Hadron Physics Selected Topics

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Outline

- Introduction to hadron physics
  - The Quark Model
  - Quantum Chromodynamics
  - Theoretical Approaches
  - Experimental Methods
- Selected hot topics
  - Heavy Quarkonium
  - X, Y, Z states
  - Open Charm
  - Baryons
  - Form Factors
- Outlook and conclusions

Introduction to Hadron Physics

The Quark Model
The strong interaction and QCD
Theoretical approaches
Experimental methods

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.

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 (e.g. muon (g-2)).

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

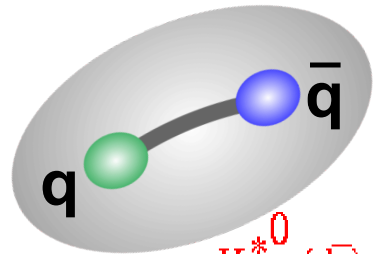
"current quark masses" $\overline{\text{MS}}$ at scale 2 GeV

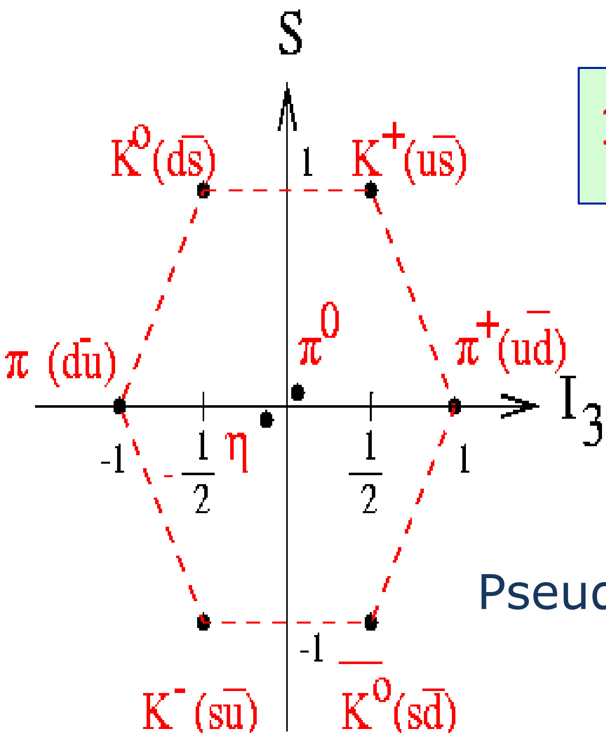
m_c=1.15 ÷1.35 GeV m_b=4.1 ÷ 4.4 GeV m_t=174.3±5.1 GeV

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

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

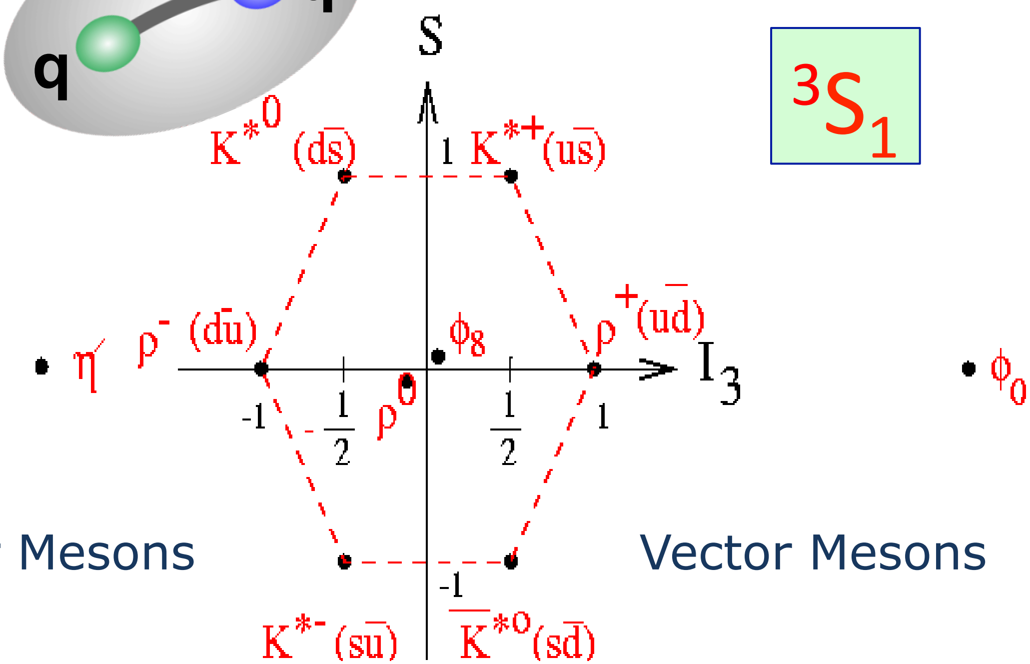
Hadrons in the Quark Model: Mesons





$^1S_0$

Pseudoscalar Mesons



$^3S_1$

Vector Mesons

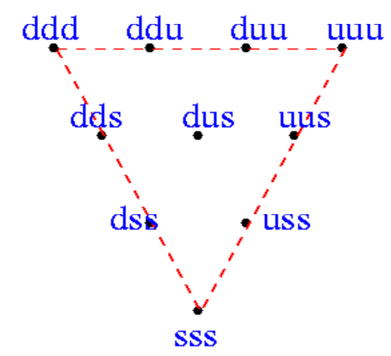
$$\vec{J} = \vec{L} + \vec{S} \qquad P = (-1)^{L+1} \qquad C = (-1)^{L+S}$$

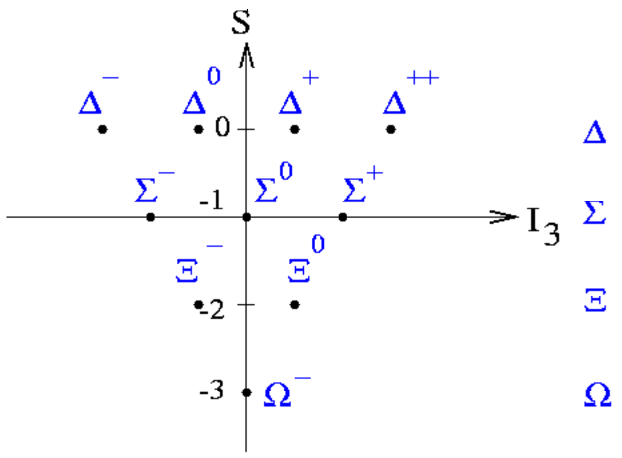
Quantum Numbers of Mesons with the Quarks u, d, s

$$\overbrace{\qquad\qquad\qquad\qquad}^{\text{nonet}}$$

$L(q\bar{q})$	$S(q\bar{q})$	J^{PC}	$I=1$	$I=\frac{1}{2}$	$I=0$	$M(MeV)$
$L=0$	$S=0$	0^{-+}	π	K	η,η'	500
	$S=1$	1^{--}	ρ	K^*	ω,ϕ	800
$L=1$	$S=0$	1^{+-}	B	Q_2	$H,?$	1250
		2^{++}	A_2	K^*	f,f'	1400
	$S=1$	1^{++}	A_1	Q_1	$D,?$	1300
		0^{++}	δ	K	ε,S^*	1150

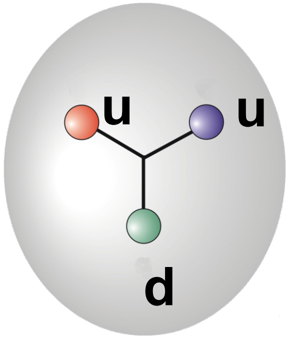
Hadrons in the Quark Model: Baryons

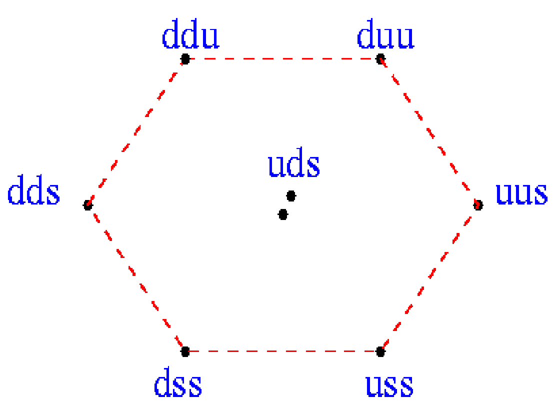


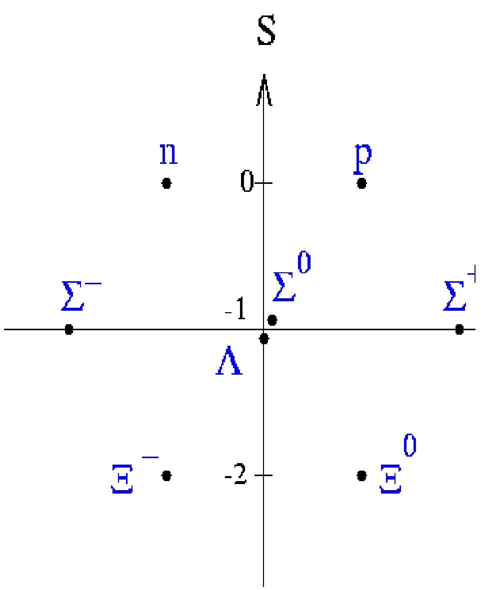


Baryon decuplet

$$J^P = \frac{3}{2}^+$$



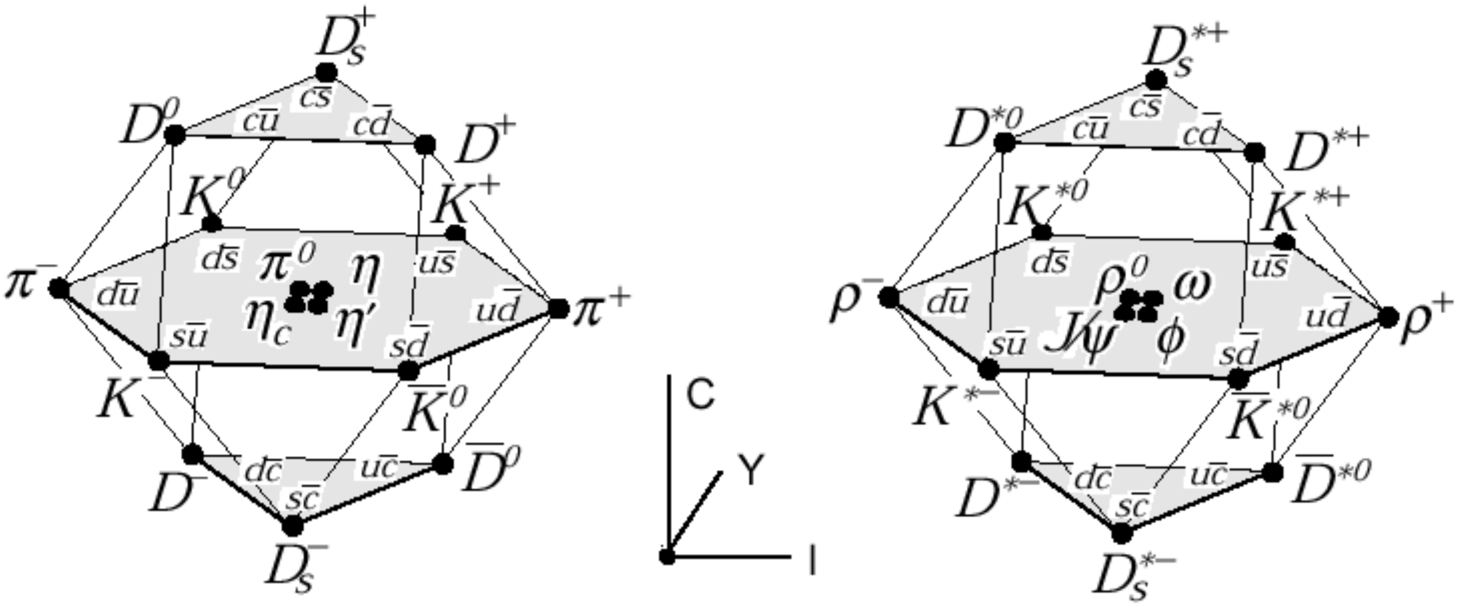




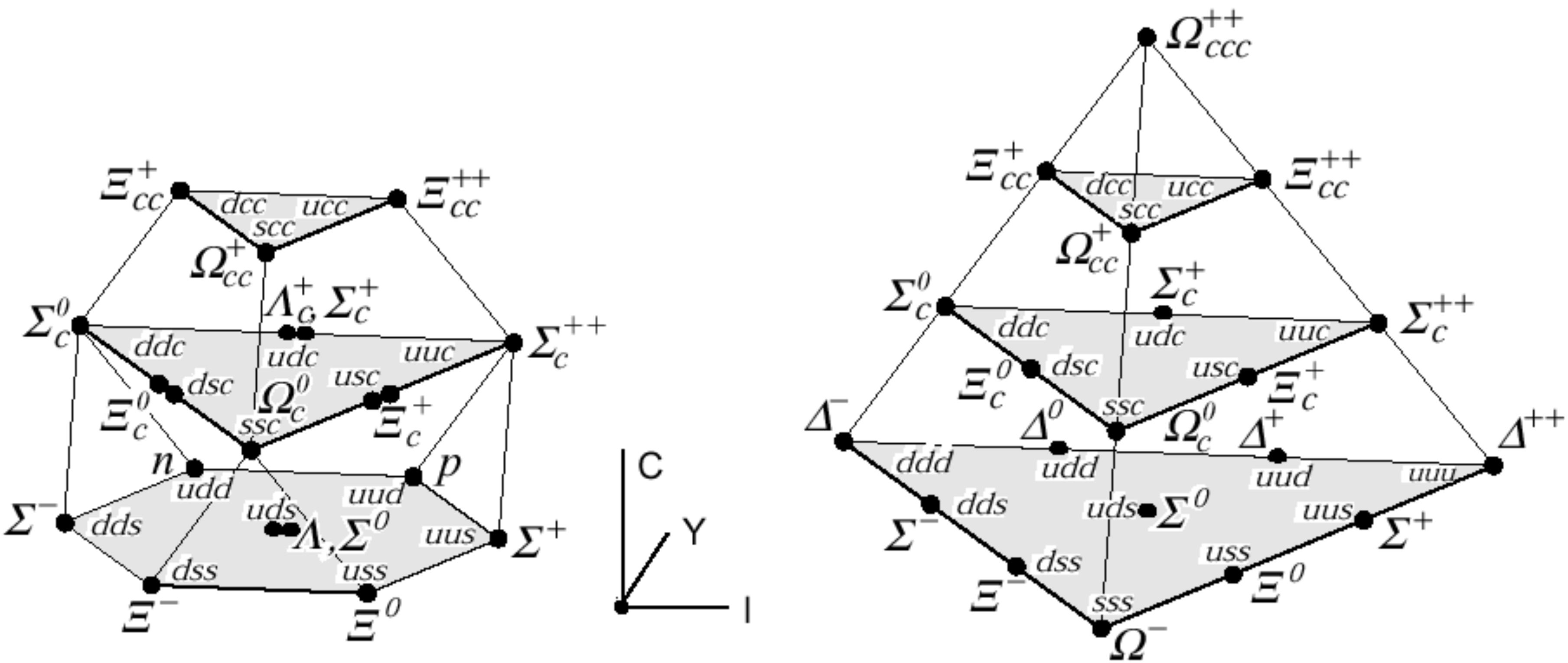
Baryon octet

$$J^P = \frac{1}{2}^+$$

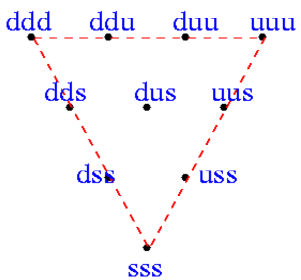
Meson States with 4 Flavours

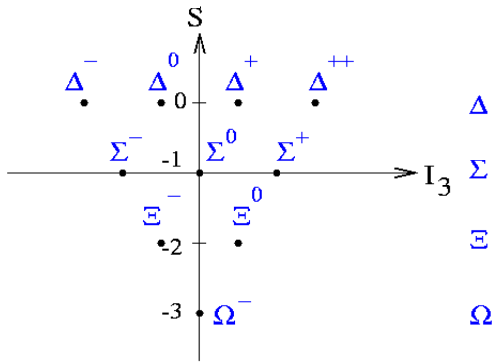


Baryon States with 4 Flavours



Colour





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

The product of the first three factors is symmetric under exchange of any pair of quarks, we require the colour wave function to be anti-symmetric

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

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

- Spin-parity $J^P = \frac{3}{2}^+$
- The wave function is symmetric under exchange of any pair of quarks
- s-wave, parallel spins, the spatial and spin wave functions are also symmetric.

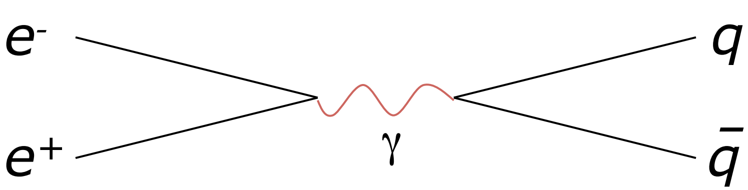
All observed hadrons are colour singlets. Colour is confined within hadrons.

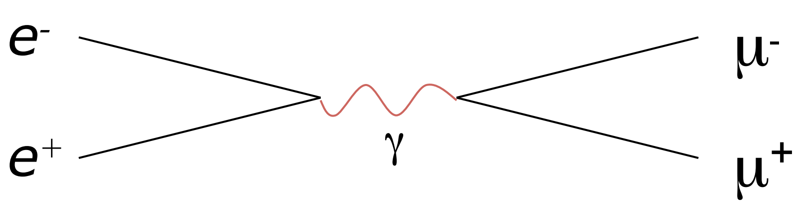
$$(qqq)_{c.s.} = \sqrt{\tfrac{1}{6}}(RGB - RBG + BRG - BGR + GBR - GRB)$$

$e^+e^- \to$ hadrons

Hadron production in e^+e^- annihilation occurs via hadronization of $q\bar{q}$ pairs produced in the process $e^+e^- \to q\bar{q}$.

The cross section can be related to the one for $e^+e^- \to \mu^+\mu^-$.





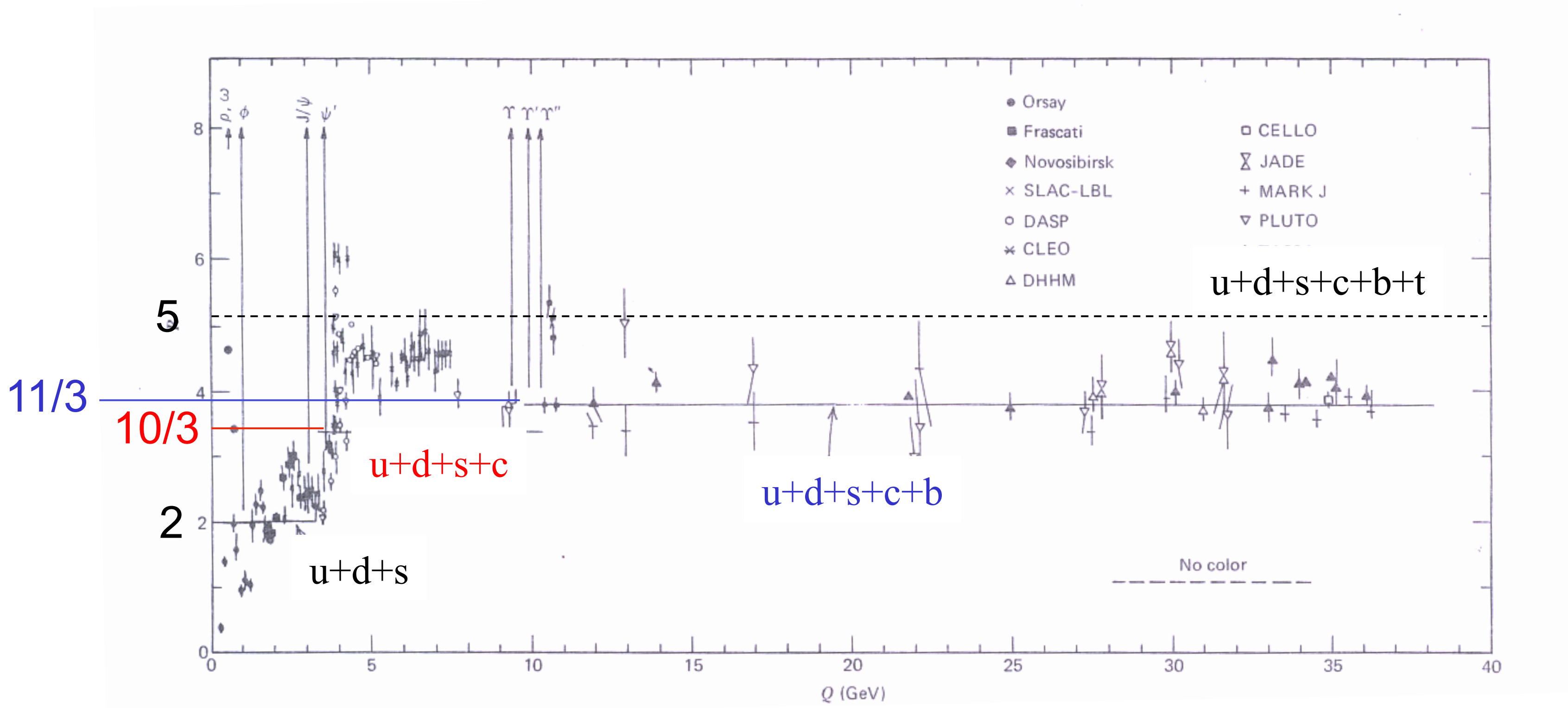
$$\sigma\left(e^+e^- \to \mu^+\mu^-\right) = \frac{4\pi}{3}\frac{\alpha^2}{s}$$

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

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

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

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



with QCD corrections

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

Quantum ChromoDynamics - QCD

QCD is the theory of quarks, gluons and their interactions. It is part of the standard model. It is a quantum field theory based on the invariance under local gauge transformations in $SU(3)_c$.

The QCD lagrangian is:

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

λ_j Gell-Mann Matrices

f_{ijk} Structure constants

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

covariant derivative:

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

gluon field tensor:

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

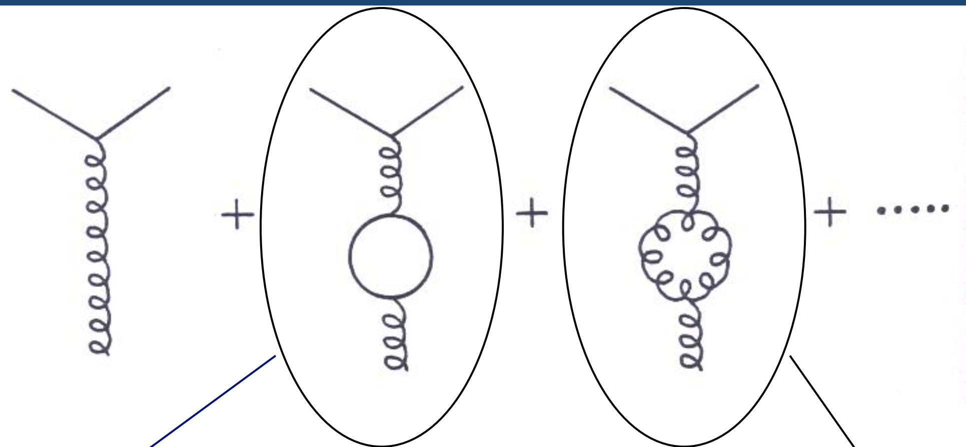
Running Coupling Constant

The renormalization of the theory introduces an energy scale: the coupling strength g becomes a "running coupling constant",
i.e. it depends on the energy scale μ.
Defining $\alpha_s(\mu) = g^2(\mu)/4\pi$ we get:

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

with $\beta_0 = 11 - 2N_f/3$
N_f is the number of quark flavors.
The scale parameter Λ is determined empirically:
$\Lambda = 0.2\ GeV$ for $N_f = 4$.

Loop Contributions in QCD



Similar to QED
same contributionfor each flavor
(the colour force is
flavor independent)

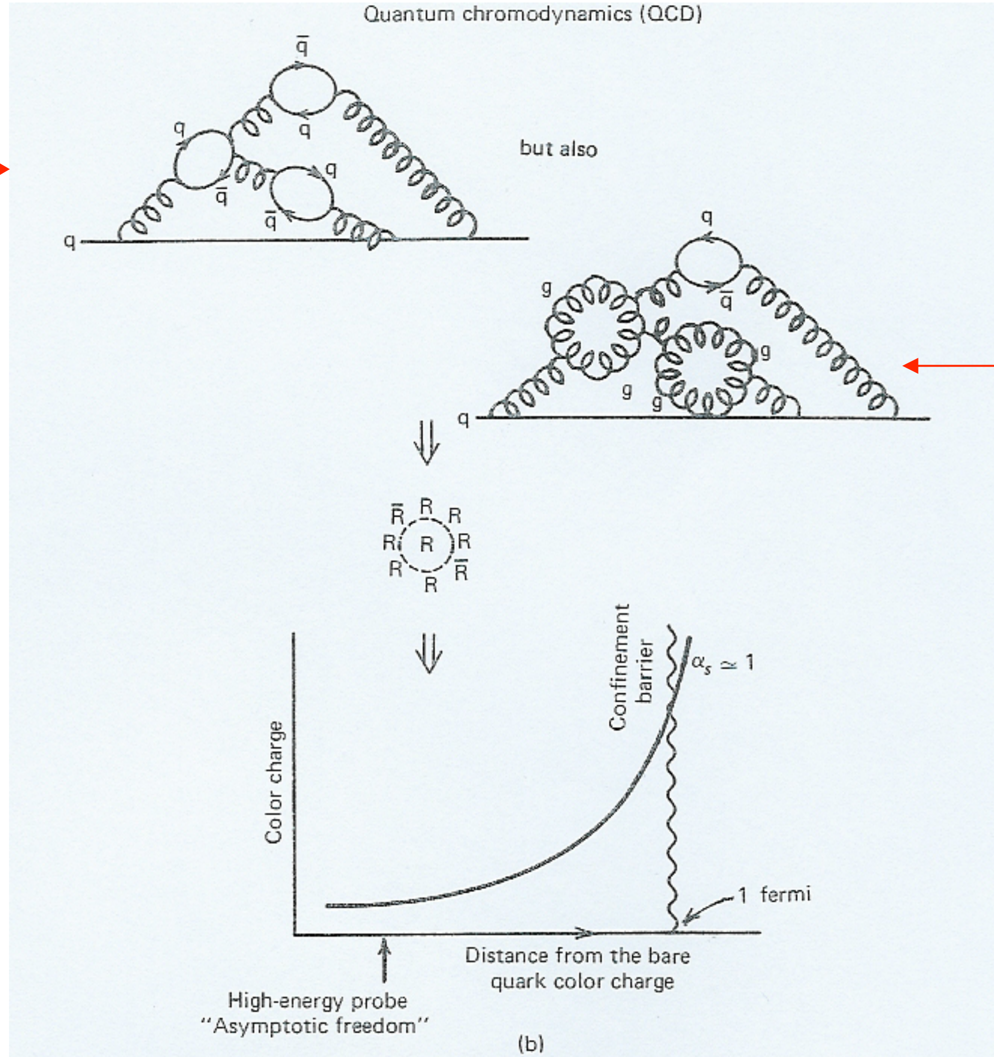
$$\frac{\alpha(\mu^2)}{3\pi} \rightarrow \frac{\alpha_3(\mu^2)}{6\pi}$$

color factor,
for each flavor.

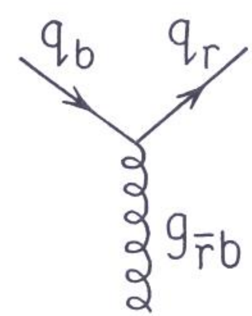
New with respect to QED
It only gives a numerical factor:
- 8 gluons, larger contribution
- opposite sign
- Asymptotic freedom

Charge screening in QCD and running of α_s

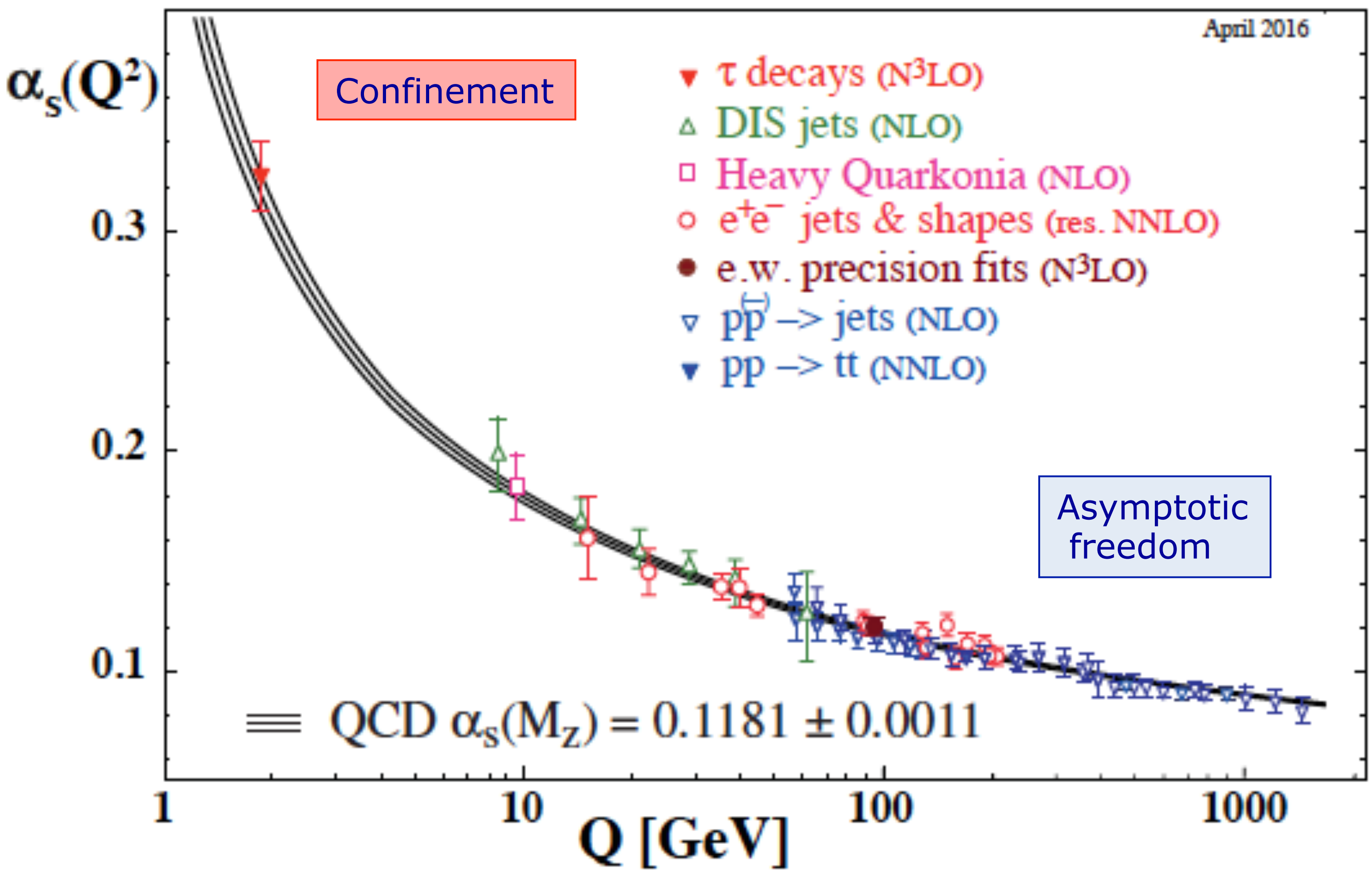
QED analogue



gluon self coupling in QCD



QCD



April 2016
$\alpha_s(Q^2)$
Confinement
τ decays (N³LO)
DIS jets (NLO)
Heavy Quarkonia (NLO)
e⁺e⁻ jets & shapes (res. NNLO)
e.w. precision fits (N³LO)
pp(̄) –> jets (NLO)
pp –> tt (NNLO)
0.3
0.2
0.1
Asymptotic freedom
QCD $\alpha_s(M_Z) = 0.1181 \pm 0.0011$
1
10
100
1000
Q [GeV]

Chiral Simmetry

In the massless quark limit, the QCD Lagrangian della QCD has a global symmetry related to the conserved chirality (handedness) of massless spin ½ particles.
With two flavors ($N_f=2$):

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

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

These transformations leave $\mathcal{L}_{\mathrm{QCD}}$ invariant in the m=0 limit: the RH and LH quark components never mix.

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

Chiral Symmetry of QCD

Six conserved Noether currents:

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

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

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

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

The corresponding charges are generators of SU(2) x SU(2):

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

If we consider the strange quark mass small it makes sense to generalize the chiral symmetry to three flavours $N_f=3$. In this case the three Pauli matrices τ_a are replaced by the 8 Gell-Mann matrices λ_a.

Spontaneous Chiral Symmetry Breaking

There is evidence from hadron spectroscopy that chiral symmetry in the limit m=0 is spontaneously broken. For dynamical reasons the vacuum is symmetric only under the subgroup $SU(2)_V$ generated by the vector charge Q^V. This is the well- known isospin symmetry (for N_f=2) or flavour symmetry (for N_f=3). If the symmetry were not broken we would observe parity doublets and the vector mesons ($J^P=1^-$) would be degenerate with the axial mesons ($J^P=1^+$), while e.g. M(ρ) = 0.77 GeV and M(a_1)= 1.23 GeV. Chiral symmetry is spontaneously broken and it breaks down to the isospin symmetry:

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

The Goldstone bosons are the 3 π in the case of 2 flavors and the 8 members of the meson octet in the case of 3 flavors.

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:

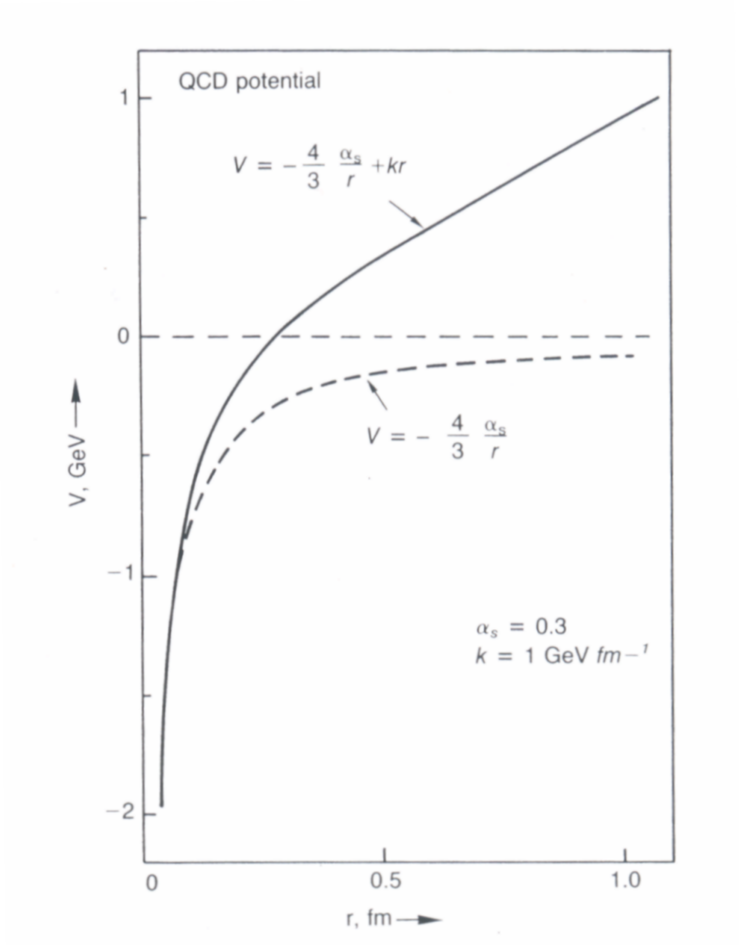
$$V(r) \xrightarrow[r \to 0]{} -\frac{4}{3}\frac{\alpha_s(r)}{r}$$

- 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
$\Lambda \sim 0.2$ 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

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

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

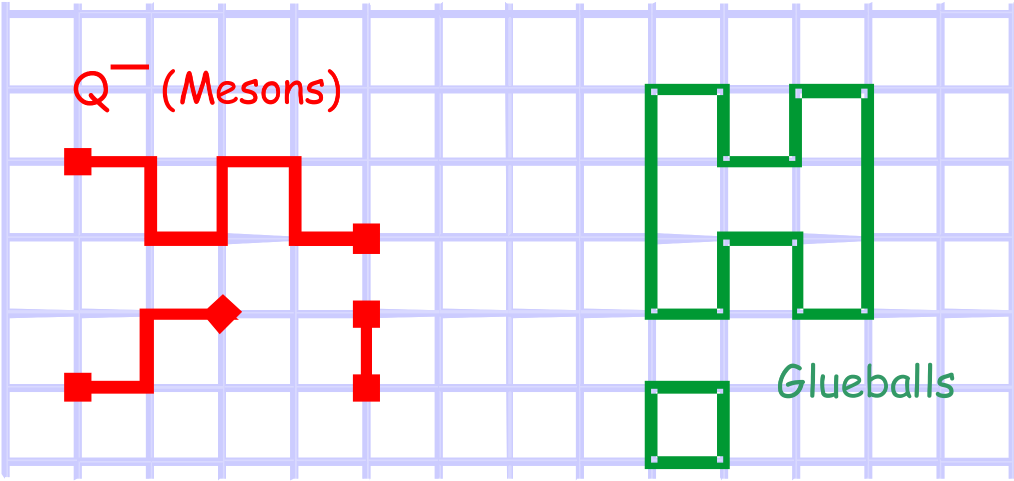
e.g. $\partial_t\phi \rightarrow [\phi(t+a) - \phi(t-a)]/2a$.

Continuum results obtained by $a \rightarrow 0$.

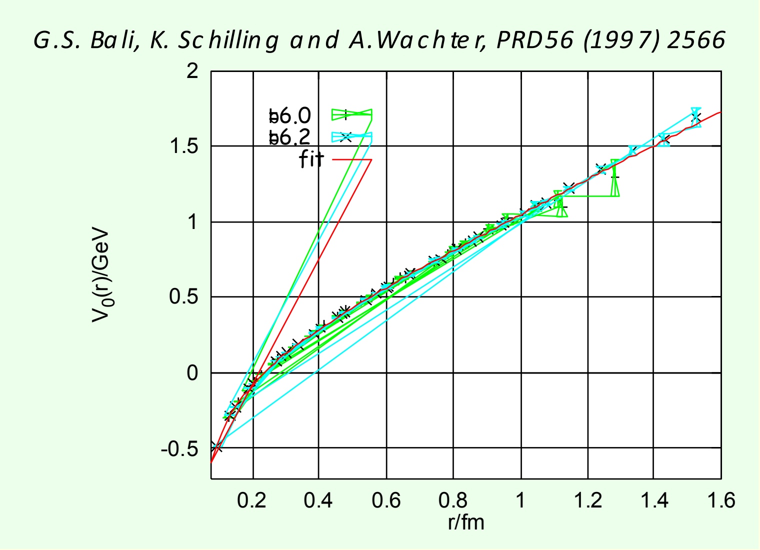
LQCD formulated in Euclidean space-time.

