Scalar Meson Photoproduction

A Donnachie and Yu S Kalashnikova

Light Scalar Isoscalar Mesons

- There is agreement that the $\sigma(500)$ is a $\pi\pi$ S-wave enhancement.
- The $f_0(980)$ is close to the $K\bar{K}$, so it is mostly (but not necesarily entirely) a $K\bar{K}$ molecule.
- The $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ are mixed states of $n\bar{n}$ and $s\bar{s}$ quarkonia and a 0^{++} glueball, although there is not agreement in detail about the mixing.
- Three different mixing scenarios have been proposed: the bare glueball is lighter than the bare $n\bar{n}$ state (L); its mass lies between the bare $n\bar{n}$ state and the bare $s\bar{s}$ state (M); or it is heavier than the bare $s\bar{s}$ state (H).
  Lee, Weingarten, Phys.Rev. D61 (2000) 014015
  Close, Kirk, Eur.Phys.J C21 (2001) 531
- Obtaining the mass of the bare glueball is very relevant for Lattice QCD. Some masses are:
  1.475 ± 70 GeV (Meyer and Teper, Phys.Lett. B605 (2005) 344)
  1.730 ± 95 GeV (Morningstar and Peardon, Phys.Rev. D60 (1999) 034509)
  1.710 ± 95 GeV (Chen et al, Phys.Rev. D73 (2006) 014516)

Scalar Radiative Decay

- Radiative transitions offer a particularly powerful means of probing the structure of hadrons and it has been shown that the radiative decays of the $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ are strongly affected by the degree of mixing between the basis $q\bar{q}$ states and the glueball.
- Radiative decay widths in keV

Decay	L	M	H
$f_0(1370) \to \gamma\rho$	443	1121	1540
$f_0(1500) \to \gamma\rho$	2519	1458	476
$f_0(1710) \to \gamma\rho$	42	94	705

(Close, Donnachie, Kalashnikova, Phys.Rev. D67 (2003) 074031)

- Photoproduction of the scalar mesons at medium energy provides an alternative to direct observation of the radiative decays. The mechanism is Reggeised ρ and ω exchange, both of which are well understood in pion photoproduction.
- The energy must be sufficiently high for the Regge approach to be applicable but not too high as the cross section decreases approximately as s^{-1}. In practice this means approximately 5 to 10 GeV photon energy.

Coupling Constants & Reggeisation

- The $SV\gamma$ couplings, g_S, can be obtained from the radiative decay widths. The ρNN and ωNN vertices depend on two couplings, a vector coupling g_V and a tensor coupling g_T.
- The ωNN couplings are rather well defined. The vector coupling, g_V^ω, lies within the range $15 < {g_V^\omega}^2/4\pi < 20$ and the tensor coupling $g_T^\omega \approx 0$. We have used $g_V^\omega = 15$ as this gives a good description of π^0 photoproduction.
- The ρNN couplings are not so well defined, with two extremes: strong or weak. Again guided by pion photoproduction we choose the strong coupling solution with $g_V^\rho = 3.4$ and $g_T^\rho = 11$ GeV^{-1}.
- The standard prescription for Reggeising the Feynman propagators, assuming a linear Regge trajectory $\alpha_V(t) = \alpha_{V0} + \alpha'_V t$, is to make the replacement

$$\frac{1}{t - m_V^2} \rightarrow \left(\frac{s}{s_0}\right)^{\alpha_V(t)-1} \frac{\pi\alpha'_V}{\sin(\pi\alpha_V(t))} \times \frac{-1 + e^{-i\pi\alpha_V(t)}}{2} \frac{1}{\Gamma(\alpha_V(t))}.$$

Comment

- This approach provides a satisfactory description of ρ and ω exchange in pion photoproduction.
  Guidal, Laget, Vanderhaeghen, Nucl.Phys. A627 (1997) 645
- This Reggeisation prescription automatically includes the zero observed at $t \approx -0.5$ GeV^2 in both ρ and ω exchange in pion photoproduction.
- We know that it is not precise as there are additional contributions, in particular from Regge cuts (required by finite-energy sum rules) and from lower-lying trajectories, e.g. that associated with $b_1(1235)$ exchange in π^0 photoproduction.
- However the overall effect of these additional contributions is expected to be small.

