Centro Fermi
Museo Storico della Fisica e
Centro Studi e Ricerche Enrico Fermi

Super-calculus and physics of strong interactions

Grant Holder: **Petros Dimopoulos**

[2/2016 - 2/2018]

Centro Fermi & Dipartimento di Fisica,
Università di Roma "Tor Vergata"

Scientific Supervisor: **Prof. Giancarlo Rossi**

FLAG Flavour Lattice Averaging Group

UNIVERSITA' DEGLI STUDI DI ROMA Tor Vergata

European Twisted Mass Collaboration

Centro Fermi, Rome, March 9, 2018

Description of the Project

➡ Exploration of the **SM** precision limits in Flavour Physics & Search of footprints of **BSM** physics.

Study of the hadronic (QCD) contribution to weak interaction processes via **LQCD** methods in synergy with the current huge investment in experimental resources.

➡ Probe **new strong interaction** effects responsible for a mechanism of **dynamical generation of fermion masses** (unrelated to the Higgs mechanism).

Study of fundamental **non-perturbative** effects in both projects requires numerical Monte Carlo simulations on **supercomputing platforms**

Simulations on large architectures
+
optimised parallelisation

- **BG/Q** **Juqueen** (Jülich) and **Fermi**-Cineca (Bologna)
- **Intel Xeon** of **Marconi**-Cineca (platforms A1, A2, A3)
- **Intel Xeon Haswell** **SuperMUC**-Leibniz Supercomputing Center (Munchen)
- **BG/Q** **Turing** (IDRIS - CNRS)
- ***Algorithms***: Hybrid Monte Carlo + many tricks for acceleration

[Prace Early and 4th, 10th , 13th regular calls (2011, 2013, 2015, 2016) & Gauss Center for Supercomputing (GCS) (2014, 2016)]

Synthesis of results & publications in 2016-2018

LQCD simulations reproducing physical pion mass physics

Employing two and four dynamical flavours

Phys.Rev. D97 (2018) no.1, 014508, Phys.Rev. D95 (2017) no.11, 114514, Phys.Rev. D96 (2017) no.5, 054516, Phys.Rev. D96 (2017) no.5, 054516, Phys.Rev. D92 (2015) no.11, 114513, EPJ Web Conf (2017)

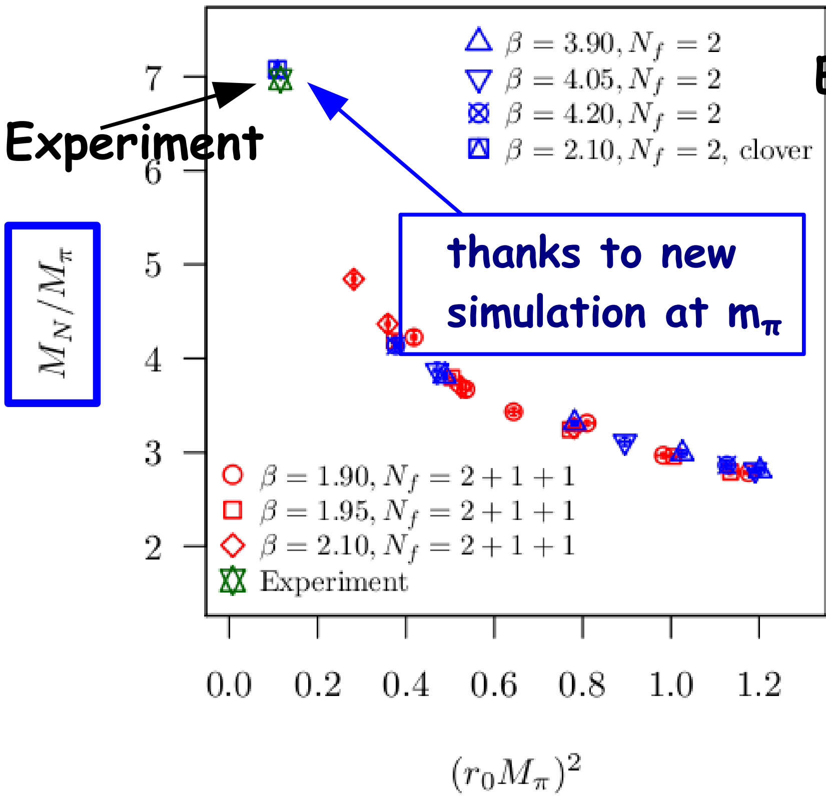
- **The goal:**
  Elimination of systematic uncertainties due to chiral extrapolation.
  Employing LQCD data to check, not being guided by, ChPT arguments.

