Overview of the $\bar{\mathrm{P}}$ANDA Experiment

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Hadron Spectroscopy: The Next Big Steps

Federal Ministry of Education and Research

STRONG 2020

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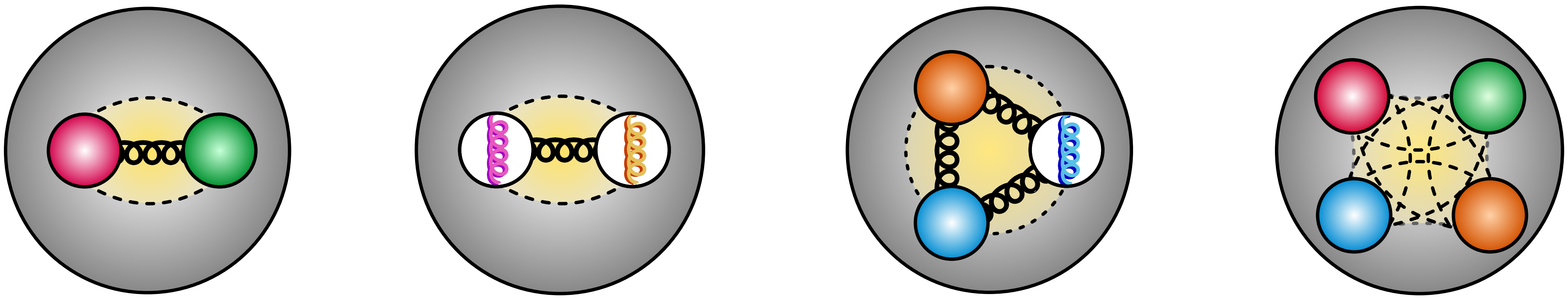
Introduction

- Different production mechanism must be compared in order to understand a particle's nature and to understand its inner structure



Meson | Glueball | Hybrid | Tetraquark

Gluon rich processes

- Charmonium decays
- $\bar{p}p$ annihilation
- pp central production
- …

QED mediated process

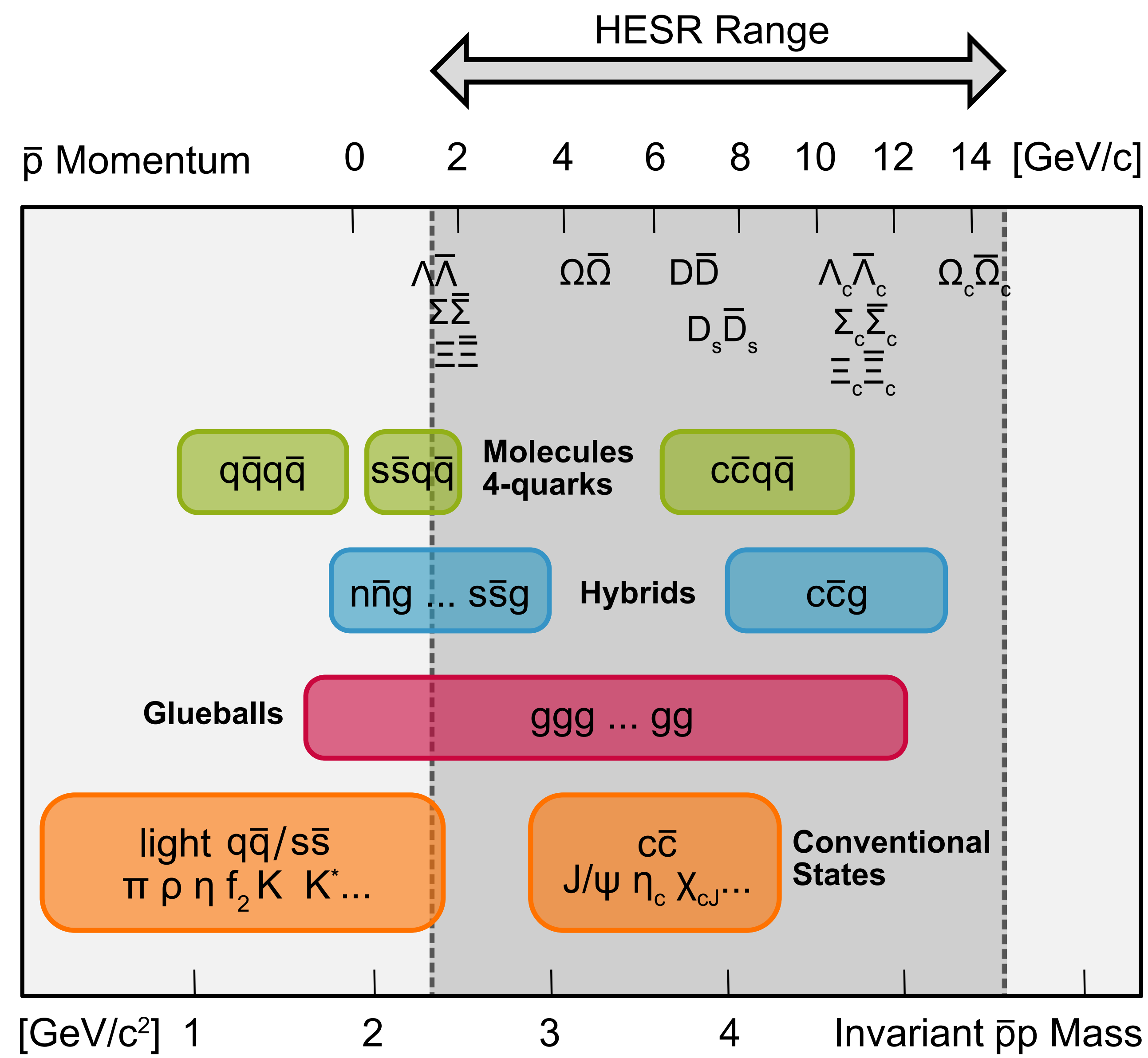
- Two-photon production

$\bar{\text{P}}$ANDA Physics Program

Hadron Spectroscopy
- Light mesons
- Exotic matter (Glueballs, Hybrids etc.)
- Charmonia (including XYZ states)
- Open Charm Physics
- Baryons and Hyperons

Nucleon Structure
- Generalised Parton Distributions (GPD)
- Transition Distribution Amplitudes (TDA)
- Time-like proton form factor
- Transverse Parton Distribution

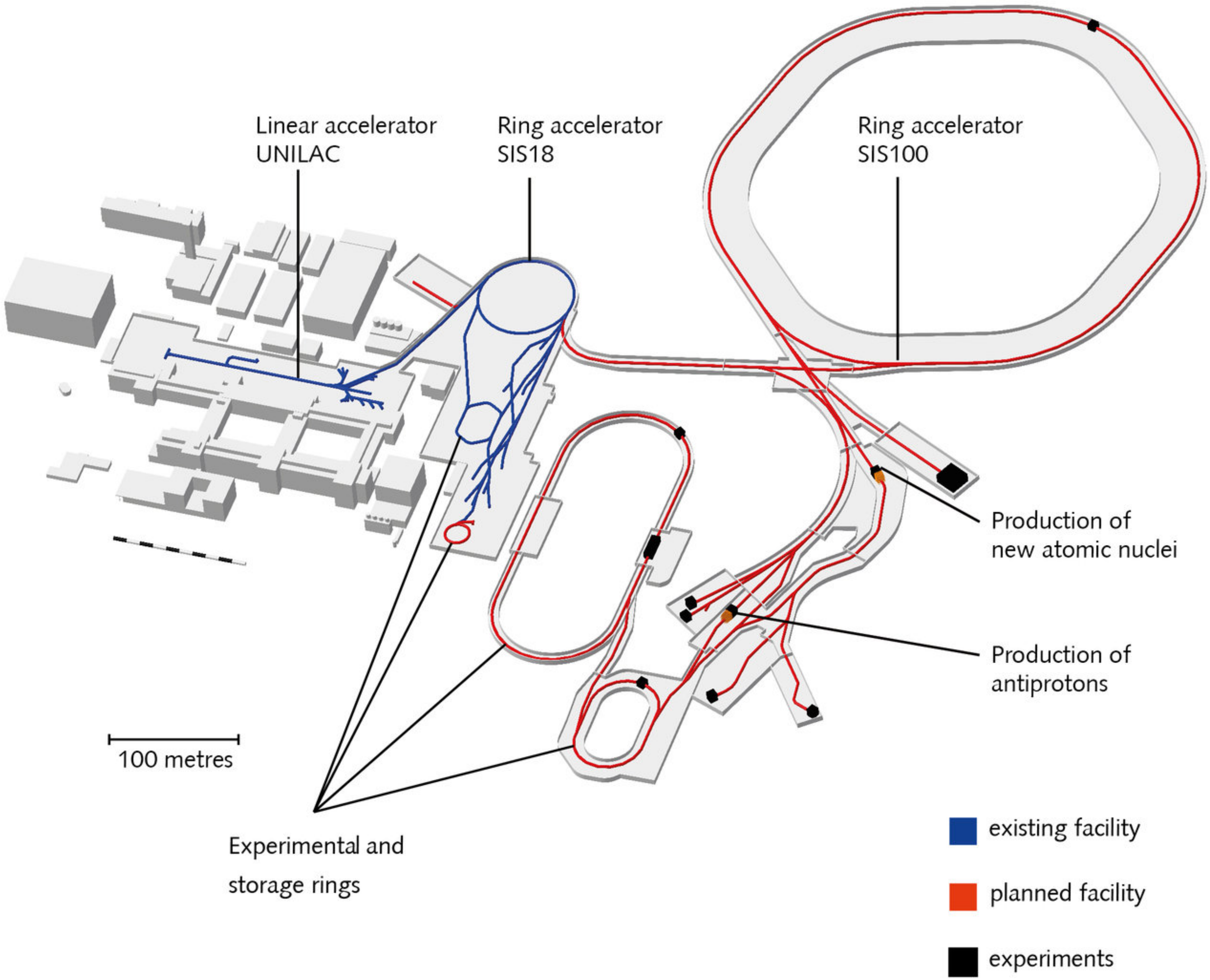
Physics of Hypernuclei



Very broad program

$\bar{\text{P}}$ANDA can contribute to various fields!