Coherent Production

- In addition to photoproduction on protons we consider coherent photoproduction on ^{4}He, encouraged in this by a recently-approved experiment at Jefferson Laboratory (E-07-009).
- Two advantages of coherent production are the elimination of background from baryon resonances, considerably simplifying partial-wave analysis of the mesonic final state, and the restriction to ω exchange which is better understood in photoproduction than is ρ exchange.
- For photoproduction on ^{4}He we assume that the cross section is given by

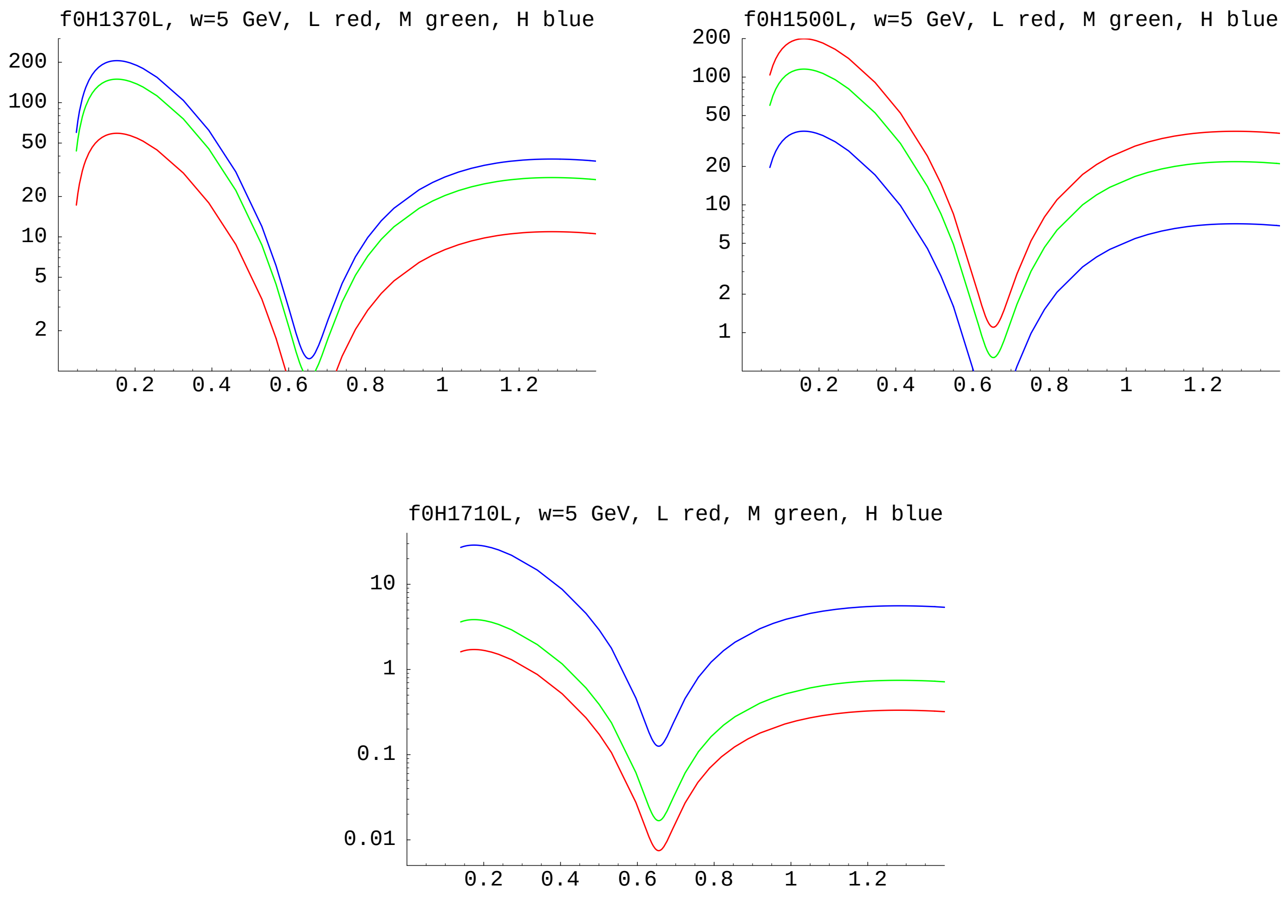
$$\frac{d\sigma(\gamma N \to f_0 \mathrm{He})}{dt} \approx \frac{d\sigma(\gamma N \to f_0 N)}{dt} \Big(4F_{\mathrm{He}}(t)\Big)^2,$$

