Lattice Meets Experiment: 2012

Can the Higgs impostor hide near the conformal window ?

Julius Kuti
University of California, San Diego

Lattice Meets Experiment 2012: Beyond the Standard Model
University of Colorado, Boulder, October 26, 2012

Lattice Meets Experiment: 2012

Thanks to Boulder group for putting the meeting together!

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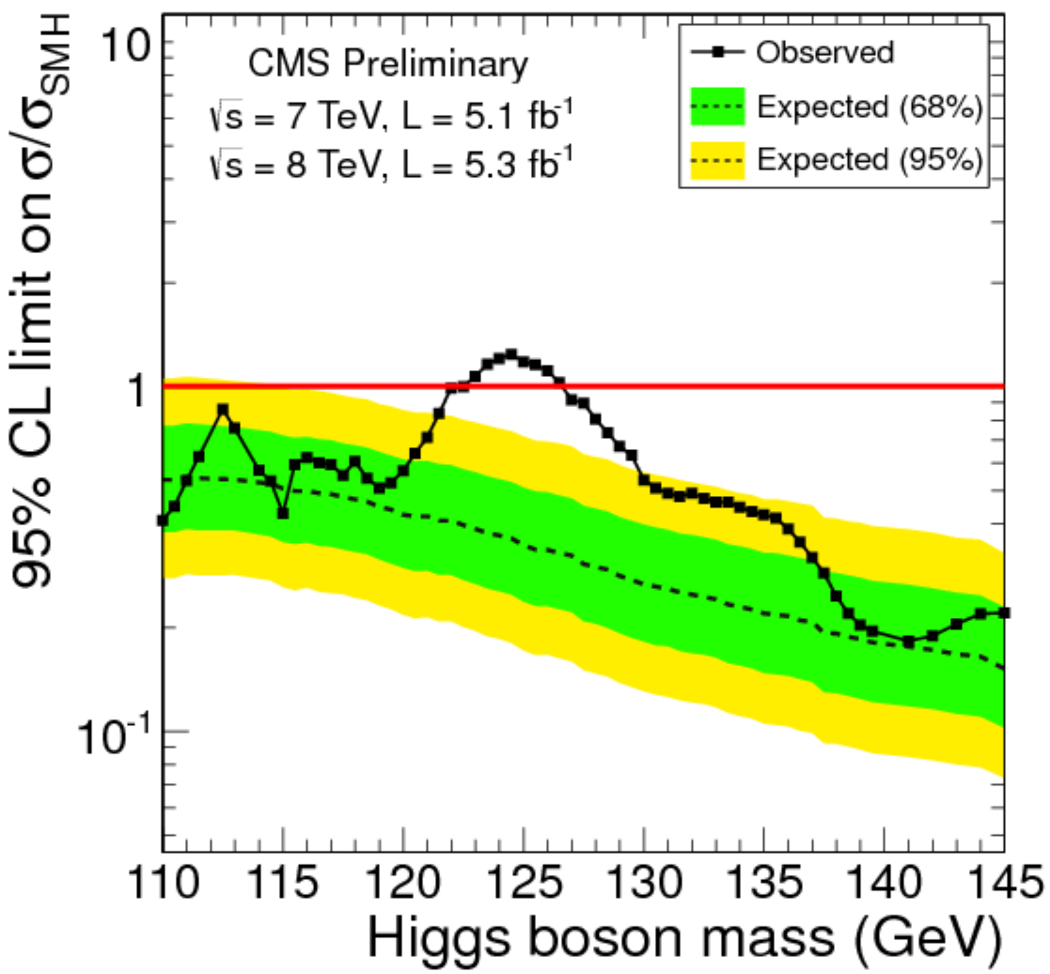
for some of the work discussed here, thanks to my collaborators :

Zoltan Fodor, Kieran Holland Daniel Nogradi,
Chris Schroeder, Chik Him Wong


CMS Preliminary
√s = 7 TeV, L = 5.1 fb-1
√s = 8 TeV, L = 5.3 fb-1
Observed
Expected (68%)
Expected (95%)
95% CL limit on σ/σSMH
Higgs boson mass (GeV)
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1
10-1
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115
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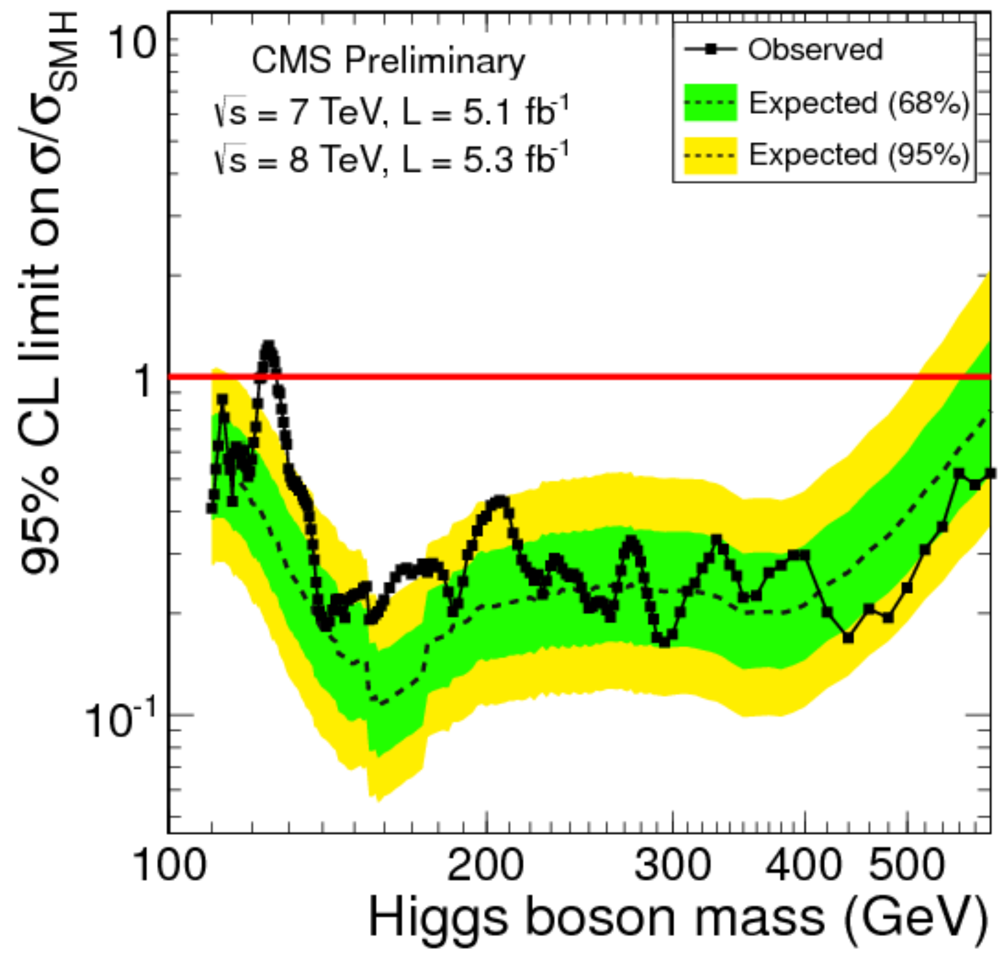
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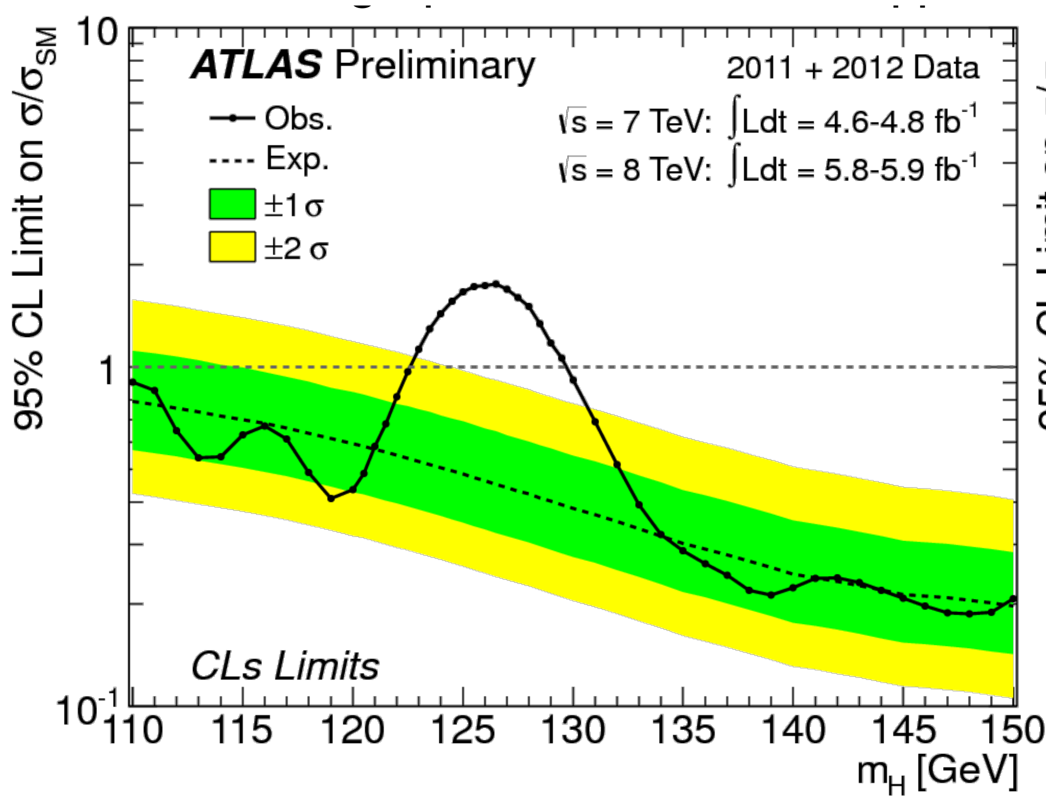
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2011 + 2012 Data
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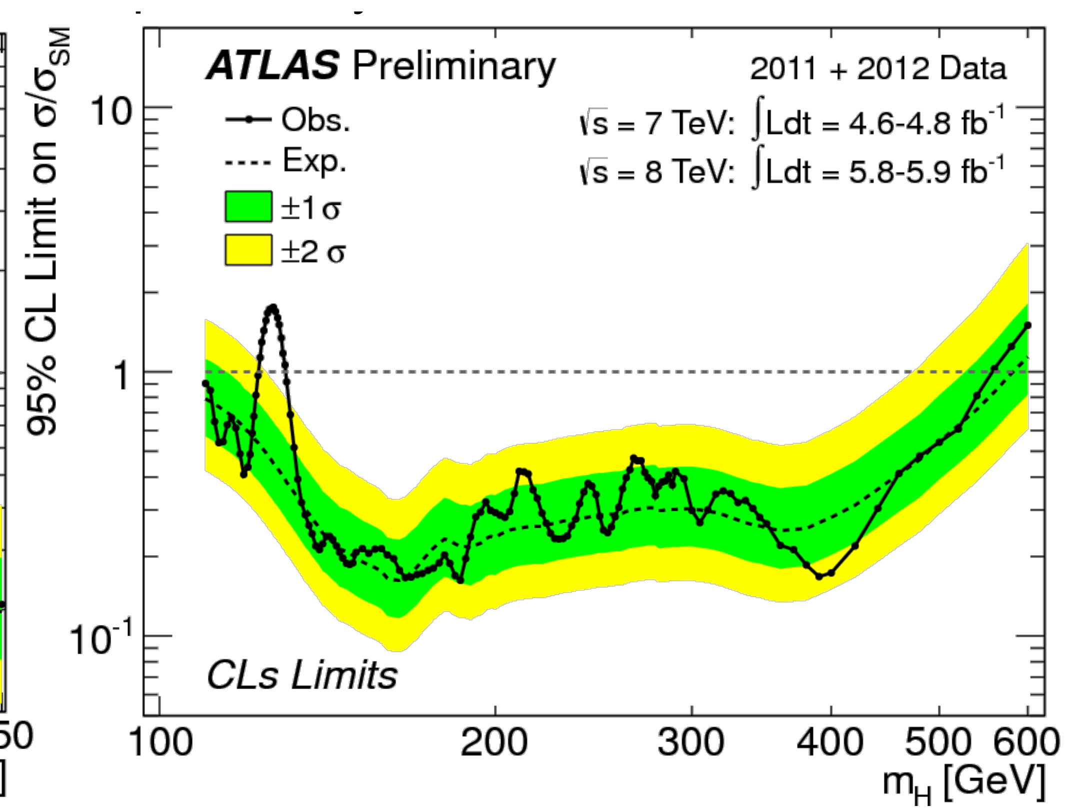
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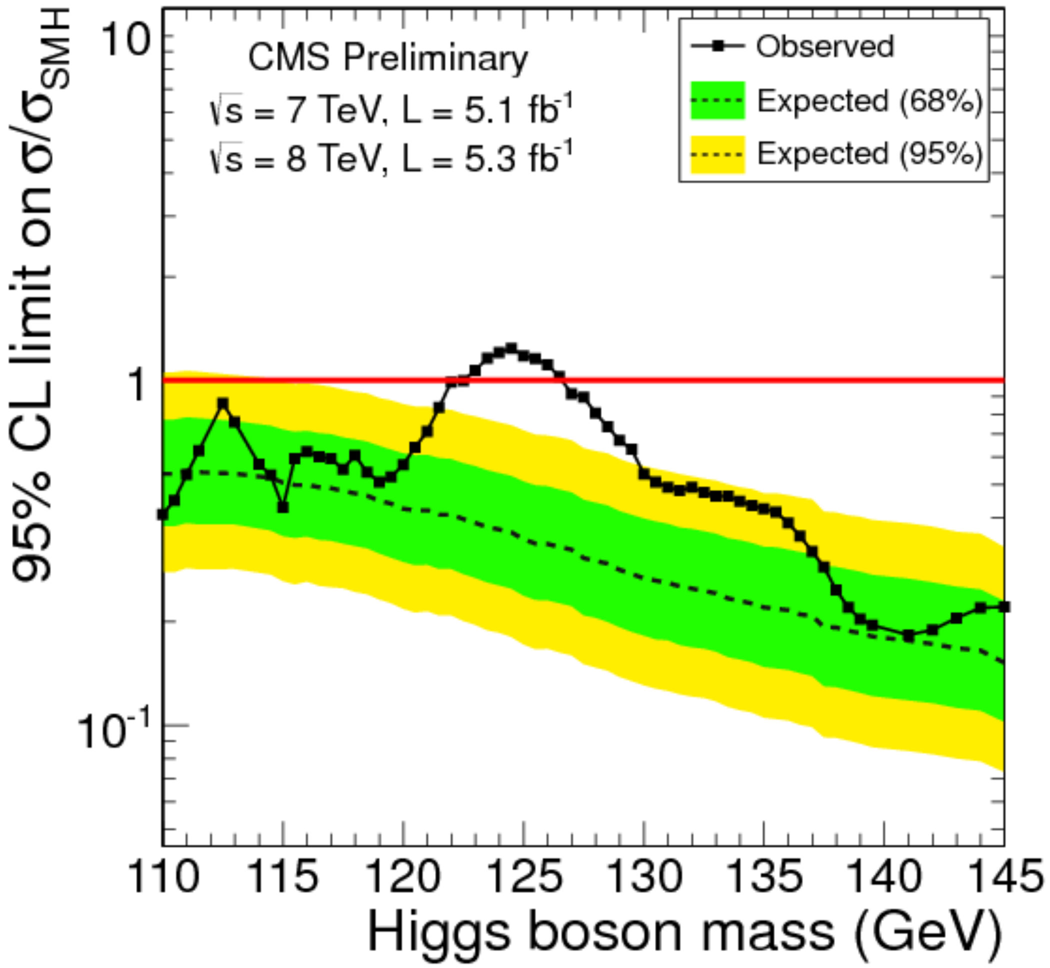
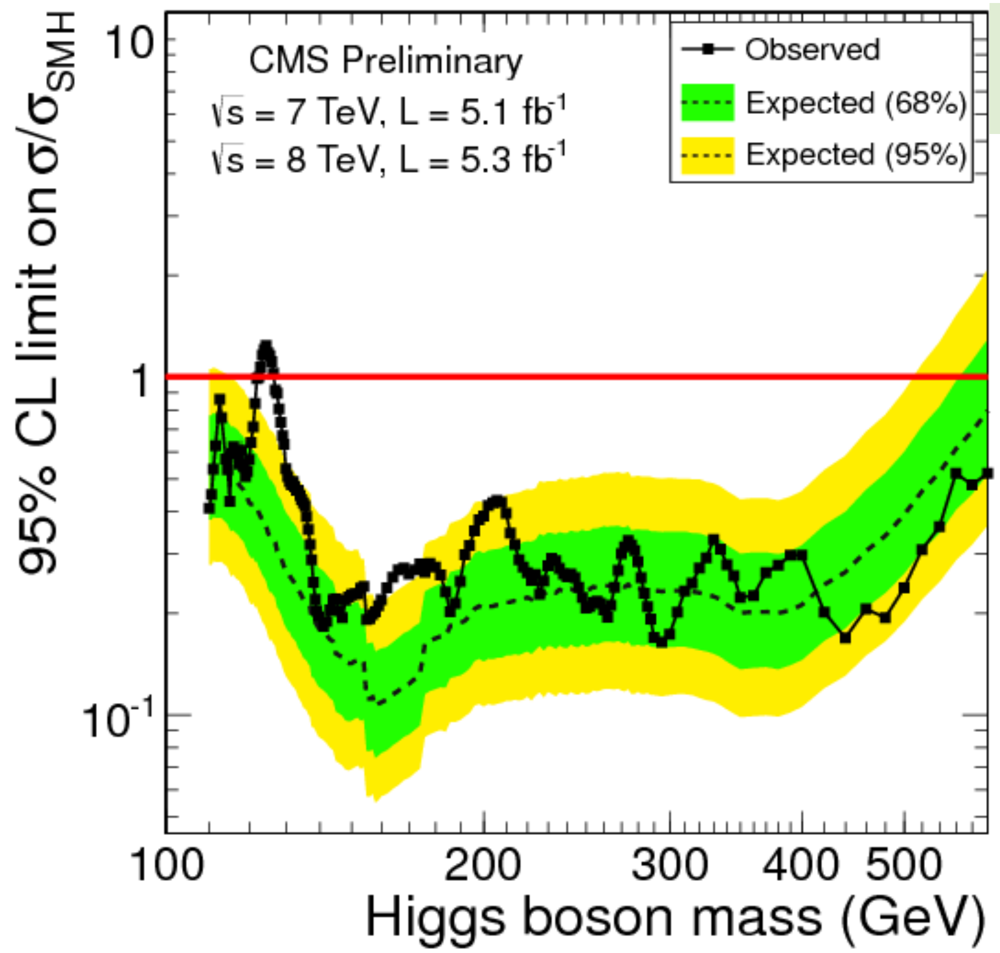
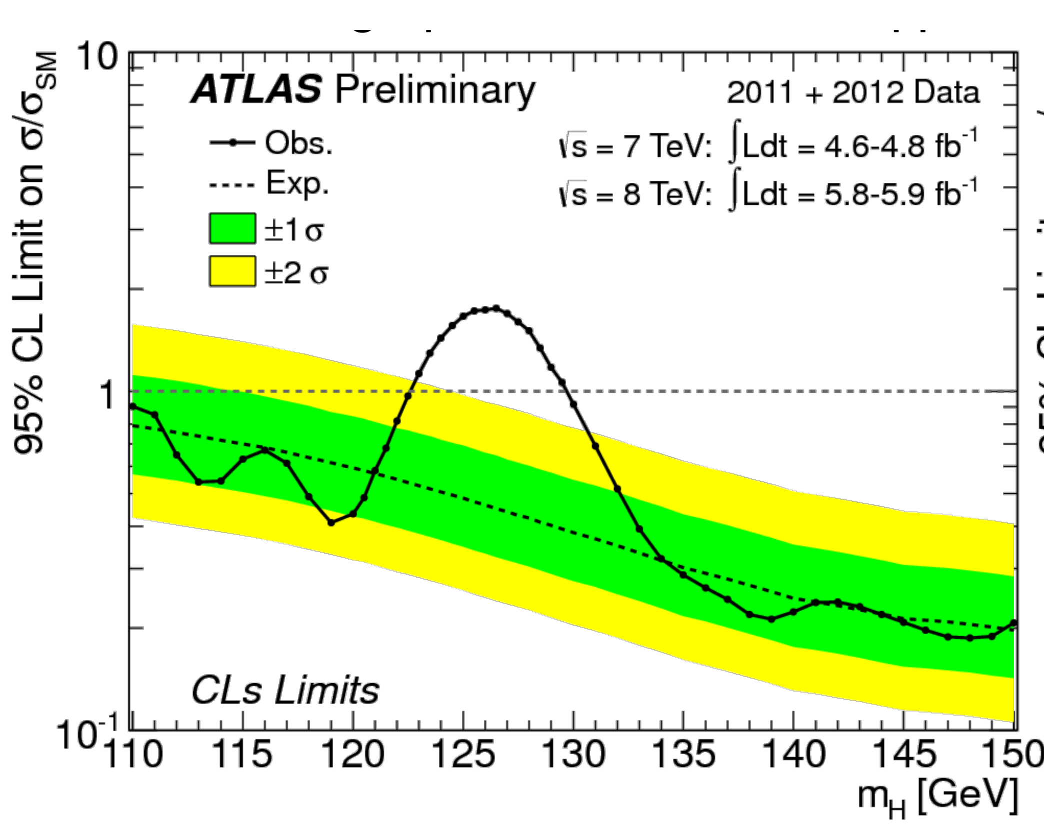
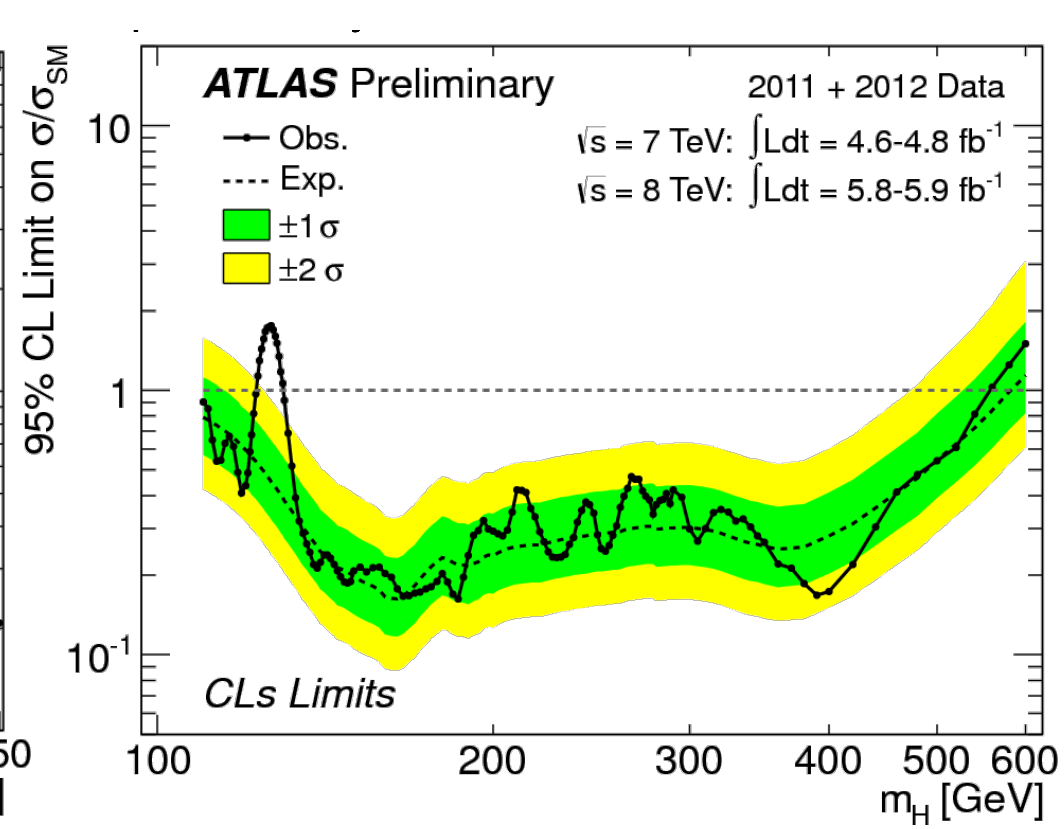
July 4th, 2012









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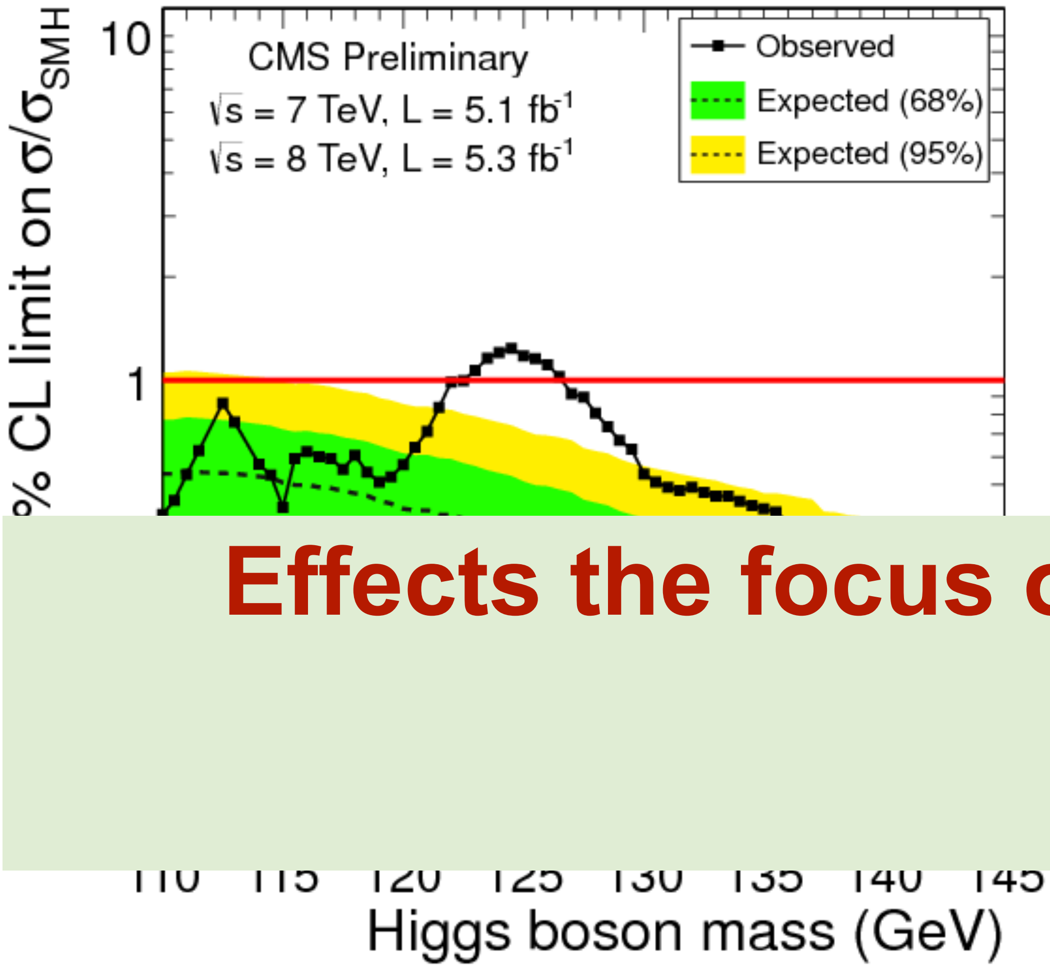
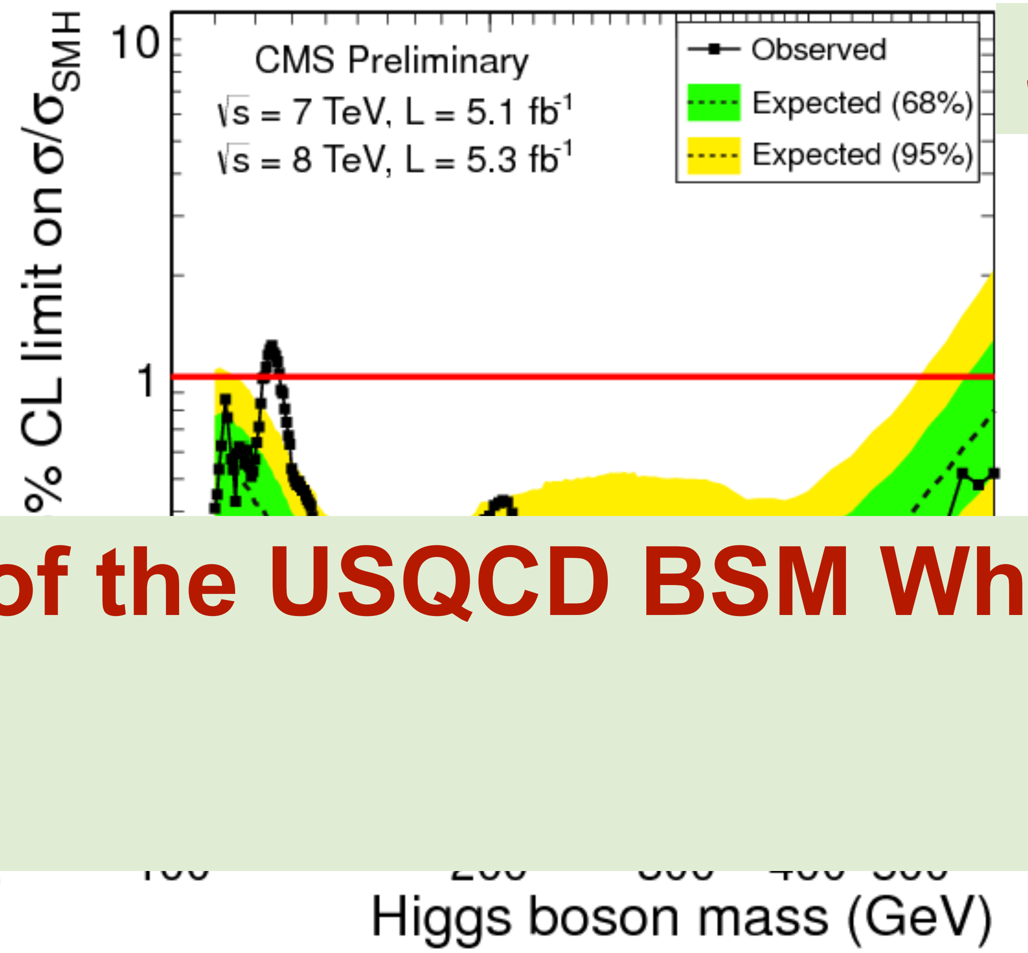
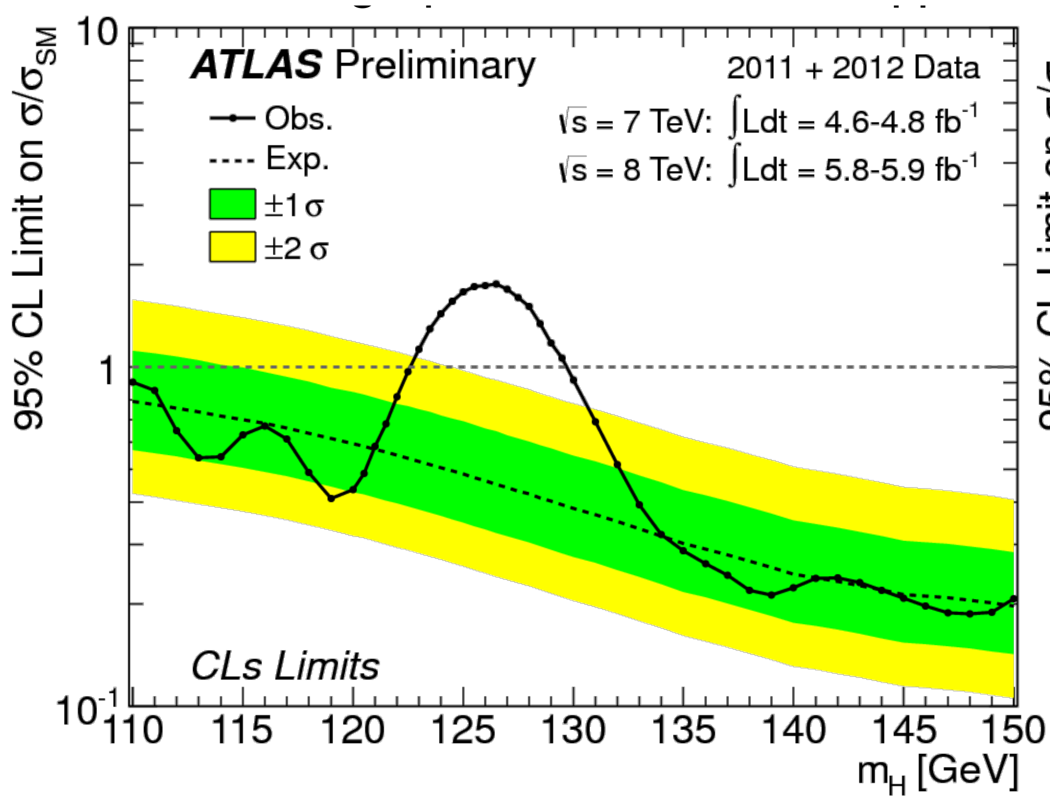
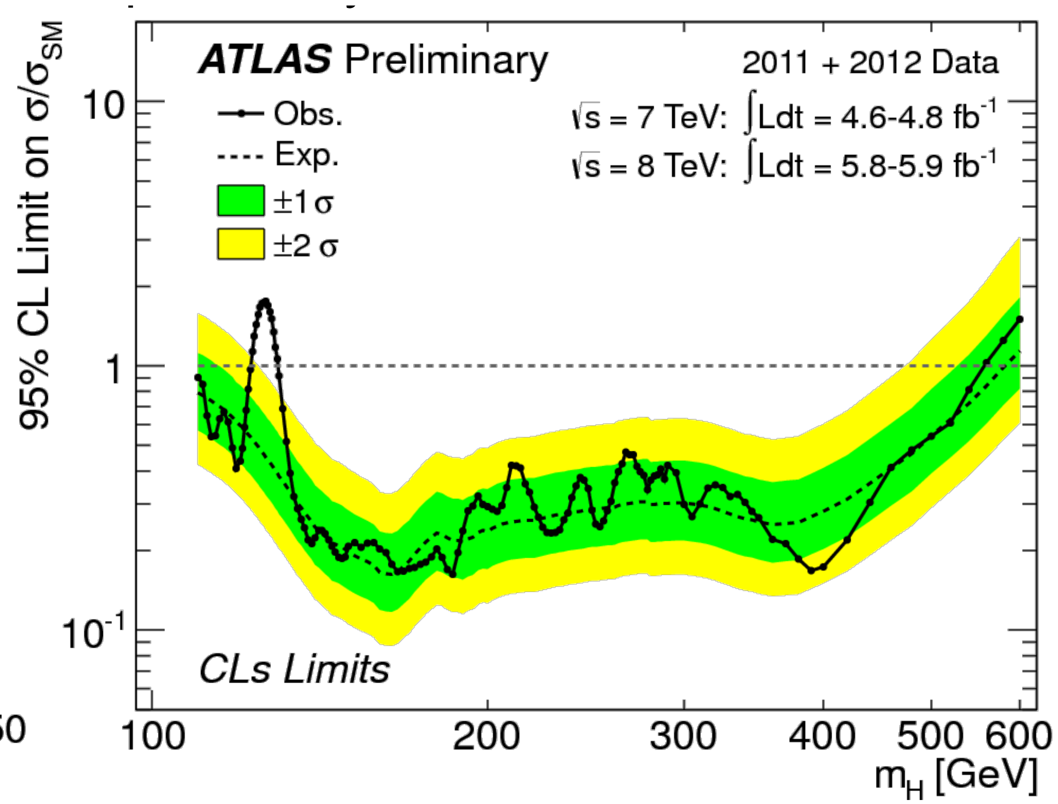




Effects the focus of the USQCD BSM White Paper





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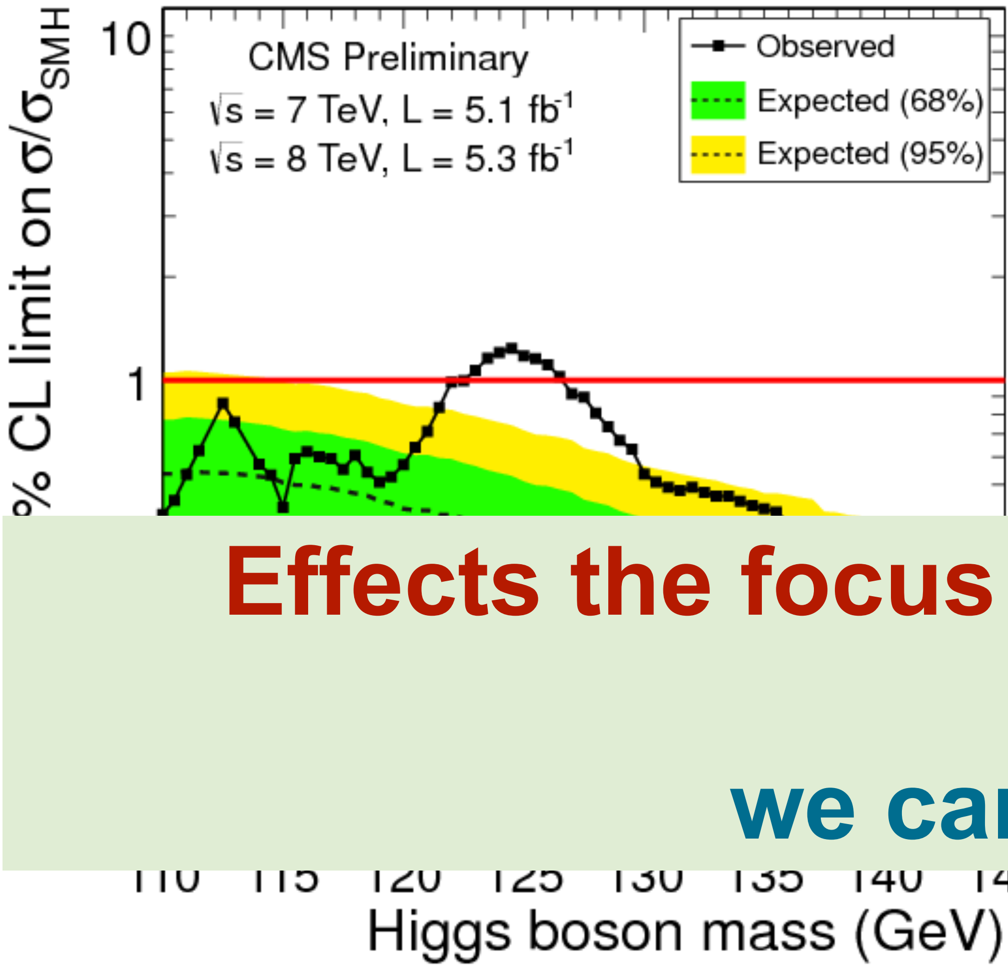

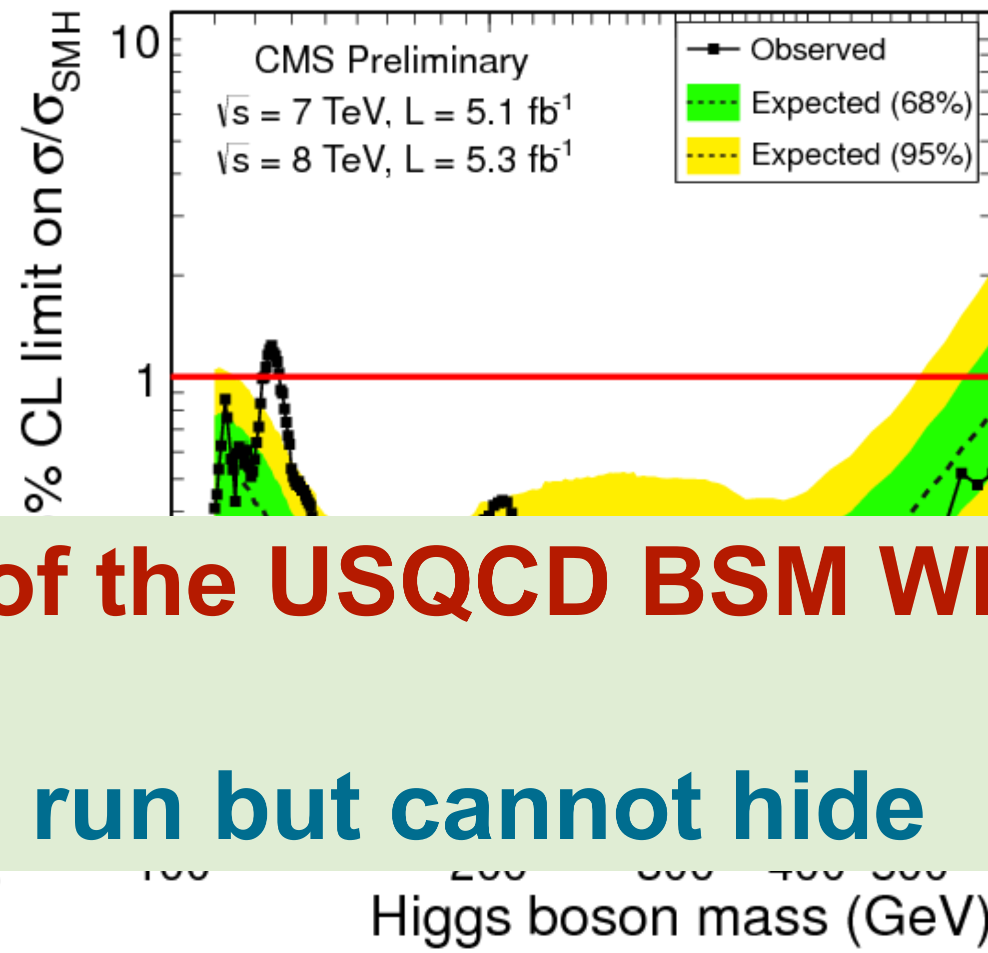

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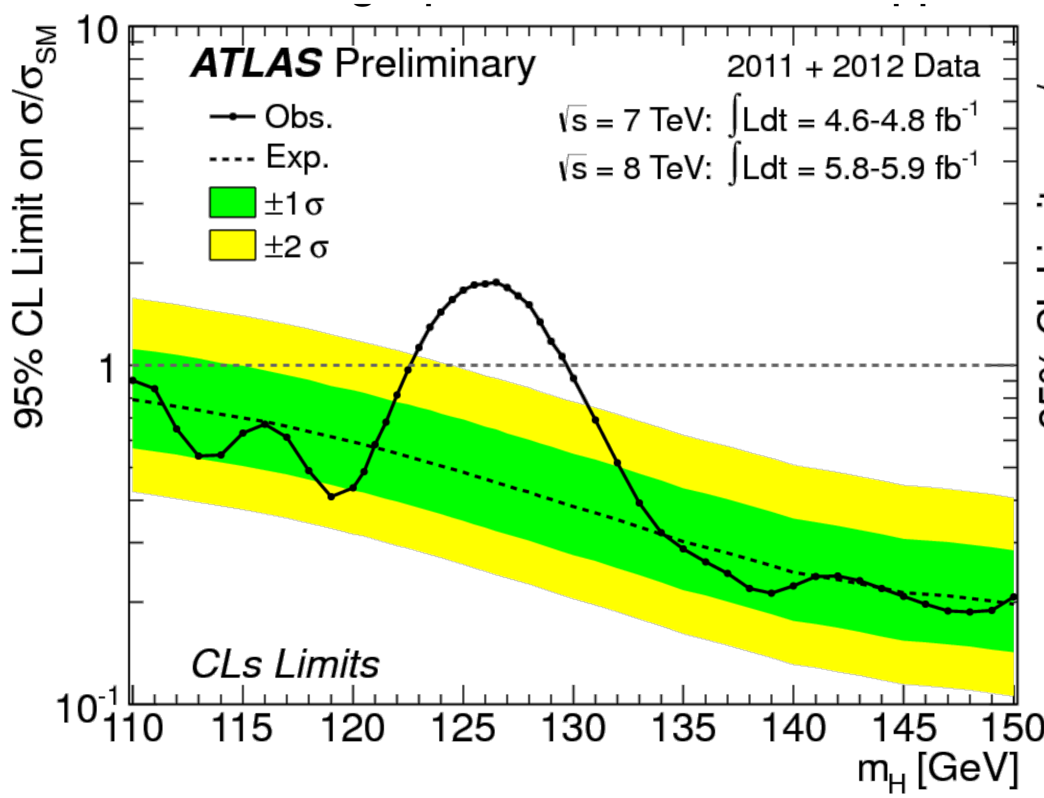
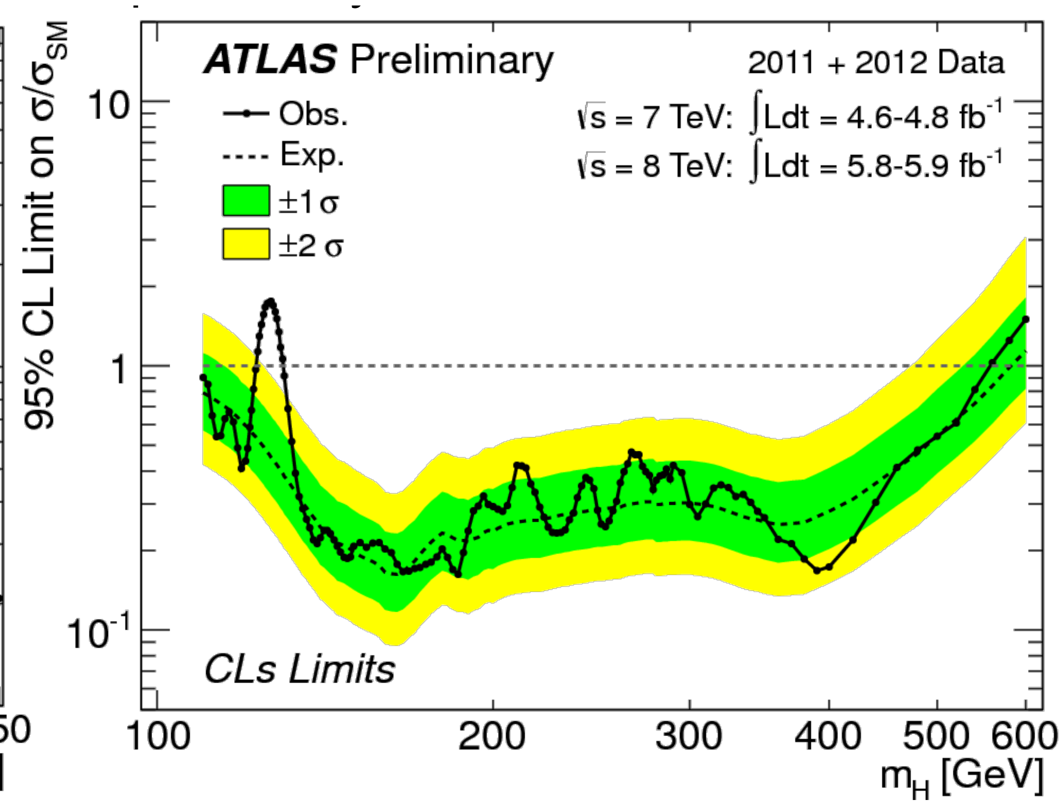
we can run but cannot hide





Conventional thinking before LHC was turned on:

- **New physics from strongly interacting particles will be found first**
  gluinos, s-quarks, technicolor, ...

