Beyond the Standard Model
on the energy frontier

USQCD lattice results of last 12 months and future plans

LQCD-ext 2012

USQCD BSM

Julius Kuti

University of California, San Diego

LQCD-ext 2012 DOE panel review, May 16, 2012

Outline

- LHC Higgs search and BSM implications
  focus of USQCD BSM

- Composite Higgs mechanism

- USQCD BSM results of last 12 months
  lead role in world-wide effort

- S-parameter (LSD)

- WW scattering (LSD)

- Composite Higgs model realizations: SU(2) adjoint and sextet SU(3)

- Cosmology connection
  (dark baryon matter and EW phase transition)

- Outlook

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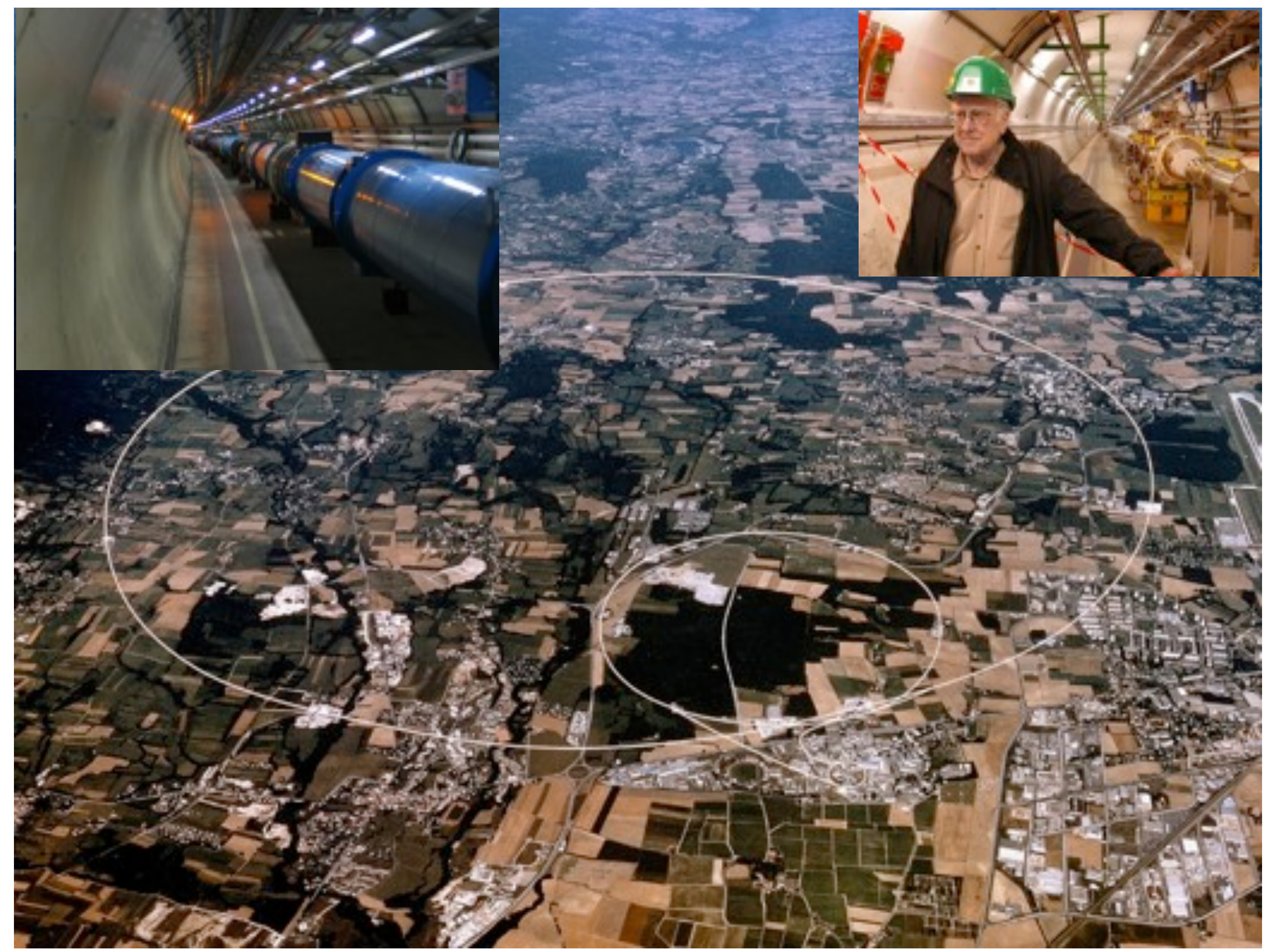
Large Hadron Collider - CERN

primary mission:

- Search for Higgs particle

- Origin of Electroweak symmetry breaking

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

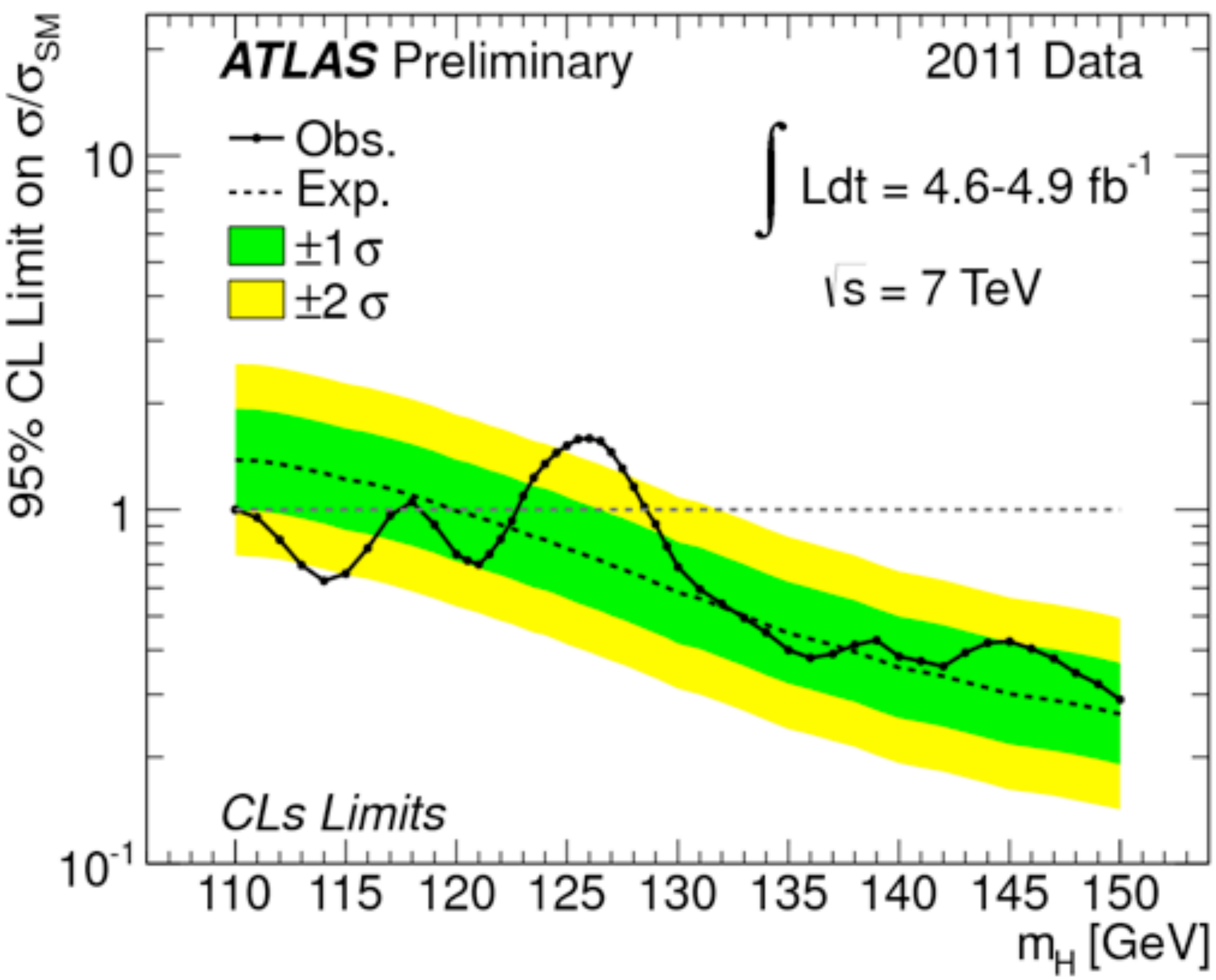


Primary focus of USQCD BSM effort and this report

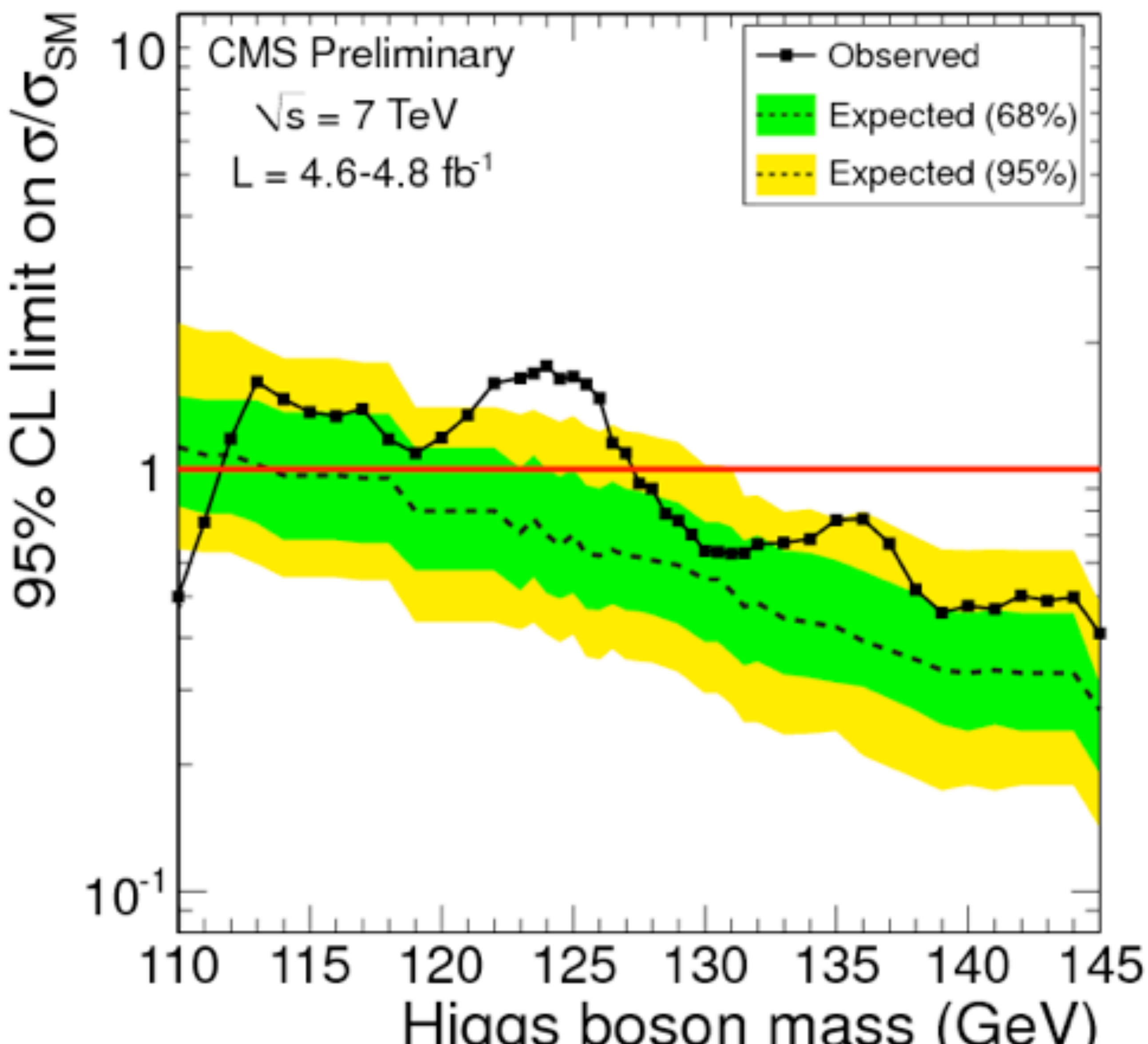
SUSY projects are progressing well with new simulations planned for next year

Atlas and CMS compared (from Vivek Sharma)

For low Higgs mass hypothesis both CMS & ATLAS see an excess in event yield over expected background



ATLAS excess at M ≈ 126 GeV



CMS excess at M ≈125 GeV

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What comes at the end of the LHC run?

- light Higgs with non-SM couplings (dilaton?)

- Heavy Higgs, or Higgsless

- SM Higgs (SUSY symmetry breaking?)

- USQCD composite Higgs and SUSY - timely efforts

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- The paradigm is important again

- Higgsless QCD-like (cutoff Λ to 3 TeV)

- changes close to conformal windo

- non-perturbative lattice studies needed

- USQCD effort will be shown on:

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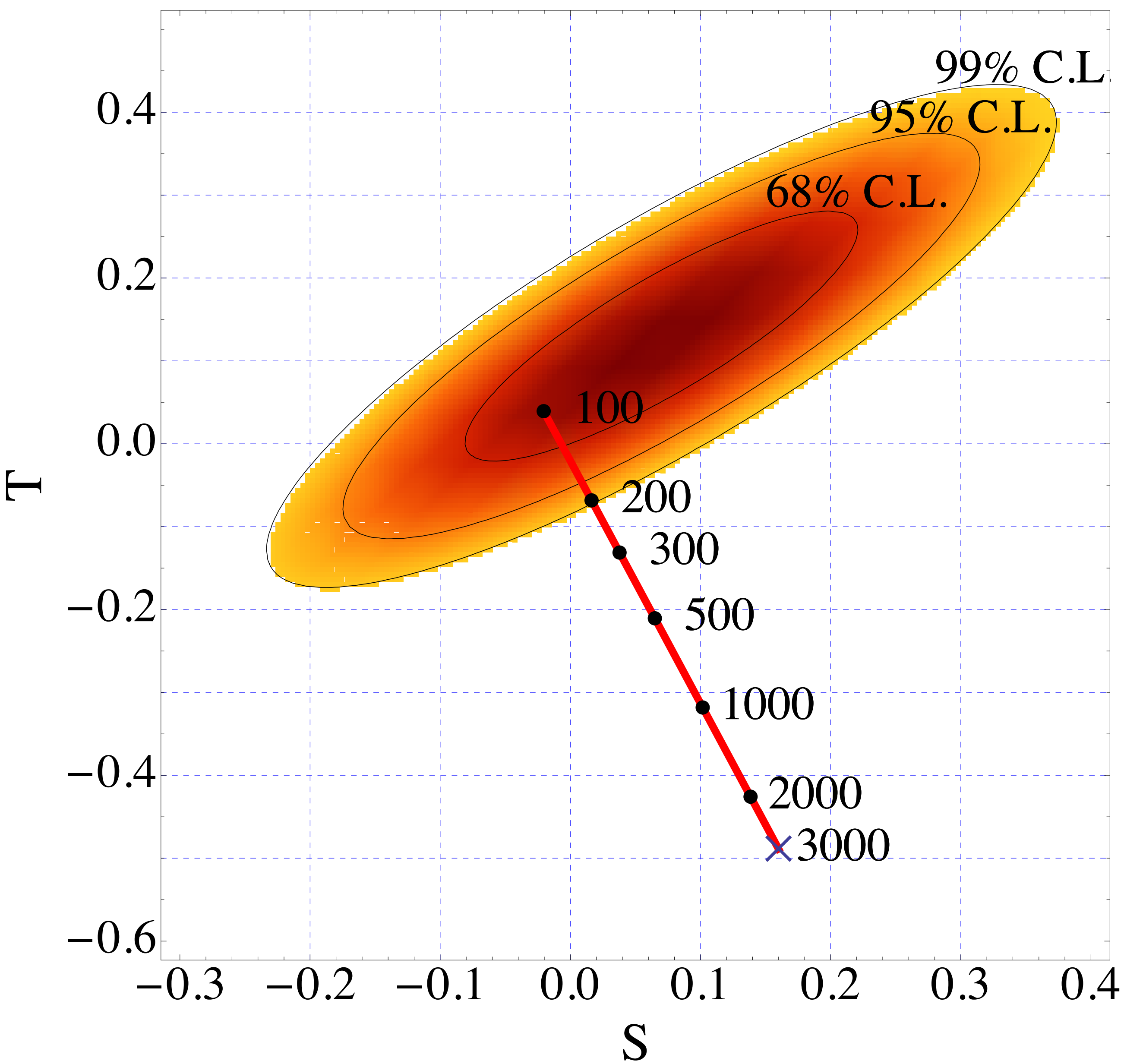

