50 Years of Antiprotons
An Anniversary Symposium
October 28 - 29, 2005
Berkeley

Annihilation Dynamics:

„where is our iota gone?“

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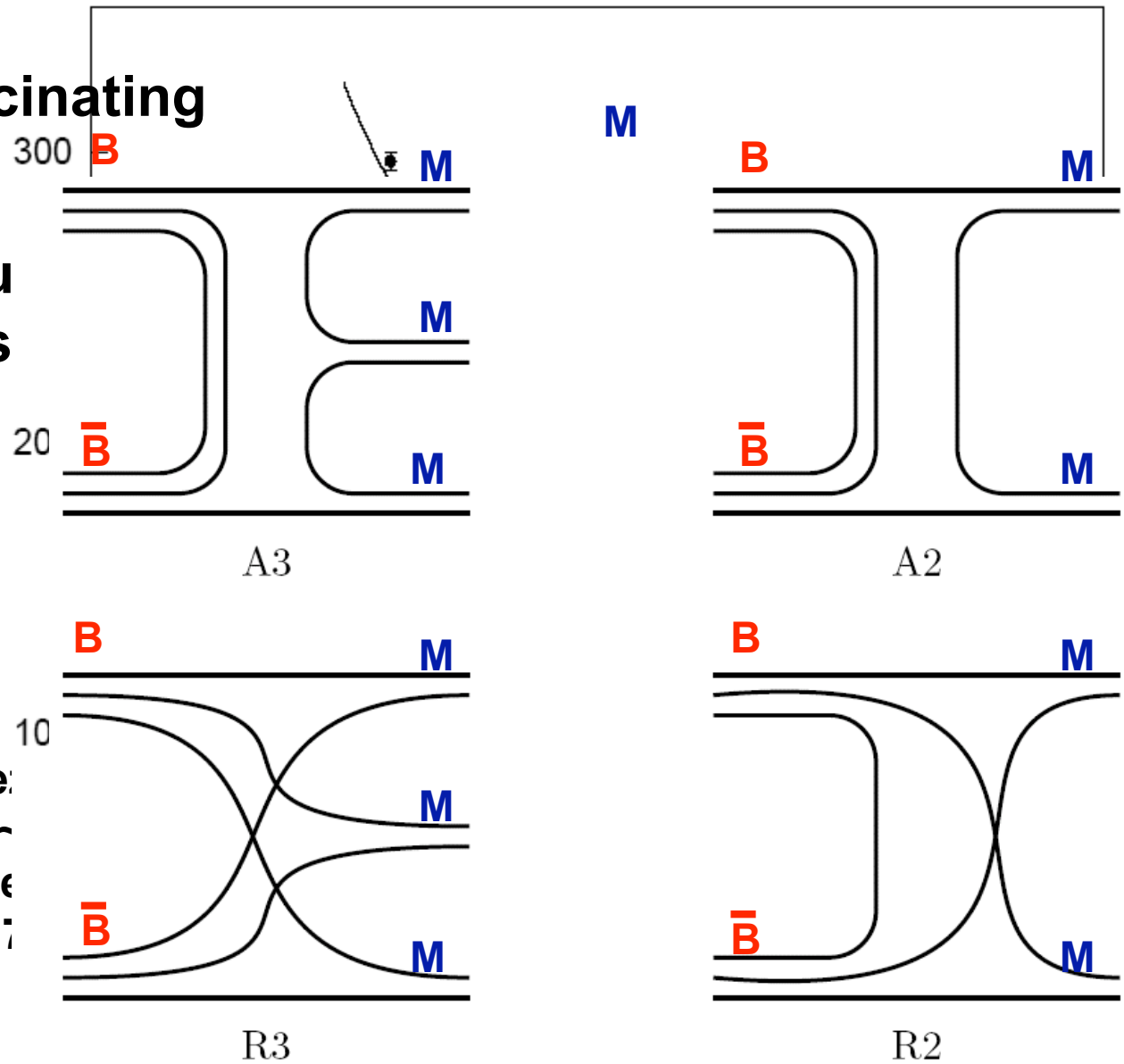
Annihilation cross section is large

Annihihilation is fascinating

Annihilation allows u
study mes



B.~C.~Maglic, L.~W.~Alvare
A.~H.~Rosenfeld and M.~L.~
``Evidence For A T = 0 Three
" Phys. Rev. Lett. 7 (1961) 1

More meson resonances have been discovered in $p\bar{p}$ annihilation since then:

- **At rest:**
- **f_0 (980) BC**
- **f_1(1285) BC**
- **f_0(1370) CBar**
- **K_1(1400) BC**
- **η(1440) BC**
- **a_0(1450) CBar**
- **f_0(1500) CBar**

BC Bubble chamber
CBar Crystal Barrel LEAR

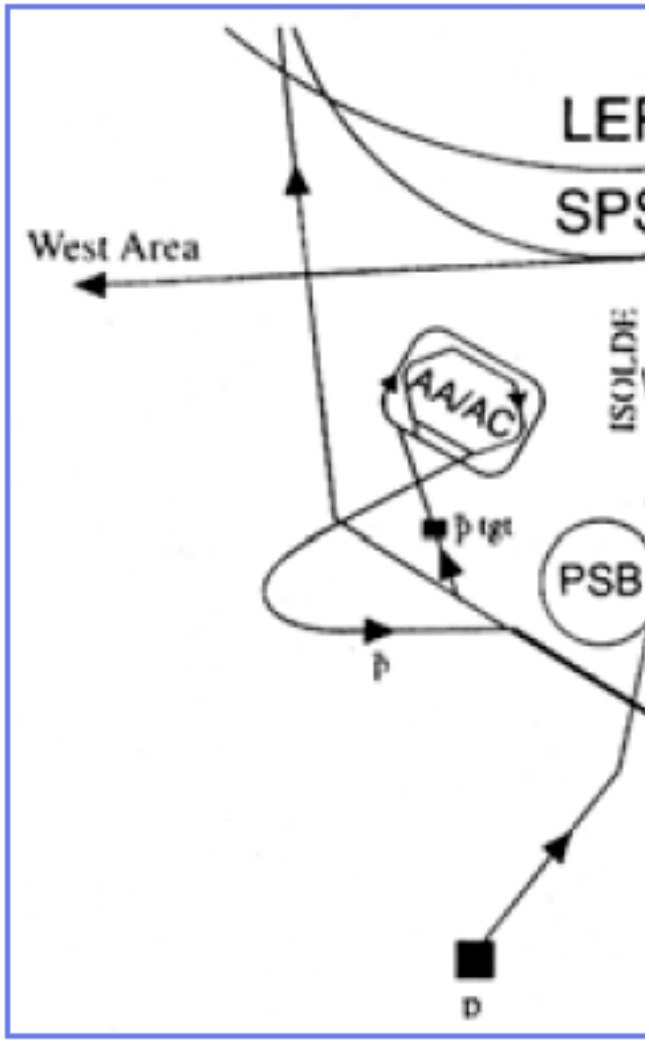
In flight:
ρ_2(1940)
ω_3(1945)
ω(1960)
b_1(1960)
ρ(1965)
h_1(1965)
f_1 (1970)
ω_2(1975)
a_2(1990)
f_2(2000)

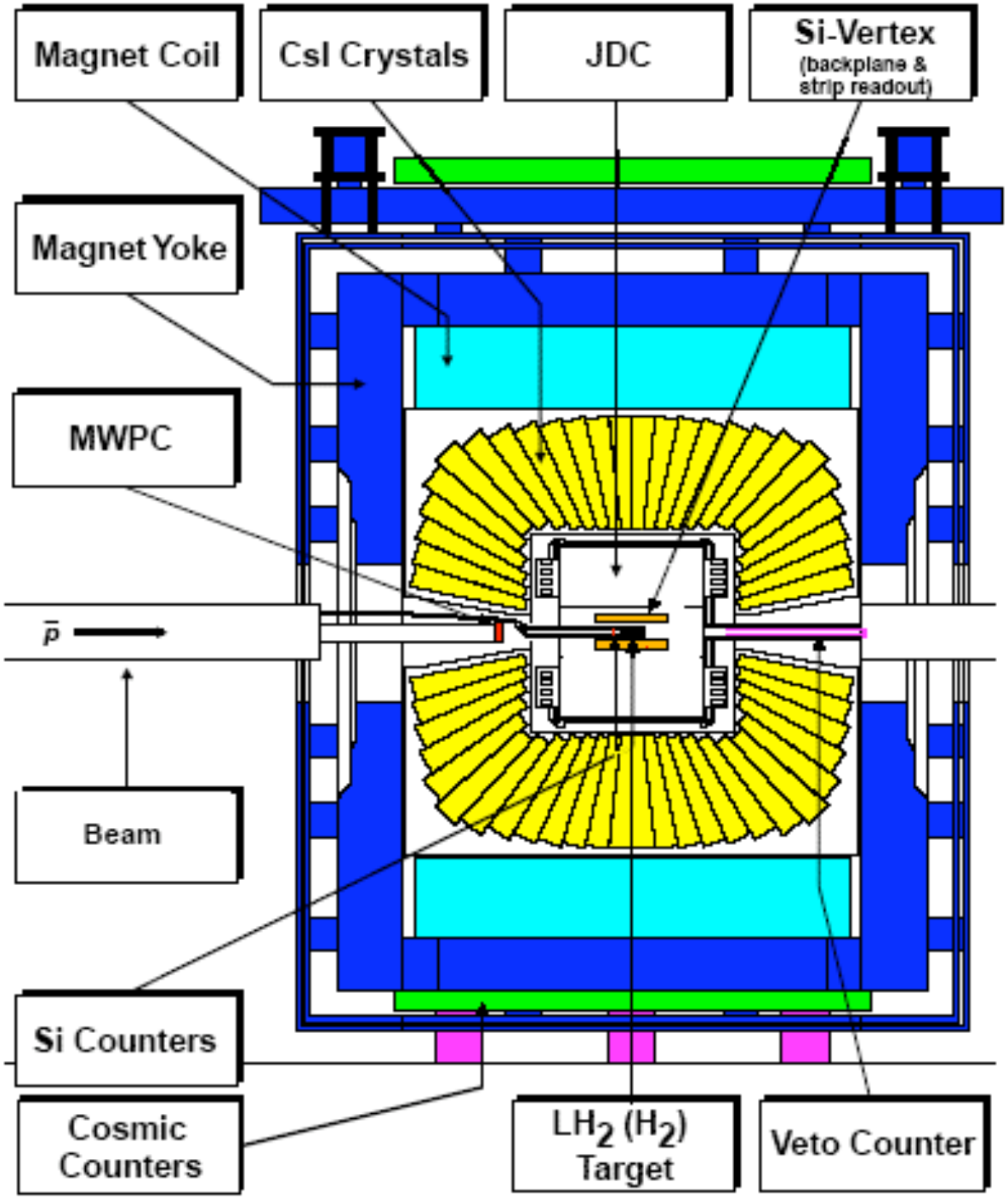
π_2(2005)
η(2010)
a_0(2020)
ρ(1965)
h_3(2025)
b_3 (2025)
η_2(2030)
f_3(2050)
f_0(2060)
π(2070)

a_3(2070)
a_2(2080)
η(2100)
b_1(1960)
ω(2145)
a_2(2175)
η (2190)
ω_2(2195)
ω(2205)
h_1(2215)

