Results from the VES experiment

D. Ryabchikov

Technische Universität München, Institute for High Energy Physics Protvino

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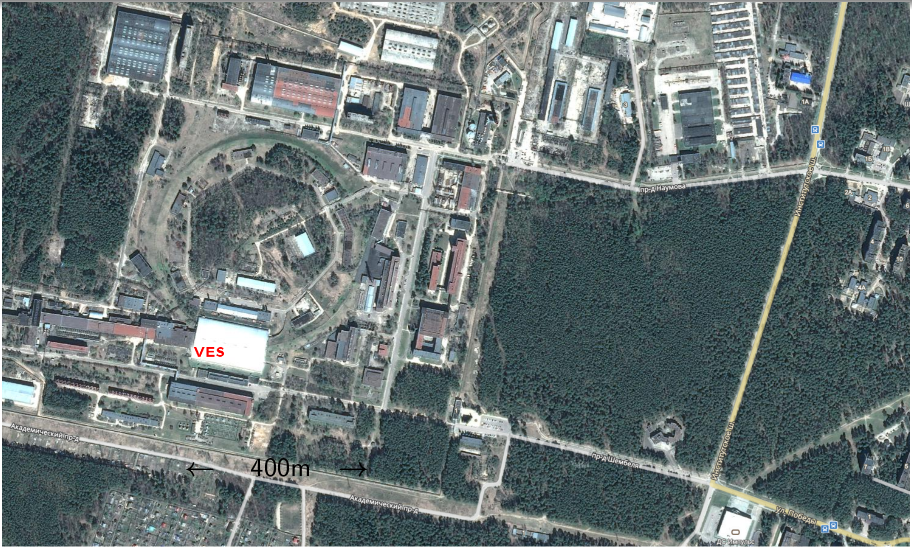
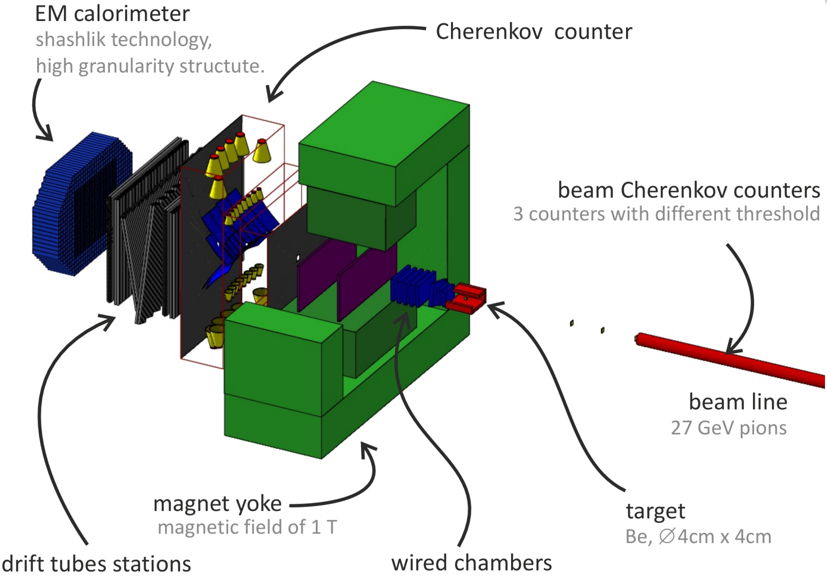
Plan of the talk

- The VES detector
- $\pi^- Be \to \pi^-\pi^-\pi^+ Be$ and $\pi^- Be \to \pi^-\pi^0\pi^0 Be$ at $p_{\pi^-} = 29$ GeV
  - Introduction to 3π analysis
  - Specific features of PWA
    - Isospin relations
    - Rank=1 applicability for diffraction on nucleus targets ?
  - Preliminary Mass-independent PWA
  - Example of preliminary Mass-dependent analysis
  - Prospectives of increased statistics for 3π states
- Summary, outlook

Institute for High Energy Physics Protvino



The VES apparatus - scheme



VES apparatus - main features and upgrade

- Secondary beam from U-70 PS: $p_{beam} = 29$ GeV ($\approx 97\ \%\ \pi^-$, $\approx 1.7\ \%\ K^-$)
- Be target ($\approx 0.1\ \lambda$)
- Magnetic spectrometer $p_{kick} = 0.56$ GeV
- Tracking system
- EM - calorimetry
- Multicell Cherenkov Counter (28 Cells) - PID for secondary tracks
- Minimum-bias trigger (Beam Killer)

The huge upgrade of VES detector - finished in 2011

- **Newly built EMC:** 1215 small (38x38 mm) + 368 big (76x76 mm) Shashlyk counters
- **New large area trackers:** Drift tubes
- **New FE electronics** for tracking detectors
- **New fast DAQ**: $4 \cdot 10^4/9s$ cycle, dead time = 22 μs)
- **New trigger** Flexible → Single - track events (first time at VES !)
- **New Detector Control System**
- **New Beam Momentum Spectrometer**
- **New off-line software** reconstruction, GEANT4 based MC, developed PWA

Introduction to 3π analysis

The main existing experimental results on 3π - systems:

- Existence and properties of $a_1(1260)$ - meson, parameters of $a_2(1320)$ and $\pi_2(1670)$ - ACCMOR (1980-1981)
- Study of $\pi(1800)$ - hybrid candidate VES, 1991-2005
- Existence and properties of spin-exotic $\pi_1(1600)$ - meson, VES $\leftrightarrow$ E852 (1992-2005), COMPASS (2009)
- First analysis of $\pi^-\pi^-\pi^+$ and $\pi^-\pi^0\pi^0$ wth same tecknics E852 (2005)
- Evidence for new narrow state $a_1(1420)$ in 3π COMPASS (2013-2015) and $\pi^-\pi^0\pi^0$ VES (2013)
- Chiral dynamics and radiative decays $a_2(1320)$ and $\pi_2(1670)$ $\rightarrow \pi\gamma$ COMPASS (2011-2014)
- Analysis of 3π with unlimited rank of spin-density matrix and $\pi^-\pi^0\pi^0$ using rank=1 VES (2013-2016)

Still high-disputed issues:

- Spin-exotic $\pi_1(1600) \to 3\pi$
- Further study of $a_1(1420)$ (tail of rescattered $a_1(1260) \to K\bar{K}\pi$?)
- Excited states $\pi_2(1880)$, $\pi_2(2100)$, $a_1(1900)$, $a_2(1700)$

Possible model-dependence of the results. What model is correct ?

Example: unlimited rank of spin-density matrix model vs. rank=1 model.

Brief introduction to mass-independent PWA

Mass-independent PWA events density:

$$\mathcal{I}(m,t',\tau) = \sum_{\varepsilon=\pm1}\sum_{r=1}^{N_r}\left|\sum_i T^{\varepsilon}_{i,r}(m,t')\bar{\psi}^{\varepsilon}_i(m,\tau)\right|^2 + FLAT$$

Normalized decay amplitude $\bar{\psi}^{\varepsilon}_i(m,\tau) = \psi^{\varepsilon}_i(m,\tau)/\sqrt{\int |\psi^{\varepsilon}_i(m,\tau')|^2\, d\rho(\tau')}$

- $\psi^{\varepsilon}_i(\tau)$ enumerated by its quantum numbers i (coherent) ε (incoherent)
- $i,\varepsilon = J^{PC}M^{\varepsilon}$ $[isobar]$ π L
- $\psi(\tau)$ has no free parameters $\rightarrow$ this makes fits very quick

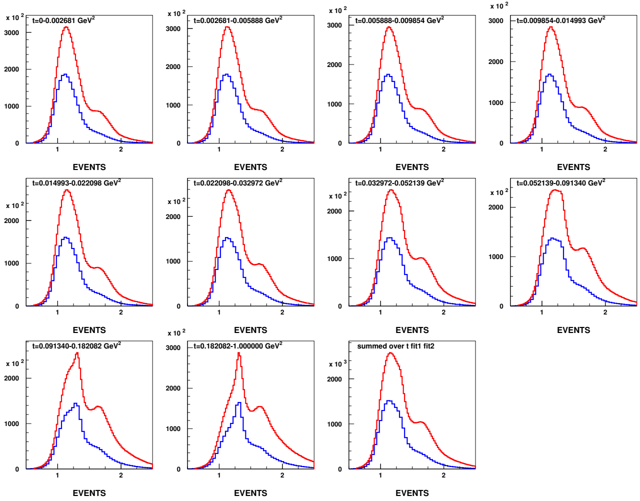
Transition amplitudes $T^{\varepsilon}_{ir}(m,t')$ fitted independently in each $(m,\ t')$ - bin
Events density expressed through spin-density matrix $\rho^{\epsilon}_{i,j}$:

$$\mathcal{I}(m,t',\tau) = \sum_{\epsilon=\pm1}\sum_{i,j}\rho^{\epsilon}_{i,j}(m,t')\bar{\psi}^{\epsilon}_i(m,\tau)\bar{\psi}^{\epsilon *}_j(m,\tau), \quad \rho^{\varepsilon}_{i,j} = \sum_{r=1}^{N_r} T^{\epsilon}_{i,r}{T^{\epsilon}_{j,r}}^*$$

Diagonal element $\rho^{\epsilon}_{i,i}$ - number of events associated with a given decay amplitude

Events input to PWA $\pi^-\pi^-\pi^+$(red) $\pi^-\pi^0\pi^0$ (blue)

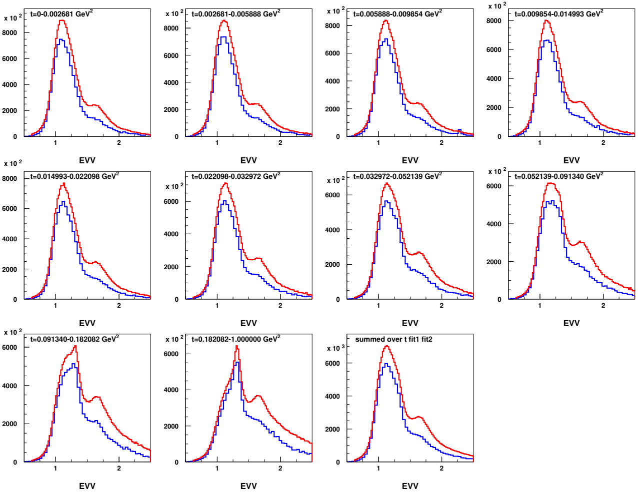
The current data was taken end of 2012



$N(\pi^-\pi^-\pi^+) = 41\ 000\ 000$ $8\ 200\ 000$ (t'=0.1-1.0 GeV^2)

