Snowmass on the Pacific @ KITP

Lattice gauge theories and the composite Higgs

(on behalf of the USQCD BSM group)

Julius Kuti

University of California, San Diego

Snowmass on the Pacific @ KITP, May 29-31, 2013

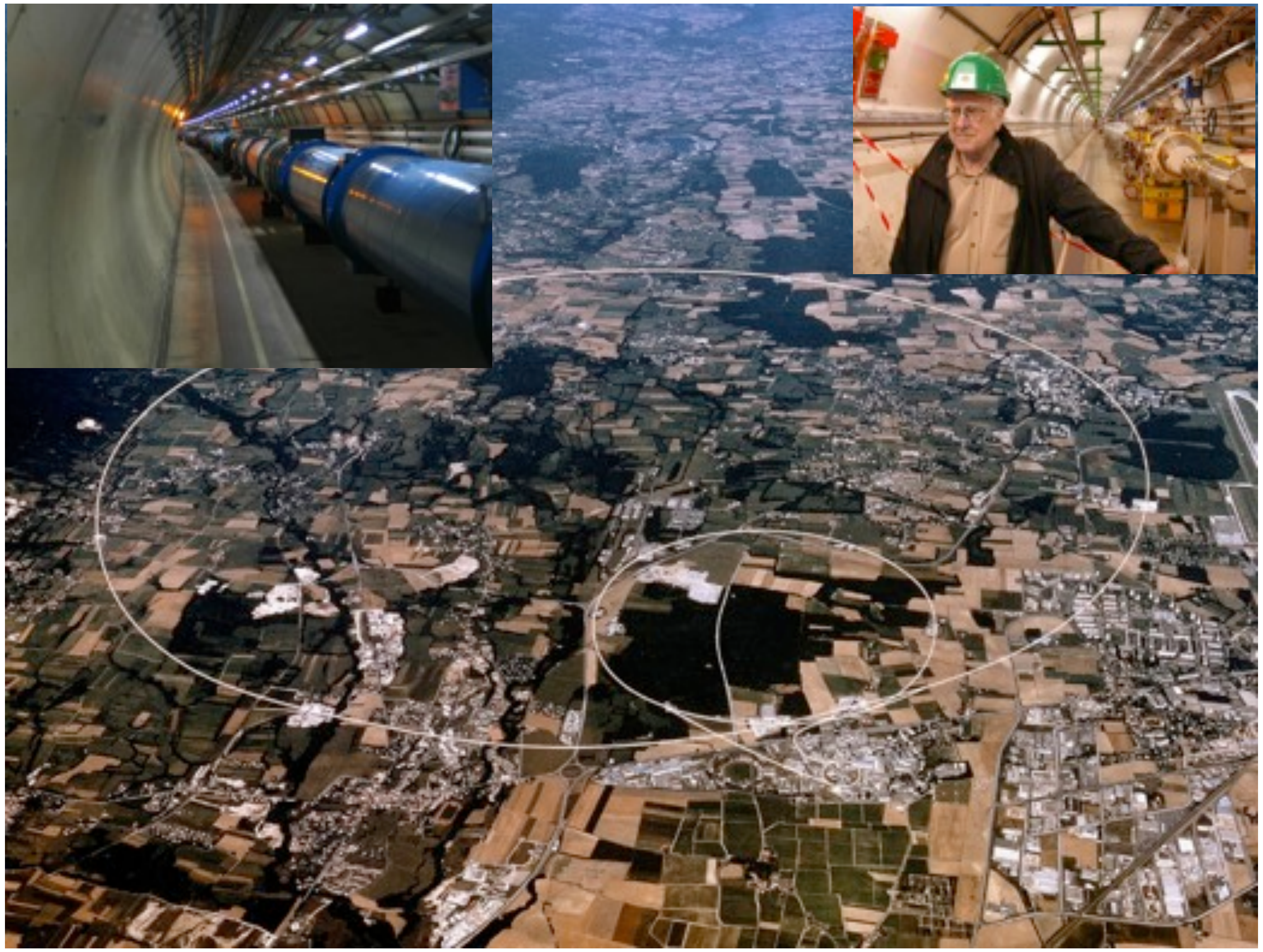
Large Hadron Collider - CERN

primary mission:

- Search for Higgs particle

- Origin of Electroweak symmetry breaking

- A Higgs-like particle is found
  Is it the Standard Model Higgs?
- Or, new strong dynamics?
- Composite Goldstone-like Higgs?
- SUSY?



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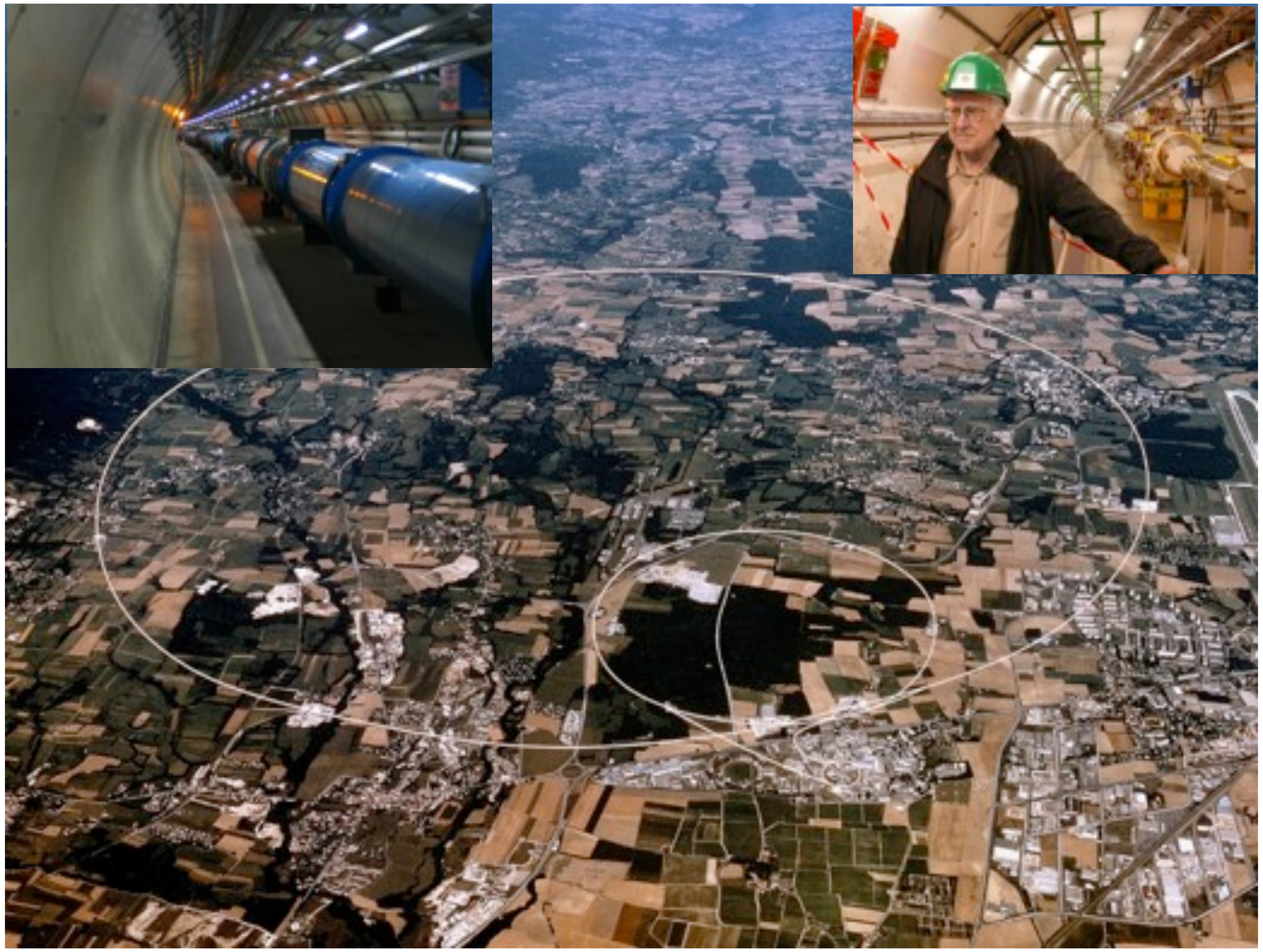

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Primary focus of USQCD BSM effort and this short talk

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:

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USQCD BSM White Paper - community based effort:

- to identify most significant lattice results of last few years
- to identify major research directions for planning
- to describe BSM lattice toolset with phenomenological applications
- estimate resources needed for the plan

New hardware proposal submitted including USQCD BSM plans

Introducing USQCD BSM groups with highlighted publications:

(approximately 1/5 of USQCD community)

select publications of Lattice Strong Dynamics (LSD) collaboration:

WW Scattering Parameters via Pseudoscalar Phase Shifts

Thomas Appelquist (Yale U.), Ron Babich, Richard C. Brower (Boston U.), Michael I. Buchoff, Michael Cheng (LLNL, Livermore), Michael A. Clark (Harvard-Smithsonian Ctr. Astrophys.), Saul D. Cohen (Washington U., Seattle), George T. Fleming (Yale U.), Joe Kiskis (UC, Davis), Meifeng Lin (Yale U.) *et al.*. Jan 2012. 8 pp.
Published in **Phys.Rev. D85 (2012) 074505**

select publication from Lattice Higgs Collaboration (LHC):

Can the nearly conformal sextet gauge model hide the Higgs impostor?

Zoltan Fodor (Wuppertal U. & IAS, Julich & Eotvos U.), Kieran Holland (U. Pacific, Stockton), Julius Kuti (UC, San Diego), Daniel Nogradi (Eotvos U.), Chris Schroeder (LLNL, Livermore), Chik Him Wong (UC, San Diego). Sep 2012. 10 pp.
Published in **Phys.Lett. B718 (2012) 657-666**

select publications of SUSY group:

Phase Structure of Lattice N=4 Super Yang-Mills

Simon Catterall, Poul H. Damgaard, Thomas Degrand, Richard Galvez, Dhagash Mehta. Sep 2012. 28 pp.
Published in **JHEP 1211 (2012) 072**

Neutralino-hadron scattering in the NMSSM

Sophie J. Underwood (Adelaide U.), Joel Giedt (Rensselaer Poly.), Anthony W. Thomas, Ross D. Young (Adelaide U.). Mar 2012. 4 pp.
Published in **Phys.Rev. D86 (2012) 035009**

select publication of Boulder BSM collaboration:

MCRG study of 8 and 12 fundamental flavors

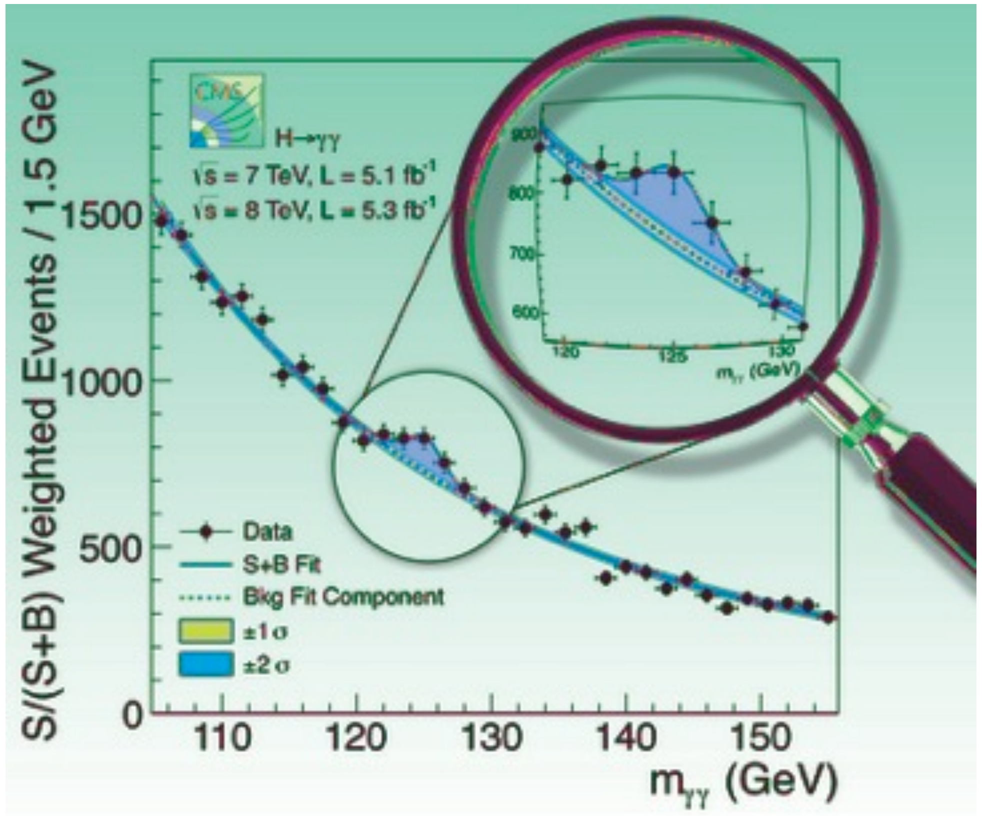
Gregory Petropoulos, Anqi Cheng, Anna Hasenfratz, David Schaich (Colorado U.). Dec 2012. 7 pp.
Published in **PoS LATTICE2012 (2012) 051**
To appear in the proceedings of Conference: C12-06-24 Proceedings
e-Print: **arXiv:1212.0053 [hep-lat] | PDF**

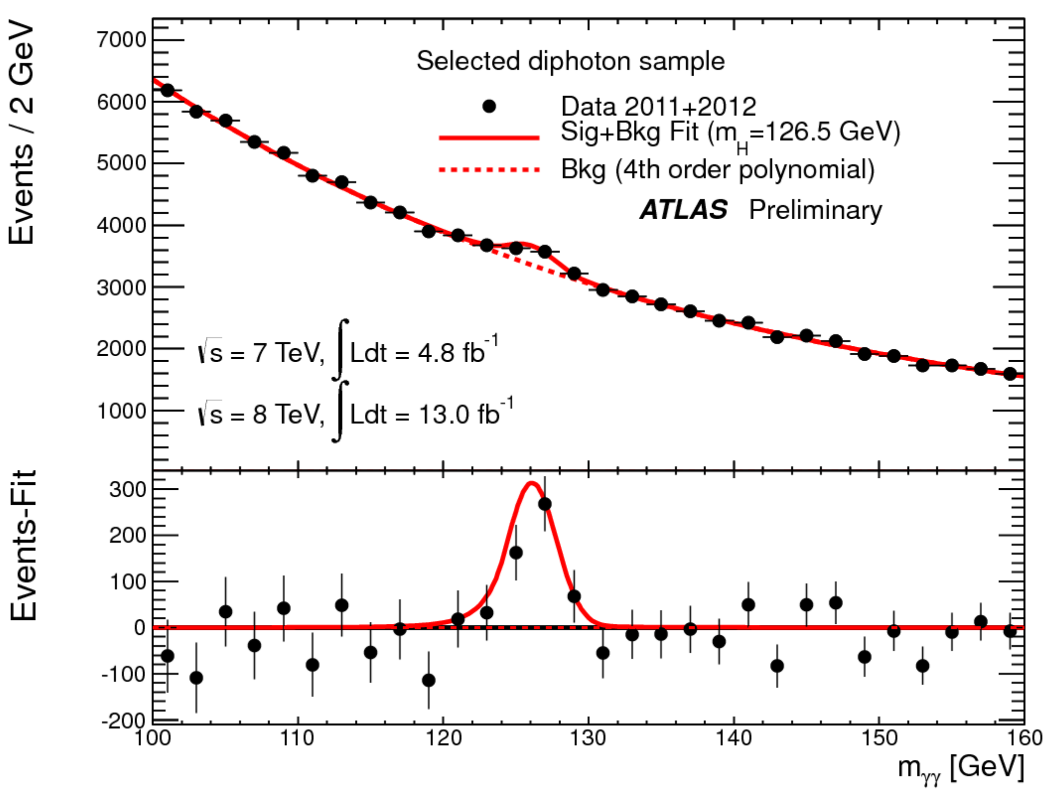
select publication of BSM finite temperature studies:

QCD with colour-sextet quarks

D.K. Sinclair, J.B. Kogut. Nov 2012. 7 pp.
Published in **PoS LATTICE2012 (2012) 026**

Rational for BSM:





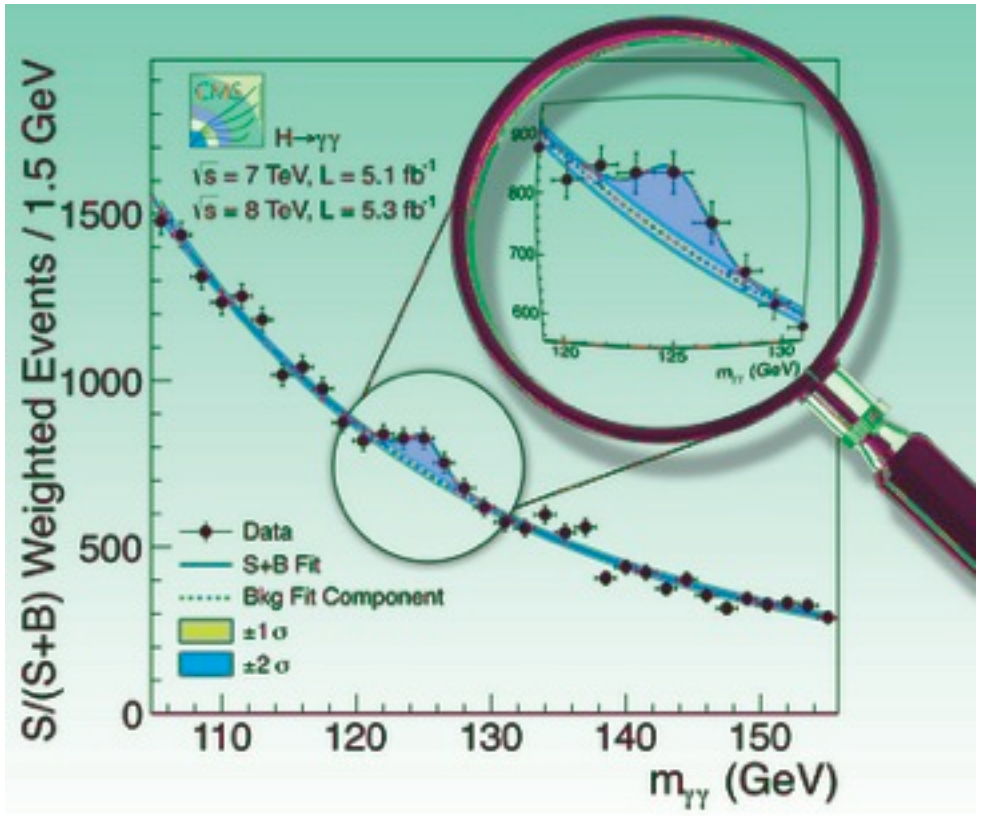
voices: a light Higgs-like scalar is found which is consistent with SM within errors and no composite states have been seen below 1 TeV, ergo no need for BSM based compositeness. Besides, how do you get a light Higgs from compositeness?

