RUHR-UNIVERSITÄT BOCHUM

Glueball Searches at PANDA

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Mini-Workshop on Glueball Searches
June 1-2, 2021

PANDA Physics Program

Strong interaction studies with anti-protons

Spectroscopy

- hidden and open charm states
- gluon-rich QCD states
- light mesons

Strangeness

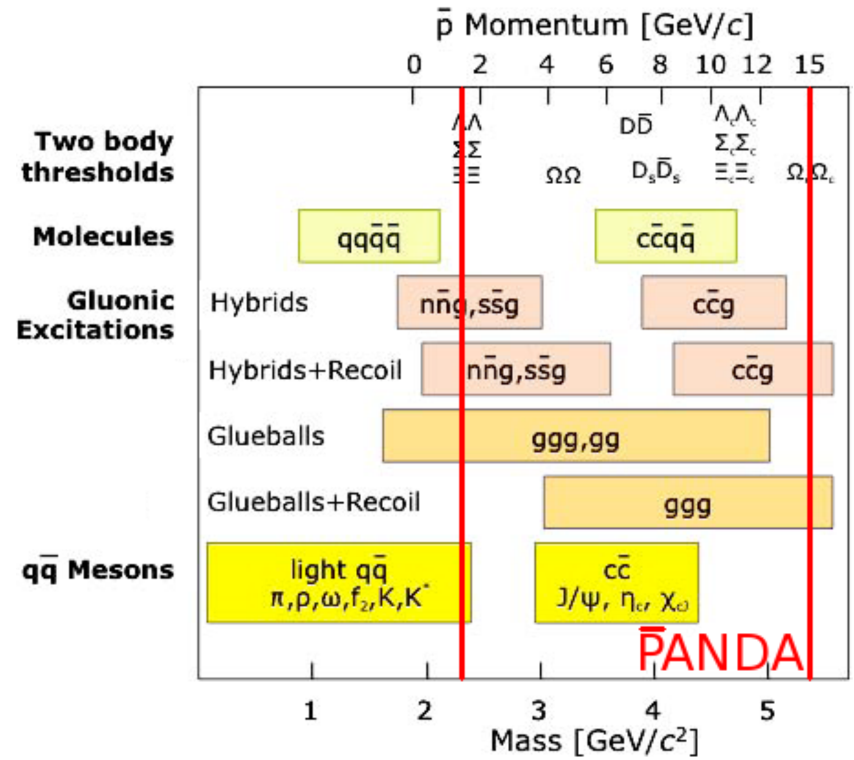
- strange baryon spectroscopy
- hyperon production and polarization
- hyperon transition form factors

Nucleon Structure

- time-like form factors
- TDAs and GPDs
- Drell-Yan processes

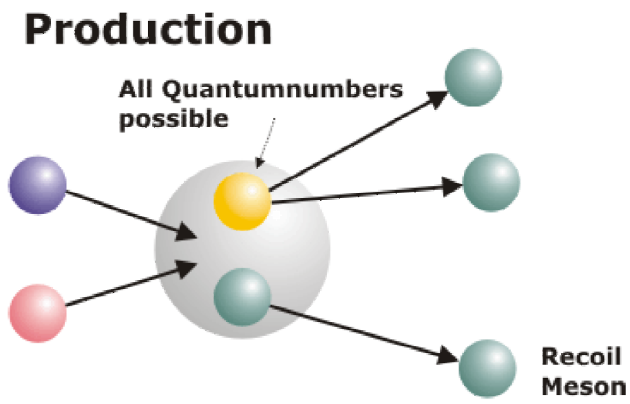
Nuclear Physics

- hadrons in nuclei
- hyperon-nucleon dynamics
- hyper-atoms and nuclei

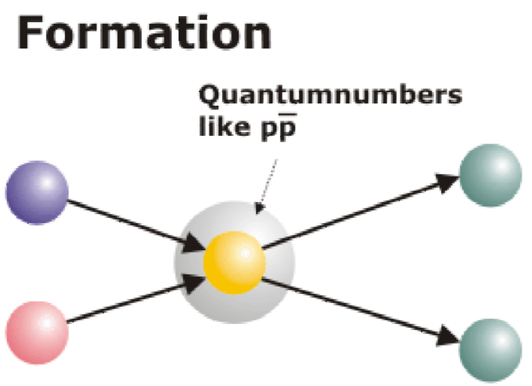


Spectroscopy with Antiprotons

- Production of all exotic and non-exotic quantum numbers with a recoil
  - high discovery potential
  - access to all quantum numbers (exotic)
  - multi-hadron final states detectable with PANDA

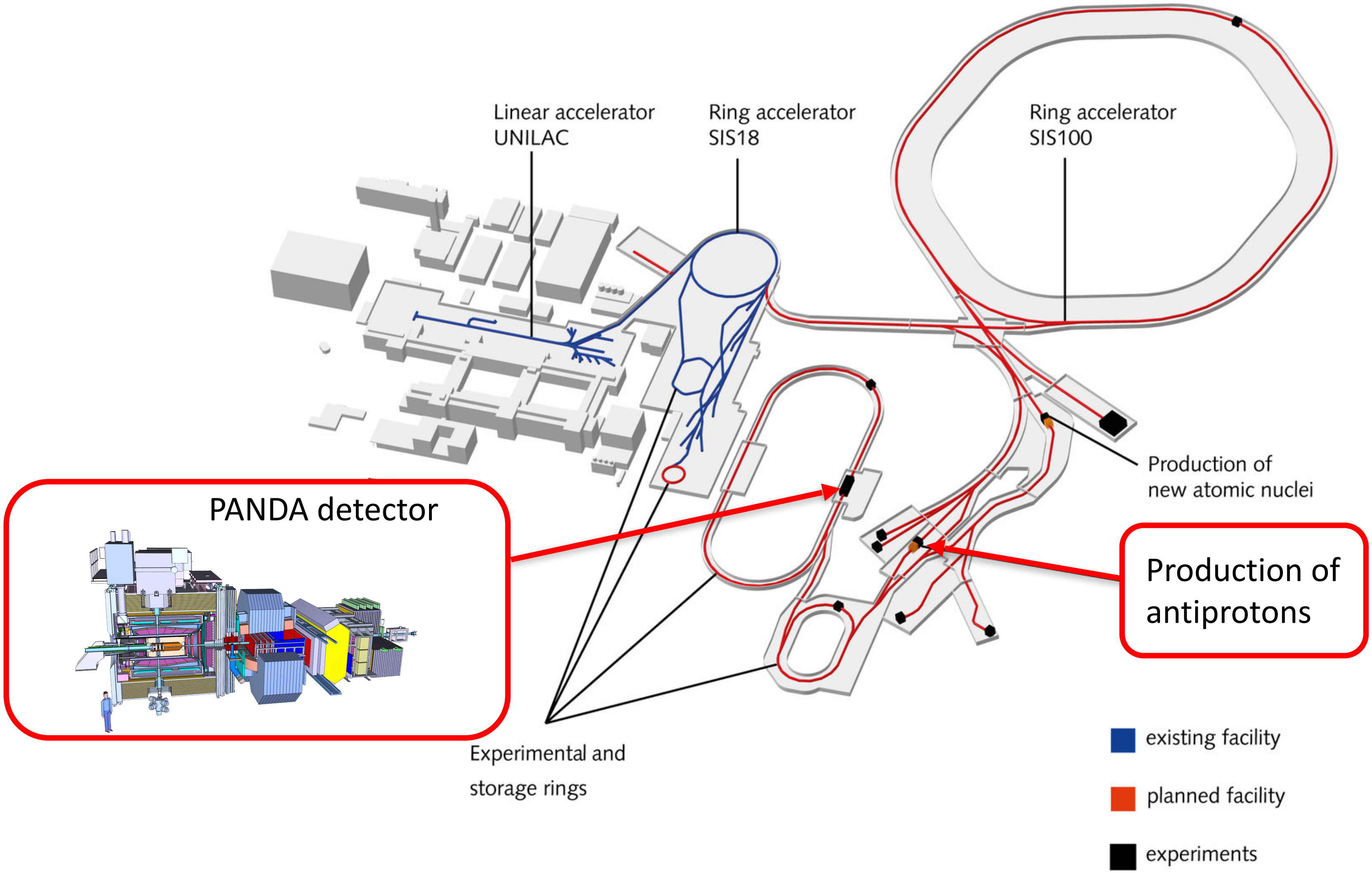


- Formation of non-exotic quantum numbers without a recoil
  - not limited to $J^{PC} = 1^{--}$ as e^+e^- machines
  - high resonant cross sections
  - precision mass and width measurements



PANDA at FAIR

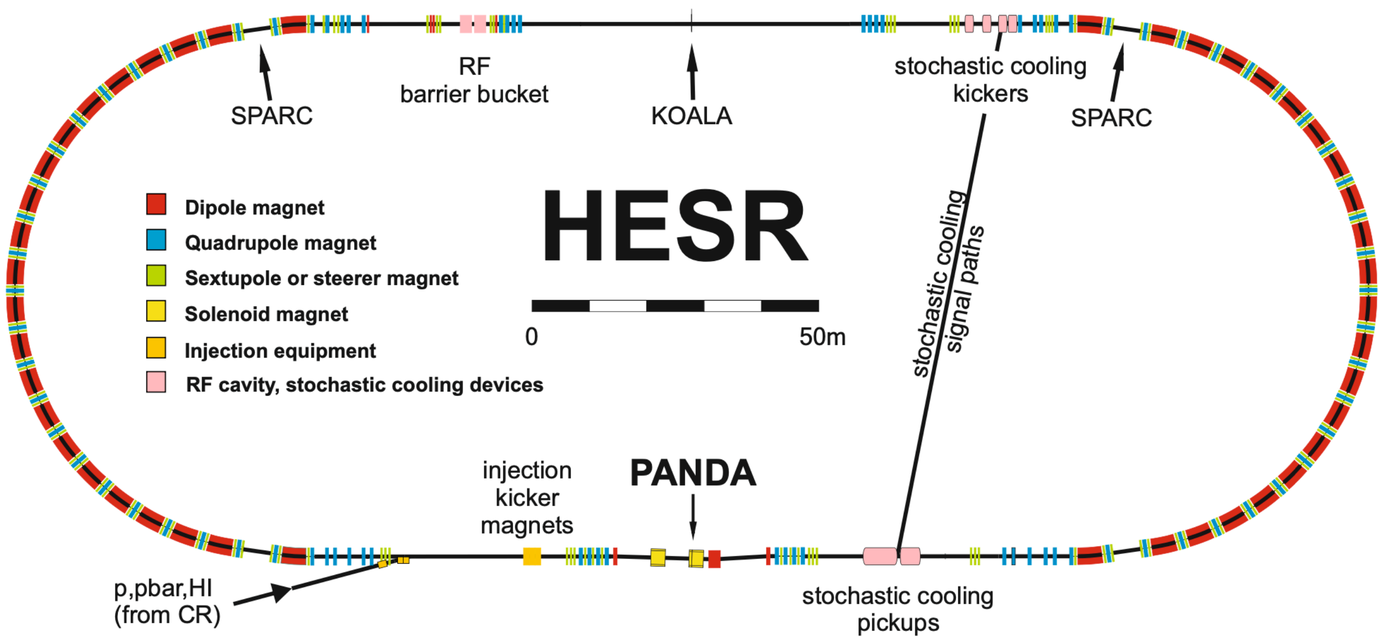
Facility for Antiproton and Ion Research, Darmstadt



Construction of FAIR

Construction site as of April 2021

High Energy Storage Ring



Momentum range

1.5 to 15 GeV/c

(E_{CMS} = 2.2 … 5.5 GeV)

Internal target ($\bar{p}p$, $\bar{p}A$)

