Lattice 2013

The Higgs Boson and the Lattice

Julius Kuti

University of California, San Diego

Mainz, Germany, August 3, 2013

Large Hadron Collider - CERN

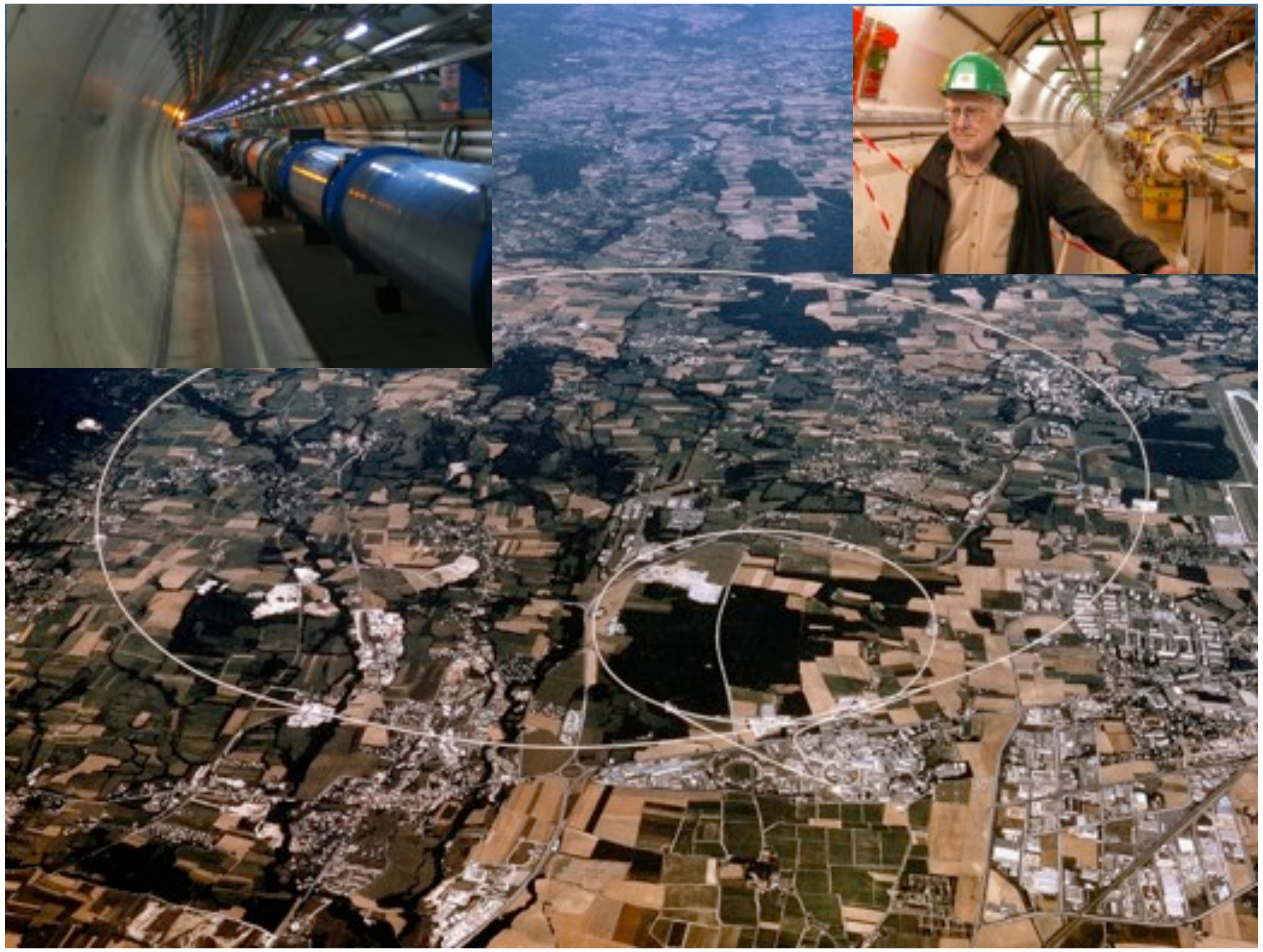
primary mission:

- Search for Higgs particle

- Origin of Electroweak symmetry breaking

- **A Higgs-like particle is found**
  Is it the Standard Model Higgs? or
- Near-conformal strong dynamics?
- Composite PNGB-like Higgs?
- SUSY?
- 5 Dim?

...



Primary focus of BSM lattice effort and this talk

LATTICE GAUGE THEORIES AT THE ENERGY FRONTIER

Thomas Appelquist, Richard Brower, Simon Catterall, George Fleming, Joel Giedt, Anna Hasenfratz, Julius Kuti, Ethan Neil, and David Schaich

(USQCD Collaboration)

(Dated: March 10, 2013)

USQCD BSM White Paper - community based effort
short synopsis is input into US Snowmass 2013 planning:

USQCD and the composite Higgs at the Energy Frontier

The recent discovery of the Higgs-like particle at 126 GeV is the beginning of the experimental search for a deeper dynamical explanation of electroweak symmetry breaking beyond the Standard Model (BSM). The USQCD collaboration has developed an important BSM research direction with the primary focus on the composite Higgs mechanism as outlined in our recent USQCD BSM white paper [1] and in this short report. Deploying advanced lattice field theory technology, we are investigating new strong gauge dynamics to explore consistency with a composite Higgs particle at 126 GeV which will require new non-perturbative insight into this fundamental problem. The organizing principle of our program is to explore the dynamical implications of approximate scale invariance and chiral symmetries with dynamical symmetry breaking patterns that may lead to the composite Higgs mechanism with protection of the light scalar mass, well separated from predicted new resonances, which maybe on the 1-2 TeV scale. Based on an underlying strongly-coupled theory, lattice calculations provide the masses and decay constants of these new particles, enabling concrete predictions for future experimental results at colliders and in dark matter searches.

On the other hand, if the higher resonances are too heavy to be directly probed at the LHC, indirect evidence for Higgs compositeness may appear for example as altered rates for electroweak gauge boson scattering, changes to the Higgs coupling constants, or the presence of additional light Higgs-like resonances. Here lattice calculations are used to derive the low energy constants in an Effective Field Theory description to predict departures of a composite Higgs dynamics from the standard model predictions. Of course as new experimental evidence from the LHC is forthcoming, BSM lattice simulations will be focused on an increasingly narrower class of candidate theories, consistent with experimental constraints, increasing its power as a theoretical tool in the search for BSM physics. Two major components of our BSM lattice program are carefully planned and coordinated, as summarized below.

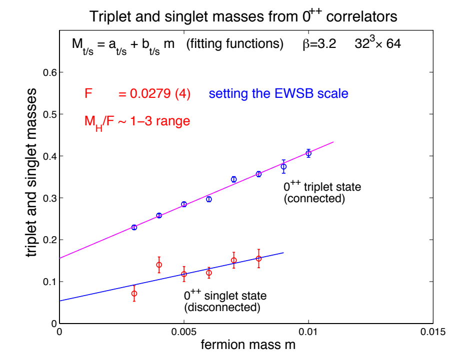


FIG. 1. This plot is unpublished and for illustration only. Some of the flavor singlet scalar data points are expected to remain in flux before final analysis and publication [3]. The ongoing work indicates the emergence of a light flavor singlet scalar state (red) with 0^{++} quantum numbers in the sextet rep of a fermion doublet with the minimal realization of the composite Higgs mechanism. Annihilation diagrams driven by strong gauge dynamics downshift the mass of the flavor singlet state close to the EWSB scale. Turning on a third massive EW singlet in the model might bring the β-function even closer to zero with minimal tuning. The fermion mass dependence of the isotriplet meson (blue) is also shown, not effected by disconnected annihilation diagram. In the chiral limit it is a heavy resonance above 1 TeV. The model predicts several resonances in the 1-2 TeV range.

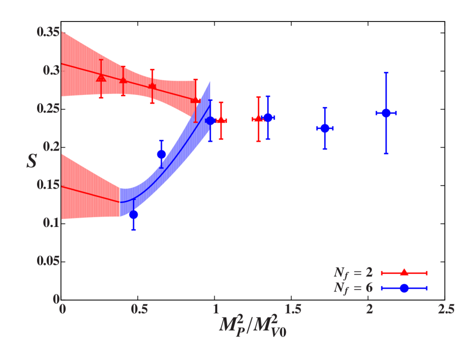
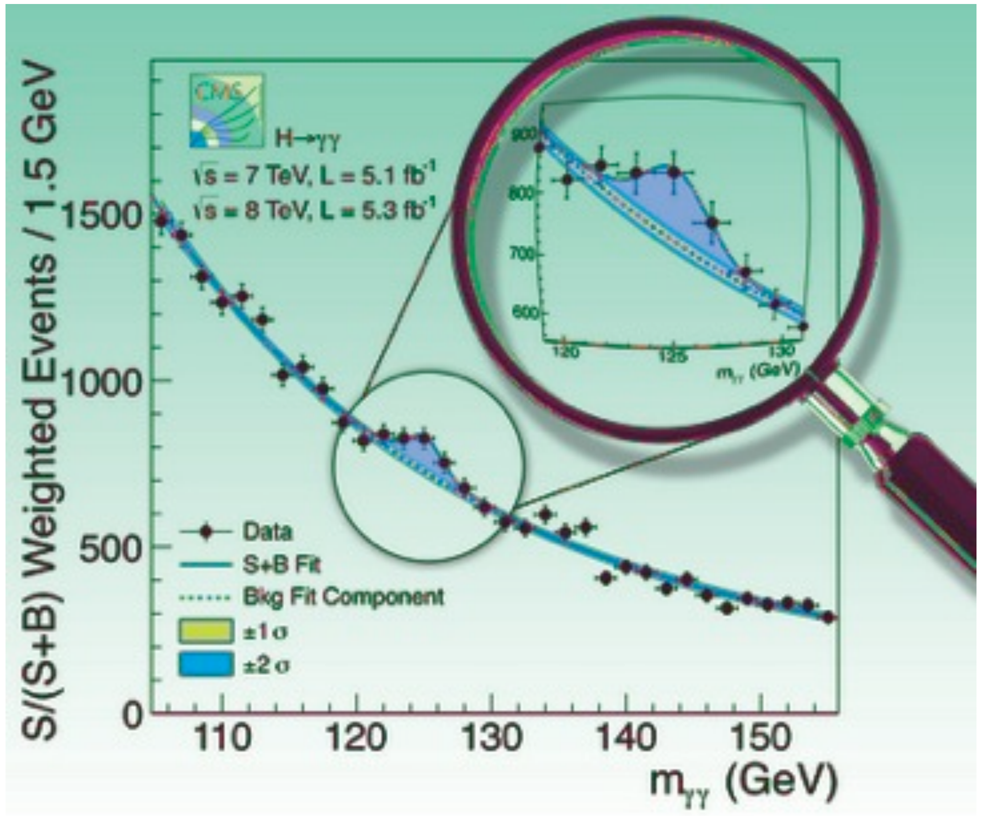
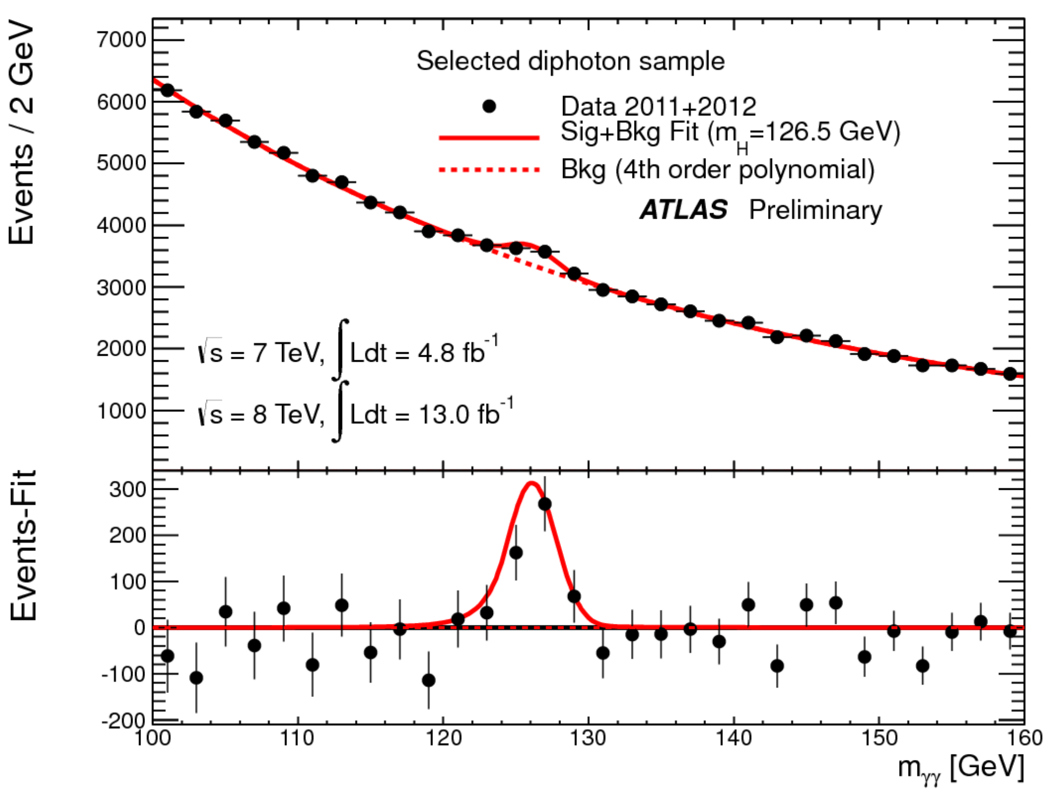


FIG. 2. From [11], lattice simulation results for the S-parameter per electroweak doublet, comparing SU(3) gauge theories with $N_f = 2$ (red triangles) and $N_f = 6$ (blue circles) degenerate strongly-coupled fermions in the fundamental representation. The horizontal axis is proportional to the pseudoscalar Goldstone boson mass squared, or equivalently the input fermion mass m. The $N_f = 2$ value of S is in conflict with electroweak precision measurements, but the reduction at $N_f = 6$ indicates that the value of S in many-fermion theories can be acceptably small, in contrast to more naïve scaling estimates [13].

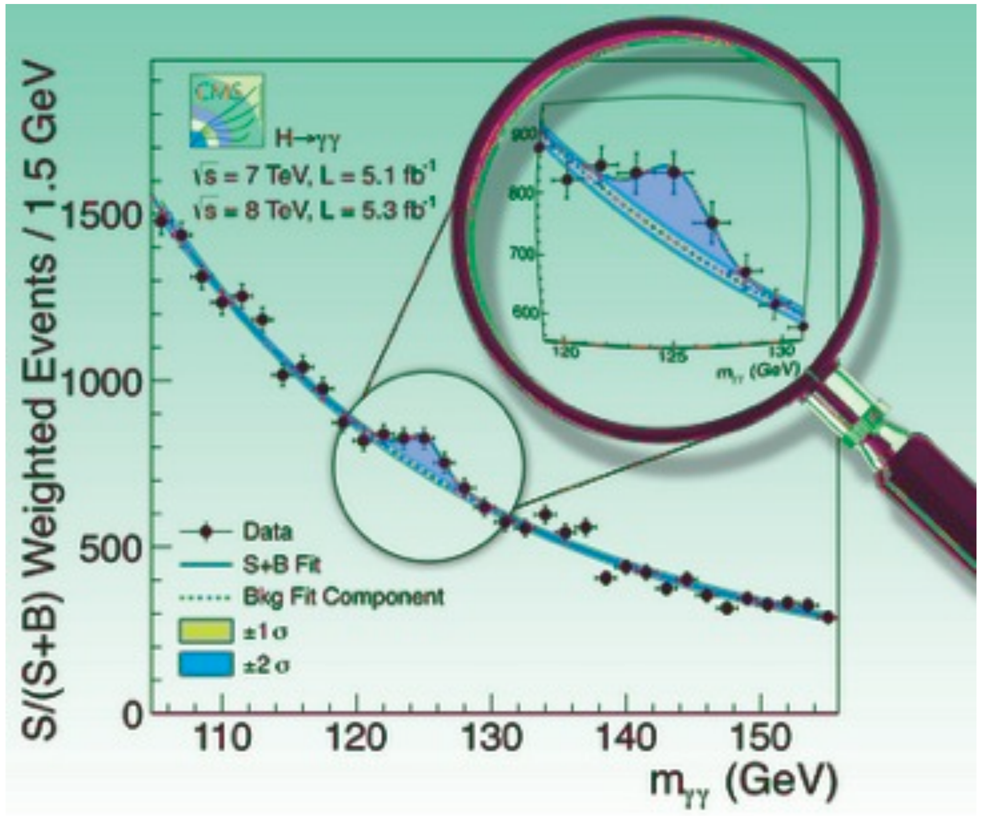
Rational for BSM:

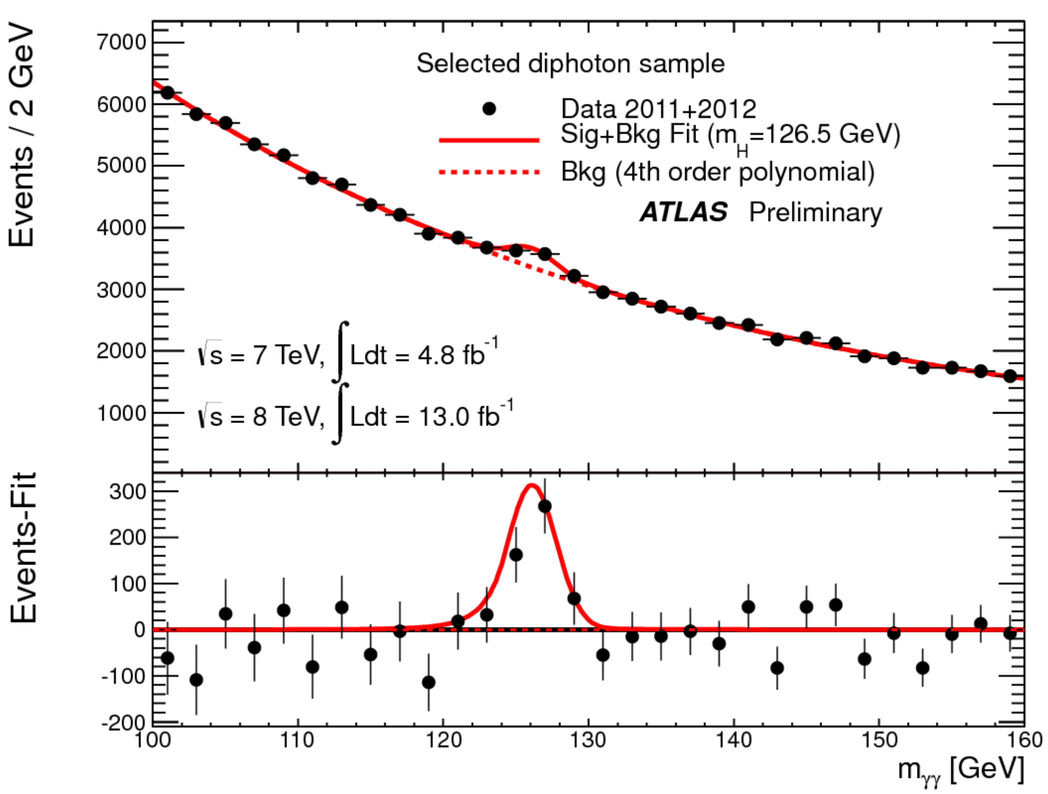




- After the Higgs is found why bother with BSM? Nothing else was seen and perhaps no new physics below the Planck scale?
- But Standard Model Higgs potential is parametrization rather than dynamical explanation
  $\lambda\phi^4$ not gauge force - severe consequences!
- Built in cutoff from triviality with quadratic divergences leading to fine tuning and the hierarchy problem; vacuum instability
- Standard Model is low energy effective theory with built in cut-off
- Can new physics from compositeness hide within LHC14 reach, or just above, with some imprint to see?
- But isn't compositeness dead anyway and we should not expect it in the LHC14 run?

Rational for BSM:





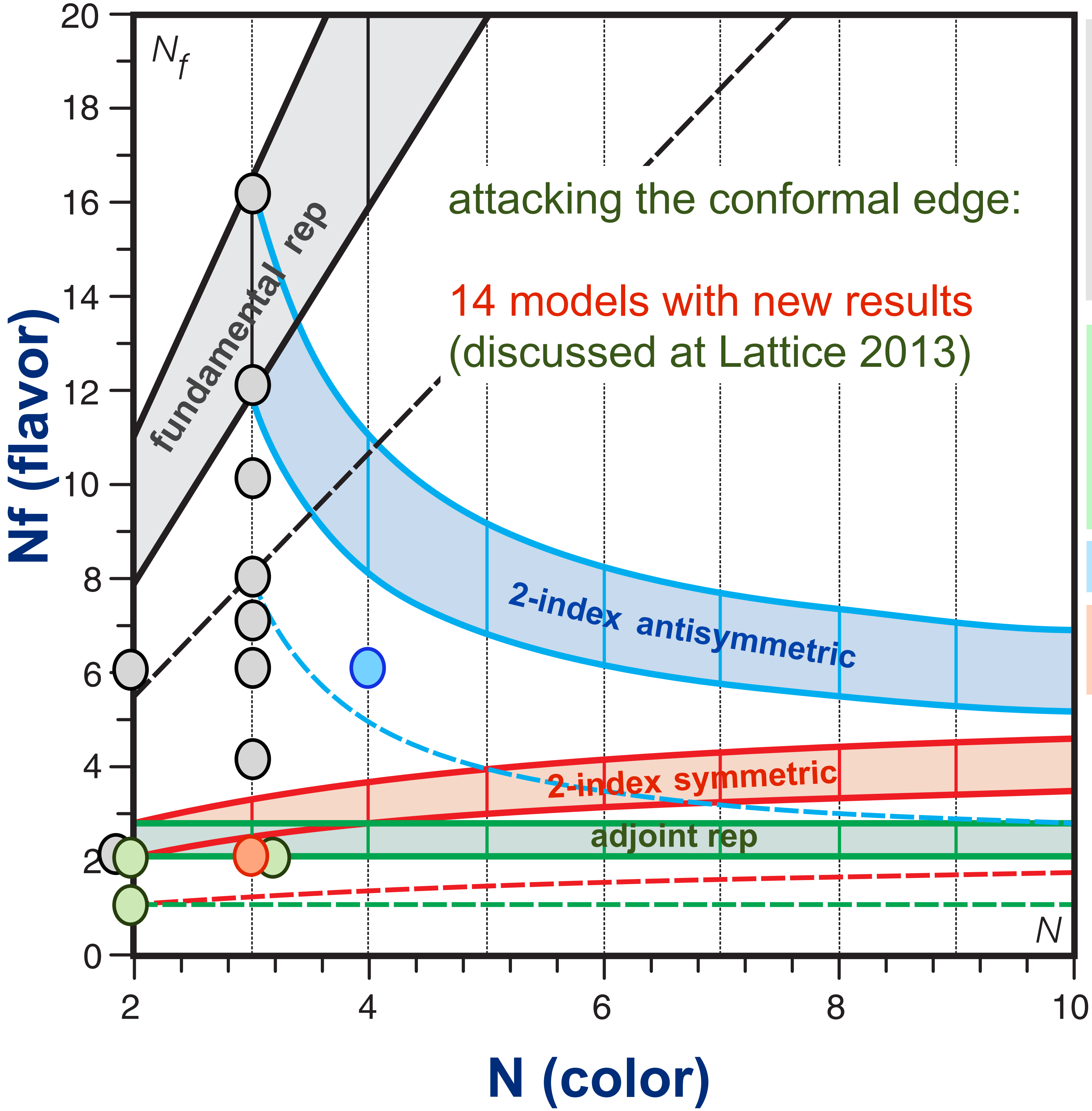
voices: a light Higgs-like scalar was found, consistent with SM within errors, and composite states have not been seen below 1 TeV. Strongly coupled BSM gauge theories are Higgs-less with resonances below 1 TeV
>> Nima and the tombstone

facts: Compositeness and a light Higgs scalar are not incompatible; search for composite states was not based on solid predictions but on naively scaled up QCD and unacceptable old technicolor guessing games.

lattice BSM plans: LHC14 will search for new physics from compositeness and SUSY, and the lattice BSM community is preparing quantitative lattice based predictions to be ruled in or ruled out.
We better get it right!

SCGT: theory space and conformal window
important for composite Higgs realization

space of color, flavor, and fermion representation



fundamental SU(3) color:
Nagai, Ohki, Schaich, Rinaldi, Miura, Hasenfratz, Ogawa, Yamazaki, Liu, Petropoulos, Yamada, Da Silva, Aoki, Iwasaki, Buchoff, Cheng

fundamental SU(2) color:
Tomii, Voronov

adjoint SU(2) color
Del Debbio, Rantaharju, Pica, Athenodoru

adjoint SU(3) color
Shamir

Two-index antisymmetric SU(4) color

Two-index symmetric SU(3) color
Wong, Sinclair, Holland

although ~30 talks, SCGT is only part of the BSM theory space! **SUSY, 5D, ...**

25 additional talks not directly obsessed with the conformal window (as I will be)

Extended theory space:

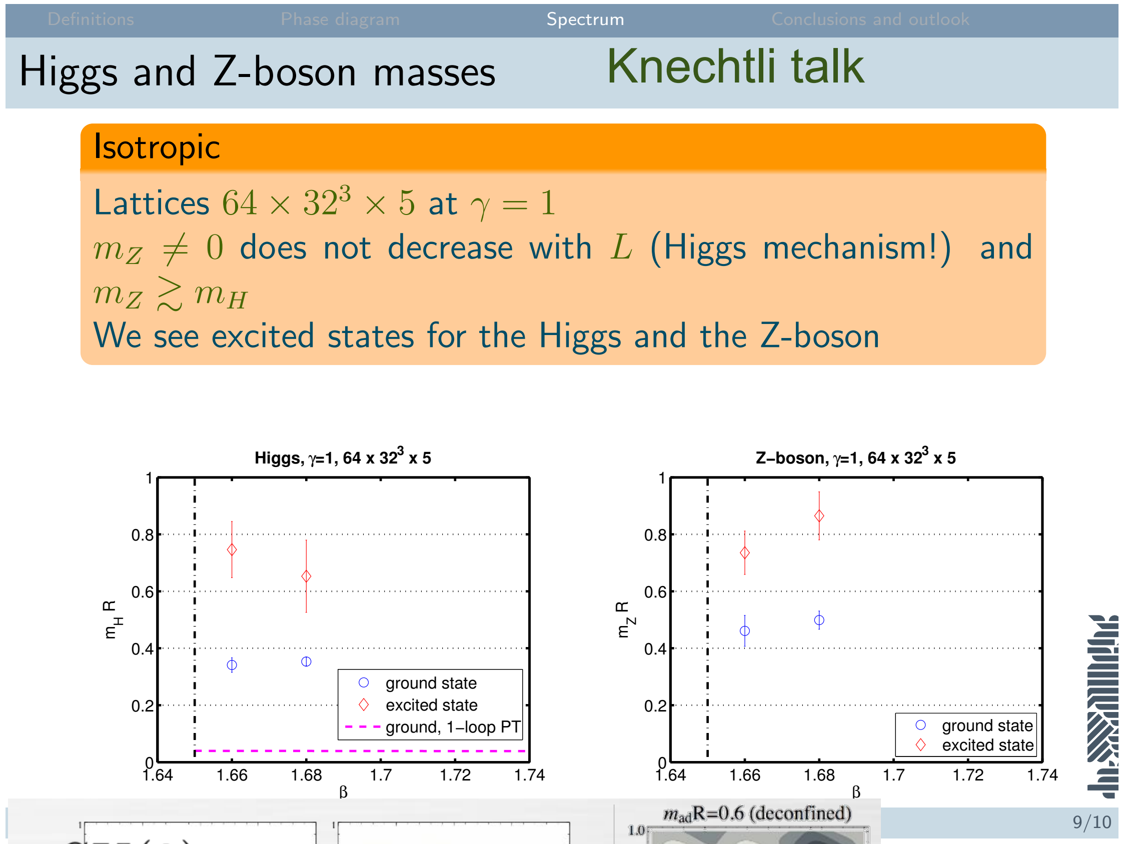
SUSY (LHC14?)
Piemonte, Munster, Steinhauer, Weir

4+1D and Gauge-Higgs unification (difficult to control the cutoff ⟶ lattice role?)
Yoneyama, Knechtli, Lambrou, Kashiwa, Hetrick, Cossu (Hosotani mechanism)

Gravity
Gorlich, Zubkov, Rindlisbacher

Higgs and Yukawa models - symmetry breaking
Maas, Knippschild, Nagy, Wurtz, Veemala

Knechtli talk



Early universe

dark matter Buchoff
MSSM Rummukainen

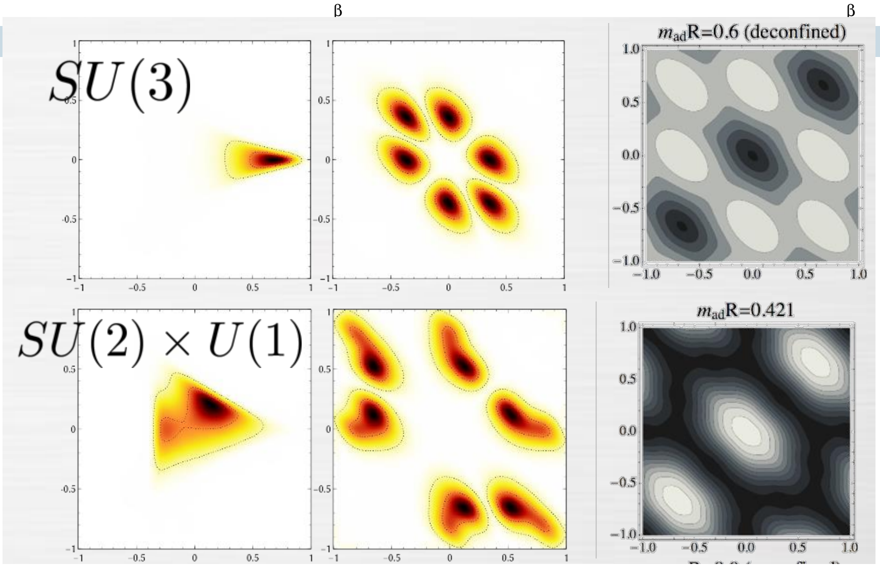
Theory tools:

Conformal radial quantization (Brower)

Large N
Tomboulis, Narayanan, Okawa, Keegan, Bali

Anomalous dimension
Pena, August

New reps
SO(4) MWT Hietanen



Cossu talk

Outline

Conformality ?

Nf=2 SU(2) MWT (illustration) ✓
Nf=12 SU(3) ???

Light Higgs near conformality

dilaton and/or light scalar close to conformal window?
running (walking) coupling
chiral condensate
finite size scaling and spectroscopy

Light composite Higgs in the PNGB scenario

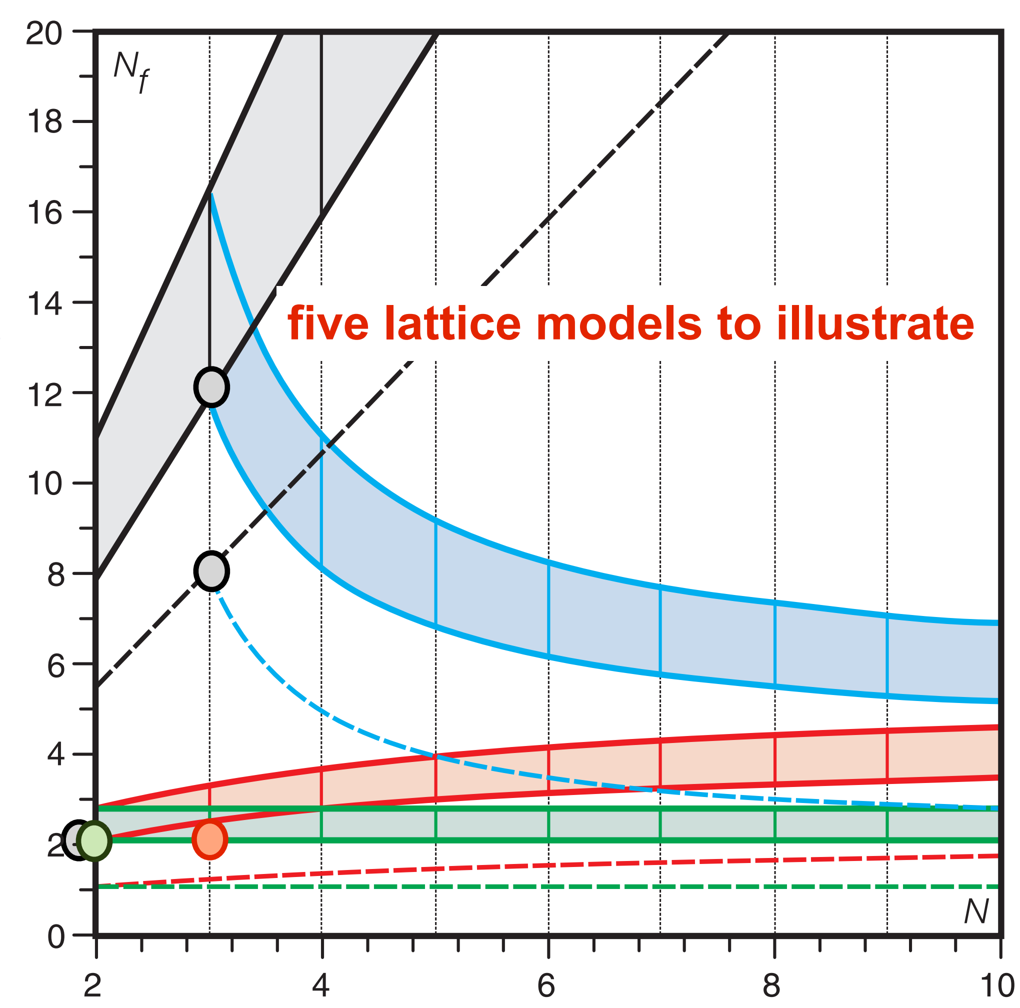
Two fermions in fundamental rep with SU(2) color

SUSY

Phenomenology

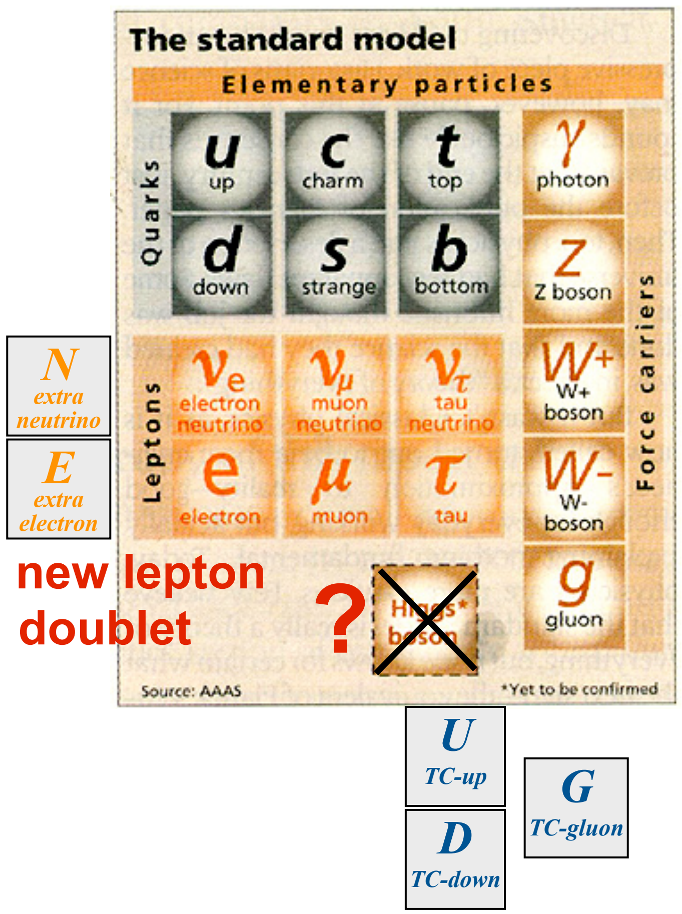
S-parameter
WW scattering
dark matter
EW phase transition

Summary and Outlook



Nf=2 SU(2) adjoint rep (MWT) and conformality

$$M_H = L^{-1} f(x) \qquad x = L^{y_m} m$$



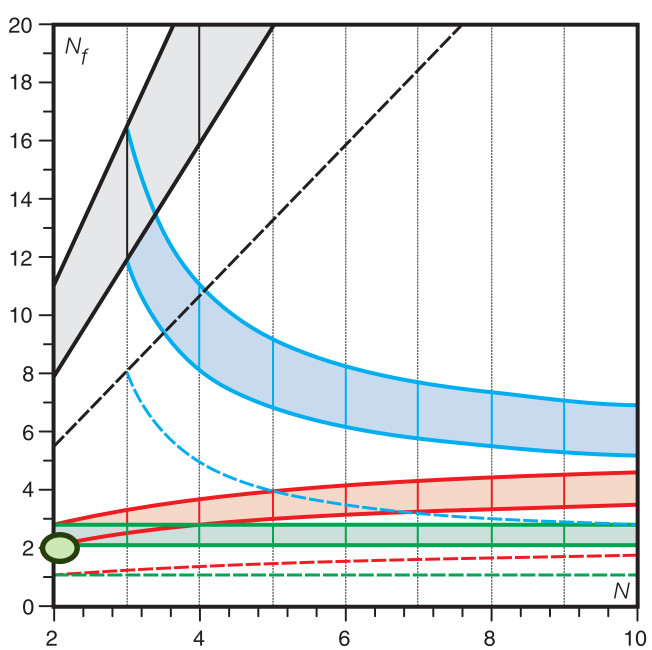
new lepton doublet ?

