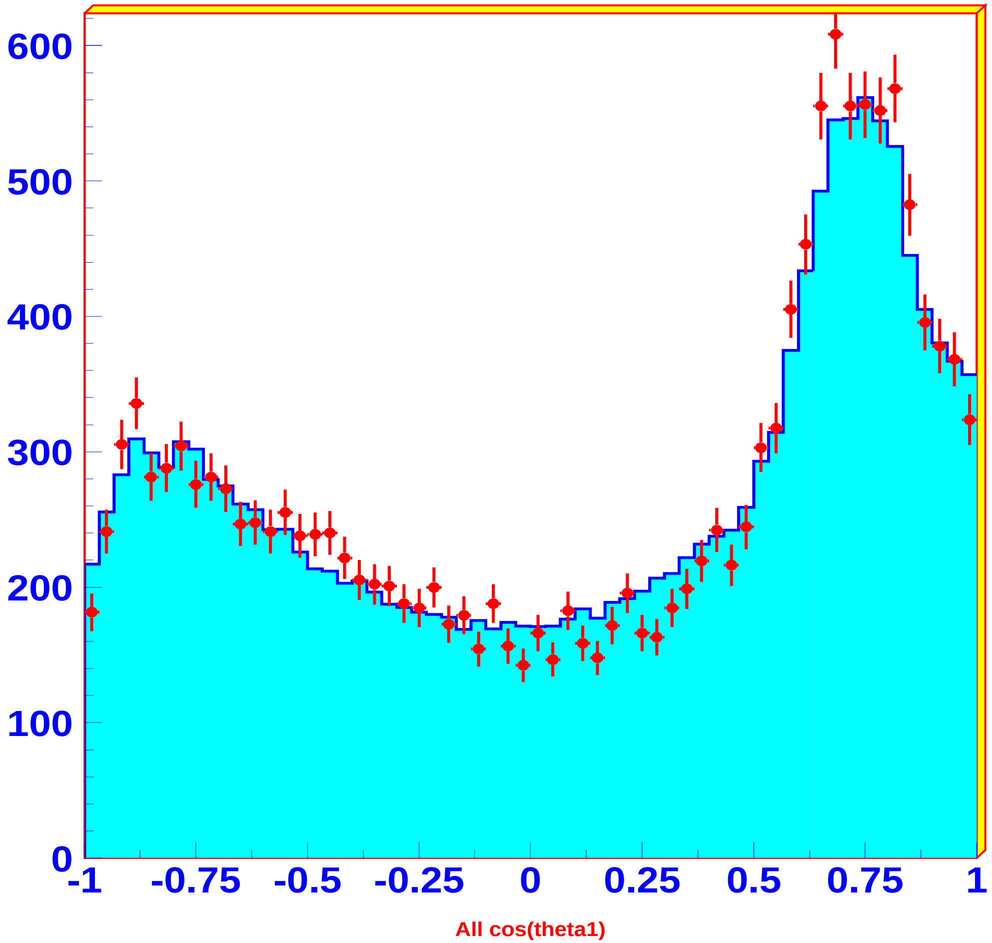


Figure 46: Angular distribution of whole mass region.

♡ Fit on angular distribution of whole mass region.

Our fit is ok!