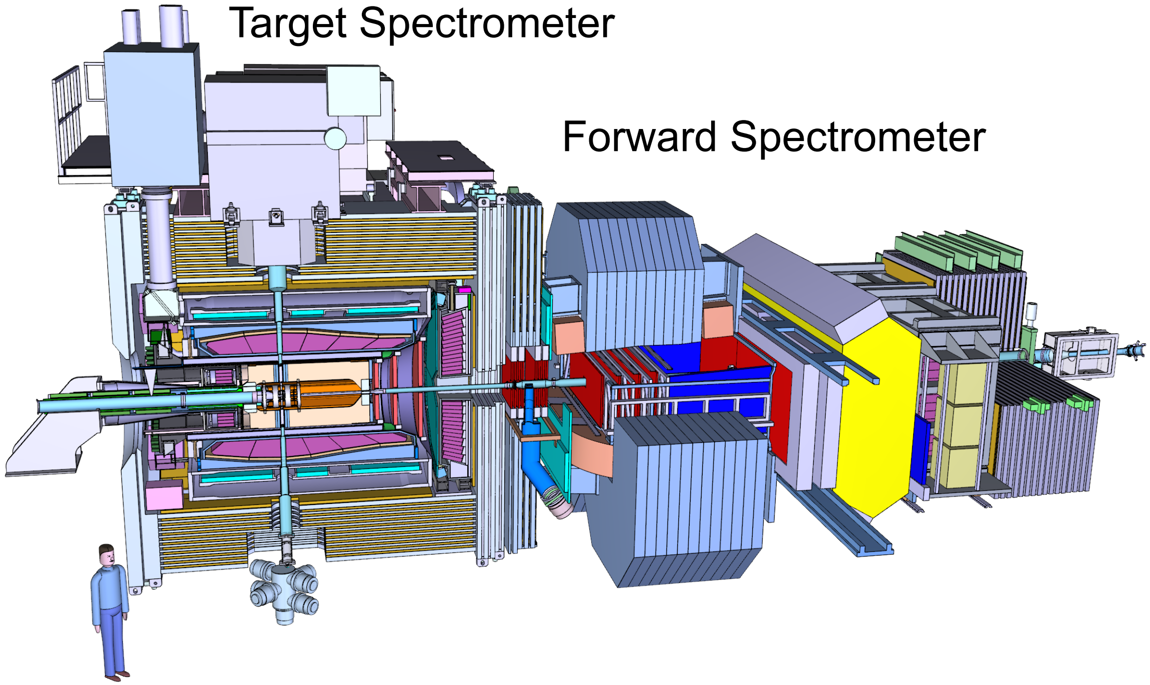
cluster jet / pellet target

high density $4x10^{15}$ cm^{-2}

Operation Modes

Mode	High Luminosity	High Resolution
$\Delta p/p$	$1 \cdot 10^{-4}$	$2 \cdot 10^{-5}$
Stored $\bar{p}$	10^{11}	10^{10}
$\mathcal{L}$ [$cm^{-2}s^{-1}$]	$2 \cdot 10^{32}$	$2 \cdot 10^{31}$

PANDA Detector



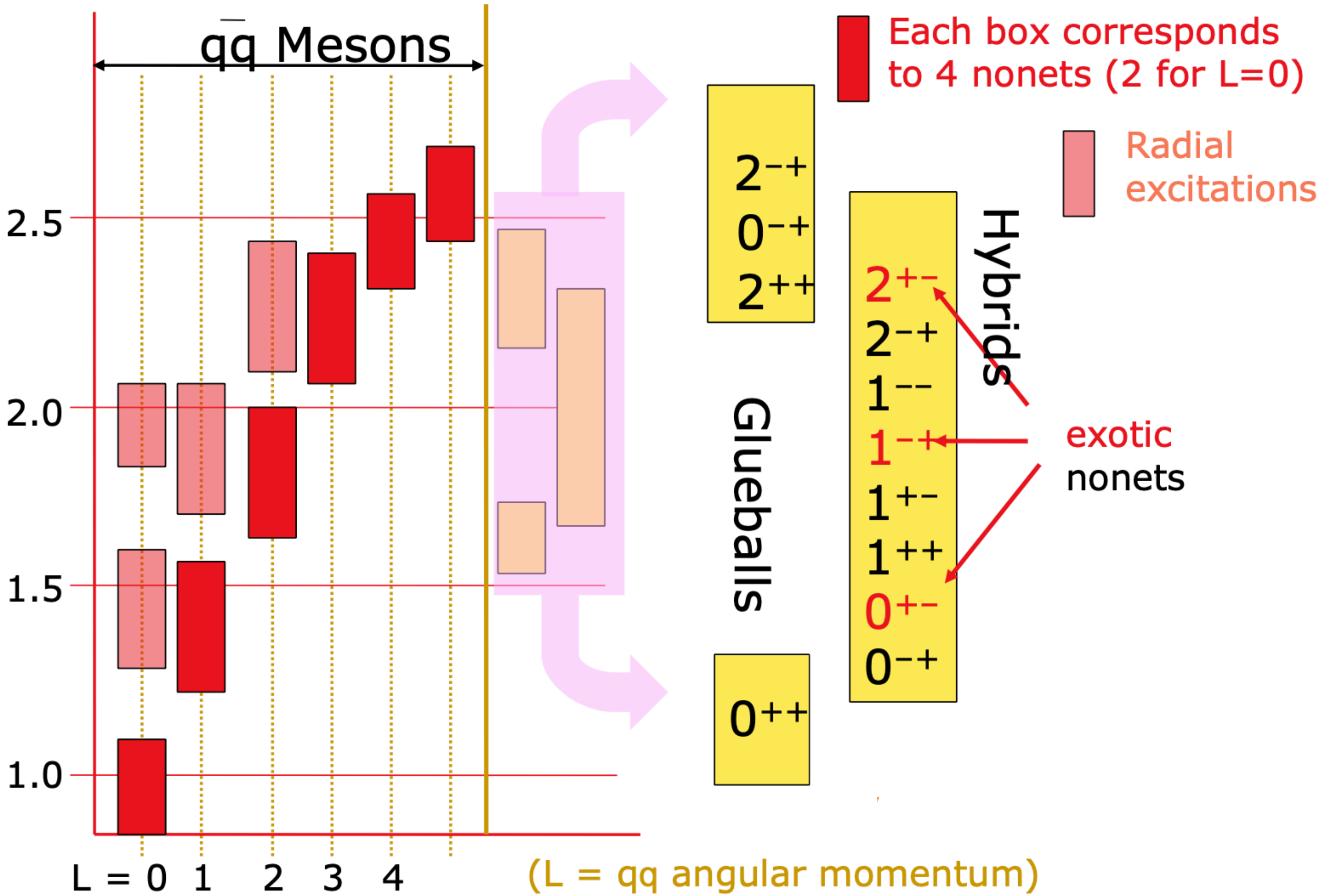
Exclusive measurements
- almost 4π coverage
- target and forward spectrometer

High event rates [10^7/s]
- sophisticated online processing
- detection of rare decay modes

Charged particle tracking (p<10 GeV/c)
- good momentum / vertex resolution
- good PID capabilities

Photon detection (E=0.02-10 GeV)
- excellent energy / angular resolution
- detection of low energetic photons

Light Meson Spectrum



Glueballs

Glueball spectrum predicted by LQCD, AdS/CFT, bag model,…

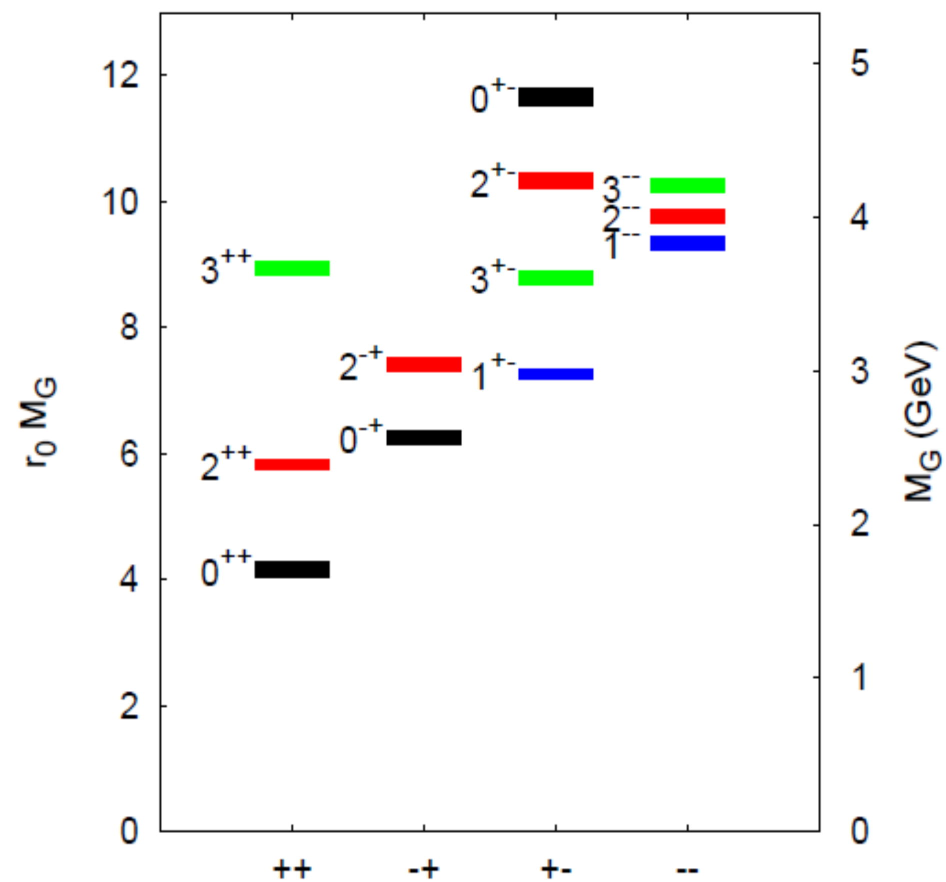
Quenched LQCD:

- Lowest states
  - $m(0^{++}) \sim 1730\,\mathrm{MeV}$
  - $m(2^{++}) \sim 2400\,\mathrm{MeV}$
  - $m(0^{-+}) \sim 2590\,\mathrm{MeV}$
- Spin-exotic glueballs (oddballs)
  - $m(2^{+-}) \sim 4230\,\mathrm{MeV}$
  - $m(0^{+-}) \sim 4780\,\mathrm{MeV}$

