CHARM 2016 - THEORY SUMMARY

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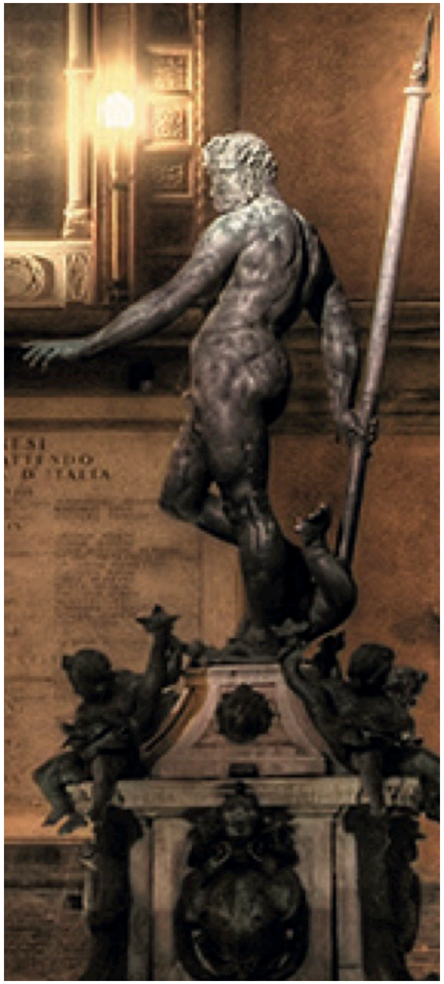


CHARM 2016, ***VIII INTERNATIONAL WORKSHOP***
ON CHARM PHYSICS
SEPTEMBER 5 - 9, 2016
BOLOGNA, ITALY
5-9 September 2016

CHARM is always looking at her sister BEAUTY!

What CHARM can do in SM what BEAUTY cannot ?

Introduction

Charm physics goals :

- High precision knowledge of SM parameters: m_c and CKM parameters V_{ci} , i=d,s,b;
- Understanding QCD in charm systems;
- Precision in experimental measurements and theoretical calculations should enable to disentangle SM physics from BSM!

Theory session at CHARM2016

- Heavy Ions
- Multi-body hadronic decays and amplitude analysis
- Leptonic, semi-leptonic and rare decays (CKM elements)
- Charm baryon decays
- Charmonium and exotics, production and spectroscopy
- CP violation, mixing and non-leptonic decays
- Open charm production and spectroscopy
- Future prospects

Lenz

CHARM and QCD

- Heavy Ions
- Charmonium and exotics, production and spectroscopy
- Open charm production and spectroscopy

Charm quark mass (Lenz)

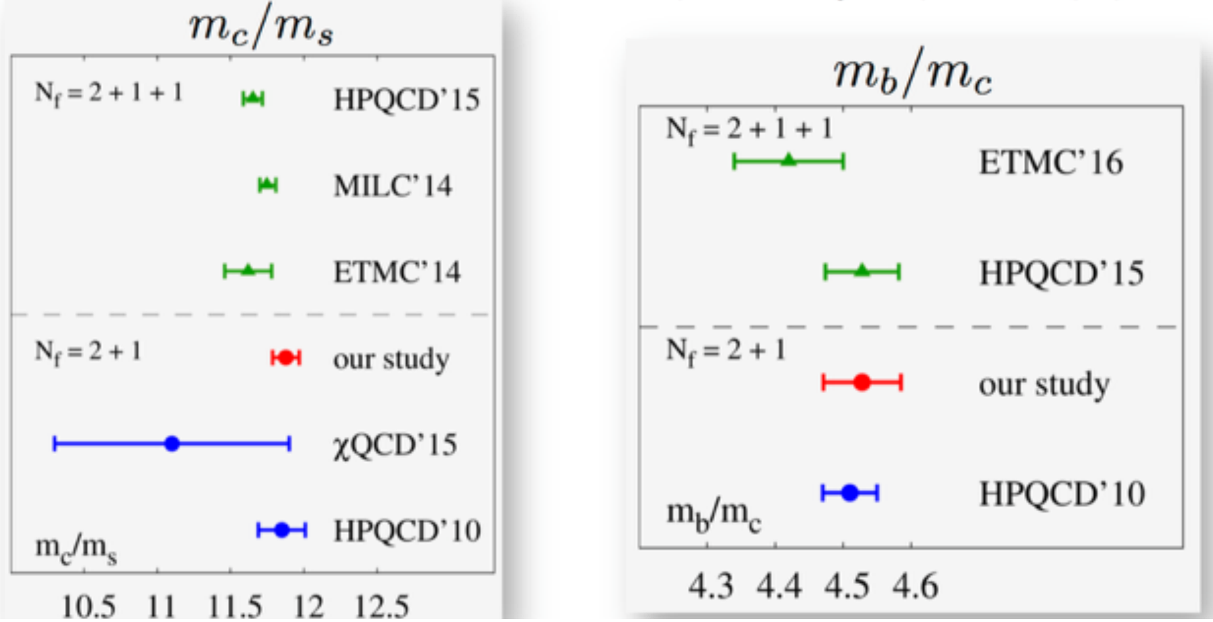
via meson masses: $m_c/m_s = 11.877(91)\,,\quad m_b/m_c = 4.528(57)$

via moments: $\alpha_s(\mu = m_c, n_f = 3) = 0.3945(75)\,,\quad m_c(\mu = m_c, n_f = 3) = 1.267(11)\ \mathrm{GeV}$

evolving with 4-loops PT in $\overline{\mathrm{MS}}$ scheme:

RunDeC package

$$\begin{cases} \alpha_s(M_Z, n_f = 5) = 0.11622(75) \\ m_s(\mu = 2\,\mathrm{GeV}, n_f = 3) = 92.0(1.5)\ \mathrm{MeV} \\ m_b(\mu = m_b, n_f = 5) = 4.184(83)\ \mathrm{GeV} \end{cases}$$



From Maezava, Lattice2016

Mae

Lattic

1606.08798

$$\boxed{m_c(\mu = m_c) = 1.267(11)\ \mathrm{GeV}.}$$

Question for future CHARM conferences: Yukawa coupling, Higgs decay $H \to c\bar{c}$

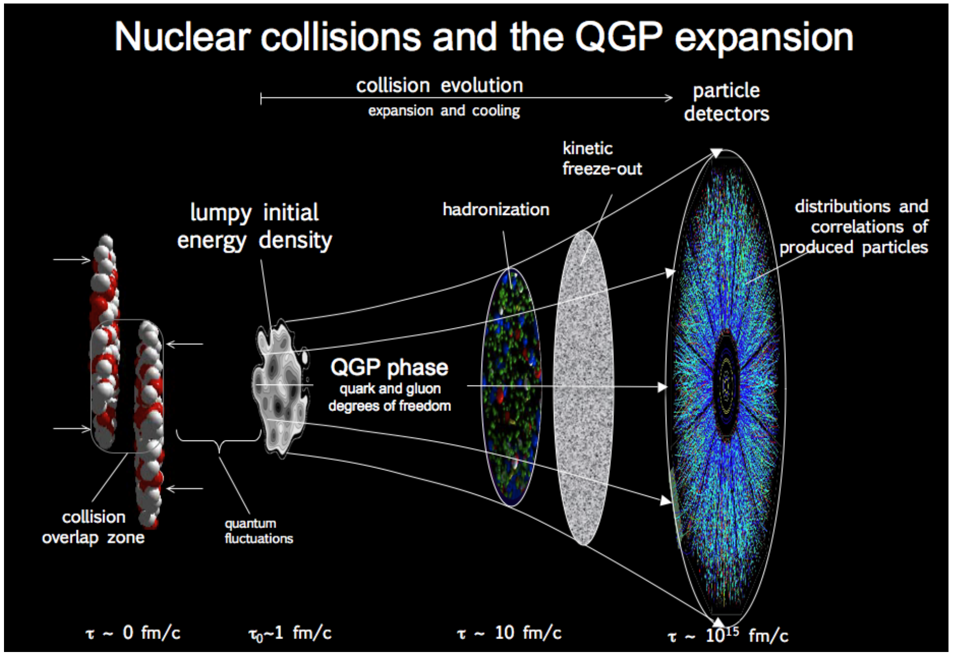
Heavy Ions

Talks by Geurts, Arleo, Beraudo, Vairo

Charm Physics with Heavy Ions

Geurts

- Studying QGP in nuclear collisions
- What can we learn from heavy quarks in nuclear collisions?
- Experimental toolkit
- Open charm and charmonium



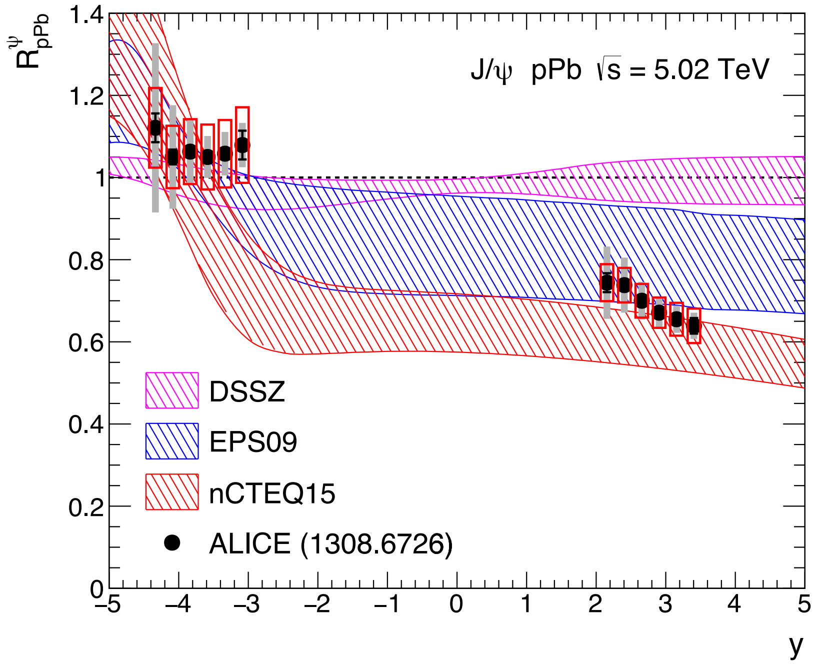
Ultrarelativistic heavy-ion collisions allow the creation of a hot and dense state of matter

- ➢ use heavy ions to scan through the QCD phase diagram

Arleo:

- J/ψ and Υ (and some excited states)
- proton-nucleus (pA) and nucleus-nucleus (AA) collisions

nPDF effects on J/ψ in pPb at LHC



$$R_{pA}(y, p_\perp) = \frac{1}{A}\,\frac{d\sigma^{pA}/dp_\perp dy}{d\sigma^{pp}/dp_\perp dy}$$

R_{pA} = 1: no (net) nuclear effects
R_{pA} <1:suppression
R_{pA} >1:enhancement

Why quarkonium production in nuclear collisions ?

Many aspects of QCD can be probed in principle

- Nuclear parton densities (nPDF) and saturation at small x
- Parton multiple scattering and induced gluon radiation
- Heavy-quark potential at finite temperature
- Quarkonium (in)elastic interaction with partons and hadrons
- Dynamics of bound state formation

Several frameworks although none of them (yet) fully satisfactory

- Non-Relativistic QCD: many successes but also some failures
  - polarization, η_c hadroproduction, J/ψ photoproduction, LDME poorly known
  - NRQCD factorization not proven to all orders
- Color Singlet Model
  - discrepancy at large $p_\perp$ cured by higher-order corrections?
- QCD factorization ($1/p_\perp$ expansion)
  - only leading powers $p_\perp^{-4}$ and $p_\perp^{-6}$ computed so far

Open charm physics with heavy Ions

Beruado

Theory-to-experiment comparison :
c-quarks interact significantly with the medium formed in heavy-ion collision, which affects both their propagation in the plasma and their hadronization.
HF-hadron spectra quenched at high-pT ,
at low-pT they display signatures of radial and elliptic flow.

Experimental challenges or theoretical questions

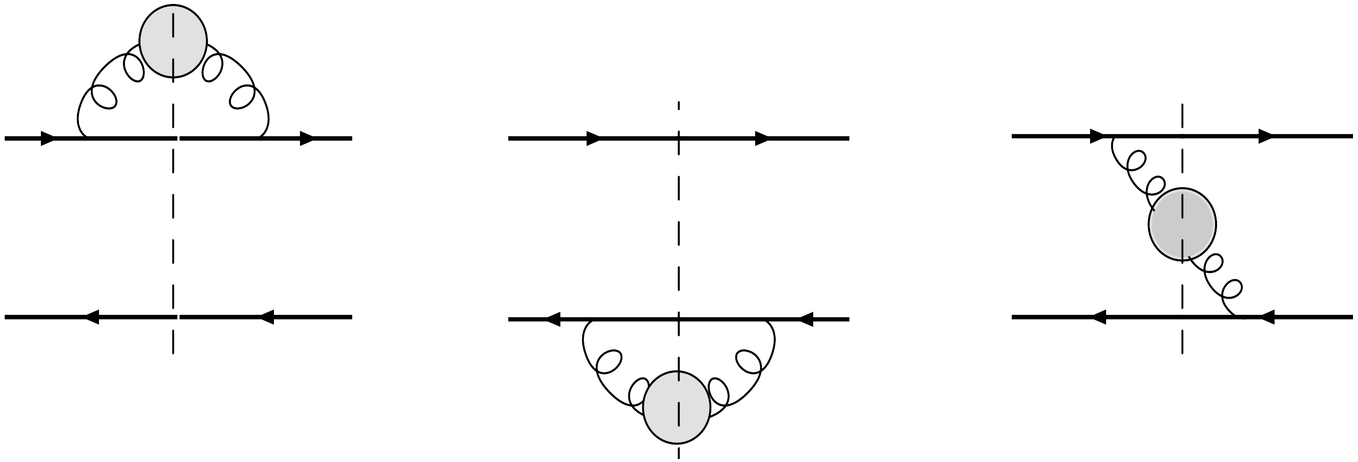
- Charm measurements down to pT → 0: flow/thermalization and total cross-section (of relevance for charmonium supression!)
- D_s and Λ_c measurements: change in hadrochemistry and total cross-section
- Beauty measurements in AA via exclusive hadronic decays: better probe, due to $M \gg \Lambda QCD, T$ (initial production and Langevin dynamics under better control)
- Charm in p-A collisions: which relevance for high-energy atmospheric muons/neutrinos (Auger and IceCube experiments)? Possible initial/final-state nuclear effects?

