Status of the PAWIAN Software

Bertram Kopf

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Outline

- Status of the PAWIAN software
  - introduction
  - supported reactions
  - supported formalisms
  - coupled channel analysis
  - supported dynamics with K-matrix representation
  - further tools

- Summary of the PWA activities with relevance for PANDA
  - Crystal Barrel @ LEAR data

PWA Software Package

PWA activities for PANDA started in Bochum in 2010 with the aims:

- to develop a generic PWA software package
- to support all physics cases to be studied at PANDA and partly at other hadron spectroscopy experiments

Software package PAWIAN (**PA**rtial **W**ave **I**nteractive **AN**alysis) already in a good shape and several analyses have been started

- Full hypothesis and other input settings defined via configuration files
- Event based maximum likelihood fit
- Minimization with MINUIT2 and prefit with genetic algorithms
- Running on multi-core CPUs and computing clusters
- qft++: decay amplitudes in various formalisms (*M. Williams (CLAS, GlueX)* Computer Physics Communications, Vol. 180, Issue 10, 2009)
- Support also coupled channel analyses

Supported Reactions

$\bar{p}p$-Annihilation

- $\bar{p}p$ coupling to initial states via s-channel characterized by $I^G(J^{PC})$
- Amplitudes in terms of LS- states
- All $I^G(J^{PC})$-LS combinations for a user-defined L_{max}
- Individual $I^G(J^{PC})$-LS combinations can be disabled

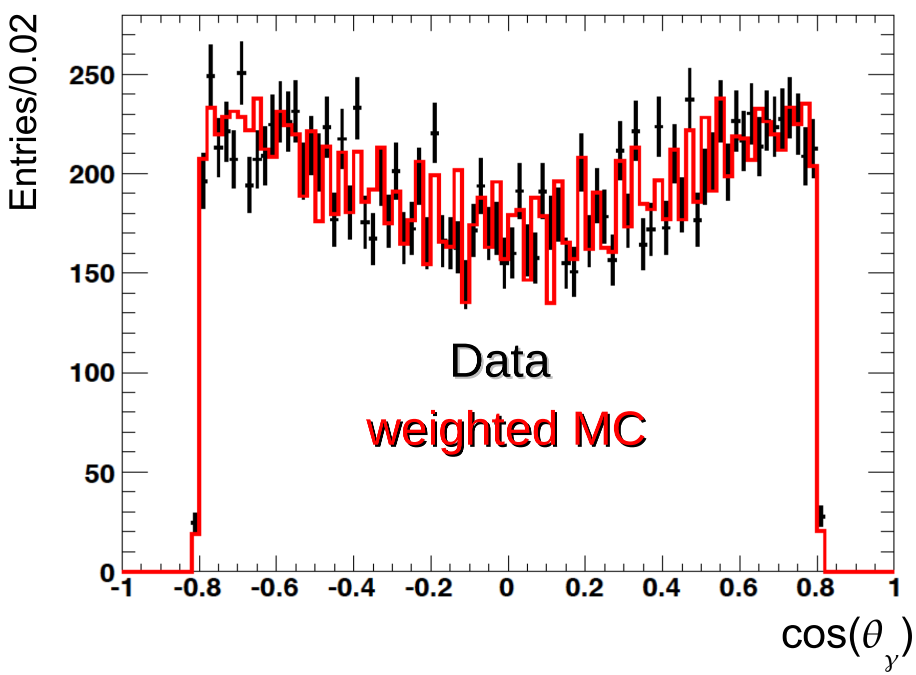
J	Singulett $\lambda = 0$	J^{PC}	Triplett $\lambda = \pm 1$	J^{PC}	Triplett $\lambda = \pm 1, 0$	J^{PC}
0	$^1S_0$	0^{-+}			$^3P_0$	0^{++}
1	$^1P_1$	1^{+-}	$^3P_1$	1^{++}	$^3S_1, {}^3D_1$	1^{--}
2	$^1D_2$	2^{-+}	$^3D_2$	2^{--}	$^3P_2, {}^3F_2$	2^{++}
3	$^1F_3$	3^{+-}	$^3F_3$	3^{++}	$^3D_3, {}^3G_3$	3^{--}
4	$^1G_4$	4^{-+}	$^3G_4$	4^{--}	$^3F_4, {}^3H_4$	4^{++}
5	$^1H_5$	5^{+-}	$^3H_5$	5^{++}	$^3G_5, {}^3I_5$	5^{--}
6	$^1I_6$	6^{-+}	$^3I_6$	6^{--}	$^3H_6, {}^3J_6$	6^{++}

