Istituto Nazionale di Fisica Nucleare

Spettroscopia Adronica

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Outline

- Introduction To QCD
- Theories and Models
  - Effective Field Theories
  - Lattice QCD
- Hadron Configurations
- Antiproton-proton Annihilations
- Experimental Results
  - Hybrids
  - Glueballs
  - Multiquarks
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Introduzione alla QCD

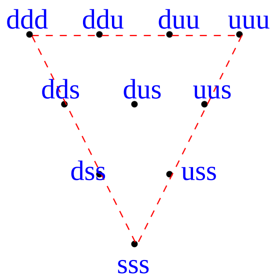
QCD (Quantum ChromoDynamics)

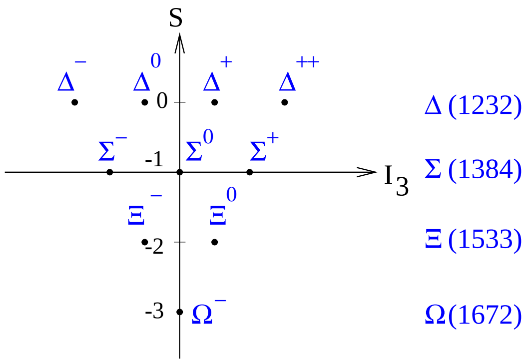
La QCD è la teoria dei quark, gluoni e delle loro interazioni.
Fa parte del Modello Standard. E' una teoria di campo quantistica con una lagrangiana semplice ed elegante che si basa interamente sulla invarianza per trasformazioni di un gruppo di gauge locale, $SU(3)_{colore}$.

Gli adroni sono composti da quark. Le forze tra quark all'interno degli adroni sono più semplici delle forze tra adroni, nello stesso modo in cui le interazioni coulombiane all'interno di un atomo sono più semplici delle interazioni interatomiche.

I quark si presentano in sei flavor (u, d, s, c, b, t). Simmetria $SU(3)_{flavor}$ (approssimata).
Simmetria di colore $SU(3)_{colore}$ esatta.

Il Decupletto Barionico





- Hanno spin-parità $J^P = \frac{3}{2}^+$
- La *funzione d'onda è simmetrica* rispetto allo scambio di una qualsiasi coppia di quark.
- Si trovano in onda *s*, hanno spin paralleli, quindi anche le funzioni d'onda spaziale e di spin sono simmetriche.

Principio di Pauli ? La soluzione sta nel fatto che i quark hanno un ulteriore grado di libertà interno, il colore, che può assumere i 3 valori *R,G,B*. I quark formano il tripletto fondamentale di una simmetria SU(3) di colore.

Gli adroni sono neutri dal punto di vista del colore, cioè appartengono a una rappresentazione di singoletto di SU(3) di colore. In questo modo la funzione d'onda è antisimmetrica.

$$(qqq)_{c.s.} = \sqrt{\tfrac{1}{6}}(RGB - RBG + BRG - BGR + GBR - GRB)$$

Il colore

Per uno stato di tre quark scriviamo la funzione d'onda come

$$\psi_{3q} = \psi_{spazio}\psi_{spin}\psi_{flavor}\psi_{colore}$$

il prodotto delle prime tre funzioni d'onda è simmetrico per lo scambio di due quark, per cui richiediamo che la parte di colore sia antisimmetrica

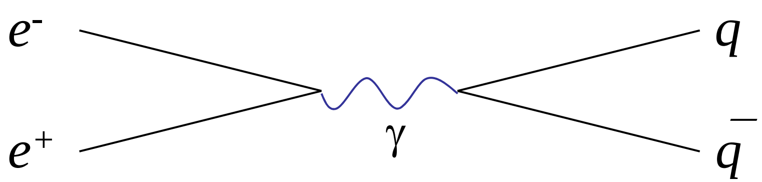
$$\psi^{\alpha} \qquad (\alpha = 1,2,3)$$

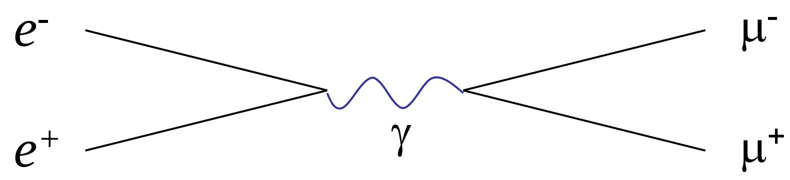
$$\psi_{colore} = \varepsilon_{\alpha\beta\gamma}\psi^{\alpha}\psi^{\beta}\psi^{\gamma}$$

- Ogni flavor esiste in tre colori, che si trasformano tra di loro sotto $SU(3)_{colore}$. (rappresentazione 3_c).
- Tutti gli adroni osservati sono singoletti di colore. (rappresentazione 1_c)

Il processo $e^+e^- \to$ adroni

La produzione di adroni in annichilazione e^+e^- avviene per adronizzazione delle coppie $q\bar{q}$ prodotte nel processo $e^+e^- \to q\bar{q}$.
La sezione d'urto totale si dunque collegare a quella per $e^+e^- \to \mu^+\mu^-$.





$$\sigma\left(e^+e^- \to \mu^+\mu^-\right) = \frac{4\pi}{3}\frac{\alpha^2}{s}$$

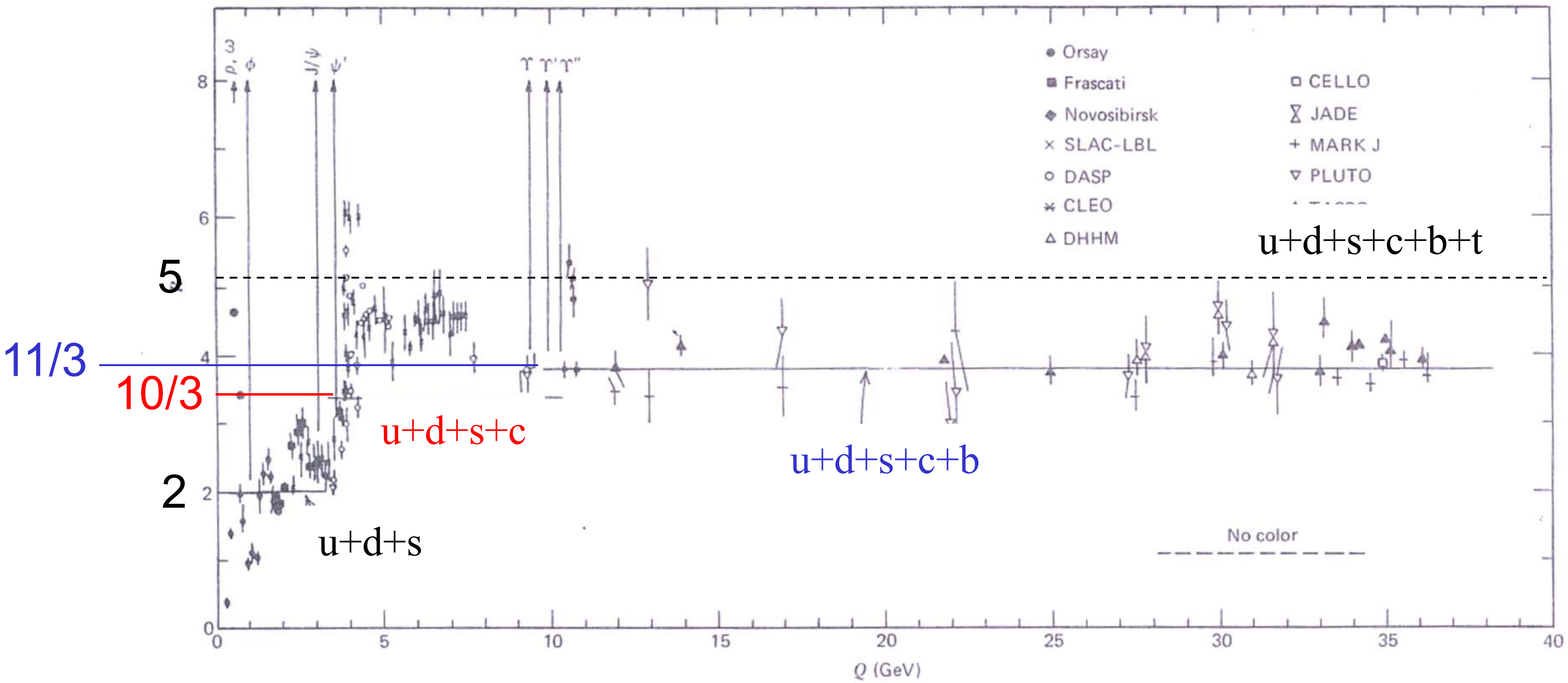
$$\sigma\left(e^+e^- \to q\bar{q}\right) = 3e_q^2\sigma\left(e^+e^- \to \mu^+\mu^-\right)$$

colore (3); e_q:

$$e_q = \begin{cases} -\frac{1}{3} & q = d, s, b \\ +\frac{2}{3} & q = u, c, t \end{cases}$$

$$\boxed{\sigma\left(e^+e^- \to adroni\right) = \sum_q 3e_q^2\sigma\left(e^+e^- \to \mu^+\mu^-\right)}$$

$$R \equiv \frac{\sigma\left(e^+e^- \to adroni\right)}{\sigma\left(e^+e^- \to \mu^+\mu^-\right)} = 3\sum_q e_q^2$$



All'aumentare dell'energia, il rapporto R aumenta ogni volta che si supera la soglia per produrre un nuovo flavour. La misura di R conferma anche che i quark si presentano in tre colori.

correzioni di QCD

$$R = 3\sum_q e_q^2\left(1 + \frac{\alpha_s(Q^2)}{\pi}\right)$$

Alla simmetria di colore $SU(3)_c$ è associata l'invarianza delle leggi della fisica sotto la trasformazione globale non abeliana di fase:

$$\psi' = e^{i\alpha_j \lambda_j / 2}\psi \qquad (j = 1,\ldots,8)$$

La trasformazione locale di fase genera una teoria dinamica che necessita dell'introduzione di 8 bosoni vettoriali di gauge (perchè ci sono 8 generatori in SU(3)) che mediano le forze tra quark. Questi quanti dell'interazione forte sono chiamati gluoni e appartengono alla rappresentazione di ottetto di $SU(3)_c$ (8_c). La simmetria di colore è esatta per cui i gluoni hanno massa nulla.

Questa teoria di gauge non abeliana è la QCD.

La natura non abeliana della teoria la rende asintoticamente libera, cioè le interazioni tra quark tendono (logaritmicamente) a zero a piccole distanze.

La Lagrangiana della QCD

I fermioni elementari della QCD, i quark, appaiono in sei flavor e sono raggruppati in un campo $\psi(x) = (u(x), d(x), s(x), c(x), b(x), t(x))^T$
dove *u(x), d(x)* etc sono spinori di Dirac a 4 componenti.
La Lagrangiana della QCD è data da:

$$\mathcal{L}_{QCD} = \overline{\psi}\left(i\gamma_\mu \mathcal{D}^\mu - m\right)\psi - \frac{1}{4} G^j_{\mu\nu} G^{\mu\nu}_j$$

con la derivata covariante:

$$\mathcal{D}_\mu = \partial_\mu - ig \sum_{j=1}^{8} \frac{\lambda_j}{2} \mathcal{A}^j_\mu(x)$$

e il tensore del campo gluonico:

$$G^i_{\mu\nu}(x) = \partial_\mu \mathcal{A}^i_\nu(x) - \partial_\nu \mathcal{A}^i_\mu(x) + g f_{ijk} \mathcal{A}^j_\mu(x) \mathcal{A}^k_\nu(x)$$

λ_j Matrici di Gell-Mann

f_{ijk} Costanti di Struttura

$\mathcal{A}^j_\mu$ Gluoni

La rinormalizzazione della teoria introduce una scala di energia: la costante di accoppiamento g diventa una “running coupling constant”, cioè dipende dalla scala di energia μ alla quale viene valutata.

Definendo $\alpha_s(\mu) = g^2(\mu)/4\pi$ si ha

$$\alpha_s(\mu) = \frac{4\pi}{\beta_0 \ln\left(\mu^2/\Lambda^2\right)}$$

con $\beta_0 = 11 - 2N_f/3$

N_f è il numero di flavor di quark.

Il parametro di scala Λ viene determinato empiricamente. Si ottiene $\Lambda = 0.2\ GeV$ per $N_f = 4$.

La costante di accoppiamento diminuisce all’aumentare dell’energia: a scale μ >> 1 GeV l’interazione diventa debole e la QCD si può trattare perturbativamente (libertà asintotica). $\alpha_s(M_Z) = 0.1176 \pm 0.0020$

A basse energie α_s diventa dell’ordine di 1 e si entra nel regime detto QCD non perturbativa.

Quarks

Light quarks	$m_q \ll \Lambda_{QCD}$	q=u, d, s
Heavy quarks	$m_Q \gg \Lambda_{QCD}$	Q=c, b, t

m_u=1.5 ÷ 4.0 MeV m_d=4 ÷ 8 MeV m_s=80 ÷ 130 MeV

"current quark masses" $\overline{\text{MS}}$ at scale 2 GeV

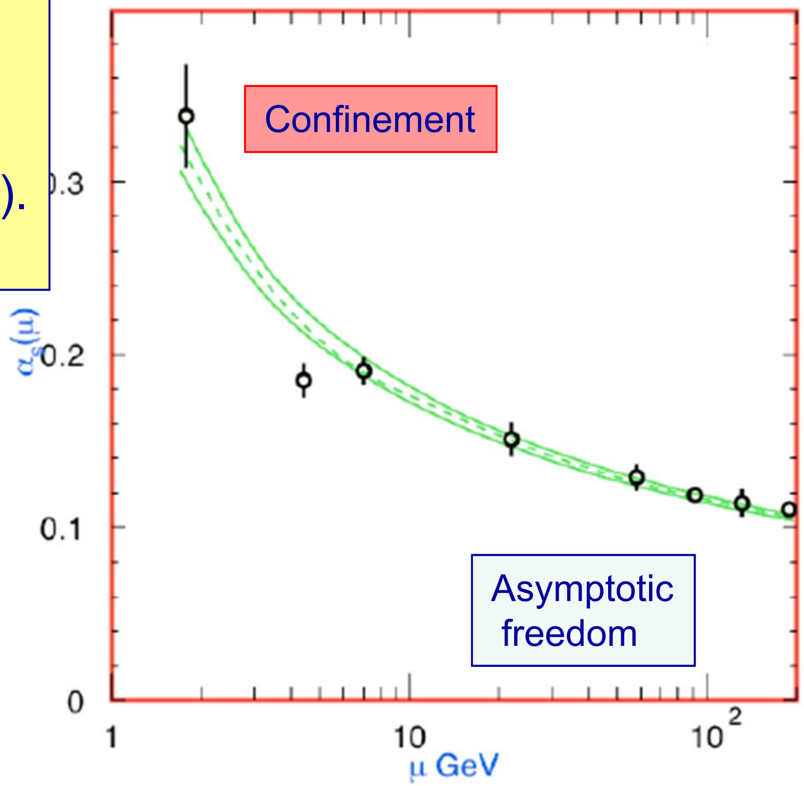
m_c=1.15 ÷1.35 GeV m_b=4.1 ÷ 4.4 GeV m_t=174.3±5.1 GeV

"running masses" in $\overline{\text{MS}}$ scheme

Hadrons containing heavy quarks have masses of order m_Q rather than of the order Λ_{QCD}.

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.

Regimi Asintotici

Ci sono due situazioni limite nelle quali la QCD è accessibile con approssimazioni controllate:

- Ad alte energie (piccole distanze < 0.1 fm) l'interazione diventa più debole e si entra nel regime perturbativo (Libertà Asintotica).
- A basse energie (grandi distanze > 1 fm) la QCD è caratterizzata dal confinamento e un vuoto non banale. Il confinamento implica la rottura spontanea di una simmetria che è esatta nel limite di massa nulla per i quark: la simmetria chirale. Questa rottura spontanea di simmetria a sua volta implica l'esistenza di tre bosoni di Goldstone pseudoscalari, identificati con i tre mesoni π nel limite di due flavor. Con tre flavor si generalizza all'ottetto pseudoscalare.

I due regimi vengono combinati a dare il potenziale:

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r$$

Simmetria Chirale

Nel limite di massa zero per i quark, la Lagrangiana della QCD ha una simmetria globale legata alla chiralità conservata di particelle di massa zero e spin ½ .
Con due flavor ($N_f=2$):

$$\psi(x)=\begin{pmatrix} u(x) \\ d(x) \end{pmatrix} \qquad \psi_{R,L}=\frac{1}{2}(1\pm\gamma_5)\psi$$

$$\psi_R \rightarrow \exp\left[i\theta_R^a \frac{\tau_a}{2}\right]\psi_R \qquad \psi_L \rightarrow \exp\left[i\theta_L^a \frac{\tau_a}{2}\right]\psi_L$$

Queste trasformazioni lasciano $\mathcal{L}_{QCD}$ invariata nel limite m=0: le componenti RH e LH dei quark non si mescolano.

$$SU(2)_R \times SU(2)_L$$

Simmetria Chirale della QCD

Sei correnti di Noether conservate:

$$J^{\mu}_{R,a}=\bar{\psi}_R\gamma_\mu(\tau_a/2)\psi_R \qquad J^{\mu}_{L,a}=\bar{\psi}_L\gamma_\mu(\tau_a/2)\psi_L$$

$$\partial_\mu J^\mu_R=\partial_\mu J^\mu_L=0$$

Corrente Vettoriale: $V_a^{\mu} = J_{R,a}^{\mu} + J_{L,a}^{\mu} = \overline{\psi}\gamma^{\mu}\frac{\tau_a}{2}\psi$

Corrente Assiale: $A_a^{\mu} = J_{R,a}^{\mu} - J_{L,a}^{\mu} = \overline{\psi}\gamma^{\mu}\gamma_5\frac{\tau_a}{2}\psi$

Le cariche corrispondenti sono generatori di SU(2) x SU(2):

$$Q_a^V = \int d^3x\,\psi^+(x)\frac{\tau_a}{2}\psi(x) \qquad Q_a^A = \int d^3x\,\psi^+(x)\gamma_5\frac{\tau_a}{2}\psi(x)$$

Nella misura in cui si può considerare piccola la massa del quark strano ha senso generalizzare la simmetria chirale a 3 flavor $N_f=3$. In questo caso le 3 matrici di Pauli τ_a vengono sostituite dalle 8 matrici di Gell-Mann λ_a.

Rottura Spontanea della Simmetria Chirale

C'è evidenza dalla spettroscopia adronica che la simmetria chirale nel limite m=0 sia rotta spontaneamente. Per motivi dinamici lo stato di vuoto è simmetrico solo sotto il sottogruppo $SU(2)_V$ generato dalla carica vettoriale Q^V. Questa è la ben nota simmetria di isospin (per N_f=2) o simmetria di flavor (per N_f=3). Infatti se la simmetria non fosse rotta ci sarebbero dei doppietti di parità e i mesoni vettoriali ($J^P=1^-$) sarebbero degeneri con quelli assiali ($J^P=1^+$), mentre per esempio M(ρ) = 0.77 GeV e M(a_1)= 1.23 GeV. La simmetria chirale è rotta spontaneamente e si riduce a quella di isospin:

$$SU(2)_R \times SU(2)_L \rightarrow SU(2)_V$$

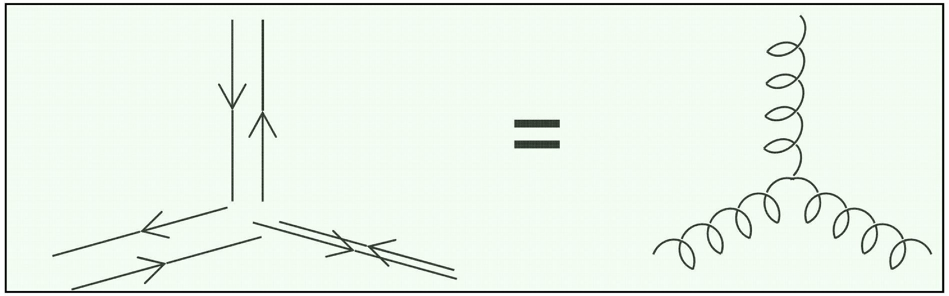
I bosoni di Goldstone sono i 3 π nel caso di due flavor e gli otto membri dell'ottetto mesonico nel caso di tre flavor.

QCD Properties

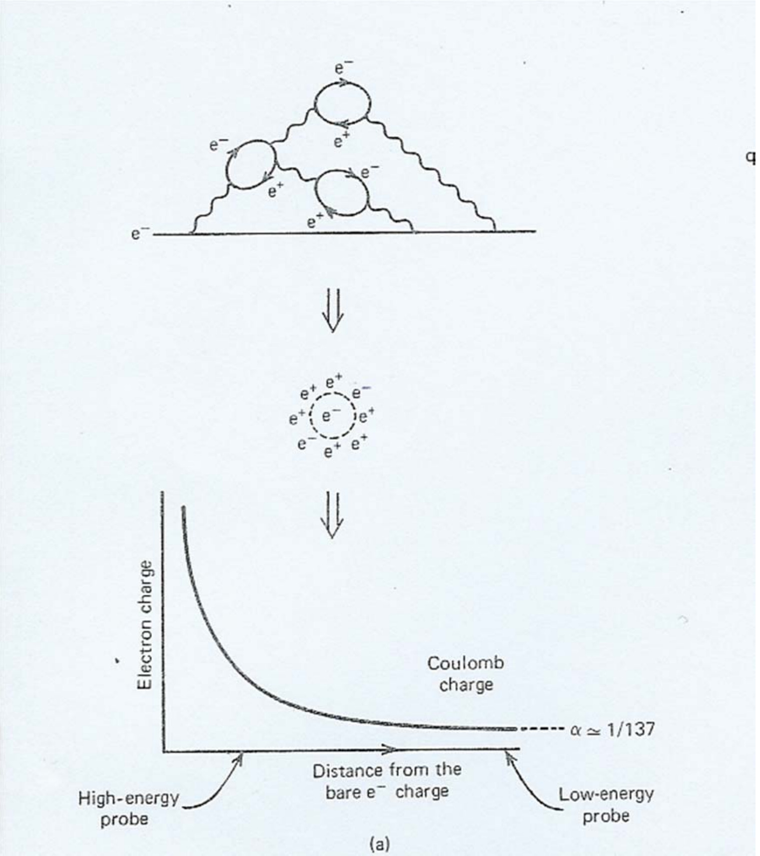
- Poincaré, P, T and C invariant.
- Non abelian gauge theory $\Rightarrow$ physical spectrum consists of color singlet states only.
- The QCD effective coupling constant $\alpha_s(q)$ decreases as the momentum transfer scale increases (asymptotic freedom)

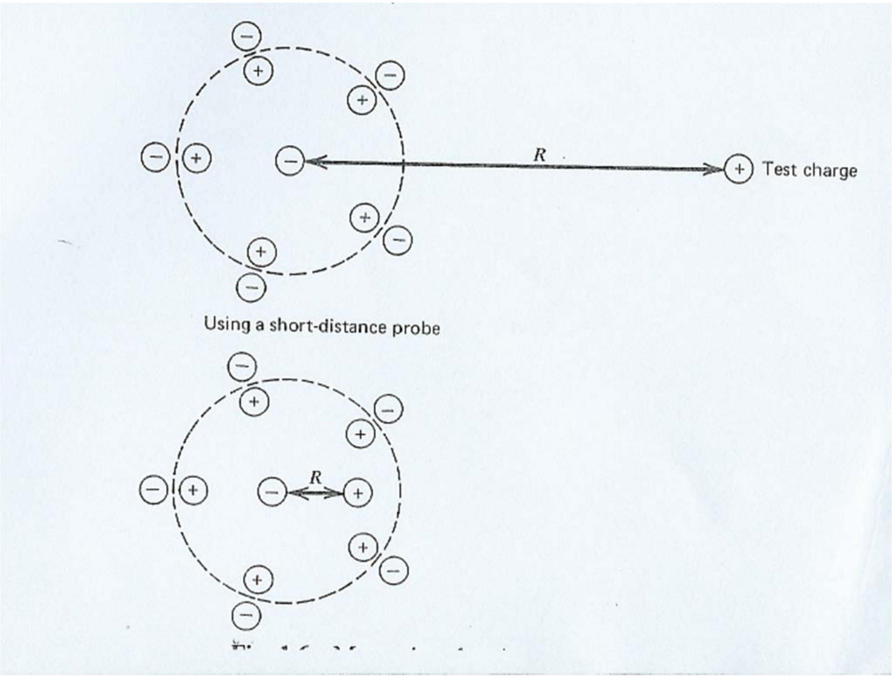
  $\Rightarrow$ perturbative calculations at high energies.
- Intrinsic scale at low energies Λ_{QCD}, main contribution to hadron masses. At $q \sim 1/\Lambda_{QCD}$, $\alpha_s(q) \sim 1$ and perturbation theory cannot be used.
- Flavor conservation.

Il fatto che i gluoni abbiano carica di colore implica l’esistenza di un accoppiamento diretto fra gluoni, per il quale non esiste l’analogo in QED.



Questo fatto ha delle implicazioni importantissime sulla schermatura di carica in QED e QCD e sull’andamento asintotico delle due interazioni.

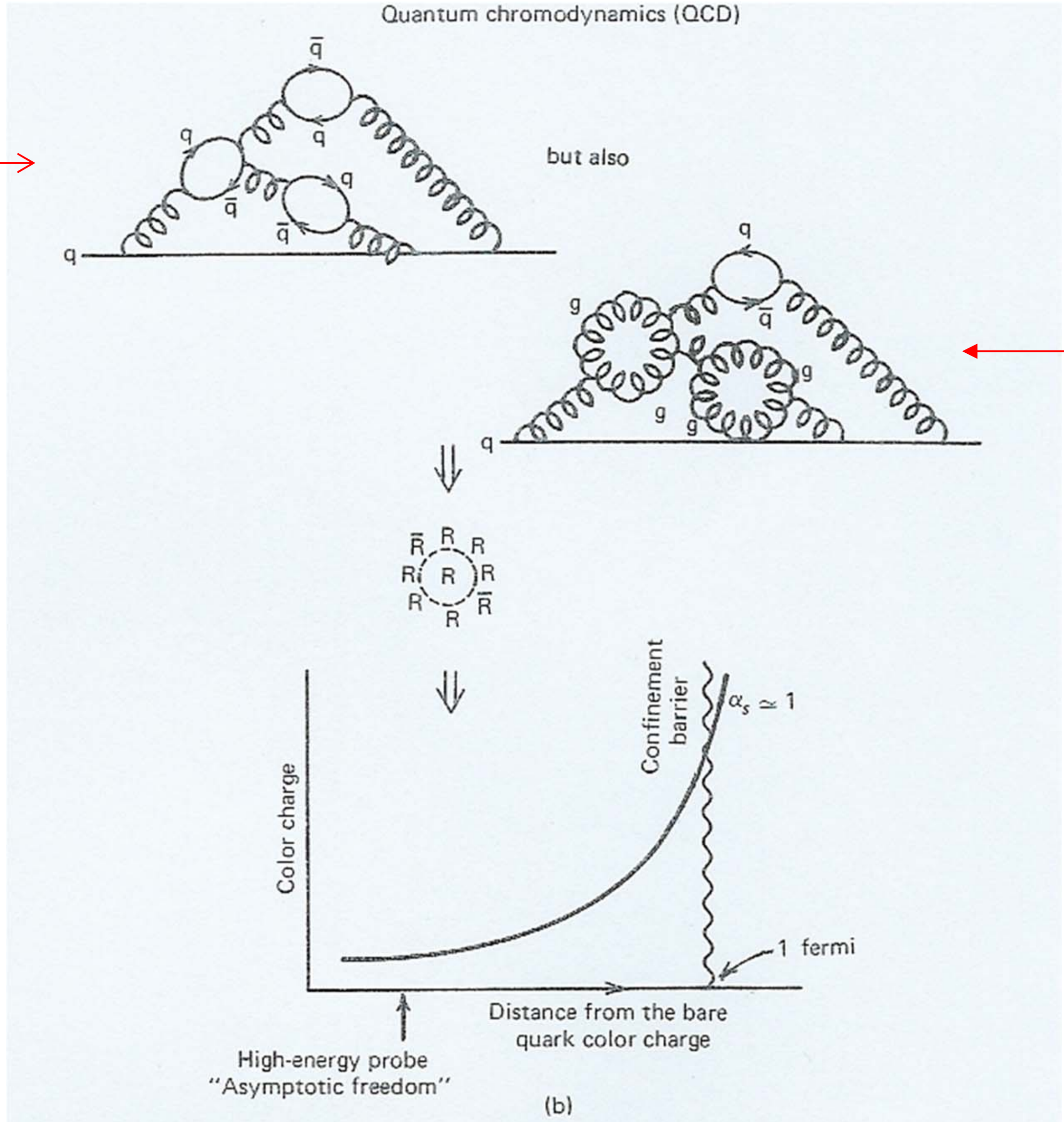




Schermatura di carica in QCD e andamento di α_S

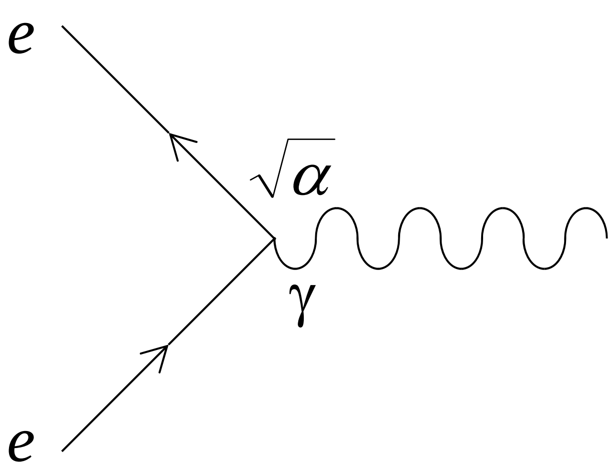
QED analog

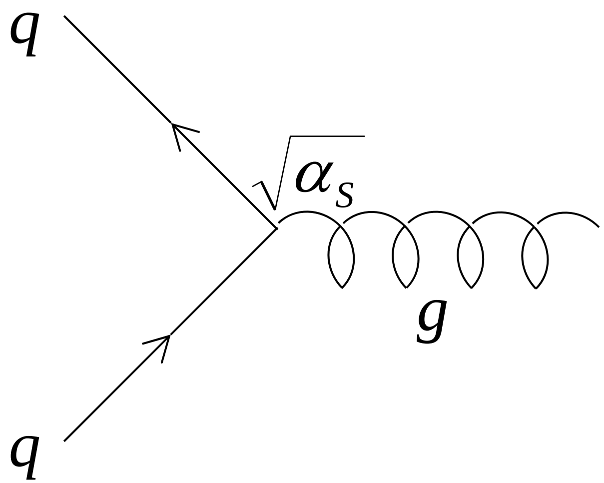
gluon self coupling in QCD



Le proprietà essenziali della QCD si possono riassumere nei seguenti punti:

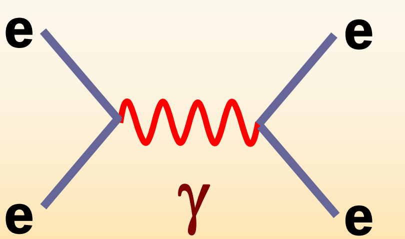
- I quark hanno una carica di colore (oltre alla carica elettrica) che può assumere 6 valori: R, G, B, $\bar{R}$, $\bar{B}$, $\bar{G}$.
- Il colore viene scambiato da 8 gluoni "bi-colorati".
- Le interazioni quark-quark si possono calcolare usando le regole di QED, con l'introduzione di un fattore di colore e la sostituzione $\sqrt{\alpha} \to \sqrt{\alpha_s}$ a ogni vertice.





- I gluoni possiedono carica di colore e possono interagire direttamente tra di loro.
- A piccole distanze α_S è sufficientemente piccola da rendere possibile il calcolo perturbativo (libertà asintotica).

QED vs QCD



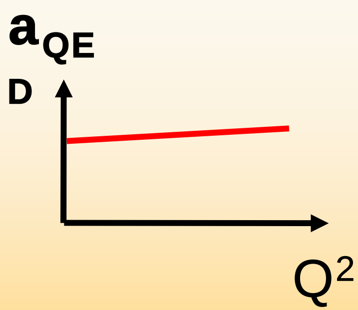
Leptons (e,μ,τ)
couple to
electric charge

Photon carries no charge

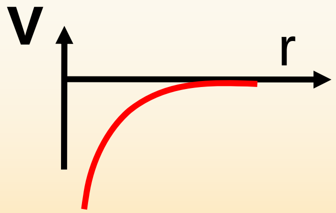
$m_e = 0.5$ MeV

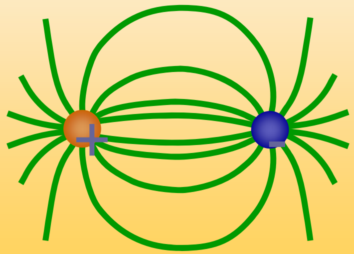
$m_p = 938$ MeV

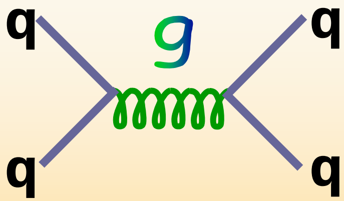
$E_b = 13$ eV



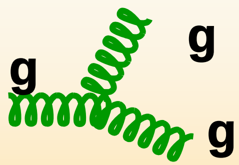
$$\alpha_{QED}(Q^2 = 0) = \frac{1}{137}$$







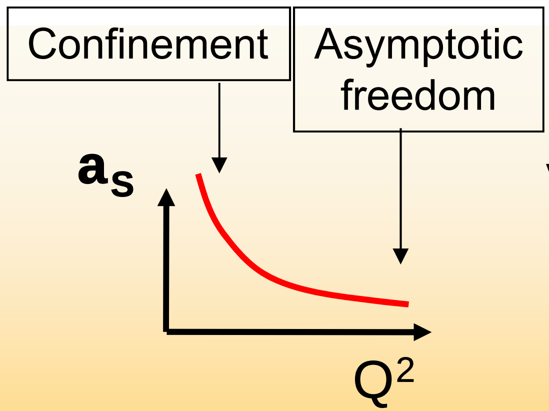
Quarks
(u,d,s,c,b,t)
couple to
3 Colourcharges



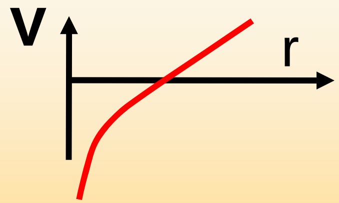
$m_u \approx$ 3 MeV

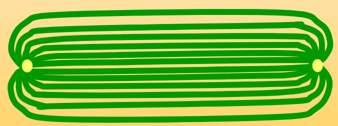
$m_d \approx$ 6 MeV

$M_p = 938$ MeV



$$\alpha_S(Q^2 = M_Z^2) \approx 0.12$$





„String“

Fisica Adronica

Introduction

Hadron physics is the study of strong interacting hadronic matter in all its manifestations, and the understanding of its properties in terms of the underlying fundamental theory, Quantum Chromodynamics or QCD.

- QCD extremely successful at high energies.
- However it is the long-distance, low-energy regime which governs the bulk of strong interactions (e.g. it determines the properties of the light-hadron spectrum). It requires understanding of non-perturbative QCD.
- At low energies $SU(3)_F$ (flavor) symmetry reasonably successful.

Where is the missing link ?

Experimental exploration of the full spectrum of states composed of quarks, antiquarks and gluons is required to understand the structure and dynamics of hadrons.

QCD is also an essential ingredient of the Standard Model and it is the incalculable strong matrix element which limit our reach for physics beyond the standard model.

- supersymmetric neutralino and dark matter puzzle.
- muon g-2.
- origin of CP violation.

Two main approaches for the study of hadronic matter:

- Static: mass, magnetic moments, spin, parity etc.
  Spectroscopy and search for exotic states.
- Dynamic: study of the intrinsic properties of constituents inside hadrons (DIS, Transversity, GPD's etc.).

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).

The Non-Relativistic Potential

The functional form of the potential is chosen to reproduce the known asymptotic properties of the strong interaction.

