Precise tests of the Standard Model from Lattice QCD

Bipasha Chakraborty

Jefferson Lab, 8th Jan, 2016

Background

University of Calcutta
Degree : B.Sc (Hons); M.Sc
Subject : Physics
Specialisation: Particle physics

University of Kentucky
Degree: MS
Research : Proton Spin puzzle using lattice QCD
Supervisor : Prof. Keh-Fei Liu
Collaboration : χQCD
Phys.Rev. D91 (2015) 1, 014505

PhD achievements

University of Glasgow

Topics

- Muon g-2
- Semileptonic decay
- Meson spectroscopy
- Quark mass tuning
- Non-perturbative renormalisation of lattice currents.

Invited talks

- **University of Cambridge** Nov, 2015
- **Swansea University** May, 2015
- **Excited QCD *2015*** Slovakia, March 2015
- **Durham University (plenary)** (DiRAC Day –Sept, 2014)

Publications

1. **Phys. Rev. D** 91 (2015) 5, 054508 (Editor's suggestion)
2. **Phys. Rev. D** 89, 114501 (2014)
3. arXiv:1512.03270 (submitted to **Phys. Rev. D**)
4. 2 in preparation
5. 5 proceedings

Funding

- **Lord Kelvin Scholarship**.
- **Gilmour Scholarship**
- European Commission’s Seventh Framework Programme (**FP7**) under **STRONGnet**, a **Marie Curie Initial Training Network** (ITN)

Communication with young physicists:

- Lab, recitation, demonstration for undergraduates
- Graduate level QFT grader
- Co-supervision - master's and junior PhD research students

Communication with public:

- University open days
- Royal Society master classes for high schoolers
- Science Slam 2015, Glasgow
- Explorathon'14 and Explorathon'15, European Researchers' Night, Scotland, funded by the European commission MARIE CURIE ACTIONS programme
- Research presentation organised by the Scottish Federation of University Women

Organisation: UK national conferences -

- Young Experimentalist And Theorist Institute - YETI'16, IPPP, Durham
- Young Theorists' Forum, Annual High Energy Physics Conference, Durham

Precision tests of the Standard Model using lattice QCD

Muon g-2: Hadronic vacuum polarisation from lattice QCD

Phys. Rev. D 89, 114501 (2014); arXiv:1512.03270 (submitted to **Phys. Rev. D**)

Semileptonic decay of mesons: D to K l ν ; scalar and vector form factors, V_{cs}

Meson mass and decay constants

Vector mesons: ϕ, ρ, j/ψ, K*

Pseudoscalar : η_s , π, K, η_c , D, K

Proton Spin Puzzle

Phys.Rev. D 91 (2015) 1, 014505

MS

Code writing and data analysis

PhD

Testing, planning resources, writing scripts and modifying MILC codes, data generation (2-pt, 3-pt), data analysis : risk analysis, co-ordination and back up plans

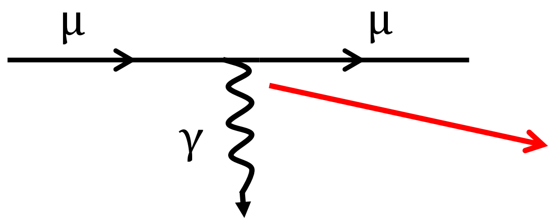
Important ingredients :

- Quark mass tuning [**Phys. Rev. D**91 (2015) 5, 054508 (Editor's suggestion)]
- Renormalisation of currents (non-perturbative)

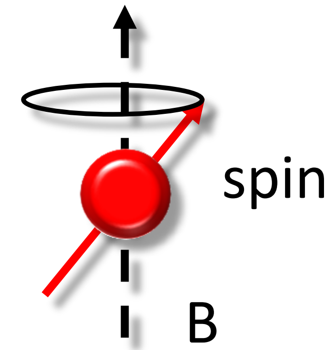
Hadronic vacuum polarisation contribution to the muon anomalous magnetic moment from lattice QCD

Relevance and Timeliness

$$\vec{\mu} = g\frac{e}{2m}\vec{S} \qquad a_\mu = \frac{g-2}{2}$$



g = 2



a_μ^{exp} = **11 659 208.9 (63)** $\times\ 10^{-10}$ **(0.54 ppm)**

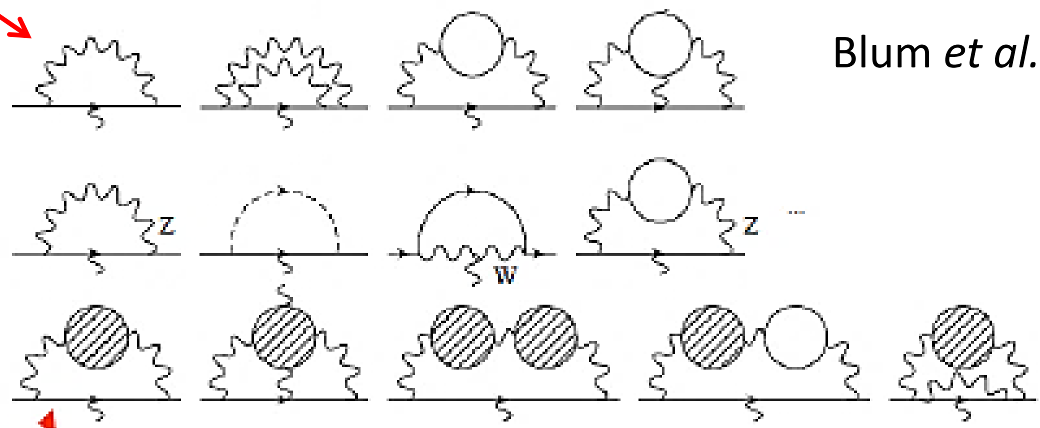
a_μ^{SM} = **11 659 182.8 (49)** $\times\ 10^{-10}$ **(0.42 ppm)**

a_μ^{exp} - $a_\mu^{SM} = 26.1(8) \times\ 10^{-10}$ 3+σ !

