Search for hybrid states in VES, E852 and COMPASS data.

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seminar 28.05.10

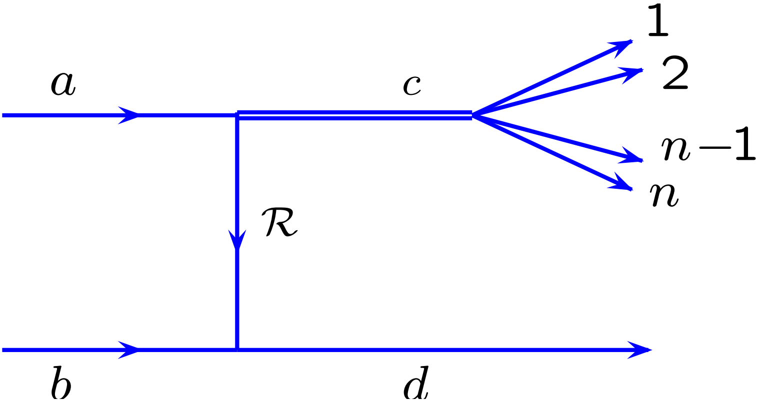
Motivation

- Bound states of Quantum Cromodynamics, which are dominantly observed in experiments, are mesons ($q\bar{q}$) and baryons (qqq)
- Quantum numbers of ordinary $q\bar{q}$ mesons are: $P = (-1)^{(L+1)}$ and $C = (-1)^{(L+S)}$. Naive quark model works rather well for classification.
- Forbidden J^{PC} combinations for mesons are $J^{PC} = 0^{--}, 0^{+-}, 2^{+-}, 1^{-+}, 3^{-+}$

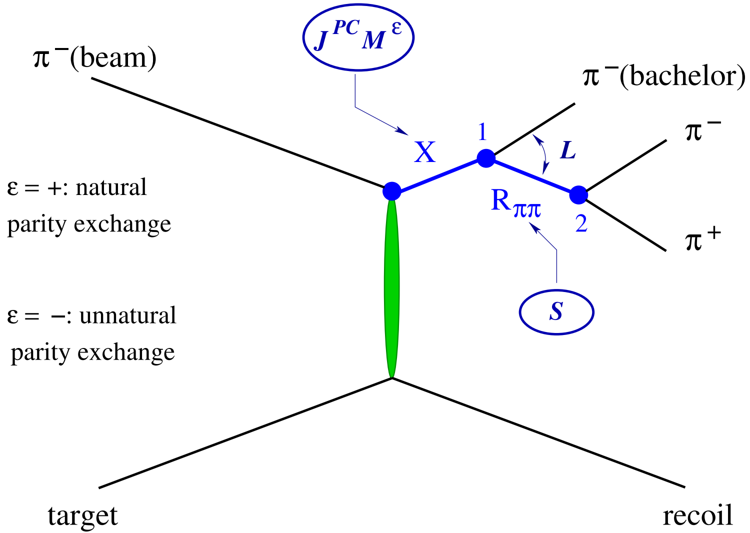
Production mechanisms

- Diffraction or charge-exchange, i.e. exchange of one reggeon (Pomeron).
- Coulomb production or Primakoff mechanism (i.e. photon exchange).
- Central production with hadron (π or proton) beam. Exchange of 2 Reggeons (Pomerons).
- Exclusive reactions with electron/muon beam.
- Formation like $p\bar{p} \to X \to$ Decay Products

Diffractive dissociation reactions



Isobar model (3-body final states)



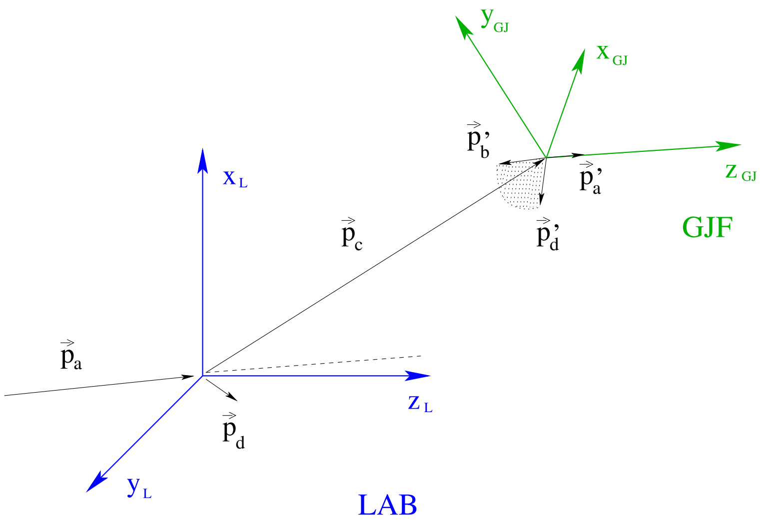
Quantum numbers. Examples of decay amplitudes

Non-relativistic tensor formalism = Zemach tensors.
$\rho(770) \rightarrow \pi^+\pi^-$
$T_i(\rho(770) \rightarrow \pi^+\pi^-) = p(\pi^-)_i$ amplitude of $\rho(770)$ decay
$P = (-1)^L P(\rho)P(\pi)$: parity conservation in decay process
$J^{PC} = 1^{++} \rightarrow \rho(770)\pi S$
$T_i(1^{++} \rightarrow \rho(770)\pi, \rho(770) \rightarrow \pi^+\pi^-) = p(\pi^-)_i BW(m(\pi^+\pi^-))$
$J^{PC} = 1^{-+} \rightarrow \rho(770)\pi P$
$T_k((\rho\pi)_L) = p(\rho)_k$ tensor of orbital angular momentum $L = 1$
$T_i(1^{-+} \rightarrow \rho(770)\pi, \rho(770) \rightarrow \pi^+\pi^-) = [\vec{p}(\pi^-) \times \vec{p}(\rho)]_i BW(m(\pi^+\pi^-))$
Break-up 3-momenta are in corresponding CM frames. Isobar rest frame is obtained by pure lorentz boost from GJ frame.
Zemach amplitudes contain orbital momentum barrier factors.
$BW(m) = \frac{1}{m^2 - m0^2 + im\Gamma_{tot}(m)}$: Breit-Wigner amplitude of the isobar

Production amplitudes

General Regge theory. Characteristic tensors language.
$\vec{z}$ is beam direction in beam-reggeon CM system $= Z_{Gottfried-Jackson}$
$\vec{x}$ is p_t of recoil with respect to beam in CM of X system $= X_{Gottfried-Jackson}$
$J^{PC} = 1^{++}$, pion beam+positive naturality exchange particle
$(\vec{z}T)$, $(\vec{x}T)$,
In terms of spin projection states $|JM>$ that means:
$(\vec{z}\vec{T}) = |10>$
$(\vec{x}\vec{T}) = |11> - |1-1>$
$J^{PC} = 1^{-+}$, pion beam+positive naturality exchange particle
$([\vec{z} \times \vec{x}]\vec{T}) = (\vec{y}\vec{T})$
In terms of spin projection $|JM>$ that means:
$(\vec{y}\vec{T}) = |11> + |1-1>$
Reflectivity basis for π-beam (generalization):
$|JM\epsilon> = |JM> - \epsilon P(-1)^{J-M}|J-M>$

