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
  - $D_{(s)}$ systems

Introduzione alla QCD

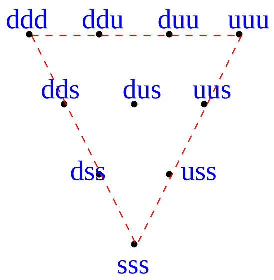
QCD (Quantum ChromoDynamics)

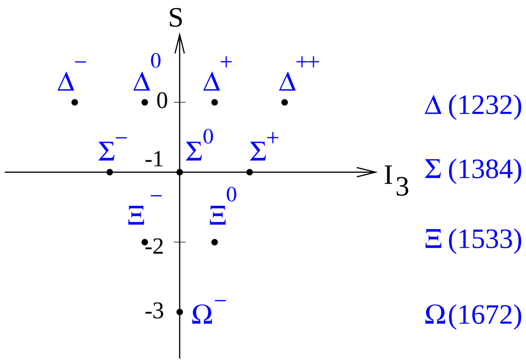
La QCD è la teoria dei quark, gluoni e delle loro interazioni.
Fa parte del Modello Standard. E' una teoria di campo quantistica con una lagrangiana semplice ed elegante che si basa interamente sulla invarianza per trasformazioni di un gruppo di gauge locale, $SU(3)_{colore}$.

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

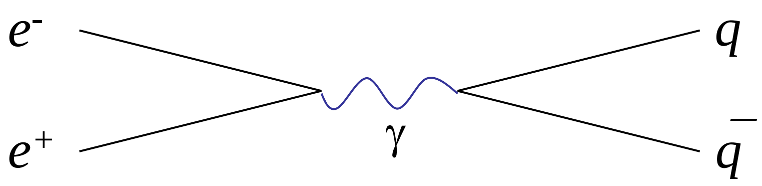
$$\psi^{\alpha} \qquad (\alpha = 1,2,3)$$

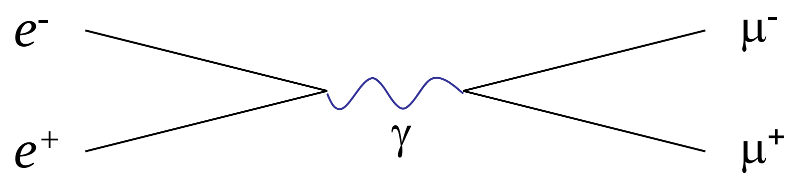
$$\psi_{colore} = \varepsilon_{\alpha\beta\gamma}\psi^{\alpha}\psi^{\beta}\psi^{\gamma}$$

- 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 $e^+e^- \to \mu^+\mu^-$.





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

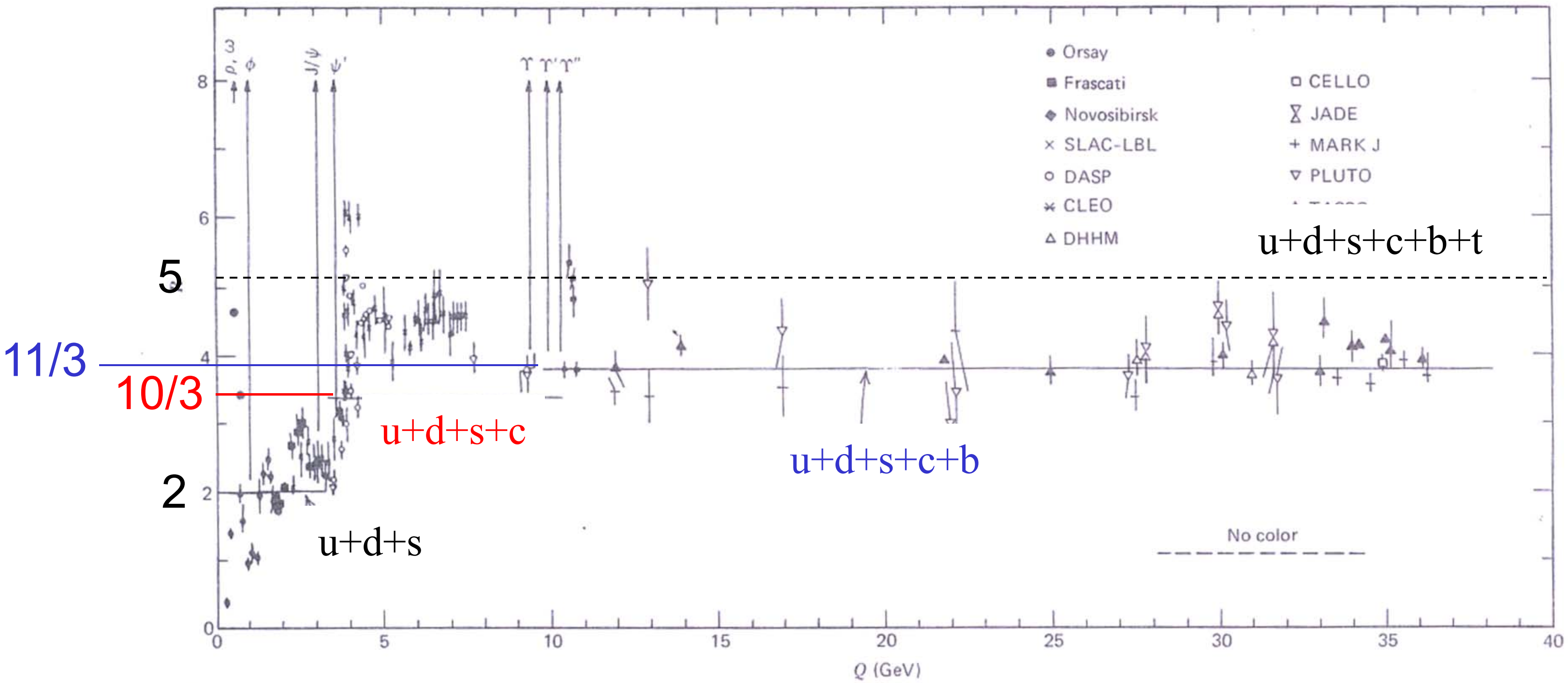
$$\sigma\left(e^+e^- \to q\bar{q}\right) = 3e_q^2\sigma\left(e^+e^- \to \mu^+\mu^-\right)$$

colore

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

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

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



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:

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

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 $m_q << \Lambda_{QCD}$ q=u, d, s

Heavy quarks $m_Q >> \Lambda_{QCD}$ Q=c, b, t

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

"current quark masses" $\overline{MS}$ 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 $\overline{MS}$ scheme

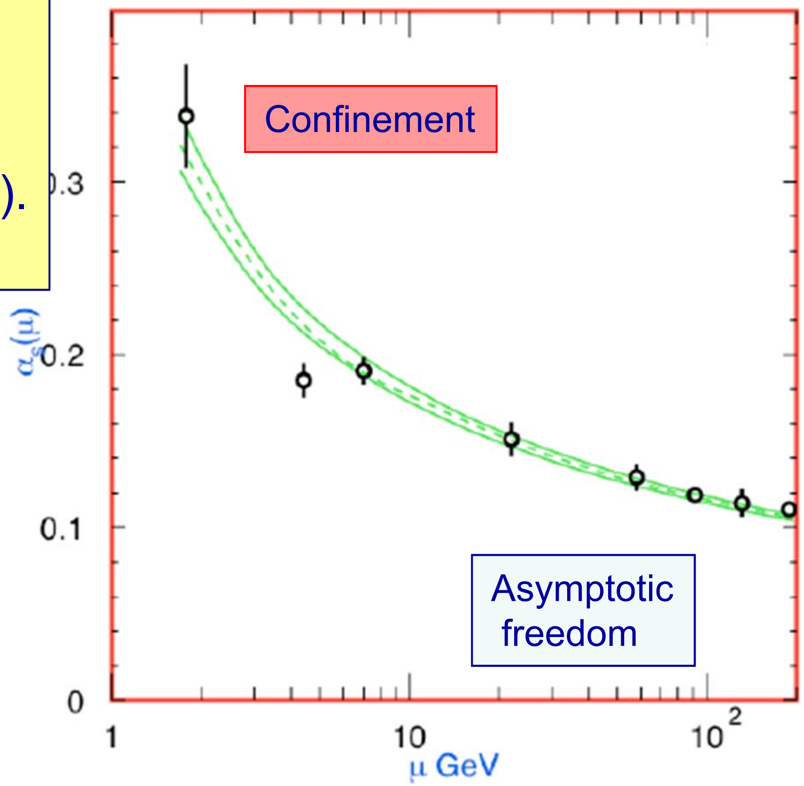
Hadrons containing heavy quarks have masses of order m_Q rather than of the order Λ_{QCD}.

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 ($N_f=2$):

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

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

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:

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

$$\partial_\mu J_R^\mu = \partial_\mu J_L^\mu = 0$$

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:

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

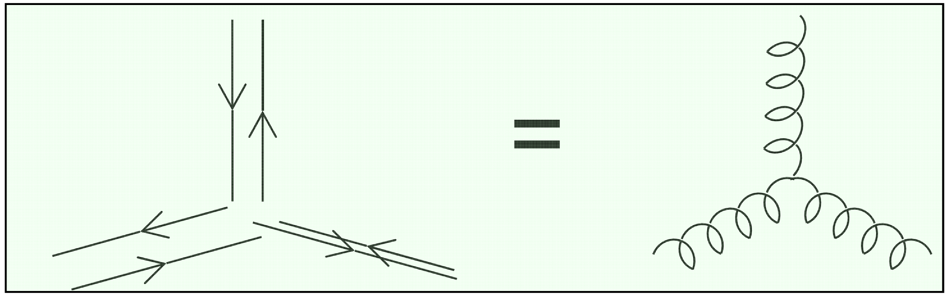
I bosoni di Goldstone sono i 3 π nel caso di due flavor e gli otto membri dell'ottetto mesonico nel caso di tre flavor.

QCD Properties

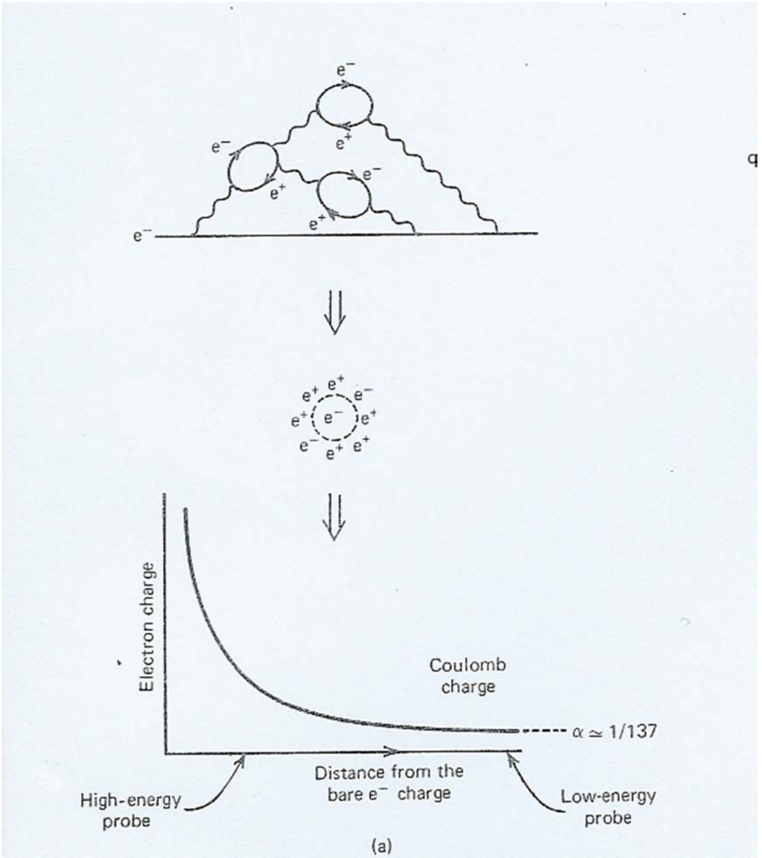
- Poincaré, P, T and C invariant.
- Non abelian gauge theory $\Rightarrow$ physical spectrum consists of color singlet states only.
- The QCD effective coupling constant $\alpha_s(q)$ decreases as the momentum transfer scale increases (asymptotic freedom)

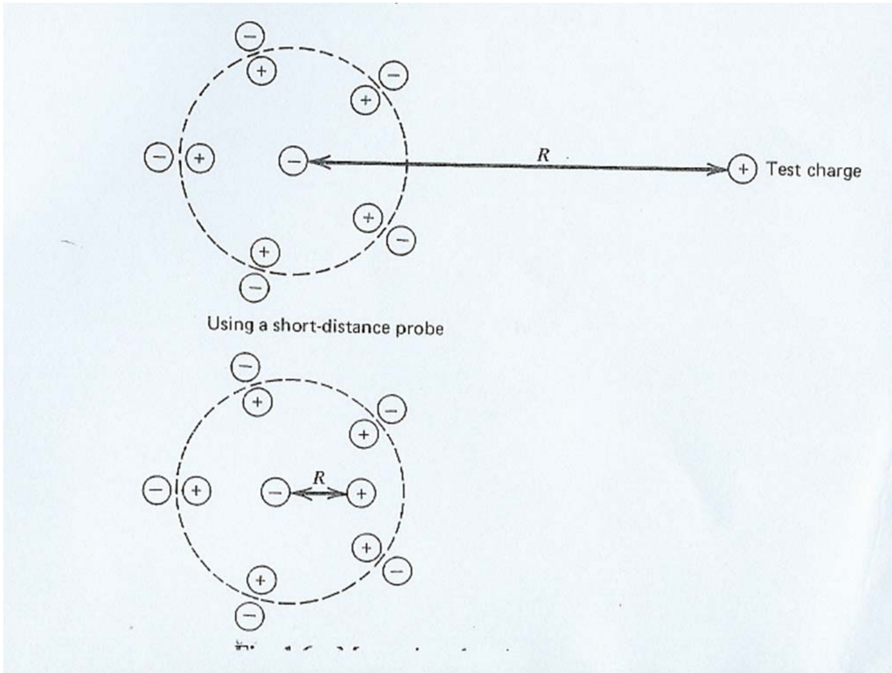
  $\Rightarrow$ perturbative calculations at high energies.
- Intrinsic scale at low energies Λ_{QCD}, main contribution to hadron masses. At $q \sim 1/\Lambda_{QCD}$, $\alpha_s(q) \sim 1$ and perturbation theory cannot be used.
- Flavor conservation.

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.



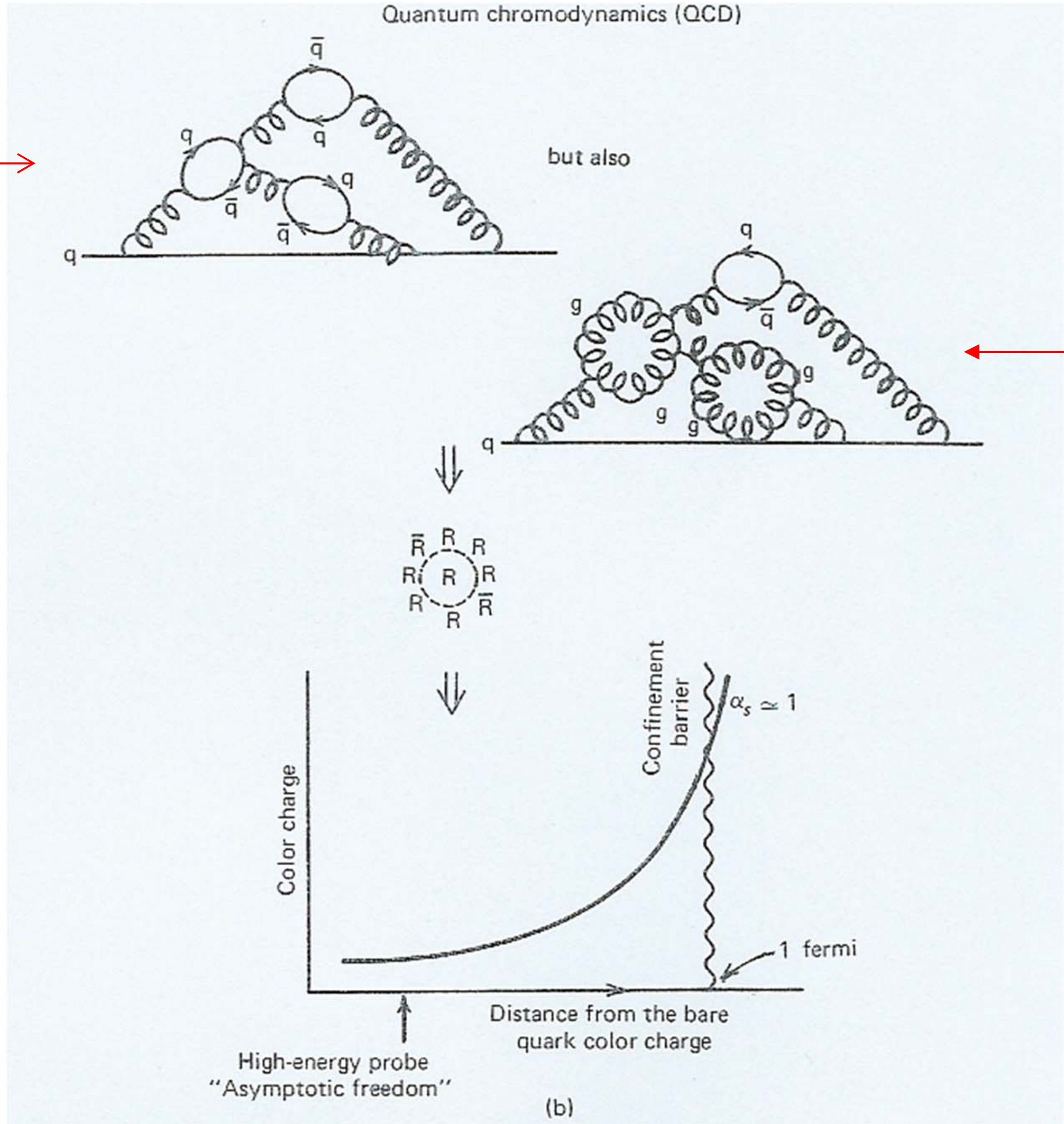
Questo fatto ha delle implicazioni importantissime sulla schermatura di carica in QED e QCD e sull'andamento asintotico delle due interazioni.