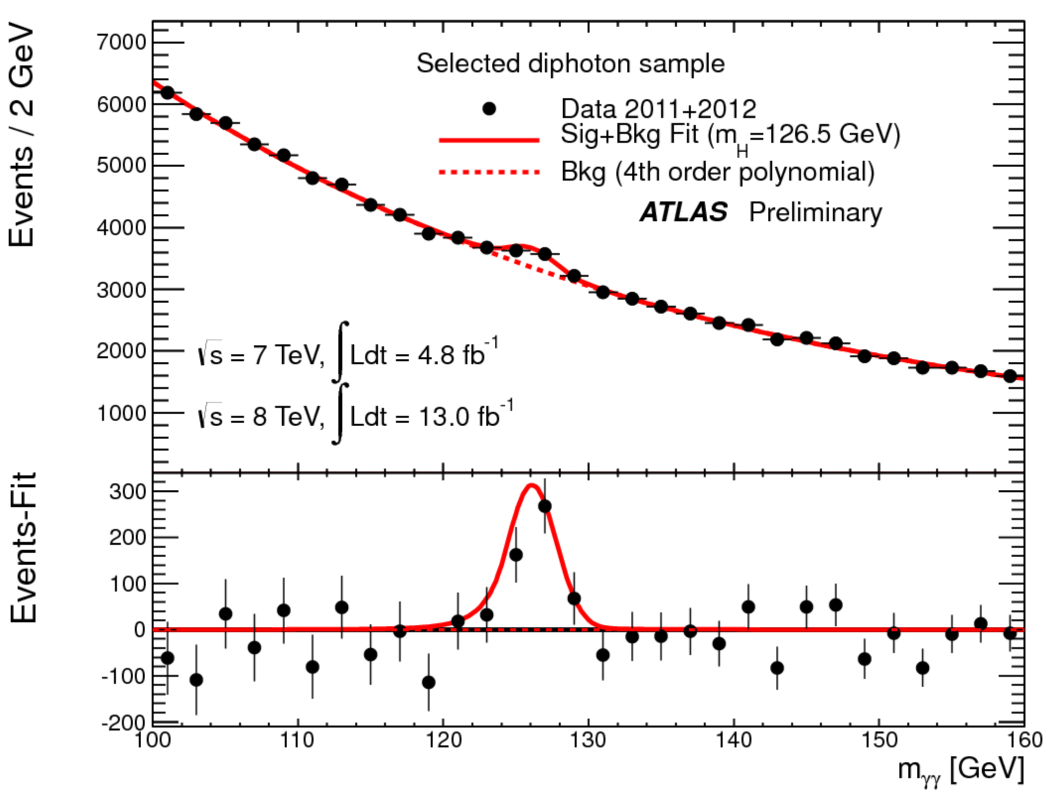
facts: Compositeness and a light Higgs scalar are not incompatible; search for composite states in the LHC7/8 runs was not based on solid predictions but on naively scaled up QCD and on unacceptable old technicolor guessing games. This alone does not make compositeness right!

plans: LHC14 will search for new physics from compositeness and SUSY, and the USQCD BSM group is preparing quantitative lattice based predictions to rule in or rule out

Rational for BSM:

three USQCD BSM directions based on gauge force:





- strongly coupled near-conformal gauge theories
  - light scalar is expected from approximate scale invariance (dilaton, or just light scalar?)
  - QCD is NOT approximately scale invariant making old technicolor guessing games irrelevant
- light pseudo-Goldstone boson (like little Higgs)
  - starts from a scalar massless Goldstone boson
  - expects to make quantitative predictions about composite spectrum above 1 TeV
- SUSY
  - for better understanding of dynamical symmetry breaking and to explore susy theory scenarios

- **We are calculating quantitative predictions for LHC14 (e.g. sextet model)**

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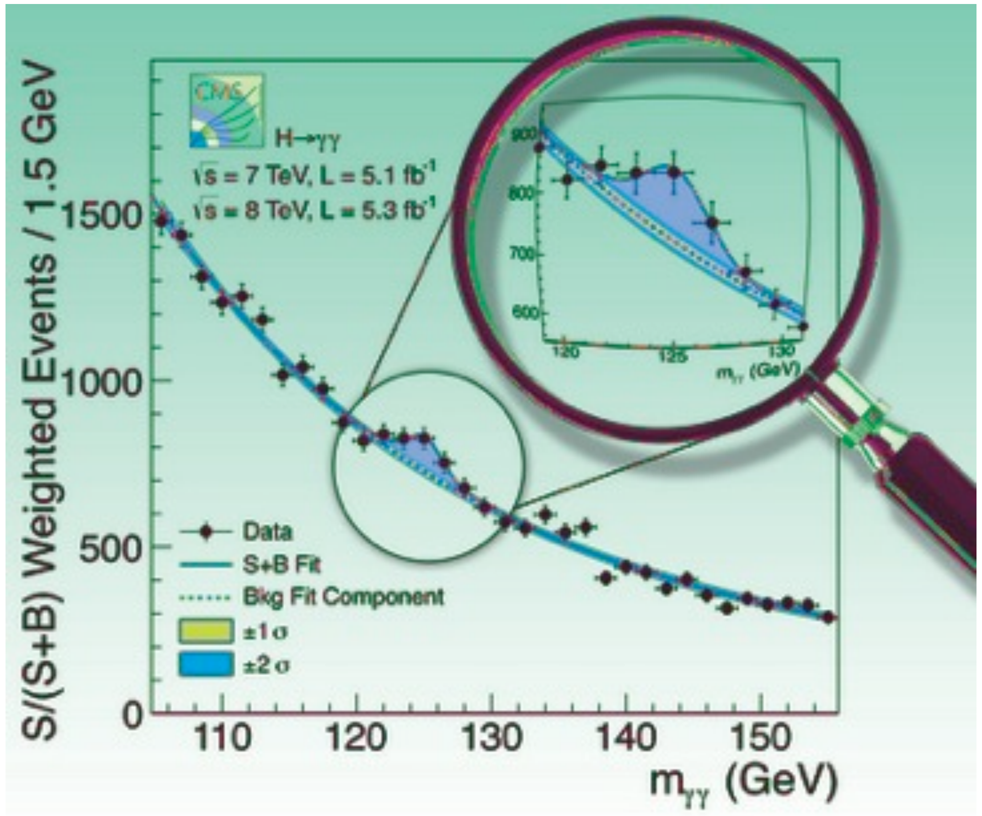

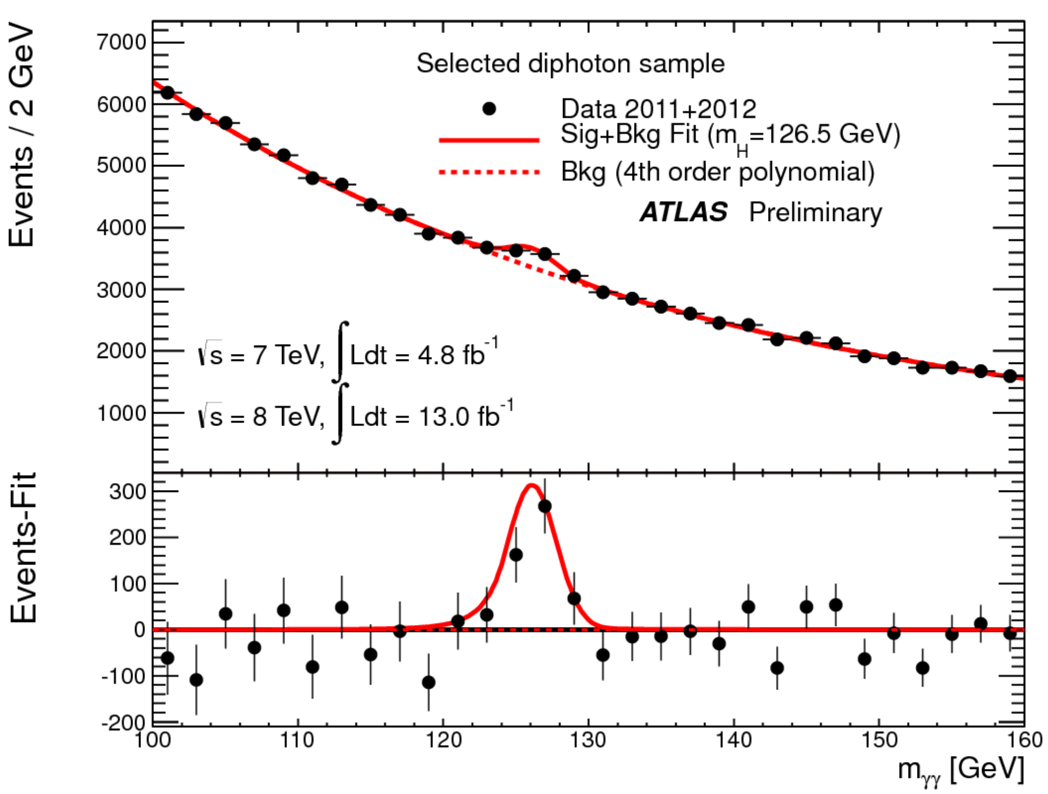

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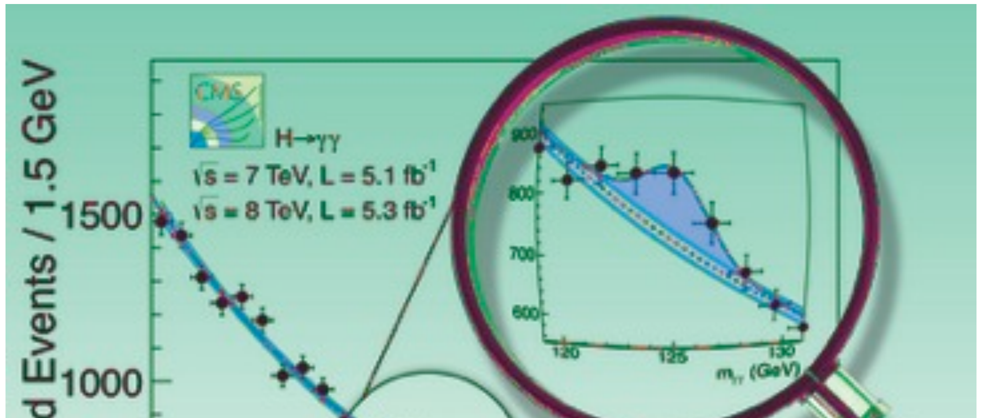

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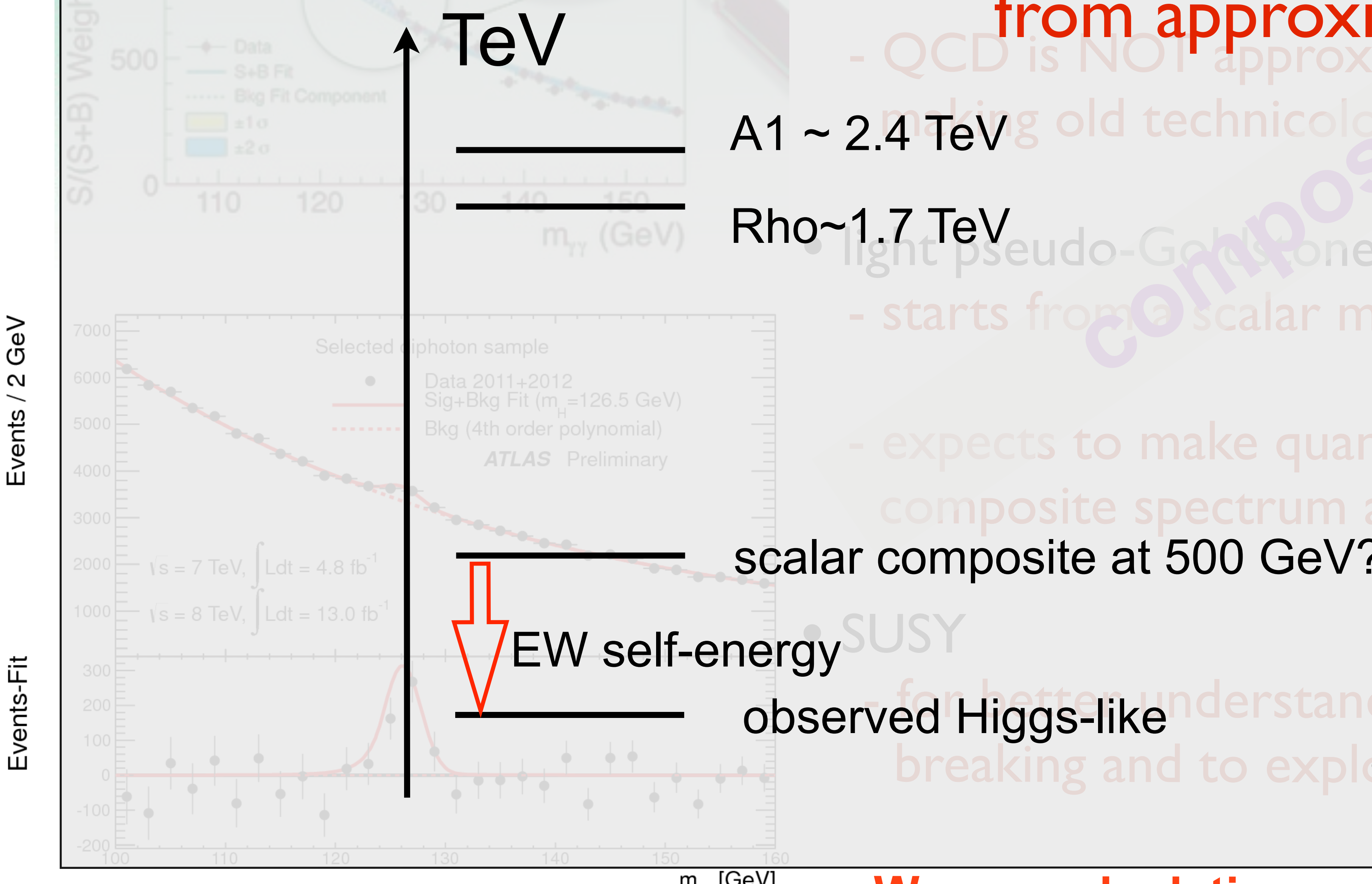

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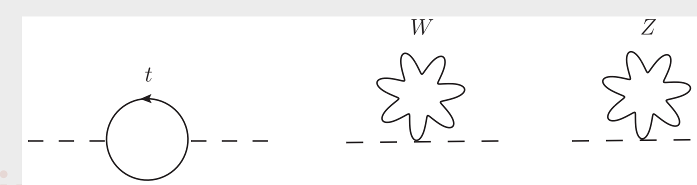

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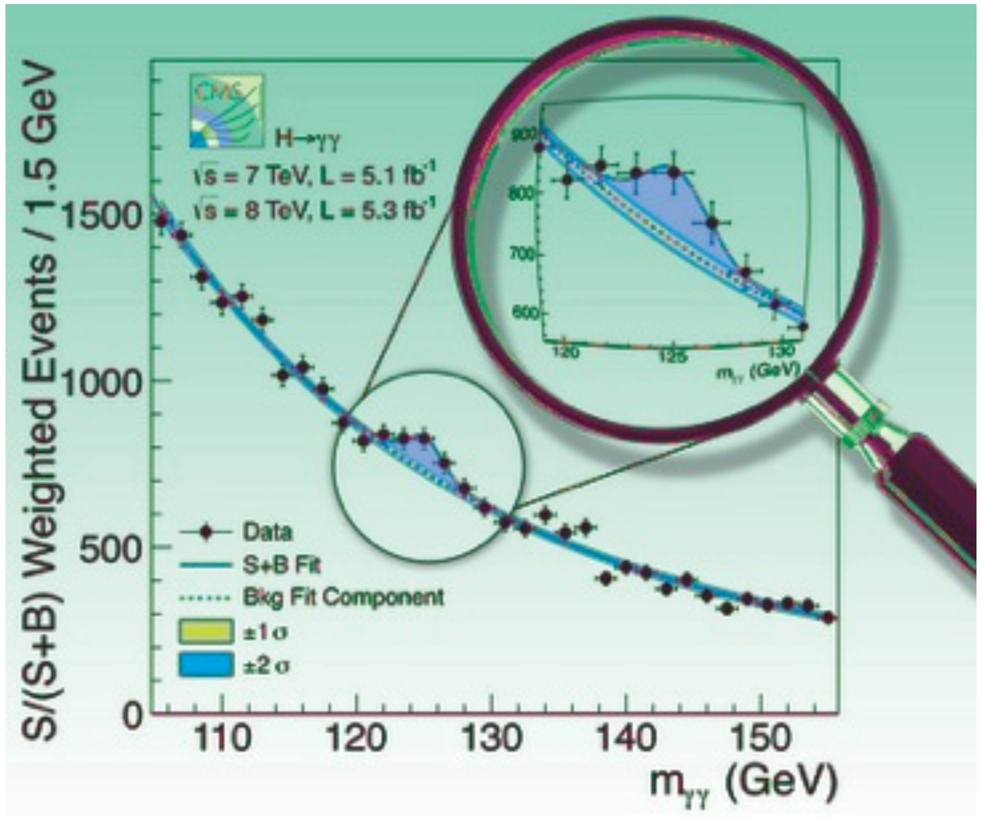