$N(\pi^-\pi^0\pi^0) = 20\ 500\ 000$ $3\ 800\ 000$ (t'=0.1-1.0 GeV^2)

Acc-Corrected events $\pi^-\pi^-\pi^+$(red) $\pi^-\pi^0\pi^0$ (blue)



Isospin relations between $\pi^-\pi^-\pi^+$ and $\pi^-\pi^0\pi^0$

Decay amplitudes for $\rho\pi$ (I=1 of 2π isobar) are connected if isospin $I(3\pi) = 1$:

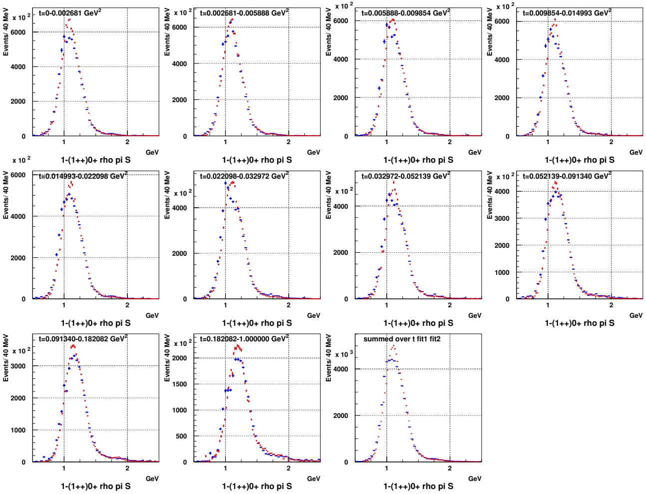
$$\sqrt{\tfrac{1}{2}}(\tfrac{1}{\sqrt{2}}[(\pi^-_{(1)}\pi^+)\pi^-_{(2)} + (\pi^-_{(2)}\pi^+)\pi^-_{(1)}]) \leftrightarrow -\sqrt{\tfrac{1}{2}}(\tfrac{1}{\sqrt{2}}[(\pi^-\pi^0_{(1)})\pi^0_{(2)} + (\pi^-\pi^0_{(2)})\pi^0_{(1)}])$$

Decay amplitudes for $f\pi$ (I=0 of 2π isobar) channels are always connected :

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

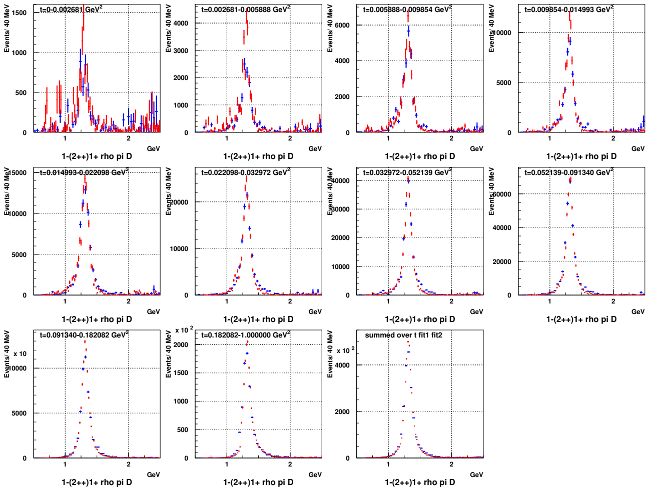
Connection means same production amplitudes.
Br=N($\pi^-\pi^0\pi^0$)/N($\pi^-\pi^-\pi^+$) is just ratio of integrals of squared decay amplitudes
1) $\rho\pi$: Br=1 as decay amplitudes have same structure up to $m(\pi^{+/-}) \to m(\pi^0)$.
3) $f\pi^-$: Br comes from different isobar decay and bose-symetrization. Br can differ from 0.5 in case of big cross-term interference on $\pi^-\pi^-\pi^+$ Dalitz-plot.
3) All corresponding relative phases in $\pi^-\pi^0\pi^0$ and $\pi^-\pi^-\pi^+$ are equal - in case of appropriate choosing of directions of "spin analyzers" (π^-- direction in 2π CMS for both systems)

$1^{++}0^+\rho(770)\pi S$ in $\pi^-\pi^-\pi^+$(red) $\pi^-\pi^0\pi^0$ (blue)

