Beyond the Standard Model: Charting Fundamental Interactions via Lattice Simulations

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LATTICE 2016

SYDDANSKUNIVERSITET.DK

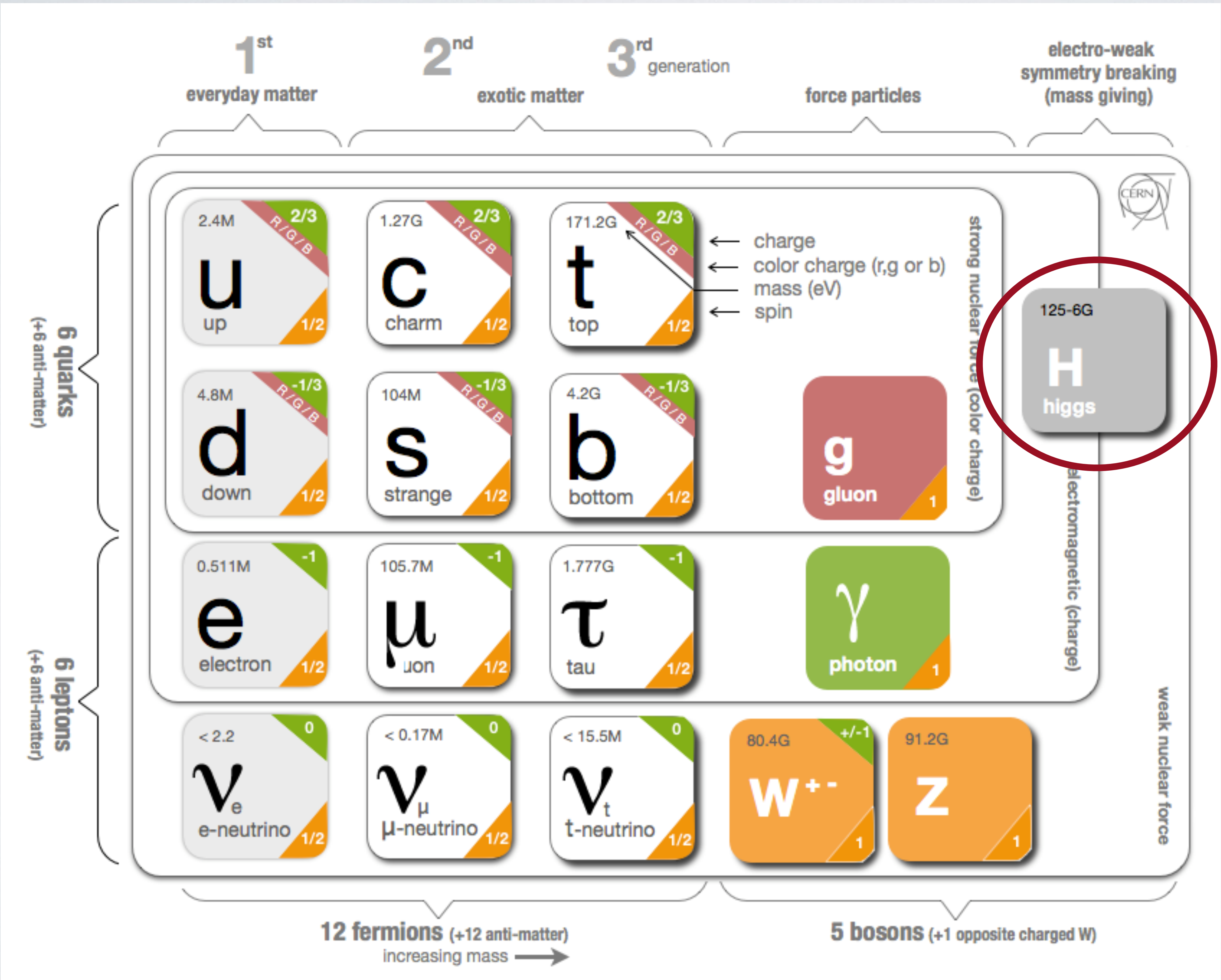
CP3 Origins
Cosmology & Particle Physics

- Thanks to the LOC for the invitation to review how "Lattice Field Theory is impacting the quest for new physics"

- Thanks to all who sent details on their work

- Apologies to all I will not be able to address
  - SUSY — **Talks on Tue by: Kanata, Giedt, Schaich, August, Joseph, Giudice**
  - extradimensions — **Talk on Thu by Alberti**
  - new mechanism for mass generation — **Talk on Thu by Garofalo**
  - non-perturbative Higgs physics — **Talks on Thu by Maas, Toerek**
  - Gauge/gravity duality — **Talk on Mon by Bennett** **Talks on Fri by Forini, Berkowitz**
  - Asymptotic Safety — **Talk on Mon by Buyukbese, Bond**

The Standard Model



Gauge Fields
+ Fermions
+ Scalar

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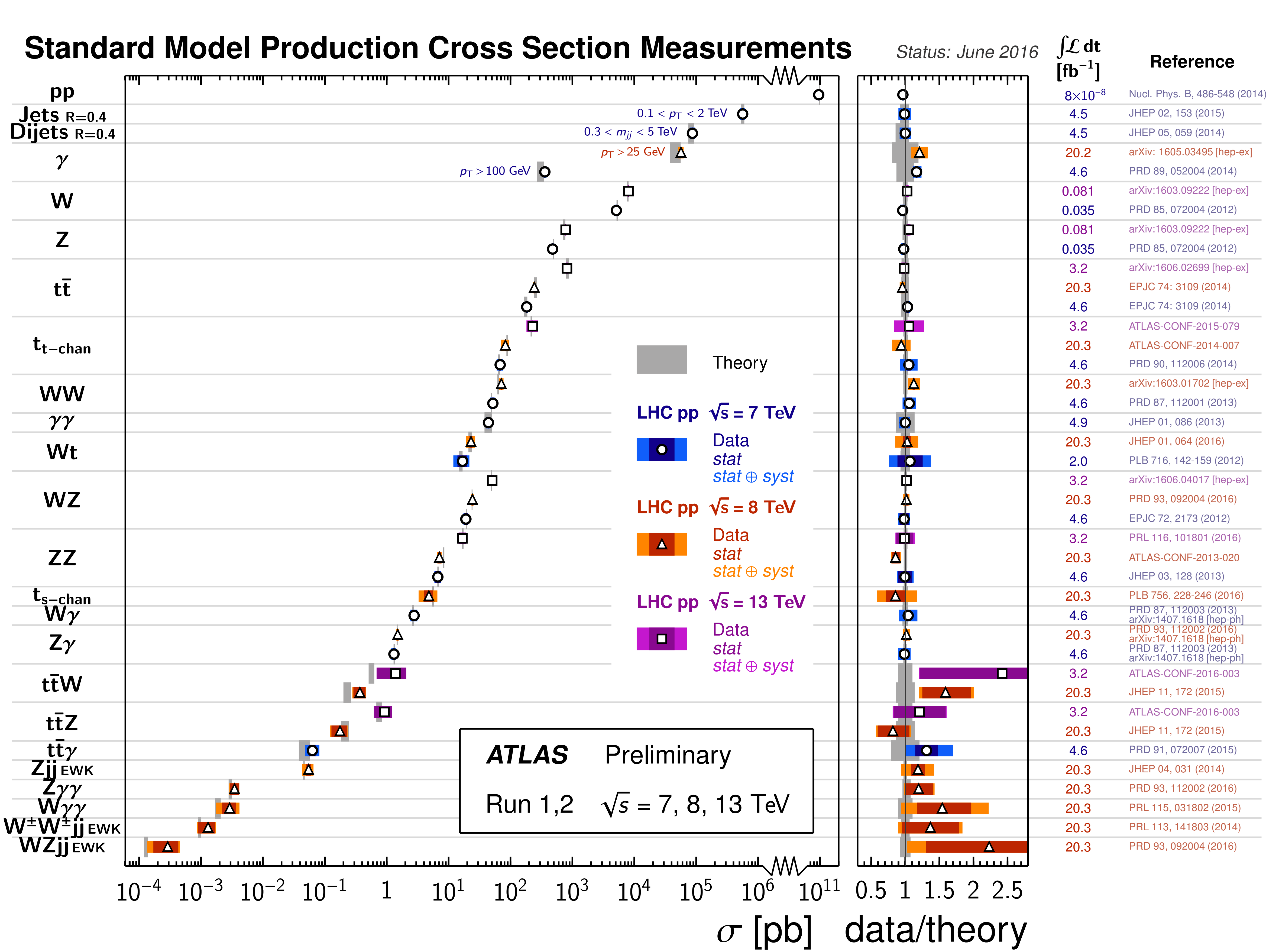
CP3 Origins
Cosmology & Particle Physics

The SM Higgs?

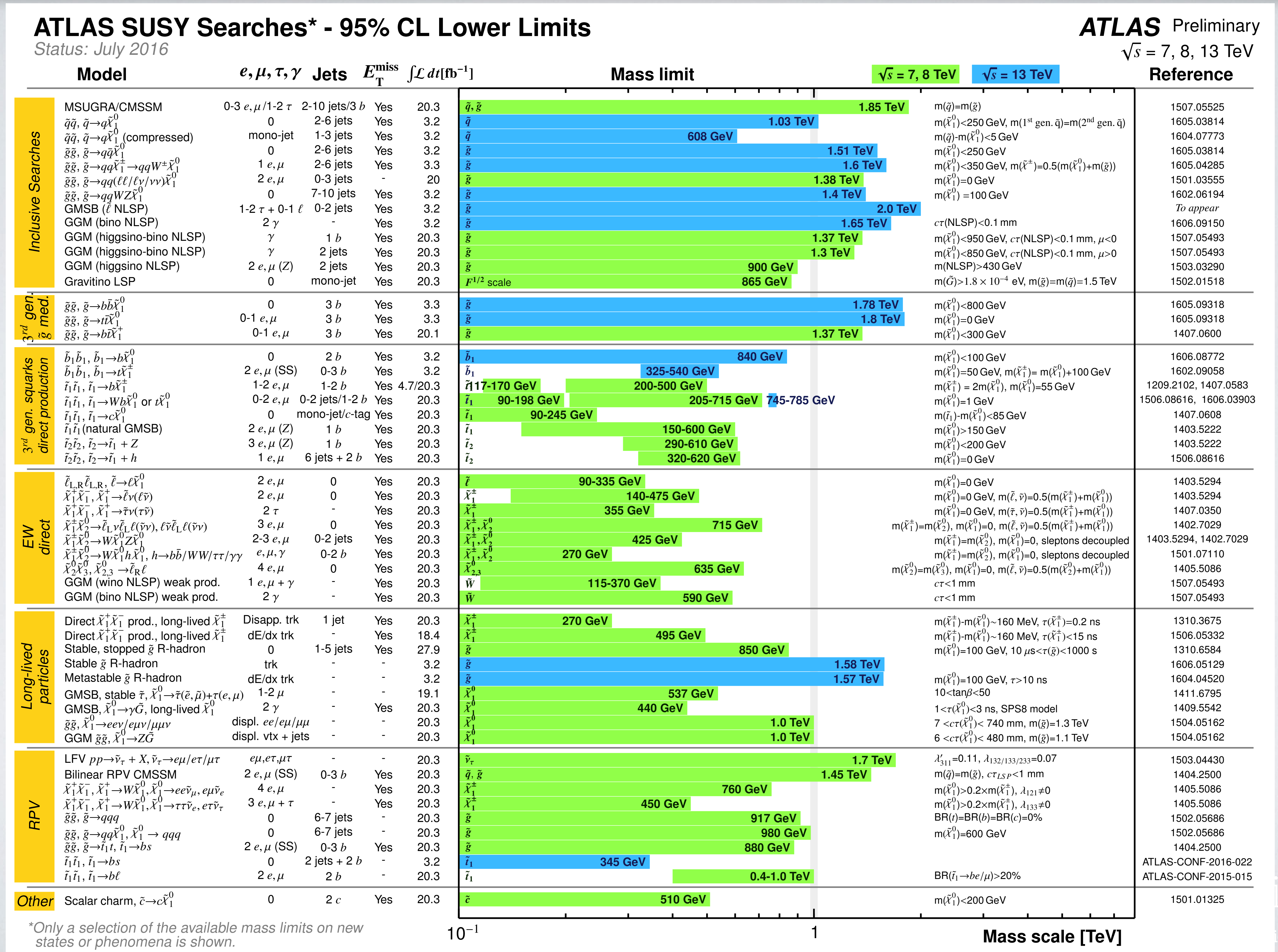
- Spin 0?
- Is it a scalar (or pseudoscalar)?
- Coupling to other SM particles proportional to their mass?
    - origin of mass
- Quantum effects consistent with SM Higgs?
- It is Elementary or Composite?

ATLAS and CMS are providing precise measurements of the properties of the Higgs and strong constraints on Beyond SM physics

The Standard Model Works



The Standard Model Works



The Standard Model Works

ATLAS Exotics Searches* - 95% CL Exclusion

Status: March 2016

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 20.3)\ \text{fb}^{-1}$ $\quad \sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt [\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	3.2	M_D 6.58 TeV	$n = 2$	1604.07773
	ADD non-resonant $\ell\ell$	2 e,μ	–	–	20.3	M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\to \ell q$	1 e,μ	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	3.6	M_{th} 8.3 TeV	$n = 6$	1512.01530
	ADD BH high $\sum p_T$	≥ 1 e,μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \ell\ell$	2 e,μ	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	20.3	G_{KK} mass 2.66 TeV	$k/\overline{M}_{Pl} = 0.1$	1504.05511
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e,μ	1 J	Yes	3.2	G_{KK} mass 1.06 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2015-075
	Bulk RS $G_{KK} \to HH \to bbbb$	–	4 b	–	3.2	G_{KK} mass 480-770 GeV	$k/\overline{M}_{Pl} = 1.0$	1606.04782
	Bulk RS $g_{KK} \to tt$	1 e,μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	1 e,μ	≥ 2 b, ≥ 4 j	Yes	3.2	KK mass 1.46 TeV	Tier (1,1), BR($A^{(1,1)} \to tt$) = 1	ATLAS-CONF-2016-013
Gauge bosons	SSM $Z' \to \ell\ell$	2 e,μ	–	–	3.2	Z' mass 3.4 TeV		ATLAS-CONF-2015-070
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	Z' mass 2.02 TeV		1502.07177
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		1603.08791
	SSM $W' \to \ell\nu$	1 e,μ	–	Yes	3.2	W' mass 4.07 TeV		1606.03977
	HVT $W' \to WZ \to qq\nu\nu$ model A	0 e,μ	1 J	Yes	3.2	W' mass 1.6 TeV	$g_V = 1$	ATLAS-CONF-2015-068
	HVT $W' \to WZ \to qqqq$ model A	–	2 J	–	3.2	W' mass 1.38-1.6 TeV	$g_V = 1$	ATLAS-CONF-2015-073
	HVT $W' \to WH \to \ell\nu bb$ model B	1 e,μ	1-2 b, 1-0 j	Yes	3.2	W' mass 1.62 TeV	$g_V = 3$	ATLAS-CONF-2015-074
	HVT $Z' \to ZH \to \nu\nu bb$ model B	0 e,μ	1-2 b, 1-0 j	Yes	3.2	Z' mass 1.76 TeV	$g_V = 3$	ATLAS-CONF-2015-074
	LRSM $W'_R \to tb$	1 e,μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e,μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	3.6	Λ 17.5 TeV	$\eta_{LL} = -1$	1512.01530
	CI $qq\ell\ell$	2 e,μ	–	–	3.2	Λ 23.1 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2015-070
	CI $uutt$	2 e,μ (SS)	≥ 1 b, 1-4 j	Yes	20.3	Λ 4.3 TeV	$\lvert C_{LL}\rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e,μ	≥ 1 j	Yes	3.2	m_A 1.0 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 250$ GeV	1604.07773
	Axial-vector mediator (Dirac DM)	0 e,μ, 1 γ	1 j	Yes	3.2	m_A 710 GeV	g_q=0.25, g_χ=1.0, $m(\chi) < 150$ GeV	1604.01306
	$ZZ\chi\chi$ EFT (Dirac DM)	0 e,μ	1 J, ≤ 1 j	Yes	3.2	M_* 550 GeV	$m(\chi) < 150$ GeV	ATLAS-CONF-2015-080
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e,μ	≥ 1 b, ≥ 3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	1 e,μ	≥ 2 b, ≥ 3 j	Yes	20.3	T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \to Wb + X$	1 e,μ	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \to Hb + X$	1 e,μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \to Zb + X$	2/$\geq$3 e,μ	$\geq$2/$\geq$1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ \to WqWq$	1 e,μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
	$T_{5/3} \to Wt$	1 e,μ	≥ 1 b, ≥ 5 j	Yes	20.3	$T_{5/3}$ mass 840 GeV		1503.05425
Excited fermions	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	3.2	q^* mass 4.4 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.05910
	Excited quark $q^* \to qg$	–	2 j	–	3.6	q^* mass 5.2 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.01530
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	3.2	b^* mass 2.1 TeV		1603.08791
	Excited quark $b^* \to Wt$	1 or 2 e,μ	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	3 e,μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e,μ,τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \to W\gamma$	1 e,μ, 1 γ	–	Yes	20.3	a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	2 e,μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2 e,μ (SS)	–	–	20.3	$H^{\pm\pm}$ mass 551 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\ell$)=1	1412.0237
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e,μ,τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e,μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q\rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1509.08059

$\sqrt{s}$ = 8 TeV $\quad \sqrt{s}$ = 13 TeV

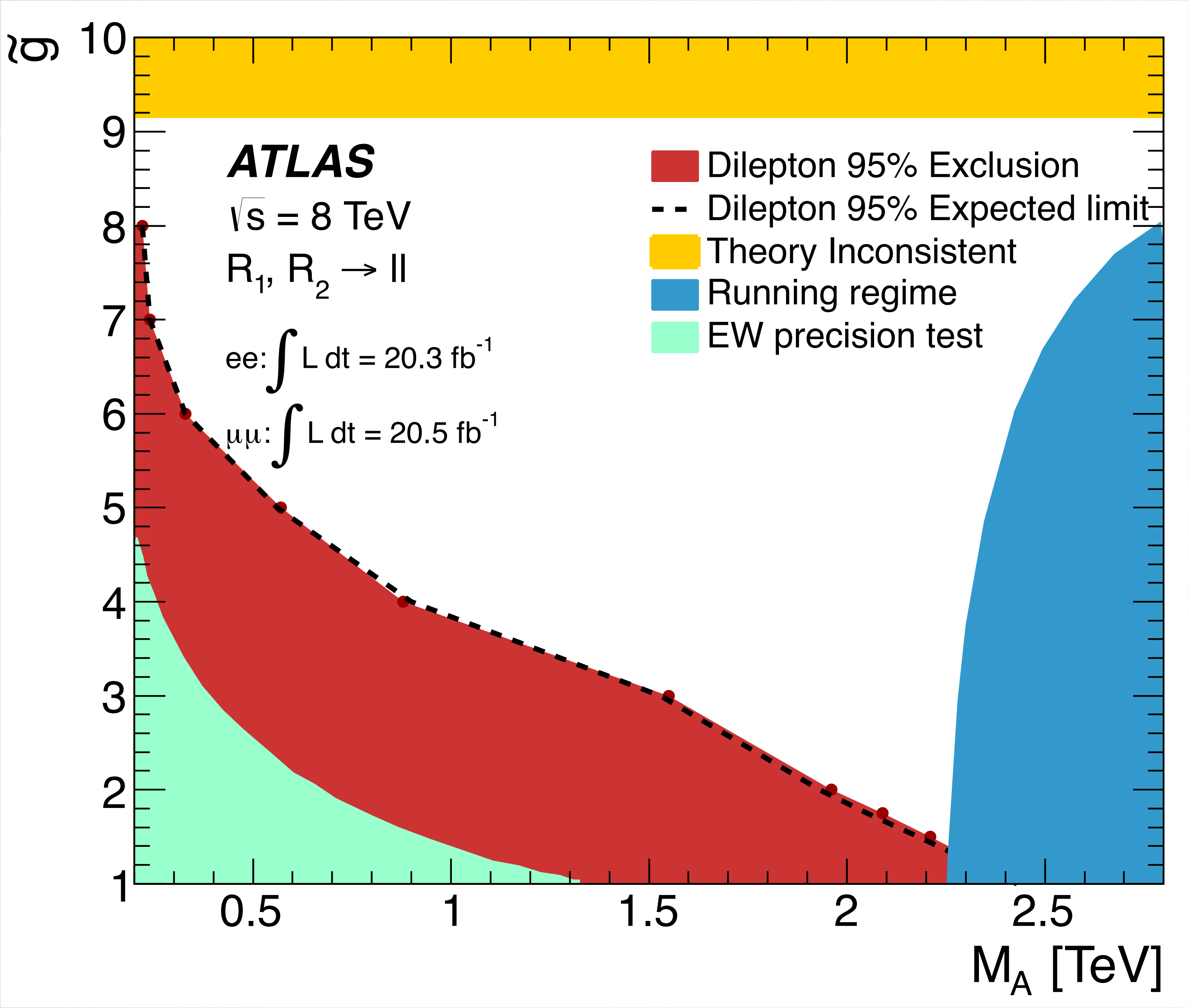
10^{-1} $\quad$ 1 $\quad$ 10 $\quad$ **Mass scale [TeV]**

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter j (J).

The Standard Model Works

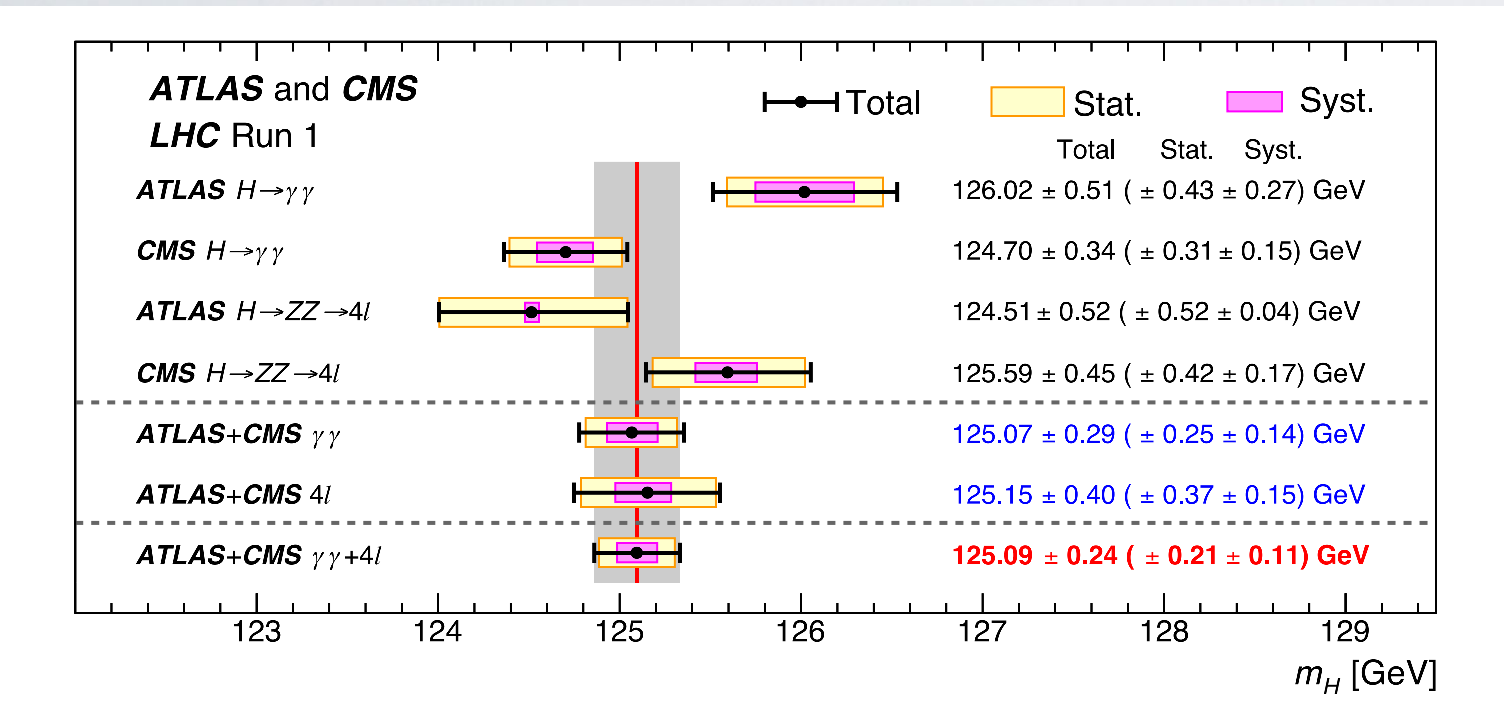
- Minimal Walking Technicolor search at LHC



Effective model for the analysis described in: Eur.Phys.J.Plus 126 (2011) 81

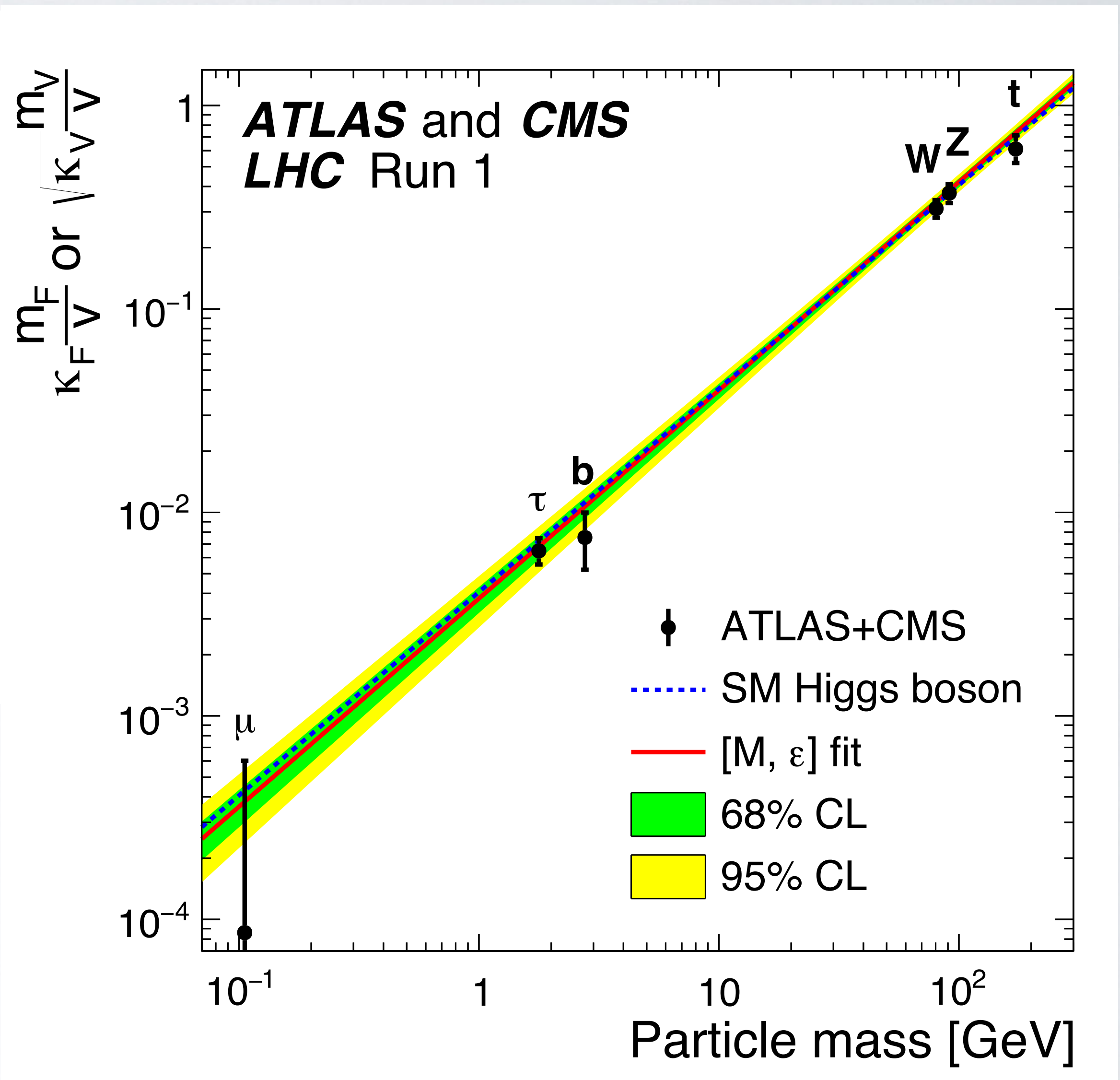
PRD 90, 052005 (2014)