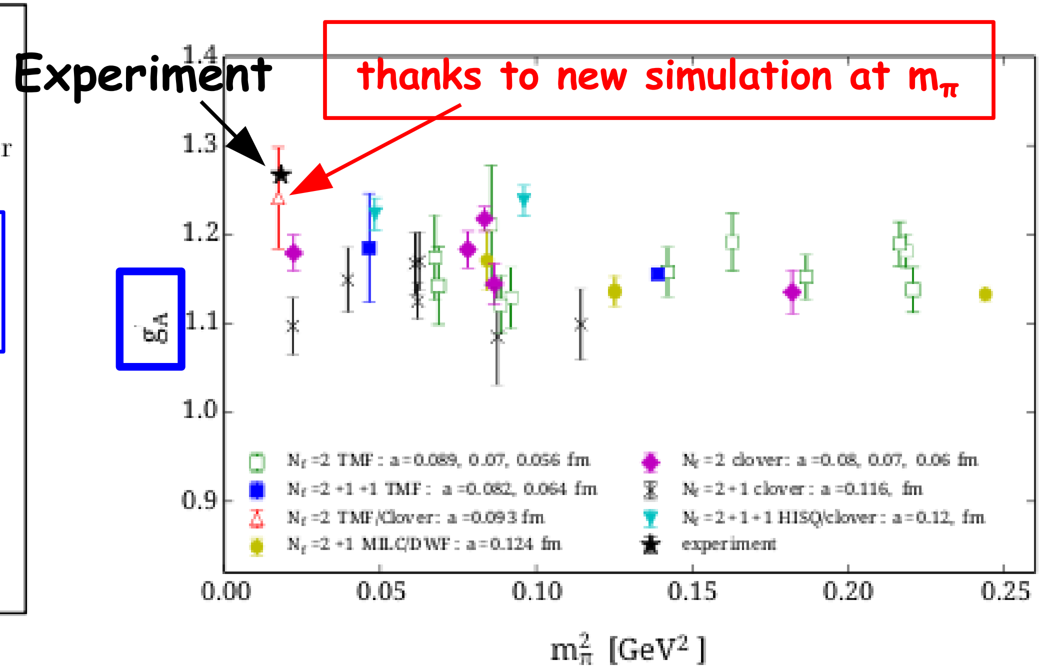
- simulations with **two physical light dynamical flavours** at one lattice spacing and on two large lattice volumes with physical dimension of 4.5 fm and 6.0 fm.

- fully realistic simulations with **two light & strange and charm dynamical flavours set as to reproduce physical π, K and D meson masses** at two lattice spacings (a third one, even smaller, started) and on large lattice volumes with physical dimension of about 5 fm.

- ***Challenging simulation task***:
  employ improved LQCD actions + advanced algorithms @ elevated CPU cost

LQCD simulations with 2-dynamical quarks set at their phys. mass values compared with older simulations