Schermatura di carica in QCD e andamento di α_S

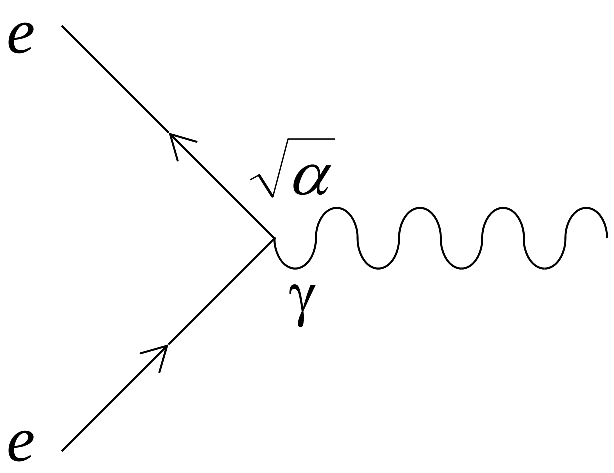
QED analog

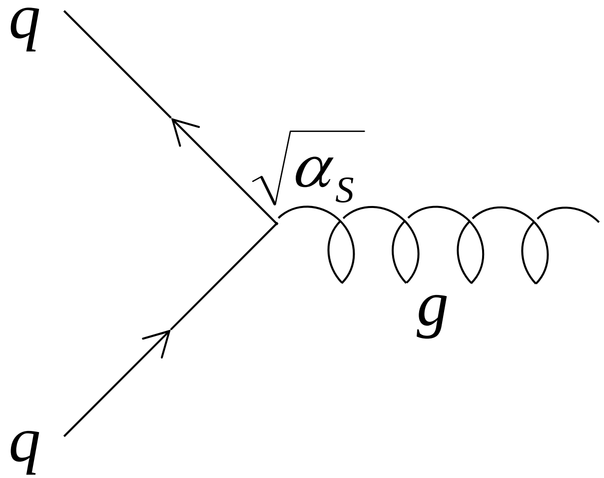


gluon self coupling in QCD

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

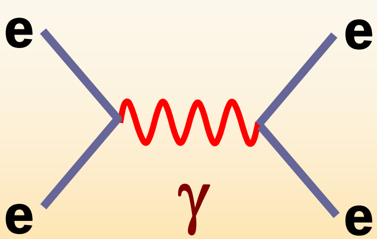
- I quark hanno una carica di colore (oltre alla carica elettrica) che può assumere 6 valori: R, G, B, $\bar{R}$, $\bar{B}$, $\bar{G}$.
- Il colore viene scambiato da 8 gluoni "bi-colorati".
- Le interazioni quark-quark si possono calcolare usando le regole di QED, con l'introduzione di un fattore di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



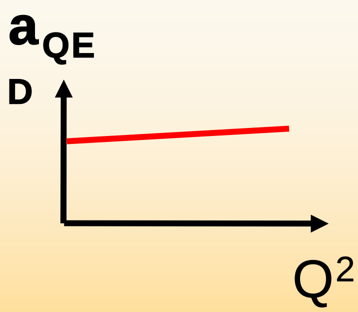
Leptons (e,μ,τ) couple to electric charge

Photon carries no charge

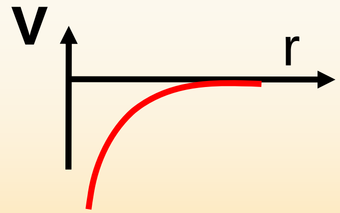
$m_e = 0.5$ MeV

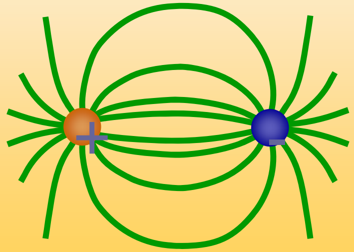
$m_p = 938$ MeV

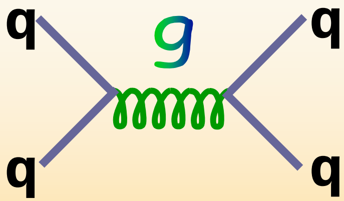
$E_b = 13$ eV



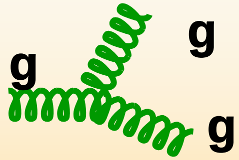
$$\alpha_{QED}(Q^2 = 0) = \frac{1}{137}$$







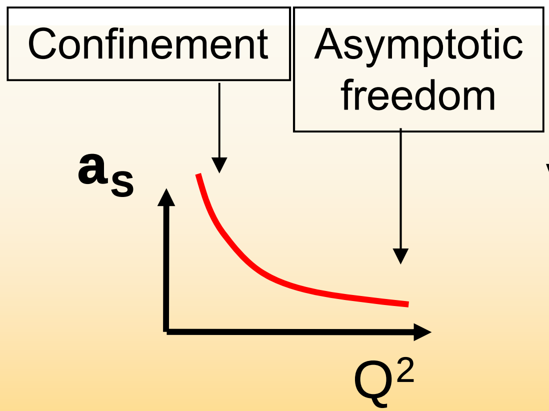
Quarks (u,d,s,c,b,t) couple to 3 Colourcharges



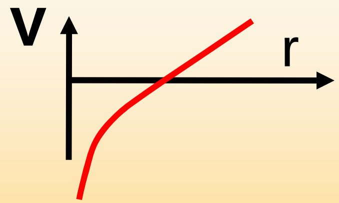
$m_u \approx$ 3 MeV

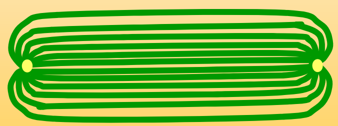
$m_d \approx$ 6 MeV

$M_p = 938$ 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.

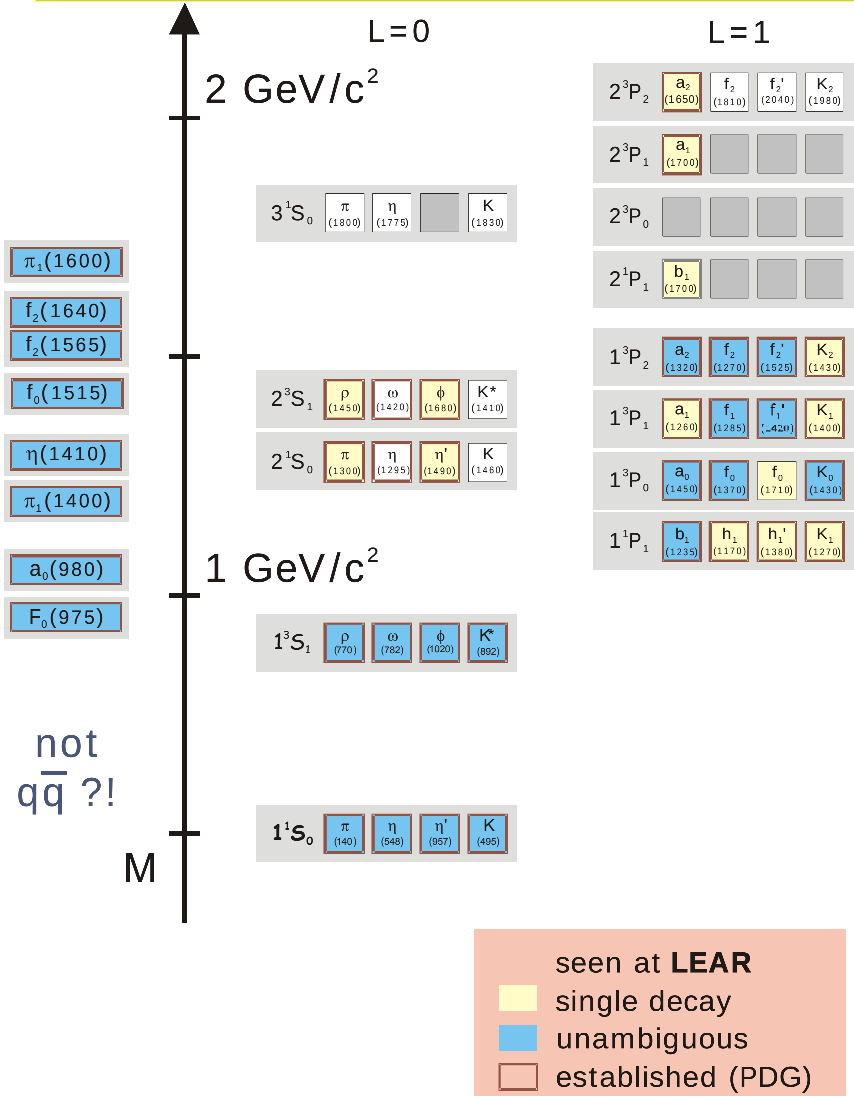
QCD is also an essential ingredient of the Standard Model and it is the incalculable strong matrix element which limit our reach for physics beyond the standard model.

- 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.).

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

Hadrons are very complicated

$q\,\bar{q}$

$+$

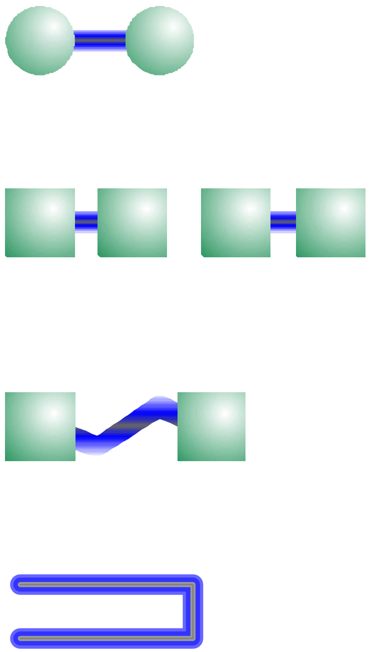
$(q\,\bar{q})\,(q\,\bar{q})$

$+$

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

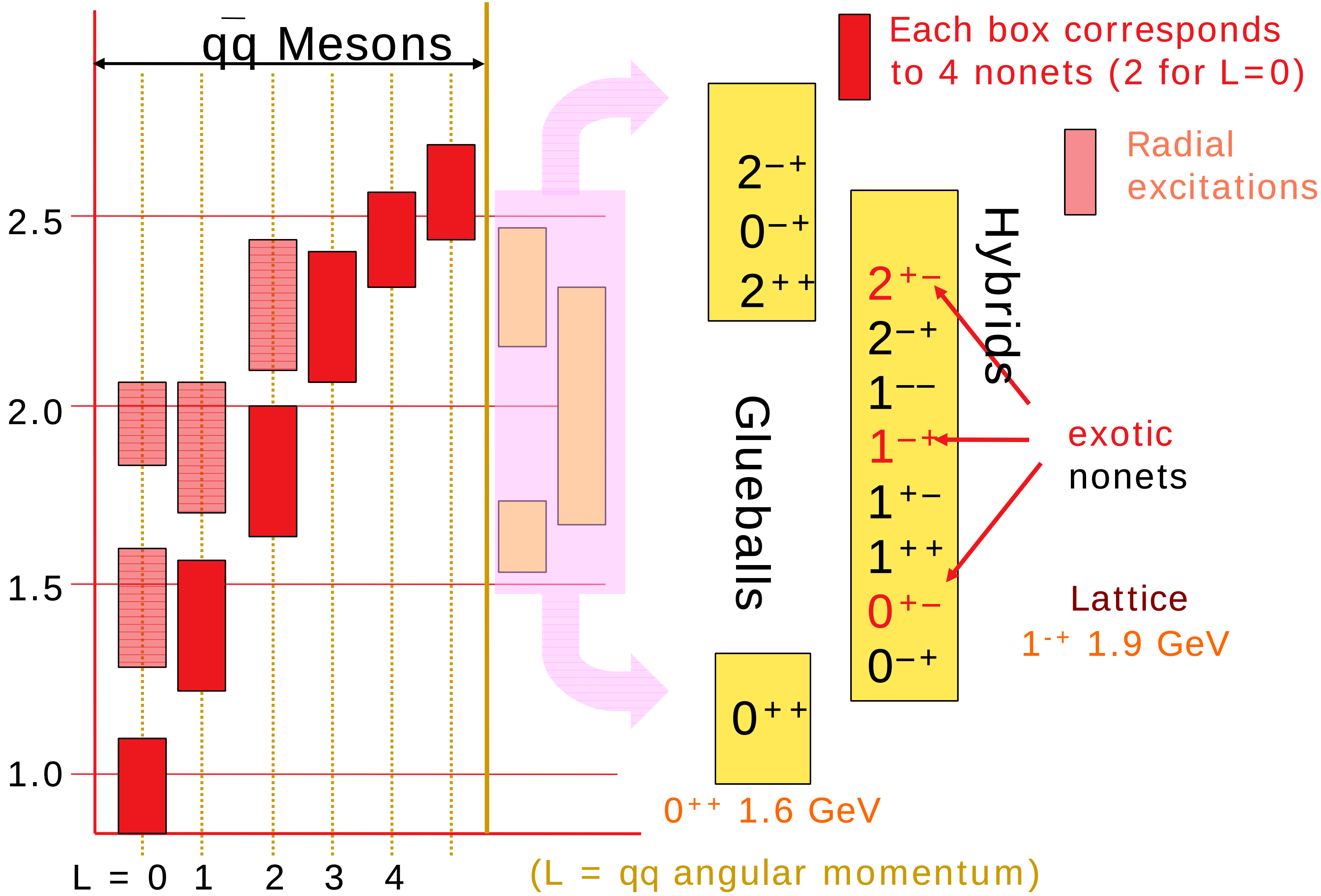
$+$

gg



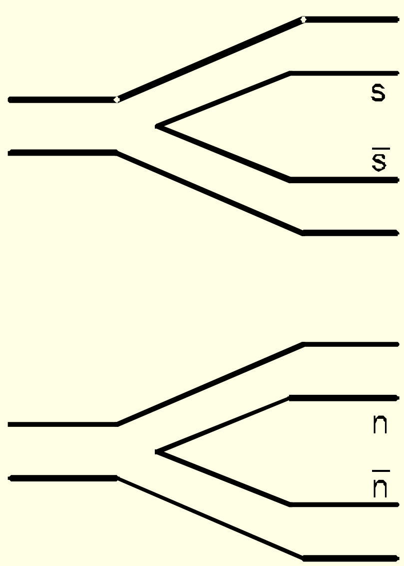
- Quarkmodels usually account for $q\,\bar{q}$ states
- Other color neutral configurations with same quantum numbers can (and will mix)
- Decoupling only possible for
  - narrow states
  - vanishing leading qq term

Light Meson Spectrum



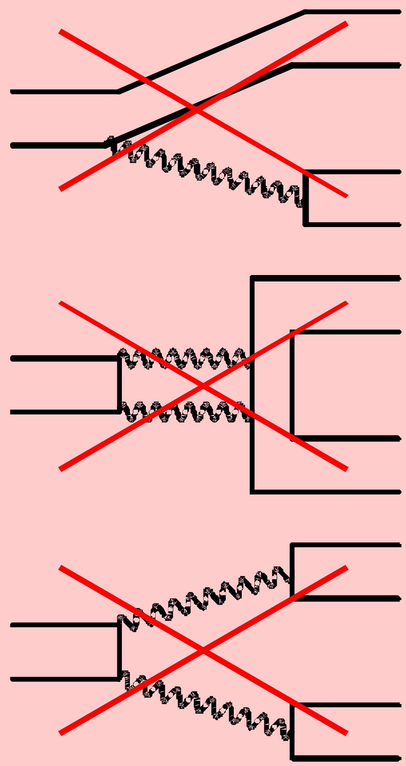
Meson Decay in the $SU(3)_F$ Picture

allowed

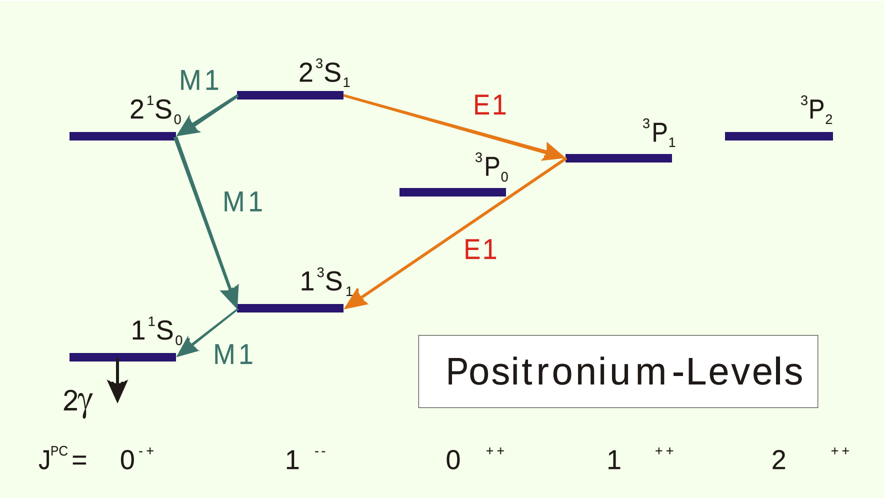


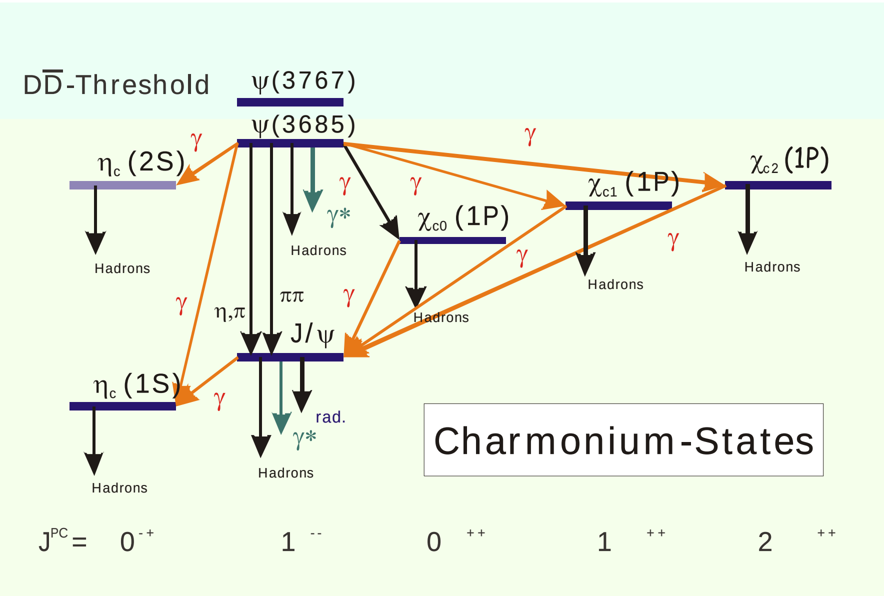
- Zweig-Rule
- Quark-antiquark-Production from the ($^3P_0$-)Vacuum
- But ! no hard gluons !

