Gluonic Excitations Workshop
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# Partial Wave Analysis results from JETSET

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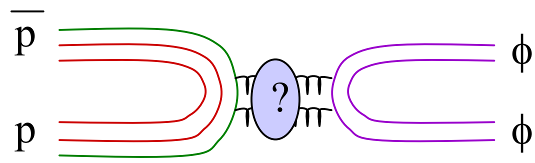
representing the Jetset collaboration
with members from
Bari, CERN, Erlangen, Freiburg, Genova, Illinois, Jülich, Oslo, Uppsala

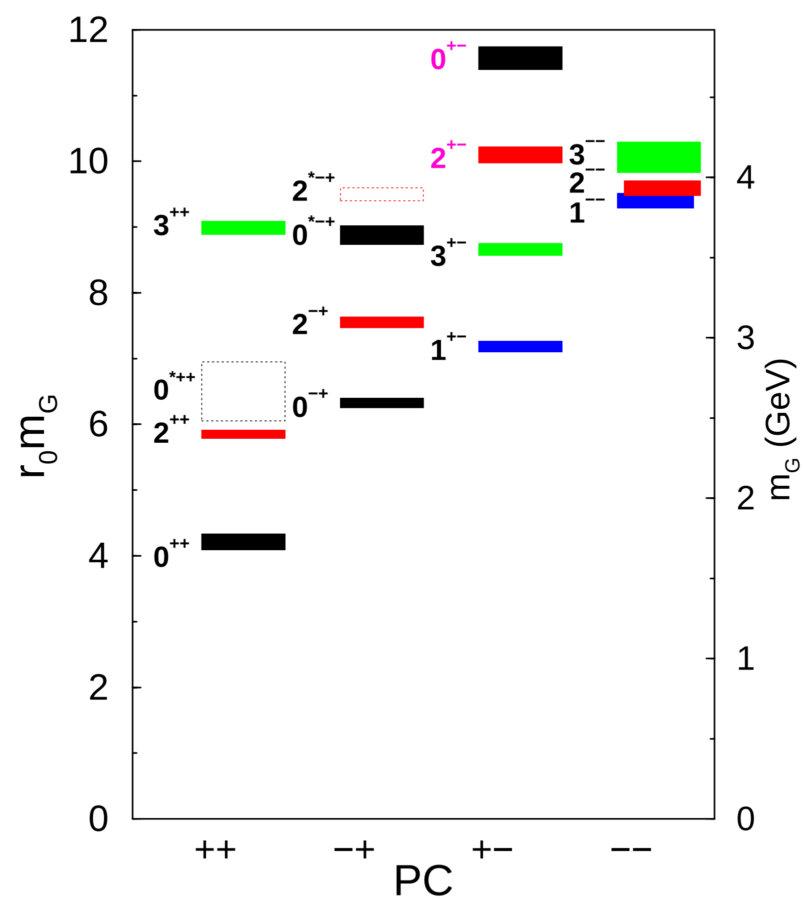
- the Jetset experiment
- PWA formalism and MC tests
- results from analysis of full data set

# The Jetset Experiment

- Measures in-flight pbar annihilation: $\bar{p}p \rightarrow \phi\,\phi$

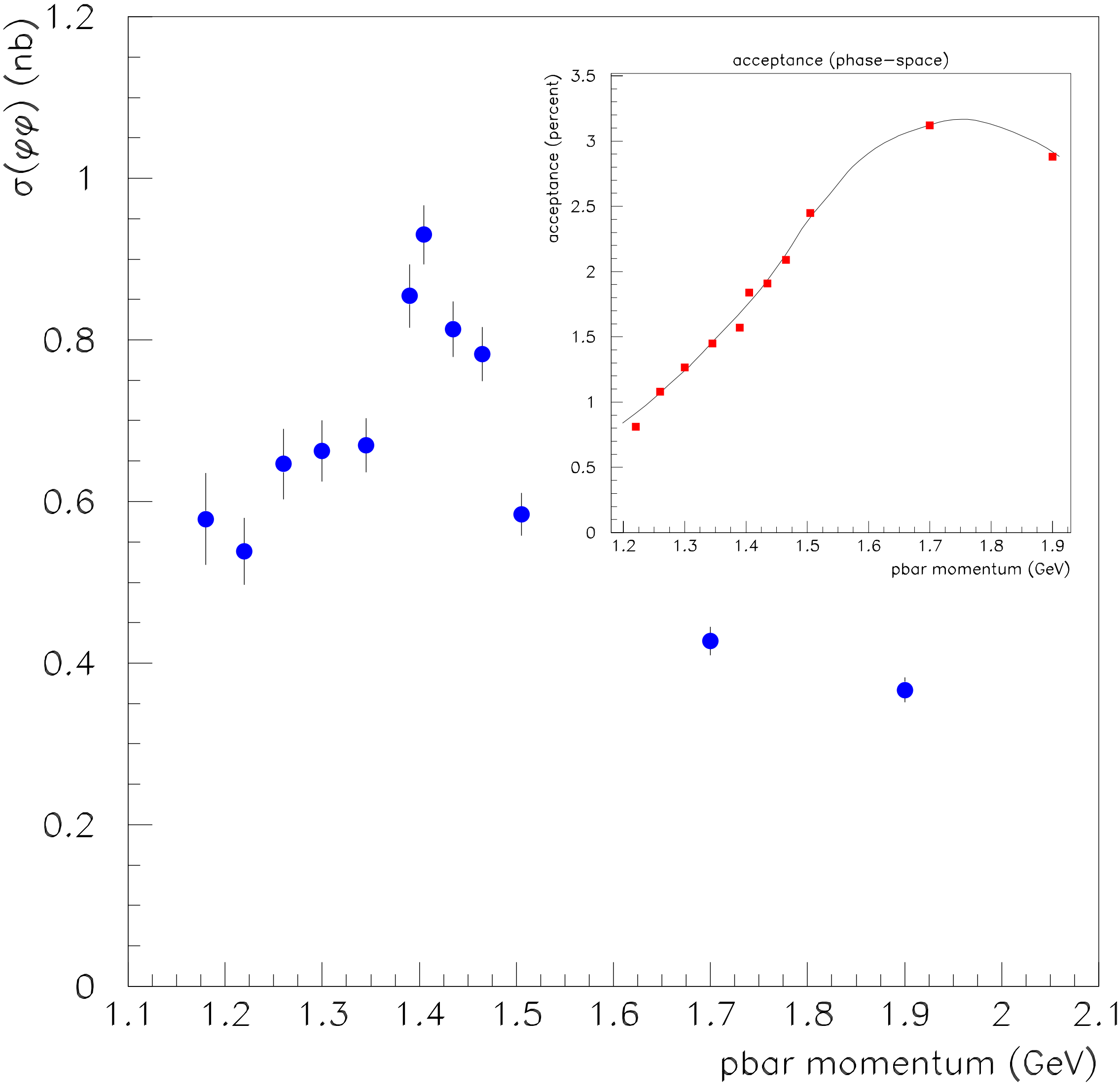



- OZI-suppressed, may form glueball resonances in s-channel




Morningstar et.al., LAT991004

# Total cross section $\bar{p}p \to \phi\phi$




Complete data set from Jetset

| point | N(φφ) | N(b.g.) | point | N(φφ) | N(b.g.) | point | N(φφ) | N(b.g.) |
|---|---|---|---|---|---|---|---|---|
| 1 | 326 | 95 | 5 | 1005 | 589 | 9 | 1318 | 877 |
| 2 | 414 | 225 | 6 | 1262 | 585 | 10 | 1056 | 943 |
| 3 | 626 | 270 | 7 | 1782 | 886 | 11 | 936 | 1592 |
| 4 | 840 | 369 | 8 | 1375 | 868 | 12 | 707 | 1666 |