$U(1)_Y$

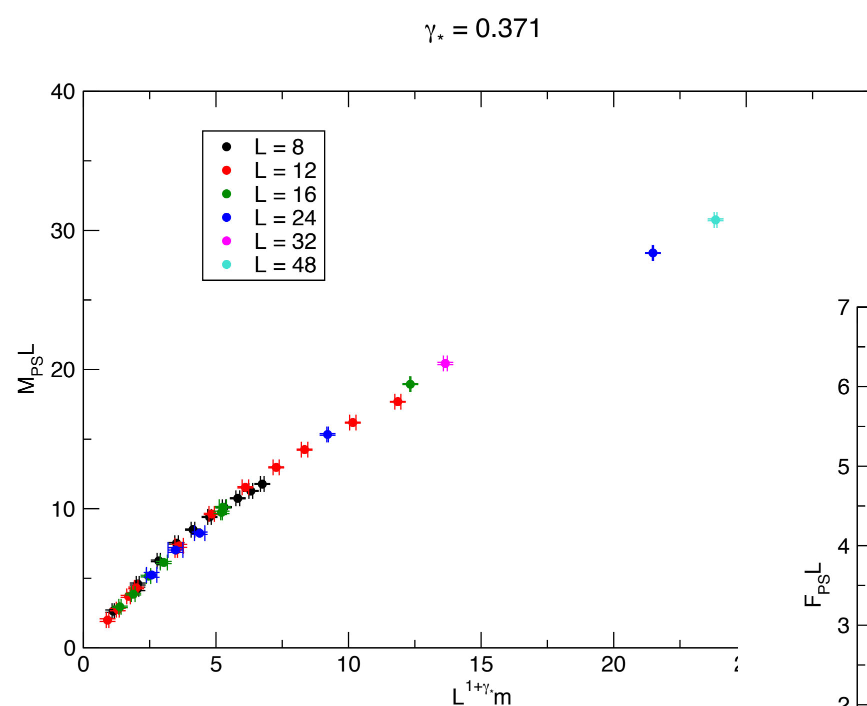
$SU(2)_L$

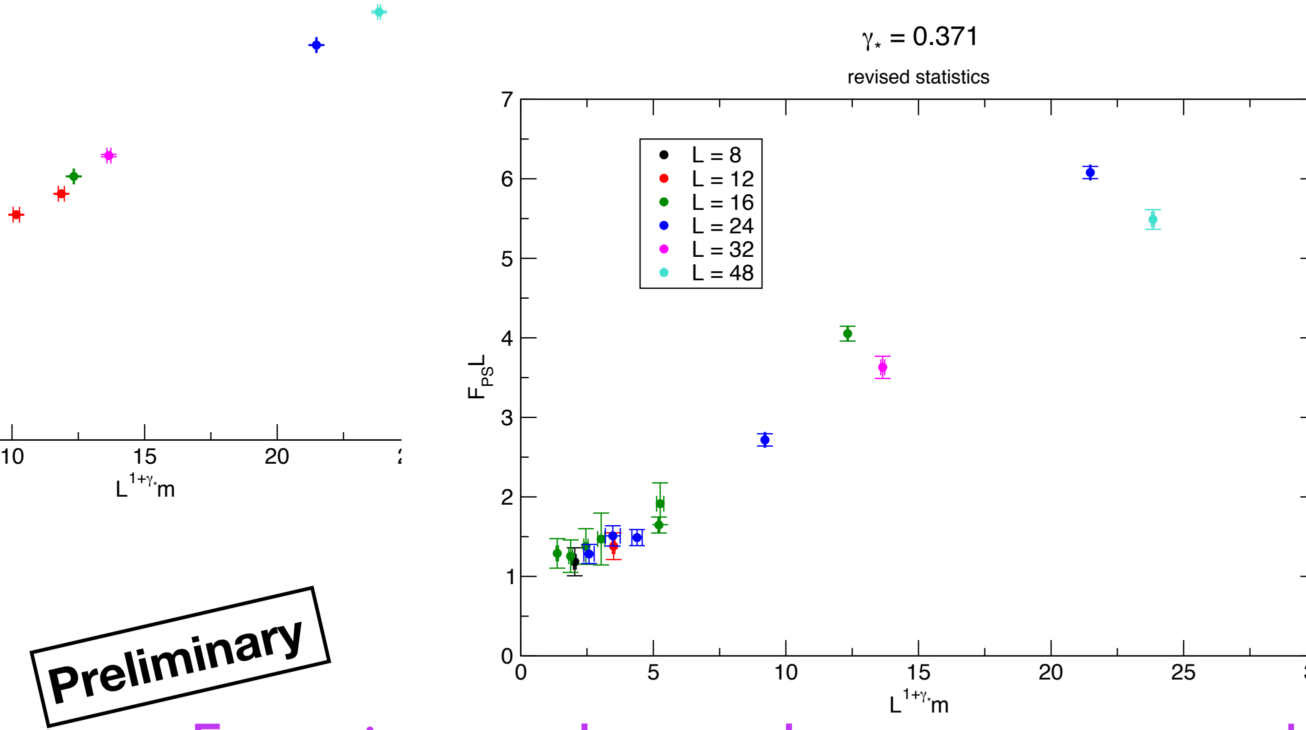
$SU(3)_C$

$SU(2)_{TC}$



FSS - example





Tuesday, 30 July 13

Del Debbio talk
Lucini
Patella
Pica
Rago
Roman

Extensive new large volume spectrum study
compatible with conformality
topology monitored

Nf=2 SU(2) adjoint rep (MWT) and conformality

$$M_H = L^{-1} f(x) \qquad x = L^{y_m} m$$

FSS - example

Del Debbio talk
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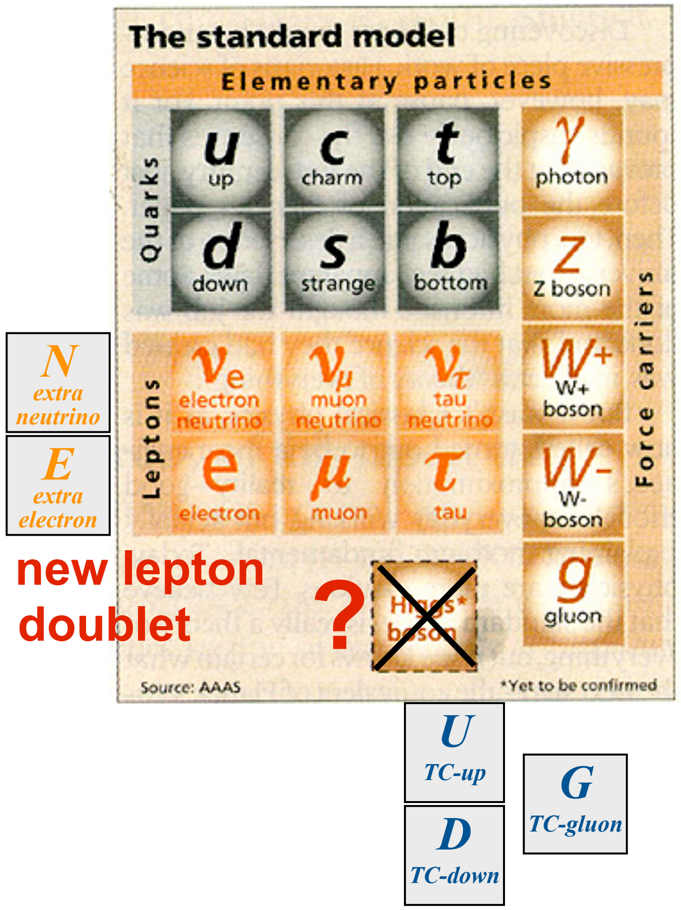
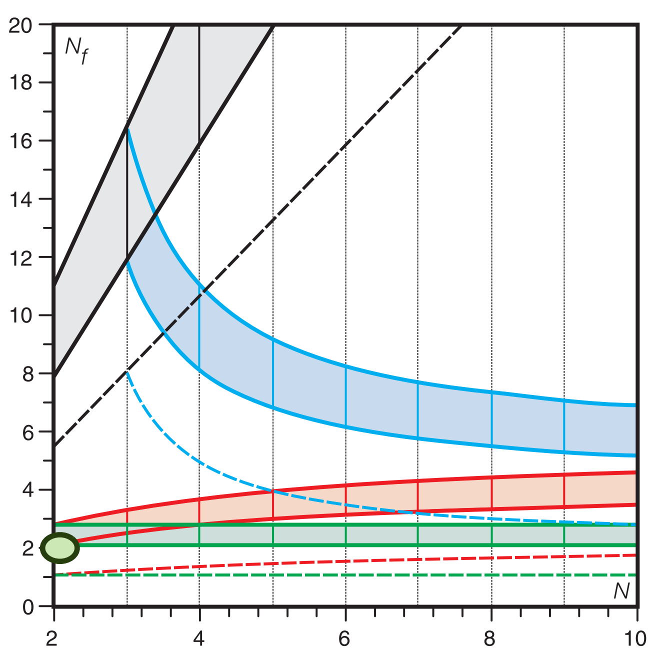
$U(1)_Y$

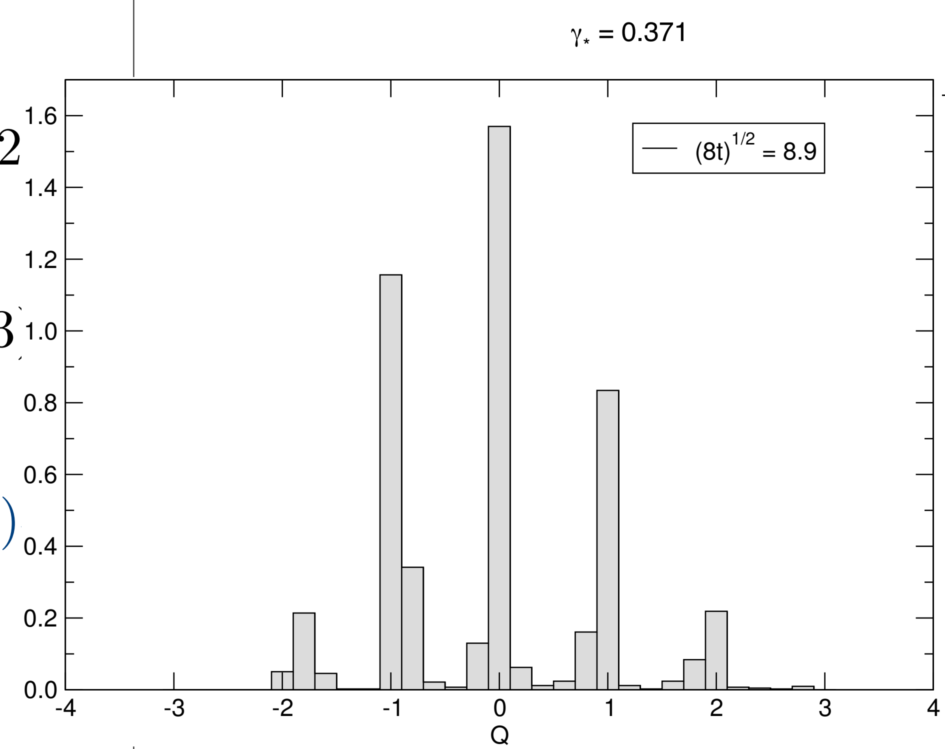
$SU(2$

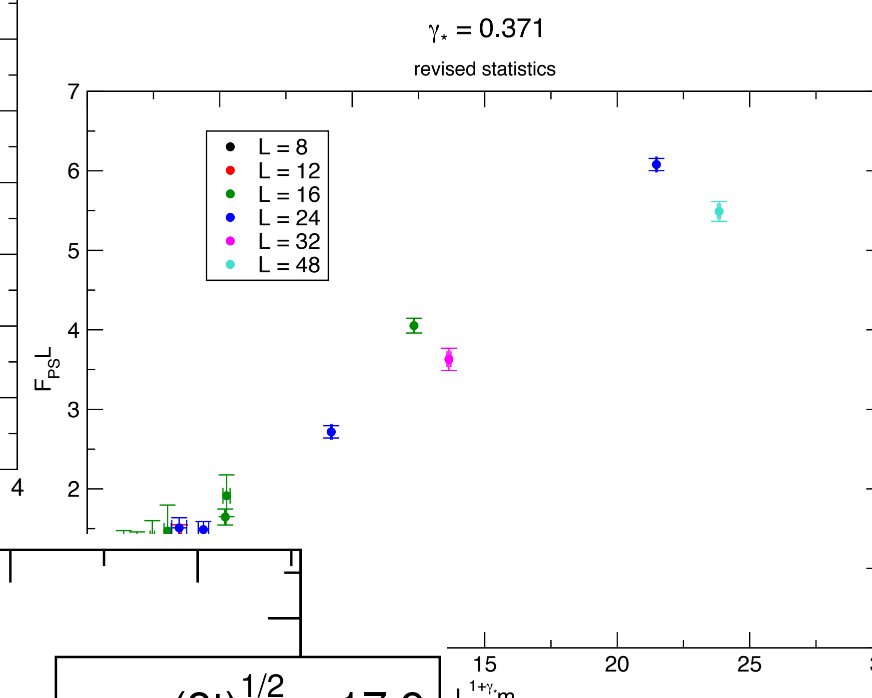
$SU(3$

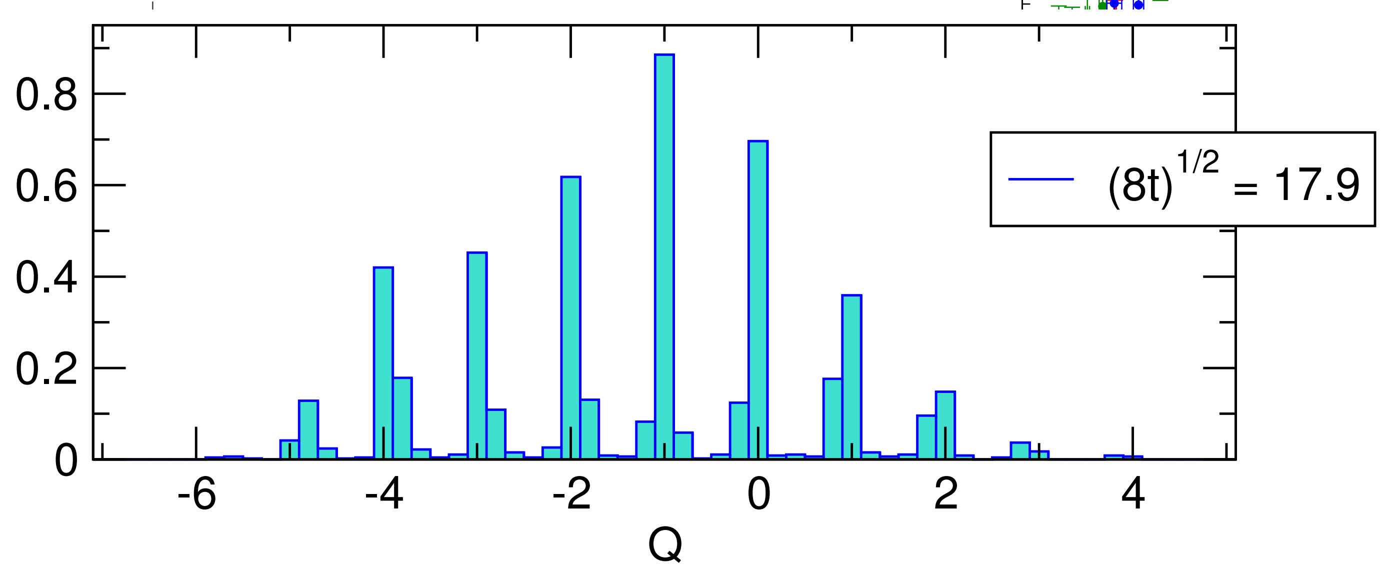
$SU(2)$











e spectrum study
ity

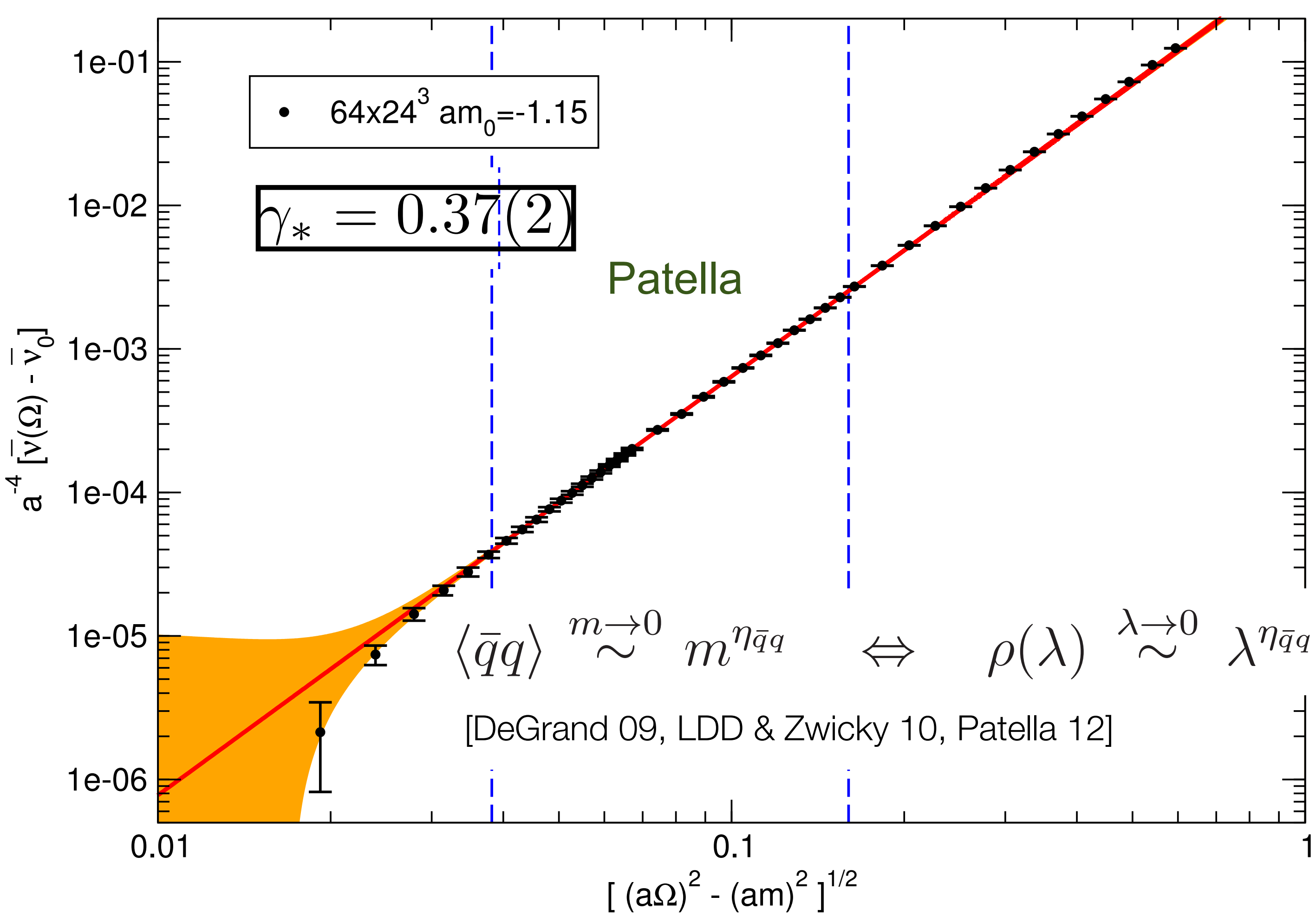
Nf=2 SU(2) adjoint rep (MWT) and conformality

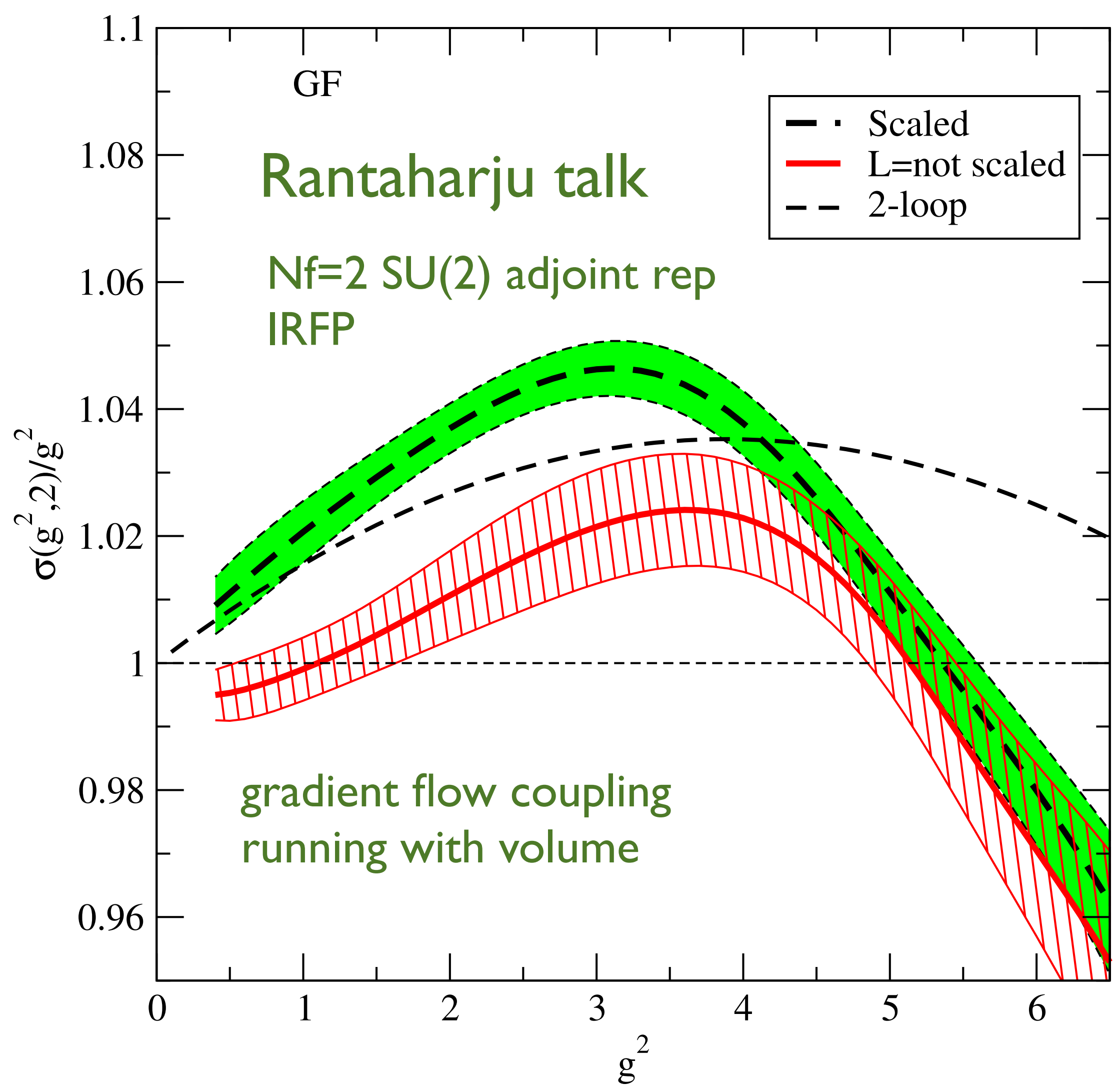
control on UV divergences: mode number density of chiral condensate

$$\rho(\lambda, m) = \frac{1}{V}\sum_{k=1}^{\infty}\langle\delta(\lambda-\lambda_k)\rangle \qquad \lim_{\lambda\to 0}\lim_{m\to 0}\lim_{V\to\infty}\rho(\lambda,m) = \frac{\Sigma}{\pi}$$ spectral density

$$\nu(M,m) = V\int_{-\Lambda}^{\Lambda} \mathrm{d}\lambda\,\rho(\lambda,m), \qquad \Lambda = \sqrt{M^2-m^2}$$ mode number density

$$\nu_{\mathrm{R}}(M_{\mathrm{R}}, m_{\mathrm{R}}) = \nu(M, m_{\mathrm{q}})$$ renormalized and RG invariant (Giusti and Luscher)





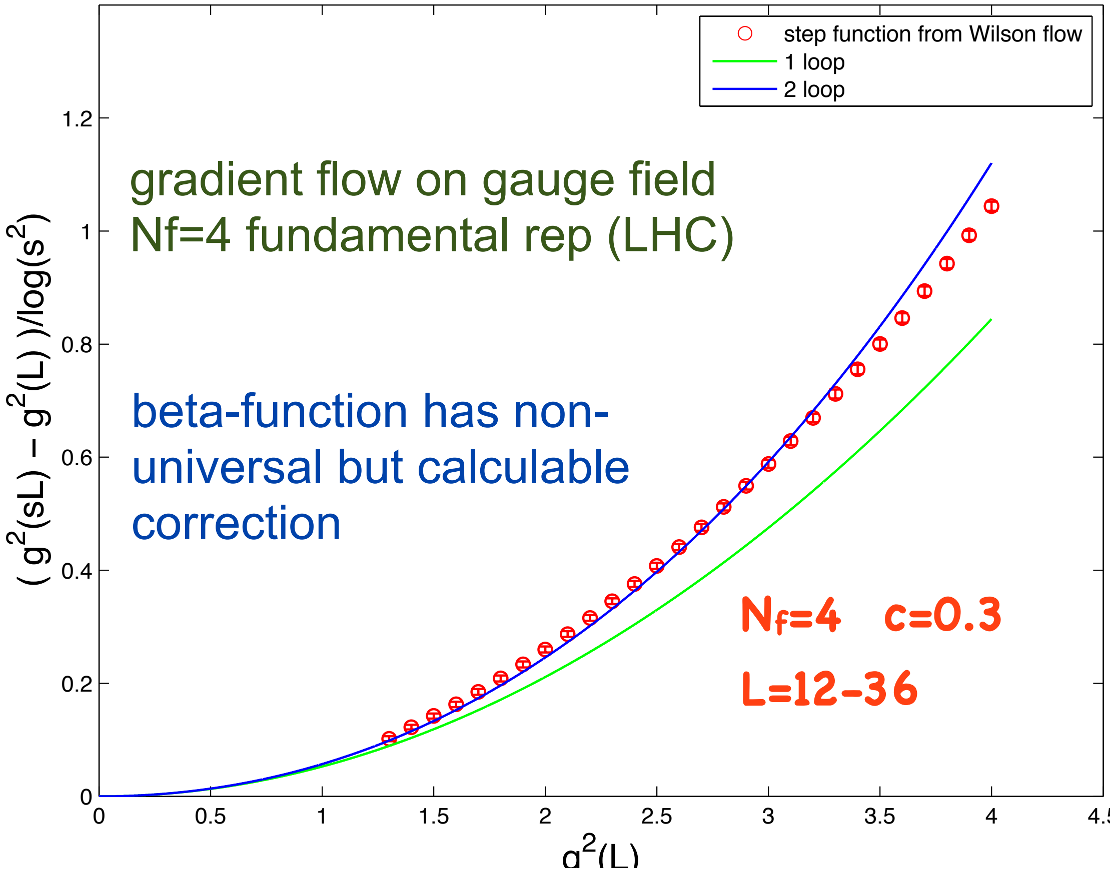
Nf=2 SU(2) adjoint rep (MWT) and conformality

Running coupling definition from gauge field gradient flow

$$\langle E(t)\rangle = \frac{3}{4\pi t^2}\alpha(q)\{1 + k_1\alpha(q) + O(\alpha^2)\}, \quad q = \frac{1}{\sqrt{8t}}, \quad k_1 = 1.0978 + 0.0075 \times N_f$$

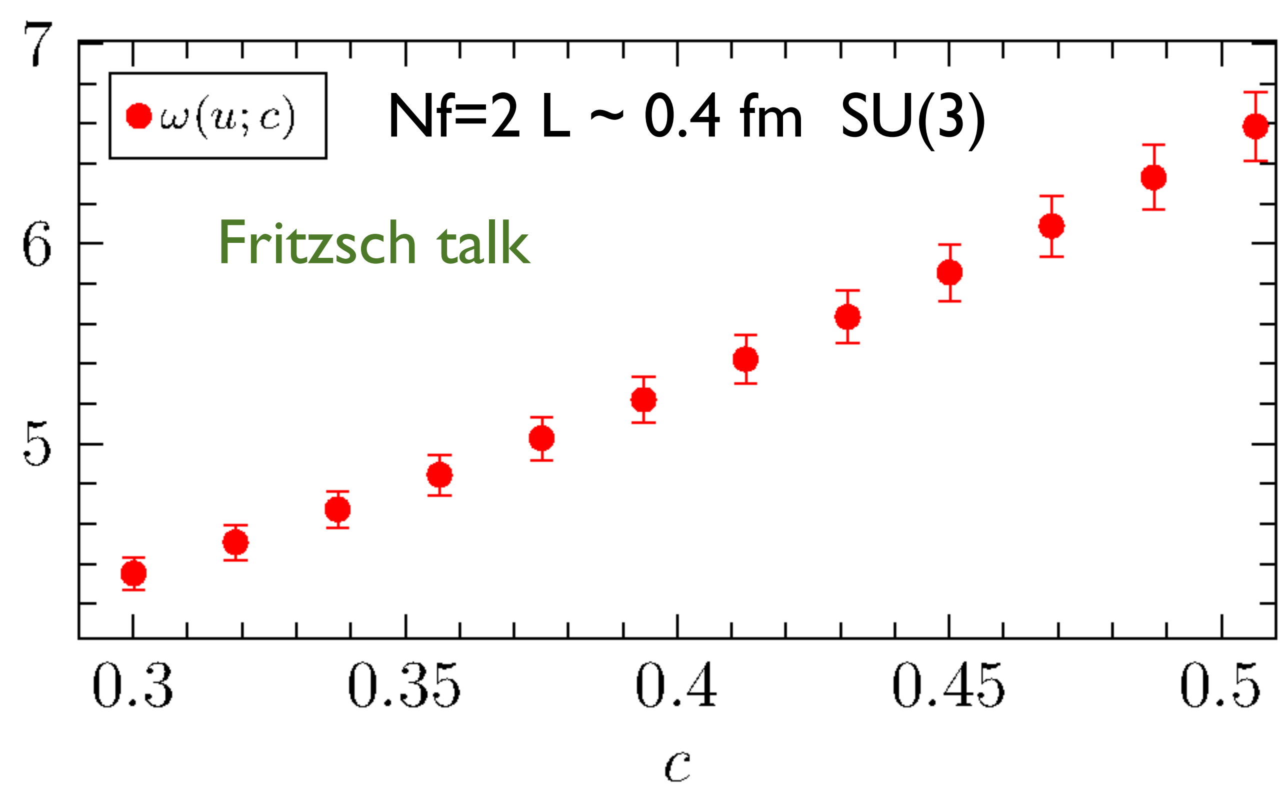
while holding $c = (8t)^{1/2}/L$ fixed: $\quad \alpha_c(L) = \frac{4\pi}{3}\frac{\langle t^2 E(t)\rangle}{1+\delta(c)}$

$$\delta(c) = \vartheta_3^4(e^{-1/c^2}) - 1 - \frac{c^4\pi^2}{3}$$



massless fermions; antiperiodic all directions
s=1.5 step Nf=4 staggered fermions; 4-stout; L=12-36
results for Nf=8 and sextet are coming

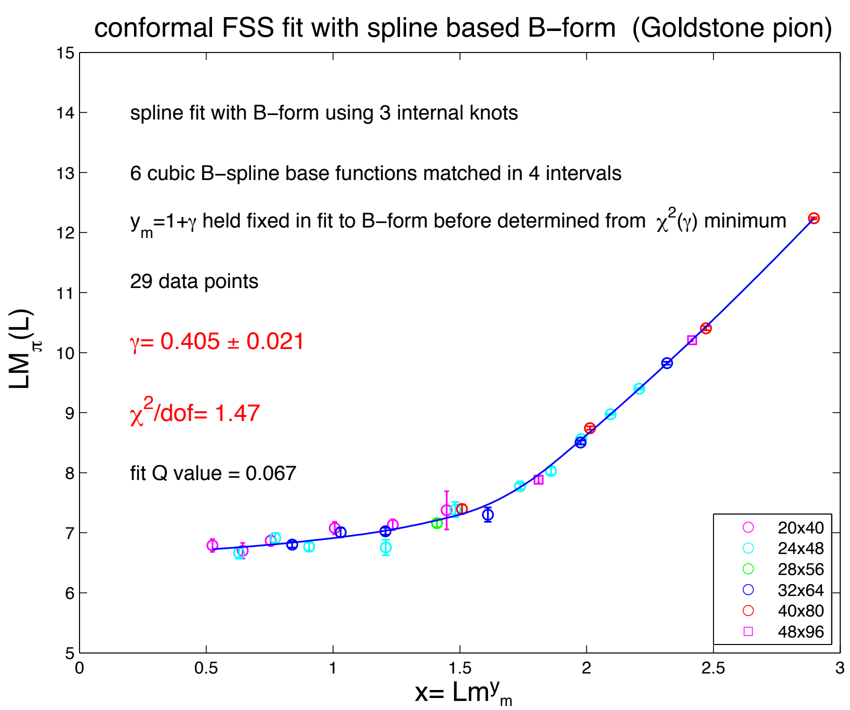
gradient flow coupling with SF boundary conditions

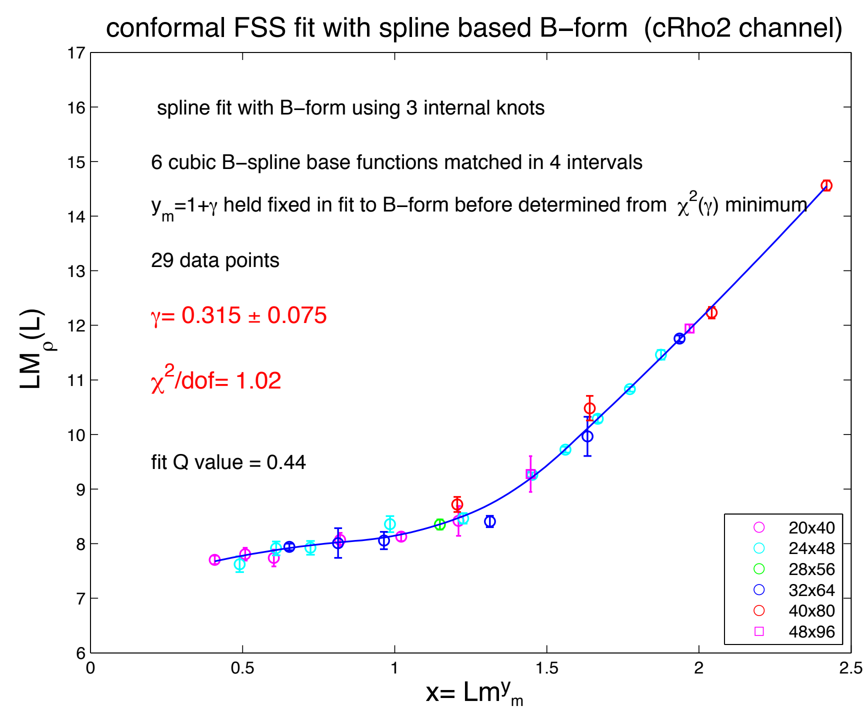


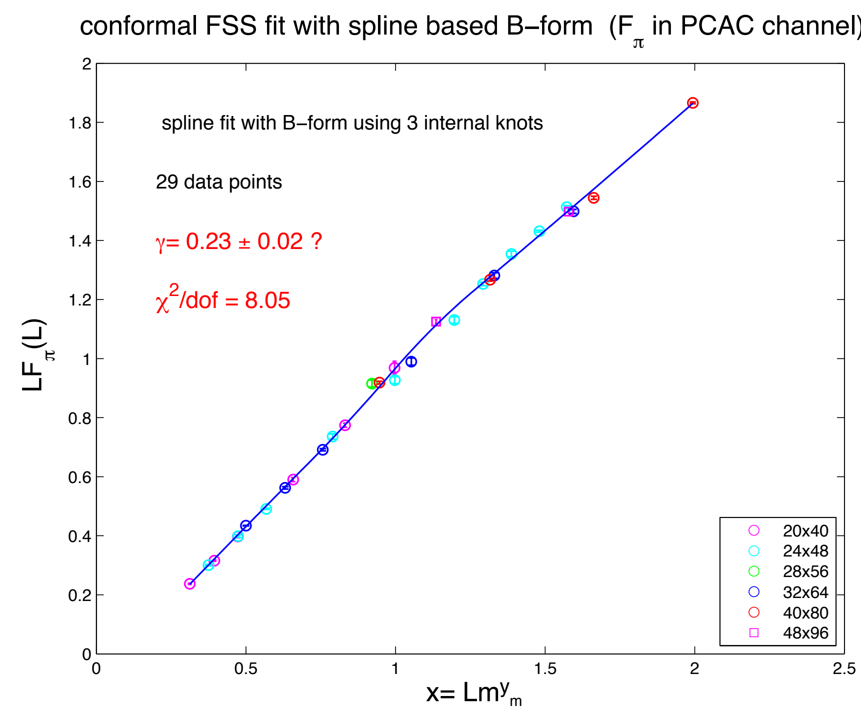
potential advantage: beta-function has conventional loop expansion

Nf=12 SU(3) fundamental rep and conformality?

