QCD su reticolo
e Fisica del Sapore

Francesco Sanfilippo, INFN, Roma Tre

Le Attività della Sezione INFN di Roma Tre
5 Luglio 2019

The people

Staff

- Marco Ciuchini
- Vittorio Lubicz
- Francesco Sanfilippo
- Silvano Simula
- Cecilia Tarantino

Postdocs

- Ryotaro Watanabe
- Marco Giovanni Pruna

Ph.D students

- Davide Giusti
- Simone Romiti

And **more** in the recent past (and in the future!)

An overlook

Our activities

1. Indirect search of physics beyond the Standard Model
2. Theoretical investigation of flavor physics sector
3. Careful verification of phenomenological anomalies

Our tools

- Global fits of experimental measurement vs theoretical predictions
- Massive simulations of Quantum Chromodynamics on the lattice

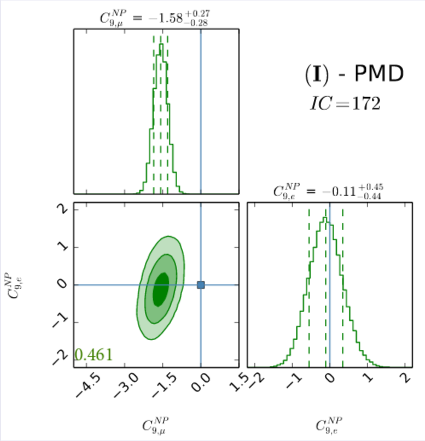
Probing New Physics via global fits

3σ violation of Lepton universality in K decays

$$R_{K^*} \equiv \frac{Br\left(B \to K^* \mu^+ \mu^-\right)}{Br\left(B \to K^* e^+ e^-\right)} = \begin{cases} 0.9 \div 1 & SM \\ 0.7(1) & EXP \end{cases}$$

"On Flavourful Easter eggs for New Phys hunger & Lepton Flavour Universality violation"

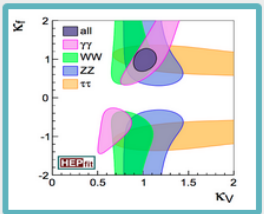
EPJ77 (2017), **M. Ciuchini, A. Coutinho,** M. Fedele, E. Franco, A. Paul, L. Silvestrini, M. Valli

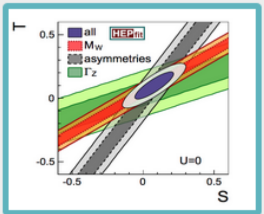


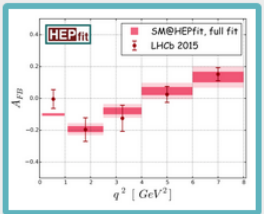
- Extend SM including lepton flavour universality violating operators
- Fit together K and K^*
- Check whether the extension can explain the violation and determine the coefficient of the operators

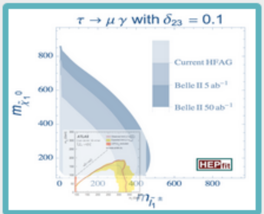
...with the help of the hadronic matrix elements...

HEPfit: a Code for the Combination of Indirect and Direct Constraints on High Energy Physics Models.









Higgs Physics

HEPfit can be used to study Higgs couplings and analyze data on signal strengths.

Precision Electroweak

Electroweak precision observables are included in HEPfit

Flavour Physics

The Flavour Physics menu in HEPfit includes both quark and lepton flavour dynamics.