- Here $F_{\mathrm{He}}(t)$ is the helium form factor (Morita, Suzuki, Prog.Theor.Phys. 86 (1991) 671)

$$F_{\mathrm{He}}(t) \approx e^{9t}$$

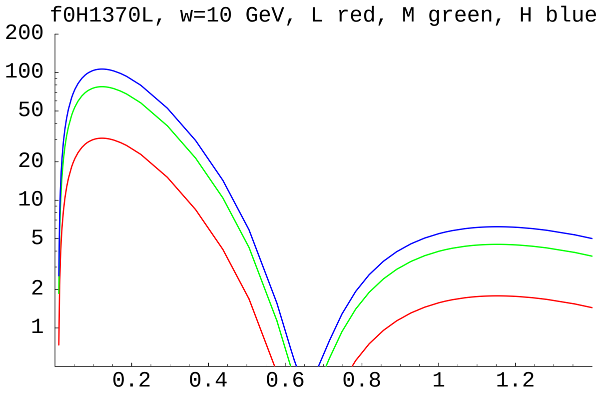
- The justification is the low level of nuclear shadowing observed on ^{4}He at the energies with which we are concerned, for both pion and photon total cross sections, and for photons can be well described by a simple vector dominance model.

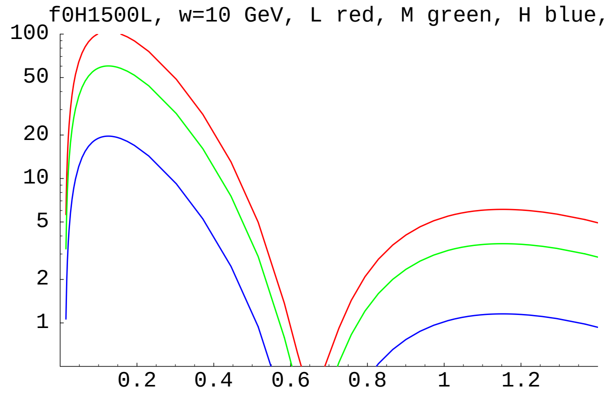
$d\sigma/dt$

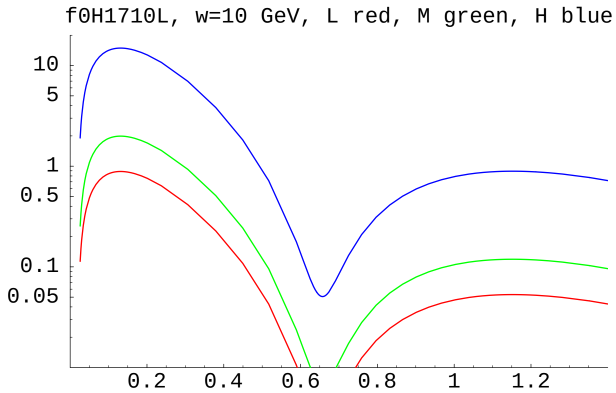


$d\sigma/dt$ in nb GeV^{-2}, proton target, $E_\gamma = 5$ GeV

$d\sigma/dt$







$d\sigma/dt$ in nb GeV^{-2}, proton target, $E_\gamma = 10$ GeV

Helium Cross Sections

- Despite their obvious advantages in minimising background, the cross sections for scalar photoproduction in helium are too small to be practicable. There are three reasons.
- Switching off ρ exchange for photoproduction on protons reduces the cross section by a factor of about 16, cancelling the factor 16 from coherent production.
- The Helium form factor suppresses the cross section except at very small t.
- There is an experimental requirement that $|t| > 0.1$ GeV^2 for the recoiling Helium to be detected.

Final States

- The charged decay modes of the scalars cannot be considered because of the very much larger cross sections in $\pi^+\pi^-$, K^+K^-, $2\pi^+2\pi^-$ and $\pi^+\pi^-2\pi^0$ from vector-meson production. These contributions can be eliminated by considering only the all-neutral channels, that is $\pi^0\pi^0$, $\eta\eta$, $\eta\eta'$ and $4\pi^0$.
- Unfortunately there is considerable uncertainty in the branching fractions of the $f_0(1370)$ and $f_0(1710)$, particularly the former.For definiteness we use the results of the WA102 collaboration which comprise a complete data set for the decay of the $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ to all pseudoscalar meson pairs (Barberis et al, Phys.Lett. B479 (2000) 59).
- Branching fractions for the scalars from WA102 as extracted by Close and Kirk

State	$\pi\pi$	$K\bar{K}$	$\eta\eta$	$\eta\eta'$
$f_0(1370)$	0.027	0.013	0.004	
$f_0(1500)$	0.337	0.107	0.061	0.032
$f_0(1710)$	0.119	0.595	0.286	