The Standard Model Works



Phys. Rev. Lett. 114, 191803

$$m_H = 125.09 \pm 0.24\,\mathrm{GeV}$$



arXiv:1606.02266

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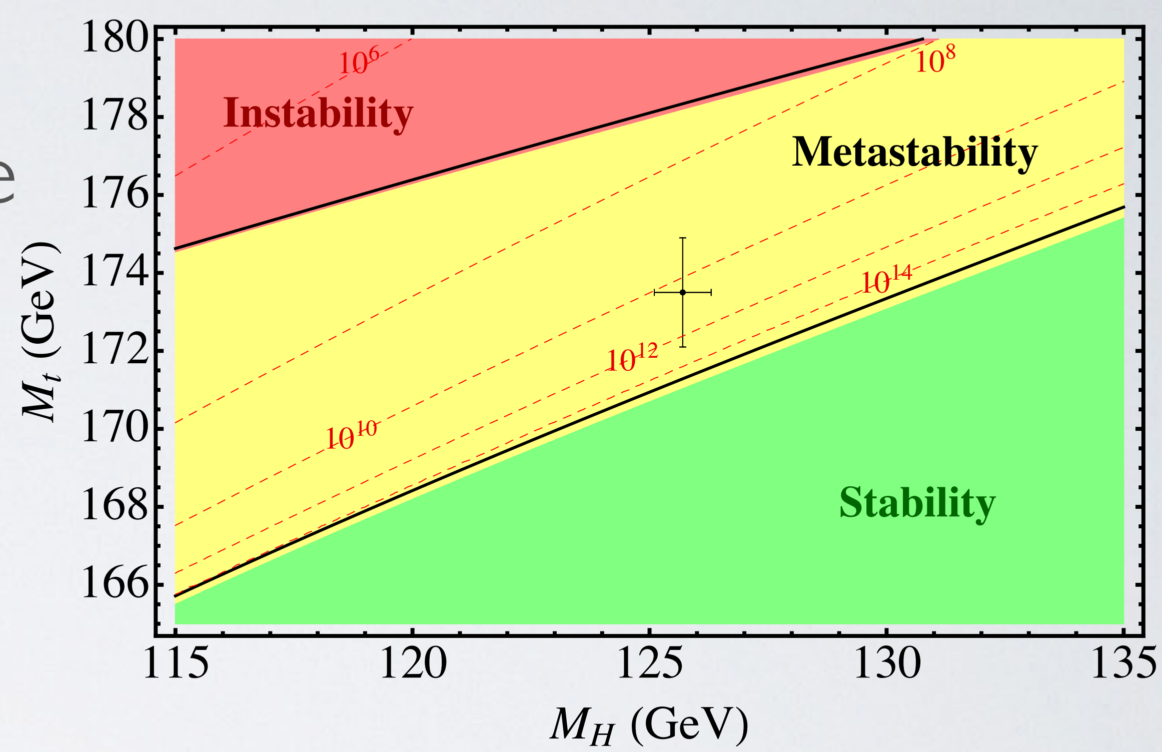
Flaws of the SM

Theoretical

- Effective description / not UV complete
- EW scale stability / naturality
- Flavour problem / undetermined fermion masses & mixing angles
- EW vacuum meta-stability…

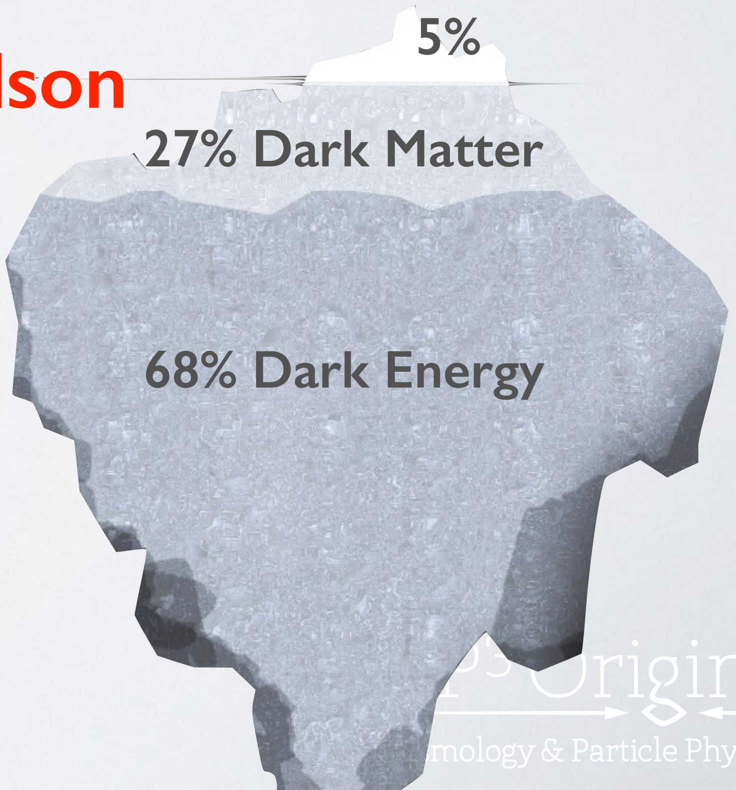
[1307.3536], [1306.3234]



Unexplained phenomena

Plenary Talk Nicholson

- Neutrino masses and their origin/nature
- Dark matter / dark energy **Plenary Talk Rinaldi**
- Matter-antimatter asymmetry
- gravity…



Flaws of the SM

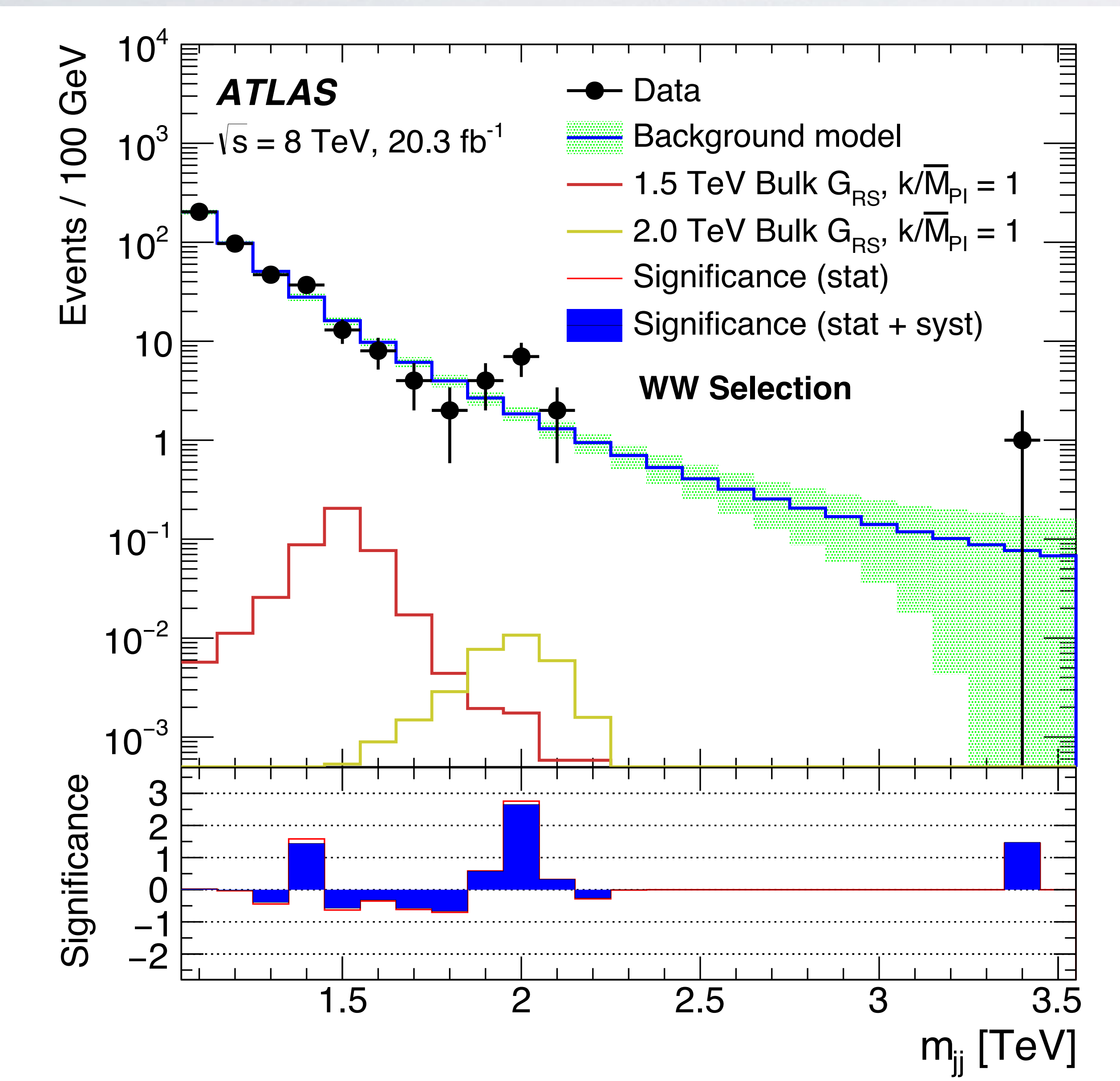
Experimental tensions

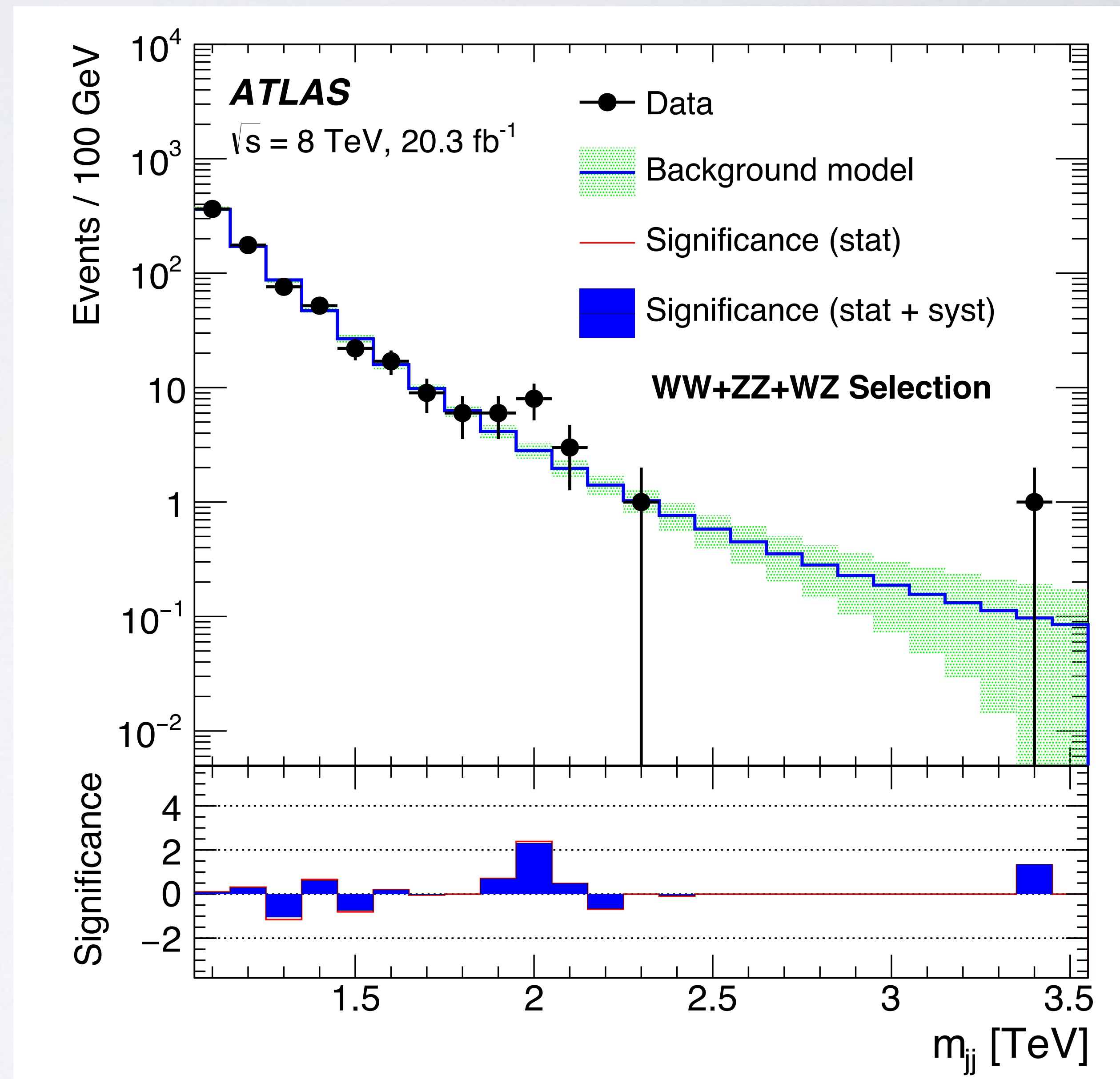
- g-2 **Plenary Talk Wittig**
- proton radius puzzle
- some few sigma deviations in heavy flavour / lepton systems
- some "*bumps*"…

Tantalising hints of new physics?

- heavy vectors ?

arXiv:1506.00962

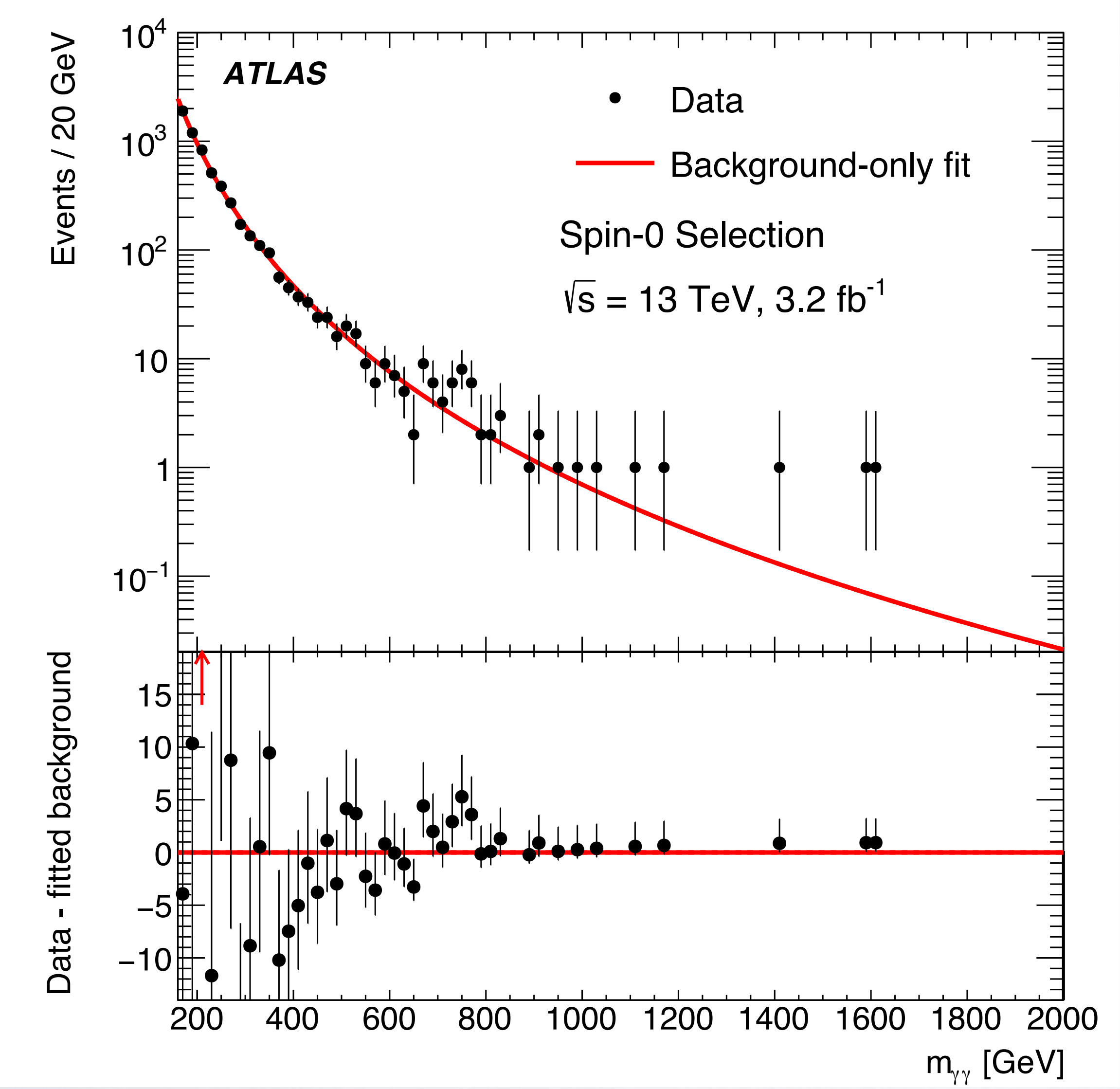


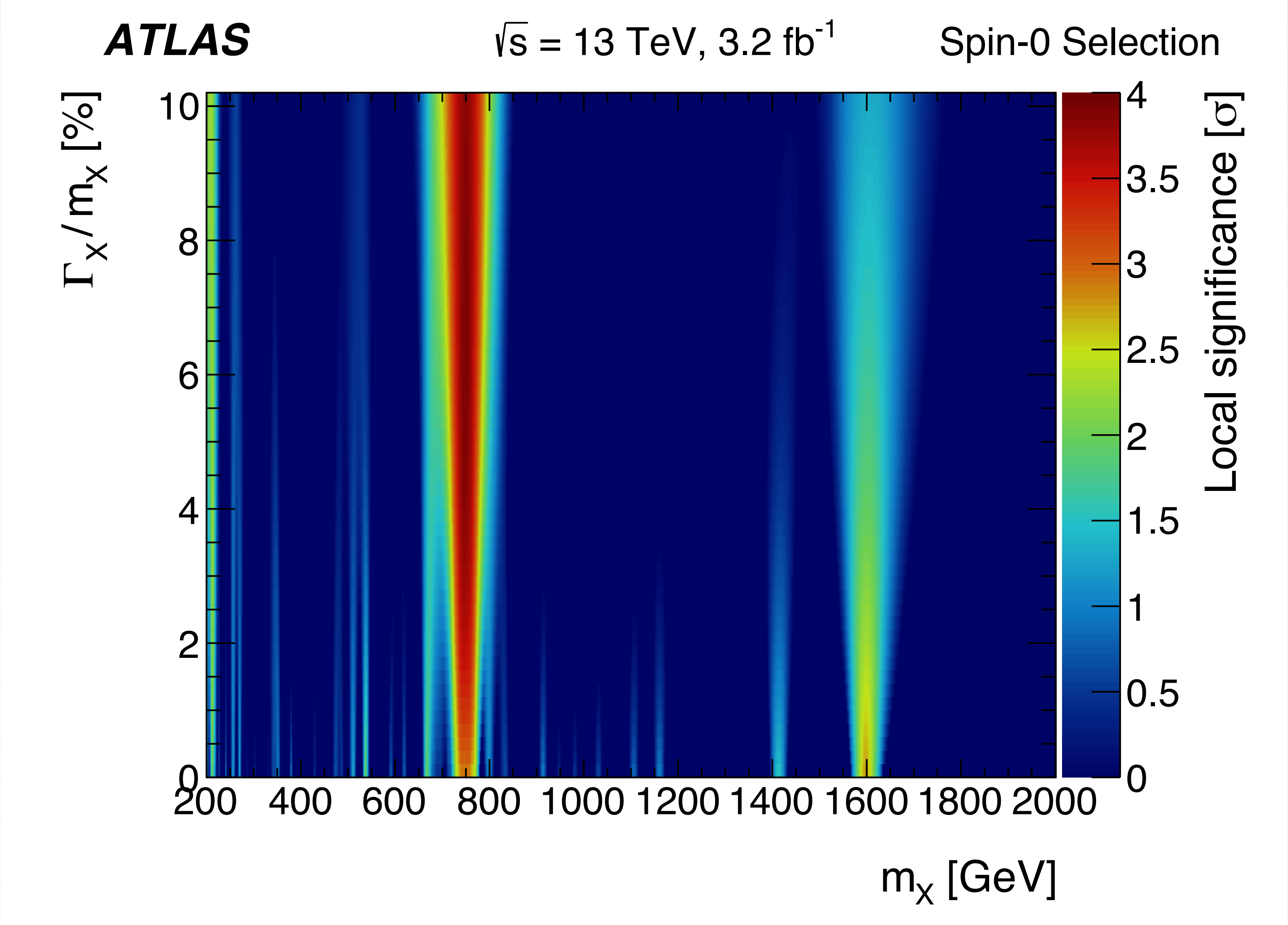


Tantalising hints of new physics?

- new scalars?

arXiv:1606.03833





Few sigmas excesses come and go…
stay tuned for updates soon

Lattice and BSM physics

- Most models for BSM traditionally based on weakly-coupled/calculable extensions. Experimental bounds are now constraining many models to tight corners of parameter space

- Strongly coupled model requiring non-perturbative dynamics are becoming more popular. In particular for the Lattice:
  Walking Technicolor and pNGB Composite Higgs

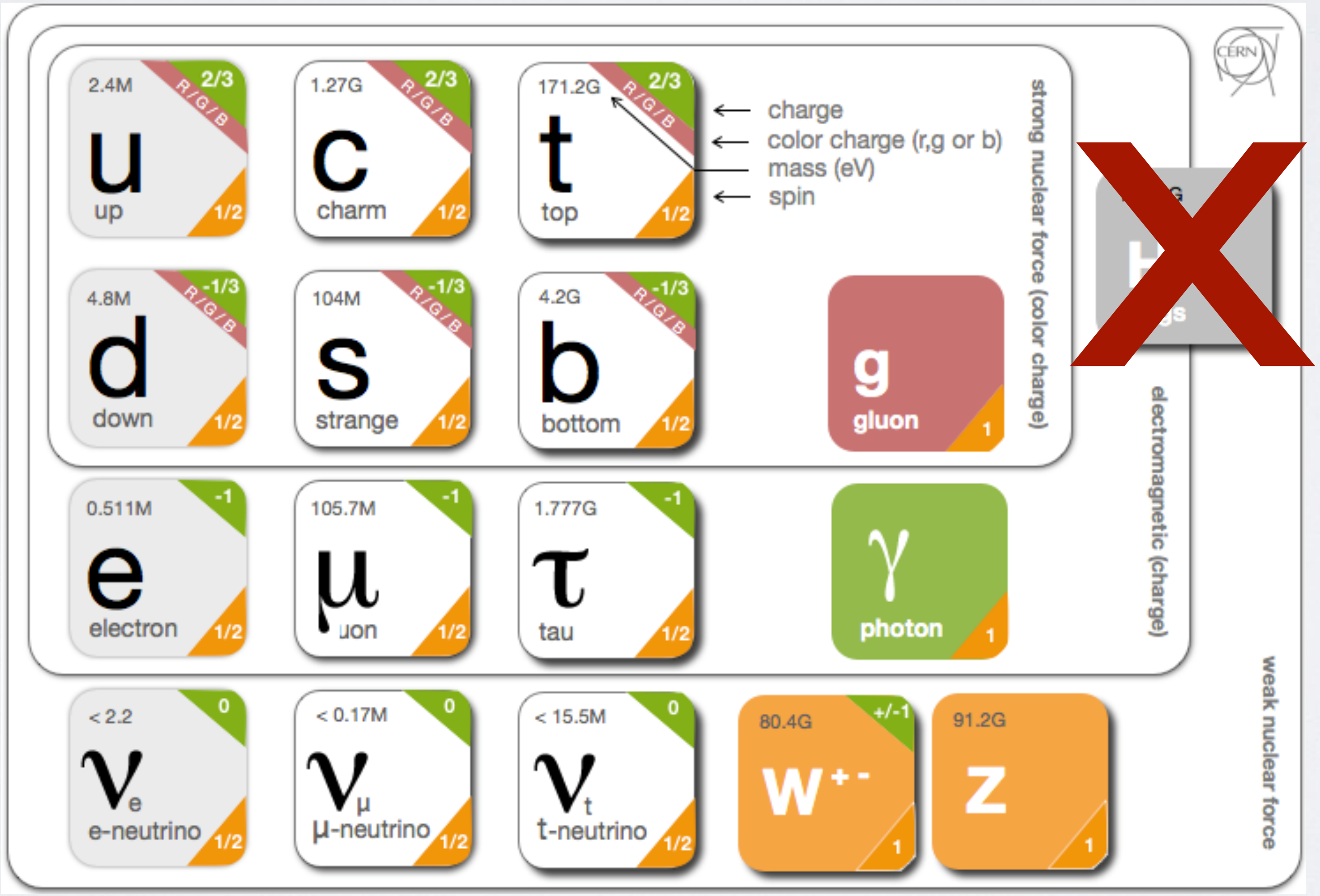
- Phenomenology needs non-perturbative input for strongly coupled models: quantum symmetries, spectrum, low energy constants, …

Lattice can provide input for BSM physics/searches!

Anatomy of Composite Higgs

$$\mathfrak{L}_{SM-Higgs}$$

$$G_{SM} = SU(3) \times SU(2) \times U(1)$$



Anatomy of Composite Higgs

$$\mathfrak{L}_{SM-Higgs} \quad \boxed{+\mathfrak{L}_{SD}}$$

$$\mathfrak{L}_{SD} = -\frac{1}{4}F_{\mu\nu}^2 + i\overline{\psi}\not{D}\psi$$

Gauge group: $G_{TC} = SU(N), SP(N), SO(N), \ldots$

Nf fermions ψ

- "Higgs Impostor": Scalar composite state
- W/Z mass generation
- new resonance spectrum (dark matter?)
- …

Anatomy of Composite Higgs

$\mathfrak{L}_{SM-Higgs}$ $\quad + \mathfrak{L}_{SD}$ $\quad \boxed{+\mathfrak{L}_{int}}$

$\mathfrak{L}_{int}$ contains:

- (effective) interactions to generate SM fermion masses, such as: $\frac{1}{\Lambda^2_{UV}} \bar{q} q O_B$, $\frac{1}{\Lambda^2_{UV}} q O_F$

  among SM fermions q and operators O from SD

- other possible dim=6 or higher operators: $\frac{1}{\Lambda^2_{UV}} \bar{q} q \bar{q} q$ $\Rightarrow$ FCNC

Anatomy of Composite Higgs

$$\mathfrak{L}_{UV}$$

$$\downarrow$$

$$\boxed{\mathfrak{L}_{SM-Higgs} \quad +\mathfrak{L}_{SD} \quad +\mathfrak{L}_{int}}$$

$$\downarrow$$

$\mathfrak{L}_{\widetilde{SM}}$ + **new physics**

UV

$\sim 10^{3\text{-}4}$ TeV

5~10 TeV

1 TeV

IR

Anatomy of Composite Higgs

$$+\mathcal{L}_{SD}$$

$\mathcal{L}_{UV}$

UV

$\sim 10^{3\text{-}4}$ TeV

On the Lattice we only study the SD in isolation

Realistic phenomenology requires taking into account back-reactions from SM and other interactions.

1. Identify quantities which only depend on the new SD
2. Compute (small?) corrections from other sectors

Ruling in or out a realistic model always requires to consider the full setting!

IR

Composite Higgs from SD?

- If EWSB is due to a new of strongly-interacting sector with fermions, one would expect, in general, composite scalar particles
- To not be excluded by experiments, this scalar states should mimic a SM-like Higgs boson: correct mass and couplings
- This could happen if the composite scalar is a light pseudo-Goldstone boson of some broken symmetry:

1	2
scale invariance symmetry (dilaton)	**Flavour symmetry (pNGB)**
Walking Technicolor	**pNGB Higgs**

I. Walking Technicolor

B. Holdom, Phys. Rev. D 24, 1441 (1981); Phys. Lett. B 150, 301 (1985)
K. Yamawaki, M. Bando and K. I. Matumoto, Phys. Rev. Lett. 56, 1335 (1986)
T. Akiba and T. Yanagida, Phys. Lett. B 169, 432 (1986)
T. W. Appelquist, D. Karabali and L. C. R. Wijewardhana, Phys. Rev. Lett. 57, 957 (1986)
T. Appelquist and L. C. R. Wijewardhana, Phys. Rev. D 35, 774 (1987); Phys. Rev. D 36, 568 (1987).

Technicolor

TCfermion condensate breaks EW

Higgs is the lightest scalar excitation of the condensate

Plus

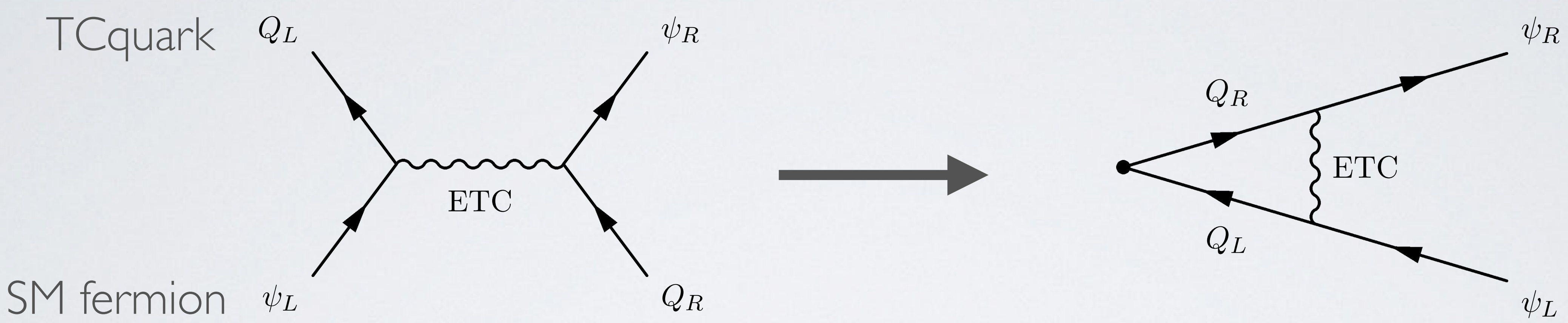
- Natural
- UV complete theories available to explore

Minus

- Fermion masses vs FCNC
- Electroweak precision data
- Light Higgs
- Higgs couplings

SM Fermion Masses

- Extended TC interactions are needed.