BSM Physics

Dynamics beyond the Standard Model can be studied by adding models in HEPfit.

http://hepfit.roma1.infn.it/index.html

HEPfit collaboration


Jorge de Blas


Debtosh Chowdhury


Marco Ciuchini


Antonio Coutinho


Otto Eberhardt


Marco Fedele


Enrico Franco


Giovanni Grilli di Cortona


Satoshi Mishima


Ayan Paul


Maurizio Pierini


Laura Reina

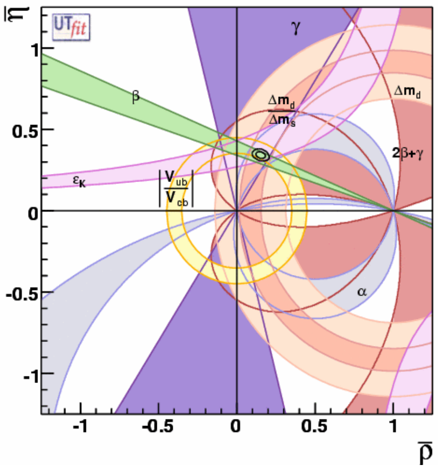

Luca Silvestrini


Mauro Valli


Norimi Yokozaki

collaboration

Since 2000...



More than 15 people from 5 Countries

C. Alpigiani, A. Bevan, M. Bona, **M. Ciuchini**, D. Derkach, E. Franco, **V. Lubicz**, G. Martinelli, F. Parodi, M. Pierini, C. Schiavi, L. Silvestrini, A. Stocchi, V. Sordini, **C. Tarantino** and V. Vagnoni

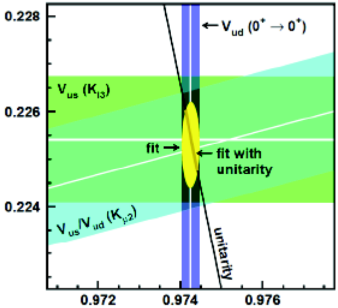
Unitarity Triangle analysis in the SM

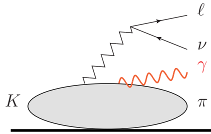
- Best determination of CKM parameters
- Test the consistency of the SM ("direct" vs "indirect" determinations)
- Provide predictions (from data..) for SM observables

Involves several non-perturbative hadronic matrix element

...To be computed with **high accuracy** (1% precision or less)

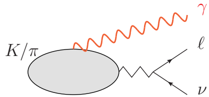
Example: CKM matrix elements from semileptonic and leptonic K and π decays





Semileptonic

$$\underbrace{\Gamma_{K\to\pi l\bar{\nu}(\gamma)}}_{experiments} \propto |V_{us}|^2 \underbrace{\left|f_+^{K\pi}(0)\right|^2}_{QCD}$$



Leptonic

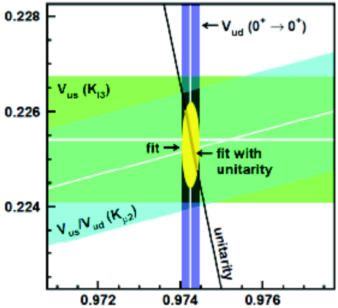
$$\underbrace{\frac{\Gamma_{K\to\ell\bar{\nu}(\gamma)}}{\Gamma_{\pi\to\ell\bar{\nu}(\gamma)}}}_{experiments} \propto \frac{|V_{us}|^2}{|V_{ud}|^2} \underbrace{\left(\frac{f_K}{f_\pi}\right)^2}_{QCD}$$

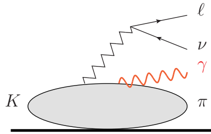
Hadronic matrix elements, lattice results

$$\begin{aligned} f_+^{K\pi}(0) &= 0.956\,(8) \\ f_K/f_\pi &= 1.193\,(5) \end{aligned}$$

in the **isospin symmetric** limit.

