The Hunt for Glueballs, Hybrids and other QCD exotics

Ulrich Wiedner
Uppsala University

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The theory of strong interaction, QCD, has two important ingredients:

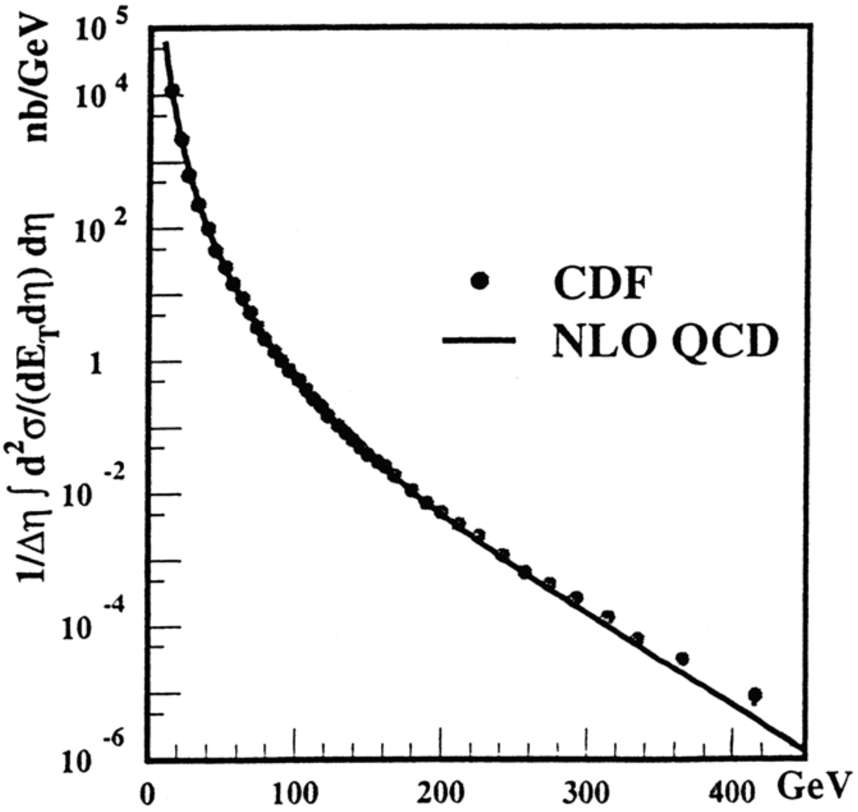
1) asymptotic freedom ⟶ perturbative QCD

2) confinement ⟶ formation of hadrons

QCD at short distances $\alpha_S \ll 1$

Perturbative QCD is extremely successful:

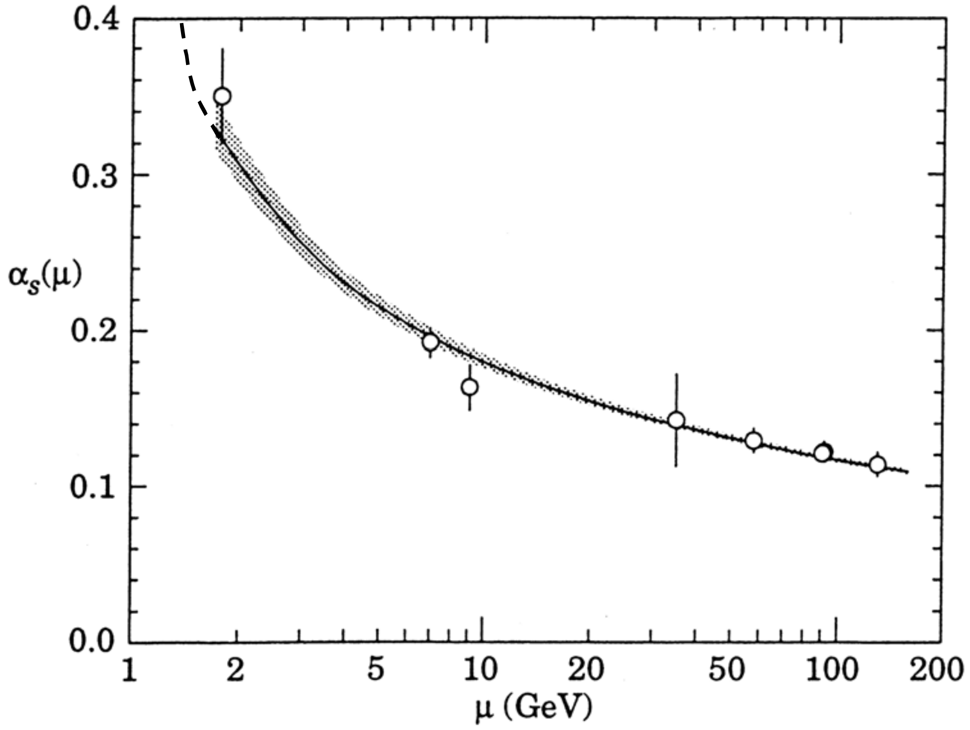
Jet production in $\bar{p}p$-collisions at $\sqrt{s} = 1.8$ TeV



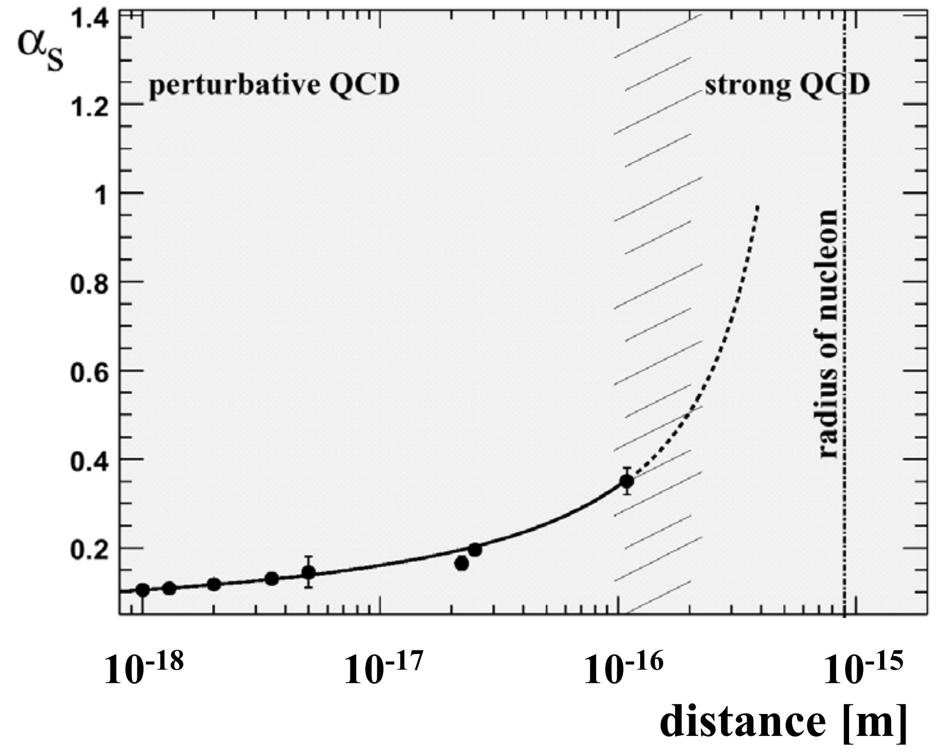
transverse jet energy

Quantitative description of the experimental cross section over 10 orders of magnitude by perturbative QCD

QCD at large distances



$\alpha_S (Q^2) \to 1$ for $Q^2 \to 1$ GeV^2

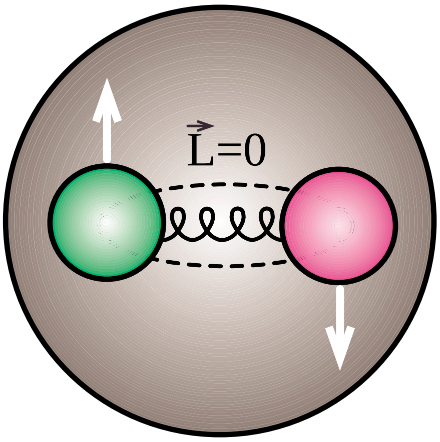


The Experimental and Theoretical Challenge

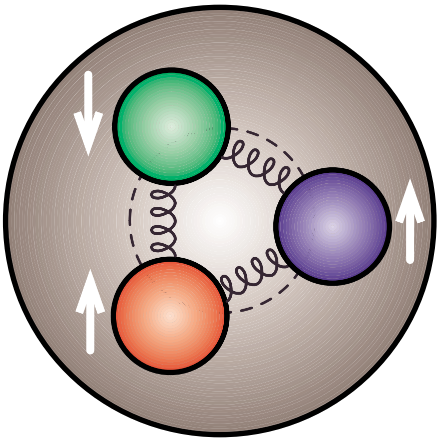
Understand non-perturbative phenomena like:

- confinement
- chiral symmetry breaking
- masses

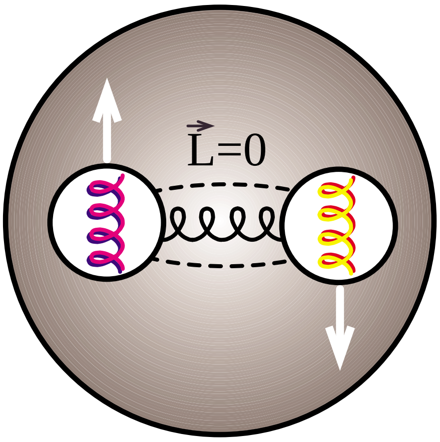
QCD



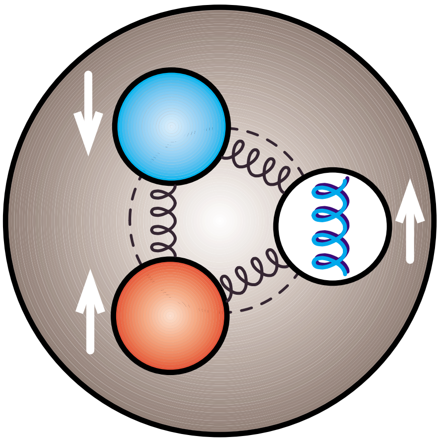
Meson (q$\bar{q}$)



Baryon (qqq)



Glueball (gg)



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

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Gluons exist:

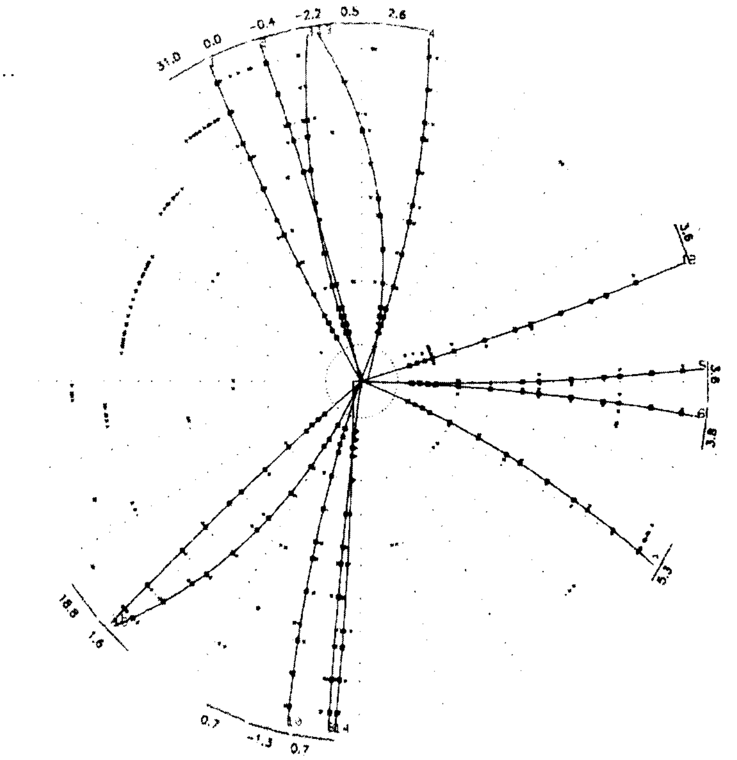
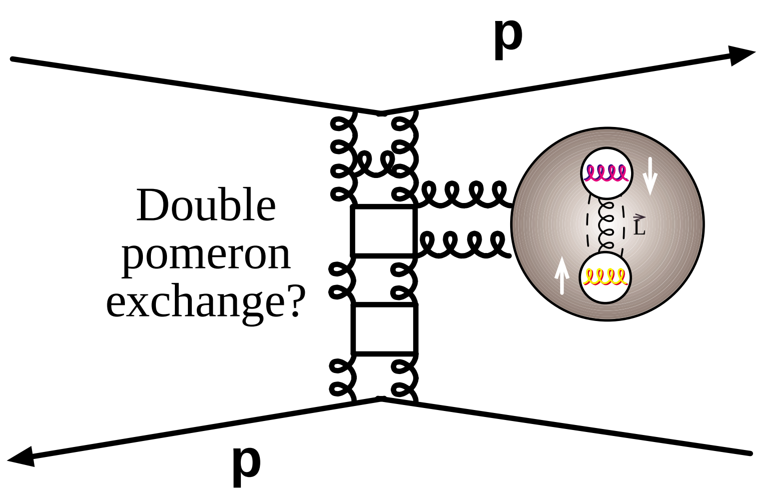


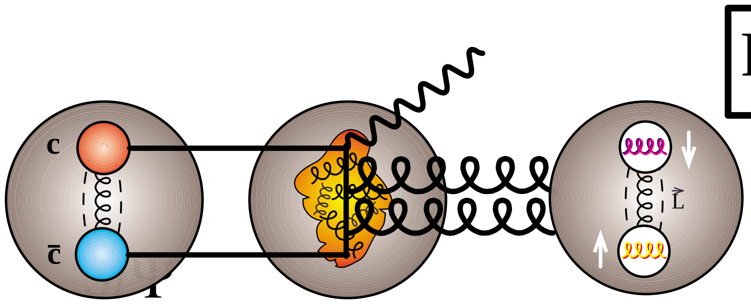
Fig. 10.19 The same as Fig. 10.17 except that this event is one of the rare, separated, three jet events. The total energy is 35.16 GeV.