# PWA Accounting

J values of the waves included in the partial wave analysis.
All waves up to J=4, L=4 in the final state were allowed.

| wave | $J^{PC}$ | L initial | S initial | L final | S final |
|---|---|---|---|---|---|
| 1 | 0−+ | 0 | 0 | 1 | 1 |
| 2 | 0++ | 1 | 1 | 0 | 0 |
| 3 | 0++ | 1 | 1 | 2 | 2 |
| 4 | 1++ | 1 | 1 | 2 | 2 |
| 5 | 2++ | 1 | 1 | 0 | 2 |
| 6 | 2++ | 1 | 1 | 2 | 0 |
| 7 | 2++ | 1 | 1 | 2 | 2 |
| 8 | 2++ | 1 | 1 | 4 | 2 |
| 9 | 2−+ | 2 | 0 | 1 | 1 |
| 10 | 2−+ | 2 | 0 | 3 | 1 |
| 11 | 2++ | 3 | 1 | 0 | 2 |
| 12 | 2++ | 3 | 1 | 2 | 0 |
| 13 | 2++ | 3 | 1 | 2 | 2 |
| 14 | 2++ | 3 | 1 | 4 | 2 |
| 15 | 3++ | 3 | 1 | 2 | 2 |
| 16 | 3++ | 3 | 1 | 4 | 2 |
| 17 | 4−+ | 4 | 0 | 3 | 1 |
| 18 | 4++ | 3 | 1 | 2 | 2 |
| 19 | 4++ | 3 | 1 | 4 | 0 |
| 20 | 4++ | 3 | 1 | 4 | 2 |
| 21 | 4++ | 5 | 1 | 2 | 2 |
| 22 | 4++ | 5 | 1 | 4 | 0 |
| 23 | 4++ | 5 | 1 | 4 | 2 |

# PWA Procedure

## Getting started:

- Fit with all waves free
  - gives full freedom to the fit -> definition of “good fit”
  - errors on amplitudes are large, meaningless
- Reduce the set of allowed waves in search of a minimal set that gives a good description of the entire data set
  - gives priority to an economical description
  - adequacy judged in comparison with full fit
  - require same set of waves for all mass bins

We found 3 dominant waves

all $2^{++}$

## Method:

1. Group the data into mass bins with sufficient statistics
2. For each bin, try all waves one-by-one, keep best, repeat

   → Sets agreed on 3 top waves.

3. Go back to beginning and put in waves two-by-two trying all pairs of waves together, then add one-by-one

   → Sets chose same set of 3 waves as dominant.

# Ambiguities

## 2 kinds:

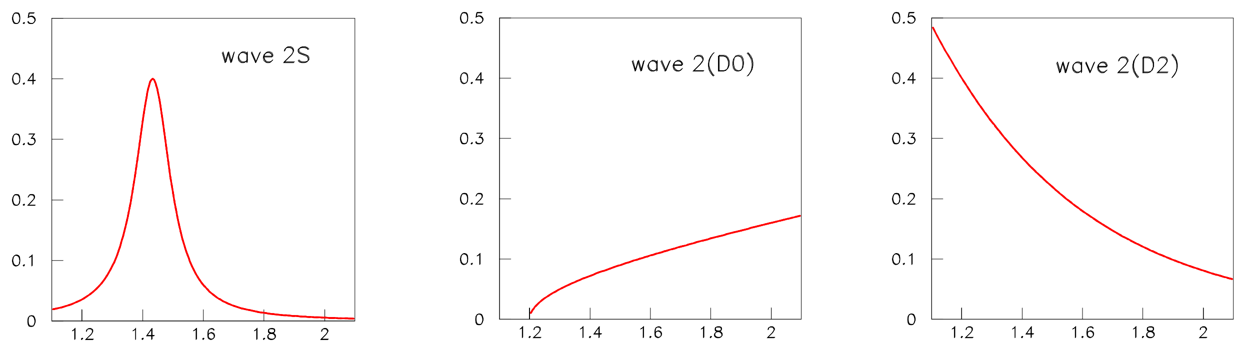
1. Essential ambiguities
   - correspond to **invariances** in angular distributions from PWA expansion
   - continuous invariances : global phases (2)
   - discrete invariances: undetermined signs (4)
   - no others believed to exist for 2($V \rightarrow 2P$)
   - irreducible even in limit of good acceptance and high statistics

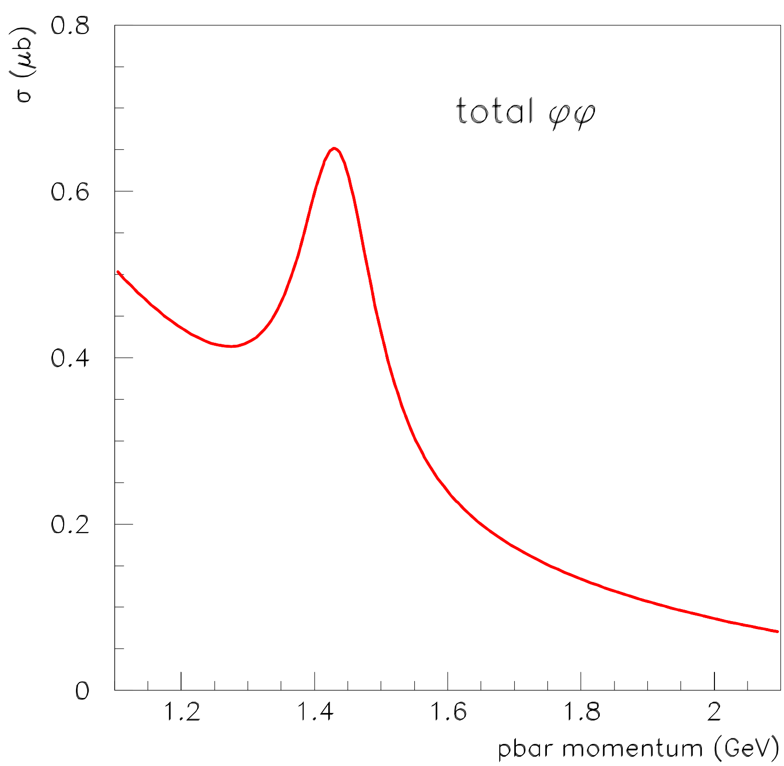
2. Statistical ambiguities
   - correspond to different angular distributions which cannot be discriminated given the available data
   - discrete (different local maxima in likelihood)
   - discovered by systematic numerical search
   - reducible by good acceptance and high statistics
   - relatively few in this data set

# Monte Carlo test

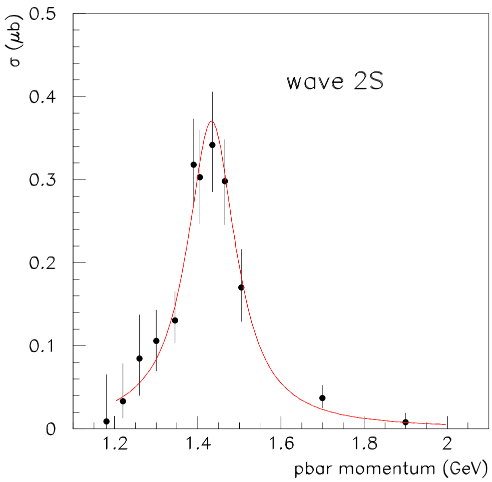
Ingredients:

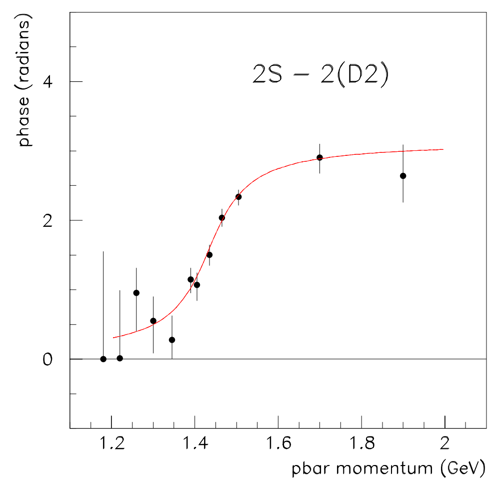
- 1 resonant wave, two non-resonant
- experimental acceptance through simulation
- same reconstruction, analysis as for real data

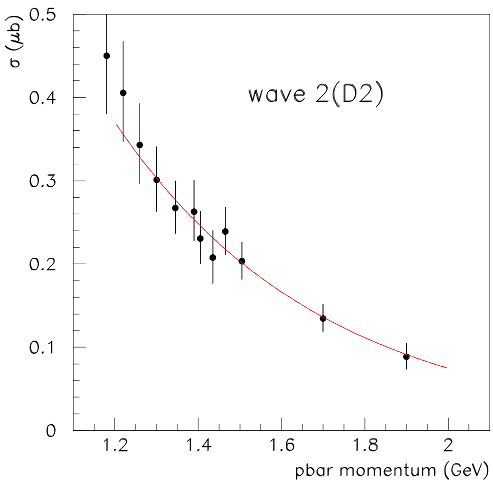


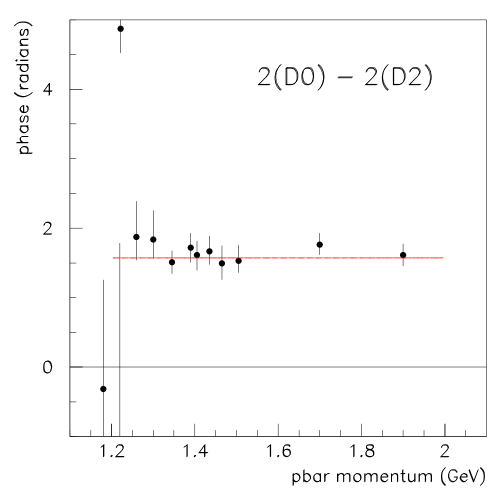



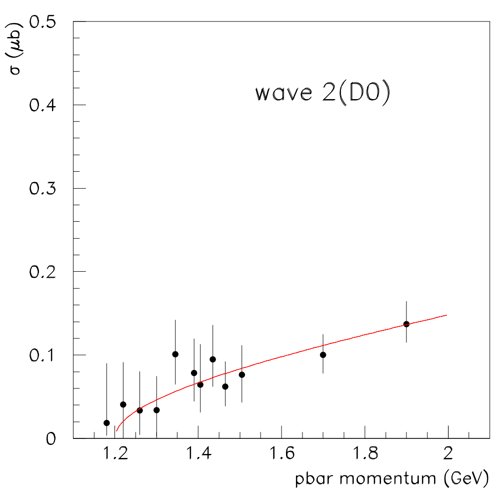
# Results of Monte Carlo test



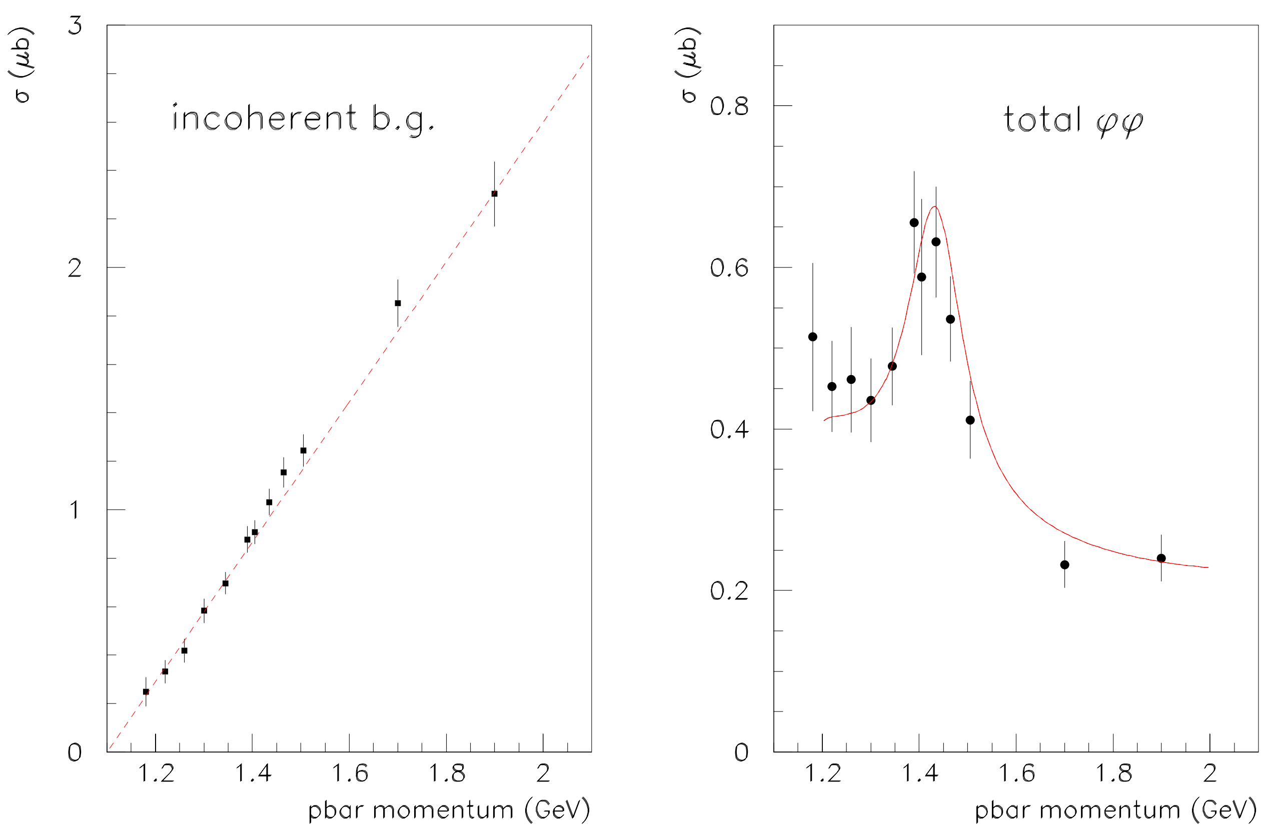



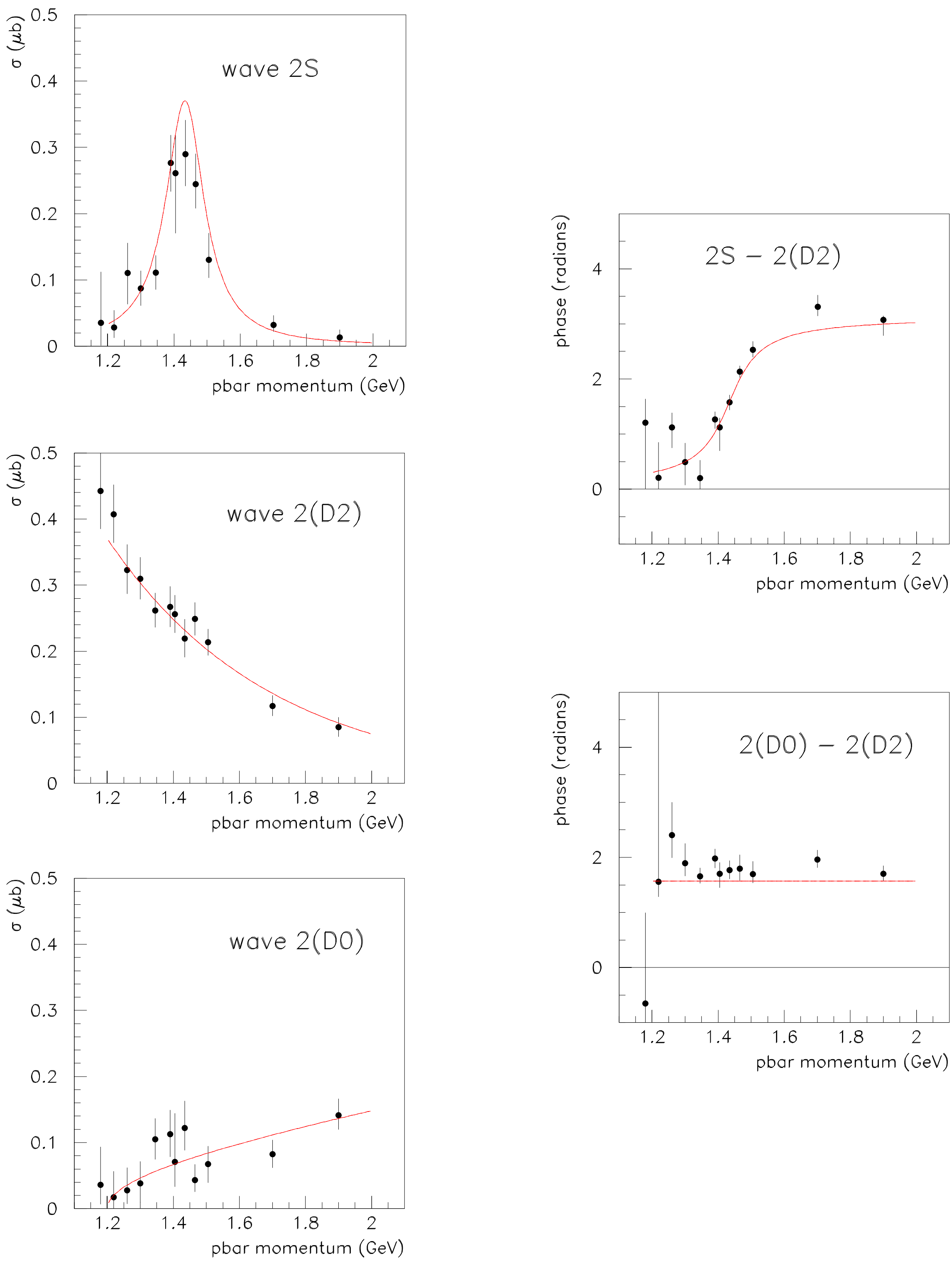



# Monte Carlo test #2

- include incoherent background