Expt. at FNAL & J-PARC will reduce uncertainty to 0.16 ppm starting 2017

Current theoretical status of muon g-2

$$\frac{\alpha_{QED}}{2\pi} = 0.00116$$



Blum *et al.* 1301.2607

QED, EW & QCD Contributes; QED dominates

LO Hadronic vacuum polarisation (HVP)

Contribution	Result ($\times 10^{-10}$)	Error
QED (leptons)	11658471.8	0.00 ppm
HVP(lo) [1]	692.3	0.36 ppm
HVP(ho)	-9.8	0.01 ppm
HLbL [2]	10.5	0.22 ppm
EW	15.4	0.02 ppm
Total SM	11659180.2	0.42 ppm

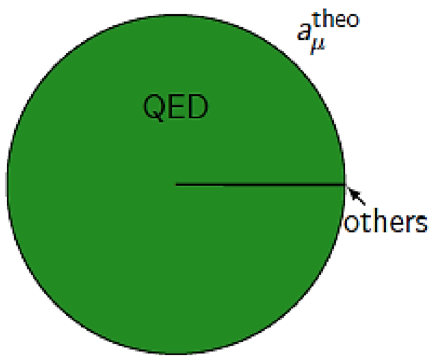


Fig. a: Result

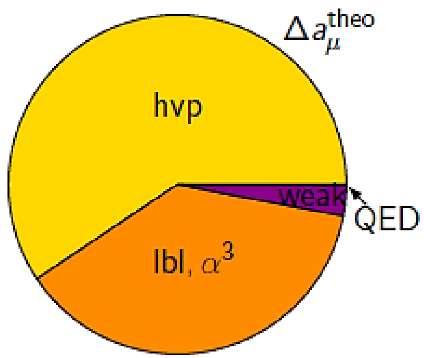


Fig. b: Error

[1] Davier *et al.* Eur. Phys. J. C71 (2011) 1515

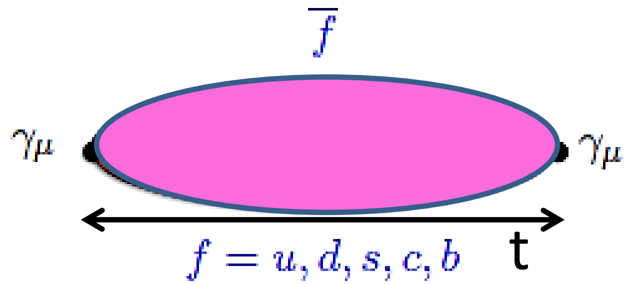
[2] Prades, de Rafael, Vainshtein, 0901.0306

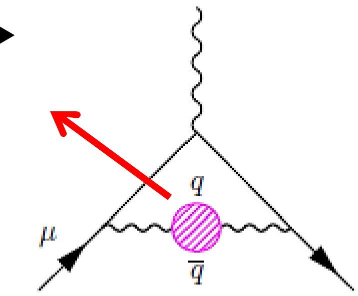
HVP from lattice QCD

Target : better than 1% in HVP

In Euclidean space,

connected contribution for flavour *i*





Blum, hep-lat/0212018

$$a_\mu^{HVP,i} = \frac{\alpha}{\pi} \int_0^\infty dq^2 f(q^2)(4\pi\alpha e_i^2)\hat{\Pi}_i\,(q^2)$$

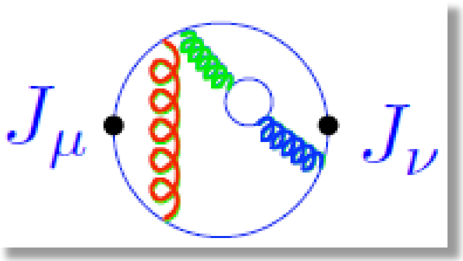
On lattice

$f(q^2)$ known, divergent function of q^2

Renormalised Vacuum Polarisation function: $\hat{\Pi}(q^2) = \Pi(q^2) - \Pi(0)$

Integrand strongly peaked at $q^2 \sim \frac{m_\mu^2}{4} \sim 0.003$ GeV²

HPQCD method for HVP calculation



Calculate correlation function on lattice

$$\langle j^j(\vec{x},t) j^j(0)\rangle$$

Time moments of lattice current-current correlators

$$G_{2n} \equiv a^4 \sum_t \sum_{\vec{x}} t^{2n} Z_V^2 \langle j^j(\vec{x},t) j^j(0)\rangle$$

$$= (-1)^n \frac{\partial^{2n}}{\partial q^{2n}} q^2 \hat{\Pi}(q^2)\Big|_{q^2=0}$$

$\hat{\Pi}(q^2) = \sum_{j=1}^{\infty} q^{2j} \Pi_j$ with $\Pi_j = (-1)^{j+1} \frac{G_{2j+2}}{(2j+2)!}$