Quarkonium dissociation and regeneration

Viaro

Gludissociation is the dissociation of quarkonium by absorption of a gluon from the medium.

Dissociation by inelastic parton scattering is the dissociation of quarkonium by scattering with gluons and light-quarks in the medium.



- effective field theories
- non relativistic bound states at zero temperature,
- study the dissociation of a quarkonium in a thermal bath of gluons and light quarks.

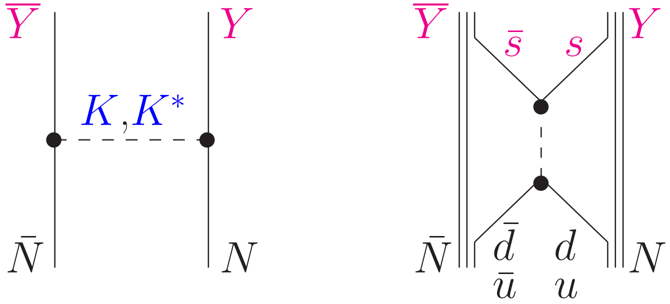
In a weakly-coupled framework, the situation is the following:

- For $E > m_D$ quarkonium decays dominantly via gludissociation (aka singlet-to-octet break up).
- For $m_D > E$ quarkonium decays dominantly via inelastic parton scattering (Landau damping).-

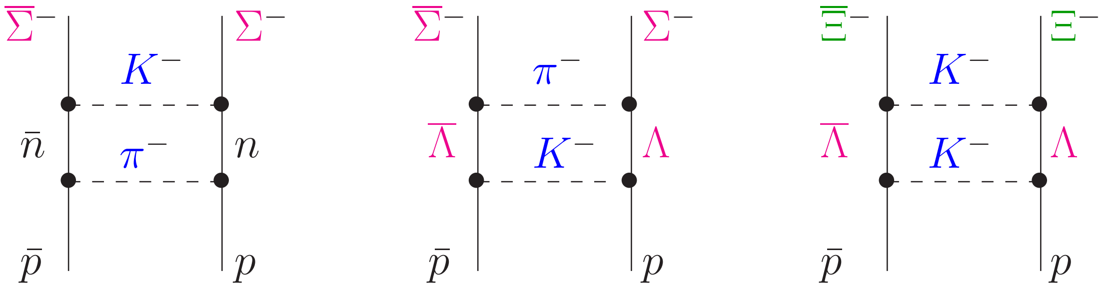
Production of charmed baryons and mesons in antiproton-proton collisions

Haidenbauer

The Jülich group has performed calculations (meson-exchange picture, χEFT) for
p̄ p → K̄ K
p̄ p → ΛΛ, ΣΣ, Ξ̄ Ξ, ... K N , K̄ N
ΛN – ΣN, ΛΛ, ...



assume *SU*(4)*f* symmetry and provide estimates for cross sections for the corresponding reactions involving charmed particles



Predictions for $\bar{p}p \to \overline{Y_c} Y_c$

- calculation performed in close analogy to the Jülich analysis of $\bar{p}p \to \overline{Y} Y$ utilizing $SU(4)$ symmetry
- $\bar{\Lambda}_c^- \Lambda_c^+$ cross sections are in the order of $1 - 7$ μb
- $\bar{\Lambda}_c^- \Lambda_c^+$ cross sections are about 10-100 times smaller than for $\bar{p}p \to \bar{\Lambda}\Lambda$
- $\bar{\Lambda}_c^- \Lambda_c^+$ cross sections are about 1000 times larger than those of most other models

Predictions for $\bar{p}p \to D\bar{D}$, $D_s\bar{D}_s$

- calculation performed in close analogy to the Jülich analysis of $\bar{p}p \to \bar{K}K$ utilizing $SU(4)$ symmetry
- $D\bar{D}$ cross sections are in the order of $30 - 250$ nb
- $D\bar{D}$ cross sections are comparable to those of other models
- $D_s\bar{D}_s$ cross sections are of comparable order of magnitude

Spectroscopy

Taks by Burns,Fernandez, Gonzalez, Pilloni, Brambilla,Wang

Talks by Rayan, Moir, Cheung, Riggio on lattice spectroscopy

Charmonium: standard and exotic

- Exotic models
- Production of exotics at LHC
- Hybridized tetraquarks
- Conclusions

Pilloni

Standard potential for charmonium:

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

(Cornell potential)

$$\alpha_s(M_Q) \sim 0.3$$

Multiscale system

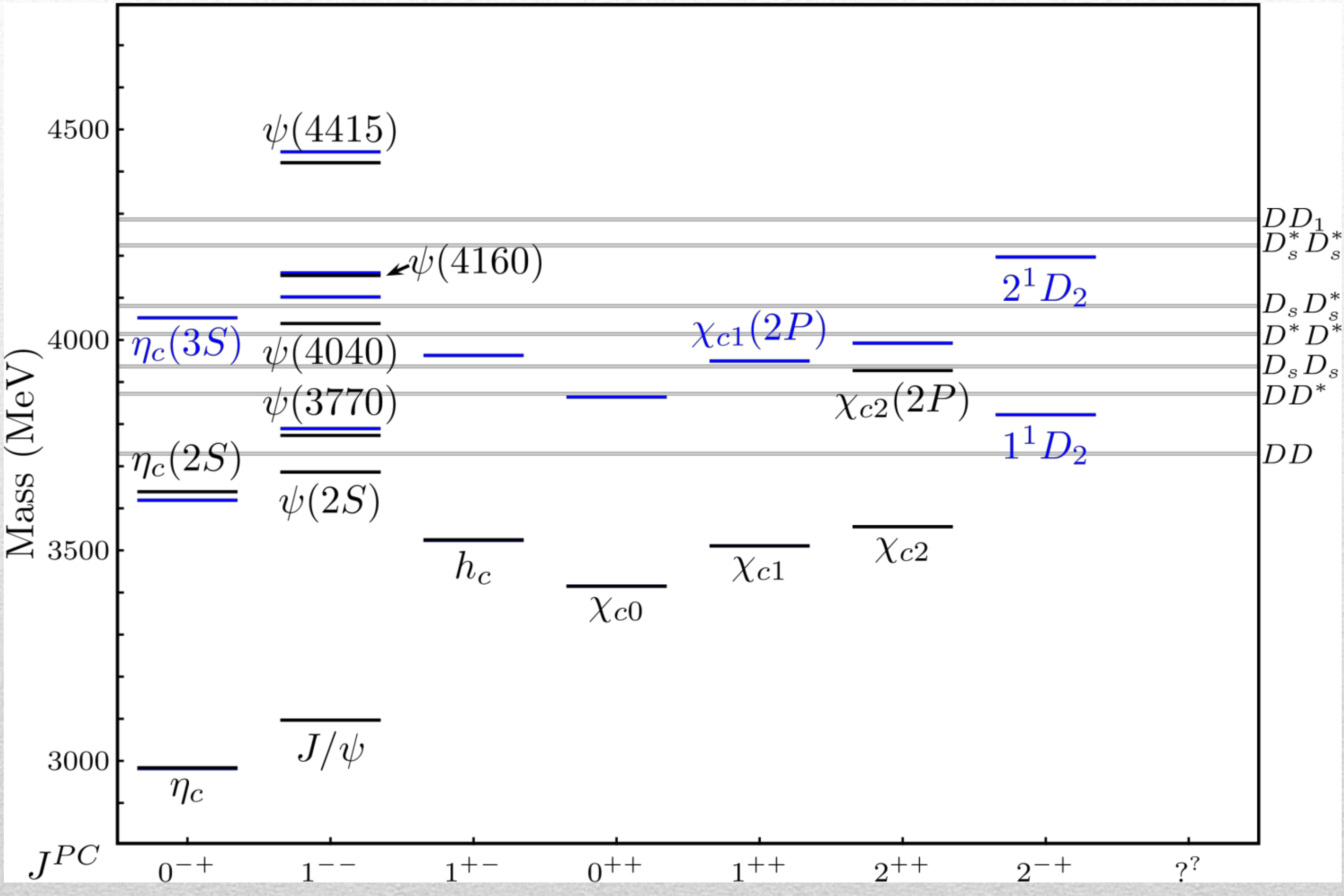
(perturbative regime) OZI-rule, QCD multipole

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

Full QCD ⟶ NRQCD ⟶ pNRQCD

Effective theories
(HQET, NRQCD, pNRQCD...)
Integrate out heavy DOF

Charmonium landscape Pilloni

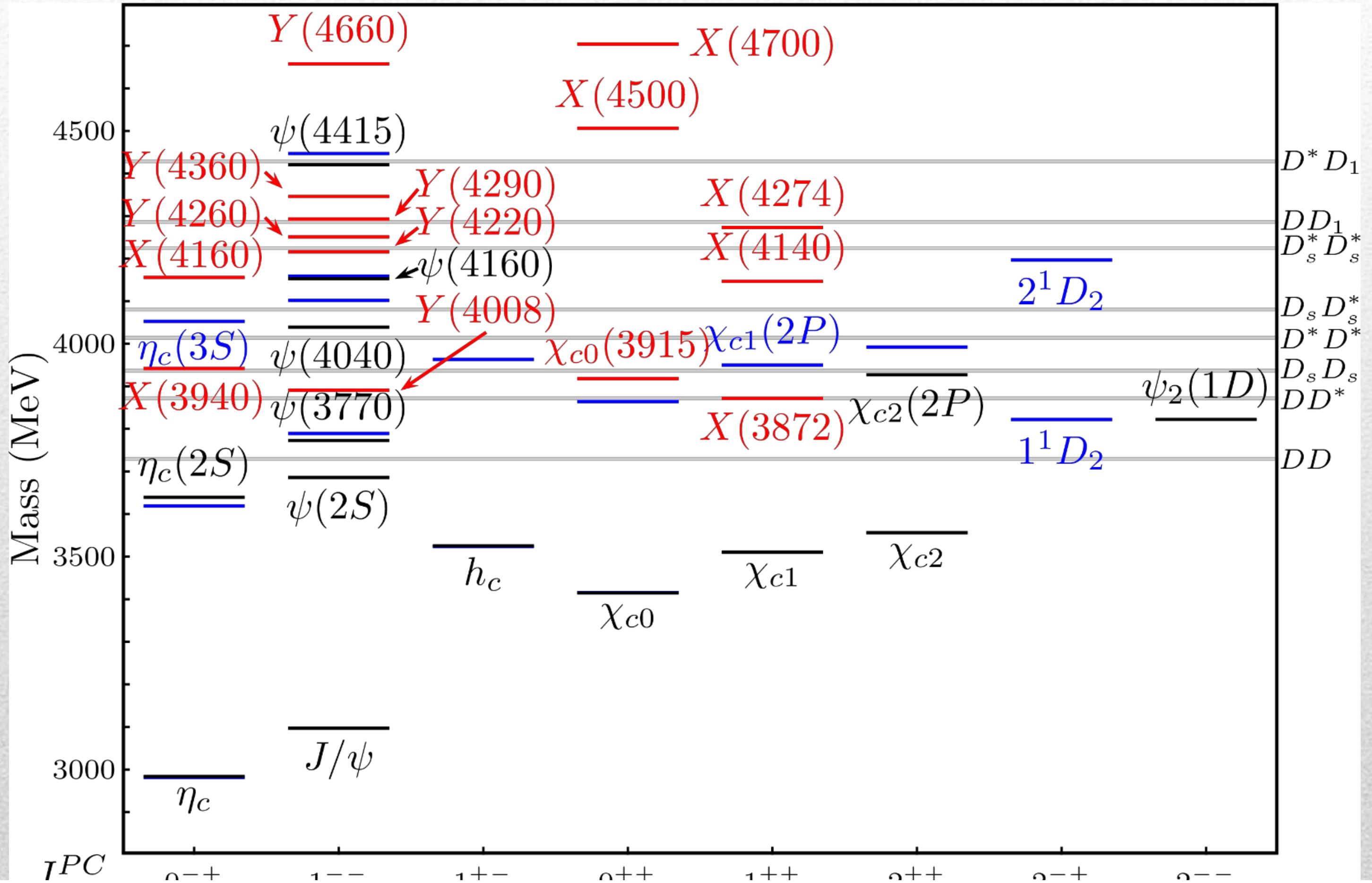


Good understanding of the spectrum, in particular below thresholds

Potential model by Radford and Repko, PRD75, 074031

Exotic landscape

Pilloni



A host of unexpected resonances have appeared

decaying mostly into charmonium + light

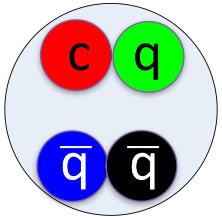
Hardly reconciled with usual charmonium interpretation

Proposed models

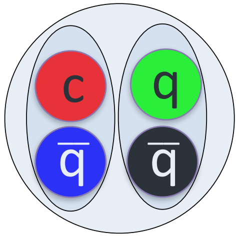
Pilloni,Wang

- Molecules or hadrons (loosely bound)
- Diquark- anti-diquark (tetraquark)
- Glueball, Hybryds