- uniform angular distribution for background
- not orthogonal to waves -- check for leakage

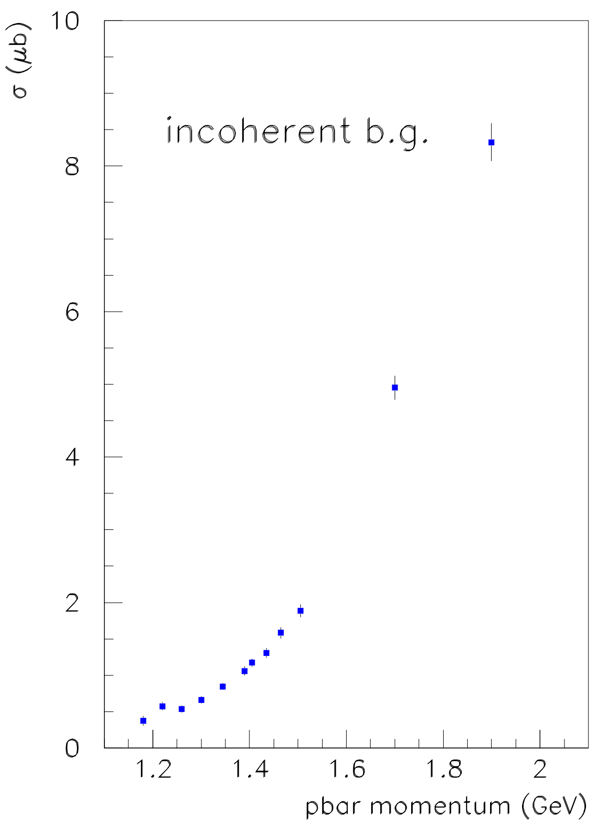


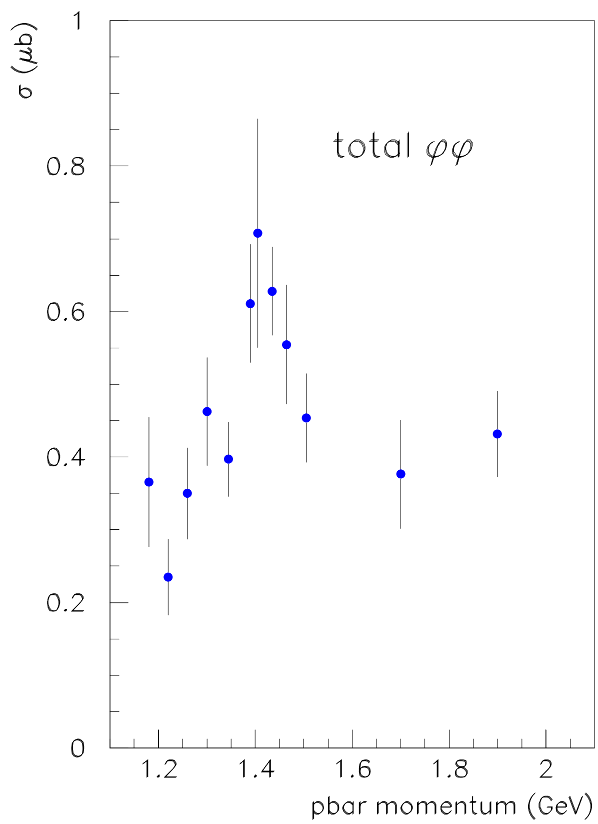
# Results of Monte Carlo test #2



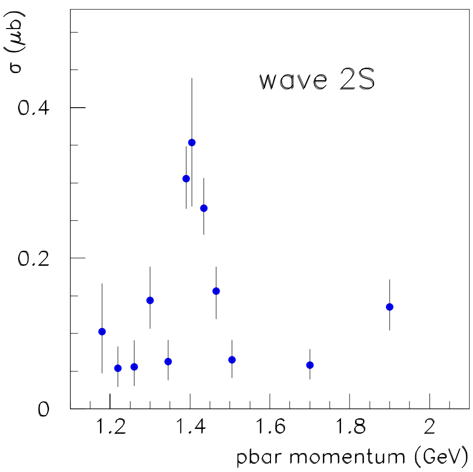
# PWA Results

- 3-wave fit identical to Monte Carlo test #2
- simultaneous fit in mass and angular distributions
- $\phi\phi$ cross section now corrected for acceptance based on measured angular distribution

