Lattice QCD and nucleon physics: selected excerpts

TSUKUBA GLOBAL SCIENCE WEEK 2018

TGSW2018 supports
the Sustainable Development Goals

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Driving Sustainable Development

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Outline

- **Introduction**
  - What is lattice QCD
  - Why do we need it?
  - How does it work?
  - How is it organized?
  - Reaching the physical pion mass

- **Nucleon physics**
  - nucleon mass
  - axial charge
  - Momentum fraction $\langle x \rangle_{u-d}$ and helicity $\langle x \rangle_{\Delta u - \Delta d}$

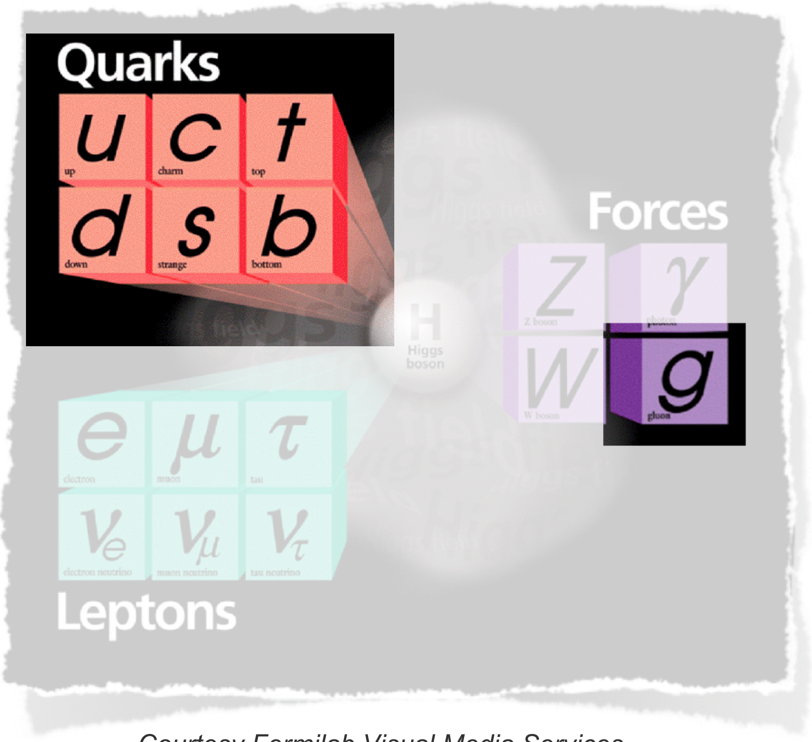
- **Renormalisation**

- **Conclusion**

Prior warning (and apologizes...):

- Presentation limited to what is studied in L.P.S.C. → necessarily restricted compared to the richness of the field
- Many subjects of interest in LQCD will not be mentioned (nuclear interactions, finite temperature, flavor physics, ...)
- Work performed in the framework of the European Twisted Mass Collaboration (ETMC). Many other competitive international collaborations exist (PACS-CS, MILC, HPQCD, BMW, ALPHA ....)

What is Lattice QCD?



Courtesy Fermilab Visual Media Services

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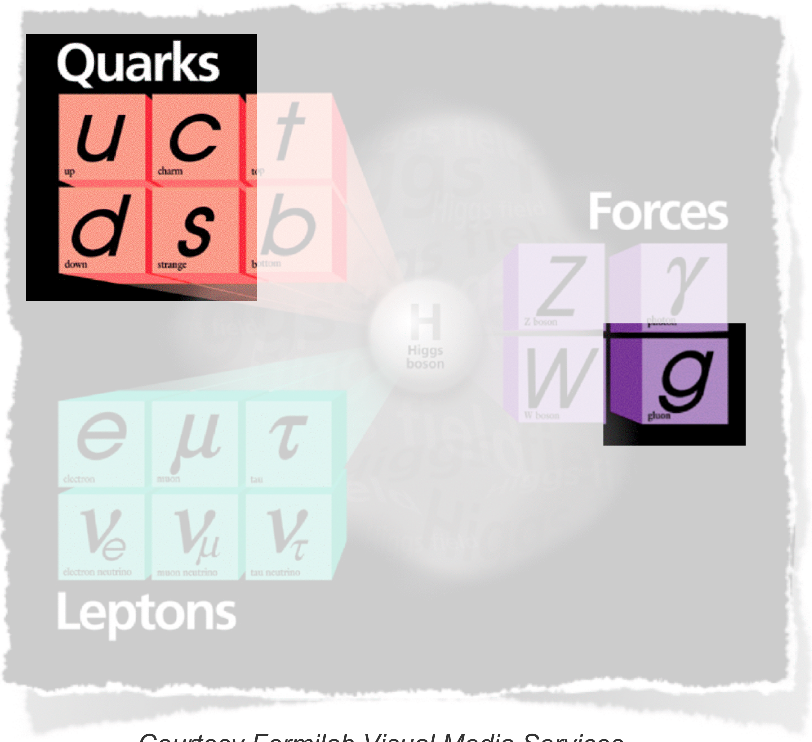

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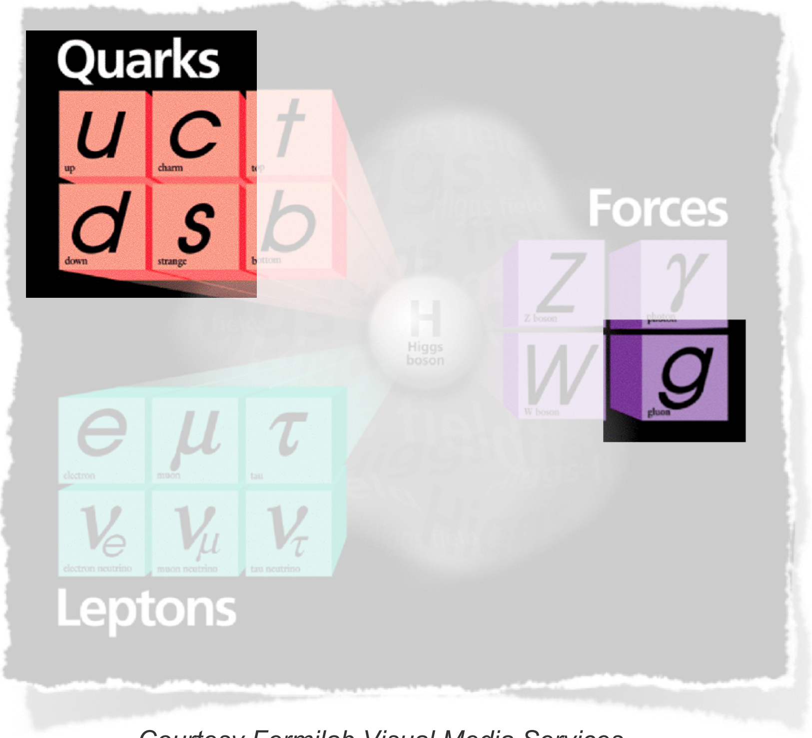

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$$\mathcal{L} = -\frac{1}{2}\mathrm{Tr}\, G_{\mu\nu}G^{\mu\nu} + \sum_{f=1}^{N_f} \bar{q}_f (i\not{D} - m_f) q_f$$