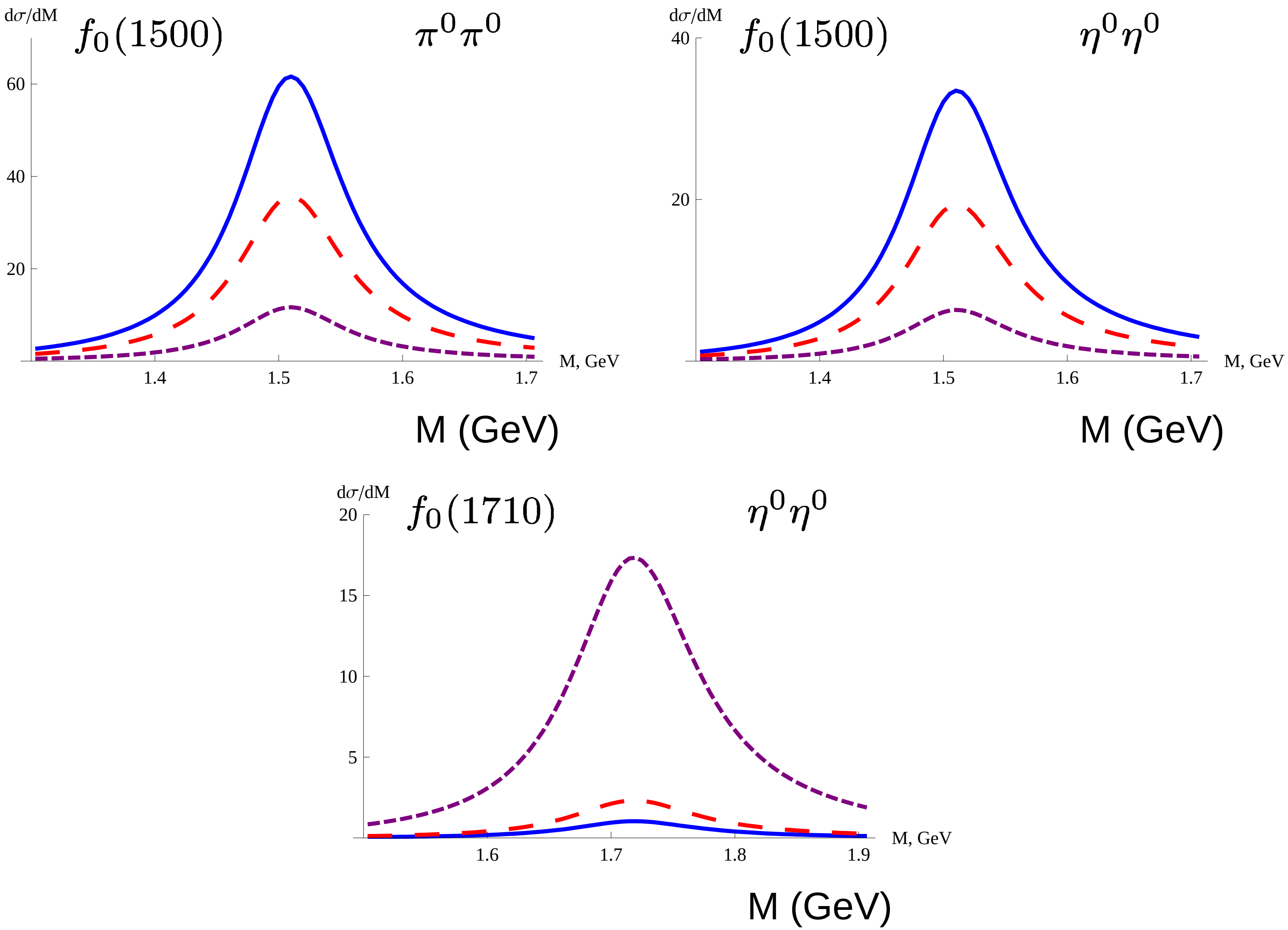
Mass Distributions

- The states are represented as relativistic Breit-Wigner resonances with energy-dependent partial widths for the pseudoscalar decays. The contribution Γ_R of non-pseudoscalar states to the total width was taken as

$$\Gamma_R = (1 - BR_{\pi\pi} - BR_{K\bar{K}} - BR_{\eta\eta} - BR_{\eta\eta'})\Gamma_0$$

- The most useful cross sections on protons are $f_0(1500)$ in $\pi^0\pi^0$ and $\eta^0\eta^0$ at the light-glueball end of the scalar mass spectrum and $f_0(1710)$ in $\eta^0\eta^0$ at the heavy-gueball end.

