INFN
Istituto Nazionale di Fisica Nucleare

Presente e Futuro della Spettroscopia Adronica

Diego Bettoni
INFN, Ferrara, Italy

Incontro Nazionale di Fisica Nucleare 2012
Laboratori Nazionali del Sud, 12-14 Novembre 2012

Outline

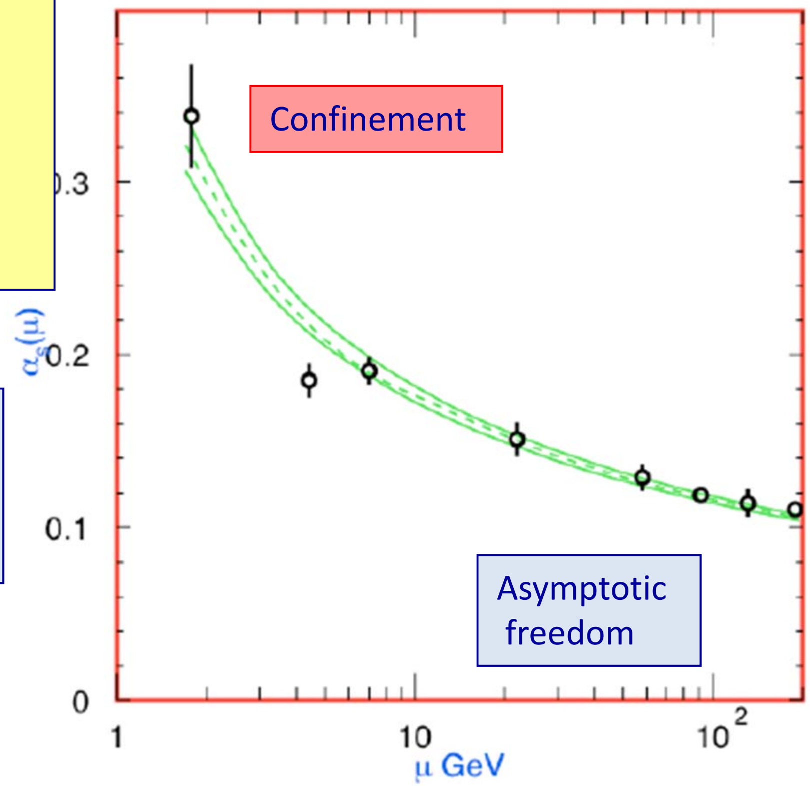
- The strong interaction and QCD
- Experimental methods for the study of hadron spectroscopy
  - Spectroscopy in e^+e^- annihilation
  - Spectroscopy in $\bar{p}p$ annihilation
- Experimental Highlights
  - Light mesons
  - Search for exotics
  - Charmonium and bottomonium
  - Open charm mesons
  - States above open charm threshold (XYZ states)
- Future Perspectives
- Conclusions

QCD

The modern theory of the strong interactions is Quantum Chromodynamics (QCD), the quantum field theory of quarks and gluons based on the non abelian gauge group SU(3). It is part of the Standard Model.

At high energies, where the strong coupling constant α_s becomes small and perturbation theory applies, QCD is well tested.

In the low-energy regime, however, QCD becomes a strongly coupled theory, many aspects of which are not understood.



Theoretical Approaches to non-perturbative QCD

- Potential models. Bound systems of heavy quarks can be treated in the framework of non-relativistic potential models, with forms which reproduce the asymptotic behaviour of QCD. Masses and widths are obtained by solving Schrödinger's equation.
- Lattice QCD (LQCD)
  - The QCD equations of motions are discretized on a 4-dimensional space-time lattice and solved by large-scale computer simulations.
  - Enormous progress in recent years (e.g. gradual transition from quenched to unquenched calculations).
  - Ever increasing precision, thanks also to sinergies with EFT.
- Effective Field Theories (EFT)

  They exploit the symmetries of QCD and the existence of hierarchies of scales to provide effective lagrangians that are equivalent to QCD for the problem at hand.
  - With quark and gluon degrees of freedom (e.g. Non Relativistic QCD or NRQCD)
  - With hadronic degrees of freedom (e.g. Chiral Perturbation Theory).

Experimental Measurements

- Spectroscopy of QCD bound states. Precision measurement of particle spectra to be compared with theory calculations. Identification of the relevant degrees of freedom.
  - light quarks, $c\bar{c}$, $b\bar{b}$
  - D meson
  - baryon
- Search for new forms of hadronic matter: hybrids, glueballs, multiquark states ...
- Hadrons in nuclear matter. Origin of mass.
- Hypernuclei.
- Study of nucleon structure.
  - Form Factors
  - GDAs
- Spin physics.

Experimental Techniques

e^+e^- collisions
direct formation
two-photon production
initial state radiation (ISR)
B meson decay
(BaBar, Belle, BES, CLEO(-c), LEP
SuperB, Belle II ...)

+ low hadronic background
+ high discovery potential
- direct formation limited to vector states
- limited mass and width resolution for non vector states

$\bar{p}p$ annihiliation
(LEAR, Fermilab E760/E835, $\bar{\text{P}}$ANDA)

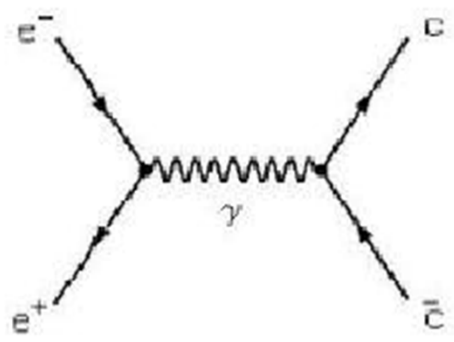
- high hadronic background
+ high discovery potential
+ direct formation for all (non-exotic) states
+ excellent mass and width resolution for all states

Hadroproduction
(CDF, D0, LHC)

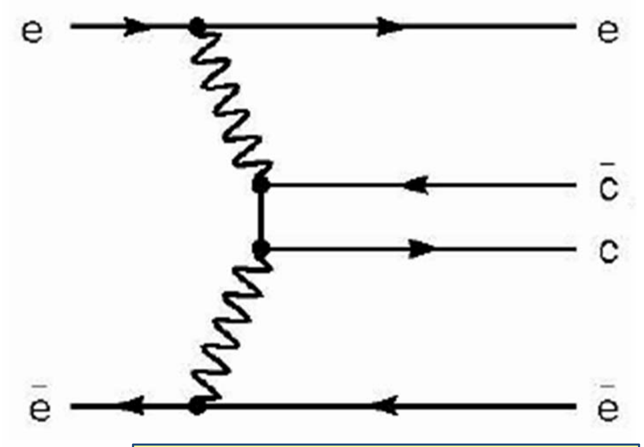
Electro- and Photo-production
(HERA,JLAB)

Hadron Production in e^+e^- Annihilation

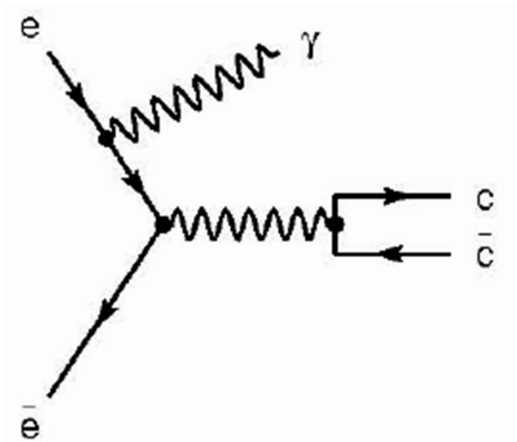
e^+e^- annihilation provides a very favourable environment for the study of hadron spectroscopy



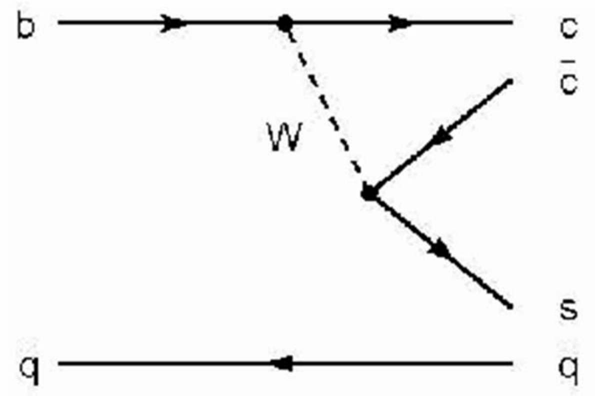
Direct Formation



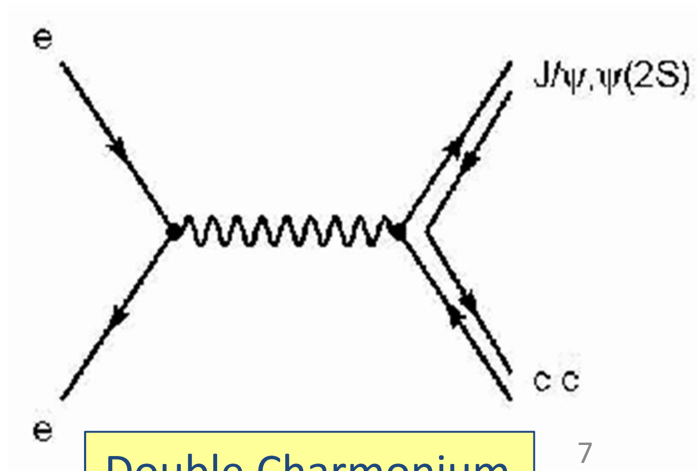
Two-Photon Production



Initial State Radiation



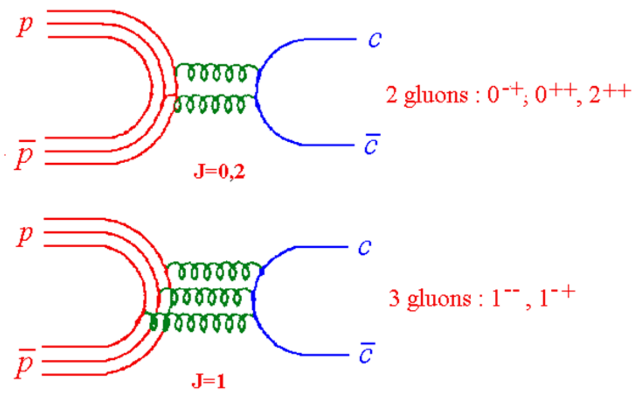
B-meson decay

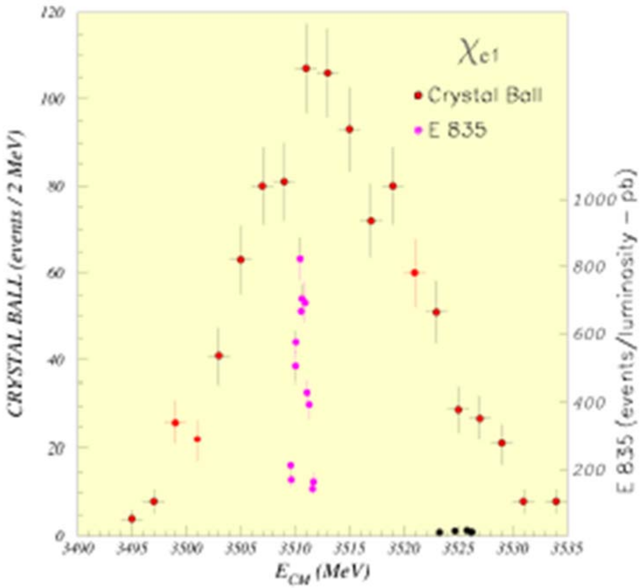


Double Charmonium

$\bar{p}p$ Annihilation

In $\bar{p}p$ collisions the coherent annihilation of the 3 quarks in the p with the 3 antiquarks in the $\bar{p}$ makes it possible to form directly states with all non-exotic quantum numbers.





The measurement of masses and widths is very accurate because it depends only on the beam parameters, not on the experimental detector resolution, which determines only the sensitivity to a given final state.

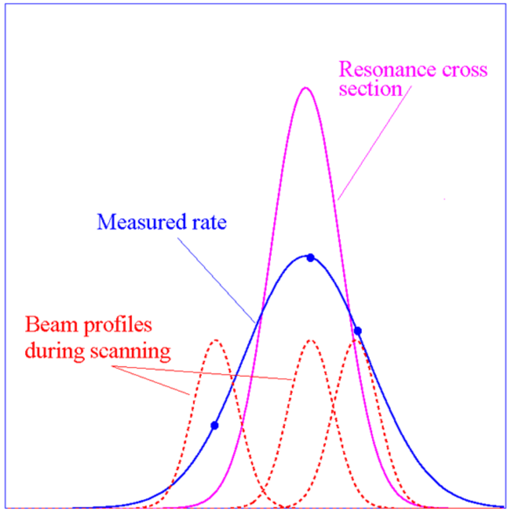
Experimental Method

The cross section for the process:

$\bar{p}p \rightarrow R \rightarrow$ final state

is given by the Breit-Wigner formula:

$$\sigma_{BW} = \frac{2J+1}{4}\frac{\pi}{k^2}\frac{B_{in}B_{out}\Gamma_R^2}{(E-M_R)^2+\Gamma_R^2/4}$$

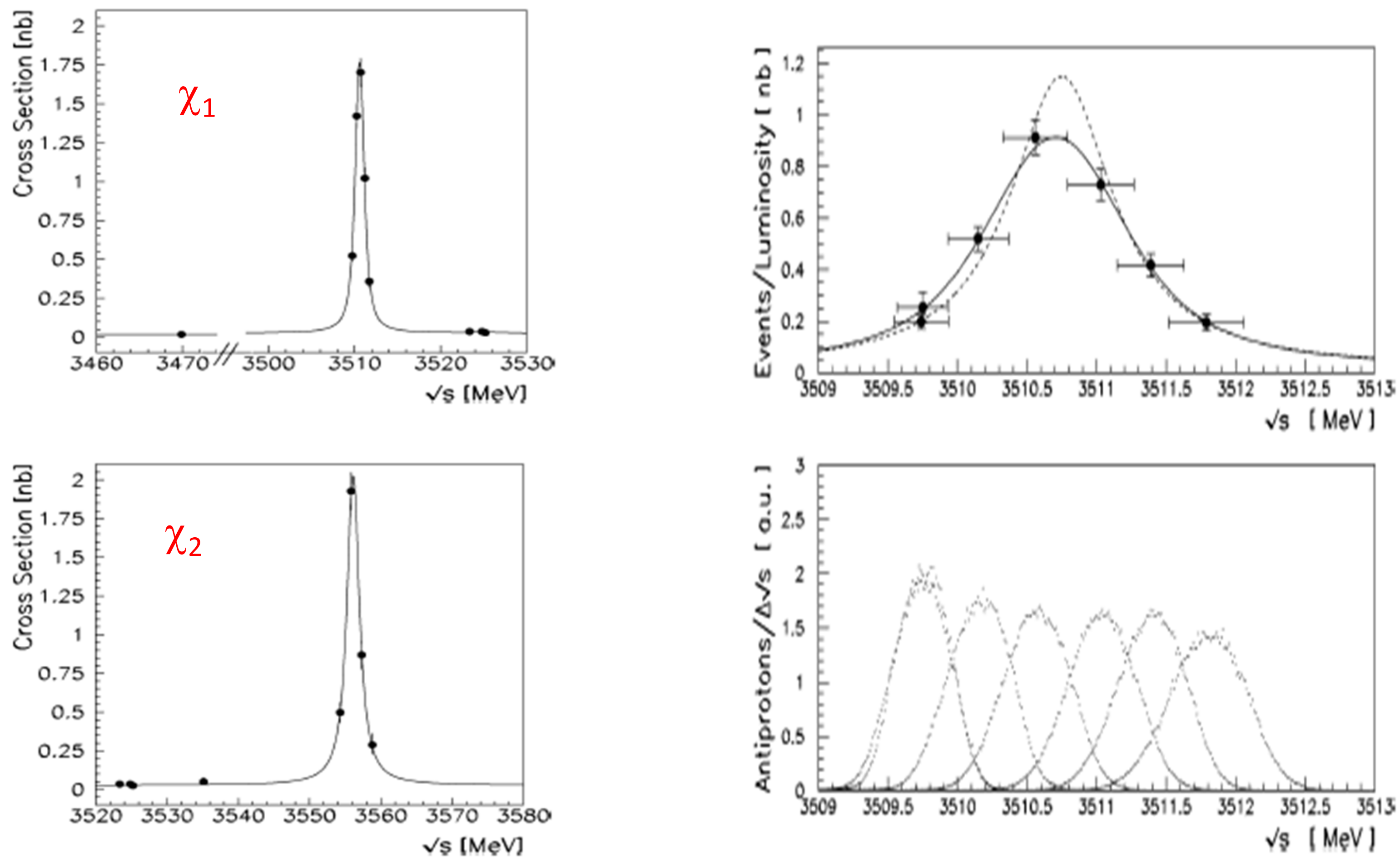


The production rate ν is a convolution of the BW cross section and the beam energy distribution function *f(E,ΔE)*:

$$\nu = L_0\{\varepsilon \int dE f(E,\Delta E)\sigma_{BW}(E) + \sigma_b\}$$

The resonance mass M_R, total width Γ_R and product of branching ratios into the initial and final state $B_{in}B_{out}$ can be extracted by measuring the formation rate for that resonance as a function of the cm energy *E*.

Example: χ_{c1} and χ_{c2} scans in Fermilab E835



Beam Energy and Width Measurement

In $\bar{p}p$ annihilation the precision in the measurement of mass and width is determined by the precision in the measurement of the beam energy and beam energy width, respectively.

$$E_{cm} = \sqrt{2}m_p(1+\gamma)^{1/2} \qquad \gamma = \frac{E_{beam}}{m_p} = \frac{1}{\sqrt{1-\beta^2}} \qquad \beta = f \cdot L$$

$$\frac{\delta E_{cm}}{E_{cm}} = \frac{\beta^2\gamma^3}{2(1+\gamma)}\sqrt{\left(\frac{\delta f}{f}\right)^2 + \left(\frac{\delta L}{L}\right)^2}$$

The beam revolution frequency *f* can be measured to 1 part in 10^7 from the beam current Schottky noise. In order to measure the orbit length L to the required precision (better than 1 mm) it is necessary to calibrate using the known mass of a resonance, e.g. the ψ′ for which ΔM = 34 keV.

η is a machine parameter which can be measured to ~ 10 %

$$\frac{\delta p}{p} = -\frac{1}{\eta}\frac{\delta f}{f}$$

η machine slip factor

Experimental Highlights

Light mesons

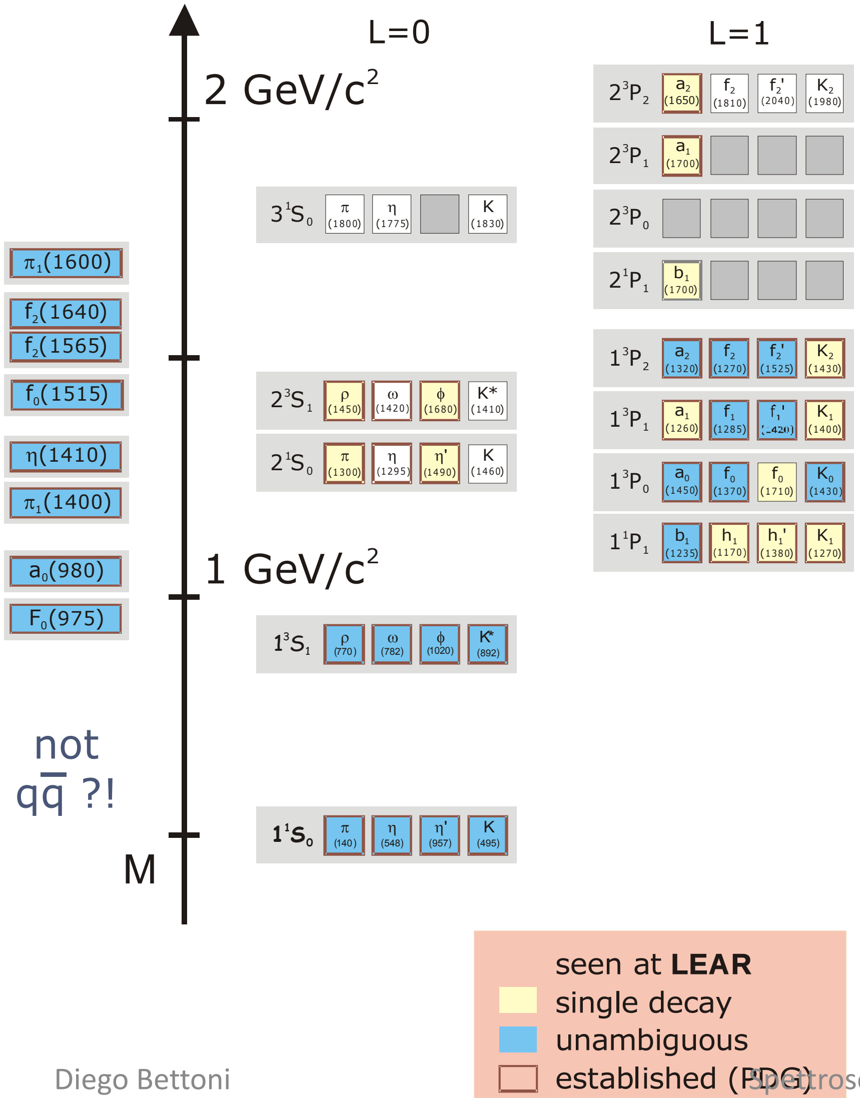
Search for exotics

Charmonium and Bottomonium

Open charm mesons

New states above open charm threshold (XYZ)

Meson Spectrum after LEAR



- The LEAR Era with the experiments
  - @ CERN
    - Asterix/Obelix
    - Crystal Barrel
    - Jetset/PS185
    - WA102/Gams
  - @ BNL
    - E818/E852
  - @ FNAL
    - E760/E835
  - @Serpukhov
    - VES/Gams

produced impressive results with high statistics and high resolution

Conventional and Exotic Hadrons

$q\bar{q}$

$+$

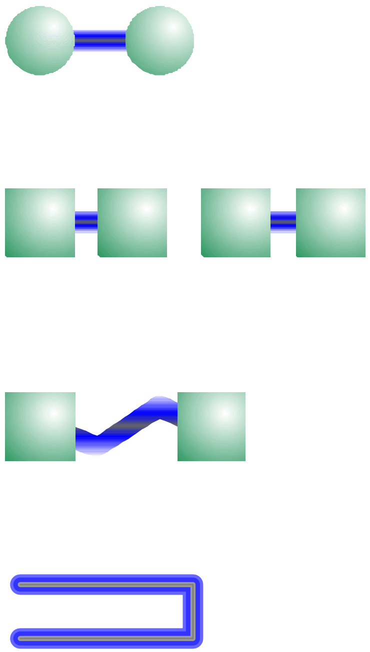
$(q\bar{q})(q\bar{q})$

$+$

$(q\bar{q})g$

$+$

gg



- Quarkmodels usually account for $q\bar{q}$ states

- Other color neutral configurations with same quantum numbers can (and will mix)

