Charm Physics: Where Color meets Flavor

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Contents

Why is charm of interest?

- Charm is an up-type quark:
  Interesting Flavour Physics
  - ... complementary to bottom and strange
  - ... different from top
- It is neither very heavy nor very light:
  Interesting QCD laboratory
  - Open Charm spectroscopy
  - Charmonia
  - Exotica

FLAVOR

Looking up ...

- Flavour Physics of charm: Compared to B and K: The roles of up and down quarks are interchanged
- Complementarity to top quark (flavour) physics
- Up-type Flavour tests are mandatory for a full test of our understanding of Flavour Physics

Charm is unique ...

- FCNC's are suppressed in the SM by GIM
- For bottom and strange:

$$\mathrm{GIM} \propto \frac{1}{16\pi^2} \frac{m_t^2 - m_u^2}{M_W^2}$$

GIM is weakened by the large Top mass

- For charm (and top):

$$\mathrm{GIM} \propto \frac{1}{16\pi^2} \frac{m_b^2 - m_d^2}{M_W^2}$$

GIM is MUCH more efficient

- Up-type FCNC's have a very small SM "pollution"
- Relative Strength of New Physics (NP) in Up vs. Down-Type FCNC's might be different
- Cleaner (but not neccessary larger) signals of new physics:

$$\left(\frac{\text{NP Signal}}{\text{SM noise}}\right)_{\text{up-type}} > \left(\frac{\text{NP Signal}}{\text{SM noise}}\right)_{\text{down-type}}$$

- Top plays a special role
  - No Top Hadrons
  - Flavour Phenomenology less rich
  - Strong interactions perturbative

$$\boxed{\text{Charm: Novel access to flavour dynamics}}$$

Flavour Physics: Charm Decays

"Bread and Butter"

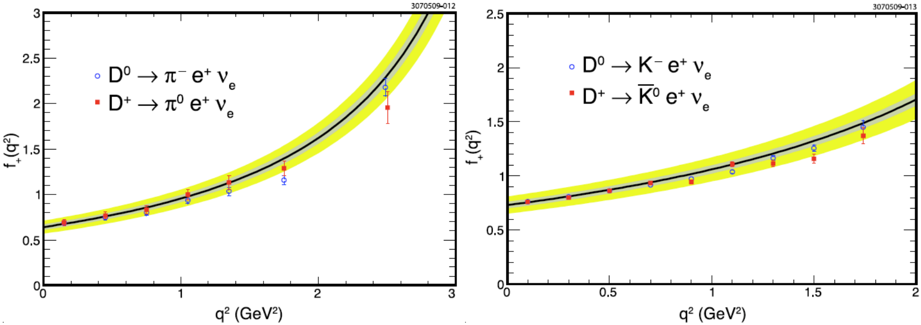
- (Semi-)leptonics: $c \to s\ell\bar{\nu}_\ell$ and $c \to d\ell\bar{\nu}_\ell$
- Non-leptonics: $c \to s\bar{q}q'$ and $c \to d\bar{q}q'$
- Access to CKM matrix elements
- Non-leptonic multiparticle decays: CP violation

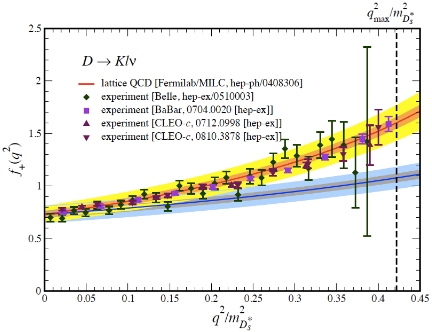
Rare and forbidden Processes

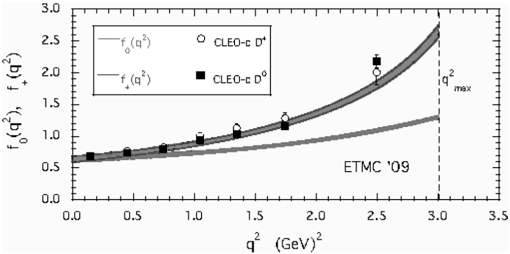
- $D_{(s)} \to \ell^+\ell^- + K^*/\rho/\omega/\phi$
  (dominated by long distance contributions)
- $D^0 \to \mu^+\mu^-$: A channel for LHCb!
  In the SM: $\mathrm{BR}(D^0 \to \mu^+\mu^-) \sim 10^{-12}$
- $D^0 \to \gamma\gamma$ (again large long distance contributions)
- "Forbidden" Modes: $D^0 \to e^+\mu^-$ etc...