$\overline{\text{P}}$ANDA at FAIR

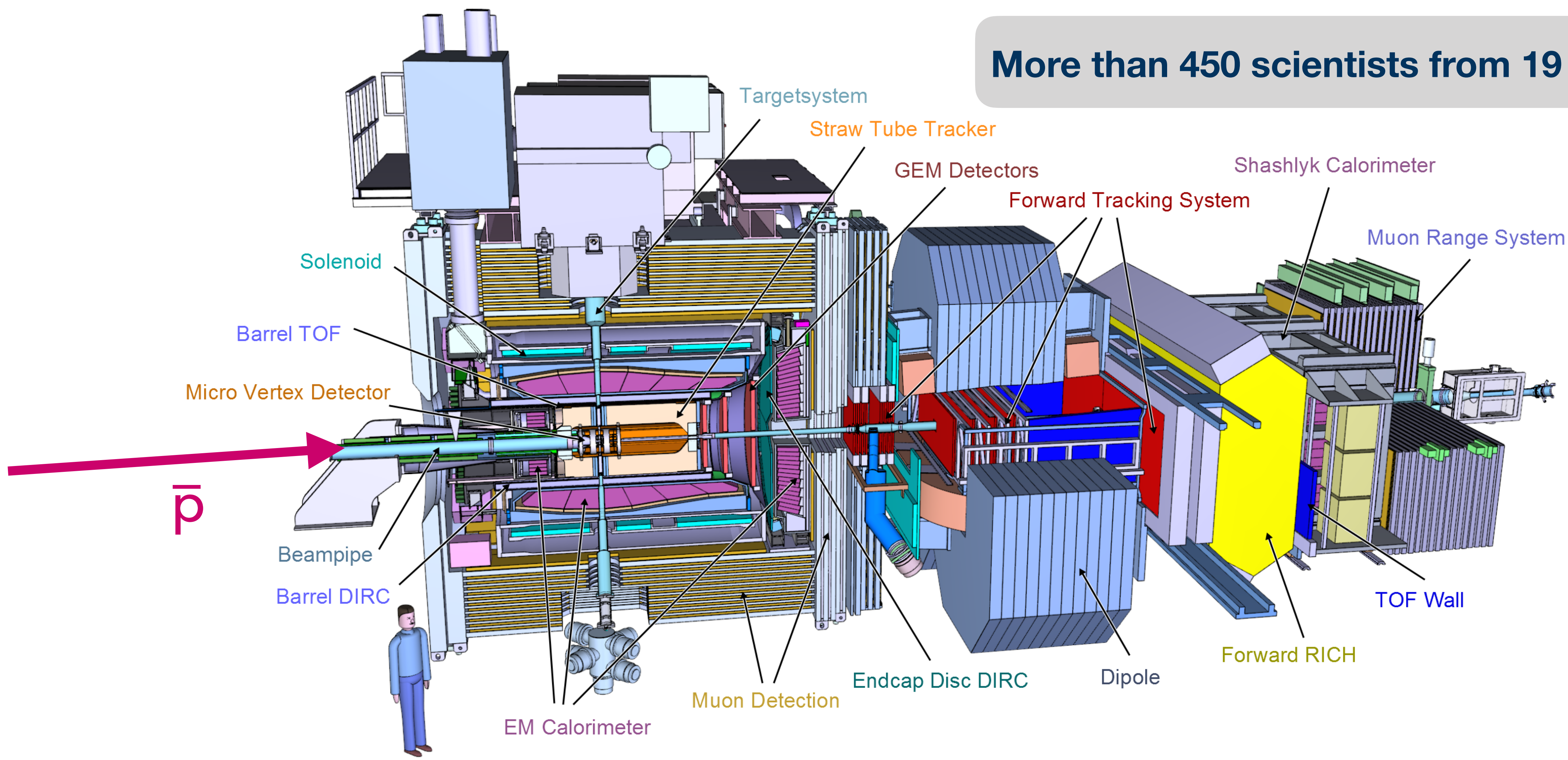


$\bar{\text{P}}$ANDA at FAIR

The $\bar{\text{P}}$ANDA Experiment

- Fixed target experiment
- Anti-proton beam momentum range: 1.5 -15 GeV/c (max. $\sqrt{s}$ = 5.5 GeV)
- Design luminosity: 10^{31} cm^{-2} s^{-1} - 10^{32} cm^{-2} s^{-1} ➡ High event rates
- Almost full coverage of solid angle due to forward dipole magnet
- Excellent momentum resolution in formation

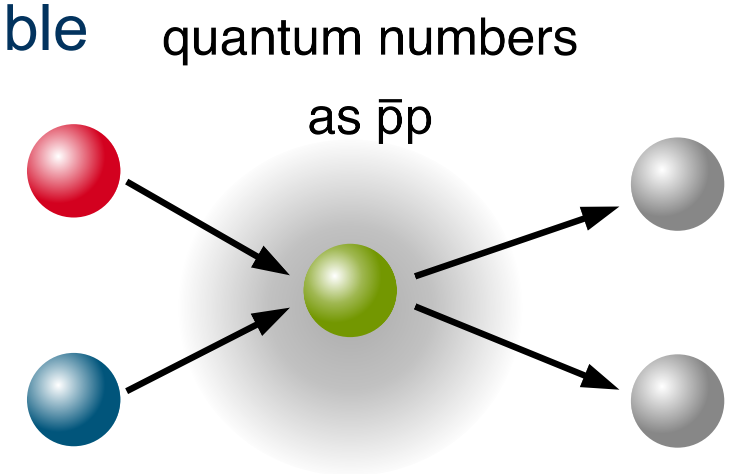
More than 450 scientists from 19 countries



Resonances in $\bar{p}p$ Annihilations

Formation:

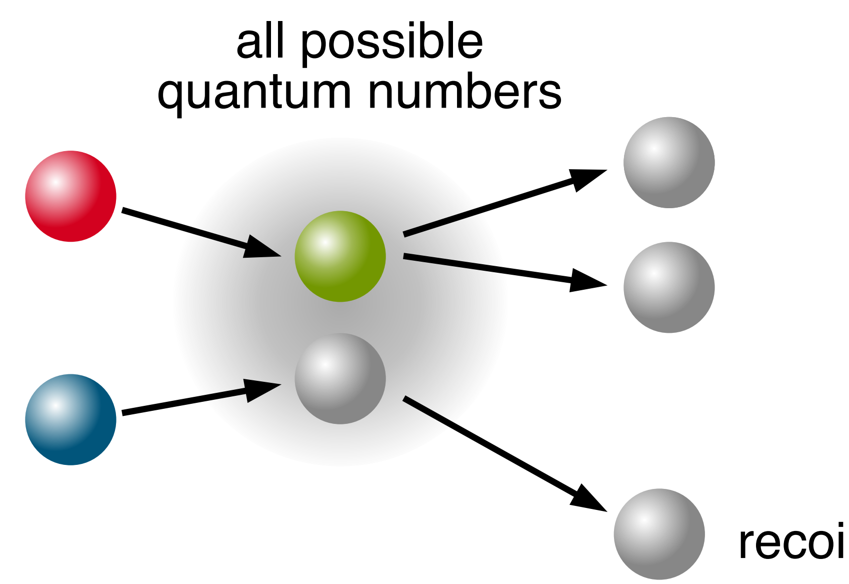
- All resonances with non-exotic quantum numbers accessible
- Not limited to $J^{PC} = 1^{--}$ states as in e^+e^- reactions
- Resolution only limited by the beam resolution
- Very precise measurements possible



Production with recoil particle:

- Resonances with exotic and non-exotic quantum numbers accessible
- high discovery potential

➡ A signal in production but non in formation would be interesting!



