Hadron Spectroscopy from Antiproton-Proton Experiments

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Outline

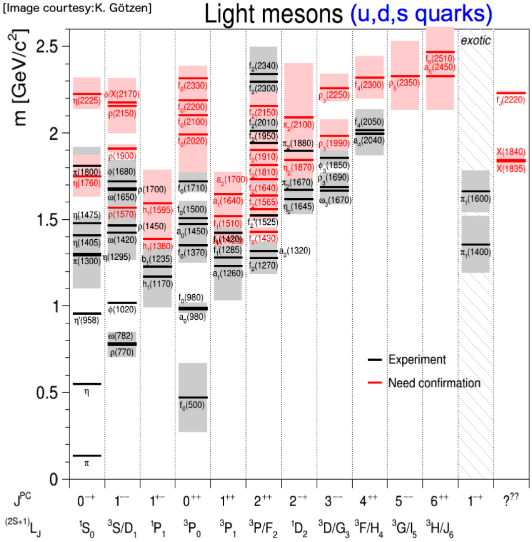
- Challenges in Hadron Spectroscopy
- Antiproton Probes
- The FAIR Facility
- The $\overline{\text{P}}$ANDA Experiment
- Feasibility Studies for $\overline{\text{P}}$ANDA
- Partial Wave Analyses with CB-LEAR In-Flight Data

Challenges in Hadron Spectroscopy: Light Quarks

- Various types of states allowed in QCD
- Possible configurations (apart from $q\bar{q}$, qqq, $\overline{qqq}$):
  - Tetraquarks ($q\bar{q}q\bar{q}$),
  - Di-quarkonia ($qq\,\overline{qq}$),
  - Molecules ($q\bar{q}\,q\bar{q}$)
  - Hybrids ($q\bar{q}g$),
  - Glueballs (gg, ggg)
  - ...
- Exotic states may exhibit exotic or non-exotic quantum numbers

⇒ Identification very difficult

- Many broad and overlapping states discovered



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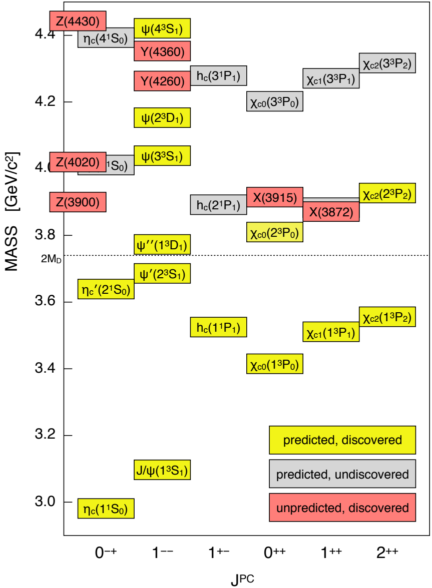
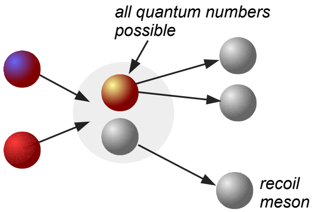


Spectroscopy using Antiprotons

- Production:
  - All exotic and non-exotic quantum numbers accessible with recoil

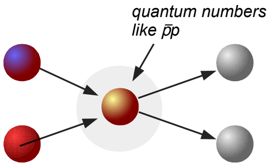
  → High discovery potential



- Formation:
  - All states with non-exotic quantum numbers directly accessible

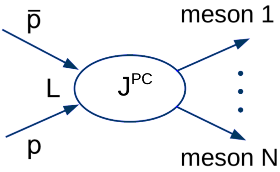
  → Not limited to $J^{PC} = 1^{--}$ as in e^+e^- annihilations

  → Precision studies of known states

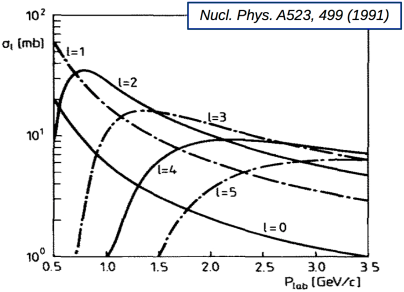


Spectroscopy using Antiprotons

- $\bar{p}p$ annihilations extremely useful for spectroscopy, but...
  - Various $\bar{p}p$ initial states contribute
  - J rises with beam momentum
  - Annihilation mechanism becomes highly complex
  - → Sophisticated and flexible tools for PWA needed
  - → Multi-purpose hermetic 4π detector needed!