Example: CKM matrix elements from semileptonic and leptonic K and π decays





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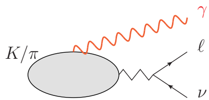

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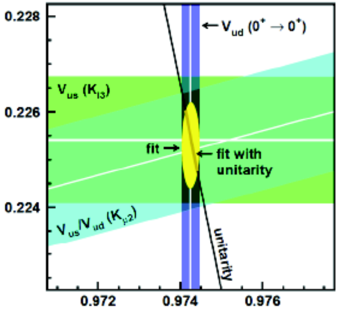
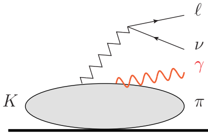
→ At current precision (0.5–1%), IB corrections **not negligible** ←

Example: CKM matrix elements from semileptonic and leptonic K and π decays





Semileptonic

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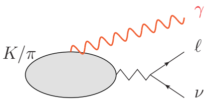

Leptonic

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Hadronic matrix elements, lattice results

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in the **isospin symmetric** limit.

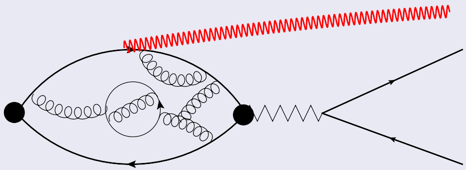
$\rightarrow$ At current precision (0.5–1%), IB corrections **not negligible** $\leftarrow$

Indeed ChPT estimates of these effects are:

$\left(f_+^{K^+\pi^0}/f_+^{K^-\pi^+}-1\right)^{QCD}=2.9(4)\%$ A. Kastner, H. Neufeld (EPJ C57, 2008)	$\left(\frac{f_{K^+}/f_{\pi^+}}{f_K/f_\pi}-1\right)^{QCD}=-0.22(6)\%$ V. Cirigliano, H. Neufeld (Phys.Lett.B700, 2011)

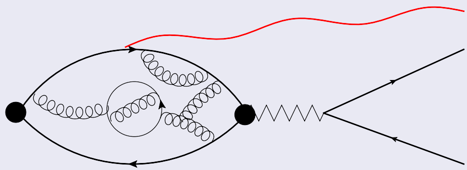
Dealing with photons

<u>Hard photons</u> - $E \sim$ many GeV



Perturbation theory

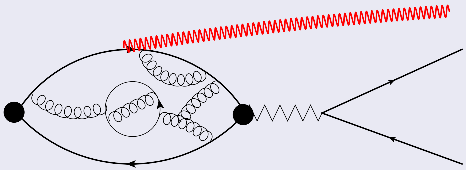
<u>Ultrasoft photons</u> - $E \sim$ few MeV



Point-like hadrons

Dealing with photons

Hard photons - $E \sim$ many GeV



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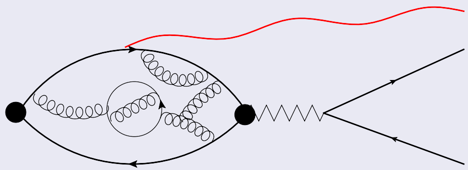
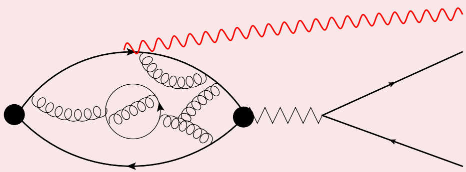
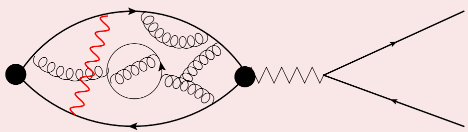


Point-like hadrons

What to do with soft photons?





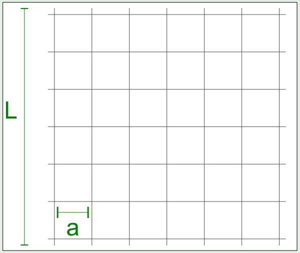
...Here we come to the rescue...

Lattice QCD

Simulate Quantum Chromodynamics on a Lattice of size L and spacing a

- Take into account all non-perturbative effects
- Start from the first principle of the theory
- All systematics can be taken into account and reduced arbitrarily

Lattice QCD is though...