Full QCD calculations challenging

- mixing with meson pairs and flavor singlet mesons

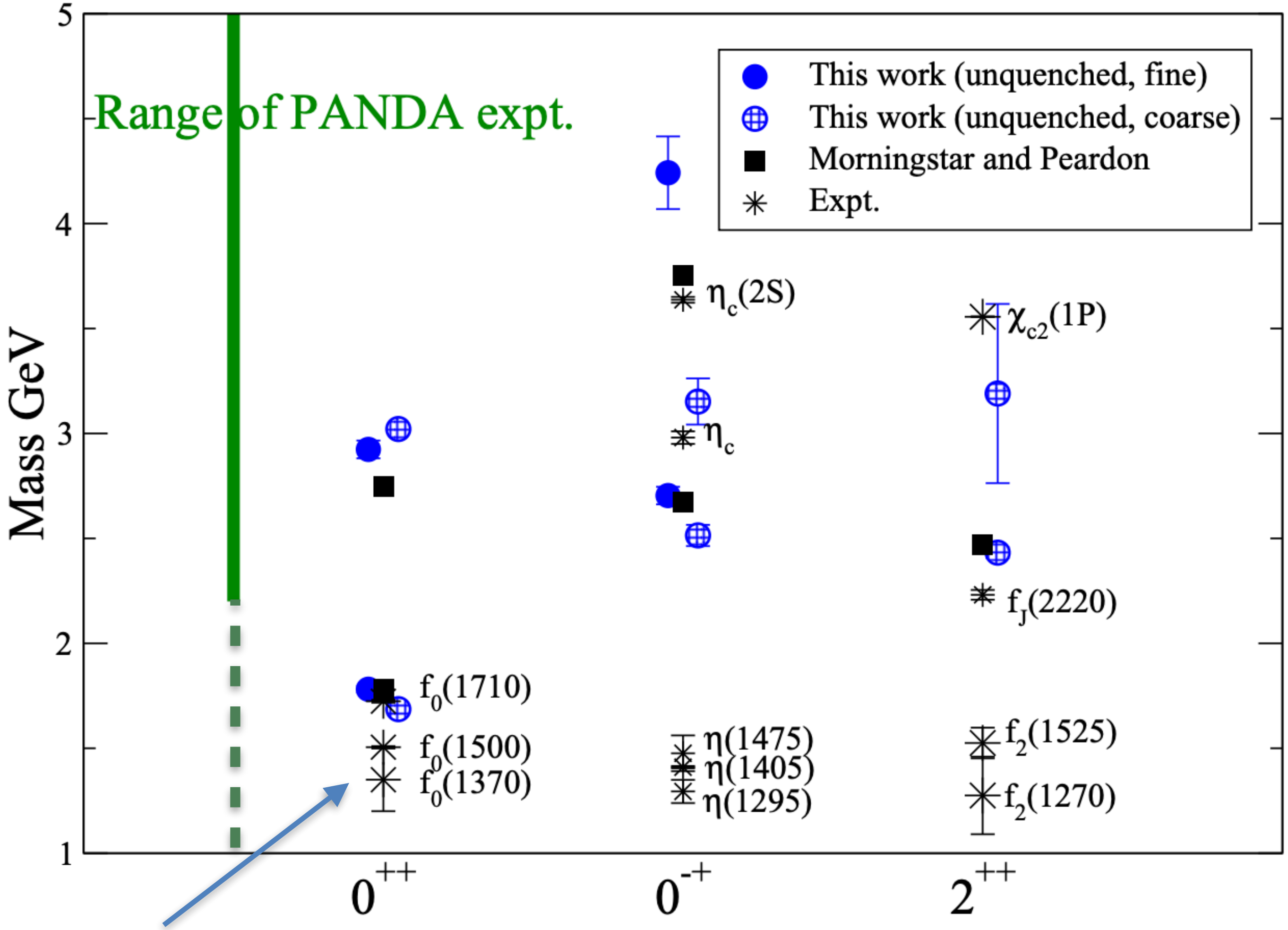
Glueball Spectrum (Lattice QCD)



Y. Chen et al, Phys. Rev. D 73, 014516 (2016)

Unquenched Calculations

UKQCD collaboration, Phys. Rev. D82, 034501 (2010)



2 $q\bar{q}$ states expected
3 observed: 2 $q\bar{q}$ + 1 glueball

Mixing of Scalar Mesons and Glueball

- mixing of $q\bar{q}$ and glueball states to observed states
- early works based on flavor-blind decays of glueball

$$\Gamma\left(gb \to \pi\pi : K\bar{K} : \eta\eta : \eta\eta' : \eta'\eta'\right) = 3 : 4 : 1 : 0 : 1$$

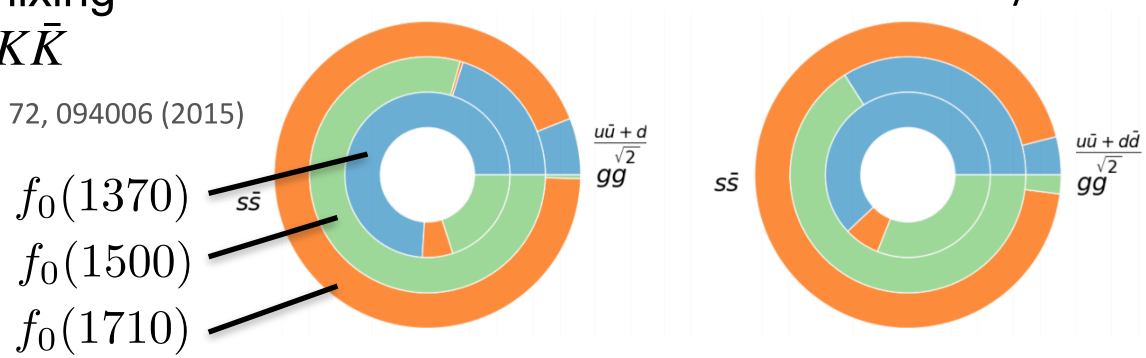
  – e.g. Amsler and Close: $f_0(1500)$ has large glueball component

- glueball decay via gg-$q\bar{q}$ mixing and direct coupling to $\pi\pi, K\bar{K}$ studied

Giacosa et al., Phys. Rev. D 72, 094006 (2015)

only via mixing

mixing and direct decay

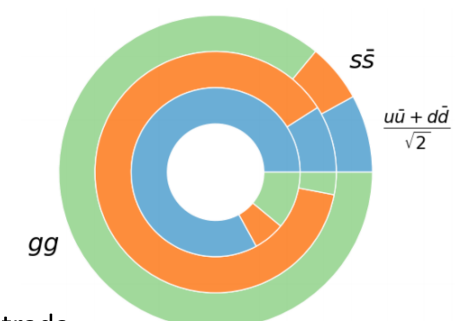


- Chanowitz suggested chiral suppression for coupling of scalar glueball to $q\bar{q}$ (~m_q)

M. Chanowitz, Phys.Rev.Lett. 95, 172001 (2005)

- flavor-suppression could give raise of large glueball component for $f_0(1710)$

S. Janowski et al, Phys. Rev. D 90, 114005 (2014)



plots from F. J. Llanes-Estrada, arXiv:2101.05366 [hep-ph]

Decay Properties

- important to measure the couplings to the various final states
- comparison with predictions may give insight into underlying decay mechanisms at work

e.g. for pure tensor glueball (m=2.2 GeV)

Holography Inspired Stringy Hadrons:

$$\Gamma\left(gb \to \boxed{\omega\omega : K^* K^*} : \phi\phi\right) = \boxed{1 : 0.3} : 0.07$$

J. Sonnenschein & D. Weissmann *Eur. Phys. J.C* 79 4, 326 (2019)

Effective field approach

$$\Gamma\left(gb \to \boxed{\omega\omega : K^* K^*} : \phi\phi\right) = \boxed{1 : 2.4} : 0.3$$

F. Giacosa et al., Phys. Rev. D72, 114021 (2005)

Witten-Sakai-Sugimoto Model (m=2.4 GeV)

$$\Gamma\left(gb \to \boxed{\omega\omega : K^* K^*} : \phi\phi\right) = \boxed{(0.053 \ldots 0.070) : (0.173 \ldots 0.250)} : (0.032 \ \ldots 0.052)$$

~ 1:3.3

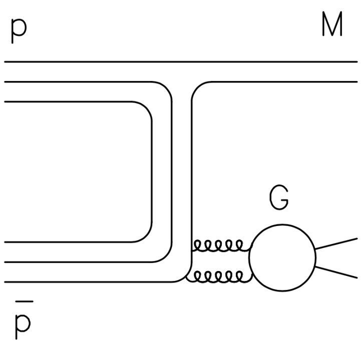
F. Bruenner et al., Phys. Rev. D 91, 106002 (2015)

Production Of Glueballs

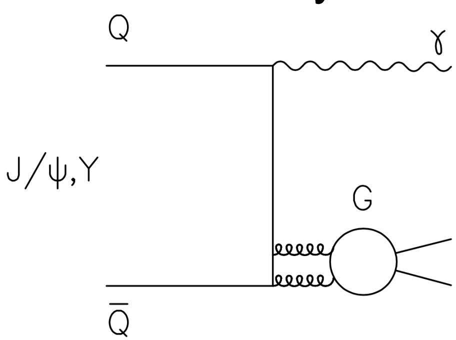
Gluon-rich environment

Suppression of Glueballs

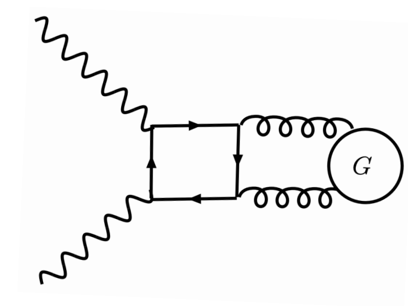
p̄p annihilations



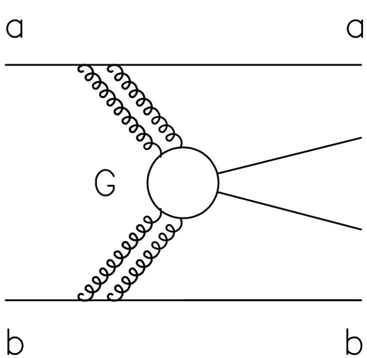
Radiative quarkonium decays



Two-photon processes



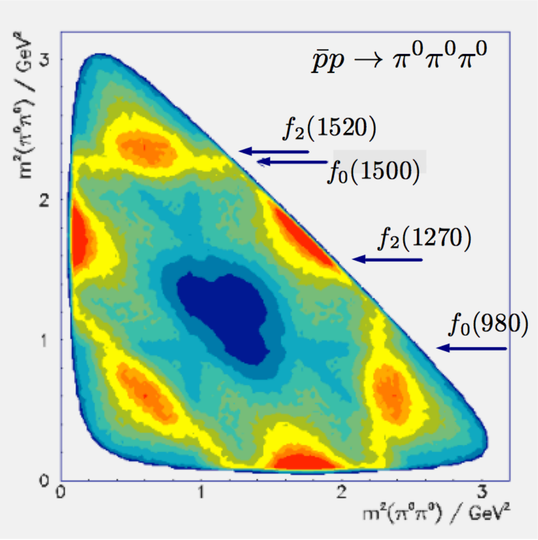
Central production



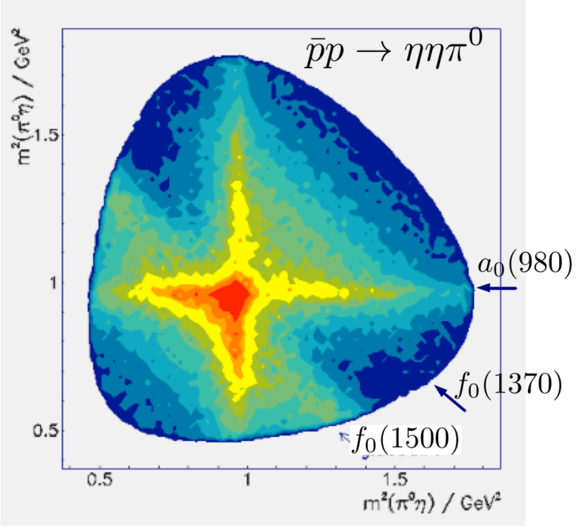
Systematic Study of $f_0(1500)$ at LEAR

- Seen in $\bar{p}p$ / $\bar{p}n$ annihilations, charmonium decays, central production, πN scattering, B and D decays
  - highest statistics in $\bar{p}p$
- Decay modes: ππ, $K\bar{K}$, ηη, ηη', 4π
- Establishment of $f_0(1500)$ in $\bar{p}p$ at rest
  - annihilations of protonium in S wave dominant
  - well defined initial state
  - studied $\bar{p}p \to (\pi^0\pi^0/K\bar{K}/\eta\eta^{(\prime)}, 4\pi)\pi^0, (\pi^0\pi^0)\eta$
  - BFs for all five decay modes measured

712k events



198k events



Crystal Barrel
Phys. Lett. B355, 425 (1995)
Phys. Lett. B358, 389 (1995)

Further Observations of $f_0(1500)$

- p̄p annihilations in-flight at Crystal Barrel/LEAR
  - larger phase-space
  - higher waves in annihilations possible
  - lower acceptance (symmetric detector)