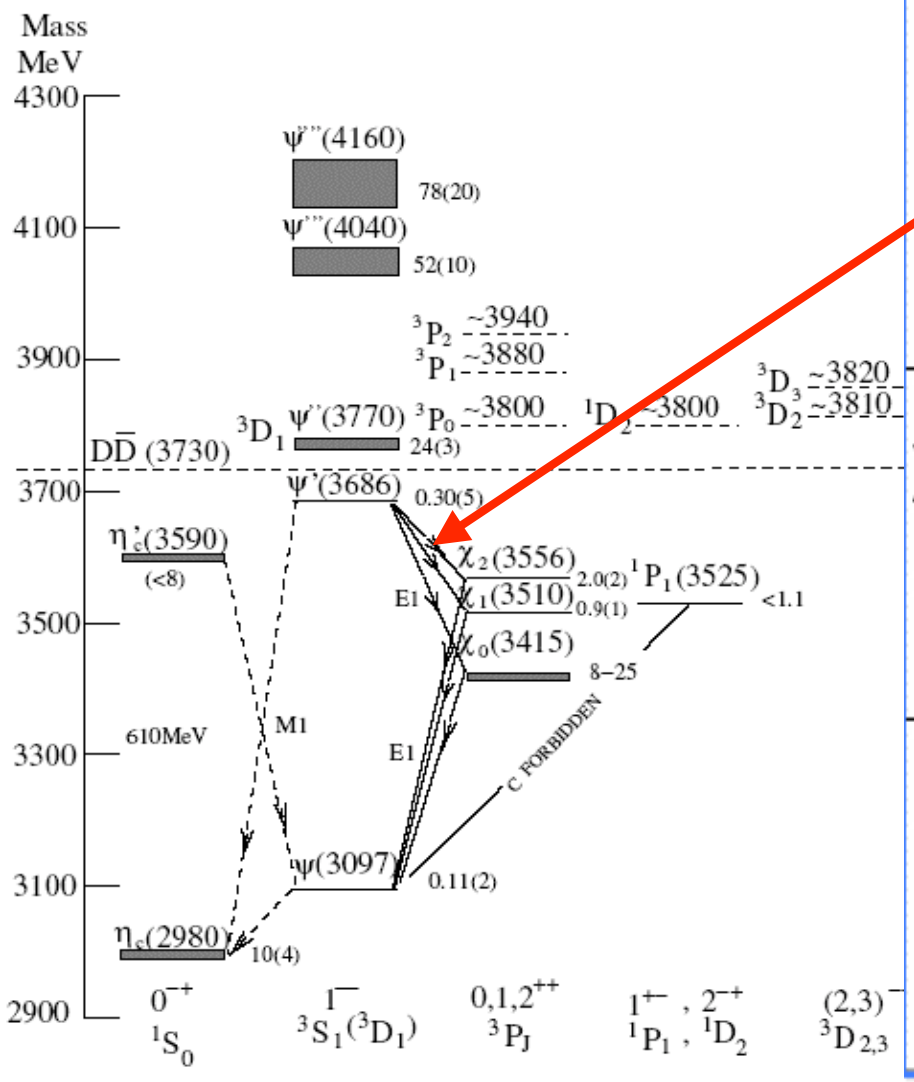
+ 22 more

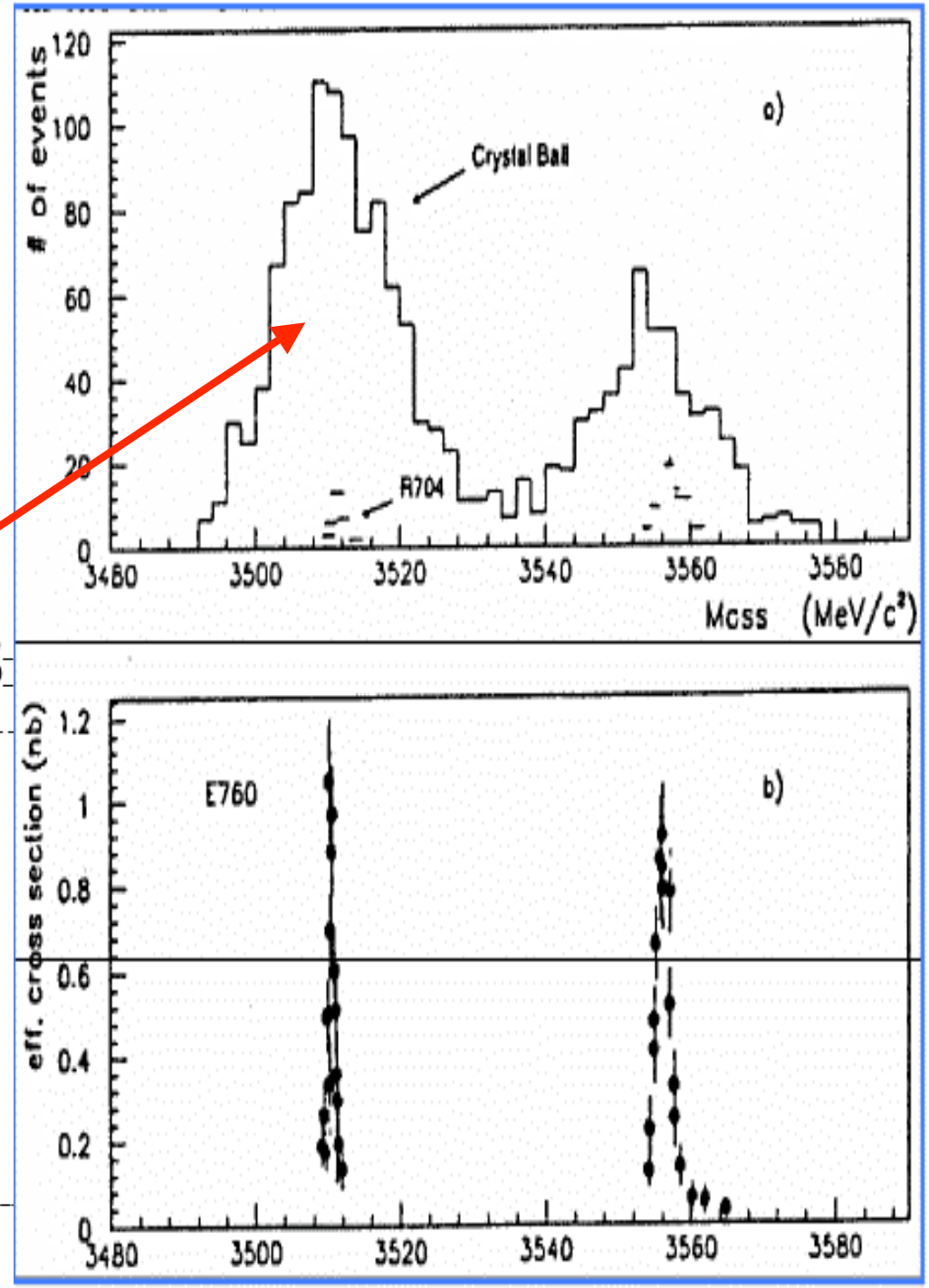
Anisovich et al., Phys Lett.

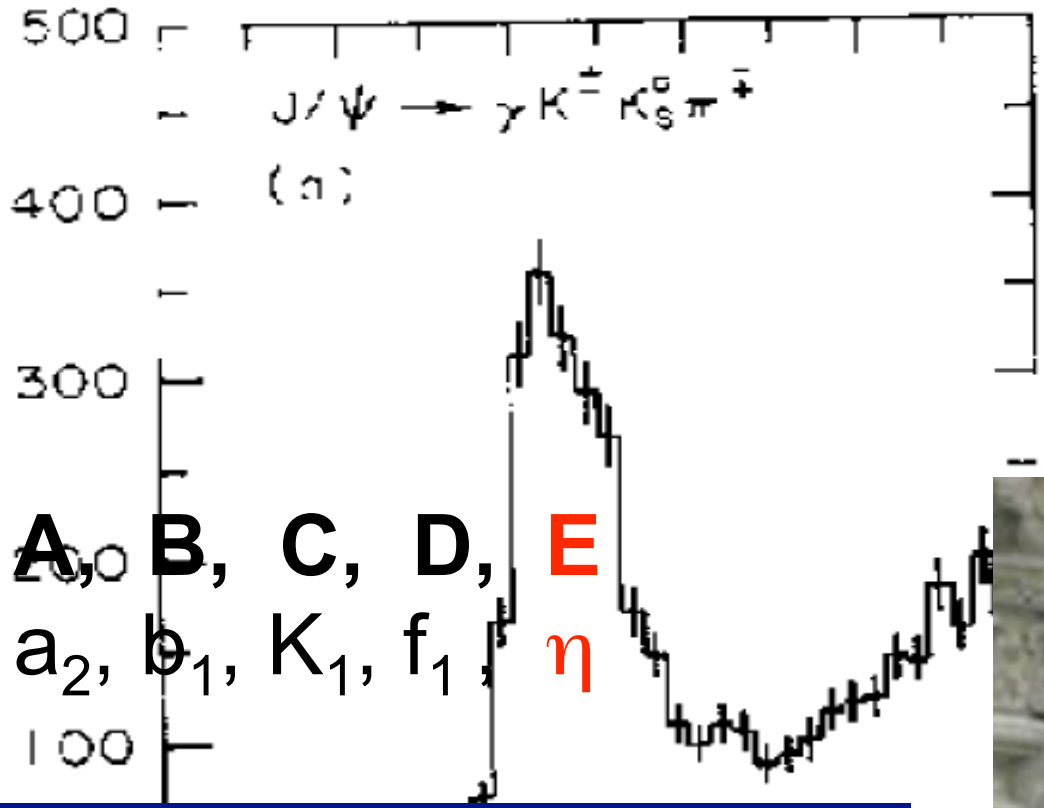

LEP
SPS
West Area
ISOLDE
AA/AC
p̄ tgt
PSB
p̄
p


Magnet Coil
CsI Crystals
JDC
Si-Vertex
(backplane & strip readout)
Magnet Yoke
MWPC
p̄
Beam
Si Counters
Cosmic Counters
LH2 (H2) Target
Veto Counter