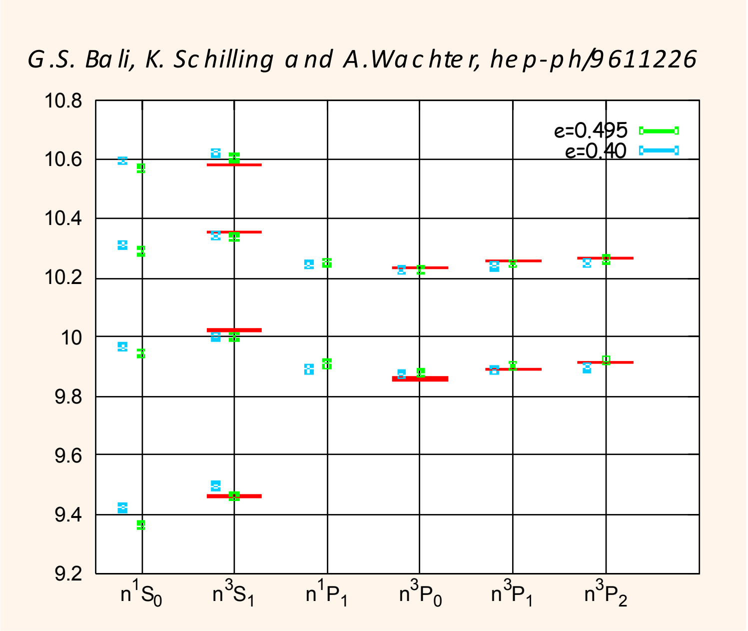
LQCD is a *first principles approach*: only parameters inherent to QCD, i.e. α_s and the quark masses. These n_f+1 parameters are fixed by matching n_f+1 low-energy quantities to their experimental values.

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



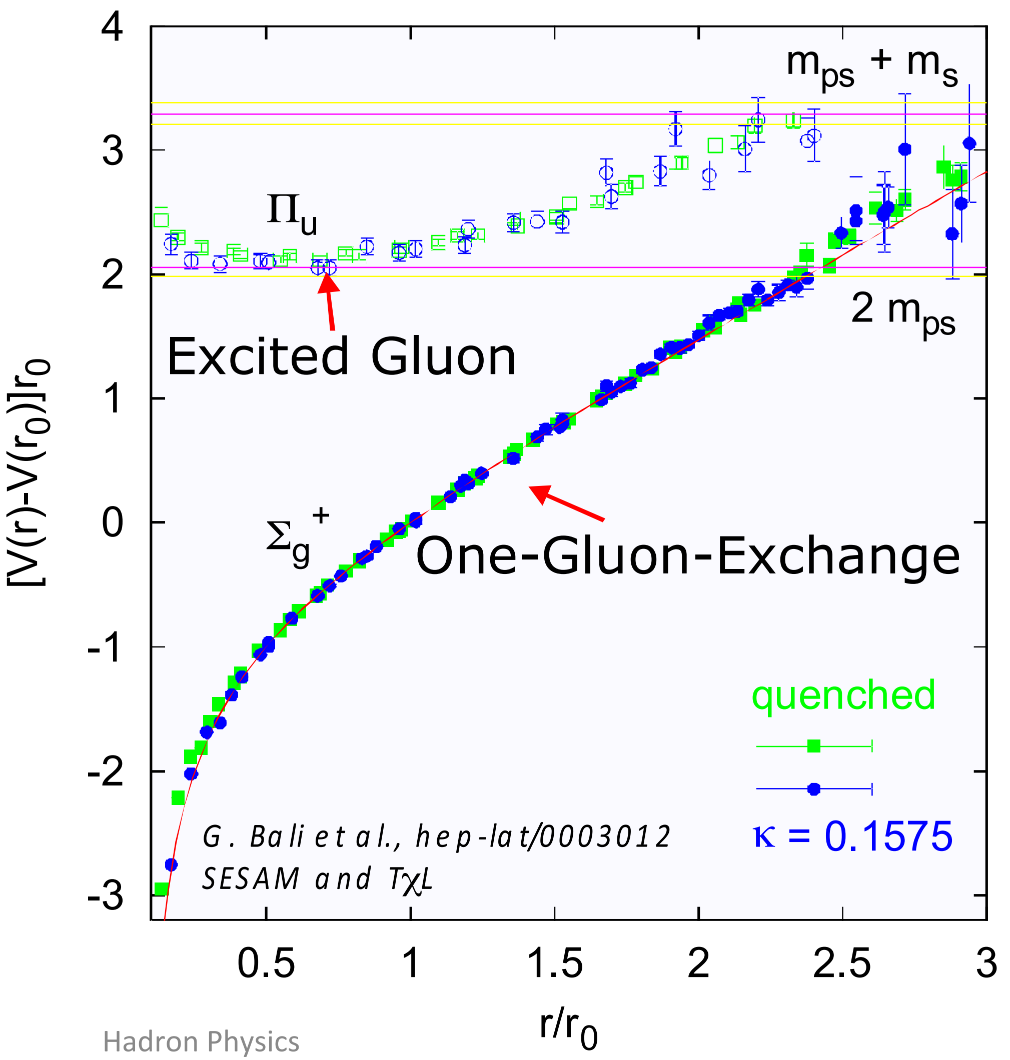


The static potential derived from LQCD confirms the Coulomb + Confinement Ansatz

$Q\bar{Q}$ Potential from LQCD

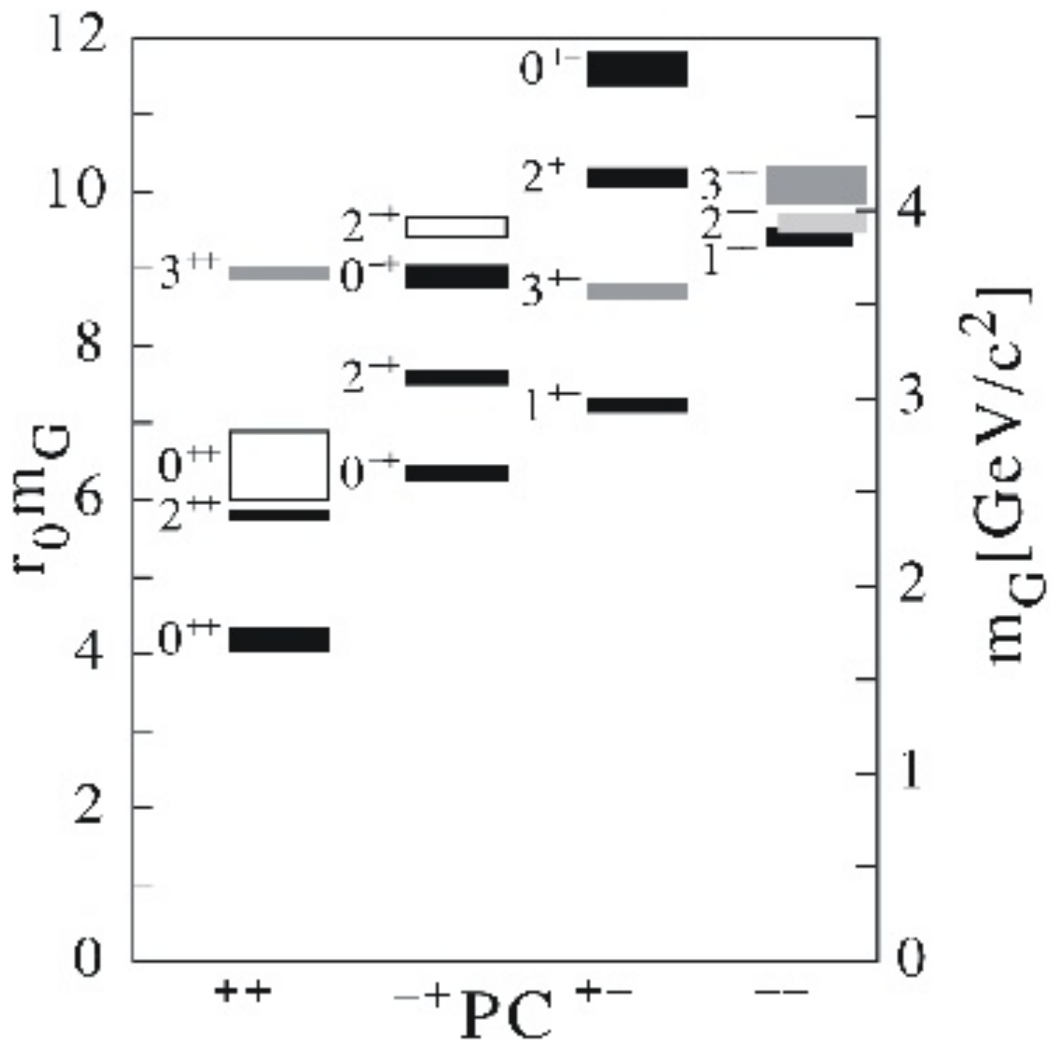
In the quenched approximation sea quarks are neglected.

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



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

Hadrons are very complicated

$q\bar{q}$

+

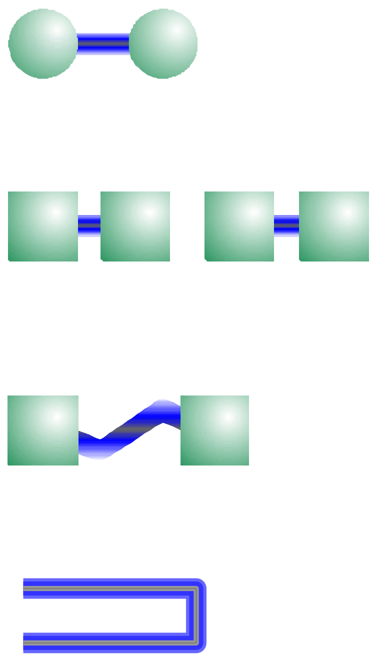
$(q\bar{q})(q\bar{q})$)

+

$(q\bar{q})g$

+

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 $q\bar{q}$ term

Definition of Hadron Configurations

$SU(3)_c$ symmetry tells us that

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

<u>is colour neutral</u>

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 $q\bar{q}$-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

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
  - PDF, GDA, TMD
- Spin physics.

Experimental Techniques

e^+e^- collisions
direct formation
two-photon production
initial state radiation (ISR)
B meson decay
(BaBar, Belle(2), BESIII, CLEO(-c), LEP)

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

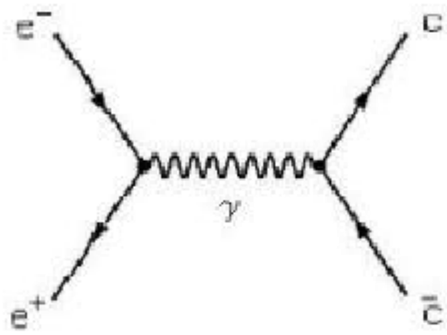
$\bar{p}p$ annihiliation
(LEAR, Fermilab E760/E835, $\bar{\text{P}}$ANDA)

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

Hadroproduction
(CDF, D0, Compass, LHC)

Electroproduction
(HERA, JLAB12)

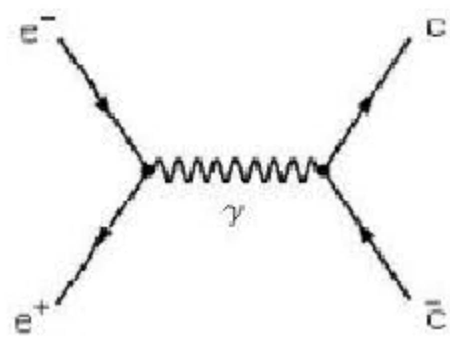
Hadron Production in e^+e^- Annihilation



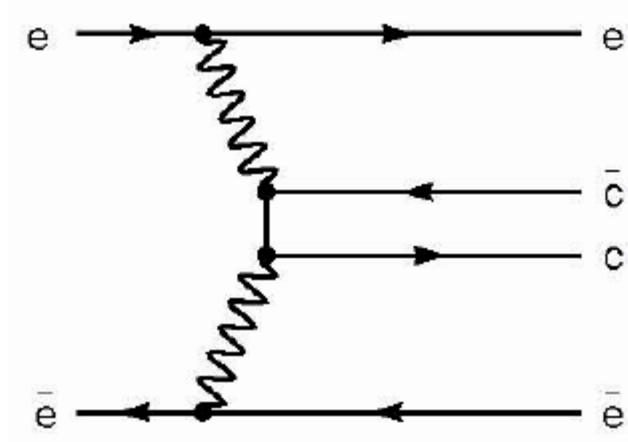
Direct Formation

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 $\psi(3770)$.

Hadron Production in e^+e^- Annihilation



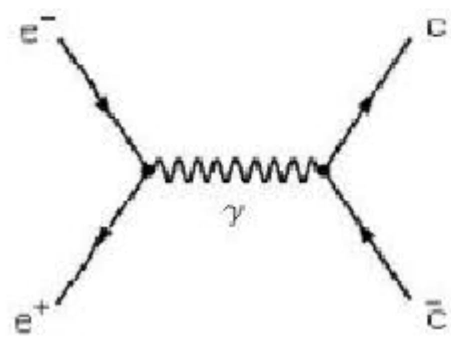
Direct Formation



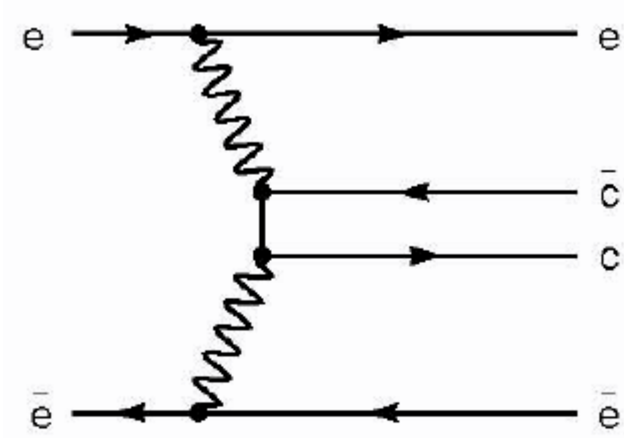
Two-Photon Production

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

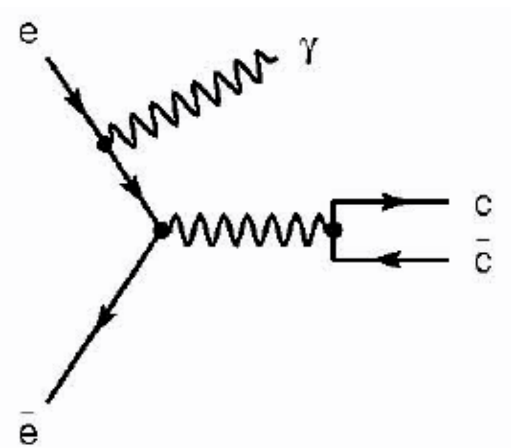
Hadron Production in e^+e^- Annihilation



Direct Formation



Two-Photon Production

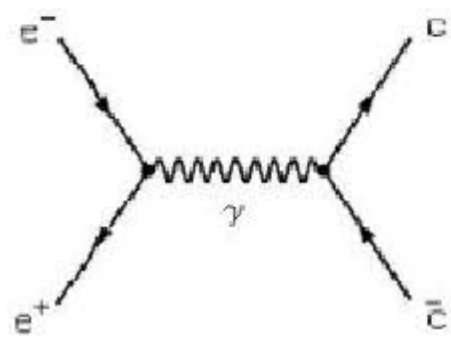


Initial State Radiation

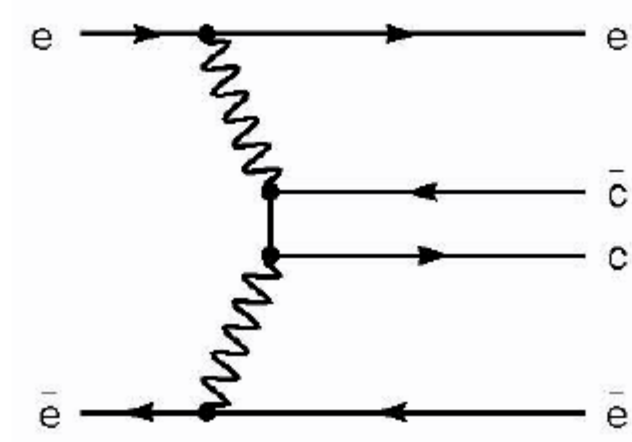
- Like in direct formation, only $J^{PC}=1^{--}$ states can be formed in ISR.
- This process allows a large mass range to be explored.
- Useful for the measurement of $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$.
- Can be used to search for new vector states.

Hadron Production in e^+e^- Annihilation

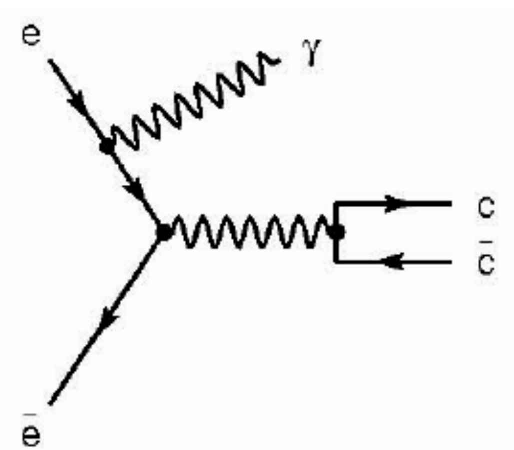
e^+e^- annihilation provides a very favourable environment for the study of hadron spectroscopy



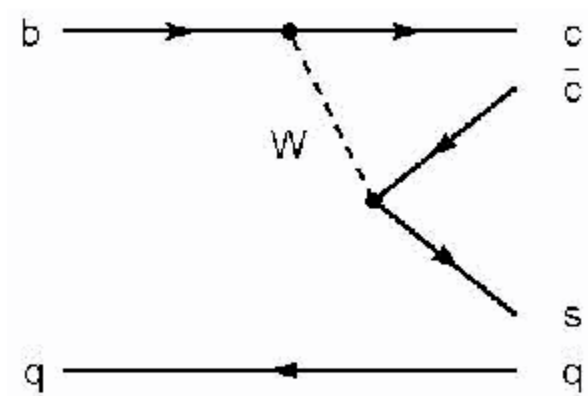
Direct Formation



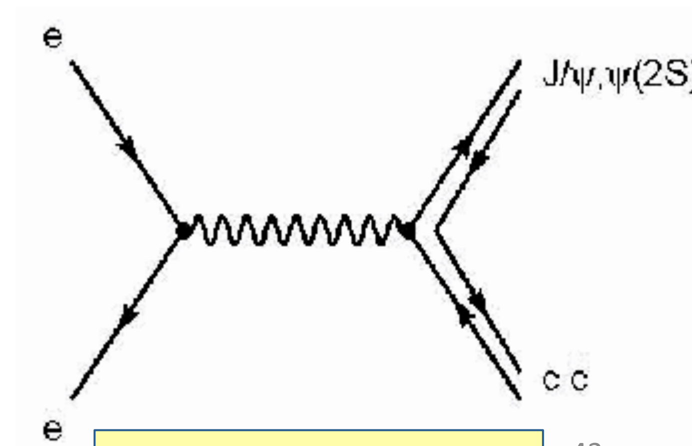
Two-Photon Production



Initial State Radiation



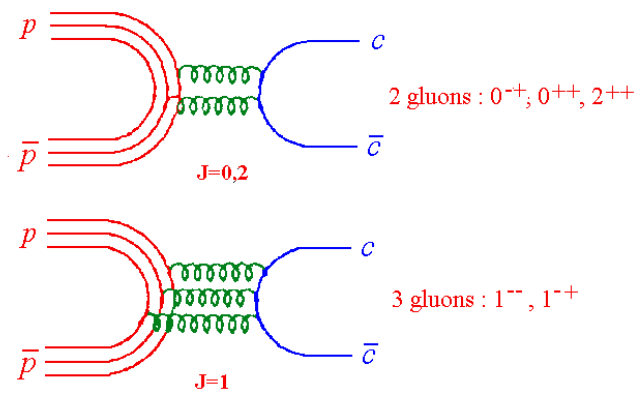
B-meson decay

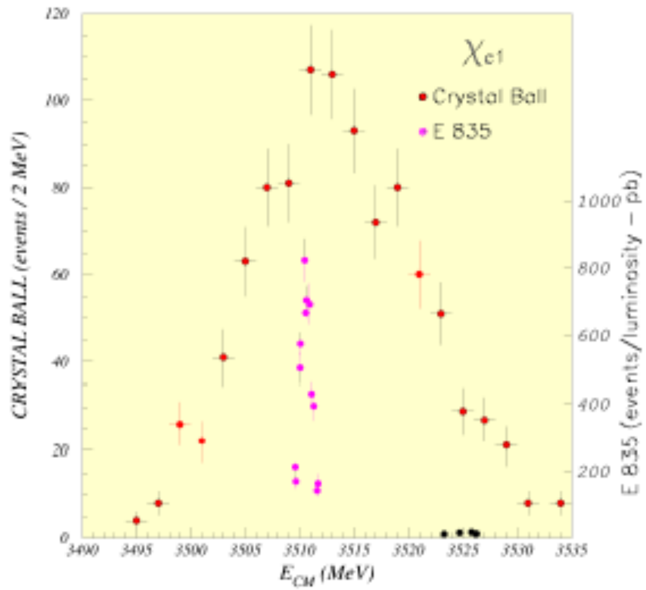


Double Charmonium

$\bar{p}p$ Annihilation

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





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

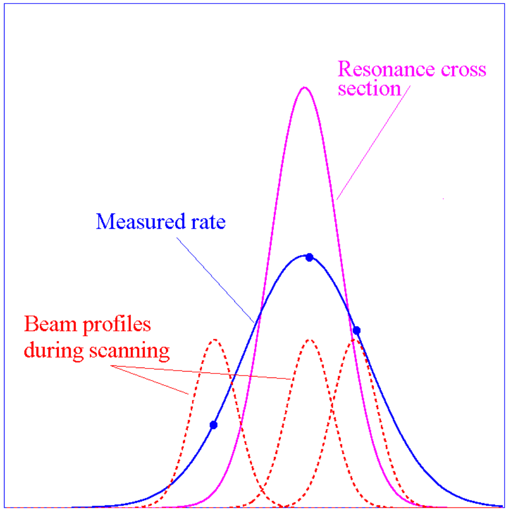
Experimental Method

The cross section for the process:

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

is given by the Breit-Wigner formula:

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

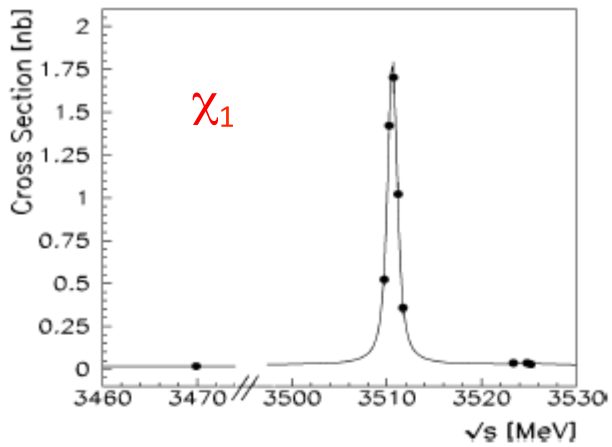


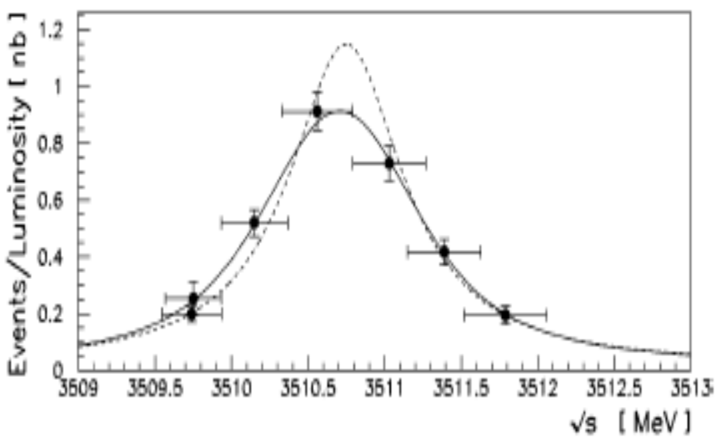
The production rate ν is a convolution of the BW cross section and the beam energy distribution function *$f(E,\Delta E)$:*

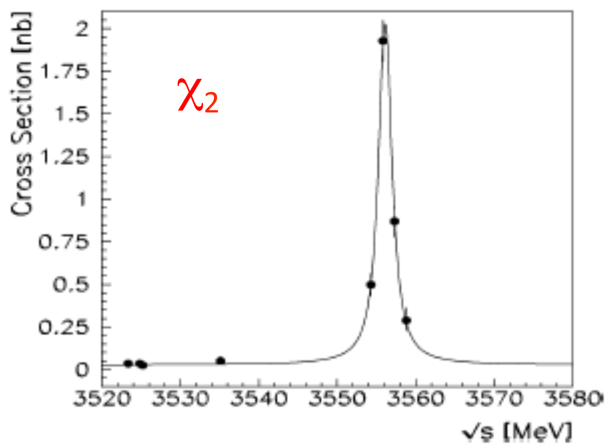
$$\nu = L_0\left\{\varepsilon \int dE f(E,\Delta E)\sigma_{BW}(E) + \sigma_b\right\}$$

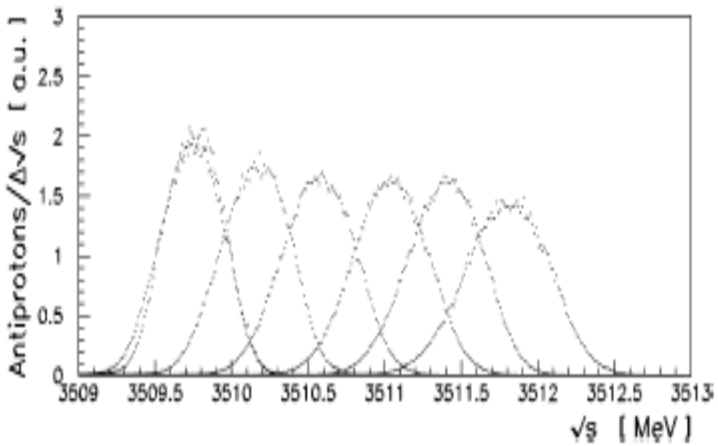
The resonance mass M_R, total width Γ_R and product of branching ratios into the initial and final state $B_{in}B_{out}$ can be extracted by measuring the formation rate for that resonance as a function of the cm energy E.

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









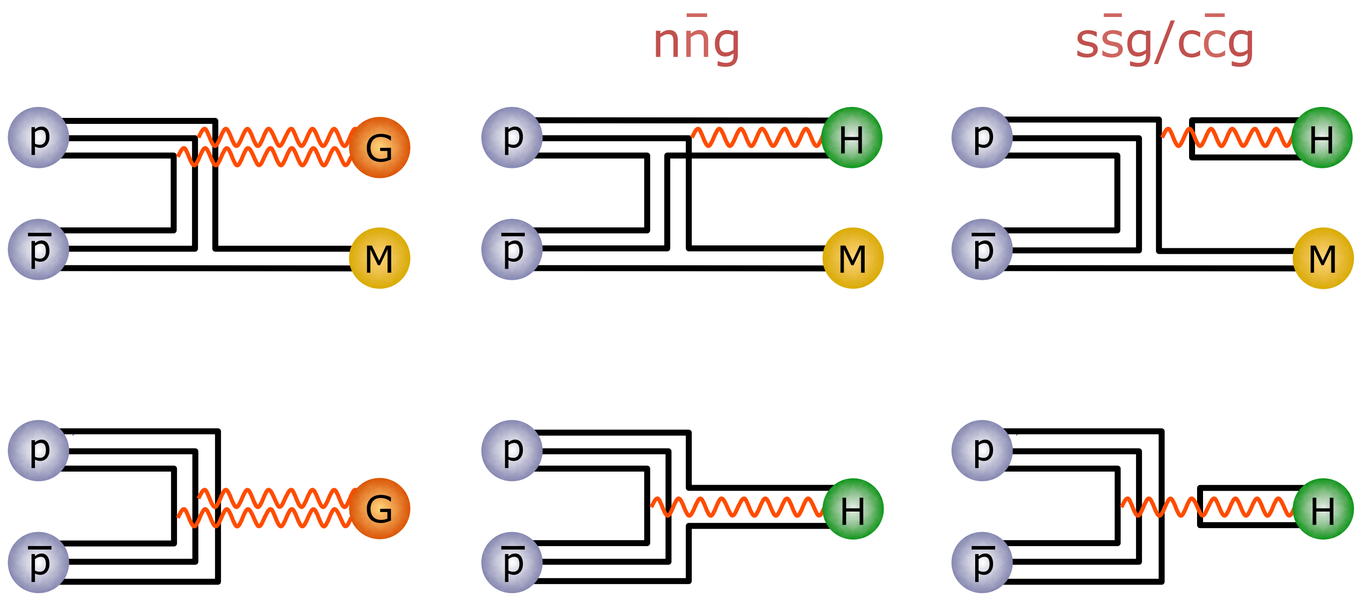
Hybrids and Glueballs in $\bar{p}p$ Annihilation

Production

all J^{PC} available

Formation

only selected J^{PC}



Gluon rich process creates gluonic excitation in a direct way

- $\bar{c}c$ 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

Selected Hot Topics

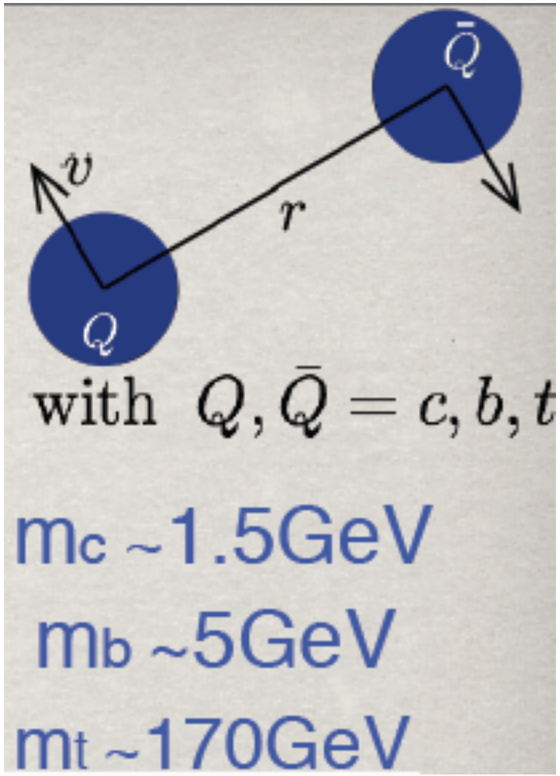
Heavy Quarkonium

The X, Y, Z States

Open Charm

Baryons

Electromagnetic Form Factors



Heavy quarkonia are non relativistic bound states multiscale systems:

$$m_Q >> m_Q v >> m_Q v^2$$

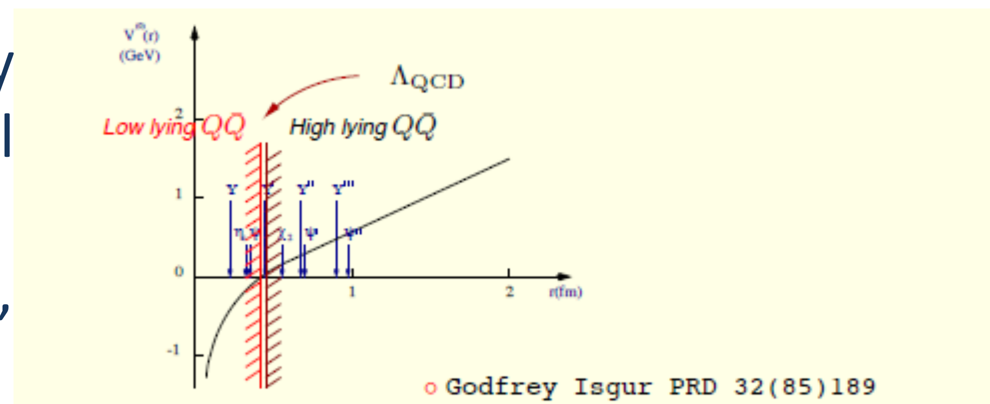
The system is non relativistic: $v_b^2 \approx 0.1 \quad v_c^2 \approx 0.3$

The mass scale is perturbative:

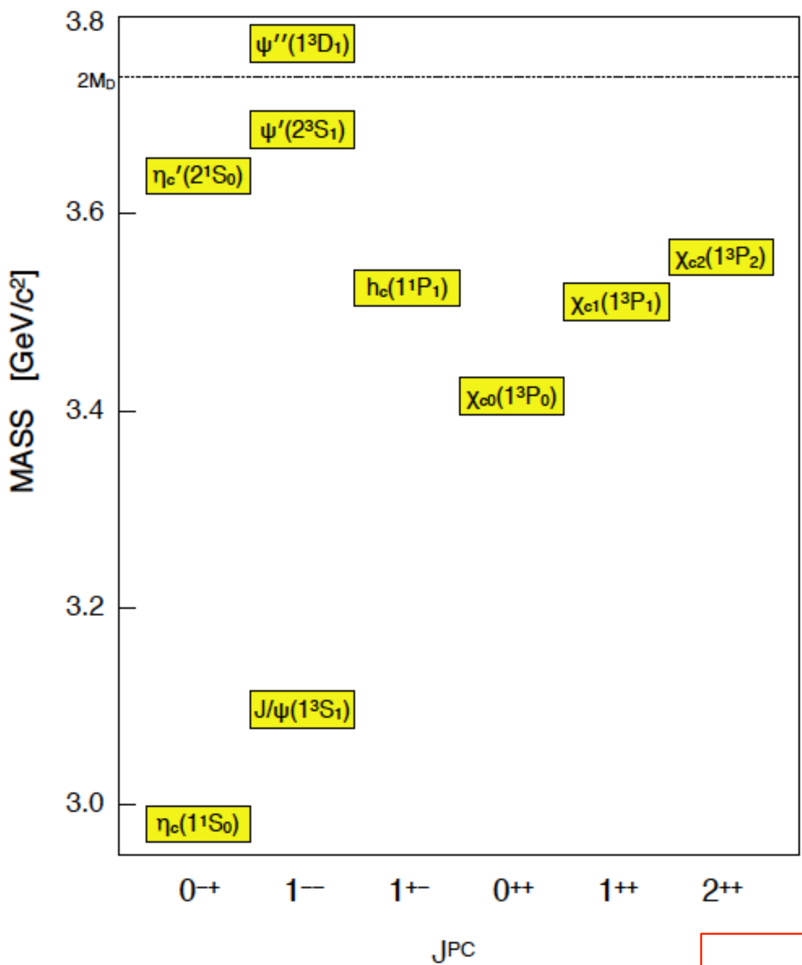
$$m_Q >> \Lambda_{QCD}$$

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

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



Charmonium Spectrum I



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

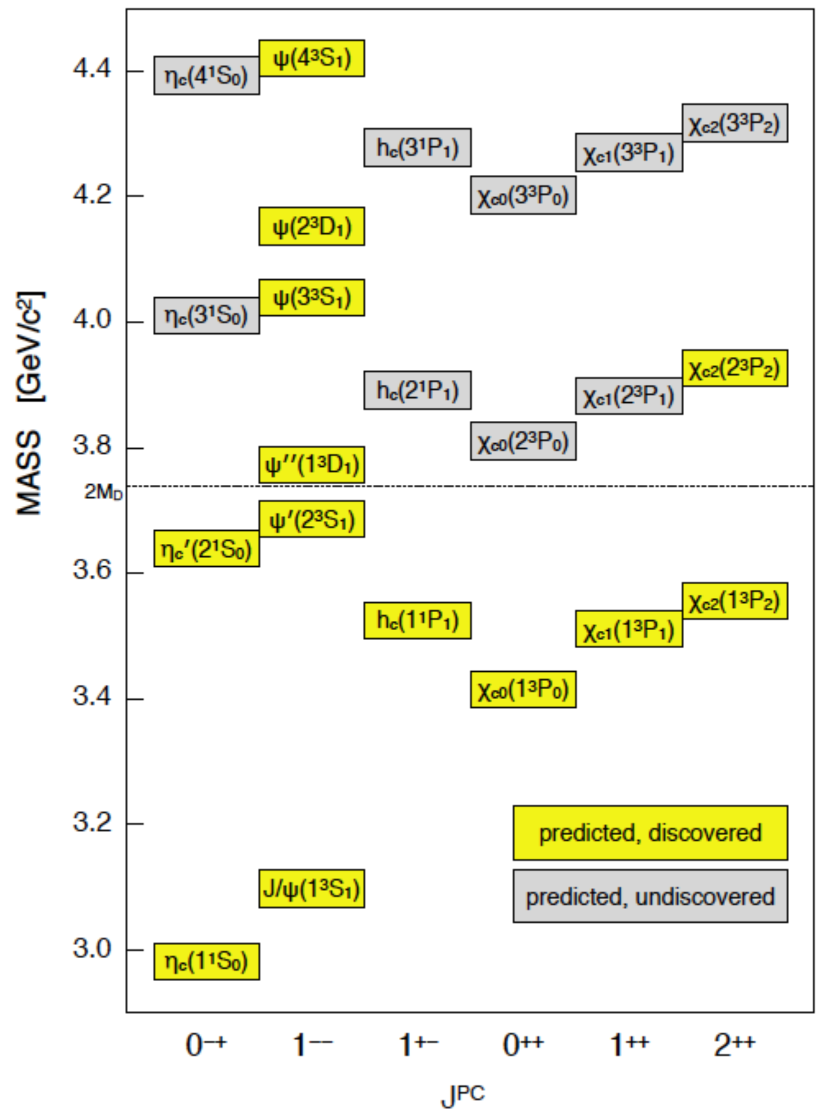
The region above threshold still to be understood:

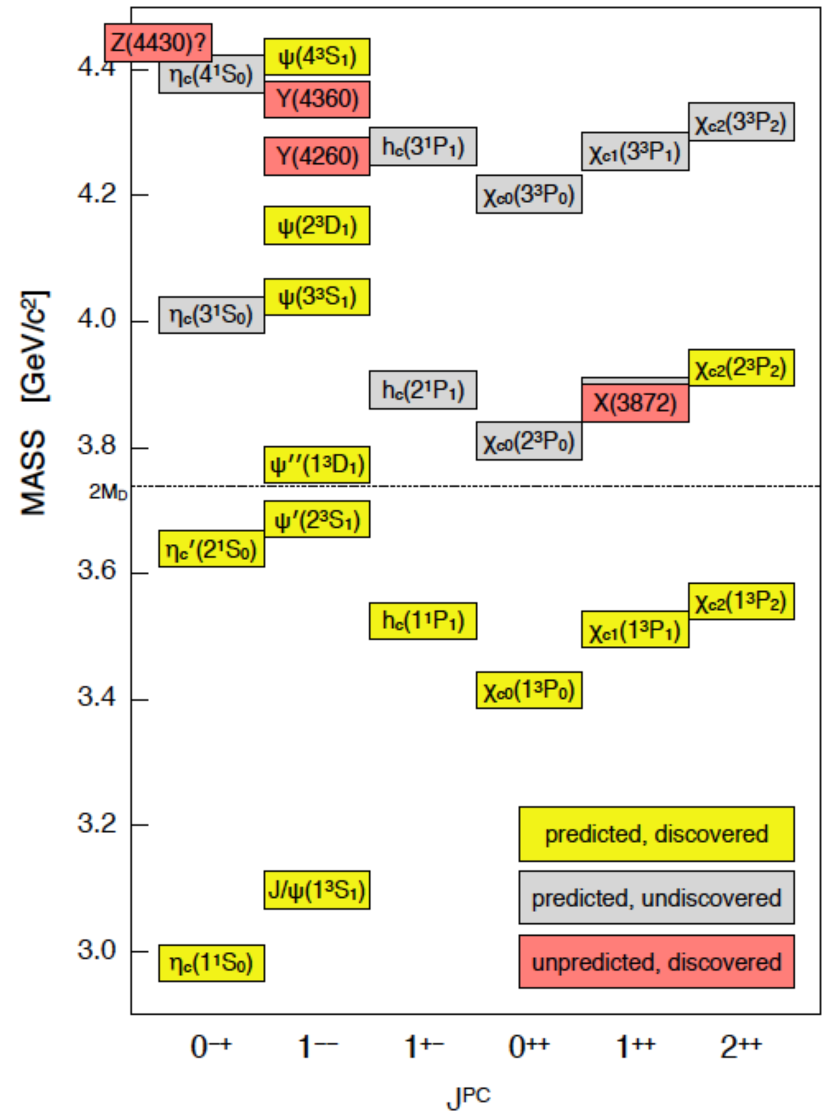
- find missing states (e.g. D-wave)
- understand nature of newly discovered states (e.g. X Y Z)