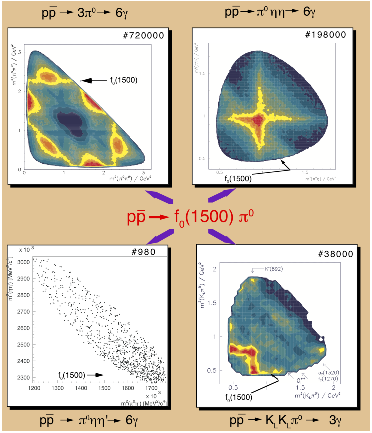
model calculations



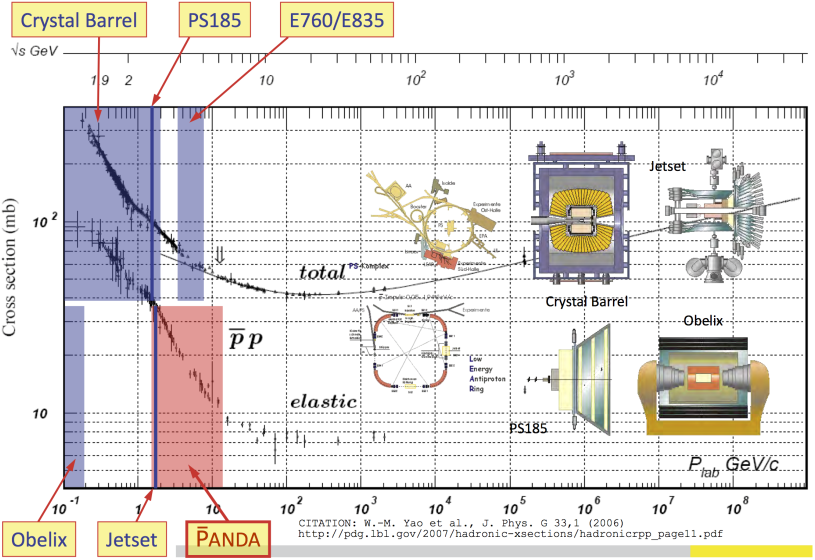
Important Results from Past $\overline{p}p$ Experiments

- Pioneering experiments using $\overline{p}p$ annihilations at CERN's LEAR ring:
  - → $N\overline{N}$ interactions, spin structure, "baryonium" (ASTERIX)
  - → Proton structure (PS170) and hyperon production (PS185)
  - → Spectroscopy and search for exotic meson resonances (Crystal Barrel, OBELIX, JETSET)
  - → Fundamental symmetries (CPLEAR)
- Ground-breaking discoveries in gluon-rich environment from Crystal Barrel

→ However: Limited beam momentum ($p_{\overline{p}} \leq 1.94\,\mathrm{GeV}/c$) and detector optimized for annihilation at rest!



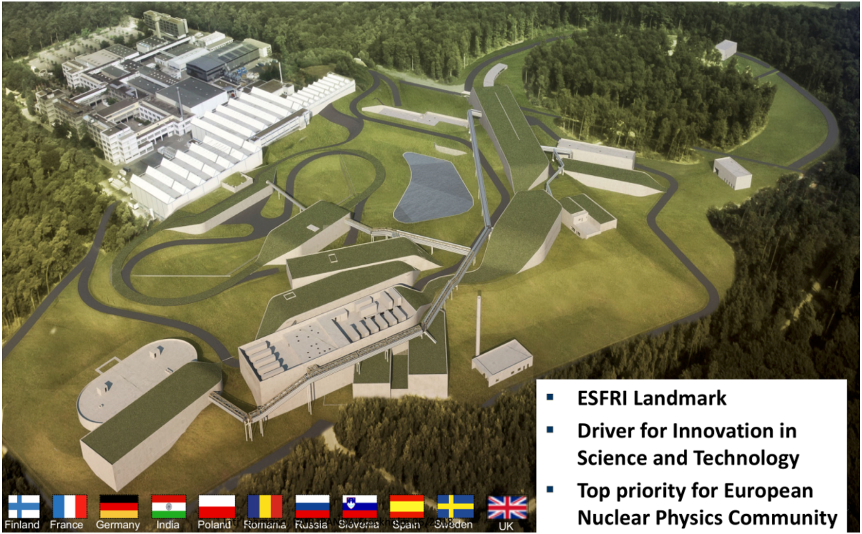
$\overline{p}p$ Cross Sections and Experiments



CITATION: W.-M. Yao et al., J. Phys. G 33,1 (2006)
http://pdg.lbl.gov/2007/hadronic-xsections/hadronicrpp_page11.pdf