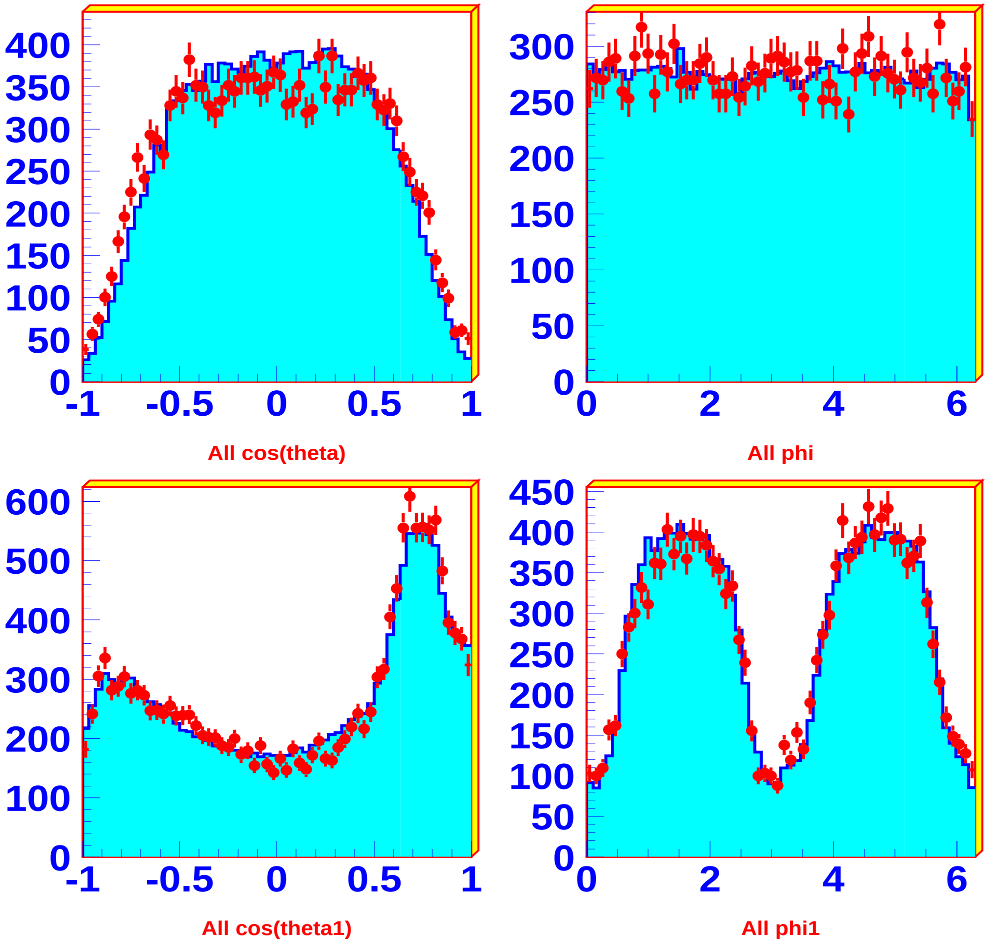
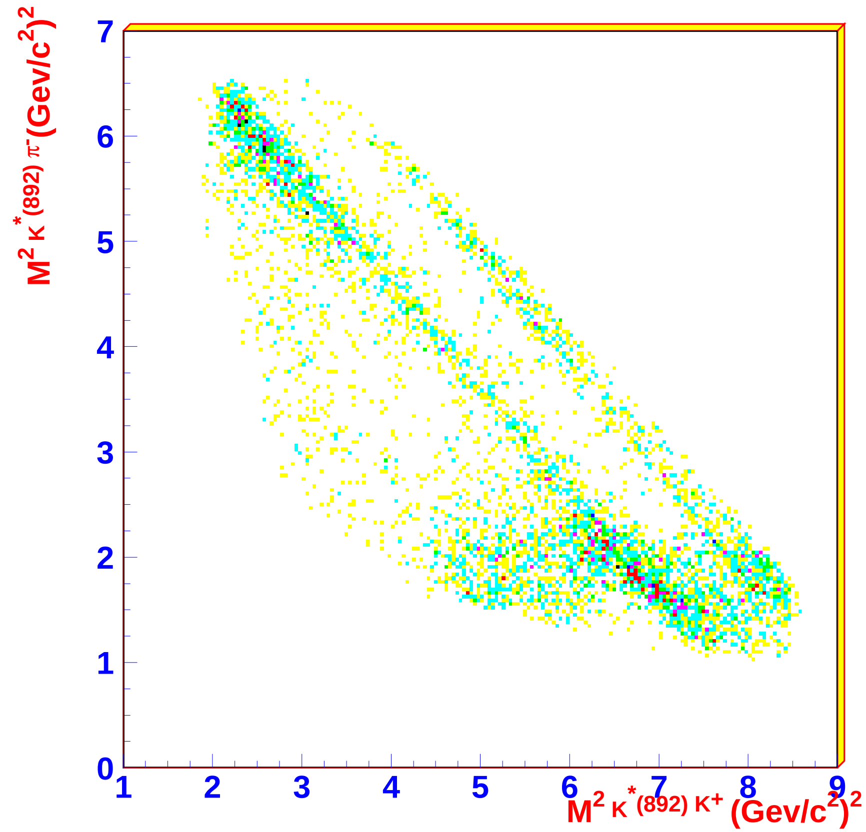


Figure 47: Angular distribution of whole mass region.