Use Pade approximant (ratio of m/n polynomials) for better q^2 behaviour

Allows us to reconstruct $\hat{\Pi}(q^2)$ and integrate

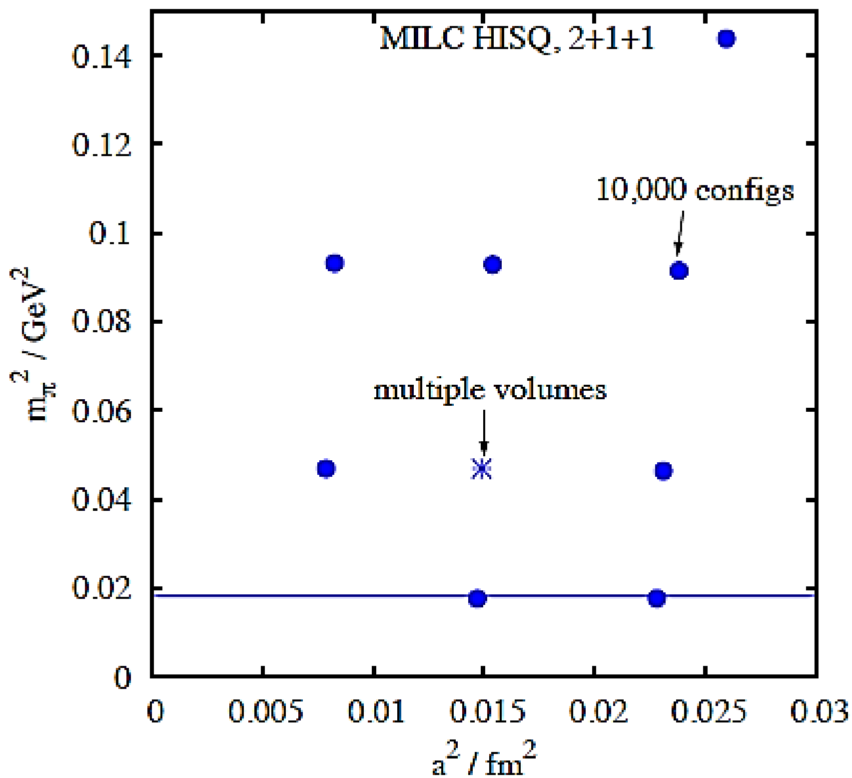
Analysis Ingredients

MILC configurations : up/down, strange, charm quarks in the sea

$m_u = m_d$

Multiple $m_{u/d}$
Including physical

Valence quark
Masses tuned
accurately



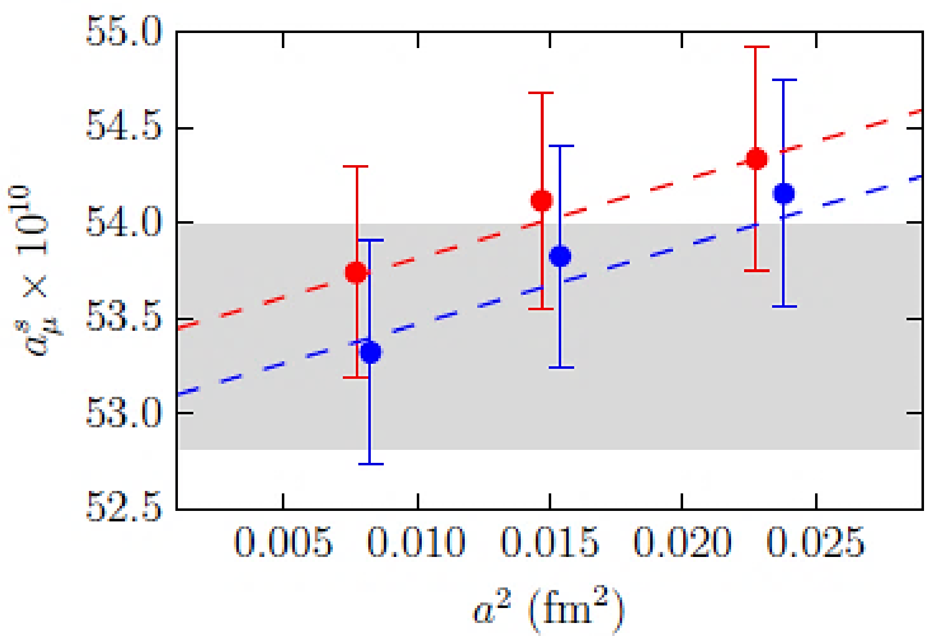
Lattice spacing
a ~ 0.09 -0.15 fm

Multiple volumes
~ (5-6 fm)^3

High statistics:
10,000 configurations
on coarsest lattice

Vector current renormalisation Z_V
calculated nonperturbatively
with high precision

Strange quark contribution to HVP



	a_μ^s
Uncertainty in lattice spacing (w_0, r_1):	1.0%
Uncertainty in Z_V:	0.4%
Monte Carlo statistics:	0.1%
$a^2 \to 0$ extrapolation:	0.1%
QED corrections:	0.1%
Quark mass tuning:	0.0%
Finite lattice volume:	$< 0.1\%$
Padé approximants:	$< 0.1\%$
Total:	1.1%

$$a^s_{\mu,lat} = a^s_\mu \times \left(1 + c_{a^2}\left(\frac{a\Lambda_{QCD}}{\pi}\right)^2 + c_{sea}\delta x_{sea} + c_{val}\delta x_{val}\right)$$

With $m^{lat}_{u/d} = m^{phys}_{u/d}$, after extrapolation to $a = 0$

$$a^s_\mu = 53.41(59) \times 10^{-10}$$

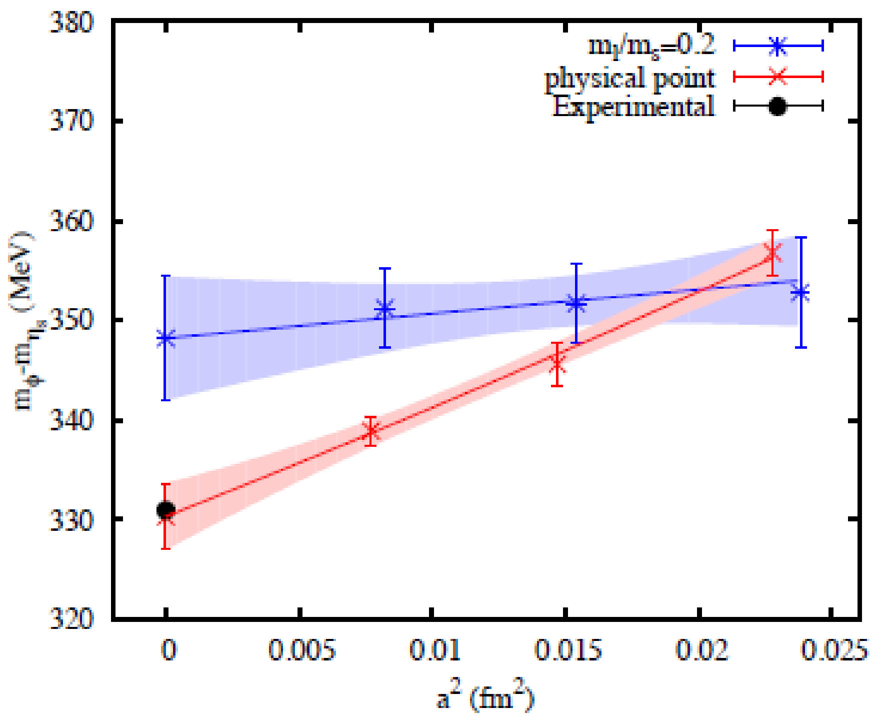
B. Chakraborty *et al., Phys. Rev. D* ***89,*** *114501 (2014)*

Check strange-strange vector correlators

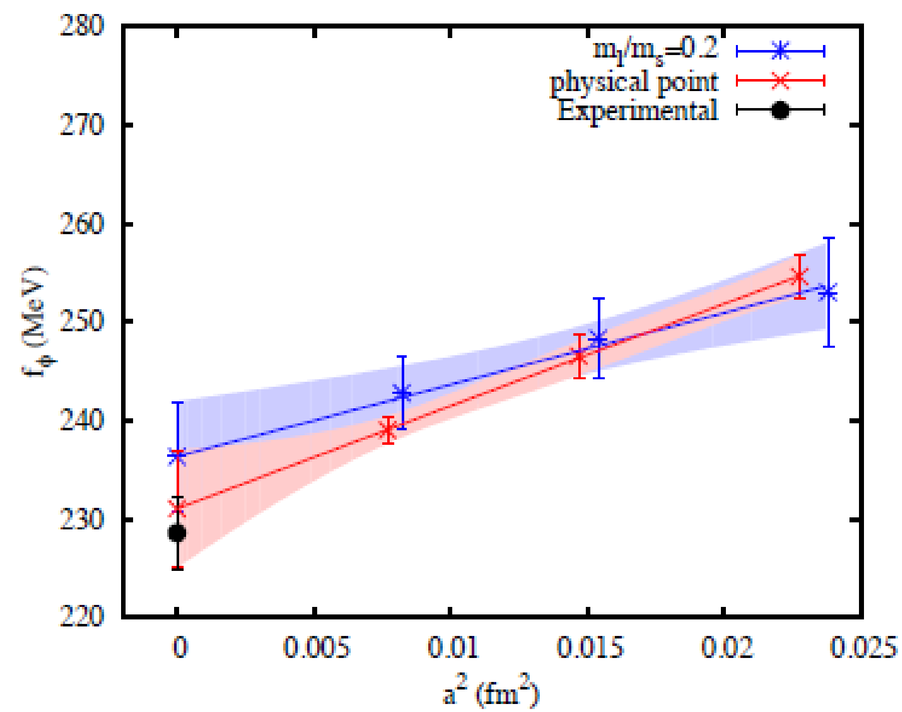
At large time : **Correlator** $\sim Ae^{-mt}$

