# Uncertainties of lattice QCD calculations of heavy–light pseudoscalar meson decay constants

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# Outline

1. Physics motivations
2. Lattice calculations: sources of systematic errors
3. $D_{(s)}$ Decays
4. $B_{(s)}$ decays

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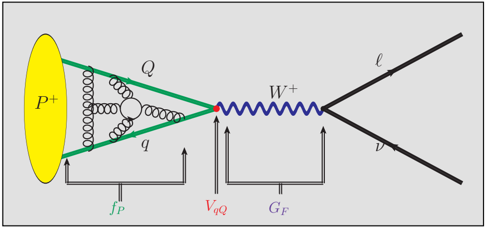
# Leptonic decays in the Standard Model

$$\Gamma(P^+ \to \ell^+ \nu_\ell) = {f_P}^2 \times \left|V_{qQ}\right|^2 \frac{{G_F}^2 m_{P^+}^3}{8\pi} \left(\frac{m_\ell}{m_{P^+}}\right)^2 \left(1 - \frac{m_\ell^2}{m_{P^+}^2}\right),$$




1. Hadronic decay constant
2. CKM matrix element
3. 4–fermion coupling

→ A comprehensive laboratory for both standard and non standard physics:

# Leptonic decays beyond the standard model

IF WE KNOW THE VALUE OF $f_P$

1. Check the CKM matrix unitarity
2. Constrain extra contributions beyond $G_F$

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$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \quad \pm 1\%$$

$\Rightarrow$ Relevant constraint on BSM models. E.G. : in $SO(10)$:

$$M_{Z'} \overset{\text{CKM}}{>} 1.4\ \text{TeV} \quad \text{VERSUS} \quad M_{Z'} \overset{\text{direct}}{>} 0.72\ \text{TeV}$$

[PDG]

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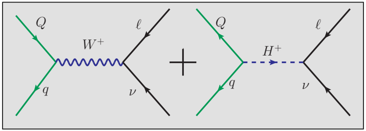
[PDG]

2. Constrain extra contributions beyond $G_F$

$G_F = \frac{g}{4\sqrt{2}M_W^2} = 1.66371(6) \times 10^{-5}\ \text{GeV}^{-2}$ from $\mu$–lifetime

[$\mu$Lan,2007]

What if:  ? in e.g. SUSY models

# Leptonic decays are clean but . . .

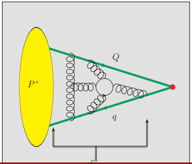
$$\Gamma(P^+ \to \ell^+ \nu_\ell) = f_P{}^2 \times \left|V_{qQ}\right|^2 \frac{G_F{}^2 m_{P^+}^3}{8\pi} \left(\frac{m_\ell}{m_{P^+}}\right)^2 \left(1 - \frac{m_\ell^2}{m_{P^+}^2}\right),$$

1. Extremely rare due to helicity suppression $\propto \left(\frac{m_\ell}{m_{P^+}}\right)^2$.

$$\Downarrow$$

SUPERB FACTORY

2. Theoretically appealing: we want the less non–perturbative QCD in the game
   - No hadron in the final state
   - $f_P$ encodes the low energy QCD: only a constant $\neq$ semi–leptonic




Non-perturbative $\Rightarrow$ Models/Sum Rules/LATTICE

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# Lattice calculations

The main source of uncertainties is due to unsolved non–perturbative QCD effects $\Leftrightarrow$ error on $f_P$

Lattice QCD is the only method to compute hadronic quantities

1. from FIRST PRINCIPLES:
   - We want no more constant that in QCD (masses / coupling)
   - We want no extra assumptions ( e.g., sum rules rely on the *global quark–hadron duality* )
2. to an arbitrary accuracy: Monte–Carlo techniques, errors fall as $1/\sqrt{N_{\text{configs}}}$

However, many sources of systematic uncertainties need to be assessed carefully

# List of systematic uncertainties

1. Effects of discretization
2. Finite size effects
3. Chiral extrapolations
4. Heavy quark treatment
5. Quenching
6. Existence of the continuum limit

# List of systematic uncertainties

1. Effects of discretization
   Discretized space with lattice spacing $a$:

$$\Phi_{\mathrm{Latt}}(a) = \Phi_{\mathrm{Cont}} + (am)\Phi_1 + (am)^2\Phi_2 + \ldots$$

   $\mathcal{O}(a)$–improved in general $\Rightarrow \Phi_1 = 0$ for all physical quantities. But what about $\Phi_{n>2}$?

$$\Downarrow$$

**BEWARE OF HEAVY QUARKS**

Typically, $a \leq 2.5\ \mathrm{GeV}^{-1}$. With the $b$ quark, $(am_b) > 1$ ! Heavy quark treatment: see 4-

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2. Finite size effects
   Finite box of size $L \simeq 2$ fm:

$$\Phi_{\mathrm{Latt}}(L) = \Phi_{\mathrm{Cont}} + C \times e^{-M_\pi L}$$

BEWARE OF LIGHT QUARKS

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3. Chiral extrapolations

   On the lattice : $m_q \gtrsim \frac{m_s^{\text{phys}}}{10}$ whereas $m_{u,d}^{\text{phys}} \approx \frac{m_s^{\text{phys}}}{25}$