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

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

Charmonium Spectrum II

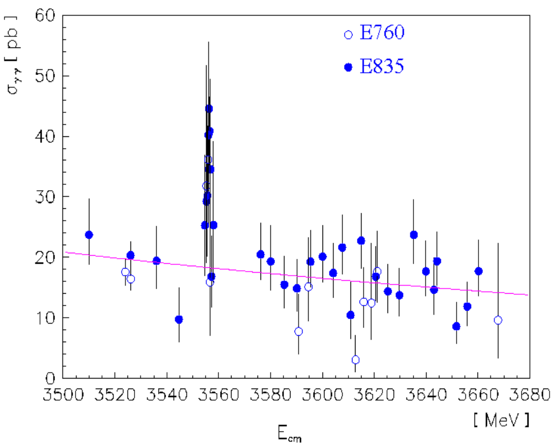


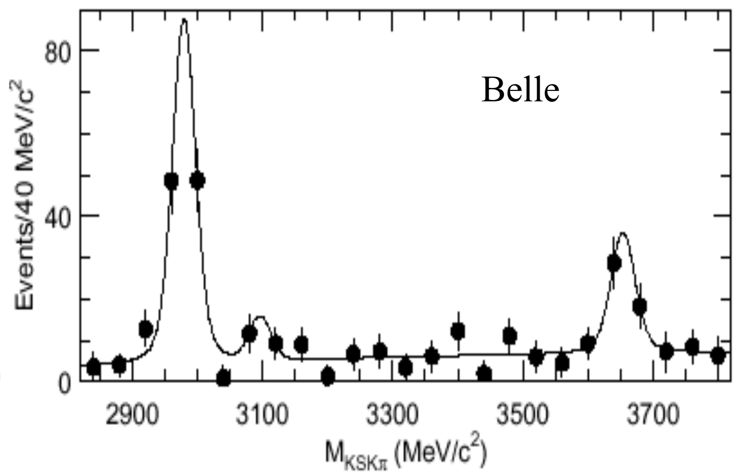


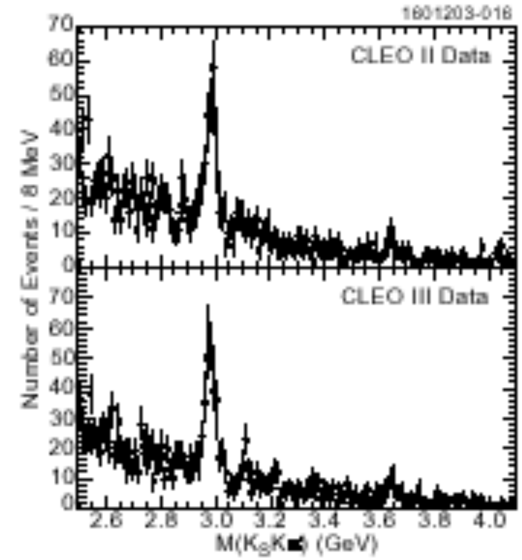
New Quarkonium States Below Open Flavor Threshold

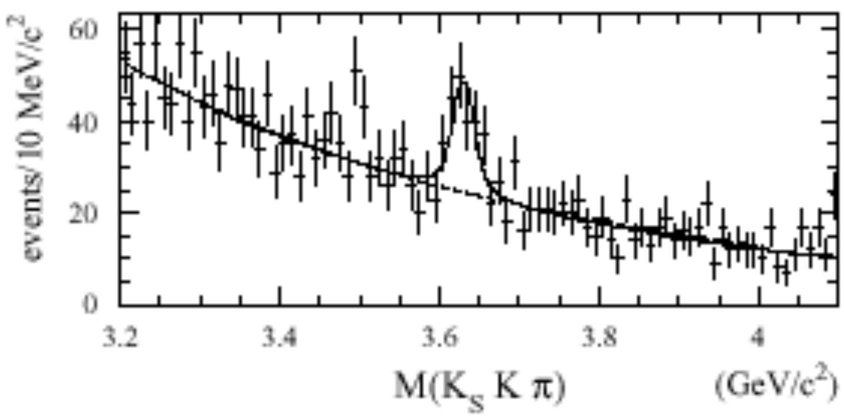
State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$h_c(1P)$	3525.41 ± 0.16	<1	1^{+-}	$\psi(2S) \to \pi^0\,(\gamma\eta_c(1S))$	CLEO [9–11] (13.2)	2004	OK
				$\psi(2S) \to \pi^0\,(\gamma...)$	CLEO [9–11] (10), BES [12] (19)		
				$p\bar{p} \to (\gamma\eta_c) \to (\gamma\gamma\gamma)$	E835 [13] (3.1)		
				$\psi(2S) \to \pi^0\,(...)$	BESIII [12] (9.5)		
$\eta_c(2S)$	3638.9 ± 1.3	10±4	0^{-+}	$B \to K\,(K^0_S K^- \pi^+)$	Belle [14,15] (6.0)	2002	OK
				$e^+e^- \to e^+e^-\,(K^0_S K^- \pi^+)$	BABAR [16,17] (7.8),		
					CLEO [18] (6.5), Belle [19] (6)		
				$e^+e^- \to J/\psi\,(...)$	BABAR [20] (np), Belle [21] (8.1)		
$X(3823)$	3823.1 ± 1.9	< 24	$?^{?-}$	$B \to K(\gamma\,\chi_{c1})$	Belle [22](3.8)	2013	NC!
B_c^+	6277 ± 6	-	0^-	$\bar{p}p \to (\pi^+ J/\psi)...$	CDF [23,24] (8.0), D0 [25] (5.2)	2007	OK
$\eta_b(1S)$	9395.8 ± 3.0	$12.4^{+12.7}_{-5.7}$	0^{-+}	$\Upsilon(3S) \to \gamma\,(...)$	BABAR [26] (10), CLEO [27] (4.0)	2008	OK
				$\Upsilon(2S) \to \gamma\,(...)$	BABAR [28] (3.0)		
				$h_b(1P, 2P) \to \gamma\,(...)$	Belle [29](14)	2012	NC!
				$\Upsilon(10860) \to \pi^+\pi^-\gamma\,(...)$	Belle [30] (14)		
$h_b(1P)$	9898.6 ± 1.4	?	1^{+-}	$\Upsilon(10860) \to \pi^+\pi^-\,(...)$	Belle [31,30] (5.5)	2011	NC!
				$\Upsilon(3S) \to \pi^0\,(...)$	BABAR [32] (3.0)		
$\eta_b(2S)$	9999 ± 4	< 24	0^{-+}	$h_b(2P) \to \gamma\,(...)$	Belle [29](4.2)	2012	NC!
$\Upsilon(1^3D_2)$	10163.7 ± 1.4	?	2^{--}	$\Upsilon(3S) \to \gamma\gamma\,(\gamma\gamma\Upsilon(1S))$	CLEO [33] (10.2)	2004	OK
				$\Upsilon(3S) \to \gamma\gamma\,(\pi^+\pi^-\Upsilon(1S))$	BABAR [34] (5.8)		
				$\Upsilon(10860) \to \pi^+\pi^-\,(...)$	Belle [31] (2.4)		
$h_b(2P)$	$10259.8^{+1.5}_{-1.2}$	?	1^{+-}	$\Upsilon(10860) \to \pi^+\pi^-\,(...)$	Belle [31,30] (11.2)	2011	NC!
$\chi_{bJ}(3P)$	10530 ± 10	?	?	$pp \to (\gamma\mu^+\mu^-)...$	ATLAS [35] (>6), D0 [36] (3.6)	2011	OK

The $\eta_c(2^1S_0)$









PDG 2016

$M(\eta_c') = 3639.2 \pm 1.2\ \mathrm{MeV}/c^2$

$\Gamma(\eta'_c) = 11.3\ ^{+3.2}_{-2.9}\ \mathrm{MeV}$

$$\Delta M_{hf}(2S)_{c\bar{c}} \equiv M(\psi(2S)) - M(\eta_c(2S)) = 46.9 \pm 1.3\ MeV$$

The $h_c(^1P_1)$

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

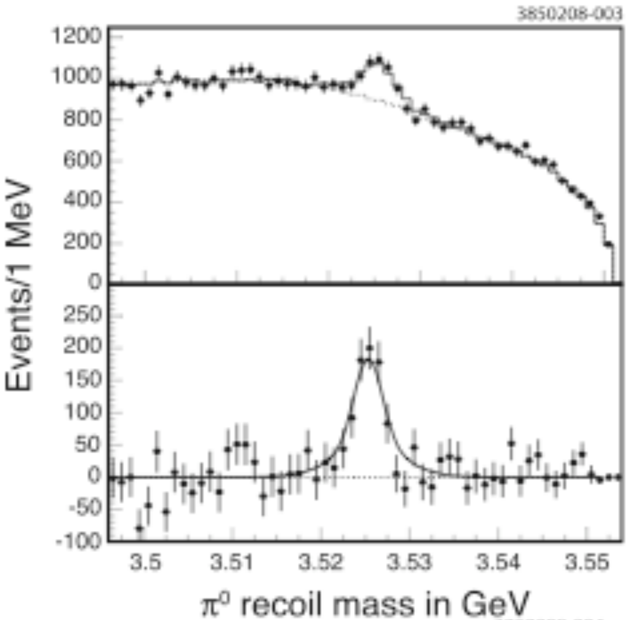
$$M_{cog} = \frac{M(\chi_0) + 3M(\chi_1) + 5M(\chi_2)}{9}$$

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

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

The $h_c(^1P_1)$

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

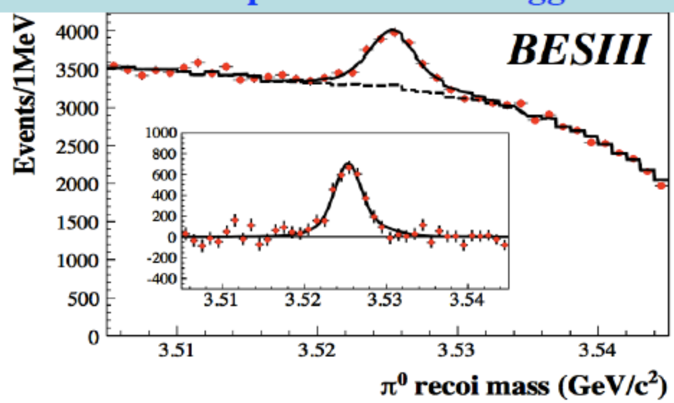


The CLEO experiment was able to find it with a significance of 13 σ in ψ' decay by means of an exclusive analysis.

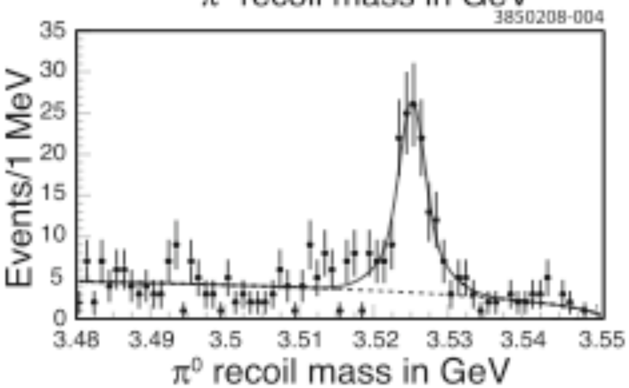
The width and the BF $\psi' \rightarrow \pi^0 h_c$ were not measured.

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

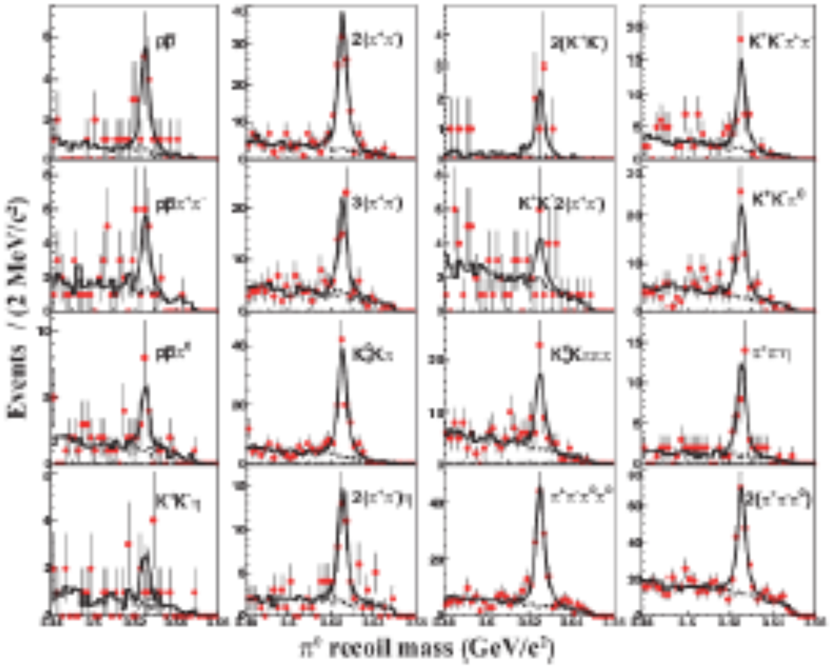


$Br(\psi' \rightarrow \pi^0 h_c)$	$(8.4 \pm 1.3 \pm 1.0) \times 10^{-4}$
$Br(h_c \rightarrow \gamma\eta_c)$	$(54.3 \pm 6.7 \pm 5.2)\%$

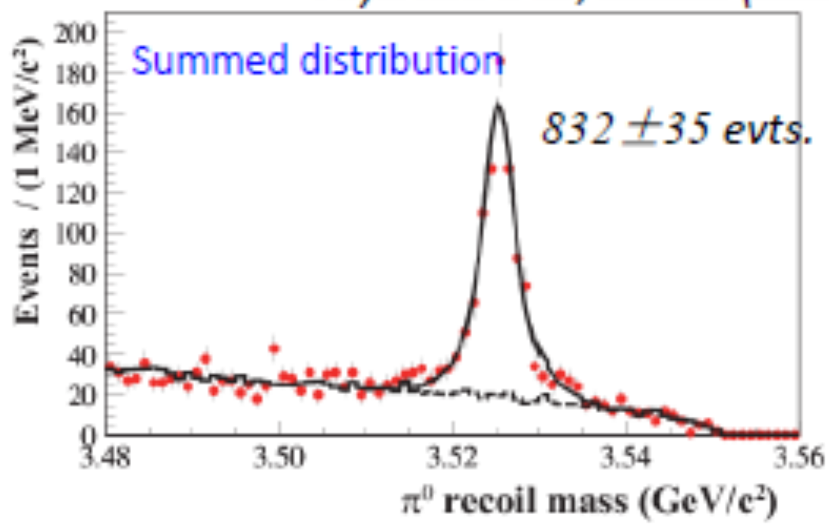
$$\Delta M_{hf}(1P) \equiv M(^3P) - M(^1P) = -0.10 \pm 0.13 \pm 0.18\,\mathrm{MeV}/c^2$$

Center of gravity of P-states

16 hadronic decays (~40% η_c decays)



Phys. Rev. D 86, 092009 (2012)

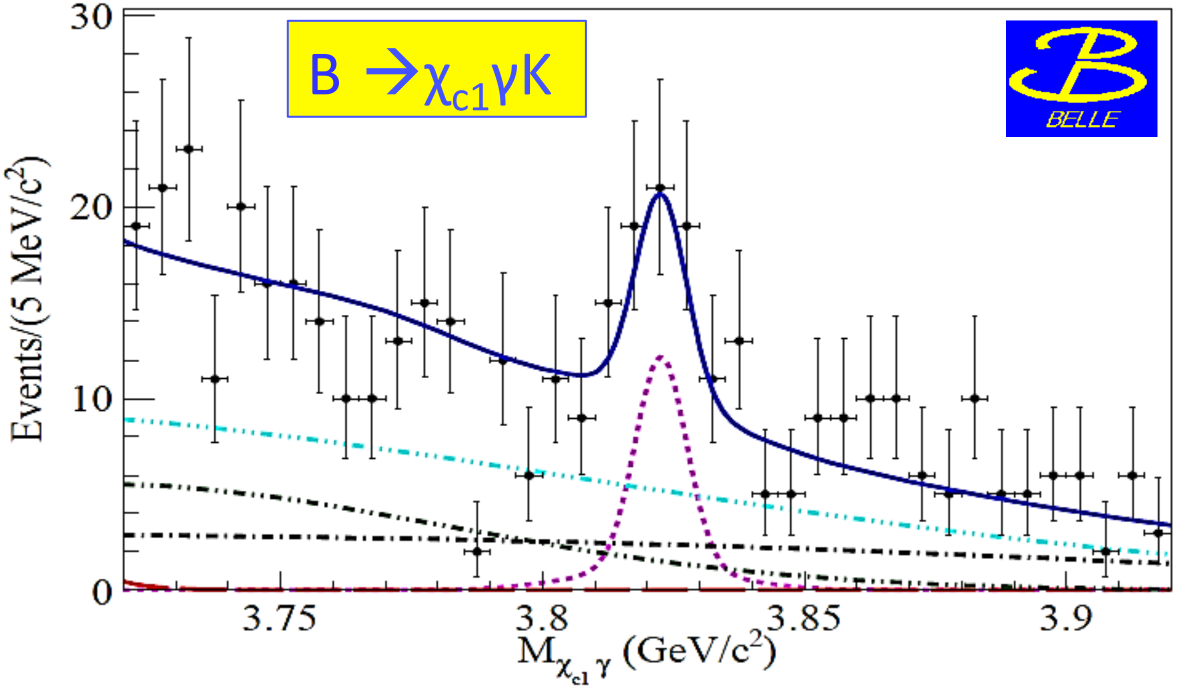


(MeV)	BESIII Exclusive	BESIII Inclusive	CLEO
mass	*3525.31±0.11±0.14*	*3525.40±0.13±0.18*	*3525.21±0.27±0.14*
width	*0.70±0.28±0.22*	*0.73±0.45±0.28*	--
$\Delta M_{hf}(1P)$	*-0.01±0.11±0.15*	*0.10±0.13±0.18*	*0.08±0.18±0.12*

Jingzhi Zhang – Charm 2013

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

X(3823)



Measured mass and width consistent with predicted values for ψ_2(1D) (^{1} D$_2$)

ribution for the
$\to (\chi_{c1}\gamma)K_S^0$
used in the fits

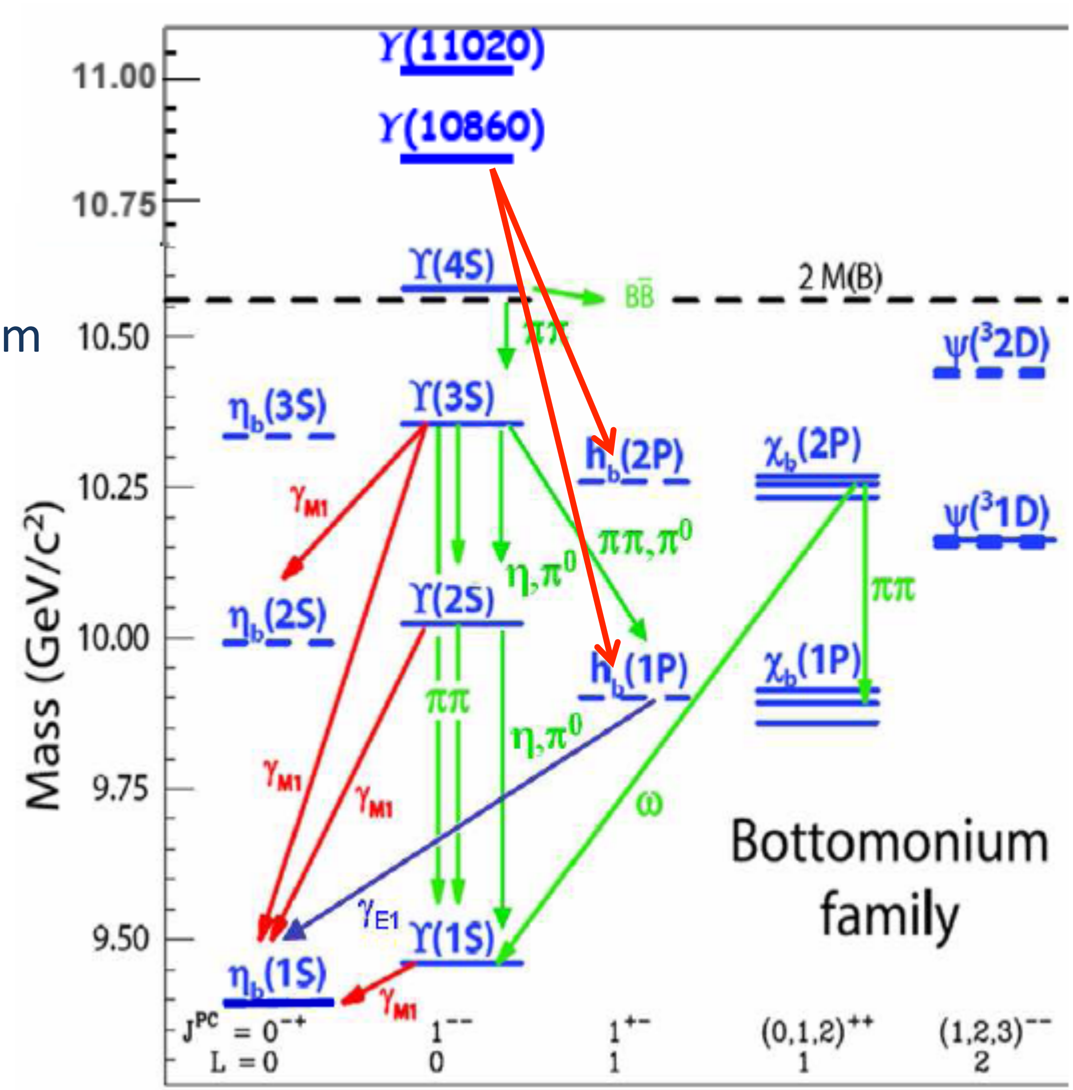
M = 3823.1 ± 1.8 ± 0.7 MeV/c^2
Γ < 24 MeV
711 fb^{-1} 3.8 σ

V. Bhardwaj et al.(Belle Collab.), Phys. Rev. Lett. **111**, 032001

Bottomonium Specroscopy

Agreement with theoretical predictions better because of:

- higher *b* quark mass
- lower value of α_s.
- dominance of Coulomb term in the potential

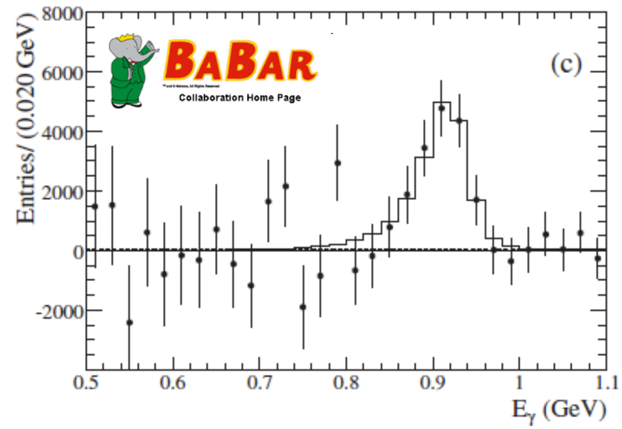


The $\eta_b(^1S_0)$ Bottomonium State

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 $\Upsilon(3S) \rightarrow \gamma\, \eta_b(1S)$ [PRL101,071801,2008]
Then confirmed in $\Upsilon(2S) \rightarrow \gamma\, \eta_b(1S)$ [PRL103, 161801,2009]
and by CLEO [PRD8,031104,2010]

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

→ BF $(\Upsilon(3S) \rightarrow \gamma\, \eta_b) = (4.5 \pm 0.5\,[\text{stat.}] \pm 1.2\,[\text{syst.}]) \times 10^{-4}$



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 $\boxed{9391.1 \pm 3.1\ \text{MeV}/c^2}$
- The hyperfine ($\Upsilon(1S)$-$\eta_b(1S)$) mass splitting is $\boxed{69.9 \pm 3.1\ \text{MeV}/C^2}$

The $h_b(^1P_1)$ Bottomonium State

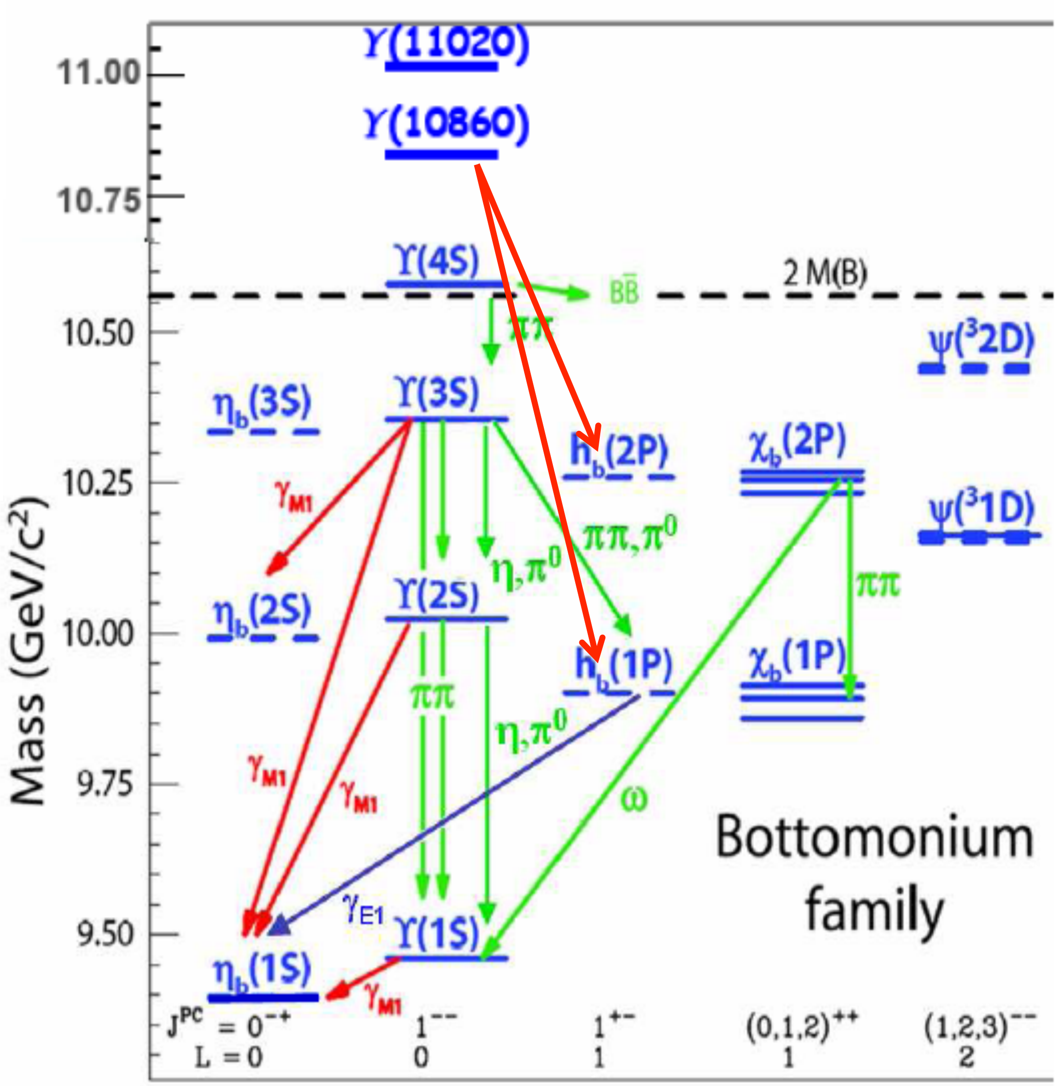
$(b\bar{b})$: S=0 L=1 $J^{PC}=1^{+-}$

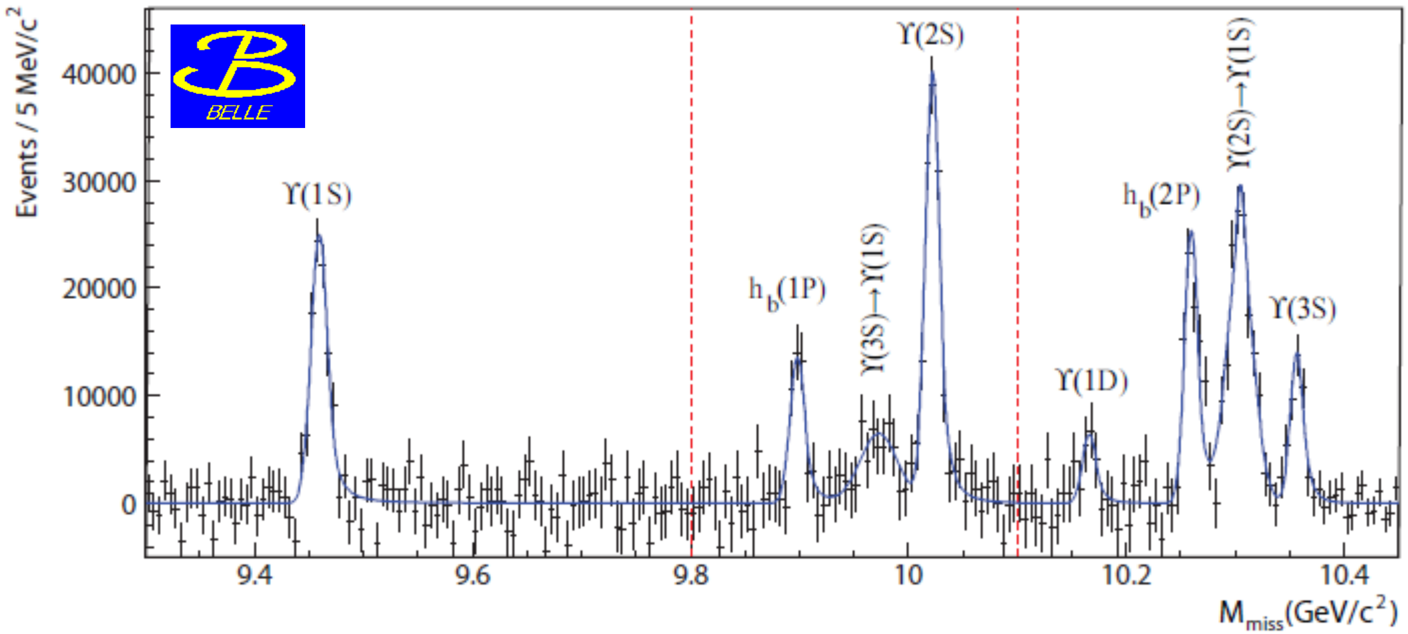
Expected mass

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

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

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





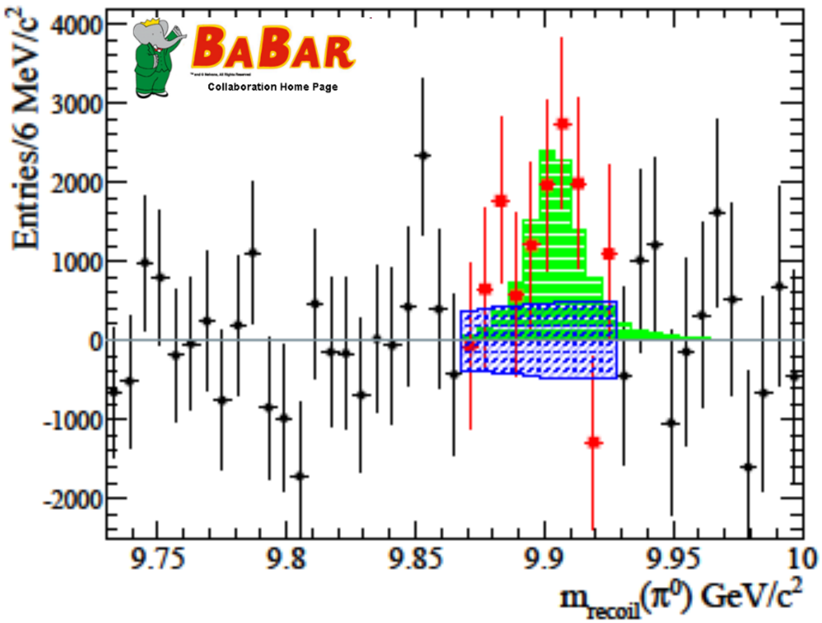
$\Upsilon(1S)$	$105.2 \pm 5.8 \pm 3.0$	$9459.4 \pm 0.5 \pm 1.0$	$18.2\,\sigma$
$h_b(1P)$	$50.4 \pm 7.8^{+4.5}_{-9.1}$	$9898.3 \pm 1.1^{+1.0}_{-1.1}$	$\boxed{6.2\,\sigma}$
$3S \to 1S$	56 ± 19	9973.01	$2.9\,\sigma$
$\Upsilon(2S)$	$143.5 \pm 8.7 \pm 6.8$	$10022.3 \pm 0.4 \pm 1.0$	$16.6\,\sigma$
$\Upsilon(1D)$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

Deviations from CoG of χ_{bJ} masses

$$\left.\begin{array}{ll} h_b(1P) & (1.6 \pm 1.5)\ \mathrm{MeV}/c^2 \\ h_b(2P) & (0.5\ ^{+1.6}_{-1.2})\ \mathrm{MeV}/c^2 \end{array}\right\}$$

consistent with zero, as expected

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



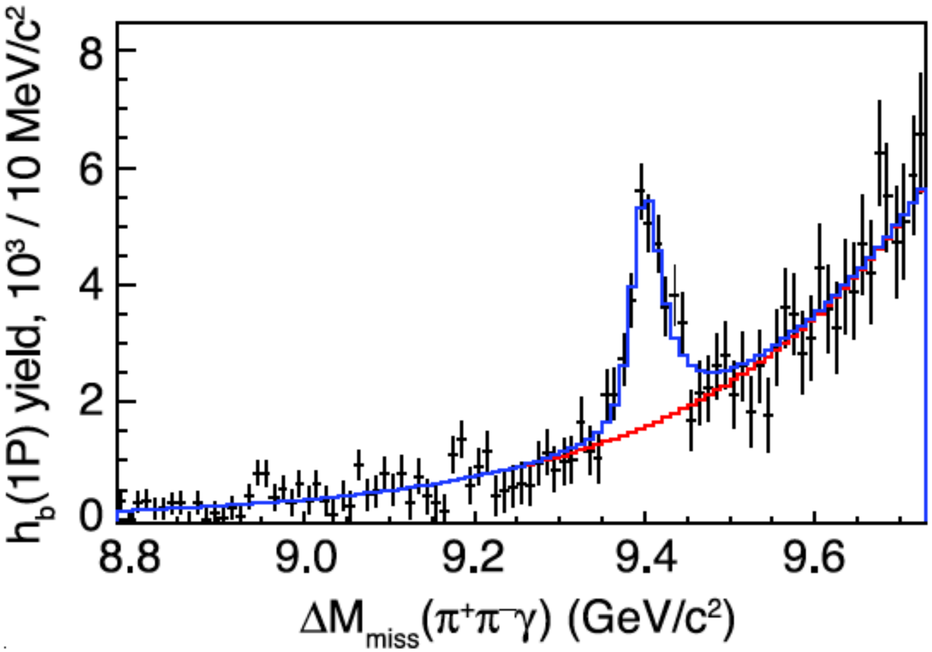
10721 ± 2806 events

Statistical significance 3.1 σ

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

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

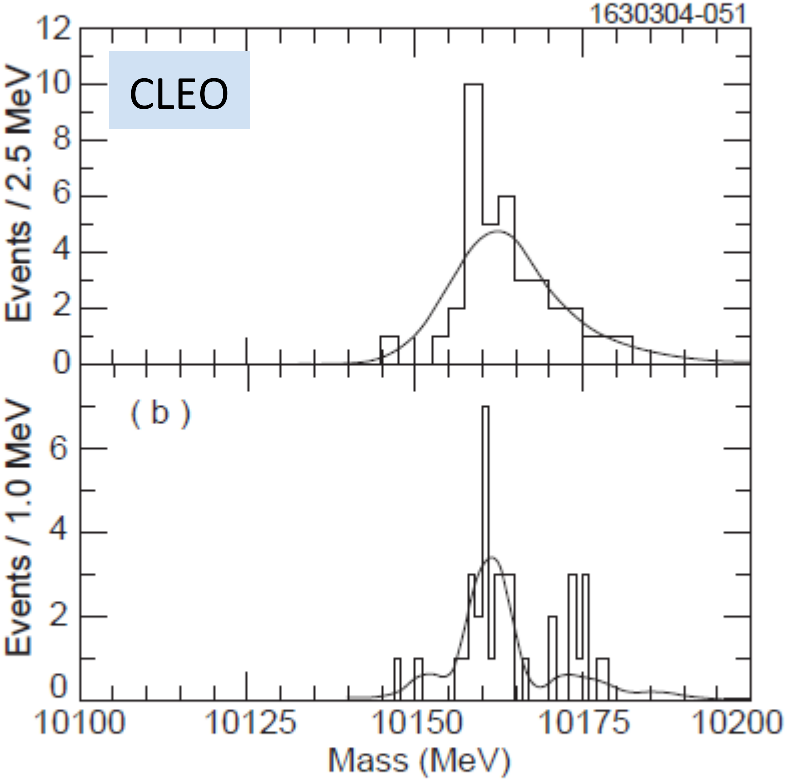
$h_b \rightarrow \gamma\eta_b$ at Belle



$BR\ (h_b \rightarrow \gamma\eta_b) = (49.8 \pm 6.8\ ^{+10.9}_{-5.2})\ \%$

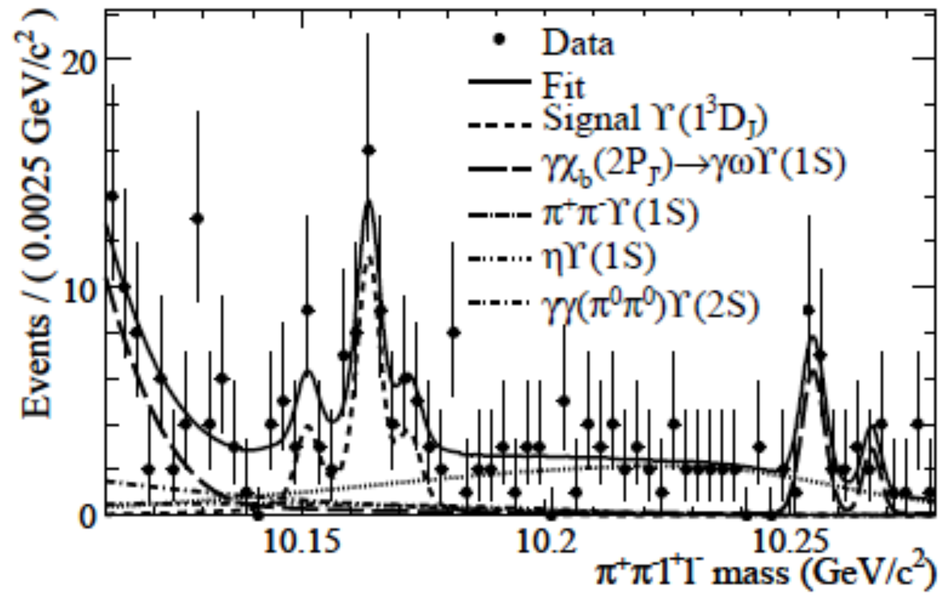
The Y(1D)

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



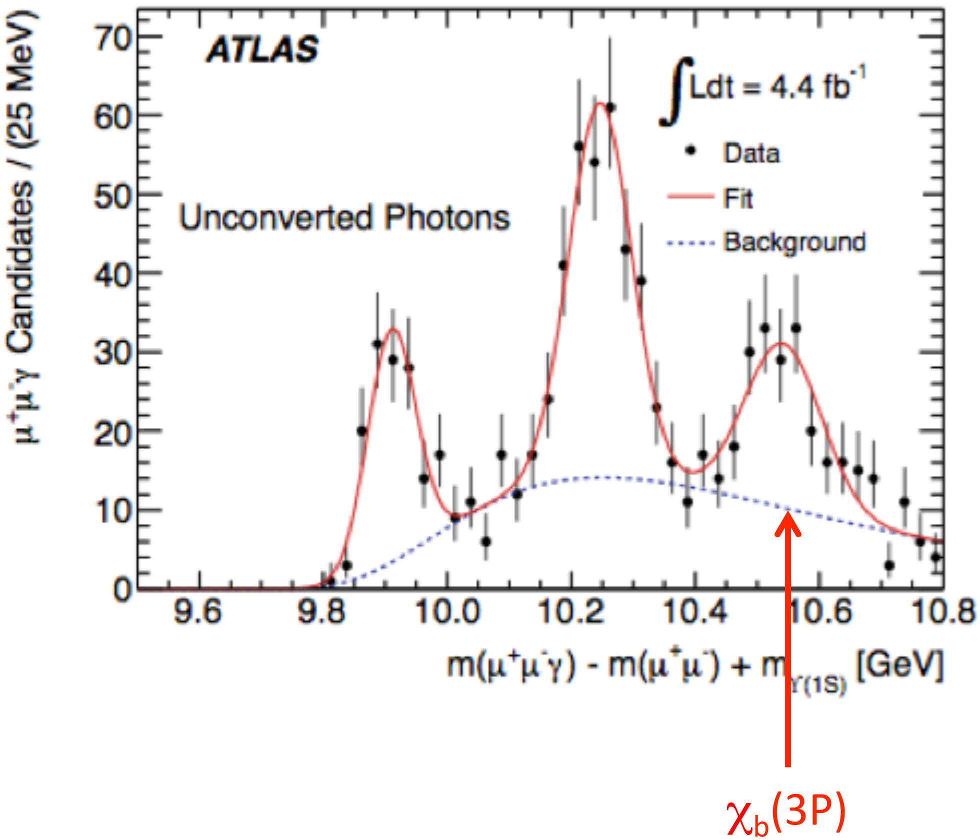
BABAR
Collaboration Home Page

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



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

The $\chi_b(3P)$



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

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

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

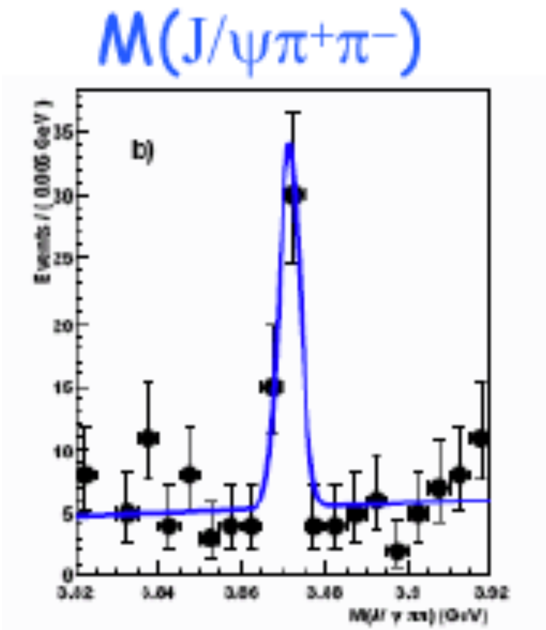
The XYZ States

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.68±0.17	< 1.2	1^{++}	$B \to K\,(\pi^+\pi^- J/\psi)$	Belle [37,38] (12.8), BABAR [39] (8.6)	2003	OK
				$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$	CDF [40–42] (np), D0 [43] (5.2)		
				$B \to K\,(\omega J/\psi)$	Belle [44] (4.3), BABAR [45] (4.0)		
				$B \to K\,(D^{*0}\overline{D}^0)$	Belle [46,47] (6.4), BABAR [48] (4.9)		
				$B \to K\,(\gamma J/\psi)$	Belle [49] (4.0), BABAR [50,51] (3.6), LHCb [52] (>10)		
				$B \to K\,(\gamma\psi(2S))$	BABAR [51] (3.5), Belle [49] (0.4), LHCb [52] (4.4)		
				$pp \to (\pi^+\pi^- J/\psi) + ...$	LHCb [53,54] (np)		
$Z_c(3900)^+$	3883.9 ± 4.5	25 ± 12	1^{+-}	$Y(4260) \to \pi^-(D\bar{D}^*)^+$	BESIII [55](np)	2013	NC!
	3891.2 ± 3.3	40 ± 8	$?^{?-}$	$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BESIII [56](8), Belle [57](5.2) T. Xiao *et al.* [CLEO data] [58](>5)	2013	OK
$Z_c(4020)^+$	4022.9 ± 2.8	7.9 ± 3.7	$?^{?-}$	$Y(4260, 4360) \to \pi^-(\pi^+ h_c)$	BESIII [59](8.9)	2013	NC!
	4026.3 ± 4.5	24.8 ± 9.5	$?^{?-}$	$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BESIII [60](10)	2013	NC!
$Z_b(10610)^+$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(10860) \to \pi(\pi\Upsilon(1S, 2S, 3S))$	Belle [61,62,63](>10)	2011	OK
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [62](16)	2011	OK
				$\Upsilon(10860) \to \pi^-(B\bar{B}^*)^+$	Belle [64](8)	2012	NC!
$Z_b(10650)^+$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(10860) \to \pi^-(\pi^+\Upsilon(1S, 2S, 3S))$	Belle [61,62](>10)	2011	OK
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [62](16)	2011	OK
				$\Upsilon(10860) \to \pi^-(B^*\bar{B}^*)^+$	Belle [64](6.8)	2012	NC!