LHC finds conflicts in conformal FSS analysis:







unable to fix with leading scaling violation to conformal FSS analysis:

$$LM = f(x) + L^{-\omega} g(x)$$

$$x = m^{1/1+\gamma} L$$

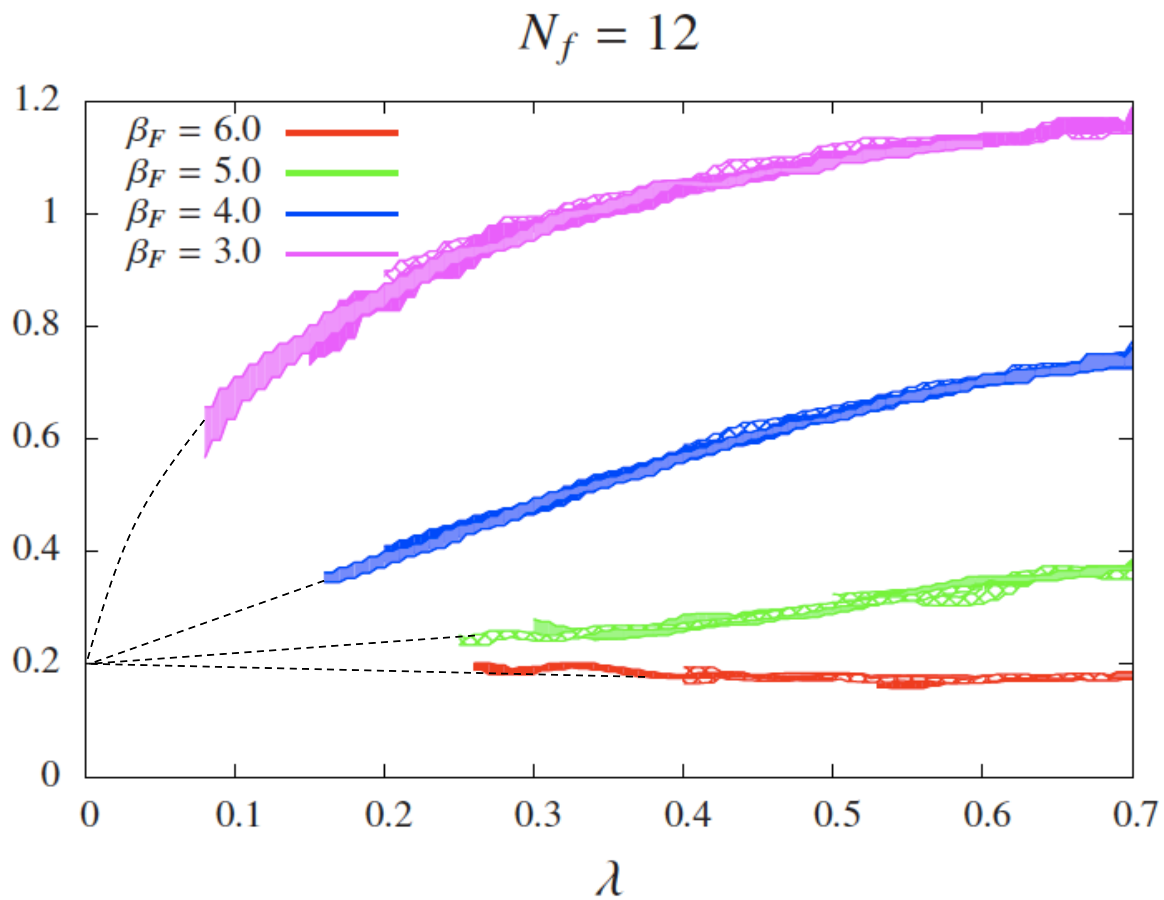
$$\omega = \beta'(g^*)$$

latKMI group did not detect this problem

In contrast, Boulder group (Hasenfratz talk) presented some results in succeeding with the fix

Nf=12 SU(3) fundamental rep and conformality?

Cheng talk for
Boulder group

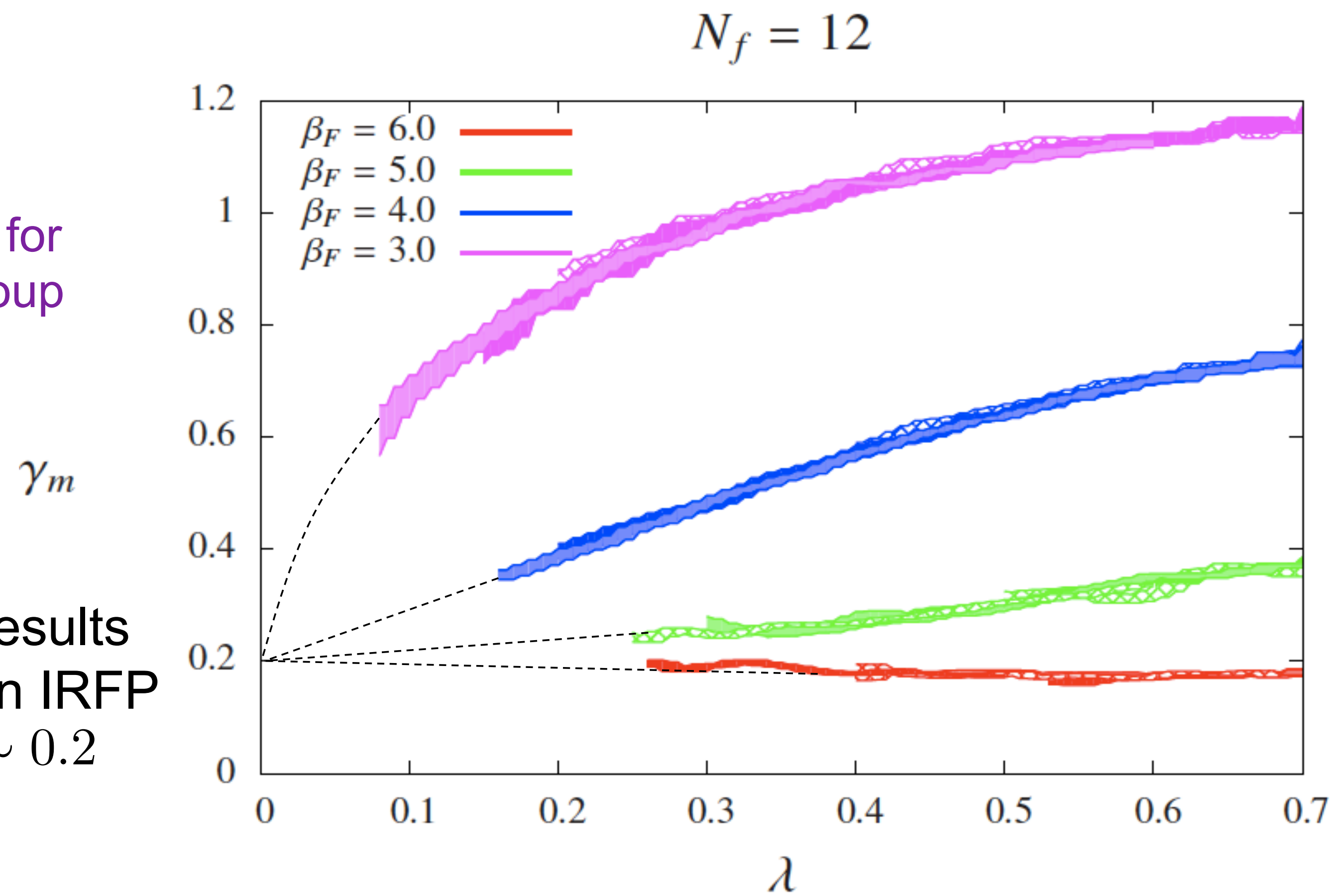


12-flavor results
indicate an IRFP
with $\gamma_m^\star \sim 0.2$

In sharp contrast:

Nf=12 SU(3) fundamental rep and conformality?

Cheng talk for Boulder group



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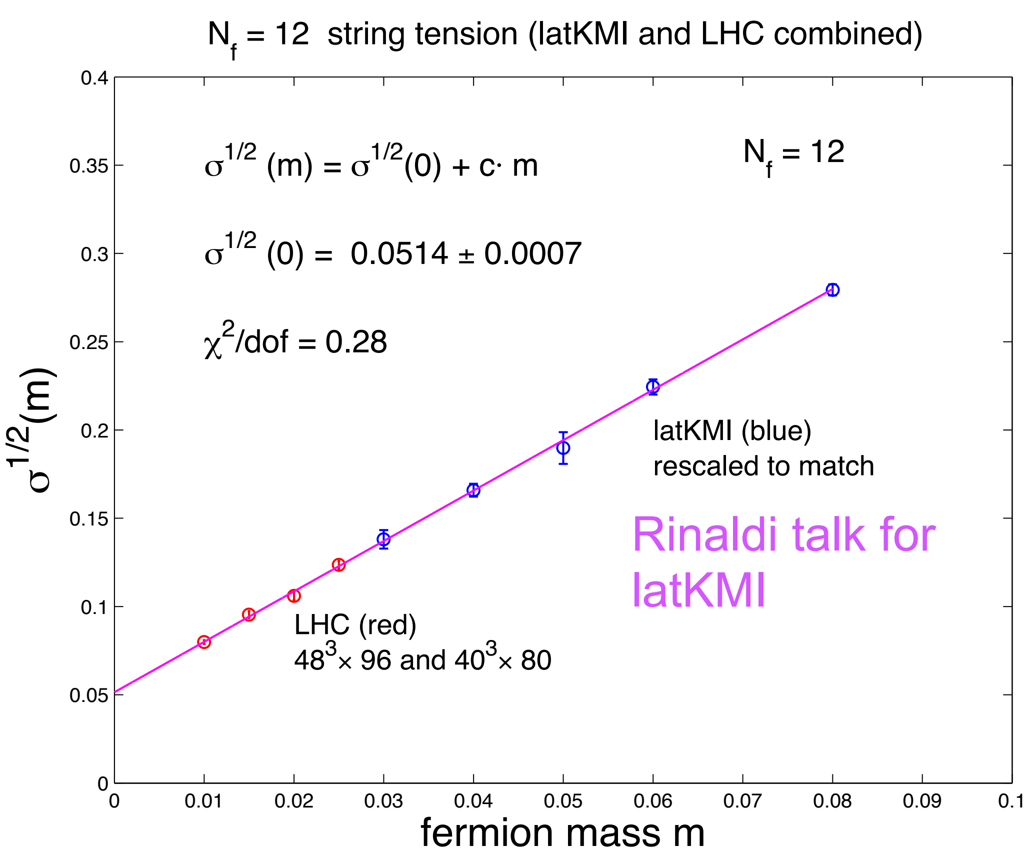
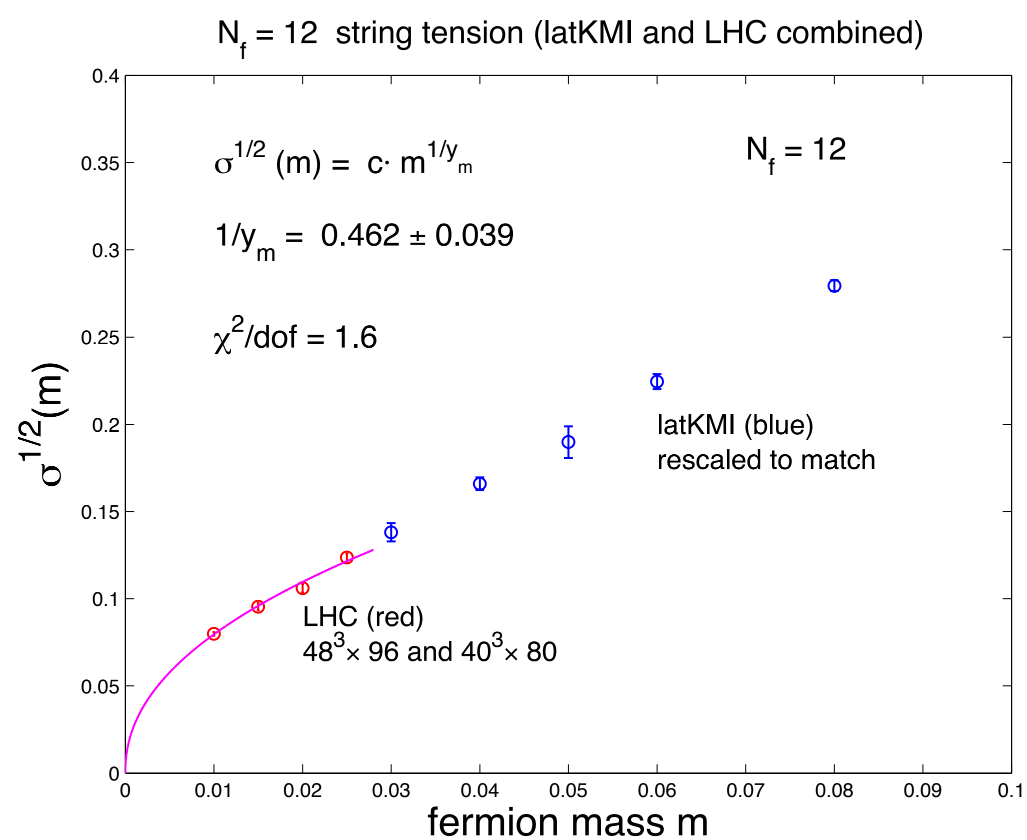


Rinaldi talk for latKMI



Nf=12 SU(3) fundamental rep and conformality?

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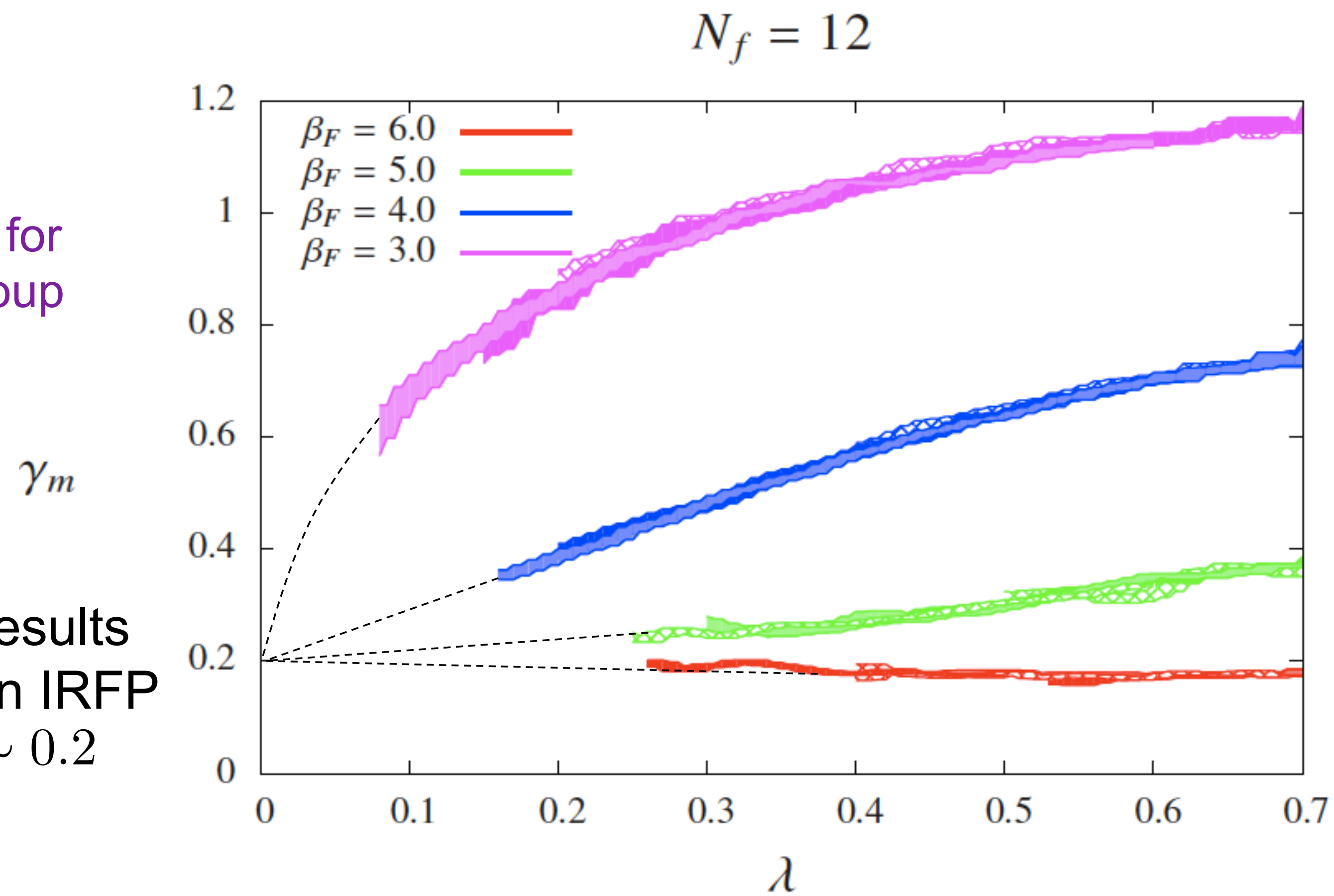
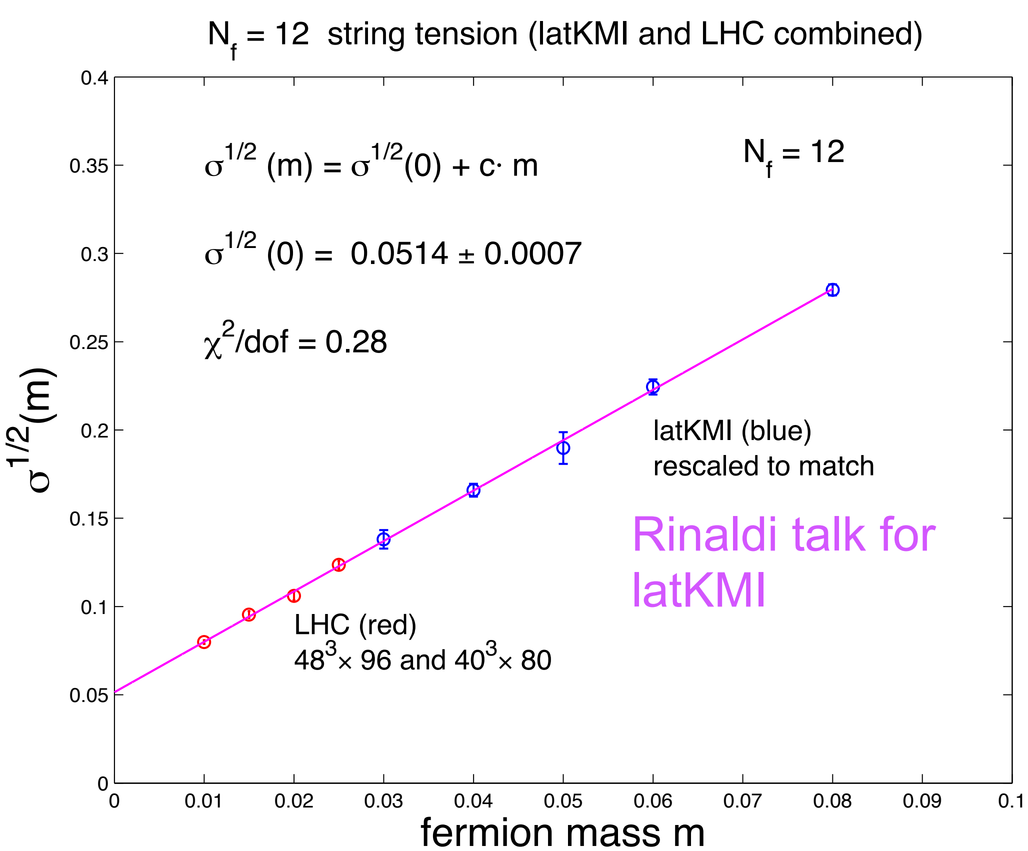


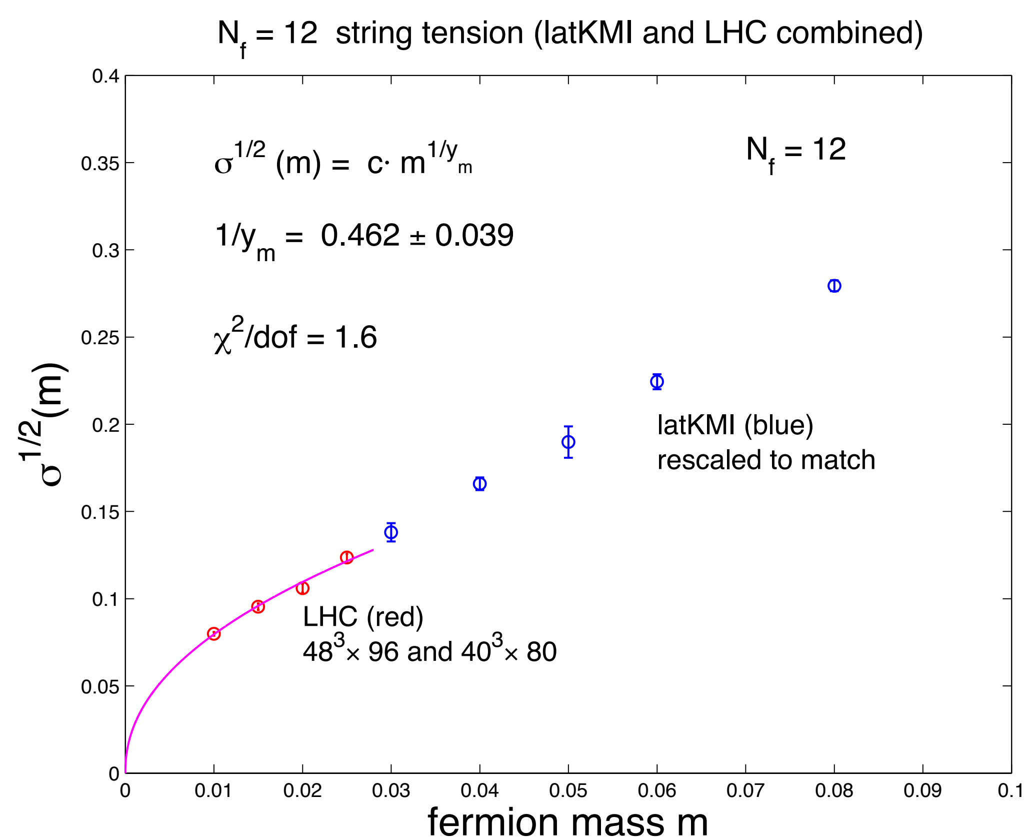
12-flavor results indicate an IRFP with $\gamma_m^\star \sim 0.2$

and I will not touch the running coupling, to be continued ...

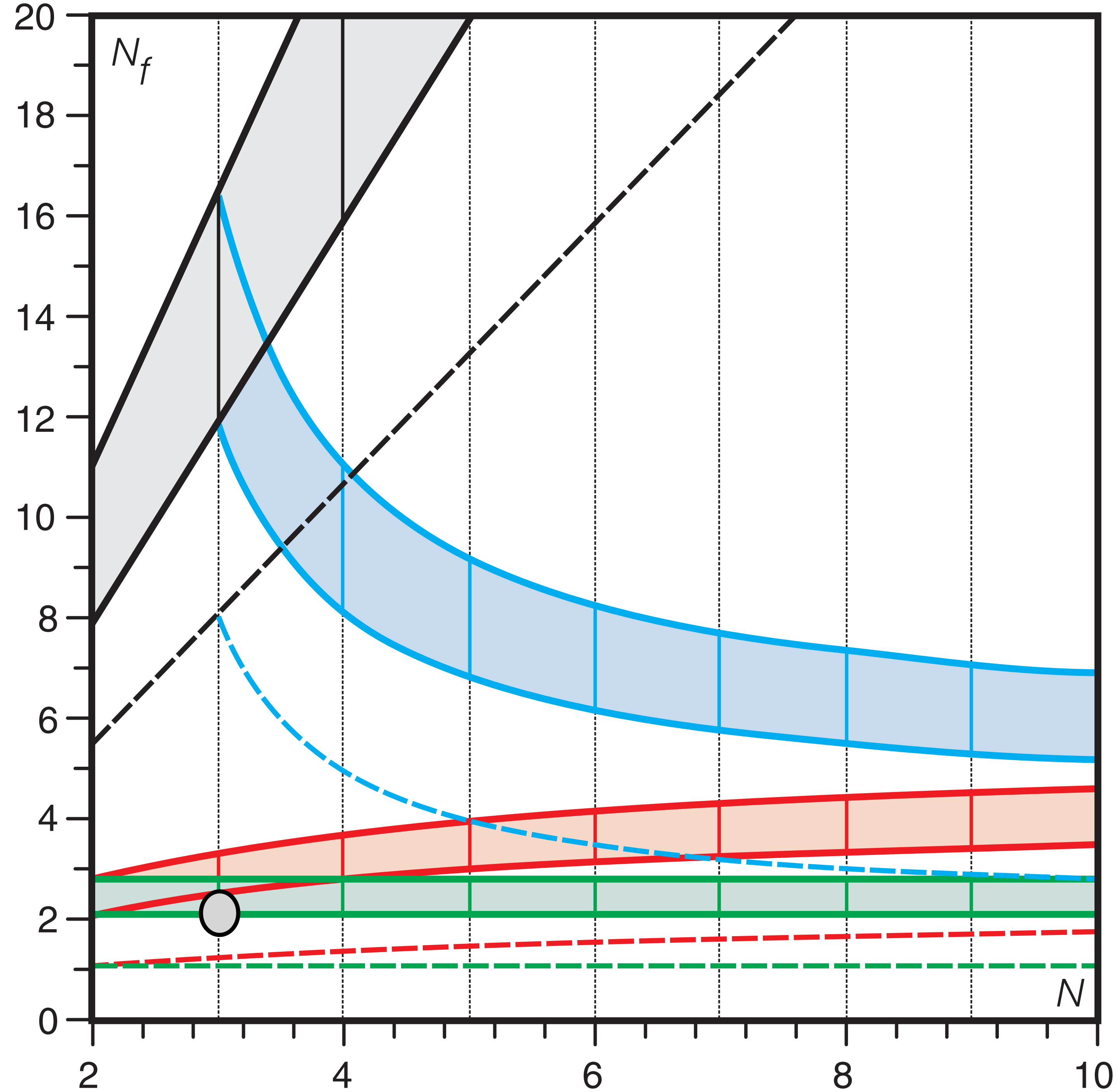
In sharp contrast:



Rinaldi talk for latKMI



light Higgs near conformality (dilaton-like?) sextet



to illustrate: sextet SU(3) color rep

one massless fermion doublet $\begin{bmatrix} u \\ d \end{bmatrix}$

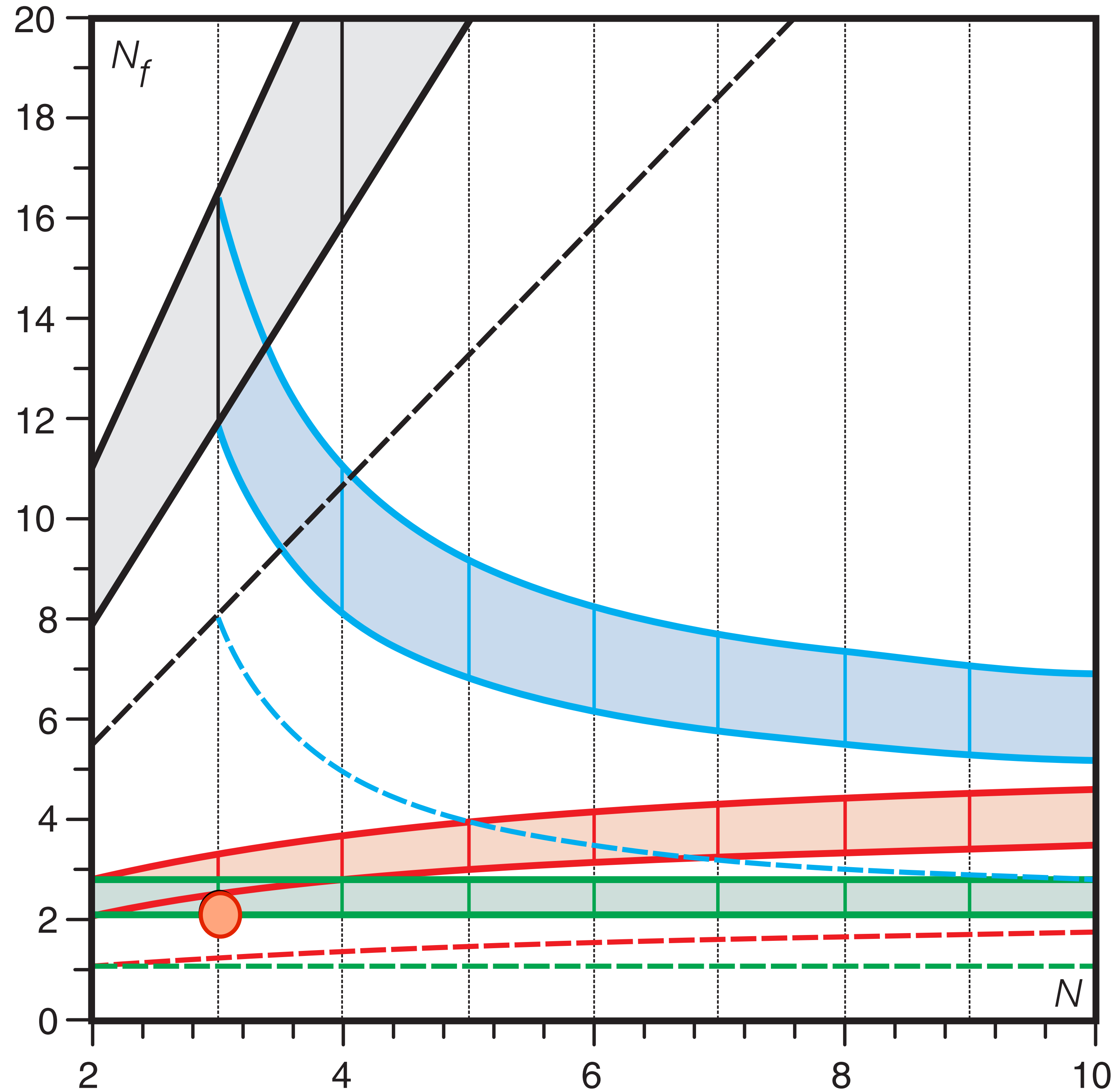
χSB on Λ~TeV scale

three Goldstone pions
become longitudinal
components of weak bosons

composite Higgs mechanism
scale of Higgs condensate ~ F=250 GeV

conflicts with EW constraints?

light Higgs near conformality (dilaton-like?) sextet



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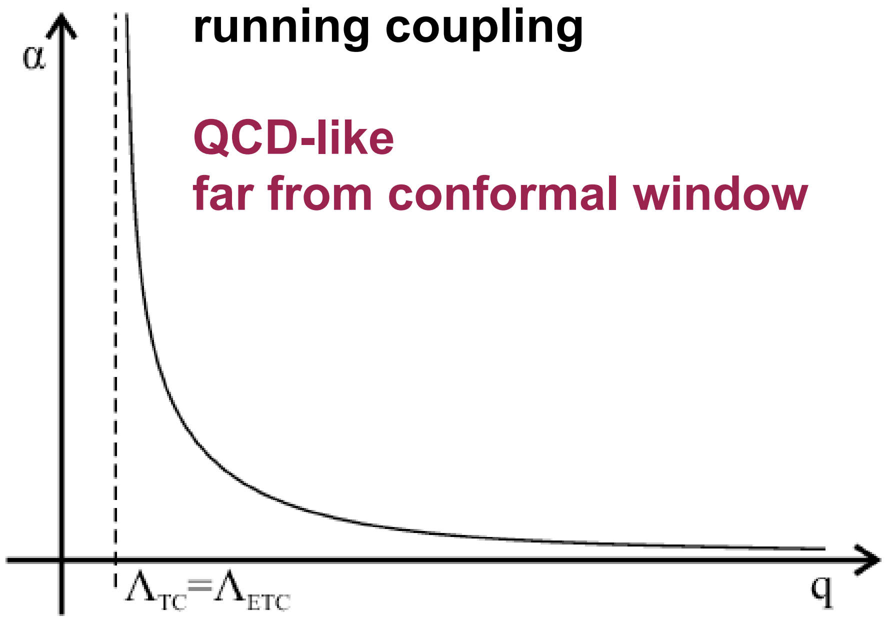

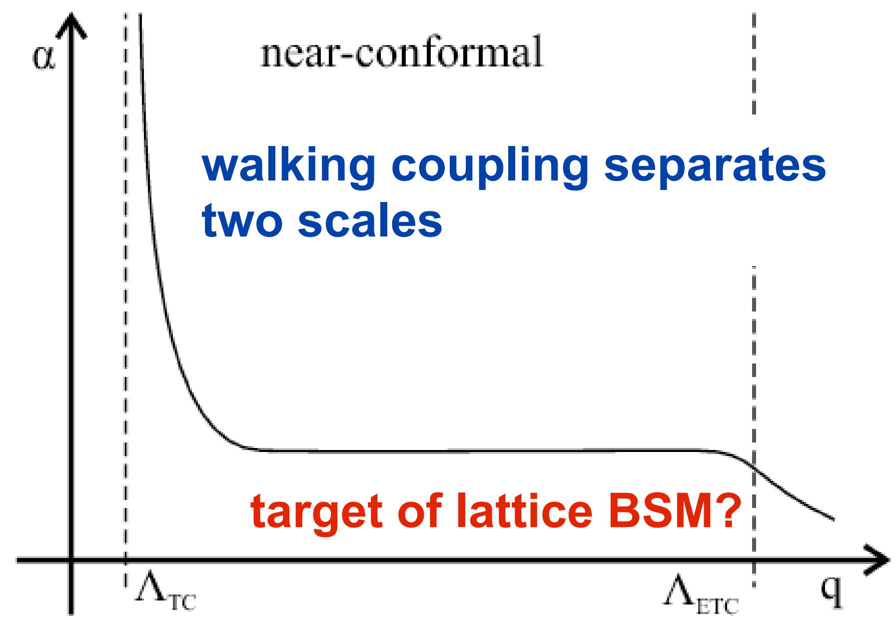

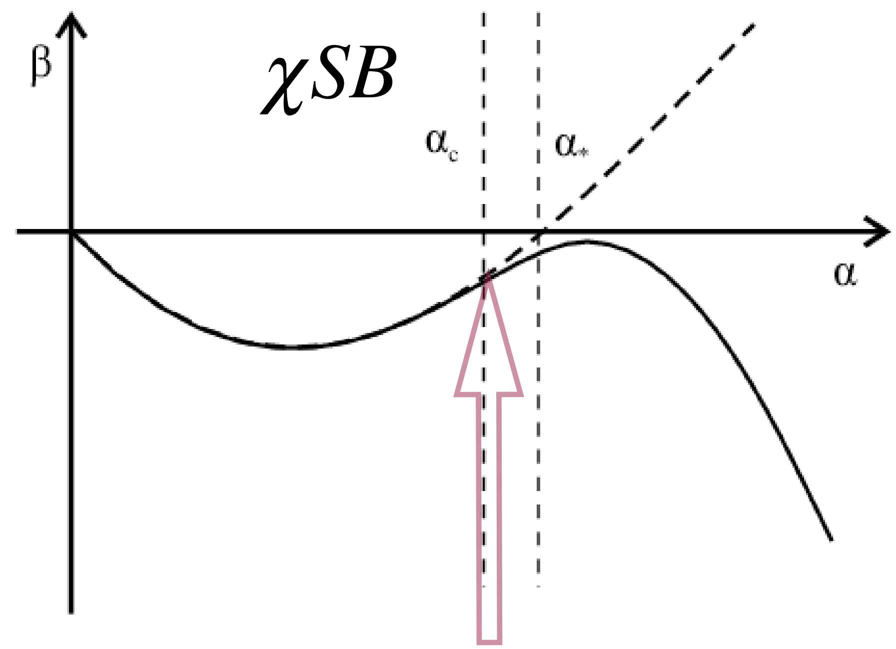

when chiral symmetry breaking
turns conformal FP into walking

to illustrate: sextet SU(3) color rep

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χSB on Λ~TeV scale

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χSB on Λ~TeV scale

walking gauge coupling?

fermion mass generation (effective EW int)

composite Higgs mechanism ?

broken scale invariance (dilaton) ?
or light non-SM composite Higgs particle?