- At small distances asymptotic freedom, the potential is coulomb-like:

$$V(r) \xrightarrow[r\to 0]{} -\frac{4}{3}\frac{\alpha_s(r)}{r}$$

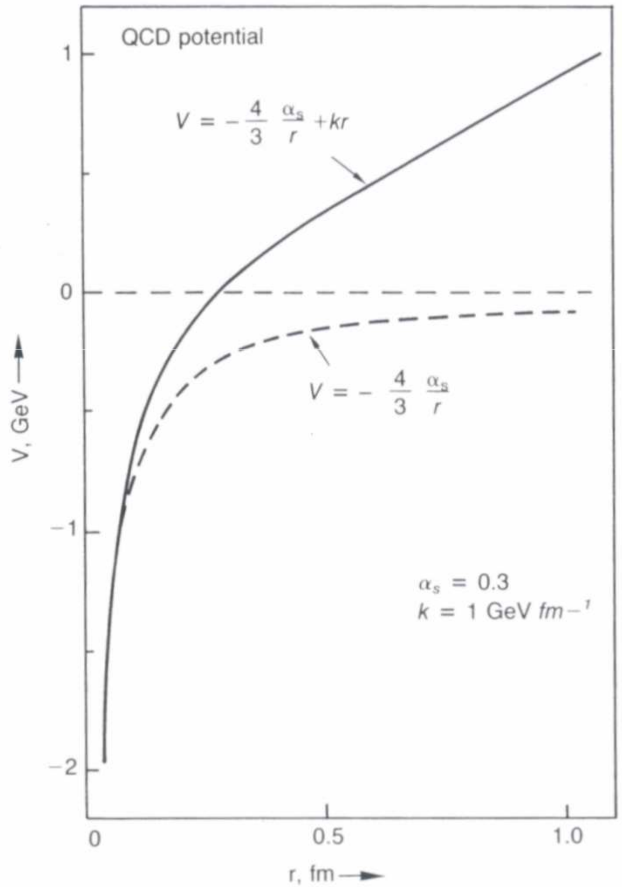
- At large distances confinement:

$$V(r) \xrightarrow[r\to\infty]{} kr$$

The Non-Relativistic Potential II

$$\alpha_s(\mu) = \frac{4\pi}{(11 - \frac{2}{3} n_f) \ln(\frac{\mu^2}{\Lambda^2})}$$

n_f = number of flavours
Λ ~ 0.2 GeV QCD scale parameter
k string constant (~ 1 GeV/fm)



The Spin-Dependent Potential

$$H_{SD} = V_{LS} + V_{SS} + V_T$$

spin-orbit
(fine structure)

$$V_{LS} = \frac{(\vec{L} \cdot \vec{S})}{2m_c^2 r}\left(3\frac{dV_V}{dr} - \frac{dV_S}{dr}\right)$$

spin-spin
(hyperfine structure)

$$V_{SS} = \frac{2\left(\vec{S}_1 \cdot \vec{S}_2\right)}{3m_c^2}\nabla^2 V_V(r)$$

tensor

$$V_T = \frac{2\left[3\left(\vec{S} \cdot \hat{r}\right)\left(\vec{S} \cdot \hat{r}\right) - S^2\right]}{12m_c^2}\left(\frac{1}{r}\frac{dV_V}{dr} - \frac{d^2 V_V}{dr^2}\right)$$

V_S and V_V are the scalar and vector components of the non-relativistic potential

The Spin-Dependent Potential II

- The Coulomb-like part of $V(r)$ corresponds to one-gluon exchange and contributes only to the vector part of the potential V_V. The scalar part is due to the linear confining potential. This could in principle contribute to both V_S and V_V, but the fit to the χ_{cJ} masses suggests that the V_V contribution is small.
- The charmonium mass spectrum can be computed also within the framework of Lattice QCD (LQCD), which is essentially QCD applied to a discreet 4-dimensional space with given spacing a.
- Non Relativistic QCD (NRQCD) provides another framework for the calculation of the heavy quarkonium spectrum. In NRQCD the various dynamical scales m, mv, mv^2 in the production and decay processes are well separated.

Effective Field Theories (EFT)

A non-relativistic bound state is characterized by at least three scales:

- mass *m* (*hard*)
- momentum transfer *mv* (*soft*)
- kinetic energy of the $q\bar{q}$ pair in the CMS $E \sim p^2/m \sim mv^2$ (*ultrasoft*)

Hierarchy of scales $\Rightarrow$ substitute QCD with simpler, but equivalent, **Effective Field Theory (EFT)**, i.e. a quantum field theory with the following properties:

- It contains the relevant degrees of freedom to describe phenomena which occur in a certain limited range of energies and momenta.
- It contains an intrinsic energy scale Λ that sets the limit of appicability of the EFT.

Effective Field Theories (EFT)

- Heavy Quark Effective Theory (HQET) describes systems with one heavy quark ($q\bar{Q}$, $Q\bar{q}$), characterized by scales *m* and Λ_{QCD}. Integrate m out and build expansion in Λ_{QCD}/m.
- Non Relativistic QCD (NRQCD) describes bound states of two heavy quarks ($Q\bar{Q}$). Integrate out only *m* and leaves lower scales as dynamical degrees of freedom.

Lattice QCD (LQCD)

The interaction is discretized on a 3 (Space) + 1 (Time) dim. Lattice

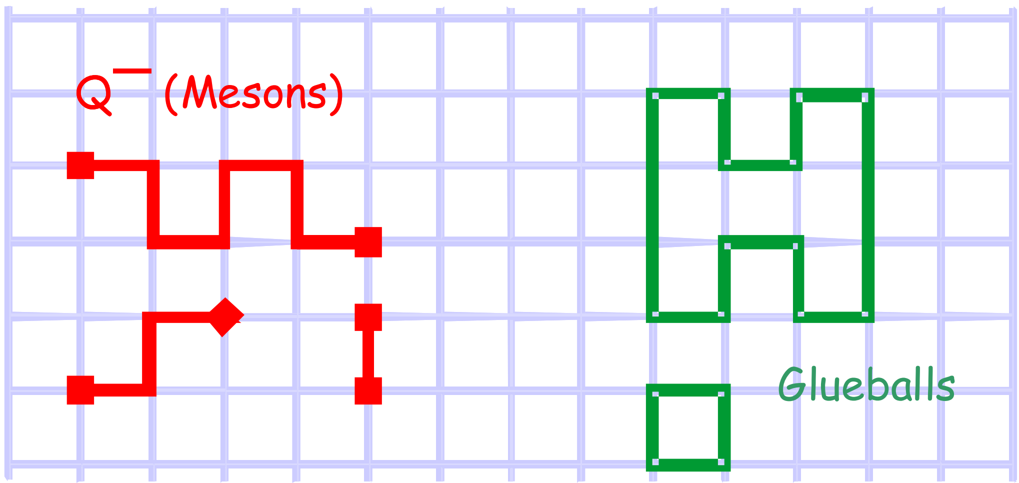
e.g. $\partial_t\phi \rightarrow [\phi(t+a) - \phi(t-a)]/2a$.

Continuum results obtained by $a \rightarrow 0$.

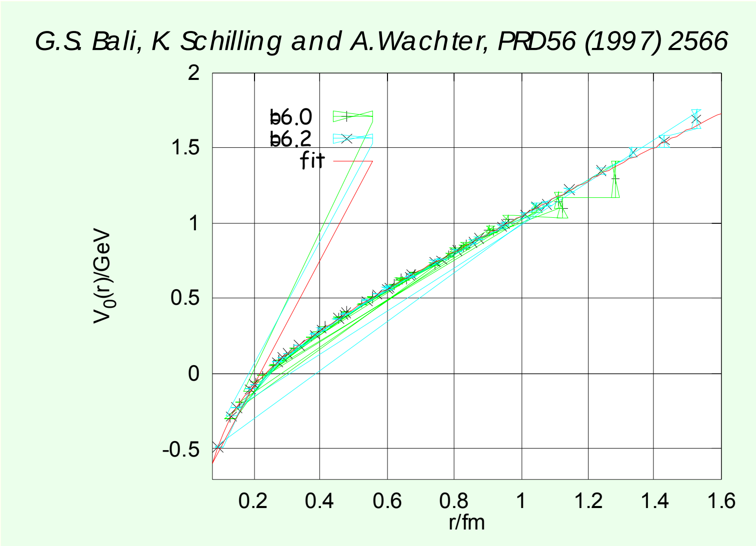
LQCD formulated in Euclidean space-time.

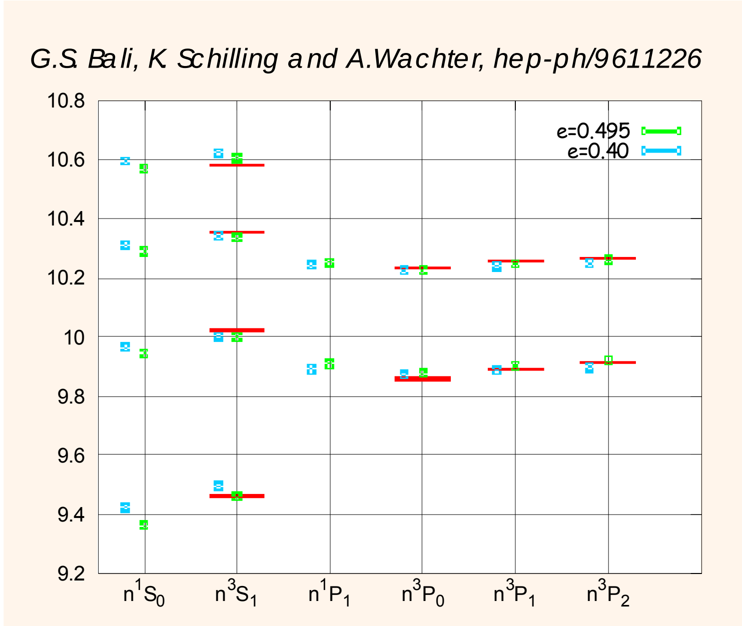
LQCD is a *first principles approach*: only parameters inherent to QCD, i.e. α_s and the quark masses. These n_f+1 parameters are fixed by matching n_f+1 low-energy quantities to their experimental values.

Observables are calculated taking their expectation values in the path integral approach $\Rightarrow$ take average of all possible "configurations" of gauge fields.



The b $\bar{b}$ Spectrum from LQCD



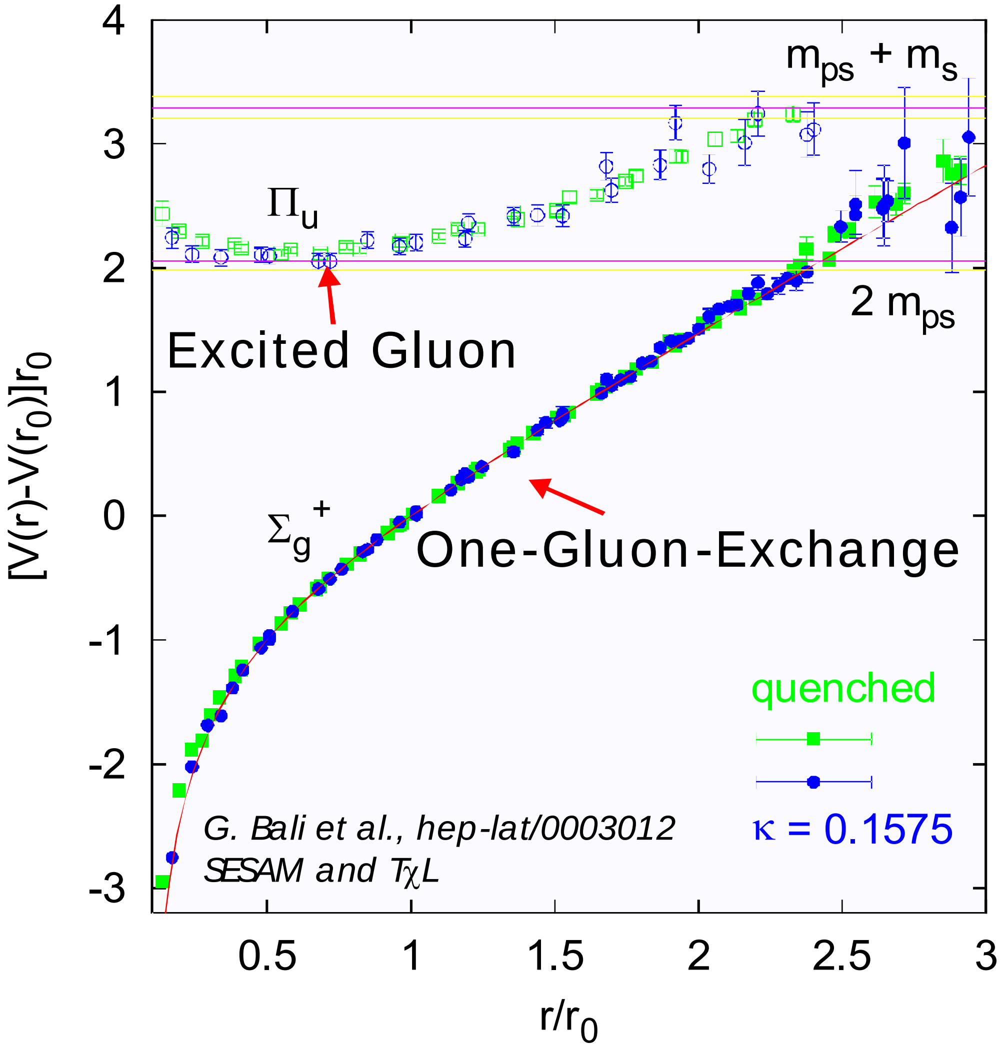


The static potential derived from LQCD confirms the Coulomb + Confinement Ansatz

Quenched vs Unquenched LQCD

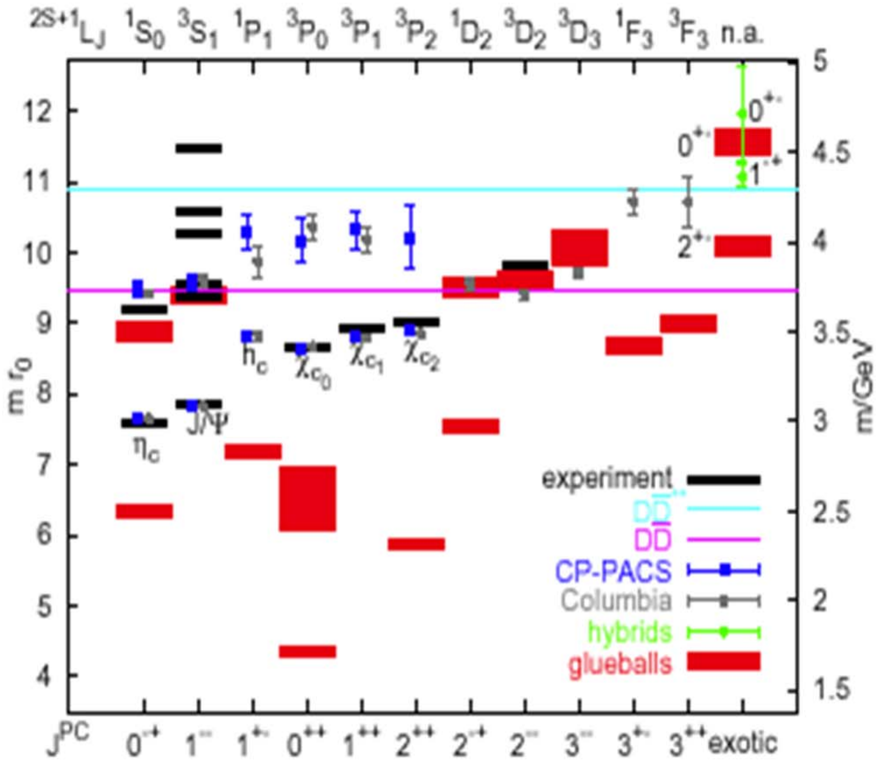
In the quenched approximation sea quarks are neglected.

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r$$



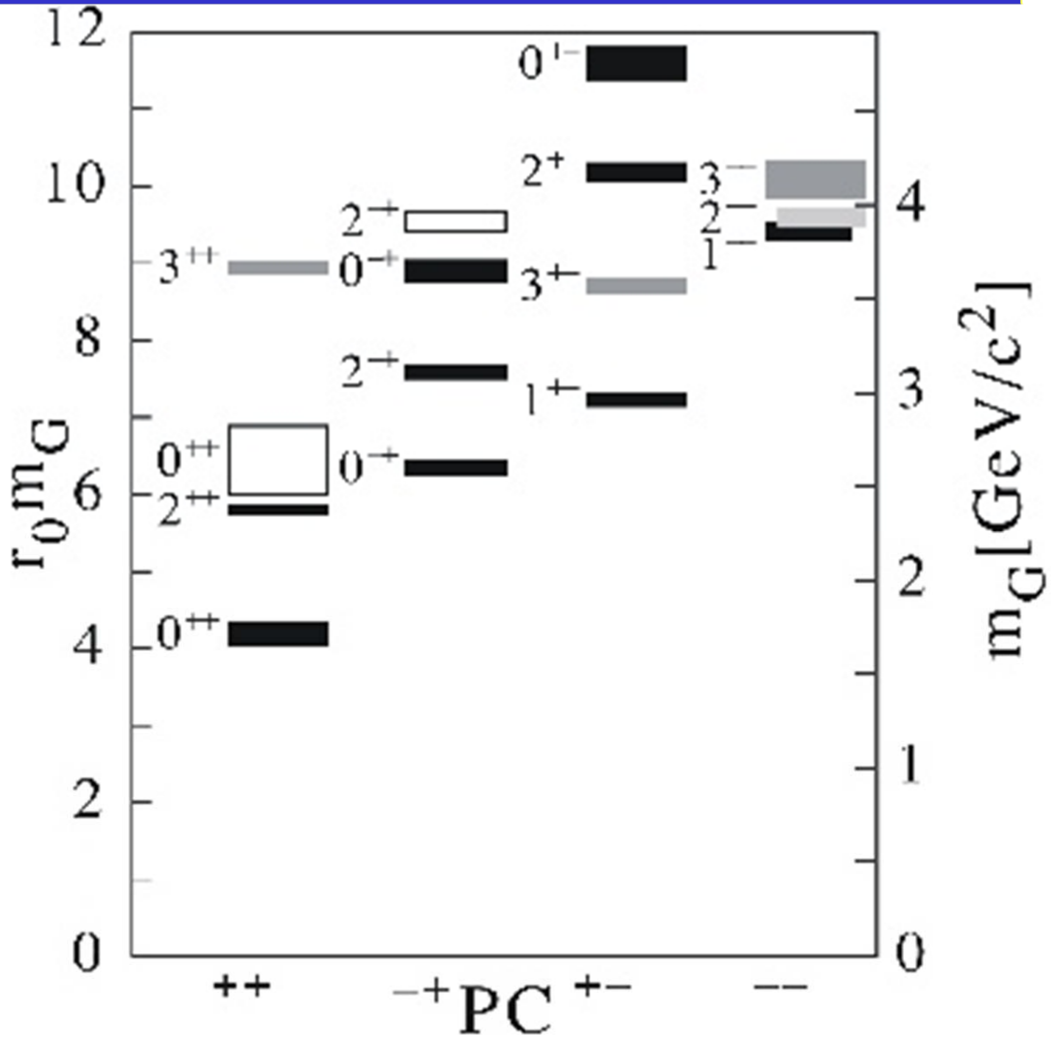
Quenched Charmonium Spectrum

J^{PC}	state	CP-PACS	Columbia	QCD-TARO	experiment	glueballs
0^{-+}	η_c	3013 (1)	3014 (4)	3010 (4)	2980(1)	2500(40)
	η_c'	3739(46)	3707(20)		3654(10)	3500(60)
1^{--}	J/ψ	3085 (1)	3084 (4)	3087 (4)	3097	
	$\psi(2S)$	3777(40)	3780(43)		3686	3700(50)
1^{+-}	h_c	3474(10)	3474(20)	3528(25)	$m(1^3P)$=3525	2830(30)
	h_c'	4053(95)	3886(92)		—	
0^{++}	χ_{c_0}	3408	3413(10)	3474(15)	3415(1)	1720(30)
	χ_{c_0}'	4008(122)	4080(75)		—	2540(120)
1^{++}	χ_{c_1}	3472 (9)	3462(15)	3524(16)	3511	
	χ_{c_1}'	4067(105)	4010(70)		—	
2^{++}	χ_{c_2}	3503(24)	3488(11)		3556	2300(25)
	χ_{c_2}'	4030(180)			—	
2^{-+}	1^1D_2		3763(22)		—	2975(30)
					—	3740(40)
2^{--}	1^3D_2		3704(33)		$X(3872)$???	3780(40)
3^{--}	1^3D_3		3822(25)		—	3960(90)
3^{+-}	1^1F_3		4224(74)		—	3410(40)
3^{++}	1^3F_3		4222(140)		—	3540(40)
0^{+-}	H_0		4714(260)		—	4560(70)
1^{-+}	H_1		4366(64)		—	
2^{+-}	H_2		4845(220)		—	3980(50)



Glueballs

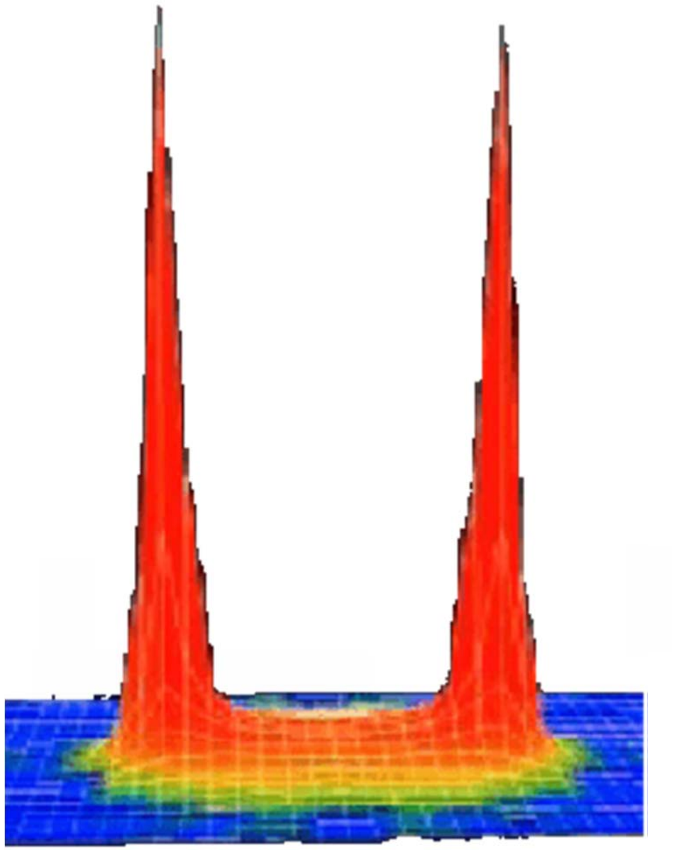
- Glueballs are the excitation of the QCD vacuum
  - Comparably easy to calculate
  - Lots of improvements in the last decade
  - Mainly due to
    - anisotropic lattices
    - improved actions



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

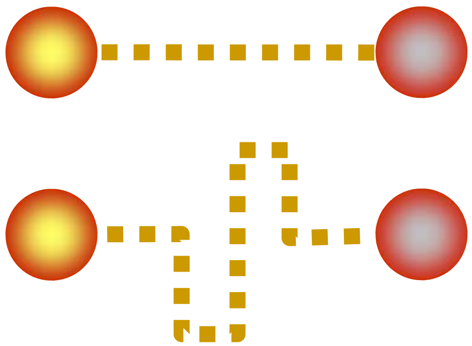
Fluxtube

The gluon field between the quark and the antiquark is like a flux of glue.
Actual states are discreet configurations.
Decays are due to flux breaking.



~ Simplified Lattice Approach

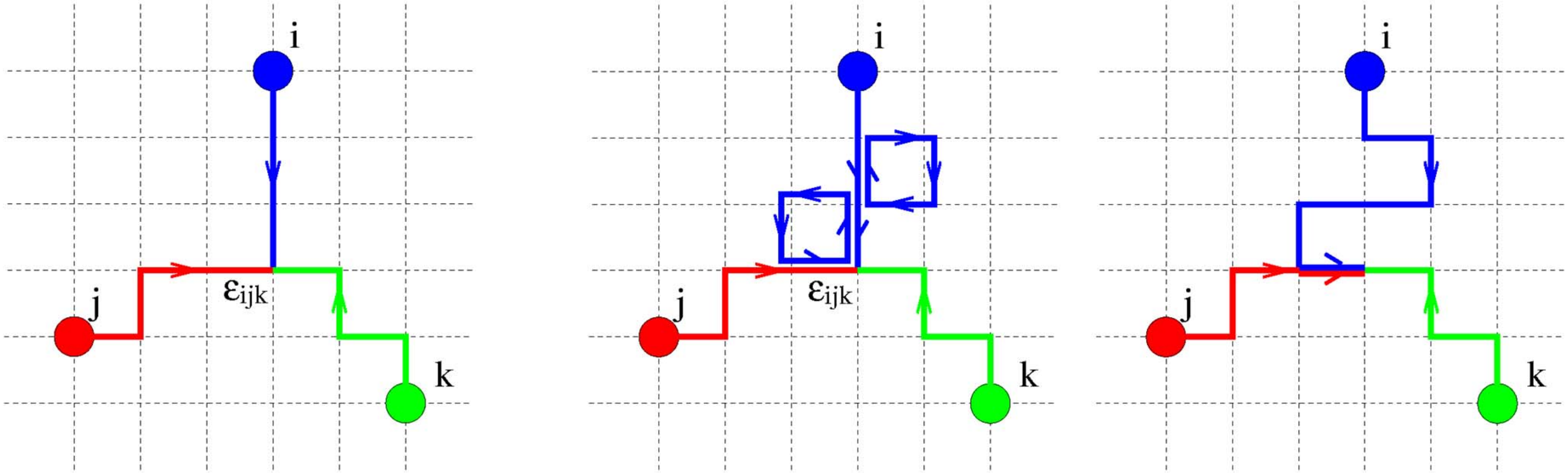
Meson



Hybrid

Flux (excited Gluon)
carries angular momentum

Example: Baryons in the Fluxtube Model



Basic idea is to reduce the amount of computing time by integrating over the whole color flux between source and drain

The excitation energy is then related to the averaged flux length for a sample of configurations

Hadrons are very complicated

$q\bar{q}$

+

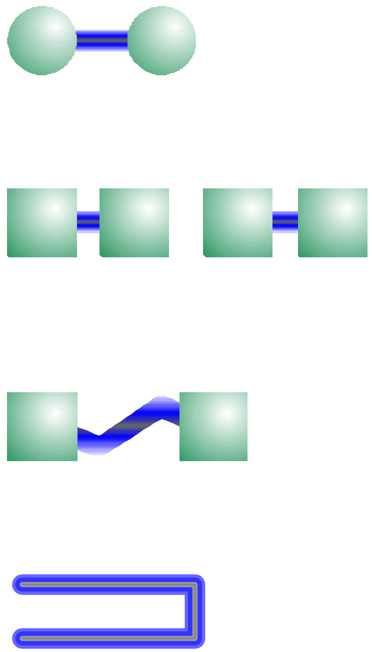
$(q\bar{q})(q\bar{q})$

+

$(q\bar{q})g$

+

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

Definition of Hadron Configurations

$SU(3)_c$ symmetry tells us that

$$(3i+n)q\ (3j+n)\ \bar{q}\ (k)g$$

is colour neutral

i=1, j=n=k=0	baryon
i=j=k=0, n=1	meson
i=j=n=0, k>1	glueball
i=j=0, n=1, k>1	meson hybrid
i=1, j=n=0, k>1	baryon hybrid
i=n=1, j=k=0	pentaquark
i=j=k=0, n=2	four-quark
i=j=k=0, n=3 or i=j=1, n=k=0	baryonium

Classification (Close and Lipkin)

Exotics of the first kind

External quantum numbers unambiguously incompatible with assignment to baryons or mesons

B=1 - baryonlike

- Q>2, Q<-1, S<-3, S>0, I>3/2, ...

B=0 - mesonlike

- |Q|>1, I>1, |S|>2, |C|>2, |S-C|>1, ...

Classification (Close and Lipkin)

Exotics of the second kind

Combination of quantum numbers not allowed for leading Fock-term

Only possible for B=0

– $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$
– cannot be formed by any unexcited qq-System

Classification (Close and Lipkin)

Exotics of the third kind – Crypto-Exotics

Internal exotic structure

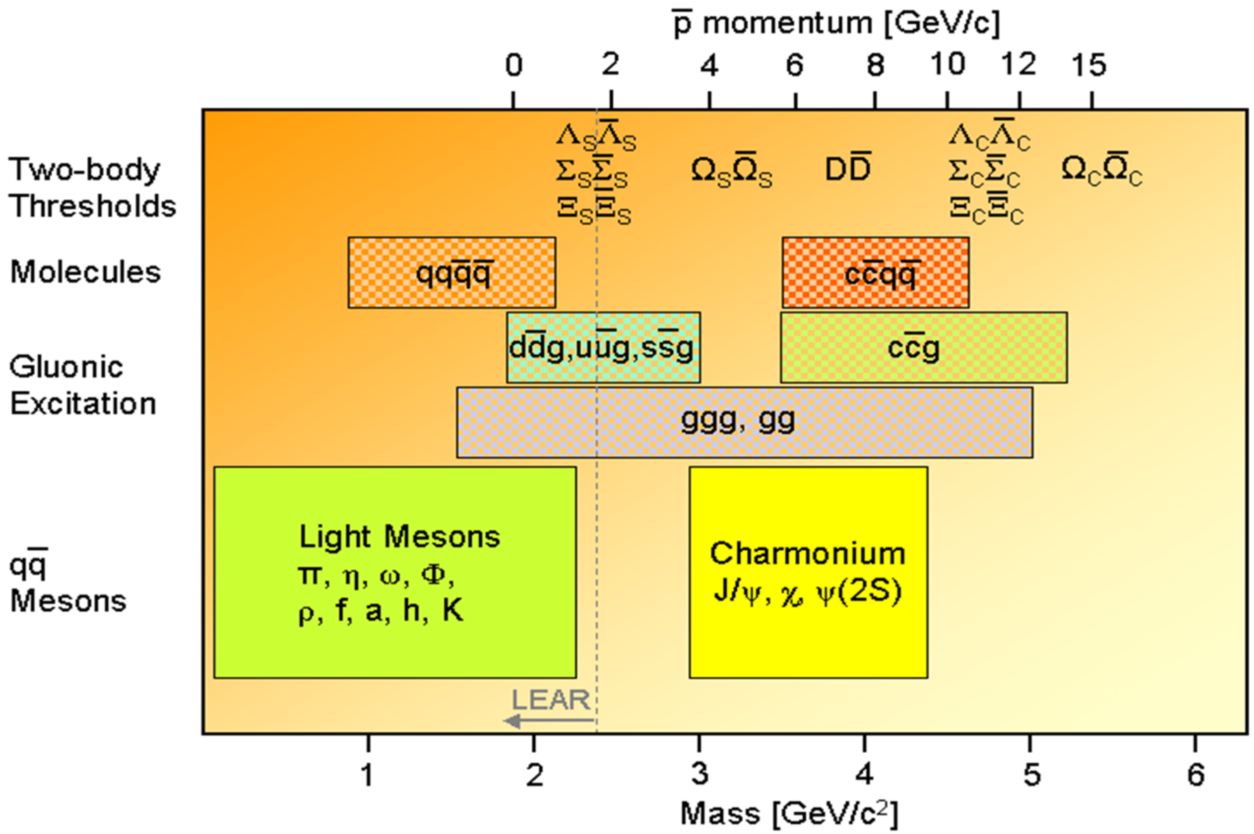
- like gluonic excitations
- like N-quarks

but no model free signature

approach:

- overpopulation of hadron multiplets
- unexpected masses and decay properties
- a well understood conventional meson picture is mandatory

Hadronic Systems



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 ...)

+ 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)

Electroproduction

(HERA)

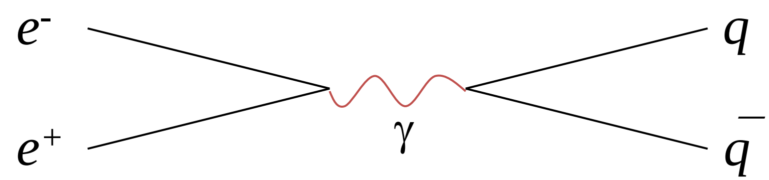
Experimental Methods

e^+e^-

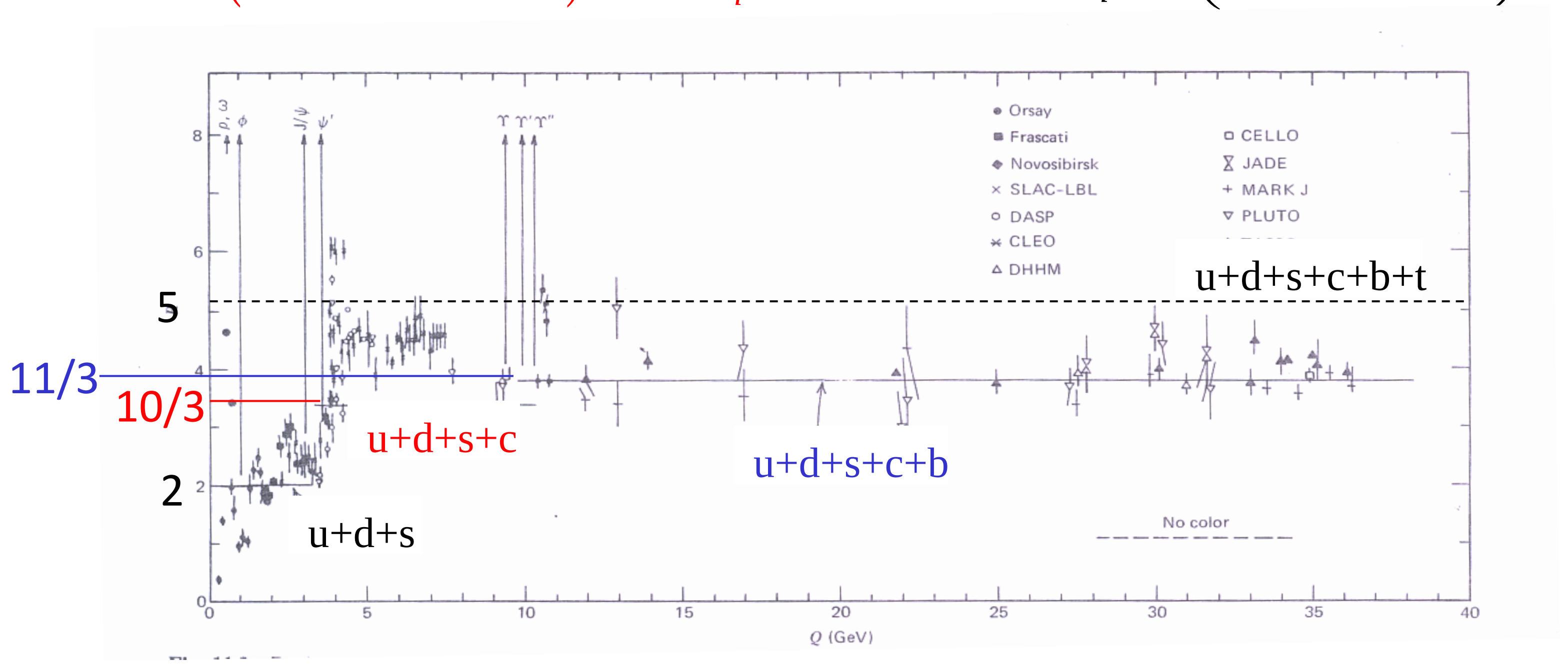
$\bar{p}p$

$e^+e^- \rightarrow$ hadrons

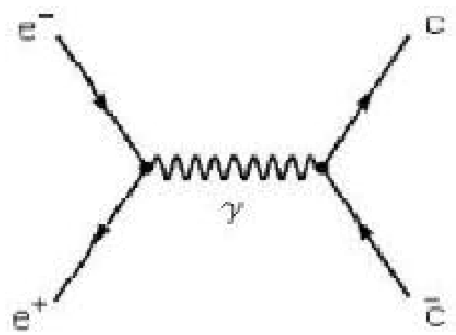
Dominated by the process $e^+e^- \rightarrow \gamma^* \rightarrow q\ \bar{q}$



$$R \equiv \frac{\sigma\left(e^+e^- \rightarrow hadrons\right)}{\sigma\left(e^+e^- \rightarrow \mu^+\mu^-\right)} = 3\sum_q e_q^2 \qquad R = 3\sum_q e_q^2\left(1 + \frac{\alpha_s(Q^2)}{\pi}\right)$$



Direct Formation (e.g. $e^+e^- \to c\bar{c}$)

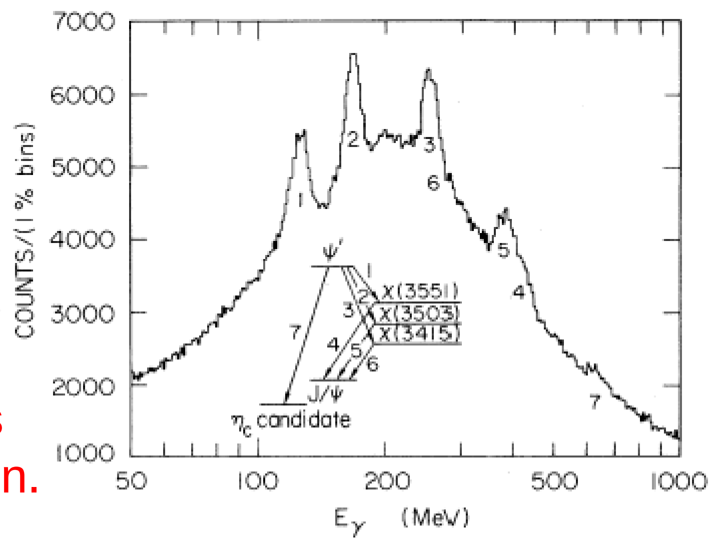


In e^+e^- annihilations direct formation is possible only for states with the quantum numbers of the photon $J^{PC}=1^{--}$: J/ψ, ψ' and $\psi(3770)$.