Example: Charm Semi-Leptonics

- History: Dedicated Charm Experiment: CLEO-c:







- From factor calculations: lattice and QCD SR
- Direct determinations of V_{cs} and V_{cd}

$$\boxed{V_{cd} = 0.225 \pm 0.005 \pm 0.003^{+0.016}_{-0.012}}$$

(Khodjamirian et al.)

Form Factor Measurements

Use the z expansion for the form factor

Becher, Hill; Boyd, Grinstein, Lebed, Lellouch, ...

$$F(t) = \frac{1}{P(t)\phi(t,t_0)} \sum_{k=0}^{\infty} a_k(t_0)(z(t,t_0))^k$$

with

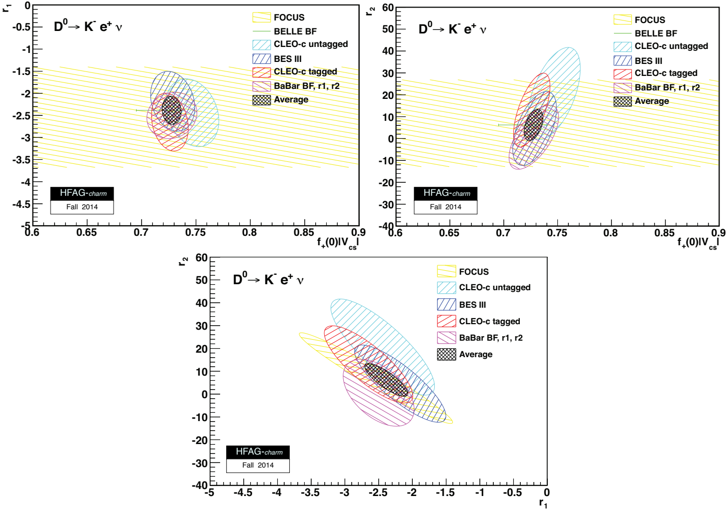
$$z(t,t_0) = \frac{\sqrt{t_+ - t} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - t} + \sqrt{t_+ - t_0}}$$

and

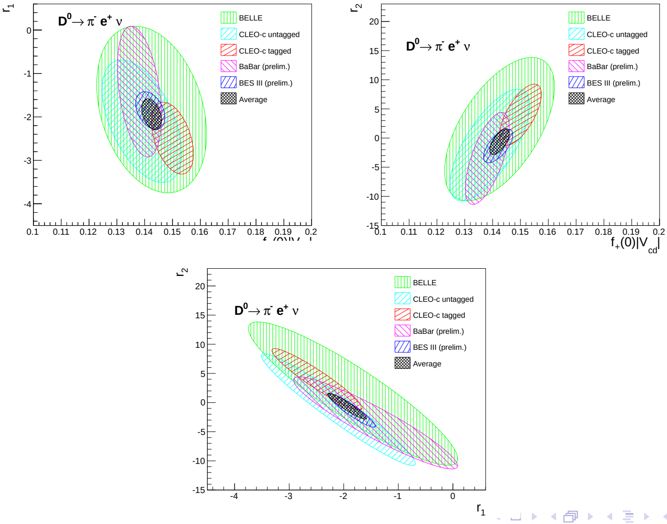
$$t_\pm = (m_D \pm m_\pi)^2 \quad \text{or} \quad t_\pm = (m_D \pm m_K)^2$$