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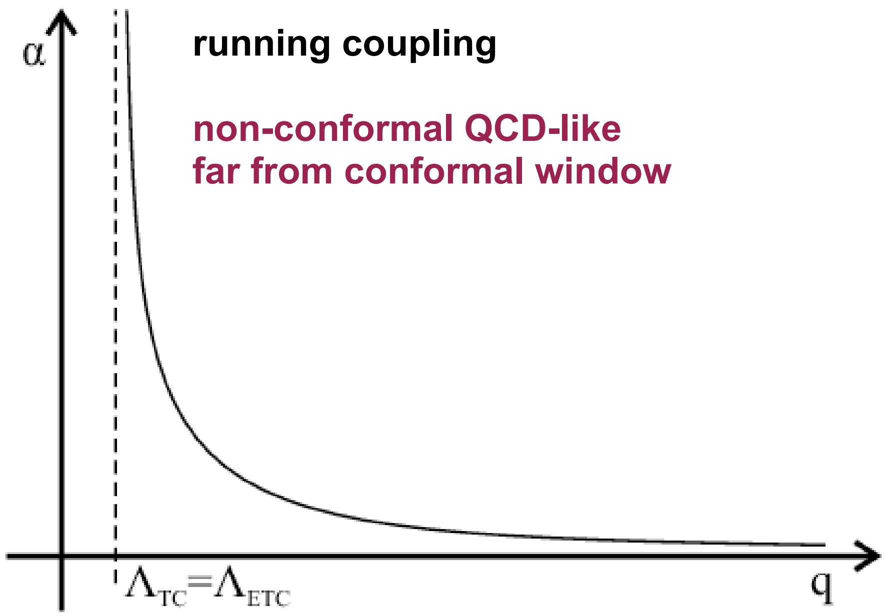
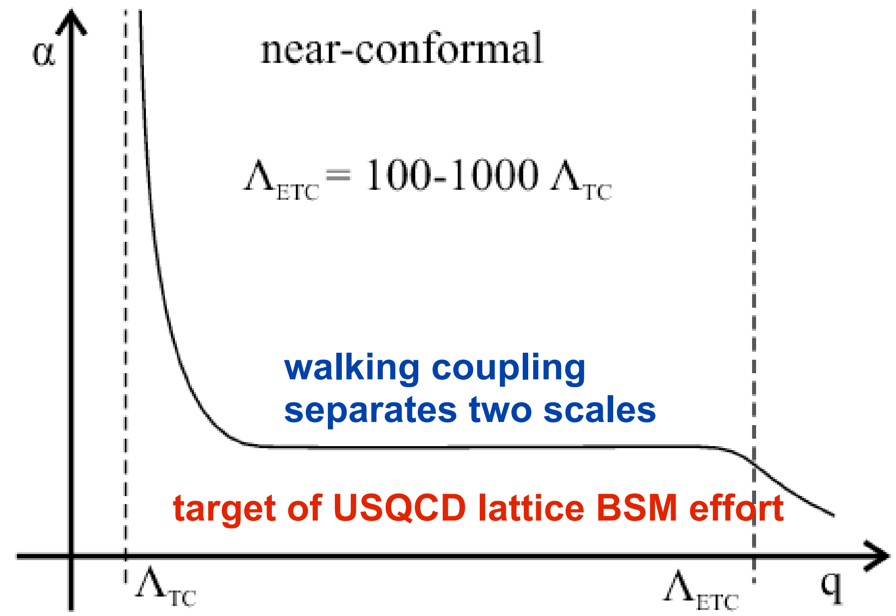
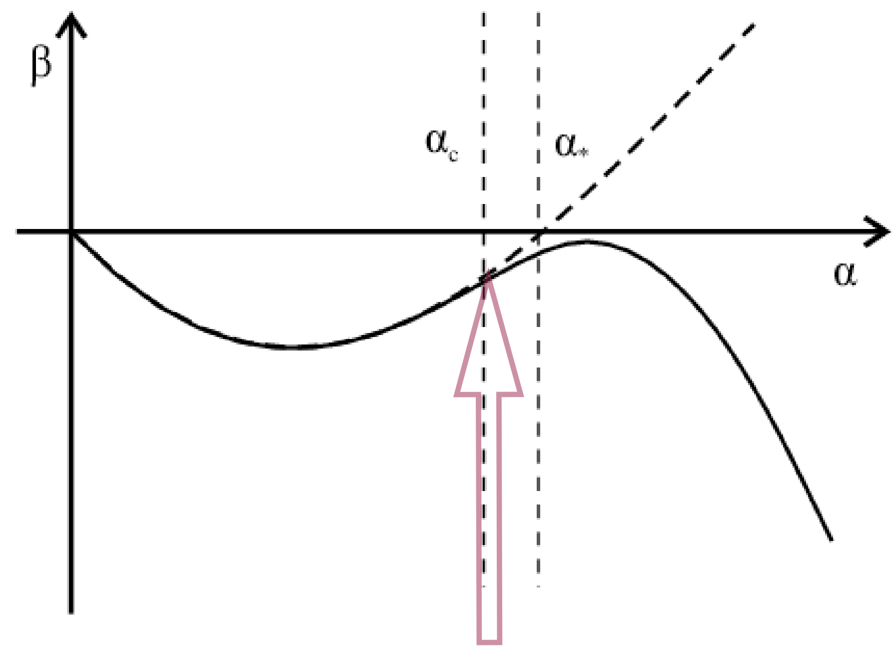
$$S = 4\pi N_D \lim_{Q^2 \to 0} \frac{d}{dQ^2} \Pi_{V-A}(Q^2) - \Delta S_{SM}$$

composite Higgs? example: Nf=2 SU(3) sextet rep TC (ETC) language used







Chiral symmetry breaking turns conformal FP into walking

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 scale invariance (Dilaton) ➔ light non-SM composite Higgs particle?
- can avoid conflict with EW precision constraints
- *candidate models require non-perturbative lattice studies*
- ***focus is on composite Higgs mechanism***

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

- one massless fermion doublet chiral SB $\begin{bmatrix} u \\ d \end{bmatrix}$
- three Goldstone pions
- become longitudinal components of weak bosons

$\Lambda_{TC} \sim TeV$

- composite Higgs mechanism scale of Higgs condensate ~ F=250 GeV
- flavor changing currents and fermion mass generation would be problems
- conflicts with EW precision constraints?

important for lattice studies in BSM theory space

important for fermion mass generation

anomalous dimension of <$\bar{\psi}\,\psi$>

generates fermion mass, want low Λ

$$\frac{(\bar{f} f)(\bar{T} T)}{\Lambda^2} \Rightarrow \frac{(\bar{f} f)(\bar{T} T)}{\Lambda^2} \left(\frac{\Lambda^2}{v_{EW}^2}\right)^{\gamma_m}$$

$$\frac{(\bar{f} f)(\bar{f} f)}{\Lambda^2} \Rightarrow \frac{(\bar{f} f)(\bar{f} f)}{\Lambda^2}$$

generates FCNC, want high Λ

from Adam Martin

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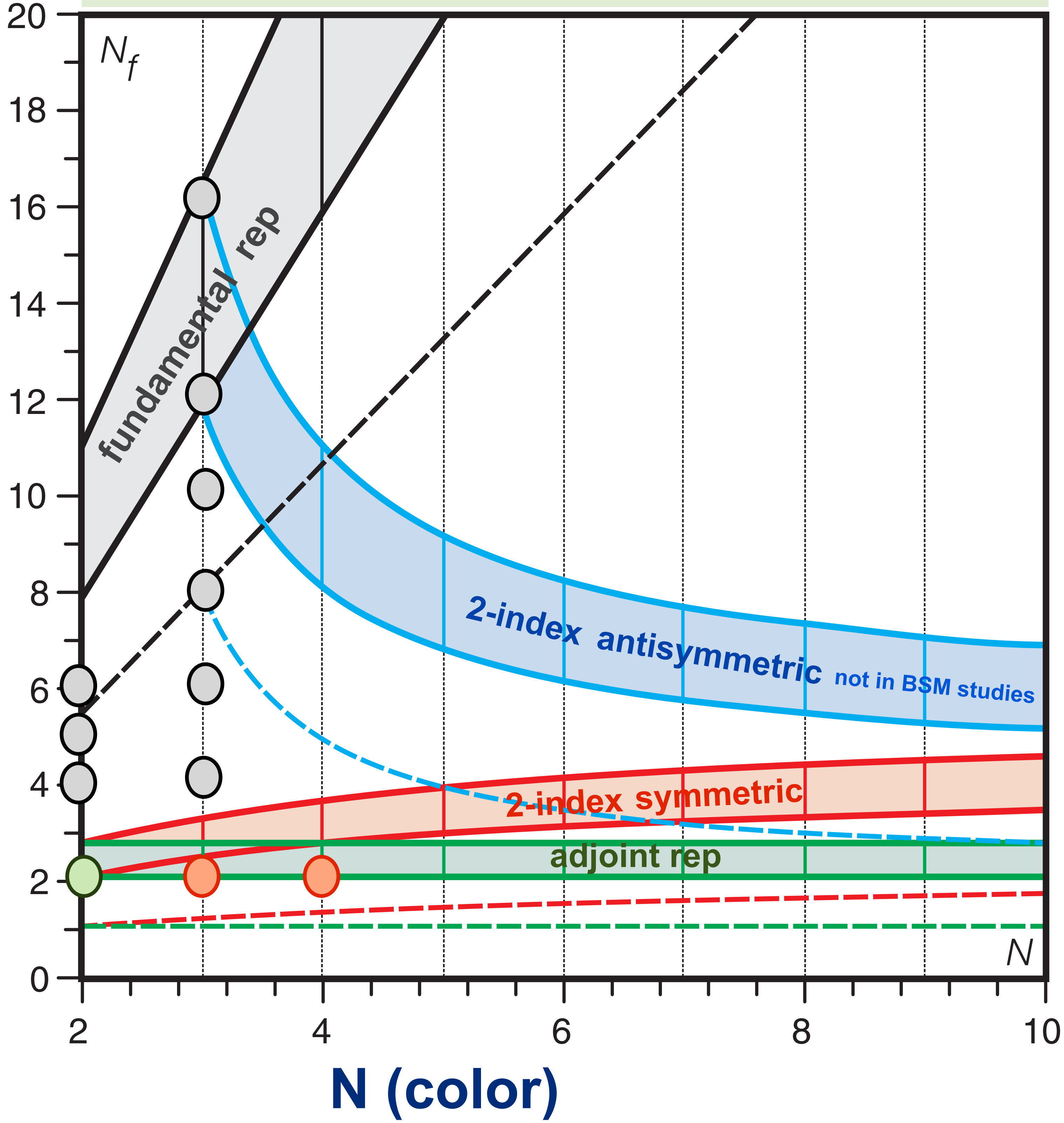
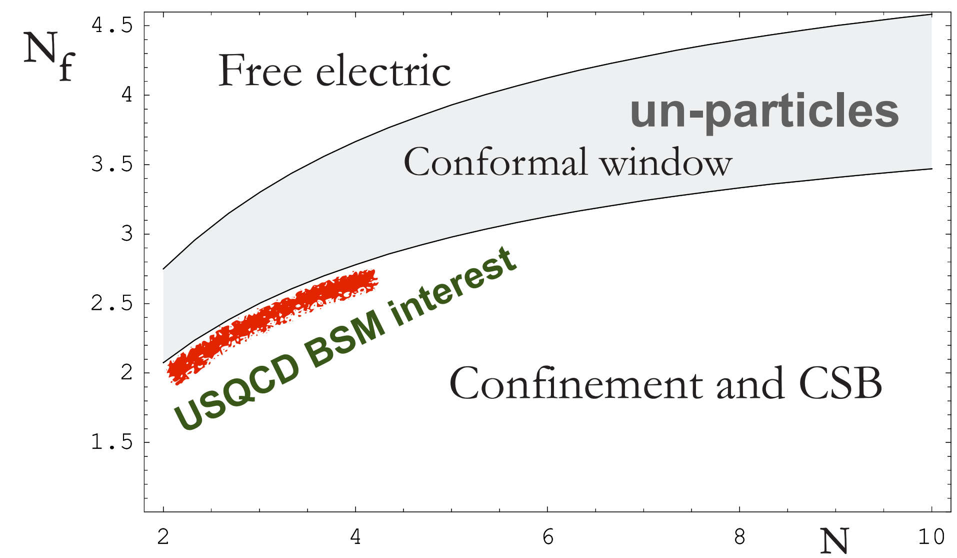
theory space and conformal window critically important for composite Higgs

space of color, flavor, and massless fermion representation



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



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

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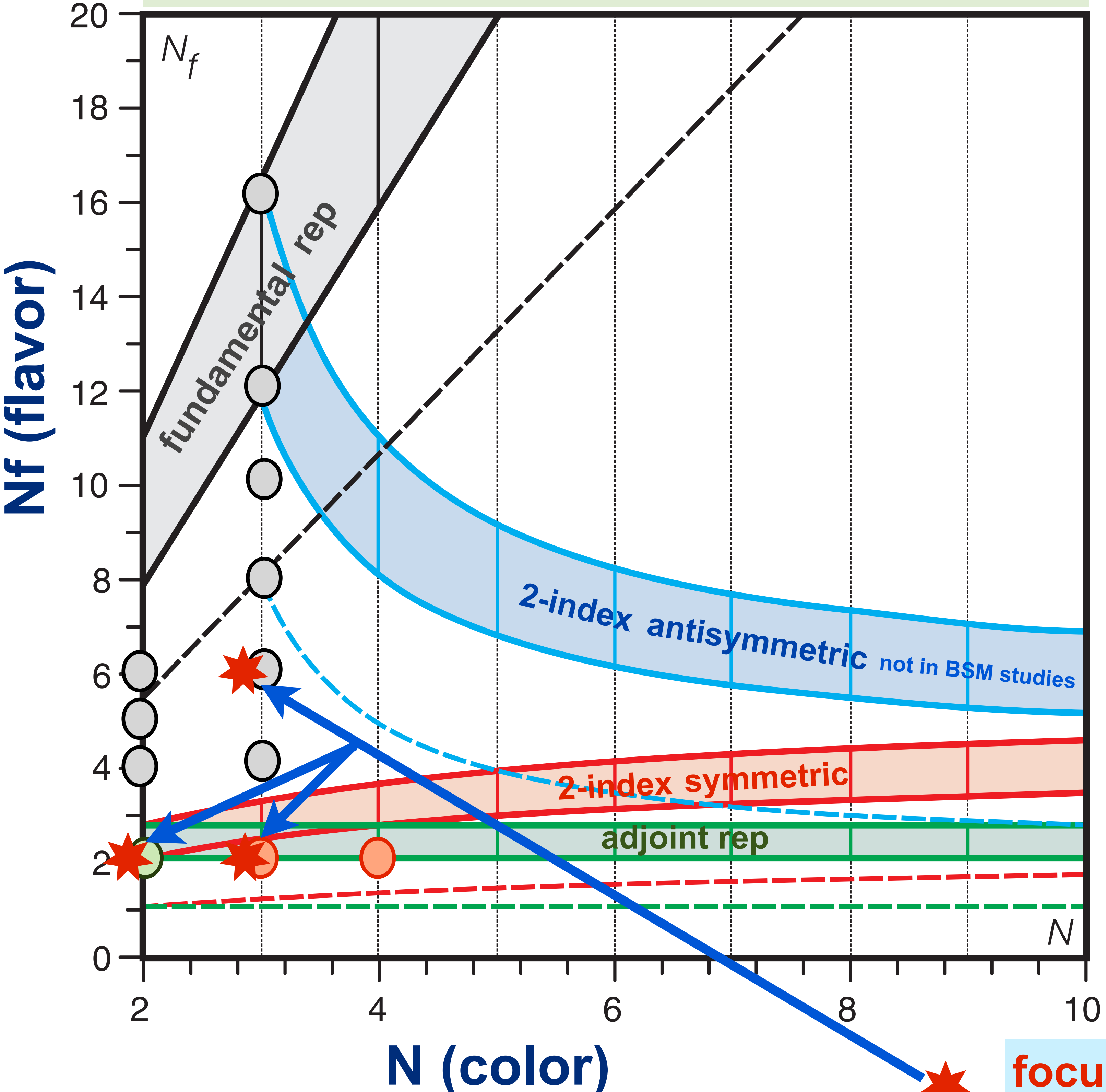

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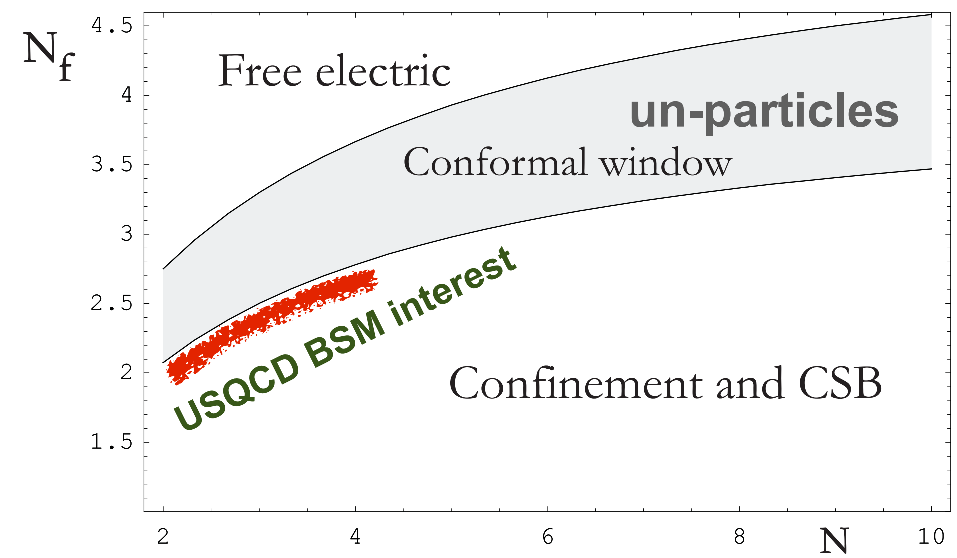

USQCD BSM results of last 12 months in 3 reps including new projects just starting

focus: USQCD BSM results - models with potential experimental implications

USQCD BSM project sites using LQCD-ext hardware & SciDAC software support

(a few years ago map was empty)

Review of results from last 12 months and plans for next 12 months

several USQCD BSM groups study the composite Higgs mechanism
TC scale - stretched to ETC scale by walking gauge coupling

fermion mass generation is open problem - new theory on ETC scale?