Early work using sextet rep:

Marciano (QCD paradigm, 1980)

Kogut,Shigemitsu,Sinclair
(quenched, 1984)

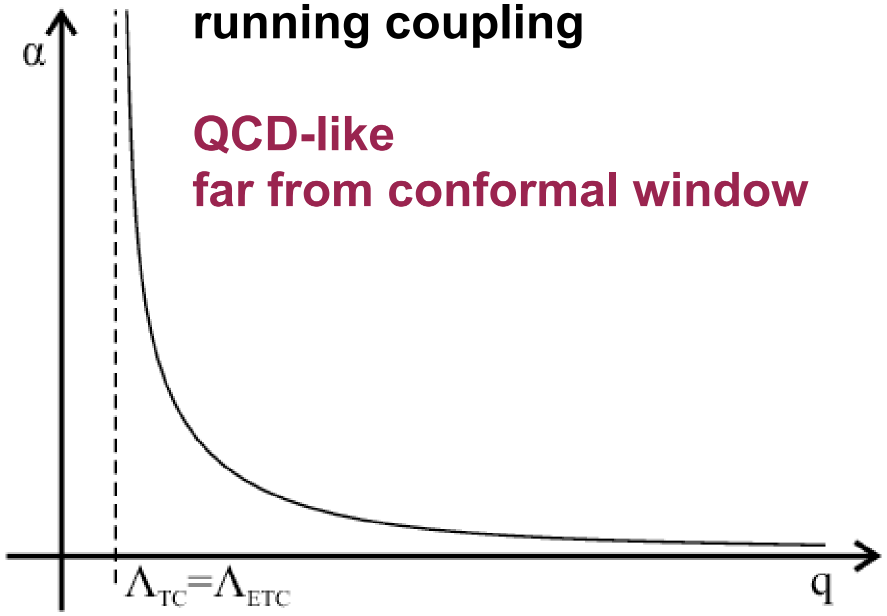
recent work:

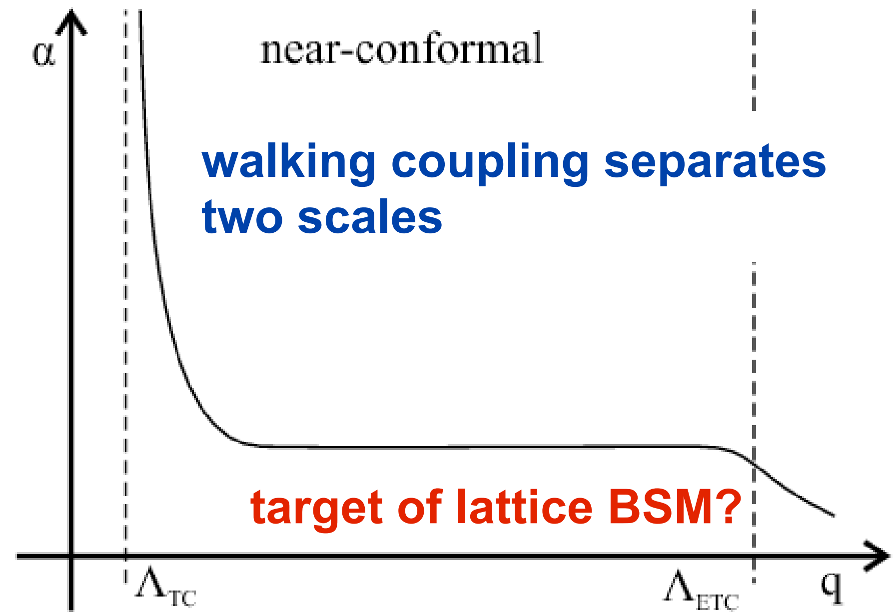
DeGrand,Shamir,Svetitsky
IRFP or walking gauge coupling

Lattice Higgs Collaboration
χSB

Kogut,Sinclair
finite temperature

light Higgs near conformality (dilaton-like?) sextet





χSB on Λ~TeV scale

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χSB

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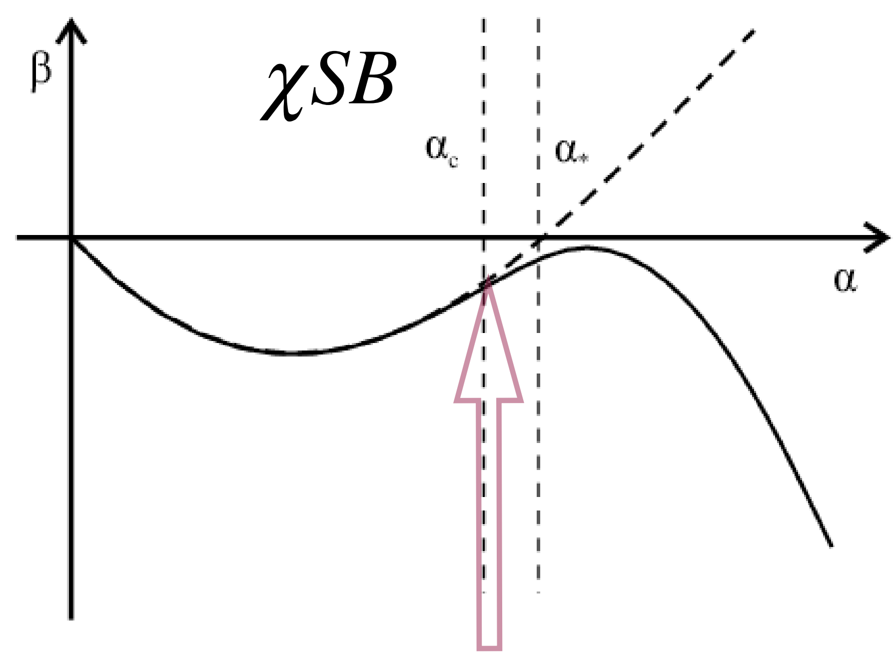
χSB on Λ~TeV scale

three Goldstone pions
become longitudinal
components of weak bosons

composite Higgs mechanism
scale of Higgs condensate ~ F=250
GeV

conflicts with EW constraints?



when chiral symmetry breaking
turns conformal FP into walking

two expectations:

(1) χSB and confinement

(2) light scalar close to CW (with walking) ?

light Higgs near conformality (dilaton-like?) sextet

$$m_\sigma^2 \simeq -\frac{4}{f_\sigma^2}\langle 0|\left[\Theta^\mu_\mu(0)\right]_{NP}|0\rangle$$

Partially Conserved Dilatation Current (PCDC)
will the gradient flow help to make it precise?
Patella talk

$$\partial_\mu \mathcal{D}^\mu = \Theta^\mu_\mu = \frac{\beta(\alpha)}{4\alpha} G^a_{\mu\nu} G^{a\mu\nu}$$

Dilatation current

$$\langle 0|\Theta^{\mu\nu}(x)|\sigma(p)\rangle = \frac{f_\sigma}{3}(p^\mu p^\nu - g^{\mu\nu}p^2)e^{-ipx}$$

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$$\left[\Theta^\mu_\mu\right]_{NP} = \frac{\beta(\alpha)}{4\alpha}\left[G^a_{\mu\nu}G^{a\mu\nu}\right]_{NP} \qquad \frac{m_\sigma}{f_\sigma} \to ?$$

light Higgs near conformality (dilaton-like?) sextet

$$m_\sigma^2 \simeq -\frac{4}{f_\sigma^2}\langle 0|\left[\Theta^\mu_\mu(0)\right]_{NP}|0\rangle$$

Partially Conserved Dilatation Current (PCDC)
will the gradient flow help to make it precise?
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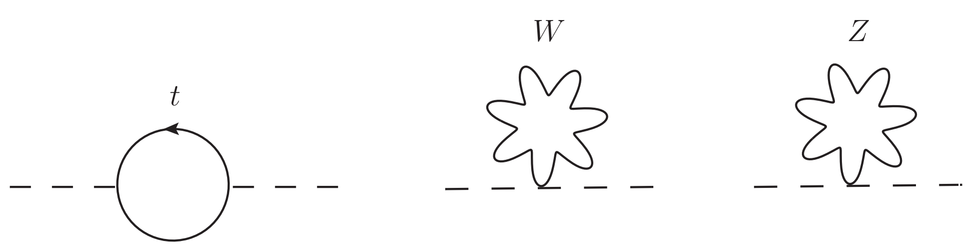
but how light is light ?
few hundred GeV Higgs impostor?

Foadi, Fransden, Sannino
open for spirited theory discussions



$$\delta M_H^2 \sim -12\kappa^2 r_t^2 m_t^2 \sim -\kappa^2 r_t^2 (600\,\mathrm{GeV})^2$$

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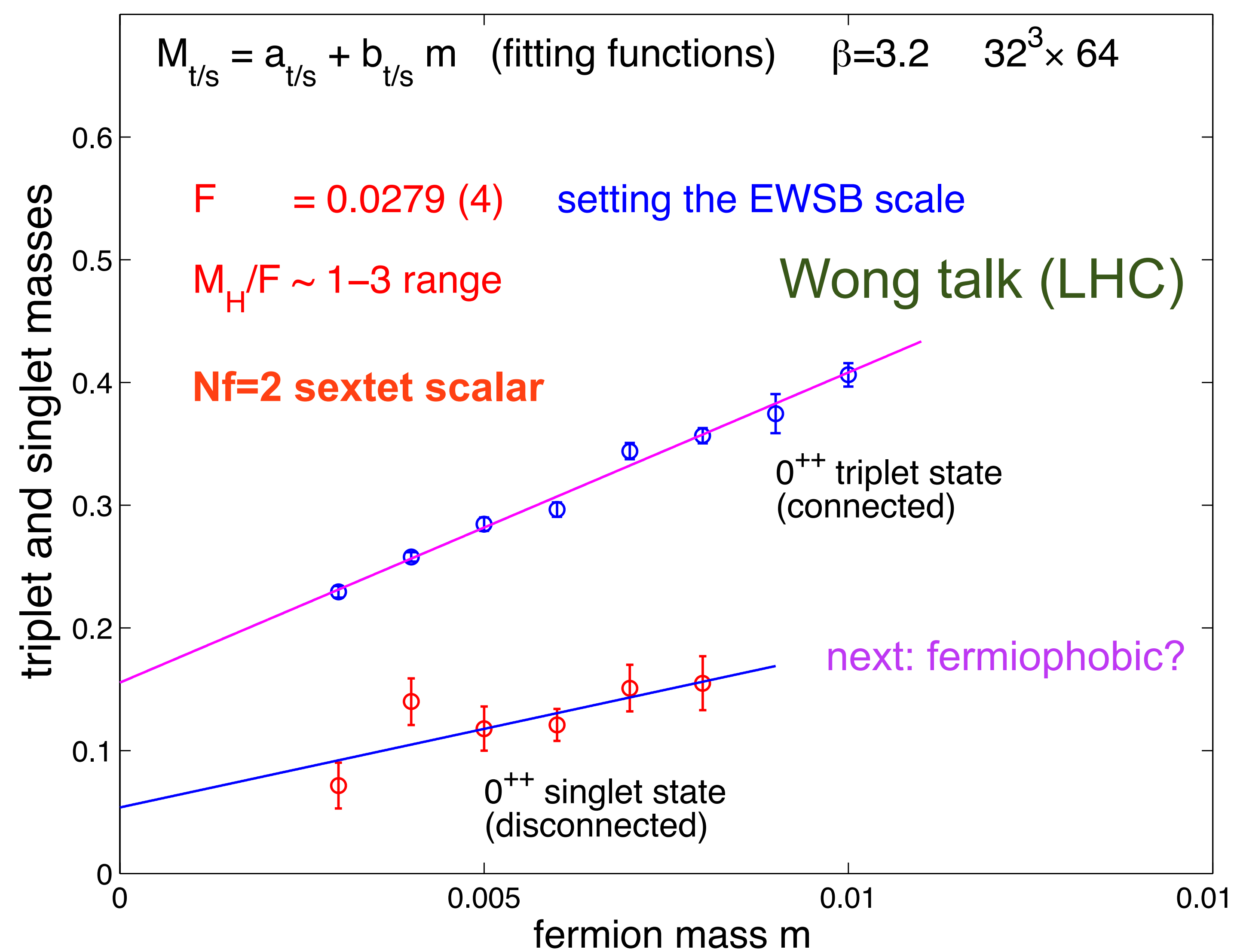
Triplet and singlet masses from 0^{++} correlators



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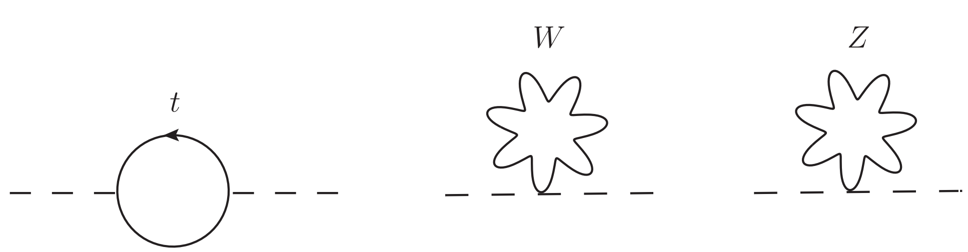

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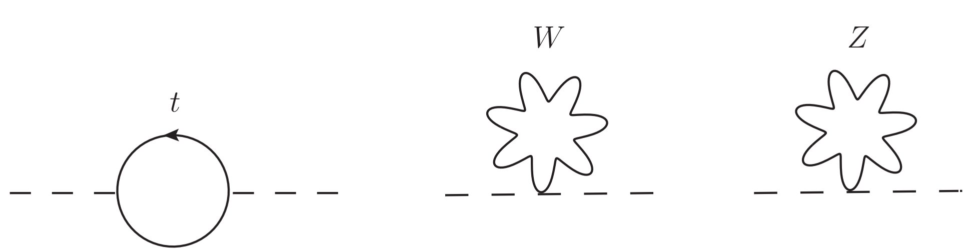

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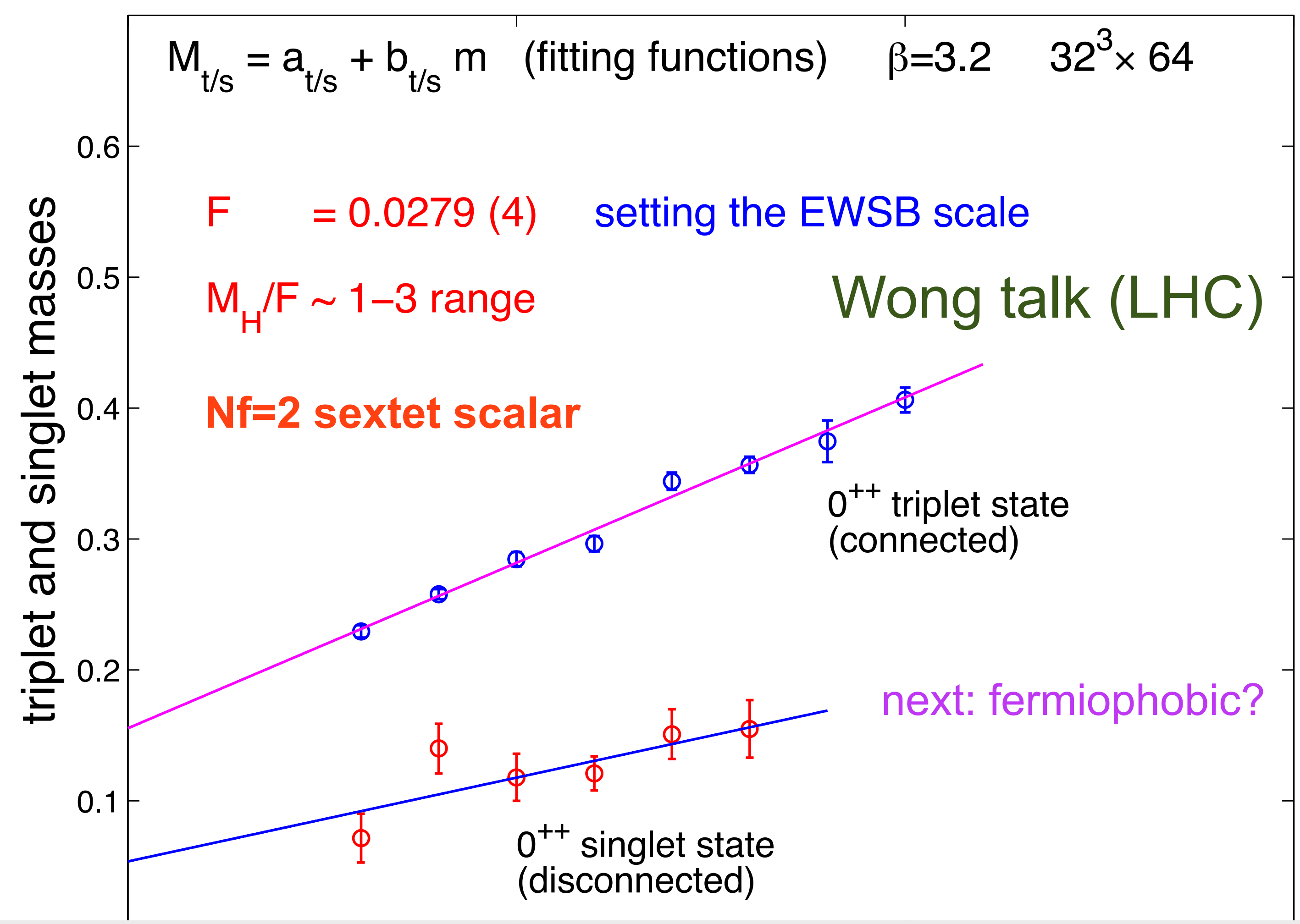
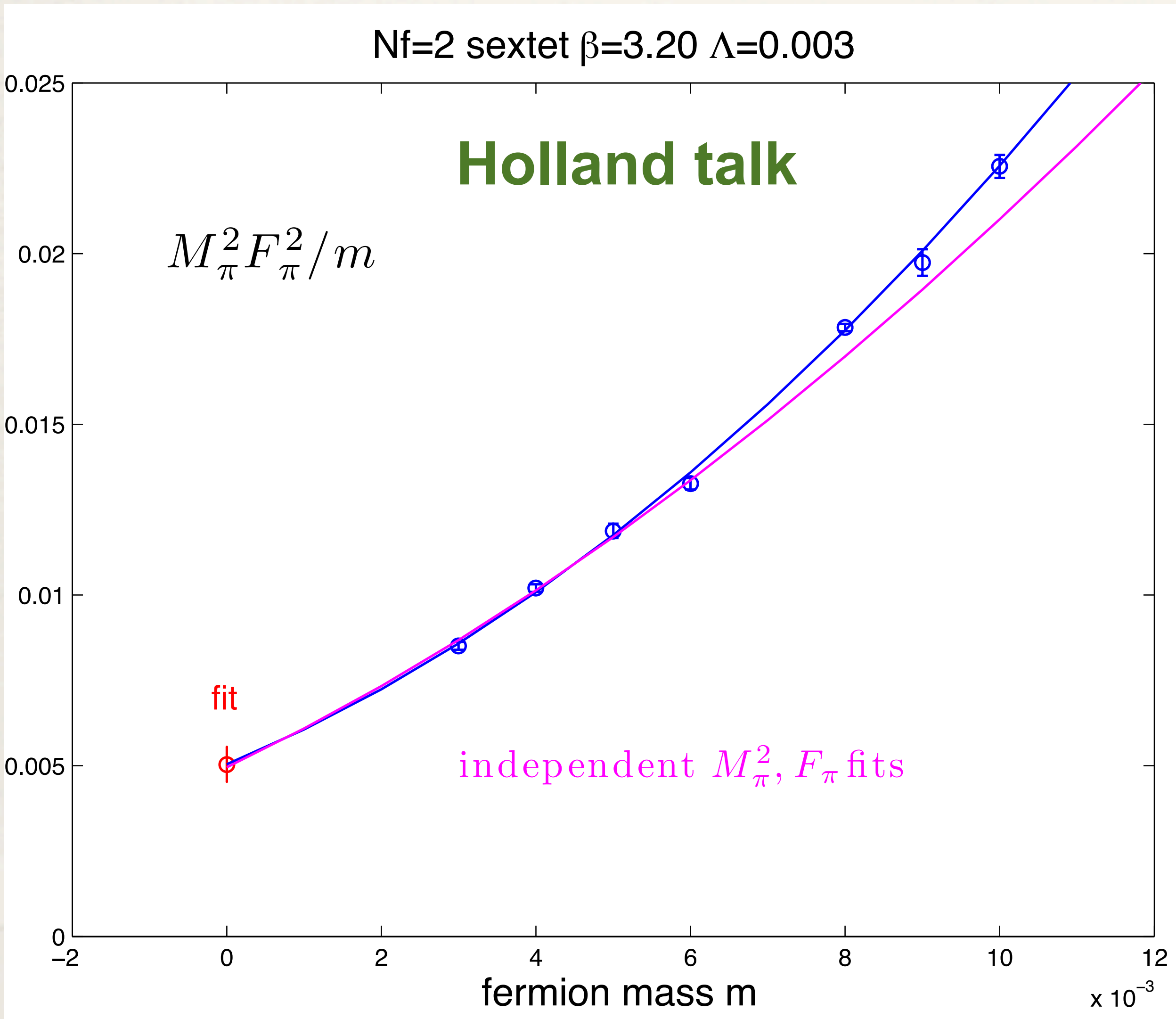


dilaton-like scalar states in SCGT, or "just a light Higgs" ?

15

light Higgs near conformality (dilaton-like?) sextet

GMOR (1) χSB and confinement ✓



GMOR relation $\langle\bar\psi\psi\rangle = 2BF^2$

$M_\pi^2 = 2B \cdot m$

rearrange

$\langle\bar\psi\psi\rangle = M_\pi^2 F_\pi^2/m$

magenta combine previous fits of M_π^2, F_π

red separate fit of $M_\pi^2 F_\pi^2/m$ data

quadratic ; larger data set

both methods consistent

value of condensate in chiral limit smaller than from extrapolations of directly measured condensate, even with subtraction

is staggered chiral PT required to achieve consistency?

Kieran Holland, Lattice 2013

light Higgs near conformality (dilaton-like?) sextet

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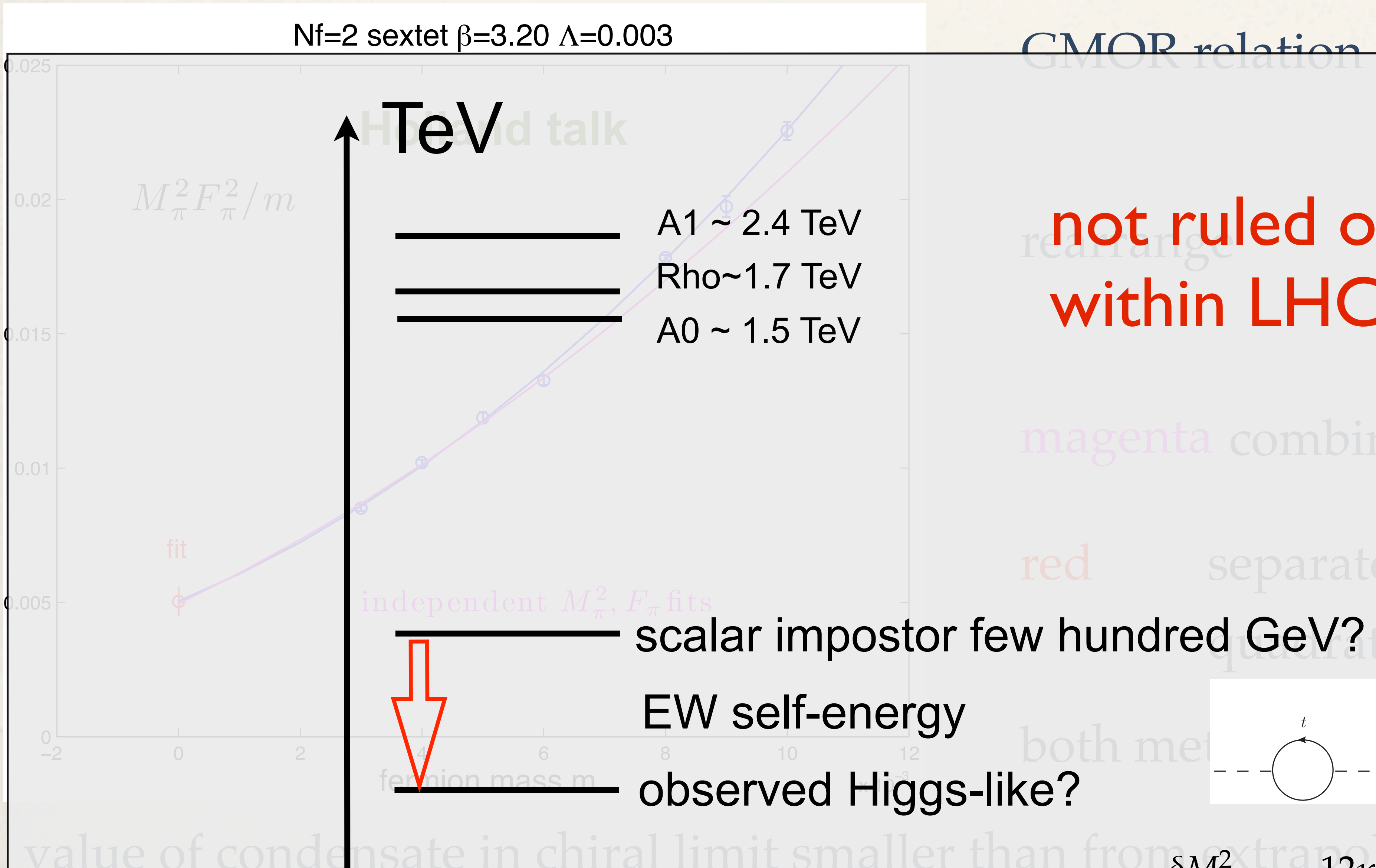

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rearrange $\langle\bar\psi\psi\rangle = M_\pi^2 F_\pi^2/m$

not ruled out, within LHC14 reach

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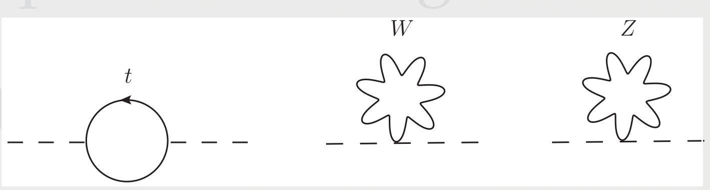
both met



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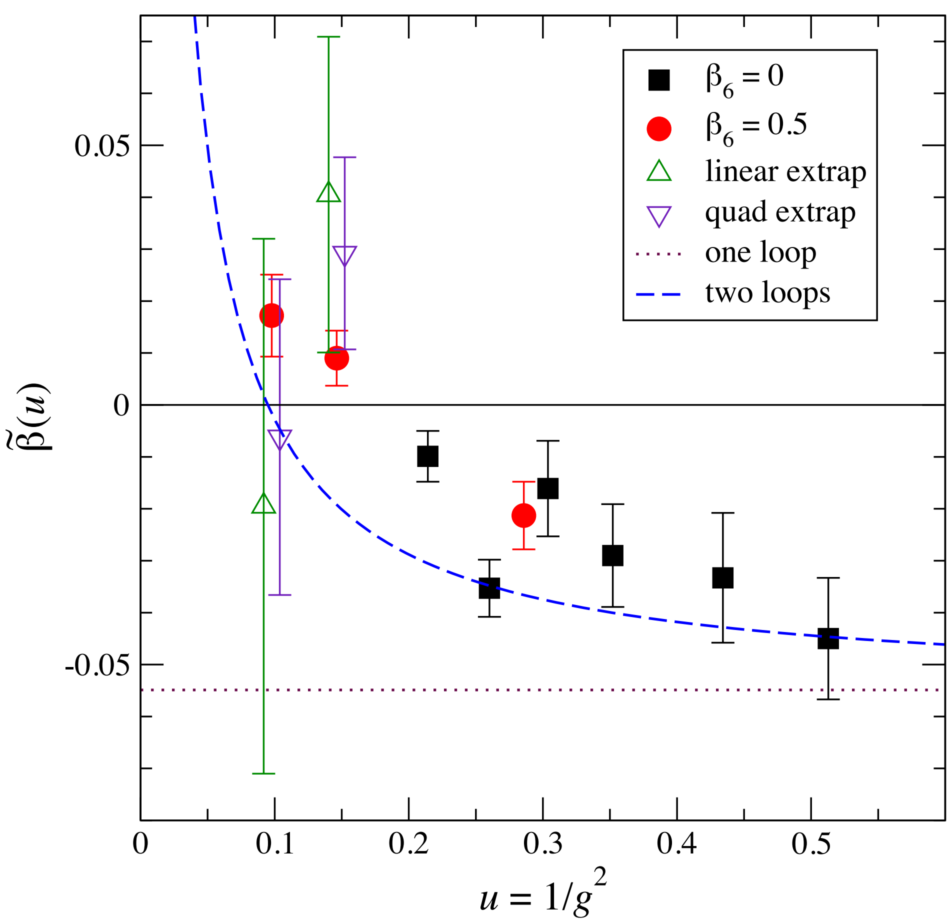
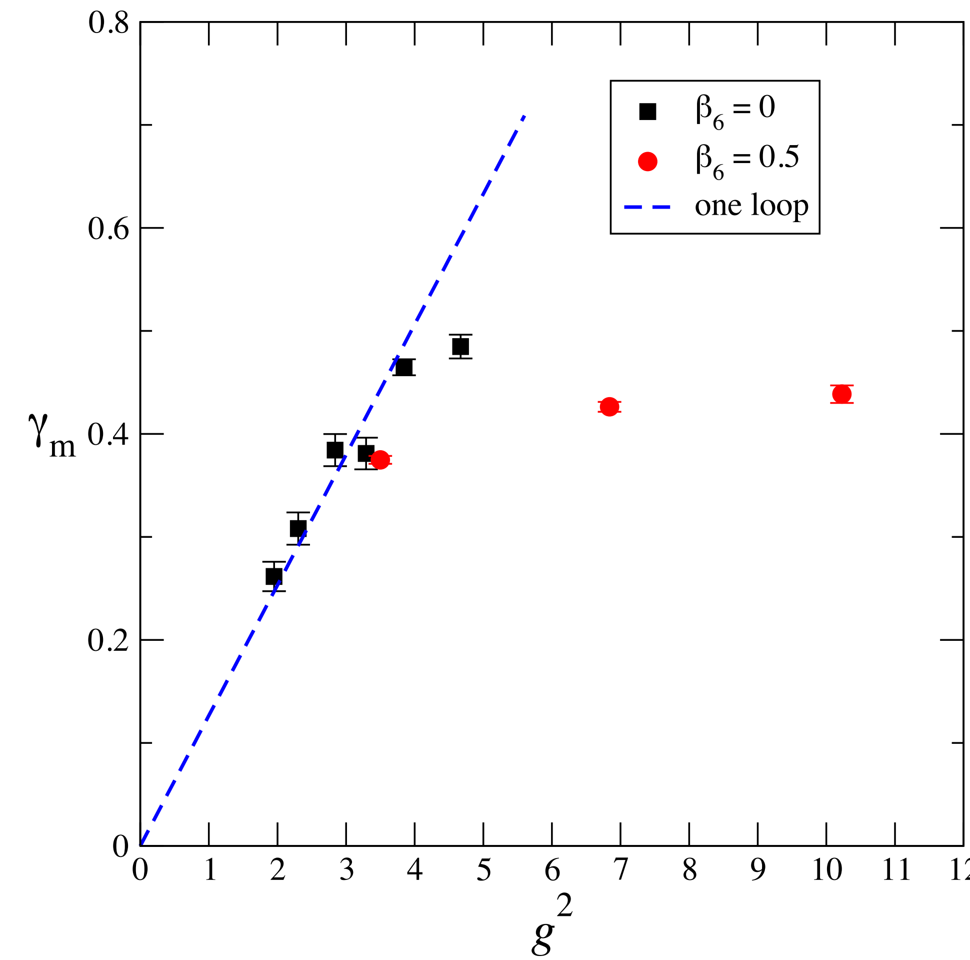
Kieran Holland, Lattice 2013

light Higgs near conformality (dilaton-like?) sextet

(2) light scalar ✓ close to CW (with walking) ?