$$r_k = a_k / a_0$$

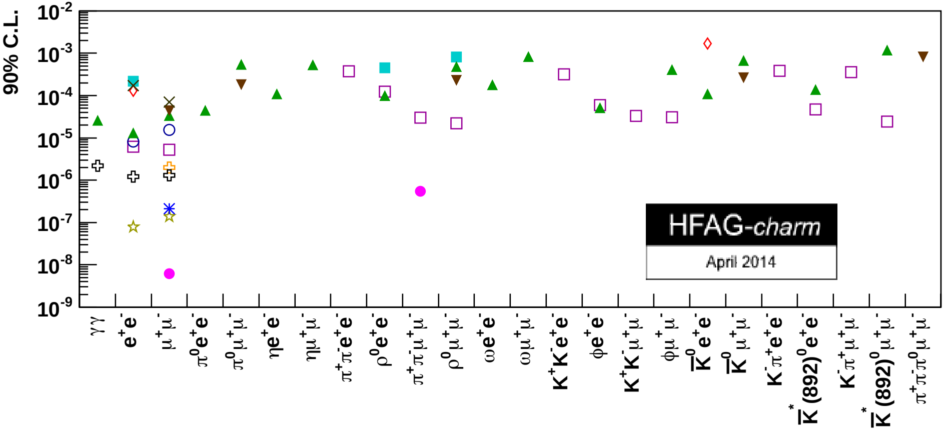
$D \to K\ell\bar{\nu}$

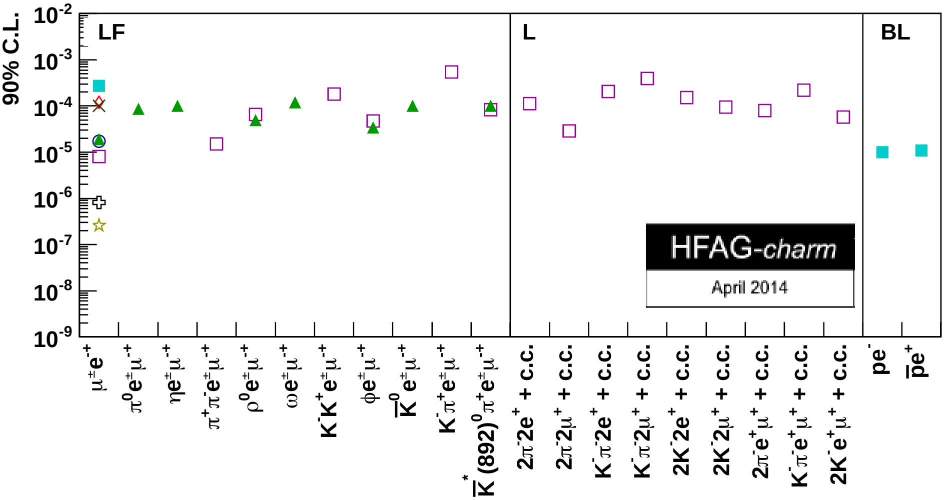


$D \to \pi \ell \bar{\nu}$



Rare and Forbidden Decays: D_0




90% C.L.
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
LF
L
BL
HFAG-charm
April 2014
μ±e∓
π0e±μ∓
ηe±μ∓
π+π−e±μ∓
ρ0e±μ∓
ωe±μ∓
K−K+e±μ∓
φe±μ∓
K̄0e±μ∓
K−π+e±μ∓
K̄*(892)0π+e±μ∓
2π−2e+ + c.c.
2π−2μ+ + c.c.
K−π−2e+ + c.c.
K−π−2μ+ + c.c.
2K−2e+ + c.c.
2K−2μ+ + c.c.
2π−e+μ+ + c.c.
K−π−e+μ+ + c.c.
2K−e+μ+ + c.c.
pe−
p̄e+

Charm Mixing

- Transitions between D^0 and $\overline{D}^0$:
  Two Mass Eigenstates in the neutral *D* System

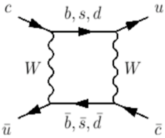
$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle \qquad |p|^2 + |q|^2 = 1$$

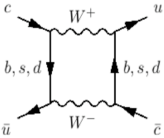
- Mixing Parameters

$$x = \frac{m_1 - m_2}{\Gamma} \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \quad \text{with} \quad \Gamma = \frac{1}{2}(\Gamma_1 + \Gamma_2)$$

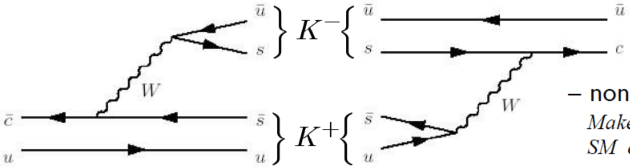
- Opens a window to new physics
- Opens the road to time-dependent CP violation

- Standard Model: At the quark level:





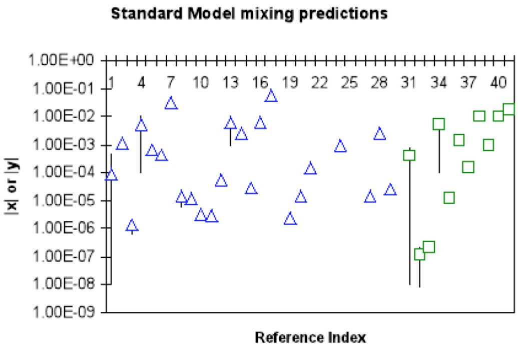
- Pollution by long distance effects



– non-perturbative contributions

Makes it difficult to precisely predict SM expectations

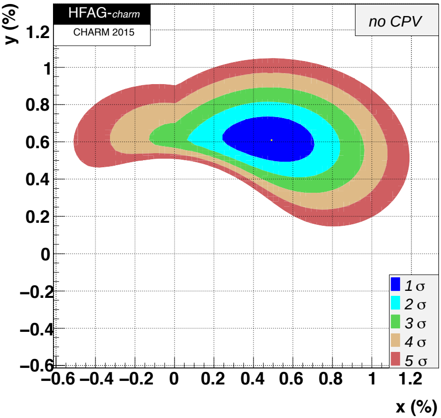
$$\boxed{\text{In the SM: } |x| \sim \mathcal{O}(10^{-3\ldots-2}),\ |y| \sim \mathcal{O}(10^{-3\ldots-2})}$$

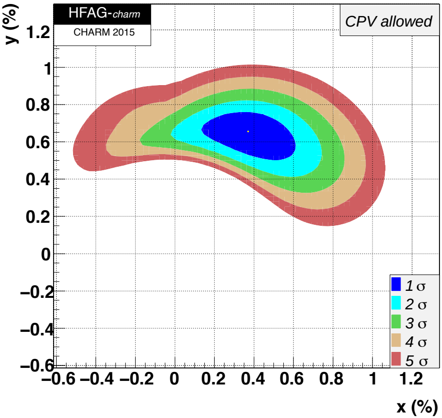


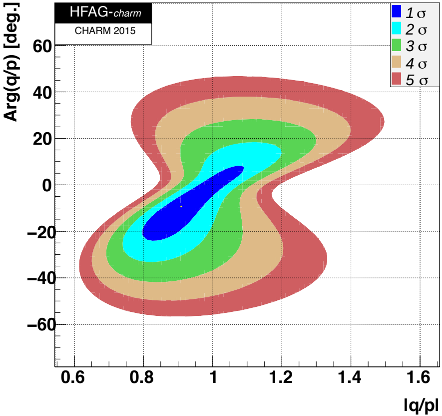
(Petrov)

- Exclusive calculations $D \to [K\pi/\pi\pi/\pi\rho/\ldots] \to \overline{D}$
  (Falk, Grossman, Ligeti, Nir, Petrov)
- Inclusive calculation:
  OPE in terms of inverse Powers of the charm mass
  (Uraltsev, Georgi, Simmons. Ricciati, Ohl)

There are data !!






HFAG-charm
CHARM 2015
1 σ
2 σ
3 σ
4 σ
5 σ
Arg(q/p) [deg.]
60
40
20
0
−20
−40
−60
0.6
0.8
1
1.2
1.4
1.6
|q/p|

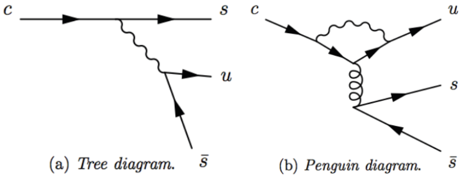
Interpretation of Charm Mixing

- Difficult, due to long distance contributions
- A scenario $|x| > 1\%$ and $|x| \gg |y|$ could be interpreted as a manifestation of NP
- ... but seems to be ruled our already
- Observations can be due to SM dynamics
- ... yet may still contain a large NP contribution
- A precise SM prediction requires a theoretical breakthrough
- Knowing x and y is also of practical importance with respect to CP violation

CP in Charm

In the SM:

- Couplings to the third family are small
- $\rightarrow$ SM Charm Physics is "two family physics"
- $\rightarrow$ only small pollution from the third family
- $\rightarrow$ CP violating effects are tiny
- Weak phase in CS decays: $V_{cs} = 1 \ldots + i\lambda^4$



(a) *Tree diagram.* (b) *Penguin diagram.*

- No weak phases in CA and DCS modes

- $D^0 - \overline{D}^0$ Oscillations open an additional window to CP

$$\mathcal{A}_{\rm CP}(t) = [x \sin \phi_{\rm CP} + y\, \epsilon_{\rm CP} \cos \phi_{\rm CP}] \left(\frac{t}{\tau}\right)$$

