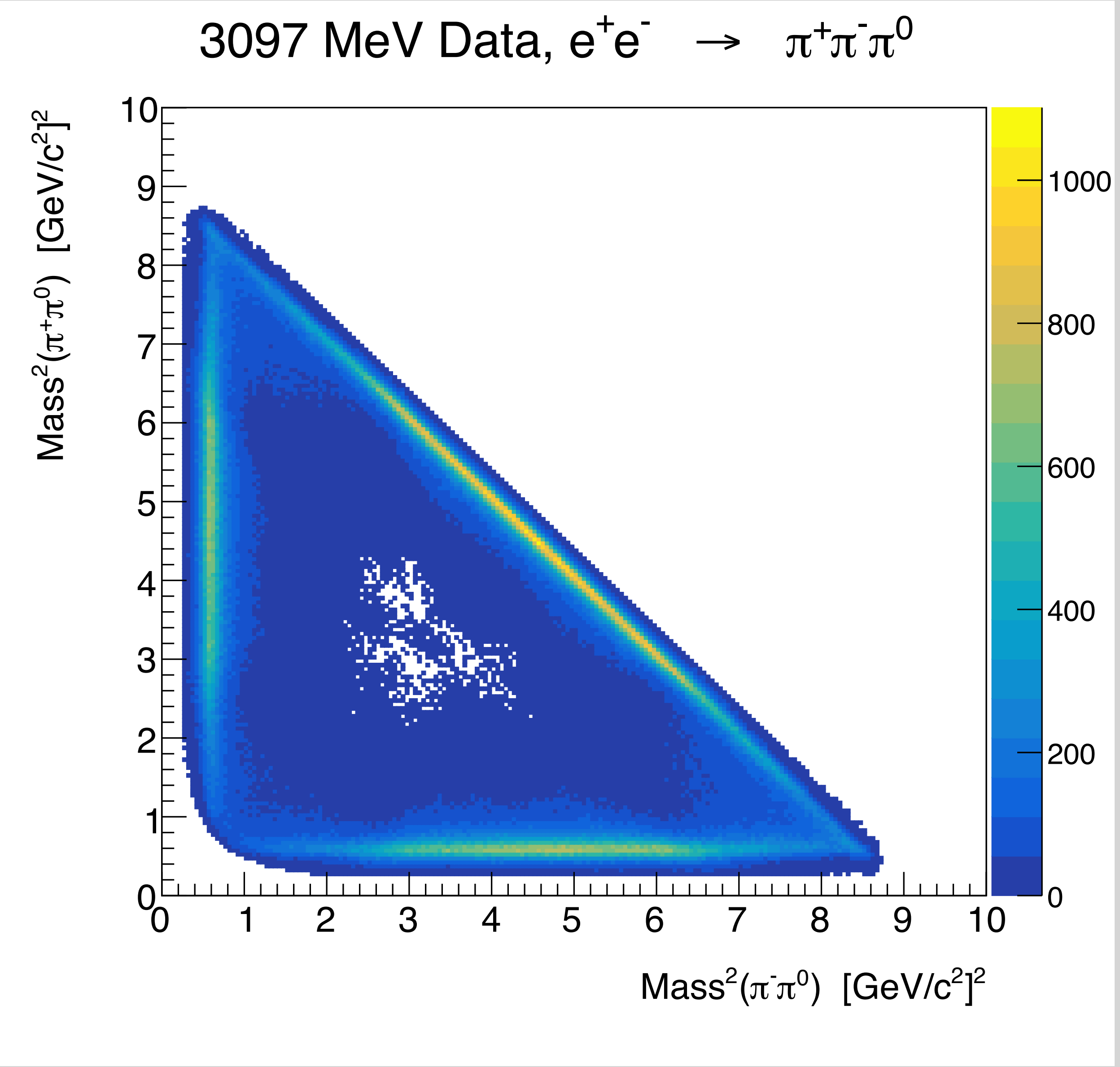
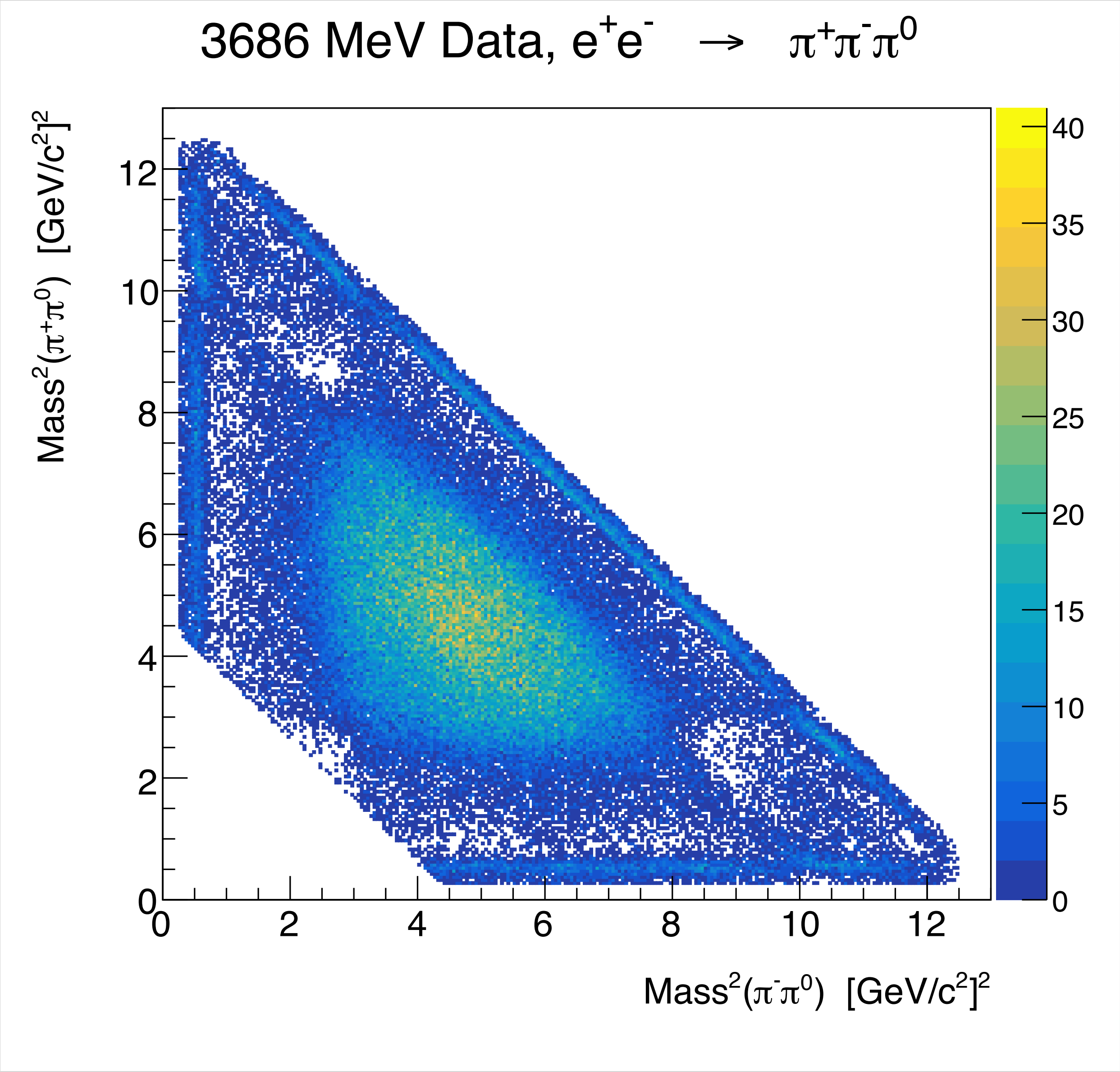
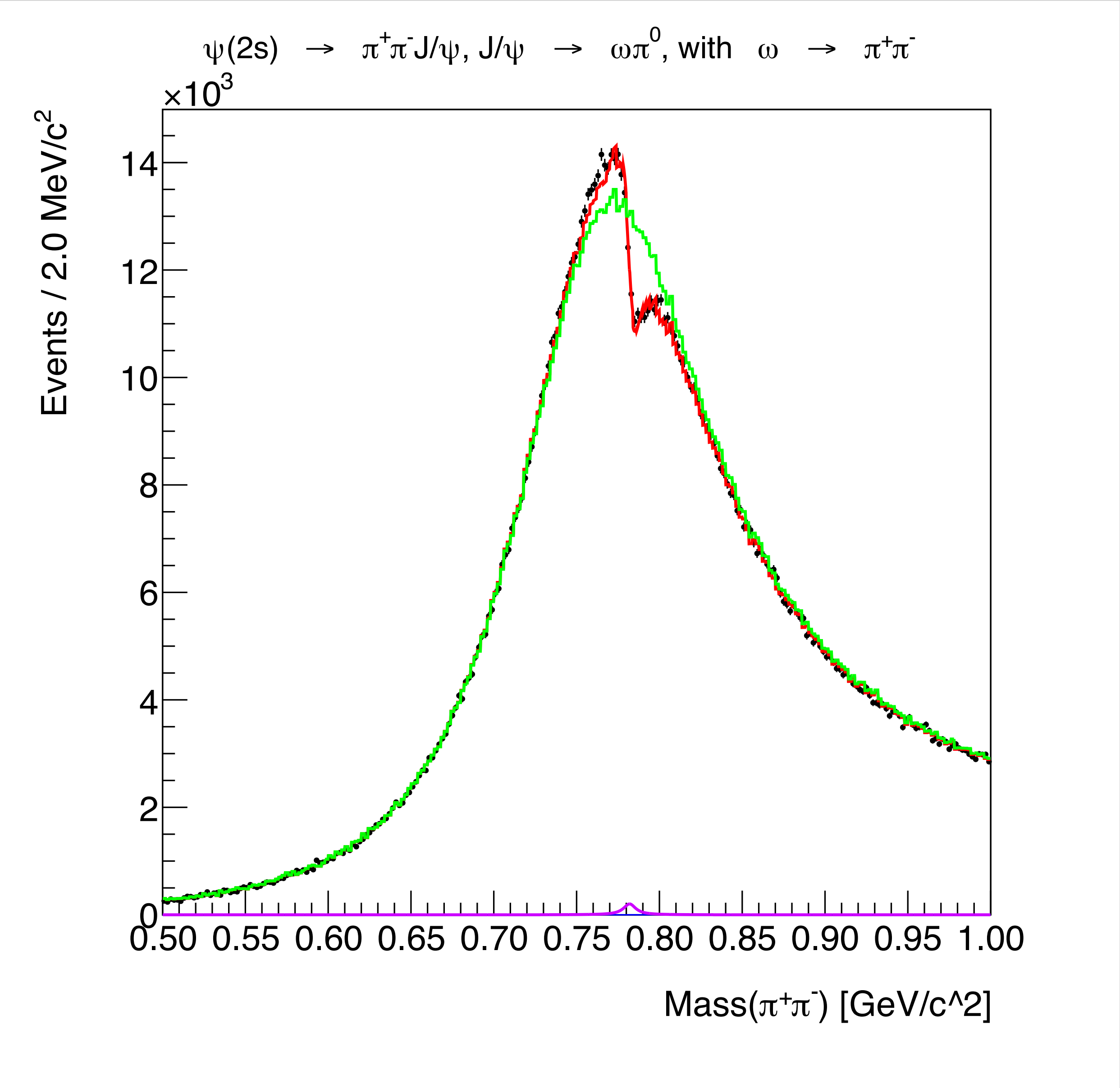
Measurement of ratio $\frac{\mathscr{B}(\omega \to \pi^+\pi^-)}{\mathscr{B}(\omega \to \pi^+\pi^-\pi^0)}$

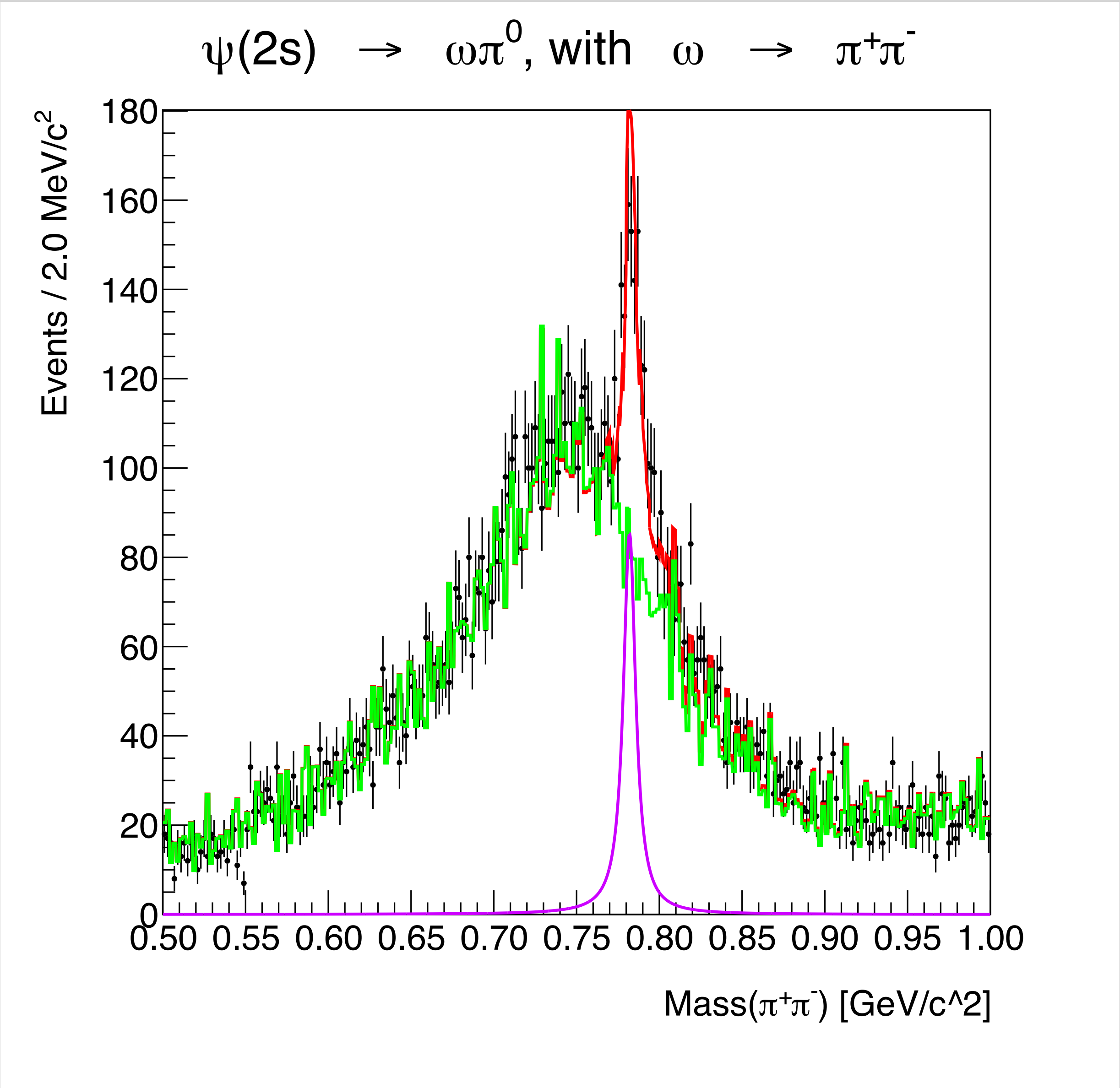
Ben Moses, Indiana University

Intro / Motivation









Intro / Motivation

- In $\pi^+\pi^-\pi^0$ final states have interference between ρ and ω decays to $\pi^+\pi^-$
- Difficult to separate ρ and ω components in general
- Off resonance though we have much less ρ contribution
- Idea: Look off resonance and try to fit ρ and ω pieces to count $N_{\omega\to\pi^+\pi^-}$
- In $\pi^+\pi^-\pi^0\pi^0$ final state have very clear signal for $\omega \to \pi^+\pi^-\pi^0$
- Then, in this way we should be able to measure the ratio of branching fractions:

$$\frac{\mathscr{B}(\omega \to \pi^+\pi^-)}{\mathscr{B}(\omega \to \pi^+\pi^-\pi^0)}$$

NEW Datasets

Year	E_CM [MeV]	$\mathscr{L}[pb^{-1}]$
2010/2011	3770	2931.8
2022	3770	4995
2016	4180	3189.0
2017	4190 - 4280 (2017 XYZ)	3859.6
2019	4130-4440	3912.2

General Event Selection

- In the $\pi^+\pi^-\pi^0\pi^0$ final state, we perform a 6C kinematic fit; that is, a 4C fit to the initial and final state four-momentum, and two 1C fits to the masses of the π^0
- In the $\pi^+\pi^-\pi^0$ final state, we similarly perform a 5C kinematic fit, as there is now only a single 1C fit to the π^0 mass
- In both cases, we select charged tracks within 10 cm of the interaction point in the beam direction, and within 1 cm in the perpendicular plane
- Photon candidates from the barrel ($|\cos(\theta)| < 0.8$) are required to have $E > 25$ MeV, while endcap photons ($0.86 < |\cos(\theta)| < 0.92$) are required to have $E > 50$ MeV
- Lastly, photon candidates are required to have $0 < t_{\text{shower}} < 700$ ns

Ratio Determination

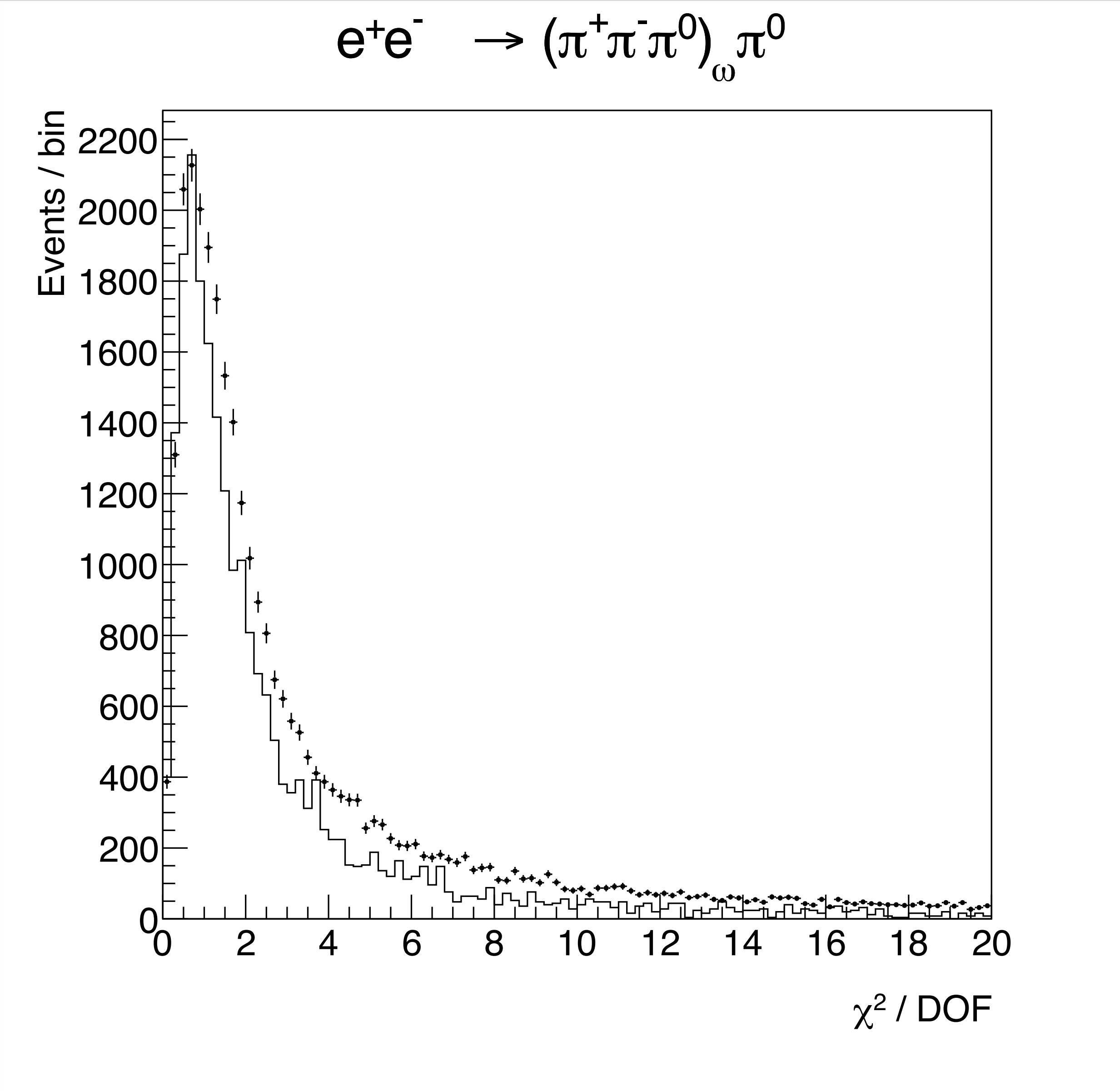
- From our fits, we can measure the ratio of branching fractions as follows:

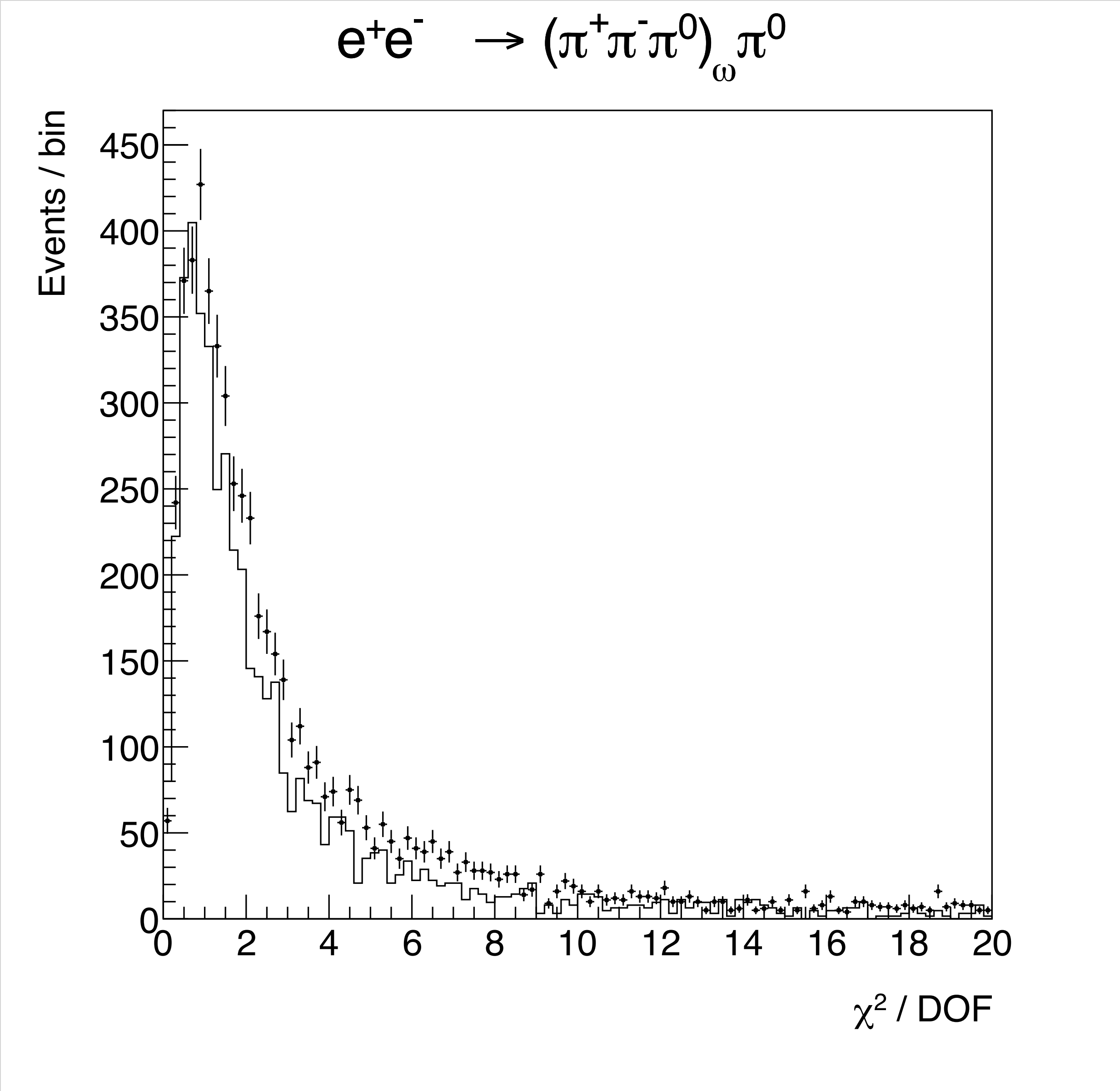
$$\frac{\mathscr{B}(\omega \to \pi^+\pi^-)}{\mathscr{B}(\omega \to \pi^+\pi^-\pi^0)} = \frac{N_{\omega\to\pi^+\pi^-}}{\epsilon_{\omega\to\pi^+\pi^-}} \frac{\epsilon_{\omega\to\pi^+\pi^-\pi^0}\mathscr{B}(\pi^0 \to \gamma\gamma)}{N_{\omega\to\pi^+\pi^-\pi^0}}$$