Supported Reactions

e^+e^--Annihilation

- Initial state characterized by $I^G(J^{PC}) = 0^-(1^{--})$, $\lambda=\pm 1$
- Expansion in LS schema results in a set of too many, not independent amplitudes
- Description with helicity amplitudes matches with the number of independent amplitudes

Example: production angle of the reaction $e^+e^- \rightarrow J/\psi \rightarrow \phi\phi\gamma$



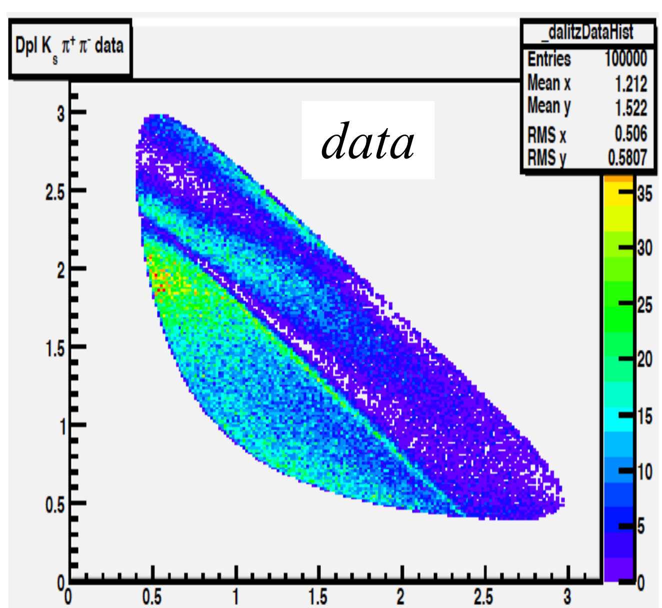
Supported Reactions

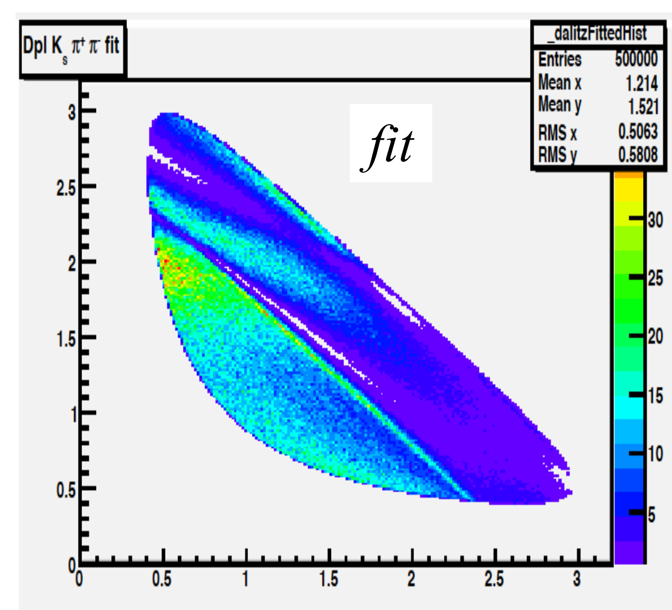
<u>Start with an isolated intermediate resonance</u>