- $\mathfrak{L}_{int}$, below Λ_{ETC} : $\quad \alpha_{ab}\dfrac{\bar{Q}T^aQ\bar{\psi}T^b\psi}{\Lambda^2_{ETC}} + \beta_{ab}\dfrac{\bar{Q}T^aQ\bar{Q}T^bQ}{\Lambda^2_{ETC}} + \gamma_{ab}\dfrac{\bar{\psi}T^a\psi\bar{\psi}T^b\psi}{\Lambda^2_{ETC}}$

SM Fermion Masses

$$\alpha_{ab}\frac{\bar{Q}T^aQ\bar{\psi}T^b\psi}{\Lambda^2_{ETC}}+\beta_{ab}\frac{\bar{Q}T^aQ\bar{Q}T^bQ}{\Lambda^2_{ETC}}+\gamma_{ab}\frac{\bar{\psi}T^a\psi\bar{\psi}T^b\psi}{\Lambda^2_{ETC}}$$

FCNC

Bound (GeV^{-2})	Λ_{ETC} $(10^3\ \mathrm{TeV})$
$-9.6 < \Re(C^1_K)\times 10^{13} < 9.6$	1.0
$\lvert C^1_D\rvert < 7.2\times 10^{-13}$	1.5
$\lvert C^1_{B_d}\rvert < 2.3\times 10^{-11}$	0.21
$\lvert C^1_{B_s}\rvert < 1.1\times 10^{-9}$	0.03
$-4.4 < \Im(C^1_K)\times 10^{15} < 2.8$	10

$$\Leftarrow C^1_i \sim \frac{1}{\Lambda^2_{ETC}}$$

$$C^1_K(\bar{s}_L\gamma^\mu d_L)(\bar{s}_L\gamma_\mu d_L)$$
$$C^1_D(\bar{c}_L\gamma^\mu u_L)(\bar{c}_L\gamma_\mu u_L)$$
$$C^1_{B_d}(\bar{b}_L\gamma^\mu d_L)(\bar{b}_L\gamma_\mu d_L)$$
$$C^1_{B_s}(\bar{b}_L\gamma^\mu s_L)(\bar{b}_L\gamma_\mu s_L)$$

Limits from UTFit coll.
See [1005.5727], [1104.1255]

SM Fermion Masses

$$\alpha_{ab}\frac{\bar{Q}T^aQ\bar{\psi}T^b\psi}{\Lambda^2_{ETC}} + \beta_{ab}\frac{\bar{Q}T^aQ\bar{Q}T^bQ}{\Lambda^2_{ETC}} + \gamma_{ab}\frac{\bar{\psi}T^a\psi\bar{\psi}T^b\psi}{\Lambda^2_{ETC}}$$

SM fermion mass

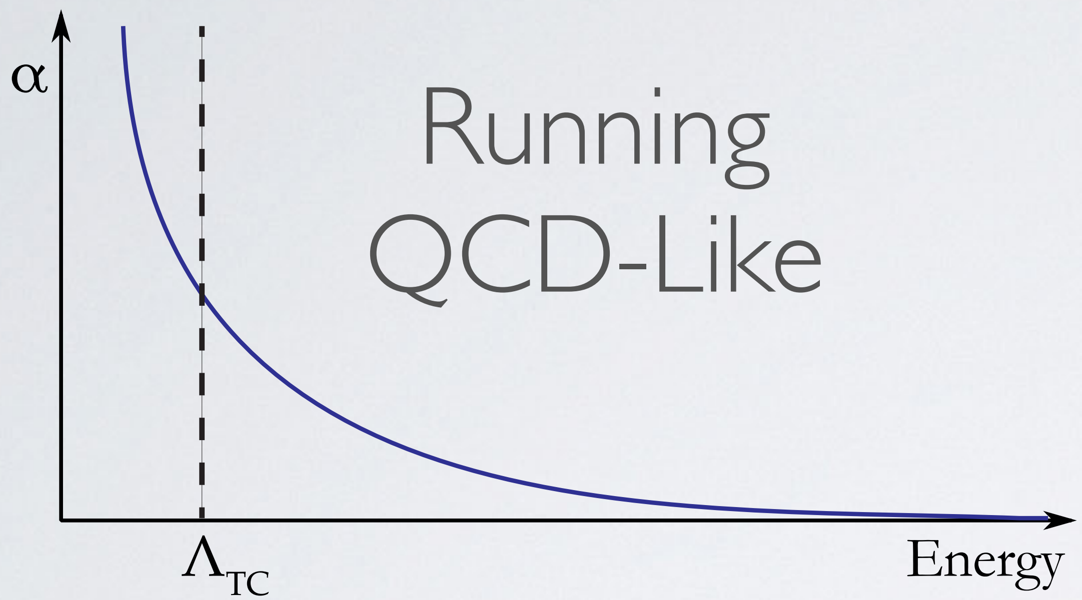
$$m \sim \frac{\langle \overline{Q}Q\rangle_{ETC}}{\Lambda^2_{ETC}} \qquad \langle \overline{Q}Q\rangle_{ETC} = \langle \overline{Q}Q\rangle_{TC}\exp\left[\int_{\Lambda_{TC}}^{\Lambda_{ETC}}\frac{\mathrm{d}\mu}{\mu}\gamma(\alpha(\mu))\right] \qquad \langle \overline{Q}Q\rangle_{TC} \approx \Lambda^3_{TC}$$

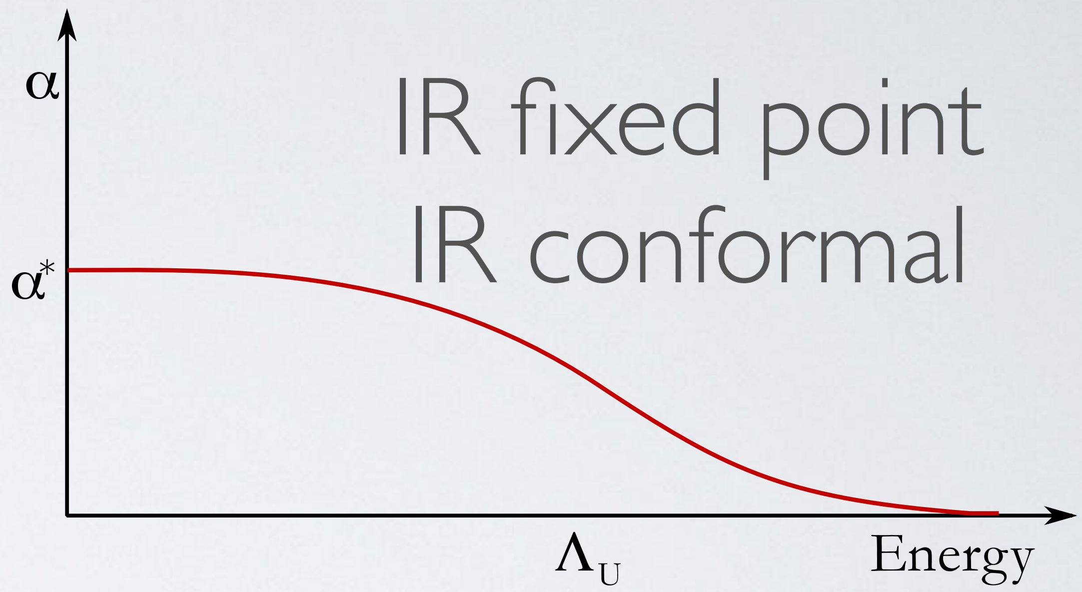
In QCD-like dynamics: $\alpha(\mu) \sim \frac{1}{\ln\mu} \quad \gamma \propto \alpha \quad \Rightarrow \quad \langle \overline{Q}Q\rangle_{ETC} \simeq \langle \overline{Q}Q\rangle_{TC}\left(\ln\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)^k$

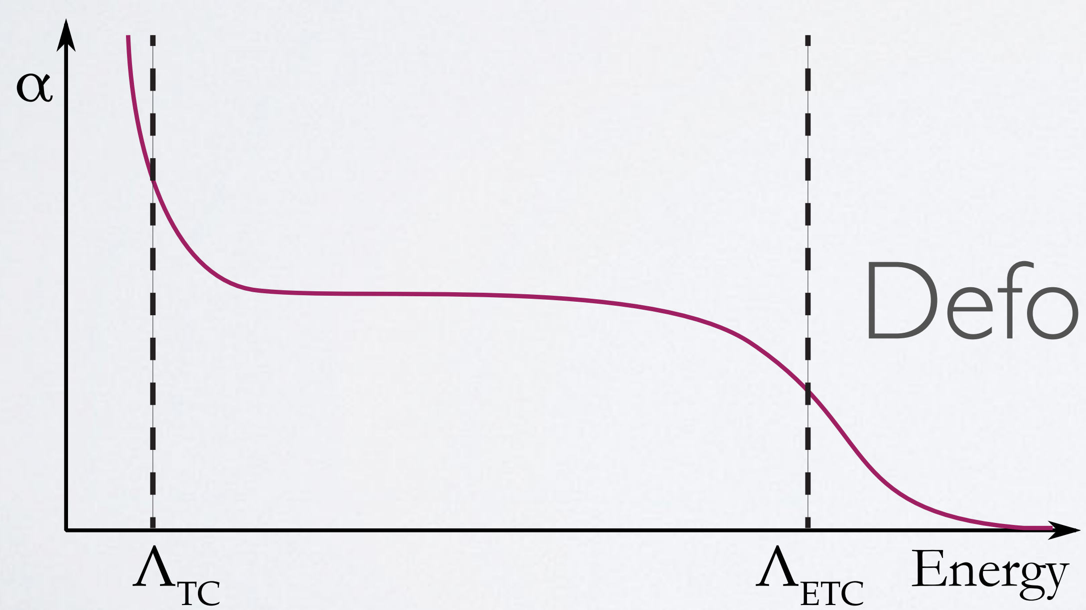
$$\Rightarrow \quad m \sim \Lambda_{TC}\left(\frac{\Lambda_{TC}}{\Lambda_{ETC}}\right)^2 \quad \sim 1\ \mathrm{MeV}$$

Need enhancement mechanism

Walking Technicolor







Walking

Deformed/"Near" IR conformal

SM Fermion Masses - Walking

$$\alpha_{ab}\frac{\bar{Q}T^aQ\bar{\psi}T^b\psi}{\Lambda^2_{ETC}}+\beta_{ab}\frac{\bar{Q}T^aQ\bar{Q}T^bQ}{\Lambda^2_{ETC}}+\gamma_{ab}\frac{\bar{\psi}T^a\psi\bar{\psi}T^b\psi}{\Lambda^2_{ETC}}$$

SM fermion mass

$$m\sim\frac{\langle\overline{Q}Q\rangle_{ETC}}{\Lambda^2_{ETC}}\qquad\langle\overline{Q}Q\rangle_{ETC}=\langle\overline{Q}Q\rangle_{TC}\exp\left[\int_{\Lambda_{TC}}^{\Lambda_{ETC}}\frac{\mathrm{d}\mu}{\mu}\gamma(\alpha(\mu))\right]\qquad\langle\overline{Q}Q\rangle_{TC}\approx\Lambda^3_{TC}$$

Extreme Walking: $\alpha(\mu)\simeq\alpha^*\quad\gamma\simeq\gamma^*\quad\Rightarrow\quad\langle\overline{Q}Q\rangle_{ETC}\simeq\langle\overline{Q}Q\rangle_{TC}\left(\frac{\Lambda_{ETC}}{\Lambda_{TC}}\right)^{\gamma^*}$

$$\Rightarrow\quad m\sim\Lambda_{TC}\left(\frac{\Lambda_{TC}}{\Lambda_{ETC}}\right)^{2-\gamma^*}\sim 1\ \mathrm{GeV}$$

Need large $\gamma^*\sim 1$

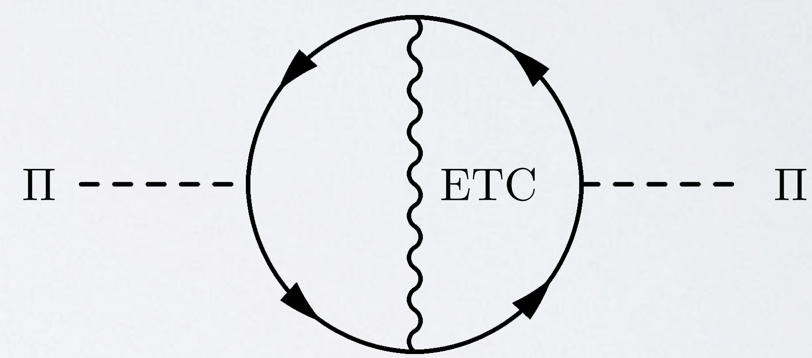
4-Fermion interactions

$$\alpha_{ab}\frac{\bar{Q}T^aQ\bar{\psi}T^b\psi}{\Lambda^2_{ETC}}+\beta_{ab}\frac{\bar{Q}T^aQ\bar{Q}T^bQ}{\Lambda^2_{ETC}}+\gamma_{ab}\frac{\bar{\psi}T^a\psi\bar{\psi}T^b\psi}{\Lambda^2_{ETC}}$$

4-F interactions

Modify SD:

- Generate mass for TCpions

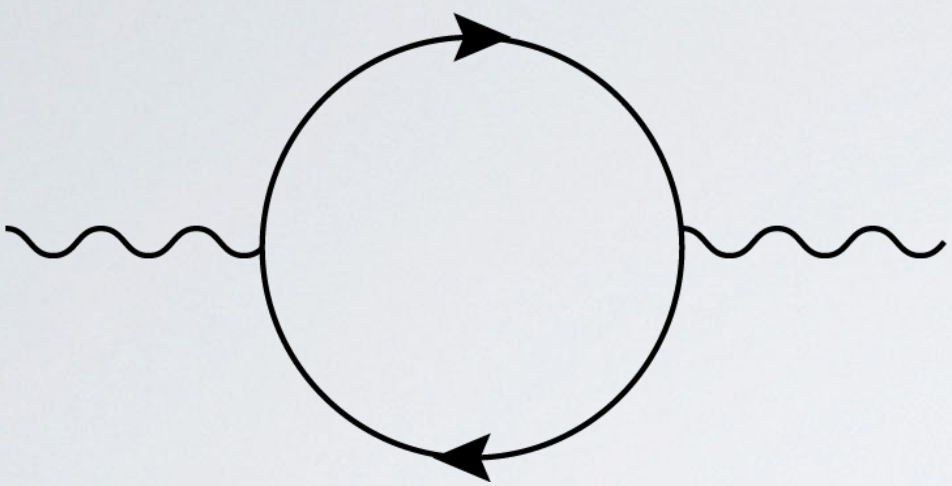


- If TC conformal:
  - change anomalous dimensions?
  - drive away from IR fixed point / generate Walking

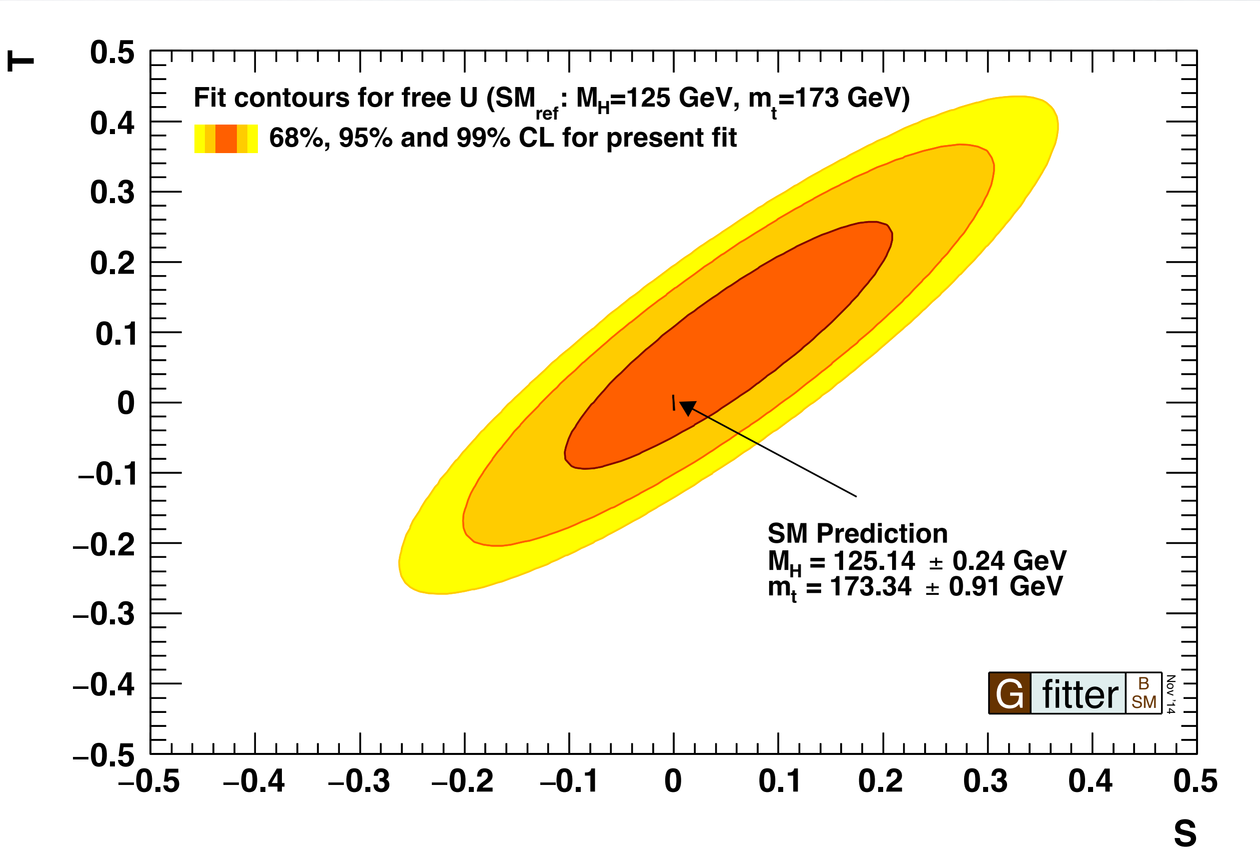
Talk Rantaharju Thu
see also: Talk Schmidt Wed

Fukano, Sannino, *"Ideal Walking"*, arXiv:1005.3340

S-parameter



$$S_{\text{naive}} = N_D \frac{D_R}{6\pi}$$

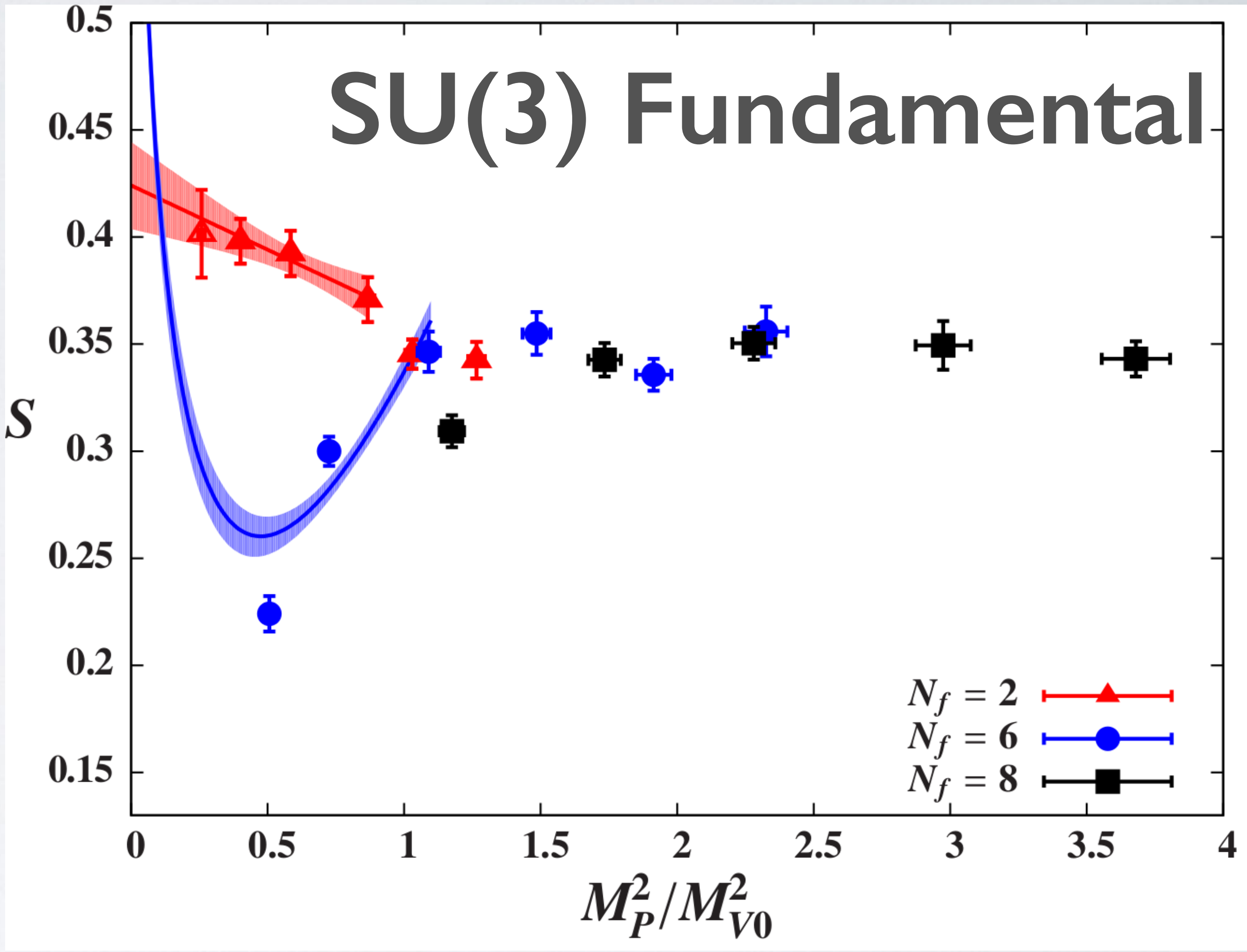


Models with small number N_D of gauged fermions favored

Some indications of reduced S-parameter near the conformal window

S-parameter

LSD collaboration,
Phys.Rev. D90 (2014) no.11, 114502
Phys.Rev.Lett. 106 (2011) 231601



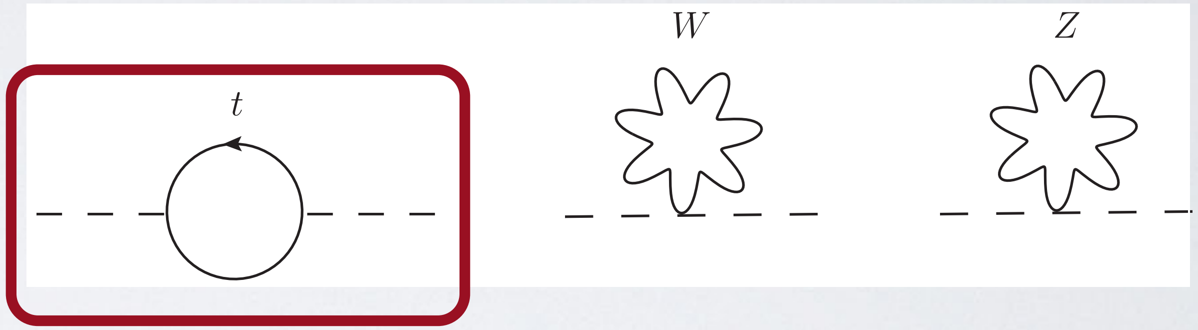
Difficult chiral extrapolation when approaching the CW

More investigations of this mechanism needed

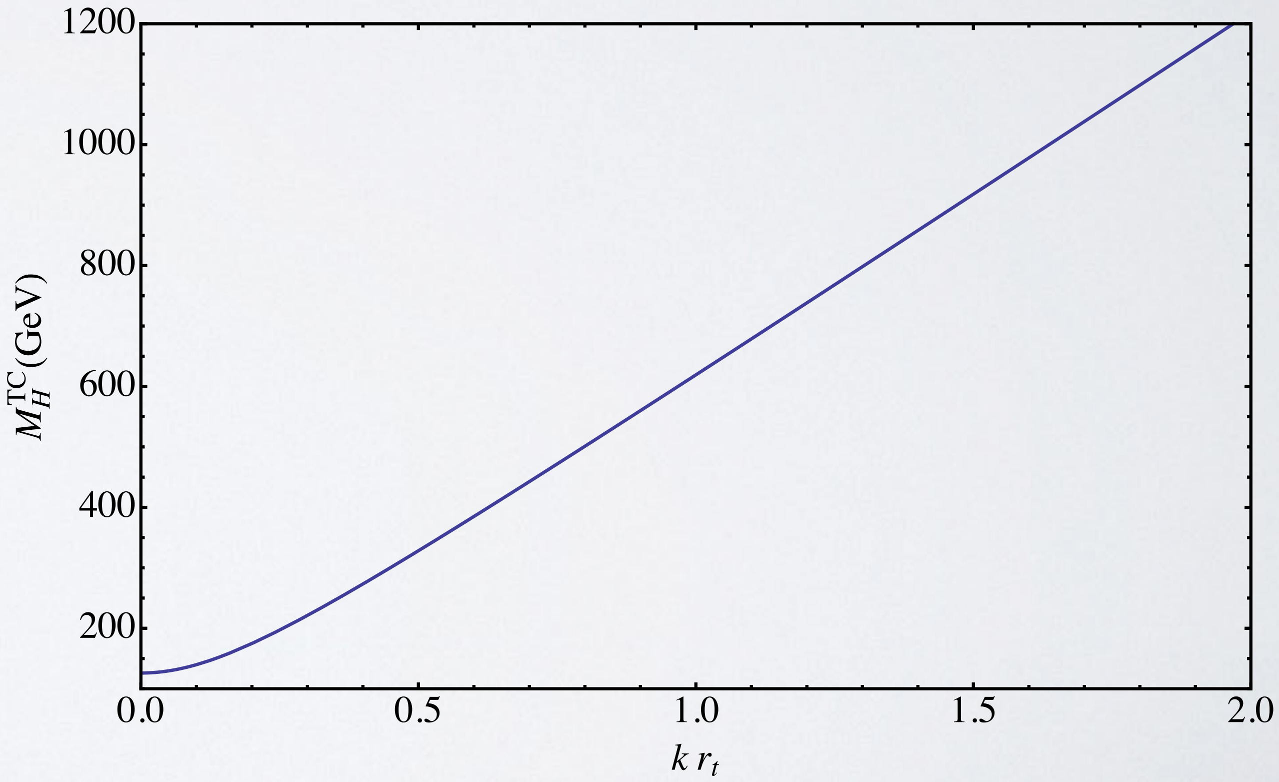
Light TC Higgs

SM radiative corrections shift the TC Higgs mass

R. Foadi, M. Frandsen, F. Sannino, Phys.Rev. D 87, 095001



$$(M_H^{\mathrm{TC}})^2 \simeq M_H^2 + 12\ \kappa^2 r_t^2 m_t^2$$



Narrow due to kinematics, similar to $f_0(980)$ in QCD

Dilaton Higgs

- Near the conformal window, as conformal invariance of the theory is approximatively restored, one can speculate the existence of an associated pNGB, **the dilaton**

Consider the theory: $\mathscr{L} = \sum_i g_i(\mu)\mathscr{O}_i(x)$, with $[\mathscr{O}_i] = d_i$

Introduce a "conformal compensator": $\chi(x) \to e^{\lambda}\chi(e^{\lambda}x)$ (under scale tranf.)

The Lagrangian is scale invariant if we replace: $g_i(\mu) \to g_i\left(\mu\frac{\chi}{f}\right)\left(\frac{\chi}{f}\right)^{4-d_i}$

where $f = \langle\chi\rangle$ is the scale of conformal symmetry breaking.

Introducing $\bar{\chi}(x) = \chi(x) - f$ and expanding around $f = \langle\chi\rangle$, we have:

$$\mathscr{L}_\chi = \frac{1}{2}\partial_\mu\bar{\chi}\partial^\mu\bar{\chi} + \frac{\bar{\chi}}{f}T^\mu{}_\mu + \cdots$$

See e.g. Goldberger, Grinstein, Skiba [0708.1463]

CP3 Origins
Cosmology & Particle Physics

Dilaton Higgs

Replacing the SM Higgs with the dilaton in the same way:

$$\mathcal{L}_{\chi,SM} = \left(\frac{2\bar{\chi}}{f} + \frac{\bar{\chi}^2}{f^2}\right)\left[m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right] + \frac{\bar{\chi}}{f}\sum_\psi m_\psi \bar{\psi}\psi$$

(at tree level) which is identical in form to the couplings of the SM Higgs.

Couplings to gluons and the photon are induced in the same way as for the SM Higgs and are also similar if $f \sim v$ (EW vev).

For Walking TC $f \sim v$ is expected since the same TCquark condensate breaks EW and conformal invariance.