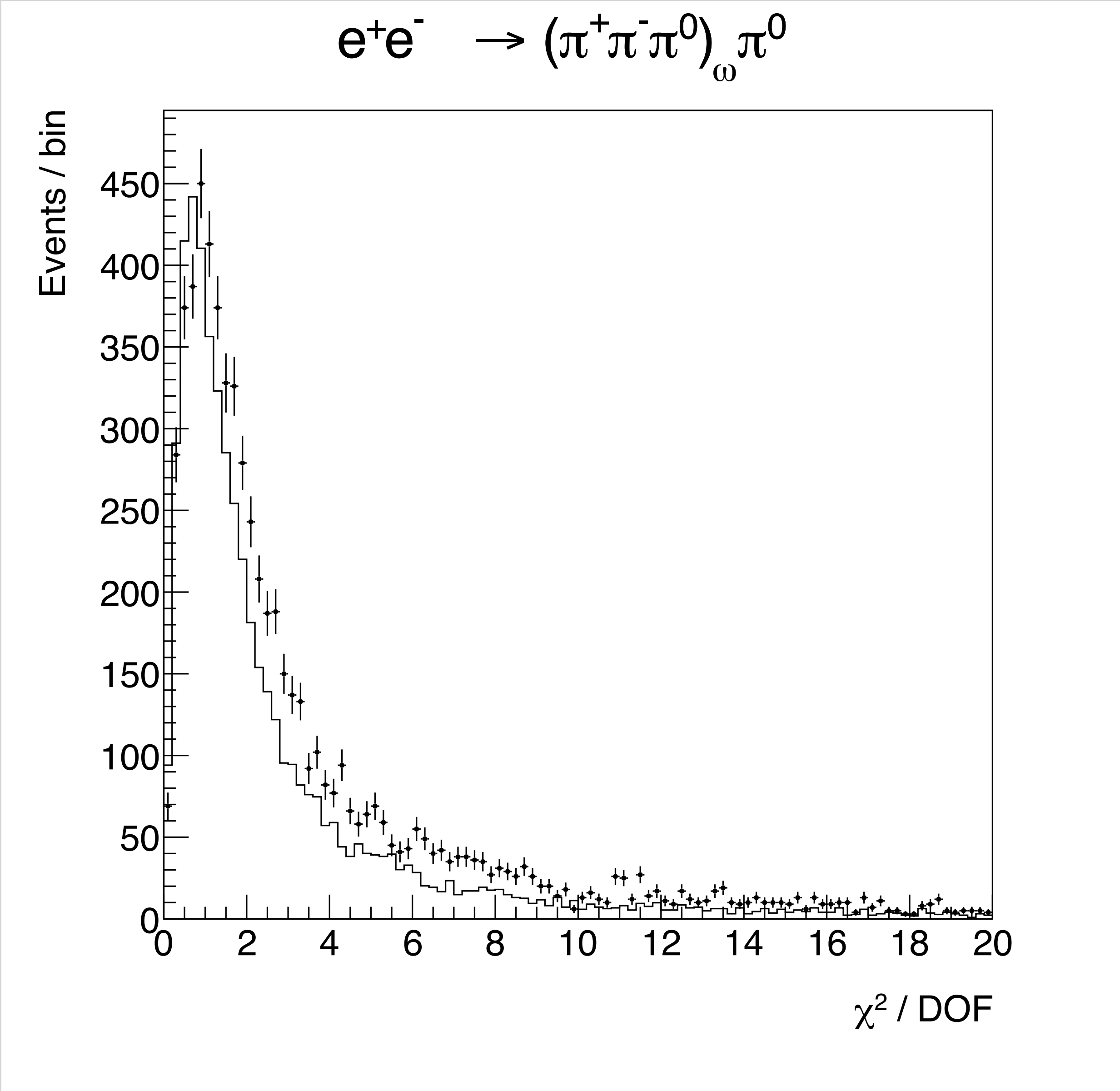
- Here, the number of observed ω in each case is taken from the fit to the data, and the detection efficiency is obtained from the fit to the signal MC divided by the number of generated events

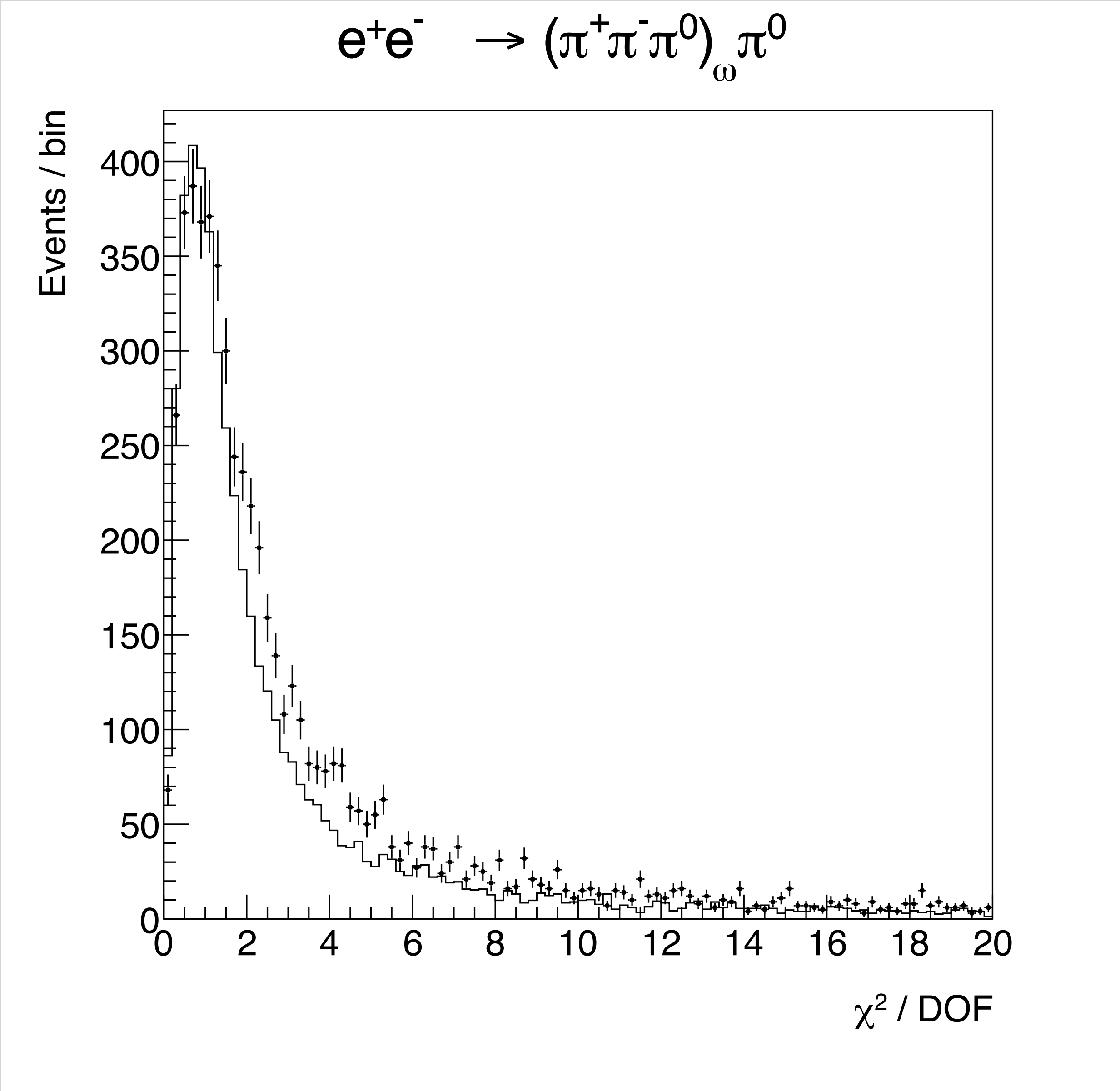
$\omega \to \pi^+\pi^-\pi^0$ cuts

- For $\omega \to \pi^+\pi^-\pi^0$ events we have a very clean signal, and so the only cut made is on the χ^2/DOF from the kinematic fit
- Plots are (left to right) from 3770 MeV, 4180 MeV, combined 2017 XYZ data, and combined 2019 XYZ data; data points are from data, and the histogram is from SIGMC, both selecting the ω signal region
- For each dataset in both data and MC we require χ^2/DOF < 5.0





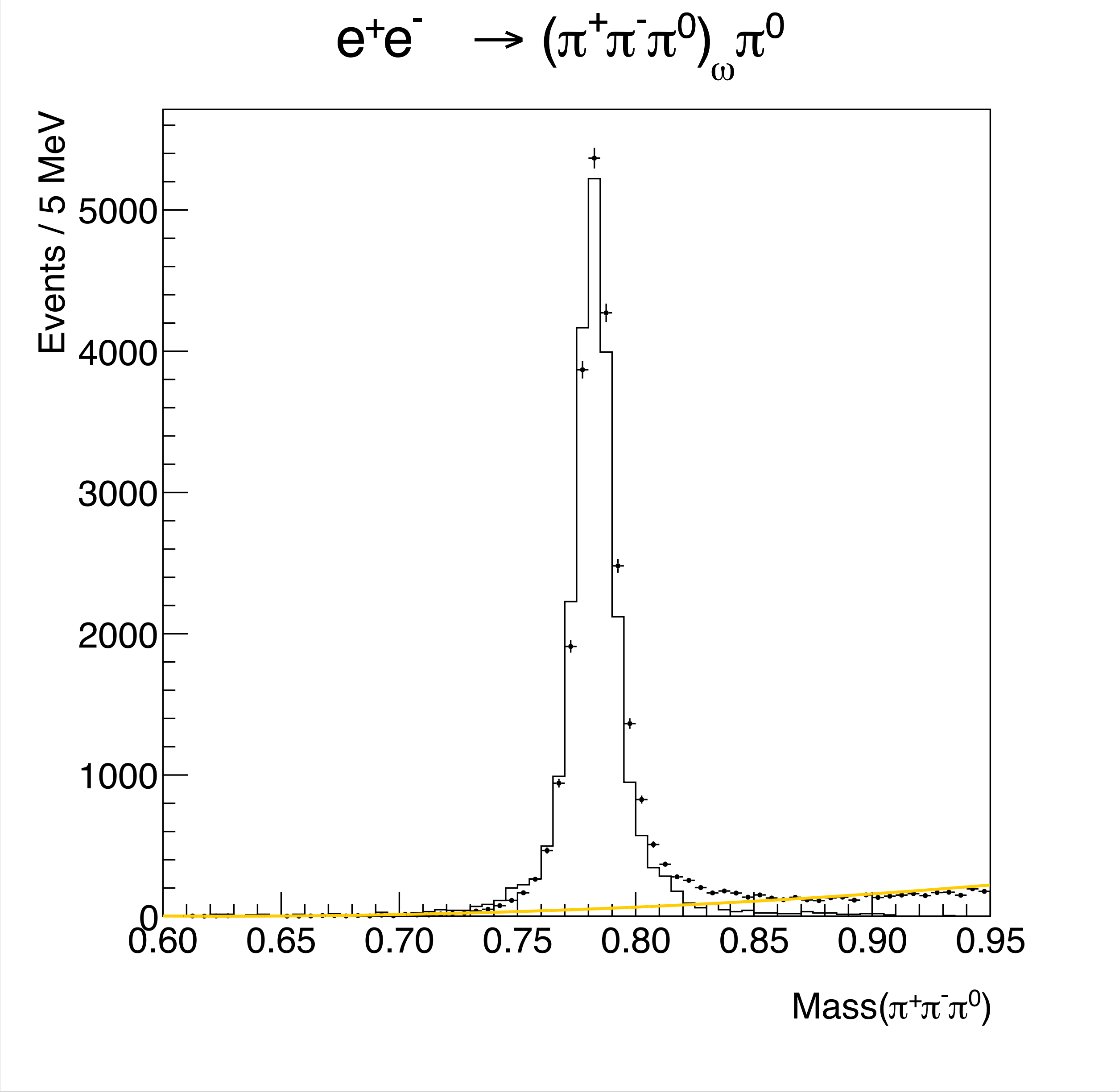


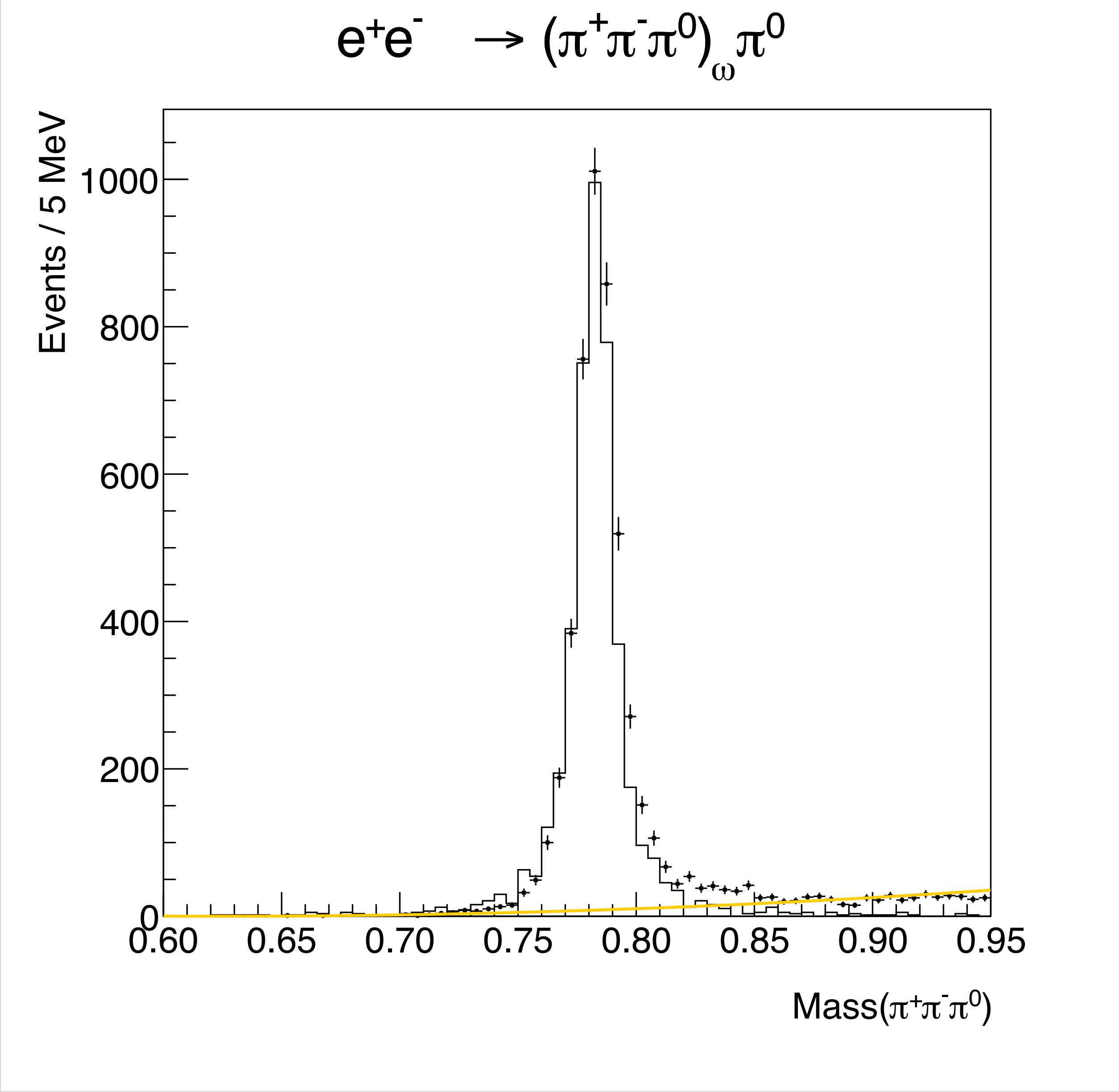


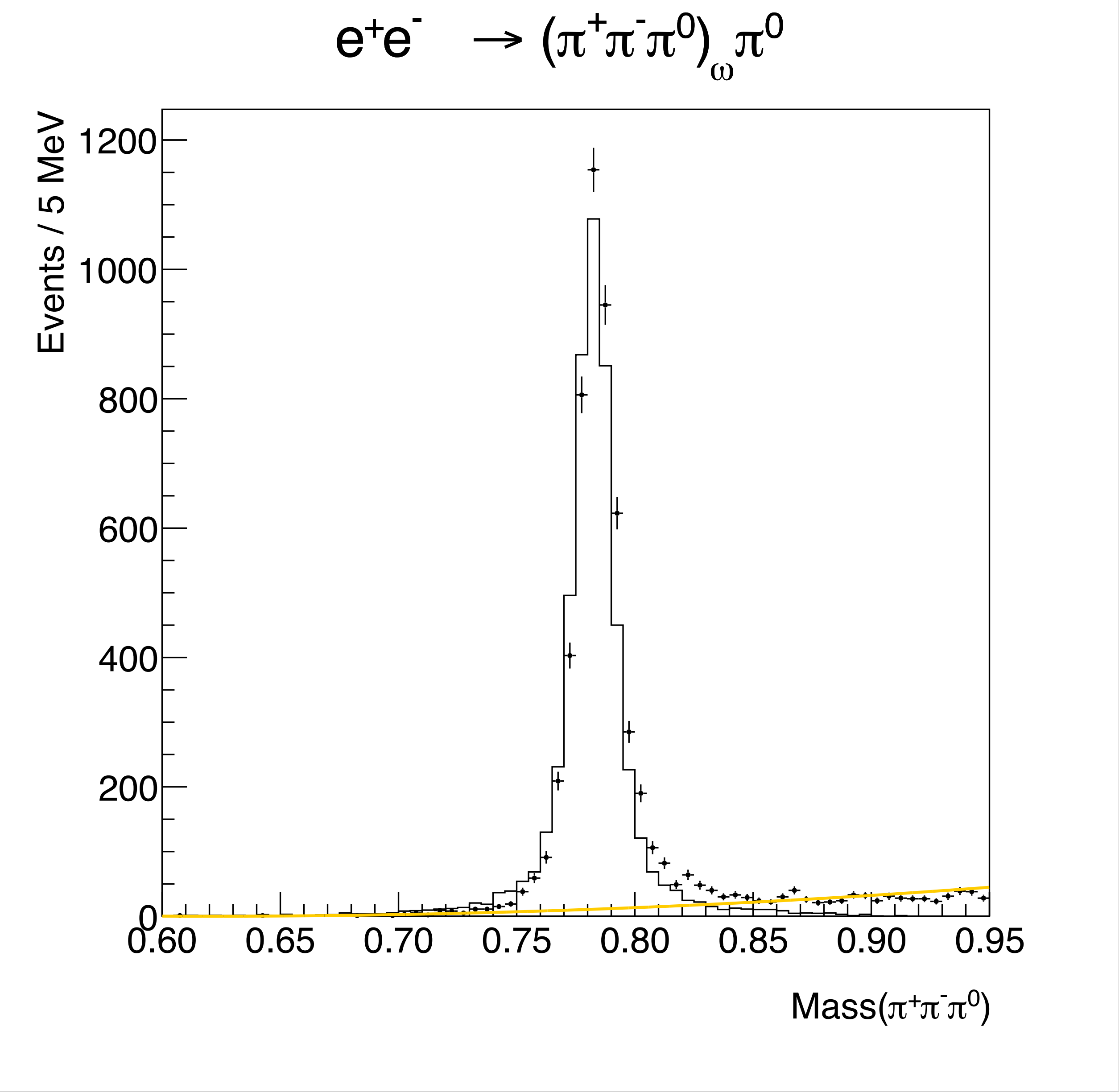
Fitting $\omega \to \pi^+\pi^-\pi^0$: Easy Part