- For the investigation of specific channels it is desired to start the PWA with an isolated and well known resonance
- Test with toy Monte Carlos: $D^0 \rightarrow K_S \pi^+ \pi^-$
  - Monte Carlo events generated with LASS parametrization for $(K\pi)_S$-wave and Anisovich K-matrix parametrization for $(\pi\pi)_S$- wave provided by A. Pitka
  - fit with $(K\pi)_S$ K-Matrix parametrization used by FOCUS

Configuration File

```
motherRes = D0

finalStateParticle = Kshort
finalStateParticle = pion+
finalStateParticle = pion-

production = Kshort pipiS
production = KPiS12- pion+
production = KPiS32- pion+

decay = Cano pipiS To pion+ pion-
decay = Cano noIso KPiS12- To Kshort pion-
decay = Cano noIso KPiS32- To Kshort pion-

addDynamics = pipiS PiPiSWaveAS
addDynamics = KPiS12- KpiSWaveIso12
addDynamics = KPiS32- KpiSWaveIso32
```





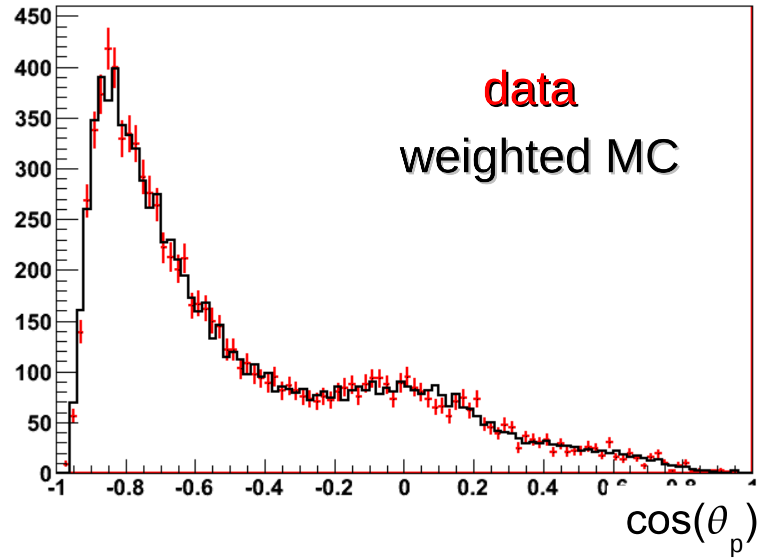
Supported Reactions

γp-Reaction

- γp-coupling of the initial states via s-channel characterized by $I(J^P)$
  - LS schema not suitable
  - representation via electric and magnetic multipoles matches with the number of independent amplitudes
  - configuration of contributing states via L_{max}
- Support all formalisms with half integral spin particles
- To be done: description of the t- and u-channel; validation

Example: production angle

of the reaction $\gamma\ p \rightarrow X\ p$



Supported Formalisms

- Helicity formalism
  - amplitudes expanded in helicities of the contributing resonances
  - fit parameter characterized by $\mathbf{A^{J^{PC}}_{\lambda 1\, \lambda 2}}$
- Canonical formalism
  - amplitudes defined by LS combinations
  - fit parameter characterized by $\mathbf{A^{J^{PC}}_{L\,S}}$
- Rarita-Schwinger formalism
  - coupling of polarization tensors with orbital angular momentum tensors
  - fit parameter characterized by $\mathbf{A^{J^{PC}}_{L\,S}}$
  - complete Lorentz-invariant formulation
  - status: working up to rank 4 tensors, validation needed

PAWIAN automatically builds the full amplitudes at runtime
by considering all relevant conservation laws

Supported Formalisms

User-friendly setting of the full decay tree and of the choice of the applied formalism via the configuration file

```
production = rho0 eta
production = omega eta
production = a2(1320)+ pion-
production = a2(1320)- pion+
production = a0(980)+ pion-
production = a0(980)- pion+
production = f2(1270) eta
production = pipiS eta

decay = Cano rho0 To pion+ pion-
decay = Cano omega To pion+ pion-
decay = Cano a2(1320)+ To pion+ eta
decay = Cano a2(1320)- To pion- eta
decay = Cano a0(980)+ To pion+ eta
decay = Cano a0(980)- To pion- eta
decay = Cano f2(1270) To pion+ pion-
decay = Cano pipiS To pion+ pion-
```