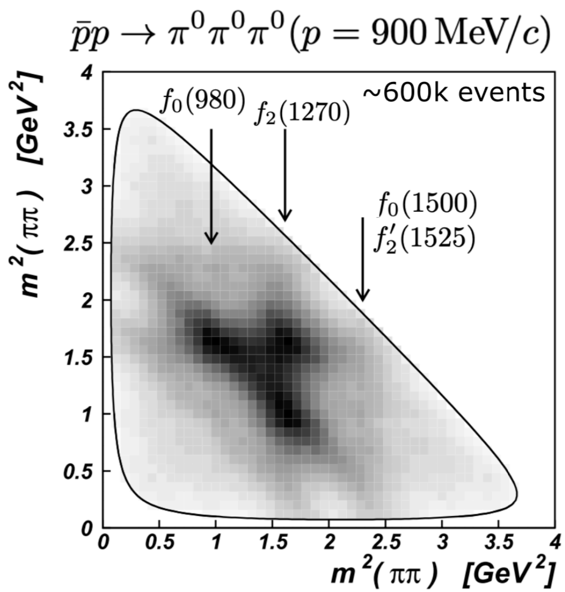
- $\bar{p}p \to \pi^0\pi^0\pi^0, \eta\eta\pi^0$ at 900 MeV/c
  - initial state: J<4
  - $f_0(1500)$ contribution: ~10%
  - $f_0(1500)$ BFs compatible with results from at-rest annihilations

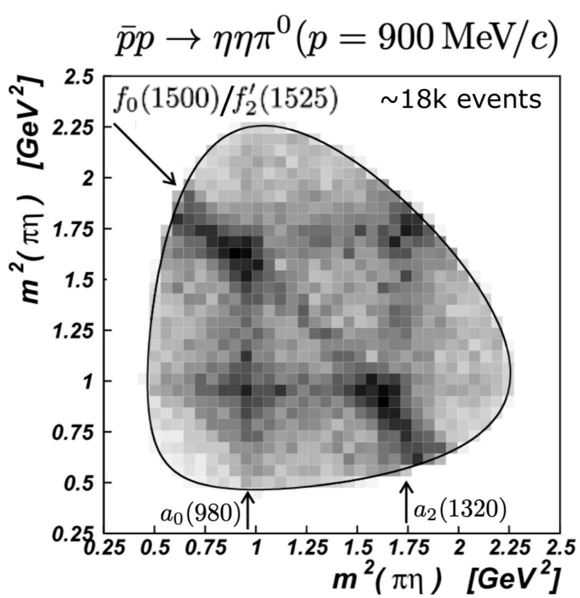
Crystal Barrel, Eur. Phys. J. C 23, 29–41 (2002)

- $\bar{p}p \to \pi^0\pi^0\eta$ in the range of 600 to 1940 MeV/c
  - $f_0(1500)$ production from 0^- initial state

A.V. Anisovich et al., Nucl.Phys.A651:253-276 (1999)

also A. V. Sarantsev et al., Phys. Lett. B 816 (2021) using CB/LEAR data



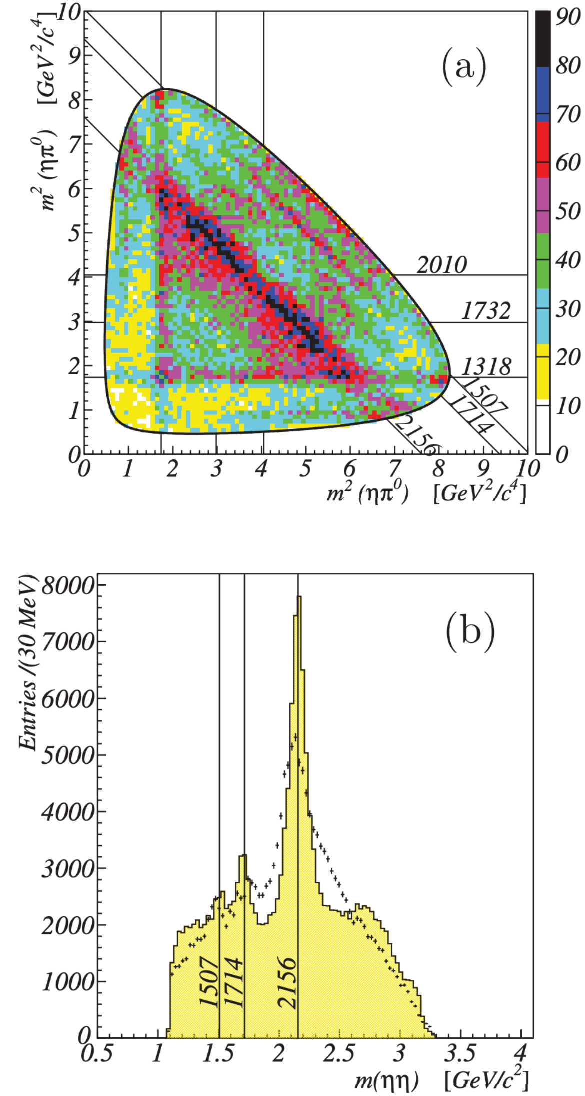


Further Observations of $f_0(1500)$

I. Uman et al, Phys. Rev. D 73, 052009 (2006)

- Analysis of $\bar{p}p \rightarrow \eta\eta\pi^0$ at p(p̄)=5.2 GeV/c
  - data from E835 at Fermilab
  - larger phase-space compared to LEAR
  - non-magnetic spectrometer, restricted to neutral channels

- $f_0(1500)$ and $f_0(1710)$ observed
  - intensity $f_0(1710) : f_0(1500) \sim 2.2$
  - compared to CB/LEAR <0.25 at 90% CL



PANDA

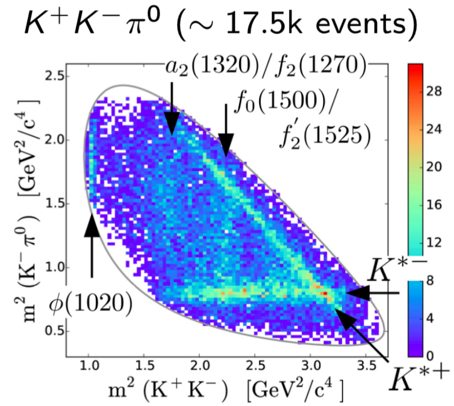
- Extend measurements of in-flight annihilations above 1.5 GeV/c
  - overlap with LEAR (between 1.5 and 1.95 GeV/c) and Fermilab
  - detector tailored for kinematics at fixed target
  - detection of final states with charged and neutral particles

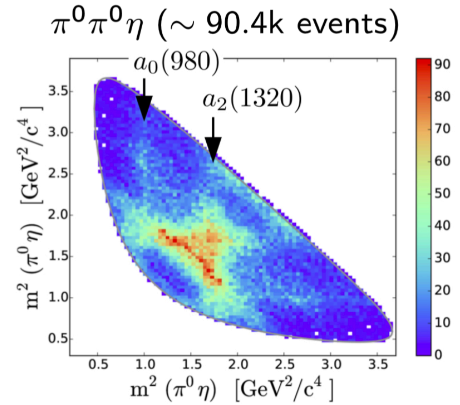
- PANDA can acquire large data samples from the beginning on
  - >10x statistics of Crystal Barrel/LEAR

PWA of CB/LEAR Data (PANDA *phase 0*)

- p̄p in flight at 900 MeV/c

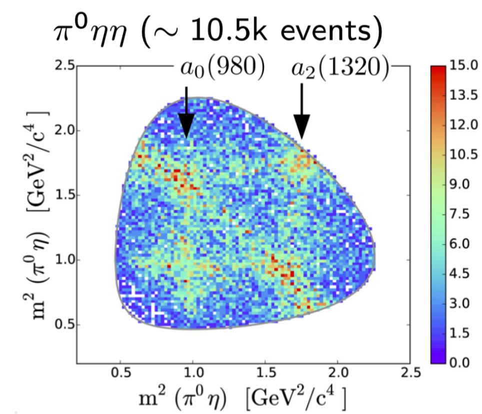
$$\bar{p}p \rightarrow K^+K^-\pi^0, \pi^0\pi^0\eta, \pi^0\eta\eta$$





- Coupled channel analysis of Crystal Barrel/LEAR data
- K-matrix description

IJ^{PC}	Poles	Channels
$0\,0^{++}$	5	5
$0\,2^{++}$	4	4
$1\,1^{--}$	3	3
$1\,1^{++}$	2	2
$1\,2^{++}$	2	2
$(K\pi)\,0^{+}$	1	2



- Breit-Wigner for isolated resonances: Φ, K*, $\pi_1(1400)$
- Scattering data I=0 (S, D wave) and I=1 (P wave)

PRD 83 (2011) 074004, Nucl.Phys.B 64 (1973) 134-162,
Nucl.Phys.B 269 (1986) 485, Nuov.Cim.A 80 (1984) 363

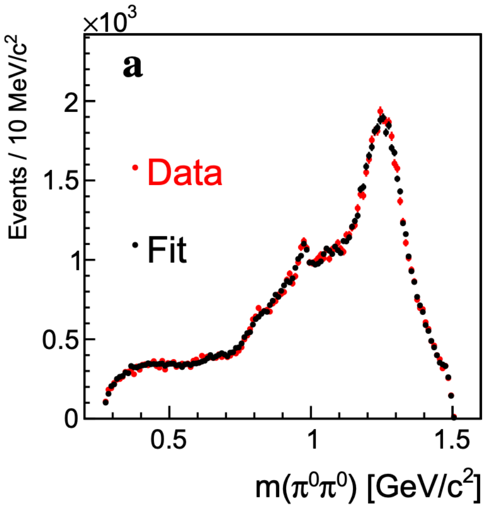
Crystal Barrel, Eur. Phys. J. C 80:453 (2020)

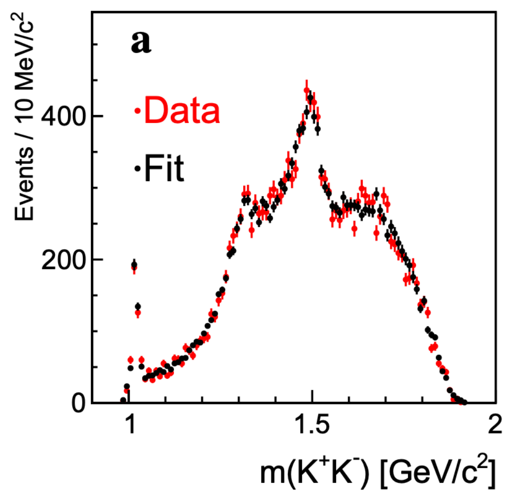
PWA Software: PAWIAN, B. Kopf et. al., Hyperfine Interact. 229 no.1-3, 69-74 (2014)

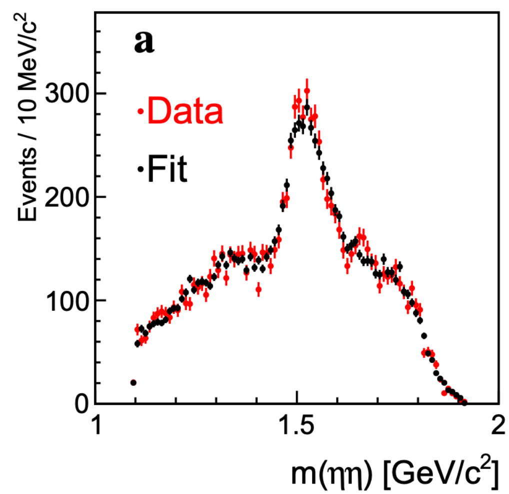
PWA of CB/LEAR Data (PANDA *phase 0*)