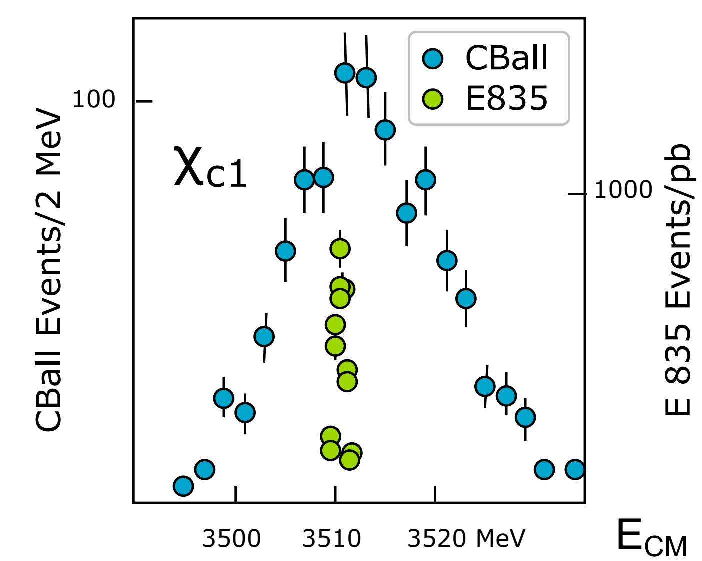
- Cross section for glueball and light hybrid production similar to light hadrons
- Cross section for charmed hybrids and molecules similar to charmed hadrons
- High-spin states possible without limitations on quantum numbers

Formation Studies at $\bar{\text{P}}$ANDA

- Resolution only limited by the beam resolution and not by the detector

Method	Limitation	Resolution
Initial state radiation	detector resolution	> 2 MeV
Energy scan with e^+e^-	beam energy resolution	1 – 2 MeV
Energy scan with $\bar{p}p$ @ $\bar{\text{P}}$ANDA	beam energy resolution	50 keV

- Prominent example: Measurement of the total width of the χ_{c1}
  - BESIII: $\psi' \to \gamma\chi_{c1}, \ \ \Gamma = \left(1.39\,^{+0.40}_{-0.38}\,^{+0.26}_{-0.77}\right)\,\text{MeV}$
  - E835: $\bar{p}p \to \chi_{c1}, \ \ \Gamma = (0.876 \pm 0.045 \pm 0.026)\,\text{MeV}$



- $\bar{\text{P}}$ANDA is expected to have a more than 5 times higher beam resolution as E835

Accelerator Mode	dp/p	L [$cm^{-2}\,s^{-1}$]
High Luminosity	$\sim 10^{-4}$	$1 \cdot 10^{32}$
High Resolution	$4 \cdot 10^{-5}$	$1 \cdot 10^{31}$

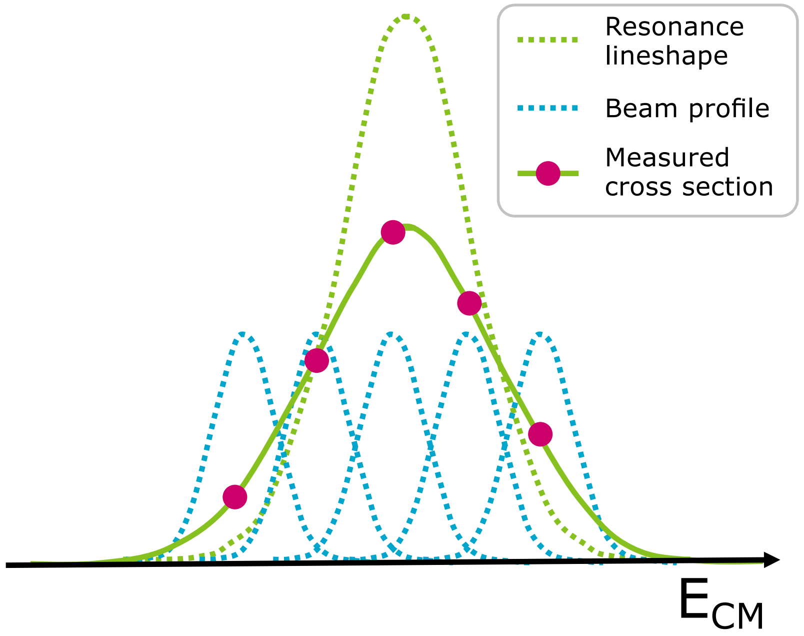
Study of $\bar{p}p \to X(3872) \to J/\psi\, \rho^0$

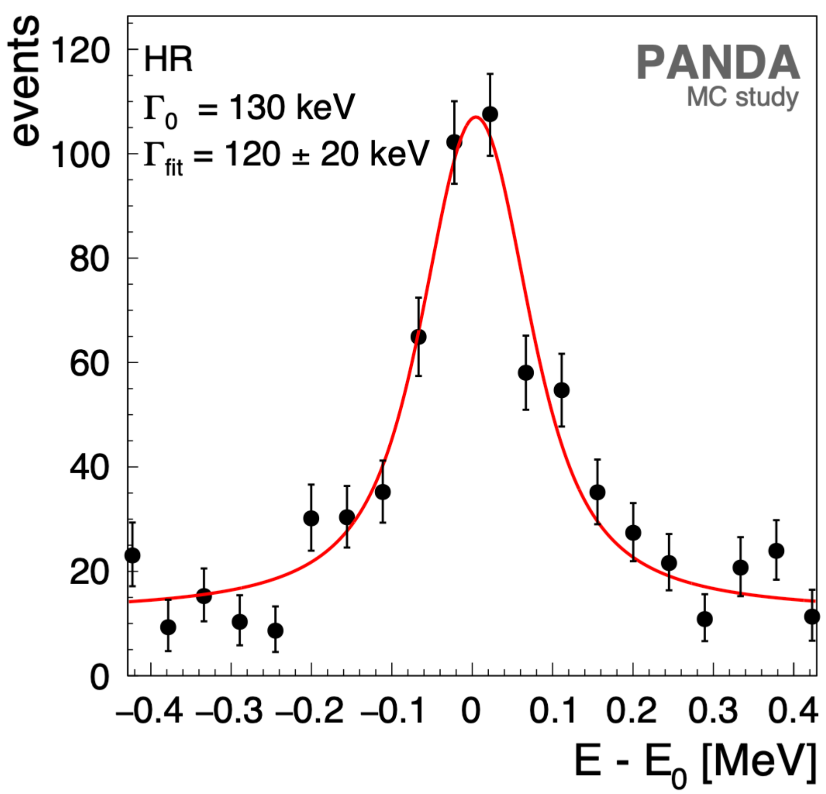
Eur. Phys. J. A (2019) **55**: 42

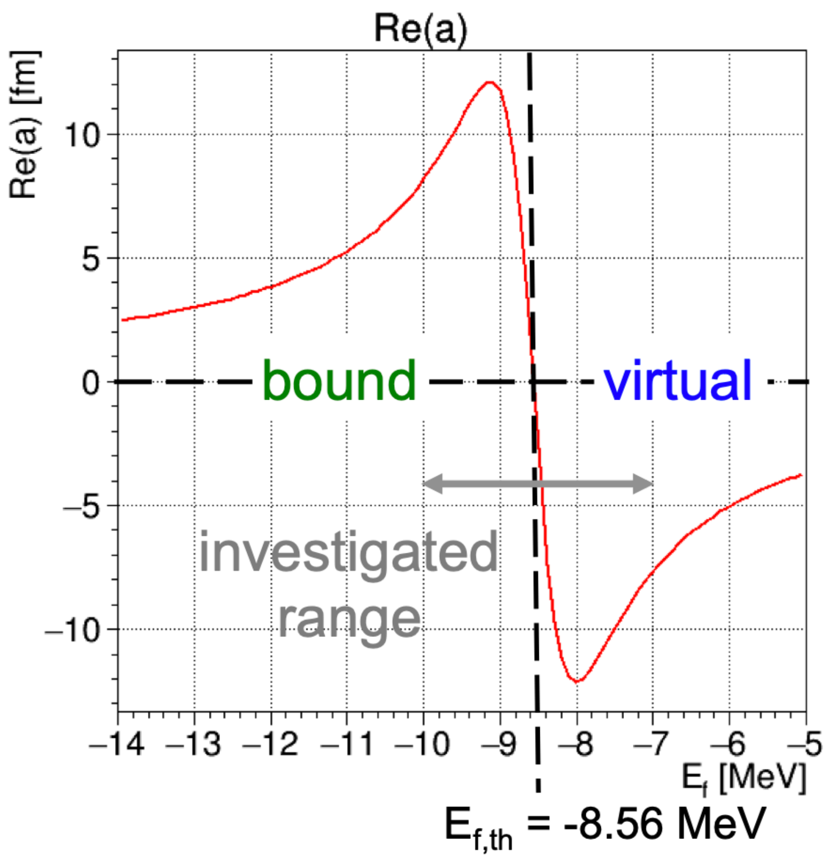
- X(3872) seen in the decay to D*D and $J/\psi\, \rho^0$ ➡ both important
- Main idea: Measure the lineshape with high precision and identify nature by determination of the Flatté energy E_f
- Analysis performed for 20 energy points around nominal mass
- Sensitivity studies to distinguish the two scenarios

➡ It is possible to distinguish with more than 90% confidence for sizeable Flatté energies $\Delta E_f := |E_{f,0} - E_{f,th}| > 700$ keV

➡ With the $\overline{\text{P}}$ANDA setup this corresponds to only about a month of data taking!