Gottfried-Jackson frame



Illinois/Protvino/Munich Program - BNL/Munich Program

- **Mass-Independent PWA**

$$\sigma_{indep}(\tau, m) = \sum_{\epsilon=\pm 1} \sum_{r=1}^{N_r} \left| \sum_i T_{ir}^{\epsilon} \psi_i^{\epsilon}(\tau, m) / \sqrt{\int \left|\psi_i^{\epsilon}(\tau', m)\right|^2 d\tau'} \right|^2$$

  - Production amplitudes $T_{ir}^{\epsilon} \rightarrow$ extended maximum likelihood fit
  - Decay amplitudes $\psi_i^{\epsilon}(\tau, m)$ (Zemach tensors, D functions)
  - Set of partial waves labeld by $i = J^{PC} M^{\epsilon} [Y] L$
    - For example in $\pi^- \pi^- \pi^+$ case $[Y] = (\pi\pi)_S, \rho(770), f_0(980), f_2(1270), \rho_3(1690)$
  - Background wave

Review on Hybrids

Quantum numbers of ordinary $q\bar{q}$ mesons are: $P = (-1)^{(L+1)}$ and $C = (-1)^{(L+S)}$.
Forbidden J^{PC} combinations are $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 3^{-+}$

Hybrids can be ordinary quantum numbers. Extra states, mixed with $q\bar{q}$ mesons.

Results on $J^{PC} = 1^{-+}$ were published by experiments E179(KEK,Japan), GAMS/NA12(IHEP-CERN), VES(IHEP,Protvino), E852(BNL,USA), Crystal Barrel(CERN) and COMPASS(CERN).

Experiment	Reaction
VES	Diffraction; charge exchange; 28-, 37-, 43-GeV/c π^- beam
E179 (KEK)	Diffraction, 6.3-GeV/c π^- beam
Crystal Barrel	$p\bar{p}$ annihilation, analysis of Dalitz plots for $\eta\pi^+\pi^-$, $\eta\pi^0\pi^0$, $\eta'\pi^+\pi^-$
GAMS/NA12	Charge exchange; 32-, 38-, 100-GeV/c π^- beam
E852 (BNL)	Diffraction; charge exchange; 18-GeV/c π^- beam

Review on Hybrids

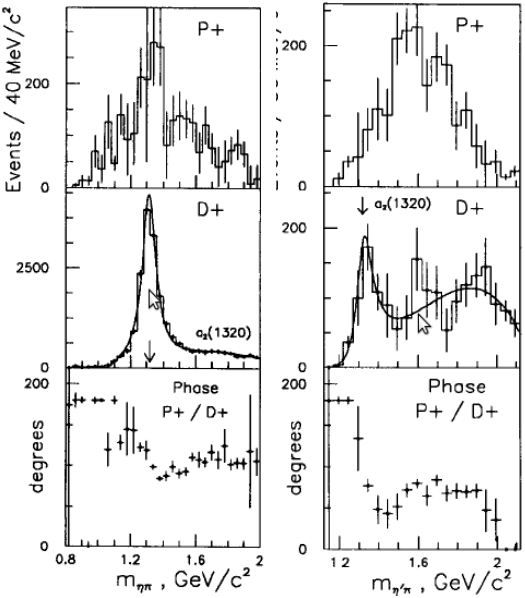
Predictions of lowest hybrid mass:

Model	Mass, GeV/c^2
Bag model	1.3–1.8
Current-tube model	1.8–2.0
Sum rules	1.3–1.5
Sum rules	2.1–2.5
Lattice QCD	1.8 ± 0.2

Predictions of lowest 1^{-+} partial widths:

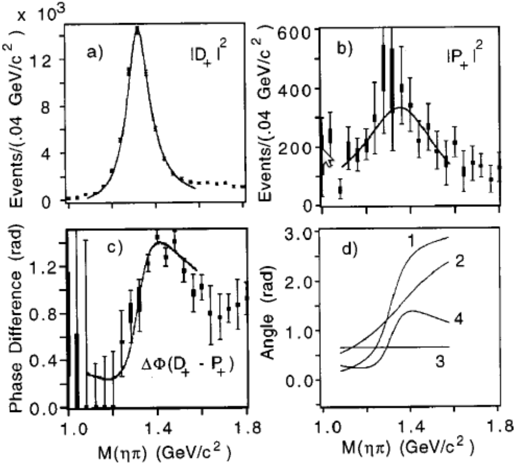
Decay mode	$b_1(1235)\pi$	$f_1(1285)\pi$	$\rho\pi$	$f_2\pi$	$\eta(\eta')\pi$
Width, MeV	170	60	5–20	0	0–10

VES $\pi^- N \to \eta\pi^-, \eta'\pi^- N$

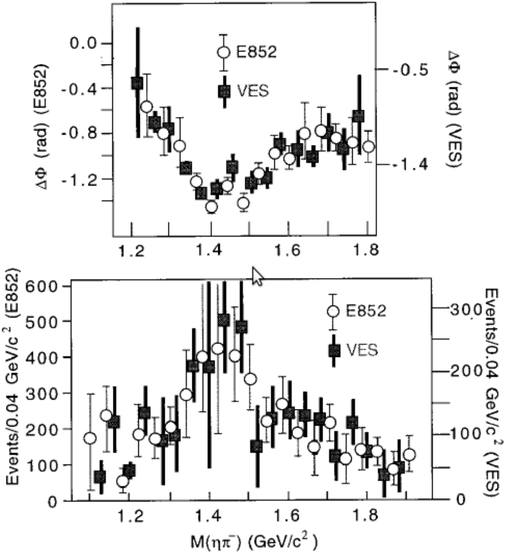


$\pi_1(1400)$ by E852

$M = 1.370 \pm 0.016 + 0.05 - 0.03$ GeV
$\Gamma = 0.385 \pm 0.040 + 0.065 - 0.105$ GeV (E852)