$\Longrightarrow$ Similar couplings to the SM Higgs,
difficult to distinguish at the experiments! Bellazzini et al. [1209.3299]

See e.g. Goldberger, Grinstein, Skiba [0708.1463]

CP3 Origins
Cosmology & Particle Physics

2. pNGB Higgs

D. B. Kaplan and H. Georgi, Phys. Lett. B 136, 183 (1984)
D. B. Kaplan, H. Georgi and S. Dimopoulos, Phys. Lett. B 136, 187 (1984)
T. Banks, Nucl. Phys. B 243, 125 (1984)
H. Georgi, D. B. Kaplan and P. Galison, Phys. Lett. B 143, 152 (1984).
H. Georgi and D. B. Kaplan, Phys. Lett. B 145, 216 (1984).
M. J. Dugan, H. Georgi and D. B. Kaplan, Nucl. Phys. B 254, 299 (1985)

Composite pNGB Higgs

Higgs is a pseudo Goldstone boson
EW symmetry broken via radiative corrections

Plus

- Higgs is light
- Gauge boson couplings

Minus

- Higgs mass
- EW vacuum alignment
- Fermion masses

pNGB Higgs

Consider a SD with global symmetry breaking pattern

$$G_F \to H_F \supseteq SU(2)_L \times SU(2)_R \times U(1)_X$$

which preserves custodial symmetry. To give the correct hypercharge to all SM fields we need a NGB with

$$\text{Higgs} = (2,2)_0 \in G_F / H_F$$

For EW breaking the minimal cosets are:

4 $(\psi_\alpha, \tilde{\psi}_\alpha)$ Complex	$SU(4) \times SU(4)'/SU(4)_D$	SU(3) Nf=4 Fund Dirac
4 ψ_α Pseudoreal	$SU(4)/Sp(4)$	SU(2) Nf=2 Fund Dirac
5 ψ_α Real	$SU(5)/SO(5)$	SU(4) Nf=2.5 2-A Dirac

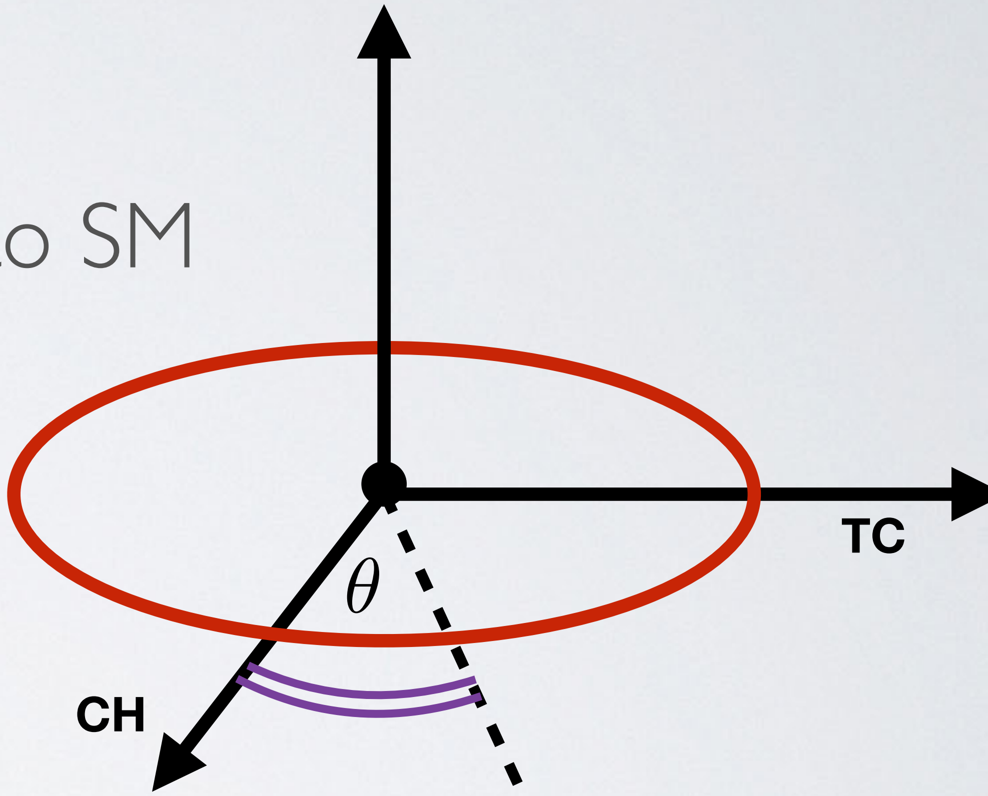
pNGB Higgs

- Loop corrections of EW gauge bosons will generate a potential for the Higgs but will not break EW symmetry (Higgs remains massless)

- However in any realistic model, couplings to SM fermions will be present

$$\frac{1}{\Lambda_{UV}^2}\bar{q}qO_B \qquad \frac{1}{\Lambda_{UV}^2}qO_F$$

ETC like Linear coupling



- in particular top quark corrections will offset the minimum and generically tend to align the vacuum in the EW symmetry breaking (TC) direction

pNGB Higgs couplings

- Another generic feature of pNGB Higgs models is that couplings to the EW gauge bosons and SM fermions mimic those of the SM Higgs for small θ

$$\frac{g_{WWh_1}}{g_{WWh}^{SM}} = 1 + C\theta + \mathcal{O}(\theta^2)$$

$$\frac{g_{tth_1}}{g_{tth}^{SM}} = 1 + D\theta + \mathcal{O}(\theta^2)$$

Partial Compositeness

Fermion masses are generated via linear couplings

$$\frac{1}{\Lambda_{UV}^2} q O_F \longrightarrow m_q \sim v \left(\frac{\Lambda}{\Lambda_{UV}} \right)^{2(\dim[O_F]-5/2)}$$

If dim[O_F]≤2.5 then large SM fermion masses can be generated.

E.g. if O_F is a baryon, then we should have γ_B≥2 (unitarity bound 3)

See also Pica, Sannino [1604.02572]

Other possibilities exist: e.g. if the new strong sector feature elementary TCcoloured scalars then O_F can be a composite ΨS which have engineering dimension 5/2, so that no anomalous dimension is needed.

Realistic models which can generate all SM masses exist.

See Sannino, Strumia, Tesi, Vigiani [1607.01659]

Partial Compositeness Models

- SU(3) with Nf>6 Fund Dirac fermions [Vecchi 1506.00623]
- For SD models with only fermions and 2 representations [Ferretti 1604.06467]

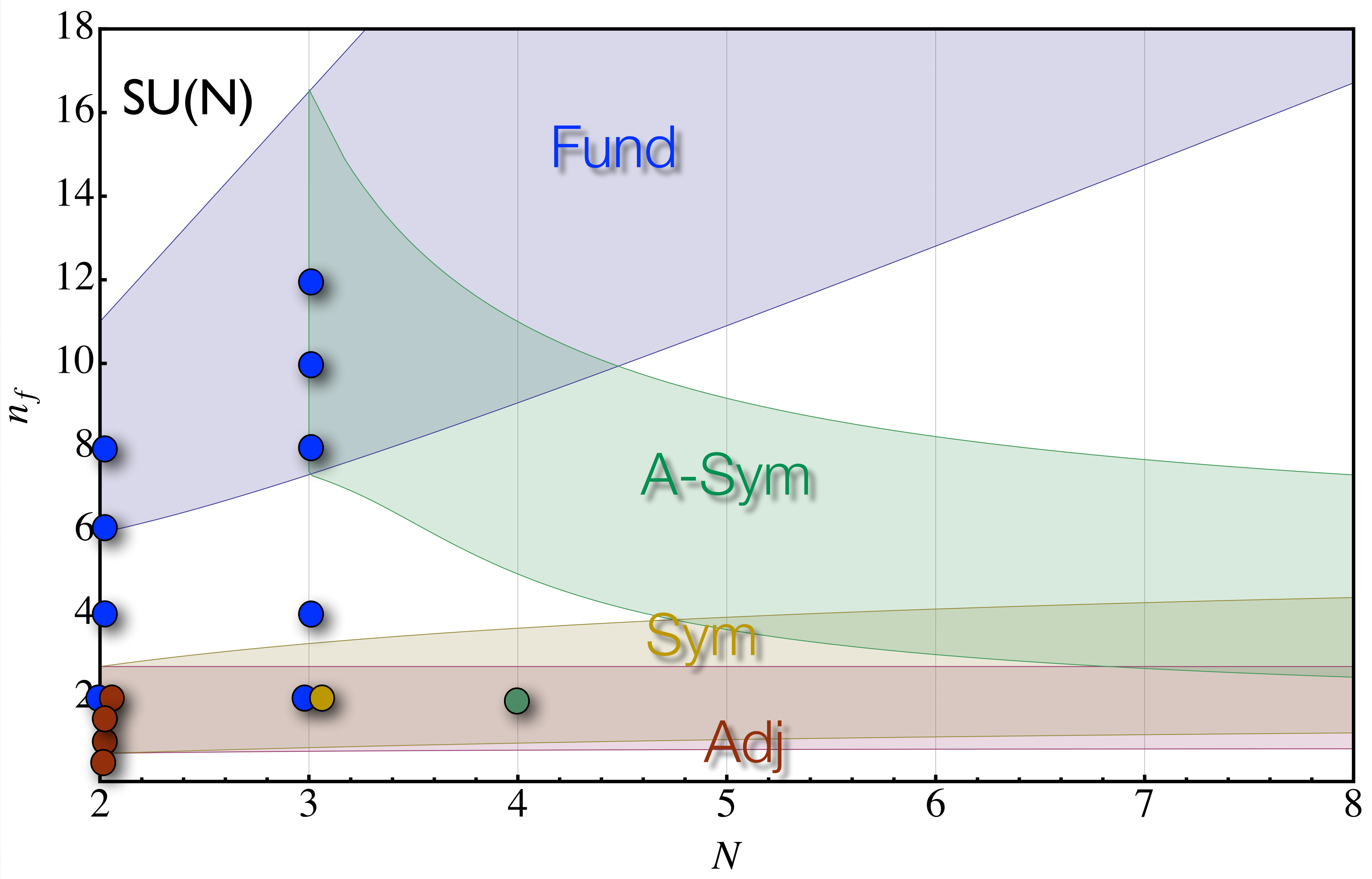
$G_{\rm HC}$	ψ	χ	G/H
$SO(7,9)$	$5\times\mathbf{F}$	$6\times\mathbf{Spin}$	$\frac{SU(5)}{SO(5)}\frac{SU(6)}{SO(6)}U(1)$
$SO(7,9)$	$5\times\mathbf{Spin}$	$6\times\mathbf{F}$	
$Sp(4)$	$5\times\mathbf{A}_2$	$6\times\mathbf{F}$	$\frac{SU(5)}{SO(5)}\frac{SU(6)}{Sp(6)}U(1)$
$SU(4)$	$5\times\mathbf{A}_2$	$3\times(\mathbf{F},\overline{\mathbf{F}})$	$\frac{SU(5)}{SO(5)}\frac{SU(3)\times SU(3)'}{SU(3)_D}U(1)$
$SO(10)$	$5\times\mathbf{F}$	$3\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	
$Sp(4)$	$4\times\mathbf{F}$	$6\times\mathbf{A}_2$	$\frac{SU(4)}{Sp(4)}\frac{SU(6)}{SO(6)}U(1)$
$SO(11)$	$4\times\mathbf{Spin}$	$6\times\mathbf{F}$	
$SO(10)$	$4\times(\mathbf{Spin},\overline{\mathbf{Spin}})$	$6\times\mathbf{F}$	$\frac{SU(4)\times SU(4)'}{SU(4)_D}\frac{SU(6)}{SO(6)}U(1)$
$SU(4)$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$6\times\mathbf{A}_2$	
$SU(5,6)$	$4\times(\mathbf{F},\overline{\mathbf{F}})$	$3\times(\mathbf{A}_2,\overline{\mathbf{A}}_2)$	$\frac{SU(4)\times SU(4)'}{SU(4)_D}\frac{SU(3)\times SU(3)'}{SU(3)_D}U(1)$

See also talk by Del Debbio [Thu]

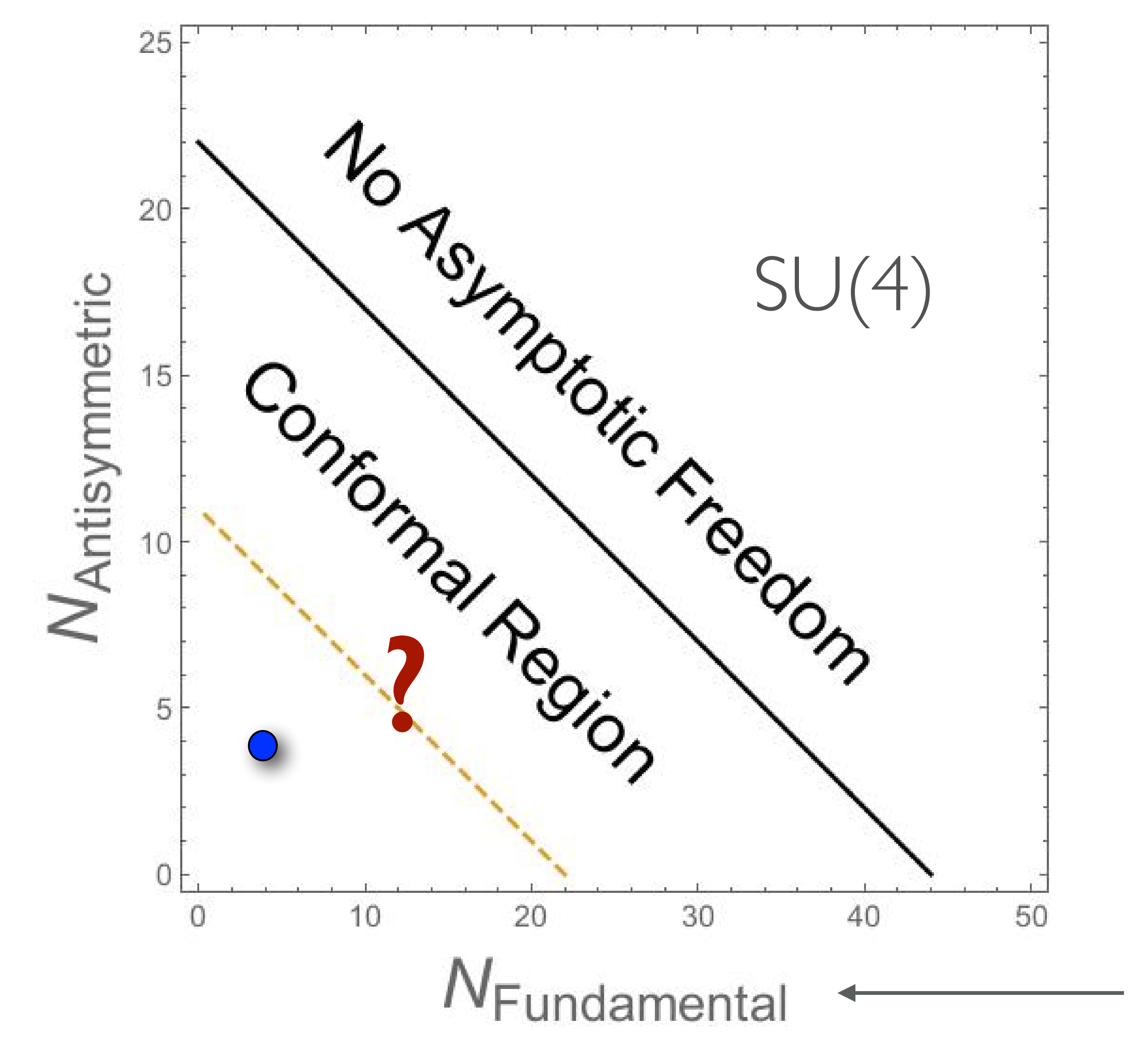
Impact of Lattice

- Location of the boundary of the Conformal Window
- Can we exhibit an IR conformal model with $\gamma^* \sim 1$?
  - or one with large anomalous dimensions for baryons ~2?
- Find SD models with light scalars / "Higgs impostors"
  - how the spectrum of SD changes when approaching the CW?
  - is the light scalar a dilaton?
- Couplings of the composite Higgs
- Spectrum, S-parameter, other LEC of viable models

SU(N) phase diagram @ Lattice 2016



Multiple Representations @ Lattice 2016



Weyl fermions

For an estimate of the conformal window, see also:
Ryttov, Sannino, Int.J.Mod.Phys. A25 (2010) 4603-4621 [0906.0307]

Conformal Window / Large γ^*

new results at Lattice 2016

Claudio Pica

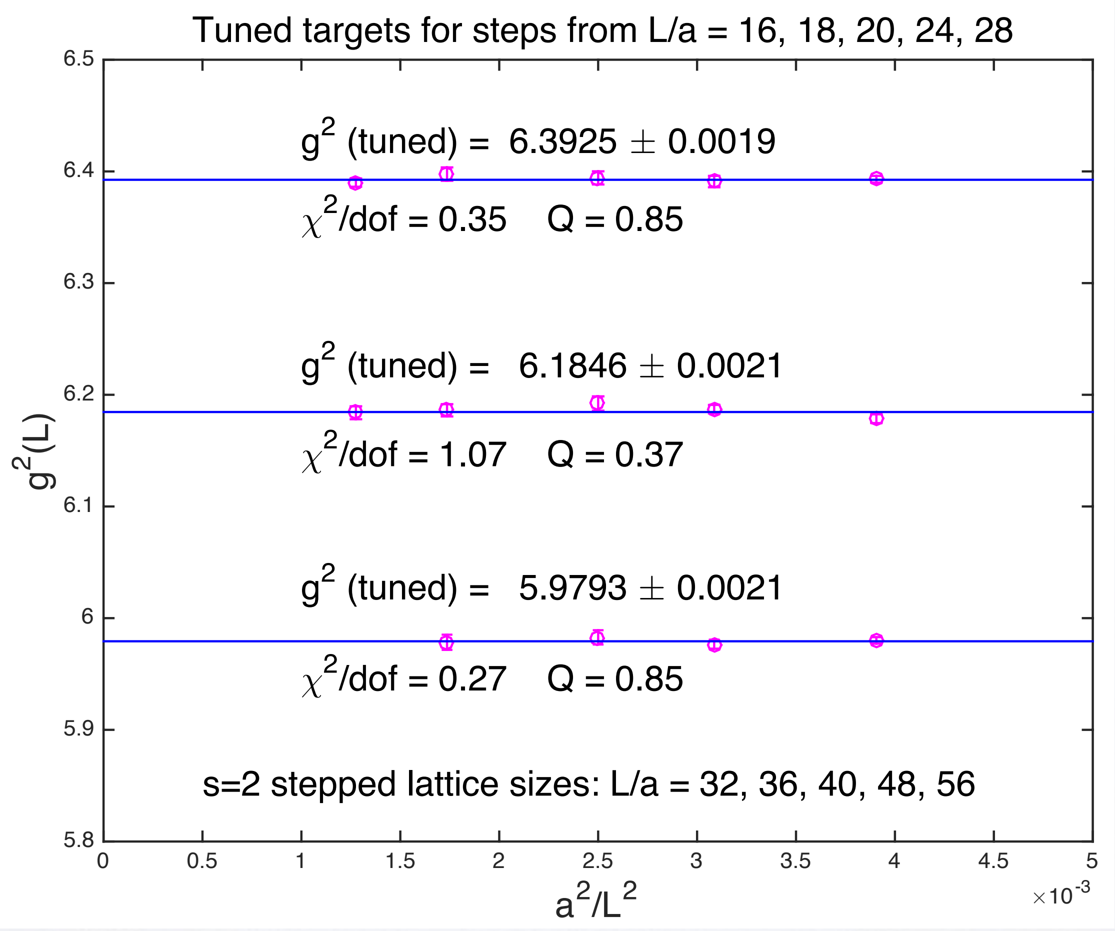
CP3 Origins
Cosmology & Particle Physics

SU(3) N_f=12

- Long history of previous studies
  (see review talks at past Lattice conferences)

Talk by Nogradi [Tue]

- New high precision study of GF coupling with controlled systematics
- Use of significantly larger volumes respect to previous state-of-the-art.



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SU(3) N_f=12

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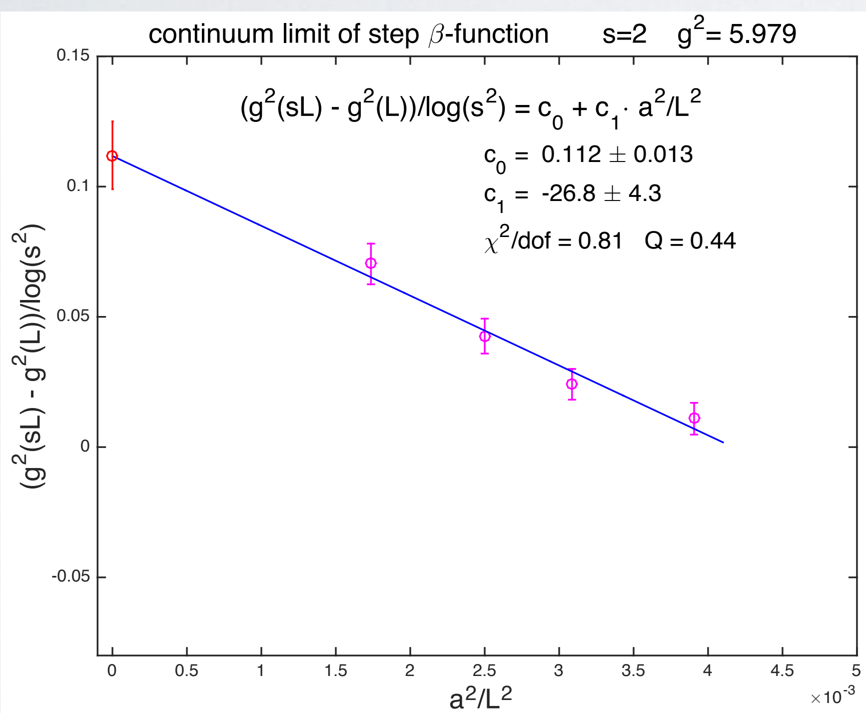
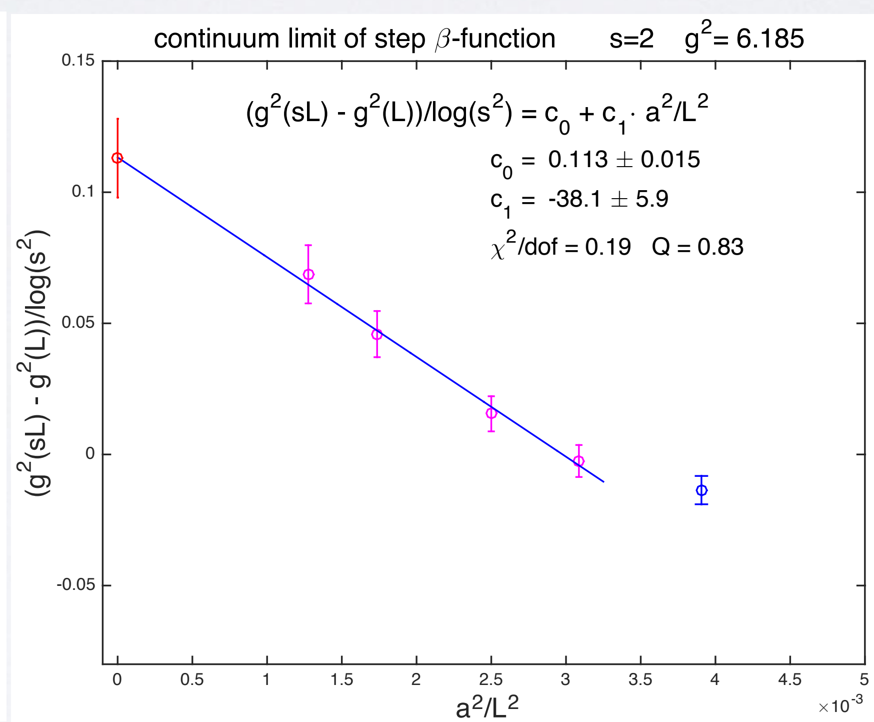
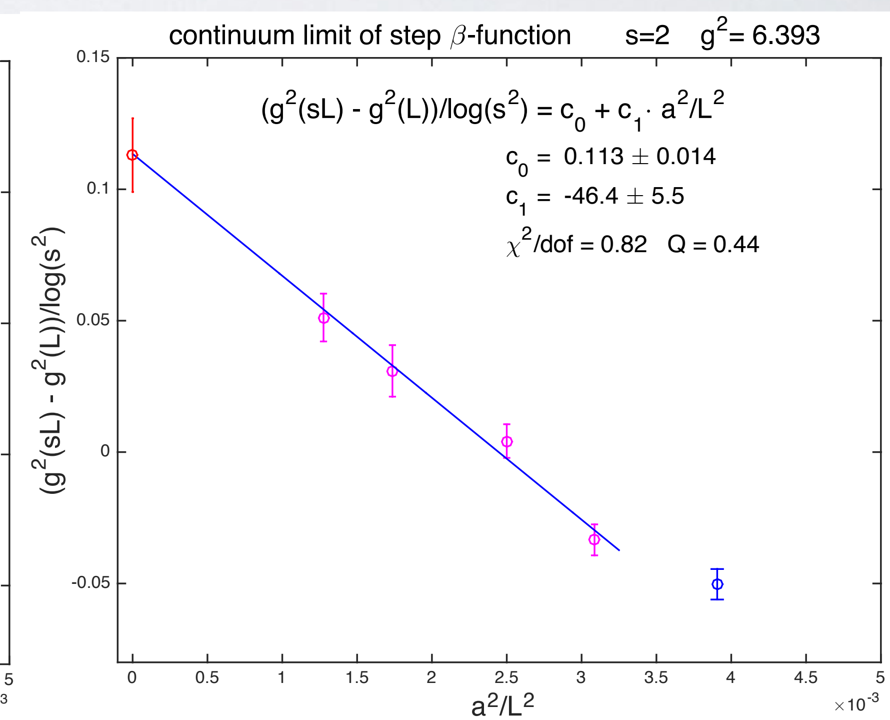




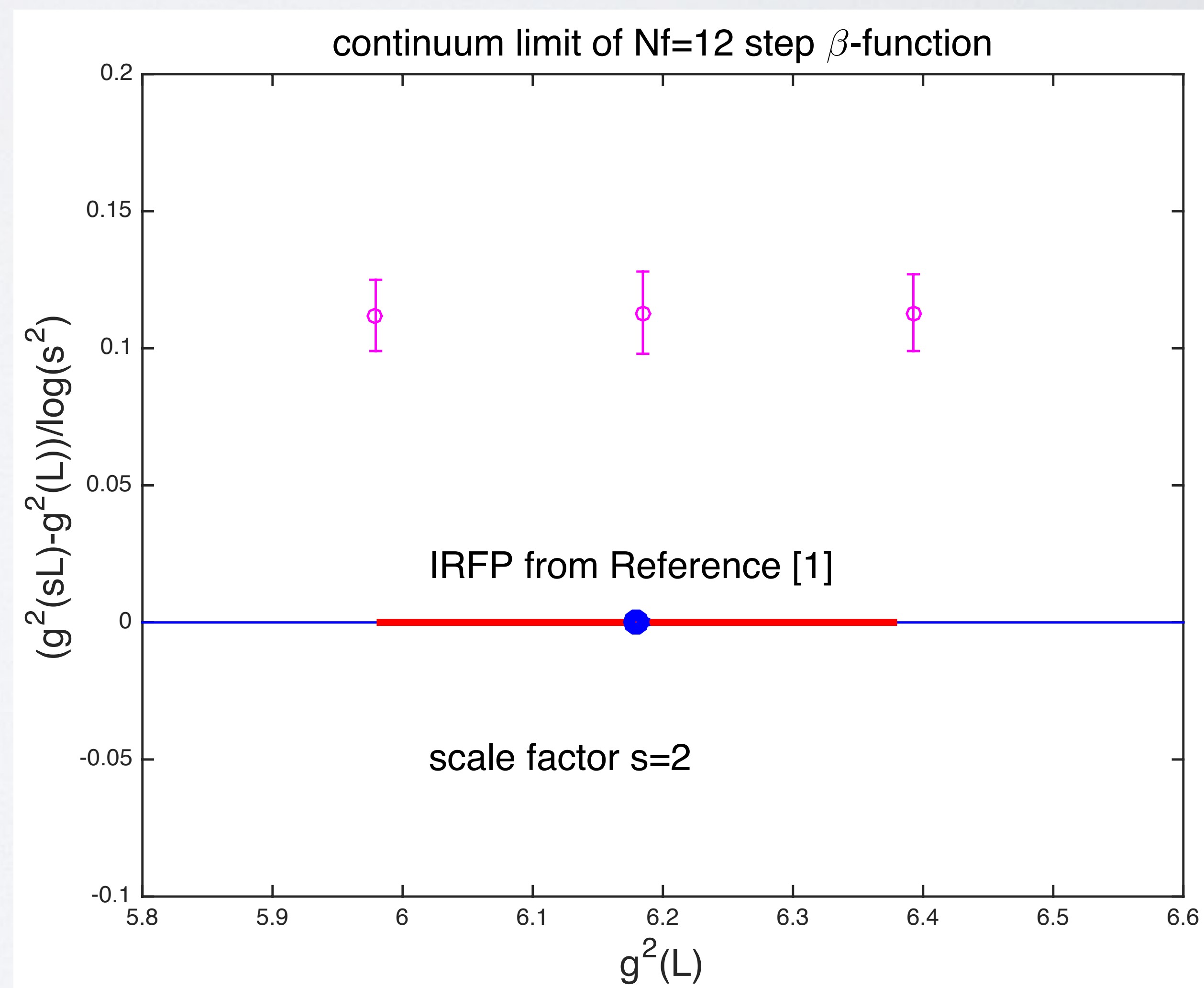


SU(3) N_f=12

- Long history of previous studies (see review talks at past Lattice conferences)

Talk by Nogradi [Tue]

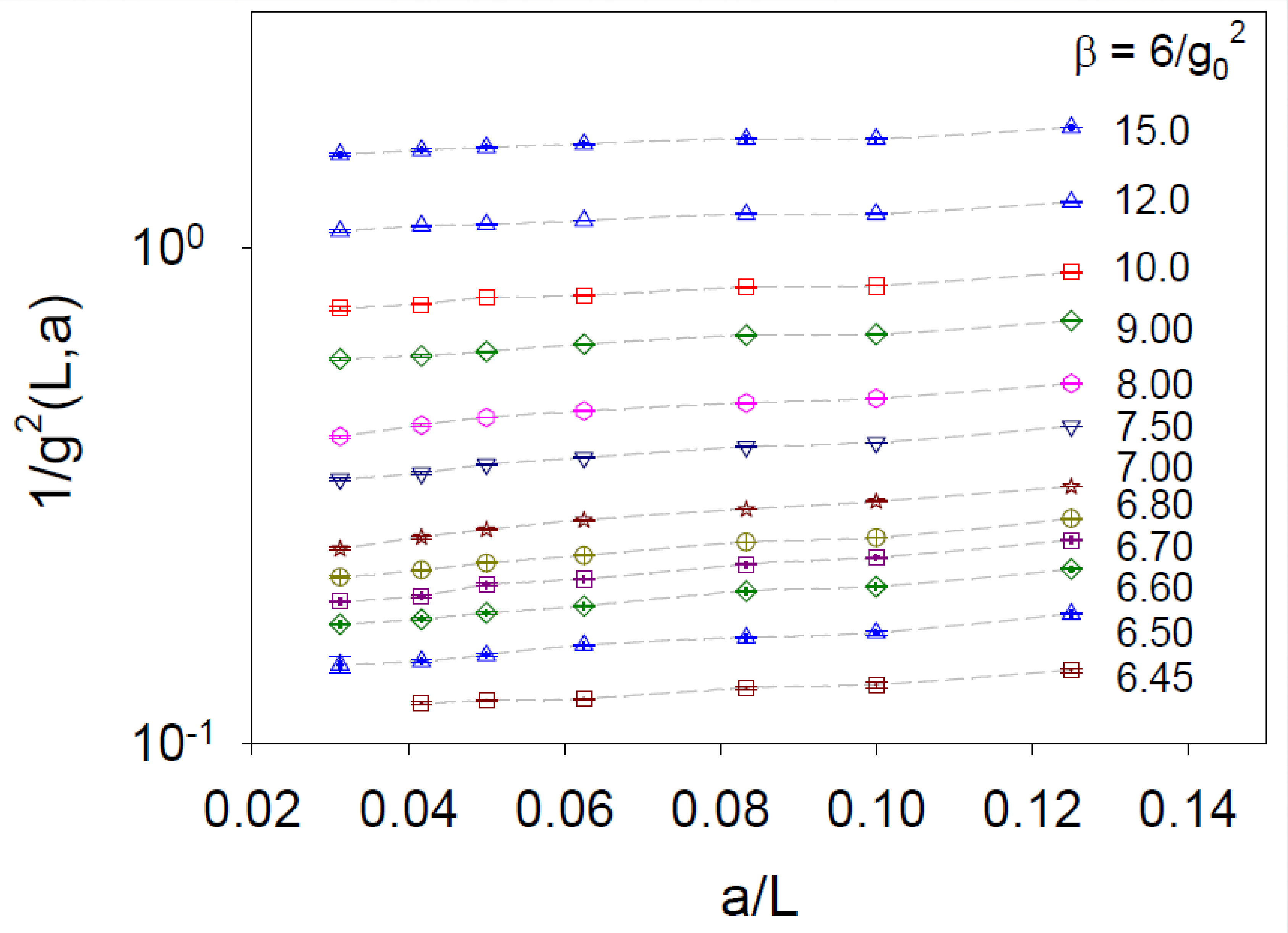
- New high precision study of GF coupling with controlled systematics
- Use of significantly larger volumes respect to previous state-of-the-art.
- Exclude fixed-point around 1-σ of previous best estimate of location
- Fixed point at higher g^2 ??