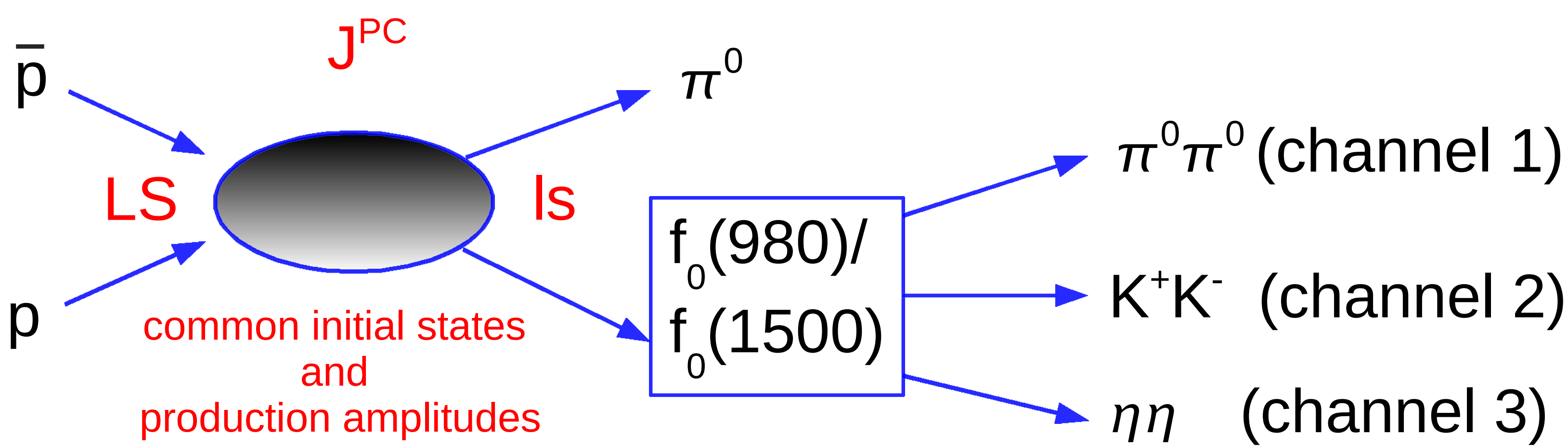
$\bar{p}p$ production channels

decay channels

Supported formalisms:
canonical ("Cano"), helicity ("Heli")
and tensor ("Tensor")

Coupled Channel Analysis

- Simultaneous fit of different decay channels
  - combination of different types of initial state reactions not yet possible
- Advantages
  - constraints due to common amplitudes
  - better conservation of the unitarity
  - better description of threshold effects
  - unique description of the dynamics (e.g. K-matrix)
  - less total fit parameters
  - less ambiguities
- Very first results presented by J. Pychy



Supported Dynamics

- Breit-Wigner parametrization
  - suitable for isolated, non-overlapping resonances far from the relevant thresholds
  - sum of two or more overlapping resonances violates the unitarity
- Flatté parametrization
  - takes into account one pole and two decay modes
  - suitable for poles at thresholds like
    - $a_0(980)$ with coupling to $\pi\eta$ and KK
    - $f_0(980)$ with coupling to $\pi\pi$ and KK
- K-matrix formalism with P-vector approximation
  - common description for all relevant poles and decay modes
  - ensures unitarity, proper description of threshold effects, . . .
  - already available
    - $(\pi\pi)_S$ wave parametrization up to 1900 MeV/c^2 with 5 poles and 5 channels by *Anisovich and Sarantsev, Eur. Phys. J. A16, 229(2003)*
    - $(K\pi)_S$ wave parametrization with one pole and two channels by Pennington and used by FOCUS, *Phys. Lett. B653 (2007) 1-11*
    - User-defined K-matrix with unlimited number of poles and decay modes and flexible definition of the background terms