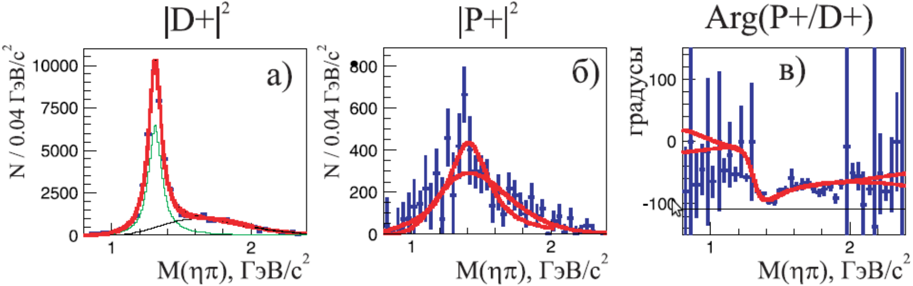


$J^P = 1^- \eta\pi^-$ VES vs. E852



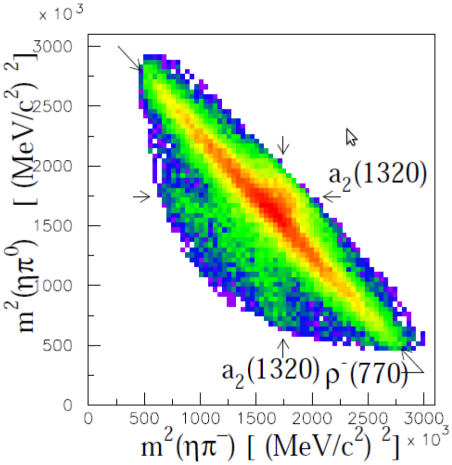
$J^P = 1^- \eta\pi^-$ VES mass-dep. fit

VES: results can be model-dependent
(full coherence forced, tail of $a_2(1320)$ unknown)
Either resonant or non-resonant model. Still resonant improves χ^2.



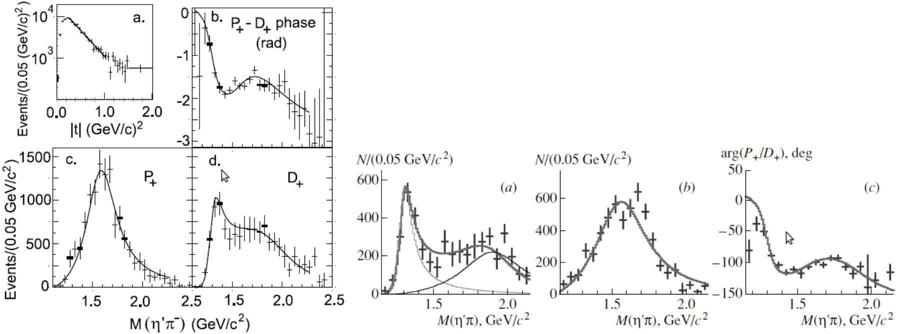
$\pi_1(1400)$ by Crystal-Barrel

$\bar{p}n \rightarrow \pi^- \pi^0 \eta$
$M \sim 1.4 GeV \Gamma \sim 0.4 GeV$ (CB, conference)
$M = 1.384 \pm 0.028 GeV \Gamma = 0.378 \pm 0.058 GeV$ (OBELIX)



$\pi^- N \to \eta'\pi^- N$ E852 and VES-mass-dep.

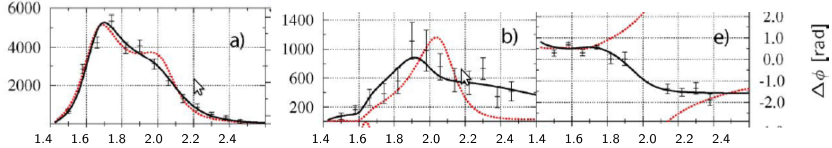
$M = 1.597 \pm 0.010 + 0.045 - 0.010$ GeV
$\Gamma = 0.340 \pm 0.040 \pm 0.050$ GeV (E852)

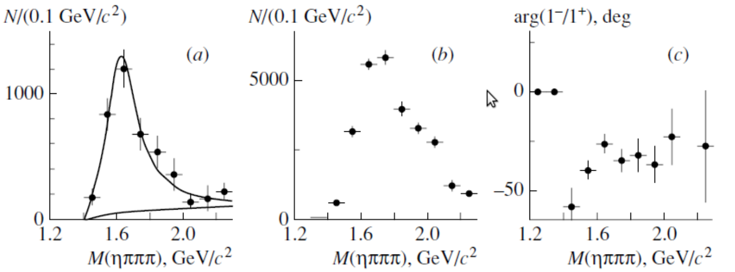


$M \sim 1.56 \pm 0.06 \Gamma \sim 0.34 \pm 0.06$ GeV ($\eta'\pi + b_1\pi$ VES)

$\pi^- N \to \eta' \pi^- N$

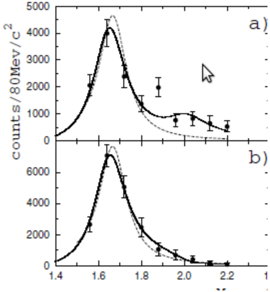
$M = 1.709 \pm 0.024 \pm 0.041$ GeV
$\Gamma = 0.333 \pm 0.052 \pm 0.049$ GeV (E852)

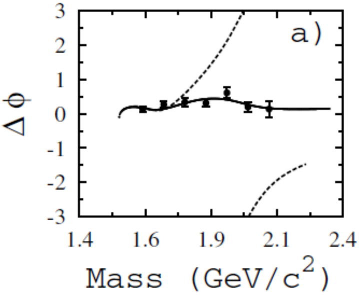


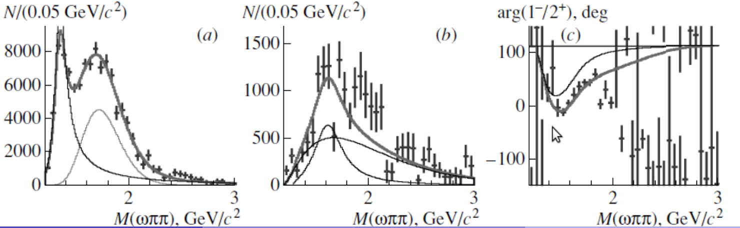


$J^{PC} = 1^{-+}$ $b_1(1235)\pi^-$ Exotic Wave

$$M = 1.664 \pm 0.008 \pm 0.010 \text{ GeV}$$
$$\Gamma = 0.185 \pm 0.025 \pm 0.028 \text{ GeV (E852)}$$

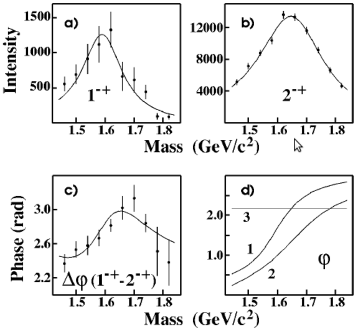


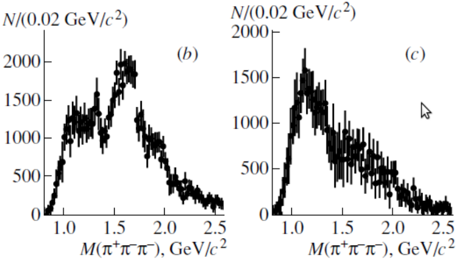




$\pi^-\pi^-\pi^+$ $J^{PC} = 1^{-+}$ Exotic Wave

$M = 1.593 \pm 0.008 + 0.029 - 0.047$ GeV
$\Gamma = 0.168 \pm 0.020 + 0.150 - 0.012$ GeV (E852)



