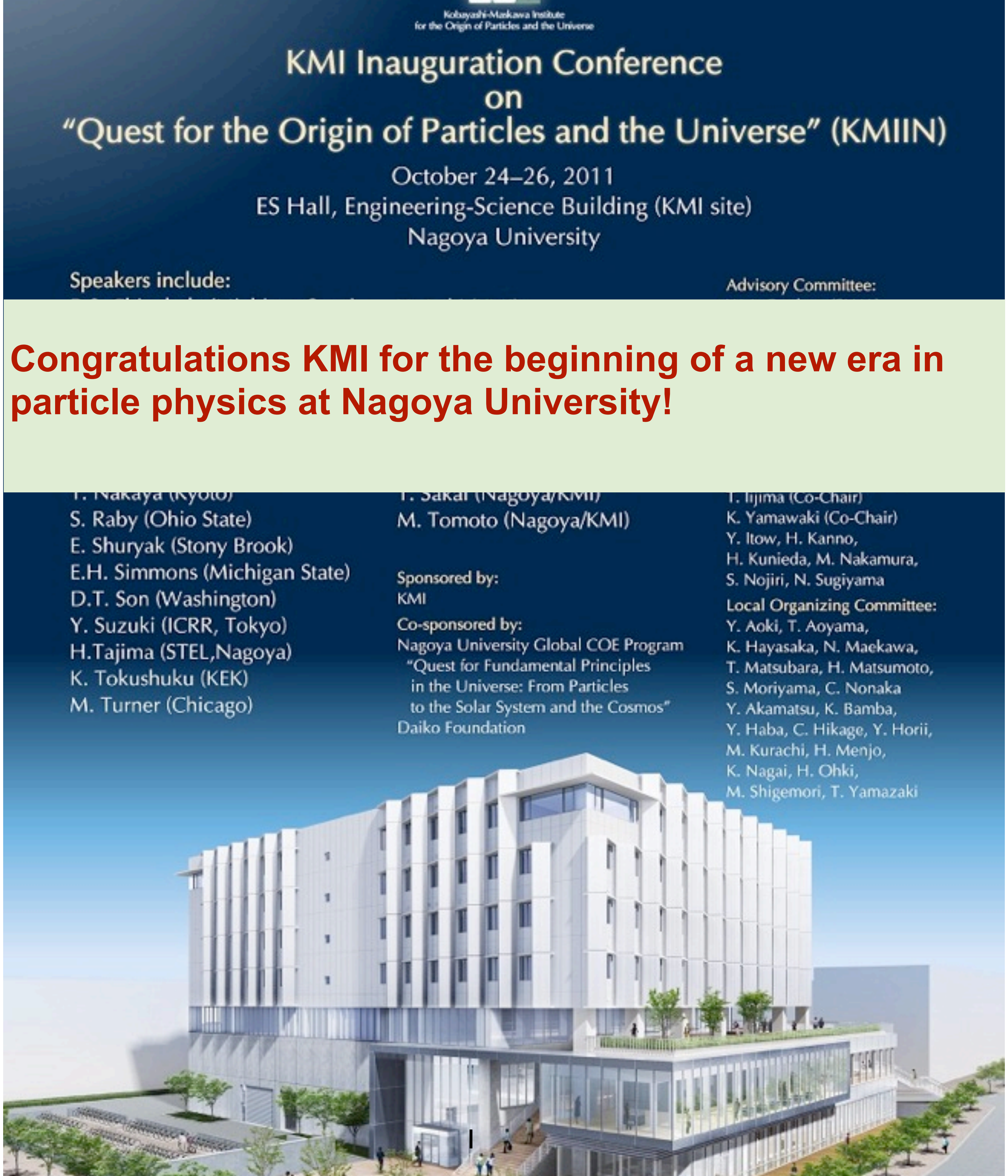


Congratulations KMI for the beginning of a new era in particle physics at Nagoya University!

Talking about compositeness in Nagoya is like bringing coal to Newcastle

Sakata:

On a Composite Model for the New Particles.
Shoichi Sakata (Nagoya U.). Sep 1956.
Published in **Prog.Theor.Phys. 16 (1956) 686-688**

Remarks on the unified model of elementary particles.
Ziro Maki, Masami Nakagawa, Shoichi Sakata (Nagoya U.). Nov 1962. 11 pp.
Published in **Prog.Theor.Phys. 28 (1962) 870-880**

CP Violation in the Renormalizable Theory of Weak Interaction.
Makoto Kobayashi, Toshihide Maskawa (Kyoto U.). KUNS-242. Feb 1973. 6 pp.
Published in **Prog.Theor.Phys. 49 (1973) 652-657**

The Nobels

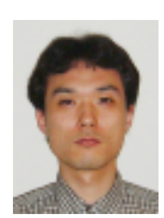
Conformal phase transition in gauge theories.
V.A. Miransky (BITP, Kiev & Nagoya U.), Koichi Yamawaki (Nagoya U.). DPNU-96-58. Nov 1996. 44 pp.
Published in **Phys.Rev. D55 (1997) 5051-5066**

YA, T.Aoyama, M.Kurachi, T.Maskawa, K.Nagai, H.Ohki,






K.Yamawaki, T.Yamazaki

名古屋大学

KMI lattice collaboration

computer bridge between generations?

Lattice Methods in the Theory Space Beyond the Standard Model

Julius Kuti

University of California, San Diego

Sakata Centennial Symposium, October 27-28, 2011

My colleagues in the Lattice Higgs Collaboration:

Zoltan Fodor, Kieran Holland, Daniel Nogradi, Chris Schroeder, Ricky Wong

What this talk is not: reviewing work from all lattice groups
only Lattice Higgs Collaboration (LHC) results

although good progress is being made by all groups

What this talk is: overview of lattice methods commonly faced in lattice work in theory space of strongly interacting gauge theories

Overall goal: SM Higgs $\Rightarrow$ Composite Higgs Mechanism
(Higgs without Higgs)

Lattice specific: cut-off, volume, fermion mass

Talk is mostly for off-lattice researchers
while they are thinking about making proposals for us

The 3 lattice specific “limitations” actually help to understand the basic physics of the models

Outline

- **Composite Higgs Mechanism at the LHC**
  lattice BSM goals in Theory Space
  world-wide lattice BSM effort
  lattice resources (GPU technology)

- **Below the Conformal Window**
  lattice specific: cut-off, volume, fermion mass
  RG flow and lattice continuum physics
  BSM specific χPT
  m=0 chiral limit and finite volume issues

- **Inside the conformal window**
  RG flow and lattice continuum physics
  finite size scaling
  running coupling and tunneling
  Nf=16 case study

- **Outlook**
  from KMIIN conference discussions: new input into lattice projects?

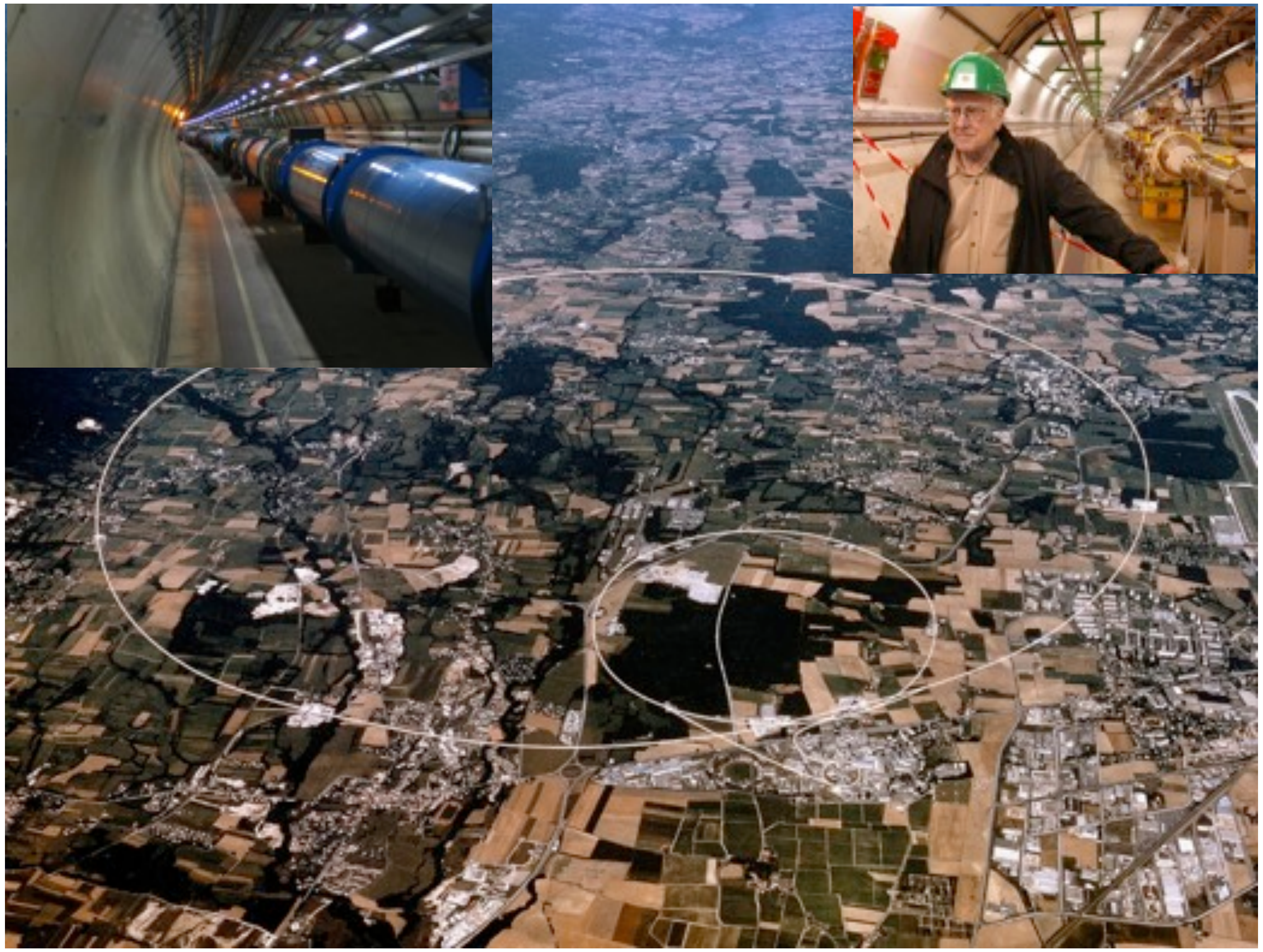
Large Hadron Collider - CERN

primary mission:

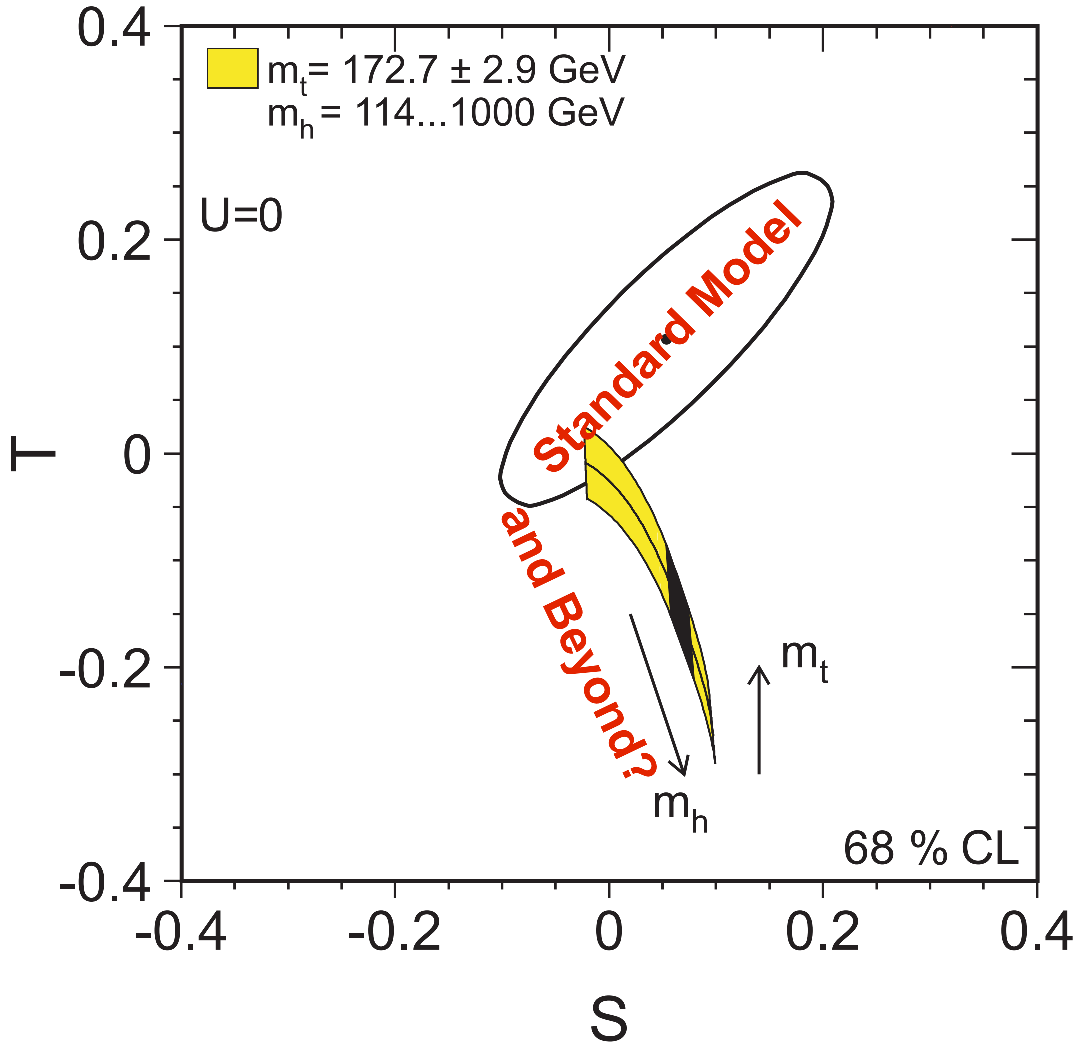
- Search for Higgs particle

- Origin of Electroweak symmetry breaking

- Is there a Standard Model Higgs particle?
- If not, what generates the masses of the weak bosons and fermions?
- New strong dynamics?
- Composite Higgs mechanism?



Primary focus of lattice BSM effort and of this talk



Two logical choices to accommodate heavy Higgs (or no Higgs) scenario:

- use some effective theory with TeV scale higher dimensional operators

- new microscopic theory on TeV scale

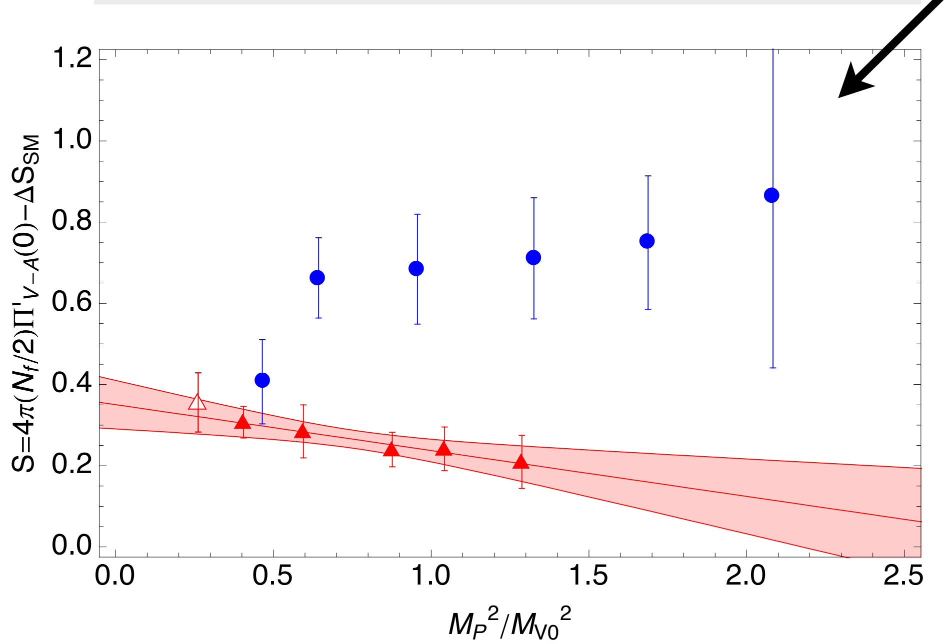
Composite Higgs mechanism - Technicolor 2.0 ?

- The paradigm is interesting again

- Requires non-perturbative lattice studies

- It is difficult, but there will be real results

Nf=2 and Nf=6 S-parameters
Lattice Strong Dynamics Collaboration (LSD)



Parity Doubling and the S Parameter Below the Conformal Window.
LSD Collaboration (Thomas Appelquist , Ron Babich, Richard C. Brower, Michael Cheng, Michael A. Clark, Saul D. Cohen, George T. Fleming, Joe Kiskis, Meifeng Lin, Ethan T. Neil, James C. Osborn, Claudio Rebbi, David Schaich, Pavlos Vranas) **Phys.Rev.Lett.**

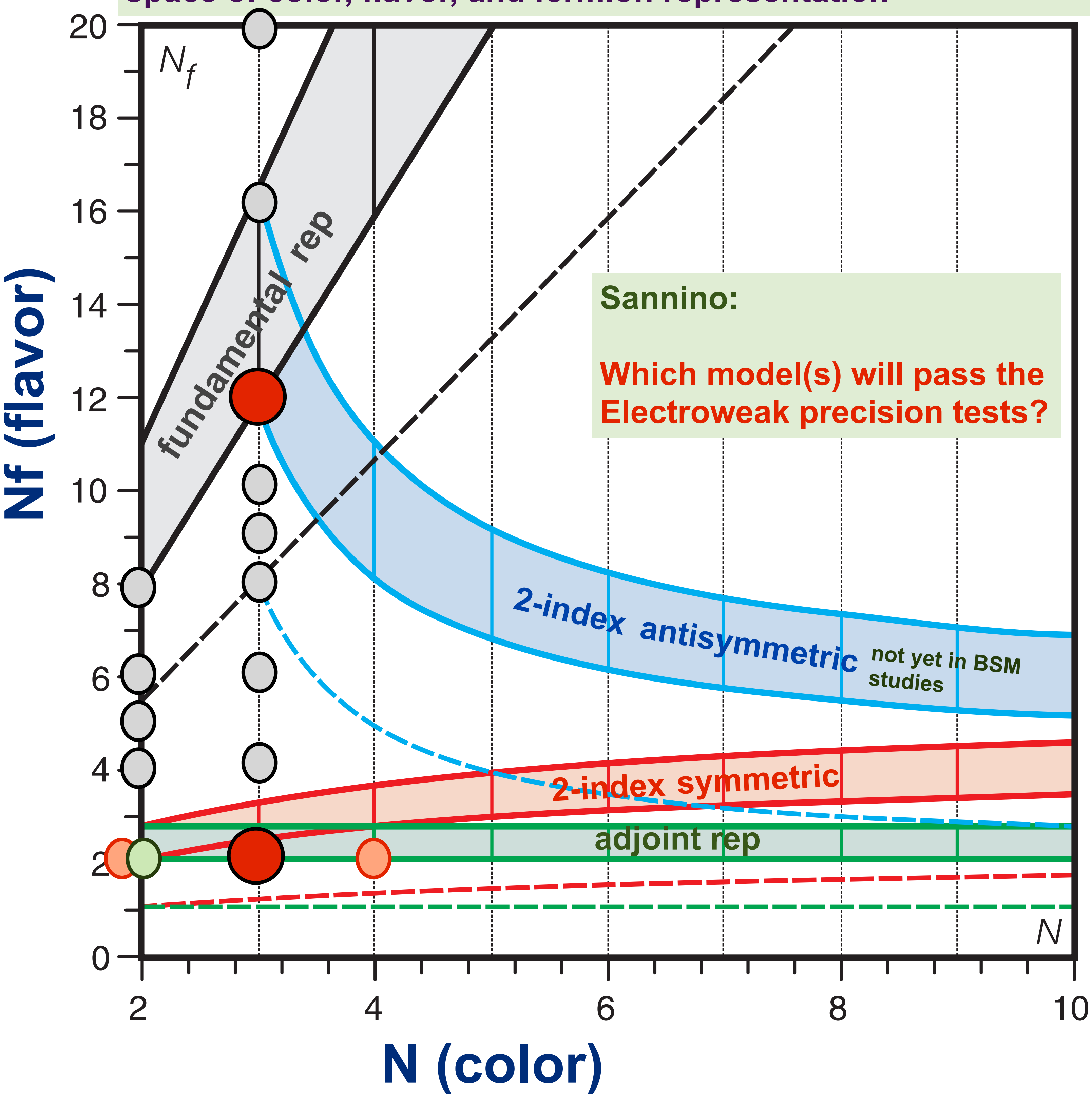
e-Print: **arXiv:1009.5967 [hep-ph]**

more phenomenology at this workshop (Fleming's talk)

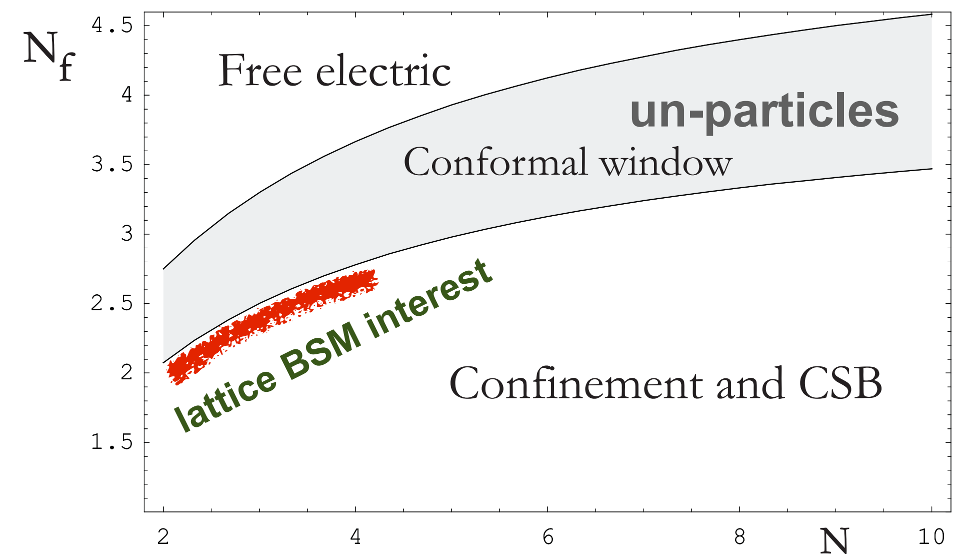
Lattice Higgs Collaboration (LHC) is working on it as well

theory space and conformal window: critically important for composite Higgs and TC/ETC

space of color, flavor, and fermion representation



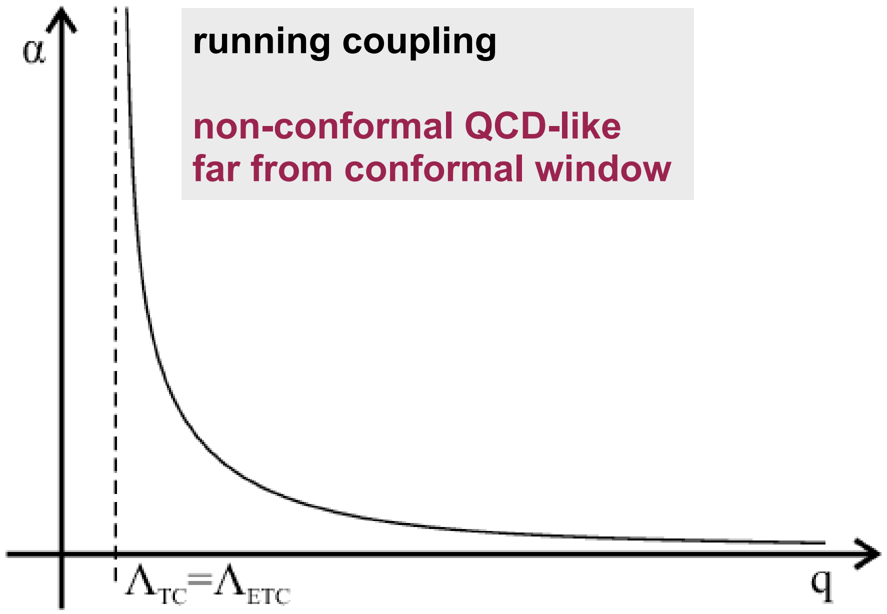
for each rep BSM interest is below conformal window but close to it:

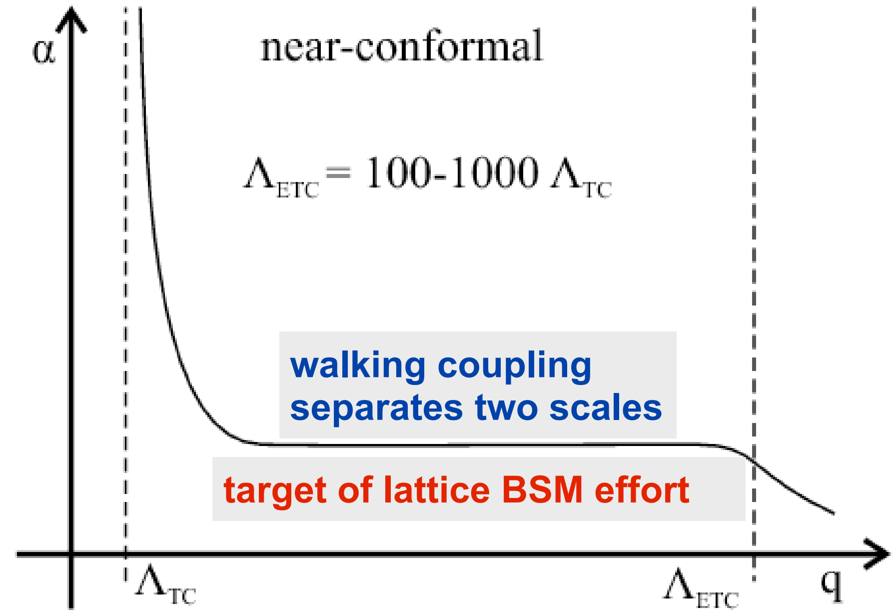


lattice results of last 3 years in 3 reps including new projects just starting

it is stimulating to have controversial results close to the conformal window: these are the interesting candidate models

Composite Higgs mechanism? (Technicolor and Extended Technicolor in the past)



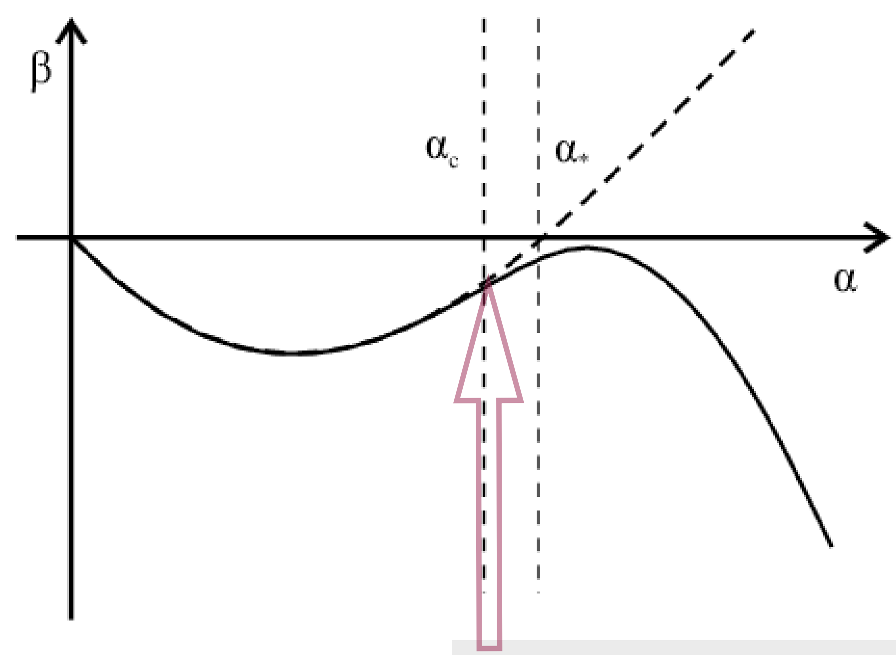


Extended Technicolor paradigm:

- requires walking gauge coupling chiral SB on $\Lambda_{TC} \sim TeV$ scale
- fermion mass generation from scale at $\Lambda_{ETC} \sim 100-1000\,\Lambda_{TC}$
- can solve problem of flavor changing currents
- composite Higgs mechanism
- broken Dilaton ➔ unusual composite Higgs particle in BSM ?
- can avoid conflict with EW precision constraints
- *candidate models require non-perturbative lattice studies*

original textbook Technicolor paradigm:

- one massless fermion doublet chiral SB $\begin{bmatrix} u \\ d \end{bmatrix}$
- three Goldstone pions
- become longitudinal components of weak bosons
- composite Higgs mechanism scale of Higgs condensate ~ F=250 GeV $\Lambda_{TC} \sim TeV$
- flavor changing currents and fermion mass generation would be problems
- conflicts with EW precision constraints



Chiral symmetry breaking turns conformal FP into walking

This is what lattice studies in BSM theory space potentially could deliver

This is all difficult and not QCD-like!

We do not know the answer, but:

If we knew what we were doing, it wouldn't be called research

A. Einstein

It is a world-wide effort:

US BSM project sites using USQCD hardware & software support

(three years ago map was almost empty)

Kudos to the Yale group for stimulation and letting the genie out !

Lattice BSM groups study the composite Higgs mechanism
TC scale - perhaps stretched to ETC scale by walking coupling?

fermion mass generation has to be built on the top of it
- some new theory on ETC scale

growing resources: **Lattice BSM GPU computing**
video games in technicolor

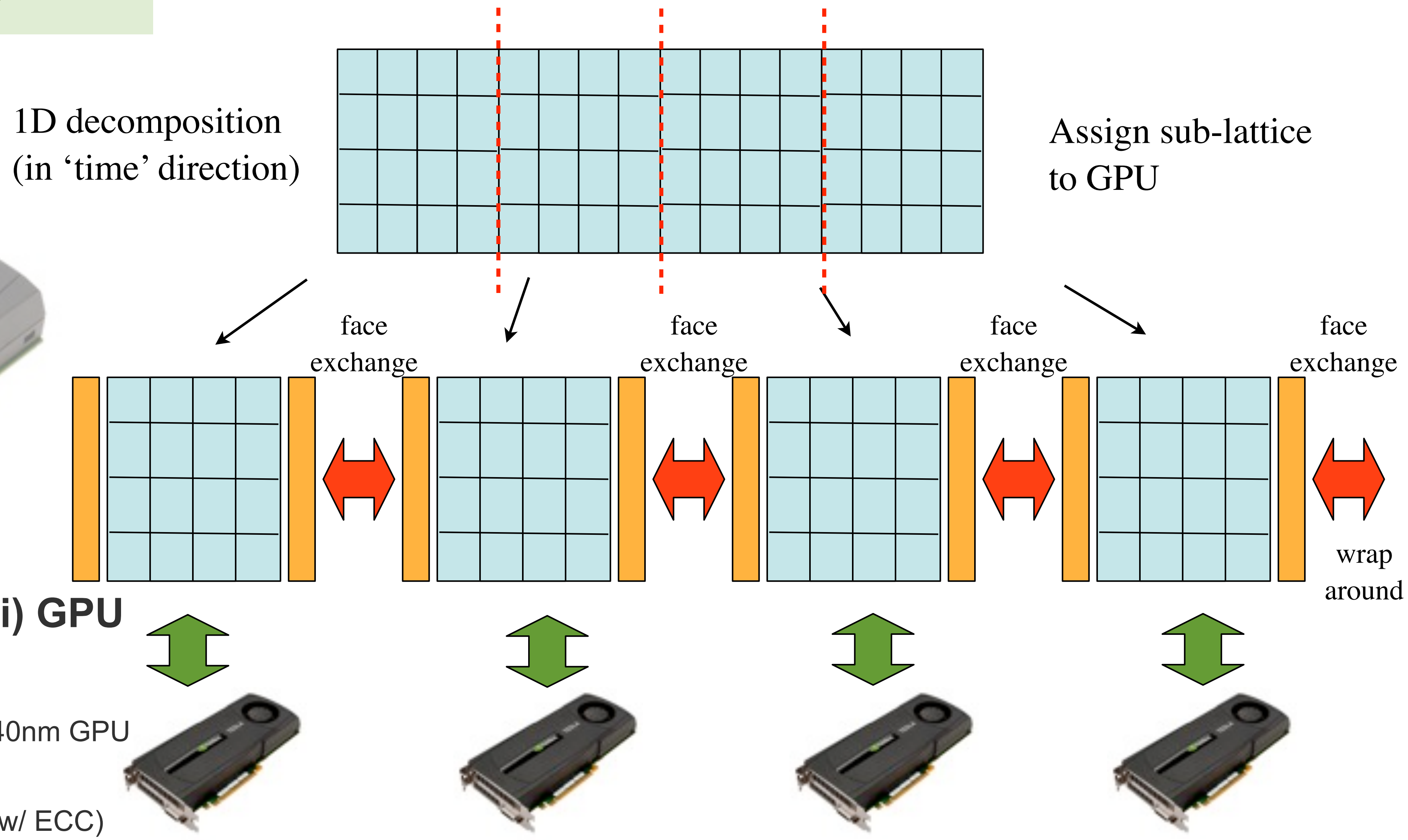
Clusters

BG/P

We have new computing technology for lattice BSM effort

Lattice Higgs Collaboration
Wuppertal technology

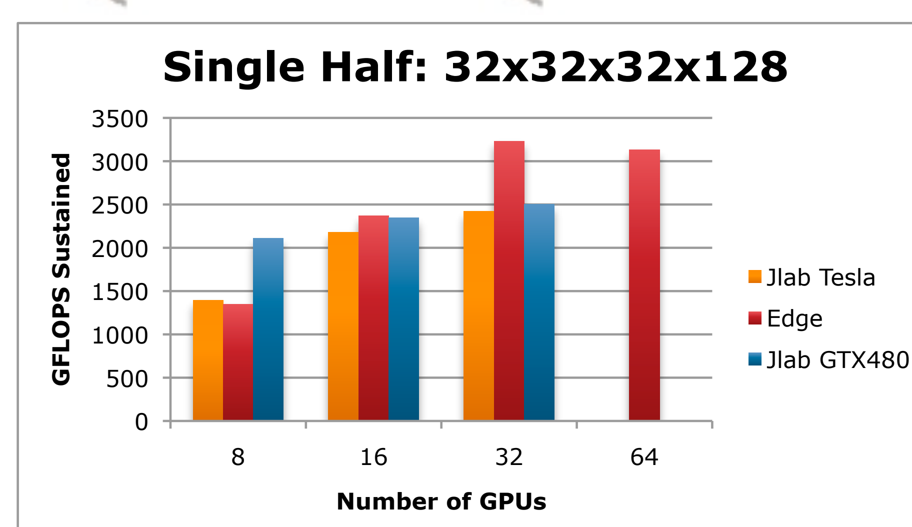
QUDA Parallelization USQCD



NVIDIA Tesla C2050 (Fermi) GPU

Silicon Mechanics Part Number: 19417
Manufacturer Part Number: 900-21030-2200-000

- NVIDIA® Tesla™ third-generation 40nm GPU
- 448 CUDA cores
- 3 GB GDDR5 Memory (2.625 GB w/ ECC)
- Dual Precision 515 GFlops
- Single Precision 1003 GFlops
- PCIe 2.0 x16 full-length, dual slot



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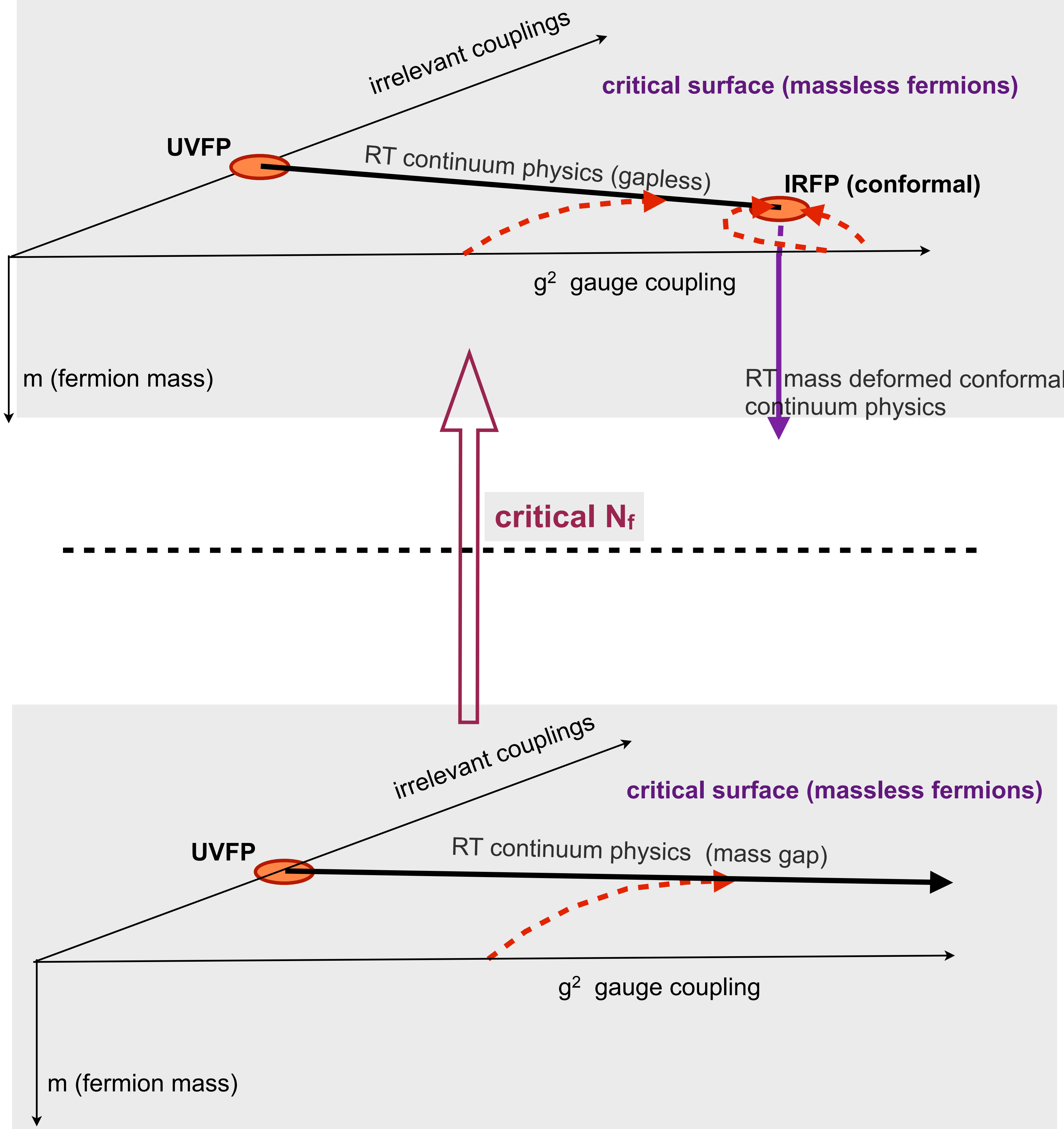
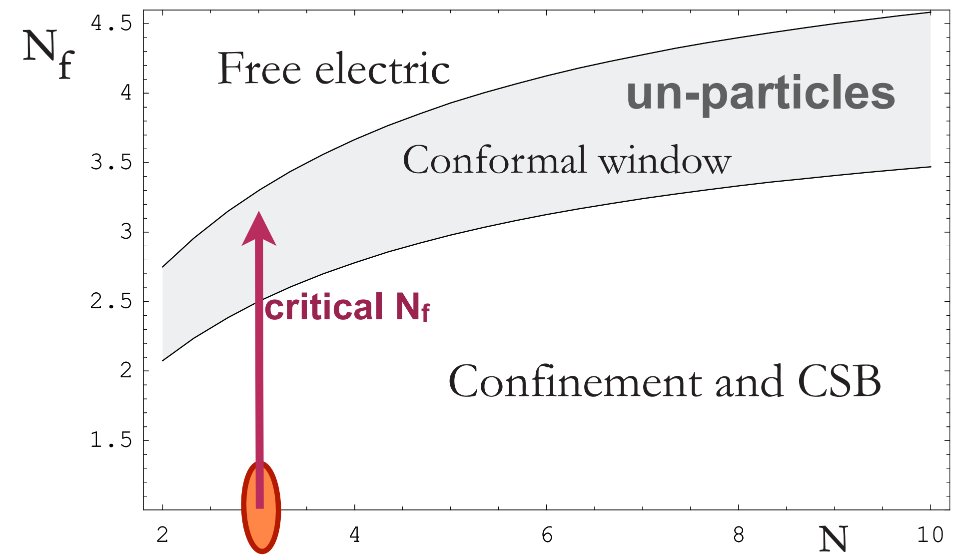
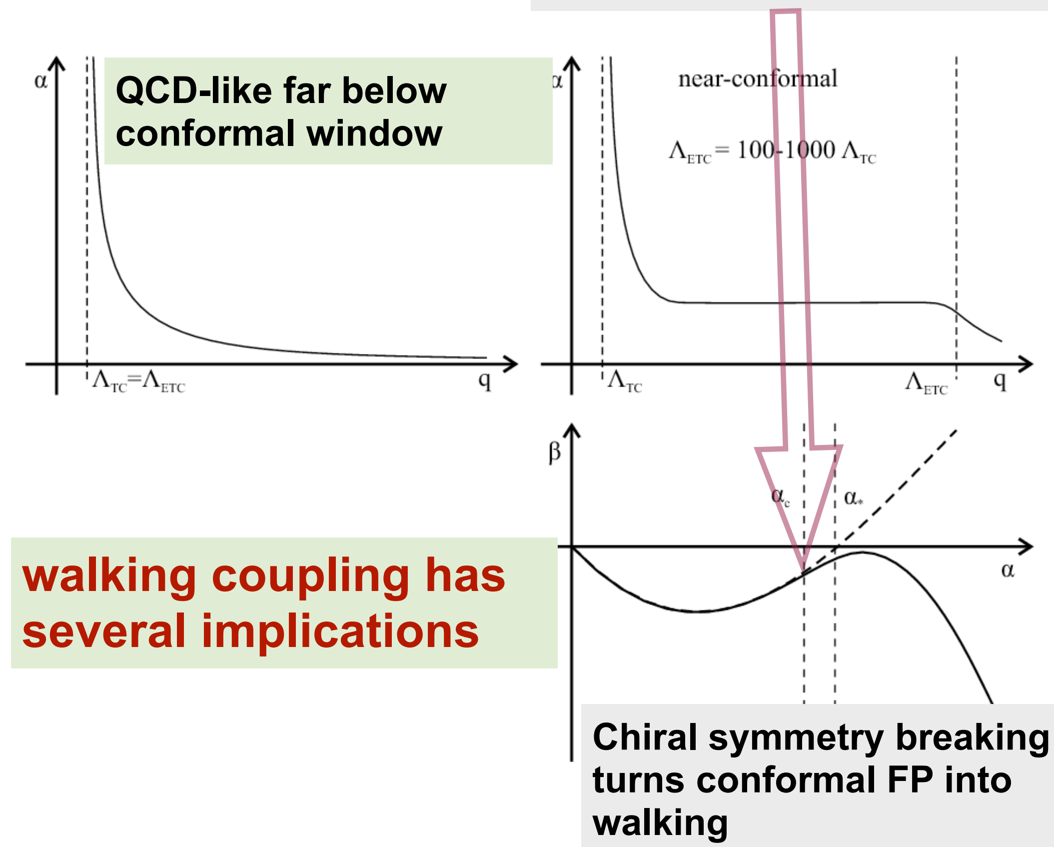
cut-off control in non-perturbative lattice calculations from RG flow



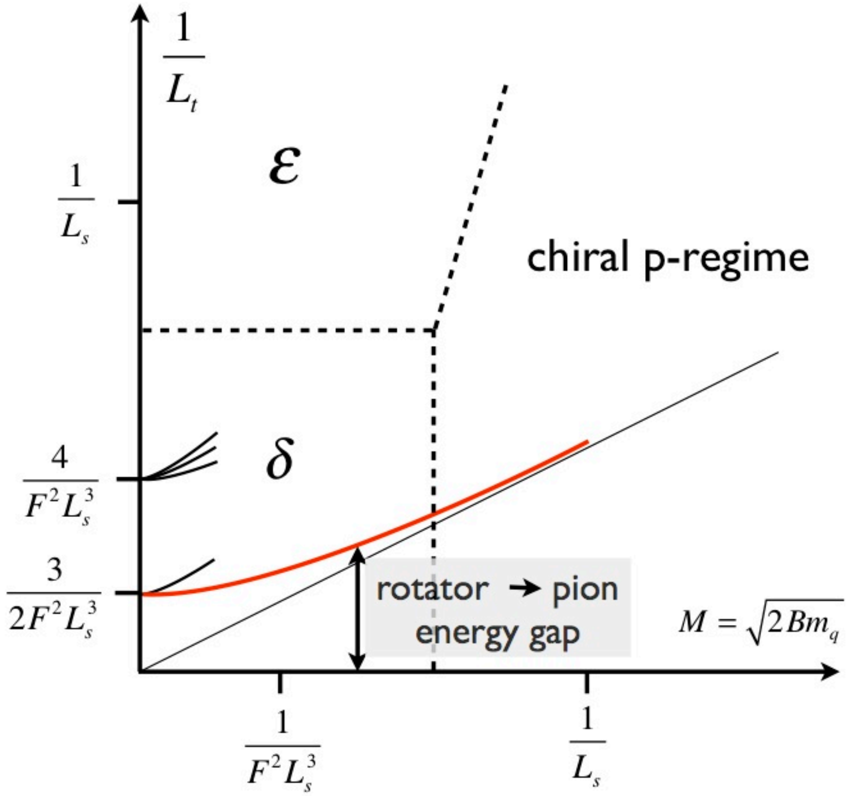
inside the conformal window:

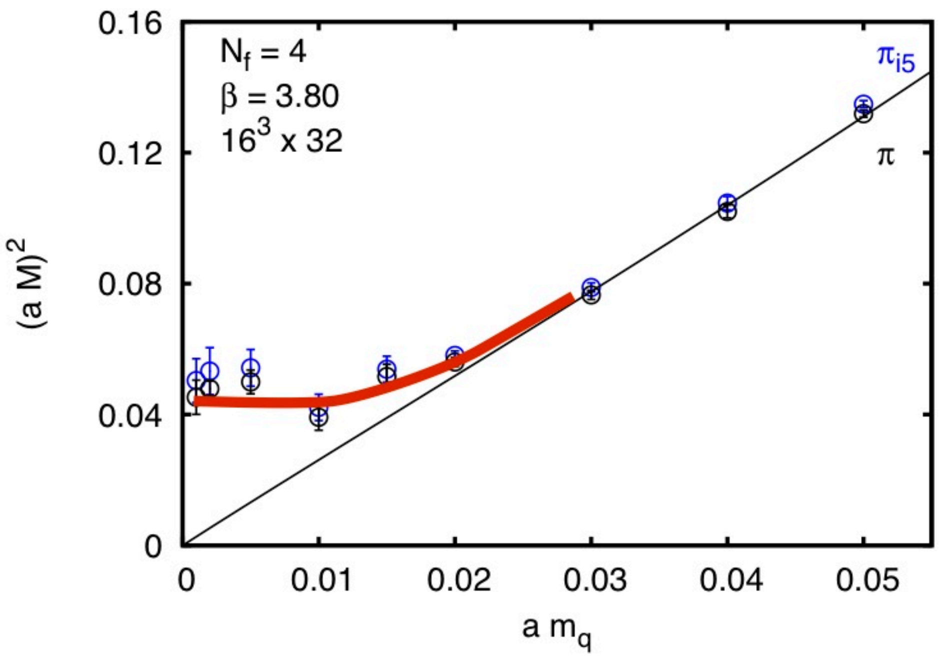


with increasing Nf walking scenario expected to arise:



Chiral regimes to identify in theory space below conformal window:





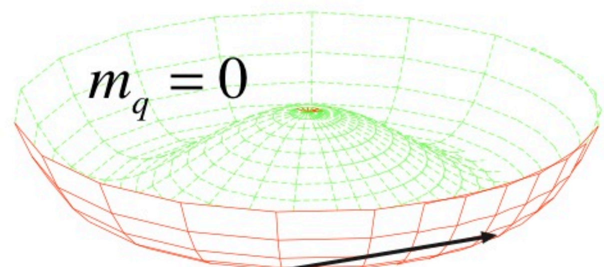
Goldstone dynamics is different in each regime

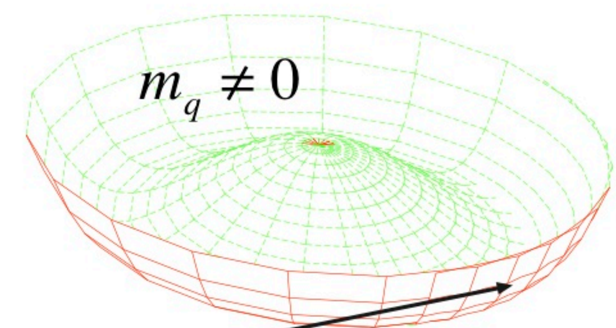
We study δ and ε-regimes (RMT)

and p-regime (probing chiral loops)

complement each other

interpretation of rotator levels in $m_q \to 0$ limit:

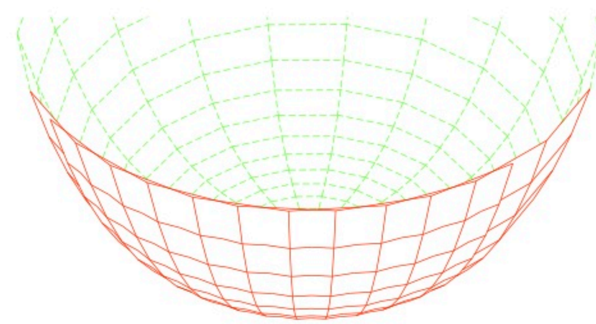




Veff: chiral condensate in flavor space

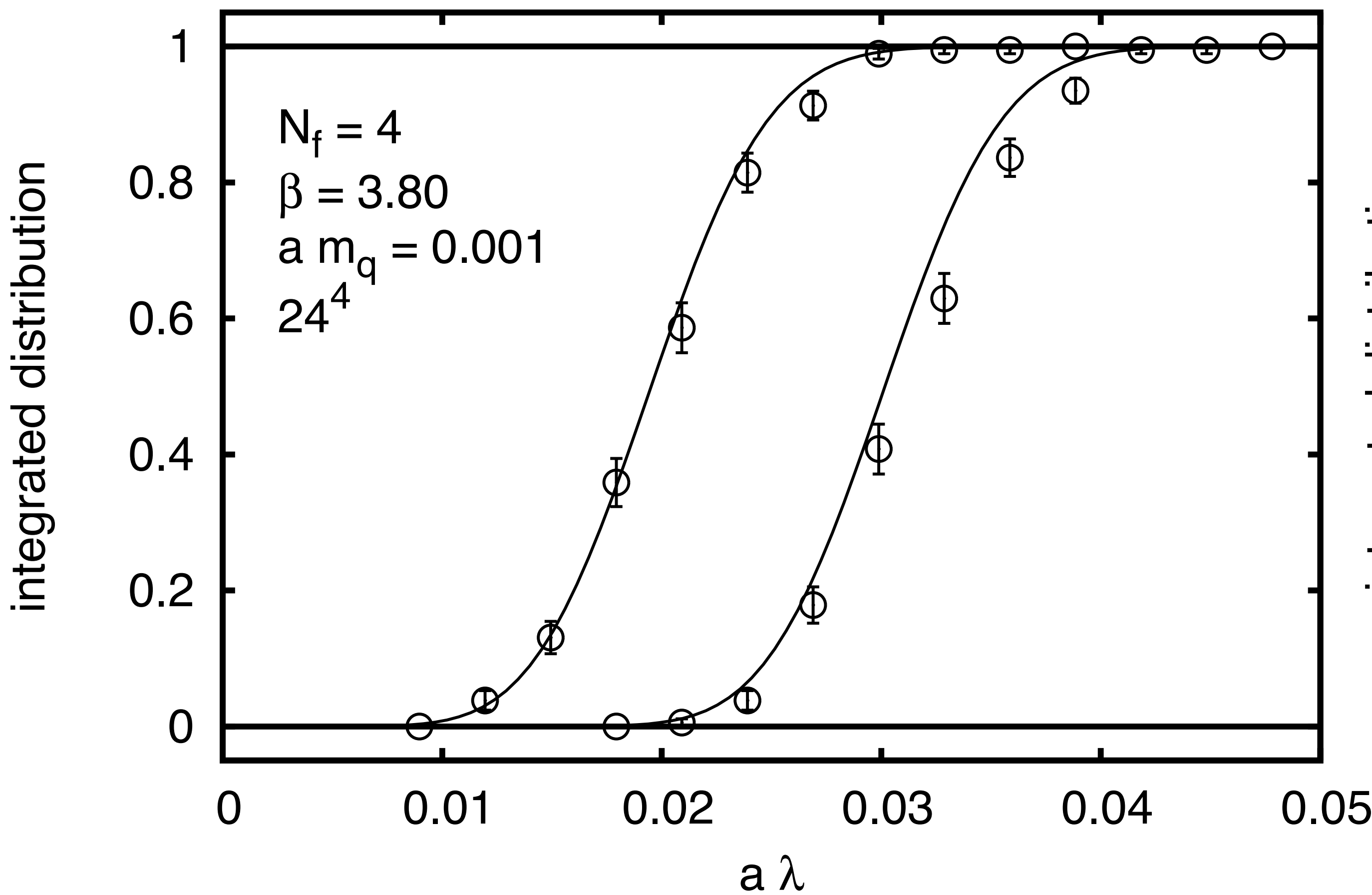
arbitrary orientation of condensate

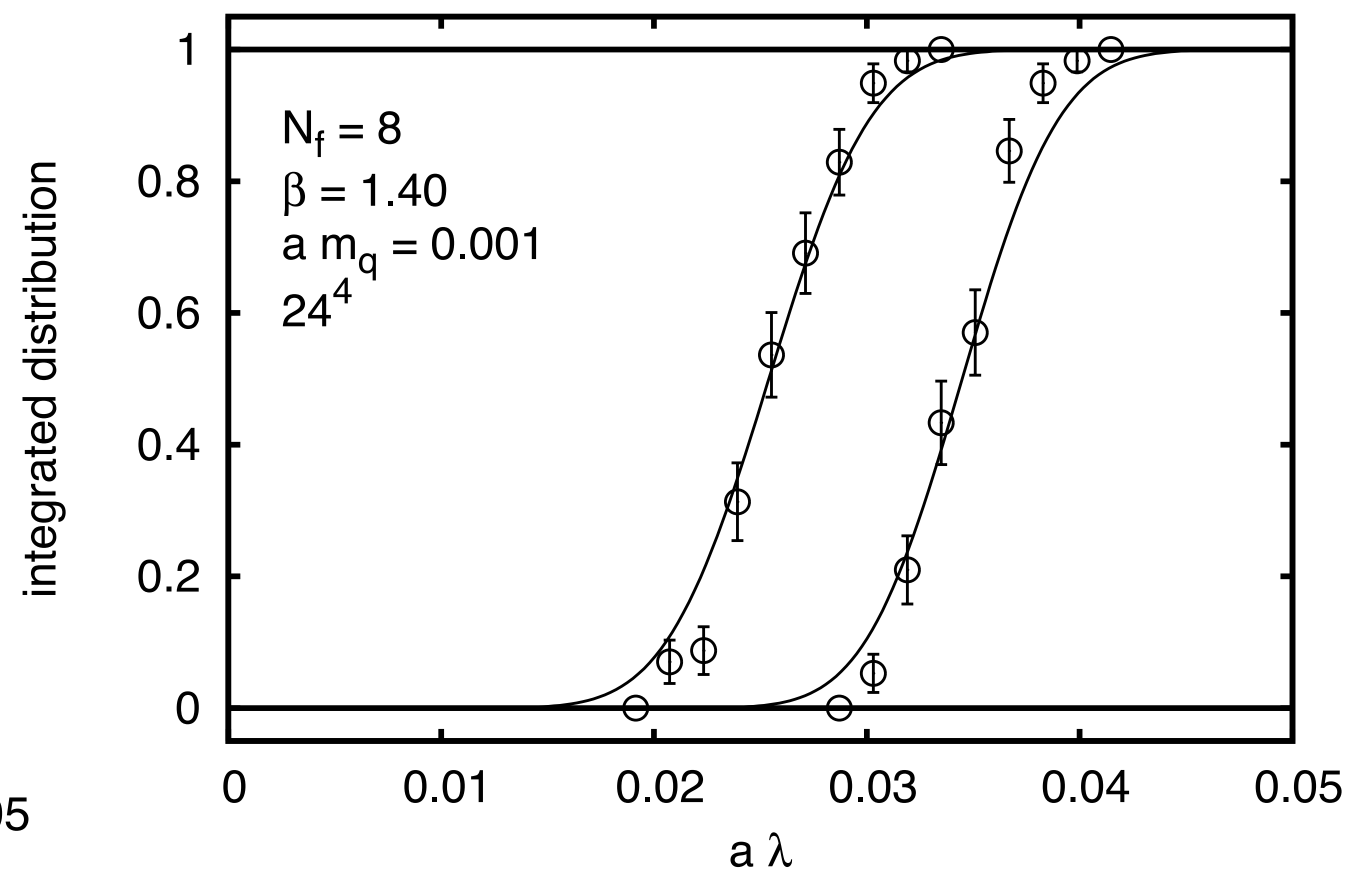
tilted condensate



Not to misidentify rotator gaps as evidence of chirally symmetric phase !

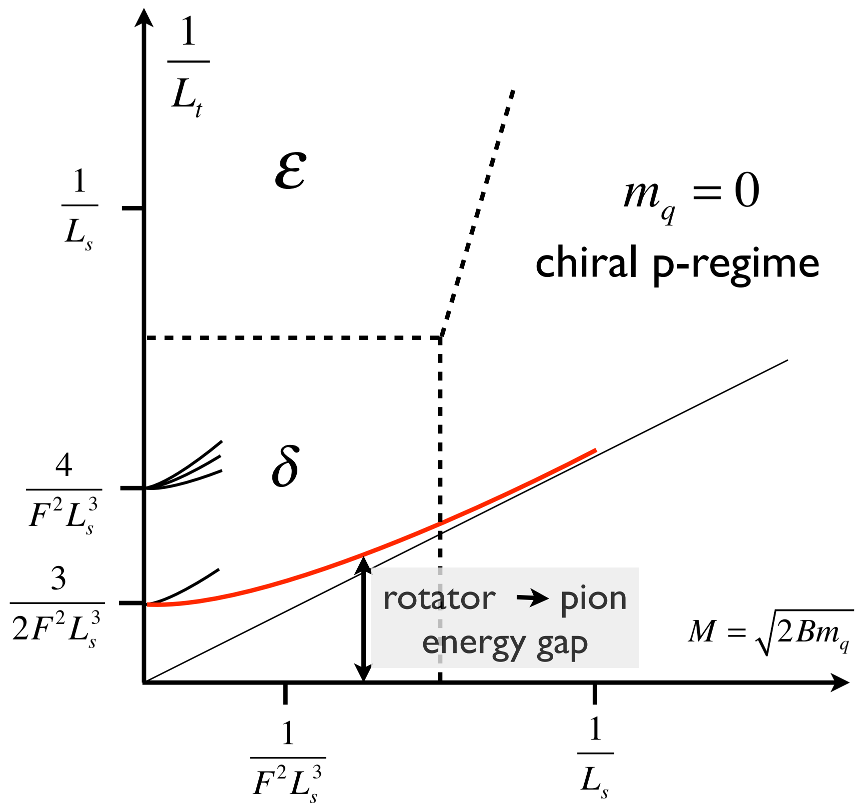
Random Matrix Theory tests in epsilon regime:





Dirac spectrum - integrated eigenvalue distributions of RMT

One-loop chiral expansion in p-regime:



Note $1/N_f$ scaling of pion mass!

warning: 2-loop ~ $(N_f)^2$ (Bijnens)

$$M_\pi^2 = M^2\left[1 - \frac{M^2}{8\pi^2 N_f F^2} ln\left(\frac{\Lambda_3}{M}\right)\right] + O((N_f)^2) \qquad M^2 = 2Bm$$

$$F_\pi = F\left[1 + \frac{N_f M^2}{16\pi^2 F^2} ln\left(\frac{\Lambda_4}{M}\right)\right] + O((N_f)^2)$$

$$M_\pi(L_s,\eta) = M_\pi\left[1 + \frac{1}{2N_f}\frac{M^2}{16\pi^2 F^2}\cdot \widetilde{g}_1(\lambda,\eta)\right] \qquad \lambda = ML_s$$

$$F_\pi(L_s,\eta) = F_\pi\left[1 - \frac{N_f}{2}\frac{M^2}{16\pi^2 F^2}\cdot \widetilde{g}_1(\lambda,\eta)\right] \qquad \tilde{g}_1(\lambda,\eta) \approx 24K_1(\lambda)/\lambda \text{ for } \eta = \frac{L_t}{L_s} \gg 1$$

Chiral expansion parameter is $N_f \frac{M^2}{16\pi^2 F^2}$ with $\ll 1$ condition

$N_f = 8$ fundamental rep in USQCD BSM project

set $N_f \frac{M^2}{16\pi^2 F^2}$ =0.3, with $a \cdot m_\rho = 0.25$ (to keep cut-off under control), and $m_\rho / F \approx 10$ (as expected), $a \cdot M_\pi \approx 0.10$ is needed

The $M_\pi \cdot L_s \approx 10$ condition (to control FSS) will require $L_s \approx 100$! Same scale as largest QCD projects!

$N_f = 2$ higher reps (like sextet) are more favorable for chiral expansion

Condition of reaching the chiral expansion regime can also be estimated from rotator spectrum $\Rightarrow$

Condition of reaching the chiral expansion regime can also be estimated from rotator spectrum $\Rightarrow$

$E_l = \frac{1}{2\theta} l(l+2)$ with $l = 0,1,2,...$ rotator spectrum for $SU(2)_f \times SU(2)_f$

with $\theta = F^2 L_s^3 (1 + \frac{C(N_f = 2)}{F^2 L_s^2} + O(1/F^4 L_s^4))$ (P. Hasenfratz and F. Niedermayer)

(there is in E_l an overall factor $\frac{N_f^2 - 1}{N_f}$ for arbitrary N_f)

$C(N_f = 2) = 0.45$, C will grow with $\sim \mathrm{N}_f$, (P.Hasenfratz, $\mathrm{O(N}_f)$ model)

there are similar considerations in the ε-regime

The rotator spectrum has the expansion parameter $\sim \mathrm{C}\frac{N_f/2}{F^2 L_s^2}$ with $\ll$ 1 condition

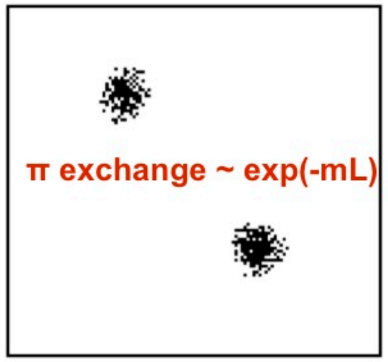
with $\mathrm{C}\frac{N_f/2}{F^2 L_s^2} = 0.3$ $FL_s \approx 2.5$ for $N_f = 8$ (USQCD project)

with $a \cdot m_\rho = 0.25$ (to keep cut-off under control), and $m_\rho / F \approx 10$ (as expected), $L_s \approx 100$ is needed!

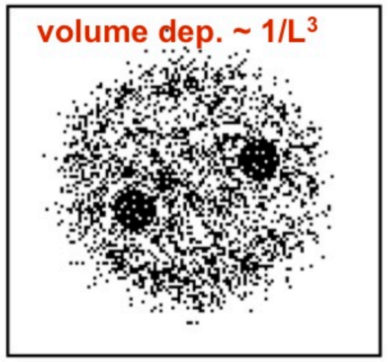
When expansion breaks down in δ – regime, same is expected in the p-regime

Deceptions of finite size behavior:

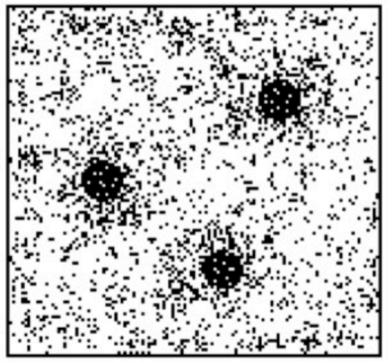
large volume hadrons point-like



squeezed wavefunction

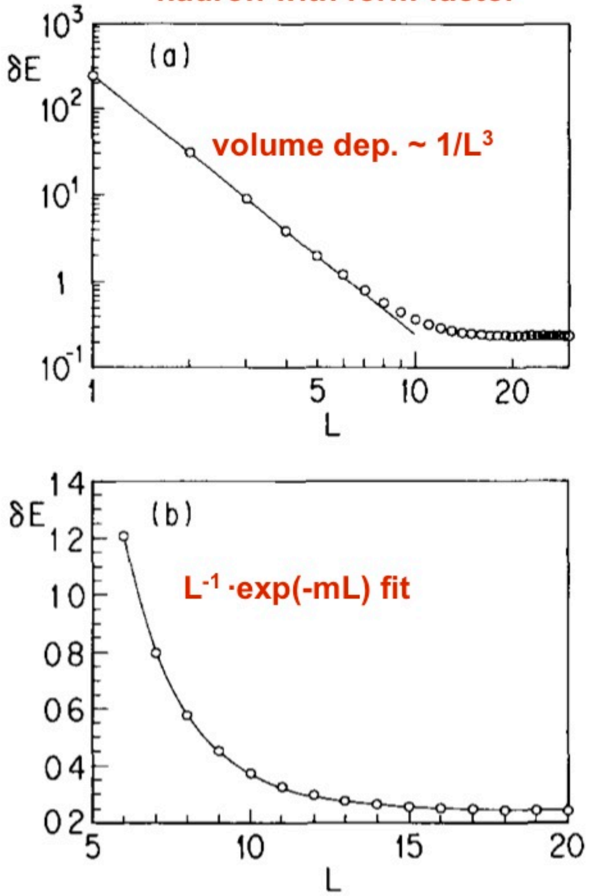


crossover to femto world



$$\hat{V}(\vec{k}) = \frac{F(\vec{k})^2}{\vec{k}^2 + m^2}$$ extended hadron with form factor $F(\vec{k})$

hadron with form-factor



$$F(k) = \frac{1}{1 + c\cdot\vec{k}^2}$$

$$F(k) = \frac{1}{1 + c\cdot\vec{k}^2}$$

$\delta E = \sum_{\vec{n}} V(\vec{n}L)$ hadrom self energy from interaction with images

$\delta E = \frac{1}{L^3}\sum_{\vec{n}} \hat{V}(\vec{n}\frac{2\pi}{L})$ Poisson resummation, $\hat{V}(\vec{k})$ is the Fourier transform

$\hat{V}(\vec{k}) = \frac{1}{\vec{k}^2 + m^2} \Rightarrow$ V(r)=$\frac{e^{-mr}}{r}$ for large r in point-like approximation

$\delta E \approx V(0) + 6V(L)$ $\quad \delta E \approx \frac{e^{-mL}}{L}$ point-like interaction for large L (non-relativistic)

Lüscher made it relativistic using field theory

Leutwyler put in the chiral vertices, hence the $\tilde{g}(mL)$ form in chiral PT

the size where the $1/L^3$ correction to the masses disappears and the exponential behavior sets in depends on the behavior of the hadron form factor

the characteristic inverse power vs. exponential behavior can frustrate at limited lattice sizes the analysis of chiral vs. conformal hypotheses

the size where the 1/L³ correction to the masses disappears and the

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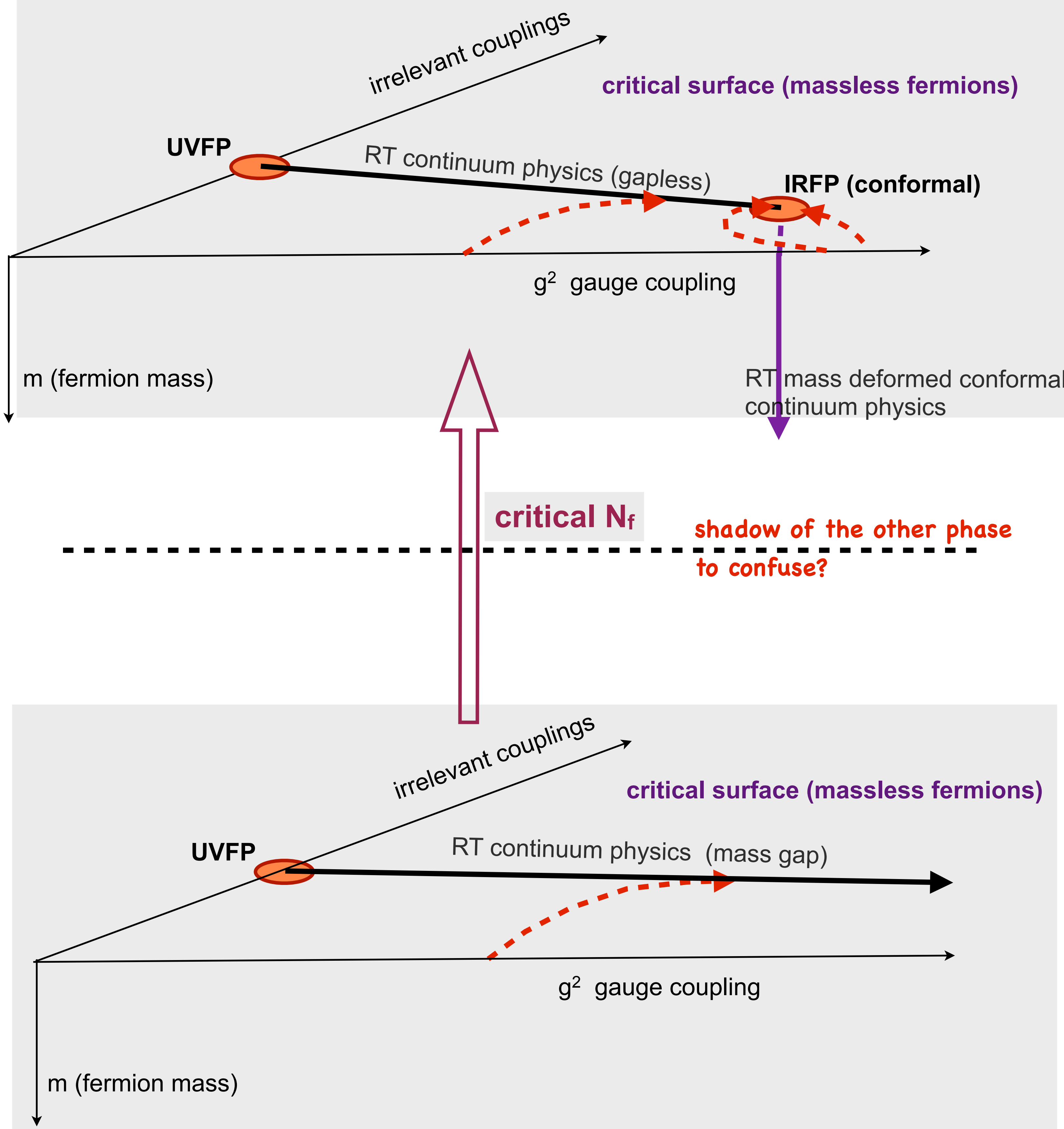
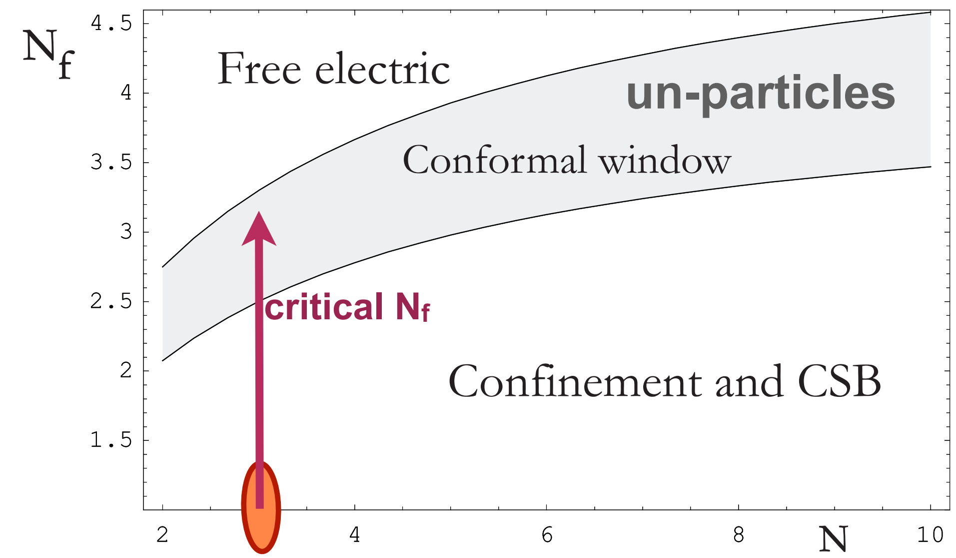
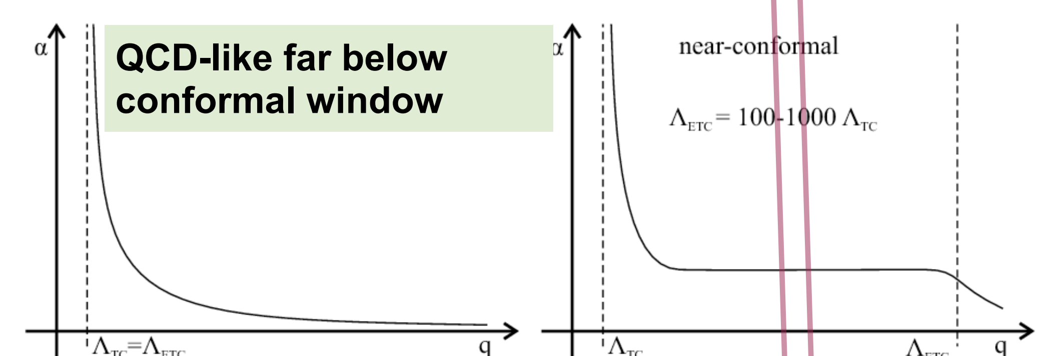
cut-off control in non-perturbative lattice calculations from RG flow