  - $\phi_{\rm CP}$: Weak Phase in $D^0 - \overline{D}^0$ mixing
  - $\epsilon_{\rm CP}$: Corresponds to the ϵ parameter for the Kaons
  - In the SM: $x, y \sim 1\%$ and $\sin \phi_{\rm CP}, \epsilon_{\rm CP} \leq 10^{-3}$

$$\boxed{\mathcal{A}_{\rm CP}(t) \sim 10^{-5} \text{ in the SM}}$$

- This is an experimental challenge
- Good news for LHCb:
  $D^0(t) \to K_s\phi, K^+K^-, \pi^+\pi^-, K^+\pi^-$

CP in Charm as Indication of New Physics

- Baryon Asymmetry: CP violation beyond CKM
- CP Asymmetries are linear in the NP amplitude
- Tiny SM Effects $\to$ Very small SM background:

$$\boxed{\mathcal{A}_{\mathrm{CP}}(t) \sim 10^{-3} \text{ in some NP models}}$$

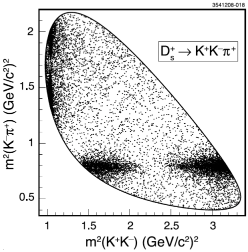
- Large CP sensitivity in final state distributions

CP Studies in Final State Distribution

Ultimate tool for CP Studies:

- Local Asymmetries will be larger than integrated ones
- Can rely on relative instead of absolute normalization
- Can give us more information on the nature of the NP

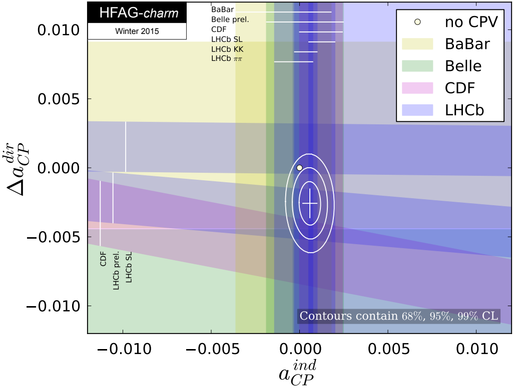
(Bigi, Hanhart, Meissner, Gardener,TM, ...)



Status of Charm CP

- There has bee some excitement concering

$$\Delta a_{CP} = a_{CP}(K^+K^-) - a_{CP}(\pi^+\pi^-)$$



COLOR

Open Charm Spectroscopy

Start from the limit $m_c \to \infty$:

- The spin of the charm quark decouples and becomes a good quantum number
- The states are characterized by the total angular momentum of the light degrees of freedom
- The spectrum of all charm hadrons falls into spin symmetry doublets (J^P notation)

$$((\ell-1)^{(-1)^{\ell+1}}, \ell^{(-1)^{\ell+1}}) \text{ for } j = \ell - 1/2 \text{ and}$$
$$(\ell^{(-1)^{\ell+1}}, (\ell+1)^{(-1)^{\ell+1}}) \text{ for } j = \ell + 1/2\,.$$

(with the orbital angular momentum ℓ of the light degrees of freedom)

However, $\Lambda_{\rm QCD}/m_c$ corrections change this picture ...

Example: first orbitally excited D mesons

Make use of Heavy Quark Symmetry:

- Spin Symmetry Doublets of orbitally excited states, labelled by the total j of the light degrees of freedom:

$$\begin{pmatrix} |D(0^+)\rangle \\ |D(1^+)\rangle \end{pmatrix} \quad j = 1/2 \qquad \text{and} \qquad \begin{pmatrix} |D^*(1^+)\rangle \\ |D^*(2^+)\rangle \end{pmatrix} \quad j = 3/2$$

- Masses in the $m_c \to \infty$ limit:

$$M(D(0^+)) = M(D(1^+)) = m_c + \bar{\Lambda}_{1/2}$$
$$M(D^*(1^+)) = M(D^*(2^+)) = m_c + \bar{\Lambda}_{3/2}$$

- $\bar{\Lambda}_{3/2} - \bar{\Lambda}_{1/2}$ does not scale with m_c!