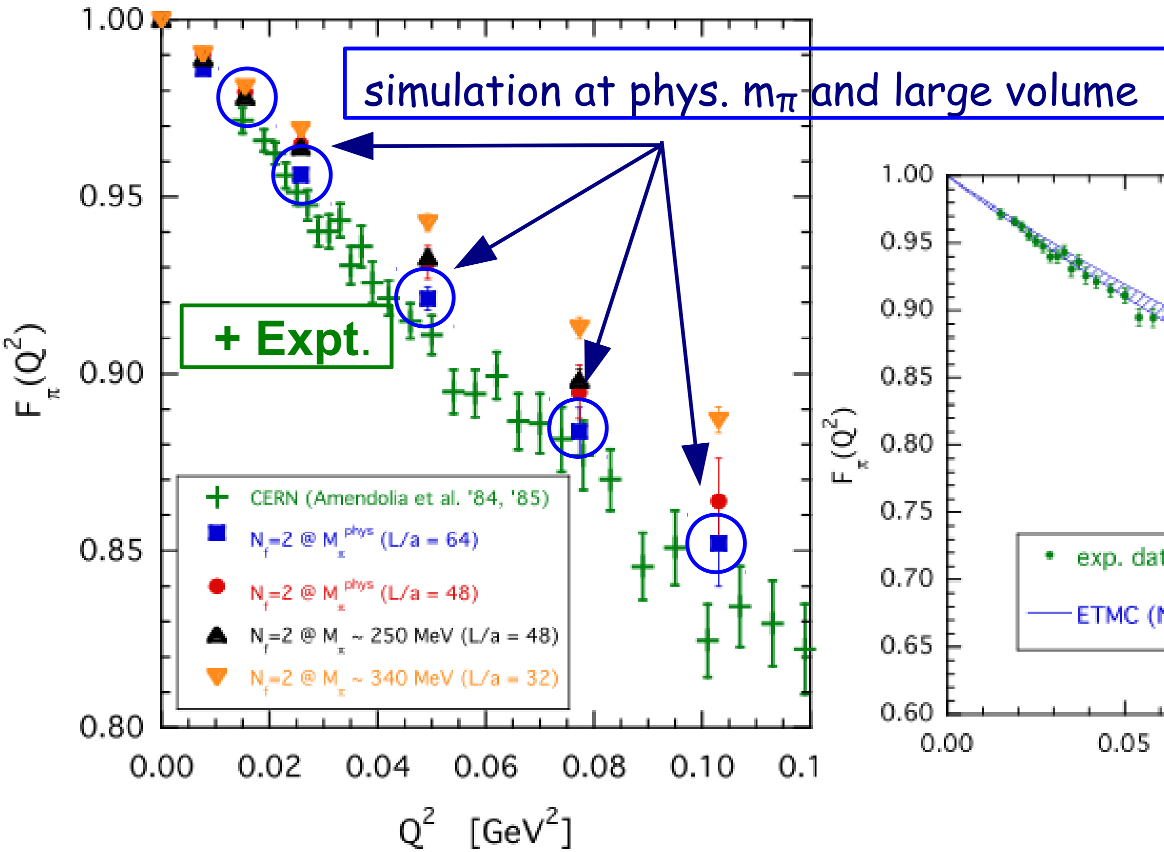


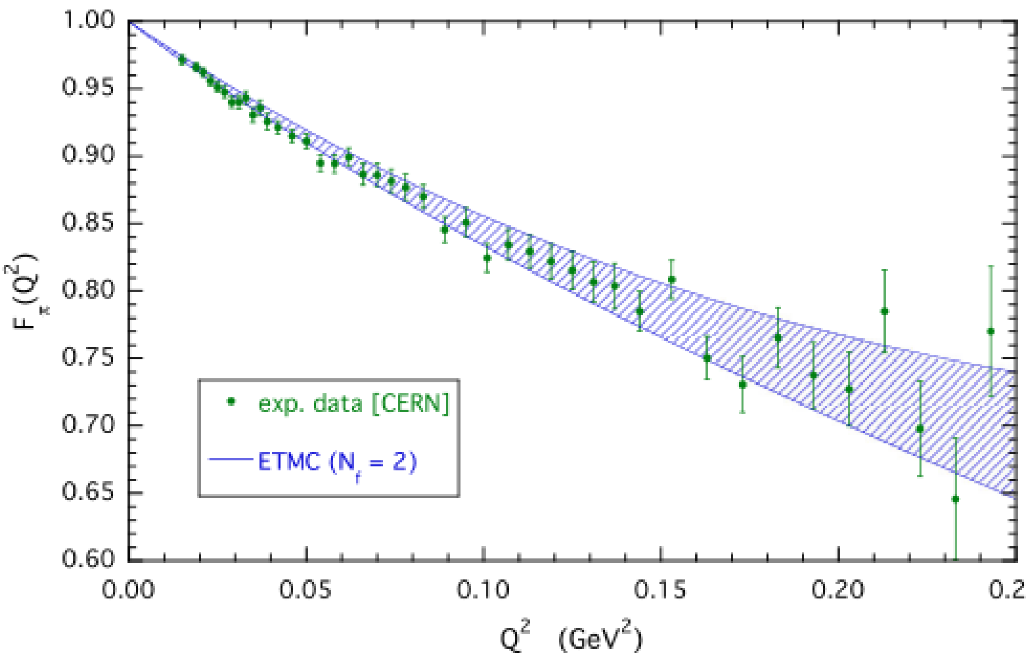


<u>Crucial achievement of Lattice QCD:</u>

physical quark lattice QCD simulations capable to achieve impressive accuracy and reproduce experimental values of improtant physical quantities.

LQCD simulations with 2-dynamical quarks set at their phys. mass values compared with older simulations