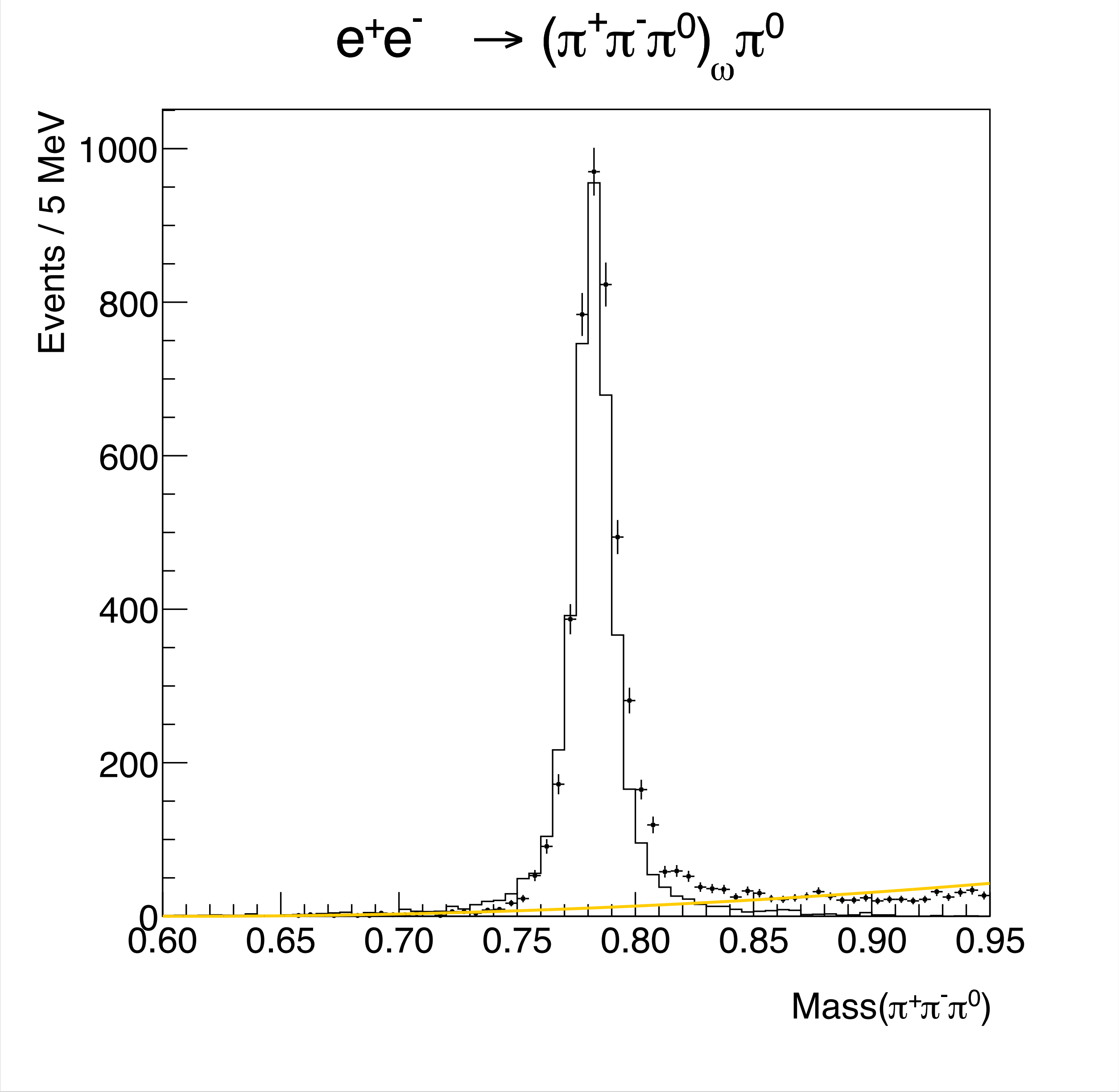
- To count $\omega \to \pi^+\pi^-\pi^0$ events we use a cutting and counting method; a polynomial is fit everywhere except the ω signal region (0.725,0.825) GeV, and I count events using a sideband subtraction method

- Plots are (left to right) from 3770 MeV, 4180 MeV, and combined 2017 XYZ data; data points are from data, and the histogram is from SIGMC



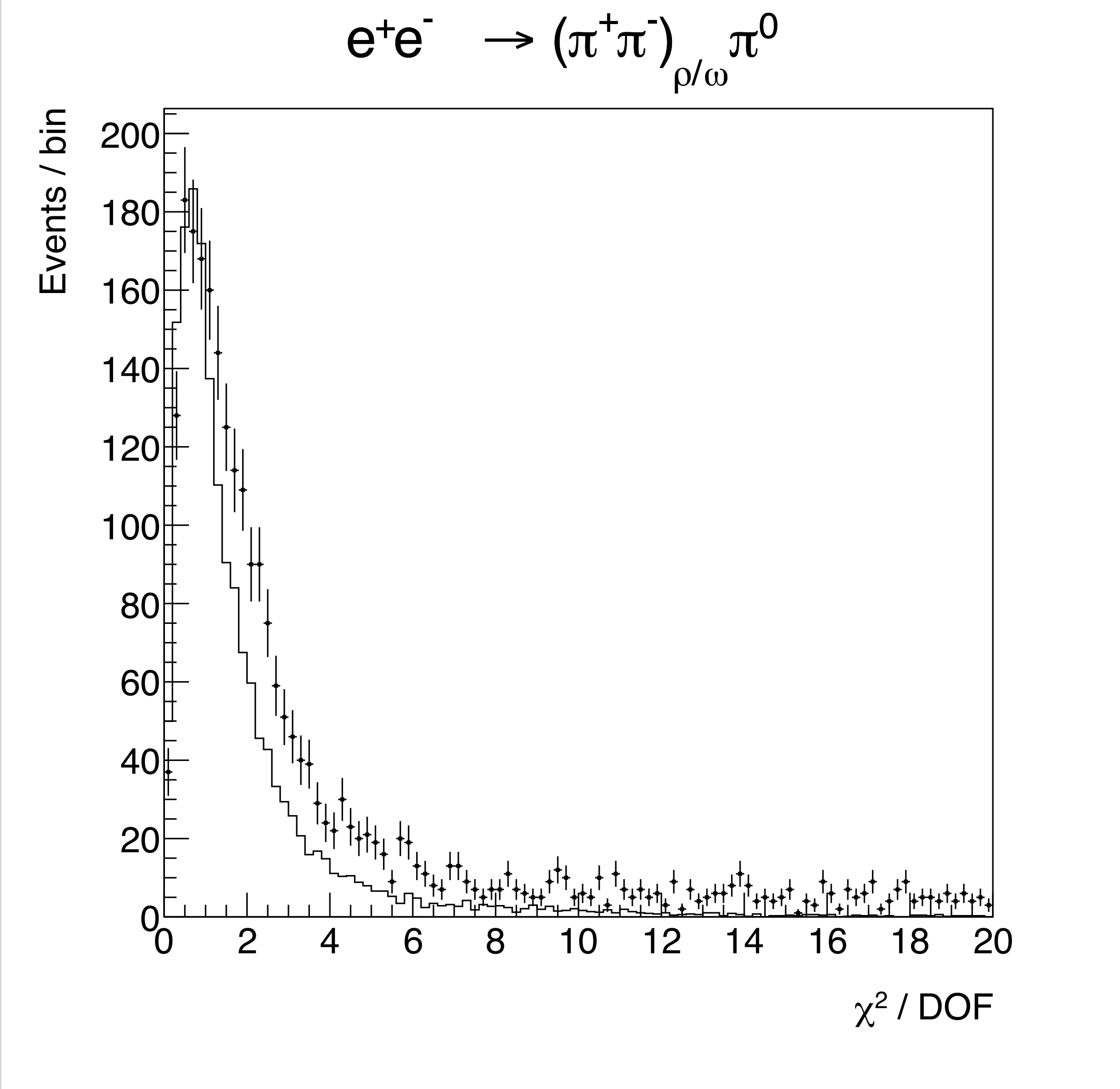


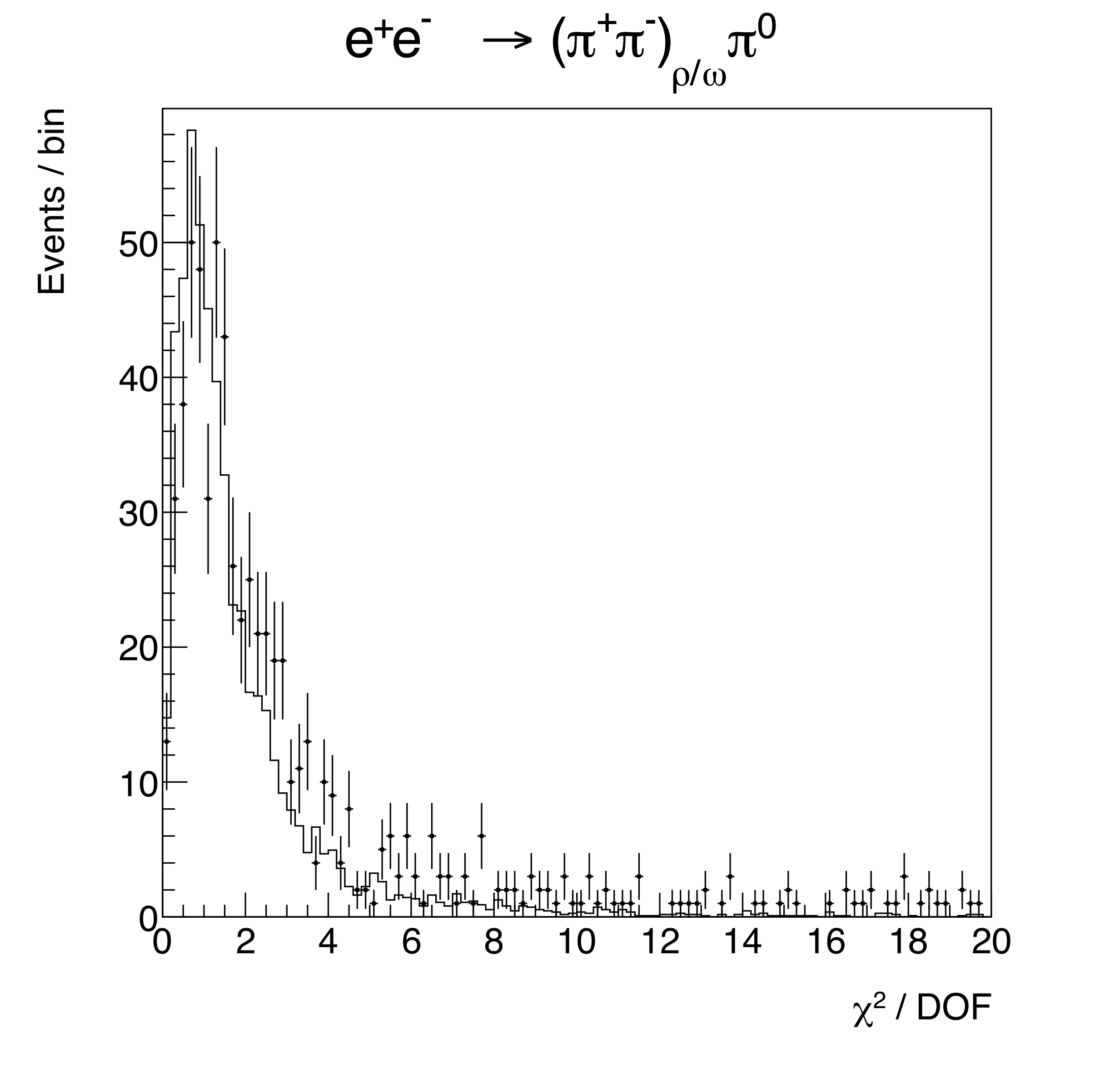


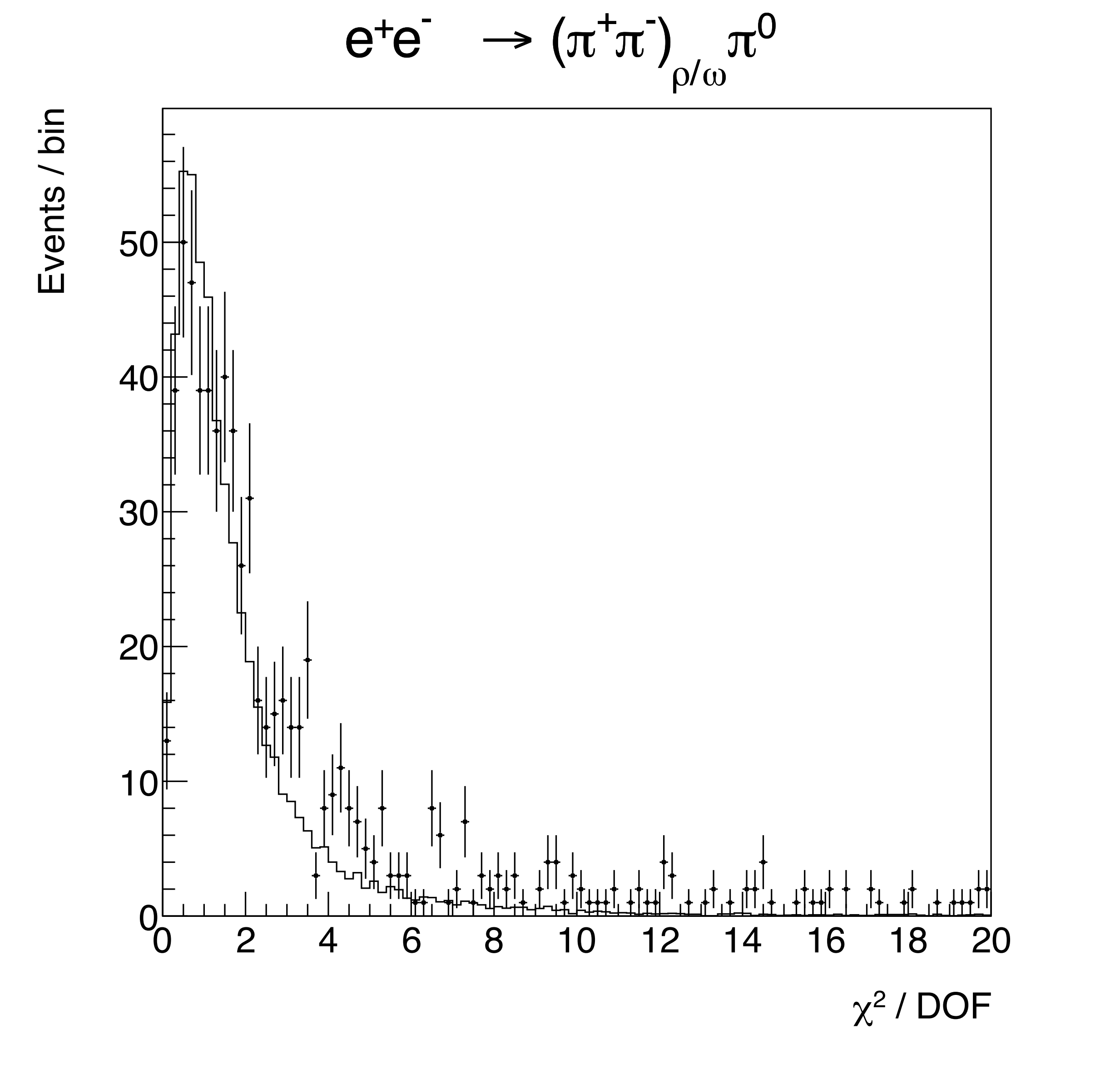


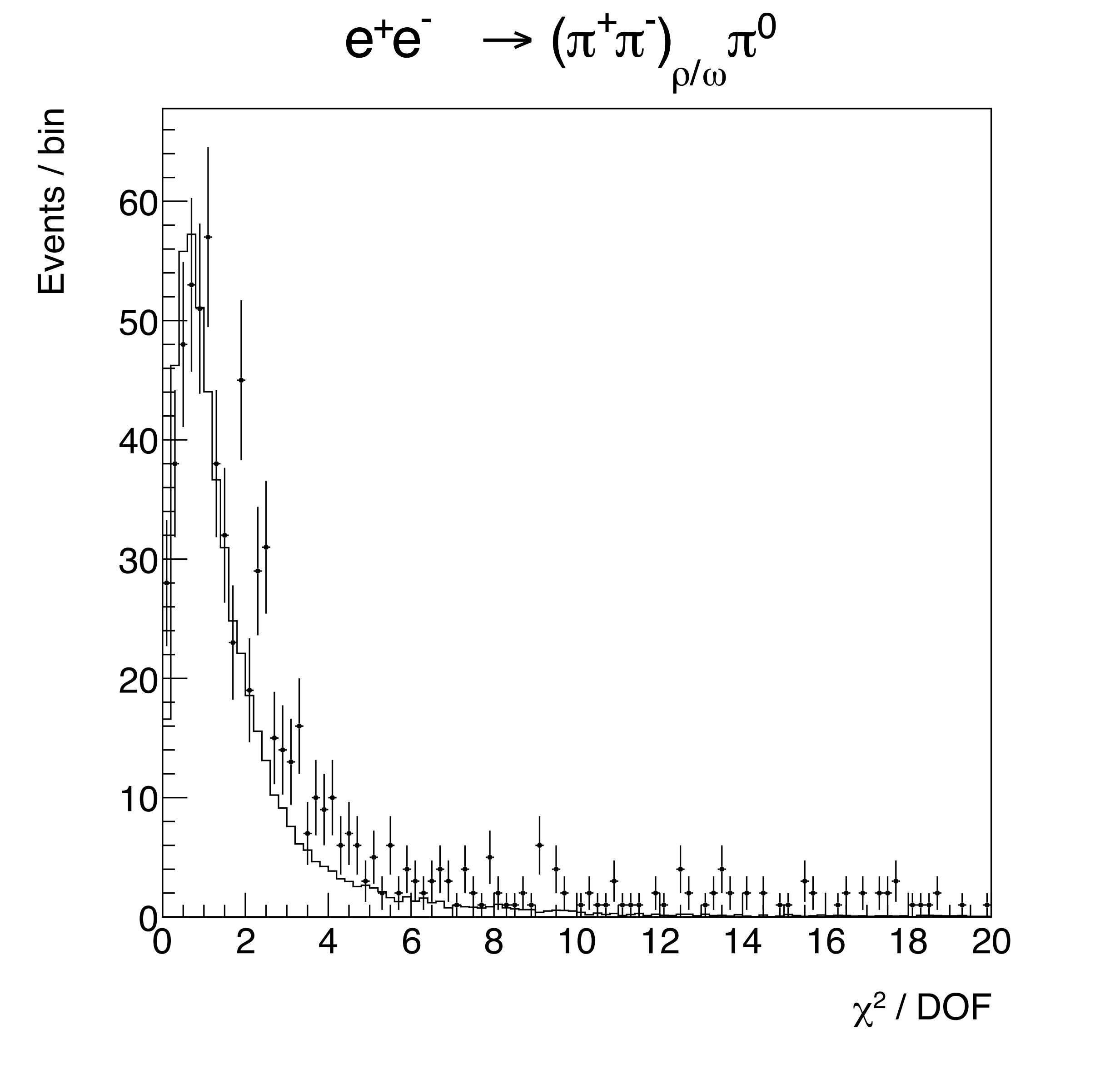
$\omega \to \pi^+\pi^-$ cuts: χ^2

- For $\omega \to \pi^+\pi^-$ events we also make a cut on the χ^2/DOF from the kinematic fit
- Plots are (left to right) from 3770 MeV, 4180 MeV, combined 2017 XYZ data, and combined 2019 XYZ data; data points are from data, and the histogram is from SIGMC, selecting the ω signal region
- For each dataset in both data and MC we require χ^2/DOF < 5.0