forbidden



QED and QCD Bound States





Electrodynamic and Chromodynamic spectrum look alike (not to scale)

- for infinite quark masses

A Coulomb-like Potential seems to be a good approach

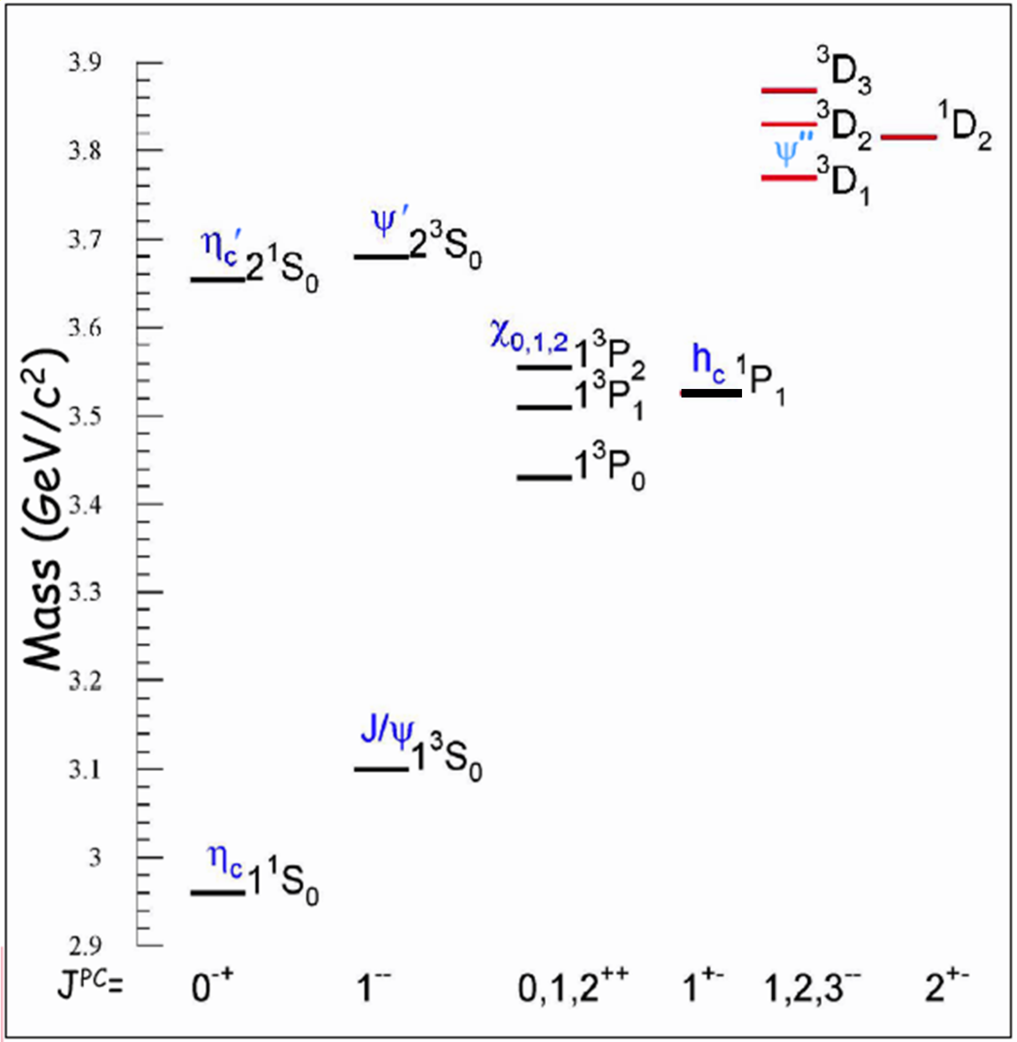
In addition one has to treat the confinement with a linearly rising potential

- confirmed by LQCD

Charmonium Physics

Open questions

- Precise measurement of mass and width for $\eta_c(2^1S_0)$ and $h_c(1^1P_1)$.
- States above threshold: D, 2P, ...
- Radiative decays
- Exclusive channels
  - helicity violation
  - 12 % rule
  - ...



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

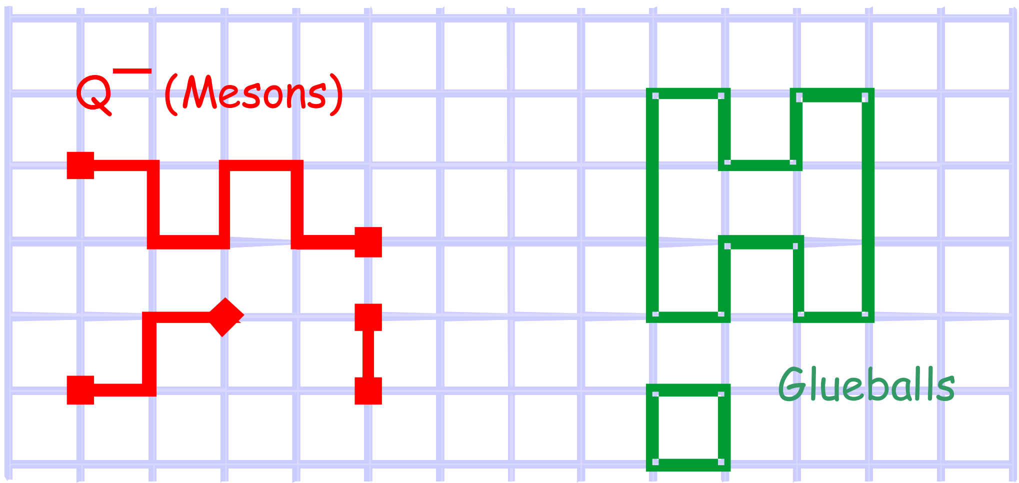
e.g. $\partial_t \phi \rightarrow [\phi(t+a) - \phi(t-a)]/2a$.

Continuum results obtained by $a \rightarrow 0$.

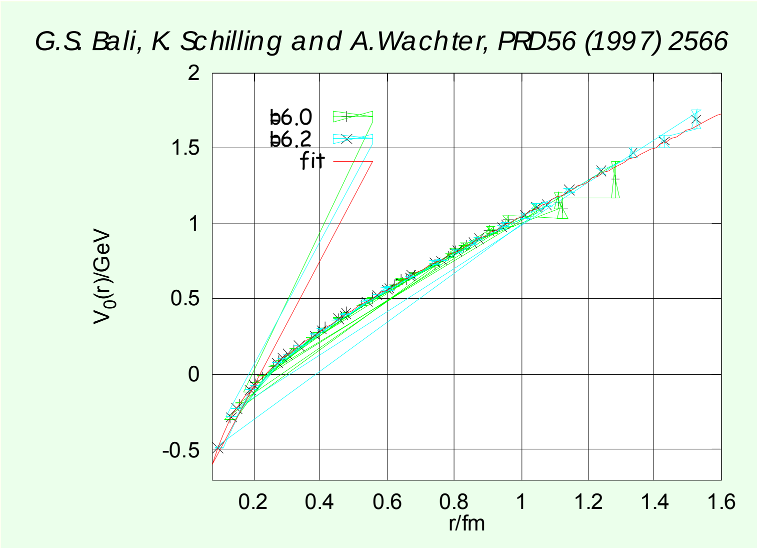
LQCD formulated in Euclidean space-time.

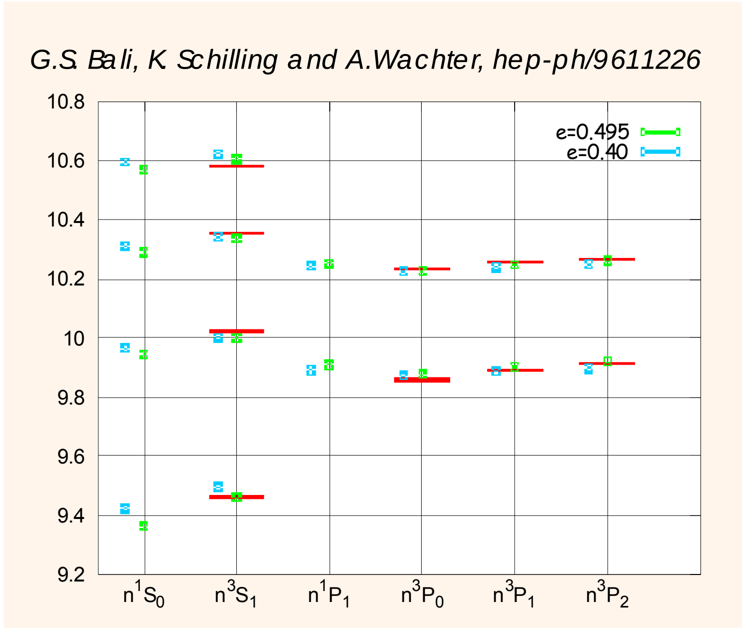
LQCD is a *first principles approach*: only parameters inherent to QCD, i.e. α_s and the quark masses. These n_f+1 parameters are fixed by matching n_f+1 low-energy quantities to their experimental values.

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



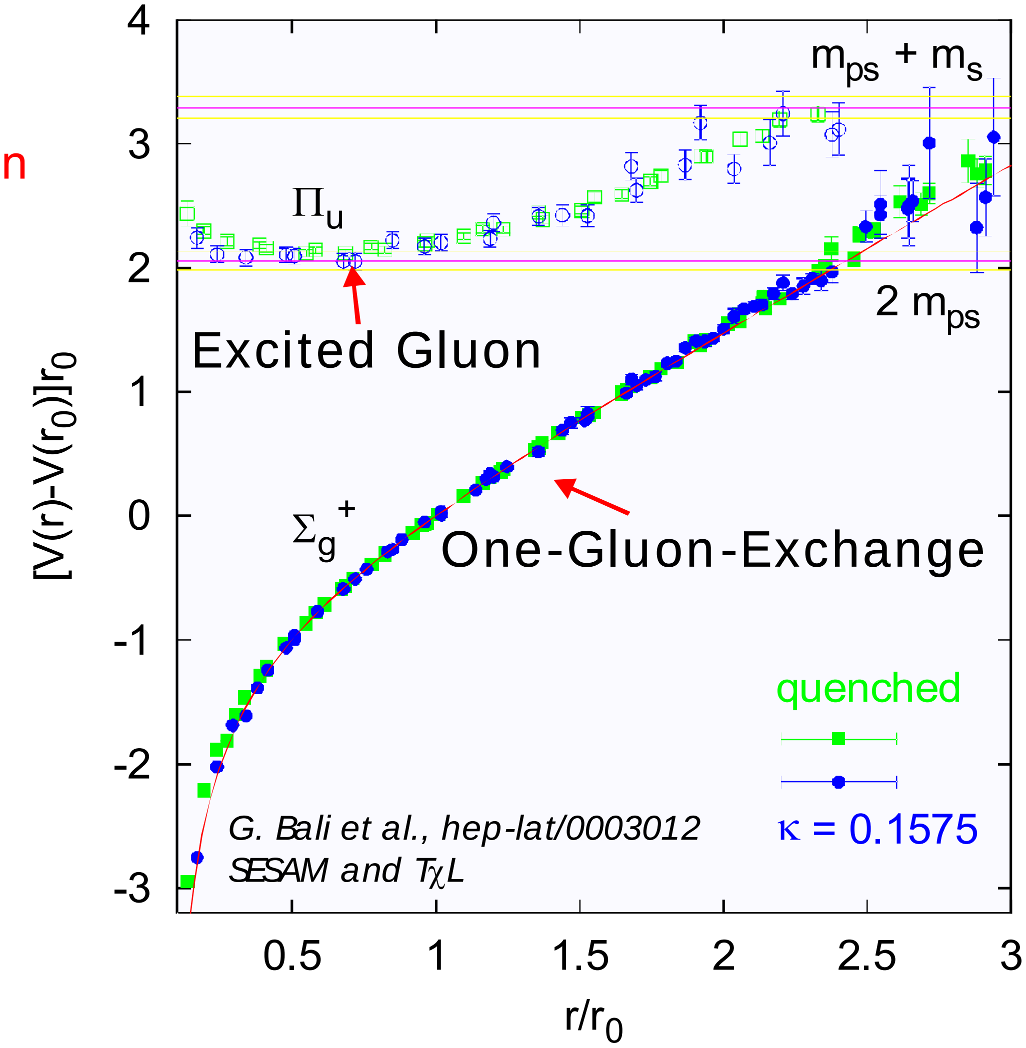


The static potential derived from LQCD confirms the Coulomb + Confinement Ansatz

Quenched vs Unquenched LQCD

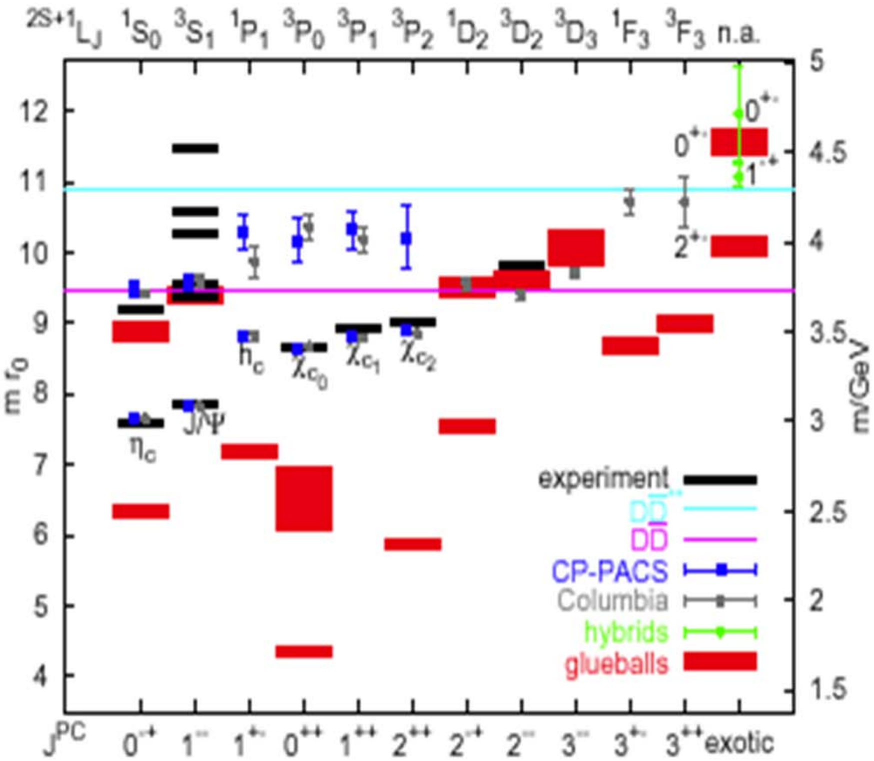
In the quenched approximation sea quarks are neglected.