- Decoupling only possible for
  - narrow states
  - vanishing leading qq term

Simplest Hybrids

S-Wave+Gluon $(q\bar{q})_8 g$ with $()_8$=coloured

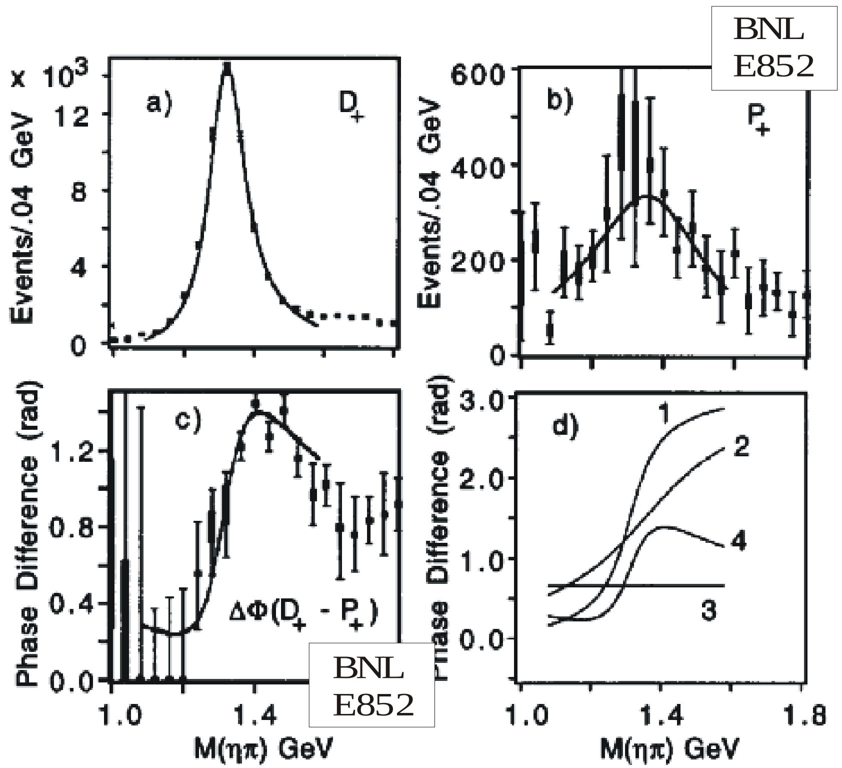
$^1S_0$ ↑↓ $^3S_1$ ↑↑

combined with a 1^+ or 1^- gluon

Gluon	1^- (TM)	1^+ (TE)
$^1S_0$, 0^{-+}	1^{++}	1^{--}
$^3S_1$, 1^{--}	0^{+-} 1^{+-} 2^{+-}	0^{-+} 1^{-+} 2^{-+}

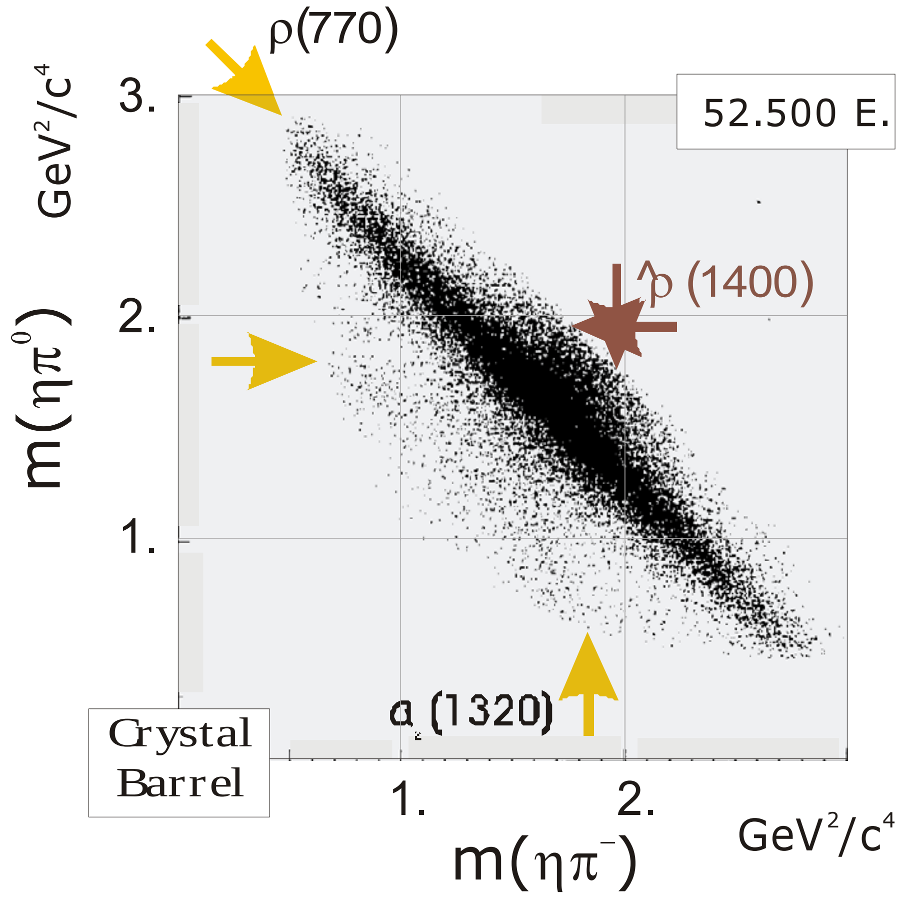
$\pi_1(1400)$ – E852 and Crystal Barrel

$\pi^- p \rightarrow \pi^- \eta\ p$ (and $\rightarrow \pi^0 \eta\ n$)



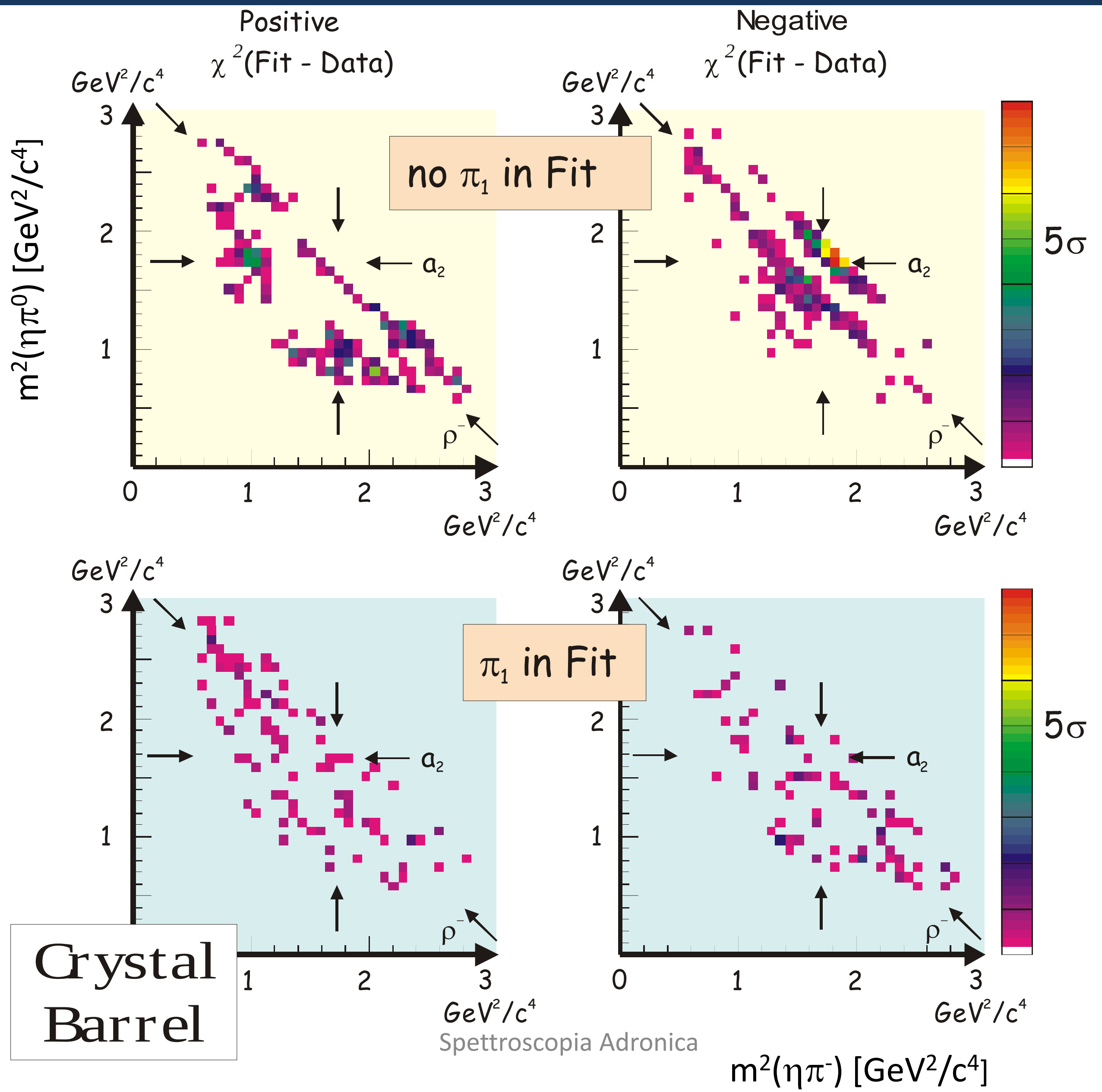
$\pi\eta$ peak @ 1.4 GeV/c^2
phasemotion at a_2 tail visible

$\bar{p}d \rightarrow \pi^- \pi^0 \eta\ p$ @ Rest in liq.D2

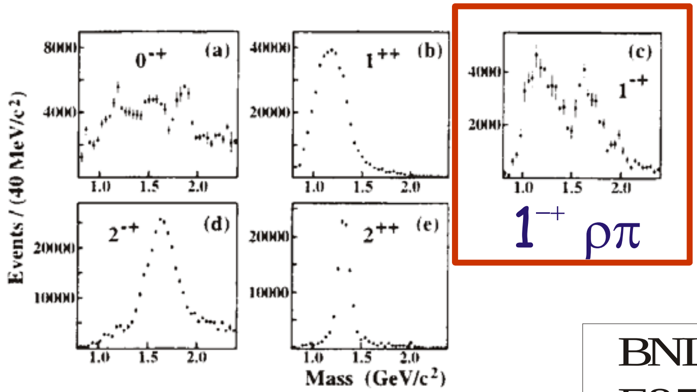


Advantage: I=1
and no Scalars

$\pi_1(1400)$ – Proof of Exotic Wave (CB)

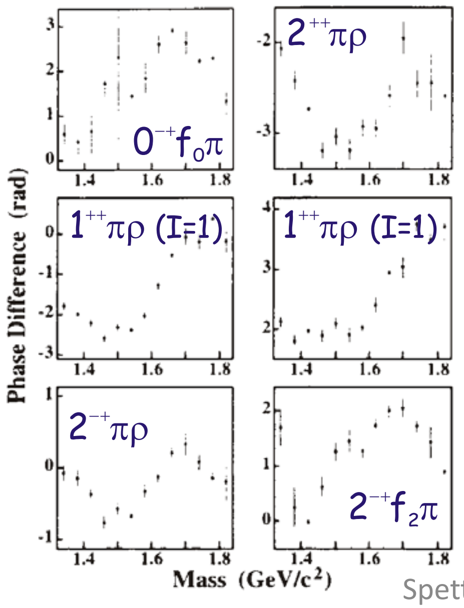


$\pi_1(1600)$



BNL
E852

$\phi(X\text{-}1^{-+})$



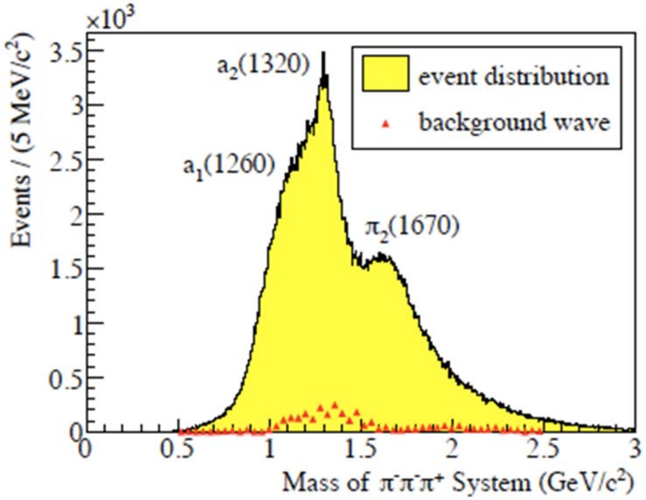
$\pi^- p \to \pi^- \rho^0 p \to \pi^- \pi^- \pi^+ p$ (E852) shows a clear resonance in the 1^{-+} wave around 1600 MeV/c^2

Also observed by the VES collaboration in the $\rho\pi$, $\eta'\pi$ and $b_1(1235)\pi$ channels.

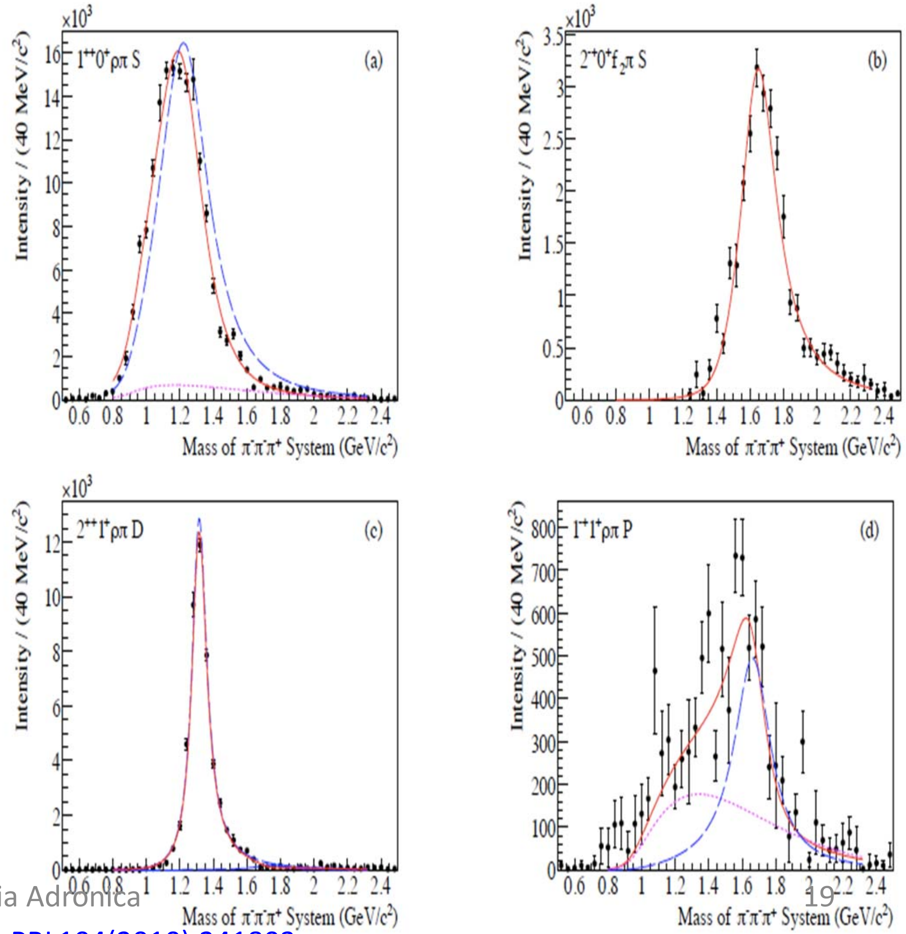
$b_1(1235)\pi$ channel confirmed by CB in $\bar{p}p \to \omega\pi^+\pi^-\pi^0$.

$\pi_1(1600)$

420.000 diffractive events $\pi^- + Pb \rightarrow X + (Pb)_{reco}$ collected by COMPASS exp. @190 GeV/c
↳ $\pi^-\pi^-\pi^+$



acceptance-corrected intensities of the three most prominent waves and of the exotic one



A Partial Wave Analysis (PWA) of this data set was performed by using the isobar model in which a multi-particle final state is described by a sequence of two-body decays

PRL104(2010) 241803

$\pi_1(1600)$

All known isovector and isoscalar ππ resonances have been included: σ(600) and $f_0(1370)$, ρ(770), $f_0(980)$, $f_2(1270)$, and $\rho_3(1690)$

σ(600)π^- with L = 0 and $J^P = 0^-$ is used to consider direct 3-body decay into $\pi^-\pi^-\pi^+$

background wave = uniform 3-body phase space added incoherently

Resonance	Mass (MeV/c^2)	Width (MeV/c^2)	Intensity (%)	Channel $J^{PC}M^{\epsilon}$[isobar]L	Mass [26] (MeV/c^2)	Width [26] (MeV/c^2)
$a_1(1260)$	$1255 \pm 6^{+7}_{-17}$	$367 \pm 9^{+28}_{-25}$	$67 \pm 3^{+4}_{-20}$	$1^{++}0^+ \rho\pi S$	1230 ± 40	$250 - 600$
$a_2(1320)$	$1321 \pm 1^{+0}_{-7}$	$110 \pm 2^{+2}_{-15}$	$19.2 \pm 0.6^{+0.3}_{-2.2}$	$2^{++}1^+ \rho\pi D$	1318.3 ± 0.6	107 ± 5
$\pi_1(1600)$	$1660 \pm 10^{+0}_{-64}$	$269 \pm 21^{+42}_{-64}$	$1.7 \pm 0.2^{+0.9}_{-0.1}$	$1^{-+}1^+ \rho\pi P$	1662^{+15}_{-11}	234 ± 50
$\pi_2(1670)$	$1658 \pm 3^{+24}_{-8}$	$271 \pm 9^{+22}_{-24}$	$10.0 \pm 0.4^{+0.7}_{-0.7}$	$2^{-+}0^+ f_2\pi S$	1672.4 ± 3.2	259 ± 9
$\pi(1800)$	$1785 \pm 9^{+12}_{-6}$	$208 \pm 22^{+21}_{-37}$	$0.8 \pm 0.1^{+0.3}_{-0.1}$	$0^{-+}0^+ f_0\pi S$	1816 ± 14	208 ± 12
$a_4(2040)$	$1885 \pm 13^{+50}_{-2}$	$294 \pm 25^{+46}_{-19}$	$1.0 \pm 0.3^{+0.1}_{-0.1}$	$4^{++}1^+ \rho\pi G$	2001 ± 10	313 ± 31

A total of 42 partial waves are included in the first step of the fit. The χ^2 fit of the spin-density matrix elements obtained for each mass bin is performed in the mass range from 0.8 to 2.32 GeV/c^2

comparison with BNL E852 results for $\pi^-p \to \pi^+\pi^\pm\pi^-\pi^0\pi^0(p/n)$ @ 18 GeV/c

resonance	decay	mass(MeV/c^2)	width(MeV/c^2)
$a_4(2040)$	$(\omega\rho)^D_2$	$1985 \pm 10 \pm 13$	$231 \pm 30 \pm 46$
$a_2(1700)$	$(\omega\rho)^S_2$	$1721 \pm 13 \pm 44$	$279 \pm 49 \pm 66$
$a_2(2000)$	$(\omega\rho)^S_2$	$2003 \pm 10 \pm 19$	$249 \pm 23 \pm 32$
$\pi_1(1600)$	$(b_1\pi)^S_1$	$1664 \pm 8 \pm 10$	$185 \pm 25 \pm 28$
$\pi_1(2000)$	$(b_1\pi)^S_1$	$2014 \pm 20 \pm 16$	$230 \pm 32 \pm 73$

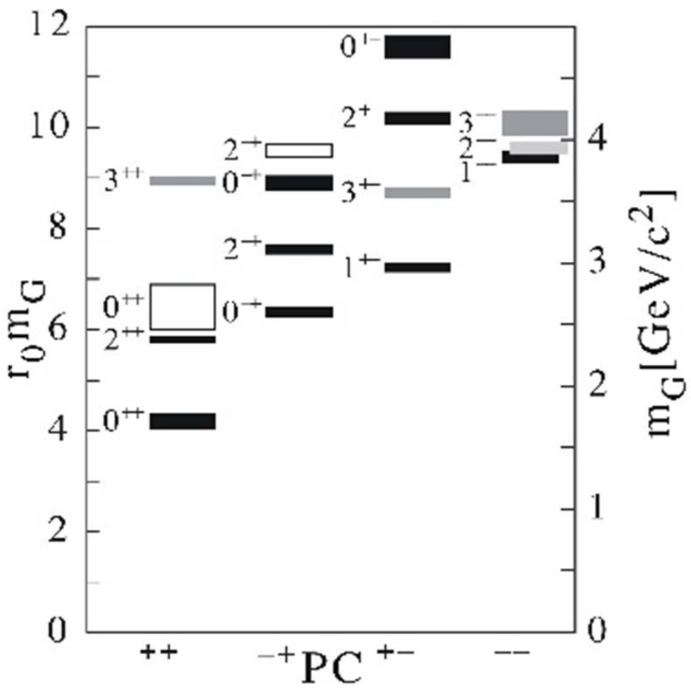
Glueballs

Detailed predictions of mass spectrum from quenched LQCD.

- Width of ground state ~ 100 MeV
- Several states predicted below 5 GeV/c^2, some exotic (oddballs)
- Exotic heavy glueballs:
  - m(0^{+-}) = 4140(50)(200) MeV
  - m(2^{+-}) = 4740(70)(230) MeV
  - predicted narrow width

Can be either formed directly or produced in $\bar{p}p$ annihilation.

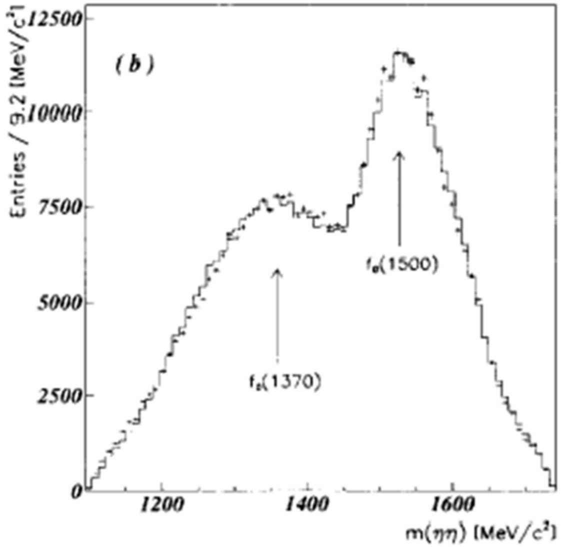
Some predicted decay modes $\phi\phi$, $\phi\eta$, $J/\psi\eta$, $J/\psi\phi$ ...



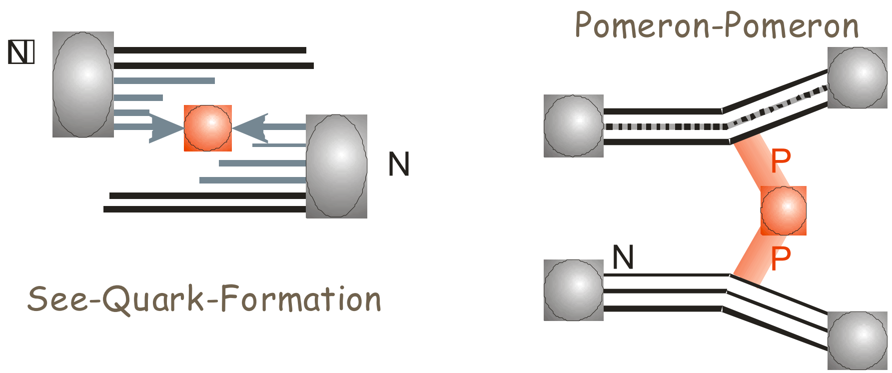
Morningstar und Peardon, PRD60 (1999) 034509
Morningstar und Peardon, PRD56 (1997) 4043

The detection of non-exotic glueballs is not trivial, as these states mix with the nearby $q\bar{q}$ states with the same quantum numbers, thus modifying the expected decay pattern.