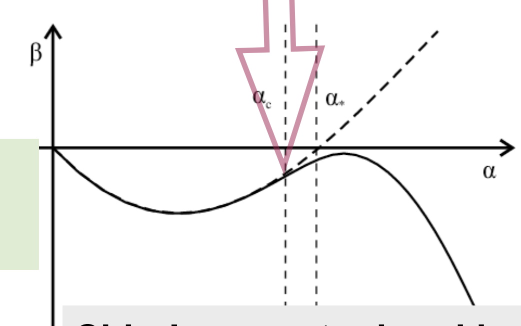
inside the conformal window:



with increasing N_f walking scenario expected to arise:

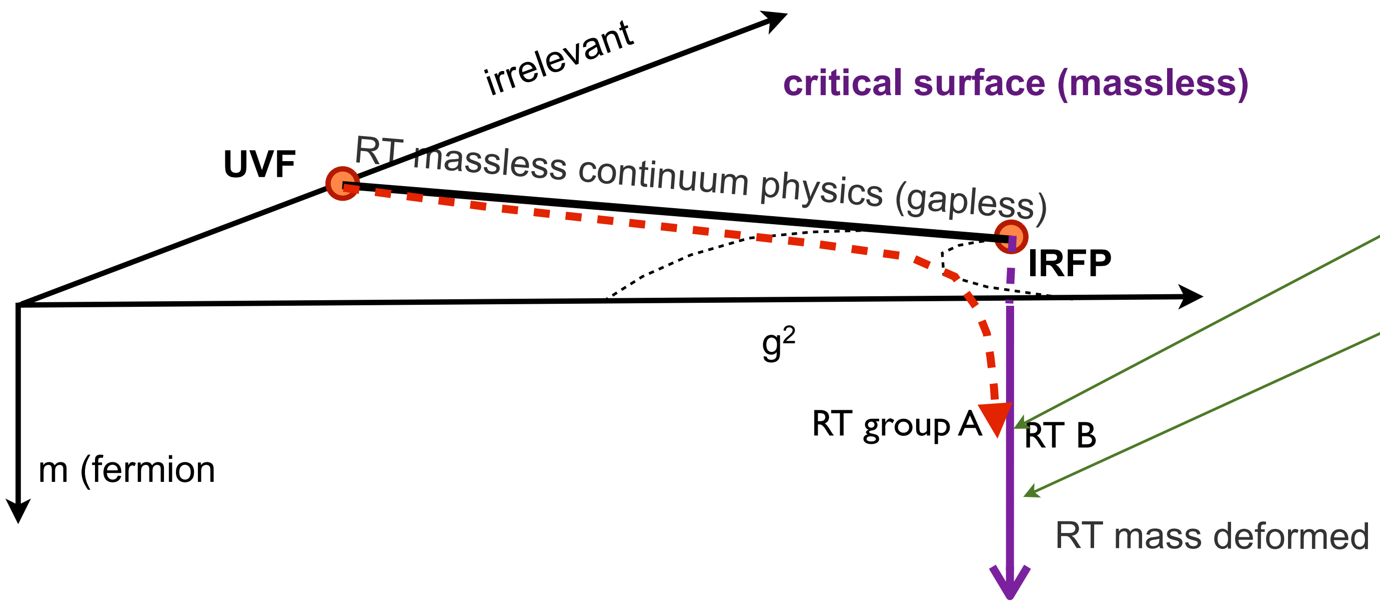


walking coupling has several implications



Chiral symmetry breaking turns conformal FP into walking

conformal scaling and scaling violations



if model had conformal IRFP

two interchangeable RT descriptions?

continuum mass deformed conformal theory is on RT coming out of IRFP

I worked out as an example all the details of 3D scalar theory (Ising model) with IRFP

textbook material

Del Debbio and collaborators early conform apps

free energy on RT:

$$f(u_1,u_2,\ldots) = g(u_1,u_2,\ldots) \; + \; b^{-d} f_s(b^{y_1}u_1, b^{y_2}u_2\ldots)$$

analytic singular

$y_1 > 0$ only relevant exponent in our case
$u_1 = t \sim m$ identified, $y_1 = y_m$ in Technicolor notation

y_2 controls scaling violations, leading correction term

analytic function which can have terms like $\sim m^k$ are typically sub-leading

Fisher and Brezin worked out most of what we know!

RG scaling of 2-point function:

$$G^{(2)}(r,m,u_2,\ldots) = b^{-2d} G(r/b, b^{y_m}m, b^{y_2}u_2,\ldots)$$

from $G^{(2)}(r,m,u_2,\ldots) \sim e^{-Mr}$ asymptotics with $M \sim m^{1/y_m}$ scaling follows

leading correction to the scaling term should be $\sim m^{\omega}$ where $\omega = \beta'(g^*)$

analysis would change with second relevant operator at IRFP!

- analytic terms exists, but no reason to be leading conformal scaling correction

- correlators of composite operators require inhomogeneous RG!

similarly, in conformal finite size scaling analysis:

$$\xi / L = f_1(x) + L^{-\omega} f_2(x) \quad \text{with} \quad x = Lm^{1/y_m}$$

correlation length measured in L units

This directly transcribes to hadron masses and F_π

finite size scaling correction terms require very accurate data

Chiral hypothesis incomplete analysis on each side **Conformal hypothesis**

chiral logs not reached yet in important models!
(like N_f=8, or N_f=12)

$$(M_\pi^2)_{NLO} = (M_\pi^2)_{LO} + (\delta M_\pi^2)_{1-loop} + (\delta M_\pi^2)_{m^2} + (\delta M_\pi^2)_{a^2 m} + (\delta M_\pi^2)_{a^4}$$

$\sim m^2$ $\sim a^2 m$ $\sim a^4$

kept cutoff term in B see LO a^2 term

$$(M_\pi^2)_{LO} = 2B\cdot m + a^2\Delta_B$$

would require more data

$$(\delta M_\pi^2)_{1-loop} = [(M_\pi^2)_{LO} + a^2]^2 \ln(M_\pi^2)_{LO}$$

$$\boxed{M_\pi^2 = c_1 m + c_2 m^2 \ + \text{logs}}$$

fitted function for all Goldstones

$$\boxed{M_{nuc} = c_0 + c_1 m \ + \ \text{logs}}$$

nucleon states, rho, a1, higgs, ...

$$(F_\pi)_{LO} = F, \quad (\delta F_\pi)_{1-loop} = [(M_\pi^2)_{LO} + a^2]\ln(M_\pi^2)_{LO}$$

chiral log regime was not reached in fermion mass range

$$(\delta F_\pi)_{m^2} \sim m, \quad (\delta F_\pi)_{a^2 m} = a^2$$

kept cutoff term in F

$$\boxed{F_\pi = F + c_1 m + \text{logs}}$$

fitted function

$$\boxed{\langle\bar\psi\psi\rangle = \langle\bar\psi\psi\rangle_0 + c_1 m + c_2 m^2 + \text{logs}}$$

chiral condensate

$$\boxed{M_\pi = c_\pi \cdot m^{1/y_m}, \qquad y_m = 1+\gamma}$$

leading conformal scaling
functional form for all hadron masses

$$\boxed{F_\pi = c_F \cdot m^{1/y_m}, \qquad y_m = 1+\gamma}$$

same critical exponent

$$\boxed{\langle\bar\psi\psi\rangle = c_\gamma \cdot m^{(3-\gamma)/y_m} + c_1 m}$$

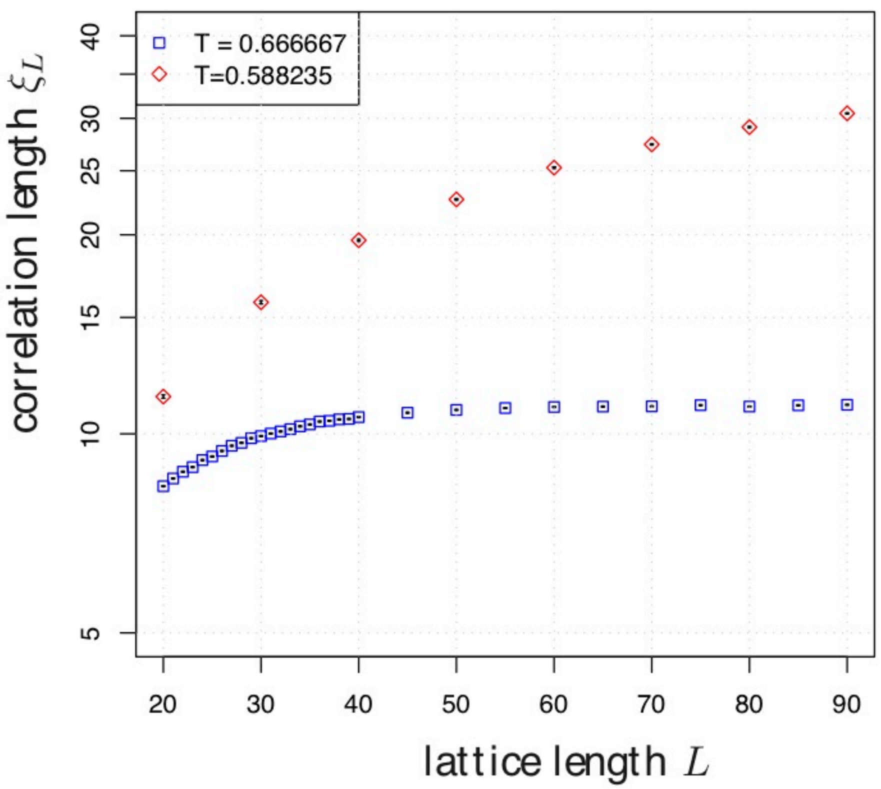
Del Debbio and Zwicky

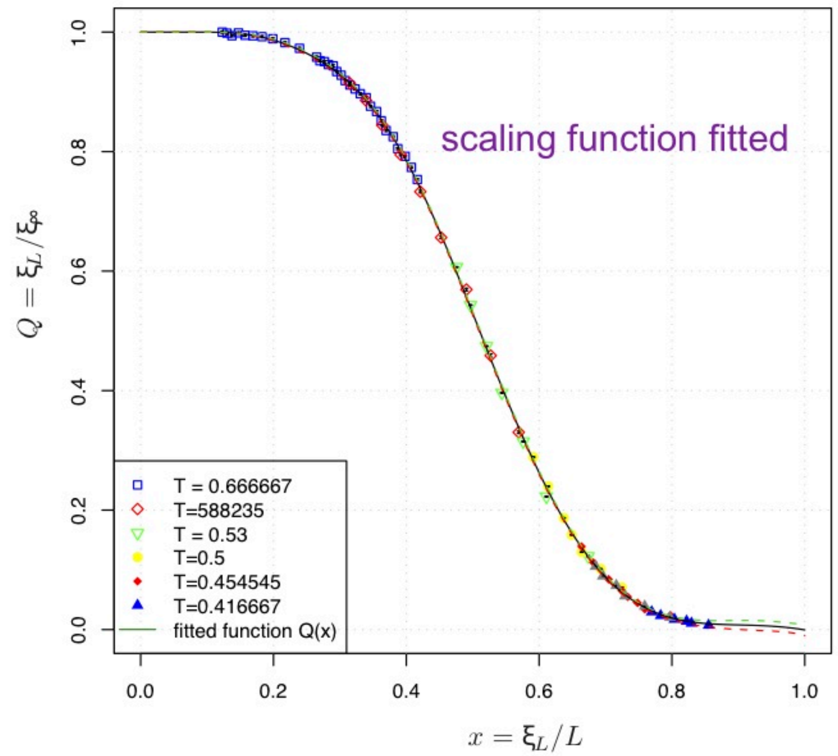
Asymptotic infinite volume limit has not been reached yet in important candidate models for conformal window

infinite volume conformal scaling violation analysis ?

conformal finite size scaling analysis and its scaling violations ?

but FSS works! 2d O(3) model UVFP (at T=1/β=0)





$$H = -\beta \sum_{\langle ij \rangle} \vec{\sigma}_i \cdot \vec{\sigma}_j \qquad m = 1/\xi = C_m \cdot \Lambda_L$$

$$\Lambda_L = 2\pi\beta \cdot \exp(-2\pi\beta)[1 + a_1/\beta + ...]$$

from Bethe ansatz:

$$m/\Lambda_{MS} = 8/e \qquad \Lambda_{MS}/\Lambda_L = 2^{5/2} e^{\pi/2}$$

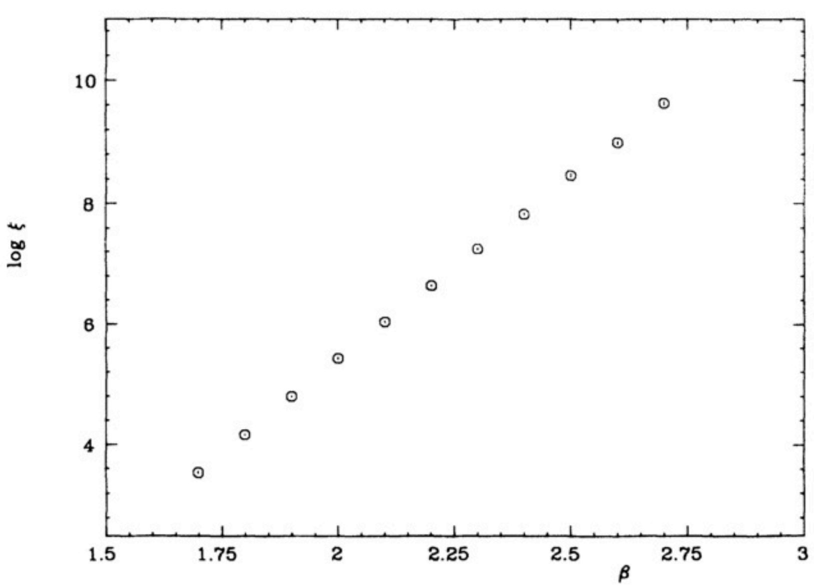
from FSS:

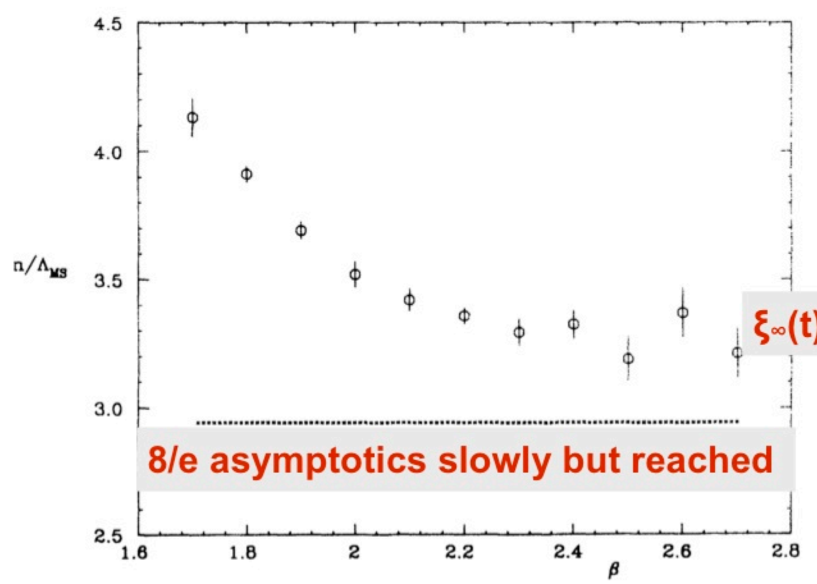
$$P_L(t) = P_\infty(t) \cdot Q_P(x(t)), \quad x(t) = \xi_L(t)/L$$

for any bulk physical quantity P(t)

$Q_P(x(t))$ does not depend on t explicitly!

applied to $P_\infty(t)=\xi_\infty(t)$



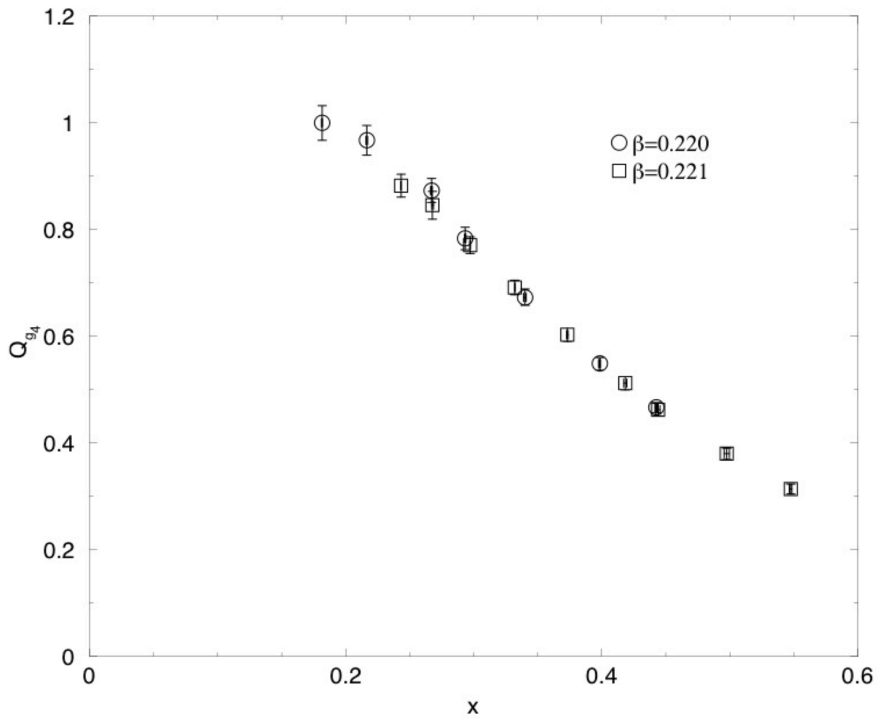


$\xi_\infty(t)$ would be ~ 22,000 at β=2.7 !

8/e asymptotics slowly but reached

FSS is enormously powerful

FSS works again! 3d Ising model IRFP $(g_4)^*$ conformal



applied again from FSS:

$$P_L(t) = P_\infty(t) \cdot Q_P(x(t)), \quad x(t) = \xi_L(t)/L$$

applied to $P_\infty(t)=g_4(t)$ renormalized coupling

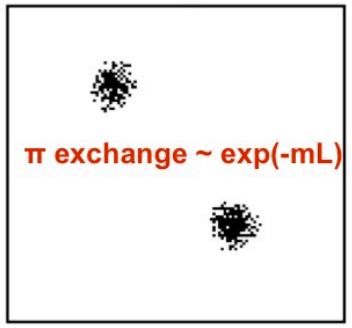
$$g_4(t) = -\frac{\chi_4(t)}{\xi^3 \cdot \chi_2(t)^2}$$

we are working on similar FSS methods in Nf=12 model
under the conformal hypothesis

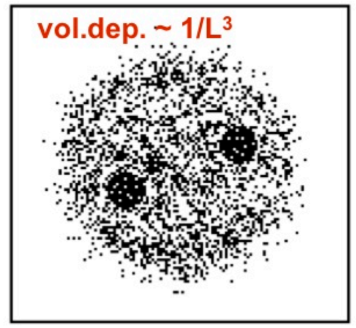
caviats:
composite operators and composite states make a similar analysis more difficult

can the two phases (chiral and conformal) get confused in FSS?

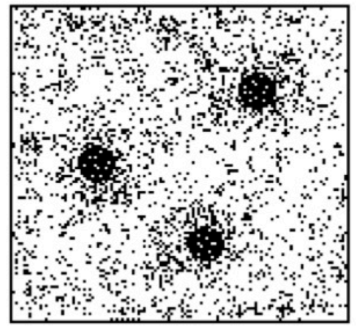
large volume
hadrons point-like

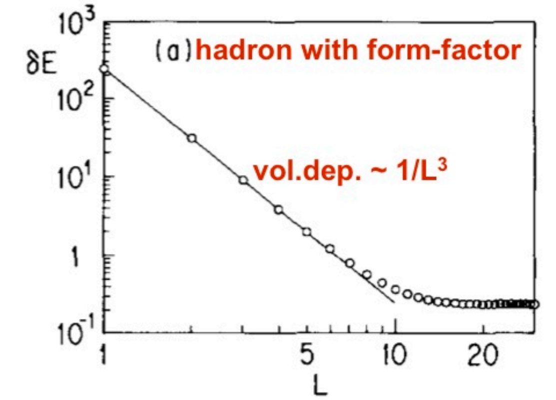


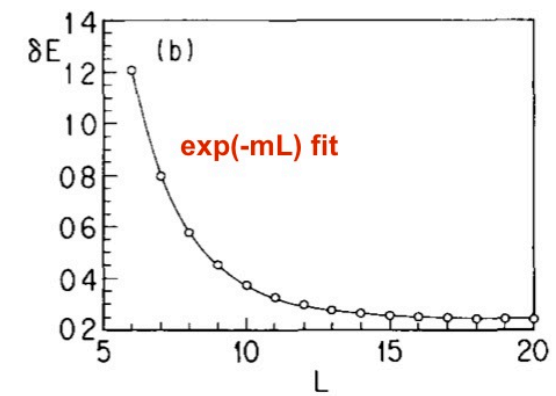
squeezed wavefunction



crossover to femto world







Nf=12 fundamental representation

Nf=12 flavors with fermions in the fundamental rep of SU(3) color gauge group
just below the conformal window?
fermion condensate, F_{ps} and hadron spectrum were determined

published data set (condensate in separate table):

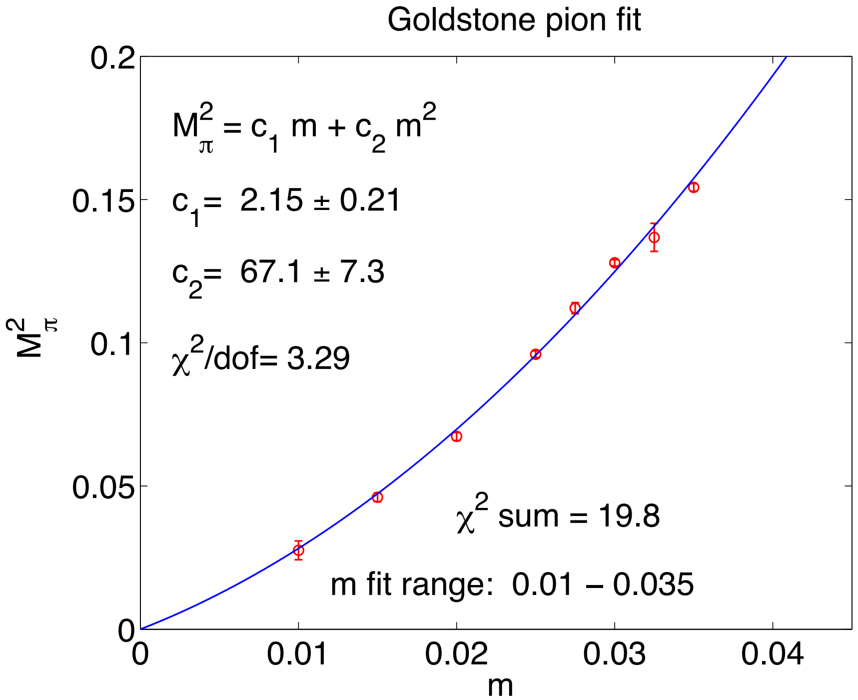
Twelve massless flavors and three colors below the conformal window.
Phys.Lett. B703 (2011) 348-358
e-Print: **arXiv:1104.3124 [hep-lat]** **Lattice Higgs Collaboration**