FAIR - Facility for Antiproton and Ion Research

Accelerator facility currently under construction near Darmstadt, Germany

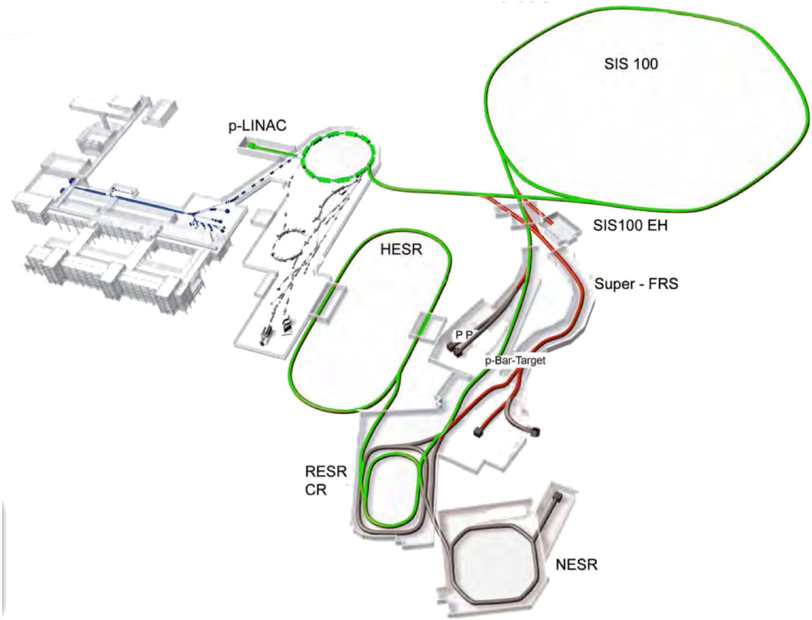


FAIR - Facility for Antiproton and Ion Research

Official ground breaking
in summer 2017

Same area now

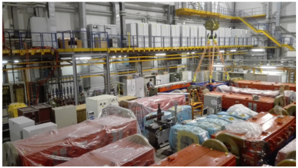
Antiprotons at FAIR

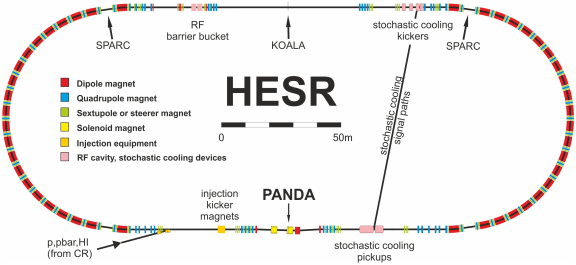


The High Energy Storage Ring (HESR)

- Slow ramping storage ring for internal target
- Circumference 574 m
- Momentum range: 1.5 – 15 GeV/c
- Avg. luminosity: $\approx 1 \cdot 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Injection of $\overline{\mathrm{p}}$ at 3.7 GeV/c
- Stochastic cooling

$\Delta p/p$	ΔE_{CM} [keV]	$\overline{\mathcal{L}}$ [1/(nb·d)]	Description
$5 \cdot 10^{-5}$	83.9	1170	Phase-1
$2 \cdot 10^{-5}$	33.6	1368	High Resolution
$1 \cdot 10^{-4}$	167.8	13683	High Luminosity



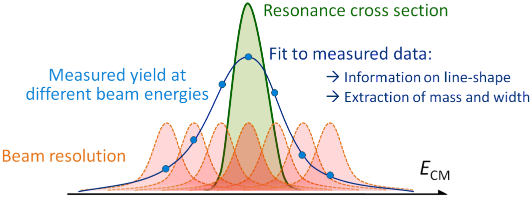


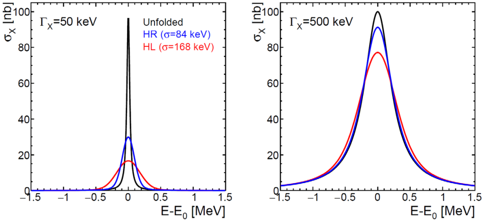
Resonance Scans

- Precise mass resolution in formation reactions
- Fine-tuned energy scan in relevant mass region necessary

→ Antiproton probes allow resonance scans for any J^{PC}!

