Pion form factor from RBC and UKQCD

CHIRAL DYNAMICS 2009

Andreas Jüttner
Institut für theoretische Kernphysik

This talk

- various talks on $f_{\pi\pi}(q^2)$ on the lattice

  G. Herdoiza, WG1 Mon 14:40,

  T. Kaneko, WG1 Mon 17:05,

  S. Aoki, Plenary, Wed 09:00

- new quality of lattice simulations:
  - $N_f \neq 0$ standard
  - small quark masses
  - small lattice spacings / large volume
  - improved momentum resolution
- here:
  - vector form factor $f_{\pi\pi}(q^2)$
  - simulations by RBC+UKQCD
  - very small space-like Q^2 region
  - applicability of chiral perturbation theory?

The pion vector form factor - non-lattice

$$\langle\pi(p')|V_\mu|\pi(p)\rangle = f_{\pi\pi}(q^2)(p+p')_\mu$$

- charge radius $\langle r_\pi^2\rangle_V = 6\frac{d}{dq^2}f_{\pi\pi}(q^2)$
- chiral perturbation theory NLO (SU(2), SU(3)) *J. Gasser & H. Leutwyler, Ann. Phys. 158 (1984) 142, Nucl. Phys., B250 (1985) 465*

$$\langle r_\pi^2\rangle_{\rm SU(3),NLO} = \frac{24L_9^r}{f_0^2} - \frac{1}{8\pi^2 f_0^2}\left(\log\frac{m_\pi^2}{\mu^2}+1\right) - \frac{1}{16\pi^2 f_0^2}\left(\log\frac{m_K^2}{\mu^2}+1\right)$$

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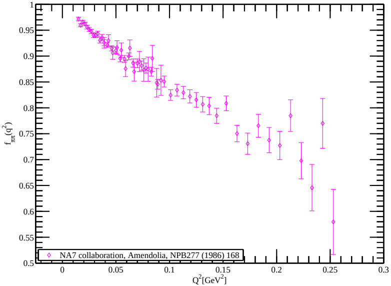
- experimental situation:



PDG average: $\langle r_\pi^2\rangle_V = 0.452(11)\mathrm{fm}^2$
Eschrich, Liesenfeld, Amendolia, Dally, Bebek, Quenzer

The pion form factor - lattice

$$\langle O\rangle|_{\rm QCD} = \frac{1}{Z}\int D[\bar{q},q,U]O\, e^{-S_{\rm QCD}}$$

- two- and three-pt. correlation functions: e.g.

$$C_3(\vec{p}',\vec{p},t) \rightarrow \frac{ZZ'}{2E(\vec{p}')E(\vec{p})}\langle\pi(p')|V_\mu|\pi(p)\rangle\left\{e^{-E(\vec{p})\dots}\dots\right\}$$

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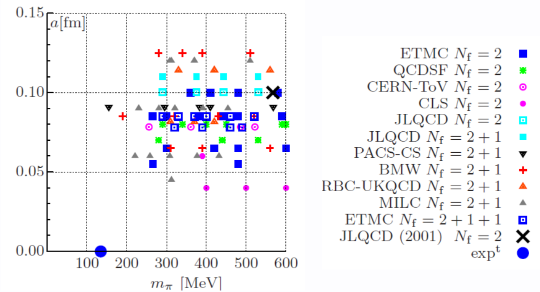
- 

a

m_q

$L \to \vec{p} = \vec{n}\frac{2\pi}{L}$

Kaon 09 talk by F. Mescia, plot by G. Herdoiza

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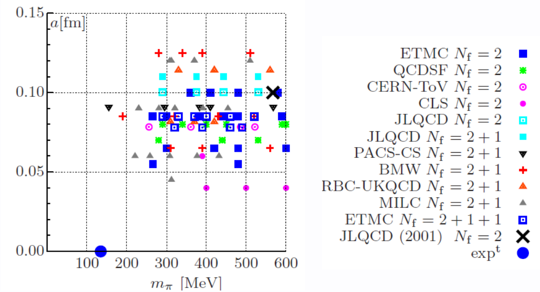
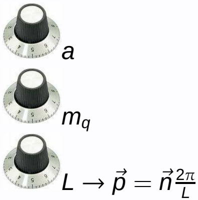
- 