All other states can be produced in the radiative decays of the vector states. For example:

$$e^+ + e^- \to \psi'(2S) \to \gamma + X$$

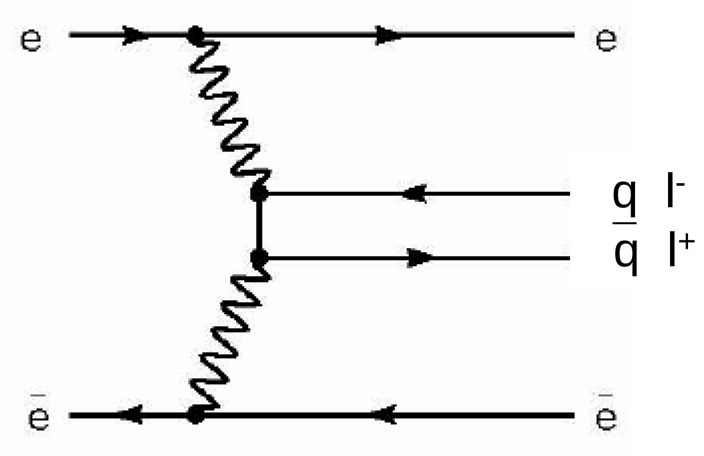
The precision in the measurement of masses and widths is limited by the detector resolution.



Crystal Ball inclusive photon spectrum

Two-photon Production $e^+e^- \to e^+e^- + (c\bar{c})$

J-even charmonium states can be produced in e^+e^- annihilations at higher energies through $\gamma\gamma$ collisions. The $(c\bar{c})$ state is usually identified by its hadronic decays. The cross section for this process scales linearly with the $\gamma\gamma$ partial width of the $(c\bar{c})$ state.



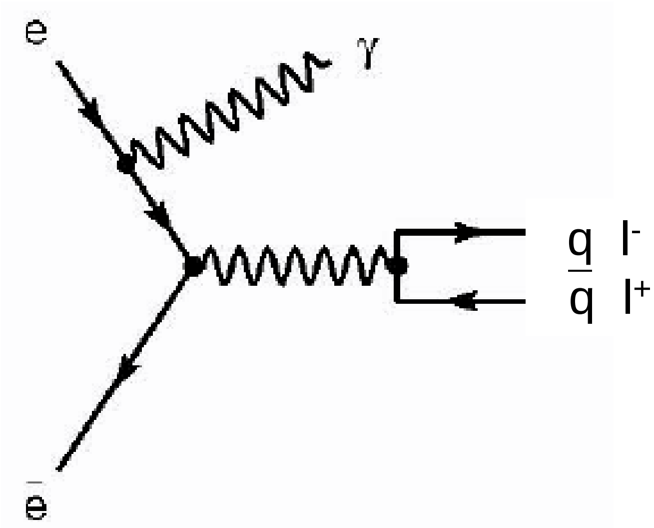
$$\sigma\left(e^+e^- \to e^+e^-(c\bar{c})\right) = \int d^5 L_{\gamma\gamma}(\alpha_i)\,\sigma\left(\gamma\gamma \to (c\bar{c})\right)$$

$$\sigma\left(\gamma\gamma \to (c\bar{c})\right) = 8\pi \frac{2J+1}{M}\Gamma_{\gamma\gamma}\frac{M\Gamma}{\left(s-M^2\right)^2 + M^2\Gamma^2}F\left(q_1^2, q_2^2\right)$$

L = Luminosity function
α= e.g. 4-momenta of out going leptons.
J,M,Γ = spin, mass ,total width of $c\bar{c}$ state.
s = cm energy of $\gamma\gamma$ system
$\Gamma_{\gamma\gamma}$ two-photon partial width
q_1,q_2 photon 4-momenta
F = Form Factor describing evolution of cross section.

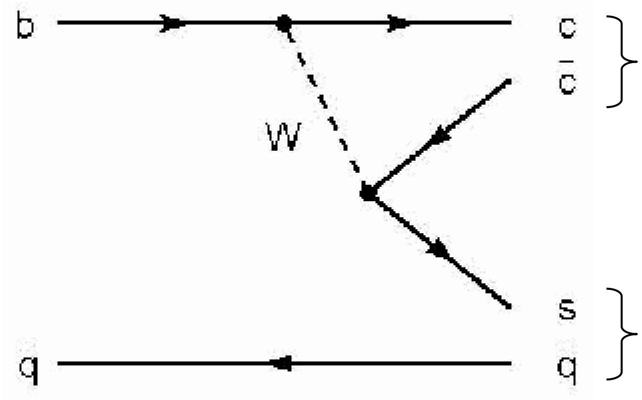
Limititations: knowledge of hadronic branching ratios and form factors used to extract the $\gamma\gamma$ partial width.

Initial State Radiation (ISR)



- Like in direct formation, only $J^{PC}=1^{--}$ states can be formed in ISR.
- This process allows a large mass range to be explored.
- Useful for the measurement of $R = \sigma(e^+e^- \to hadrons)/\sigma(e^+e^- \to \mu^+\mu^-)$.
- Can be used to search for new vector states.

B-Meson Decay



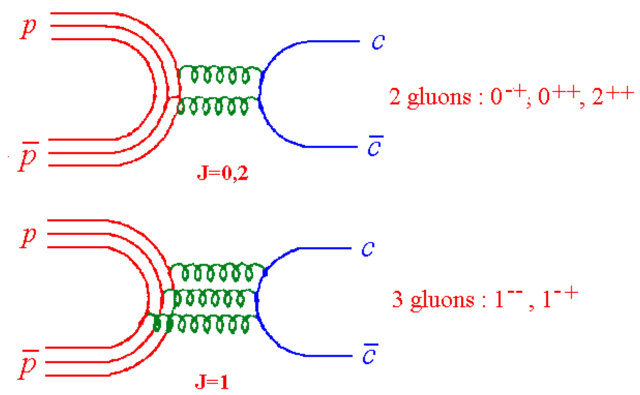
$J/\psi, \psi', \psi(3770), \eta_c, \eta'_c, \chi_{c0}, \chi_{c1}, D^{(*)}, \bar{D}^{(*)}, X(3872)$

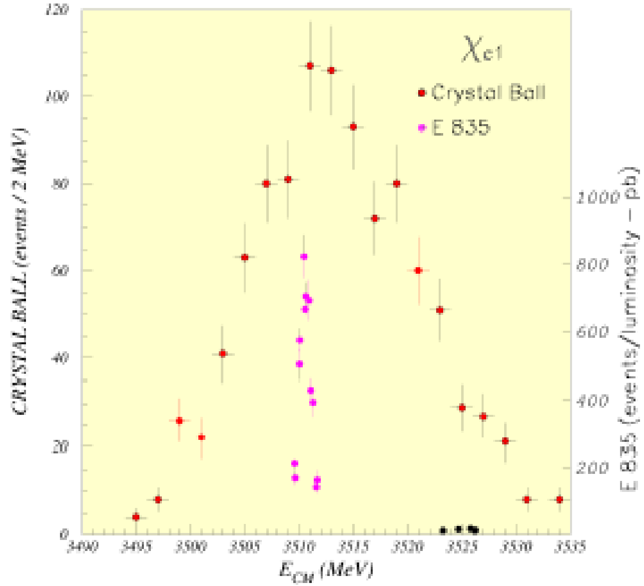
$K^{\pm}, K_S, K_L, K^*(890), K(1270)...$

Charmonium states can be produced at the B-factories in the decays of the B-meson.
The large data samples available make this a promising approach.
States of any quantum numbers can be produced.
η'_c and X(3872) discoveries illustrate the capabilities of the B-factories for charmonium studies.

$\bar{p}p$ Annihilation

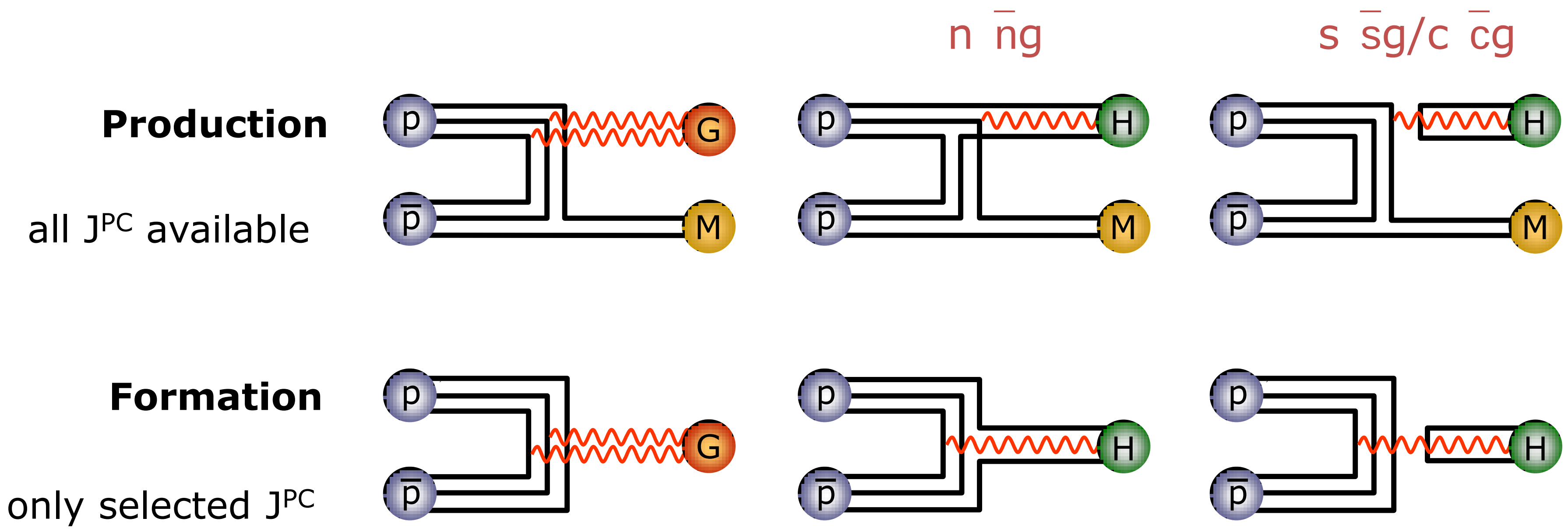
In $\bar{p}p$ collisions the coherent annihilation of the 3 quarks in the p with the 3 antiquarks in the $\bar{p}$ makes it possible to form directly states with all non-exotic quantum numbers.





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.

Hybrids and Glueballs in $\bar{p}p$ Annihilation



Gluon rich process creates gluonic excitation in a direct way

- $c\bar{c}$ requires the quarks to annihilate (no rearrangement)
- yield comparable to charmonium production
- even at low momenta large exotic content has been proven
- Exotic quantum numbers can only be achieved in production mode

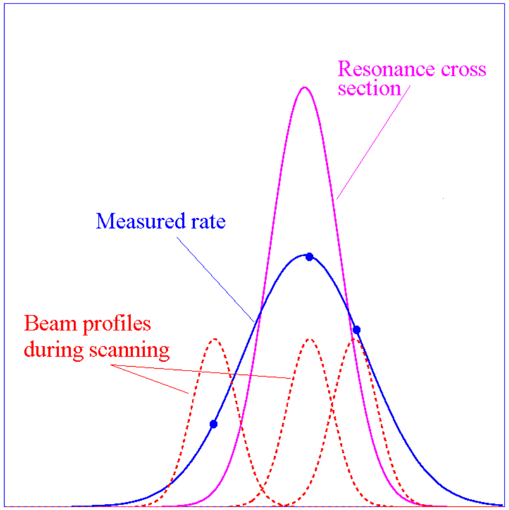
Experimental Method

The cross section for the process:

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

is given by the Breit-Wigner formula:

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

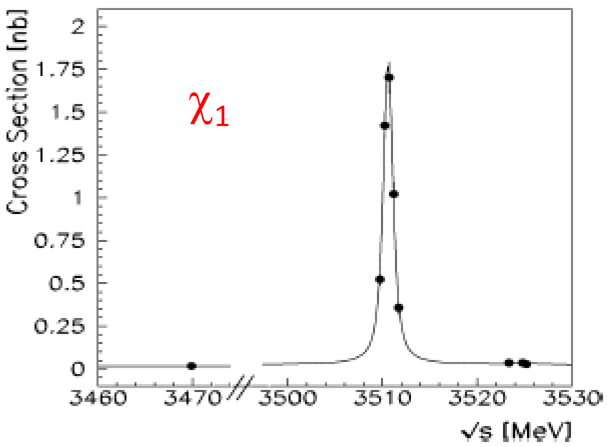


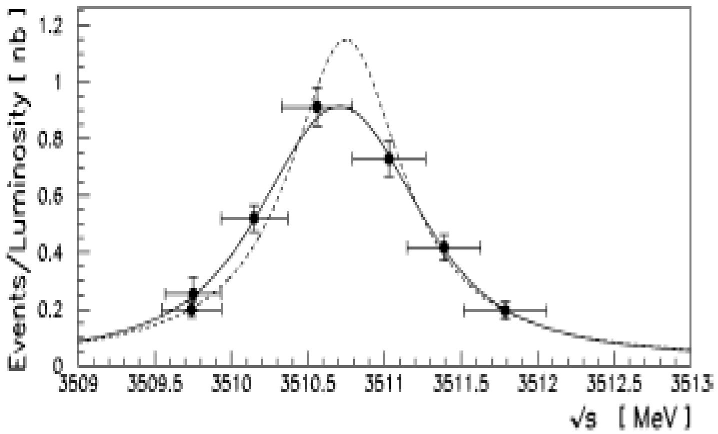
The production rate ν is a convolution of the BW cross section and the beam energy distribution function $f(E,\Delta E)$:

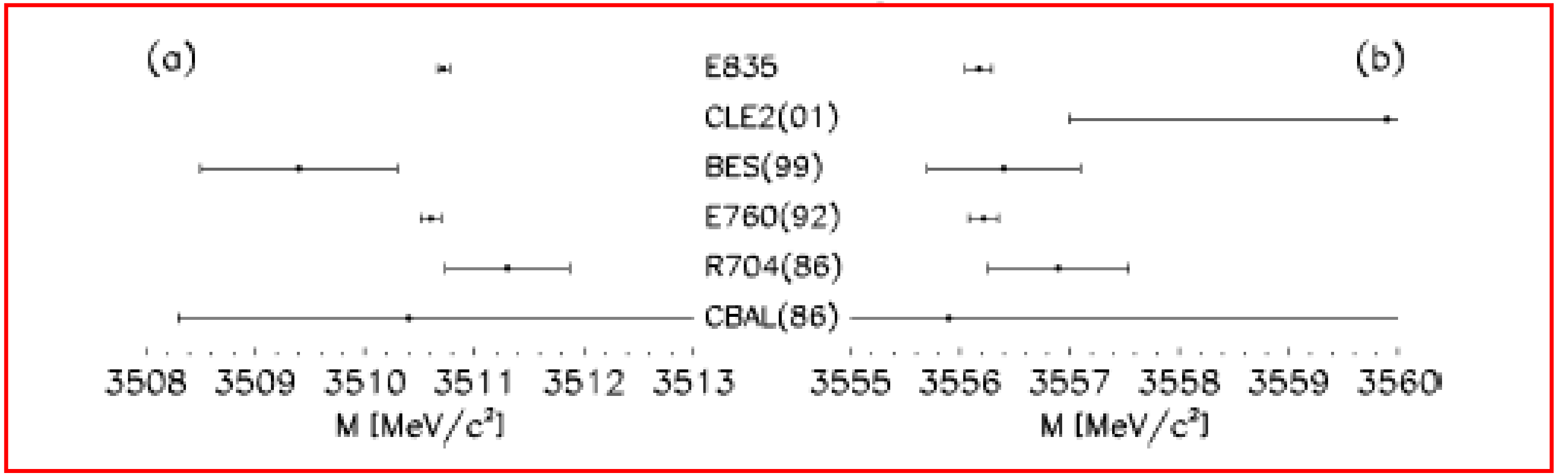
$$\nu = L_0\left\{\varepsilon \int dE f(E,\Delta E)\sigma_{BW}(E)+\sigma_b\right\}$$

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







$D_{(s)}$ systems

Charm (c) + Light Quark (u,d,s)

H-Atom of QCD

Annihilation of the charm quantum number

D-Mesons have no strong decay

only (electro-)weak decays possible

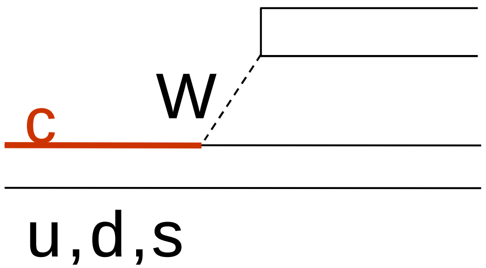
Long lifetime $c\tau \sim 100\text{-}300\mu m$

Many decays to light mesons

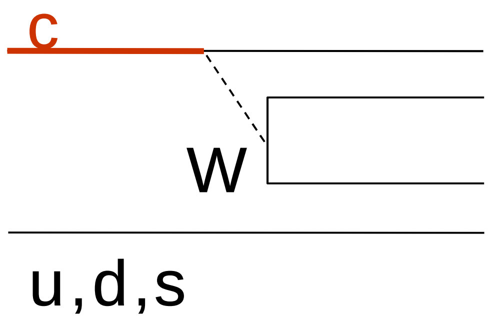
clean Spin-Parity $J^{PC}=0^{-+}$ for spectroscopy

$D_{(s)}$ Decays

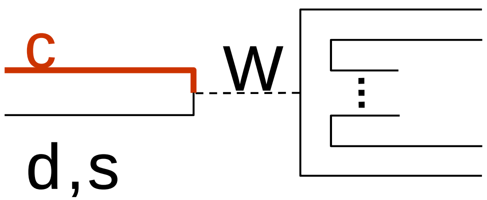
W-Emission (external)



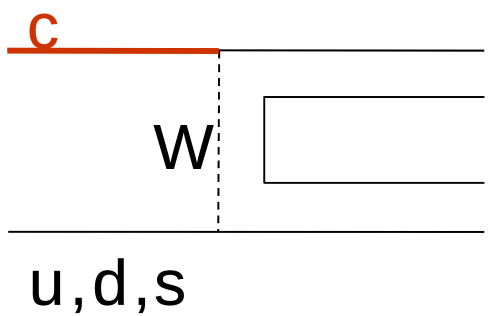
W-Emission (internal)



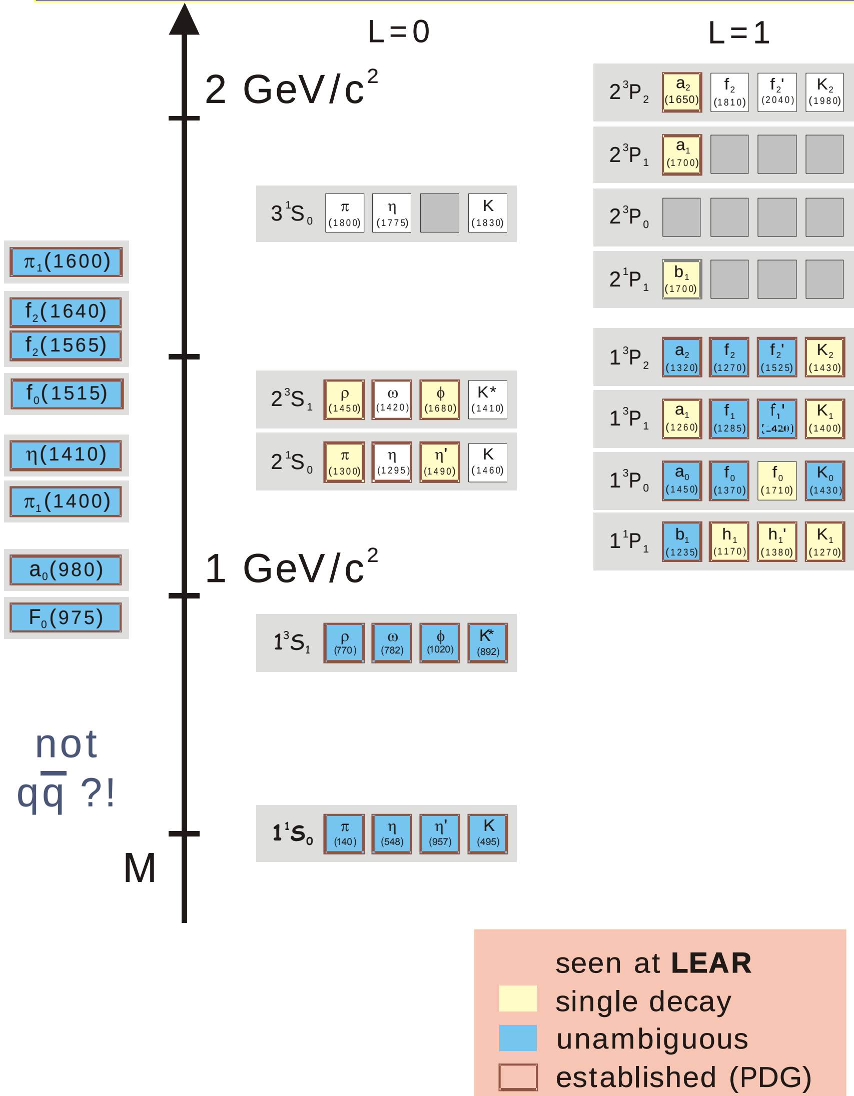
W-Annihilation



W-Exchange



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

Hybrids

- Light hybrids
  - Predictions
  - Candidates
- Charmonium hybrids
  - Predictions

Simplest Hybrids

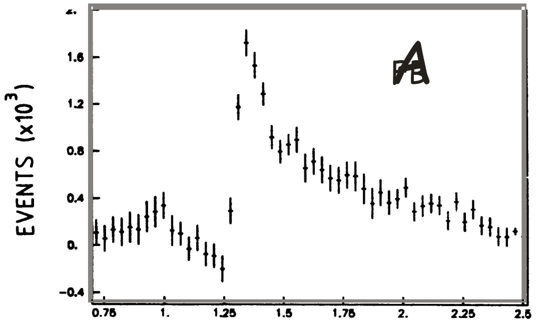
S-Wave+Gluon $(qq)_8g$ with $()_8$=coloured

$^1S_0$ ↑↓ $^3S_1$ ↑↑

combined with a 1^+ or 1^- gluon

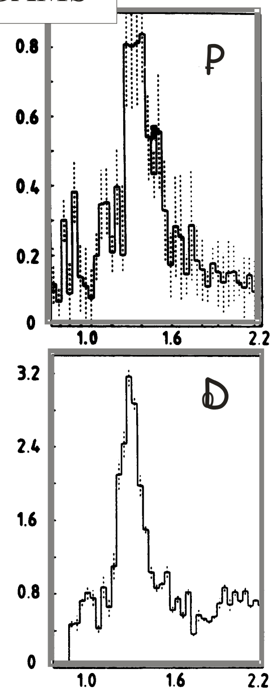
Gluon	1^- (TM)	1^+ (TE)
$^1S_0$, 0^{-+}	1^{++}	1^{--}
$^3S_1$, 1^{--}	0^{+-} 1^{+-} 2^{+-}	0^{-+} 1^{-+} 2^{-+}

π_1(1400) - History



GAMS

GAMS



1988 GAMS published strong FB-asymmetry in the reaction

- → $\pi^- p \rightarrow \pi^0 \eta$ n

verifies Apel et al.and called M(1405)

1991 GAMS: PWA ambiguous,

- → 8 solutions
- → not all support $\pi\eta$ P-wave

1992 KEK-E179:

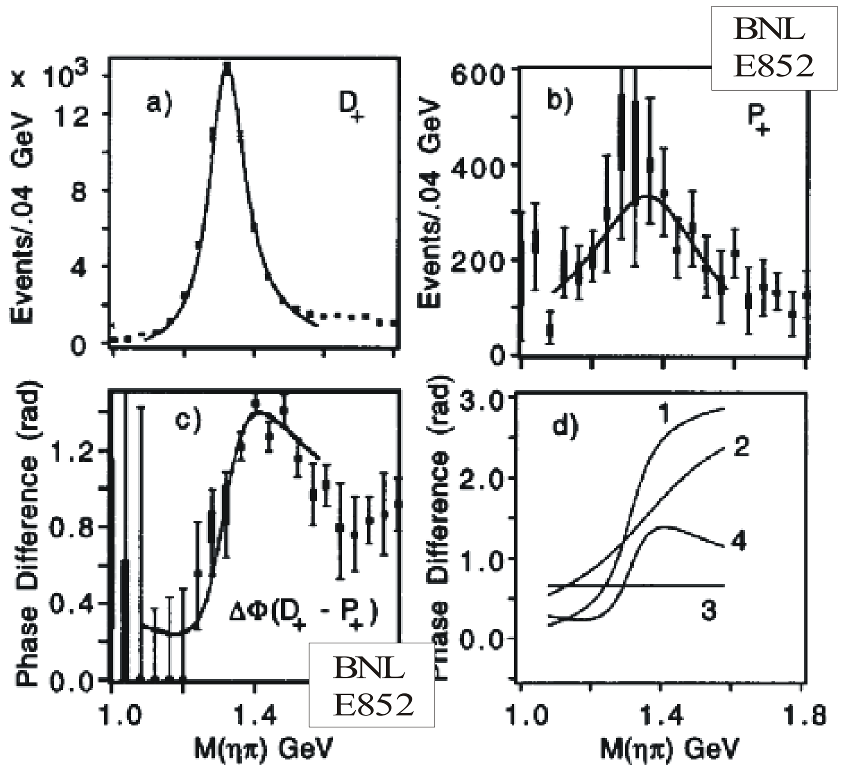
- → all solutions need an exotic wave
  but acceptance unclear

1994 CB: PS-197

- → $\pi\eta$-P-Wave in $\pi\pi\eta$
- → large Width
- → Resonance? questionable

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

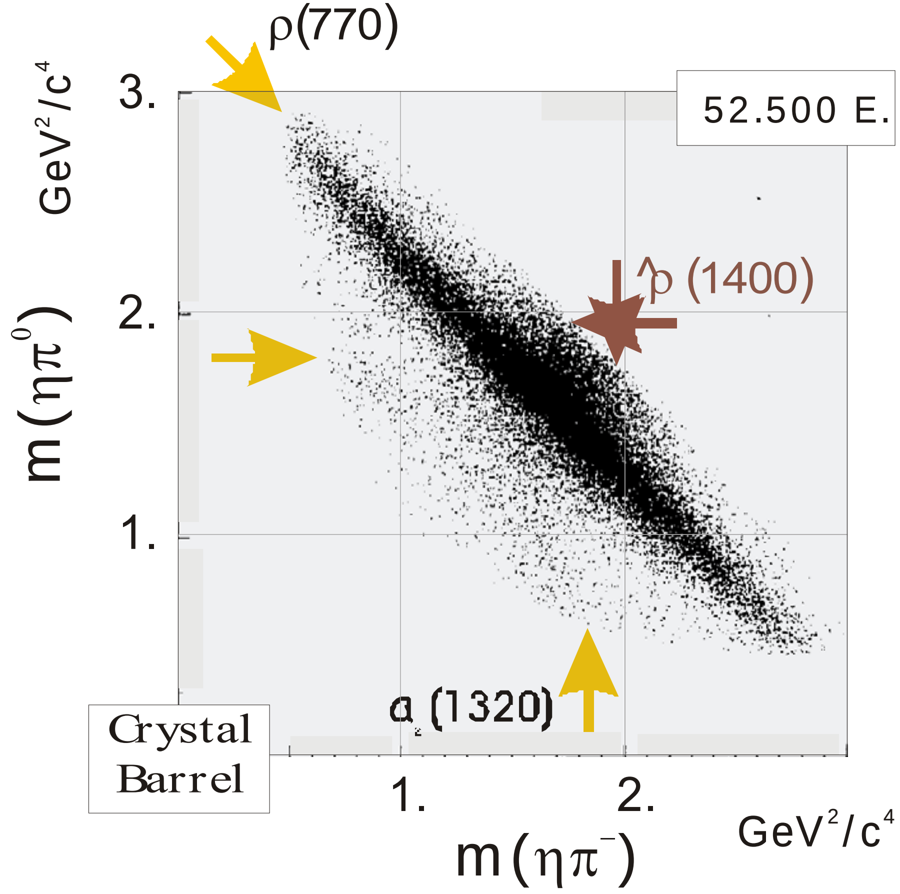
$\pi^- p \to \pi^- \eta\ p$ (and $\to \pi^0 \eta\ n$)



$\pi\eta$ peak @ 1.4 GeV/c^2

phasemotion at a_2 tail visible

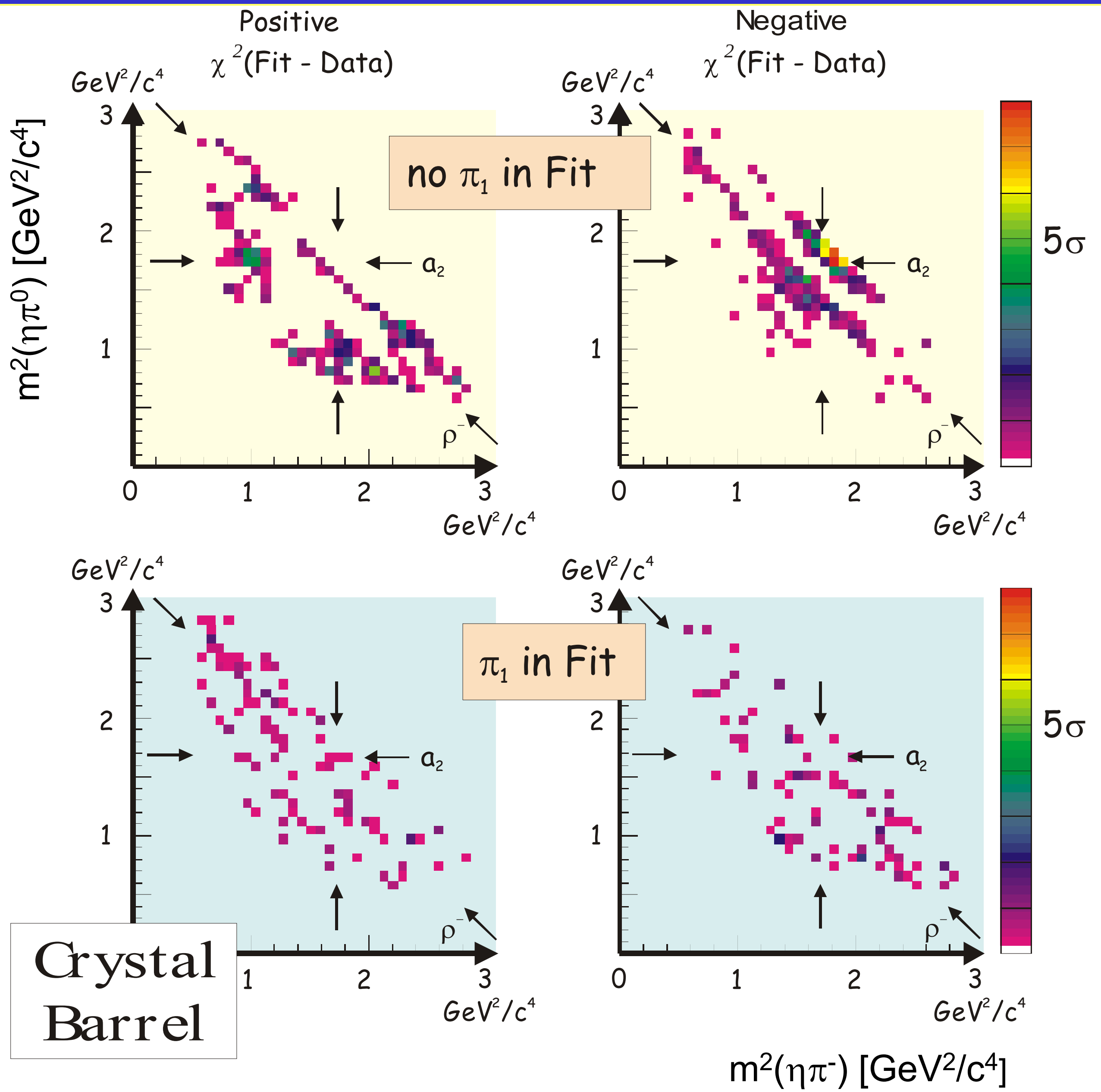
$\bar{p}d \to \pi^-\pi^0\eta\ p$ @ Rest in liq.D2



Advantage: I=1

and no Scalars

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

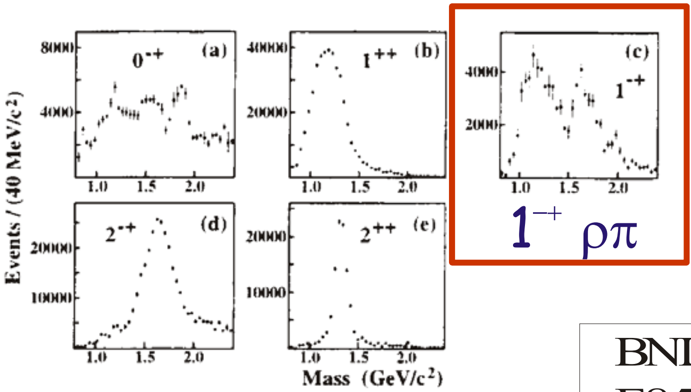


π_1(1400) Summary

Exp	Year	Mass	Width	Channel
GAMS	1988	1406±20	189±20	$\pi^0\eta$
E179	1993	1323±5	143±13	$\pi^-\eta$
VES	1993	~1300	~300	$\pi^-\eta$
	1997	~1300	>500	$\pi^-\eta$
CB	1994	1200-1600	400-1000	$\pi^0\eta$
	1998	1360±25	220±90	$\pi^0\eta$
E852	1997	$1370\pm16^{+50}_{-30}$	$385\pm40^{+65}_{-105}$	$\pi^-\eta$
CB	1998	1400±20±20	$310\pm50^{+50}_{-30}$	$\pi^0\eta$ $\pi^-\eta$

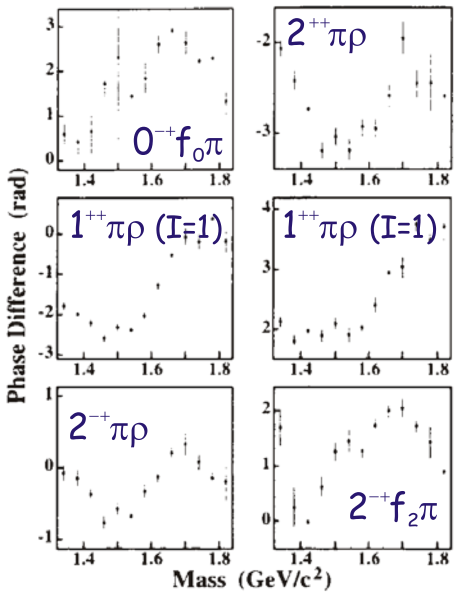
Exotic wave is evident

$\pi_1(1600)$



BNL
E852

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



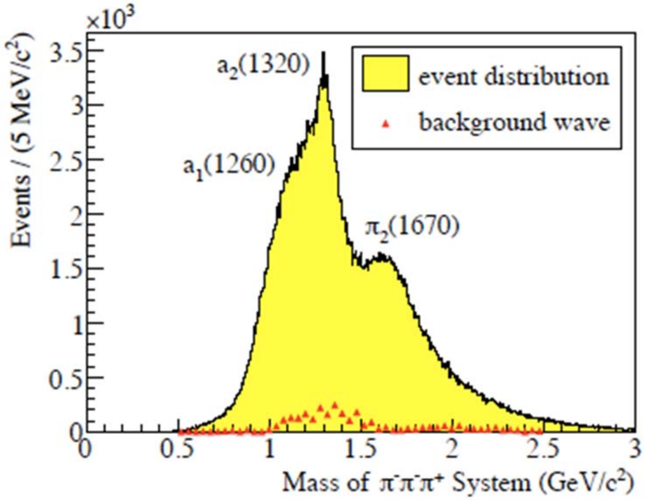
$\pi^- p \to \pi^- \rho^0 p \to \pi^- \pi^- \pi^+ p$ (E852) shows a clear resonance in the 1^{-+} wave around 1600 MeV/c^2

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

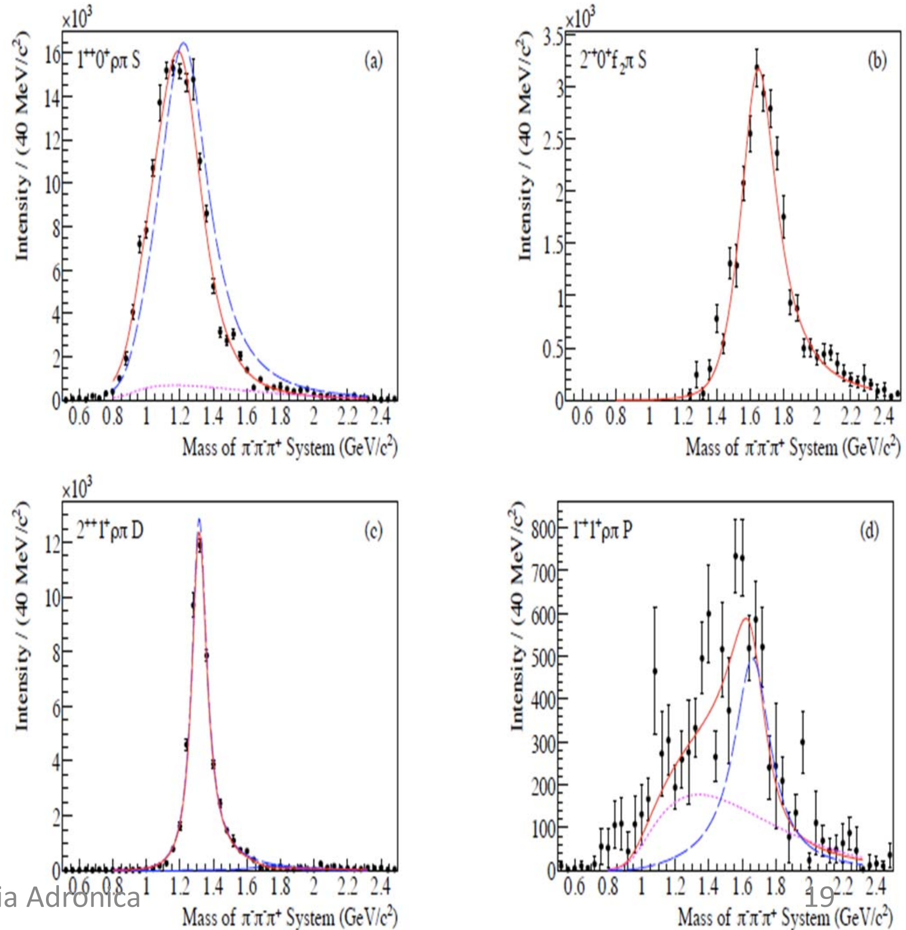
$b_1(1235)\pi$ channel confirmed by CB in $\bar{p}p \to \omega\pi^+\pi^-\pi^0$.