Fermilab E835:

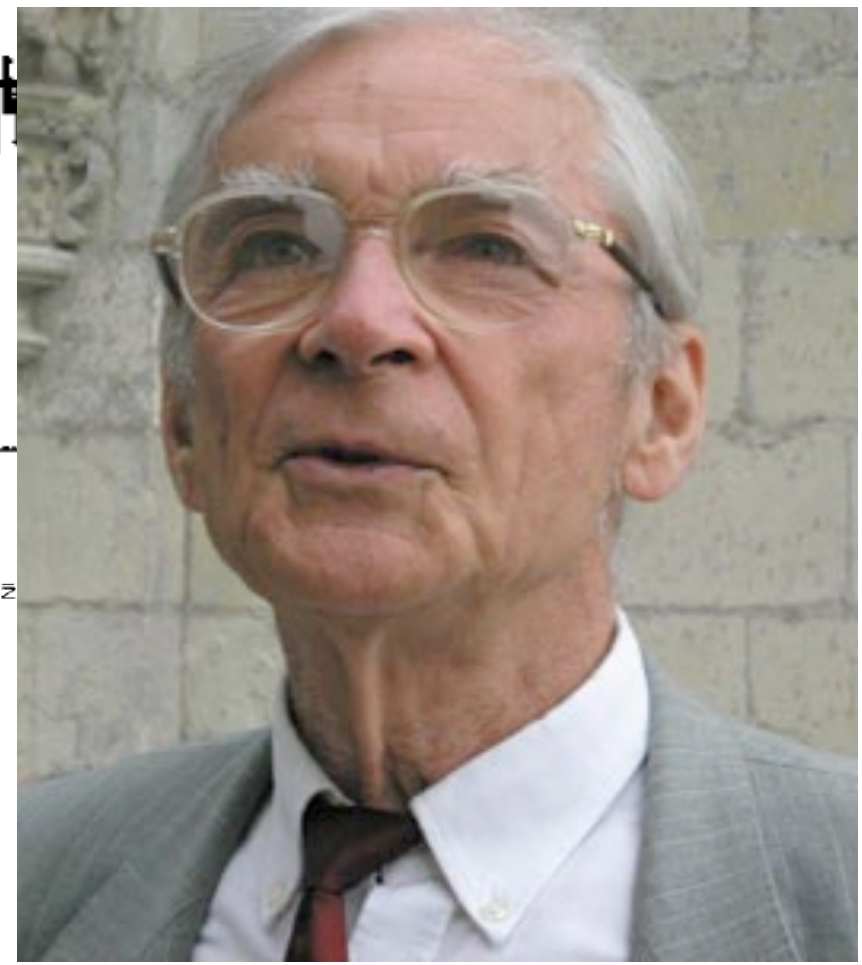






A, B, C, D, E

a_2, b_1, K_1, f_1, η



Two quantitative tests:

F. E. Close, G. R. Farrar and Z. p. Li, Phys. Rev. D 55 (1997) 5749.

$$\text{Stickiness } S = N_l \left(\frac{m_{\mathrm{R}}}{K_{\mathrm{J}\to\gamma\mathrm{R}}} \right)^{2l+1} \frac{\Gamma_{\mathrm{J}\to\gamma\mathrm{R}}}{\Gamma_{\mathrm{R}\to\gamma\gamma}} ,$$

$$\text{Gluiness} \qquad G = \frac{9\, e_q^4}{2} \left(\frac{\alpha}{\alpha_s} \right)^2 \frac{\Gamma_{\mathrm{R}\to\mathrm{gg}}}{\Gamma_{\mathrm{R}\to\gamma\gamma}} ,$$

L3 collaboration:

$S_\eta = 1$ $\qquad S_{\eta'} = 3.6 \pm 0.3$ $\qquad S_{\eta(1440)} = 79 \pm 26.$

$G_{\eta'} = 5.2 \pm 0.8$ $\qquad G_{\eta(1440)} = 41 \pm 14.$

M. Acciarri *et al.*, Phys. Lett. B 501 (2001) 1.

PDG 2004: The $\eta(1440)$ is split

Pseudoscalar mesons:

S. Eidelman *et al.*, Phys. Lett. B 592 (2004) 1.

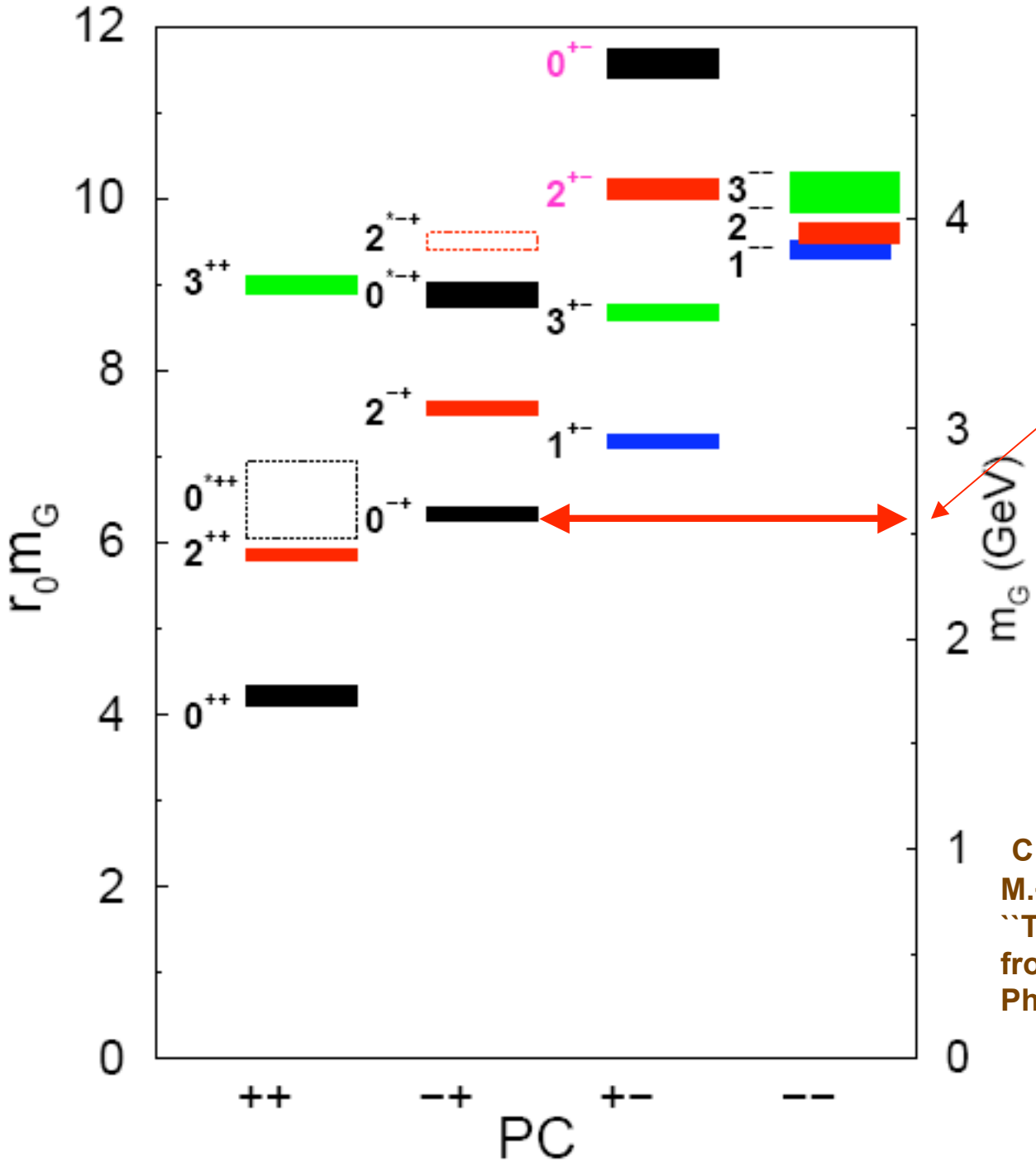
π	η		η'	K
$\pi(1300)$	$\eta(1295)$	$\eta(1405)$	$\eta(1475)$	$K(1460)$
$n\bar{n}$	$n\bar{n}$	glueball	$s\bar{s}$	$n\bar{s}$

same masses

ideally mixed

$\eta(1405) \to a_0(980)\pi, \sigma\eta$

$\eta(1475) \to K\bar{K}^* + \bar{K}K^*$

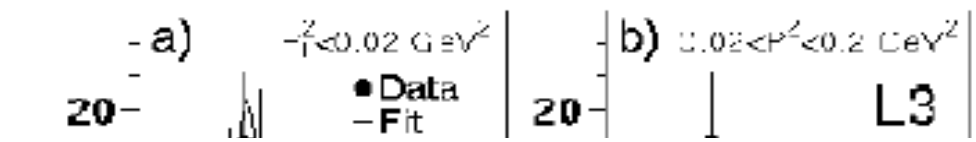


0^{-+} glueball expected at 2.6 GeV !