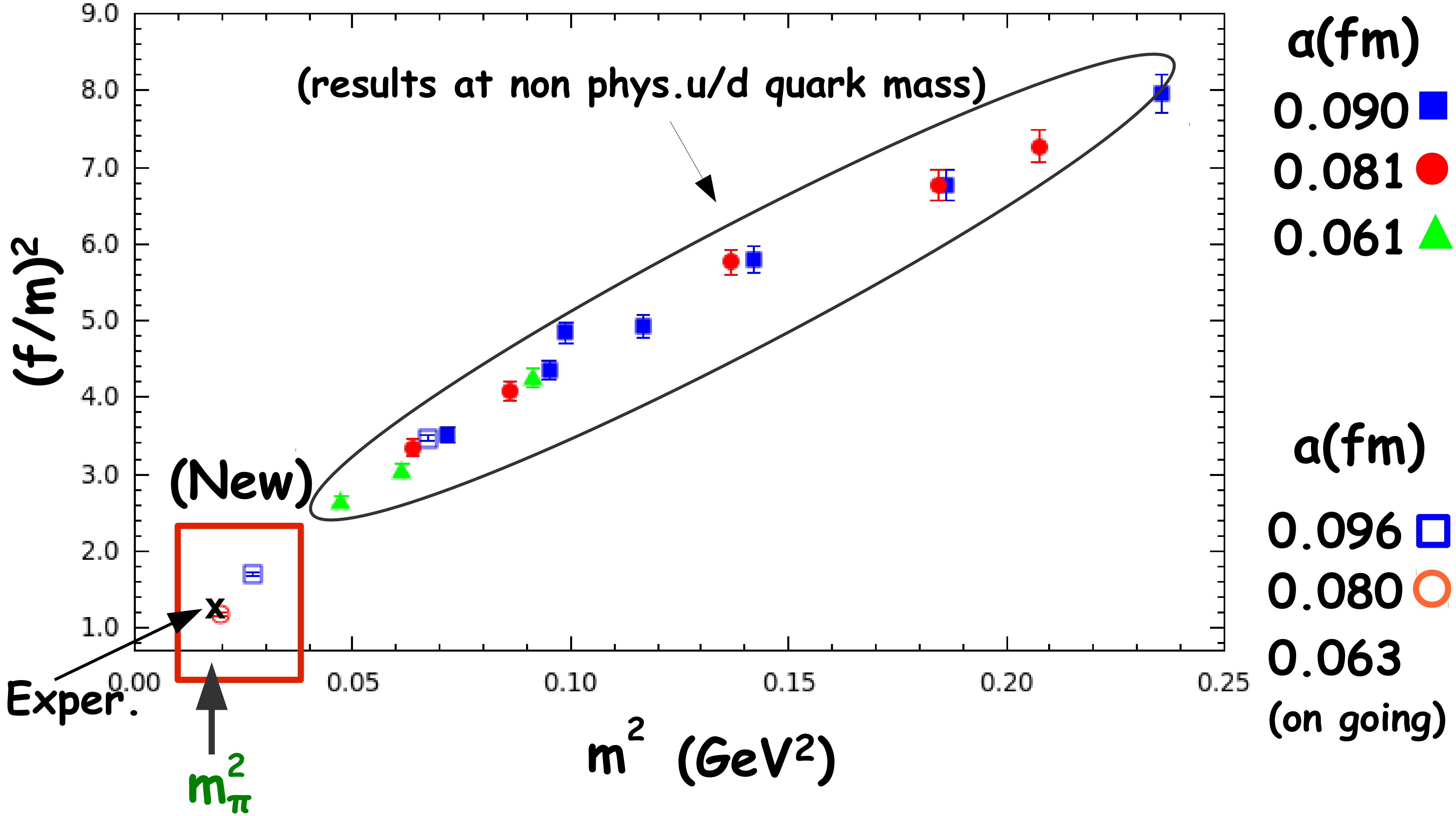




<u>Crucial achievement of Lattice QCD:</u>

physical quark lattice QCD simulations capable to achieve impressive accuracy and reproduce experimental values of improtant physical quantities.

LQCD simulations with 4-dynamical quarks set at their phys. mass values compared with older simulations



- ongoing **large scale simulations** at and very close to the physical pion mass on Marconi-Cineca and SuperMUC-LSC at three values of lattice spacing

LQCD simulations with 4-dynamical quarks: Renormalisation Constants

Special effort has been dedicated to performing extra large scale simulations (O(10) new ensembles) suitable for the non-perturbative computation of the Renormalisation Constants (RCs).

RCs are necessary for the correct determination of QCD observables (quark masses and matrix elements) in the continuum limit.

High precision determination of the RCs has been carried out (2017) with subpercent total uncertainties.

"Simulating twisted mass fermions at physical light, strange and charm quark masses", ETMC (to appear)

Dynamical generation of elementary particle masses

- A Novel Mechanism :

Frezzotti & Rossi Phys. Rev. D92 (2015)

EPJ Web of Conf. (2017), PoS (LAT2016)

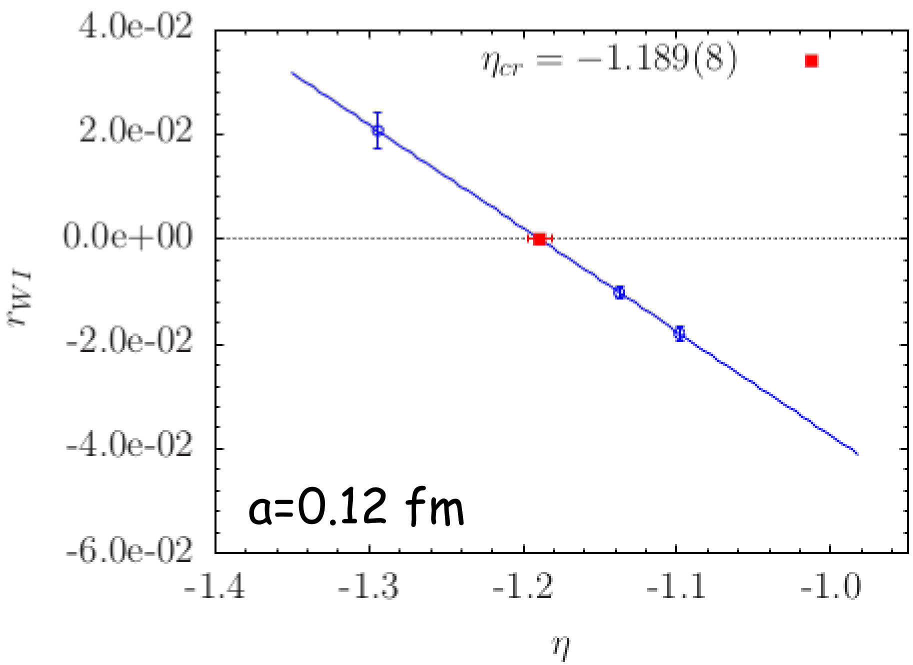
- Model of strongly interacting fermions coupled to scalar field via Yukawa interaction
  - enjoying global χ-symmetry (leading to massless fermions following PT)
  - while χ-fermion symmetry is broken at the UV scale by the presence of an irrelevant (Wilson-like) term