$\pi_1(1600)$

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



PRL104(2010) 241803

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

$\pi_1(1600)$

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

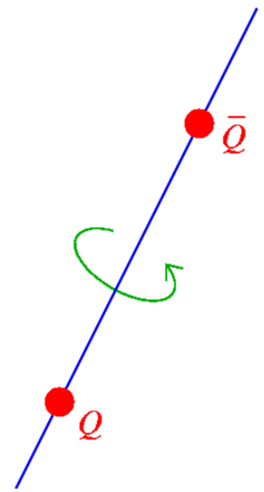
A total of 42 partial waves are included in the first step of the fit. The χ^2 fit of the spin-density matrix elements obtained for each mass bin is performed in the mass range from 0.8 to 2.32 GeV/c^2

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

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

Heavy-quark hybrid mesons

- more amenable to theoretical treatment than light-quark hybrids
  - early work:
    Hasenfratz, Horgan, Kuti, Richards (1983)
    Perantonis, Michael (1990)
- possible treatment like diatomic molecule
  (Born-Oppenheimer)
  - slow heavy quarks ←→ nuclei
  - fast gluon field (and light quarks) ←→ electrons
- gluons provide adiabatic potentials $V_{qq}(r)$
  - gluons fully relativistic, interacting
  - potentials computed in lattice simulations
  - nonrelativistic quark motion described in *leading order* by solving Schrödinger equation
- conventional mesons from Σ_g^+ hybrids from Π_u,Σ_u^-



LQCD ccg 1^{-+} vs. cc 1^{--} (J/ψ)

1^{-+} $m(c\bar{c}g)$	Model	Group	Reference
4390±80 ±200	isotropic	MILC97	PRD56(1997)7039
4317±150	isotropic	MILC99	NPB93Supp(1999)264
4287	isotropic	JKM99	PRL82(1999)4400
4369±37 ±99	anisotropic	ZSU02	hep-lat 0206012
$\Delta(1^{-+},1^{--})$ $m(c\bar{c}g)-m(c\bar{c})$			
1340±80 ±200	isotropic	MILC97	PRD56(1997)7039
1220±150	isotropic	MILC99	NPB93Supp(1999)264
1323±130	anisotropic	CP-PACS99	PRL82(1999)4396
1190	isotropic	JKM99	PRL82(1999)4400
1302±37 ±99	anisotropic	ZSU02	hep-lat 0206012

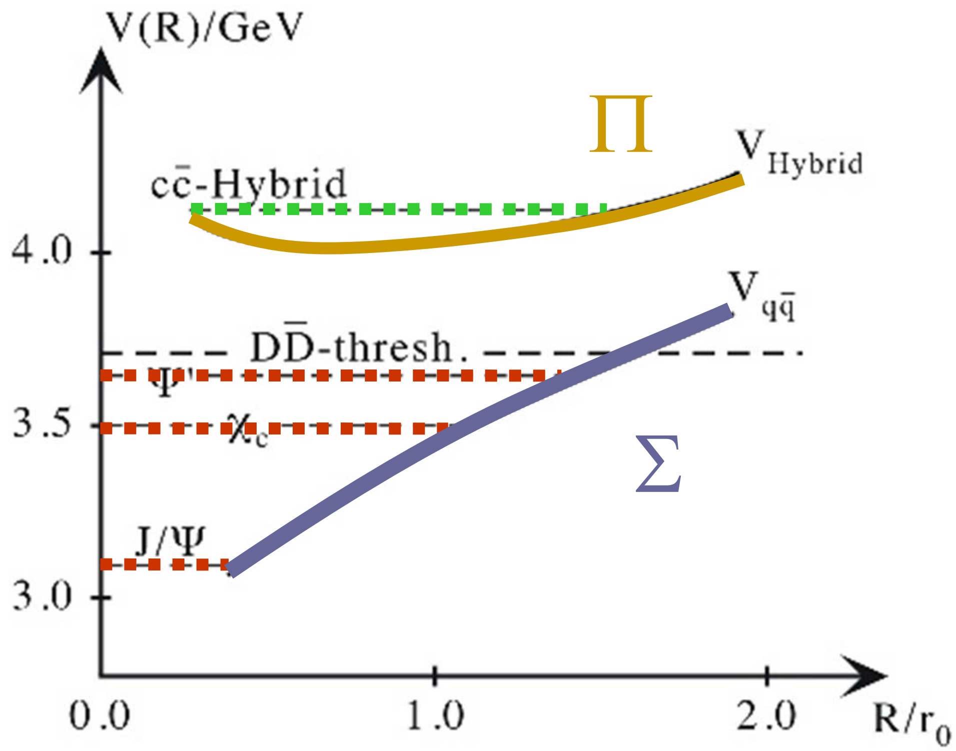
Charmed Hybrids

Gluonic excitations of the quark-antiquark-potential
may lead to bound states

LQCD:

- Π potential
– m_H ~ 4.2-4.5 GeV

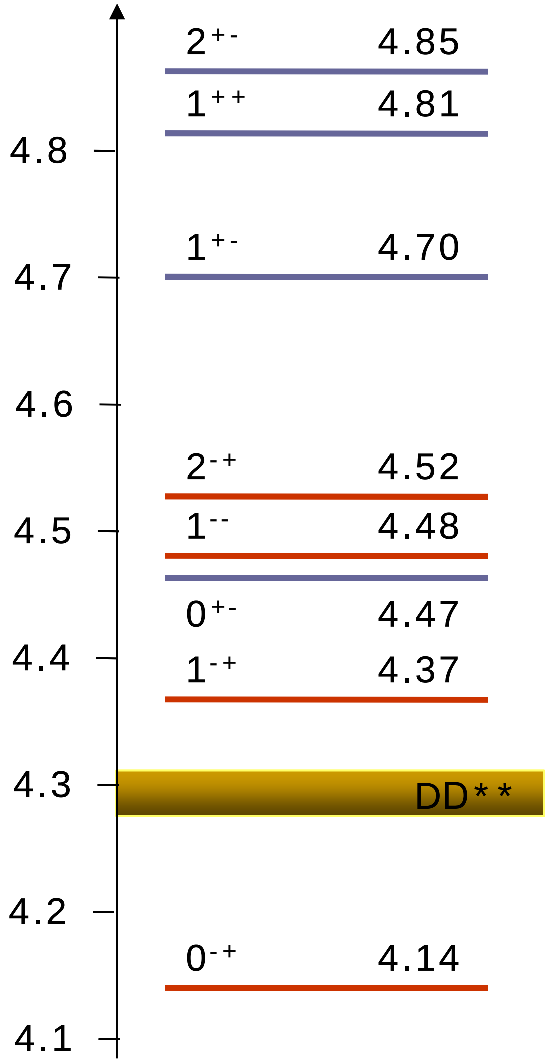
Light charmed hybrids could be as narrow as → O(5-50 MeV)



important $<r^2>$ and $r_{Breakup}$

Charmed Hybrid Level Scheme

- $1^{--}(0,1,2)^{-+} < 1^{++}(0,1,2)^{+-}$
  - JKM00, NPB83Suppl83(2000)304 and Manke, PRD57(1998)3829
- L-Splitting
  - $\Delta m \sim 100\text{-}250$ MeV/c^2 for 1^{-+} to 0^{+-}
- S-Splittings
  - Page thesis,1995 and PRD35(1987)1668
  - 4.14 (0^{-+}) to 4.52 GeV/c^2 (2^{-+})
- consistent w/LQCD
  - JKM, NPB86suppl(2000)397, PLB478(2000) 151



Charmed Hybrids – Decays

Fluxtube-Model predicts DD** (+c.c.) decays

- if m_H<4290 MeV/c^2 below DD_0(+c.c.)
- □ → Γ_H < 50 MeV

Some exotics can decay neither to DD nor to DD* (+c.c.)

- e.g.: $J^{PC}(H)=0^{+-}$
  - fluxtube forbidden: $J/\psi f_2$, $J/\psi(\pi\pi)_S$, $\eta_c h_1$
  - fluxtube allowed: $\chi_{c0}\omega$, $\chi_{c0}\phi$, $\chi_{c2}\omega$, $\chi_{c2}\phi$, $h_{1c}\eta$
- Small number of final states with small phase space
  - favours a narrow resonance
- if DD** (+c.c.) possible → still very small phase space

But! be prepared for surprises

measure DD nor to DD* (+c.c.) waves as well

Scalars and Glueballs

Predictions

Production Modes

Scalar States

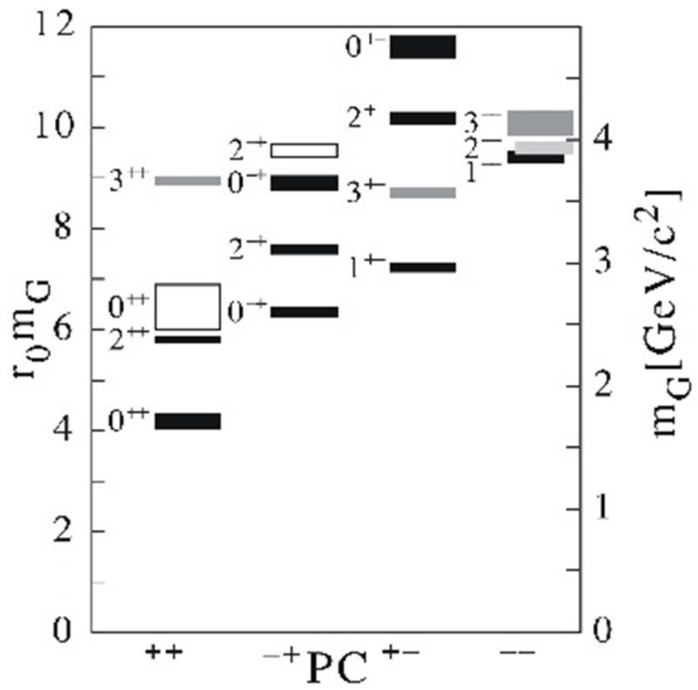
Glueballs

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.

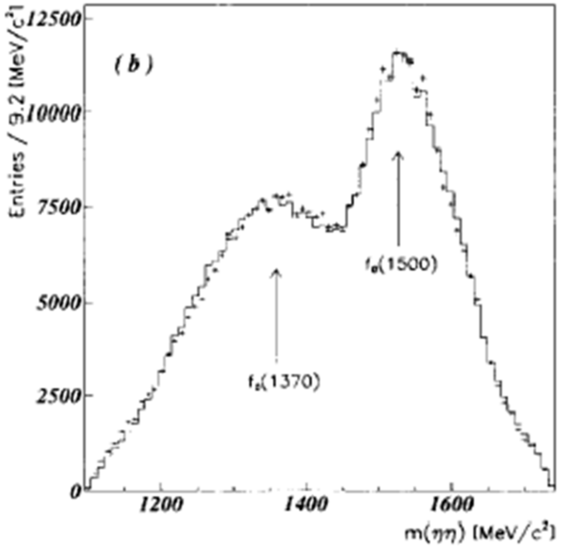
Some predicted decay modes $\phi\phi$, $\phi\eta$, $J/\psi\eta$, $J/\psi\phi$ ...



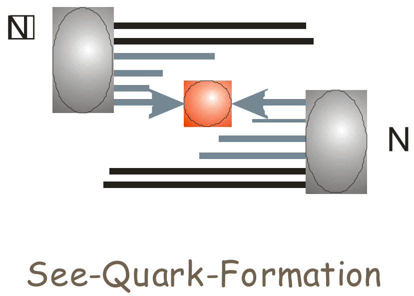
Morningstar und Peardon, PRD60 (1999) 034509
Morningstar und Peardon, PRD56 (1997) 4043

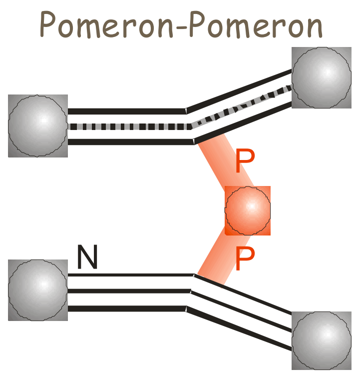
The detection of non-exotic glueballs is not trivial, as these states mix with the nearby $q\bar{q}$ states with the same quantum numbers, thus modifying the expected decay pattern.

- 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**:

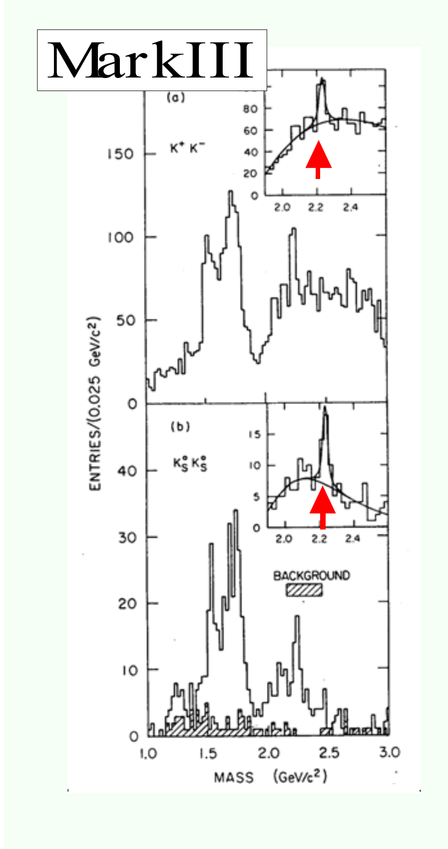
$a_0(980)$, $K^*_0(1430)$, $f_0(980)$, $f_0(1500)$ n=1, 0^{++} scalar nonet
$a_0(1450)$, $K^*_0(1950)$, $f_0(1370)$, $f_0(1710)$ n=2, 0^{++} scalar nonet

Tensor Glueball

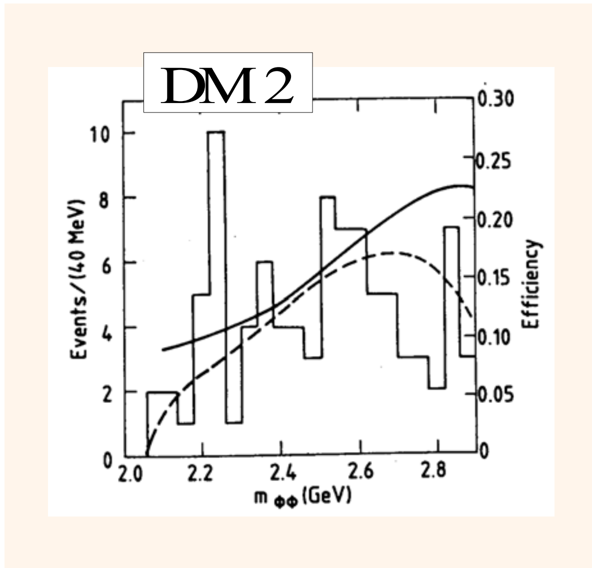
If there is a scalar glueball with a mass of 1.44 GeV/c^2 then LQCD predicts a tensor glueball with a mass around 2.0 GeV/c^2.

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

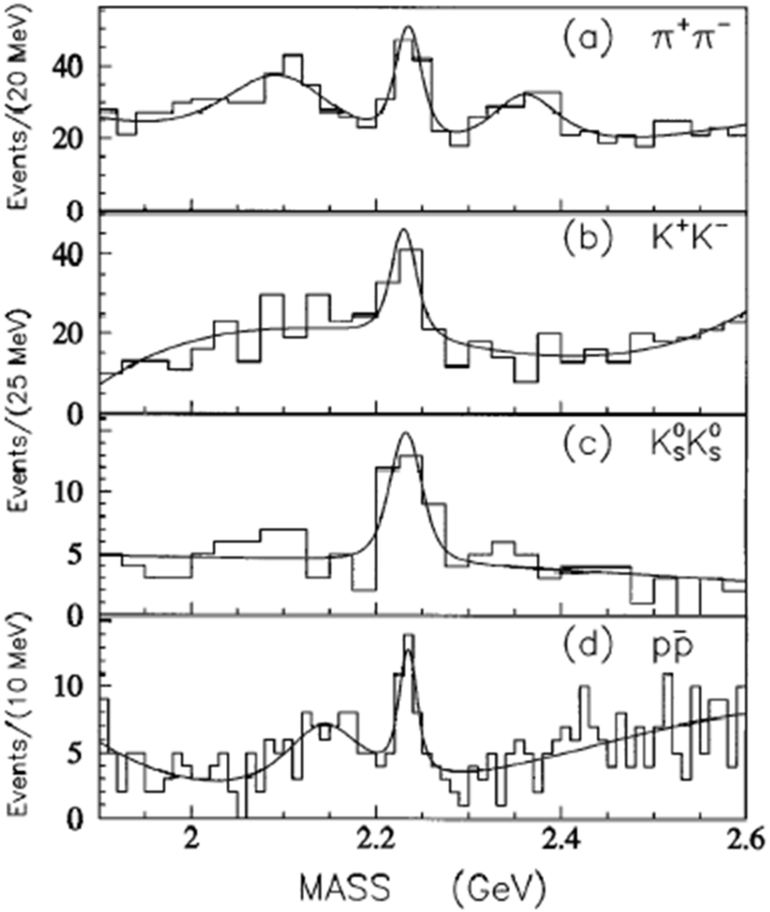
into $K\bar{K}$



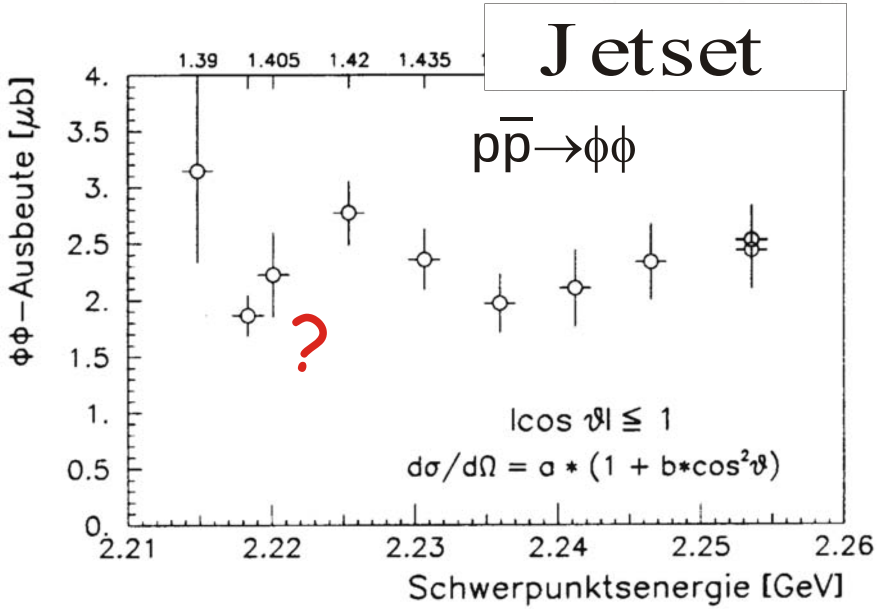
into $\phi\phi$



$\xi(2220)$ confirmed by BES



$\xi(2220)$ NOT confirmed by JETSET ...



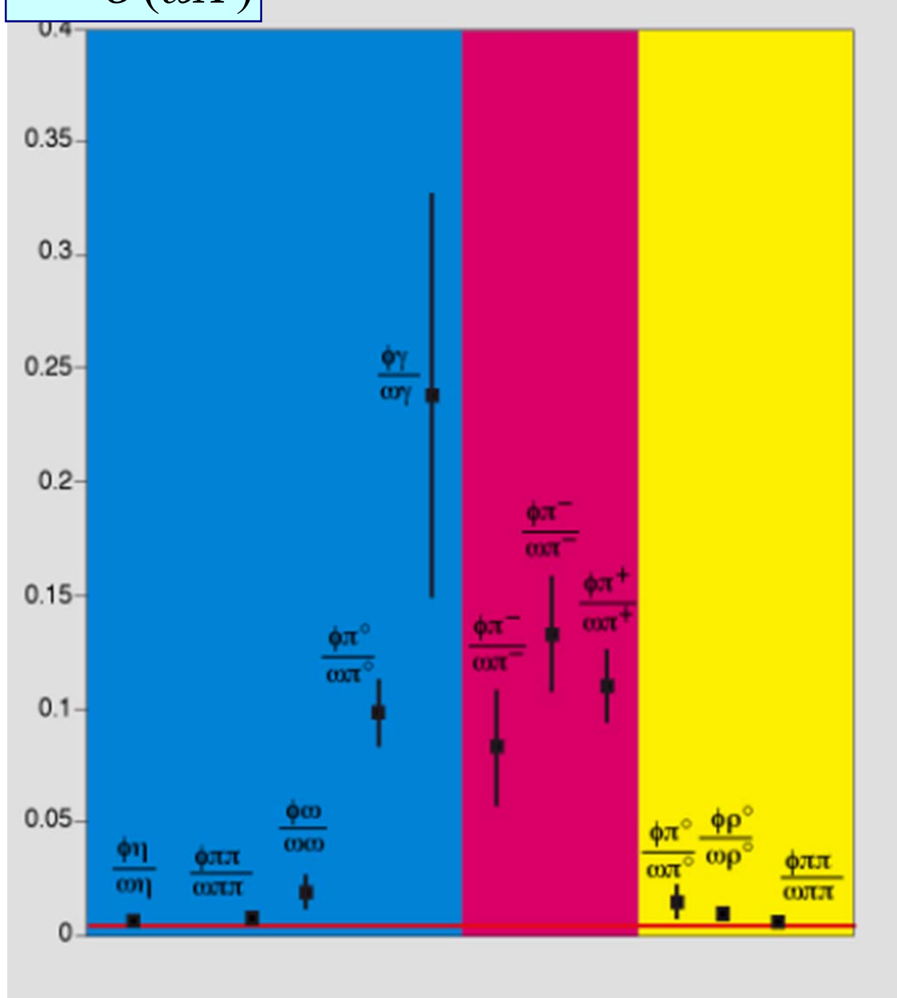
... $\xi(2220)$ NOT seen by Crystal Barrel either

Tensor Glueball situation still confused

OZI Rule Violations

$$R = \frac{\sigma(\phi X)}{\sigma(\omega X)}$$

$\bar{p}$ annihilation at rest



$$R = \frac{\sigma(\phi X)}{\sigma(\omega X)} = f \cdot \tan^2(\theta_v - \theta_i)$$

Strange quark content of the nucleons.

- "Shakeout" (intrinsic s $\bar{s}$ component)
- "Rearrangement"
- The reaction

$$\bar{p}p \to \phi\phi$$

provides additional evidence for intrinsic s $\bar{s}$ pairs in nucleon.

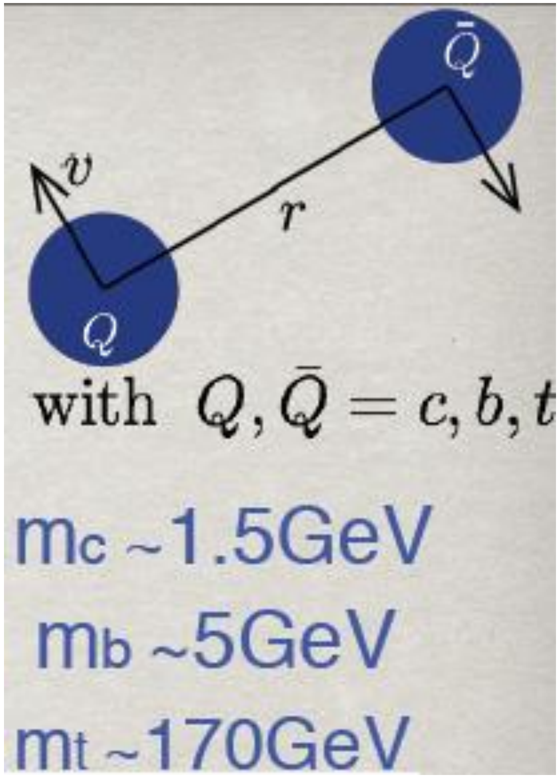
$$\sigma(\bar{p}p \to \phi\phi) = \sigma(\bar{p}p \to \omega\omega)\tan^4(\theta_v - \theta_i)$$

Prediction ≈ 10 nb

Measurement ≈ 3700 nb

Quarkonium

- Charmonium below threshold
- Bottomonium below threshold
- Quarkonium above threshold and XYZ states



Heavy quarkonia are non relativistic bound states multiscale systems:

$$m_Q \gg m_Q v \gg m_Q v^2$$

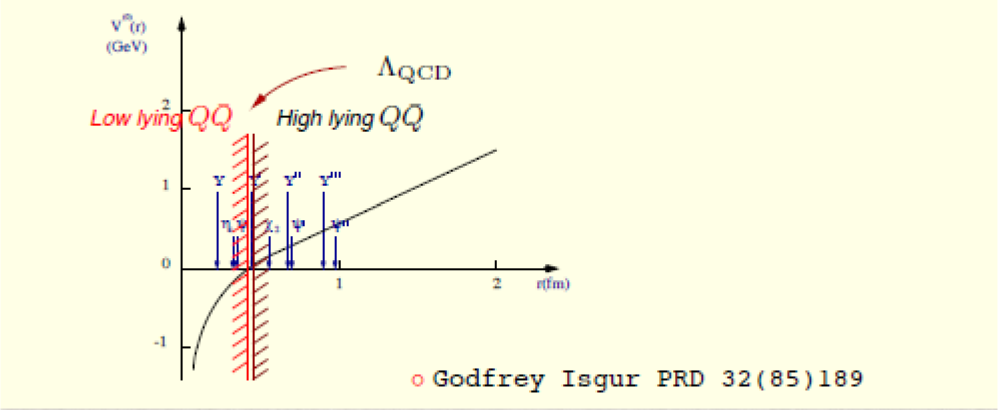
The system is non relativistic: $v_b^2 \approx 0.1 \quad v_c^2 \approx 0.3$

The mass scale is perturbative:

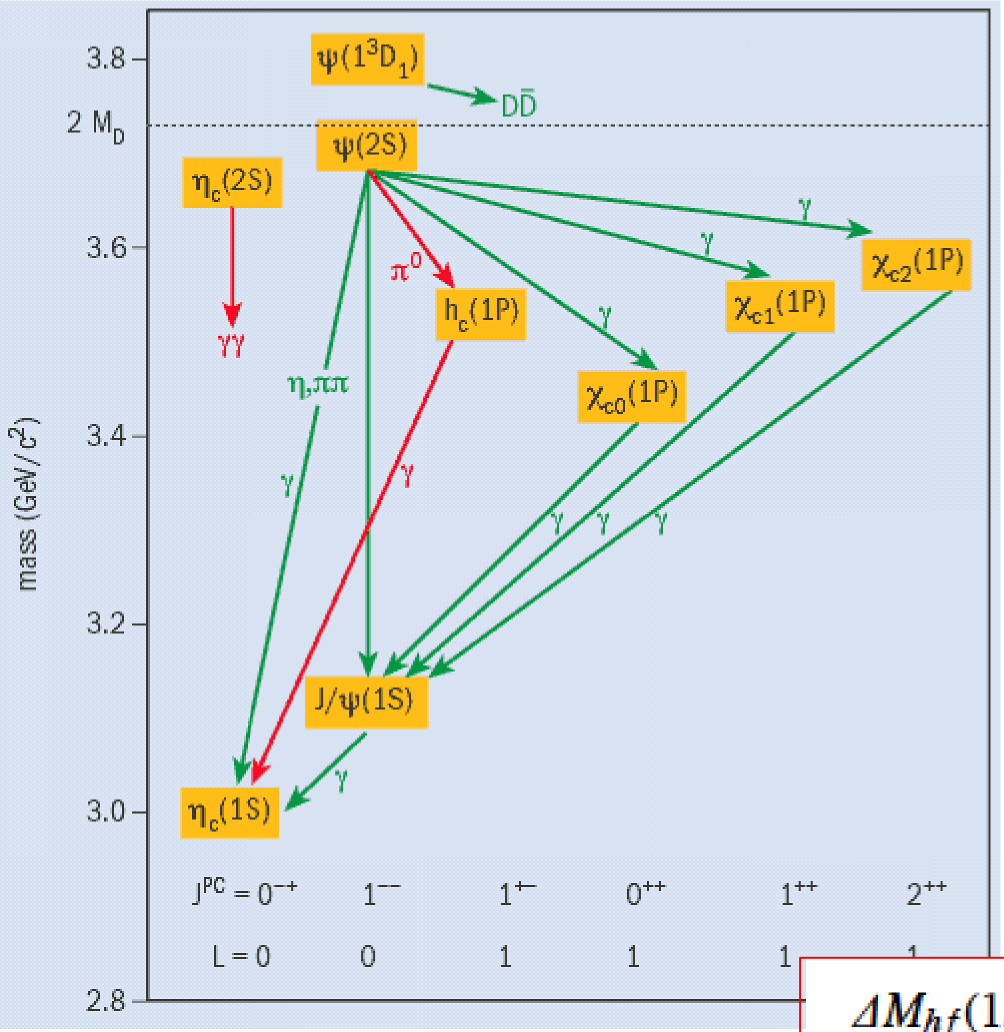
$$m_Q \gg \Lambda_{QCD}$$

$$m_b \approx 5\ GeV \qquad m_c \approx 1.5\ GeV$$

The structure of separated energy scales makes quarkonium an ideal probe of (de)confinement.
Quarkonia probe the perturbative, non perturbative and transition regimes.