The XYZ States

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment ($\#\sigma$)	Year	Status
$\chi_{c0}(3915)$	3917.4 ± 2.7	28^{+10}_{-9}	0^{++}	$B \to K\,(\omega J/\psi)$	Belle [66] (8.1), BABAR [67,65] (19)	2004	OK
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle [68] (5.3), BABAR [69,45] (5.8)	2005	OK
				$e^+e^- \to e^+e^-\,(\omega J/\psi)$	Belle [70] (7.7), BABAR [45] (np)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\overline{D}^*)$	Belle [71] (6.0)	2007	NC!
				$e^+e^- \to J/\psi\,(\ldots)$	Belle [21] (5.0)		
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [72] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K\,(\pi^+\chi_{c1}(1P))$	Belle [73] (5.0), BABAR [74] (1.1)	2008	NC!
$Y(4140)$	4145.8 ± 2.6	18 ± 8	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [75,76](5.0), Belle [77](1.9),	2009	NC!
					LHCb [78](1.4), CMS [79](>5)		
					D0 [80](3.1)		
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\overline{D}^*)$	Belle [71] (5.5)	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K\,(\pi^+\chi_{c1}(1P))$	Belle [73] (5.0), BABAR [74] (2.0)	2008	NC!
$Y(4260)$	4263^{+8}_{-9}	95 ± 14	1^{--}	$e^+e^- \to \gamma\,(\pi^+\pi^- J/\psi)$	BABAR [81,82] (8.0)	2005	OK
					CLEO [83] (5.4), Belle [72] (15)		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [84] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [84] (5.1)		
				$e^+e^- \to (f_0(980) J/\psi)$	BaBar [85](np), Belle [57](np)	2012	OK
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BESIII [56](8), Belle [57](5.2)	2013	OK
				$e^+e^- \to (\gamma\, X(3872))$	BESIII [86](5.3)	2013	NC!
$Y(4274)$	4293 ± 20	35 ± 16	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [76](3.1), LHCb [78](1.0),	2011	NC!
					CMS [79](>3), D0 [80](np)		
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \to e^+e^-\,(\phi J/\psi)$	Belle [87] (3.2)	2009	NC!
$Y(4360)$	4361 ± 13	74 ± 18	1^{--}	$e^+e^- \to \gamma\,(\pi^+\pi^-\psi(2S))$	BABAR [88] (np), Belle [89] (8.0)	2007	OK
$Z(4430)^+$	4458 ± 15	166^{+37}_{-32}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [90,91,92](6.4), BaBar [93](2.4)	2007	OK
				$B^0 \to \psi(2S)\pi^- K^+$	LHCb [94](13.9)		
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma\,(\Lambda_c^+\Lambda_c^-)$	Belle [95] (8.2)	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma\,(\pi^+\pi^-\psi(2S))$	Belle [89] (5.8)	2007	NC!
$\Upsilon(10860)$	10876 ± 11	55 ± 28	1^{--}	$e^+e^- \to (B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}(\pi))$	PDG [96]	1985	OK
				$e^+e^- \to (\pi\pi\Upsilon(1S,2S,3S))$	Belle [97,62,63](>10)	2007	OK
				$e^+e^- \to (f_0(980)\Upsilon(1S))$	Belle [62,63](>5)	2011	OK
				$e^+e^- \to (\pi Z_b(10610,10650))$	Belle [62,63](>10)	2011	OK
				$e^+e^- \to (\eta\Upsilon(1S,2S))$	Belle [98](10)	2012	OK
				$e^+e^- \to (\pi^+\pi^-\Upsilon(1D))$	Belle [98](9)	2012	OK
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [99](2.3)	2008	NC!

The X(3872) Discovery



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

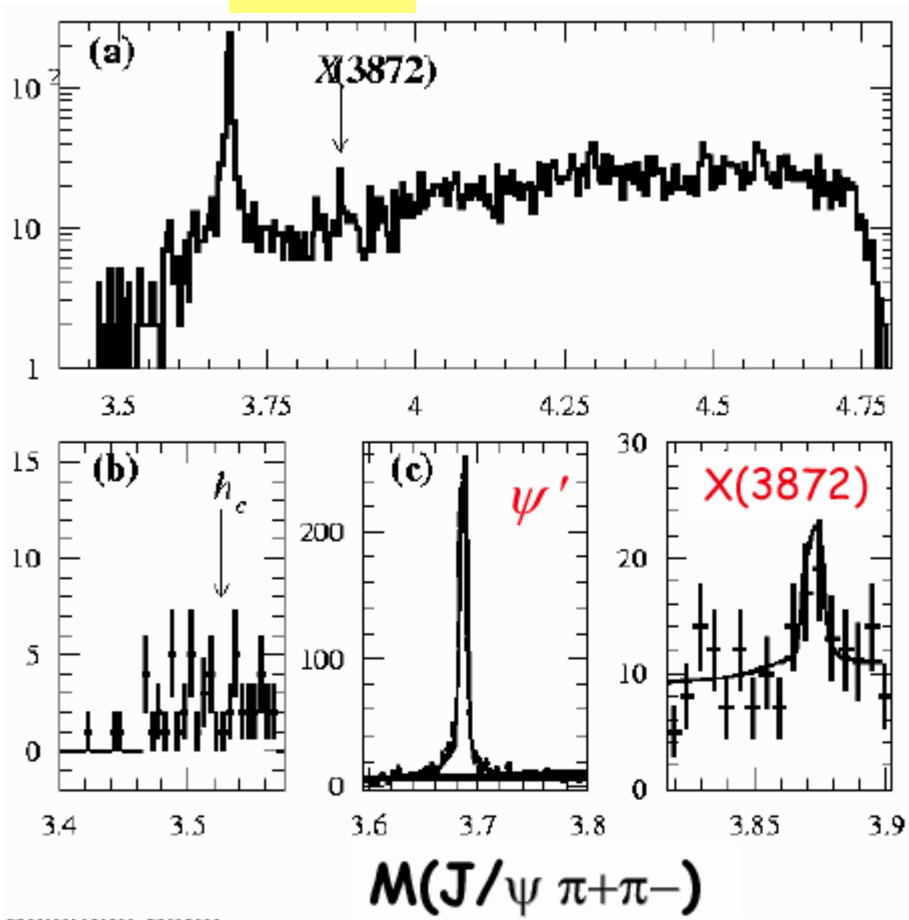
$B^\pm \to K^\pm (J/\psi\pi^+\pi^-)$, $J/\psi \to \mu^+\mu^-$ or e^+e^-

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

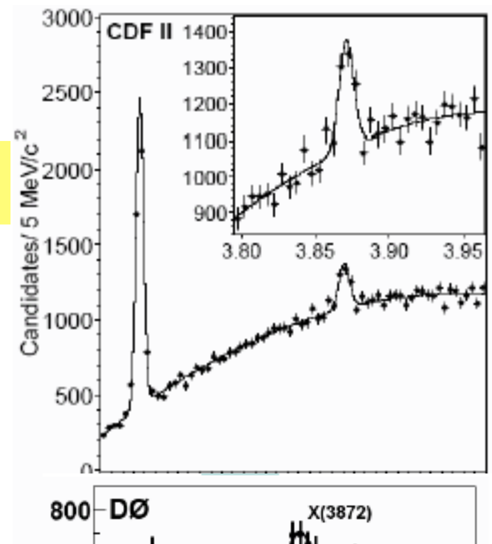
$$\frac{\Gamma\left(X(3872) \to \gamma\chi_{c1}\right)}{\Gamma\left(X(3872) \to \pi^+\pi^- J/\psi\right)} < 0.89 \quad (90\% C.L.)$$

The X(3872) Confirmation

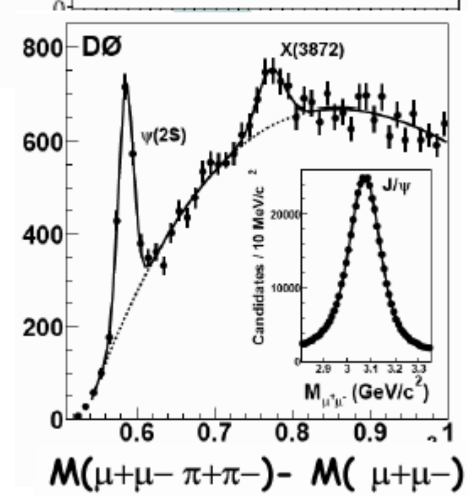
BaBar



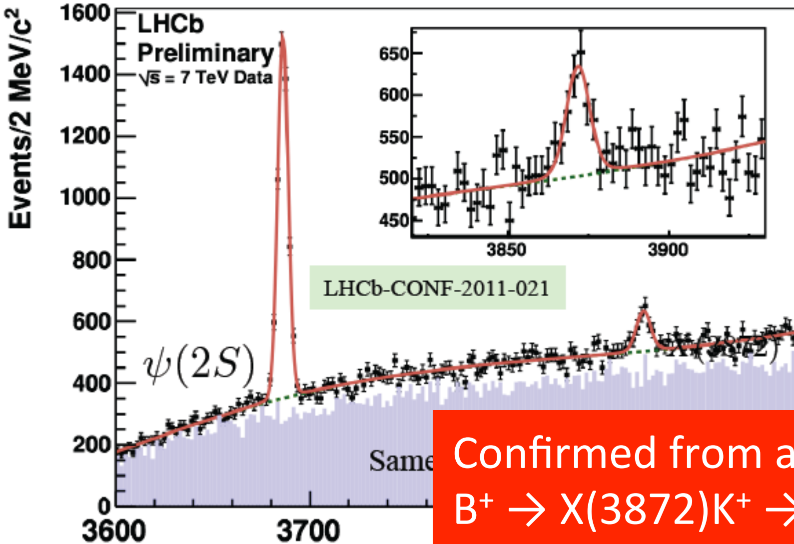
CDF



D0

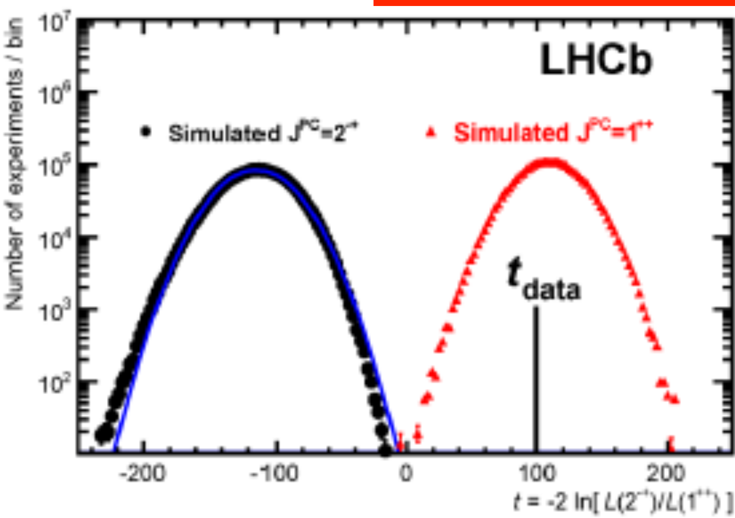


The X(3872) at LHCb

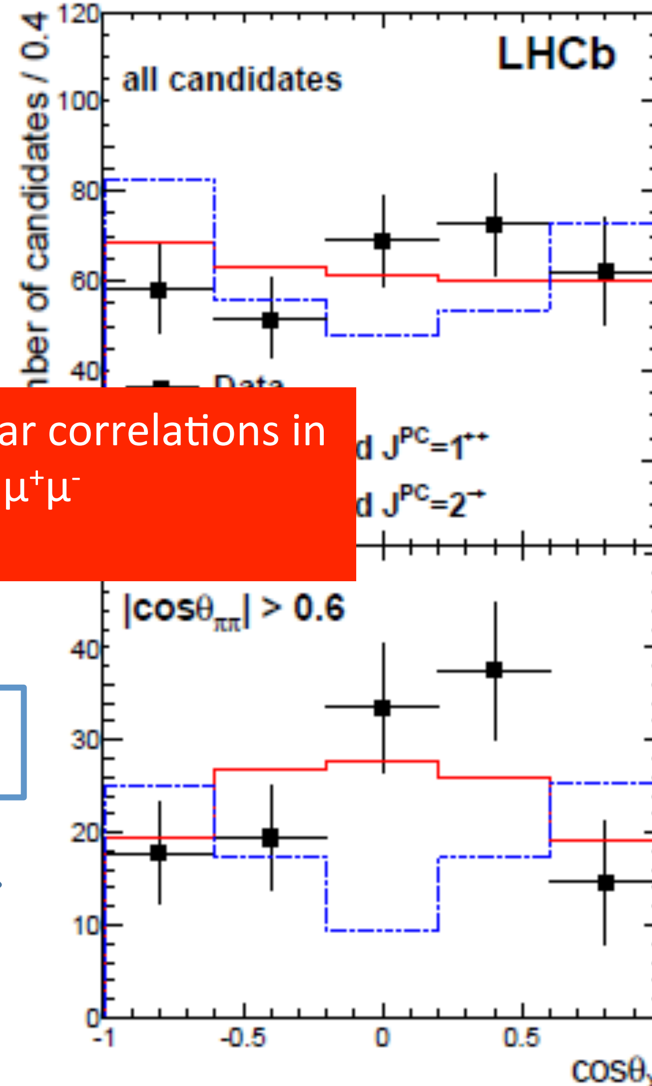


Confirmed from analysis of angular correlations in $B^+ \to X(3872)K^+ \to \pi^+\pi^- J/\Psi$, $J/\Psi \to \mu^+\mu^-$

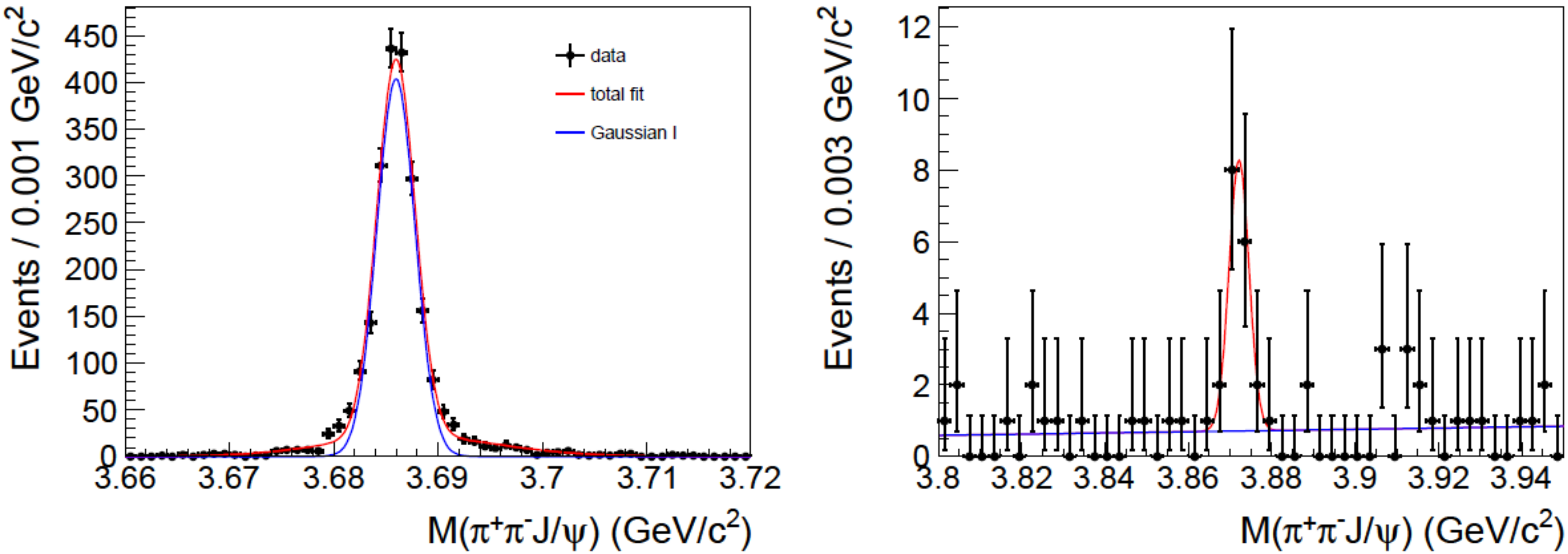
arXiv:1504.06339v1



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



The X(3872) at BES III



ISR ψ' signal is used for rate, mass, and mass resolution calibration.
$N(\psi')=1242$; Mass=3685.96±0.05 MeV; $\sigma_M=1.84 \pm 0.06$ MeV

BESIII preliminary

N(X(3872))=15.0±3.9 **5.3σ**

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

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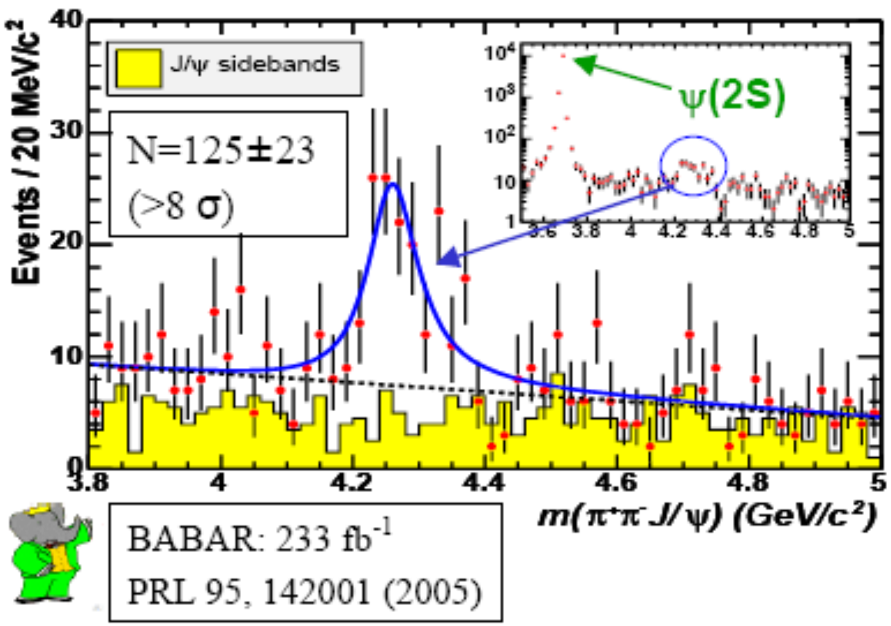
What is the X(3872) ?

- 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 $\bar{c}c$, K*X smaller than $\bar{c}c$
  - $Y(4260) \rightarrow \gamma + X(3872)$ [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:

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

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

Confirmed by CLEO, CLEO III, Belle, BESIII

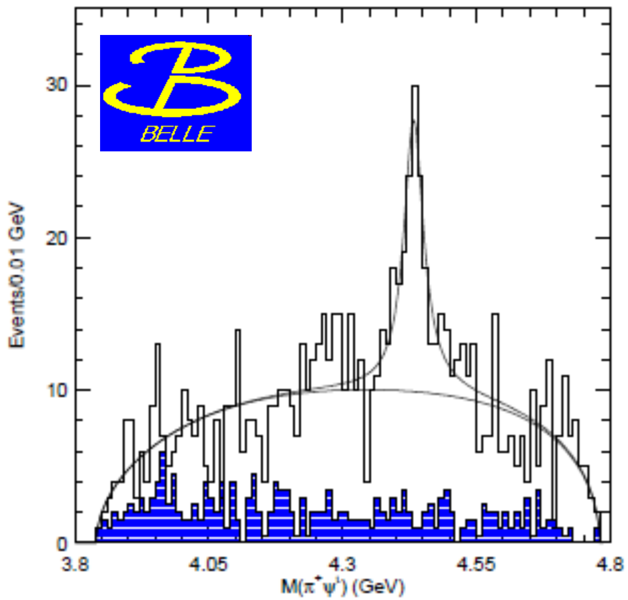
From PDG:

$$M = 4250 \pm 9\ MeV/c^2$$
$$\Gamma = 108 \pm 12\ MeV$$

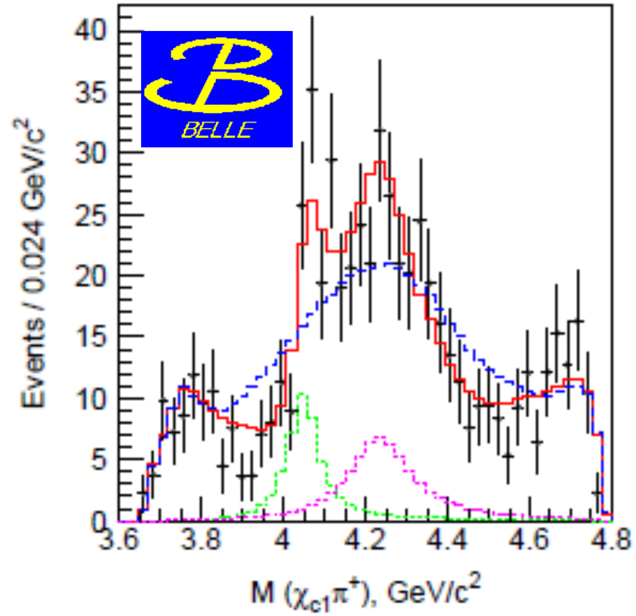
Weak coupling consistent with hybrid meson. Shows up as very small maximum near the deep minimum between conventional charmonium states $\psi(4160)$ and $\psi(4415)$

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

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



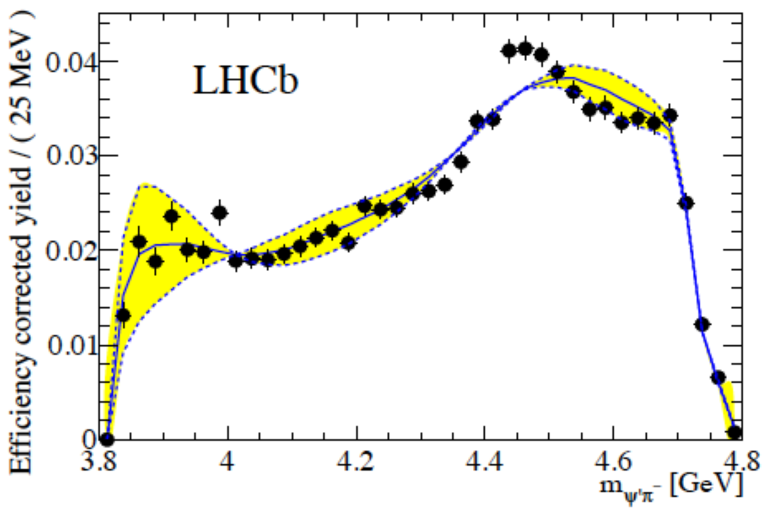
$Z_1^+(4050) \rightarrow \chi_{c1}\pi^+$, $Z_2^+(4250) \rightarrow \chi_{c1}\pi^+$

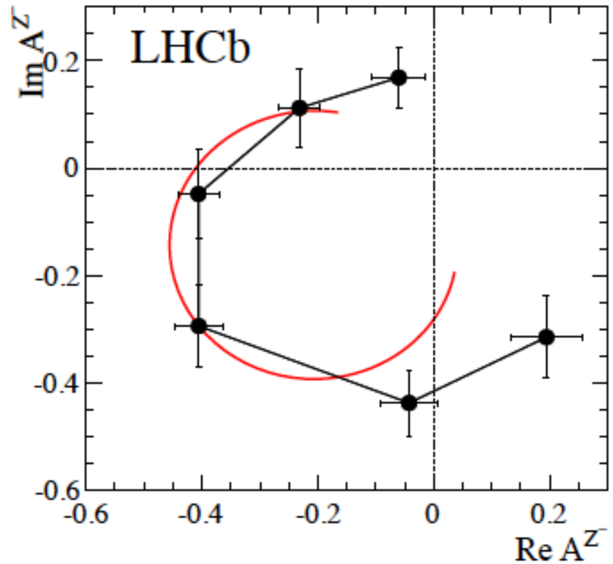


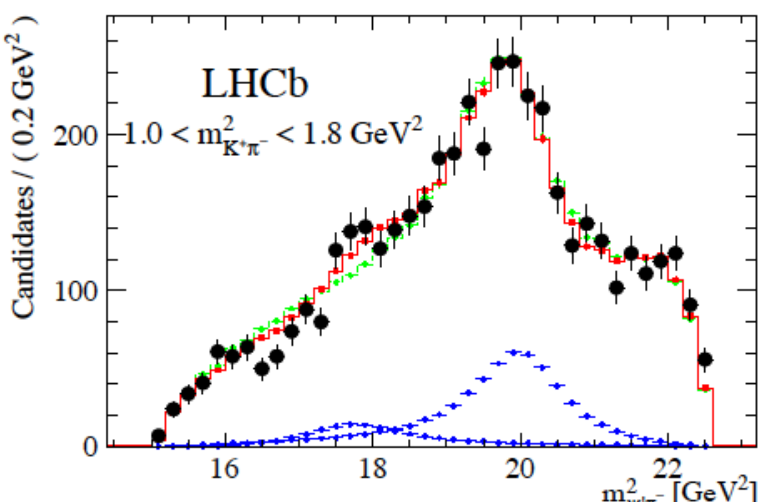
Not confirmed by BaBar that also studied the $J/\psi\pi^- K^+$ and $J/\psi\pi^- K_0^s$ channels.
The $J/\psi\pi K$ final state was also studied by Belle, who did not find any evidence of Z.
Belle confirmed the Z in a Dalitz reanalysis.

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

$Z^-(4430)$ at LHCb

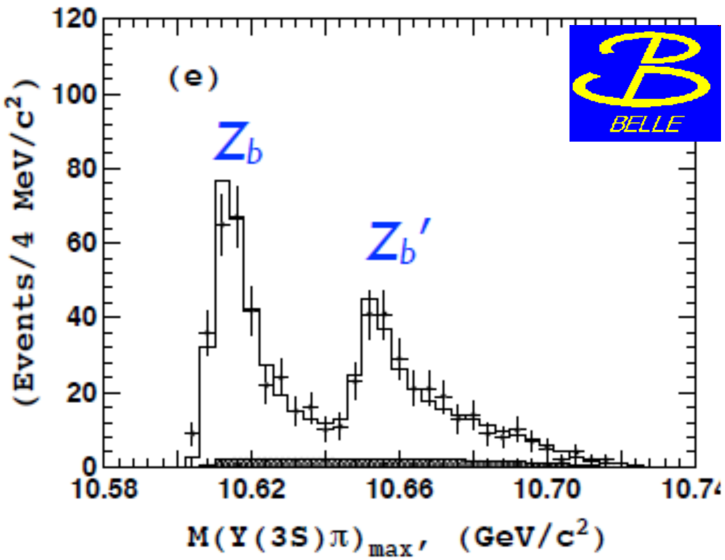






$B^0 \to K^+\psi(2S)\pi^-$
$M = 4475 \pm 7\ ^{+15}_{-25}$ MeV
$\Gamma = 172 \pm 13\ ^{+37}_{-34}$ MeV
$J^P = 0^+$

$Z_b(10610)$ 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 ?

$Z_c^+(3900)$

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

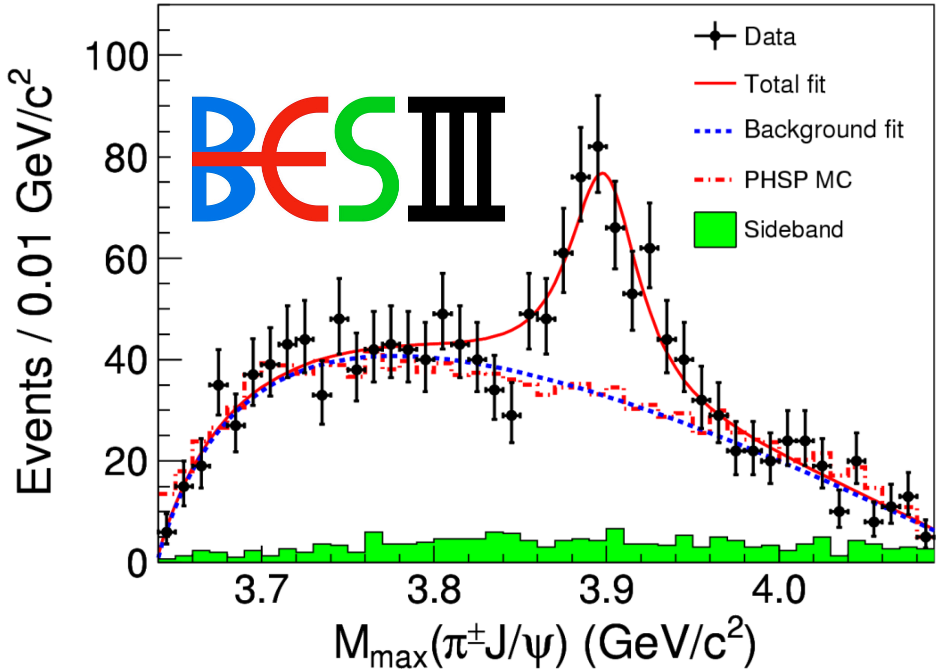
1477 events – 525 pb-1

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

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

Minimal quark content $b\bar{b}u\bar{d}$

$Z_c(3900)^{\pm}$



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

$Z_c^+(3900)$

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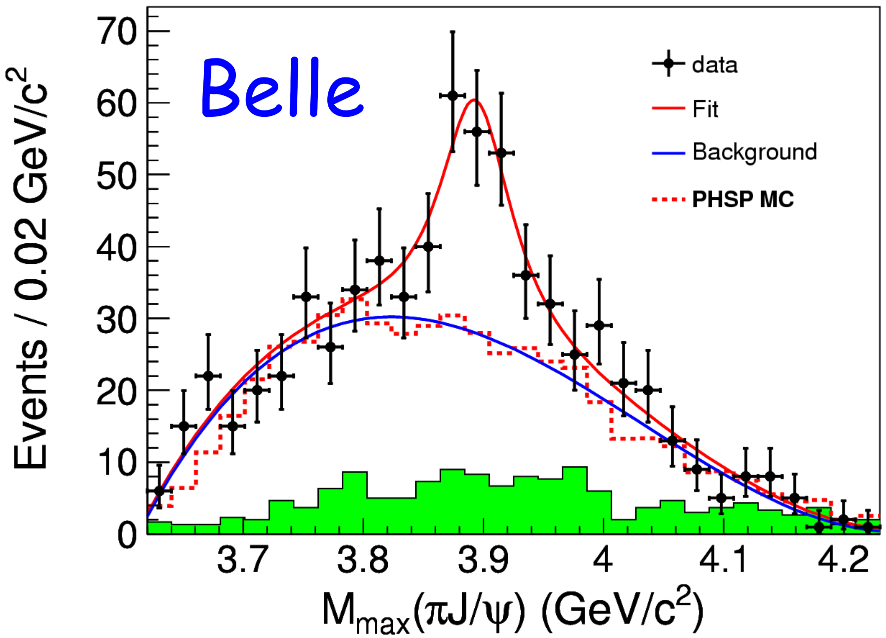
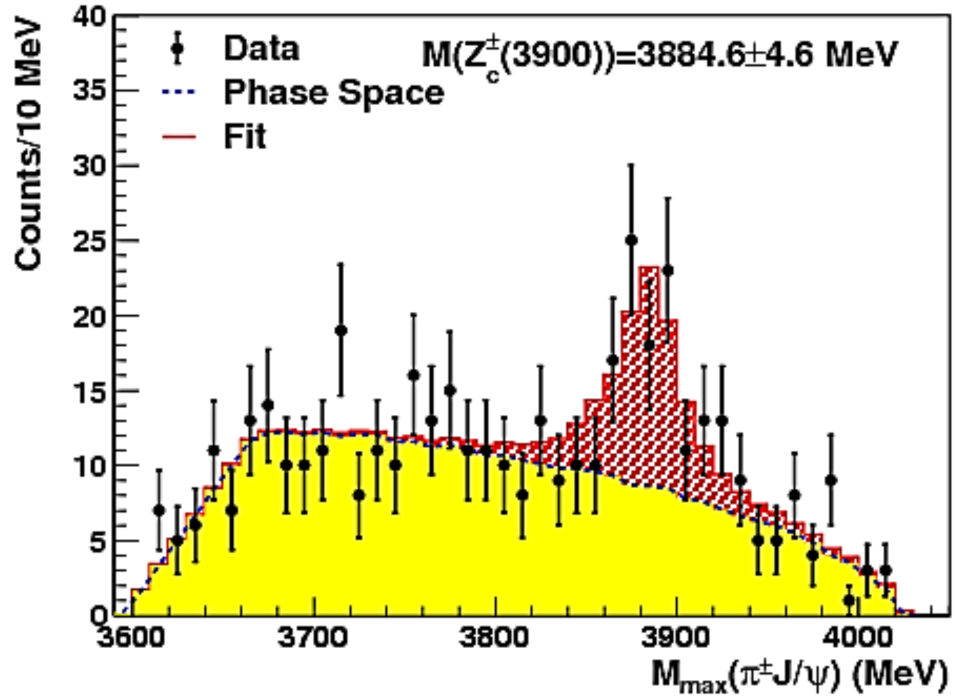
Belle with ISR: 1304.0121



CLEOc data at 4.17 GeV: 1304.3036



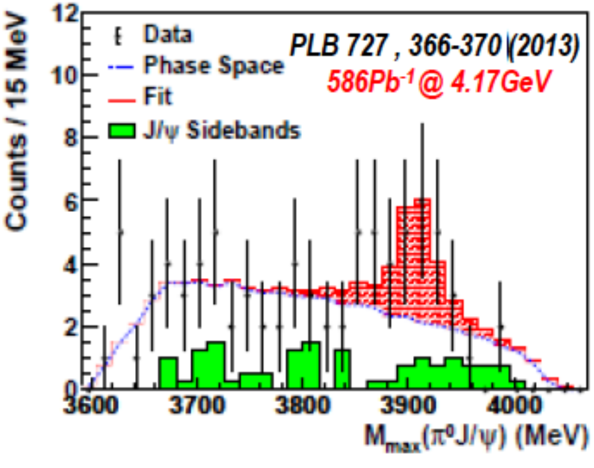
M = 3894.5±6.6±4.5 MeV
Γ = 63±24±26 MeV
159 ± 49 events
>5.2σ

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

$Z_c^0(3900)$ in $e^+e^- \to \pi^0\pi^0 J/\psi$

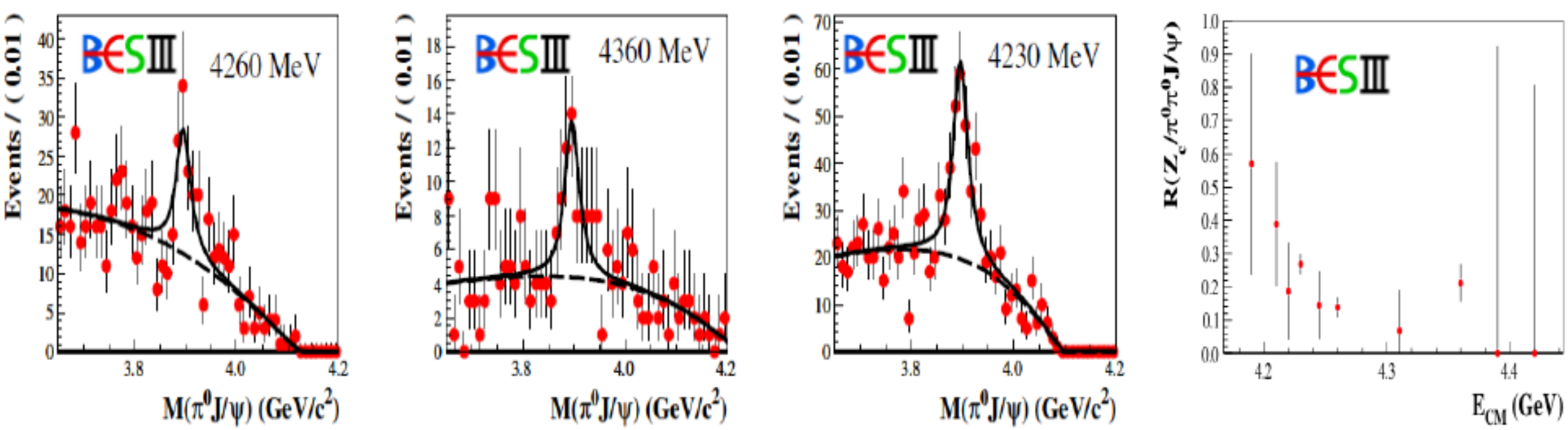
Has an isospin partner, $Z_c(3900)^0$?