- Conjecture:
  - A critical (value of the Yukawa coupling of the) model can be determined in the Wigner phase for which scalars decouple from fermions and χ-fermion symmetry gets restored (up to cutoff effects)
  - residual cutoff effects trigger dynamical χSB in the Nambu-Goldstone phase → dynamically generated fermion masses

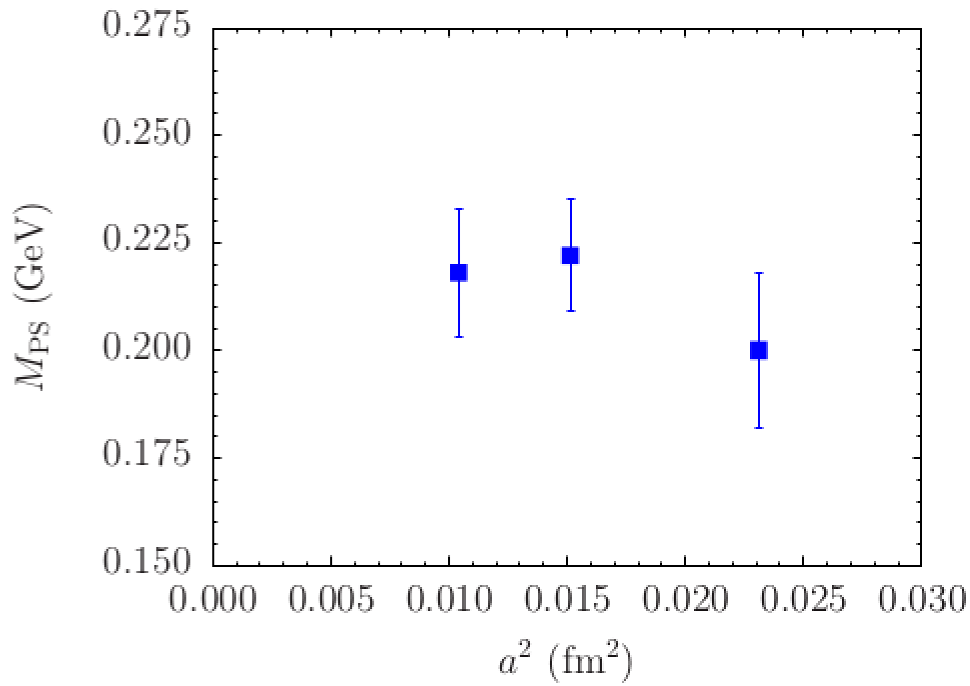
⟶ The intrinsic non-perturbative nature of the mechanism requires lattice methods and numerical simulations

⟶ Perfectly falsifiable BSM conjecture

In the **Wigner phase** determination of the **critical Yukawa coupling** → investigation of chiral fermion symmetry restoration (up to cutoff effects) via WI



In the **NG-phase** at the critial point, (while zero quark mass has been imposed) **dynamically generated quark mass** is expected to arise



Simulations on Marconi-Cineca and Jureca(Julich):

- Simulations at three lattice spacings (a = 0.15, 0.12, 0.10 fm) in Wigner and NG phases
- Planning simulations at a fourth (finer) lattice spacing
- Careful checks for residual systematic uncertainties (on going)

Flavour Lattice Averaging Group (FLAG)

Eur.Phys.J. C77 (2017) no.2, 112

FLAG collaboration comprises experts from USA, Europe and Japan in Lattice Field Theory, Chiral Perturbation Theory and Standard Model phenomenology.