Meson Production
("Gluon-rich" processes)



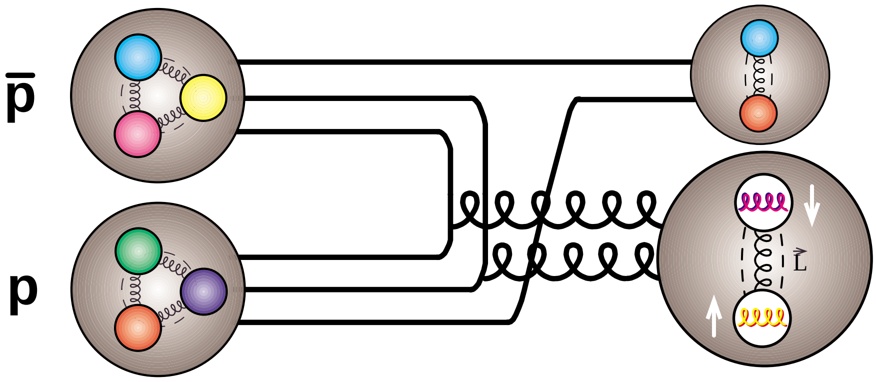
Central Production

WA 79, WA 102



Radiative J/Ψ decays

Mark III,
DM2,
BES



$\bar{p}p$ Annihilation

ASTERIX,
Crystal Barrel,
OBELIX

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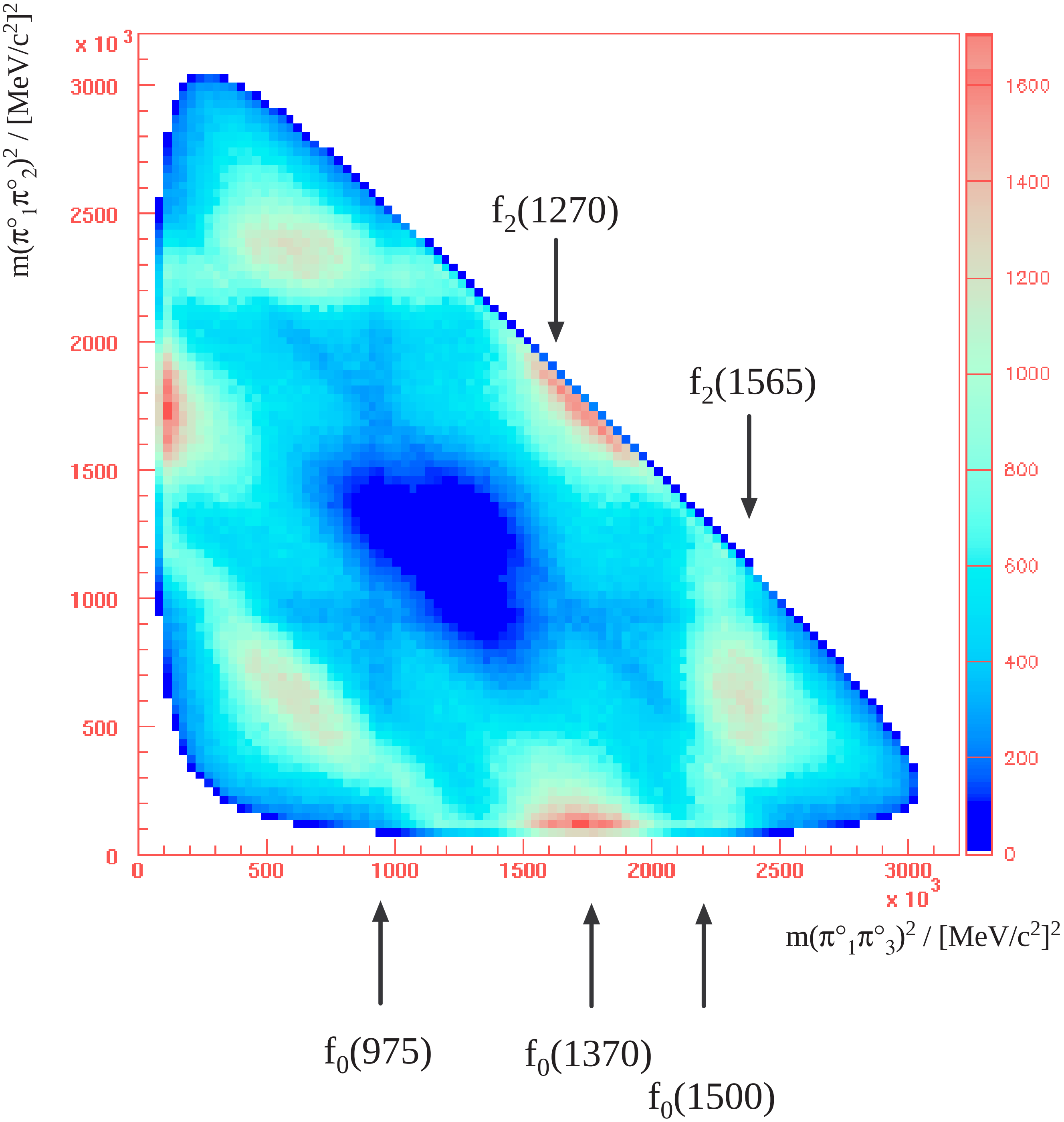
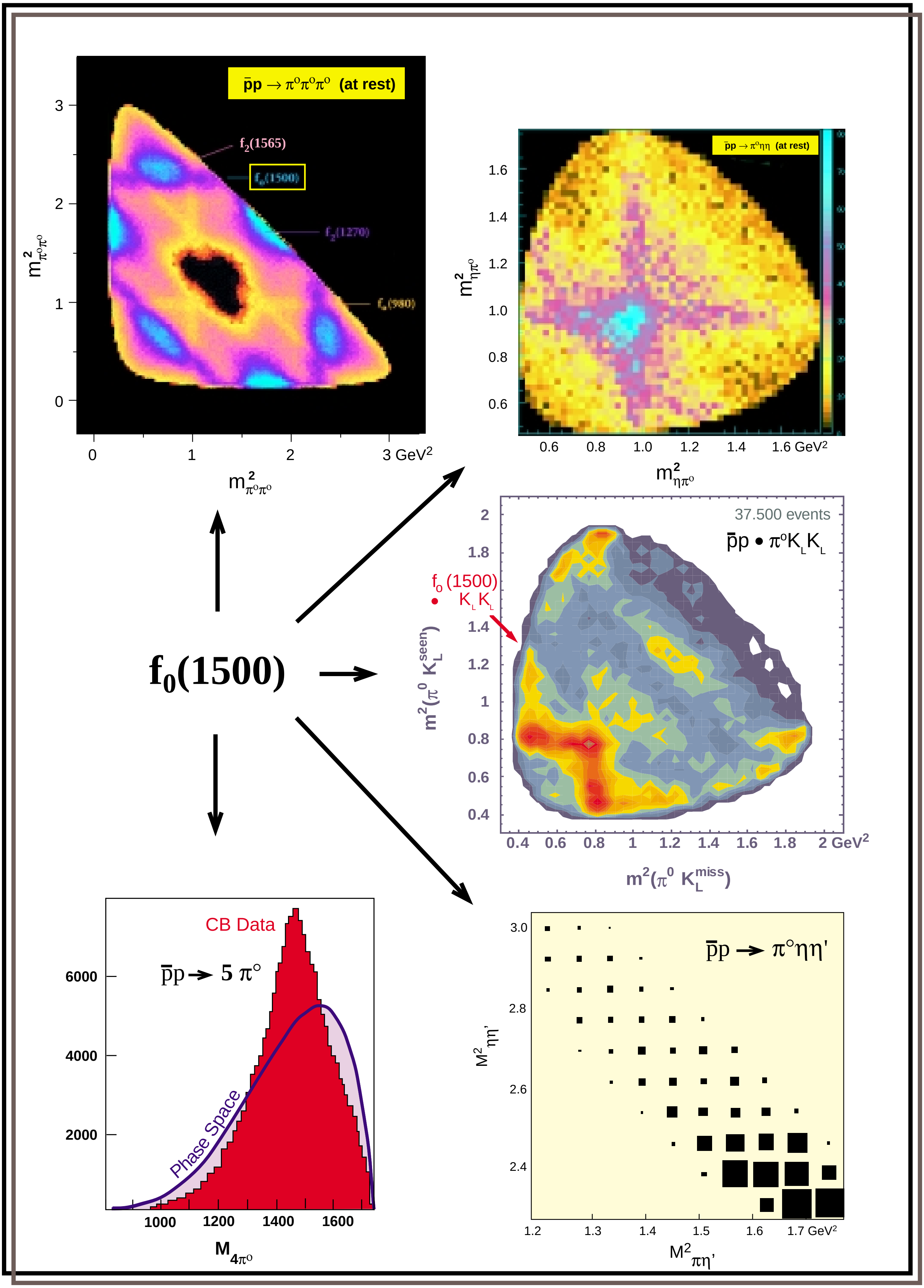
$\bar{p}p \longrightarrow 6\gamma$

$\pi^\circ\pi^\circ\pi^\circ$ Dalitz plot

700,000 events = 6 × 700,000 entries





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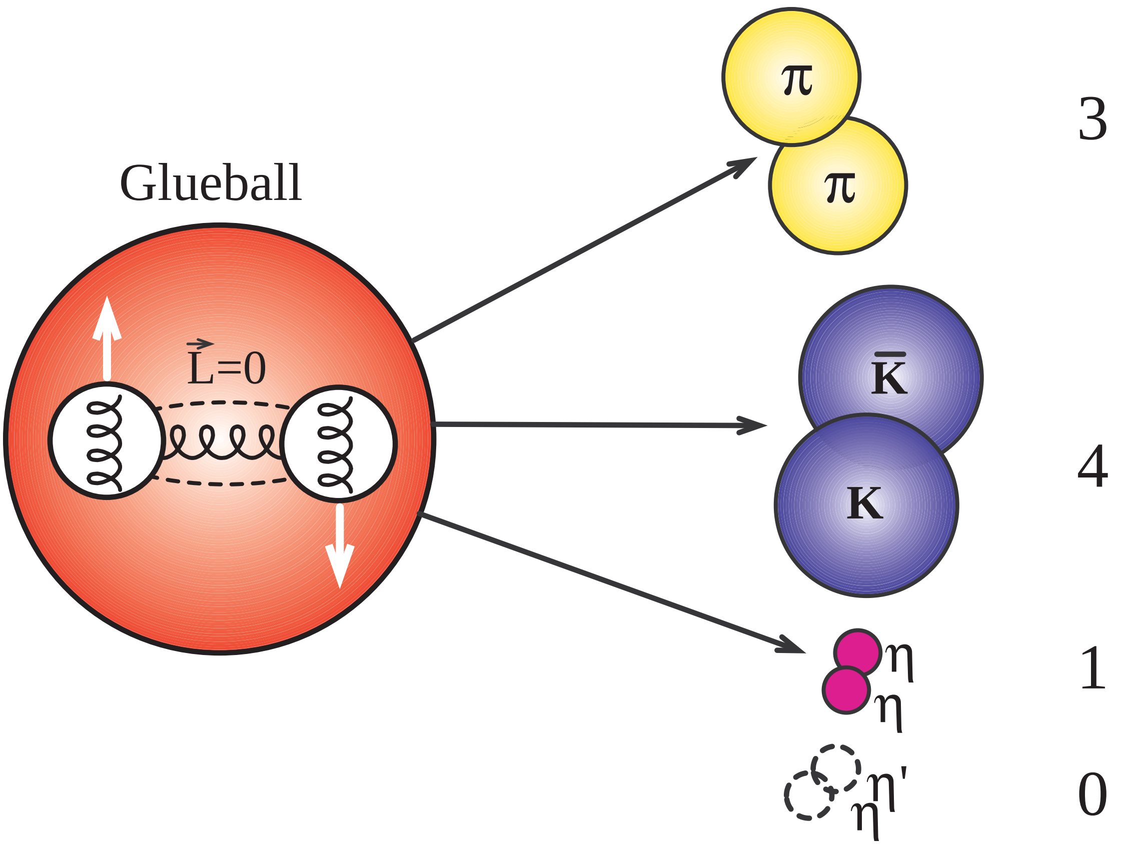
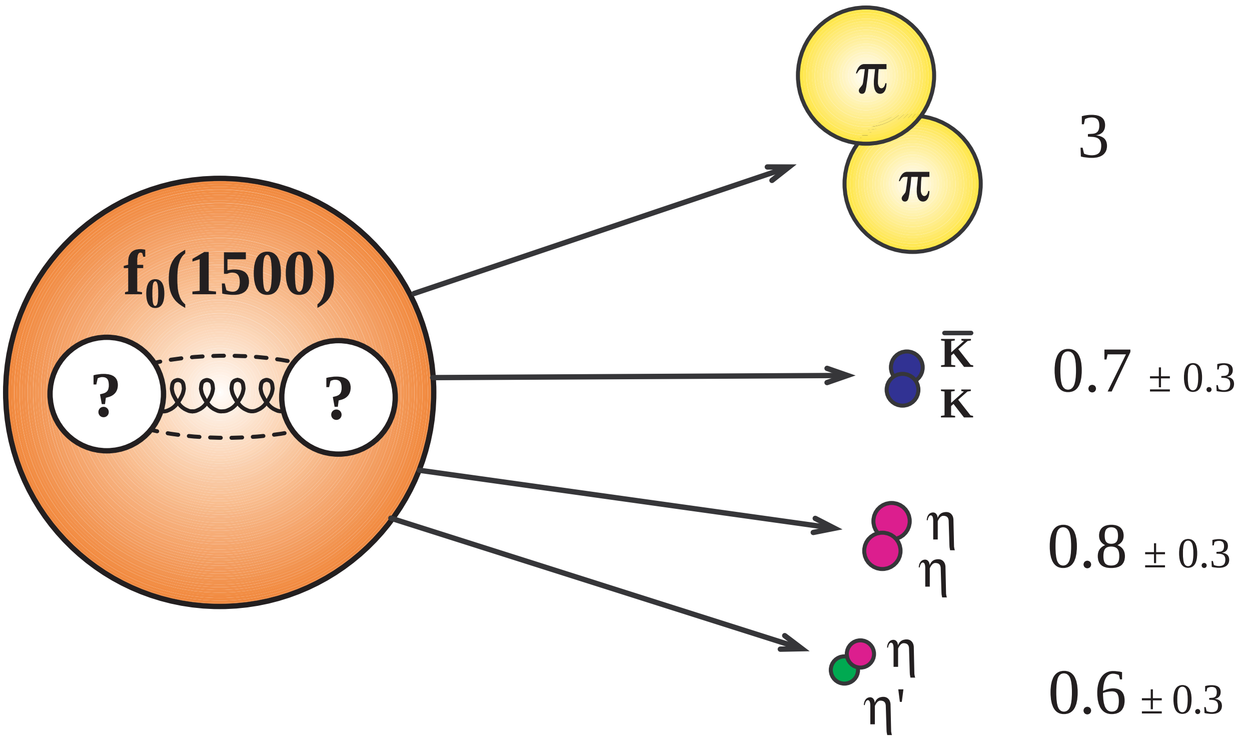
Decay properties





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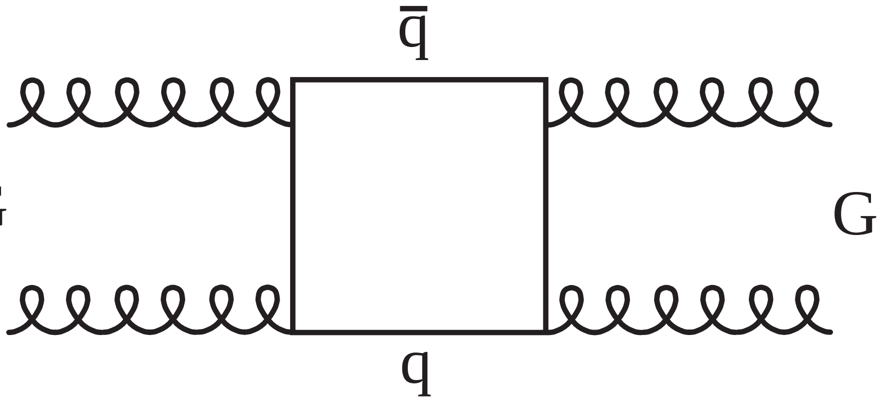
Can this decay pattern be explained ?



Glueball-meson mixing

Interpretation difficult !

Help from theory ?