   $\Rightarrow$ An extrapolation is needed toward the physical pion mass

   - Extrapolate the measure behavior (linear, quadratic)
   - Use chiral perturbation theory $\Rightarrow$ (potentially large) logarithms effects

   $\Downarrow$

   BEWARE OF THE LOGS

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3. Chiral extrapolations ⇒ BEWARE OF THE LOGS
4. Heavy quark treatment

Heavy quark integrated out and its effects included in $1/m_b$ expansion on the lattice ⇒ problem with scales $m_q < \Lambda_{\mathrm{QCD}} < 1/a < m_b$.

**Beware!**

How to match non-perturbatively the effective theory on the lattice to the continuum QCD is still an open question

5. Quenching
6. Existence of the continuum limit

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5. Quenching
   - Calculation used to be carried out in the quenched approximation $N_f = 0$
     $\Rightarrow$ Systematic uncertainty incalculable a priori.
     Now, $N_f = 2$, $N_f = 2 + 1$, $N_f = 2 + 1 + 1$.
   - Beware of partial quenching: sea quarks $\neq$ valence quarks
6. Existence of the continuum limit

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6. Existence of the continuum limit

Beware of staggered quarks ! Very cheap to simulate ⇔ smallest statistical error bars

BUT

they induce the non-localities $\Longrightarrow$

a/ how to know if the continuum theory is indeed QCD?;
b/ how to quantify those effects and include them in the error-budget?

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5. Quenching ⇒ $N_f = ?$, BEWARE PARTIAL QUENCHING
6. Existence of the continuum limit ⇒ NON-LOCALITY OF STAGGERED QUARKS?

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# Lattice calculations of $f_{D_{(s)}}$

⇒ Newest unquenched results

1. Staggered+Fermilab strategy (FNAL 2008 ) - PRELIMINARY

$$f_D = 207(11)\ \mathrm{MeV}\ , \quad f_{D_s} = 249(11)\ \mathrm{MeV}\ , \quad f_{D_s}/f_D = 1.20(3)$$

2. Staggered+HiSQ (HPQCD 2008 )

$$f_D = 208(4)\ \mathrm{MeV}\ , \quad f_{D_s} = 241(3)\ \mathrm{MeV}\ , \quad f_{D_s}/f_D = 1.16(1)$$

3. Twisted mass QCD (ETMC 2008) - PRELIMINARY

$$f_D = 197(7)(12)\ \mathrm{MeV}\ , \quad f_{D_s} = 244(4)(11)\ \mathrm{MeV}\ , \quad f_{D_s}/f_D = 1.24(4)$$

4. Wilson improved (Orsay 2008 - PRELIMINARY

$$f_D = 199(23)\ \mathrm{MeV}$$

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- FSE and chiral extrapolation: $m_q \geq \frac{m_s}{10}$ and large volumes : OK
- Heavy quark: Effective treatment à la *Fermilab*: OK
- Quenching: fully unquenched, $N_f = 2 + 1$ : OK
- Renormalization: perturbative
- Continuum limit: staggered quarks

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- FSE and chiral extrapolation: $m_q \geq \frac{m_s}{10}$ and large volumes : OK
- Heavy quark: fully propagating: OK
- Quenching: partially quenched, $N_f = 2 + 1$, valence quarks $\neq$ sea quarks
- Renormalization: non perturbative : OK
- Continuum limit: staggered quarks

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- FSE and chiral extrapolation: $m_q \geq \frac{m_s}{5}$ and large volumes: OK
- Heavy quark: fully propagating: OK
- Quenching: $N_f = 2$, OK?
- Renormalization: non perturbative : OK BUT non perturbative effects of the twisting need to carefully studied
- Continuum limit: OK

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$\Rightarrow$ Newest unquenched results

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$$f_D = 199(23)\ \mathrm{MeV}$$

- FSE and chiral extrapolation: $m_q \geq \frac{m_s}{3}$ and large volumes: OK
- Heavy quark: fully propagating: OK
- Quenching: $N_f = 2$, OK?
- Renormalization: non perturbative : OK
- Continuum limit: OK

$\Downarrow$

**Cleanest method**

But errors much large wrt other regularizations

# Issues on chiral extrapolations

## Chiral logs and $D^*$ decay width

- $$f_P\sqrt{m_P}(m_\pi) = \Phi_0\left[1 - \frac{1+3g^2}{(4\pi f_0)^2} m_\pi^2 \log m_\pi^2 + c_\phi m_\pi^2\right]$$
- $$\Gamma(D^{*+} \to D^0\pi^+) = \frac{g^2}{6\pi f_\pi^2}|\vec{q}|^3$$