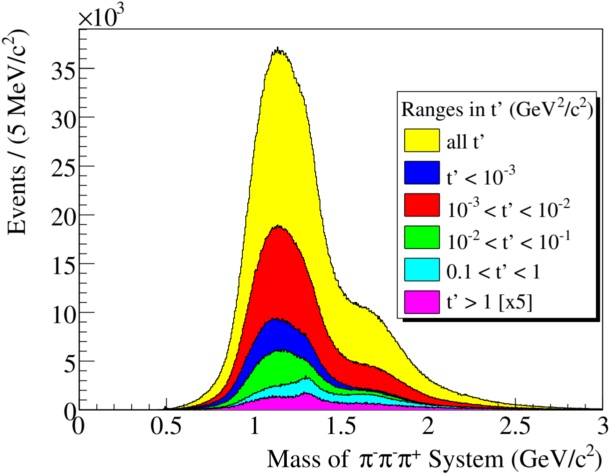


VES(left) claims model-dependence of exotic peak.
Latest E852 publication claims no evidence of 1^{-+} in $\pi^-\pi^-\pi^+$. However, "phase-locked" behavior with $\pi_2(1670)$ is mentioned.

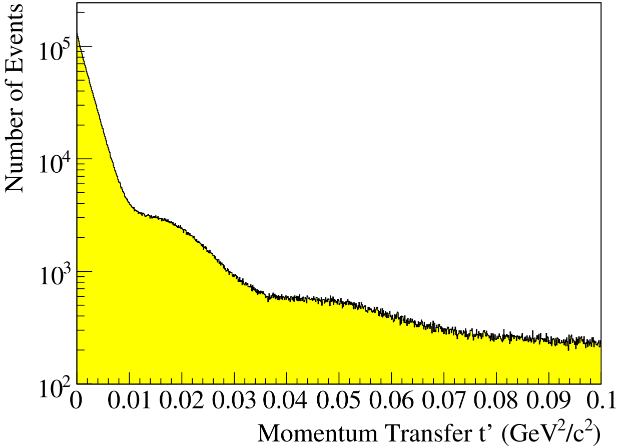
Conclusion on existing status of 1^{-+}

- $\pi_1(1400)$ and $\pi_1(1600)$ still are highly disputed states (especially 1-st one).
- Studied dominantly in diffractive mechanism of production

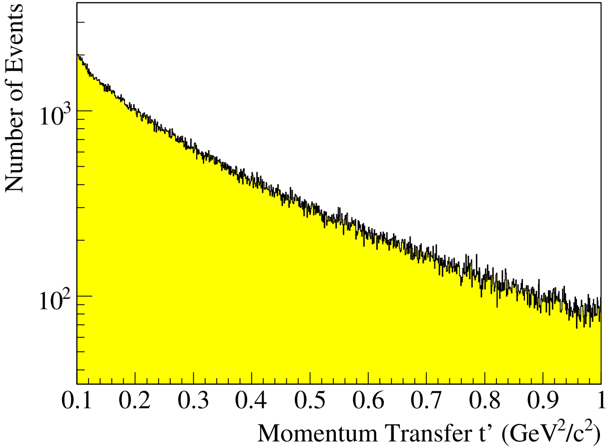
COMPASS Pb target data 2004: mass spectrums in different t' intervals



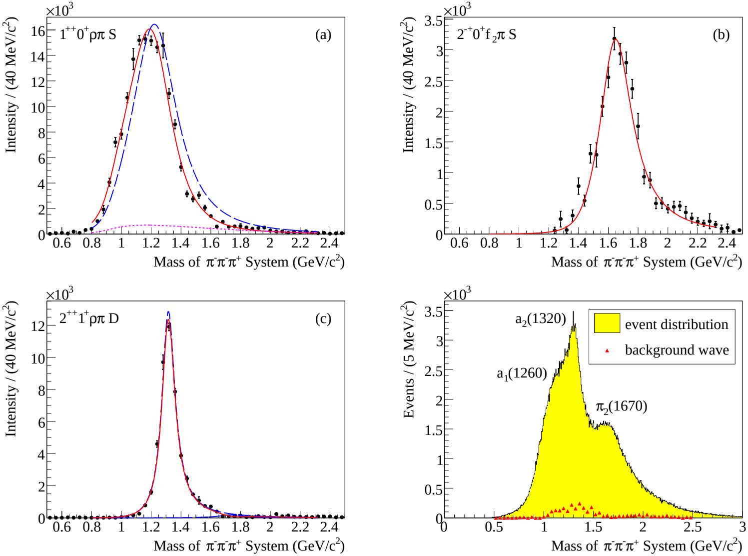
Pb target data 2004: low t and Primakoff region



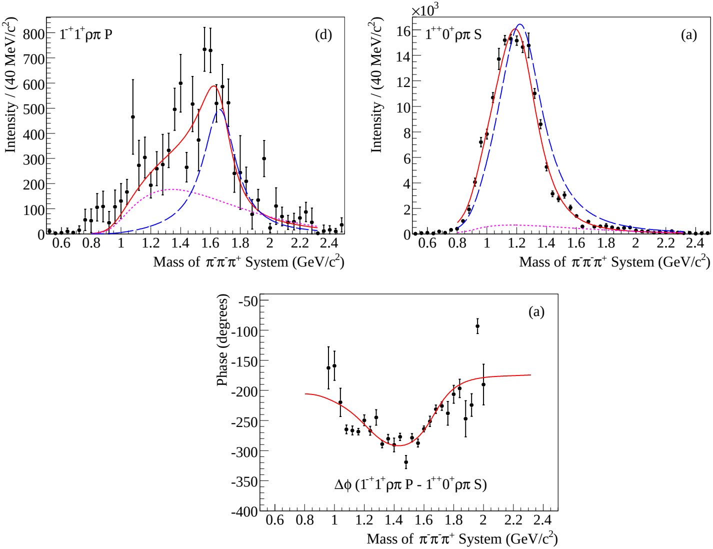
Pb target data 2004: high-t incoherent region