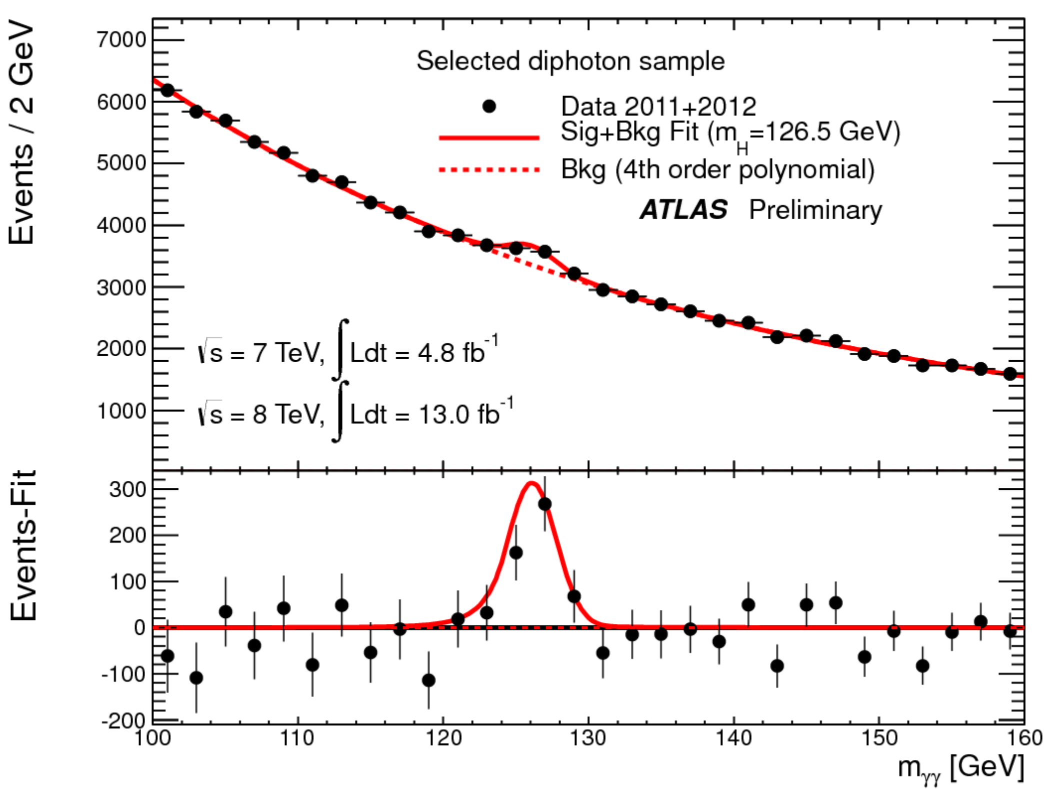

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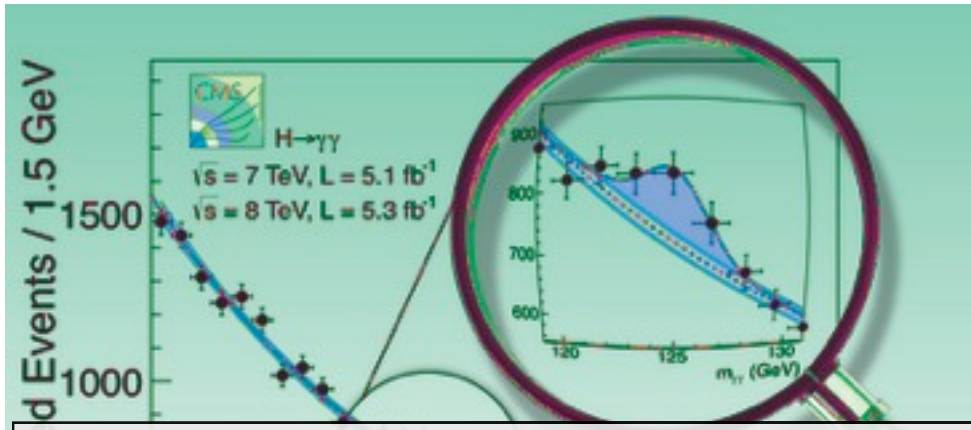

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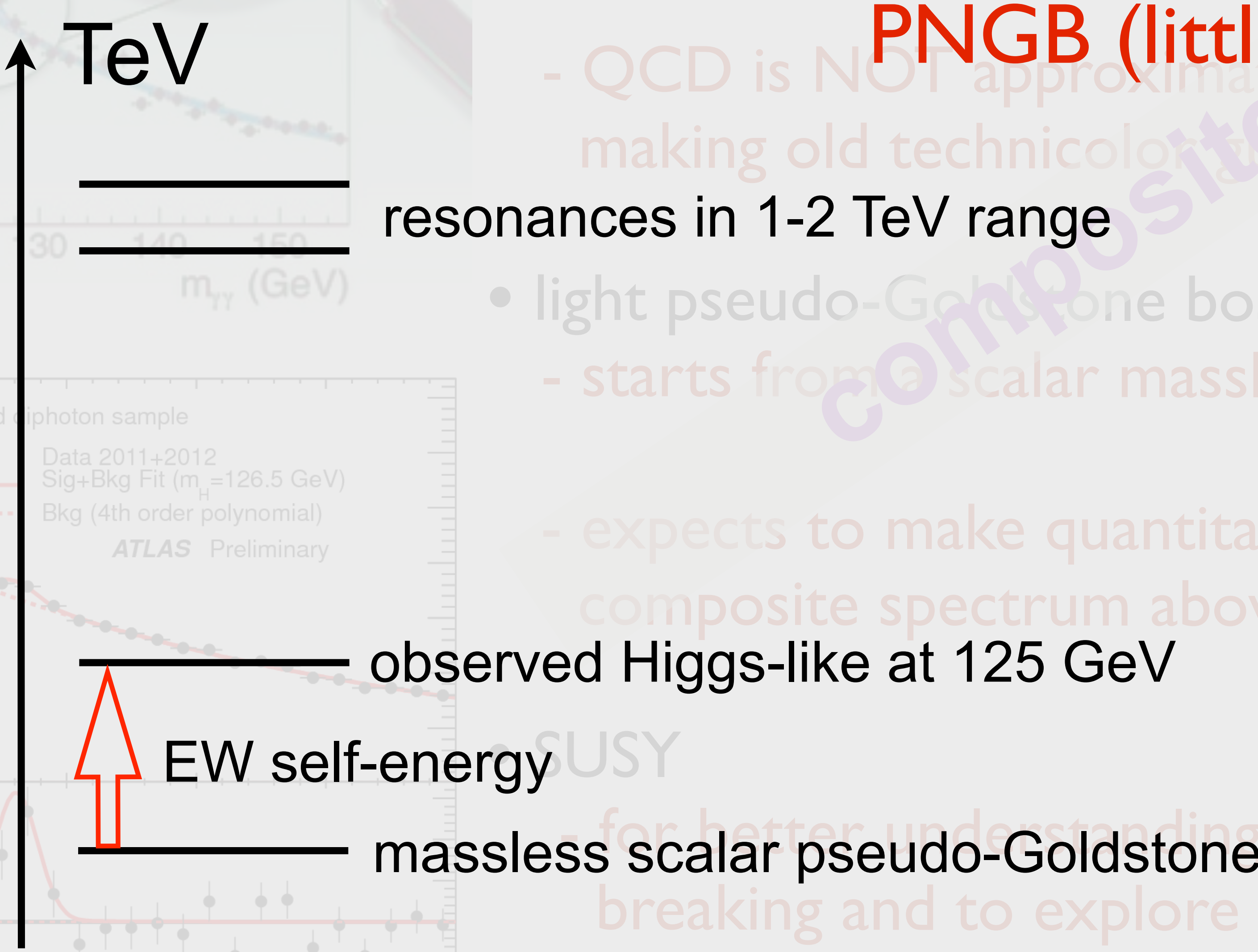
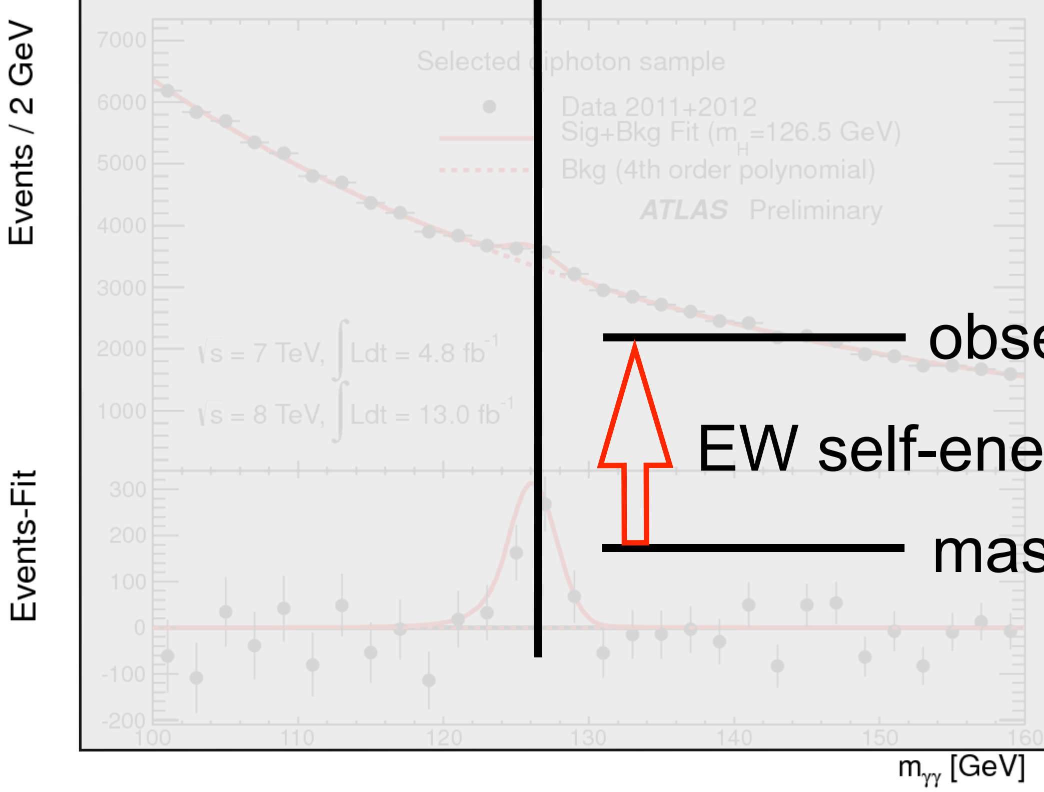
compositeness

PNGB (little Higgs) scenario





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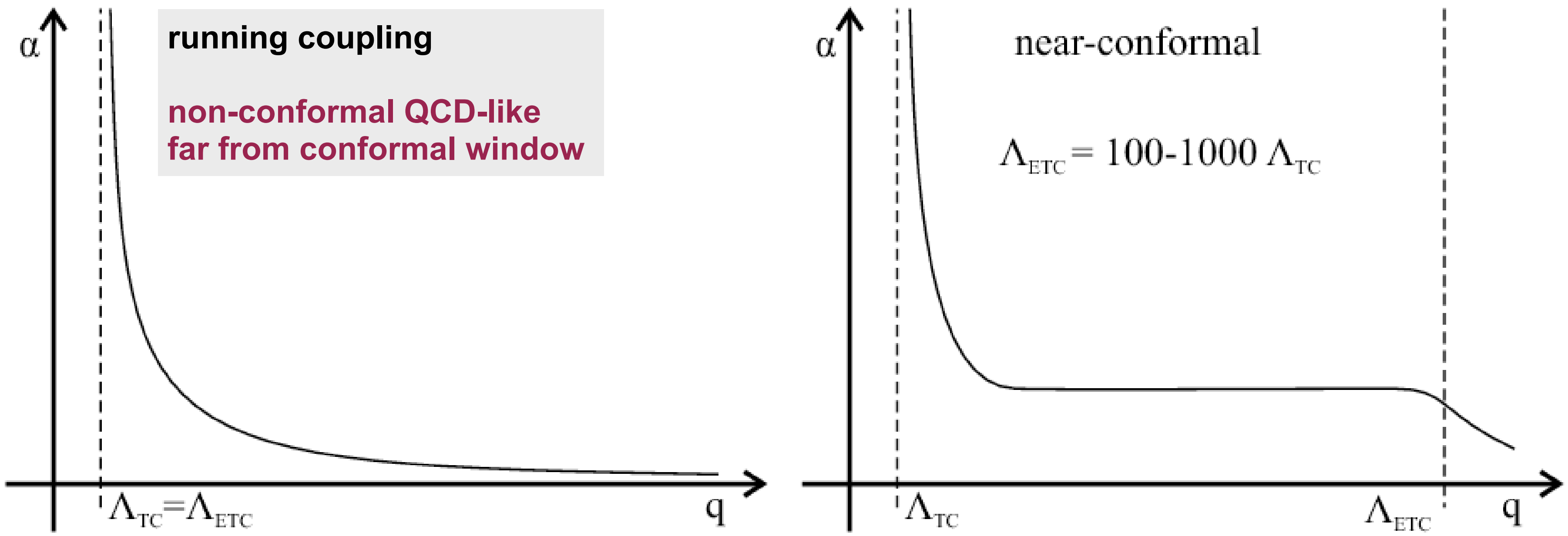
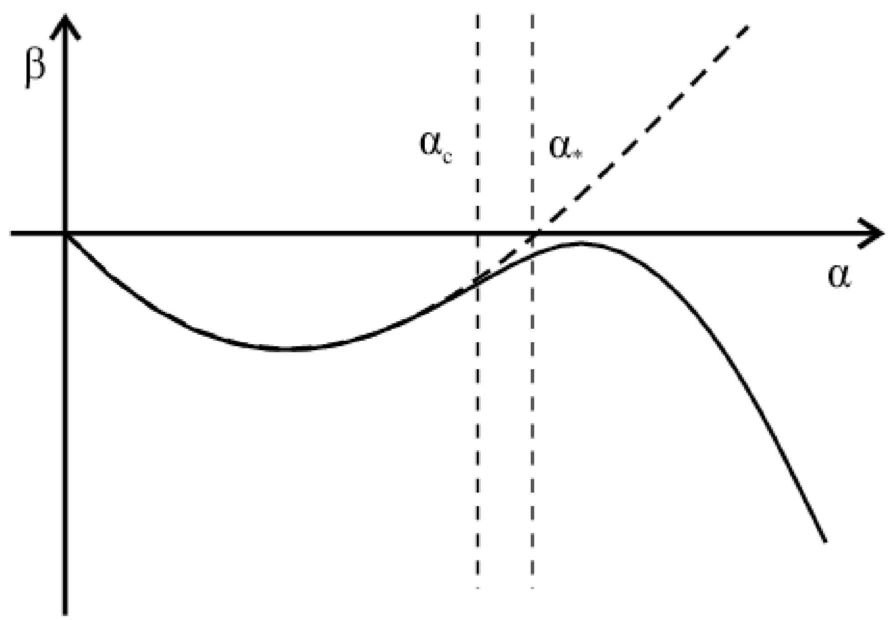
The light Higgs near conformality (dilaton-like?)



original textbook Technicolor paradigm:

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



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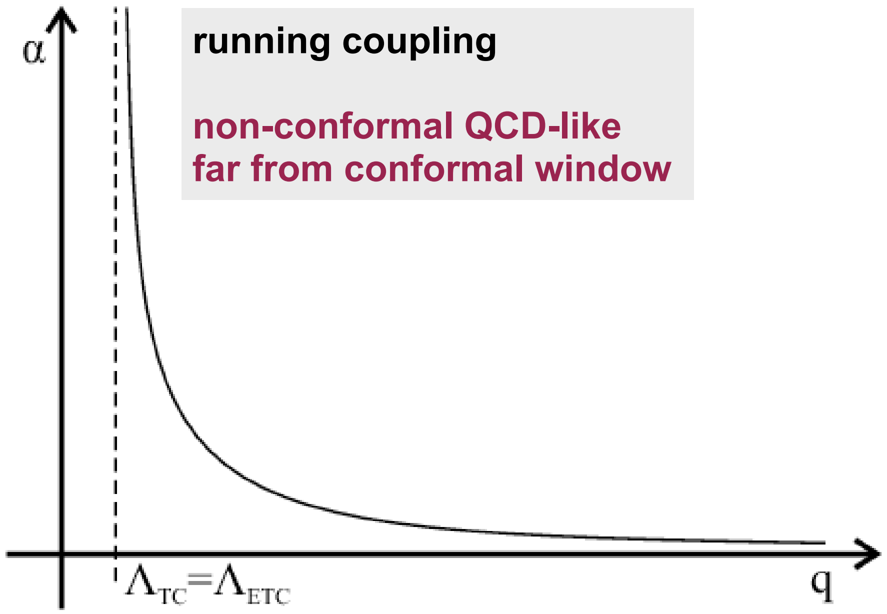

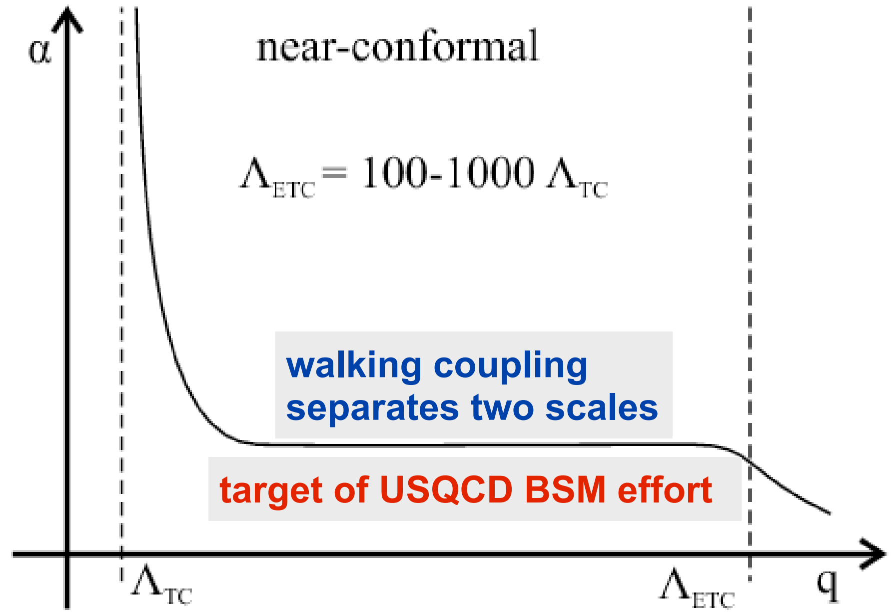

Extended Technicolor paradigm:

- 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*

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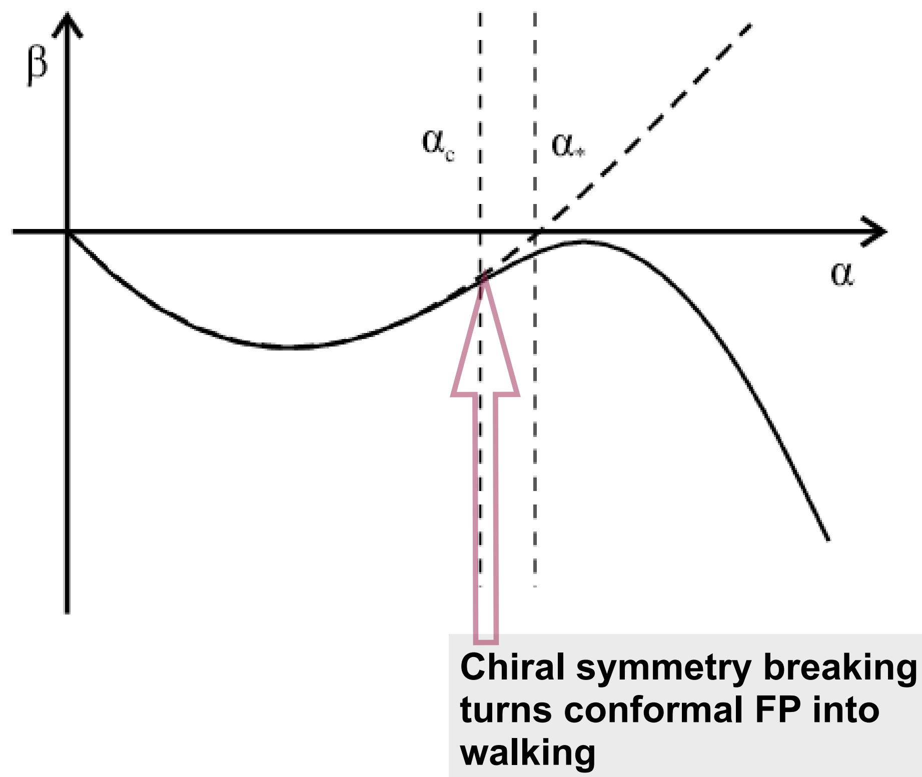
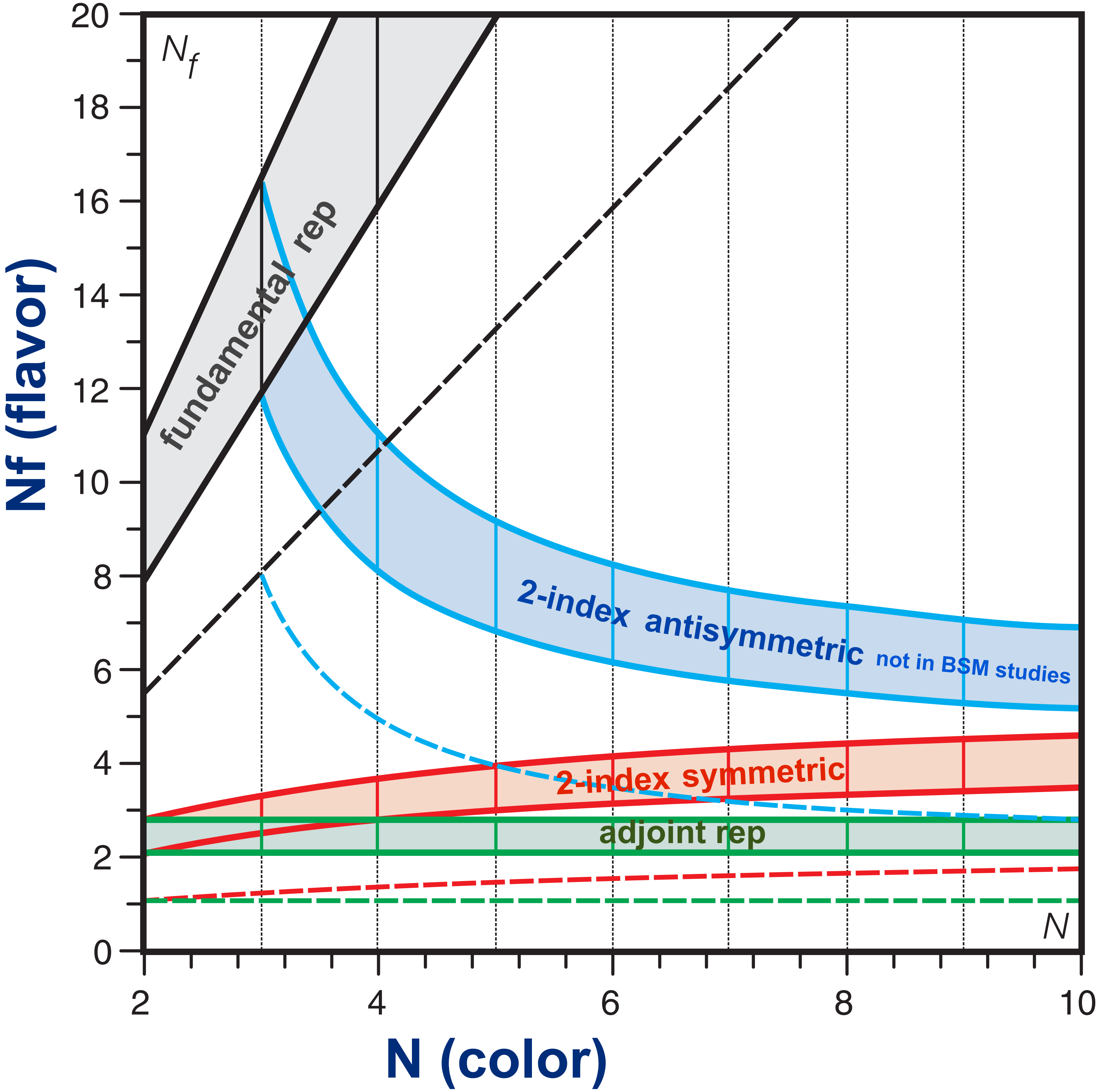


The light Higgs near conformality (dilaton-like?)

theory space and conformal window
color, flavor, and massless fermion representation



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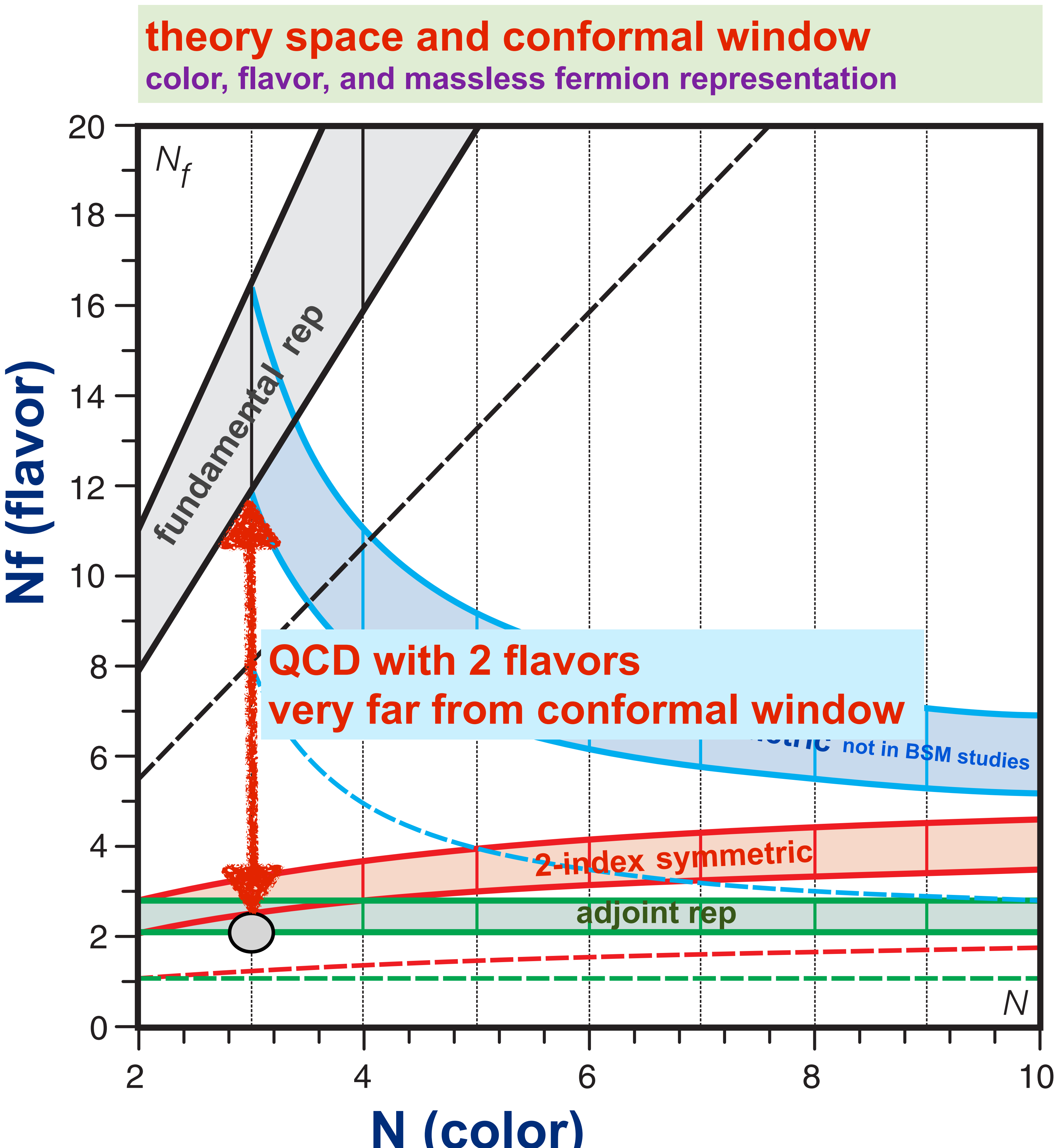

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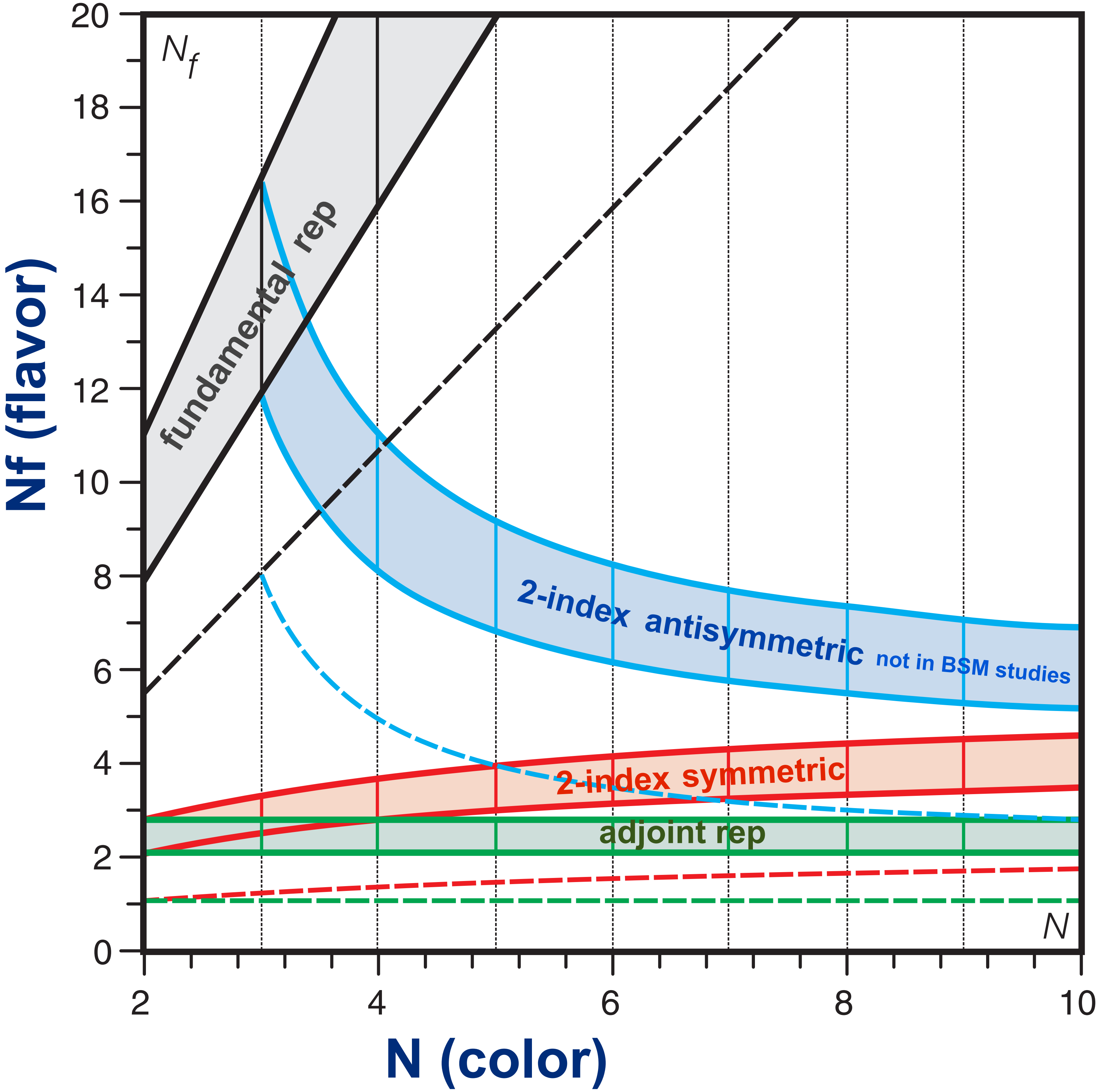

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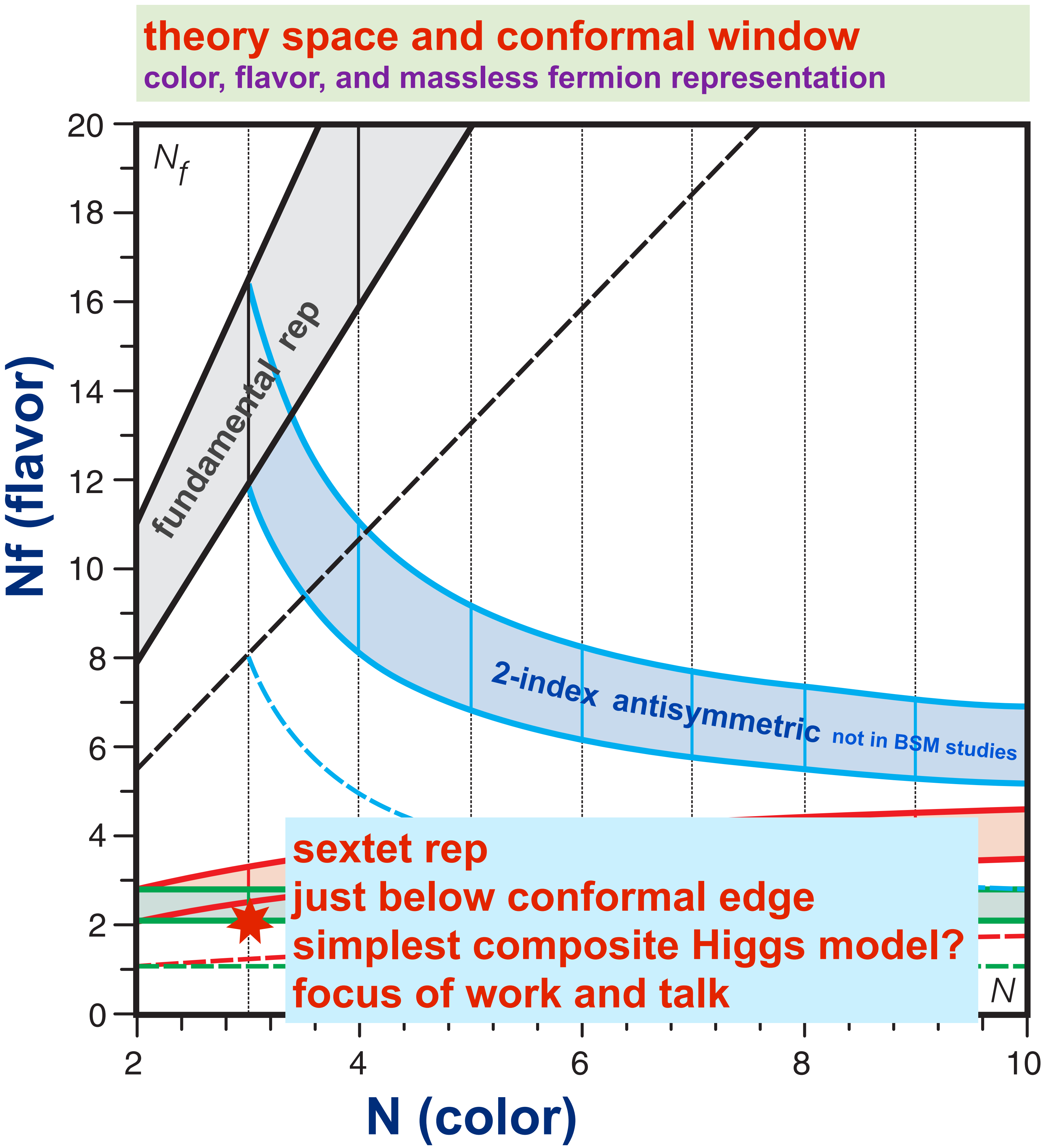