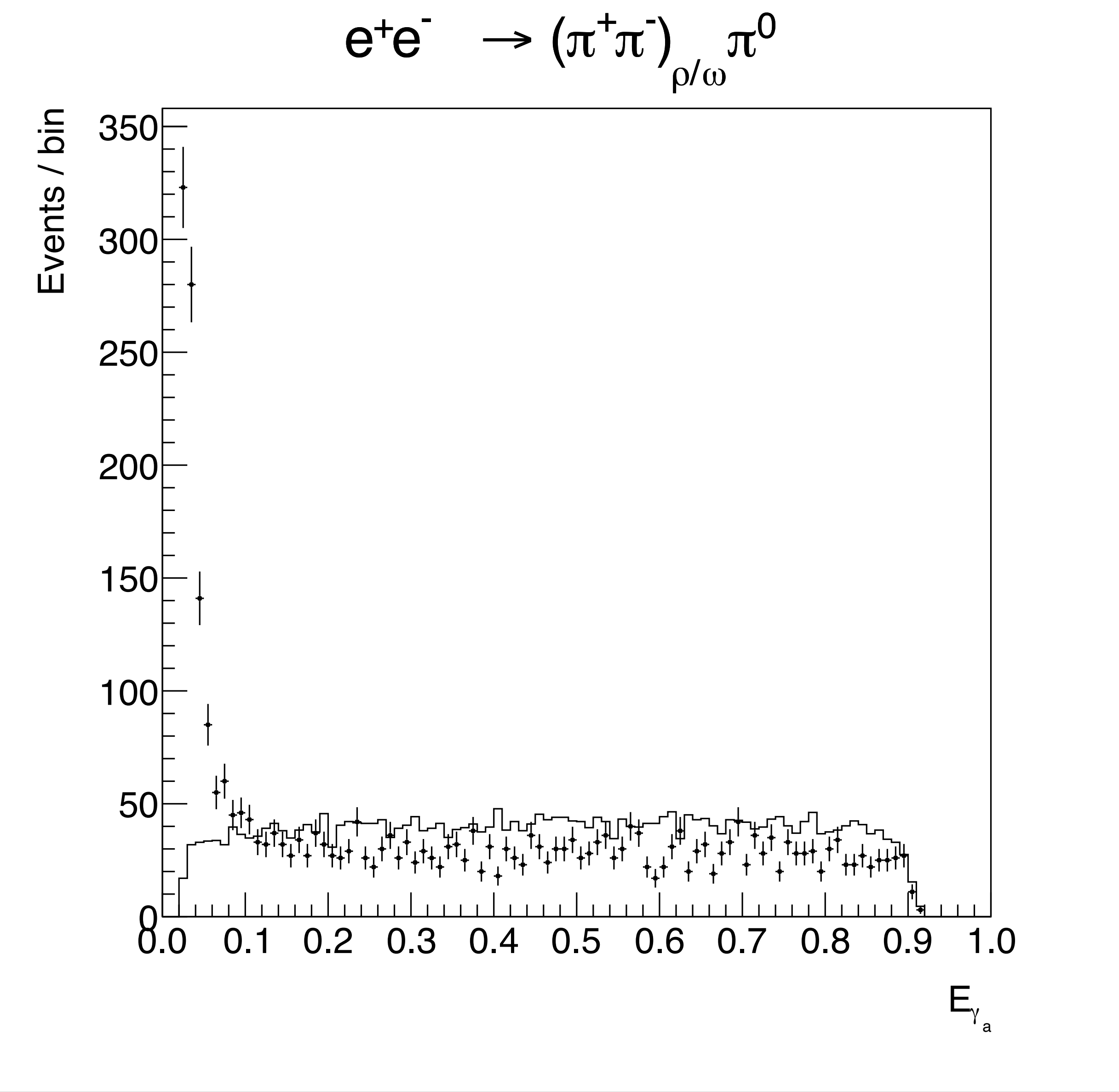


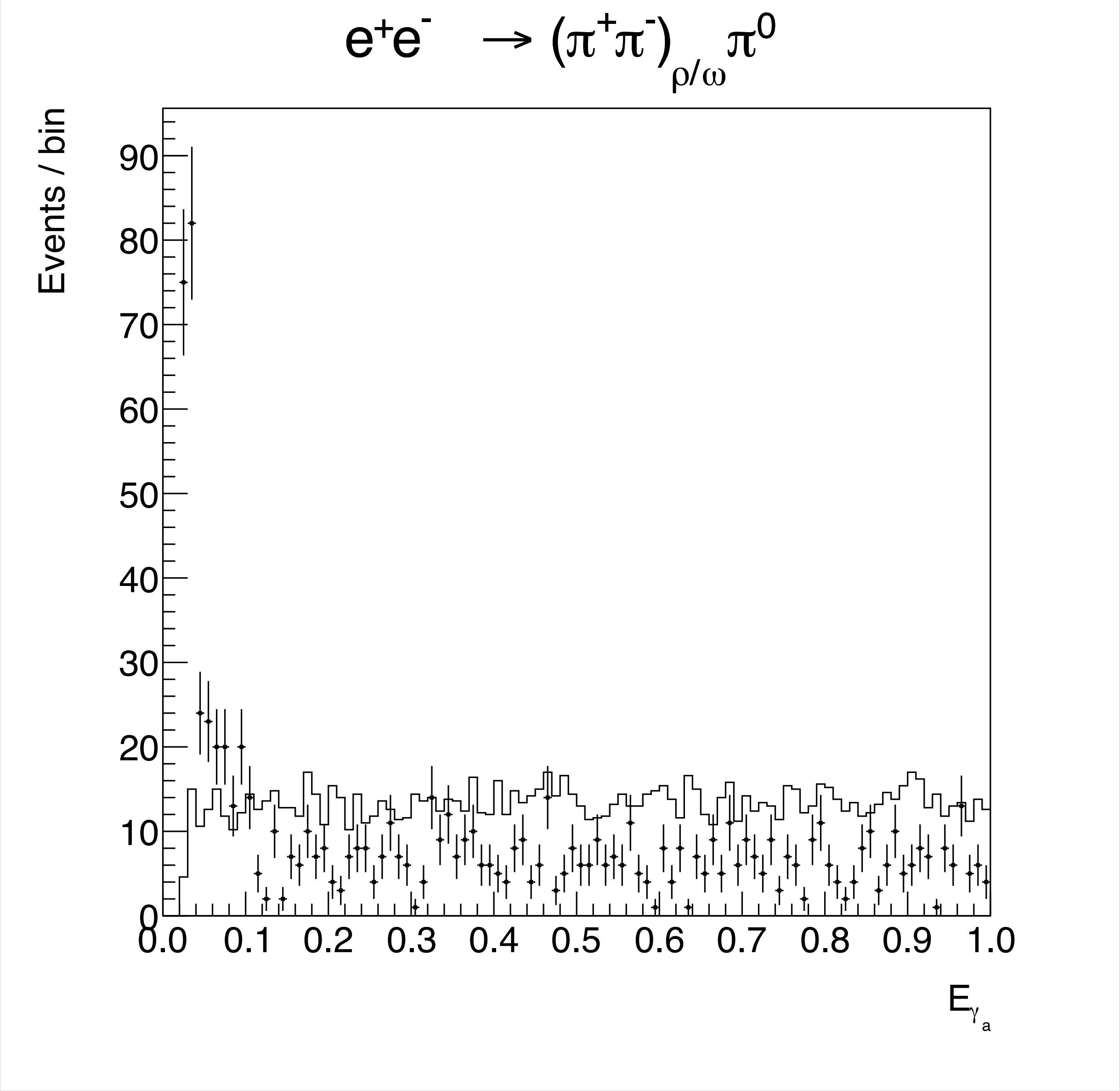


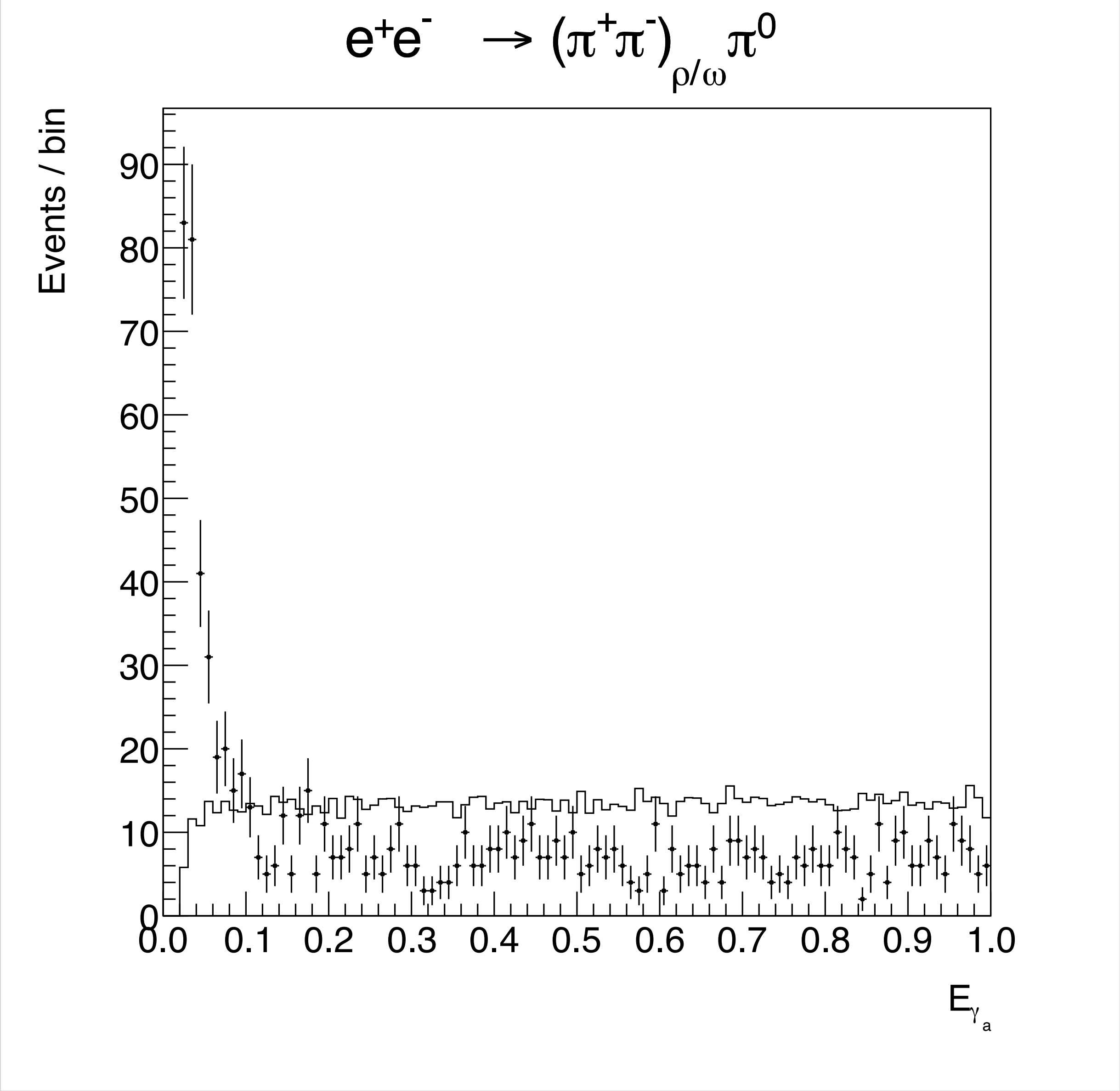


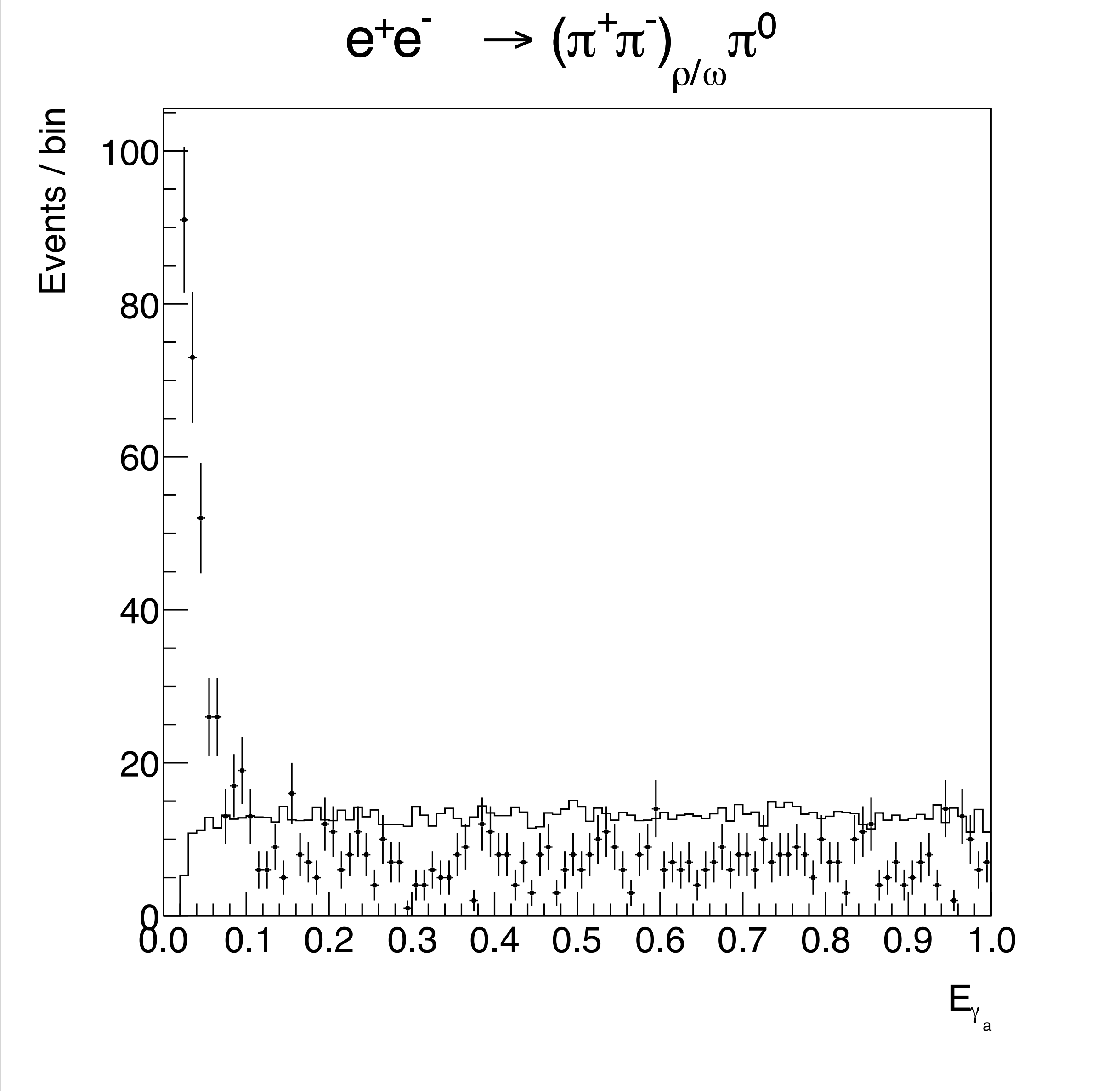
$\omega \to \pi^+\pi^-$ cuts: E_γ

- After the χ^2 cut, there is some remaining background from a low-energy photon from the π^0 decay
- Plots are (left to right) from 3770 MeV, 4180 MeV, combined 2017 XYZ data, and combined 2019 XYZ data; data points are from data, and the histogram is from SIGMC, selecting the ω signal region, showing the energy of this photon
- For each dataset in both data and MC we require $E_{\gamma_a} > 0.2$



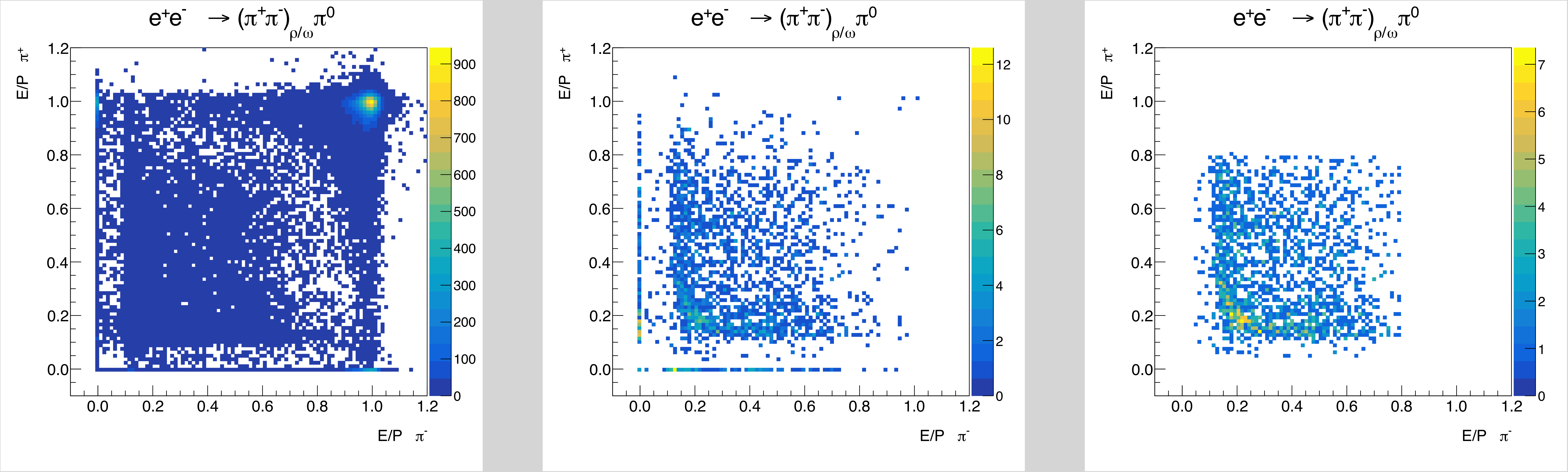






$\omega \to \pi^+\pi^-$ cuts: E/P

- 2D plots of E/P for the two charged tracks from 3770 MeV data (same cut applied to each dataset)
- Left To Right: First two cuts and all masses, First two cuts + omega signal region, including new E/P cut
- For each track, require: $0.05 < E/P < 0.8$

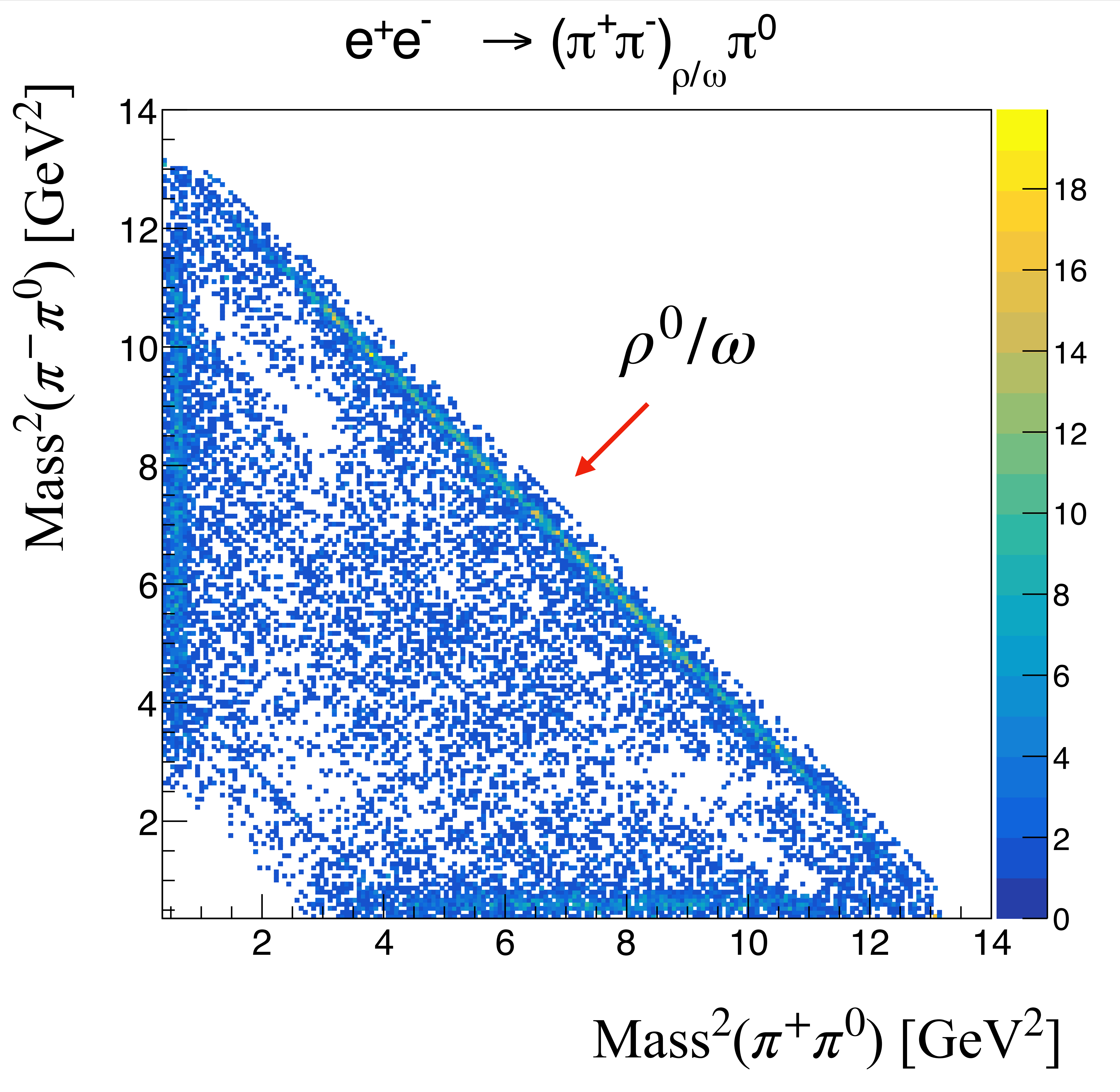


Fitting $\omega \to \pi^+\pi^-$

- Final mass distributions after all cuts for (left to right) 3770 MeV, 4180 MeV, and XYZ dataset; datapoints are from data, and histogram from SIGMC tagging the ω

- To fit the $\pi^+\pi^-$ mass spectrum, need to separate ρ and ω components

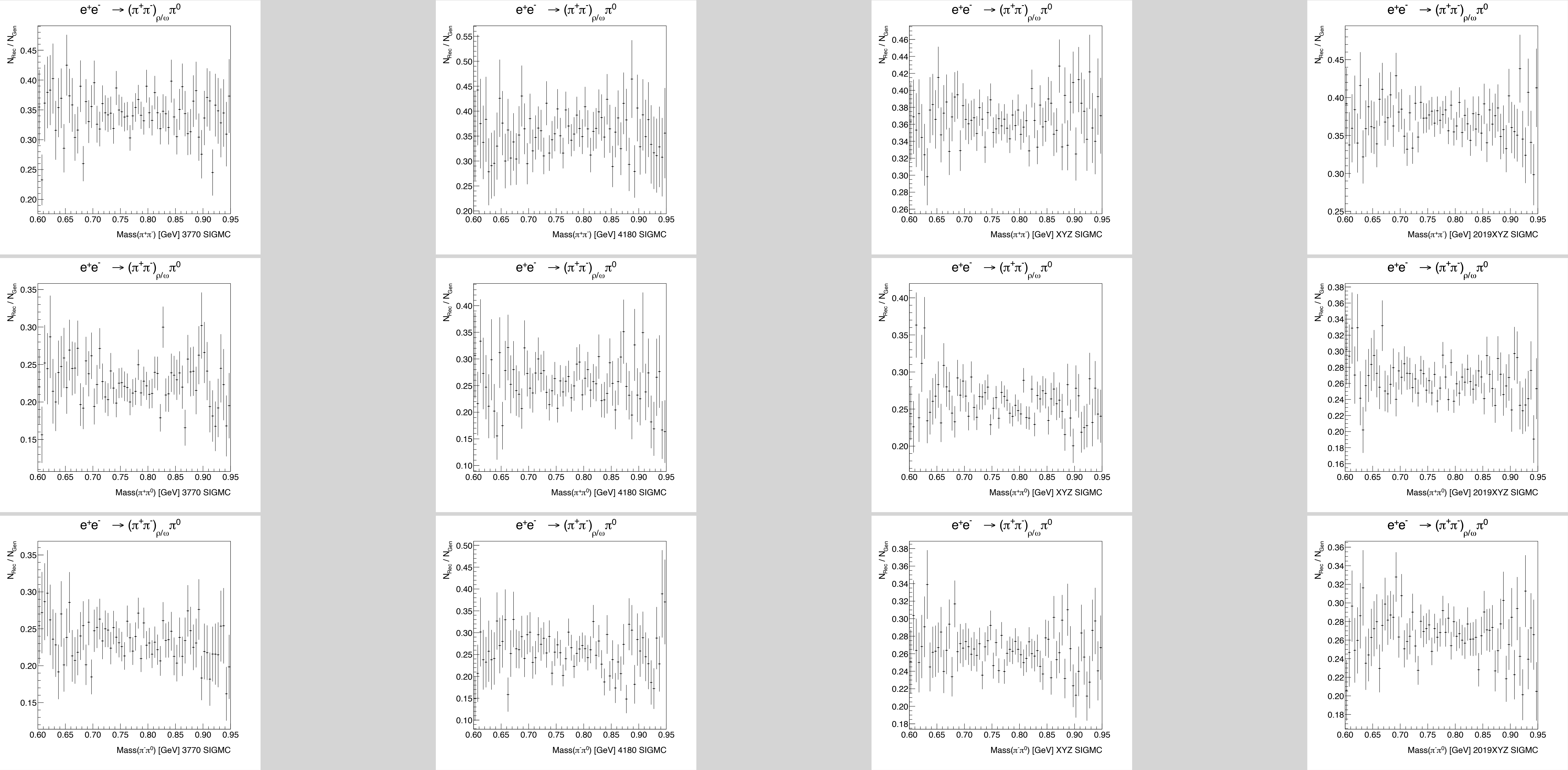
Dalitz Plot from 3770 MeV Data after all selection cuts



Efficiency Check

- In the following fits, we make use of the $\rho^{+/-}$ [mass($\pi^{+/-}\pi^0$)] shape in data
- This shape is either used directly in the fits, or in a simultaneous fit to the charged and neutral channels
- In addition to the shape, we can use the $\rho^{+/-}$ to also constrain the size of the ρ^0
- If the efficiency of each of the three ρ's is sufficiently flat as a function of $\pi\pi$ mass, we can use it for the size constraint
- That is, we measure and use the difference in efficiency between the charged and neutral channels to constrain the sizes of the charged and neutral shape, with one overall size parameter
- The following slide shows that these efficiencies are sufficiently flat for this purpose

Efficiency as function of mass (ρ^0,ρ^+,ρ^-)