Gluon

Fermions + quark-gluon interaction

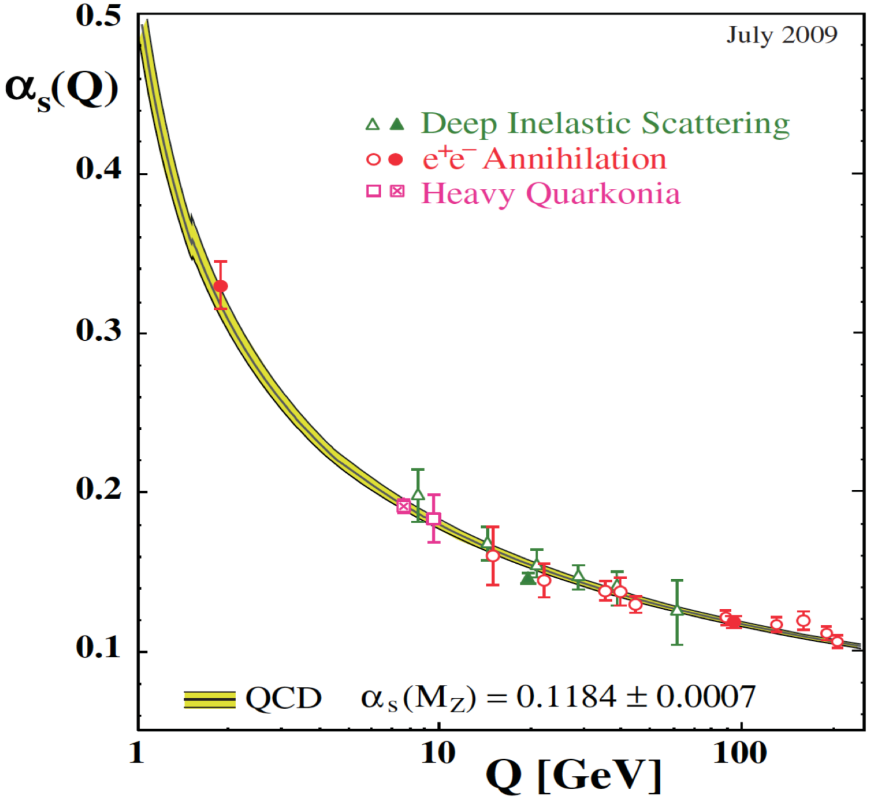
- Formulated by K. Wilson in 1974 (Phys.Rev. D10 (1974) 2445-2459): gauge theories on a space-time lattice and demonstration that lattice gauge theories at strong coupling lead to confinement
- Regularization of QCD (inherent to all field theories) by space-time discretization
- has become a standard tool

Why do we need it?

- Perturbative QCD (pQCD) very successful in describing many phenomena
- **BUT** limited to an energy range where $\alpha_S << 1$

Salient feature of QCD : Asymptotic freedom

→ pQCD cannot describe physics at GeV scale



Particle Data Group, 2010

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Bound states cannot be described by perturbations

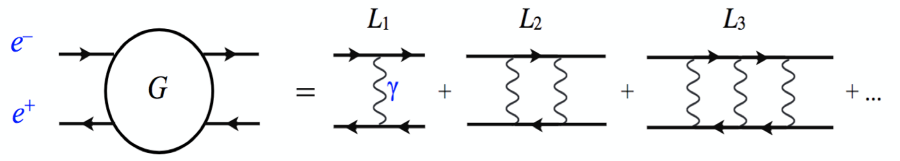
→ pQCD cannot describe bound states, whatever scale

Understanding bound states in QCD is crucial, because of confinement

<u>Simple example of positronium :</u>

No finite order diagram for $e^+e^- \longrightarrow e^+e^-$ has a positronium pole

Positronium pole arises from a divergent infinite sum of diagrams



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Spontaneous breaking of chiral symmetry

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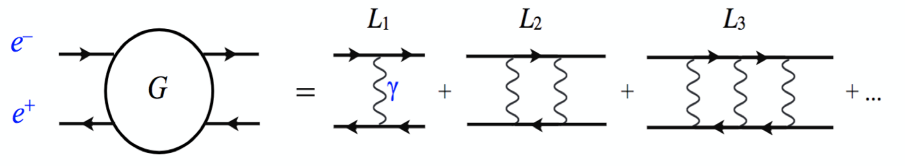
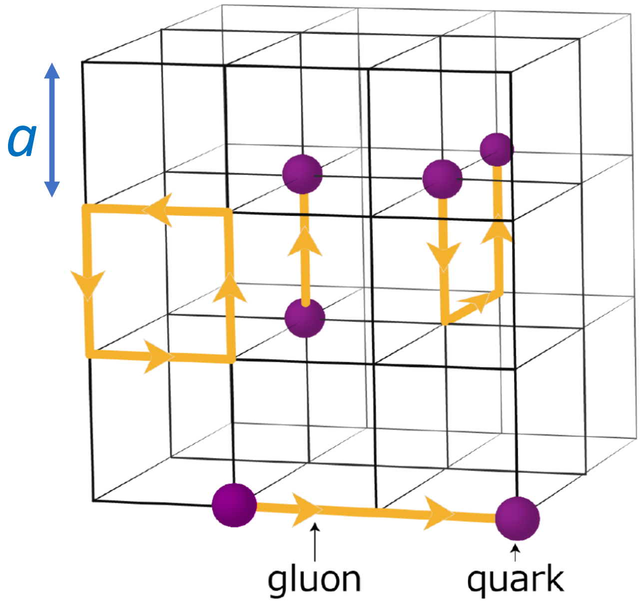


Lattice QCD:

- Only rigorous and systematic non perturbative method to solve QCD *ab initio*
- Aim: provide solutions of this fundamental theory of matter without uncontrolled uncertainties and with precisions rivaling those of experiments.

How does it work?

- QCD must be regularized in IR and UV
- LQCD is a possible regularization
- Principle:
  - space-time is discretized: $x_\mu = a n_\mu,\ n_\mu \in \mathbb{Z}$
  - quark : $\Psi(x)$ on the lattice sites
  - gluon : $U_\mu(x) \in SU(3)$ on the lattice links
  - discretized action: $S = S_G + S_F$



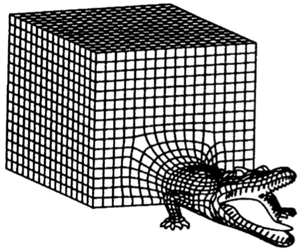
  - formulation of QFT in terms of Feynman path integrals with complex time (t⟶ it)
  - observables obtained by $\langle \mathcal{O} \rangle = \frac{1}{Z} \int DU\, Dq\, D\bar{q}\ \mathcal{O}(U, q, \bar{q}) e^{-S_E}$
  - $\langle \mathcal{O} \rangle$ computed by Monte Carlo methods, inspired by statistical physics

Calculations based on stochastic methods: very demanding in terms of computing power.

How it is organized?