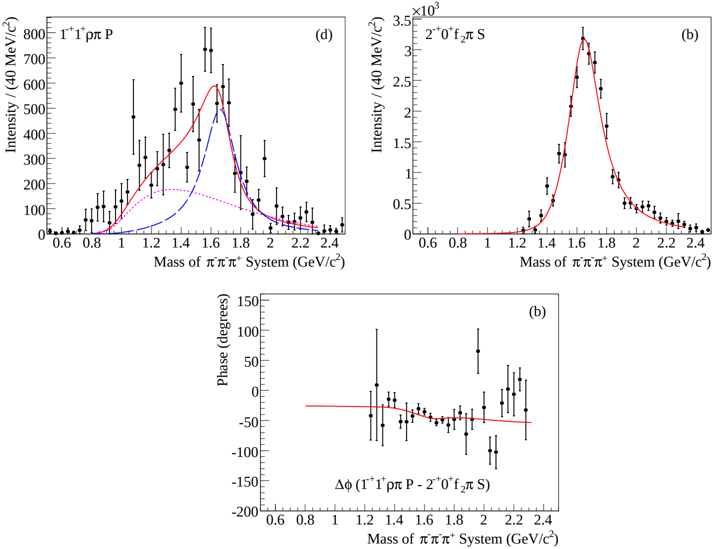
Intensities of Major Waves



$J^{PC} = 1^{-+}$ Exotic Wave



$J^{PC} = 1^{-+}$ Exotic Wave

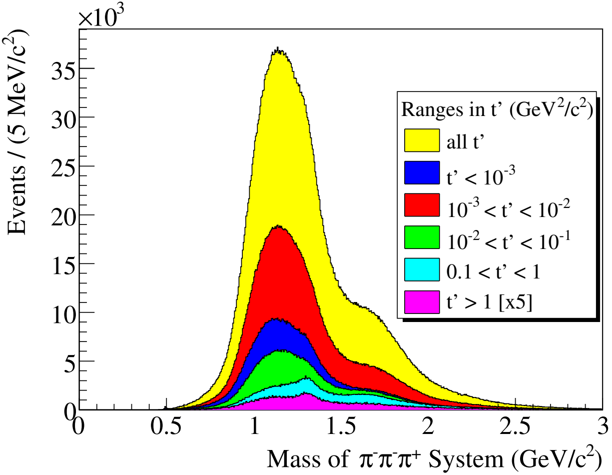


summary of 2004 $\pi^-\pi^-\pi^+$

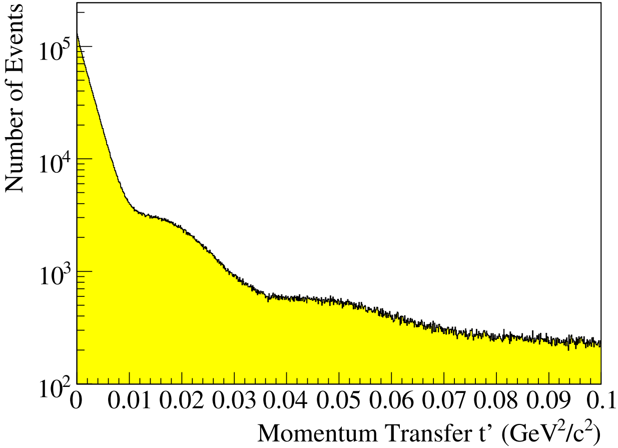
- Existing mesonic resonances are confirmed (consistent with PDG)
- observation of high-disputed $\pi_1(1600)$ is declared. Mass and width are determined.
  BW parameters[1] for $\pi_1(1600)$:
  - $M = \left(1660 \pm 10^{+0}_{-64}\right) \mathrm{MeV/c^2}$
  - $\Gamma = \left(269 \pm 21^{+42}_{-64}\right) \mathrm{MeV/c^2}$
- Extended systematidc study is performed.

[1] A. Alekseev *et. al.*, COMPASS Collaboration, arXiv:0910.5842v1 (2009)
Accepted for print in PL.

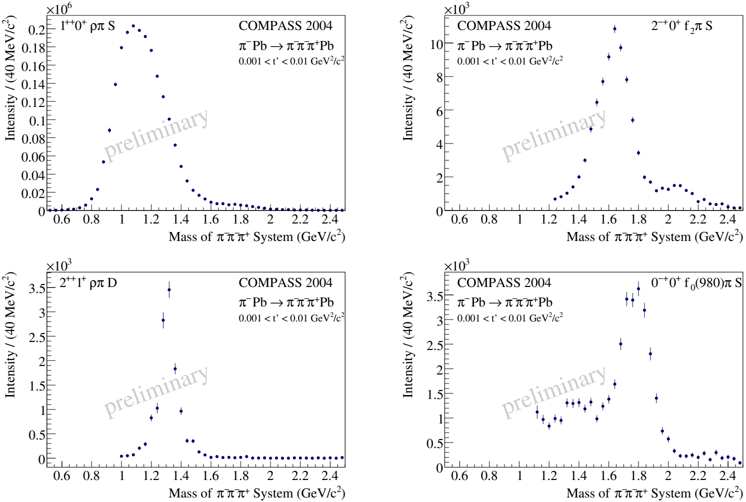
Lead target data 2004: mass spectrums in different t' intervals



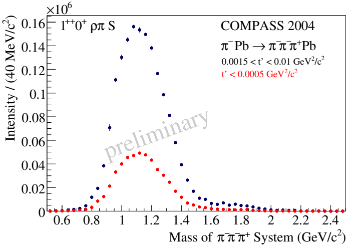
Pb target data 2004: low t and Primakoff region

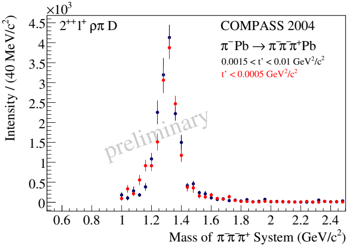


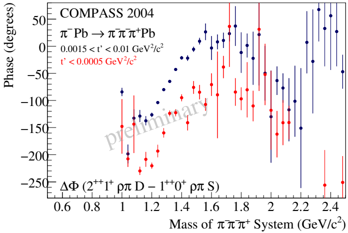
Low-t and Primakoff region: Intensities of Major Waves



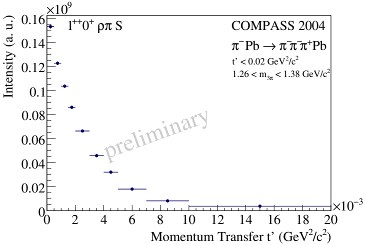
a1-a2 and relative phase: from Coulomb to strong