BESIII Preliminary



- $2.8 fb^{-1}$ data at 10 energy points from 4260~4420 MeV
- $Z_c(3900)^0$ is observed clearly at E_{cm}=4230, 4260, 4360MeV
- BESIII preliminary results :
  - M= 3894.8 $\pm$ 2.3 MeV, Γ = 29.6 $\pm$ 8.2 MeV
  - Significance = 10.4 σ
- $R(Z_c^0/\pi^0\pi^0 J/\psi)=N(Z_c^0(3900))/N(\pi^0\pi^0 J/\psi)$, E_{cm} dependence

Neutral isospin partner, $Z_c(3900)^0$ observed



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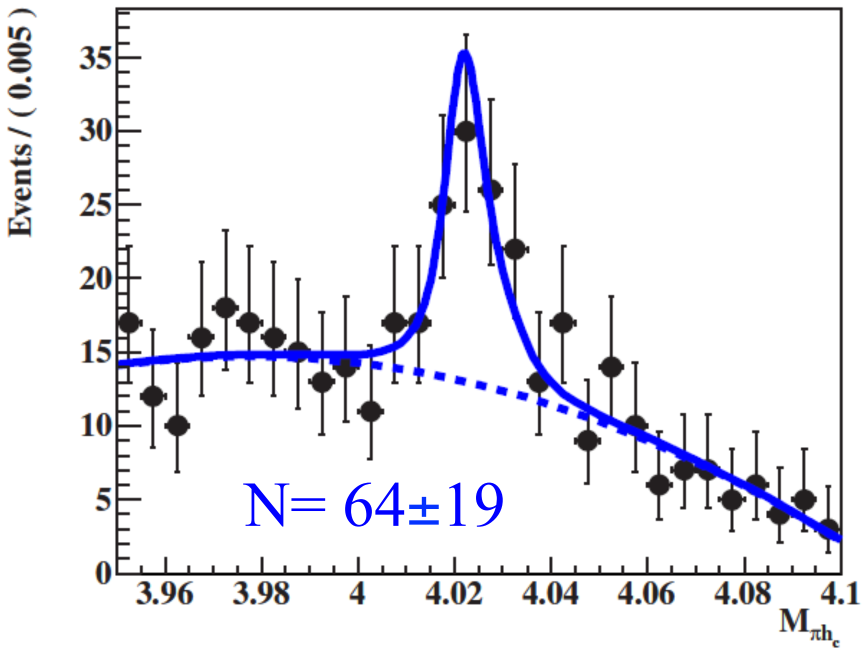
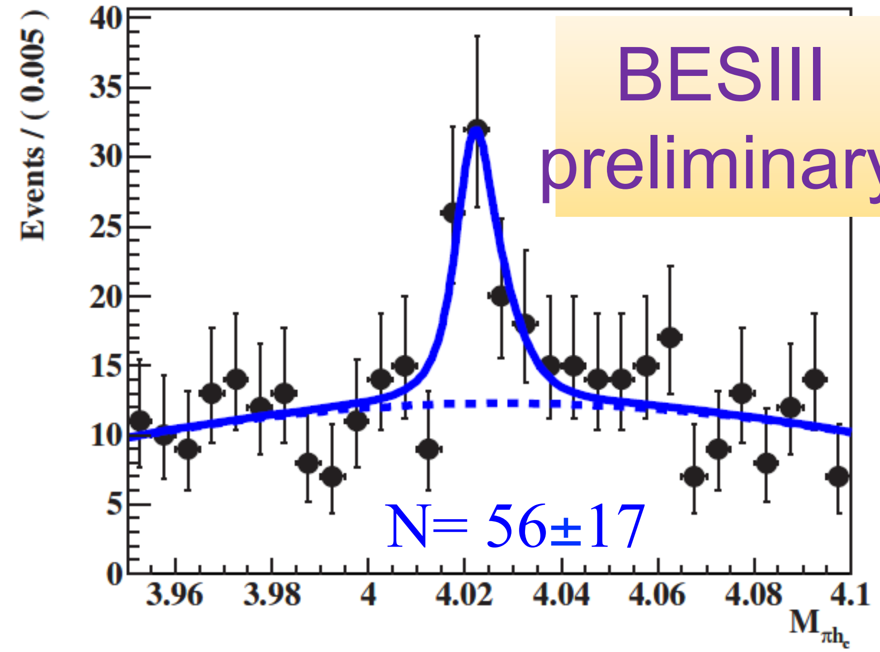
BESIII $e^+e^- \to \pi Z_c(4020) \to \pi^+\pi^- h_c(1P)$

Ecm=4.26 GeV



Ecm=4.36 GeV



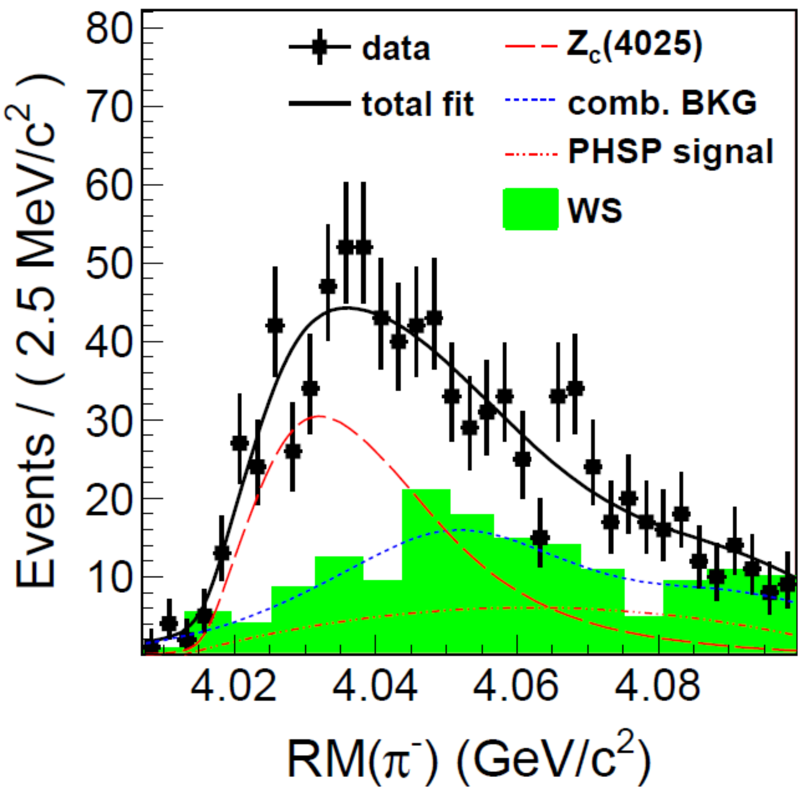
Simultaneous fit to 4.26/4.36 GeV data and 16 η_c decay modes. 6.4σ

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

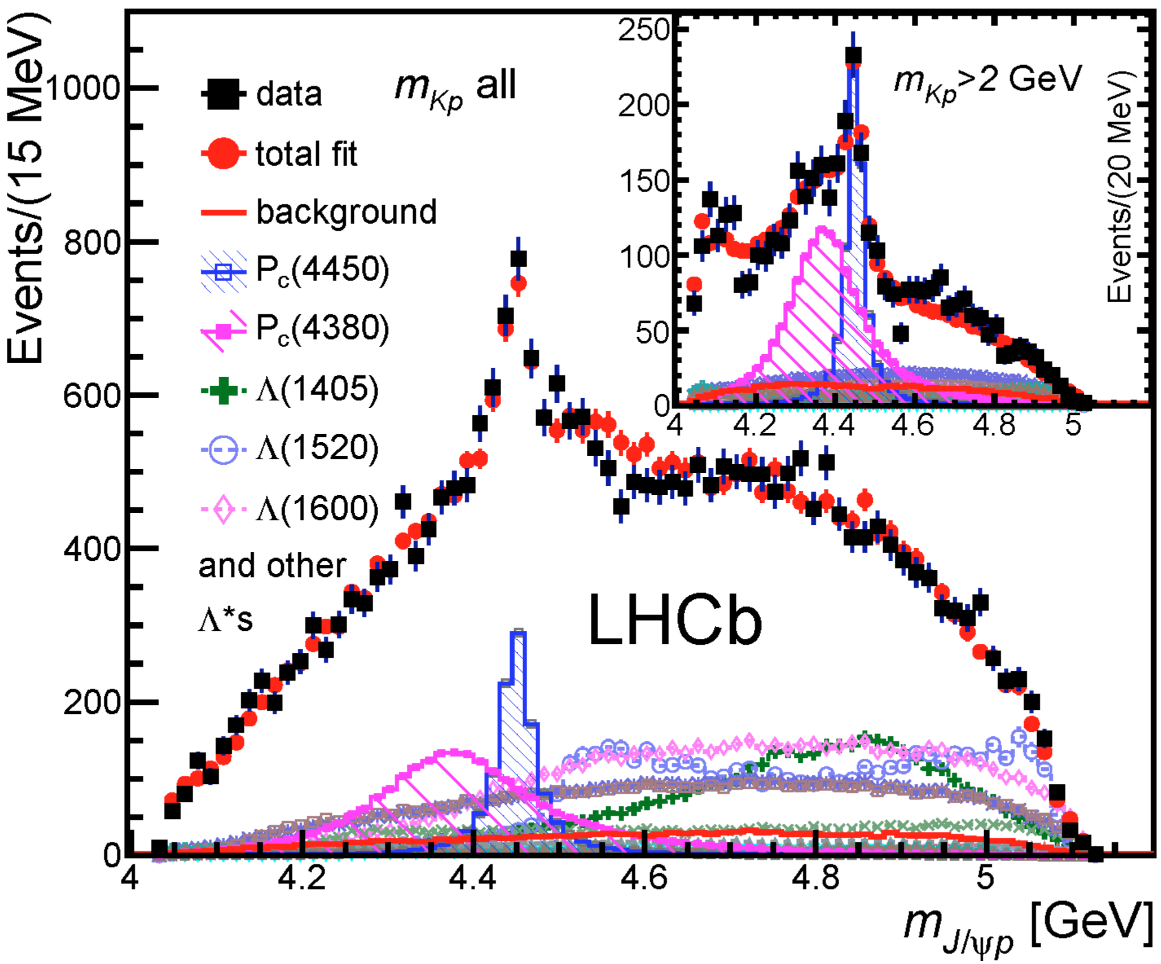
$M(Z_c(4025)) = 4026.3 \pm 2.6 \pm 3.7$ MeV;

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

BESIII: 1308.2760

The LHCb Pentaquark

$\Lambda^0_b \rightarrow P^+_c K^- J/\psi p K^-$



M = 4449.8±1.7±2.5 MeV
Γ = 39±5±19 MeV

M = 4380±8±29 MeV
Γ =205±18±86 MeV

Models for XYZ Mesons

- conventional quarkonium $Q\bar{Q}$
- quarkonium hybrids $Q\ \bar{Q}\ g$
- quarkonium tetraquarks $Q\ \bar{q}\ q\ \bar{Q}$
  - compact tetraquark
  - meson molecule
  - diquark-onium
  - hadro-quarkonium

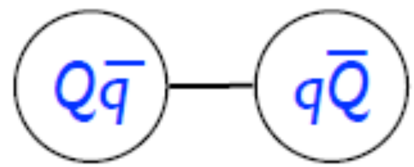
Eric Braaten – Charm 2013

Models for XYZ Mesons

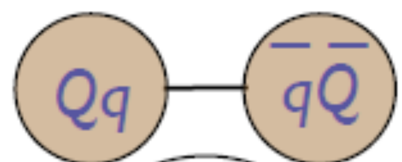
quarkonium tetraquarks

- compact tetraquark

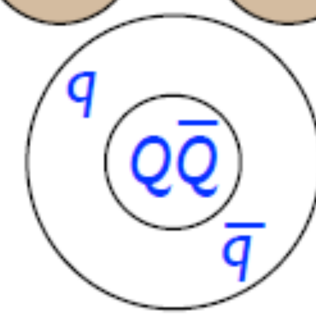
- meson molecule



- diquark-onium



- hadro-quarkonium



- Born-Oppenheimer tetraquark! arXiv:1305.6905

Eric Braaten – Charm 2013

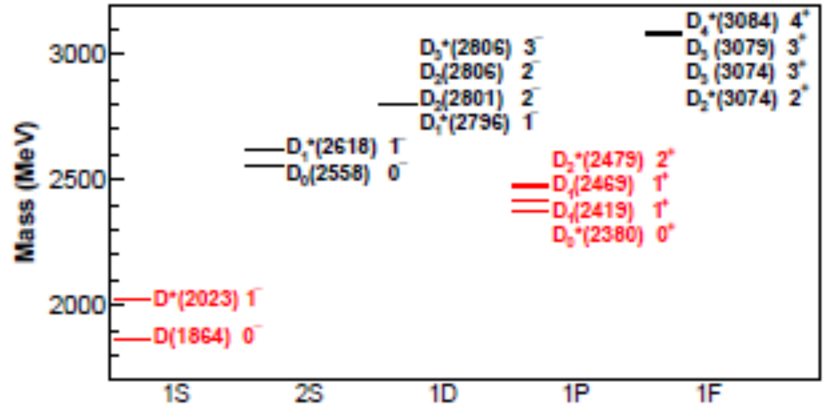
Open Charm

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

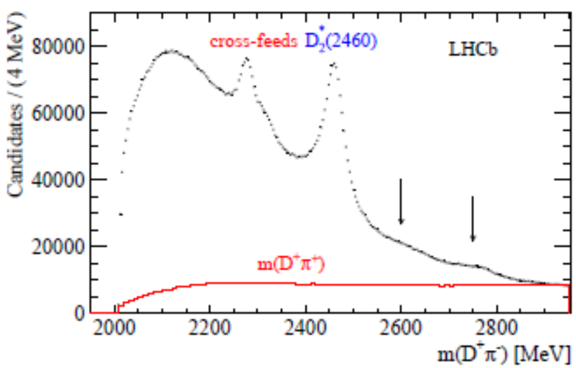
- Ground states (D, D^*) and two of the 1P states $D_1(2420)$ and $D_2^*(2460)$ experimentally well established since they are narrow.
- Broad L=1 states $D_0^*(2400)$ and $D_1'(2430)$ found by BaBar and Belle in exclusive B decays
- Babar found 4 new states decaying to $D\pi$ and $D^*\pi$.



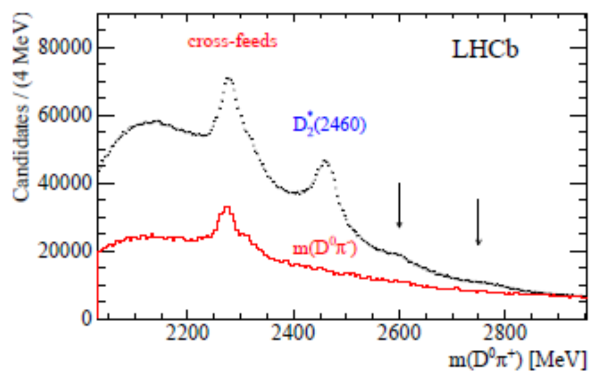
Resonance	Channel(Fit)	Efficiency (%)	Yield (x10^3)	Mass (MeV/c^2)	Width (MeV)	Significance
$D_1(2420)^0$	$D^{*+}\pi^-$ (C)		102.8±1.3±2.3	2420.1±0.1±0.8	31.4±0.5±1.3	
	$D^{*+}\pi^-$ (E)	1.09 ± 0.03	214.6±1.2±6.4	2420.1(fixed)	31.4(fixed)	
$D_2^*(2460)^0$	$D^+\pi^-$ (A)	1.29 ± 0.03	242.8±1.8±3.4	2462.2±0.1±0.8	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

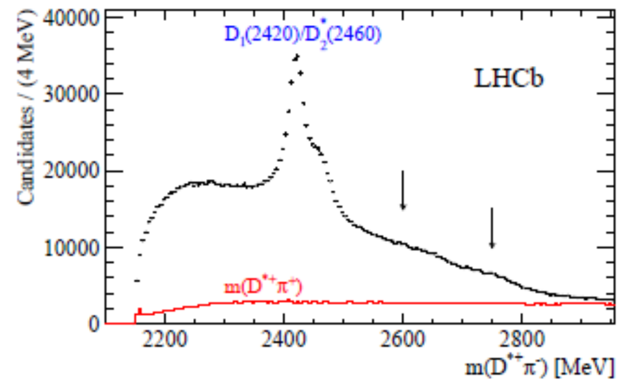
$D^+\pi^-$ and $D^+\pi^+$ mass spectra.



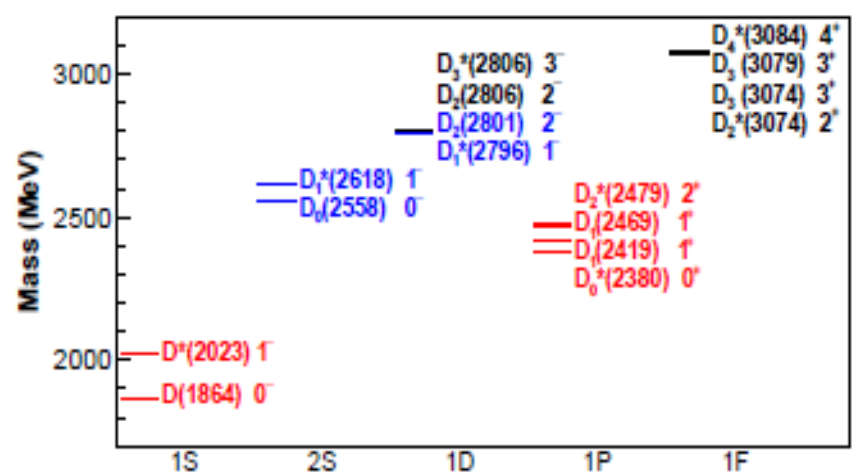
$D^0\pi^+$ and $D^0\pi^-$ mass spectra.



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



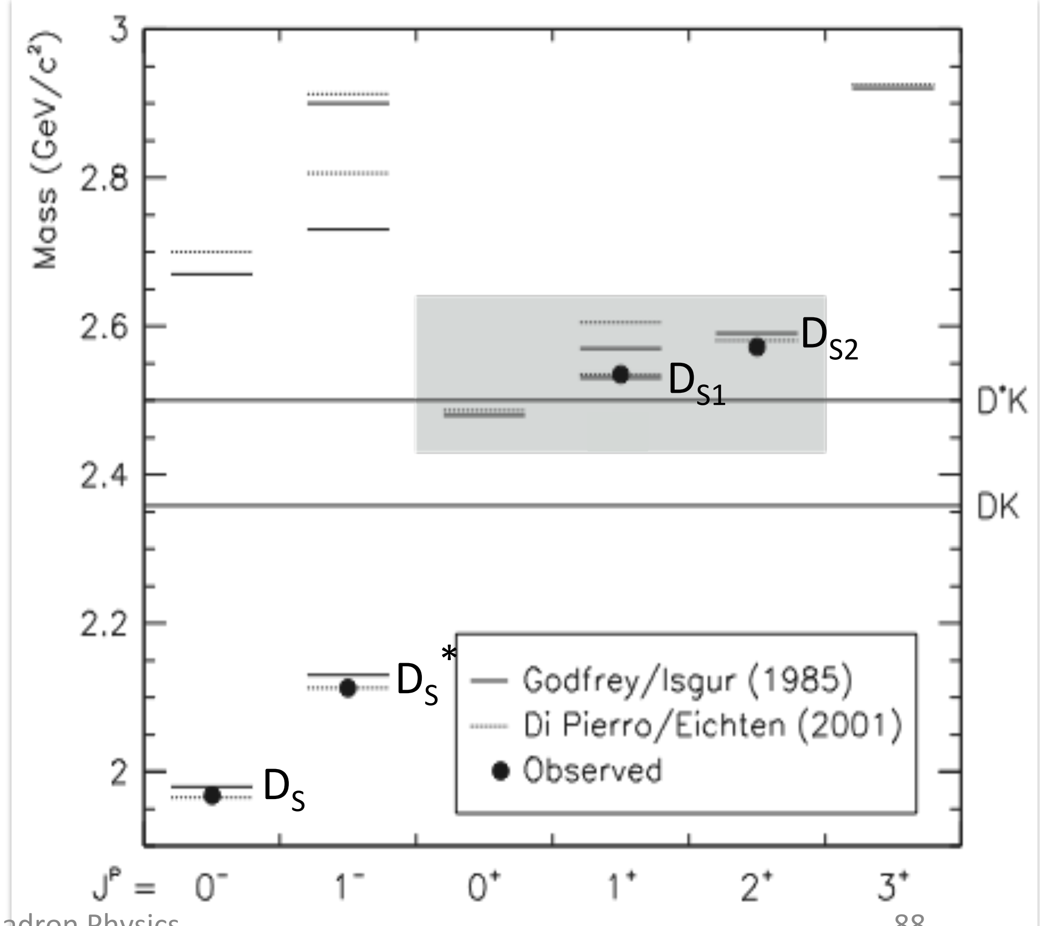
Resonance	Final state	Mass (MeV)			Width (MeV)		
$D_1(2420)^0$	$D^{*+}\pi^-$	2419.6 ±	0.1	± 0.7	35.2 ±	0.4	± 0.9
$D_2^*(2460)^0$	$D^{*+}\pi^-$	2460.4 ±	0.4	± 1.2	43.2 ±	1.2	± 3.0
$D_J^*(2650)^0$	$D^{*+}\pi^-$	2649.2 ±	3.5	± 3.5	140.2 ±	17.1	± 18.6
$D_J^*(2760)^0$	$D^{*+}\pi^-$	2761.1 ±	5.1	± 6.5	74.4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



D_s States

For the states $c(\bar{u}/\bar{d})$ 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 $D_S(c\bar{s})$ mesons with good accuracy



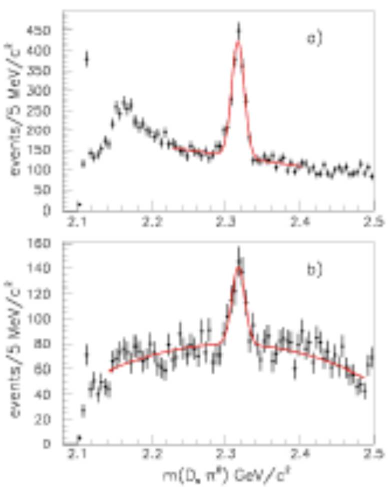
B. Aubert et al., PRD74, 032007 (2006).

D_s States

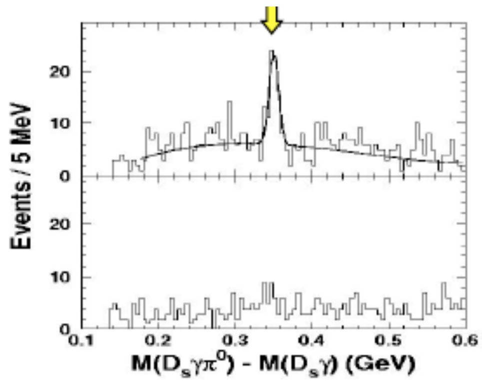
The discovery of the new D_{SJ} states has brought into question potential models

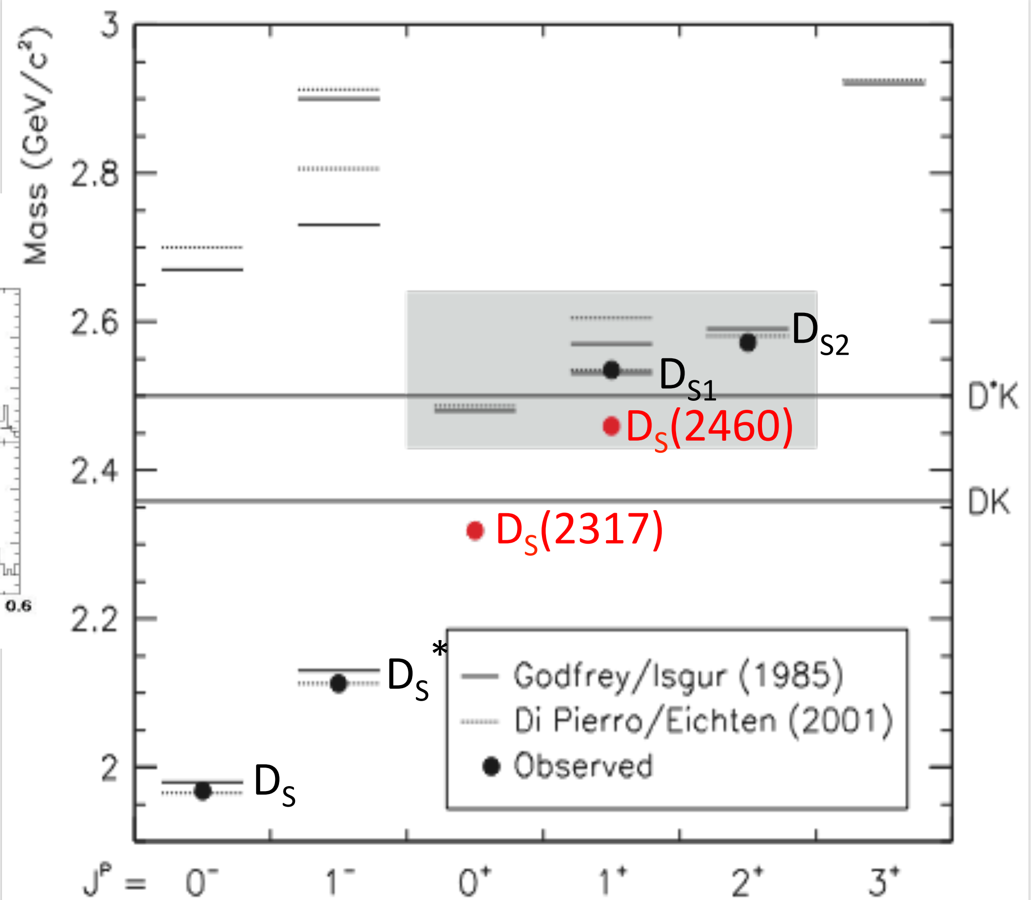
Two new states $D_S(2317)$ and $D_S(2460)$ were discovered in $e^+e^- \to \bar{c}c$ events, then observed in B decays by Babar, Belle and CLEO

BaBar $D_S(2317)$



CLEO $D_S(2460)$

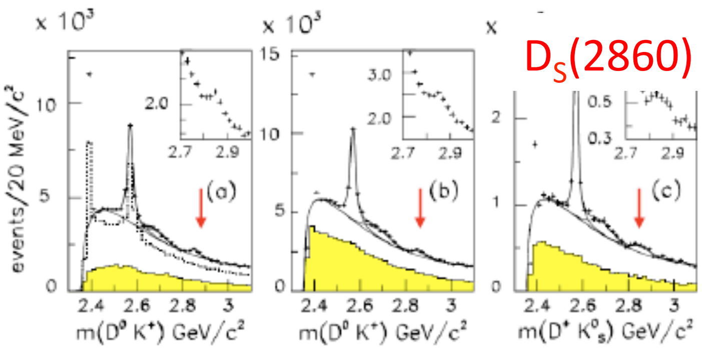




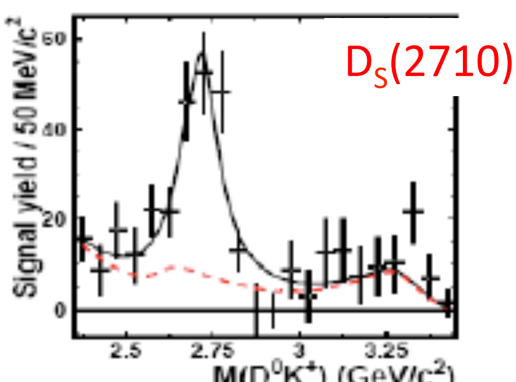
The identification of these states as the 0^+ and 1^+ $\bar{c}s$ states is difficult within the potential model

D_s States

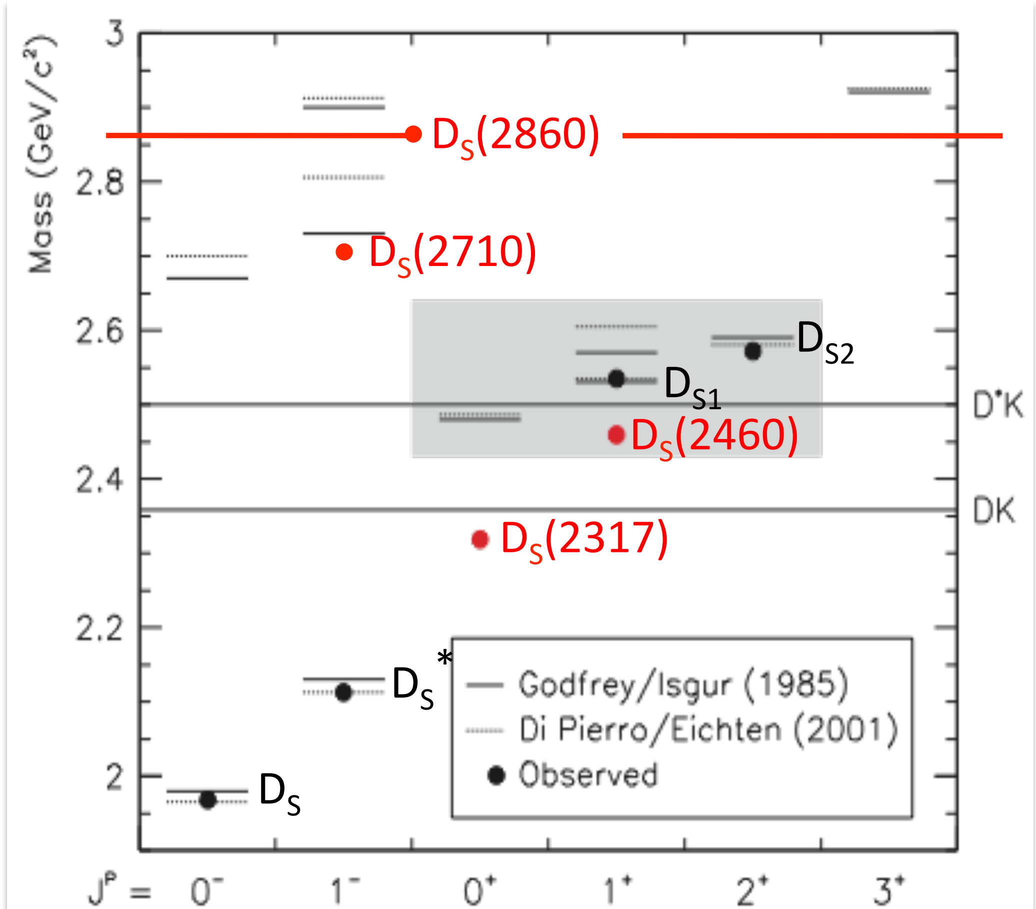
The discovery of the new D_{SJ} states continued …



BaBar Collab., PRL 97 (06) 222001



Belle Collab, PRL 100 (08) 092001



D_s States

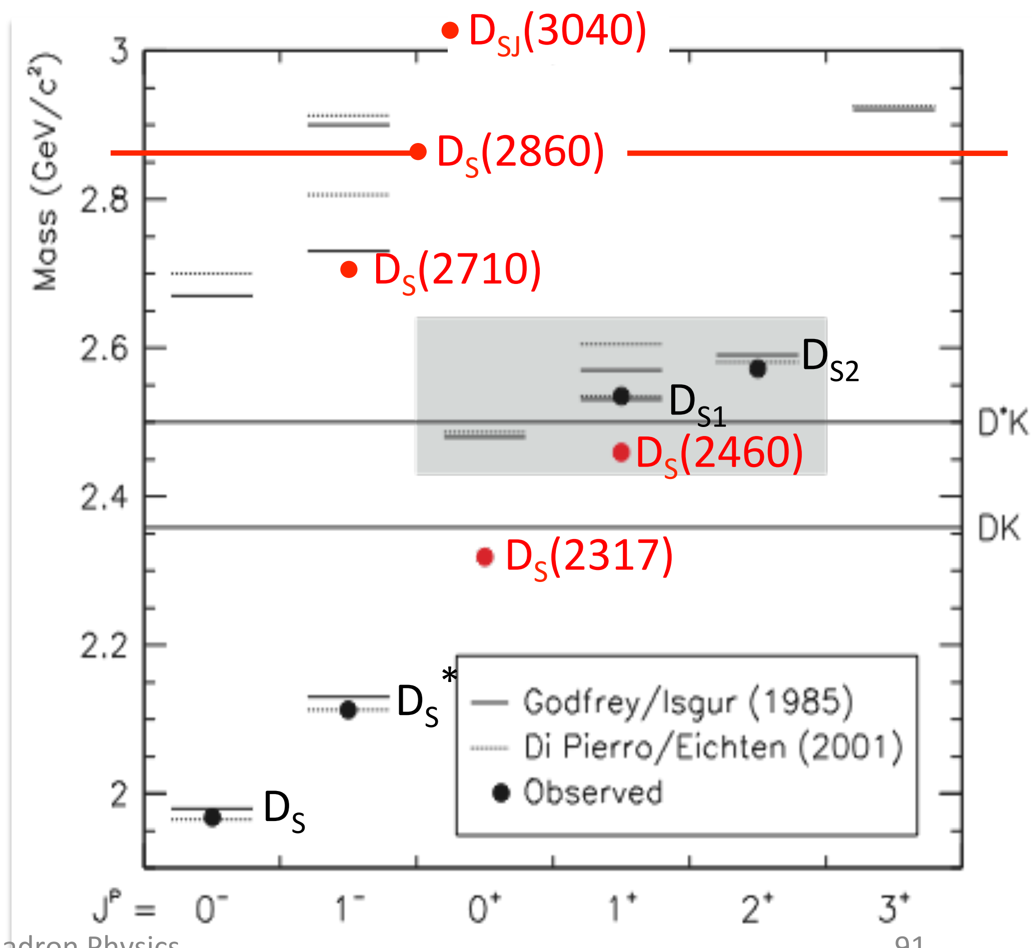
The assignment of the q.n. to the $D_S(2710)$ was possible thanks to an analysis performed by BaBar studying *DK*, *D*K* final states.

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

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

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

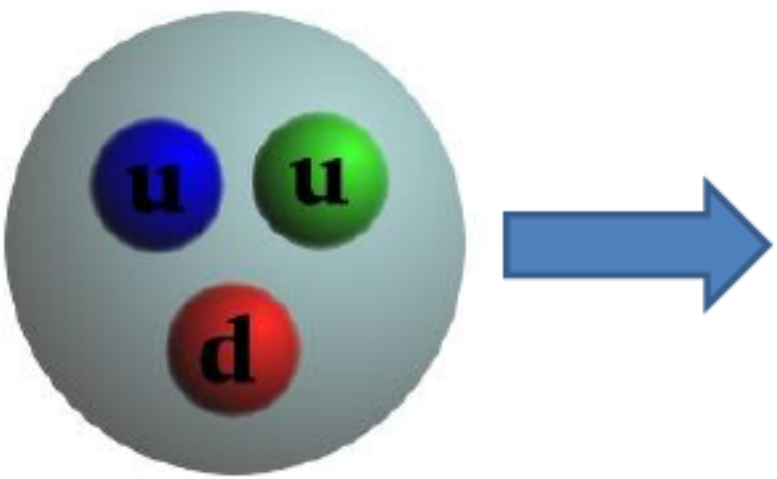
$$m(D_{sJ}(3040)) = 3044 \pm 8_{\rm stat}(^{+30}_{-5})_{\rm syst}\ {\rm MeV}/c^2,$$
$$\Gamma = 239 \pm 35_{\rm stat}(^{+46}_{-42})_{\rm syst}\ {\rm MeV}.$$

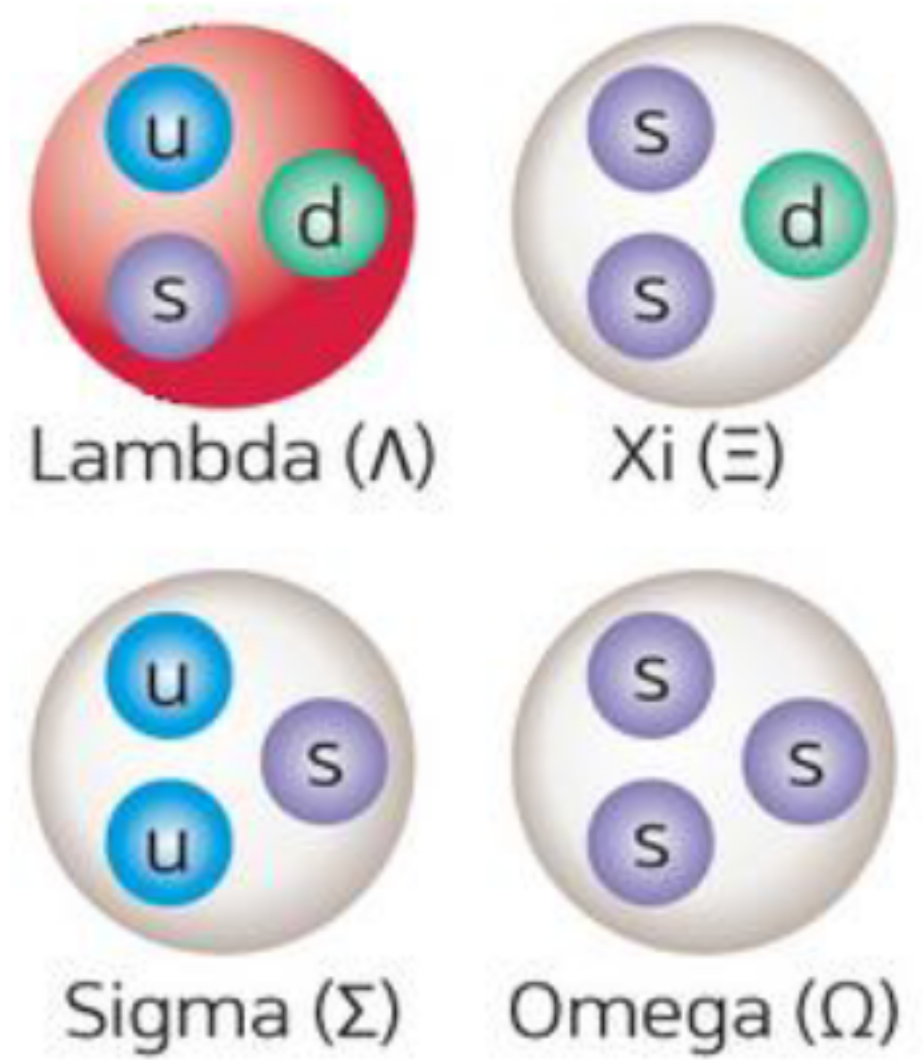


There is a problem for the potential models in describing excited states

Strange and Charmed Hyperons

What happens if we replace one of the light quarks in the proton with one - or many - heavier quark(s)?