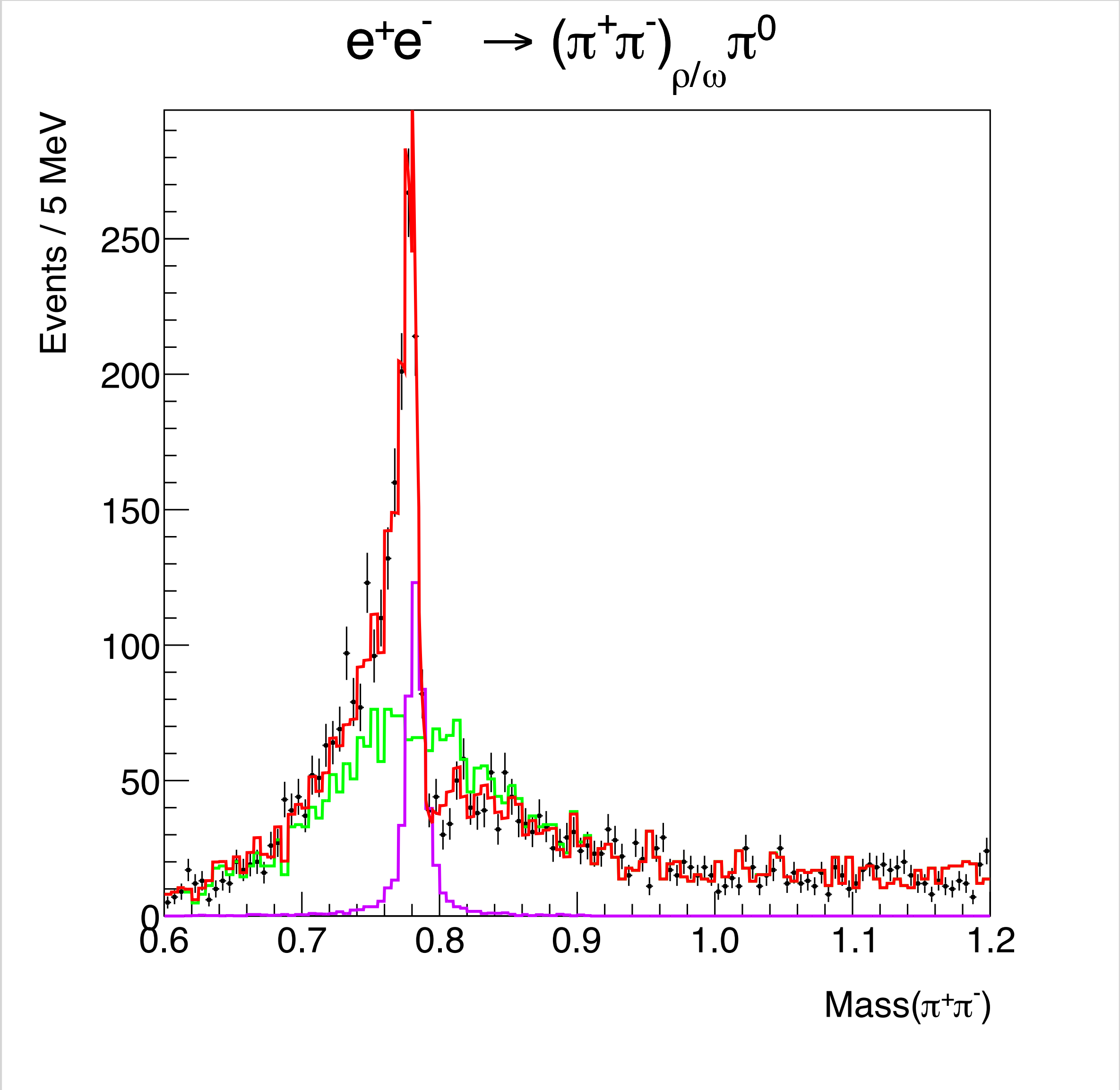
3770 4180 2017 XYZ 2019 XYZ

First Fits: using charged ρ histogram

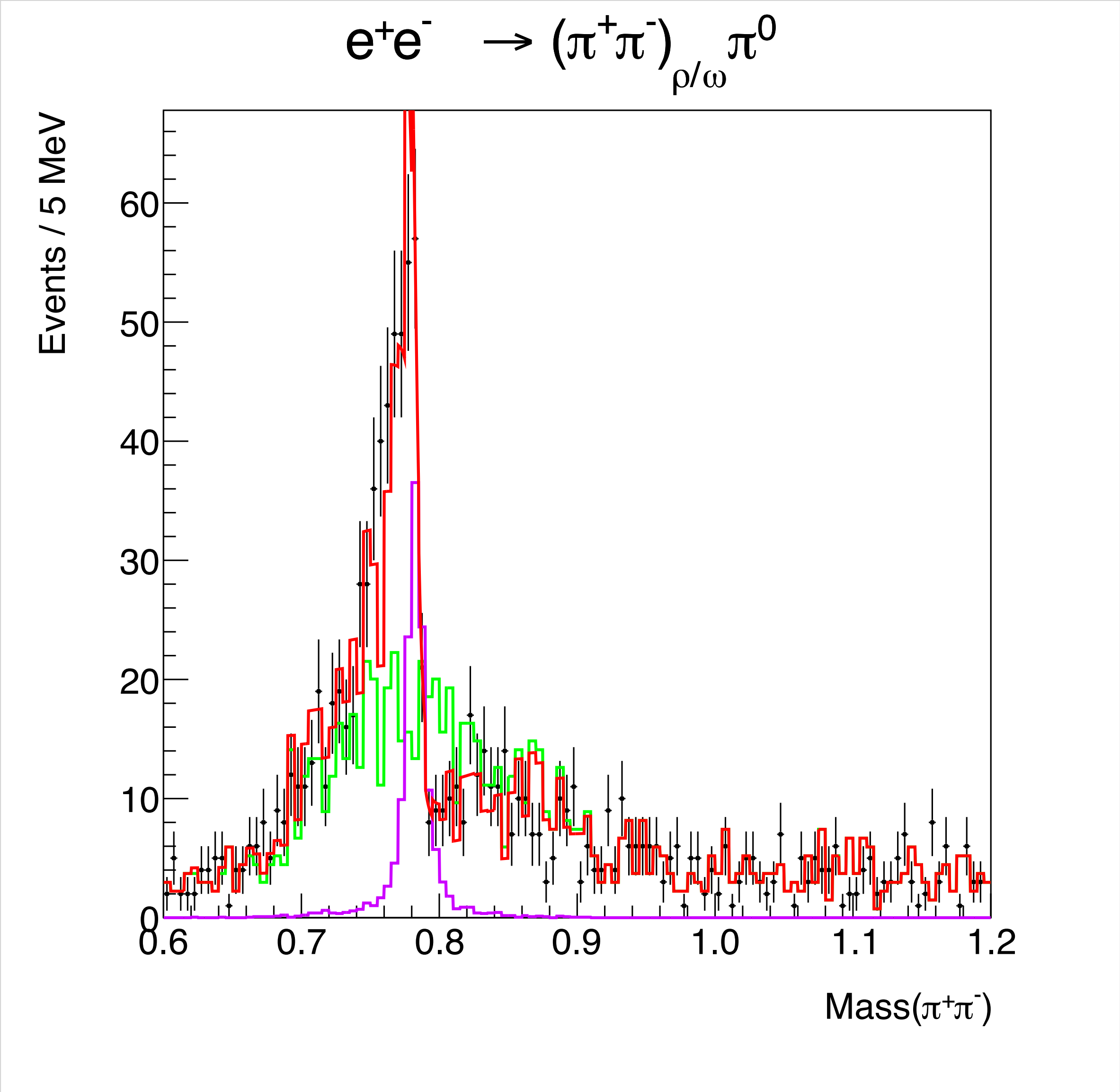
- ρ shape (green) taken from $\rho^{+/-}$ mass in data; ρ Breit-Wigner phase attached, size constrained based on efficiency difference of charged and neutral ρ

- ω shape taken from signal MC of $\omega \to \pi^+\pi^-$; ω Breit-Wigner phase attached, size parameter free; relative phase between the two shapes free