DeGrand
Shamir
Svetitsky

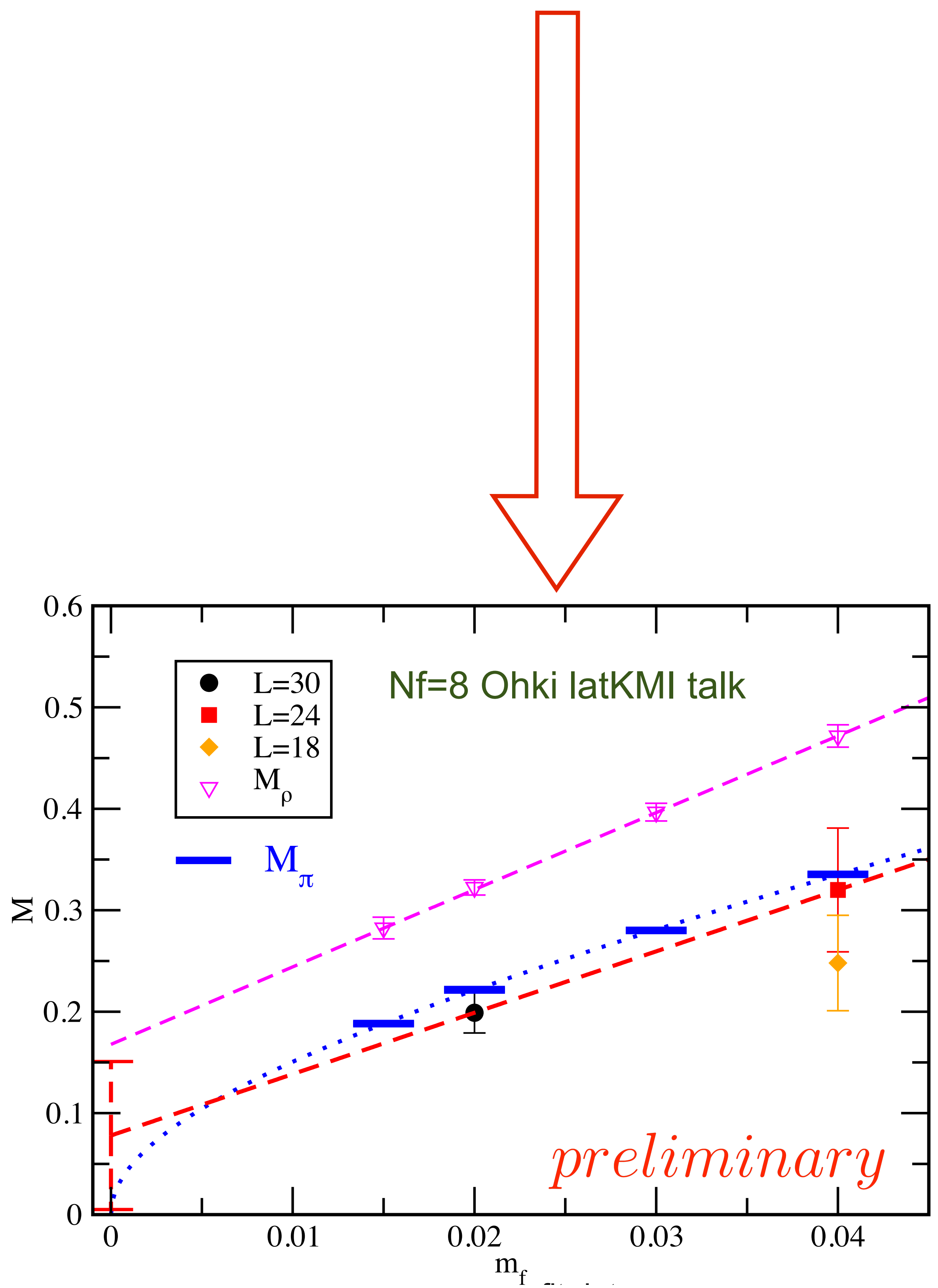


authors: We cannot confirm the existence of an infrared fixed point

in final analysis anomalous dimension remains ~ 0.4 at large renormalized couplings

LHC group has the gradient flow beta function (no zero) and the anomalous dimension growing above 0.4 (from Dirac spectrum). To complete analysis before submission.

light Higgs near conformality (dilaton-like?) Nf=8



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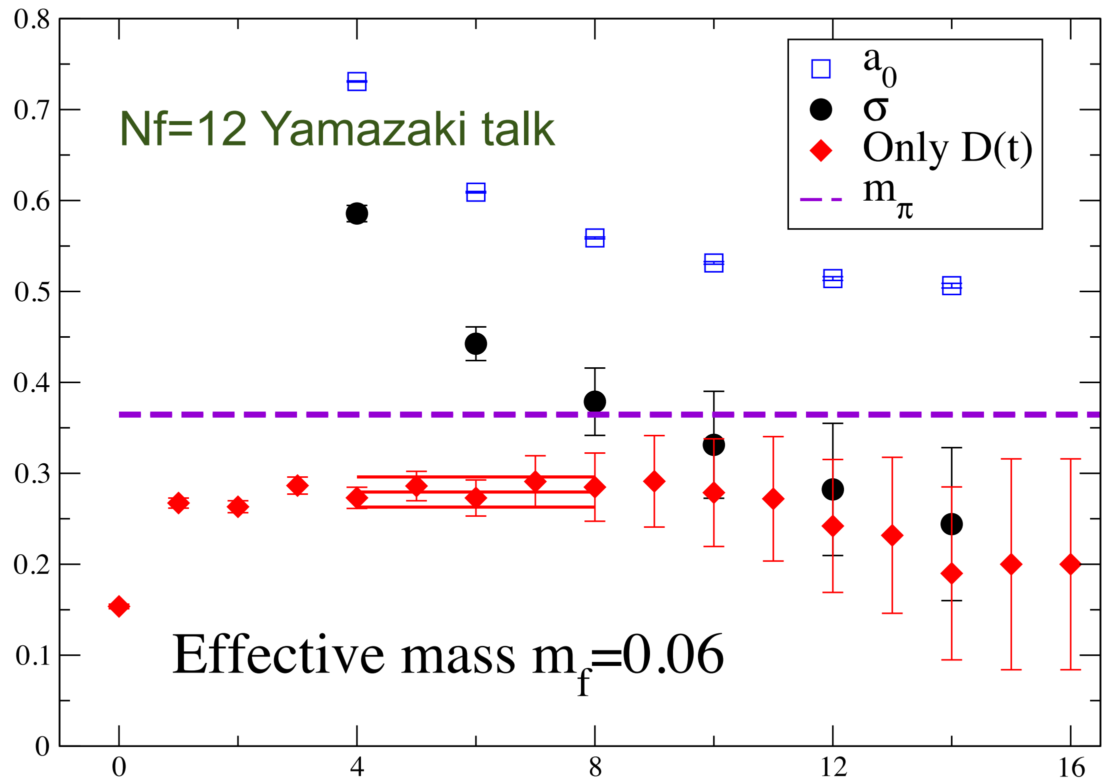


Non-singlet scalar

a_0: $-C_+(t)$

Singlet scalar

σ: $3D_+(t) - C_+(t)$

σ: $D(t)$ i.e. $m_\sigma < m_{a_0}$

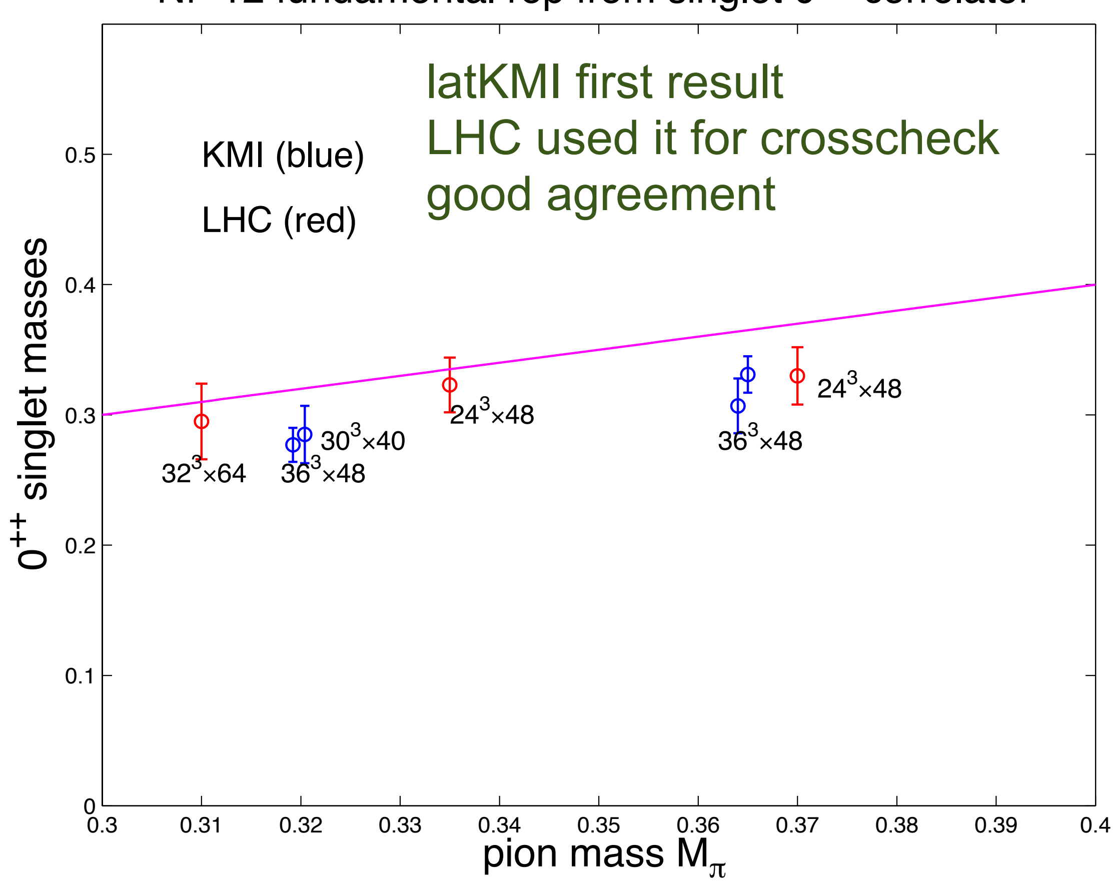
Consistent m_σ

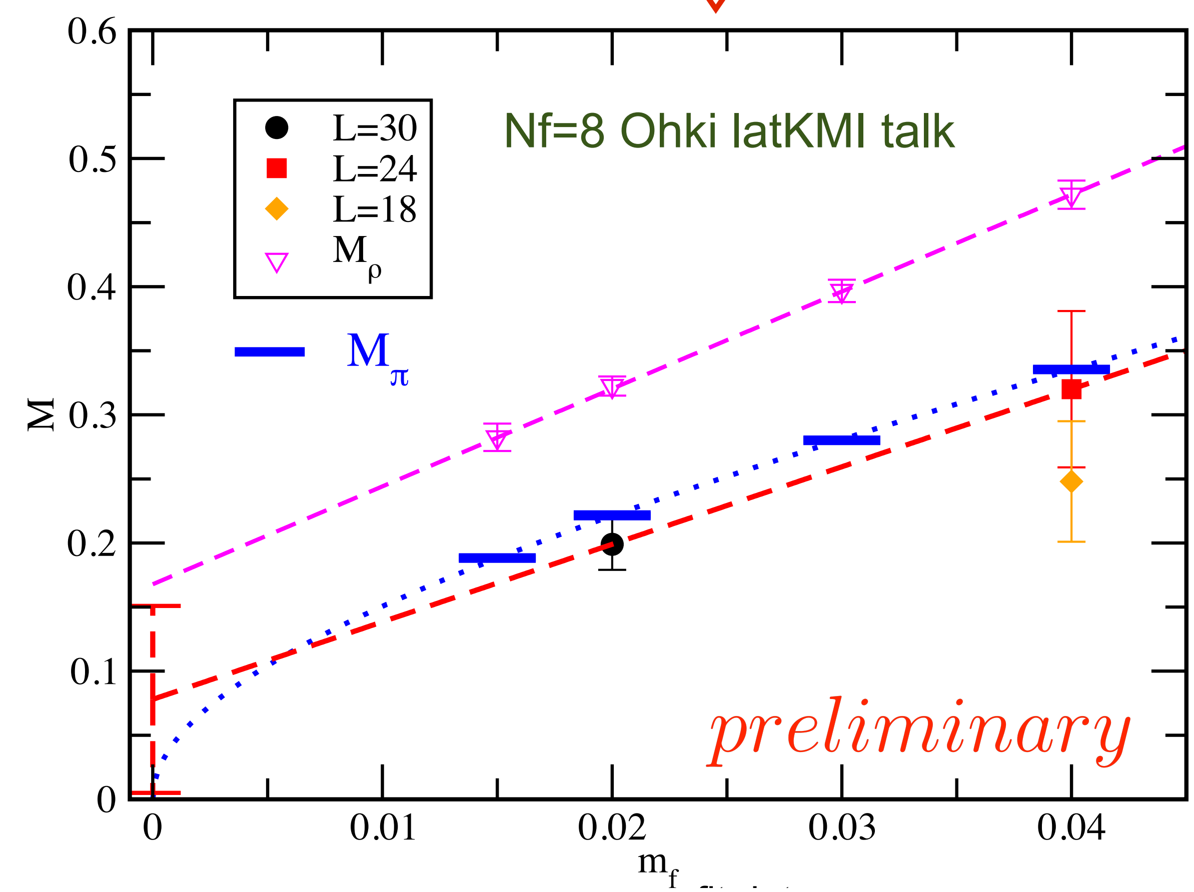
with smaller error

also Jin and Mawhinney

$m_\sigma < m_\pi$ at $m_f = 0.06$

Nf=12 fundamental rep from singlet 0^{++} correlator





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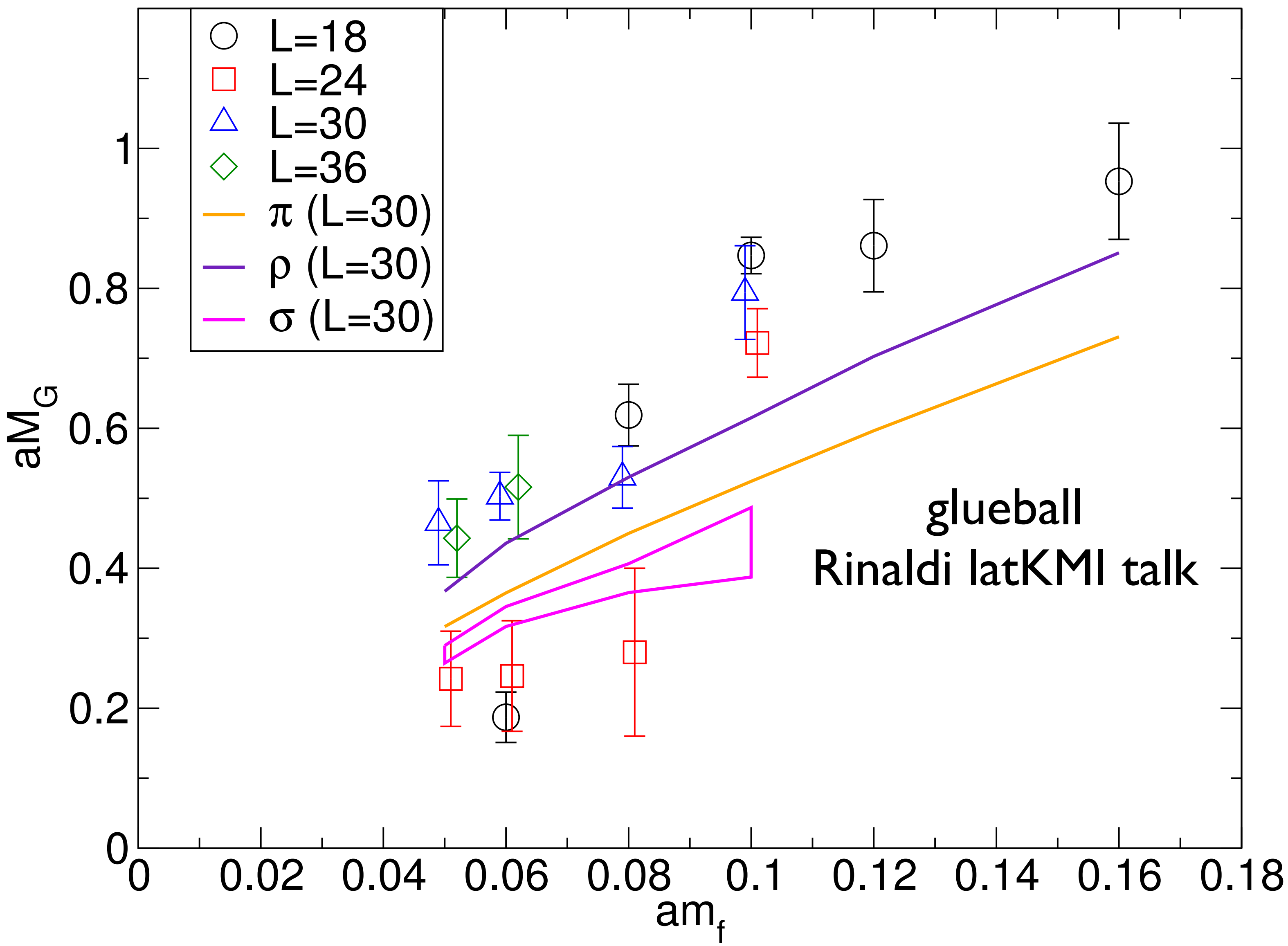


calar

$C_+(t)$

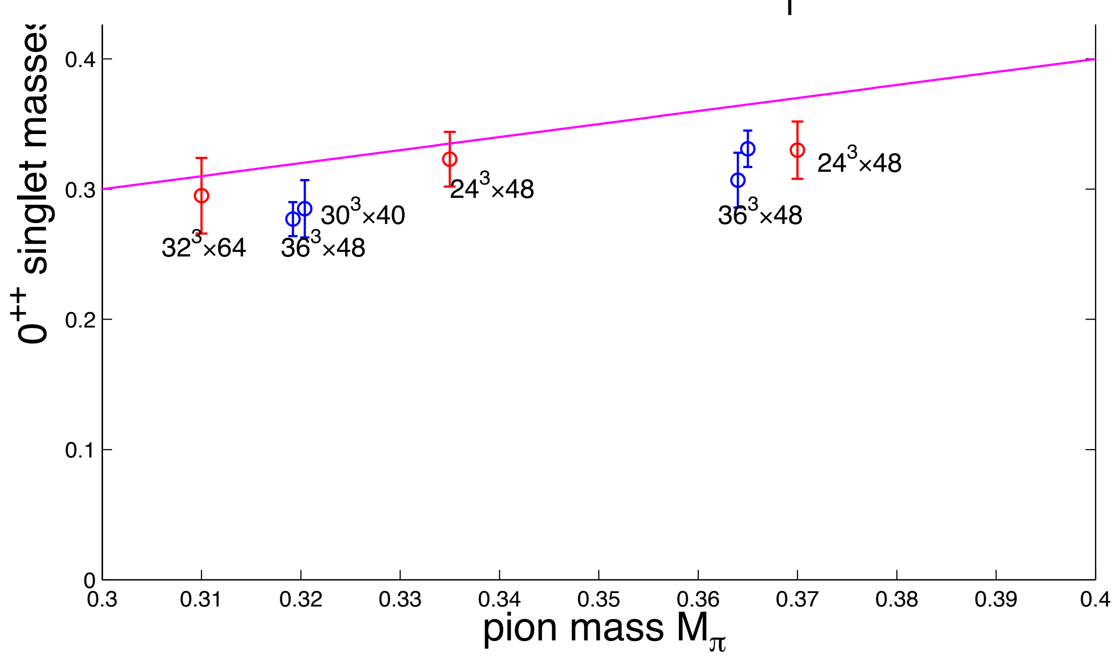
$m_\sigma < m_{a_0}$

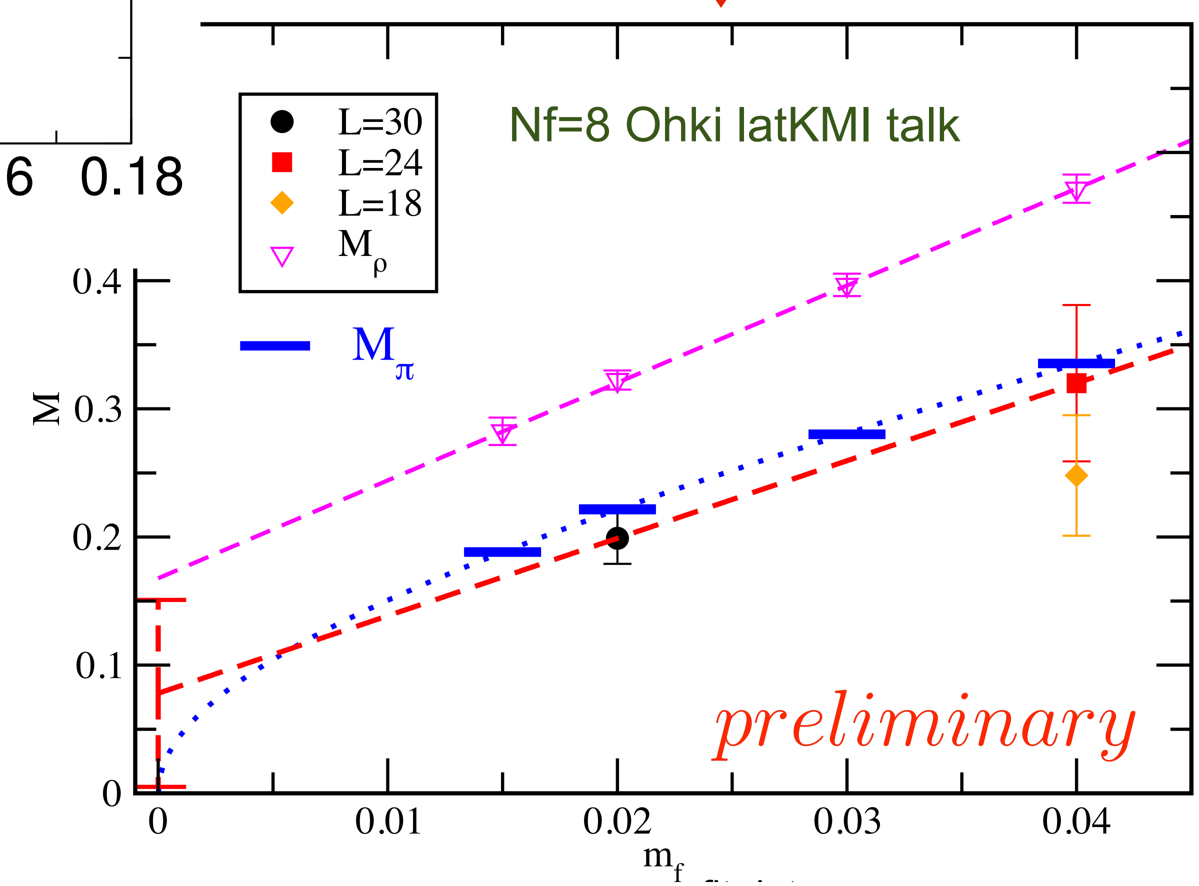
σ

aller error

whinney

$m_f = 0.06$





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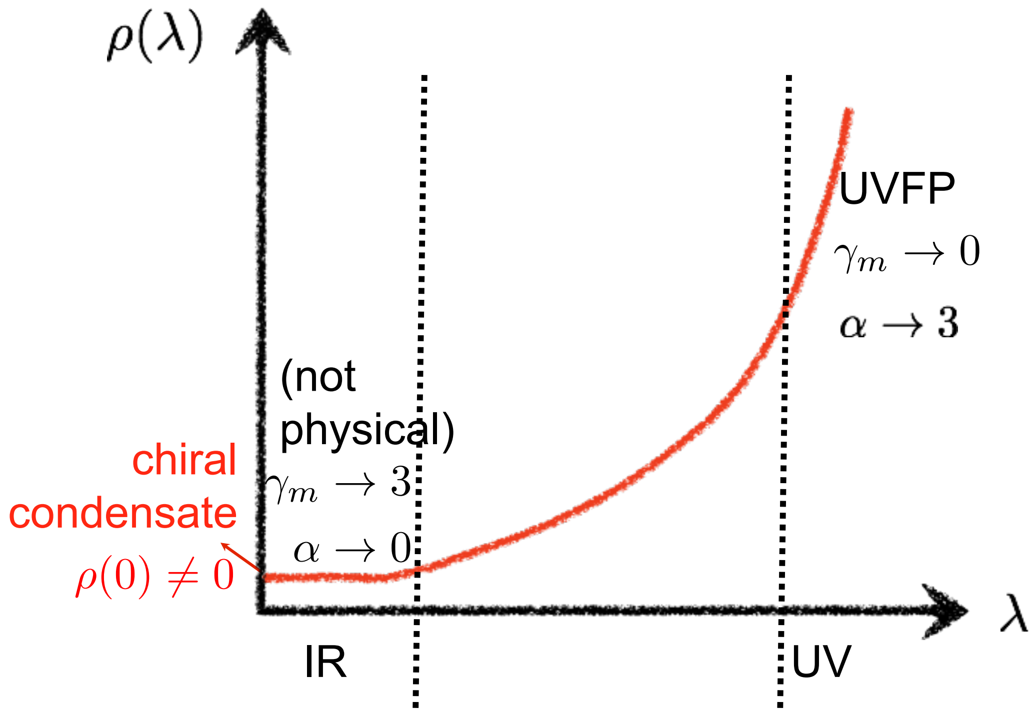
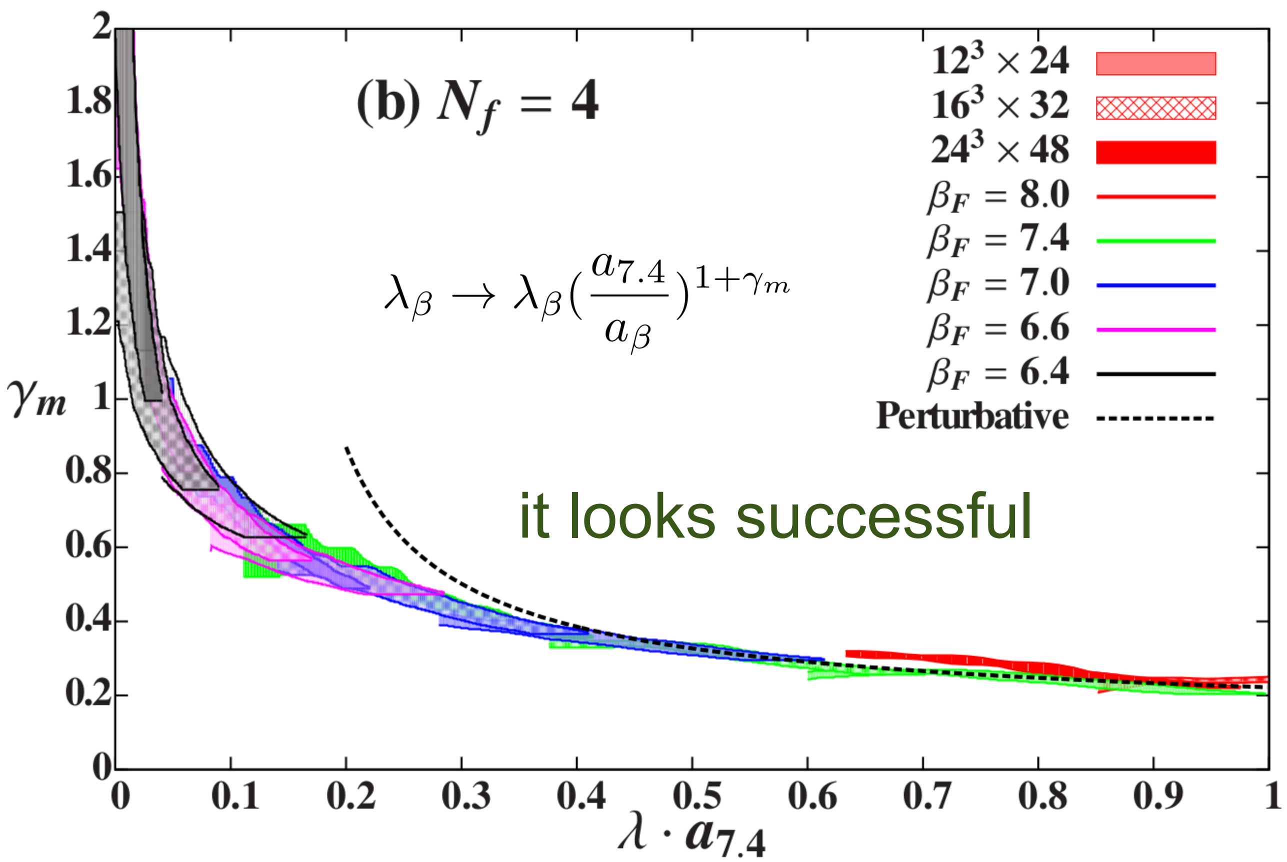


Fit:

$\nu(\lambda) \propto \lambda^{1+\alpha(\lambda)}$
(in limited range)

$$1 + \gamma_m = \frac{4}{\alpha + 1}$$

Boulder group:
Cheng talk
Hasenfratz
Petropoulos
Schaich



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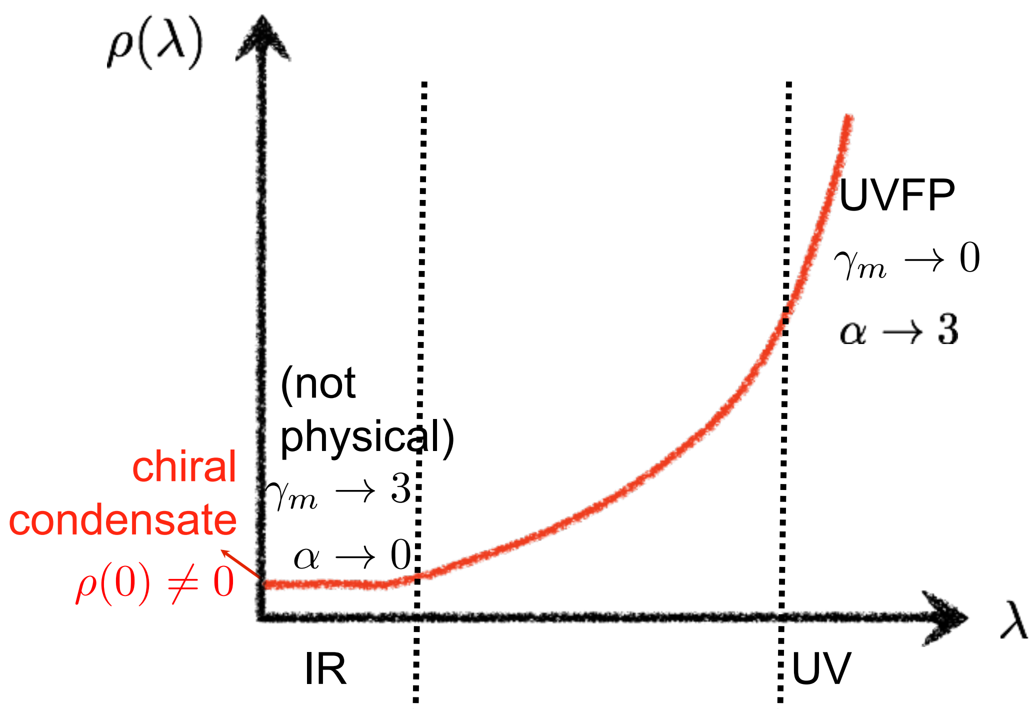

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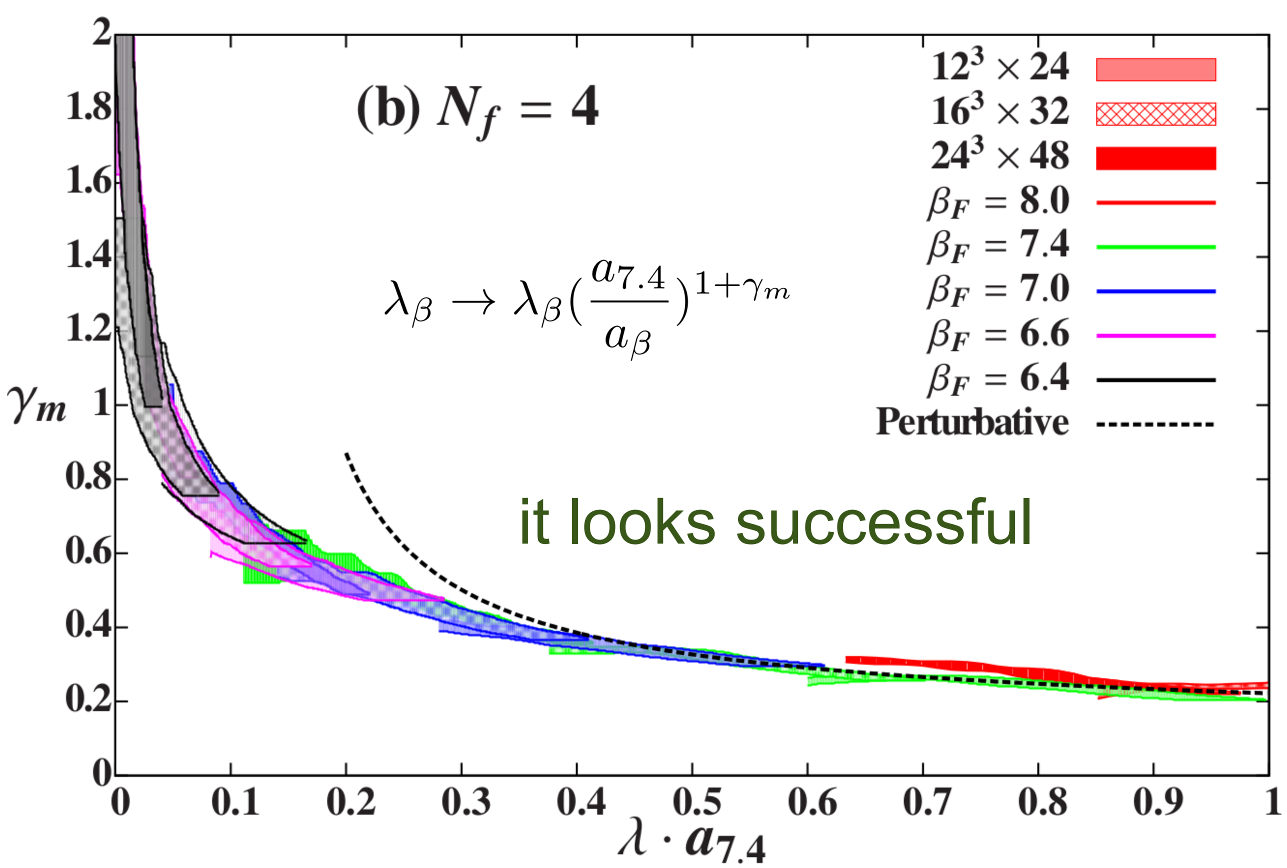