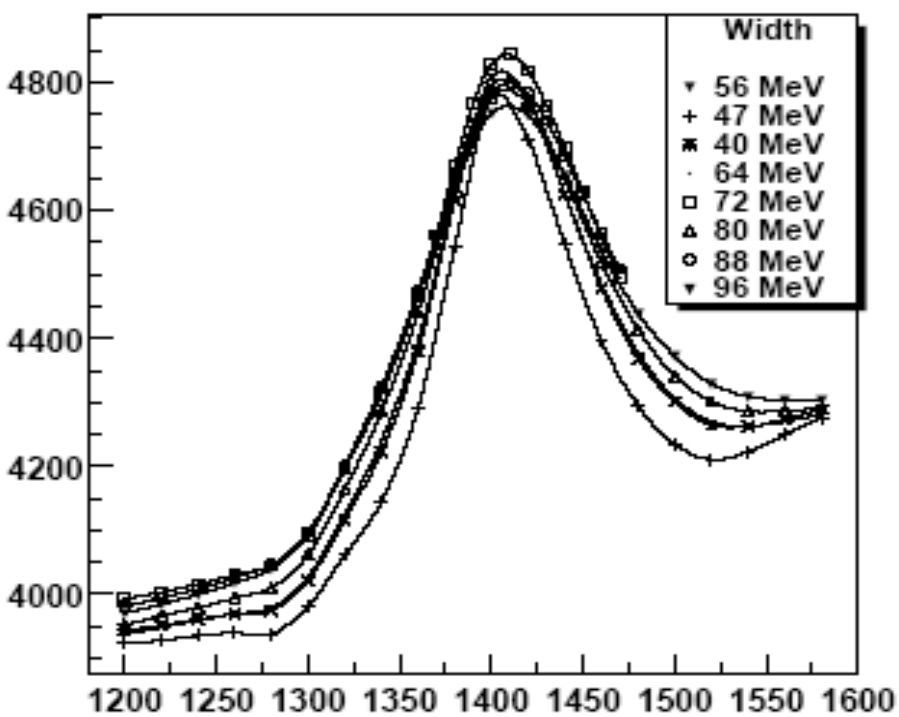
C.~J.~Morningstar and M.~J.~Peardon, ``The glueball spectrum from an anisotropic lattice study,'' Phys. Rev. D 60 (1999) 034509.

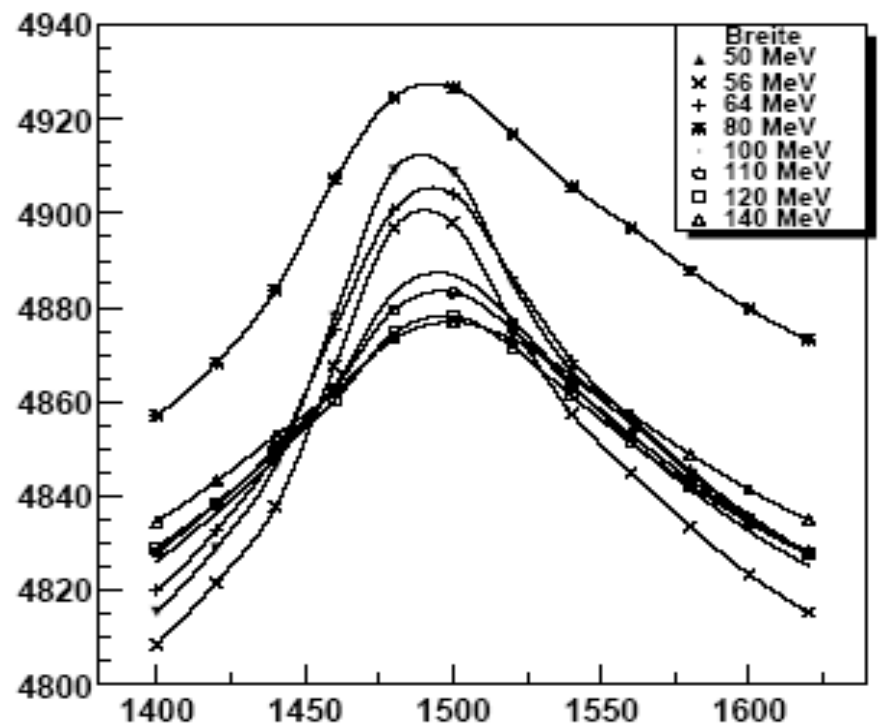
The η(1295):

- Only seen in pion induced reactions
- Not seen in radiative J/ψ decays
- Not seen in 2γ fusion ($Cleo_c$)



$q^2 \to 0$:





Scan for a 0^+0^{-+} resonance, η_L:

$M = 1407 \pm 5, \Gamma = 57 \pm 9$ MeV.

Search for second resonance, η_H:

$M = 1490 \pm 15, \Gamma = 74 \pm 10$ MeV.

The split η(1440):

T.~Barnes, F.~E.~Close, P.~R.~Page and E.~S.~Swanson, ``Higher quarkonia,'' Phys. Rev. D 55 (1997) 4157

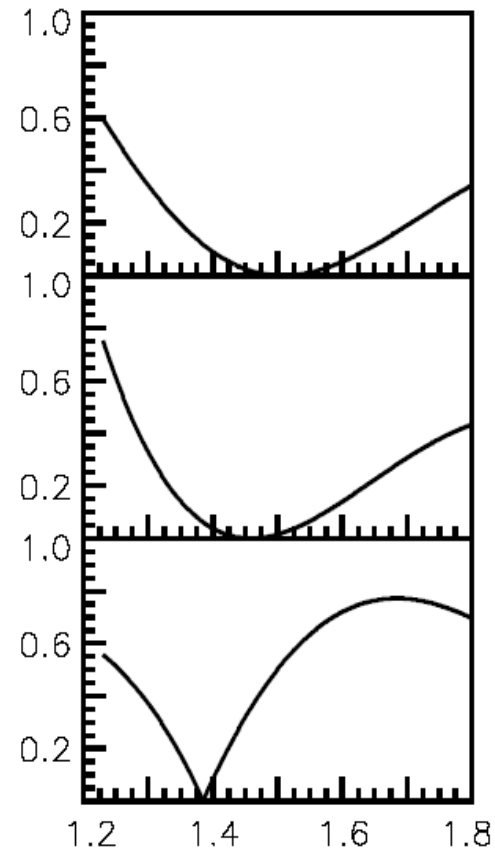
BW =

$$\frac{m_0\sqrt{\Gamma_0}}{m_0^2 - m^2 - i m_0 \left(\sum_i \frac{\rho_i(m)}{\rho_i(m_0)}\,\Gamma_i B_{L_i}^2\right)} \begin{pmatrix} \sqrt{\frac{\Gamma_1}{\rho_1(m_0)}}\,B_{L_1} \\ \sqrt{\frac{\Gamma_2}{\rho_2(m_0)}}\,B_{L_2} \\ \sqrt{\frac{\Gamma_2}{\rho_2(m_0)}}\,B_{L_3} \end{pmatrix}$$

M:

$$\Gamma_{A\to BC} = 2\pi \frac{pE_B E_C}{M_A} \sum_{\mathrm{LS}} \boxed{\mathcal{M}_{\mathrm{LS}}|^2} \qquad \boxed{\mathcal{M}_{\mathrm{LS}}} = \frac{\gamma}{\pi^{1/4}\beta^{1/2}} \boxed{\mathcal{P}_{\mathrm{LS}}(x)} e^{-x^2/12}$$