$1/m_c$ corrections

- Kinetic energy and choromomagnetic moment:

$$\mathcal{H}_{1/m} = \frac{1}{2m_c}\bar{c}(iD_\perp)^2 c + \frac{g_s}{2m_c}\bar{c}(\vec{\sigma}\cdot\vec{B})c$$

- Kinetic energy is spin independent and is absorbed into the mass definition

$$M_j = m_c + \bar{\Lambda}_j + \frac{1}{2m_c}\mu_\pi^2$$

Mass shift is independent of j

- Chromomagnetic moment depends on the spins:

$$\vec{K} = \vec{J} + \vec{\sigma} = \vec{L} + \vec{s} + \vec{\sigma} \quad \begin{cases} \vec{L}\text{: Orbital Angular Momentum} \\ \vec{s}\text{: Light Quark Spin} \\ \vec{\sigma}\text{: Heavy Quark Quark Spin} \end{cases}$$

- Simple parametrization: The gyro-chromo-magnetic factors of the orbital motion and of the light quark spin are different:

$$\vec{B} \sim \alpha' \vec{L} + \beta' \vec{s} = \alpha \vec{J} + \beta \vec{s}$$

- The Spin dependent part of the Hamiltonian becomes (schematically)

$$H_{1/m} = \int d^3\vec{x}\, \frac{g_s}{2m_c} \bar{c}(\vec{\sigma} \cdot \vec{B}) c = g(\vec{J} \cdot \vec{\sigma}) + g'(\vec{s} \cdot \vec{\sigma})$$

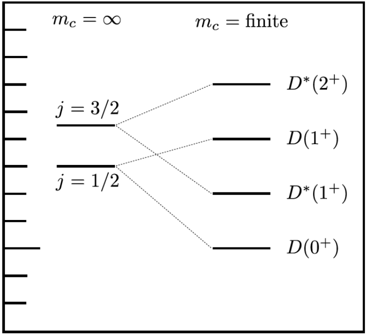
- $|D^*(2^+)\rangle$ and $|D(0^+)\rangle$ are Eigenstates of H

$$H|D^*(2^+)\rangle = \left(M_{3/2} + \frac{3}{4}g + \frac{1}{4}g'\right)|D^*(2^+)\rangle$$
$$H|D(0^+)\rangle = \left(M_{1/2} - \frac{3}{4}g + \frac{1}{4}g'\right)|D(0^+)\rangle$$

- There is a mixing between the two 1^+ states:

$$H|D(1^+)\rangle = \left(M_{1/2} + \frac{1}{4}g - \frac{1}{12}g'\right)|D(1^+)\rangle + \frac{\sqrt{2}}{3}g'\,|D^*(1^+)\rangle$$
$$H|D^*(1^+)\rangle = \left(M_{3/2} - \frac{5}{4}g - \frac{5}{12}g'\right)|D^*(1^+)\rangle + \frac{\sqrt{2}}{3}g'\,|D(1^+)\rangle$$

- Parametrically, the mixing is $g' \sim 1/m_c$, however, it is numerically of the same order as $\bar{\Lambda}_{3/2} - \bar{\Lambda}_{1/2}$
- Expect a significant mixing!

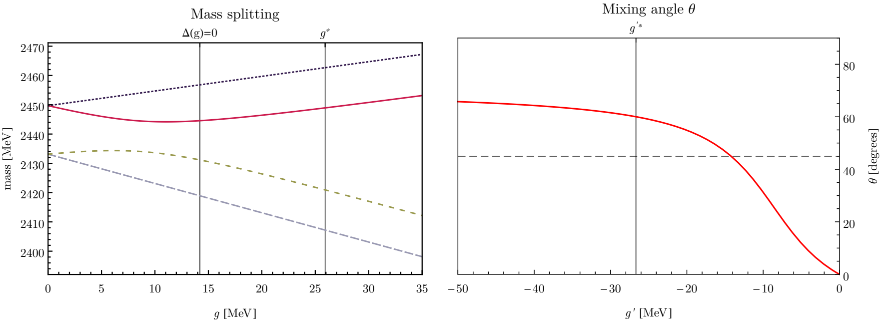


State	Mass [MeV]	Width [MeV]
$D(0^+)$	2318 ± 29	267 ± 40
$D(1^+)$	2421.4 ± 0.6	27.4 ± 2.5
$D^*(1^+)$	2427 ± 40	384 ± 120
$D^*(2^+)$	2462.6 ± 0.6	49 ± 1.3

- Assignment of the states:
  $j = 1/2$ are wide, $j = 3/2$ are narrow.