Use of Large Volumes is mandatory close to IR point!

SU(3) Fund N_f=10

- Updates [arXiv:1603.08854] with larger 32 volume **Talk by Chiu [Tue]**
- Finite volume GF coupling with Optimal Domain-Wall fermion action



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- Updates [arXiv:1603.08854] with larger 32 volume **Talk by Chiu [Tue]**
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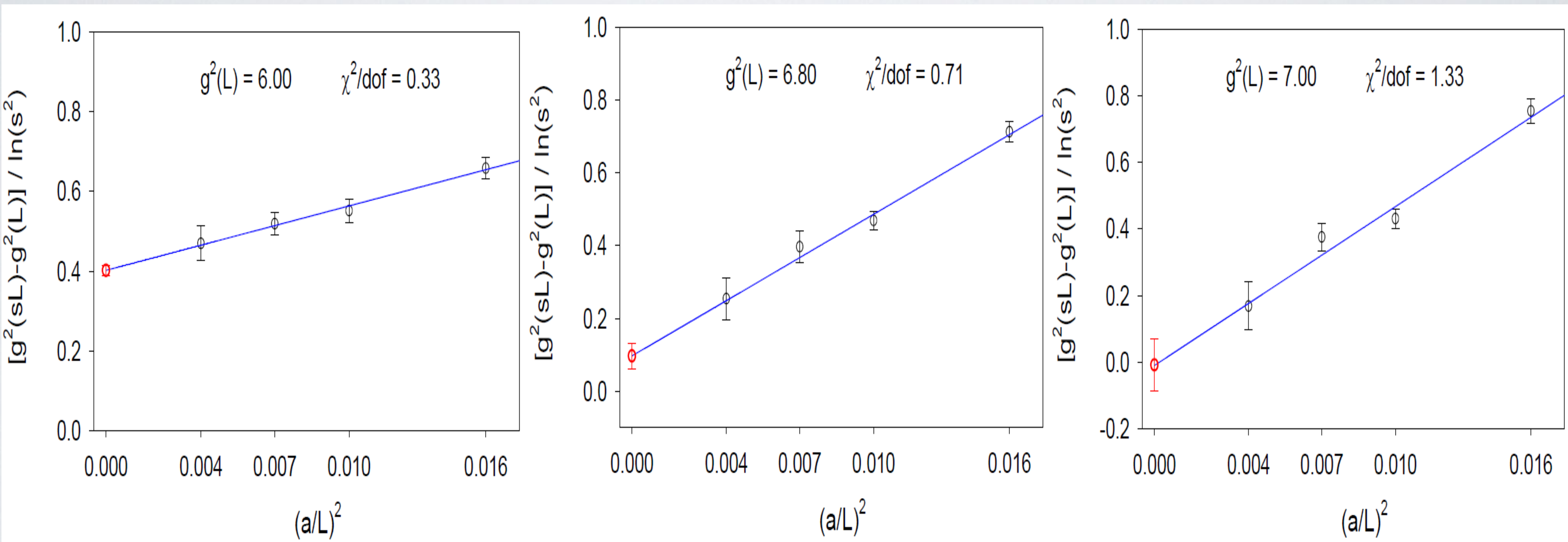

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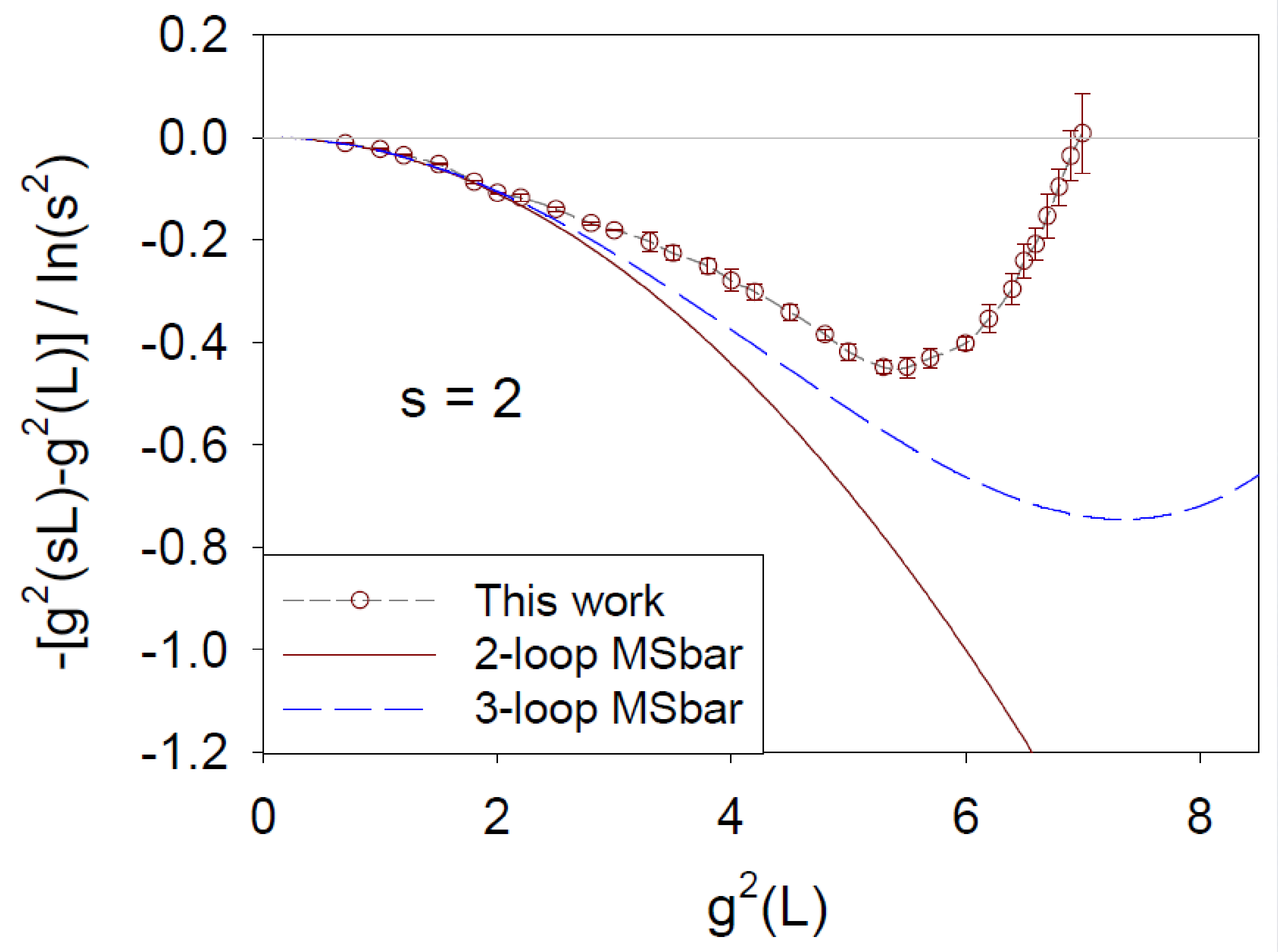
SU(3) N_f=10

- Updates [arXiv:1603.08854] with larger 32 volume **Talk by Chiu [Tue]**
- Finite volume GF coupling with Optimal Domain-Wall fermion action

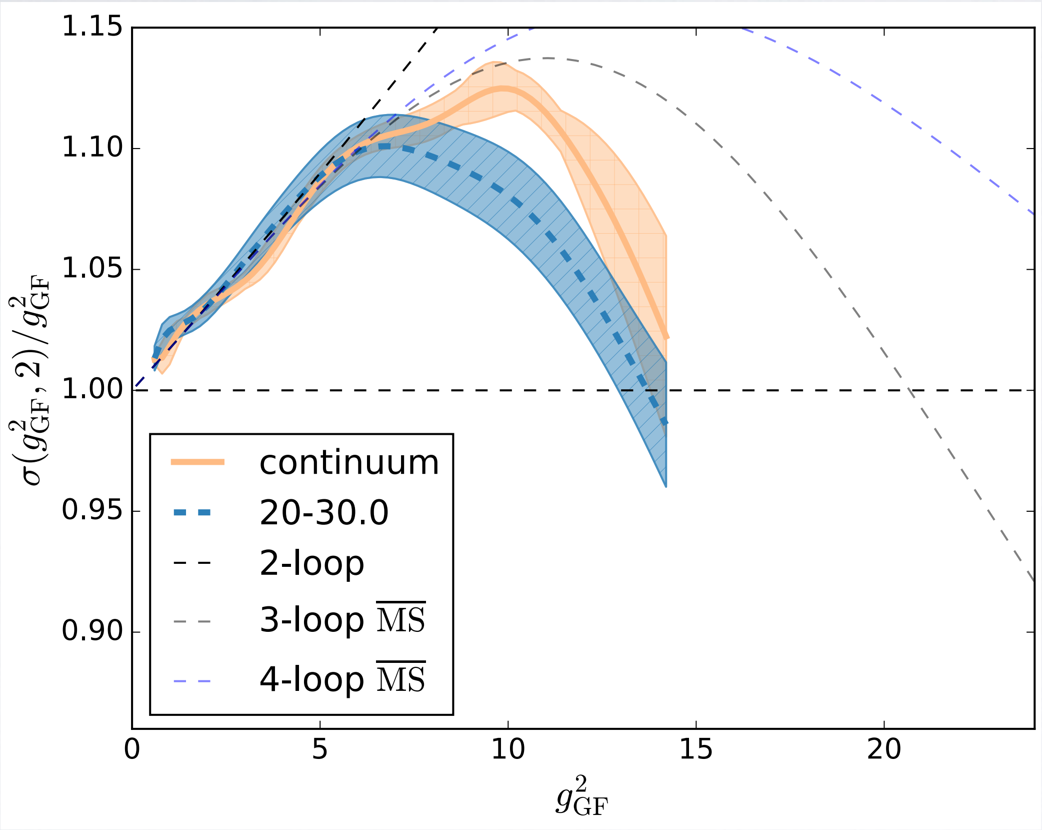
- Largest volume still running
- Estimate of systematic error of continuum extrapolation needed
- Anomalous dimensions γ^* ?

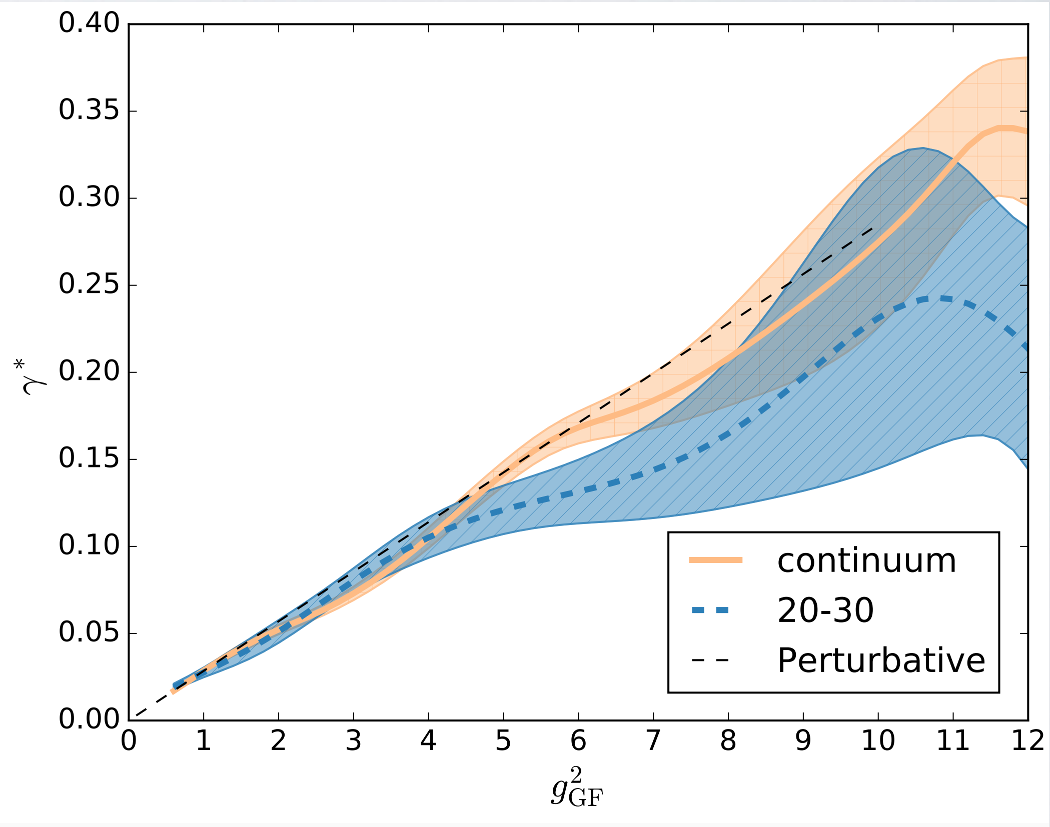


SU(2) Fund N_f=6

Talk by Leino [Thu]
Posters by Tähtinen, Soursa [Tue]

- measure of GF coupling with SF bc
  Similar method to previous N_f=8 determination





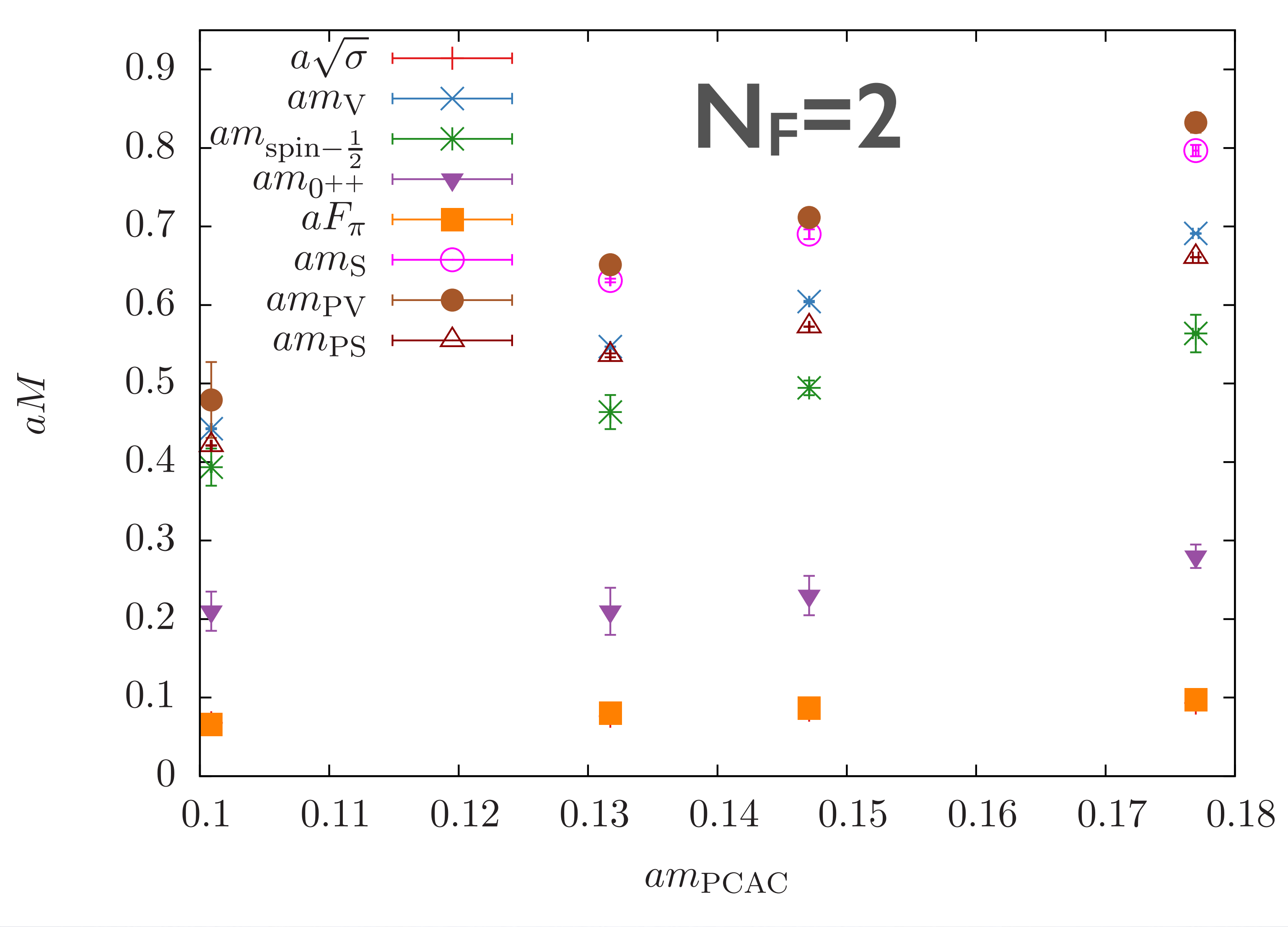
- extrapolation near FP still affected by systematics: larger volumes required?
- small γ^* ?

N_f	β	γ_M	γ_{SD}	γ_{SF}
6	0.5	0.382(12)	0.280(2)	0.142(27)
	0.6	0.314(7)	0.231(2)	0.414(63)
	0.8	0.248(3)	$\sim$ 0.16	0.157(21)
8	0.6	0.293(30)	$\sim$ 0.13	0.072(24)
	0.8	0.238(31)	0.111(1)	0.109(14)

SU(2) Adj N_f=2, 3/2

Talk by Bergner [Mon]

- Spectrum (including scalar) and γ^*
  - new results for N_f=2, 3/2
  - 2 lattice spacings



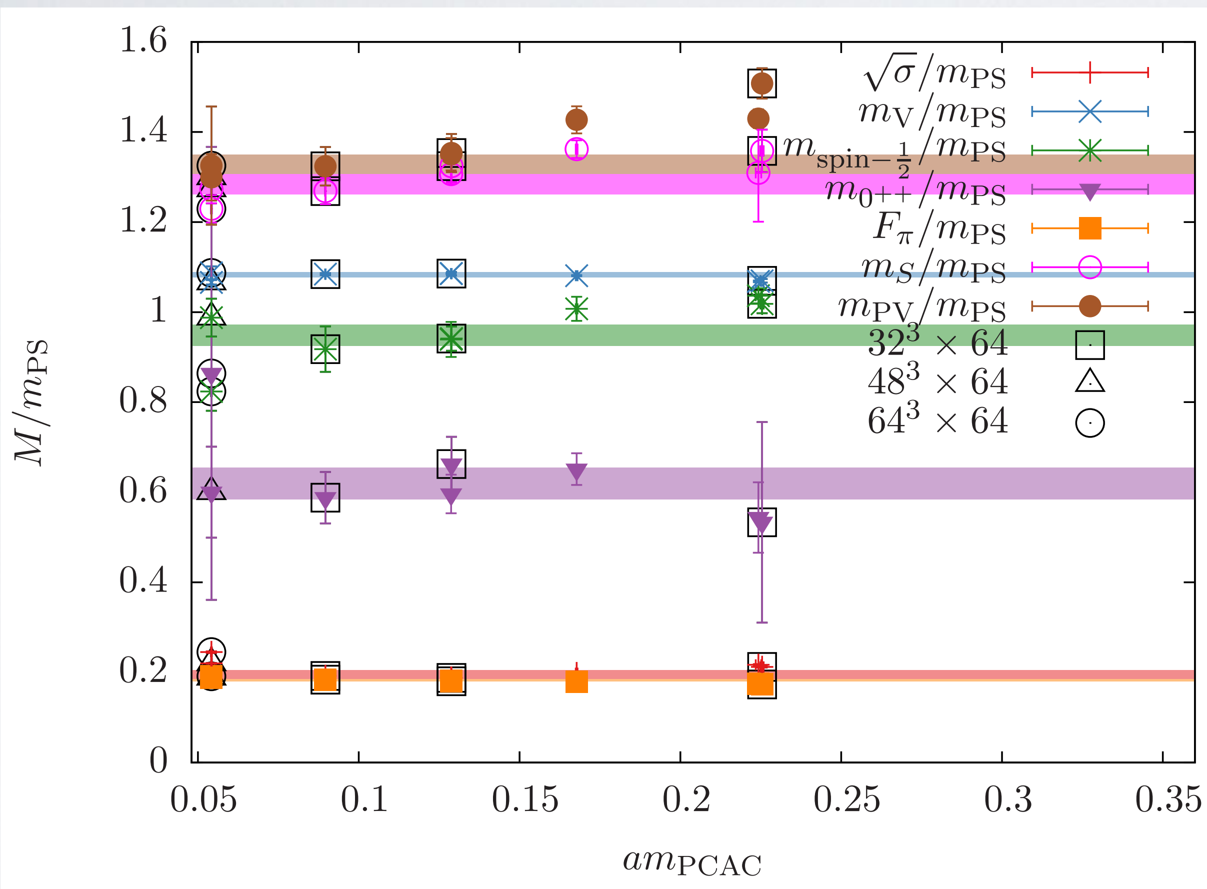
SU(2) Adj N_f=2, 3/2

Talk by Bergner [Mon]

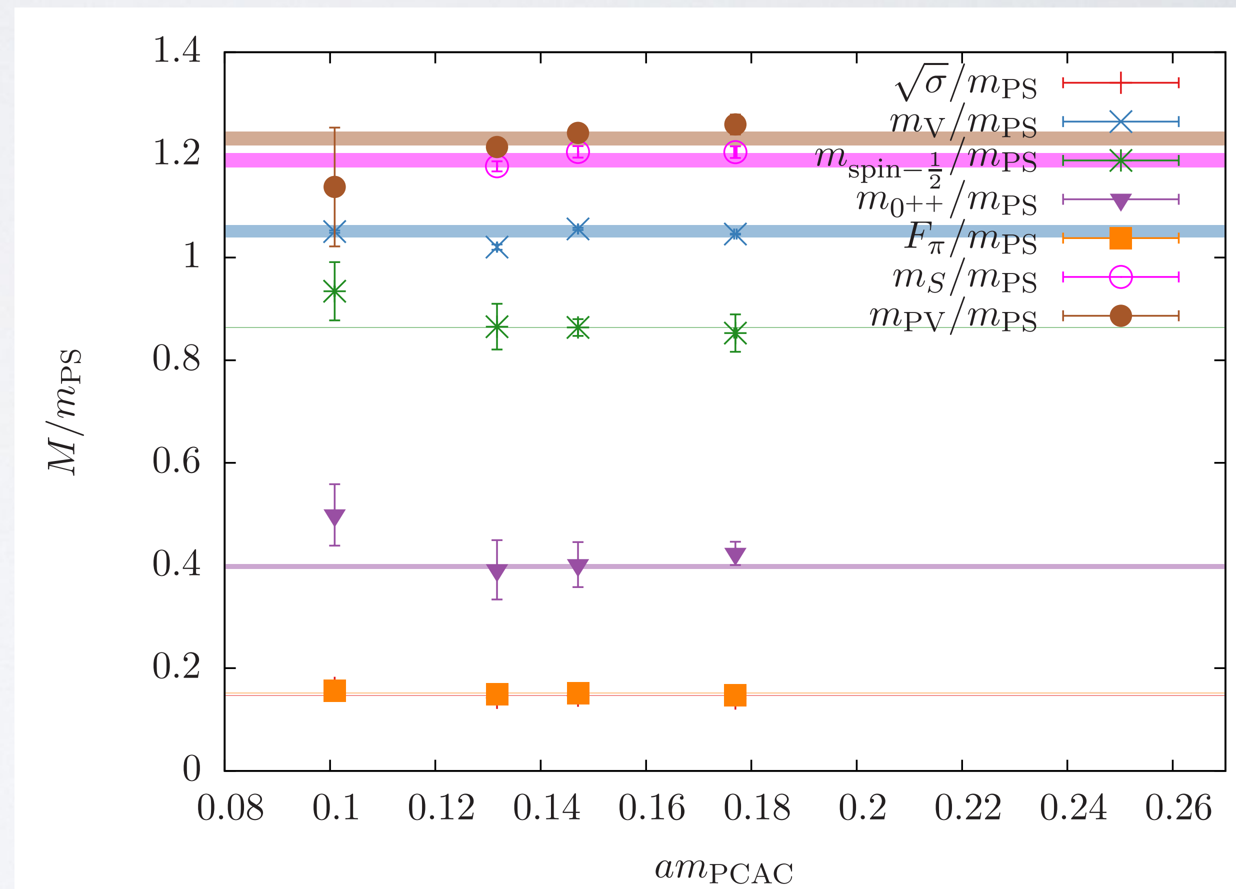
- Spectrum (including scalar)

N_F=2

β=1.5



β=1.7



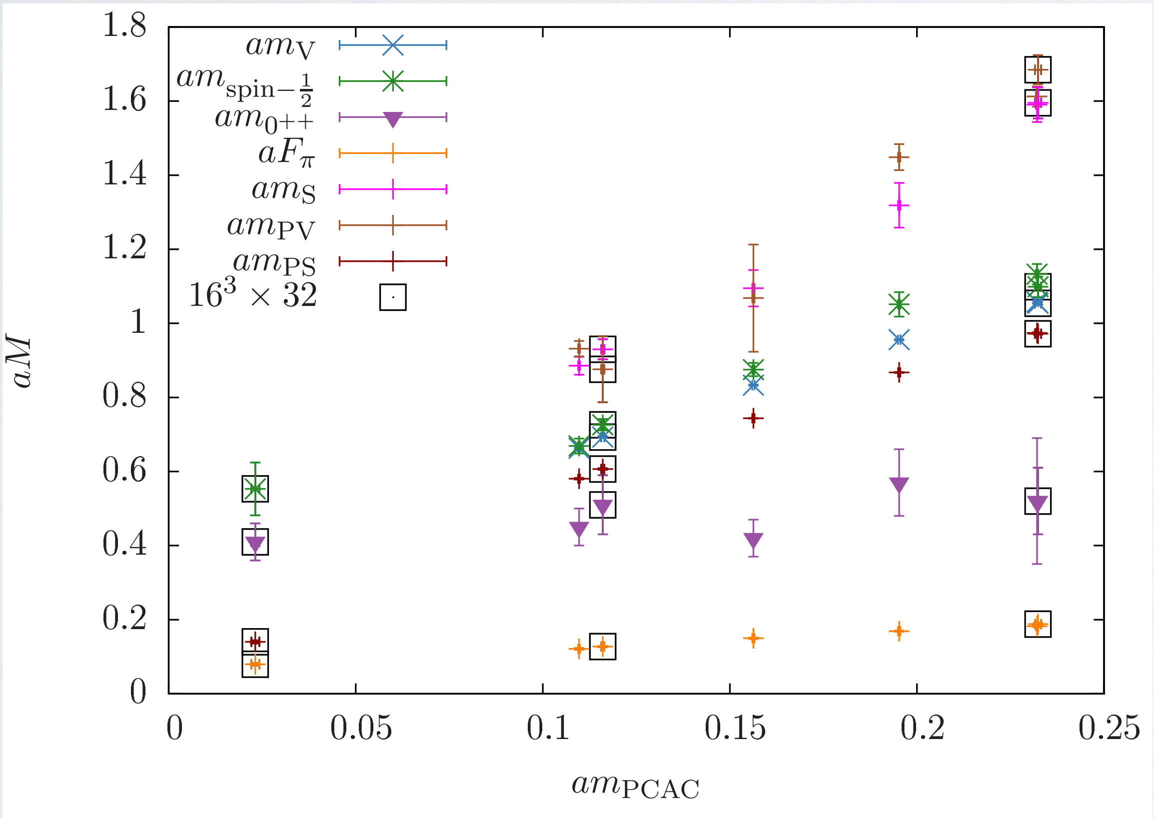
Significant β dependence, Finite size effects at small quark mass.