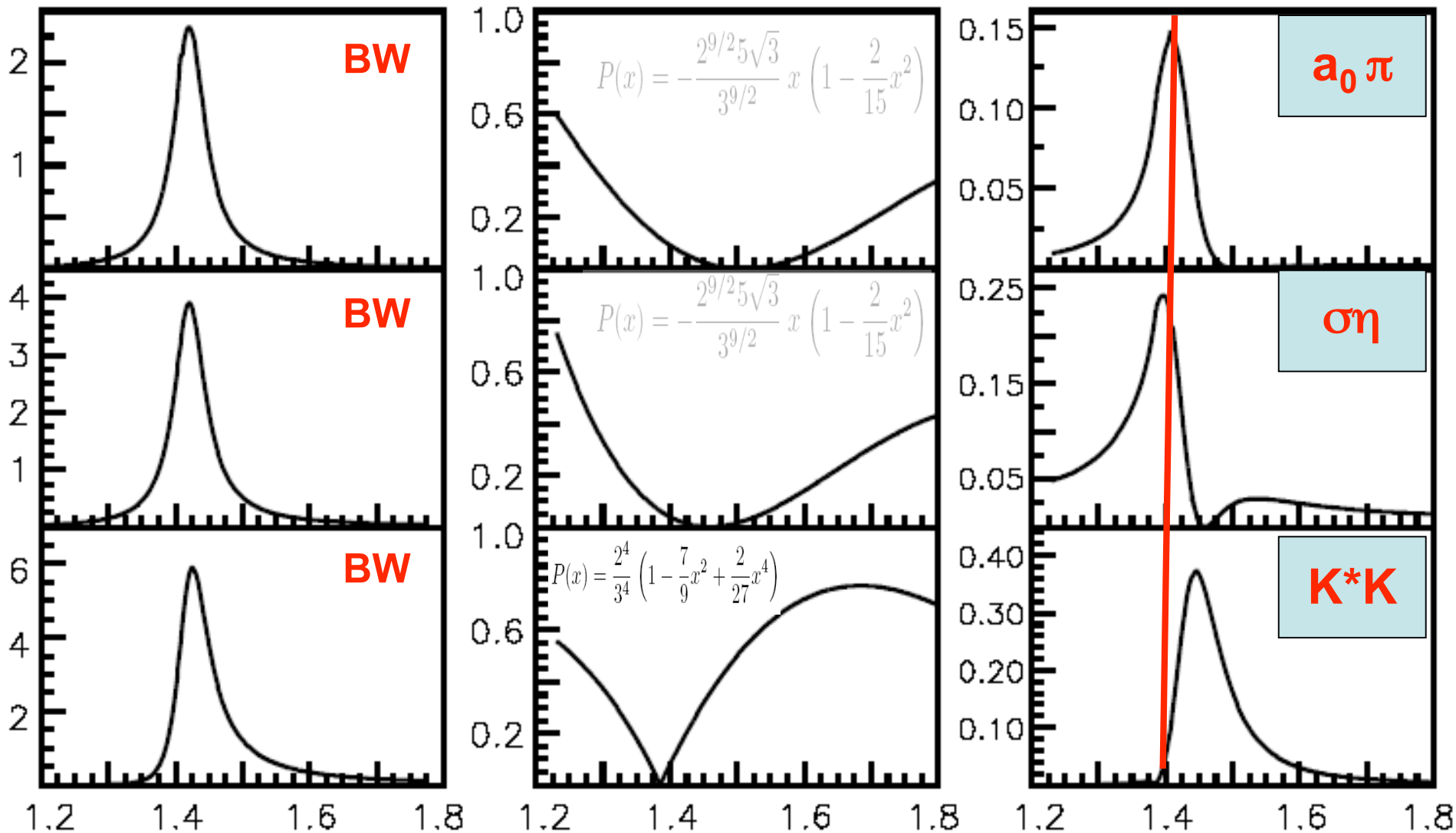
x=q/β



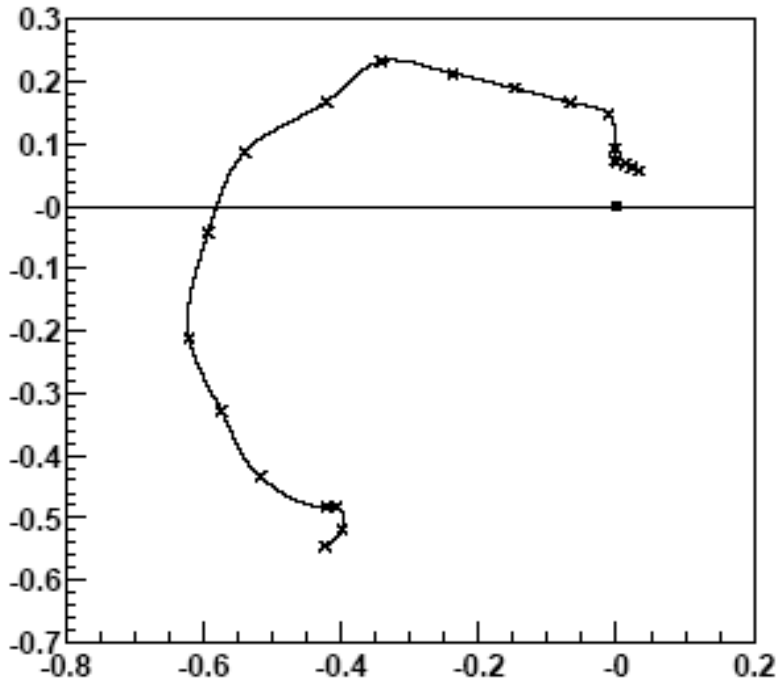
$$\boxed{P(x)} = -\frac{2^{9/2}5\sqrt{3}}{3^{9/2}}\, x \left(1 - \frac{2}{15}x^2\right)$$

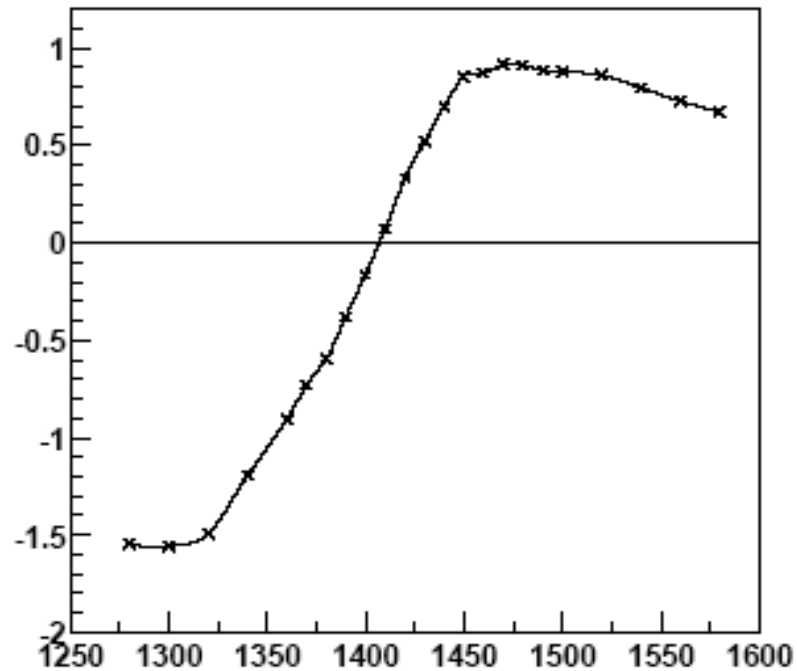
$$\boxed{P(x)} = \frac{2^4}{3^4}\left(1 - \frac{7}{9}x^2 + \frac{2}{27}x^4\right)$$

The split η(1440):



Phase motion





Complex amplitude and phase motion of $a_0(980)\pi$.

From 1300 to 1500 MeV, phase varies by π.

Only one resonance in mass interval.

The $\sigma\eta$ exhibits the same behaviour.

What is $\eta(1295)$?

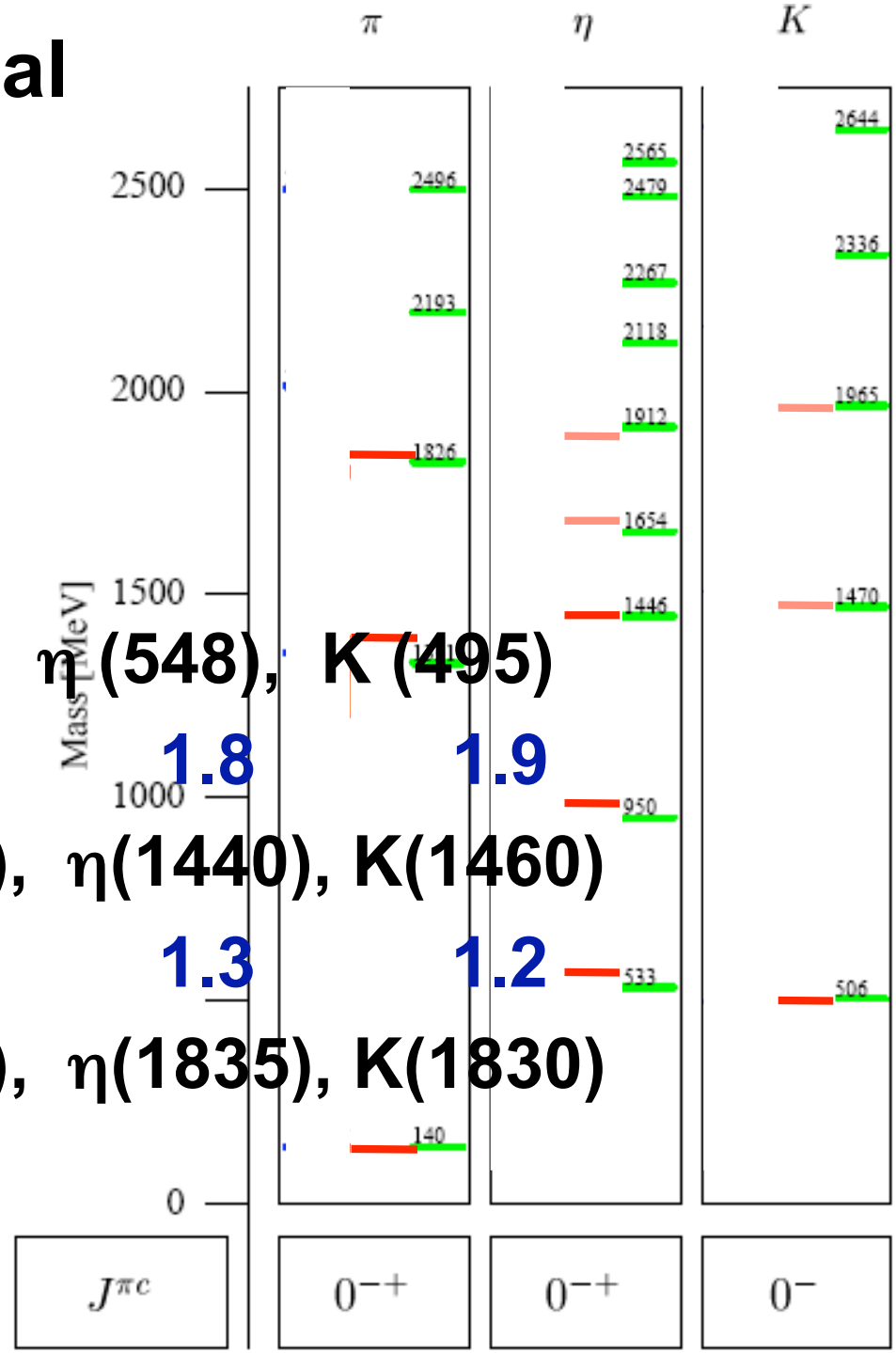
Not $q\bar{q}$

Exotic ?

Deck–type background ?