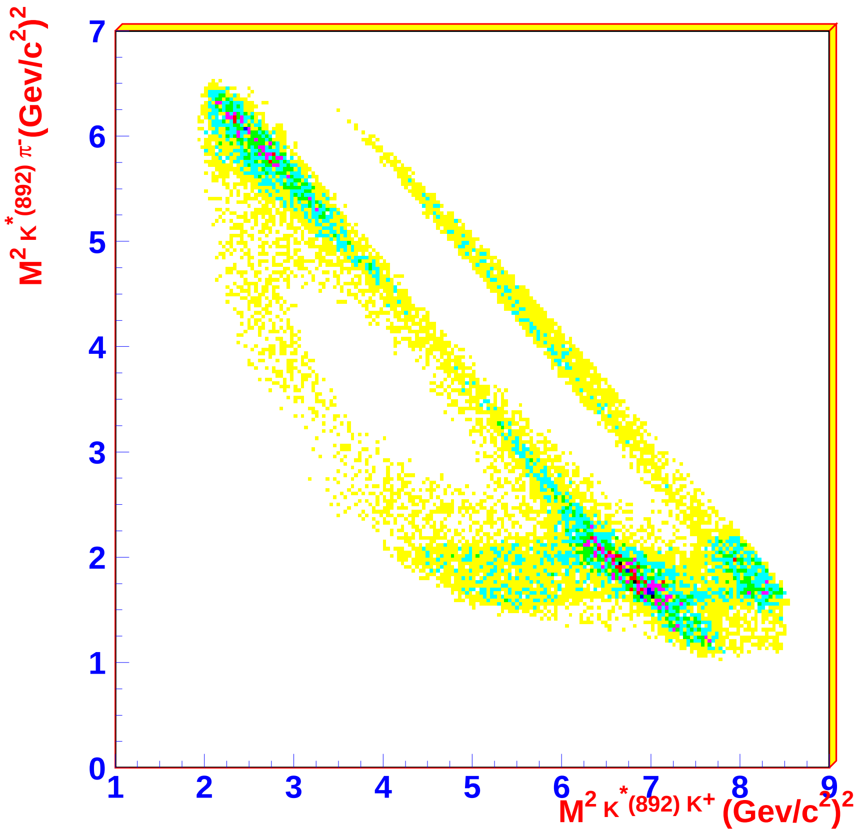


Figure 48: LEFT: data, EIGHT: fit

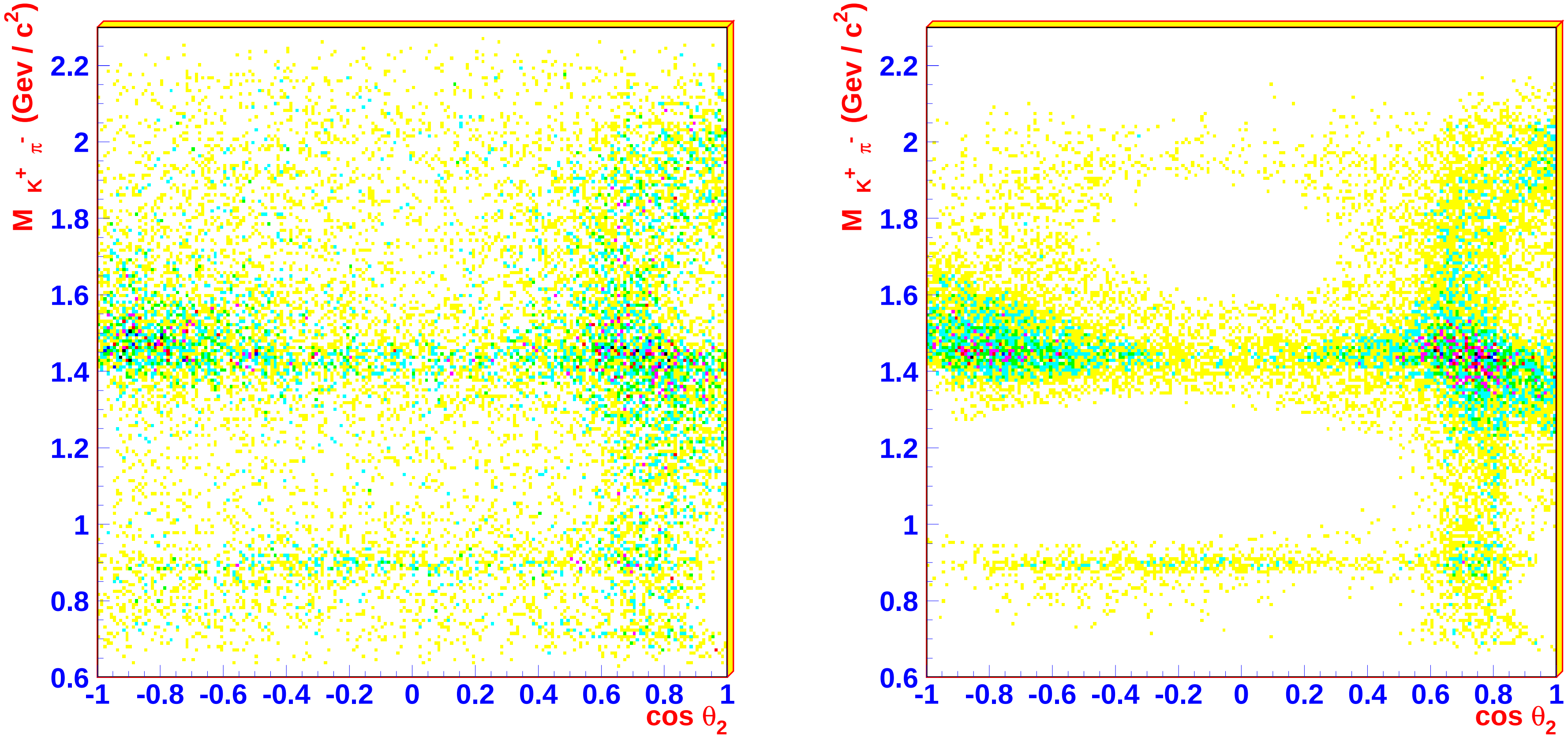


Figure 49: LEFT: data, Right: fit

♡ Results

1. The low mass enhancement at about 800 MeV is not come from phase space effects, not come from background events.

2. It is a 0^+ resonance in this channel.

3. Mass and width(Preliminary):

$$BW_\kappa = \frac{1}{m_\kappa^2 - s - i\sqrt{s}\Gamma_\kappa(s)}, \qquad \Gamma_\kappa(s) = \frac{g_\kappa^2 p_1(s)}{8\pi s},$$

$$M_\kappa = 877 \pm 85 Mev,$$
$$\Gamma_\kappa = 346 \pm 89 Mev$$

Another independent fit:

$$BW_\kappa = \frac{1}{m_\kappa^2 - s - i\sqrt{s}\Gamma_\kappa(s)}, \quad \Gamma_\kappa(s) = (s - s0)\Gamma_0 \rho_{\pi K}(s), \quad s0 = m_K^2 - m_\pi^2/2.$$

Pole:$(M, \Gamma) = (810 \pm 40,\ 800 \pm 100)$ MeV.