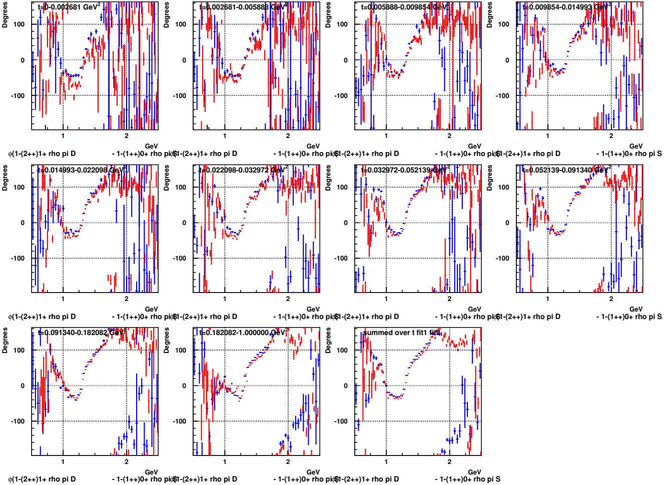


Isospin relations for intensity - approx. satisfied in each (m, t) - bin

$2^{++}1^{+}\rho(770)\pi D$ in $\pi^-\pi^-\pi^+$(red) $\pi^-\pi^0\pi^0$ (blue)

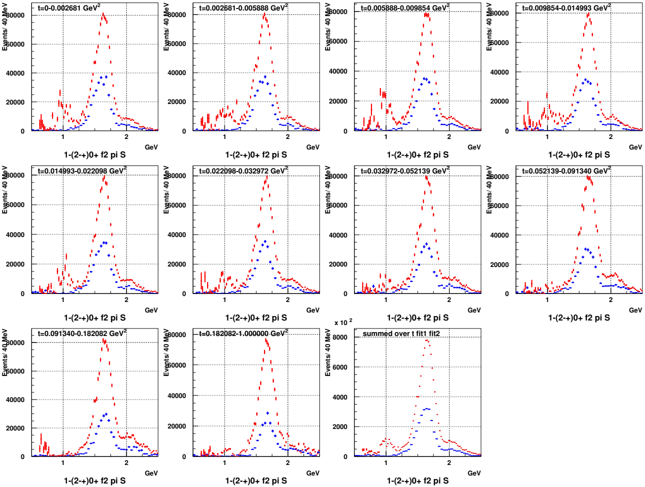


Isospin relations for intensity - approx. satisfied in each (m, t) - bin



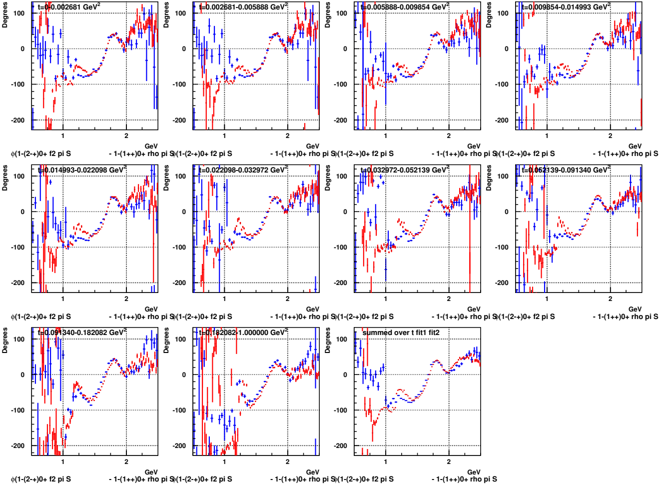
Isospin relations for relative phase - approx. satisfied in each (m, t) - bin

$2^{-+}0^{+}f_2\pi S$ in $\pi^-\pi^-\pi^+$(red) $\pi^-\pi^0\pi^0$ (blue)



Isospin relations for intensity - approx. satisfied in each (m, t) - bin

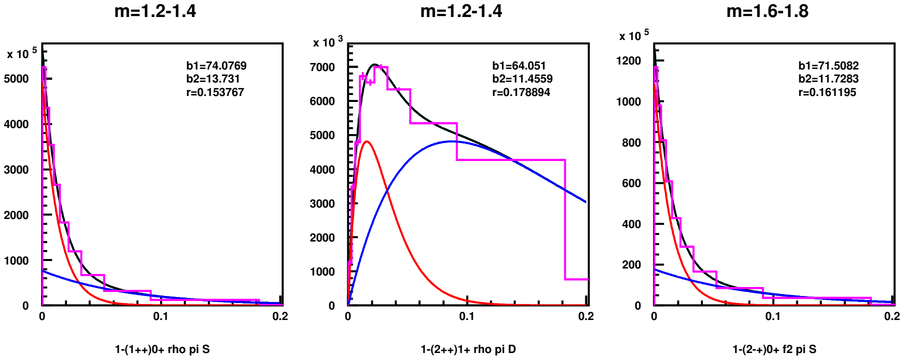
Phase of $2^{-+}0^+ f_2\pi S$ $\pi^-\pi^-\pi^+$(red) $\pi^-\pi^0\pi^0$ (blue)



Isospin relations for relative phase - approx. satisfied in each (m, t) - bin

$\frac{dN}{dt}$ for $1^{++}0^{+}\rho\pi S$, $2^{++}1^{+}\rho\pi D$, $2^{-+}0^{+}f_2\pi S$

t'-dependence of partial-wave intensities, integrated in broad $m(\pi^-\pi^-\pi^+)$ regions
Fit function $\frac{dN}{dt} = x\ t'^M\ (e^{-b_c t'} + r \quad e^{-b_i t'})$