Charmonium Spectroscopy



All 8 states below open charm threshold are well established experimentally, although some precision measurements still needed (e.g. $\eta_c(2S)$, h_c)

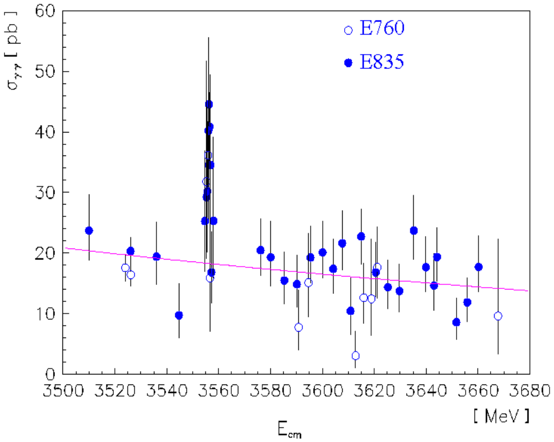
The region above threshold still to be understood:

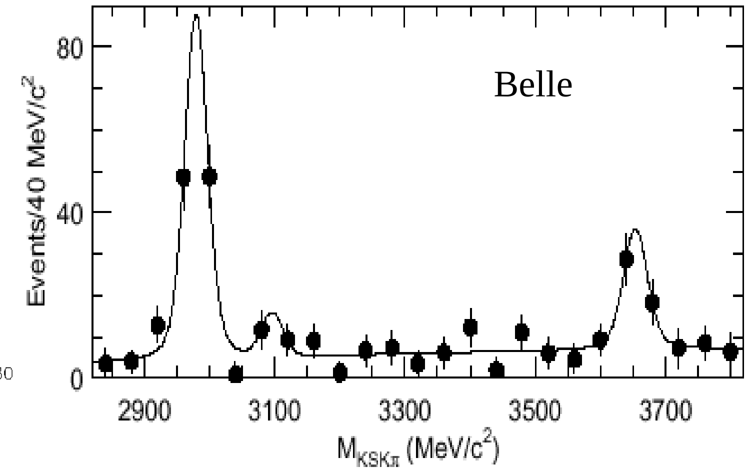
- find missing states (e.g. D-wave)
- understand nature of newly discovered states (e.g. X Y Z)

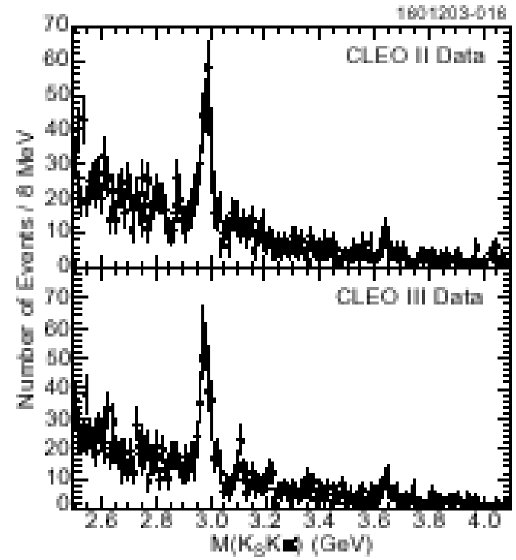
Hyperfine splitting of quarkonium states gives access to V_{SS} component of quark potential model

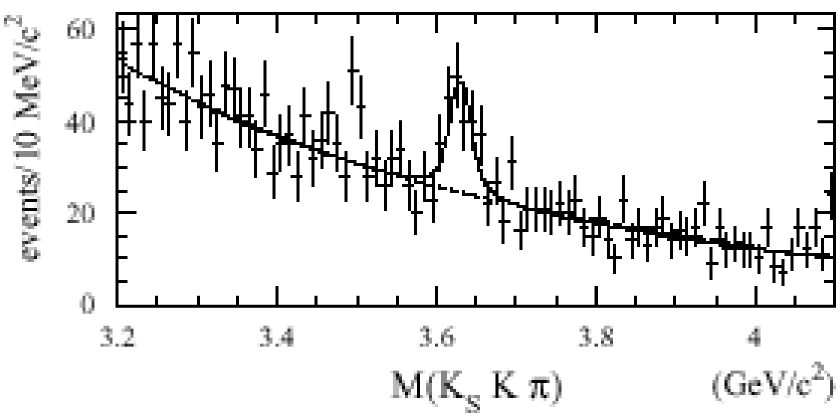
$$\Delta M_{hf}(1S)_{c\bar{c}} \equiv M(J/\psi) - M(\eta_c) = 116.6 \pm 1.0 \text{ MeV}$$

The $\eta_c(2^1S_0)$









PDG 2012

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

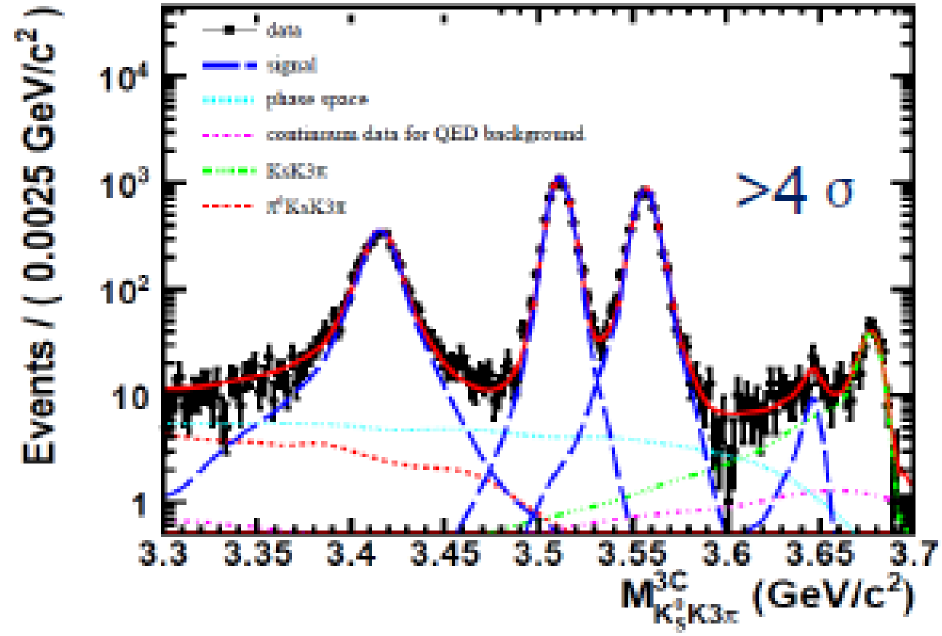
$\Gamma(\eta'_c) = 10 \pm 4$ MeV

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

Evidence $\eta_c(2S) \to K_sK^{+-}\pi^{-+}\pi^{+}\pi^{-}$

PRD 87,052005(2013)

- For $\eta_c(2S)$, only two measured decay Brs are available: $KK\pi$ and $K^+K^-\pi^+\pi^-\pi^0$
- $\psi' \to \gamma\eta_c(2S)$: M1 transition
- Search for more $\eta_c(2S)$ decay modes
- To measure the mass, width of $\eta_c(2S)$



$M = 3646.9 \pm 1.6 \pm 3.6$ MeV/c^2

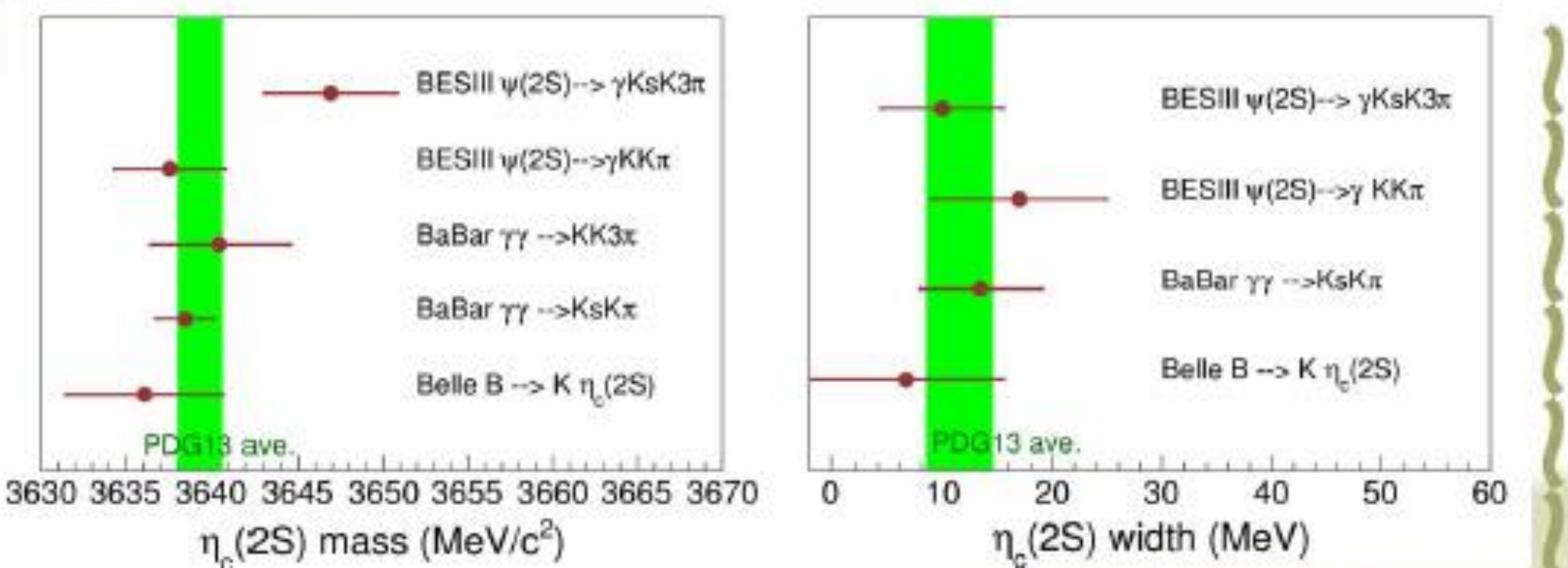
$\Gamma = 9.2 \pm 4.8 \pm 2.9$ MeV

$B(\psi' \to \gamma\eta_c(2S)) \times B(K_sK^{+-}\pi^{-+}\pi^{+}\pi^{-}) = (7.03 \pm 2.10 \pm 0.70) \times 10^{-6}$

The measured M and Γ are consistent with values in PRL109, 042003 (2012)

Chengping Shen – PIC 2013

Summary for $\eta_c(2S)$



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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

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

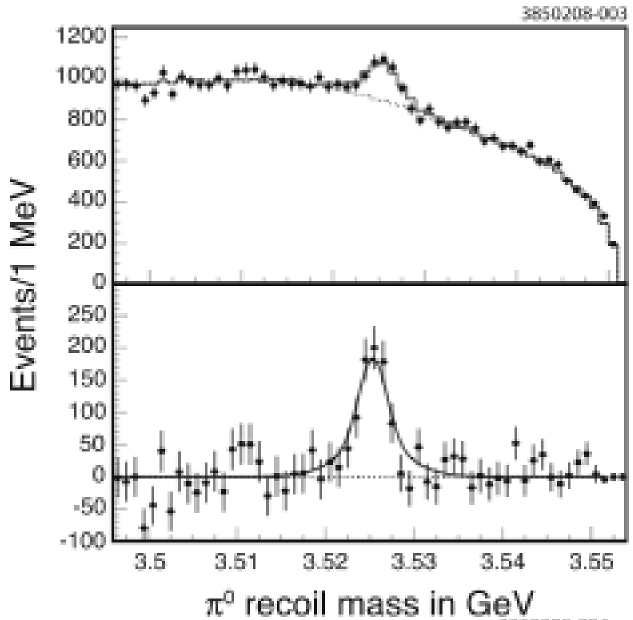
- The width is expected to be small $\Gamma(h_c) \leq 1$ MeV.
- The dominant decay mode is expected to be $\eta_c+\gamma$, which should account for $\approx$ 50 % of the total width.
- It can also decay to J/ψ:

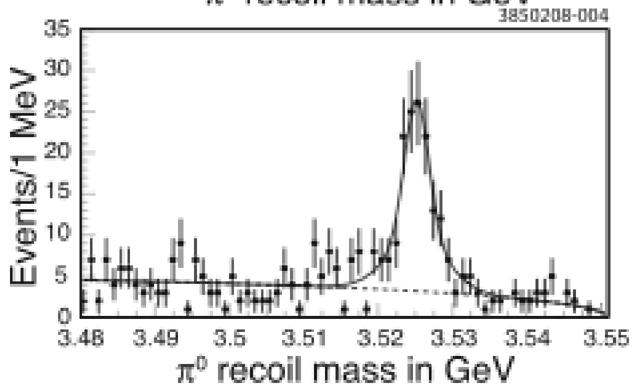
$J/\psi + \pi^0$	violates isospin
$J/\psi + \pi^+\pi^-$	suppressed by phase space and angular momentum barrier

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



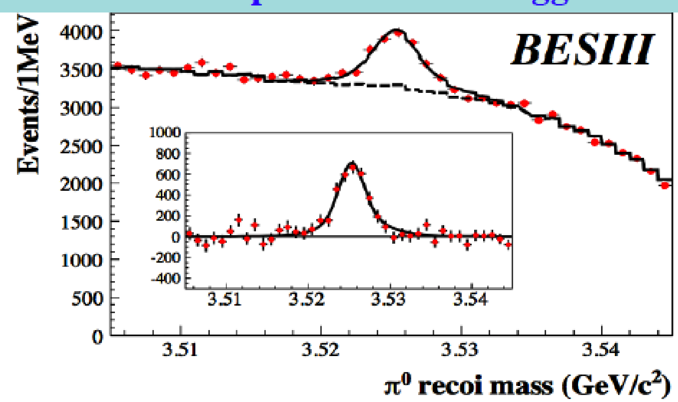


The CLEO experiment was able to find it with a significance of 13 σ in ψ' decay by means of an exclusive analysis.

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



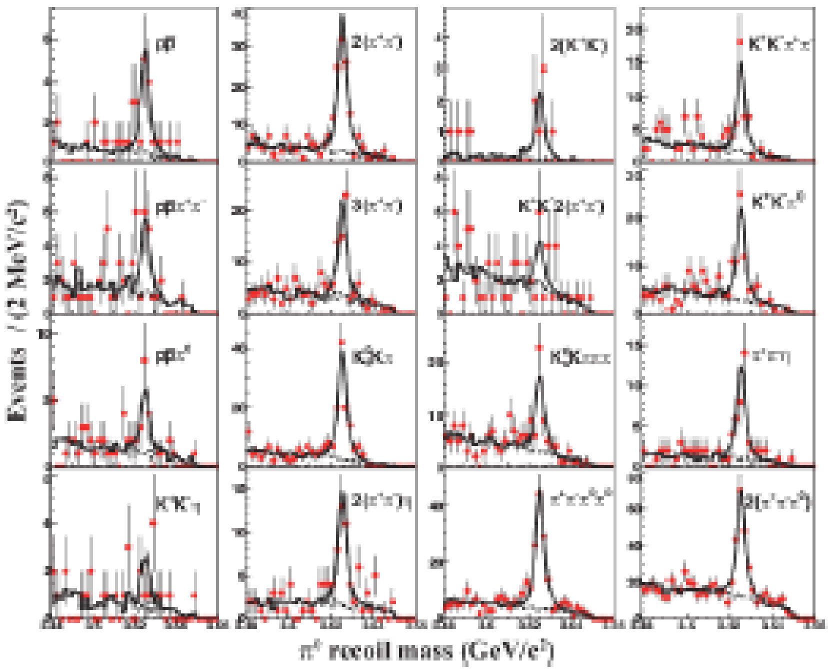
Significance = 18.6σ
$M(h_c)$=3525.40±0.13MeV
$N(h_c)$= 3679±319
$\Gamma(h_c)$ = 0.73±0.45MeV
χ^2/d.o.f = 33.5/36

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

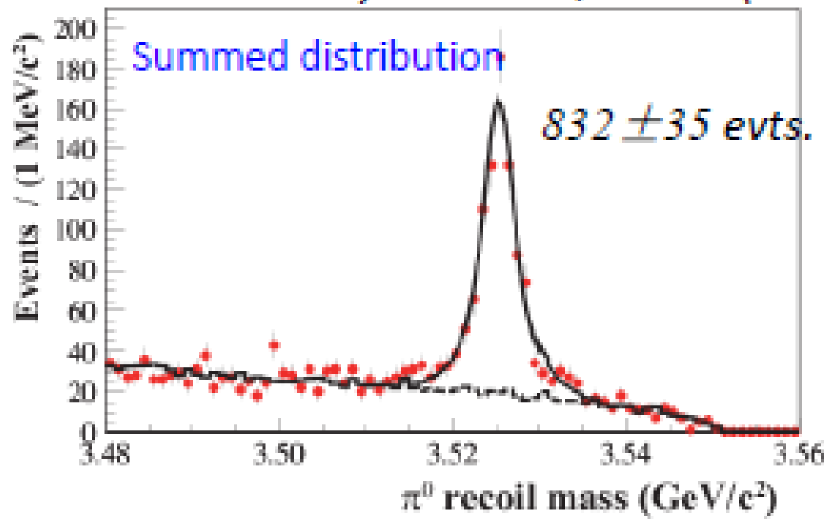
$$\Delta M_{hf}(1P) \equiv M(^3P) - M(^1P) = -0.10 \pm 0.13 \pm 0.18 \text{ MeV} / c^2$$

Center of gravity of P-states

BESIII 16 hadronic decays (~40% η_c decays)



Phys. Rev. D 86, 092009 (2012)



(MeV)	BESIII Exclusive	BESIII Inclusive	CLEO
mass	$3525.31 \pm 0.11 \pm 0.14$	$3525.40 \pm 0.13 \pm 0.18$	$3525.21 \pm 0.27 \pm 0.14$
width	$0.70 \pm 0.28 \pm 0.22$	$0.73 \pm 0.45 \pm 0.28$	--
$\Delta M_{hf}(1P)$	$-0.01 \pm 0.11 \pm 0.15$	$0.10 \pm 0.13 \pm 0.18$	$0.08 \pm 0.18 \pm 0.12$

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BESIII: PRL 104 132002 (2010)
CLEOc: PRL 101 182003 (2008)

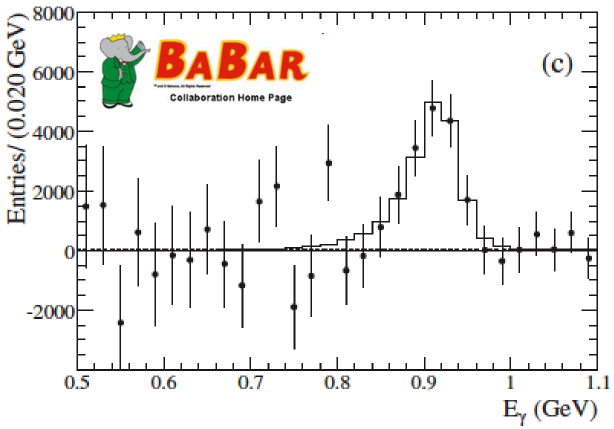
21

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]
and by CLEO [PRD8,031104,2010]

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 $E_\gamma = 921.2^{+2.1}_{-2.8}(\text{stat})\,\text{MeV}$
- 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

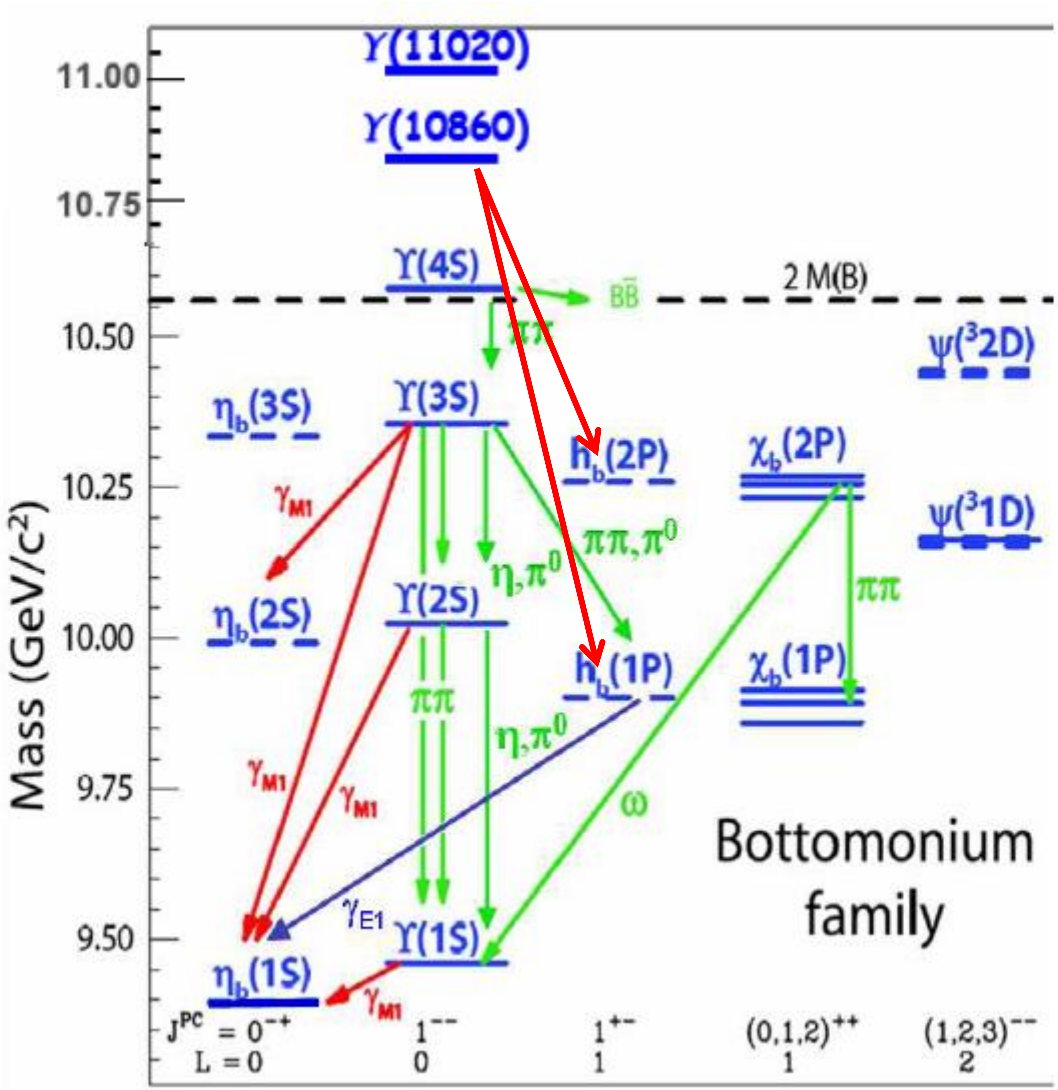
$(b\bar{b})$: S=0 L=1 $J^{PC}=1^{+-}$

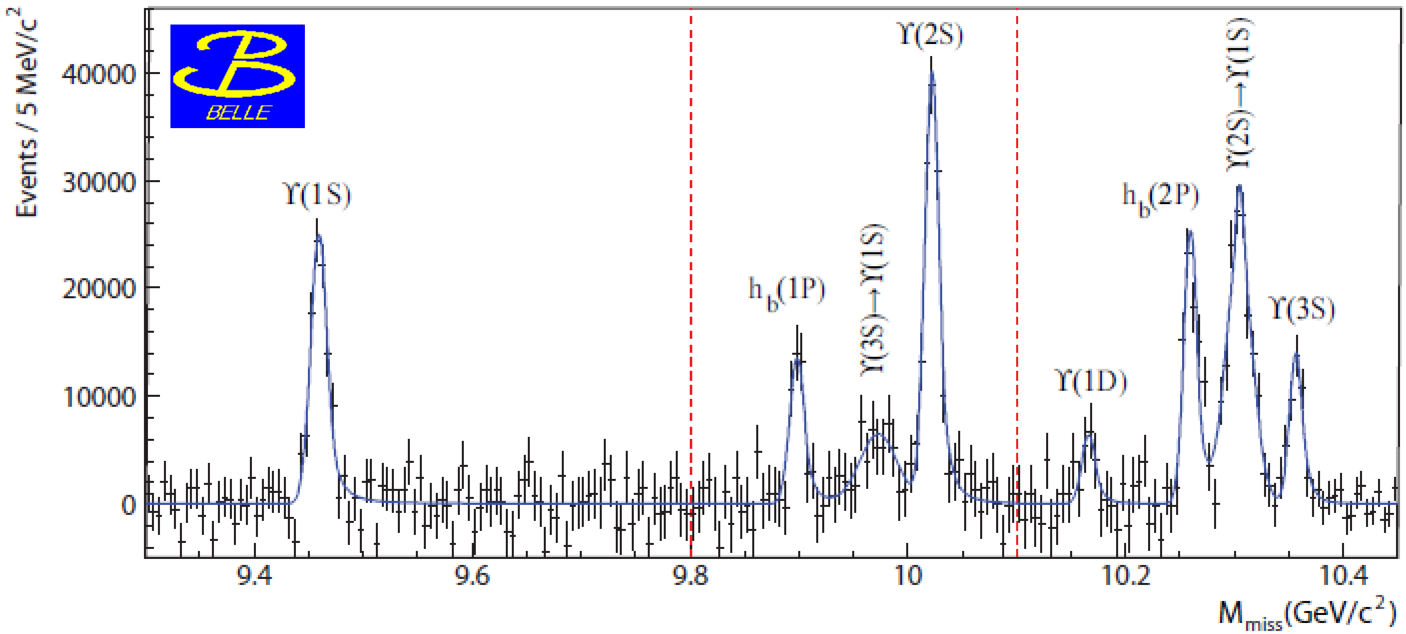
<u>Expected mass</u>

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

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

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





$\Upsilon(1S)$	$105.2 \pm 5.8 \pm 3.0$	$9459.4 \pm 0.5 \pm 1.0$	$18.2\,\sigma$
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	$9898.3 \pm 1.1^{+1.0}_{-1.1}$	$6.2\,\sigma$
$3S \to 1S$	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	$2.4\,\sigma$
$h_b(2P)$	$84.4 \pm 6.8^{+23.}_{-10.}$	$10259.8 \pm 0.6^{+1.4}_{-1.0}$	$12.4\,\sigma$
$2S \to 1S$	$151.7 \pm 9.7^{+9.0}_{-20.}$	$10304.6 \pm 0.6 \pm 1.0$	$15.7\,\sigma$
$\Upsilon(3S)$	$45.6 \pm 5.2 \pm 5.1$	$10356.7 \pm 0.9 \pm 1.1$	$8.5\,\sigma$

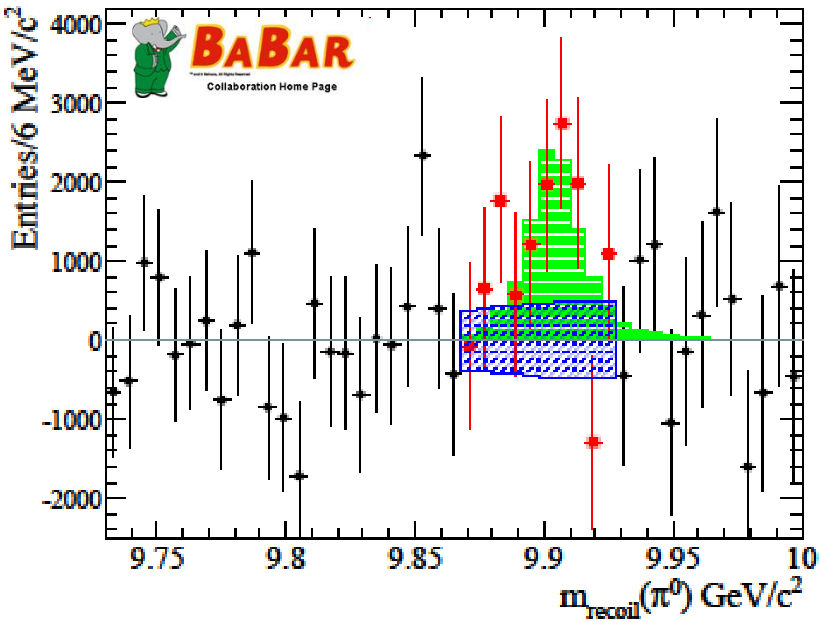
Deviations from CoG of χ_{bJ} masses

$h_b(1P)$ (1.6 ± 1.5) MeV/c²

$h_b(2P)$ $(0.5\ ^{+1.6}_{-1.2})$ MeV/c²

consistent with zero, as expected

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



10721 ± 2806 events

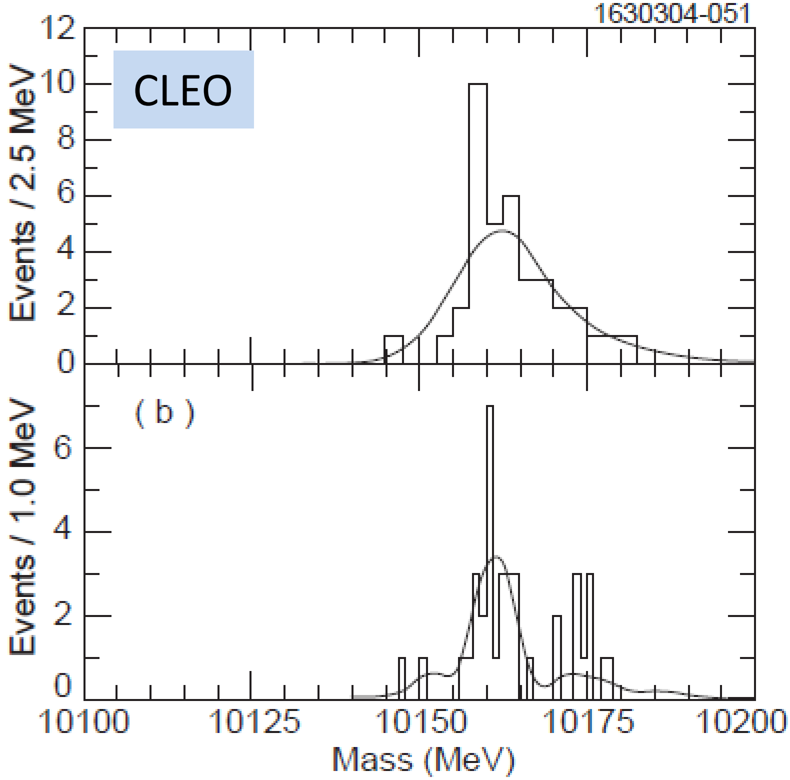
Statistical significance 3.1 σ

$$M\left(h_b\right) = \left(9902 \pm 2 \pm 1\right) MeV / c^2$$

$$B\left(\Upsilon(3S) \rightarrow \pi^0 h_b\right) \times B\left(h_b \rightarrow \gamma\eta_b\right) = \left(4.3 \pm 1.1 \pm 0.9\right) \times 10^{-4}$$

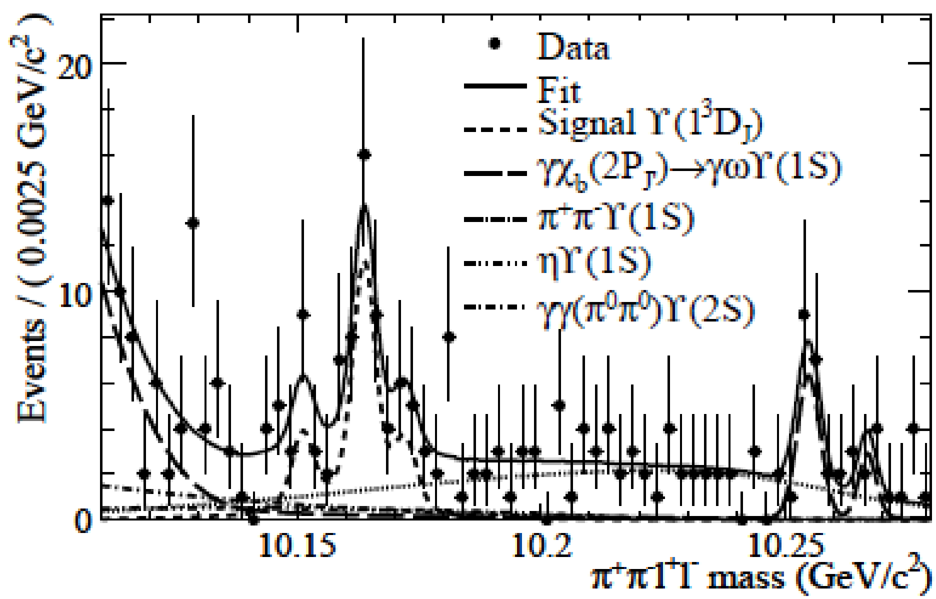
The Υ(1D)

$\Upsilon(3S) \to \gamma\chi_b(2P),\ \chi_b(2P) \to \gamma\Upsilon(1D),\ \Upsilon(1D) \to \gamma\chi_b(1P),\ \chi_b(1P) \to \gamma\Upsilon(1S)$



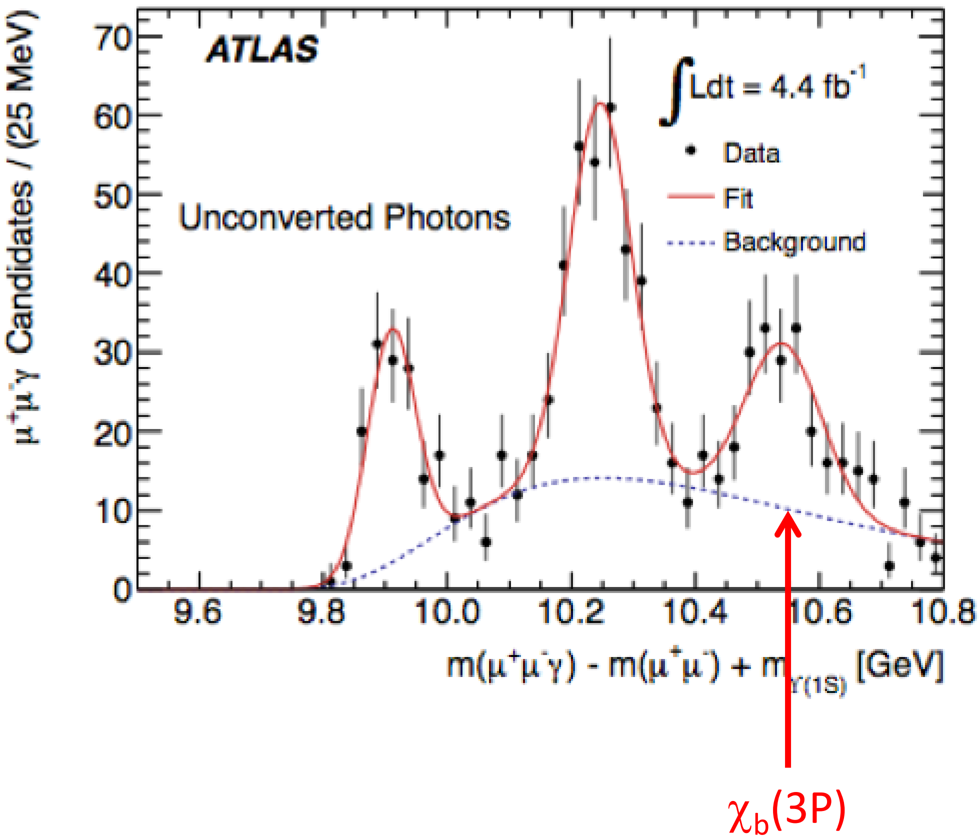
BABAR Collaboration Home Page

$\Upsilon(3S) \to \gamma\gamma\Upsilon(1^3D_J) \to \gamma\gamma\pi^+\pi^-\Upsilon(1S)$



$$M\left(1^3D_2\right) = (10164.5 \pm 0.8 \pm 0.5)\ MeV/c^2$$

The $\chi_b(3P)$



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

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

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

The XYZ States

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment (#σ)	1st observation
$X(3823)$	3823.1±1.9	< 24	$?^{?-}$	$B \to K + (\chi_{c1}\gamma)$	Belle [4] (3.8)	Belle 2013
$\mathbf{X(3872)}$	3871.68±0.17	< 1.2	1^{++}	$B \to K + (J/\psi\, \pi^+\pi^-)$	Belle [5, 6] (12.8), *BABAR* [7] (8.6)	Belle 2003
				$p\bar{p} \to (J/\psi\, \pi^+\pi^-) + ...$	CDF [8–10] (np), DØ [11] (5.2)	
				$B \to K + (J/\psi\, \pi^+\pi^-\pi^0)$	Belle [12][a] (4.3), *BABAR* [13][a] (4.0)	
				$B \to K + (D^0\bar{D}^0\pi^0)$	Belle [14, 15][a] (6.4), *BABAR* [16][a] (4.9)	
				$B \to K + (J/\psi\, \gamma)$	Belle [17][a] (4.0), *BABAR* [18, 19][a] (3.6)	
				$B \to K + (\psi(2S)\,\gamma)$	*BABAR* [19][a] (3.5), Belle [17][a] (0.4)	
				$pp \to (J/\psi\, \pi^+\pi^-) + ...$	LHCb [20] (np)	
$\mathbf{X(3915)}$	3917.5 ± 1.9	20±5	0^{++}	$B \to K + (J/\psi\, \omega)$	Belle [21] (8.1), *BABAR* [22] (19)	Belle 2004
				$e^+e^- \to e^+e^- + (J/\psi\, \omega)$	Belle [23] (7.7), *BABAR* [13, 24](7.6)	
$\boldsymbol{\chi_{c2}(2P)}$	3927.2 ± 2.6	24±6	2^{++}	$e^+e^- \to e^+e^- + (D\bar{D})$	Belle [25] (5.3), *BABAR* [26] (5.8)	Belle 2005
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi + (D^*\bar{D})$	Belle [27] (6.0)	Belle 2007
				$e^+e^- \to J/\psi + (...)$	Belle [28] (5.0)	
$\mathbf{G(3900)}$	3943 ± 21	52±11	1^{--}	$e^+e^- \to \gamma + (D\bar{D})$	*BABAR* [29] (np), Belle [30] (np)	*BABAR* 2007
$Y(4008)$	4008^{+121}_{-49}	226±97	1^{--}	$e^+e^- \to \gamma + (J/\psi\, \pi^+\pi^-)$	Belle [31] (7.4)	Belle 2007
$\mathbf{Y(4140)}$	4144.5 ± 2.6	15^{+11}_{-7}	$?^{?+}$	$B \to K + (J/\psi\, \phi)$	CDF [32, 33] (5.0), CMS [34] (>5)	CDF 2009
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi + (D^*\bar{D}^*)$	Belle [27] (5.5)	Belle 2007

