# Light-Quark Spectroscopy with Antiproton-Proton Annihilation

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Chicago, 3 August 2000

# What Is It About Antiprotons That Makes Me Skip My Vacation To Give This Talk?

Ulrich Wiedner

# Why Are Antiproton-Proton Annihilations Superior For Hadron Spectroscopy?

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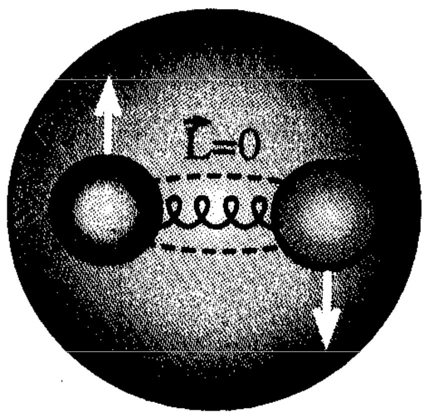
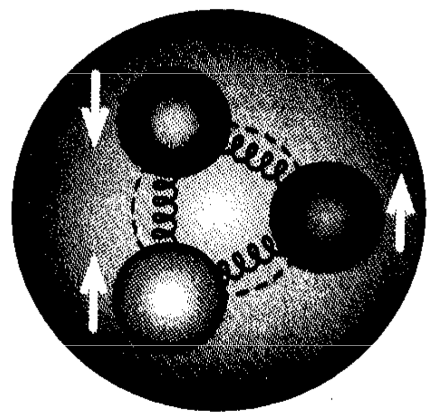
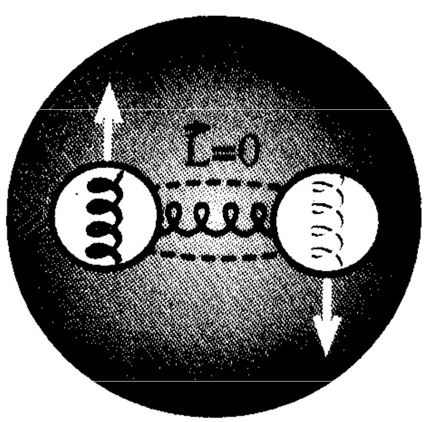
# QCD



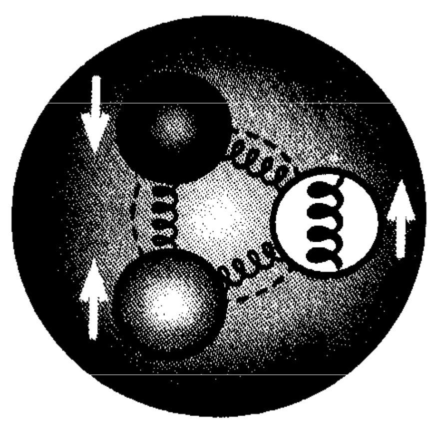

Meson ($q\bar{q}$)



Baryon ($qqq$)

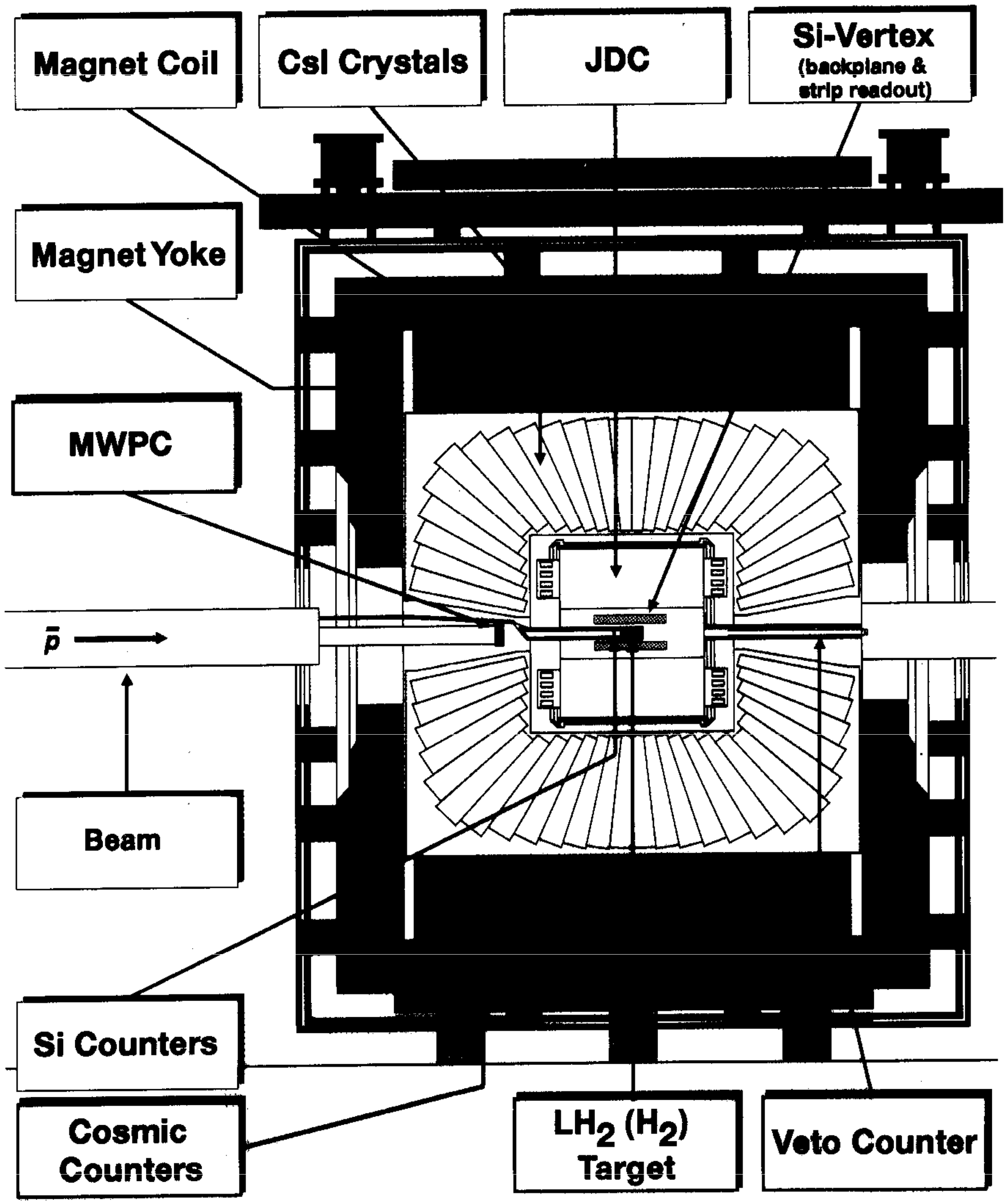



Glueball ($gg$)