- In 1995 through a simultaneous fit to the channels $\pi^0\eta\eta$, $\pi^0\pi^0\eta$ and $3\pi^0$ produced in $\bar{p}p$ annihilations Crystal Barrel discovered three new resonances:
  - isovector $a_0(1450)$
  - isoscalar $f_0(1370)$ and $f_0(1500)$



- Confirmed by OBELIX in analysis of $\pi^+\pi^-\pi^0$, $K^+K^-\pi^0$, $KK^0_S\pi$ in $\bar{p}p$ annihilation at rest.
- Confirmed by WA102 in central pp collisions at CERN.



- Crystal Barrel and OBELIX data also confirm the broad $f_0(600)$ and the narrow $f_0(980)$, <u>neither of which are believed to be $q\bar{q}$ states</u>.

Scalar Mesons

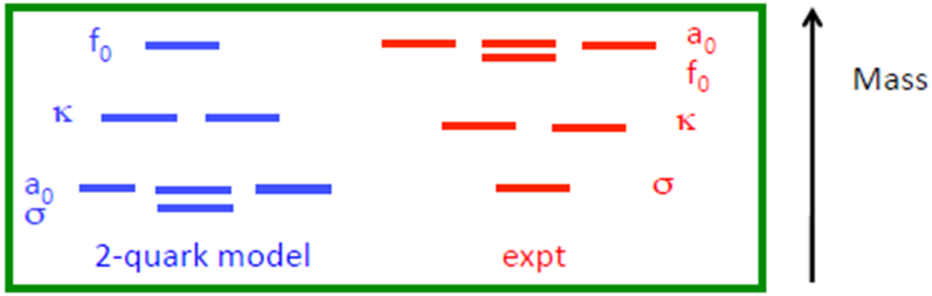
The PDG classification of the 0^{++} scalar mesons is tentative, because the number of states is bigger than 9.

- $a_0(980)$ and $a_0(1450)$ isovectors
- $f_0(600)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$ isoscalars
- $K^*_0(1430)$ and $K^*_0(1950)$ isodoublets.

BUT:

The $a_0(980)$, $f_0(600)$ and $f_0(980)$ are considered non-$q\bar{q}$ states, they are considered exotic candidates (multiquark or $K\bar{K}$ states).

It is then natural to assume that the $f_0(1370)$, $a_0(1450)$ and the strange $K^*_0(1430)$ are in the same SU(3) nonet. A higher-mass isoscalar is required as the ninth member, but we have two: $f_0(1500)$, $f_0(1710)$.



The answer is to include a glueball.

Meson-Glueball Mixing

LQCD calculations predict for the lightest glueball a scalar with a mass in the range 1.45 – 1.75 GeV/c^2. A combined analysis of the complete set of two-body decays of the $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ into pseudoscalar mesons determined the mixing angles and the mass m_G of the bare glueball.

$$|f_0(1710)\rangle = 0.39|gg\rangle + 0.91|s\bar{s}\rangle + 0.14|N\bar{N}\rangle$$

$$|f_0(1500)\rangle = -0.69|gg\rangle + 0.37|s\bar{s}\rangle - 0.62|N\bar{N}\rangle$$

$$|f_0(1370)\rangle = 0.60|gg\rangle - 0.13|s\bar{s}\rangle - 0.79|N\bar{N}\rangle$$

$$|N\bar{N}\rangle = \frac{|u\bar{u} + d\bar{d}\rangle}{\sqrt{2}}$$

$$m_G = 1440 \pm 16 \; MeV/c^2$$

We have the following picture:

$a_0(1450)$, $K^*_0(1430)$, $f_0(1370)$, $f_0(1710)$ 0^{++} scalar nonet
$f_0(600)$, $f_0(980)$, $a_0(980)$ multiquark or $K\bar{K}$ states
$f_0(1500)$ scalar glueball

In this scenario it is fair to say that the lightest glueball was discovered at LEAR.

There are, however, **alternative viewpoints**:

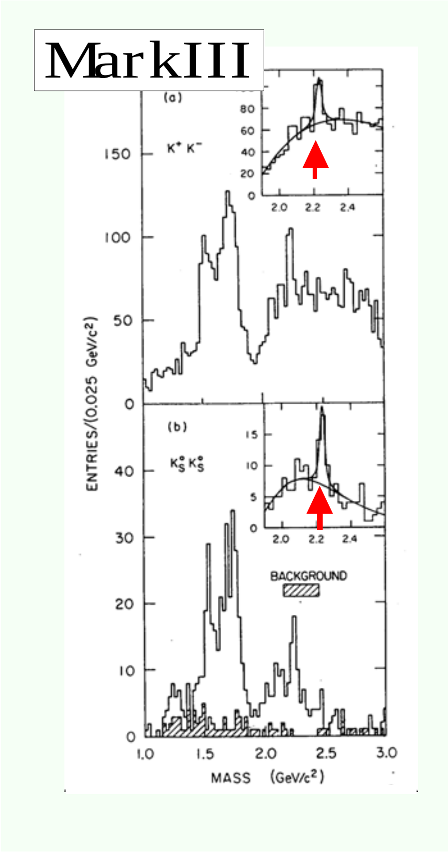
$a_0(980)$, $K^*_0(1430)$, $f_0(980)$, $f_0(1500)$ n=1, 0^{++} scalar nonet
$a_0(1450)$, $K^*_0(1950)$, $f_0(1370)$, $f_0(1710)$ n=2, 0^{++} scalar nonet

Tensor Glueball

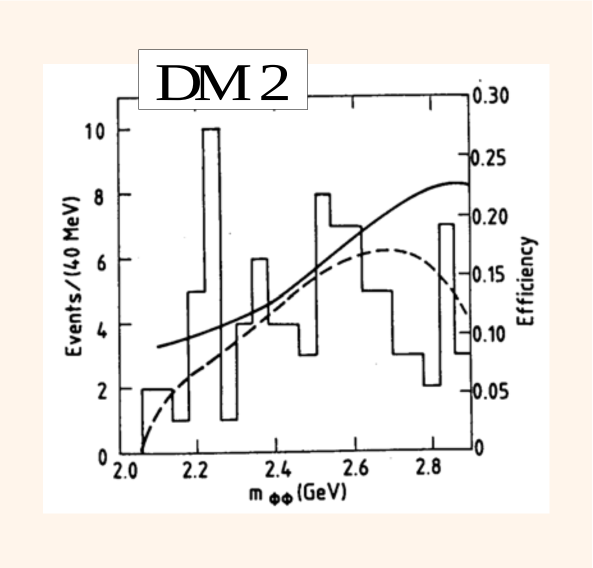
If there is a scalar glueball with a mass of 1.44 GeV/c^2 then LQCD predicts a tensor glueball with a mass around 2.0 GeV/c^2.

First candidate observed in 1986 in radiative J/ψ decays, named **ξ(2220)**.

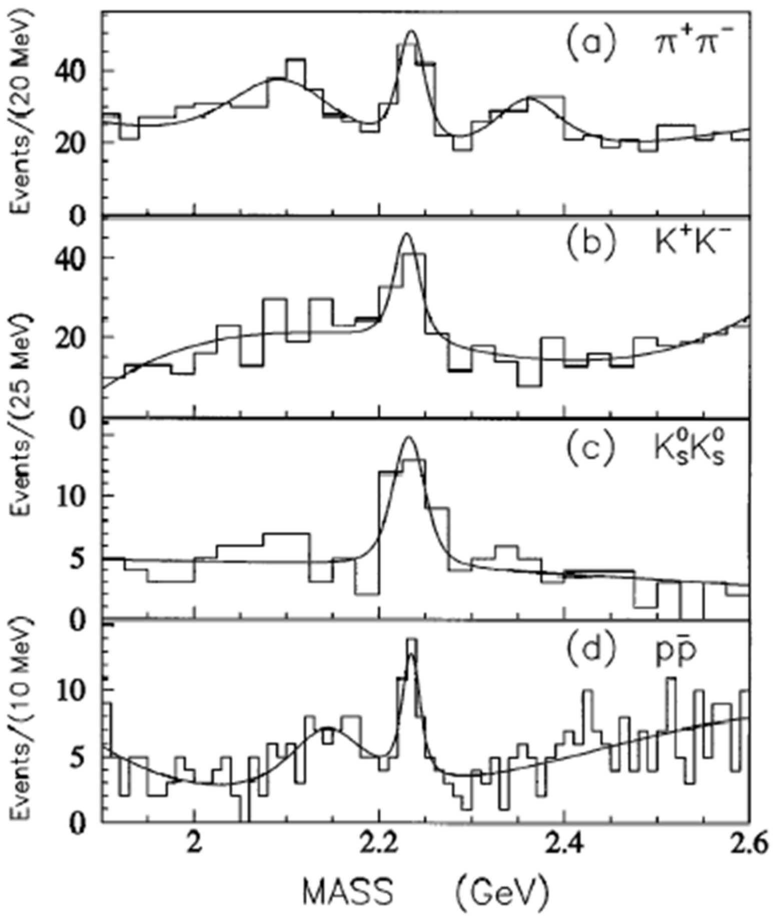
into $K\bar{K}$



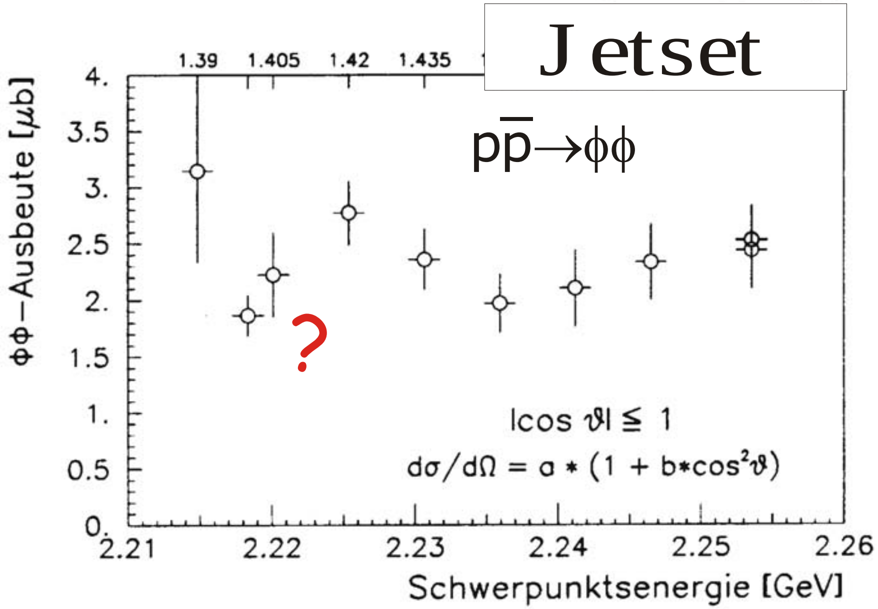
into $\phi\phi$



ξ(2220) confirmed by BES



ξ(2220) NOT confirmed by JETSET ...



... ξ(2220) NOT seen by Crystal Barrel either

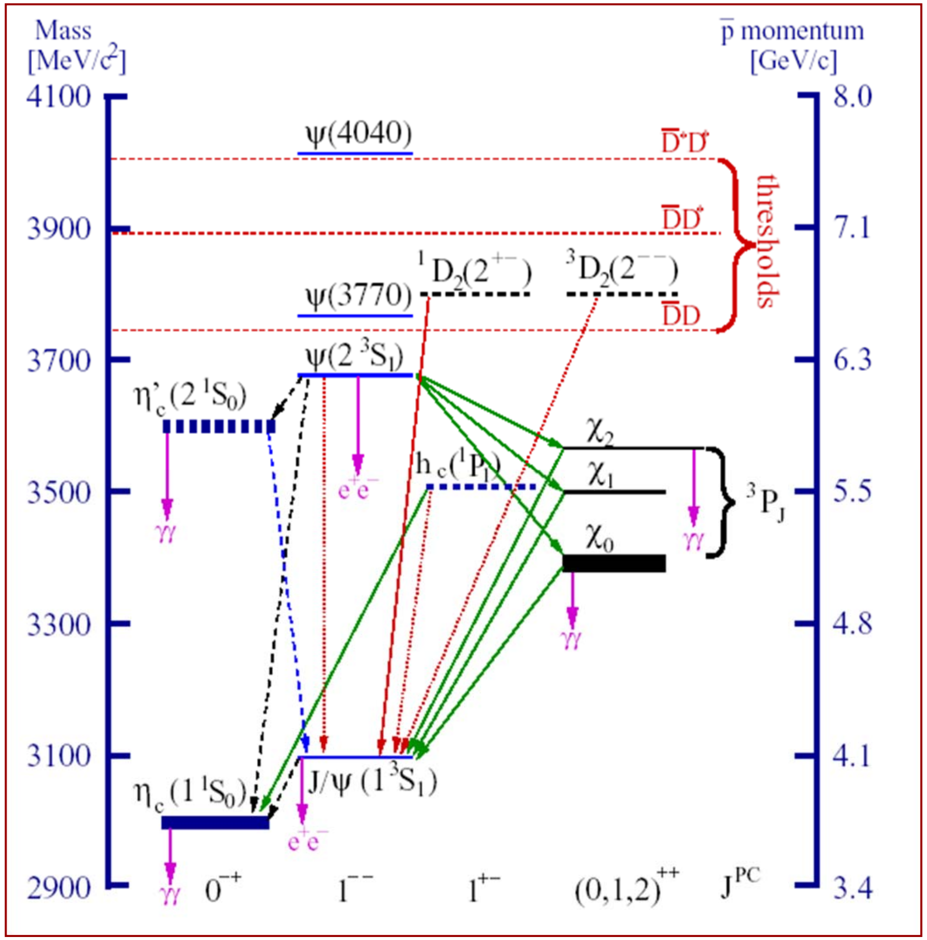
Tensor Glueball situation still confused

Charmonium Spectroscopy

Charmonium is a powerful tool for the understanding of the strong interaction. The high mass of the c quark ($m_c \sim 1.5$ GeV/c^2) makes it plausible to attempt a description of the dynamical properties of the ($c\bar{c}$) system in terms of non relativistic potential models, in which the functional form of the potential is chosen to reproduce the known asymptotic properties of the strong interaction. The free parameters in these models are determined from a comparison with experimental data.

$\beta^2 \approx 0.2 \quad \alpha_s \approx 0.3$

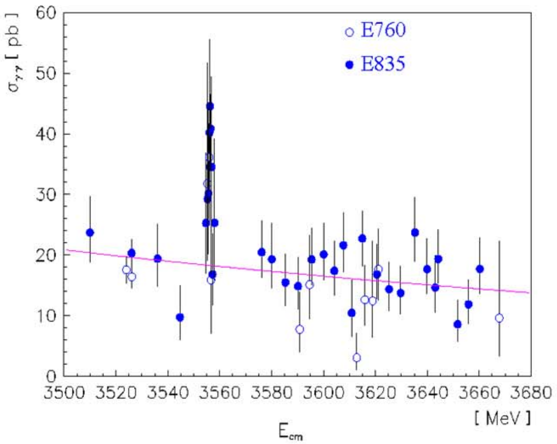
Non-relativistic potential models + Relativistic corrections + PQCD + LQCD

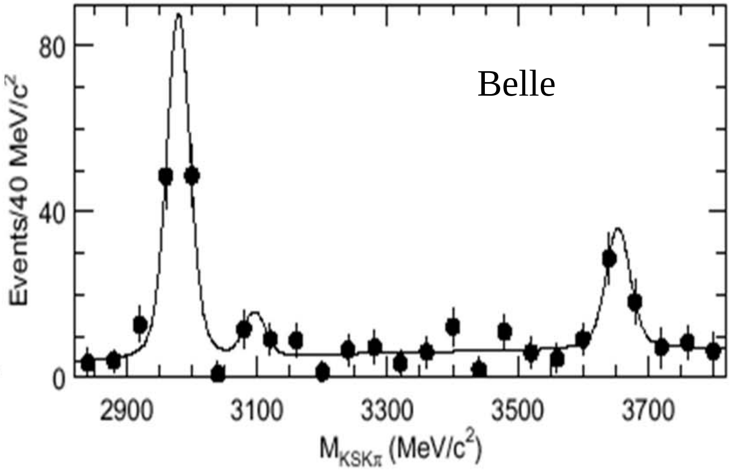


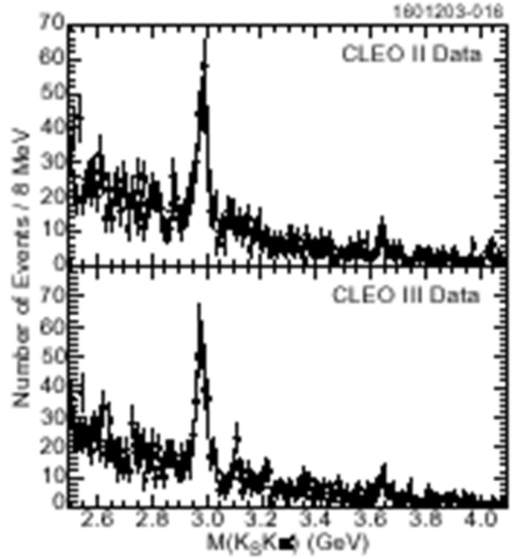
Hyperfine splitting of charmonium states gives access to V_{SS} component of quark potential model

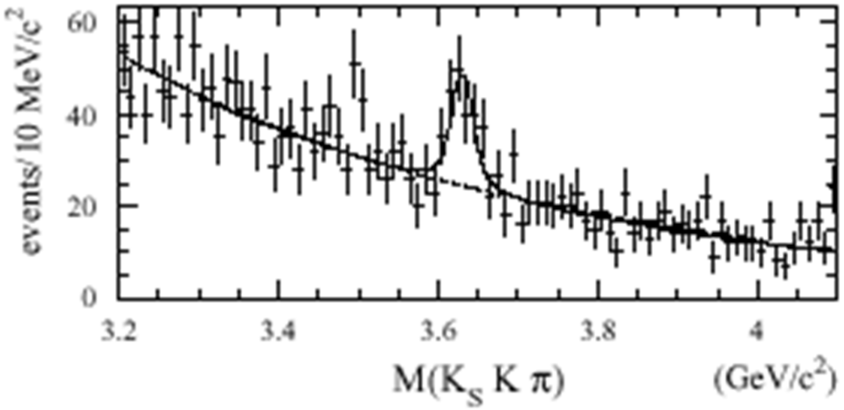
$$\Delta M_{hf}(1S)_{c\bar{c}} \equiv M(J/\psi) - M(\eta_c) = 116.6 \pm 1.0 \text{ MeV}$$

The $\eta_c(2^1S_0)$









PDG 2012

$M(\eta_c') = 3638.9 \pm 1.3$ MeV/c^2

$\Gamma(\eta'_c) = 10 \pm 4$ MeV

$$\Delta M_{hf}(2S)_{c\bar{c}} \equiv M(\psi(2S)) - M(\eta_c(2S)) = 47.2 \pm 1.3 \, MeV$$

The $h_c(^1P_1)$

- Quantum numbers $J^{PC}=1^{+-}$.
- The mass is predicted to be within a few MeV of the center of gravity of the $\chi_c(^3P_{0,1,2})$ states

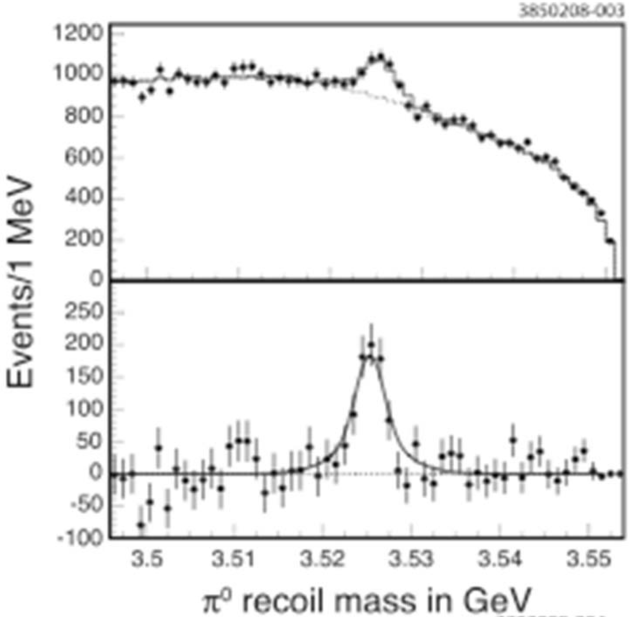
$$M_{cog} = \frac{M(\chi_0) + 3M(\chi_1) + 5M(\chi_2)}{9}$$

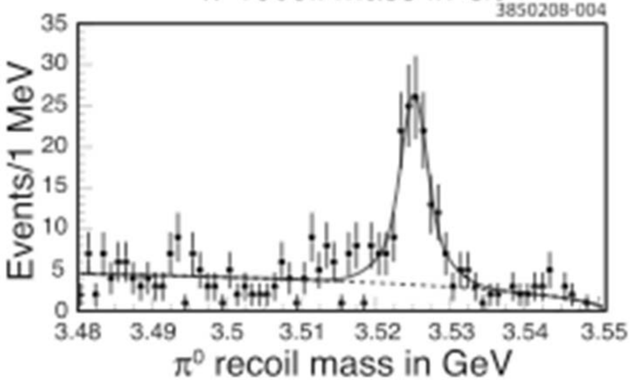
- The width is expected to be small $\Gamma(h_c) \leq 1$ MeV.
- The dominant decay mode is expected to be $\eta_c+\gamma$, which should account for $\approx$ 50 % of the total width.
- It can also decay to J/ψ:

$J/\psi + \pi^0$	violates isospin
$J/\psi + \pi^+\pi^-$	suppressed by phase space and angular momentum barrier

The $h_c(^1P_1)$

$e^+e^- \to \psi' \to \pi^0 h_c \to (\gamma\gamma)(\gamma\eta_c)$ The ψ' decay mode is isospin violating



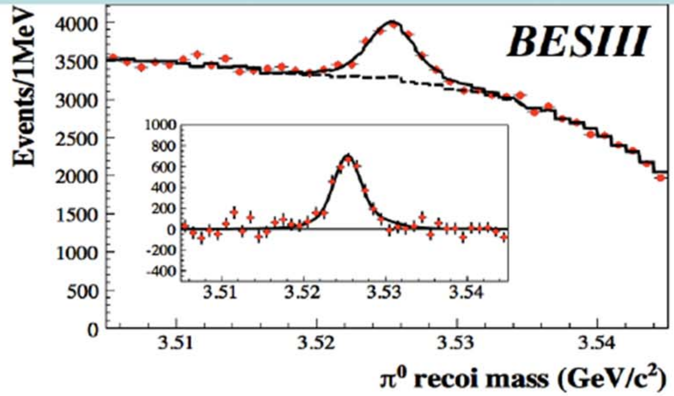


The CLEO experiment was able to find it with a significance of 13 σ in ψ' decay by means of an exclusive analysis.

The width and the BF $\psi' \to \pi^0 h_c$ were not measured.

