Exotic Mesons: Measurement Techniques, Recent Evidence and Future Searches

Colloquium at CUA Department of Physics

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February 6, 2013

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Outline

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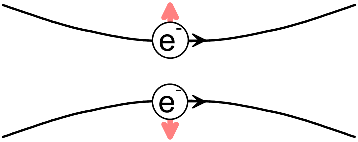
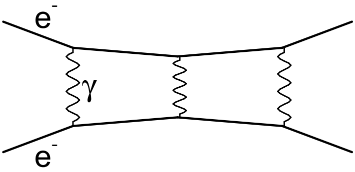
Perspectives on Interaction



Classical view of interactions

- smooth field permeates space
- continuous change in momentum from resulting force
- deterministic outcome

Perspectives on Interaction



Quantum field view of interactions

- field quanta (*e.g.* photons) distributed through space
- discrete momentum kicks from exchange of these force carriers
- probabilistic outcome from superposition of possible scattering states

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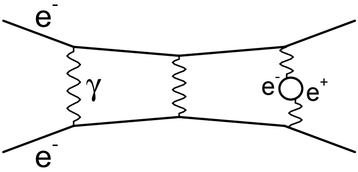

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- more than forces: particle creation/annihilation
  subtle but precisely calculated and confirmed effect in electrodynamics!
  (*e.g.* Lamb shift)

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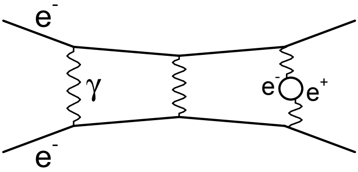

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- e^+/e^- pair pulled out of vacuum!
  What else is in there?
- no longer safe to assume interactions occur in empty space

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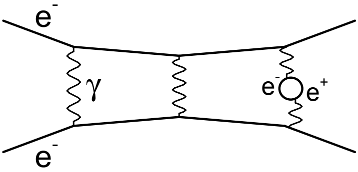

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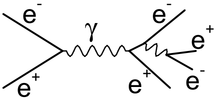
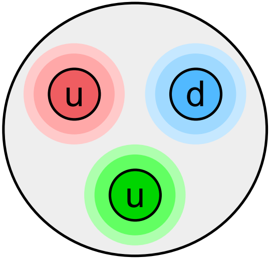
- more than forces: particle creation/annihilation
  subtle but precisely calculated and confirmed effect in electrodynamics!
  (*e.g.* Lamb shift)
- new particles can also be liberated from the vacuum:



Quarks

The Proton...



...turned out to have substructure!

Spin 1/2 "quarks":

charge	I	II	III
$+2/3$	**up**	**charm**	**top**
$-1/3$	**down**	**strange**	**bottom**

- A new theory, *Quantum Chromodynamics* (QCD), and 3 sets of charges proposed:

$+$	$-$
red	anti-red (cyan)
green	anti-green (magenta)
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- All quark composites (*hadrons*) must end up "white"
- New force carrier (gauge boson): *gluon*
  - carries a pair of color charges!
  - couples to quarks and other gluons

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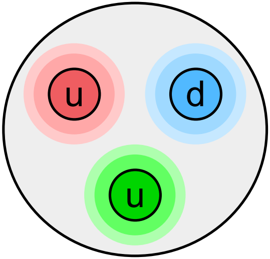

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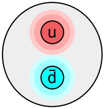

Consider a simpler object:
$\Leftarrow$ quark-anti-quark pair, *i.e.* "meson"
(π^+ in this case)

Quarks

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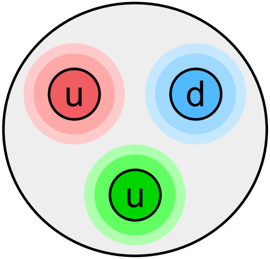

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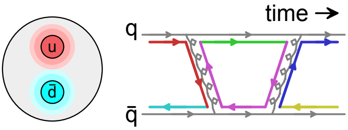