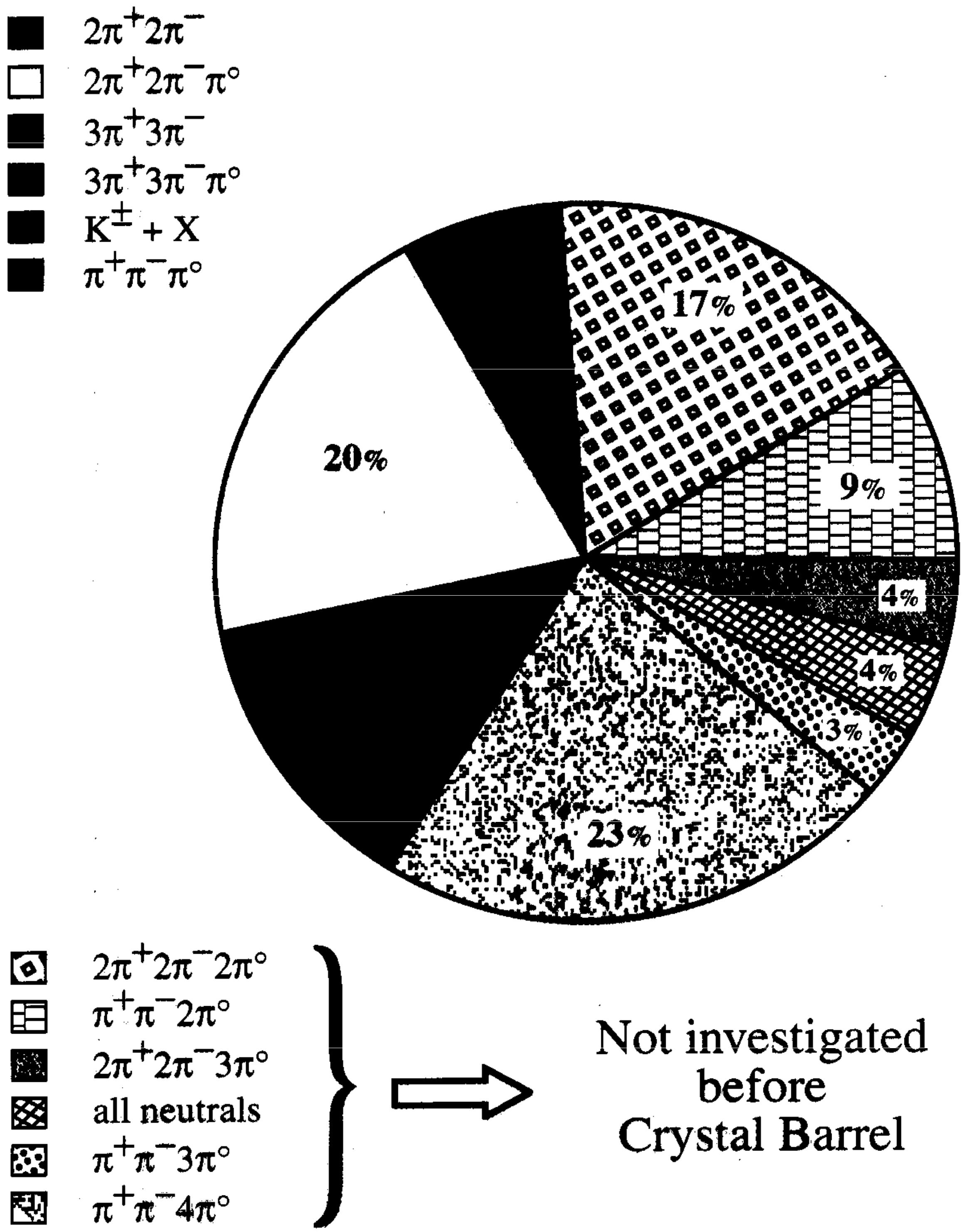


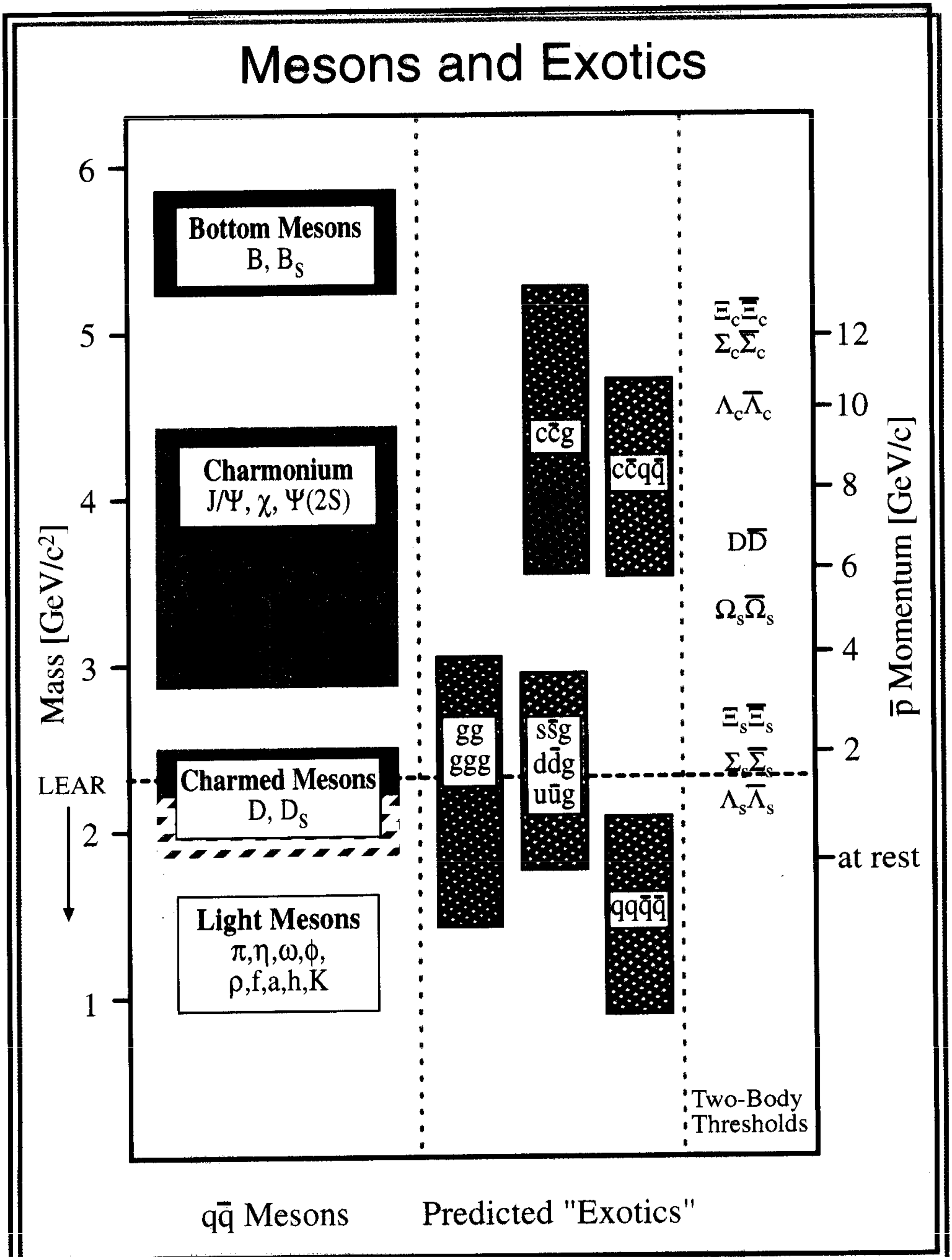
Hybrid ($q\bar{q}g$)

# Crystal Barrel detector

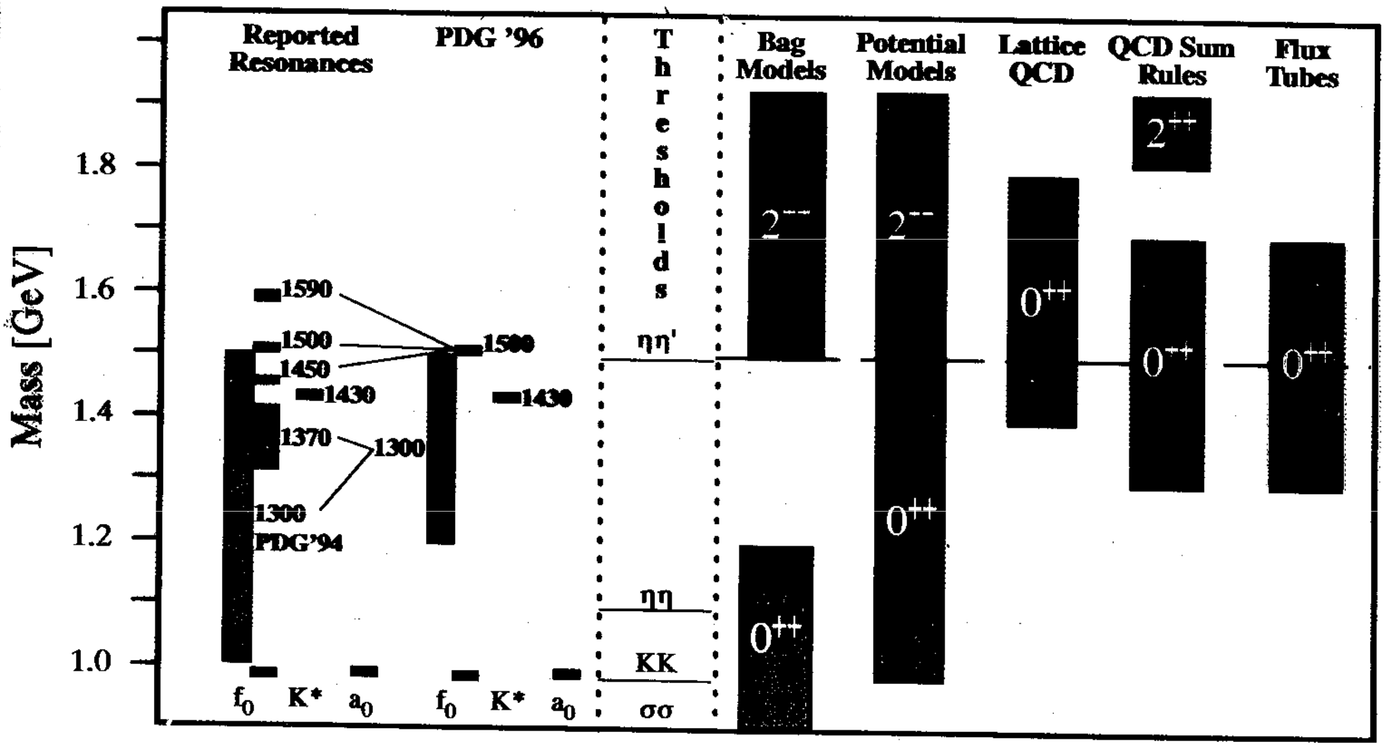


# Distribution of final states




Mesons and Exotics
Bottom Mesons
B, B_S
Charmonium
J/Ψ, χ, Ψ(2S)
Charmed Mesons
D, D_S
Light Mesons
π,η,ω,φ,
ρ,f,a,h,K
LEAR
Mass [GeV/c²]
6
5
4
3
2
1
cc̄g
cc̄qq̄
gg
ggg
ss̄g
dd̄g
uūg
qqq̄q̄
Ξ_cΞ̄_c
Σ_cΣ̄_c
Λ_cΛ̄_c
DD̄
Ω_sΩ̄_s
Ξ_sΞ̄_s
Σ_sΣ̄_s
Λ_sΛ̄_s
12
10
8
6
4
2
at rest
p̄ Momentum [GeV/c]
Two-Body
Thresholds
qq̄ Mesons
Predicted "Exotics"

# Resonances and Glueball Predictions

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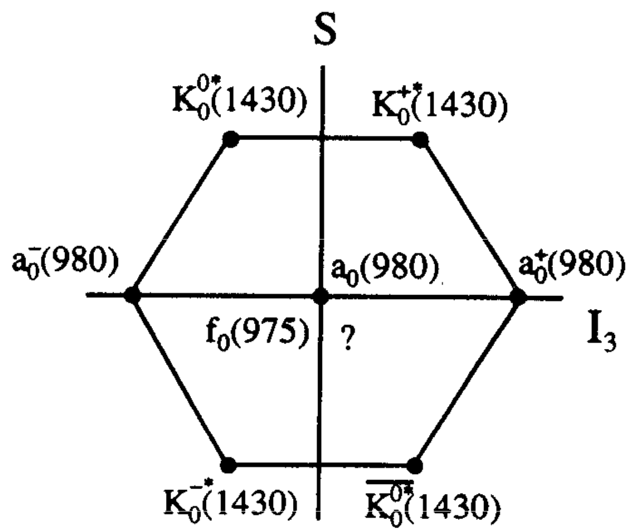
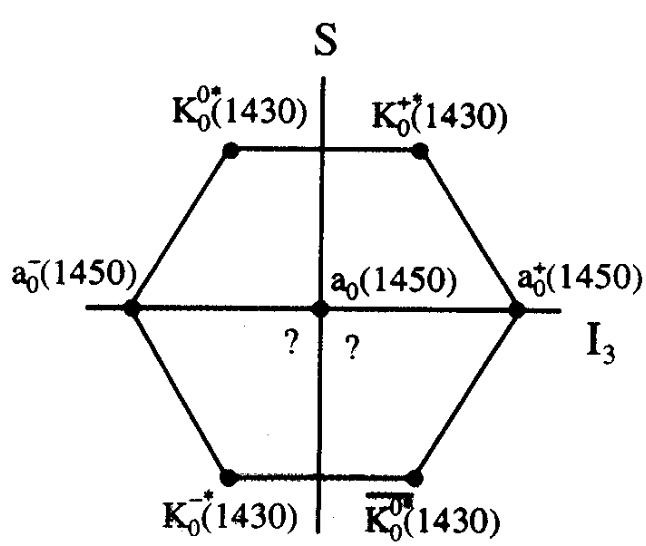
The old possible nonet of scalar mesons:




Crystal Barrel sees a new isovector state:

$a_0(1450)$: $M = 1450 \pm 40$ MeV $\pi\eta$
$\Gamma = 270 \pm 40$ MeV

A new possible nonet:



# Isoscalar $0^{++}$ resonances seen by Crystal Barrel

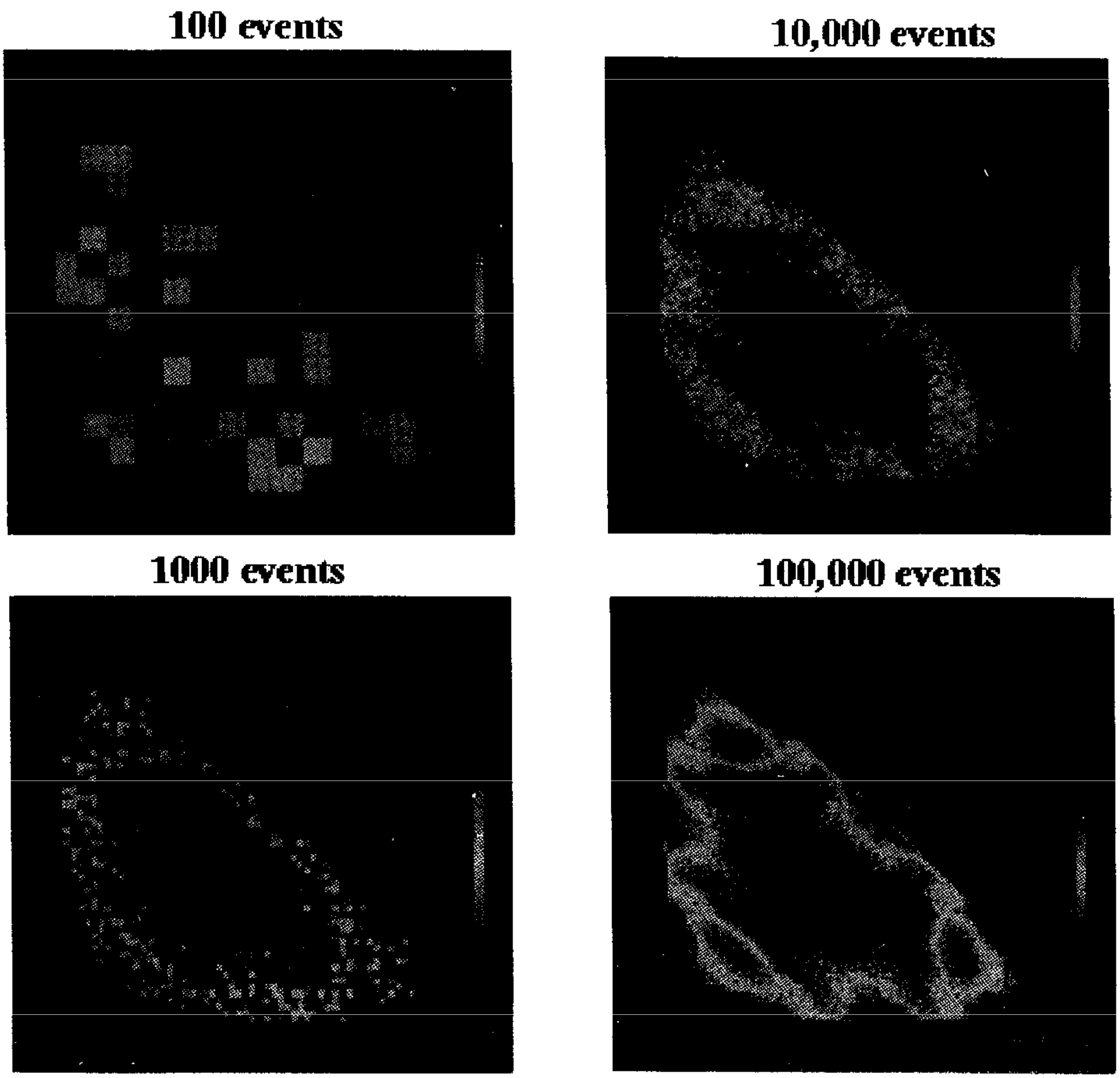
| | | Decay mode |
|---|---|---|
| $f_0(975)$: | $M = 980 \pm 20$ MeV | $\pi\pi$ |
| | $\Gamma = 100 \pm 20$ MeV | |
| $f_0(1370)$: | $M = 1365 \pm 50$ MeV | $\pi\pi$ $\eta\eta$ $4\pi$ |
| | $\Gamma = 270 \pm 80$ MeV | |
| $f_0(1500)$: | $M = 1511 \pm 8$ MeV | $\pi\pi$ $\eta\eta$ $\eta\eta'$ |
| | $\Gamma = 116 \pm 17$ MeV | $K\bar{K}$ |

+ other experiments:

| | | |
|---|---|---|
| $f_0(1450)$: | $M = 1446 \pm 5$ MeV | $4\pi$ |
| | $\Gamma = 56 \pm 12$ MeV | |
| $f_0(1590)$: | $M = 1581 \pm 10$ MeV | $\eta\eta'$ $\eta\eta$ $4\pi$ |
| | $\Gamma = 180 \pm 17$ MeV | |
| $f_0(1525)$: | $M = 1525$ MeV | $K\bar{K}$ |
| | $\Gamma = 90$ MeV | |
| $f_J(1710)$: | $M = 1709 \pm 5$ MeV | $K\bar{K}$ $\pi\pi$ |
| | $\Gamma = 140 \pm 12$ MeV | |

**Too many resonances**

# The importance of statistics for partial wave analysis ...


100 events
10,000 events
1000 events
100,000 events

# Interpretation of the results:

| | |
|---|---|
| $f_0(975)$, $a_0(980)$: | KK-molecules |
| $f_0(1370)$: | Nonet member |
| $f_0(1525)$, $f_J(1710)$: | Nonet member |
| $f_0(1500) = f_0(1590) = f_0(1450)$: | Exotic |

**Why is the $f_0(1500)$ an exotic?**

# Lattice QCD

larger lattices + finer granularity = *progress*:

| | Data | Lattice |
|---|---|---|
| K* | 896 | 898 ± 12 |
| $\phi$ | 1022 | 1026 ± 25 |
| p | 938 | 936 ± 80 |

predictions for *glueballs*:

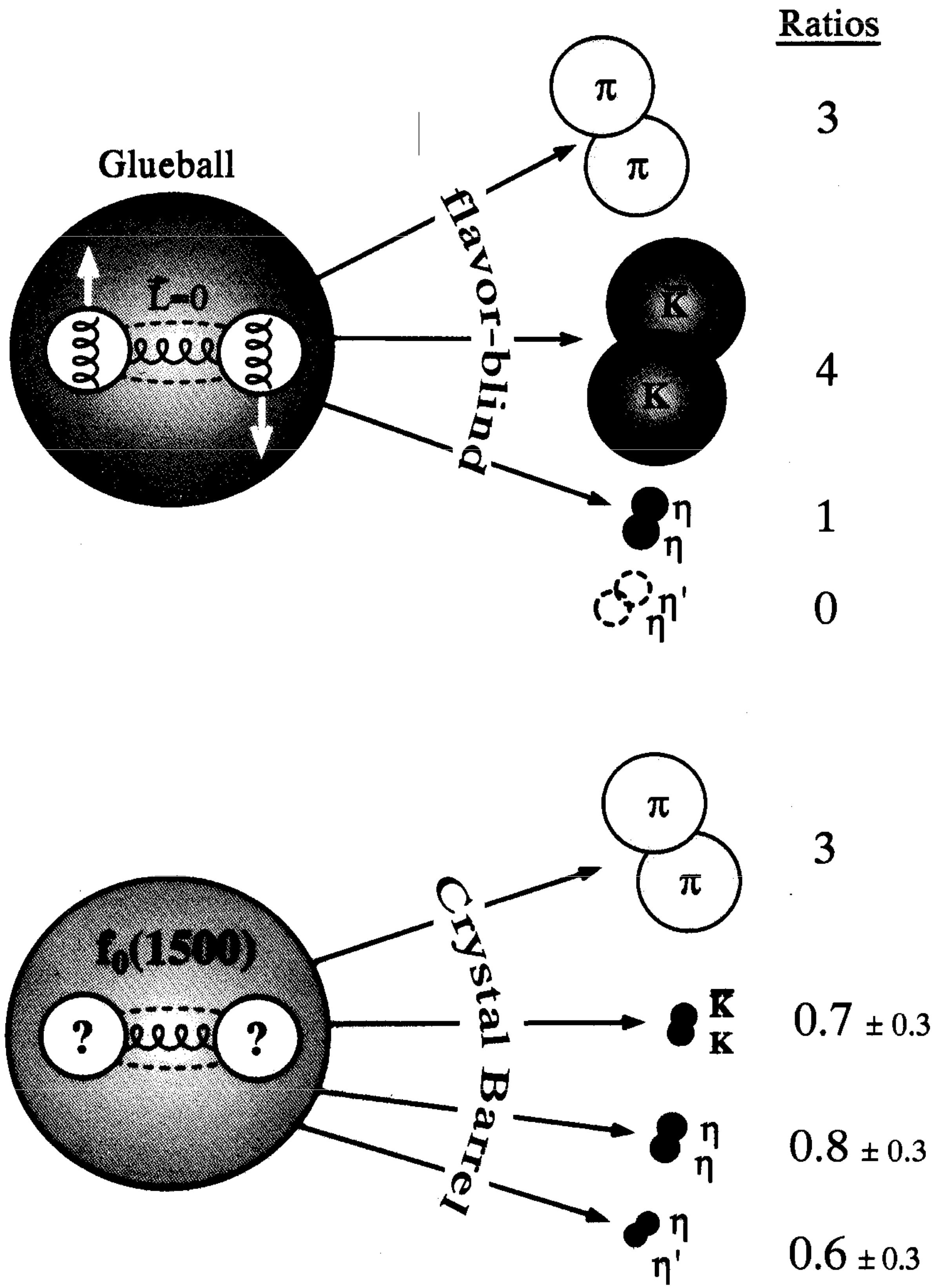
| | GF-11 [1] | UKQCD [2] |
|---|---|---|
| Glueball ($0^{++}$) | 1740 ± 70 ± ? | 1572 ± 85 ± 150 |
| Glueball ($2^{++}$) | 2360 ± 130 ± ? | 2220 ± 100 ± 77 |
| Glueball ($0^{-+}$) | | 2156 ± 260 ± 75 |

(1) J. Sexton et al., Phys.Rev.Lett. 75, 4563 (1995)
(2) F.E. Close et al., Preprint RAL-96-040 (1996)

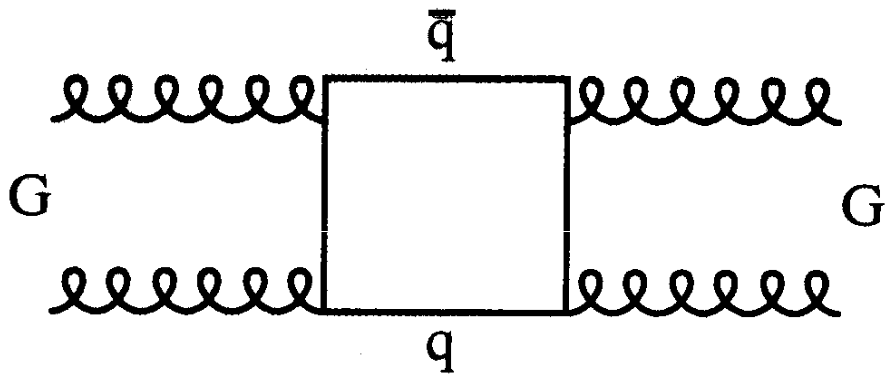
sources for *systematic errors*:

- transformation of $\sqrt{\sigma} \rightarrow$ MeV
- extrapolation to continuum limit
- quenched approximation (no $q\bar{q}$ loops)
- mixing with near-by $q\bar{q}$ states

# Decay properties



# Can this decay pattern be explained ?




Glueball-meson mixing

↓

Interpretation difficult !