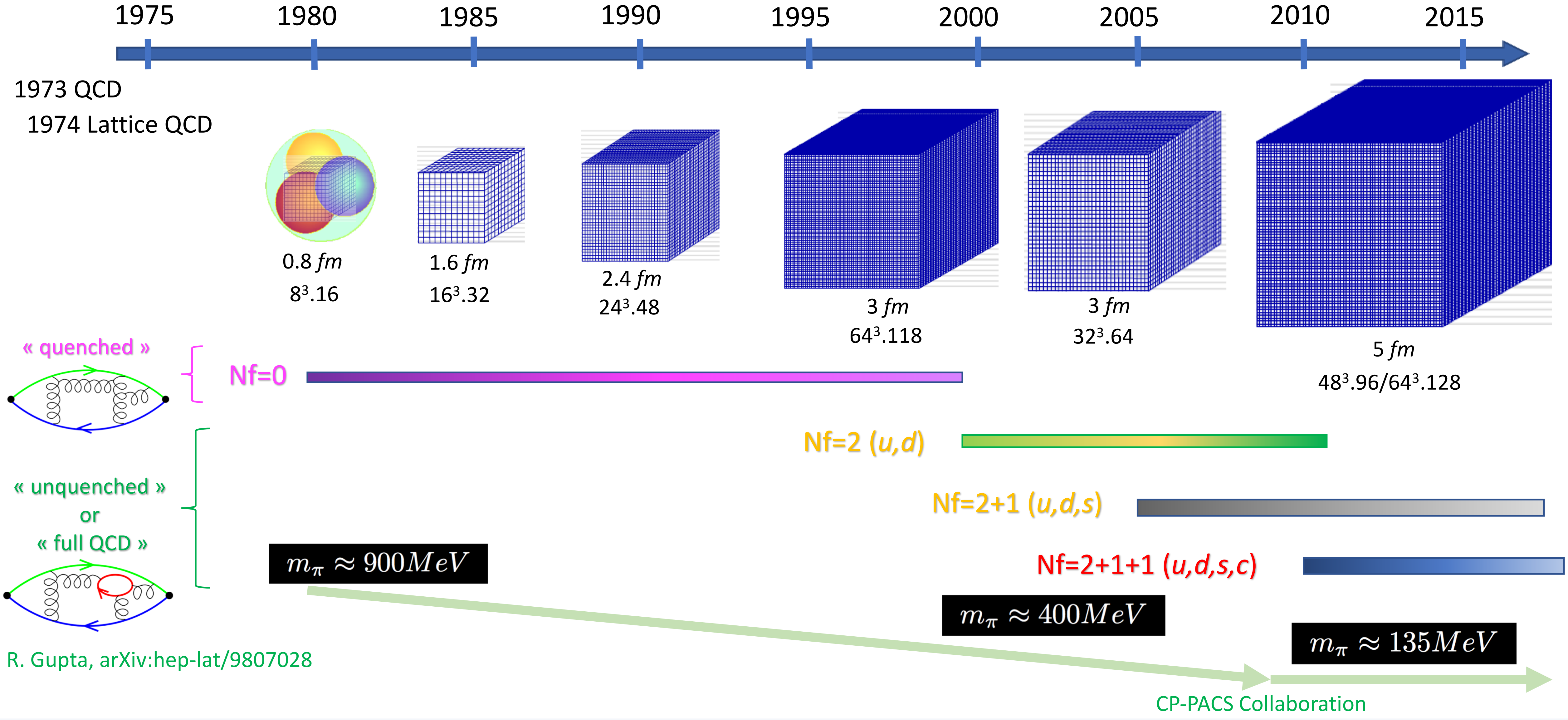
- Different QCD action discretizations ➔ different international collaborations
- Pooling of computing resources and manpower inside a given collaboration
- Typical steps of a lattice QCD simulation:

1. Gauge field (or configurations) generation using Monte Carlo methods (HMC) on HPC - most demanding part of the computation
2. Quark propagators calculation by solving a large linear system (HPC)
3. Analysis (or post-treatment), i.e. computations of expectation values of operators, chosen depending on the problem we are interested + statistical study (CPU/GPU farms)
4. Control of systematics (discretization effects,…) by repeating steps 1.2.3. for several lattice parameters (lattice spacing, volume,….)



Reaching the physical pion mass

Adapted from A. Ukawa, Tsukuba University, « Lattice QCD at the turning point » (2010)

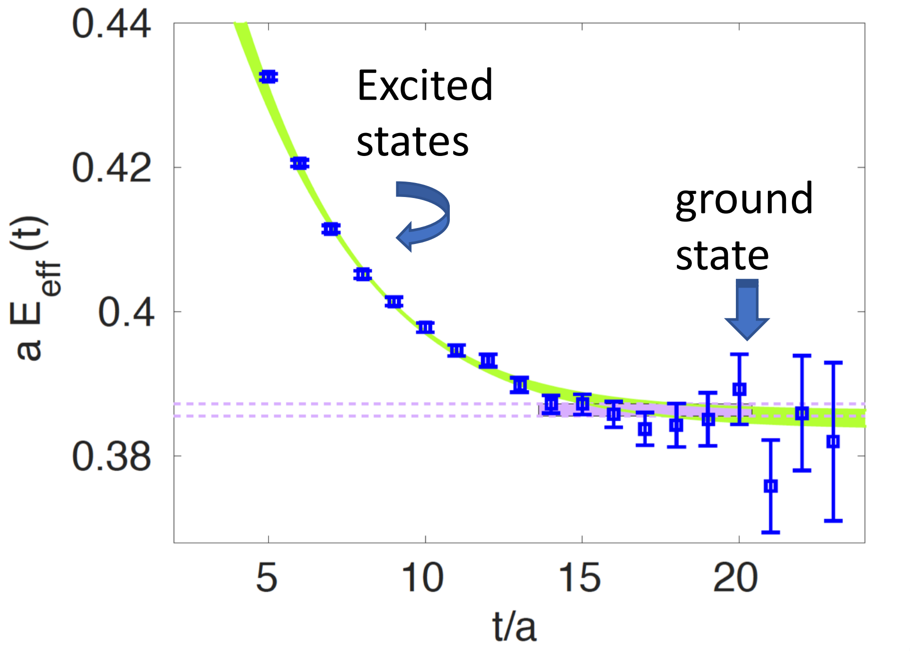


Nucleon physics

Described by an « interpolating field »: $J^N(x) = \varepsilon^{abc}[\mathbf{u}^{T\,a}(x)C\gamma_5\mathbf{d}^b(x)]\,\mathbf{u}^c(x)$

Observables computed studying the expectation values of operators built from this interpolating field

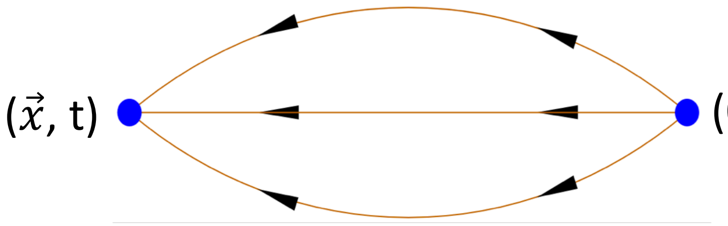
Simplest example: ab-initio computation of nucleon mass (I)



$$C(t) \sim \sum_{\vec{x}} \langle J^N(\vec{x},t)\bar{J}^N(0)\rangle \quad \propto e^{-m_N.t} + \ldots \text{ at large time } t$$

