THEORY SUMMARY

Luca Silvestrini

INFN, Rome

- Impossible (due to my limitations) to do justice to the >20 theory talks presented at this conference
- Will give a personal view, so forgive me if I under/misrepresent your work

INFN Istituto Nazionale di Fisica Nucleare

erc European Research Council
Funding for top researchers from anywhere in the world

INTRODUCTION

- Spectacular exp. progress is leading us into the precision charm physics era, calling for substantial theoretical advances
- Charm physics at the forefront of NP searches, ample room for exp and th improvements
- Complementarity between K and D physics allows to fully exploit the constraining power of flavour physics

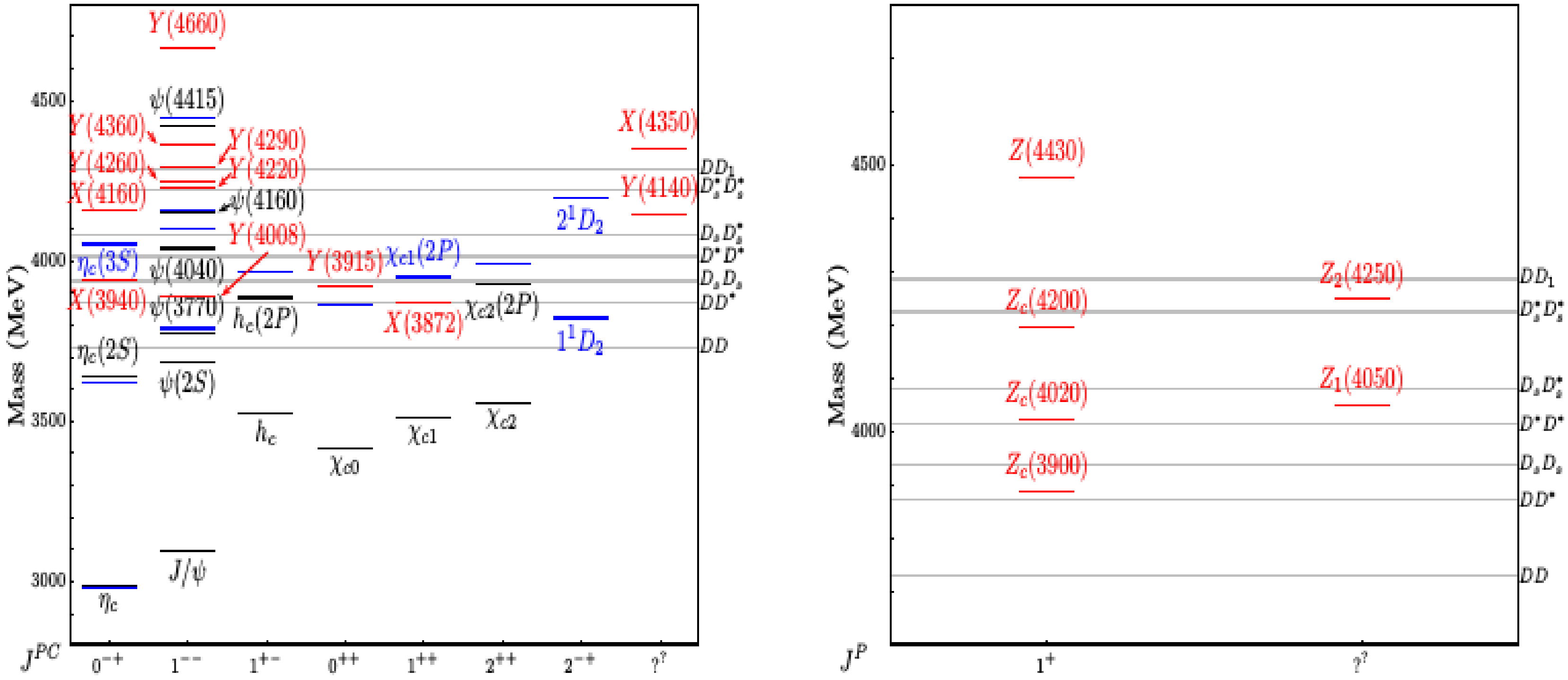
- Charm properties
  - production
  - spectroscopy
  - mass, Y, decay constant, form factors
- NP-sensitive, th. clean observables
  - CPV in mixing
  - few rare decays
- Potentially NP-sensitive but requiring significant th. improvements
  - CPV in nonleptonic decays
  - more rare decays

CHARM PROPERTIES

SPECTROSCOPY

$c\bar{c}$ spectrum 12 years after $X(3872)$ discovery

A. Esposito, A. Guerrieri, F.P., A. Pilloni, A. Polosa, IJMPA30 (2014) 04n05, 1530002



- All $c\bar{c}$ states below open c threshold identified
- All $J^{PC} = 1^{--}$ $c\bar{c}$ states filled
- New neutral and charged particles above threshold
- Some may be charmonia, others not (exotica, X, Y, Z), in particular the charged ones (the neutral ones have quantum numbers compatible with charmonia)

- Exotics as loosely bound charmed meson molecules:
  - economic description of several exotic states very close to threshold
  - challenged by prompt production at LHC
- Exotics as compact tetraquarks:
  - many predictions of additional states, dep. on diquark interactions (type I & II)
  - supported by observ. of new charged states
  - diquark dynamics rich and very interesting

R. Lebed

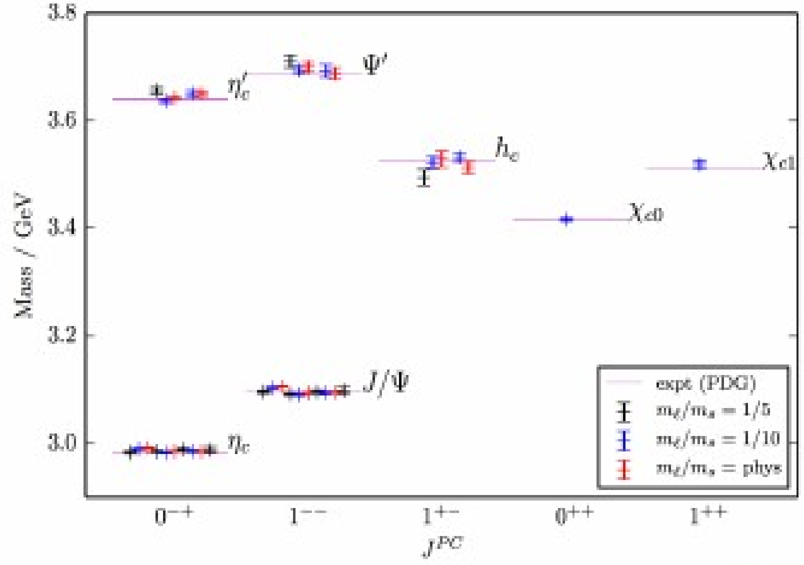
- Decays in specific channels could discriminate between models

A. Esposito

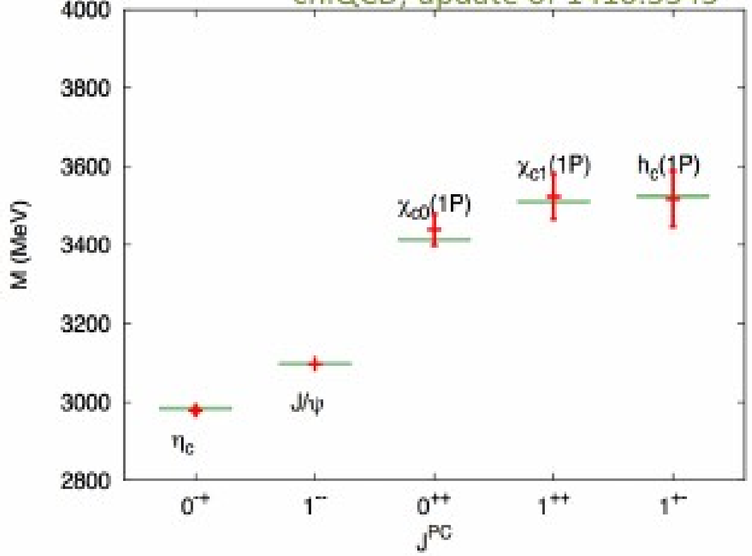
Charmonia well below $D\underline{D}$: recent precision results

$m=E$ ($P=0$): $a\to 0$, $L\to\infty$, $m_q\to m_q^{phy}$

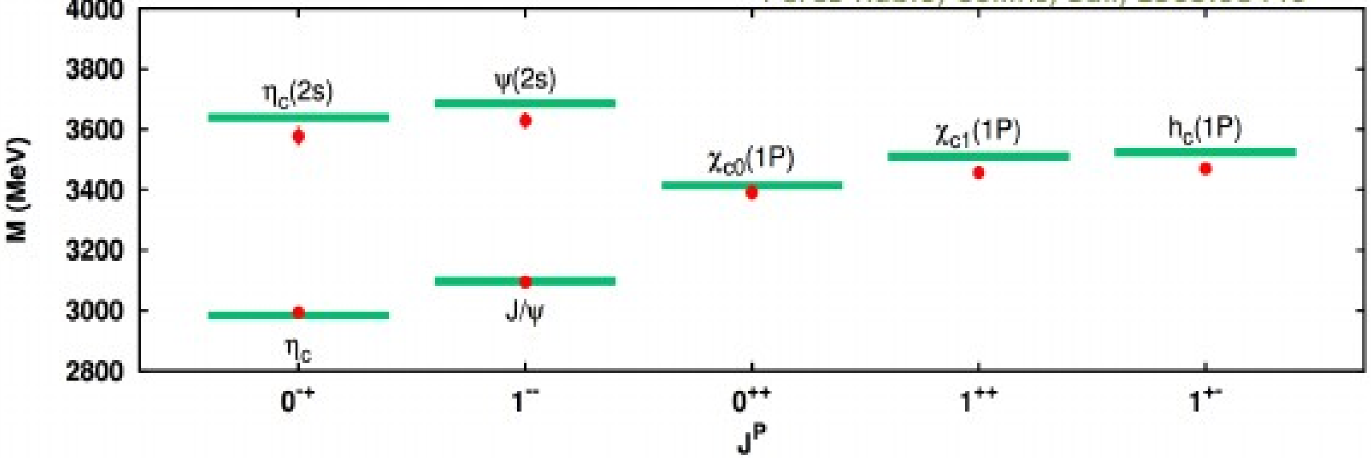
HPQCD, 1411.1318



chiQCD, update of 1410.3343



Perez-Rubio, Collins, Bali, 1503.08440



see also:

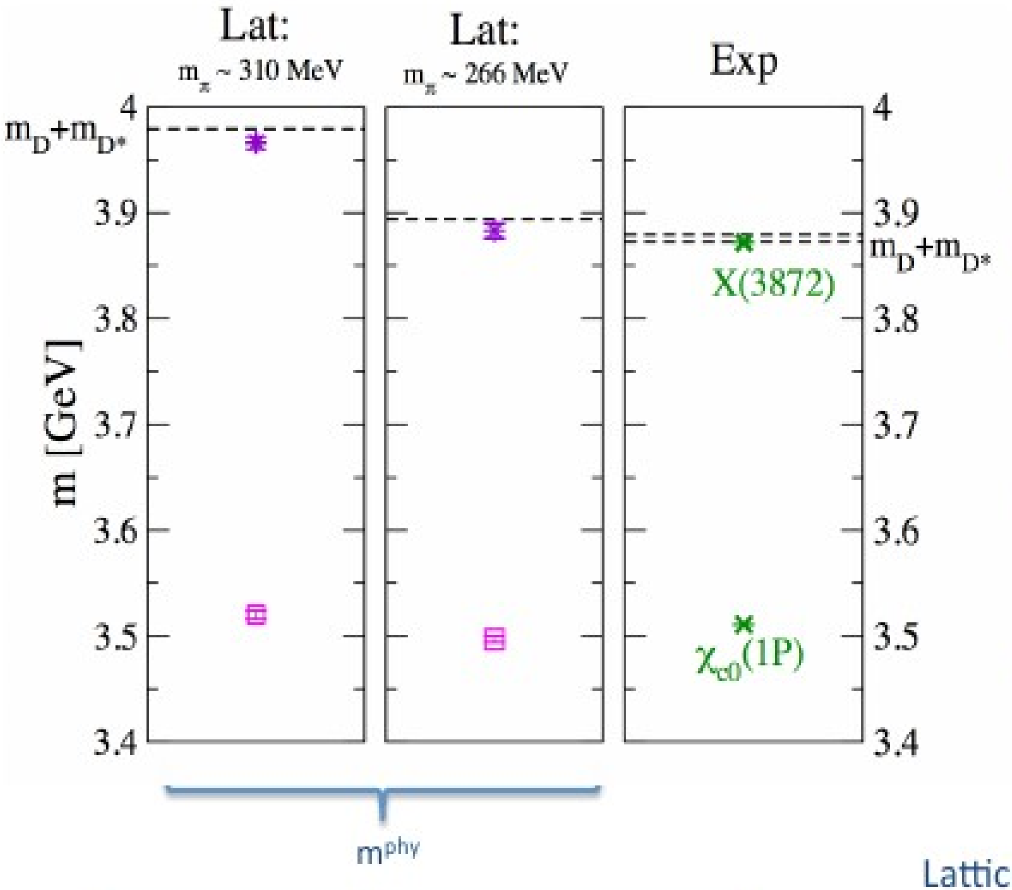
FNAL/MILC, 1412.1057

The omission of charm annihilation is the main remaining uncertainty

CHARMONIA ABOVE D-$\bar{D}$

- Maiani-Testa no-go theorem: correlation functions on the lattice always dominated by state with lowest energy, prevents study of interacting multi-meson states
- Finite volume effects allow to overcome this difficulty for two-meson states.
- Three-particle case being explored, but still need substantial progress

X(3872) as bound state from $D\underline{D}^*$ scattering, $J^{PC}=1^{++}$, I=0



$\mathcal{O}: \bar{c}\,c, D\bar{D}^*$

- ground state: $\chi_{c1}(1P)$
- $D\underline{D}^*$ scattering matrix near th. determined
- A pole of $T \propto \frac{1}{\cot\delta - i} = \infty$ found just below th. (violet star)
- The pole attributed to X(3872), which is a shallow bound state in both simulations
- Position of DD* threshold depends on $m_{u/d,}$ and may be affected by discretization effects related to charm quark

X(3872)	m - $(m_{D0}+m_{D0^*})$
lat (m_π=310 MeV)	- 13 ± 6 MeV
lat (m_π=266 MeV)	- 13 ± 6 MeV
exp	- 0.14 ± 0.22 MeV

Lattice evidence for X(3872):

- $m_\pi \approx 266$ MeV, a=1.24 fm, L= 2 fm

[S.P. and Leskovec: 1307.5172, PRL 2013]

- $m_\pi \approx 310$ MeV, a=.15 fm, L=2.4 fm , HISQ

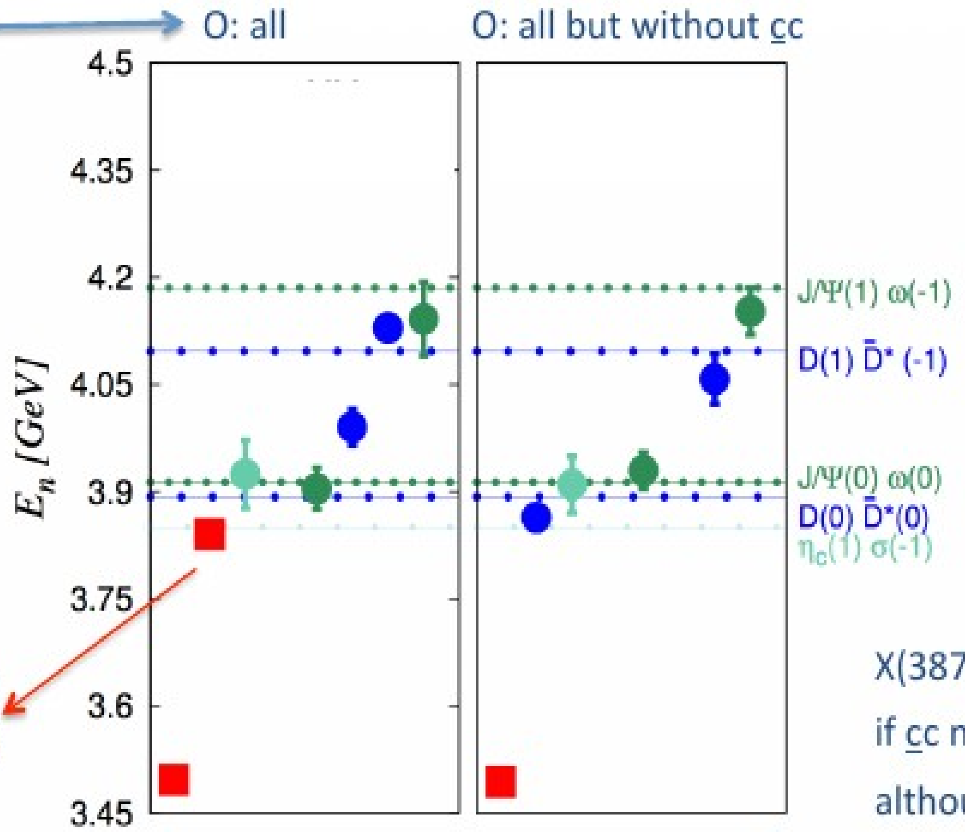
[Lee, DeTar, Na, Mohler , update of proc 1411.1389]

See also R. Molina

Which Fock components are essential for X(3872) with I=0 ?

$$\mathcal{O}: \ \underbrace{\bar{c}\,c, \quad D\bar{D}^*}_{\text{essential}}, \ J/\psi\omega, \ \chi_{c1}\eta, \ \eta_c\sigma, \ \underbrace{[\overline{cu}]_{3c}[cu]_{3c}, \ [\overline{cu}]_{6c}[cu]_{6c}}_{\text{do no seem not essential}}$$

interpolating fields



upper red square is candidate for X(3872): it is found only if cc in the basis

X(3872) not found

if cc not in the basis,

although [cu][cu] in the basis

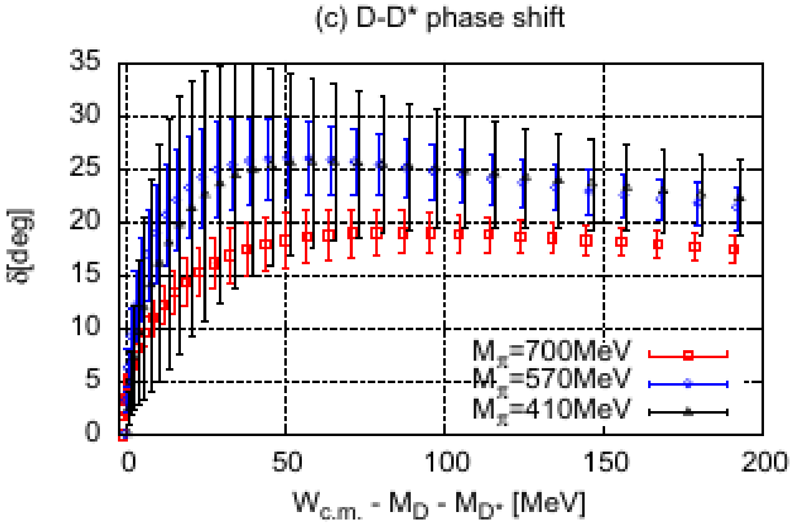
energies of eigenstates on lattice E(L)
(these are not m^{phy})

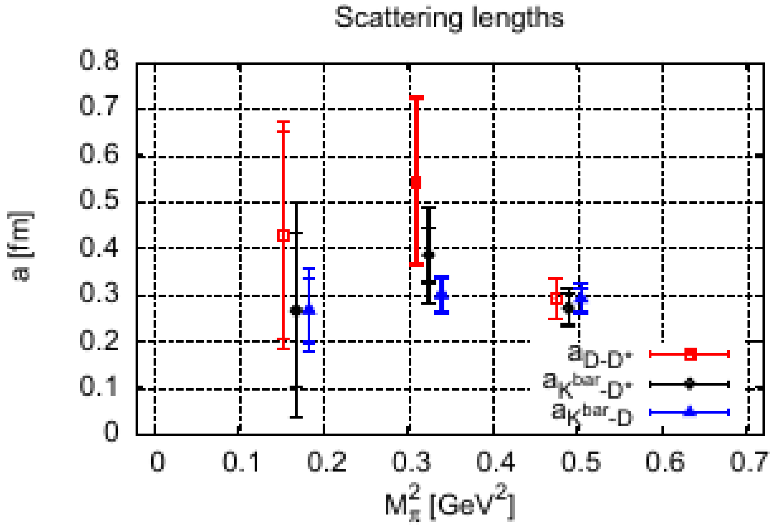
[M. Padmanath, C.B. Lang, S.P., 1503.03257]

Tetraquarks with the HALQCD method: Results

`Ikeda et al. PLB 729 85-90 (2014)`

- Repulsive interaction in all $I = 1$ channels considered
- Attractive interaction in all $I = 0$ channels considered



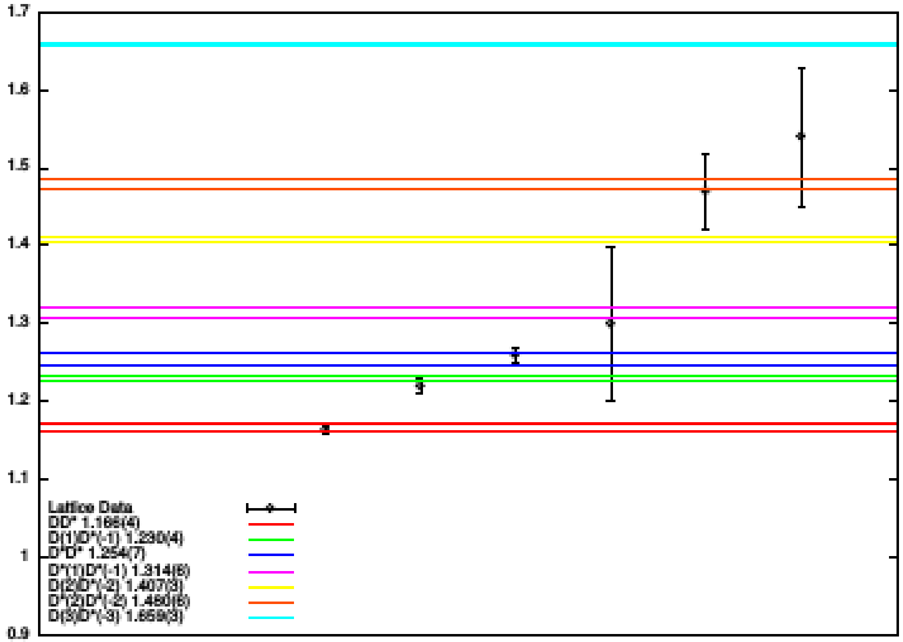


- No bound states or resonances at simulated m_π
- Attraction becomes more prominent at light pion masses
- Authors have some indication that BB^* with $IJ^P = 01^+$ is bound