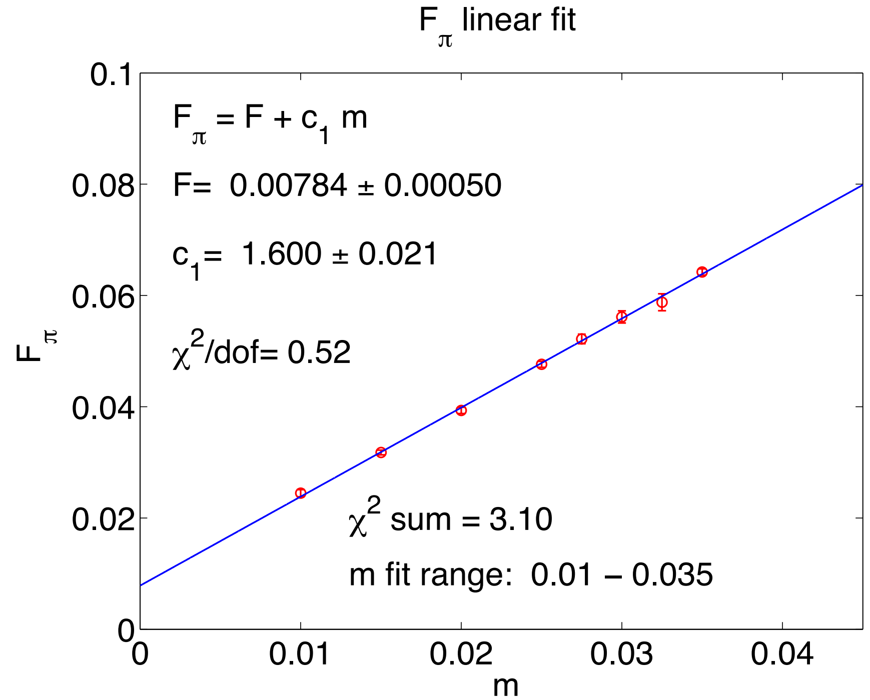
mass	lattice	M_π	F_π	M_{i5}	M_{sc}	M_{ij}	M_{nuc}	M_{pnuc}	M_{Higgs}	M_{rho}	M_{A1}
0.0100	$32^3 \times 64$	0.2195(35)	0.02234(46)	0.2171(31)	0.194(10)	0.195(11)	0.386(16)	0.387(22)	0.2162(53)	0.239(19)	0.246(21)
0.0100	$40^3 \times 80$	0.1819(28)	0.02382(39)	0.1842(29)	0.1835(35)	0.1844(44)	0.3553(93)	0.352(16)	0.2143(81)	0.2166(73)	0.237(12)
0.0100	$48^3 \times 96$	0.1647(23)	0.02474(49)	0.1650(13)	0.16437(95)	0.1657(10)	0.3066(69)	0.3051(81)	0.247(13)	0.1992(28)	0.2569(83)
0.0150	$32^3 \times 64$	0.2322(34)	0.03168(64)	0.2319(11)	0.2318(17)	0.2341(16)	0.4387(60)	0.4333(84)	0.2847(33)	0.2699(41)	0.324(16)
0.0150	$40^3 \times 80$	0.2200(23)	0.03167(53)	0.2210(21)	0.2218(30)	0.2239(34)	0.4095(84)	0.411(10)	0.291(11)	0.2574(36)	0.327(14)
0.0150	$48^3 \times 96$	0.2140(14)	0.03153(51)	0.2167(16)	0.2165(17)	0.2185(18)	0.3902(67)	0.3881(84)	0.296(13)	0.2506(33)	0.3245(87)
0.0200	$40^3 \times 80$	0.2615(17)	0.03934(56)	0.2736(22)*	0.2651(8)	0.2766(42)*	0.4673(62)	0.4699(66)	0.330(17)	0.3049(28)	0.361(32)
0.0250	$32^3 \times 64$	0.3098(18)	0.04762(53)	0.3179(17)	0.3183(18)	0.3231(20)	0.563(12)	0.563(14)	0.4137(88)	0.3683(19)	0.469(14)
0.0275	$24^3 \times 48$	0.3348(29)	0.05218(85)	0.3430(18)	0.3425(25)	0.3471(26)	0.609(21)	0.628(23)	0.460(16)	0.4050(69)	0.523(34)
0.0300	$24^3 \times 48$	0.3576(15)	0.0561(11)	0.3578(15)*	0.3726(29)	0.3790(40)	0.640(12)*	0.633(16)*	0.470(15)	0.4160(26)*	0.5222(90)*
0.0325	$24^3 \times 48$	0.3699(66)	0.0588(15)	0.3790(34)	0.3814(62)	0.3879(62)	0.680(18)	0.686(26)	0.500(21)	0.4481(39)	0.548(31)
0.0350	$24^3 \times 48$	0.3927(17)	0.06422(57)	0.4065(18)	0.4074(19)	0.4149(26)	0.703(28)	0.741(20)	0.538(30)	0.4725(64)	0.669(65)

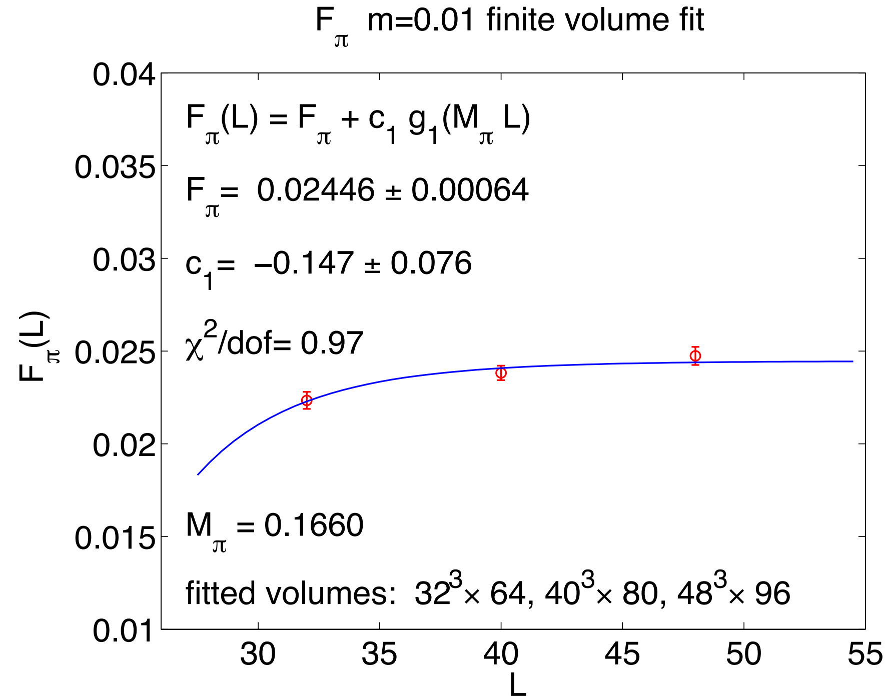
tested with two opposite hypotheses (chiSB vs. conformal symmetry)

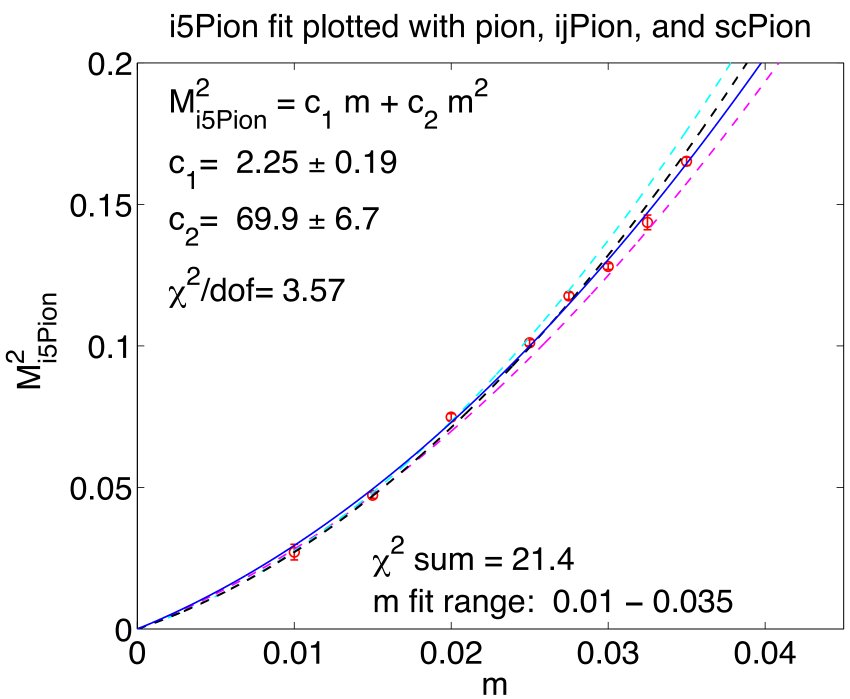
assumptions:
- with exception of condensate only minimal leading functions are applied in both hypotheses
- global analysis is used in different channel combinations and linear term is added to condensate to account for UV effects
- continuum fitting at fixed gauge coupling without further tests of cutoff effects (will be addressed)

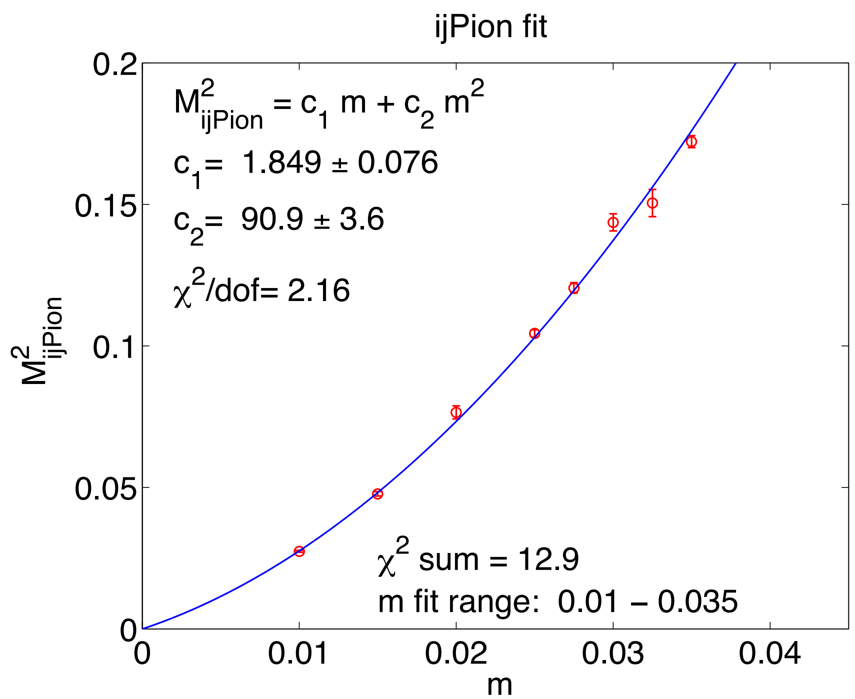
Nf=12 Goldstone spectrum and F_{ps} (Lattice Higgs Collaboration)

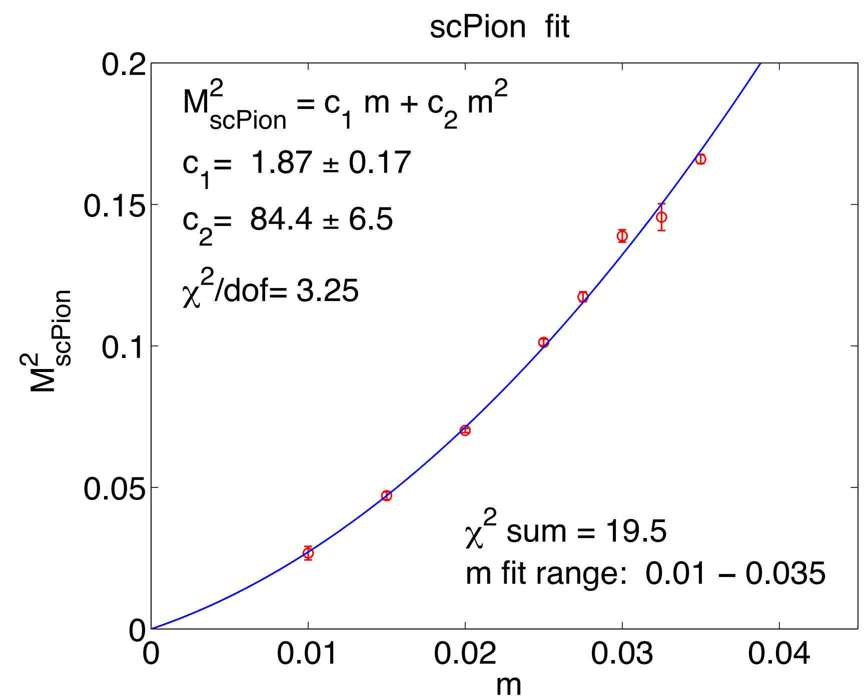












Chiral condensate (LHC)

mass	lattice	$\langle\bar\psi\psi\rangle$	$\langle\bar\psi\psi\rangle - m\cdot\chi_{con}$
0.0100	$48^3\times 96$	0.134896(47)	0.006305(73)
0.0150	$48^3\times 96$	0.200647(31)	0.012685(56)
0.0200	$40^3\times 80$	0.266151(72)	0.022069(76)
0.0250	$32^3\times 64$	0.33147(10)	0.03462(12)
0.0275	$24^3\times 48$	0.36372(40)	0.04133(59)
0.0300	$32^3\times 32$	0.396526(84)	0.04974(13)
0.0325	$24^3\times 48$	0.42879(33)	0.05781(45)
0.0350	$24^3\times 48$	0.46187(27)	0.06807(40)

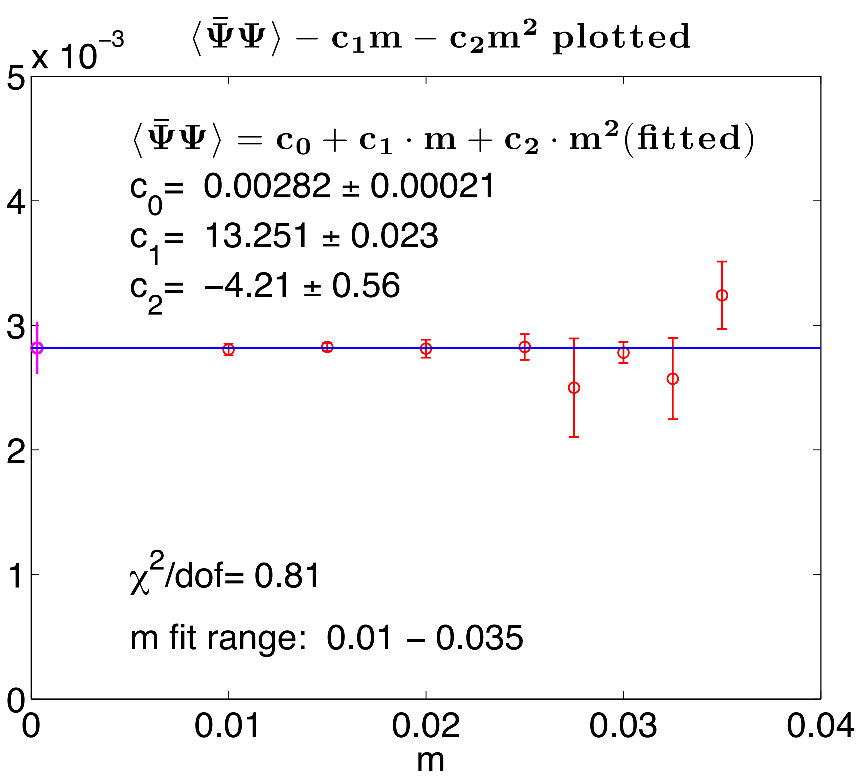
$$\langle\bar\psi\psi\rangle = -2m\cdot\int_0^\mu \frac{d\lambda\rho(\lambda)}{m^2+\lambda^2}$$

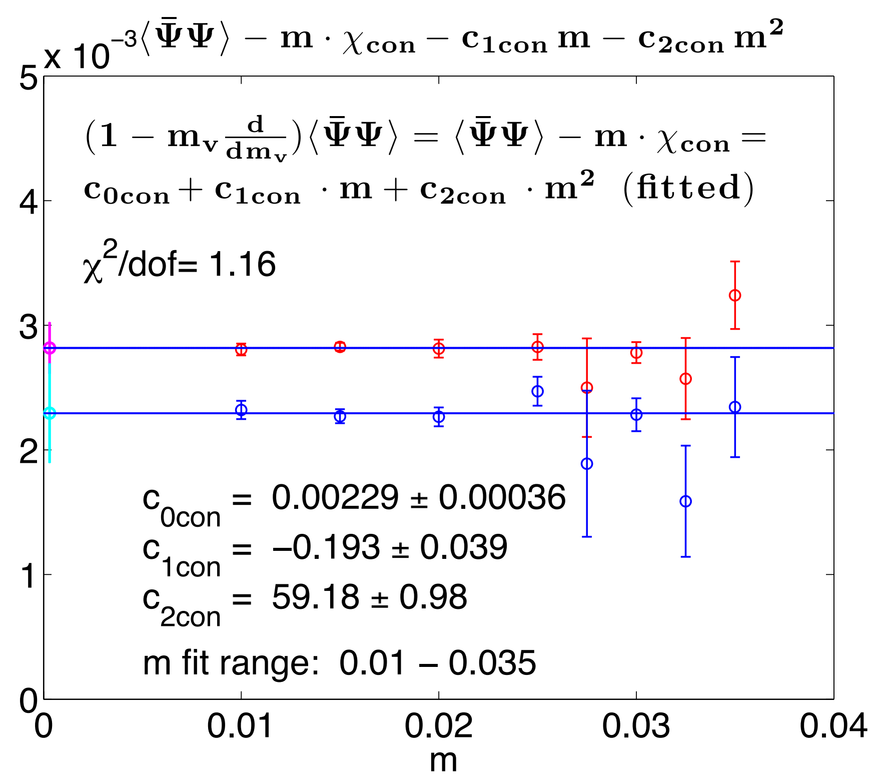
$$= -2m^5\cdot\int_\mu^\infty \frac{d\lambda}{\lambda^4}\frac{\rho(\lambda)}{m^2+\lambda^2} + c_1\cdot m + c_3\cdot m^3$$

$$(1-m_v\frac{d}{dm_v})\langle\bar\psi\psi\rangle\,|_{m_v=m} = \langle\bar\psi\psi\rangle - m\cdot\chi_{con}\,,$$

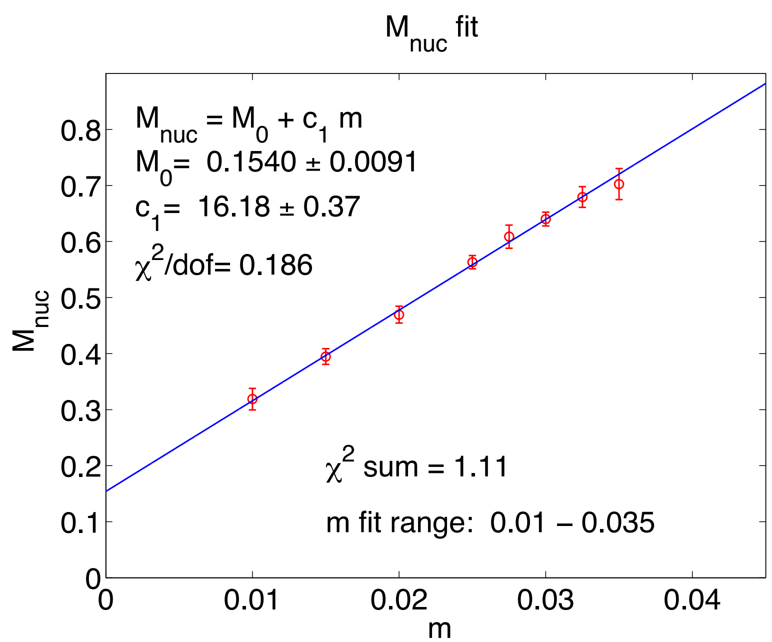
$$\chi = \frac{d}{dm}\langle\bar\psi\psi\rangle = \chi_{con}+\chi_{disc}\,,$$

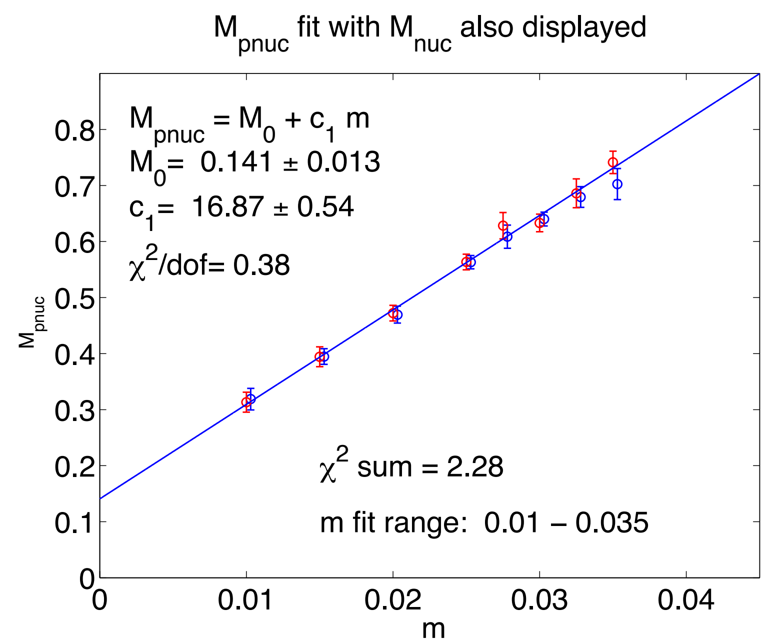
$$\chi_{con} = \frac{d}{dm_v}\langle\bar\psi\psi\rangle_{pq}\,|_{m_v=m}\ .$$

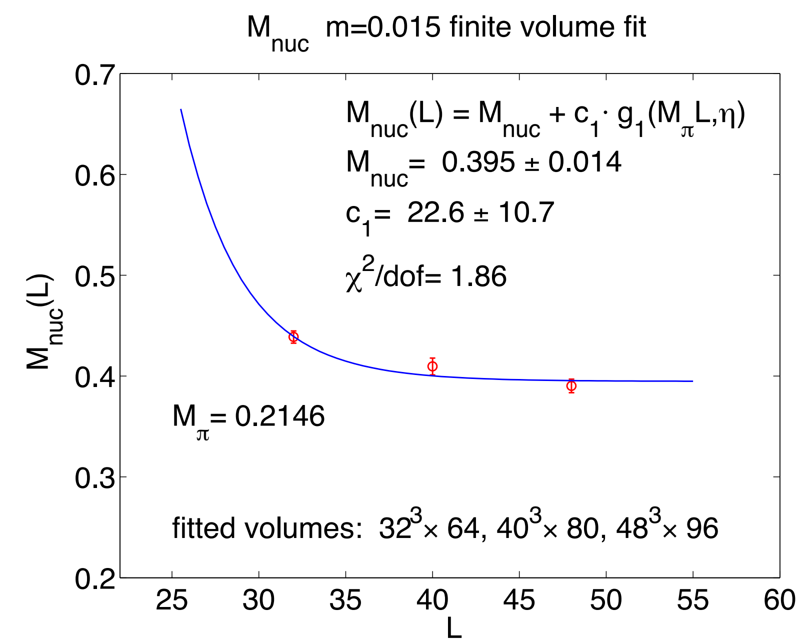


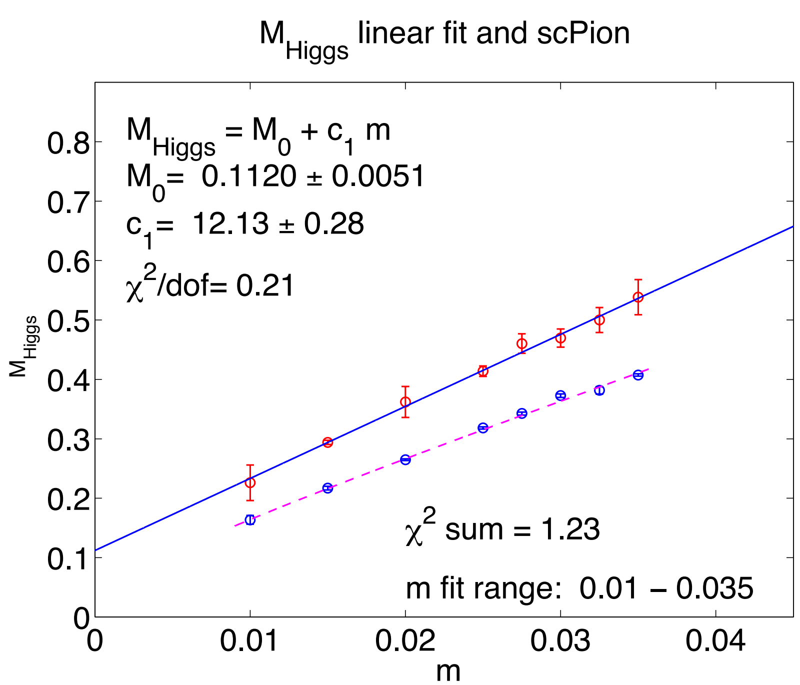


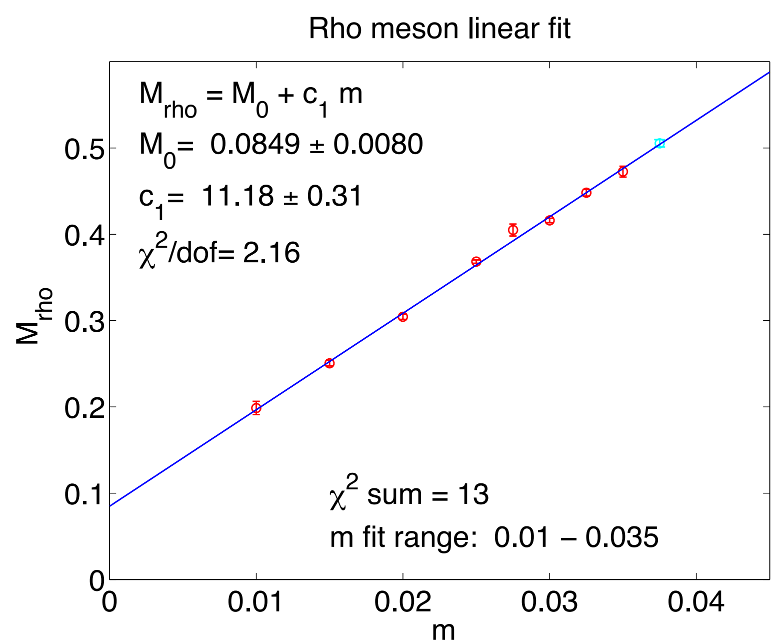
Nf=12 Hadron spectrum (LHC)