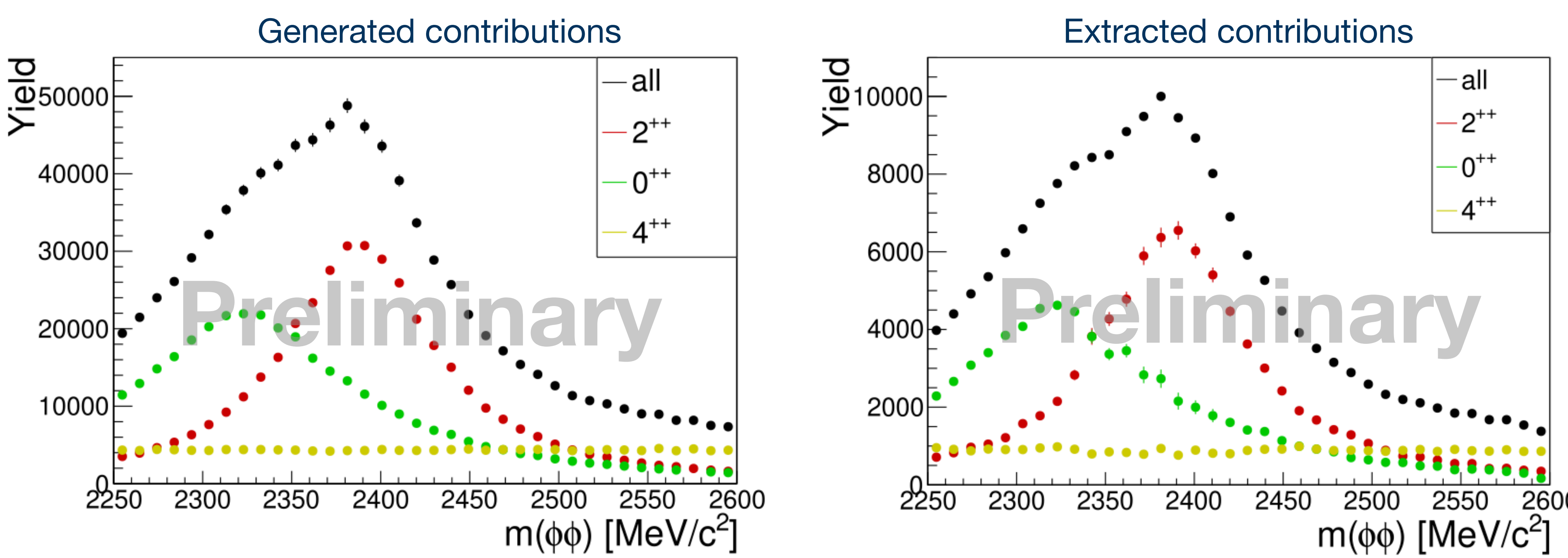




see talk by Frank Nerling for more details

Formation Studies at $\overline{\text{P}}$ANDA

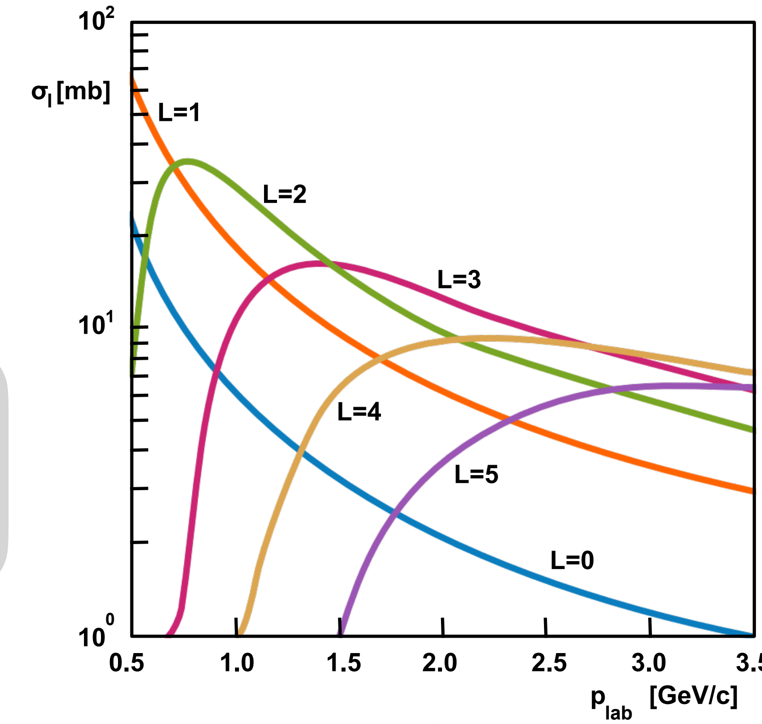
- Mass independent analysis of the process $\bar{p}p \rightarrow \phi\phi$ (ongoing)
- Offers gluon rich environment
- Lattice QCD calculations predict tensor glueball at 2.4 GeV/c^2 Phys.Rev. D73 (2006) 014516
- JETSET experiment: cross section exceeds expectation by two orders of magnitude JETSET, Phys.Rev.D57,5370
  - ➡ Hint for intermediate process involving glue?
- Identify resonances in the $\phi\phi$ system by model independent partial wave analysis describing the whole decay chain
- Toy MC generated based on 2 channel K-matrix model, including a hypothetical tensor state
- Extract magnitude and phase motion of the 2^{++} wave
- 36 data points between 2.25 GeV and 2.6 GeV, 10^4 toy MC events per scan point



Production Studies and PWA at $\bar{\text{P}}$ANDA

- Production channels are more complicated due contributing intermediate processes
- Partial wave analyses help to identify intermediate resonances and their properties
- Challenges:
  - Many contributing initial $\bar{p}p$ states
  - Sophisticated tools need to be applied to describe overlapping resonances in various decay channels

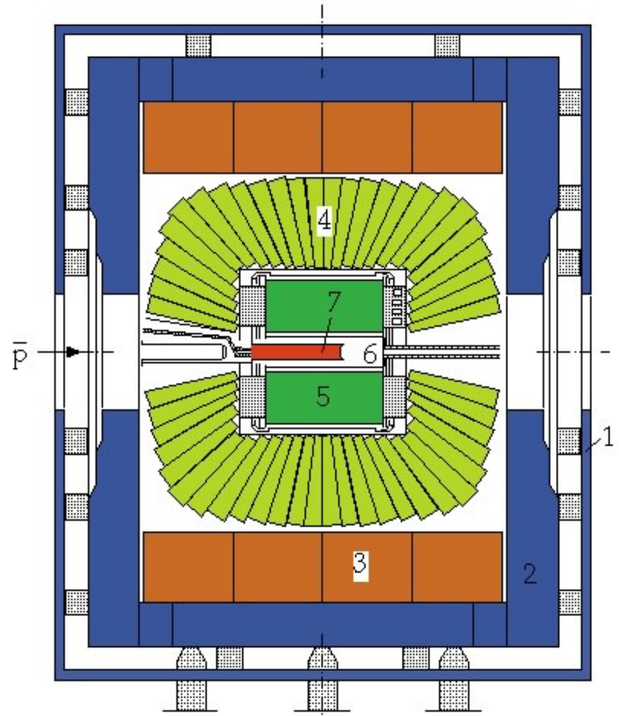
based on Nucl. Phys. A523, 499 (1991)



Analyses of Crystal Barrel at LEAR data are an excellent opportunity for the investigation of physics aspects relevant for $\bar{\text{P}}$ANDA

- Crystal Barrel was in operation from 1989 - 1996
  - Fixed target experiment at LEAR
  - $\bar{p}p$ annihilation at rest and in flight ➡ observation of light scalars!
  - Highest beam momentum 1.94 GeV/c

➡ Overlap with $\bar{\text{P}}$ANDA



$\bar{\text{P}}$ANDA will have a 100 times higher luminosity!

➡ 1 year data taking becomes 3.5 days!

Production Studies and PWA at $\bar{\text{P}}$ANDA

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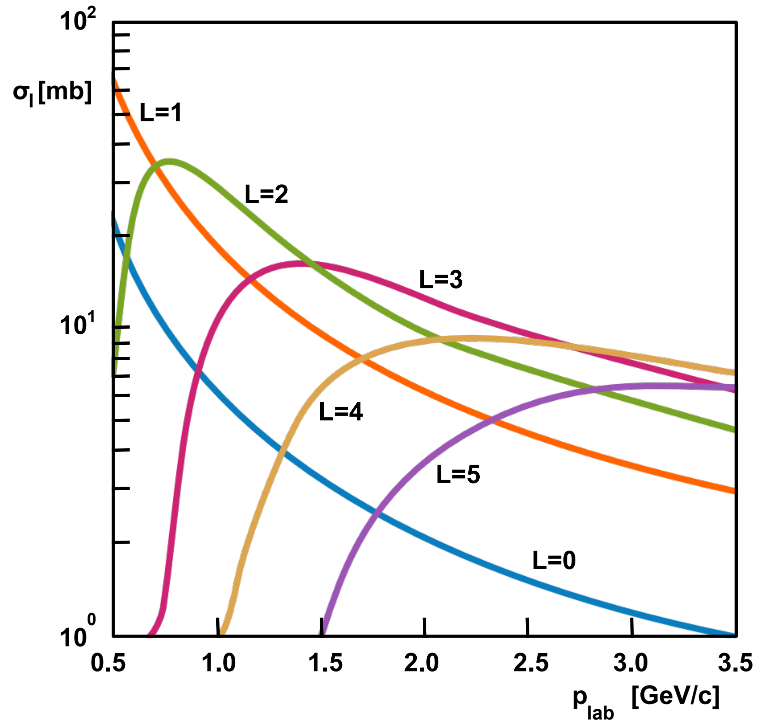