- 32 new USQCD BSM 2011-2012 publications

(size of BSM effort ~ 20% of USQCD)

- impact: over 200 citations for new papers
- USQCD BSM is competing well world-wide in this field

Approaching Conformality with Ten Flavors.
Thomas Appelquist, Richard C. Brower, Michael I. Buchoff, Michael Cheng, Saul D. Cohen, George T. Fleming, Joe Kiskis, Meifeng Lin, Heechang Na, Ethan T. Neil *et al.*. FERMILAB-PUB-12-111-T,LLNL-JRNL-548639,NSF-KITP-12-069.
e-Print: **arXiv:1204.6000 [hep-ph]**

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.
FERMILAB-PUB-12-012-T,LLNL-JRNL-499587.
Published in **Phys.Rev. D85 (2012) 074505**
e-Print: **arXiv:1201.3977 [hep-lat]**

Lattice Simulations and Infrared Conformality.
T. Appelquist, G.T. Fleming, M.F. Lin (Yale U.), E.T. Neil (Fermilab), D.A. Schaich (Boston U
FERMILAB-PUB-11-269-T.
Published in **Phys.Rev. D84 (2011) 054501**
e-Print: **arXiv:1106.2148 [hep-lat]**

Parity Doubling and the S Parameter Below the Conformal Window.
LSD Collaboration (Thomas Appelquist (Yale U.) *et al.*). Sep 2010. 4 pp.
Published in **Phys.Rev.Lett. 106 (2011) 231601**
e-Print: **arXiv:1009.5967 [hep-ph]**

Twelve massless flavors and three colors below the conformal window.
Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chris Schroeder (Wuppertal U. & IAS, Julich & Eotvos U.)
Kieran Holland (U. Pacific, Stockton), Julius Kuti (UC, San Diego), Daniel Nogradi (Eotvos U
Published in **Phys.Lett. B703 (2011) 348-358**
e-Print: **arXiv:1104.3124 [hep-lat]**

Chiral symmetry breaking in fundamental and sextet fermion representations of SU(3) color.
Zoltan Fodor, Kieran Holland, Julius Kuti, Daniel Nogradi, Chris Schroeder. Mar 2011. 14 pp
e-Print: **arXiv:1103.5998 [hep-lat]**

Twelve fundamental and two sextet fermion flavors
Zoltan Fodor (Wuppertal U.), Kieran Holland (U. Pacific, Stockton), Julius Kuti, Daniel Nogra
Published in **PoS LAT2011 (2011) 073**

MCRG study of 12 fundamental flavors with mixed fundamental-adjoint gauge action.
Anna Hasenfratz. Dec 2011. 7 pp.
e-Print: **arXiv:1112.6146 [hep-lat]**
2.
Novel phase in SU(3) lattice gauge theory with 12 light fermions.
Anqi Cheng, Anna Hasenfratz, David Schaich. Nov 2011. 4 pp.
e-Print: **arXiv:1111.2317 [hep-lat]**

Infrared fixed point of the 12-fermion SU(3) gauge model based on 2-lattice MCRG matching.
Anna Hasenfratz (Colorado U.). Jun 2011. 4 pp.
Published in **Phys.Rev.Lett. 108 (2012) 061601**
e-Print: **arXiv:1106.5293 [hep-lat]**

Lattice QCD with 12 Degenerate Quark Flavors.
Xiao-Yong Jin, Robert D. Mawhinney (Columbia U.). Mar 2012. 7 pp.
Published in **PoS LATTICE2011 (2011) 066**
e-Print: **arXiv:1203.5855 [hep-lat]**

Investigating the sign problem for two-dimensionalN=(2,2)andN=(8,8)attice super Yang--Mills theories.
Richard Galvez, Simon Catterall (Syracuse U.), Anosh Joseph (Los Alamos), Dhagash Mehta (Syracuse U.). Jan 2012. 7 pp.
LA-UR-11-12253.
Published in **PoS LATTICE2011 (2011) 064**
To appear in the proceedings of Conference: C11-07-10
e-Print: **arXiv:1201.1924 [hep-lat]**

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Published in **PoS LATTICE2011 (2011) 078**
To appear in the proceedings of Conference: C11-07-10
e-Print: **arXiv:1112.5413 [hep-lat]**

On the sign problem in 2D lattice super Yang-Mills.
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Published in **JHEP 1201 (2012) 108**
e-Print: **arXiv:1112.3588 [hep-lat]**

Non-abelian gauged NJL models on the lattice.
Simon Catterall, Richard Galvez, Jay Hubisz, Dhagash Mehta, Aarti Veernala. Dec 2011. 19 pp.
e-Print: **arXiv:1112.1855 [hep-lat]**

Systematic Errors of the MCRG Method
Simon Catterall, Luigi Del Debbio, Joel Gi
Published in **PoS LATTICE2011 (2011) 0**
Conference: C11-07-10
e-Print: **arXiv:1110.1660 [hep-ph]**

MCRG Minimal Walking Technicolor.
Simon Catterall (Syracuse U.), Luigi Del D
EDINBURGH-2011-23.
Published in **Phys.Rev. D85 (2012) 09450**
e-Print: **arXiv:1108.3794 [hep-ph]**

An Object oriented code for simulating
Simon Catterall (Syracuse U.), Anosh Jos
Published in **Comput.Phys.Commun. 18**
e-Print: **arXiv:1108.1503 [hep-lat]**

Perturbative renormalization of lattice
Simon Catterall (Syracuse U.), Eric Dzien
Anosh Joseph (Syracuse U.), Robert Wel
SU-4252-912.
Published in **JHEP 1104 (2011) 074**
e-Print: **arXiv:1102.1725 [hep-th]**

Neutralino-hadron scattering in the NMSSM.
Sophie J. Underwood (Adelaide U.), Joel Giedt (Rensselaer Poly.), Anthony W. Thomas, Ross D. Young (Adelaide U.)..
ADP-12-08-T775.
e-Print: **arXiv:1203.1092 [hep-ph]**

Backward running or absence of running from Creutz ratios.
Joel Giedt, Evan Weinberg (Rensselaer Poly.). 2011. 7 pp.
Published in **PoS LATTICE2011 (2011) 238**
Conference: C11-07-10

Finite size scaling in minimal walking technicolor.
Joel Giedt, Evan Weinberg. Jan 2012. 5 pp.

A deconstruction lattice description of the D1/D5 brane world-volume gauge theory.
Joel Giedt (Rensselaer Poly.). 2011. 18 pp.
Published in Adv.High Energy Phys. 2011 (2011) 241419

Backward running or absence of running from Creutz ratios.
e-Print: arXiv:1105.0607 [hep-lat]

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Chen Chen, Joel Giedt, Joseph Paki (Rensselaer Poly.). Apr 2011. 19 pp.
Published in Phys.Rev. D84 (2011) 025001
e-Print: arXiv:1104.1126 [hep-lat]

Effects of flavor-symmetry violation from staggered fermion lattice simulations of graphene.
Joel Giedt (Rensselaer Poly.), Andrew Skinner (Skidmore Coll. & Rensselaer Poly.), Saroj Nayak (Rensselaer Poly.).
Published in Phys.Rev. B83 (2011) 045420
e-Print: arXiv:0911.4316 [cond-mat.str-el]

SU(4) lattice gauge theory with decuplet fermions: Schr\'odinger functional analysis.
Thomas DeGrand, Yigal Shamir, Benjamin Svetitsky. Feb 2012. 15 pp.
FERMILAB-PUB-12-036-T.
e-Print: **arXiv:1202.2675 [hep-lat]**

Mass anomalous dimension in sextet QCD.
Thomas DeGrand (Colorado U.), Yigal Shamir, Benjamin Svetitsky (Tel Aviv U.). Jan 2012. 9 pp.
FERMILAB-PUB-12-031-T.
e-Print: **arXiv:1201.0935 [hep-lat]**

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Thomas DeGrand, Yigal Shamir, Benjamin Svetitsky (Colorado U.). Oct 2011. 7 pp.
FERMILAB-CONF-11-715-T,COLO-HEP-568.
Published in **PoS LATTICE2011 (2011) 060**
To appear in the proceedings of Conference: C11-07-10
e-Print: **arXiv:1110.6845 [hep-lat]**

Finite-size scaling tests for spectra in SU(3) lattice gauge theory coupled to 12 fundamental flavor fermions.
Thomas DeGrand (Colorado U.). Sep 2011. 8 pp.
COLO-HEP-565.
Published in **Phys.Rev. D84 (2011) 116901**
e-Print: **arXiv:1109.1237 [hep-lat]**

Infrared fixed point in SU(2) gauge theory with adjoint fermions.
Thomas DeGrand (Colorado U.), Yigal Shamir, Benjamin Svetitsky (Tel Aviv U.). Feb 2011. 17 pp.
FERMILAB-PUB-11-714-T.
Published in **Phys.Rev. D83 (2011) 074507**
e-Print: **arXiv:1102.2843 [hep-lat]**

It is a world-wide effort (USQCD plays leading role)

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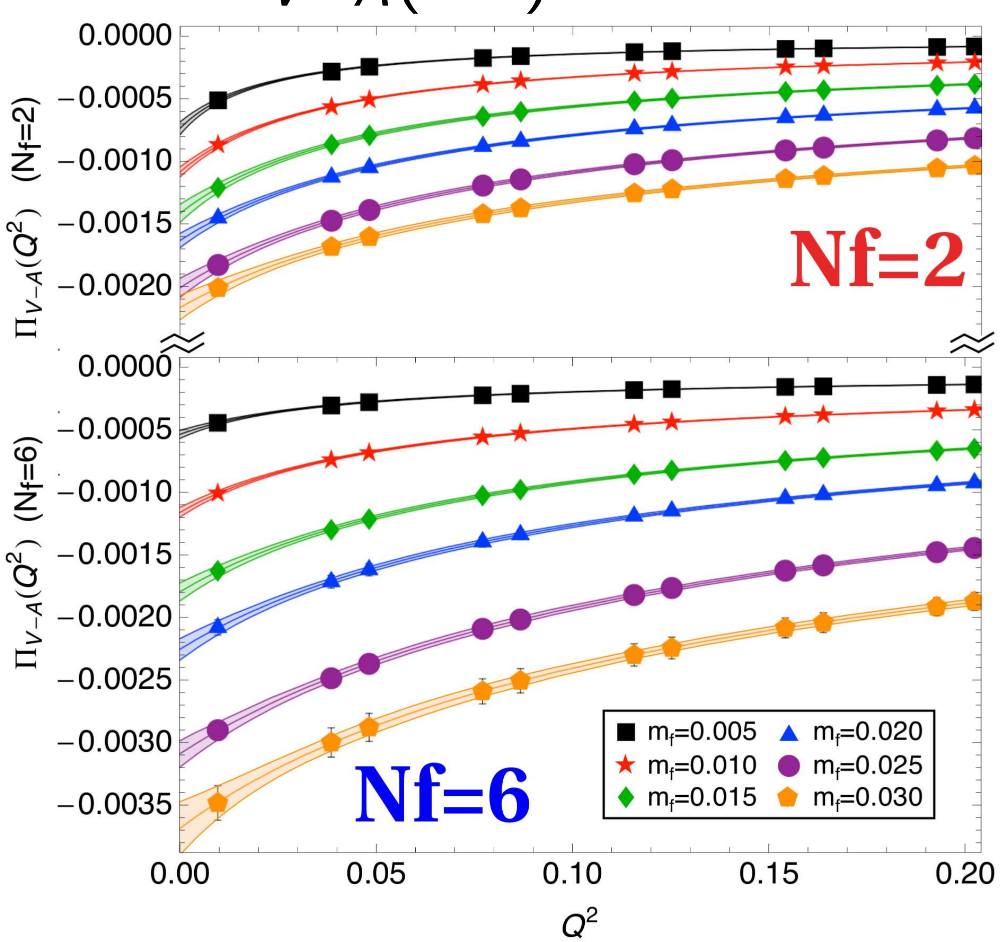
S parameter

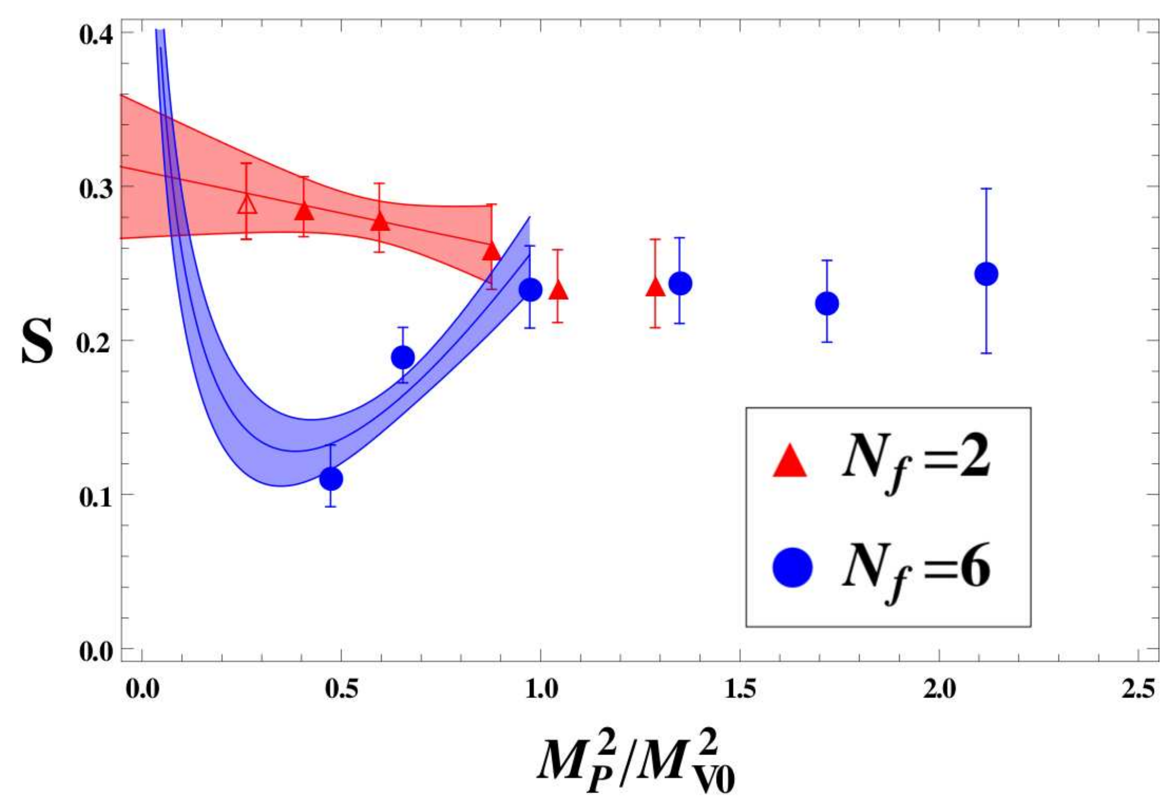
LSD Collaboration, PRL 106:231601 (2011)