Toy formula for adding coherent+incoherent processes

Adding coherent+incoherent density matrices:

- example : 2x2 matrix; M=0 and M=1 states
- phase is assumed to be the same for 2 processes
- if b_c, b_i are universal and $r_1 = r_2 \to Coh = 1$
- in general, different t^M factors are cancelled

$$\begin{pmatrix} e^{-b_c t} & \sqrt{t}\, e^{-b_c t} \\ & t e^{-b_c t} \end{pmatrix} + \begin{pmatrix} r_1 e^{-b_i t} & \sqrt{r_1 r_2}\sqrt{t}\, e^{-b_i} \\ & t \cdot r_2 e^{-b_i t} \end{pmatrix}$$

$$Coh = \frac{\cancel{\sqrt{t}}\left(e^{-b_c t} + \sqrt{r_1 r_2}\, e^{-b_i t}\right)}{\cancel{\sqrt{t}}\sqrt{\left(e^{-b_c t} + r_1 e^{-b_i t}\right)\left(e^{-b_c t} + r_2 e^{-b_i t}\right)}}$$

Mass-independent PWA events density:

$$\mathcal{I}(m,t',\tau) = \sum_{\varepsilon=\pm1}\sum_{r=1}^{N_r}\left|\sum_i T_{i,r}^{\varepsilon}(m,t')\bar{\psi}_i^{\varepsilon}(m,\tau)\right|^2$$

The model for global $m(3\pi)$ - dependence

$$\mathcal{I}(m,t',\tau) = \sum_{\epsilon}\sum_{r}\left|\sum_i\sum_k C_{ikr}^{\epsilon} BW_{ik}(m,t',\zeta)\sqrt{\int |\psi_i^{\varepsilon}(\tau',m)|^2\, d\rho(\tau')}\bar{\psi}_i^{\epsilon}(\tau,m)\right|^2$$

Comparing mass-indep and global mass-dep :

$$\rho_{i,j}^{\epsilon}(m,t') = \sum_{r}\sum_{k,l} C_{ikr}^{\epsilon} C_{jlr}^{\epsilon *} BW_{ik}(m,t',\zeta) BW_{jl}^{*}(m,t',\zeta)\sqrt{\int |\psi_i^{\varepsilon}(m,\tau')|^2\, d\rho(\tau')}\sqrt{\int$$

Mass-independent intensities normalized to number of observed events $\rightarrow$ mass-dependent inensities contain opening phase-space factors

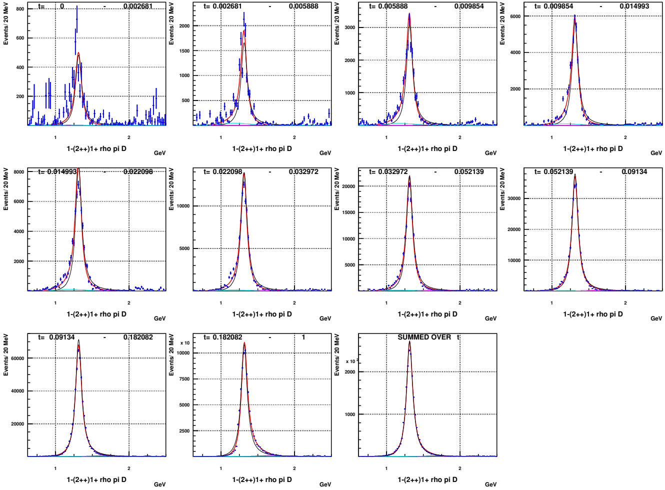
The current mass-dependent fit

The sub-set of partial waves fitted mass-dependently:

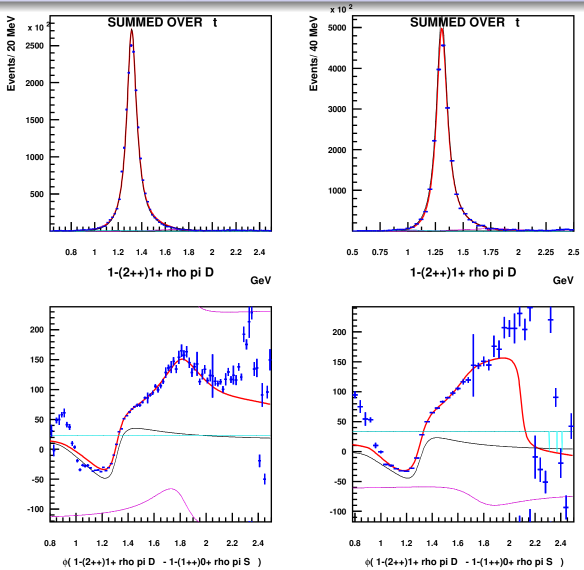
- $1^{++}0^{+}\rho(770)\pi S$
- $2^{++}1^{+}\rho(770)\pi D$
- $2^{++}1^{+}f_2(1270)\pi P$
- $0^{-+}0^{+}f_0(980)\pi S$
- $1^{++}0^{+}f_0(980)\pi P$
- $2^{-+}0^{+}f_2(1270)\pi S$
- $4^{++}1^{+}\rho(770)\pi G$
- $4^{++}1^{+}f_2(1270)\pi F$

The following mass-dependent fit curves and following numbers are NOT to be considered as final results !