(cusp – kinematical effect)



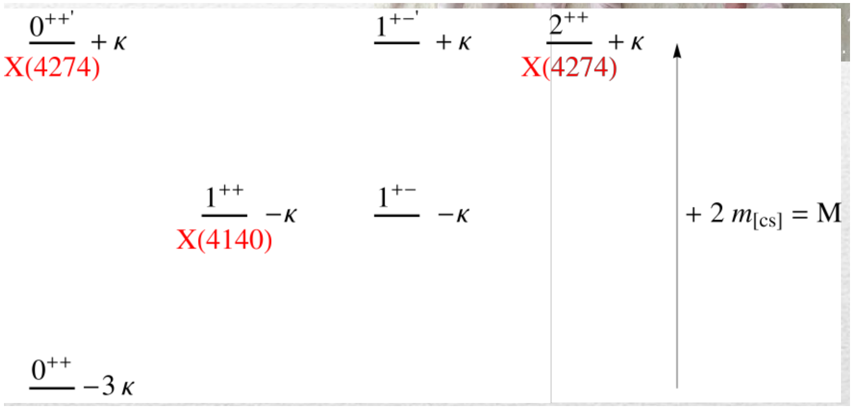
Tetraquark

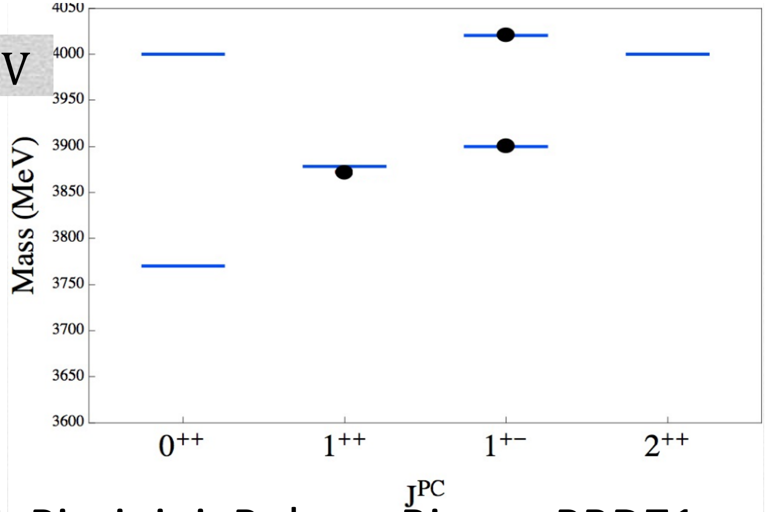


Hadron Molecule

$$H = \sum_{dq} m_{dq} + 2 \sum_{i<j} \kappa_{ij}\, \vec{S_i} \cdot \vec{S_j}\, \frac{\lambda_i^a}{2} \frac{\lambda_j^a}{2}$$

$$\kappa_{cq} = 67 \text{ MeV}$$



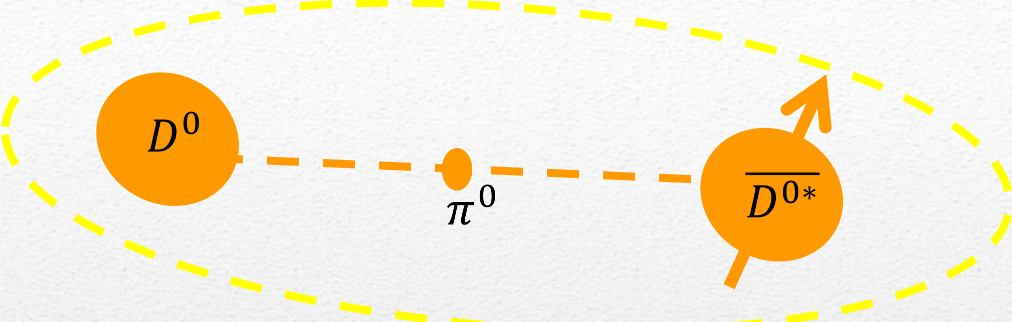


Maiani, Polosa and Riquer, arXiv:1607.02405
Esposito, AP, Polosa, to appear

Maiani, Piccinini, Polosa, Riquer PRD71 014028 Faccini, Maiani, Piccinini, AP, Polosa, Riquer PRD87 111102 Maiani, Piccinini, Polosa, Riquer PRD89 114010

Loosely bound molecule

Tornqvist, Z.Phys. C61, 525
Braaten and Kusunoki, PRD69 074005
Swanson, Phys.Rept. 429 243-305
Talk by T. Burns



$X(3872) \sim \bar{D}^0 D^{*0}$ $\quad Z_c'(4020) \sim \bar{D}^{*0} D^{*}$
$Z_c(3900) \sim \bar{D}^0 D^{*+}$ $\quad Y(4260) \sim \bar{D} D_1$

A deuteron-like meson pair, the interaction is mediated by the exchange of light mesons

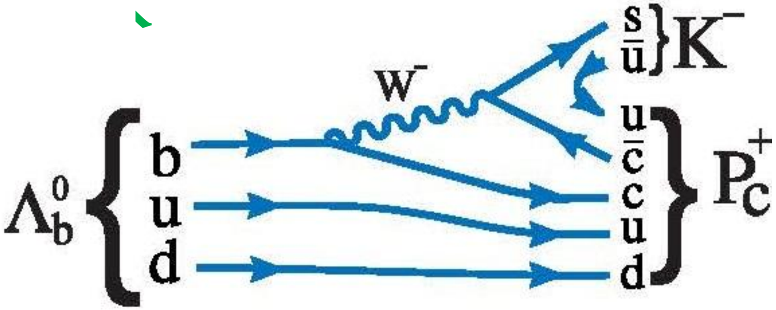
- Some model-independent relations (Weinberg's theorem, shallow states theory) ✓
- Good description of decay patterns (mostly to constituents) and $\mathrm{X}(3872)$ isospin violation ✓
- States appear close to thresholds ✓ (but $Z(4430)$ ✗)
- Lifetime of costituents has to be $\gg 1/m_\pi$
- Binding energy varies from -70 to -0.1 MeV, or even positive (repulsive interaction) ✗
- Unclear spectrum (a state for each threshold?) – depends on potential models ✗

$$V_\pi(r) = \frac{g_{\pi N}^2}{3}(\vec{\tau_1}\cdot\vec{\tau_2})\left\{[3(\vec{\sigma_1}\cdot\hat{r})(\vec{\sigma_2}\cdot\hat{r}) - (\vec{\sigma_1}\cdot\vec{\sigma_2})]\left(1 + \boxed{\frac{3}{(m_\pi r)^2} + \frac{3}{m_\pi r}}\right) + (\vec{\sigma_1}\cdot\vec{\sigma_2})\right\}\frac{e^{-m_\pi r}}{r}$$

Needs regularization, cutoff dependence

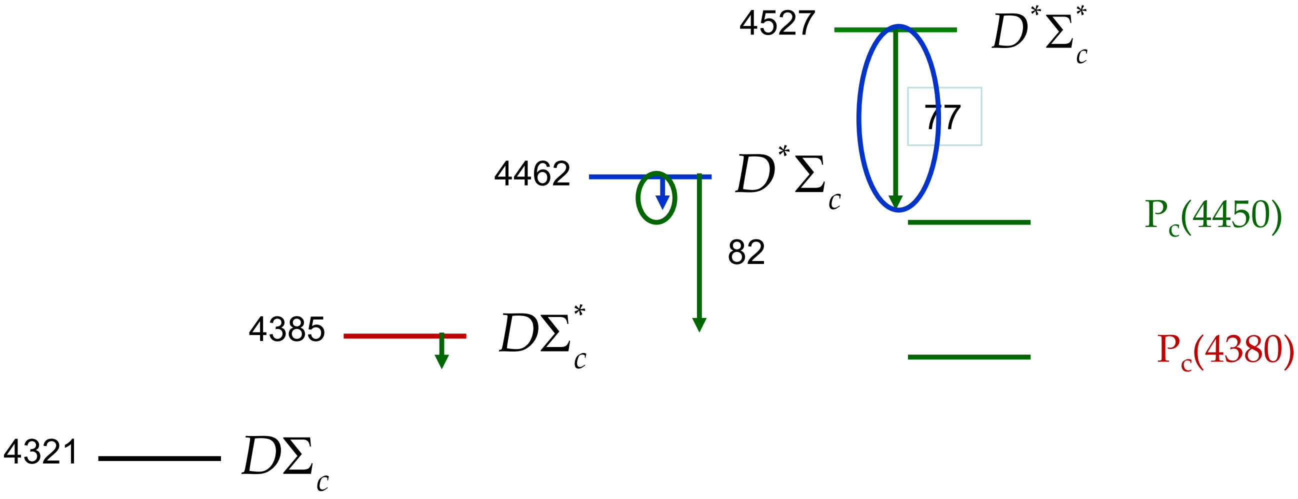
From J/ψ to LHCb pentaquarks

Fernández: The model: constituent quarks, coupled channels $^3P_0$ model



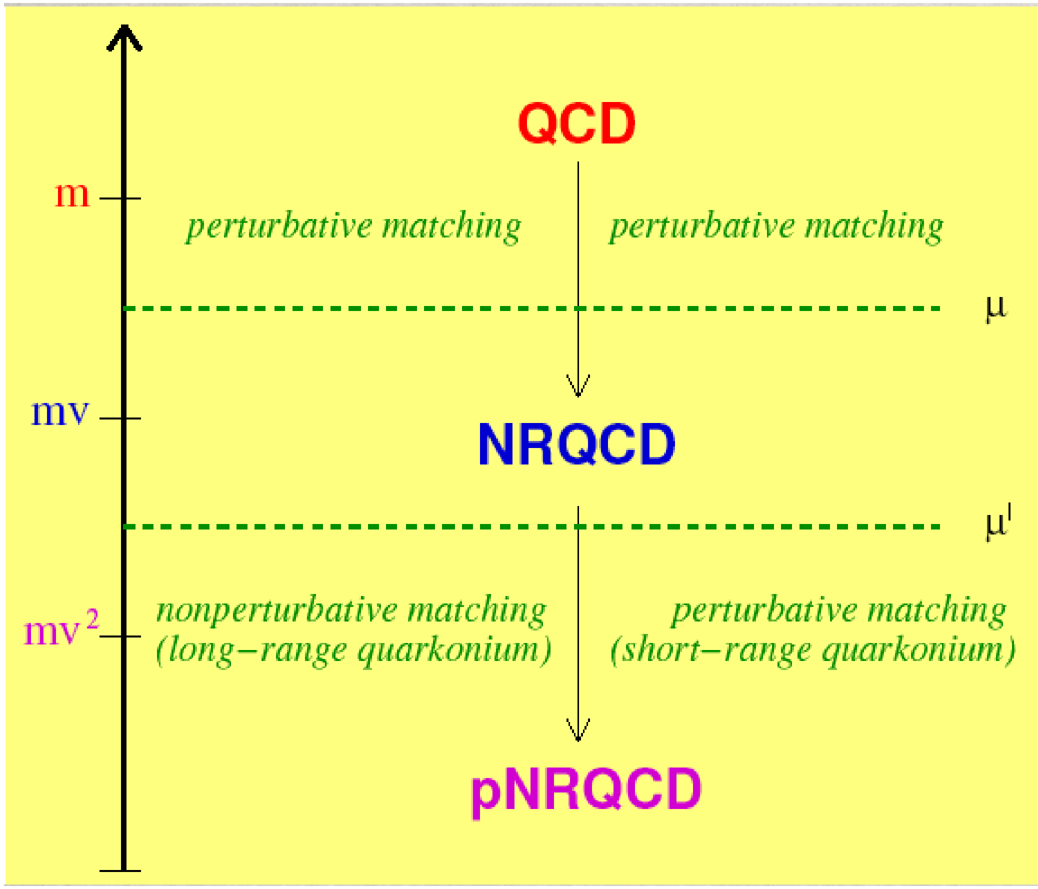
$$M_{P_c(4380)} = 4380 \pm 8 \pm 29\,\text{MeV},$$
$$M_{P_c(4450)} = 4449.8 \pm 1.7 \pm 2.5\,\text{MeV}$$

$$\Gamma_{P_c(4380)} = 205 \pm 18 \pm 86\,\text{MeV},$$
$$\Gamma_{P_c(4450)} = 39 \pm 5 \pm 19\,\text{MeV}.$$