$$|D_1(1^+)\rangle = \cos\theta\,|D(1^+)\rangle + \sin\theta\,|D^*(1^+)\rangle$$
$$|D_2(1^+)\rangle = -\sin\theta\,|D(1^+)\rangle + \cos\theta\,|D^*(1^+)\rangle$$

- "Level Crossing": The mixing angle is larger than 45°



$$\boxed{g \sim g',\ \theta \sim 60^\circ}$$

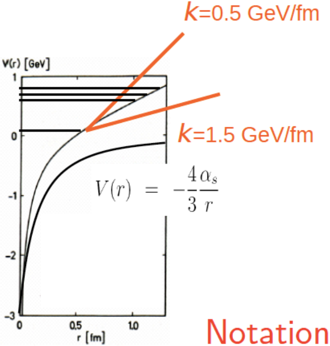
“Standard” Charmonia

- Spectroscopy in the framework of non-relativistic charm quarks with e.g. Cornell potential:

  - Coulomb-Potential
    + Confinement-Term

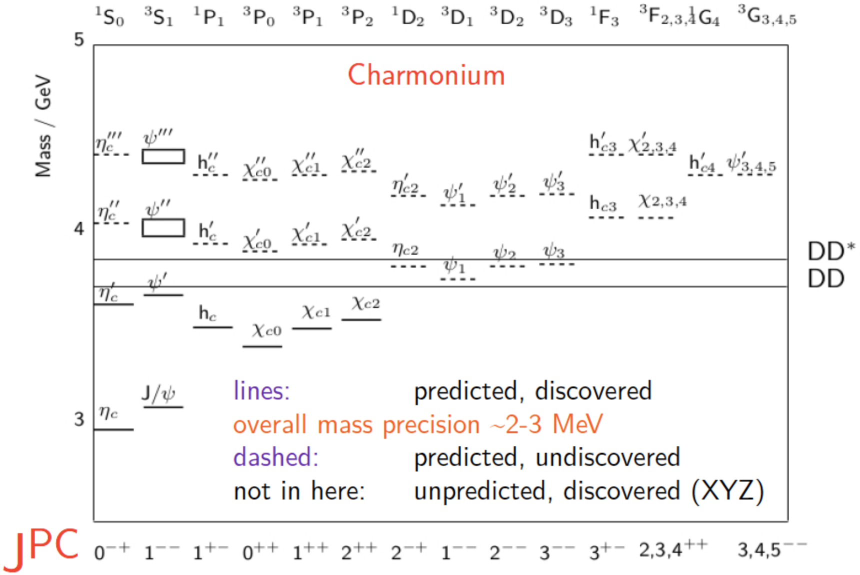
$$
\begin{array}{lrl}
 & V(r) = & -\frac{4}{3}\frac{\alpha_s}{r} + \boxed{kr} \\
\text{spin-spin} & & +\frac{32\pi\alpha_s}{9m_c^2}\delta_r \vec{S}_c\vec{S}_{\bar{c}} \\
\text{spin-orbit} & & +\frac{1}{m_c^2}\left(\frac{2\alpha_s}{r^3} - \frac{k}{2r}\right)\vec{L}\vec{S} \\
\text{tensor} & & +\frac{1}{m_c^2}\frac{4\alpha_s}{r^3}\left(\frac{3\vec{S}_c\vec{r}\cdot\vec{S}_{\bar{c}}\vec{r}}{r^2} - \vec{S}_c\vec{S}_{\bar{c}}\right)
\end{array}
$$

  - solve Schrödinger equation
    (quark mass heavy → non-relativistic)
    → states