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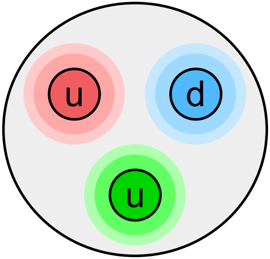

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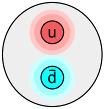

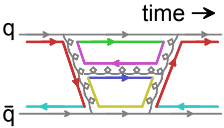

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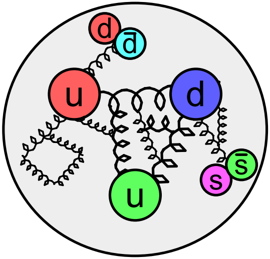

More complex view:

- *valence* quarks
- *sea* quarks
- proton mass, spin depend on the full dynamics!

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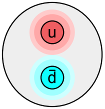
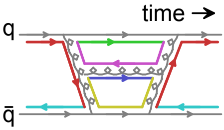


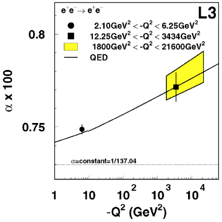


Coupling Strength

Electromagnetism (QED)

coupling constant: α

(fine structure constant)



L3 Collab, Phys. Lett. B **623**, 26 (2005)

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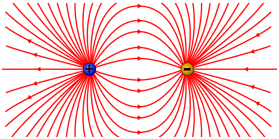
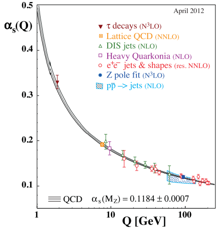
Electric Dipole



Strong Interaction (QCD)

coupling constant: α_s



Particle Data Group, 2012

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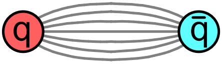
Meson



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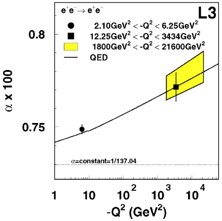

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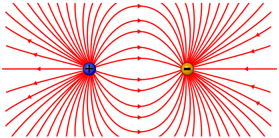

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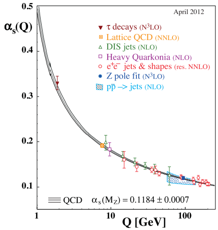

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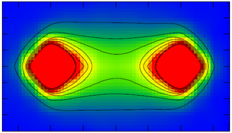


Introduction Overview

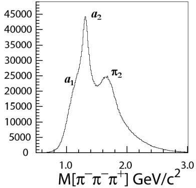
Concepts covered so far:

1. Nature of Fields
   - fields are quantized with discrete interactions
   - beyond forces, give rise to interactions that can create particles
2. Quarks and Their Composites – *Hadrons*
   - protons, neutrons, and later discovered pions, kaons, etc. are composite objects
   - so far understood as made of 2 or 3 *valence* quarks, with important dynamics of surrounding fields, other quarks, etc.
3. Quantum Chromodynamics – a special interaction holding quarks together
   - uses *gluons* as carriers which themselves have charge ⇒ self-interacting!
   - gets stronger at larger distances!
   - field condenses into dense regions
   - strong but confined – the condensed field vacates the rest of space

Probing Hadrons: Spectroscopy

How did we explore quantum mechanics and atomic systems in the early days?
Spectroscopy!