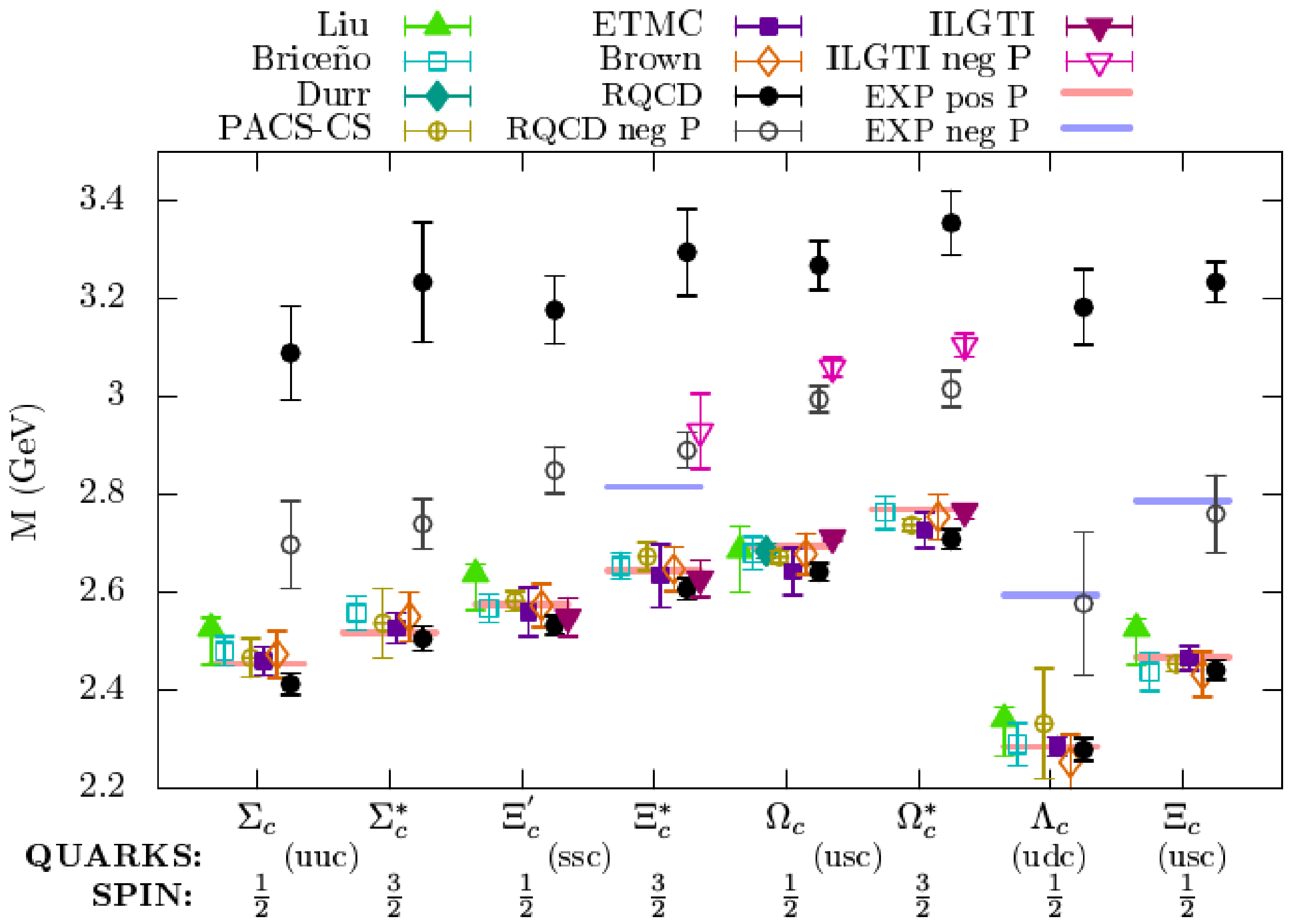
Search for doubly charmed tetraquarks (preliminary)

Guerrieri et al. arXiv:1411.2247

- 2 flavor simulation with $a = 0.075\text{fm}$ and $m_\pi = 490\text{MeV}$ and lighter than physical m_{charm}
- Considers $[cc][\bar{u}\bar{d}]$ tetraquarks with $IJ^P = 01^+, 11^+$
- Basis of tetraquark and meson-meson interpolators (also smeared)
- No additional low-lying energy level observed (just meson-meson states)



Low lying singly charm baryons



Bali *et. al.*, arXiv:1503.08440[hep-lat].

- **Ground states more or less in agreement between all lattice results and experiments.**
- **Improving control over the systematic and statistical uncertainties.**
- **The excited state determination : challenging!**
- **Systematic spin identification : Even more challenging!!**

Quarkonium Production

G. Bodwin

- At high-p_T, expect factorization in v exp. :
  $\sigma \approx (\sigma_{QQ} \times \text{pdf}) \times (QQ \rightarrow \text{quarkonium})$
- Proven only at NLO
- predictions depend on LD matrix elements
- Combine w. L ($1/p_T^4$) and NL (m_Q^2/p_T^6) fragm. to get dominant effects at large p_T
- J/ψ hadroproduction well described, problems with photoprod. and w. η_c hadropr.

See also H. Zhang, A. Luchinsky

Quarkonium production in matter

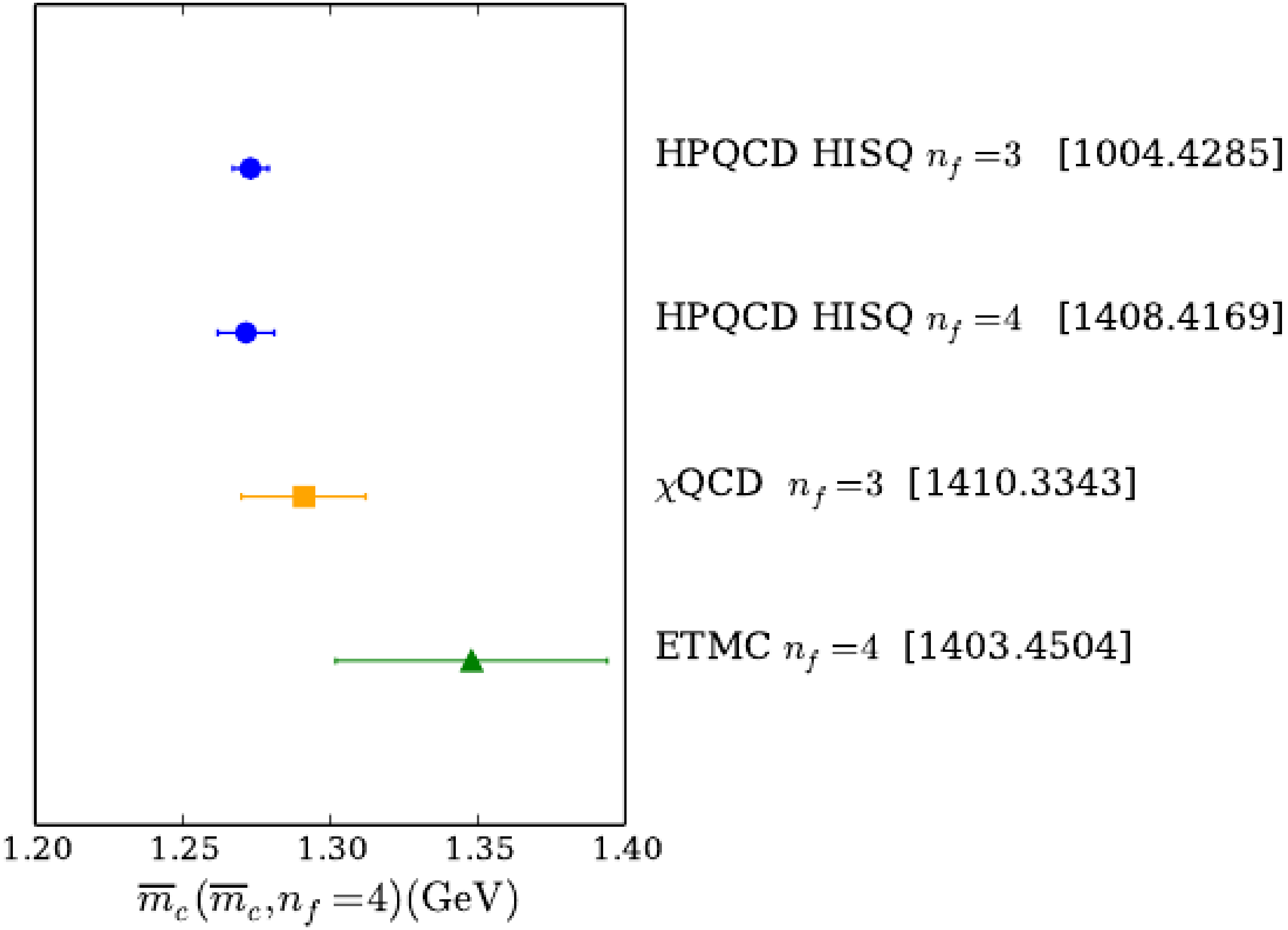
J. Qiu

- ❑ Heavy quarkonium production has been a powerful tool to test and challenge our understanding of strong interaction and QCD
- ❑ Both initial-state and final-state multiple scattering are relevant for nuclear dependence of Quarkonium production – could redistribute both the p_T and y dependence
- ❑ Final-state multiple scattering could be an effective source of J/ψ suppression because of the sharp threshold behavior
- ❑ Heavy quarkonium production in hot medium is still an open problem/challenge – a lot of effort are underway

See M. Nahrgang for open HF prod. in matter and W.K. Lai for prod. asymmetry in vacuum

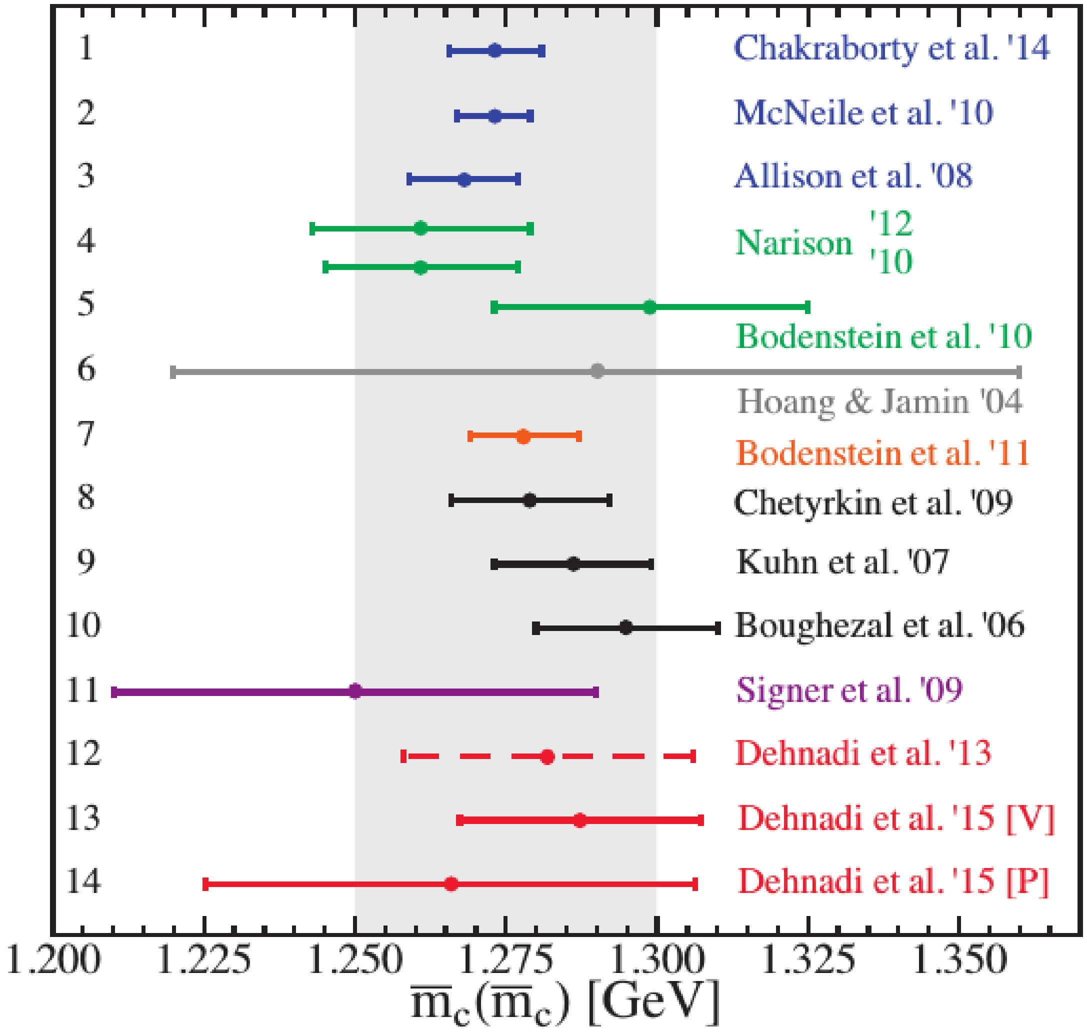
See also talks by Vogt, Yu, Zhao in parallel one