Strange and Charmed Baryons

- Light quark (*u*, *d*) systems:
  - Highly non-perturbative interactions.
  - Relevant degrees of freedom are hadrons.

- Systems with strangeness
  - Scale: $m_s \approx 100$ MeV ~ $\Lambda_{QCD} \approx 200$ MeV.
  - Relevant degrees of freedom?
  - **Probes QCD in the intermediate domain.**

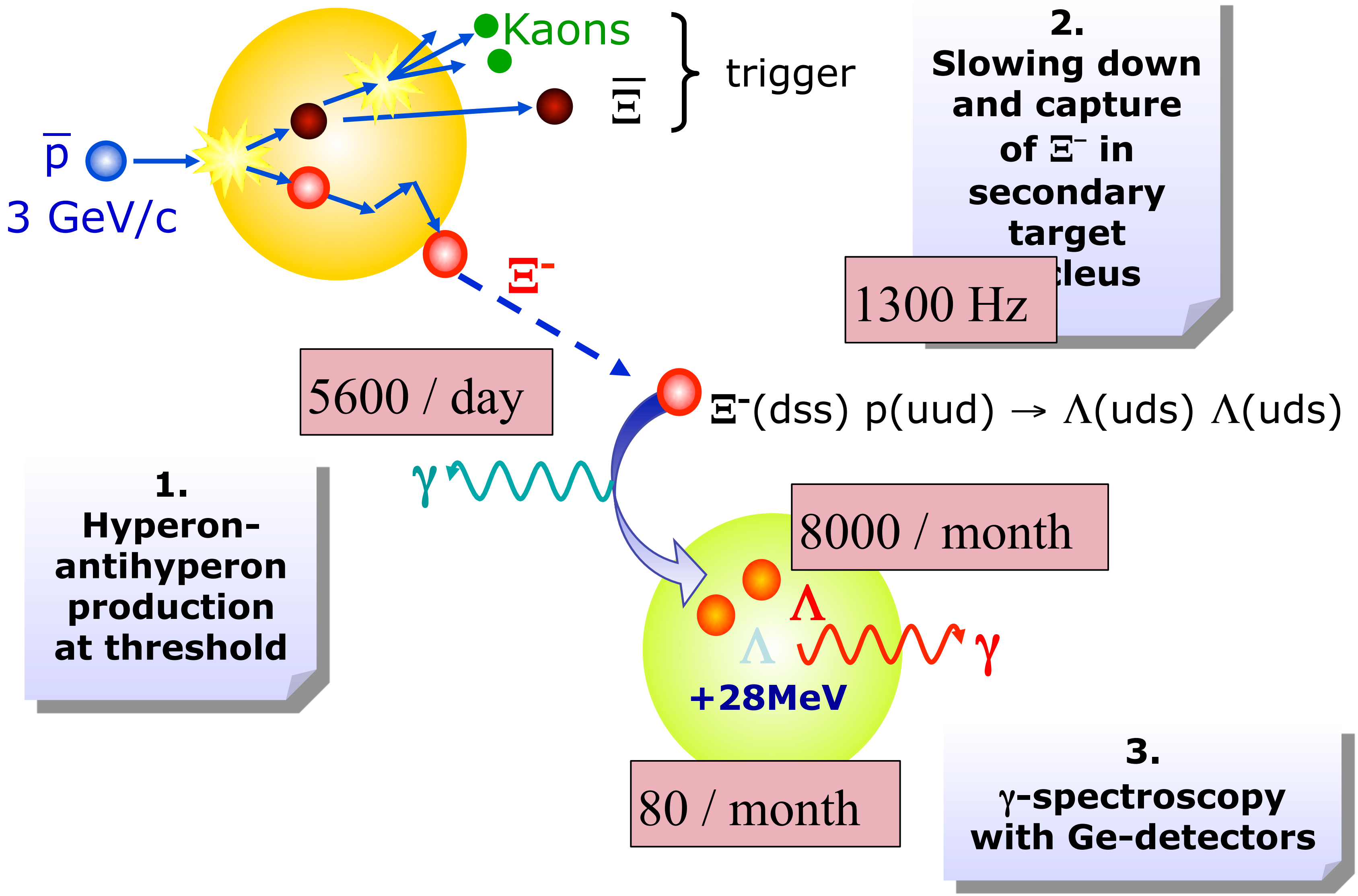
- Systems with charm
  - Scale: $m_c \approx 1300$ MeV.
  - Quark and gluon degrees of freedom more relevant.
  - **By comparing strange and charmed hyperons we learn about QCD at two different energy scales.**

Hypernuclear Physics

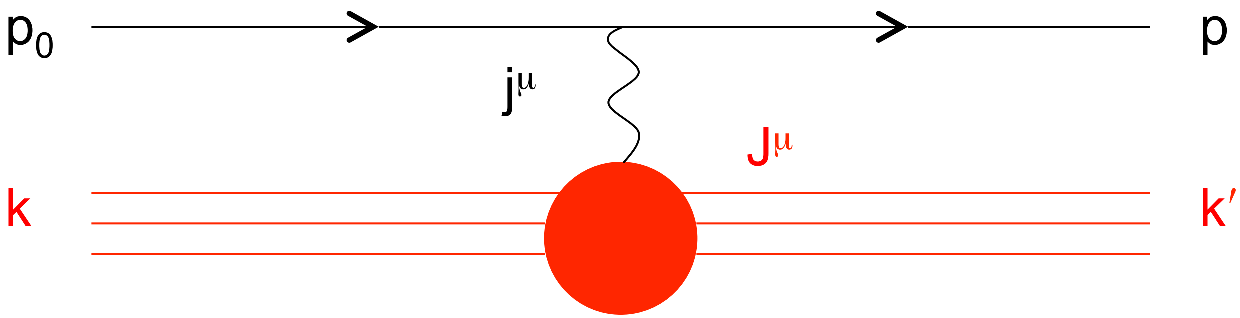
Hypernuclei, systems where one (or more) nucleon is replaced by one (or more) hyperon(s) (Y), allow access to a whole set of nuclear states containing an extra degree of freedom: strangeness.

- Probe of nuclear structure and its possible modifications due to the hyperon.
- Test and define shell model parameters.
- Description in term of quantum field theories and EFT.
- Study of the YN and YY forces (single and double hypernuclei).
- Weak decays ($\Lambda \to \pi N$ suppressed, but $\Lambda N \to NN$ and $\Lambda\Lambda \to NN$ allowed $\Rightarrow$ four-baryon weak interaction)
- Hyperatoms
- Experimentally: in 50 years of study 35 single, 6 double hypernuclei established

Production of Double Hypernuclei



Introduction



$$J^\mu = e\left[F_1(q^2)\gamma^\mu + \frac{\kappa}{2M}F_2(q^2)i\sigma^{\mu\nu}q_\nu\right]$$

$$F_1^p(0) = 1 \quad F_2^p(0) = 1$$

$$F_1^n(0) = 0 \quad F_2^n(0) = 1$$

Dirac and Pauli
Form Factors

Sachs Form Factors

$$G_E \equiv F_1 + \frac{\kappa q^2}{4M^2} F_2$$

$$G_M \equiv F_1 + \kappa F_2$$

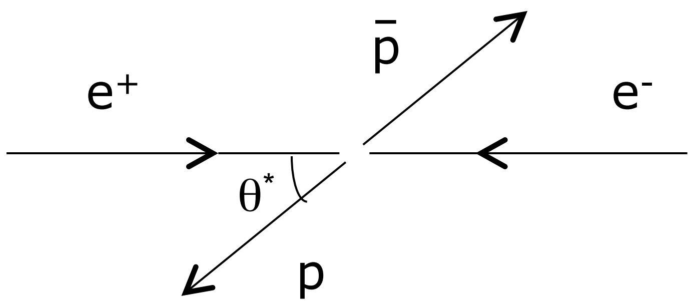
- G_E and G_M are Fourier transforms of nucleon charge and magnetization density distributions (in the Breit Frame).

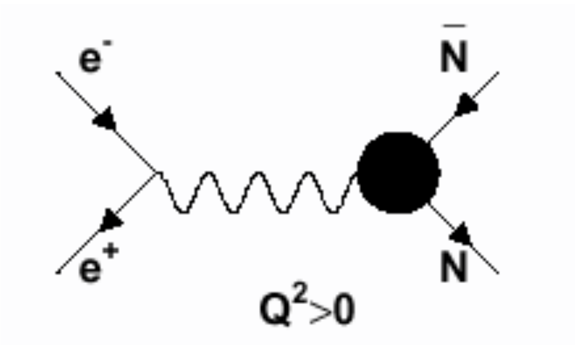
- Spacelike form factors are real, timelike are complex.

- The analytic structure of the timelike form factors is connected by dispersion relations to the spacelike regime.

- By definition they do not interfere in the expression of the cross section, therefore, in the timelike case, only polarization observables allow to get the relative phase.

$e^+ + e^- \to \bar{N} + N$





$$s = Q^2 > 0$$

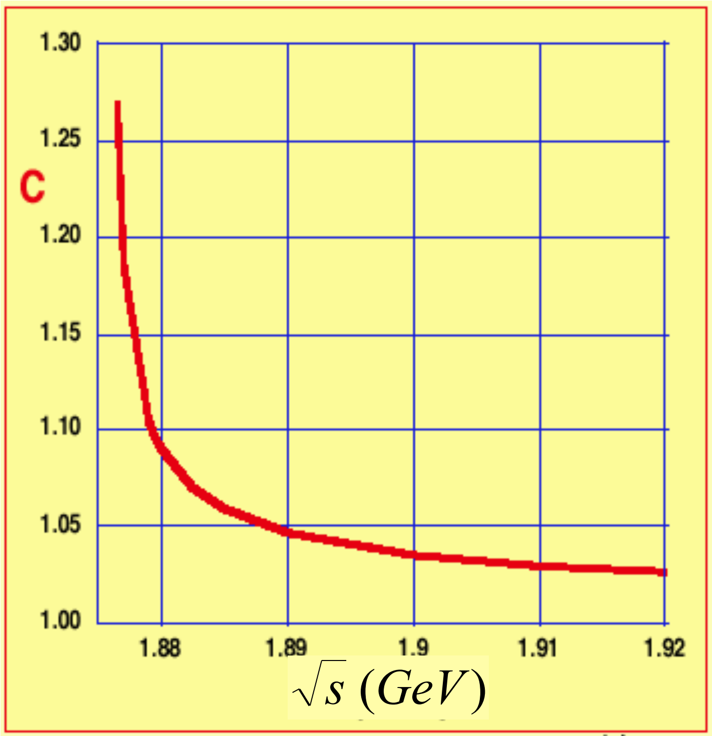
$$\sigma = \frac{4\alpha^2 \pi \beta C}{3s}\left[|G_M(s)|^2 + \frac{2m_N^2}{s}|G_E(s)|^2 \right]$$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4s}\left[|G_M(s)|^2 (1+\cos^2\theta^*) + \frac{4m_N^2}{s}|G_E(s)|^2 \sin^2\theta^* \right]$$

C is the Coulomb correction factor, taking into account the QED coulomb interaction. Important at threshold.

$$\boxed{C = \frac{1}{1-e^{-y}}}$$

$$y = \frac{2\pi\alpha M_N}{\beta\sqrt{s}}$$



$$C \xrightarrow[s\to 4M_N^2]{} \frac{1}{\beta}$$ ⇒ σ finite

$$\boxed{\sigma\left(4M_N^2\right) = \frac{\pi^2\alpha^3}{4M_N^2}\left|G_E(4M_N^2)\right|^2 \approx 0.1\,nb}$$

There is no Coulomb correction in the neutron case.

Form Factor Properties

- At threshold $G_E = G_M$ by definition, if F_1 and F_2 are analytic functions with a continuous behaviour through threshold.

$$G_E\,(4m_p^{\,2}) = G_M\,(4m_p^{\,2})$$

- Timelike G_E and G_M are the analytical continuation of non spin flip and, respectively, spin flip spacelike form factors. Since timelike form factors are complex functions, this continuity requirement imposes theoretical constraints.
- Two-photon contribution can be measured from asymmetry in angular distribution.

Form Factor Properties

- Perturbative QCD and analyticity relate timelike and spacelike form factors, predicting a continuous transition and spacelike-timelike equalitity at high Q^2.
- At high Q^2 PQCD predicts:

$$\boxed{F_1(Q^2) \propto \frac{\alpha_s^2(Q^2)}{Q^4} \qquad F_2(Q^2) \propto \frac{\alpha_s^2(Q^2)}{Q^6}}$$

- Naïve prediction for the neutron:

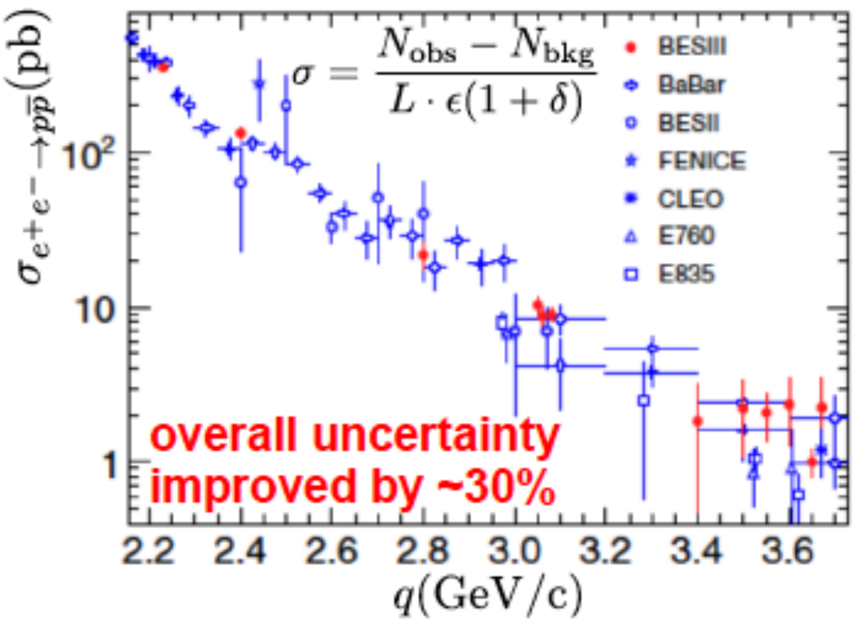
$$\boxed{\left|\frac{G_M^n}{G_M^p}\right|^2 \approx \left(\frac{q_d}{q_u}\right)^2 = 0.25}$$

Timelike FF: Some Open Questions

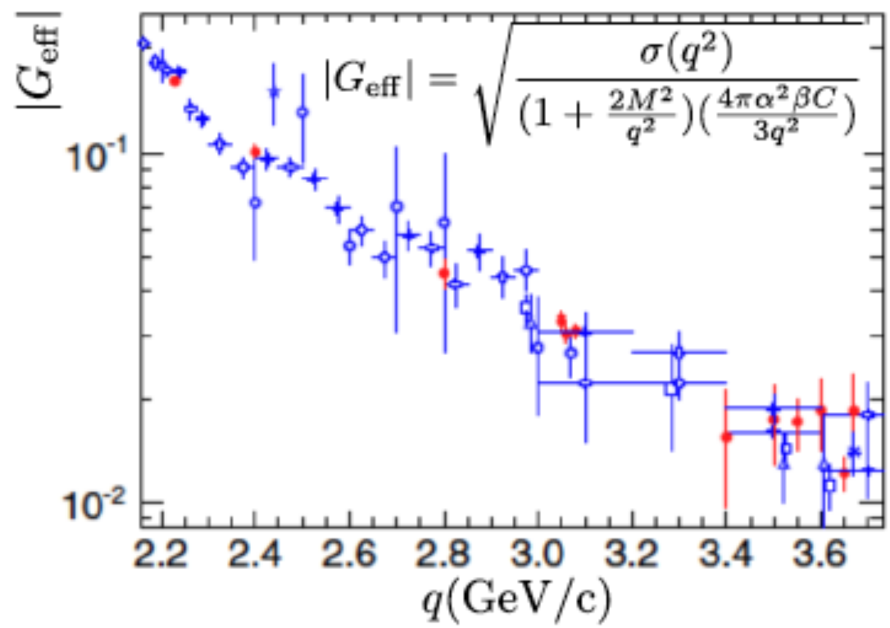
- Unpolarized measurements only yield moduli of FF
- Proton
  - Due to the low value of the cross sections and the consequent limited statistics, most experiments could not determine $|G_M|$ and $|G_E|$ separately from the analysis of the angular distributions, but determined an effective FF.
  - Phases of FF unknown
  - Measurements limited to $q^2 < 20$ GeV^2.
- Neutron
  - basically only one experiment at low q^2 (FENICE)
- Other baryon FF measurements scarce

Proton Timelike Form Factor

Born cross section



Effective form factor



Cristina Morales (Helmholtz-Institut Mainz) Bormio 2017

Proton Spacelike Form Factors

$e^- p \rightarrow e^- p$

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} \times \left[\left(F_1^2 - \frac{\kappa^2 q^2}{4M^2} F_2^2\right)\cos^2\frac{\theta}{2} - \frac{q^2}{2M^2}\left(F_1 + \kappa F_2\right)^2 \sin^2\frac{\theta}{2}\right]$$

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{Rutherford} \times \left[\frac{G_E^2 + \tau G_M^2}{1+\tau}\cos^2\frac{\theta}{2} + 2\tau G_M^2 \sin^2\frac{\theta}{2}\right]$$

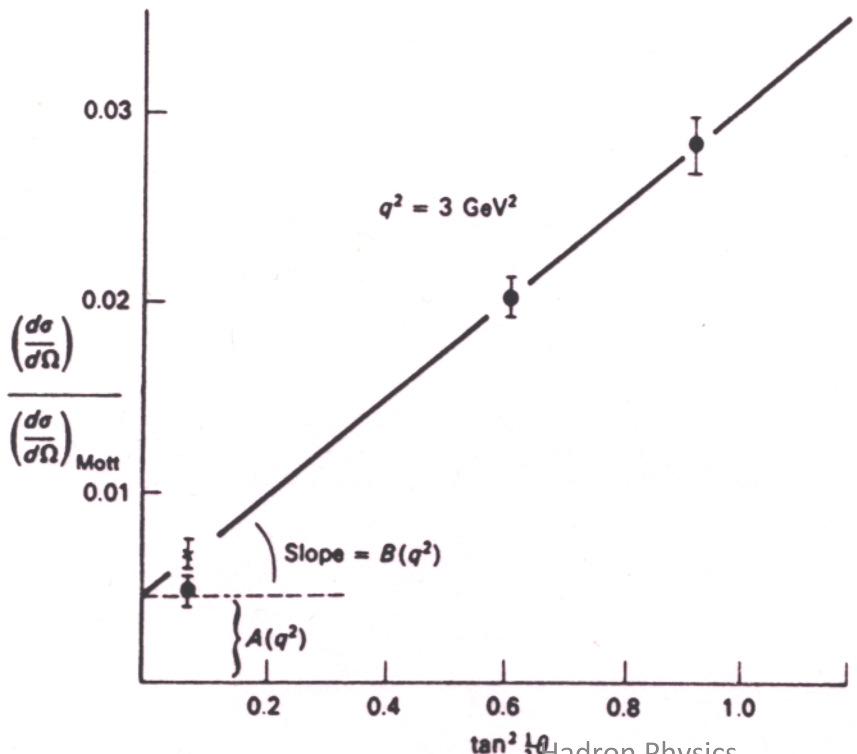
$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \times \left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\frac{\theta}{2}\right] \qquad \tau = \frac{q^2}{4M^2}$$

Rosenbluth Formula

$$G_E = G_E\left(q^2\right) \qquad G_M = G_M\left(q^2\right) \qquad G_E^p(0) = 1 \qquad G_E^n(0) = 0$$

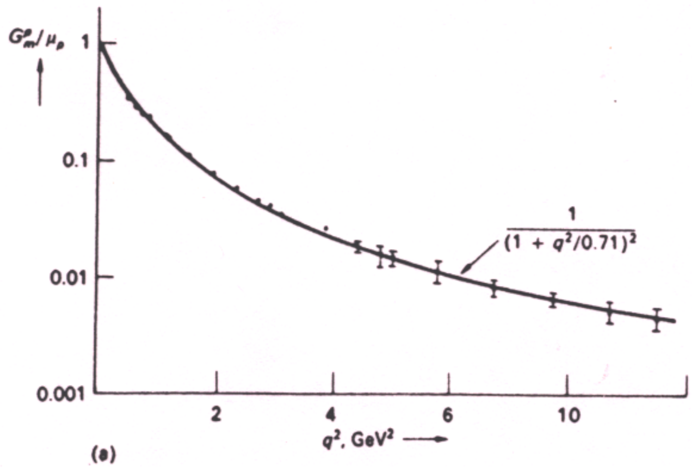
$$G_M^p(0) = +2.79 \qquad G_M^n(0) = -1.91$$

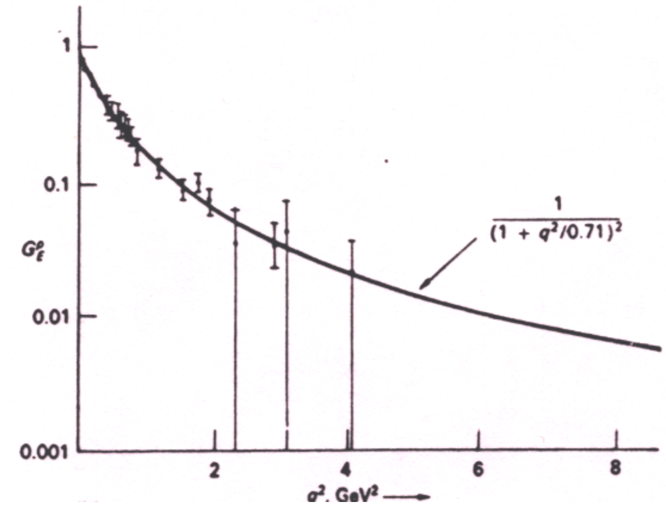
$$\left(\frac{d\sigma}{d\Omega}\right) \Big/ \left(\frac{d\sigma}{d\Omega}\right)_{Mott} = A\left(q^2\right) + B\left(q^2\right)\tan^2\frac{\theta}{2}$$



Rosenbluth Plot

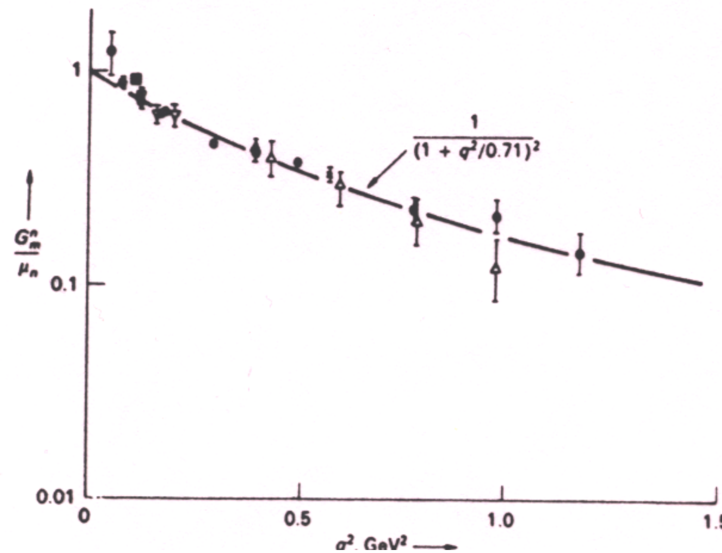
Nucleon Spacelike Form Factors



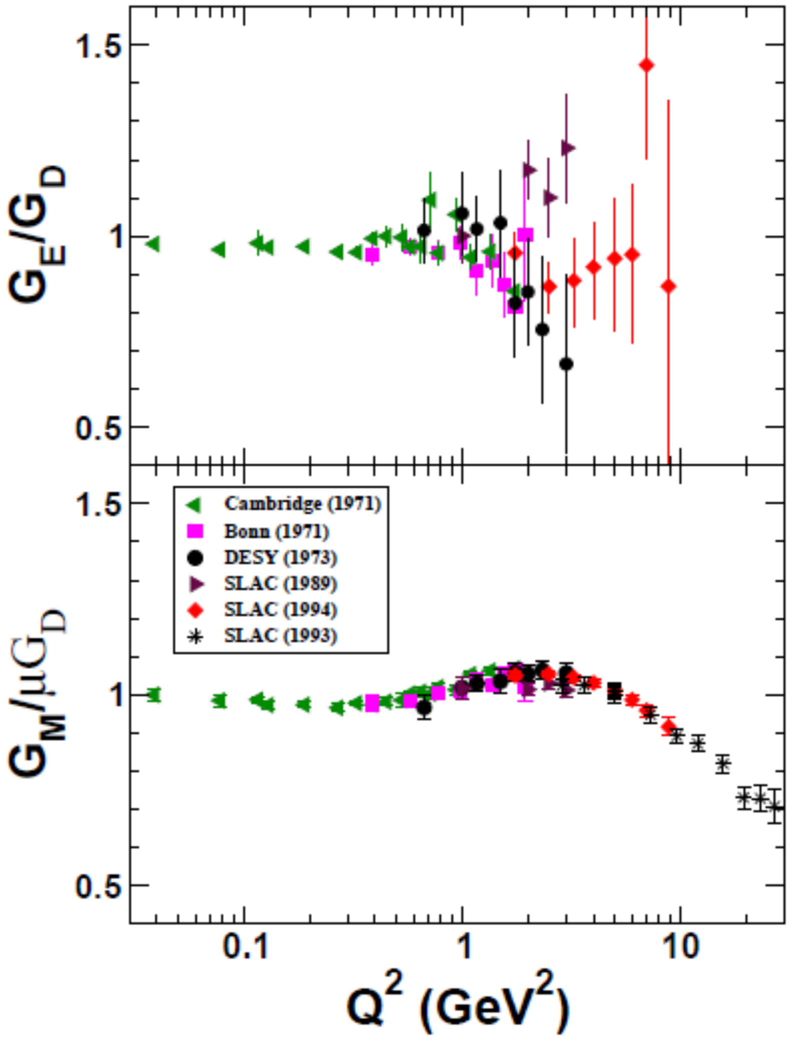


$$G_E^p\left(q^2\right) = \frac{G_M^p\left(q^2\right)}{\left|\mu_p\right|} = \frac{G_M^n\left(q^2\right)}{\left|\mu_n\right|} = G\left(q^2\right)$$

$$G_E^n\left(q^2\right) = 0$$



Proton Form Factors : G_M and G_E



At all Q^2

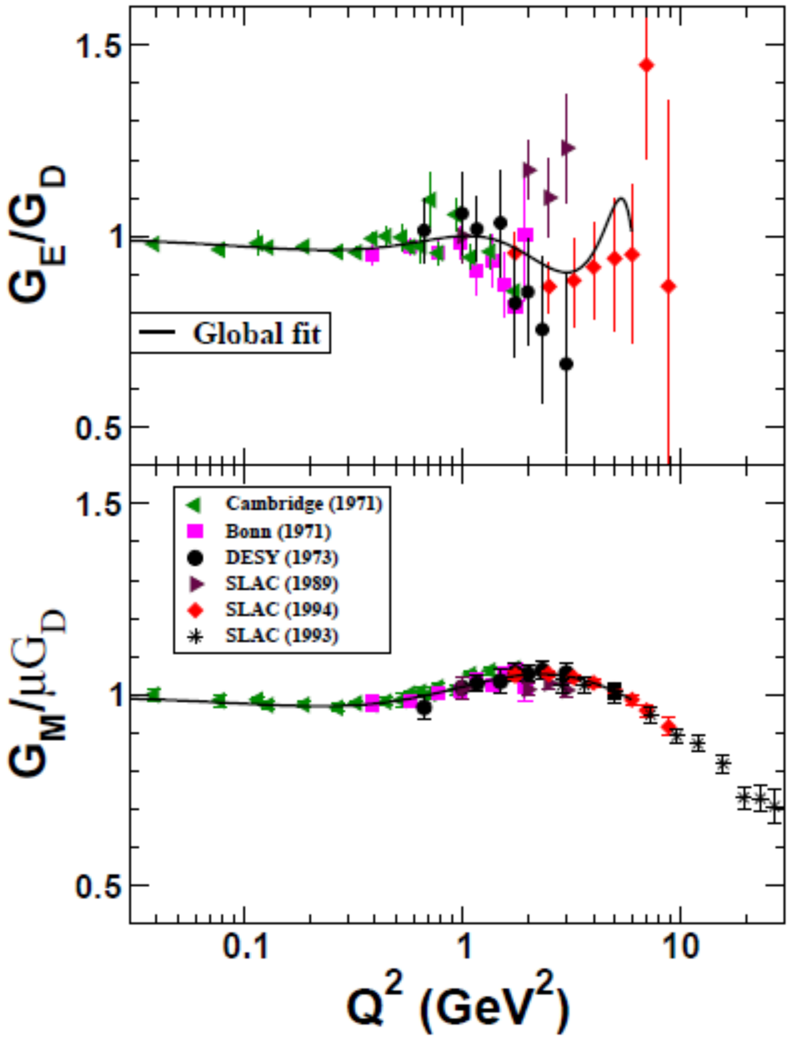
→ G_M well measured

At $Q^2 > 1$

→ Error on G_E large

Nucleon05 – p.4/26

Proton Form Factors : G_M and G_E



At all Q^2

→ G_M well measured

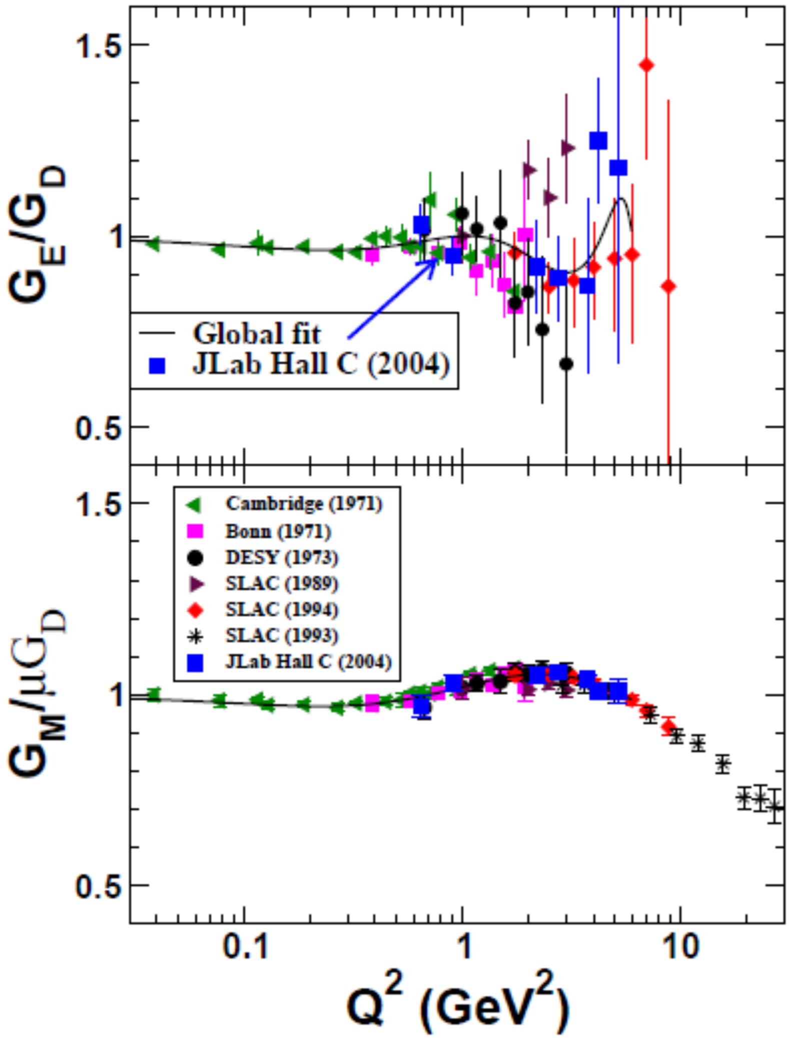
At $Q^2 > 1$

→ Error on G_E large

→ Recent global fit to world cross section data

J. Arrington PRC 69, 02201R (2004)

Proton Form Factors : G_M and G_E



At all Q^2

→ G_M well measured

At $Q^2 > 1$

→ Error on G_E large

→ Recent global fit to world cross section data

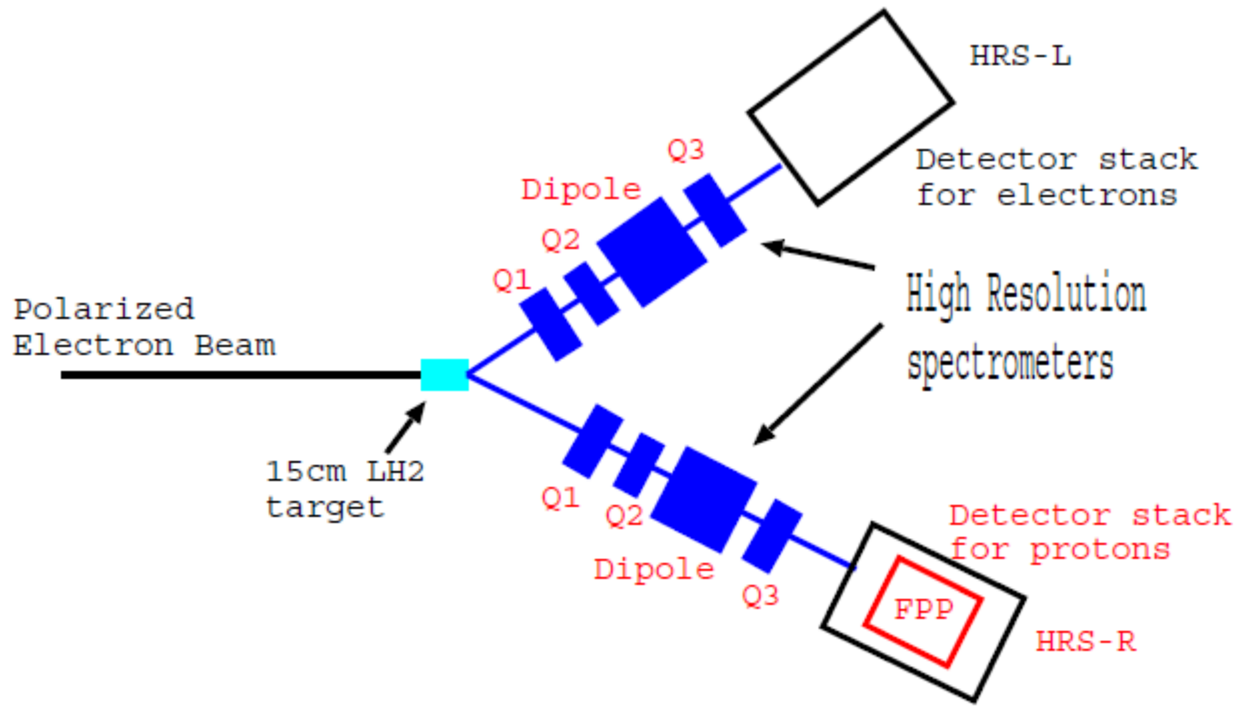
J. Arrington PRC 69, 02201R (2004)

→ Recent Hall C data

M. E. Christy, PRC 70, 015206 (2004)

Nucleon05 – p.4/26

JLab Recoil Polarization Experiments

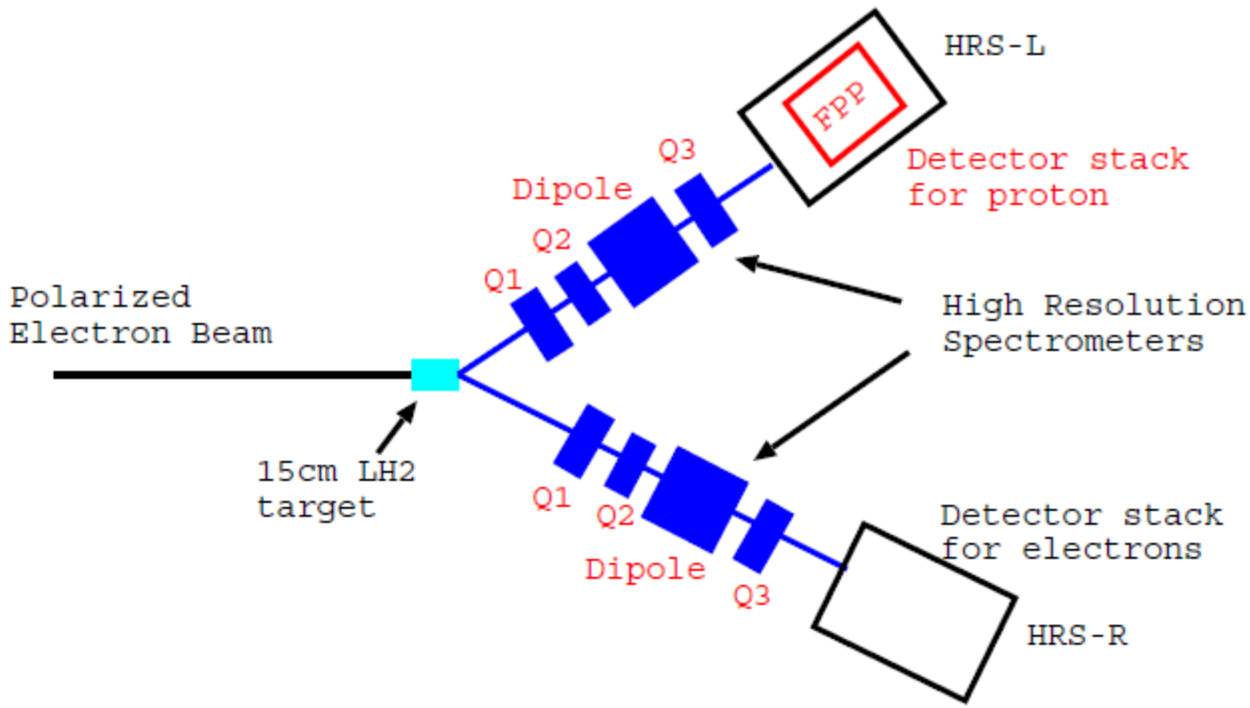


1st JLab experiment Electrons detected HRS-L
Protons detected HRS-R

Covered Q^2 from 0.5 to 3.5 GeV^2.

Nucleon05 – p.5/26

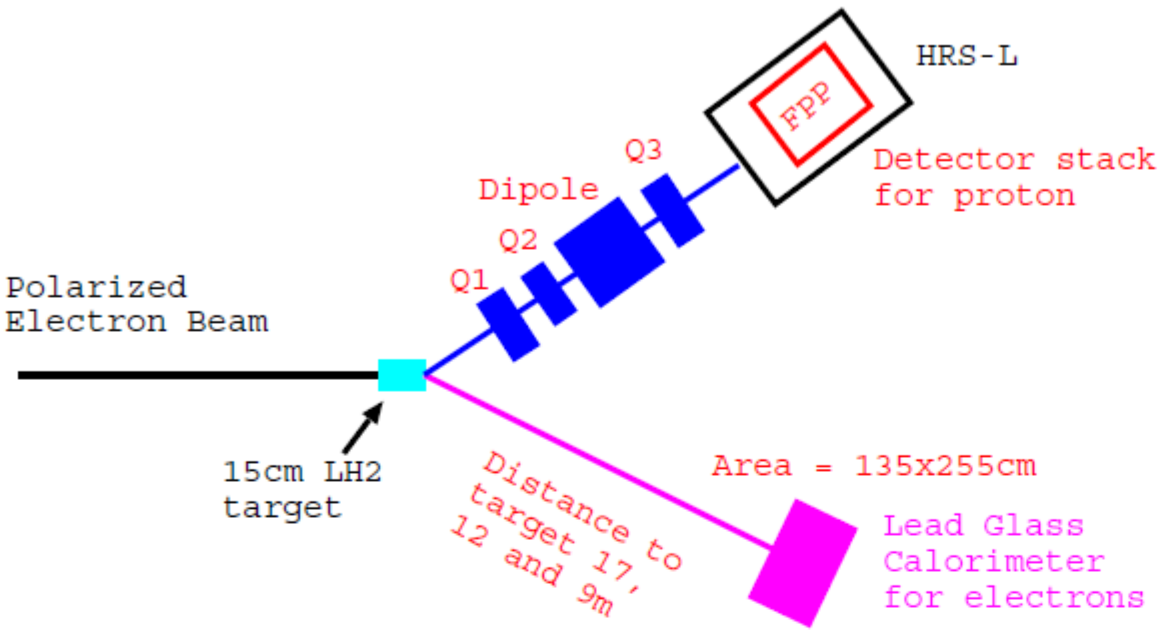
JLab Recoil Polarization Experiments



2nd JLab experiment Protons detected HRS-L

Covered Q^2 from 3.5 to 5.6 GeV^2.