$2^{++}1^{+}\rho^{0}(770)\pi^{-}D$ m-dep fit in 10 t' bins for $\pi^{-}\pi^{-}\pi^{+}$



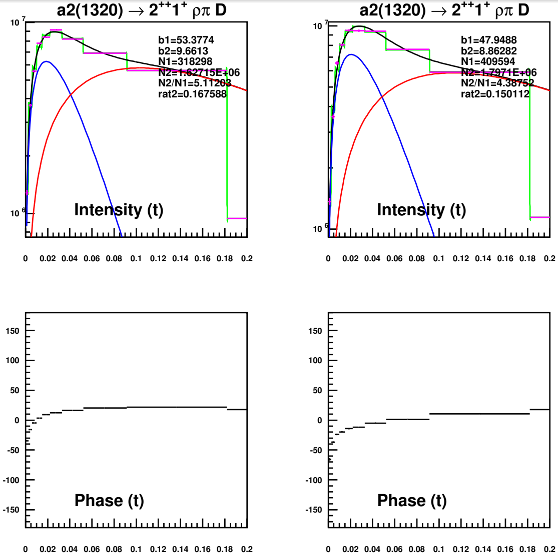
$2^{++}1^{+}\rho(770)\pi D$ intens and phase (m) - combined t



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

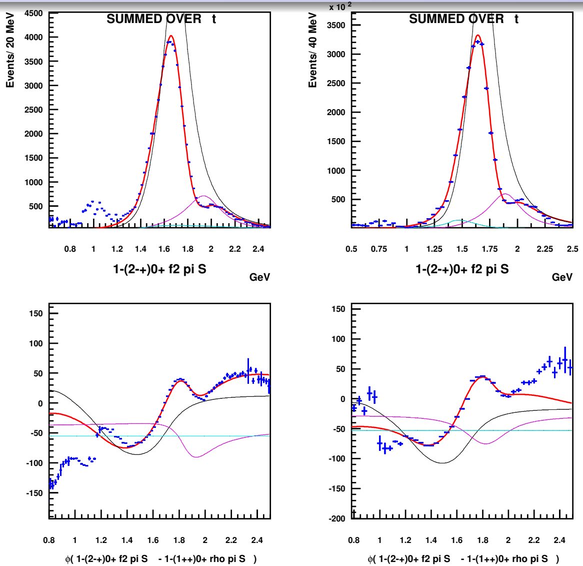
$a_2(1320)$ $M = 1.319$ $\Gamma = 0.103$ $M = 1.315$ $\Gamma = 0.124$

$a_2(1320)$ intens and prod. phase (t)



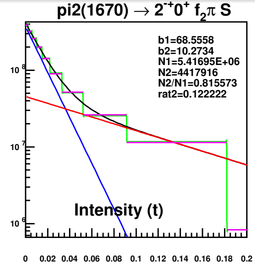
$\pi^-\pi^-\pi^+$ $\pi^-\pi^0\pi^0$

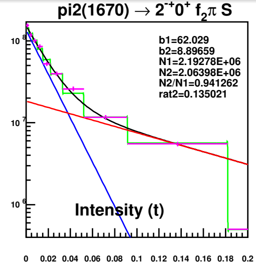
$2^{-+}0^+ f_2 \pi^- S$ intens and phase (m)

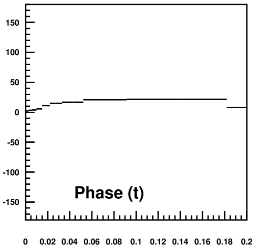


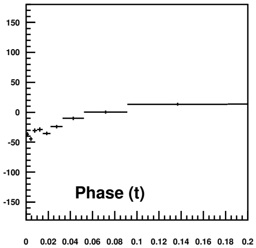
$\pi_2(1670)$	$M = 1.690$	$\Gamma = 0.308$	$M = 1.678$	$\Gamma = 0.319$
$\pi_2(1880)$	$M = 1.940$	$\Gamma = 0.380$	$M = 1.890$	$\Gamma = 0.370$

$\pi_2(1670)$ intens and prod-phase (t)