- work out the bound states, their excitations, line shapes from theory
- compare to experimentally-measured spectrum



Doing the same for hadrons is fruitful but challenging $\rightarrow$

- strong coupling $\Rightarrow$ no perturbative calculations possible
  How to cope?
  - build simpler models and try to calibrate to the full theory
  - numerical methods – *lattice QCD*, but very computationally expensive
- short-lived $\Leftrightarrow$ broad resonances – hard to disentangle, identify states
  Solution: look at more than energy (mass) spectra
  $\rightarrow$ **Partial Wave Analysis (PWA)**
  - decomposition of scattered intensity into states with different angular distributions
    $\Rightarrow$ get **angular momentum q.n.** of original states from angular correlations
  - determination of wave (amplitude) components gives **phase**

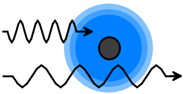
Hadron Spectroscopy Example

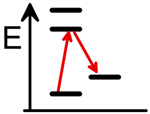
How do we do spectroscopy on hadrons?
How does it compare with atomic/optical spectroscopy?

Atomic spectroscopy:

send in light, see at what frequencies the sample absorbs

ionize sample, detect emitted light (from discrete transitions)

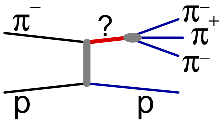


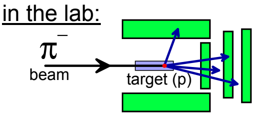


Hadron spectroscopy:

create a particle/resonance in collision, analyze it from debris

- only descendent particles are detected
- use energy/momentum conservation to reconstruct original system properties
- map out its c.o.m. energy (mass) spectrum





Hybrid Mesons

Excitation modes of bound particles teach us about the internal field.

But can we study the field more directly?

- Can a meson's condensed field (flux tube) vibrate?
- How would we detect/identify this?

Mesons are identified by J^{PC} quantum numbers:

- $\vec{J} = \vec{L} + \vec{S}, \quad \vec{S} = \vec{S_1} + \vec{S_2} = 0, 1$
- **P**arity: symmetry under space inversion; $P = (-1)^{L+1}$
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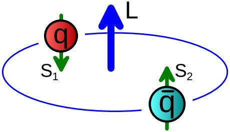

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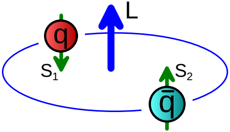

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$\therefore$ $q\bar{q}$ quantum numbers:

J	$--$	$++$	$-+$	$+-$
0		0^{++}	0^{-+}	
1	1^{--}	1^{++}		1^{+-}
2	2^{--}	2^{++}	2^{-+}	

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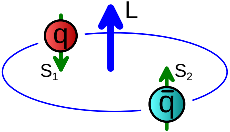

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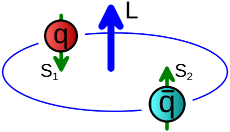

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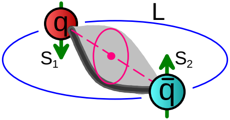


Exotic states $\Longrightarrow$ unambiguous signature of new degrees of freedom

Outline

Decay Amplitude Angular Distribution

Like a bound state, scattering/decay has some characteristic angular momentum.

Consider a P-wave ($L = 1$) decay $\Rightarrow$

Each decay like this samples the probability distribution given by this θ, ϕ-dependent amplitude.

$\therefore$ We should be able to get the L quantum number from the angular distribution of particles in a detector!

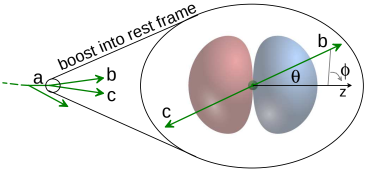


Figure : Illustration of a 2-body decay analysis.

Finding Original Amplitude: Maximum Likelihood Method

Goal: Find the most likely probability distribution to have generated your data.