$J/\psi\phi$ the X(4140) signal appears as a threshold cusp

QCD theory of quarkonium- multiscale theory

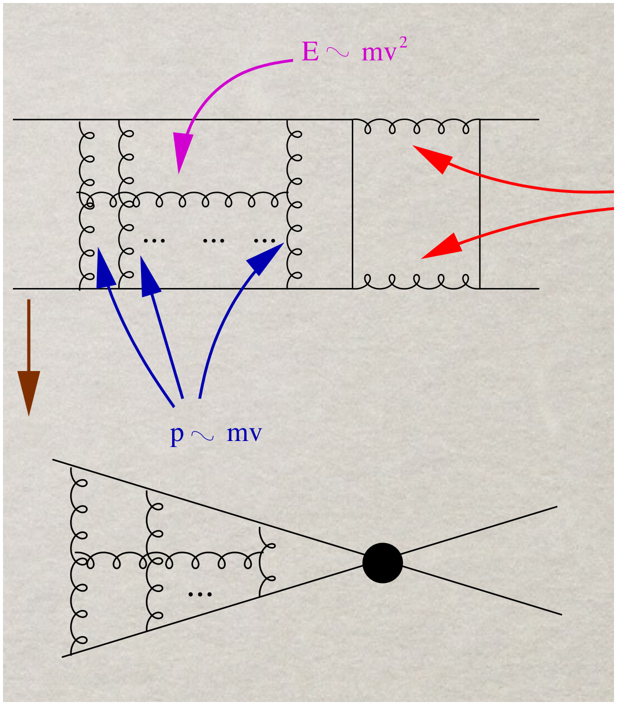


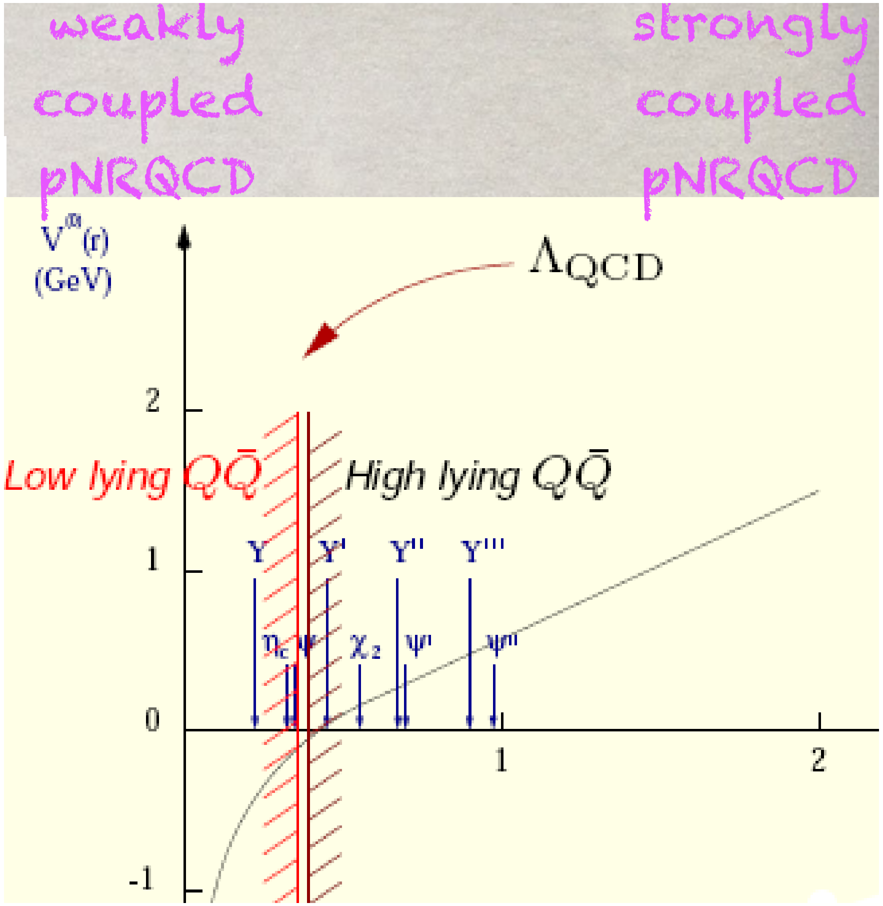
Color degrees of freedom
3X3=1+8
singlet and octet QQbar

Soft (relative momentum)

Ultra soft
(binding energy)t

Quarkonium with NR EFT:
potential NonRelativistic QCD (pNRQCD)

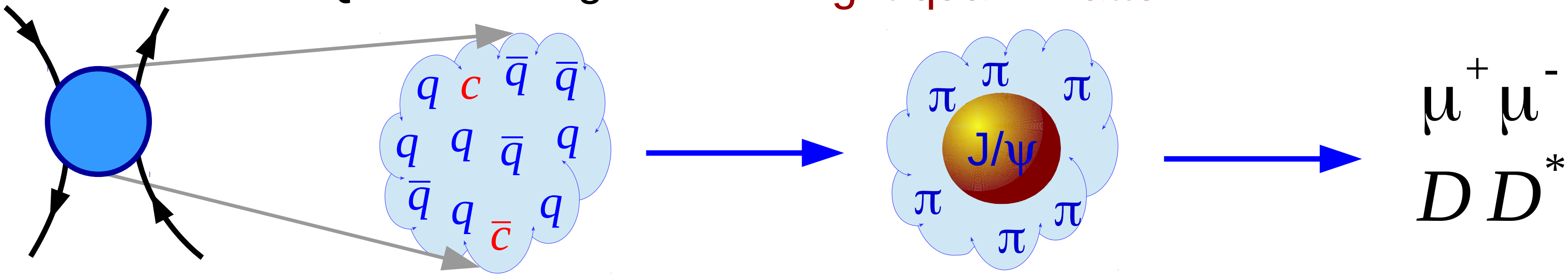




$$\mathcal{L}_{\mathrm{pNRQCD}} = \sum_k \sum_n \frac{1}{m^k} c_k(\alpha_{\mathrm{s}}(m/\mu)) \times V(r\mu', r\mu) \times O_n(\mu', \lambda)\, r^n$$

Successful description of spectra!

Properties of J/ψ in light quark matter



Heavy Ion Collision

Production of new Quarks and gluons

J/ψ surrounded by light quark matter

Subsequent Decays can be measured

Subject of this study

- Previous Studies include
  - Chiral Lagrangians

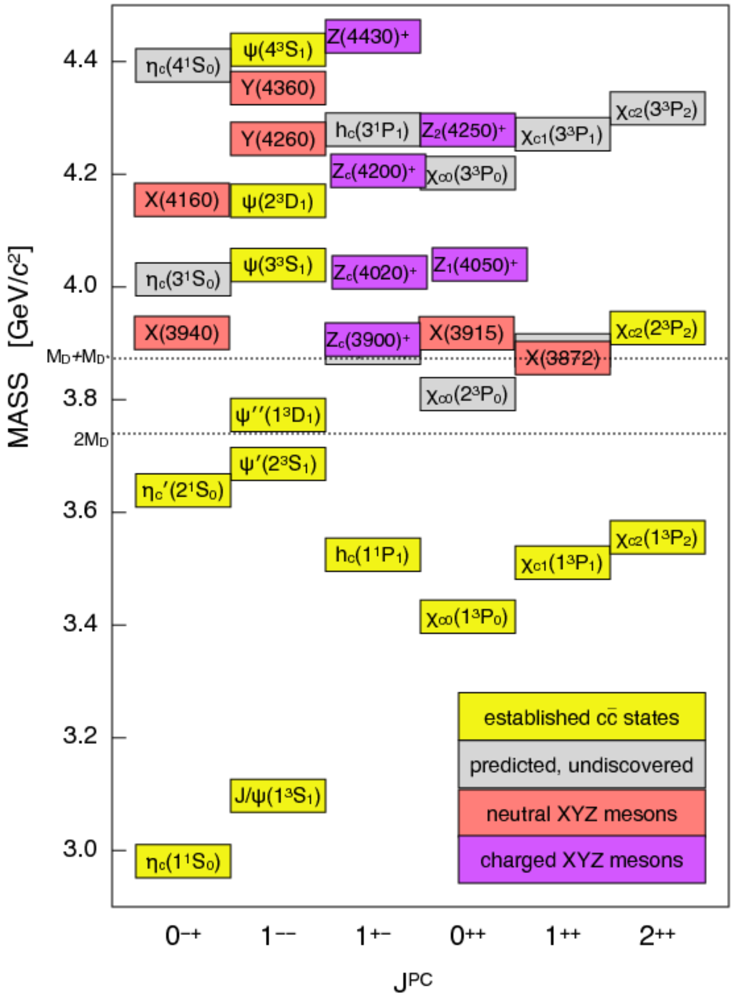
    Haglin and C. Gale, PRC 63; Blaschke et al., PPNL 9 (2012) 7;...
  - Quark model Calculations

    Zhou and Xu, PRC 85; Maiani et al., NP A 741 (2004) 273,NP A 748 (2005) 209;...
- Here: at the same time

- SU(4) Chiral Lagrangian
  - Effective Lagrangian
  - Unitarized Amplitudes
- Finite Temperatures
  - Imaginary Time Formalism

Charmonium, Hybrid and Exotic Spectroscopy with Charm Quarks in Lattice QCD

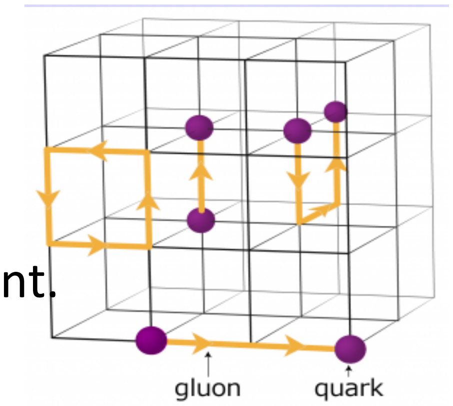
Ryan, Cheung,G



- Plethora of unexpected charmonium-like (X , Y , Z) states discovered experimentally
- Masses and widths of some D_s states significantly lower than those expected from quark model.
- Tetraquarks? Molecules? Cusps? Hybrids?
- First principles calculations using lattice QCD to understand these states.

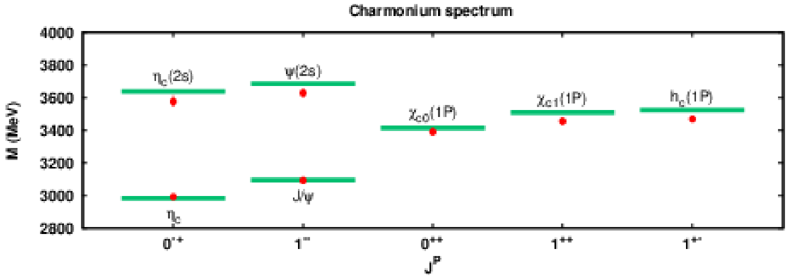
Charmonium below threshold - “gold-plated”

Ryan

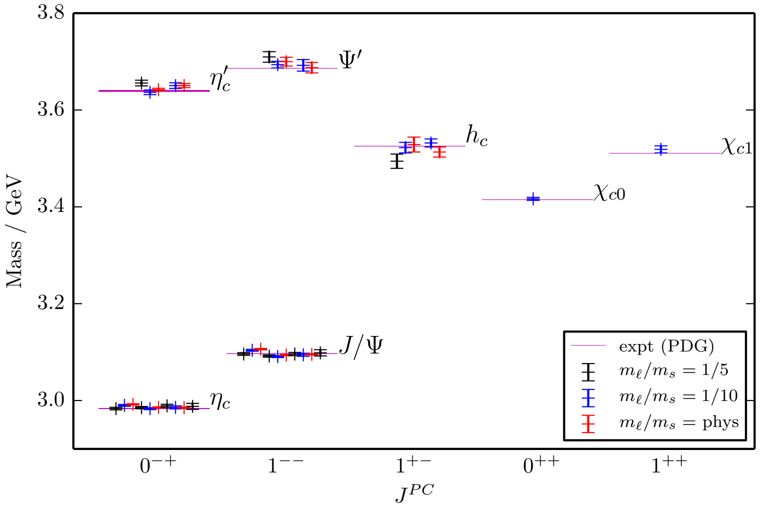


- Methods: tested, validated; Different actions in agreement.
- High statistics and improved actions for precise results.
- Simulation at m^{phys}_q or extrapolation $m \rightarrow m^{phys}_q$.
- Discretisation errors $O(am_c)$ and $O(am_b)$ under control.

Perez-Rubio, Collins, Bali 1503.08440



Charmonium, HPQCD 1411.1318



No disconnected diagrams in $\bar{c}c$ spectrum: OZI suppressed - assumed to be small ⇒ mixing with lighter states not included.

X,Y, Z,

Prelovsek & Leskovec 1307.5172

Padmanath, Lang, Prelovsek 1503.03257
Prelovsek, Lang, Leskovec, Mohler:
1405.7615

X(3872) not found if $\bar{c}c$ not in basis.