→ Help from theory ?

J. Sexton et al., Phys.Rev.Lett. 75, 4563 (1995):

$f_0(1370) = -0.43\,|G\rangle + 0.25\,|s\bar{s}\rangle + 0.87\,|1/\sqrt{2}\,(u\bar{u}+d\bar{d})\rangle$

$f_0(1500) = -0.22\,|G\rangle + 0.91\,|s\bar{s}\rangle - 0.36\,|1/\sqrt{2}\,(u\bar{u}+d\bar{d})\rangle$

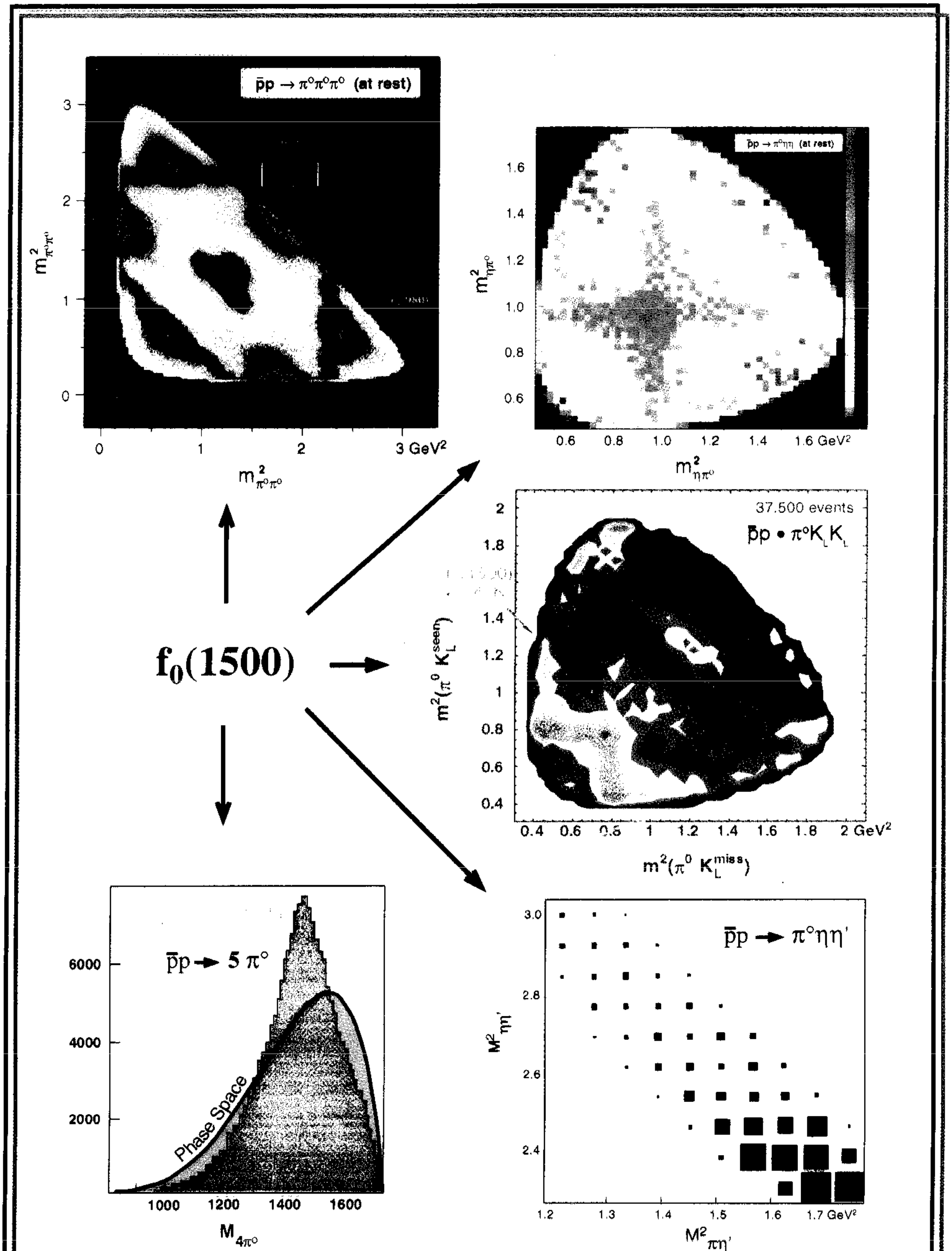
$f_0(1720) = 0.88\,|G\rangle + 0.33\,|s\bar{s}\rangle + 0.34\,|1/\sqrt{2}\,(u\bar{u}+d\bar{d})\rangle$

C. Amsler, F. Close, Phys.Rev. D53, 295 (1996); F. Close, LEAP96:

[illegible] $= -0.50\,|G\rangle + 0.13\,|s\bar{s}\rangle + 0.86\,|1/\sqrt{2}\,(u\bar{u}+d\bar{d})\rangle$

[illegible] = [illegible] $- 0.61\,|s\bar{s}\rangle + 0.43\,|1/\sqrt{2}\,(u\bar{u}+d\bar{d})\rangle$

[illegible] $= 0.60\,|G\rangle - 0.76\,|s\bar{s}\rangle + 0.22\,|1/\sqrt{2}\,(u\bar{u}+d\bar{d})\rangle$



p̄p → π°π°π° (at rest)
3
2
1
0
$m^2_{\pi^0\pi^0}$
0
1
2
3 GeV²
$m^2_{\pi^0\pi^0}$
p̄p → π°ηη (at rest)
1.6
1.4
1.2
1.0
0.8
0.6
$m^2_{\eta\pi^0}$
0.6
0.8
1.0
1.2
1.4
1.6 GeV²
$m^2_{\eta\pi^0}$
f0(1500)
37.500 events
p̄p • π°KLKL
2
1.8
1.4
1.2
1
0.8
0.6
0.4
$m^2(\pi^0 K_L^{seen})$
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2 GeV²
$m^2(\pi^0 K_L^{miss})$
p̄p → 5 π°
6000
4000
2000
Phase Space
1000
1200
1400
1600
$M_{4\pi^0}$
p̄p → π°ηη'
3.0
2.8
2.6
2.4
$M^2_{\eta\eta'}$
1.2
1.3
1.4
1.5
1.6
1.7 GeV²
$M^2_{\pi\eta'}$

# Can we learn something from the decay width ?

$\Gamma\,(f_0(1500)) \rightarrow \eta\eta,\ \eta\eta',\ KK \approx 15$ MeV

<u>no $s\bar{s}$ state</u>

$\Gamma\,(f_0(1500)) \rightarrow 4\pi,\ \pi\pi \approx 100$ MeV

$\Gamma\,(f_0(1500)) \rightarrow \pi\pi \approx 20 - 30$ MeV

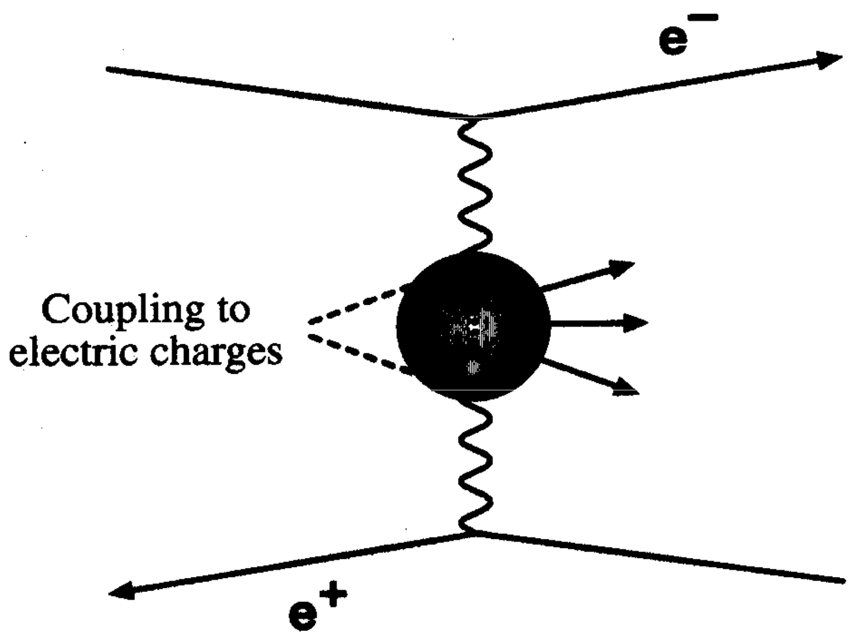
Quark models and other nonets:

$\Gamma\,(K^*) < \Gamma\,(a_0) < \Gamma\, s\bar{s}) < \Gamma\,(n\bar{n})$

287±14 MeV    270±40 MeV

<u>no $n\bar{n}$ state</u>

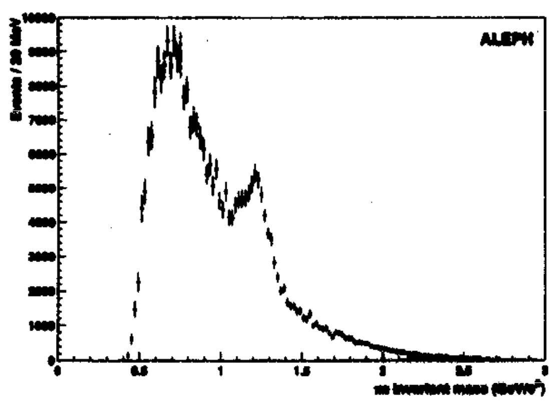
# Meson Production in $\gamma\gamma$ Collisions

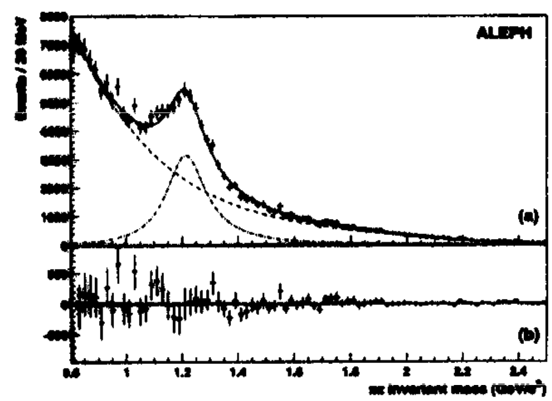



... acts as an "Anti-Glueball Filter".