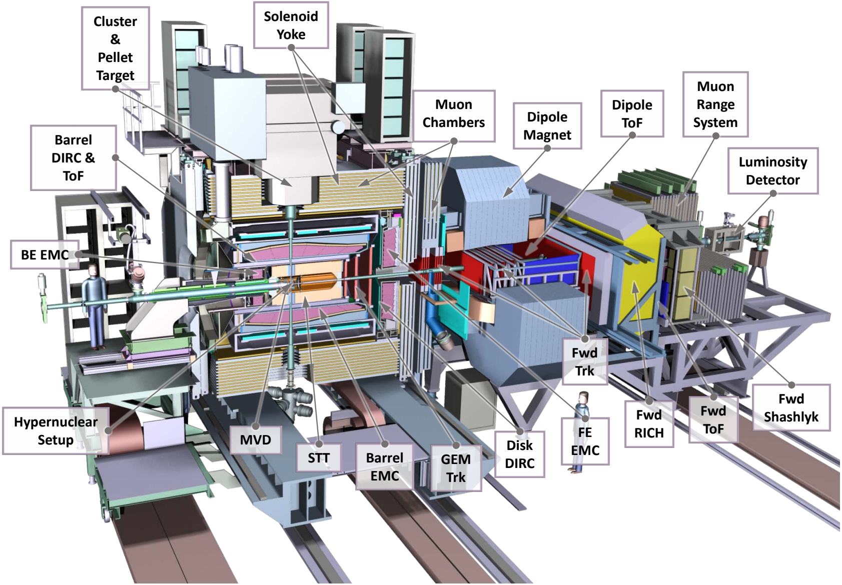
→ Need accelerator with fine tunable E_{cm}!





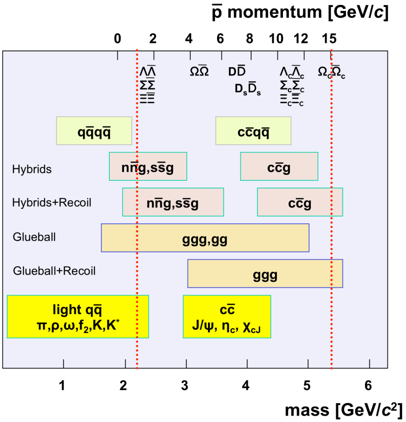
K. Götzen

The $\overline{\text{P}}$ANDA Detector



Physics Program

- Hadron spectroscopy
  - Light mesons
  - Charmonium
  - Open charm
  - Search for exotics
  - Baryons (double strange, charmed)
- Baryon anti-baryon production
- Mesons in nuclei
- Hypernuclei
- Proton structure



Feasibility Study: $X(3872)$ Line Shape Scan

- First of the *XYZ* states "accidentally" discovered by Belle in 2003

$\rightarrow$ Very close to $D^0\overline{D}^{*0}$ threshold

$\rightarrow$ Narrow: $\Gamma(X) < 1.2\,\text{MeV}$

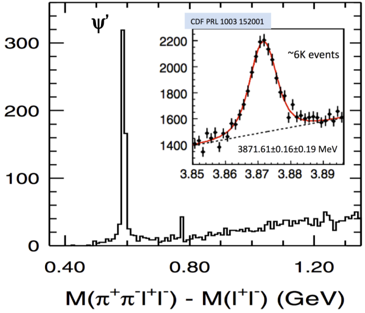
$\rightarrow$ Observed in various production modes and decay channels

$\rightarrow$ Interpretation as tetraquark, molecular state, mixture, ... still unresolved

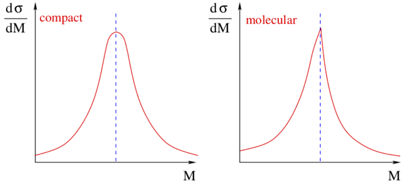
$\rightarrow$ Exact knowledge of the line shape can help to determine nature of this state

$\rightarrow$ Precise $\overline{p}p$ scan needed!

[Belle, PhysRevLett.91 (2003) 262001]



[Rev.Mod.Phys. 90, 015004 (2018), Guo, Hanhart, Meißner, Wang, Zhao, Zou]



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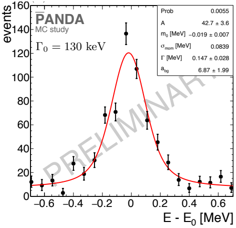
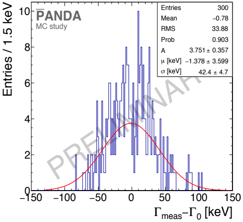
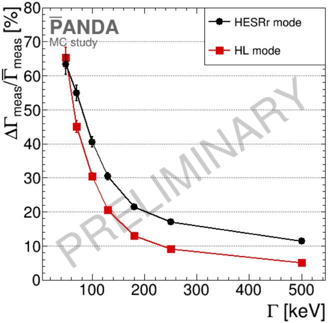






- Example: 20 E_{cms} points, 1.4 MeV around nominal mass
- $\Gamma_0 = 130$ keV, 2 days/E_{cms} (Phase1-mode)

→ Extract Γ from energy dependent yield

→ Repeat toy MC experiment 300 times

→ Determine accuracy of width extraction

- Achievable performance quantified

$\Delta\Gamma/\Gamma = 20\%$: HL > 130 keV

P1 > 200 keV

- P̄ANDA will be able to perform precise line shape scans of narrow resonances
- Extraction of 1^+ component via PWA also possible