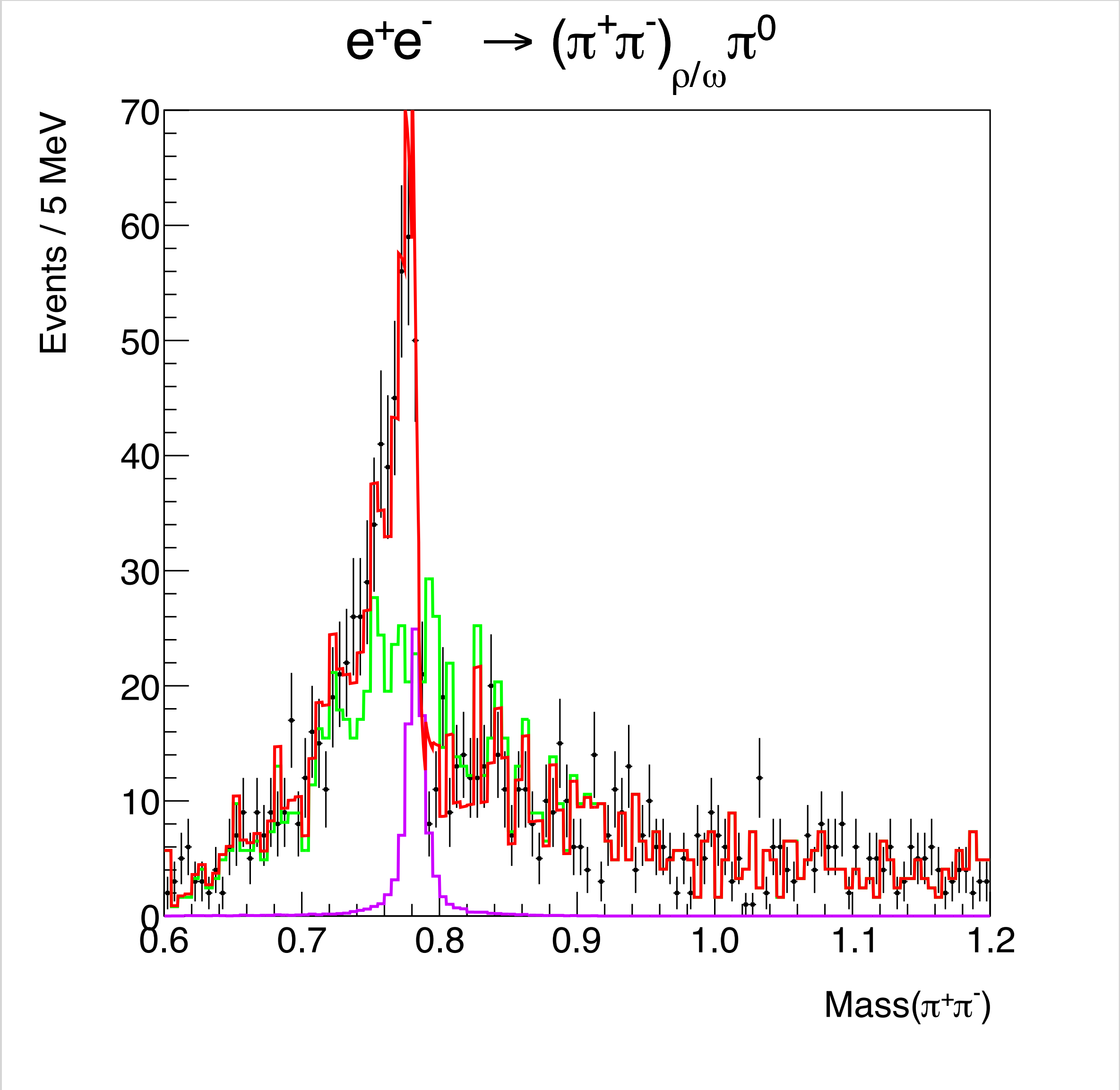
- Total fit shape shown in red



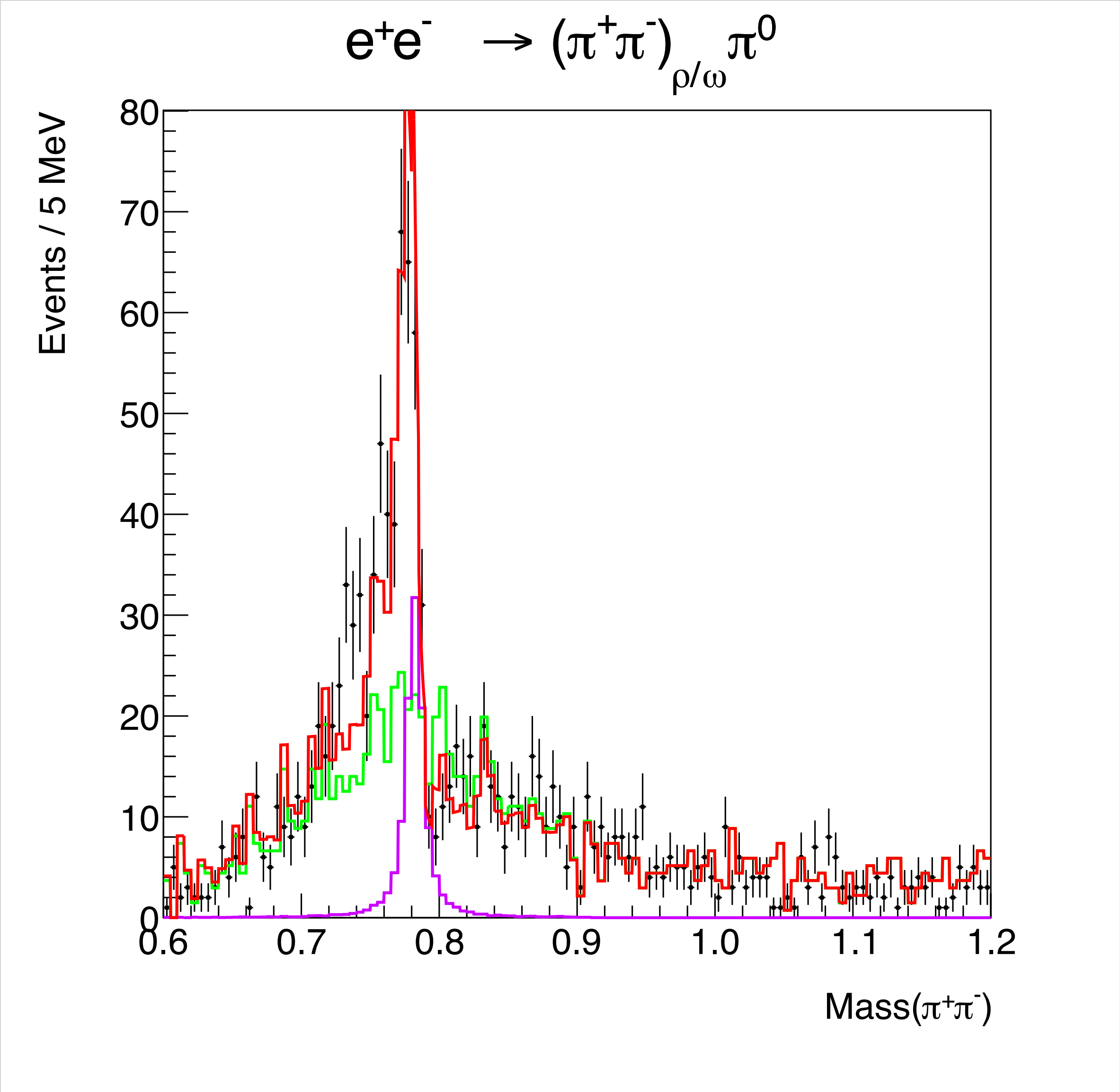
3770



4180



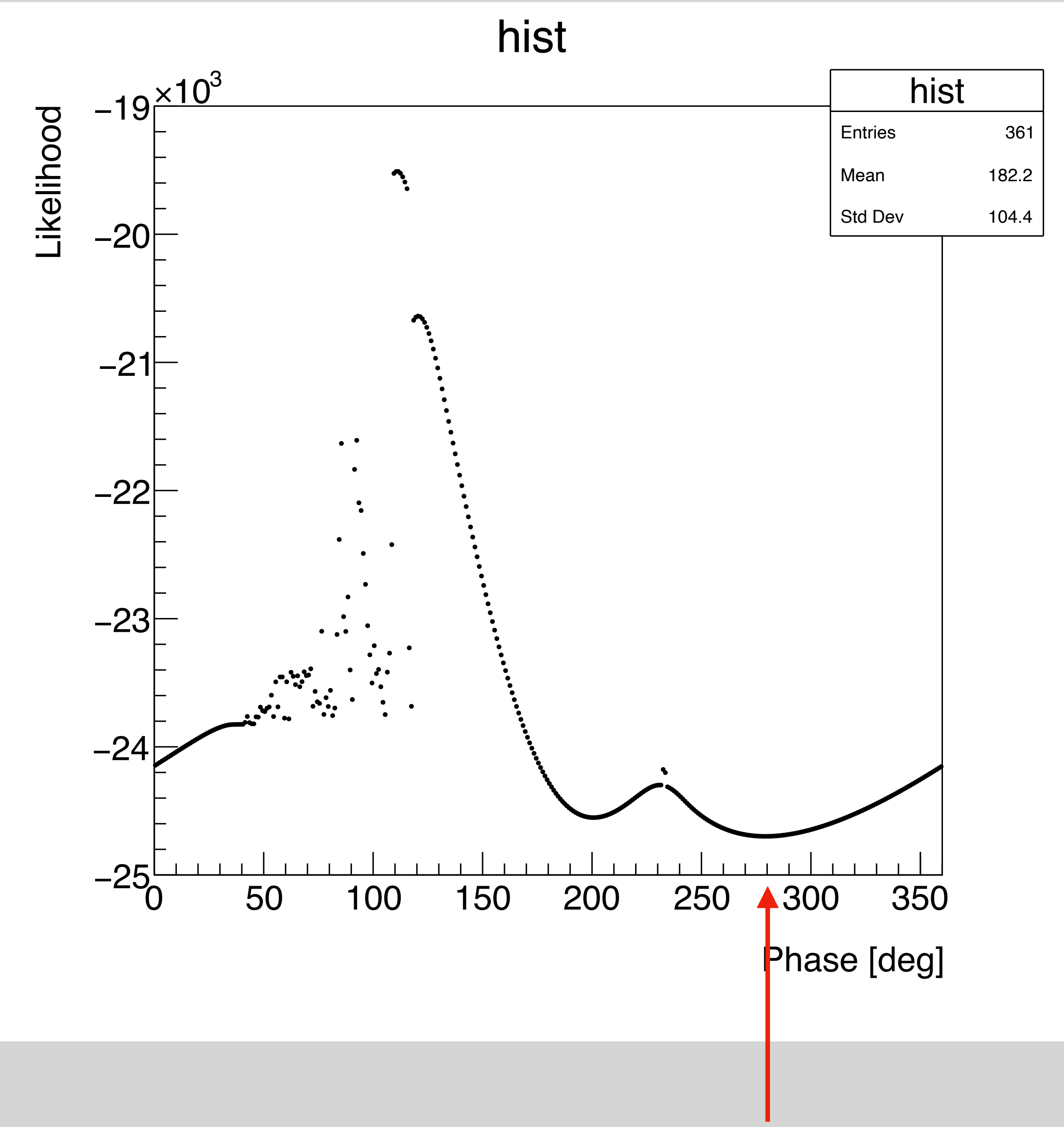
2017 XYZ



2019 XYZ

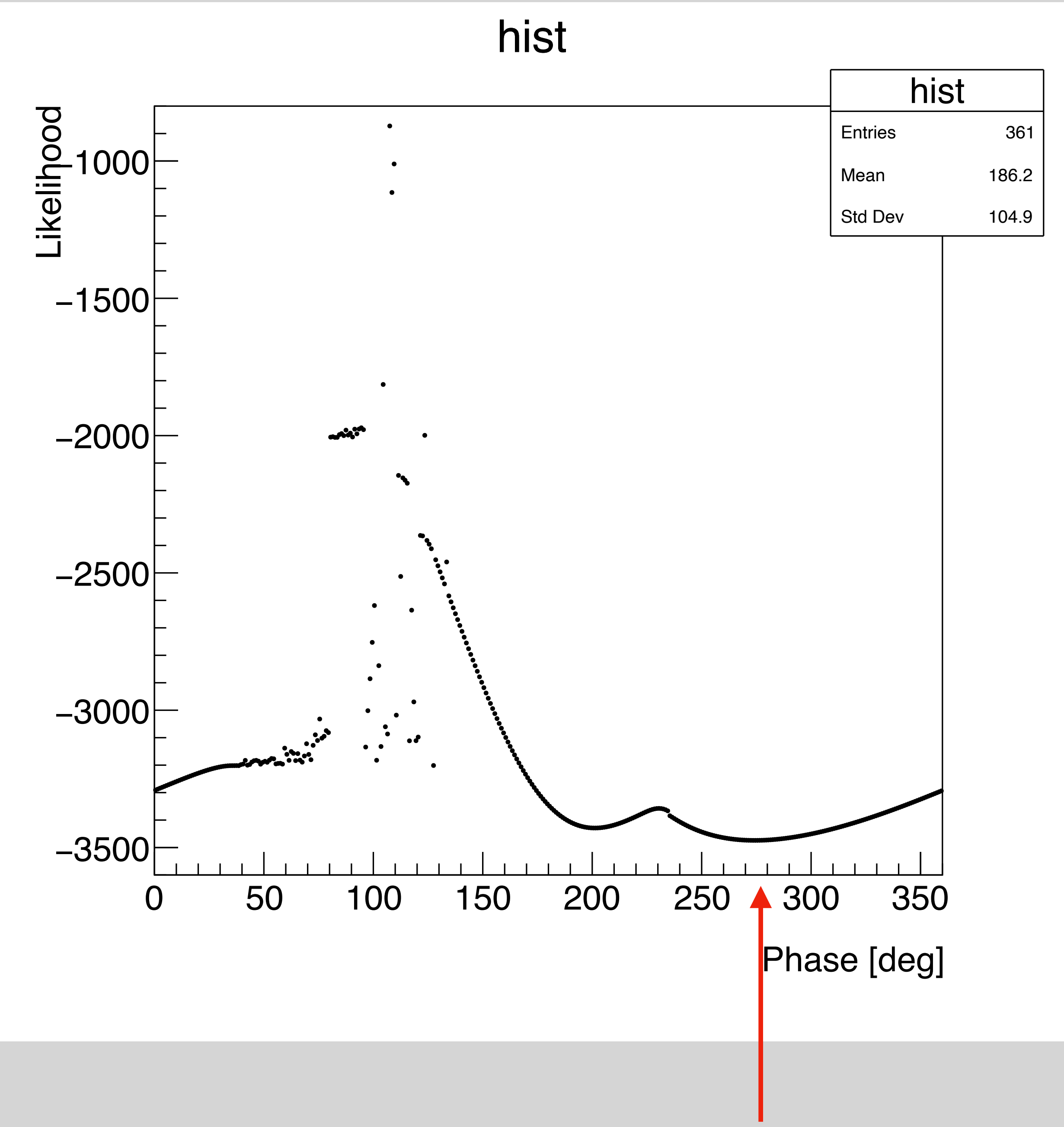
Likelihood Scans of Relative Phase

3770



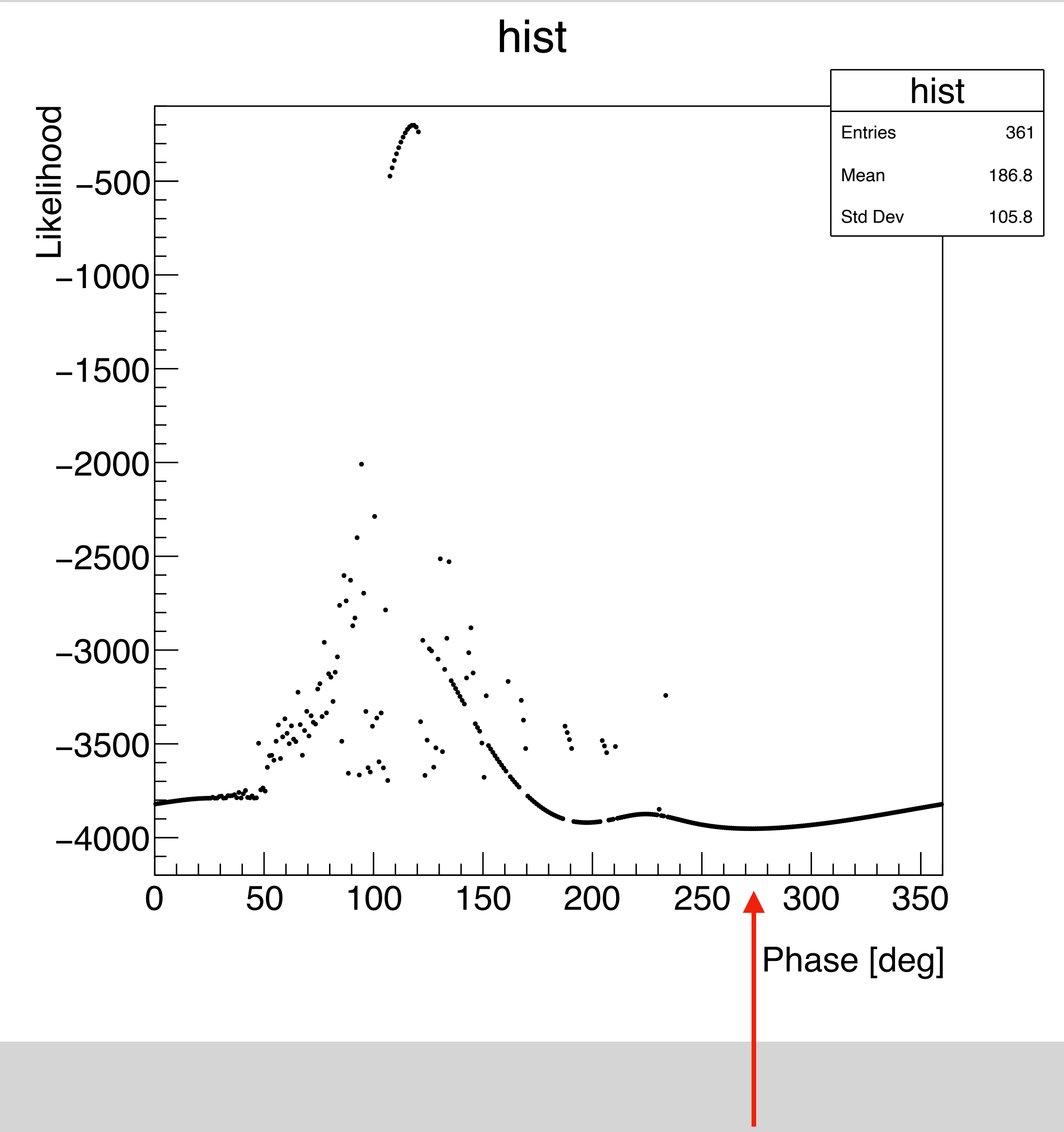
Min $\phi = 280$ deg

4180



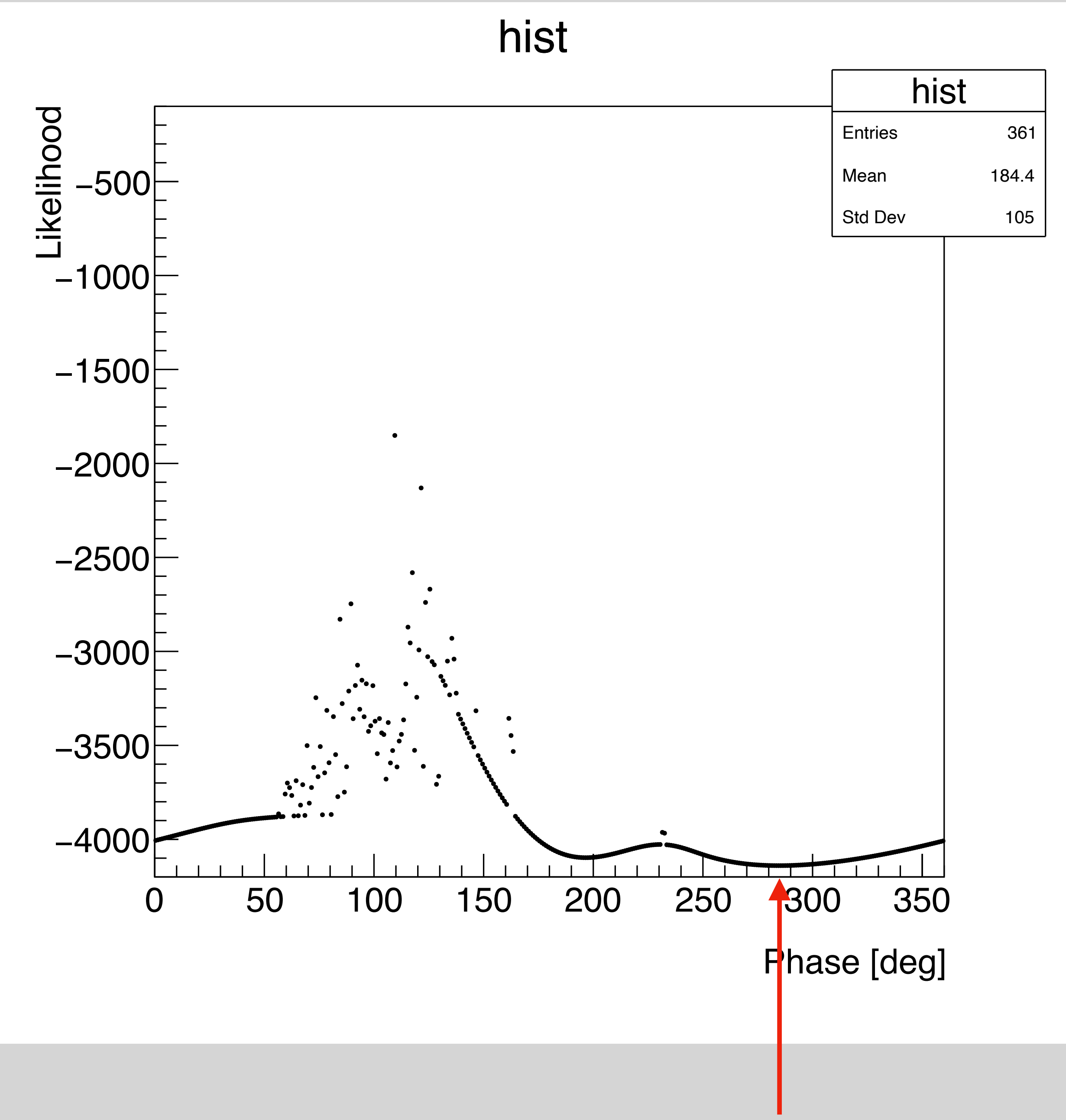
Min $\phi = 275$ deg

2017 XYZ



Min $\phi = 273$ deg

2019 XYZ



Min $\phi = 285$ deg

Results

$$\frac{\mathscr{B}(\omega \to \pi^+\pi^-)}{\mathscr{B}(\omega \to \pi^+\pi^-\pi^0)}(\times 10^{-3})$$

Dataset	Wider Histogram Fit
3770	14.23 ± 0.72
4180	21.2 ± 1.9
2017 XYZ	12.8 ± 1.3
2019 XYZ	18.2 ± 1.7
Total	-
PDG Value	17.2 ± 1.4

Second Fits: Breit-Wigner ρ

- Simultaneous fits to charged and neutral $\pi\pi$ channels
- Charged channel ($\pi^{+/-}\pi^0$) fitted with Breit-Wigner + polynomial
- Neutral channel constrained to have same mass and width, and sizes constrained by efficiencies of the two channels; and the polynomial shape is constrained to be the same for background under the ρ's
- In neutral channel, the ρ shape interferes with the ω shape with a free relative phase
- Fits to both channels shown in following slide
- Green=ρ, Purple=ω, Blue=Full $\rho + \omega$ amplitude (including interference), Yellow=Polynomial, and the total fit is shown in red

BW ρ, polynomial for background

3770

4180

2017 XYZ

2019 XYZ

Results

$$\frac{\mathscr{B}(\omega \to \pi^+\pi^-)}{\mathscr{B}(\omega \to \pi^+\pi^-\pi^0)}(\times 10^{-3})$$

Dataset	Wider Histogram Fit	Constrained BW Fit
3770	14.23 ± 0.72	15.25 ± 0.75
4180	21.2 ± 1.9	20.4 ± 1.9
2017 XYZ	12.8 ± 1.3	14.9 ± 1.5
2019 XYZ	18.2 ± 1.7	19.2 ± 1.7
Total	-	-
PDG Value	17.2 ± 1.4	-

Third Fits: Gounaris-Sakurai ρ

- Simultaneous fit to charged and neutral channels in the same manner as previous slide

- Parameters constrained as before; Now, ρ shape is from Gounaris-Sakurai (below)

An alternative model to the R-dependent Blatt–Weisskopf form factor in the Breit–Wigner amplitude is provided by the Gounaris–Sakurai formula [36],

$$\mathrm{BW}_{\rho}^{\mathrm{GS}}(s\,|\,m_{\rho},\Gamma_{\rho}) = \frac{m_{\rho}^{2}\left[1+d(m_{\rho})\Gamma_{\rho}/m_{\rho}\right]}{m_{\rho}^{2}-s+f(s,m_{\rho},\Gamma_{\rho})-i\,m_{\rho}\Gamma(s,m_{\rho},\Gamma_{\rho})}, \tag{S4}$$

where,

$$\Gamma(s,m,\Gamma_0) = \Gamma_0\frac{m}{\sqrt{s}}\left[\frac{p_{\pi}(s)}{p_{\pi}(m^2)}\right]^{3}, \tag{S5}$$

$$d(m) = \frac{3}{\pi}\frac{m_{\pi}^{2}}{p_{\pi}^{2}(m^2)}\log\left[\frac{m+2p_{\pi}(m^2)}{2m_{\pi}}\right]+\frac{m}{2\pi p_{\pi}(m^2)}-\frac{m_{\pi}^{2}m}{\pi p_{\pi}^{3}(m^2)}, \tag{S6}$$

$$f(s,m,\Gamma_0) = \frac{\Gamma_0 m^2}{p_{\pi}^{3}(m^2)}\left[p_{\pi}^{2}(s)\left[h(s)-h(m^2)\right]+(m^2-s)p_{\pi}^{2}(m^2)h'(m^2)\right], \tag{S7}$$

$$h(s) = \frac{2}{\pi}\frac{p_{\pi}(s)}{\sqrt{s}}\log\left[\frac{\sqrt{s}+2p_{\pi}(s)}{2m_{\pi}}\right], \tag{S8}$$

- Green=ρ, Purple=ω, Blue=Full $\rho + \omega$ amplitude (including interference), Yellow=Polynomial, and the total fit is shown in red

Wider Fits, GS, polynomial

3770 | 4180 | 2017 XYZ | 2019 XYZ

Results

$$\frac{\mathscr{B}(\omega \to \pi^+\pi^-)}{\mathscr{B}(\omega \to \pi^+\pi^-\pi^0)}(\times 10^{-3})$$

Dataset	Wider Histogram Fit	Constrained BW Fit	Constrained GS Fit
3770	14.23 ± 0.72	15.25 ± 0.75	15.15 ± 0.75
4180	21.2 ± 1.9	20.4 ± 1.9	20.3 ± 1.9
2017 XYZ	12.8 ± 1.3	14.9 ± 1.5	14.8 ± 1.4
2019 XYZ	18.2 ± 1.7	19.2 ± 1.7	19.0 ± 1.7
Total	-	-	-
PDG Value	17.2 ± 1.4	-	-

BW ρ, no polynomial

3770

4180

2017 XYZ

2019 XYZ

Results

$$\frac{\mathscr{B}(\omega \to \pi^+\pi^-)}{\mathscr{B}(\omega \to \pi^+\pi^-\pi^0)}(\times 10^{-3})$$

Dataset	Wider Histogram Fit	Constrained BW Fit	Constrained GS Fit	BW, NO poly
3770	14.23 ± 0.72	15.25 ± 0.75	15.15 ± 0.75	16.56 ± 0.79
4180	21.2 ± 1.9	20.4 ± 1.9	20.3 ± 1.9	23.8 ± 2.1
2017 XYZ	12.8 ± 1.3	14.9 ± 1.5	14.8 ± 1.4	17.7 ± 1.6
2019 XYZ	18.2 ± 1.7	19.2 ± 1.7	19.0 ± 1.7	23.7 ± 2.0
Total	-	-	-	-
PDG Value	17.2 ± 1.4	-	-	-

GS ρ, NO polynomial

3770

4180

2017 XYZ

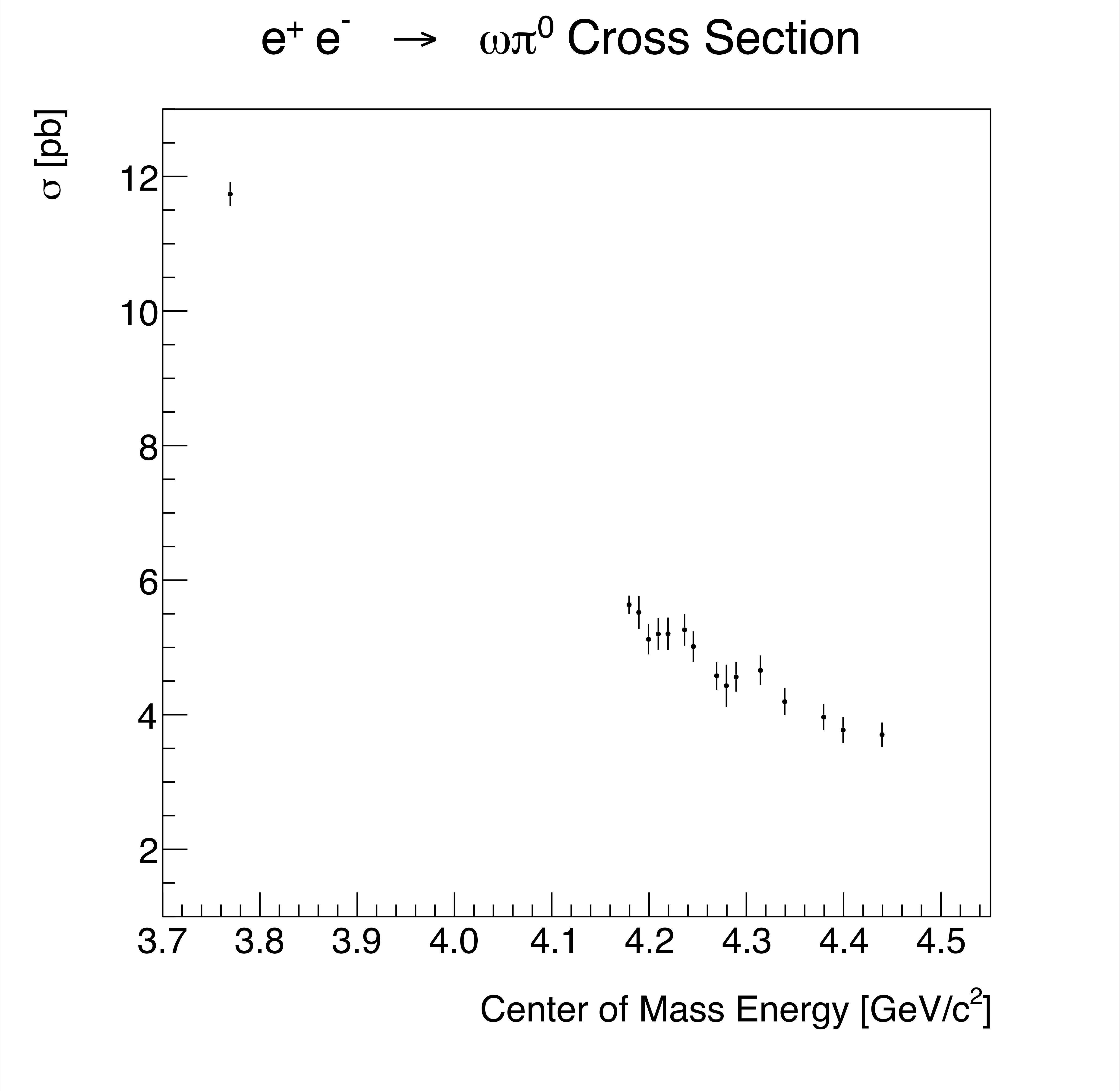
2019 XYZ

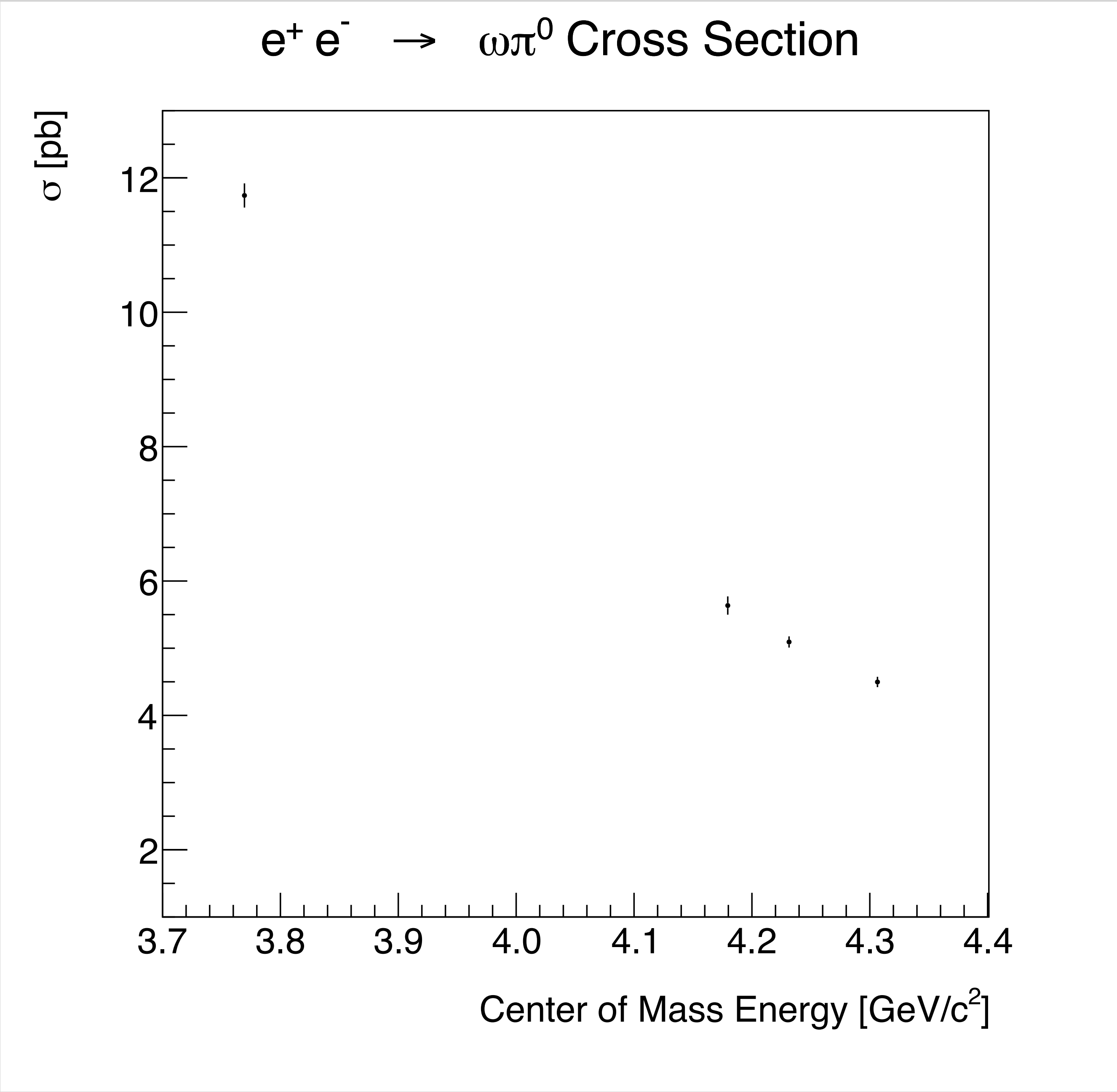
Results

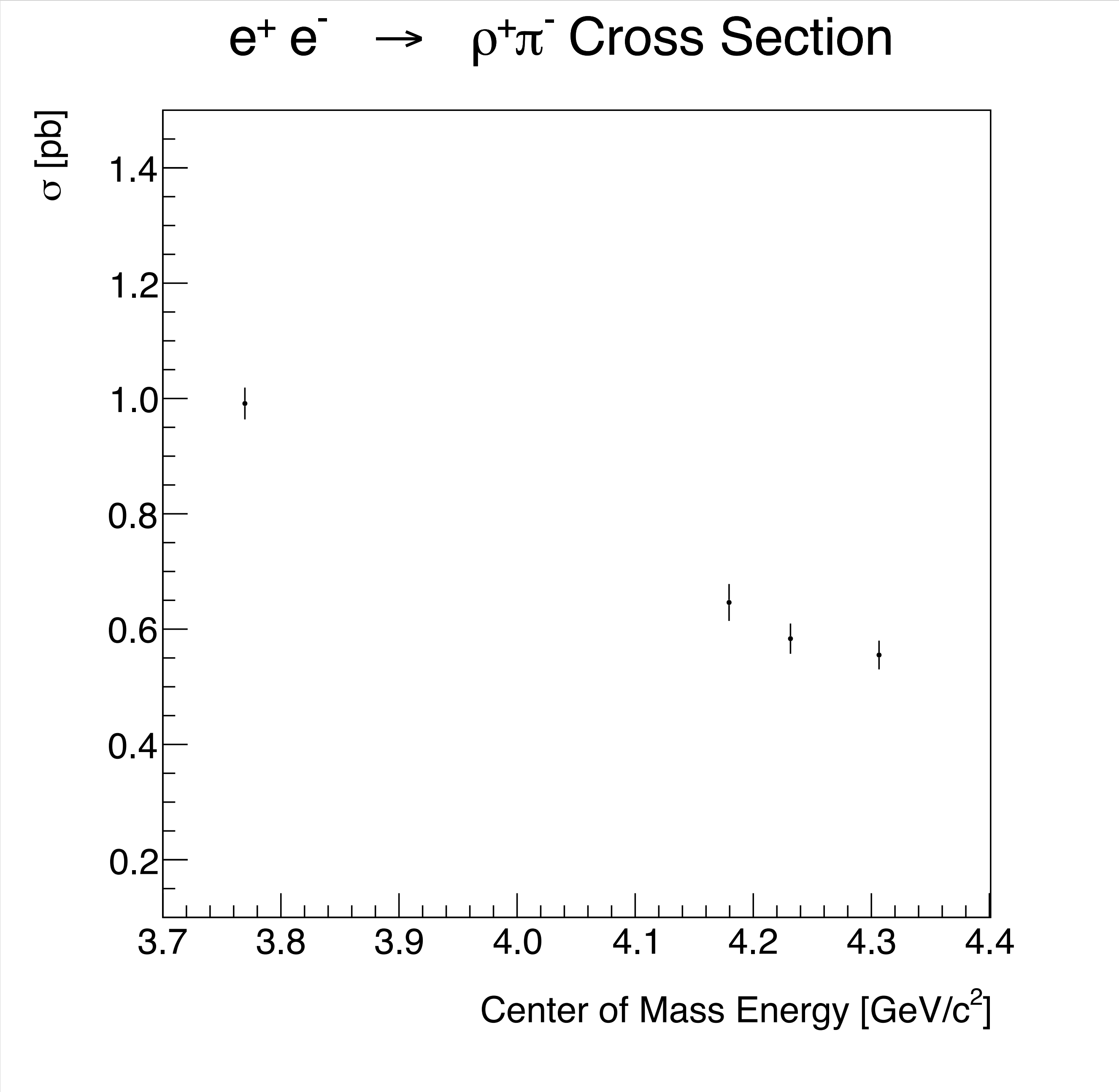
$$\frac{\mathscr{B}(\omega \to \pi^+\pi^-)}{\mathscr{B}(\omega \to \pi^+\pi^-\pi^0)}(\times 10^{-3})$$