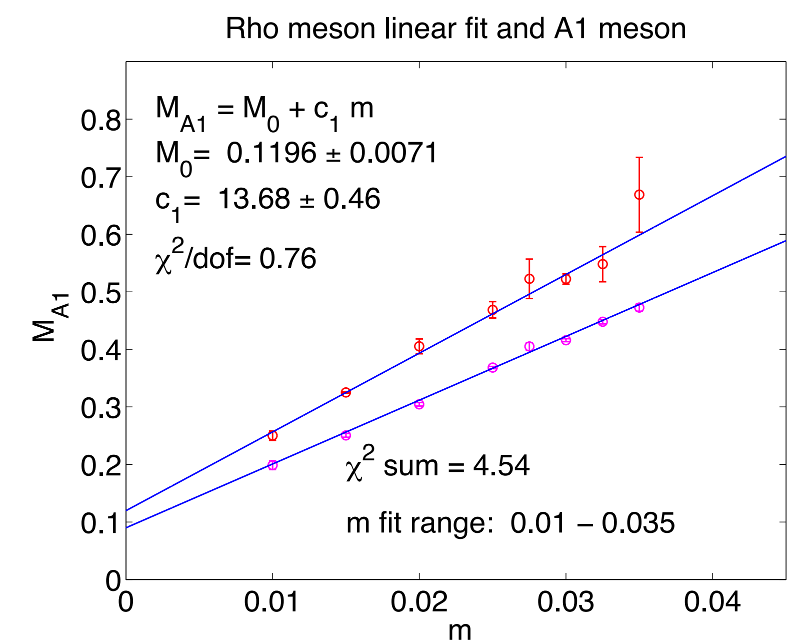




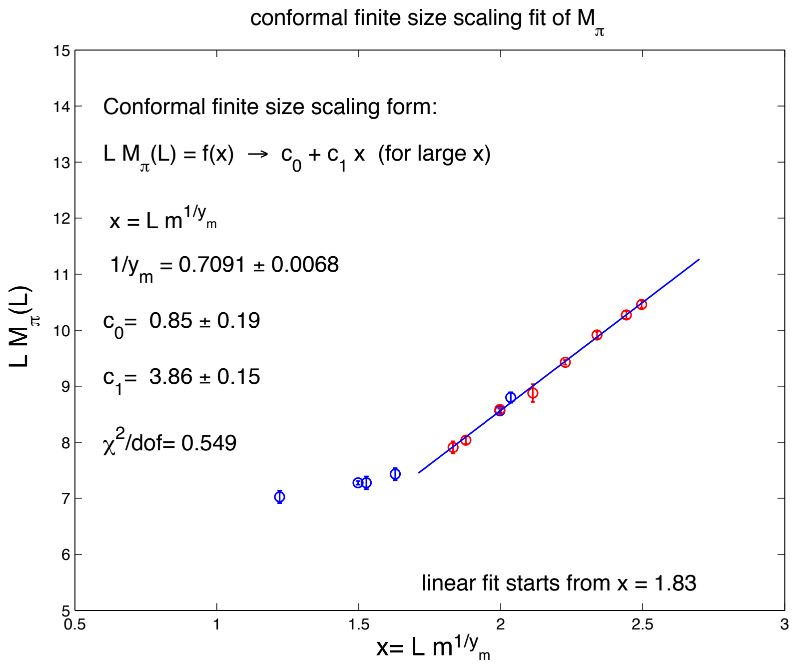


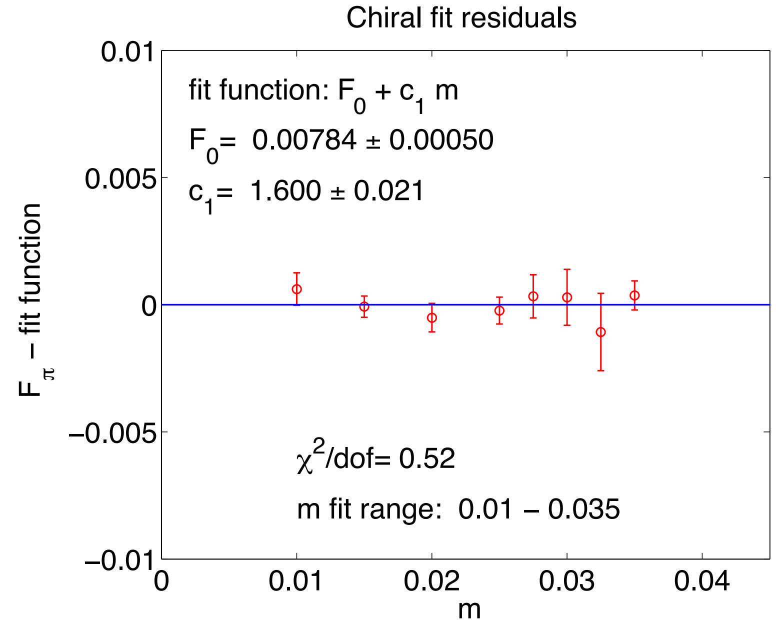


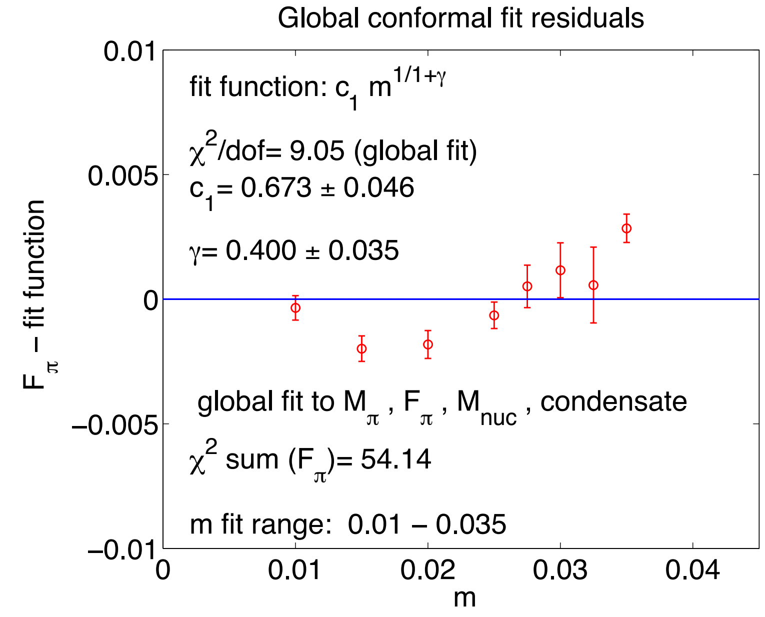


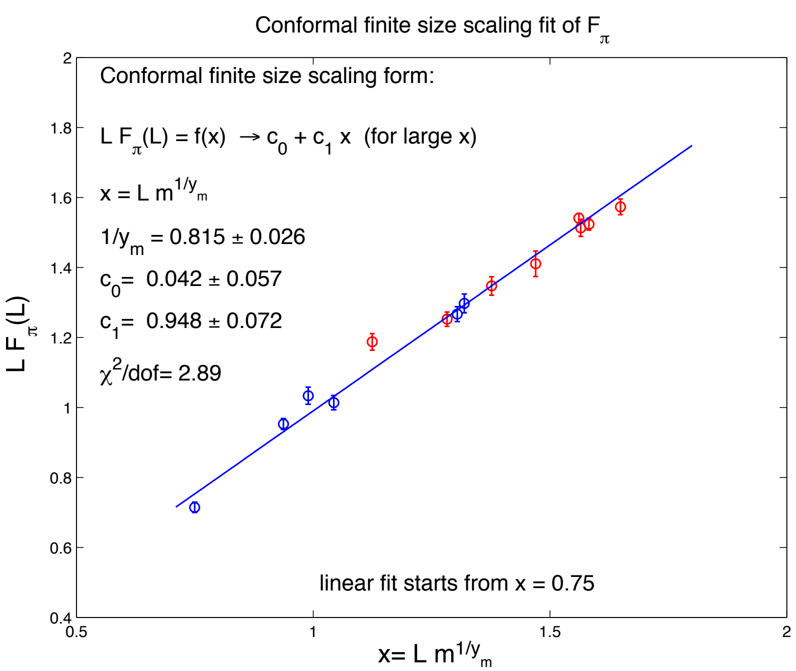


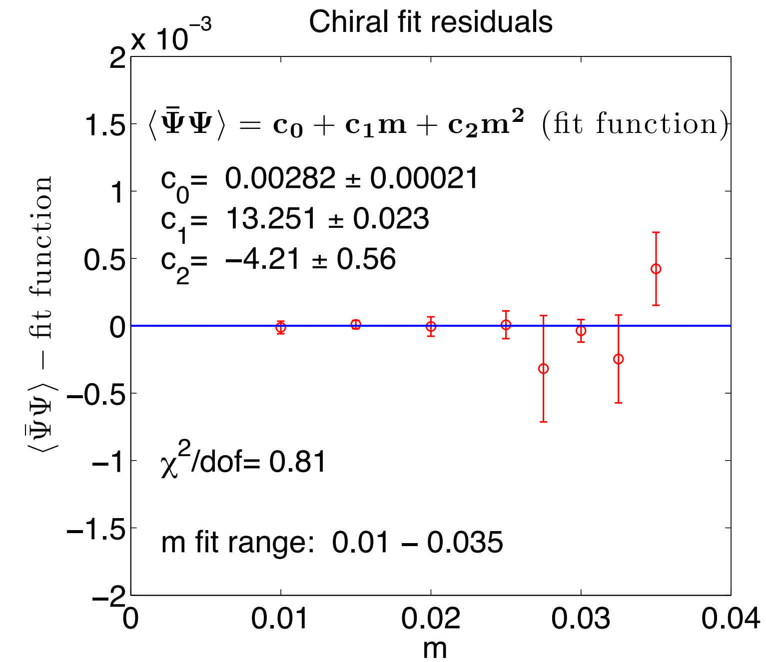
Limited comparison of the two Nf=12 hypotheses (LHC)

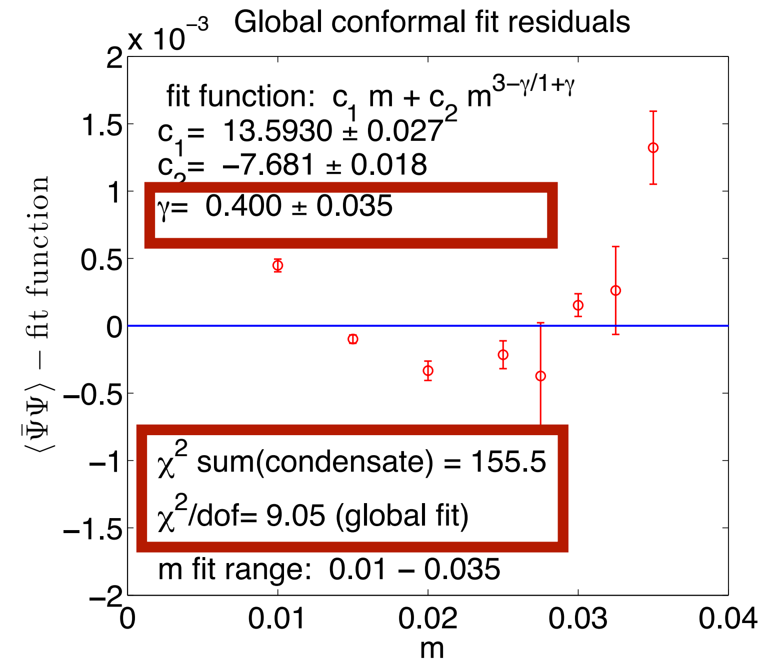










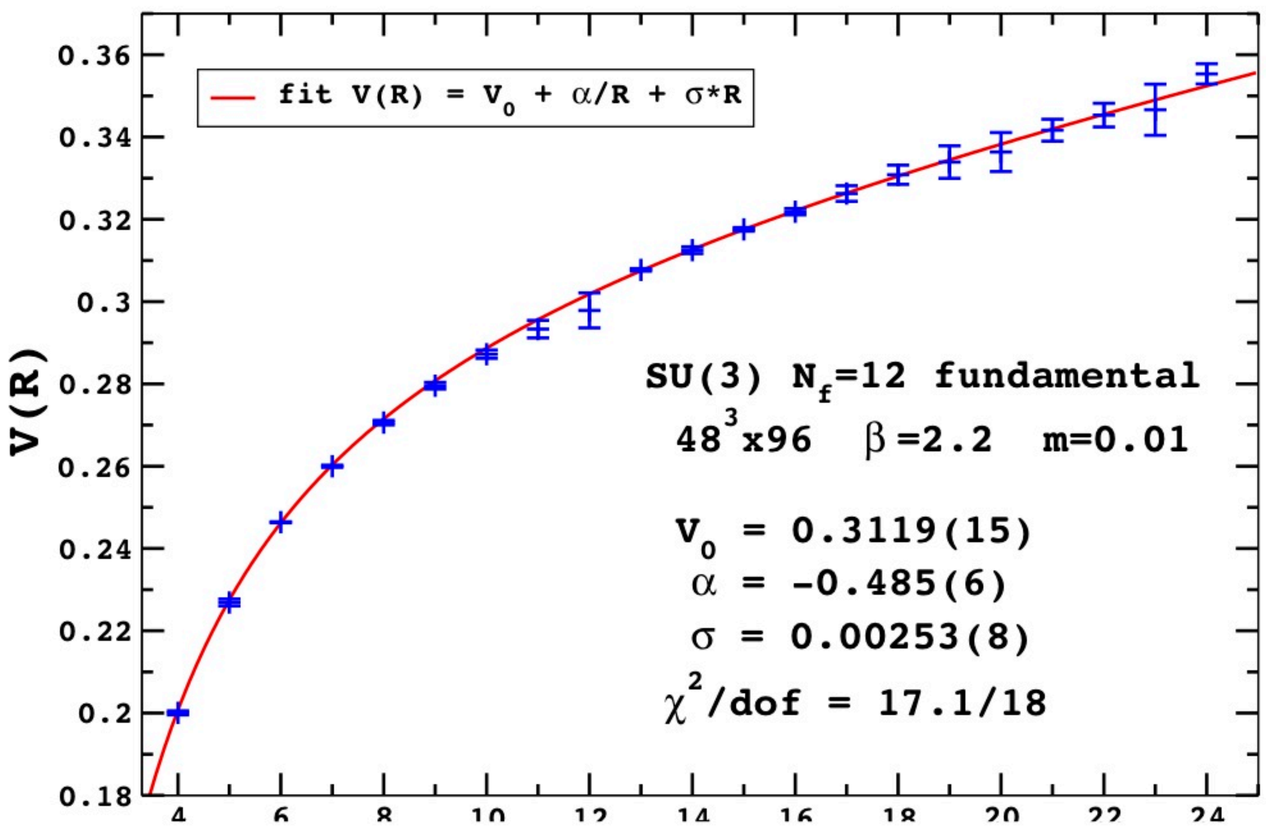


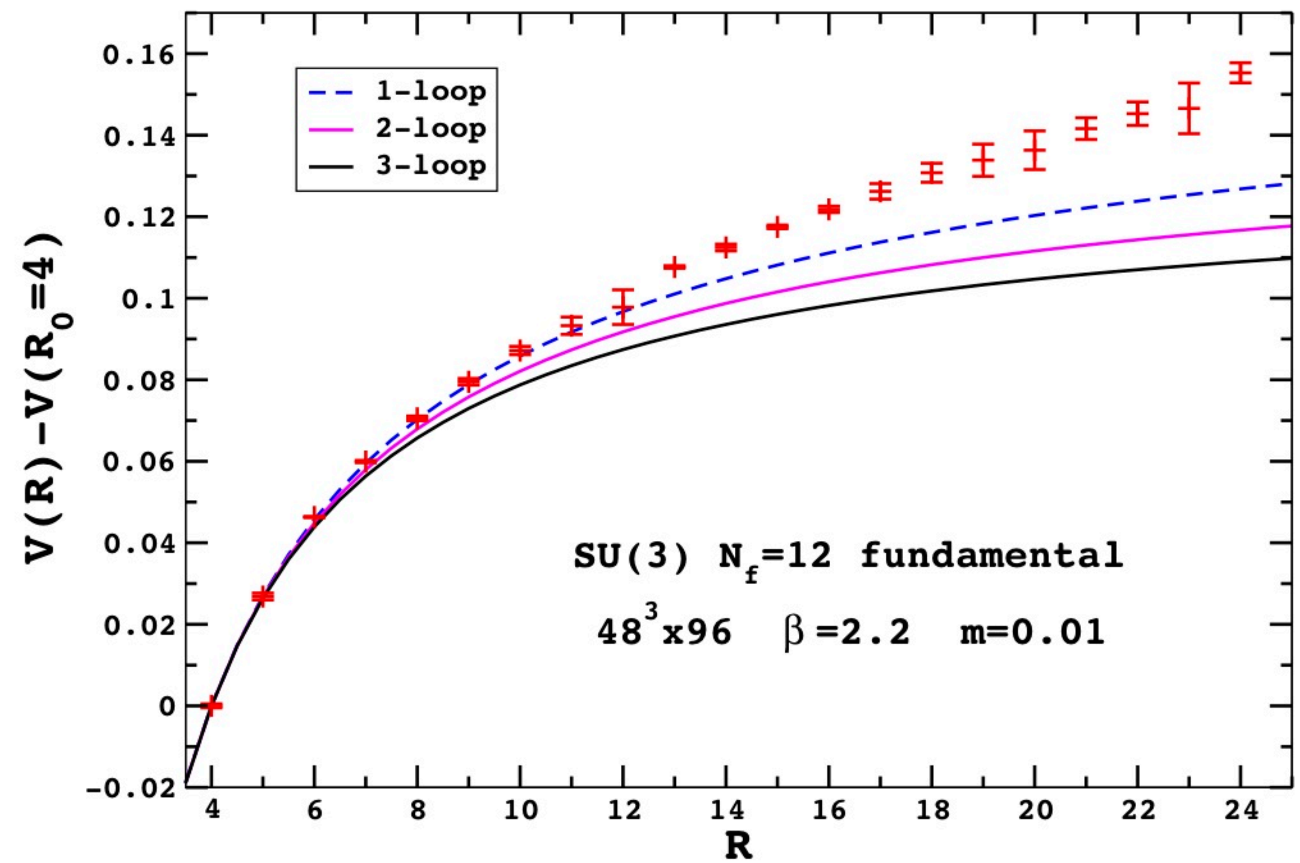
re-analysis of Appelquist et al. adds analytic non-leading terms: conformal OK

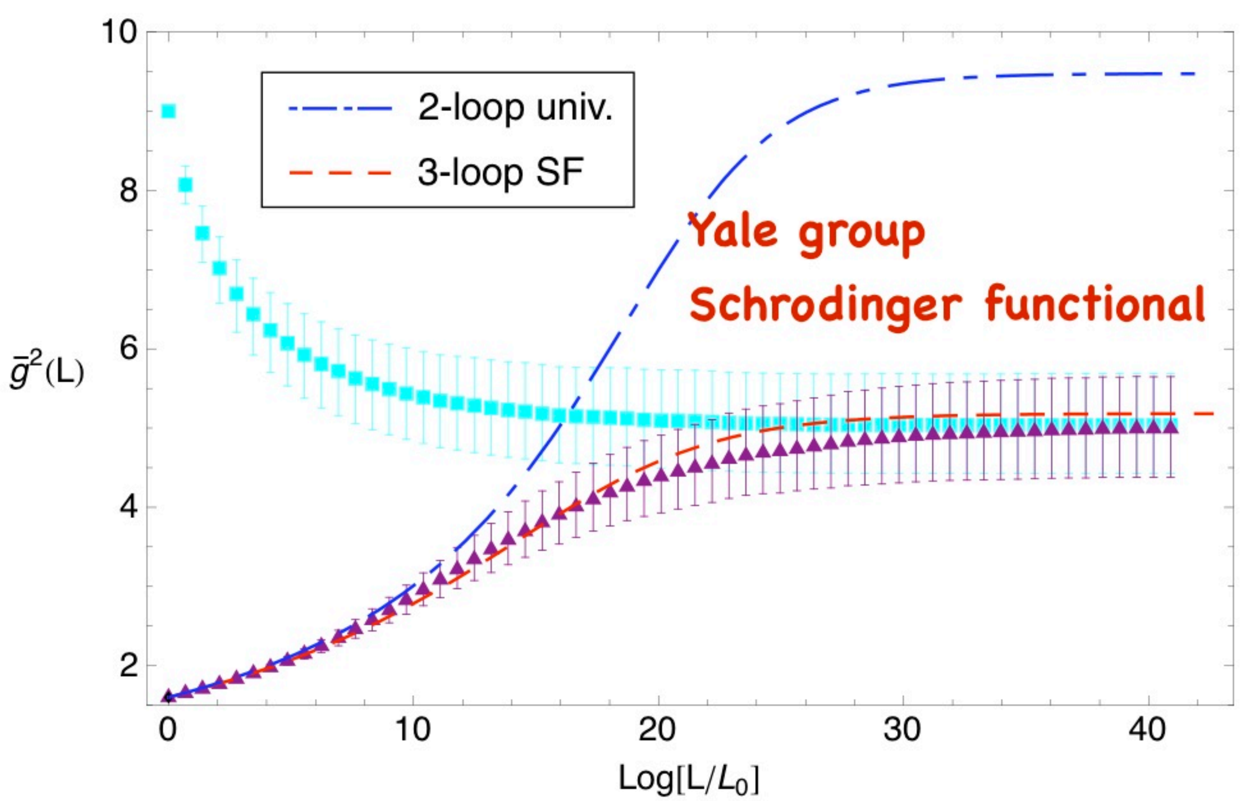
new FSS analysis from Lattice Higgs Collaboration: conformal not OK ... to continue

DeGrand's objection (ignoring Lattice 2011 LHC analysis)

Nf=12 running coupling from static force



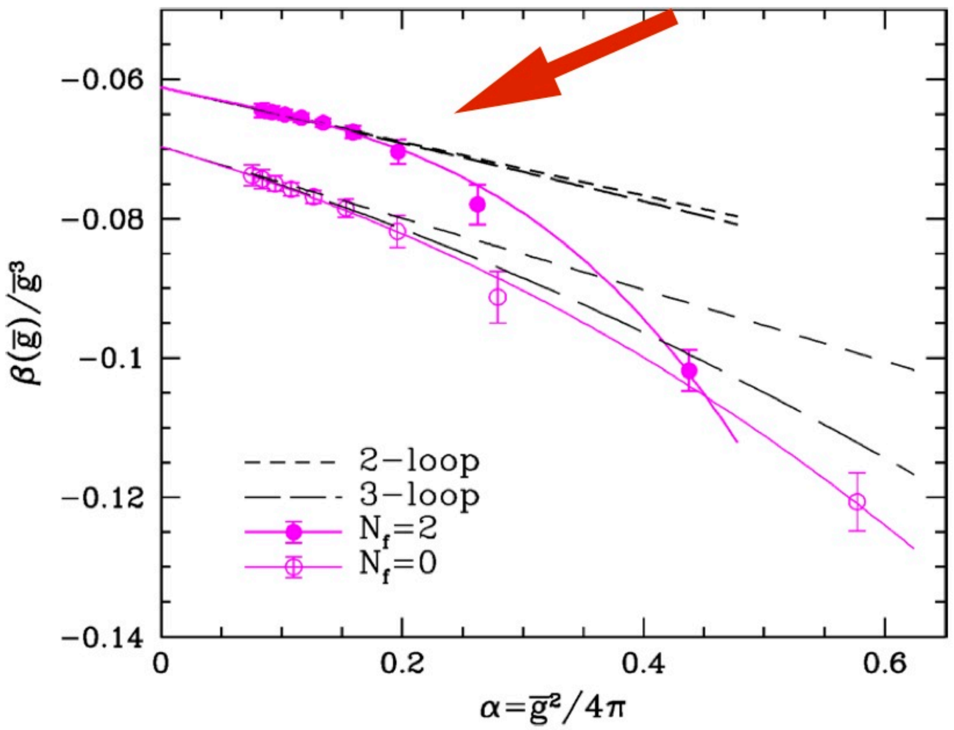




m --> 0 and a --> 0 limits ?