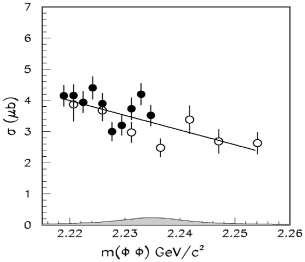
Search for the Tensor Glueball in $\bar{p}p \to \phi\phi$

- JETSET observed unexpectedly large magnitude for $\bar{p}p \to \phi\phi$ cross section
- Tensor resonances found in PWA of $\pi^- p \to \phi\phi n$ *PRL 49, 1620 (1982)*
- Tensor resonances observed in $J/\psi \to \gamma\phi\phi$ (BESIII)
- Feasibility study for $\bar{p}p \to \phi\phi$ at $\overline{\text{P}}$ANDA

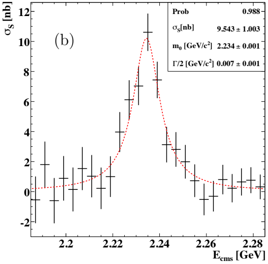
$\to$ Extended study for cross section scan in glueball mass region underway

$\to$ Extraction of 2^+ contribution for each scan point

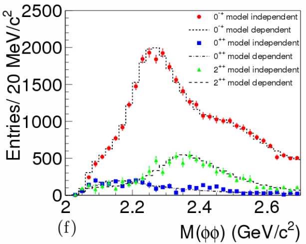
JETSET, Phys.Rev.D57,5370



PANDA arxiv:0903.3905



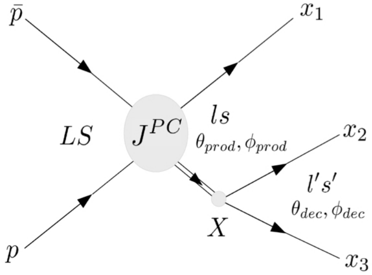
BESIII, Phys.Rev.D93,112011



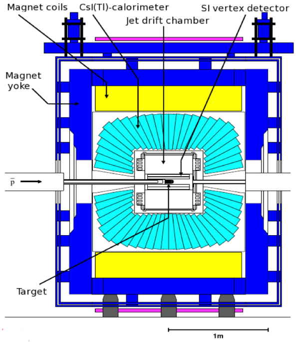
Antiproton-Proton Annihilations: Crystal Barrel @ LEAR

- Full PWA (initial to final state)

[Image courtesy: J.Pychy]



- Fixed target experiment at LEAR (CERN)
- Data taking: 1989-1996
- $\overline{p}p$ annihilation in flight and at rest
- $p_{\overline{p}} = (0.105...1.94)\,\text{GeV}/c$
  - $\Rightarrow$ Momentum overlap with $\overline{\text{P}}$ANDA!



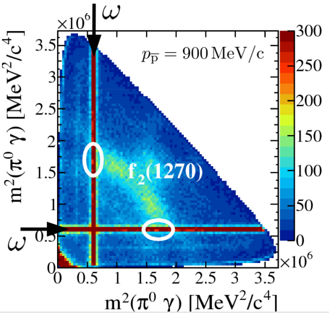
$\bar{p}p \to \omega\pi^0$

- Simple reaction with easy access to the initial $\bar{p}p$ system
- Two decay modes ($\omega \to \pi^0\gamma$, $\pi^+\pi^-\pi^0$) analyzed at $p_{\bar{p}} = 0.6 - 1.94\,\text{GeV}/c$

$\Rightarrow$ Determination of L_{max} and the ω Spin-Density matrix (SDM)

- SDM provides information about production process
- SDM elements were derived from the angular decay distributions ("Schilling method") as well as from production amplitudes derived from PWA fit

Eur.Phys.J. C75 (2015) 3, 124



- Significant background present after application of kinematic fit

$\Rightarrow$ e.g. from $\bar{p}p \to f_2(1270)\pi^0 \to 3\pi^0$

$\Rightarrow$ Successfully removed using event based background subtraction method!