- **Higgs is more difficult to find, particularly a light Higgs**

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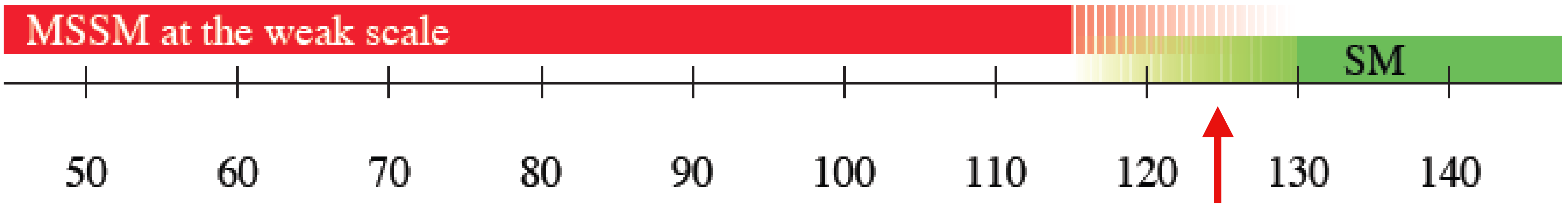
Shrewd choice from Mother Nature: borderline for SUSY and SM (vacuum instability)



Is this the Higgs boson?

spin 0? parity?

$H \to \gamma\gamma$ (s=0 or 2 in s-wave)

$H \to bb$ and $H \to \tau\tau$ (favors s=0 in s-wave)

$H \to ZZ^* \to$ 4 leptons, or $WW^* \to$ 4 leptons (will nail down spin)

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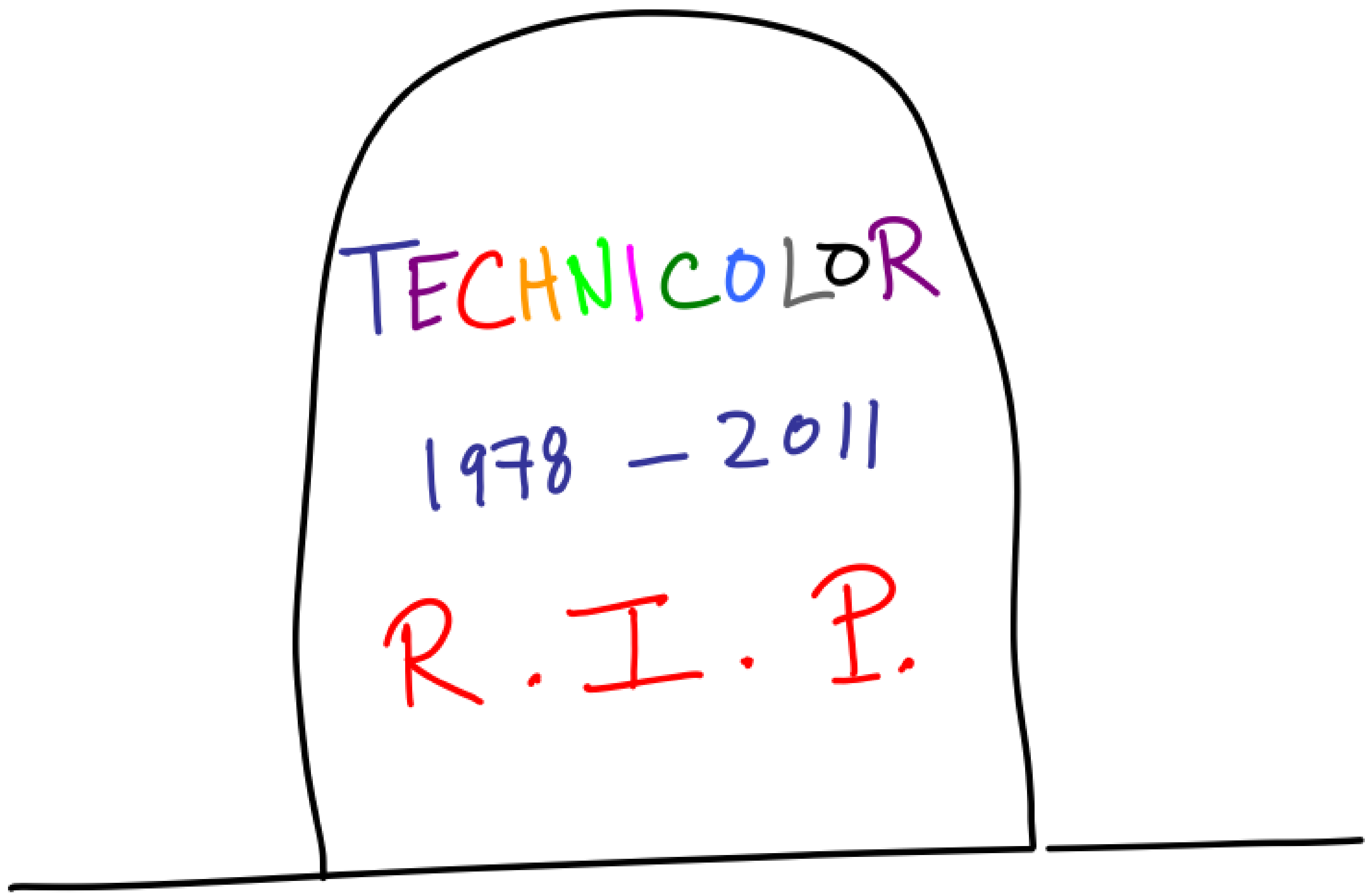
How do we plan USQCD with the new Higgs-like particle?

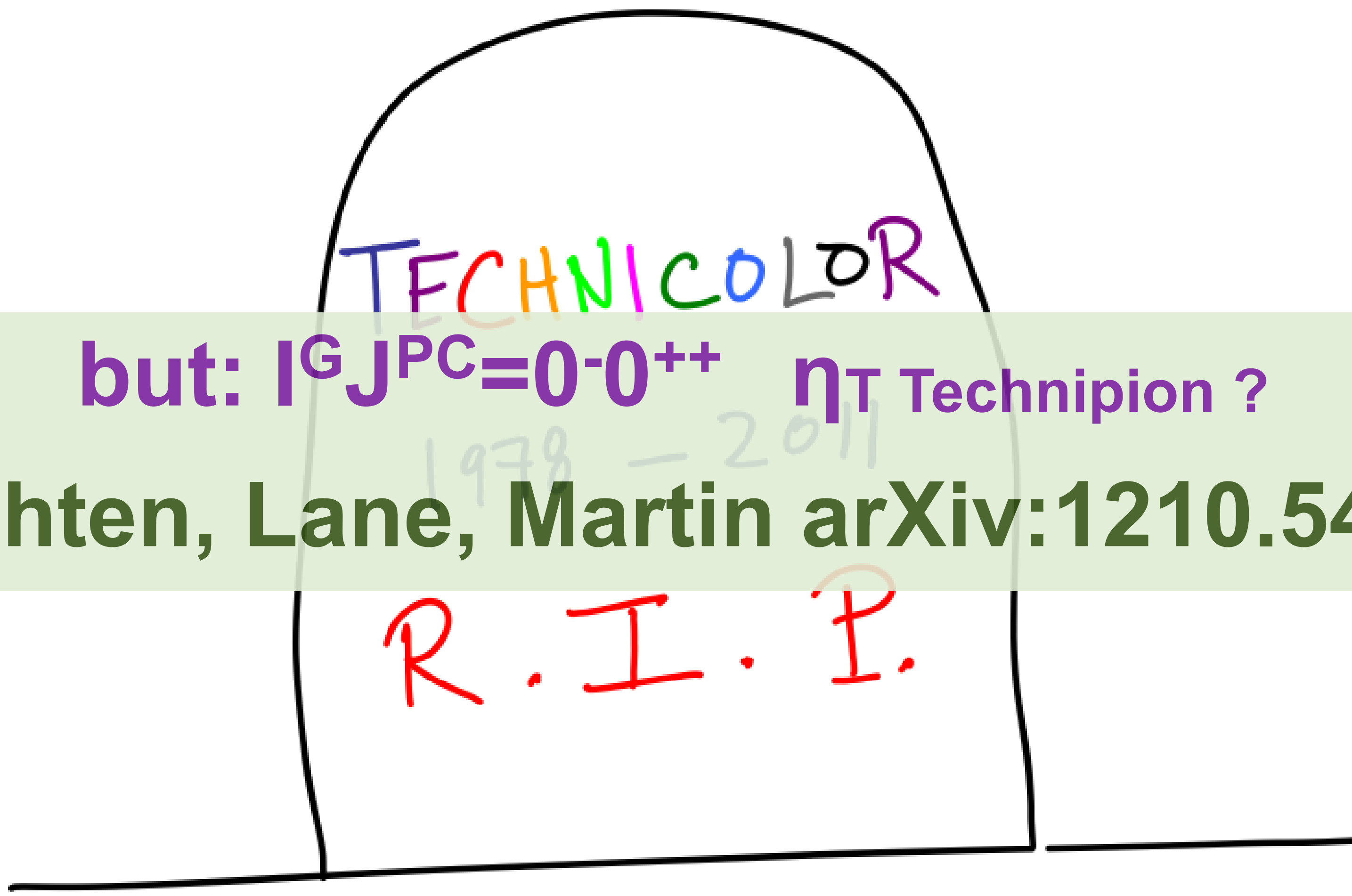
Arkani-Hamed '12

TRIUMPH OF WEAK COUPLING



Arkani-Hamed ‘12

Triumph of Weak Coupling



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Eichten, Lane, Martin arXiv:1210.5462

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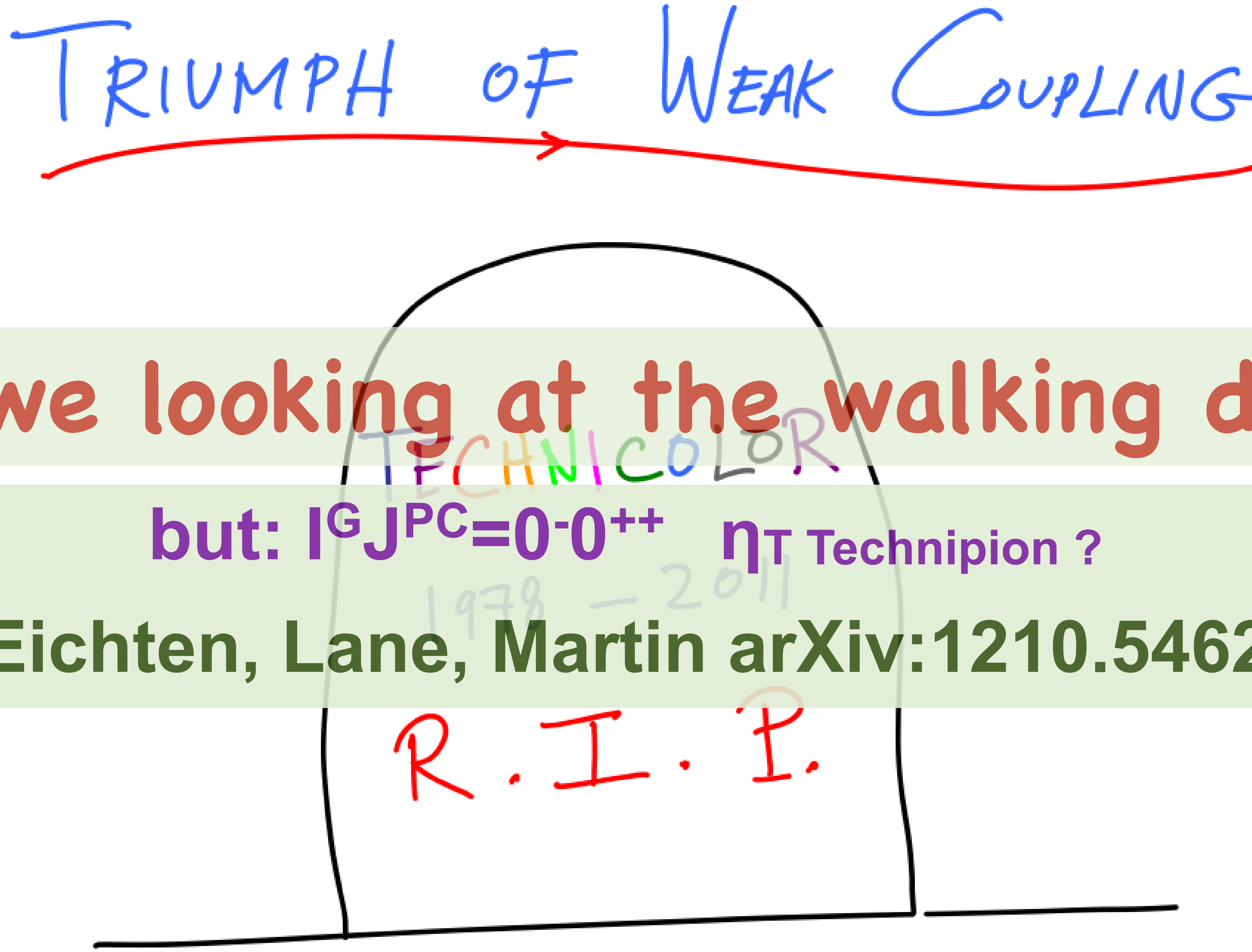

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Why is SUSY not on the Tombstone?

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Outline

how large Theory Space is needed?

light scalar and dilaton mechanism close to CW

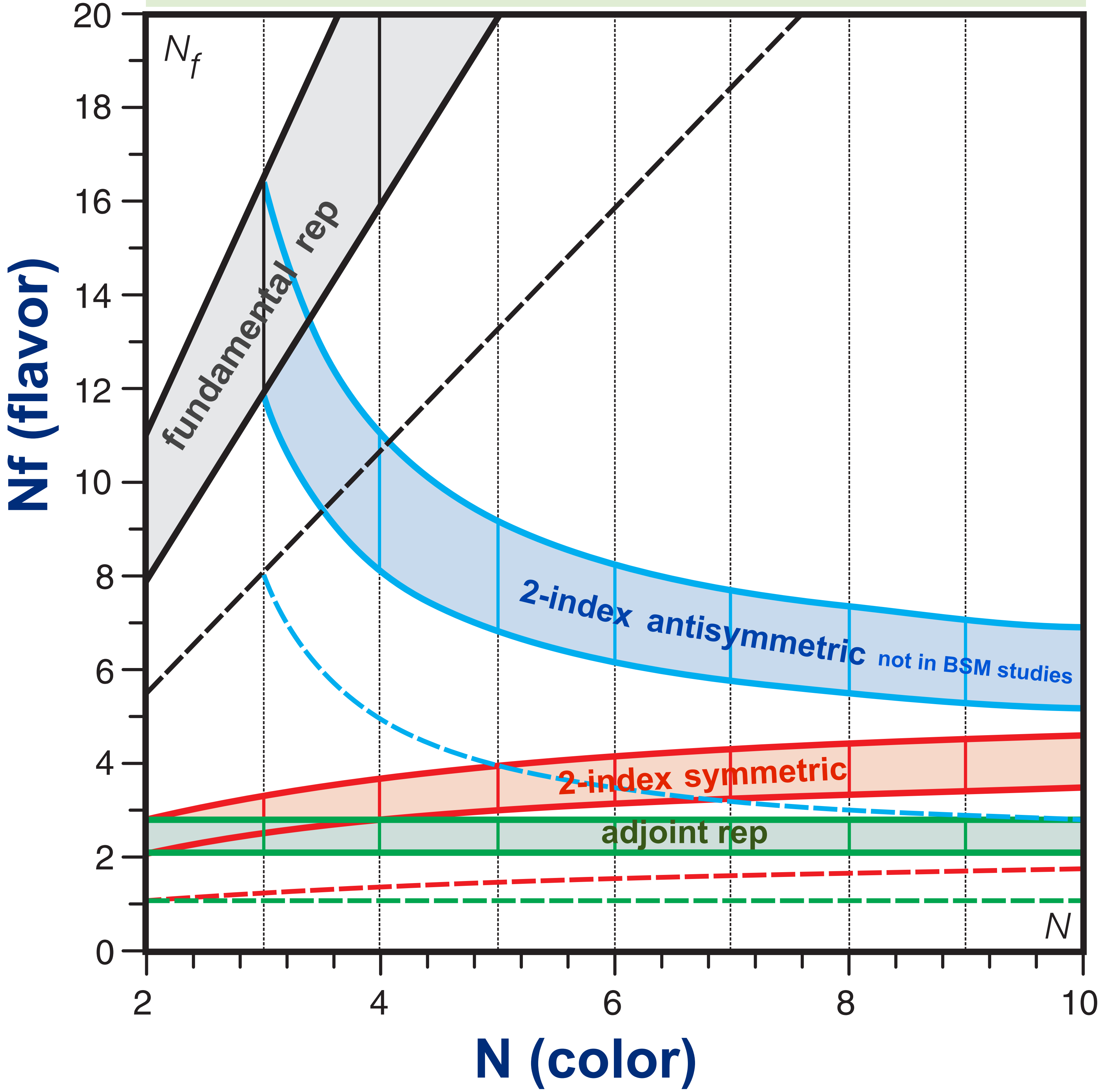
chiral condensates and spectroscopy

running (walking) coupling

light scalar spectroscopy

Summary and outlook

theory space and conformal window
is the Higgs impostor hiding close to CW?
space of color, flavor, and massless fermion representation



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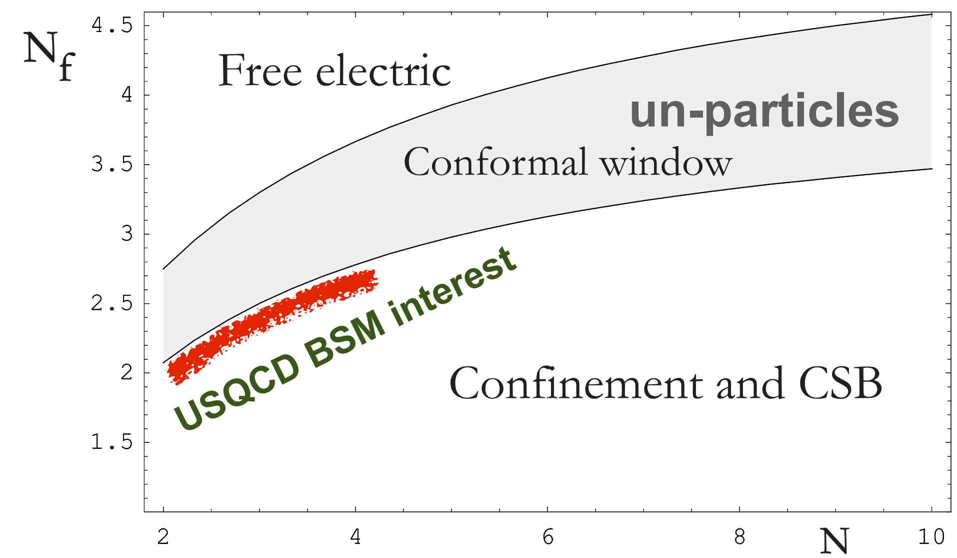

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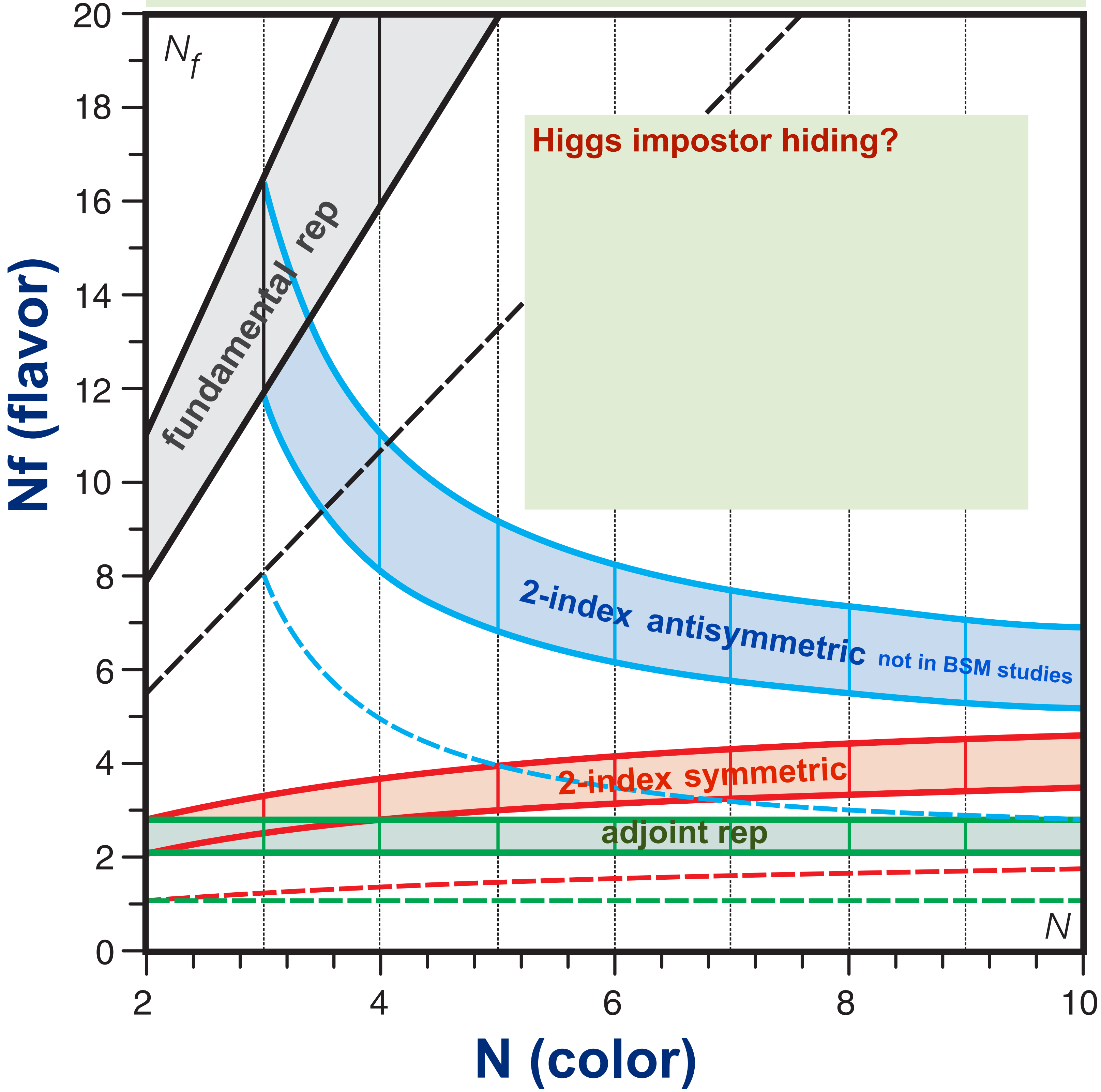

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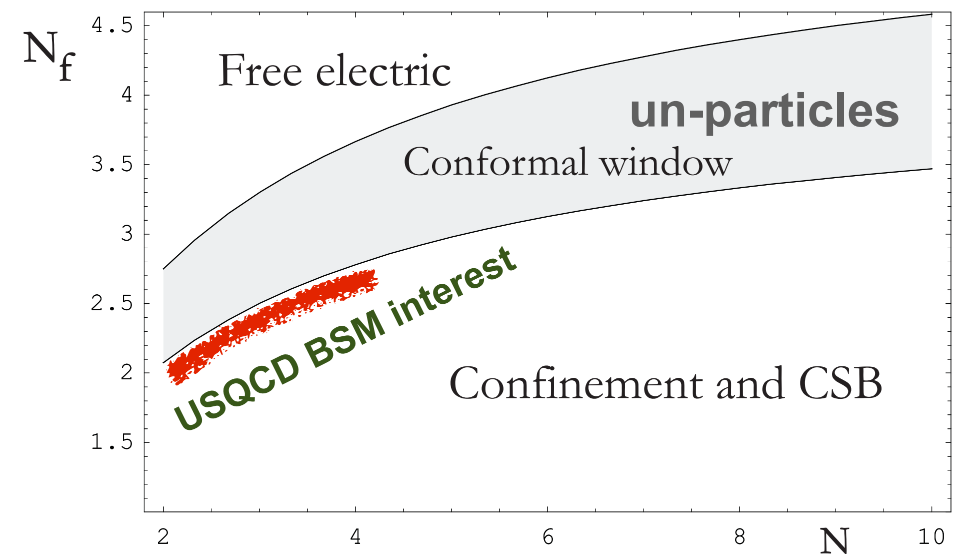

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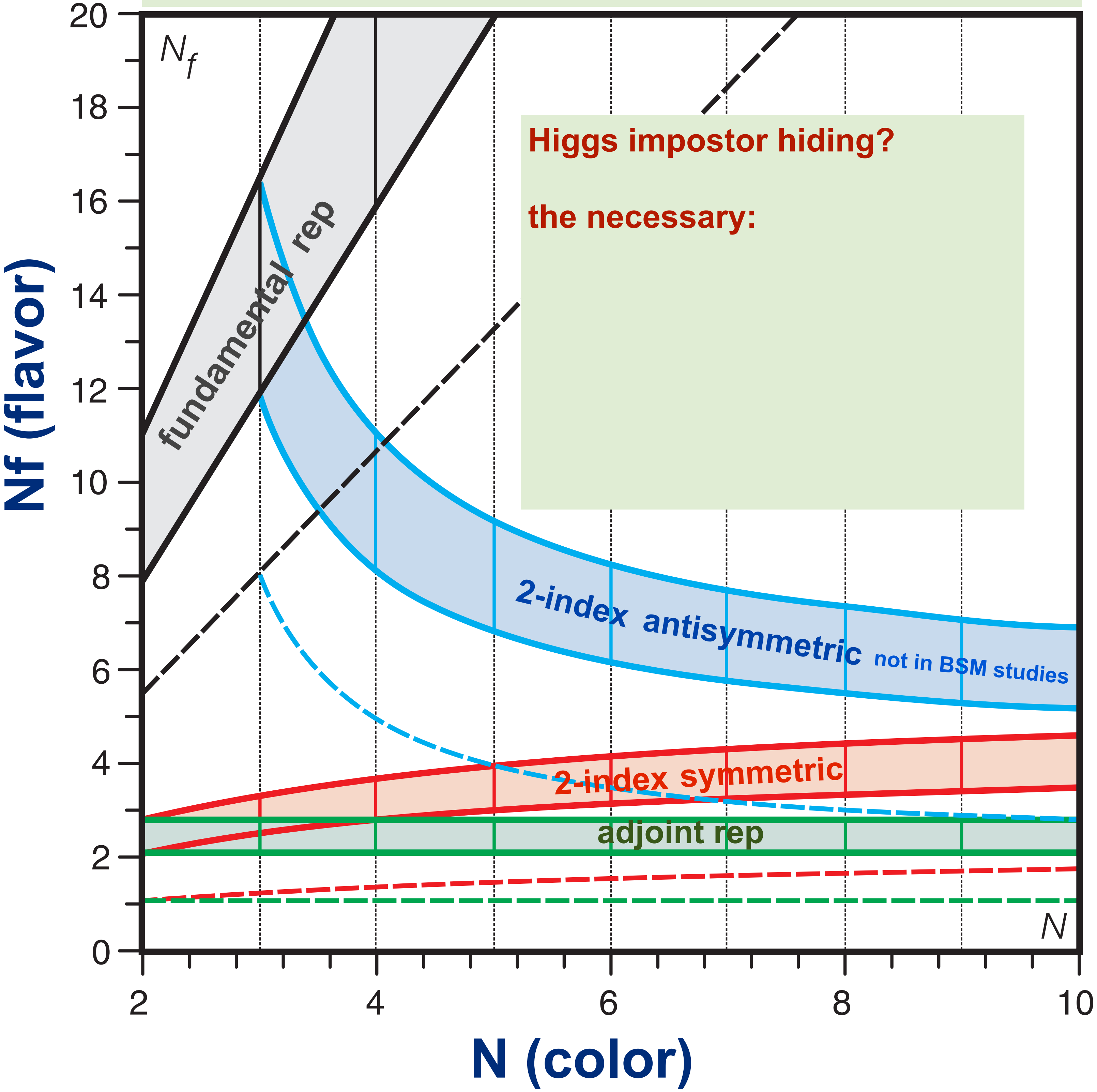

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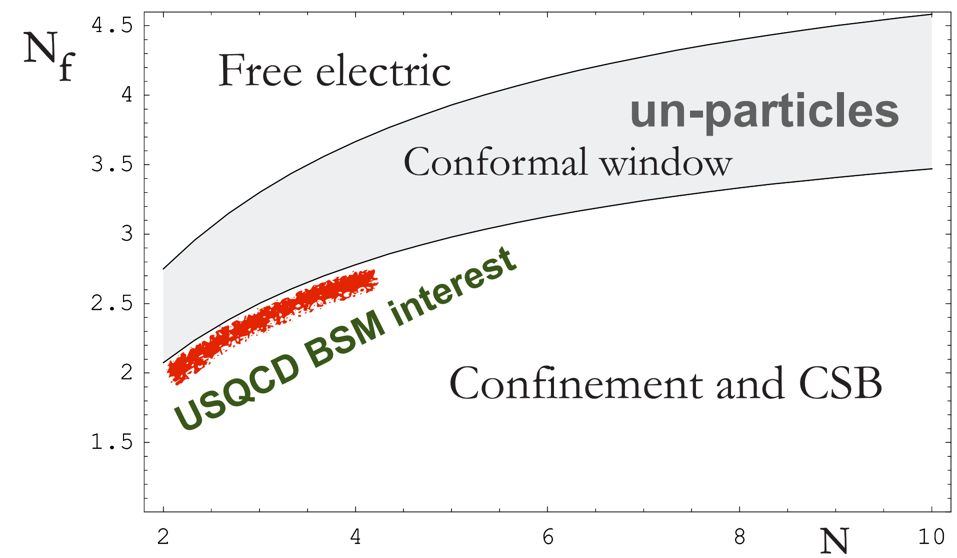

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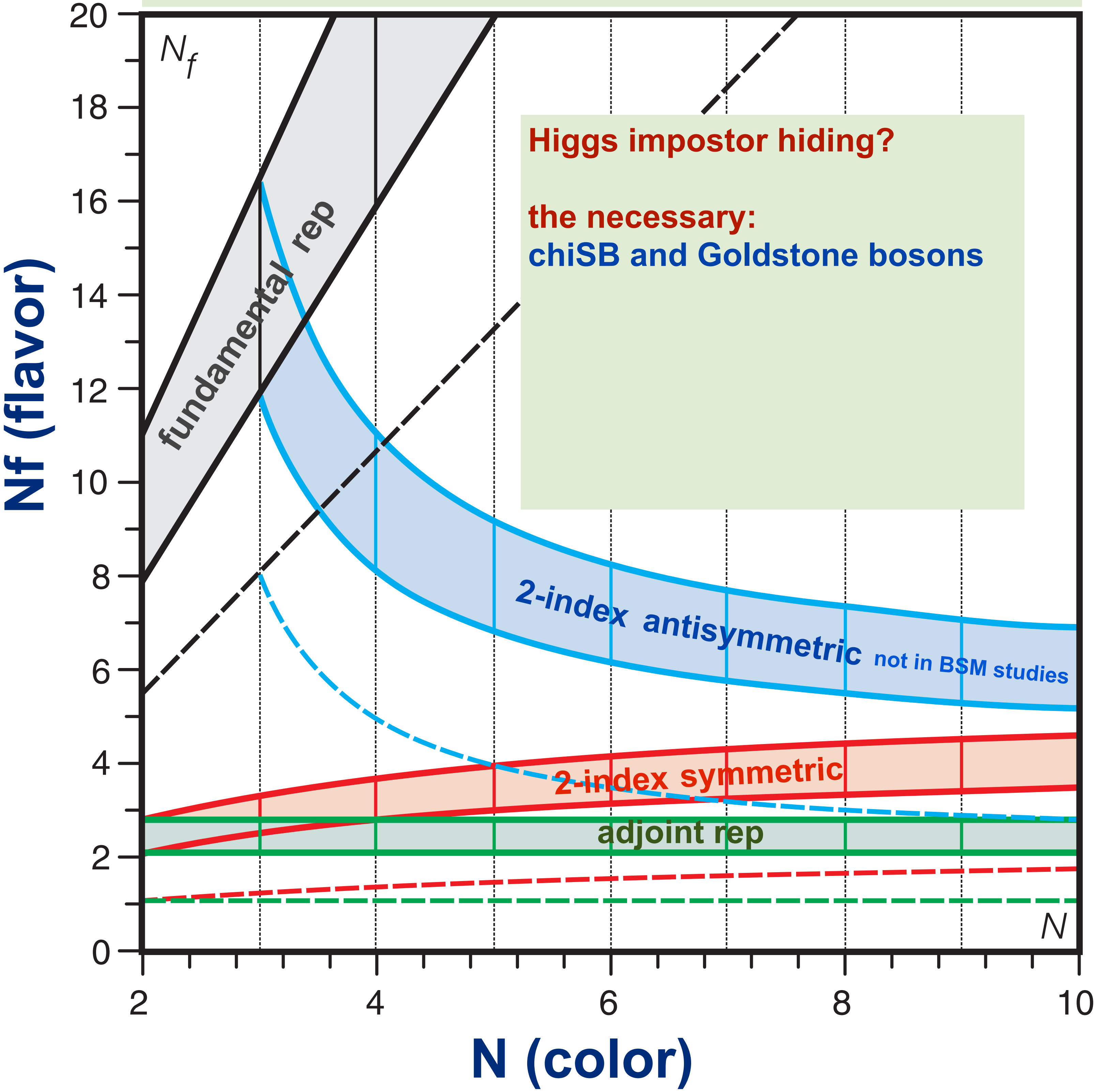

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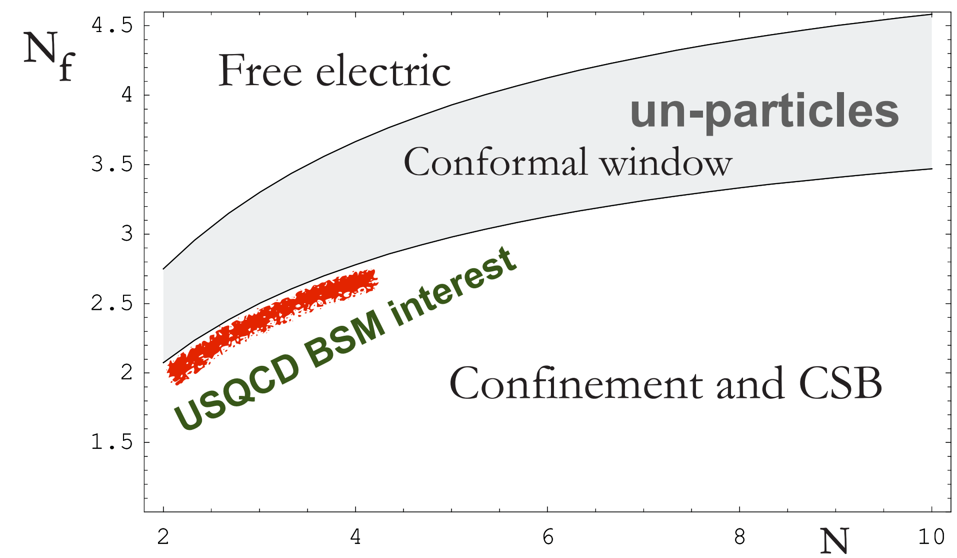

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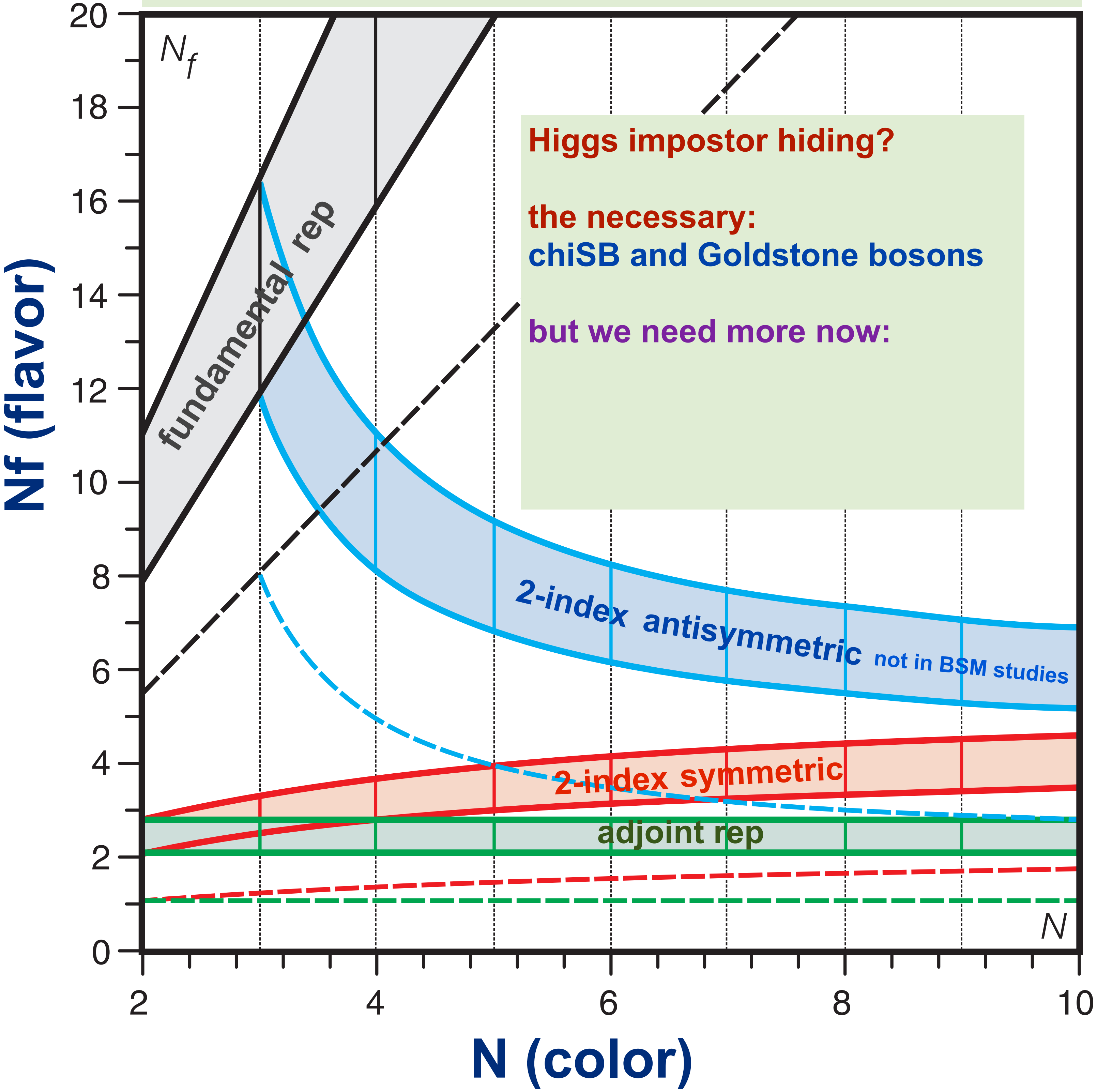