Construct a likelihood function with:

- probability of having seen all the detected events $\vec{x}_1 \ldots \vec{x}_N$:
- Poisson probability of having seen the number of detected events

$$\mathcal{L} = \mathrm{Pois}(\mu;\mathrm{N}) \prod_i^N P(\vec{x}_i; u_1, u_2 \ldots u_n) = \frac{e^{-\mu}\mu^N}{N!} \prod_i^N \frac{1}{\mu} \left| \sum_\alpha^n c_\alpha \Psi_\alpha(\vec{x}_i) \right|^2$$

μ is the total expected in the detector, calculated via Monte Carlo *i.e.* sampling of events $\vec{y}_1 \ldots \vec{y}_{N_{\mathrm{gen}}}$ weighted by

- candidate probability distribution
- detector acceptance

$\models\Rightarrow$

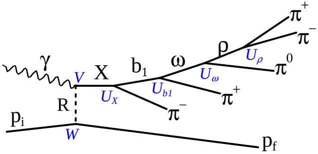
$$\mu = \frac{1}{N_{\mathrm{gen}}} \sum_i^{N_{\mathrm{acc}}} \left| \sum_\alpha^n c_\alpha \Psi_\alpha(\vec{x}_i) \right|^2$$

Other methods exist, but in all cases, Monte Carlo samples computed with detector simulation are needed.

Example: simulated $\gamma p \to Xp \to b_1\pi p$

Let us simulate the following reaction:

$$\gamma p \to Xp \to b_1^{\pm}\pi^{\mp} \to \omega\pi^{\pm}\pi^{\mp}p \to \pi^+\pi^-\pi^0\pi^{\pm}\pi^{\mp}p$$



with two amplitude components for resonance X:

$$J^{PC} = 1^{--}, \{\mathrm{M}, \Gamma\} = \{1.89, 0.16\}\ \mathrm{GeV}$$
$$J^{PC} = 2^{+-}, \{\mathrm{M}, \Gamma\} = \{2.00, 0.25\}\ \mathrm{GeV}$$

This means generating 5-pion final state events according to the probability distribution of this production/decay process.

A variant of **GEANT** software is used to simulate flight of particles through the detector, and data acquisition.

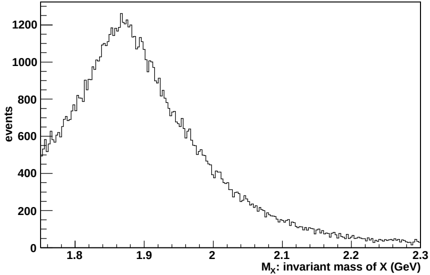


Figure : Resulting invariant mass distribution of the X resonance

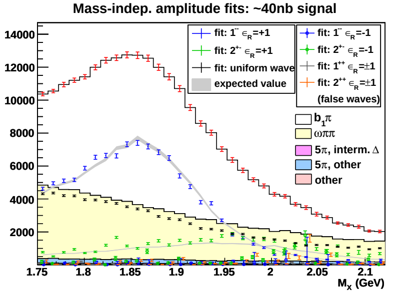
Amplitude Fit Results: 40 nb 2^{+-} & Pythia (GlueX)

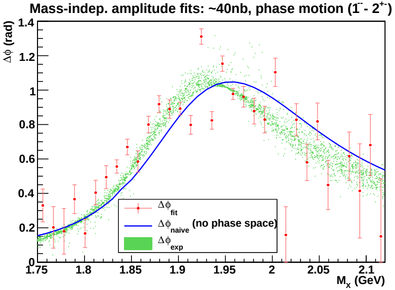
Cross-section scaling:

- Pythia, a particle event generator approximating the dominant known reactions is used to create background
  13.9 G evts @ 9 GeV photon beam energy $\sim$ 260 h run time
- $b_1\pi$: 18 M evts $\sim$ 25% 2^{+-}

Conclusions:

- one can pull out the individual waves
- some leakage seen between waves





Outline

Evidence for Exotic Mesons

The tentative observations of exotic states thus far: (masses and widths from PDG)