# $\gamma\gamma$ Collisions from ALEPH

## (Anti-Glueball Filter)




no $f_0(1500)$

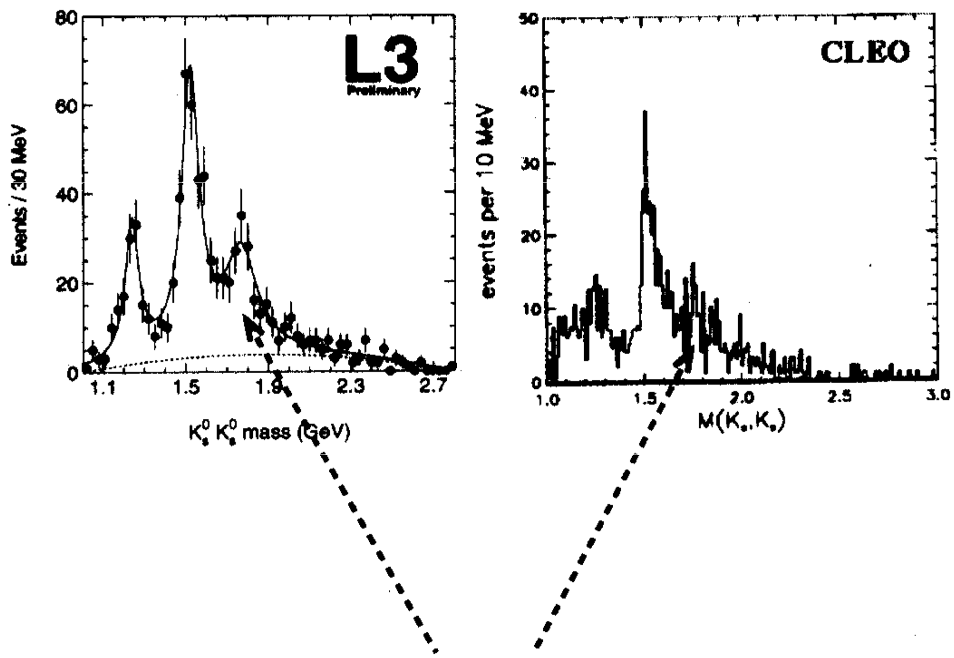
upper limit:

$$\Gamma(\gamma\gamma \rightarrow f_0(1500)) \bullet BR(f_0(1500) \rightarrow \pi^+\pi^-) < 0.31\ \text{keV}$$

Phys. Lett. B472 (2000) 189.

# Other Glueball Candidates: $f_J(1710)$

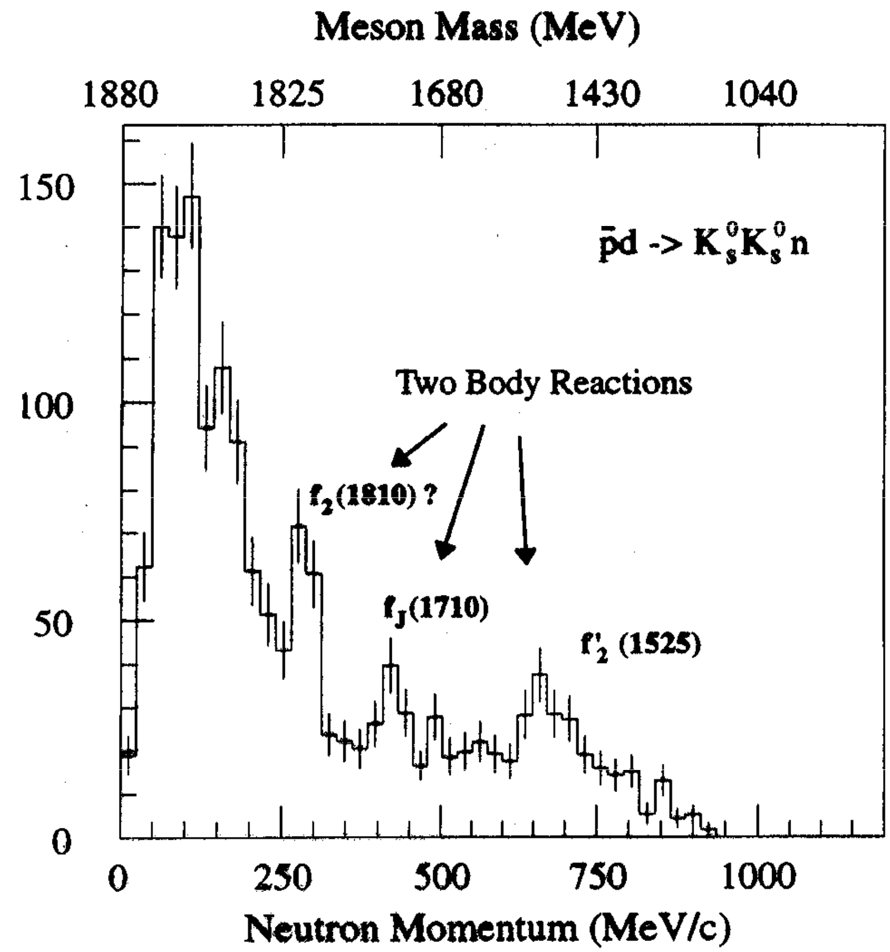
6




Not a glueball, possibly $\bar{s}s$
Spin unclear ($0^{++}$ or $2^{++}$)

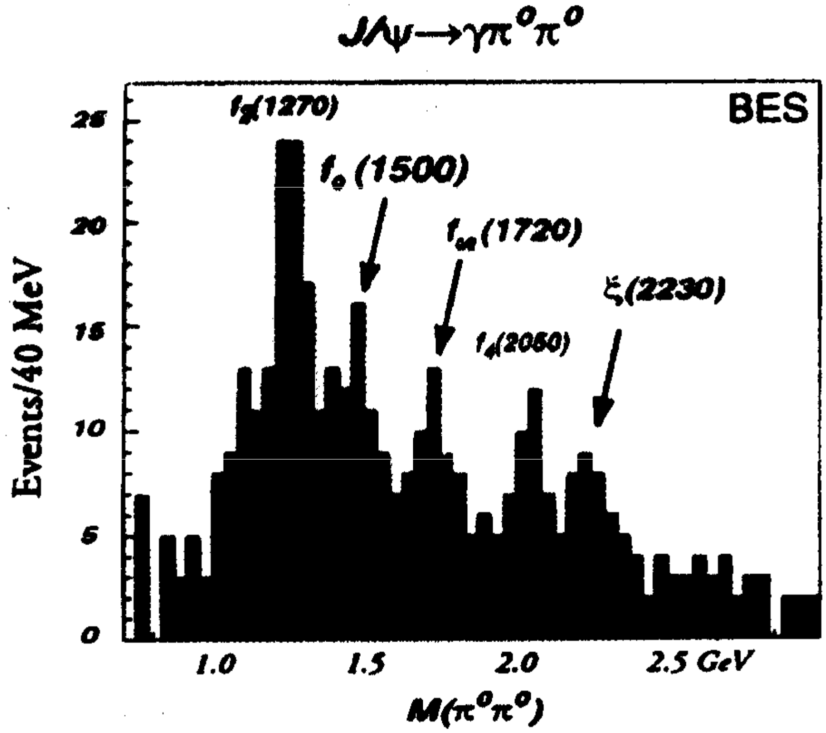
S. Braccini, Meson2000

# $\bar{p}d \rightarrow K_sK_sn$

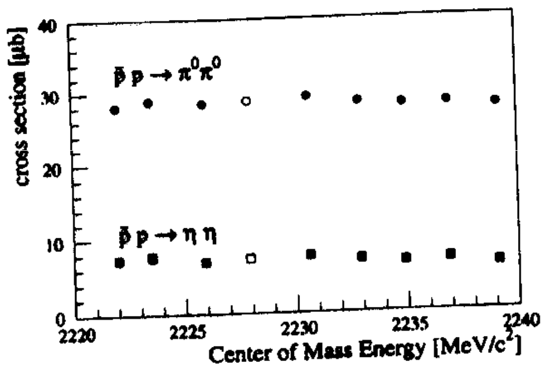


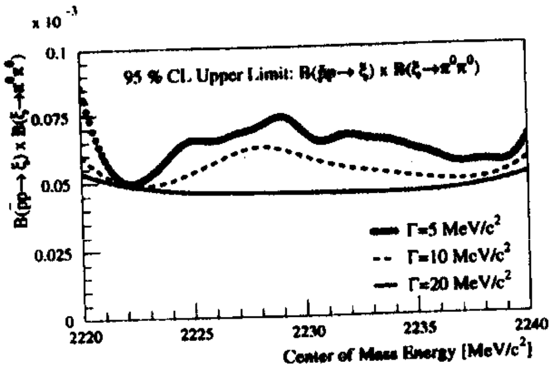
# New Results on radiative J/Ψ Decays

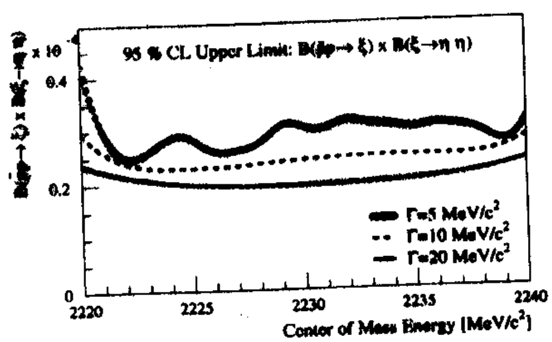
## BES Collaboration (ICHEP 96)