Annihilate a state with quantum number of the nucleon at space-time *x*

Create a state with quantum number of the nucleon at space-time (0,0)



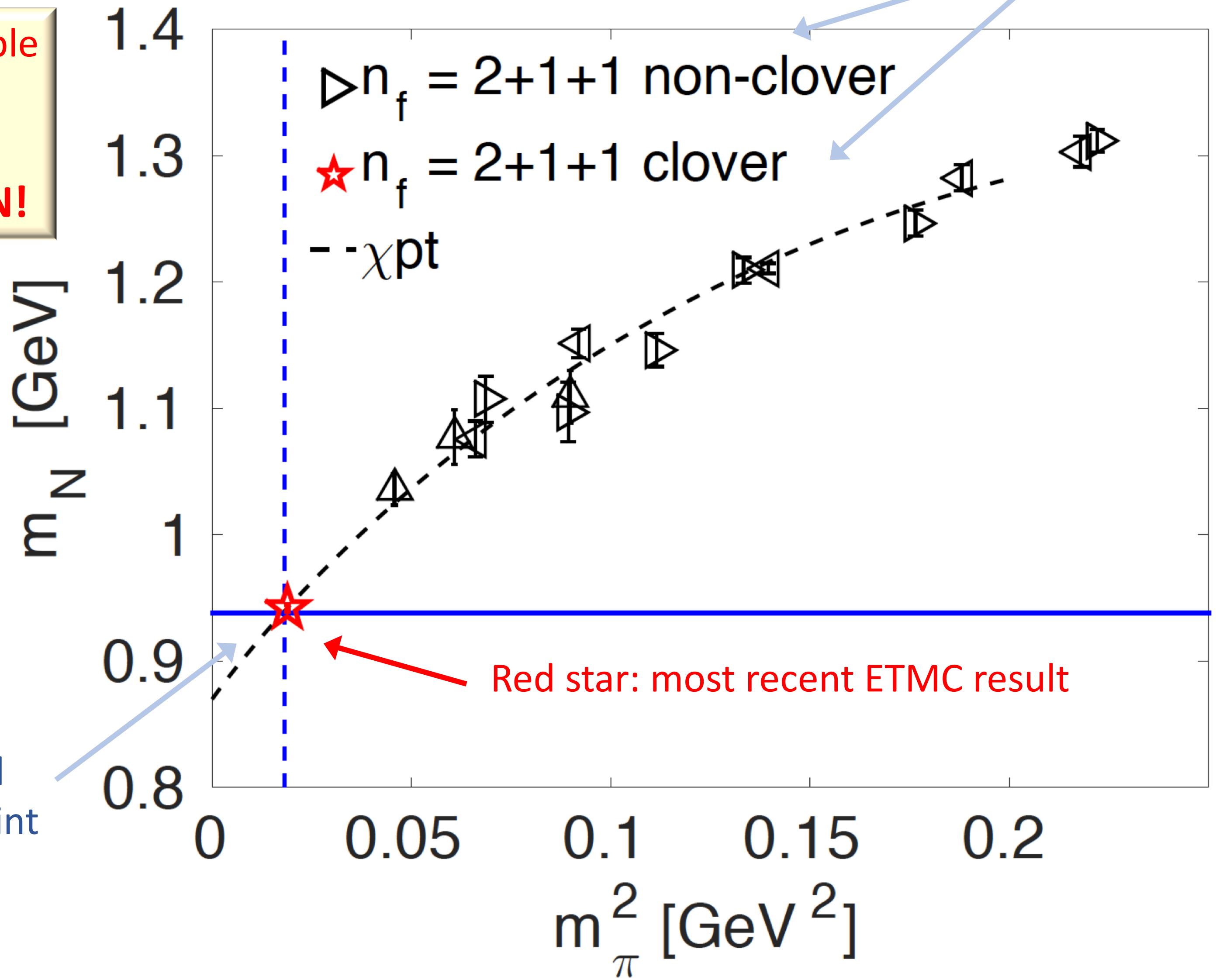
« 2 point-function »

Nucleon mass (II)

QCD with *u,d (degenerate), s* and *c* quarks

Mass of most of the visible matter in the Universe
=
STRONG INTERACTION!

slightly different discretizations



Red star: most recent ETMC result

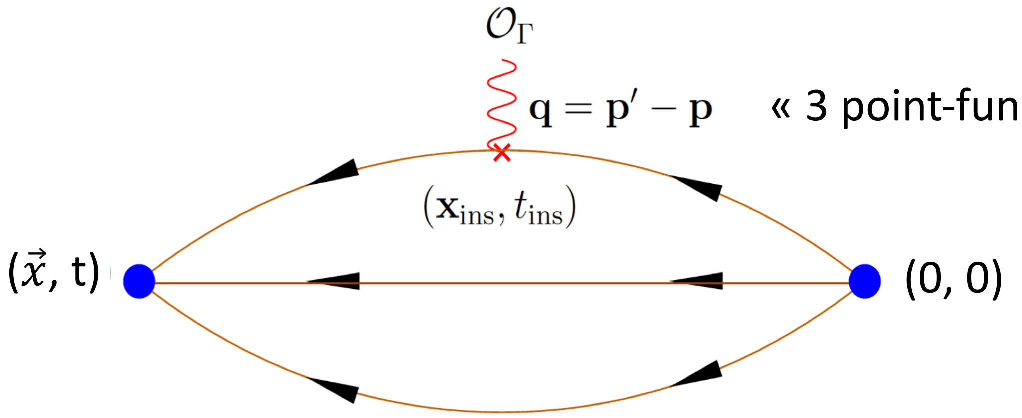
Crossing of blue dashed and solid lines: experimental point