Constraint from vacuum polarizations $\Pi^{\mu\nu}(Q)$ of EW gauge bosons

$$S = 4\pi N_D \lim_{Q^2 \to 0} \frac{d}{dQ^2} \Pi_{V-A}(Q^2) - \Delta S_{SM}$$

$\Pi_{V-A}(Q^2)$





(Linear+chiral log fits to guide the eye)

from David Schaich

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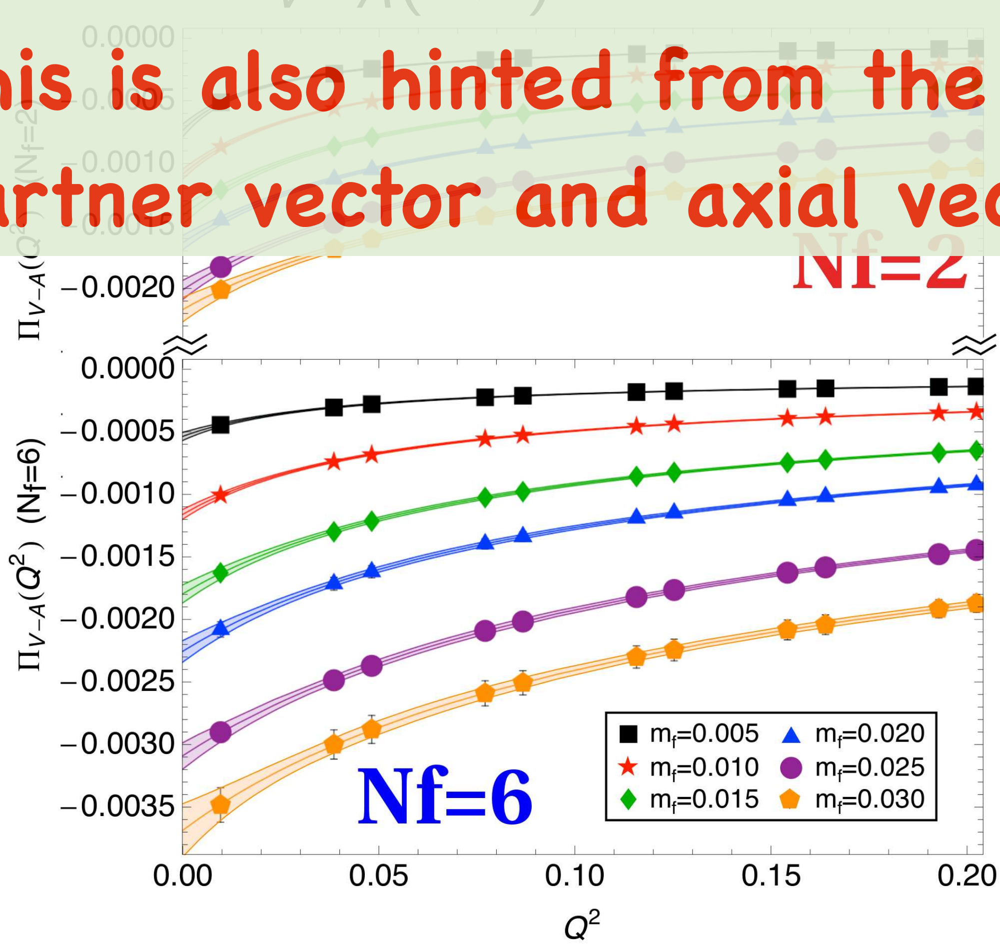
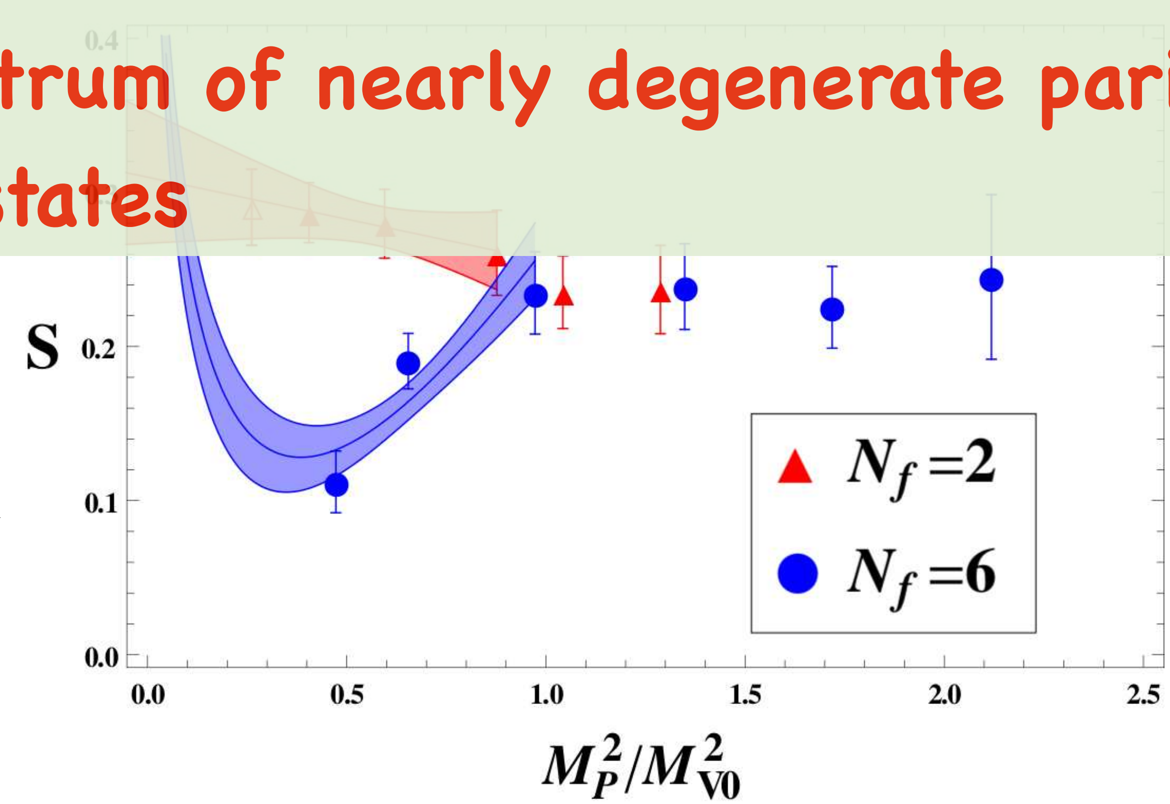
Behavior of S-parameter is not QCD-like as we get closer to the conformal window and toward walking coupling scenario

This is also hinted from the spectrum of nearly degenerate parity partner vector and axial vector states

$\Pi_{V-A}(Q^2)$





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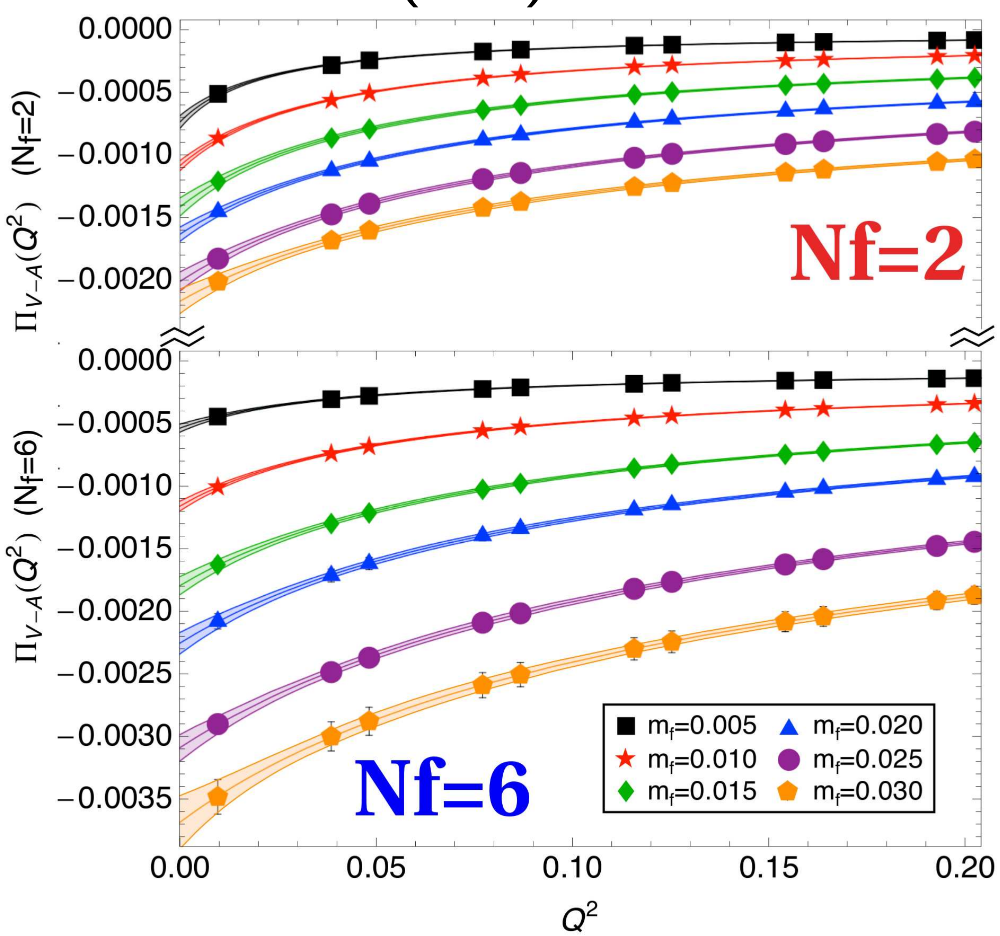

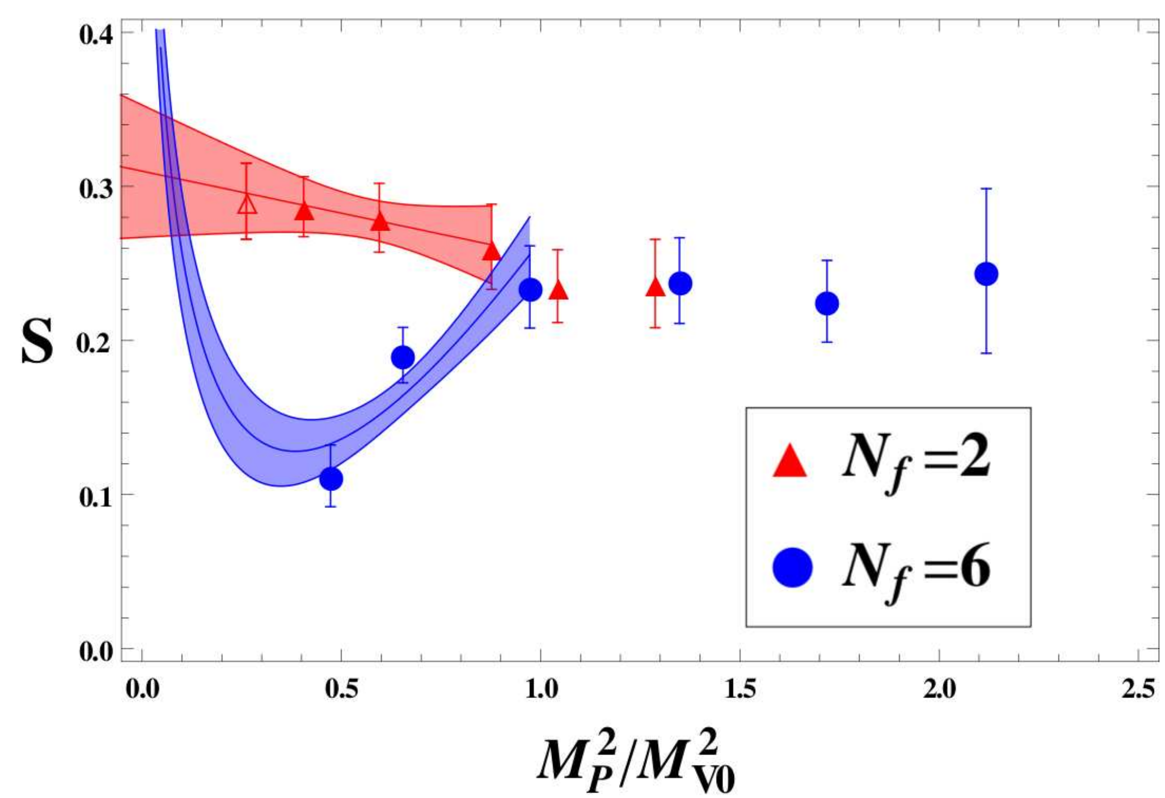

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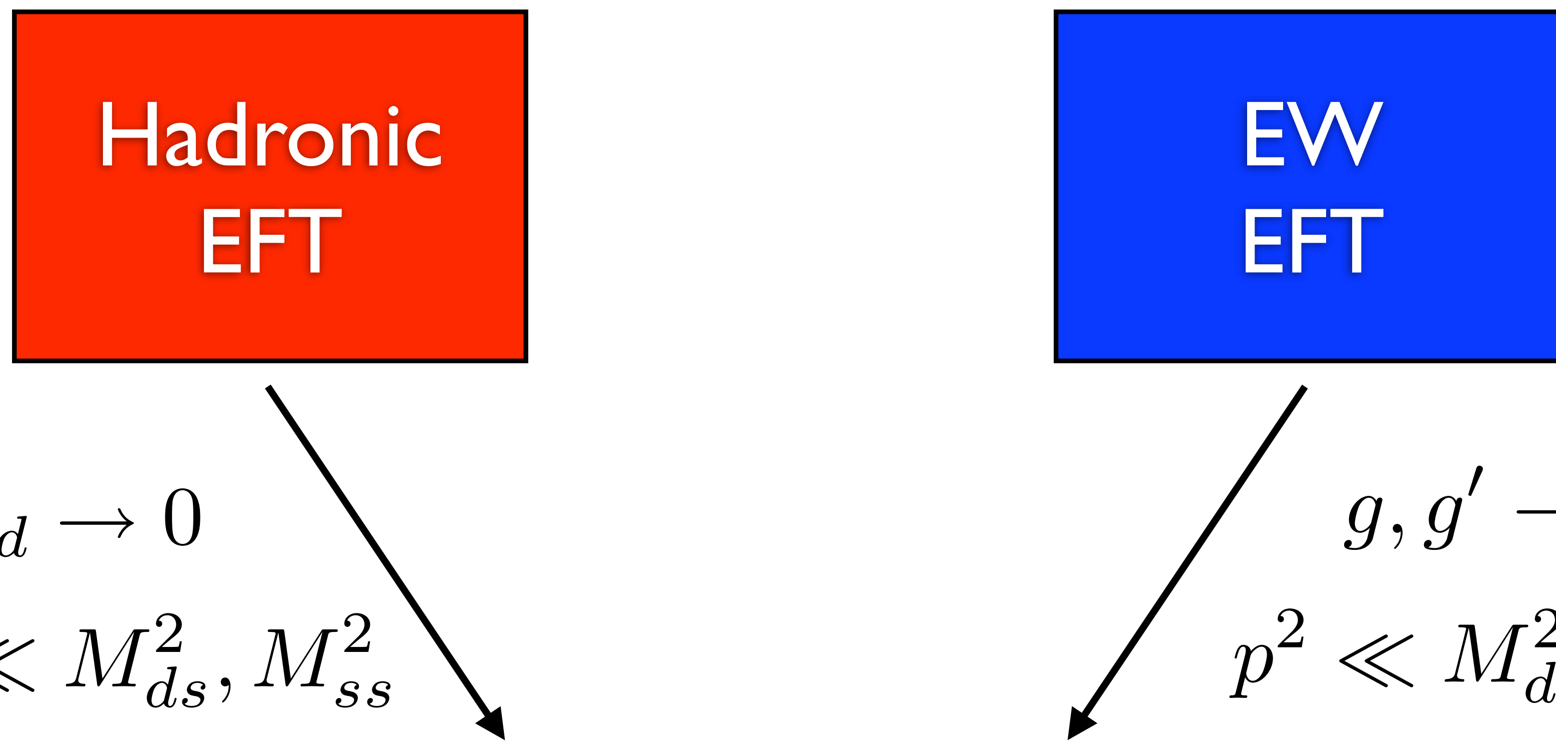
WW scattering