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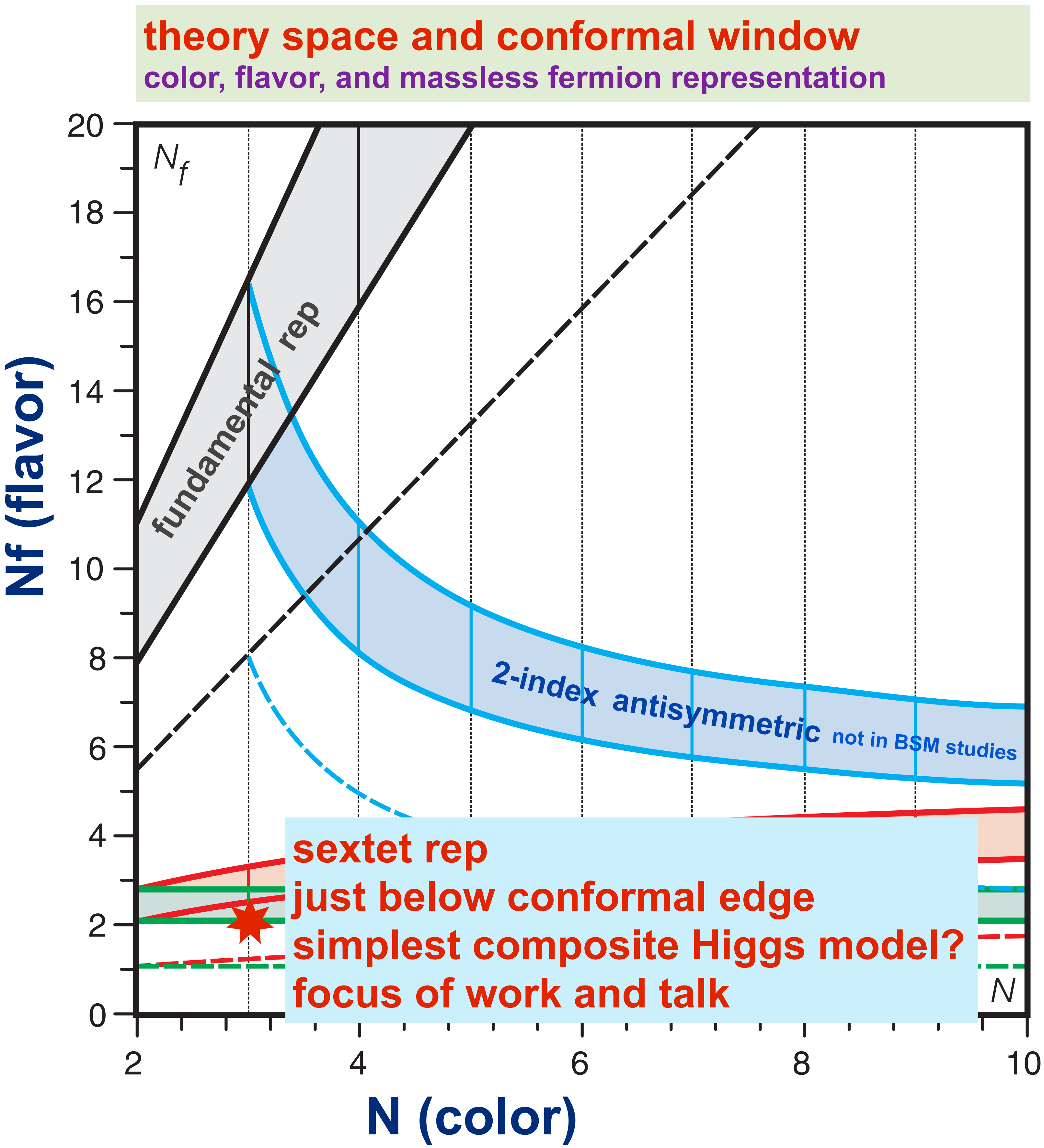


characteristics of nearly scale invariant gauge theories:

very small beta function with gauge coupling slowly changing with scale

chiral condensate with large B/F

the only input parameter is the gauge coupling which is set by the vev from the condensate

The light Higgs near conformality (dilaton-like?)

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

Partially Conserved Dilatation Current (PCDC)

there are two different expectations when conformal window is approached: $g(\mu=\Lambda)=g_c$

1. dilaton mass parametrically vanishes $m_\sigma^2 \simeq (N_f^c - N_f)\cdot\Lambda^2$ $\frac{m_\sigma}{f_\sigma}\to 0$

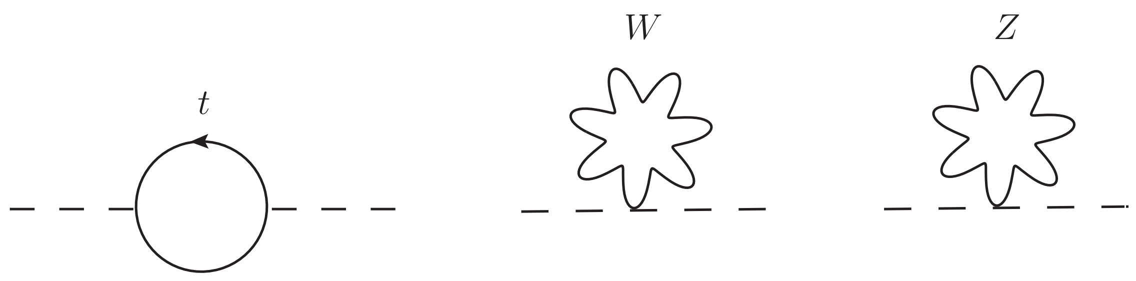
2. dilaton mass finite in the limit $f_\sigma \simeq \Lambda$ $\frac{m_\sigma}{f_\sigma}\to const$

important role of $\frac{f_\pi}{f_\sigma}$ in electroweak phenomenology

both scenarios expect light Higgs-like dilaton

but how light is light ?

400-500 GeV dynamical Higgs as impostor?
Sannino



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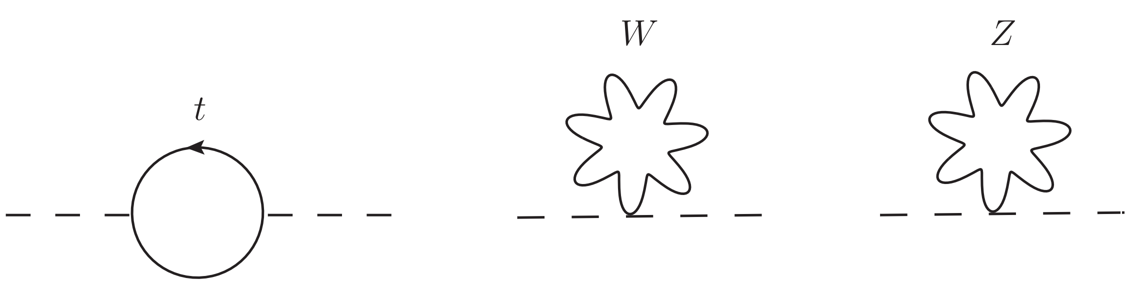

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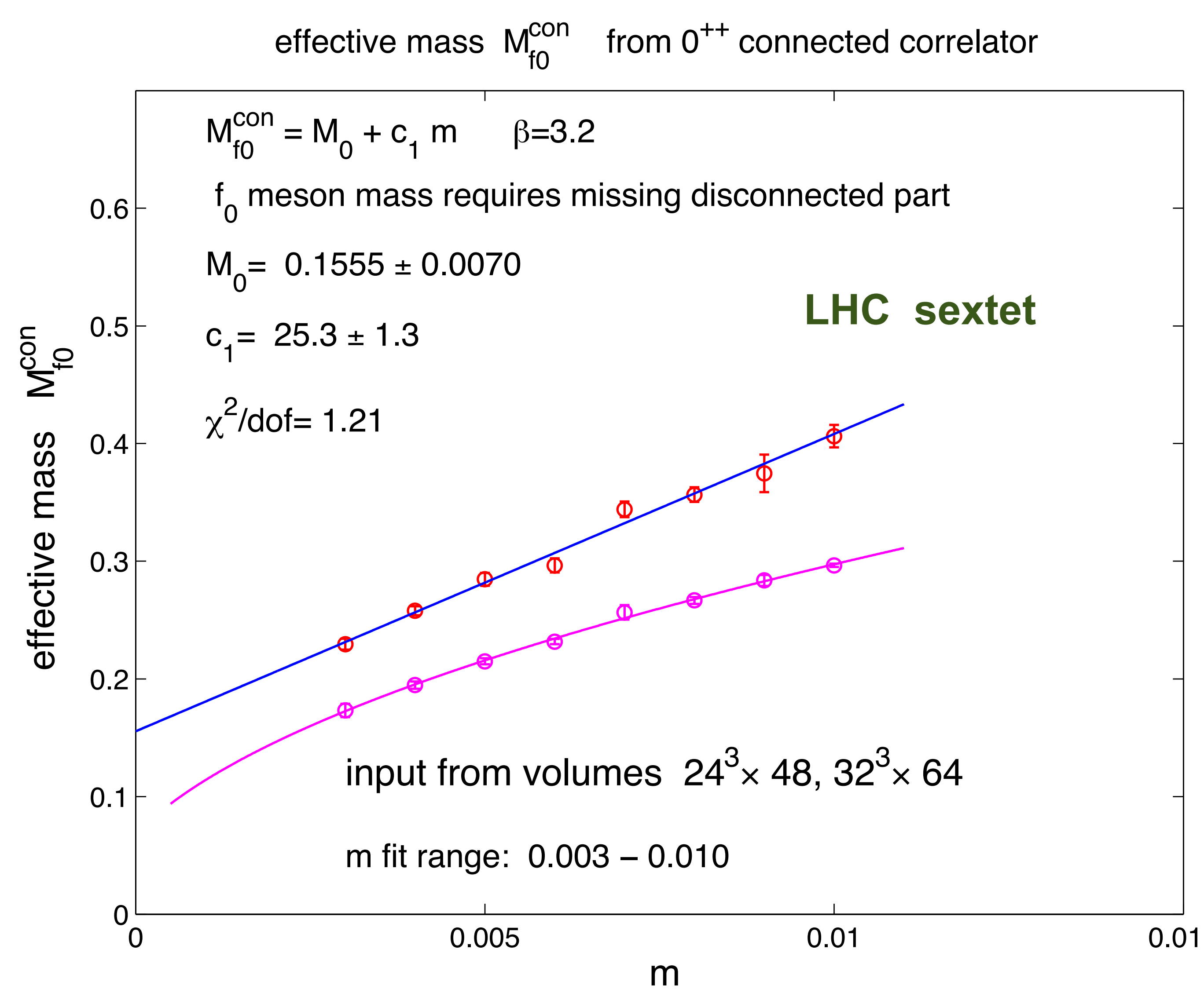

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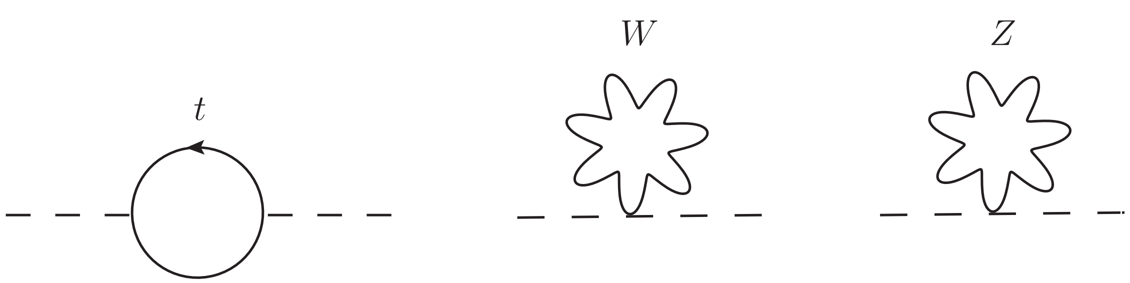

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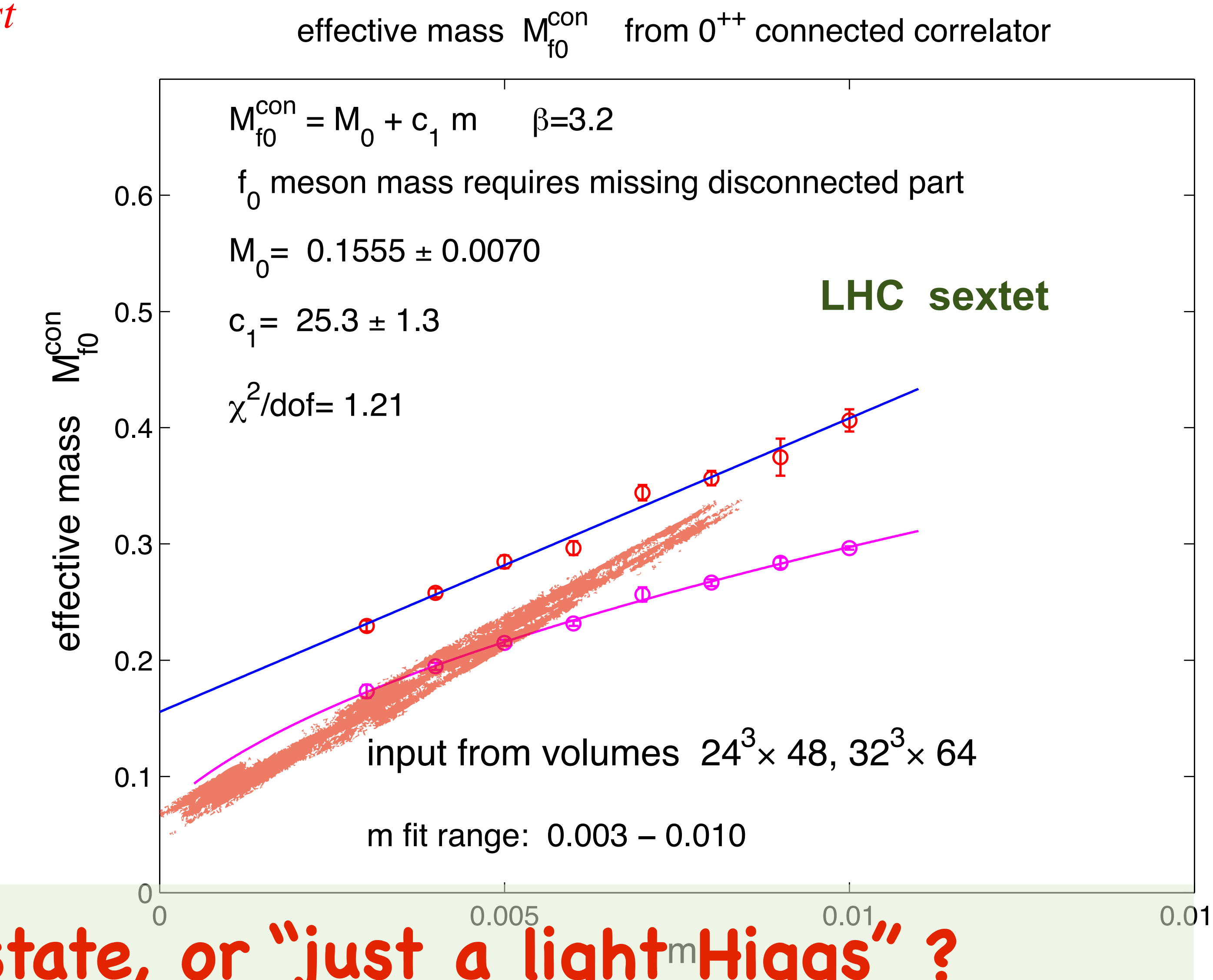

is this SCGT dilaton-like scalar state, or "just a light Higgs" ?

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tunable for light dilaton state close to conformal window?

2. dilaton mass finite in the limit $f_\sigma \sim \Lambda \quad \frac{m_\sigma}{f_\sigma} \to \mathrm{const}$

- N_f is not continuously tunable

important role of $\frac{m_\sigma}{f_\sigma}$ in electroweak phenomenology

both scenarios expect light Higgs-like dilaton

- fermion mass term ?

but how light is light ?

- four-fermion operators ?