Lattice $64^3.128$
2+1+1
Physical quark masses
Lattice spacing *a ~ 0.08 fm*

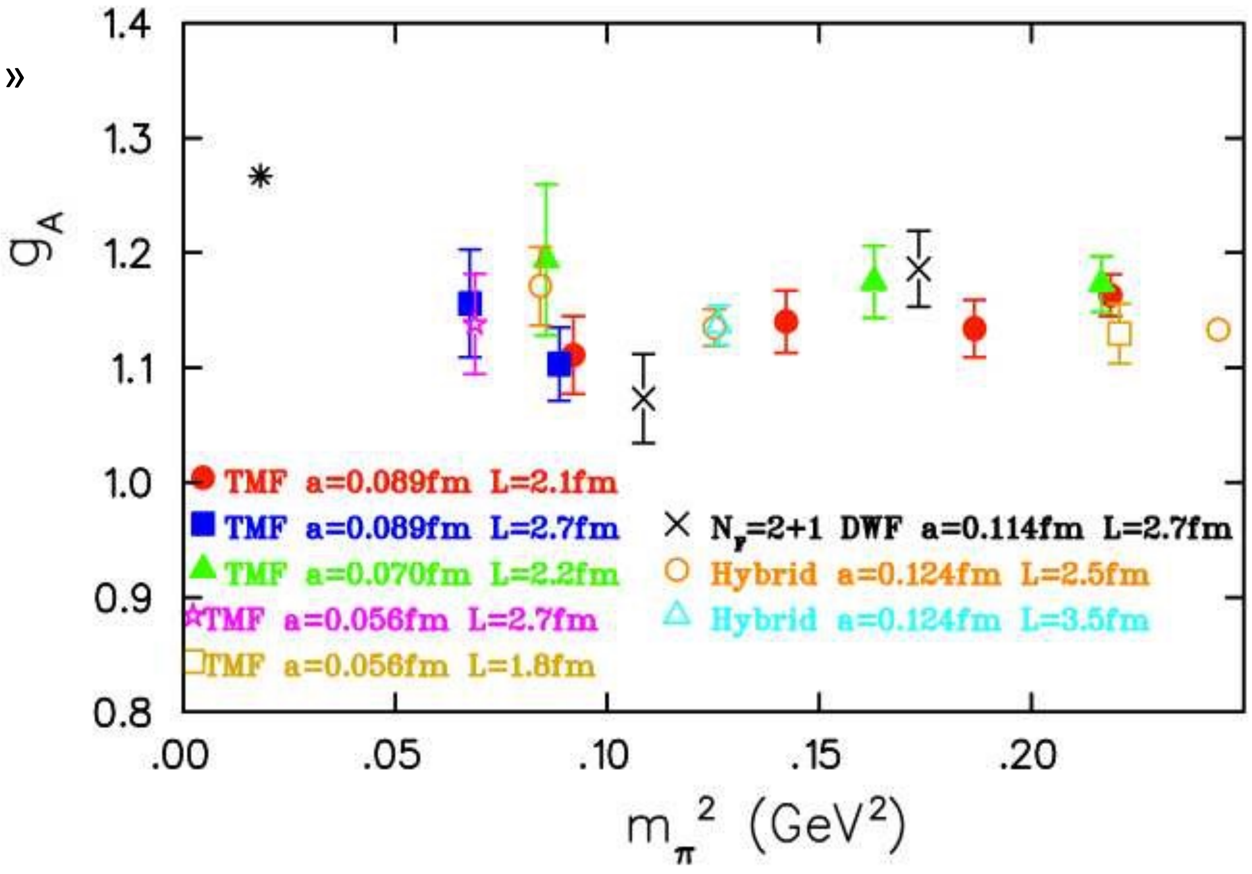
C. Alexandrou et al., arXiv:1807.00495 submitted to Phys.Rev. D

Axial charge of the nucleon

- g_A= nucleon axial charge



- Well known from β-decay of the neutron
- Key parameter for understanding the chiral structure of the nucleon
- Considered as a « benchmark » quantity for lattice QCD
- Suffered from a longstanding uncertainty due to its strong dependence in pion mass



g_A vs pion mass squared for different fermion actions (2010)

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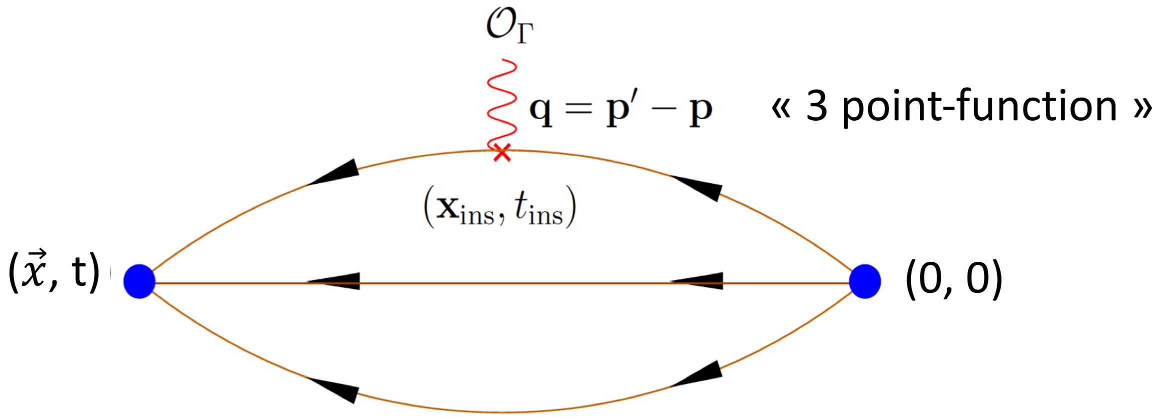

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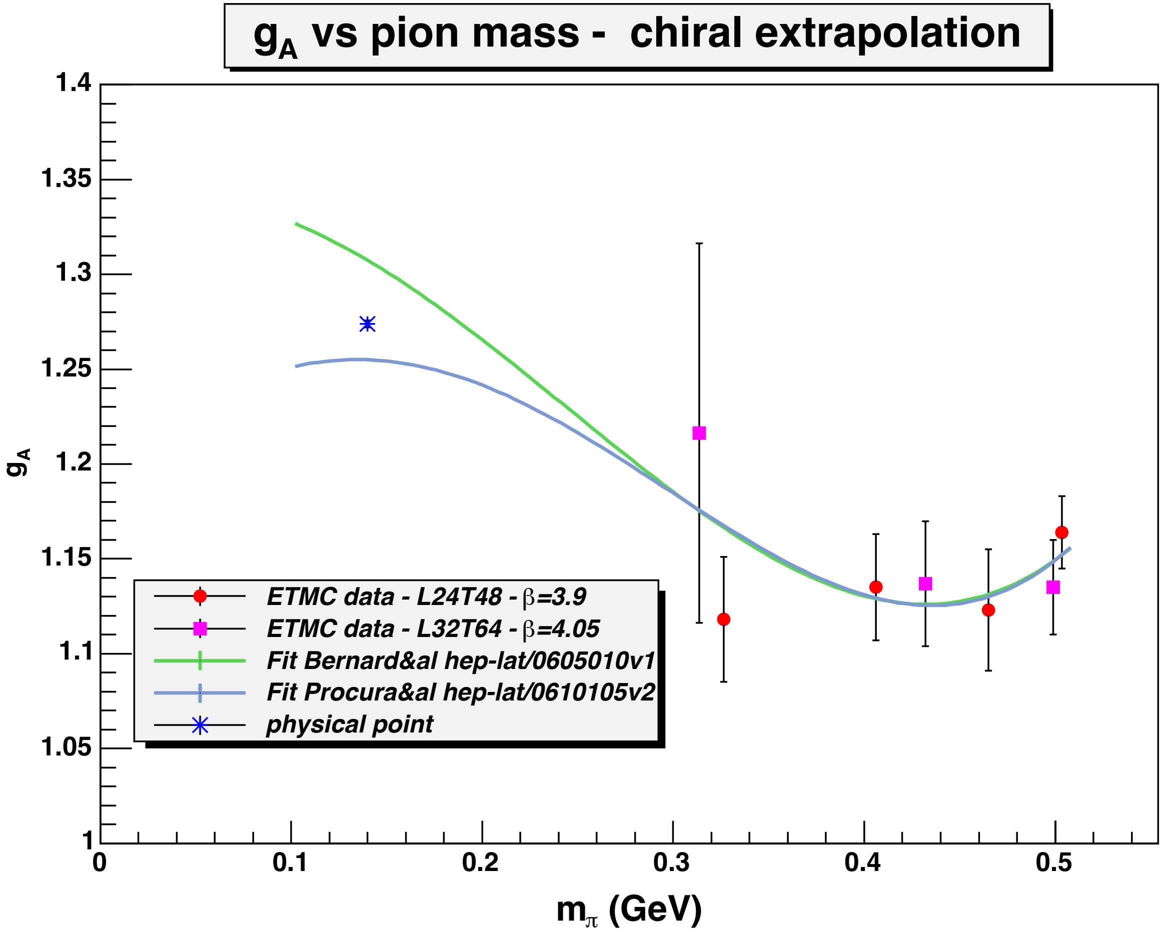