LSD Collaboration, PRD 85:074505 (2012)

Direct (but difficult!) probe of electroweak symmetry breaking



$m_d \to 0$

$p^2 \ll M_{ds}^2, M_{ss}^2$

$g, g' \to 0$

$p^2 \ll M_{ds}^2, M_{ss}^2$

$$\frac{f^2}{4}\mathrm{tr}(\partial_\mu U^\dagger \partial^\mu U) + \alpha_5 \left[\mathrm{tr}(\partial_\mu U^\dagger \partial^\mu U)\right]^2 + \alpha_4 \left[\mathrm{tr}(\partial_\mu U^\dagger \partial_\nu U)\right]^2$$

Low-energy *S*-wave "$I = 2$" pseudoscalar scattering on the lattice
$\longrightarrow$ hadronic chiral lagrangian LECs ℓ_1 and ℓ_2
$\rightsquigarrow$ electroweak chiral lagrangian LECs α_4 and α_5

from David Schaich

WW scattering

LSD Collaboration, PRD 85:074505 (2012)

Direct (but difficult!) probe of electroweak symmetry breaking

Hadronic EFT

EW EFT

Importance in Higgs-less LHC scenario

used to be the "no-lose theorem"

$m_d \to 0$

$p^2 \ll M_{ds}^2, M_{ss}^2$

$g, g' \to 0$

$p^2 \ll M_{ds}^2, M_{ss}^2$

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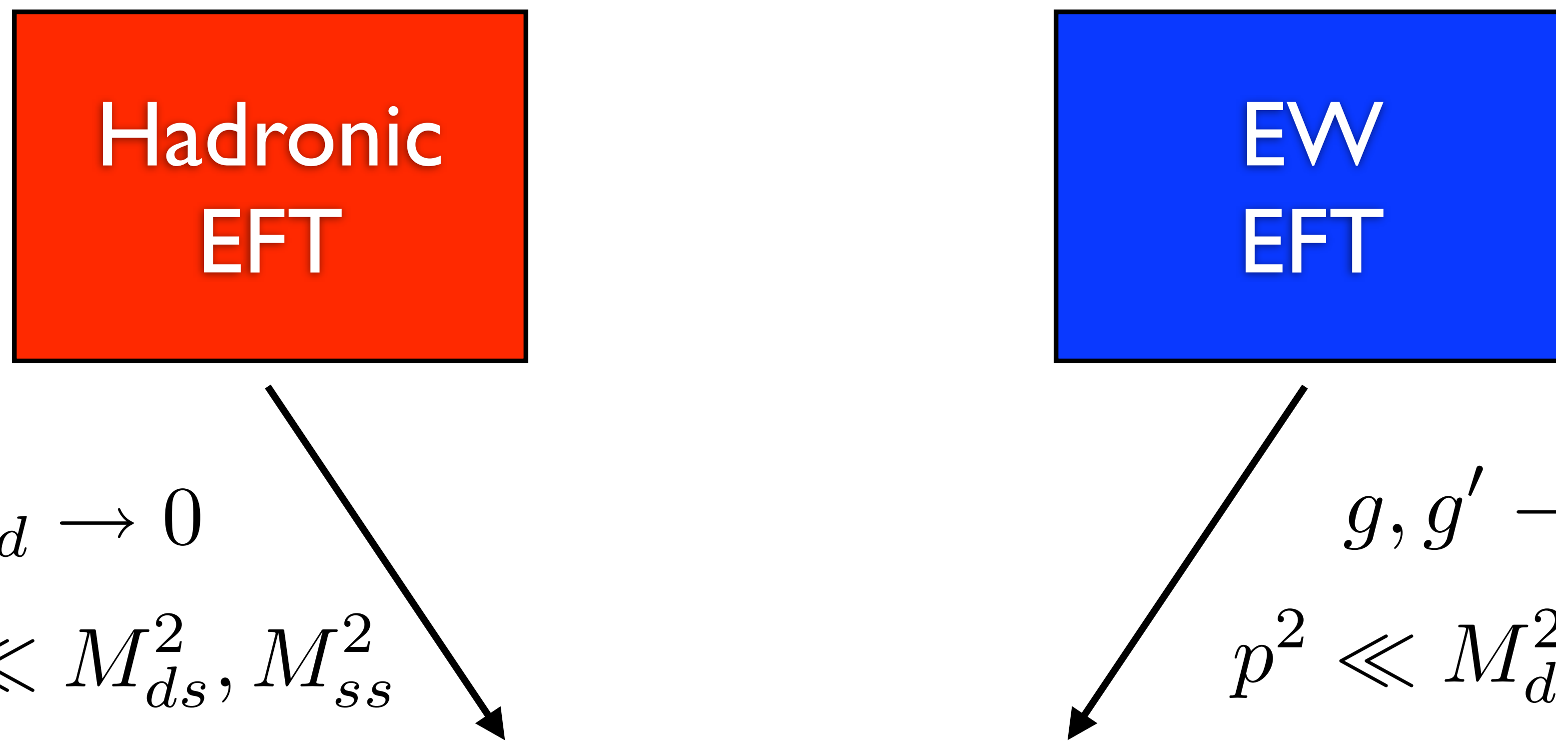

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WW scattering

LSD Collaboration, PRD 85:074505 (2012)

For $N_f = 2$, $\alpha_4 + \alpha_5 = \left(3.34 \pm 0.17^{+0.08}_{-0.71}\right) \times 10^{-3} - \Delta S_{SM}$

(dominant systematic error from chiral fit)

D-wave scattering or form factors needed to separate α_4 and α_5

Unitarity bounds $\alpha_4 + \alpha_5 \geq 1.14 \times 10^{-3}$ and $\alpha_4 \geq 0.65 \times 10^{-3}$

Expected LHC bounds (99% confidence level after 100/fb at 14 TeV):

$$-7.7 < \alpha_4 \times 10^3 < 15 \qquad -12 < \alpha_5 \times 10^3 < 10$$

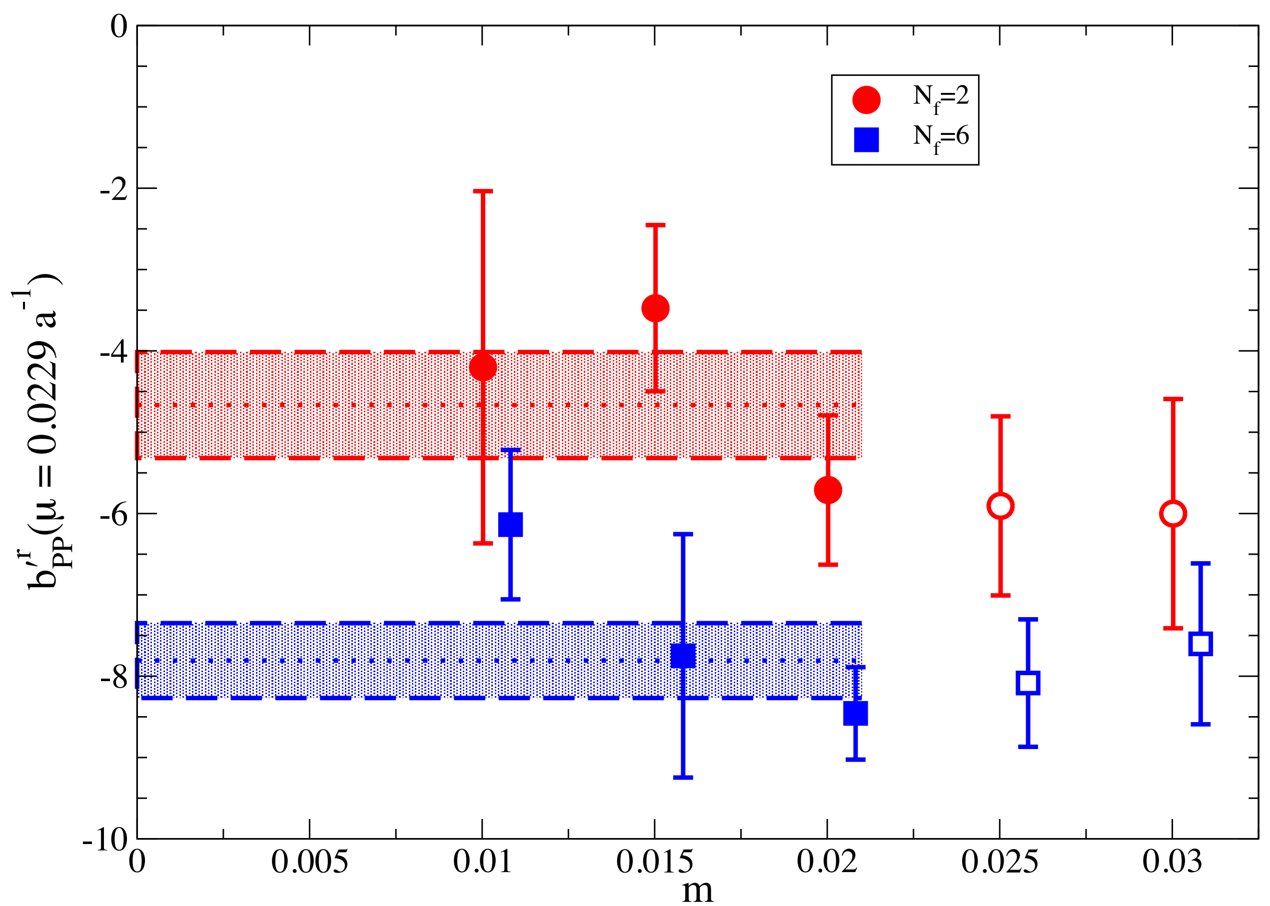
For $N_f = 6$,

reorganize χPT in terms of measured M_P and F_P

Directly compare LECs for $N_f = 2$ and $N_f = 6$

$b'_{PP} \propto L_0 + 2L_1 + 2L_2 + L_3 - 2L_4 - L_5 + 2L_6 + L_8$

No explicit N_f-dependence



from David Schaich

Outline

- LHC Higgs search and BSM implications
  focus of USQCD BSM

- Composite Higgs mechanism

- USQCD BSM results of last 12 months
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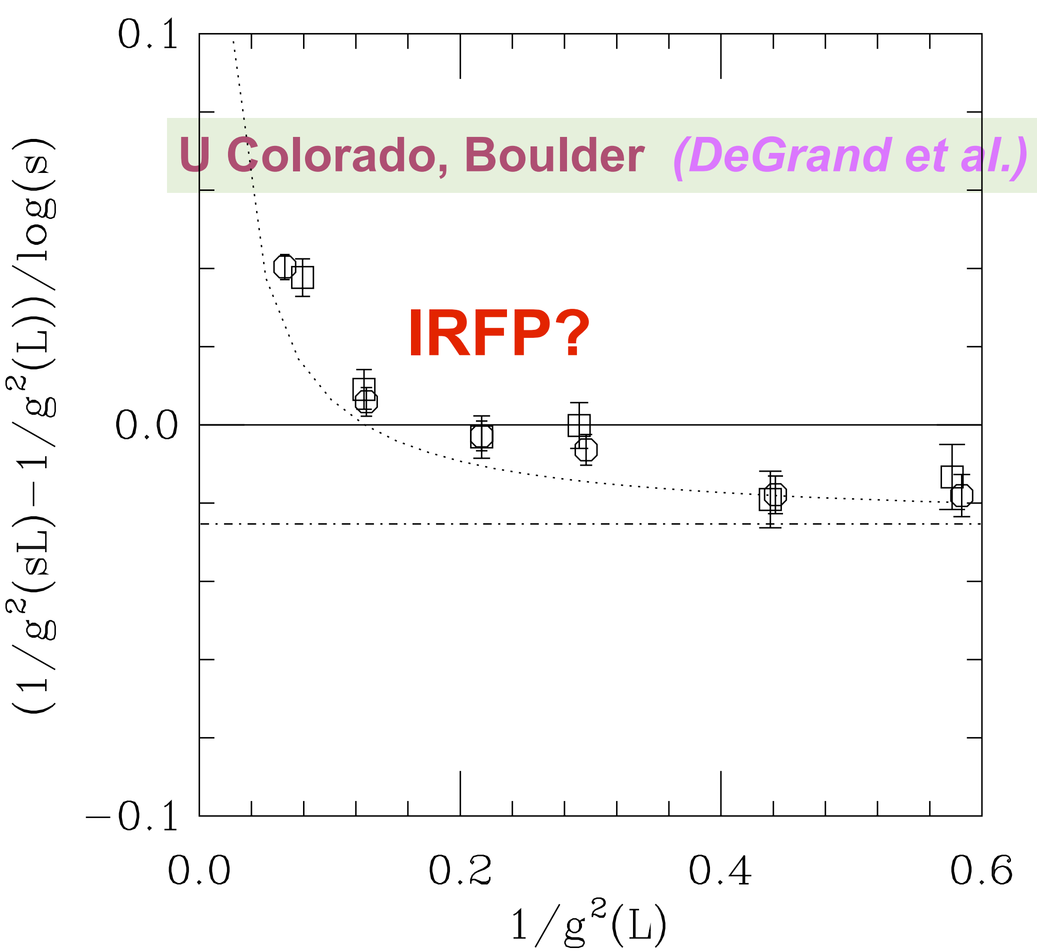
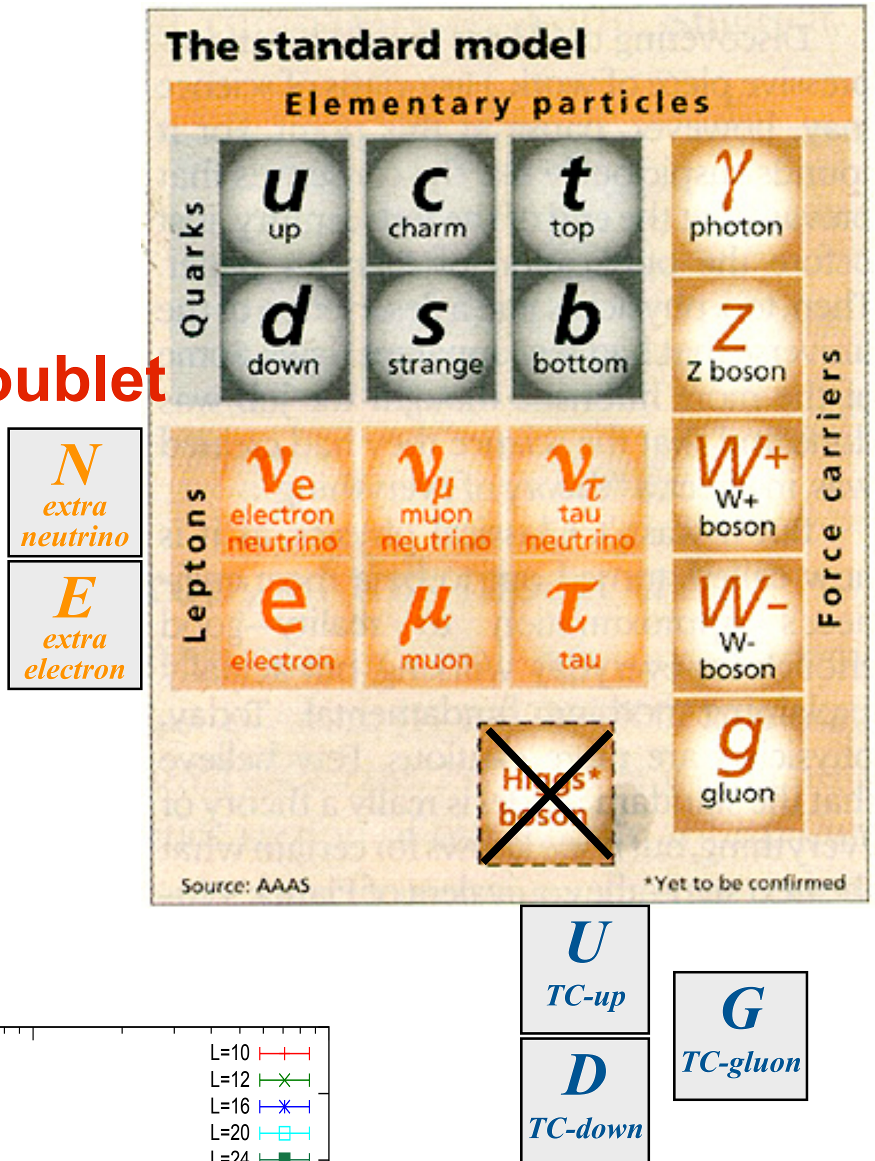
adjoint SU(2) color representation Nf=2 (with fourth family) - phenomenology?