Pseudoscalar radial excitations

Mass spectra
(Bonn model, green):



π(138) , η (958) , η (548), K (495)

ΔM^2 = 1.9 1.8 1.8 1.9

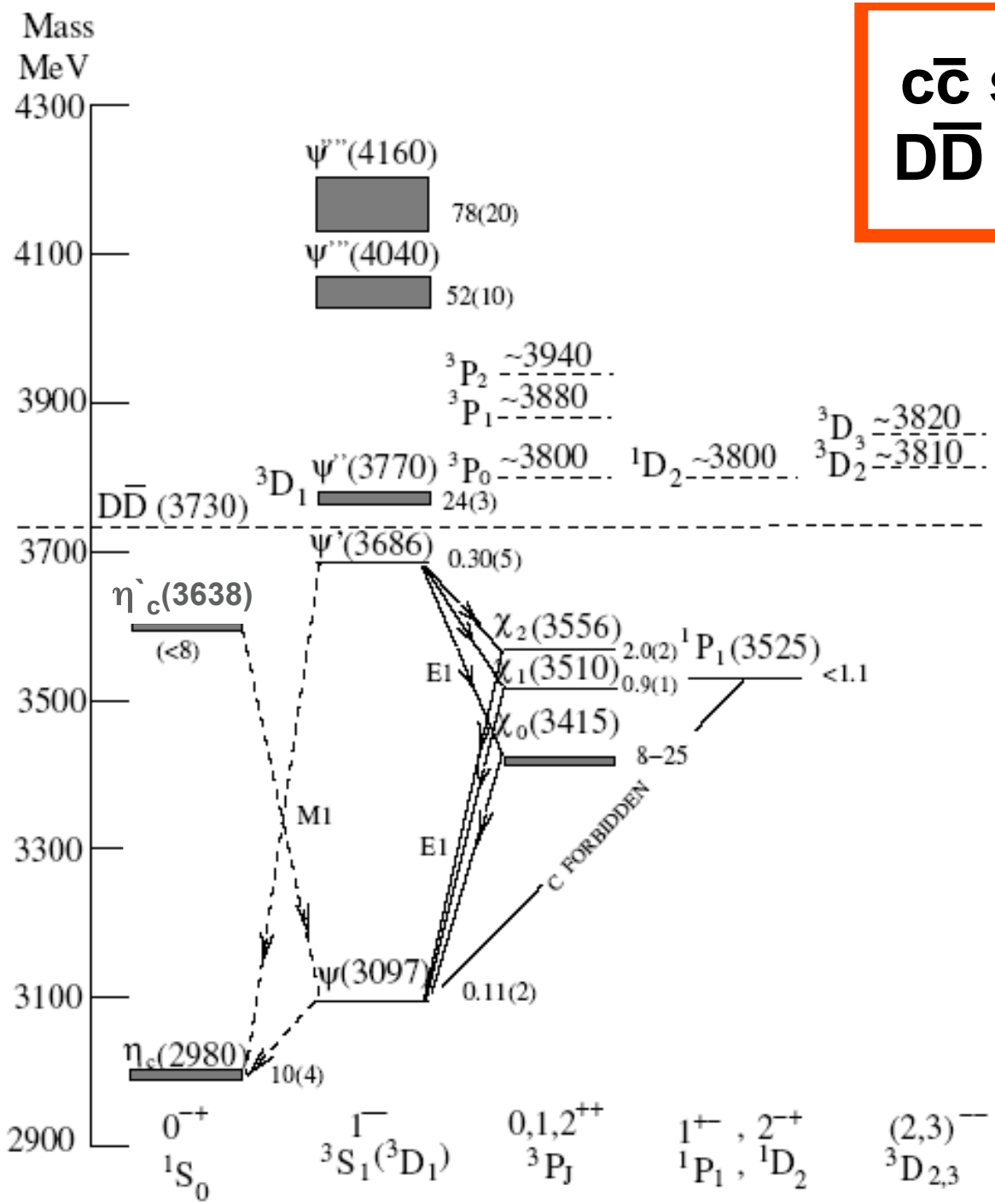
π(1375), η(1645), η(1440), K(1460)

ΔM^2 = 1.4 1.4 1.3 1.2

π(1800), η(2040), η(1835), K(1830)

Summary on the $\eta(1440)$:

- K and π first and second radial excitations are identified
- The $\eta(1295)$ is not a $q\bar{q}$ state
- The $\eta(1405)$ and $\eta(1475)$ are one state
- There is one η state in the 1200 to 1500 MeV mass range, not three
- The $\eta(1440)$ is the first η radial excitation, the $\eta(1835)$ could be the second one.
- The radial excitation of the $\eta(958)$ could be the $\eta(1645)$, and $\eta(2040)$ the second one



$c\bar{c}$ spectroscopy below $D\bar{D}$ threshold complete.

New:

η_c'
h_{1c}
X(3872)
X(3940)
Y(3940)
Z(3930)
X(4260)

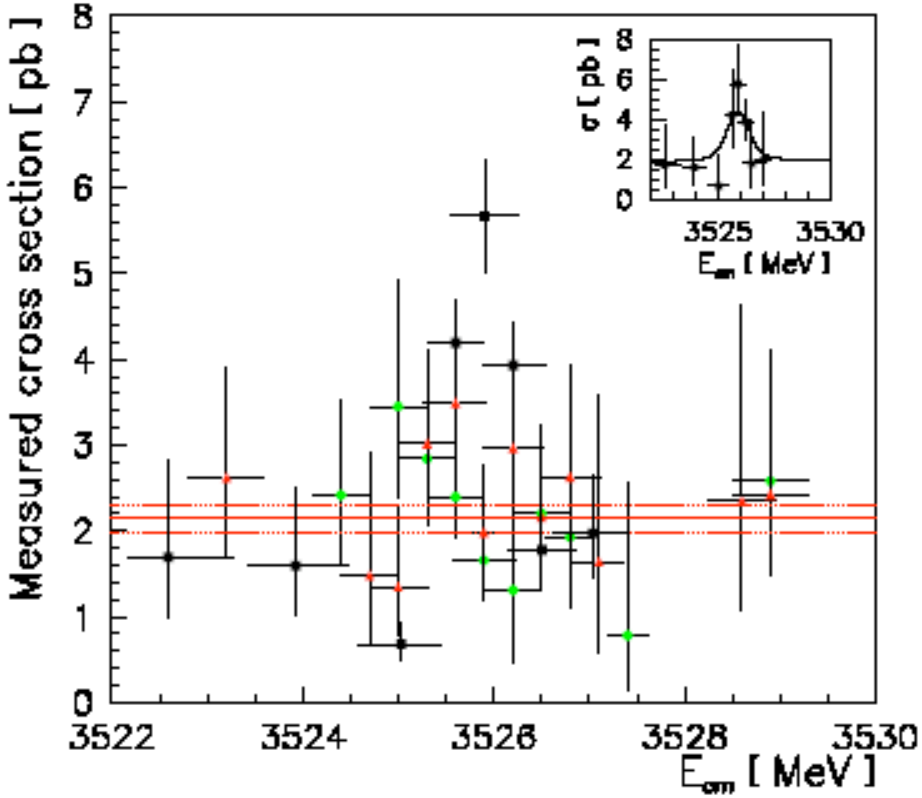
$\bar{c}$ d

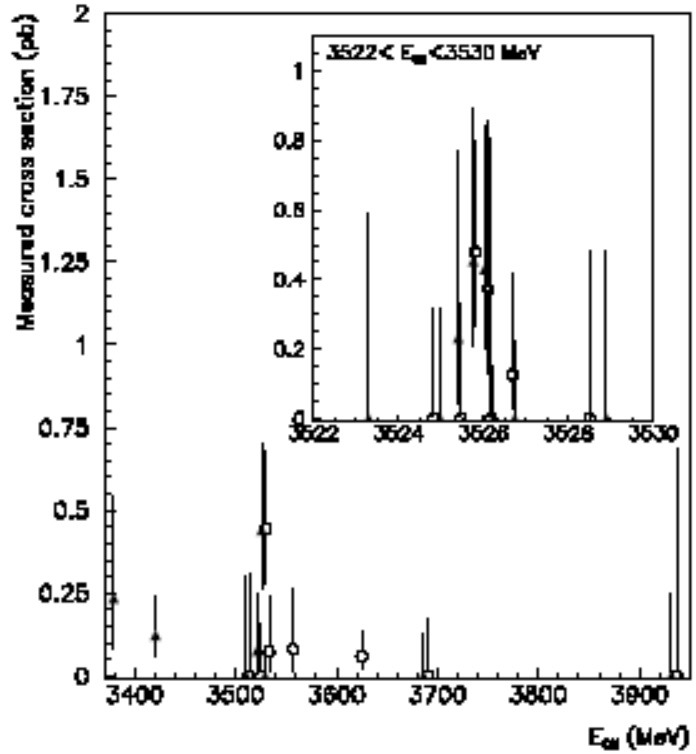
D

D_s

$h_{1c}(3524)$

Fermilab E835 Results for h_c Search





E835: $p\bar{p} \to h_c \to \pi^0 J/\psi$

No statistically significant signal

E835: $p\bar{p} \to h_c \to \gamma\eta_c$

$M(h_c) = 3525.8 \pm 0.2 \pm 0.2$ MeV

significance $\approx 3\sigma$

squares (normalized E760 data), open circles (1997 data), triangles (2000 data)