g_A vs pion mass squared with chiral fits (2010)

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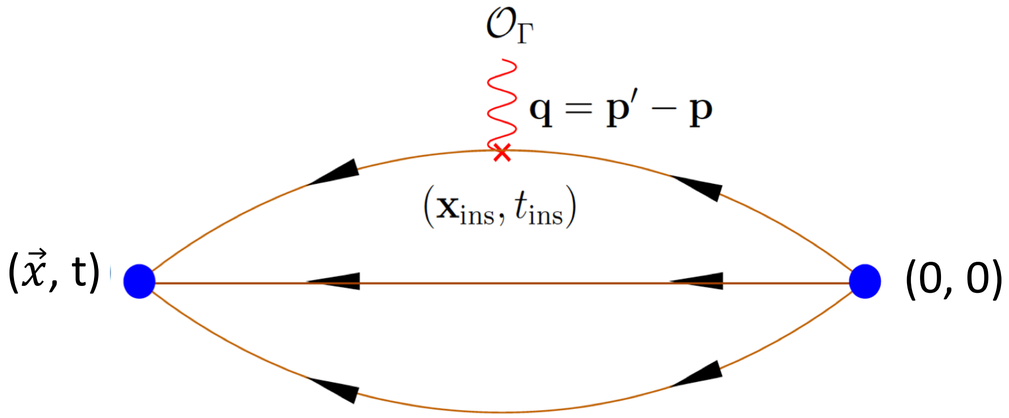

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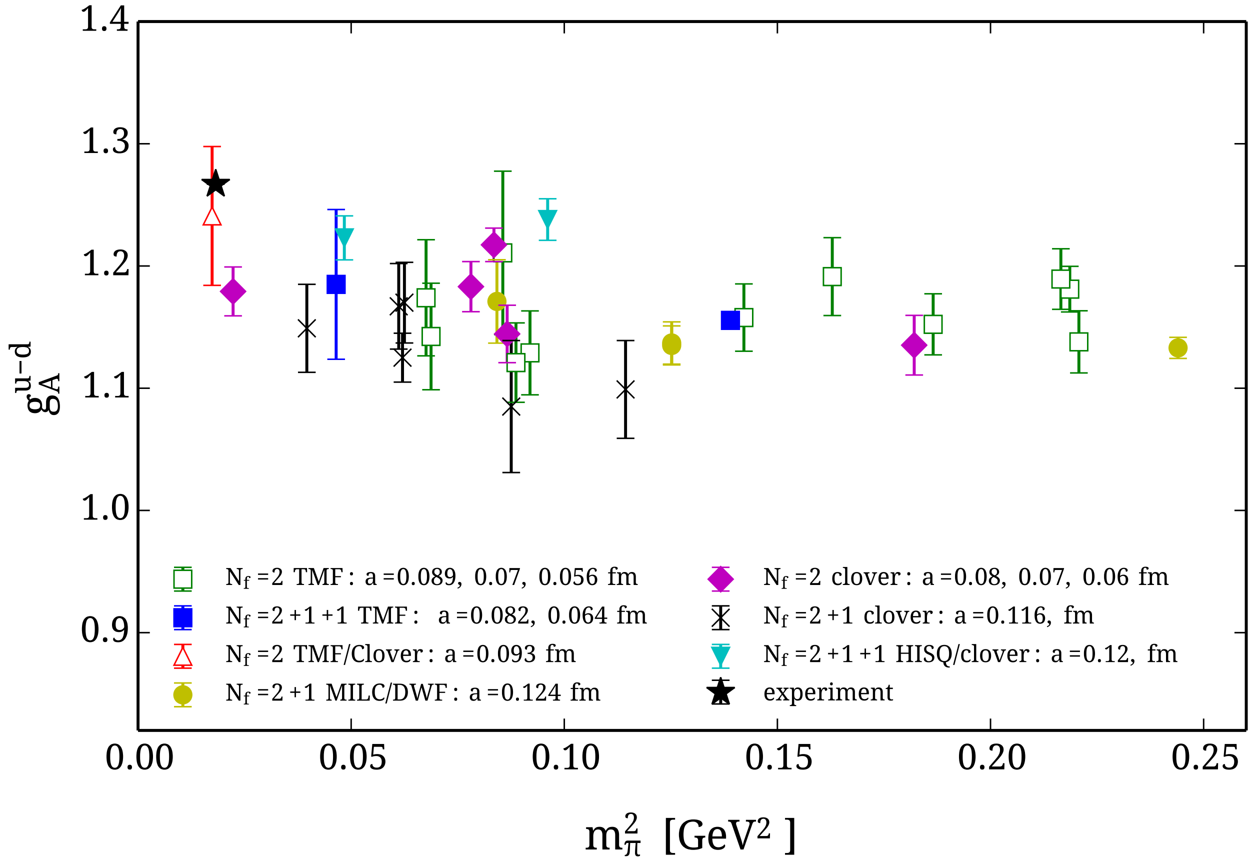
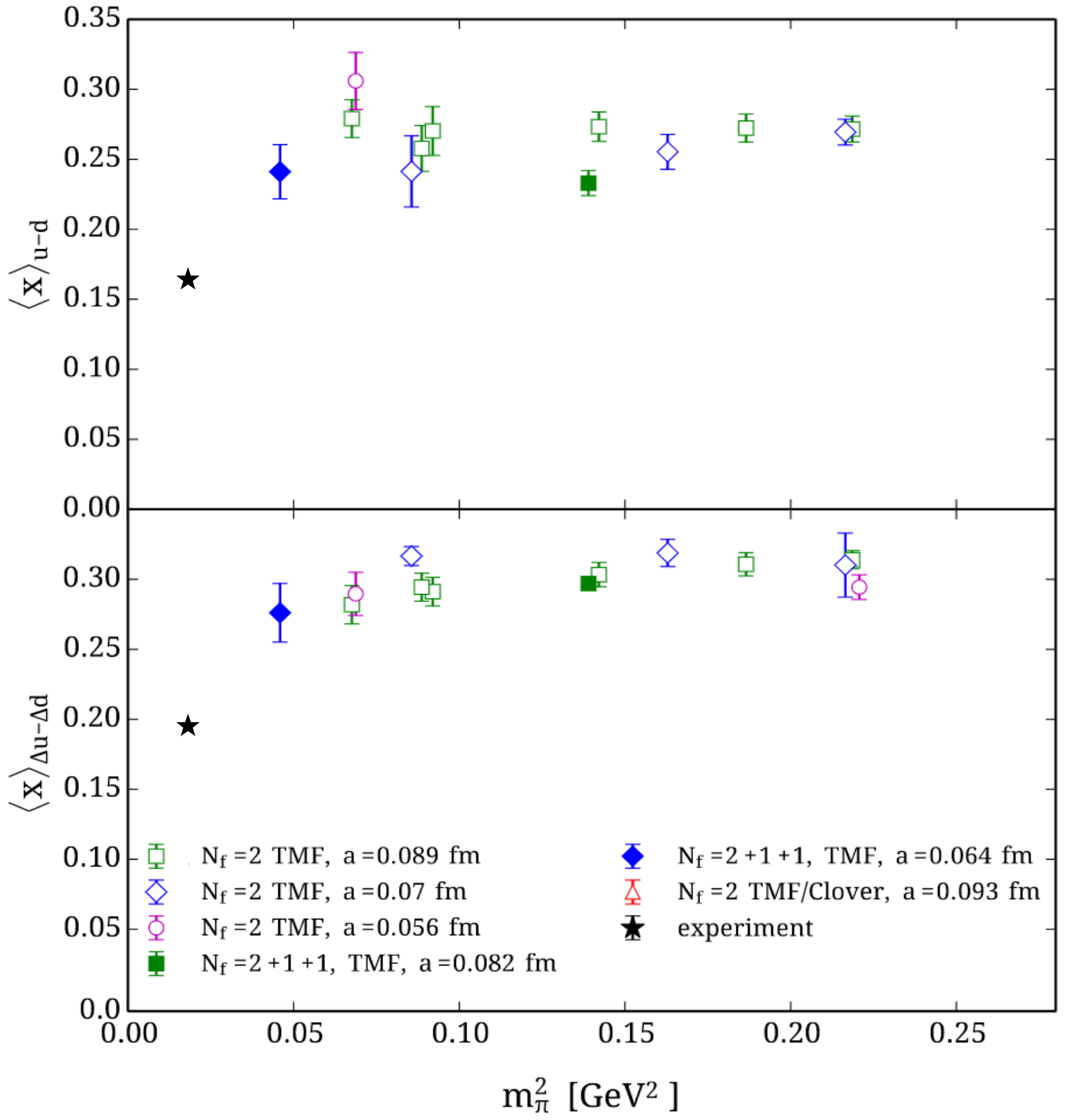