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

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

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

$$f_0(1710) = 0.88\,|G> + 0.33\,|s\bar{s}> + 0.34\,|1/\sqrt{2}\,(u\bar{u}+d\bar{d})>$$

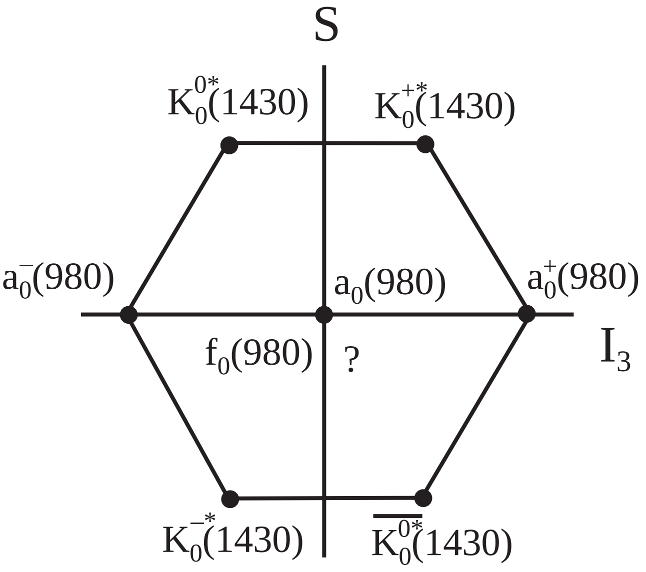
C. Amsler, F. Close, Phys.Rev. D53, 295 (1996); F. Close, LEAP96:

$$f_0(1370) = -0.50\,|G> + 0.13\,|s\bar{s}> + 0.86\,|1/\sqrt{2}\,(u\bar{u}+d\bar{d})>$$

$$f_0(1500) = 0.61\,|G> - 0.61\,|s\bar{s}> + 0.43\,|1/\sqrt{2}\,(u\bar{u}+d\bar{d})>$$

$$f_0(1710) = 0.60\,|G> - 0.76\,|s\bar{s}> + 0.22\,|1/\sqrt{2}\,(u\bar{u}+d\bar{d})>$$

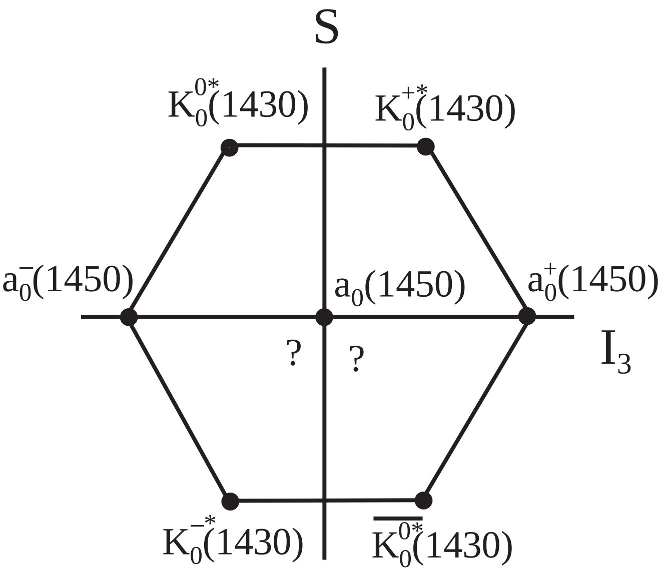
The old possible nonet of scalar mesons:



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

\+ other experiments:

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

Too many resonances

Interpretation of the results:

$f_0(980)$, $a_0(980)$: KK-molecules

$f_0(1370)$: Nonet member

$f_0(1525)$, $f_0(1710)$: Nonet member

$f_0(1500) = f_0(1590) = f_0(1450)$: Exotic

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

Can we learn something from the decay width ?

$$\Gamma\ (f_0(1500)) \longrightarrow \eta\eta,\ \eta\eta',\ KK \sim 15\ \text{MeV}$$

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

$$\left.\begin{array}{l}\Gamma\ (f_0(1500)) \longrightarrow 4\pi,\ \pi\pi \sim 100\ \text{MeV} \\ \Gamma\ (f_0(1500)) \longrightarrow \pi\pi \sim 20 - 30\ \text{MeV}\end{array}\right\}$$

Quark models and other nonets:

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

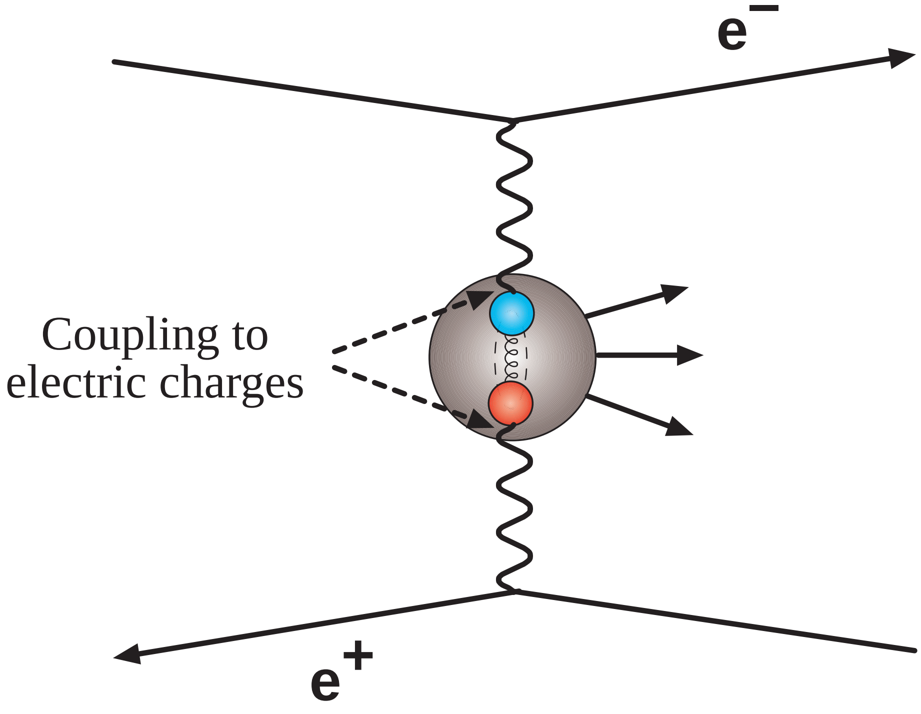
287±14 MeV

270±40 MeV

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

The width of the $f_0(1500)$
$\Gamma = 116 \pm 17$ MeV
does not fit into the 0^{++} nonet

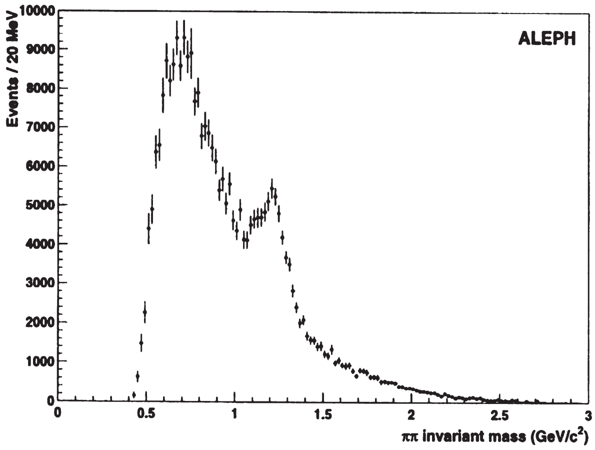
Meson Production
in
$\gamma\gamma$ Collisions

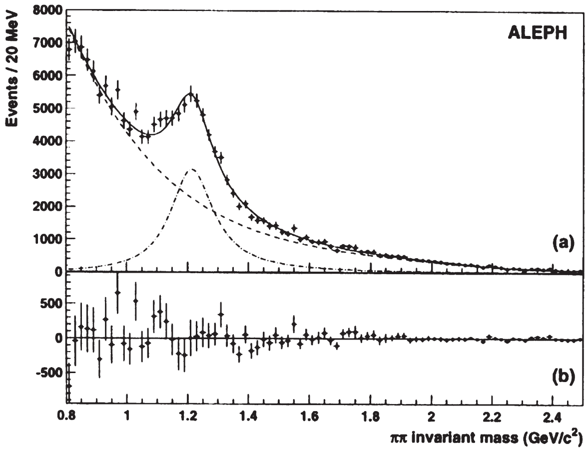


... acts as an "Anti-Glueball Filter".

$\gamma\gamma$ Collisions from ALEPH

(Anti-Glueball Filter)





no $f_0(1500)$

upper limit:

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

Phys. Lett. B472 (2000) 189.

Glueball – meson mixing occurs when both decay into the same final states.

The light scalar (0^{++}) glueball can decay solely into pseudoscalar mesons and $\rho\rho$, *just like any other light quark meson*.

→ mixing unavoidable

Solution:

Understand the complete light-quark meson spectrum experimentally and theoretically.

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^{-+}	🟦 π	🟦 η, η'	**K**
$1\ {}^3S_1$	1^{--}	🟦 ρ	🟦 ω, ϕ	**K*(892)**
$1\ {}^1P_1$	1^{+-}	🟦 **b$_1$(1235)**	**h$_1$(1170)**, 🟦 h$_1$(1380)	**K$_{1B}$**†
$1\ {}^3P_0$	0^{++}	🟦 **a$_0$(1450)***	🟦 **f$_0$(1370)***, **f$_0$(1710)***	**K$_0$*(1430)**
$1\ {}^3P_1$	1^{++}	**a$_1$(1260)**	🟦 **f$_1$(1285), f$_1$(1420)**	**K$_{1A}$**†
$1\ {}^3P_2$	2^{++}	🟦 **a$_2$(1320)**	🟦 **f$_2$(1270), f$_2$'(1525)**	**K$_2$*(1430)**
$1\ {}^1D_2$	2^{-+}	🟦 **π$_2$(1670)**	🟦 η$_2$(1645), η$_2$(1870)	**K$_2$(1770)**
$1\ {}^3D_1$	1^{--}	🟦 **ρ(1700)**	**ω(1650)**	**K*(1680)**‡
$1\ {}^3D_2$	2^{--}	🟦	🟦	**K$_2$(1820)**
$1\ {}^3D_3$	3^{--}	**ρ$_3$(1690)**	**ω$_3$(1670)**, **ϕ$_3$(1850)**	K$_3$*(1780)
$1\ {}^3F_4$	4^{++}	🟦 **a$_4$(2040)**	**f$_4$(2050)**, f$_4$(2220)	**K$_4$*(2045)**
$2\ {}^1S_0$	0^{-+}	🟦 **π(1300)**	🟦 **η(1295), η(1440)**	K(1460)
$2\ {}^3S_1$	1^{--}	🟦 **ρ(1450)**	**ω(1420), ϕ(1680)**	**K*(1410)**‡
$2\ {}^3P_2$	2^{++}	🟦	f$_2$(1810), **f$_2$(2010)**	K$_2$*(1980)
$3\ {}^1S_0$	0^{-+}	**π(1800)**	η(1760)	K(1830)

🟦 contributions from LEAR experiments

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Higher-mass Glueballs

Higher mass glueballs (e.g. 2^{++}) can have decay modes that are OZI suppressed for (u and d) mesons like $\phi\phi$ or $\phi\eta$.

The observation of such decay modes makes a strong case for a glueball appearance.

Glueballs with exotic quantum numbers do not mix with mesons and should be narrow (bump hunting).

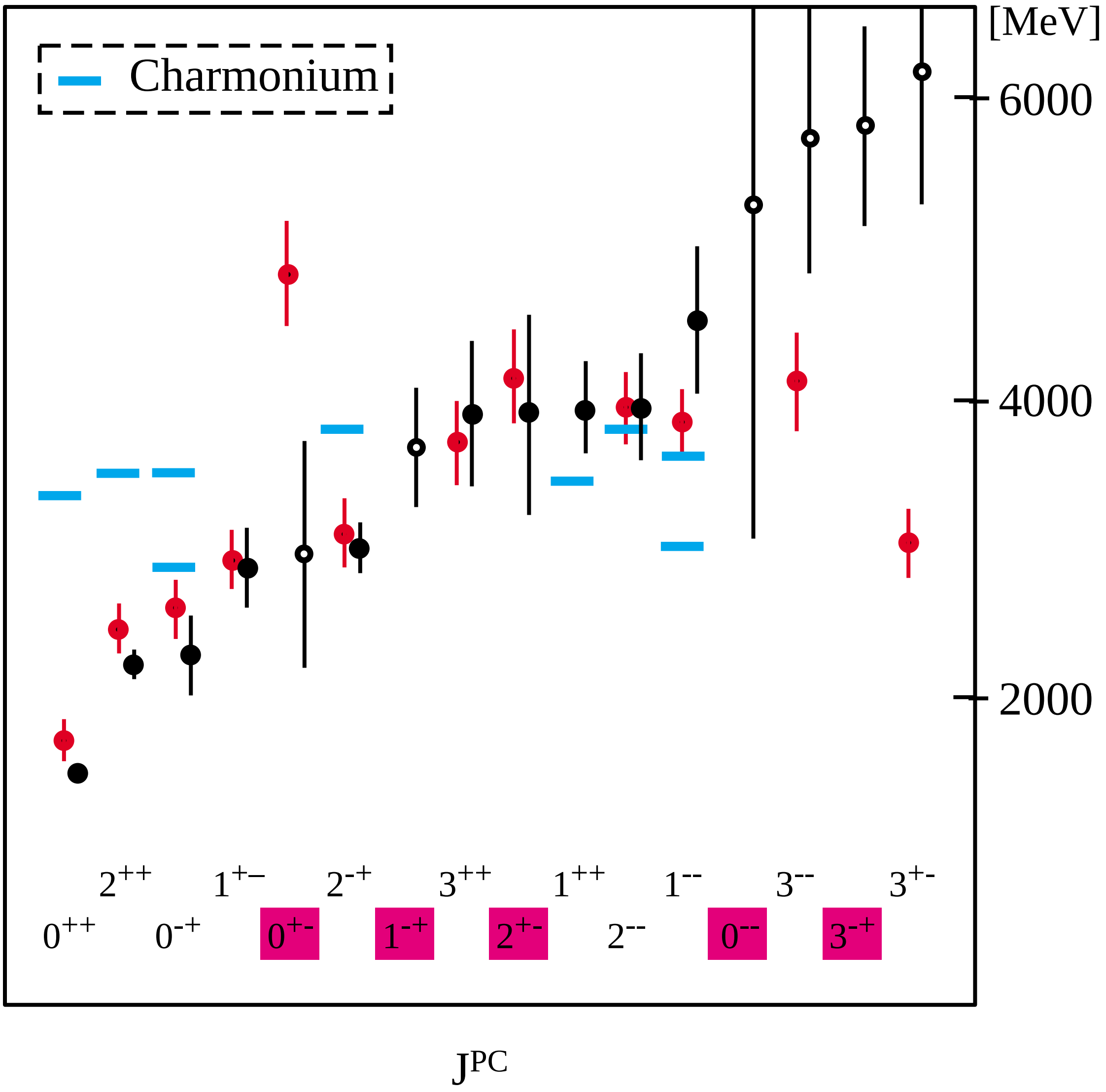
Lattice based calculations:

NO light mesons may exist > 3.2 GeV
(string breaking and color screaning)

M. Brisodova et al., Phys. Lett. B460, 1 (1999)
M. Brisudova et al., Phys. Rev. D61, 054013 (200)

ANY glueball could be narrow if $M_G >$ 3.2 GeV
and
ANY signal (besides $c\bar{c}$ states) could be a glueball or exotic

Charmonium States and Predicted Glueballs



● UKQCD Collaboration, G. S. Bali et al., Phys. Lett. B309 (1993) 378.