[RUB, J.Pychy]

$\bar{p}p \to \omega\pi^0$

Eur.Phys.J. C75 (2015) 3, 124

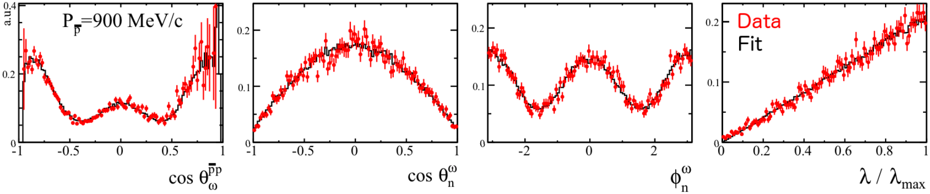
$\omega \to \pi^+\pi^-\pi^0$

momentum [MeV/c]	L_{max}	significance of likelihood ratio $\frac{\ln L(L_{max})}{\ln L(L_{max}-1)}$	$\frac{\ln L(L_{max}+1)}{\ln L(L_{max})}$
900	4	$2.2\,\sigma$	$0.13\,\sigma$
1525	4	$9.0\,\sigma$	$0.90\,\sigma$
1642	5	$3.2\,\sigma$	$0.06\,\sigma$
1940	5	$>10\,\sigma$	$1.04\,\sigma$

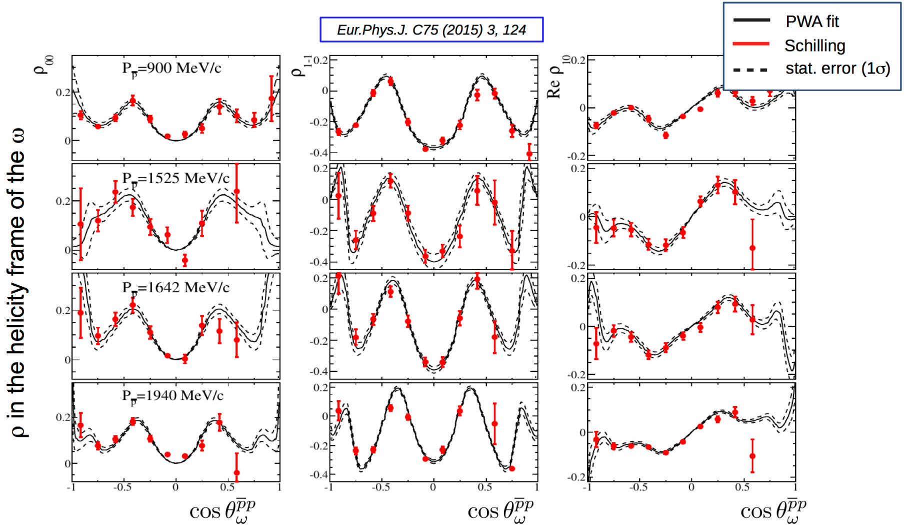
$\omega \to \pi^0\gamma$

momentum [MeV/c]	L_{max}	significance of likelihood ratio $\frac{\ln L(L_{max})}{\ln L(L_{max}-1)}$	$\frac{\ln L(L_{max}+1)}{\ln L(L_{max})}$
600	2	$>10\,\sigma$	$1.05\,\sigma$
900	4	$6.5\,\sigma$	$0.22\,\sigma$
1050	4	$>10\,\sigma$	$0.01\,\sigma$
1350	5	$5.6\,\sigma$	$0.03\,\sigma$
1525	5	$>10\,\sigma$	$0.25\,\sigma$
1642	5	$5.0\,\sigma$	$8{\cdot}10^{-3}\,\sigma$
1800	5	$>10\,\sigma$	$0.55\,\sigma$
1940	5	$>10\,\sigma$	$0.69\,\sigma$

$\omega \to \pi^+\pi^-\pi^0$ $\quad p_{\bar{p}} = 900\,\mathrm{MeV/c}$



- Significant alignment observed, heavily dependent on production angle



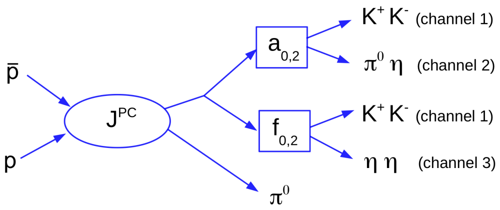
Coupled Channel Analysis - Motivation

[all coupled channel results: Ph.D. thesis J.Pychy, RUB]

- Simultaneous fit of $\bar{p}p \to K^+K^-\pi^0$, $\pi^0\pi^0\eta$, $\pi^0\eta\eta$ channels
- Many resonances appear in two, or all three channels

→ Advantages: Constraints due to common amplitudes, common description of the dynamics (K-matrix), less fit parameters

- Why these channels?
  - Possibility to distinguish a and f resonances!
  - Special interest in $K^+K^-\pi^0$: Comparison of $\bar{p}p \to \phi\pi^0$ with $\omega\pi^0$, production process of K^*, K^*K channel closely related to D^*D channels relevant for $\overline{\text{P}}$ANDA