phenomenologically viable only if below the conformal window and has large anomalous mass dimension (Sannino MWTC)

U Colorado, Boulder *(DeGrand et al.)*



4th lepton doublet

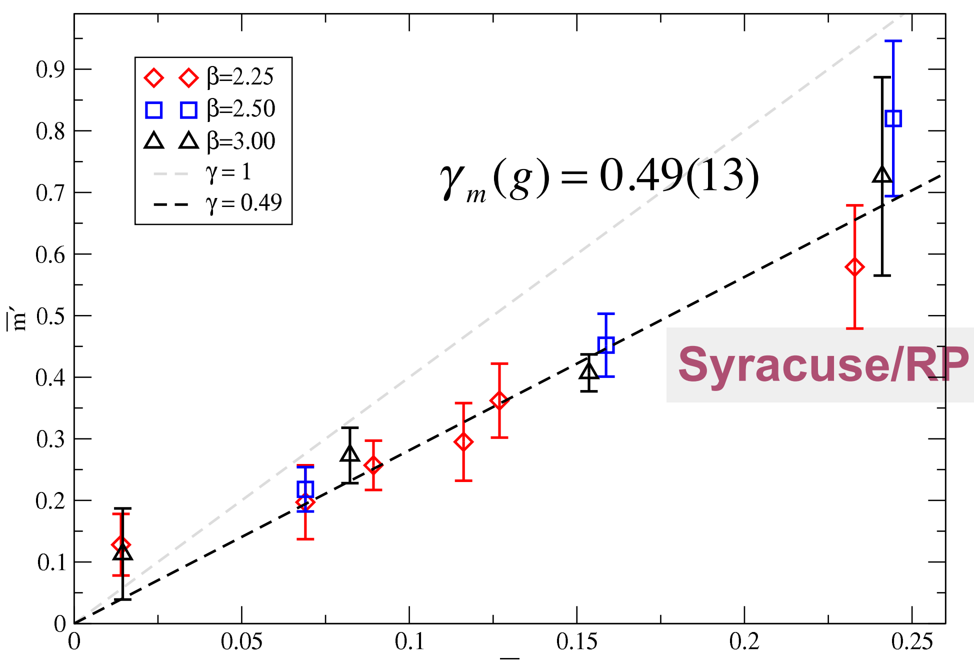


$U(1)_Y$

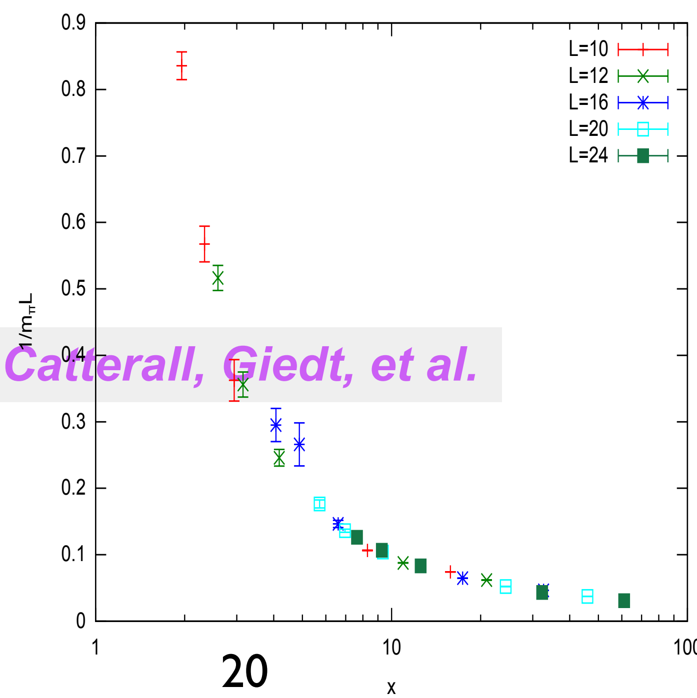
$SU(2)_L$

$SU(3)_C$

$SU(2)_{TC}$

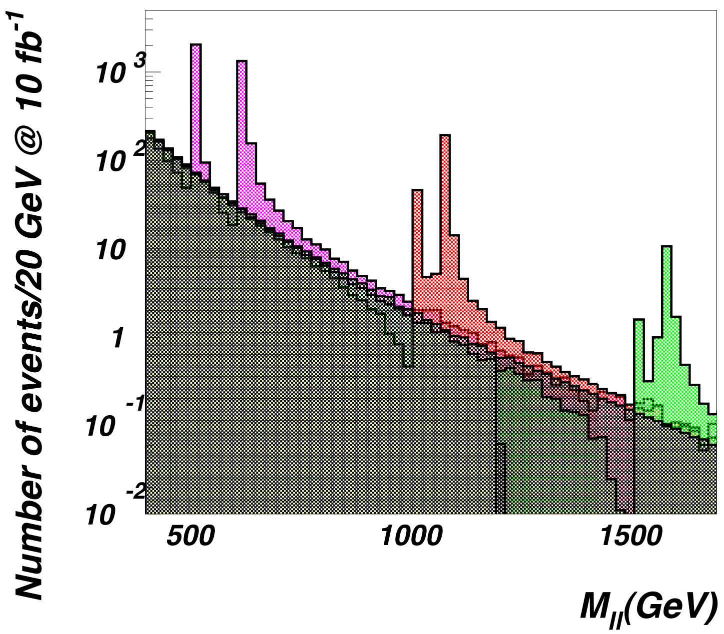


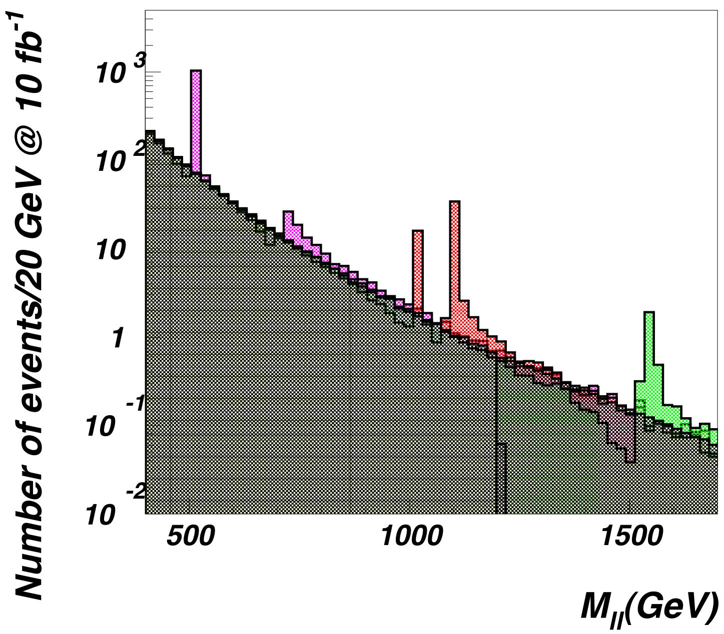
Syracuse/RPI *Catterall, Giedt, et al.*



adjoint SU(2) color representation Nf=2 (with fourth family) - phenomenology?

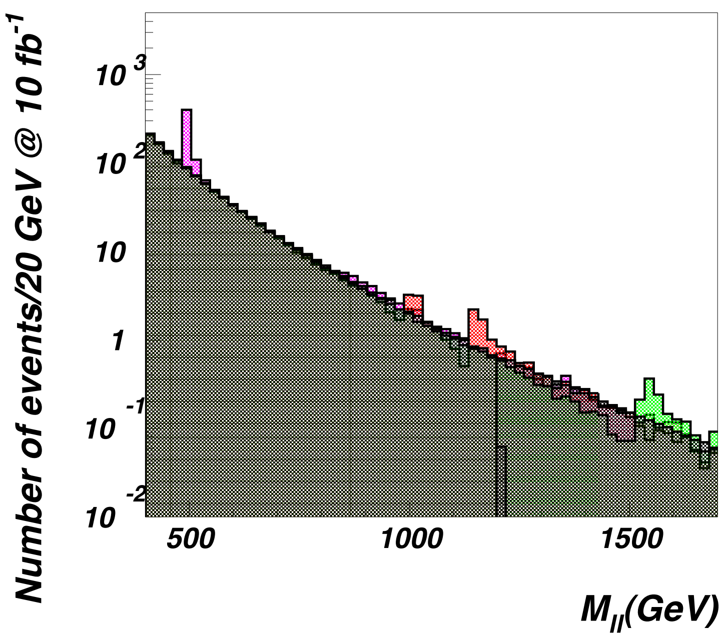
phenomenology can start before conformality is resolved (generic) Sannino MWTC

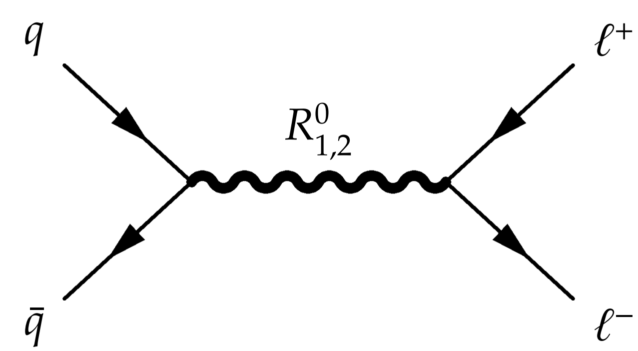




Drell-Yen production of composite vector bosons on the TeV scale

from Sannino et al.



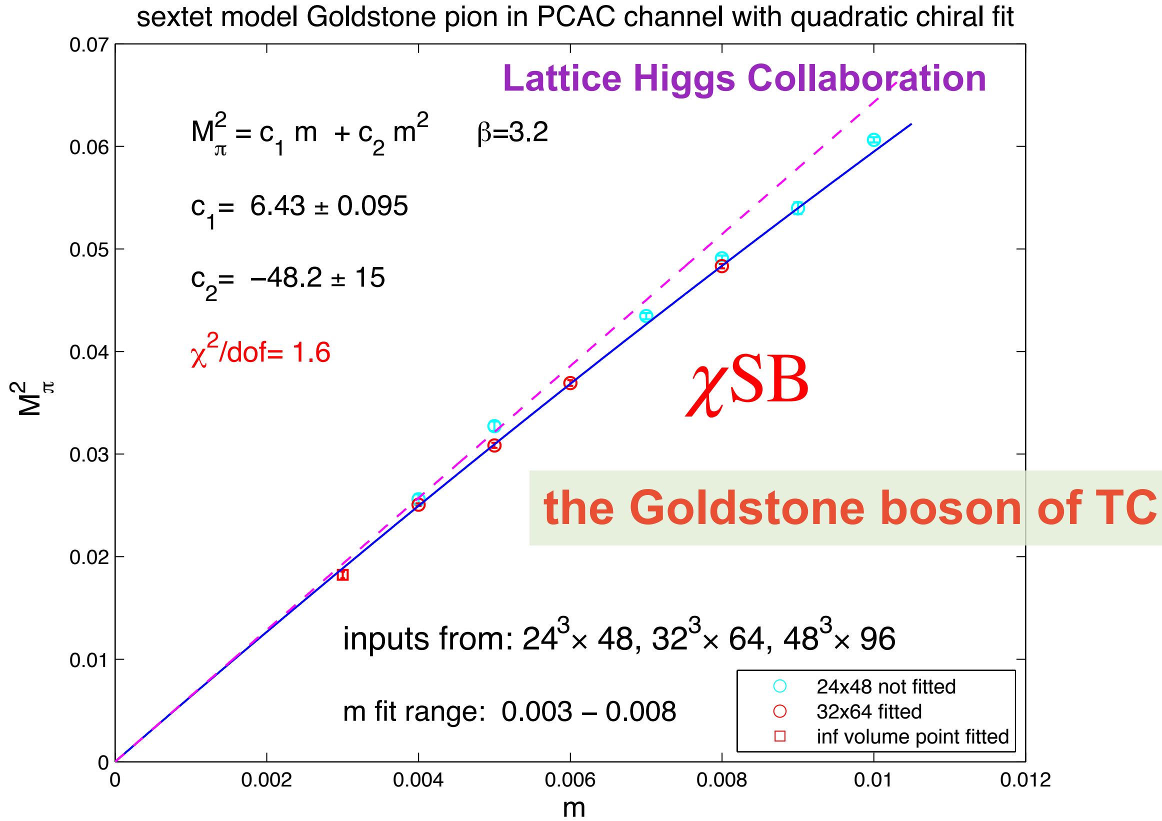


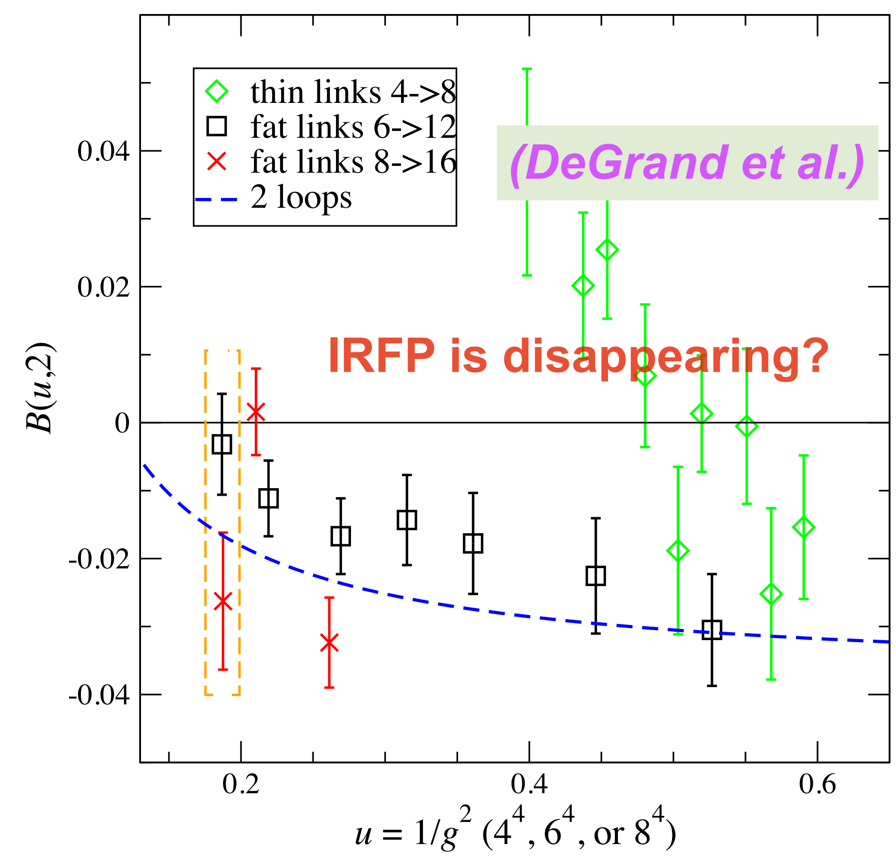
Feynman diagram of TeV scale new vector meson production