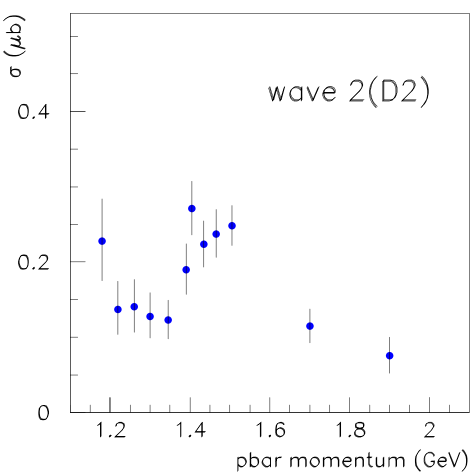


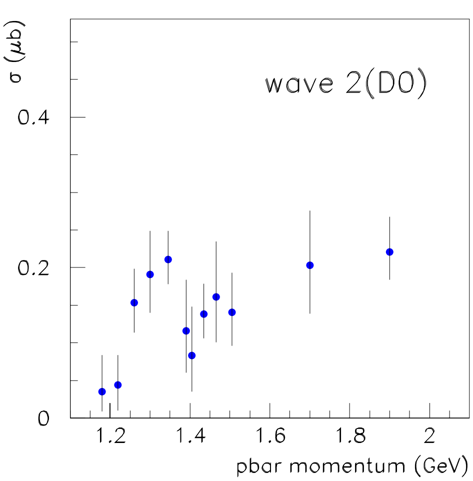
# 3-wave fit



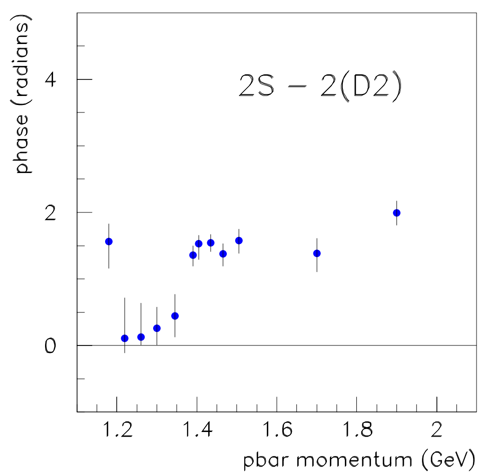
wave 2S
σ (μb)
0.4
0.2
0
1.2
1.4
1.6
1.8
2
pbar momentum (GeV)

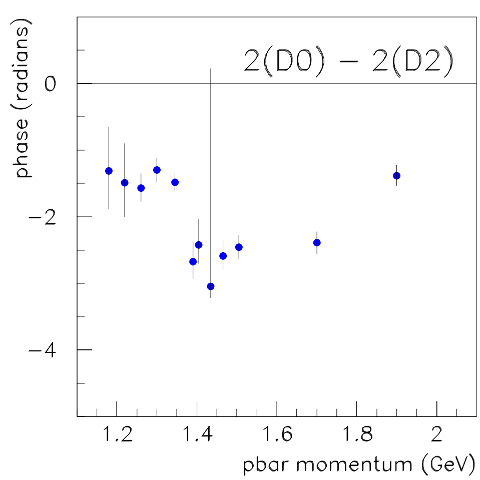
wave 2(D2)
σ (μb)
0.4
0.2
0
1.2
1.4
1.6
1.8
2
pbar momentum (GeV)

wave 2(D0)
σ (μb)
0.4
0.2
0
1.2
1.4
1.6
1.8
2
pbar momentum (GeV)

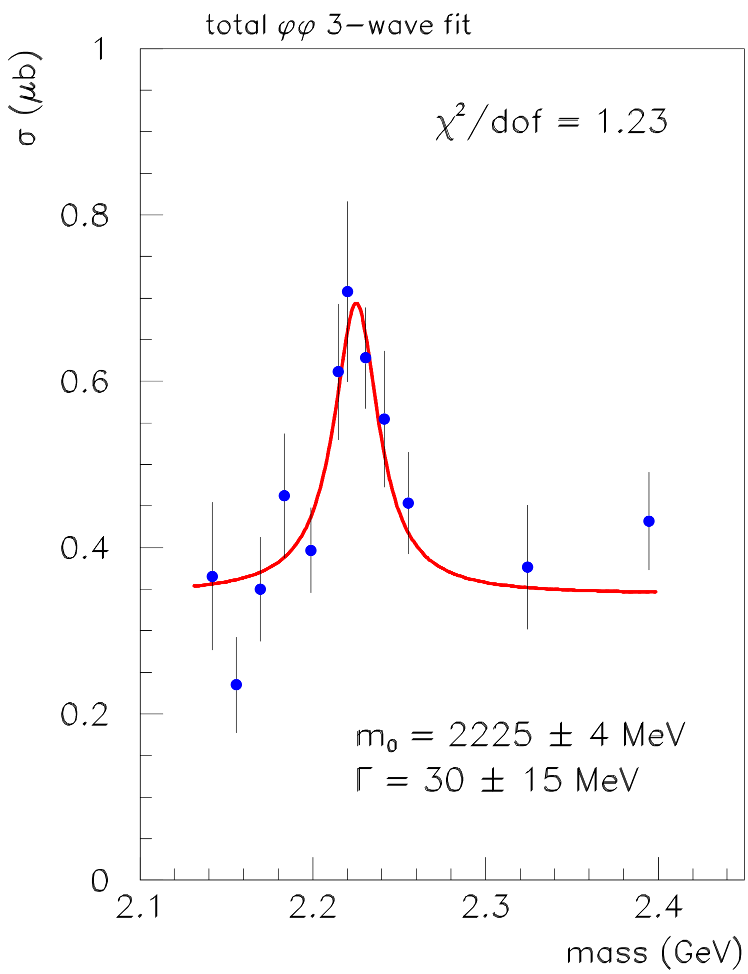



2S − 2(D2)
phase (radians)
4
2
0
1.2
1.4
1.6
1.8
2
pbar momentum (GeV)

2(D0) − 2(D2)
phase (radians)
0
−2
−4
1.2
1.4
1.6
1.8
2
pbar momentum (GeV)

# Possible Interpretation




- narrow peak seen in raw cross section
- PWA reveals 3 dominant waves in $2^{++}$
- rapid phase motion seen in two waves as expected for a Breit-Wigner resonance