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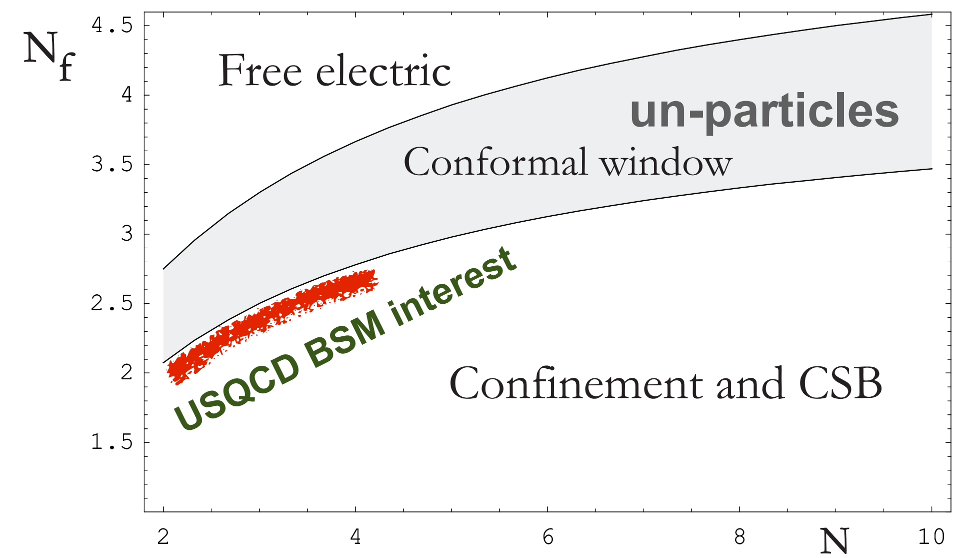

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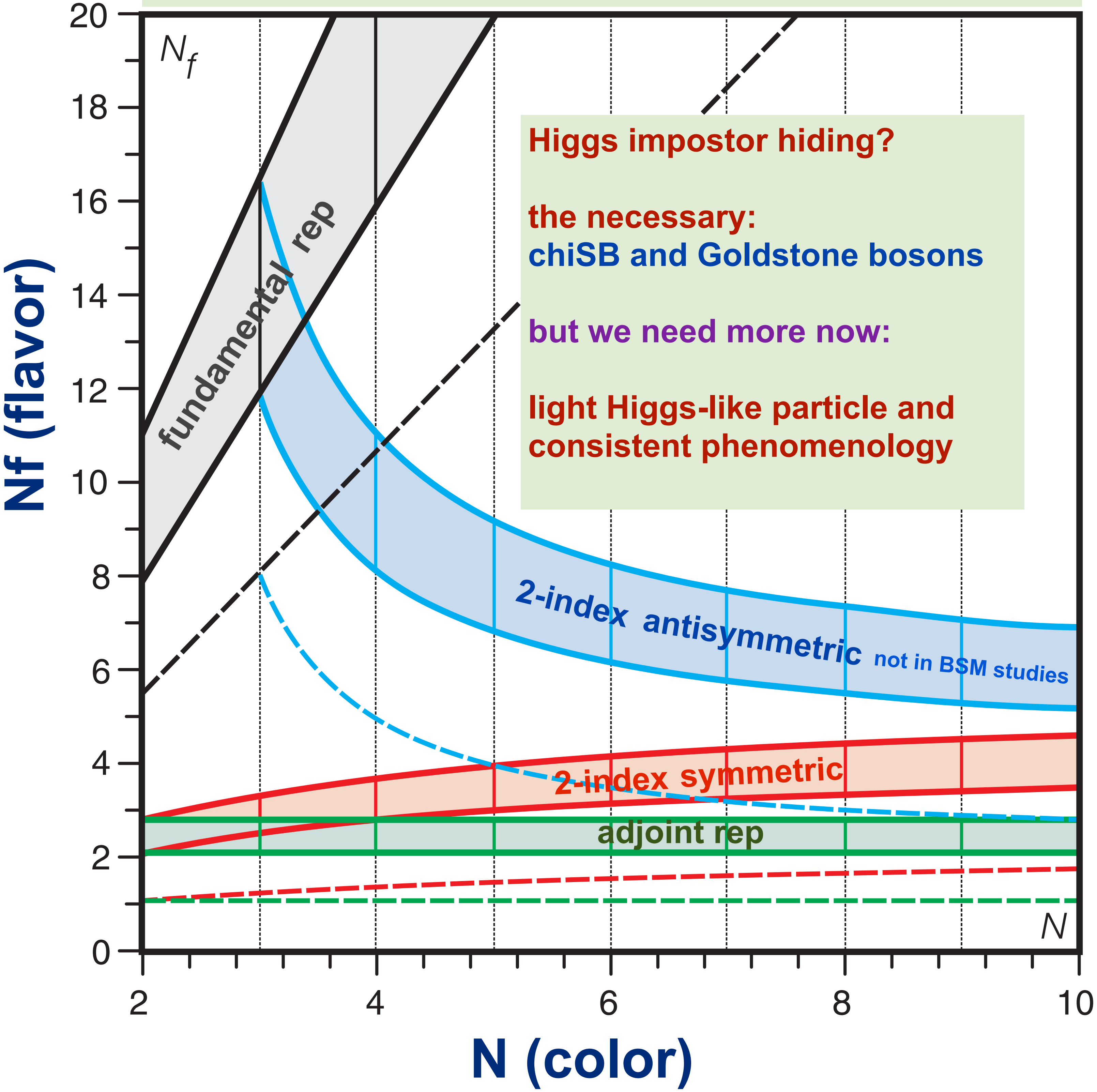

Higgs impostor hiding?

the necessary:
chiSB and Goldstone bosons

but we need more now:

light Higgs-like particle and consistent phenomenology

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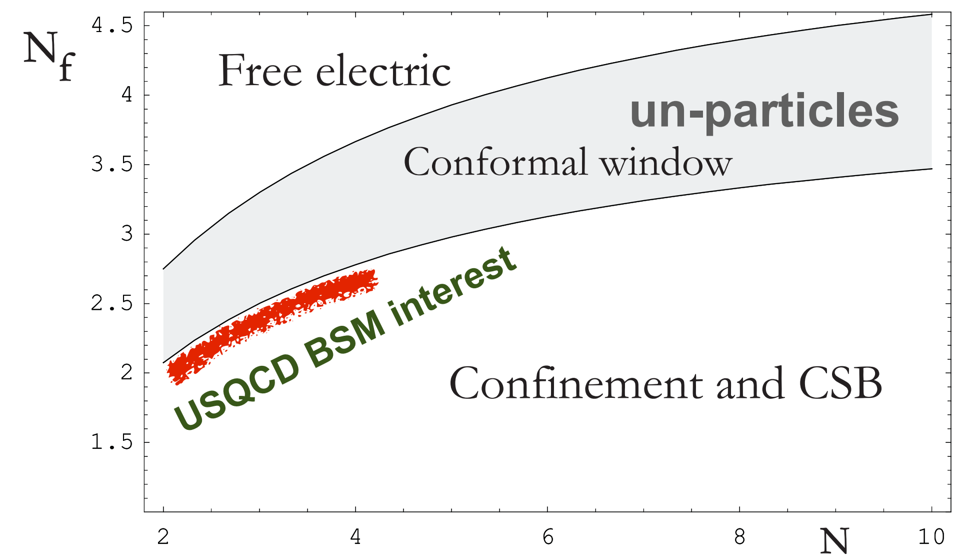

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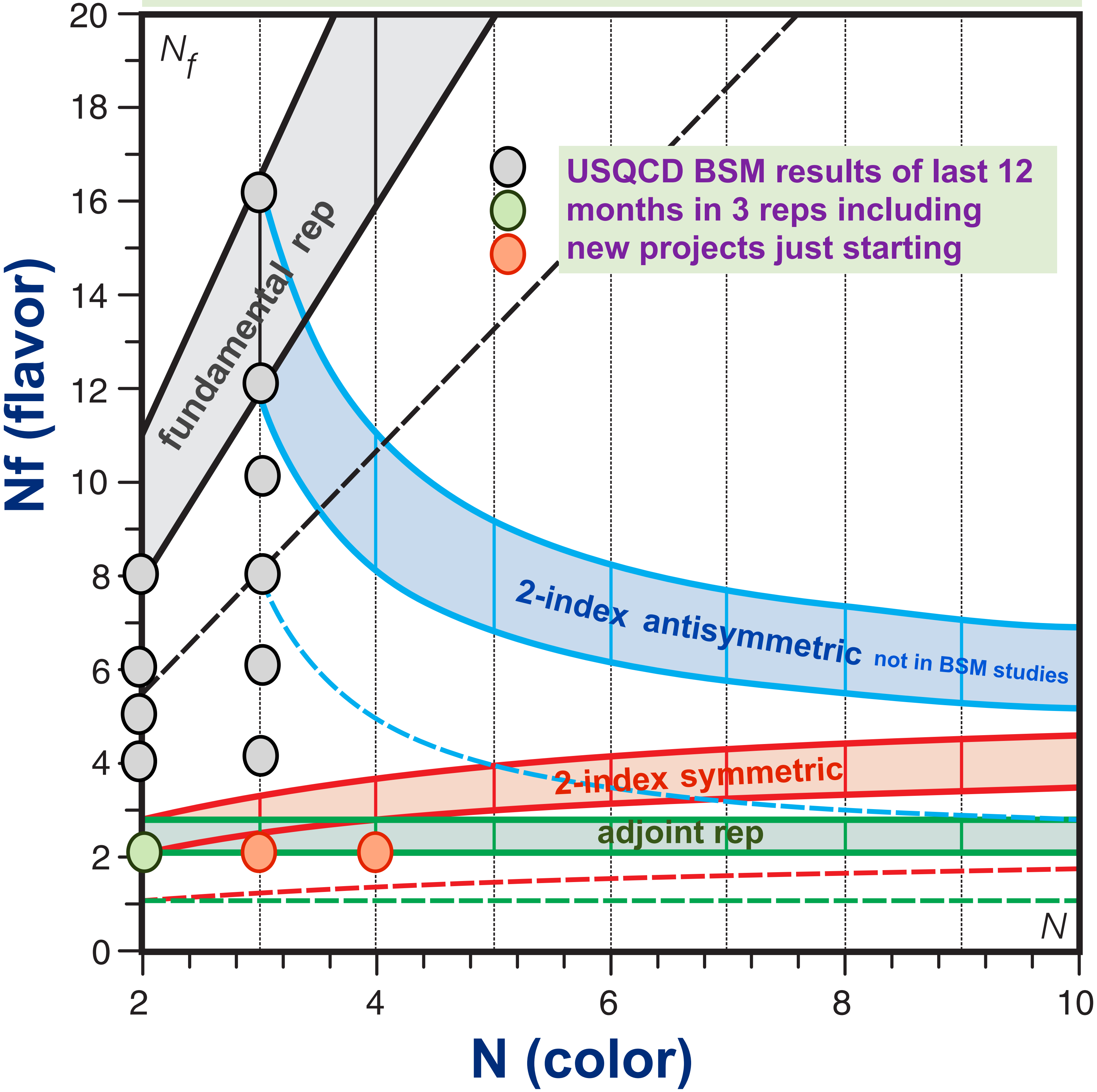

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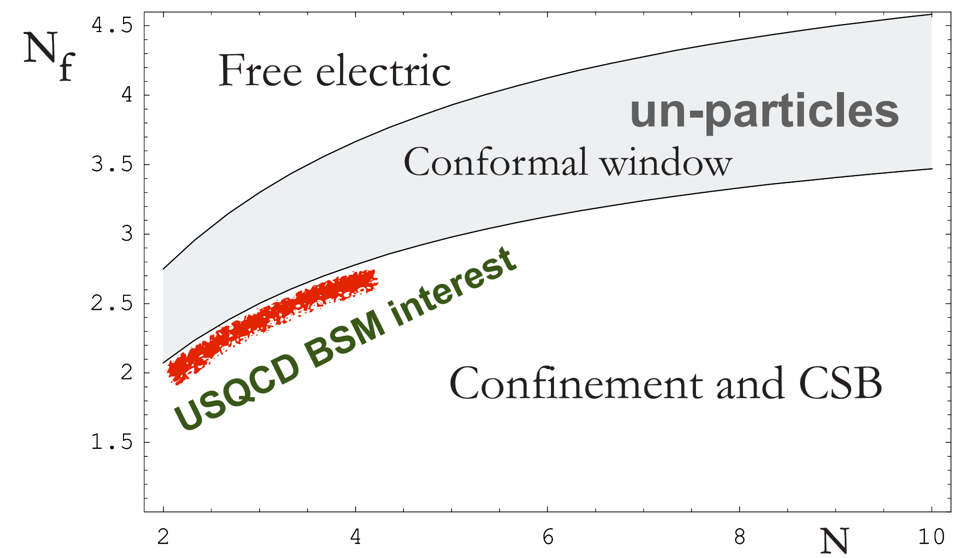

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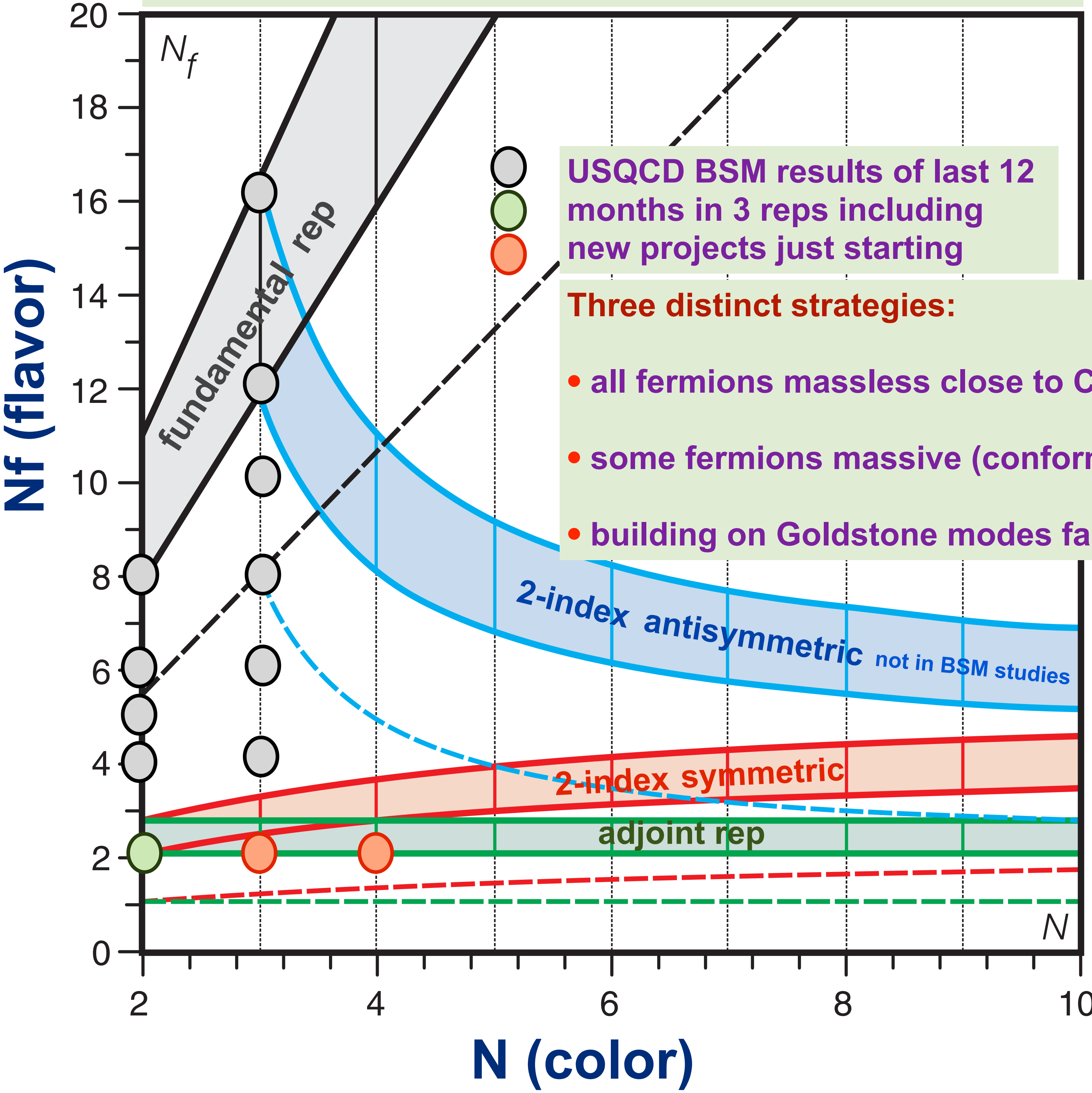

USQCD BSM results of last 12 months in 3 reps including new projects just starting

Three distinct strategies:

- **all fermions massless close to CW with chiSB (dilaton?)**
- **some fermions massive (conformal Technicolor close to CW)**
- **building on Goldstone modes far from CW (like little Higgs?)**

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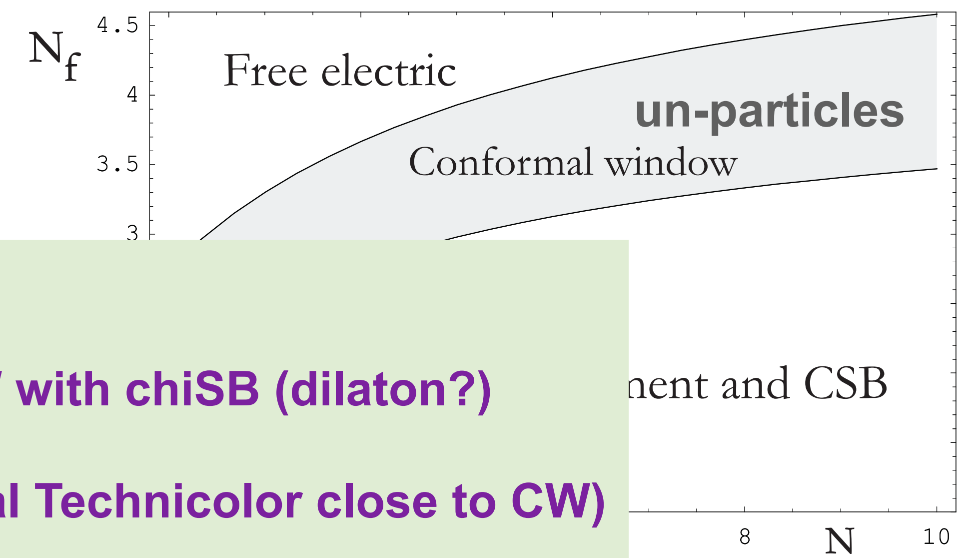

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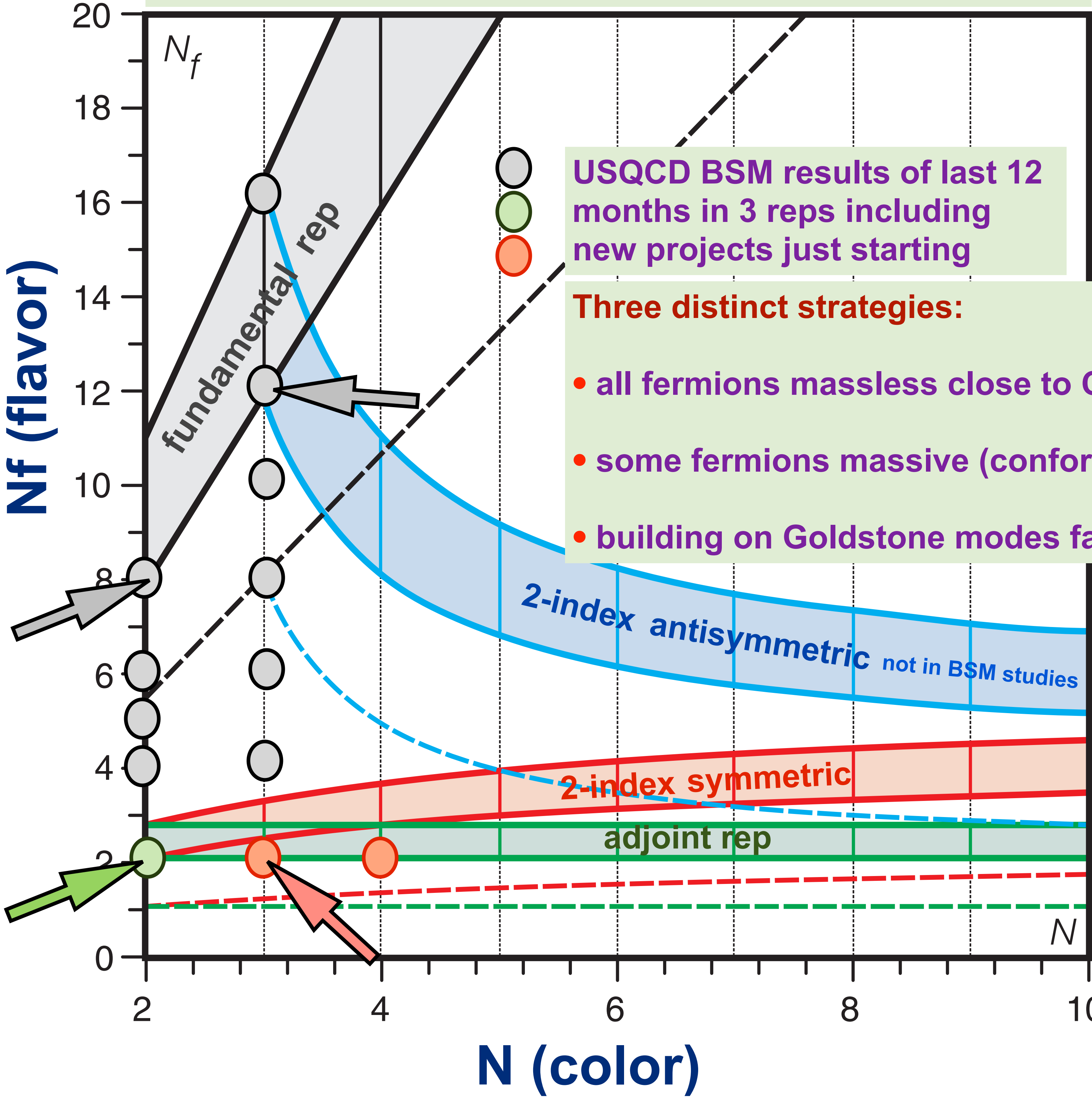

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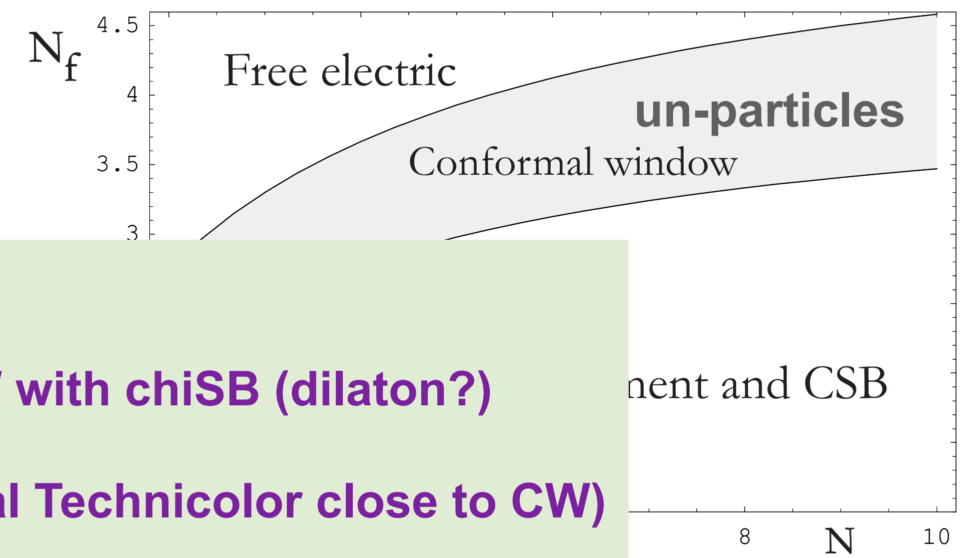

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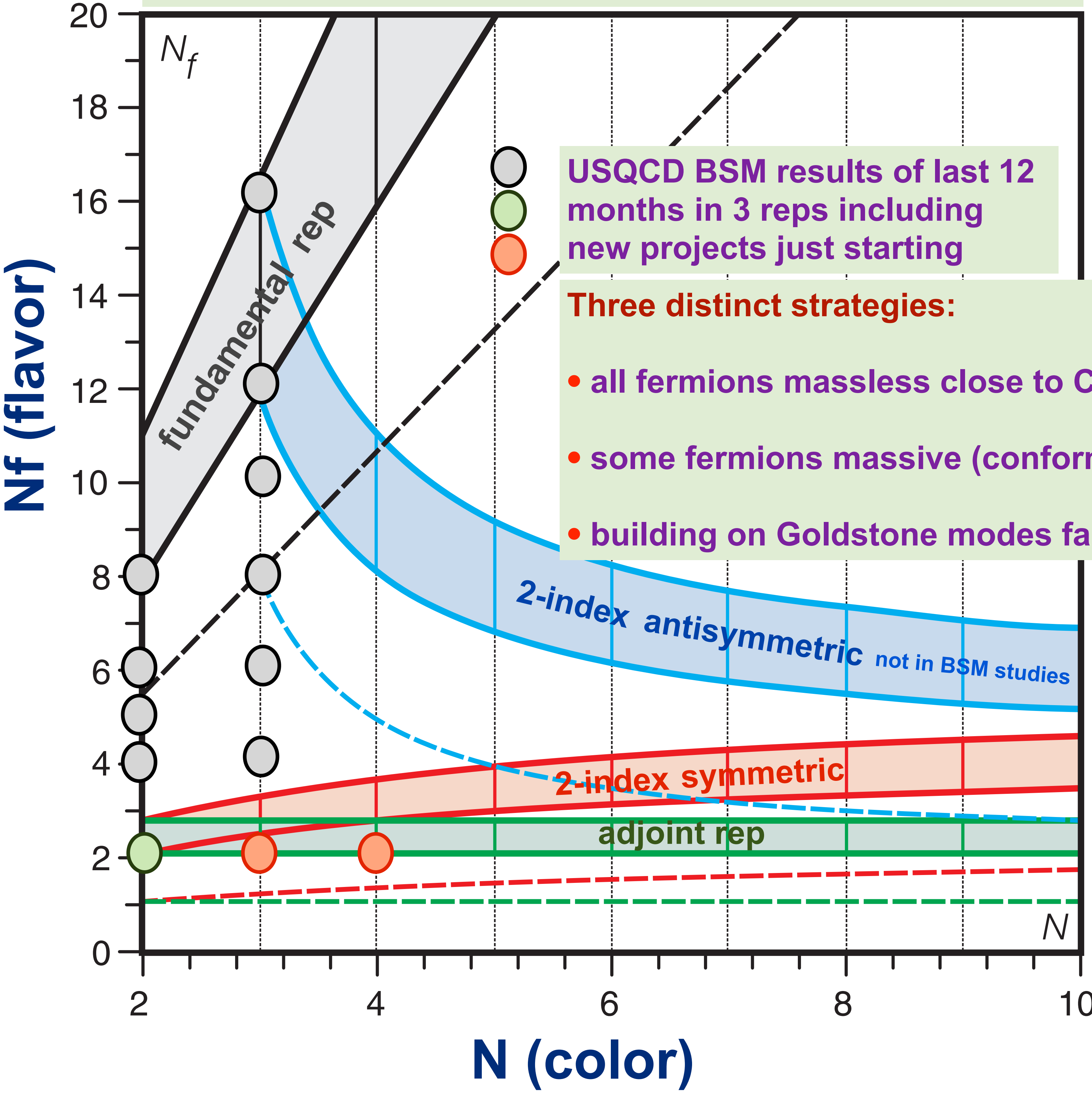

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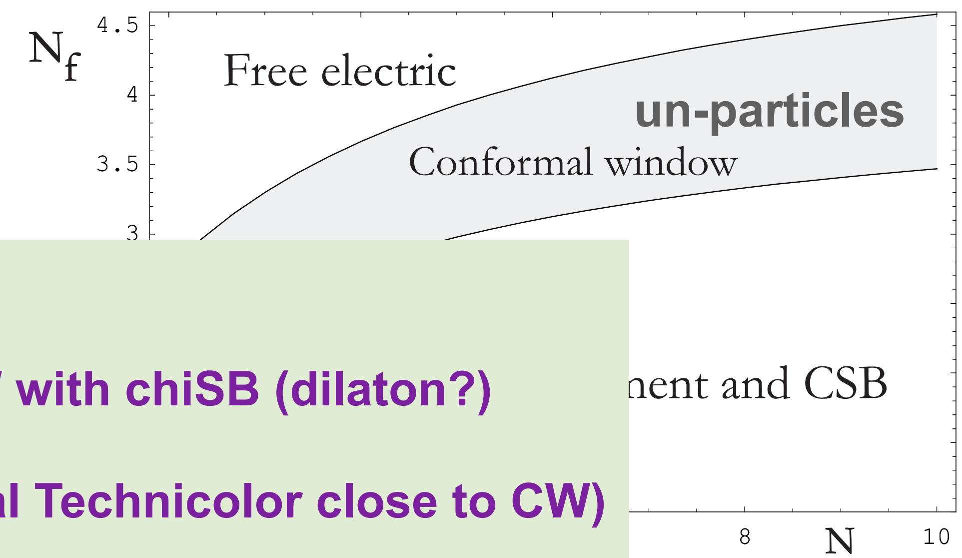
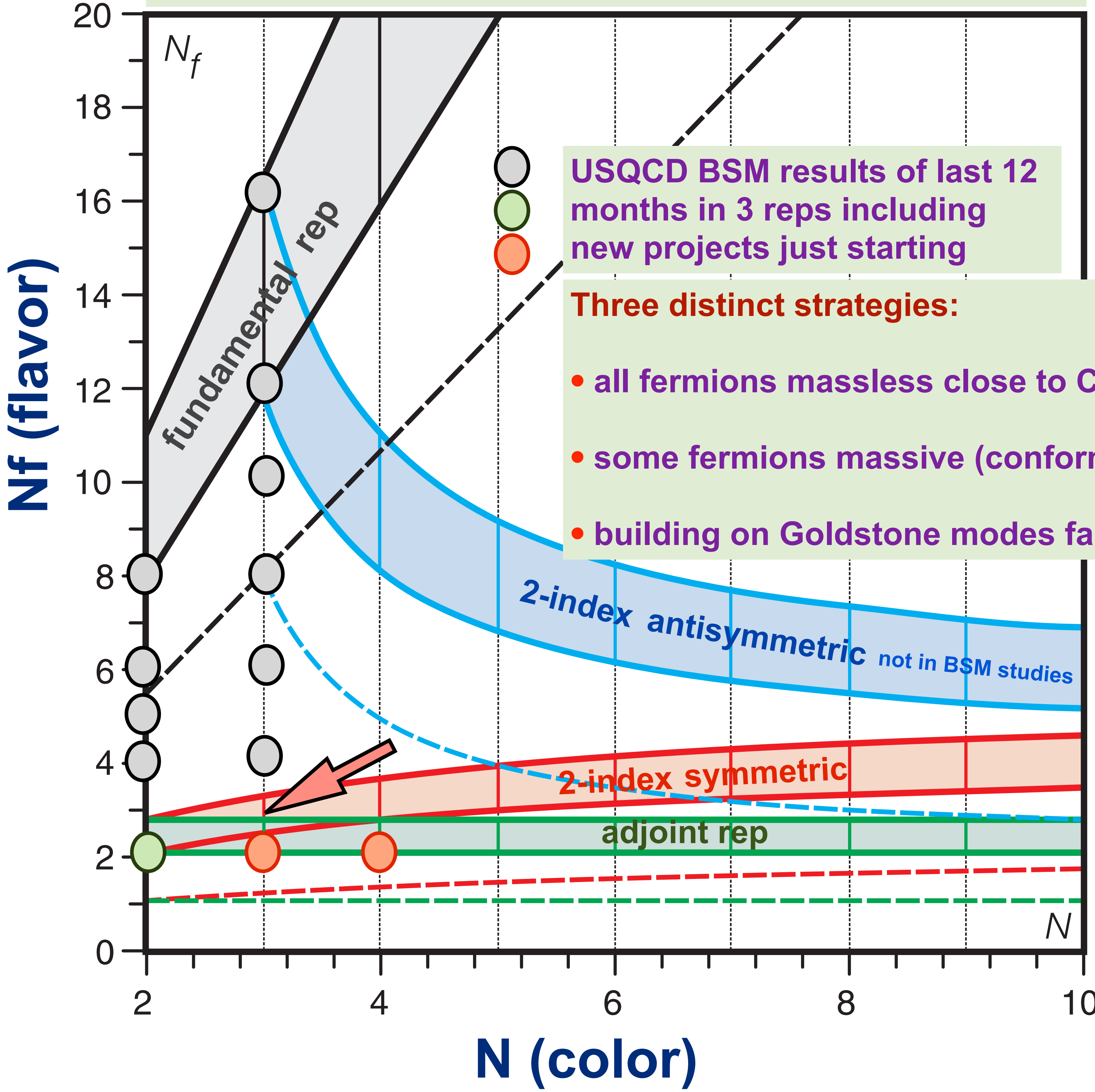


theory space and conformal window
is the Higgs impostor hiding close to CW?

space of color, flavor, and massless fermion representation



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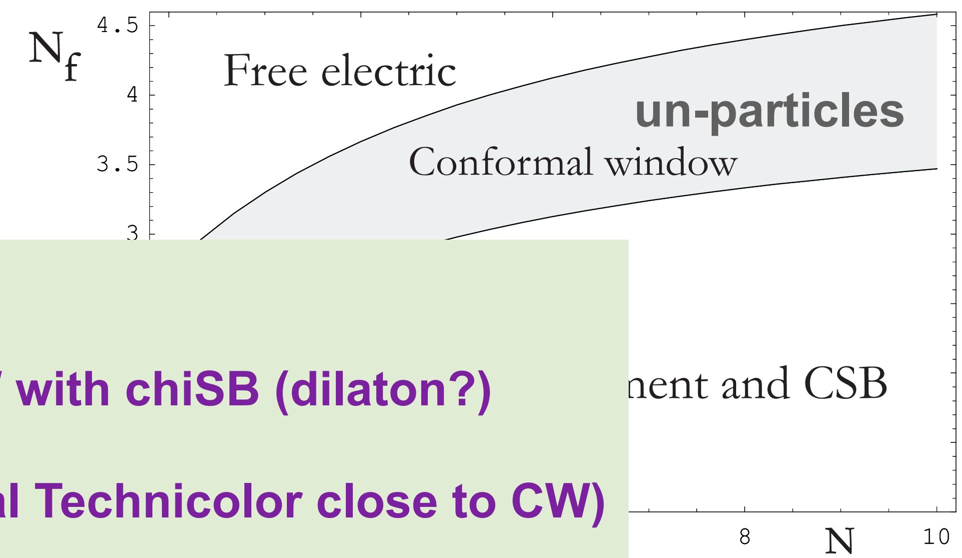

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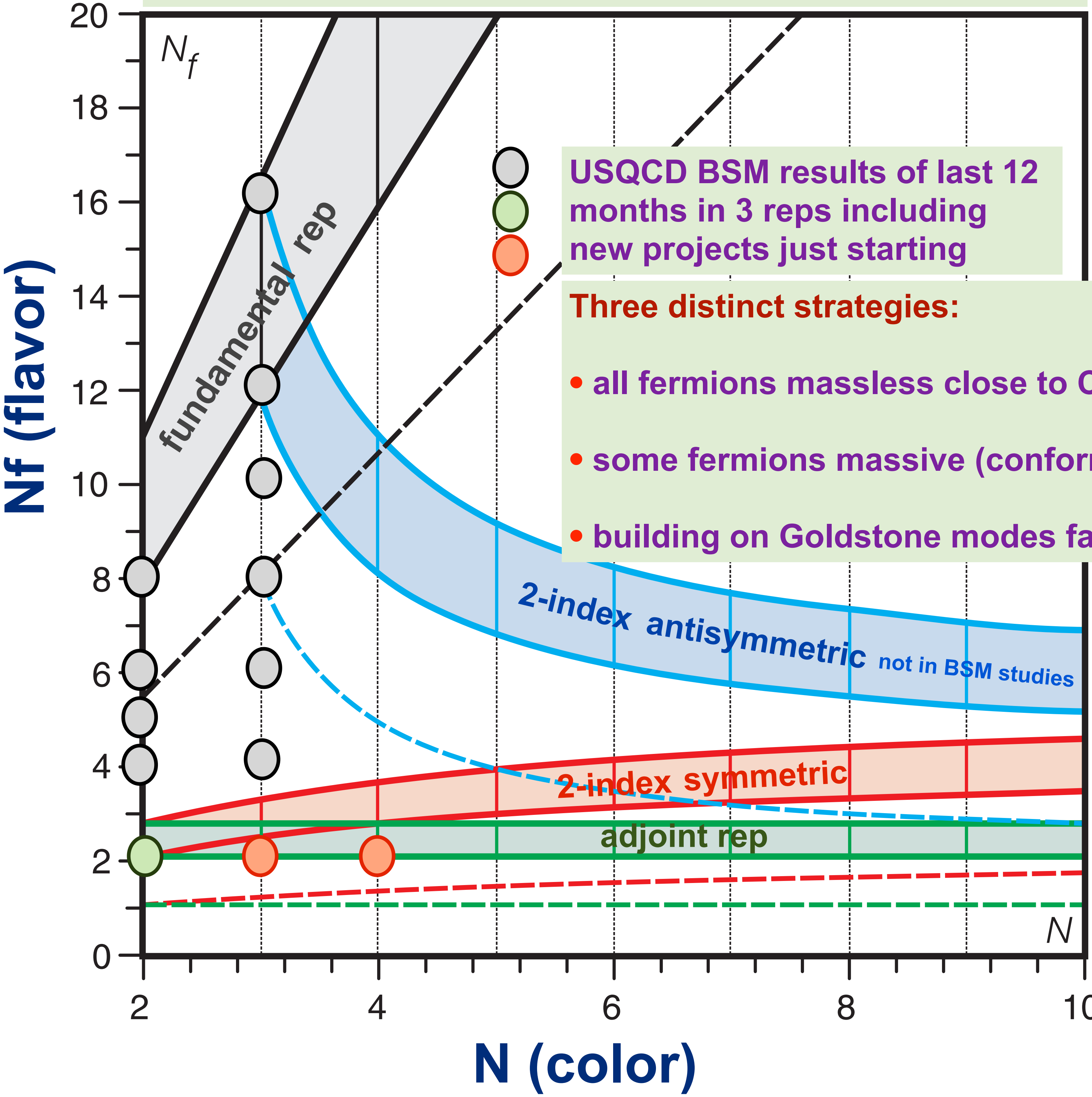

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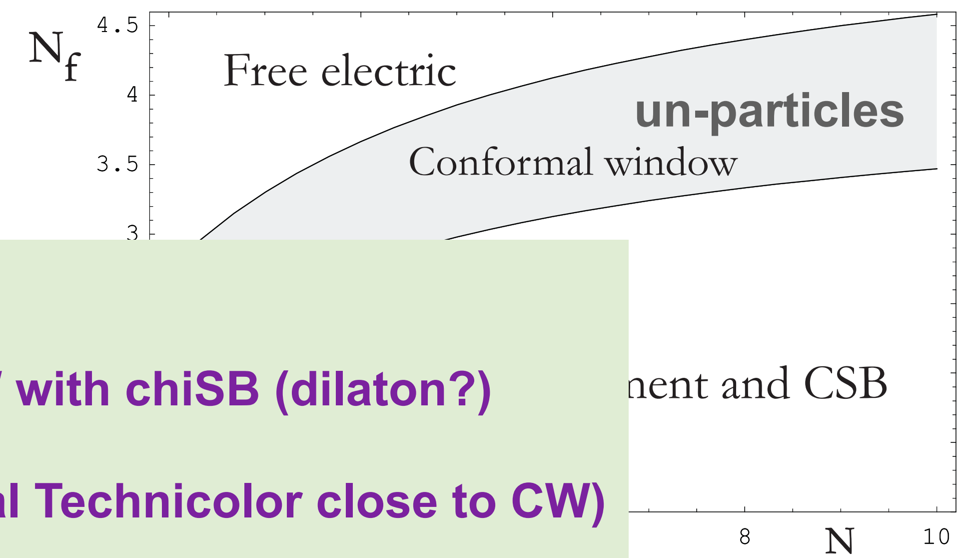

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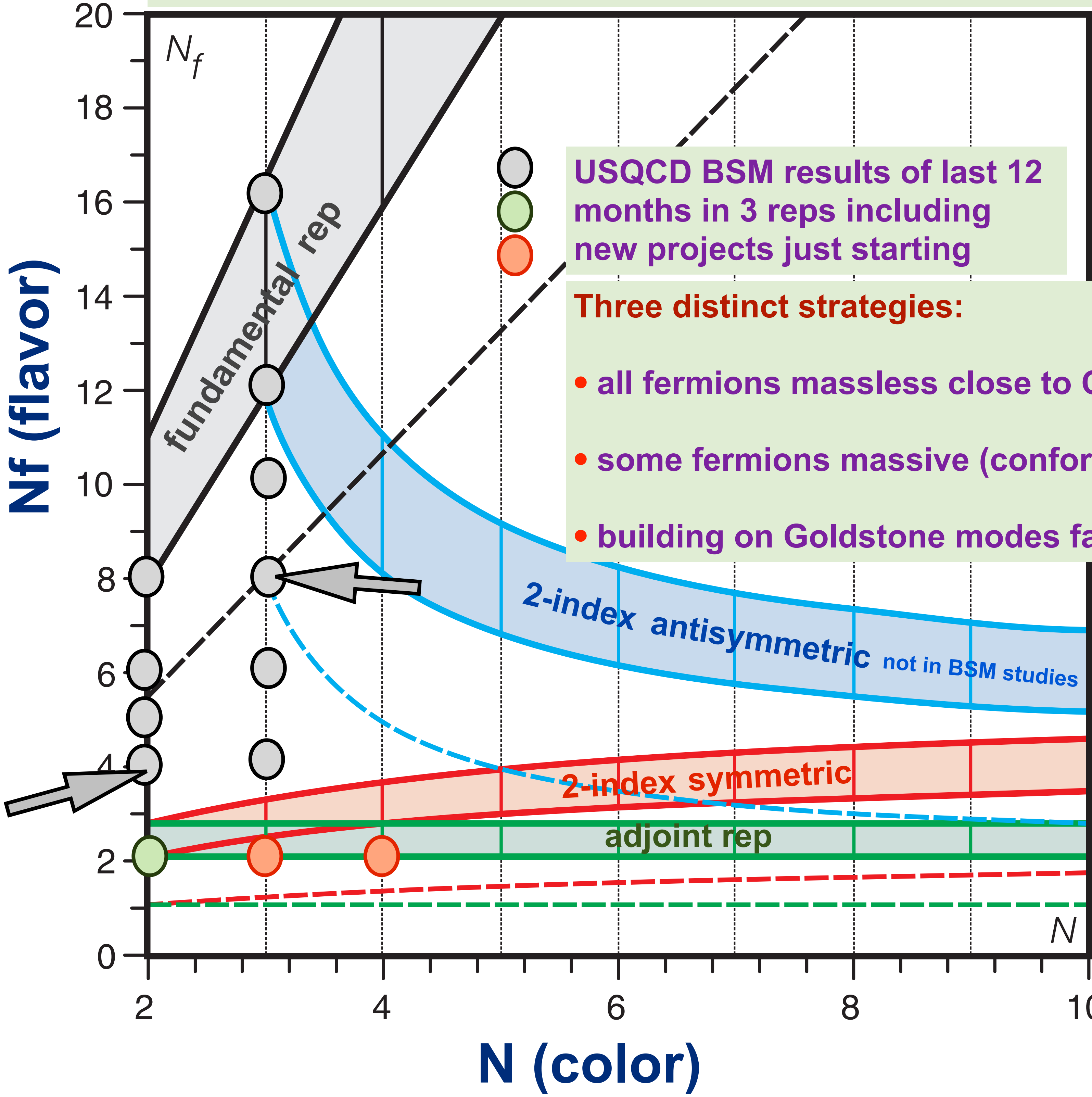