ϕ-meson mass

Related to decay constant (annihilation amplitude)



Experimental $\Gamma(\phi \to e^+ + e^-)$ used for f_ϕ



Light quark (connected) contribution to HVP

Additional challenges:
1. Noisy data
2. Finite volume error
3. ππ contribution

New ingredient to handle noisy data:

$$G(t) = \begin{cases} G_{data}(t), & t \leq t^* \\ G_{fit}(t), & t > t^* \end{cases}$$

From Monte Carlo

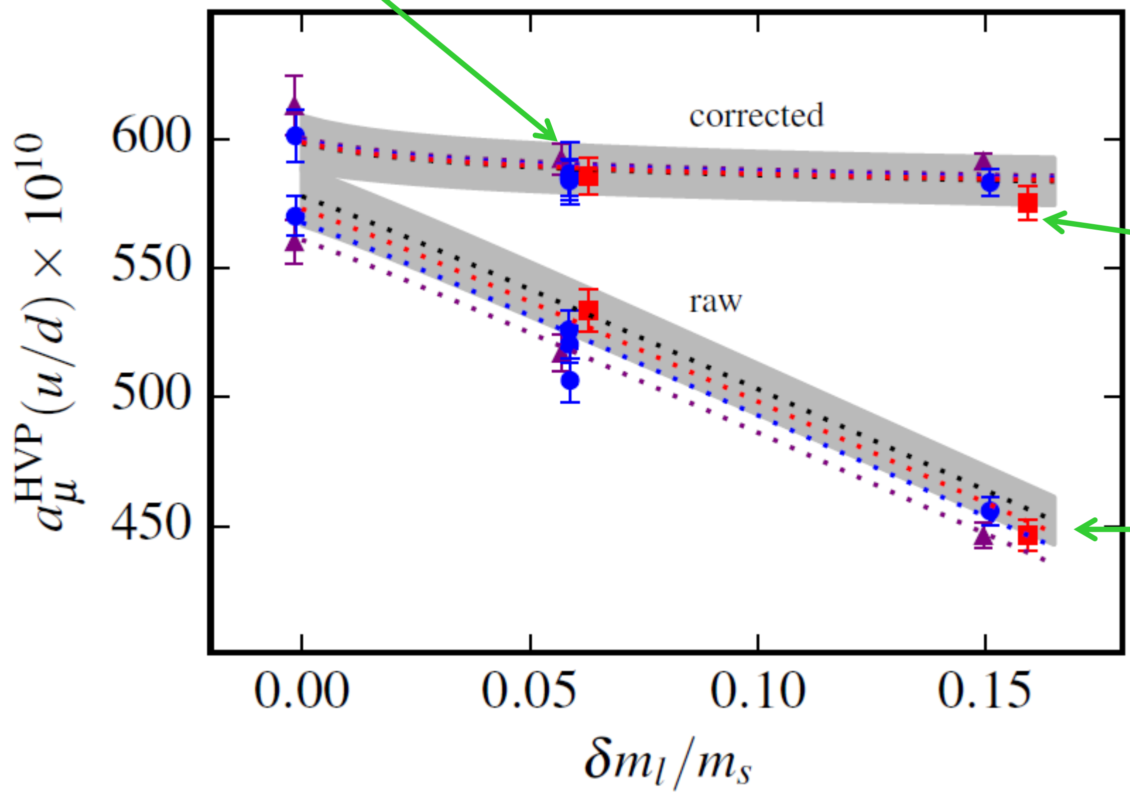
From multi-exponential fit

$t^* = 1.5fm = 6/\rho$

\+ **Smearings at source-sink**

$m_u = m_d$

Multiple volumes



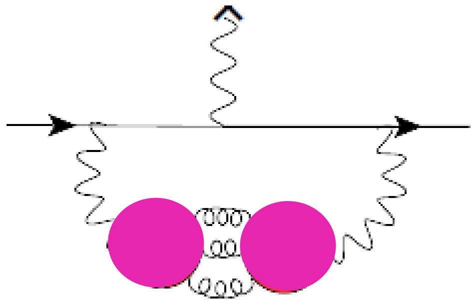
Ensemble size **10,000**

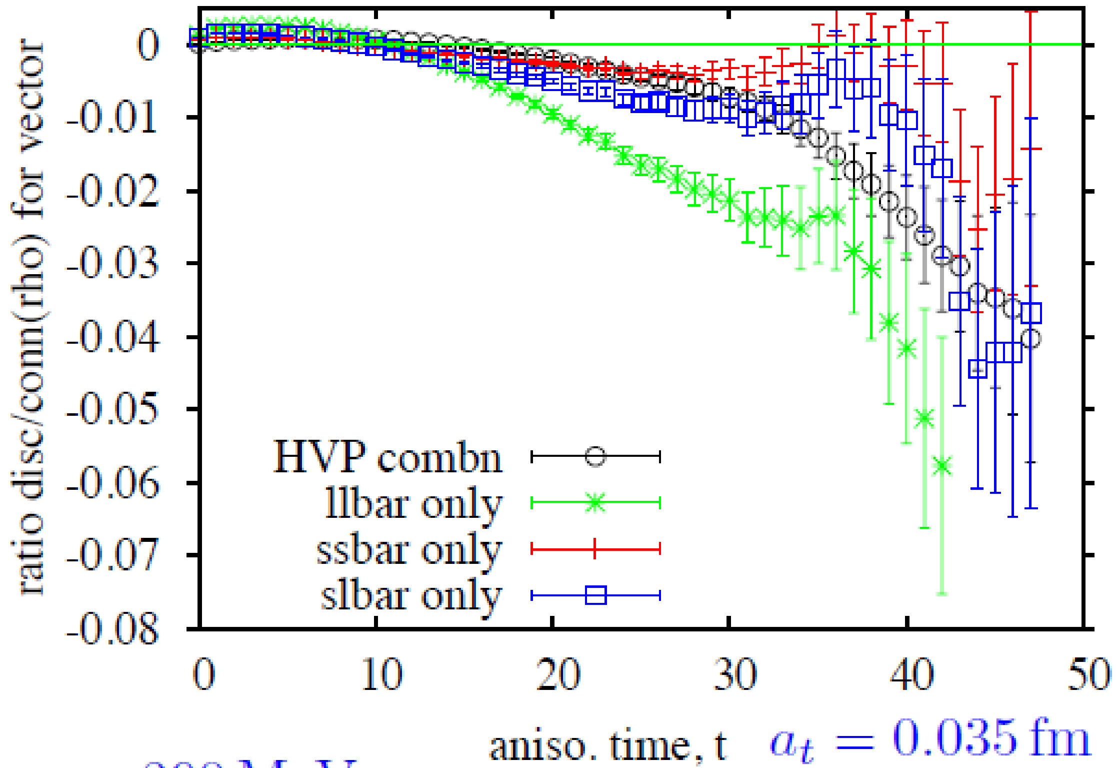
Finite volume Error, no corrections for Pion mass