Analyses of Crystal Barrel at LEAR data are an excellent opportunity for the investigation of physics aspects relevant for $\bar{\text{P}}$ANDA

- First studies performed with Crystal Barrel in flight data
  - Investigations of $\bar{p}p$ initial states in $\bar{p}p \rightarrow \omega\, \pi^0$
  - Coupled channel analysis of $\bar{p}p \rightarrow \pi^0 \pi^0 \eta$, $\pi^0 \eta\, \eta$ and $K^+ K^- \pi^0$

Study of $\bar{p}p \rightarrow \omega\pi^0$

Eur. Phys. J. C75 (2015) 124

- Several Crystal Barrel data sets at different $\bar{p}$ beam momenta analyzed ranging from $p_{\bar{p}}$ = 600-1940 MeV/c
- The ω was reconstructed in two main decay modes $\pi^+\pi^-\pi^0$ and $\gamma\pi^0$
- In accordance to theory it was found that L_{max} increases from 2 to 5

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

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

The decay $\omega \rightarrow \pi^+\pi^-\pi^0$ could be studied much better with the $\bar{\text{P}}$ANDA detector

$\omega \rightarrow \gamma\pi^0$

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

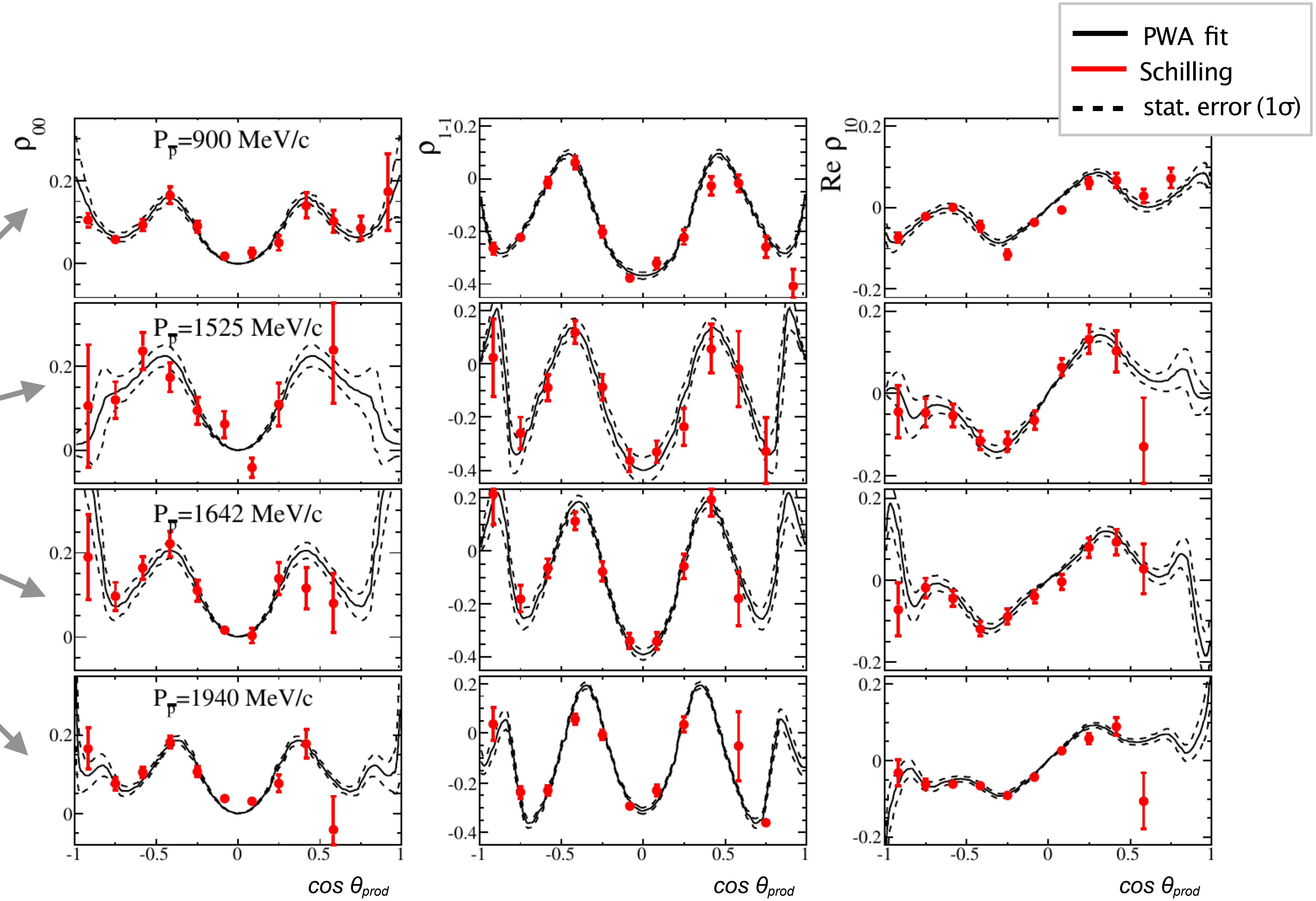
Study of $\bar{p}p \rightarrow \omega\pi^0$

Eur. Phys. J. C75 (2015) 124

- Extraction of the spin density matrix (SDM) of the ω
  - SDM contains the full information of the production mechanism
  - significant alignment and dependence on the production angle visible

Spin alignment!

Probably resonances in formation involved?



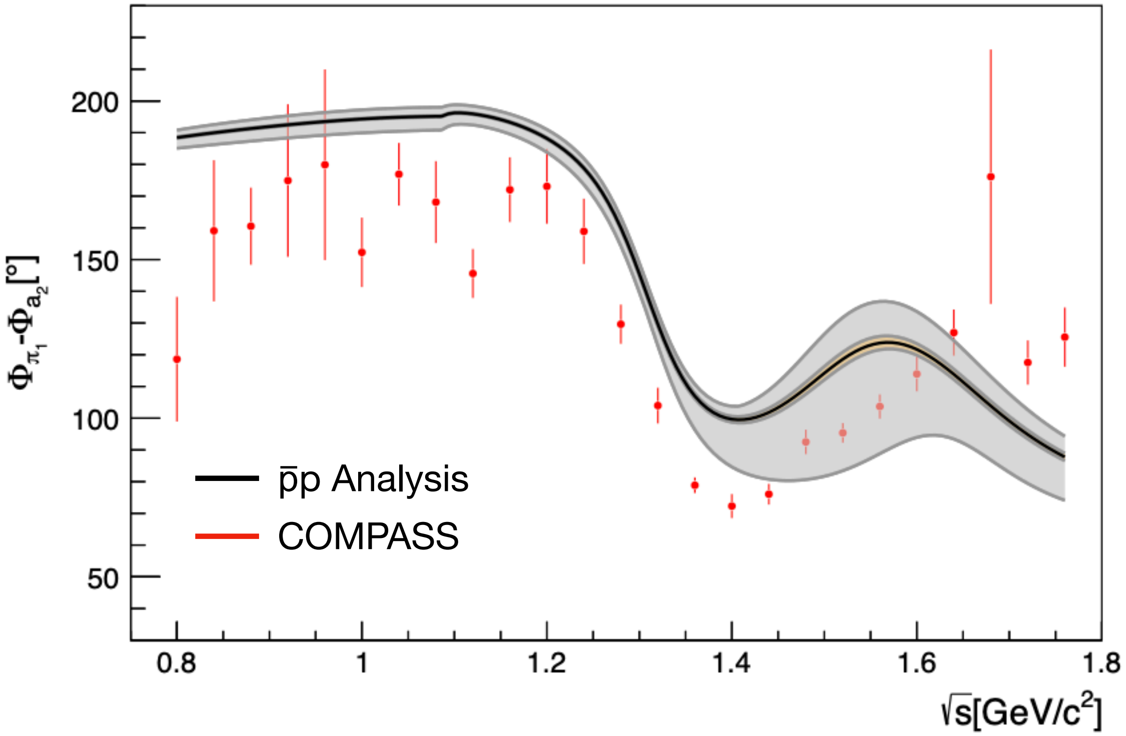
Coupled Channel Analysis of $\bar{p}p \to \pi^0 \pi^0 \eta$, $\pi^0 \eta \eta$ and $K^+ K^- \pi^0$

- Describing simultaneously
  - Crystal Barrel data sets at 900 MeV/c
  - ππ scattering data for I=0 S- and D-wave and I=1 P-wave
- Many a_0, a_2, f_0 and f_2 resonances contributing
  - Described using the K-Matrix formalism in the P-vector approach
  - Constraints due to common production amplitudes and pole parameters
- Exotic π_1 wave significantly contributing in the $\pi^0\eta$ system!