● C. Morningstar, M. Peardon; Phys. Rev. D 60 (1999) 034509

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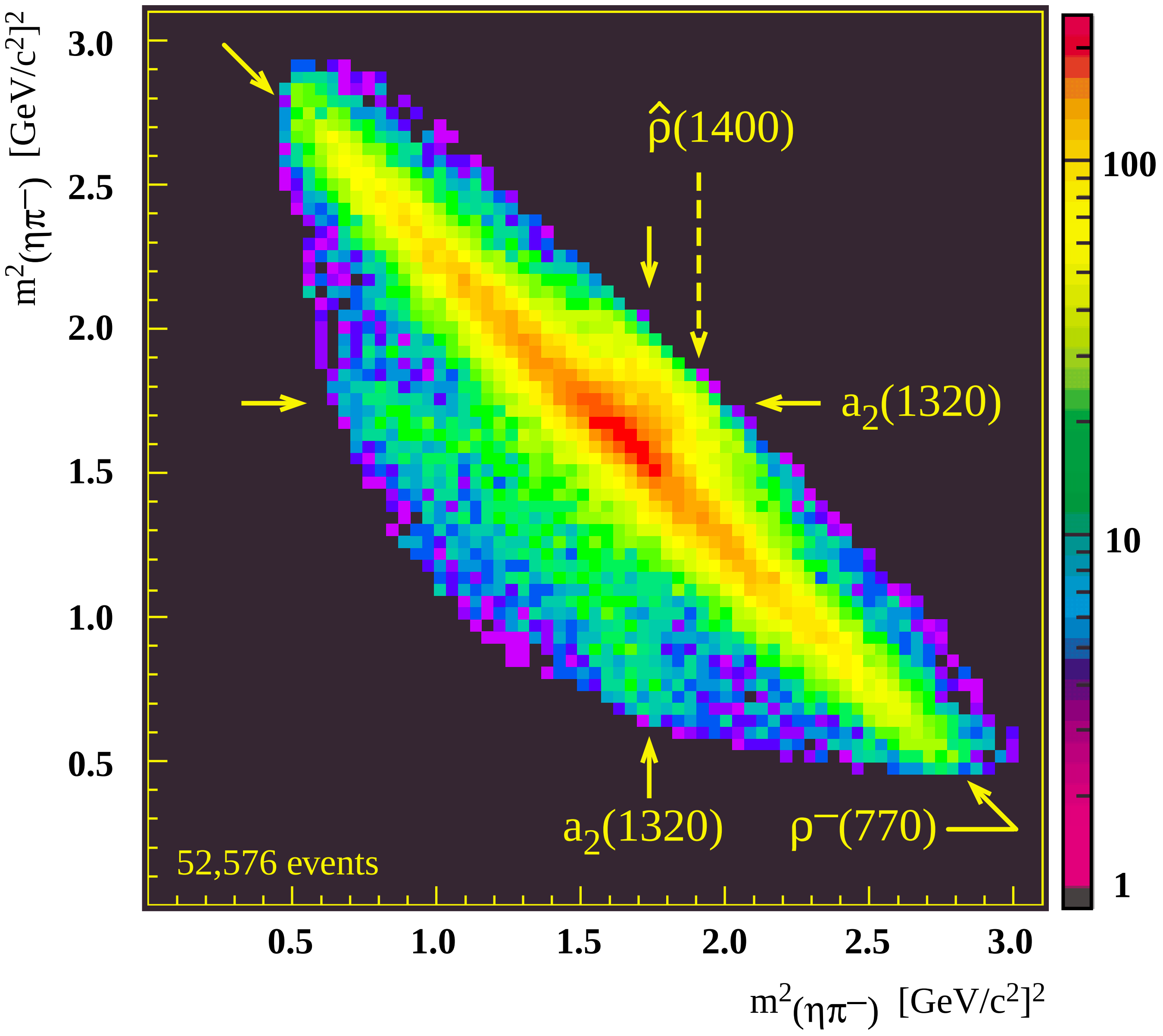
$$\bar{p}d \rightarrow \pi^-\pi^\circ\eta + p$$

spectator
(<100 MeV/c)



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

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

Mass: 1400 ± 30 MeV

Width: 310 ± 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:

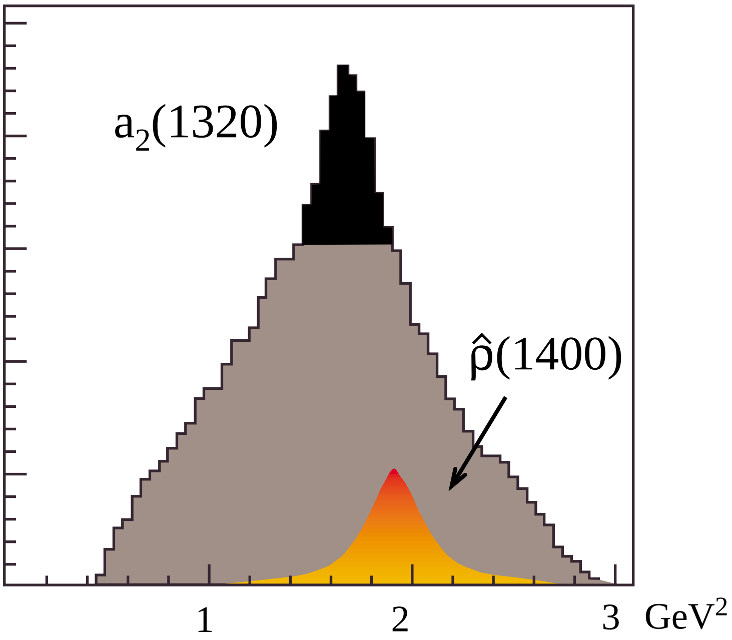
$\pi^- p \rightarrow (\pi^\circ\eta)n$ (GAMS/CERN, 100 GeV/c, 1988)

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

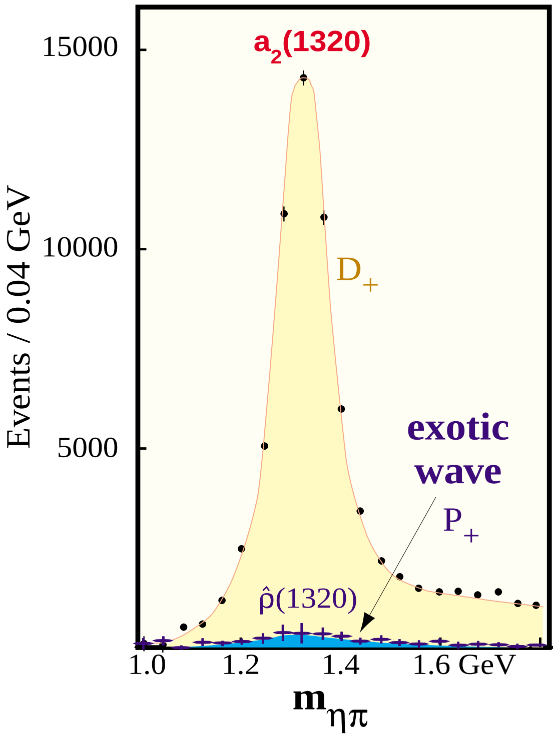
$\pi^- p \rightarrow (\pi^\circ\eta)n$ (E852/Brookhaven, 18 GeV/c, 1997)

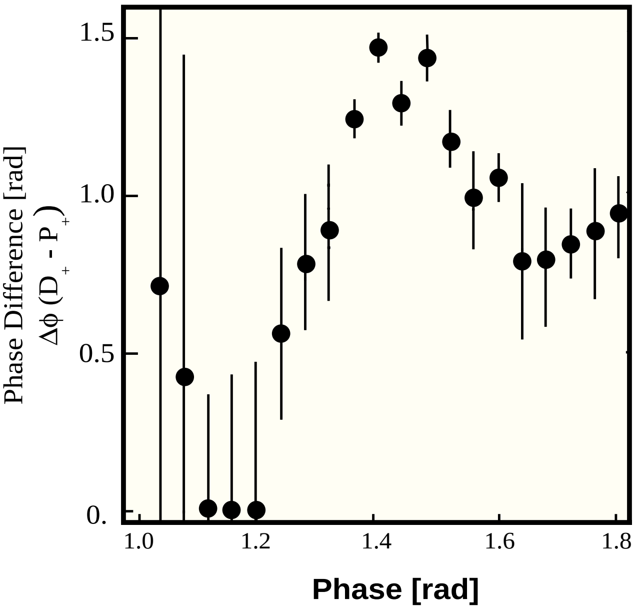
M: 1300 – 1400 MeV, G: 150 – 400 MeV

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



vs. production in 18 GeV/c π^- 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

A second exotic particle ($J^{PC}=1^{-+}$)

Crystal Barrel:

$\bar{p}p \longrightarrow \pi^+\pi^-\eta'$

$\pi_1(1600)$: $M = 1563 \pm 30$ MeV/c^2
$\Gamma = 195 \pm 50$ MeV/c^2

preliminary, LEAP2000 conference

BNL (E852):

$\pi^-p \longrightarrow \rho\pi^-p$

$\pi_1(1600)$: $M = 1593 \pm 8$ MeV/c^2
$\Gamma = 168 \pm 20$ MeV/c^2

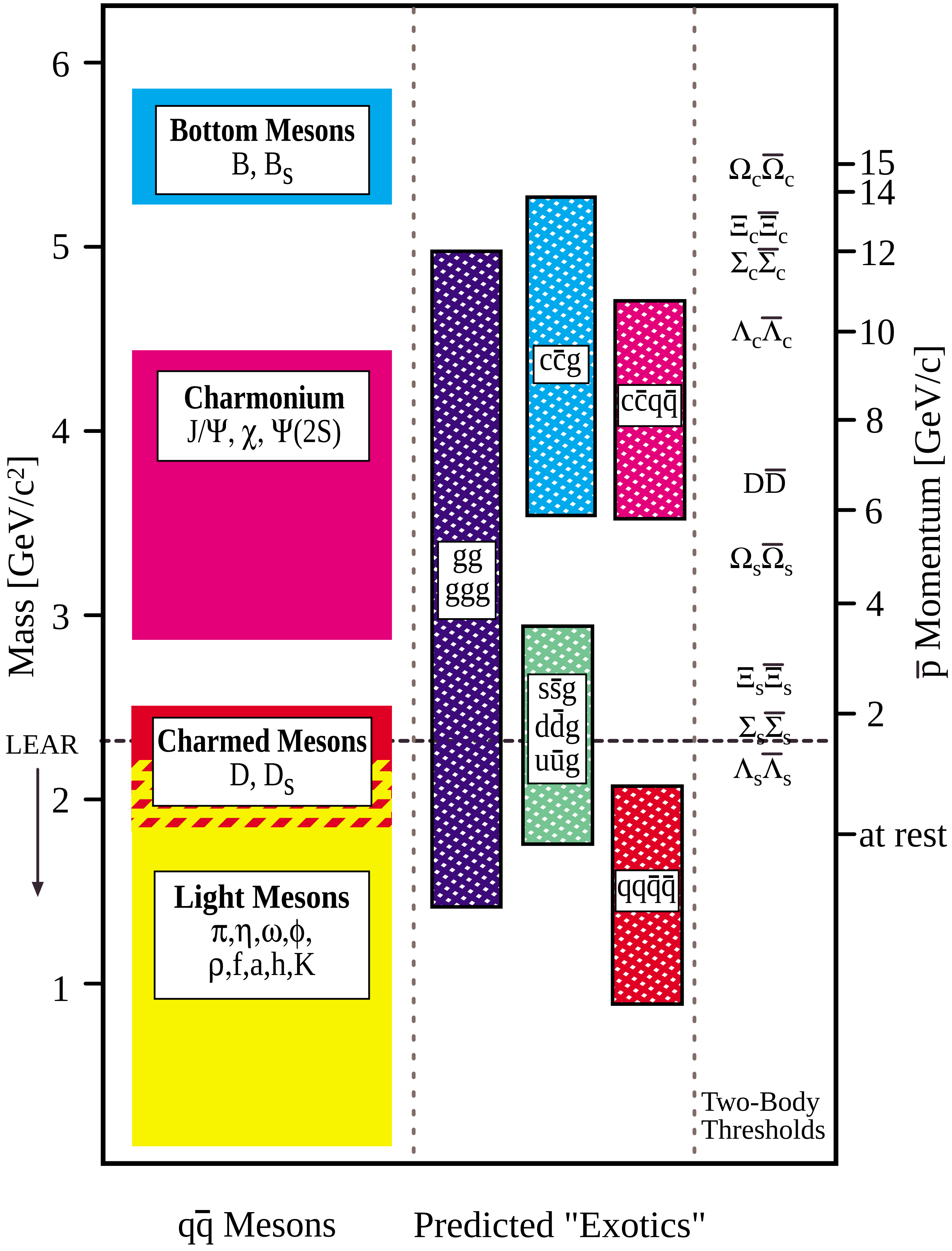
Phys. Rev. Lett. 81 (1998) 5760

Fit of Dalitz plot

preliminary, Joerg Reinhardt, Bonn

ρ	$(\pi\pi)_\mathrm{S}$	$\mathrm{a}_2(1320)$	$\mathrm{a}_0(1450)$	π_1 $(1585{,}160)$	$\ln L$
22.72	77.28	-	-	-	164.2
18.68	80.78	0.53	-	-	158.31
33.75	40.35	0.01	25.9	-	134.1
24.26	64.0	1.23	2.39	8.04	126.63
22.72	77.28	-	-	-	164.2
18.68	80.78	0.53	-	-	158.31
27.15	64.7	1.33	-	6.82	127.83
24.26	64.0	1.23	2.39	8.04	126.63
				$(1567.7{,}158.2)$	
26.93	64.5	1.28	-	7.08	127.28
				$(1563{,}195.0)$	
23.64	61.3	1.24	3.76	10.1	125.86