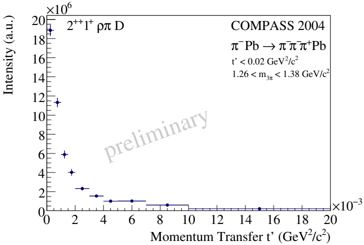


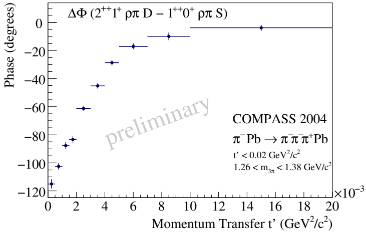




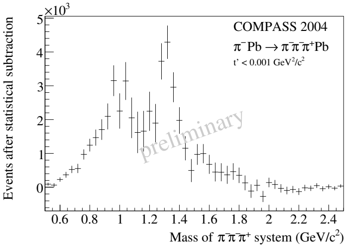
a1-a2 and relative phase: in t/ bins

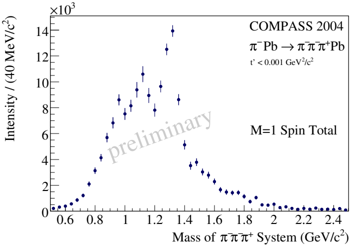






Primakoff signal selection, 2 methods



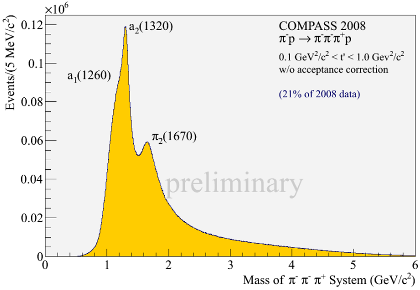


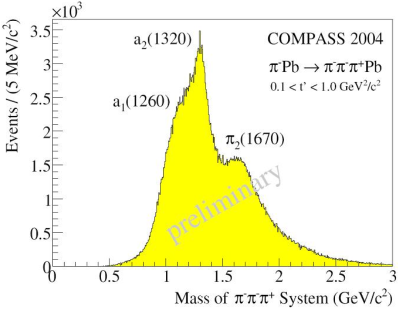
Conclusions on low-t and Primakoff preliminary results

- low-t' M=0 amplitudes and Natural-Parity exchange dominate. Mass-dependent fits are needed. Deck effect coherent background must be respected in addition to resonances
- For M=1 states a clear transition from Coulomb (Primakoff) mechanism to strong (diffractive) mechanisms is observed.
  Expressed in:
  - M=1 waves have sharp spike at $t' < 10^{-3} GeV^2$
  - M=1 waves have fast motion of their production phase in $0 < t' < 10^{-2} GeV^2$
- Individual M=1 intensities and interferences are to be studied:
  - $a_2(1320)$ its radiative widths + details of interference between Coulomb and strong amps
  - $a_1(1260)$ Primakoff production
  - $\pi_2(1670)$ – ?? radiative widrhs
  - 1^{-+} Primakoff production
  - low-mass Chiral-Perturbation theory diagram

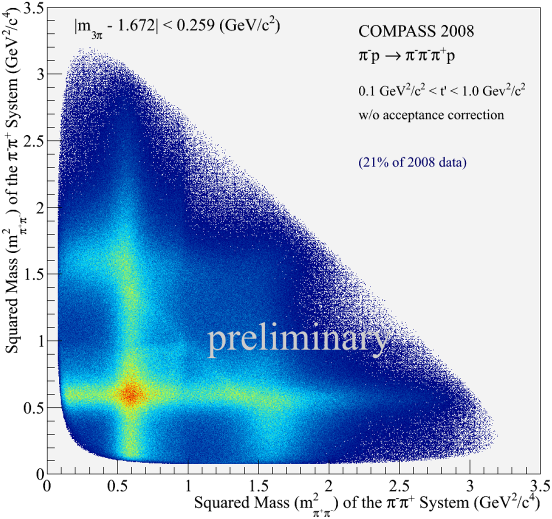
2008 $\pi^-\pi^-\pi^+$ vs. 2004 $\pi^-\pi^-\pi^+$

- 190 GeV π^- beam (dominating)
- 40cm liquid hydrogen target
- Exclusive reaction selection (E_{beam}, $\delta\phi$, N_γ =0 -cuts finally)
- Only high t' ($t' > 0.07\text{GeV}^2/\text{c}^2$) 2008 because of RPD trigger
- $\sim$ **96M events**





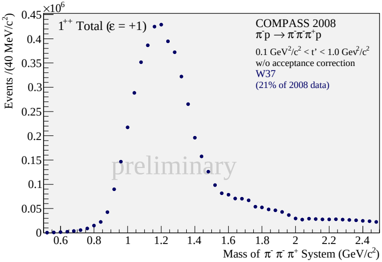
Example of Dalitz plot in $\pi_2(1670)$-region

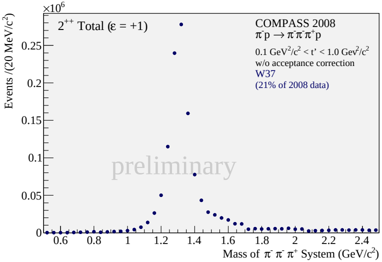


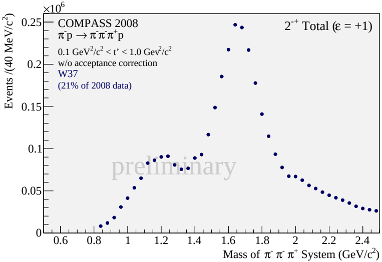
Mass-Independent PWA

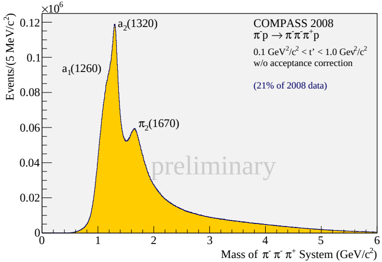
- Illinois/Protvino/Munich Program used.
- Same wave set (42 waves) and thresholds as for 2004 data.
- No acceptance correction applied yet.
- 40 MeV/c^2 mass bins.
- 10 fits per mass bin.
- D-Functions instead of Zemach-Tensors for parametrisation of decay amplitudes.
- Same mass range as for 2004 data: 0.5-2.5 GeV/c^2.

Intensities of dominant J^{PC} states









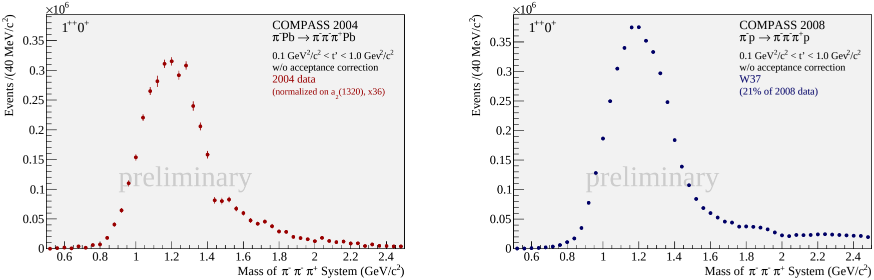


Figure: Total Intensities for $J^{PC} = 1^{++}$ with $M = 0$ (2004 red, 2008 blue)

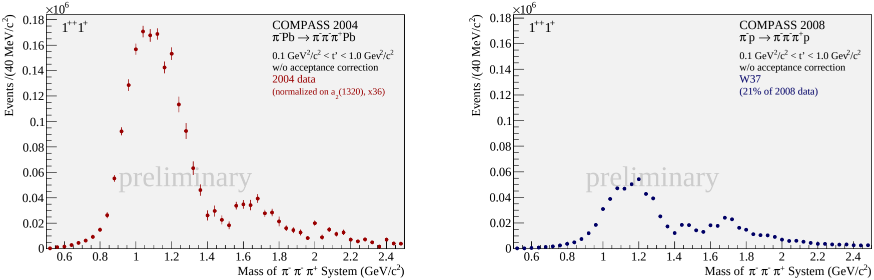


Figure: Total Intensities for $J^{PC} = 1^{++}$ with $M = 1$ (2004 red, 2008 blue)