m_c comparison plot



Charm mass determinations

From QCD sum rules

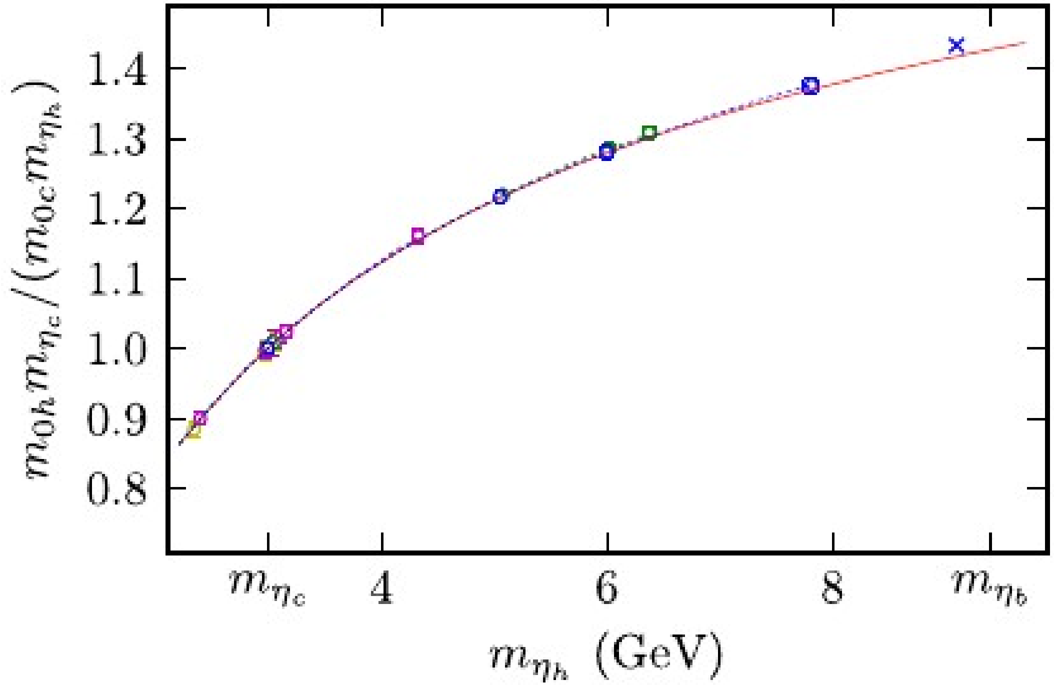


[Dehnadi, Hoang, & VM '15]

V. Mateu

m_b/m_c

HPQCD [1004.4285]

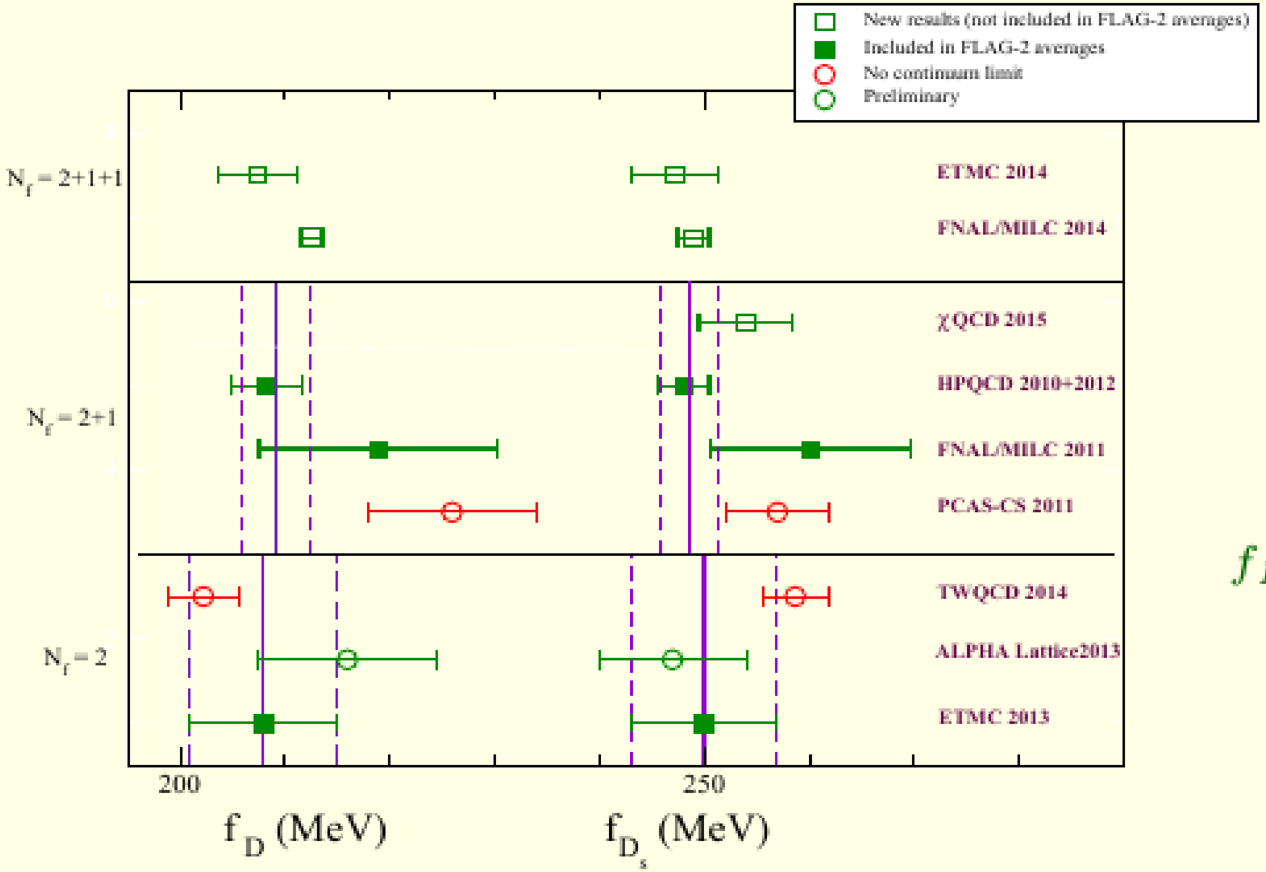


$m_b/m_c = 4.49(4)$ HPQCD [1004.4285]

$m_b/m_c = 4.40(8)$ ETMC [1411.0484]

A. Lytle

2. Leptonic D decays



$\mathbf{FLAG-2, N_f = 2}$

$$f_D = (208 \pm 7)\ MeV$$

$$f_{D_s} = (250 \pm 7)\ MeV$$

$\mathbf{FLAG-2, N_f = 2+1}$

$$f_D = (209.2 \pm 3.3)\ MeV$$

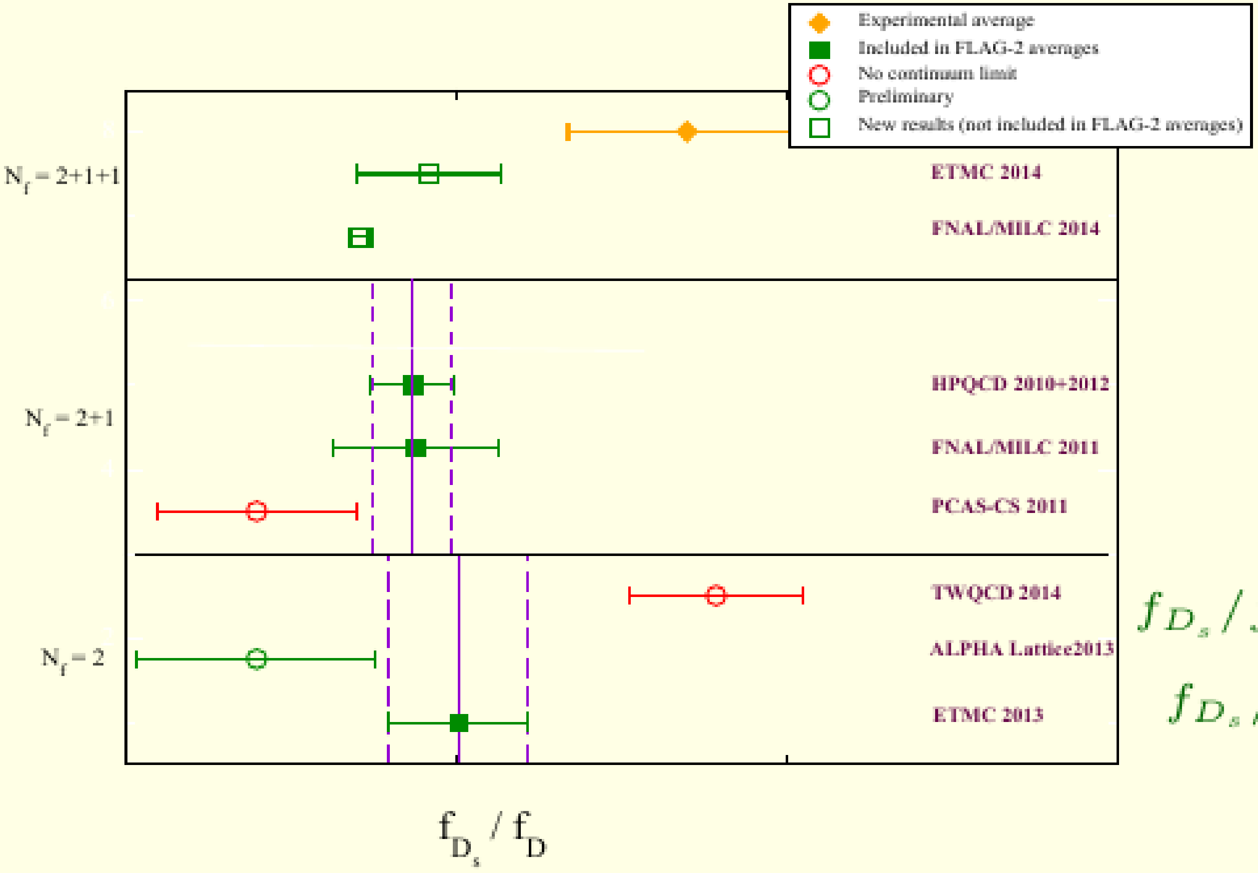
$$f_{D_s} = (248.6 \pm 2.7)\ MeV$$

FNAL/MILC $N_f = 2+1+1$

$$f_{D+} = 212.6^{+1.1}_{-1.2}\,\text{MeV} \qquad f_{D_s} = 249.0^{+1.3}_{-1.5}\,\text{MeV}$$