Quark-line disconnected contribution

Vanishes if $m_u = m_d = m_s$

since, $\sum_i e_i = 0$





$m_\pi = 390$ MeV

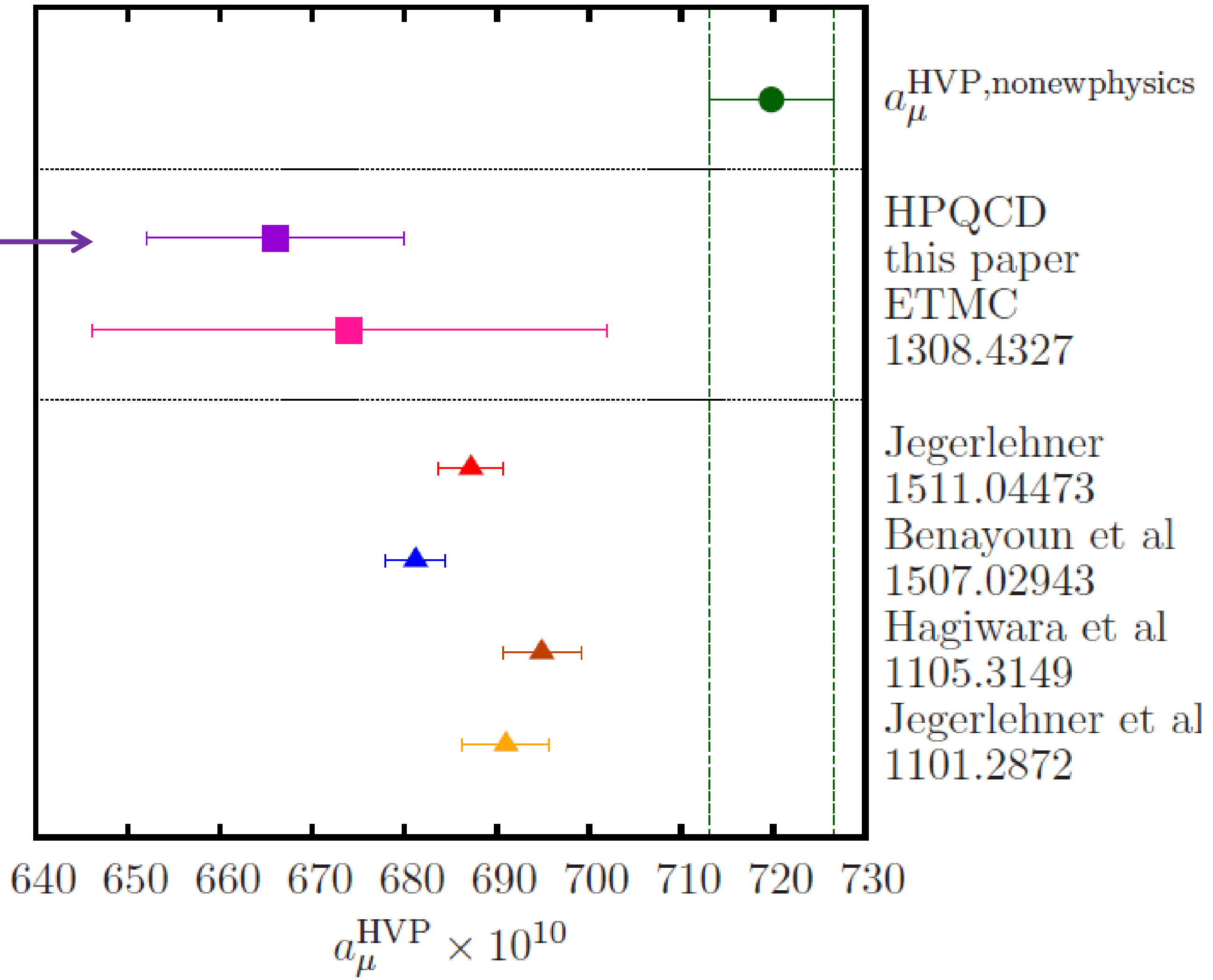
HVP disconnected contribution :

- Negative
- 0.2(1.5)% of the connected

Hadron Spectrum + HPQCD arXiv: 1512.03270 (submitted to Phys. Rev. D)

Lattice – Continuum comparison

3.5σ from no new physics

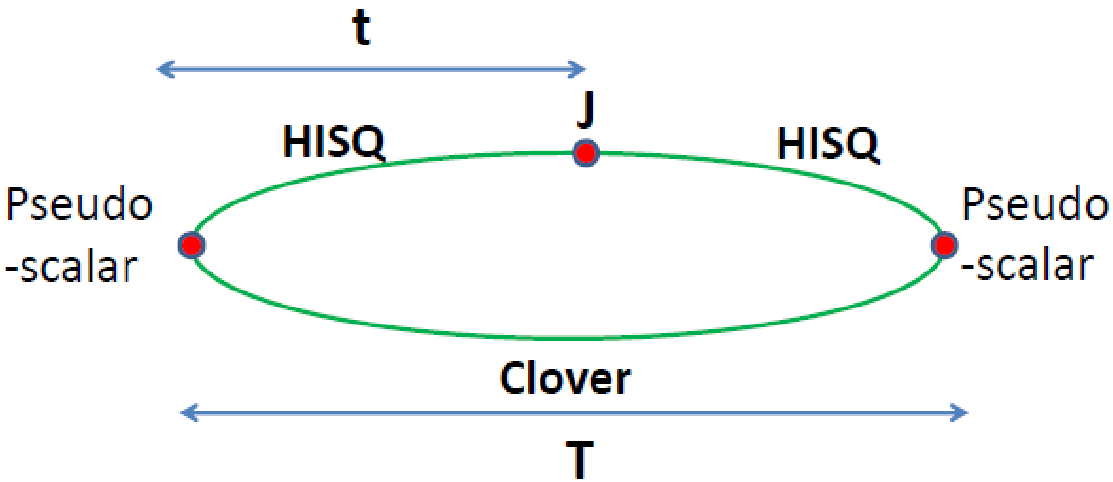


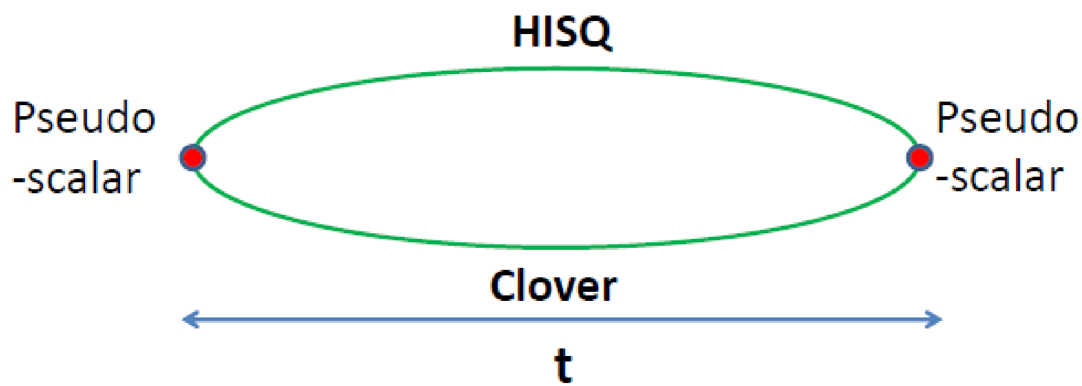
Lattice calculation using u,d,s,c sea quarks + physical valence quarks