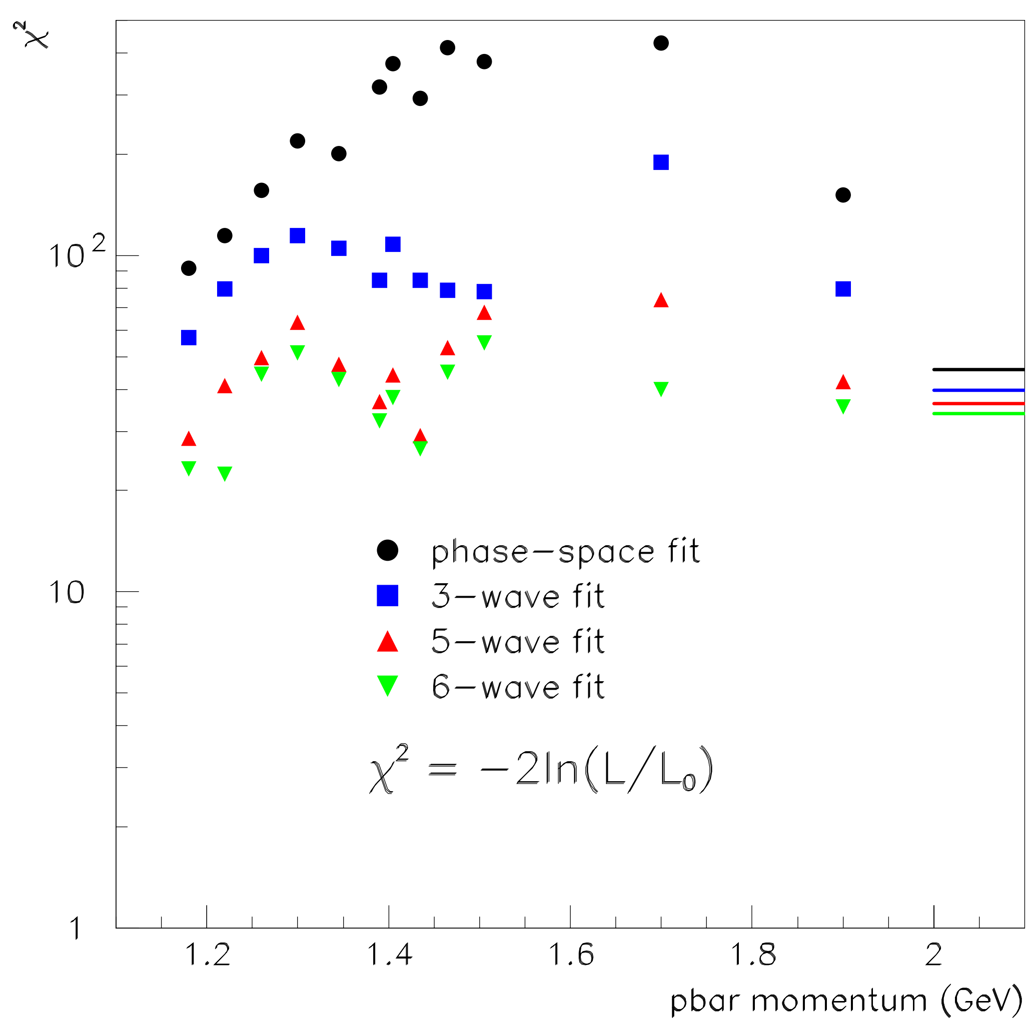
# Quality of the fit

- To check goodness of fit, use likelihood ratio test

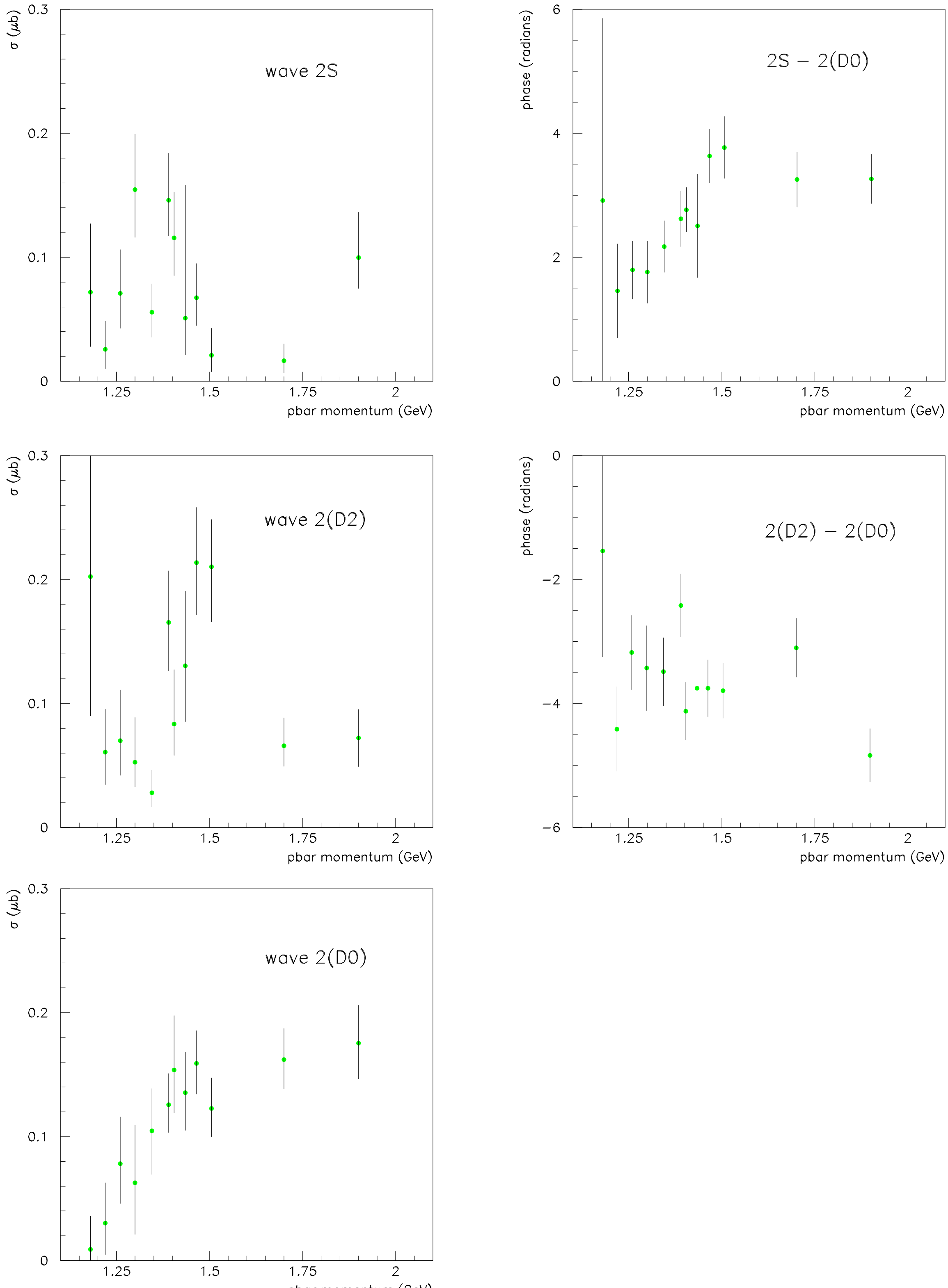
  - Define $\chi^2 = -2\,ln\left(\frac{L}{L_0}\right)$

    where $L_0$ is the likelihood maximum over the full parameter space and $L$ is the likelihood maximum over some restricted part.

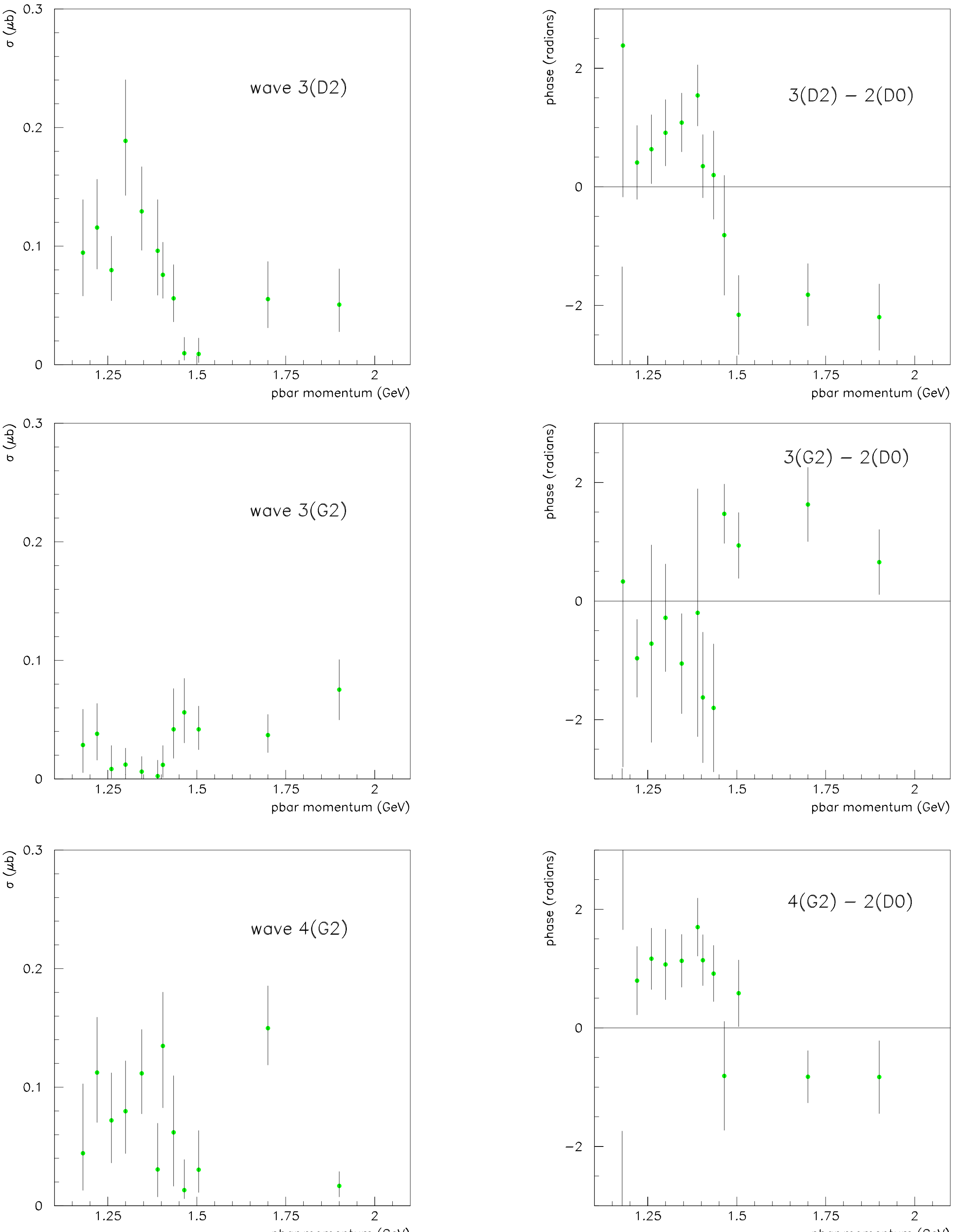
- For large N, behaves like chi-square with $n\text{-}n_0$ d.o.f.