Configuration of the Dynamics

```
addDynamics = rho0 BreitWigner
addDynamics = omega BreitWigner
addDynamics = a2(1320)+ BreitWigner
addDynamics = a2(1320)- BreitWigner
addDynamics = a0(980)+ Flatte K+ K
addDynamics = a0(980)- Flatte K- K
addDynamics = f2(1270) BreitWigner
```

Breit-Wigner and Flatté

```
addDynamics = pipiS PiPiSWaveAS
```

K-matrix with $(\pi\pi)_S$- wave

Separate file for generic K-matrix

```
addDynamics = aMatrix+ KMatrix ./kMatrixa0.cfg
```

```
noOfChannels = 2
noOfPoles    = 2

gFactor = pion0 eta     0.8675565176315263      0.343722950741845
gFactor = K+ K-         1.158571512534554       1.331184263998505


pole = a980 1.026117294351137
pole = a1450 1.525550946236624


projection = pion0 eta
useBarrierFactors = false
orbitalMomentum = 1

orderKMatrixBackground = -1
useAdler0 = false
s0Adler = 0.23
snormAdler = 0.265839
```

K-Matrix Parametrization: $(\pi\pi)_S$-wave

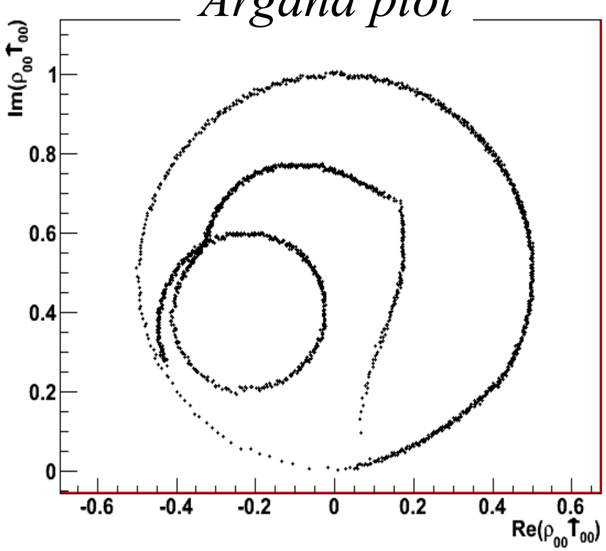
- Parametrization by *Anisovich and Sarantsev, Eur. Phys. J. A16, 229(2003)*
- 5 poles and 5 different channels up to 1900 MeV/c^2

TABLE I. K-matrix parameters from a global analysis of the available $\pi\pi$ scattering data from threshold up to 1900 MeV$/c^2$ [39]. Masses and coupling constants are given in GeV$/c^2$.

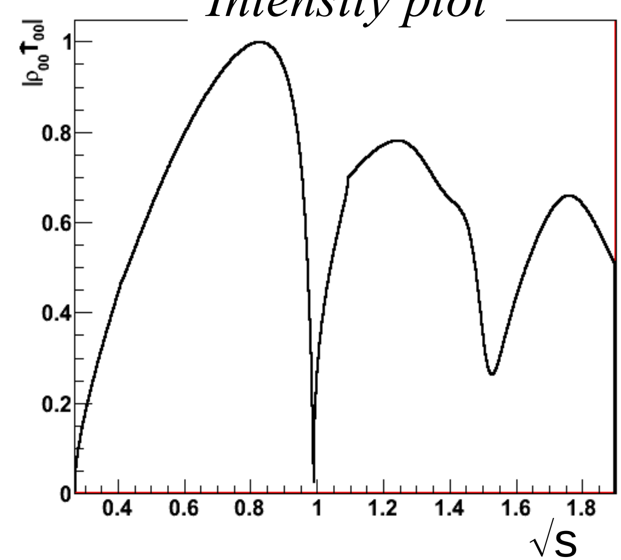
m_α	$g^\alpha_{\pi^+\pi^-}$	$g^\alpha_{K\bar{K}}$	$g^\alpha_{4\pi}$	$g^\alpha_{\eta\eta}$	$g^\alpha_{\eta\eta'}$
0.651 00	0.228 89	−0.553 77	0.000 00	−0.398 99	−0.346 39
1.203 60	0.941 28	0.550 95	0.000 00	0.390 65	0.315 03
1.558 17	0.368 56	0.238 88	0.556 39	0.183 40	0.186 81
1.210 00	0.336 50	0.409 07	0.856 79	0.199 06	−0.009 84
1.822 06	0.181 71	−0.175 58	−0.796 58	−0.003 55	0.223 58
$s_0^{\rm scatt}$	$f_{11}^{\rm scatt}$	$f_{12}^{\rm scatt}$	$f_{13}^{\rm scatt}$	$f_{14}^{\rm scatt}$	$f_{15}^{\rm scatt}$
−3.926 37	0.233 99	0.150 44	−0.205 45	0.328 25	0.354 12
s_{A0}	s_A				
−0.15	1				