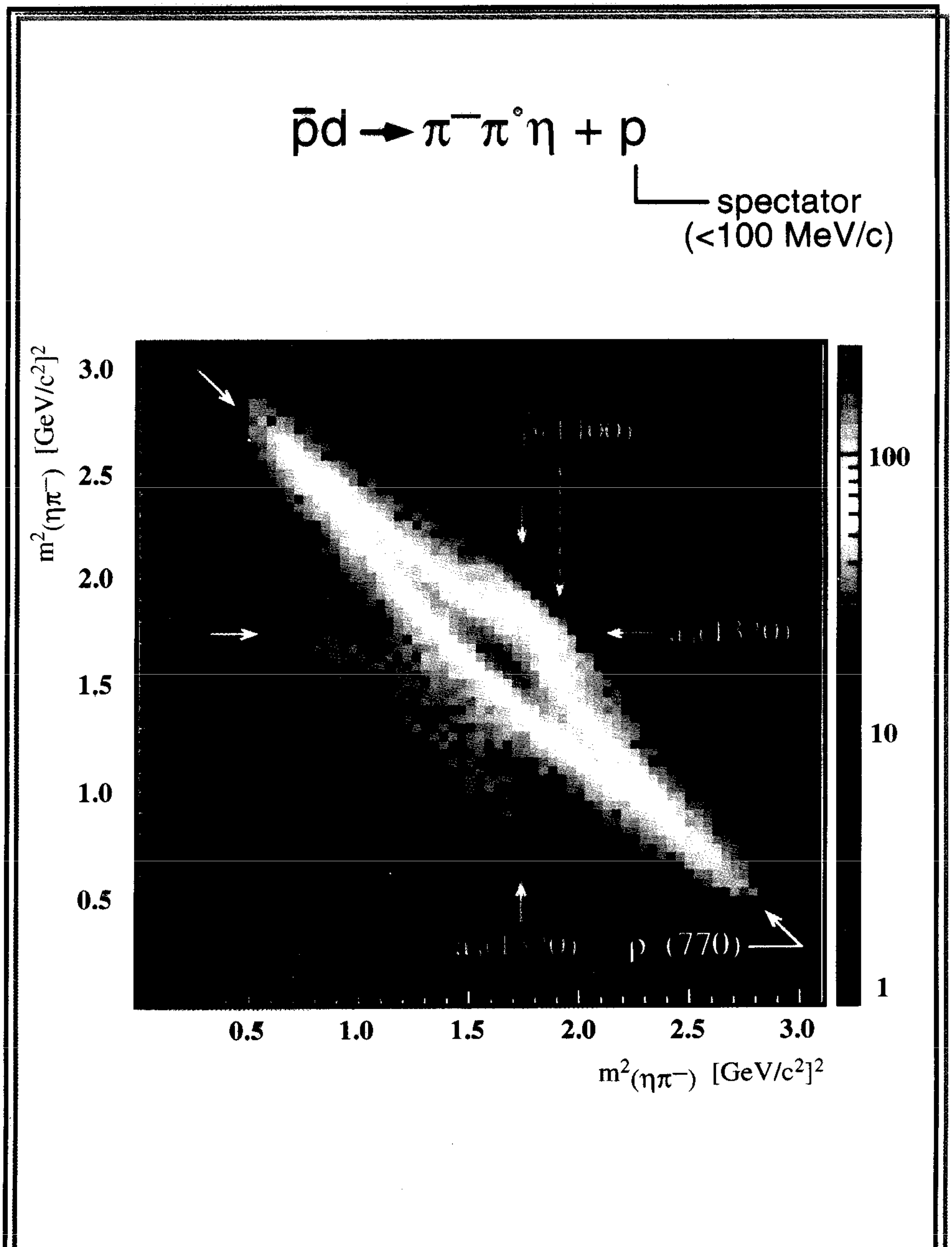
# Other Glueball Candidates: ξ(2230)



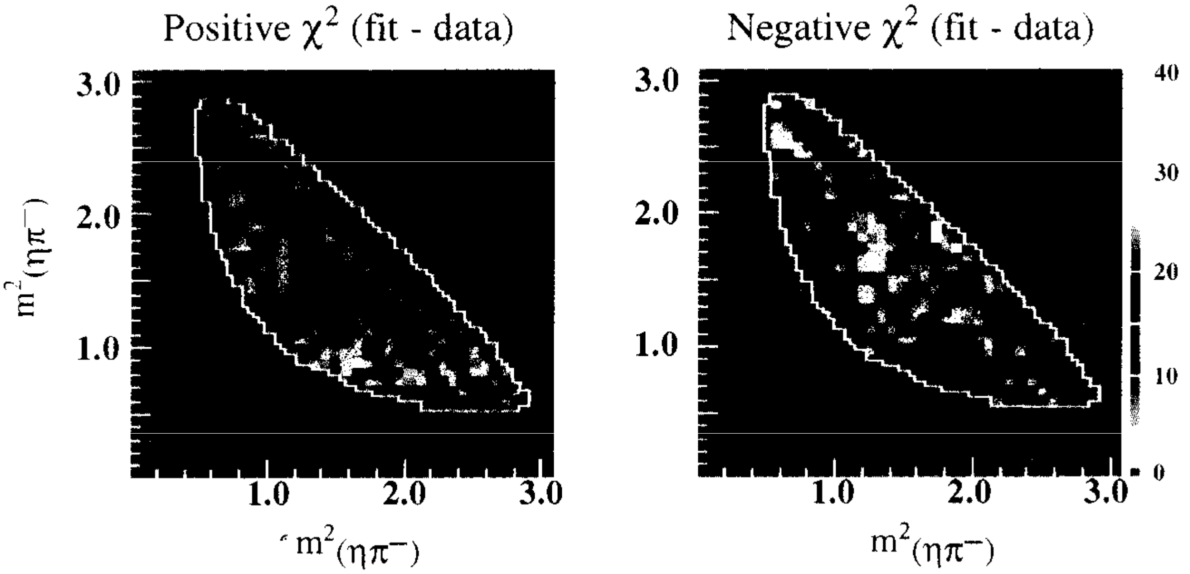




Crystal Barrel: NO narrow ξ(2230)


$\bar{p}d \rightarrow \pi^-\pi^\circ\eta + p$
spectator
(<100 MeV/c)
3.0
2.5
2.0
1.5
1.0
0.5
$m^2(\eta\pi^-)$ [GeV/$c^2$]$^2$
ρ (770)
100
10
1
0.5
1.0
1.5
2.0
2.5
3.0
$m^2(\eta\pi^-)$ [GeV/$c^2$]$^2$

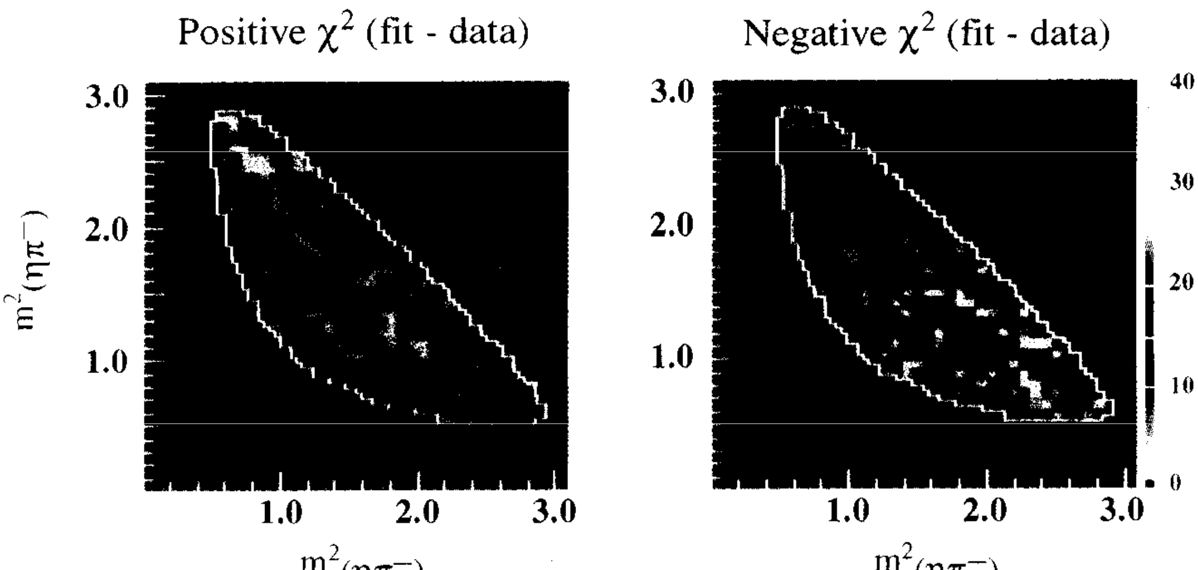
# Difference data-fit with "standard" resonances

$\chi^2 = 3.07$ / d.o.f




# Include "exotic" ($J^{PC} = 1^{-+}$) $\hat{\rho}(1400)$ in fit

$\chi^2 = 1.29$ / d.o.f



# Properties of the $\hat{\rho}(1400)$

Decay: $(\eta\pi)_{L=1}$

Mass: $1400 \pm 30$ MeV

Width: $310 \pm 70$ MeV

Quantum Numbers: $J^{PC} = 1^{-+}$ $(I=1)$

not possible from $q\bar{q}$

$$\vec{J} = \vec{L} + \vec{S}$$

$$P = (-)^{L+1}$$

$$C = (-)^{L+S}$$

Previous indications of this resonance:

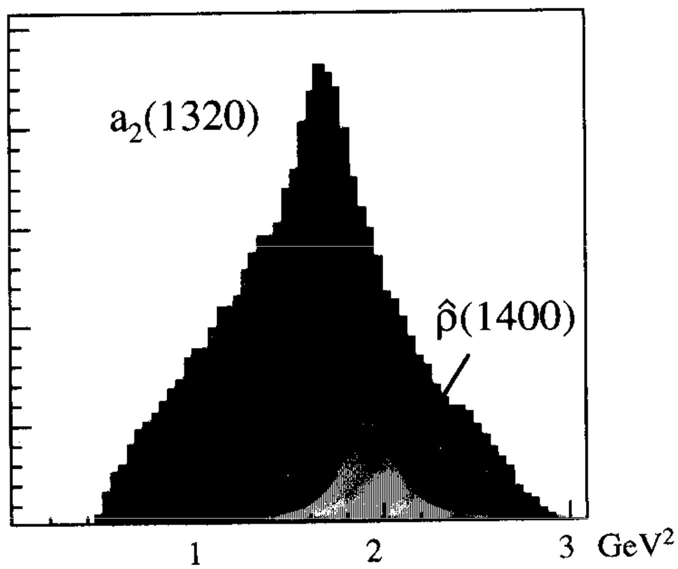
$\pi^- p \rightarrow (\pi^\circ \eta)n$ (GAMS/CERN, 100 GeV/c, 1988)

$\pi^- p \rightarrow (\pi^\circ \eta)n$ (VES/Serpukhov, 100 GeV/c, 1993)

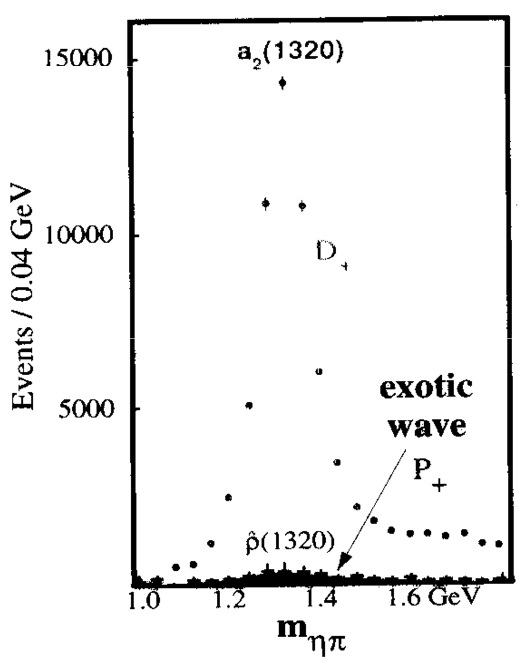
$\pi^- p \rightarrow (\pi^\circ \eta)n$ (E852/Brookhaven, 18 GeV/c, 1997)