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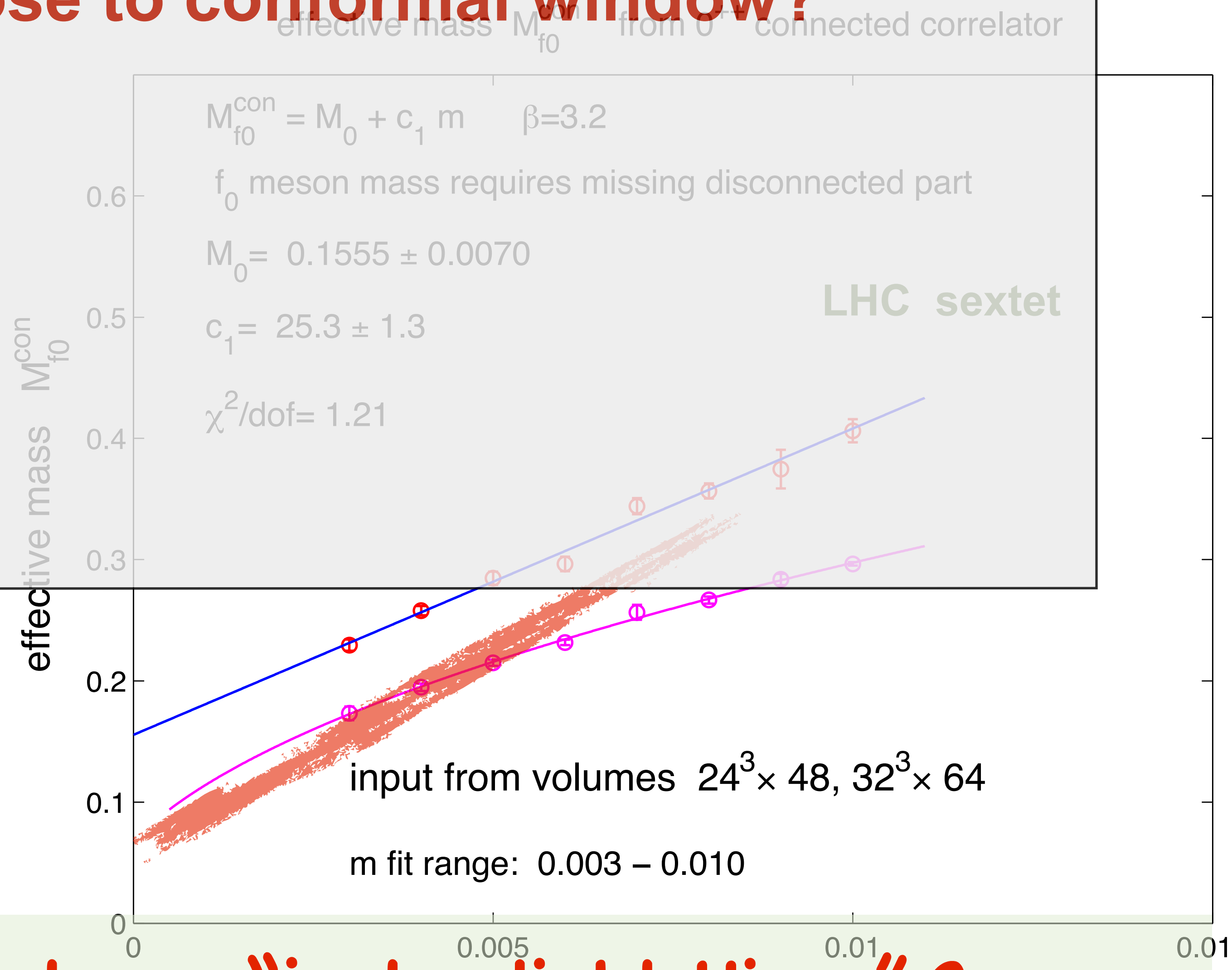

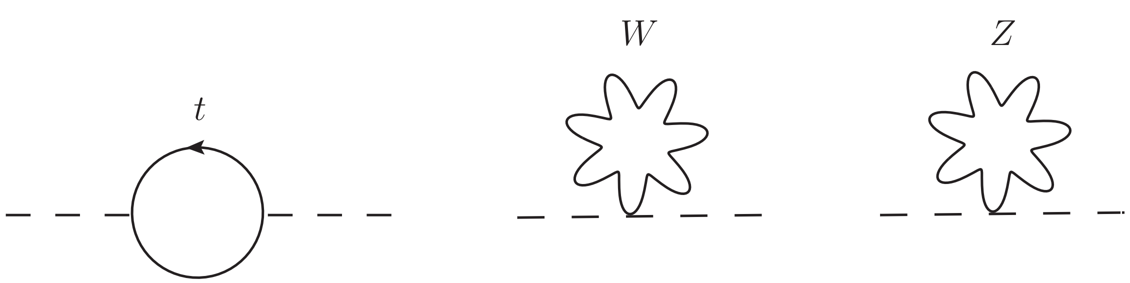

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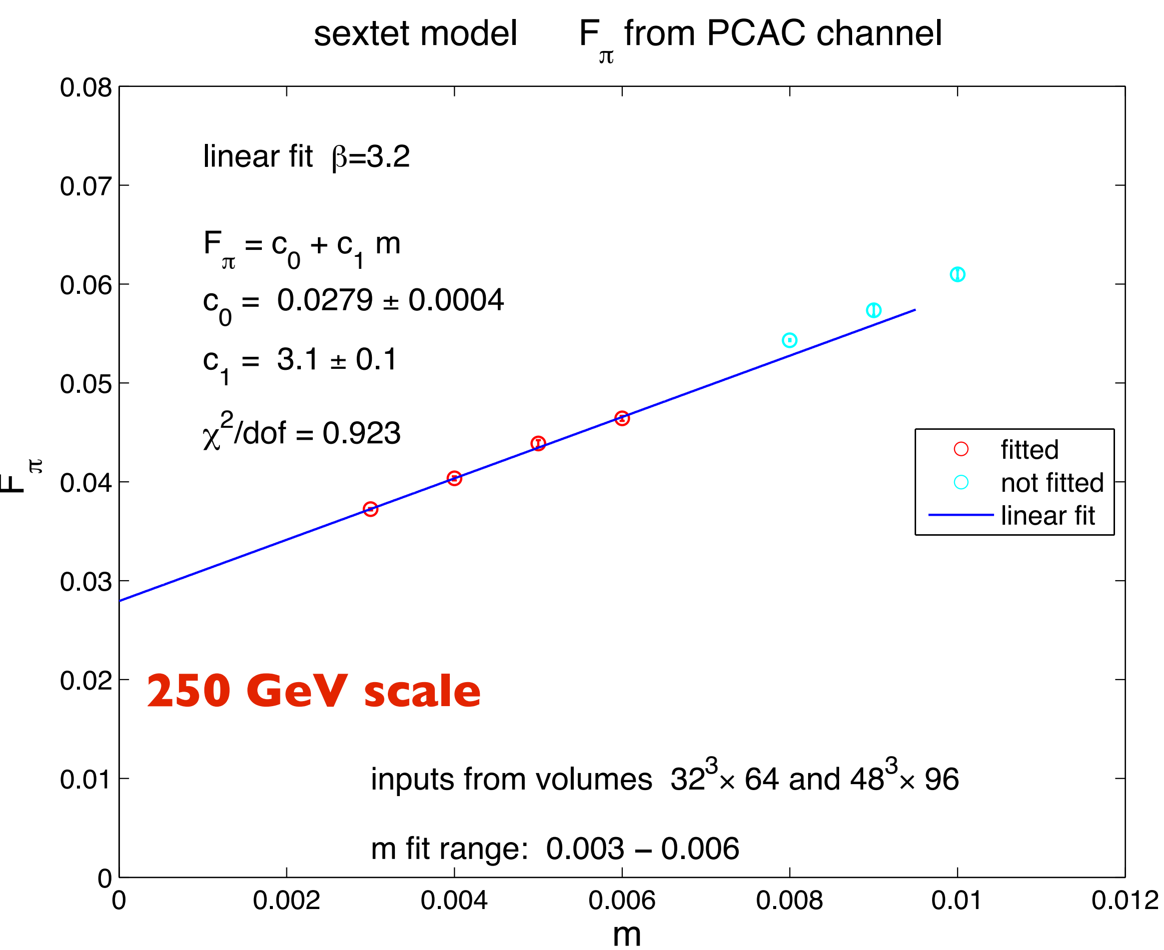
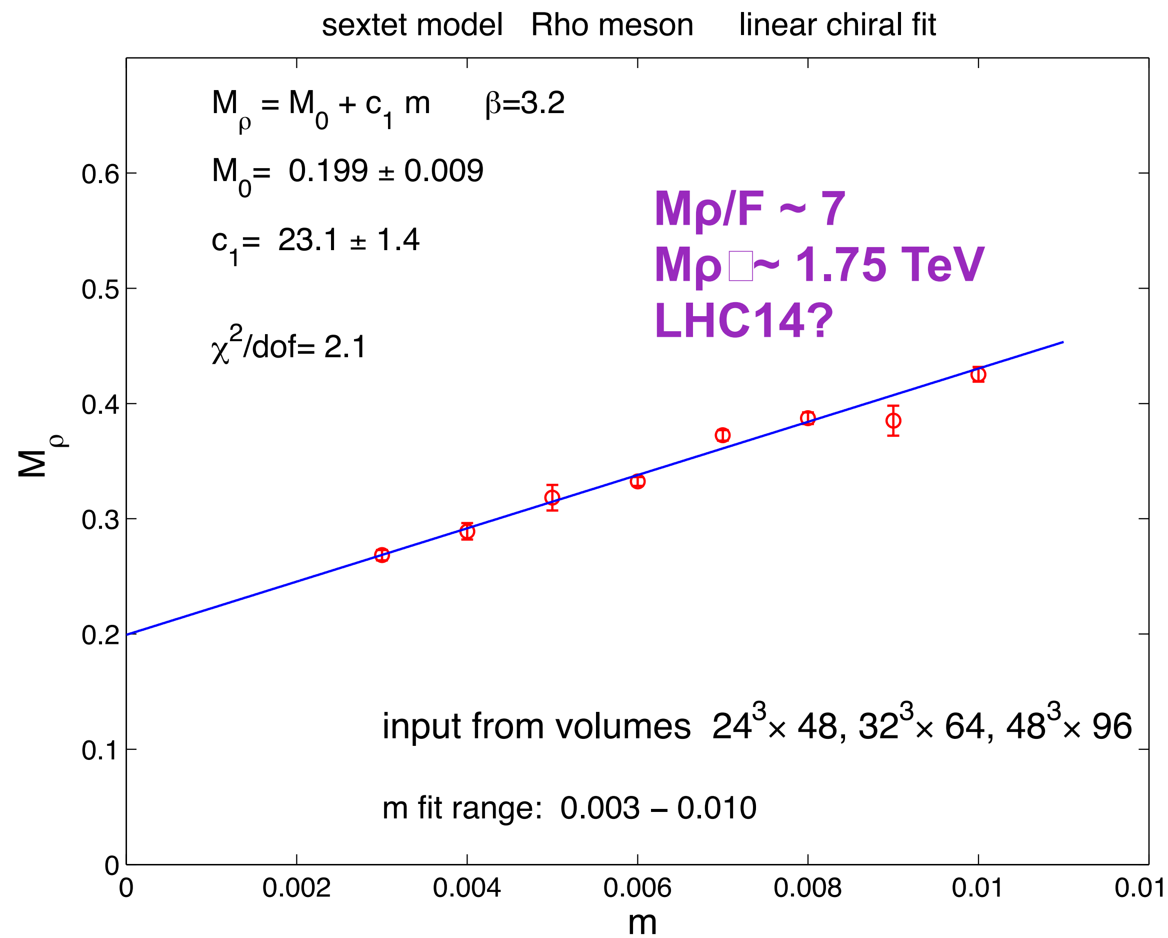
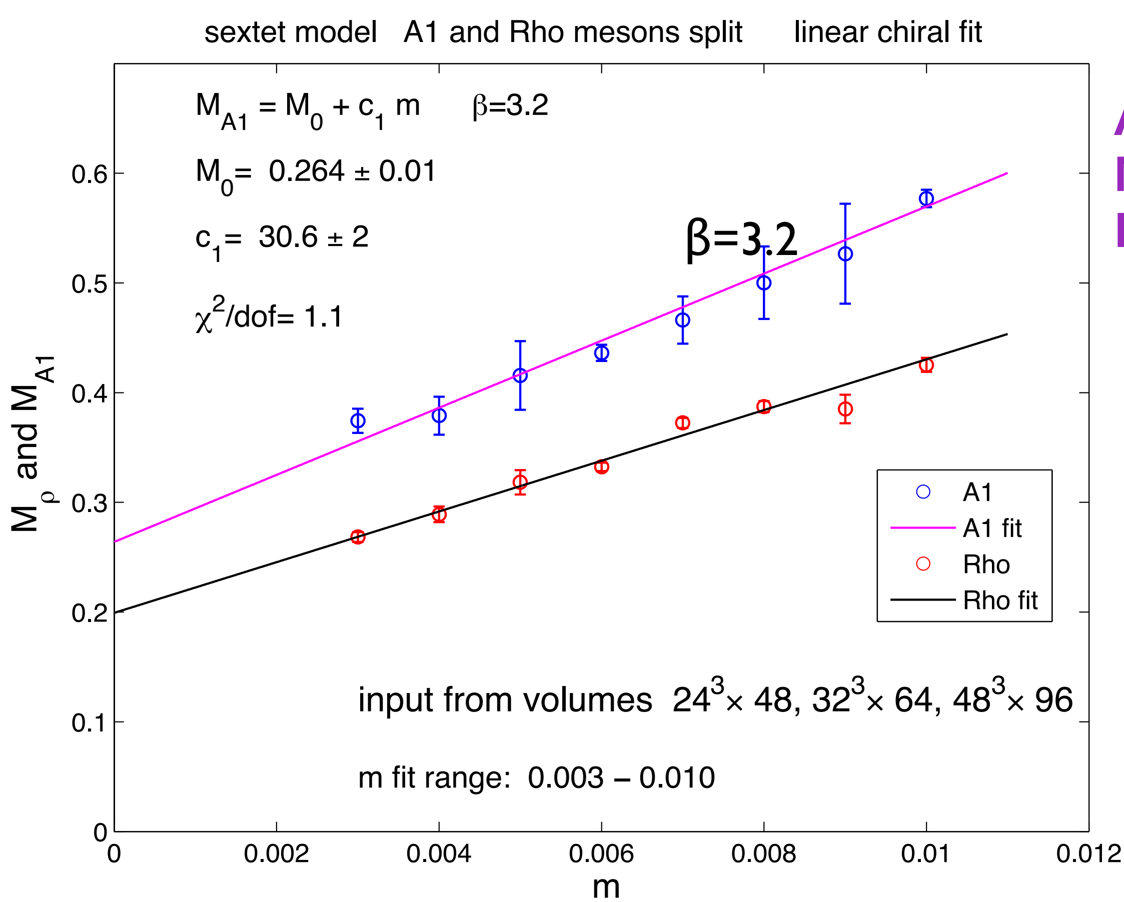


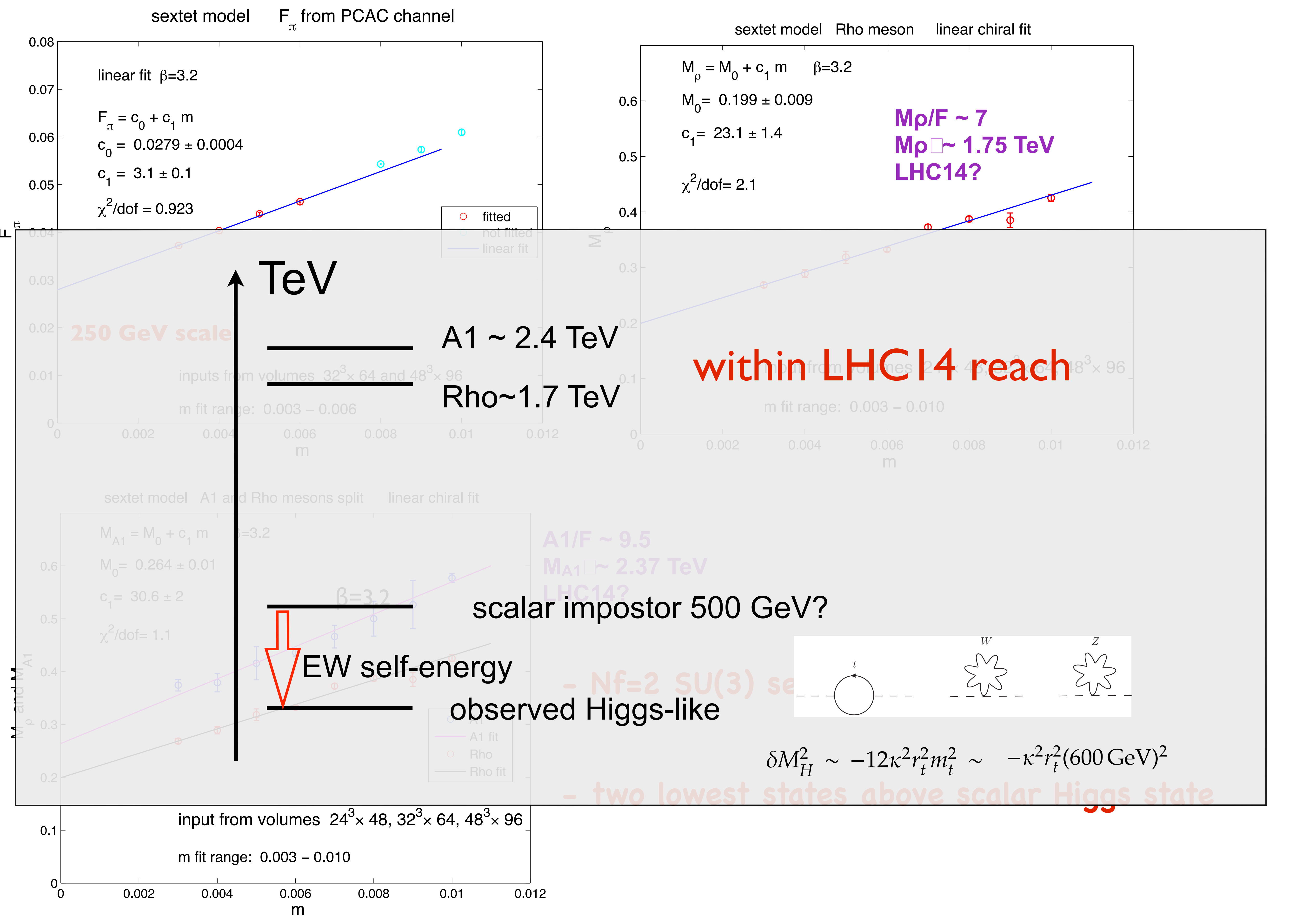




A1/F ~ 9.5
M_{A1} ~ 2.37 TeV
LHC14?