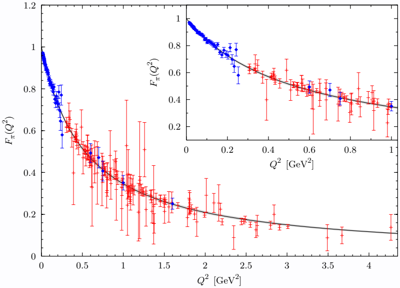
Kaon 09 talk by F. Mescia, plot by G. Herdoiza

- periodic boundary conditions for lattice fermions

$$q(x_i + \hat\mu L) = q(x_i) \to E(\vec p) = \sqrt{m_\pi^2 + (\vec n\tfrac{2\pi}{L})^2}$$

Form factors in a finite volume

- Lattice QCD results by QCDSF (2007) and experiment:



QCDSF Eur.Phys.J.C51:335-345,2007

- lower bound for accesible Q^2-values due to finite volume:

$$Q^2_{\mathrm{min}} = 2m_\pi(m_\pi - \sqrt{m_\pi^2 + (2\pi/L)})$$

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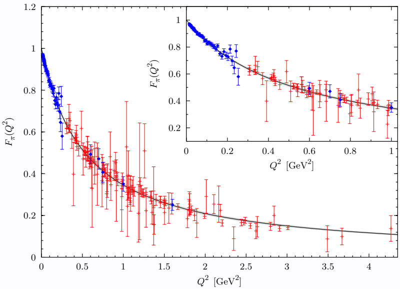

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- it is now possible to go below this bound ...

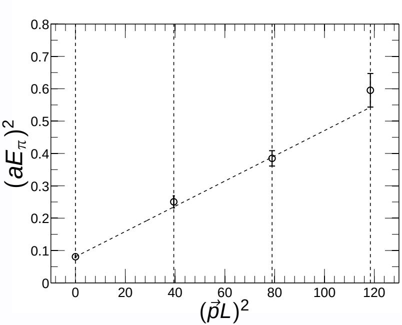
Twisted boundary conditions

periodic bc's

$$q(x_i + L) = q(x_i)$$

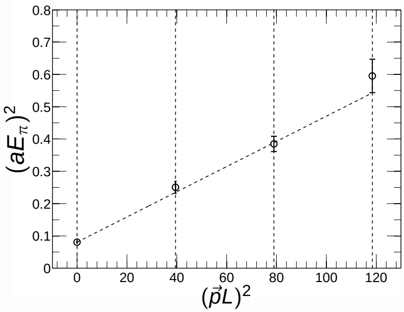
$$\vec{p}_{quark} = \vec{n}\frac{2\pi}{L}$$

$$E_\pi = \sqrt{m_\pi^2 + (\vec{n}\frac{2\pi}{L})^2}$$



Twisted boundary conditions

periodic bc's	twisted bc's
	Bedaque PLB539(2004) *Divitiis et al., PLB 595 (2004) 408* *Bedaque, Chen, PLB 616:208-214,2005* *Sachrajda, Viladoro, PLB 609:73-85,2005* *...*
$q(x_i + L) = q(x_i)$	$q(x_i + L) = e^{i\theta_i} q(x_i)$
$\vec{p}_{quark} = \vec{n}\frac{2\pi}{L}$	$\vec{p}_{quark} = \vec{n}\frac{2\pi}{L} + \frac{\vec{\theta}}{L}$
$E_\pi = \sqrt{m_\pi^2 + (\vec{n}\frac{2\pi}{L})^2}$	$E_\pi = \sqrt{m_\pi^2 + (\vec{n}\frac{2\pi}{L} + \frac{\vec{\theta}_u - \vec{\theta}_d}{L})^2}$



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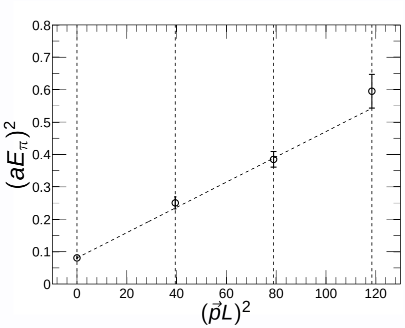