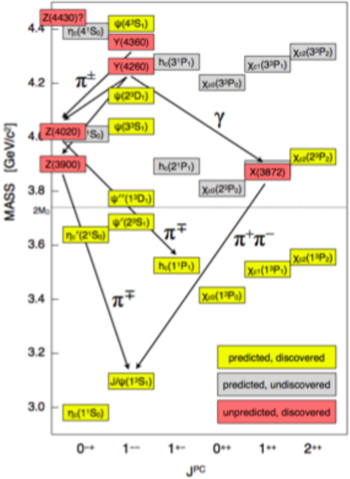
Notation

Alternatively: Lattice simulations


$^1S_0$ $^3S_1$ $^1P_1$ $^3P_0$ $^3P_1$ $^3P_2$ $^1D_2$ $^3D_1$ $^3D_2$ $^3D_3$ $^1F_3$ $^3F_{2,3,4}$ $^1G_4$ $^3G_{3,4,5}$
Mass / GeV
5
4
3
Charmonium
η_c''' ψ''' h_c'' χ_{c0}'' χ_{c1}'' χ_{c2}''
η_{c2}' ψ_1' ψ_2' ψ_3'
h_{c3}' $\chi_{2,3,4}'$ h_{c4}' $\psi_{3,4,5}'$
h_{c3} $\chi_{2,3,4}$
η_c'' ψ'' h_c' χ_{c0}' χ_{c1}' χ_{c2}'
η_{c2} ψ_1 ψ_2 ψ_3
DD*
DD
η_c' ψ'
h_c χ_{c0} χ_{c1} χ_{c2}
η_c J/ψ
lines: predicted, discovered
overall mass precision ~2-3 MeV
dashed: predicted, undiscovered
not in here: unpredicted, discovered (XYZ)
JPC
0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++} 2^{-+} 1^{--} 2^{--} 3^{--} 3^{+-} $2,3,4^{++}$ $3,4,5^{--}$

- Transitions and decays:
  - Non-relativistic QCD:
    v/c expansion of full QCD
    effective field theory approach
  - QCD sum rules:
    QCD based, no expansion.
- ... fairly well under control, no fundamental problems
- ... except:

Comment on Exotica



(fig. borrowed from Gianfranco Morello, poster at this conference)

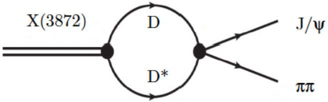
Theoretical Explanations

TETRAQUARK

Diquarks
are colored

Maiani, Riquer, Piccinini, Polosa, Burns;
Ebert, Faustov, Galkin; Chiu, Hsieh;
Ali, Hambrock, Wang

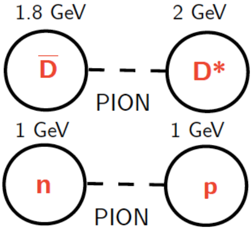
THRESHOLD CUSP



Bugg; Swanson

MOLECULE

Intriguing Analogon



Tornqvist; Swanson; Braaten, Kusonoki,
Wong; Voloshin; Close, Page
Guo, Hanhart, Meissner

(Slide from S Lange)

- From the point of view of QCD their existence is less puzzling!
- ... however, why are these states so narrow?
- Moreover, in QCD the notion of "tetraquark" or "meson molecule" is almost meaningless
- In QCD: Interpolating field operators

$$\langle X(J^{PC})|O^{J^{PC}}(x)|0\rangle \neq 0$$

for a state X with quantum numbers J^{PC}

- many possibilities: $O^{J^{PC}}(x) \to O_n^{J^{PC}}(x)$

Examples

- Isoscalar $J^{PC} = 0^{++}$:
  $\bar{u}u + \bar{d}d \quad G^a_{\mu\nu} G^{\mu\nu,a} \dots$
- Isoscalar $J^{PC} = 1^{--}$:
  $\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d \quad \bar{s}\gamma_\mu s \quad \bar{c}\gamma_\mu c \quad \bar{s}\gamma_\mu s\, \bar{c}c \quad \bar{s}\gamma_\mu s\, G^a_{\mu\nu} G^{\mu\nu,a} \dots$
- $\dots$

What is the relation between the field content of the operators to the particle content of the state? None!
There is even RG mixing between the operators with identical quantum numbers
However ...

One may take the correlation function

$$T_{mn}(x) = \langle 0 | T[O_m^{J^{PC}}(x) O_n^{J^{PC}}(0)] | 0 \rangle$$

- Dispersion relation: Study the spectral functions
- Compare in the euclidean with the perturbative result a la QCD sum rules
- Try to understand how these states can be so narrow
- Simulations on the lattice become feasible
- Do "Real" Tetraquarks exist: $(\bar{c}s\bar{u}d) \to D_s^* \pi$?

A QCD-based theory for these states does not (yet) exist!

Conclusions

Charm Physics is quite unexplored!

- A lot of experimental information in the near future:
    - LHCb
    - BES III
    - BELLE II
    - PANDA (?!)
- More theoretical effort is needed
    - Lattice simulations for charm become feasible
    - Exploration of flavor in the up-type sector
    - Fascinating QCD lab: Spectroscopy, strong decays ....