finite volume effects ?

running coupling and tunneling



Schrödinger Functional N_f=0 and N_f=2
massless fermions
Alpha collaboration

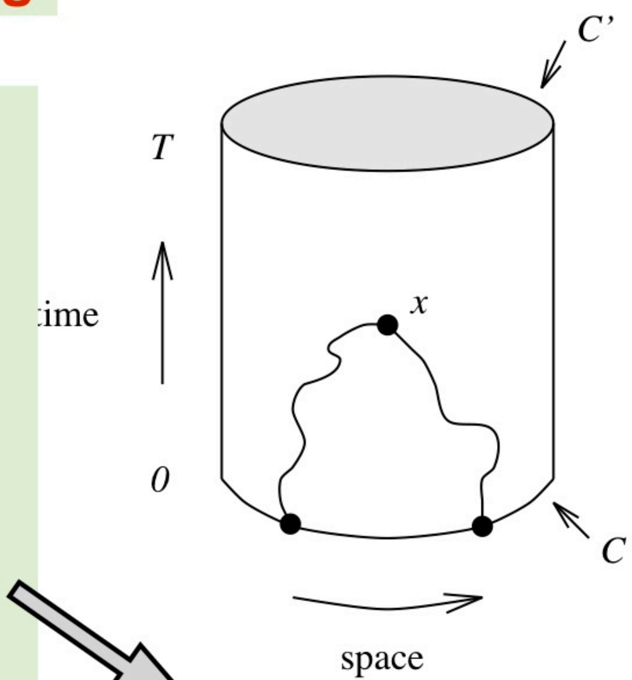
around g^2 ~ 2.5 the N_f=2 β-function breaks away from perturbative form where 2-loop and 3-loop still run closely together

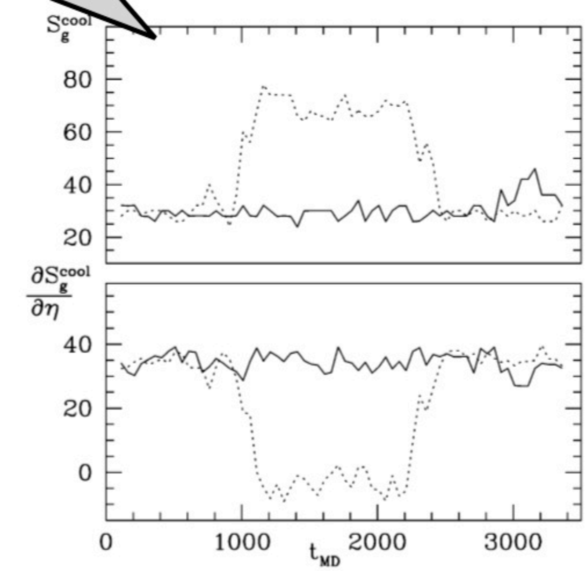
g^2 ~ 2.5 is the onset of tunneling
(most likely to a metastable local minimum)

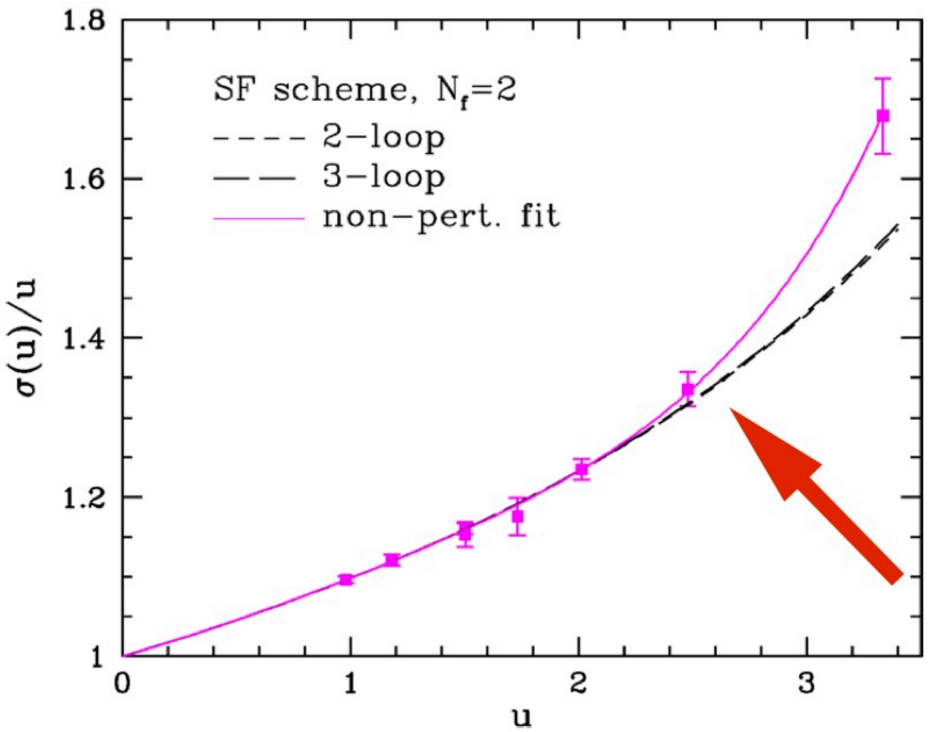
running becomes non-perturbative in very small box where L_{max} < 0.4 fm

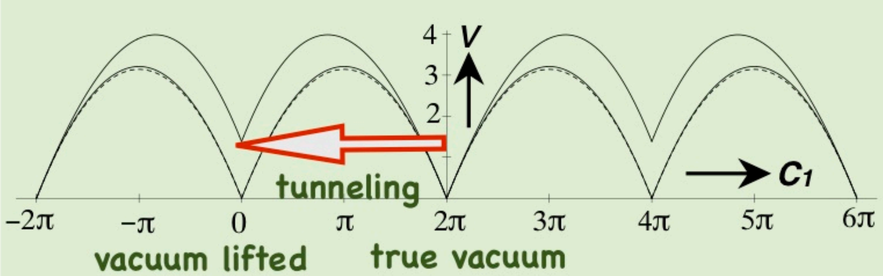
Why, and what is the underlying physics?

We need to understand femto physics better for the interpretation of the running coupling $g^2(L)$ in the presence of tunneling



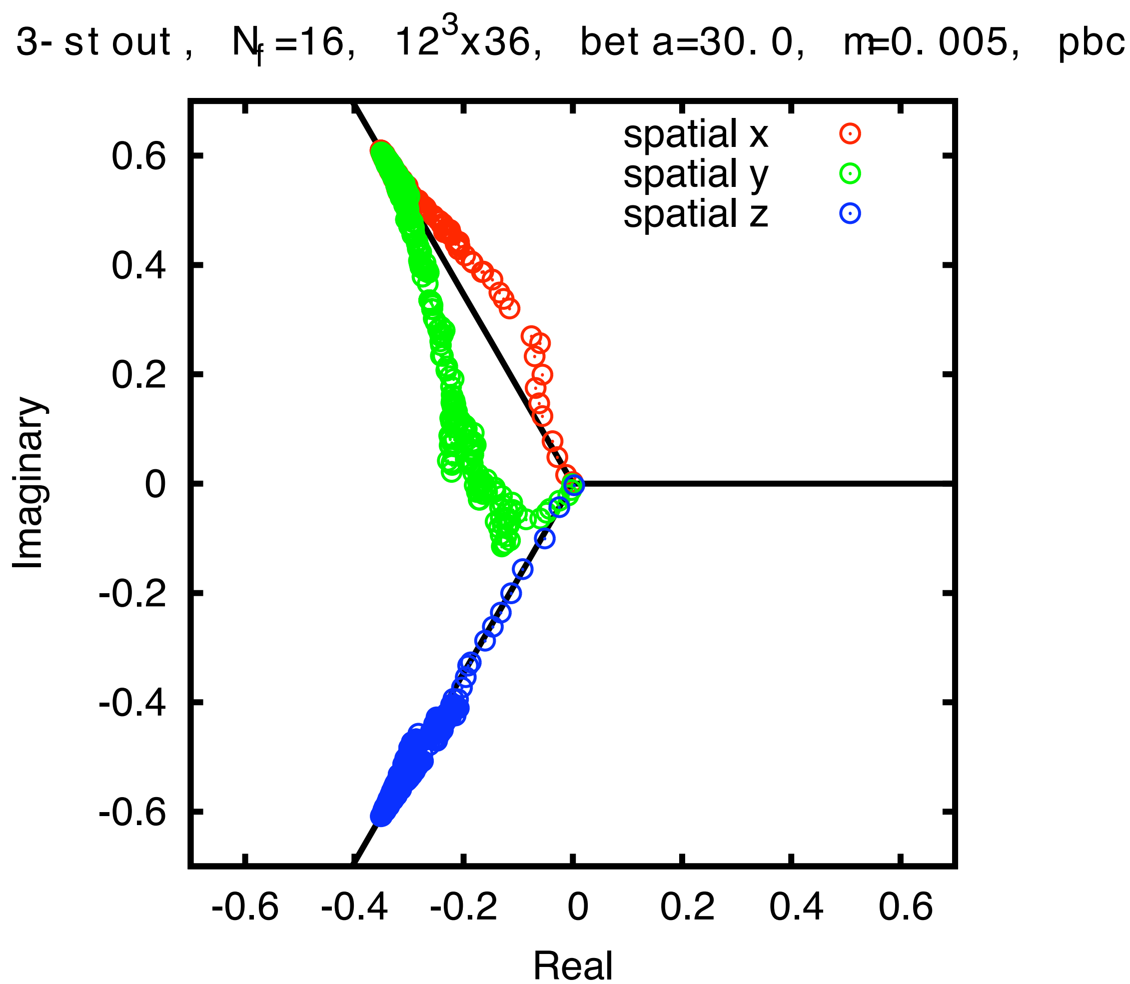


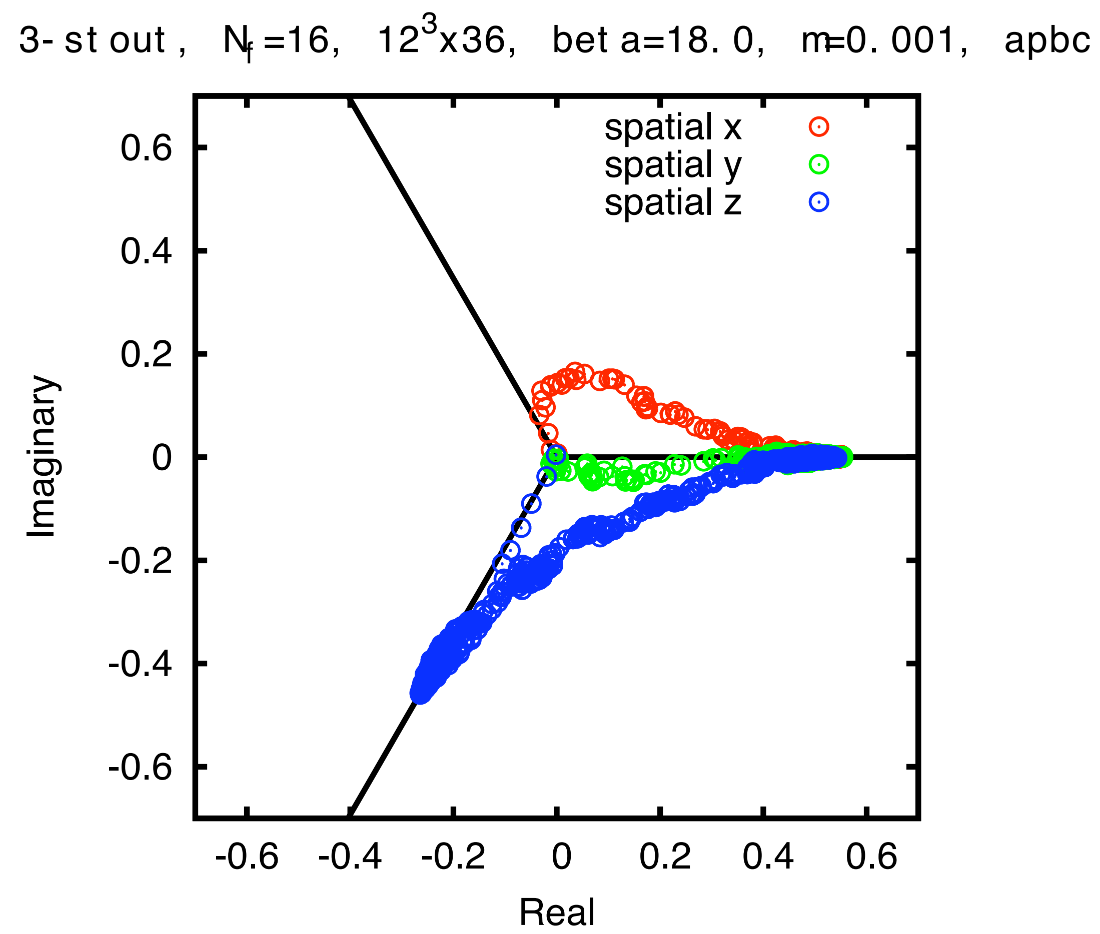




Nf=16 weak coupling case study inside the conformal window shows the dynamics

Nf=16 inside conformal window femto volume with tunneling

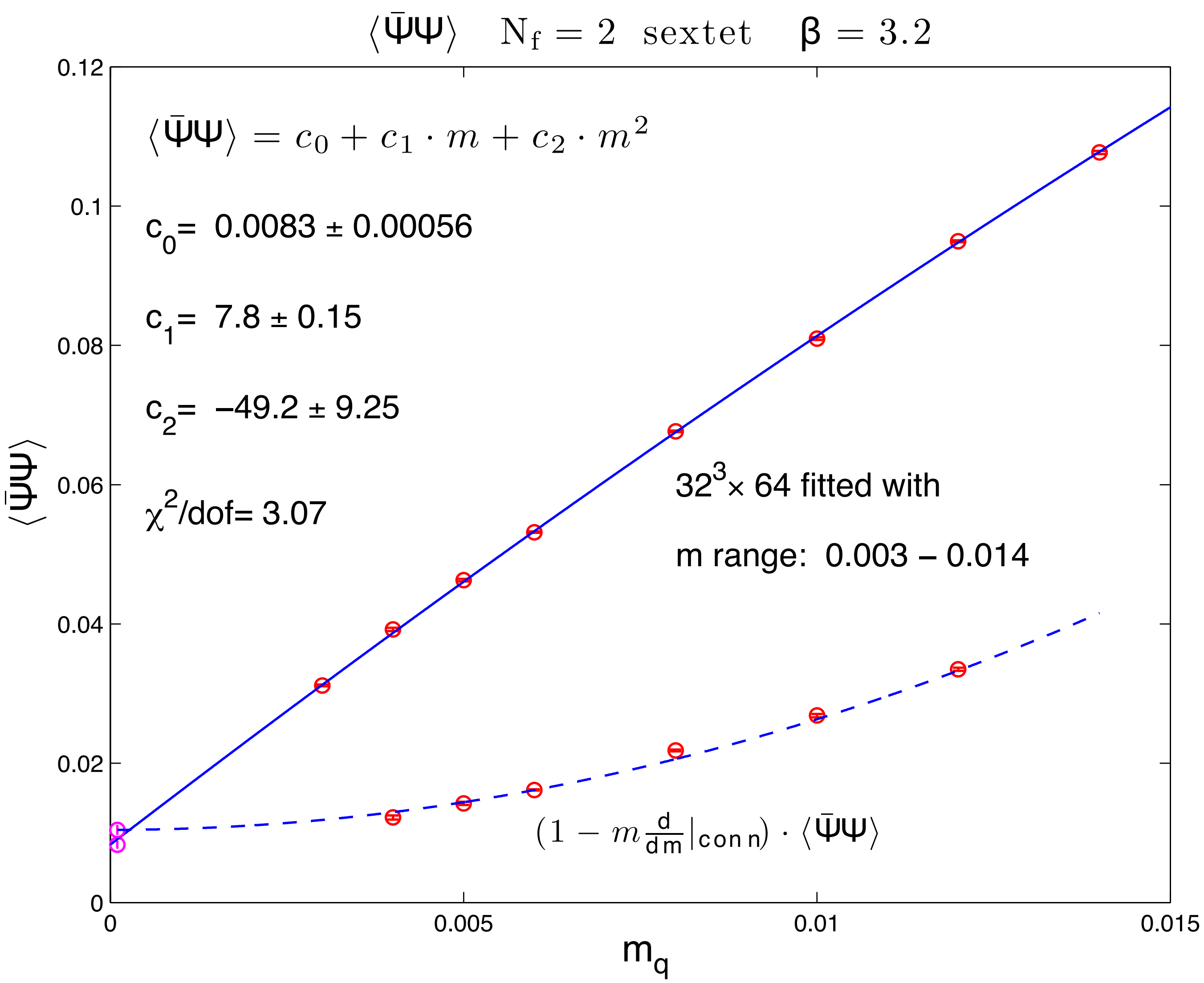


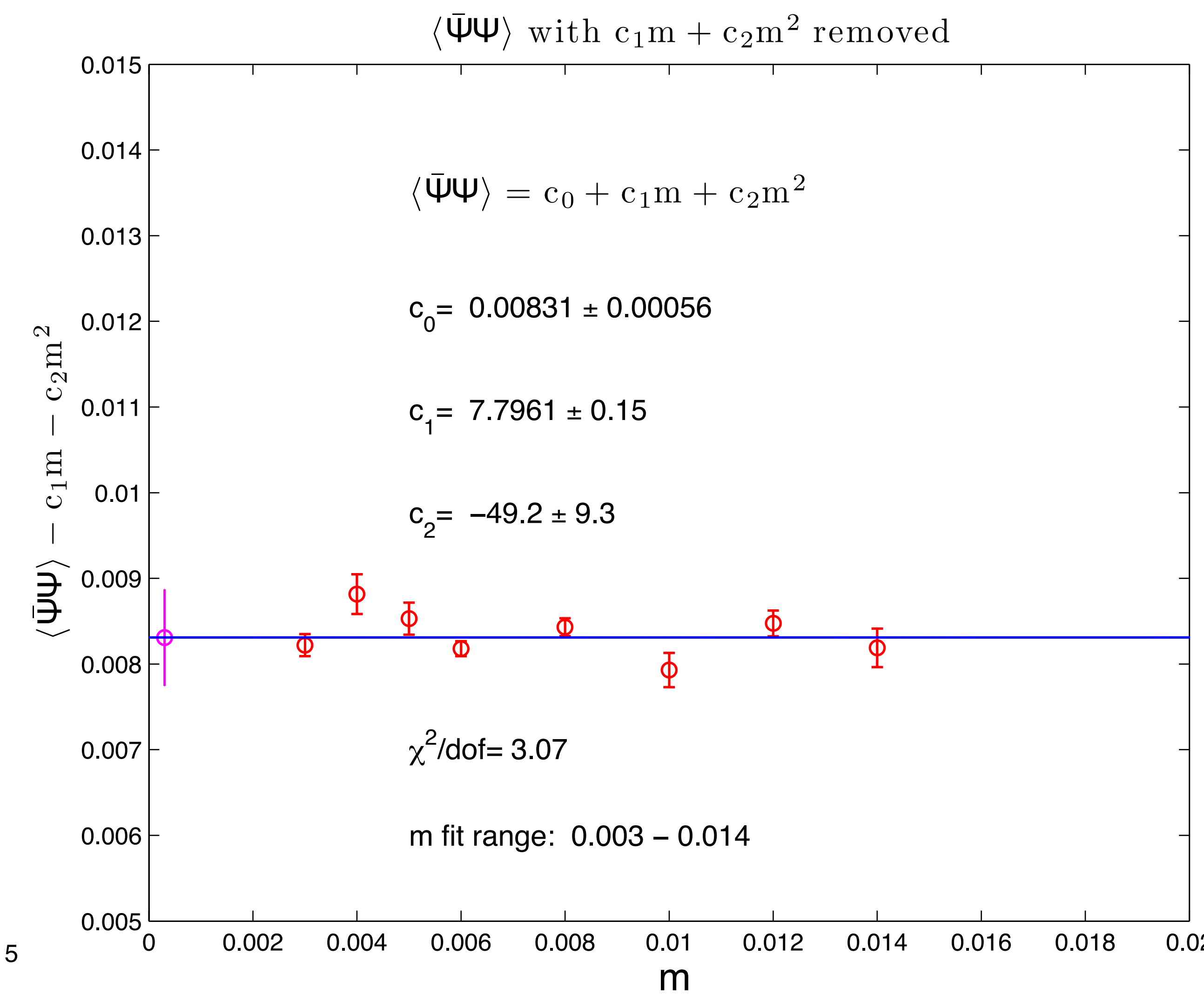


How is this effecting running coupling calculations?