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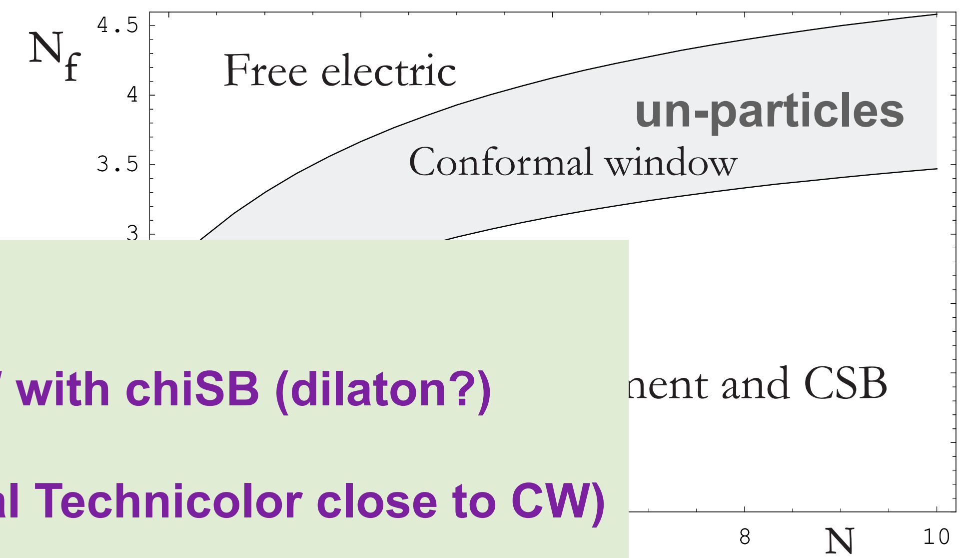

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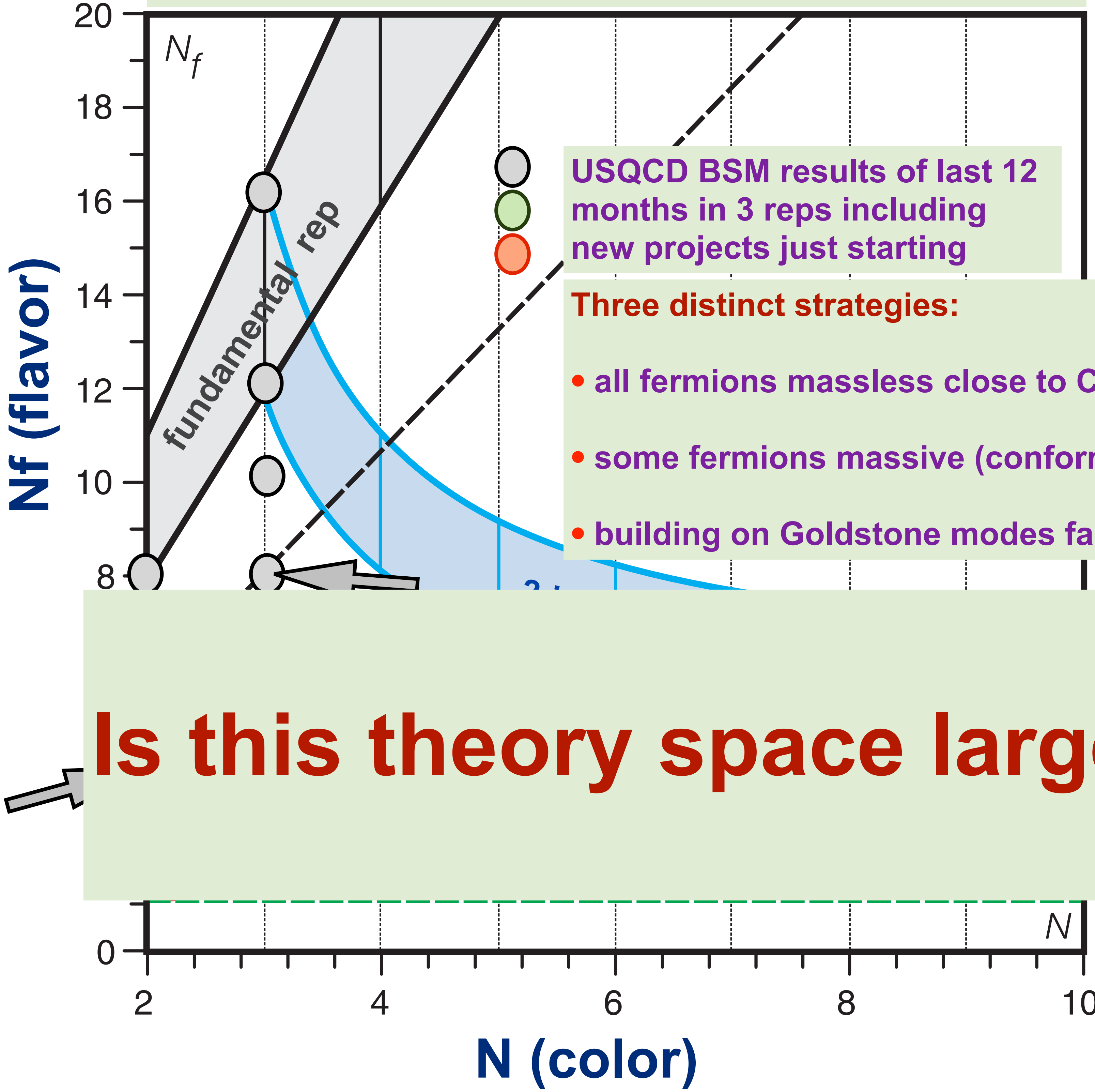

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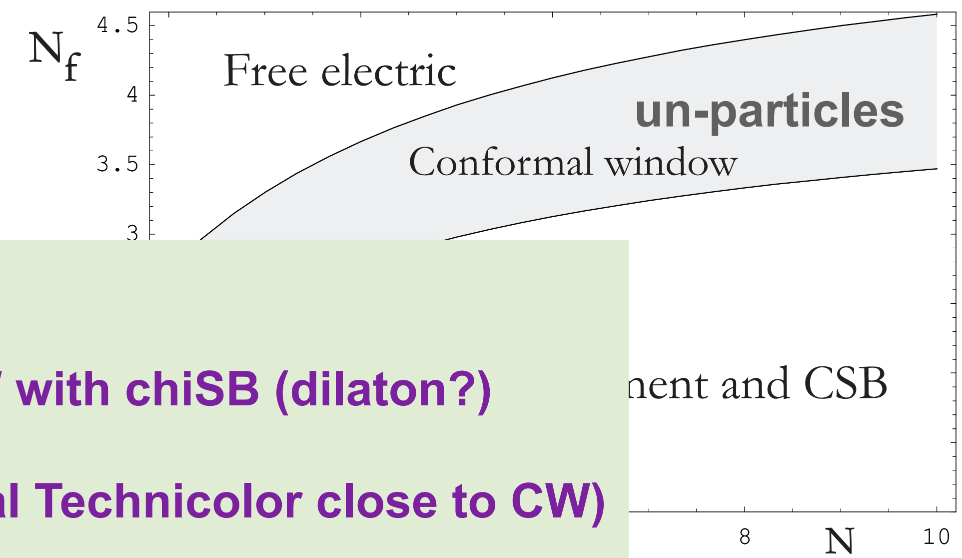

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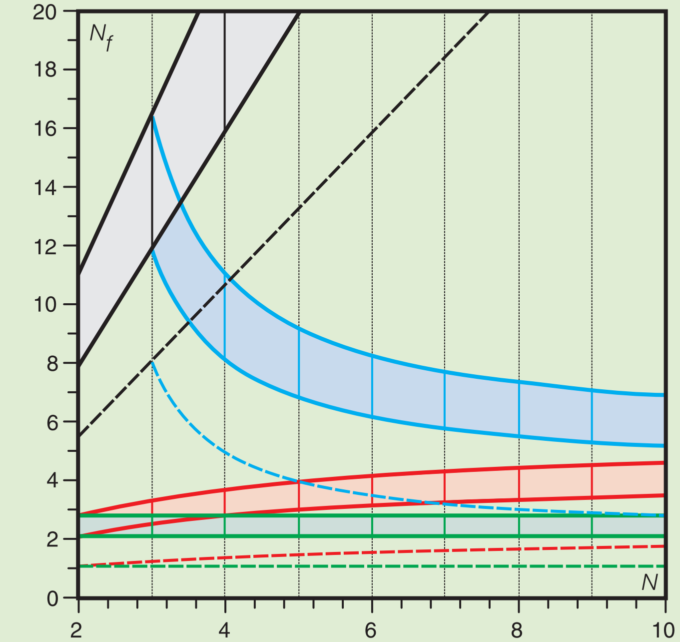

most projects stay close to conformal window

expected model features when “close enough”?

walking coupling?

separation of two scales to facilitate dilaton mechanism?

light scalar?

there are candidate models but only limited results

very difficult issues on-lattice and off-lattice

let us try first the simplest model:

simple realization of composite Higgs: Nf=2 SU(3) sextet representation

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original Technicolor paradigm replaced with
sextet SU(3) color rep:

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

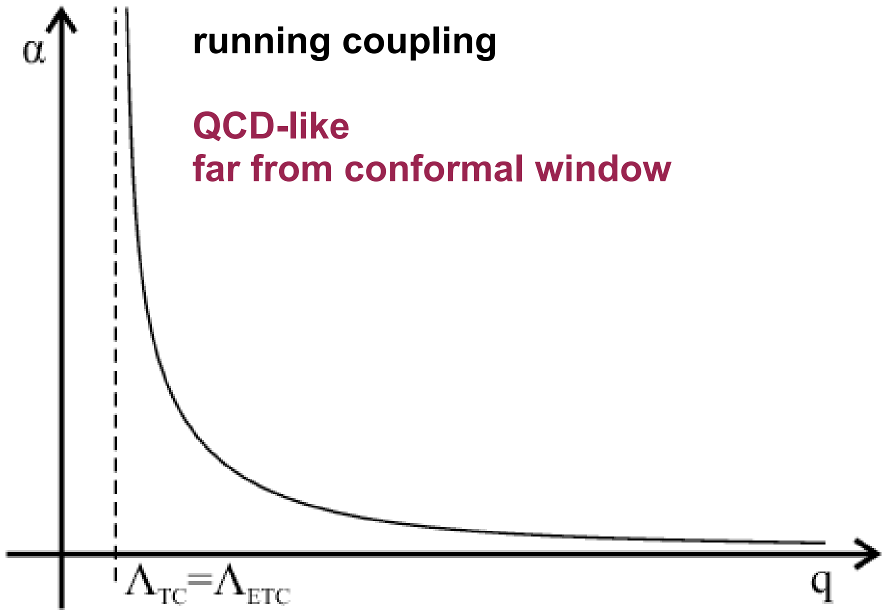
χSB on Λ~TeV scale

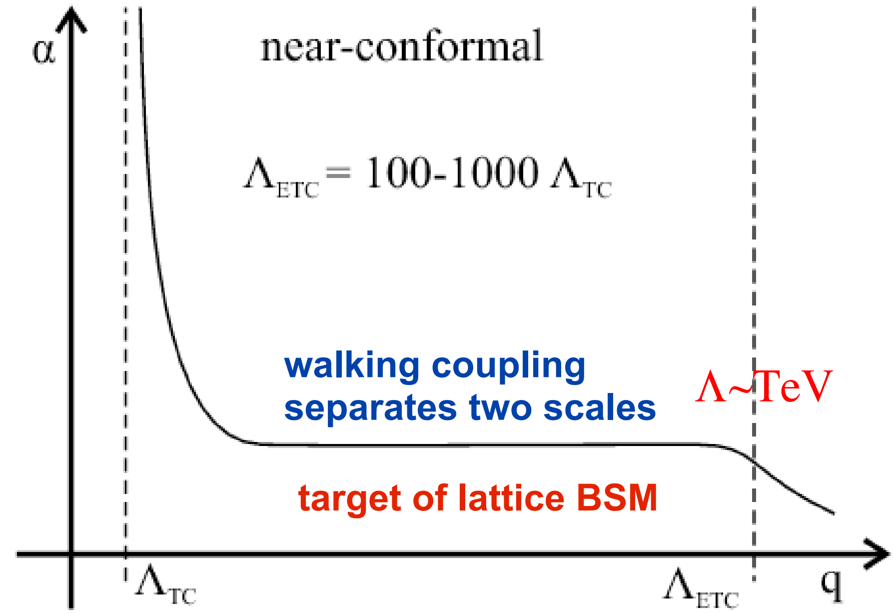
three Goldstone pions
become longitudinal
components of weak bosons

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

conflicts with EW precision constraints?

simple realization of composite Higgs: Nf=2 SU(3) sextet representation





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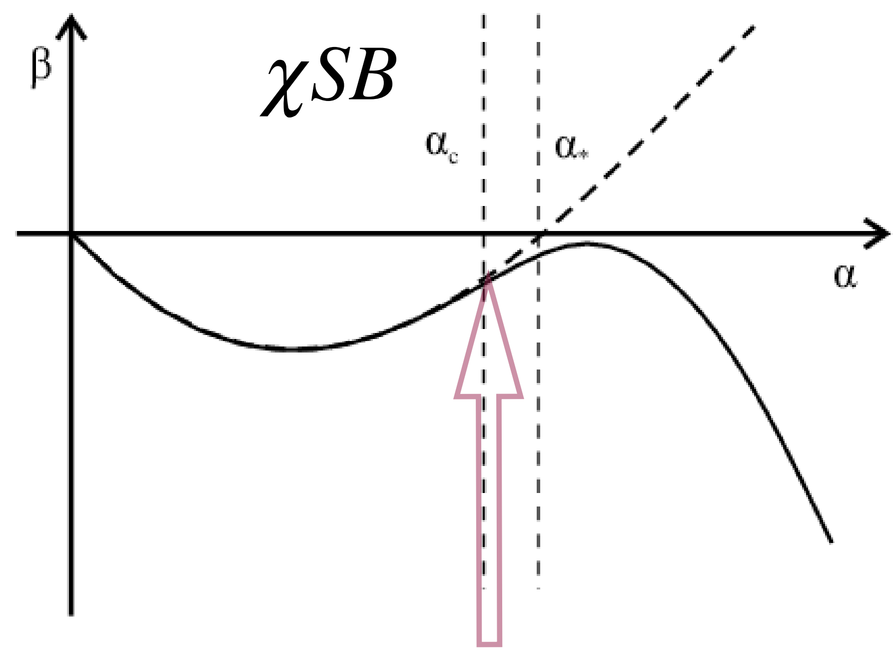

when chiral symmetry breaking
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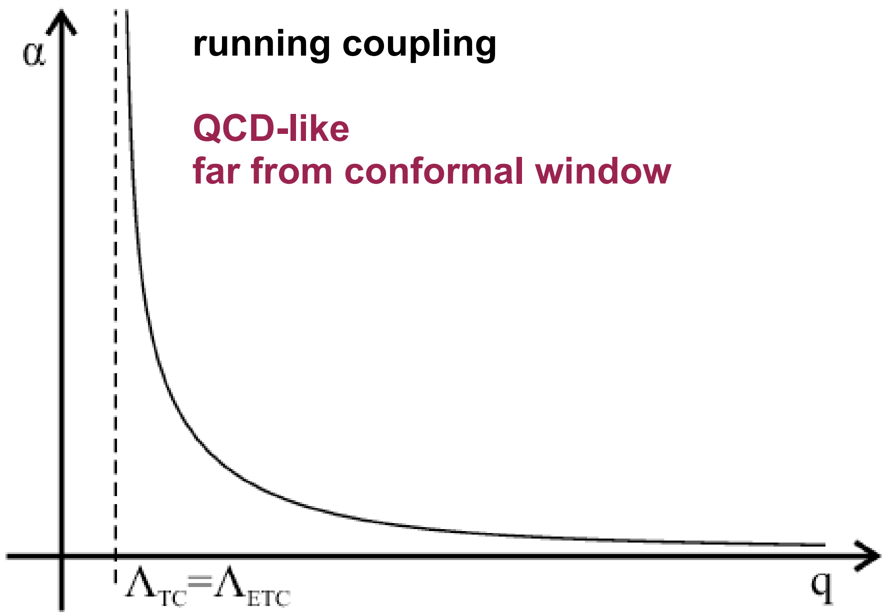

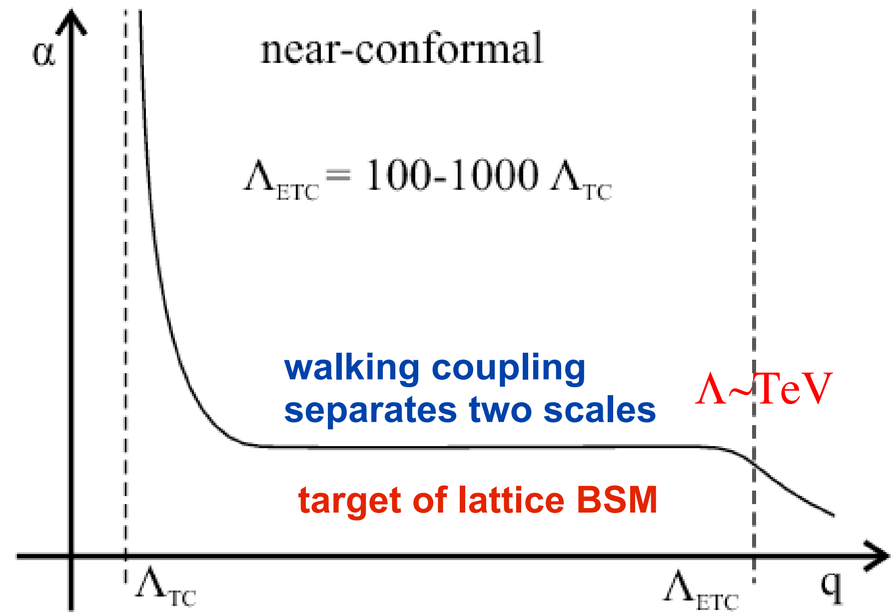

χSB on Λ~TeV scale

walking gauge coupling

fermion mass generation not addressed

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broken scale invariance (dilaton)
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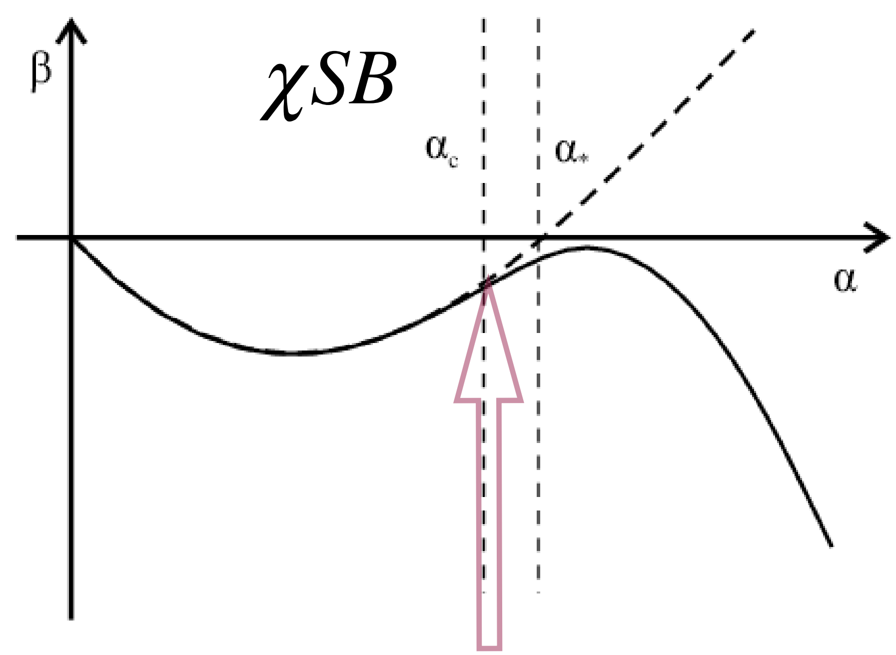

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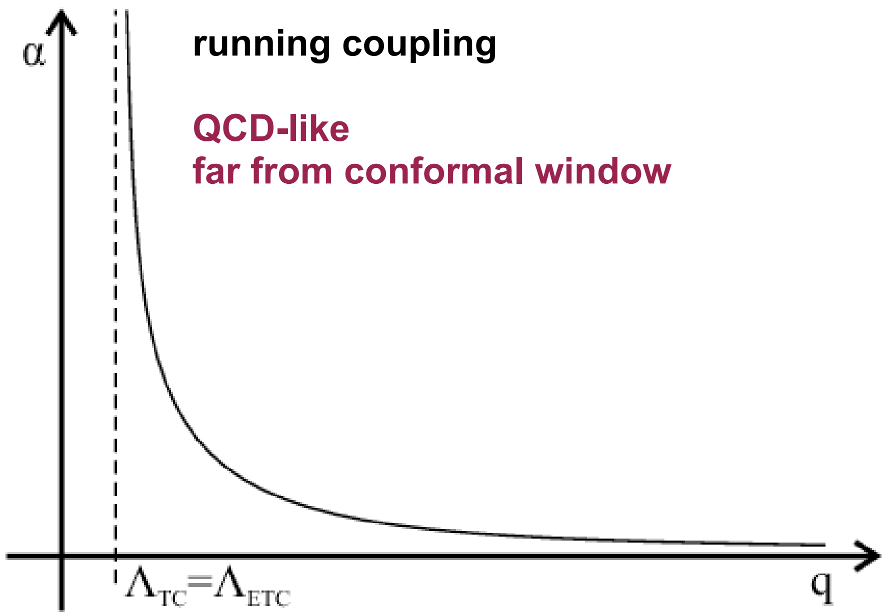

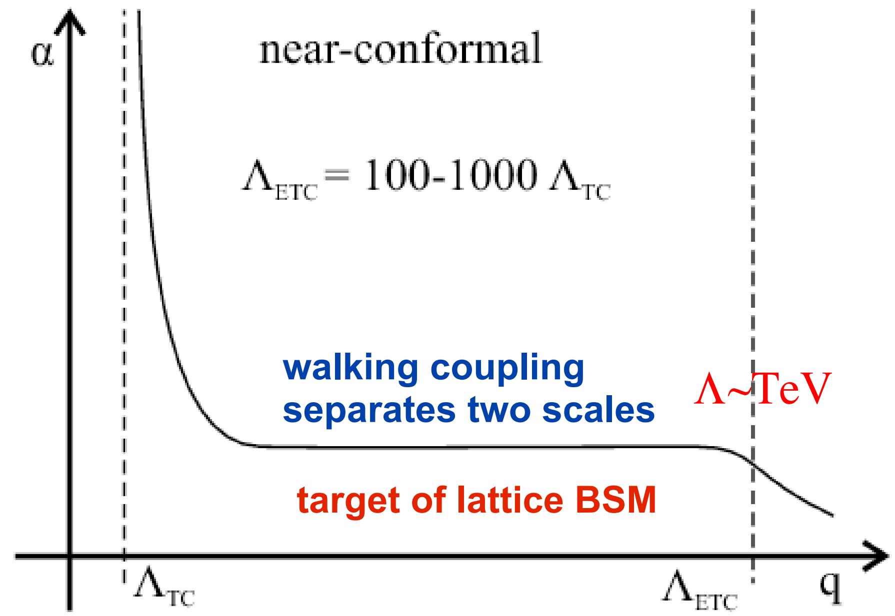

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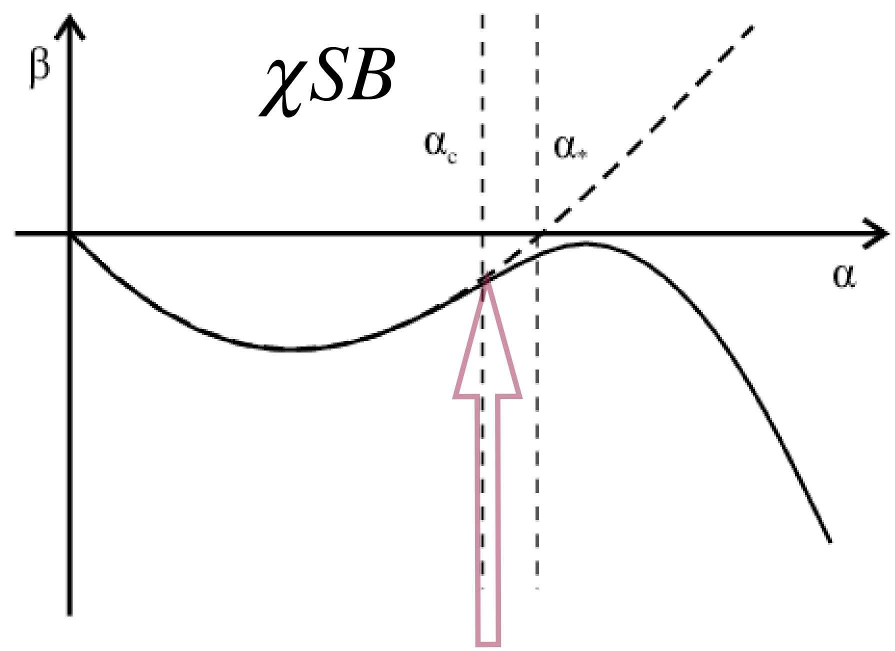

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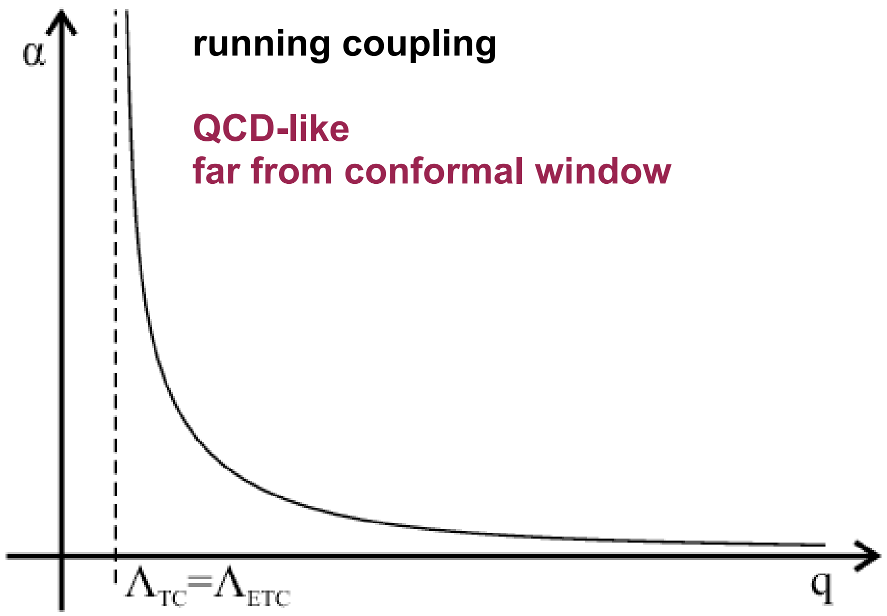

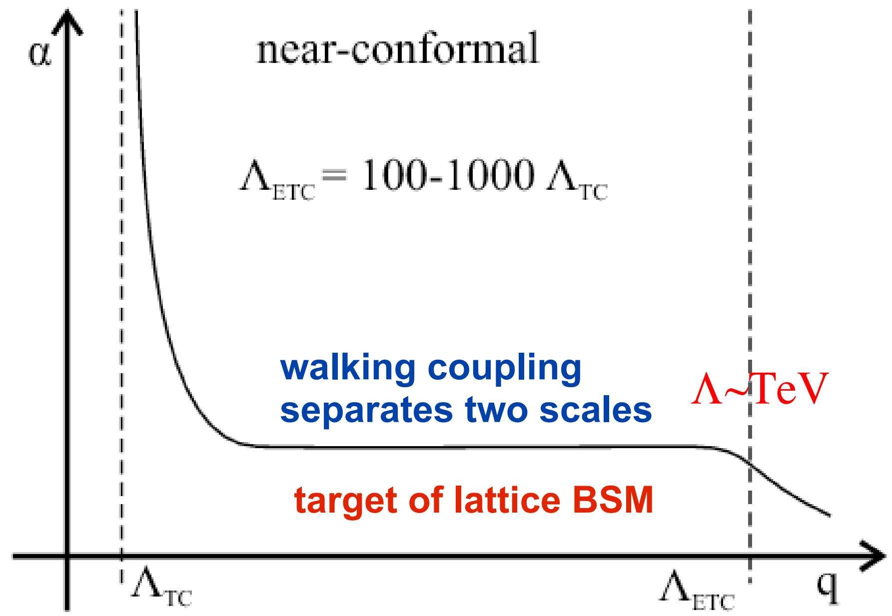

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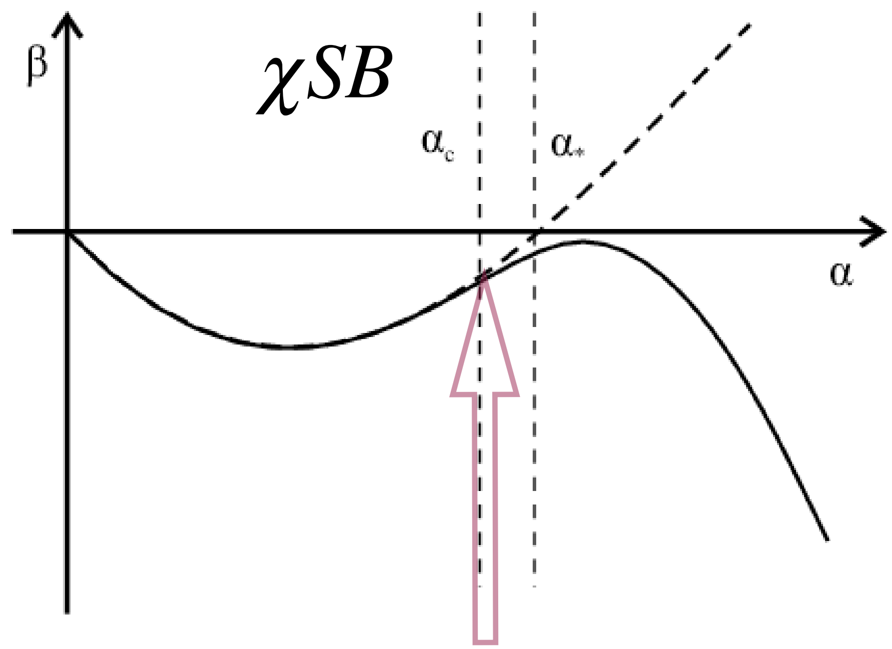

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role of third massive fermion flavor? Conformal Technicolor?

dilaton as Higgs impostor?

The dilaton: pseudo-Goldstone particle of broken scale invariance

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scale anomaly (RG invariant)

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

$$\mathcal{D}^\mu = \Theta^{\mu\nu} x_\nu$$

Dilatation current
symmetric energy-momentum tensor

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Looking for PCDC relation among three unknowns:

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2. dilaton decay constant f_σ
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long history of PCDC relation
only non-perturbative part kept in derivation

recently:
Bai and Appelquist Phys.Rev. D82 (2010) 071701
Matsuzaki and Yamawaki arXiv:1206.6703[hep-ph]

earlier:
Dietrich, Sannino, Phys.Rev. D 72 (2005) 055001
and others ...

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

Partially Conserved Dilatation Current (PCDC)

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Partially Conserved Dilatation Current (PCDC)

there are two different expectations on limit of right-hand side ratio when conformal window is approached:

1. dilaton mass parametrically vanishes when CW approached $m_\sigma^2 \simeq (N_f^c - N_f)\cdot\Lambda^2$ **Bai and Appelquist**

$g(\mu=\Lambda)=g_c$ **where ChiSB is triggered**

$\frac{m_\sigma}{f_\sigma}\to 0$

2. dilaton mass remains finite in the limit as measured in $f_\sigma \simeq \Lambda$ **units** **Yamawaki et al.** $\frac{m_\sigma}{f_\sigma}\to const$

Realistic BSM models have not been built with parametric tuning close to the conformal window. For example, the sextet model is at some intrinsically determined position near the conformal window and only non-perturbative lattice calculations can explore the physical properties of the scalar particle.

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there are two different expectations on limit of right-hand side ratio when conformal window is approached:

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is this separation meaningful? **G. Rossi**

better lattice methods?

BSM lattice tools and tasks?

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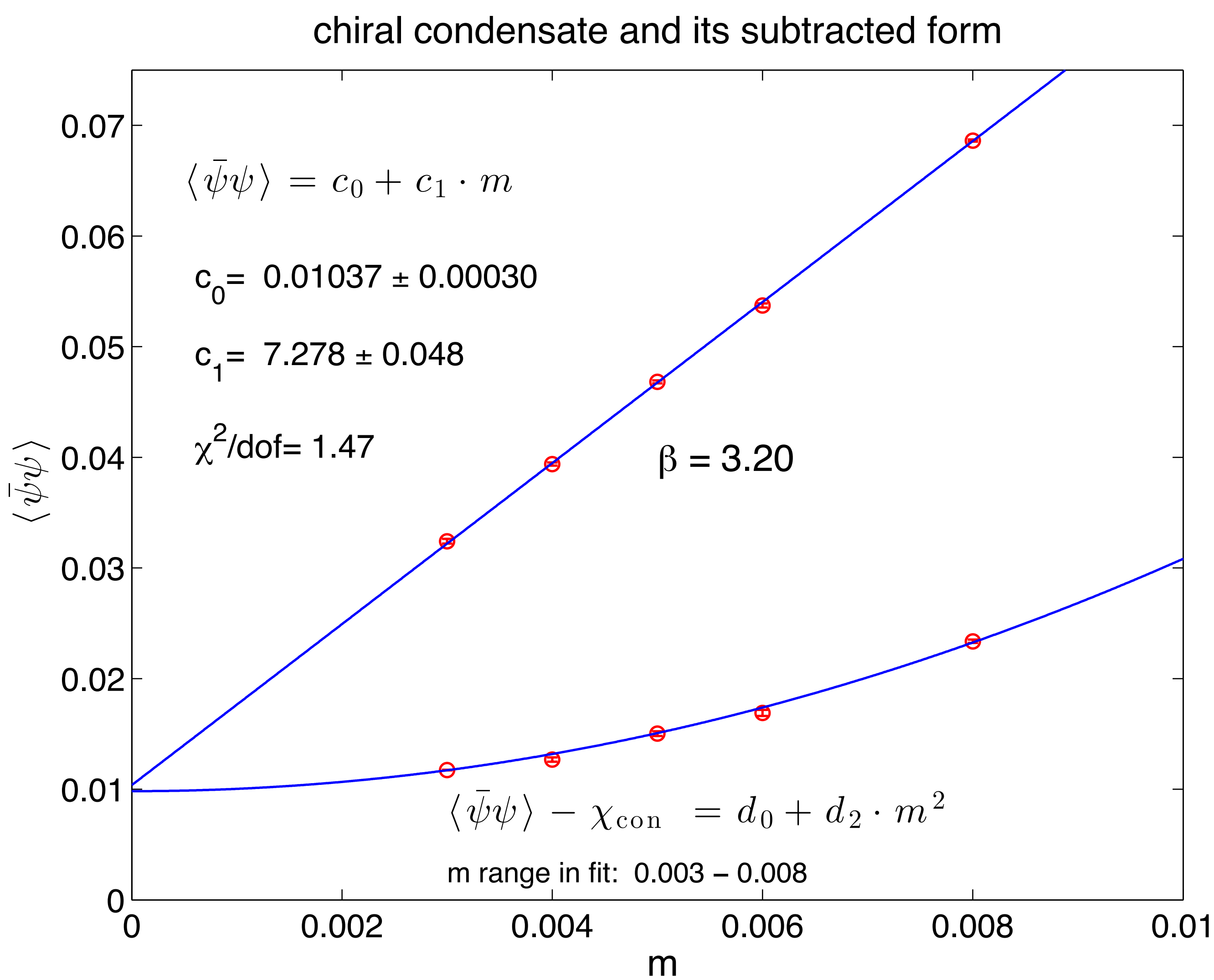
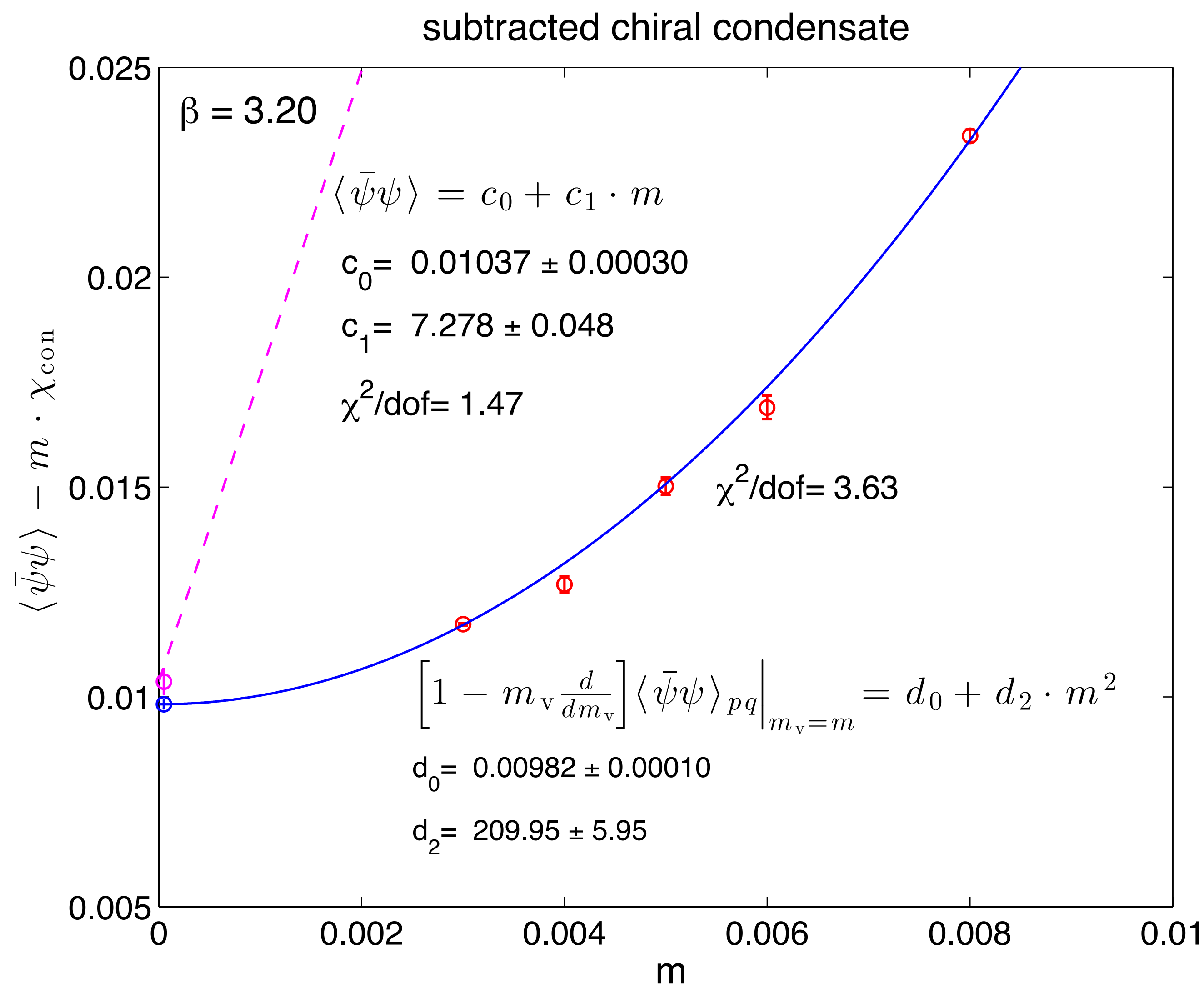
hard even in QCD where we know the answer!

and we have only a small fraction of QCD resources chiral symmetry breaking at $m \neq 0$