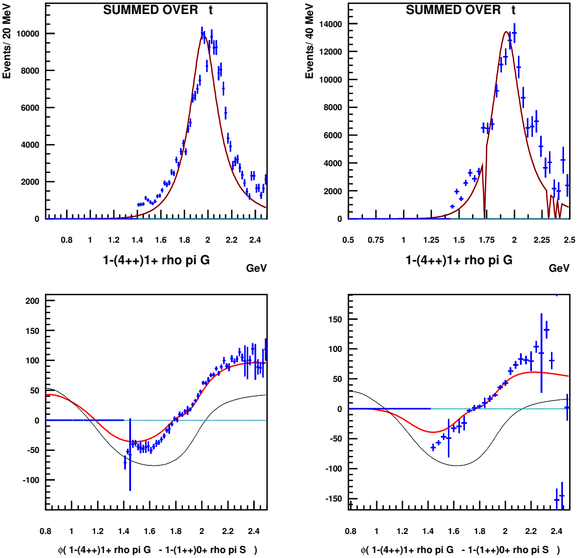






$\pi^-\pi^-\pi^+$ $\pi^-\pi^0\pi^0$

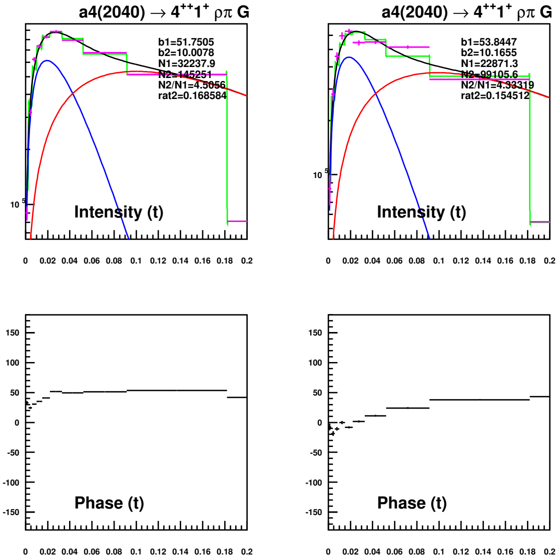
$4^{++}1^{+}\rho\pi G$ intens and phase (m)

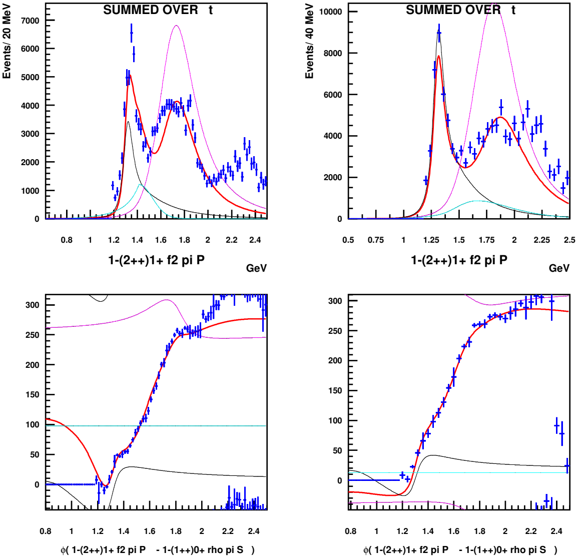


$\pi^-\pi^-\pi^+$ $\pi^-\pi^0\pi^0$

$a_4(2050)$ $M = 1.950$ $\Gamma = 0.294$ $M = 1.910$ $\Gamma = 0.317$

$a_4(2050)$ intens and phase (t)

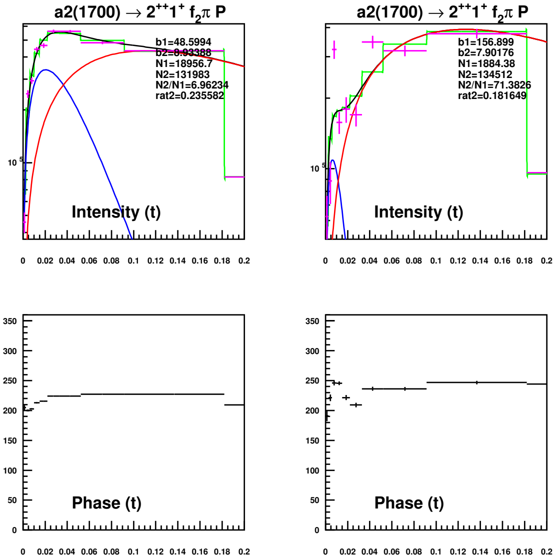




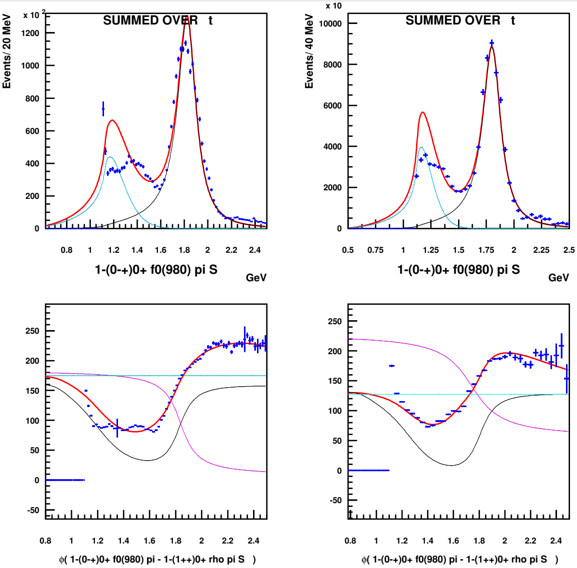
$\pi^-\pi^-\pi^+$ $\pi^-\pi^0\pi^0$

$a_2(1700)$ $M = 1.690$ $\Gamma = 0.430$ $M = 1.780$ $\Gamma = 0.550$

$a_2(1700)$ intens and phase (t)