- **Simulation cost:** $[\#points]^{k>1} = \left[(L/a)^4\right]^k$
  (scales: $a \ll 1/M_H$, $L \gg 1/M_\pi$)
- **Early solution:** $\#points = 4^4$
- **Nowadays:** $\#points = 48^3 \times 96 \div 64^3 \times 128$
  - D physics: $M_D/M_\pi \sim 15$, $M_{J/\psi}/M_\pi \sim 22$
  - B physics: $M_B/M_\pi \sim 40$, $M_\Upsilon/M_\pi \sim 70$

Bilions of degrees of freedom to simulate!

Computational resources

Marconi Supercomputer at Cineca

Our Equipment

- 50M core hours per year allocated through INFN agreement ($\sim$**6k cores per year**)
- 50M core hours more through European projects (PRACE) and national calls (ISCRA)
- Custom simulation codes (NISSA - developed locally since 2009) able to **scale efficiently** up to $\mathcal{O}(1000)$ cores

All of this requires **LARGE** collaborations...

RM123 collaboration (since 2011)

3) Roma Tre

D.Giusti,
V.Lubicz,
S.Romiti,
F.S,
S.Simula,
C.Tarantino

1) La Sapienza

M.Di Carlo,
L.Maio,
G.Martinelli

2) Tor Vergata

G.deDivitiis,
P.Dimopoulos,
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Extended Twisted Mass Collaboration

Our broader lattice collaboration

- ∼30 among staff, postdoc and students across 8 countries
- Large simulations at the physical Pion mass
- Even more computational resources

RM123 collaboration

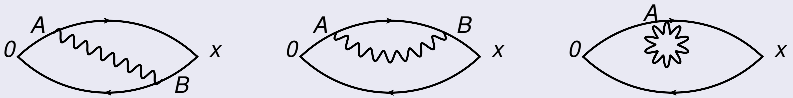
One nicer than the other one

Publications

- "*Isospin breaking effects due to the up-down mass difference in Lattice QCD*", [JHEP 1204 (2012)]
- "*Leading isospin breaking effects on the lattice*", [PRD87 (2013)]
- *"QED Corrections to Hadronic Processes in Lattice QCD"*, [PRD91 (2015)]
- *"Finite-Volume QED Corrections to Decay Amplitudes in Lattice QCD"*, [PRD95 (2017)]
- *"Leading isospin-breaking corrections to π, K and D meson masses with TM fermions"*, [PRD95 (2017)]
- *"Strange and charm HVP contributions to $(g_\mu - 2)$ including QED corrections"*, [JHEP 1710 (2017]
- *"First lattice calculation of the QED corrections to leptonic decay rates"*, [PRL120 (2018)]
- *"EM and strong isospin-breaking corrections to the $g_\mu - 2$ from Lattice QCD+QED"*, [PRD99 (2019)]

Diagrams

Fermionically connected - easy part (so to say)



(gluons not drawn, connecting fermion lines in all possible ways)

Diagrams

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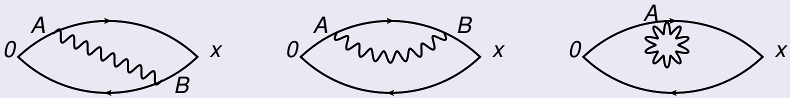
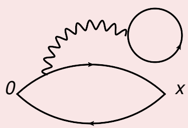
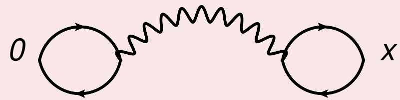


(gluons not drawn, connecting fermion lines in all possible ways)

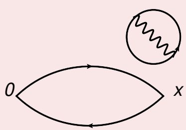
Disconnected - various degree of nastiness - work is in progress to include



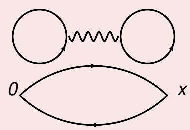
"monocle"



"handcuffs"