Nf=2 SU(3) sextet chiral condensate





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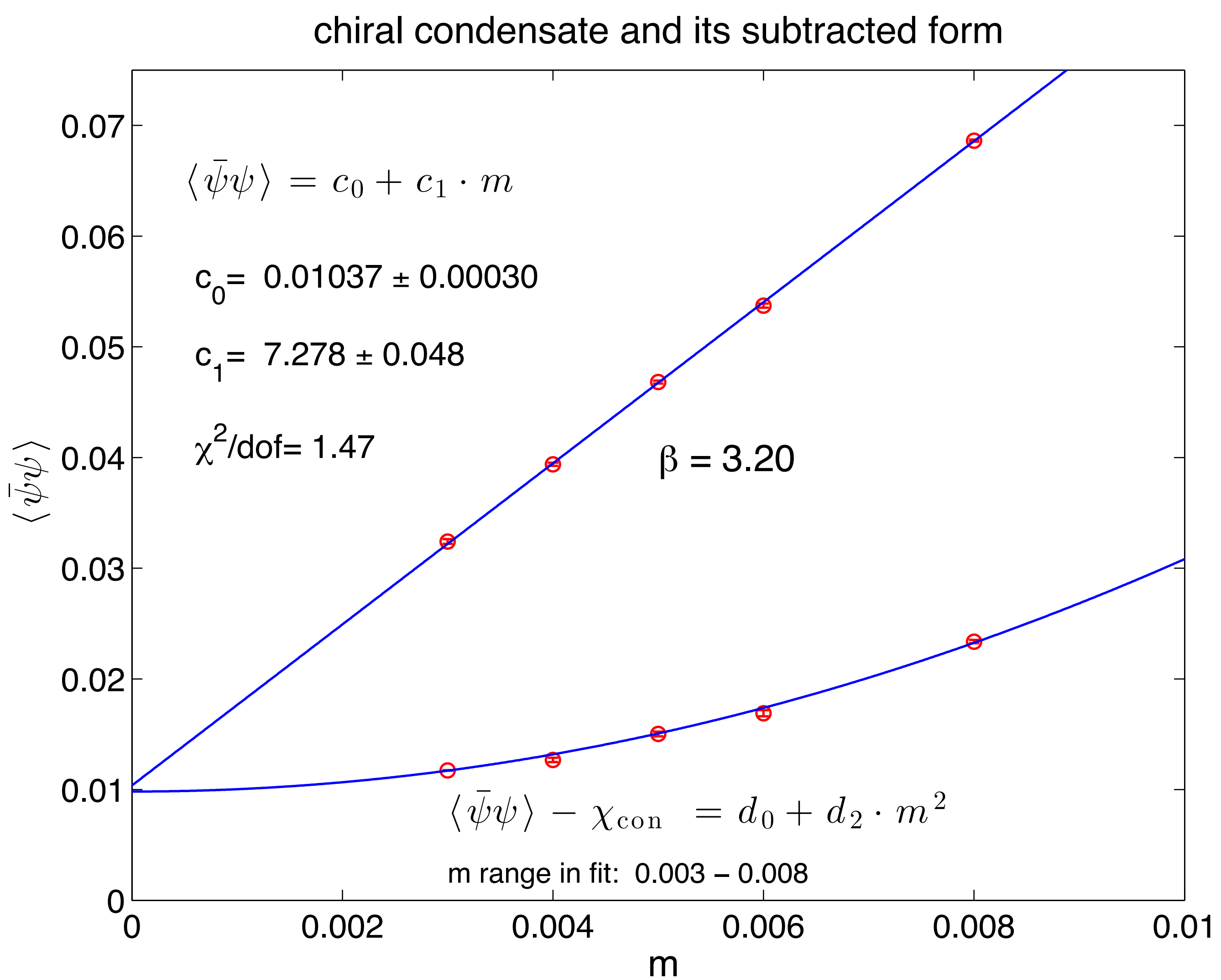

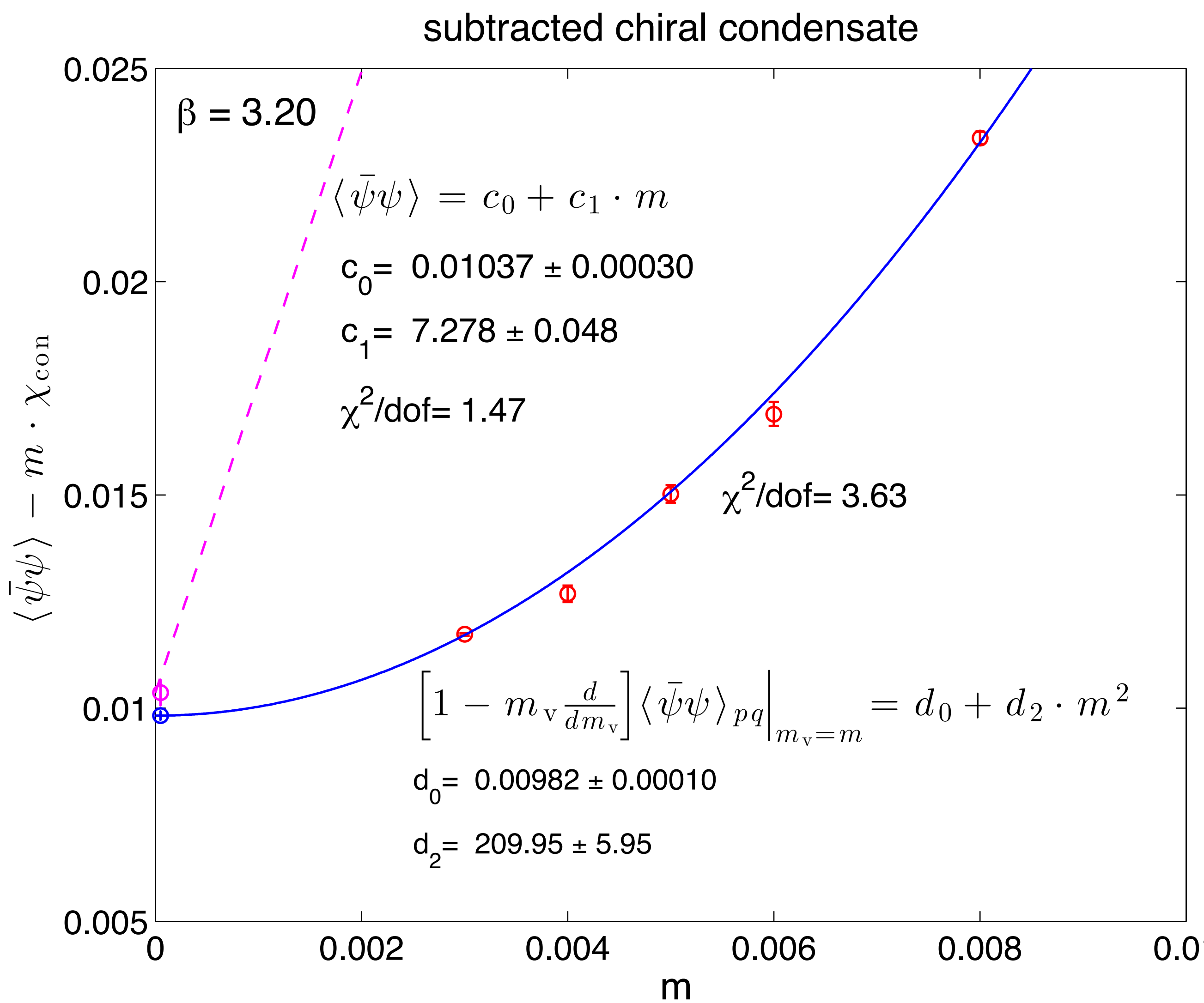

two independent determinations of the chiral condensate

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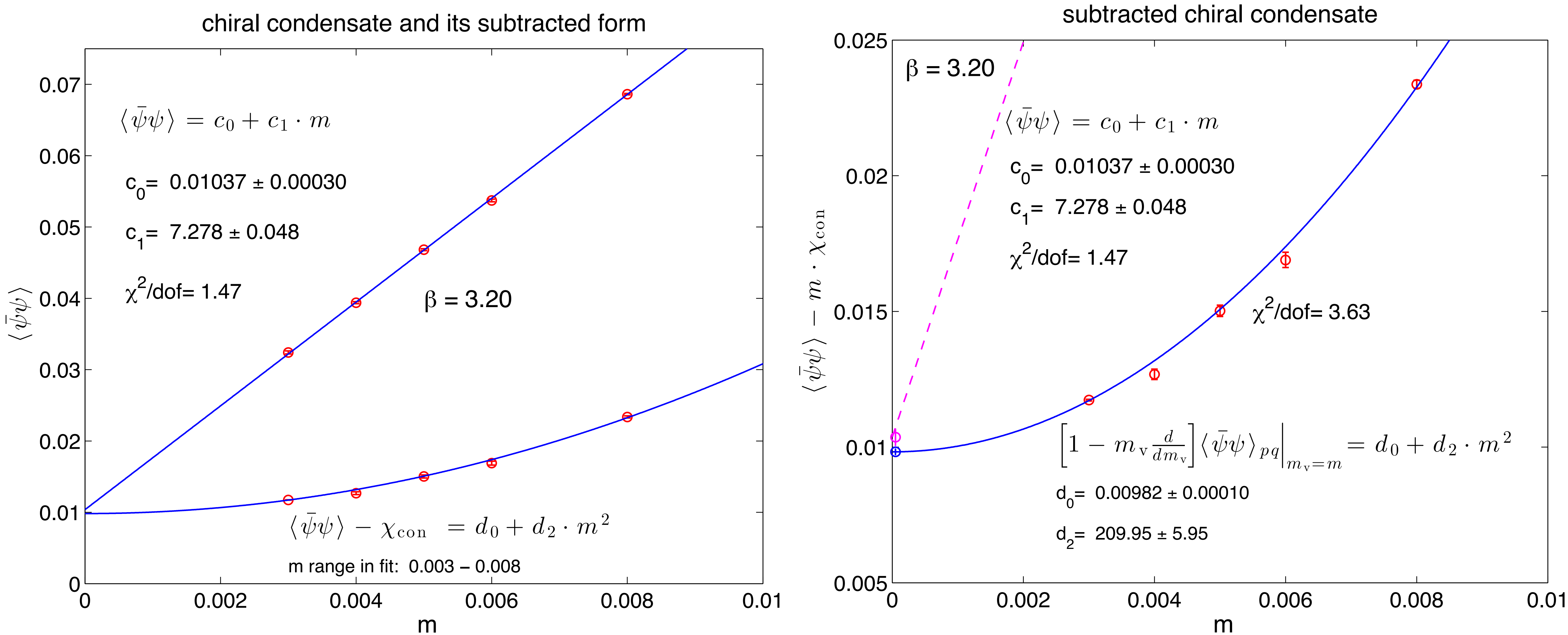

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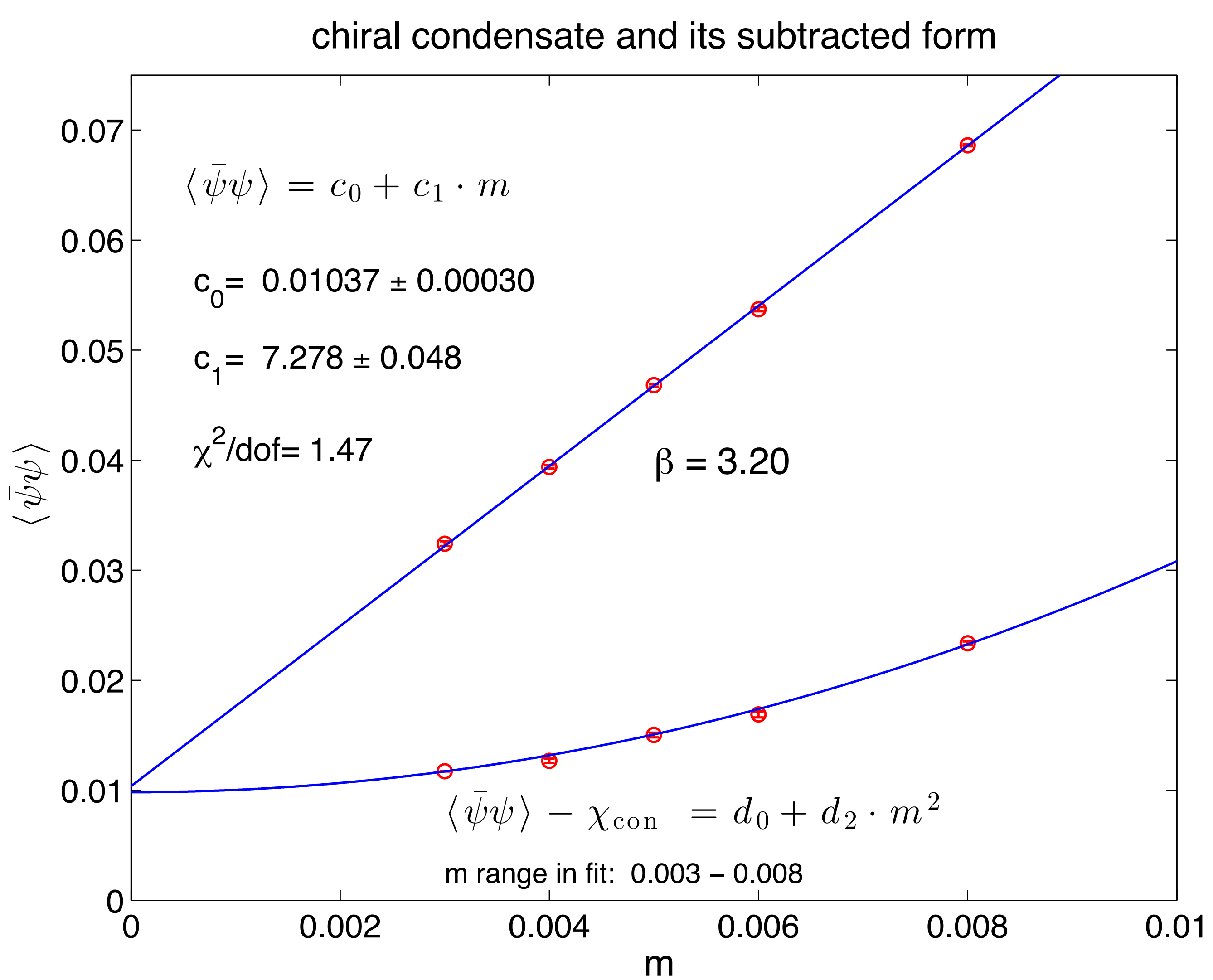

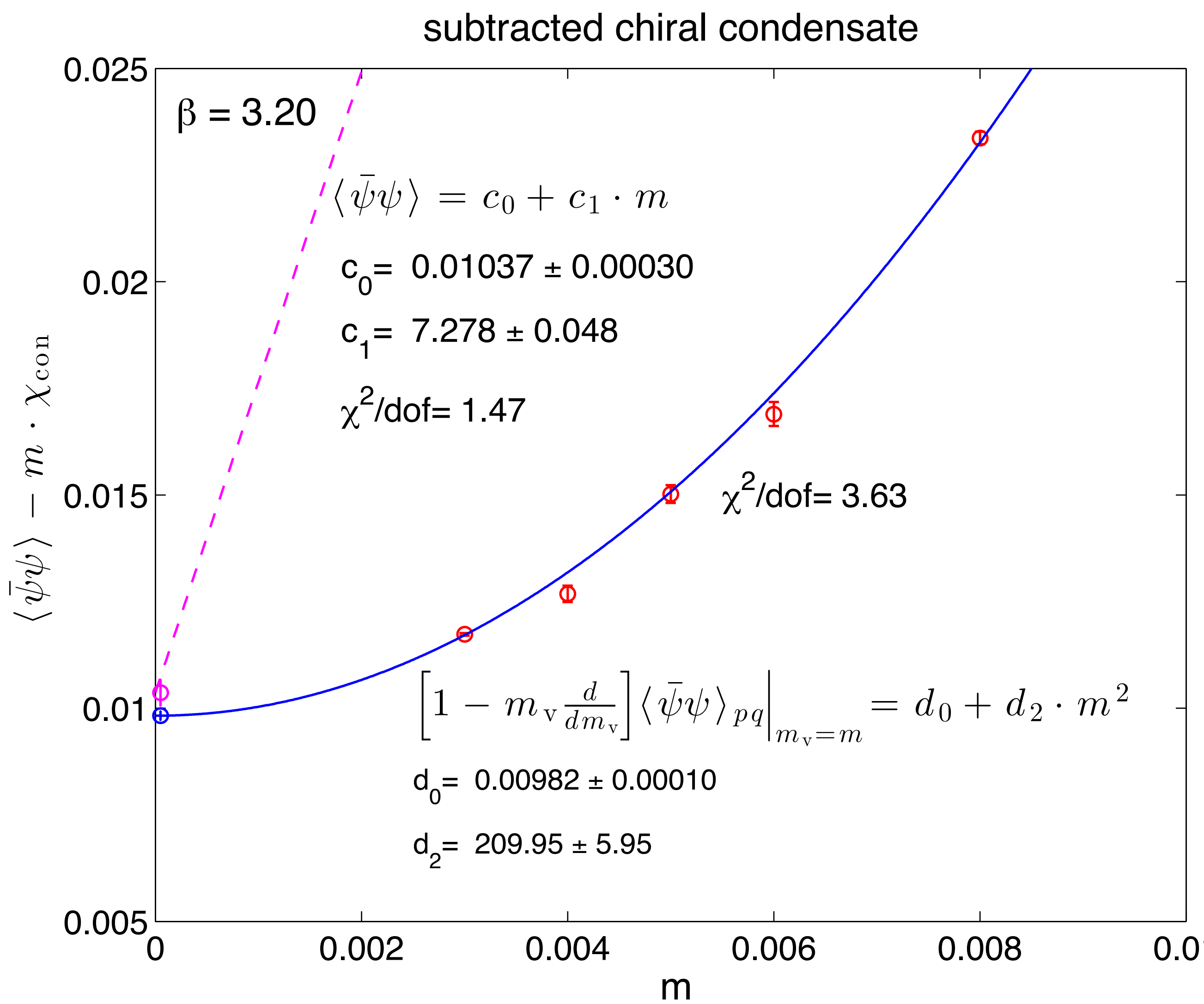

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consistently non-vanishing in chiral limit

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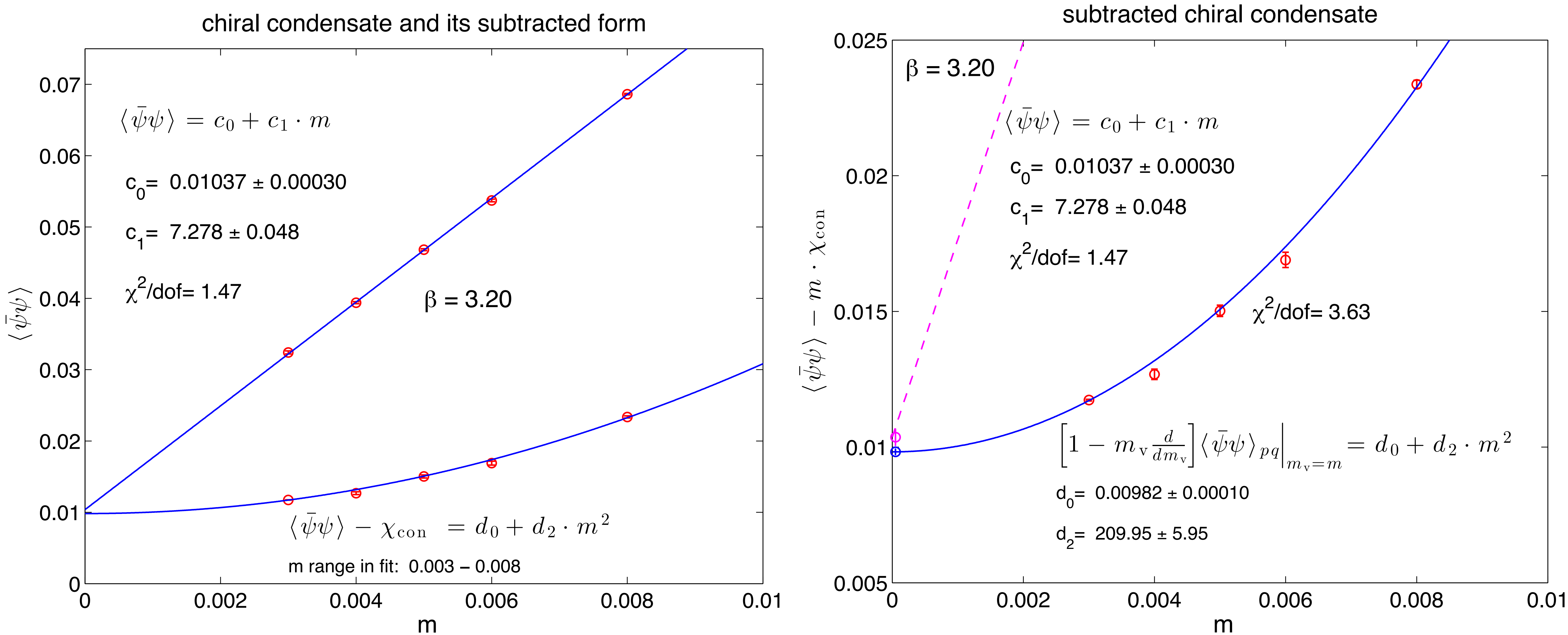

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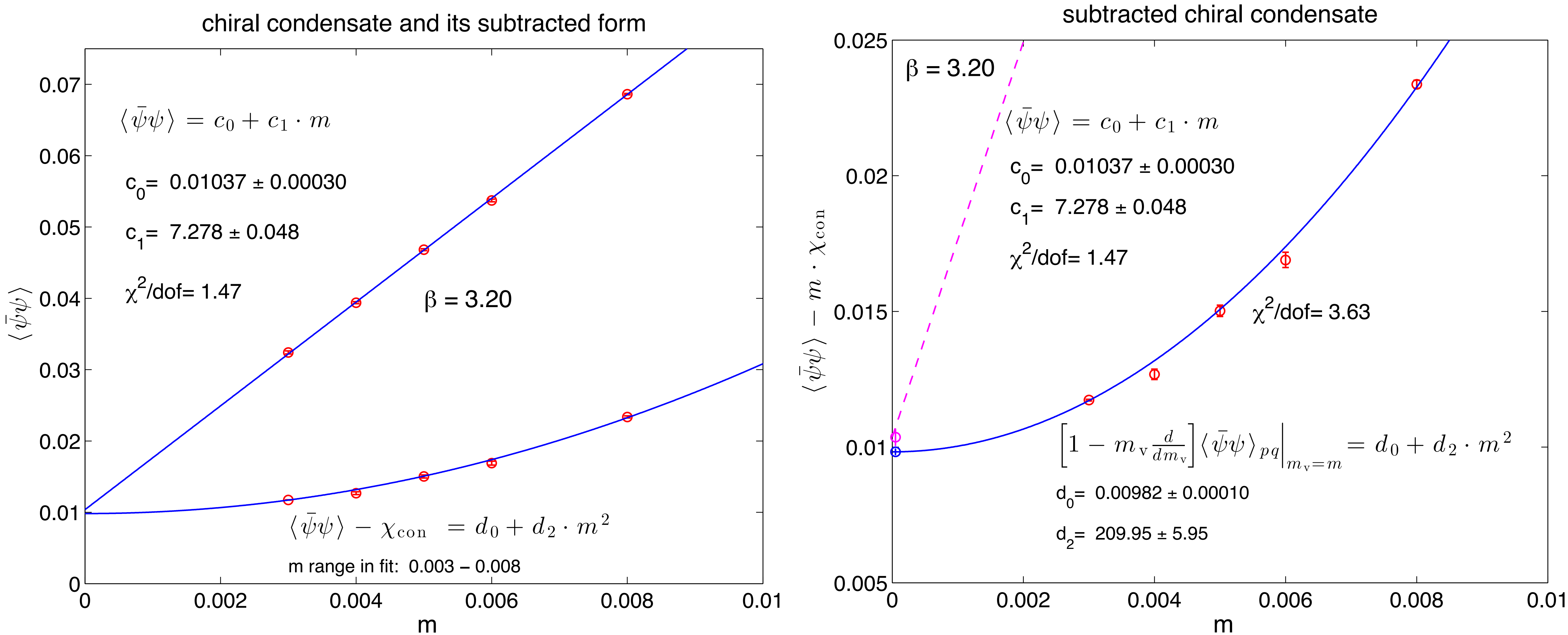

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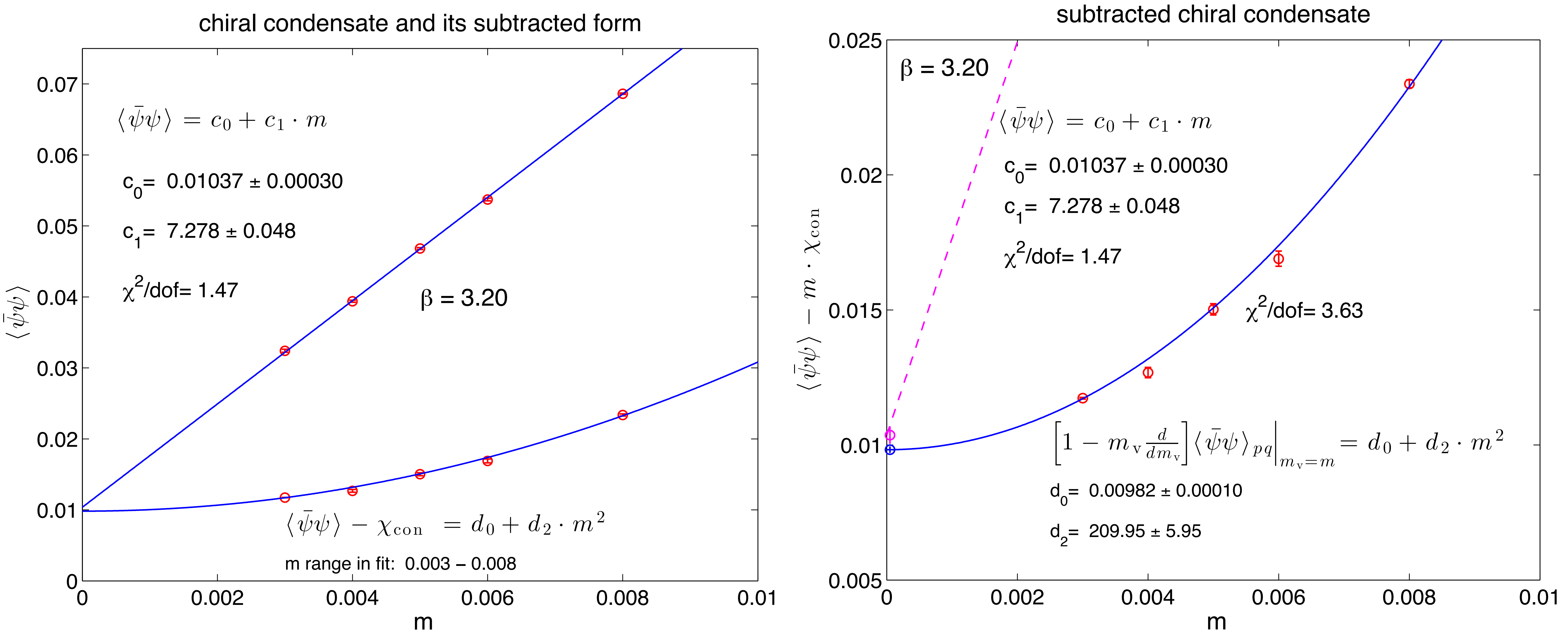

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spectral density analysis more powerful (Giusti and Luscher, Boulder group, Patella ...)

complete control on UV divergences: node 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

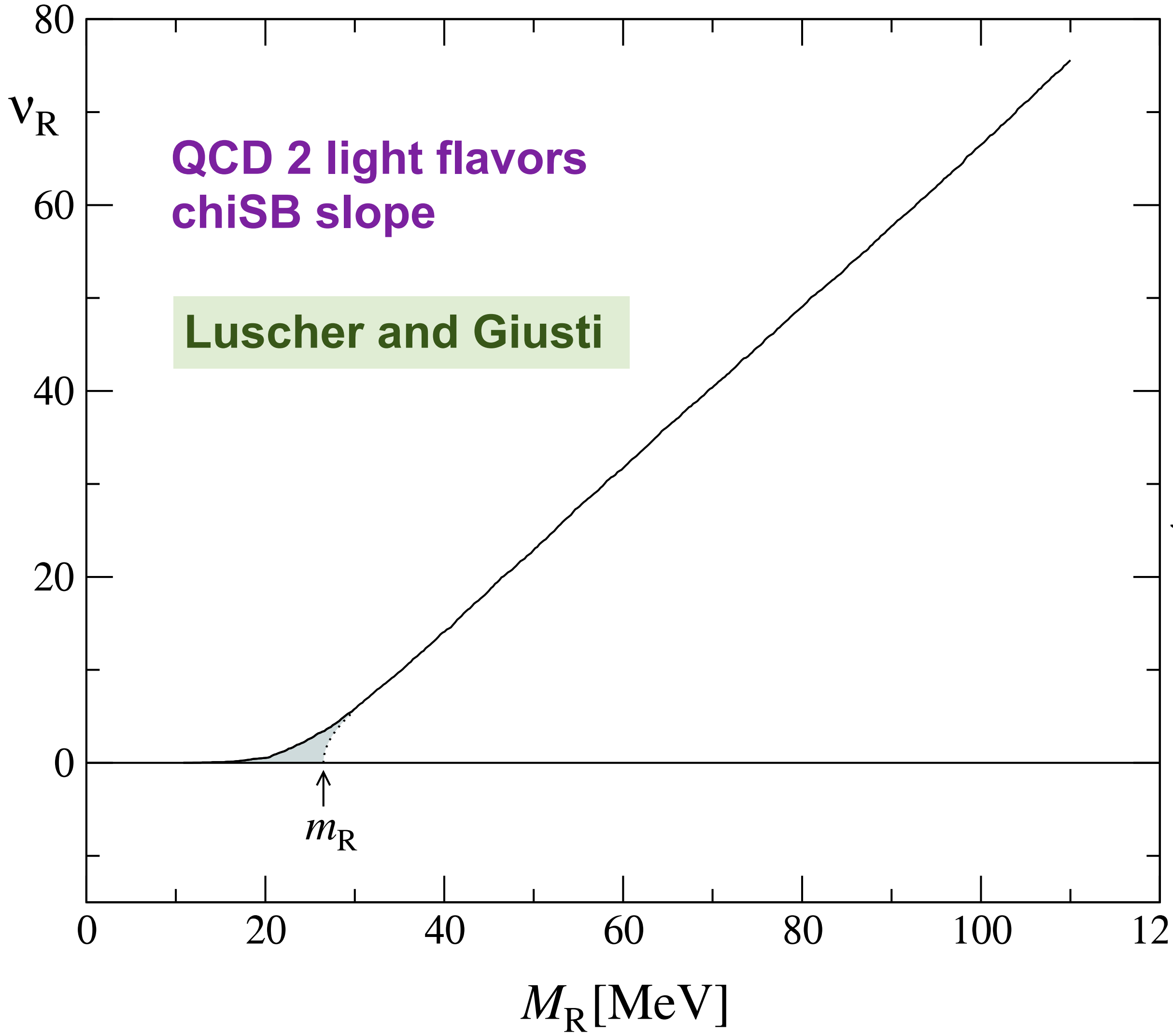
$$\nu(M,m) = V\int_{-\Lambda}^{\Lambda} \mathrm{d}\lambda\, \rho(\lambda,m), \qquad \Lambda = \sqrt{M^2 - m^2}$$

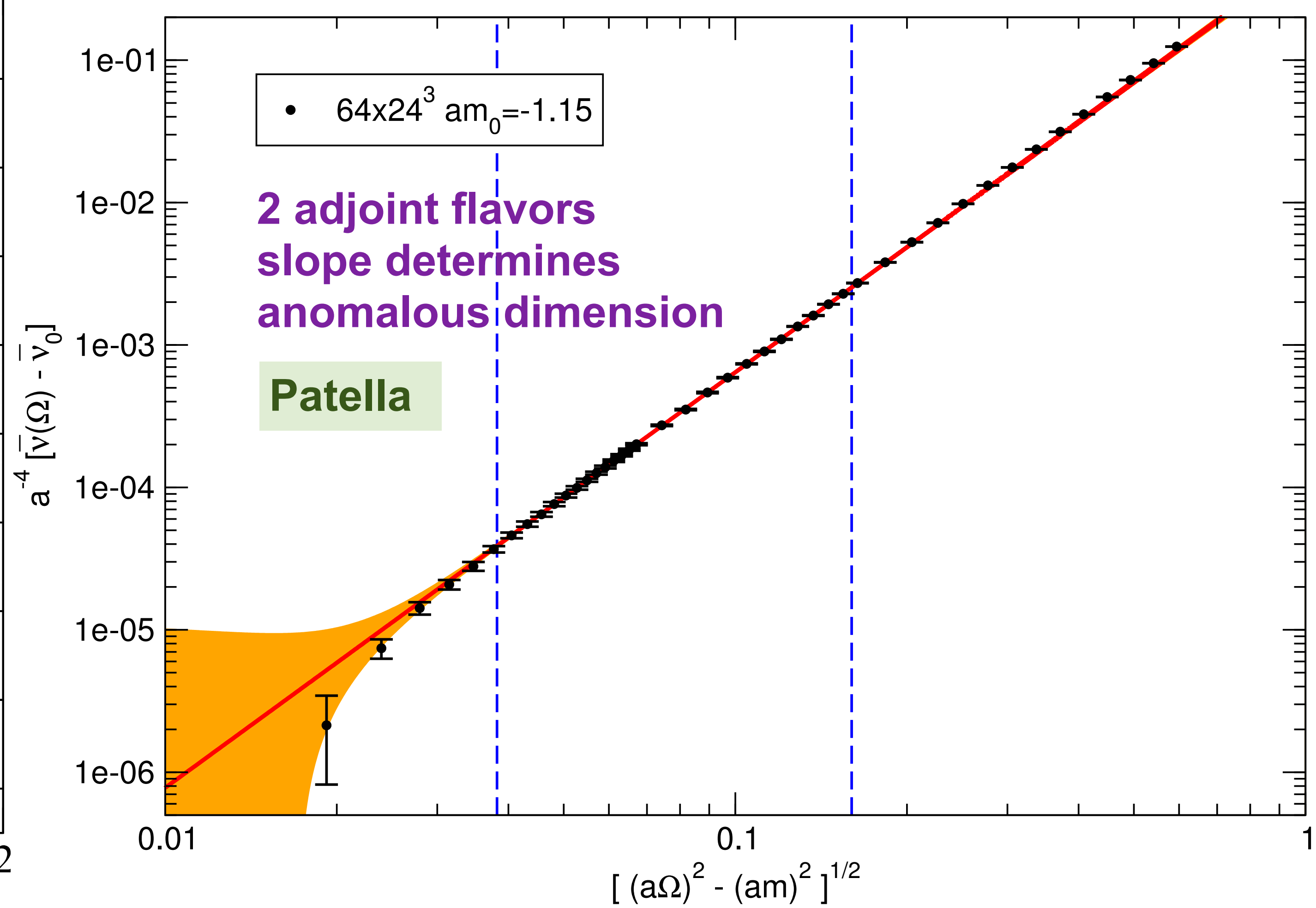
node number density

$$\nu_{\mathrm{R}}(M_{\mathrm{R}}, m_{\mathrm{R}}) = \nu(M, m_{\mathrm{q}})$$

renormalized and RG invariant

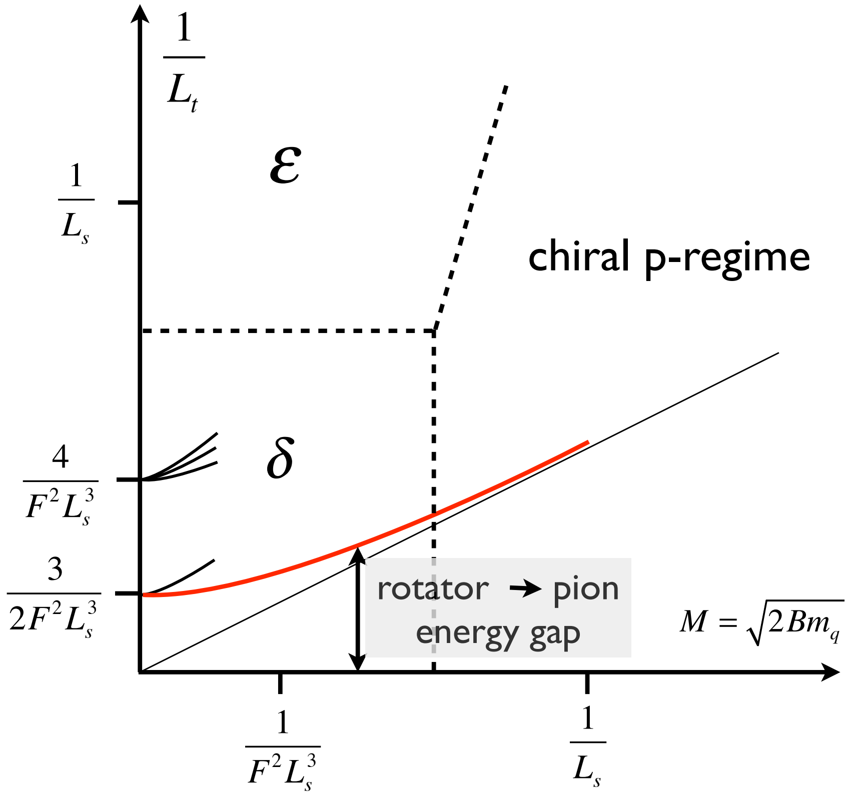
Luscher and Giusti
Boulder group (Schaich talk?)
Patella
earlier DeGrand

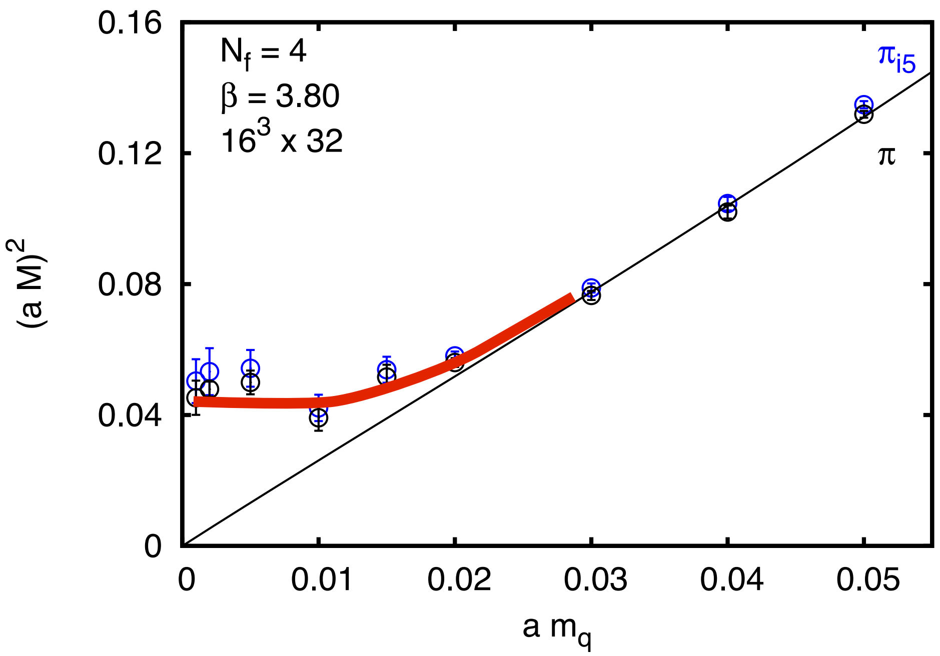




spectroscopy and force $m \neq 0$

mass deformed chiral SB in finite volume below conformal window:





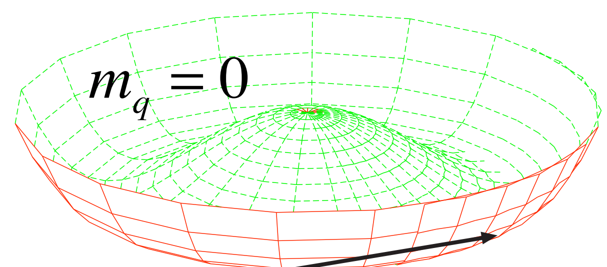
Goldstone dynamics is different in each regime

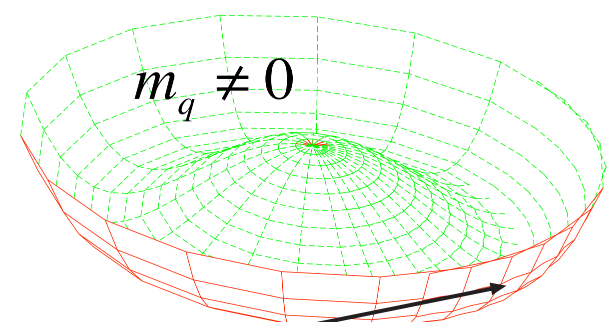
study of δ and ε-regimes (RMT)

and p-regime (probing chiral loops)

complement each other

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

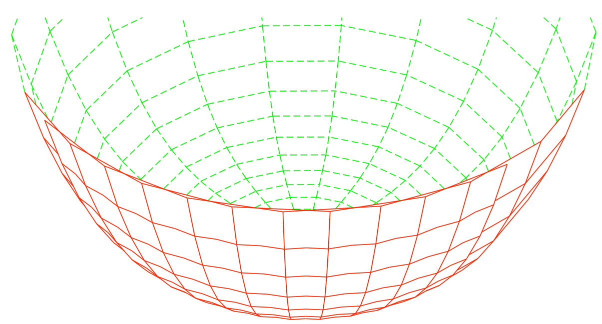




Veff: chiral condensate in flavor space

arbitrary orientation of condensate

tilted condensate



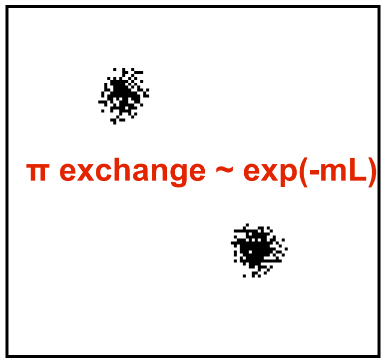
Not to misidentify rotator gaps as evidence of chirally symmetric phase !

sextet simulations are in the p-regime β=3.2 and β=3.25

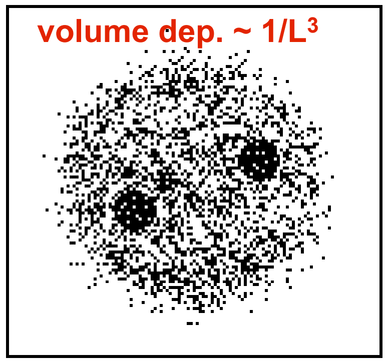
crossover of asymptotic finite volume behavior :

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

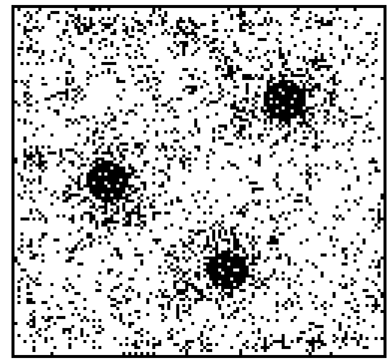
large volume
hadrons point-like



squeezed wave-function



crossover to femto world



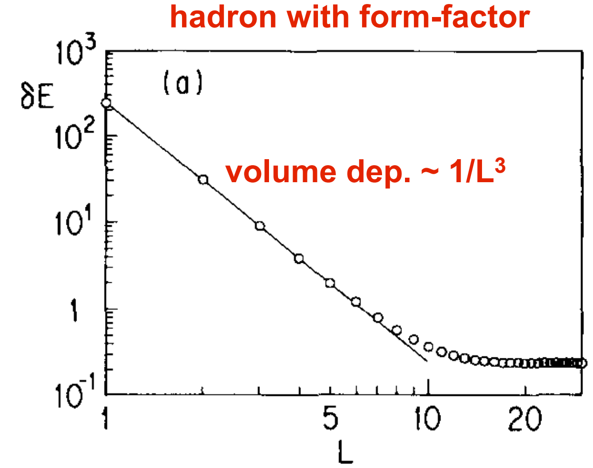
$$\delta E = \sum_{\vec{n}} V(\vec{n}L)$$ hadrom self energy from interaction with images