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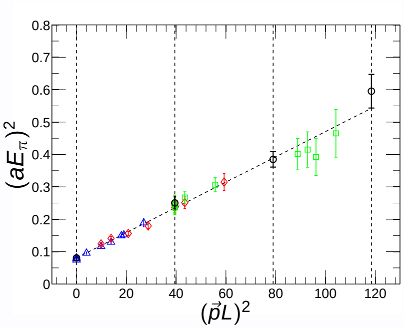

J. Flynn, A. J., C. Sachrajda, PLB 632:313-318, 2006

Twisted boundary conditions

- periodic fields $\tilde{q}(x)$: $\underbrace{q(x)}_{\text{twisted}} = \exp(i\Theta_i/Lx_i)\tilde{q}(x) = V(x)\underbrace{\tilde{q}(x)}_{\text{periodic}}$

$$\begin{aligned}\mathcal{L}_{\tilde{q}} &= \bar{\tilde{q}}(x)\left(\not{D} + (V^{\dagger}(x)\not{\partial}V(x)) + M\right)\tilde{q}(x) \\ &= \bar{\tilde{q}}(x)(\tilde{\not{D}} + M)\tilde{q}(x)\end{aligned}$$

  where $\tilde{D}_\mu = D_\mu + iB_\mu$ with $B_i = \Theta_i/L$ and $B_4 = 0$.
- free quarks in a constant background vector field

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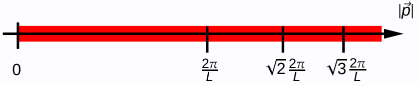
- free quarks in a constant background vector field
- Free twisted quark propagator:

$$\tilde{S}^{\text{free}}(x,\theta) \equiv \langle \tilde{q}(x)\bar{\tilde{q}}(0)\rangle|_\theta = \int \frac{dp_4}{2\pi}\frac{1}{L^3}\sum_{\vec{p}=\frac{2\pi}{L}\vec{n}} \frac{e^{ip\cdot x}}{i(\not{p}+\not{B})+M}$$

quark mom. $\vec{p}_{\text{lat}} = \frac{2\pi}{L}\vec{n} + \frac{\vec{\theta}}{L}$



Twisted goldstone bosons

- apply twisting to finite volume chiral effective theory:

$$\mathcal{L}^{(2)}_{\chi\mathrm{PT}}(\theta = 0) = \frac{f^2}{8}\mathrm{tr}\left[\left(\partial_\mu \Sigma^\dagger\right)\left(\partial^\mu \Sigma\right)\right] - \frac{f^2}{8}\mathrm{tr}\left[\Sigma^\dagger \chi + \chi^\dagger \Sigma\right]$$

  Construction of the twisted chiral Lagrangian:

$$\Sigma(x + \hat{i}L) = U_i \Sigma(x) U_i{}^\dagger \qquad \Sigma \text{ is } N_f \times N_f \text{ unitary}$$

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- reparametrize

$$\tilde{\Sigma}(x) = e^{-i\Theta\cdot x/L}\Sigma(x)e^{i\Theta\cdot x/L}$$

to get

$$\mathcal{L}^{(2)}_{\chi PT}(\theta) = \frac{f^2}{8}\mathrm{tr}\left[\tilde{D}^\mu\tilde{\Sigma}^\dagger\tilde{D}_\mu\tilde{\Sigma}\right] - \frac{f^2}{8}\mathrm{tr}\left[\tilde{\Sigma}\chi^\dagger + \chi\tilde{\Sigma}^\dagger\right]$$

where

$$\tilde{D}_\mu\tilde{\Sigma} = \partial_\mu\tilde{\Sigma} + i[B_\mu,\tilde{\Sigma}]$$

Twisted goldstone bosons

Effect of twist:

- neutral mesons:

$$[B_i, \pi^0] = 0 \rightarrow \text{no shift}$$

no effect on neutral pions

- charged mesons:

$$[B_i, \pi^\pm] = \pm \frac{\theta_{u,i} - \theta_{d,i}}{L} \pi^\pm$$

$$E_{\pi^\pm} = \sqrt{m_{\pi^\pm}^2 + (\vec{p}_{\text{lat}} - \frac{\vec{\theta}_u - \vec{\theta}_d}{L})^2}$$