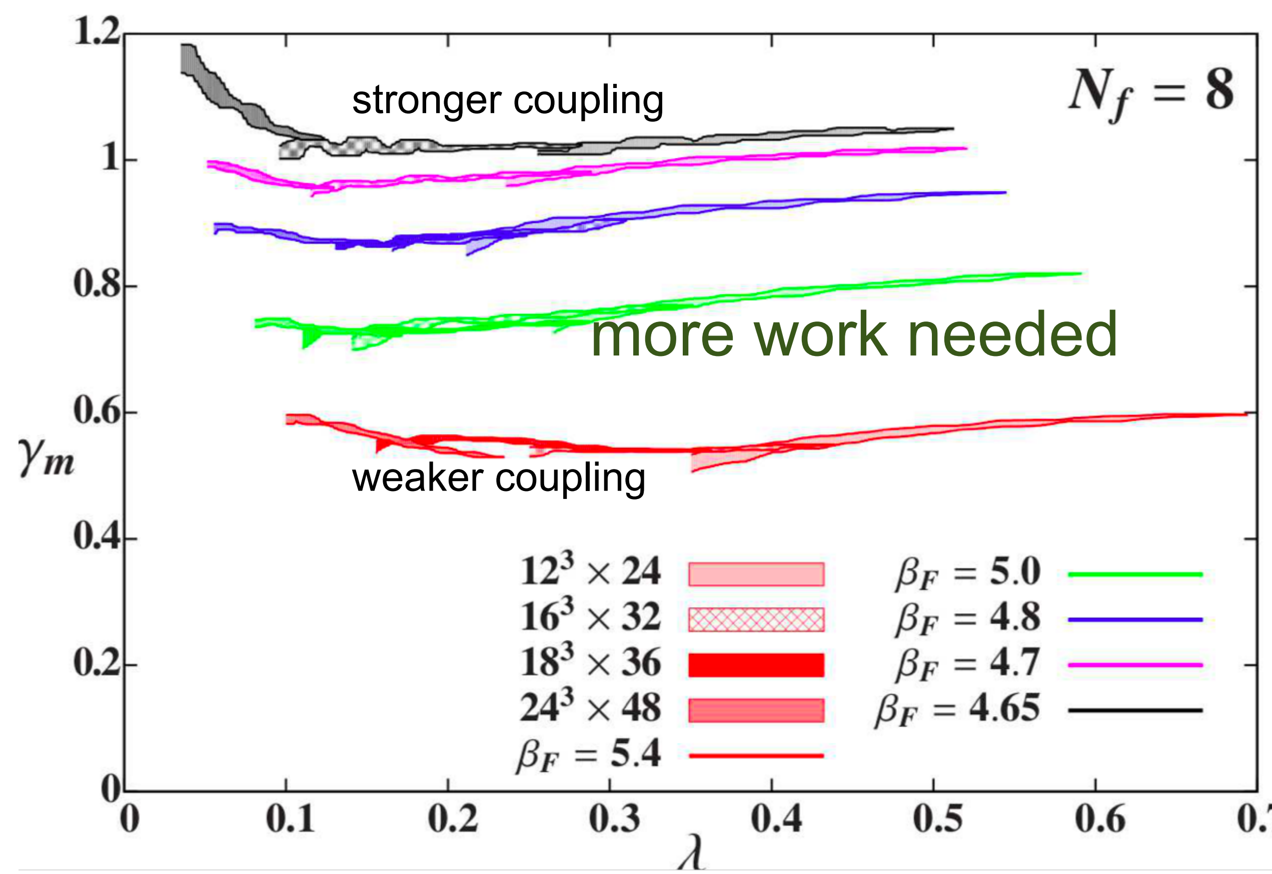

light Higgs near conformality (dilaton-like?) Nf=8

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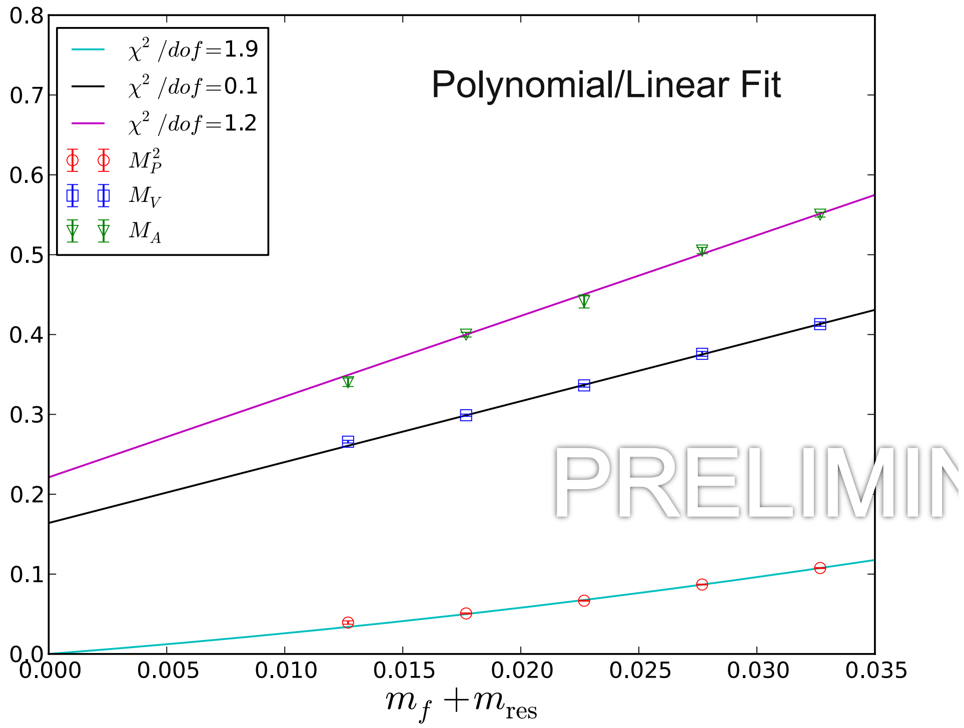
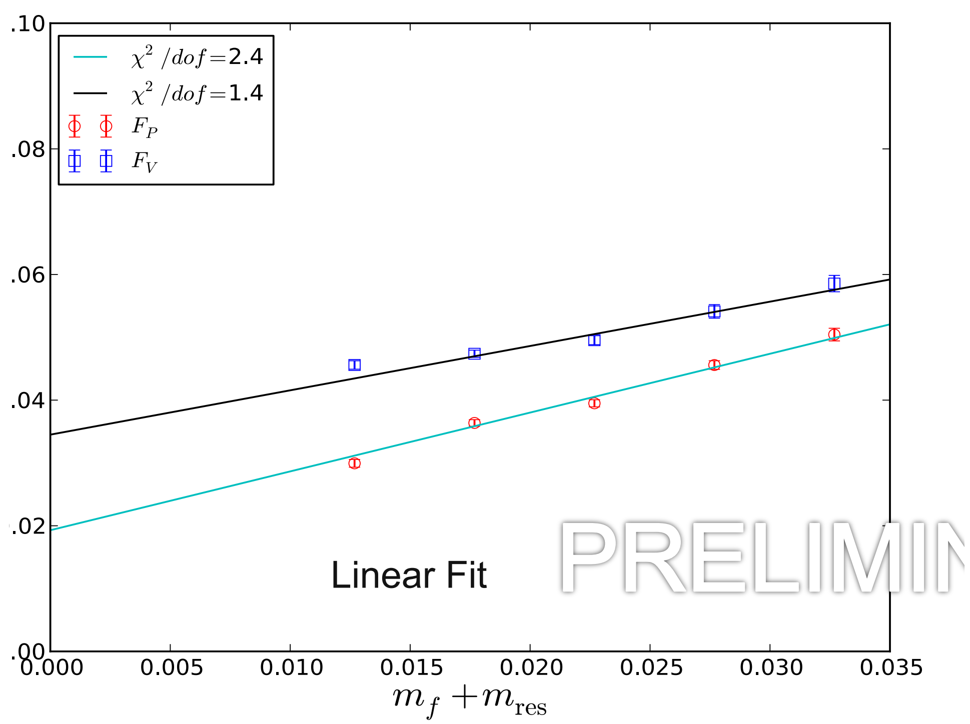
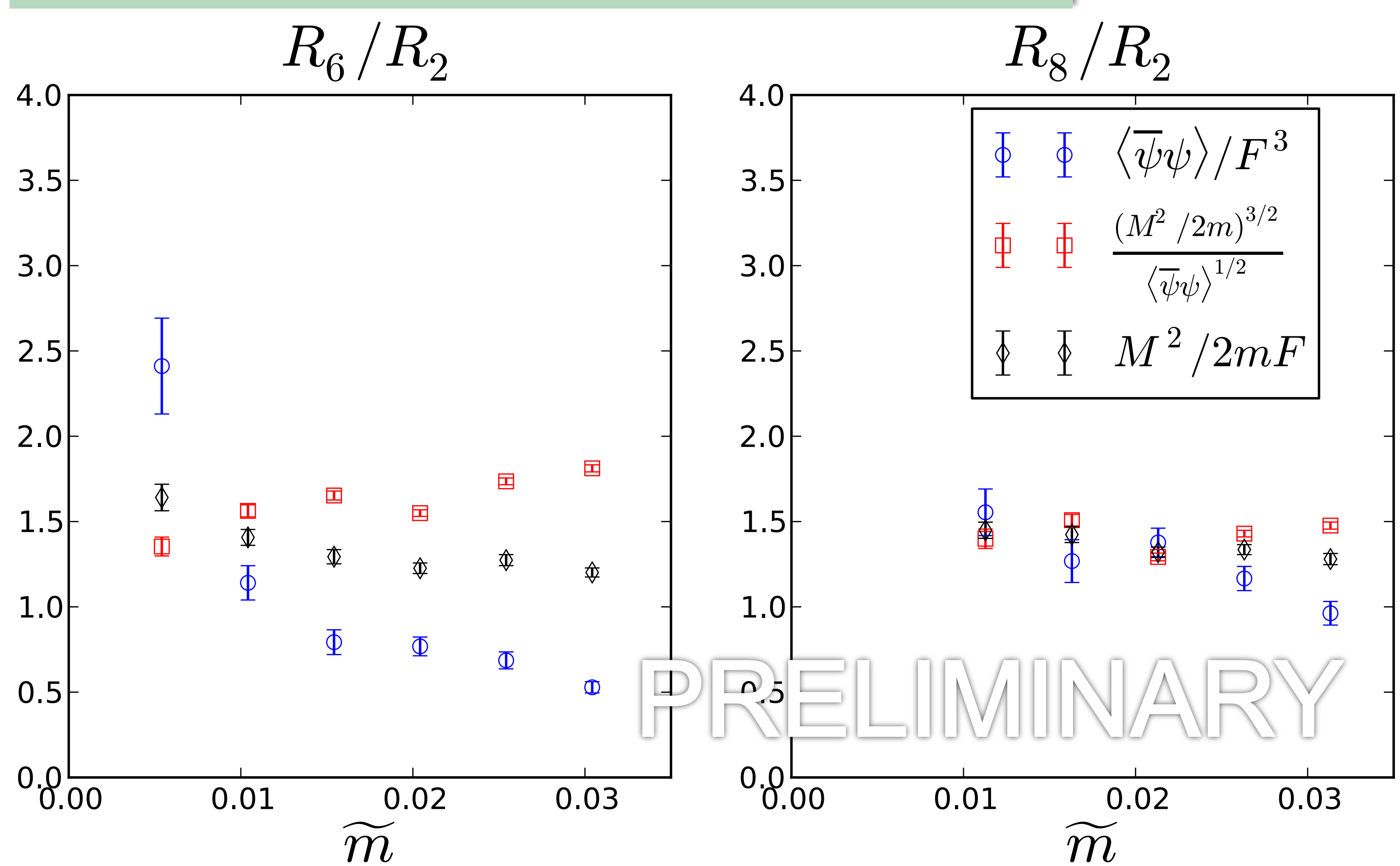


LSD group Meifeng Lin poster



Chiral Condensate



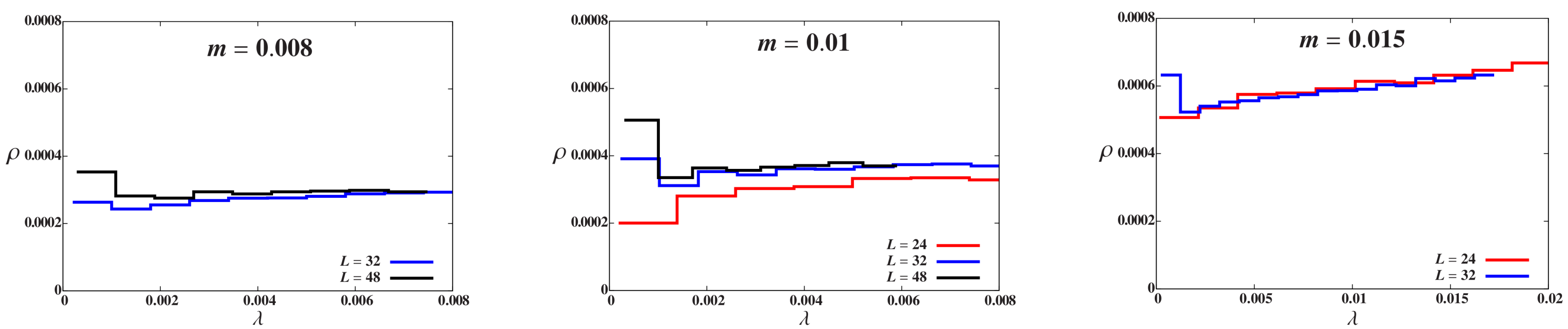
light Higgs near conformality (dilaton-like?) Nf=8

Chiral condensate from Dirac eigenmode number

Address valence mass effects in $\langle \overline{\psi}\psi \rangle$
by analyzing the eigenvalues of the massless Dirac operator

Schaich talk
with
Boulder group
and USBSM INCITE

Compare $\rho(\lambda)$ on different volumes with fixed sea mass:



going for large volumes

Good agreement up to expected finite-volume effects,
and topological zero-mode effects in first bin

Extract $\Sigma_{m_s} \equiv \pi\rho(\lambda \to 0)$ from derivative of mode number $\nu \sim \int \rho \, d\lambda$

unsettled question: does the Nf=8 model hide a Higgs impostor?

Higgs as a pseudo-Goldstone boson

- strong dynamics identifying the Higgs as a **scalar** pseudo-Nambu-Goldstone boson (PNGB)

- in strongly coupled gauge theories with fermions in real or pseudo-real reps of the gauge group Goldstone scalars emerge

- this PNGB Higgs mechanism plays a critical role in **little Higgs** models

- in little Higgs models global symmetries and their symmetry breaking patterns cancel the quadratic divergences of the Higgs mass with little fine tuning to ~ 10 TeV

- this provides phenomenologically interesting models with weakly coupled extensions of the SM with PNGB Higgs scalars

- project to demonstrate that viable UV complete theories exist with strong gauge sector replacing the weakly coupled elementary (mexican hat) Higgs.

Higgs as a pseudo-Goldstone boson

Minimal PNGB model:

- SU(2) color gauge group with Nf=2 fundamental massless fermions

- additional steril flavors with Nf > 2 can be added to drive the theory close to or into the conformal window (?)

- pseudo-real SU(2) color group enlarges SU(Nf)xSU(Nf) vector-axial vector symmetry to SU(2Nf) flavor symmetry combining 2Nf left/right 2-component chiral spinors

- most attractive channel breaks SU(2Nf) to Sp(2Nf). If explicit masses are given to Nf-2 flavors the remaining 2 massless flavors yield SU(4)/Sp(4) coset with 5 Goldstone bosons demonstrated in lattice simulation! Lewis,Pica,Sannino

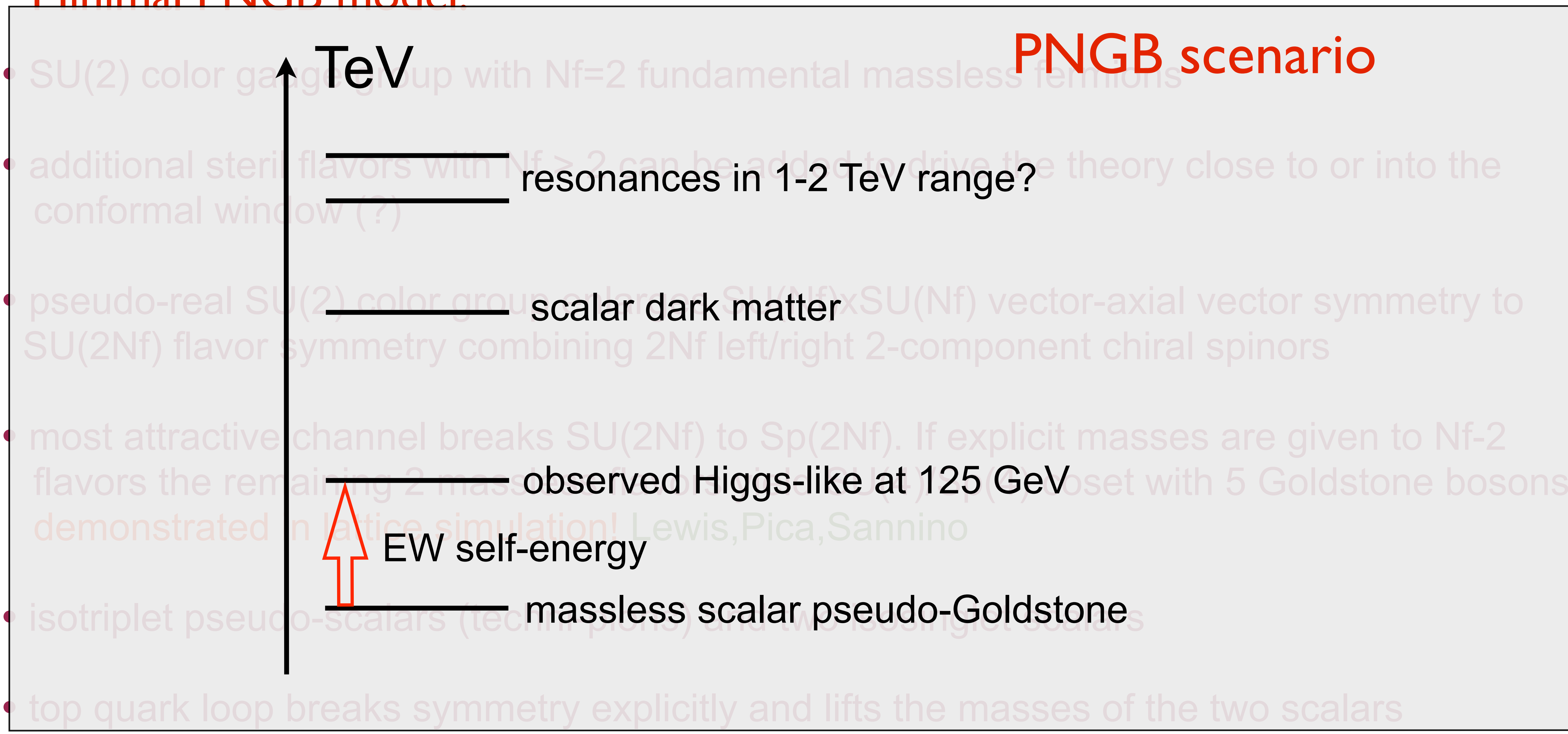
- isotriplet pseudo-scalars (techni-pions) and two isosinglet scalars

- top quark loop breaks symmetry explicitly and lifts the masses of the two scalars

- the lighter is the composite Higgs (PC=+1) and heavier is scalar dark matter candidate (PC=-1)

Higgs as a pseudo-Goldstone boson

Minimal PNGB model:



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Studies of supersymmetric theories on the lattice

Lattice 2013 talks:
Piemonte, Munster, Steinhauer, Weir

Studies of supersymmetric theories on the lattice

Lattice 2013 talks:
Piemonte, Munster, Steinhauer, Weir

- New theoretical formulations
- improved algorithms
- increased computer power

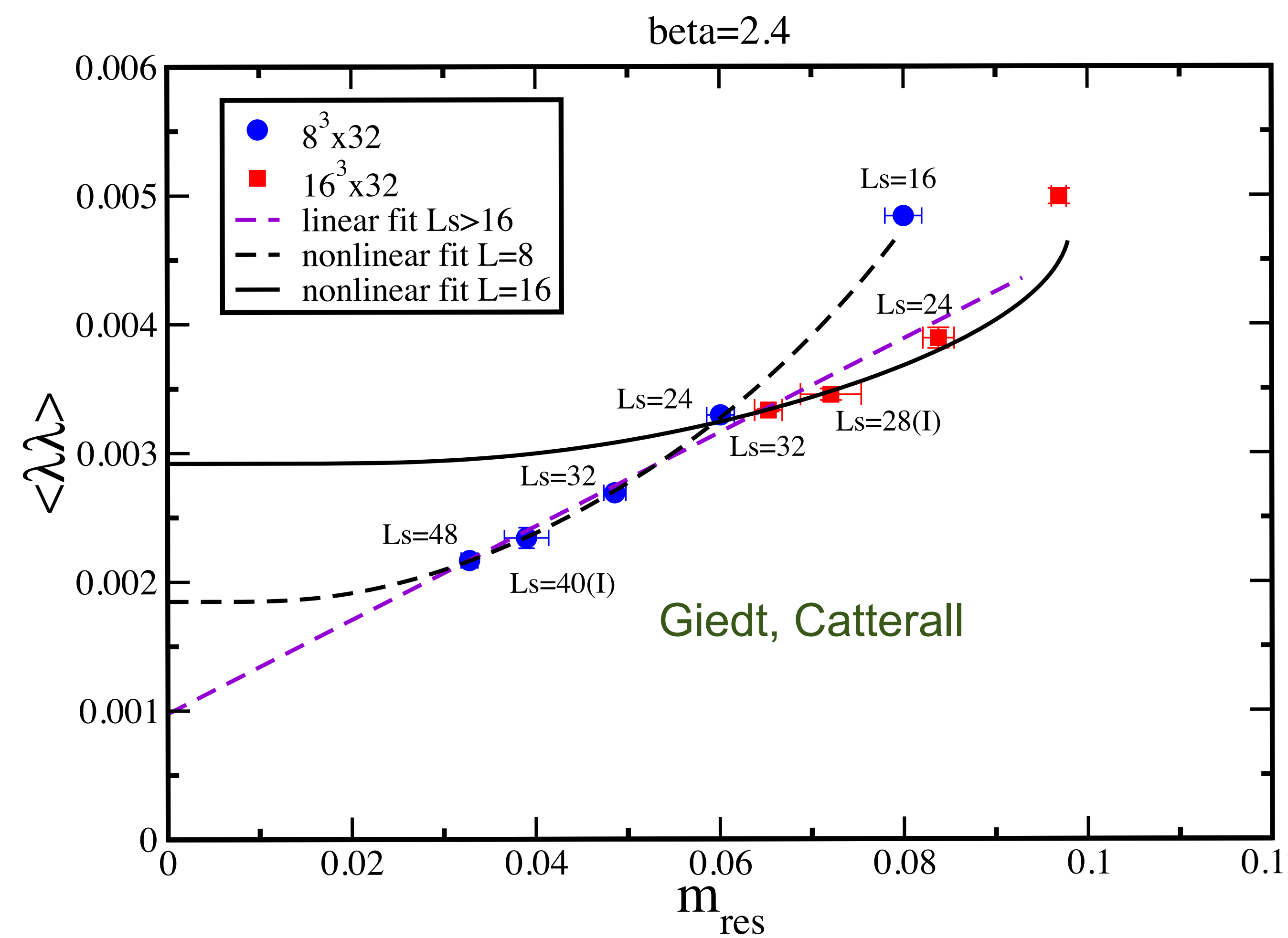
pioneering studies of N=1 and N=4 super Yang-Mills

N=1 super Yang-Mills is supersymmetric pure gauge QCD

first step to super QCD   can play the role of non-perturbative SUSY breaking in high scale hidden sector

Gaugino condensate vs residual mass
SU(2) N=1 super Yang-Mills
DW fermions

next goal is super QCD investigating the simplest system with metastable vacua (four colors and five flavors)



Studies of supersymmetric theories on the lattice

SUSY and the LHC

- If SUSY is correct explanation for what we are seeing at LHC, it must be broken.

- That breaking (because of no go theorems etc) must be non-perturbative in character and hence the lattice potentially offers a good tool to understand it.

- Low energy constants that encode the SUSY breaking in any effective low energy SUSY model (e.g. MSSM) are determined by non perturbative quantities in the sector that breaks SUSY (e.g. super QCD).

- Thus measuring these condensates via lattice simulation helps to constrain the parameter space of any BSM SUSY low energy theory. Again this could be the MSSM or something else.

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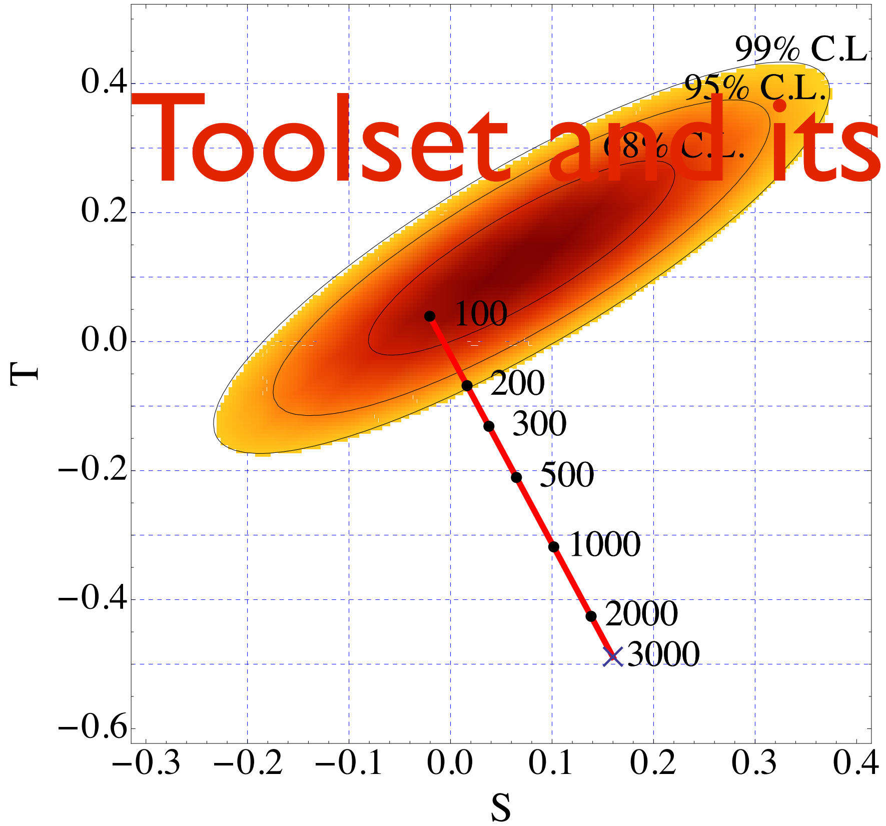
Non-perturbative N=4 super Yang-Mills

- holographic dilaton connection in pursuing light Higgs?
  - dilaton is simple to realize (translations along flat directions)
  - N=4 lattice action has flat directions (protected by exact lattice supersymmetry)

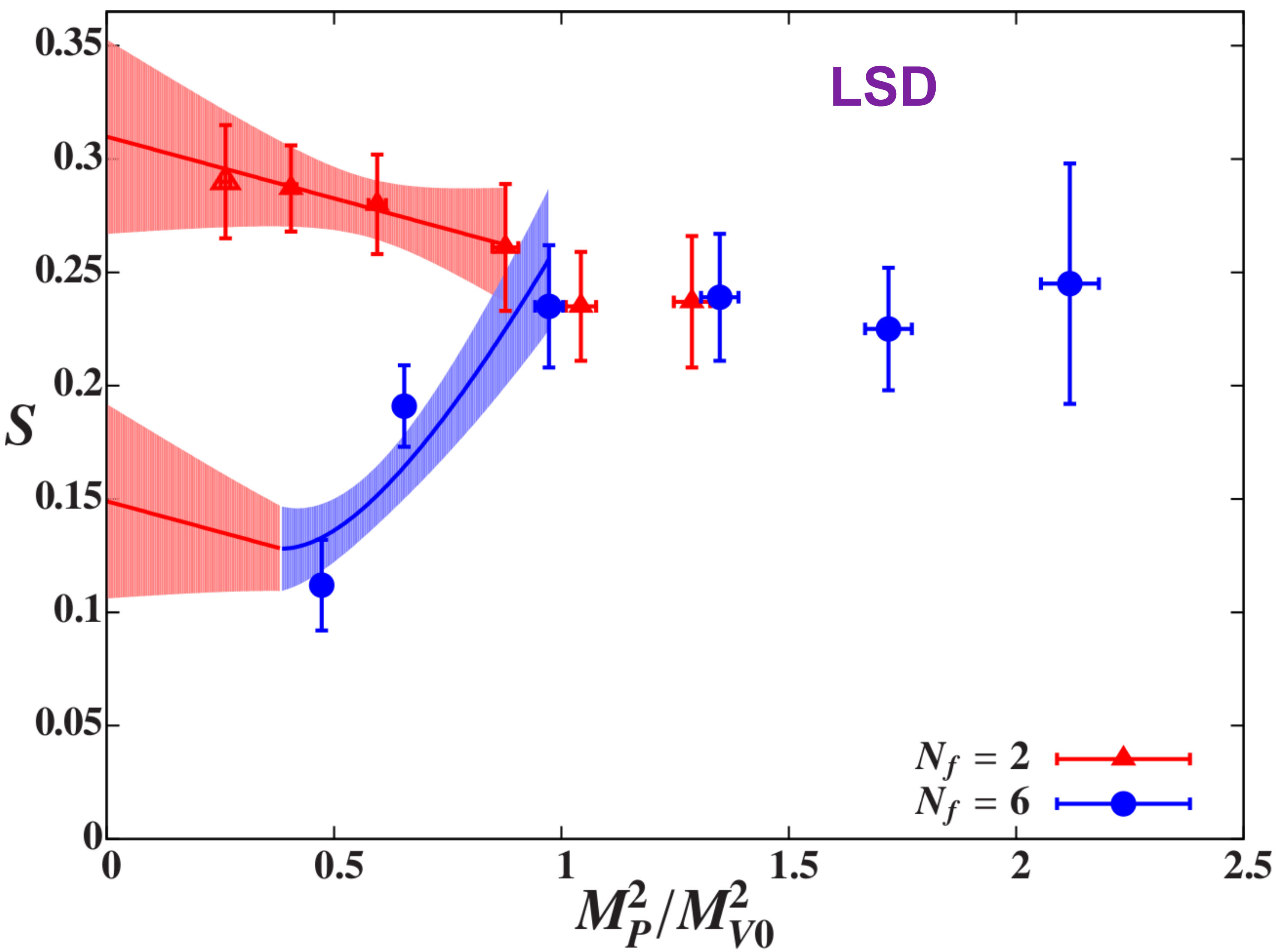
- exploring holographic connections between gauge theories and string/gravity theories

Toolset and its phenomenological applications



S-parameter

LSD group with several phenomenological explorations

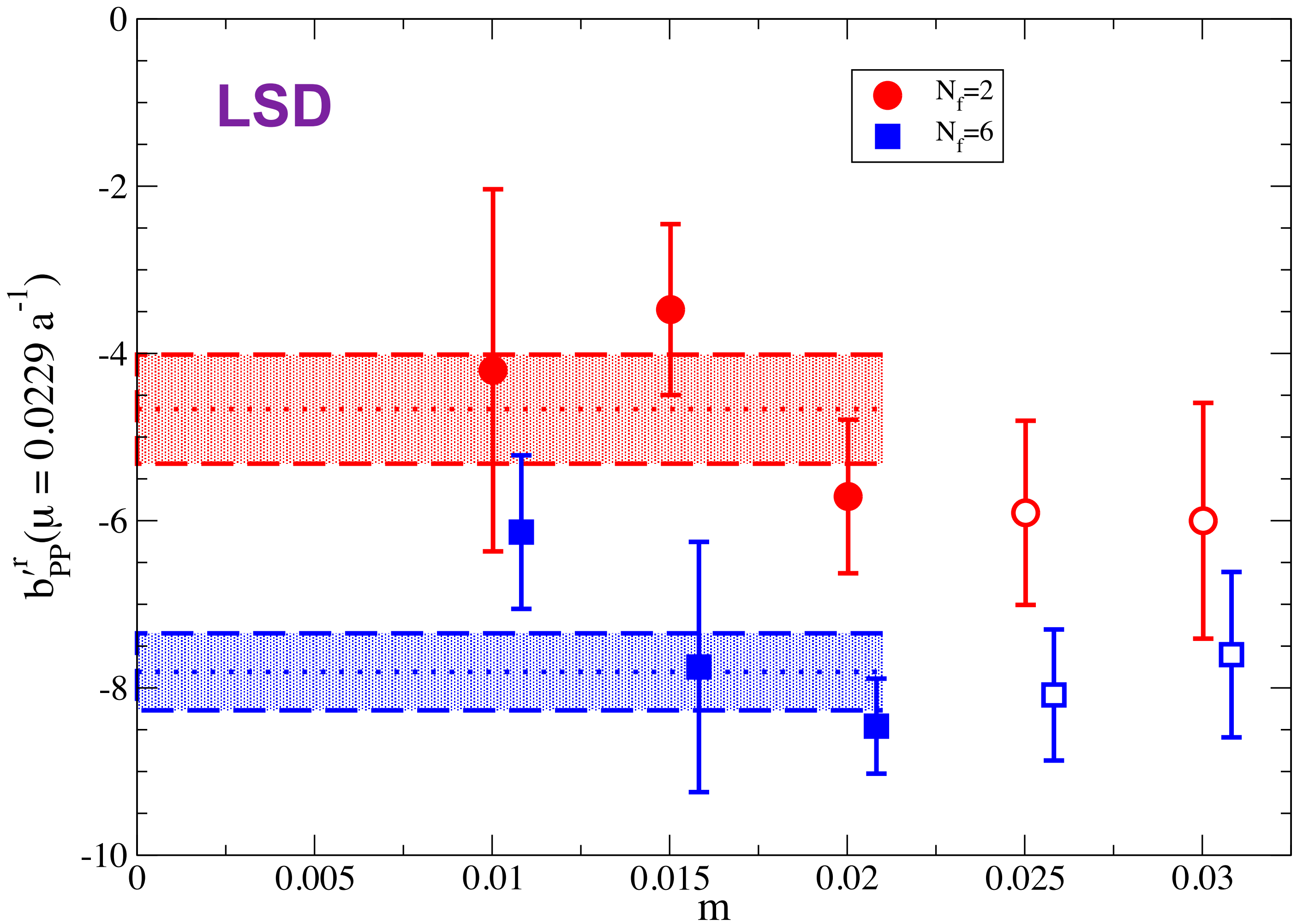


- near CW S-parameter is not increasing according to the naive scaling based on QCD and earlier expected by phenomenologists
- without non-perturbative BSM lattice work phenomenology is misinforming in model building

Toolset and its phenomenological applications

WW scattering

(what if cross section gets stronger than expected from weakly coupled SM Higgs?)