G.T. Bodwin et al., arXiv:1307.7425v3 [hep-ph]

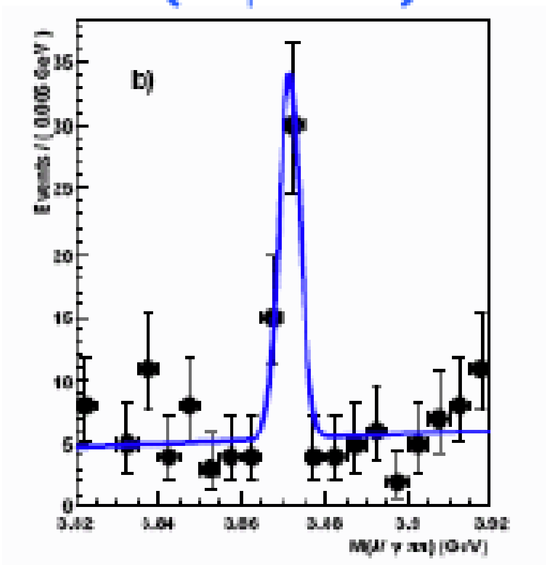
The XYZ States

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment ($\#\sigma$)	1st observation
$\mathbf{Y(4260)}$	4263^{+8}_{-9}	95 ± 14	1^{--}	$e^+e^- \to \gamma + (J/\psi\,\pi^+\pi^-)$	*BABAR* [35, 36] (8.0), CLEO [37] (5.4)	*BABAR* 2005
					Belle [31] (15)	
				$e^+e^- \to (J/\psi\,\pi^+\pi^-)$	CLEO [38] (11)	
				$e^+e^- \to (J/\psi\,\pi^0\pi^0)$	CLEO [38] (5.1)	
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K + (J/\psi\,\phi)$	CDF [33] (3.1)	CDF 2010
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-\,(J/\psi\,\phi)$	Belle [39] (3.2)	Belle 2009
$\mathbf{Y(4360)}$	4361 ± 13	74 ± 18	1^{--}	$e^+e^- \to \gamma + (\psi(2S)\,\pi^+\pi^-)$	*BABAR* [40] (np), Belle [41] (8.0)	*BABAR* 2007
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma\,(\Lambda_c^+\Lambda_c^-)$	Belle [42] (8.2)	Belle 2007
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma + (\psi(2S)\,\pi^+\pi^-)$	Belle [41] (5.8)	Belle 2007
$\mathbf{Z_c^+(3900)}$	3898 ± 5	51 ± 19	$1^{?-}$	$Y(4260) \to \pi^- + (J/\psi\,\pi^+)$	BESIII [43] (np), Belle [44] (5.2)	BESIII 2013
				$e^+e^- \to \pi^- + (J/\psi\,\pi^+)$	Xiao *et al.* [45][a] (6.1)	
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K + (\chi_{c1}(1P)\,\pi^+)$	Belle [46] (5.0), *BABAR* [47] (1.1)	Belle 2008
$Z_2^+(4250)$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	?	$B \to K + (\chi_{c1}(1P)\,\pi^+)$	Belle [46] (5.0), *BABAR* [47] (2.0)	Belle 2008
$Z^+(4430)$	4443^{+24}_{-18}	$107^{+113}_{-\ 71}$	?	$B \to K + (\psi(2S)\,\pi^+)$	Belle [48, 49] (6.4), *BABAR* [50] (2.4)	Belle 2007
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\Upsilon(nS)\,\pi^+\pi^-)$	Belle [51, 52] (2.0)	Belle 2010
$Z_b^+(10610)$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(5S) \to \pi^- + (\Upsilon(nS)\,\pi^+),\ n=1,2,3$	Belle [53, 54] (16)	Belle 2011
				$\Upsilon(5S) \to \pi^- + (h_b(nP)\,\pi^+),\ n=1,2$	Belle [53, 54] (16)	
$Z_b^+(10650)$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(5S) \to \pi^- + (\Upsilon(nS)\,\pi^+),\ n=1,2,3$	Belle [53, 54] (16)	Belle 2011
				$\Upsilon(5S) \to \pi^- + (h_b(nP)\,\pi^+),\ n=1,2$	Belle [53, 54] (16)	

G.T. Bodwin et al., arXiv:1307.7425v3 [hep-ph]

The X(3872) Discovery

$M(J/\psi\pi^+\pi^-)$



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

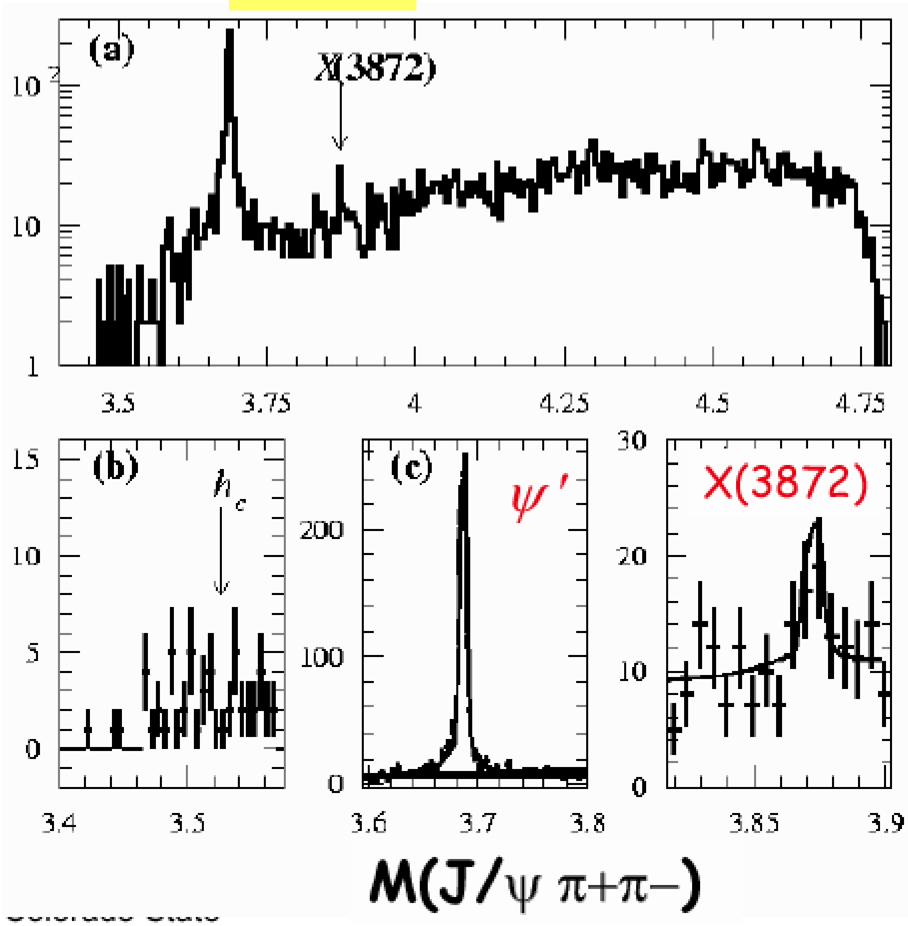
$B^\pm \to K^\pm (J/\psi\pi^+\pi^-)$, $J/\psi \to \mu^+\mu^-$ or e^+e^-

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

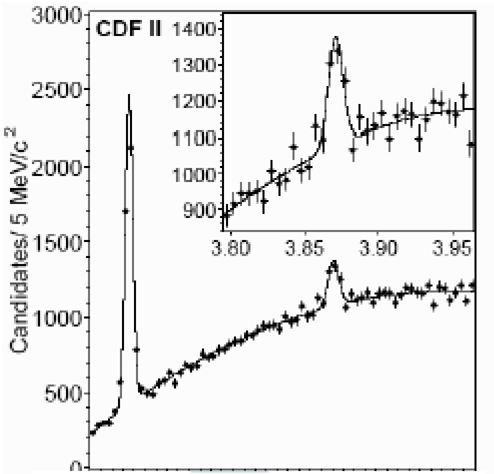
$$\frac{\Gamma\left(X(3872) \to \gamma\chi_{c1}\right)}{\Gamma\left(X(3872) \to \pi^+\pi^- J/\psi\right)} < 0.89 \quad (90\%\,C.L.)$$

The X(3872) Confirmation

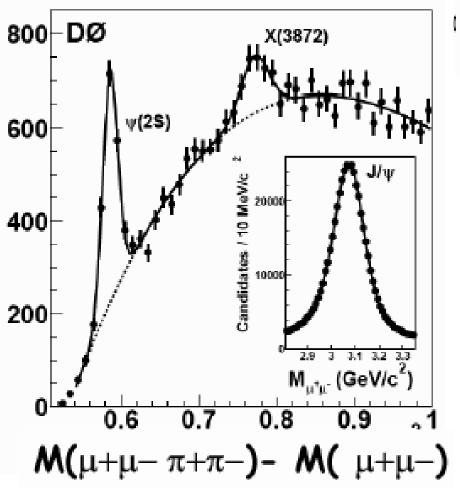
BaBar



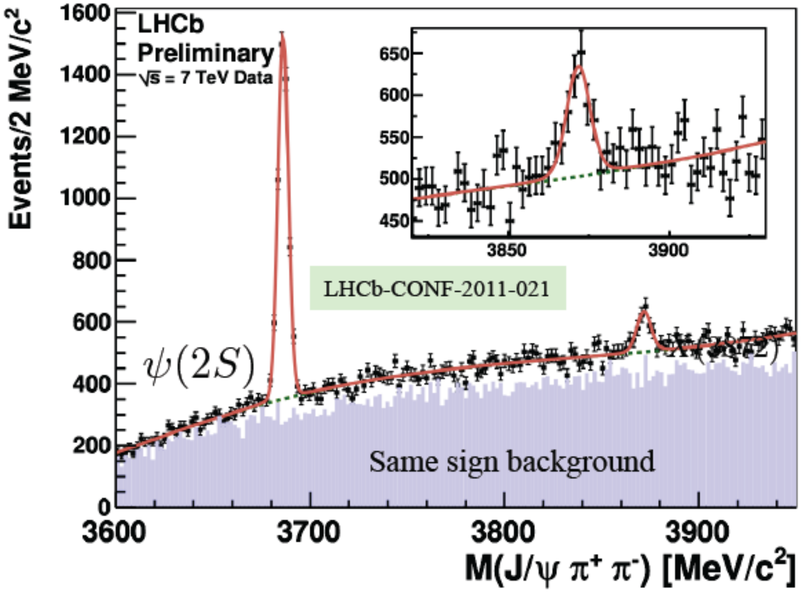
CDF

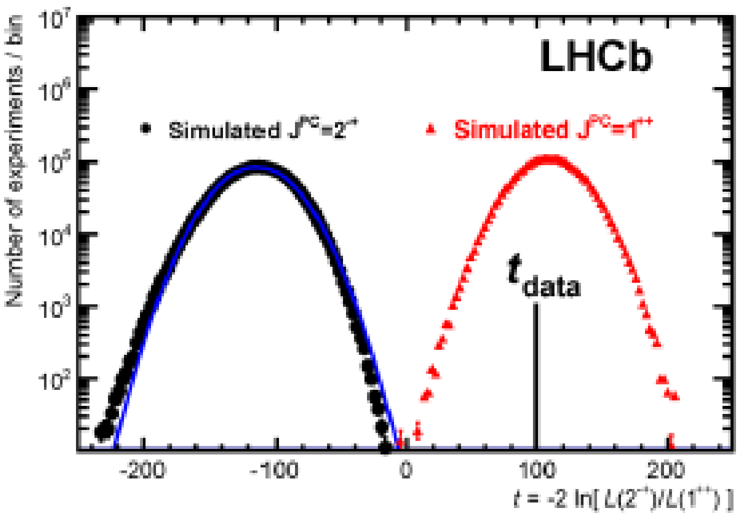


D0

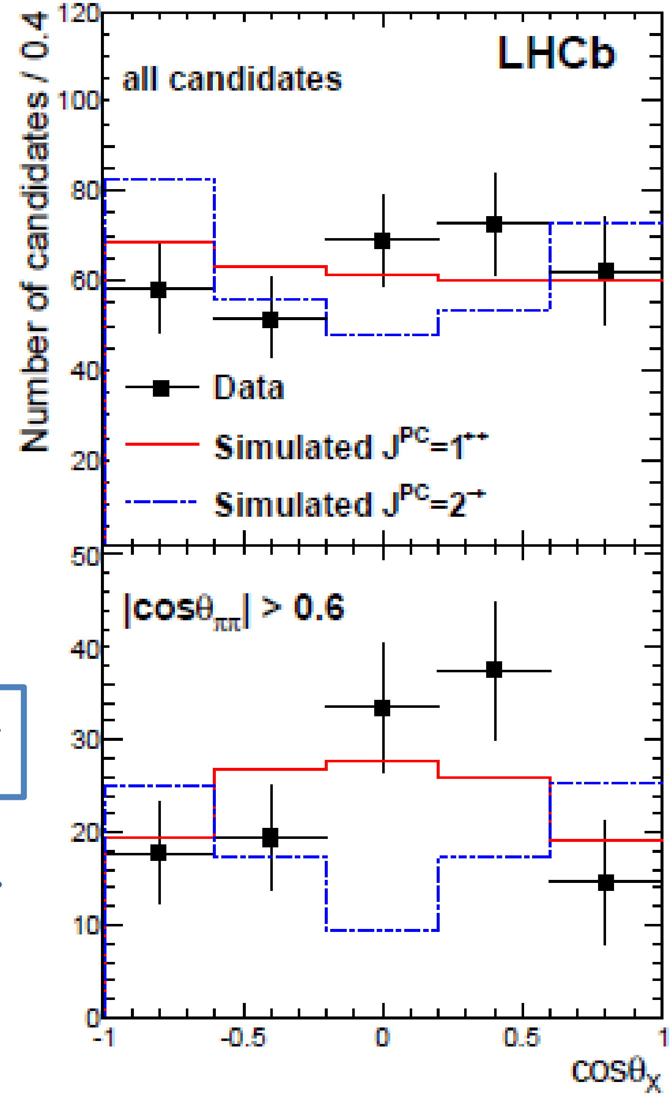


The X(3872) at LHCb

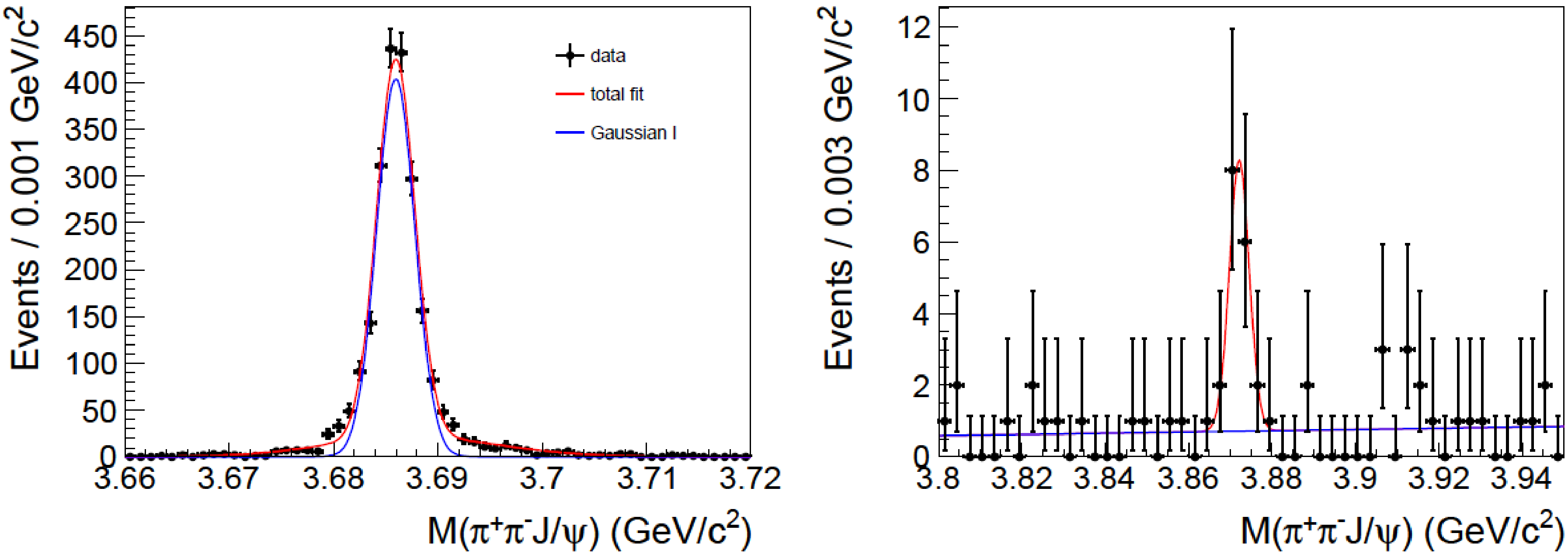




$J^{PC} = 1^{++}$



The X(3872) at BES III



ISR ψ' signal is used for rate, mass, and mass resolution calibration.

N(ψ')=1242 ; Mass=3685.96±0.05 MeV; σ_M=1.84 ±0.06 MeV

N(X(3872))=15.0±3.9 **5.3σ**

BESIII preliminary

M(X(3872)) = 3872.1±0.8±0.3 MeV [PDG: 3871.68 ±0.17 MeV]

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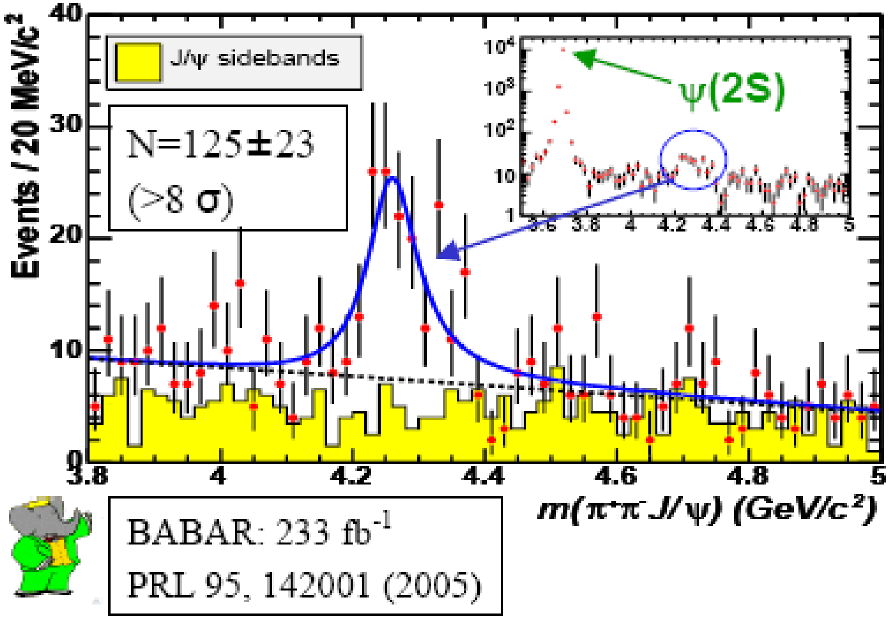
What is the X(3872) ?

- Mass: Very close to $\bar{D}^0 D^{*0}$ threshold
- Width: Very narrow, < 1.2 MeV
- Small binding energy implies huge separation ~ 5 fm
- $J^{PC}=1^{++}$ [LHCb]
- Production
  - in $\bar{p}p/pp$ collison – rate similar to charmonia
  - In B decays – KX similar to $c\bar{c}$, K*X smaller than $c\bar{c}$
  - $Y(4260) \rightarrow \gamma + X(3872)$ [BESIII]
- Decay BR: open charm ~ 50%, charmonium~O(%)
- Nature (very likely exotic)
  - Loosely $\bar{D}^0 D^{*0}$ bound state (like deuteron?)?
  - Mixture of excited χ_{c1} and $\bar{D}^0 D^{*0}$ bound state?
  - Many other possibilities (if it is not χ'_{c1}, where is χ'_{c1}?).

Y(4260)



Discovered by BaBar in ISR events:

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

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

Confirmed by CLEO, CLEO III, Belle, BESIII

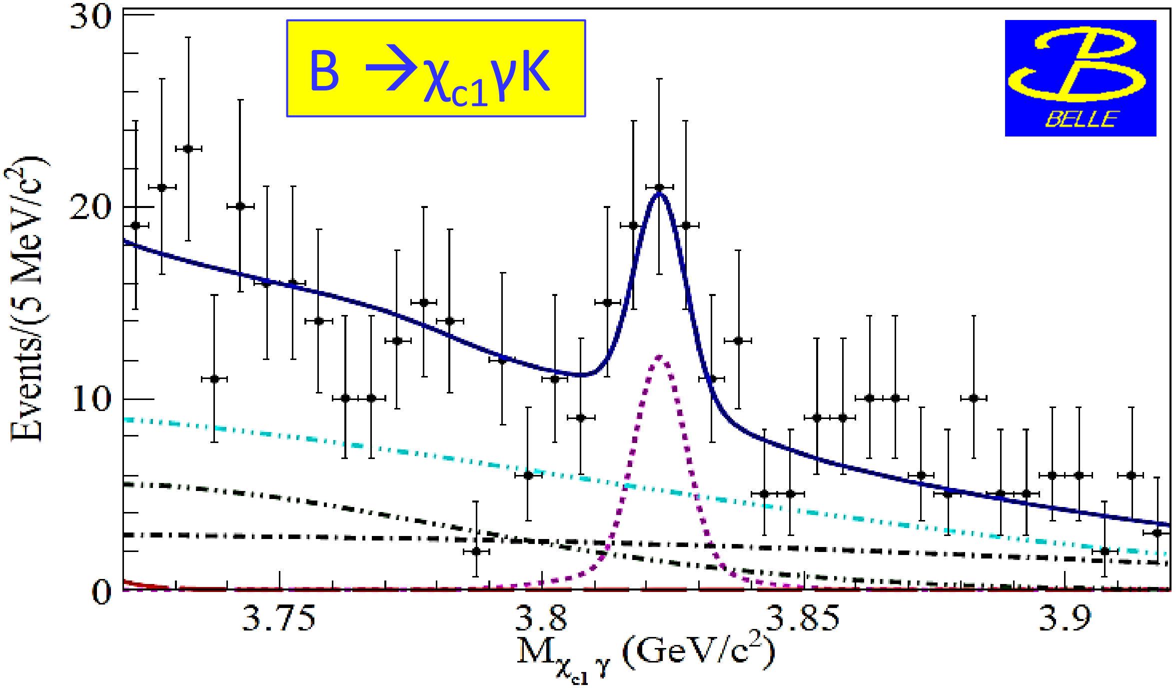
From PDG:

$$M = 4250 \pm 9 \ MeV/c^2$$

$$\Gamma = 108 \pm 12 \ MeV$$

Weak coupling consistent with hybrid meson. Shows up as very small maximum near the deep minimum between conventional charmonium states ψ(4160) and ψ(4415)

X(3823)



Measured mass and width consistent with predicted values for $\psi_2(1D)$ ($^1D_2$)

M = (3823.1 ± 1.8 ± 0.7 MeV/c^2

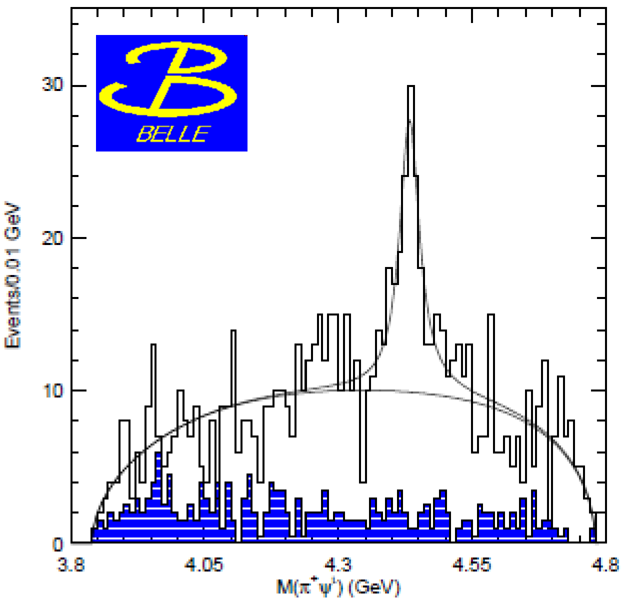
Γ < 24 MeV

711 fb^{-1} 3.8 σ

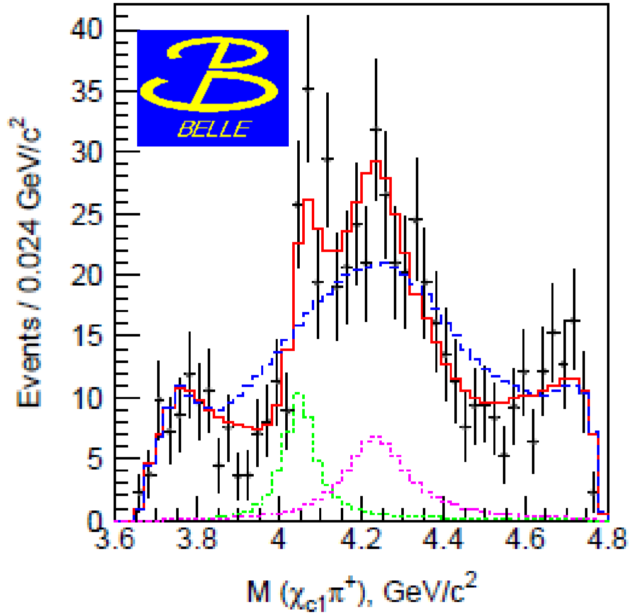
arXiv:1304.3975 (submitted to PRL)

$Z^+(4430)$, $Z_1^+(4050)$, $Z_2^+(4250)$

$Z^+(4430) \rightarrow \psi(2S)\pi^+$



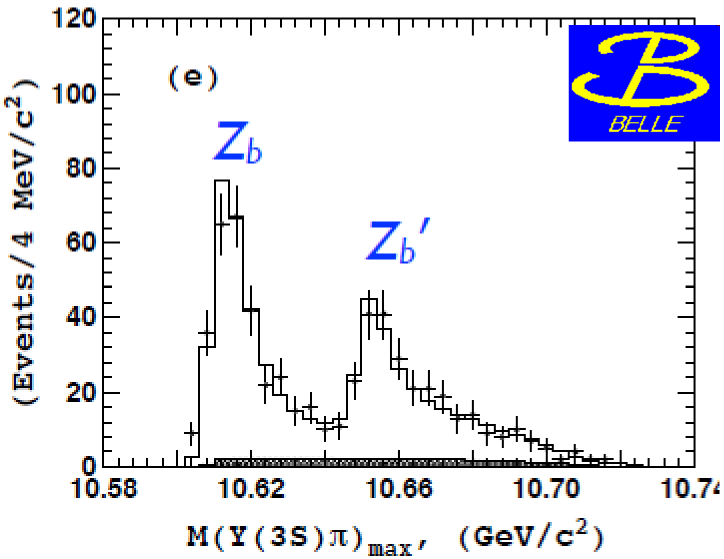
$Z_1^+(4050) \rightarrow \chi_{c1}\pi^+$, $Z_2^+(4250) \rightarrow \chi_{c1}\pi^+$



Not confirmed by BaBar that also studied the $J/\psi\pi^- K^+$ and $J/\psi\pi^- K_0^s$ channels.
The $J/\psi\pi K$ final state was also studied by Belle, who did not find any evidence of Z.
Belle confirmed the Z in a Dalitz reanalysis.

Not confirmed by BaBar which did not find evidence of a signal in the exotic $\chi_{c1}\pi^+$ channel.

$Z_b(10610)$ and $Z_b(10650)$



- $Z_b^+(10610)$ and $Z_b^+(10650)$
- Discovered by Belle in 2011 in $\pi^+\pi^-$ transitions from $\Upsilon(5S)$.
- Both decay to $\Upsilon(nS)\pi^+$ and $h_b(nP)\pi^+$. 5σ evidence for neutral isospin partner of $Z_b^+(10610)$.
- Minimal quark content $b\ \bar{b}u\ \bar{d}$

The $Z_b^+(10610)$ and $Z_b^+(10650)$ lie very close to the BB* and B*B* thresholds, respectively.
Molecular states ?

$Z_c^+(3900)$

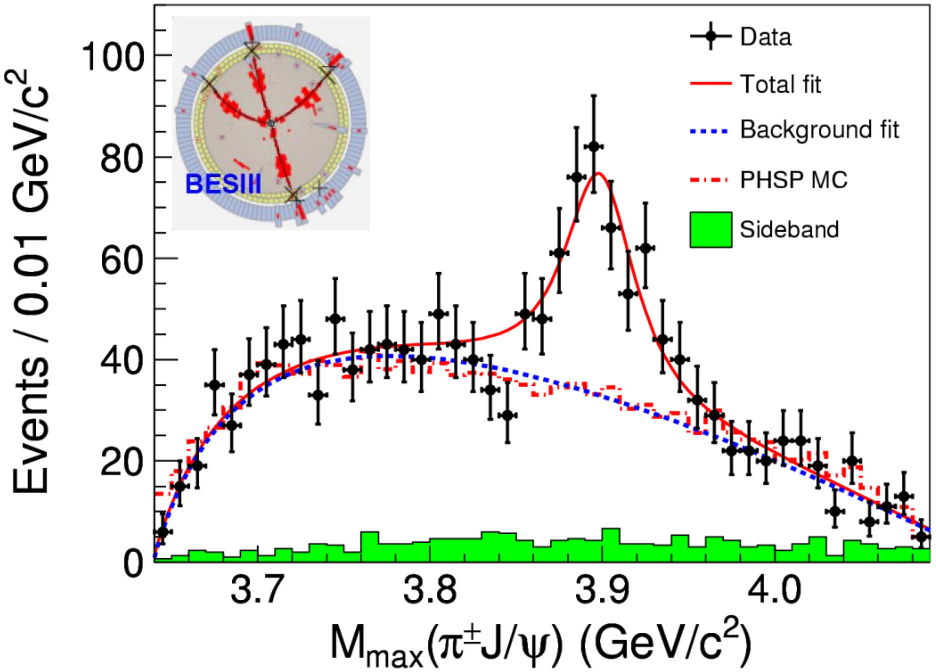
$Y(4260) \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow l^+l^-$

1477 events – 525 pb-1

σ = (62.9 ± 1.9 ± 3.7) pb consistent with Y(4260) production

A structure observed in the $J/\psi\pi^\pm$ mass spectrum

$Z_c(3900)^\pm$



$M = 3899.0 \pm 3.6 \pm 4.9$ MeV
$\Gamma = 46 \pm 10 \pm 20$ MeV
307 ± 48 events
$>8\sigma$

$Z_c^+(3900)$

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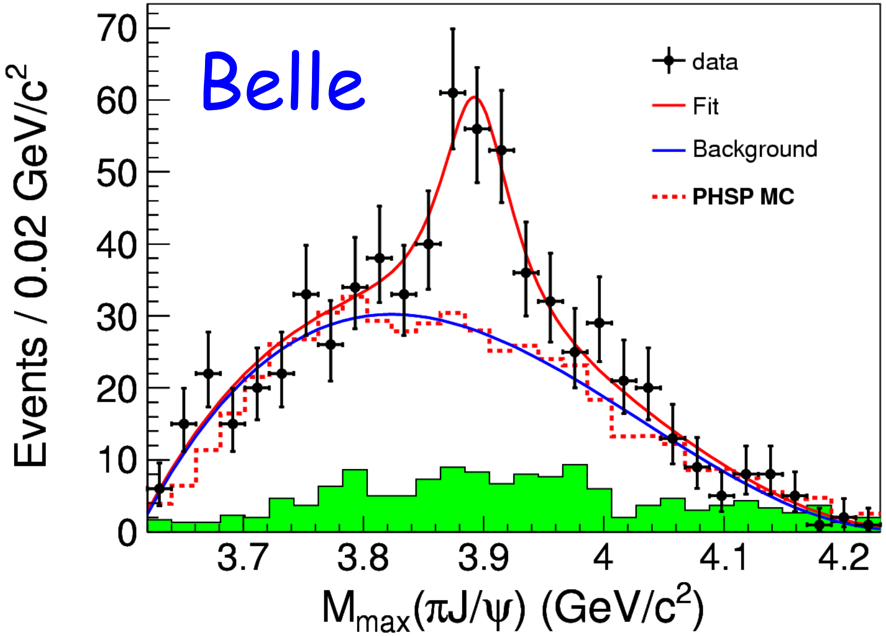
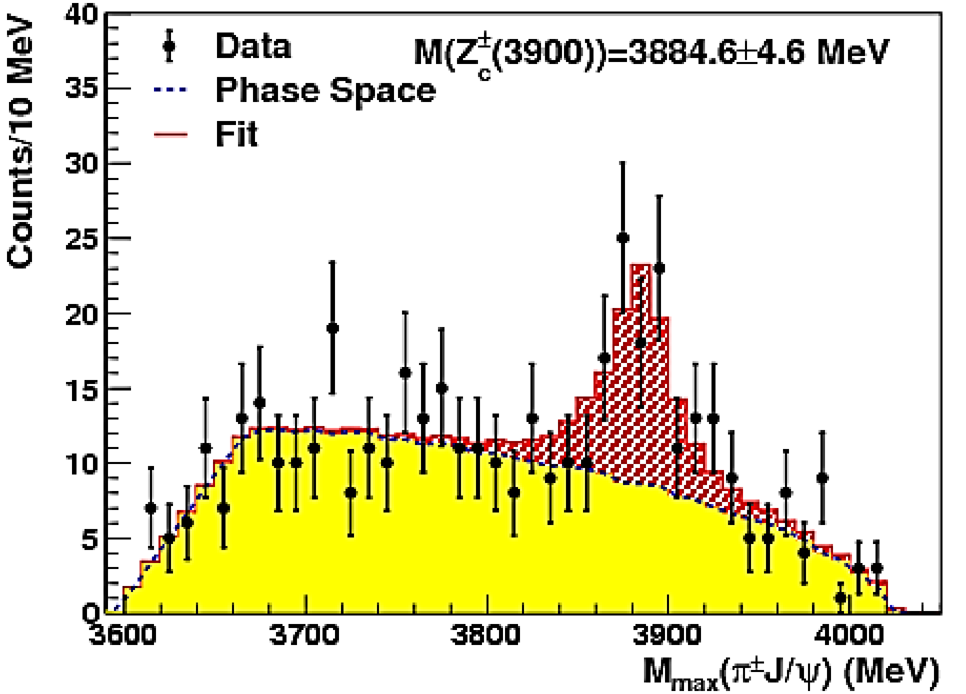
Belle with ISR: 1304.0121