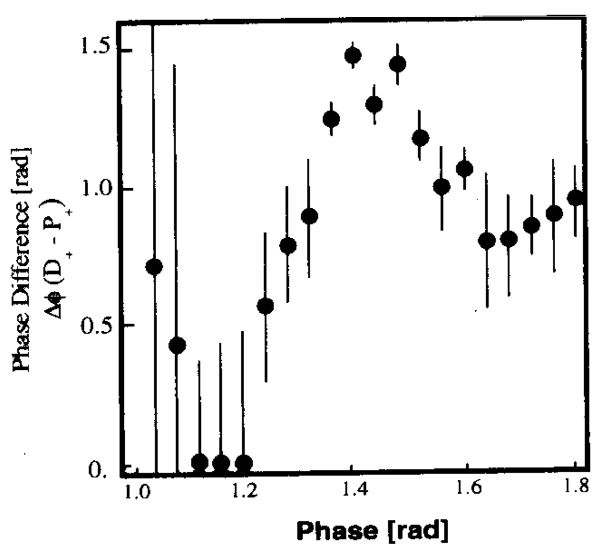
M: 1300 – 1400 MeV, Γ: 150 – 400 MeV

# Hybrid production in $\bar{p}p$ annihilation



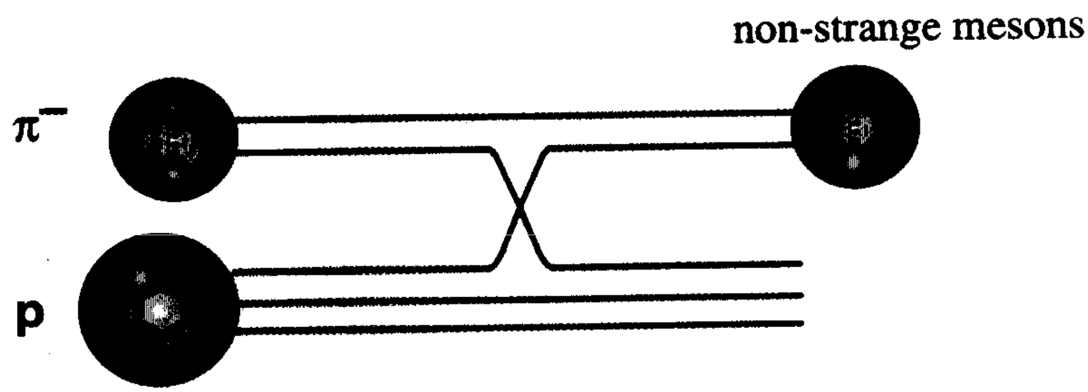

## vs. production in 18 GeV/c $\pi^-$ beam (BNL-E852)

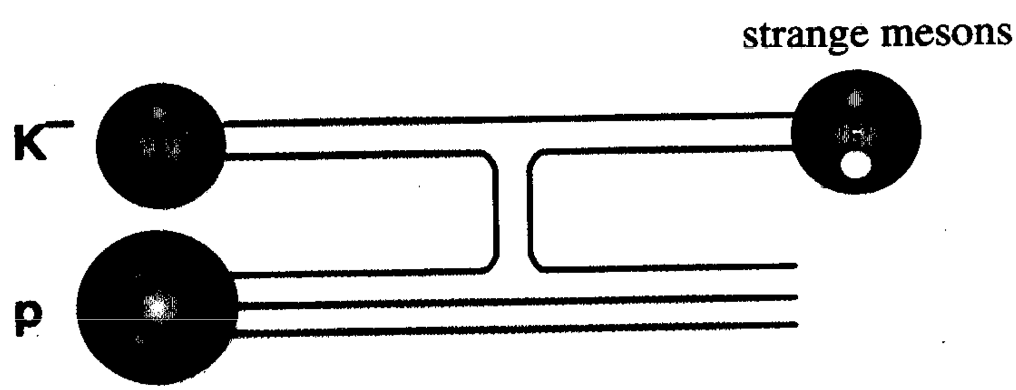



- Complicated analysis (x 10 more amplitudes for high L-waves, exchange)
- **Dominant $a_2(1320)$; feedthrough to P+ wave, background (few percent)**
- Phase motion relative to $a_2(1320)$ indication of resonance

# Meson Production with Hadron Beams

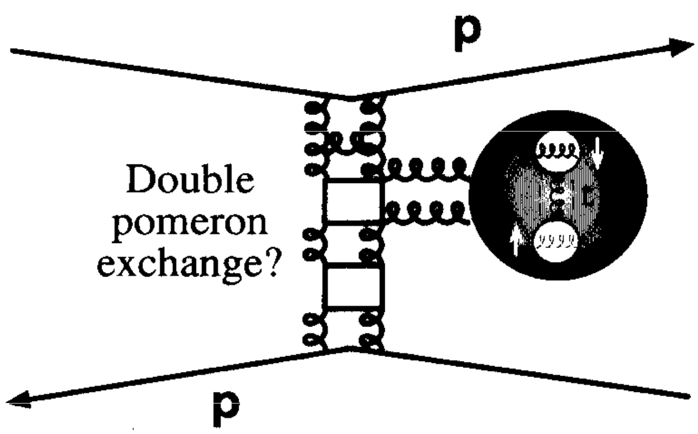



GAMS (CERN), LASS (SLAC), BNL experiments, etc.

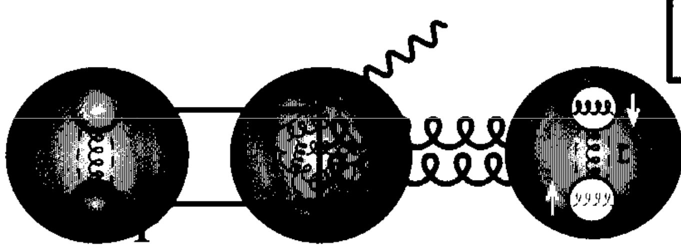
... produces mainly objects containing quarks.

# Meson Production
## ("Gluon-rich" processes)



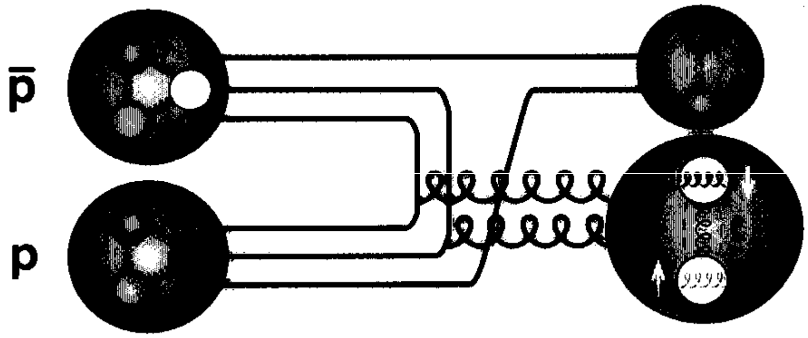

Central Production

WA 79, WA 102



Radiative J/Ψ decays

Mark III,
DM2,
BES




p̄p Annihilation

ASTERIX,
Crystal Barrel,
OBELIX

# CEBAF Hall D project

Tagged γ beam:
$10^7$–$10^8$ $s^{-1}$

$E_{max}$= 12 GeV

VDM: γ "=" ρ, ω, ϕ
9 : 2 : 1

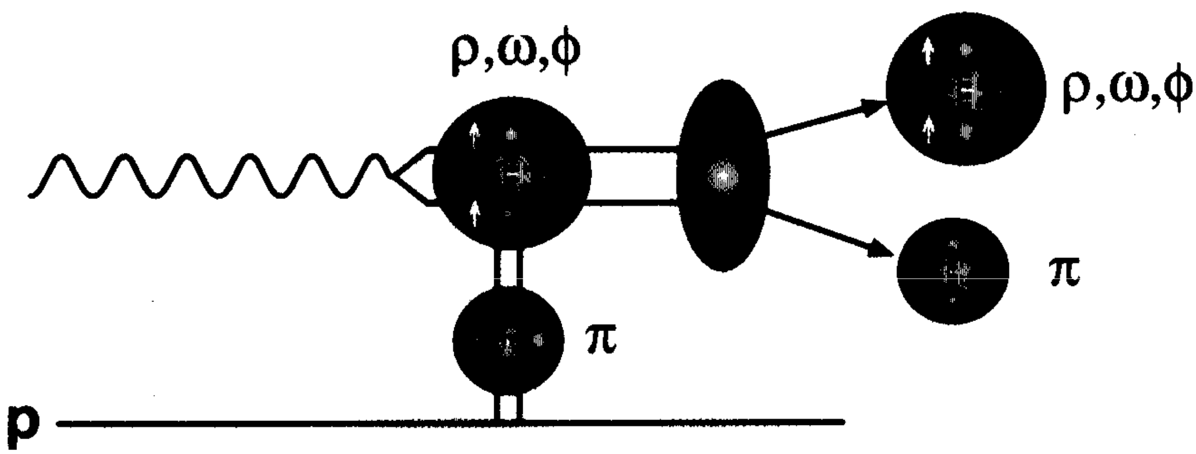
Meson spectroscopy
up to 3 GeV/$c^2$

BUT:
hadronic suppression
factor $10^4$

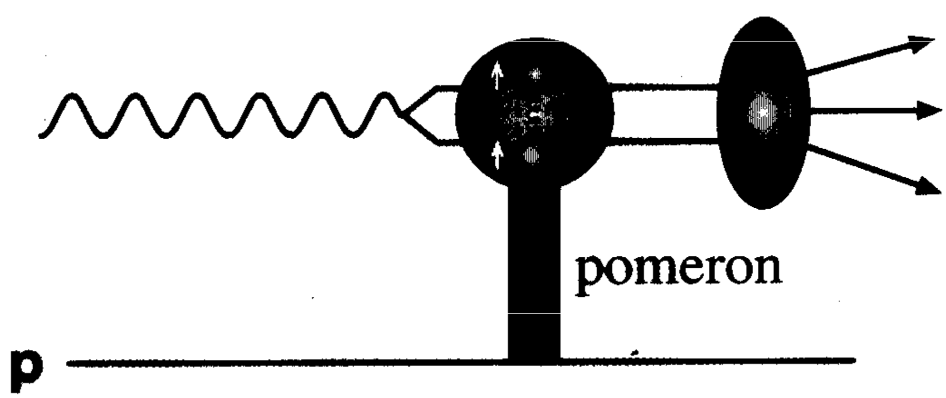
Statistics: Gain of 1-2 orders of magnitude
in *certain* channels (2 y).

# Peripheral Production at CEBAF
## (t-channel exchanges)

Lower energies: meson exchange




Higher energies: diffractive scattering
(pomeron exchange)




Ulrich Wiedner

# Photoproduction of Hadrons

— requires a hermetic detector to observe the full decay chain.