A similar analysis, with higher statistic, was also done by BES

π^0 recoil mass spectrum in E1-tagged analysis



Significance = 18.6σ
M(h_c)=3525.40±0.13Me
V
N(h_c)= 3679±319
Γ(h_c) = 0.73±0.45MeV
χ^2/d.o.f = 33.5/36

Br($\psi' \to \pi^0 h_c$)	(8.4±1.3±1.0) ×10^{-4}
Br($h_c \to \gamma\eta_c$)	(54.3±6.7±5.2)%

$$\Delta M_{hf}(1P) \equiv M(^3P) - M(^1P) = -0.10 \pm 0.13 \pm 0.18 \text{MeV}/c^2$$

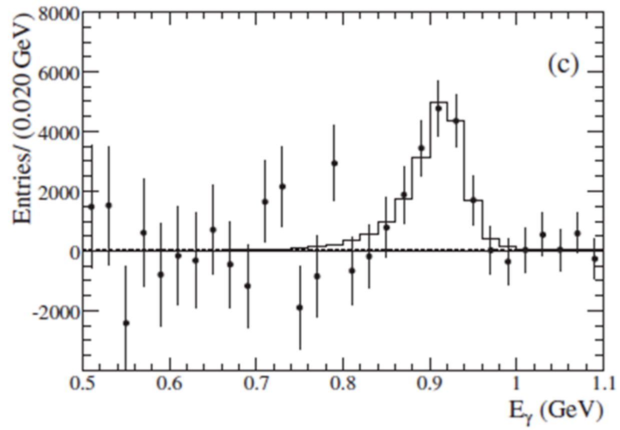
Center of gravity of P-states

The $\eta_b(^1S_0)$ Bottomonium State

The $\Upsilon(1^3S_1)$ state of bottomonium was discovered in 1977.
The ground state spin-singlet partner, $\eta_b(1^1S_0)$, has been found only recently by the BaBar Collaboration by studing $\Upsilon(3S) \to \gamma\, \eta_b(1S)$ [PRL101,071801,2008]
Then confirmed in $\Upsilon(2S) \to \gamma\, \eta_b(1S)$ [PRL103, 161801,2009]

The observation of the η_b is an important validation of Lattice QCD predictions

➔ BF ($\Upsilon(3S) \to \gamma\, \eta_b$) = (4.5 ± 0.5 [stat.] ± 1.2 [syst.]) x 10^{-4}



Mass of the $\eta_b(1S)$:

- Peak in γ energy spectrum at $E_\gamma = 921.2^{+2.1}_{-2.8}(\mathrm{stat})\,\mathrm{MeV}$
- Corresponds to η_b mass 9391.1±3.1 MeV/c^2
- The hyperfine ($\Upsilon(1S)$-$\eta_b(1S)$) mass splitting is 69.9 ± 3.1 MeV/C^2

The $h_b(^1P_1)$ Bottomonium State

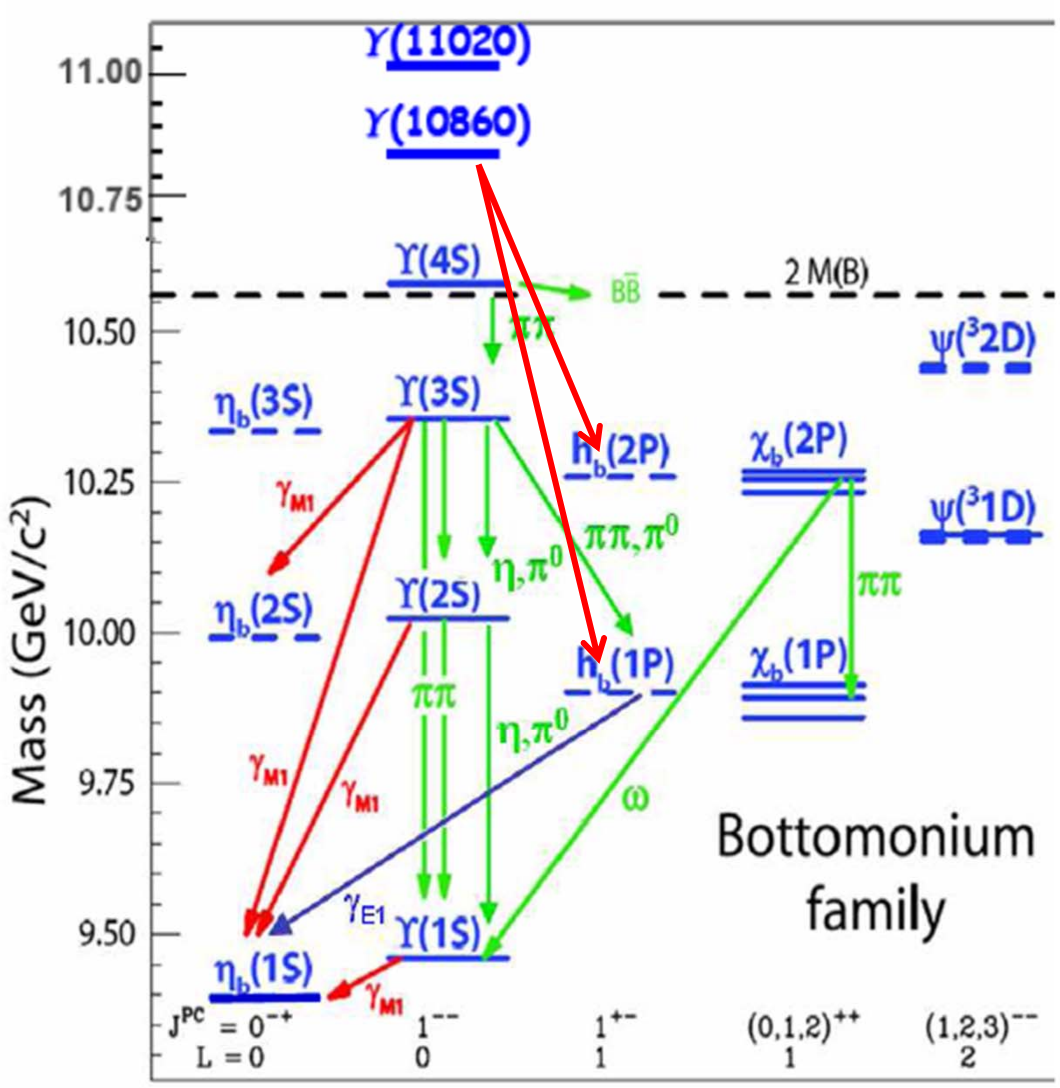
$(b\bar{b})$: S=0 L=1 $J^{PC}=1^{+-}$

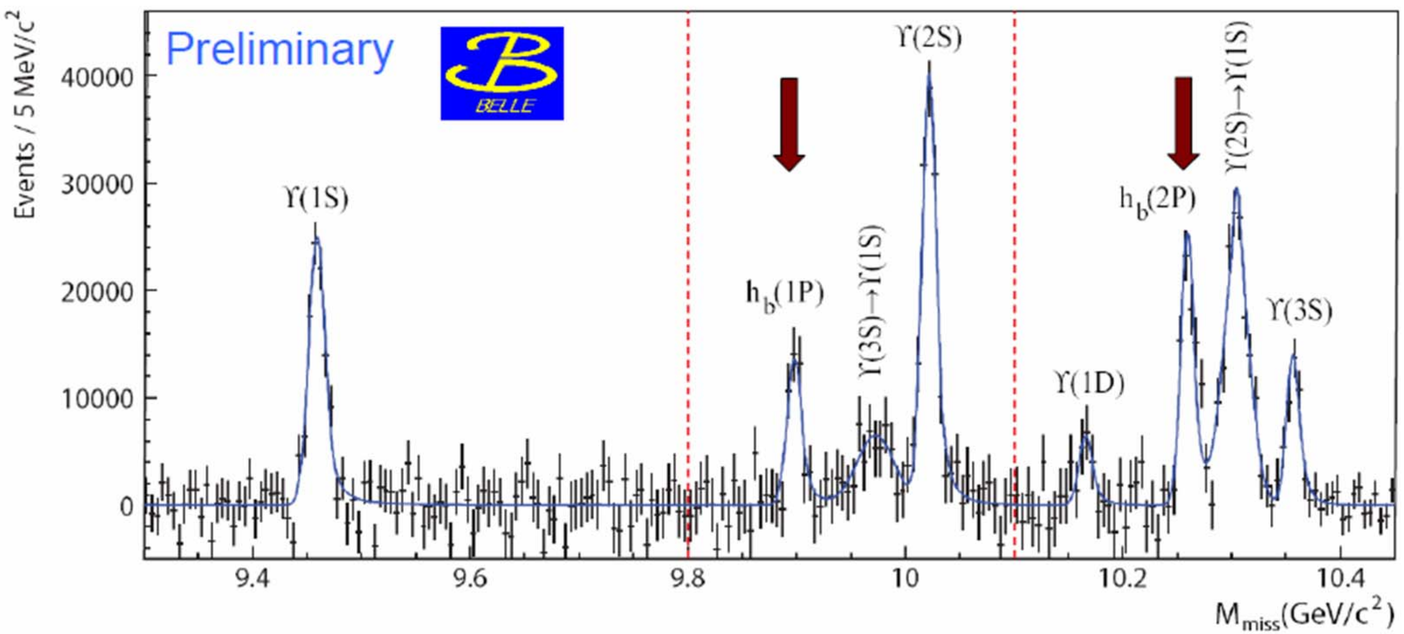
Expected mass

$\approx (M\chi_{b0} + 3\, M\chi_{b1} + 5\, M\chi_{b2}) / 9$

$\Delta M_{HF} \Rightarrow$ test of hyperfine interaction

For h_c $\Delta M_{HF} = -0.12 \pm 0.30$ MeV, expect smaller deviation for $h_b(nP)$





	Yield, 10^3	Mass, MeV/c^2	Significance
$\Upsilon(1S)$	$105.2 \pm 5.8 \pm 3.0$	$9459.4 \pm 0.5 \pm 1.0$	$18.2\,\sigma$
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	$9898.3 \pm 1.1^{+1.0}_{-1.1}$	$6.2\,\sigma$
$3S \to 1S$	56 ± 19	9973.01	$2.9\,\sigma$
$\Upsilon(2S)$	$143.5 \pm 8.7 \pm 6.8$	$10022.3 \pm 0.4 \pm 1.0$	$16.6\,\sigma$
$\Upsilon(1D)$	22.0 ± 7.8	10166.2 ± 2.6	$2.4\,\sigma$
$h_b(2P)$	$84.4 \pm 6.8^{+23.}_{-10.}$	$10259.8 \pm 0.6^{+1.4}_{-1.0}$	$12.4\,\sigma$
$2S \to 1S$	$151.7 \pm 9.7^{+9.0}_{-20.}$	$10304.6 \pm 0.6 \pm 1.0$	$15.7\,\sigma$
$\Upsilon(3S)$	$45.6 \pm 5.2 \pm 5.1$	$10356.7 \pm 0.9 \pm 1.1$	$8.5\,\sigma$

Deviations from CoG of χ_{bJ} masses

$h_b(1P)$ (1.6 ± 1.5) MeV/c^2
$h_b(2P)$ $(0.5\ ^{+1.6}_{-1.2})$ MeV/c^2

consistent with zero, as expected

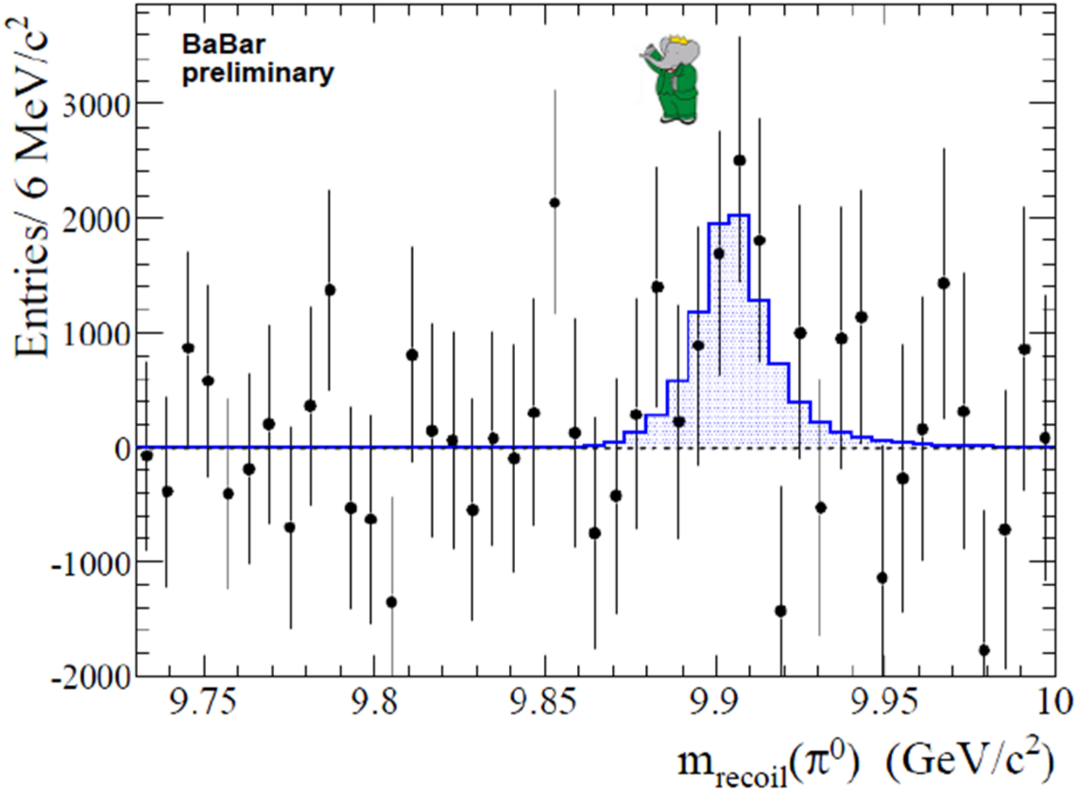
Evidence for $\Upsilon(3S)\to\pi^0 h_b(1P)$

Preliminary

122 M $\Upsilon(3S)$

arXiv:1102.4565

$m_{recoil}(\pi^0)$ background subtracted



9145±2804 signal events

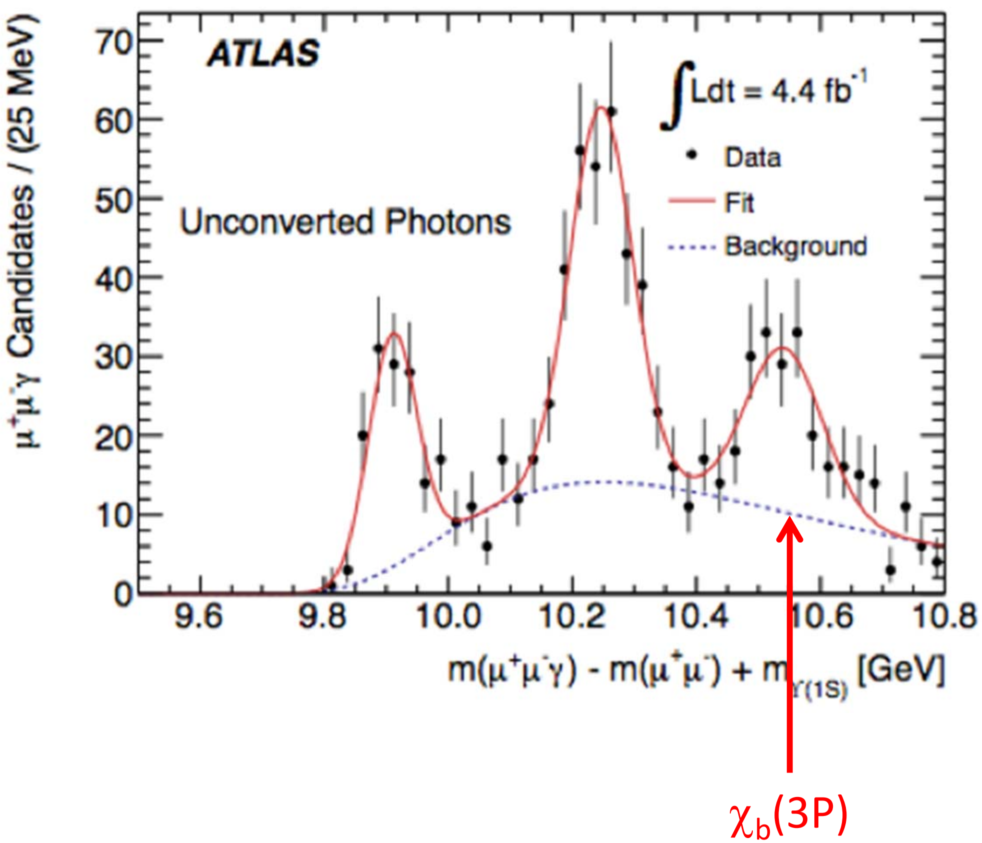
$M(h_b)$= (9902±4(stat)±1(syst)) MeV/c²
consistent with predictions

Statistical significance
(from $\sqrt{\Delta\chi^2}$): 3.2 σ
including systematic error: 3.0 σ

$\mathcal{B}(\Upsilon(3S)\to\pi^0 h_b(1P))\times\mathcal{B}(h_b(1P)\to\gamma\eta_b(1S))=(3.7\pm1.1\pm0.7)\times10^{-4}$

evaluated at the expected mass value
$M(h_b)$=9900 MeV/c²

The $\chi_b(3P)$



$\chi_b(3P) \rightarrow \Upsilon(1S) + \gamma$

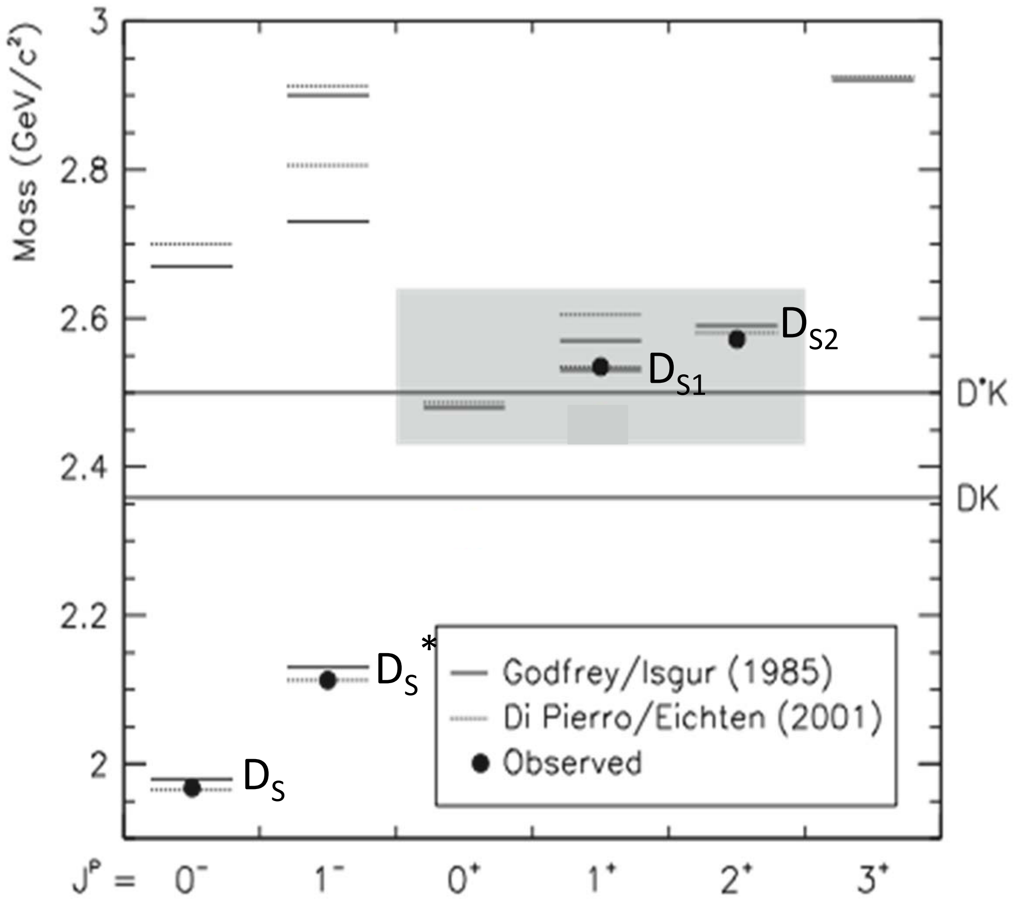
$\chi_b(3P) \rightarrow \Upsilon(2S) + \gamma$

$M(\chi_b(3P)) = 10.539 \pm 0.004\ (stat) \pm 0.008\ (syst)\ GeV/c^2$

Open Charm States

For the states c(u/d) theory and experiment were in agreement.

The quark model describes the spectrum of heavy-light systems and it was expected to be able to predict unobserved excited D_S(cs) mesons with good accuracy



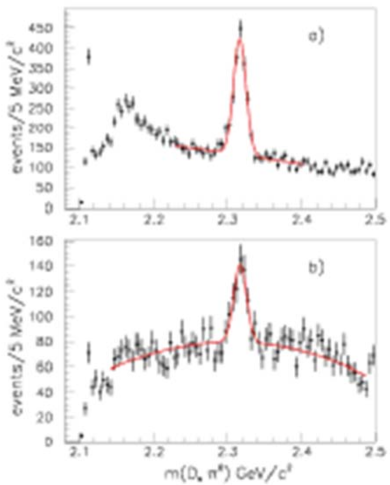
B. Aubert et al., PRD74, 032007 (2006).