Production of $f_0(1500)$ and $f_0(1710)$ observed

their contributions to the 0^{++} wave have not been extracted

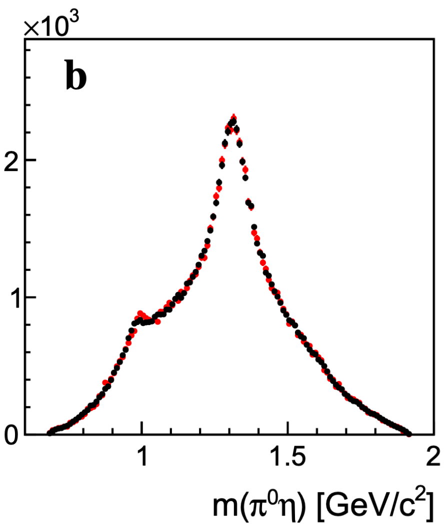


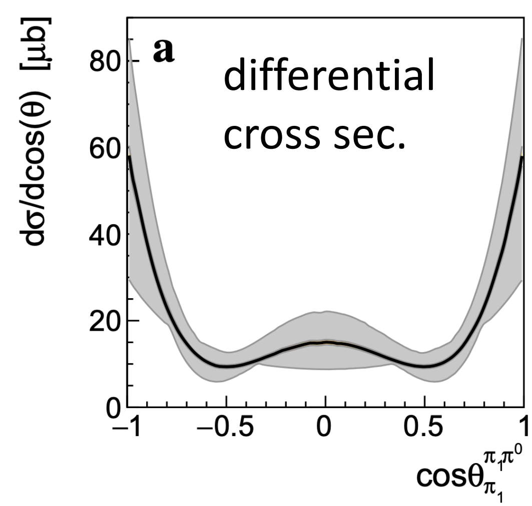




For the $\eta\pi\pi$ channel an exotic 1^{-+} $\pi\eta$ wave is observed

cross section $\sim 36\,\mu\mathrm{b}$





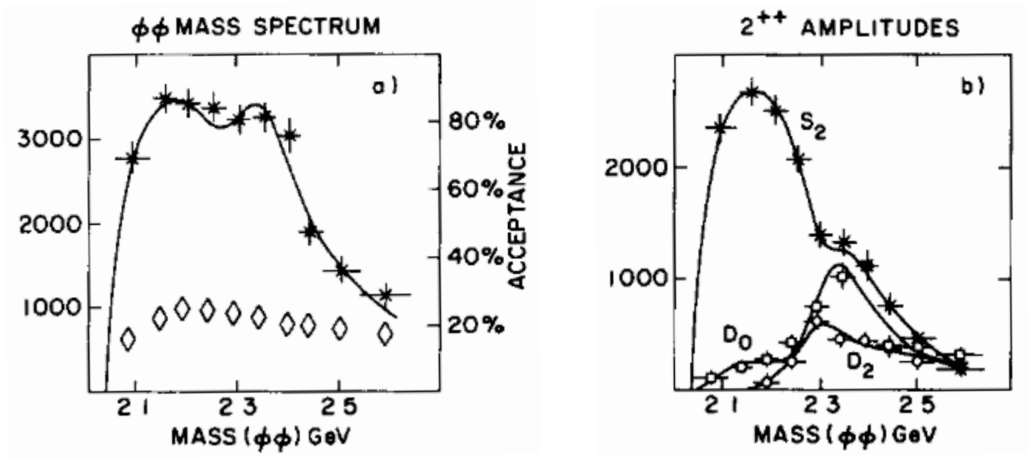
Crystal Barrel, Eur. Phys. J. C 80:453 (2020)

Tensor Resonances in the ΦΦ system

$\pi^- p \to \phi\phi n$ at 22 GeV/c by Etkin et al.

Phys.Lett.B 201, 568-572 (1988)

- OZI suppressed process
- observation of three tensor states



Resonance	Mass [MeV]	Width [MeV]	Production	Decays
$f_2(2010)$	2011^{+60}_{-80}	202 ± 60	πN	$\phi\phi, K\bar{K}$
$f_2(2300)$	2297 ± 28	149 ± 40	$\pi N, \gamma\gamma$	$\phi\phi, K\bar{K}$
$f_2(2340)$	2345^{+50}_{-40}	322^{+70}_{-60}	$\pi N, \bar{p}p, J/\psi$	$\phi\phi, \eta\eta$

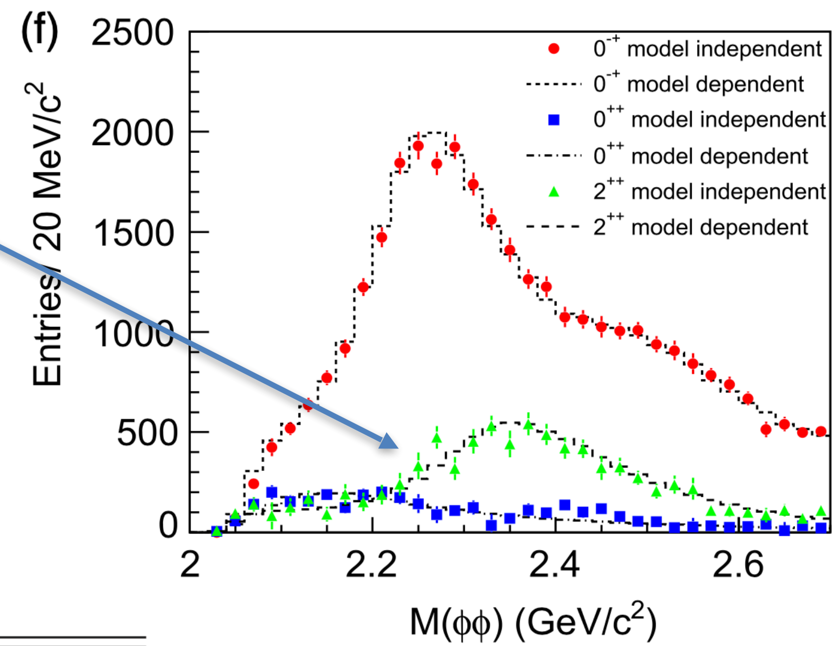
Possible scenario: mixing of 1^3F_2 and $2\ ^3F_2$ $q\bar{q}$ states and glueball

Tensor Resonances in the ΦΦ system

BESIII: PWA of $J/\psi \to \gamma\phi\phi$

- exploiting 1.3B J/ψ events
- ~13k events in the 2^{++} wave

Observation of three 2^{++} states previously seen in πN scattering



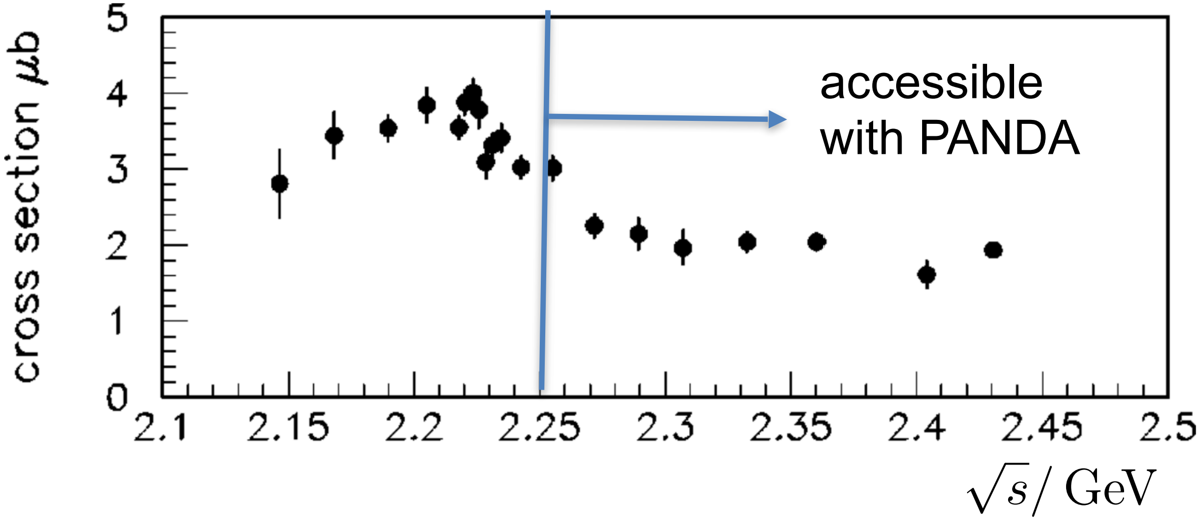
Resonance	M (MeV/c^2)	Γ (MeV/c^2)	B.F. ($\times 10^{-4}$)	Sig.
$\eta(2225)$	2216^{+4+21}_{-5-11}	185^{+12+43}_{-14-17}	$(2.40 \pm 0.10^{+2.47}_{-0.18})$	28σ
$\eta(2100)$	2050^{+30+75}_{-24-26}	$250^{+36+181}_{-30-164}$	$(3.30 \pm 0.09^{+0.18}_{-3.04})$	22σ
$X(2500)$	$2470^{+15+101}_{-19-23}$	230^{+64+56}_{-35-33}	$(0.17 \pm 0.02^{+0.02}_{-0.08})$	8.8σ
$f_0(2100)$	2101	224	$(0.43 \pm 0.04^{+0.24}_{-0.03})$	24σ
$f_2(2010)$	2011	202	$(0.35 \pm 0.05^{+0.28}_{-0.15})$	9.5σ
$f_2(2300)$	2297	149	$(0.44 \pm 0.07^{+0.09}_{-0.15})$	6.4σ
$f_2(2340)$	2339	319	$(1.91 \pm 0.14^{+0.72}_{-0.73})$	11σ
0^{-+} PHSP			$(2.74 \pm 0.15^{+0.16}_{-1.48})$	6.8σ

BESIII, Phys. Rev. D 93, 112011 (2016)

ΦΦ in Antiproton-Proton Annihilations

- JETSET at LEAR: $\bar{p}p \rightarrow \phi\phi$ (scan)
- Large cross section observed at threshold
  - O(100) larger than expected from OZI allowed $\bar{p}p \rightarrow \omega\omega$
  - possible explanation: gluonic contributions, $K\bar{K}$ rescattering, intermediate hyperon-pair production, intrinsic strange of proton ?

JETSET, Phys. Rev. D 57, 5370 (1998)



Limited phase-space at LEAR
PWA to address resonance production not published

ΦΦ Scan at PANDA

Toy MC study addressing PWA of $\bar{p}p \rightarrow \phi\phi$ at $\sqrt{s} > 2.25 GeV$

- first step towards full feasibility study
- detector efficiency and response not (!) included

Data generated using K-matrix

- 36 scan points of 200 keV width each
- apply PWA to extract intensities and phases

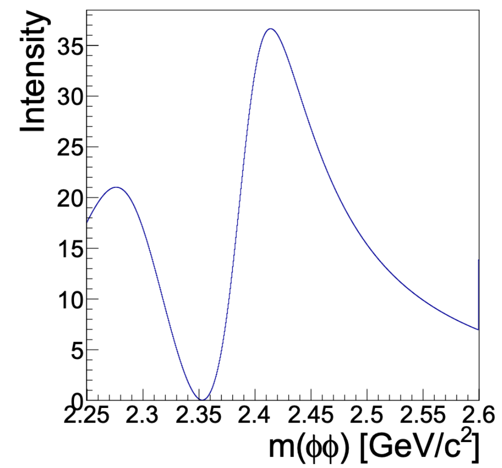
PWA Software: PAWIAN
B. Kopf et. al., Hyperfine Interact. 229 no.1-3, 69-74 (2014)