Dataset	Wider Histogram Fit	Constrained BW Fit	Constrained GS Fit	BW, NO poly	GS, NO poly
3770	14.23 ± 0.72	15.25 ± 0.75	15.15 ± 0.75	16.56 ± 0.79	17.83 ± 0.82
4180	21.2 ± 1.9	20.4 ± 1.9	20.3 ± 1.9	23.8 ± 2.1	23.5 ± 2.0
2017 XYZ	12.8 ± 1.3	14.9 ± 1.5	14.8 ± 1.4	17.7 ± 1.6	17.4 ± 1.6
2019 XYZ	18.2 ± 1.7	19.2 ± 1.7	19.0 ± 1.7	23.7 ± 2.0	23.3 ± 1.9
Total	-	-	-	-	-
PDG Value	17.2 ± 1.4	-	-	-	-

Cross Sections







Next Steps

E_{CM} [GeV]	Year	Runs	Luminosity [pb^{-1}]	Boss Version
3.773	2010/2011 + 2022	11414 - 13988, 14395 - 14604, 20448 - 23454, 70522 - 73929	7926.8	7.0.9
4.180	2016	43716 - 47066	3160.0	7.0.9
4.190	2017	47543 - 51498	526.7	7.0.9
4.200	2017	47543 - 51498	526.0	7.0.9
4.210	2017	47543 - 51498	517.1	7.0.9
4.220	2017	47543 - 51498	514.6	7.0.9
4.237	2017	47543 - 51498	530.3	7.0.9
4.246	2017	47543 - 51498	538.1	7.0.9
4.270	2017	47543 - 51498	531.1	7.0.9
4.280	2017	47543 - 51498	175.7	7.0.9
4.130	2019	59163 - 59573	401.5	7.0.9
4.160	2019	59574 - 59896	408.7	7.0.9
4.290	2019	59902 - 60363	502.4	7.0.9
4.315	2019	60364 - 60805	501.2	7.0.9
4.340	2019	60808 - 61242	505.0	7.0.9
4.380	2019	61249 - 61762	522.7	7.0.9
4.400	2019	61763 - 62285	507.8	7.0.9
4.440	2019	62286 - 62823	569.9	7.0.9
4.610	2020	64314 - 64360	103.65	7.0.9
4.620	2020	63075 - 63515	521.53	7.0.9
4.640	2020	63516 - 63715	551.65	7.0.9
4.660	2020	63718 - 663852	529.43	7.0.9
4.680	2020	63867 - 664015, 64365 - 65092	1667.39	7.0.9
4.700	2020	64028 - 64313	535.54	7.0.9
4.740	2021	65208 - 65307	163.87	7.0.9
4.750	2021	65322 - 65494	366.55	7.0.9
4.780	2021	65495 - 65645	511.47	7.0.9
4.840	2021	65647 - 65864	525.16	7.0.9
4.914	2021	65867 - 65935	207.82	7.0.9
4.946	2021	65938 - 66224	159.28	7.0.9
3.810	2013	33490 - 33556	50.54	7.0.9
3.900	2013	33572 - 33657	52.61	7.0.9
4.009	2013	23463 - 24141	482.0	7.0.9
4.090	2013	33659 - 33719	52.86	7.0.9
4.190	2013	30372 - 30437	43.33	7.0.9
4.210	2013	31983 - 32045	54.95	7.0.9
4.220	2013	32046 - 32140	54.60	7.0.9
4.230	2013	30438 - 30491, 32239 - 33484	1100.94	7.0.9
4.245	2013	32141 - 32226	55.88	7.0.9
4.260	2013	29677 - 30367, 31561 - 31981	828.4	7.0.9
4.310	2013	30492 - 30557	45.08	7.0.9
4.360	2013	30616 - 31279	543.9	7.0.9
4.390	2013	31281 - 31325	55.57	7.0.9
4.420	2013	31327 - 31390, 36773 - 38140	1090.7	7.0.9
4.470	2013	36245 - 36393	111.09	7.0.9
4.530	2013	36398 - 36588	112.12	7.0.9
4.575	2013	36603 - 36699	48.93	7.0.9
4.600	2013	35227 - 36213	586.9	7.0.9

- Have run over more data (from XYZ datasets) to include in analysis
- Will now start grouping datasets based on E_{CM} instead of years
- Plan to measure ratio at different E_{CM} ranges, as well as relative phase
- Should help determine whether interference is really different as a function of E_{CM}

BACKUP

Ideas?

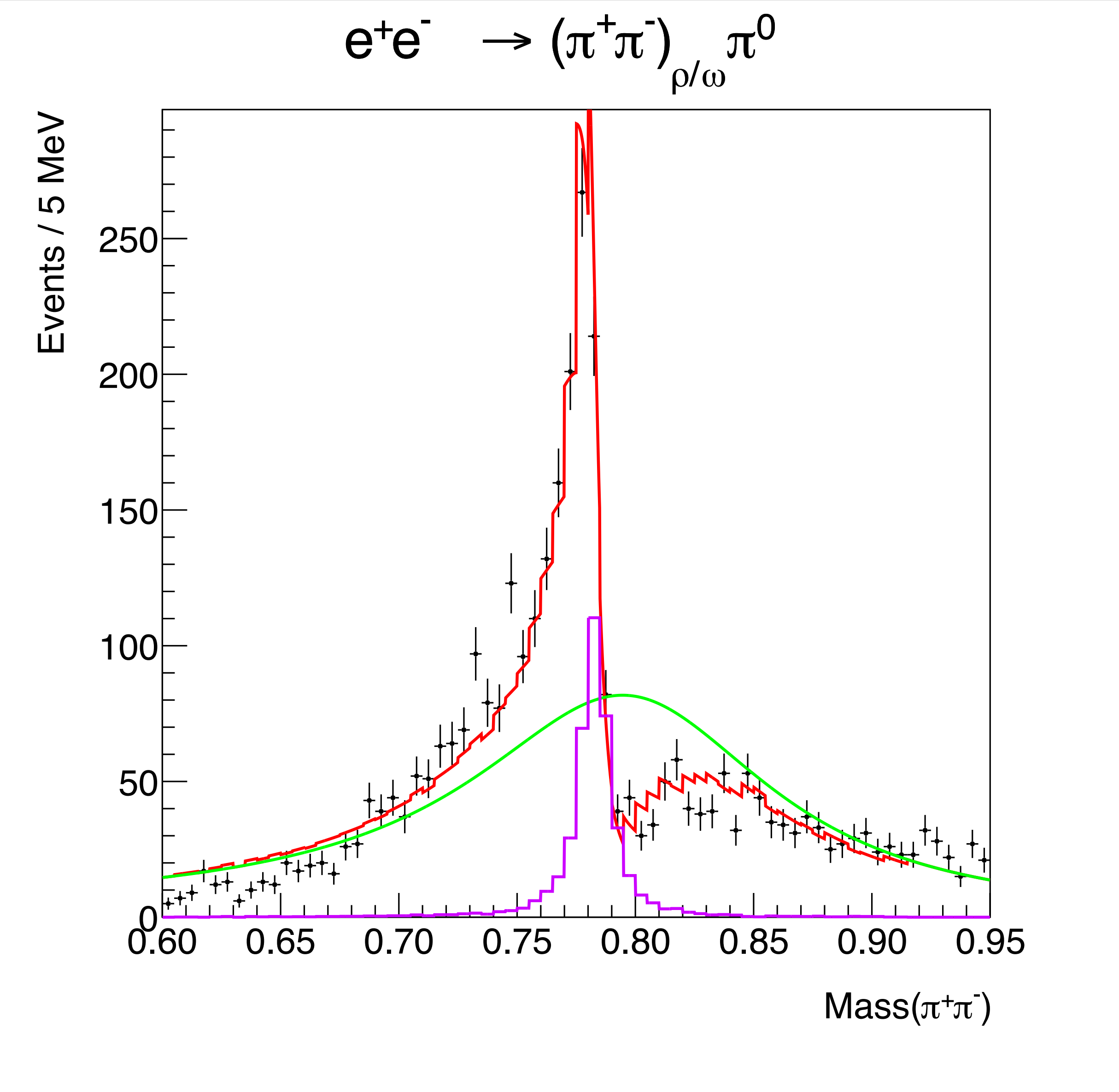
- Have 3pi phase space MC; maybe use that shape as background
- Talked about simultaneous/global fit to different datasets constraining BF ratio, seems difficult
- BUT: maybe add additional scaling parameter in fits (like with the rho efficiencies) which scales based on $\sigma(e^+e^- \to \omega\pi^0)$ and/or luminosities for particular datasets
- Have not performed fits to total dataset (including new 2019 XYZ points) yet
- 2019 XYZ samples all seemed too low statistics to use individually, but maybe useful to try

Datasets

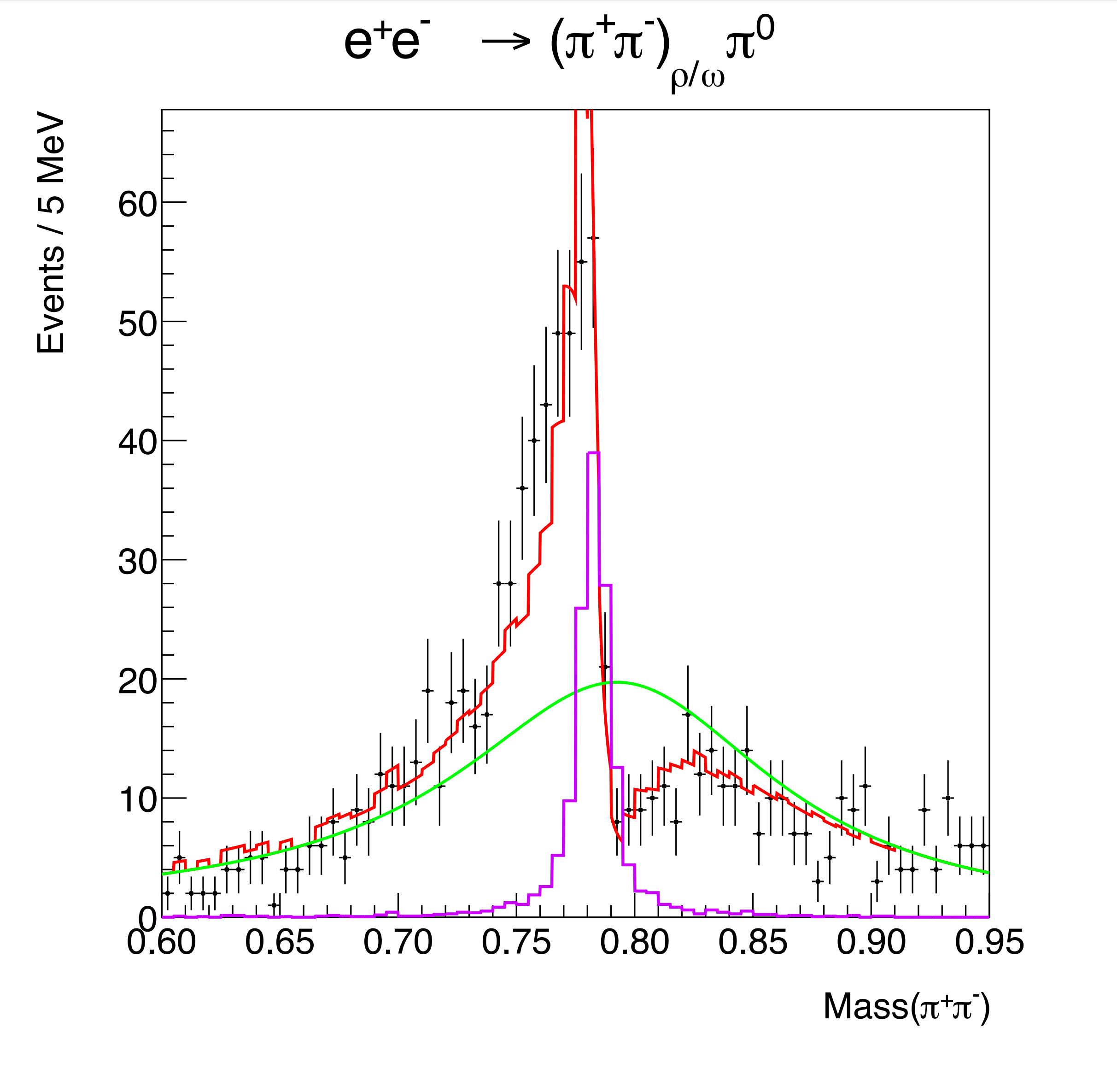
Year	E_CM [MeV]	$\mathscr{L}[pb^{-1}]$
2010/2011	3770	2931.8
2022	3770	4995
2016	4180	3189.0
2017	4190 - 4280 (XYZ)	3859.6

Fits: First Iteration

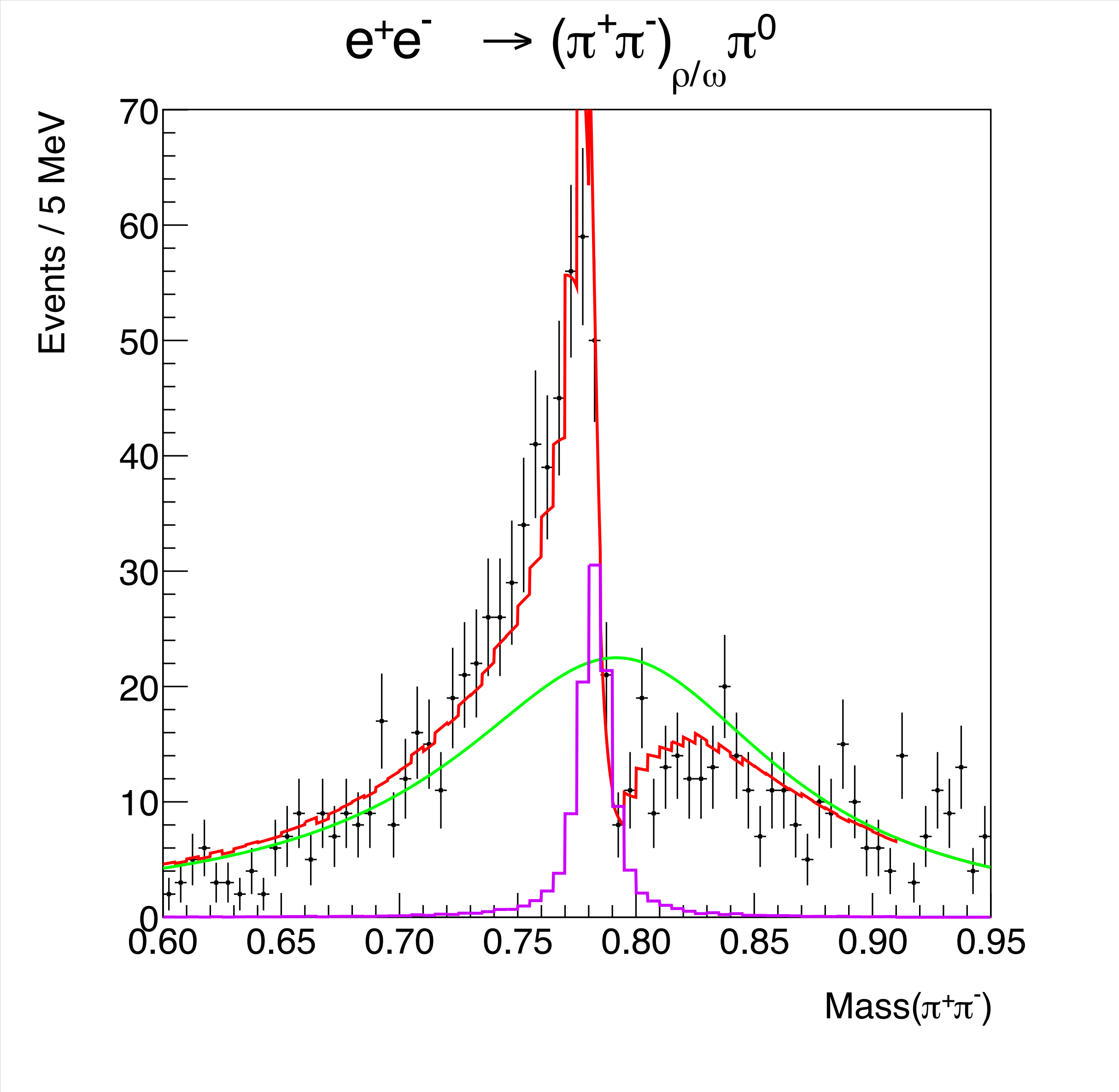
- Performing simultaneous fit to charged (ρ^+/ρ^-) and neutral channels, constraining mass and width of the ρ
- Rho modeled by Gounaris Sakurai shape (green), Mass and width constrained by charged rho's; omega shape taken from signal MC (purple)



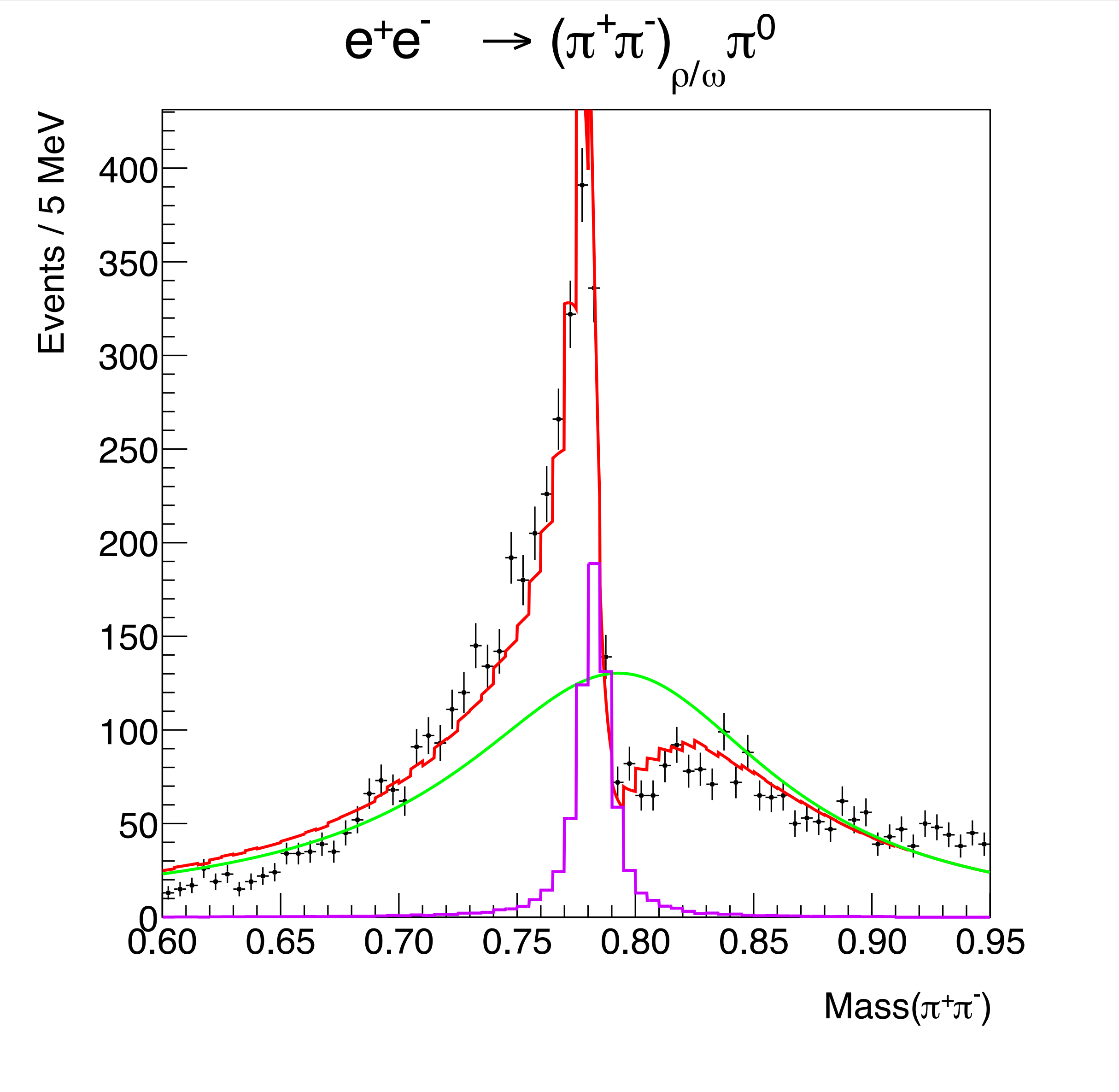
3770



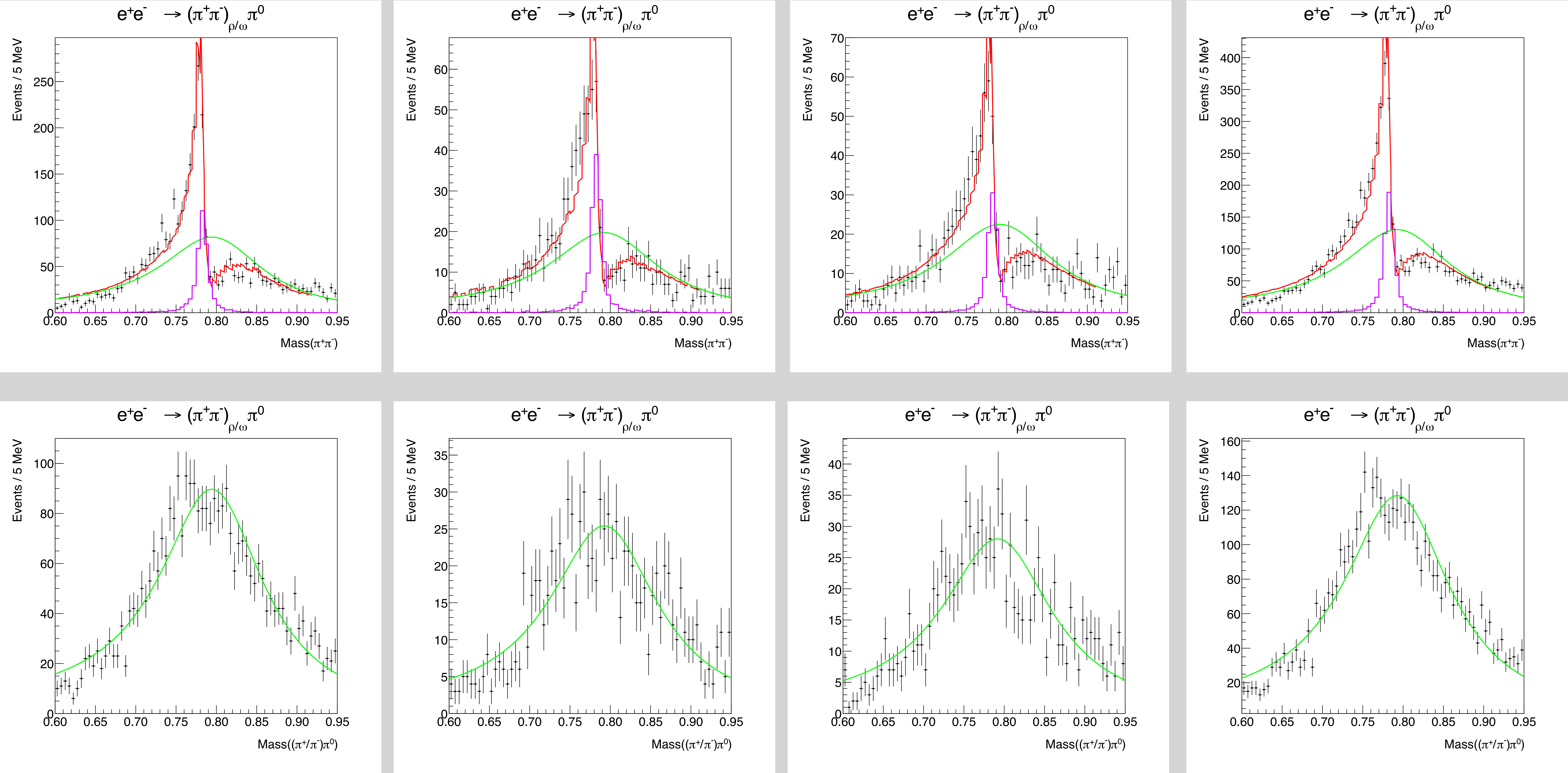
4180



XYZ



Total



3770 4180 XYZ Total

$\mathcal{B}(\omega \to \pi^+\pi^-)/\mathcal{B}(\omega \to \pi^+\pi^-\pi^0)$ Results