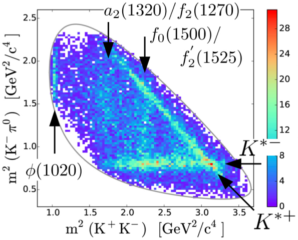
Coupled Channel Analysis - Selection and Techniques

- Clean data samples prepared at $p_{\overline{p}} = 0.9\,\mathrm{GeV}/c$
- Kinematic fits, event-based background subtraction
- 5-pole, 5-channel K-matrix for $(\pi\pi)_S$-wave
  [Eur. Phys. J.A16, 229(2003)]
- 1-pole, 2-channel K-matrix for $(K\pi)_S$-wave
  [Phys.Lett.B653 (2007) 1-11]
- SDM of ϕ, a_2, f_2 can be extracted

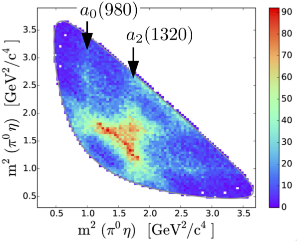
Resonance	Dynamics	$K^+K^-\pi^0$	$\pi^0\pi^0\eta$	$\pi^0\eta\eta$
ϕ	rel. BW.	X		
$\phi(1680)$	rel. BW.	X		
$K^{*\pm}$	rel. BW.	X		
$K_0^*(1430)$	$K\pi$-S-wave	X		
f_0	$\pi\pi$-S-wave	X (1)	X (2)	X (1)
$a_0(980)$	k-matrix	X (1)	X (1)	X (2)
$a_0(1450)$	k-matrix	X (1)	X (1)	X (2)
$a_2(1320)$	k-matrix	X (1)	X (1)	X (2)
$a_2(1700)$	k-matrix	X (1)	X (1)	
$f_2(1270)$	k-matrix	X (1)	X (2)	
$f_2'(1525)$	k-matrix	X (1)		X (1)
$\rho_3(1700)$	k-matrix	X		
$\pi_1^0(1400)$	rel. BW.		X (1)	X (2)

X basis fit X current best fit X alternative fits

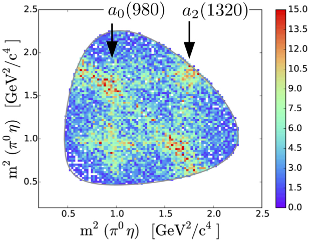
$K^+K^-\pi^0$ ($\sim$ 17.3k events)



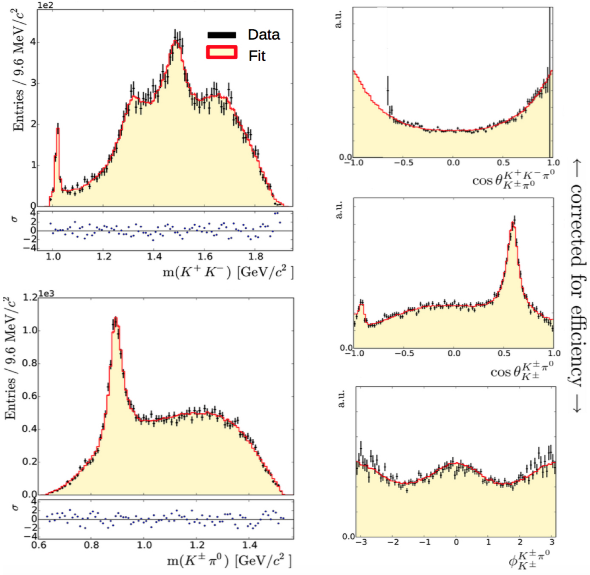
$\pi^0\pi^0\eta$ ($\sim$ 97k events)



$\pi^0\eta\eta$ ($\sim$ 10.9k events)

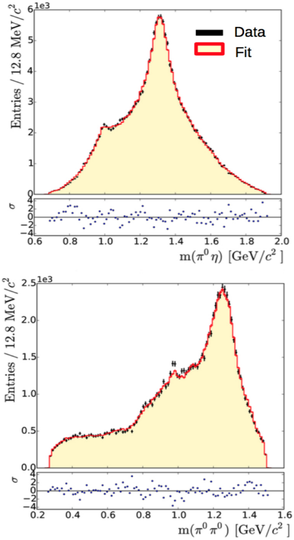


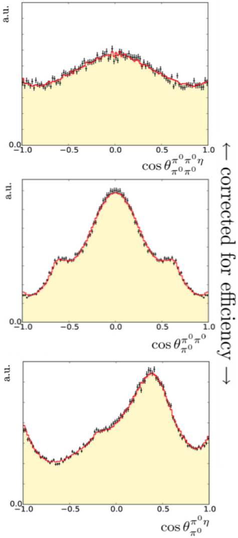
$\bar{p}p \to K^+K^-\pi^0$

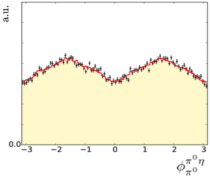


Resonance	Cont. [%]
K^*	38.0 ±0.9
f_2 matrix	18.5 ±1.2
$(K\pi)_S$	17.8 ±1.1
$(KK)_S$	16.4 ±1.1
a_2 matrix	14.4 ±0.6
$\phi(1680)$	11.3 ±0.6
ϕ	1.91 ±0.23
a_0 matrix	0.58 ±0.03
Σ	118.9 %