E. Gamiz

2. Leptonic D decays



$$\mathbf{FLAG-2, N_f = 2}$$

$$f_{D_s}/f_D = 1.20 \pm 0.020$$

$$\mathbf{FLAG-2, N_f = 2+1}$$

$$f_{D_s}/f_D = 1.187 \pm 0.012$$

$N_f = 2+1+1$:

$$f_{D_s}/f_{D^+}\big|_{\rm FNAL/MILC} = 1.1712^{+31}_{-34}$$

$$f_{D_s}/f_D\big|_{\rm ETMC} = 1.192 \pm 0.022$$

Experiment: Average from G. Rong, CKM2014, 1411.3868 and unitarity values $|V_{cs}| = 0.97343 \pm 0.00015$, $|V_{cd}| = 0.22522 \pm 0.00061$ from PDG2014:

$$f_{D_s}/f_{D^+}\big|_{\rm exp.} = 1.270 \pm 0.036$$

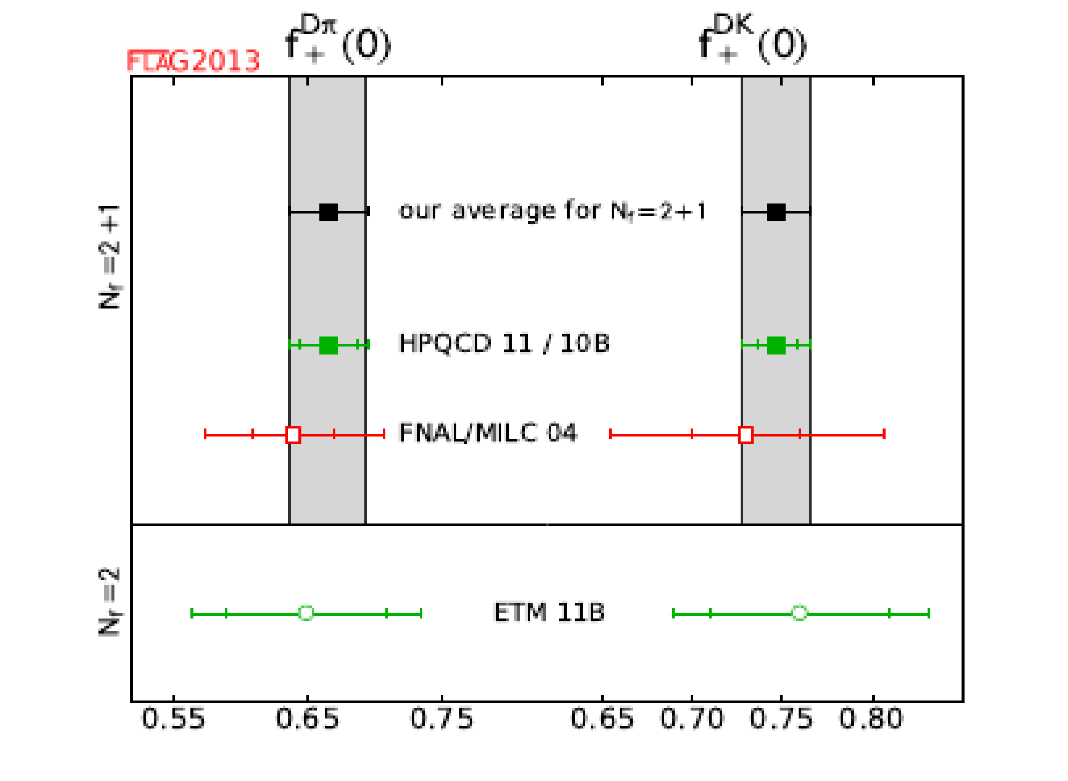
2.7σ larger than $N_f = 2+1+1$ FNAL/MILC result

and 2.3σ larger than $N_f = 2+1$ FLAG-2 average

E. Gamiz

3. Semileptonic D decays: $q^2 = 0$

Important reduction of errors in the lattice determination of the form factors $f_+^{D\pi(K)}(0)$ by the **HPQCD Collaboration**, Phys.Rev.D82:114506(2010), due mainly to



* Use a relativistic action, HISQ, to describe light and charm quarks.

* Absolutely normalized current

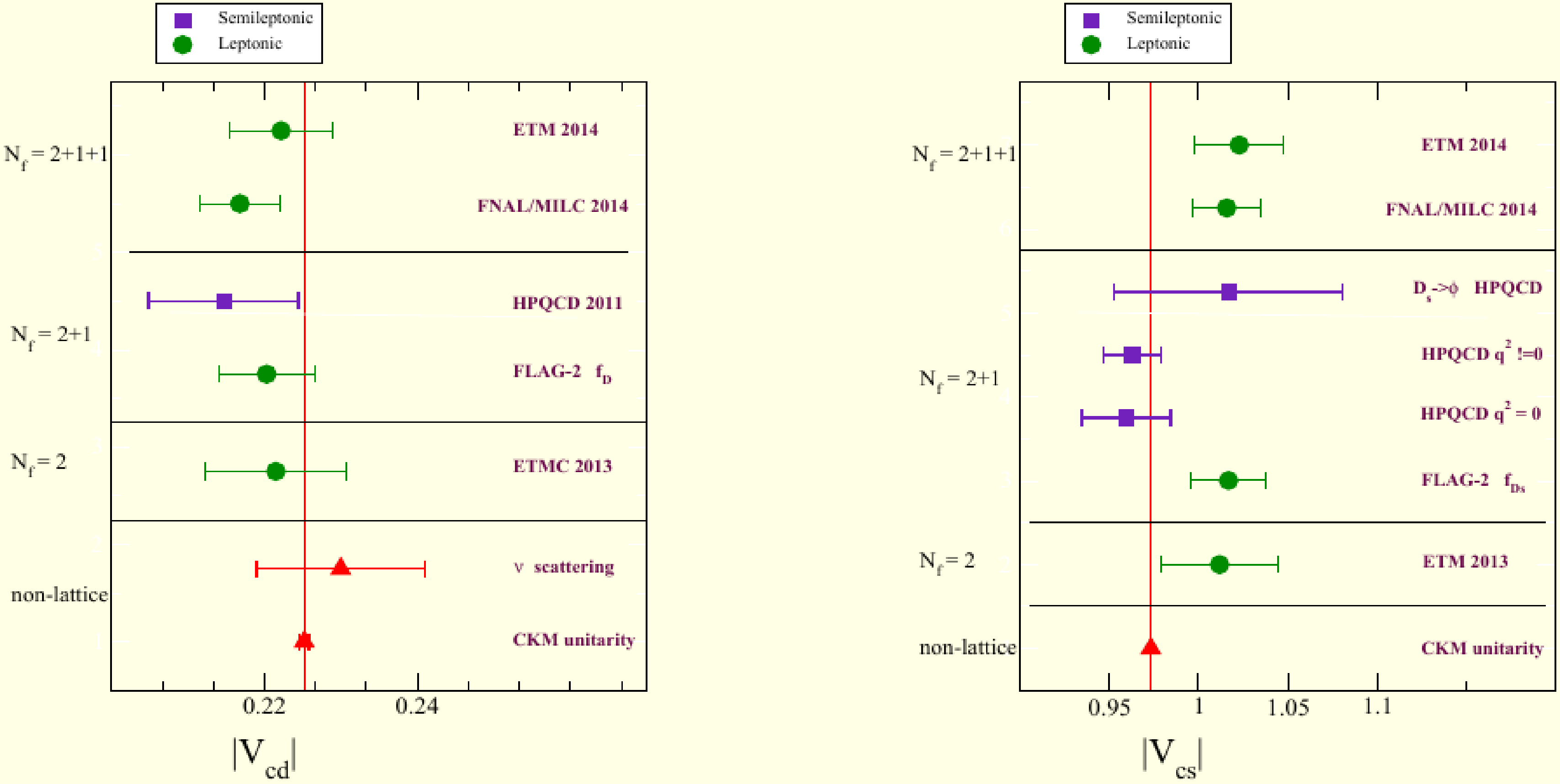
HPQCD, 1008.4562, 1109.1501

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

\# Work in progress: $N_f = 2+1+1$ **FNAL/MILC**, 1411.1651 with physical quark masses.

E. Gamiz

4. $|V_{cd}|$, $|V_{cs}|$: CKM unitarity in the second row



* $|V_{cd}|$: Pretty good agreement between different determinations, but some tension $N_f = 2+1+1$ FNAL/MILC leptonic-unitarity.

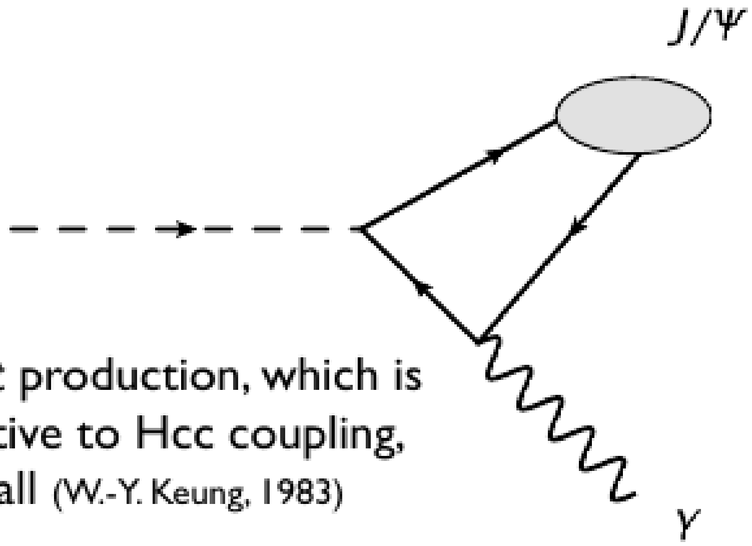
* $|V_{cs}|$: Slight tensions leptonic-semileptonic ($D \to Kl\nu$) and leptonic-unitarity.