Ground state: $\chi_{c1}(1P)$
$D\bar{D}$ scattering: pole just below thr.
Location of thr., finite volume effects controlled?
13 expected 2-meson states found

First coupled channel results with charm quarks by HAL QCD suggest Z_c^+ is not a resonance.
HAL QCD recently did a first coupled-channel analysis [1602.03465].
$\pi J/\Psi - \rho \eta_c - \bar{D} D$

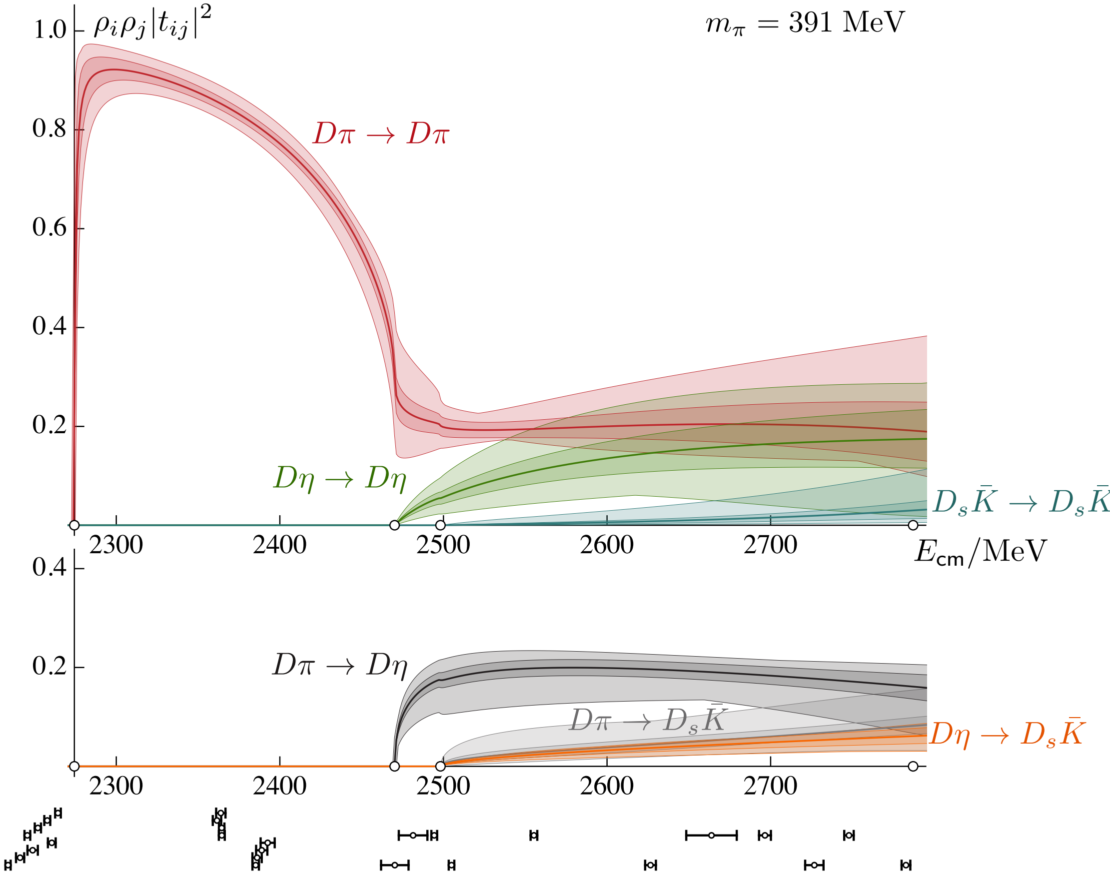
Challenges:

- The : Z_c^+ (and most of the XYZ states) lies above several thresholds and
- so decay to several two-meson final states
- requires a coupled-channel analysis for a rigorous treatment
- on a latice the number of relevant coupled-channels is large for high energies.

Scattering of charmed mesons from lattice QCD Dπ, Dη, Ds K̄ scattering

Moir (Hadron Spectrum Collaboration) (1607.07093)

First lattice QCD calculation of coupled-channel scattering including heavy quarks Dπ, Dη, Ds K̄ scattering (at m_π = 391 MeV)



0^+: near-threshold bound-state pole c.f. D0∗(2400)
1−: deeply-bound pole c.f. D∗(2007)
2^+: narrow resonance c.f. D_2∗(2460)

DK scattering (at m_π = 391 MeV)
0^+: bound-state pole c.f. D∗ (2317)

Gonzales

Strong decays of X(3915)

i) have been analyzed from a conventional as well as from an unconventional quark model description.

ii) The X(3915) to D bar D decay can not discriminate between both descriptions once momentum dependent corrections are taken into account.

iii) The X(3915) to J/ψω decay can not be consistently explained from a Cornell description. However, an unconventional description may accommodate all the experimental information predicting a quite big branching ratio for this OZI non allowed decay.

iv) The PDG assignment of X(3915) as a conventional state should not be taken for granted.

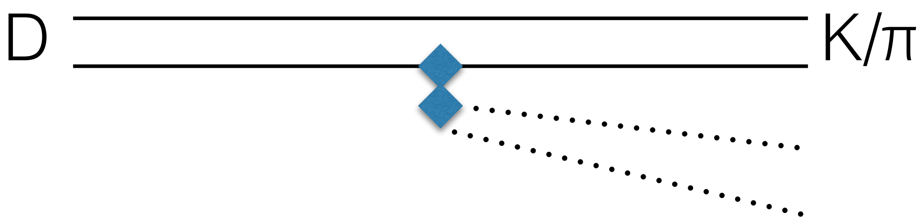
CHARM and ELECTRO- WEAK INTERACTION

- Charge current decays: leptonic and semileptonic
- FCNC processes, D mixing and rare decays
- Nonleptonic decays and CP asymmetry

QCD needed!

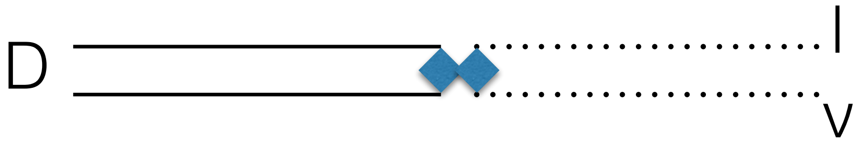
Leptonic, semileptonic and rare decays

Košnik, El-Khadra, Riggio



$$f_+^{D\to\pi}(0) = 0.666(29)$$
$$f_+^{D\to K}(0) = 0.747(19)$$

[FLAG based on FNAL/MILC '14 and ETM '14]



$$f_D = (212.15 \pm 1.45)\,\mathrm{MeV}$$
$$f_{D_s} = (248.83 \pm 1.27)\,\mathrm{MeV}$$

[FLAG based on HPQCD '10, '11]

CKMFitter
(using unitarity)

$$|V_{cd}| = 0.22529^{+0.00041}_{-0.00032}$$
$$|V_{cs}| = 0.973394^{+0.000074}_{-0.000096}$$

Direct extraction using lattice (HFAG+FLAG)

$$|V_{cd}| = 0.2164(63)$$
$$|V_{cs}| = 1.008(21)$$

Leptonic*

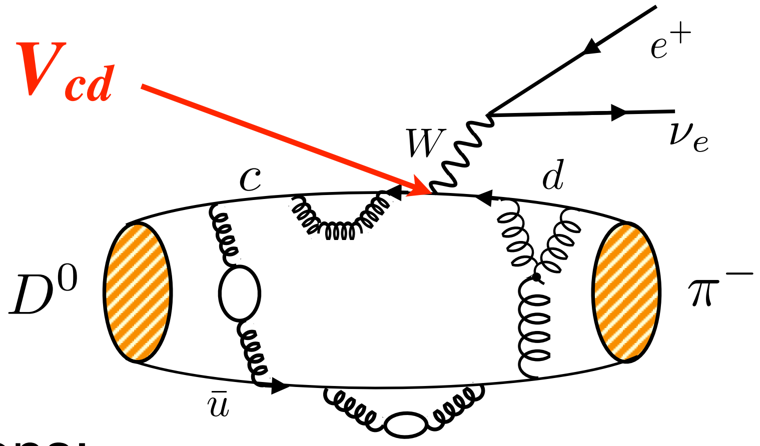
$$|V_{cd}| = 0.214(12)$$
$$|V_{cs}| = 0.975(32)$$

Semileptonic*

Lattice QCD in leptonic and semileptonic

El-Khadra:

example: $D \to \pi \ell \nu$



generic weak process involving hadrons:

$$\boxed{\text{(experiment)} = \text{(known)} \times \text{(}\textbf{CKM element}\text{)} \times \text{(had. matrix element)}}$$

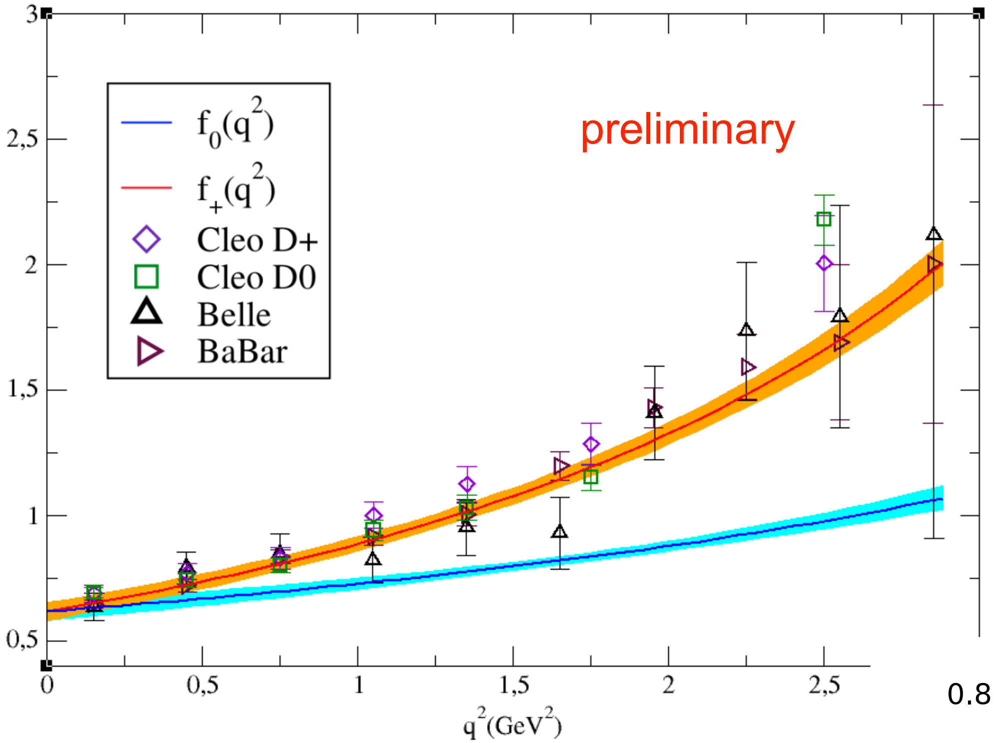
Lattice QCD

- $V \to \infty$ infinite volume limit
- $a \to 0$ continuum extrapolation
- $\mu_{light}^{sim} \to m_{light}^{phys}$ chiral extrapolation

three extrapolations

Riggio

Form factors for D semileptonic decays

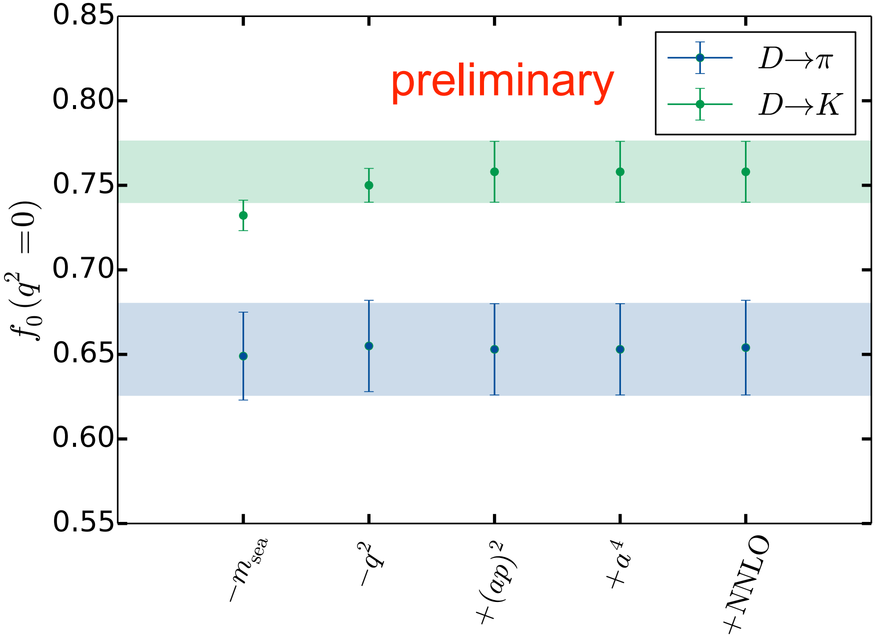


Three different values of the lattice spacing: 0.06 *fm* ÷ 0.09 *fm*

Different volumes: 2 *fm* ÷ 3 *fm*

Pion masses in range 210 ÷ 440 MeV

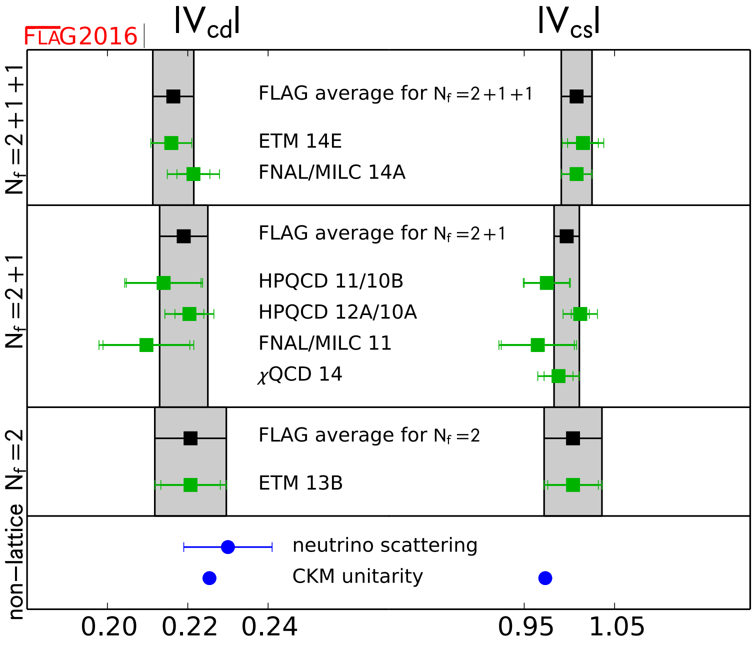
$$f_+^{D\to\pi}(0) = 0.631(40)$$



Implications for $|V_{cs}|$, $|V_{cd}|$

El-Khadra

S. Aoki et al (FLAG review, arXiv:1607.00299)



errors on $|V_{cs}|$ and $|V_{cd}|$ are dominated by experiment (PDG 2015, arXiv:509.02220):

$$\boxed{\begin{aligned}|V_{cd}| &= 0.217\ (1)_{\mathrm{LQCD}}\ (5)_{\mathrm{exp}}\\ |V_{cs}| &= 1.007\ (4)_{\mathrm{LQCD}}\ (16)_{\mathrm{exp}}\end{aligned}}$$