Finite volume effects, partial twisting

- finite volume effects with twist

Sachrajda, Viladoro, PLB 609:73-85,2005

$$\xi^{\theta}{}_s(L,M) \quad = \quad \frac{1}{L^3}\sum_{\vec{k}} \frac{1}{(\vec{k}+\vec{\theta}/L)^2+M^2)^s} - \int \frac{d^3k}{(2\pi)^3}\frac{1}{(\vec{k}^2+M^2)^s} = \xi^{0}{}_s(L,M)\frac{\sum_i \cos(\theta_i)}{3}$$

$\xi_s^0(L,M) \approx e^{-LM}$ for ME with max. one particle in either initial or final state

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- partial quenching/twisting in QCD

$$\begin{aligned}\mathcal{Z}^{\rm PQ}_{\rm QCD} &= \int DU \prod_{Q=\{q_v,q_s,q_g\}} D\bar{Q}DQ\, e^{-S_{\rm YM}-\sum_{Q=\{q_v,q_s,q_g\}}\bar{Q}(\not{D}+m_Q)Q} \\ &= \int DU \prod_{N_V}\frac{(\det\not{D}(\theta_v)+m_v)}{(\det\not{D}(\theta_v)+m_v)}(\det\not{D}(\theta_s)+m_s)\, e^{-S_{\rm YM}}\end{aligned}$$

  - field theoretic frame work for correlation functions computed with sea quark mass m_s/twist θ_s and valence quark mass $m_v=m_g$/twist $\theta_v=\theta_g$
  - partial quenching/twisting can be studied in chiral perturbation theory: standard $SU(N)$-flavour group $\rightarrow SU(N_v+N|N_v)$

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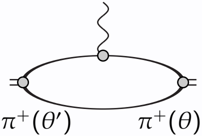
  - partial quenching/twisting can be studied in chiral perturbation theory: standard $SU(N)$-flavour group $\to SU(N_v + N|N_v)$
- expressions for FVE change only slightly

momentum can be tuned continously in practical simulations

Partially twisted bc's and the pion's vector form factor

- $$q^2 = (E_\pi(\theta') - E_\pi(\theta))^2 - \left(\frac{\vec{\theta}' - \vec{\theta}}{L}\right)^2$$



$\langle\pi^+(\vec{\theta}')|\bar{u}\gamma_\mu u|\pi^+(\vec{\theta})\rangle$

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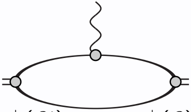

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F.-J. Jiang, B.C. Tiburzi PLB 645:314-321, 2007

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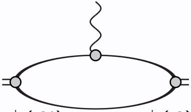

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$$\overset{\text{SU(3)}}{\underset{}{\overset{\text{PQ}}{=}}} \langle \pi^+(\vec{\theta}')|\bar{u}\gamma_\mu s|\bar{K}^0(\vec{\theta})\rangle$$

UKQCD JHEP 0705:016,2007

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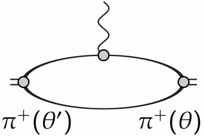

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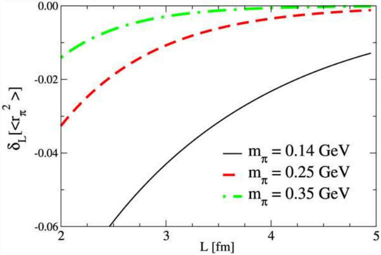
- finite volume effects (one pion at rest, the other one twisted)



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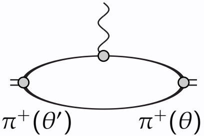

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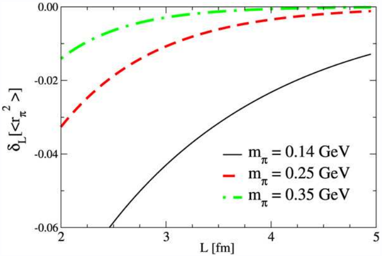
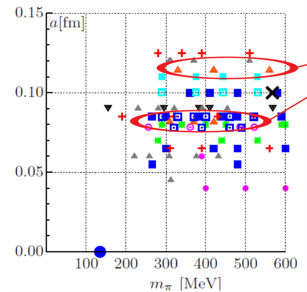