$d\sigma/dM$

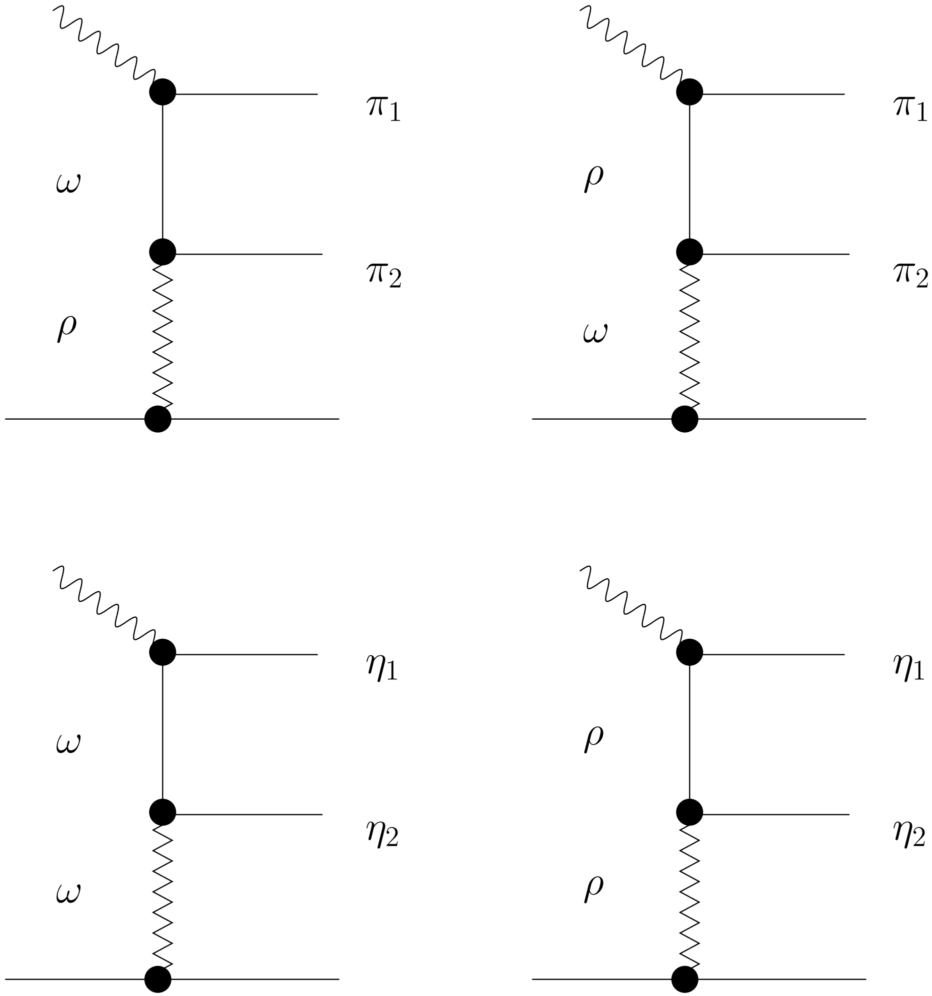


dσ/dM
$f_0(1500)$
$\pi^0\pi^0$
60
40
20
1.4
1.5
1.6
1.7
M, GeV
M (GeV)
dσ/dM
40
$f_0(1500)$
$\eta^0\eta^0$
20
1.4
1.5
1.6
1.7
M, GeV
M (GeV)
dσ/dM
20
$f_0(1710)$
$\eta^0\eta^0$
15
10
5
1.6
1.7
1.8
1.9
M, GeV
M (GeV)