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

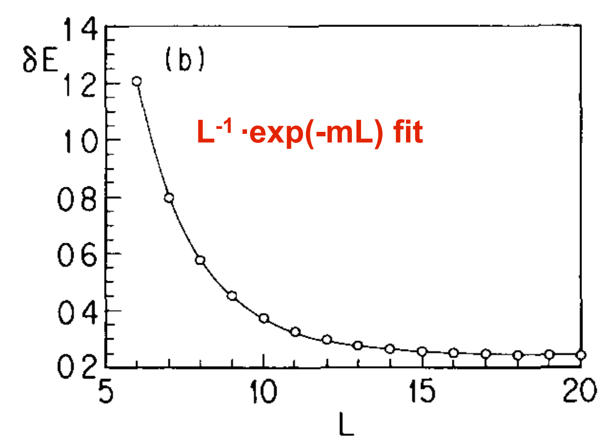
$$\hat{V}(\vec{k}) = \frac{1}{\vec{k}^2 + m^2} \Rightarrow \text{V(r)} = \frac{e^{-mr}}{r}$$ for large r in point-like approximation

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

hadron with form-factor



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



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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

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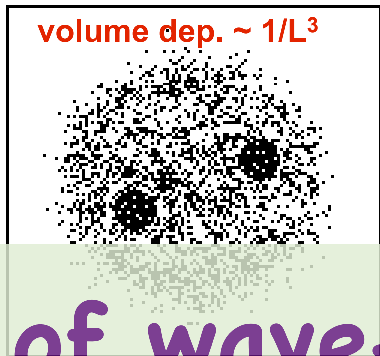

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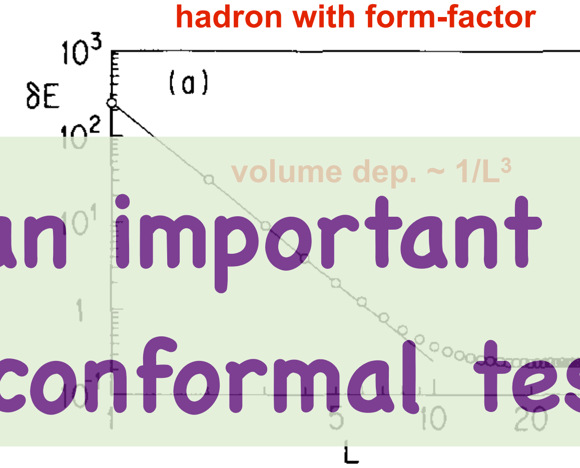

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Squeezing of wave-functions is an important effect potentially confusing chiral and conformal tests

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

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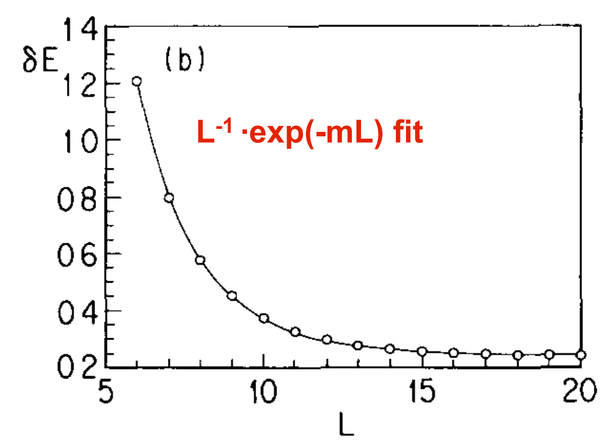

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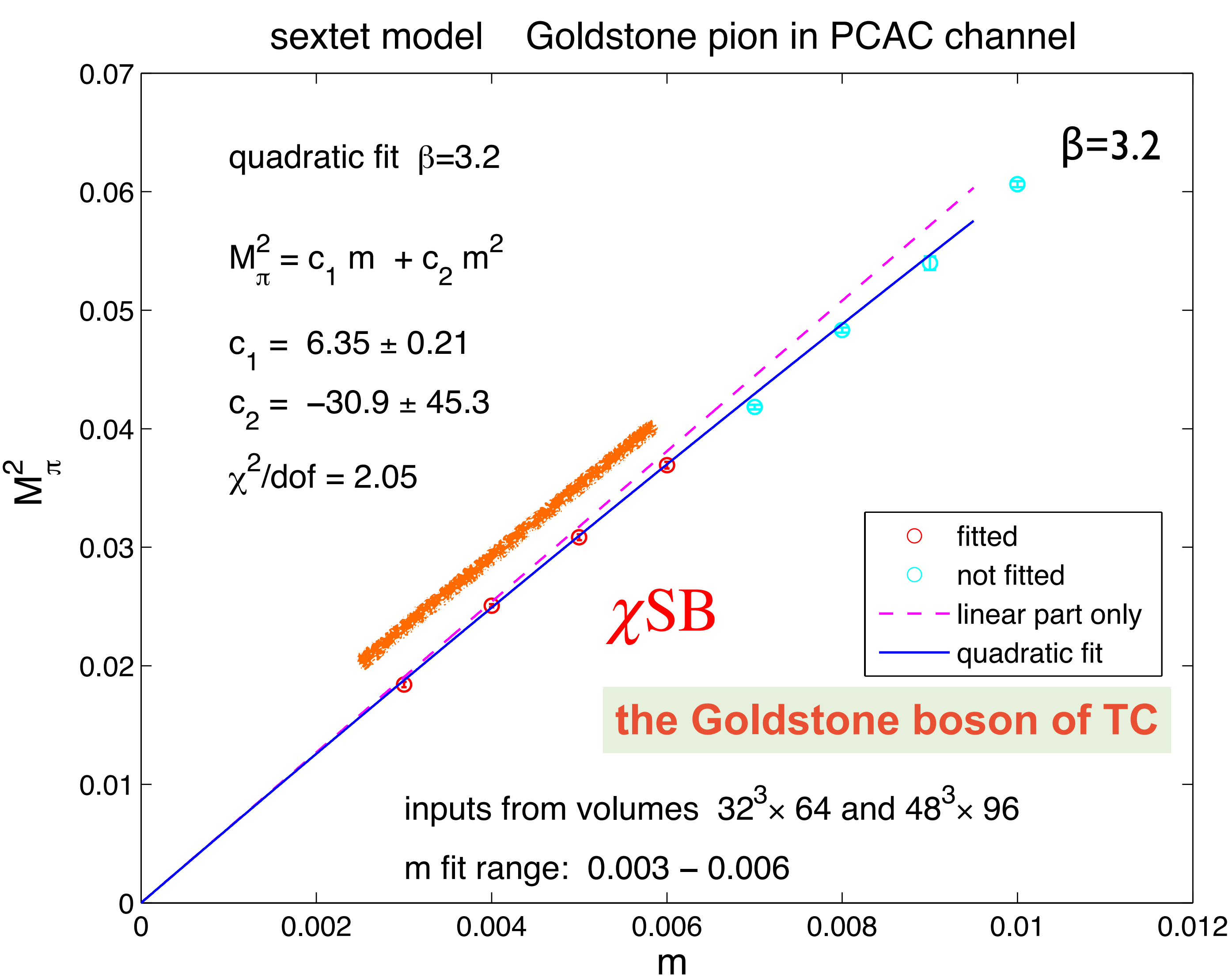
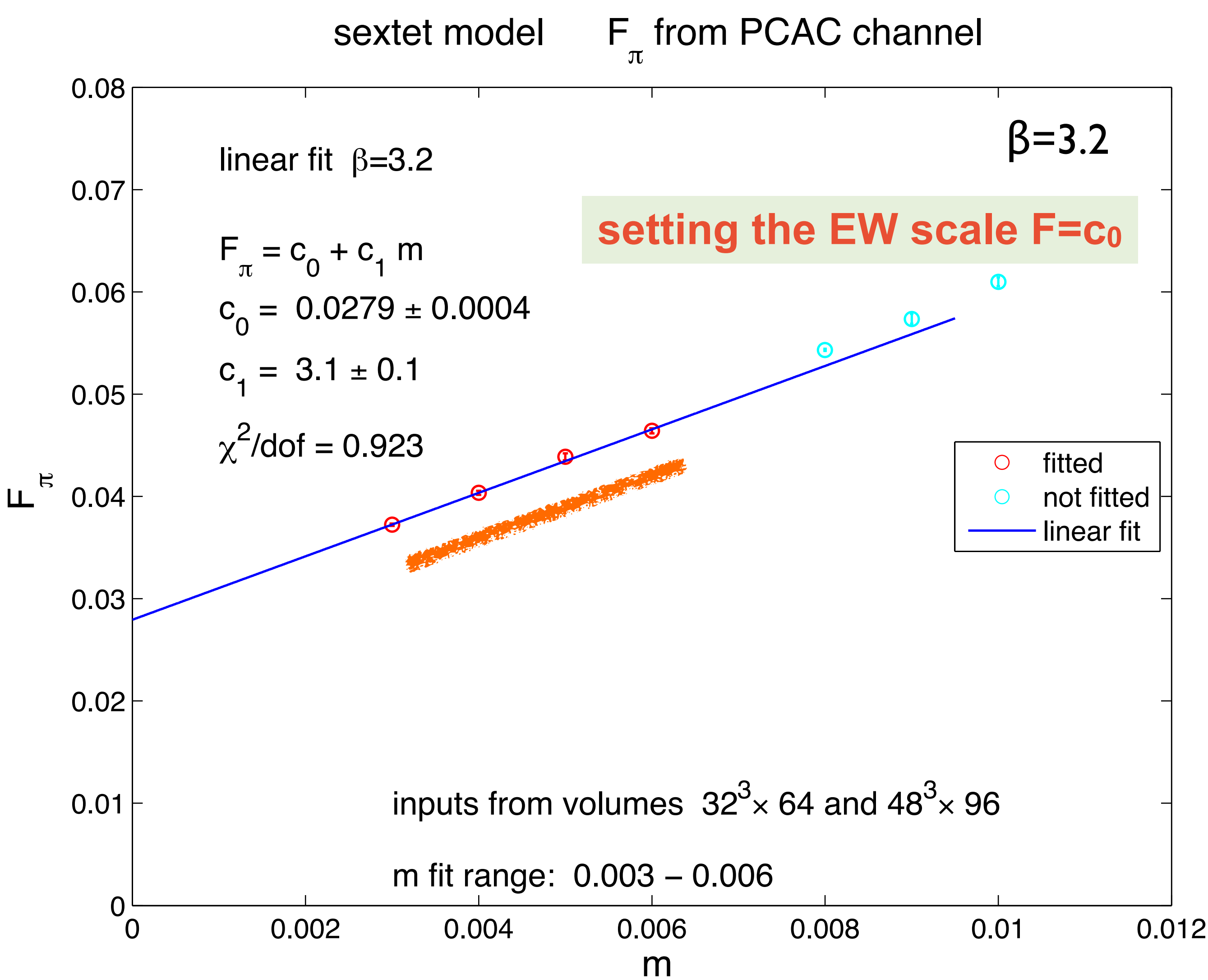
Nf=2 SU(3) sextet chiral fits of M_π and F_π



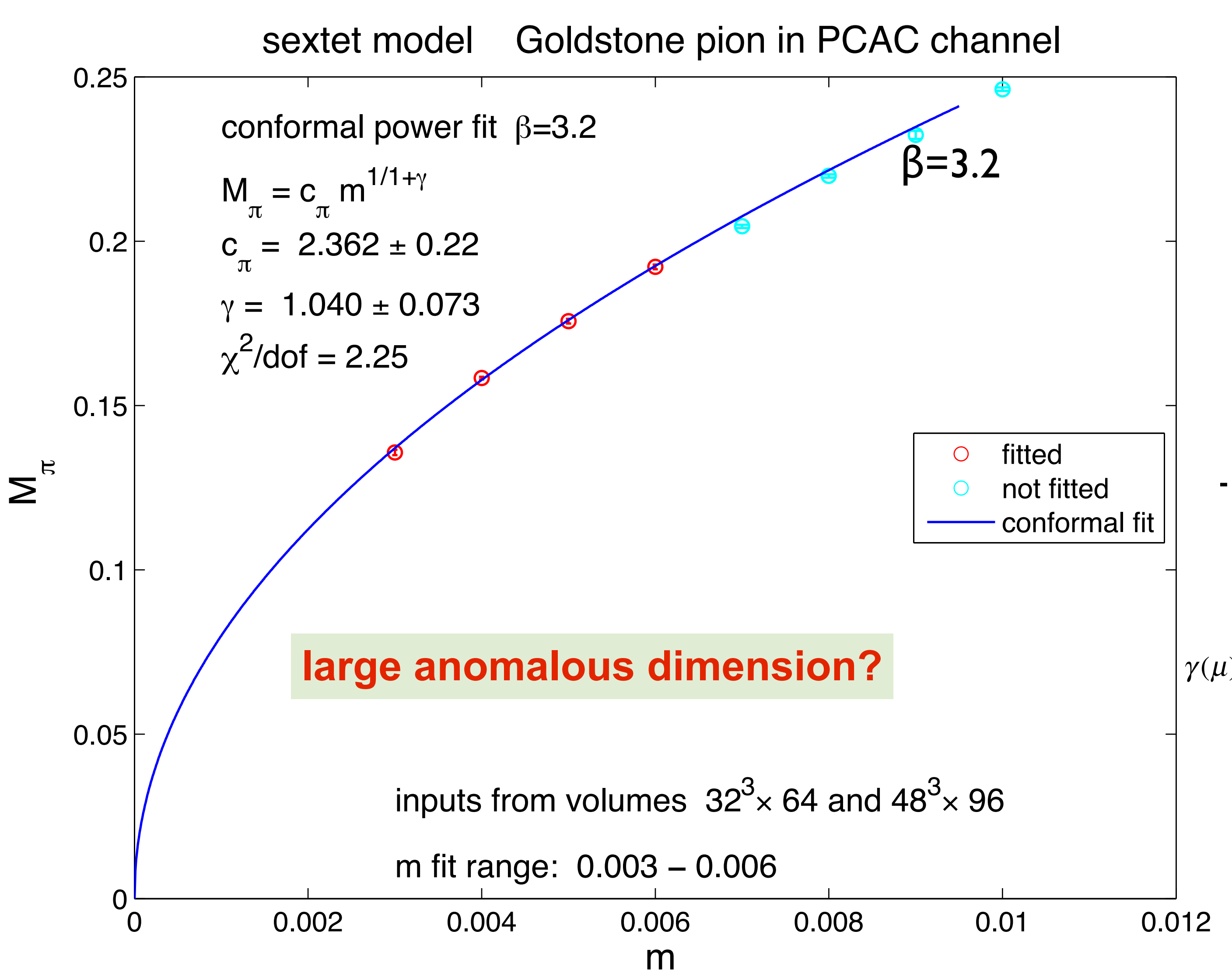


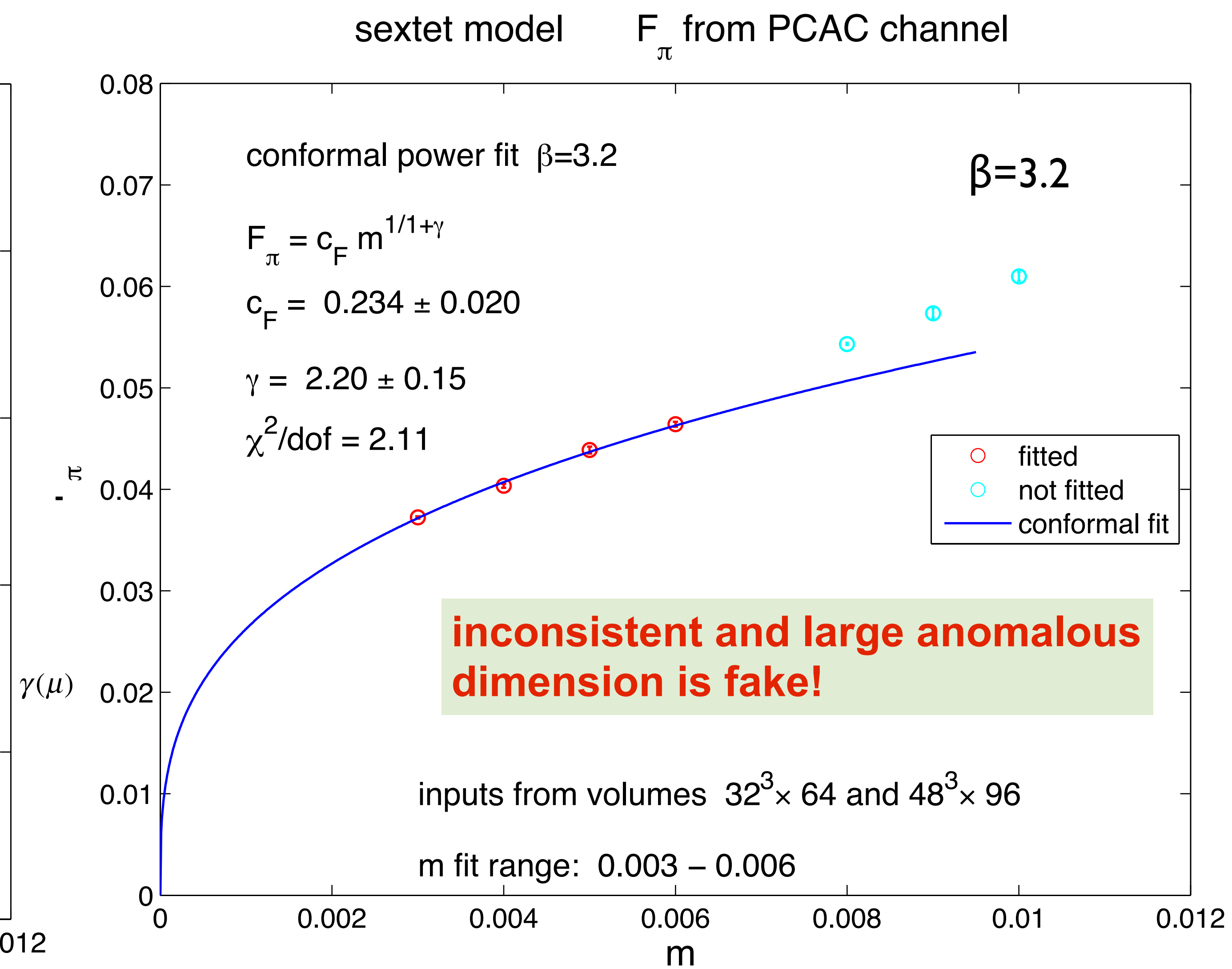
m=0.003-0.006 range close to chiral log regime? Nf=2 helps, more QCD-like

log detection will require more precise data

consistency with partially quenched staggered chiral perturbation theory?

conformal hypothesis breaks down in global fits:

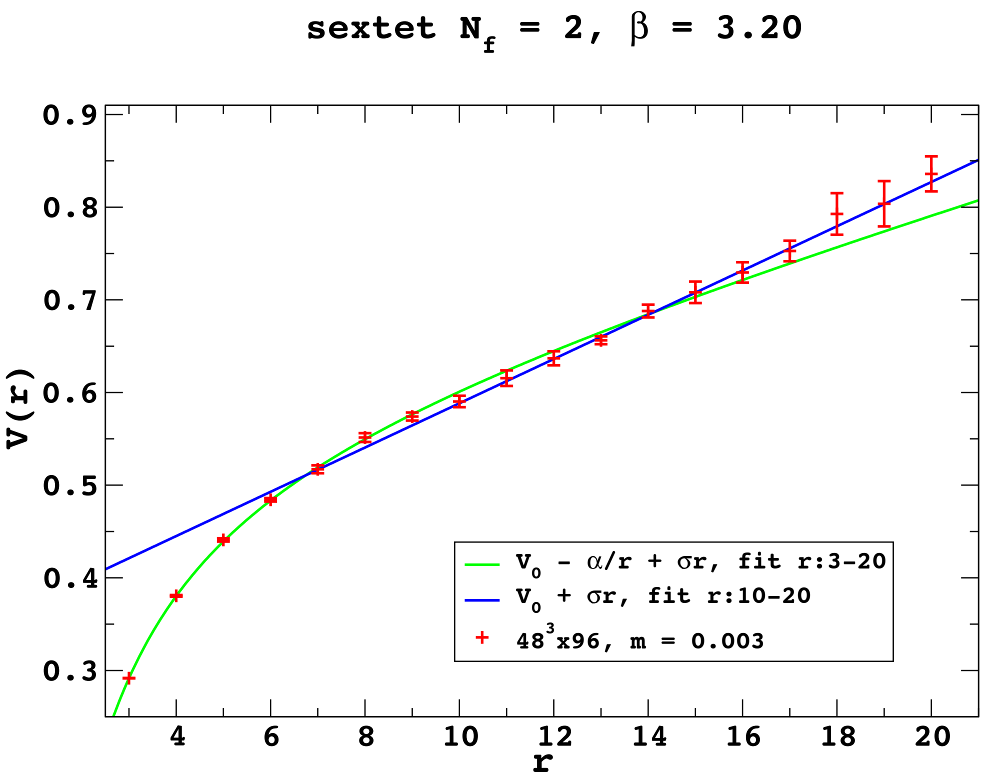


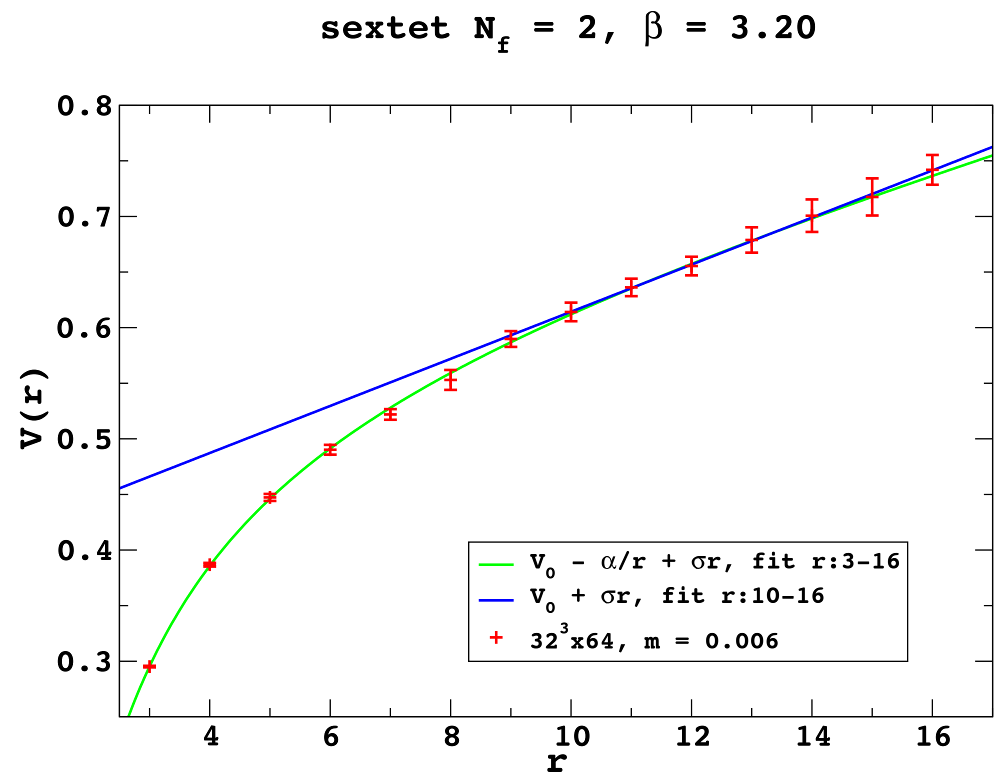


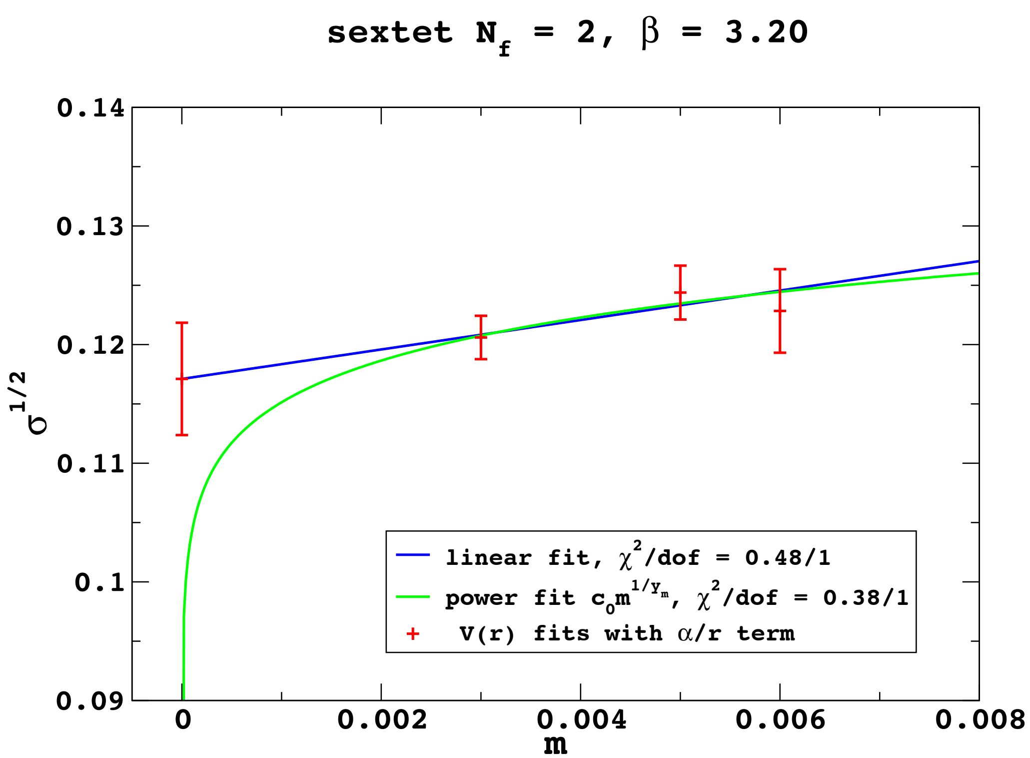
large effective "critical exponents" (γ) are forced by chiral behavior in far infrared

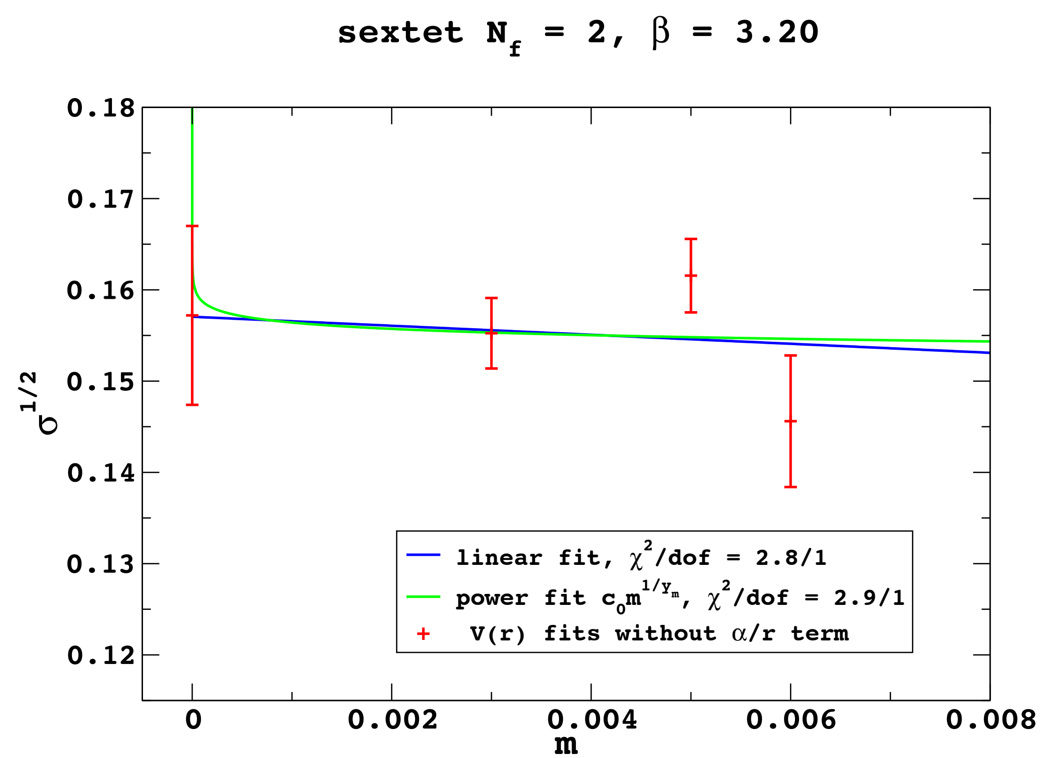
it is not the running $\gamma(\mu)$ at scale μ!

sextet simulations confining force at finite m? (LHC group)









1/1+γ ~0.04(4) ?

running coupling at $m=0$

running coupling at m=0

Schrodinger functional

running coupling at m=0

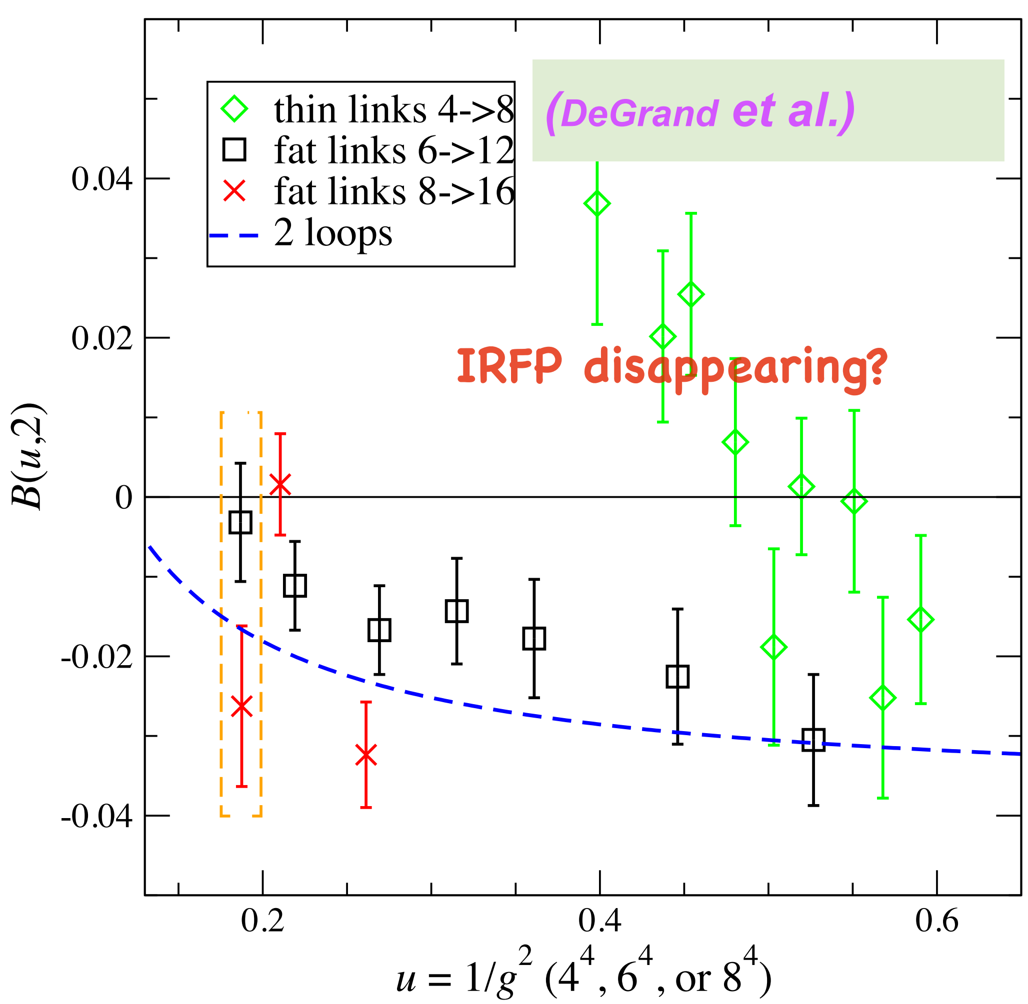
Schrodinger functional

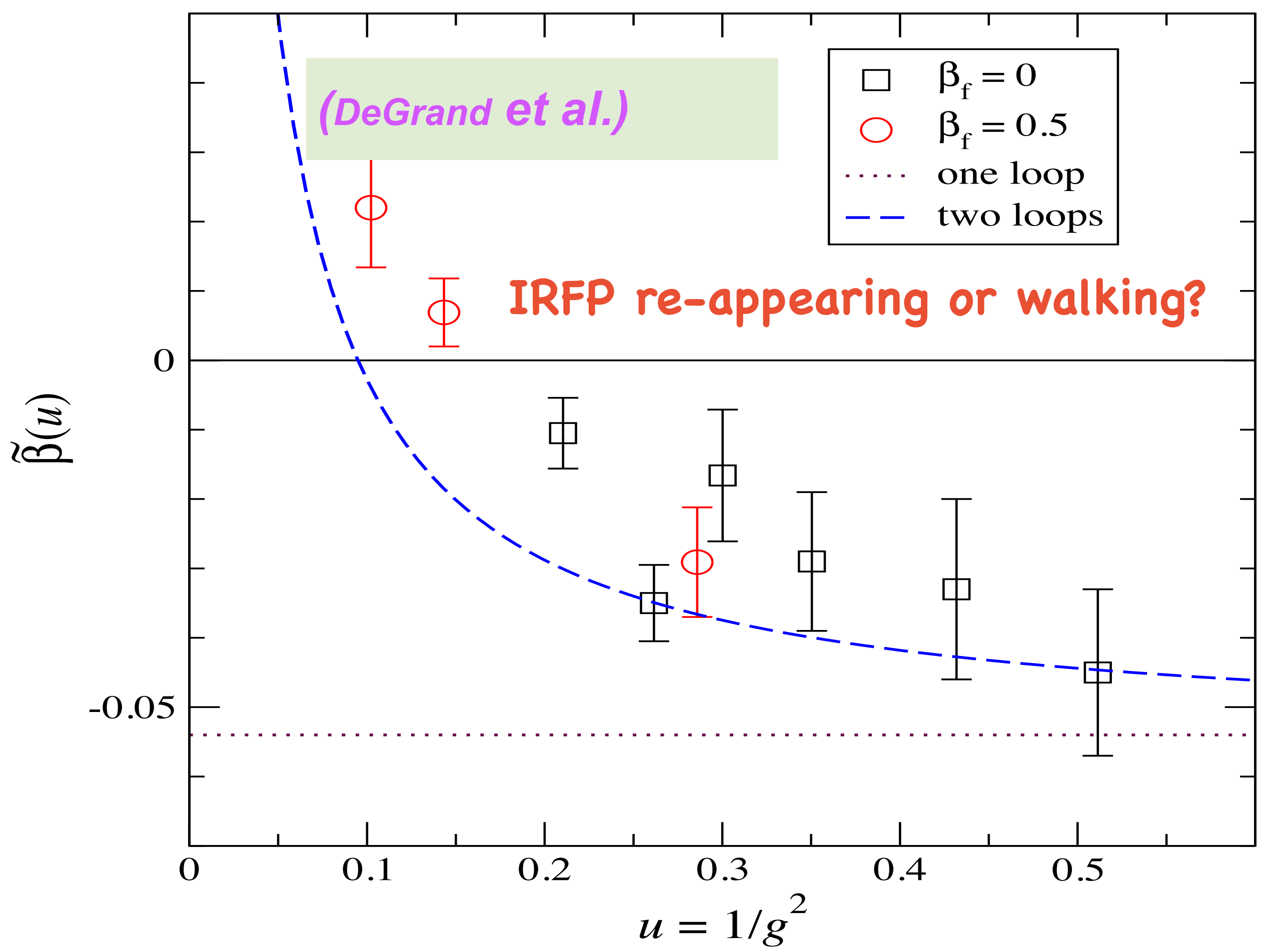
New gradient flow coupling

DeGrand et al. find: Nf=2 sextet beta function may have an IRFP zero, or walks?

good work and difficult model

chiral symmetry breaking is not inconsistent with the results ➜ walking?





Some independent method using a different running coupling scheme?

LHC group

Running coupling definition from gauge field gradient flow

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

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t is the gradient flow time

Running coupling definition (range is $(8t)^{1/2}$) :

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

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

3rd Jacobi function

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3rd Jacobi function

massless fermions; antiperiodic all directions s=1.5 step

N_f=4 staggered fermions; 4-stout; L=12-18; 16-24; 24-36

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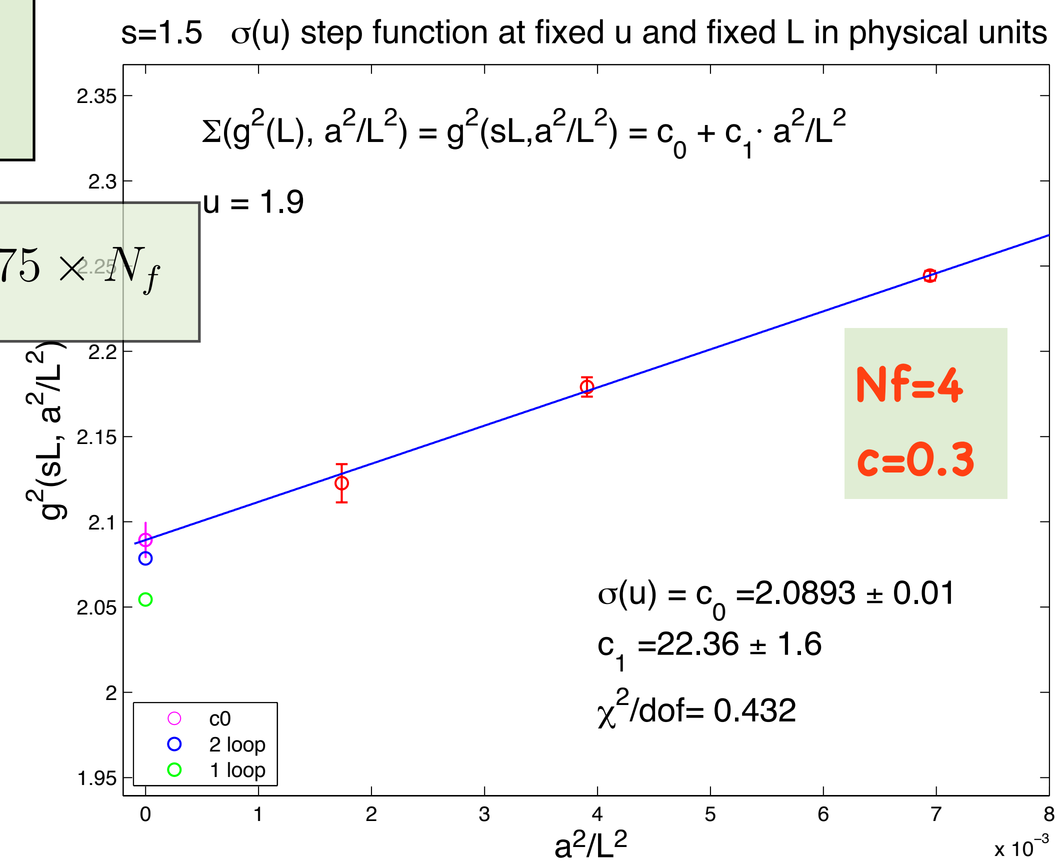

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3rd Jacobi function

massless fermions; antiperiodic all directions s=1.5 step

N_f=4 staggered fermions; 4-stout; L=12-18; 16-24; 24-36

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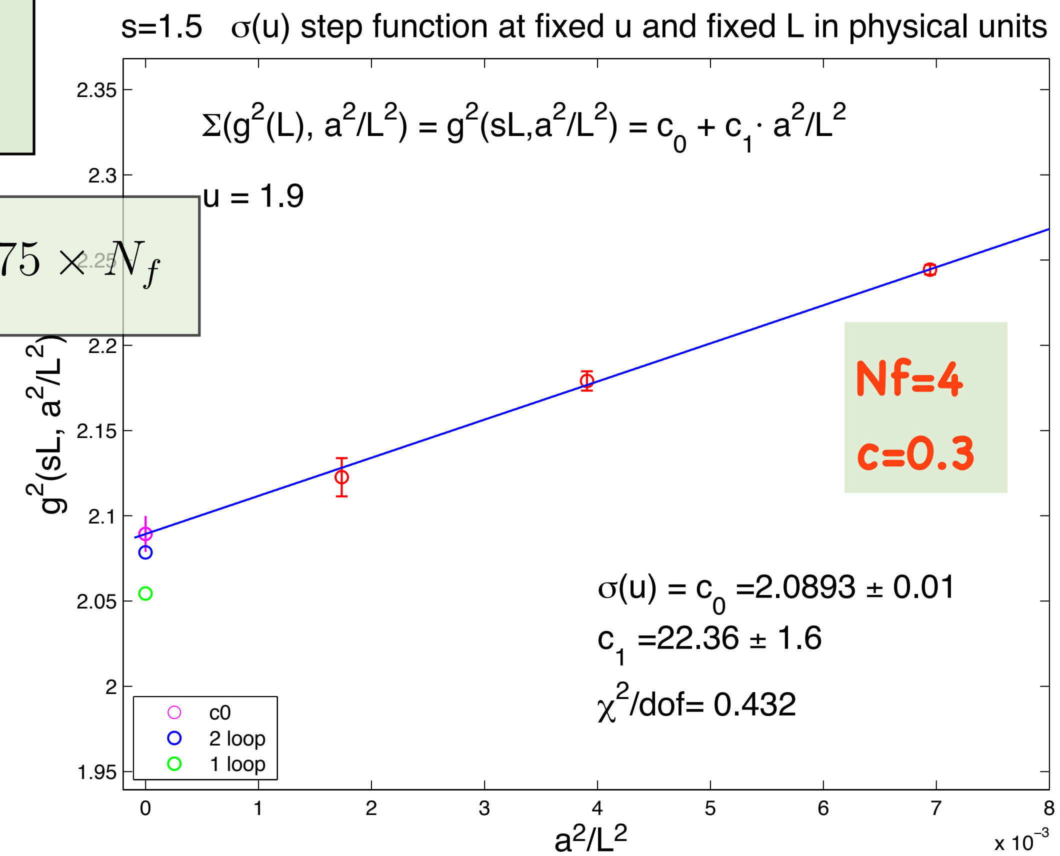