CLEOc data at 4.17 GeV: 1304.3036



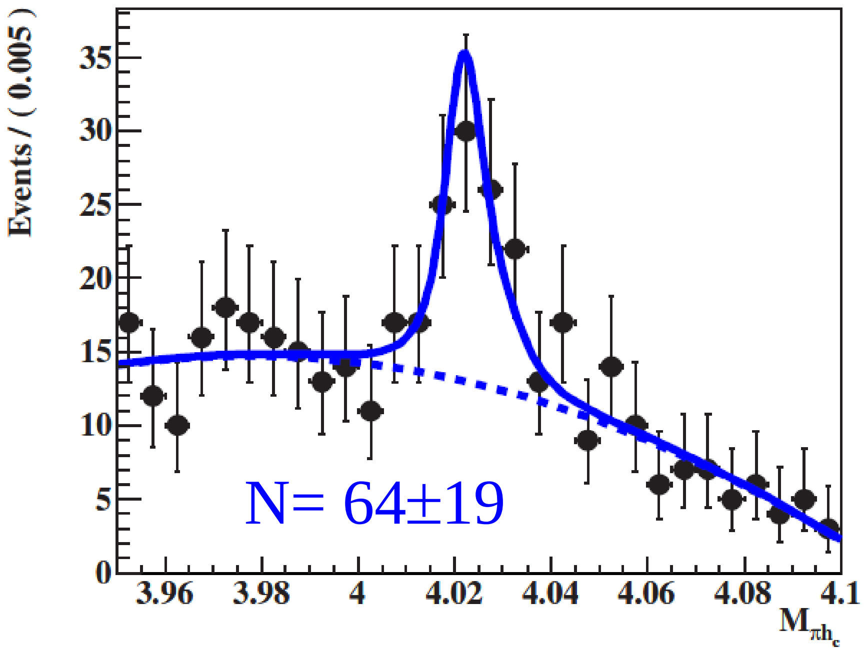


M = 3894.5±6.6±4.5 MeV
Γ = 63±24±26 MeV
159 ± 49 events
>5.2σ

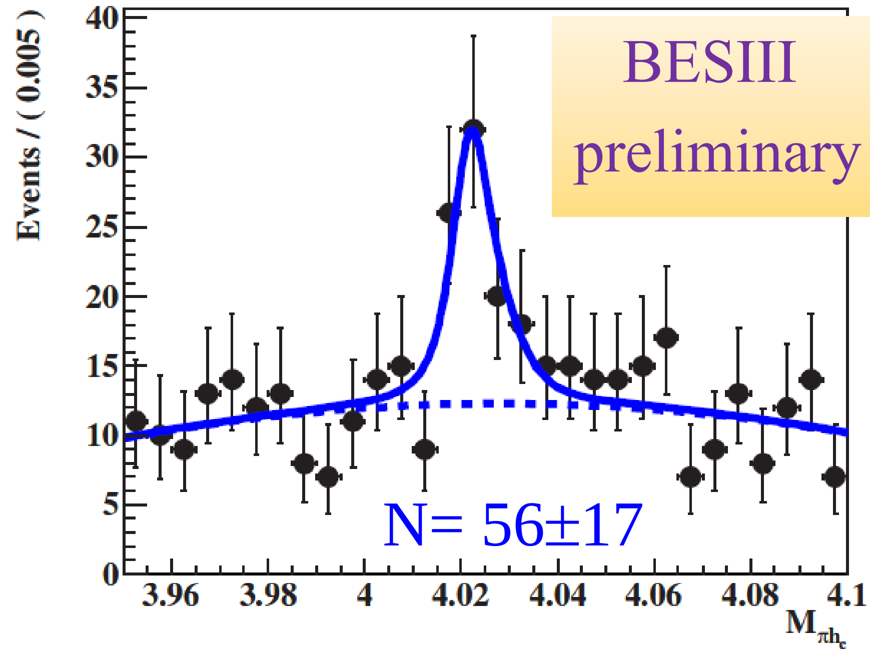
M = 3885±5±1 MeV
Γ = 34±12±4 MeV
81 ± 20 events
6.1σ

$e^+e^- \to \pi Z_c(4020) \to \pi^+\pi^- h_c(1P)$

Ecm=4.26 GeV



Ecm=4.36 GeV



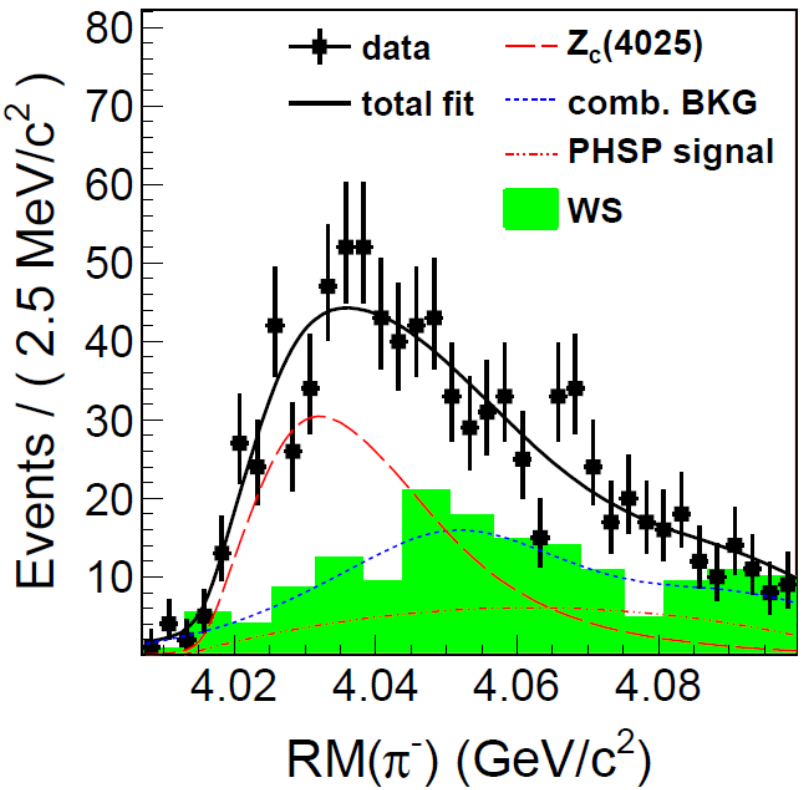
Simultaneous fit to 4.26/4.36 GeV data and 16 η_c decay modes. 6.4σ

$M(Z_c(4020)) = 4021.8 \pm 1.0 \pm 2.5$ MeV;

$\Gamma(Z_c(4020)) = 5.7 \pm 3.4 \pm 1.1$ MeV

C. Yuan – Charm 2013

$e^+e^- \to \pi Z_c(4025) \to \pi^- (D^* \bar{D}^*)^+ + c.c.$



Fit to $\pi^{\pm}$ recoil mass yields 401±47 $Z_c(4025)$ events. **>10σ**

$M(Z_c(4025)) = 4026.3 \pm 2.6 \pm 3.7$ MeV;

$\Gamma(Z_c(4025)) = 24.8 \pm 5.6 \pm 7.7$ MeV

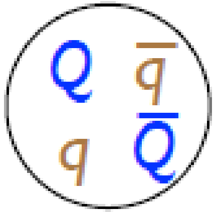
BESIII: 1308.2760

Models for XYZ Mesons

- conventional quarkonium

- quarkonium hybrids

- quarkonium tetraquarks
  - compact tetraquark
  - meson molecule
  - diquark-onium
  - hadro-quarkonium

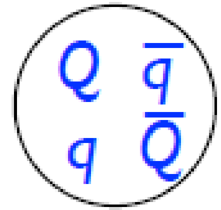


Eric Braaten – Charm 2013

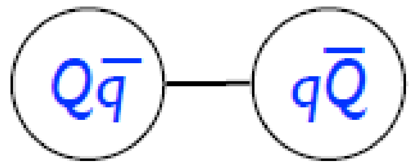
Models for XYZ Mesons

quarkonium tetraquarks

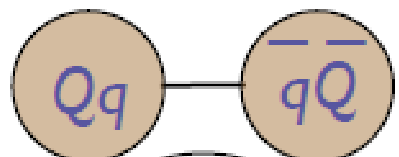
- compact tetraquark



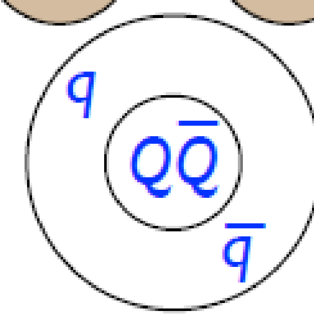
- meson molecule



- diquark-onium



- hadro-quarkonium



- Born-Oppenheimer tetraquark! arXiv:1305.6905

Eric Braaten - Charm 2013

Open Charm

- Charm Meson Spectroscopy
  - D_s States

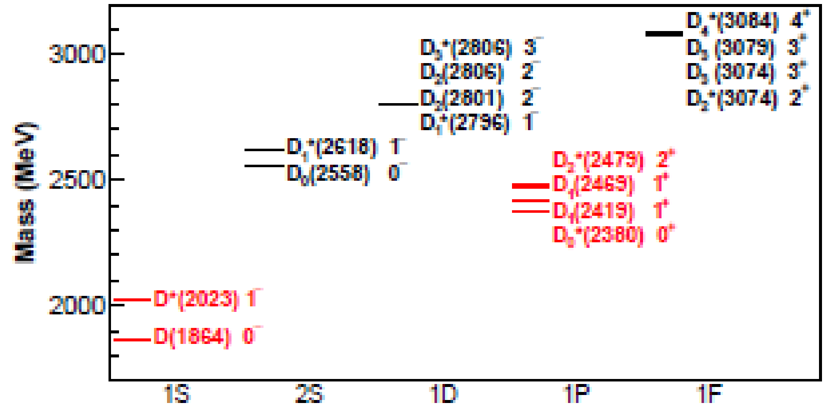
Open Charm

Interest of charm

- Strong interactions
  - QCD laboratory
  - Intermediate case between heavy and light quarks
  - Interesting spectroscopy
  - Strong decay modes
- Weak interactions
  - Complementary to measurements with b quarks
  - Mixing and CP violation
  - Possible window to physics beyond the Standard Model

Charm Meson Spectroscopy

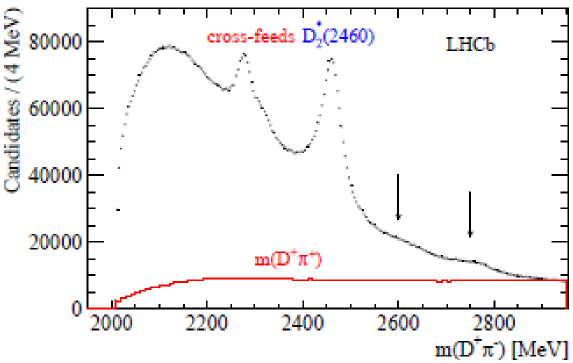
- Ground states (D, D*) and two of the 1P states $D_1(2420)$ and $D_2^*(2460)$ experimentally well established since they are narrow.
- Broad L=1 states $D_0^*(2400)$ and $D_1'(2430)$ found by BaBar and Belle in exclusive B decays
- Babar found 4 new states decaying to $D\pi$ and $D^*\pi$.



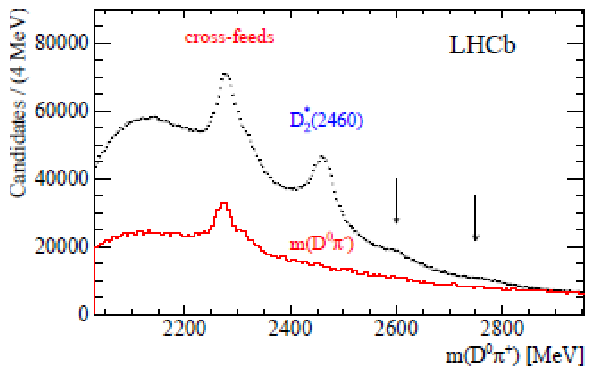
Resonance	Channel(Fit)	Efficiency (%)	Yield (x10^3)	Mass (MeV/c^2)	Width (MeV)	Significance
$D_1(2420)^0$	$D^{*+}\pi^-$ (C)		102.8±1.3±2.3	2420.1±0.1±0.8	31.4±0.5±1.3	
	$D^{*+}\pi^-$ (E)	1.09 ± 0.03	214.6±1.2±6.4	2420.1(fixed)	31.4(fixed)	
$D_2^*(2460)^0$	$D^+\pi^-$ (A)	1.29 ± 0.03	242.8±1.8±3.4	2462.2±0.1±0.8	50.5±0.6±0.7	
	$D^{*+}\pi^-$ (E)	1.12 ± 0.04	136±2±13	2462.2(fixed)	50.5(fixed)	
$D(2550)^0$	$D^{*+}\pi^-$ (C)		34.3±6.7±9.2	2539.4±4.5±6.8	130±12±13	3.0σ
	$D^{*+}\pi^-$ (E)	1.14 ± 0.04	98.4±8.2±38	2539.4(fixed)	130(fixed)	
$D^*(2600)^0$	$D^+\pi^-$ (A)	1.35 ± 0.05	26.0±1.4± 6.6	2608.7±2.4±2.5	93±6±13	3.9σ
	$D^{*+}\pi^-$ (D)		50.2±3.0±6.7	2608.7(fixed)	93(fixed)	7.3σ
	$D^{*+}\pi^-$ (E)	1.18 ± 0.05	71.4±1.7±7.3	2608.7(fixed)	93(fixed)	
$D(2750)^0$	$D^{*+}\pi^-$ (E)	1.23 ± 0.07	23.5±2.1±5.2	2752.4±1.7±2.7	71±6±11	4.2σ
$D^*(2760)^0$	$D^+\pi^-$ (A)	1.41 ± 0.09	11.3±0.8±1.0	2763.3±2.3±2.3	60.9±5.1±3.6	8.9σ
$D_2^*(2460)^+$	$D^0\pi^+$ (B)		110.8±1.3±7.5	2465.4±0.2±1.1	50.5(fixed)	
$D^*(2600)^+$	$D^0\pi^+$ (B)		13.0±1.3±4.5	2621.3±3.7±4.2	93(fixed)	2.8σ
$D^*(2760)^+$	$D^0\pi^+$ (B)		5.7±0.7±1.5	2769.7±3.8±1.5	60.9(fixed)	3.5σ

D mesons at LHCb

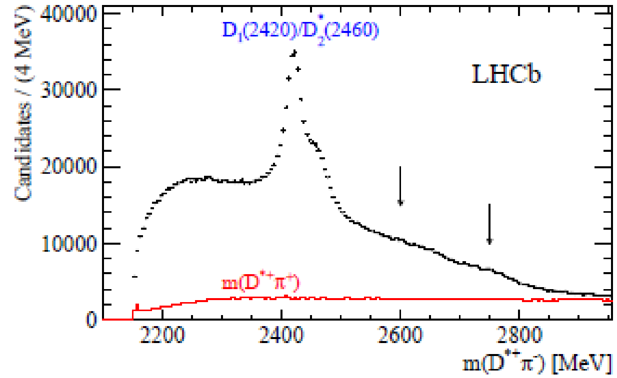
$D^+\pi^-$ and $D^+\pi^+$ mass spectra.



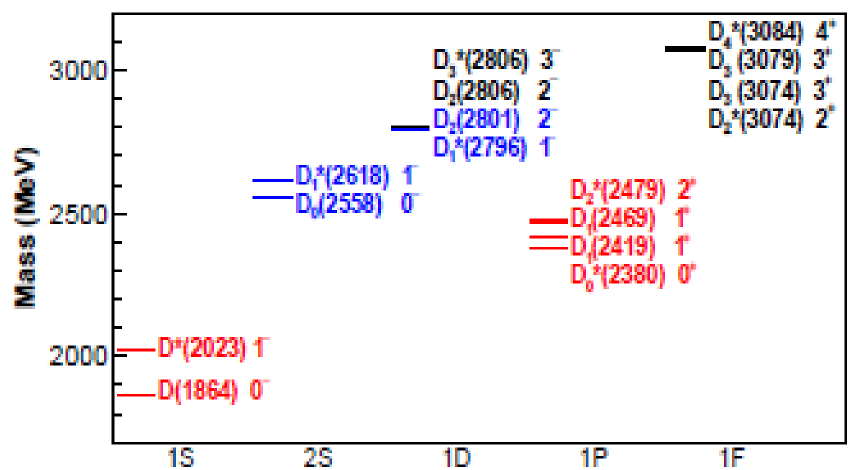
$D^0\pi^+$ and $D^0\pi^-$ mass spectra.



$D^{*+}\pi^-$ and the $D^{*+}\pi^+$ mass spectra.



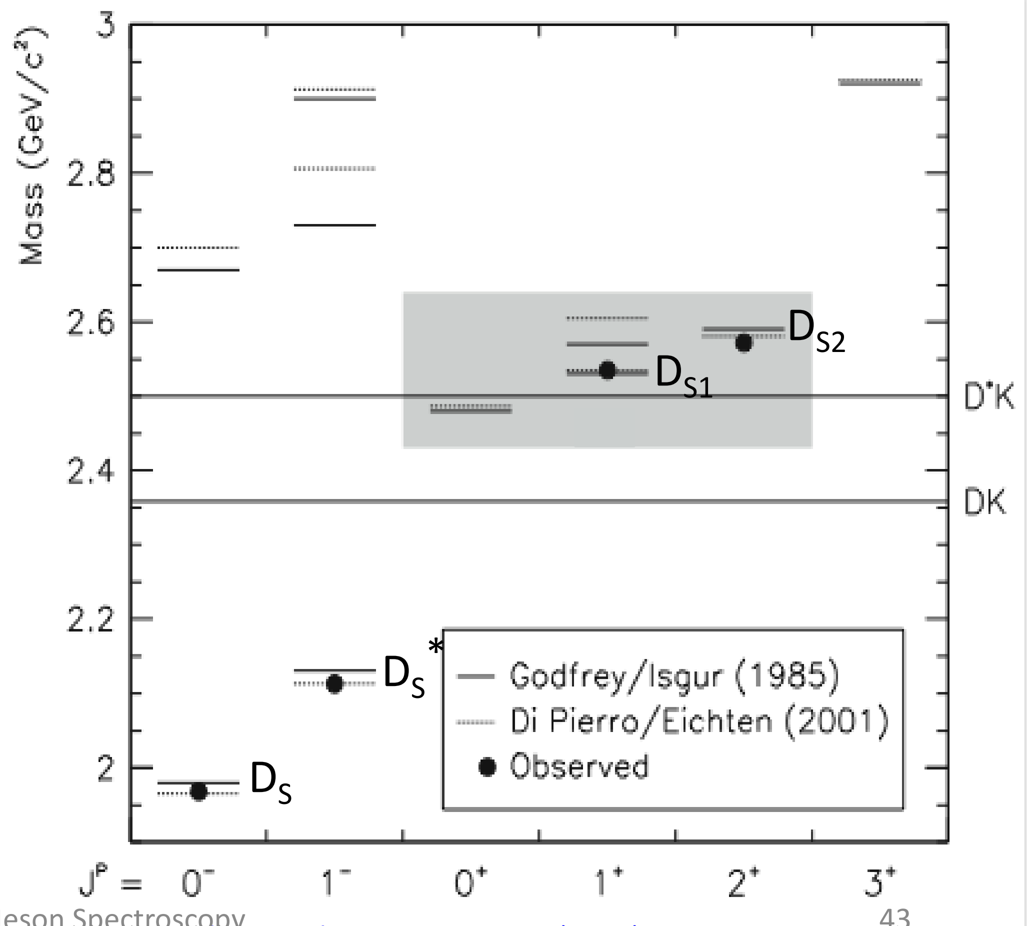
Resonance	Final state	Mass (MeV)	Width (MeV)
$D_1(2420)^0$	$D^{*+}\pi^-$	$2419.6 \pm 0.1 \pm 0.7$	$35.2 \pm 0.4 \pm 0.9$
$D_2^*(2460)^0$	$D^{*+}\pi^-$	$2460.4 \pm 0.4 \pm 1.2$	$43.2 \pm 1.2 \pm 3.0$
$D_J^*(2650)^0$	$D^{*+}\pi^-$	$2649.2 \pm 3.5 \pm 3.5$	$140.2 \pm 17.1 \pm 18.6$
$D_J^*(2760)^0$	$D^{*+}\pi^-$	$2761.1 \pm 5.1 \pm 6.5$	$74.4 \pm 3.4 \pm 37.0$
$D_J(2580)^0$	$D^{*+}\pi^-$	$2579.5 \pm 3.4 \pm 5.5$	$177.5 \pm 17.8 \pm 46.0$
$D_J(2740)^0$	$D^{*+}\pi^-$	$2737.0 \pm 3.5 \pm 11.2$	$73.2 \pm 13.4 \pm 25.0$
$D_J(3000)^0$	$D^{*+}\pi^-$	2971.8 ± 8.7	188.1 ± 44.8
$D_2^*(2460)^0$	$D^+\pi^-$	$2460.4 \pm 0.1 \pm 0.1$	$45.6 \pm 0.4 \pm 1.1$
$D_J^*(2760)^0$	$D^+\pi^-$	$2760.1 \pm 1.1 \pm 3.7$	$74.4 \pm 3.4 \pm 19.1$
$D_J^*(3000)^0$	$D^+\pi^-$	3008.1 ± 4.0	110.5 ± 11.5
$D_2^*(2460)^+$	$D^0\pi^+$	$2463.1 \pm 0.2 \pm 0.6$	$48.6 \pm 1.3 \pm 1.9$
$D_J^*(2760)^+$	$D^0\pi^+$	$2771.7 \pm 1.7 \pm 3.8$	$66.7 \pm 6.6 \pm 10.5$
$D_J^*(3000)^+$	$D^0\pi^+$	3008.1 (fixed)	110.5 (fixed)



D_s 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



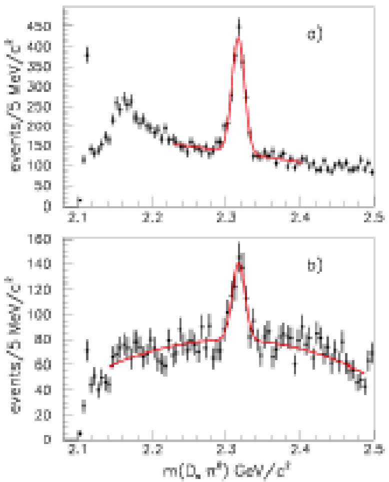
B. Aubert et al., PRD74, 032007 (2006).

D_s States

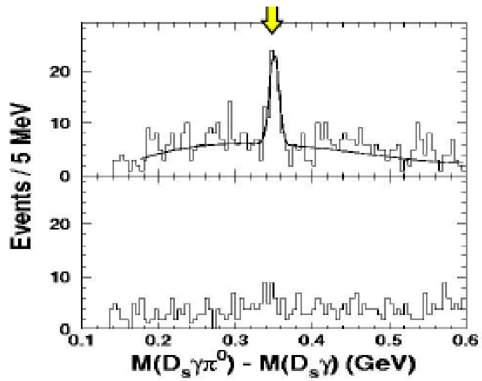
The discovery of the new D_{SJ} states has brought into question potential models

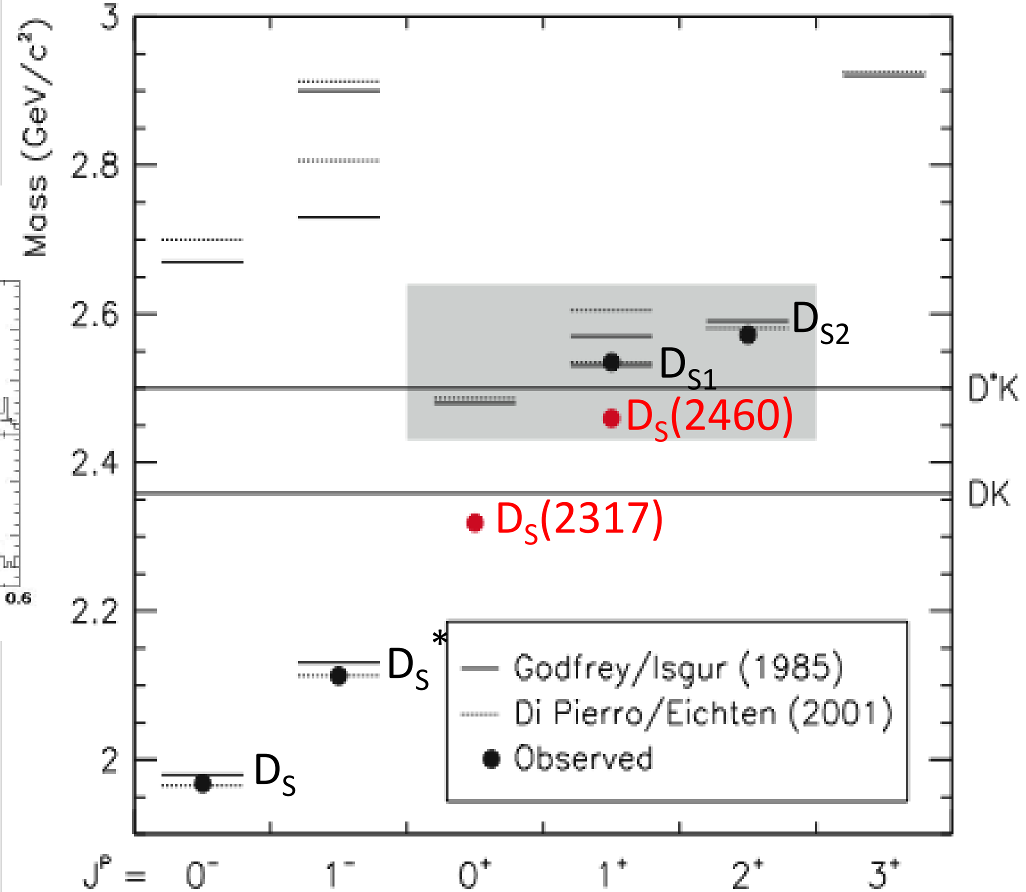
Two new states $D_S(2317)$ and $D_S(2460)$ were discovered in $e^+e^- \rightarrow cc$ events, then observed in B decays by Babar, Belle and CLEO

BaBar $D_S(2317)$



CLEO $D_S(2460)$

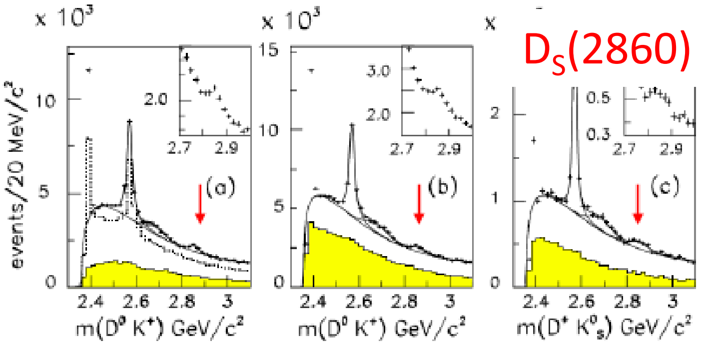




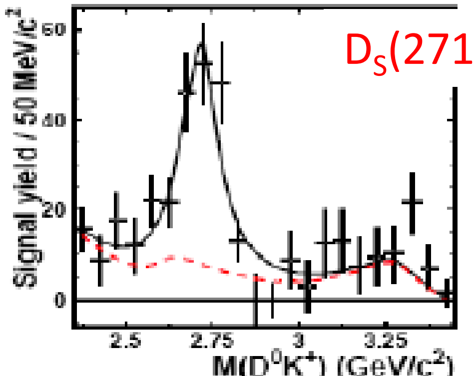
The identification of these states as the 0^+ and 1^+ cs states is difficult within the potential model

D_s States

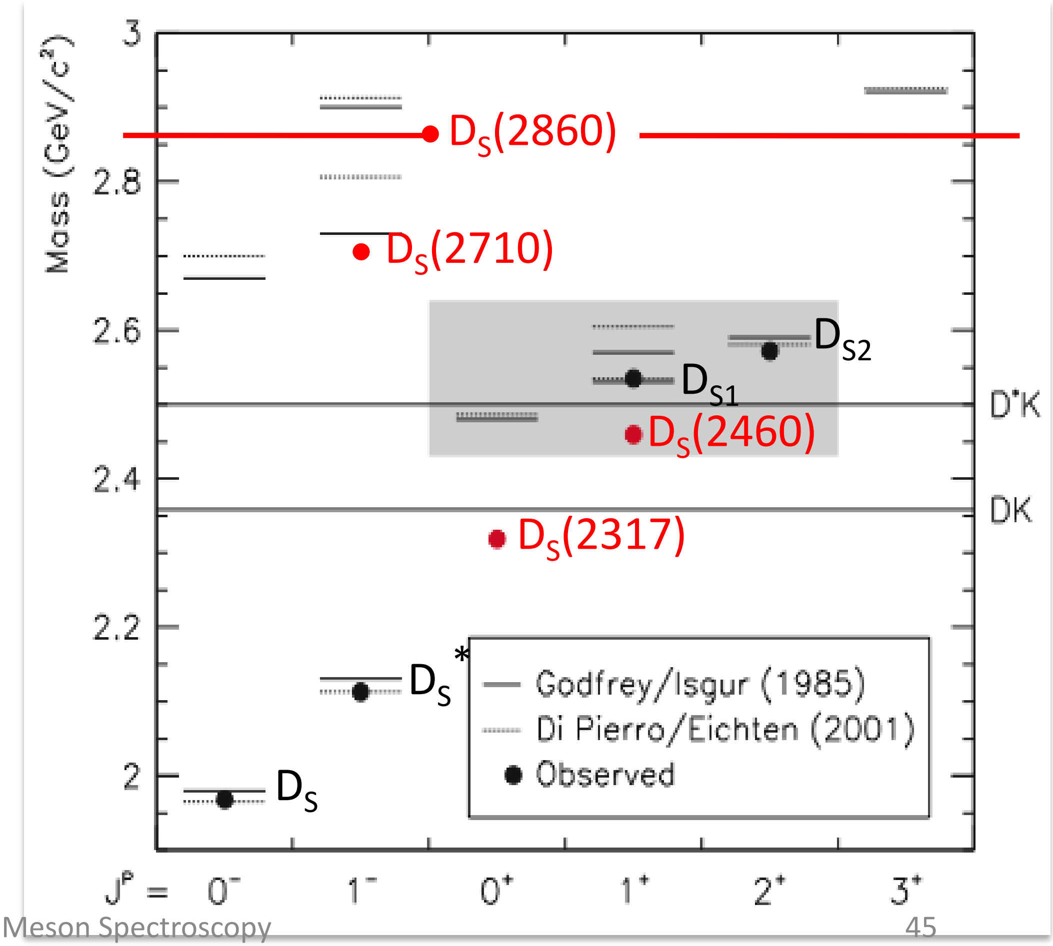
The discovery of the new D_{SJ} states continued …



BaBar Collab., PRL 97 (06) 222001



Belle Collab, PRL 100 (08) 092001



D_s States

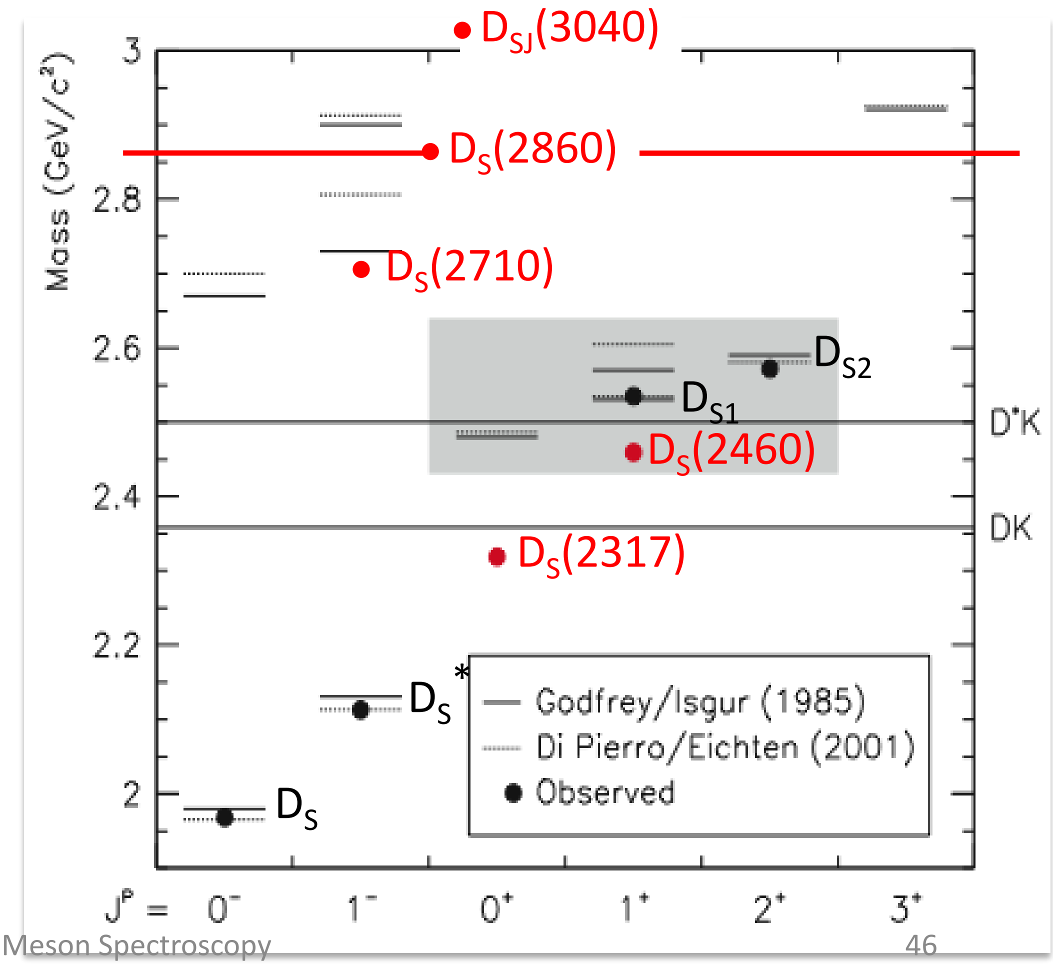
The assignment of the q.n. to the $D_s(2710)$ was possible thanks to an analysis performed by BaBar studying *DK*, *D*K* final states.

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

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

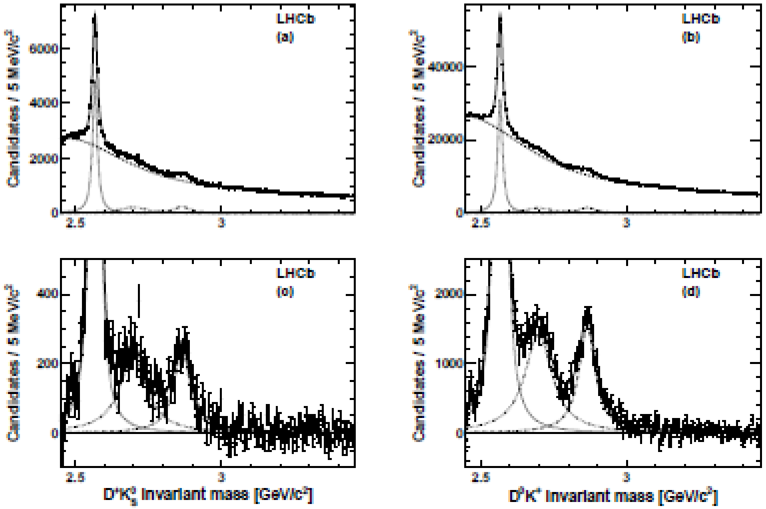
$$m(D^*_{sJ}(2860)^+) = 2862 \pm 2_{\rm stat}(^{+5}_{-2})_{\rm syst}\ {\rm MeV}/c^2,$$
$$\Gamma = 48 \pm 3_{\rm stat} \pm 6_{\rm syst}\ {\rm MeV},$$

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



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

Measurement of D_s Parameters at LHCb



Resonances observed by BaBar and Belle have been confirmed.

All results are in agreement.

Statistical uncertainties improved by a factor 2.