see talk by Bertram Kopf for more details

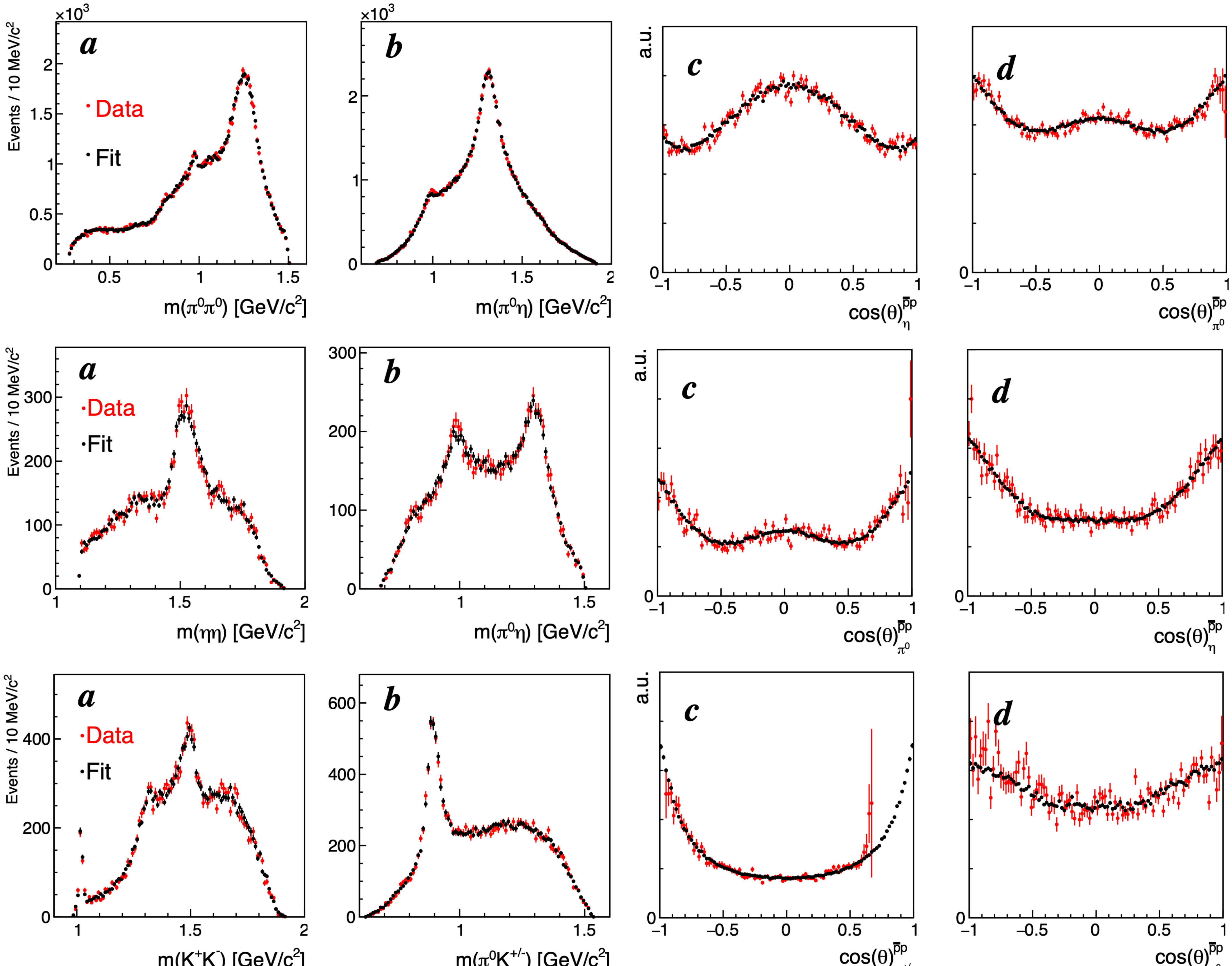
	contribution (in %) for channel $\pi^0\pi^0\eta$	$\pi^0\eta\eta$	$K^+K^-\pi^0$
$f_0\,\pi^0$		$23.7 \pm 1.2 \pm 2.3$	$7.4 \pm 0.3 \pm 4.1$
$f_0\,\eta$	$10.7 \pm 0.4 \pm 1.8$		
$f_2\,\pi^0$		$30.1 \pm 1.3 \pm 2.7$	$17.1 \pm 0.7 \pm 10.0$
$f_2\,\eta$	$52.3 \pm 0.8 \pm 5.0$		
$\rho\,\pi^0$			$17.2 \pm 1.0 \pm 4.0$
$a_0\,\pi^0$	$22.4 \pm 0.4 \pm 1.0$		$6.1 \pm 0.2 \pm 2.8$
$a_0\,\eta$		$28.6 \pm 1.1 \pm 7.5$	
$a_2\,\pi^0$	$33.0 \pm 0.6 \pm 2.9$		$6.4 \pm 0.2 \pm 2.9$
$a_2\,\eta$		$18.8 \pm 1.1 \pm 5.6$	
$K^*(892)^{\pm}K^{\mp}$			$45.0 \pm 1.3 \pm 11.0$
$(K\pi)^{\pm}_S K^{\mp}$			$6.1 \pm 0.4 \pm 4.9$
$\phi(1020)\,\pi^0$			$2.5 \pm 0.3 \pm 0.3$
$\pi_1\,\pi^0$	$16.7 \pm 0.5 \pm 3.0$		
Σ	$135.0 \pm 1.2 \pm 8.7$	$101.2 \pm 2.4 \pm 11.7$	$107.8 \pm 1.9 \pm 12.5$

T-Matrix phase difference in agreement!



Eur. Phys. J.C 80 (2020) 5, 453

Coupled Channel Analysis of $\bar{p}p \rightarrow \pi^0\pi^0\eta$, $\pi^0\eta\eta$ and $K^+K^-\pi^0$



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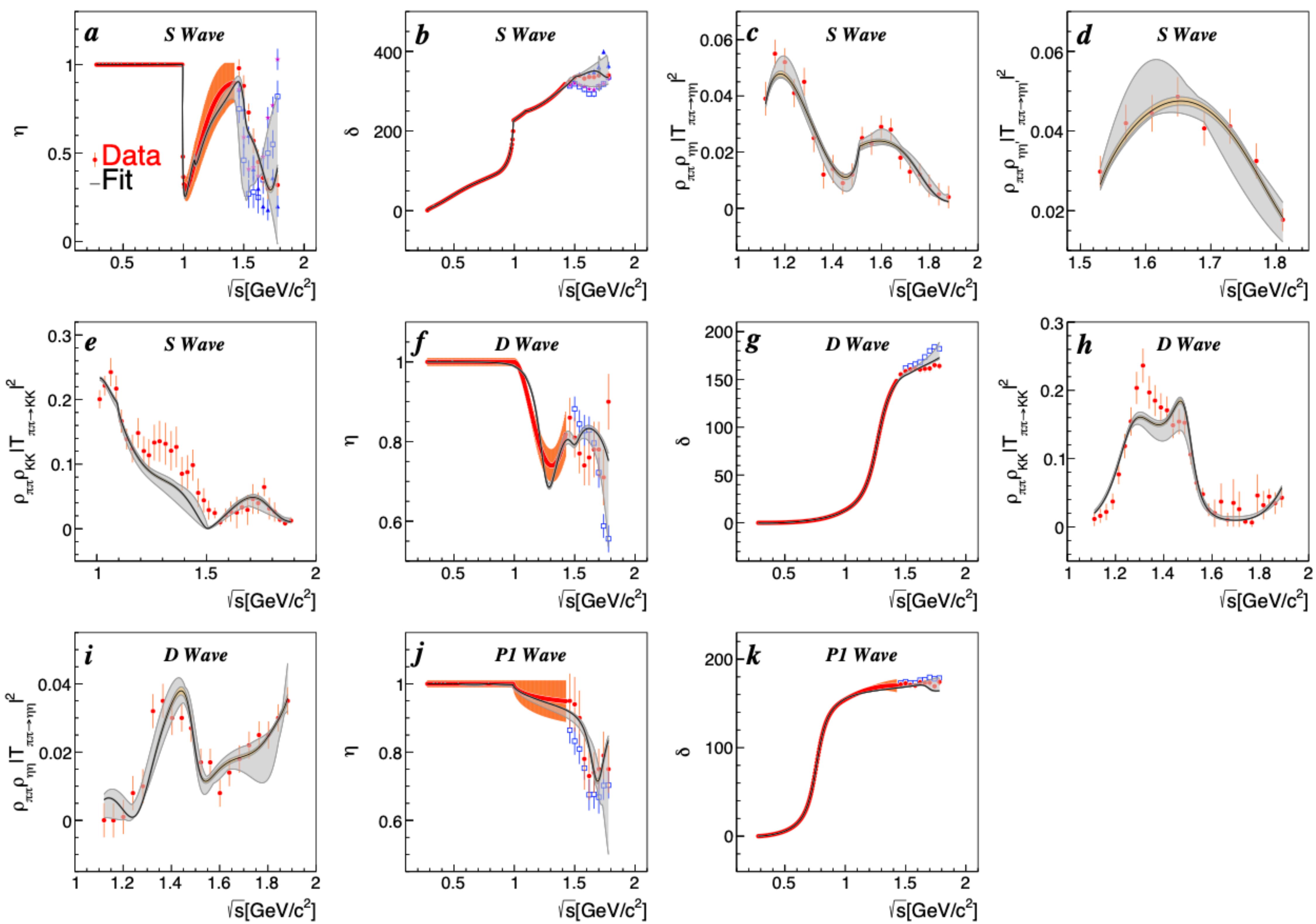