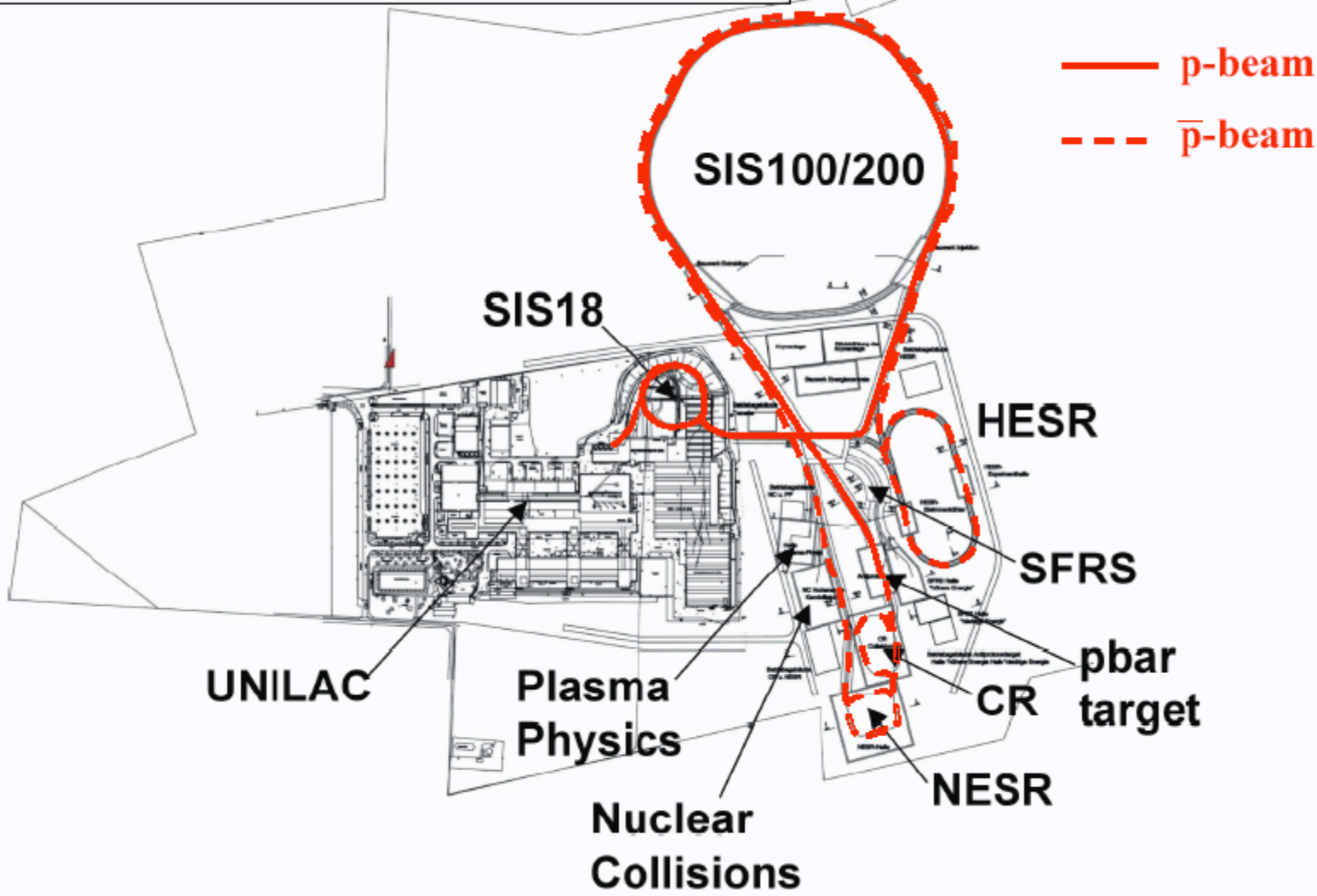
$h_{1c}(3524)$

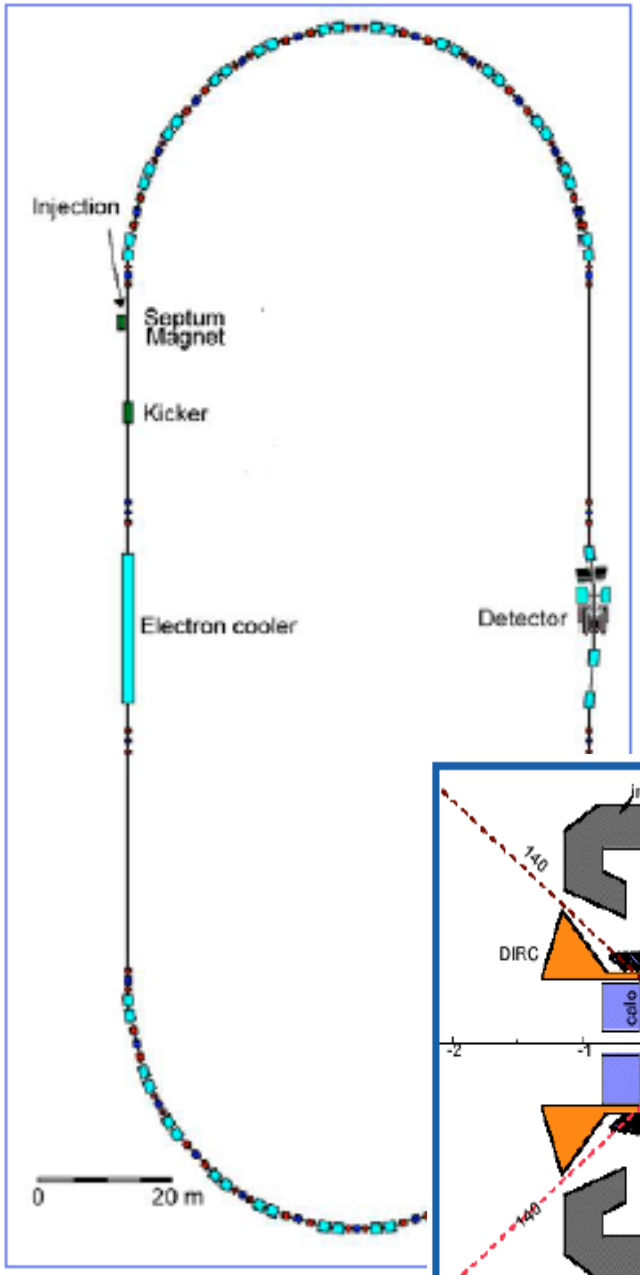
M = [3523.6 +/- 0.9 (stat) +/- 0.5 (sys)] MeV/c^2
δ = [1.8 +/- 0.9 (stat) +/- 0.5 (sys)] MeV/c^2.

cog = $[5\cdot(2^{++})+3\cdot(1^{++})+1\cdot(0^{++})]/9$

δ_{cog} = 0
confinement
potential is scalar

Layout of proposed new GSI facility



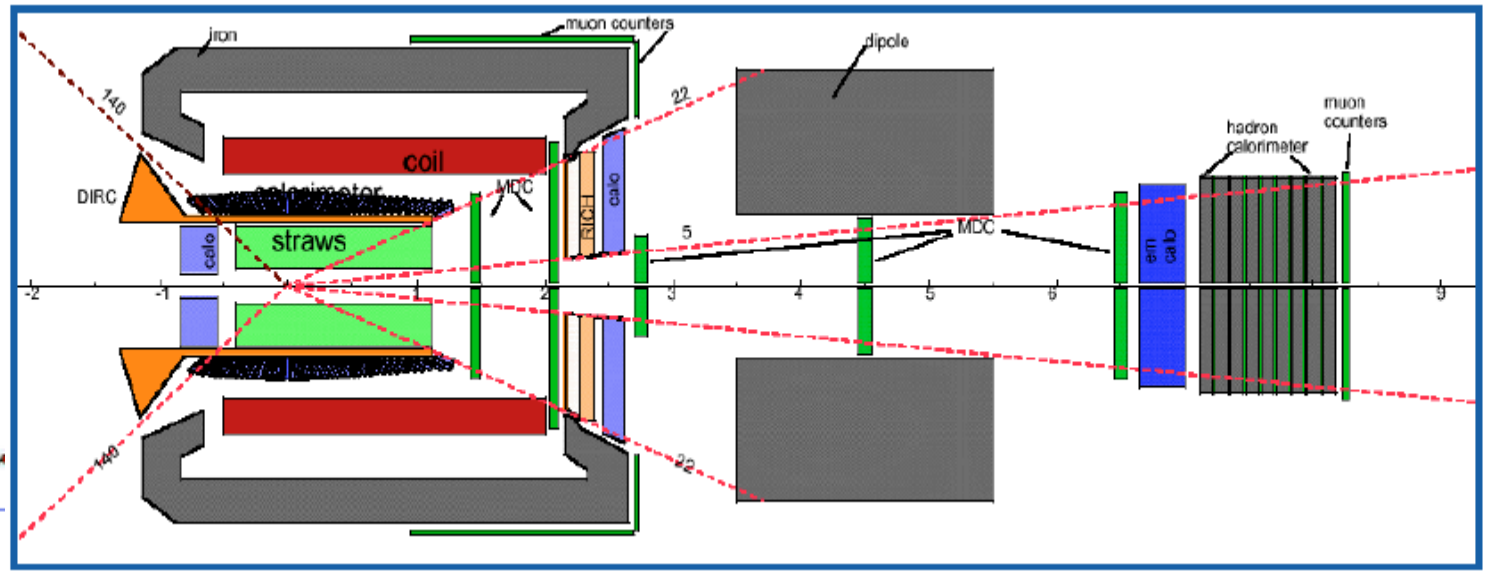


PANDA (Strong Interaction Studies with Antiprotons):

- Momentum: 1.5 to 15 GeV/c
- Number of particles: up to $5*10^{11}$
- Maximum luminosity: < $2*10^{32}$ $cm^{-2}s^{-1}$
- Transverse emittance: 0.001 to 0.1 mm mrad
- Momentum spread: $\pm 1*10^{-5}$ to $\pm 1*10^{-4}$
- Interaction point wich β < 1 m

high luminosity mode: $2*10^{32} cm^{-2} sec^{-1}$
spread $\sigma(p)/p \sim 10^{-4}$

high resolution mode $10^{31} cm^{-2} sec^{-1}$
spread $\sigma(p)/p \sim 10^{-5}$



Physics with antiprotons had a great past:

- Antiprotonic atoms
- Antimatter
- CP violation
- Annihilation studies
- Meson spectroscopy
- Jets
- W production
- Top quark