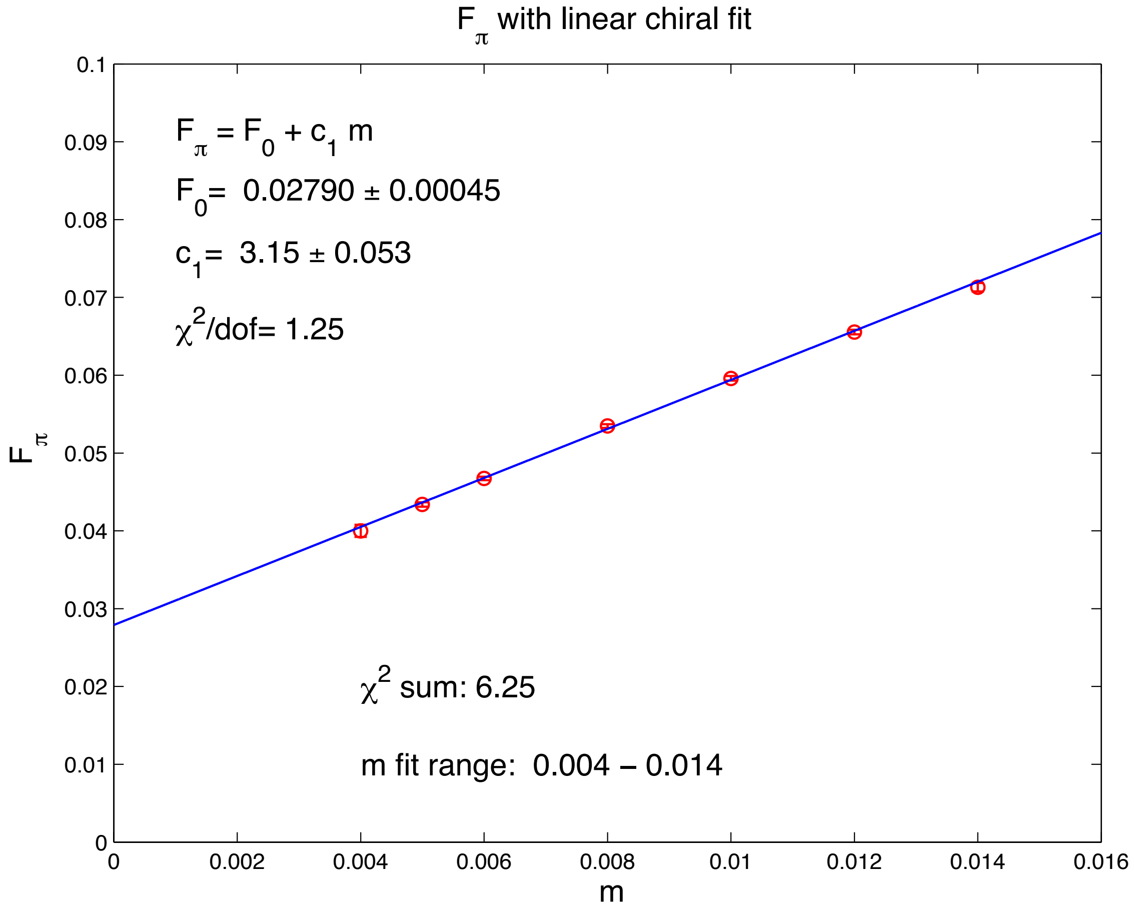
Nf=2 sextet representation

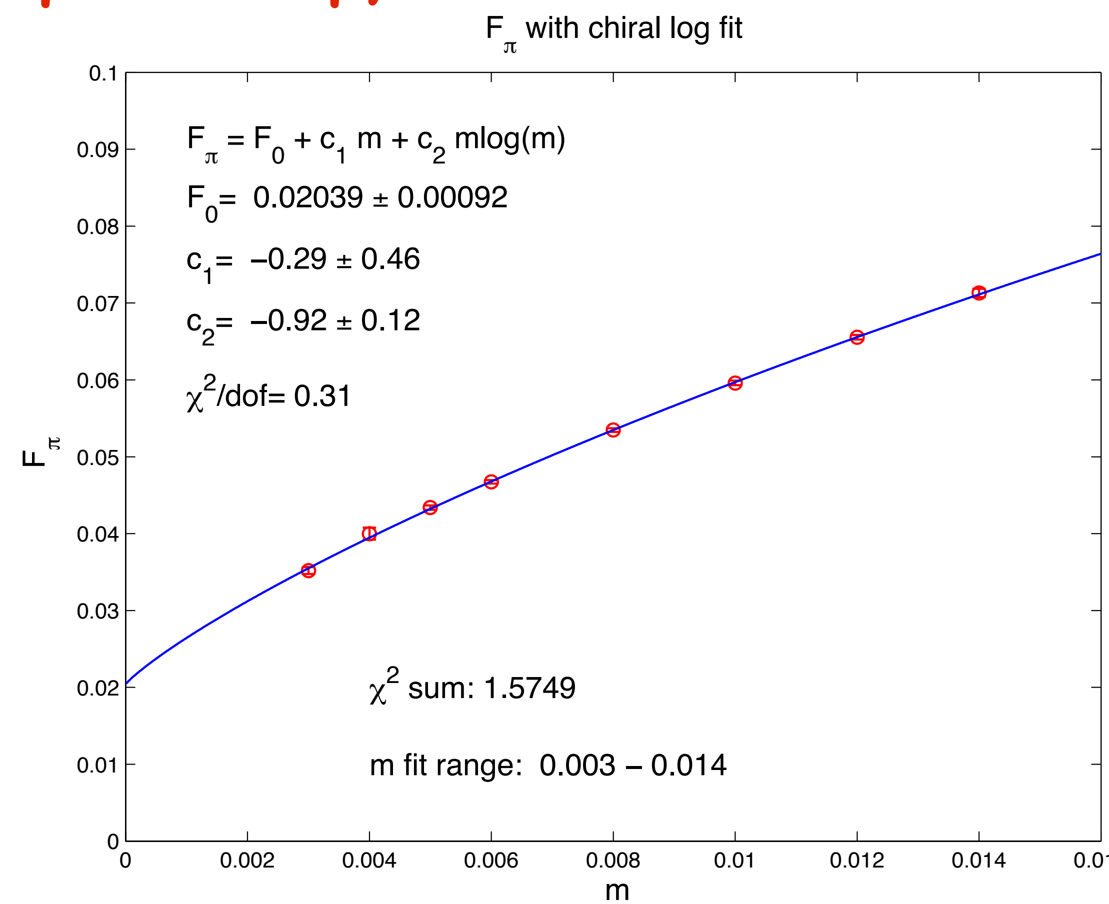
Nf=2 sextet chiral condensate

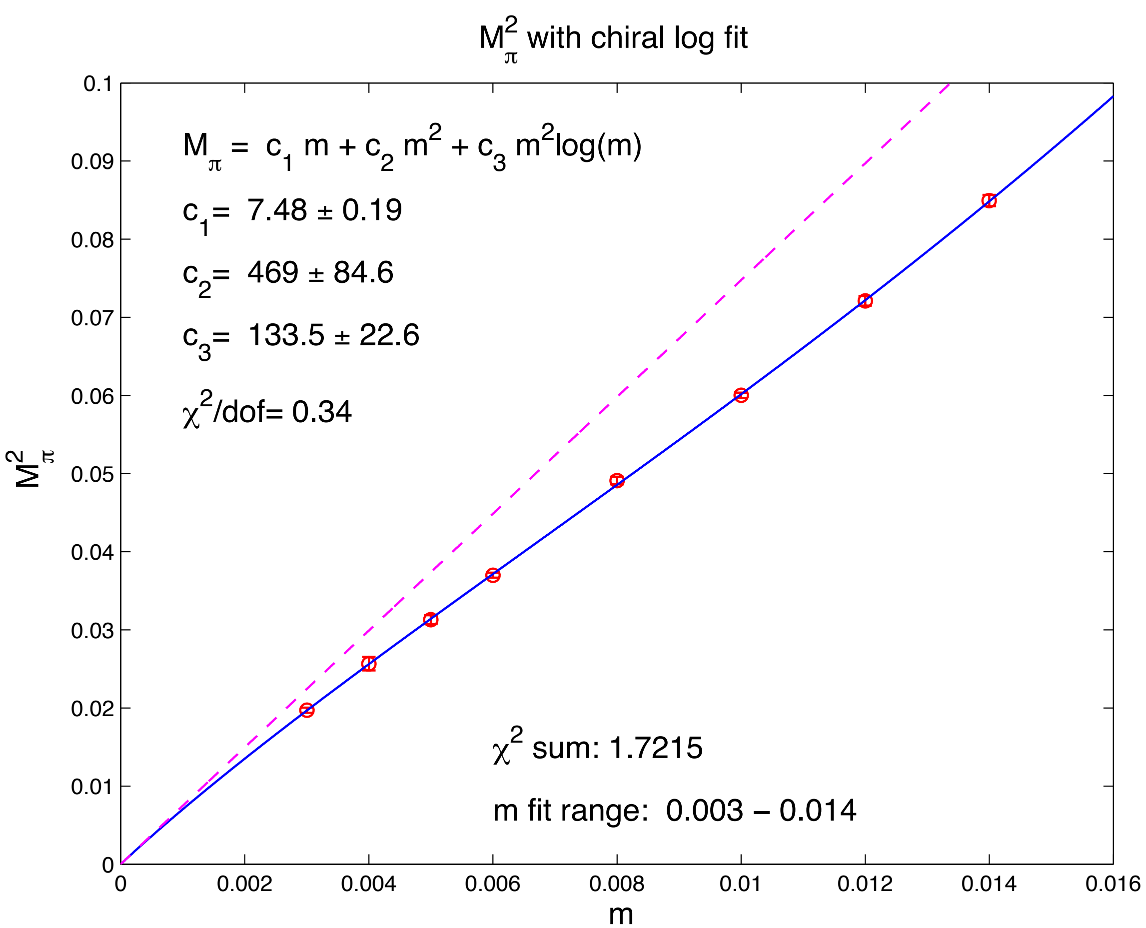


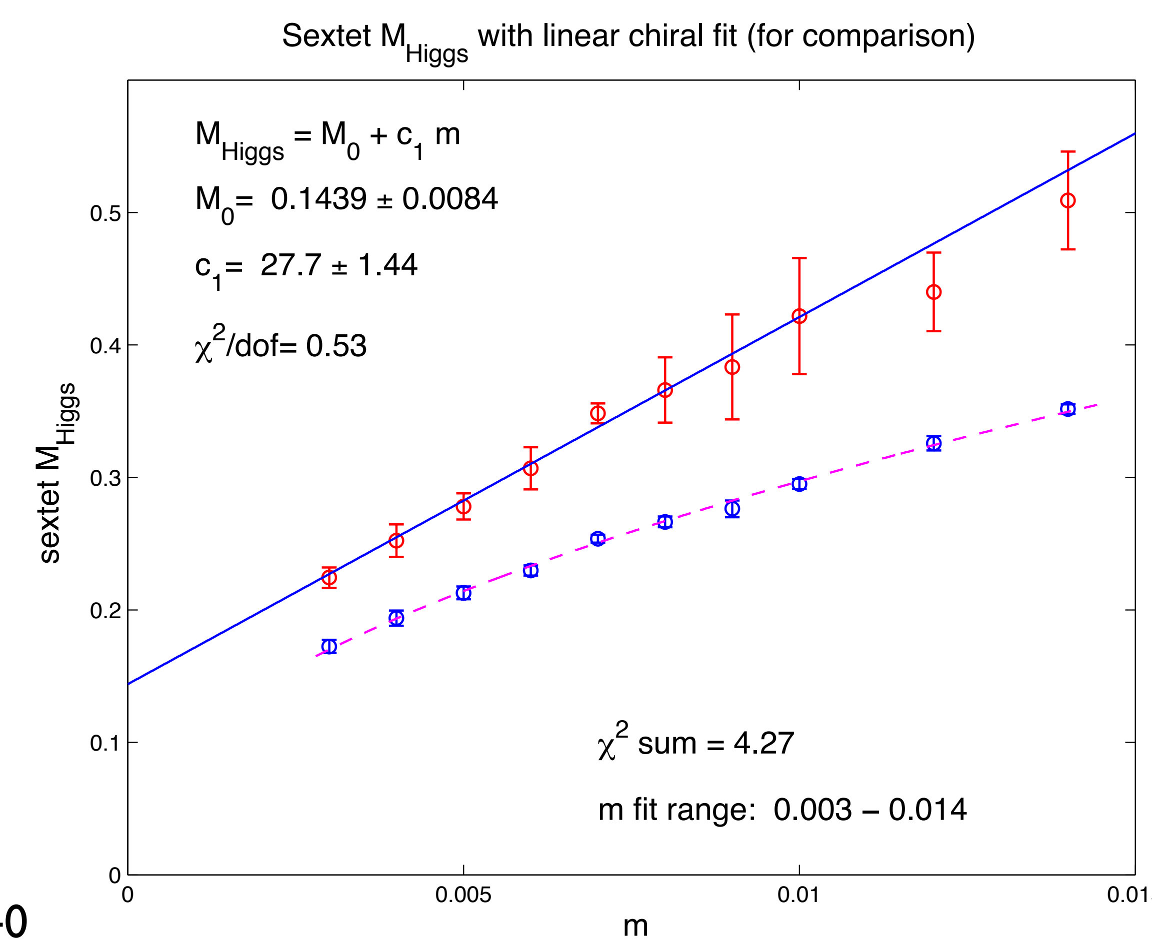


Nf=2 sextet spectroscopy

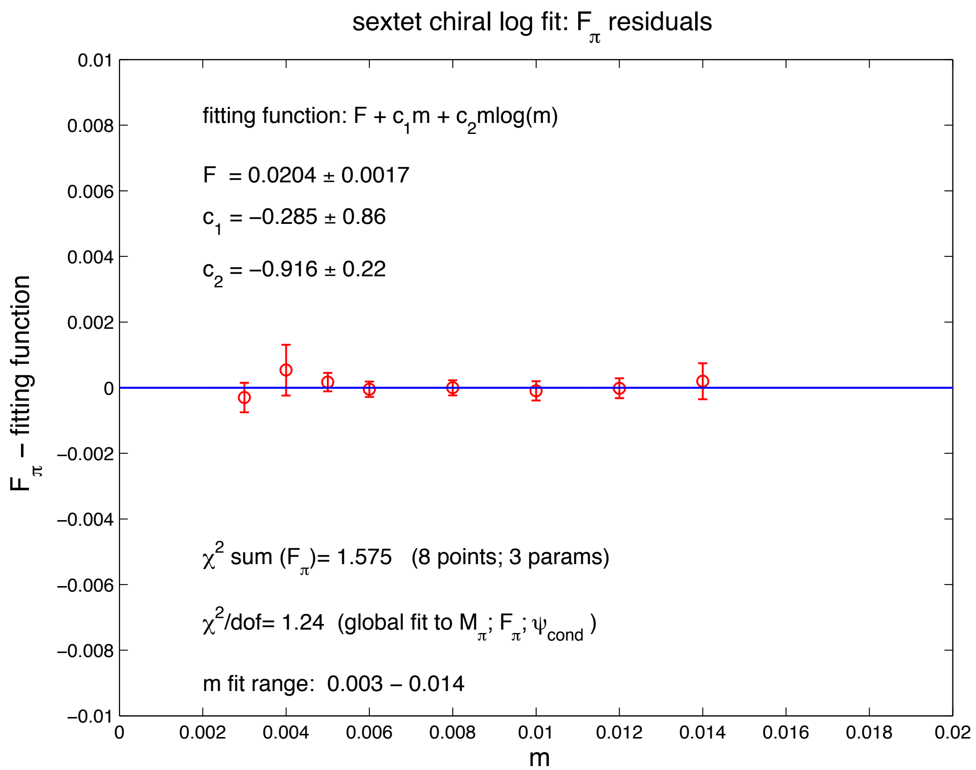


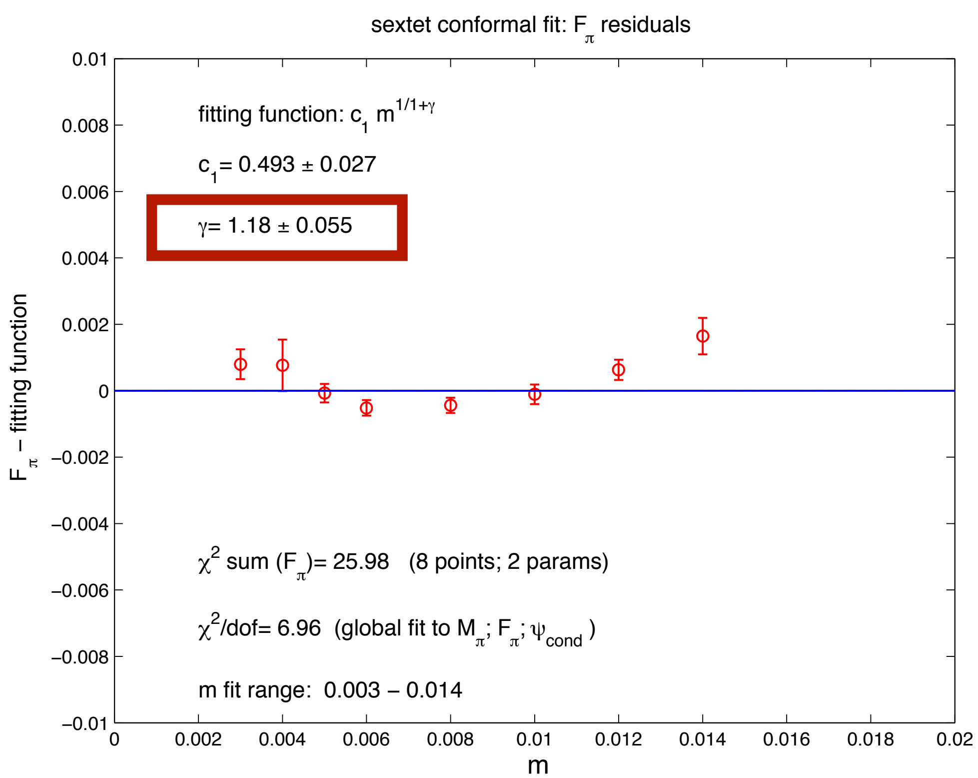


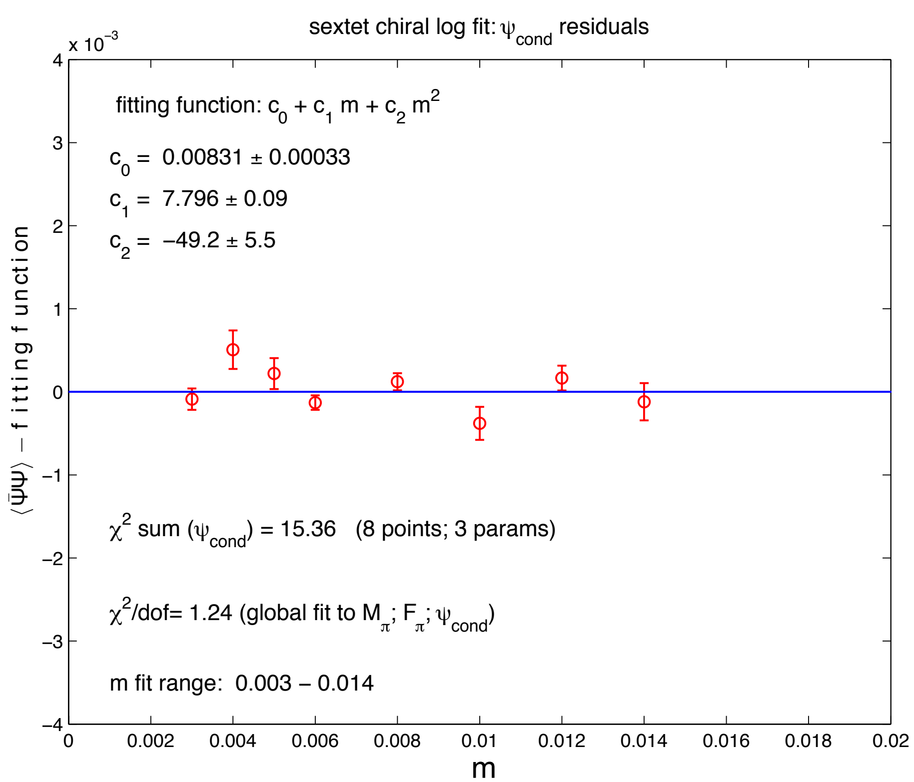


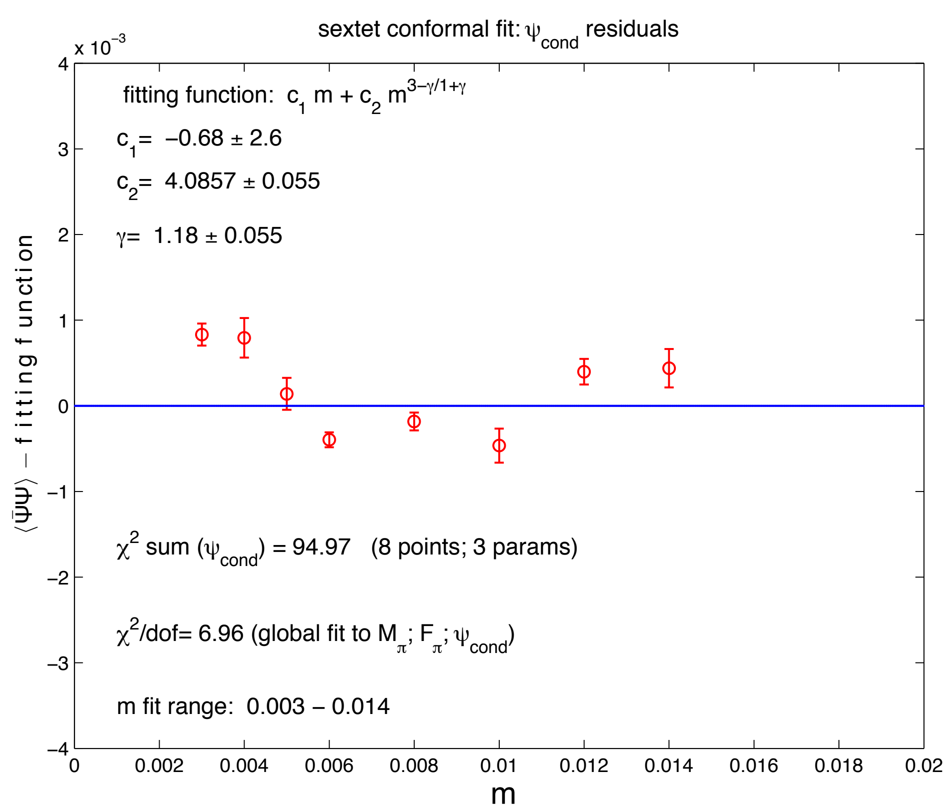


Limited comparison of Nf=2 sextet hypotheses (LHC)

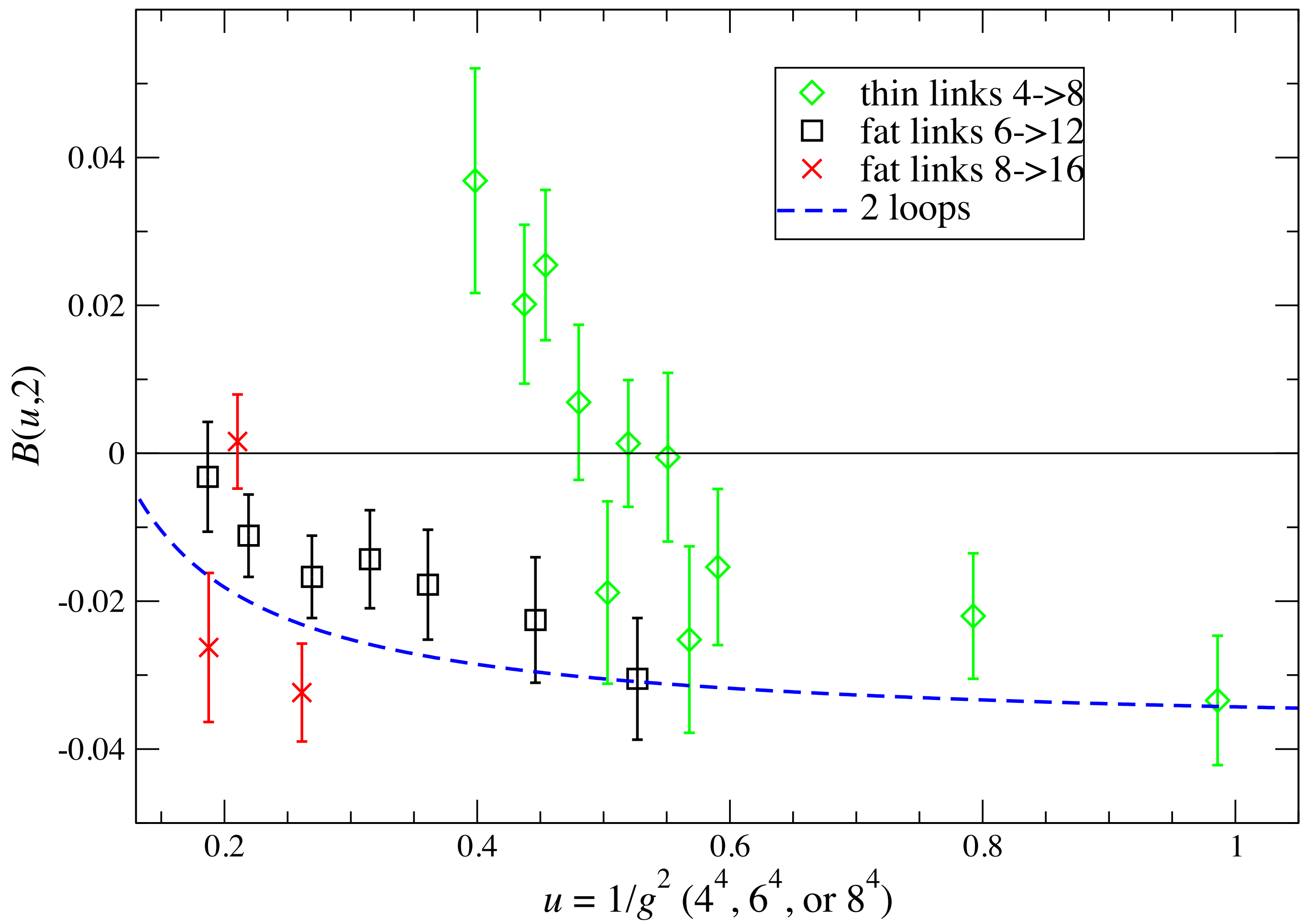








DeGrand and collaborators claim:
Nf=2 sextet beta function has an IRFP zero



But from this calculation γ ~ 0.4 is almost three times smaller than the Lattice Higgs Collaboration value

Outline

- Composite Higgs Mechanism at the LHC
lattice BSM goals in Theory Space
world-wide lattice BSM effort
lattice resources (GPU technology)

- Below the Conformal Window
lattice specific: cut-off, volume, fermion mass
RG flow and lattice continuum physics
BSM specific χPT
m=0 chiral limit and finite volume issues

- Inside the conformal window
RG flow and lattice continuum physics
finite size scaling
running coupling and tunneling
Nf=16 case study

- Outlook
from KMIIN conference discussions: new input into lattice projects?

Summary and outlook

- We have technology to deal with lattice specific issues: cut-off, volume, fermion mass
RG flow and lattice continuum physics
BSM specific χPT
m=0 chiral limit and finite volume issues
Two model studies

- Inside the conformal window
RG flow and lattice continuum physics
importance of finite size scaling
running coupling and tunneling
Nf=16 case study

- Outlook
we have only seen so far the tip of the iceberg of what lattice BSM can do
for example: FSS analysis of current correlators in m->0 limit   Lattice Higgs Collaboration
phenomenology   Strong Lattice Dynamics Collaboration
workshop discussions: new input into lattice projects?