Open Charm States

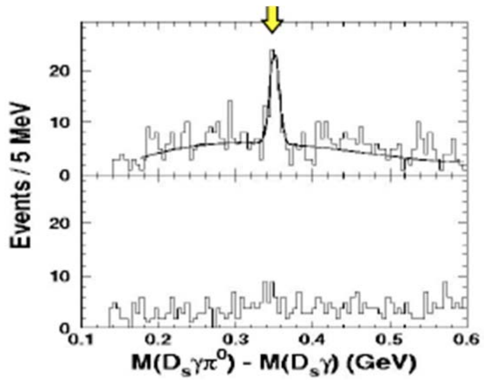
The discovery of the new D_{SJ} states has brought into question potential models

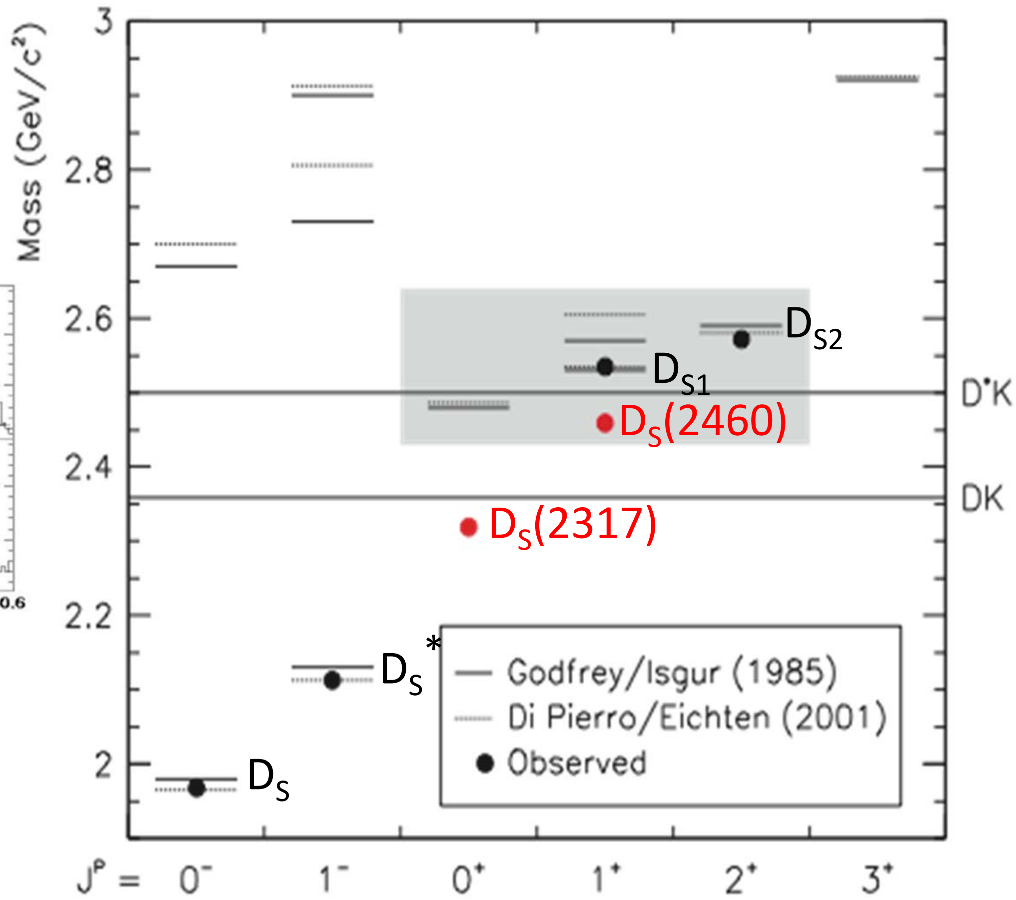
Two new states $D_S(2317)$ and $D_S(2460)$ were discovered in $e^+e^- \to cc$ events, then observed in B decays by Babar, Belle and CLEO

BaBar $D_S(2317)$



CLEO $D_S(2460)$

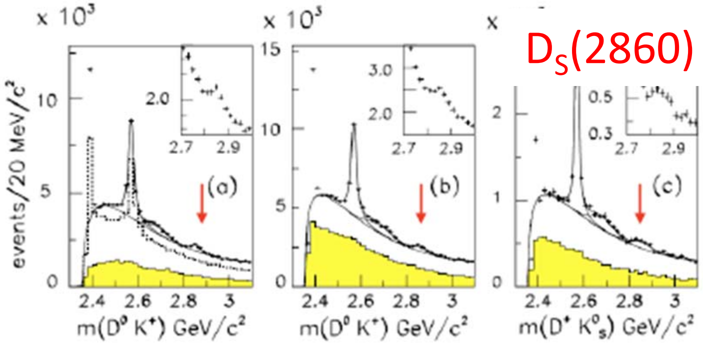




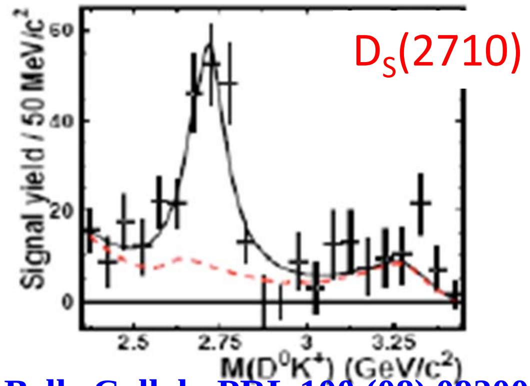
The identification of these states as the 0^+ and 1^+ cs states is difficult within the potential model

Open Charm States

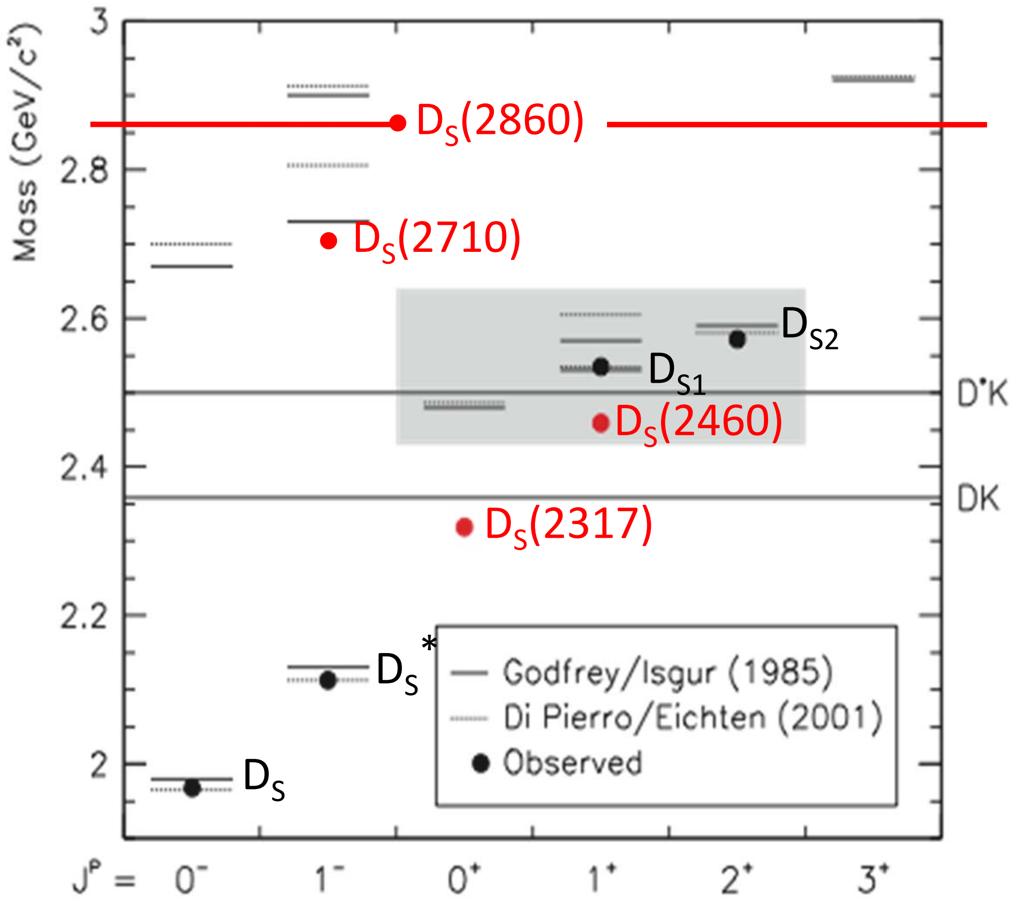
The discovery of the new D_{SJ} states continued …



BaBar Collab., PRL 97 (06) 222001



Belle Collab, PRL 100 (08) 092001



Open Charm States

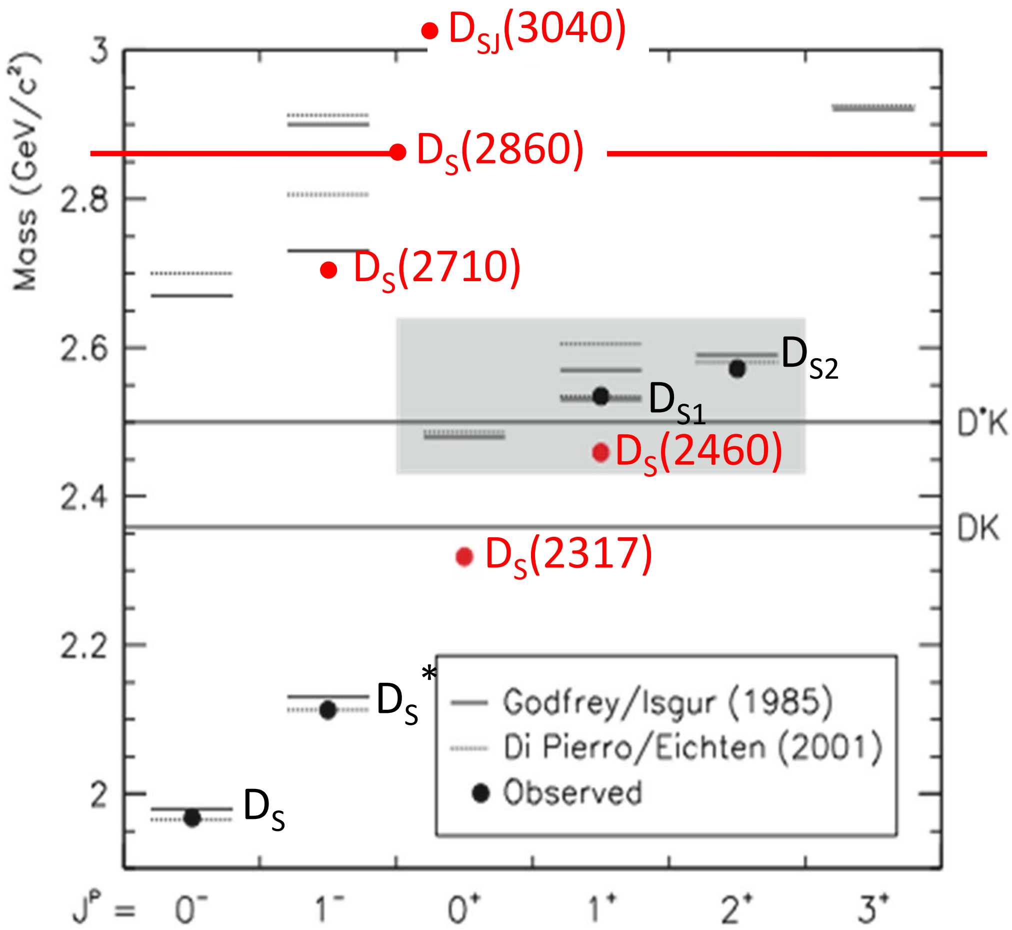
The assignment of the q.n. to the $D_S(2710)$ was possible thanks to an analysis performed by BaBar studying *DK*, *D*K* final states.

In the same analysis another broad structure in the *D*K* distribution $D_{SJ}(3040)$

$$m(D^*_{s1}(2710)^+) = 2710 \pm 2_{\rm stat}(^{+12}_{-7})_{\rm syst}\ {\rm MeV}/c^2,$$
$$\Gamma = 149 \pm 7_{\rm stat}(^{+39}_{-52})_{\rm syst}\ {\rm MeV},$$

$$m(D^*_{sJ}(2860)^+) = 2862 \pm 2_{\rm stat}(^{+5}_{-2})_{\rm syst}\ {\rm MeV}/c^2,$$
$$\Gamma = 48 \pm 3_{\rm stat} \pm 6_{\rm syst}\ {\rm MeV},$$

$$m(D_{sJ}(3040)) = 3044 \pm 8_{\rm stat}(^{+30}_{-5})_{\rm syst}\ {\rm MeV}/c^2,$$
$$\Gamma = 239 \pm 35_{\rm stat}(^{+46}_{-42})_{\rm syst}\ {\rm MeV}.$$

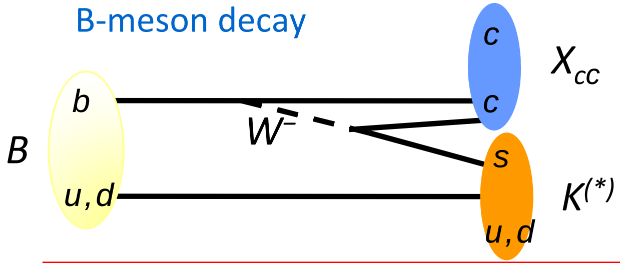


There is a problem for the potential models in describing excited states

The XYZ States

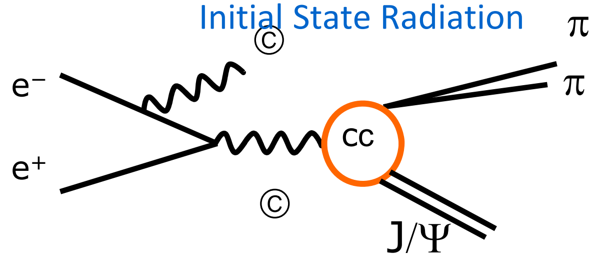
Over past few years a wealth of new states has been discovered, mostly at the B-factories, in the region above open charm threshold. These states are usually associated to charmonium, because they decay into charmonium, but their nature is not at all understood.

B-meson decay



X(3872) Belle, Babar, Cleo, CDF, D0
Y(3940) Belle, Babar
Y(4140)? CDF
Z(4430), $Z_1(4050)$, $Z_2(4250)$ } Belle

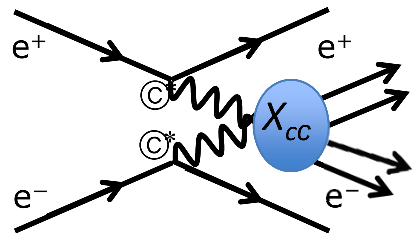
Initial State Radiation



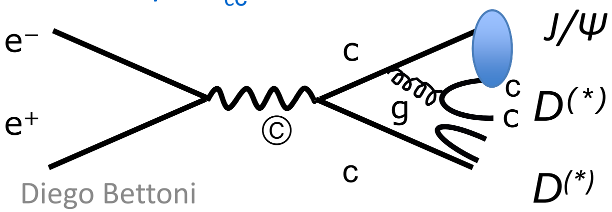
1^{--} states
X(4008)? Belle
Y(4260) BaBar, Belle, Cleo
Y(4350) BaBar, Belle
Y(4660) Belle

X(3915) Belle
Z(3930) Belle
Y(4350) Belle

γγ-collisions

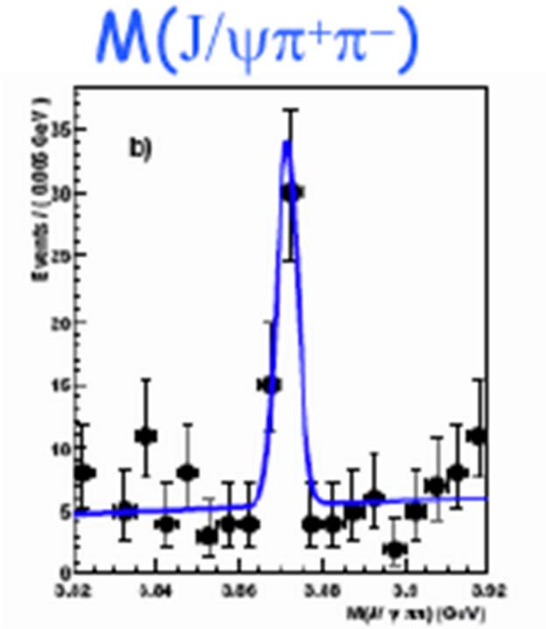


Associate production
$e^+e^- \longrightarrow J/\Psi\ X_{cc}$



X(3940) Belle
X(4160) Belle

The X(3872) Discovery



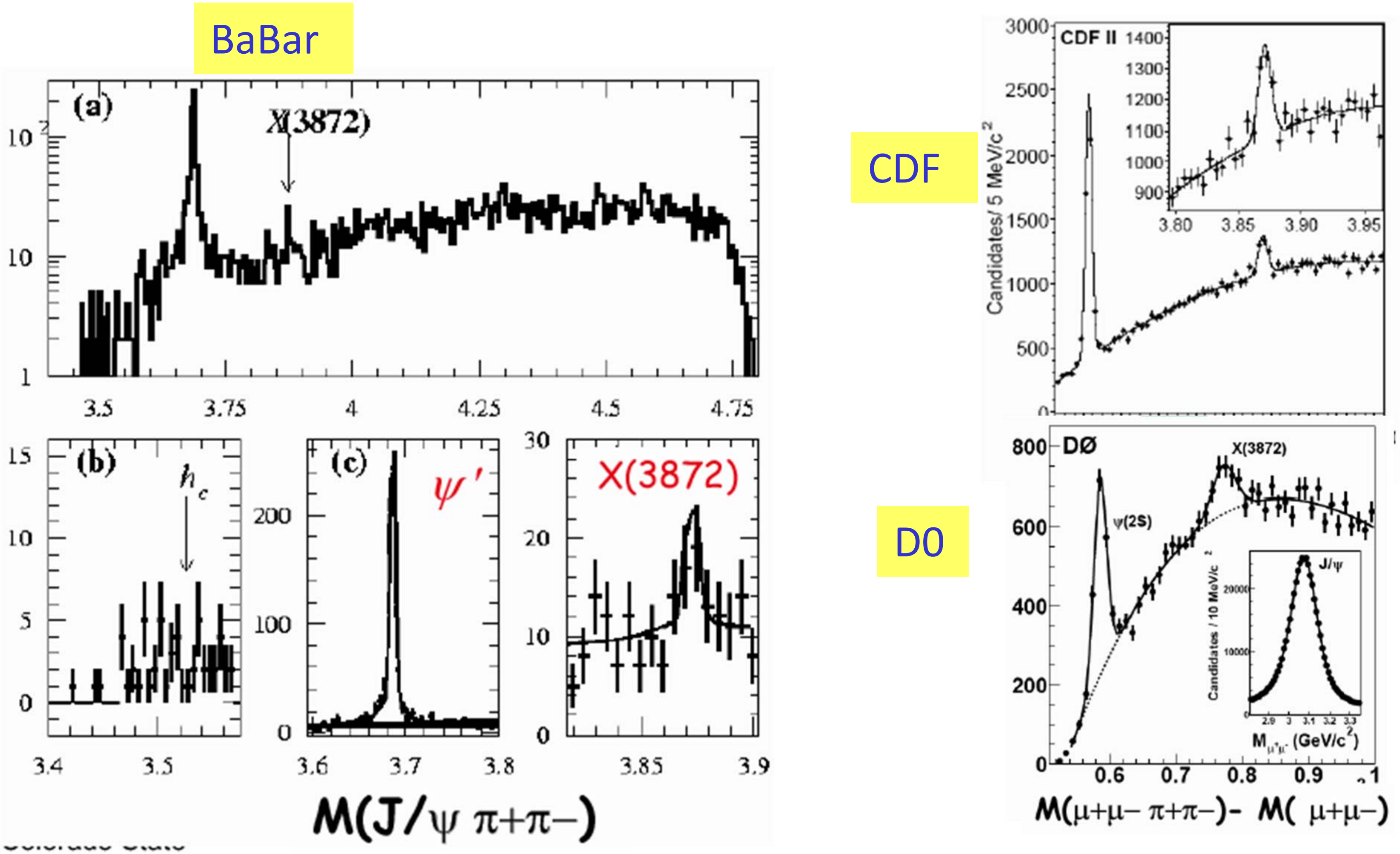
New state discovered by Belle in the hadronic decays of the B-meson:

$B^{\pm} \rightarrow K^{\pm} (J/\psi\pi^{+}\pi^{-})$, $J/\psi \rightarrow \mu^{+}\mu^{-}$ or $e^{+}e^{-}$

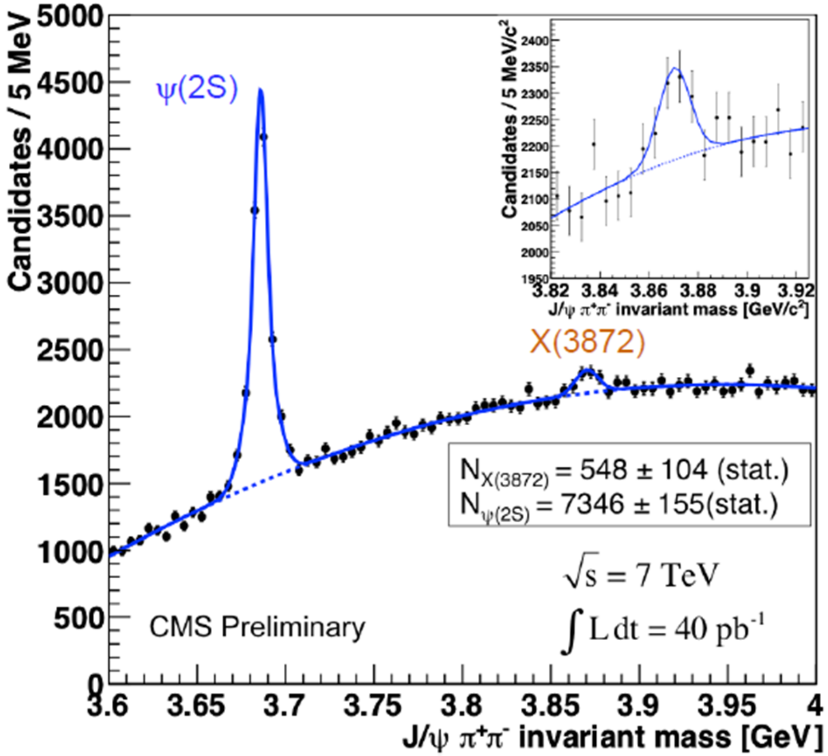
M = 3872.0 $\pm$ 0.6 $\pm$ 0.5 MeV
Γ < 2.3 MeV (90 % C.L.)

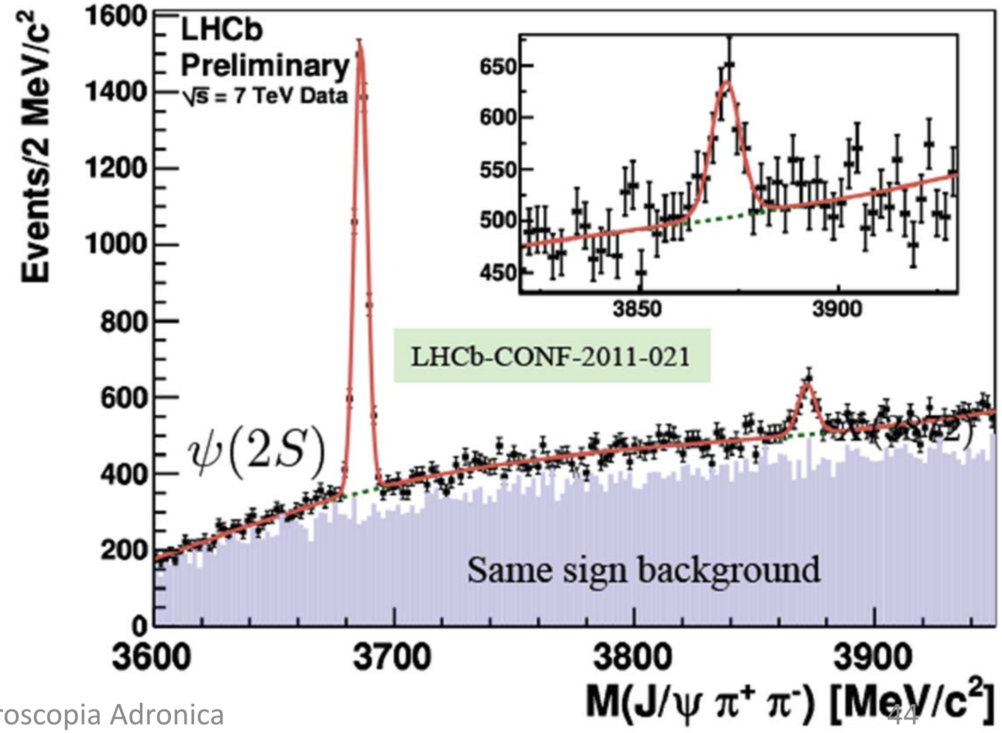
$$\frac{\Gamma\left(X(3872) \rightarrow \gamma\chi_{c1}\right)}{\Gamma\left(X(3872) \rightarrow \pi^{+}\pi^{-} J/\psi\right)} < 0.89 \quad (90\% C.L.)$$

The X(3872) Confirmation



The X(3872) at LHC





X(3872) Quantum Numbers

- Non observation in ISR (BaBar, CLEO) rules out $J^{PC}=1^{--}$.
- $\gamma J/\psi$ decay implies C = +1.
- From $\pi\pi J/\psi$ decay:
  - Angular correlations (Belle and CDF) rule out 0^{++} and 0^{-+}.
  - Mass distribution rules out 1^{-+} and 2^{-+}.
- $D^0 \bar{D}^0 \pi^0$ decay mode rules out 2^{++}.