Mesons and Exotics



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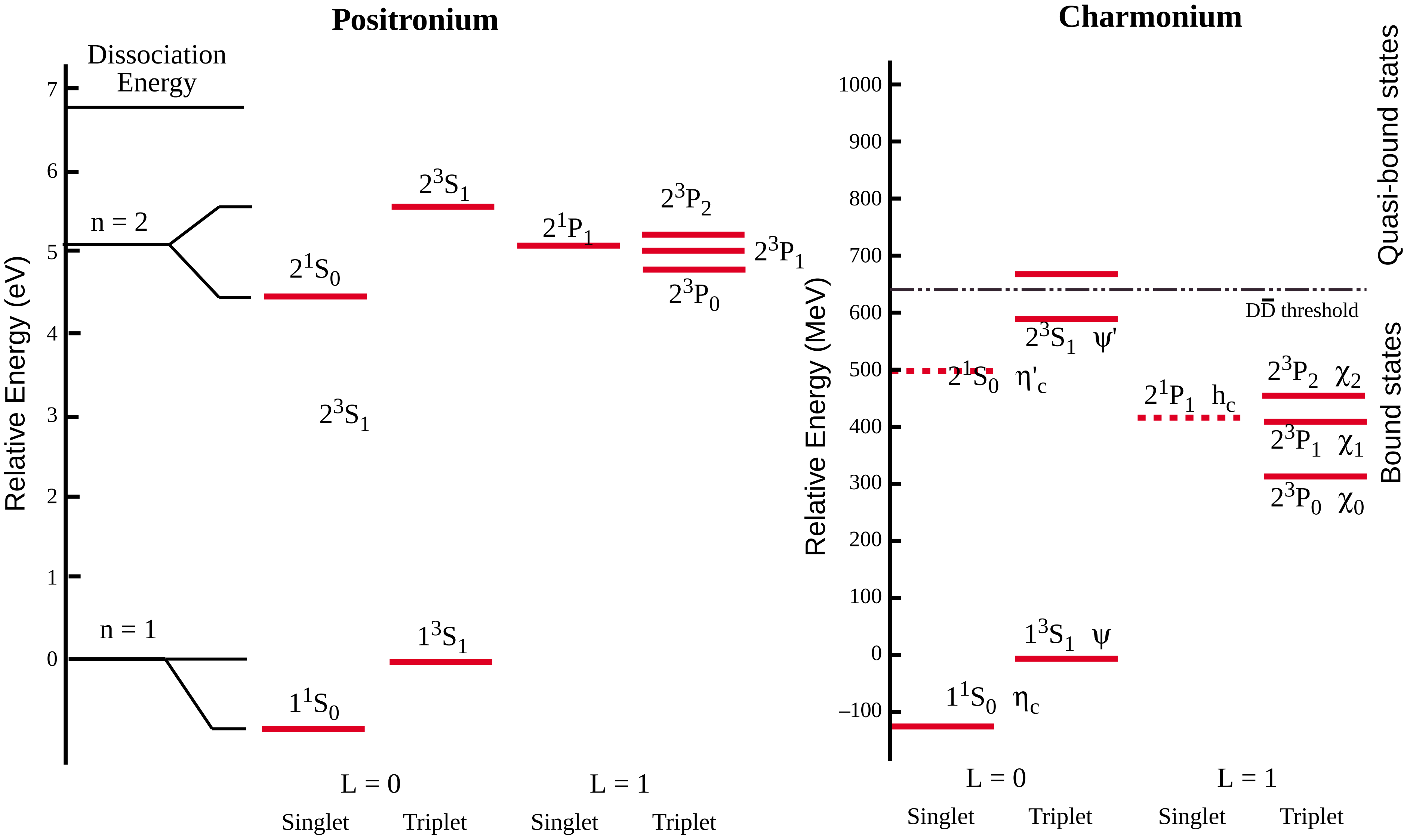

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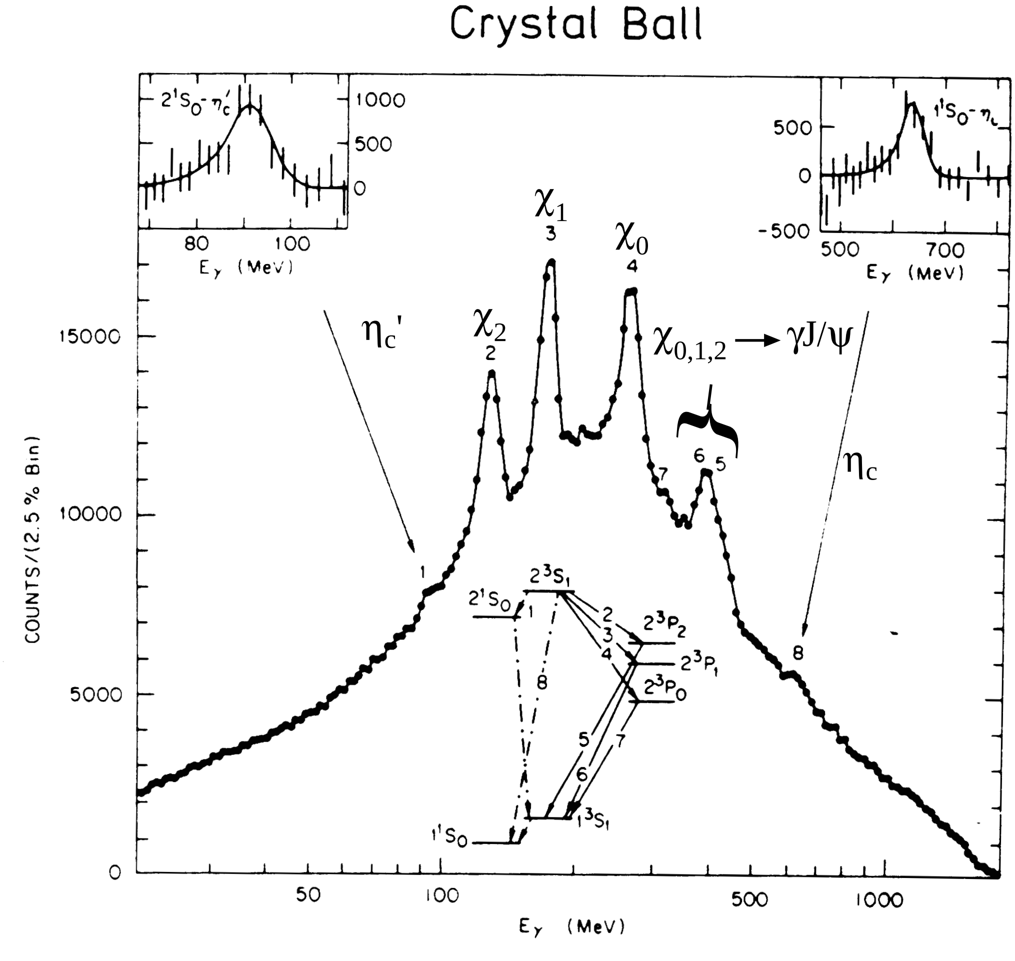
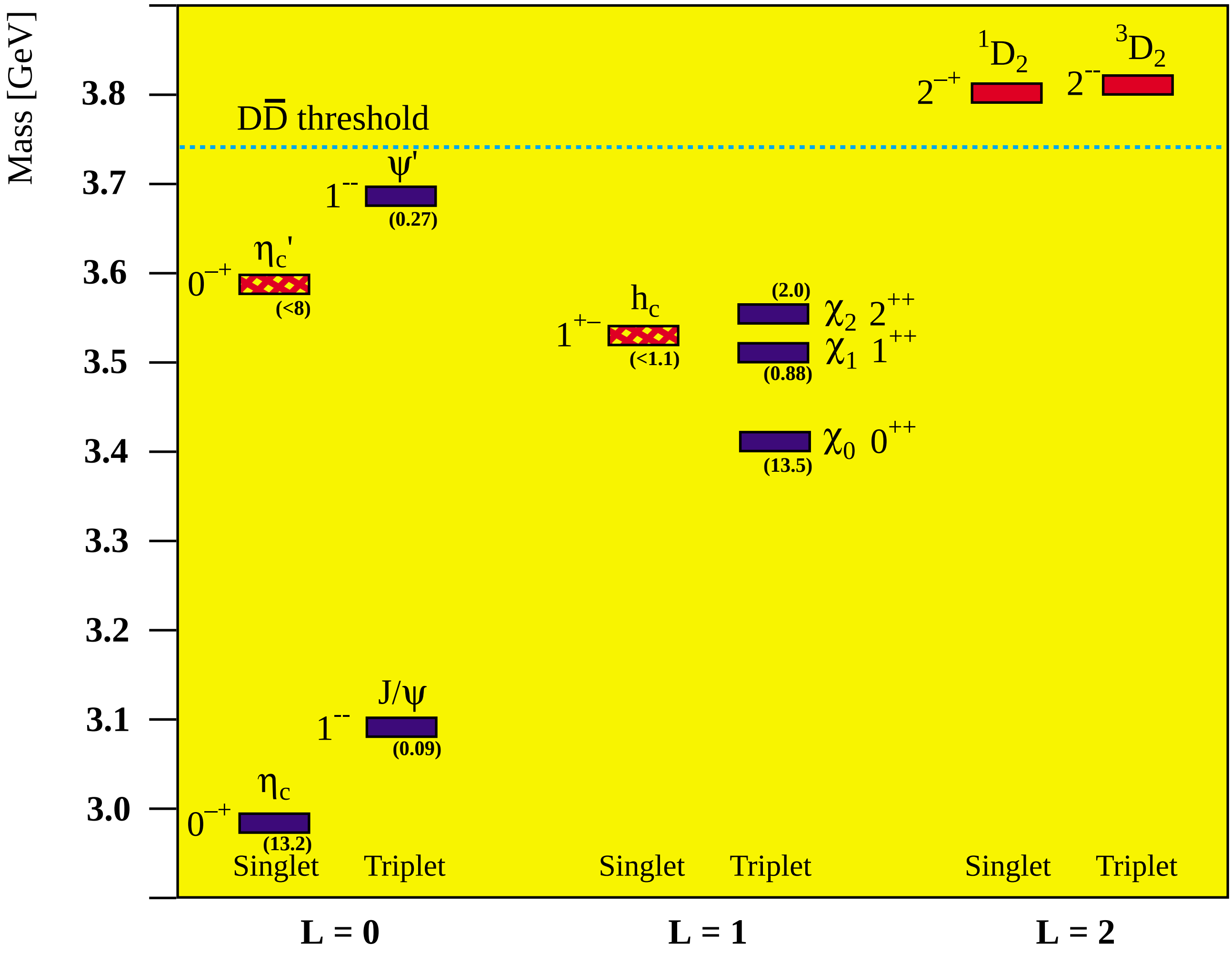
Charmonium Spectrum



Charmonium spectrum ...

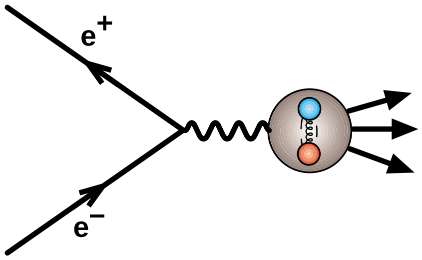


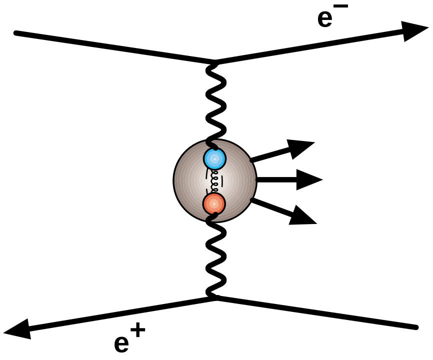
... "clean" and understood.

⇓

Identification of additional states easier than in the light meson sector.

Meson production: e^+e^- vs. $\bar{p}p$

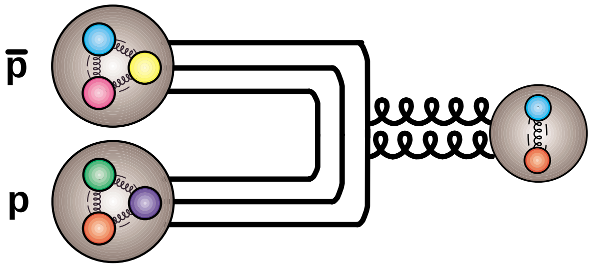


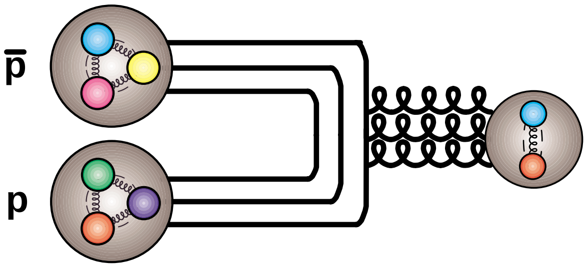


$J^{PC} = 1^{--}$

$J = 0, 2$
$C = +$

2-γ experiments difficult, since it is mostly
1-γ annihilation ⟶ restricted q.n. (1^{--}).





$J = 0, 2, \ldots$
$C = +$

$J = 1$
$C = -$

All quantum numbers possible
⟶ all mesons can be produced directly.

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Production:

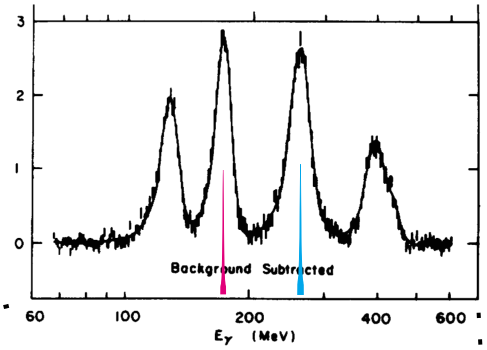
$e^+e^- \to \psi'$

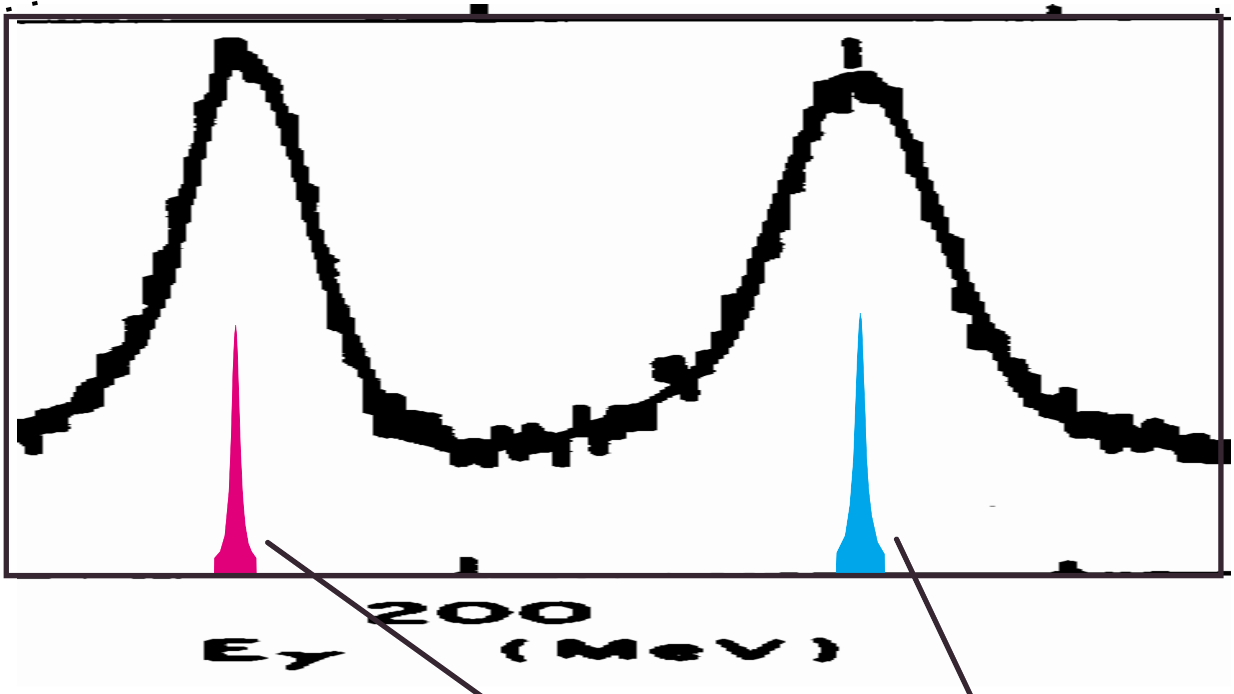
↳ $\gamma\,\chi_{1,2}$

↳ $\gamma\,\gamma\,J/\psi$

↳ $\gamma\,\gamma\,e^+e^-$

Crystal Ball





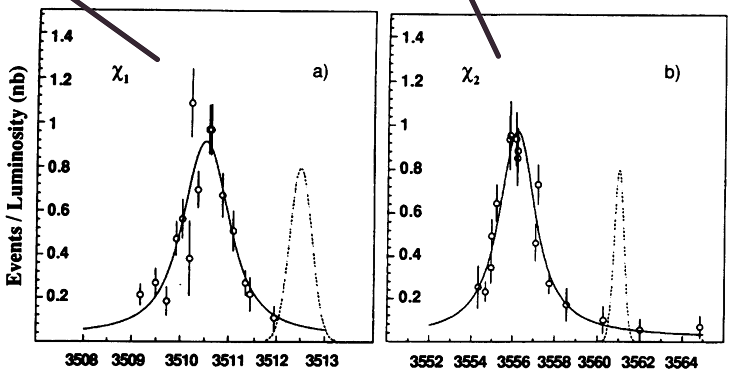
E 760 (Fermilab)