Dataset	Ratio ($\times 10^{-3}$)
3770	14.19 ± 0.76
4180	26.1 ± 2.3
XYZ	18.1 ± 1.7
Total	14.84 ± 0.58
PDG Value	17.2 ± 1.4

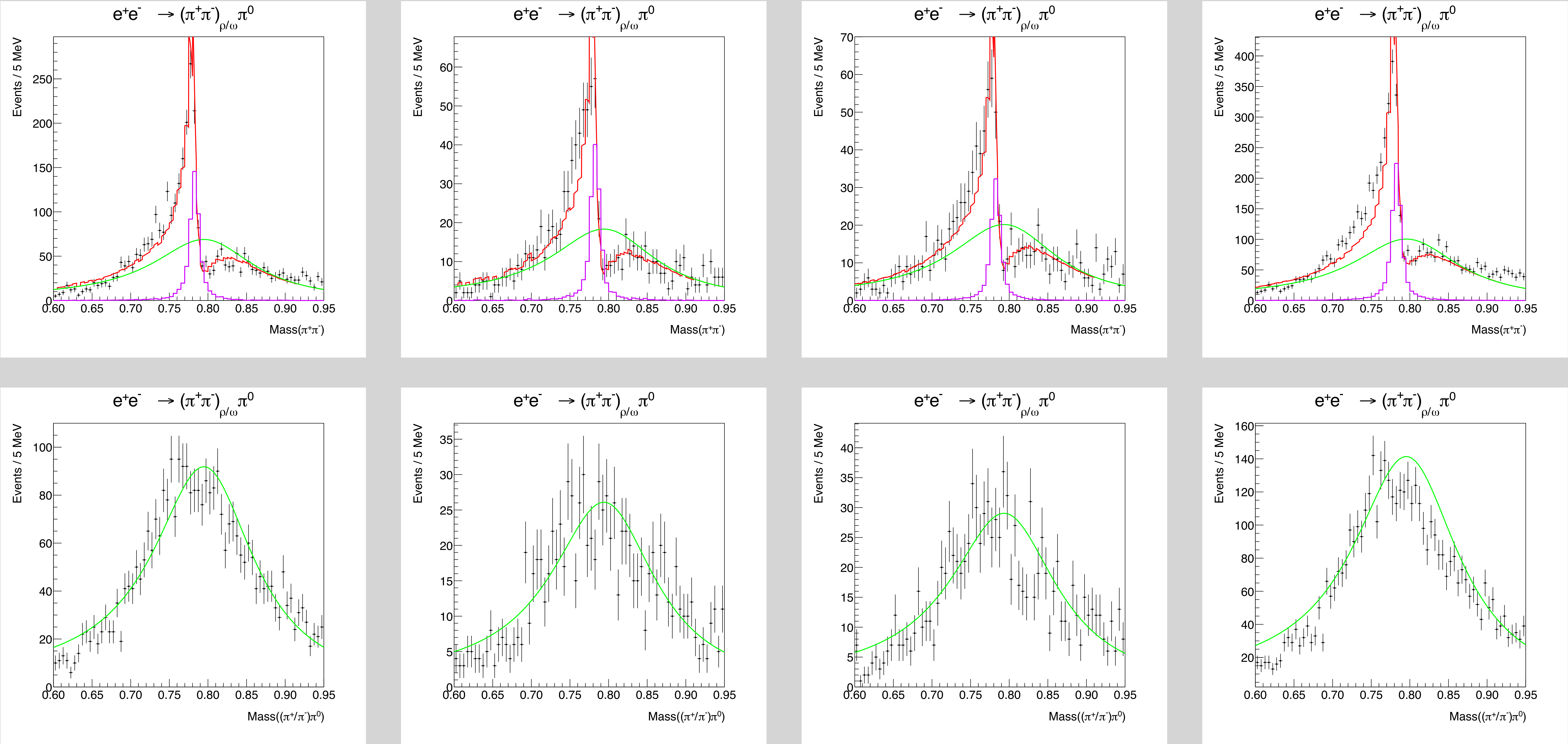
Second Fits: Breit-Wigner ρ

3770 4180 XYZ Total

Third Fits: Gounaris Sakurai ρ, size constrained

3770 4180 XYZ Total

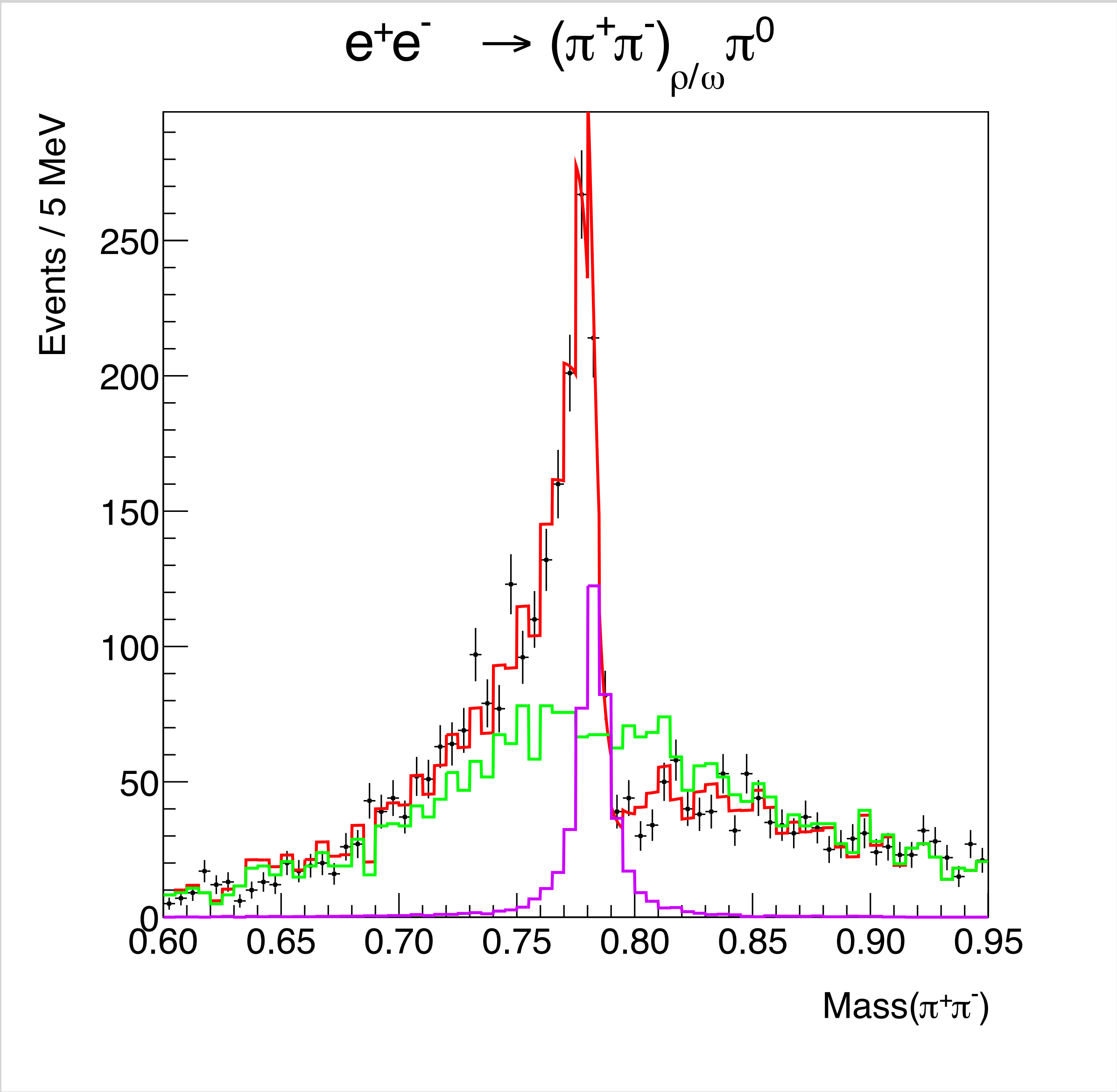
Fourth Fits: Breit-Wigner ρ, size constrained



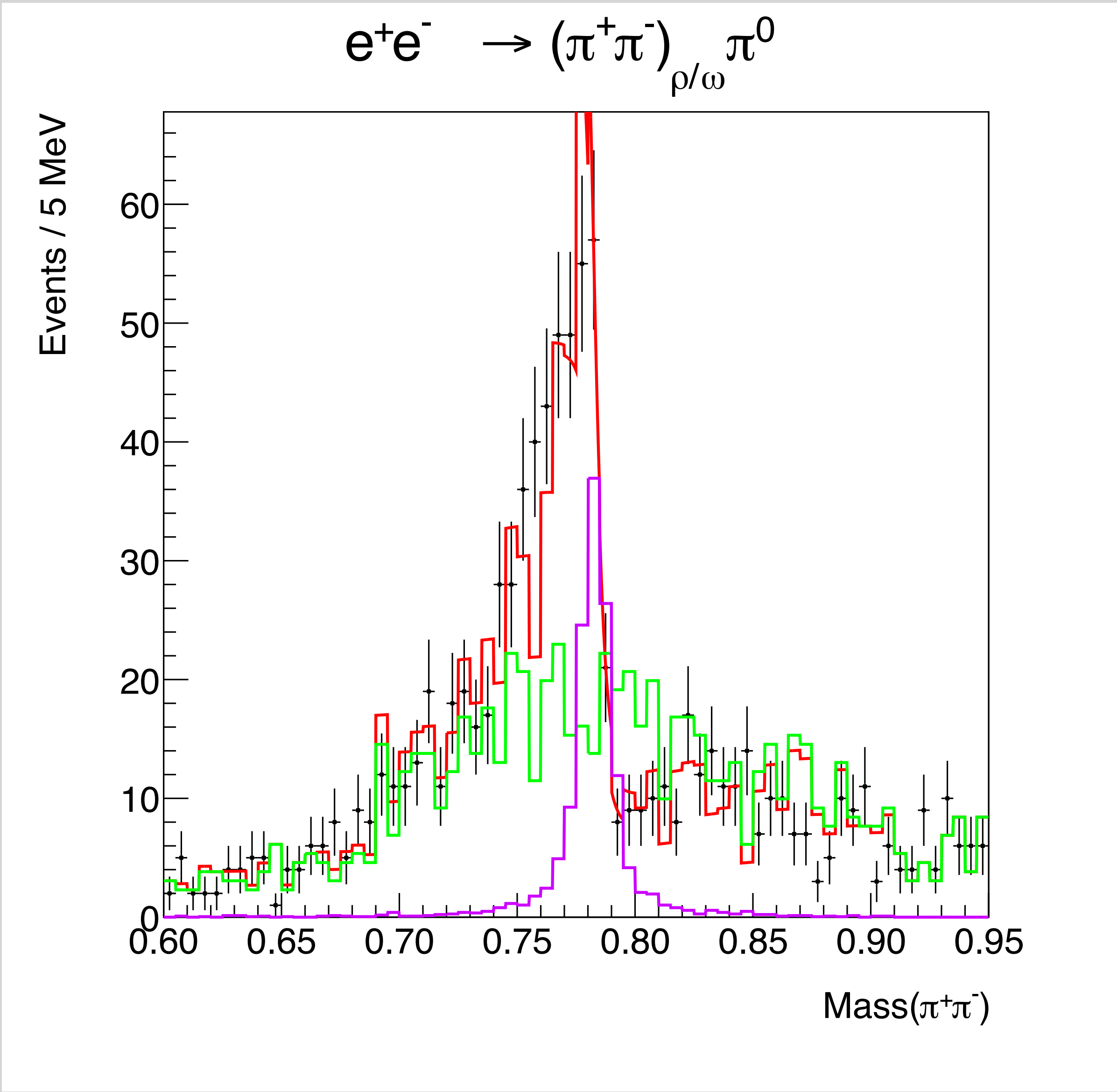
3770 4180 XYZ Total

Fifth Fits: ρ shape from data

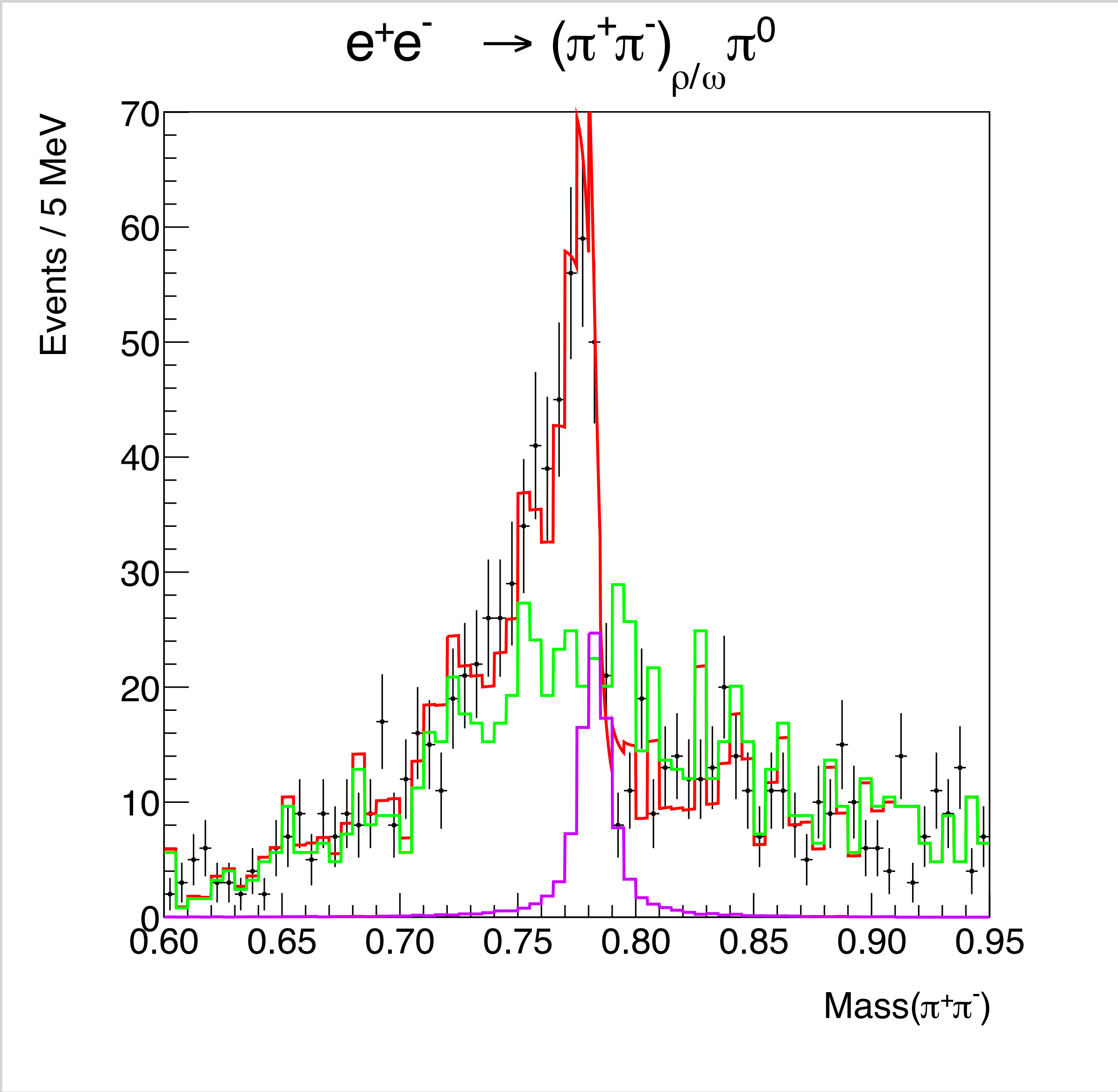
- Now using histogram shape of charged ρ from data, constraining size of neutral ρ in fits using efficiencies as in last simultaneous fits
- ω shape again taken from signal MC, amplitudes have appropriate Breit-Wigner phases attached and are able to interfere with a free relative phase between the two



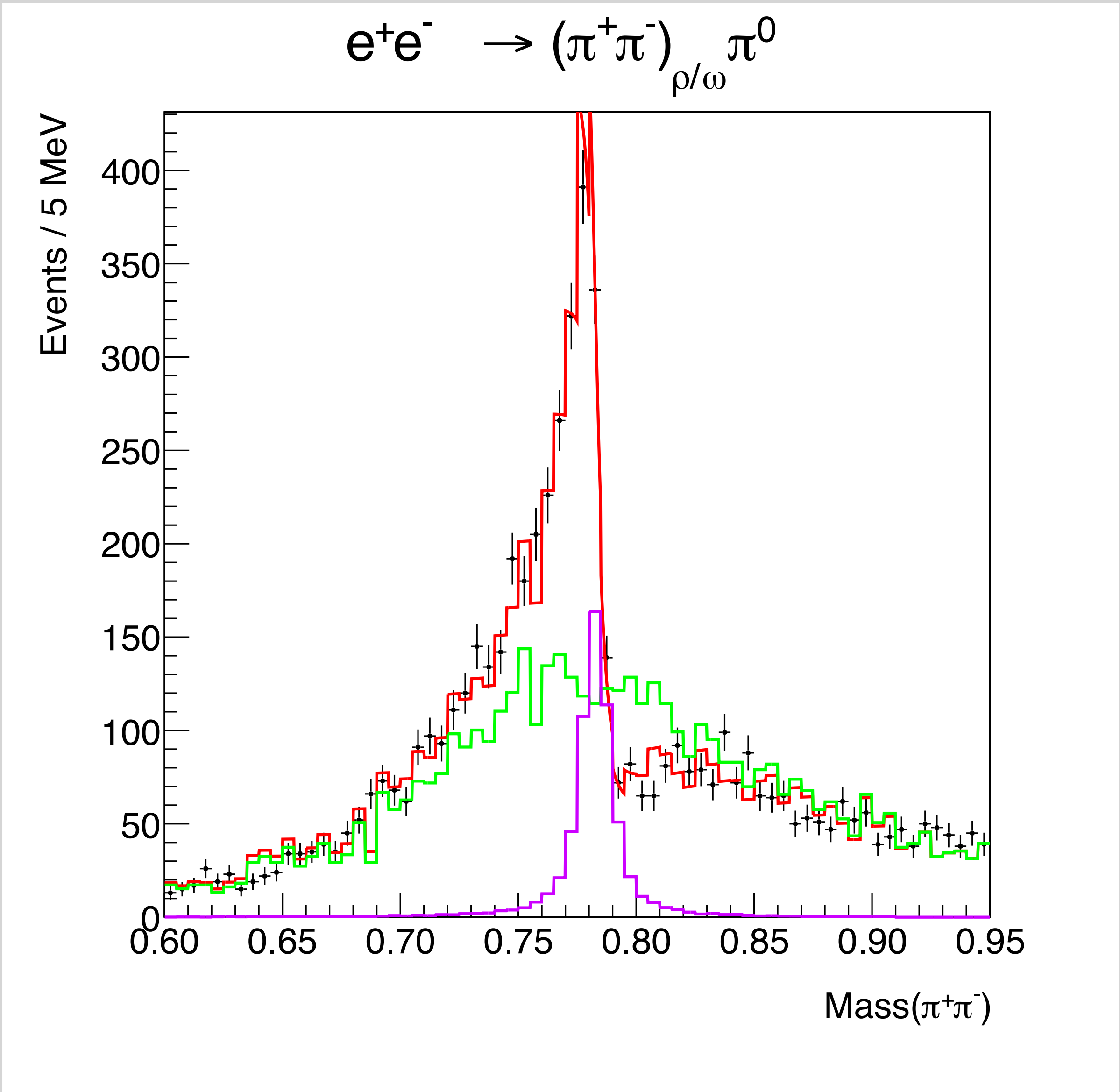
3770



4180



XYZ



Total

Fitting $\omega \to \pi^+\pi^-$: Gounaris Sakurai

- To fit the $\pi^+\pi^-$ mass spectrum, I now use a more sophisticated amplitude given by the Gounaris-Sakurai formula:

An alternative model to the R-dependent Blatt–Weisskopf form factor in the Breit–Wigner amplitude is provided by the Gounaris–Sakurai formula [36],

$$\mathrm{BW}^{\mathrm{GS}}_{\rho}(s \,|\, m_\rho, \Gamma_\rho) = \frac{m_\rho^2\left[1 + d(m_\rho)\Gamma_\rho/m_\rho\right]}{m_\rho^2 - s + f(s, m_\rho, \Gamma_\rho) - i\, m_\rho \Gamma(s, m_\rho, \Gamma_\rho)}, \tag{S4}$$

where,

$$\Gamma(s, m, \Gamma_0) = \Gamma_0 \frac{m}{\sqrt{s}}\left[\frac{p_\pi(s)}{p_\pi(m^2)}\right]^3, \tag{S5}$$

$$d(m) = \frac{3}{\pi}\frac{m_\pi^2}{p_\pi^2(m^2)}\log\left[\frac{m + 2p_\pi(m^2)}{2m_\pi}\right] + \frac{m}{2\pi p_\pi(m^2)} - \frac{m_\pi^2 m}{\pi p_\pi^3(m^2)}, \tag{S6}$$

$$f(s, m, \Gamma_0) = \frac{\Gamma_0 m^2}{p_\pi^3(m^2)}\left[p_\pi^2(s)\left[h(s) - h(m^2)\right] + (m^2 - s)p_\pi^2(m^2)h'(m^2)\right], \tag{S7}$$

$$h(s) = \frac{2}{\pi}\frac{p_\pi(s)}{\sqrt{s}}\log\left[\frac{\sqrt{s} + 2p_\pi(s)}{2m_\pi}\right], \tag{S8}$$

$$\mathcal{M} = \frac{p_\pi(s)}{p_\pi(m_\rho)}\left\{\mathrm{BW}^{\mathrm{GS}}(s, m_\rho, \Gamma_\rho)\left[1 + A_\omega^{\mathrm{GS}}\, e^{i\phi_\omega}\, \mathrm{BW}_\omega(s, m_\omega, \Gamma_\omega)\right] + A_{\rho'}^{\mathrm{GS}}\, e^{i\phi_{\rho'}}\, \mathrm{BW}^{\mathrm{GS}}(s, m_{\rho'}, \Gamma_{\rho'})\right\}. \tag{S9}$$