π_1 state	Mass (GeV)	Width (GeV)	Prod.	Decays	Experiments
1400	1.351 ± 0.03	0.313 ± 0.040	$\pi^- p$, $\bar{p}n$	$\pi^- \eta$,$\pi^0 \eta$	E852, CBAR
1600	1.662 ± 0.015	0.234 ± 0.050	$\pi^- p$, $\bar{p}p$	$\eta' \pi$, $b_1 \pi$, $f_1 \pi$, $\rho \pi$	E852, CBAR, VES, COMPASS
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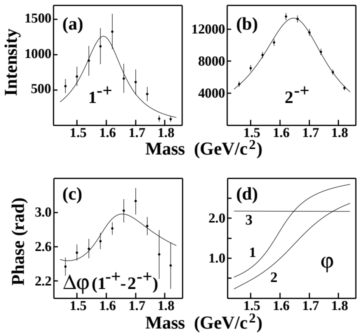
Background: Experiment E852 at Brookhaven's AGS.

18 GeV/c π^- beam on a liquid H_2 target

Reaction: $\pi^- p \to \pi^-\pi^+\pi^- p$

Figure:

a) $\pi_1(1600)$ 1^{-+} wave
b) the dominant $\pi_2(1670)$ 2^{-+} wave
c) the relative phase
d) individual phases:
   1. $1^{-+}[\rho(770)]P1^+$
   2. $2^{-+}[f_2(1270)]S0^+$
   3. relative production phase



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Reanalysis: $\times 10$ more data, more waves to describe $\pi_2(1670)$:

- $\pi_1(1600)$ enhancement vanishes
- phase motion persists!

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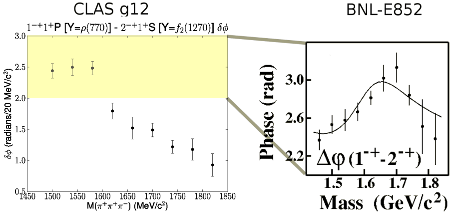
Background: CEBAF Large Acceptance Spectrometer (CLAS) at JLab

5.7 GeV photon beam on a liquid H_2 target

Reaction: $\gamma p \rightarrow (X)n \rightarrow \pi^+\pi^-\pi^+$

Figure: No phase motion consistent with $\pi_1(1600)$ 1^{-+} resonance observed



Possible explanations:

- $\pi_1(1600)$ production just suppressed in charge exchange
- small cross-section in photoproduction (contrary to models)

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Background: spectrometer at CERN's SPS with π, p, K (?) beams

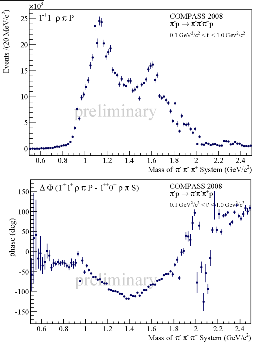
190 GeV π^- beam on a liquid H_2 target

Reaction: $\pi^- p \rightarrow \pi^-\pi^+\pi^- p$

Figure:

Top: exotic $1^{-+}\rho\pi$ P-wave invariant mass

Bottom: phase difference with a_1 1^{++}



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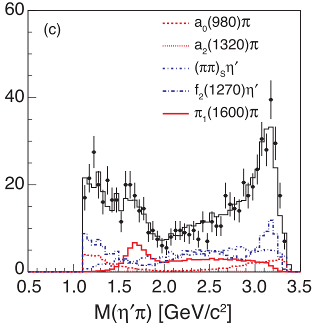
Background: CLEO-c @ Cornell e^+/e^- storage ring

colliding e^+/e^- beams

Reaction: $e^+/e^- \rightarrow \psi(2S) \rightarrow \gamma\chi_{c1} \rightarrow \eta'\pi^+\pi^-$

Figure:

Amplitude invariant mass projections for $\chi_{c1} \rightarrow \eta'\pi^+\pi^-$ decay



G. S. Adams *et al.* [CLEO Collaboration], Phys. Rev. D **84**, 112009 (2011)

Using Photon Beams

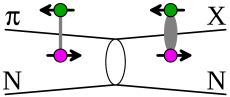
Data so far: production (mostly) with π beams

Is the exotic hybrid production suppressed?