# 6-wave fit

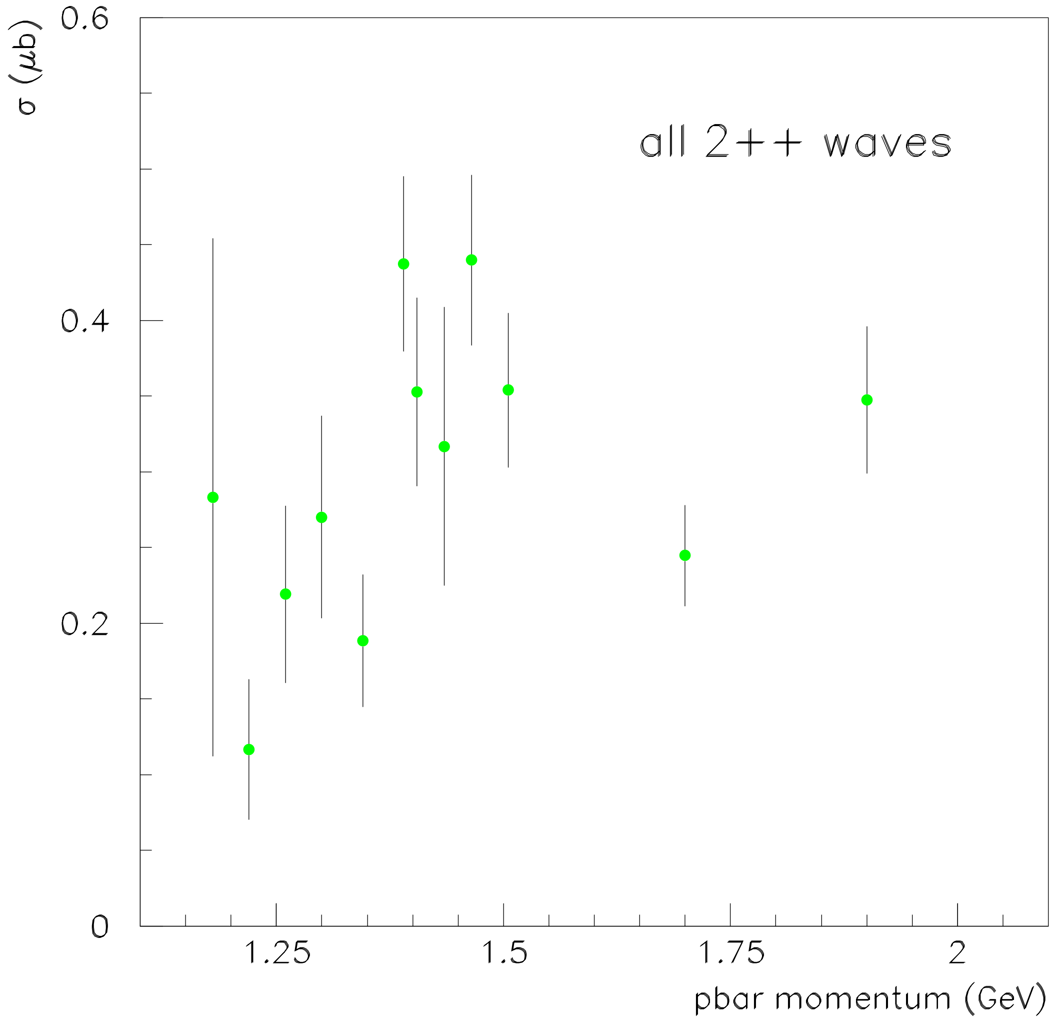

wave 2S
2S − 2(D0)
wave 2(D2)
2(D2) − 2(D0)
wave 2(D0)
σ (μb)
phase (radians)
pbar momentum (GeV)
0
0.1
0.2
0.3
2
4
6
−2
−4
−6
1.25
1.5
1.75

# 6-wave fit



wave 3(D2)
3(D2) − 2(D0)
wave 3(G2)
3(G2) − 2(D0)
wave 4(G2)
4(G2) − 2(D0)
σ (μb)
phase (radians)
pbar momentum (GeV)

# Total $2^{++}$ from 6-wave fit




- Some strength in $2^{++}$ has moved to $3^{++}$
- No obvious narrow structure is visible in $2^{++}$
- Phase motion seen does not correspond to a simple Breit-Wigner resonance
- Statistical errors do not justify a serious attempt to perform a multiple-pole fit

# Conclusions

- PWA has been performed of the reaction

$$p\,\bar{p} \rightarrow \phi\phi$$

- 3 dominant waves were found, all $2^{++}$.
- Rapid phase motion seen in two waves consistent with a narrow $2^{++}$ resonance.