F.-J. Jiang, B.C. Tiburzi PLB 645:314-321, 2007

- choose q^2 arbitrarily small $\rightarrow$ compute charge radious without any phenomenological fit

RBC+UKQCD calculations of $f_{\pi\pi}(q^2)$



from Kaon 09 talk by F. Mescia, plot by G. Herdoiza

RBC+UKQCD simulation

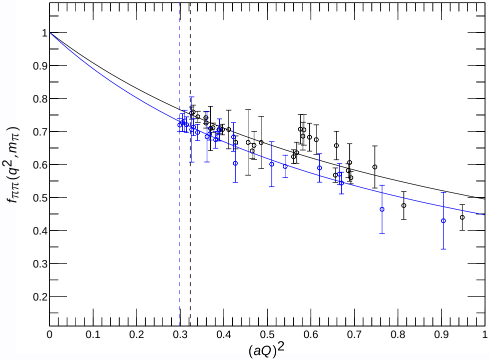
UKQCD+RBC PRD76:014504,2007,PRD, 78:114509,2008

- DWF
- $a \approx 0.11$fm & 0.09fm
- $m_\pi \gtrsim 300$MeV

First try:

$$\langle \pi(p')|V_\mu|\pi(p)\rangle = f_{\pi\pi}(q^2)(p+p')_\mu$$

- exploratory study by UKQCD $m_\pi = 590\text{MeV}$ $m_\pi = 480\text{MeV}$ $a = 0.11\text{fm}$, $L = 2\text{fm}$



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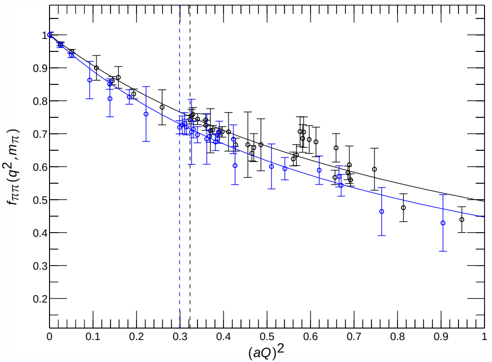

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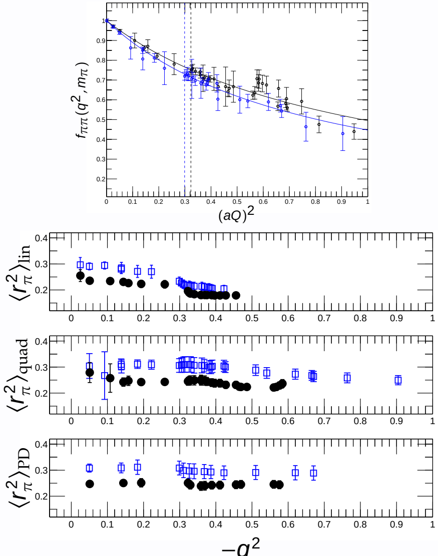
First try:

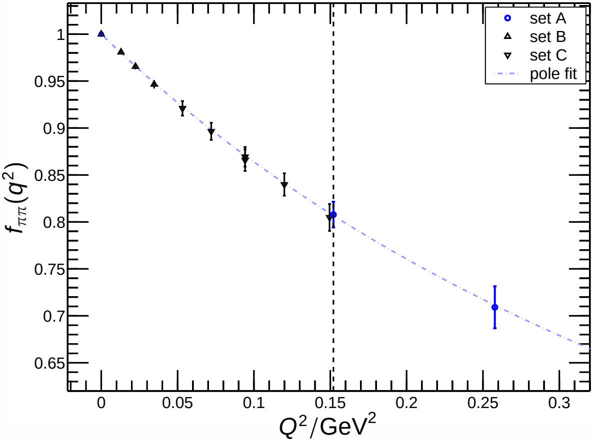
- exploratory study by UKQCD $m_\pi = 590\text{MeV}$ $m_\pi = 480\text{MeV}$ $a = 0.11\text{fm}$, $L = 2\text{fm}$



UKQCD JHEP 0705:016,2007

Closer to the real world ...