E. Gamiz

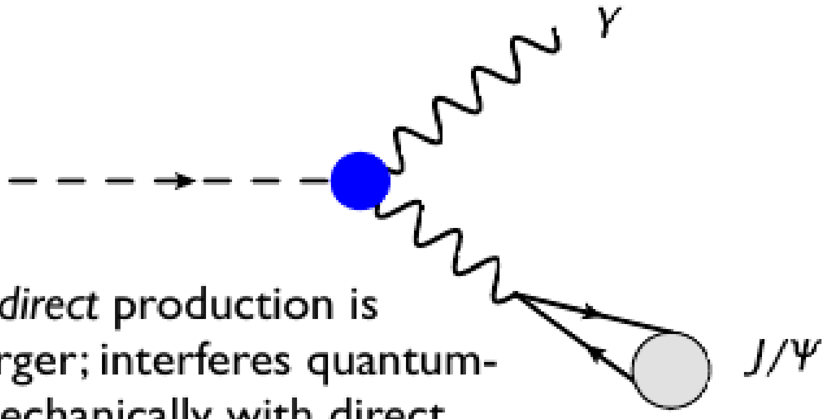
Charm coupling to the Higgs

See also Z. Zhang

- Access this coupling using H→J/Ψ+γ! Bodwin, FP, Stoynev, Velasco 1306.5770



Direct production, which is sensitive to Hcc coupling, is small (W.-Y. Keung, 1983)



Indirect production is larger; interferes quantum-mechanically with direct production

- Larger indirect mechanism drags up the direct one; provides sensitivity to the Hcc coupling
- Theoretically very clean; few-percent uncertainties: Bodwin, Chung, Ee, Lee, FP 1407.6695
- Interference gives unique information on the phase of the Hcc coupling

Theory prediction for J/ψ

- Partial width for general Hcc coupling (Bodwin, FP, Stoynev, Velasco 1306.5770):

$g_{Hcc}=\kappa_c\,(g_{Hcc})_{SM}$

$$\Gamma(H\to J/\psi+\gamma)=\left|(11.9\pm0.2)-(1.04\pm0.14)\kappa_c\right|^2\times10^{-10}\ \mathrm{GeV}$$

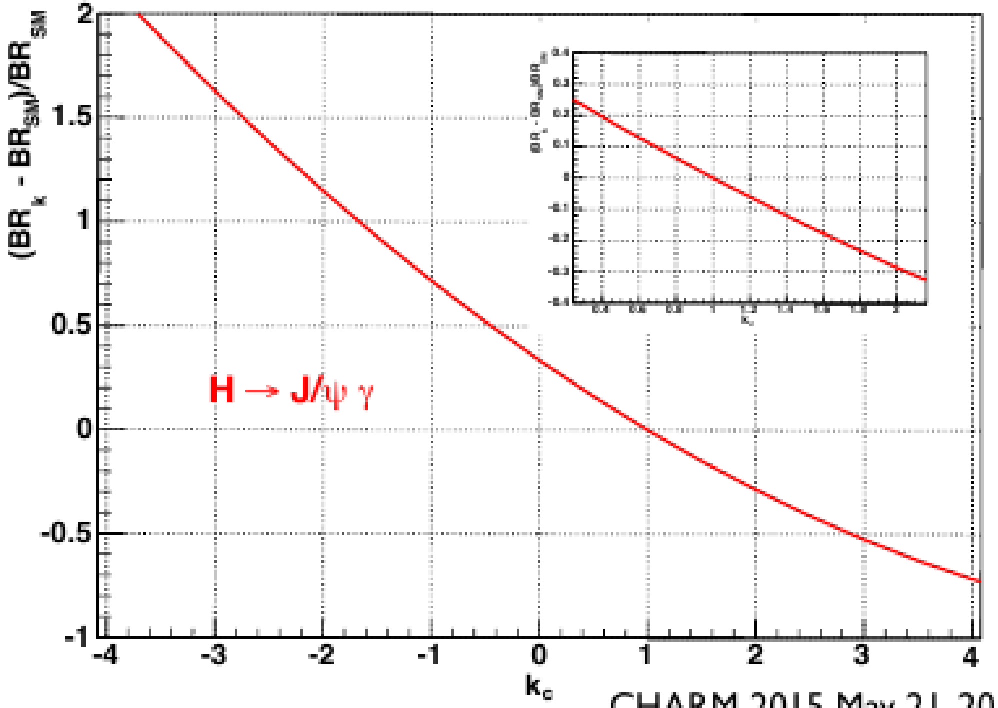
Dominant uncertainty on indirect amplitude: leptonic width of J/ψ

Dominant uncertainty on direct amplitude: uncalculated v^4 corrections in NRQCD

- Branching ratio in the SM:

$$\boxed{\mathcal{B}_{\rm SM}(H\to J/\psi+\gamma)=2.79^{+0.16}_{-0.15}\times10^{-6}}$$

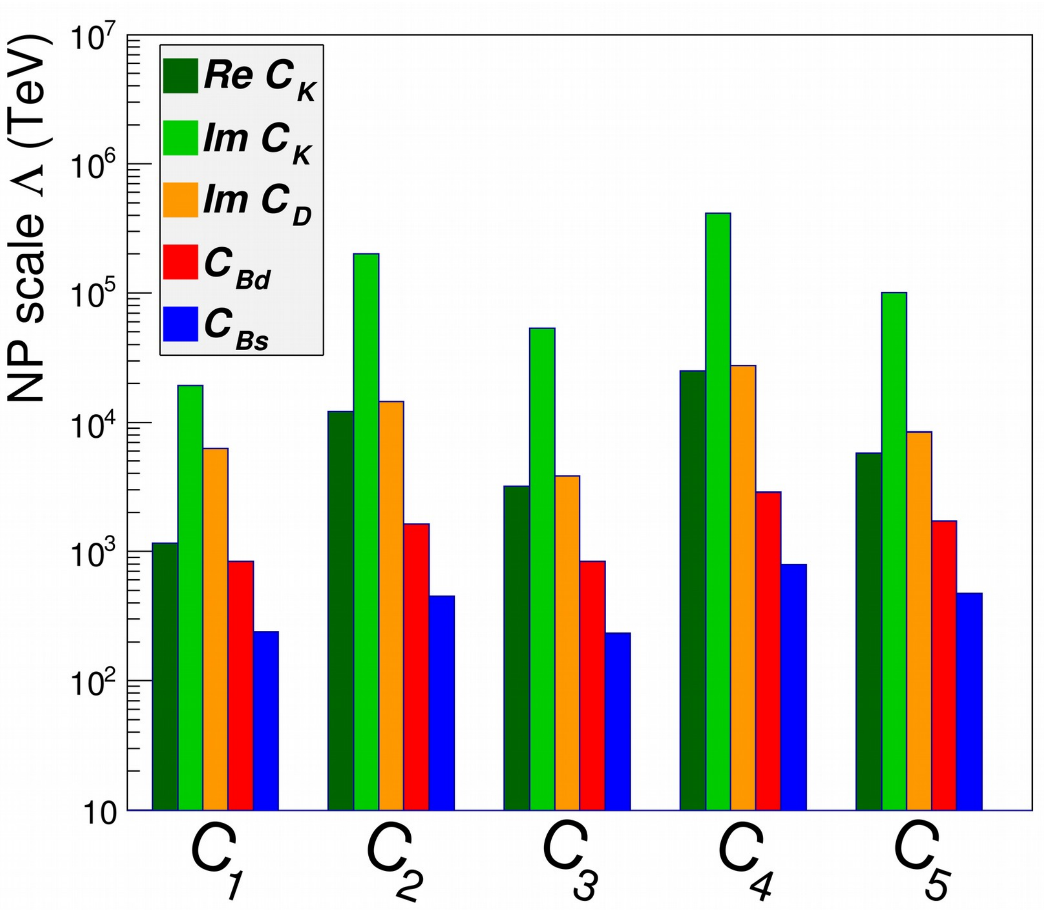
This is a 3 ab^{-1} measurement! Only possible with a high luminosity LHC; O(100) $l^+l^-\gamma$ events in the SM after acceptance×efficiency



NP-sensitive, th. clean

CPV IN MIXING AND NP

- CP violation in $\Delta F=2$ processes is the most sensitive probe of NP, reaching scales of $O(10^5)$ TeV
- CPV in D mixing gives best bound after ε_K
- How far can we push it?



D MIXING

- D mixing is described by:
  - Dispersive $D \to \bar{D}$ amplitude M_{12}
    - SM: long-distance dominated, not calculable
    - NP: short distance, calculable w. lattice
  - Absorptive $D \to \bar{D}$ amplitude Γ_{12}
    - SM: long-distance, not calculable
    - NP: negligible
  - Observables: $|M_{12}|$, $|\Gamma_{12}|$, $\Phi_{12}=\arg(\Gamma_{12}/M_{12})$

See F.S. Yu

GIM ⇔ SU(3) (U-spin)

- Use CKM unitarity

  $V_{cd}V_{ud}^* + V_{cs}V_{us}^* + V_{cb}V_{ub}^* = \lambda_d + \lambda_s + \lambda_b = 0$

- eliminate λ_d and take λ_s real (all physical results convention independent)
- imaginary parts suppr. by $r=\mathrm{Im}\,\lambda_b/\lambda_s=6.5\;10^{-4}$
- M_{12}, Γ_{12} have the following structure:

  $\lambda_s^2\,(f_{dd}+f_{ss}-2f_{ds}) + 2\lambda_s\lambda_b\,(f_{dd}-f_{ds}-f_{db}+f_{sb}) +O(\lambda_b^2)$

GIM $\Leftrightarrow$ SU(3) (U-spin)

- Write long-distance contributions to M_{12} and Γ_{12} in terms of U-spin quantum numbers:

  $\lambda_s^2\ (\Delta U=2) + \lambda_s\lambda_b\ (\Delta U=2 + \Delta U=1) + O(\lambda_b^2)$

  $\sim \lambda_s^2\, \varepsilon^2 + \lambda_s\lambda_b\varepsilon$

- CPV effects at the level of $r/\varepsilon \sim 2\ 10^{-3} \sim 1/8°$ for "nominal" SU(3) breaking $\varepsilon \sim 30\%$

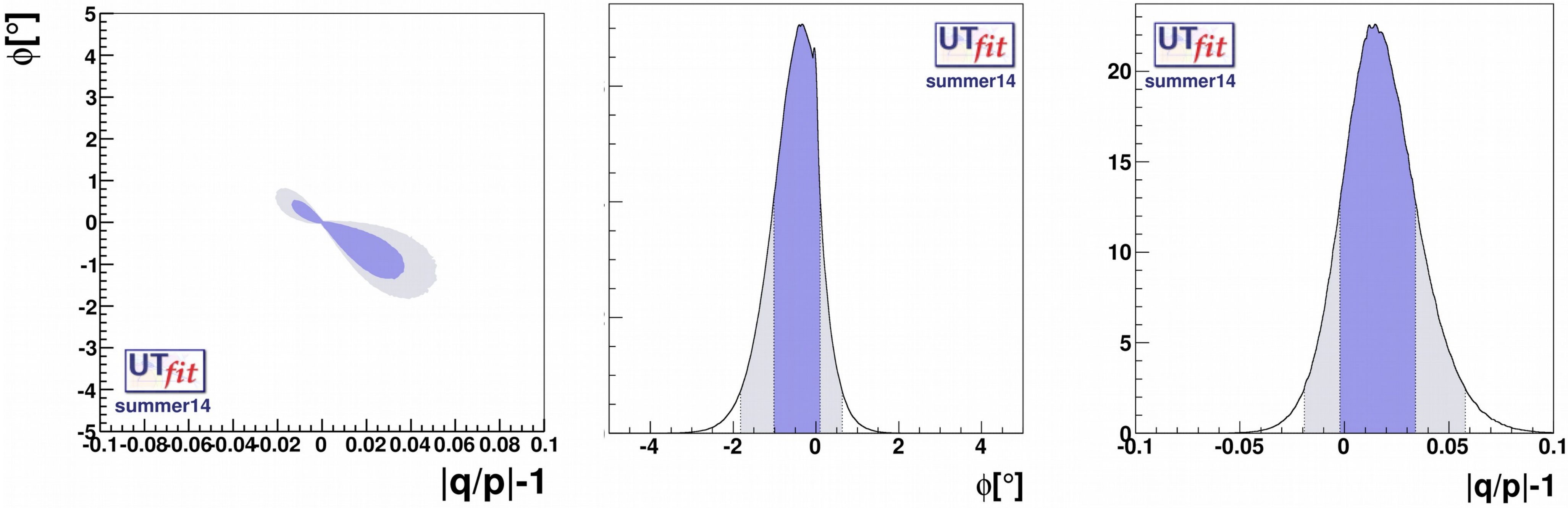
- Given present experimental errors, it is perfectly adequate to assume that SM contributions to both M_{12} and Γ_{12} are real
- all decay amplitudes relevant for the mixing analysis can also be taken real
- NP could generate a nonvanishing phase for M_{12}
- Fit all data with universal parameters x, y, $|q/p|$ and $\phi \sim \arctan((1-|q/p|)x/y)$.