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



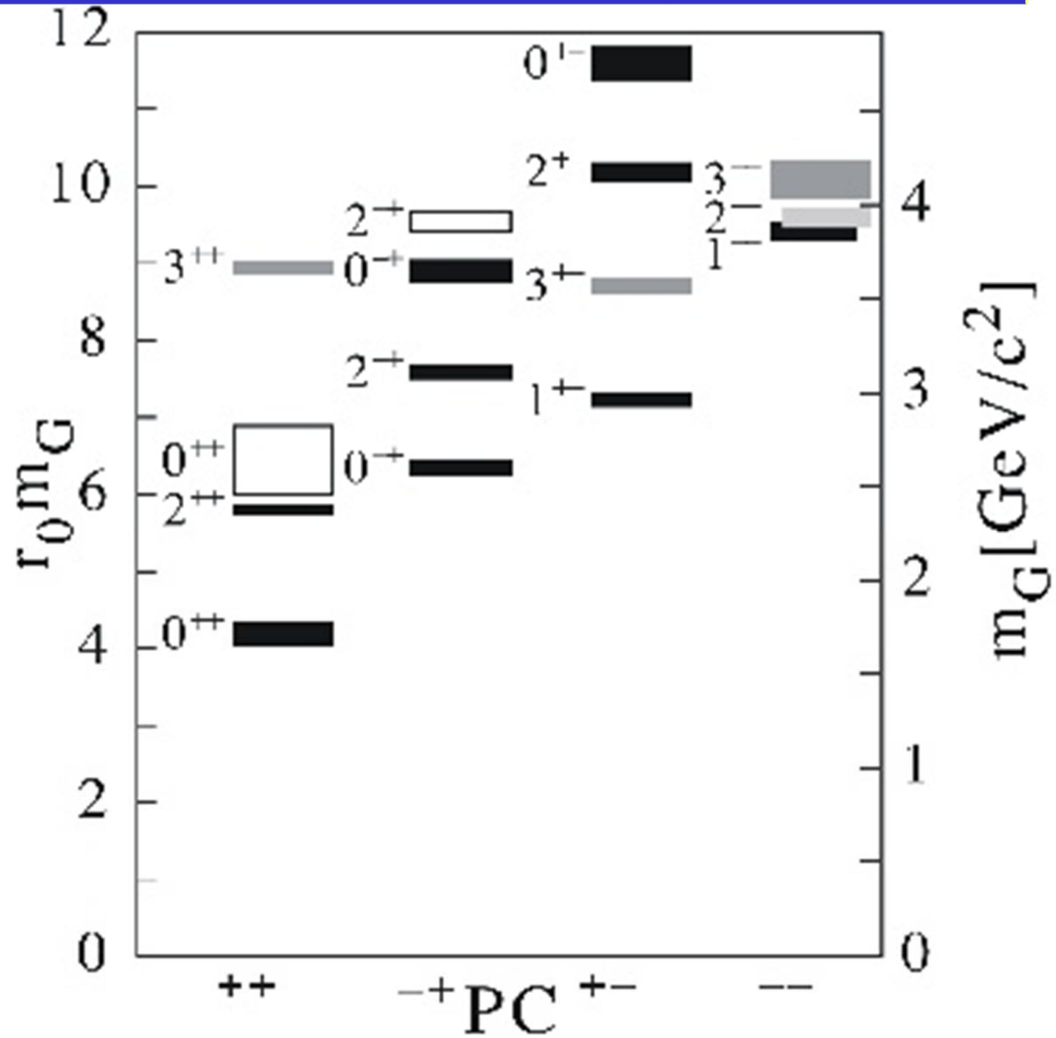
Quenched Charmonium Spectrum

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)	$m(1^1P)$=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

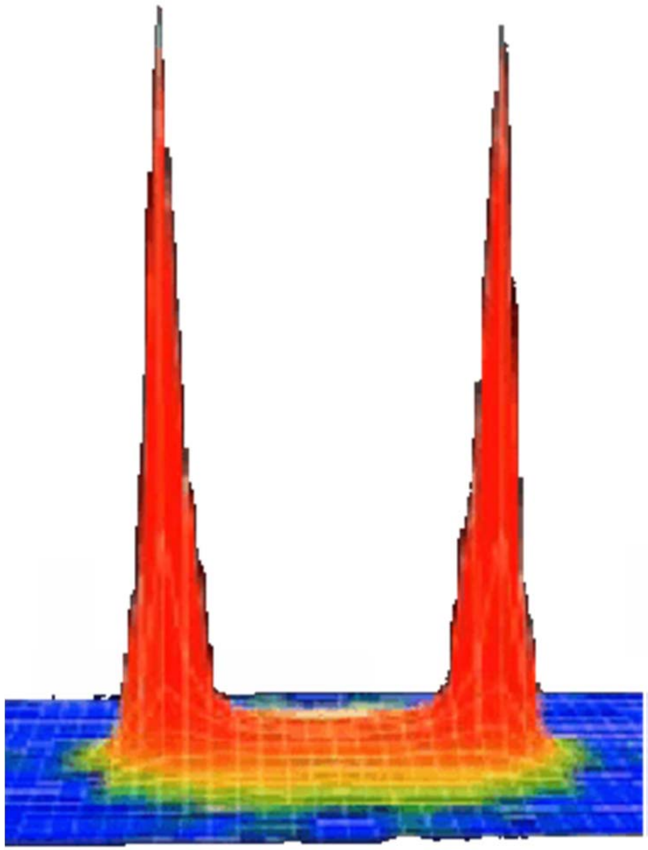
- Glueballs are the excitation of the QCD vacuum
  - Comparably easy to calculate
  - Lots of improvements in the last decade
  - Mainly due to
    - anisotropic lattices
    - improved actions



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

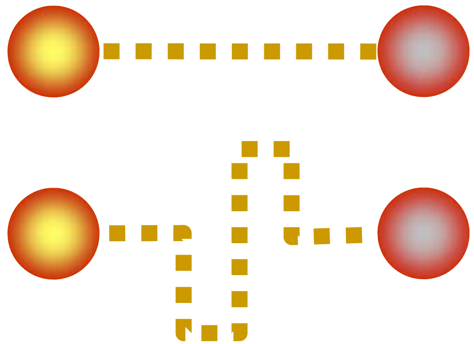
Fluxtube

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

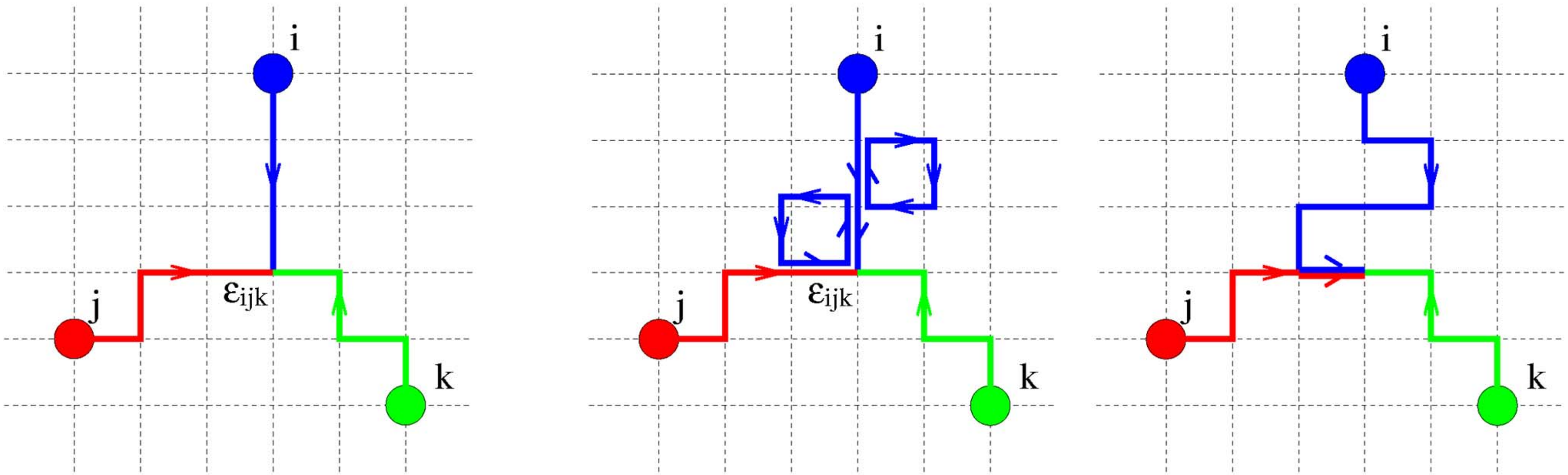
Meson



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

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

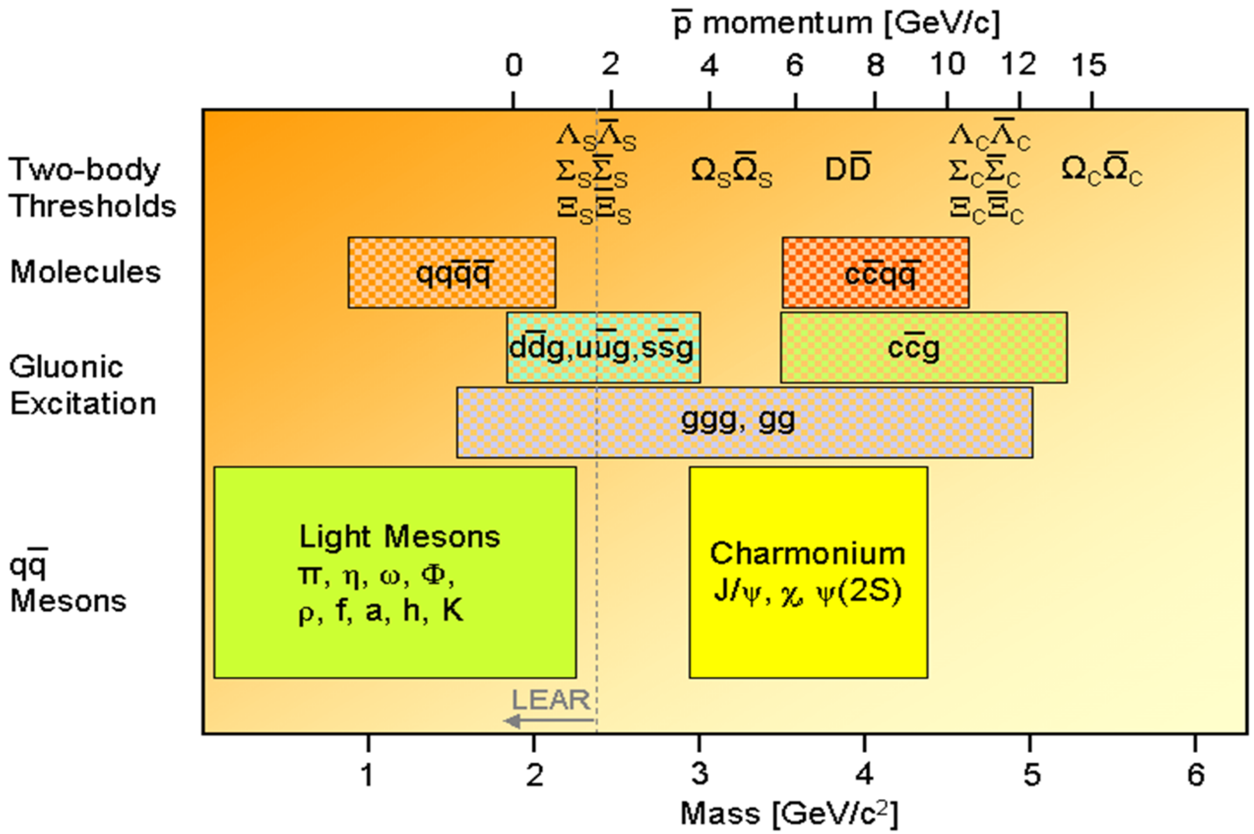
approach:

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

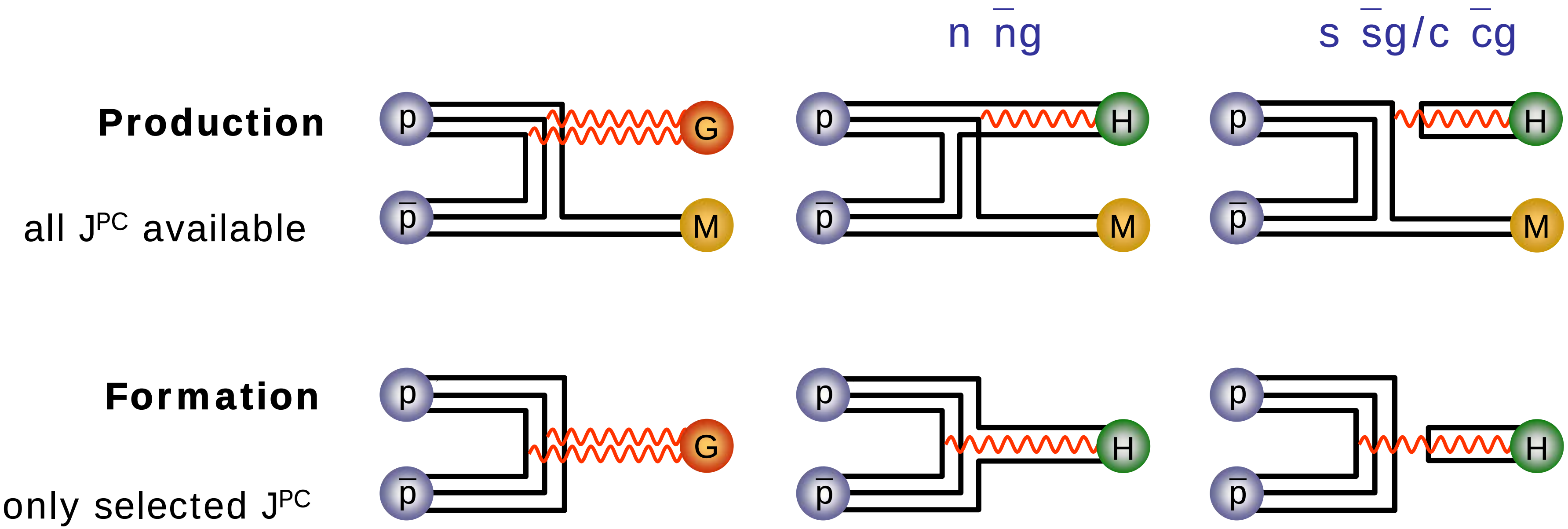
Antiproton-Proton Annihilation in Flight

- Annihilation in flight
  - scattering process: no well defined initial state
  - maximum angular momentum rises with energy
- Advantages
  - larger phase space
  - formation experiments
- Disadvantages
  - many waves due to large phase space
  - many waves interfere with each other

Hadronic Systems



Exotic Production/Formation 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

$D_{(s)}$ 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

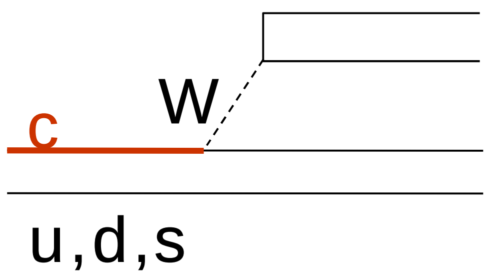
Long lifetime $c\tau \sim 100\text{-}300\mu m$

Many decays to light mesons

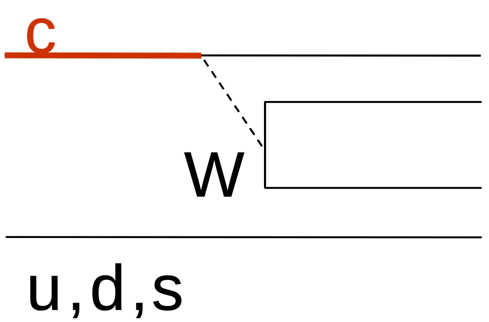
clean Spin-Parity $J^{PC}=0^{-+}$ for spectroscopy

$D_{(s)}$ Decays

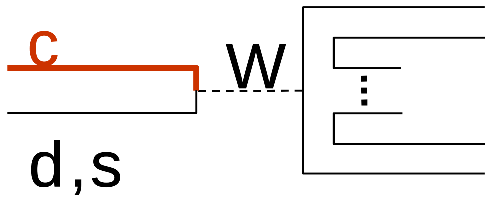
W-Emission (external)



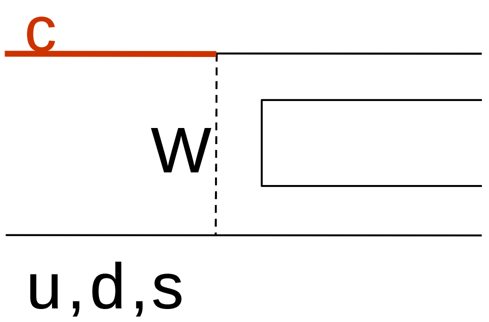
W-Emission (internal)



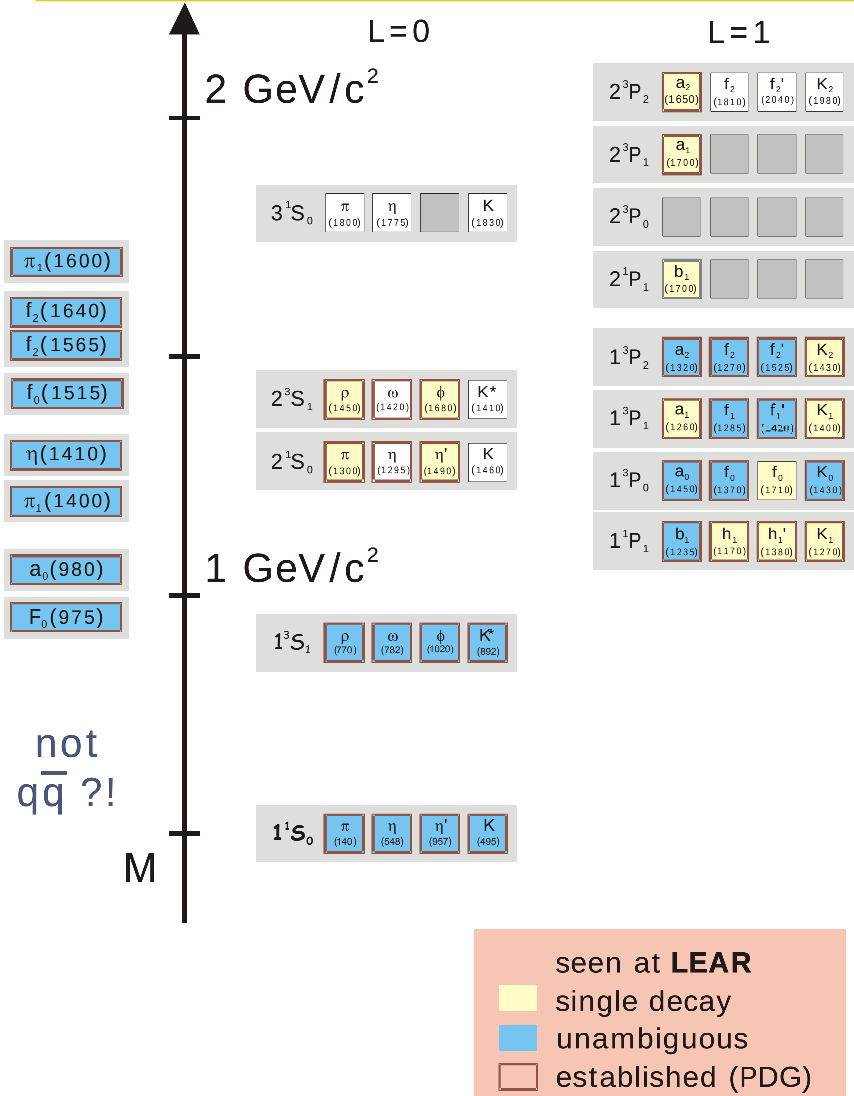
W-Annihilation



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

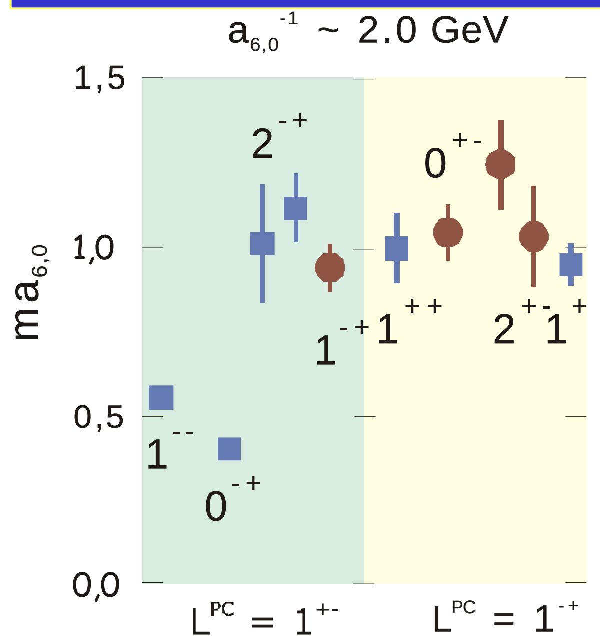
S-Wave+Gluon $(qq)_8 g$ with $()_8$=coloured