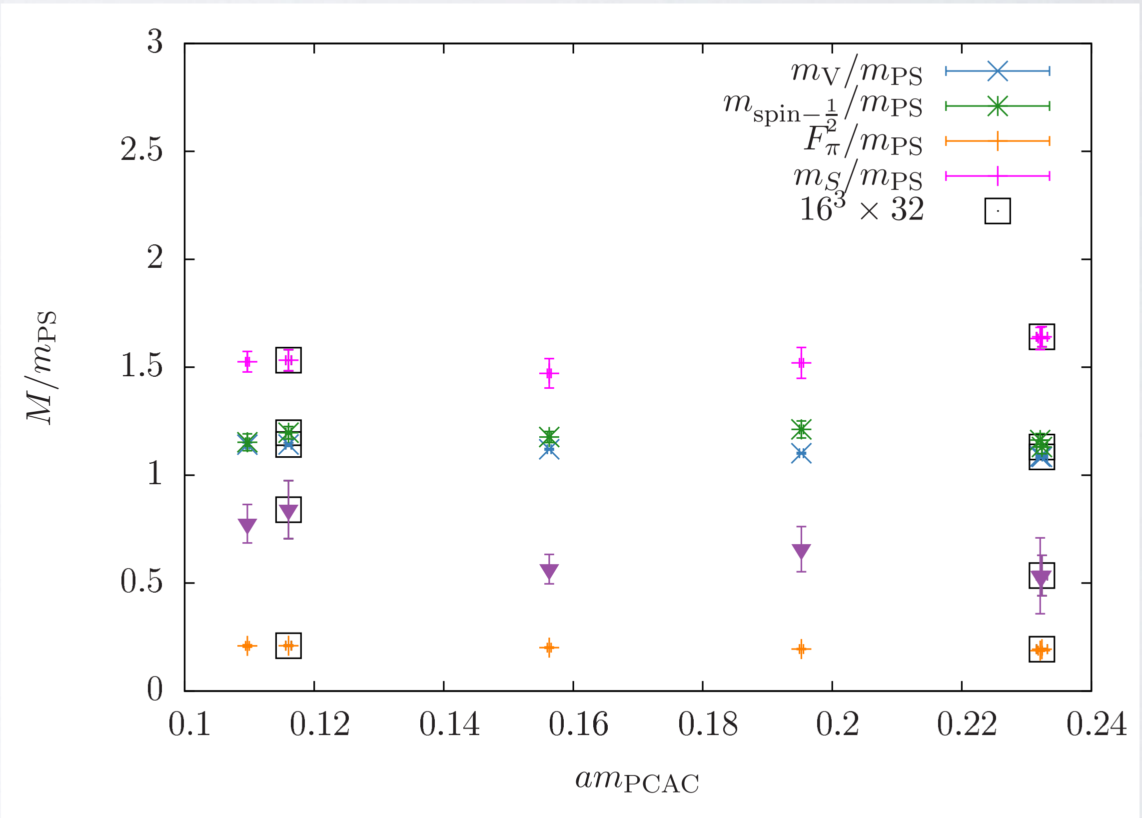
SU(2) Adj N_f=2, 3/2

- First results for N_f=3/2

Talk by Bergner [Mon]

N_F=3/2





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SU(2) Adj N_f=2, 3/2, 1, 1/2

Talk by Bergner [Mon]

Theory	scalar particle	γ_* small β	γ_* larger β
$N_f = 1/2$ SYM	part of multiplet	–	–
$N_f = 1$ adj QCD	light	0.92(1)	0.75(4)*
$N_f = 3/2$ adj QCD	light	0.40(5)*	0.32(5)*
$N_f = 2$ adj QCD	light	0.376(3)	0.274(10)

(* preliminary)

- Significant β dependence, needs to be clarified
  - corrections to scaling? larger volumes?
- **Very large volumes required** as demonstrated in [arXiv:1512.08242] for N_f=2
- Large γ^* for N_f=1 ? Inside the CW?
  - See also [1412.5994]

Models Light σ Scalars

new results at Lattice 2016

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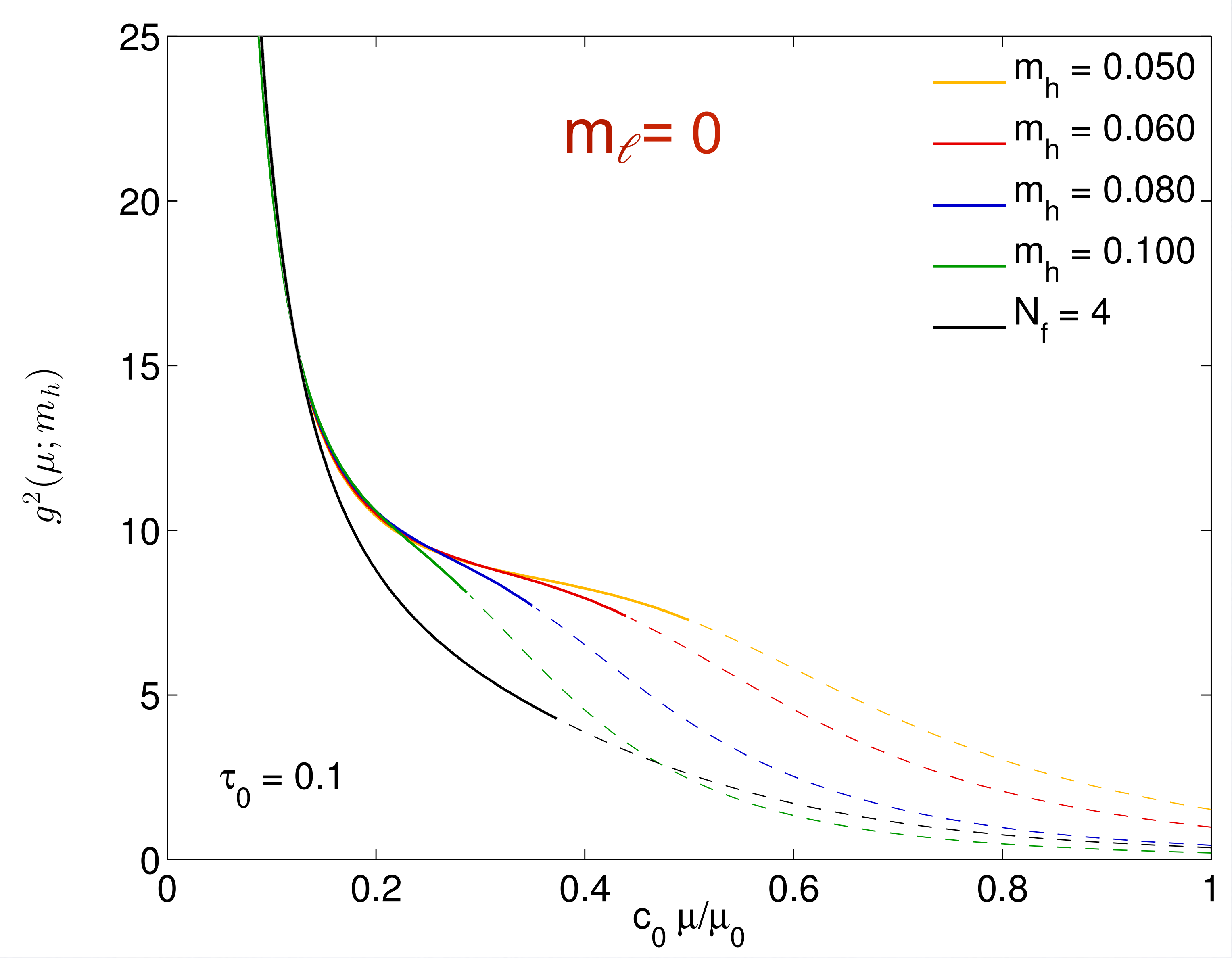
SU(3) Fund N_f=4l+8h

Talks by Hasenfratz, Rebbi [Mon]

- Mass deformation induces "Walking"



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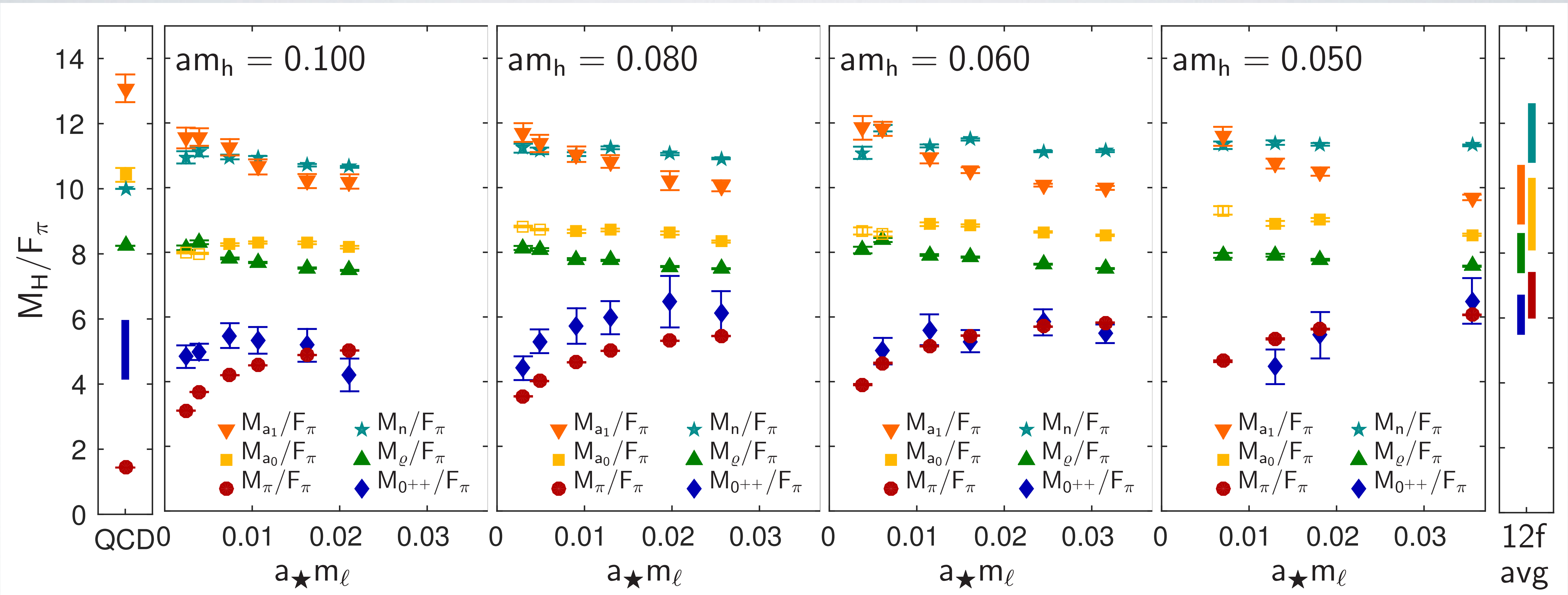
SU(3) Fund N_f=4l+8h

See also [1512.02576]

Talks by Hasenfratz, Rebbi [Mon]



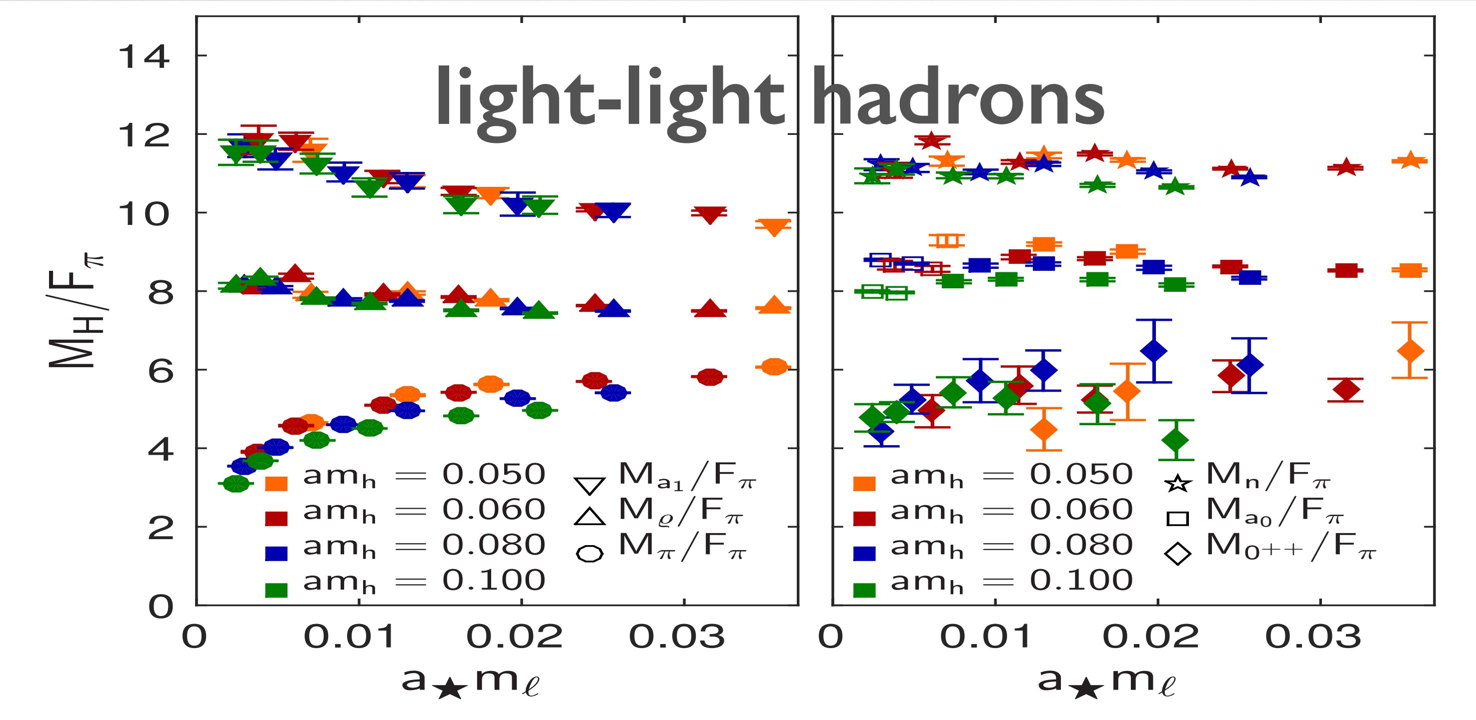
- Light scalar as m_h is decreased.
  - How light is it? Requires controlled extrapolation…
- Other ratios appear only mildly dependent on m_h , i.e "QCD-like"

SU(3) Fund N_f=4l+8h

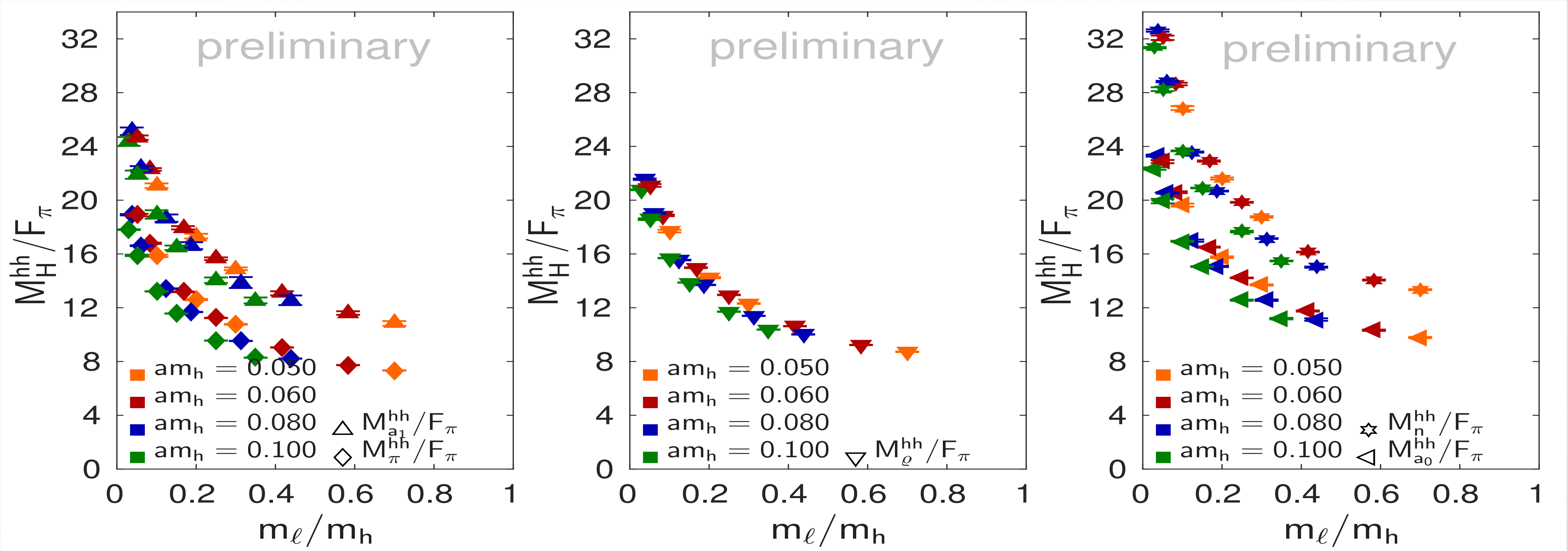
Talks by Hasenfratz, Rebbi [Mon]

- Hyperscaling in spectrum expected close to an IR fixed point:

$$M_{H_1}/F_\pi = \tilde{\Phi}_H(m_\ell/m_h)(1+c_0 m_h^\omega)$$



heavy-heavy



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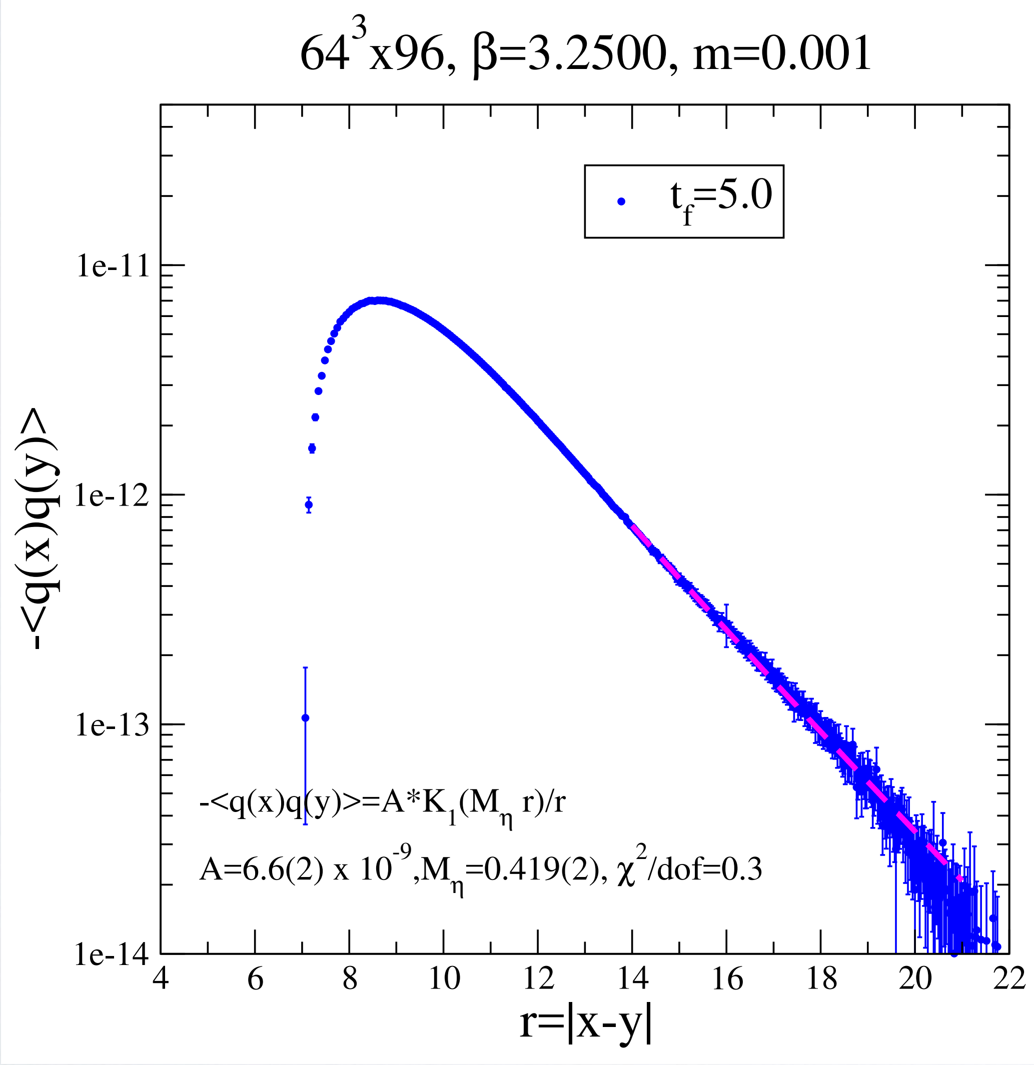
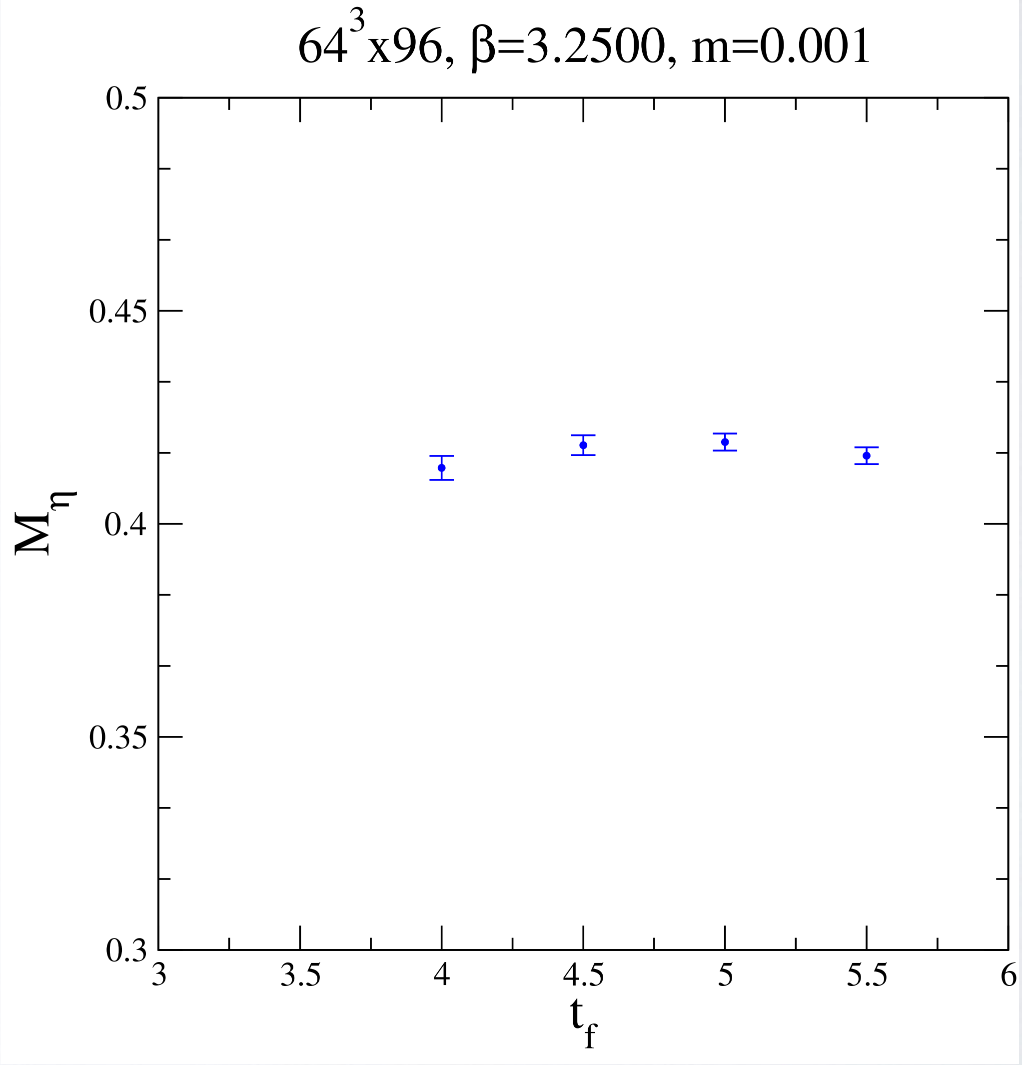
SU(3) Sextet N_f=2

Talks by Kuti, Wong for LHC [Mon,Tue]

- New: Preliminary η' from topological charge density with WF smearing
- Relatively heavy η' ~ 3TeV (assuming F_{ps}=246GeV)

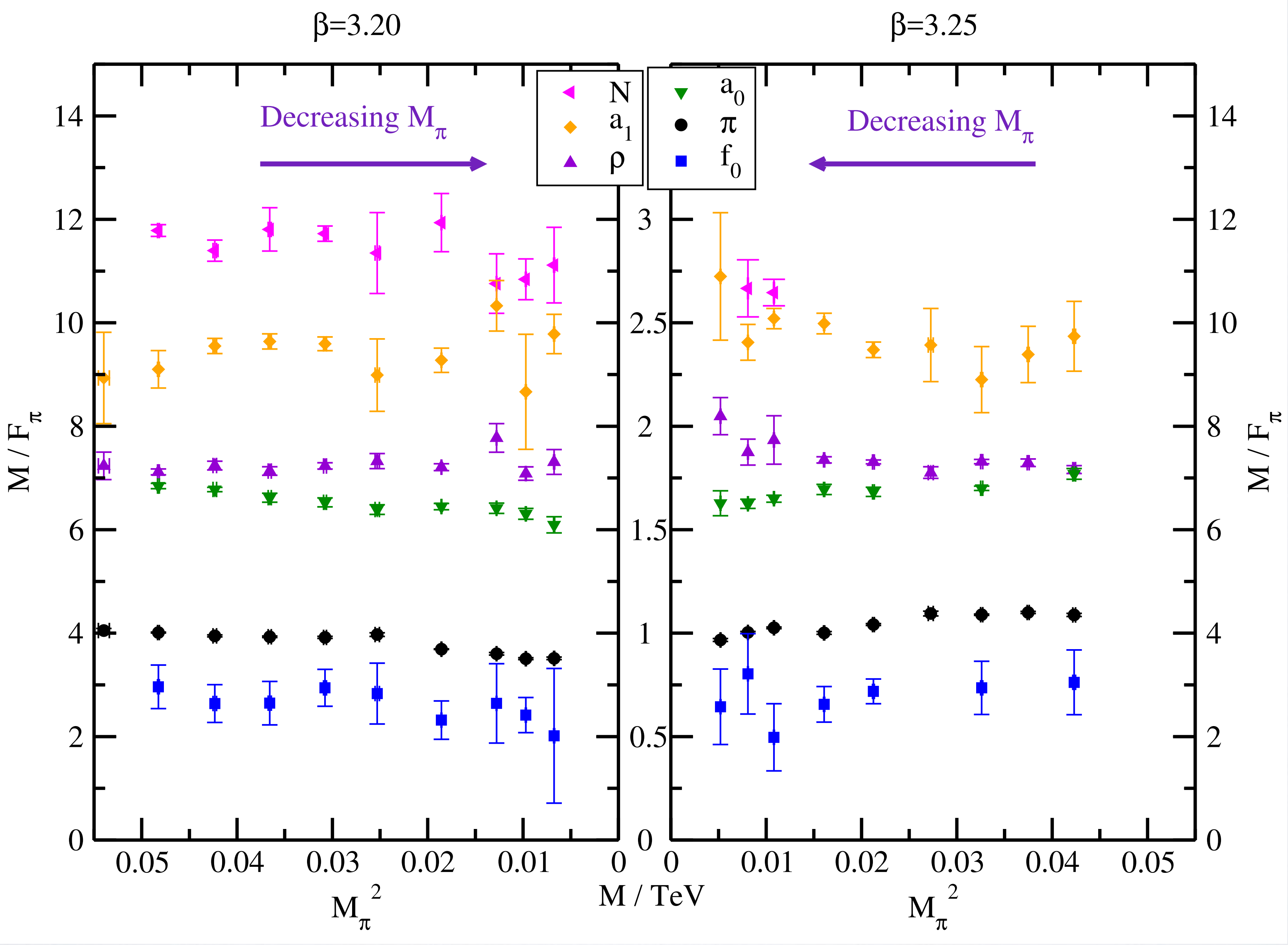




SU(3) Sextet N_f=2

Talks by Kuti, Wong for LHC [Mon,Tue]

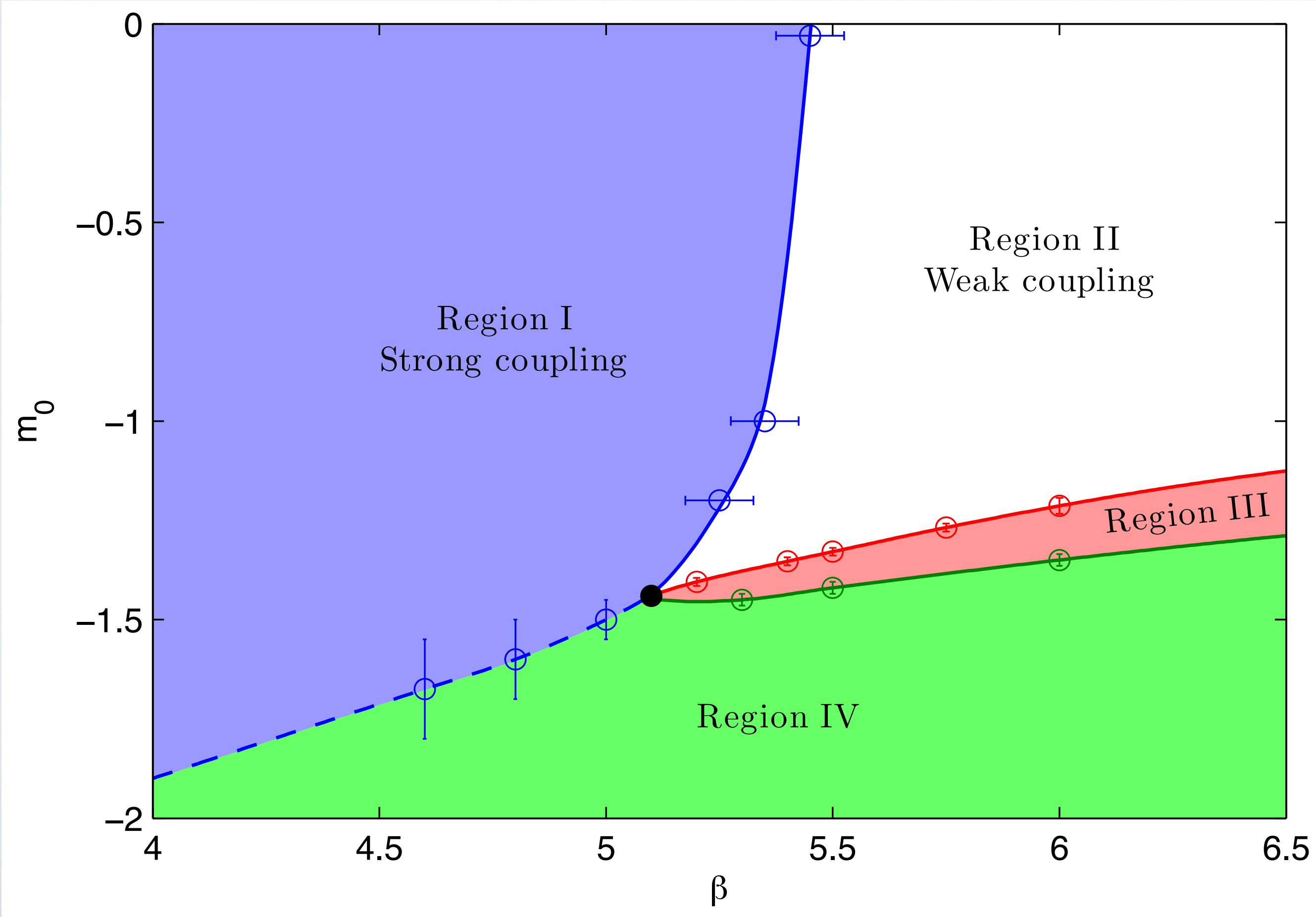
- Nearly conformal model with light σ
- Spectrum not compatible with mass-deformed hyper scaling
- Problem of chiral extrapolation in presence of a light σ