In future : Increase statistics, QED and isospin effects, disconnected piece

More Calculations underway (Mainz, BMW, RBC/UKQCD, …)

Nonperturbative renormalisation of vector currents



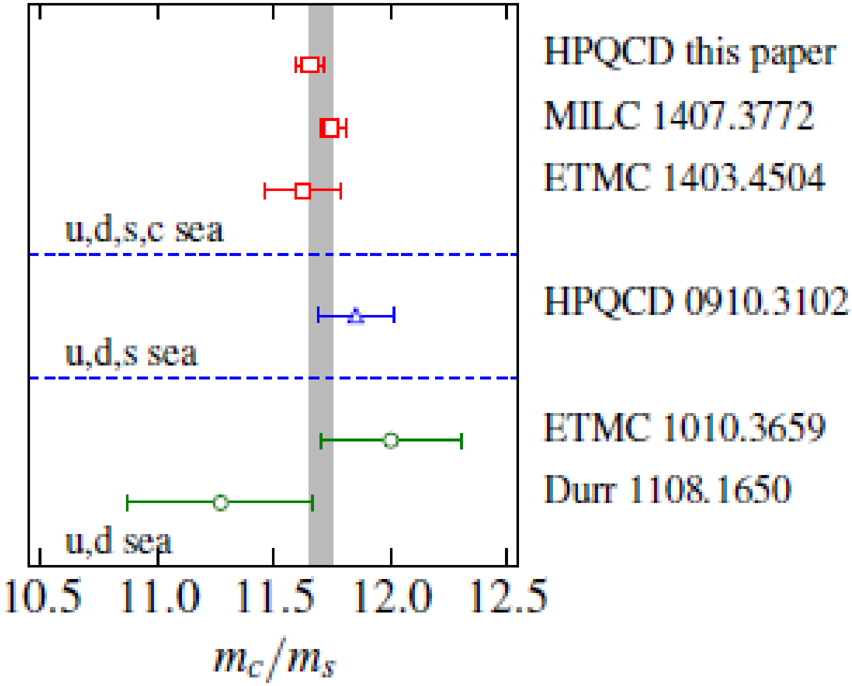


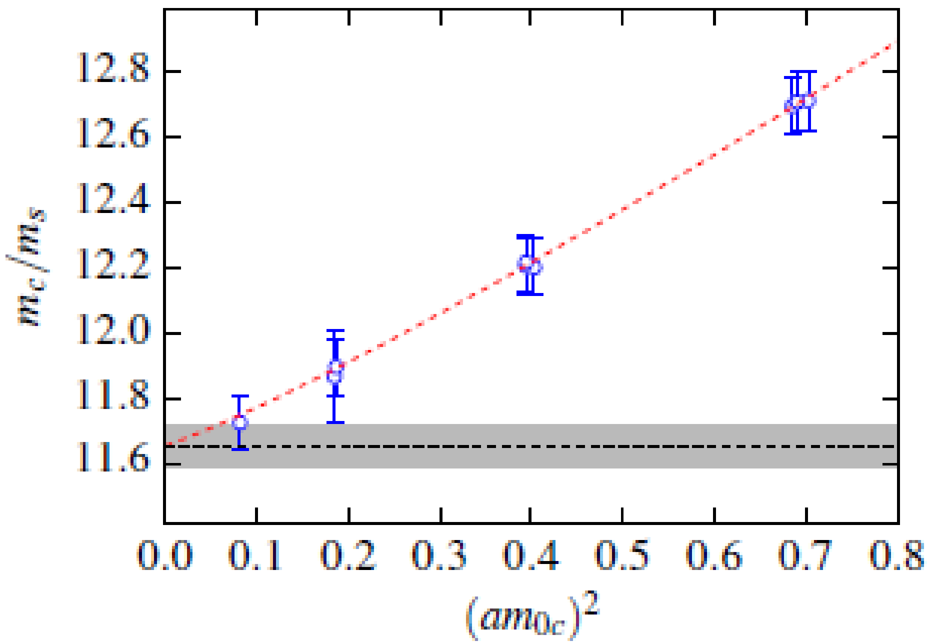
$$1 = Z_{V^4_{\bar{q}q}} \langle H_q | V^4_{\bar{q}q} | H_q \rangle$$

B. Chakraborty et. al, PoSLATTICE 2013, 309

Quark mass tuning

$$m_{\overline{MS}}(\mu) = Z(a\mu)m_{latt}$$





$$\left.(m_{q1,latt}) \middle/ (m_{q2,latt})_{a=0}\right. = \left. m_{q1,\overline{MS}}(\mu) \middle/ m_{q2,\overline{MS}}(\mu)\right.$$

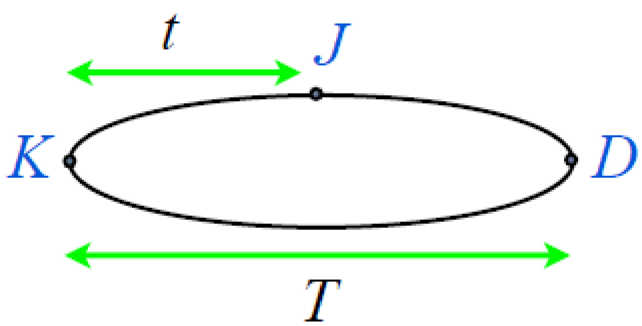
$m_s^{\overline{MS}}(2\text{ GeV}) = 92.2(13)\text{MeV}$