- potentially important for LHC14 machine upgrade
- based on equivalence theorem and chiPT

T. Appelquist, R. Babich, R. C. Brower, M. I. Buchoff, M. Cheng, S. D. Cohen, G. T. Fleming, J. Kiskis, M. F. Lin, E. T. Neil, J. C. Osborn, C. Rebbi, D. Schaich, S. Syritsyn, G. Voronov, P. Vranas, and J. Wasem (Lattice Strong Dynamics (LSD) Collaboration)

Toolset and its phenomenological applications

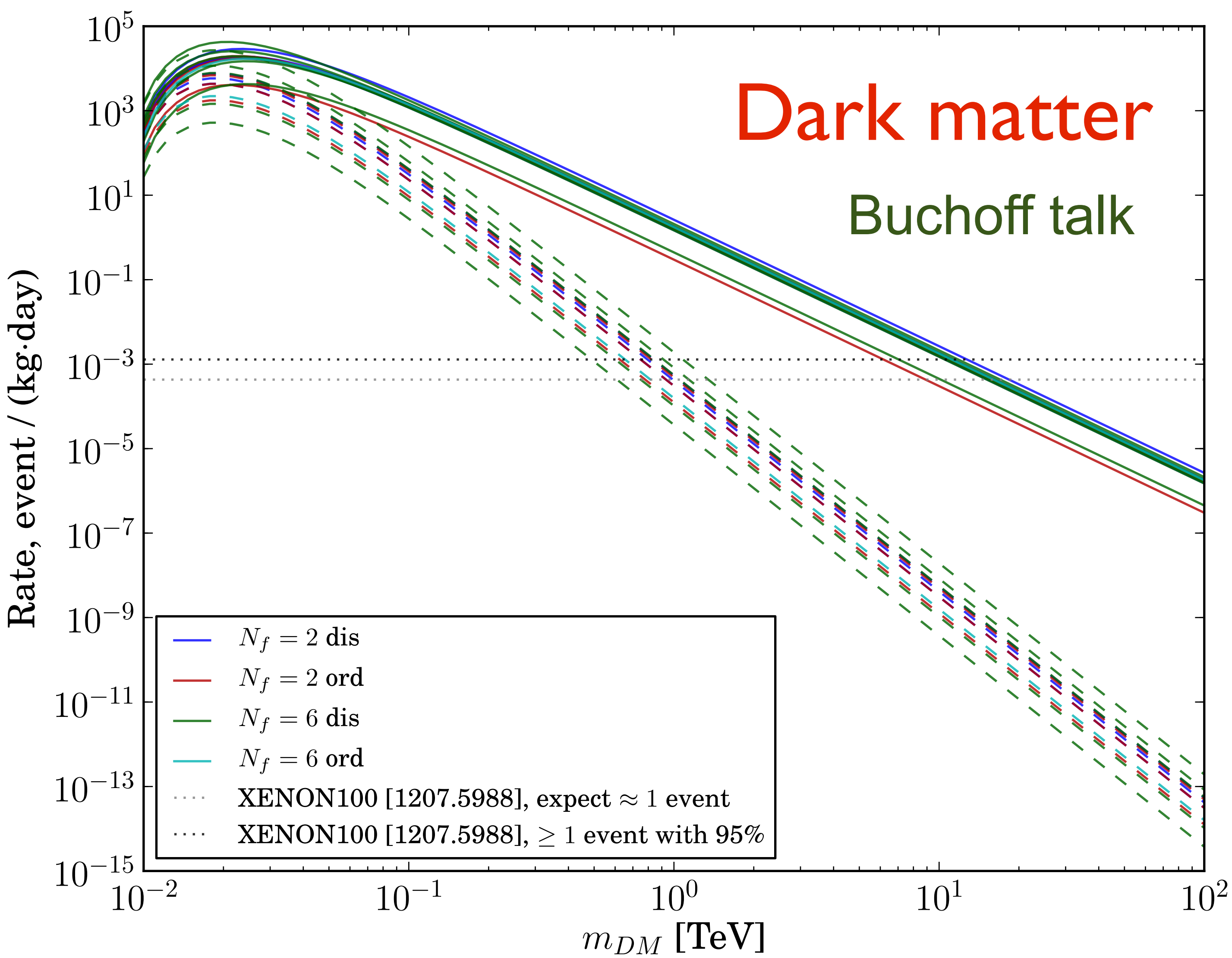
The Total Energy of the Universe:

Vacuum Energy (Dark Energy) ~ 67 %
Dark Matter ~ 29 %
Visible Baryonic Matter ~ 4 %

Dark matter

self-interacting?

T. Appelquist, R. C. Brower, M. I. Buchoff, M. Cheng, S. D. Cohen, G. T. Fleming, J. Kiskis, M. F. Lin, E. T. Neil, J. C. Osborn, C. Rebbi, D. Schaich, C. Schroeder, S. Syritsyn, G. Voronov, P. Vranas, and J. Wasem (Lattice Strong Dynamics (LSD) Collaboration)



lattice BSM phenomenology of dark matter
LSD

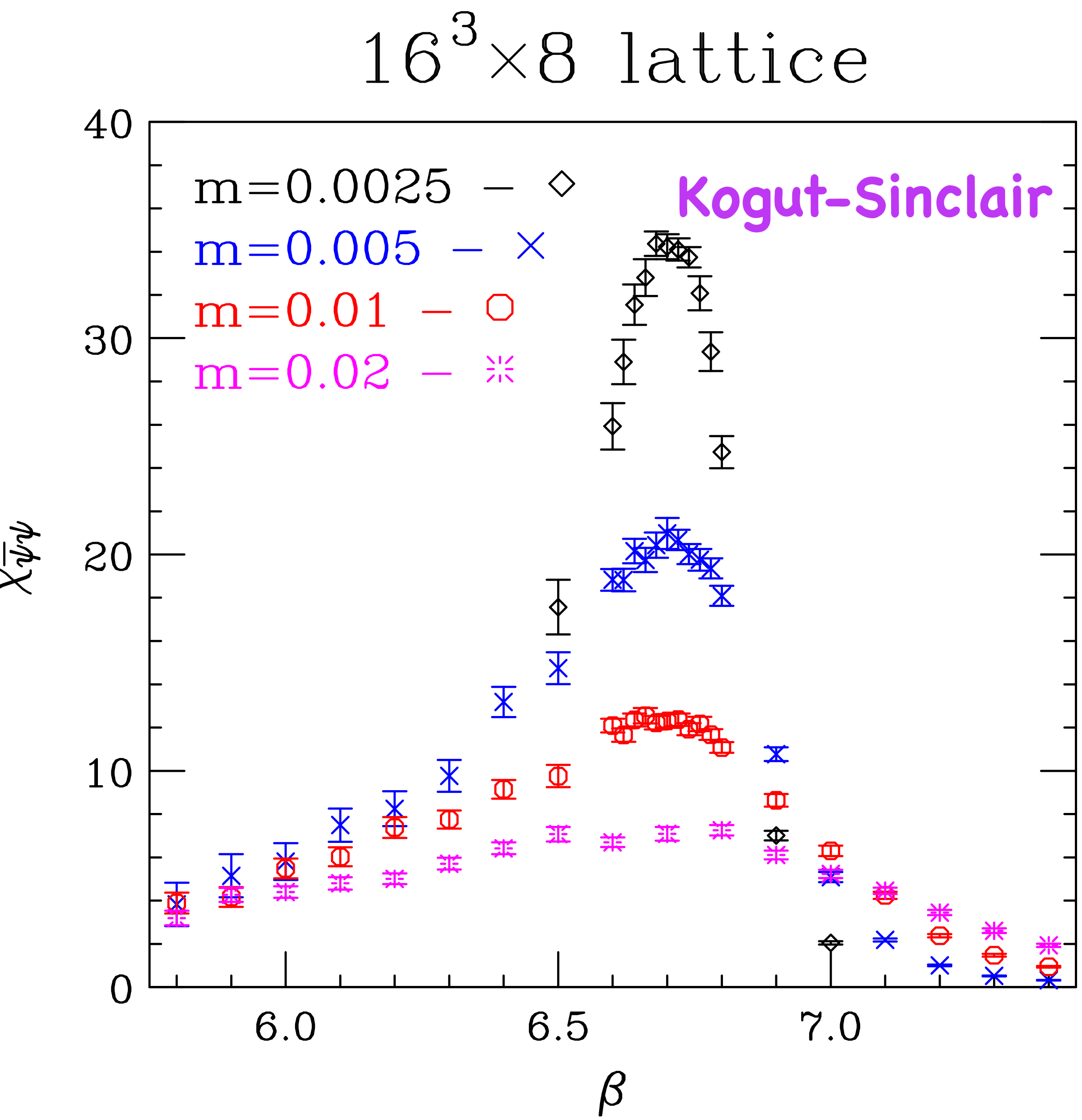
- Nf=2 Qu=2/3 Qd = -1/3
  udd neutral dark matter candidate
- Nf=6 3 replicas of Nf=2
- dark matter candidates
  electroweak active in the application
- there is room for electroweak singlet
  dark matter particles (SU(2) PNGB)

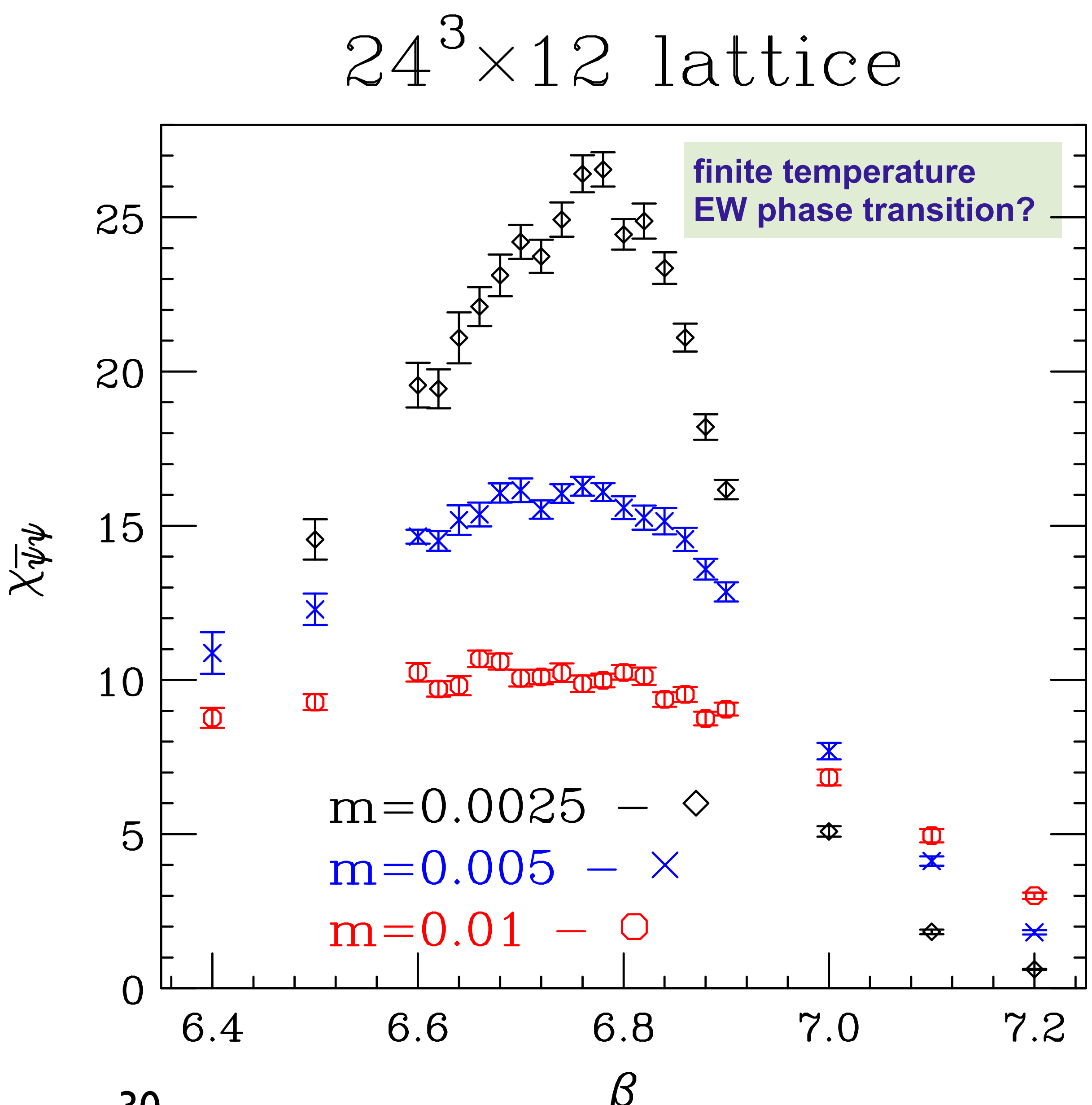
Toolset and its phenomenological applications

Kogut-Sinclair consistent with χSB phase transition (Sinclair talk)

relevance in early cosmology

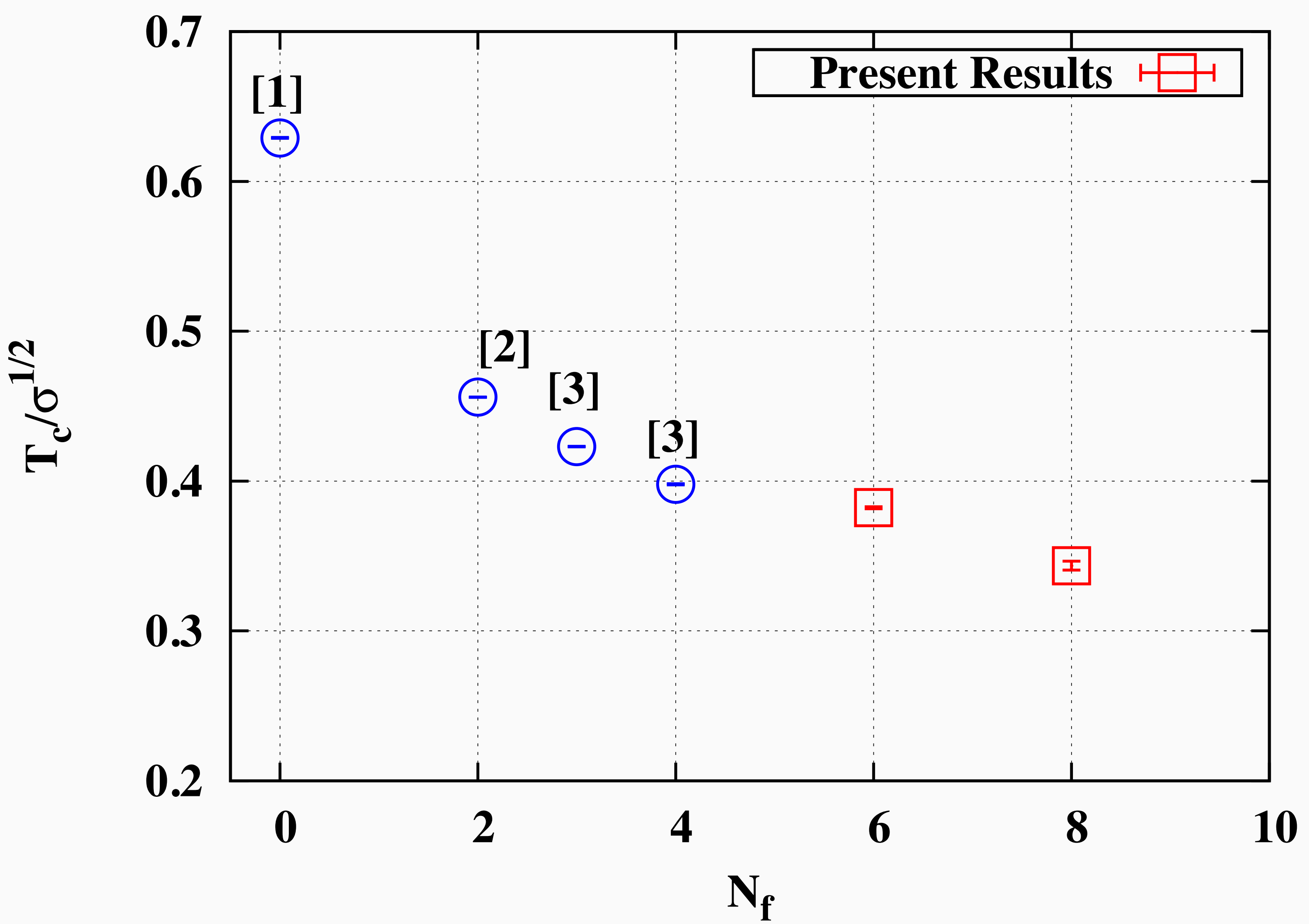
Third massive fermion flavor (electroweak singlet) dark matter?





Toolset and its phenomenological applications

	Albert Deuzeman	University of Bern, Switzerland
	Maria Paola Lombardo	Laboratori Nazionali di Frascati, Rome, Italy
talk	Kohtaroh Miura	KMI, Nagoya University, Japan
	Elisabetta Pallante	University of Groningen, Netherlands
talk	Tiago Nunes Da Silva	University of Groningen, Netherlands



Summary and Outlook

Conformality ?

Nf=2 SU(2) MWT (illustration)
Nf=12 SU(3) ???

Light Higgs near conformality

dilaton and/or light scalar close to conformal window?
running (walking) coupling
chiral condensate
finite size scaling and spectroscopy

Light composite Higgs in the PNGB scenario

Two fermions in fundamental rep with SU(2) color

SUSY

Phenomenology

S-parameter
WW scattering
dark matter
EW phase transition

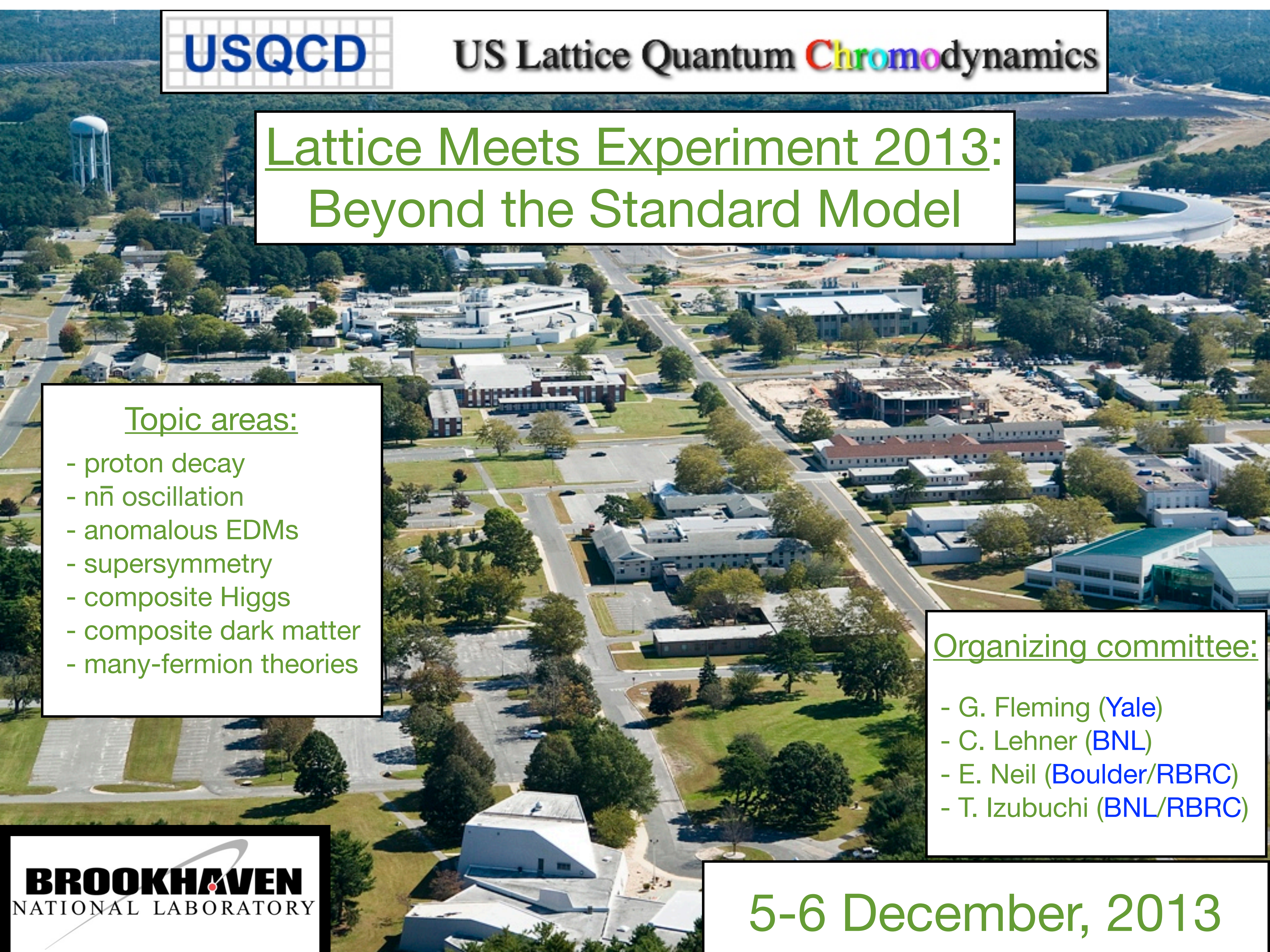
We have 1.5 Higgs impostor candidate(s)

more coming? Voronov talk Nf=6 SU(2) ?

a lot more work is needed to investigate viability

USQCD US Lattice Quantum Chromodynamics

Lattice Meets Experiment 2013: Beyond the Standard Model



Topic areas:

- proton decay
- $n\bar{n}$ oscillation
- anomalous EDMs
- supersymmetry
- composite Higgs
- composite dark matter
- many-fermion theories

Organizing committee:

- G. Fleming (Yale)
- C. Lehner (BNL)
- E. Neil (Boulder/RBRC)
- T. Izubuchi (BNL/RBRC)

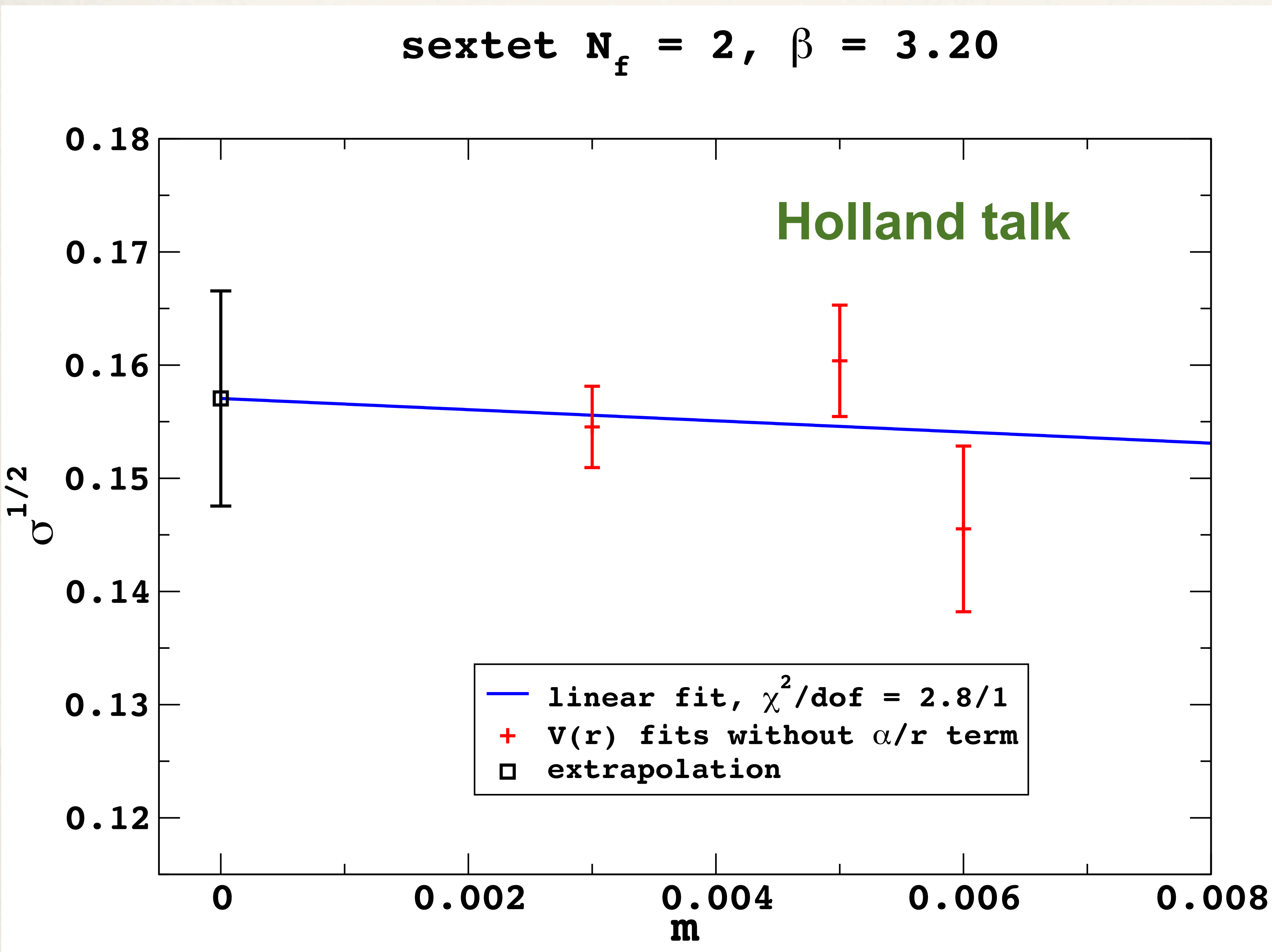
BROOKHAVEN NATIONAL LABORATORY

5-6 December, 2013

backups

light Higgs near conformality (dilaton-like?) sextet

static fermion potential (1) χSB and confinement ✓



PoS 2012, 1211.3548

linear behavior in fermion potential at larger separation

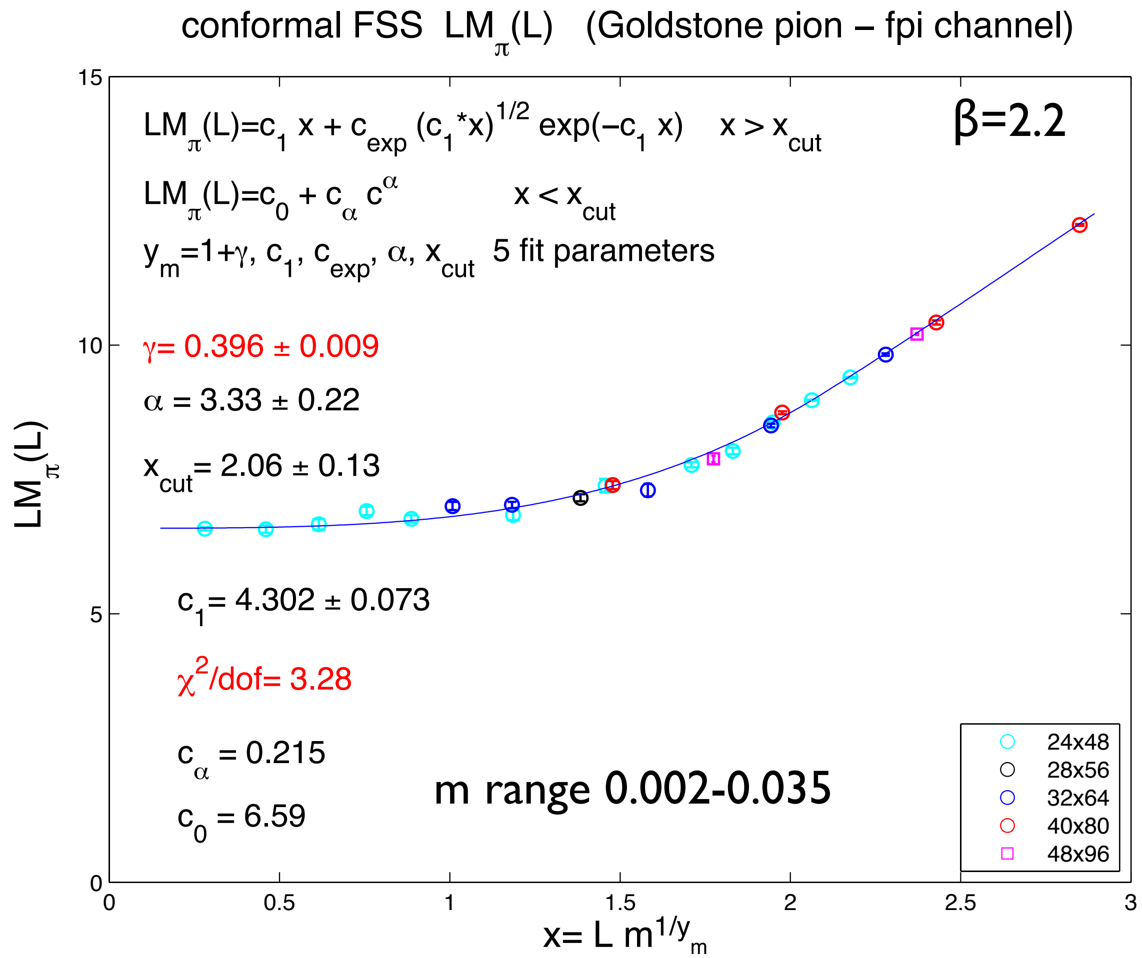
string tension insensitive to fermion mass

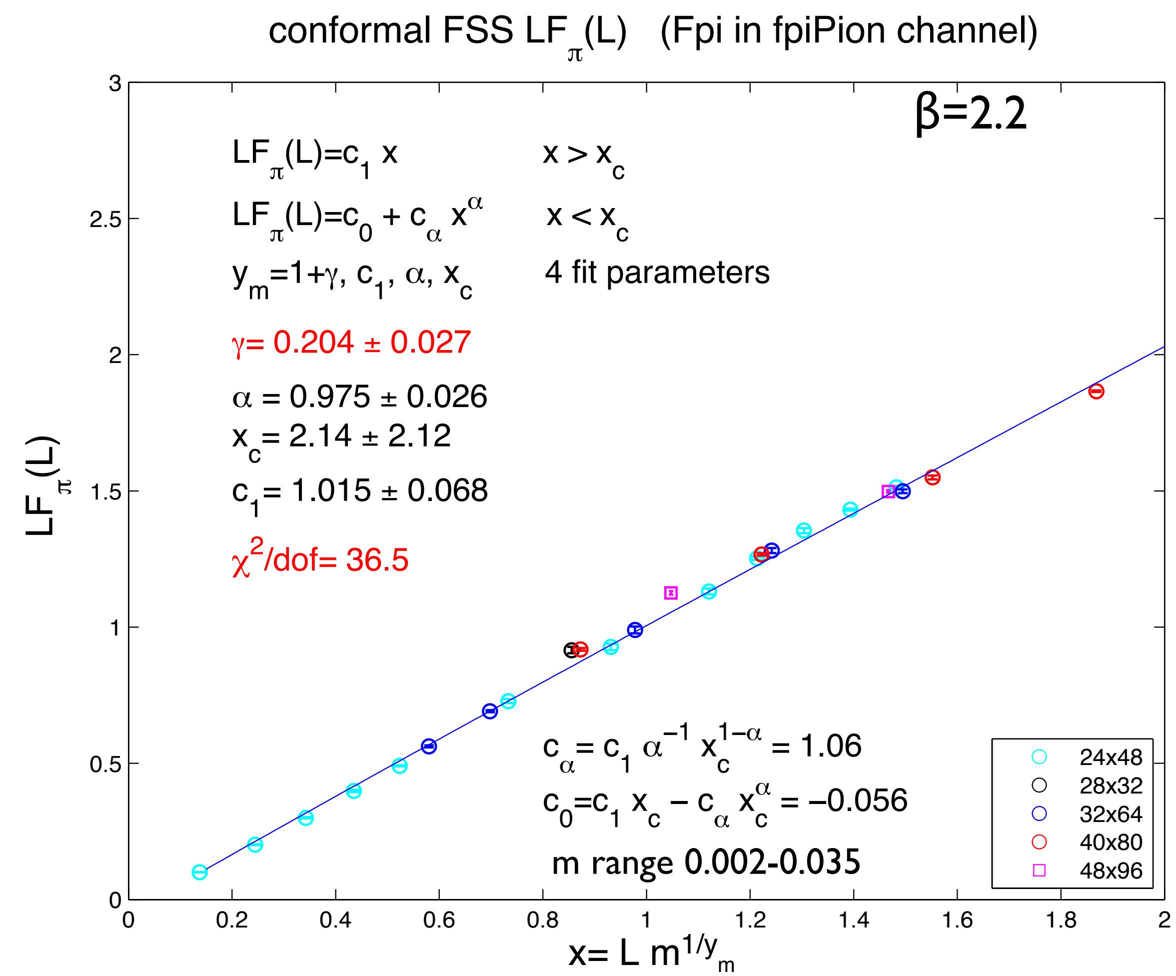
non-zero in chiral limit

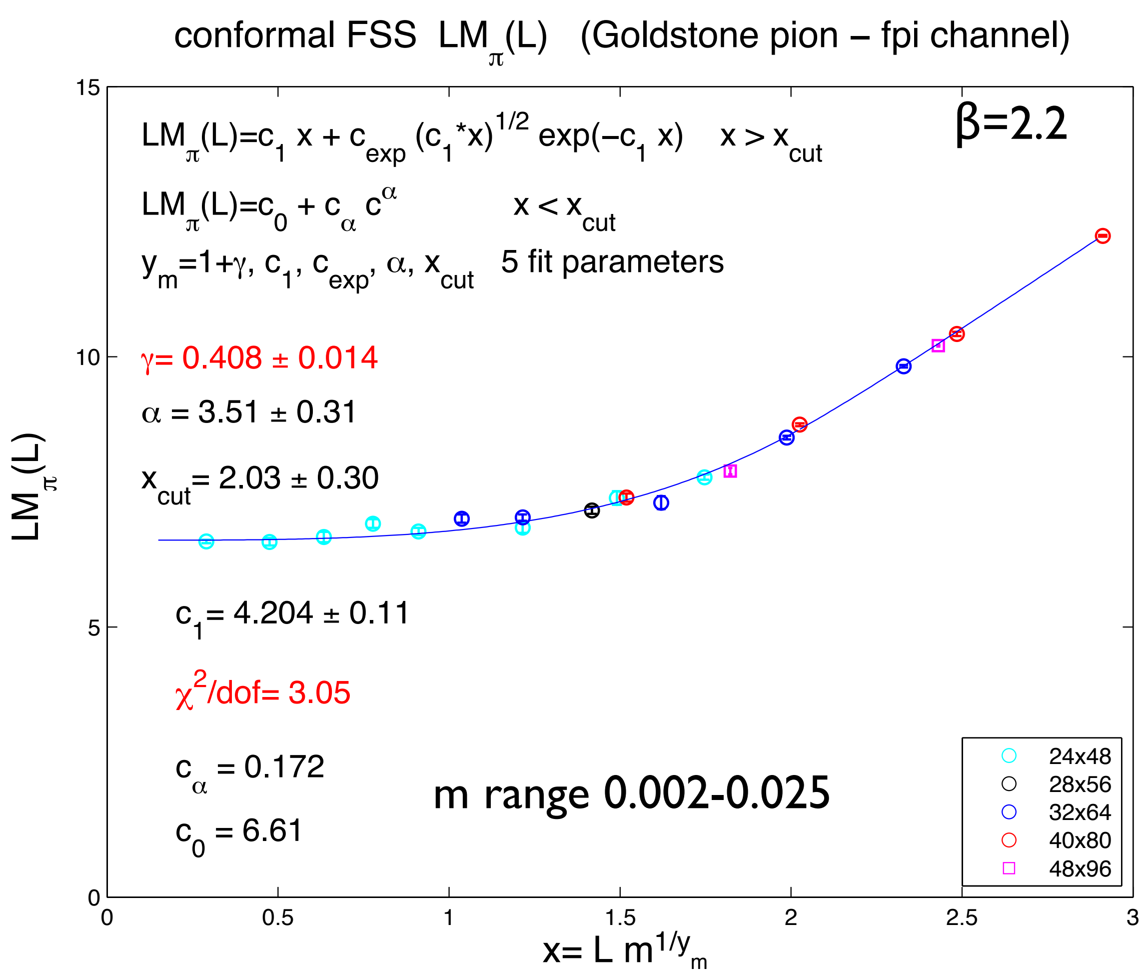
further evidence theory is not conformal