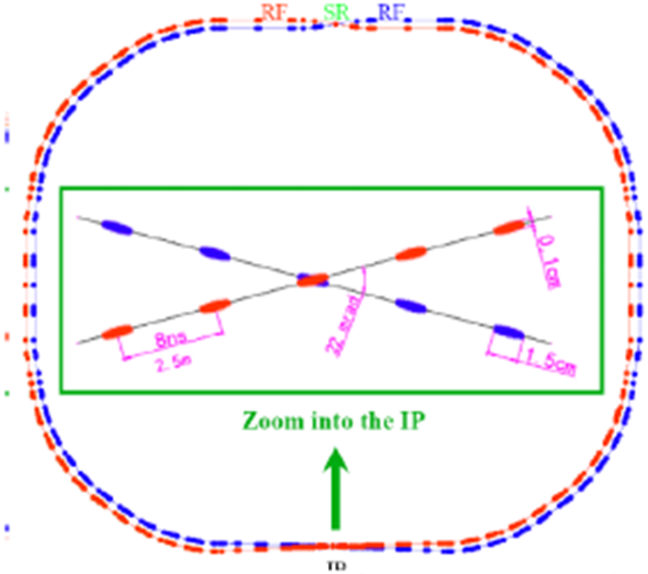
$$
\begin{aligned}
m(D^*_{s1}(2710)^+) &= 2709.2 \pm 1.9(\text{stat}) \pm 4.5(\text{syst})\ \text{MeV}/c^2,\\
\Gamma(D^*_{s1}(2710)^+) &= 115.8 \pm 7.3(\text{stat}) \pm 12.1(\text{syst})\ \text{MeV}/c^2,\\
m(D^*_{sJ}(2860)^+) &= 2866.1 \pm 1.0(\text{stat}) \pm 6.3(\text{syst})\ \text{MeV}/c^2,\\
\Gamma(D^*_{sJ}(2860)^+) &= 69.9 \pm 3.2(\text{stat}) \pm 6.6(\text{syst})\ \text{MeV}/c^2.
\end{aligned}
$$

Present and Future Facilities

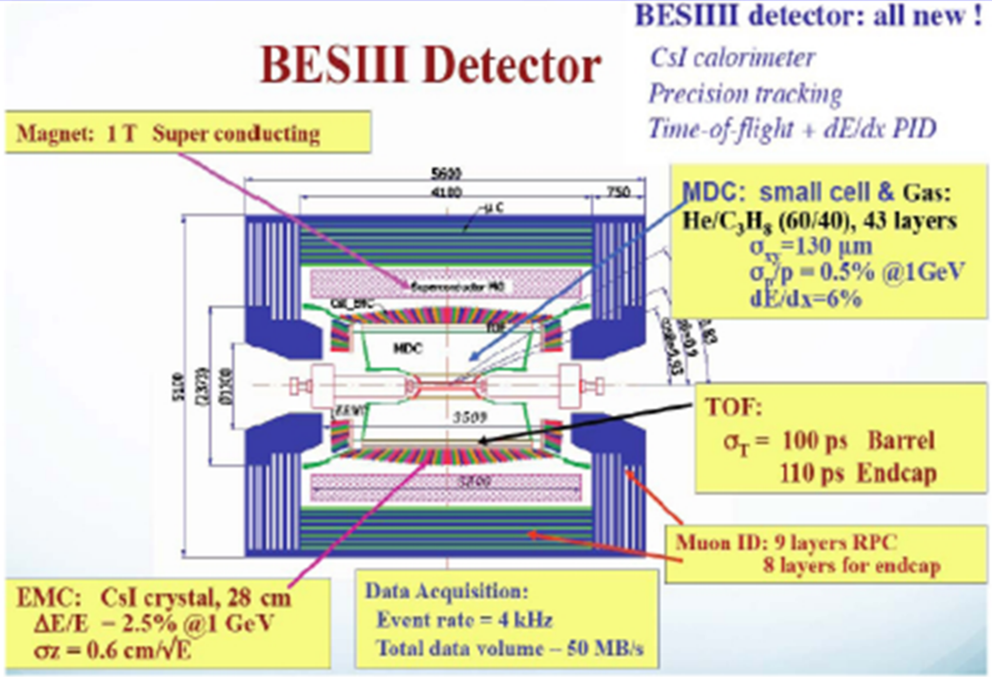
- Intensity frontier:
  - BES III at BEPC (charm factory)
  - Belle 2 (bottom factory)
  - $\overline{\text{P}}$ANDA at FAIR ($\bar{p}p$ annihilation up to 5.5 GeV)
- Energy frontier
  - LHCb
  - Atlas and CMS

BEPCII/BESIII

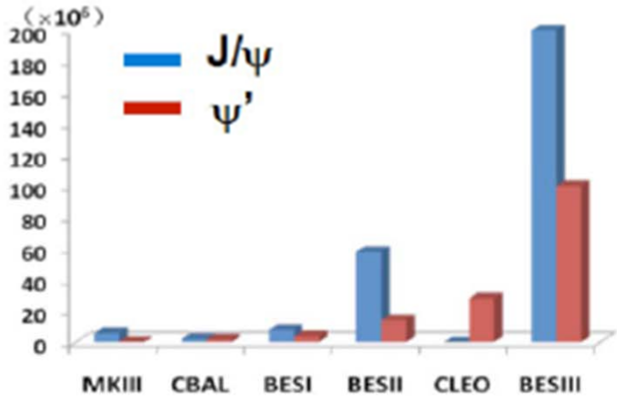
BEPCII storage rings

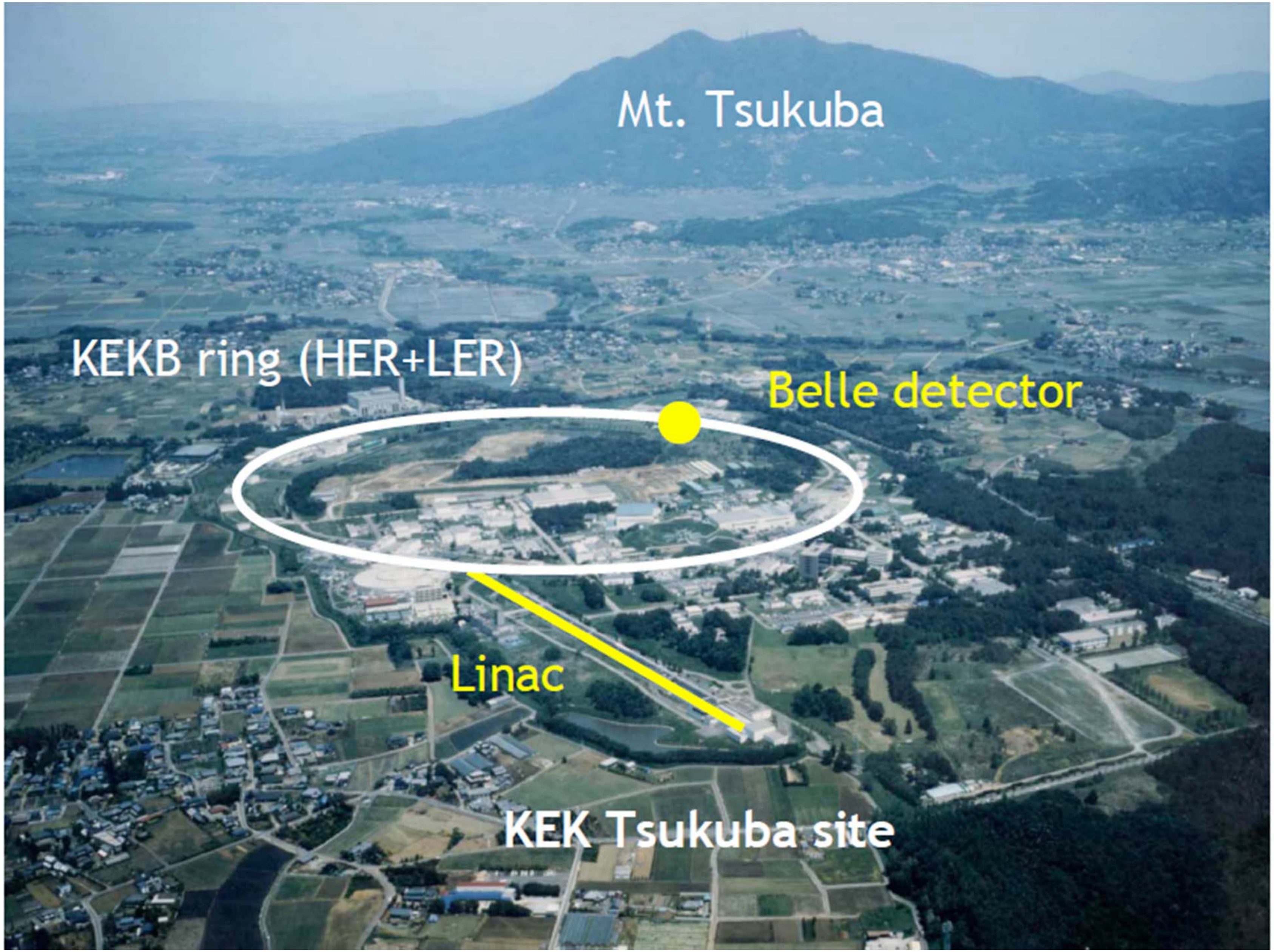


Beam energy:
1.0-2.3 GeV
Design Luminosity:
1×10^{33} cm^{-2}s^{-1}
Optimum energy:
1.89 GeV
Energy spread:
5.16×10^{-4}
No. of bunches:
93
Bunch length:
1.5 cm
Total current:
0.91 A
Circumference:
237m

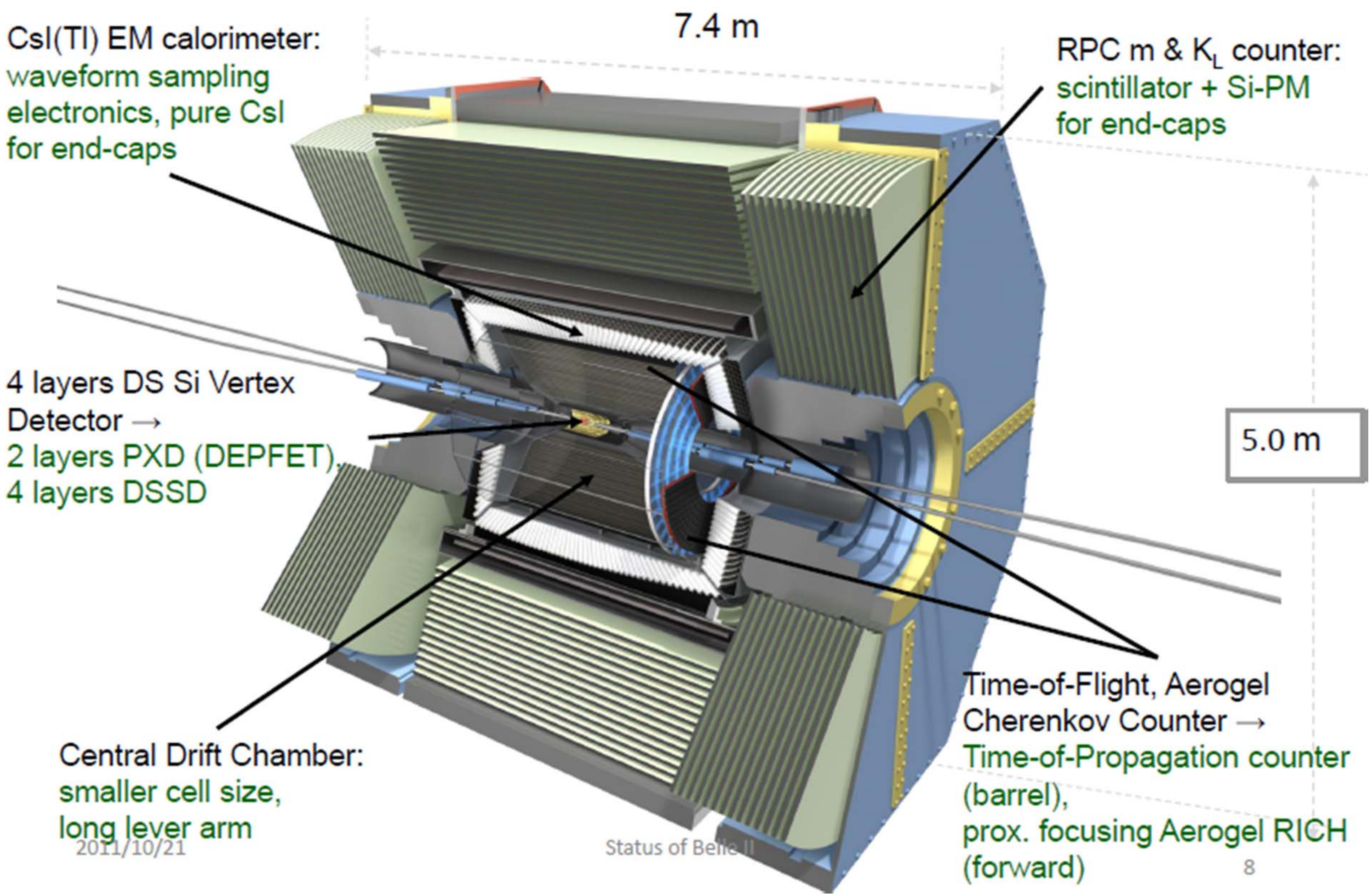


- So far BESIII has collected :
  - 2009: 225 Million J/ψ
  - 2009: 106 Million ψ'
  - 2010-11: 2.9 fb^{-1} $\psi(3770)$ (3.5 × CLEO-c 0.818fb^{-1})
  - May 2011: 0.5fb^{-1} @4010 MeV (one month) for Ds and XYZ spectroscopy
- BESIII will also collect:
  - more J/ψ, ψ', $\psi(3770)$
  - data at higher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

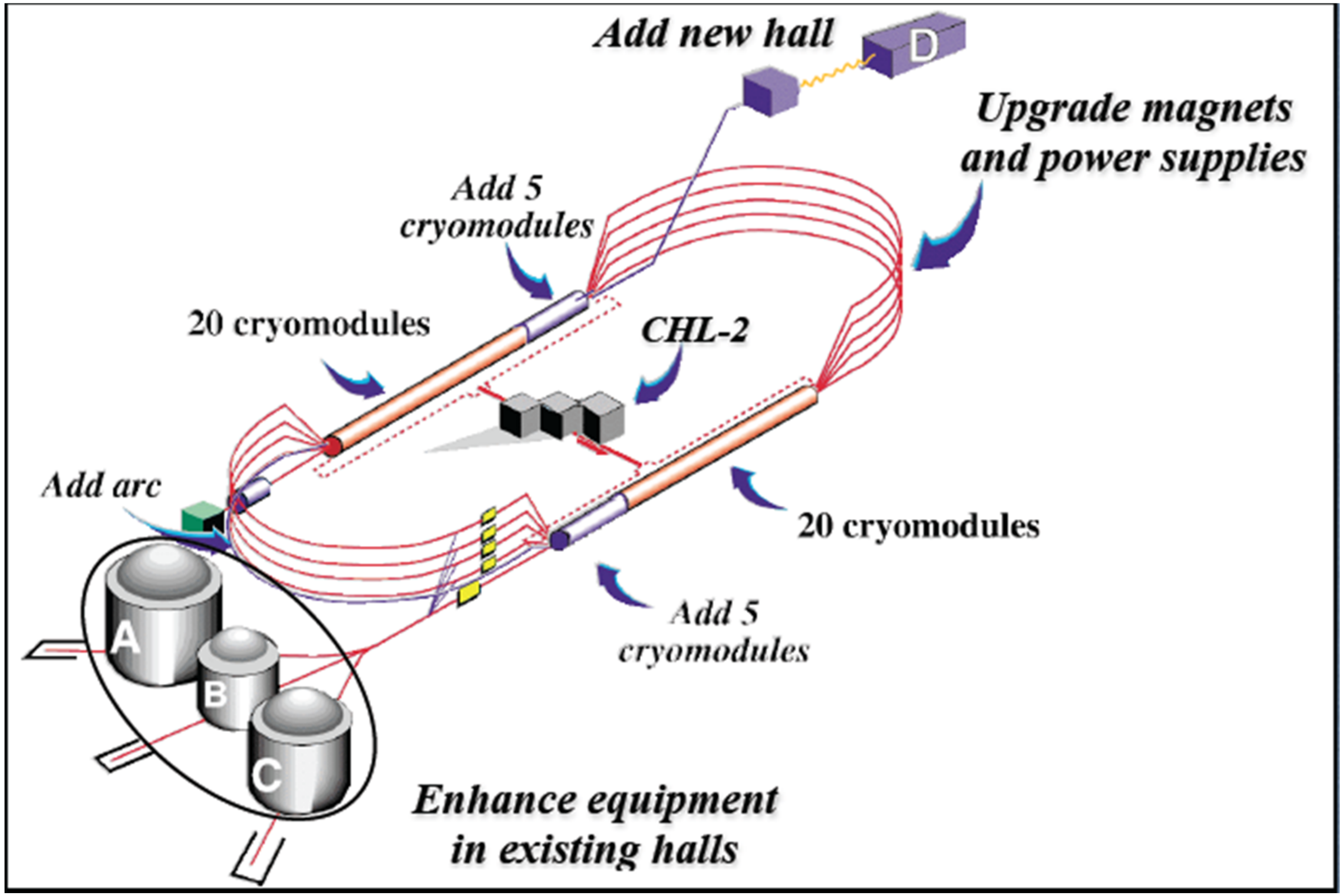



Mt. Tsukuba
KEKB ring (HER+LER)
Belle detector
Linac
KEK Tsukuba site

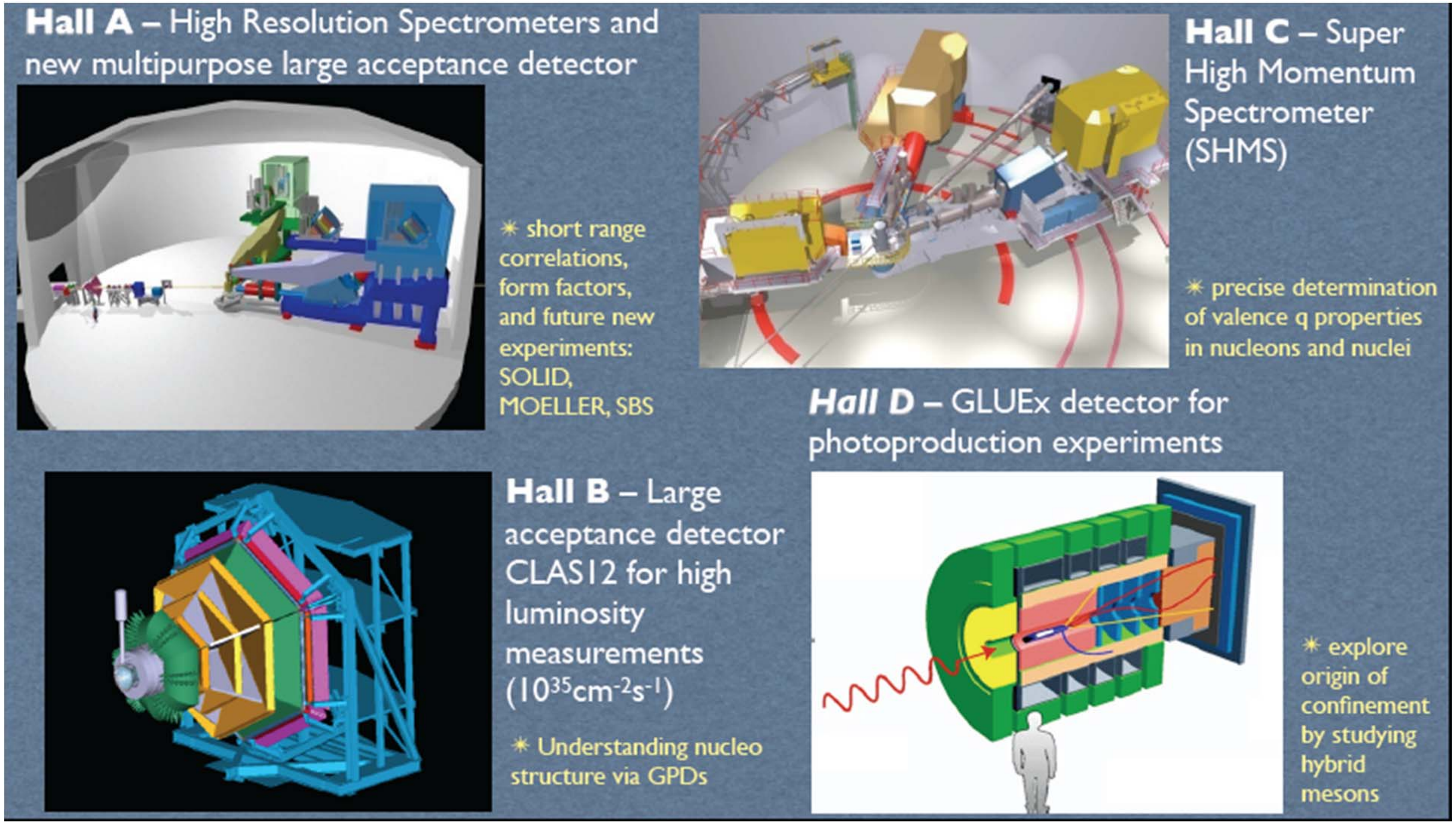
Belle II: design concept



The JLAB 12 GeV Upgrade



The 12 GeV Equipment



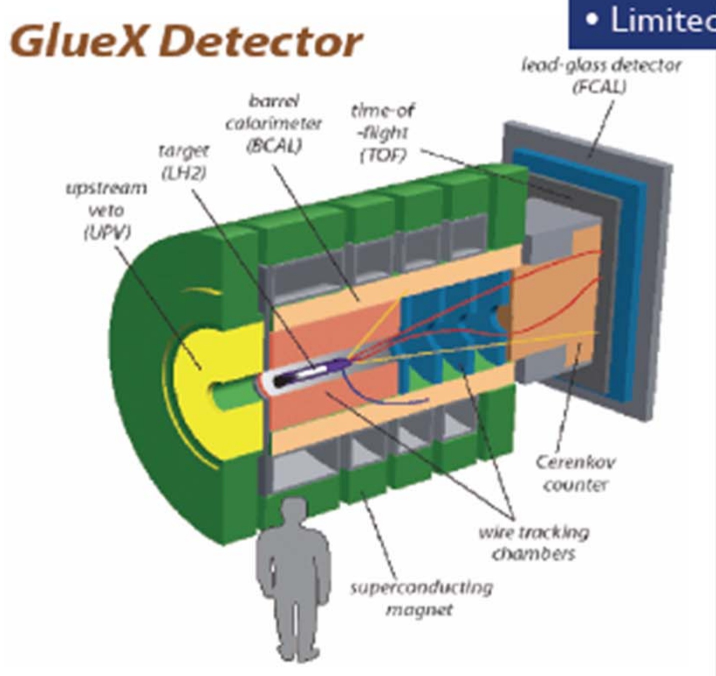
M. Battaglieri – Erice 2011

Meson spectroscopy with photons at JLab-12 GeV

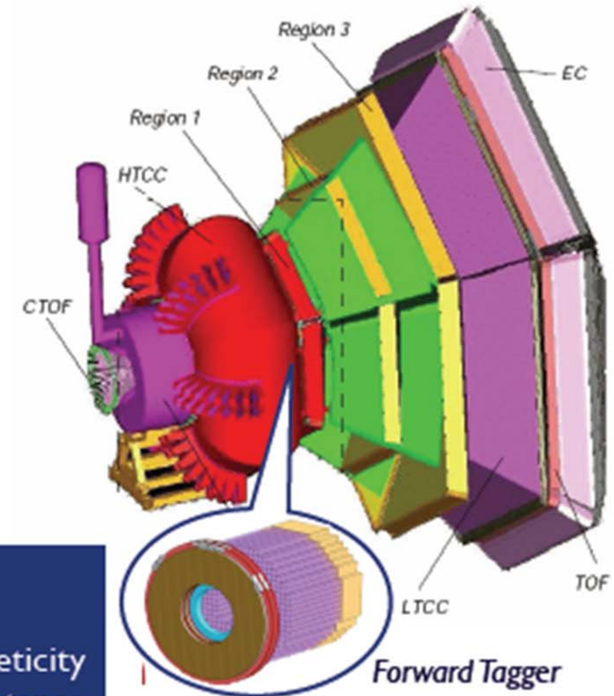
- Determination of JPC of meson states requires PWA
- Decay and production of exclusive reactions
- Good acceptance, energy resolution, particle identification

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

Hall-D - GlueX Detector



Hall-B - CLAS12 Detector



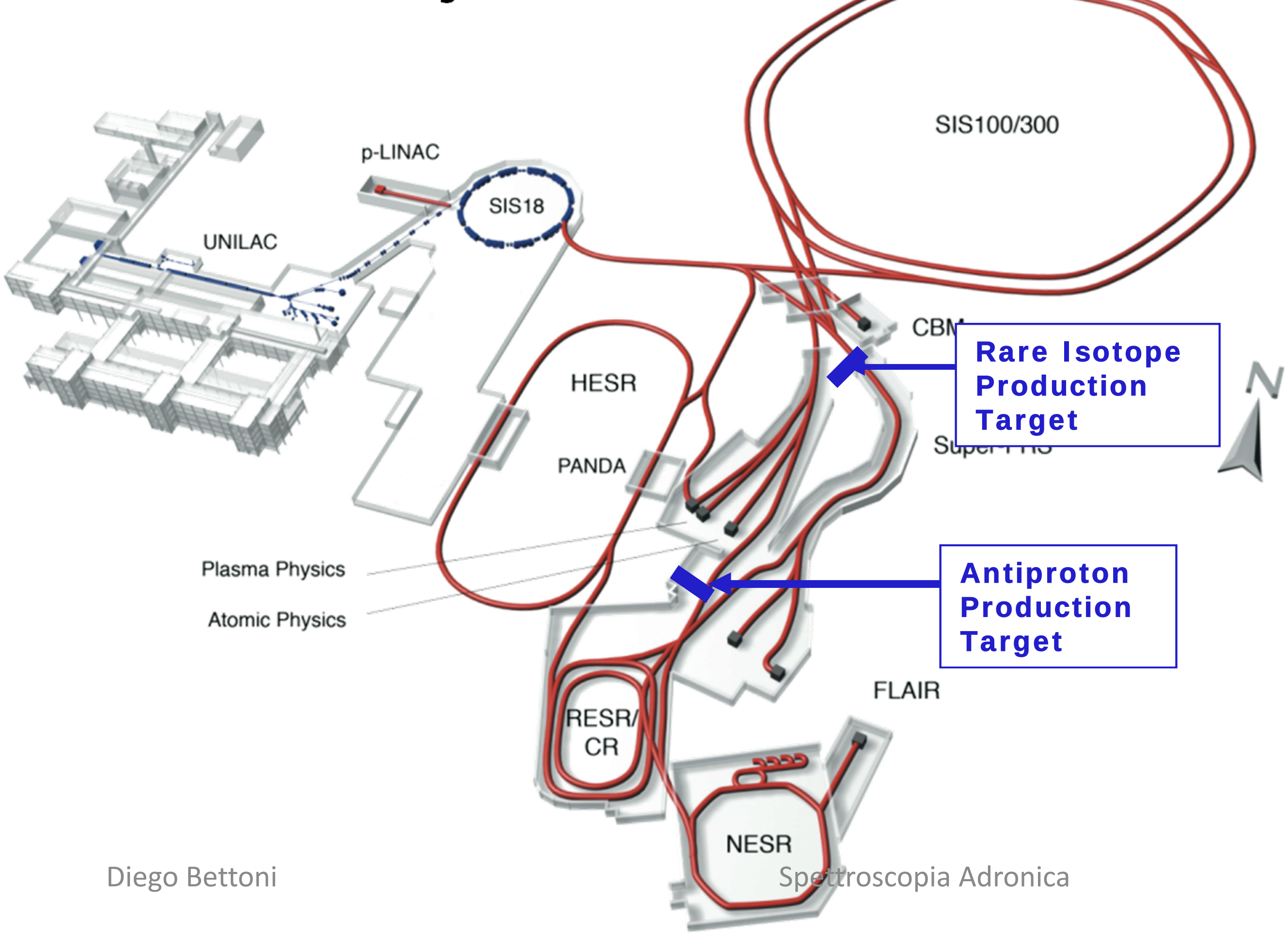
- Good resolution
- Good pID
- Reasonable hermeticity
- Un-uniform acceptance

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
- **10^{11}** stored and cooled antiprotons for **Antimatter** creation

High-Energy Storage Ring

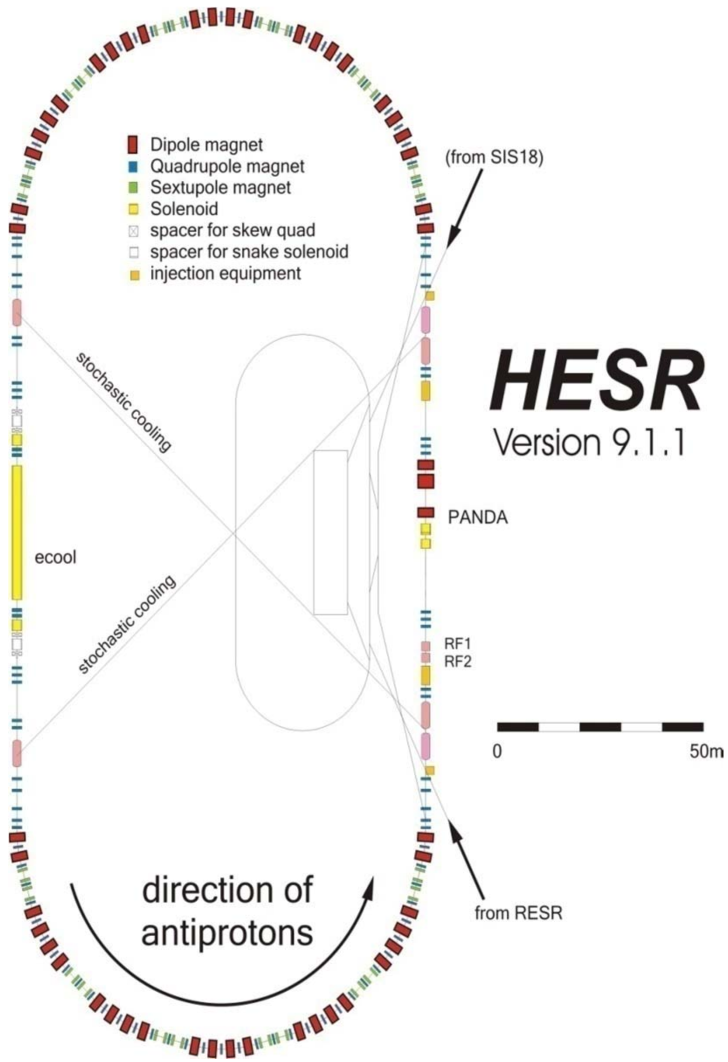
- Production rate 2×10^7/sec
- P_{beam} = 1 - 15 GeV/c
- N_{stored} = 5×10^{10} $\bar{p}$
- Internal Target

High resolution mode

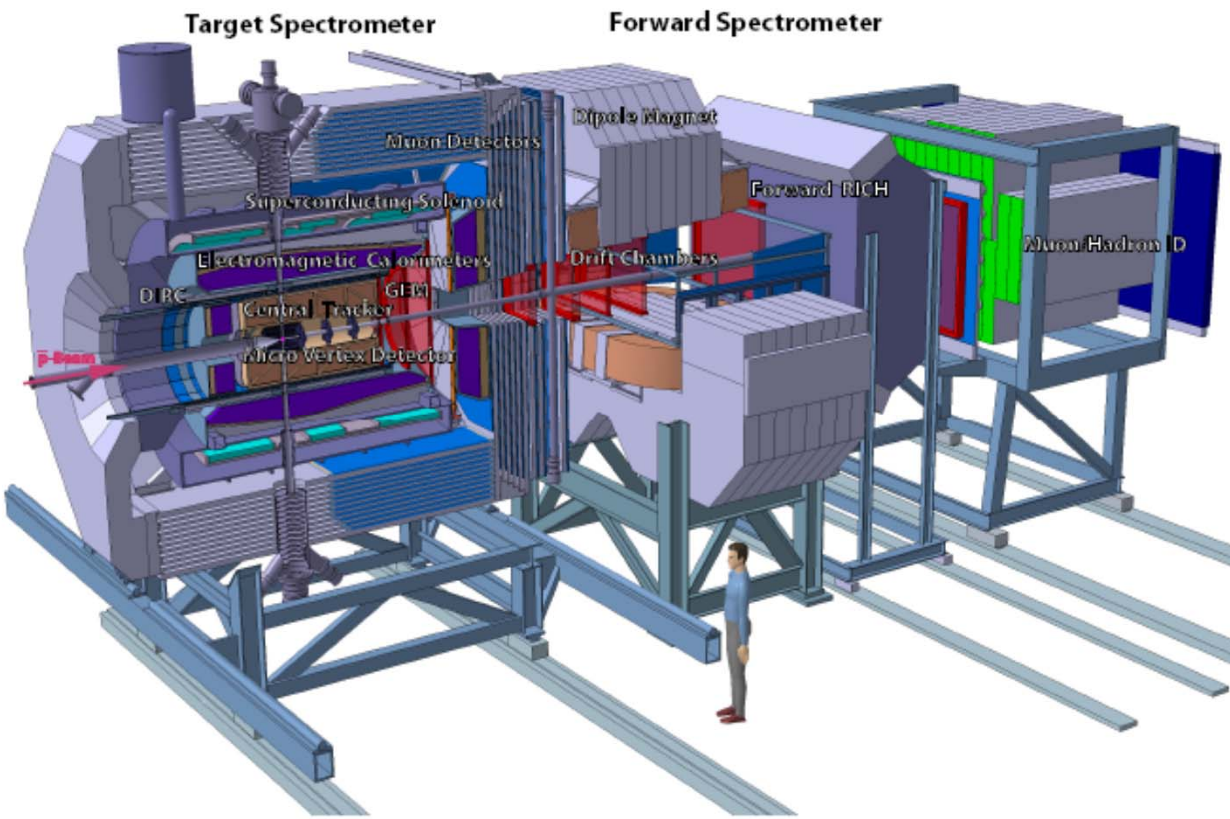
- $\delta p/p \sim 10^{-5}$ (electron cooling)
- Lumin. = 10^{31} cm^{-2} s^{-1}

High luminosity mode

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



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

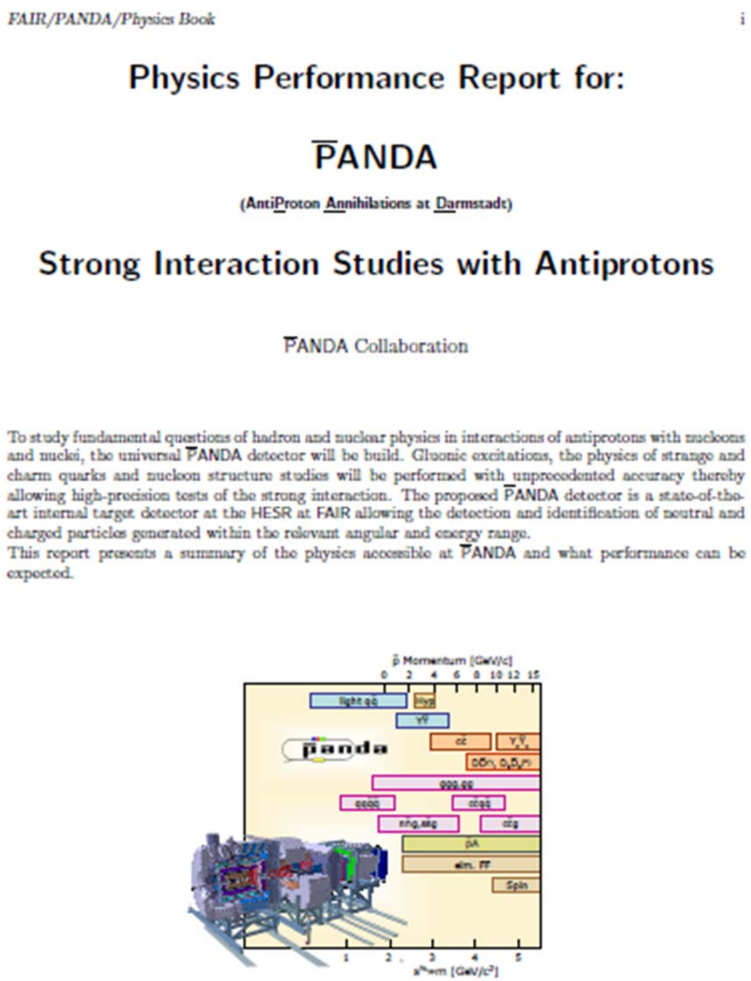


Detector Requirements

- (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

$\overline{\text{P}}$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:

$\overline{\text{P}}$ANDA

(AntiProton Annihilations at Darmstadt)

Strong Interaction Studies with Antiprotons

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

To study fundamental questions of hadron and nuclear physics in interactions of antiprotons with nucleons and nuclei, the universal $\overline{\text{P}}$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 $\overline{\text{P}}$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 $\overline{\text{P}}$ANDA and what performance can be expected.

ArXiV:0903.3905