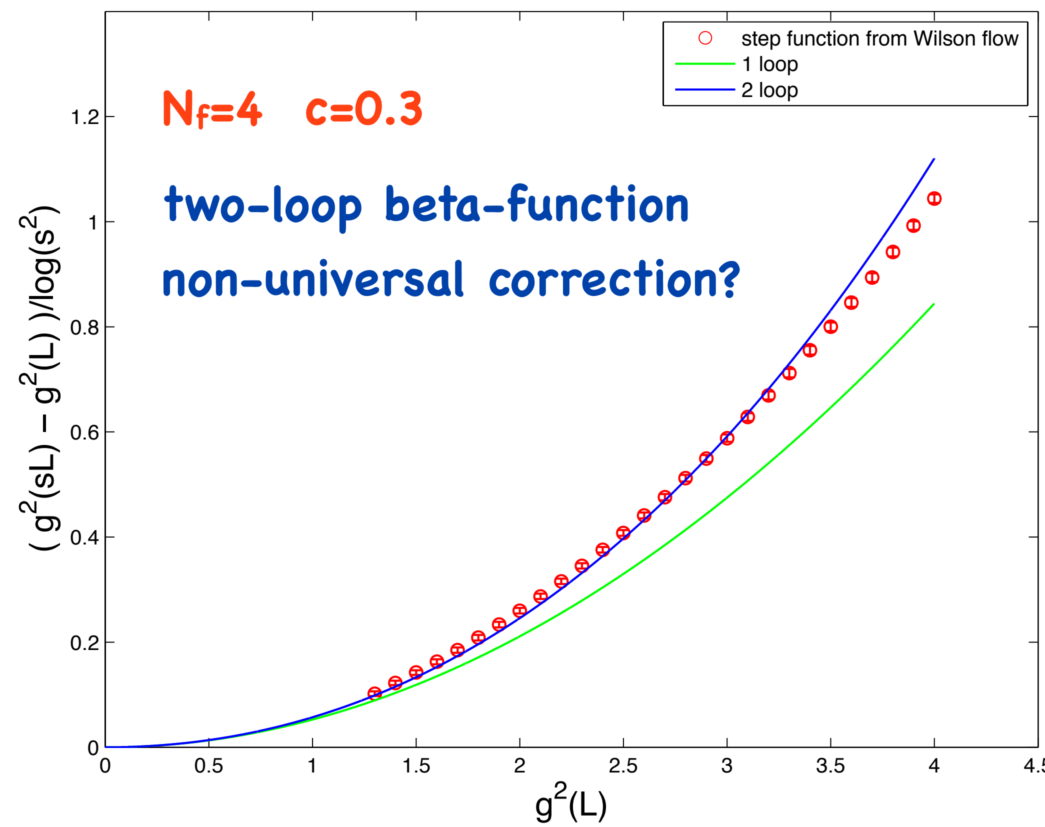

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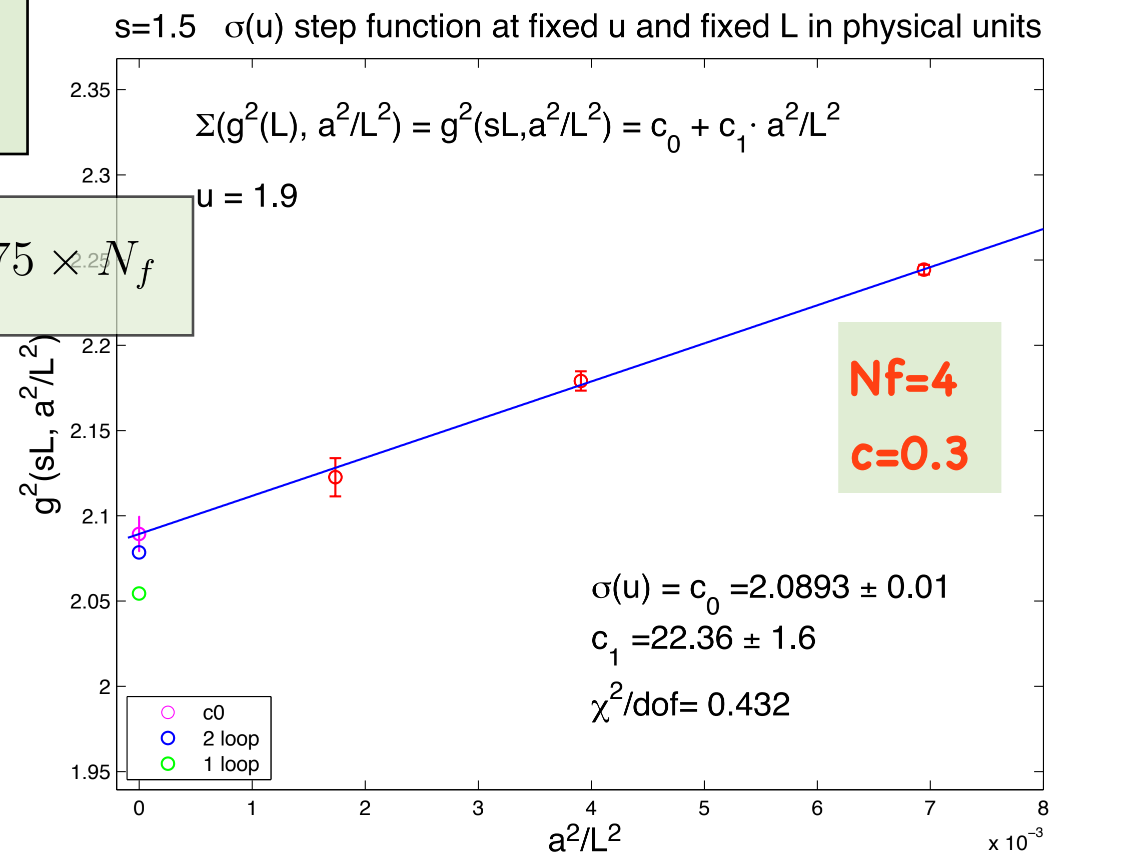
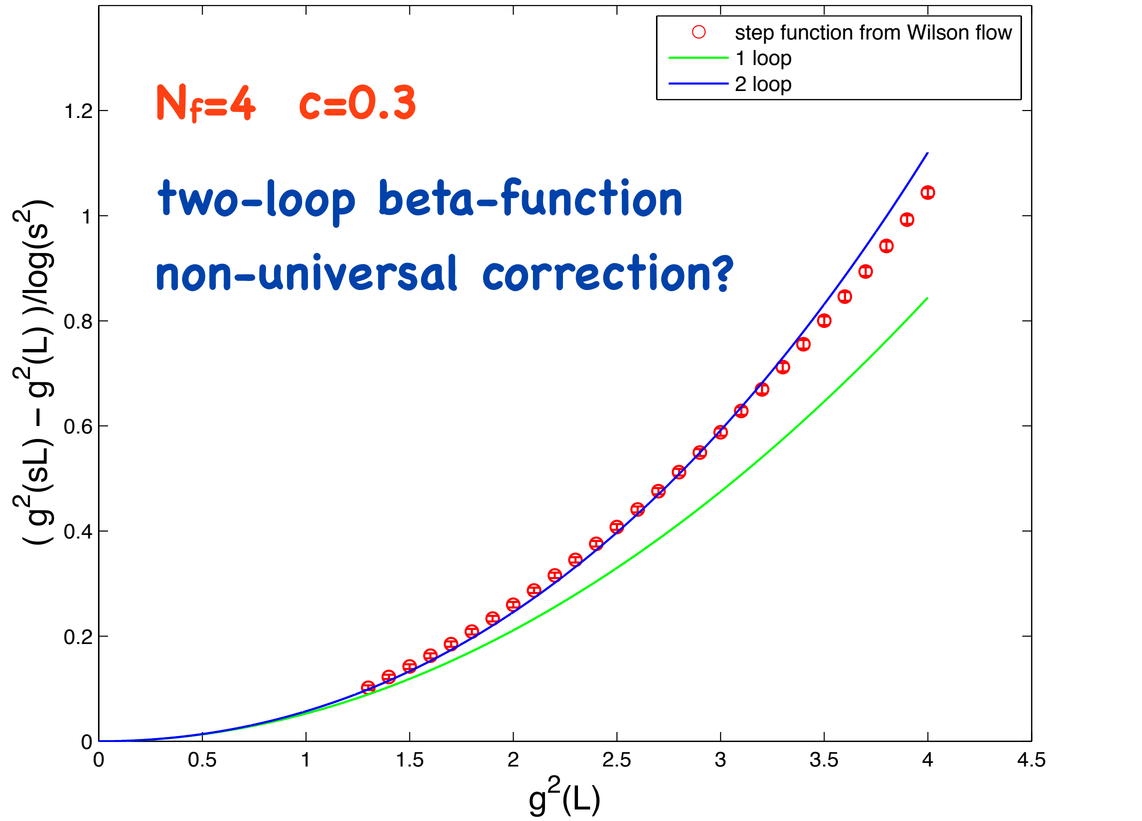
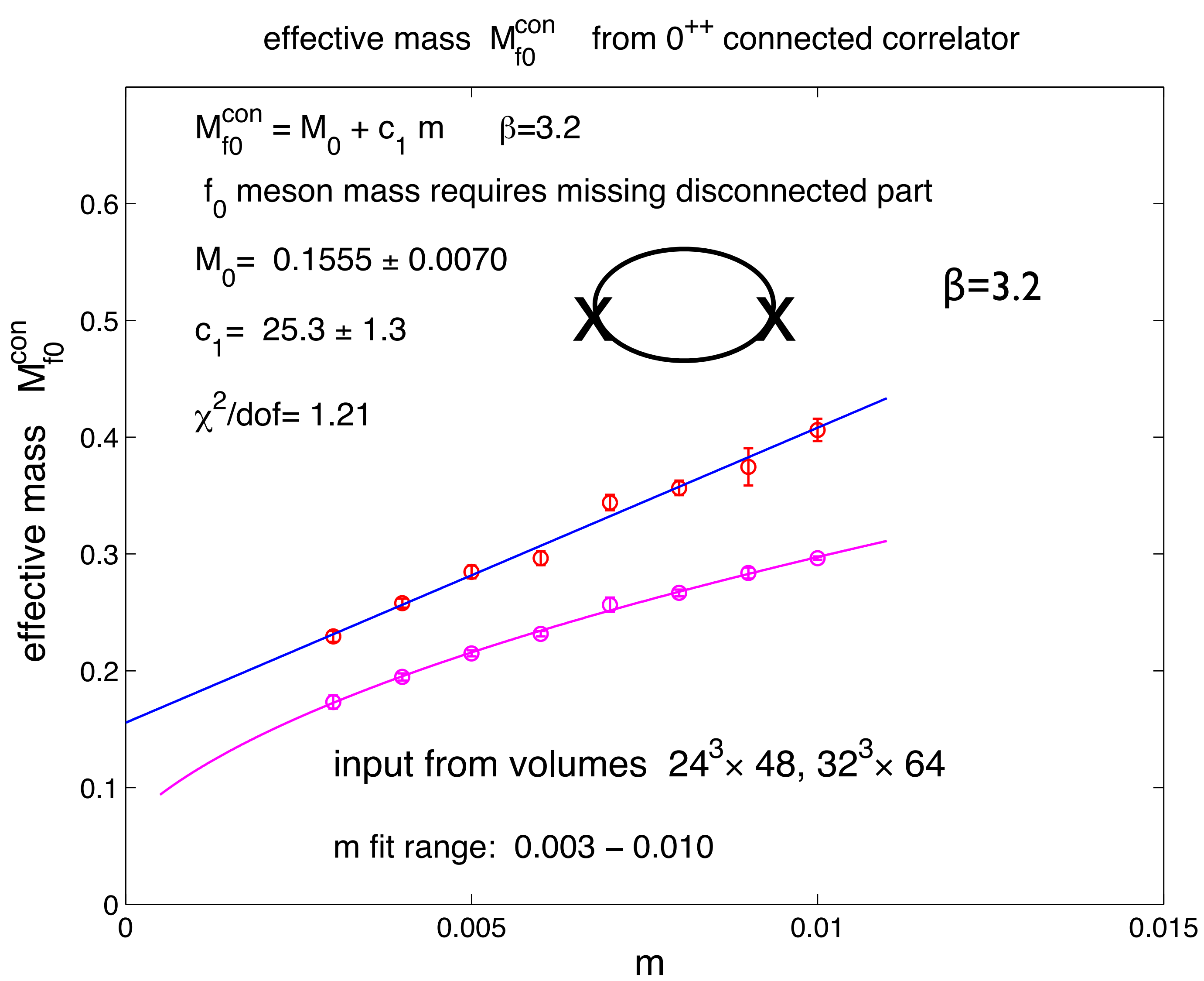
run production now in sextet model





light scalar? (Higgs impostor?)

Nf=2 SU(3) sextet chiral fits: f_0 state with 0^{++} quantum numbers:



$M(f_0)/F \sim 6$
without disconnected diagram:

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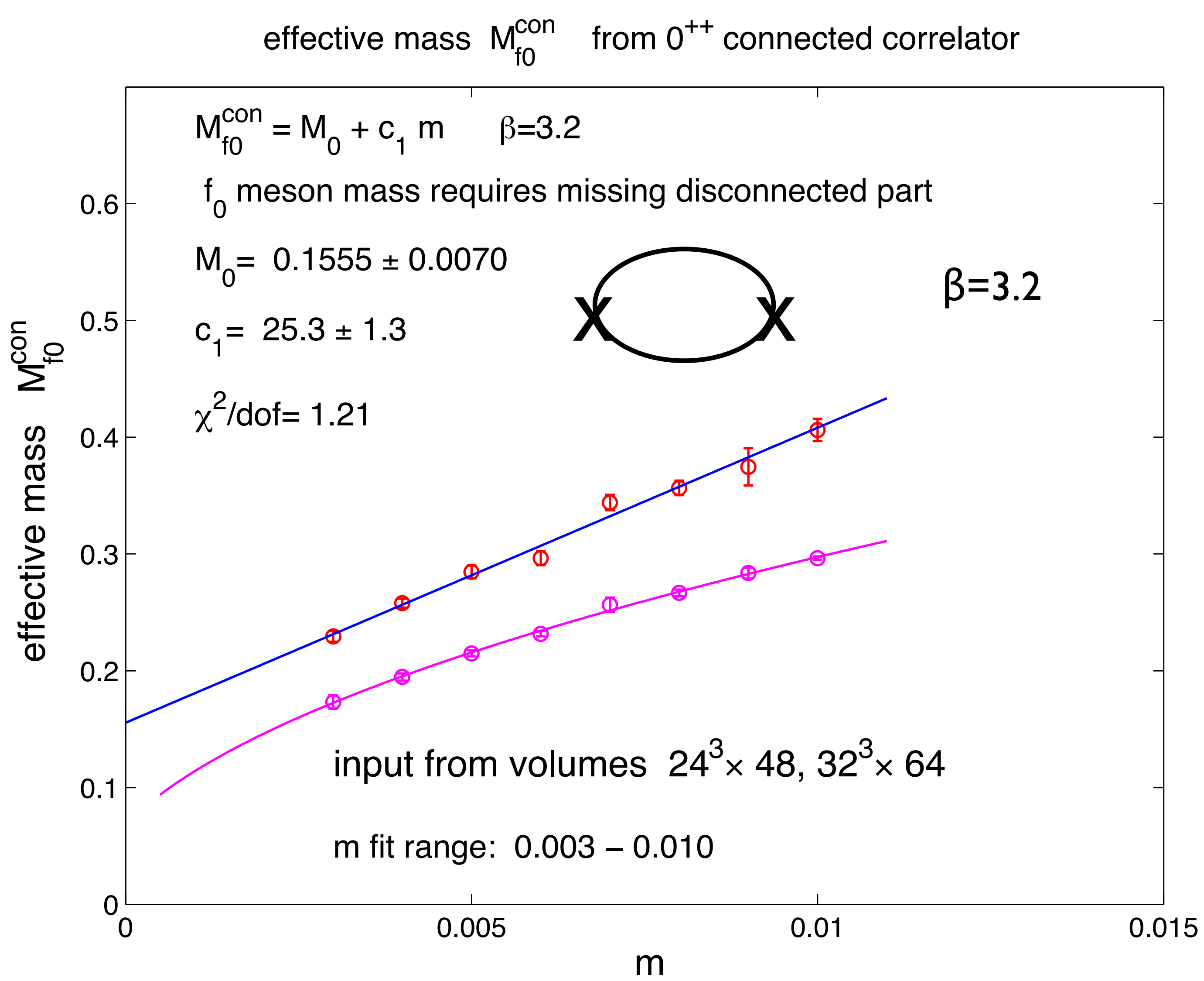

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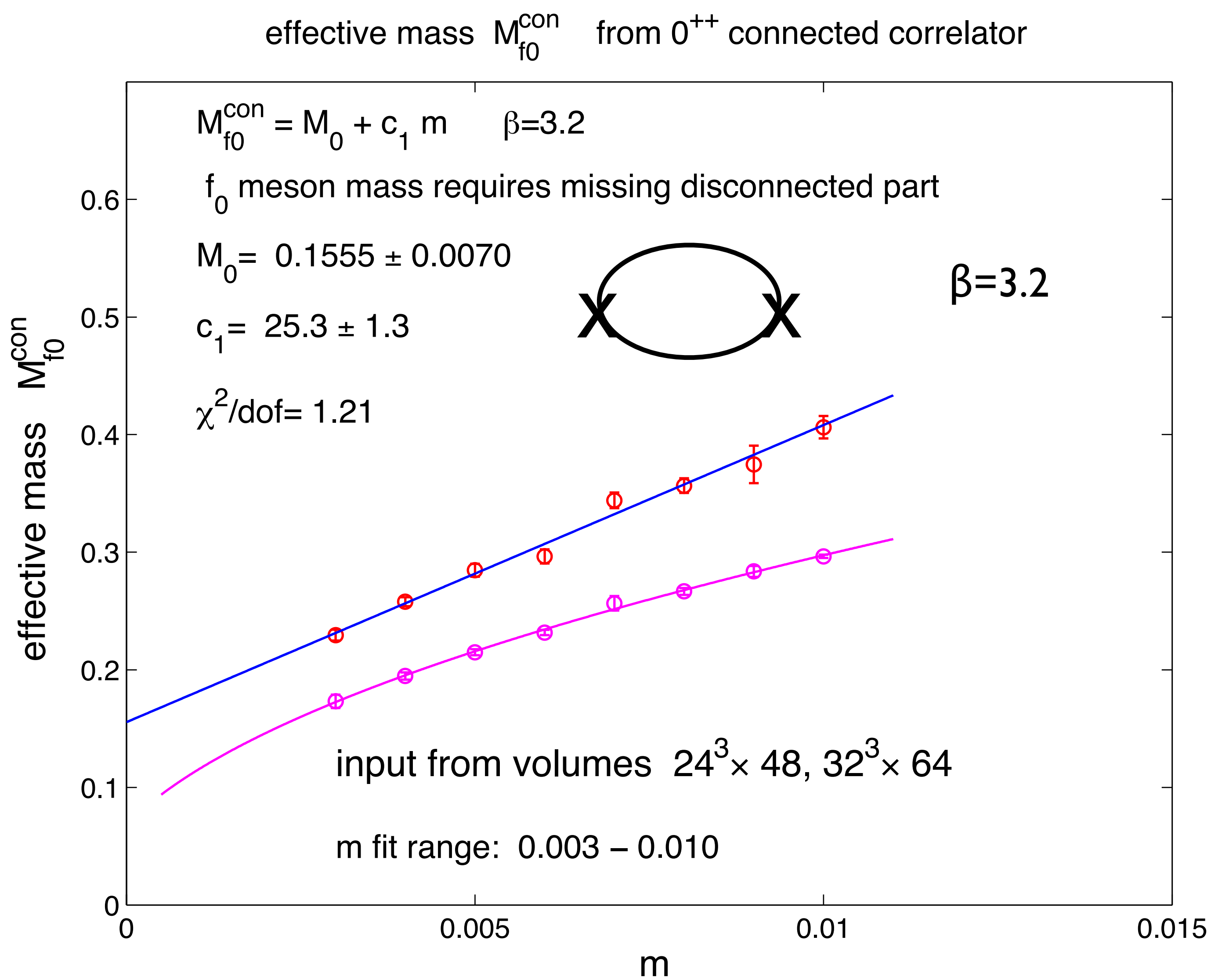

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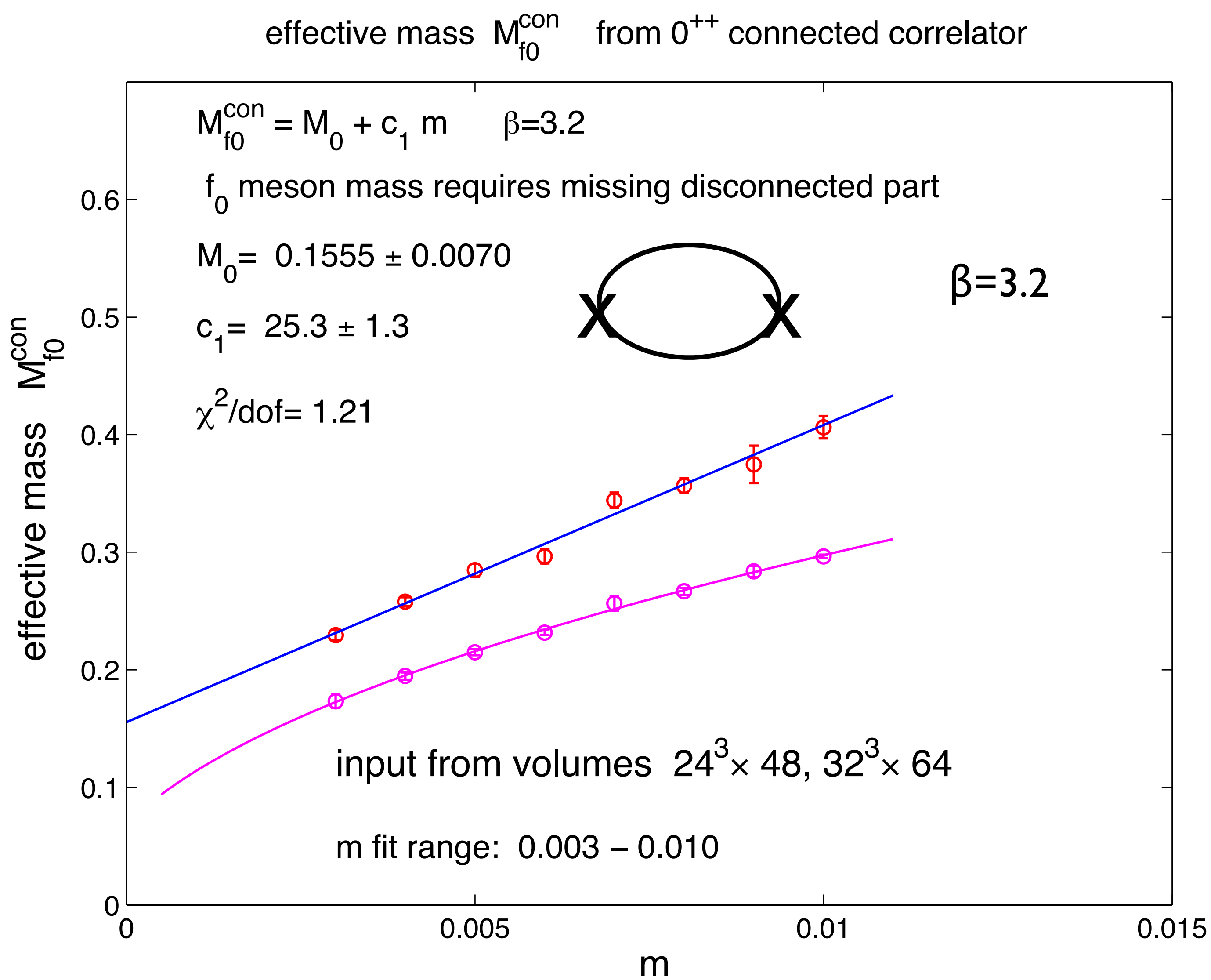

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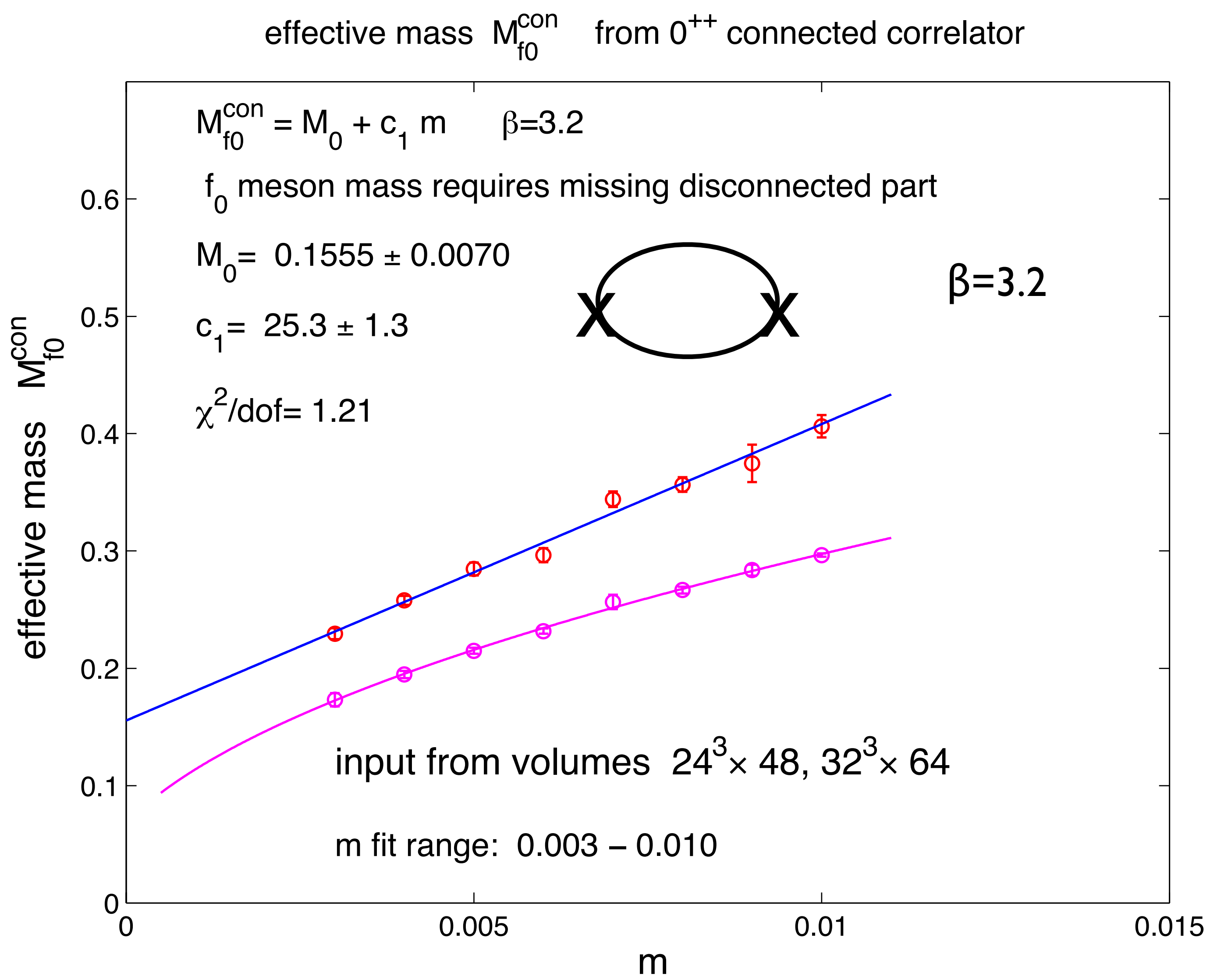

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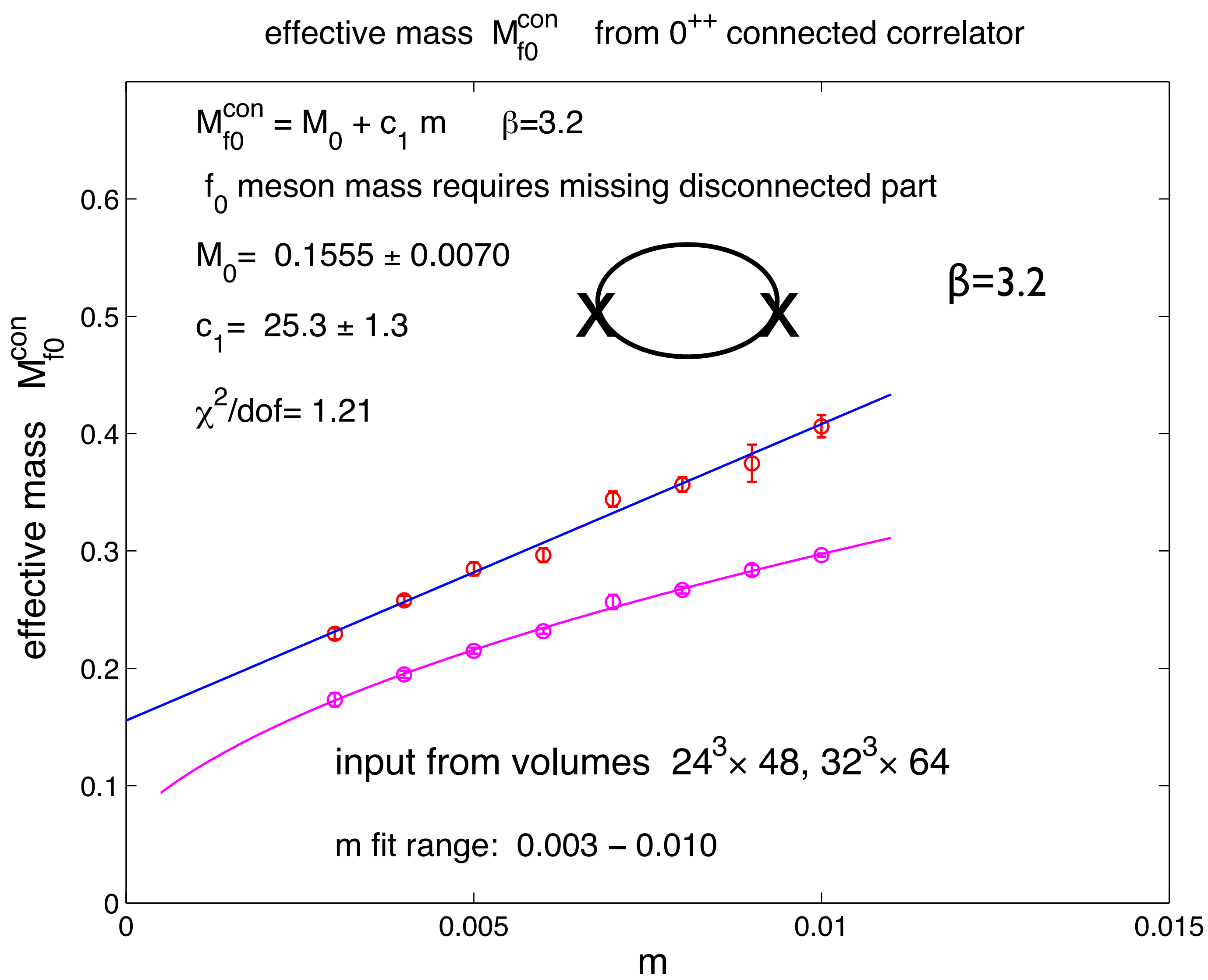

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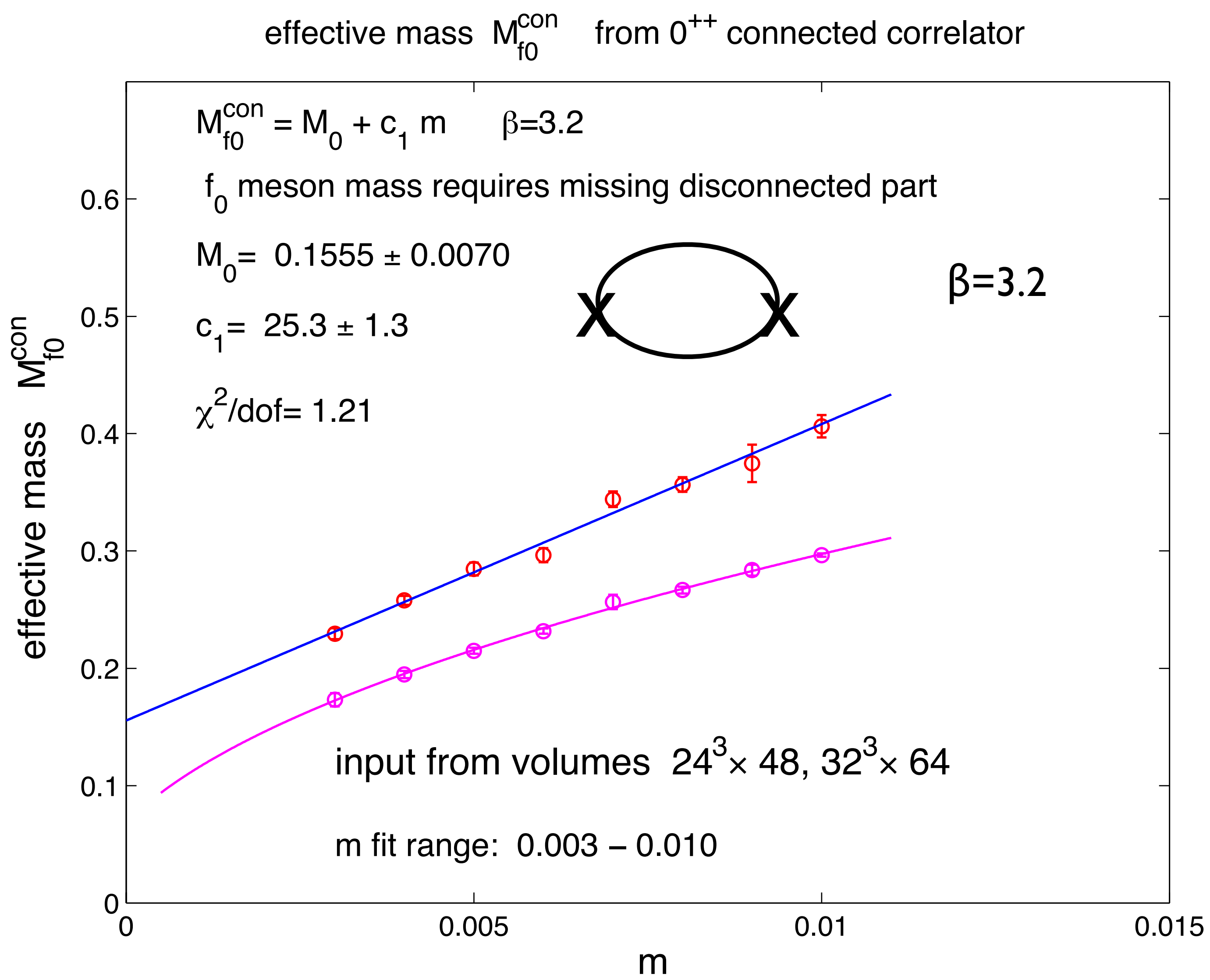

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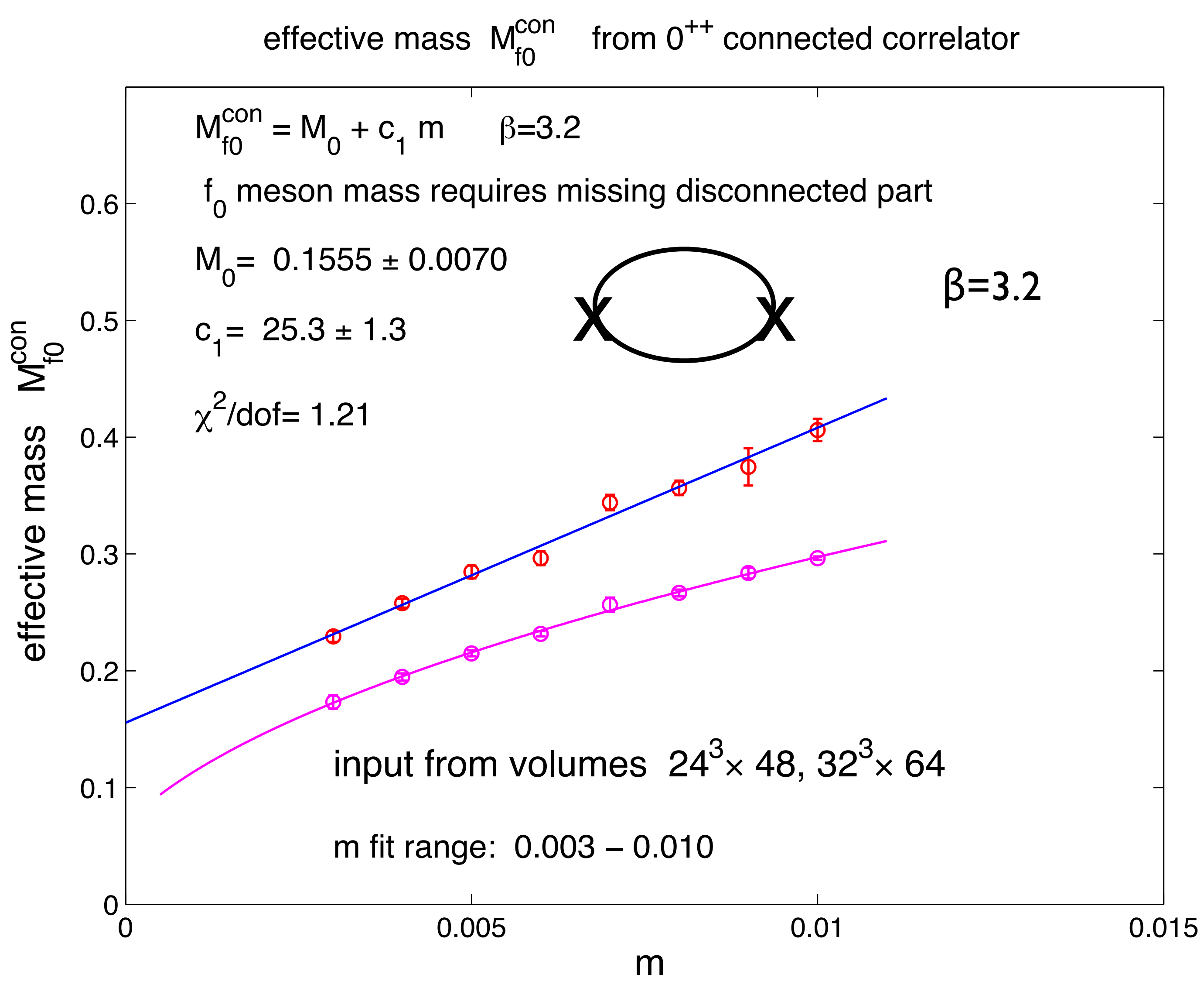

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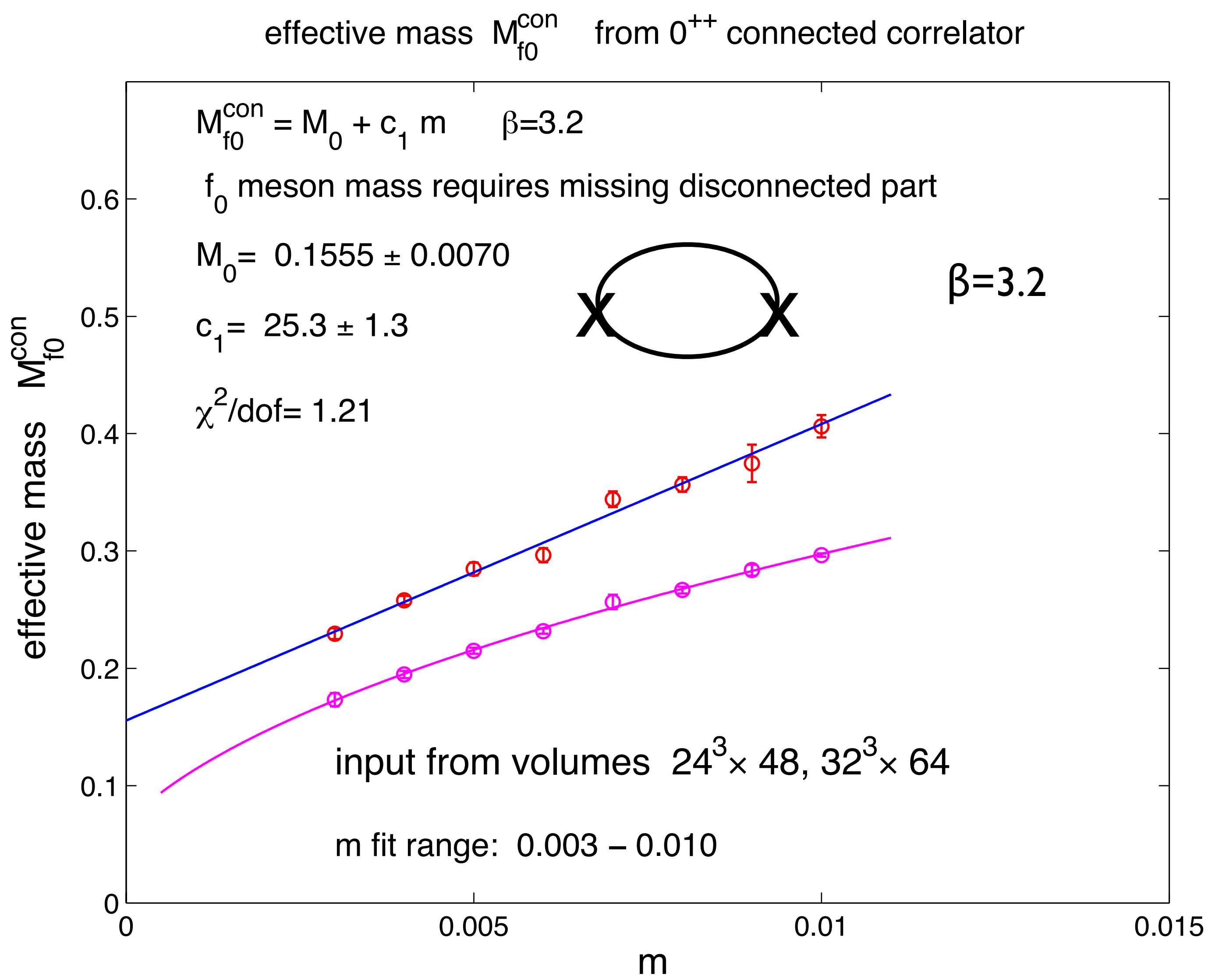

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staggered fermions with rooting presents added complications (Bernard et al.)