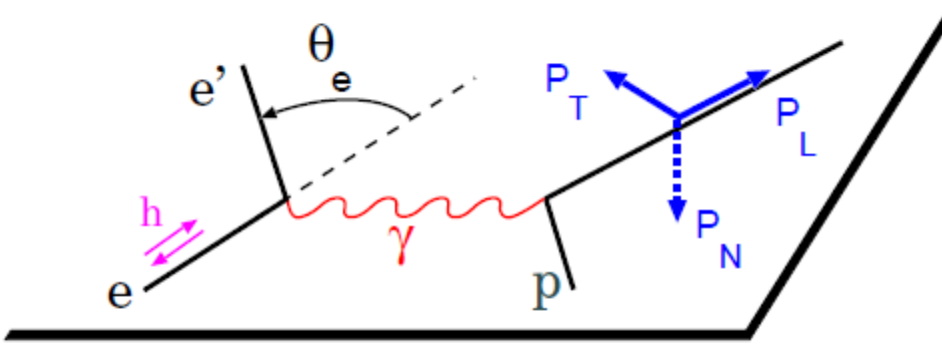
JLab Recoil Polarization Experiments



2nd JLab experiment Protons detected HRS-L
Electrons detected calorimeter

Covered Q^2 from 3.5 to 5.6 GeV^2.

Spin Transfer Reaction $^1\mathbf{H}(\vec{e}, e'\vec{p})$



Helicity dependent : P_N, P_T, P_L

$P_N = 0$ for elastic

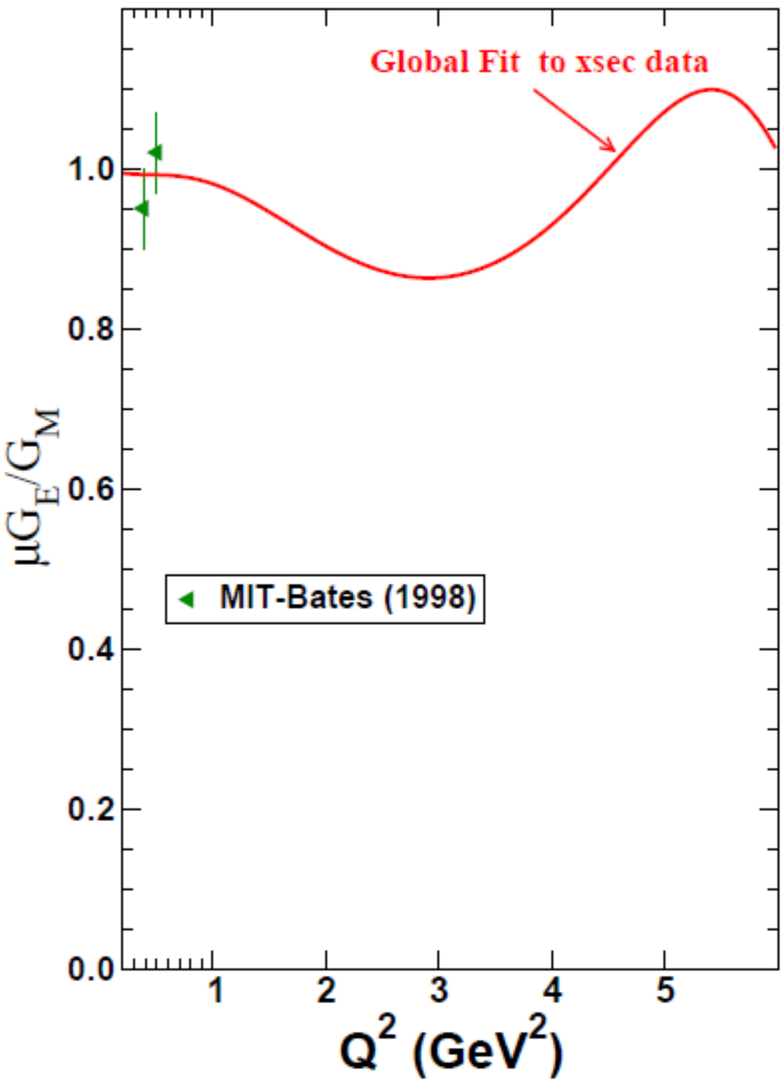
In 1γ approx.

Helicity independent $P_N = 0$

$$\frac{G_E}{G_M} = -\frac{P_T}{P_L}\frac{E_e+E_{e'}}{2M}\tan\left(\frac{\theta_e}{2}\right)$$

- Experiments detect the electron and proton in coincidence
- Proton spin measured by second scattering in polarimeter
- Experiments done at MIT-Bates, Mainz and JLab

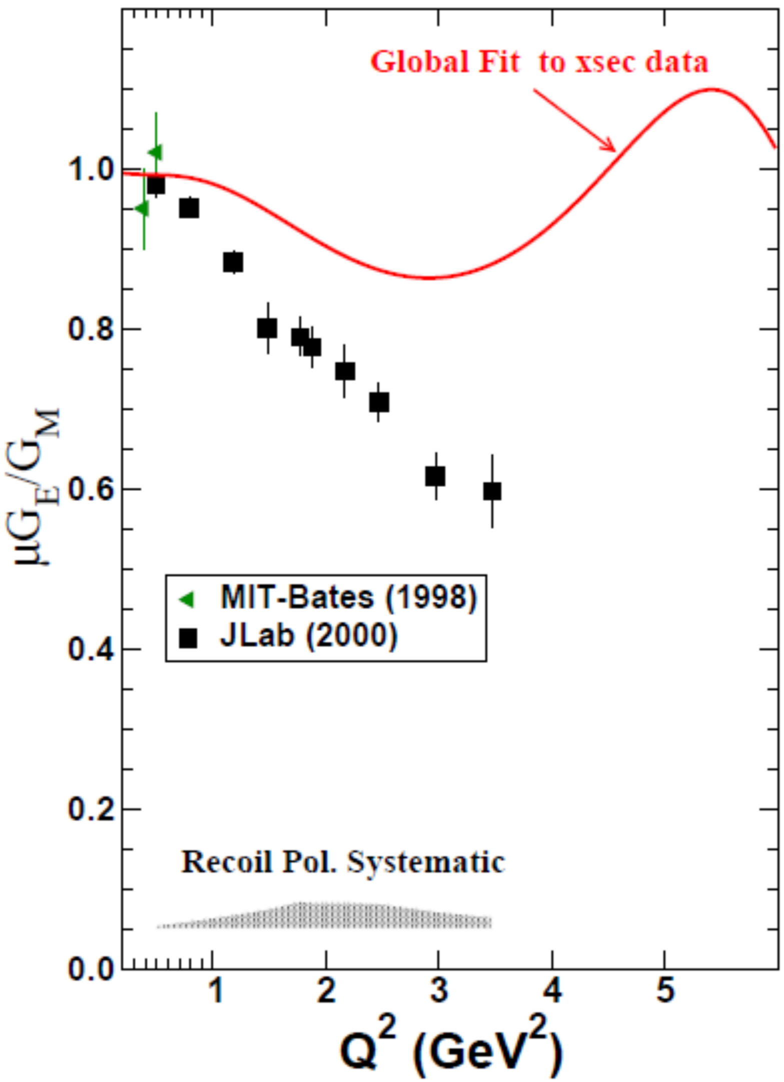
G_E/G_M from recoil polarization



- MIT-Bates experiment

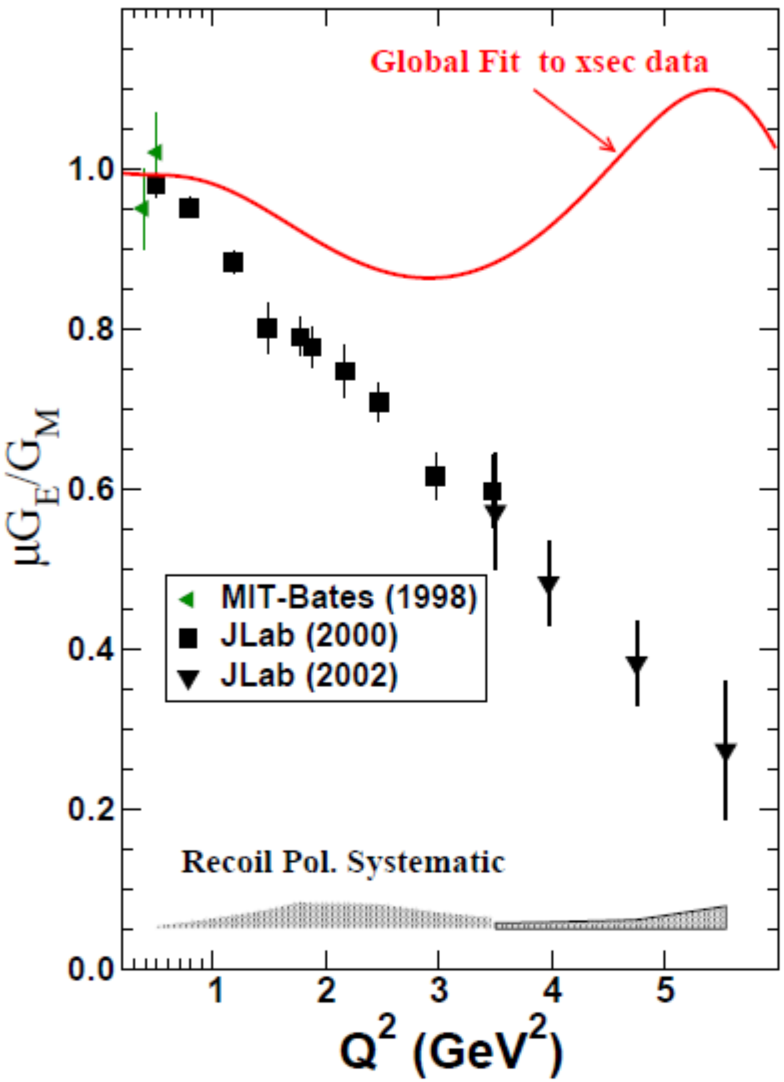
Nucleon05 – p.10/26

G_E/G_M from recoil polarization



- MIT-Bates experiment
- 1st JLab experiment
  Used two HRS

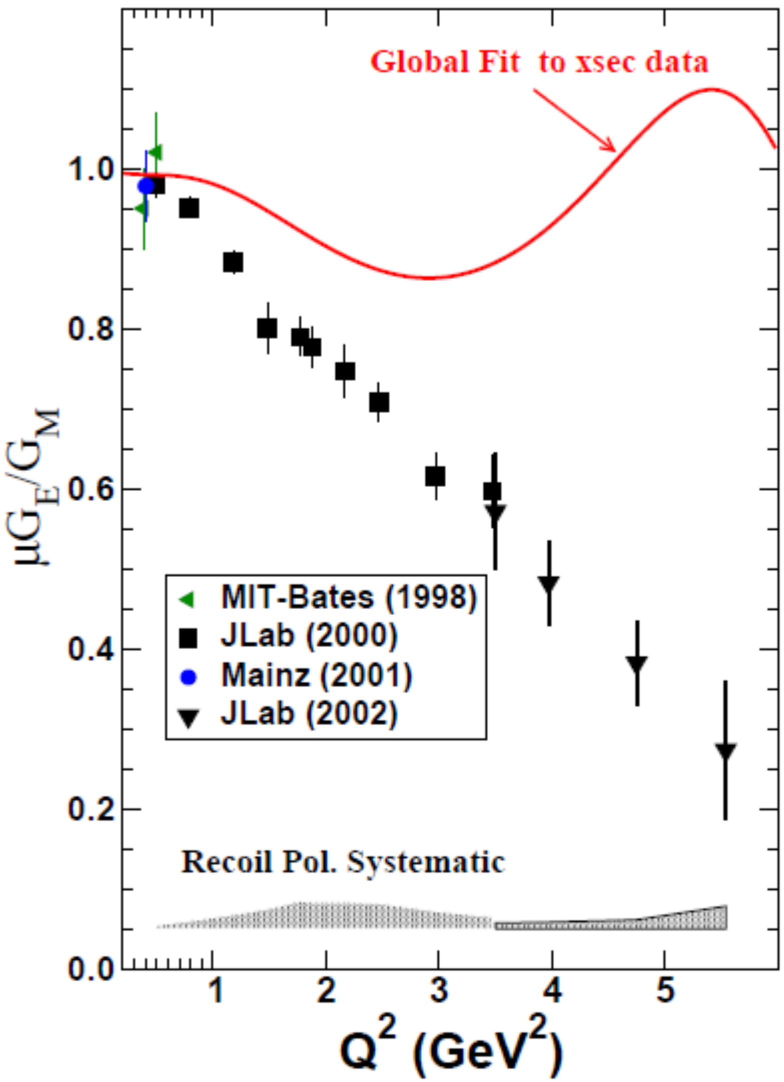
G_E/G_M from recoil polarization



- MIT-Bates experiment
- 1st JLab experiment
  Used two HRS
- 2nd JLab experiment
  Used HRS+Calo

Nucleon05 – p.10/26

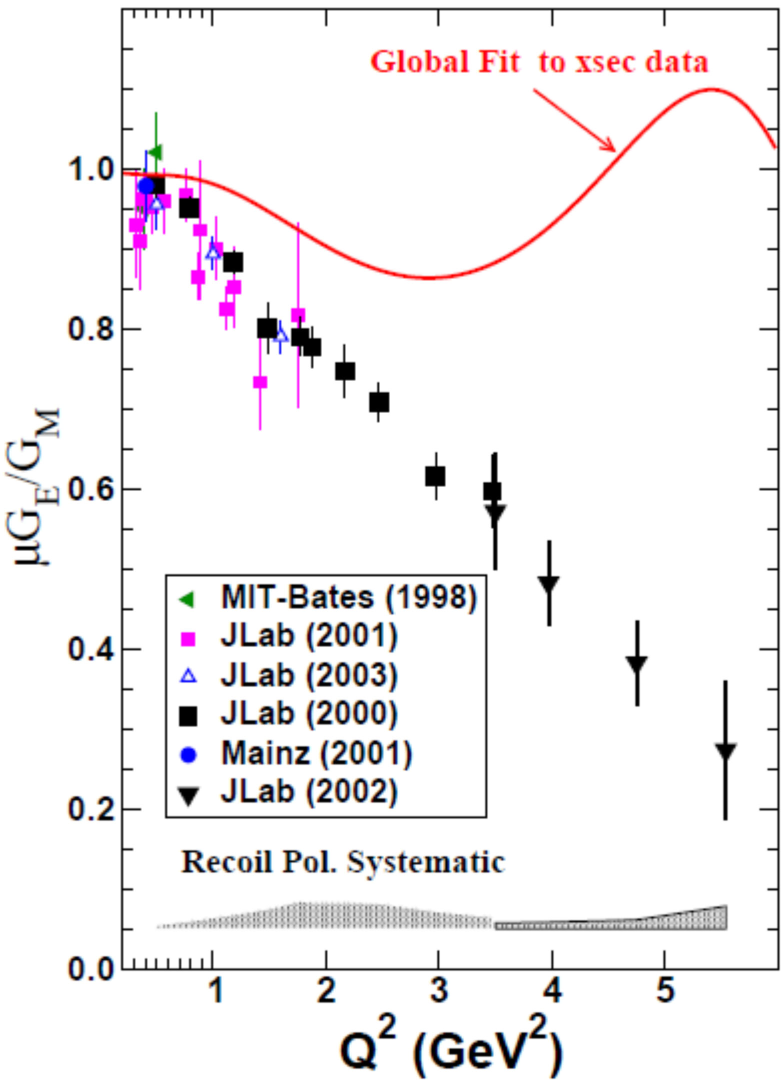
G_E/G_M from recoil polarization



- MIT-Bates experiment
- 1st JLab experiment
  Used two HRS
- 2nd JLab experiment
  Used HRS+Calo
- Mainz experiment

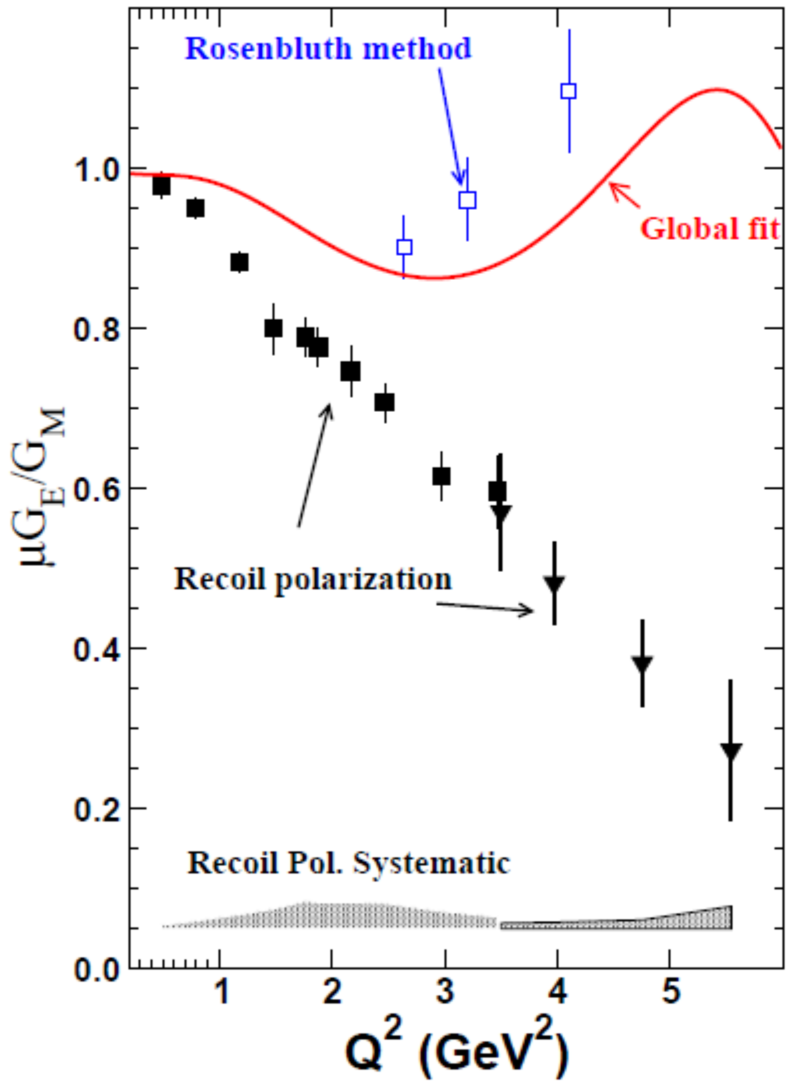
Nucleon05 – p.10/26

G_E/G_M from recoil polarization



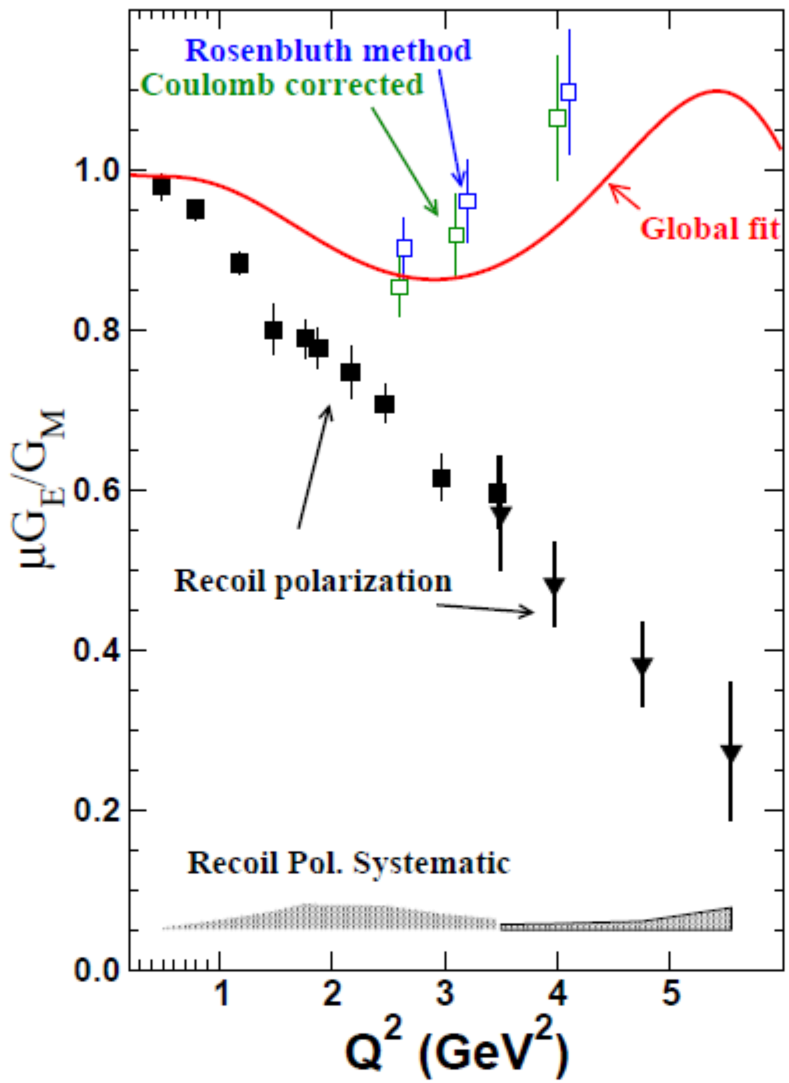
- MIT-Bates experiment
- 1st JLab experiment
  Used two HRS
- 2nd JLab experiment
  Used HRS+Calo
- Mainz experiment
- Secondary part of other JLab experiments.

Comparison of G_E/G_M



- Hall A Rosenbluth G_E/G_M agrees with previous cross section measurements
- Discrepancy between G_E/G_M from recoil polarization and from cross section measurement persistent

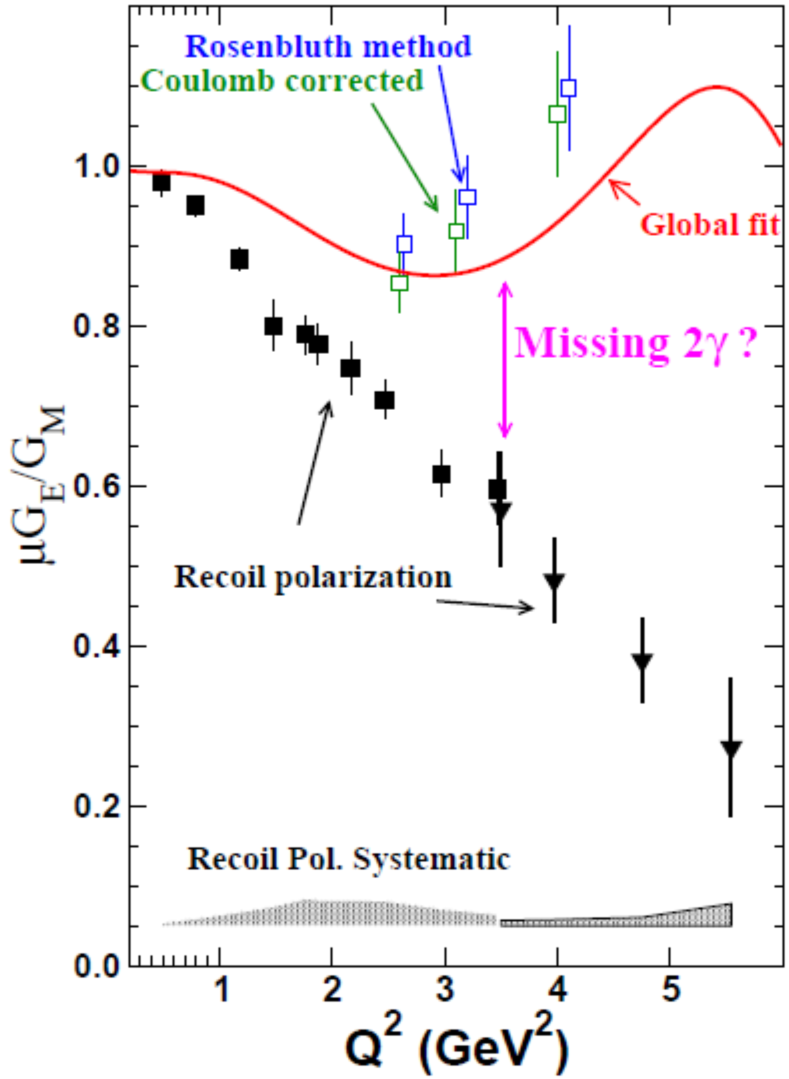
Comparison of G_E/G_M



- Coulomb correction (soft multi-γ) is small correction to xsec data

Nucleon05 – p.13/26

Comparison of G_E/G_M



- Coulomb correction (soft multi-γ) is small correction to xsec data
- Missing physics from 2γ exchange?

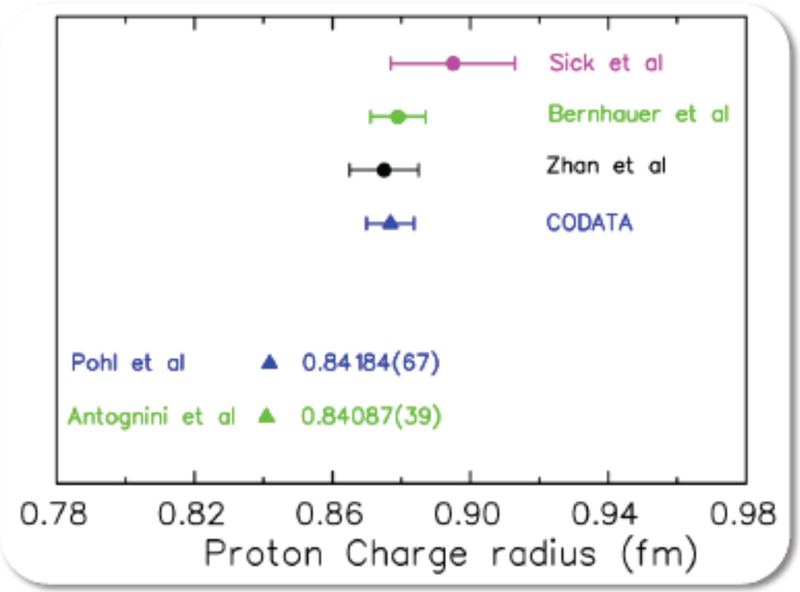
$$\sigma_r \propto \frac{\epsilon}{\tau} G_E^2 + G_M^2 + \epsilon \sigma_{2\gamma}(\epsilon, Q^2)$$

Explain discrepancy with

$$\sigma_{2\gamma}(\epsilon, Q^2) \sim 6\%$$

with small ϵ, Q^2 dependence

Proton Radius Puzzle



μH data:

Pohl et al. (2010)
Antognini et al. (2013)

$R_E = 0.8409 \pm 0.0004$ fm

7.9 σ difference

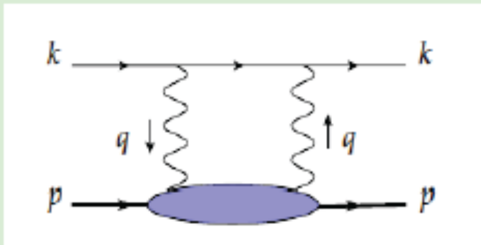
ep-data:

Bernauer et al. (2010, 2013)
Zhan et al. (2011)

$R_E = 0.8770 \pm 0.0045$ fm

corrections to Lamb shift: 300 μeV below expectation

proton structure corrections:



$\Delta E = (-33 \pm 2)$ μeV

Carlson, Vdh (2011)
+ Birse, McGovern (2012)

Outlook and Conclusions

Experimental Facilities

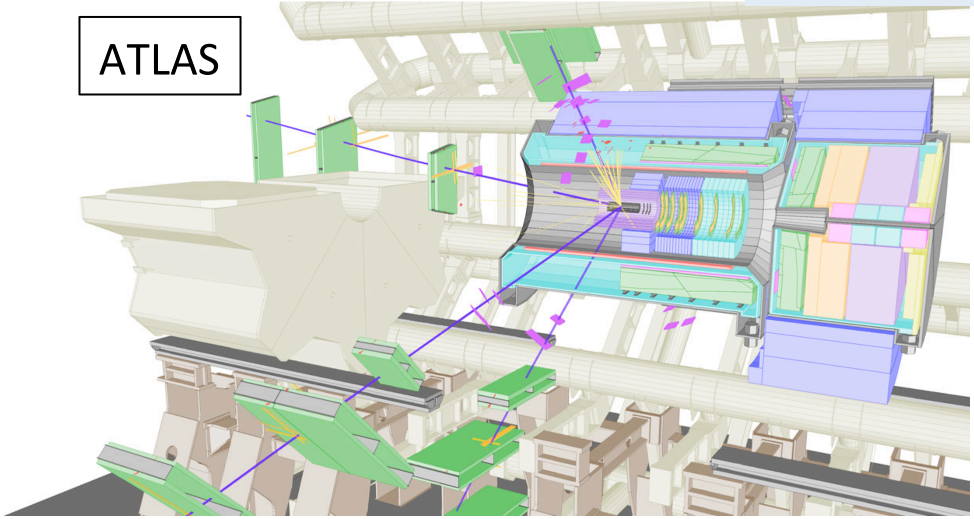
Conclusions

The Facilities

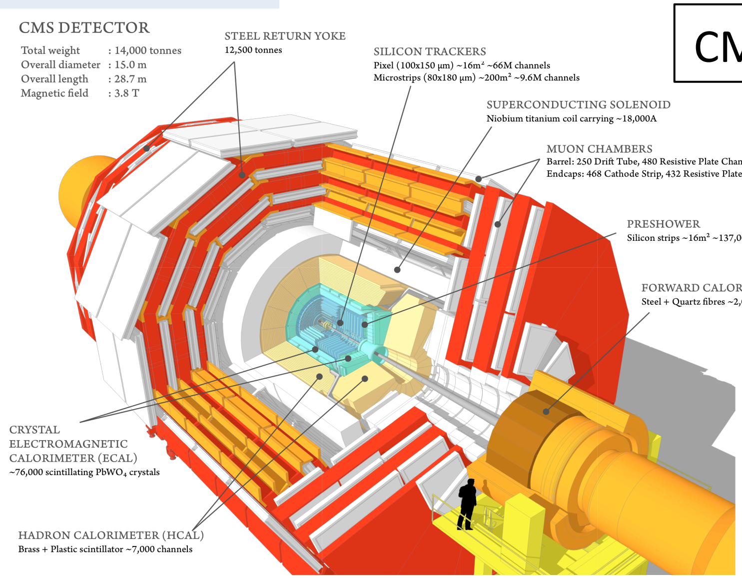
- The LHC Experiments
- BES III at BEPC
- Belle 2
- JLAB 12 GeV upgrade
- $\bar{\text{P}}$ANDA at FAIR
- Compass @ CERN
- ELSA@Bonn
- MAMI, MESA

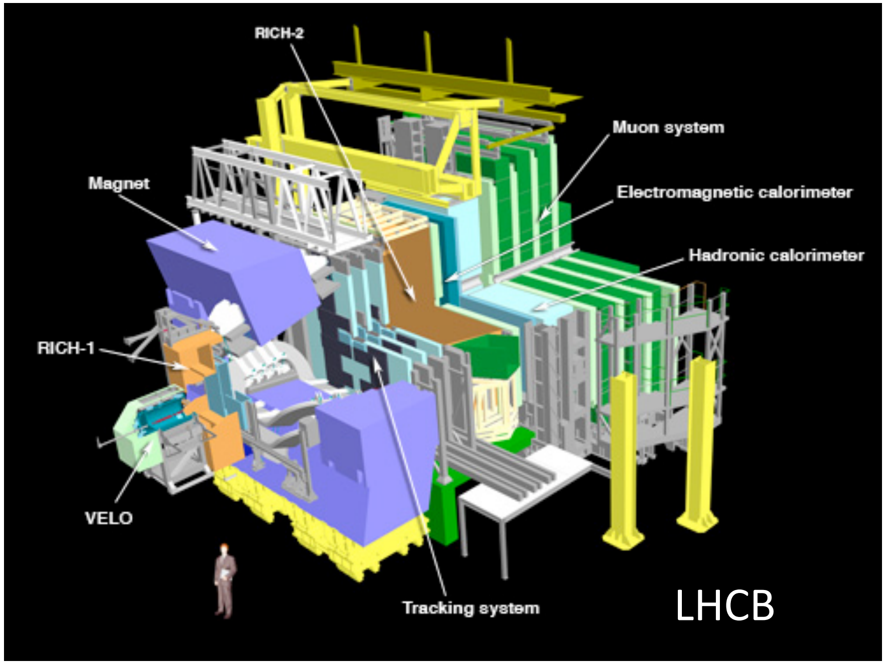
LHC Experiments

ATLAS

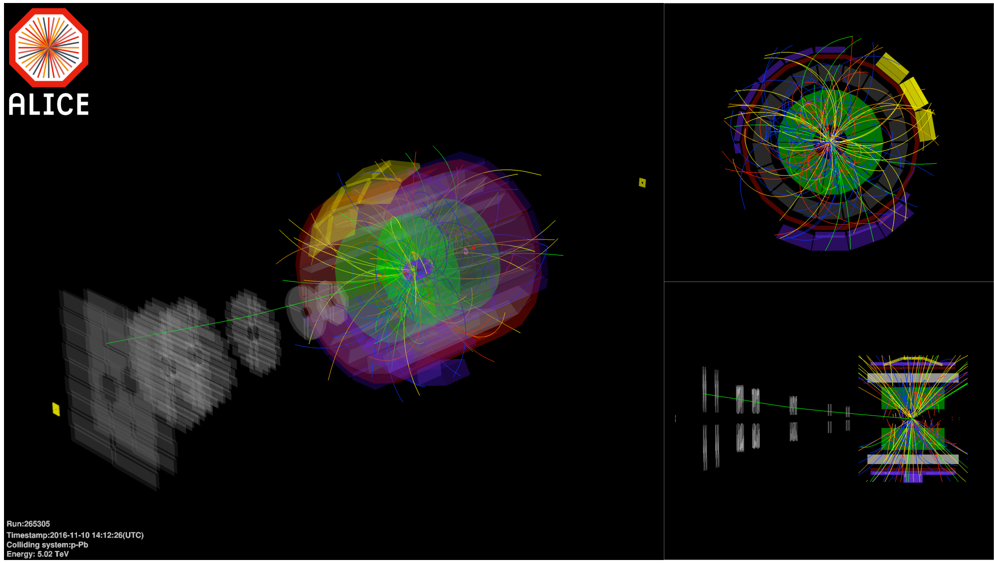


CMS

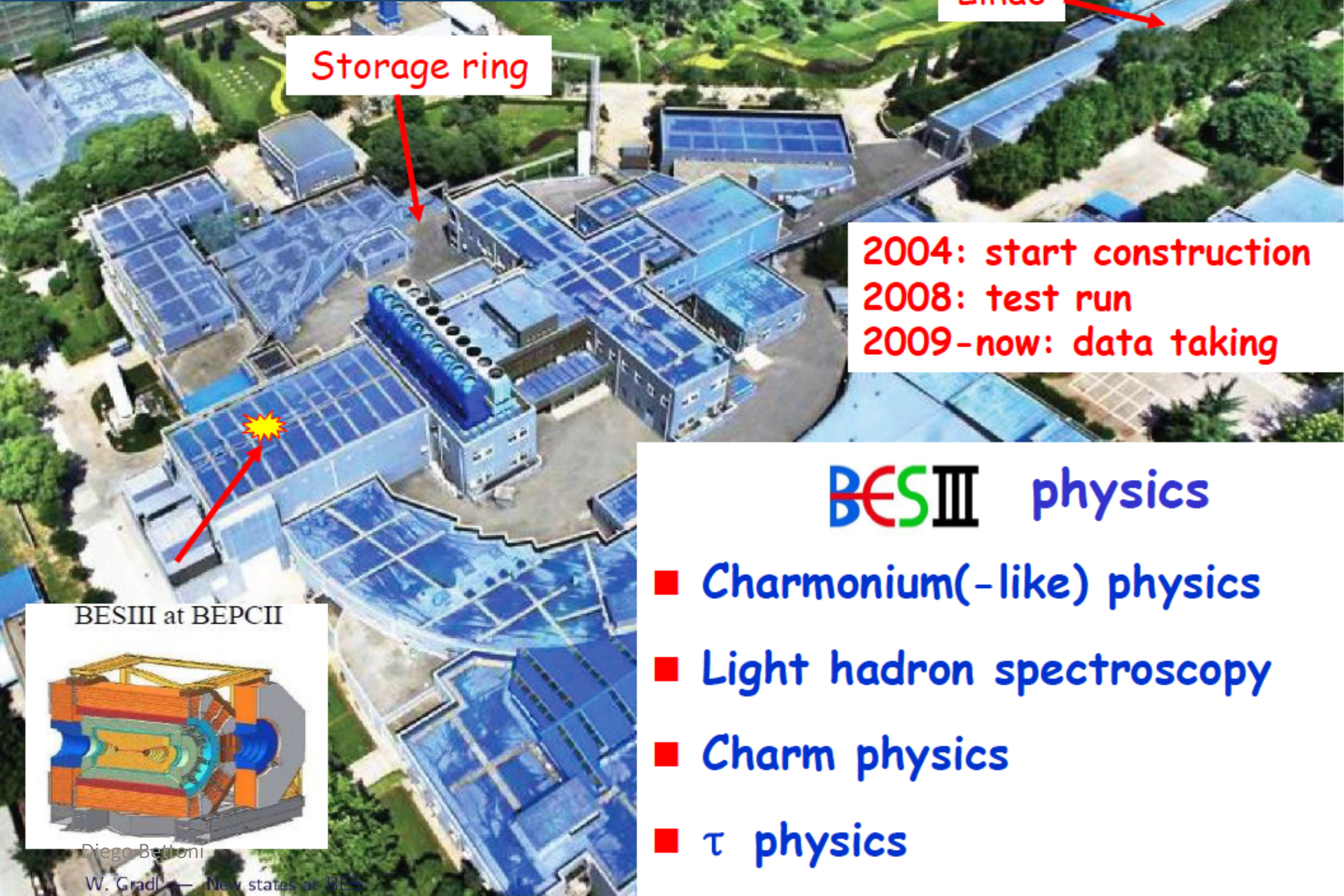




LHCB



BEPCII/BESIII



2004: start construction
2008: test run
2009-now: data taking

BESIII at BEPCII

BESIII physics

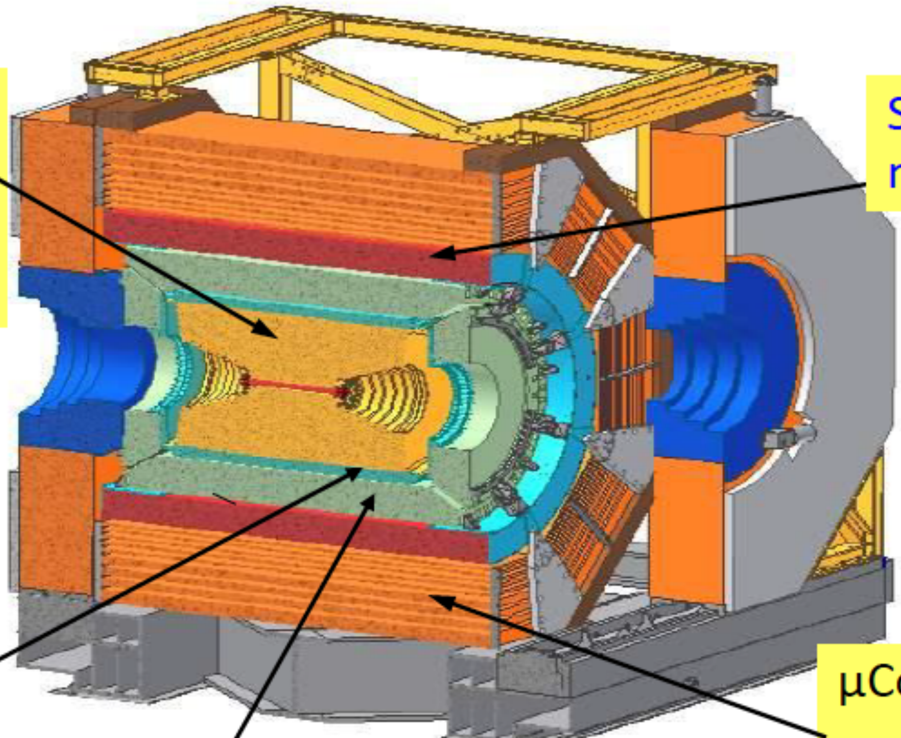
- Charmonium(-like) physics
- Light hadron spectroscopy
- Charm physics
- τ physics