Spectra obtained with PAWIAN

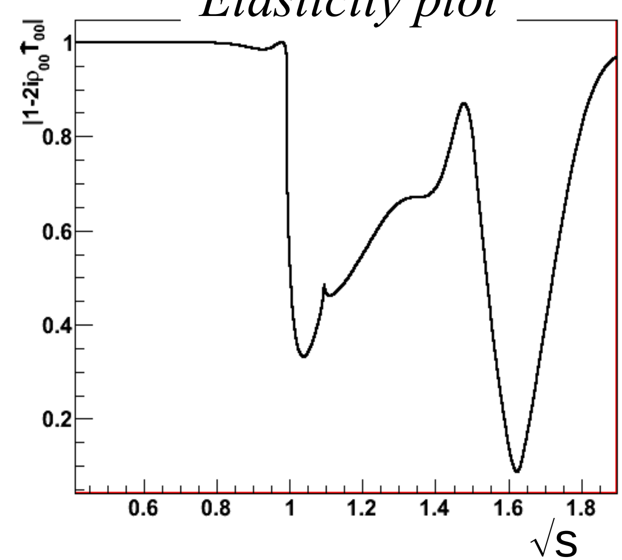
Argand plot



Intensity plot



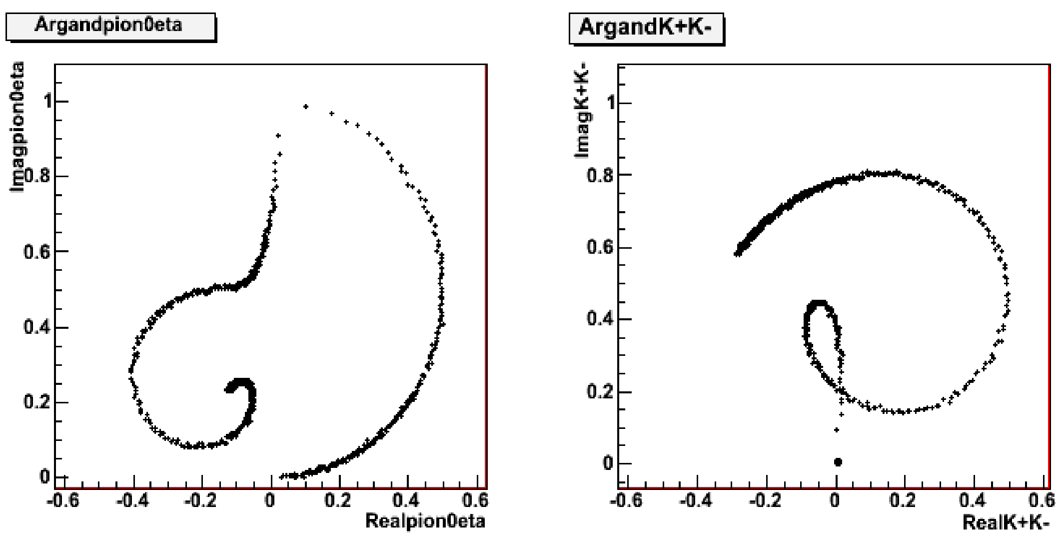
Elasticity plot



K-Matrix for a_0-Poles

- PWA fit of the channel $\bar{p}p \rightarrow \pi^+\pi^-\eta$ @ 900 MeV/c
- 2 poles $a_0(980)$ and $a_0(1450)$ and 2 different channels $\pi\eta$ and KK