CPV IN MIXING TODAY

- Summer14 UTfit average:

See next talk for updated HFAG averages

$x = (3.5 \pm 1.5)\,10^{-3}$, $y = (5.8 \pm 0.6)\,10^{-3}$,
$|q/p|-1 = (1.5 \pm 1.9)\,10^{-2}$,
$\phi = \arg(q/p) = (-0.44 \pm 0.59)^\circ$

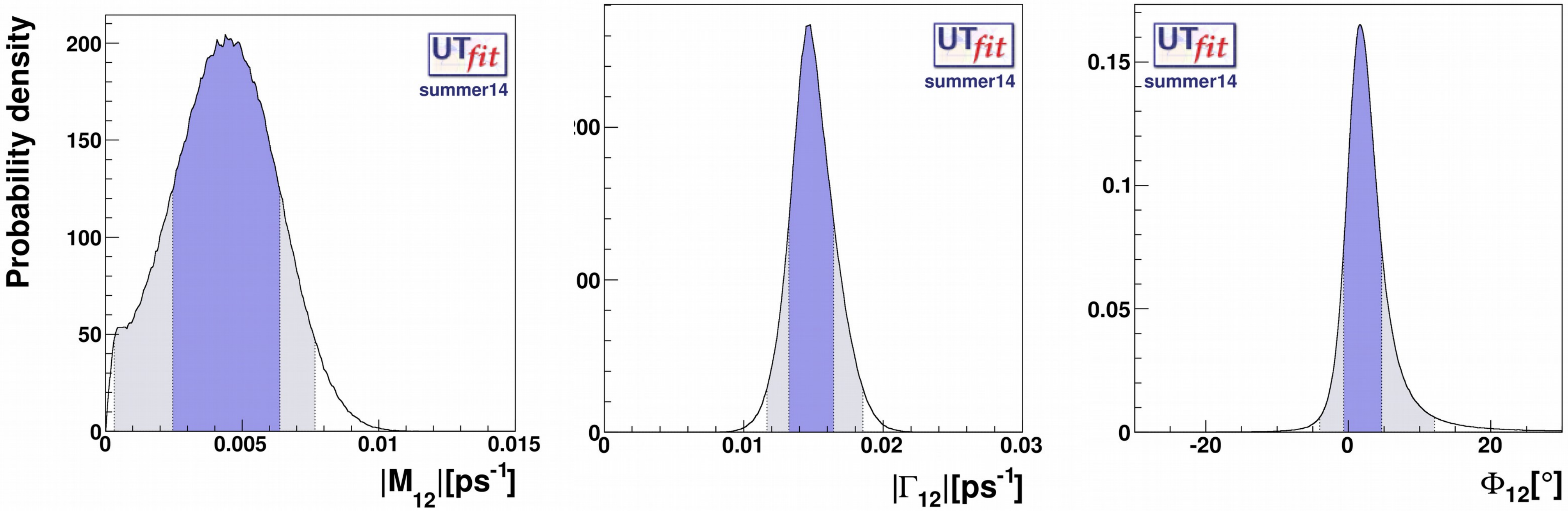


CPV IN MIXING TODAY II

- The corresponding results on fundamental parameters are

$|M_{12}| = (4 \pm 2)/\mathrm{fs}$, $|\Gamma_{12}| = (14 \pm 1)/\mathrm{fs}$

and $\Phi_{12} = (2 \pm 3)^\circ$



BEYOND THE "REAL SM"

- CPV contributions to $\phi_{\Gamma 12}$ are enhanced by $1/\varepsilon$, while this is not the case for $\delta\phi_f$
- can go beyond the "real SM" approximation by adding one universal phase $\phi_{\Gamma 12}$ and fitting for ϕ_{12} and $\phi_{\Gamma 12}$ or, equivalently, for ϕ_{M12} and $\phi_{\Gamma 12}$

See A. Kagan's talk for details

CHARM CPV @ LHCb UPGRADE

- Expected errors w. LHCb upgrade:
  - $\delta x=1.5\ 10^{-4}$, $\delta y=10^{-4}$, $\delta|q/p|=10^{-2}$, $\delta\phi=3°$ (from $K_s\pi\pi$); $\delta y_{CP}=\delta A_\Gamma=4\ 10^{-5}$ (from K^+K^-)
- Allows to experimentally determine $\phi_{\Gamma 12}$ with a reach on CPV @ the degree level:
  - $\delta\phi_{M12} = \pm 1°$ (17 mrad) and
    $\delta\phi_{\Gamma 12} = \pm 2°$ (34 mrad) @ 95% prob.
  - $\Lambda > 10^5$ TeV

CHARM CPV @ HI-LUMI

- XFX: "Extreme" flavour experiment (LHCb upgrade L x 100)

see e.g. talk by G. Punzi @
1st Future Hadron Collider Workshop

- Naïve extrapolation, scaling LHCb upgrade estimates:
  - $\delta x=1.5\ 10^{-5}$, $\delta y=10^{-5}$, $\delta|q/p|=10^{-3}$, $\delta\phi=.3°$ (from $K_s\pi\pi$); $\delta y_{CP}=\delta A_\Gamma=4\ 10^{-6}$ (from K^+K^-)
  - $\delta\phi_{M12} = \pm\ 0.1°$ (1.7 mrad) and $\delta\phi_{\Gamma12} = \pm\ 0.2°$ (3.4 mrad) @ 95% prob.
  - $\Lambda>3\ 10^5$ TeV, close to the bound from ε_K

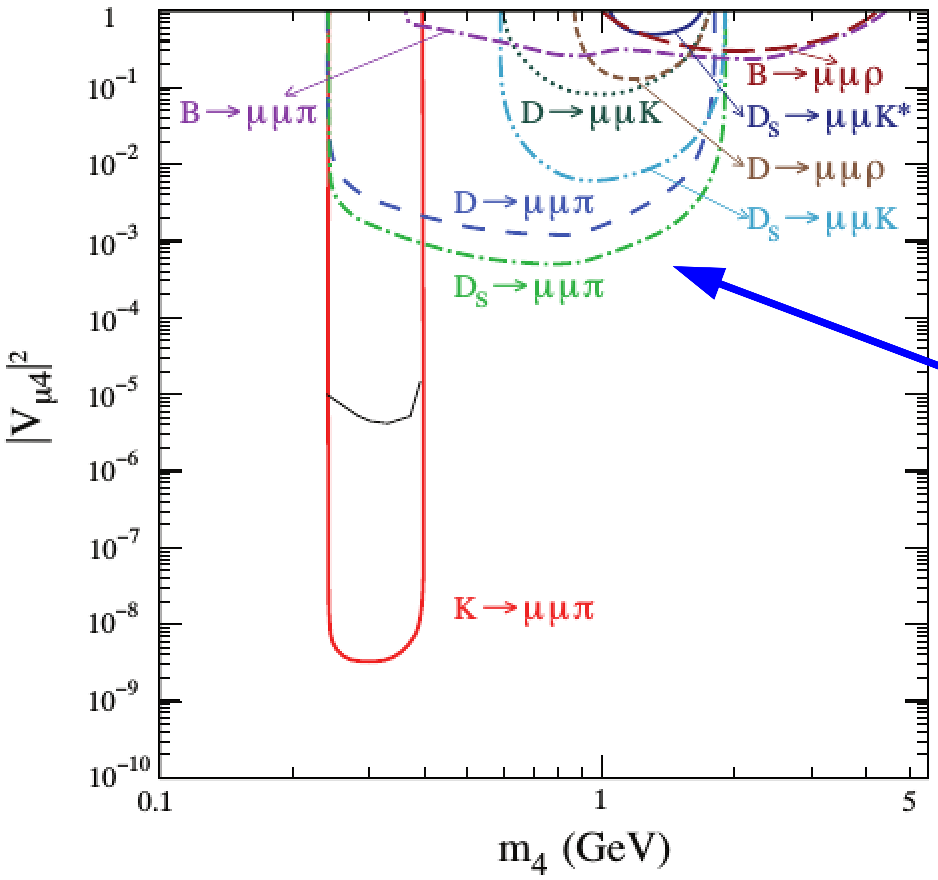
Lepton flavour violating decays

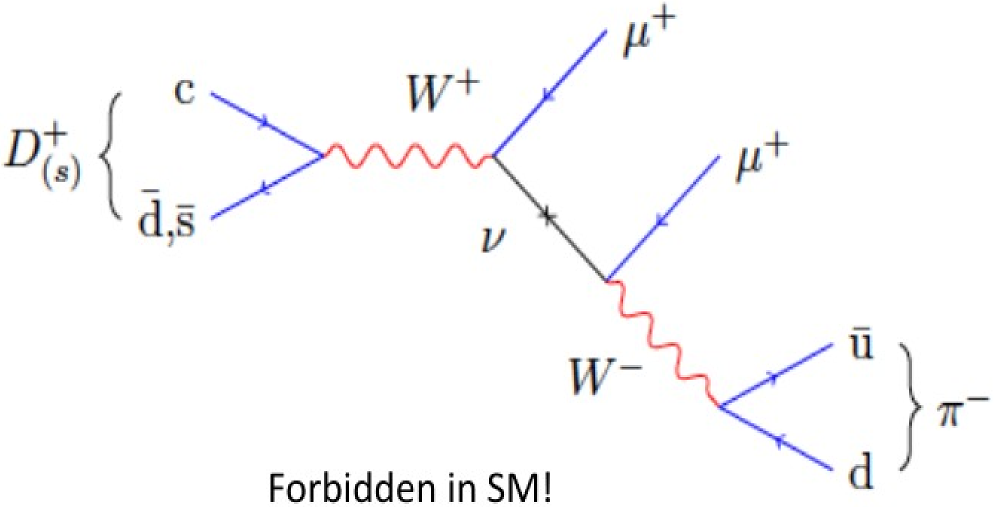
S. Fajfer

$$\mathcal{B}(D^+ \to \pi^- \mu^+ \mu^+) < 2.2\,(2.5) \times 10^{-8}$$
$$\mathcal{B}(D_s^+ \to \pi^- \mu^+ \mu^+) < 1.2\,(1.4) \times 10^{-7}$$

R. Aaij et al. (the LHCb collaboration), PLB 724 (2013) 203.

Search for Majorana ν's in LNV D decays





Forbidden in SM!

Improved by 2-3 orders of magnitude

Atre et al. '09

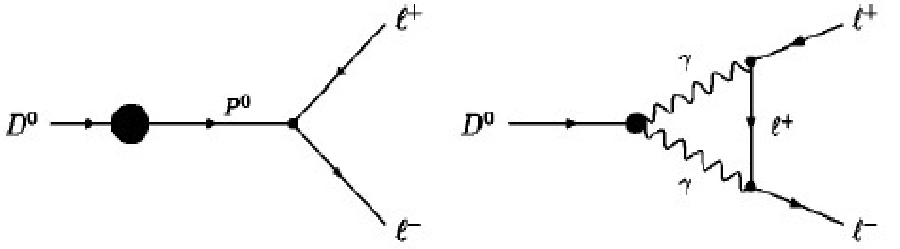
$\mathrm{D} \to \mu^+\mu^-$

max: $\mathrm{V_{ub}V_{cb}^*}|\mathrm{C_{10}^{NP}}| < 0.364$

R. Aaij et al. (the LHCb collaboration), PLB 725 (2013) 15.

$$BR(D \to \mu^+\mu^-) < 6.2(7.6) \times 10^{-9}$$

$$\mathrm{BR_{SM}^{SD}}\left(\mathrm{D^0} \to \mu^+\mu^-\right) \sim 6 \times 10^{-19}$$



LD dominant!