Physics with antiprotons have a bright future

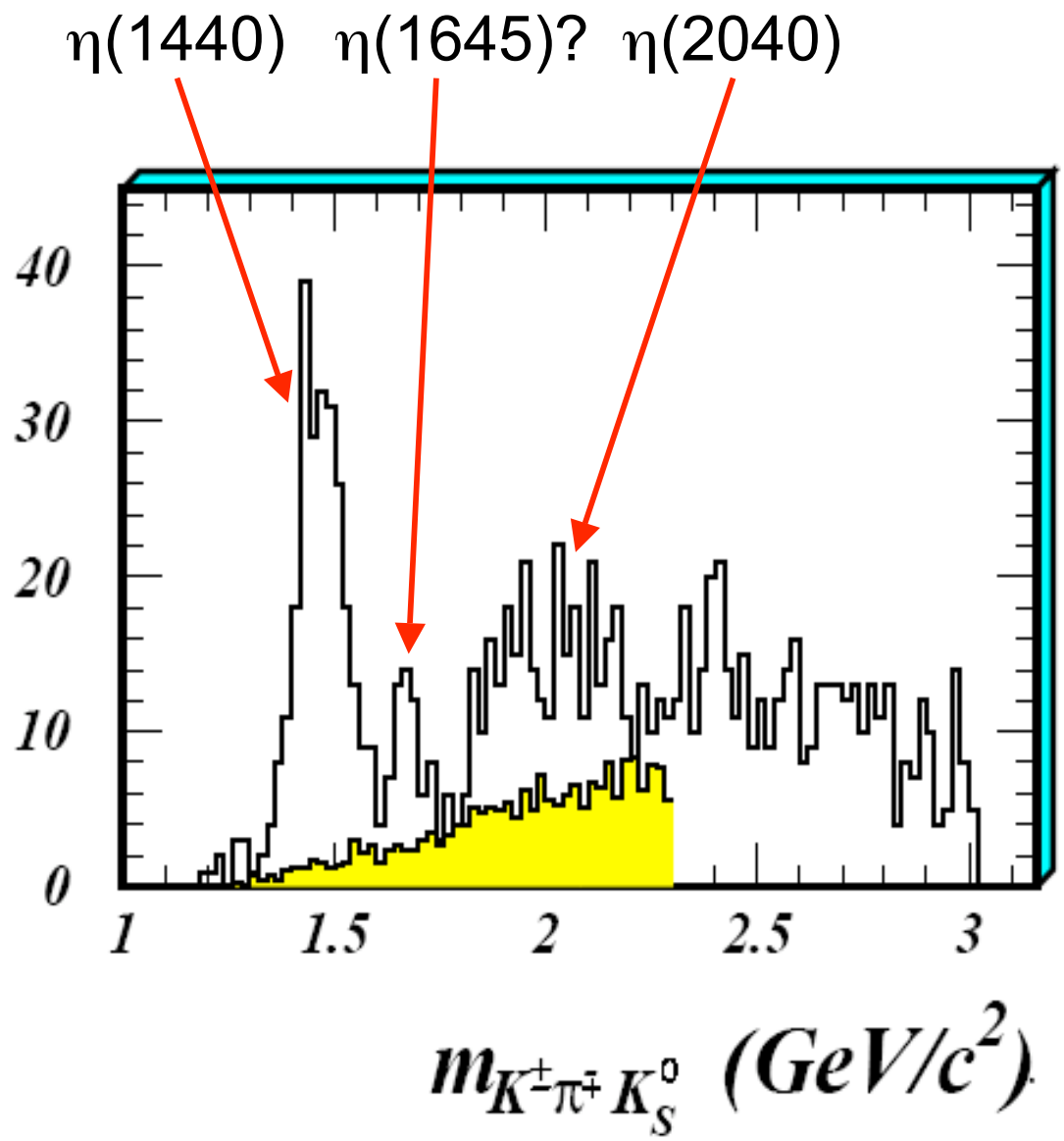
- Charmonium spectroscopy
- Hybrids with hidden charm
- D physics
- Light meson spectroscopy
- $N\bar{N}$ interactions
- Antihydrogen spectroscopy

$N^{2S+1}L_J$	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^{+-}	$b_1(1235)$	$h_1(1170), h_1(1380)$	$K_{1B}^{\dagger}$
$1\ ^3P_0$	0^{++}	$a_0(1450)^*$	$f_0(1370)^*, f_0(1710)^*$	$K_0^*(1430)$
$1\ ^3P_1$	1^{++}	$a_1(1260)$	$f_1(1285), f_1(1420)$	$K_{1A}^{\dagger}$
$1\ ^3P_2$	2^{++}	$a_2(1320)$	$f_2(1270), f_2'(1525)$	$K_2^*(1430)$
$1\ ^1D_2$	2^{-+}	$\pi_2(1670)$	$\eta_2(1645), \eta_2(1870)$	$K_2(1770)$
$1\ ^3D_1$	1^{--}	$\rho(1700)$	$\omega(1650)$	$K^*(1680)^{\ddagger}$
$1\ ^3D_2$	2^{--}			$K_2(1820)$
$1\ ^3D_3$	3^{--}	$\rho_3(1690)$	$\omega_3(1670), \phi_3(1850)$	$K_3^*(1780)$
$1\ ^3F_4$	4^{++}	$a_4(2040)$	$f_4(2050), f_4(2220)$	$K_4^*(2045)$
$2\ ^1S_0$	0^{-+}	$\pi(1300)$	$\eta(1295), \eta(1440)$	K(1460)
$2\ ^3S_1$	1^{--}	$\rho(1450)$	$\omega(1420), \phi(1680)$	$K^*(1410)^{\ddagger}$
$2\ ^3P_2$	2^{++}		$f_2(1810), f_2(2010)$	$K_2^*(1980)$
$3\ ^1S_0$	0^{-+}	$\pi(1800)$	$\eta(1760)$	K(1830)

PDG table and Contributions to light meson spectroscopy from $p\bar{p}$ annihilation

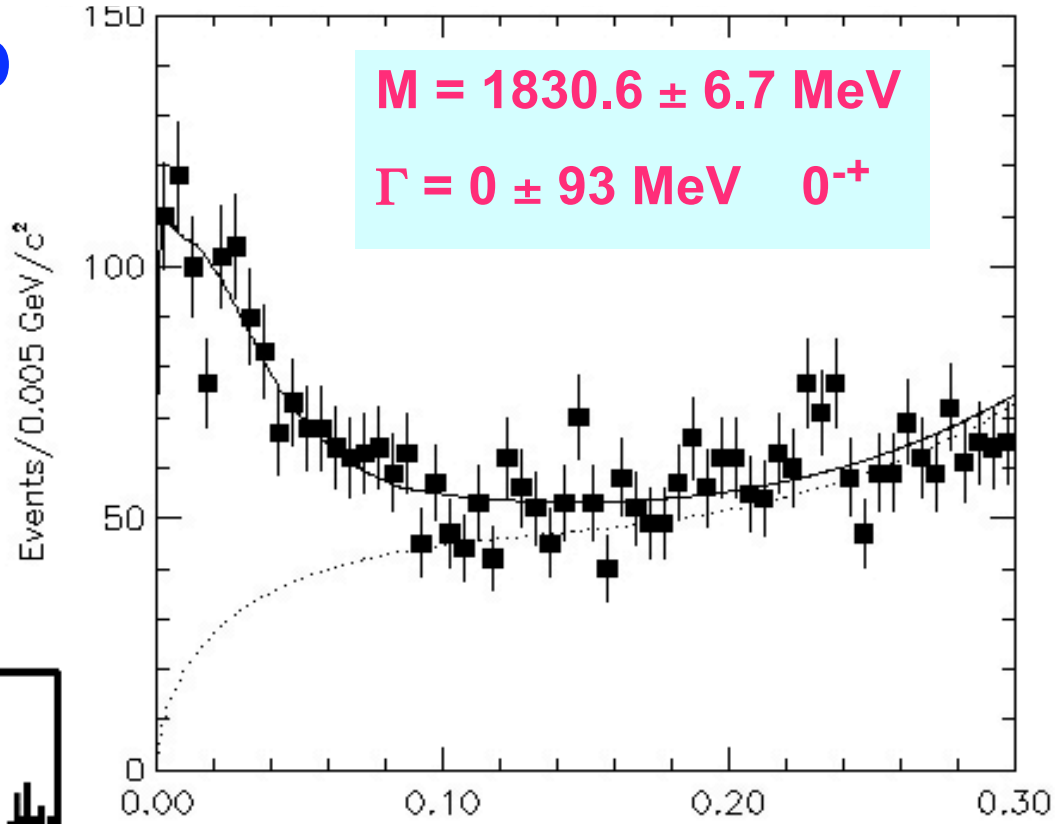
BES data on isoscalars with 0^{-+}

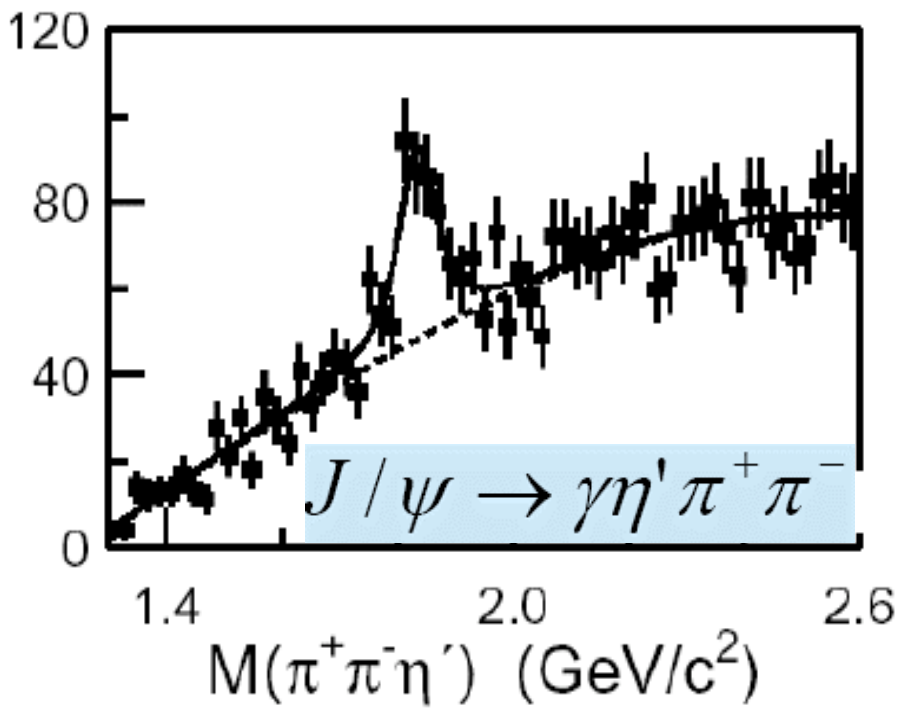
$J/\psi \rightarrow \gamma(K\bar{K}\pi)$



BES $J/\psi \rightarrow \gamma \bar{p} p$

Effect of $p\bar{p}$
Not a radial excitation





$N_{obs} = 264 \pm 54$

$M = 1833.7 \pm 6.1 \pm 2.7\ \mathrm{MeV/c^2}$

$\Gamma = 67.7 \pm 20.3 \pm 7.7\ \mathrm{MeV/c^2}$