- **Review (covering about 400 pages) of lattice results relevant to low-energy physics and Flavour Physics Phenomenology of the SM**

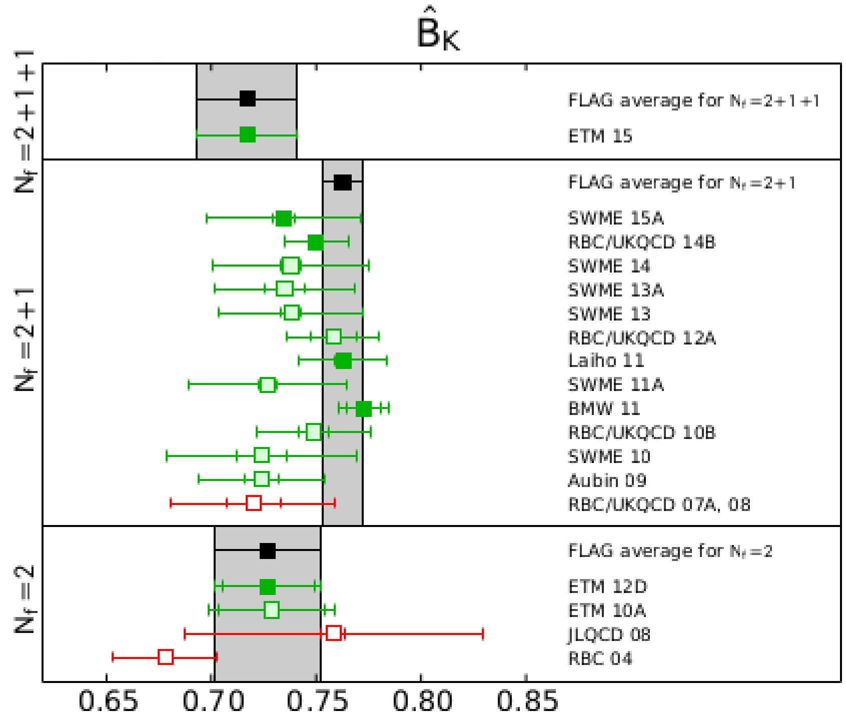
Aim: provide the most representative and reliable current determinations of a large number of QCD observables measured on the lattice.

- **Make LQCD results accessible to the particle-physics phenomenologists and experimentalists.**
- FLAG collaboration is to provide updates, in the form of a peer reviewed publication, roughly on a biennial basis.

Flavour Lattice Averaging Group (FLAG)

FLAG collaboration comprises experts from USA, Europe and Japan in Lattice Field Theory, Chiral Perturbation Theory and Standard Model phenomenology.

P.D. is the correspondent person of the Working Group on Kaon Mixing computations



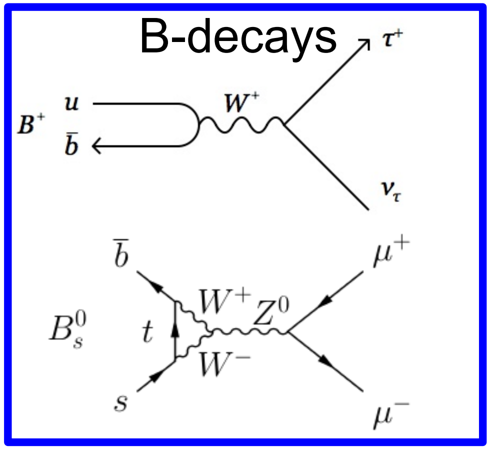
Updates are regularly provided in the **FLAG website**

http://itpwiki.unibe.ch/ag

B-physics & Lattice QCD

Phys.Rev. D93 (2016) no.11, 114505,
Nucl.Part.Phys.Proc. 273-275 (2016)

- **Lattice QCD simulations with four dynamical flavours** (simulations not at phys. m_π)
- Present CPU limitations do not allow direct (reliable) simulations at m_b
- However **clever combination of lattice observables with HQET leads to optimal control of discretisation effects even at the scale of b-quark mass.**



observable	f_{Bs}	f_B	f_{Bs}/f_B	m_b	m_b/m_c	m_b/m_s
precision %	2.2	3.1	2.2	2.3	1.8	2.7

★ LQCD B-meson decay constants required for full interpretation of the respective decays studied in **LHCb and BelleII** → extract predictions for CKM matrix elements

★ Lattice QCD-achieved precision in these rare B(s)-decays is higher than the Expt. one.

★ m_b (precise) determination required in one of the Higgs decays modes **(LHC)**.

$f_B \Leftrightarrow |V_{ub}|$

$f_{Bs} \Leftrightarrow |V_{tb}^* V_{ts}|$

$f_{Bs} / f_B \Leftrightarrow |V_{ts} / V_{td}|$ (via B-mixing)