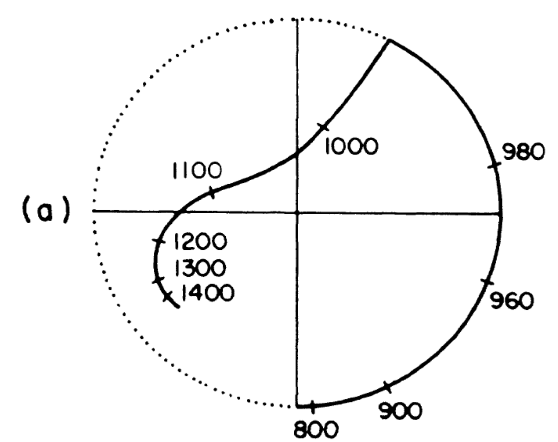
<u>Obtained Argand-Plots</u>



Argand-Plot for $\pi\eta$ from

J. Weinstein, N. Isgur

Phys. Rev. D41 (1990) 2236



Extraction of the Resonance Poles

- PDG: resonance parameters are defined by the relevant pole position of the T-matrix in the complex energy plane → unique representation and independent of the production mechanism and decay channels

- Generally: pole position of the K-matrix ≠ pole position of the T-matrix

- First (stand alone) tools available for the numerical calculation of the pole position

- Still to be done
  - implementation into the general part of PAWIAN
  - validation

Further Tools

- Easy handling of fit parameter
  - dumping
  - renaming, merging
  - fixing
- Event generator based on fit results
  - output in HEP-MC format
- QA
  - histogramming and creation of a root-tree via configuration file
  - goodness-of-fit tests
    - comparison between different models: Bayesian Information Criterion, Akaike Information Criterion, likelihood ratio test
    - quality how good the data can be described: energy test *(J.Pychy)*

PWA related to PANDA

- Analysis of Crystal Barrel @ LEAR data
  - $\bar{p}p$ annihilation with beam momenta up to 1.94 GeV/c → overlap with PANDA
  - offline software installed and running
  - raw data available on disk
- Investigation of $\bar{p}p$ annihilation process and production mechanism of vector mesons at various beam momenta (0.6-1.94 GeV/c)
  - $\bar{p}p \rightarrow \omega \pi^0 \rightarrow (\gamma\pi^0)\,\pi^0$
  - $\bar{p}p \rightarrow \omega \pi^0 \rightarrow (\pi^+\pi^-\pi^0)\,\pi^0$
  - $\bar{p}p \rightarrow K^+K^-\pi^0$ with the focus on $\phi\pi^0$ and $K^{*\pm}K^{\mp}$

  } *J. Pychy (PhD Thesis)*
- Identification of intermediate resonances in $\bar{p}p$ reactions
  - $\bar{p}p \rightarrow \pi^+\pi^-\eta$ in flight. *E. Köz (Master Thesis)*
  - $\bar{p}p \rightarrow K^+K^-\pi^0$ and $\bar{p}p \rightarrow \pi^+\pi^-\pi^0$ in flight, *J. Pychy (PhD Thesis)*
  - $\bar{p}p \rightarrow \pi^+\pi^-\pi^0\pi^0$ in flight, *A. Mustafa (Master Thesis)*
  - $\bar{p}p \rightarrow \omega\pi^0\eta$ in flight, *M. Richter (Master Thesis)*
  - $\bar{p}p \rightarrow \omega\pi^0\pi^0$ in flight, *F. Wischnewski (Bachelor Thesis)*