BESIII Detector

Drift Chamber (MDC)

$\sigma P/P\ (^0/_0) = 0.5\%(1\text{GeV})$

$\sigma_{dE/dx}\ (^0/_0) = 6\%$



Super-conducting magnet (1.0 tesla)

$1.3 \times 10^9\ J/\psi$
$0.5 \times 10^9\ \psi(2S)$
$\psi(3770)$
4.23, 4.26, 4.36 GeV

Time Of Flight (TOF)

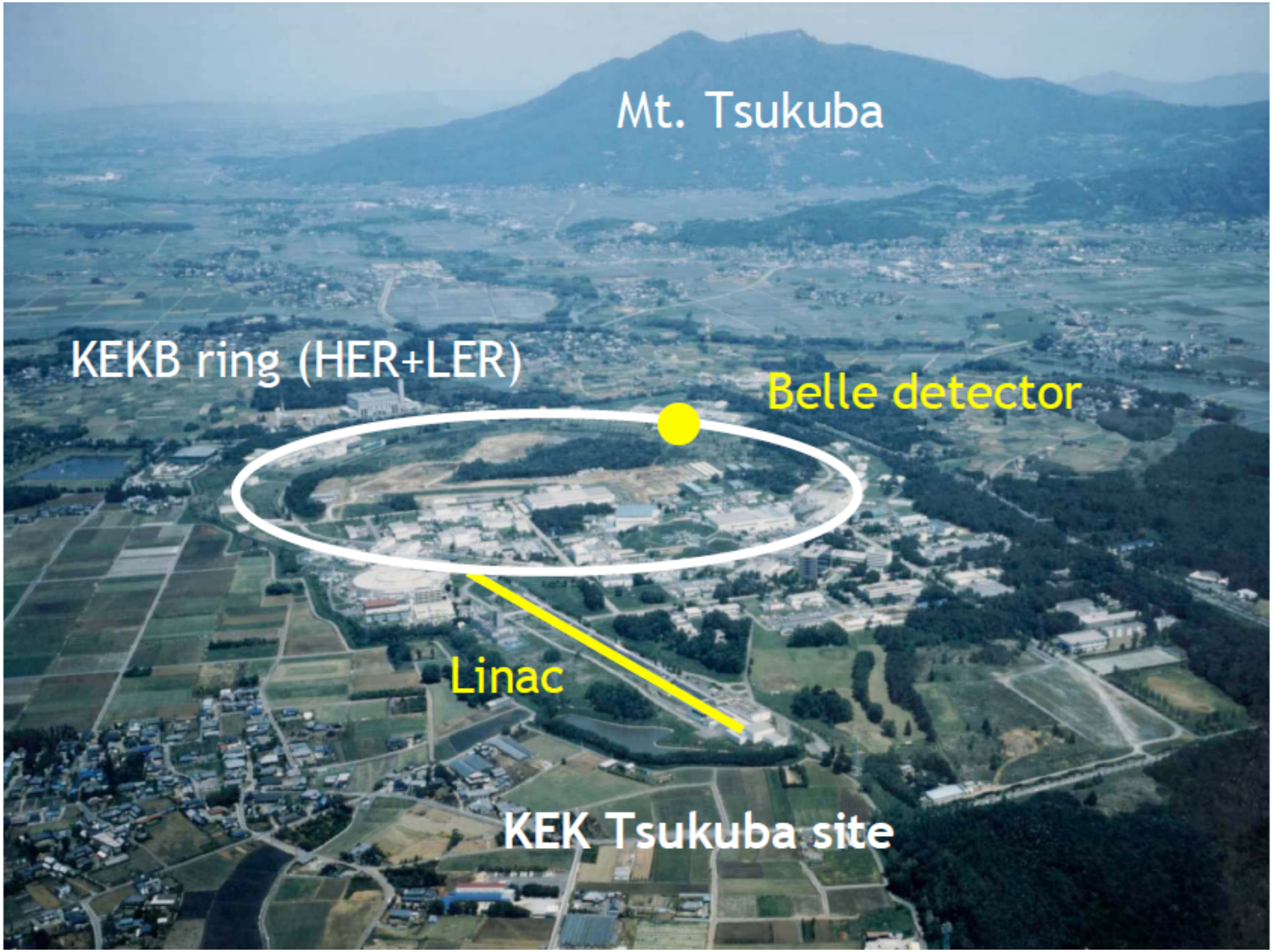
σ_T: 90 ps Barrel
110 ps endcap

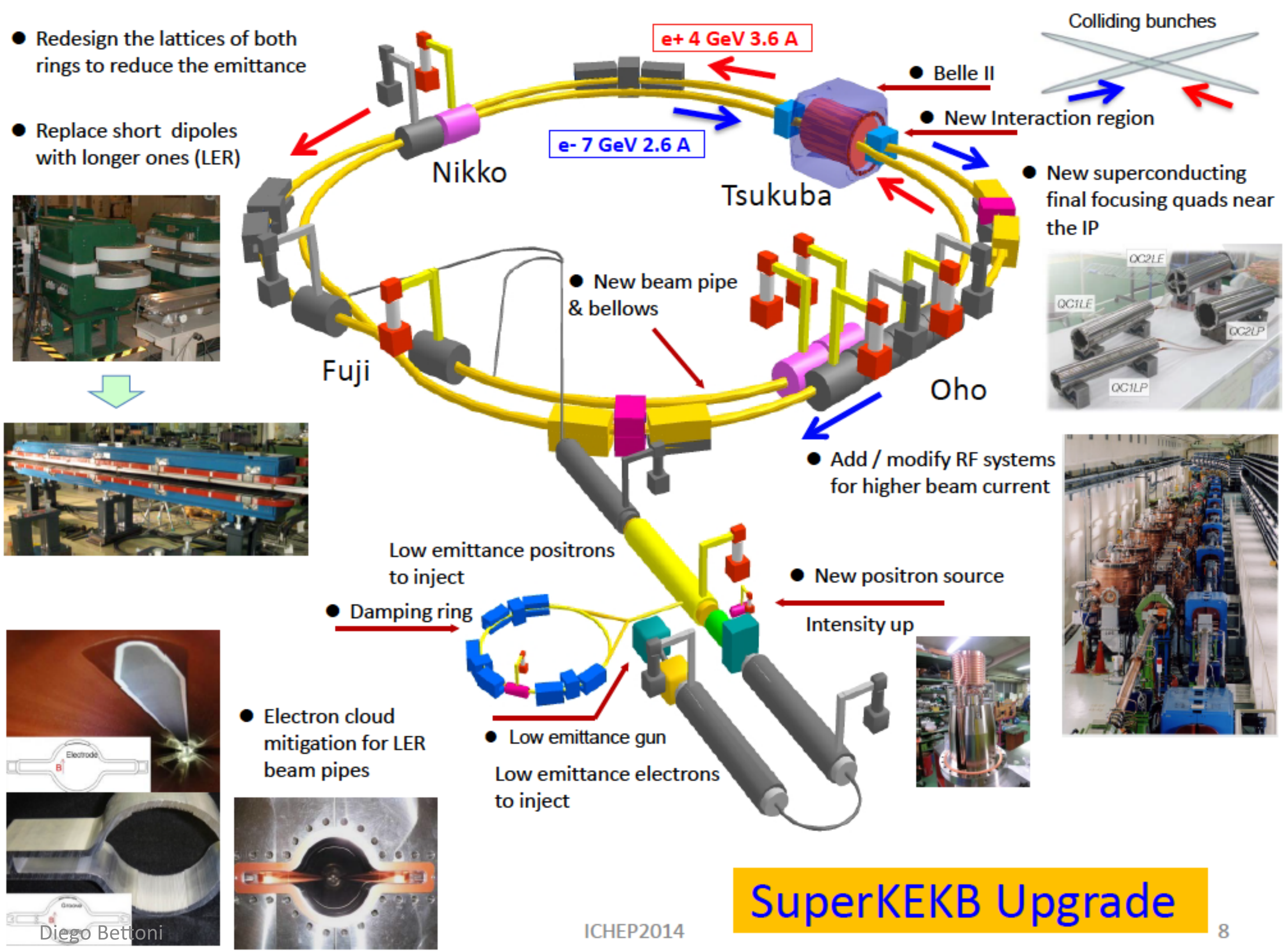
μCounter

8- 9 layers RPC

$\delta R\Phi$=1.4 cm~1.7 cm

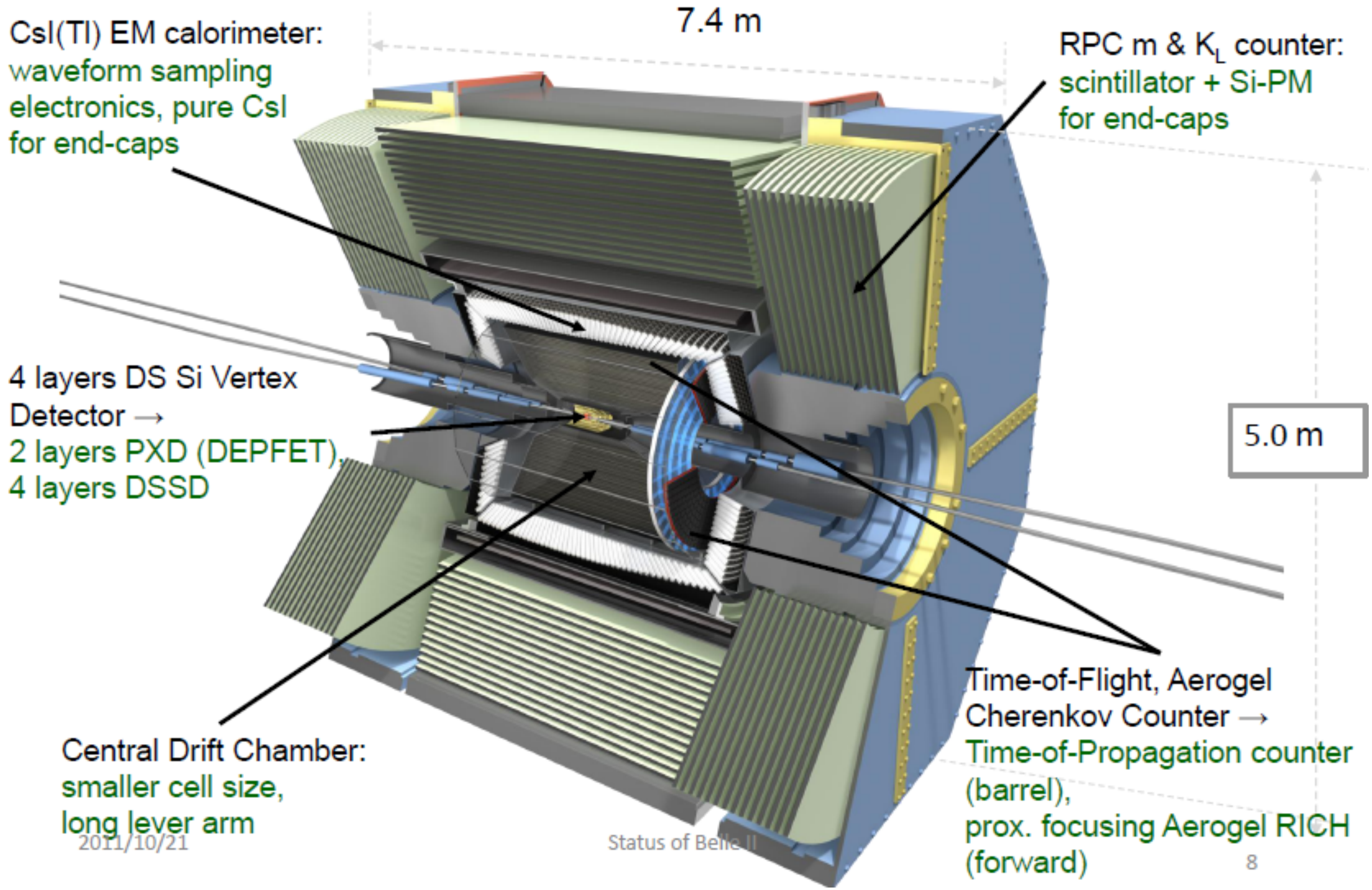
EMC: $\sigma E/\sqrt{E}(^0/_0)$ = 2.5 % (1 GeV)
(CsI) $\sigma_{z,\phi}$(cm) = 0.5 - 0.7 cm/$\sqrt{E}$


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

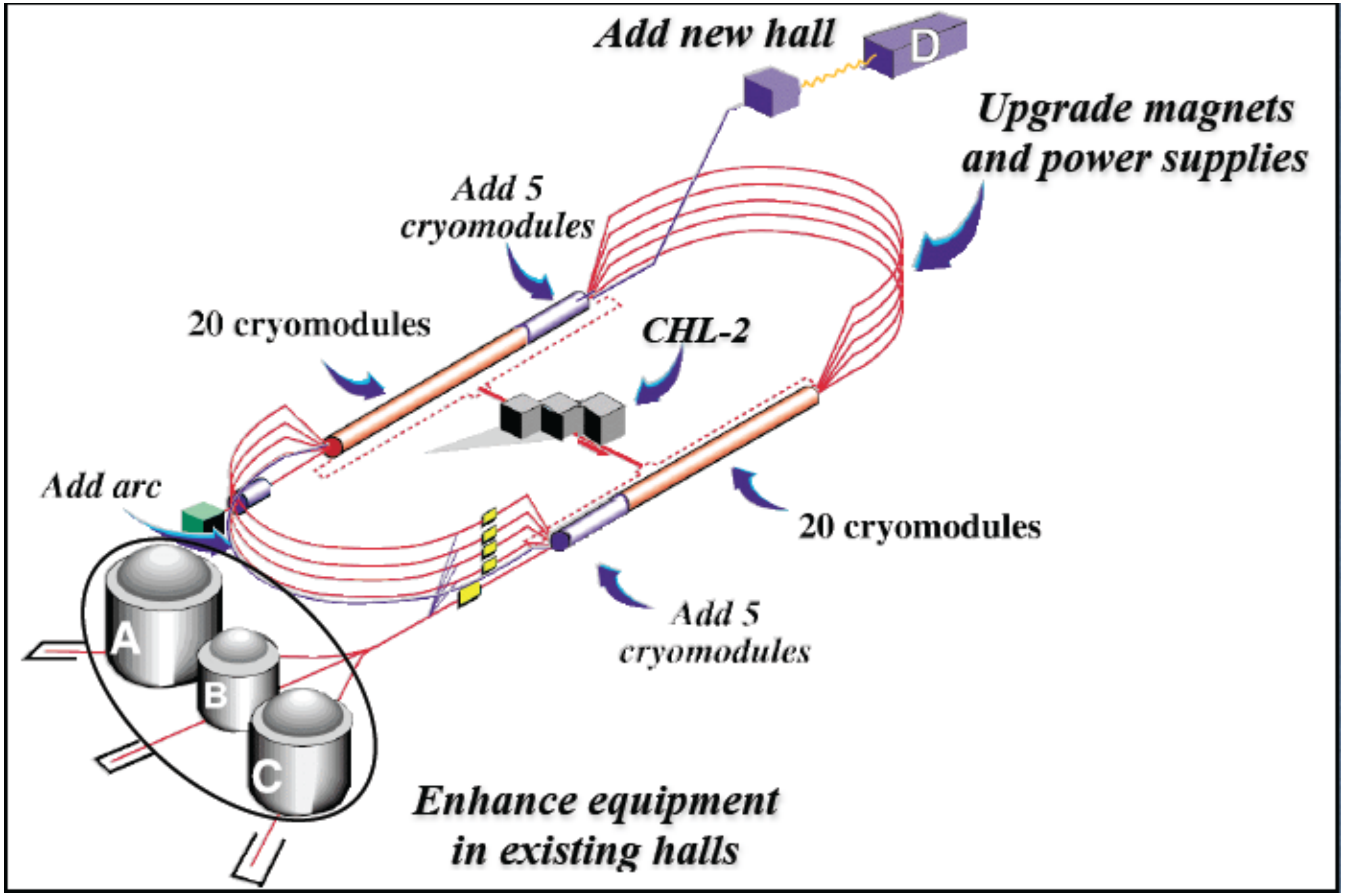


Redesign the lattices of both rings to reduce the emittance
Replace short dipoles with longer ones (LER)
e+ 4 GeV 3.6 A
e- 7 GeV 2.6 A
Colliding bunches
Belle II
New Interaction region
New superconducting final focusing quads near the IP
QC2LE
QC1LE
QC2LP
QC1LP
Nikko
Tsukuba
Fuji
Oho
New beam pipe & bellows
Add / modify RF systems for higher beam current
Low emittance positrons to inject
Damping ring
New positron source
Intensity up
Electron cloud mitigation for LER beam pipes
Electrode
Low emittance gun
Low emittance electrons to inject
SuperKEKB Upgrade

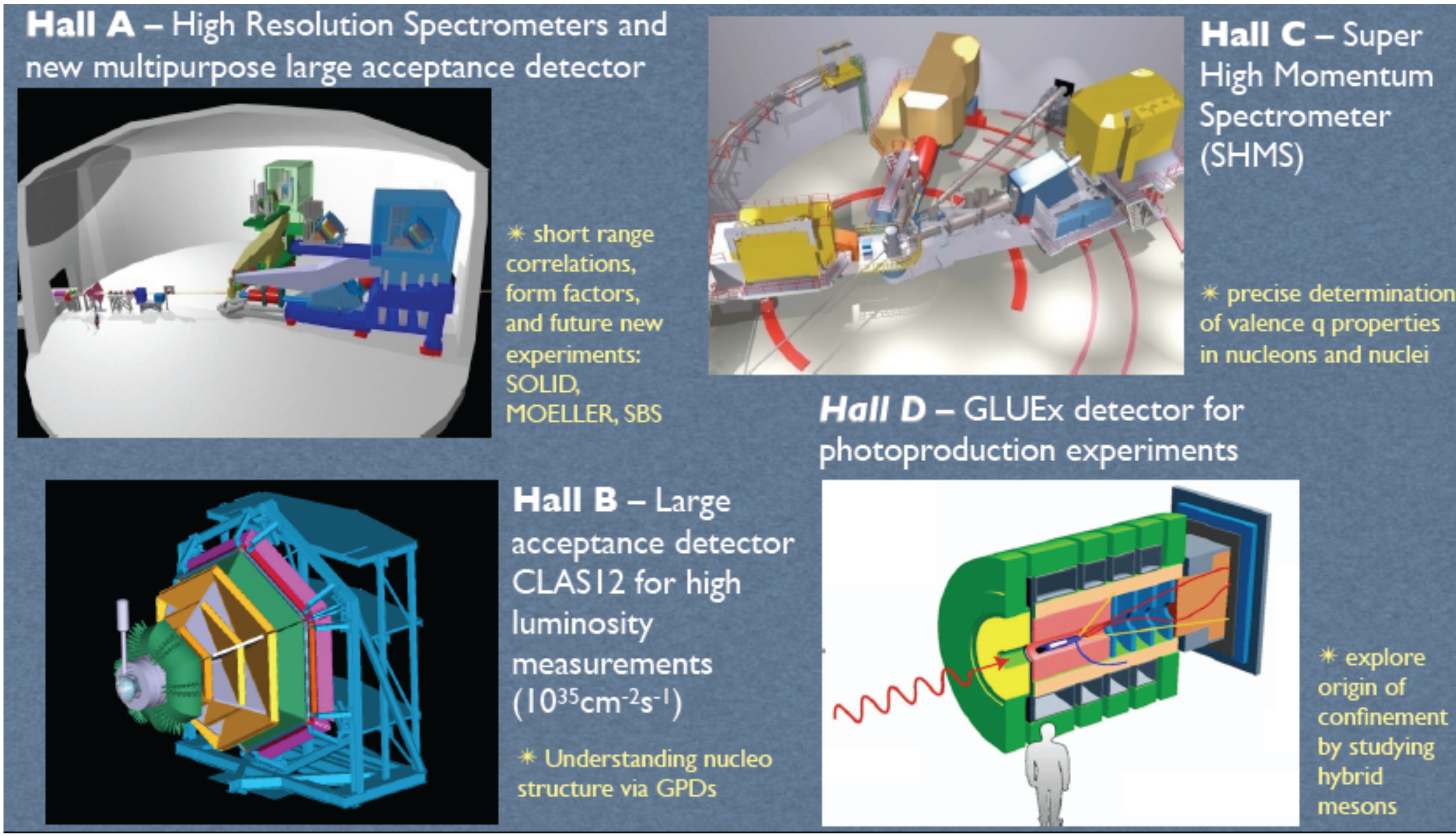
Belle II: design concept



The JLAB 12 GeV Upgrade



The 12 GeV Equipment



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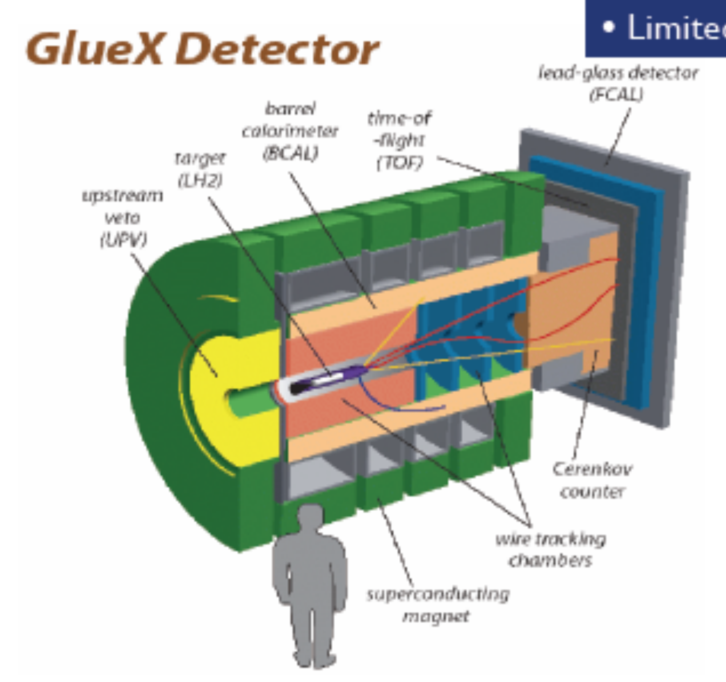
Meson spectroscopy with photons at JLab-12 GeV

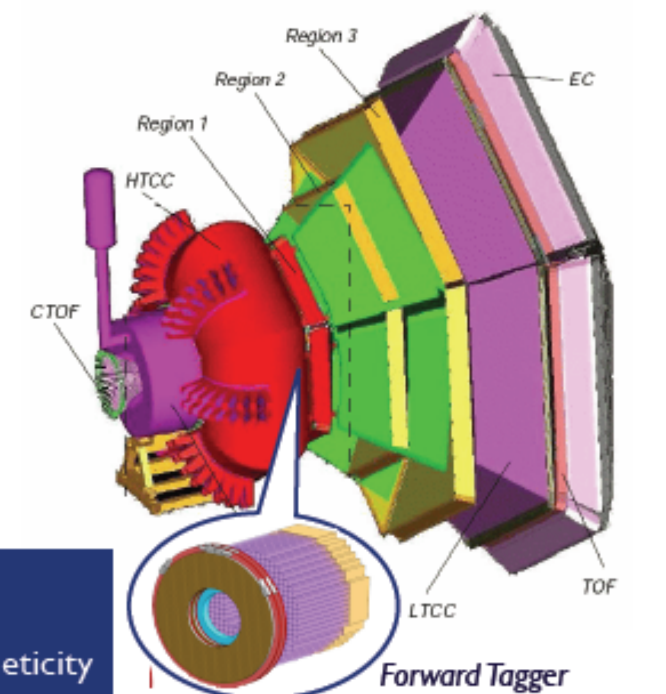
- Determination of JPC of meson states requires PWA
- Decay and production of exclusive reactions
- Good acceptance, energy resolution, particle identification

Hall-D - GlueX Detector

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



Hall-B - CLAS12 Detector



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

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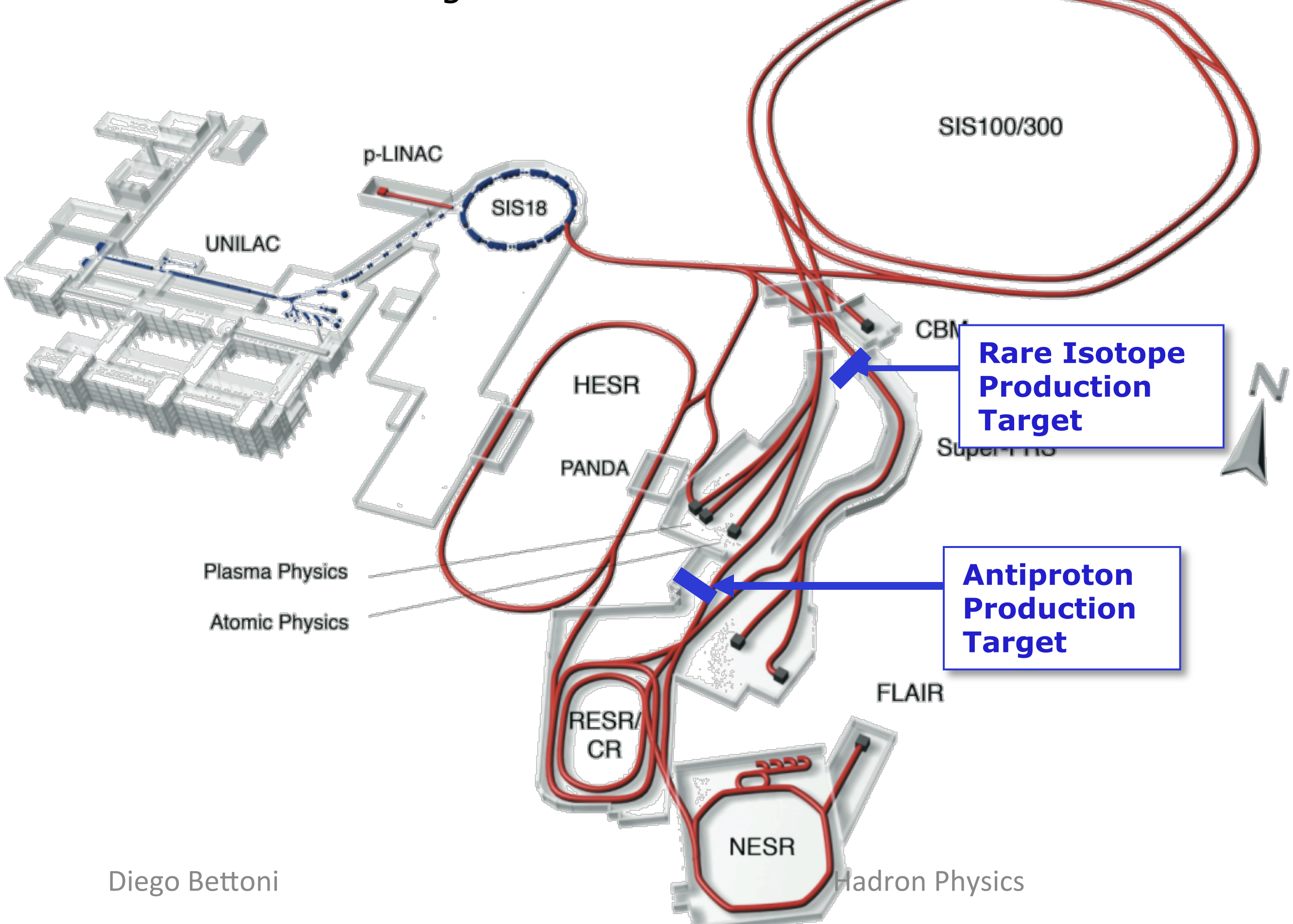
The FAIR Complex

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**

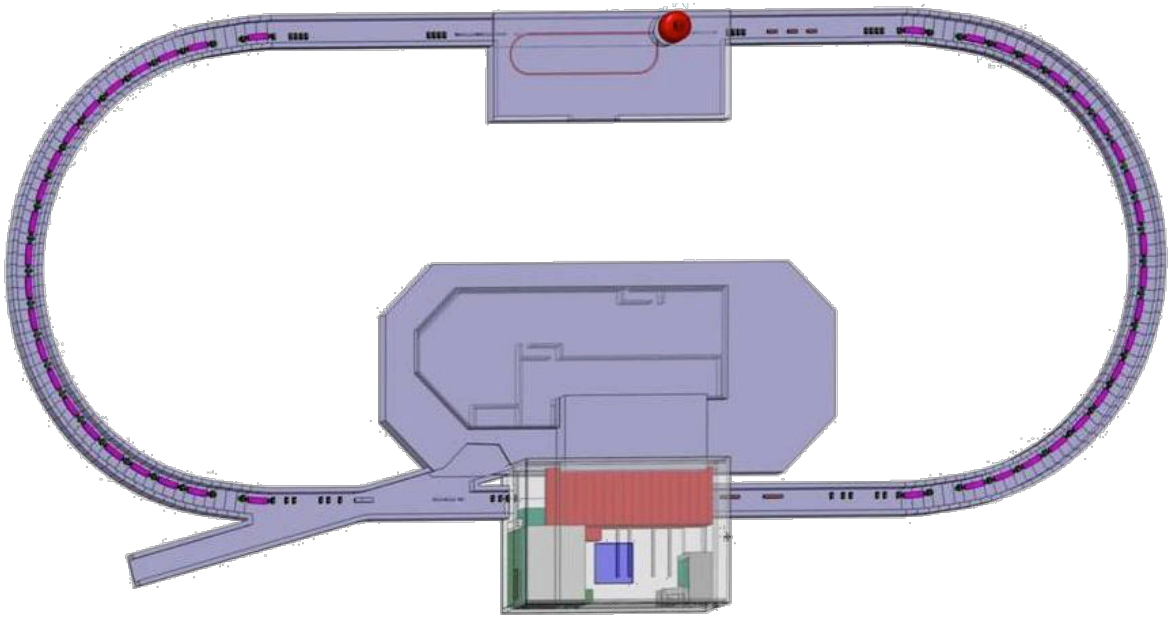
Secondary Beams

- **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

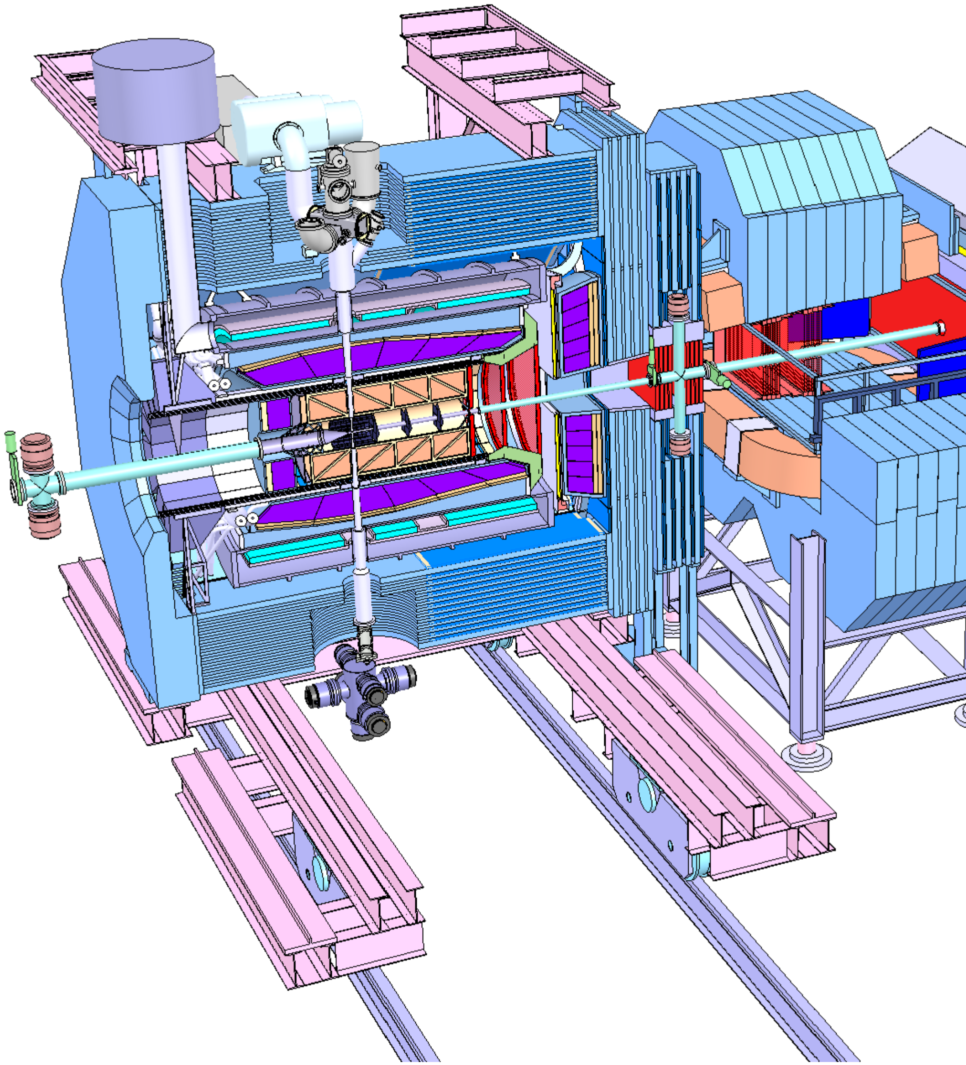
$P_{beam} = 1.5 - 15$ GeV/c

Internal Target 4×10^{15} cm^{-2}

Modularized Start Version (MSV0-3)

$L \sim 10^{31} cm^{-2} s^{-1}$ $\Delta p/p \sim 5 \times 10^{-5}$

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



Detector requirements:

- 4π acceptance

- High rate capability: $2\times10^{7}\ s^{-1}$ interactions
- Efficient event selection

→ *Continuous acquisition*

- Momentum resolution ~1%
- Vertex info for D, K^0_S, Y (cτ = 317 μm for $D^\pm$)

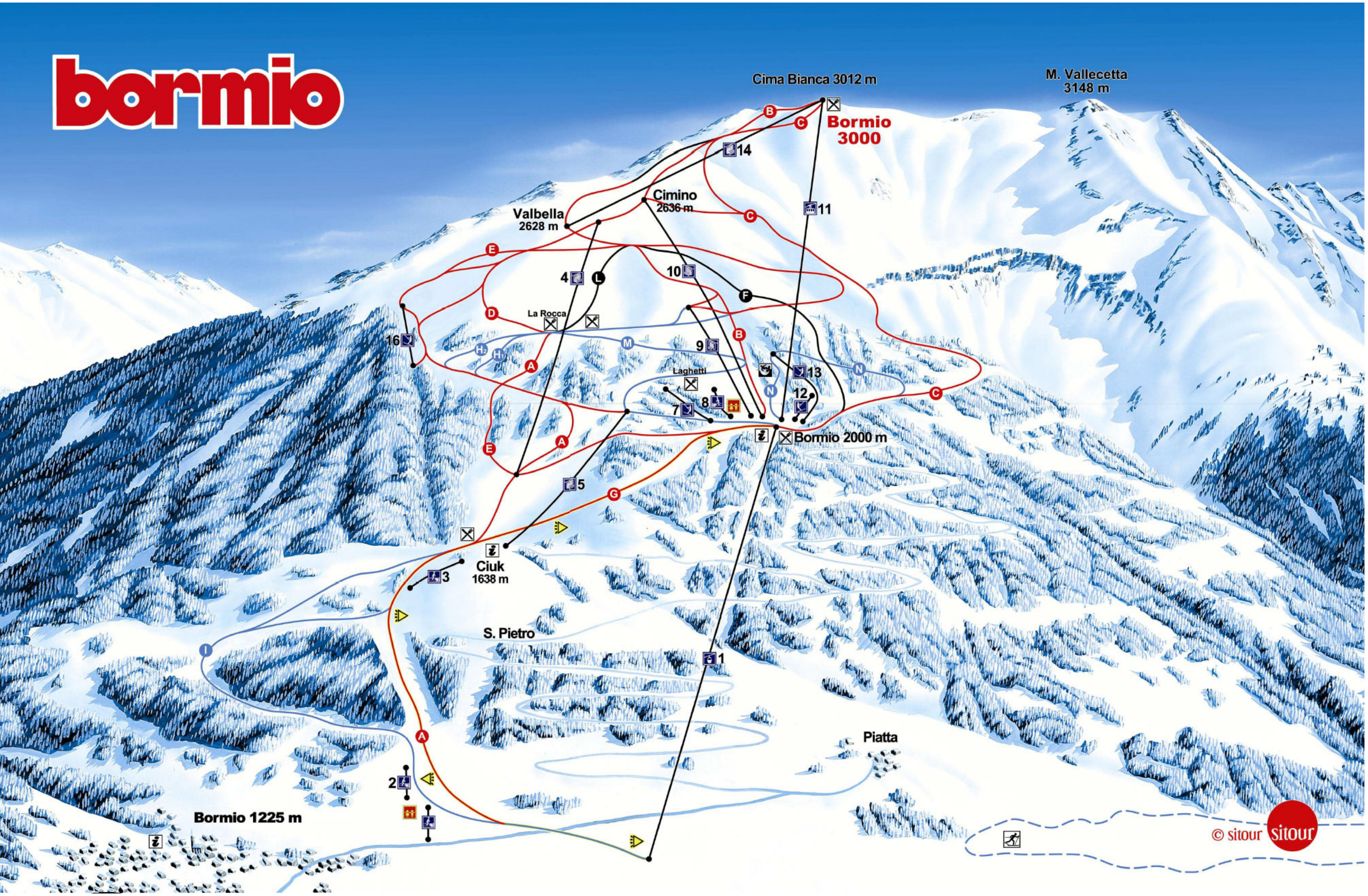
→ *Good tracking*

- Good PID (γ, e, μ, π, K, p)

→ *Cherenkov, ToF, dE/dx*

- γ-detection 1 MeV – 10 GeV

→ *Crystal Calorimeter*



Piste

A Stelvio
B Stella Alpina
C Bimbi al sole
D Praimont
E S. Ambrogio
F Betulle
G Genziana
H1 Ermellini 1
H2 Ermellini 2
I Bosco basso
L Valbella
M La Rocca
N Nevada

Impianti

1 Bormio - Bormio 2000
2 Campo Scuola Bormio
3 Ciuk
4 Fontana Longa - Valbella
5 Laghetti
7 Baby 2000
8 Marmotta
9 Pian dei Larici
10 Bormio 2000 - Cimino
11 Bormio 2000 - Cima Bianca
12 Nevada Est
13 Nevada Ovest
14 Valbella - Bormio 3000
16 Rocca Est

Conclusions

- Hadron spectroscopy is an invaluable tool for a deeper understanding of the strong interaction and QCD.
- Exciting new experimental results achieved over the past two decades thanks to many experiments at hadron machines and e^+e^- colliders.
  - Quarkonium states below threshold
  - X, Y, Z states reveal new sector of QCD spectrum
  - Open charm states
- Progress in theory
  - Lattice QCD
  - Effective Field Theories
- For the near and medium term future first rate results are expected from
  - LHC
  - e^+e^- colliders (BES III, Belle2).
  - JLAB 12 GeV (CLAS12 and GlueX)
  - PANDA at FAIR
- Complementary approaches