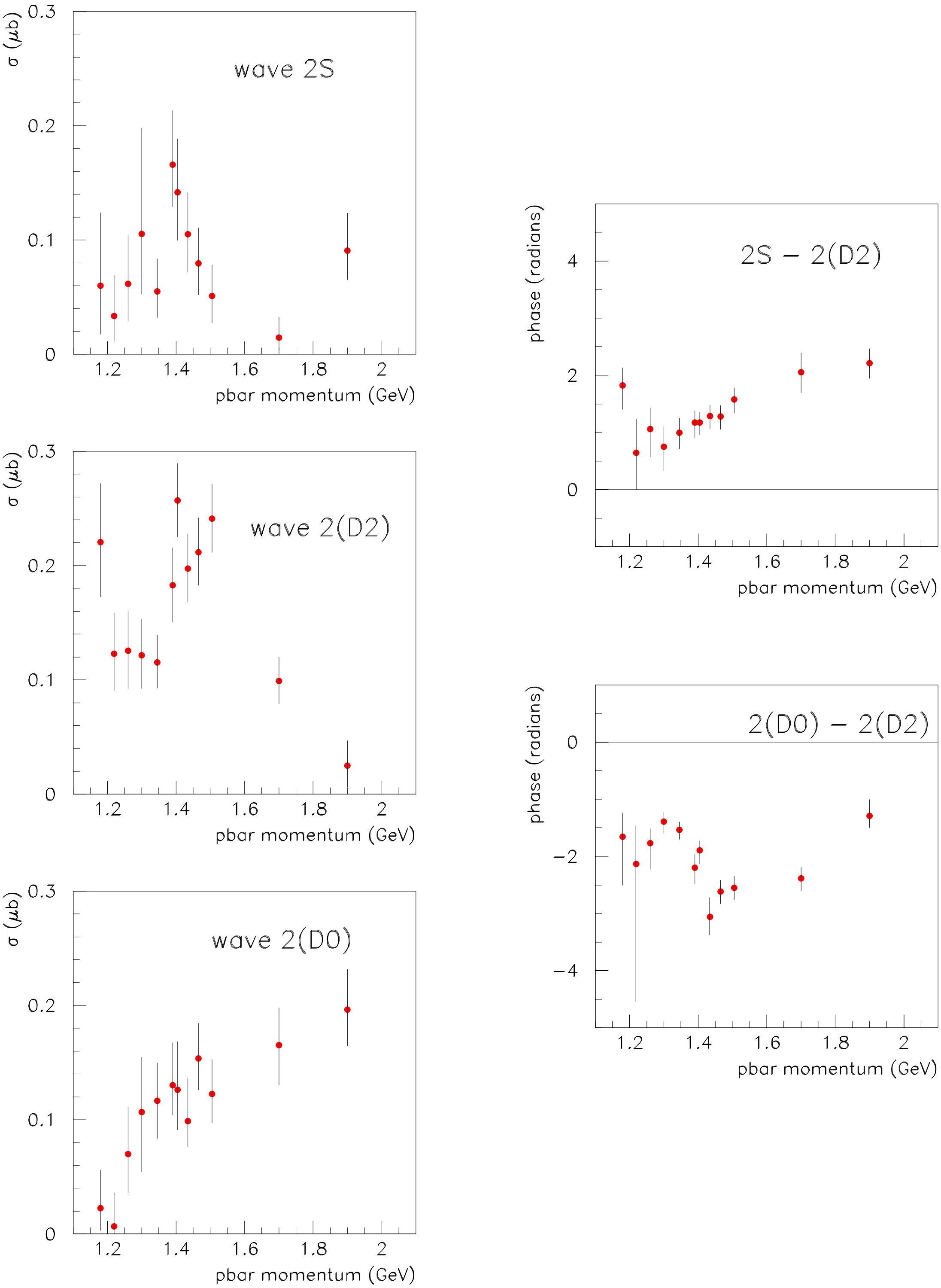
**BUT**

- The fit shows significant improvement if more waves are added, up to 6.
- Statistical errors do not permit a clear interpretation of 6-wave solution, but it does not favour a single narrow resonance.

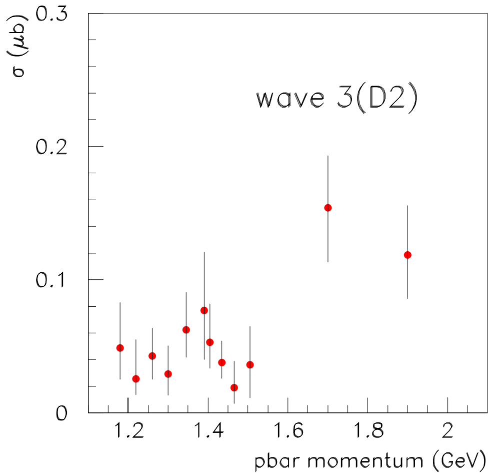
**AND**

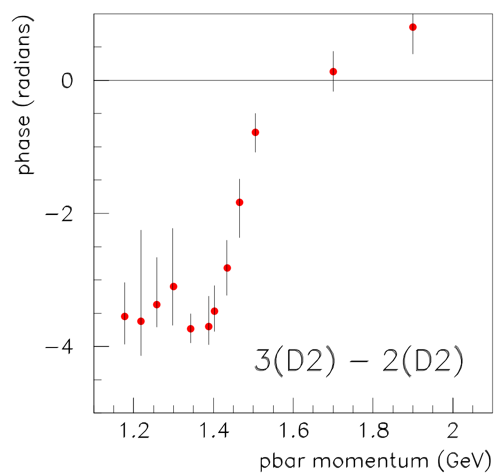
- Possible interference between the $\phi\phi$ and an underlying $f_0,f_0$ background should be taken into account.

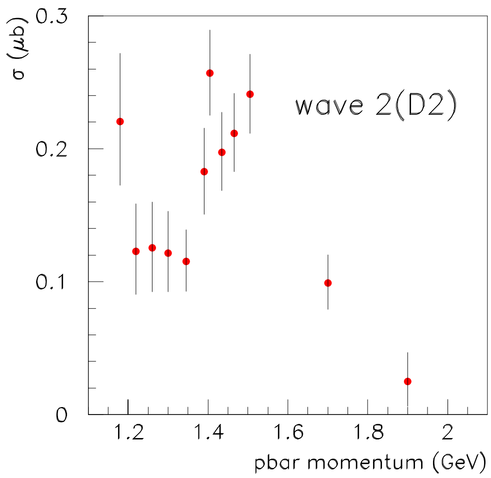
# 5-wave fit

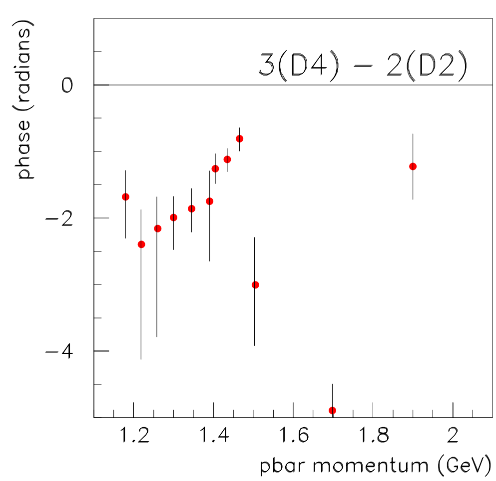

σ (μb)
wave 2S
pbar momentum (GeV)
σ (μb)
wave 2(D2)
pbar momentum (GeV)
σ (μb)
wave 2(D0)
pbar momentum (GeV)
phase (radians)
2S − 2(D2)
pbar momentum (GeV)
phase (radians)
2(D0) − 2(D2)
pbar momentum (GeV)

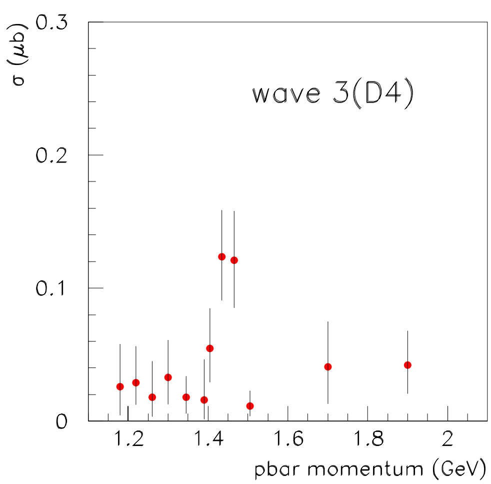
# 5-wave fit


σ (μb)
0.3
0.2
0.1
0
wave 3(D2)
1.2
1.4
1.6
1.8
2
pbar momentum (GeV)


phase (radians)
0
−2
−4
3(D2) − 2(D2)
1.2
1.4
1.6
1.8
2
pbar momentum (GeV)


σ (μb)
0.3
0.2
0.1
0
wave 2(D2)
1.2
1.4
1.6
1.8
2
pbar momentum (GeV)


phase (radians)
0
−2
−4
3(D4) − 2(D2)
1.2
1.4
1.6
1.8
2
pbar momentum (GeV)


σ (μb)
0.3
0.2
0.1
0
wave 3(D4)
1.2
1.4
1.6
1.8
2
pbar momentum (GeV)