- UKQCD $m_\pi = 330\text{MeV}$ $a = 0.11\text{fm}$, $L = 2.7\text{fm}$



UKQCD JHEP 0807:112,2008

Fits

- currently we have results for only one pion mass $m_\pi = 330\text{MeV}$
- we fit the NLO ansatz $f_{\pi\pi}^{\mathrm{SU(2),NLO}}(q^2) = 1 + \frac{1}{f^2}\left[-2l_6^r q^2 + 4\tilde{\mathcal{H}}(m_\pi^2, q^2, \mu^2)\right]$

J. Gasser & H. Leutwyler Ann. Phys. 158 (1984) 142

further input: pion decay constant in the $SU(2)$ chiral limit $f = 115(8)$ MeV (normalisation s.t. $f_\pi^{\text{phys}} = 130.7(4)\text{MeV}$)

UKQCD+RBC Phys. Rev. Lett. 2008

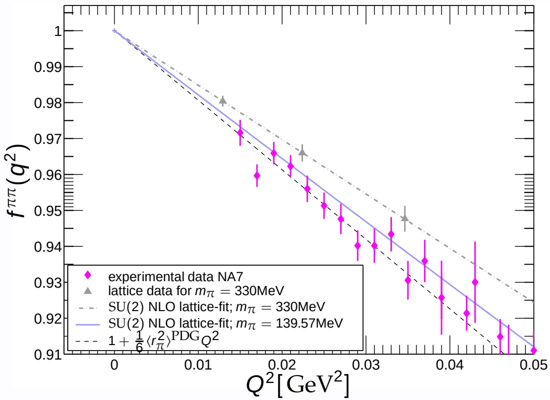
- this gives

$$l_6(m_\rho) = -0.0093(10)$$

$$\langle r_\pi^2\rangle|_{m_\pi=330\mathrm{MeV}} = 0.354(31)\text{fm}^2 \rightarrow \langle r_\pi^2\rangle = 0.418(31)\text{fm}^2$$

UKQCD JHEP 0807:112,2008

Summary of UKQCD results

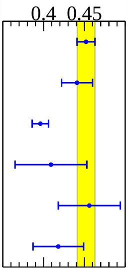


UKQCD arXiv:0804.3971

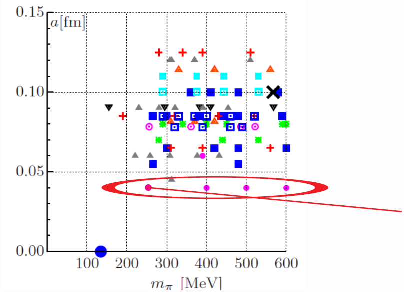
experimental data from NA7 Nucl. Phys. 1986

Results for the charge radius

collaboration		technique	$\langle r_\pi^2 \rangle_\chi [\mathrm{fm}^2]$
PDG			0.452(11)
QCDSF/UKQCD *EPJ C51 (2007) 335345*	$N_f = 2$	Clover	0.441(19)
JLQCD *hep-lat/0510085*	$N_f = 2$	Clover	0.396(10)
JLQCD *arXiv:0905.2465*	$N_f = 2$	Overlap	0.409(44)
ETM *arXiv:0812.4042*	$N_f = 2$	twisted mass	0.456(38)
RBC+UKQCD *JHEP 0807:112,2008*	$N_f = 2 + 1$	Domain Wall	0.418(31)



Mainz/CLS $N_f = 2$ effort



from Kaon 09 talk by F. Mescia, plots by G. Herdoiza

Coordinated Lattice Simulations (CLS) *Berlin, CERN, DESY-Zeuthen, Madrid, Mainz, Rome, Valencia*

- improved Wilson
- $a \gtrsim 0.04$fm
- $m_\pi \gtrsim 250$MeV (planned)

Discussion

- discussion (RBC+UKQCD)
  - 2nd (finer) lattice spacing under way
  - no statement on applicability of NLO χPT possible

    RBC+UKQCD: three/four unitary simulation points $am_\pi \gtrsim$ 300MeV on 0.1/0.09 fm lattices
  - not enough data points for NNLO (cf. ETM *arXiv:0812.4042*)
- interesting question
  - what is the influence of the vector resoncance? - is χPT the right theory for the simulated quark masses?