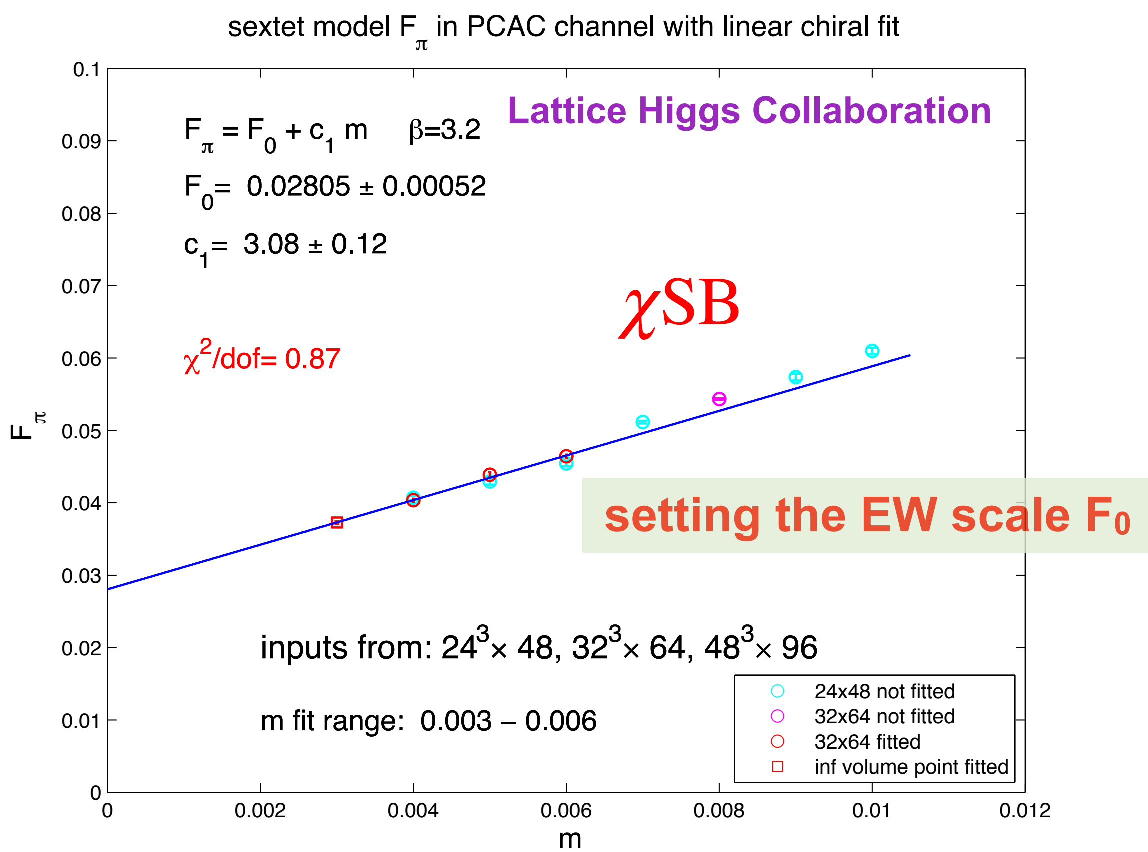
Dilepton invariant mass distribution $M_{\ell\ell}$ for $pp \to R_{1,2} \to \ell^+\ell^-$ signal

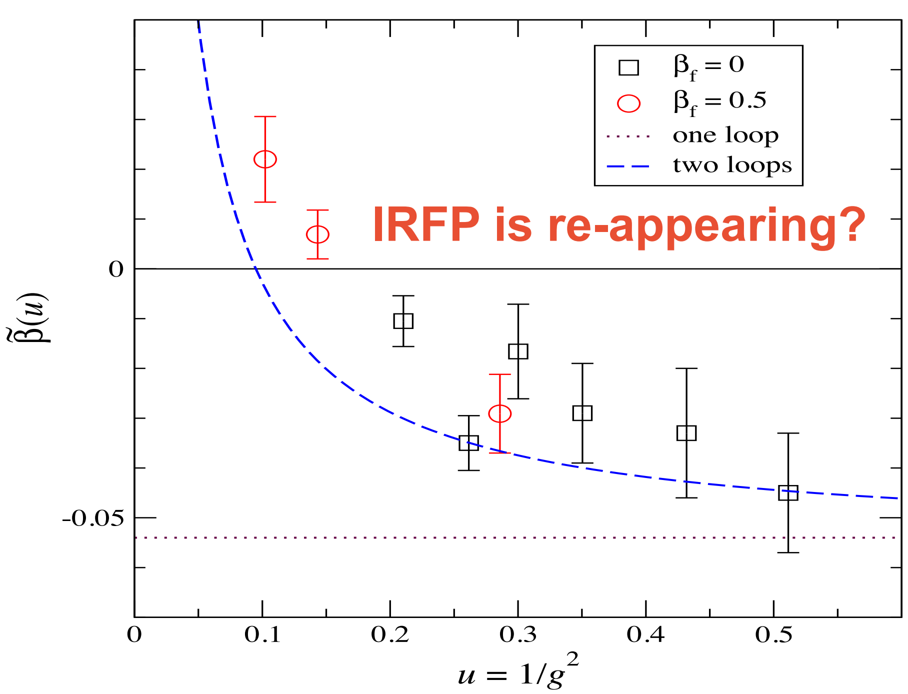
SU(3) sextet color representation Nf=2 (minimal composite Higgs) - phenomenology?

phenomenologically viable below the conformal window: has large anomalous mass dimension should be called MWTC

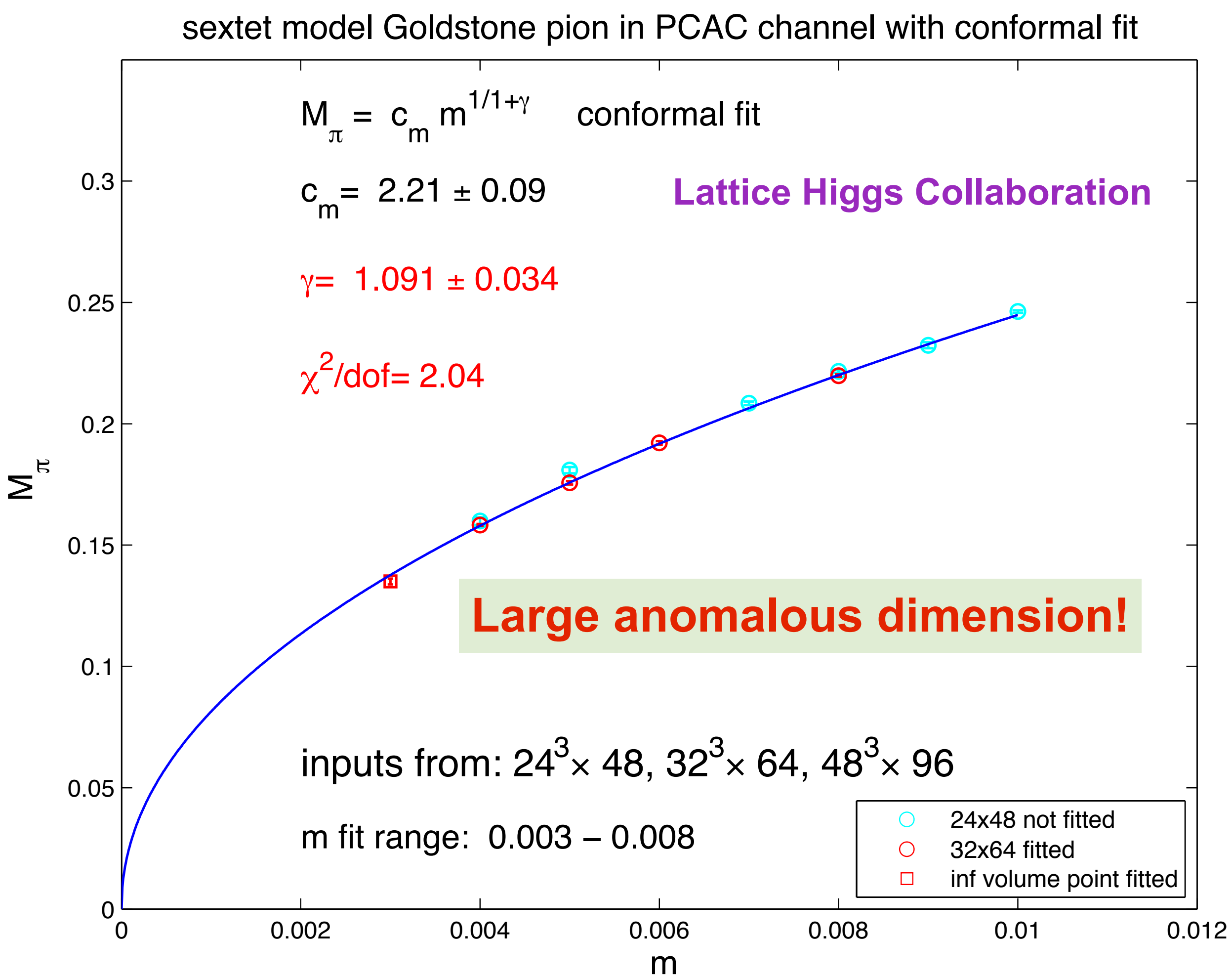


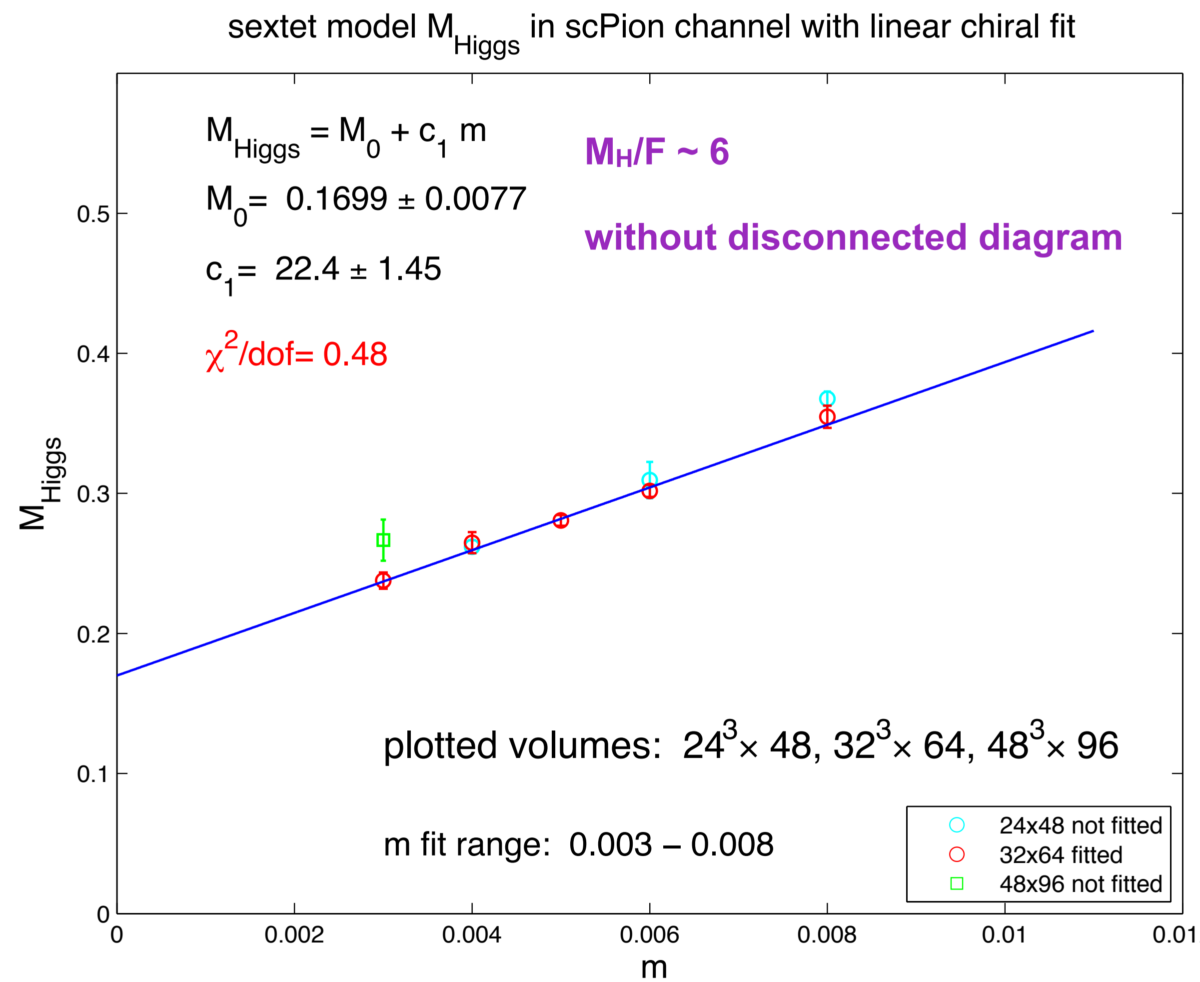


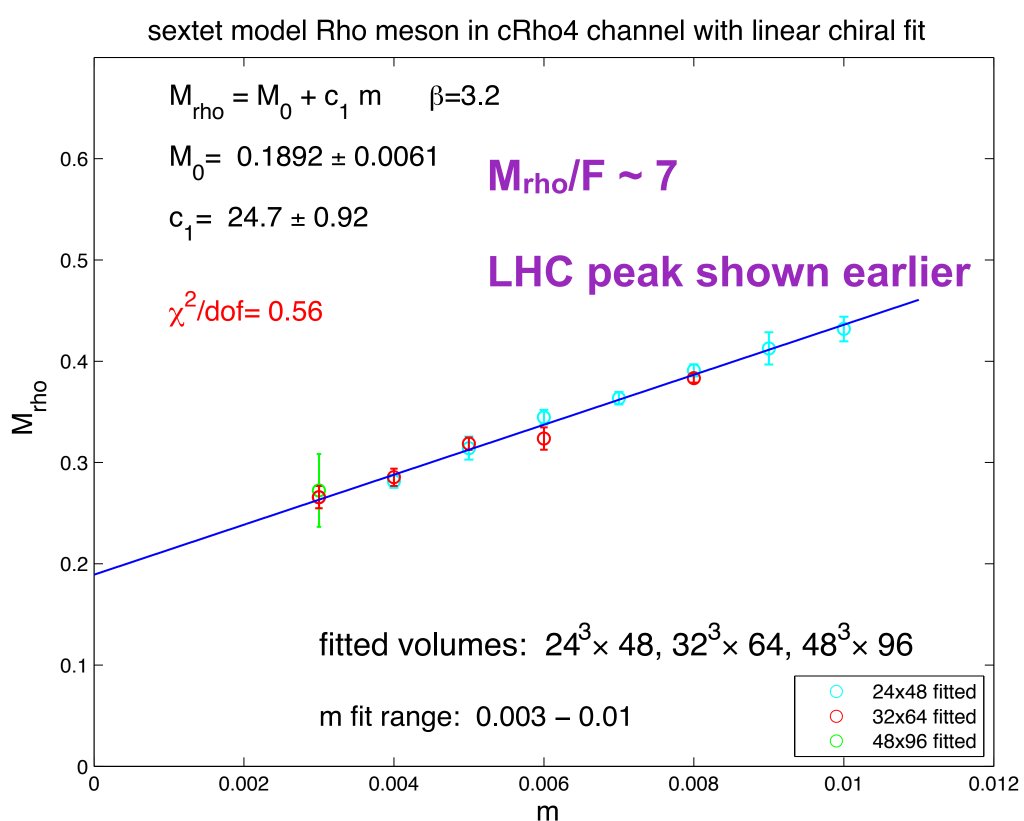




SU(3) sextet color representation Nf=2 (minimal composite Higgs) - phenomenology?







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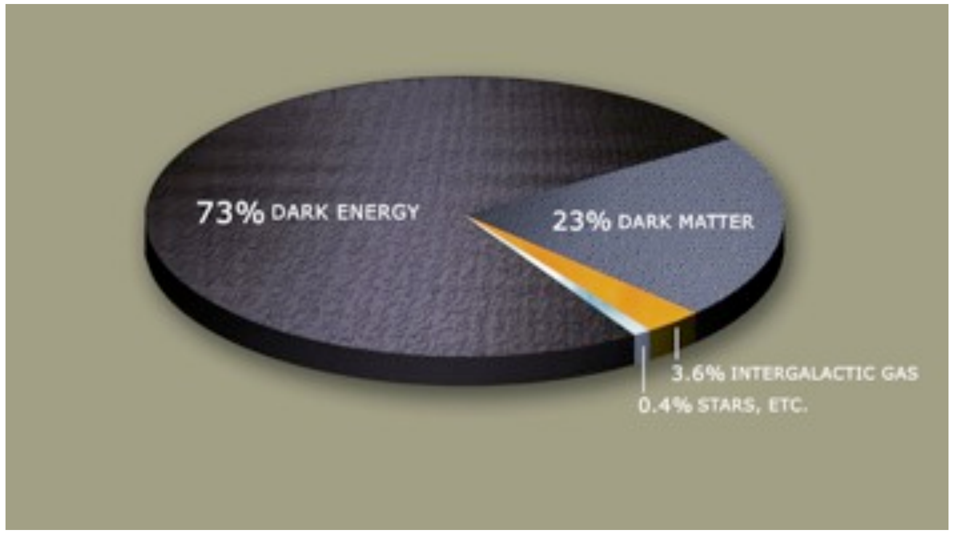
<u>technicolor & Dark Matter:</u>



- lightest technibaryon can be stable by analog of $U(1)_B$

- an initial matter/anti-matter asymmetry gets shared among baryons, leptons, technibaryons via sphalerons

(Chivukula, Barr, Fahri, Nussinov)

- can get observed Ω_{DM}/ Ω_B easily for ~ TeV scale DM

must be electrically neutral, EW singlets to avoid direct detection

Then leading operators are charge radius and polarizability:

ex.) $$\frac{B^* B\, v_\mu\, \partial_\nu F^{\mu\nu}}{\Lambda_{TC}^2}, \frac{B^* B\, F_{\mu\nu} F^{\mu\nu}}{\Lambda_{TC}^3}$$

lattice input?