Formation:

$\bar{p}p \to \chi_{1,2}$

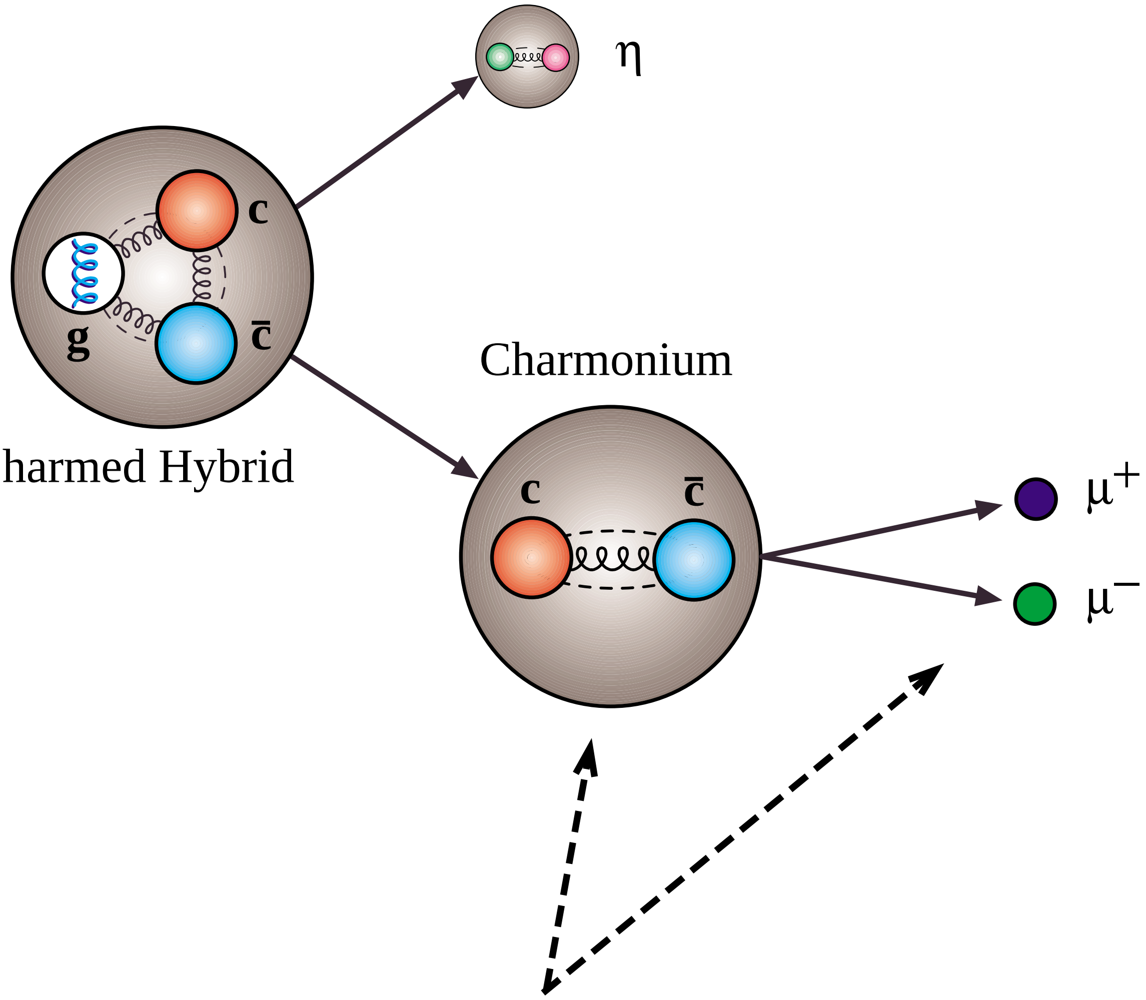
↳ $\gamma\,J/\psi$

↳ $\gamma\,e^+e^-$



σ_m (beam) = 0.5 MeV

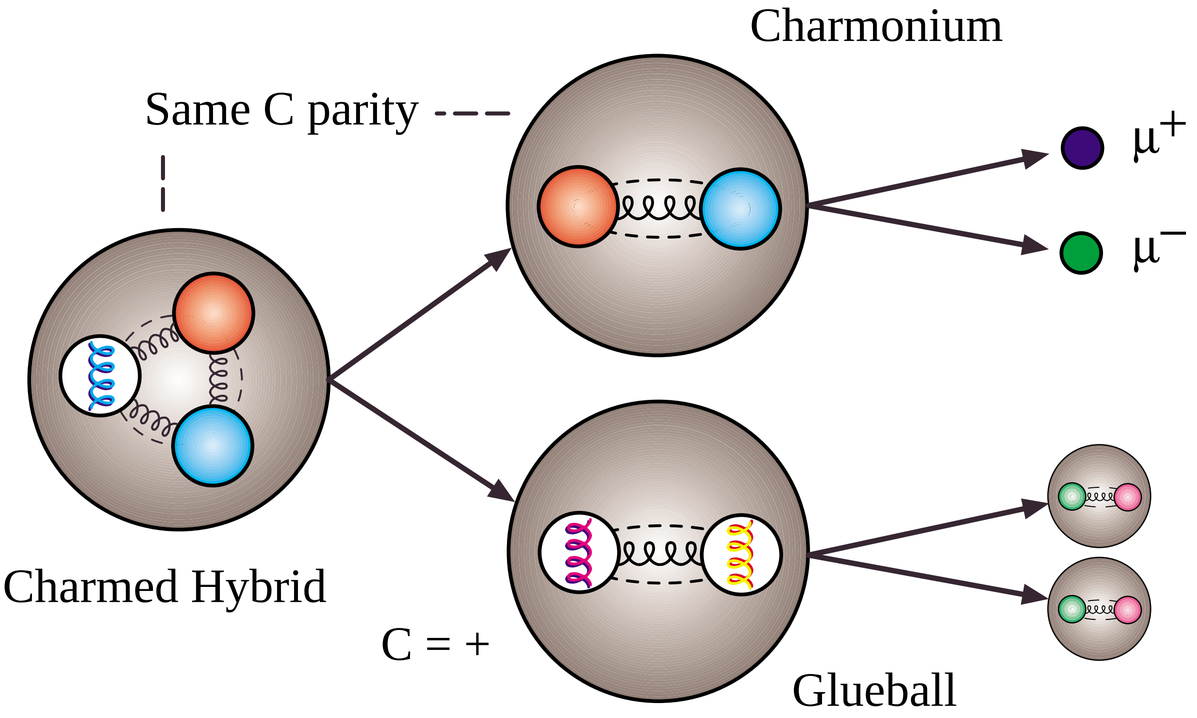
Decay of charmed hybrids



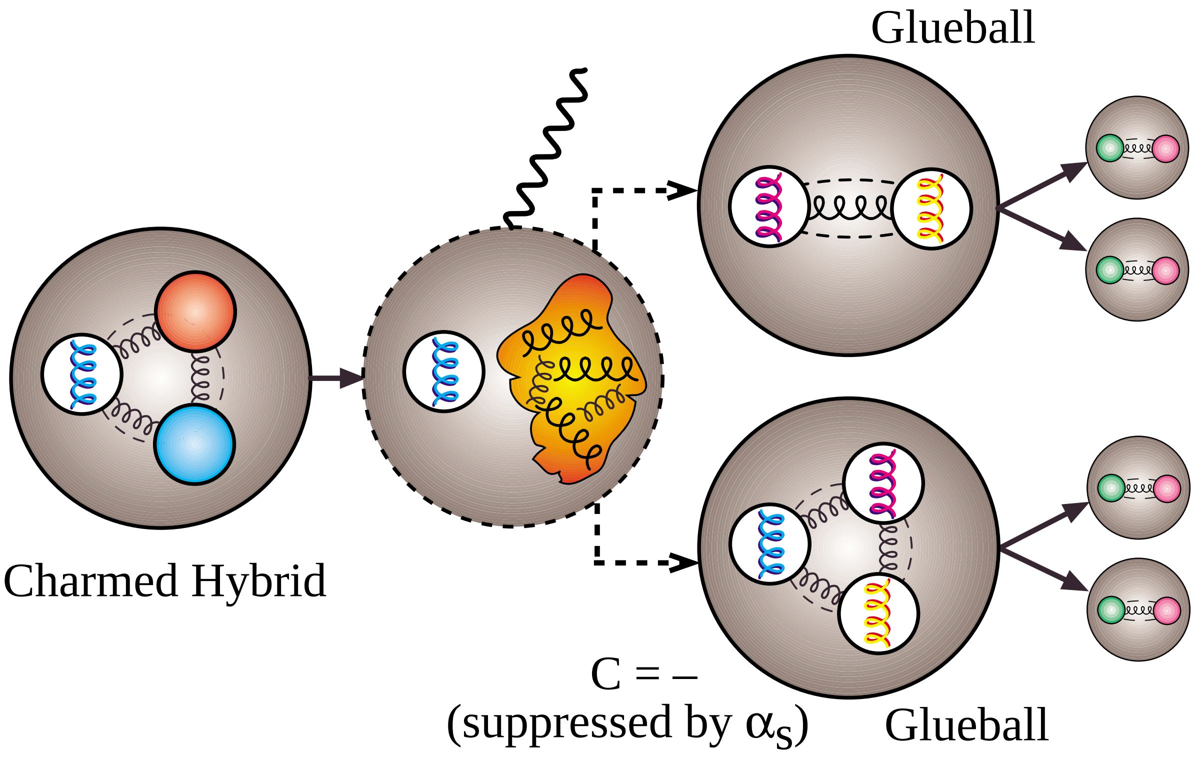
Decay of charm into leptons provides a clean "tag".

Ulrich Wiedner

Glueball Production in $c\bar{c}g$ Decays



Cascade decay



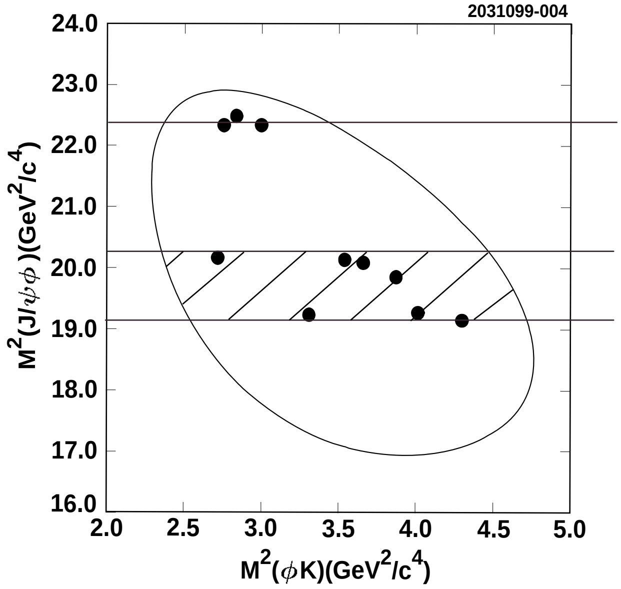
Decay by annihilation

Ulrich Wiedner

New Results from CLEO

$B \longrightarrow J/\psi\phi K$

Phys. Rev. Lett. 84, 1393 (2000)



4.7 GeV/c^2

4.5 GeV/c^2

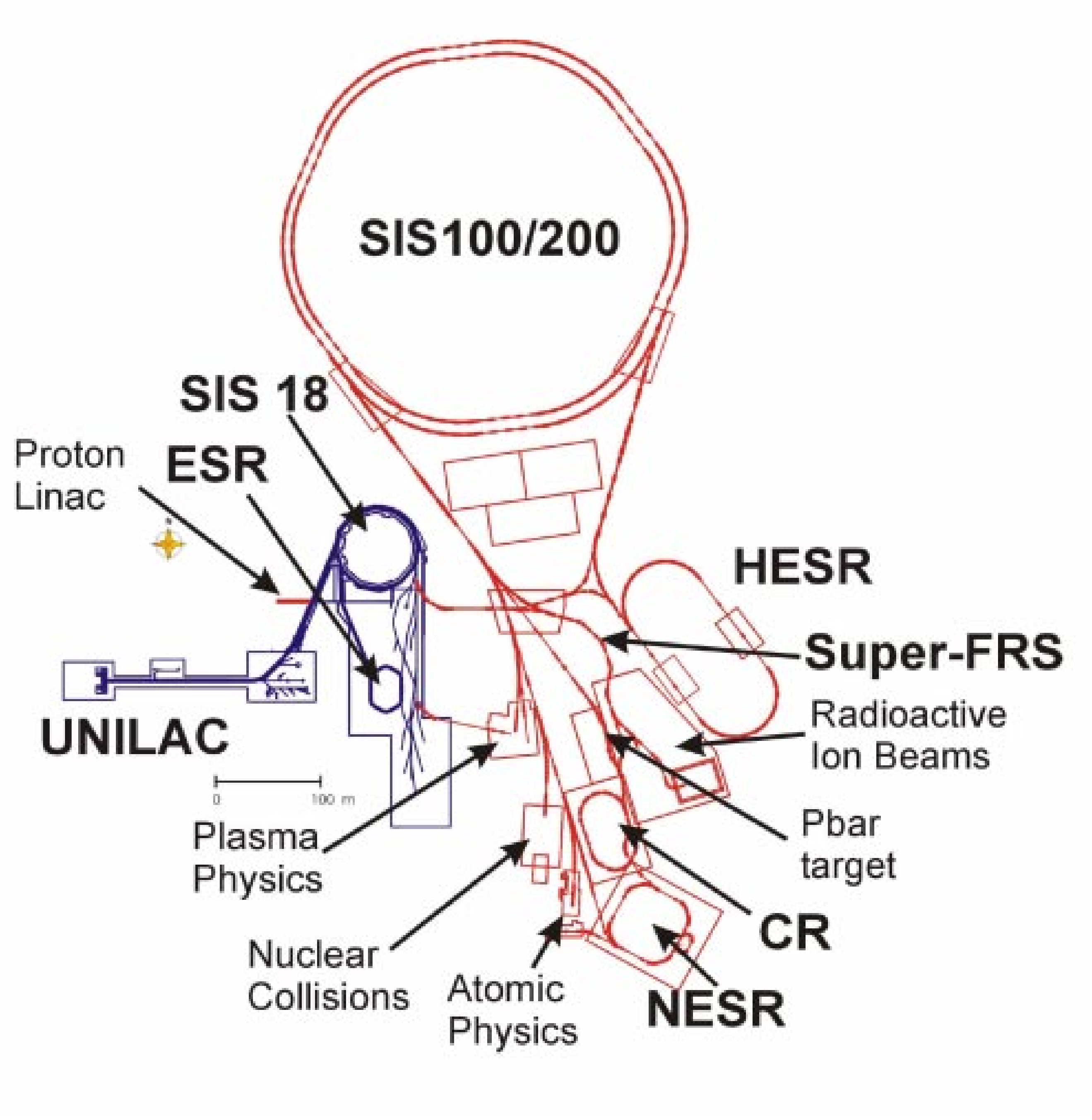
4.35 GeV/c^2

FIG. 4. Dalitz plot for the 10 $B \to J/\psi\,\phi K$ candidates in data. The kinematic boundary is represented by solid line.