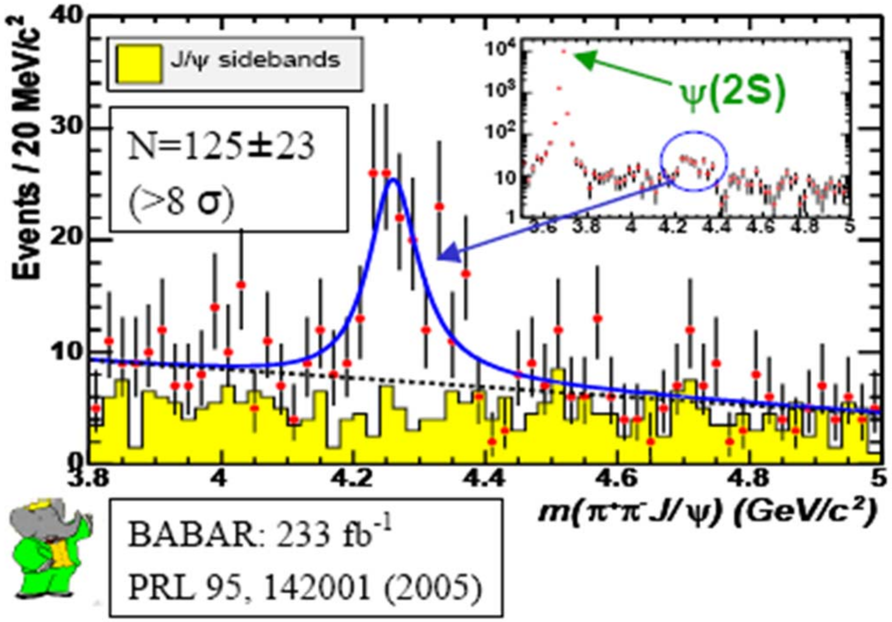
Most likely assignment is $J^{PC}=1^{++}$.

What is the X(3872) ?

- If X(3872) is a charmonium state, the most natural hypotheses are the 1^3D_2 and 1^3D_3 (1^{--}) states. In this case the non-observation of the expected radiative transitions is a potential problem, but the present experimental limits are still compatible with these hypotheses. Ruled out by quantum number assignments.
- The charmonium hybrid ($c\bar{c}g$) interpretation has been proposed by Close and Godfrey. However present calculations indicate higher mass values (around 4100 MeV/c^2) for the ground state. Absence of $J/\psi\eta$ mode a potential problem.
- A tetraquark.
- A glueball.
- Due to its closeness to the $D^0 \bar{D}^{*0}$ threshold the X(3872) could be a $D^0 \bar{D}^{*0}$ molecule. In this case decay modes such as $D^0 \bar{D}^0\pi^0$ might be enhanced. Most likely interpretation ?

Further experimental evidence needed: search for charged partners, search for further decay modes, in particular the radiative decay modes.

Y(4260) Discovery



New state discovered by BaBar in ISR events:

$e^+e^- \rightarrow \gamma_{ISR}\pi^+\pi^- J/\psi$

Assuming single resonance:

$$M = 4259 \pm 8^{+2}_{-6}\ MeV/c^2$$

$$\Gamma = 88 \pm 23^{+6}_{-4}\ MeV$$

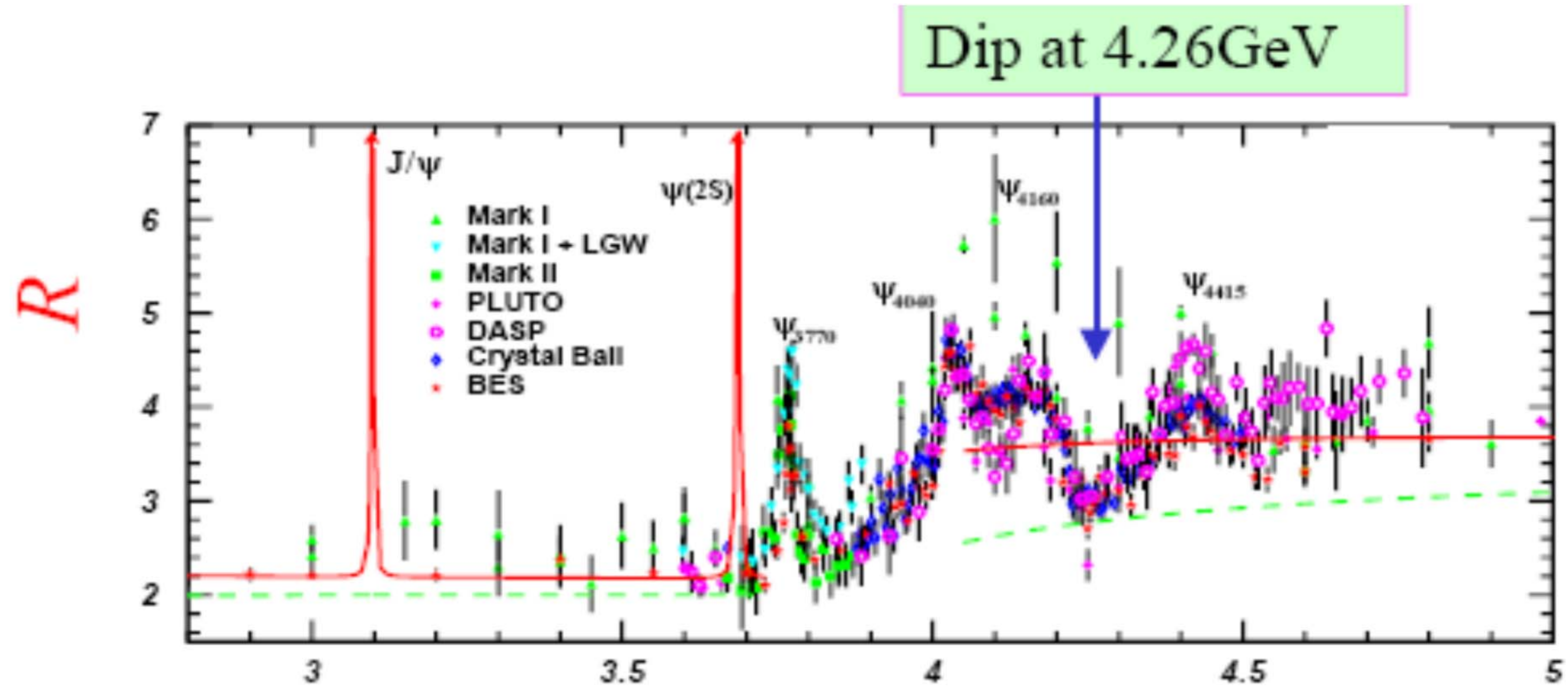
$J^{PC} = 1^{--}$

$$\sigma\left(e^+e^- \rightarrow Y, Y \rightarrow \pi^+\pi^- J/\psi\right) = (51 \pm 12)\,pb$$

$$\Gamma^Y_{ee} \times B(Y \rightarrow \pi^+\pi^- J/\psi) = \left(5.5 \pm 1.0^{+0.8}_{-0.7}\right) eV$$

Properties of Y(4260)

Confirmed by CLEO, CLEO III, Belle
Local minimum in $e^+e^- \rightarrow$ hadrons cross section.

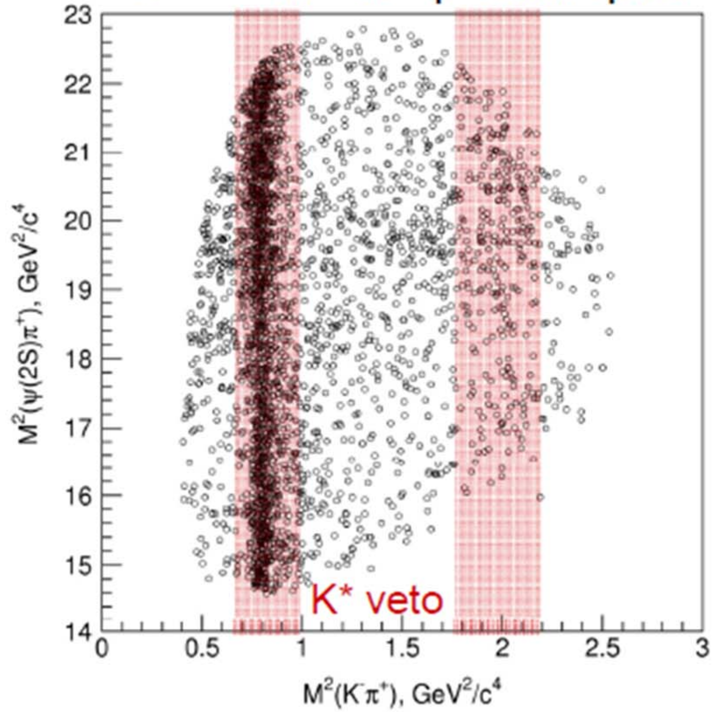


No available vector state slot in charmonium spectrum

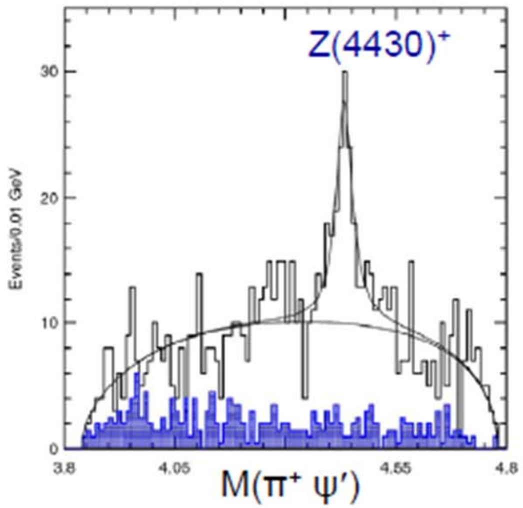
Z(4430)$^+$

Observation of Z(4430)$^+ \to \pi^+\psi'$

Belle, PRL100,142001



projection with K* veto applied



$$M = (4433 \pm 4 \pm 2)\ \mathrm{MeV}/c^2$$
$$\Gamma = (45^{+18+30}_{-13-13})\ \mathrm{MeV}$$

$$\mathcal{B}(\bar{B}^0 \to K^- Z(4430)^+) \times \mathcal{B}(Z(4430)^+ \to \pi^+\psi') = (4.1 \pm 1.0 \pm 1.4) \times 10^{-5}$$

Significance 6.5σ.

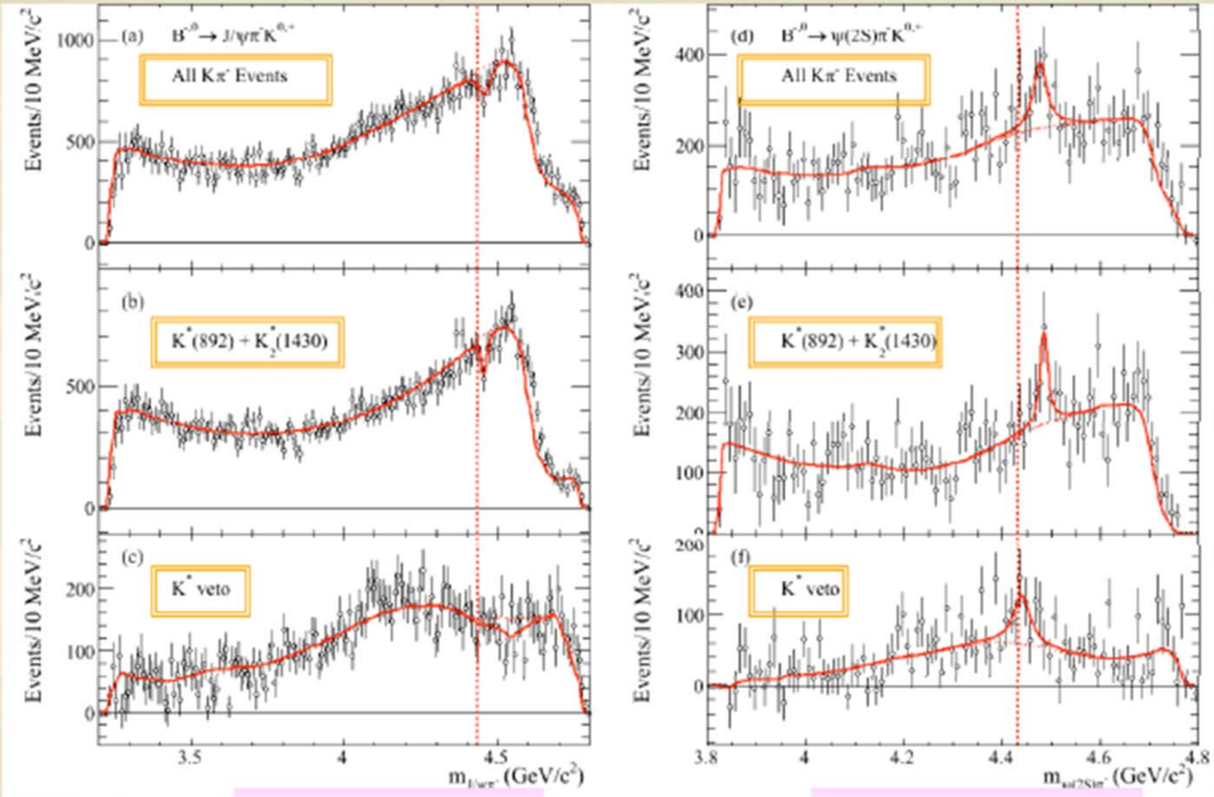
Interference of L=0,1,2 waves in Kπ$^+$ system can not produce such a narrow structure.

R. Mizuk, La Thuile

FIT TO ψπ DISTRIBUTION

Z(4430)⁻

Four free parameters; m_Z, Γ_Z, N_Z, and $N_{K\pi^-,bkg}$



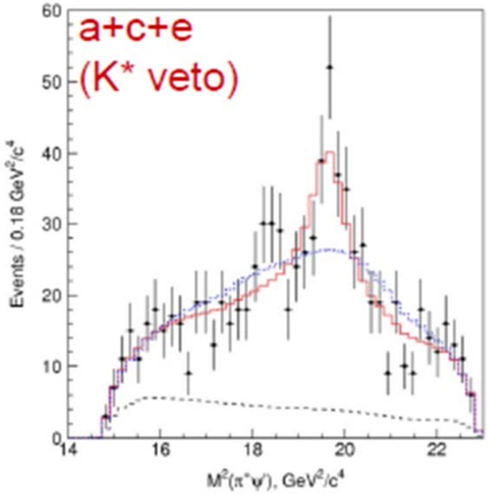
NO OR NEGATIVE SIGNAL	m=4476±8, Γ=32±16, 2.7σ
NO OR NEGATIVE SIGNAL	m=4483±3, Γ=17±12, 2.5σ
NO OR NEGATIVE SIGNAL	m=4439±8, Γ=41±33, 1.9σ

$m_{J/\psi\pi^-}$ (GeV/c^2) $m_{\psi(2S)\pi^-}$ (GeV/c^2)

No significant Z(4430)⁻ signal is observed

R. Mizuk, La Thuile

Z(4430)$^+$



Preliminary

Dalitz analysis results

$$M = (4443^{+15+17}_{-12-13})\ \mathrm{MeV}/c^2$$

$$\Gamma = (109^{+86+57}_{-43-52})\ \mathrm{MeV}$$

$$\mathcal{B}(\bar{B}^0 \to K^- Z(4430)^+) \times \mathcal{B}(Z(4430)^+ \to \pi^+ \psi') = (3.2^{+1.8+5.3}_{-0.9-1.6}) \times 10^{-5}$$

Significance 6.4σ

Belle confirms Z(4430) signal

Belle and BaBar data are not incosistent, but due to a different understanding of the background the significance of the Z(4430) changes dramatically.

Outlook and Conclusions

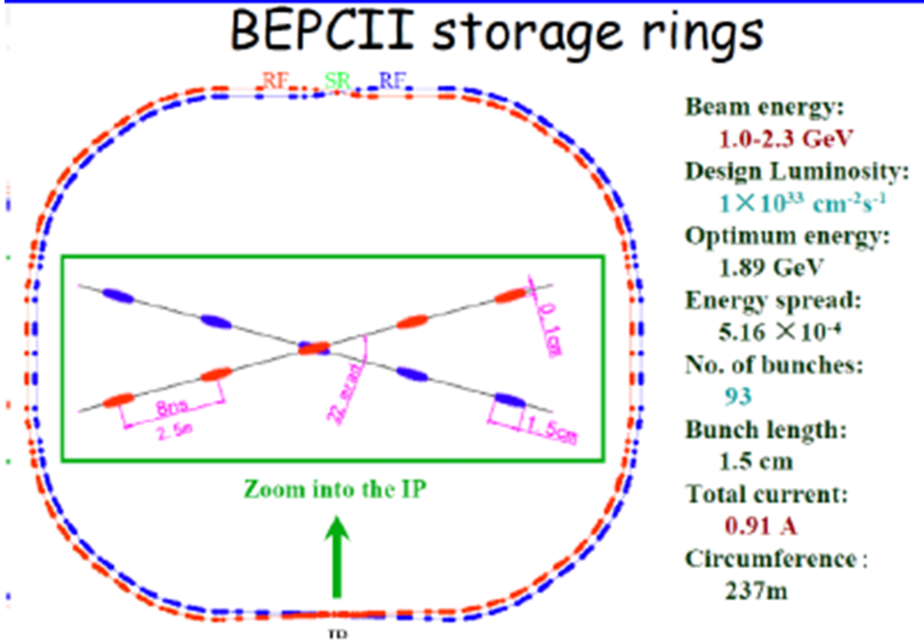
The future

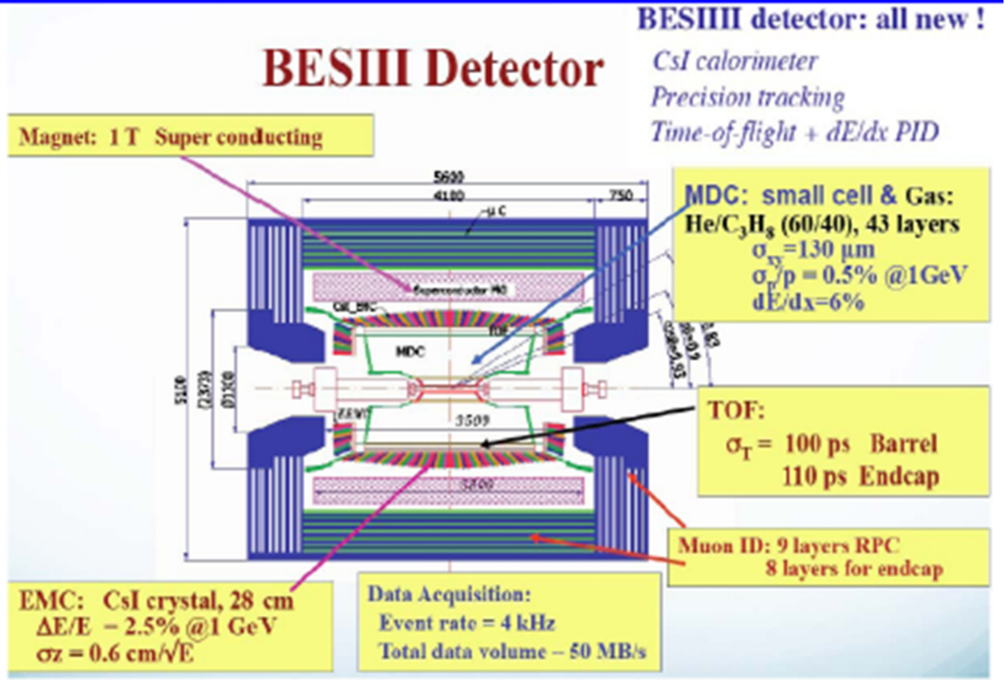
The $\overline{\text{P}}$ANDA Experiment at FAIR

The Future

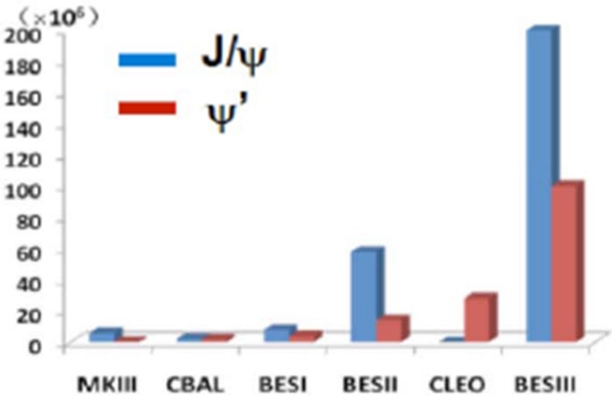
- BES III at BEPC
- SuperB, Belle 2
- LHC
- JLAB 12 GeV upgrade
- $\overline{\text{P}}$ANDA at FAIR

BEPCII/BESIII

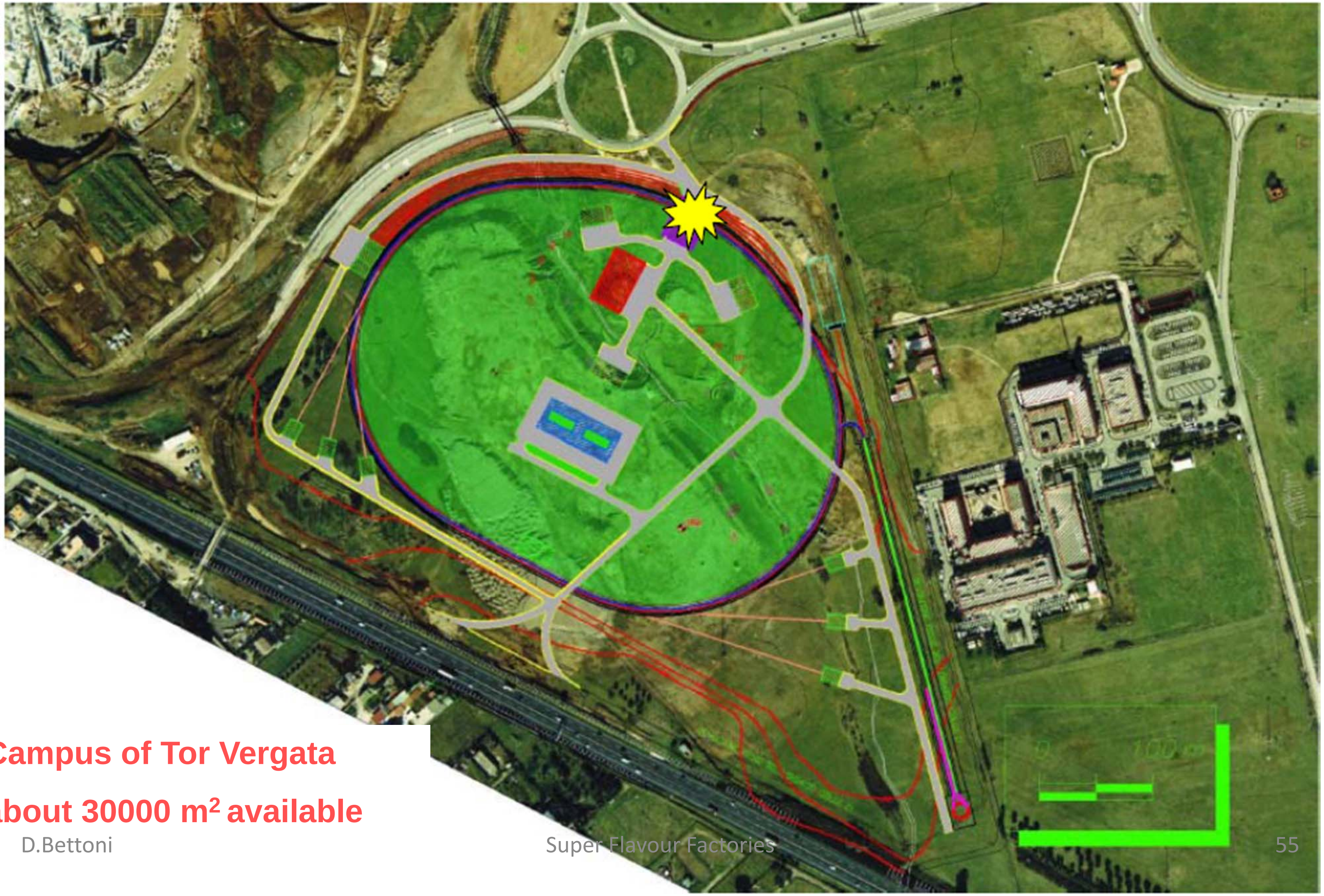




- So far BESIII has collected :
  - 2009: 225 Million J/ψ
  - 2009: 106 Million ψ'
  - 2010-11: 2.9 fb^{-1} $\psi(3770)$ (3.5 × CLEO-c 0.818fb^{-1})
  - May 2011: 0.5fb^{-1} @4010 MeV (one month) for Ds and XYZ spectroscopy
- BESIII will also collect:
  - more J/ψ, ψ', $\psi(3770)$
  - data at higher energies (for XYZ searches, R scan and Ds physics)