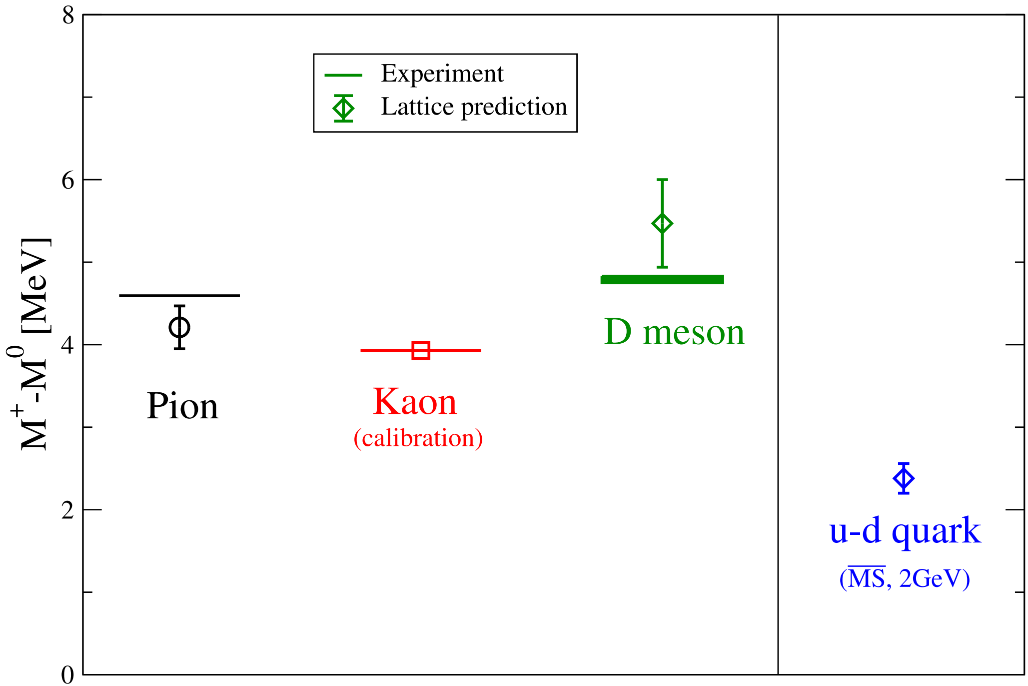


"blinking"