$^1S_0$ ↑↓ $^3S_1$ ↑↑

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^{-+}

Light Hybrid LQCD Predictions



UKQCD '96/'97, quenched QCD

masses ~ 2 GeV/c^2 comparable to masses from the fluxtube-model but:

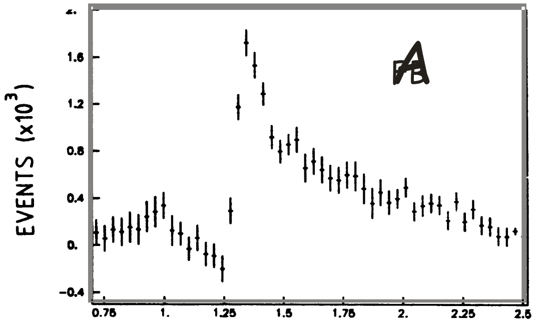
LQCD predicts

a light vector (~ 1,2 GeV/c^2)

and a pseudoscalar (< 1 GeV/c^2)

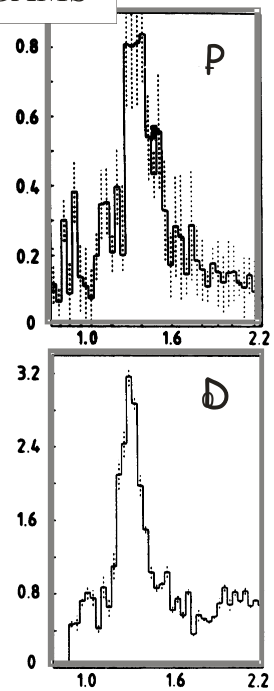
Group	m(1-+)	Ref
UKQCD ,97	1.87	Lacock et al, PLB401,308
MILC ,97	1.97	Bernard et al, PRD56 7039
MILC 99	2.11	Bernard et al, NPB 73,264
Lacock & Schilling	1,9	NPB73,261

π_1(1400) - History



GAMS

GAMS



1988 GAMS published strong FB-asymmetry in the reaction

- → $\pi^- p \to \pi^0 \eta$ 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:

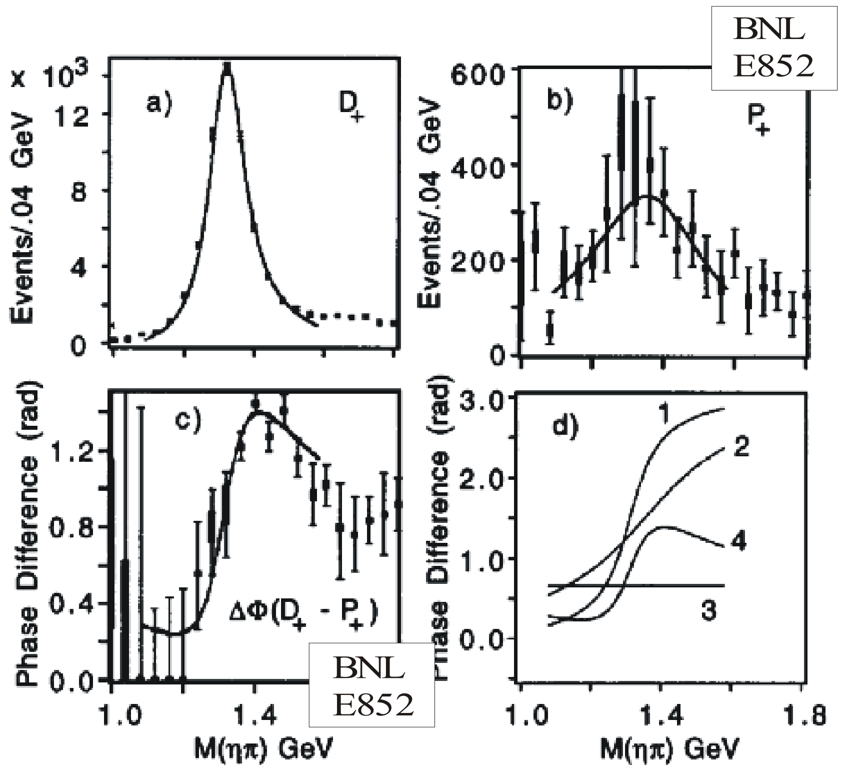
- → all solutions need an exotic wave
  but acceptance unclear

1994 CB: PS-197

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

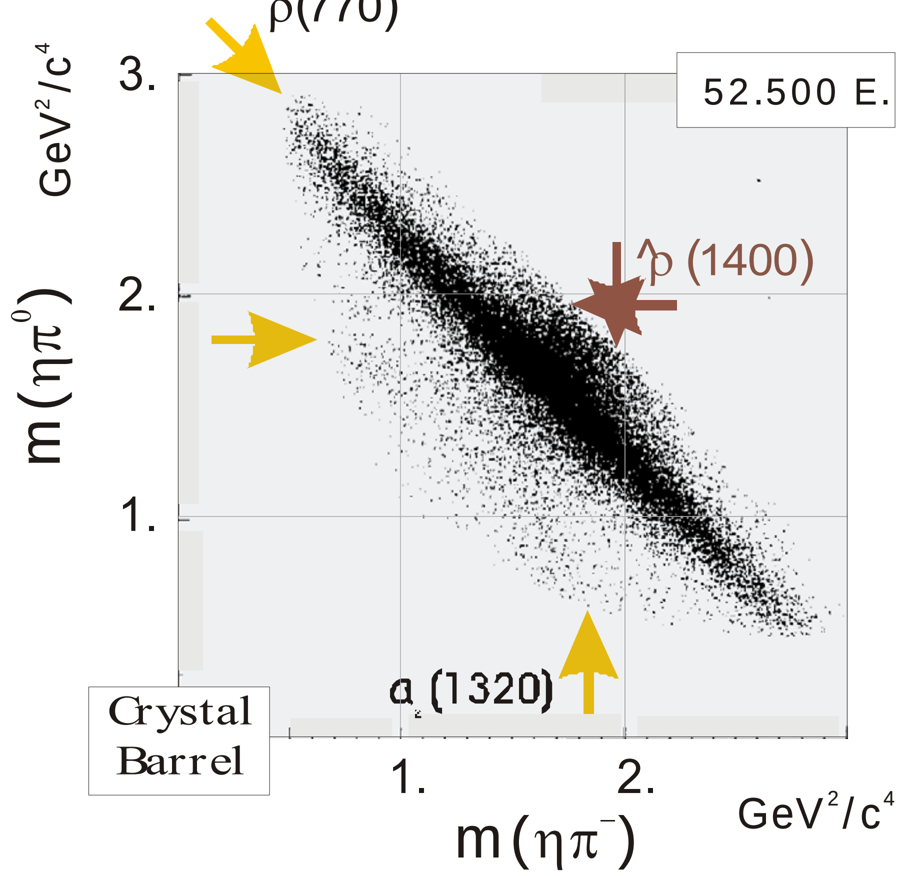
π_1(1400) – E852 and Crystal Barrel

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



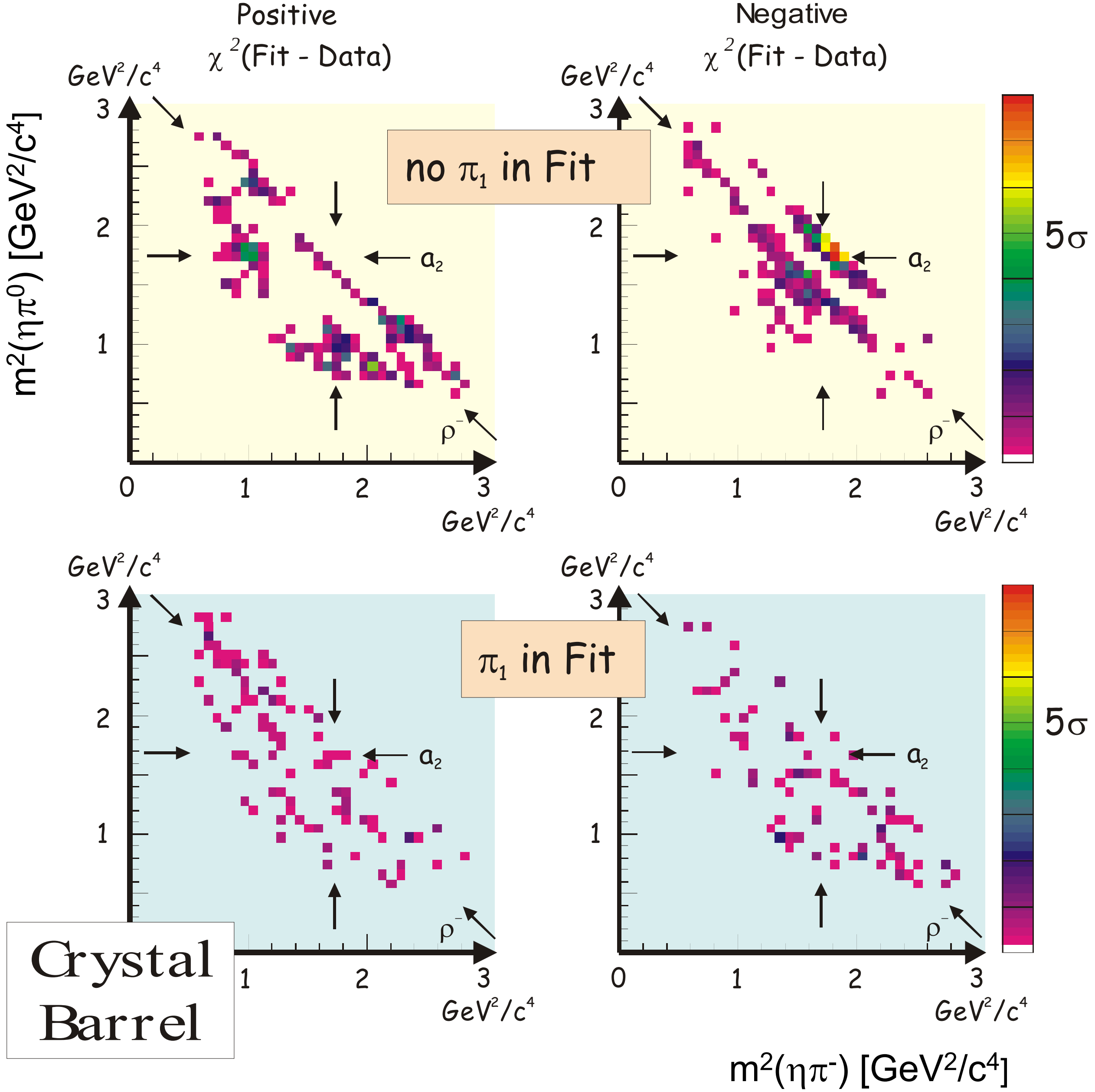
$\pi\eta$ peak @ 1.4 GeV/c^2
phasemotion at a_2 tail visible

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



Advantage: I=1
and no Scalars

π_1(1400) – Proof of Exotic Wave (CB)

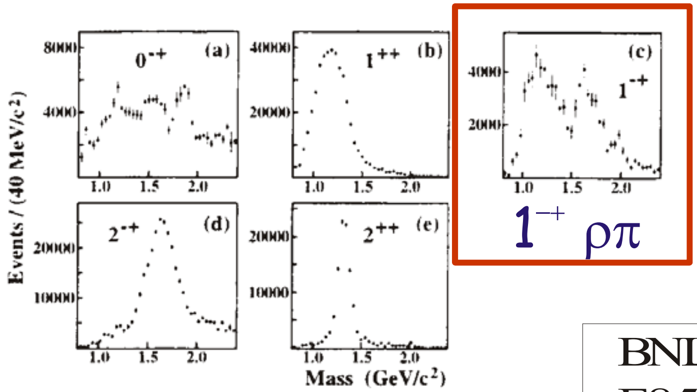


$\pi_1(1400)$ Summary

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	$310\pm50^{+50}_{-30}$	$\pi^0\eta$ $\pi^-\eta$

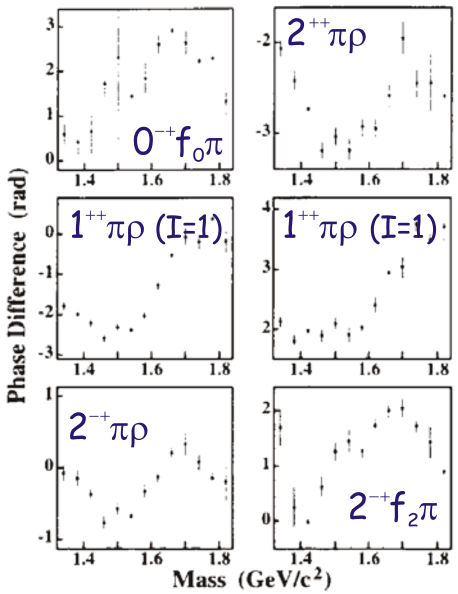
Exotic wave is evident

$\pi_1(1600)$



BNL
E852

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



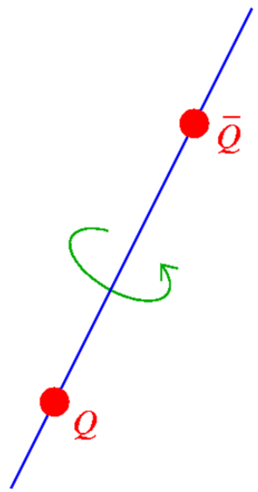
$\pi^- p \rightarrow \pi^- \rho^0 p \rightarrow \pi^- \pi^- \pi^+ p$ (E852) shows a clear resonance in the 1^{-+} wave around 1600 MeV/c^2

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 $\bar{p}p \rightarrow \omega\pi^+\pi^-\pi^0$.

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

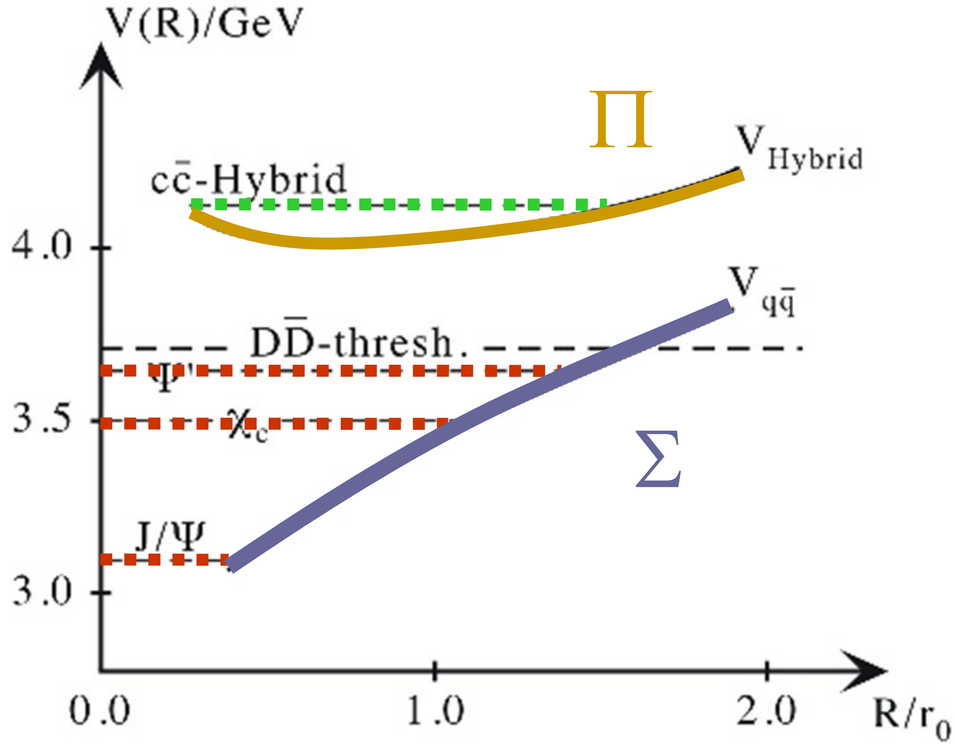
Gluonic excitations of the quark-antiquark-potential
may lead to bound states

LQCD:

 Π potential

– $m_H \sim$ 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

- $\Delta m \sim$ 100-250 MeV/c^2 for 1^{-+} to 0^{+-}

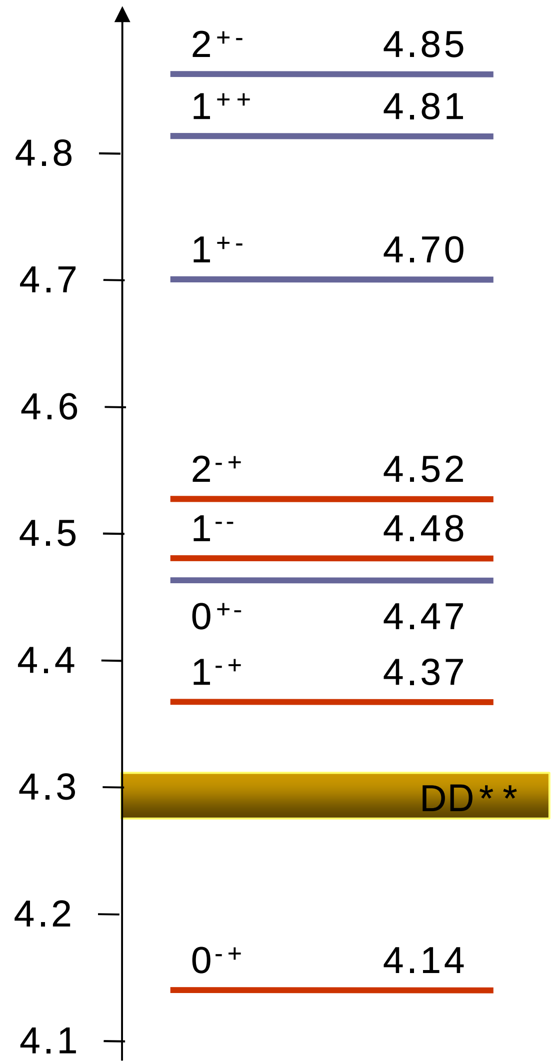
S-Splittings

– 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.)
- □ → $\Gamma_H <$ 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

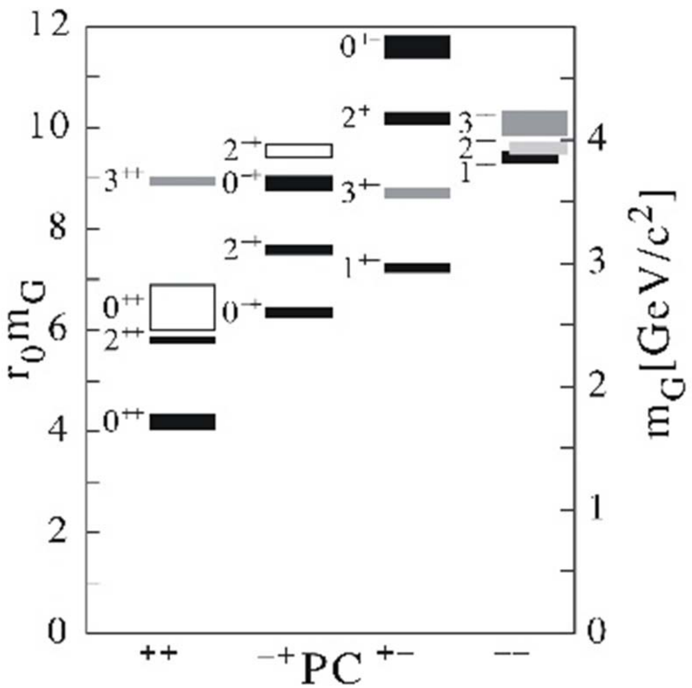
Glueballs

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.