(based on the PDG average of 2+1 & 2+1+1 flavor LQCD results; average is dominated by FNAL/MILC)

2σ tension with unitarity:

$$\boxed{|V_{cs}|^2 + |V_{cd}|^2 + |V_{cb}|^2 - 1 = 0.064(32)}$$

Charm charged current decays: chance for NP

Košnik

- NP in charged curreμnt processes
- (like in B: in angular correlations of B -> K*μμ, RK and $R_{D(D^*)}$

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{cs}\left[(\bar{s}_L\gamma^\mu c_L)(\bar{\nu}_L\gamma_\mu \ell) + c_S^{(\ell)}(\bar{s}c)(\bar{\nu}_L\ell_R) + c_P^{(\ell)}(\bar{s}\gamma_5 c)(\bar{\nu}_L\ell_R)\right]$$

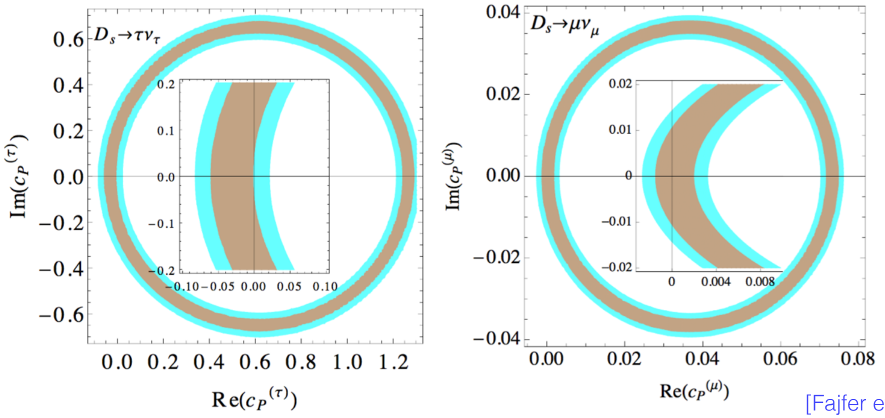
[Fajfer et al, 1502.07488]
[Barranco et al, 1303.3896]

$D \to K l \nu_l$ can probe c_S

$\boxed{D \to l\nu_l}$

$D \to K^* l \nu_l$

c_P can probed c_P



[Fajfer et al, 1502.07488]

Naive New Physics
scale sensitivity, $c_P \sim v^2/M^2$

M> 1.7 TeV

Typical UV realisations involve either charged scalar (two Higgs doublet model), charged vector (W’, WR), or leptoquark with charge 5/3, 2/3, or 1/3.

Charm physics as a part of flavour physics

Flavor physics in the Standard Model

- Absence of FCNC at tree level (& GIM suppression of FCNC @loop level)
- Almost no CP violation at tree level
- Flavour Physics is extremely sensitive to New Physics (NP)
- In competition with Electroweak Precision Measurements

(Martinelli@CHARM2016)

CHARM FCNC processes

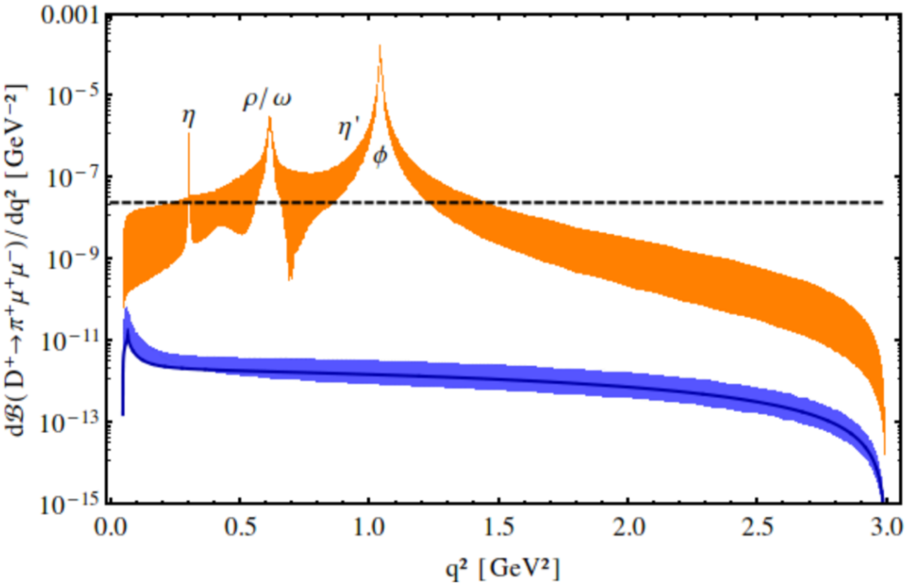
Rare charm decays

- Flavour changing neutral currents in the up sector are few: D-bar D mixing, rare (semi)-leptonic decays, rare top decays.

- Charm is the only low-energy probe of up-quark flavour changing neutral currents (FCNCs)

- GIM broken locally by long-distance effects. Resonances distinguish s and d quarks. Genuine FCNCs are severely obscured.

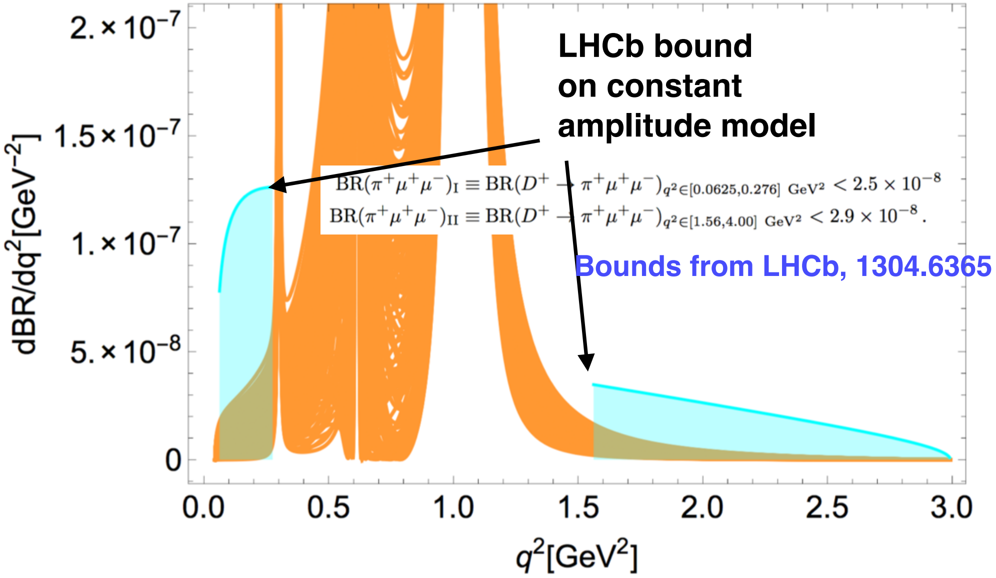
  De Boer, Hiller 1510.0031



$$\mathcal{H}_{\mathrm{eff}} = \boxed{\lambda_d \mathcal{H}^d + \lambda_s \mathcal{H}^s} - \boxed{\frac{4G_F\lambda_b}{\sqrt{2}} \sum_{i=3,\dots,10,S,P,\dots} C_i \mathcal{O}_i}$$

Tree-level 4-quark operators

(Short-distance) penguin operators



LHCb bound on constant amplitude model

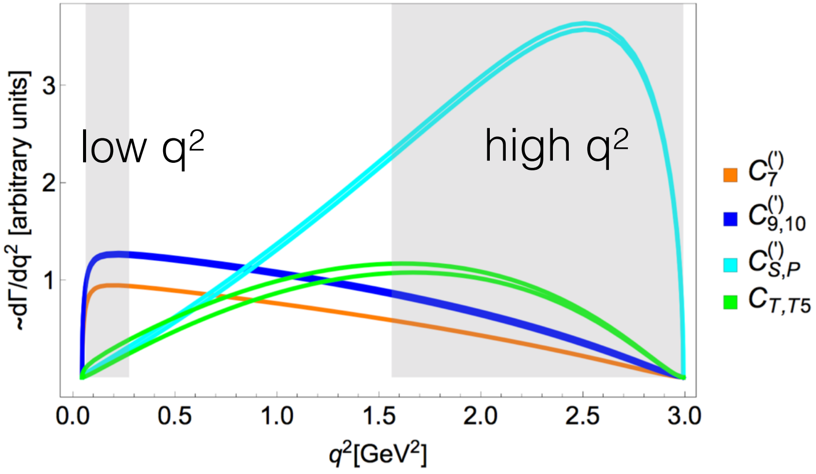
$$\mathrm{BR}(\pi^+\mu^+\mu^-)_{\mathrm{I}} \equiv \mathrm{BR}(D^+ \to \pi^+\mu^+\mu^-)_{q^2\in[0.0625,0.276]\ \mathrm{GeV}^2} < 2.5\times10^{-8}$$

$$\mathrm{BR}(\pi^+\mu^+\mu^-)_{\mathrm{II}} \equiv \mathrm{BR}(D^+ \to \pi^+\mu^+\mu^-)_{q^2\in[1.56,4.00]\ \mathrm{GeV}^2} < 2.9\times10^{-8}.$$

Bounds from LHCb, 1304.6365

SF, NK, 1510.00965;

For each kinematical distribution ``i'' set $C_i = 1$



$$\tilde{C}_i \equiv V_{cb}^* V_{ub} C_i$$

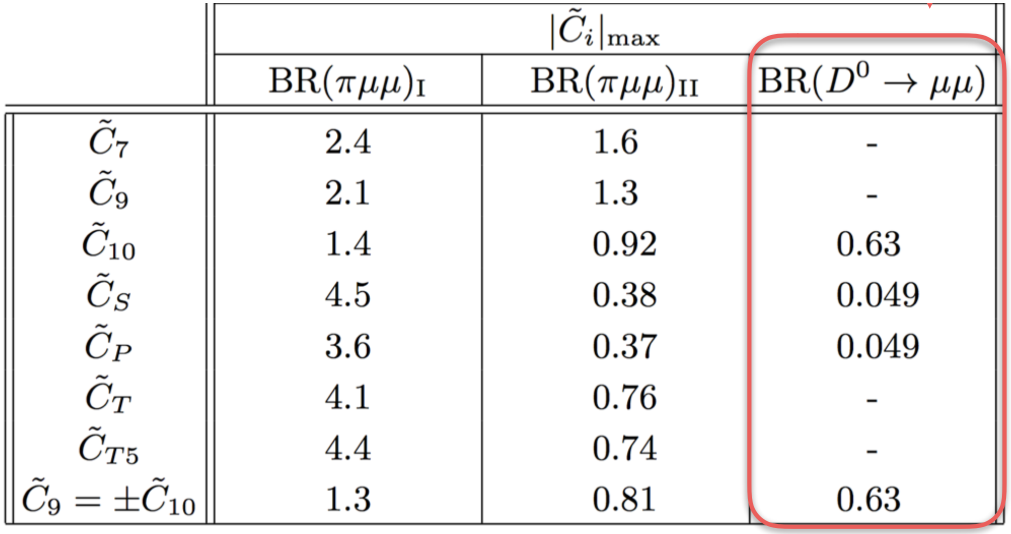
Low-q^2 region naively more sensitive to dipole, vector and axial vector operators;

High-q^2 best suited to constrain (pseudo)tensor (T, T_5) and (pseudo)scalar (S,P)

$$\mathrm{Br}(D^0 \to \mu\mu) < 6.2 \times 10^{-9}$$

LHCb1 (1305.5059)

Concrete models of BSM



	$\lvert\tilde{C}_i\rvert_{\max}$		
	$\mathrm{BR}(\pi\mu\mu)_{\mathrm{I}}$	$\mathrm{BR}(\pi\mu\mu)_{\mathrm{II}}$	$\mathrm{BR}(D^0 \to \mu\mu)$
$\tilde{C}_7$	2.4	1.6	-
$\tilde{C}_9$	2.1	1.3	-
$\tilde{C}_{10}$	1.4	0.92	0.63
$\tilde{C}_S$	4.5	0.38	0.049
$\tilde{C}_P$	3.6	0.37	0.049
$\tilde{C}_T$	4.1	0.76	-
$\tilde{C}_{T5}$	4.4	0.74	-
$\tilde{C}_9 = \pm\tilde{C}_{10}$	1.3	0.81	0.63

- **weak triplet boson**: if to explain $R_{D^{(*)}}$ the bounds on τ→3μ and $D\underline{D}$ imply no observable effect on rare D decays
- **scalar leptoquark in rep. (3,2,7/6)**: $D\underline{D}$ is also competitive, effect in A_{FB}
- **vector leptoquark in rep. (3,1,5/3)**: sensitive to rare D decays
- **leptoquarks with flavour structure**
- **2HDM**: scalar operators, sensitive to $D^0 \to \mu\mu$
- **Z'** models are typically better probed in $D\underline{D}$
- **MSSM**, **vector like quark singlets, warped dimensions**,

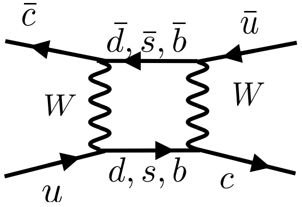
If a model tries to hide from B and K constraints it is likely it will hit the FCNC constraints in the charm sector

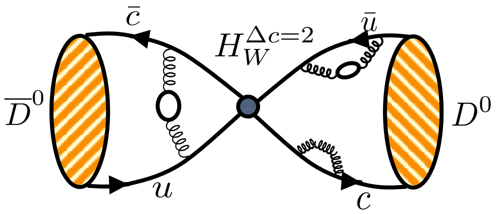
Greljo et al, 1506.01705,
de Boer, Hiller, 1510.00311;
Burdman hep-ph/0112235;
Fajfer, NK1510.00965;
Paul et al 1212.4849; Golowich 0903.2830