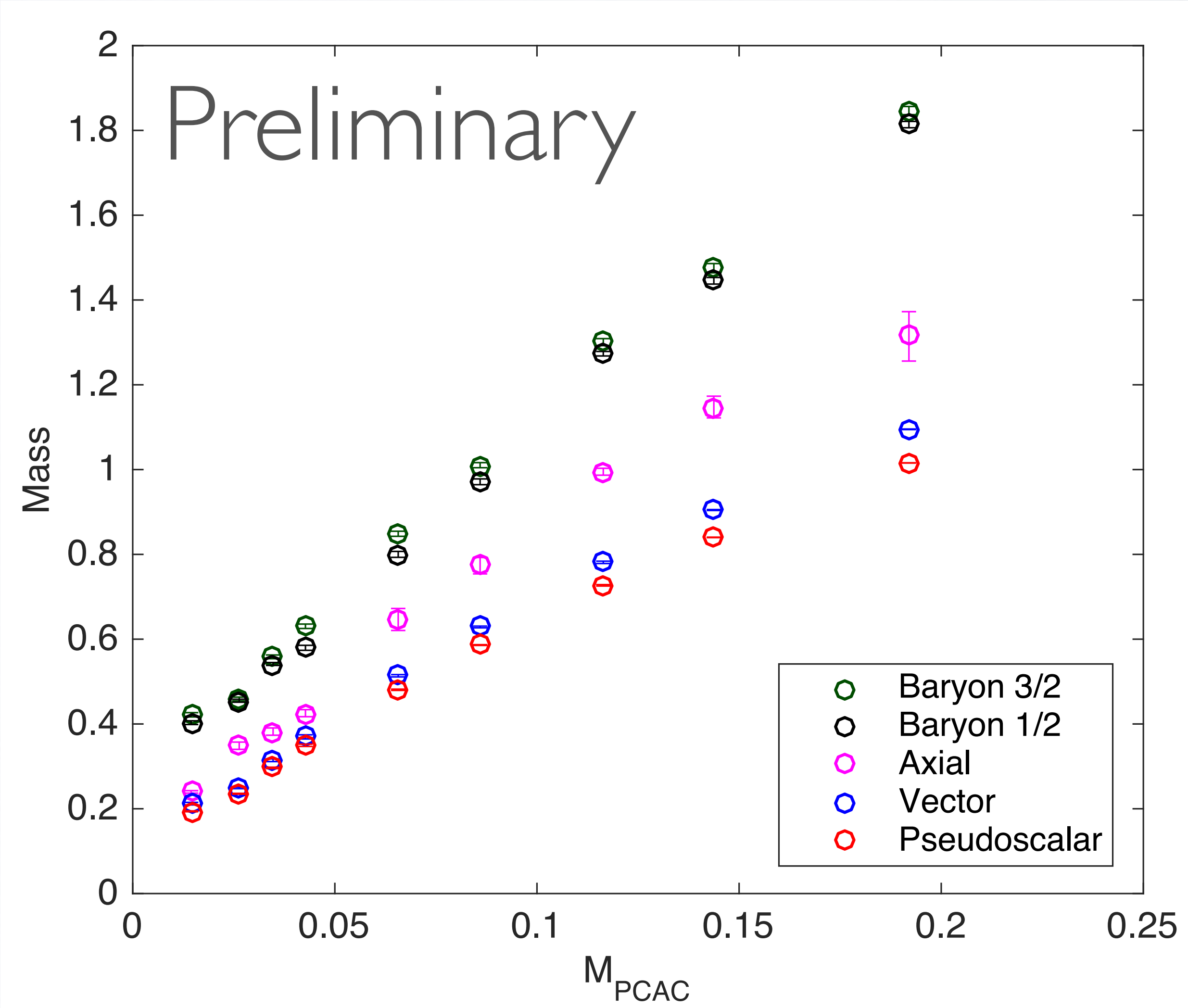


SU(3) Sextet N_f=2

Talk by Hansen [Thu]

- Sextet model with non-improved Wilson fermions
- Study of the phase diagram, spectrum, w_0/t_0 scale setting
- Preliminary analysis shows no clear signs of ChSB, but conformal hypothesis does not fit well data





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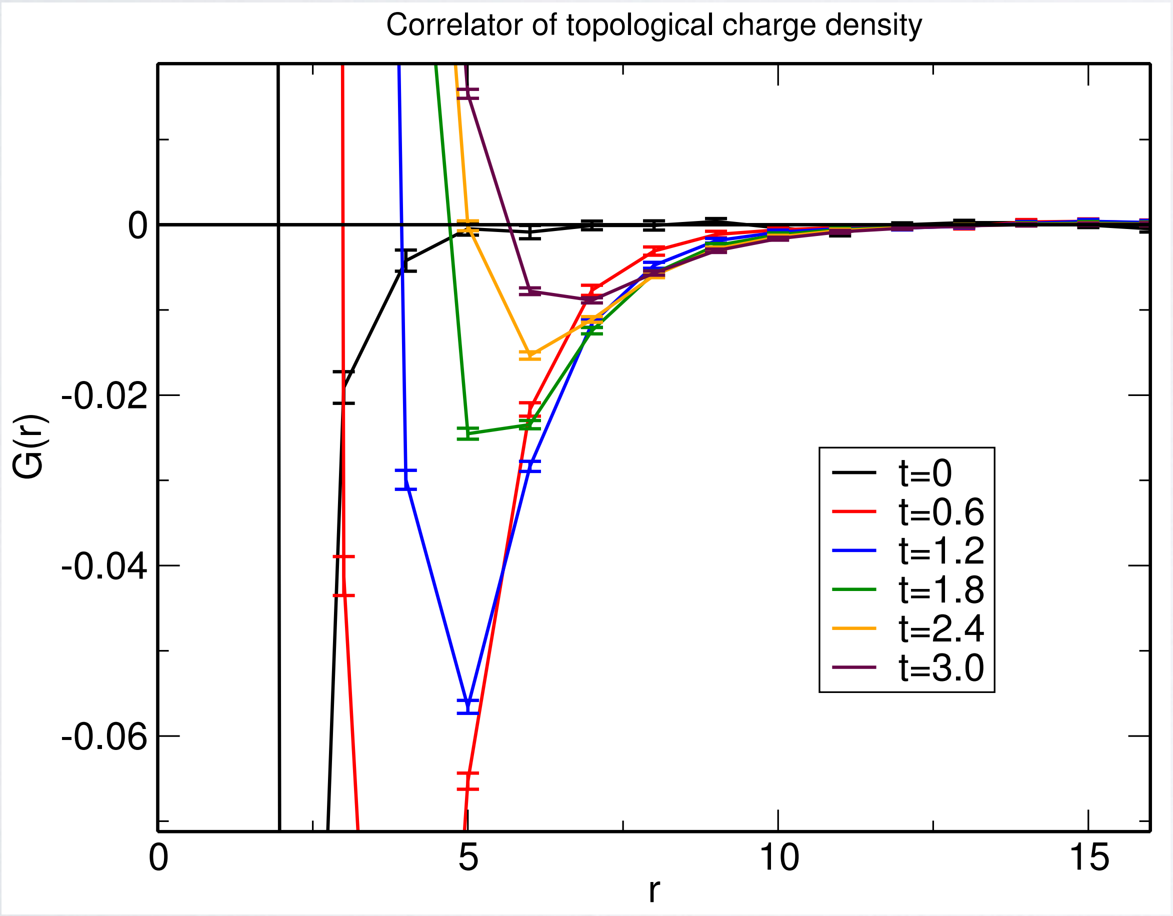
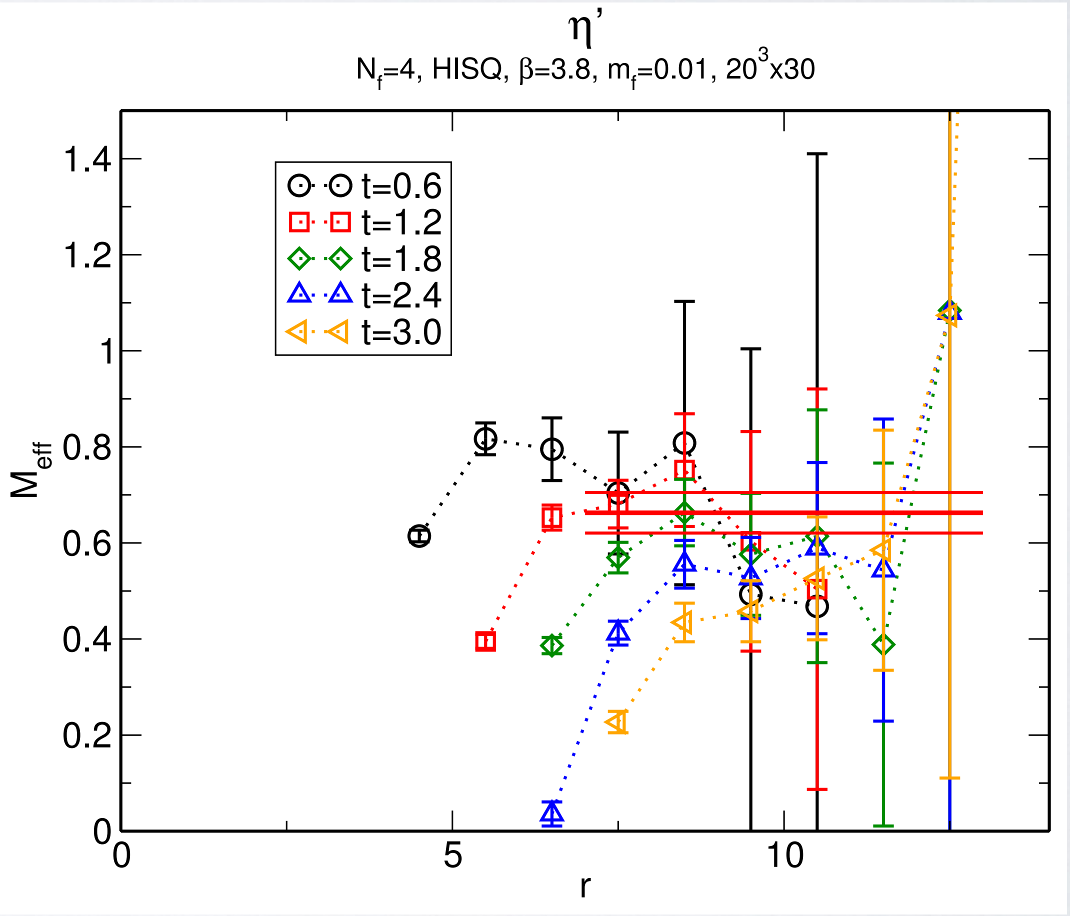
Cosmology & Particle Physics

SU(3) Fund N_f=8, 4

Talk by Aoki for LatKMI [Tue]

- Updated spectrum for N_f=8, see LatKMI [1403.5000]
- New results for N_f=4
- New: η' mass from topological charge density with WF smearing

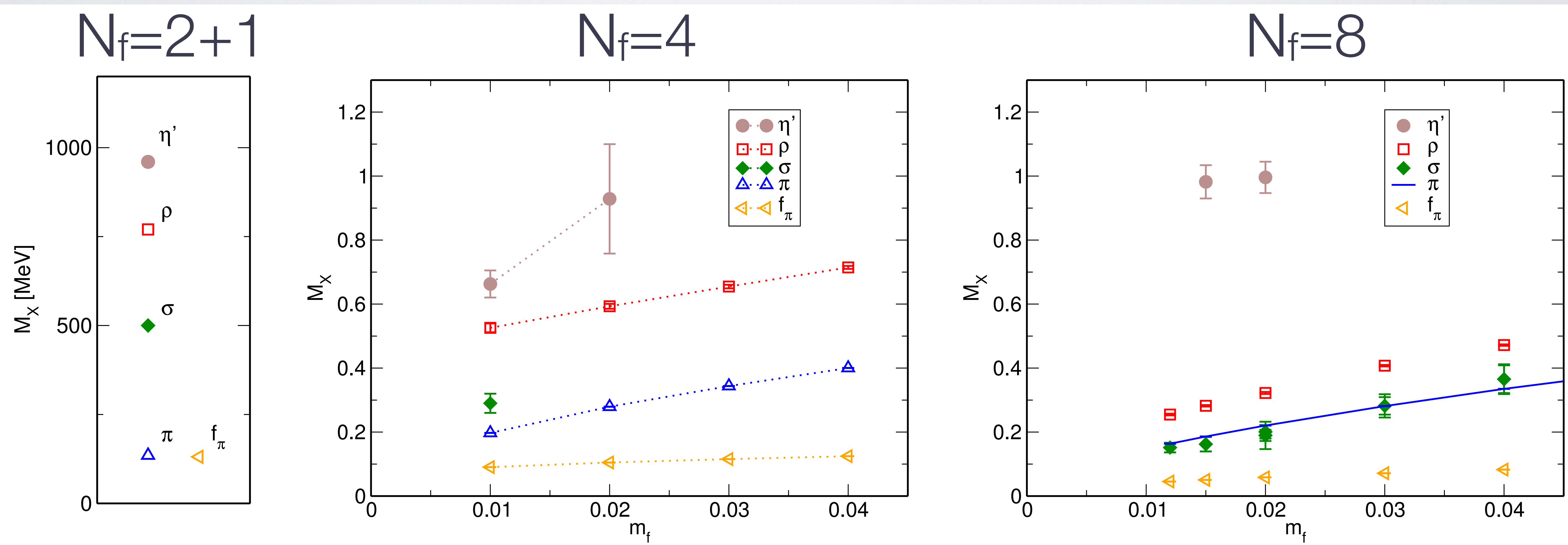




SU(3) Fund N_f=8, 4

Talk by Aoki for LatKMI [Tue]

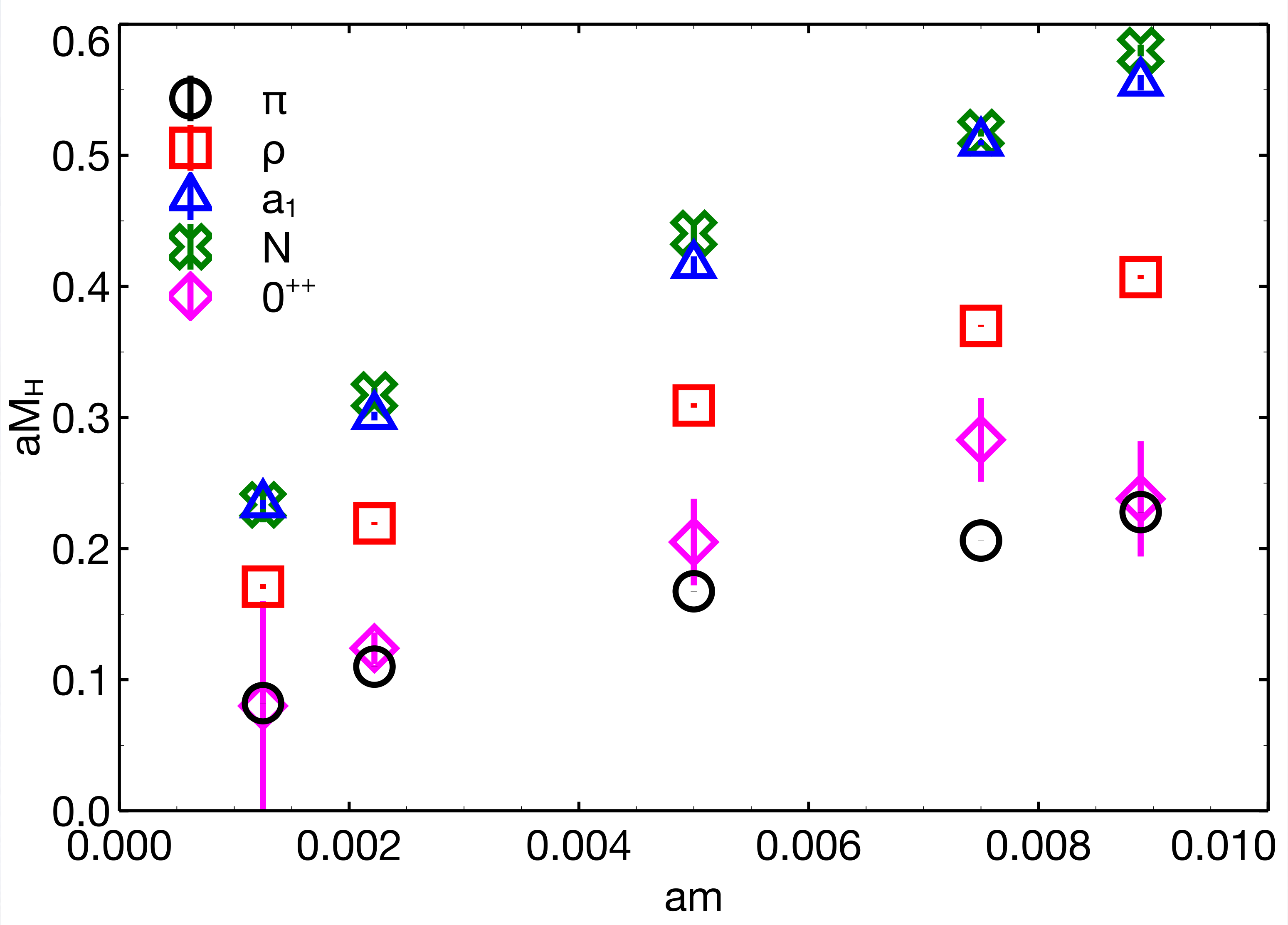
- Preliminary results show heavy η' as approaching the CW.
  - is there a reason for this enhancement? [Matsuzaki, Yamawaki JHEP2015]
- Light σ for N_f=8, compatible with pion mass in the explored mass range



SU(3) Fund N_f=8

Talks by Fleming, Gasbarro for LSD [Tue]

- Updated spectrum for N_f=8, see LSD [1601.04027]
- Use of new action respect to previous USBSM studies allows use of coarser lattices



SU(3) Fund N_f=8

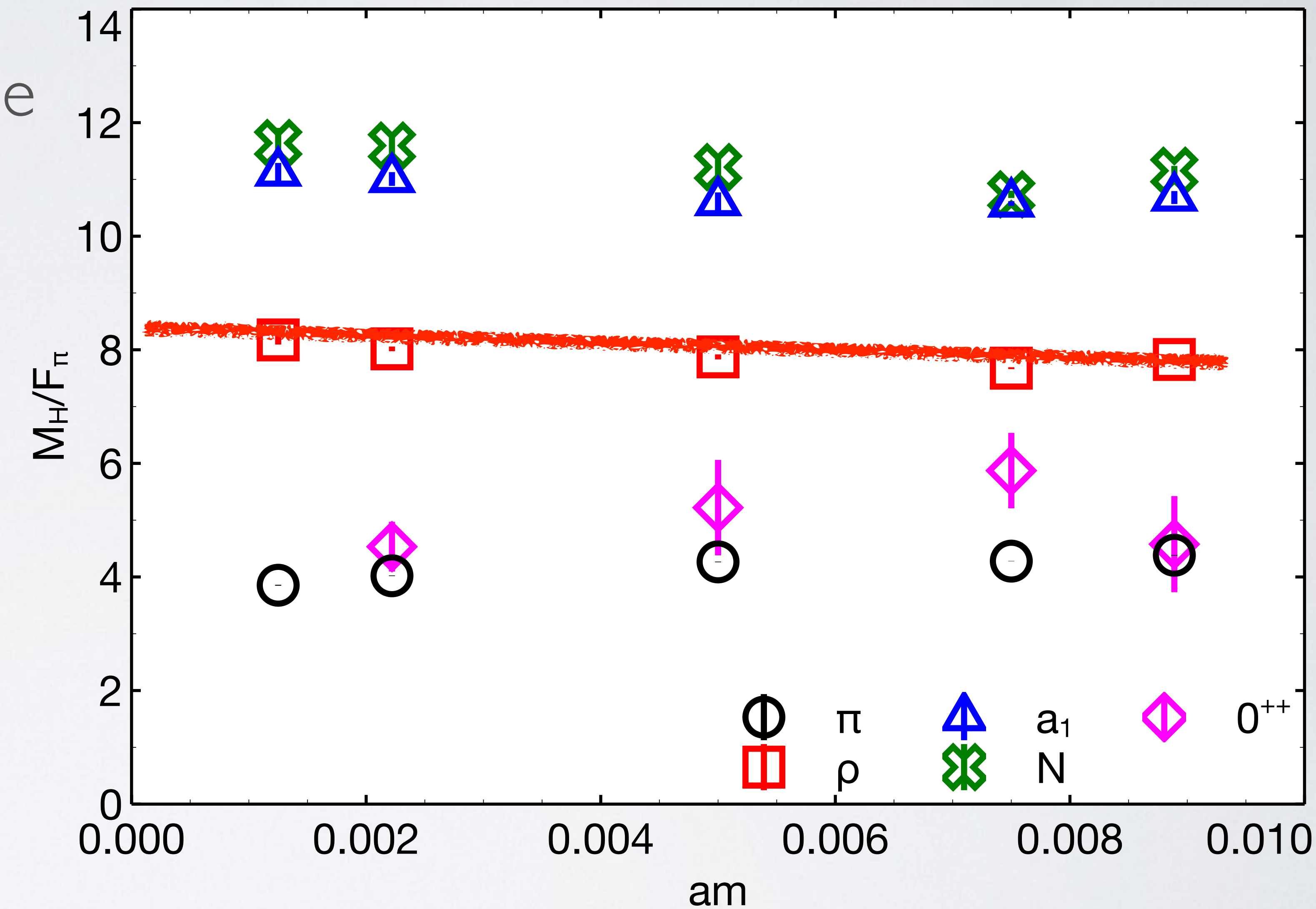
Talks by Fleming, Gasbarro for LSD [Tue]

- M_V/F_{PS}~8 like in QCD
- Use vector meson dominance and KSRF relation

$$\Gamma_\rho \approx \frac{g^2_{\rho\pi\pi} M_\rho}{48\pi} \approx \frac{M^3_\rho}{96\pi F^2_\pi}$$

to estimate Γ_ρ/M_ρ~20%

- Too broad to explain LHC excess?



- What about the scalar?

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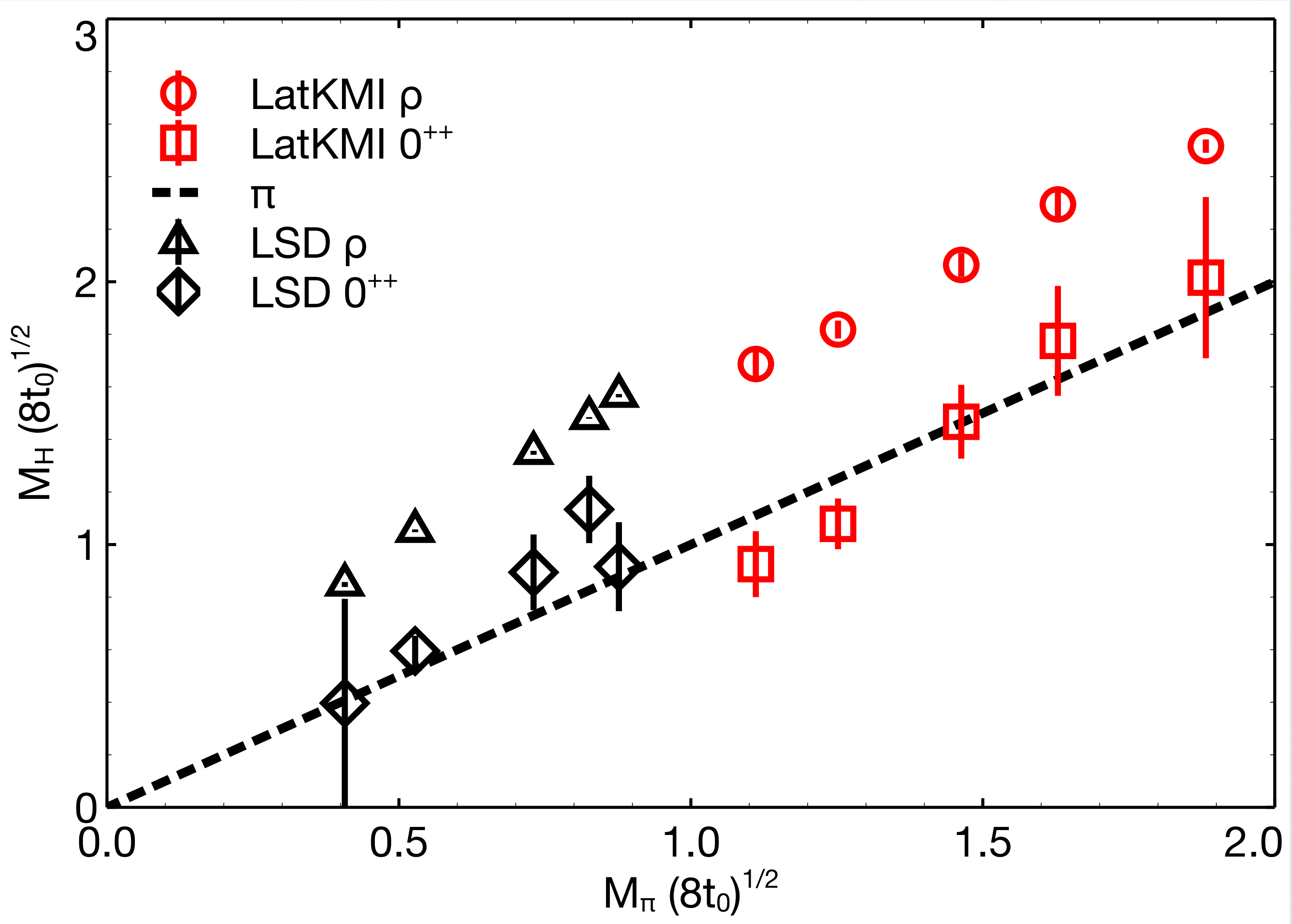
SU(3) Fund N_f=8

Talks by Fleming, Gasbarro for LSD [Tue]

- Good agreement with LatKMI
- Scalar as light as pions



- IF dilaton-like, σ is expected to become much lighter than ρ
- Not clear how to extrapolate: different extrapolations give wildly different results

Need good effective description of pi-σ system

Effective action for pi-σ dilaton

Talks by Shamir, Golterman [Mon]

- Near CW assume $\partial_\mu S_\mu = T_{\mu\mu} \sim (n_f - n_f^*)^\eta$ at the ChSB scale
- Systematic expansion in: m, p^2, 1/N, n_f-n_f^*
- LO Lagrangian (τ dilaton):

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_\pi + \mathcal{L}_\tau + \mathcal{L}_m + \mathcal{L}_d \\
\mathcal{L}_\pi &= (f_\pi^2/4)\, e^{2\tau} \mathrm{tr}\,(\partial_\mu \Sigma^\dagger \partial_\mu \Sigma) \\
\mathcal{L}_\tau &= (f_\tau^2/2)\, e^{2\tau} (\partial_\mu \tau)^2 \\
\mathcal{L}_m &= -(m f_\pi^2 B_\pi/2)\, e^{y\tau} \mathrm{tr}\left(\Sigma + \Sigma^\dagger\right) \\
\mathcal{L}_d &= [\tilde{c}_{00} + (n_f - n_f^*)(\tilde{c}_{01} + \tilde{c}_{11}\tau)]\, f_\tau^2 B_\tau\, e^{4\tau}
\end{aligned}
$$

Effective action for pi-σ dilaton

Talks by Shamir, Golterman [Mon]

- Results (more in Shamir, Golterman talks):

$$m_\pi^2 = 2\hat{B}_\pi m e^{(y-2)v(m)}$$

$$m_\tau^2 = 4\tilde{c}_{11}(n_f - n_f^*)\hat{B}_\tau e^{2v(m)}(1 + (4-y)v(m))$$

$$\frac{\langle\overline{\psi}\psi\rangle}{\hat{f}_\pi^3} = -\frac{B_\pi}{f_\pi}\exp\left[\gamma_m^*\left(\frac{1}{4} + \frac{\tilde{c}_{00}}{\tilde{c}_{11}(n_f - n_f^*)}\right)\right]$$

$$-(\beta(g^2)/g^2)\left\langle F^2\right\rangle = \hat{f}_\tau^2 m_\tau^2$$

- Use EFT to "test" diatonic nature of light scalar from Lattice data
  - close enough to CW?
  - need higher order corrections?
  - correct assumptions for EFT?