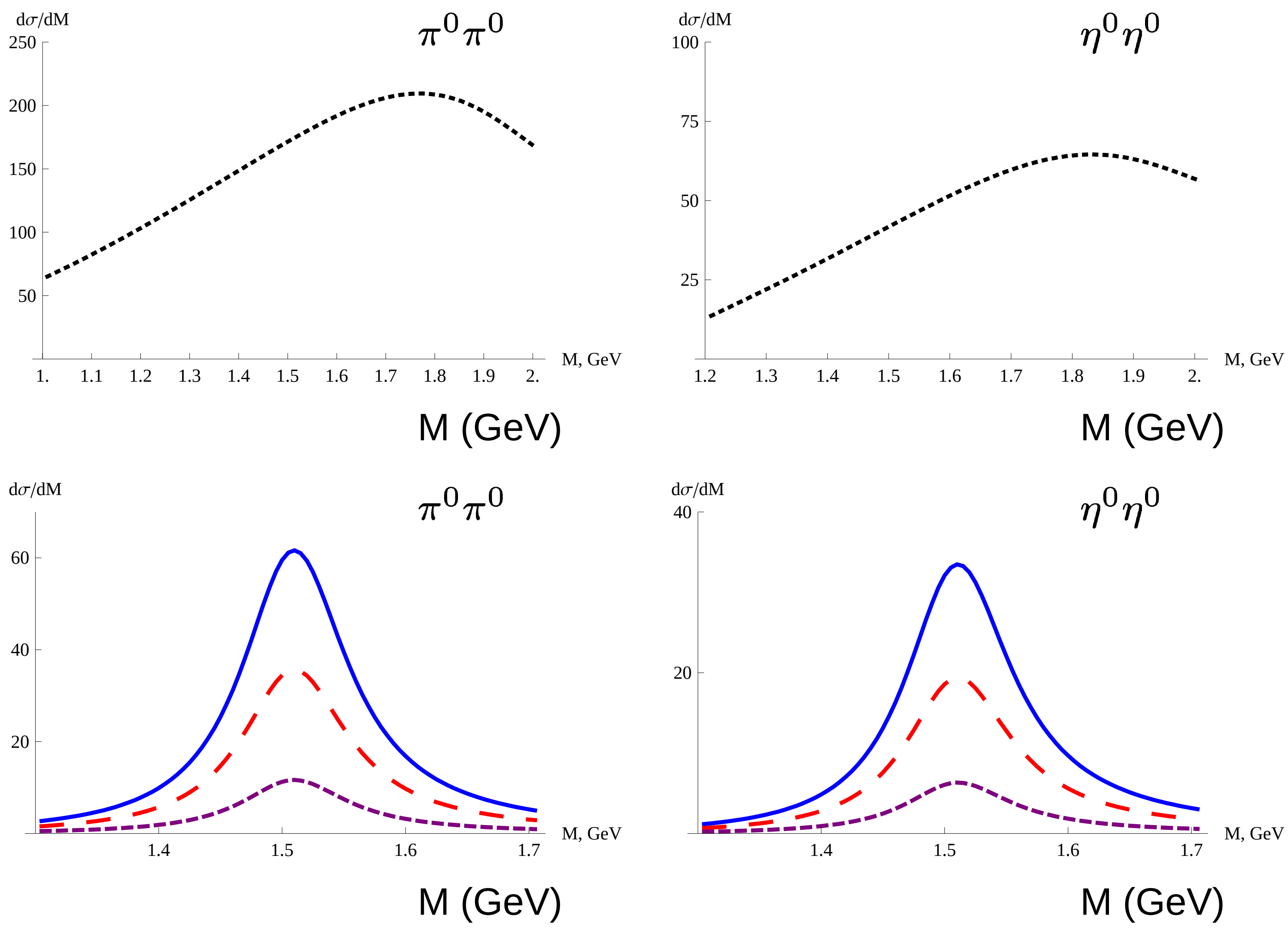
Backgrounds

- There are four sources of background:
  $\gamma p \to \pi^0/\eta^0 N^*$, $N^* \to \pi^0/\eta^0 p$
  $\gamma p \to f_2(1270)p$, $f_2(1270) \to \pi^0\pi^0$
  $\gamma p \to f_2'(1525)p$, $f_2'(1525) \to \eta^0\eta^0$
  $\pi^0\pi^0$ and $\eta^0\eta^0$ continuum.
- The first of these is not readily calculable.
  The second can be calculated in our model (work in progress).
  The third is expected to be small (OZI rule).
  The fourth has been calculated.