Study of Excited Baryons via the $\bar{\Xi}^{+}\Lambda K^{-}$ Final State

arXiv: 2201.03852

- Baryon studies especially interesting at P̄ANDA due to high production cross sections
- Knowledge in strange baryon sector very sparse
- All decay modes - charged and neutral - accessible
- Feasibility study performed to determine the spin and parity QN for specific Ξ resonances
- $\Xi(1690)^{-}$ and $\Xi(1820)^{-}$ were simulated including detector response
- Model includes interference effects, proper angular distributions and barrier factors

➡ Fit was able to identify the correct spin and parity quantum numbers and resonance parameters

- Of course, the models used are a limited representation of reality and can be improved

$p_{\bar{p}}$ (GeV/c)	Reaction	Rate (s^{-1}) at 10^{31}cm^{-2}s^{-1}
1.64	$\bar{p}p \to \bar{\Lambda}\Lambda$	44
1.77	$\bar{p}p \to \bar{\Sigma}^{0}\Lambda$	2.4
6.0	$\bar{p}p \to \bar{\Sigma}^{0}\Lambda$	5.0
4.6	$\bar{p}p \to \bar{\Xi}^{+}\Xi^{-}$	0.3
7.0	$\bar{p}p \to \bar{\Xi}^{+}\Xi^{-}$	0.1
4.6	$\bar{p}p \to \bar{\Lambda}K^{+}\Xi^{-} + \text{c.c}$	0.2

Eur. Phys. J. A (2021) **57**: 184

Δ AIC values for $\Xi(1690)^{-}$

Gen. ↓ / Fit →	$1/2^{+}$	$1/2^{-}$	$3/2^{+}$	$3/2^{-}$
$1/2^{+}$	0.0	2,550.6	2,310.6	2,706.8
$1/2^{-}$	316.7	0.0	328.2	2,332.2
$3/2^{+}$	4,973.9	5,228.0	0.0	584.6
$3/2^{-}$	5,345.6	3,118.6	833.1	0.0

Δ (AIC+BIC) values for $\Xi(1820)^{-}$

Gen. ↓ / Fit →	$1/2^{+}$	$1/2^{-}$	$3/2^{+}$	$3/2^{-}$
$1/2^{+}$	0.0	139.9	158.7	208.1
$1/2^{-}$	96.8	0.0	211.1	887.4
$3/2^{+}$	7473.3	7604.5	0.0	198.4
$3/2^{-}$	7617.6	6900.8	490.2	0.0

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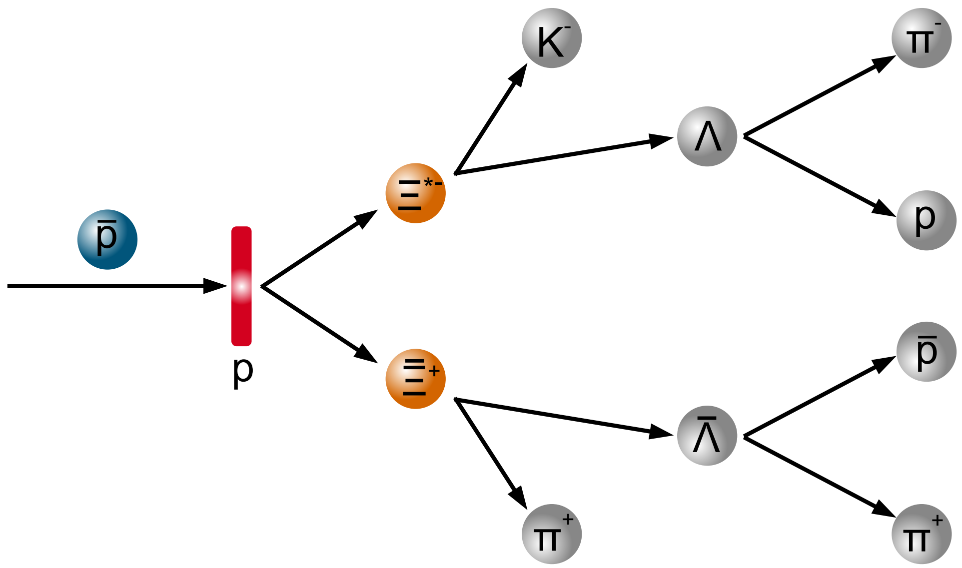

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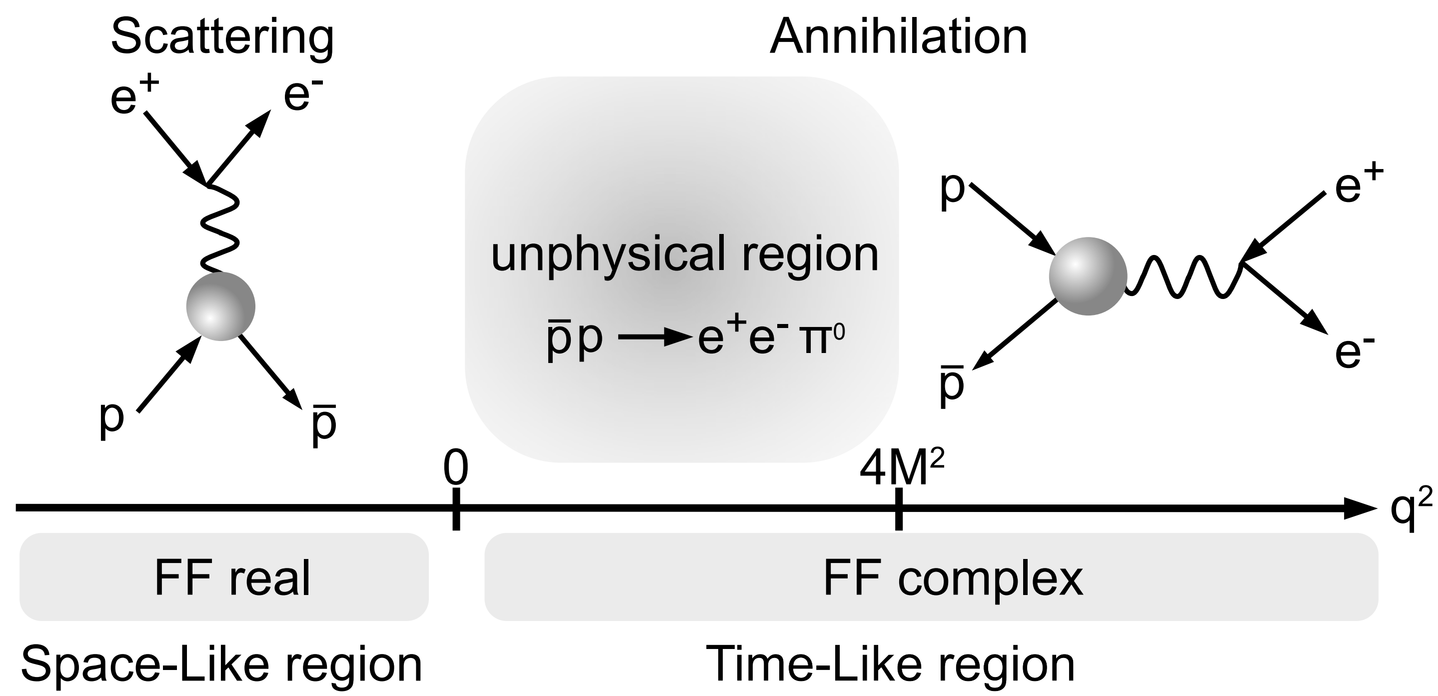
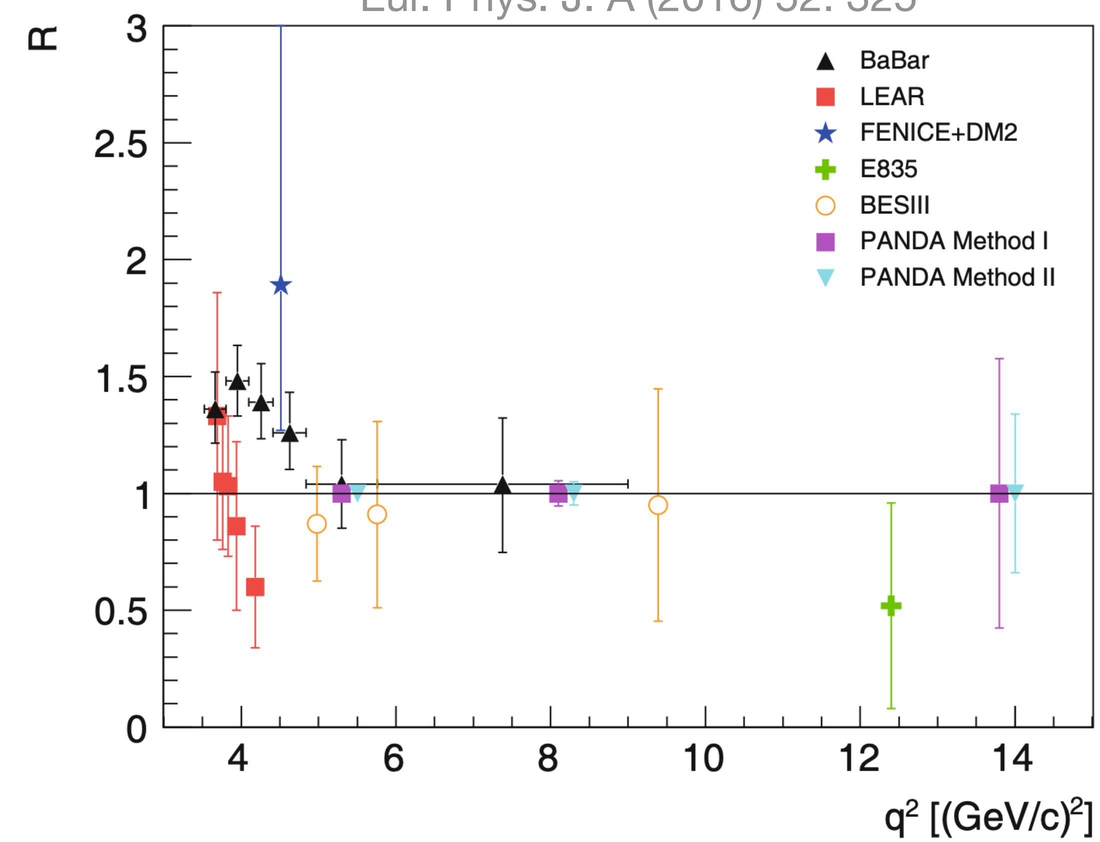
Electromagnetic Form Factors of the Proton