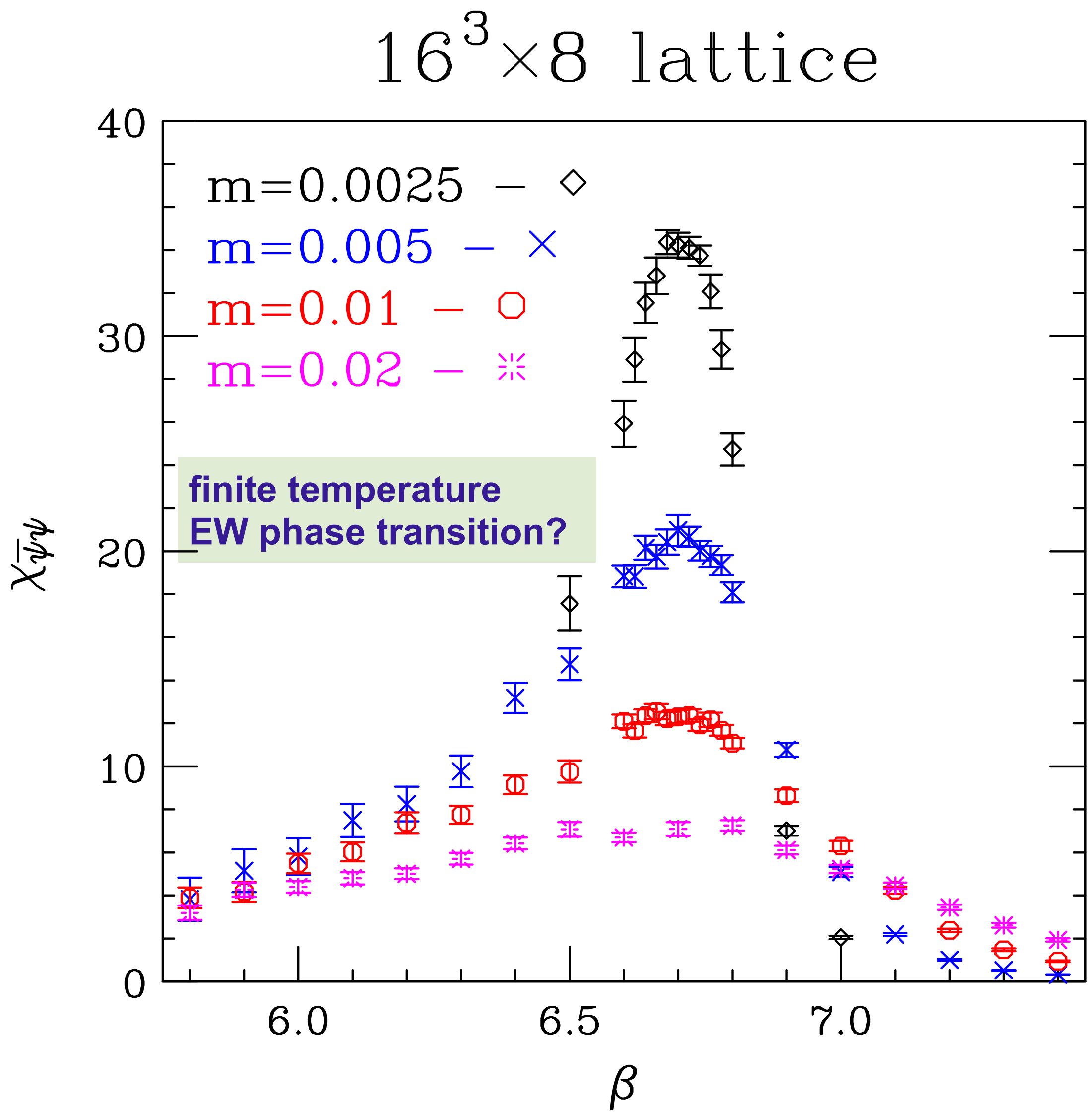
from Adam Martin

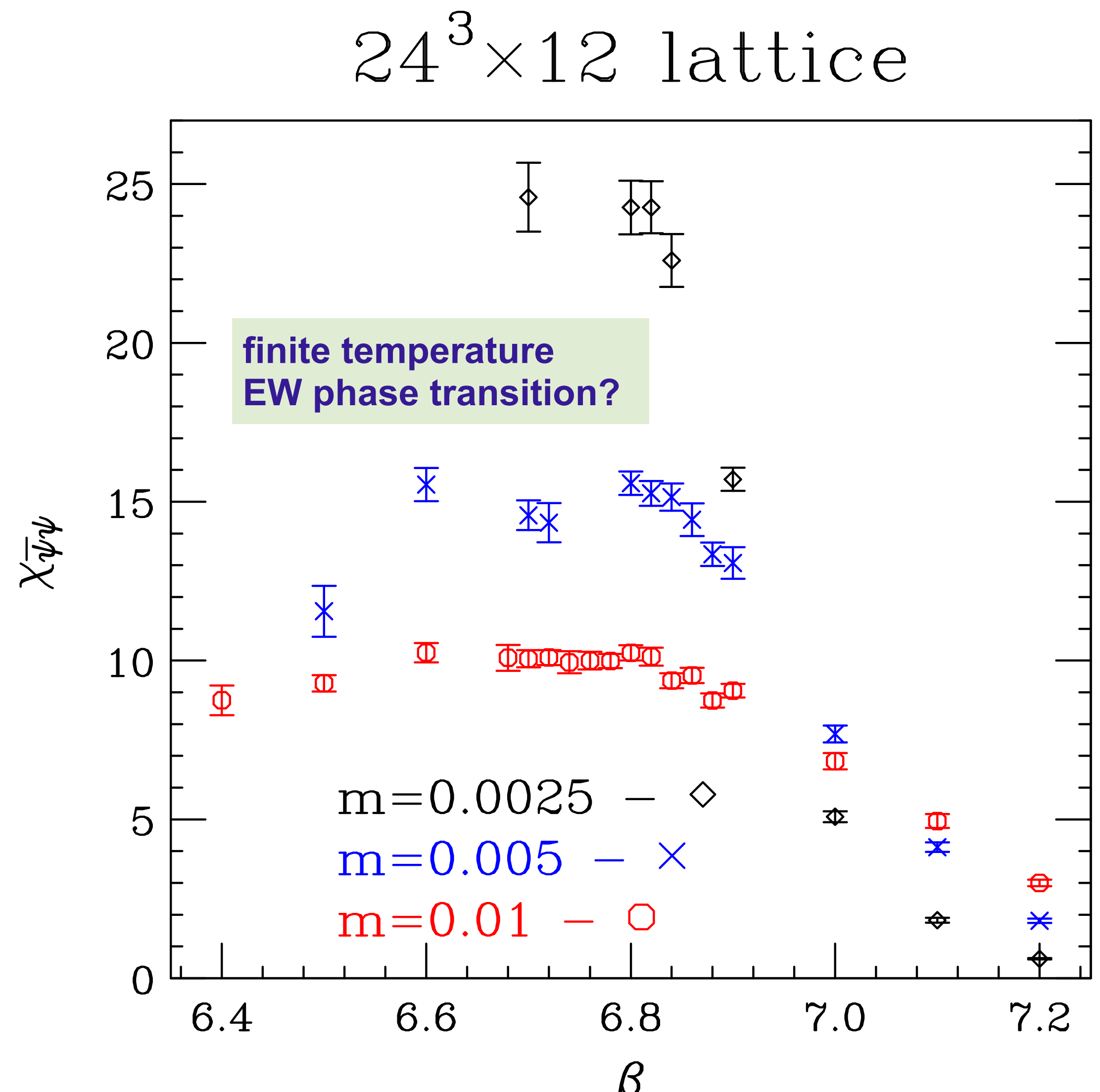
EW phase transition in composite Higgs model - early universe

sextet model ***(Kogut-Sinclair)***

Sinclair is USQCD member but project is not using USQCD resources!

potential implications in early cosmology





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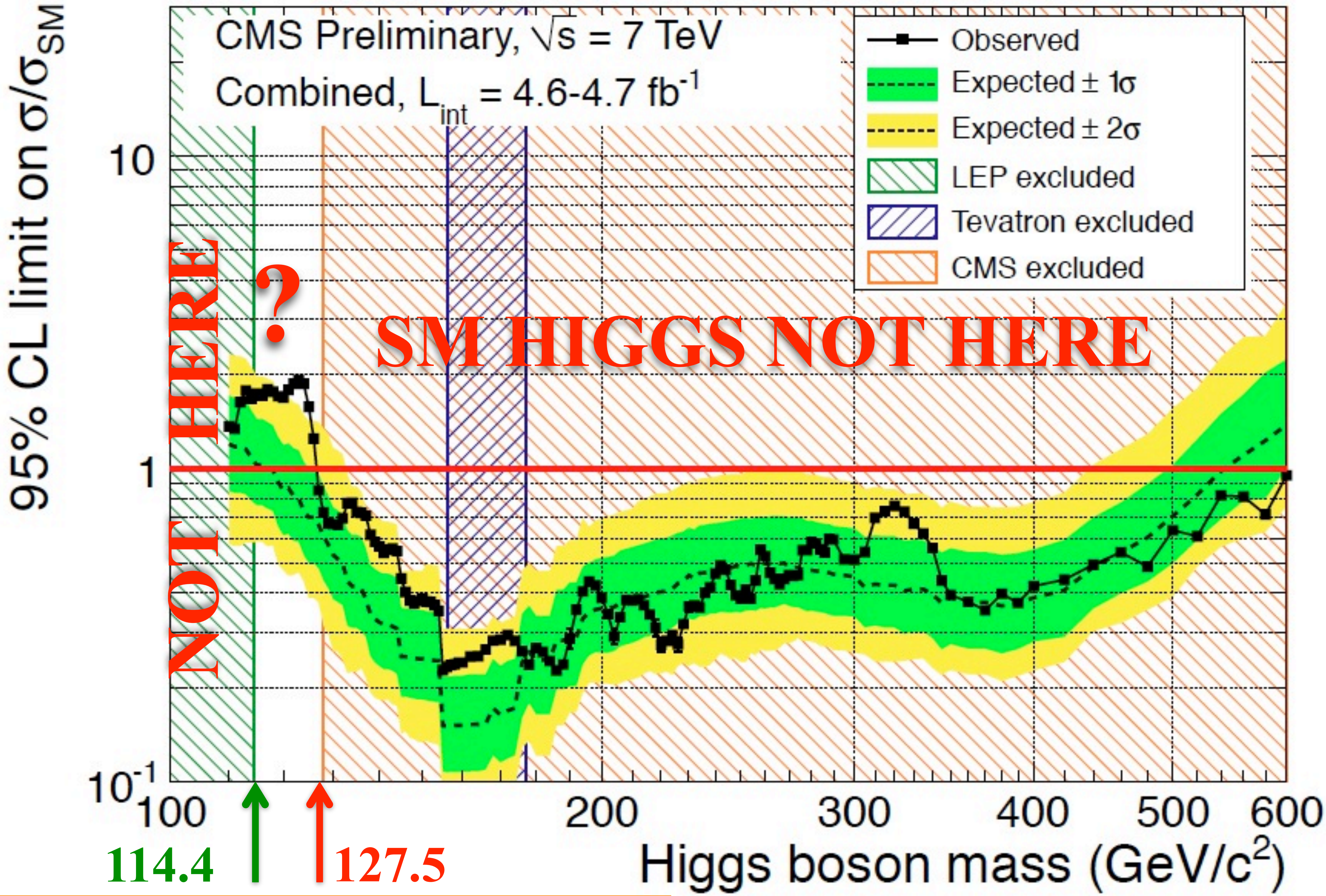
Summary and outlook

- USQCD is playing leadership role in studies of BSM physics on energy frontier
    - Searching for candidate composite Higgs models and computing their properties
    - Supersymmetric extension SM - susy breaking needs lattice input with ultimate goal to understand soft parameters in MSSM
- Covers two main approaches to understanding EW symmetry breaking at LHC
- Much learned in last 12 months - Hard but making good progress
- Excellent pilot work on S-parameter and WW scattering (important future goal)
- Composite Higgs model realizations: SU(2) adjoint and sextet SU(3)
- Technicolor spectroscopy (important future goal)
- Cosmology connection
  (dark baryon matter and EW phase transition)
- USQCD BSM research is important part of our SciDAC-3 plan

backup slides

CMS Higgs search (from Vivek Sharma)

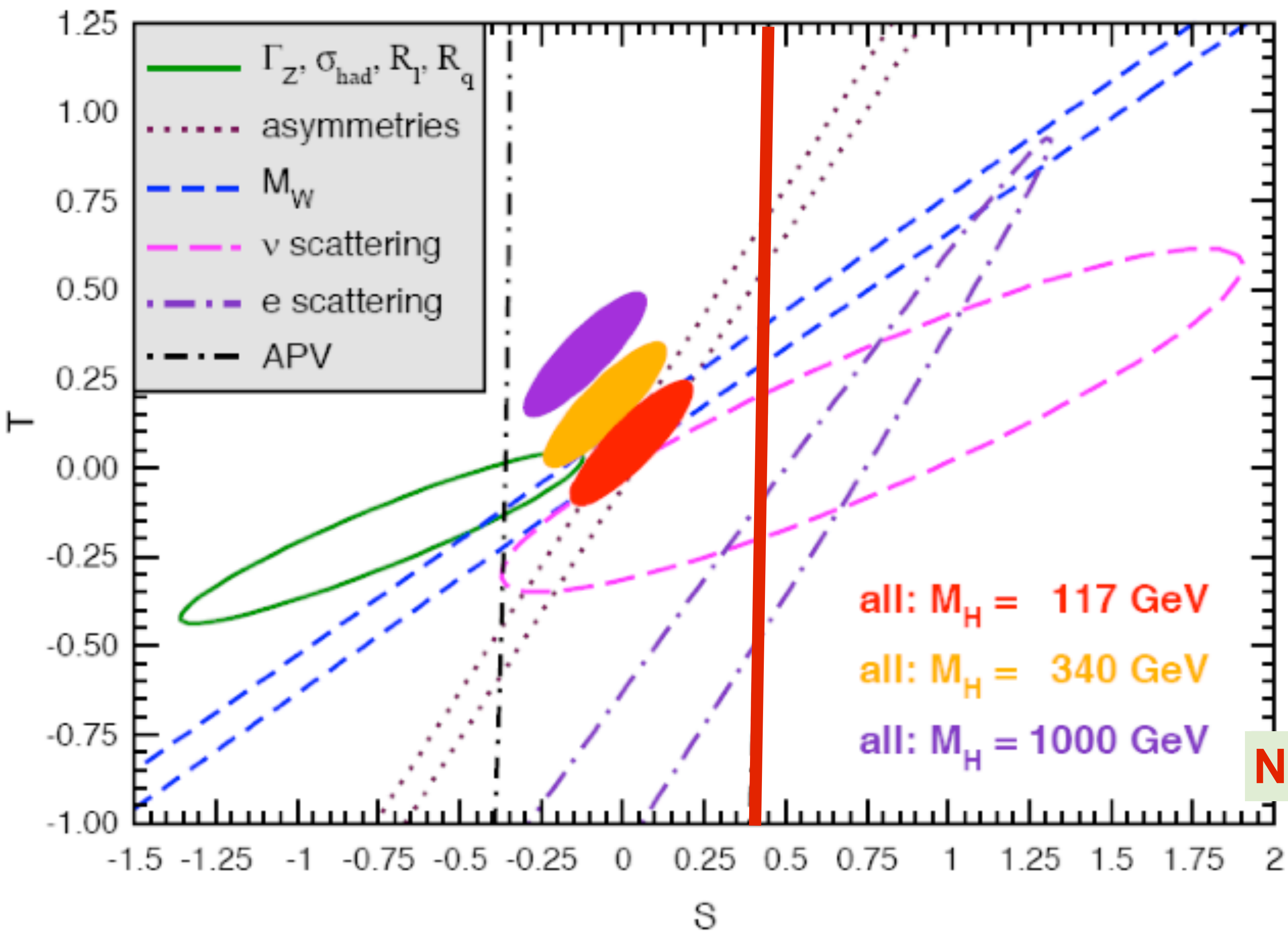


Remaining corridor of uncertainty

precision electroweak parameters:

if TeV-scale dynamics is QCD-like, expect S~0.3

or even higher !



what about in a near-conformal theory?

New LSD results will be shown

$$S = 4\pi N_D \lim_{Q^2 \to 0} \frac{d}{dQ^2} \Pi_{V-A}(Q^2) - \Delta S_{SM}$$

from Adam Martin