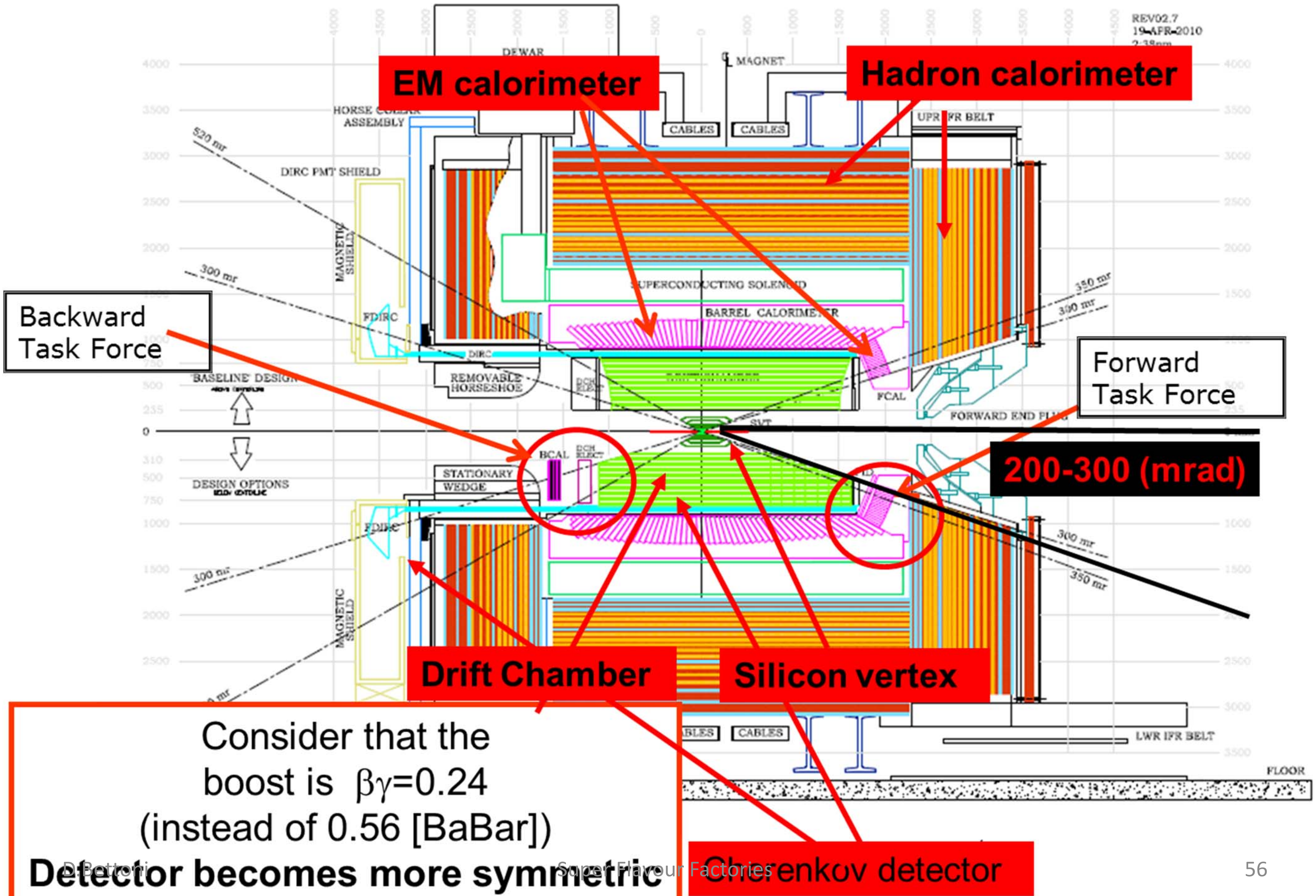
SuperB



Campus of Tor Vergata

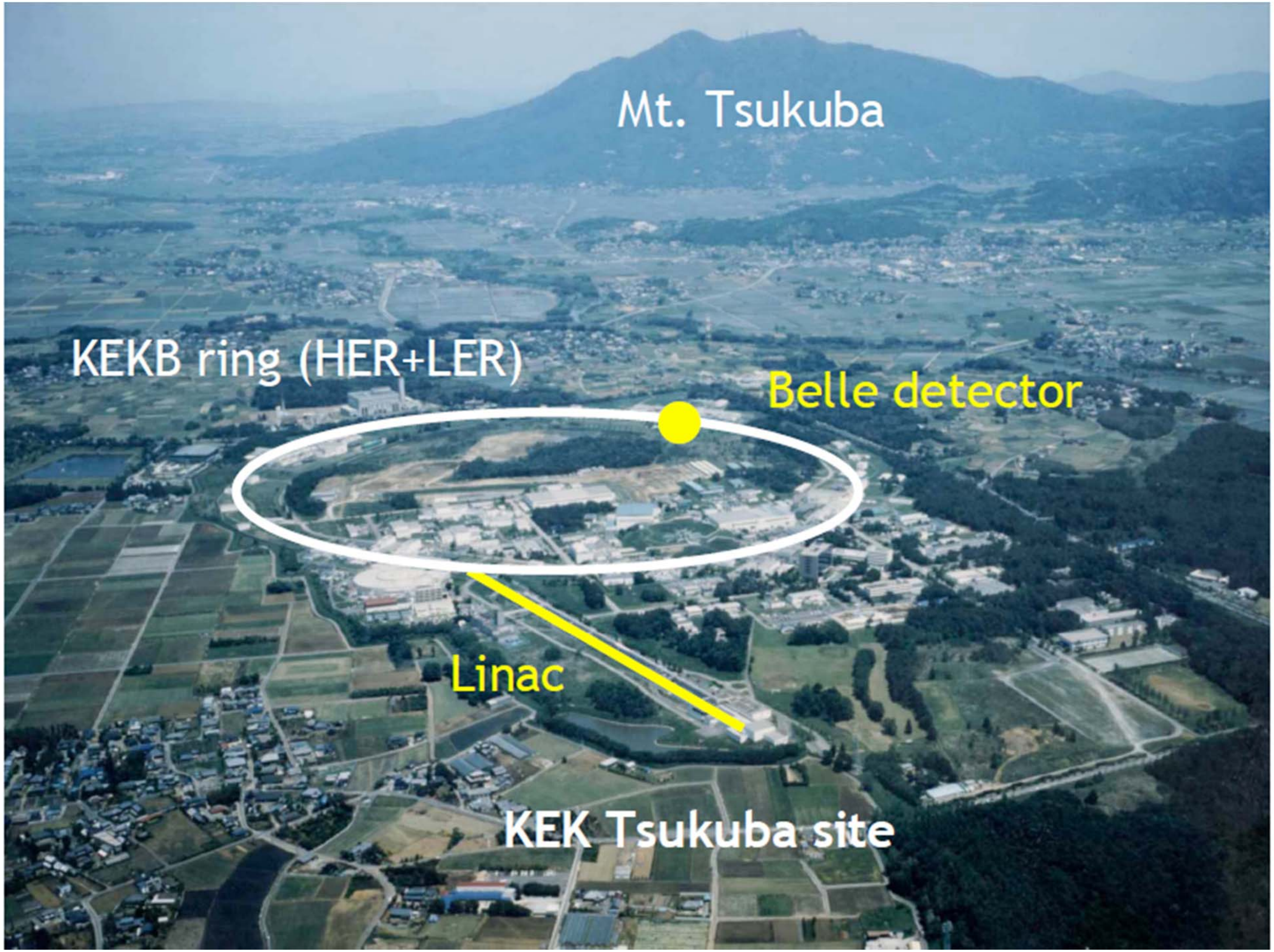
about 30000 m^2 available

Detector Design (with *fewer* options)

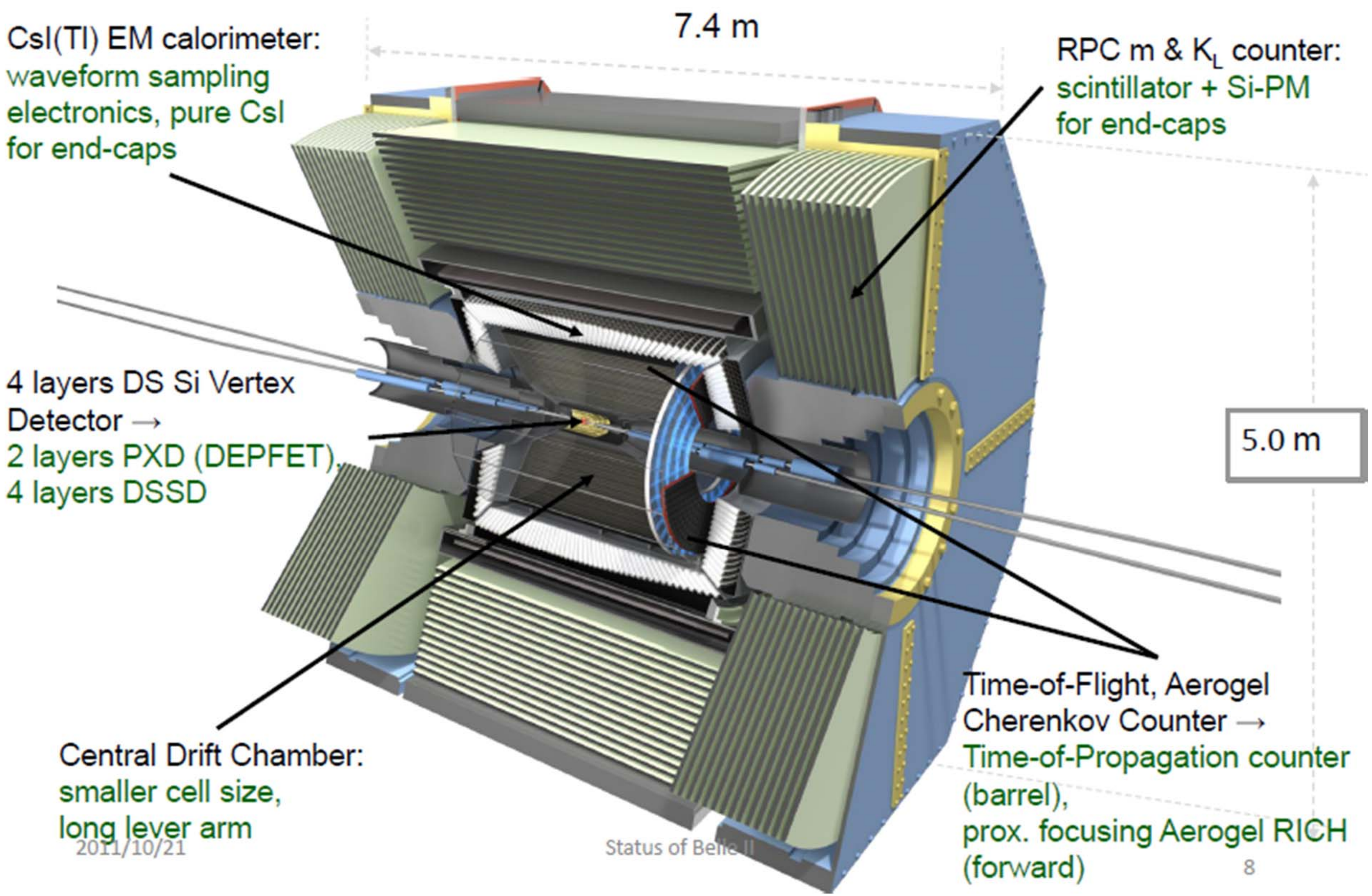


Consider that the boost is $\beta\gamma$=0.24 (instead of 0.56 [BaBar])

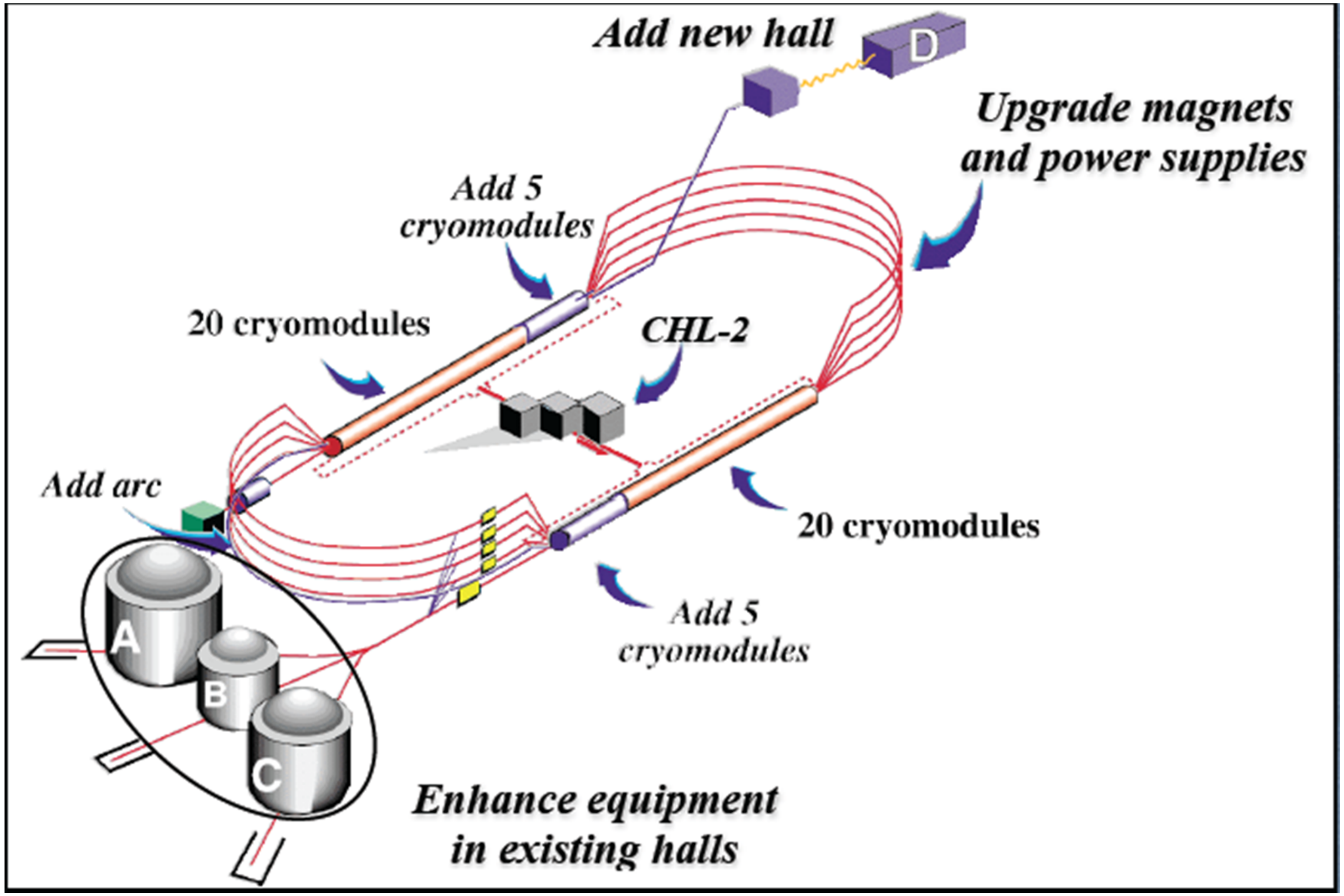
Detector becomes more symmetric


Mt. Tsukuba
KEKB ring (HER+LER)
Belle detector
Linac
KEK Tsukuba site

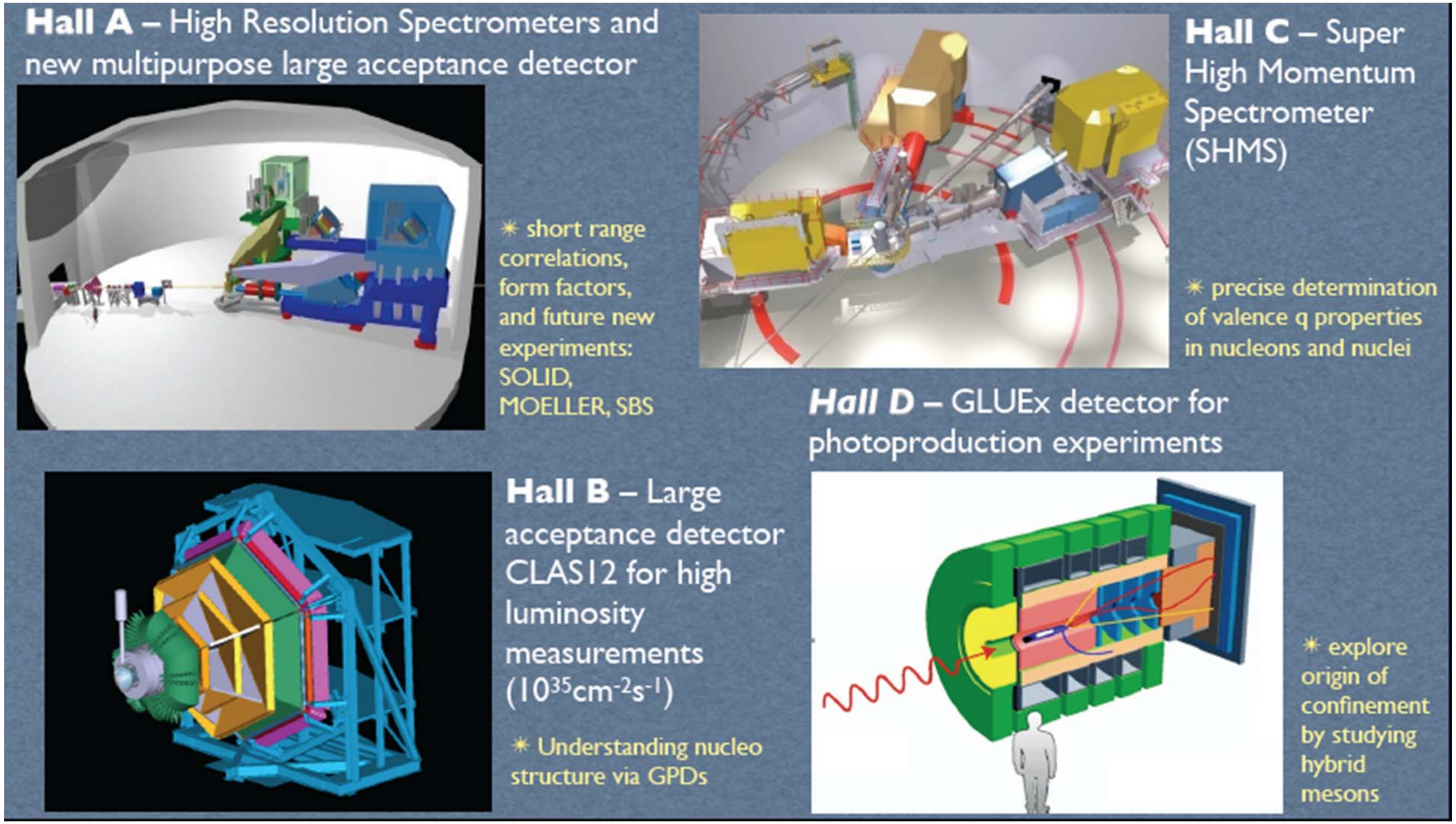
Belle II: design concept



The JLAB 12 GeV Upgrade



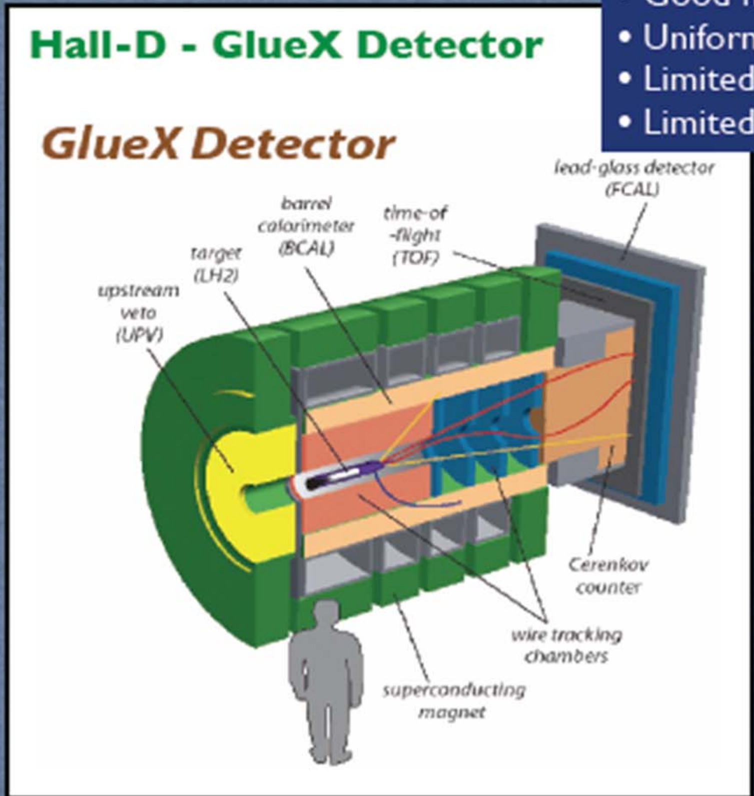
The 12 GeV Equipment



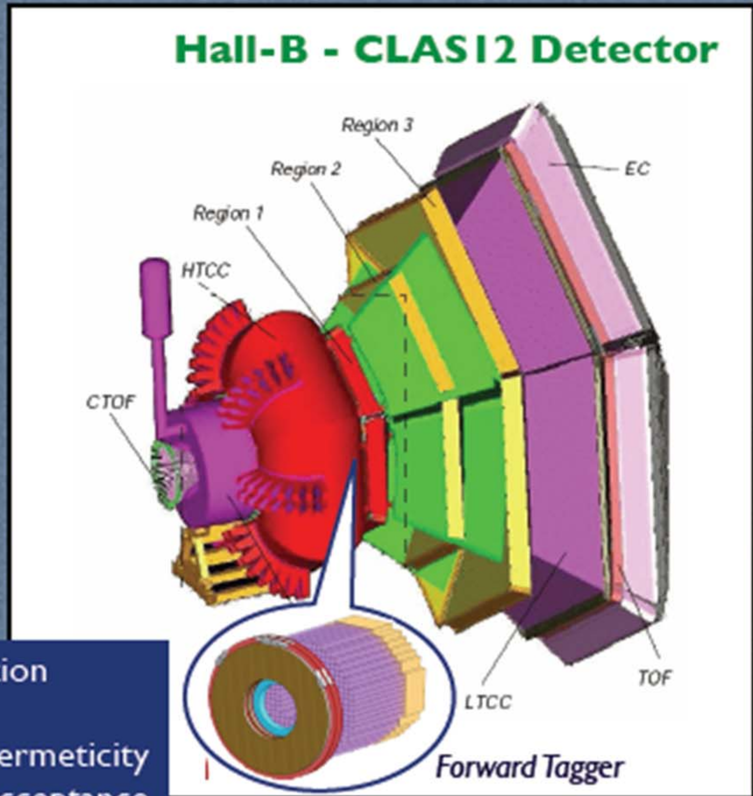
M. Battaglieri – Erice 2011

Meson spectroscopy with photons at JLab-12 GeV

- Determination of JPC of meson states requires PWA
- Decay and production of exclusive reactions
- Good acceptance, energy resolution, particle identification