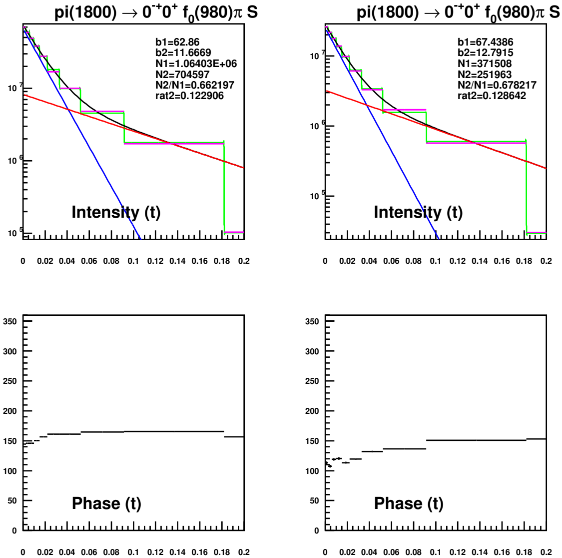


$0^{-+}0^{+}f_0(980)\pi S$ intens and phase (m)

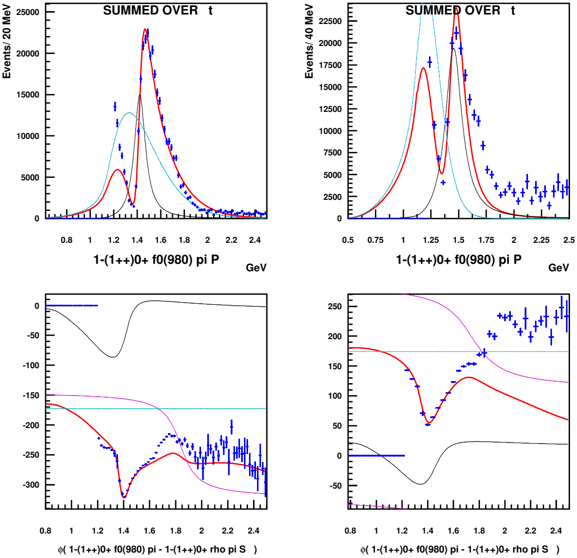


$M = 1.820 \quad \Gamma = 0.191$ $\qquad$ $M = 1.800 \quad \Gamma = 0.199$

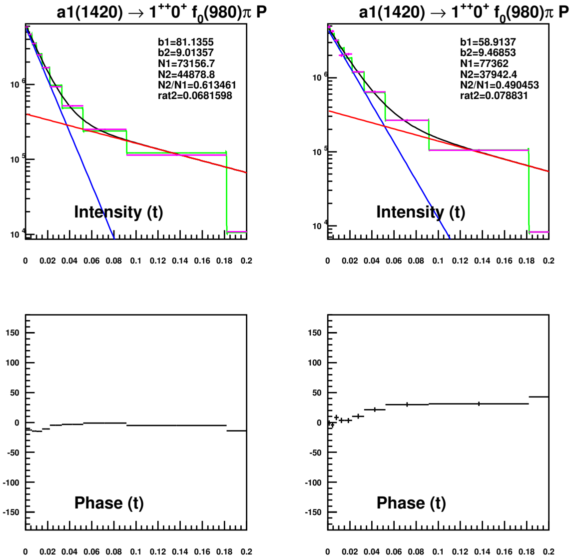
$\pi(1800)$ intens and phase (t)



$1^{++}0^+ f_0(980)\pi P$ intens and phase (m)



$M = 1.419 \quad \Gamma = 0.115$ $\qquad$ $M = 1.450 \quad \Gamma = 0.188$



a1(1420) → 1++0+ f0(980)π P
b1=81.1355
b2=9.01357
N1=73156.7
N2=44878.8
N2/N1=0.613461
rat2=0.0681598
Intensity (t)
a1(1420) → 1++0+ f0(980)π P
b1=58.9137
b2=9.46853
N1=77362
N2=37942.4
N2/N1=0.490453
rat2=0.078831
Intensity (t)
Phase (t)
Phase (t)

Summary

- The mass independent PWA, using rank=1 fit model and 10 t′ intervals is first applied for both $\pi^-\pi^-\pi^+$ and $\pi^-\pi^0\pi^0$ systems, diffractively produced on Be nucleus
- The preliminary mass-dependent PWA results are first compared between $\pi^-\pi^-\pi^+$ and $\pi^-\pi^0\pi^0$ systems

Outlook

- Further developement of the mass independent PWA
  - Comparison of rank=1 vs. unlimited rank density-matrix model
  - Partial coherence model ?
  - Free-isobarred analysis for both $\pi^-\pi^-\pi^+$ and $\pi^-\pi^0\pi^0$
- Further developement of the mass-dependent PWA
  - Choosing of the best mass-dependent wave sub-set
  - Choosing of resonant and background parametrization (t'-dependent background shape ?)
  - Full study of local minima and spurious solutions in the mass-dep fit