- Nf=2 SU(3) sextet M_ρ and $M(A_1)$

- two lowest states above scalar Higgs state


sextet model F_π from PCAC channel
linear fit β=3.2
F_π = c_0 + c_1 m
c_0 = 0.0279 ± 0.0004
c_1 = 3.1 ± 0.1
χ²/dof = 0.923
fitted
sextet model Rho meson linear chiral fit
M_ρ = M_0 + c_1 m β=3.2
M_0= 0.199 ± 0.009
c_1= 23.1 ± 1.4
χ²/dof= 2.1
Mρ/F ~ 7
Mρ ~ 1.75 TeV
LHC14?
TeV
A1 ~ 2.4 TeV
Rho~1.7 TeV
within LHC14 reach
scalar impostor 500 GeV?
EW self-energy
observed Higgs-like
t
W
Z
δM²_H ~ −12κ²r²_t m²_t ~ −κ²r²_t(600 GeV)²
input from volumes 24³× 48, 32³× 64, 48³× 96
m fit range: 0.003 – 0.010
m

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 simulations!**

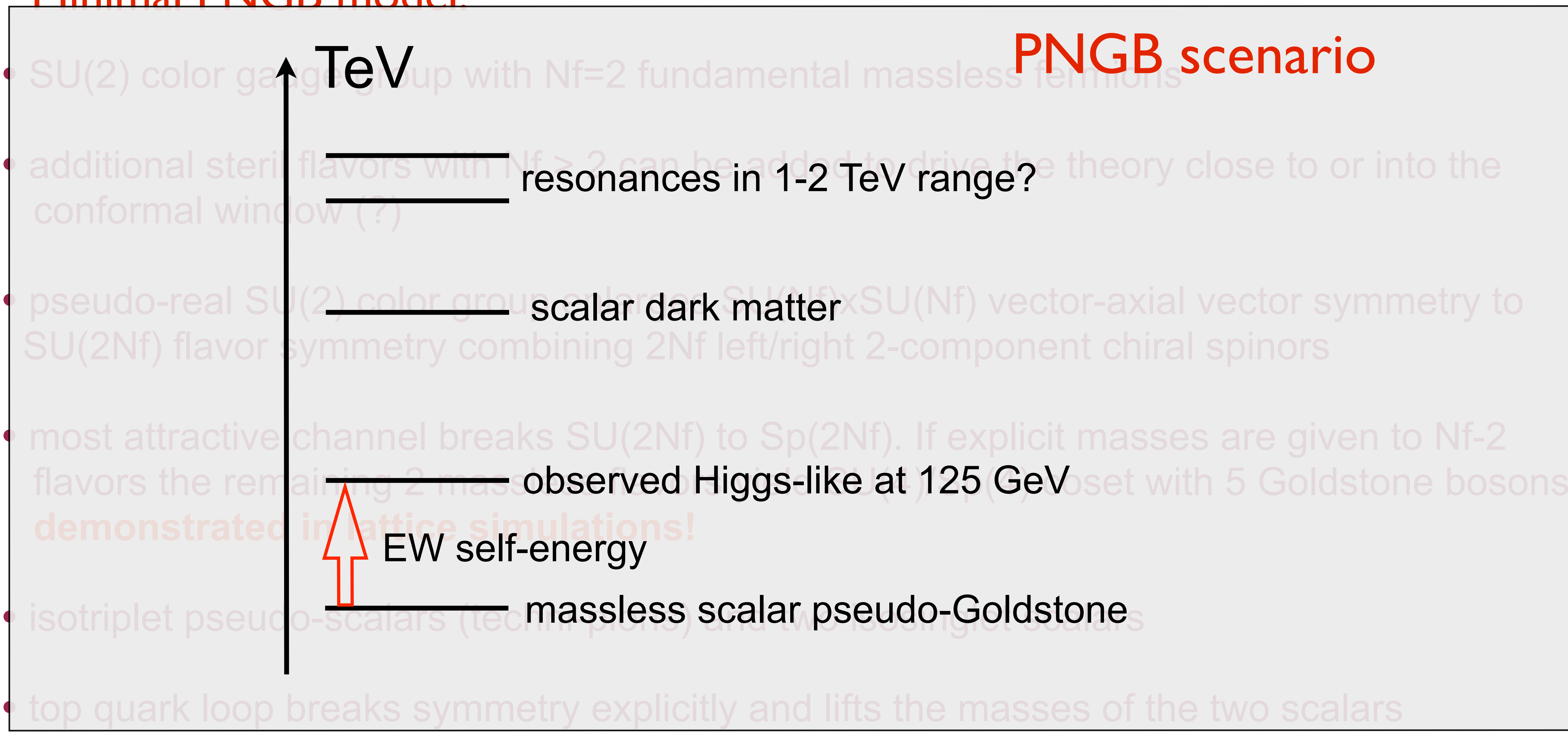
- isotriplet pseudo-scalars (techni-pions) and two isosinglet scalars

- 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

- **New theoretical formulations**
- **improved algorithms**
- **increased computer power**

→ 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

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

Toolset and its phenomenological applications

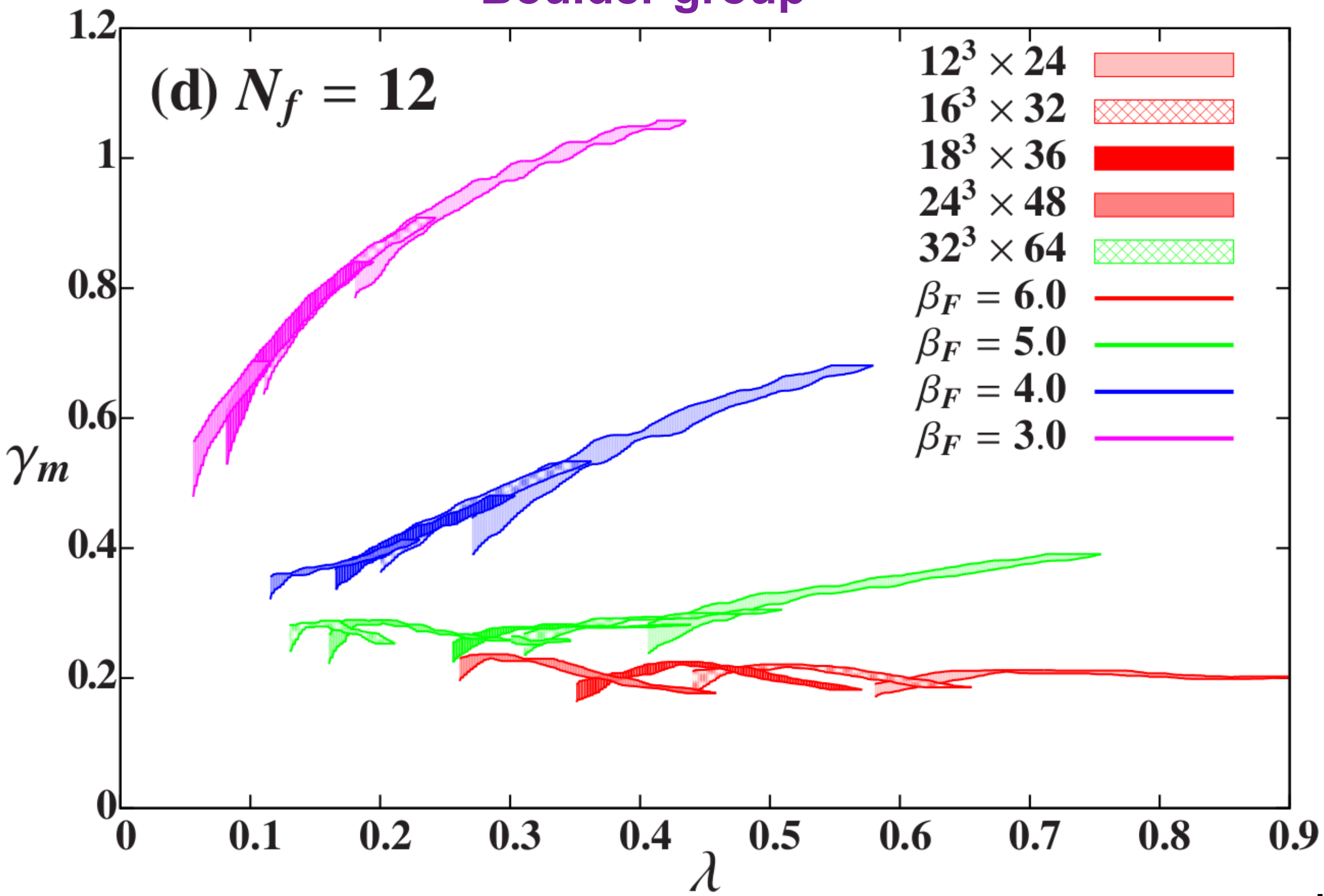
chiSB, Dirac spectrum, Anomalous dimension

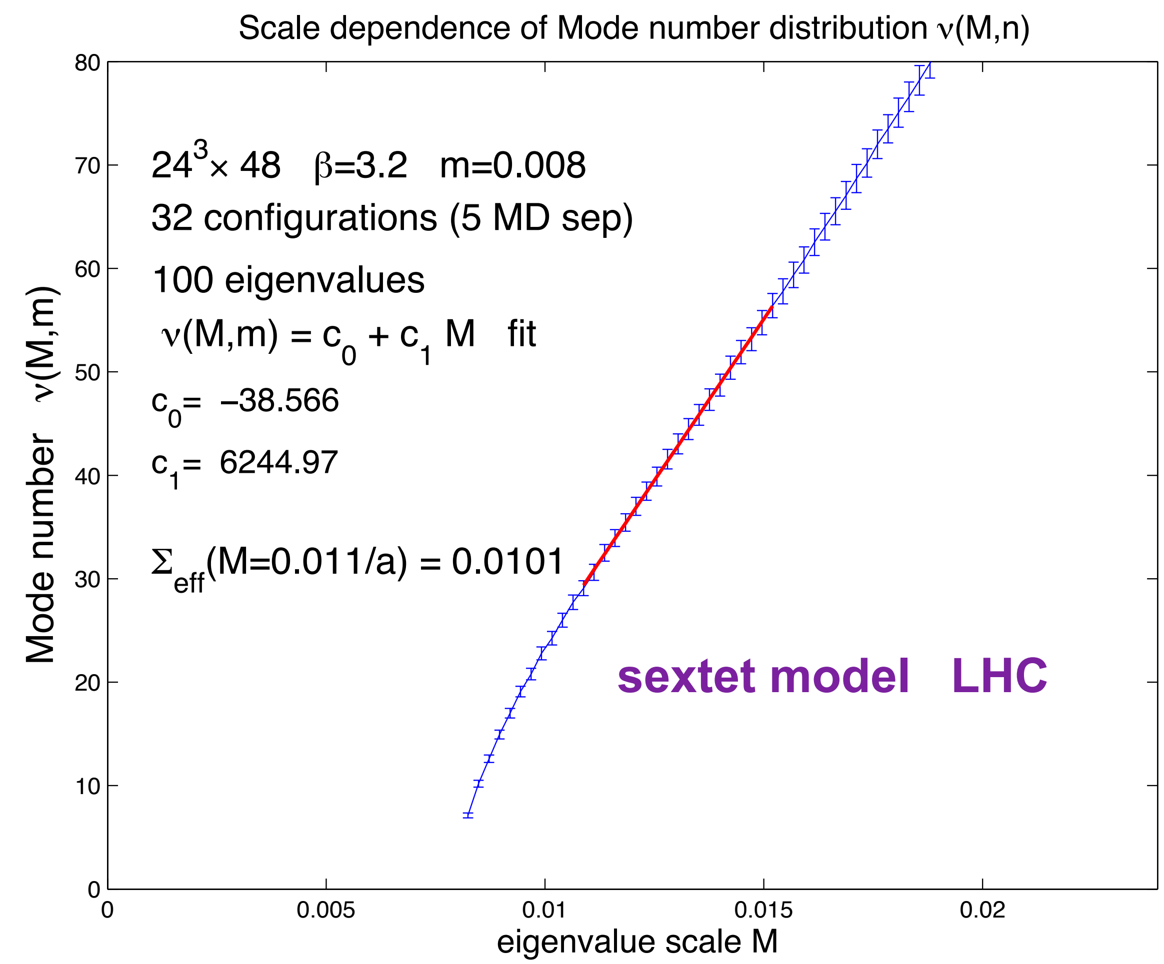
$$\lim_{\lambda\to 0}\lim_{m\to 0}\lim_{V\to\infty}\rho(\lambda,m)=\frac{\Sigma}{\pi}$$ spectral density

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

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

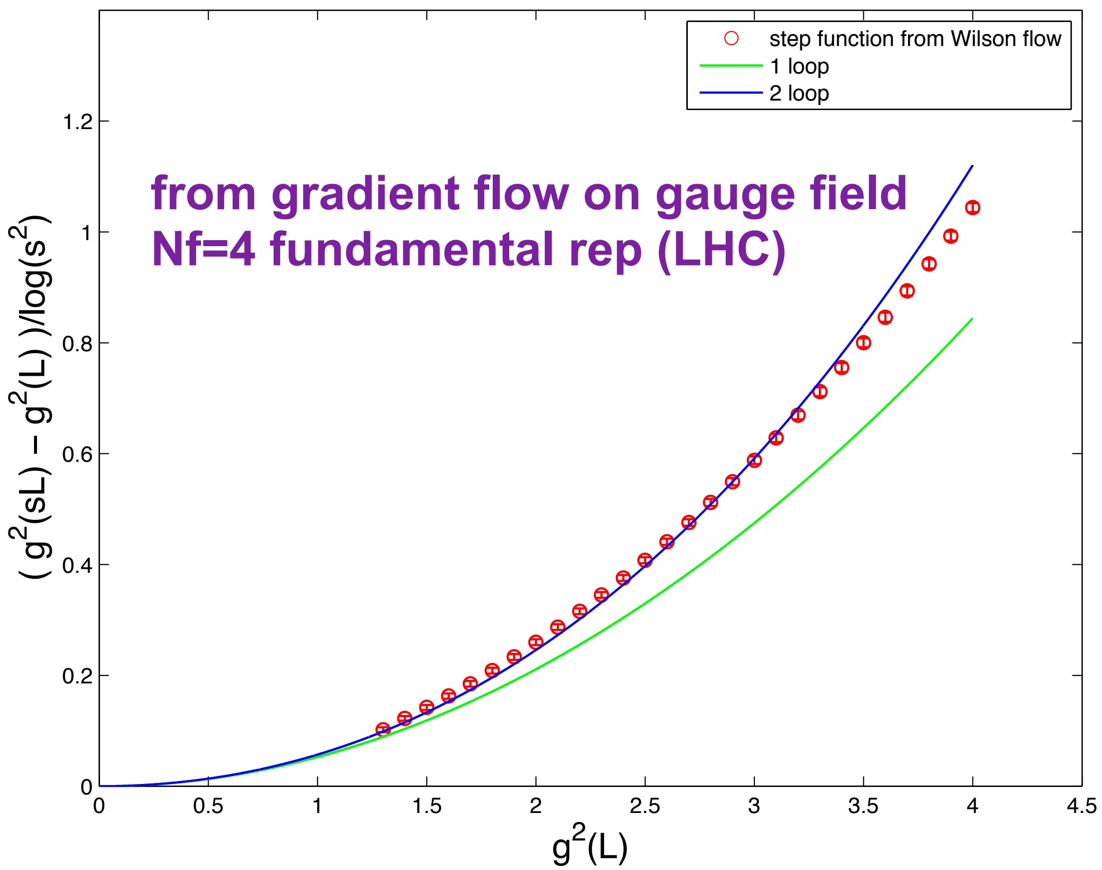
Boulder group

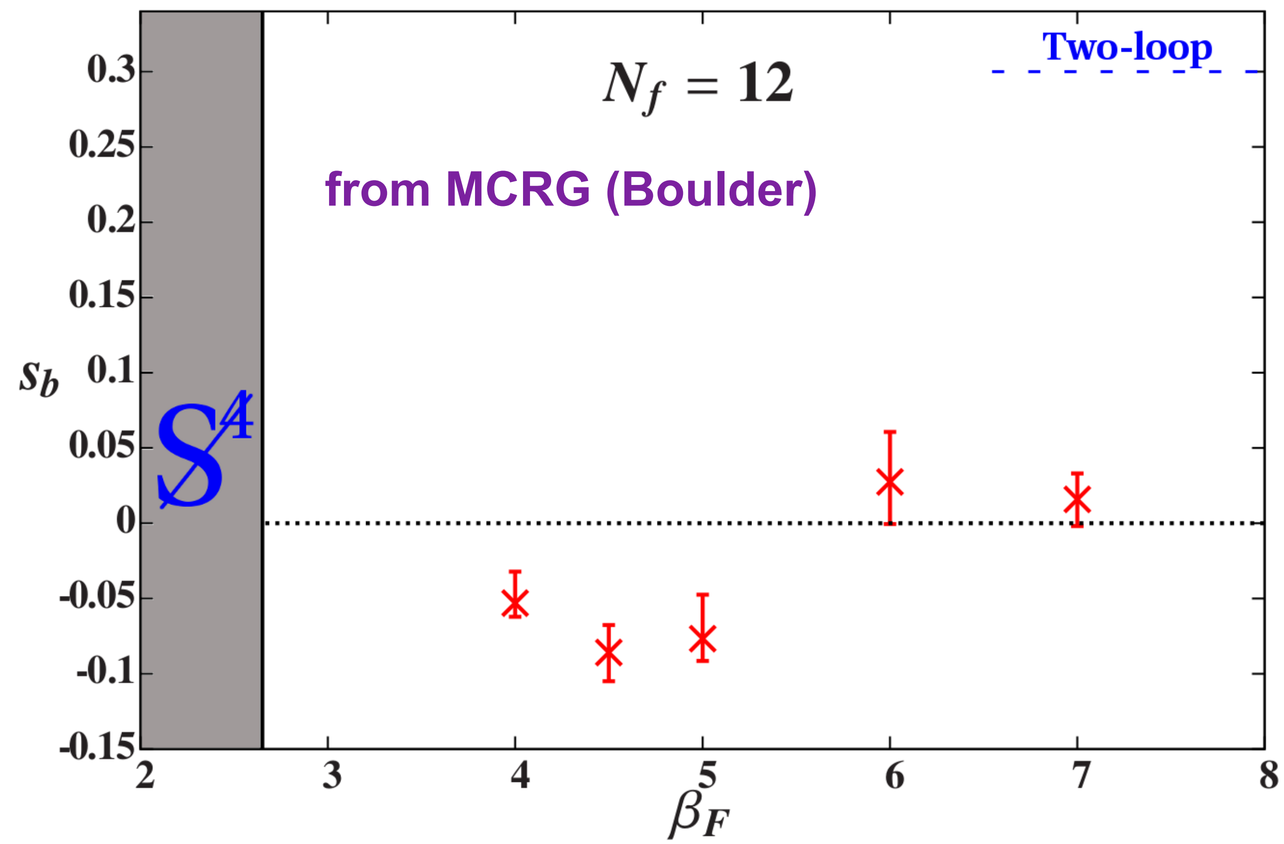




Toolset and its phenomenological applications

Running coupling and beta-function (to understand the new gauge force)