- Good hermeticity
- Uniform acceptance
- Limited resolution
- Limited pID



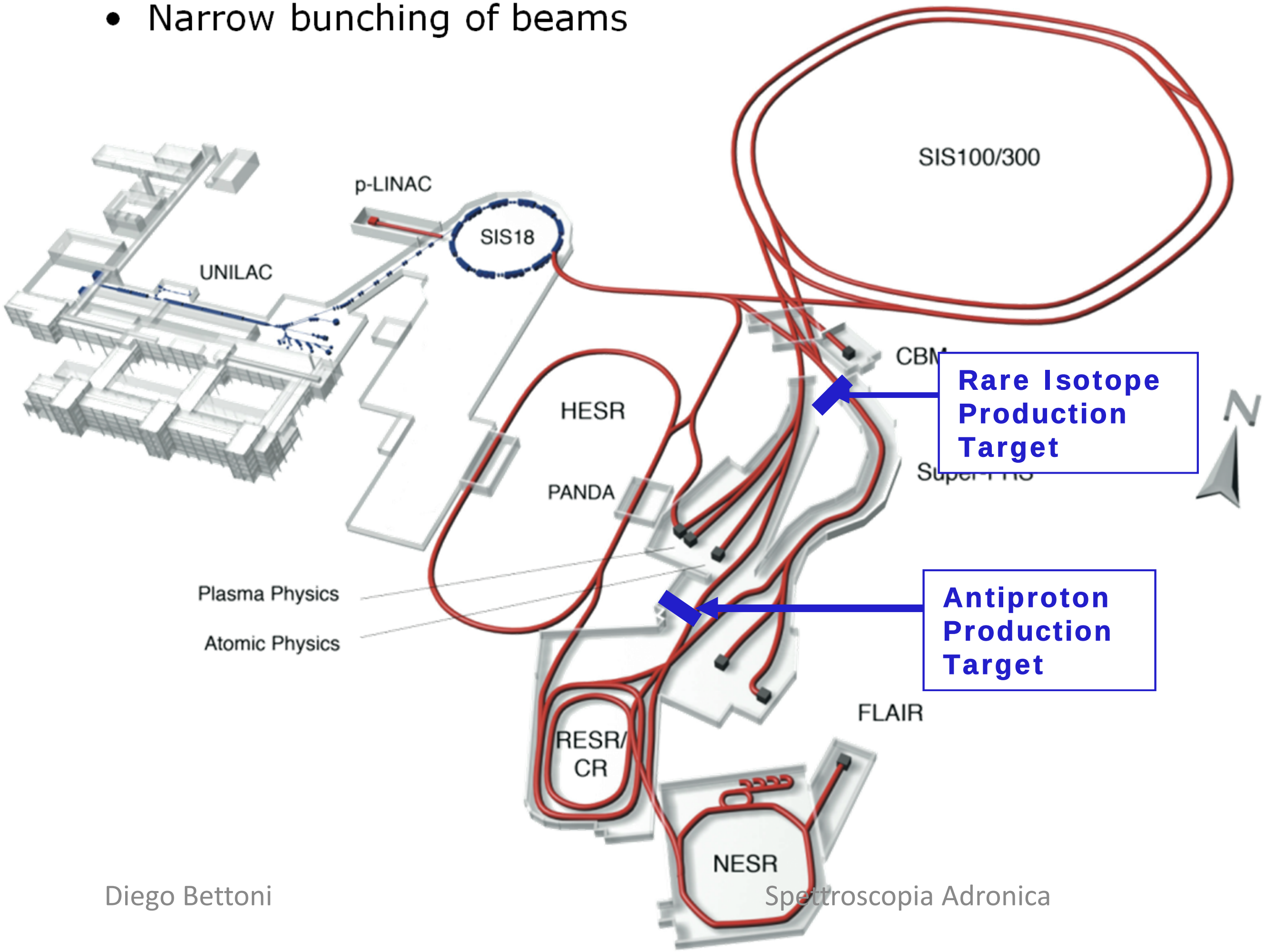
- Good resolution
- Good pID
- Reasonable hermeticity
- Un-uniform acceptance

M. Battaglieri – Erice 2011

The FAIR Complex

Key Technologies

- Beam cooling
- Rapidly cycling superconducting magnets
- Narrow bunching of beams



Primary Beams

- **All elements** up to Uranium
- Factor 100-**1000** over present intensity
- **50ns bunching**

Secondary Beams

- **Rare isotope beams** up to a factor **of 10 000** in intensity over present
- Low and high energy **antiprotons**

Storage and Cooler Rings

- Rare isotope beams
- e^-– Rare Isotope collider
- $\mathbf{10^{11}}$ stored and cooled antiprotons for **Antimatter** creation

High-Energy Storage Ring

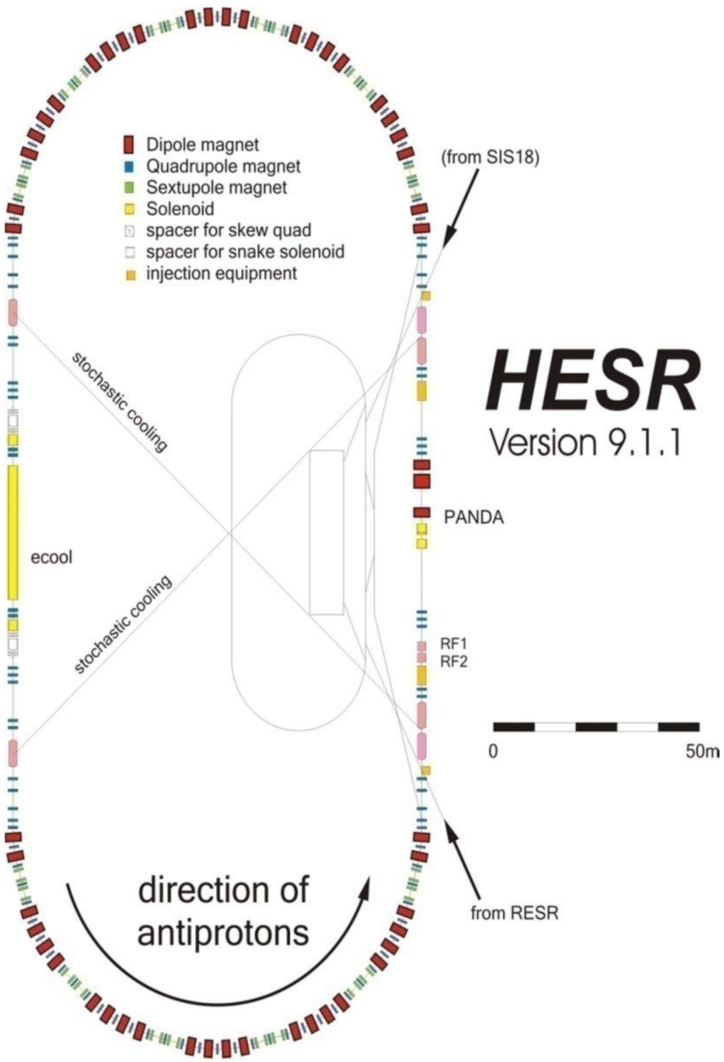
- Production rate 2x10^7/sec
- P_{beam} = 1 - 15 GeV/c
- N_{stored} = 5x10^{10} $\bar{p}$
- Internal Target

High resolution mode

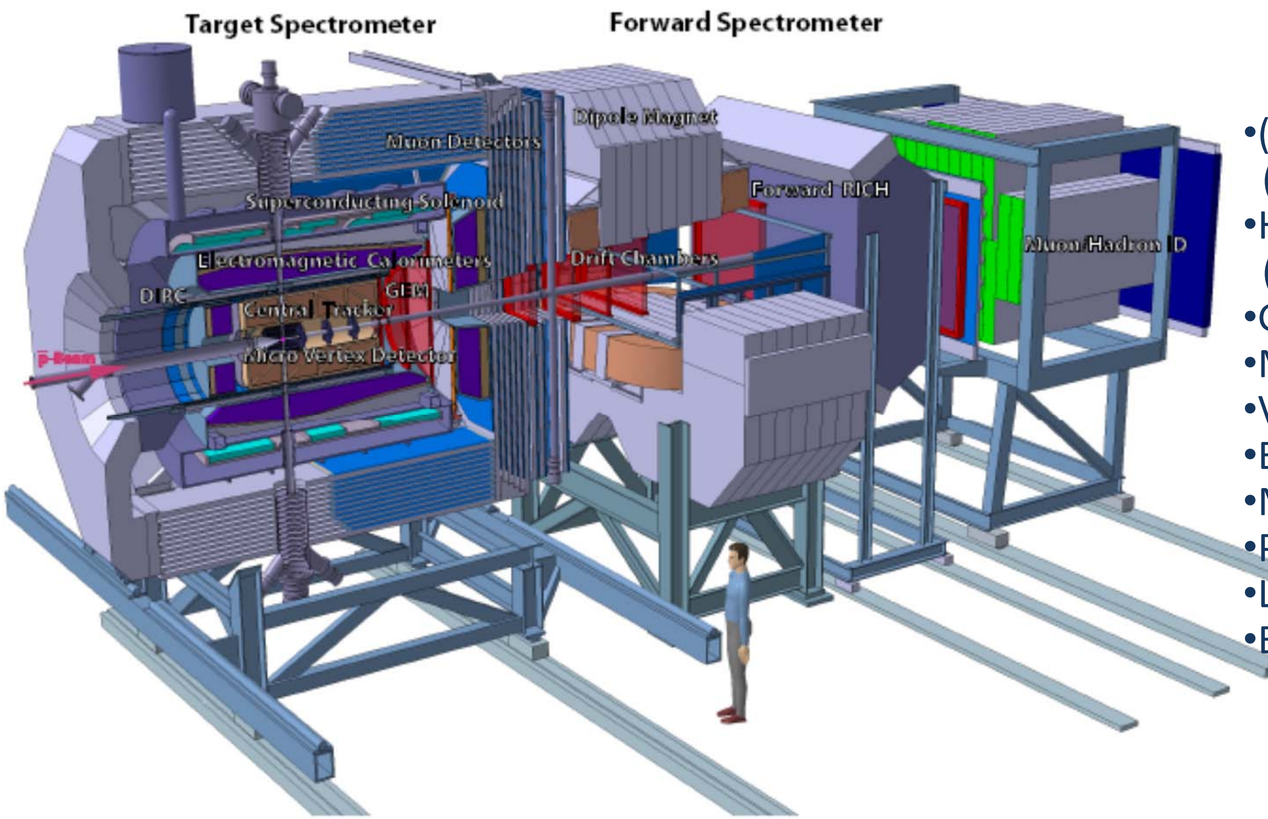
- $\delta p/p \sim 10^{-5}$ (electron cooling)
- Lumin. = 10^{31} cm^{-2} s^{-1}

High luminosity mode

- Lumin. = 2 x 10^{32} cm^{-2} s^{-1}
- $\delta p/p \sim 10^{-4}$ (stochastic cooling)



$\bar{\text{P}}$ANDA Detector



Detector Requirements

- (Nearly) 4π solid angle coverage (partial wave analysis)
- High-rate capability (2×10^7 annihilations/s)
- Good PID (γ, e, μ, π, K, p)
- Momentum resolution ($\approx$ 1 %)
- Vertex reconstruction for D, K^0_s, Λ
- Efficient trigger
- Modular design
- Pointlike interaction region
- Lepton identification
- Excellent calorimetry
  - Energy resolution
  - Sensitivity to low-energy photons

$\overline{\mathrm{P}}$ANDA Physics Program

- HADRON SPECTROSCOPY
  - CHARMONIUM
  - GLUONIC EXCITATIONS
  - HEAVY-LIGHT SYSTEMS
  - STRANGE AND CHARMED BARYONS
- NON PERTURBATIVE QCD DYNAMICS
- HADRONS IN THE NUCLEAR MEDIUM
- NUCLEON STRUCTURE
  - GDA
  - DRELL-YAN
  - PROTON ELECTROMAGNETIC FORM FACTORS

FAIR/PANDA/Physics Book i

Physics Performance Report for:

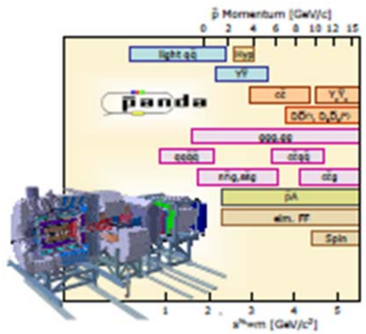
$\overline{\mathrm{P}}$ANDA

(AntiProton Annihilations at Darmstadt)

Strong Interaction Studies with Antiprotons

$\overline{\mathrm{P}}$ANDA Collaboration

To study fundamental questions of hadron and nuclear physics in interactions of antiprotons with nucleons and nuclei, the universal $\overline{\mathrm{P}}$ANDA detector will be build. Gluonic excitations, the physics of strange and charm quarks and nucleon structure studies will be performed with unprecedented accuracy thereby allowing high-precision tests of the strong interaction. The proposed $\overline{\mathrm{P}}$ANDA detector is a state-of-the-art internal target detector at the HESR at FAIR allowing the detection and identification of neutral and charged particles generated within the relevant angular and energy range.
This report presents a summary of the physics accessible at $\overline{\mathrm{P}}$ANDA and what performance can be expected.



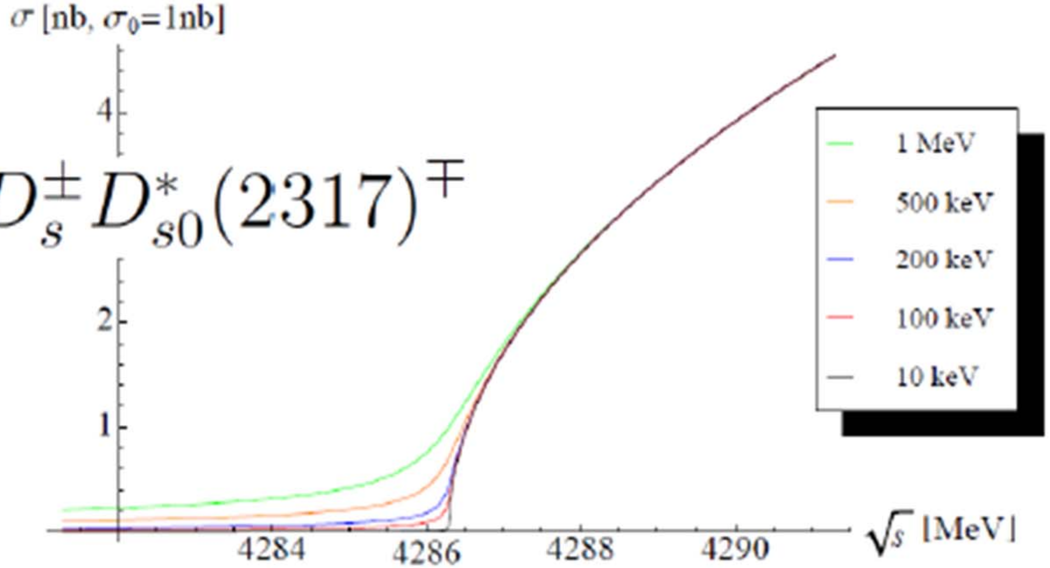
ArXiV:0903.3905

Excitation Function Scan of the D_{s0}*(2317)

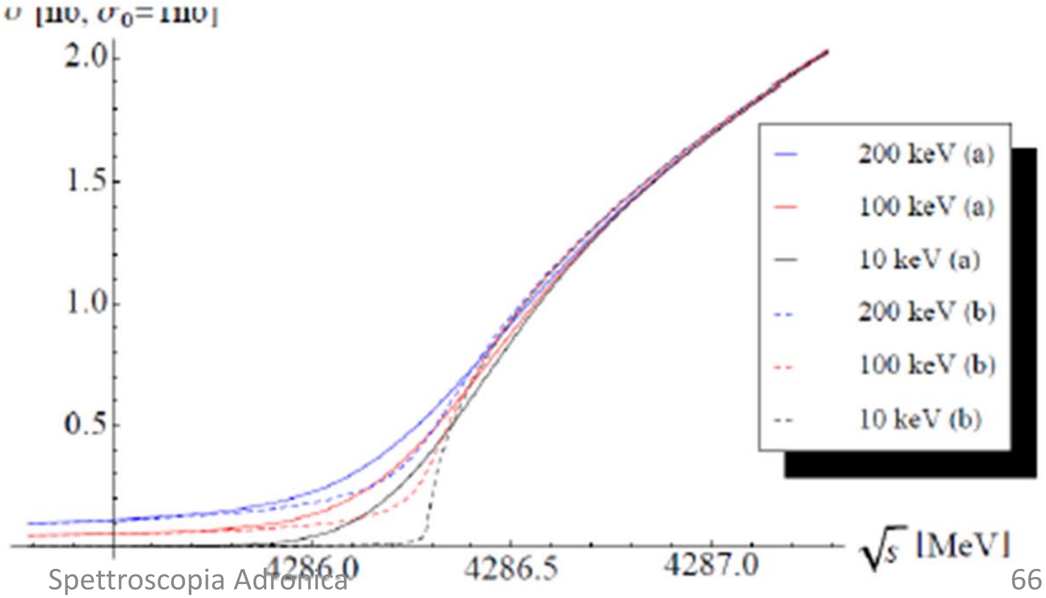
Method

$$\bar{p}p \rightarrow D_s^{\pm} D_{s0}^{*}(2317)^{\mp}$$

Sensitivity to width



Effect of the beam resolution $\Delta p/p \sim 10^{-4}$

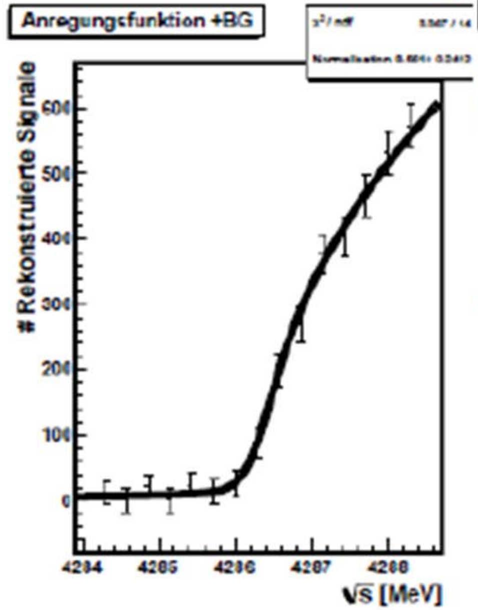


M. Mertens, Juelich

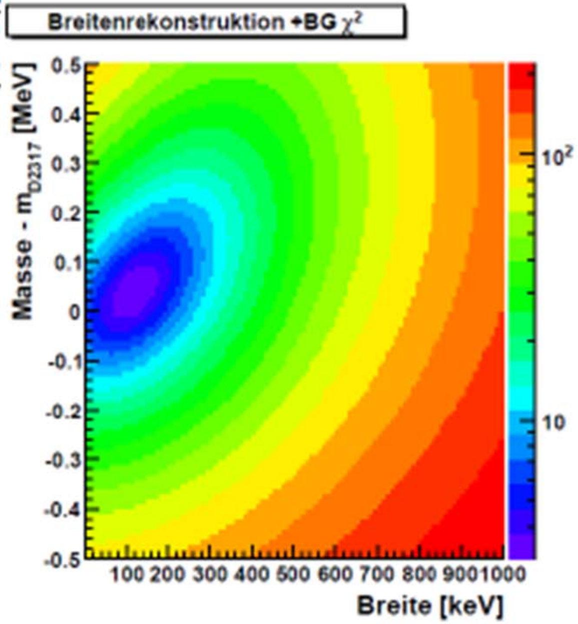
Jim R

Excitation Function Scan of the $D_{s0}^*(2317)$

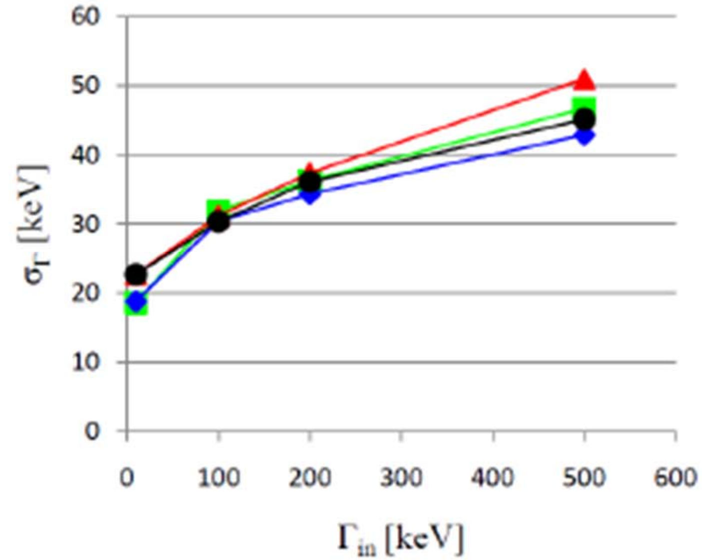
Simulated excitation function



χ²-contour



Resolution of the width



Conclusions

- Hadron spectroscopy is an invaluable tool for a deeper understanding of the strong interaction and QCD.
- Considerable advancement in our knowledge of hadron spectroscopy has been achieved over the past two decades thanks to many experiments at hadron machines and e^+e^- colliders.
- For the near and medium term future first rate results are expected from
  - LHC
  - e^+e^- colliders (BES III, B-factories, Super B-factories).
  - JLAB 12 GeV (CLAS12 and GlueX)
  - PANDA at FAIR
- Complementary approaches