g_A vs pion mass squared for different fermion actions (2015)

C. Alexandrou et al., Phys.Rev. D92 (2015) 11, 114513, arXiv: 1507.04936

Momentum fraction $<x>_{u-d}$ and helicity $<x>_{\Delta u-\Delta d}$

- An additional step in complexity : 3-point function with derivative operator
- Experimental values extracted from global analysis of collider data
- Has persistently come out too high from lattice calculations
- Concentrated effort to removing each source of systematic errors (pion mass, excited states,...)



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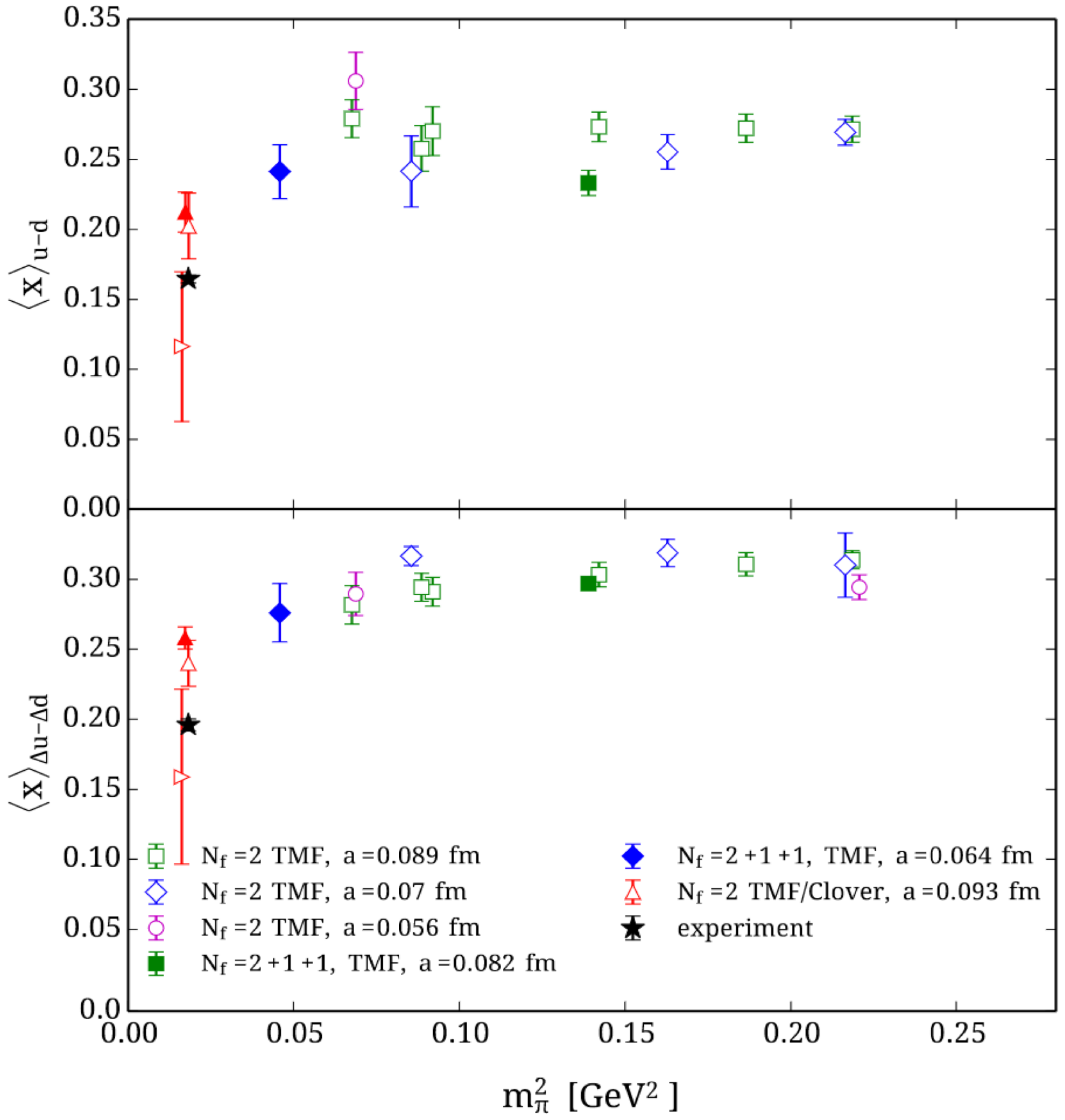
Encouraging recent results
→ Longstanding puzzle soon resolved ?