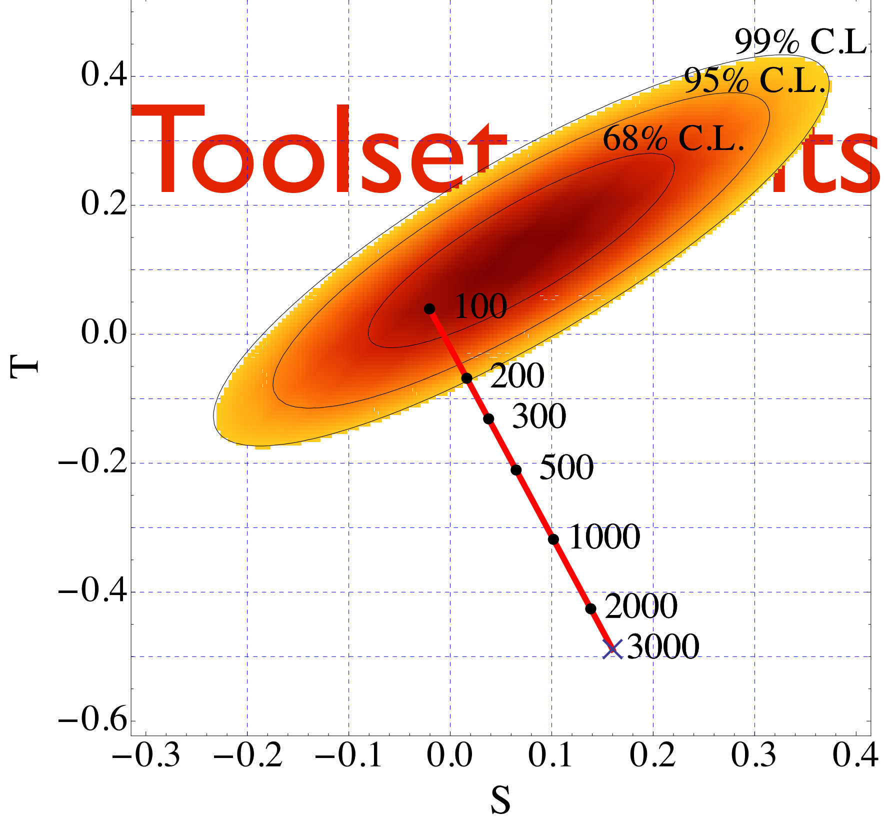




gradient flow on gauge field is beautiful realization of Wilson's exact RG with continuous momentum integration - Luscher

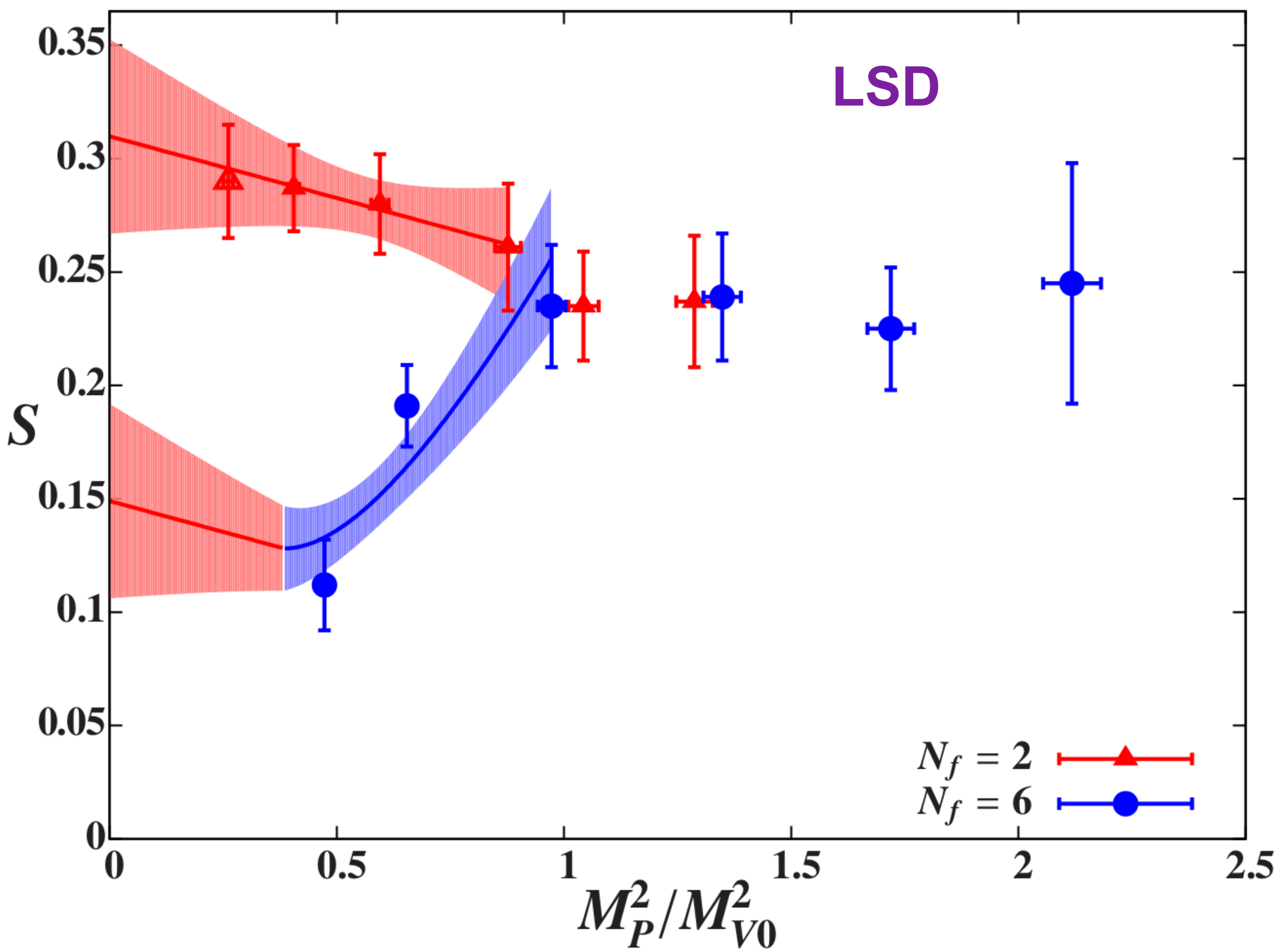
complements Schrodinger functional method (LSD)

Toolset ... ts phenomenological applications



S-parameter

LSD group with several
phenomenological explorations



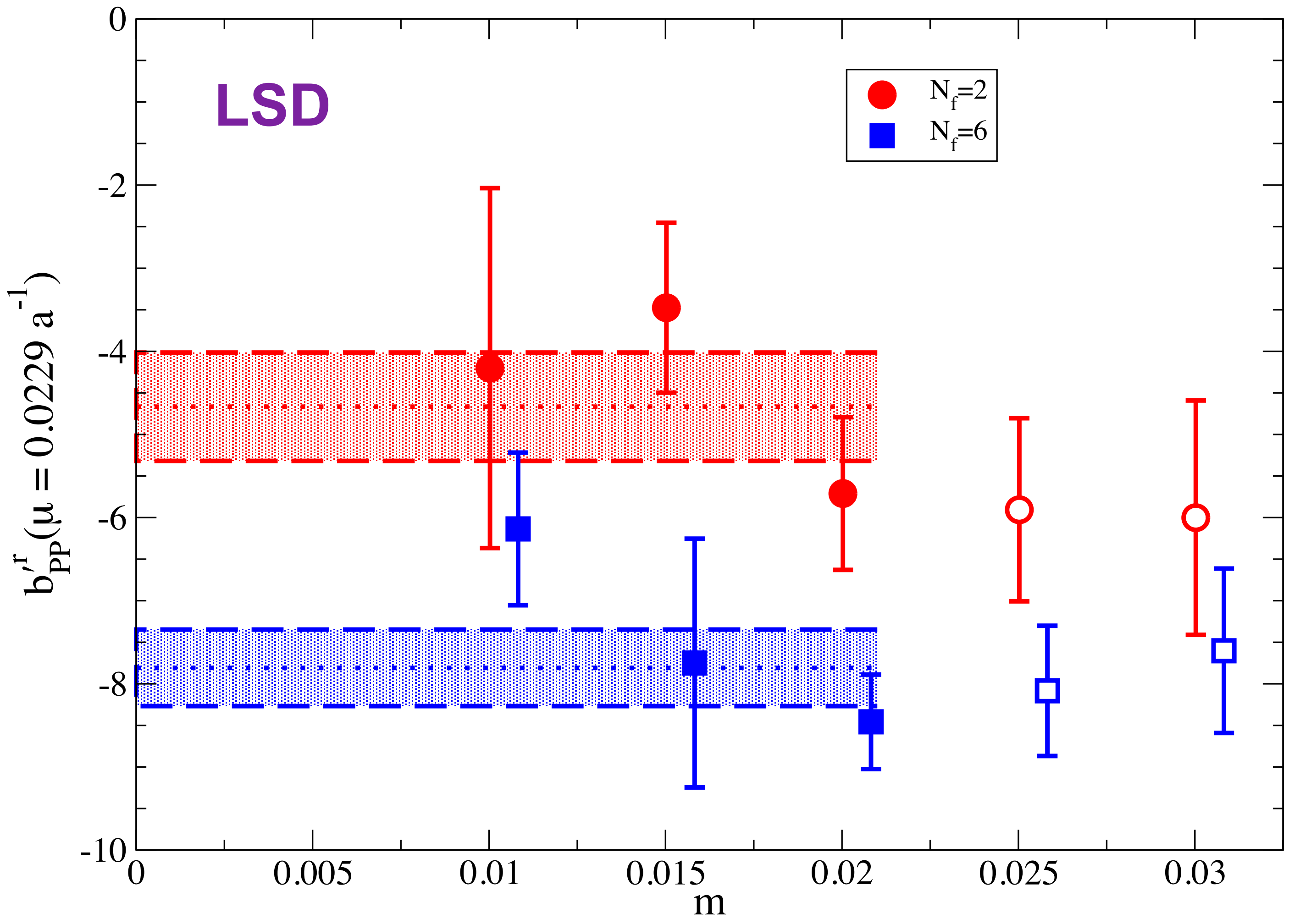
- near CW S-parameter is not increasing according to the naive scaling based on QCD and earlier expected by phenomenologists

- without non-perturbative BSM lattice work phenomenology is misinforming in model building

Toolset and its phenomenological applications

WW scattering

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



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

Toolset and its phenomenological applications

The Total Energy of the Universe:

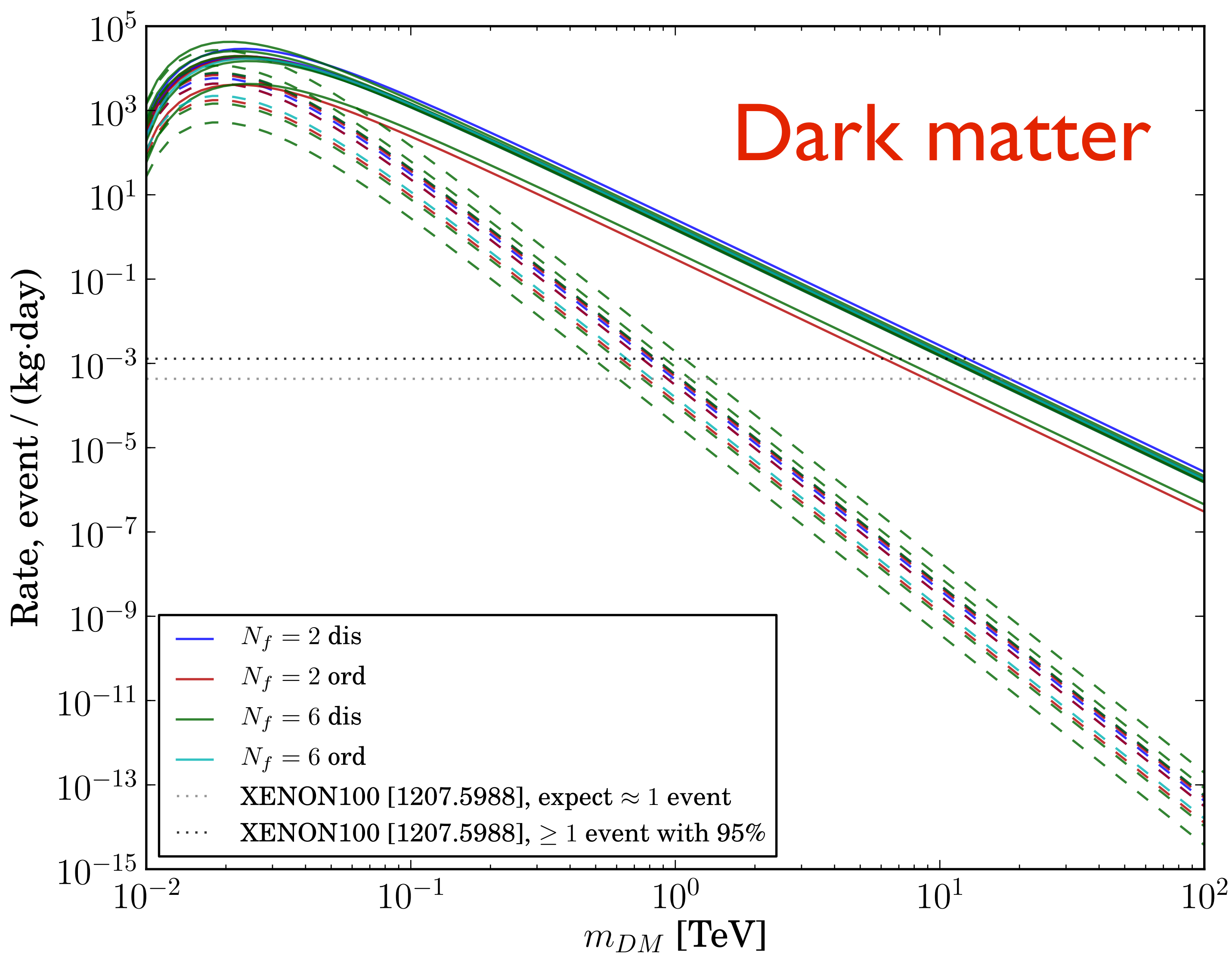
Vacuum Energy (Dark Energy) ~ 67 %

NonBaryonic Dark Matter ~ 29 %

Visible Baryonic Matter ~ 4 %

Dark matter

self-interacting?



LSD group - first USQCD BSM paper on dark matter

- dark matter candidates electroweak active in the application
- there is room for electroweak singlet dark matter particles

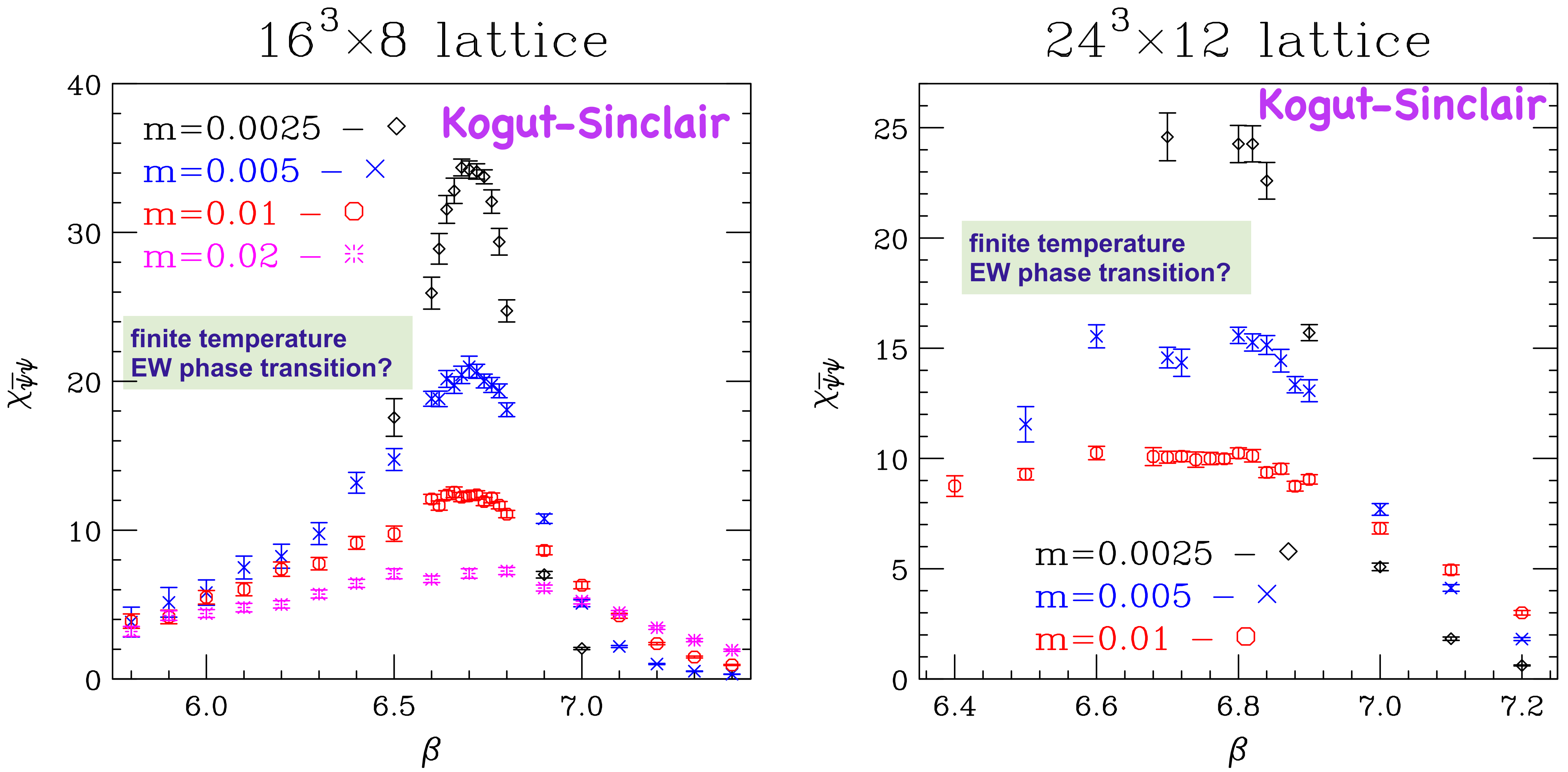
EW phase transition in sextet model - early universe

Kogut-Sinclair consistent with χSB phase at T=0

relevance in early cosmology

We are planning to run sextet thermo after model passed other tests

Third massive fermion flavor (electroweak singlet) dark matter?



Summary

Calculational goals of USQCD BSM program and future plans:

- To determine whether a composite dilaton-like particle or light Higgs can emerge in near-conformal quantum field theories for LHC14 testing
- To investigate strongly coupled gauge theories with a composite Higgs built from a pseudo-Nambu-Goldstone boson
- To investigate the nature of N=1 SUSY breaking with matter multiplets targeting super QCD
  (N=4 conformal SUSY remains test bed for AdS/CFT theoretical conjectures)