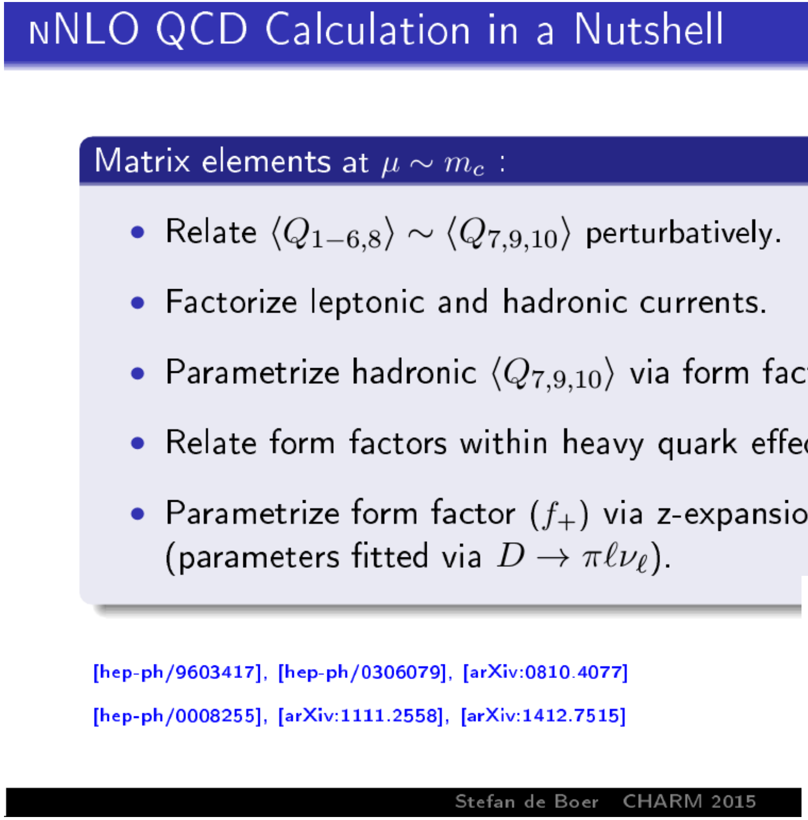
$$\mathrm{BR_{SM}^{LD}}(D^0 \to \mu^+\mu^-) = 2.7 \times 10^{-5} \times \mathrm{BR}(D^0 \to \gamma\gamma) \simeq 2.7 - 8 \times 10^{-13}$$

A. Paul et al, PRD 82 (2012) 094006,
G. Burdman et al., PRD 66 (2002) 014009,
E. Golowich, J. Hewett, S. Pakvasa, A. Petrov, Phys.Rev. D79 (2009) 114030

NP-sensitive, th. challenging

Decays with hadrons in the f.s.

- Evaluation of (nonlocal) matrix elements problematic:
  - Not heavy enough to apply QCDF
  - Extremely difficult on the lattice
- Aim for order-of-magnitude NP that could emerge on hadronic uncertainties or
- Use some symmetry argument to get rid of hadronic matrix elements



NNLO QCD Calculation in a Nutshell

Matrix elements at $\mu \sim m_c$:

- Relate $\langle Q_{1-6,8}\rangle \sim \langle Q_{7,9,10}\rangle$ perturbatively.
- Factorize leptonic and hadronic currents.
- Parametrize hadronic $\langle Q_{7,9,10}\rangle$ via form factors.
- Relate form factors within heavy quark effective theory.
- Parametrize form factor (f_+) via z-expansion (parameters fitted via $D \to \pi \ell \nu_\ell$).

[hep-ph/9603417], [hep-ph/0306079], [arXiv:0810.4077]
[hep-ph/0008255], [arXiv:1111.2558], [arXiv:1412.7515]

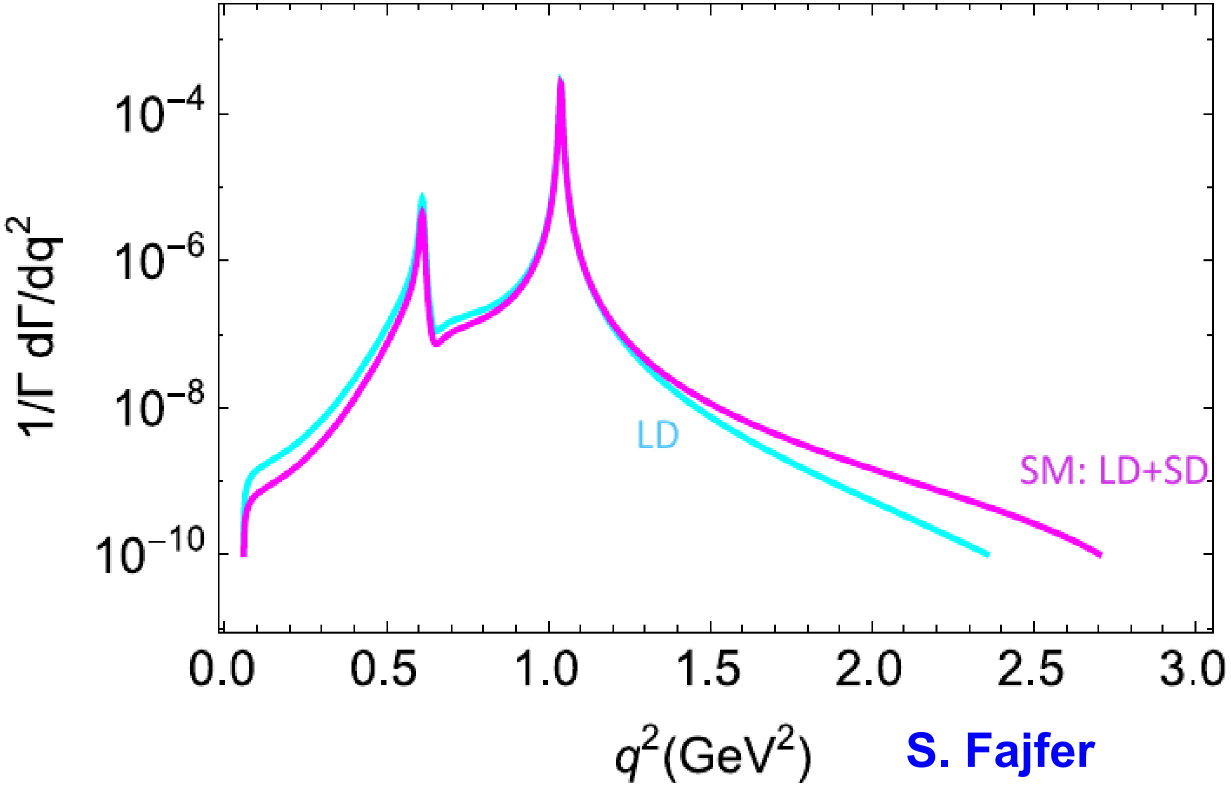
Stefan de Boer CHARM 2015

These operators induce nonperturbative LD contributions

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

Obtain a bound on NP from LHCb upper bound:

max: $\boxed{V_{ub}V_{cb}^*|C_9^{NP}| < 1.87}$



S. Fajfer

CPV IN SCS D DECAYS

- CPV in SCS D decays suppressed by Im $(V_{ub}V_{cb}/V_{us}V_{cs})$ P/T = 6.5 10^{-4} P/T
- Need an estimate of P/T to give a bound on SM CPV and search for NP, unless $A_{CP}^{exp} \gg 10^{-3}$
- or use symmetry arguments to get rid of hadronic matrix elements

TESTING FOR NP USING $\Delta I=3/2$

Y. Grossman, A. Kagan, JZ, 1204.3557

- the general idea:
  - in SM $\Delta I=3/2$ comes from tree operators (up to very small EWP)
    - it carries no weak phase
  - test if $\Delta I=3/2$ amplitude is CPV
    - if it is ⇒ found NP!

THE IMPLEMENTATION

- we want to isolate $\Delta I=3/2$ amplitudes
- for D^0 and D^+ decays this means identifying I=2 final state
  - so can use $D\to\pi\pi$, $\rho\pi,\rho\rho$ decays
  - but not $D\to KK$ decays
- for D_s^+ decays need to isolate I=3/2 final state
  - $D_s\to\pi K,\ldots$ decays
- need to be careful about isospin breaking
  - all sum rules valid to 2nd order in isospin breaking
  - corrections expected at $O(10^{-4})$
  - present experimental errors at $O(10^{-2})$ to $O(10^{-3})$

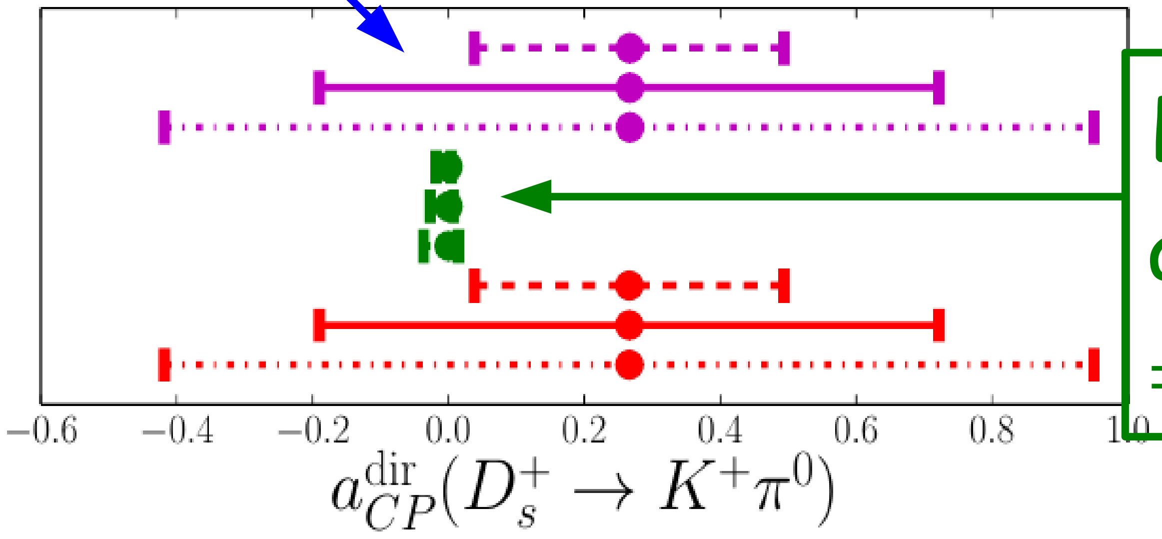
- Cannot isolate NP in $\Delta I=1/2$ with isospin
- Could SU(3) provide an estimate of P/T?
  - Exact SU(3) does not describe BR's
  - Beyond exact SU(3), all reduced matrix elements generated ⇒ no prediction (except for few sum rules valid to $O(\varepsilon^2)$)
- SU(3) might help in identifying a hierarchy of amplitudes, but more dynamical info needed to predict CPV

See also A. Paul

Implications of sum rule II, future scenario [preliminary]

But: Assuming better measurements of the branching ratios by a factor of $\sqrt{50}$ changes the picture:

No th. assumption ⇒ no prediction



Bold th. assumption ⇒ prediction

Green: prediction from $a_{CP}^{\mathrm{dir}}(D^+ \to \overline{K}^0K^+)$, $a_{CP}^{\mathrm{dir}}(D_s^+ \to K^0\pi^+)$, and global fit to branching ratios.

Magenta: same as blue, but without $1/N_c$ constraints.

Red: measurement. Dotted: 1σ, solid: 2σ, dot-dashed: 3σ.

Not shown: error from $\mathrm{SU(3)}_F$ breaking in $P_s + P_d$.

Notice

CONCLUSIONS

- Constantly improving experimental results are challenging our theoretical understanding of charm physics
- Interesting open problems in spectroscopy and production in vacuum and in matter could lead us to a much deeper understanding of QCD dynamics

CONCLUSIONS II

- The ever-increasing samples of D decays at LHCb, BESIII, BelleII, LHCb upgrade and possibly τ/c and XFX might provide us with evidence for NP
- A combined attack to seemingly impossible problems such as nonleptonic D decays using all possible tools will eventually allow us to fully exploit their potential NP sensitivity