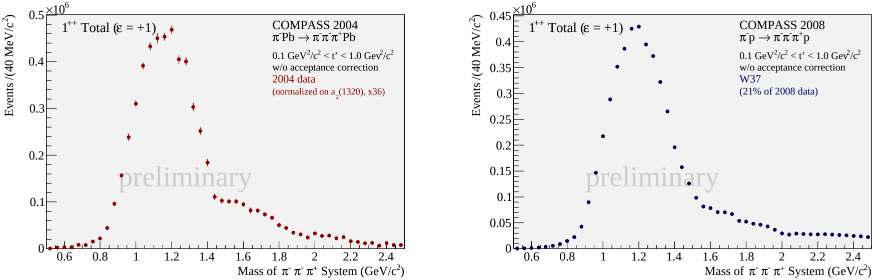
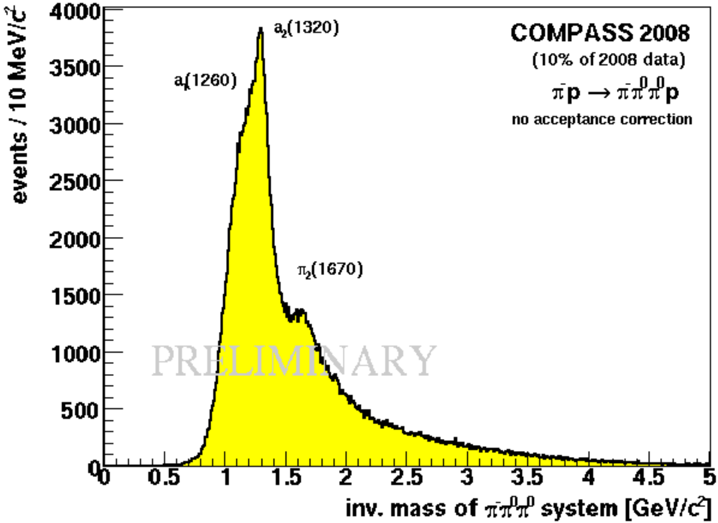
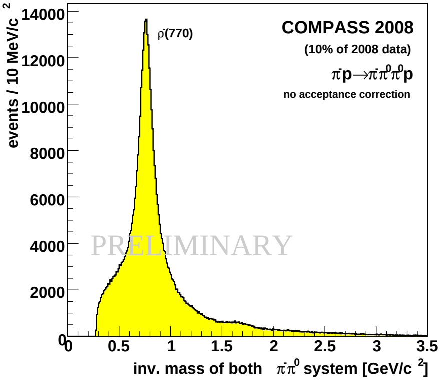


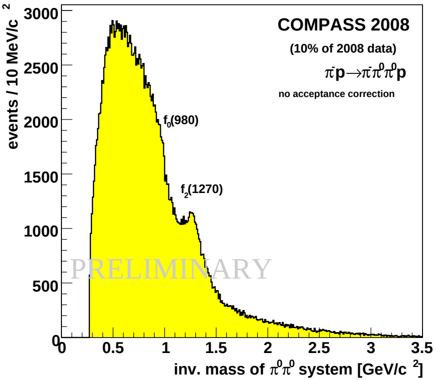
Figure: Total Intensities for $J^{PC} = 1^{++}$ (2004 red, 2008 blue)

$\pi^-\pi^0\pi^0$ mass spectrum



$\pi^-\pi^0\pi^0$ on proton target, 2008 data





PWA of 3π systems: Isospin structure added

Now common routine using d-functions is used for both $\pi^-\pi^0\pi^0$ and $\pi^-\pi^-\pi^+$.

Decay amplitudes for $\rho\pi$ and $\rho_3\pi$ channels (connected only for isospin I=1):

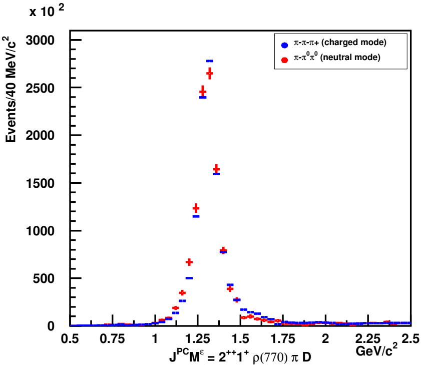
$$\sqrt{\tfrac{1}{2}}\left(\tfrac{1}{\sqrt{2}}[(\pi^-_{(1)}\pi^+)\pi^-_{(2)} + (\pi^-_{(2)}\pi^+)\pi^-_{(1)}]\right) \rightarrow -\sqrt{\tfrac{1}{2}}\left(\tfrac{1}{\sqrt{2}}[(\pi^-\pi^0_{(1)})\pi^0_{(2)} + (\pi^-\pi^0_{(2)})\pi^0_{(1)}]\right)$$

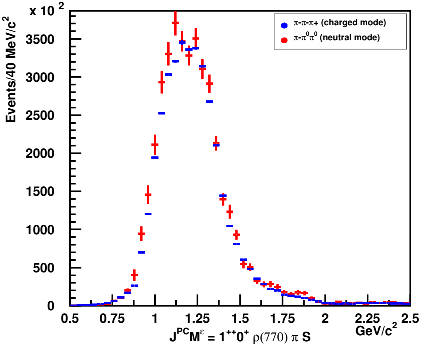
Decay amplitudes for $f_2(1270)\pi$ and $f_0\pi$ channels (always connected):

$$\sqrt{\tfrac{2}{3}}\left(\tfrac{1}{\sqrt{2}}[(\pi^-_{(1)}\pi^+)\pi^-_{(2)} + (\pi^-_{(2)}\pi^+)\pi^-_{(1)}]\right) \rightarrow -\sqrt{\tfrac{1}{3}}\left((\pi^0_{(1)}\pi^0_{(2)})\pi^- \right)$$

Connection means same production amplitudes. If so, ratio of integrals of decay amplitudes squared gives Br=N($\pi^-\pi^0\pi^0$)/N($\pi^-\pi^-\pi^+$)
1) assuming isospin I=1 for $\rho\pi$, obtain relative Br = 1, as decay amplitudes are same up to $m(\pi^{+/-}) \rightarrow m(\pi^0)$. Will have same distributions $\pi^- \rightarrow \pi^0, \pi^+ \rightarrow \pi^-$.
3) for $f_2\pi^-$ and $f_0\pi^-$ decay channels (I=1) Br occurs from isobar decay but could vary from 0.5 in case of big cross-term interference on $\pi^-\pi^-\pi^+$ Dalitz-plot.
3) for I=1 in $\rho\pi$ all corresponding relative phases in $\pi^-\pi^0\pi^0$ and $\pi^-\pi^-\pi^+$ must be equal