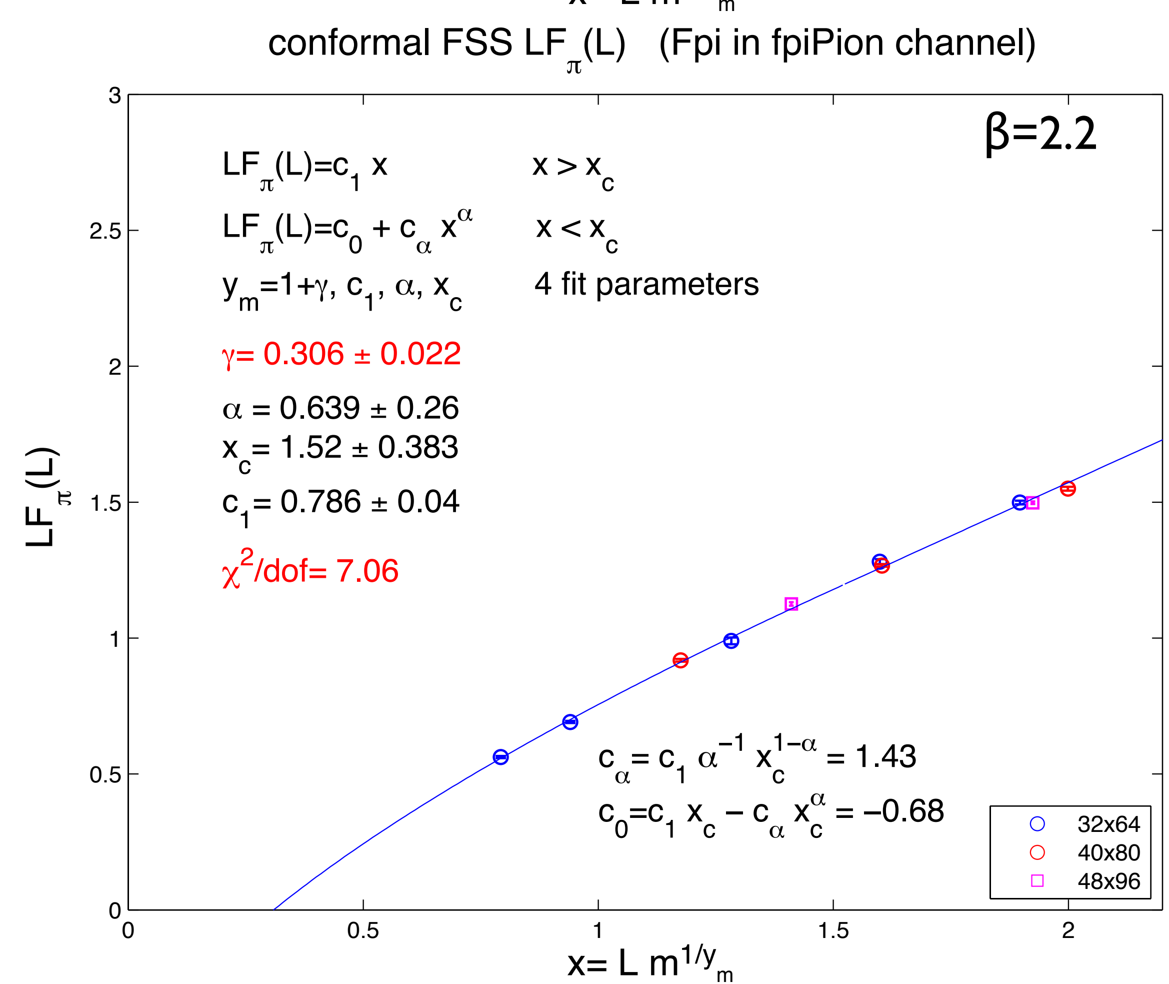
Kieran Holland, Lattice 2013

conformal scaling test with FSS



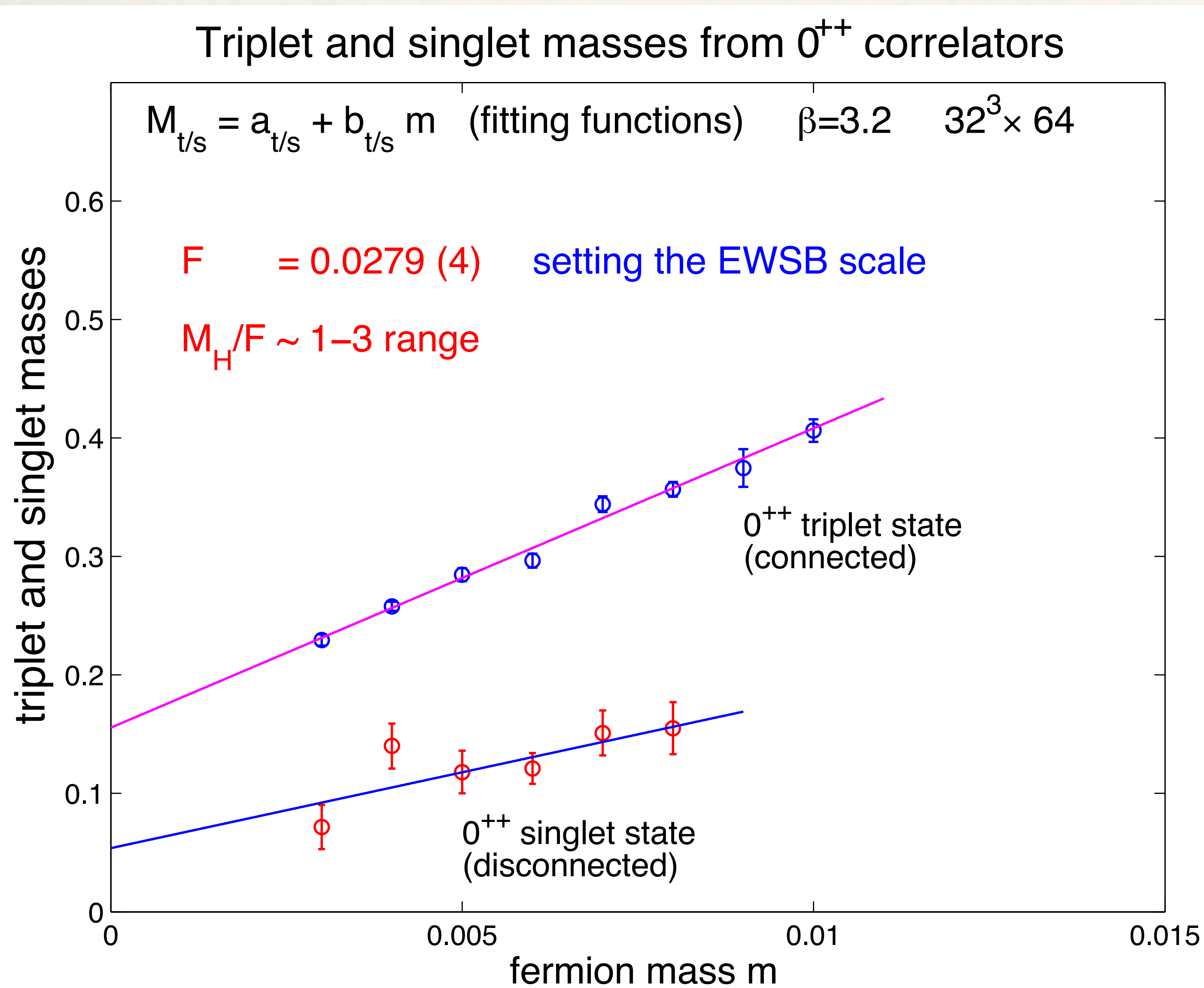






light Higgs near conformality (dilaton-like?)

light composite scalar - Higgs impostor



New Ricky Wong Mon 6:30

flavor singlet scalar measured on same ensembles

challenge: disconnected diagrams

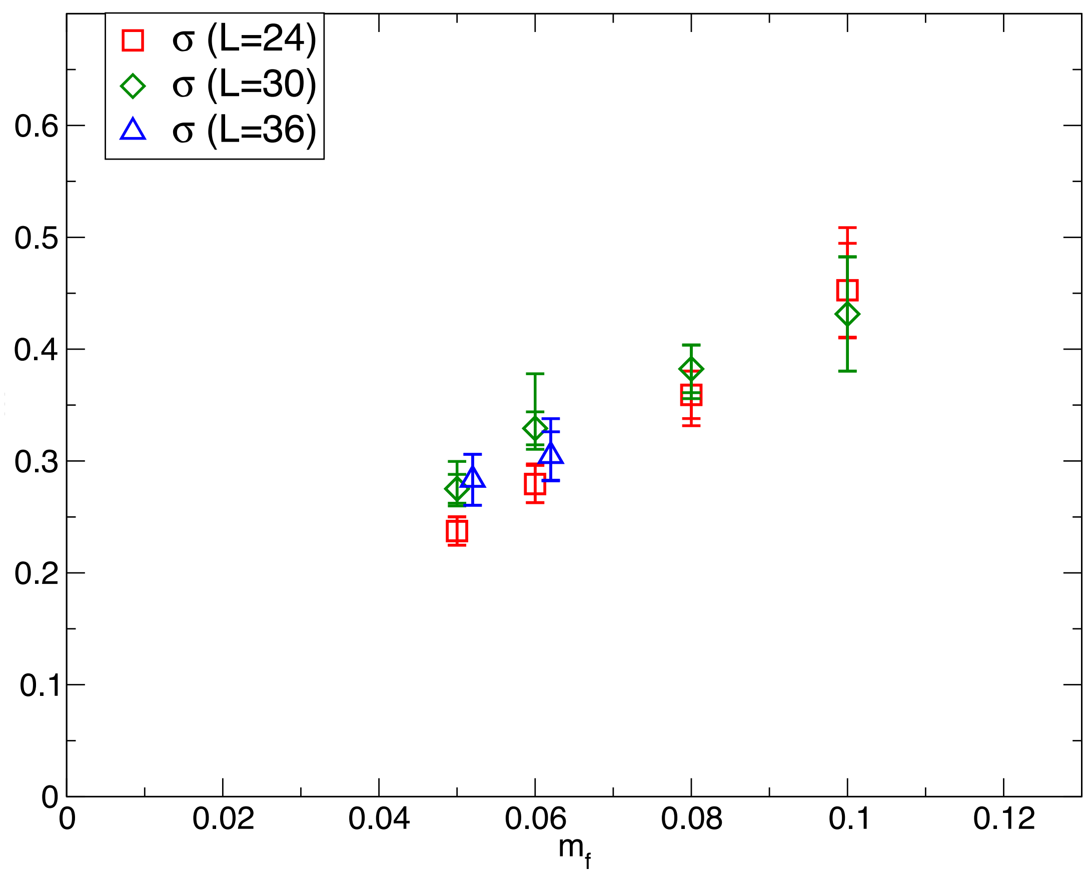
composite scalar appears light

possible connection to nearby conformal window

dilaton interpretation?

the statement that strongly-interacting theories are Higgs-less looks wrong

→ crucial issue in post-Higgs discovery era


σ (L=24)
σ (L=30)
σ (L=36)
0
0.1
0.2
0.3
0.4
0.5
0.6
0
0.02
0.04
0.06
0.08
0.1
0.12
m_f

Strategy I: L=∞ extrapolation first and then scaling test in m

Chiral hypothesis (in)complete analysis on both sides **Conformal hypothesis**

chiral logs not reached yet!
(N_f=8, or N_f=12) N_f=2 sextet easier reach

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

$\sim m^2$ kept; $\sim a^2 m$ cutoff term in B; $\sim a^4$ 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

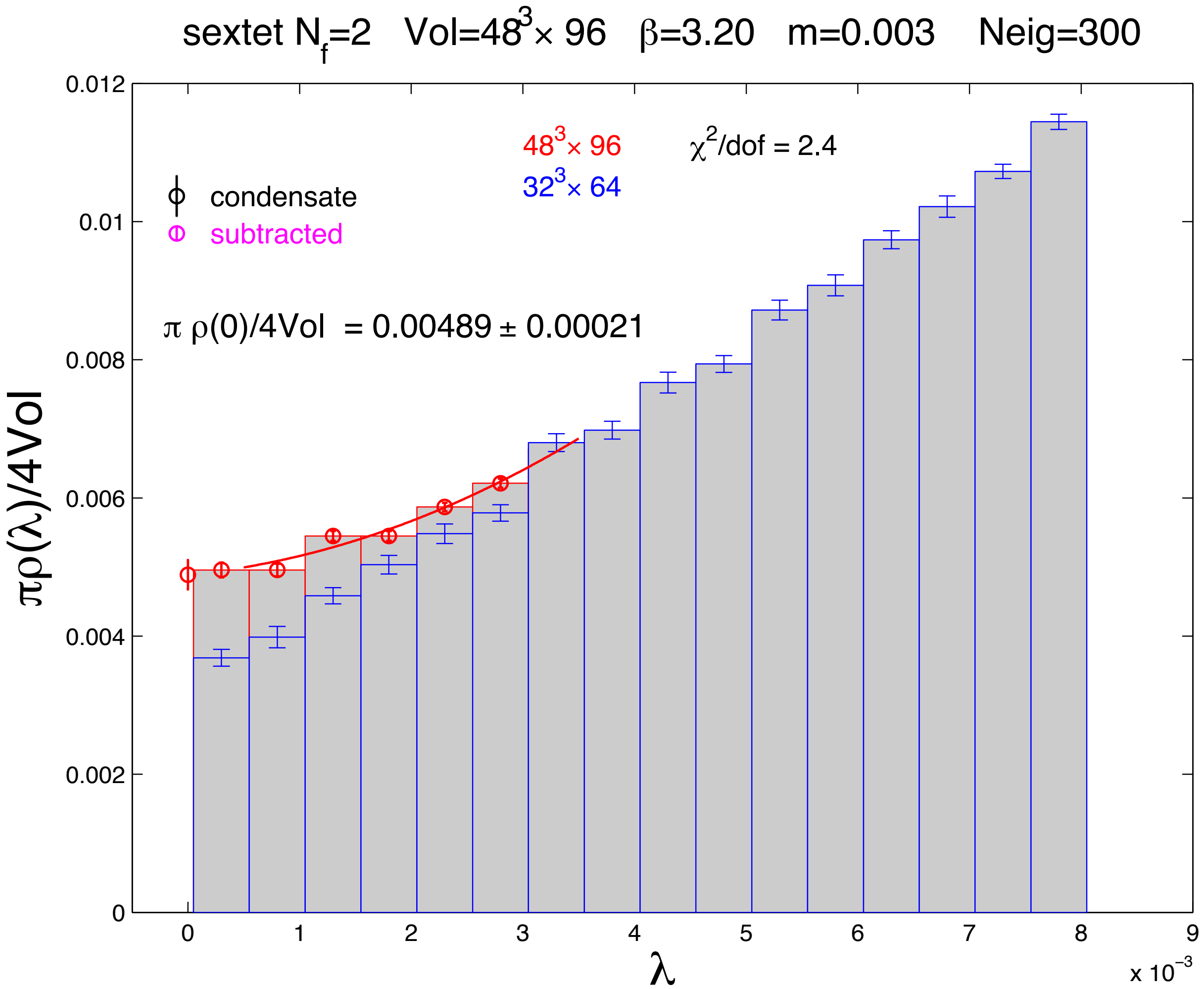
$$\boxed{\langle\bar\psi\psi\rangle = c_\gamma \cdot m^{(3-\gamma)/y_m} + c_1 m}$$

Del Debbio and Zwicky

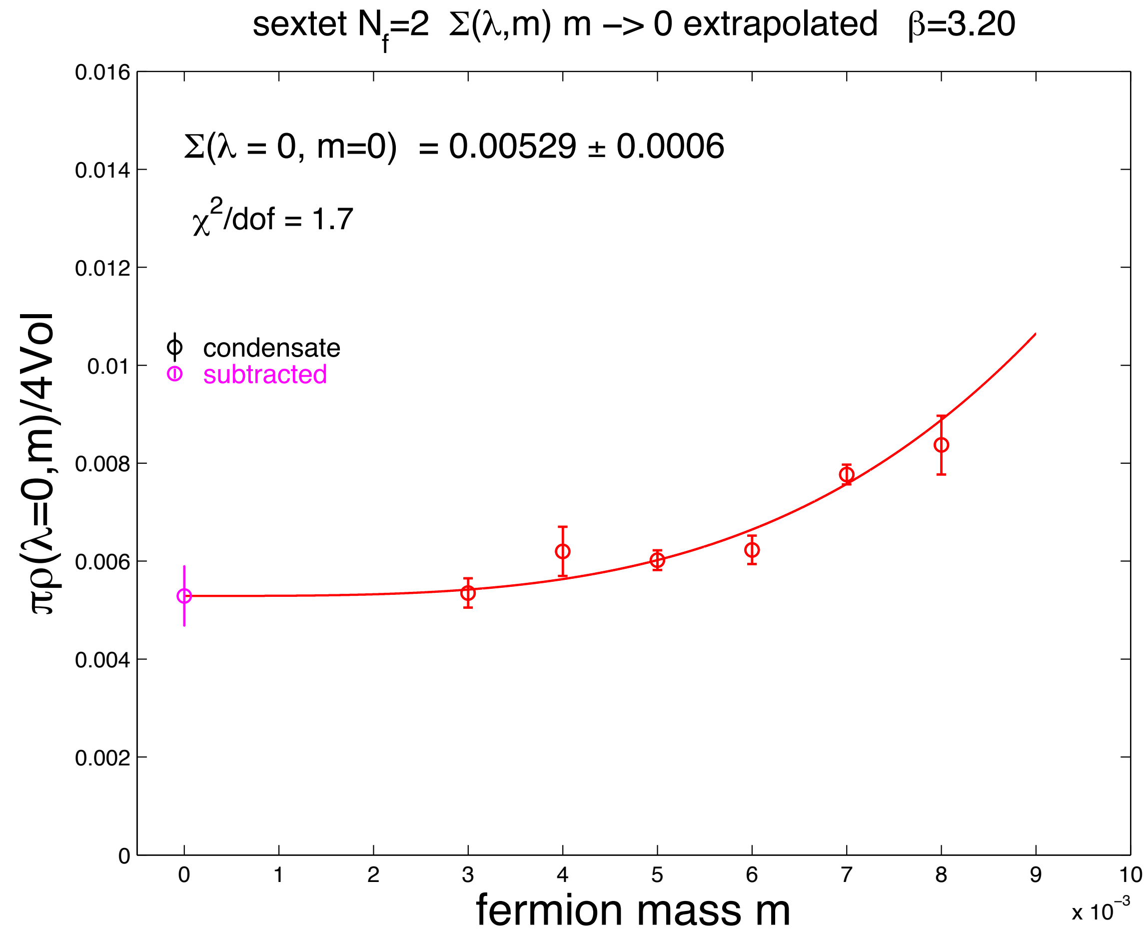
Asymptotic infinite volume limit has not been reached yet in important candidate models for conformal window

infinite volume conformal scaling violation analysis ?

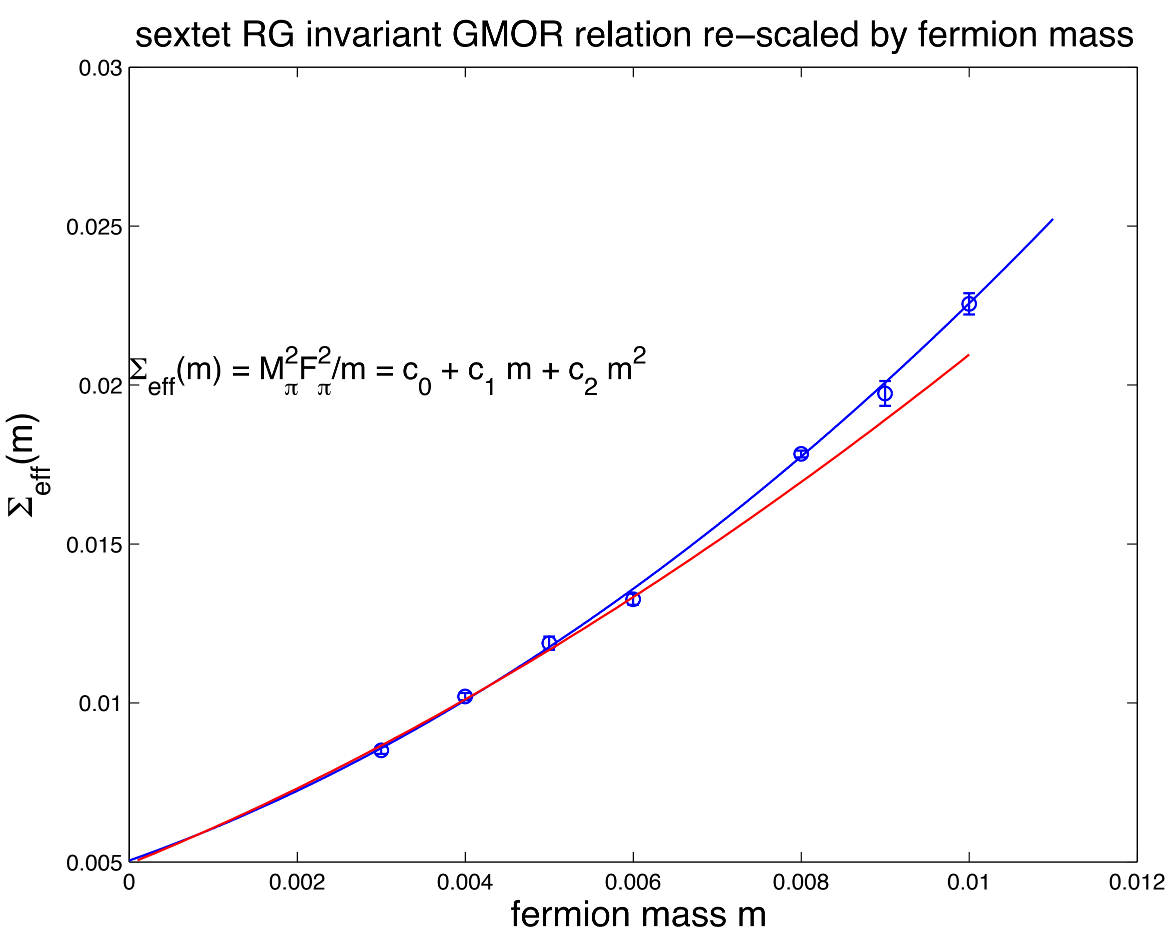
conformal finite size scaling analysis and its scaling violations ?



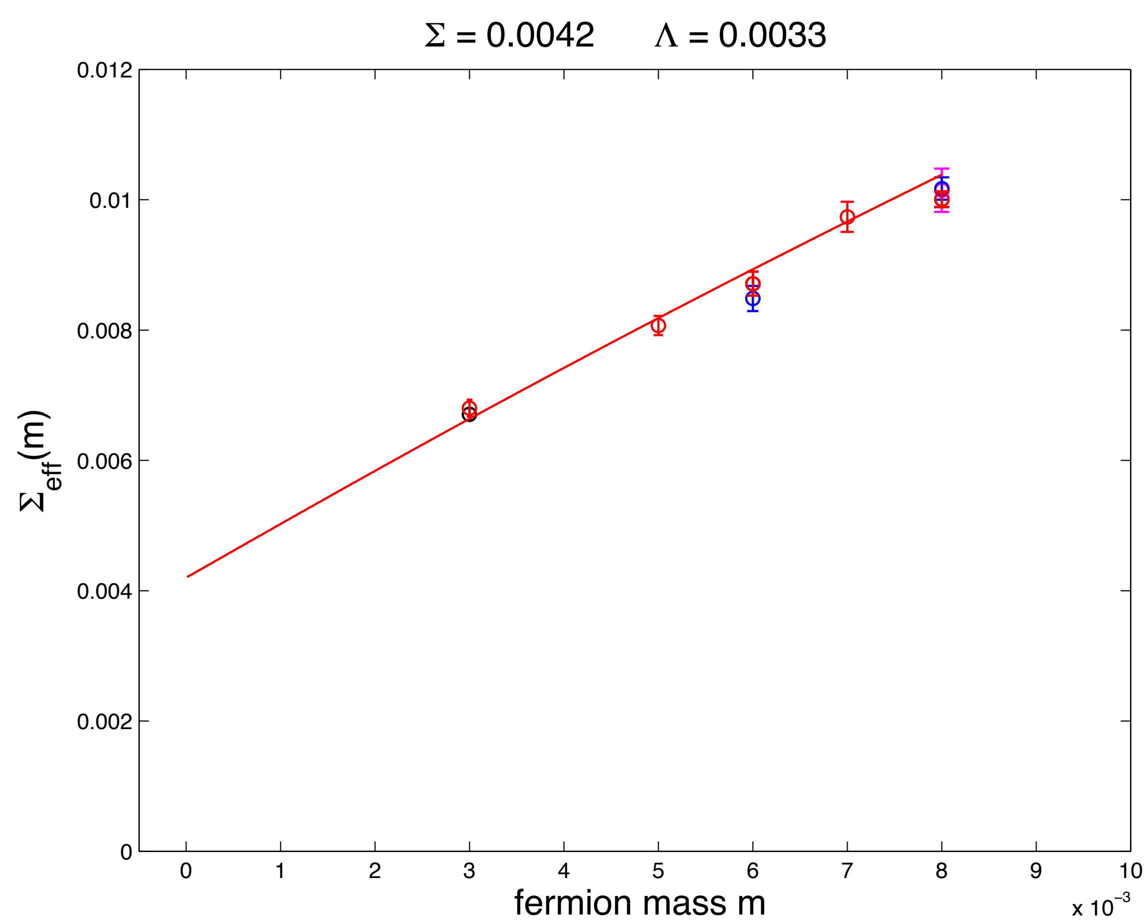
sextet N_f=2 Vol=48^3 × 96 β=3.20 m=0.003 Neig=300
48^3 × 96
32^3 × 64
χ^2/dof = 2.4
condensate
subtracted
π ρ(0)/4Vol = 0.00489 ± 0.00021
πρ(λ)/4Vol
λ
x 10^-3



sextet N_f=2 Σ(λ,m) m –> 0 extrapolated β=3.20
Σ(λ = 0, m=0) = 0.00529 ± 0.0006
χ^2/dof = 1.7
condensate
subtracted
πρ(λ=0,m)/4Vol
fermion mass m
x 10^-3

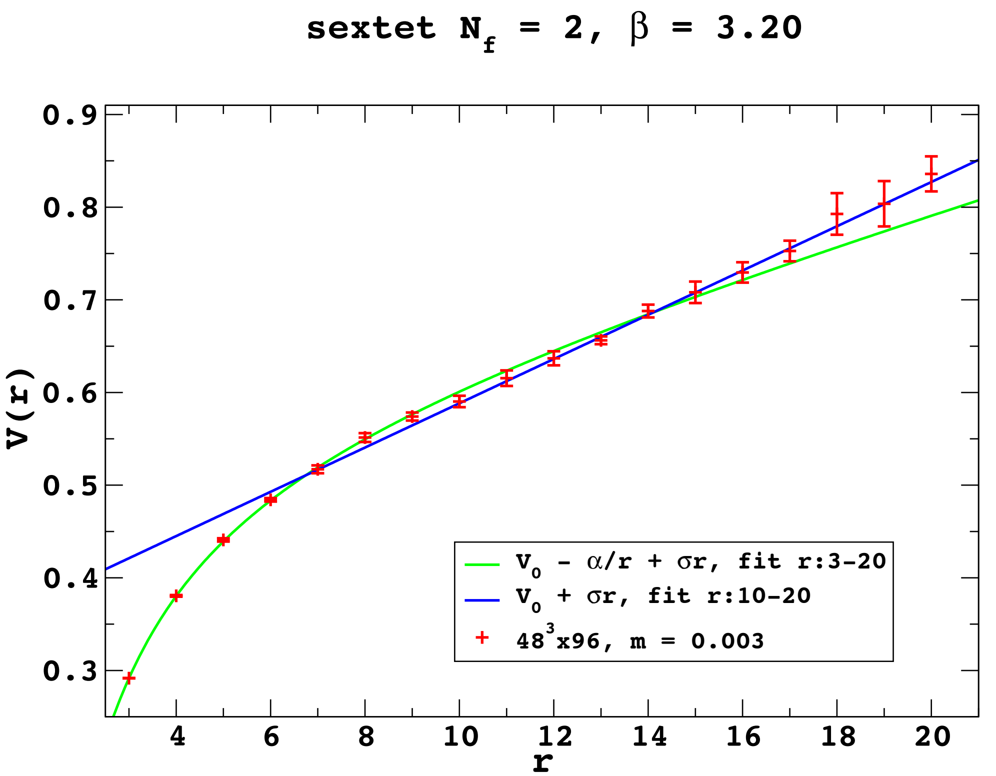


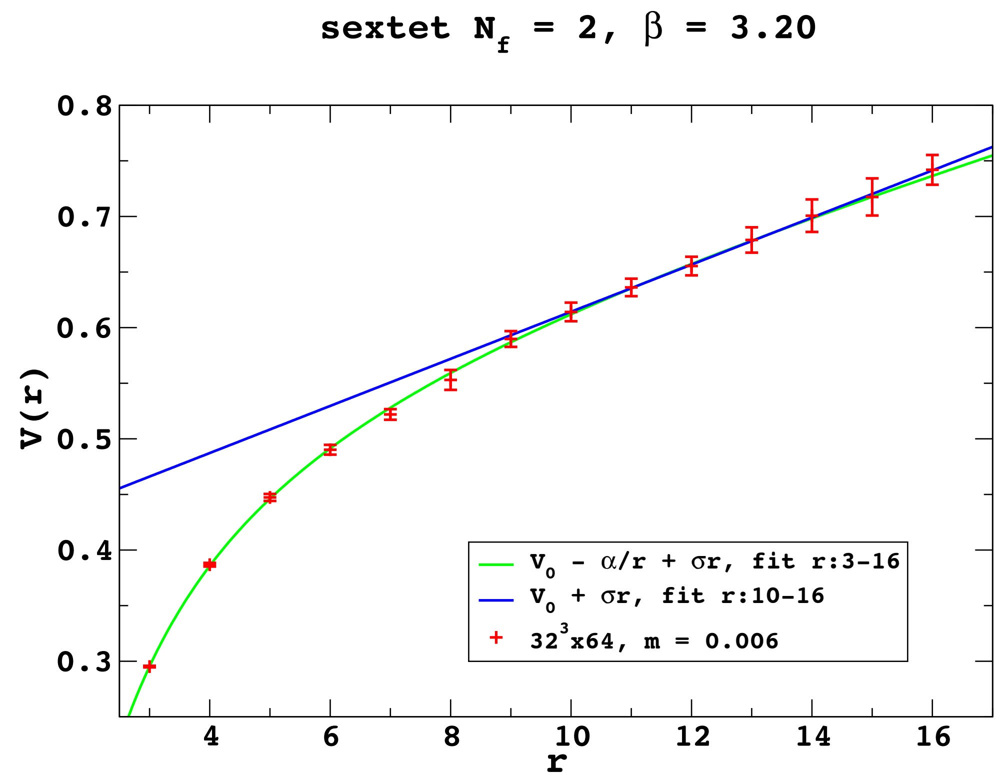
sextet RG invariant GMOR relation re-scaled by fermion mass
Σ_eff(m) = M_π^2F_π^2/m = c_0 + c_1 m + c_2 m^2
Σ_eff(m)
fermion mass m

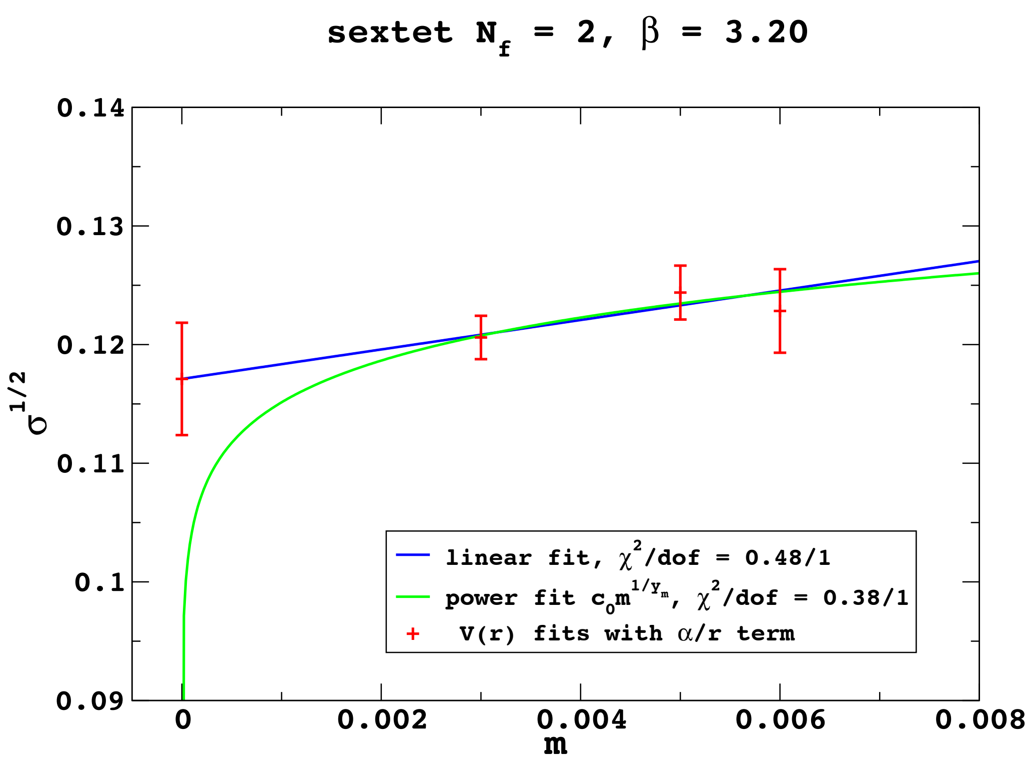


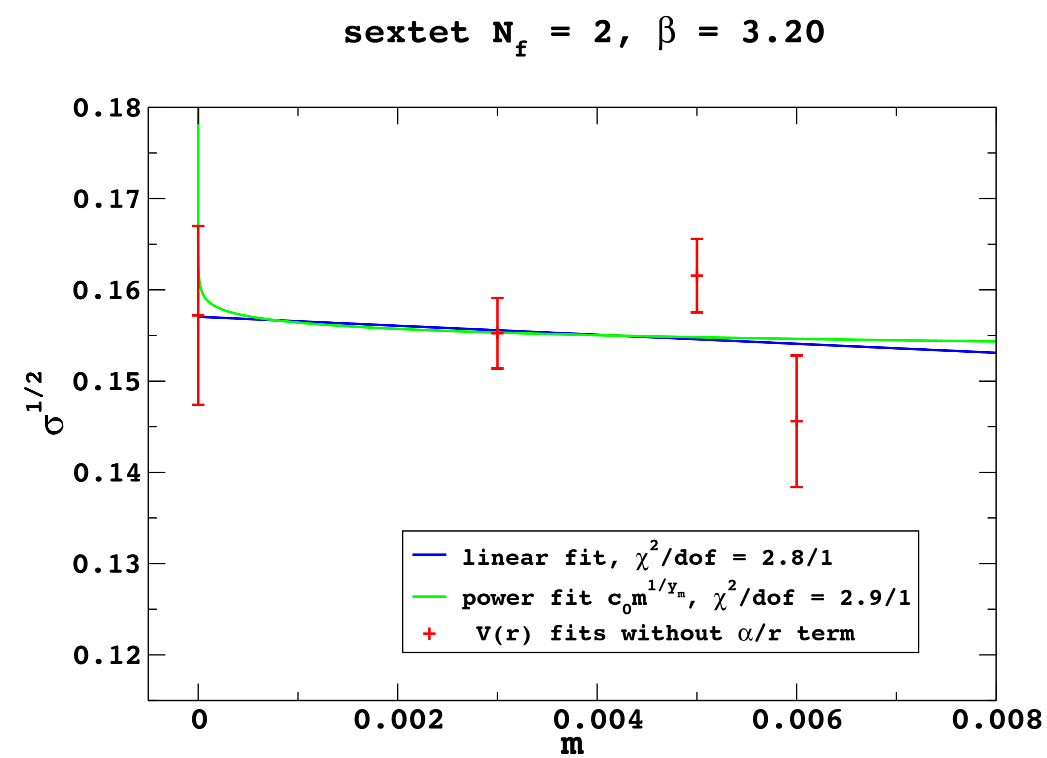
Σ = 0.0042 Λ = 0.0033
Σ_eff(m)
fermion mass m
x 10^-3

sextet simulations confining force at finite m (LHC group)









1/1+γ ~0.04(4) ?   conformal γ~infinite would be needed