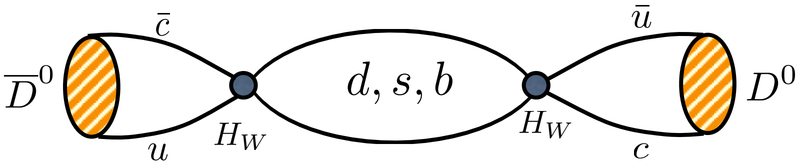
$D-\bar{D}$ mixing

In talks by Lenz, El-Khadra, Martinelli and Ciuchini

$$M_{12}-\frac{i}{2}\Gamma_{12} \;\propto\; \langle D^0|H_W^{\Delta c=2}|\overline{D}^0\rangle \;+\; \sum_n \frac{\langle D^0|H_W^{\Delta c=1}|n\rangle\langle n|H_W^{\Delta c=1}|\overline{D}^0\rangle}{M_D-E_n+i\epsilon}$$







short distance

long distance

"Simple"

can use the same methods as for *B* mixing (and decay constants, form factors)

BSMs with heavy new particles can contribute here

"Hard"

- large contribution
- intermediate state can include multiple (>2) hadrons: formalism for multi-hadron states still under development (Hansen & Sharpe, arXiv:1602.00324, 2016 PRD)

✦ not a problem for Kaon mixing

➟ first calculation of long-distance contribution already exists (RBC/UKCD, arXiv:1406.0916, 2014 PRL)

In the SM and beyond: $\mathcal{H}_{\text{eff}} = \sum_{i=1}^{5} c_i(\mu)\mathcal{O}_i(\mu)$

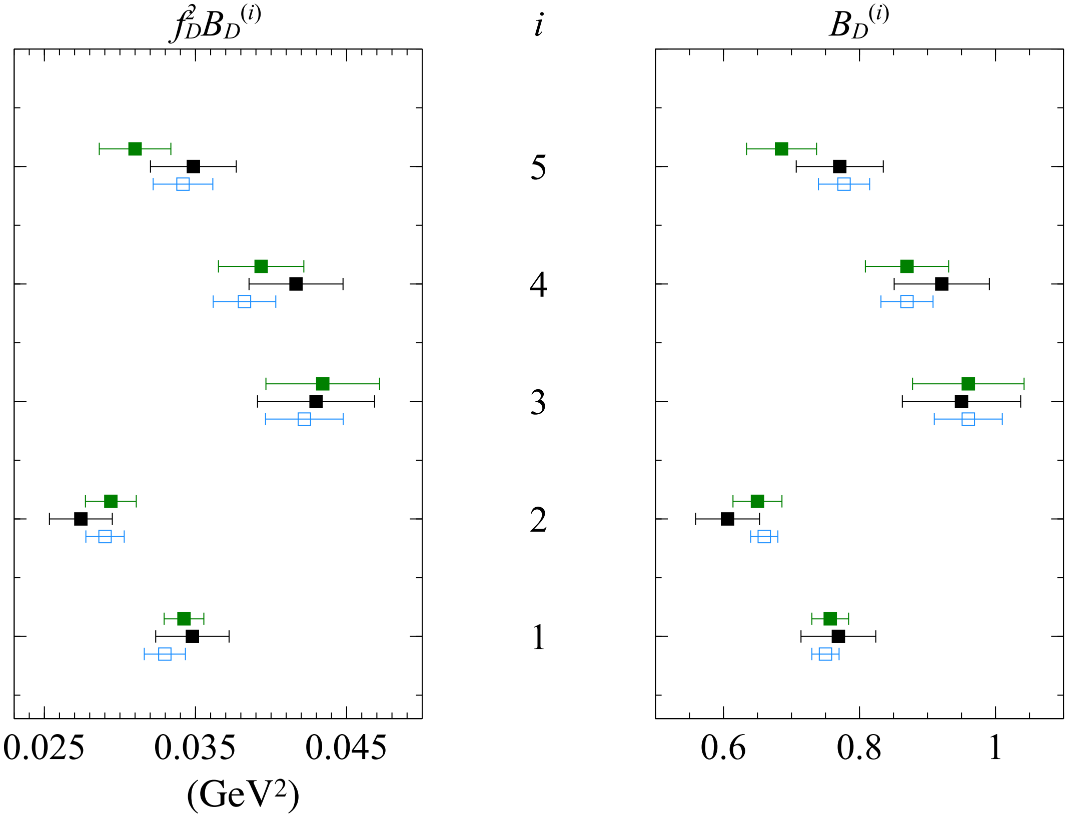
$$\langle \mathcal{O}_i \rangle \equiv \langle D^0 | \mathcal{O}_i | \overline{D}^0 \rangle(\mu) = e_i M_D^2 f_D^2 B_D^{(i)}(\mu)$$

choose $\mu = 3$ GeV

$\mu = 3$ GeV

A. Kronfeld @ Lattice 2016 (plot by C.C. Chang)

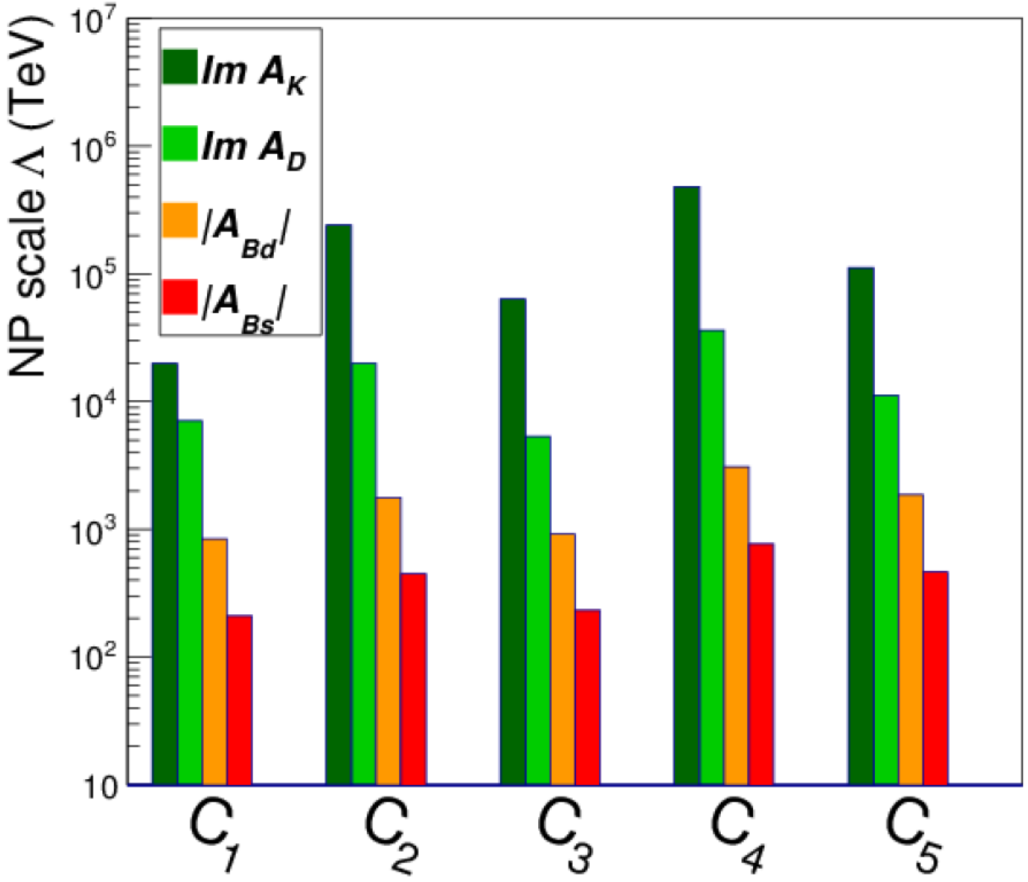
- ETM:
  $n_f = 2+1+1$
  arXiv:1505.06639
- Fermilab/MILC:
  $n_f = 2+1$
- ETM:
  $n_f = 2$
  arXiv:1403.7302



El-Khadra

Comparison with other meson mixing

Λ (TeV)	K CPV	D CPV	B_d CPC	B_s CPC
lower bound	4.8×10^5	3.6×10^4	3.1×10^3	760

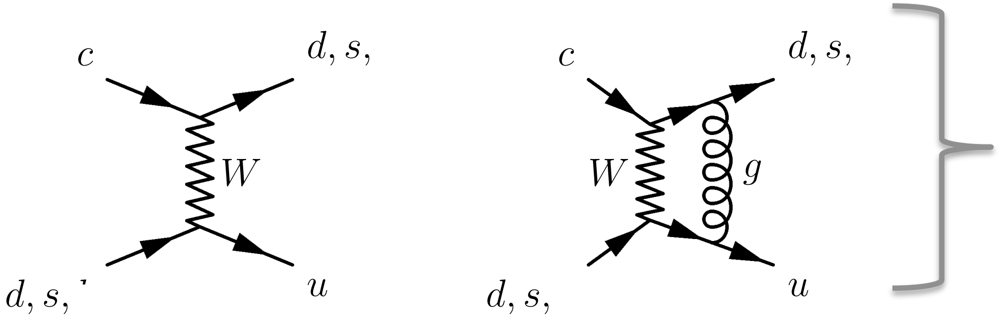


Ciuchini

Nonleptonic weak decays

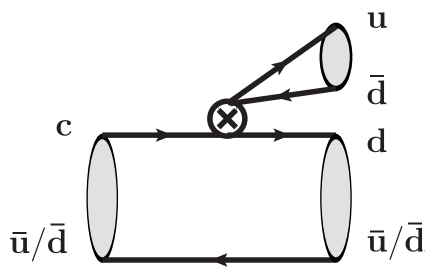
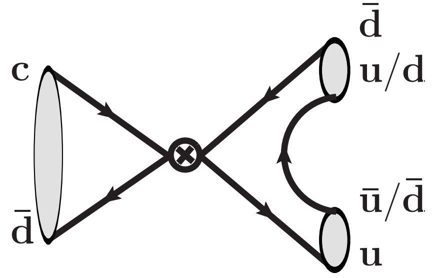
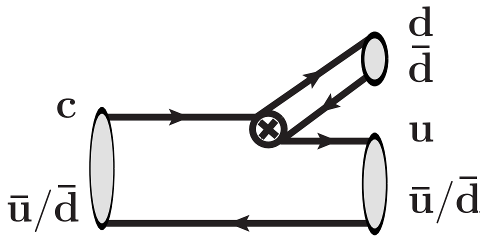
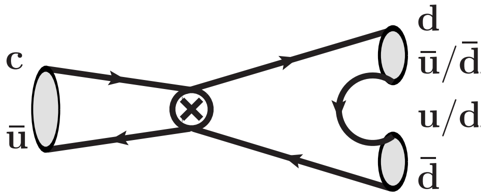
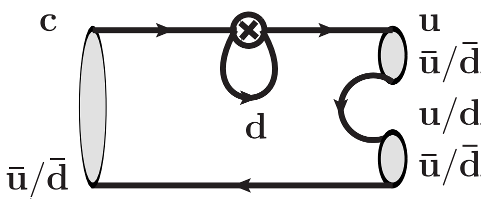
On the quark level leading contributions are:

$$H_{\text{eff}}^{\Delta C=\Delta S} = \frac{G_F}{\sqrt{2}} U_{ud} U_{cs}^{*} [C_2 \bar{s}^{\alpha} \gamma_{\mu}(1-\gamma_5) c_{\alpha} \bar{u}^{\beta} \gamma^{\mu}(1-\gamma_5) d_{\beta} \\ + C_1 \bar{u}^{\alpha} \gamma_{\mu}(1-\gamma_5) c_{\alpha} \bar{s}^{\beta} \gamma^{\mu}(1-\gamma_5) d_{\beta}] + \mathrm{H.c.}\ ,$$



It is very simple on the quark level

Two body decays, based on factorisation and FSI, (assumed to be dominated by nearby resonances)
included in the paper Buccella et al, hep-ph/9411286
Santorelli talk!

Name	Diagrams
T	
A	
C	
E	
P_d	

There are recent analysis based od $SU(3)_F$ flavor symmetry breaking:
Hiller, Jung, Schacht,
1211.3734; Muller, Nierste, Schacht 1503.06759;
Gronau 1501.03272, Santorelli
a global fit to topological amplitudes using all available branching ratios and the experimental information on the strong phase difference .