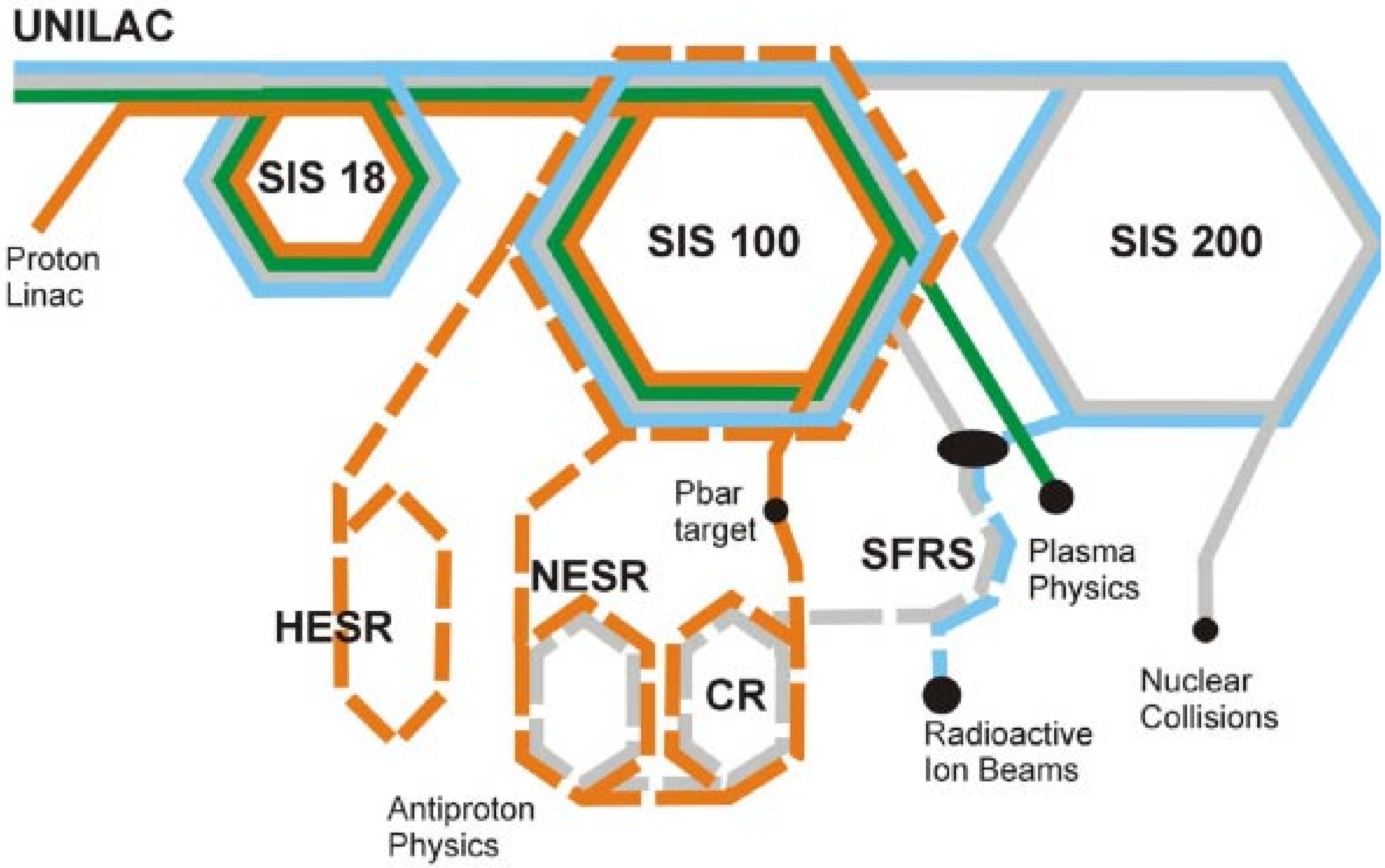
Indications for a J/ψϕ resonances?

BABAR can expect ~300 events within 5 years.

The new GSI Accelerator Complex



Parallel Operation of Beams



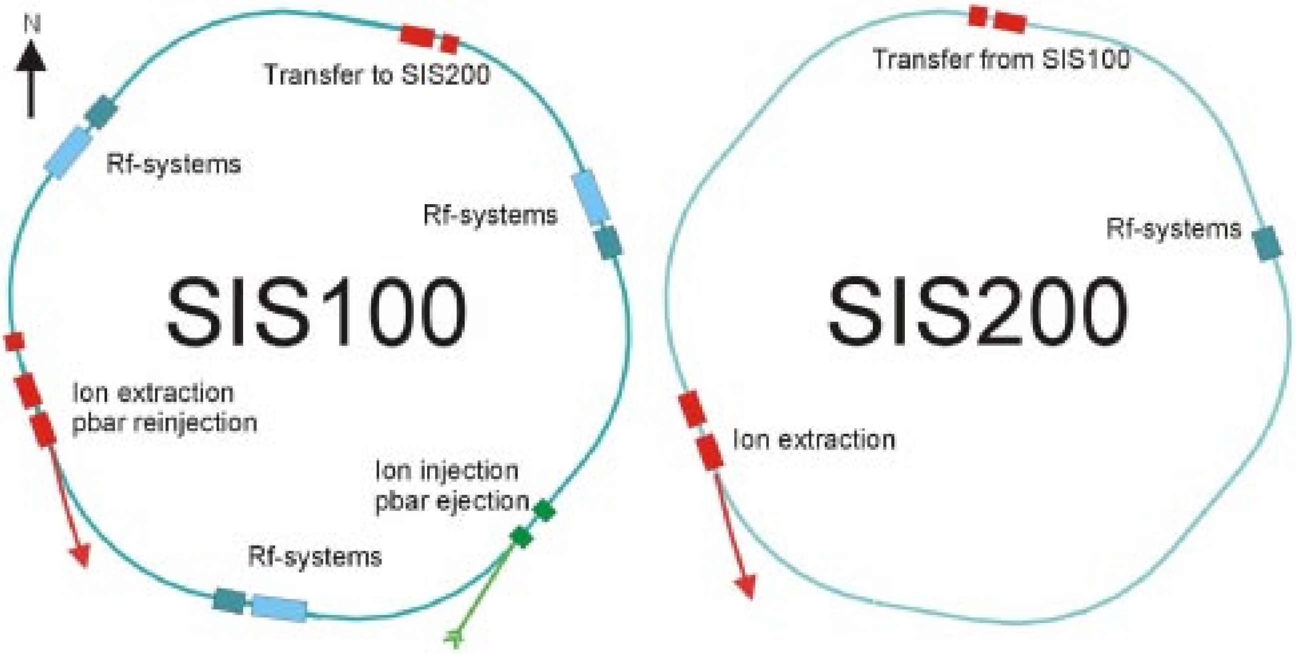
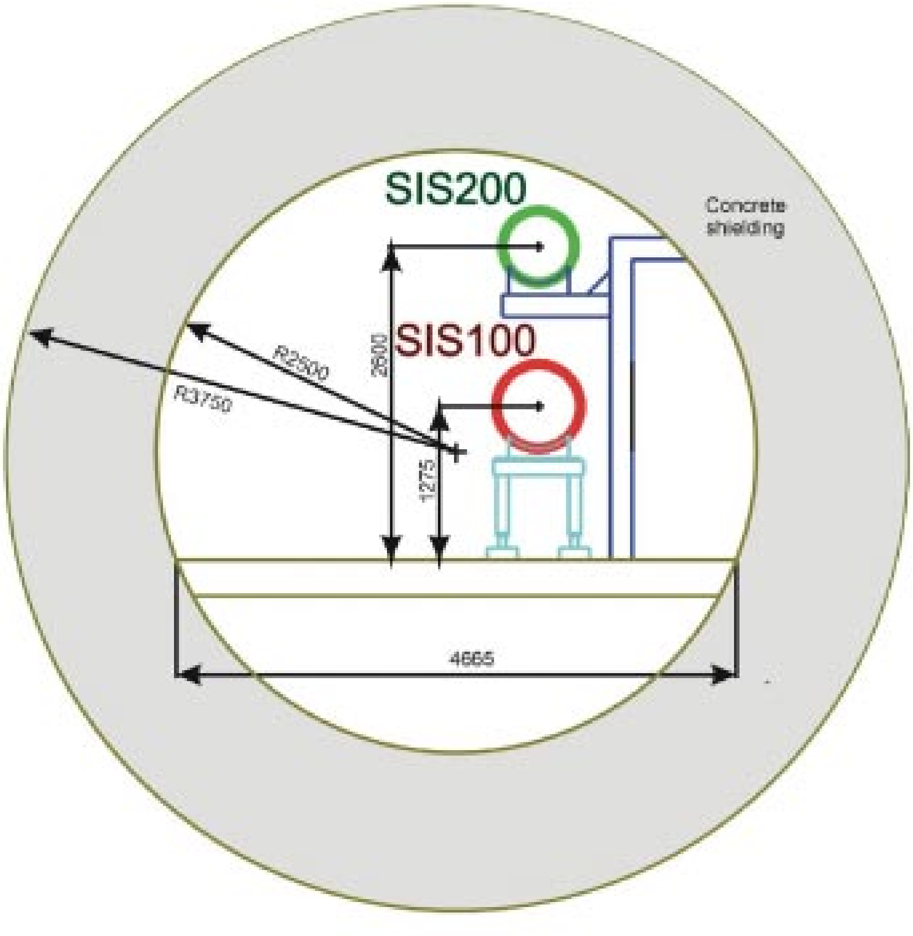
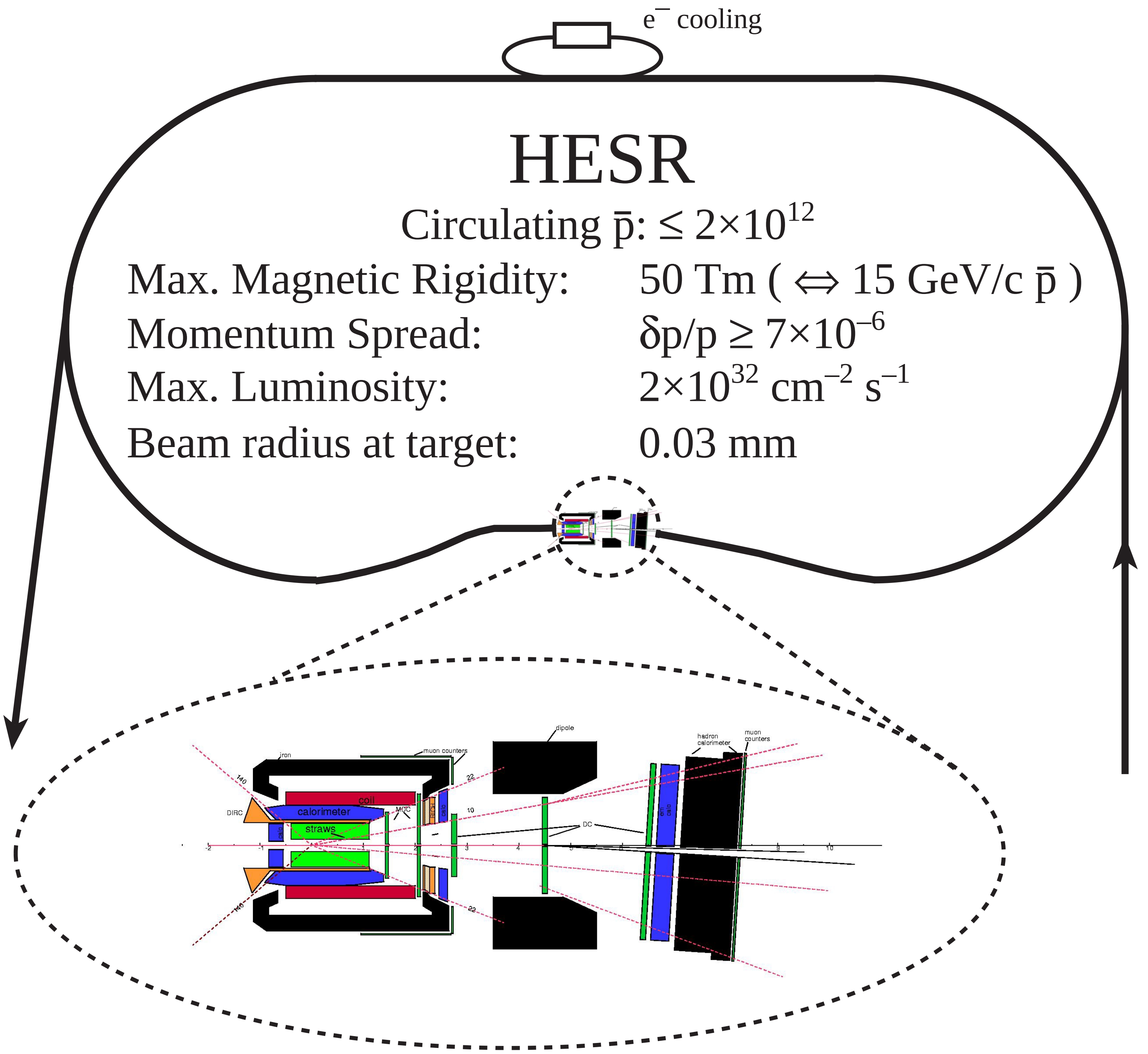


Figure 3.4.1: Schematic layout of the two-ring synchrotron facility. Both rings have a circumference of 1083.60 m with six straight sections.