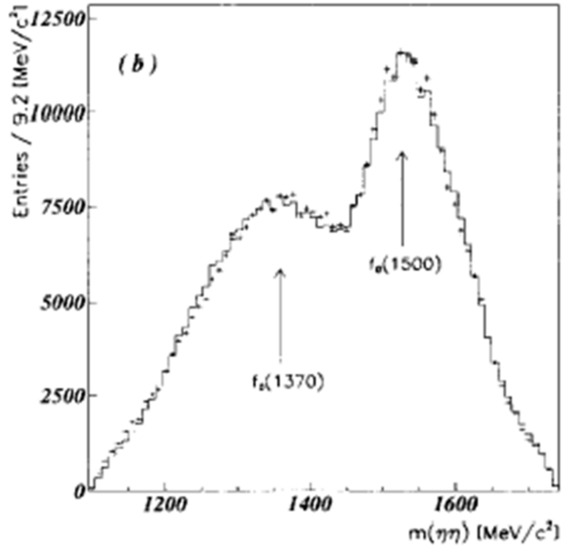
Some predicted decay modes $\phi\phi$, $\phi\eta$, $J/\psi\eta$, $J/\psi\phi$ ...



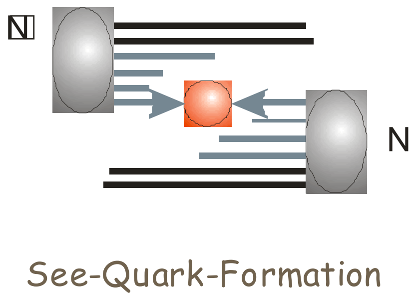
Morningstar und Peardon, PRD60 (1999) 034509
Morningstar und Peardon, PRD56 (1997) 4043

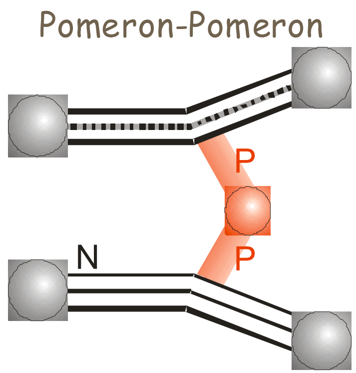
The detection of non-exotic glueballs is not trivial, as these states mix with the nearby $q\bar{q}$ states with the same quantum numbers, thus modifying the expected decay pattern.

- 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 $f_0(1500)$



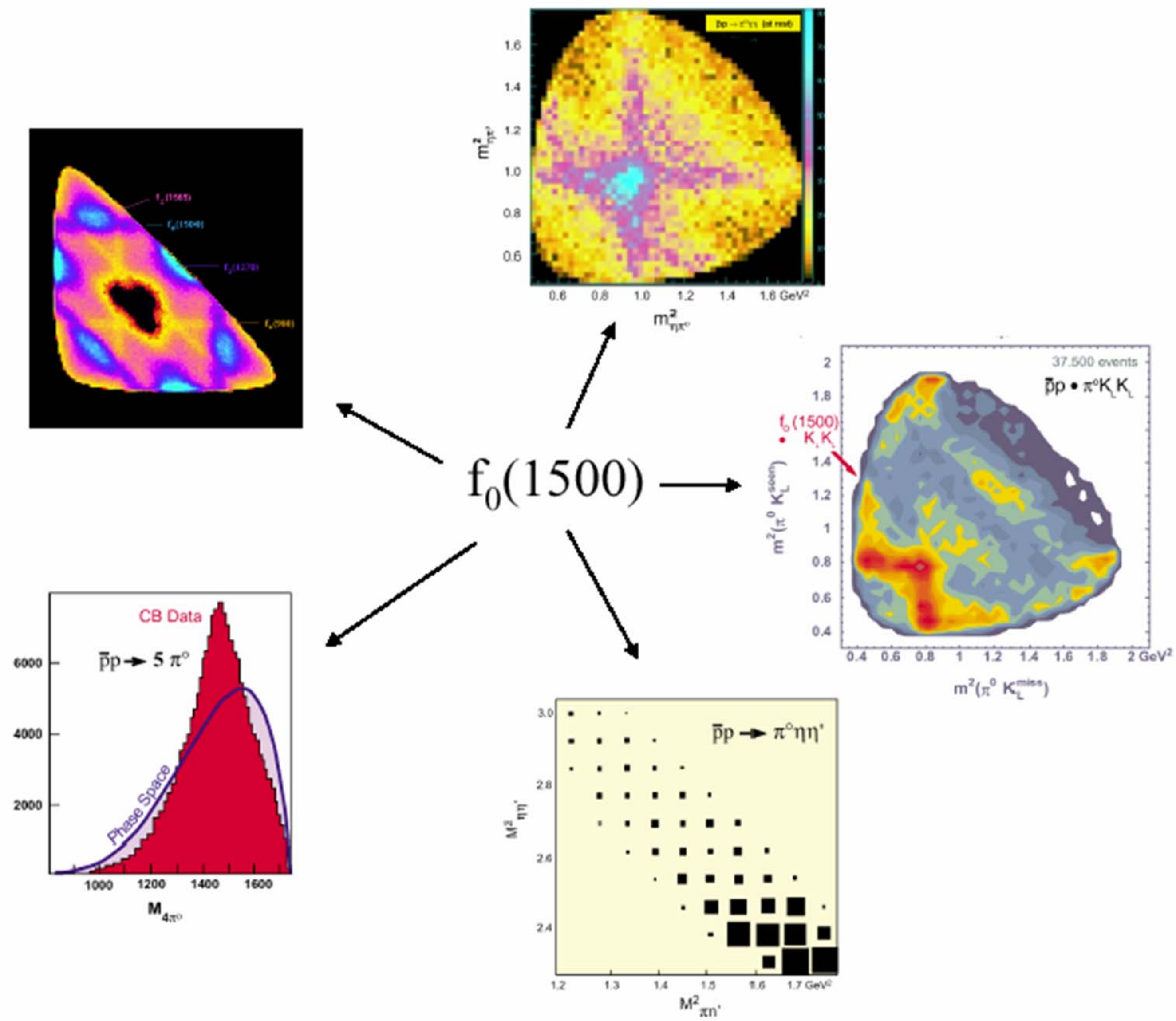
- Confirmed by OBELIX in analysis of $\pi^+\pi^-\pi^0$, $K^+K^-\pi^0$, $KK^0_S\pi$ in $\bar{p}p$ annihilation at rest.
- Confirmed by WA102 in central pp collisions at CERN.





- 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>.

$f_0(1500)$ Crystal Barrel data



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**:

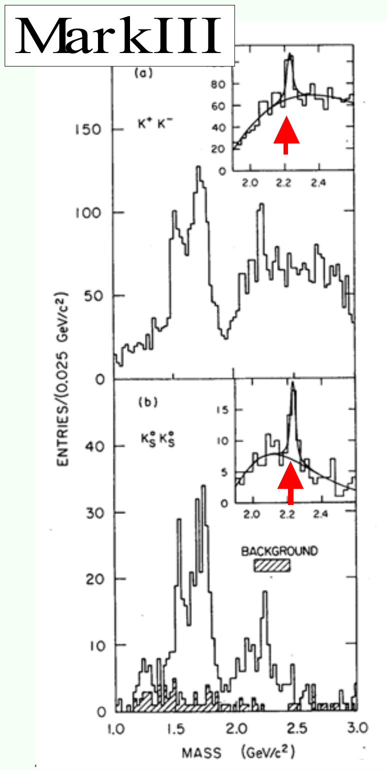
$a_0(980)$, $K^*_0(1430)$, $f_0(980)$, $f_0(1500)$ n=1, 0^{++} scalar nonet
$a_0(1450)$, $K^*_0(1950)$, $f_0(1370)$, $f_0(1710)$ n=2, 0^{++} scalar nonet

Tensor Glueball

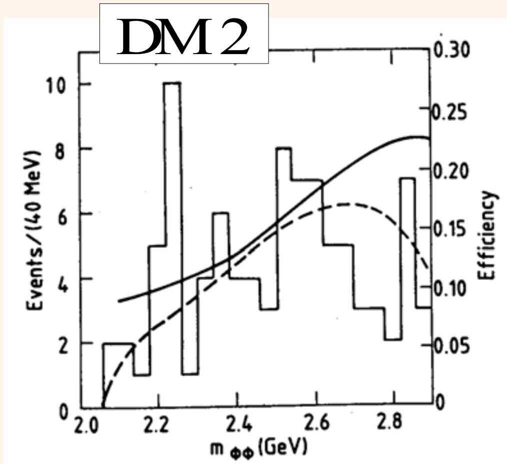
If there is a scalar glueball with a mass of 1.44 GeV/c^2 then LQCD predicts a tensor glueball with a mass around 2.0 GeV/c^2.

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

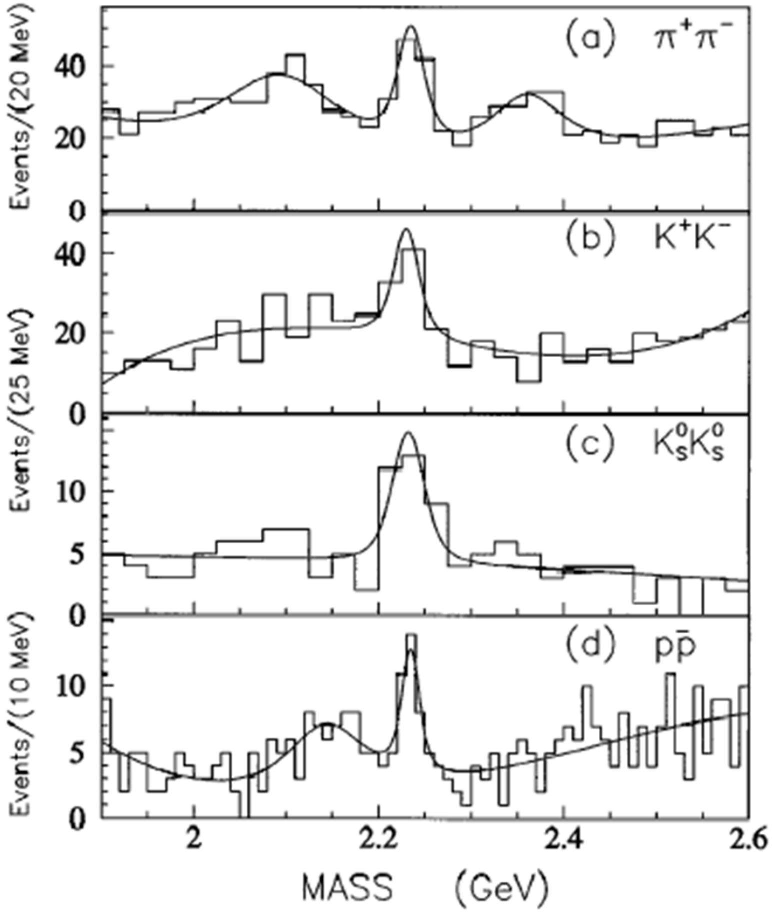
into $K\bar{K}$



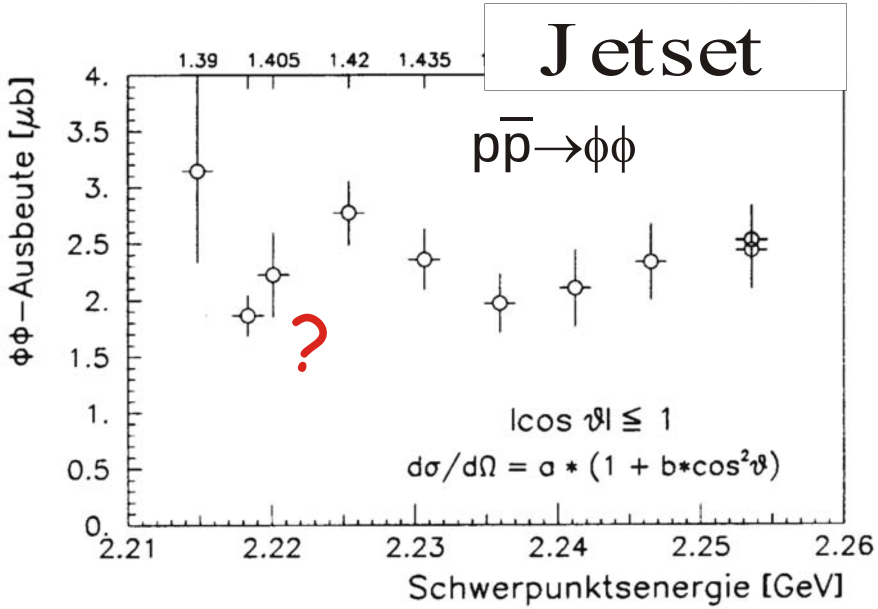
into $\phi\phi$



ξ(2220) confirmed by BES



ξ(2220) NOT confirmed by JETSET ...



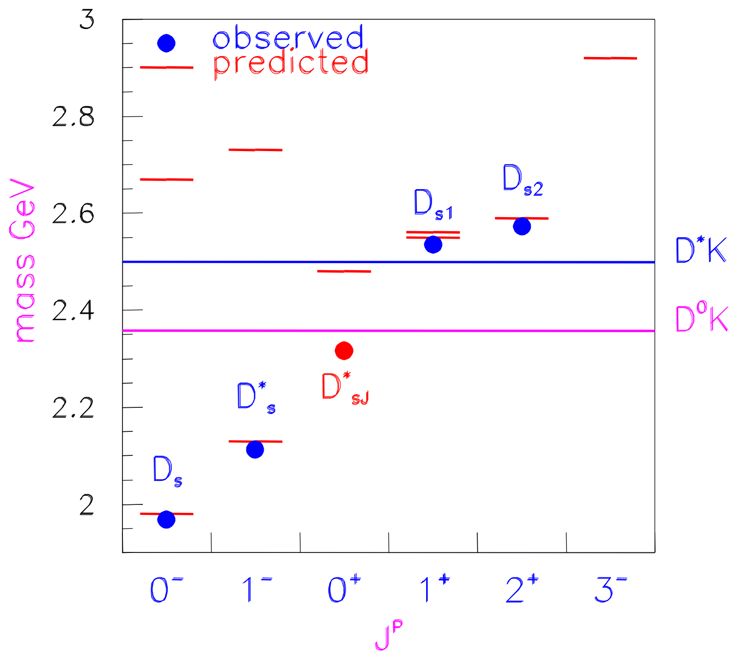
... ξ(2220) NOT seen by Crystal Barrel either

Tensor Glueball situation still confused

Heavy-Light Systems

Introduction

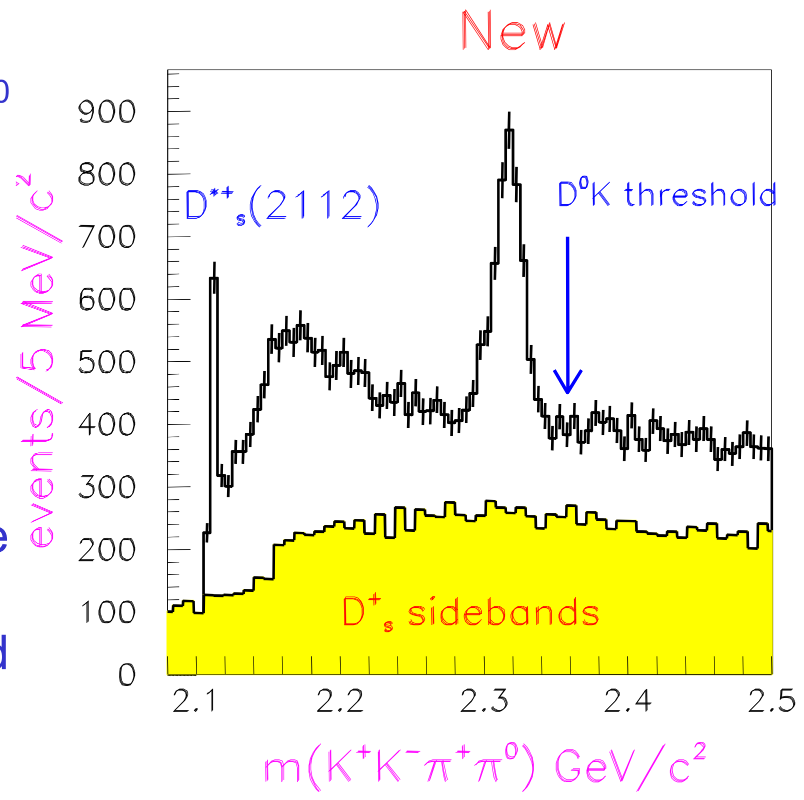
- Quark potential models are used to describe the D_s sector
  - E.g., model of Godfrey, Isgur & Kokoski
- Four experimentally observed states
  - D_s, $D_s(2112)$, $D_{s1}(2536)$, $D_{s2}(2573)$
- Some missing states
  - Two with masses ~ 2.4 to 2.6 GeV
    - Decaying to D^0K, difficult to see
- A state below D^0K threshold could be narrow
- Observation: a state at 2317 MeV, below D^0K threshold



S. Godfrey and N. Isgur, *Phys. Rev.* **D32**, 189 (1985);
S. Godfrey and R. Kokoski, *Phys. Rev.* **D43**, 1679 (1991).
M. Di Pierro and E. Eichten, *Phys. Rev.* **D64**, 114004 (2001).