Toy Data for ΦΦ Scan at PANDA

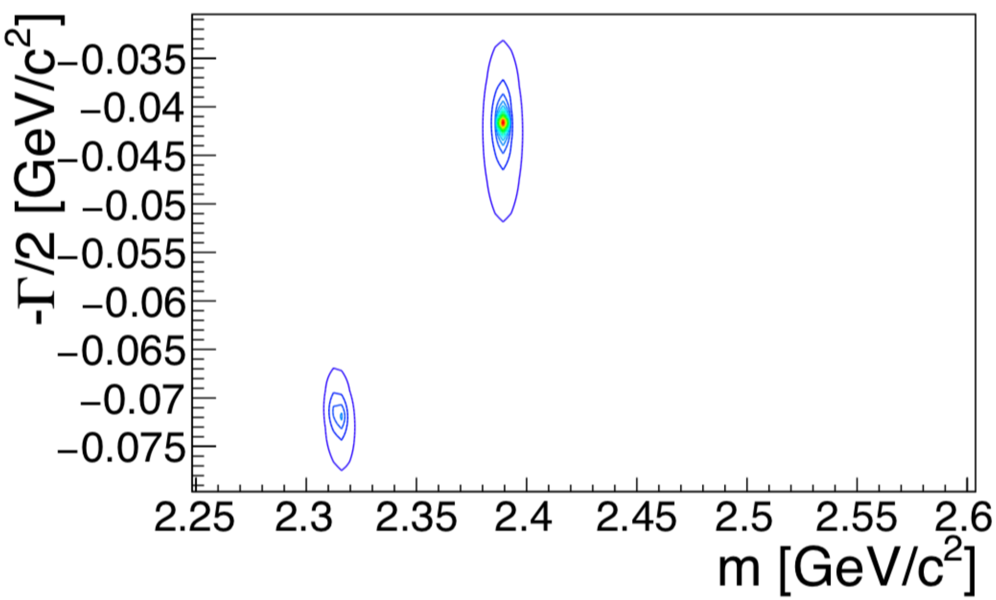
Assumed scenario:

- two 2^{++} poles with couplings to $K\bar{K}$ and ΦΦ and
- non-resonant 4^{++} contribution in ΦΦ and $K\bar{K}$

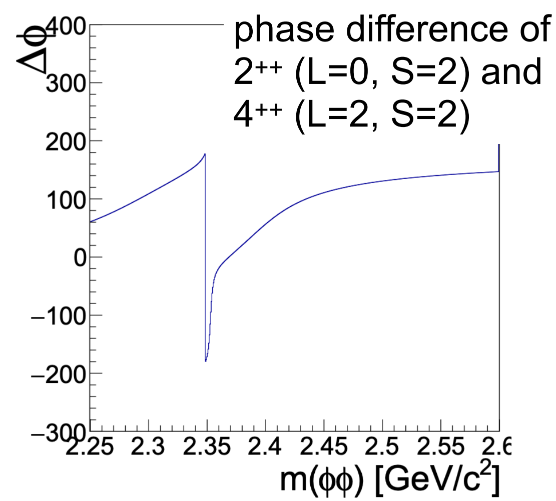
Intensity in ΦΦ



Poles in complex energy plane



Relative Phase for ΦΦ

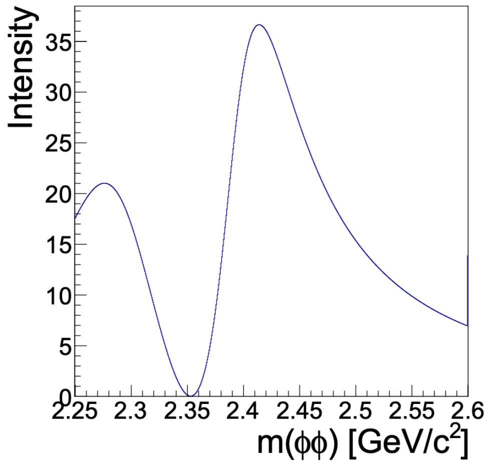


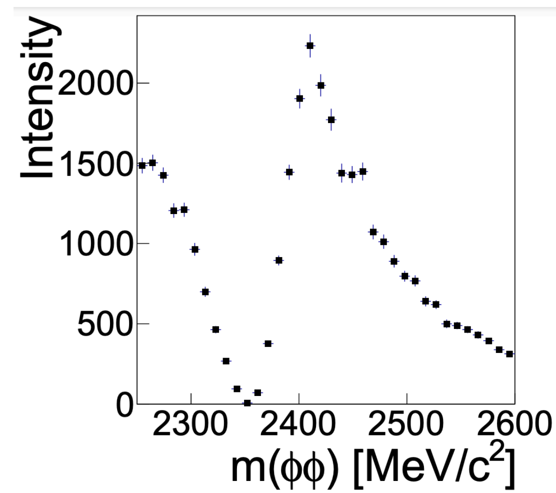
ΦΦ Scan at PANDA

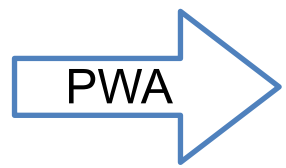
generated

extracted

Intensities

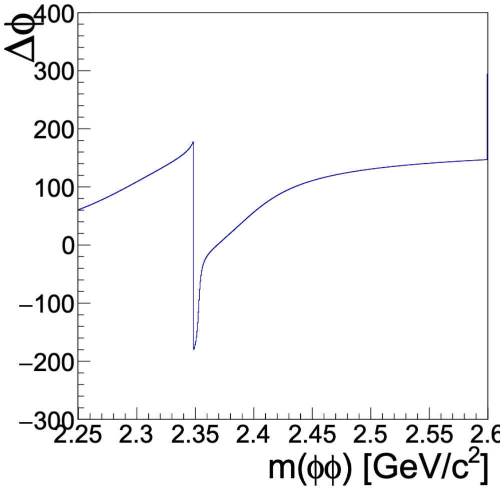


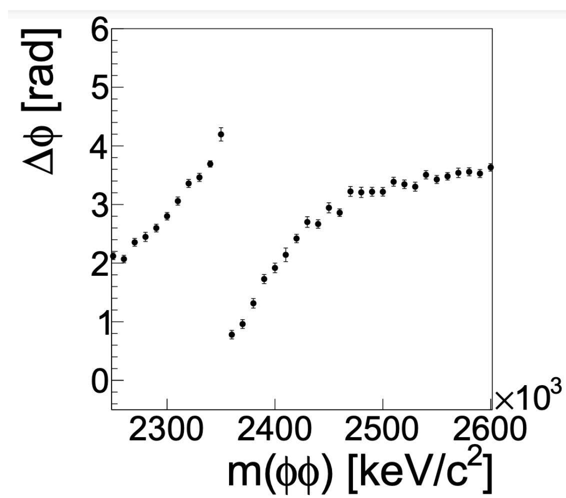




all possible J^{PC} hypotheses fitted and ranked

Phase

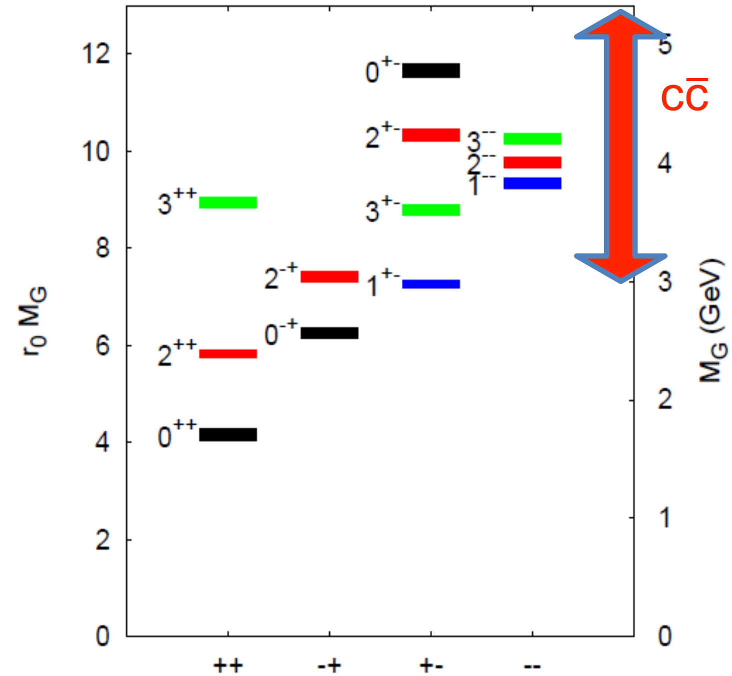




Heavy Glueballs

- glueballs predicted in the charmonium mass range
- search would be in parallel to charmonium program at PANDA
- possible final states $\phi\eta, \phi\phi, J/\psi\eta, J/\psi\phi$
- expect less mixing effects compared to light quark sector (as argued by P. Page*)
  – no light hadrons above 3.1 GeV
  – small mixing with $c\bar{c}$ due to high charm mass
  – decays of *C-odd* states into two lighter glueballs (0^{++},2^{++},0^{-+}) C-parity forbidden

Y. Chen et al, Phys. Rev. D 73, 014516 (2016)



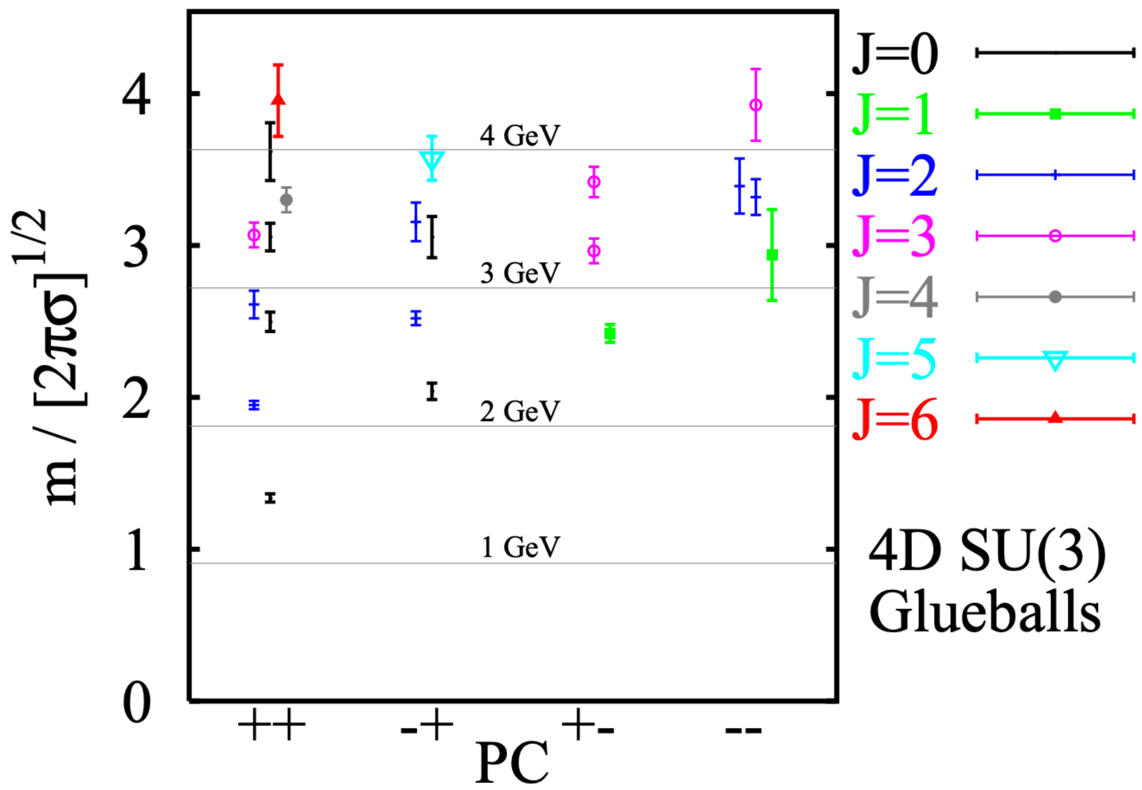
- glueballs with exotic J^{PC}
  – structure different from glueballs with conventional J^{PC}
  – could be narrow following above arguments
  – not seen in all LQCD calculations

* arXiv:0107016 [hep-ph]

Excited Glueballs

- Higher spin and excited states predicted by Meyer and Teper (LQCD)