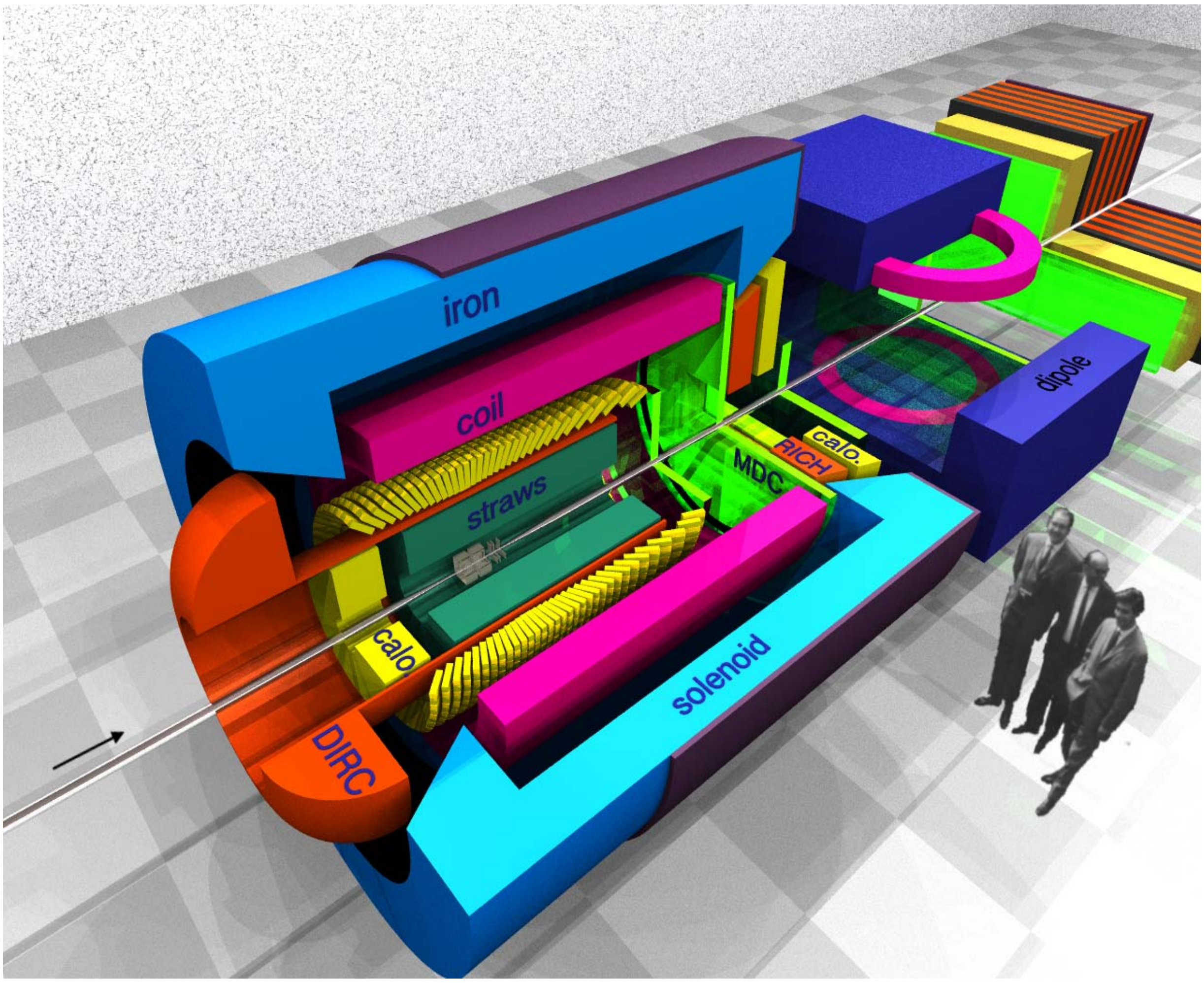


HESR

Circulating $\bar{p}$: $\leq 2\times10^{12}$

Max. Magnetic Rigidity:	50 Tm ($\Leftrightarrow$ 15 GeV/c $\bar{p}$)
Momentum Spread:	$\delta p/p \geq 7\times10^{-6}$
Max. Luminosity:	2×10^{32} cm^{-2} s^{-1}
Beam radius at target:	0.03 mm

Universal Detector

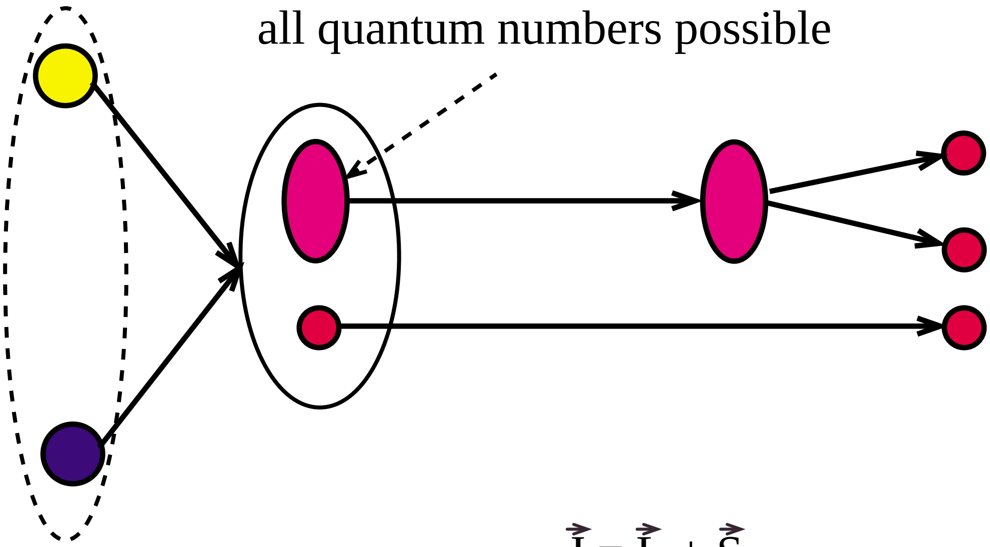


Detector features:

tracking of charged particles
measurement and identification of γ, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$
high rate capability
sophisticated and fast trigger scheme

How to make resonances?

Produktion experiments:



all quantum numbers possible

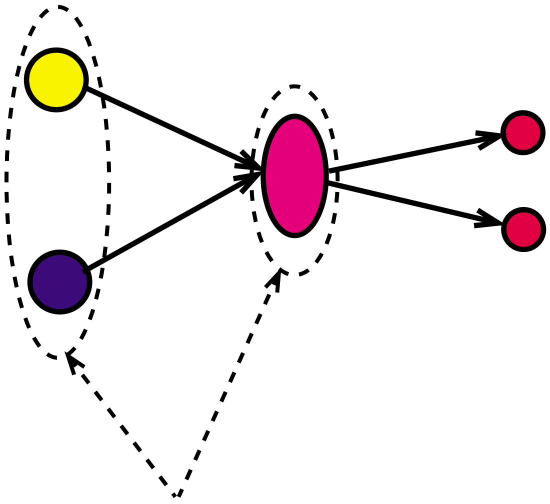
J^{PC} ‑ ‑ ‑ ‑ ‑ → Fermion-Antifermion

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

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

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

Formation experiments:



identical quantum numbers

Production vs. Formation

Production experiments can produce exotic J^{PC}.

Formation experiments cannot produce exotic J^{PC}.

Signal in production but no signal in formation

very interesting

A detector should be suited for both:

production and formation

The HESR is not only **a unique facility**, it is the **only one** that allows to study:

Glueballs, Hybrids, Hadrons

Hybrids in e^+e^-:

Lattice:

WEAK direct production even of 1^{--} states, since wavefunction at the origin is small.

C. Michael, Nucl. Physt. A655, 12c (1999)

B-decays lack statistics.

Central production in pp collisions:

Difficult to see even normal charmonium states.

Charmonium Production in $\bar{p}p$

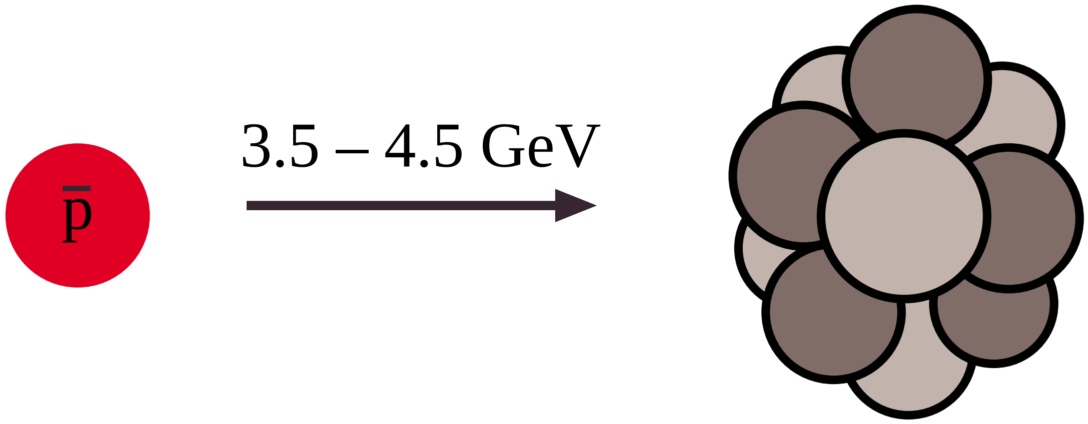
$c\bar{c}$	J^{PC}	M [MeV]	Γ_{tot} [MeV]	Decay mode	$\sigma(M)$* [pb]	Events/ day**
η_c	0^{-+}	2980	13.2	$\gamma\gamma$	550	4400
η_c	0^{-+}	2980	13.2	$\phi\phi$	3100	24800
η_c' ???	0^{-+}	3594		$\gamma\gamma$	120	960
J/ψ	1^{--}	3097	0.087	$e^+e^-/\mu^+\mu^-$	630000	5040000
ψ'	1^{--}	3686	0.277	$e^+e^-/\mu^+\mu^-$	4480	35840
ψ'	1^{--}	3686	0.277	$J/\psi\ X$	17600	140800
χ_{c0}	0^{++}	3415	14	$\gamma\gamma$	30	240
χ_{c0}	0^{++}	3415	14	$\gamma\ J/\psi$	52	416
χ_{c1}	1^{++}	3511	0.88	$\gamma\ J/\psi$	3600	28800
χ_{c2}	2^{++}	3556	2.0	$\gamma\ J/\psi$	3700	29600
χ_{c2}	2^{++}	3556	2.0	$\gamma\gamma$	220	1760
$c\bar{c}g$	1^{--}	(4100)	(0.2)	($J/\psi\eta$***)	(120)	(960)
$c\bar{c}g$	1^{-+}	(4000)	???	($J/\psi\ \omega,\phi,\gamma$)	(9)	(75)

* For selected decay mode

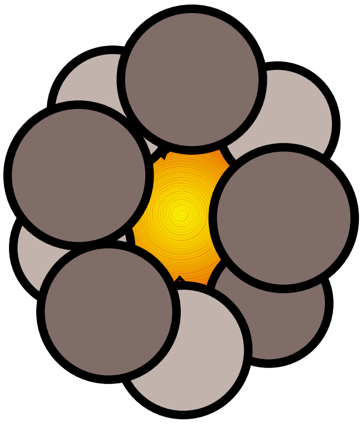
** $L = 2\times10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, 50 % detection and accelerator efficency
Integrated luminosity = 4 pb^{-1}/ day

*** 1% B.R. for this decay mode

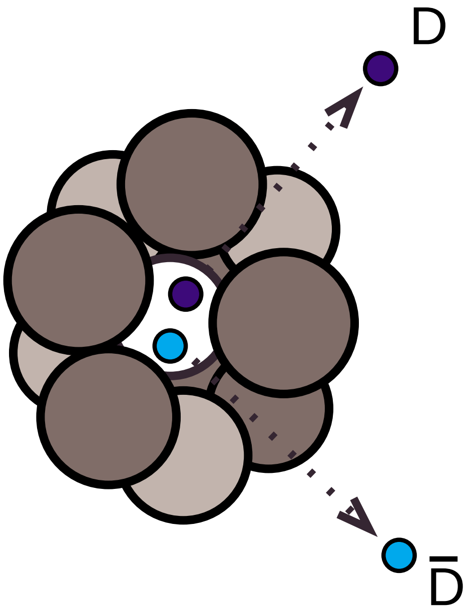
$\bar{p}$ – Nucleus Interaction



3.5 – 4.5 GeV



$\bar{p}A \rightarrow \psi + (A-1)$

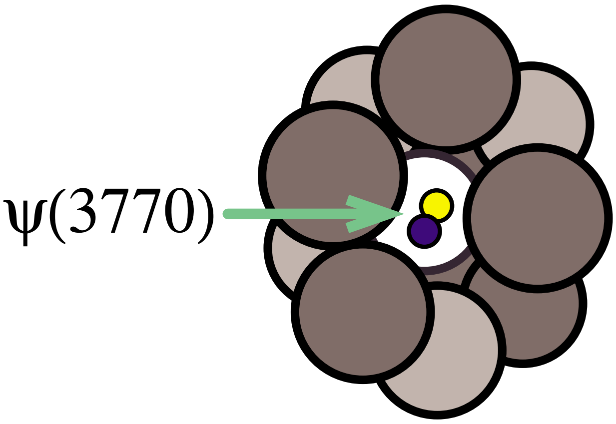


ψ ($c\bar{c}$) decays into $D\bar{D}$

D mesons interact
with rest nucleus

Ulrich Wiedner

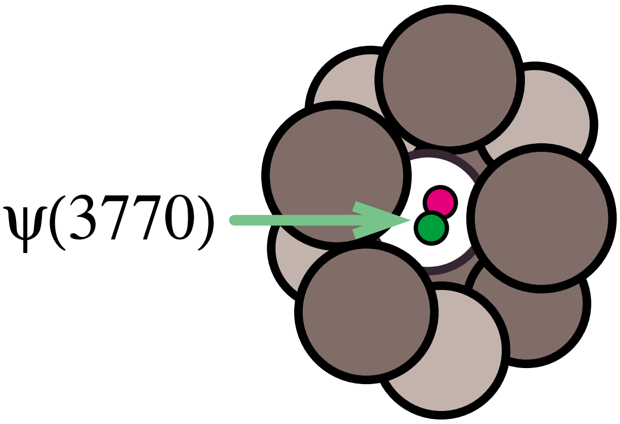
$D^- = d\bar{c}$



quark – nucleus
interaction
=
d (or $\bar{d}$) – nucleus
interaction*

● $D^+ = \bar{d}c$

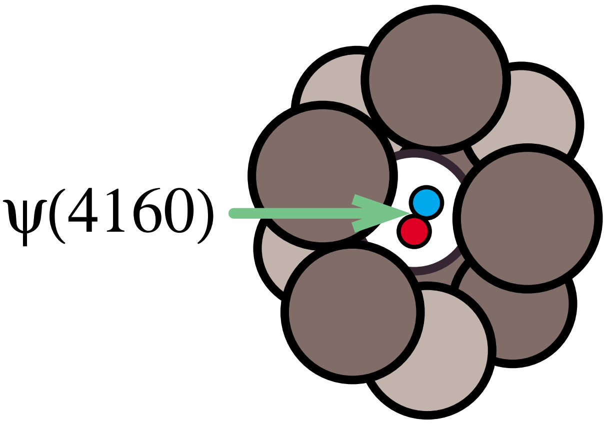
$\bar{D}^0 = u\bar{c}$



quark – nucleus
interaction
=
u (or $\bar{u}$) – nucleus
interaction*

● $D^0 = \bar{u}c$

$D_s^- = s\bar{c}$



quark – nucleus
interaction
=
s (or $\bar{s}$) – nucleus
interaction*

● $D_s^+ = \bar{s}c$

* ignoring c (or $\bar{c}$) – nucleus interaction

Ulrich Wiedner

Measurements:

- rate at different nuclear targets
- angular distributions
- comparison to hydrogen

$D_s^{\pm}$ can be distinguished from $D^{\pm}$ by their distinct decay into ϕ + anything (18 %).

Experimental techniques:

- wire targets (like in HERAb)
- pellet targets (like in WASA-CELSIUS)
- D – triggers

Topics not mentioned

Baryon Pair Production:

charmed: study threshold production for understanding of c production mechanism

strange: ΩΩ produced via triple kaon exchange?
comparison of production rates: ΩΩ vs. ϕϕϕ

CP Violation

Charm Physics in Nuclei:

J/Ψ - N cross section: color transparency?

exotic states of nuclear matter?

charmonium nucleus bound states?

mass shift of charmonium states in nuclear matter:
(charmonium states are narrow below $D\bar{D}$ threshold!)

Summary

- The first QCD exotics have been found in high statistics and high precision 4π experiments.
- Their production rate is comparable to those of normal mesons in $\bar{p}p$ annihilations.
- Other glueballs and hybrids must exist.
- Studying the charmonium energy range simplifies life (small, well known states).
- E760/E835 has prooven how well suited $\bar{p}p$ is for precision spectroscopy.
- Many issues in normal charmonium spectroscopy are still unsettled.
- Charmed hybrids (< 4.3 GeV) show up as additional small states.

A dedicated accelerator with excellent beam properties designed together with a high statistics, high precision experiment is a world class facility for hadron physics.