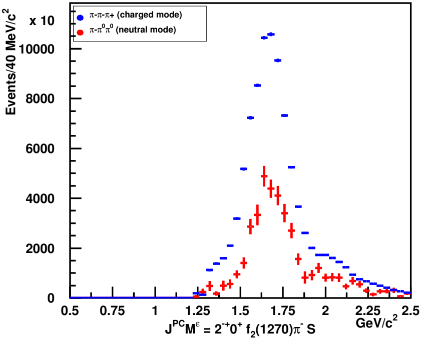
$2^{++}1^+\rho\pi D, 1^{++}0^+\rho\pi S$ $\pi^-\pi^0\pi^0$ $\pi^-\pi^-\pi^+$

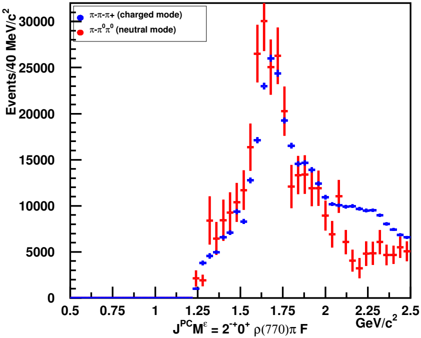




PWA results $\pi^-\pi^0\pi^0$ compared to $\pi^-\pi^-\pi^+$

$2^{-+}0^+ f_2\pi S, 2^{-+}0^+ \rho\pi F$ $\pi^-\pi^0\pi^0$ $\pi^-\pi^-\pi^+$



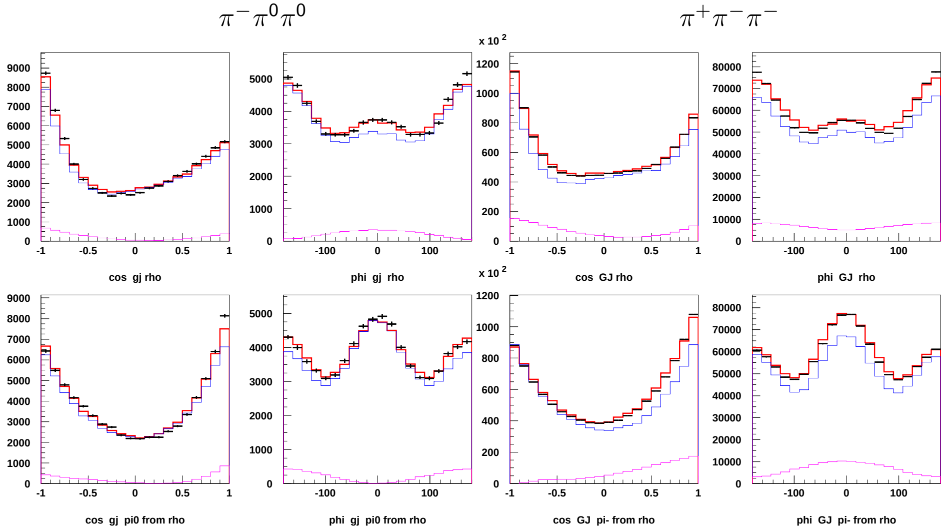


Intensities $\pi^-\pi^0\pi^0$ $\pi^+\pi^-\pi^-$

Br = N($\pi^-\pi^0\pi^0$)/N($\pi^-\pi^-\pi^+$), calculated from isobar model amplitudes:
Br($X \to \rho(770)\pi$ S) = 1. (up to $m(\pi^-) = m(\pi^0)$)
Br($0^{-+} f_0(1400)\pi$ S) = 0.26 (at 1.3 GeV) = 0.29 (at 1.8 GeV)
Br($0^{-+} f_0(980)\pi$ S) = 0.44 (at 1.8 GeV)
Br($1^{++} f_0(1400)\pi$ P) = 0.80 (at 1.3 GeV)
Br($2^{-+} f_2(1270)\pi$ S) = 0.50 (at 1.67 GeV)

Angular distributions

blue: predict from $\rho\pi$ waves only, must have same shapes if I=1 only in $\rho\pi$



conclusions on $\pi^-\pi^0\pi^0$ vs. $\pi^+\pi^-\pi^-$ analysis

- Equal intensities show dominance of $I = 1$ states decaying to $\rho\pi$. (Not just obvious for 1^{++} as it is not only $a_1(1260)$ but also Deck background, which can be produced by Pomeron and also ρ-exchange and so $I = 2$ not excluded).
- For $\pi_2 \to f_2(1270)\pi$ calculated branching is 0.5 and observed one is close to 0.5. Sensitive to acceptance for calo-clusters !
- For $f_0\pi$ decay channels there are significant deviations for $N(\pi^-\pi^0\pi^0)/N(\pi^-\pi^-\pi^+)$ from 0.5 are expected. This must be taken into the account for extracting cross-sections and branchings of $\pi(1300)$, $\pi(1800)$ and $a_1(1260) \to f_0\pi$
- In case of $I = 1$ only, all relative phases between similar states should be equal in all mass bins (already observe, to-be-released!!)
- Angular distributions for corresponding variables from $\rho\pi$ selections look similar for $\pi^-\pi^0\pi^0$ versus $\pi^-\pi^-\pi^+$. Effect of non-$\rho\pi$ contributions is estimated by predict from PWA.
- Compairing of intensity and phase of $J^p = 1^-$ wave $\pi^-\pi^0\pi^0$ and $\pi^+\pi^-\pi^-$ can confirm that it is really I=1 state. Work in progress.

Central Production

- Parity conservation in production and decay process.
- Equal reggeons (in case of 2 pomerons). Not required in Reggeon-Pomeron case
- Isobar model for N-particle decay amplitudes (same as we use in diffractive production).

A.B Kaidalov, V.A. Khoze, A.D. Martin and M.G. Ryskin "Central exclusive diffractive production as a spin-parity analyser: from hadrons to Higgs"
F.E. Close, A. Kirk, G. Shuler "Dynamics of Glueball and $q\bar{q}$ production in the central region of pp collisions".

Examples of amplitudes

$T_{i..j}$ is J^{PC} decay amplitude with cartesian coordiantes (tensor formalism)

0^{++}

$\sim constT$ or $(\vec{x}_1\vec{x}_2)T$

0^{-+}

$([\vec{x}_1 \times \vec{x}_2]\vec{z}_1)$

1^{++}

$([\vec{x}_1 \times \vec{x}_2]T)$ - asymmetric

$([\vec{x}_1 \times \vec{z}_1]T)$ - $([\vec{x}_2 \times \vec{z}_1]T)$

1^{--}

$(\vec{z}_1 T)$ - asymmetric, OK !

1^{-+}

$(\vec{x}_1 T) + (\vec{x}_2 T)$

In case of $R_1 = \pi$ above approach gives you reflectivity basis for diffraction.