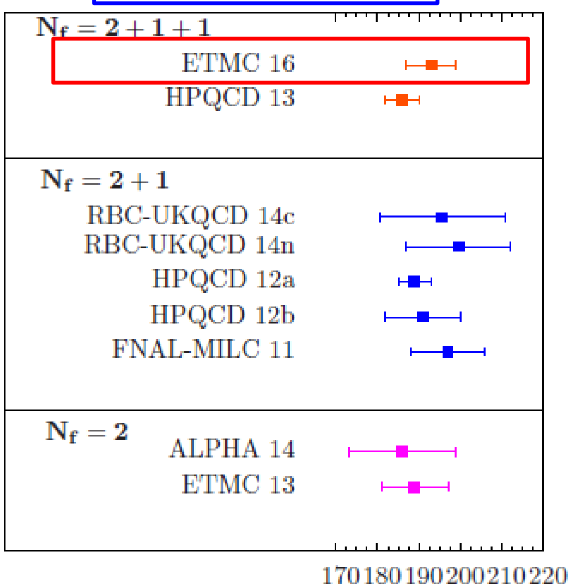
$m_b \Leftrightarrow H \to b\bar{b}$

B-physics & Lattice QCD

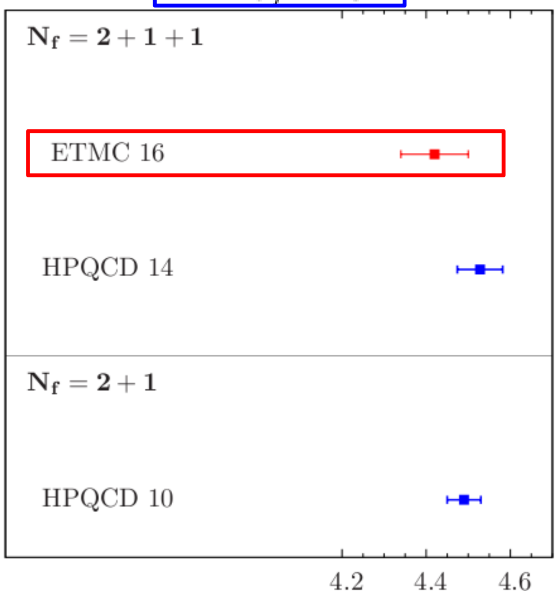
- **Lattice QCD simulations with four dynamical flavours**
  (simulations not at phys. m_π)

LQCD World Plots

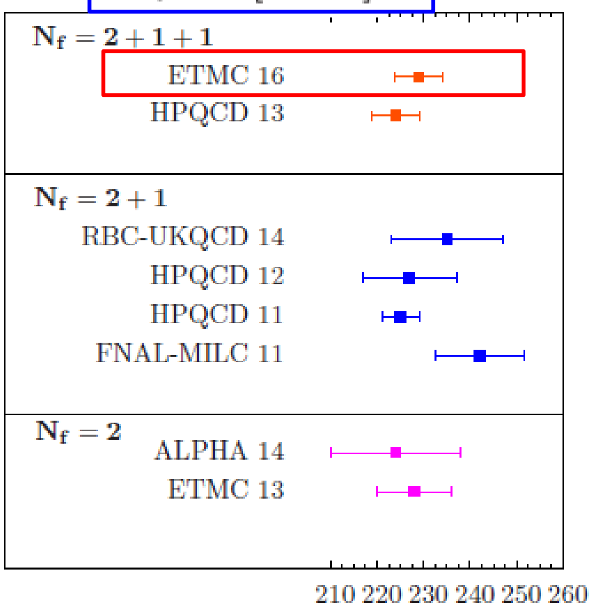
f_B [MeV]



m_b/m_c



f_{Bs} [MeV]



CENTRO FERMI
Museo Storico della Fisica e
Centro Studi e Ricerche Enrico Fermi

Conclusions and Outlook

- Joint effort between LQCD theoretical computations and experimental measurements for improving the SM precision in the flavour sector.

- A big and challenging project in progress comprising optimised algorithms, realisation of high CPU-cost LQCD simulations with large statistics aiming at attacking the main sources of systematic uncertainties.

➡ Target: reduced uncertainties for physical observable determinations in the π, K, D and B region .

- Extensive study of a dynamical generation mechanism of elementary fermion masses in BSM physics.

➡ Aim: prove (or disprove) the occurrence of the conjectured non-perturbative fermion mass generation phenomenon.

- Compilation and critical review of world LQCD results by FLAG Collaboration

➡ Provide representative summaries of results for use from the particle phenomenology community (updated FLAG Review to appear in feb 2019).

Publications in 2016-2018

1. **Non-Perturbative Renormalisation and Running of BSM Four-Quark Operators in $N_f = 2$ QCD**
P. Dimopoulos, G. Herdoiza, M. Papinutto, D. Preti, C. Pena, A. Vladikas
(sottomesso a Eur. Phys. J), arXiv: 1801.09455 [hep-lat],

2. **The pion vector form factor from Lattice QCD at the physical point**
C. Alexandrou, S. Bacchio, P. Dimopoulos, J. Finkenrath *et al.*
(ETM Collaboration)
Phys.Rev. **D97** (2018) no.1, 014508
doi:10.1103/PhysRevD.97.014508, arXiv: 1710.10401[hep-lat],

3. **Review of lattice results concerning low-energy particle physics**
S. Aoki, Y. Aoki, D. Becirevic, C. Bernard, T. Blum, G. Colangelo, M. Della Morte, P. Dimopoulos, *et al.*
(FLAG Working Group)
Eur.Phys.J. **C77**, no.2, 112, 2017
doi:10.1140/epjc/s10052-016-4509-7, arXiv:1607.00299 [hep-lat],