Santorelli:

$$\langle PP|\mathscr{H}|D\rangle \sim \langle \mathbf{1}\oplus\mathbf{8}\oplus\mathbf{27}|\left(\mathbf{3}\oplus\overline{\mathbf{6}}\oplus\mathbf{15}\right)|\overline{\mathbf{3}}\rangle$$

Wigner-Eckart theorem:

$$\langle\mathbf{8}||\mathbf{15}||\overline{\mathbf{3}}\rangle \quad \langle\mathbf{27}||\mathbf{15}||\overline{\mathbf{3}}\rangle \quad \langle\mathbf{8}||\overline{\mathbf{6}}||\overline{\mathbf{3}}\rangle$$

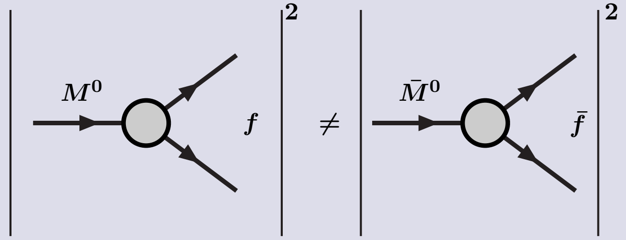
Fit reduced from 17 amplitudes on 5 complex r educed matrix elements

Santorelli:

CP Violation in the Decays: The Direct CPV

This occurs when the decay amplitudes for CP conjugate processes into final states f and $\bar{f}$ are different in modulus

$$|\mathscr{A}(M^0 \to f)| \neq |\mathscr{A}(\bar{M}^0 \to \bar{f})|$$



A nonzero direct CP asymmetry is present only when the decay amplitude is

$$\mathscr{A} = A_1\, e^{\imath\delta_1} + A_2\, e^{\imath\delta_2}$$

the CP conjugate amplitude is

$$\bar{\mathscr{A}} = A_1^*\, e^{\imath\delta_1} + A_2^*\, e^{\imath\delta_2}$$

and the CP asymmetry is:

$$a_{\mathrm{CP}}^{dir} = \frac{|\mathscr{A}|^2 - |\bar{\mathscr{A}}|^2}{|\mathscr{A}|^2 + |\bar{\mathscr{A}}|^2} = \frac{2\,\Im(A_1^*\,A_2)\,\sin(\delta_1 - \delta_2)}{|A_1|^2 + |A_2|^2 + 2\,\Re(A_1^*\,A_2)\,\cos(\delta_1 - \delta_2)}$$

CP Asymmetries: The SCS case

The amplitudes are made of two parts. For the D^0, for example, we have:

$$\mathscr{A}^{SCS} = \frac{1}{2}(V_{cs}^* V_{us} - V_{cd}^* V_{ud}) A^{(1,2)}\ e^{\imath\delta} - \frac{1}{2} V_{cb}^* V_{ub} A^{(P)}\ e^{\imath\delta'}$$

and so the direct CP asymmetry is given by

$$a_{CP}^{dir} \approx \eta A^2 \lambda^4 \sin(\delta - \delta') \left[\frac{A^{(P)}}{A^{(1,2)}}\right] \approx (6 \times 10^{-4}) \sin(\delta - \delta') \left[\frac{A^{(P)}}{A^{(1,2)}}\right]$$

- Strong phase difference could be large due to the resonances
- Penguin amplitude of the order of tree amplitude

$$a_{CP}^{dir} \approx 10^{-4} \div 10^{-3}$$

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

$$\begin{aligned} \Delta A_{\mathrm{CP}} &= (-0.82 \pm 0.21 \pm 0.11)\% && (\mathrm{LHCb}\,(2012)) \\ &= (-0.62 \pm 0.21 \pm 0.10)\% && (\mathrm{CDF}\,(2012)) \\ &= (-0.87 \pm 0.41 \pm 0.06)\% && (\mathrm{Belle}\,(2012)) \end{aligned}$$

$$\Delta A_{\mathrm{CP}} = -(0.16 \pm 0.19)\%$$

HFAG (July 2016)

Multi-body charm decays

Rademacker: Why to study it?

QM is intrinsically complex:

- Wave functions/transition amplitudes etc: $\psi = a\, e^{i\alpha}$. Observable: $|\psi|^2$. Only half the information. How do I get the rest?

- Note that the rest is very interesting - CP violation in the SM comes from phases!
- Answer: Interference effects:

$$\psi_{\text{total}} = a\, e^{i\alpha} + b\, e^{i\beta} + \ldots$$
$$|\psi_{\text{total}}|^2 = |a\, e^{i\alpha} + b\, e^{i\beta} + \ldots| = a^2 + b^2 + 2ab\cos(\alpha - \beta) + \ldots$$

Derkach

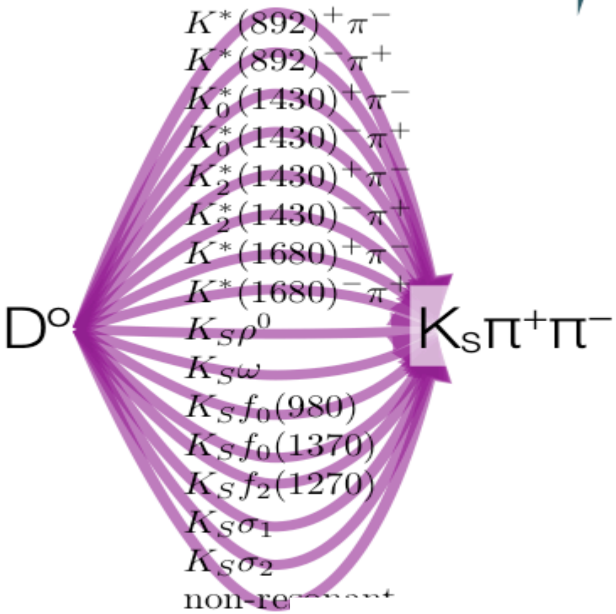
Not only that:

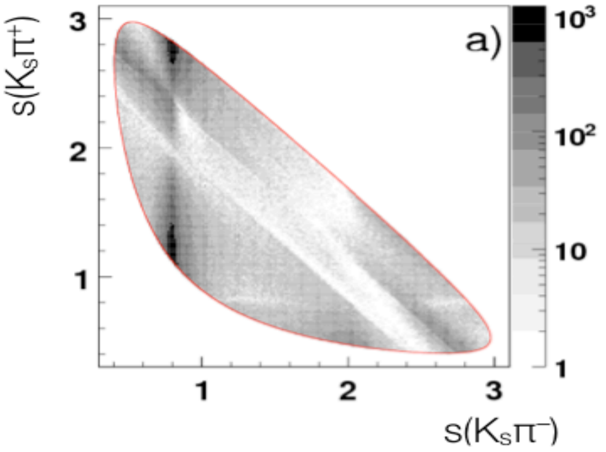
Charm inputs are of great importance to the gamma combination and thus to the search of NP effects.

Many interfering decay paths contribute to the same final state

Described by a sum of complex amplitudes

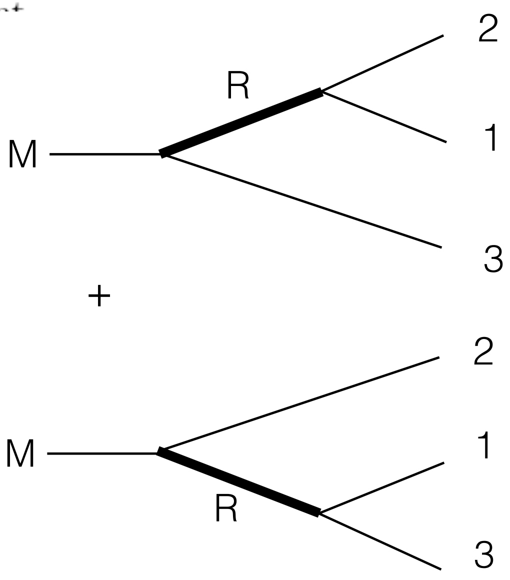
$$A(s_+, s_-) = \sum_k a_k(s_+, s_-)\, e^{i\phi_k(s_+, s_-)}$$

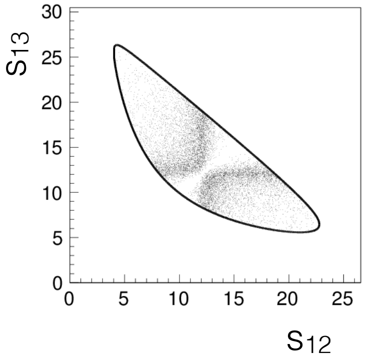




BaBar Phys. Rev. Lett. 105, 081803 (2010).

$|A(s_+, s_-)|^2$ represented in a Dalitz plot





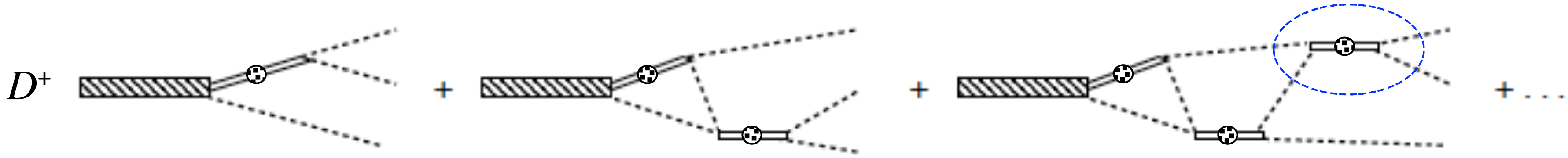
$$d\Gamma = \frac{1}{(2\pi)^2\, 32 M^3} |\mathcal{M}_{fi}|^2 ds_{12} ds_{13}$$

Coupled-channel Dalitz plot analysis of $D^+ \to K^-\pi^+\pi^+$ decay

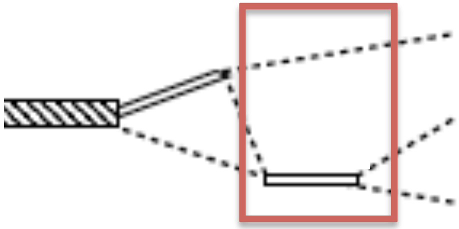
Nakamura

- Partial wave decay amplitudes can be extracted
- Information of hadron interactions and resonances thereby
- CPV analysis, new physics search

two-meson
scattering amplitude



$D^+ \to K^- \pi^+ \pi^+$



scattering model developed

Channels (partial wave)	$(\bar{K}\pi)_S^{I=1/2}\pi$,	$(\bar{K}\pi)_P^{I=1/2}\pi$,	$(\bar{K}\pi)_D^{I=1/2}\pi$,	$(\pi\pi)_P^{I=1}\bar{K}$,	$(\bar{K}\pi)_S^{I=3/2}\pi$,	$(\pi\pi)_S^{I=2}\bar{K}$
resonances	κ, $K_0^*(1430)$	$K^*(892)$	$K_2^*(1430)$	$\rho(770)$		

No flat background

Large hadronic rescattering effects!

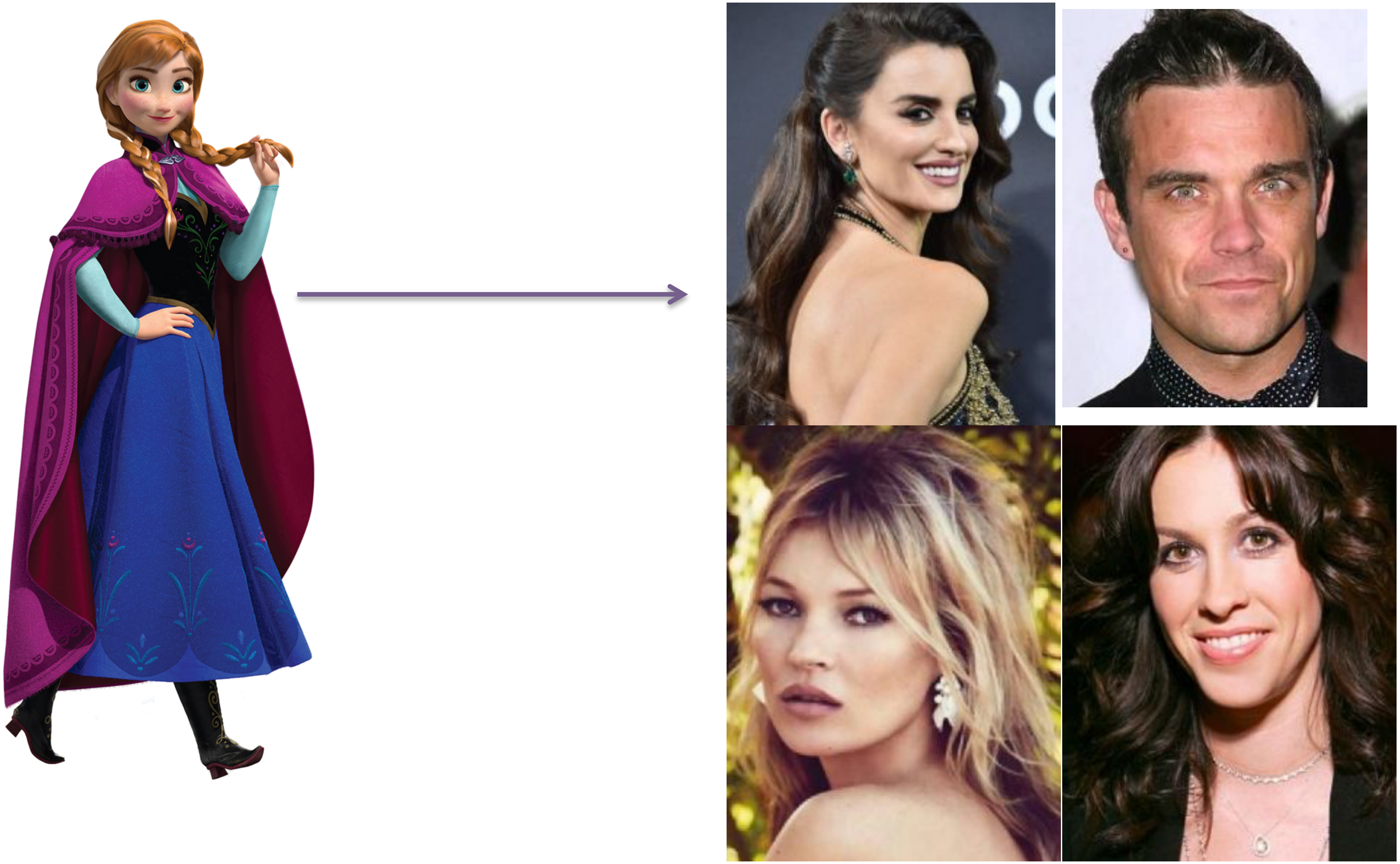
Closing remark

CHARM 2015 → CHARM 2016

Progress in Charm in QCD

CHARM in EW interactions

CHARM is now 42 years old!



Facing interesting future!