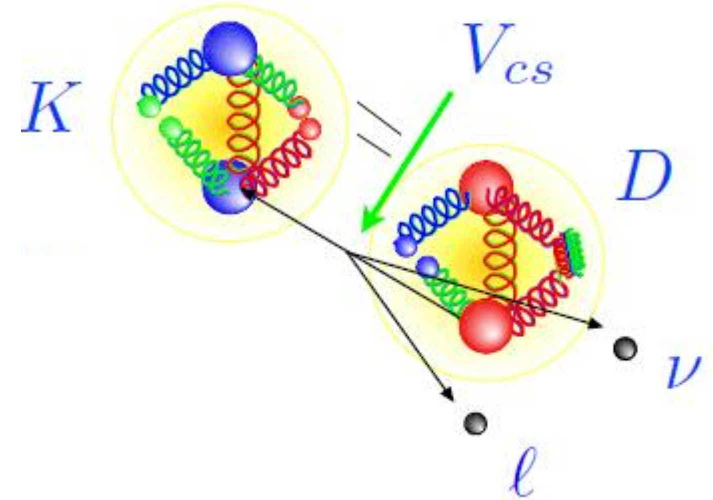
Phys. Rev. D 91 (2015) 5, 054508

Flavour physics

Semileptonic decay : form factors; V_{cs}

$$\frac{d\Gamma^{D\to K}}{dq^2} = \frac{G_F^2 p^3}{24\pi^3}|V_{CS}|^2|f_+^{D\to K}(q^2)|^2$$





$$q^\mu = p_D^\mu - p_K^\mu$$

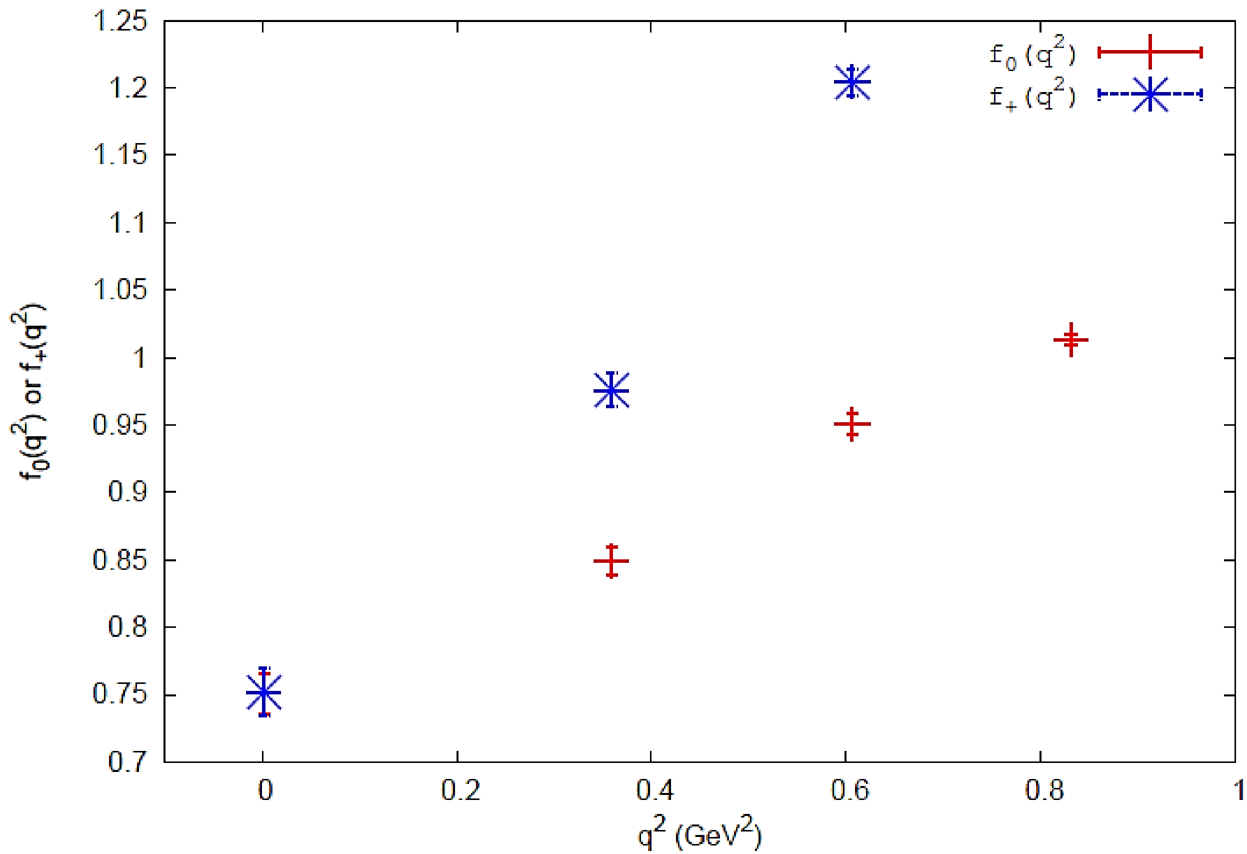
Twisted B.C.

$$\langle K|S|D\rangle = f_0^{D\to K}(q^2)\frac{M_D^2 - M_K^2}{m_{0_C} - m_{0_S}}$$

$$\langle K|V^\mu|D\rangle = f_+^{D\to K}(q^2)\left[p_D^\mu + p_K^\mu - \frac{M_D^2 - M_K^2}{q^2}q^\mu\right]$$