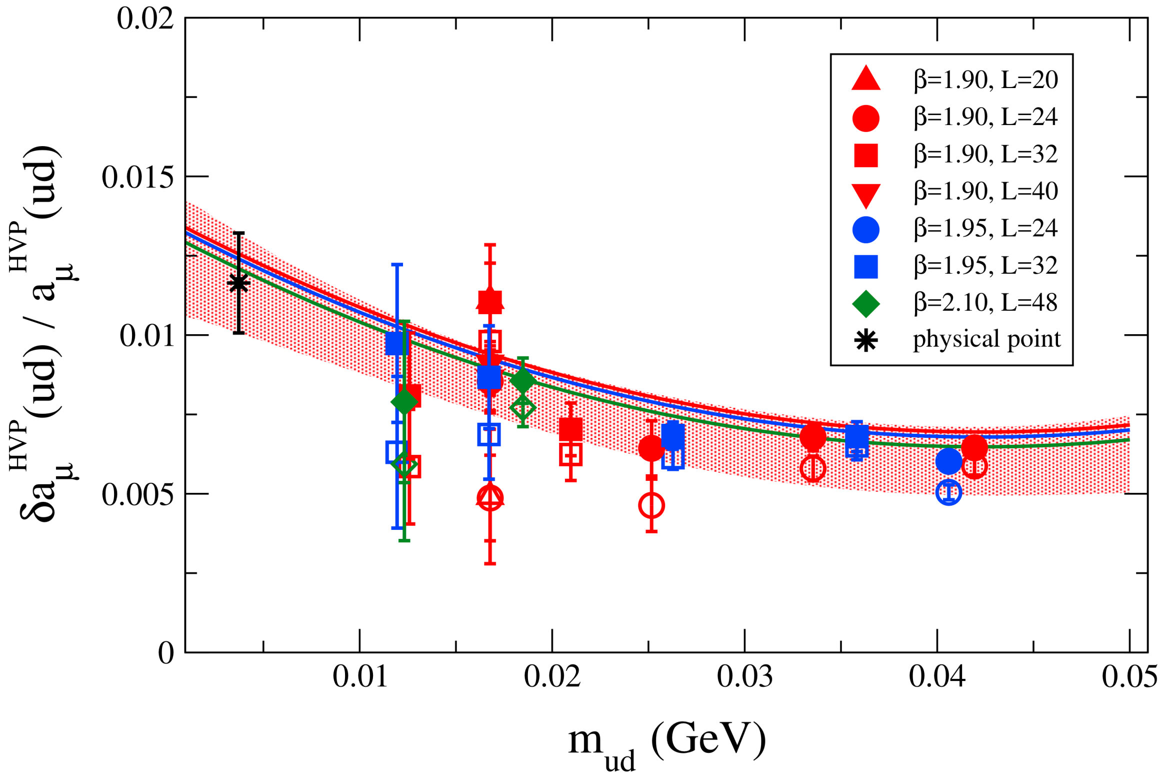


"laughing"

Some results, meson mass (perturbative expansion)



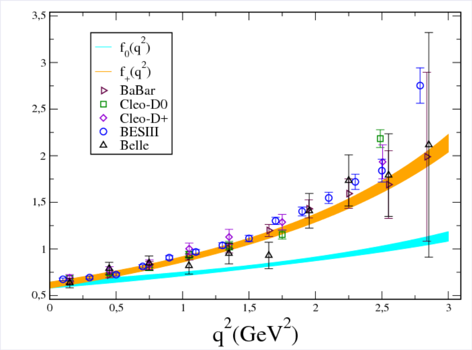
RM123 coll., "*Leading isospin-breaking corrections to pion, K and D mesons*", PRD95 (2017)



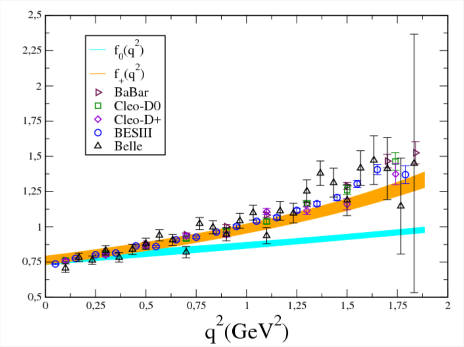
β=1.90, L=20
β=1.90, L=24
β=1.90, L=32
β=1.90, L=40
β=1.95, L=24
β=1.95, L=32
β=2.10, L=48
physical point
δa_μ^HVP(ud) / a_μ^HVP(ud)
m_ud (GeV)
0.02
0.015
0.01
0.005
0
0.01
0.02
0.03
0.04
0.05

Semileptonic form factors for $D \to K/\pi\ell\nu$ [PRD96 (2017) - V.Lubicz et al]

$D \to \pi\ell\nu$



$D \to K\ell\nu$



Determination of V_{cd} and V_{cs} on a bin-by-bin analysis of $\Gamma_{D\to K\pi\ell\nu}\left(q^2\right)$

A long lasting tradition

"The $K \to \pi$ vector form-factor at zero momentum transfer on the lattice" - Nucl.Phys. B705 (2005)
*D. Becirevic, G. Isidori, **V. Lubicz**, G. Martinelli, **F. Mescia**, **S. Simula**, **C. Tarantino**, G. Villadoro*

A promising future... (?!?)

$\to$ First steps to compute the form factors for $B \to K^{(*)}\ell\ell$ needed for $R\left(K^{(*)}\right)$

THANK YOU!