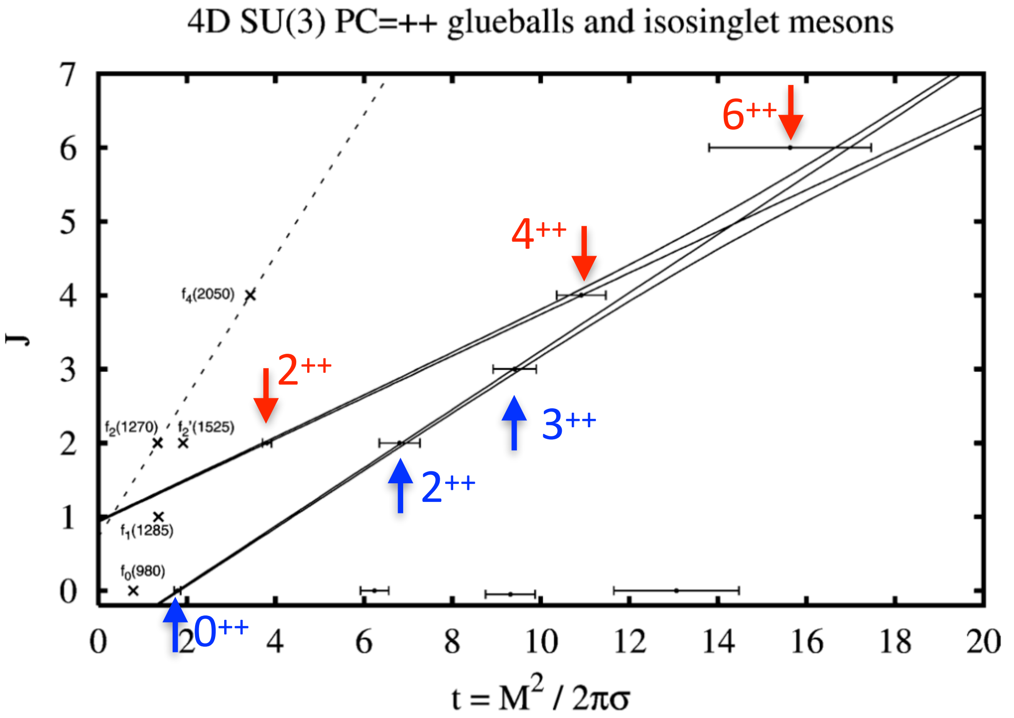
H. B. Meyer and M. J. Teper, Phys.Lett. B605, 344-354 (2005)



Regge Trajectories

- Higher spin and excited states predicted by Meyer and Teper (LQCD)
- States on Regge trajectories link to string model of glueballs

H. B. Meyer and M. J. Teper, Phys.Lett. B605, 344-354 (2005)



leading trajectory only *even*$^{++}$: rotating open string

subleading trajectroy (J=1 absent): phononic closed string

Experimental identification of the states on trajectories can give insight into the structure of glueballs

Summary

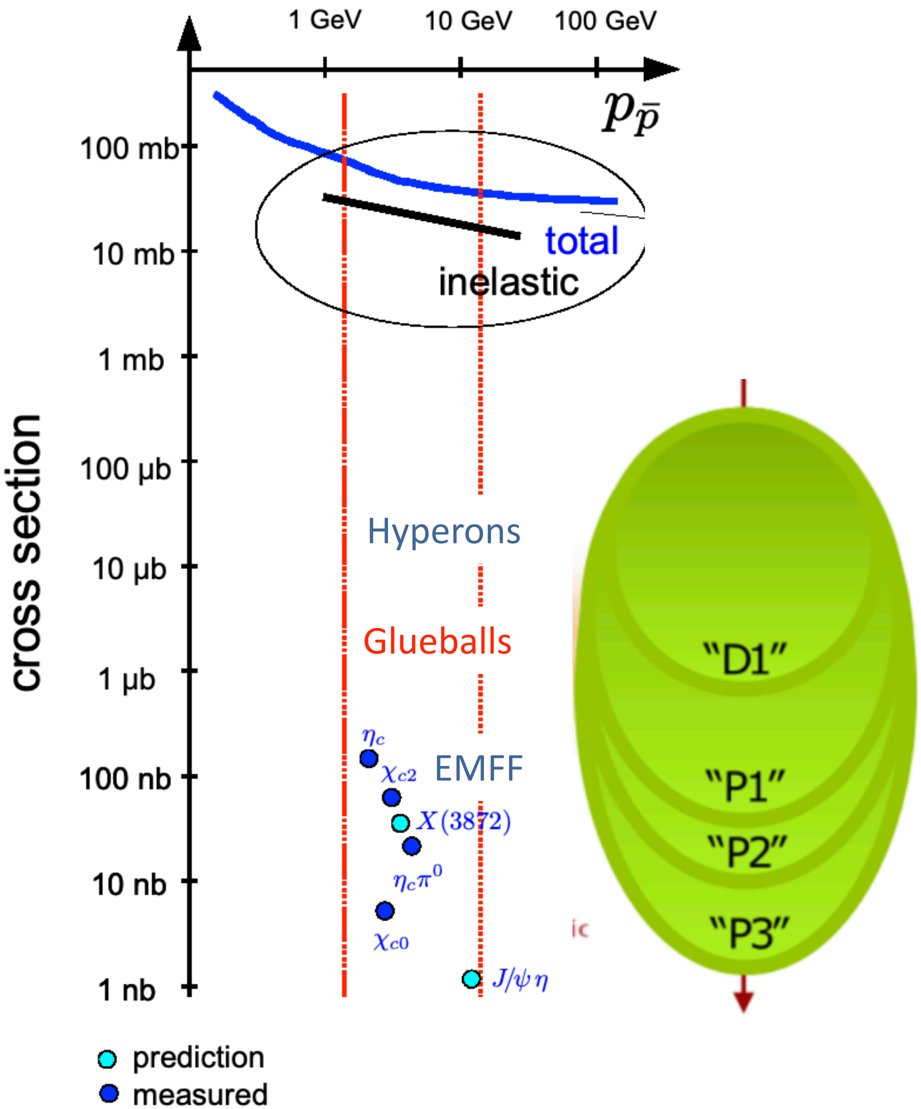
- Glueball spectrum well accessible at PANDA
  - large cross sections for conventional meson and glueball production

- From the beginning of operation PANDA will collect competitive data samples
  - extending measurements at LEAR and Fermilab
  - detector designed for in in-flight annihilations to charged/neutral final states

- Key measurements
  - search for tensor glueball in $\bar{p}p \rightarrow \phi\phi$ scan
  - heavy glueballs in the charmonium mass range
  - spin-exotic glueballs