$$+f_0^{D\to K}(q^2)\frac{M_D^2-M_K^2}{q^2}q^\mu \quad \to f_0(0) = f_+(0)$$

Shape of the form factors : $D \to K l\nu$



- Chiral – continuum extrapolation
- Include bin-bin correlation

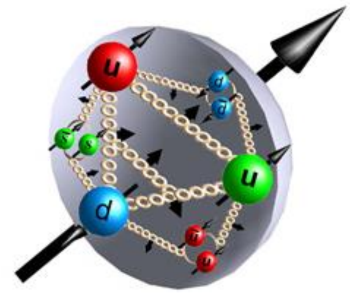
Transferable skills learned

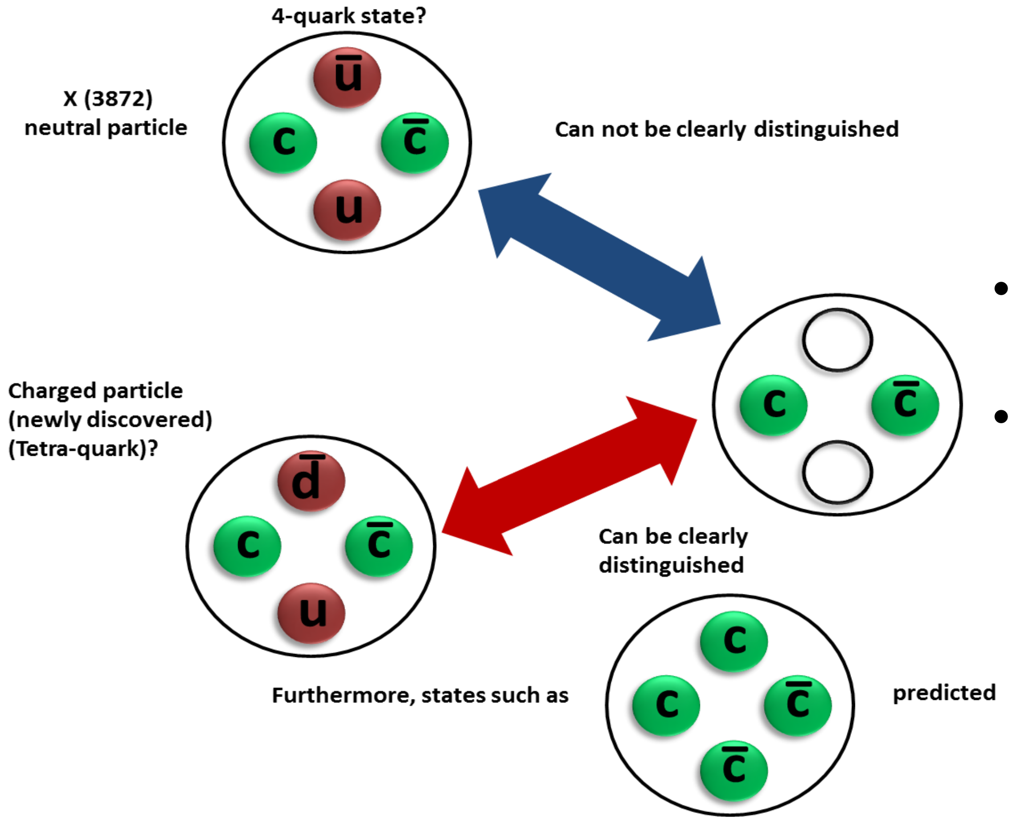
- C, C++, Python, Bash.
- Handling MILC codes, Corrfitter, lsqfit.
- Written data generation and analysis scripts.
- Data generation: propagators, 2-pt correlators, 3-pt correlators, sequential technique, local and non-local currents, HISQ and clover quarks, Gaussian smearings, disconnected correlators, all-to-all propagators method using random noise vector.
- Data analysis : Bayesian multi-exponential fit, generalised eigenvalue method, jacknife, bootstrap, z-expansion, chiral-continuum extrapolation, finite volume corrections.
- Testing, planning resources, risk analysis, co-ordination and back up plans.
- Integrating individual effort with collaborative effort.
- Handling multiple projects – time management and organisation.

Future Plans: relevant to 12 GeV upgrade at JLAB

Nucleons

- The helicity distribution of the constituents within the nucleon
- Calculating GPDs and TMDs – physical quark, chiral symmetry, finer lattices, larger volume, disconnected contribution





Mesons

- Spectroscopy of exotic mesons; radiative transitions.
- Application of scattering theory methods to the phenomenology of multi-hadron final states.

Acknowledgement

PhD Advisor: Prof. Christine Davies (Glasgow)

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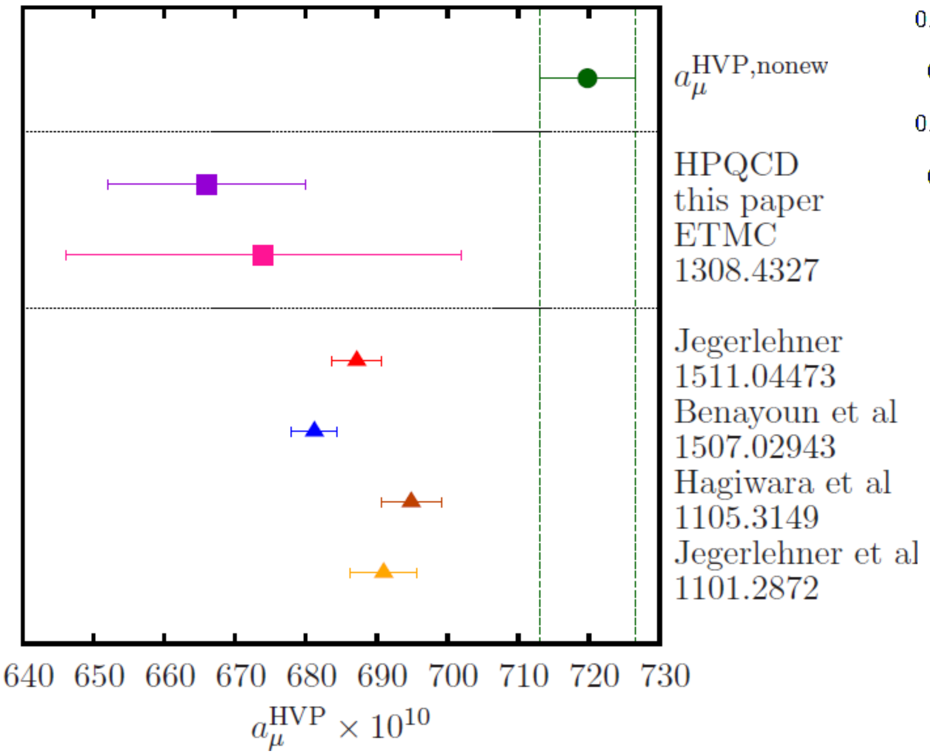
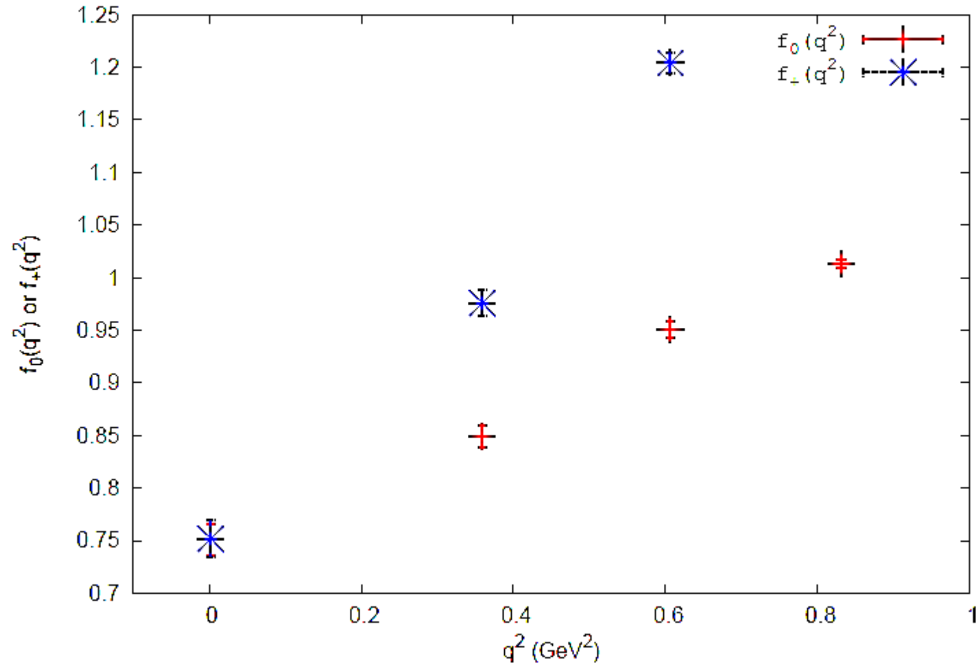
Prof. Mike Peardon (Dublin)
Prof. Sinead Ryan (Dublin)
Dr Thomas Teubner (Liverpool)

HVP contribution to the anomalous magnetic moment of muon





Form factors in D to K semileptonic decay