$\bar{p}p \rightarrow \pi^0\pi^0\eta$

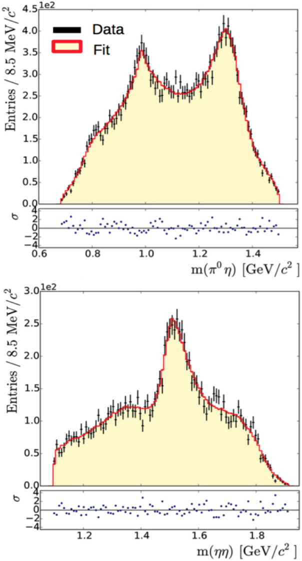


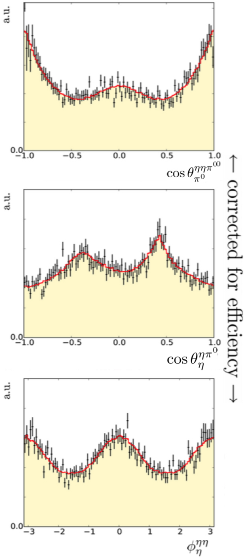


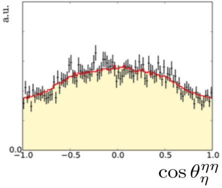


Resonance	Cont. [%]
a_2 matrix	52.5 ±0.6
f_2 matrix	31.5 ±0.6
$(\pi\pi)_S$	20.9 ±0.6
a_0 matrix	19.1 ±0.5
Σ	124.0

$\bar{p}p \to \pi^0\eta\eta$





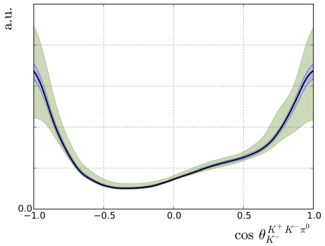


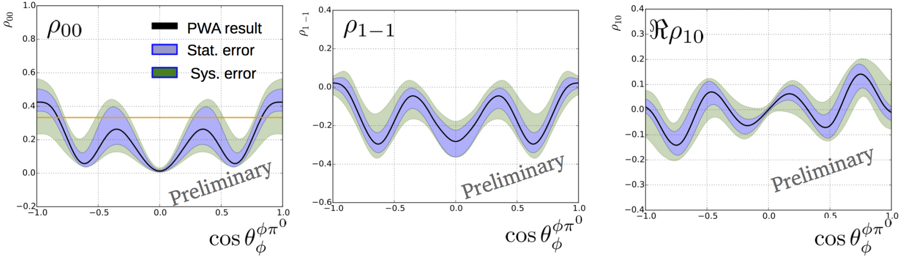
Resonance	Cont. [%]
$(\eta\eta)_S$	52.2 ±2.0
a_2 matrix	30.9 ±1.3
f_2 matrix	11.8 ±0.4
a_0 matrix	11.1 ±0.9
Σ	106.0

Coupled Channel Analysis

- Selection of hypothesis using different approaches (*BIC*, *AIC*, LRT)
- Asymmetric distribution of the K^* production angle
- SDM of the ϕ extracted:

⇒ Alignment visible, similar behavior as SDM elements of the ω





Summary

- FAIR and $\overline{\text{P}}$ANDA are on a good way
  - $\rightarrow$ $\overline{\text{P}}$ANDA hall available in end of 2021
  - $\rightarrow$ expect physics with $\bar{p}$-beams in HESR $\approx$ 2025!
- Antiprotons are unique, decisive probes to tackle open questions in hadron spectroscopy
- Feasibility studies well underway

$\rightarrow$ Precise line shape scans of narrow states possible in startup phase (*Phase-1 physics*)

- Analysis of Crystal Barrel/LEAR data using PWA / sophisticated analysis methods:

$\rightarrow$ Ideally suited as preparation for challenges arising at $\overline{\text{P}}$ANDA!

- More feasibility studies and simulations upcoming - stay tuned!

Thank you for your Attention!

Collaboration

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U Bonn
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