Preliminary Results–Particle(s) Mixing in $J^{PG} = 0^{++}$ Channel

- Lowest Energy Levels: Mixture of f_0(or σ), G_S and $I = 0$ S-Wave of $\pi\pi$ at rest
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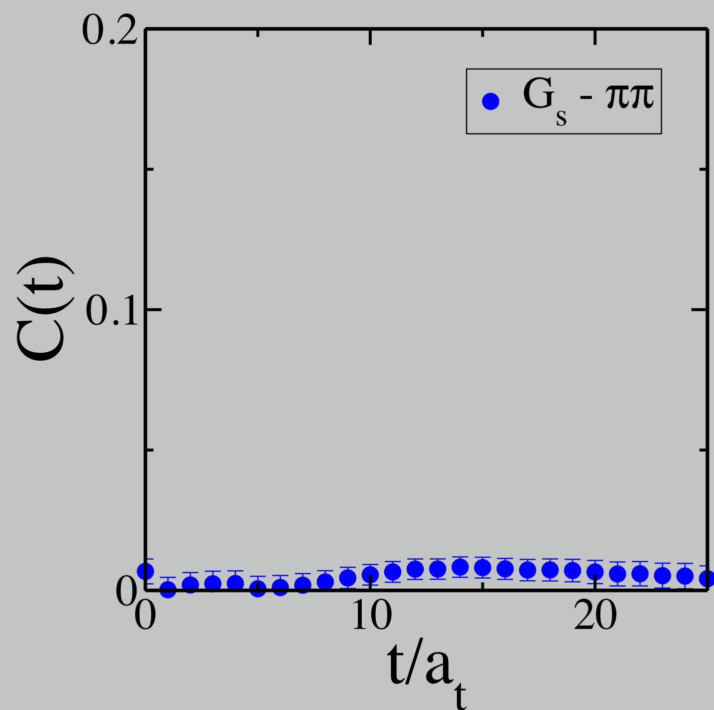
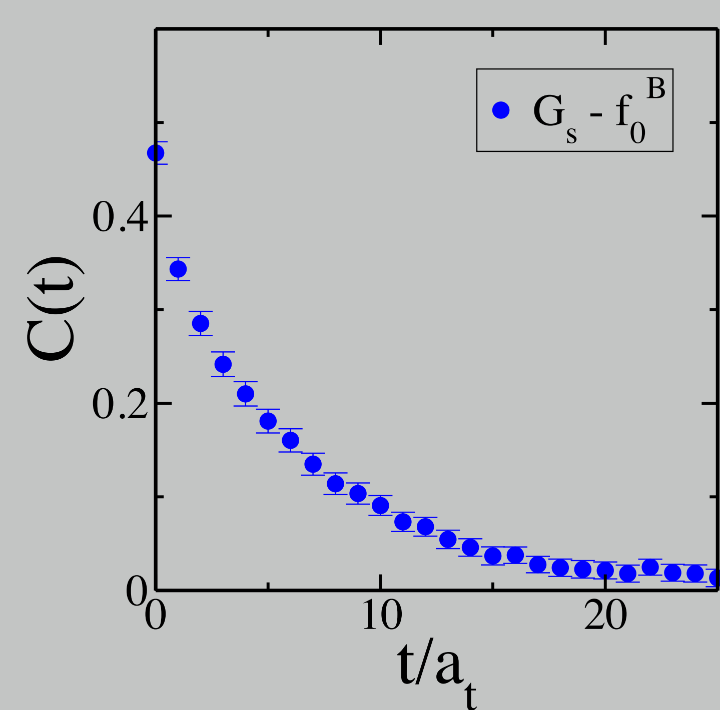
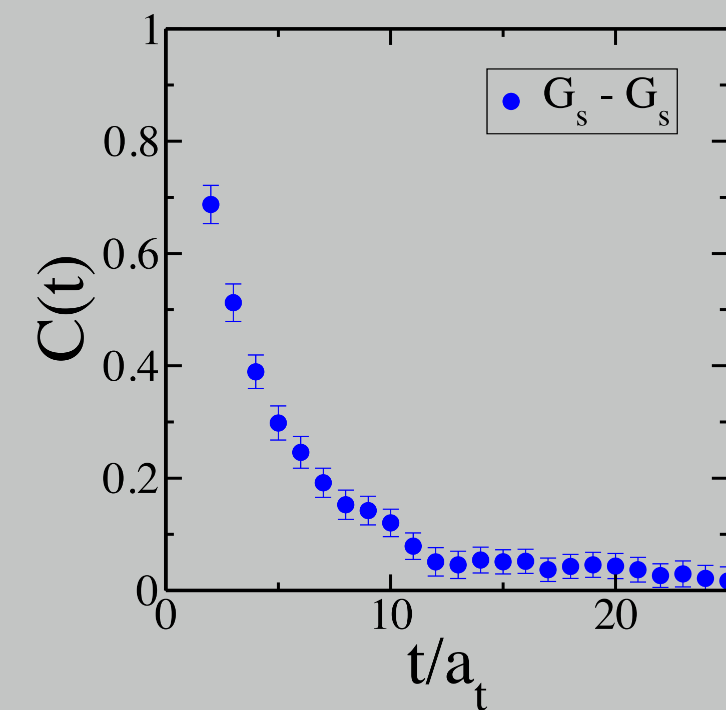
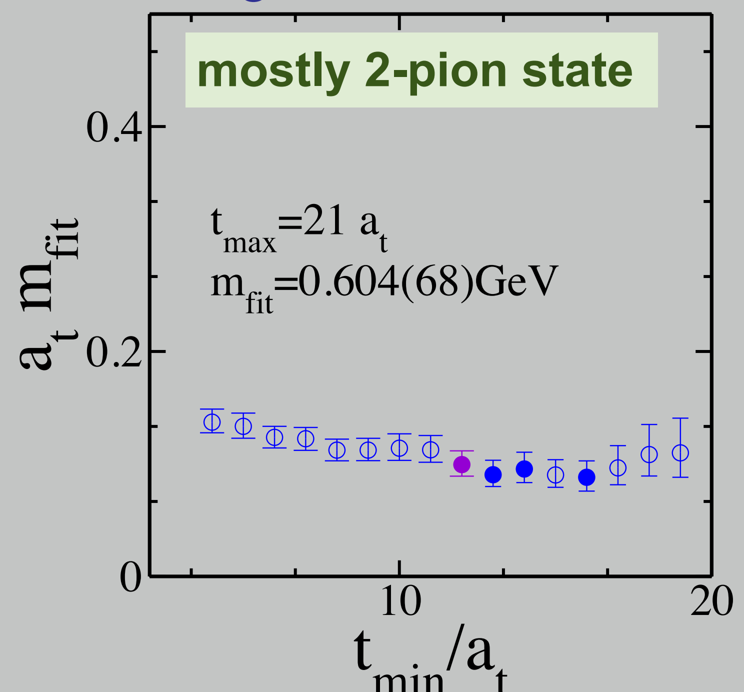


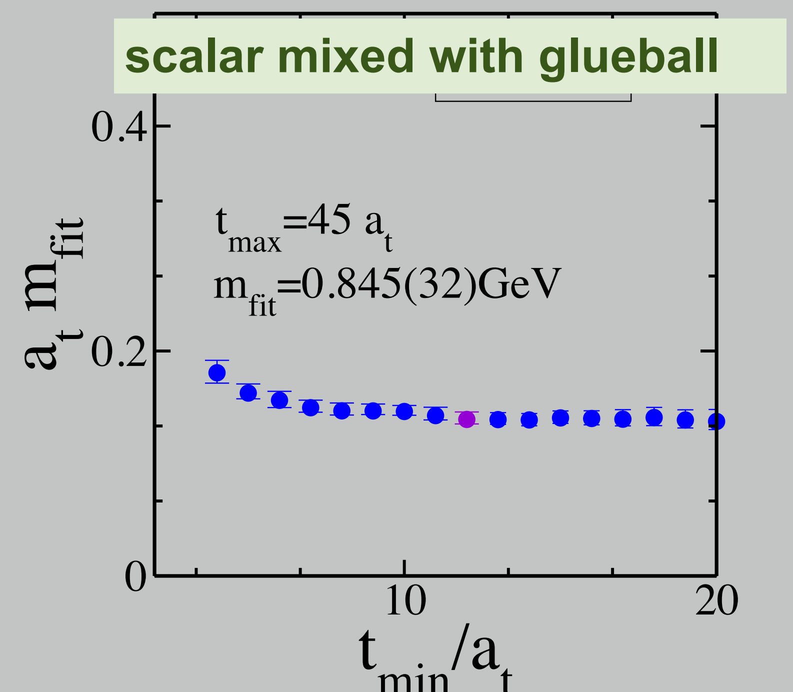




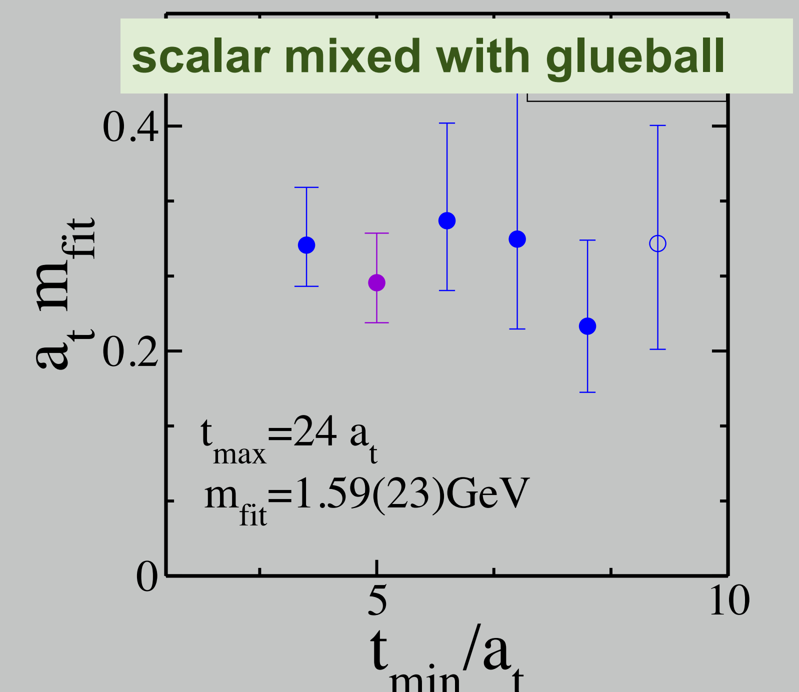
- After Diagonalization



Level 0: $\pi\pi$ Dominates



Level 1: f_0 Dominates



Level 2: G_S and f_0 Dominate

Preliminary Results–Particle(s) Mixing in $J^{PG} = 0^{++}$ Channel

Excited States and Multi-Hadron Scattering using the Stochastic LapH Method

Chik Him Wong[1*], John Bulava[2], Justin Foley[3], You-Cyuan Jhang[1], Keisuke Juge[4], David Lenkner[1], Colin Morningstar[1]
[1]Carnegie Mellon University, Pittsburgh, US [2]NIC, DESY Zeuthen, Germany
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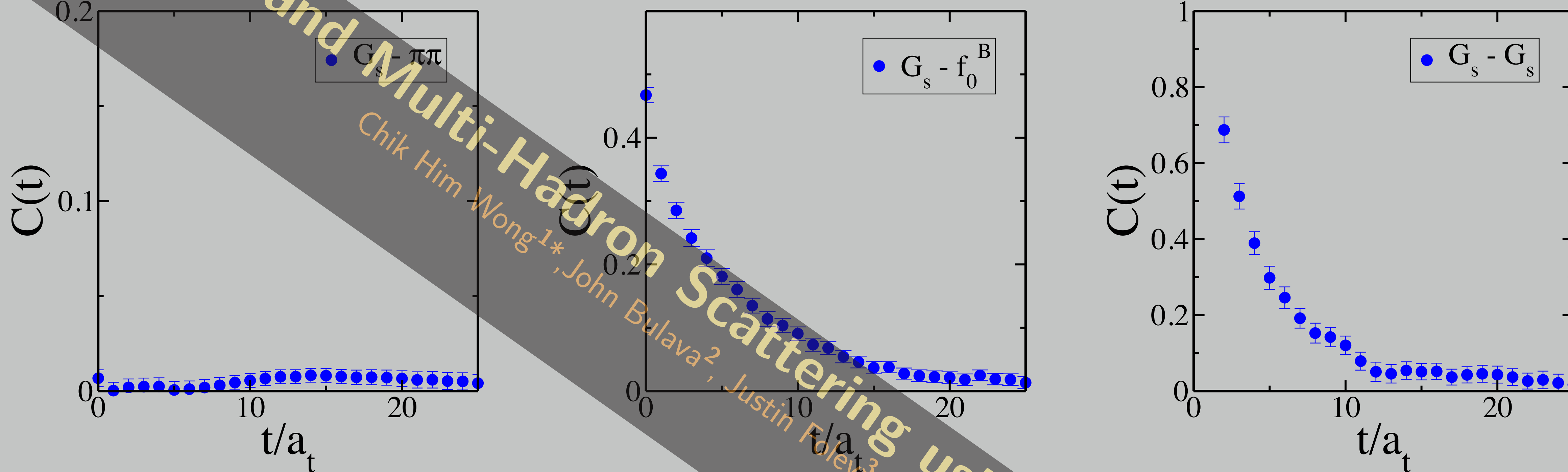

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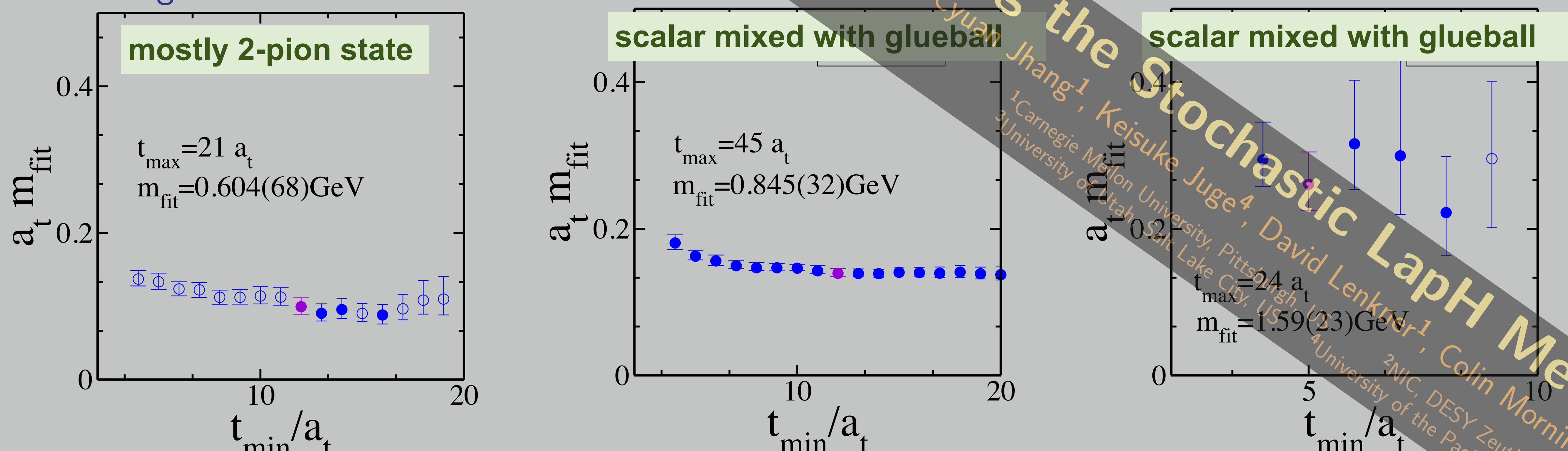

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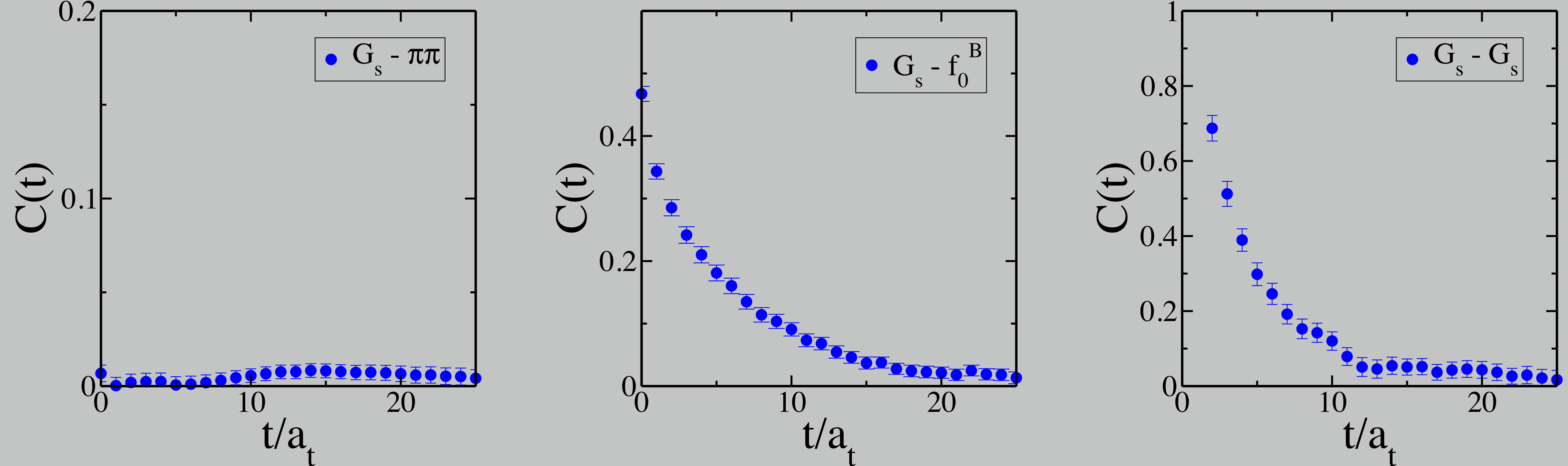

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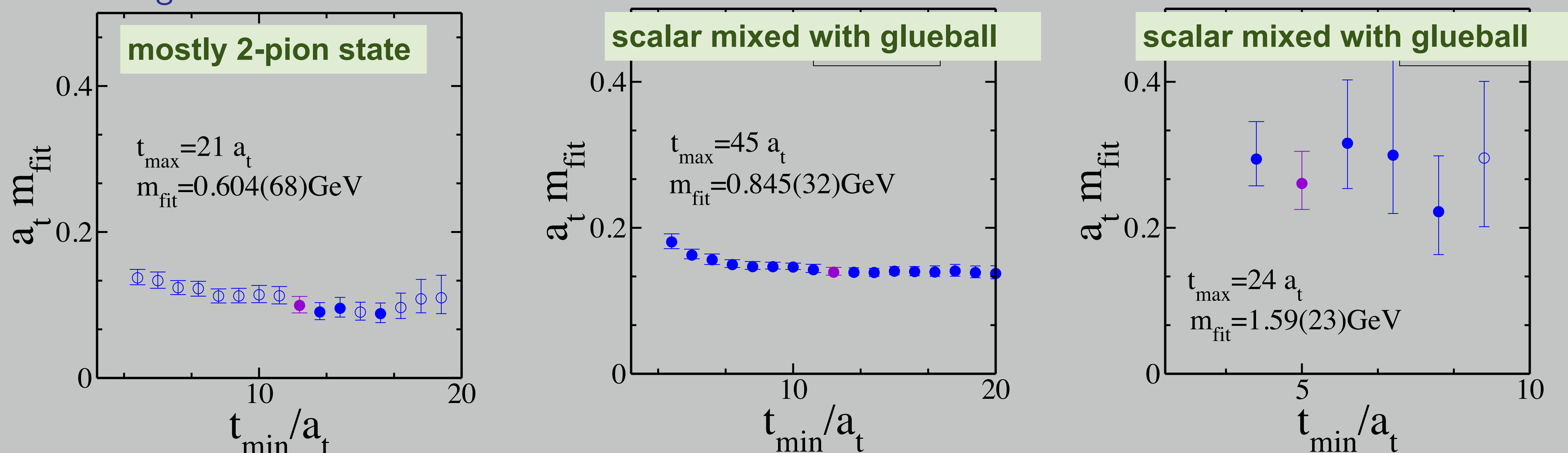

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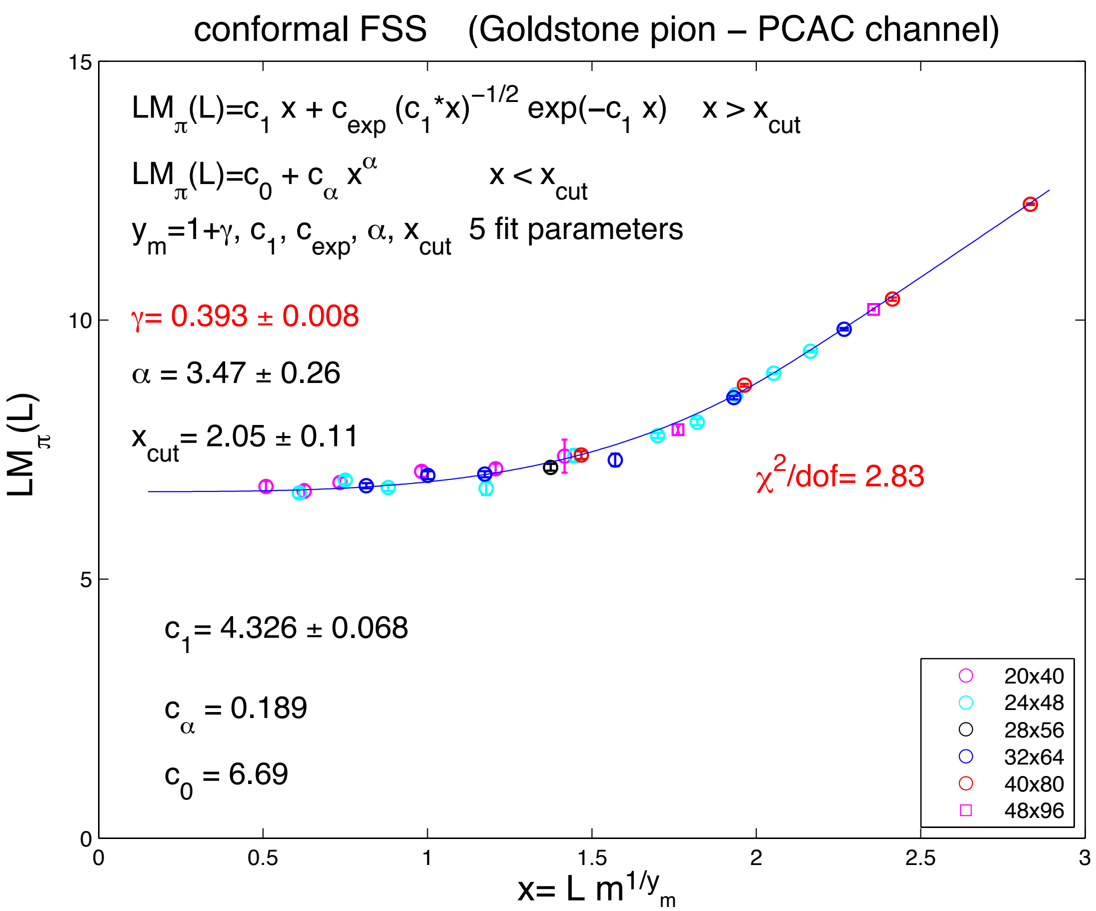
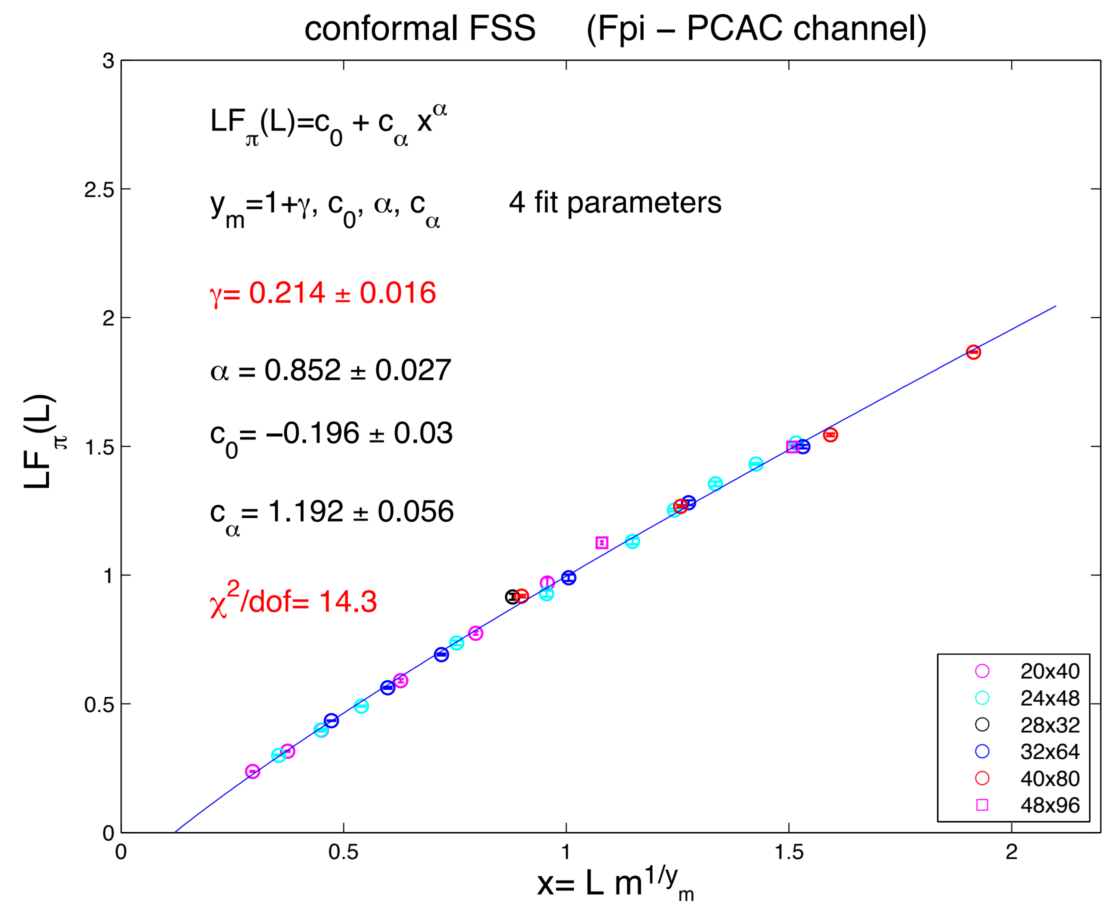
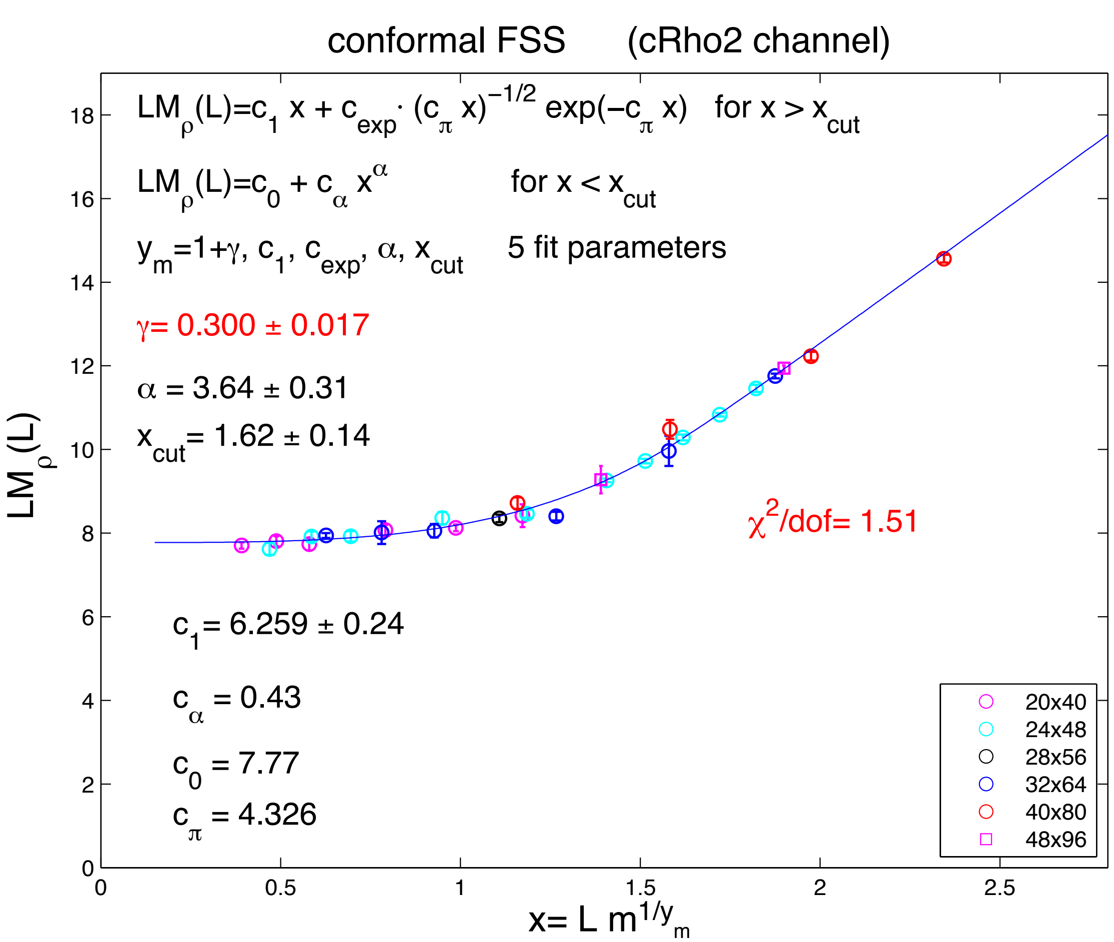
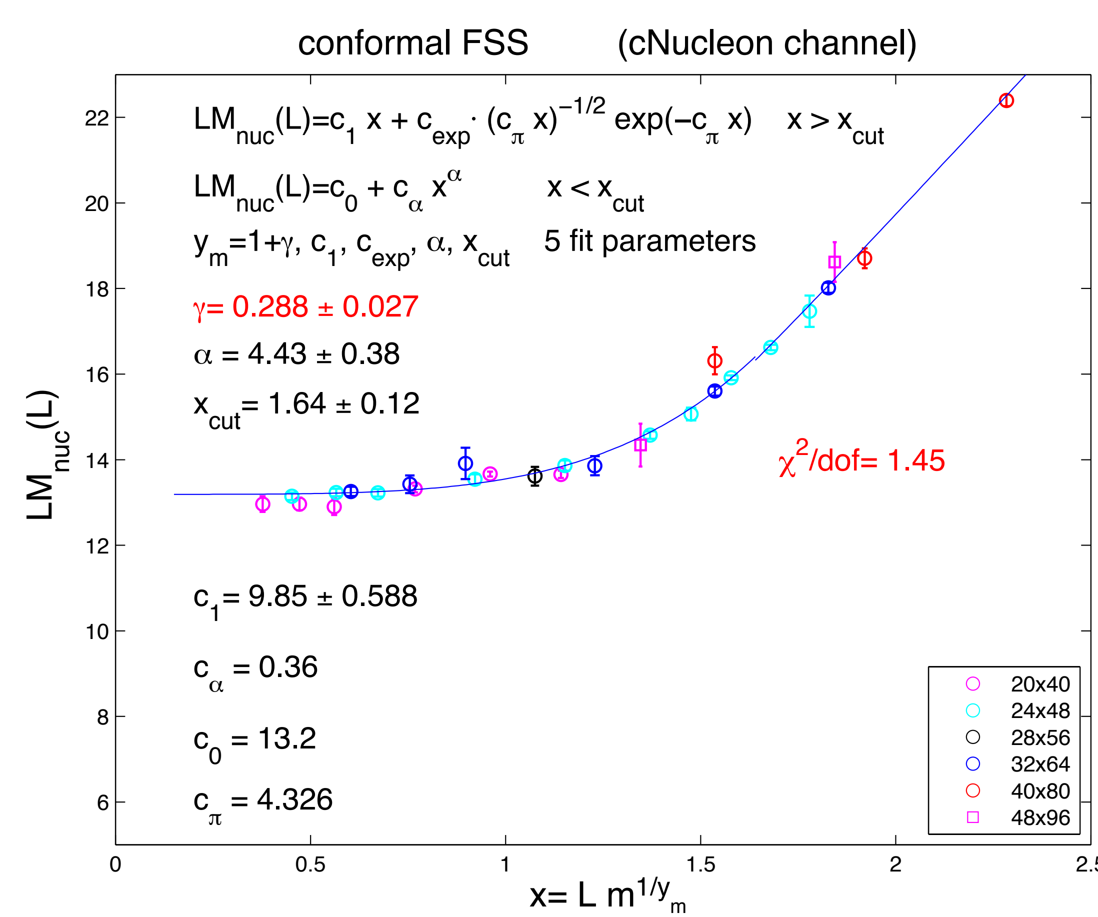
backup slides

conformal scaling test with FSS - physical model fit (spline fit similar)

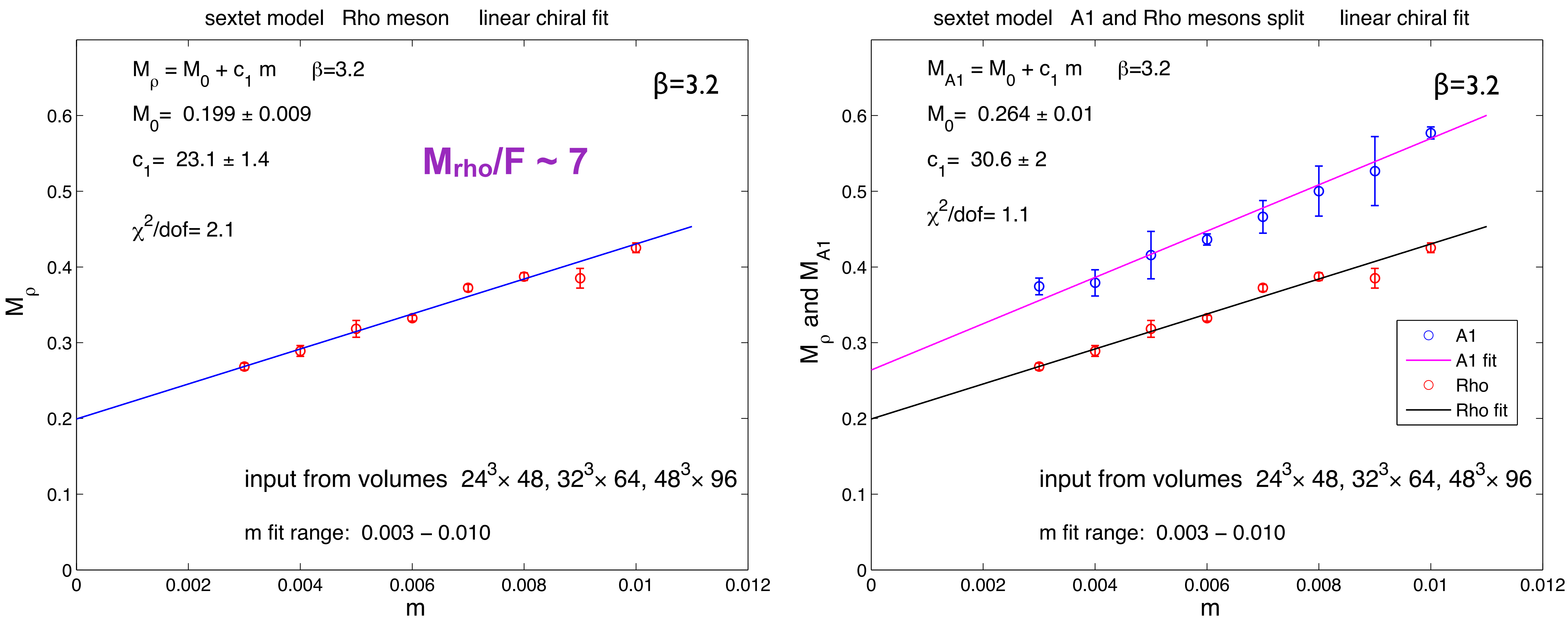








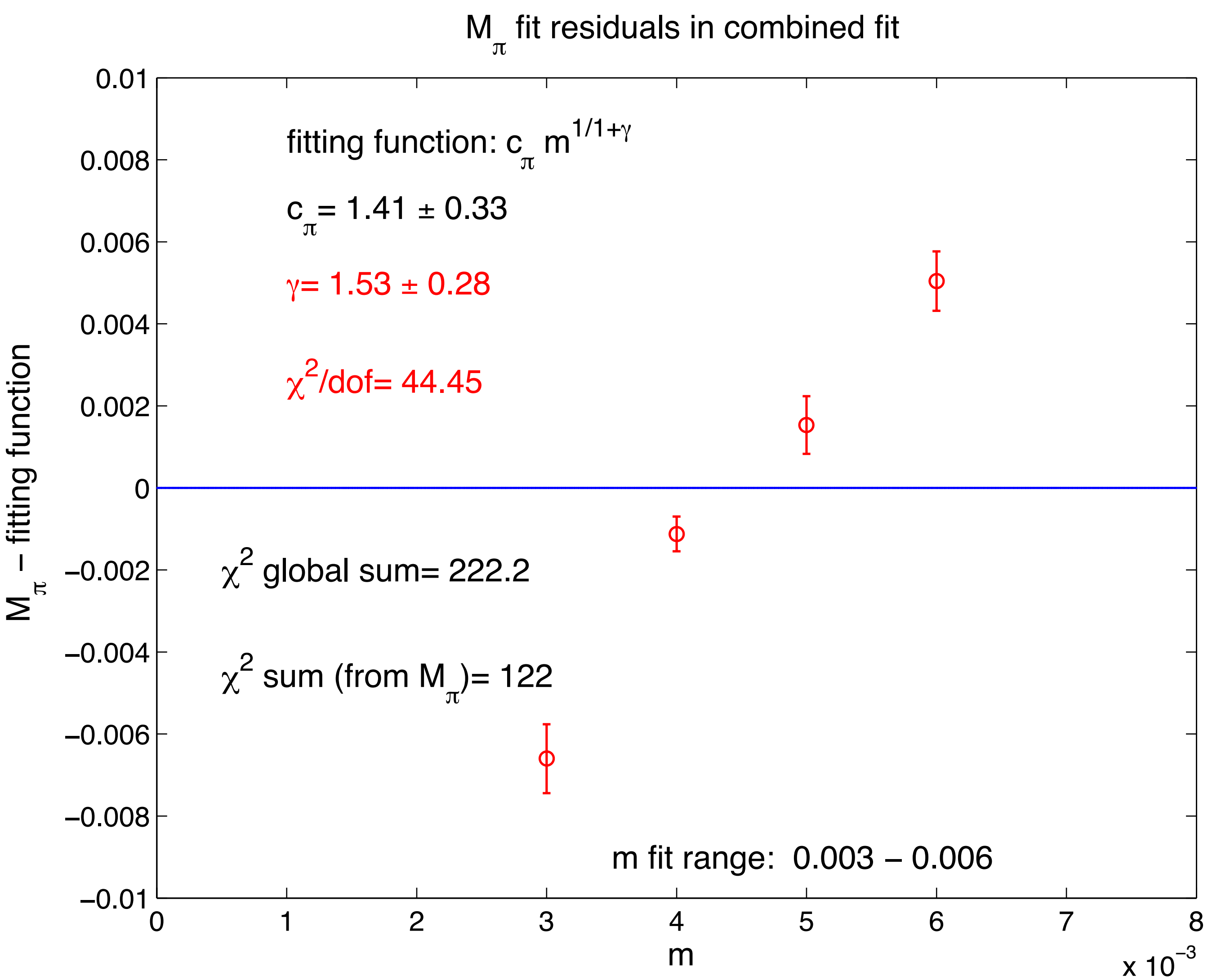
Nf=2 SU(3) sextet chiral fits M_ρ and $M(A_1)$

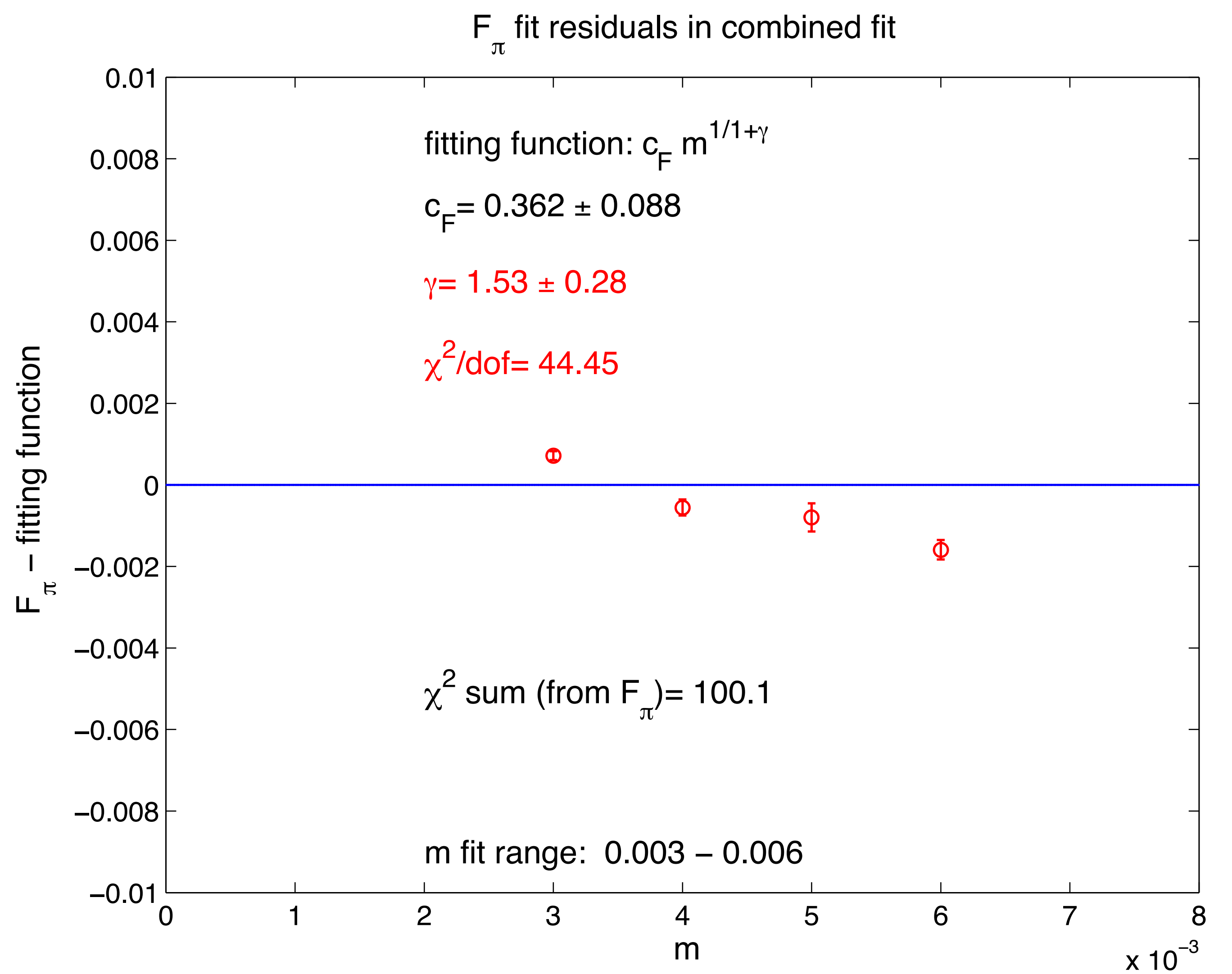


M_ρ remains heavy in massless fermion limit

parity partners remain split in massless fermion limit

conformal hypothesis breaks down in global fits:





large and inconsistent critical exponents γ

are we close enough to the critical surface?

fix with scaling violation terms? don't think so

EW phase transition in sextet model - early universe

Kogut-Sinclair consistent with χSB phase at T=0

relevance in early cosmology

We are planning to run sextet thermodynamics

Third massive fermion flavor (electroweak singlet) dark matter?