$D_S^{\pm}\pi^0$ Mass Spectrum for $D_S^{\pm}$ Signal and Sideband Regions

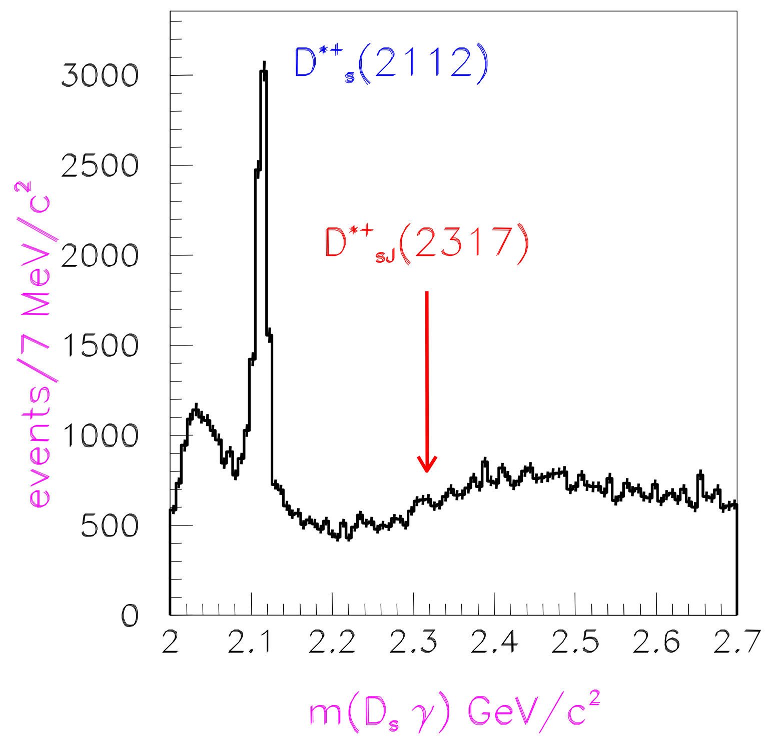
- Combine $D_S^{\pm}$ candidates from signal and sideband regions with π^0 candidates
  - Narrow signal seen near 2.32 GeV/c^2
  - ~2200 events
- No signal seen in sideband regions
  - Shows signal is associated with the $D_S^{\pm}$
  - Other checks show also associated with the π^0
- Also see known state at 2.112 GeV/c^2



$D_{sJ}^*(2317)^{\pm}$ - Other Decay Modes

- Studied decay modes
  1. $D_S^{\pm}\gamma$
  2. $D_S^{\pm}\gamma\gamma$
  3. $D_S^{*\pm}(2112)\gamma$
  4. $D_S^{\pm}\pi^0\pi^0$
  5. $D_S^{\pm}\pi^0\gamma$
- No significant signals seen with current statistics in first four decay modes
- Possible structure near 2.46 GeV/c^2 in $D_S^{\pm}\pi^0\gamma$

Example: $D_S^{\pm}\gamma$



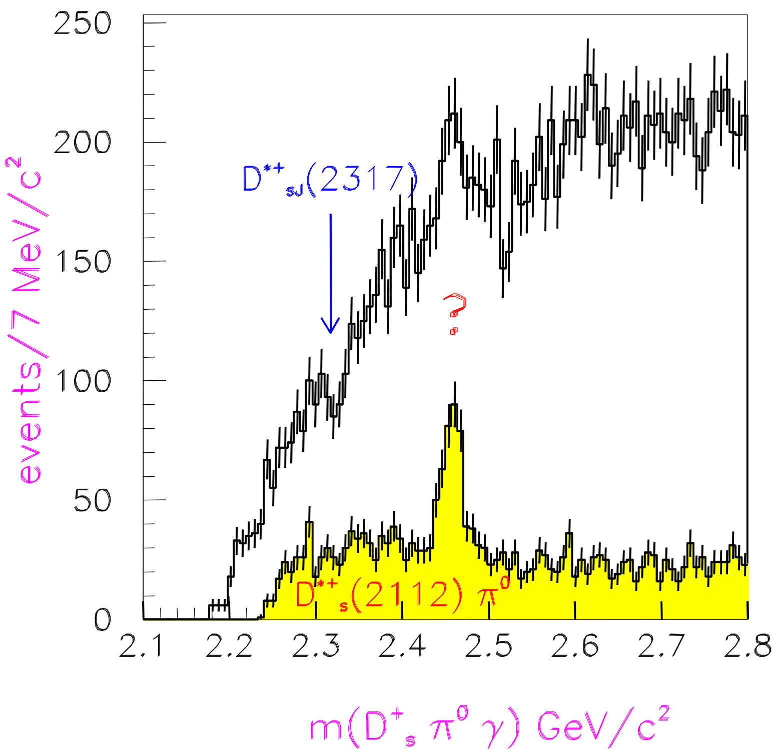
A Possible $D_{sJ}^*(2317)^\pm$ to $D_S^\pm\pi^0\gamma$ Decay?

Small peak where

- $D_S(2112)^\pm \to D_S^\pm\gamma$ and $D_{SJ}(2317)^\pm \to D_S^\pm\pi^0$ overlap

A state at 2.46 GeV/c^2

- $e^+e^- \to X(2460)^\pm X_{recoil}$ with $\to D_S(2112)^\pm\pi^0$
- would mimic a peak in $D_S^\pm\pi^0$ near 2.32 GeV/c^2
- But expected width ~ 15 MeV
- If decay is 100% to $D_S^\pm\pi^0$ only ~1/6 of observed peak at 2.32 GeV/c^2 explainable



Not only source of 2.32 GeV/c^2 signal

Possible signal at 2.46 GeV/c - Requires additional detailed study

Summary

We observe a narrow signal in in the inclusive $D_S^{\pm}\pi^0$ mass spectrum with fitted parameters

$$m=2316.8\pm0.4 \text{ MeV}/c^2$$

$$\sigma=8.6\pm0.4 \text{ MeV}/c^2$$

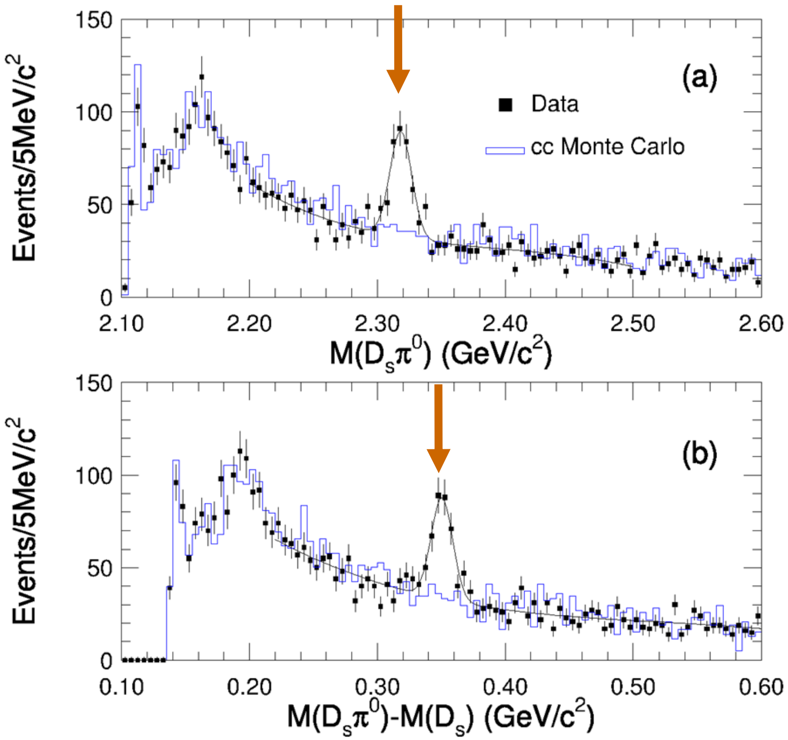
with a systematic error on the mass . 3 MeV/c^2

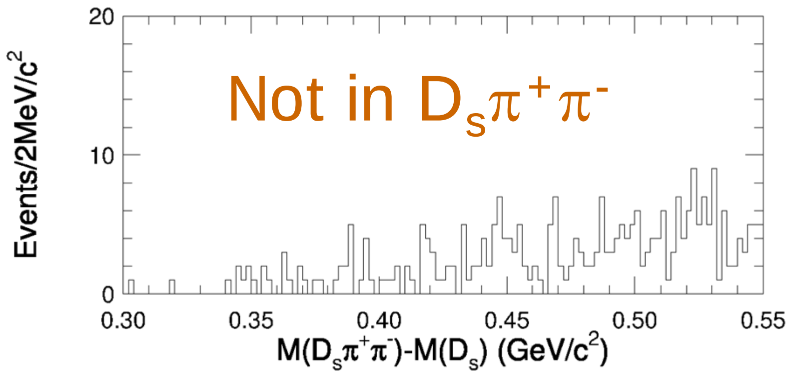
- Observed width consistent with experimental resolution
- Intrinsic width small, $\Gamma < 10$ MeV

Small peak at 2.46 GeV/c^2 in $D_S^{\pm}\pi^0\gamma$ seen, needs more study

Work in progress for $D_S^{\pm}\pi^{\pm}$ modes

CLEO Sees it Too





They use 13.5 fb^{-1}

- Signal seen in $D_s\pi^0$
- Not seen in $D_s\pi^+\pi^-$, $D_s\gamma$, $D_{s1}(2112)\gamma$

Signal has 230^{+31}_{-29} events (» same yield/fb^{-1} as BABAR).

Conclusions

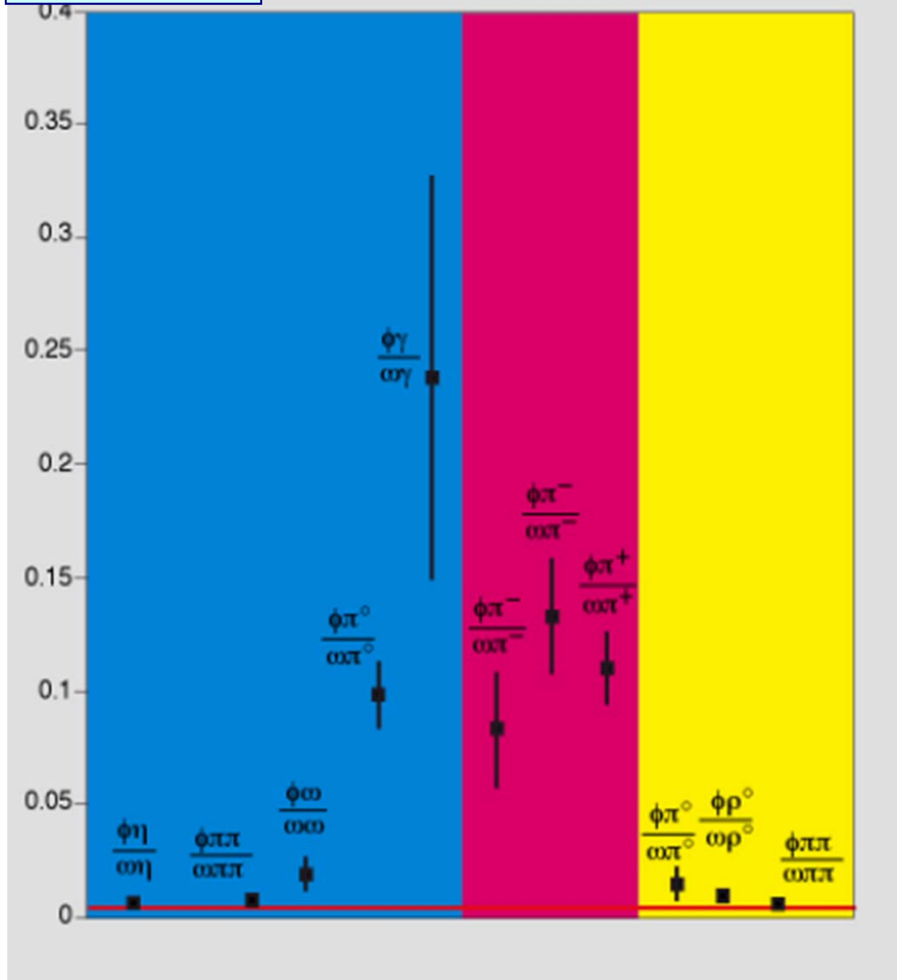
- $D_{sJ}^*(2317)^{\pm}$ does not fit into existing potential model expectations
  - Godfrey & Isgur (1985), Godfrey & Kokoski (1991)
  - Below DK threshold
- Small width likely related isospin violating decay
- Could be a four-quark scalar state
  - Suggested by R.L. Jaffe, H.J. Lipkin in 1977
  - Will have similarities & differences with light-quark scalar states and charm, non-strange scalar states
  - Analogous to Belle's non-strange 2290 MeV/c^2 state?
- Interesting times ahead

S. Godfrey and N. Isgur, *Phys. Rev.* **D32**, 189 (1985);
S. Godfrey and R. Kokoski, *Phys. Rev.* **D43**, 1679 (1991).
M. Di Pierro and E. Eichten, *Phys. Rev.* **D64**, 114004 (2001).
R.L. Jaffe, *Phys. Rev*. D15, 267 (1977); *Phys. Rev*. **D15**, 281 (1977).
H.J. Lipkin, *Phys. Lett*. **70B**, 113 (1977); *Phys. Lett*. **172B**, 242 (1986);
N. Isgur and H.J. Lipkin, *Phys. Lett*. **99B**, 151 (1981).

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.

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

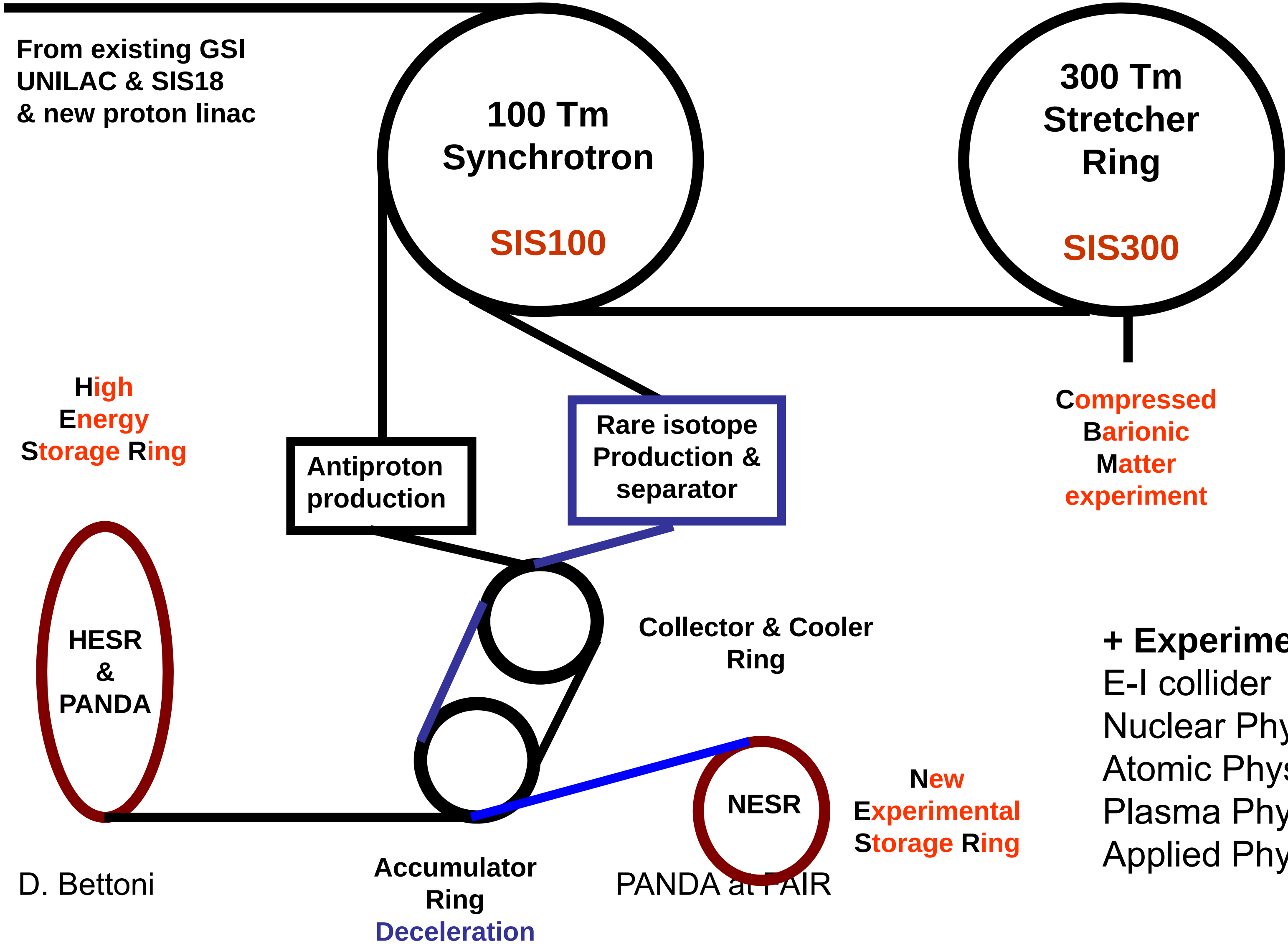
Prediction ≈ 10 nb

Measurement ≈ 3700 nb

$\bar{\text{P}}$ANDA AT GSI

FAIR at a glance

The FAIR Complex



+ Experiments:

E-I collider
Nuclear Physics
Atomic Physics
Plasma Physics
Applied Physics

Unprecedented System Parameters at FAIR

Beam Intensity:

- primary heavy-ion beam intensity increases by x 100 – x 1000
- secondary beam intensity increases by up to x 10000

Beam Energy:

- heavy-ion energy : x 30

Beam Variety:

- antiprotons
- protons to uranium & radioactive ion beams

Beam Precision:

- cooled antiproton beams
- intense cooled radioactive ion beams

Beam Pulse structure:

- optimized for experiments: from dc to 50 ns

Parallel Operation:

- full accelerator performance for up to four different and independent experiments and experimental programs

High-Energy Storage Ring

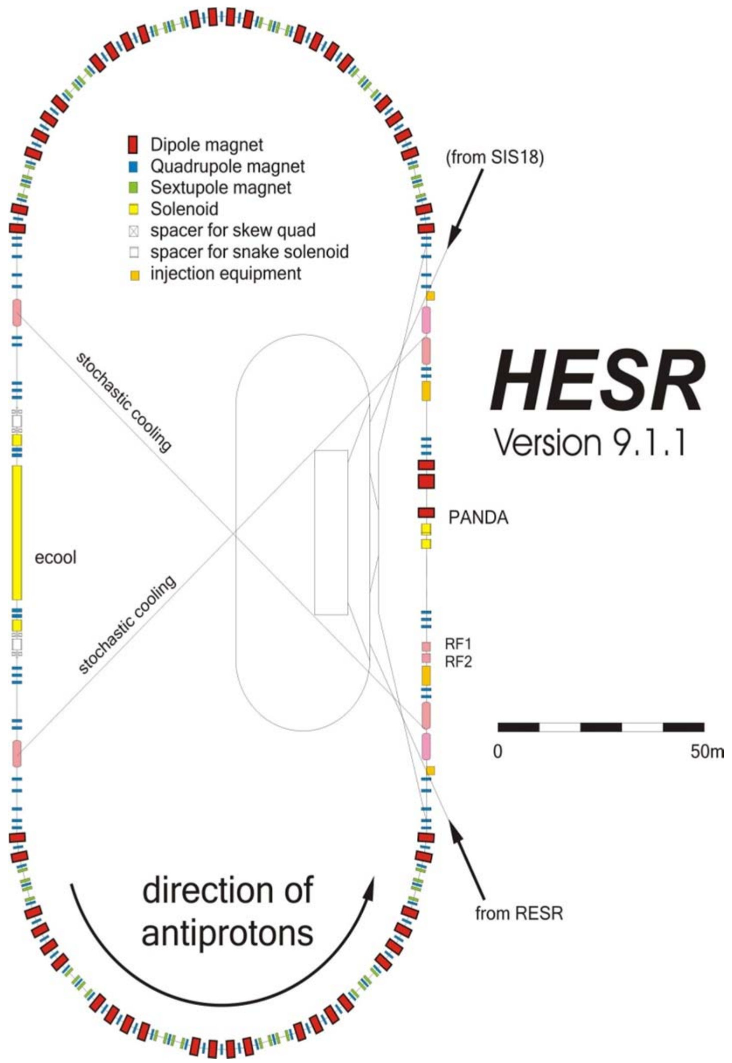
- Production rate $2x10^7$/sec
- P_{beam} = 1 - 15 GeV/c
- N_{stored} = $5x10^{10}$ $\bar{p}$
- Internal Target

High resolution mode

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

High luminosity mode

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



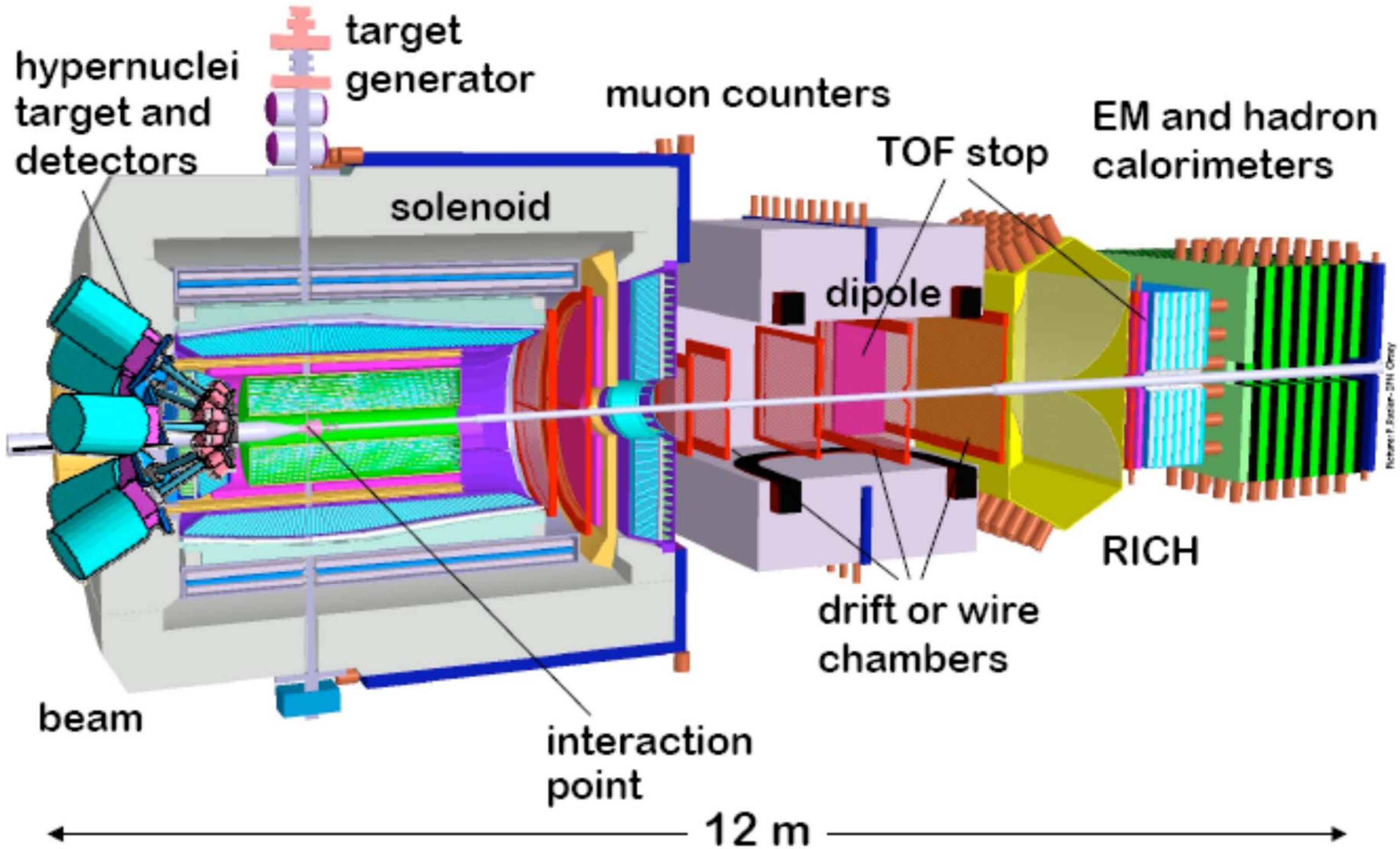
PANDA Physics Program

- Charmonium Spectroscopy. Precision measurement of masses, widths and branching ratios of all ($c\bar{c}$) states (hydrogen atom of QCD).
- Search for gluonic excitations (hybrids, glueballs) in the charmonium mass range (3-5 GeV/c^2).
- Search for modifications of meson properties in the nuclear medium, and their possible relation to the partial restoration of chiral symmetry for light quarks.
- Precision γ-ray spectroscopy of single and double hypernuclei, to extract information on their structure and on the hyperon-nucleon and hyperon-hyperon interaction.
- Electromagnetic processes (DVCS, D-Y, FF ...) , open charm physics

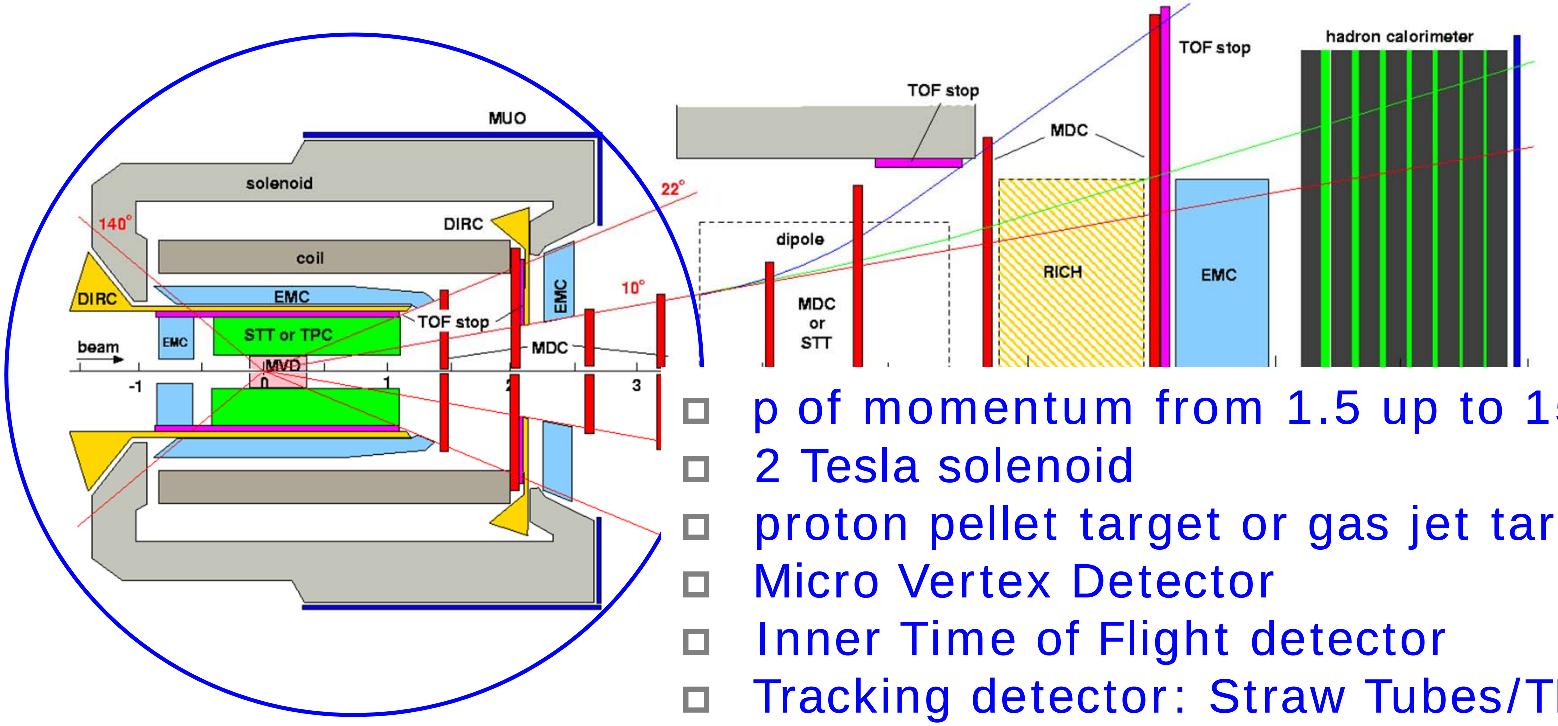
The Detector

- 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
- For Charmonium:
  - Pointlike interaction region
  - Lepton identification
  - Excellent calorimetry
    - Energy resolution
    - Sensitivity to low-energy photons

Panda Detector

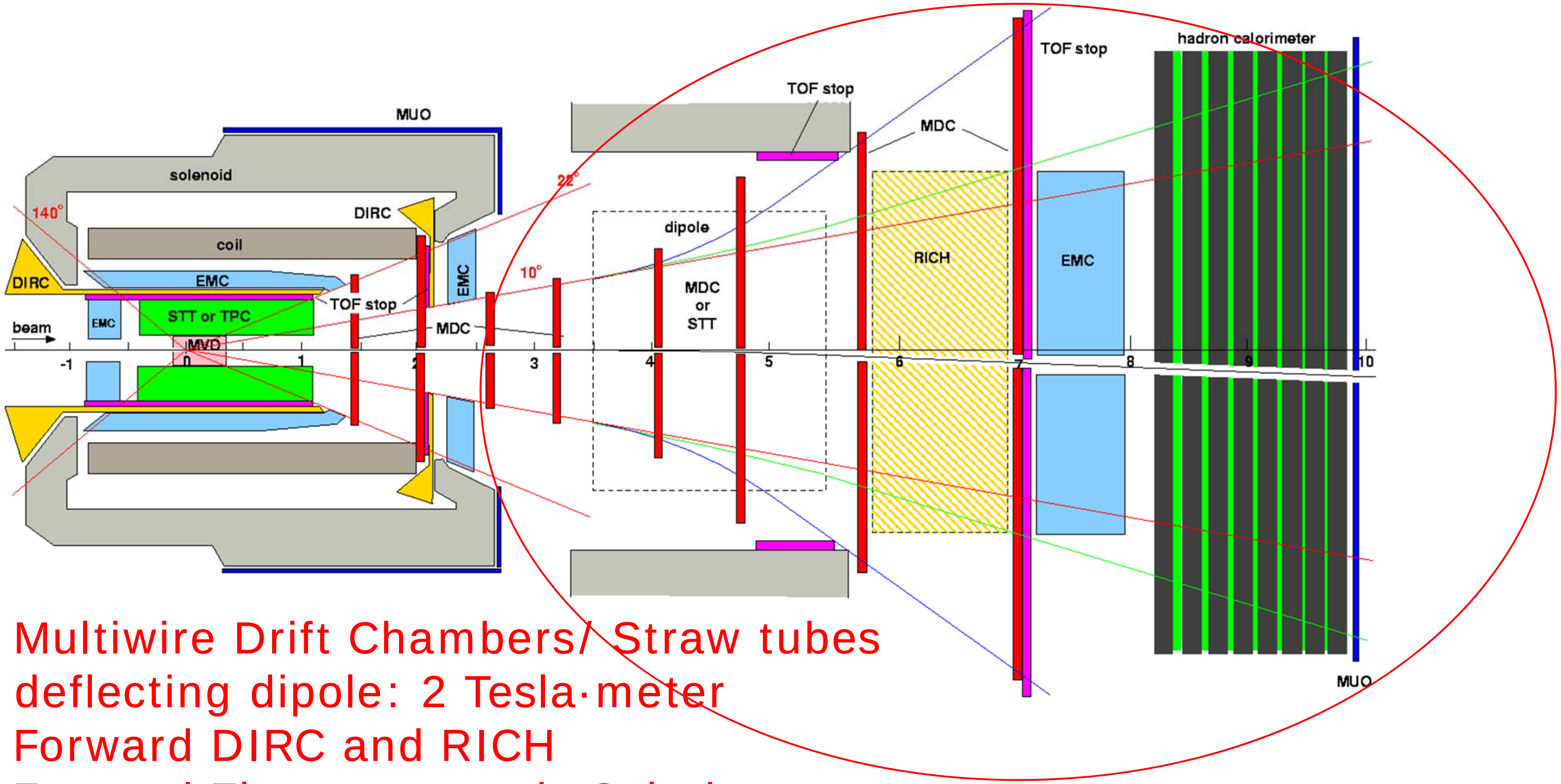


Target Spectrometer



- p of momentum from 1.5 up to 15 GeV/c
- 2 Tesla solenoid
- proton pellet target or gas jet target
- Micro Vertex Detector
- Inner Time of Flight detector
- Tracking detector: Straw Tubes/TPC
- DIRC
- Electromagnetic Calorimeter
- Muon counters
- Multiwire Drift Chambers

Forward Spectrometer



- Multiwire Drift Chambers/ Straw tubes
- deflecting dipole: 2 Tesla·meter
- Forward DIRC and RICH
- Forward Electromagnetic Calorimeters
- Time of Flight counters
- Hadron Calorimeter

PANDA Collaboration

- At present a group of **350 physicists** from 47 institutions of 15 countries

Austria – Belaruz - China - Finland - France - Germany – Italy – Poland – Romania - Russia – Spain - Sweden – Switzerland - U.K. – U.S.A..

Basel, Beijing, Bochum, Bonn, IFIN Bucharest, Catania, Cracow, Dresden, Edinburg, Erlangen, Ferrara, Frankfurt, Genova, Giessen, Glasgow, GSI, Inst. of Physics Helsinki, FZ Jülich, JINR Dubna, Katowice, Lanzhou, LNF, Mainz, Milano, Minsk, TU München, Münster, Northwestern, BINP Novosibirsk, Pavia, Piemonte Orientale, IPN Orsay, IHEP Protvino, PNPI St. Petersburg, Stockholm, Dep. A. Avogadro Torino, Dep. Fis. Sperimentale Torino, Torino Politecnico, Trieste, TSL Uppsala, Tübingen, Uppsala, Valencia, SINS Warsaw, TU Warsaw, AAS Wien

http://www.gsi.de/panda