- Electric G_E and magnetic G_M proton FFs are analytical functions of q^2
  - At low q^2, probe the size of the nucleus
  - At high q^2, test QCD scaling
- ➡ Fundamental quantities!
- ➡ But very little data and only ratio R is measured



- Feasibility studies performed for $\bar{p}p \rightarrow e^+ e^-, \mu^+ \mu^-$
- Studies suggest that P̄ANDA will be able to
  - measure in the muon final state for the first time
  - improve measurements with higher statistics
  - access relative phase and absolute values for G_E and G_M

Eur. Phys. J. A (2016) 52: 325



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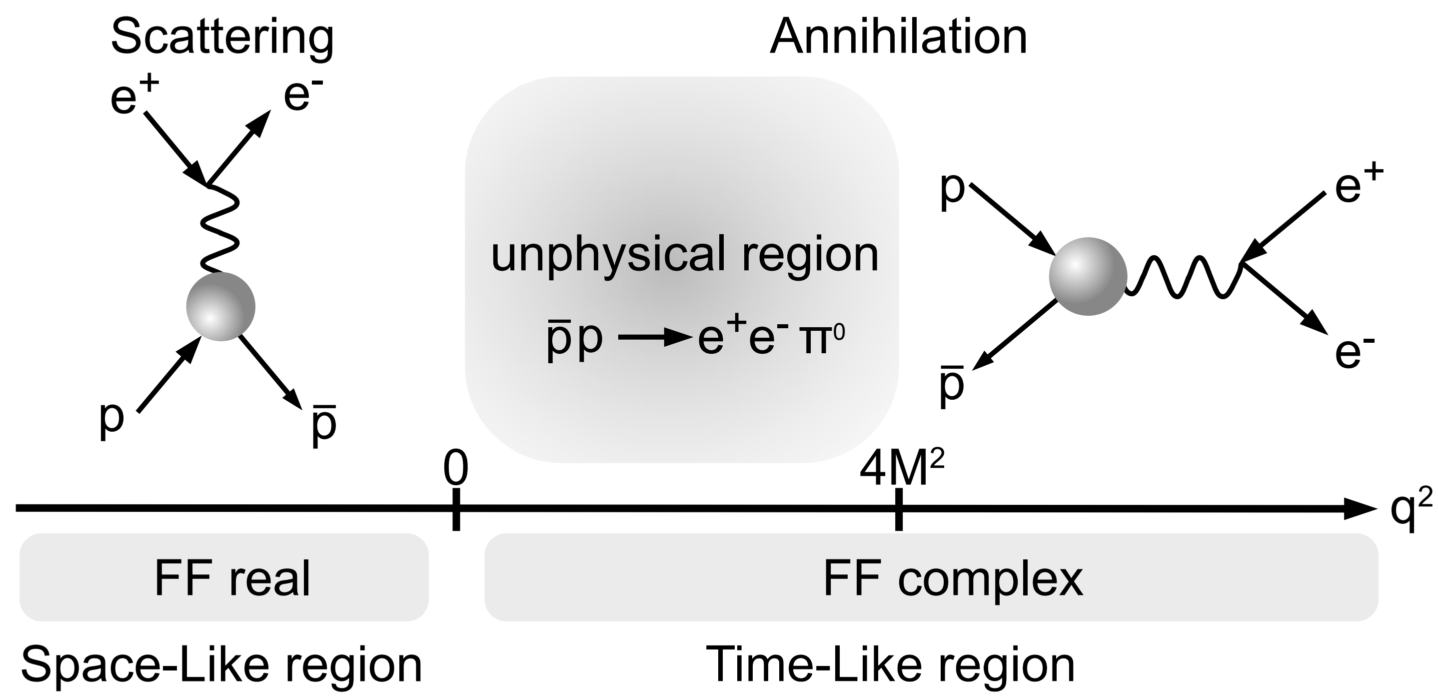

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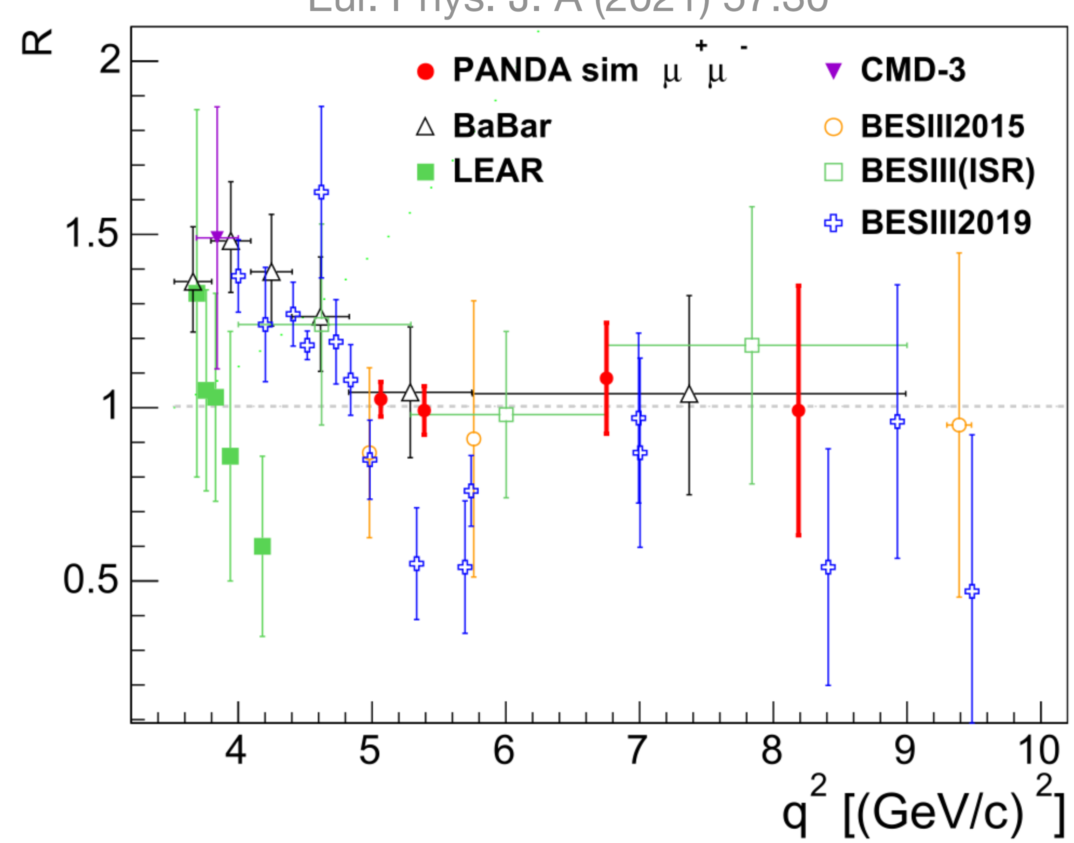
Eur. Phys. J. A (2021) 57:30



Summary

- Antiprotons are unique, decisive probes to tackle open questions in hadron spectroscopy
- $\bar{\text{P}}$ANDA will play an important role in the regime of spectroscopy
  - Gluon rich environment ➡ high event rate
- Formation ➡ Precise measurements of widths
  - Precise line shape scans of narrow states possible in startup phase (Day-1 physics)
- Production ➡ Study of exotic quantum numbers using
  - Sophisticated PWA tools available
  - Valuable experiences from Crystal Barrel beyond a proof of concept
- Discovery potential very high!
- Already very promising studies performed

- Just snippet of the possibilities $\bar{\text{P}}$ANDA will have
- All over the world there is lack of antiproton beams which showed great capabilities in the past
- More feasibility studies and simulations upcoming - stay tuned!


Thanks for listening
and stay healthy!