Wilson improved (Orsay 2008)- PRELIMINARY

$$g_c^{N_f=2} = 0.60(3)$$

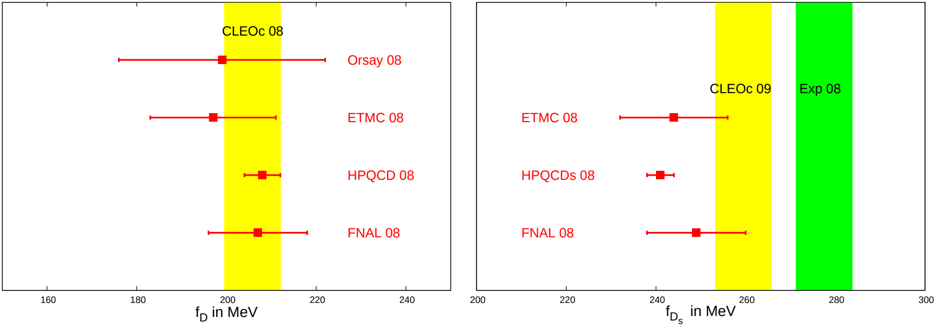
CAN $\Gamma(D^{*+} \to D^0\pi^+)$ BE MEASURED EXPERIMENTALLY ?

# Agreement with experiment

## How to compare with experiment?

ASSUMING

- $G_f$ FROM $\mu$ LIFETIME
- $V_{cd} = V_{us}$ AND $V_{cs} = V_{ud}$ FROM CKM UNITARITY



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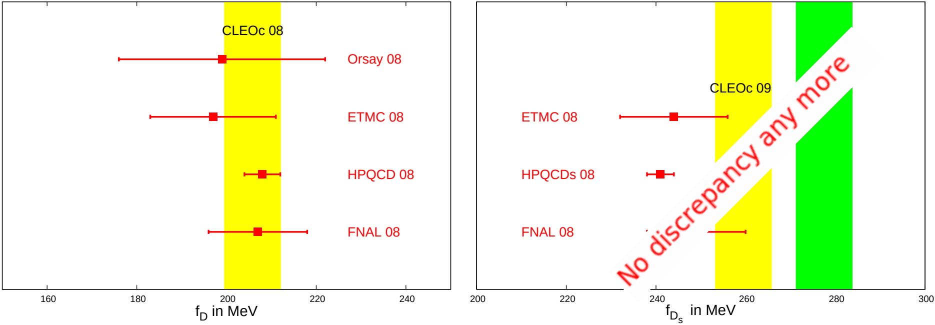

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$$f_B = 195(11)\ \mathrm{MeV}\ , \quad f_{B_s} = 243(11)\ \mathrm{MeV}\ , \quad f_{B_s}/f_B = 1.25(4)$$

2. Staggered+NRQCD (HPQCD 2005 )

$$f_B = 216(22)\ \mathrm{MeV}\ , \quad f_{B_s} = 260(26)\ \mathrm{MeV}\ , \quad f_{B_s}/f_B = 1.20(3)$$

3. Quenched QCD - (Alpha 2008) - CLEAN

$$f_{B_s}^{\mathrm{N_f}=0} = 193(7)\ \mathrm{MeV}\ ,$$

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- Quenching: $N_f = 2 + 1$, OK
- Renormalization: Perturbative
- Continuum limit: Staggered quarks

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- Renormalization: perturbative
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3. Quenched QCD - (Alpha 2008) - CLEAN

$$f_{B_s}^{\mathrm{N_f}=0} = 193(7)\ \mathrm{MeV}\ ,$$

- Quenching: $N_f = 0$
- Renormalization: non perturbative:
  1. First step: $f_P$ at $m_Q = \infty$ - non perturbative renormalization of HQET
  2. Second step: $f_P$ around $m_Q \approx m_c$ - non perturbative renormalization of QCD
  3. Interpolation in $1/m_Q$ to $B_s$-meson

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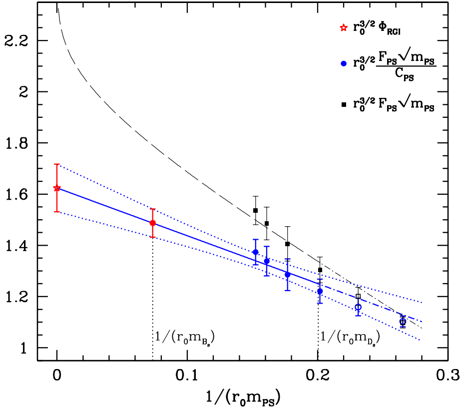


[arXiv:0710.2201]

a/ $\Phi = f_P\sqrt{m_P}$

b/ $r_o = 0.5$ fm

c/ $C_{\mathrm{PS}}$ is a matching coefficient

# Summary and outlook

## Precision tests in the leptonic decays require

- Flavor factory at high accuracy
- Lattice calculation at a similar accuracy

## On the lattice side, beware of

- Correctness of the action
- Renormalization
- Discretization errors
- Correct chiral extrapolations

## On the experimental side

- Need of high statistic events : helicity suppression
- Beware of soft photons !! $\Leftarrow$ Are the soft photons handled properly?