4. **Isospin-0 $\pi\pi$ s-wave scattering length from twisted mass lattice QCD**
L. Liu, S. Bacchio, P. Dimopoulos, J. Finkenrath *et al.*
(ETM Collaboration)
Phys.Rev. **D96** (2017) no.5, 054516
doi:10.1103/PhysRevD.96.054516, arXiv:1612.02061 [hep-lat],

5. **Nucleon scalar and tensor charges using lattice QCD simulations at the physical value of the pion mass**
C. Alexandrou, M. Constantinou, P. Dimopoulos, R. Frezzotti *et al.*
(ETM Collaboration)
Phys. Rev. **D95**, 114514, 2017
doi:10.1103/PhysRevD.95.114514, arXiv:1703.08788 [hep-lat],

Publications in 2016-2018

6. **Mass of the b-quark and B-decay constants from N_f=2+1+1 twisted-mass Lattice QCD**
   A. Bussone, N. Carrasco, P. Dimopoulos, R. Frezzotti *et al.*
   (ETM Collaboration)
   Phys. Rev. **D93** 114505, 2016
   doi:10.1103/PhysRevD.93.114505, arXiv:1603.04306 [hep-lat],

7. **Simulating QCD at the Physical Point with $N_f = 2$ Wilson Twisted Mass Fermions at Maximal Twist**
   A. Abdel-Rehim, C. Alexandrou, F. Burger, M. Constantinou, P. Dimopoulos *et al.*
   (ETM Collaboration)
   Phys.Rev. **D95** 094515, 2017
   doi:10.1103/PhysRevD.95.094515, arXiv:1507.05068 [hep-lat],

8. **Simulation of an ensemble of Nf=2+1+1 twisted mass clover-improved fermions at physical quark masses**
   C. Alexandrou, S. Bacchio, P. Charalambous, P. Dimopoulos *et al.*
   European Physical Journal (EPJ) Web of Conferences (LATTICE2017) (to appear), arXiv: 1712.09579

9. **Testing a non-perturbative mechanism for elementary fermion mass generation: numerical results**
   S. Capitani, G.M. De Divitiis, P. Dimopoulos, R. Frezzotti *et al.*
   European Physical Journal (EPJ) Web of Conferences (LATTICE2017), arXiv: 1710.10216.

10. **Testing a non-perturbative mechanism for elementary fermion mass generation: lattice setup**
    S. Capitani, G.M. De Divitiis, P. Dimopoulos, R. Frezzotti *et al.*
    European Physical Journal (EPJ) Web of Conferences (LATTICE2017), arXiV: 1710.10956.

Publications in 2016-2018

11. **Check of a new non-perturbative mechanism for elementary fermion mass generation**
S. Capitani, G.M. De Divitiis, P. Dimopoulos, R. Frezzotti *et al.*
Pos (LATTICE2016) 212; arXiv:1611.03997[hep-lat].

12. **Isospin-0 $\pi\pi$ scattering from twisted mass lattice QCD**
L. Liu, S. Bacchio, P. Dimopoulos, J. Finkenrath *et al.*
Pos (LATTICE2016) 119; arXiv:1701.08961[hep-lat].

13. **Heavy flavour precision physics from $N_f = 2+1+1$ lattice simulations**
A. Bussone, N. Carrasco, P. Dimopoulos, R. Frezzotti *et al.*
Nucl. Part. Phys. Proc. 273, 2016 (ICHEP 2014)
doi:10.1016/j.nuclphysbps.2015.09.265
arXiv:1411.0484[hep-lat].

Two representative publications in 2017:

- **Review of lattice results concerning low-energy particle physics**,
S. Aoki *et al.* Eur.Phys.J. **C77** (2017) no.2, 112.

- **First physics results at the physical pion mass from Nf=2 Wilson twisted mass fermions at maximal twist**
A. Abdel-Rehim *et al.* Phys.Rev. **D95** (2017) no.9, 094515.

<u>Un vivo ringraziamento al Centro Fermi</u> per il finanziamento di due progetti (2013-2015, 2016-2018), per il supporto economico delle missioni e per aver dato la possibiltà di proseguire una linea di ricerca che ha fruttato riconoscimenti sul piano internazionale con

- 29 pubblicazioni in totale, con ~800 citazioni su INSPIRES
- risultati riportati su Particle Data Group (PDG) e su varie review
- 3 presentazioni su invito
- membro del Flavour Lattice Averaging Group (FLAG)

Un vivo ringraziamento al Centro Fermi per il finanziamento di due progetti (2013-2015, 2016-2018), per il supporto economico delle missioni e per aver dato la possibiltà di proseguire una linea di ricerca che ha fruttato riconoscimenti sul piano internazionale con

- 29 pubblicazioni in totale, con ~800 citazioni su INSPIRES
- risultati riportati su Particle Data Group (PDG) e su varie review
- 3 presentazioni su invito
- membro del Flavour Lattice Averaging Group (FLAG)

Thank you for your attention!