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Renormalisation

- Essential ingredient of Lattice QCD calculations

  - Discretisation → provides a natural regularisation
    What is computed on a lattice: « bare » observable: *Obs(a)* (regularized quantities)

  - Continuum limit → renormalisation
    Renormalisation = procedure to take the limit $a \to 0$: *Obs(a)* → Physical Observables

$$\mathcal{O}_R = Z_{\mathcal{O}} \mathcal{O}_B$$

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- Renormalization allows, from bare quantities computed on the lattice, to obtain physical observables. It is thus mandatory to make meaningful predictions of observables

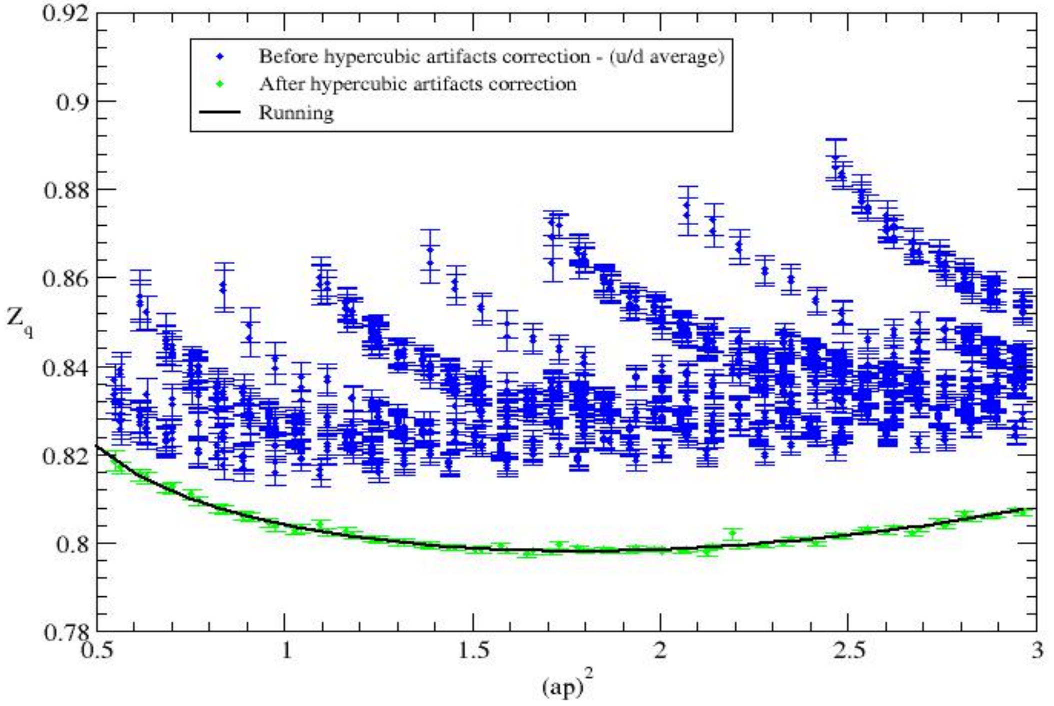
- Direct influence of the accuracy of $Z_{\mathcal{O}}$ on observables

Large program of RCs computation using RI-MOM type schemes developed in L.P.S.C. since several years

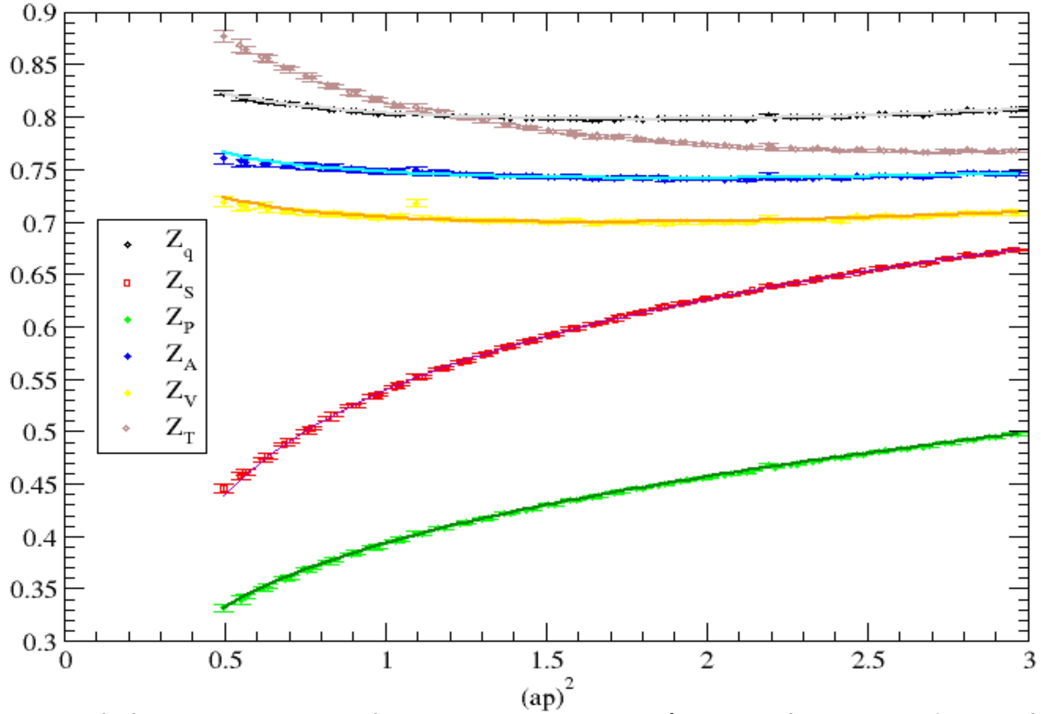
Dealing with lattice artifacts: an example of challenge to face

Treatment of lattice hypercubic artifacts

- Scalar quantities in the continuum: $Z(p^2)$ rotationally invariant (*O(4)* group)
- Scalar quantities on an hypercube : $Z(p^2, p^{[4]}, p^{[6]}, p^{[8]}, ...)$ (*H(4)* group) → lattice artifacts
- Illustration *see also B. Blossier et al, Phys.Rev. D91 (2015) no.11, 114507)*



Quark renormalisation constant Zq vs $(ap)^2$ before (blue points) and after (green points) hypercubic artifacts correction



Fermion bilinear renormalisation constants (Zq, scalar, pseudo-scalar, axial, vector, tensor) vs $(ap)^2$ after hypercubic artifacts correction + running

Conclusion

- Importance of Nucleon physics for understanding QCD
- Also crucial for New Physics
- K. Wilson (Lattice 1989, Capri): «One lesson is that LQCD could require a 10^8 increase of computing power AND spectacular algorithmic advances before ... interaction with experiment takes place ».

At that time, a supercomputer would offer 20 Gflops + « Moore's laws » → 10^8 = 40 years

→ we are somehow 10 years in advance

- Exciting time for LQCD, with many developments and exp./th. comparisons to come in the next few years
- Developing « strong interactions » between L.P.S.C. and Tsukuba University would be very fruitful

Thank you for your attention