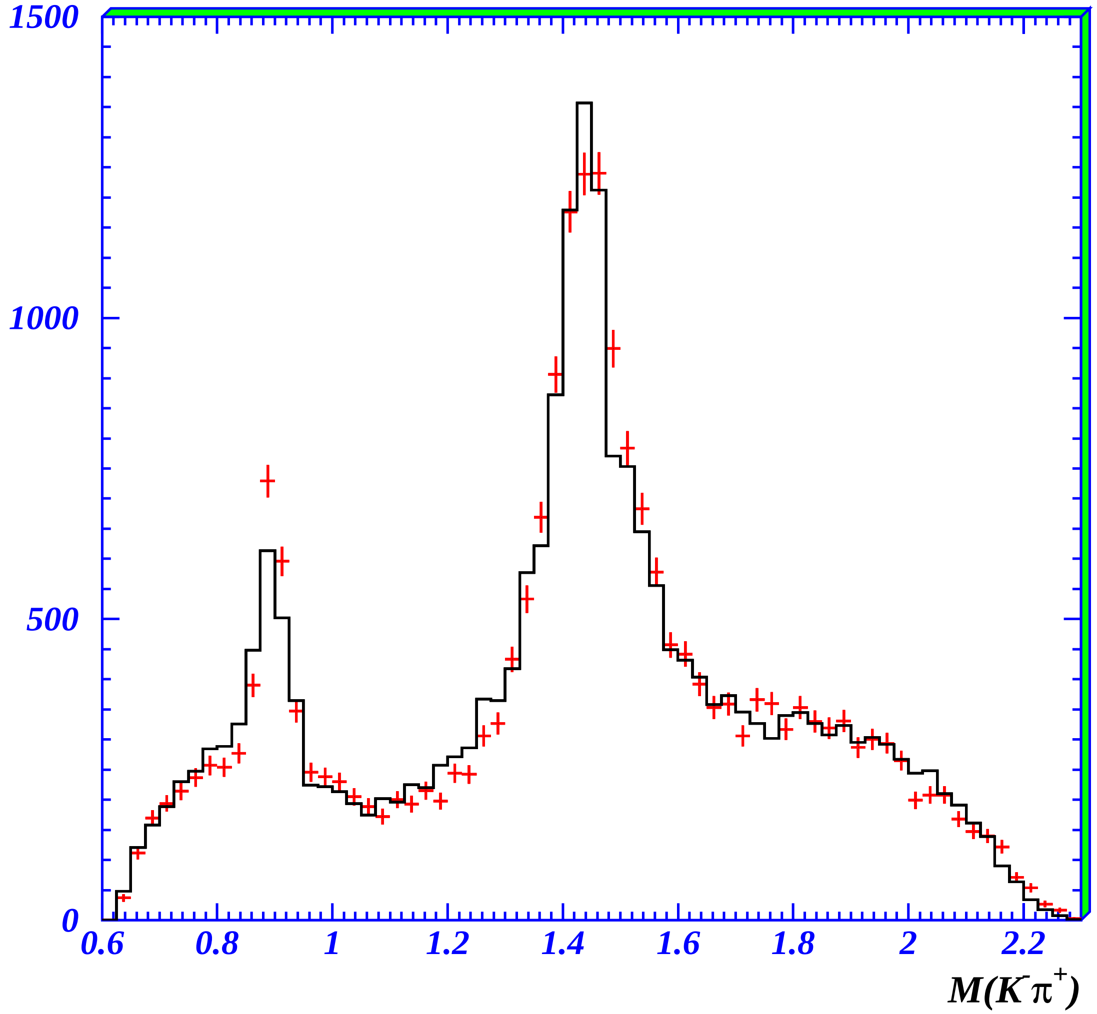


Figure 50: Fit on mass spectrum of whole mass region by another fit.

♡ Discussions

1. In J/ψ hadronic decay, both signals of σ and κ are clearly observed.

2. According to quark model, the ordinary $q\bar{q}$ scalar meson nonet with lowest mass is 1^3P_0 states. Its orbital angular momentum is excited to P wave. The mass of them can not be as low as 480-880 MeV. Both σ and κ can not be filled into the quark model for ordinary $q\bar{q}$ mesons.

3. Up to now, there are at least two theories that may explain the nature of these new particles. One theory considers the σ and κ as chiral scalar particles, another theory considers the σ and κ as 4 quark states.