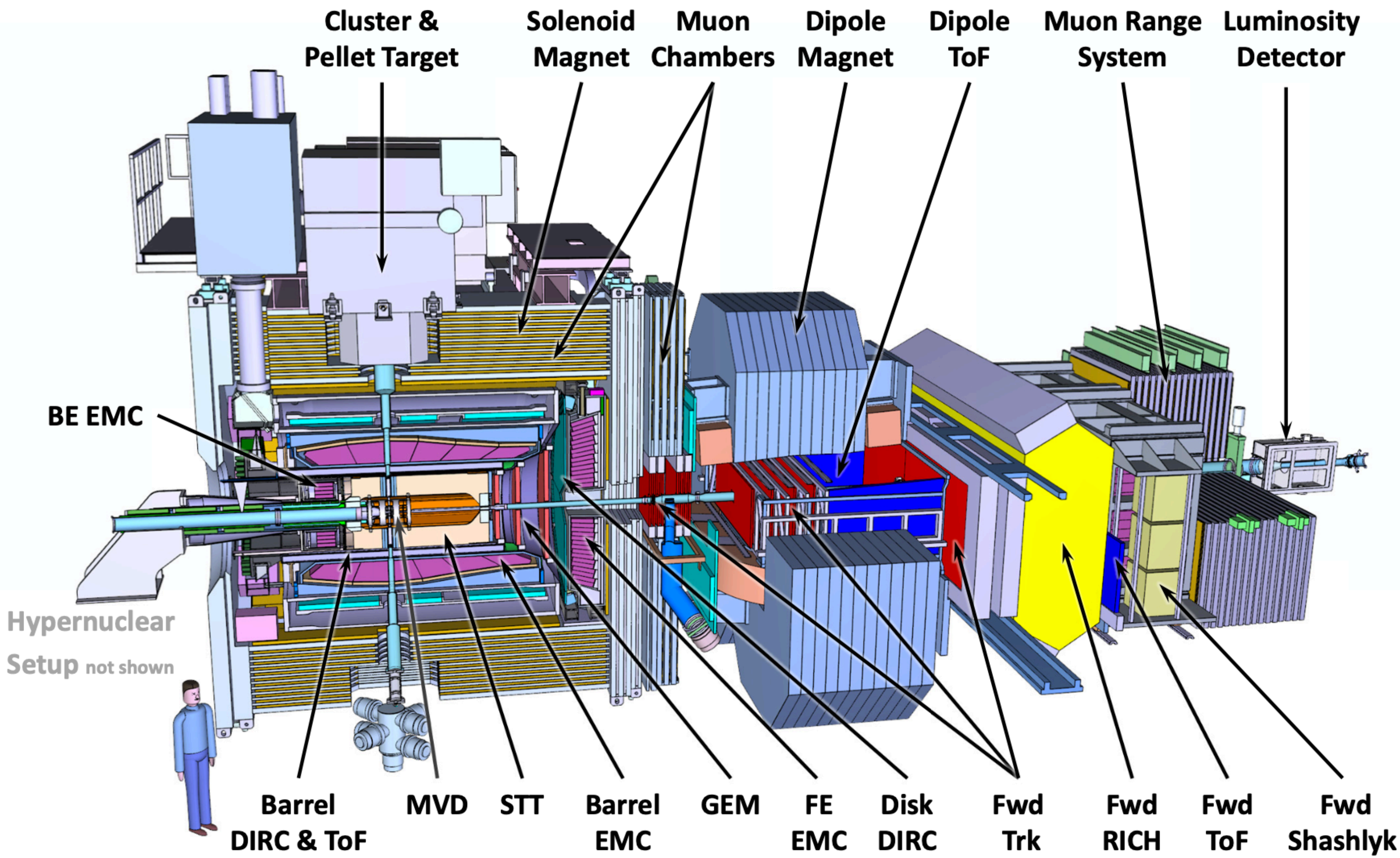
Backup Slides

Physics At Phase 1 to 3

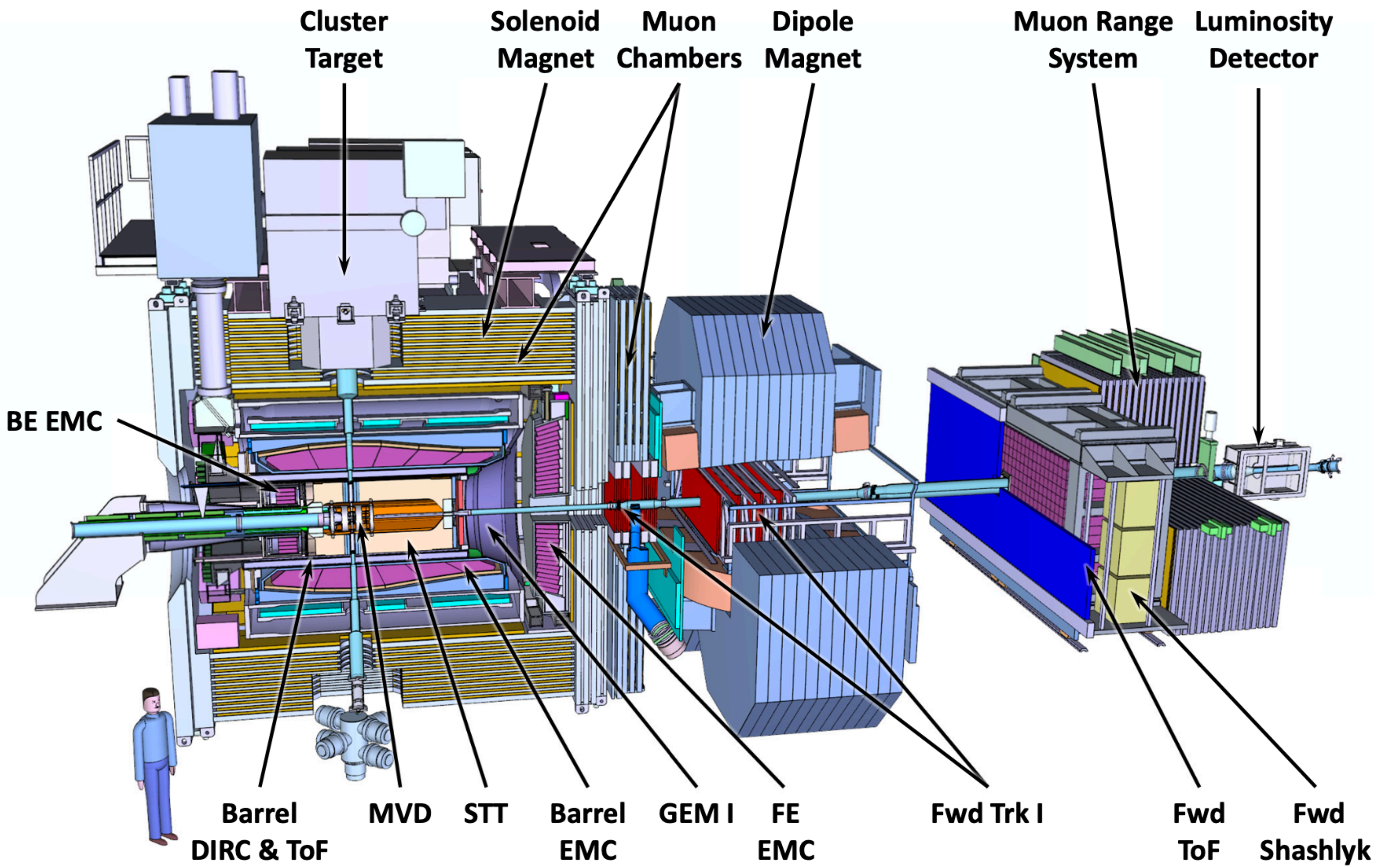


Physics sensitivity at various phases of the experiment

PANDA Detector (Full Setup)



PANDA Detector (Start Setup)



The $f_0(1500)$ in J/ψ decays

- Also observed in radiative J/ψ decays
  - J/ψ → γ4π (re-analysis of MARK III data, 1999)
  - J/ψ → γππ (BES II, 2006)
  - J/ψ → γηη (BES III, 2013)

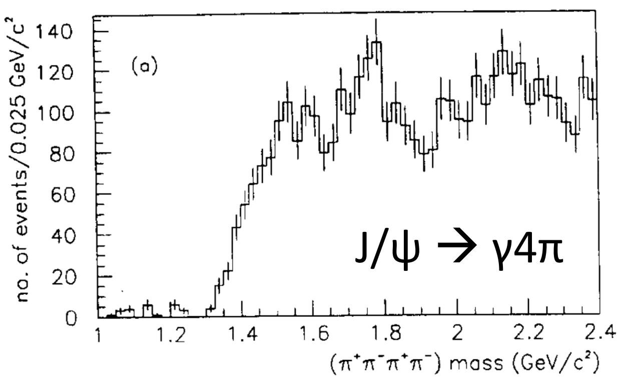
Phys. Lett. B353 (1995) 378-384

Phys. Lett. B642 (2006) 441-448

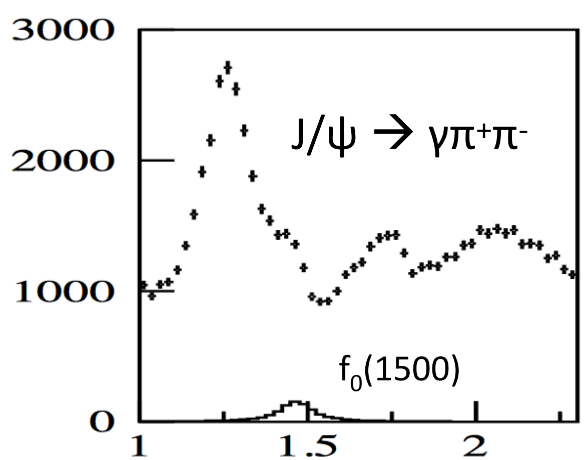
Phys. Rev. D87 (2013) 9, 092009

- Branching fraction J/ψ → $\gamma f_0(1500)$: 10^{-4}
  - 100k produced $f_0(1500)$ in 10^9 J/ψ decays recorded by BES III

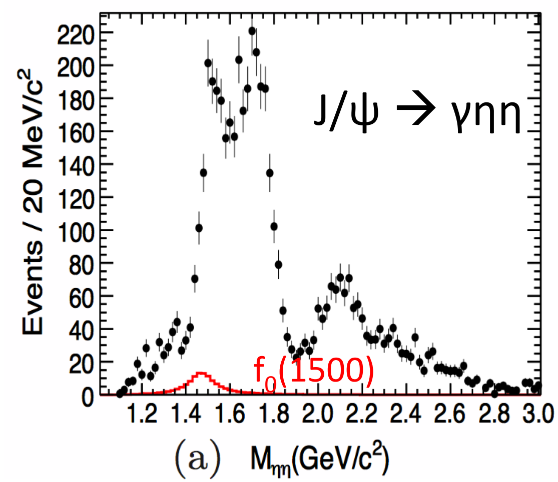
MARK III data, ~2M J/ψ events
~5000 reconstructed events



BES II, 58M J/ψ events
~100k reconstructed events



BES III, 225M J/ψ events
~5000 reconstructed events

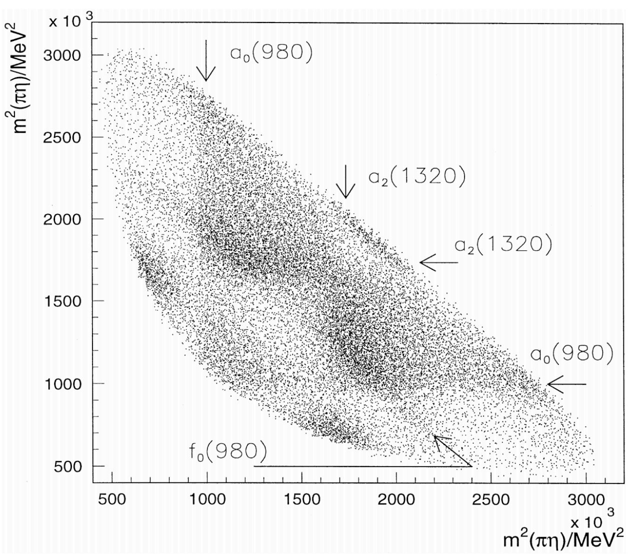


Light Spin-Exotics

- Hybrids predicted in the mass region above ~2 GeV
  - lightest spin-exotic state: 1^{-+} state
- Exotic 1^{-+} wave
  - seen in πp scattering, antiproton annihilations and χ_{c1} decays
  - continuing discussion about ηπ and η'π P-wave

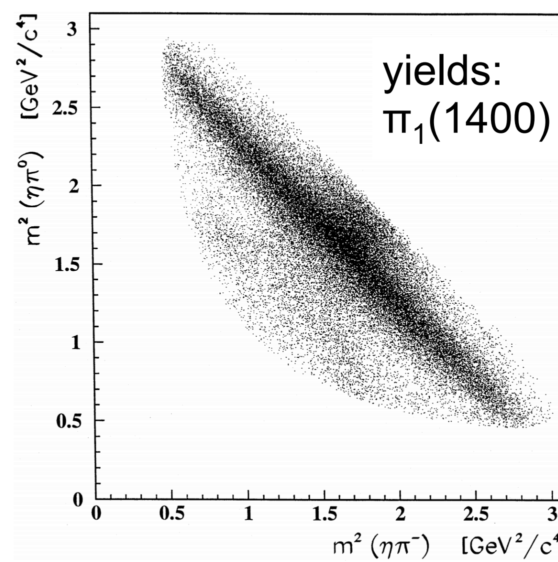
$\bar{p}p \to \eta\pi^0\pi^0$

at rest on gaseous H_2 target



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

at rest



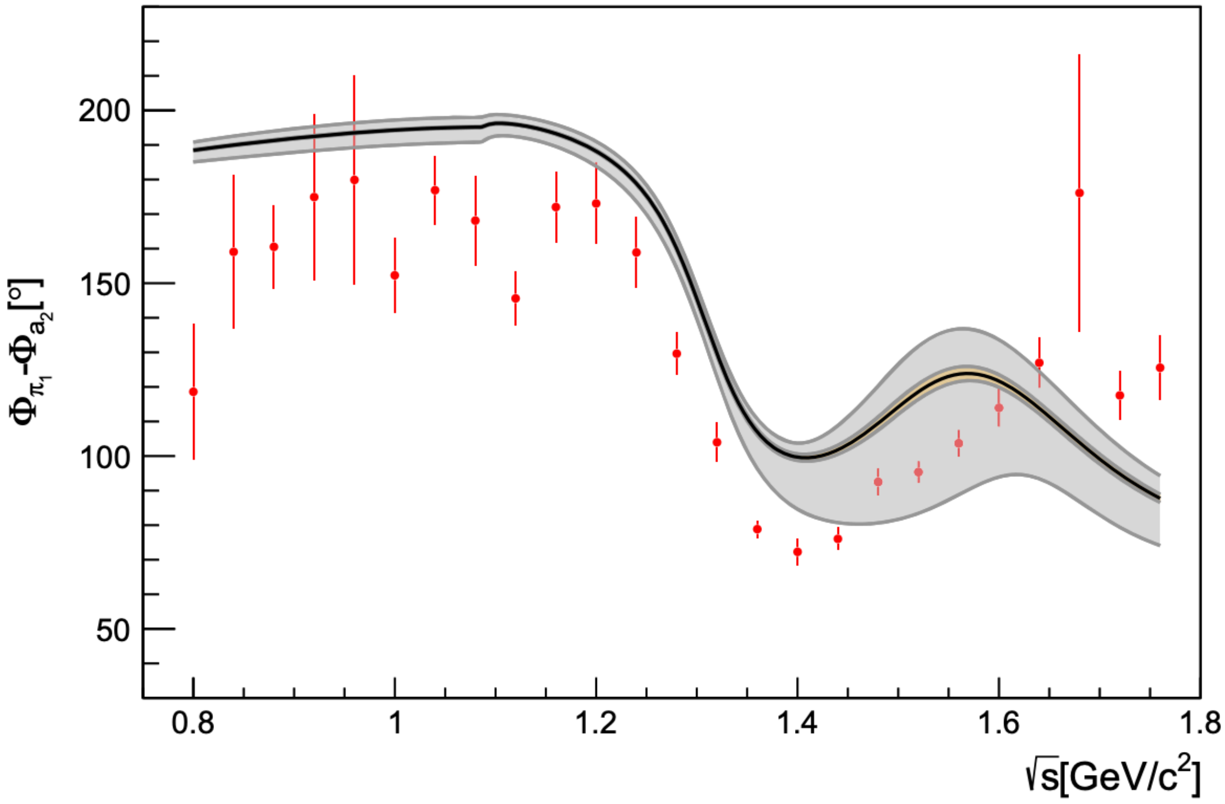
yields:
$\pi_1(1400) \sim a_2(1320)$

Crystal Barrel
Phys. Lett. B 446, 349 (1999), Phys. Lett. B 423, 175-184 (1998)

Spin Exotic 1^{-+} $\eta\pi$ wave

Phase difference for π_1 and a_2

COMPASS data
Fit result to $\bar{p}p$ data



Crystal Barrel, Eur. Phys. J. C 80:453 (2020)