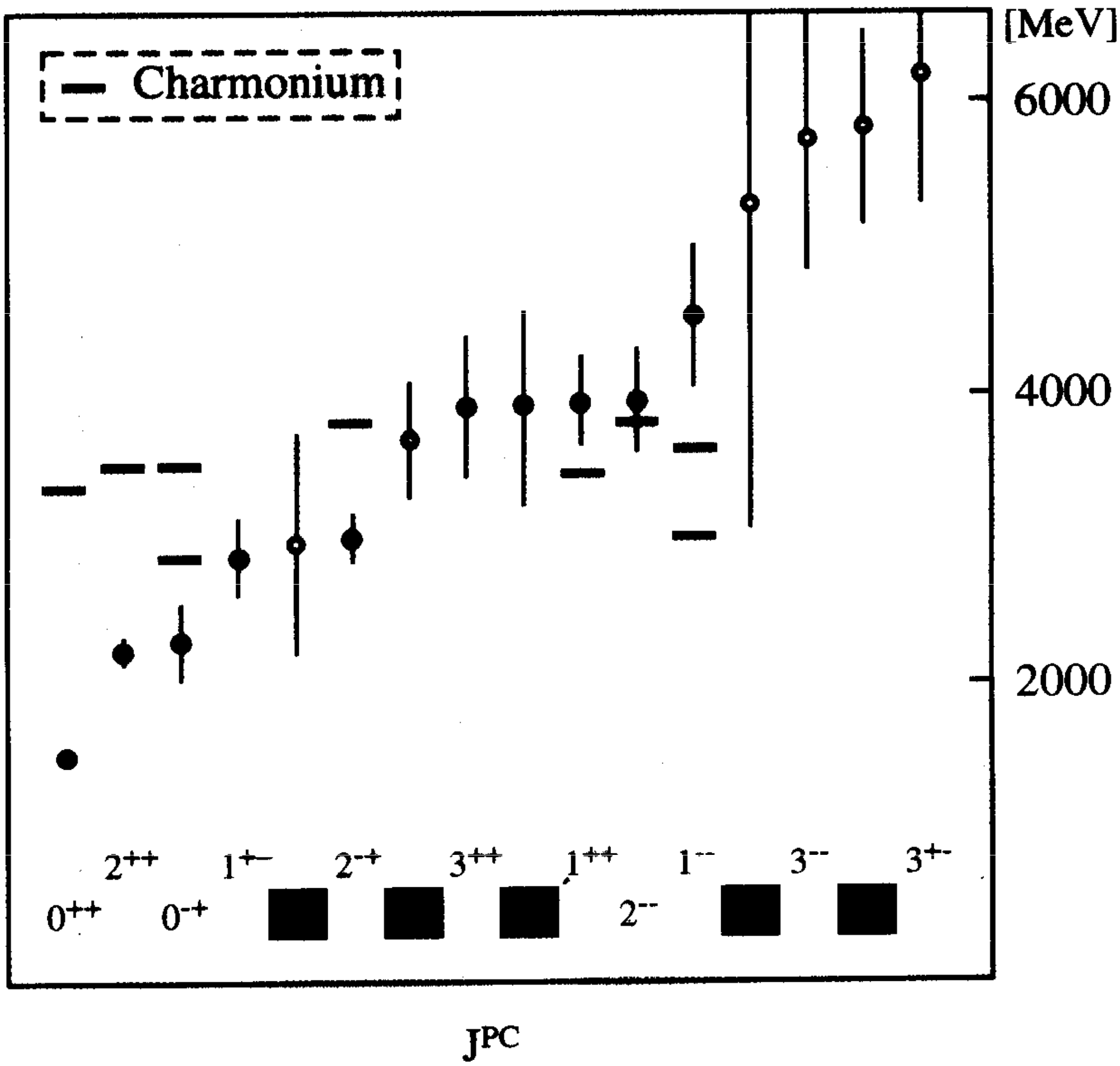
— suffers from a hadronic suppression factor.

— has a complicated, highly ambiguous PWA.

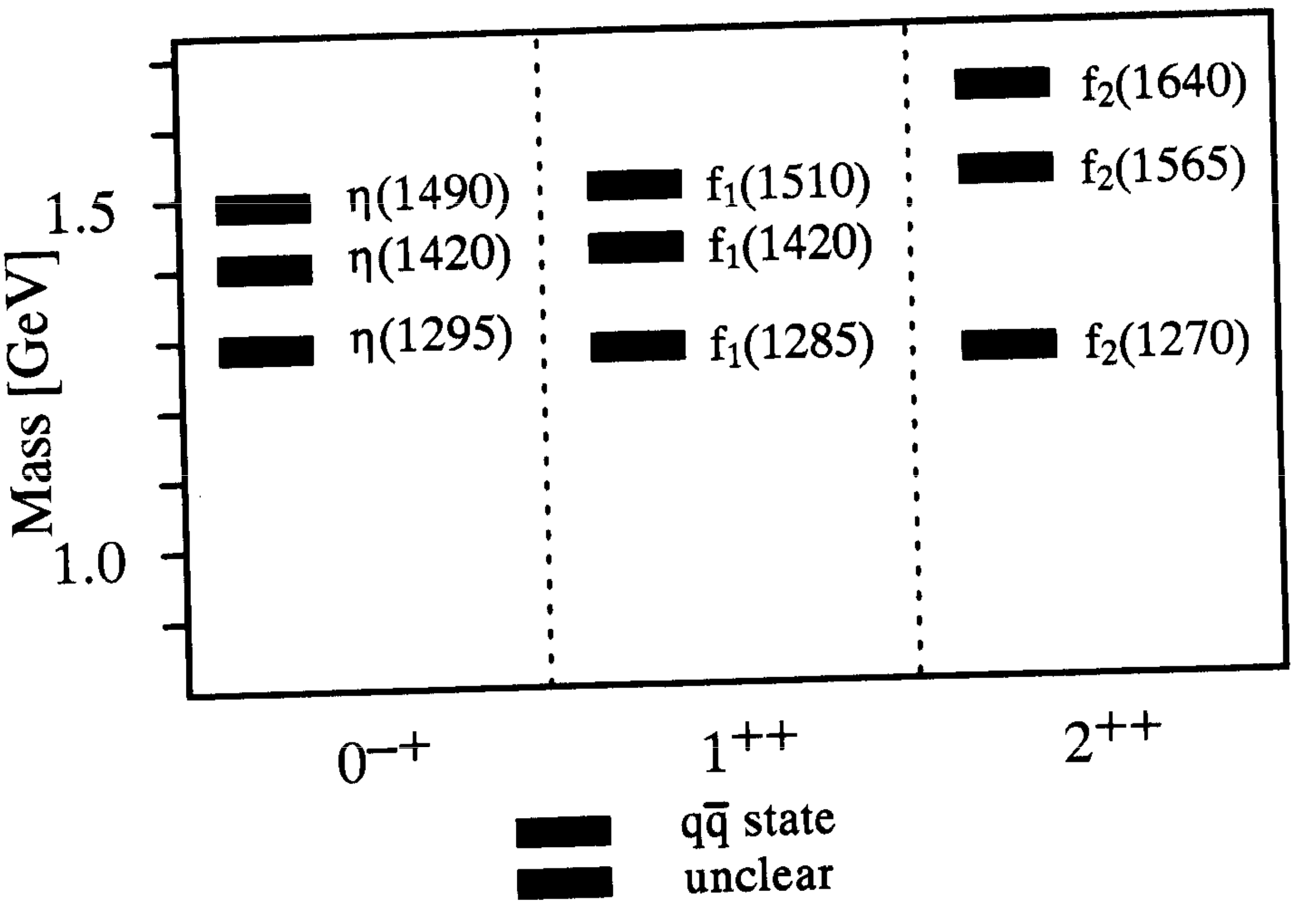
— might require polarization.

— produces detectable gluonic objects?

# Charmonium States and Predicted Glueballs



# Open Questions in Meson Nonets




$f_1(1420)$ = KK* molecule ? [ $(0^- + 1^-)_S = 1^+$ ]

$f_2(1640)$ = ωω molecule ? [ $(1^- + 1^-)_S = 2^+$ ]

η(1420)/η(1490) behaves like a glueball
(seen e.g. in radiative J/Ψ decays)

but $M(0^{-+})_G > 2.1$ GeV

Gluinoball ?

G. Farrar, Phys. Rev. D51 (1995) 3904
G. Farrar, RU-95-25, hep-ph/9508291

# Review of Particle Physics 2000

| $N\ ^{2S+1}L_J$ | $J^{PC}$ | $u\bar{d}$, $u\bar{u}$, $d\bar{d}$ $I = 1$ | $u\bar{u}$, $d\bar{d}$, $s\bar{s}$ $I = 0$ | $\bar{s}u$, $\bar{s}d$ $I = 1/2$ |
|---|---|---|---|---|
| $1\ ^1S_0$ | $0^{-+}$ | [illegible] | [illegible] | **K** |
| $1\ ^3S_1$ | $1^{--}$ | [illegible] | [illegible] | **K*(892)** |
| $1\ ^1P_1$ | $1^{+-}$ | [illegible] | **$h_1$(1170)**, [illegible] | **$K_{1B}$** † |
| $1\ ^3P_0$ | $0^{++}$ | [illegible] | [illegible] | **$K_0$*(1430)** |
| $1\ ^3P_1$ | $1^{++}$ | **$a_1$(1260)** | [illegible] | **$K_{1A}$** † |
| $1\ ^3P_2$ | $2^{++}$ | [illegible] | [illegible] | **$K_2$*(1430)** |
| $1\ ^1D_2$ | $2^{-+}$ | [illegible] | [illegible] | **$K_2$(1770)** |
| $1\ ^3D_1$ | $1^{--}$ | [illegible] | **ω(1650)** | **K*(1680)** ‡ |
| $1\ ^3D_2$ | $2^{--}$ | [illegible] | [illegible] | **$K_2$(1820)** |
| $1\ ^3D_3$ | $3^{--}$ | **$\rho_3$(1690)** | **$\omega_3$(1670)**, **$\phi_3$(1850)** | $K_3$*(1780) |
| $1\ ^3F_4$ | $4^{++}$ | [illegible] | **$f_4$(2050)**, $f_4$(2220) | **$K_4$*(2045)** |
| $2\ ^1S_0$ | $0^{-+}$ | [illegible] | [illegible] | K(1460) |
| $2\ ^3S_1$ | $1^{--}$ | [illegible] | ω(**1420**), **φ(1680)** | **K*(1410)** ‡ |
| $2\ ^3P_2$ | $2^{++}$ | [illegible] | $f_2$(1810), **$f_2$(2010)** | $K_2$*(1980) |
| $3\ ^1S_0$ | $0^{-+}$ | **π(1800)** | η(1760) | K(1830) |

■ contributions from LEAR experiments

# Summary

- Very successful meson spectroscopy experiments using antiprotons.
- The first QCD exotics have been found in high statistics and high precision $4\pi$ experiments.
- Their production rate is comparable to those of normal mesons in $\bar{p}p$ annihilations.
- Other glueballs and hybrids must exist.
- Non-perturbative QCD far from being understood.
- Hadron physics requires hadron beams.