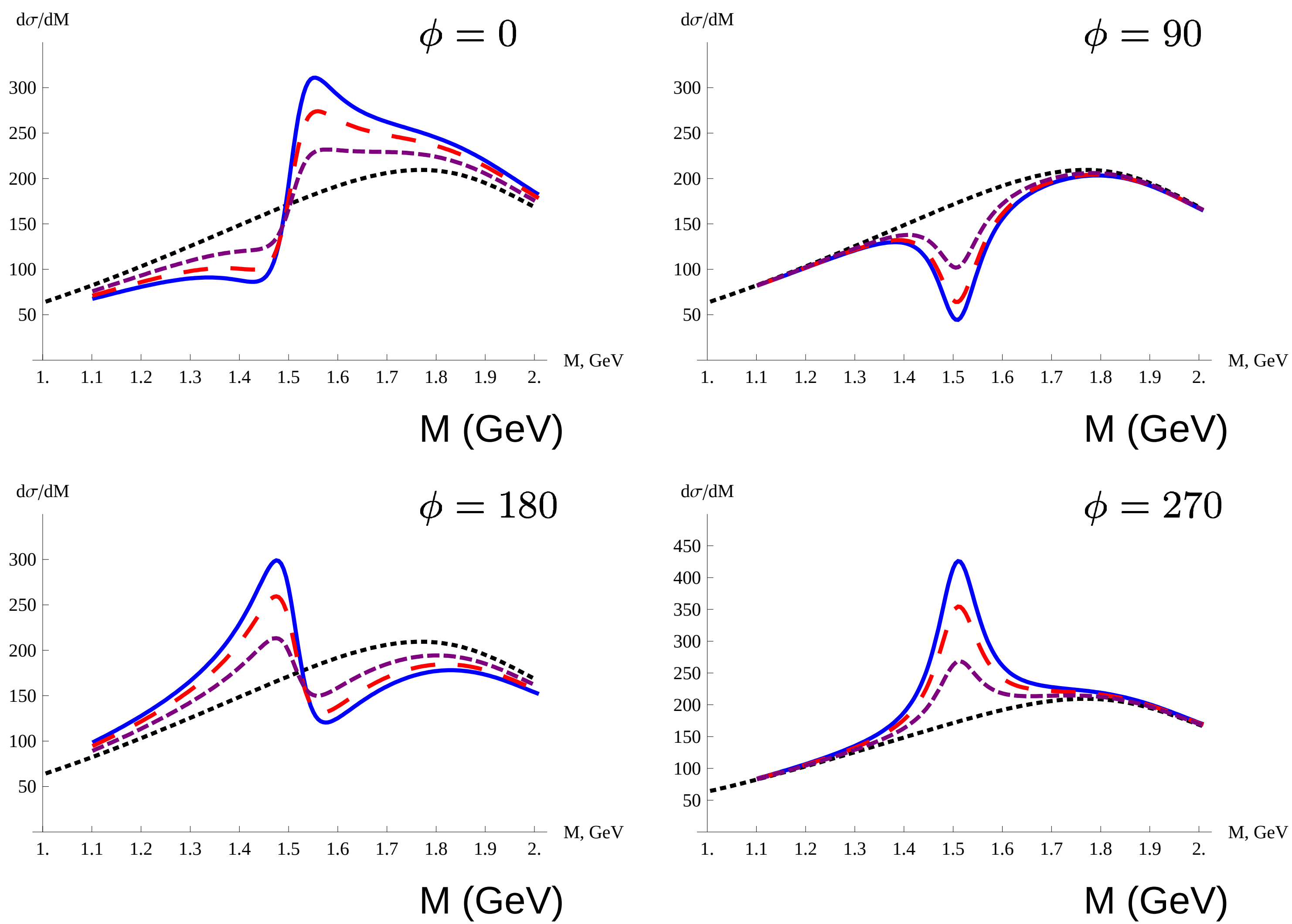
Continuum Background



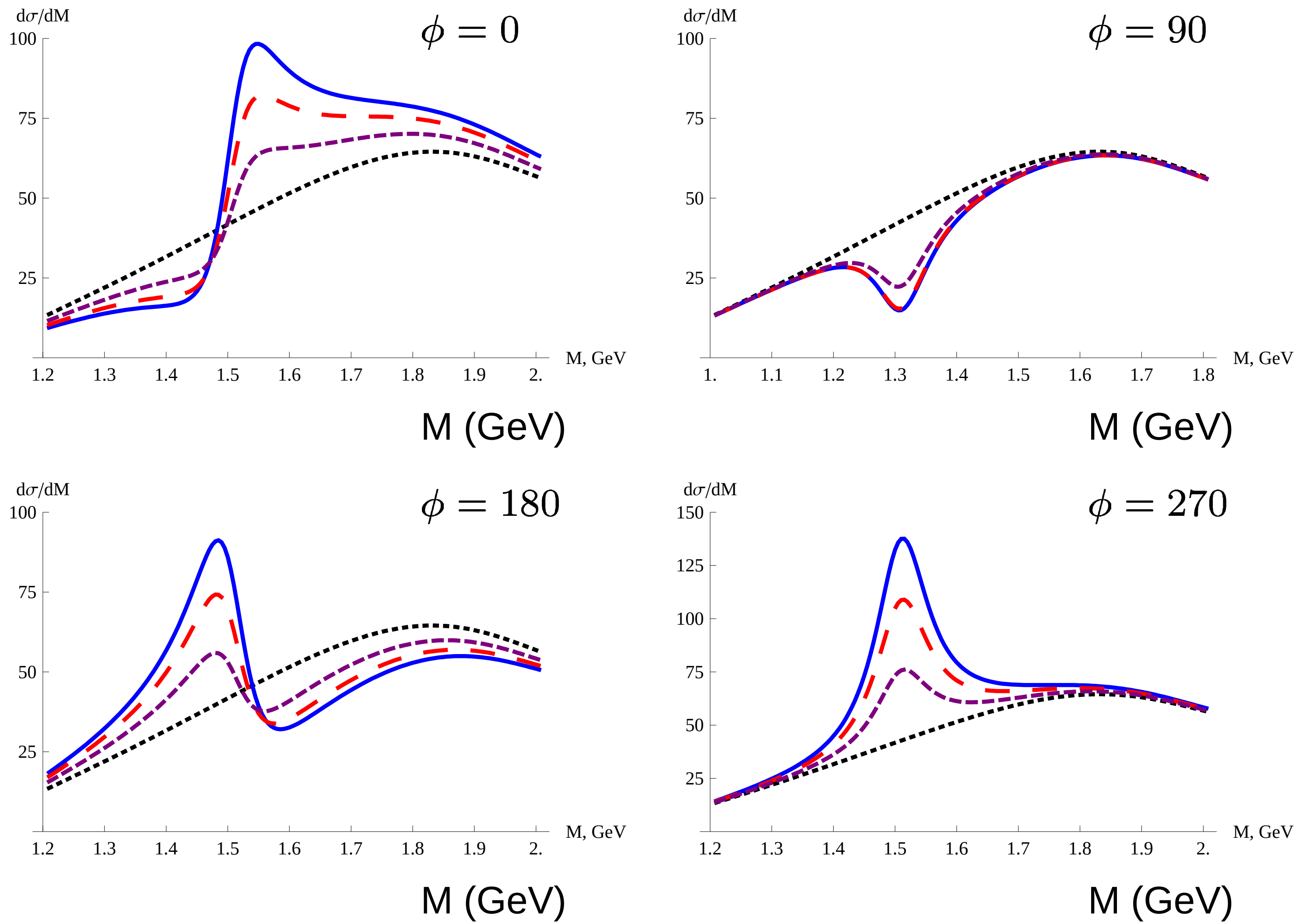
Continuum $d\sigma/dM$



$\pi^0\pi^0$ Interference $d\sigma/dM$



$\eta^0\eta^0$ Interference $d\sigma/dM$



Conclusions

- The cross sections on helium are too small to be practicable.
- The most useful cross sections on protons are $f_0(1500)$ in $\pi^0\pi^0$ and $\eta^0\eta^0$ at the light-glueball end of the scalar mass spectrum and $f_0(1710)$ in $\eta^0\eta^0$ at the heavy-gueball end.
- The experimental options are to compare $f_0(1500)$ and $f_0(1710)$ in the $\eta^0\eta^0$ channel, which minimises theoretical uncertainties but is sensitive to branching ratios, or to concentrate on $f_0(1500)$ in $\pi^0\pi^0$ and $\eta^0\eta^0$, which is sensitive to theoretical uncertainties but branching ratios are rather firm.
- If $\gamma p \to 4\pi^0 p$ could be measured then studying the $f_0(1370)$ could be a practical proposition as the 4π decays of the $f_0(1370)$ are the dominant ones and $4\pi^0$ is a significant fraction of these.
  (Crystal Barrel Collaboration, Eur.Phys.J. C19 (2001) 667)
- The $4\pi^0$ decay of the $f_0(1500)$ is small, so this channel provides a clean signal of the $f_0(1370)$.
- The Crystal Barrel results are in the form of a $4\pi^0/2\pi^0$ ratio. However their $\pi\pi$ branching fraction is somewhat less than that of WA102, so there is some uncertainty in the absolute photoproduction cross section.

$f_0(980)$

- Work is in progress, calculating in a variety of models. Preliminary results show that measuring the cross section is practicable and it can be used to distinguish between models.
- L.H. figure: $q\bar{q}$ model, direct electromagnetic coupling dominates
  (Kalashnikova et al, Phys.Rev. C73 (2006) 045203)
  R.H. figure: molecular model, production via pion and kaon loops
  (Achasov and Shestakov, Phys.Rev. D72 (2005) 013006)
  kaon loop (blue), pion loop (red), full model (black)