A possible argument: the spin flip needed for exotic q.n. is suppressed.

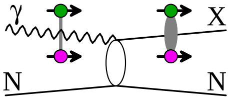
Proposal: use $S = 1$ beam $\rightarrow$ photons!

Meson J^{PC} q.n. production scenarios without quark spin flip (flux-tube model):



π beam ($S = 0$)

$\mathbf{0}^{--}$	0^{++}
1^{--}	1^{++}
2^{--}	2^{++}



γ beam ($S = 1$)

0^{-+}	$\mathbf{0}^{+-}$
$\mathbf{1}^{-+}$	1^{+-}
2^{-+}	$\mathbf{2}^{+-}$

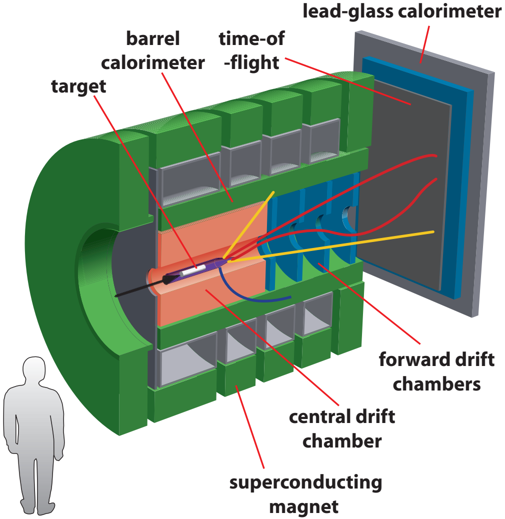
Criticism:

- Spin flip suppression may not be an issue for light quarks
- Search by CLAS (g12) did not see a signal for $\pi_1(1600)$

Gluonic Excitations Experiment (GlueX)

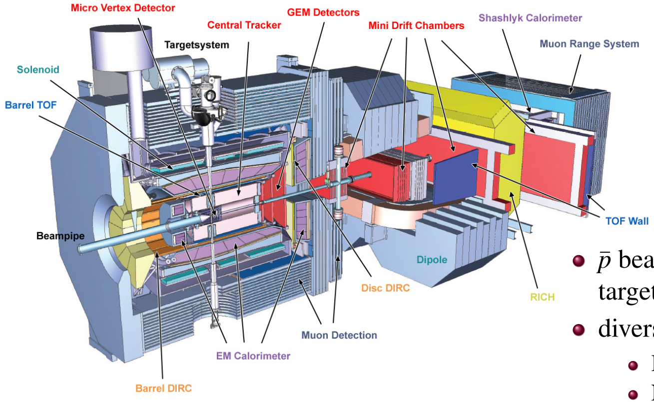
GlueX detector is being assembled in the new Hall D in Jefferson Lab, Newport News, VA

- 9 GeV (tagged) polarized photon beam on liquid H_2 target
- hermetic, low dead time detector for high statistics angular analysis



Anti-Proton Annihilation at Darmstadt (PANDA)

PANDA: a multi-purpose detector is being designed for the Facility for Antiproton and Ion Research (FAIR) project GSI, Darmstadt, Germany



- $\bar{p}$ beam on a flexible jet/fixed target system
- diverse program:
  - Hadron Spectroscopy
  - Nucleon Structure
  - Hypernuclei
  - Hadrons in-medium

Summary

- Strong Interaction described by Quantum Chromodynamics: creates bound states that are difficult to study
- Overlapping resonances disentangled with Partial Wave Analysis, which yields states' quantum numbers and relative phases
- Hybrid Mesons (with excited flux tube identified by exotic quantum numbers) offer a new way to probe the dynamics of the gluon field
- Tantalizing hints of these from past experiments, particularly for $\pi_1(1600)\ 1^{-+}$ state
- A new generation of experiments coming online to study these with good coverage and high statistics:
    - GlueX with photo-production
    - PANDA through $p\bar{p}$ collisions