pNGB Higgs

new results at Lattice 2016

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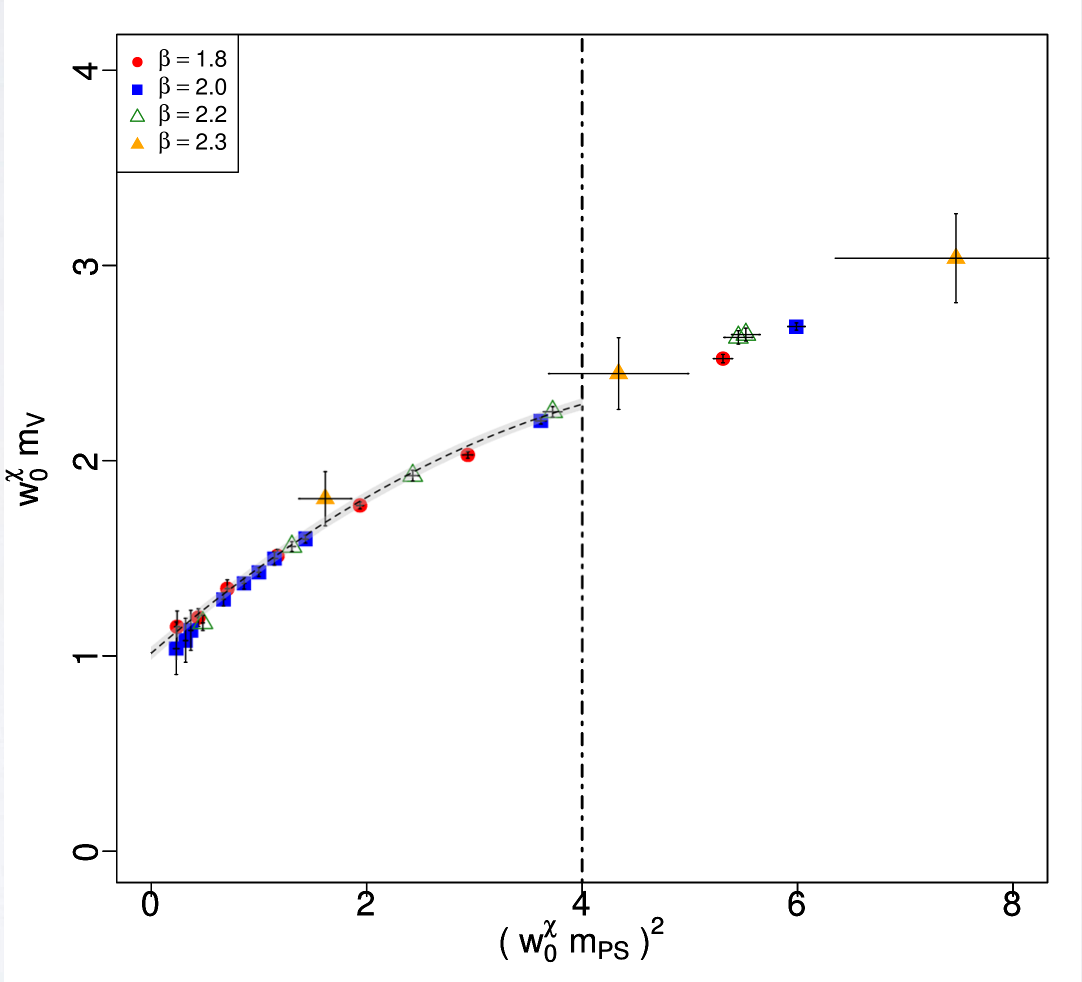
SU(2) Fund N_f=2

Talks by Drach, Janowski [Mon,Thu]

- Simple realistic model for pNGB Higgs — Cacciapaglia, Sannino, JHEP04(2014)111; Arbey et al. [1502.04718]
- First full determination of spectrum including σ and η'
  - 4 lattice spacings
  - scale setting via w_0
  - non-perturbative renormalization in RI-MOM scheme
  - both chiral and continuum extrapolation (better control of systematics needed to reduce errors)

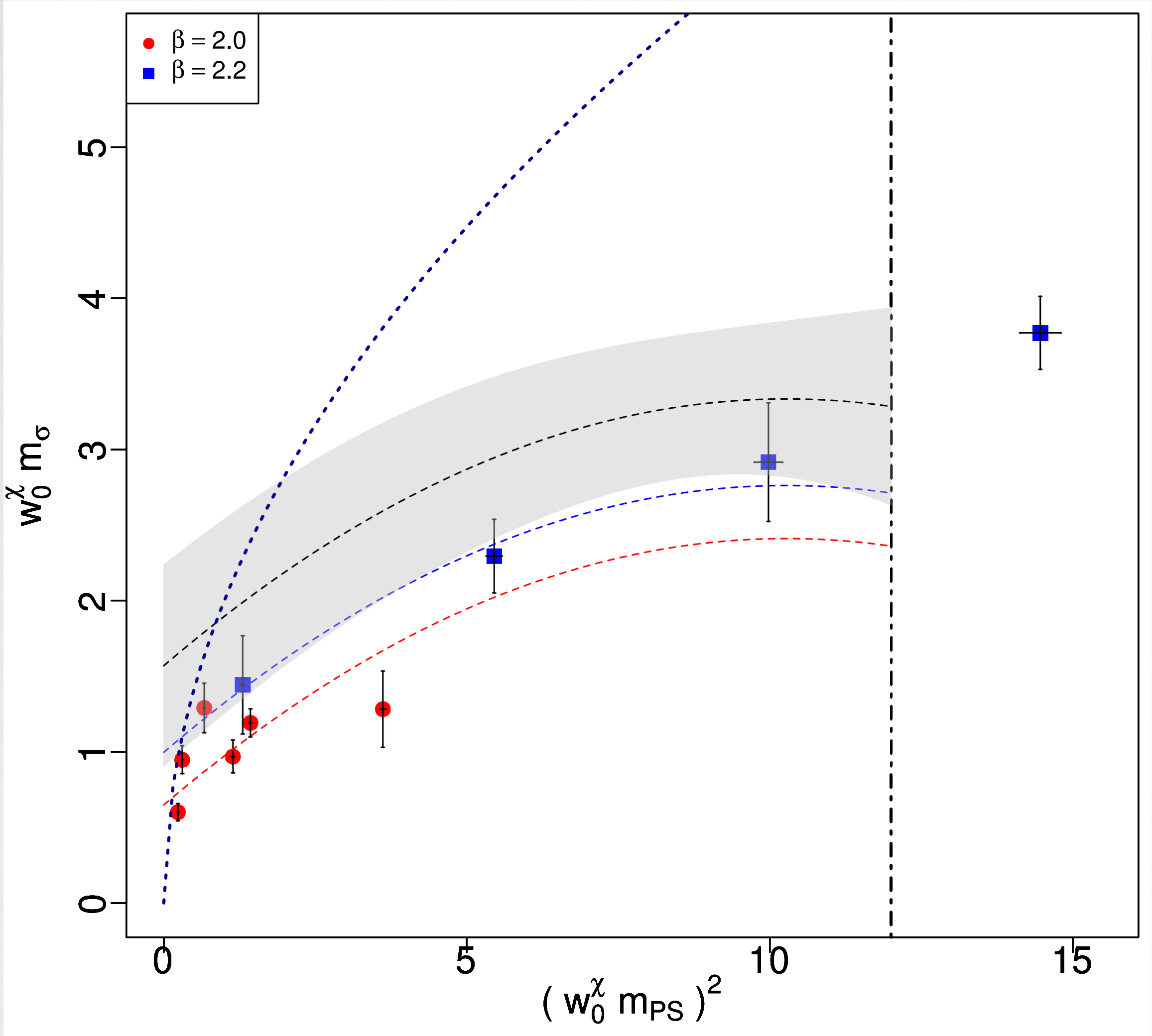


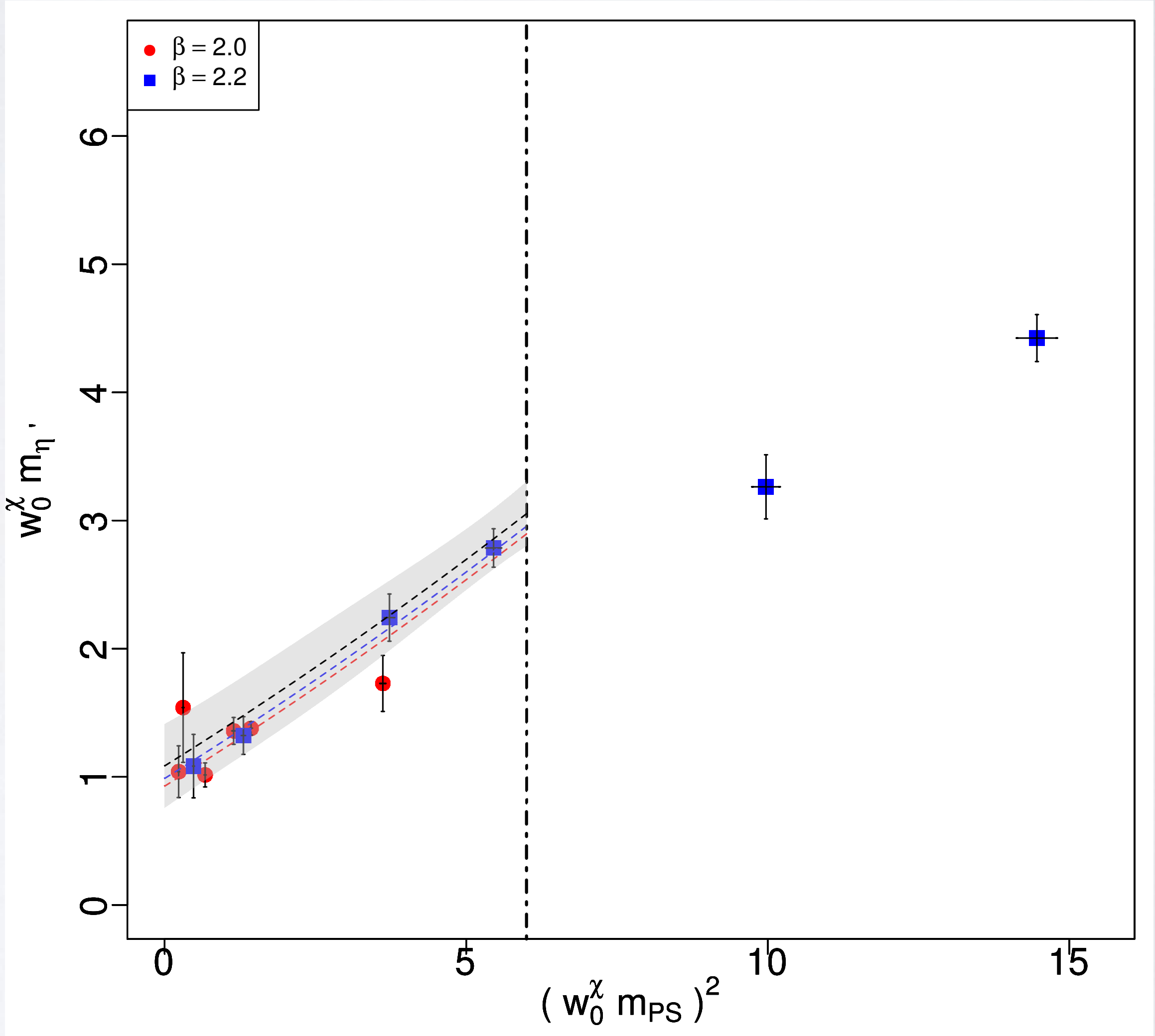
Based on [1602.06559], [1607.06654]

SU(2) Fund N_f=2

Talks by Drach, Janowski [Mon,Thu]

- new scalar spectrum

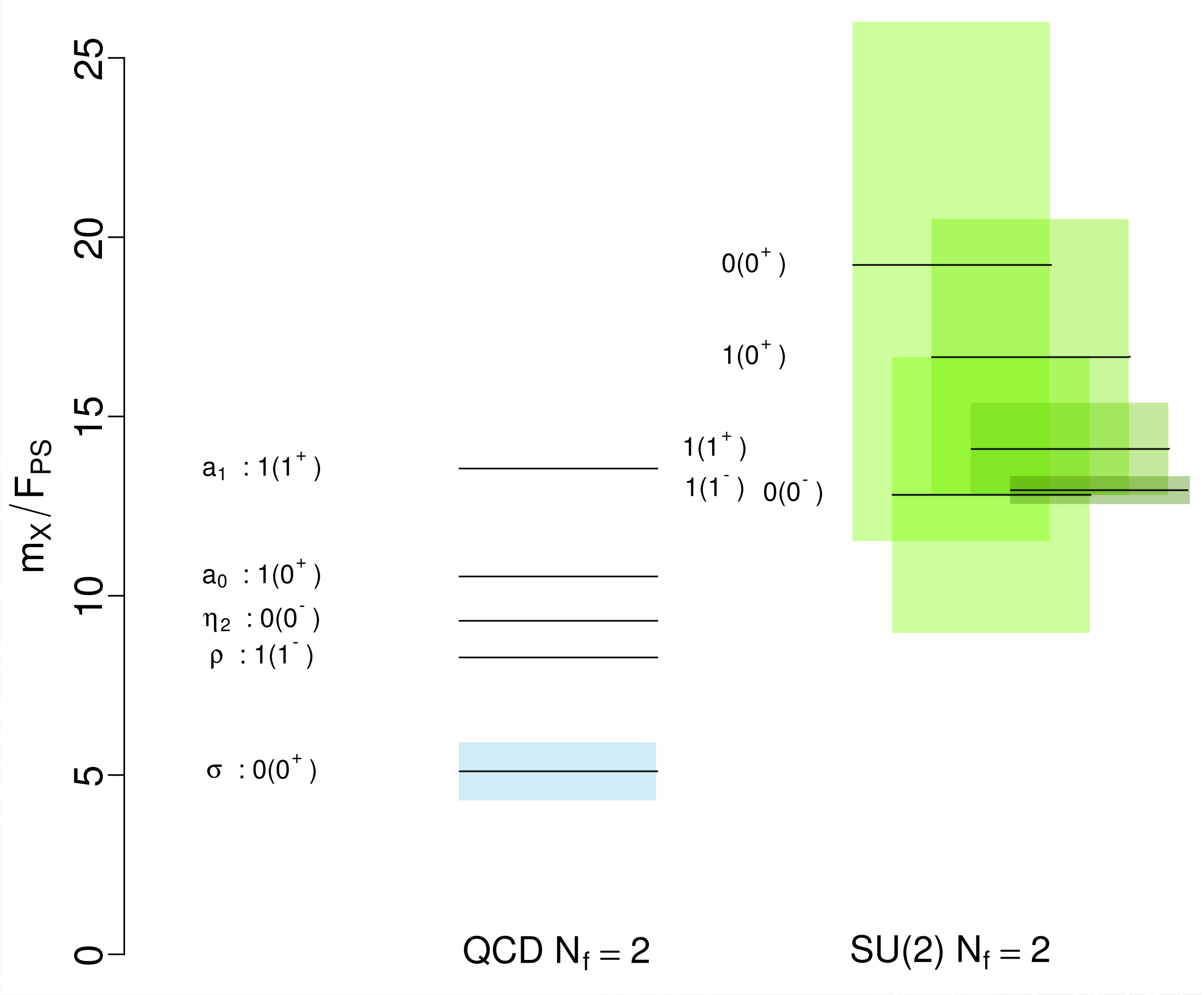




SU(2) Fund N_f=2

Talks by Drach, Janowski [Mon,Thu]

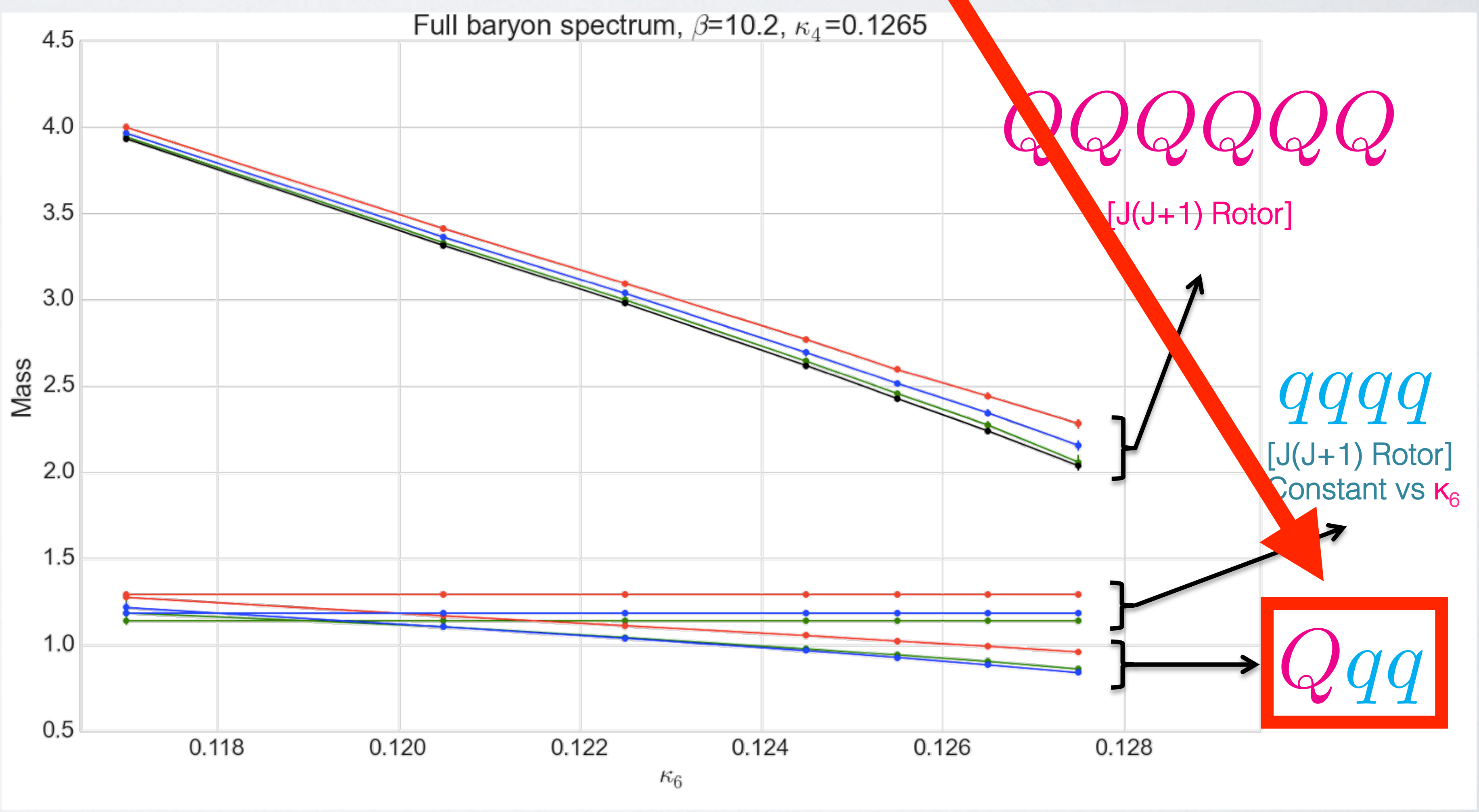
- Spectrum of heavy resonances >15 TeV (depends on EW vacuum alignment angle)
- Better control of extrapolations needed
- Predicts pNGB Higgs with no extra resonances to be seen at LHC, barring extra pNGB in the spectrum



SU(4) N_f= 2F + 2 Sextet

Talk by Jay [Thu]

- First investigation of model with 2 irreps, same as Ferretti's [1404.7137]
- Partially quenched (sextet) exploration of "chimera" baryons
  - can be light → good for phenomenology
  - anomalous dimensions?



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SU(4) N_f=2 Sextet

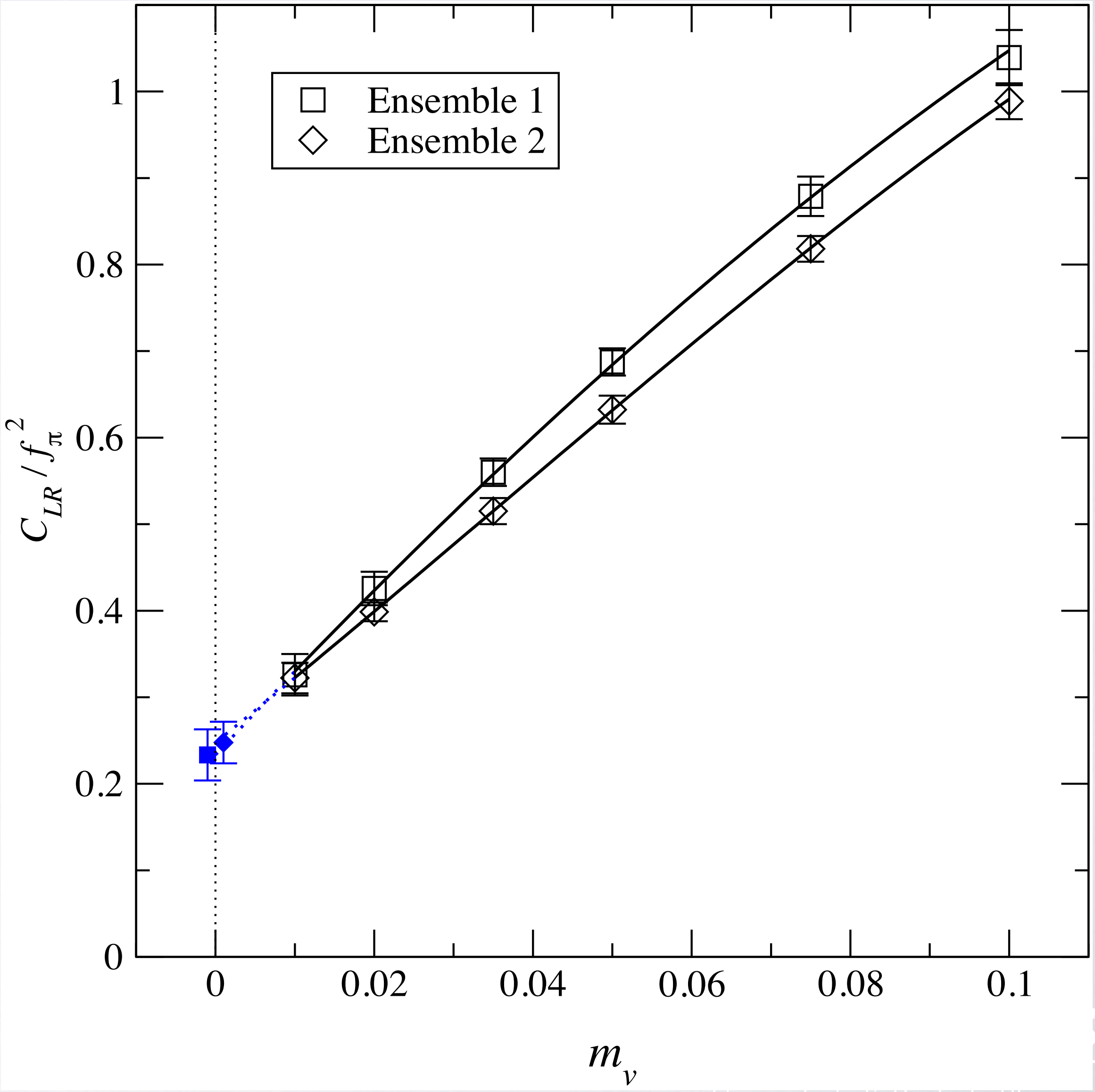
Talk by Svetitsky [Thu]

- Radiative contribution to pNGB Higgs potential from EW gauge bosons

$$V_{EW}(h) = (3g^2 + g'^2) C_{LR} \left(\frac{h}{f}\right)^2 + O(h^4) \qquad C_{LR} = \int_0^\infty dq^2 q^2 \Pi_{LR}(q^2)$$

$$(q^2 \delta_{\mu\nu} - q_\mu q_\nu) \Pi_{LR}(q^2) = -\int d^4x e^{iqx} \langle J^L_\mu(x) J^R_\nu(0) \rangle$$

- Currents calculated with overlap fermions on 2 sea actions
- Alternative method via "Minimal Hadron Approximation" consistent



Conclusions

- Much activity and progress both on model exploration and tools
- Lattice simulations yield first principle results for the SD dynamics which can provide crucial input for model building
- **BAD**:
    - Despite many efforts, still controversy on the location of the Conformal Window. Need better methods?
    - IR conformal models with large γ^*: where are they?
    - Difficult to control systematics for "walking" models

Conclusions

- Much activity and progress both on model exploration and tools
- Lattice simulations yield first principle results for the SD dynamics which can provide crucial input for model building
- **GOOD**:
  - Phenomenologically interesting models are being investigated:
    1) strongly coupled models with light scalars;
    2) pNGB Higgs models
  - New tools for BSM models are being developed
  - (Preliminary) Results for the resonance spectrum of many models (Nc, Nf, irrep) are available
    Already useful for model builders?

Conclusions

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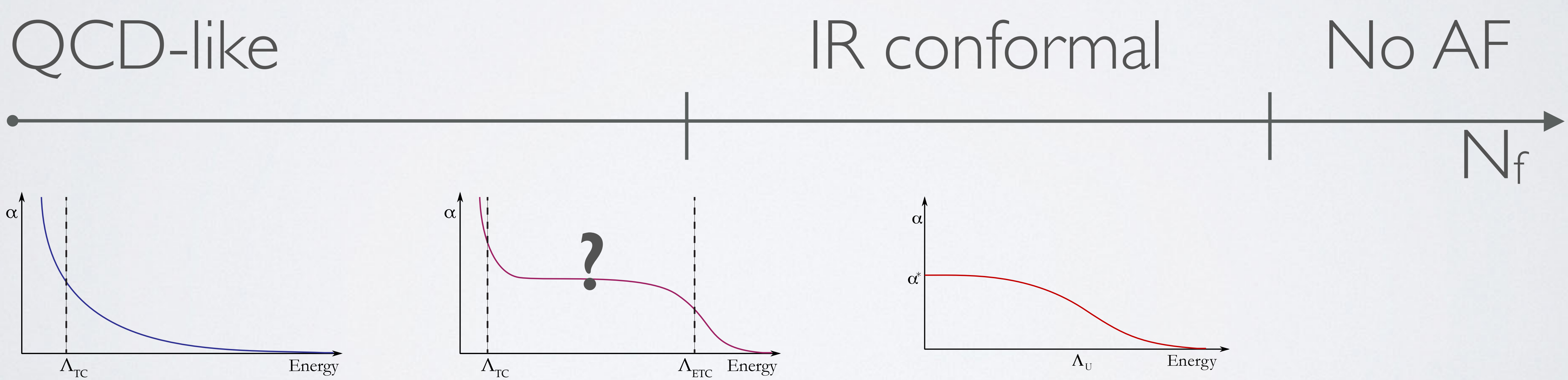
    Already useful for model builders?

Thank you!

Conformal Window

- Gauge Group: SU, SO, SP, Exceptional
- Matter Representation(s)
- # of Flavors per Representation



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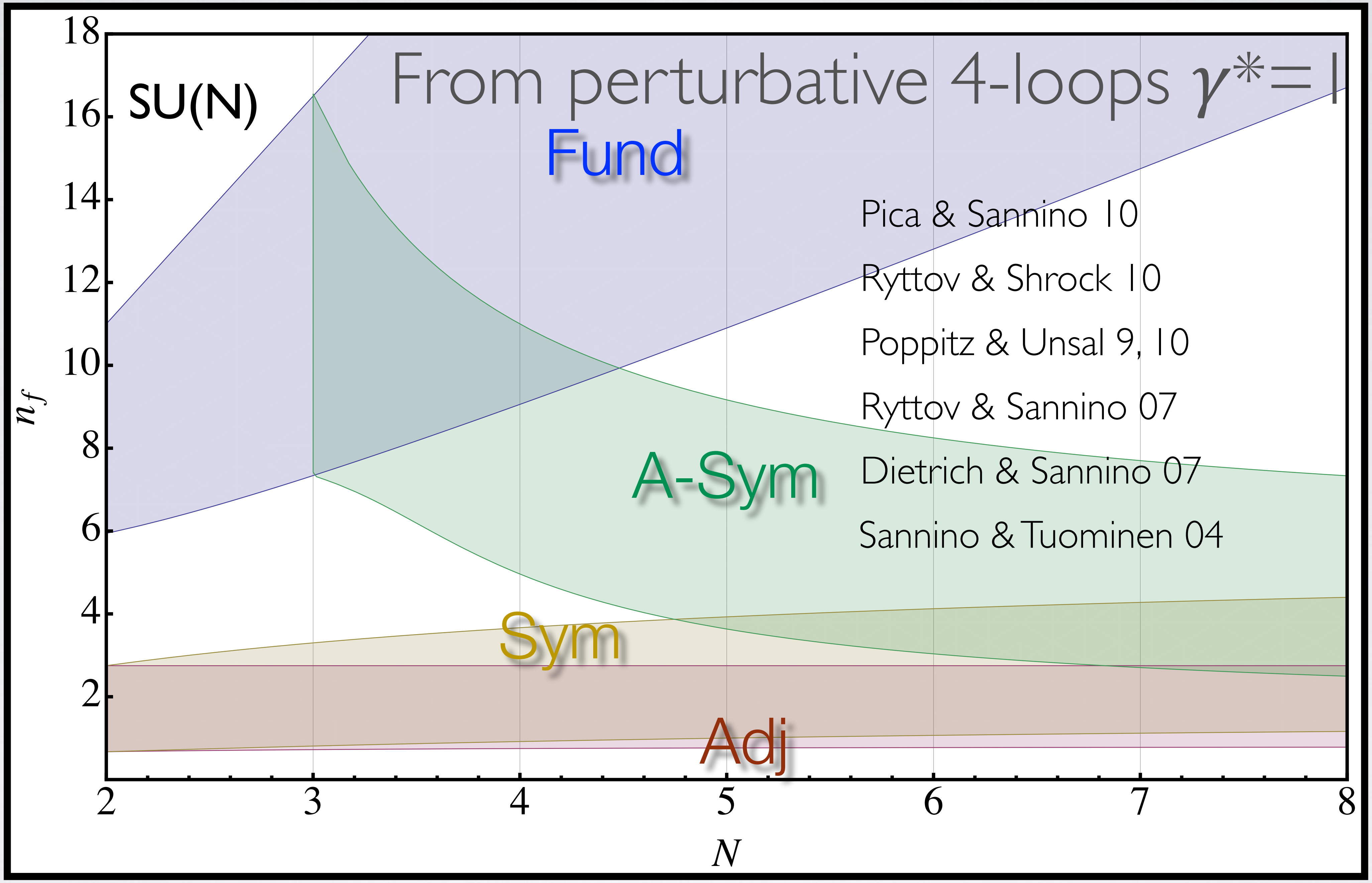
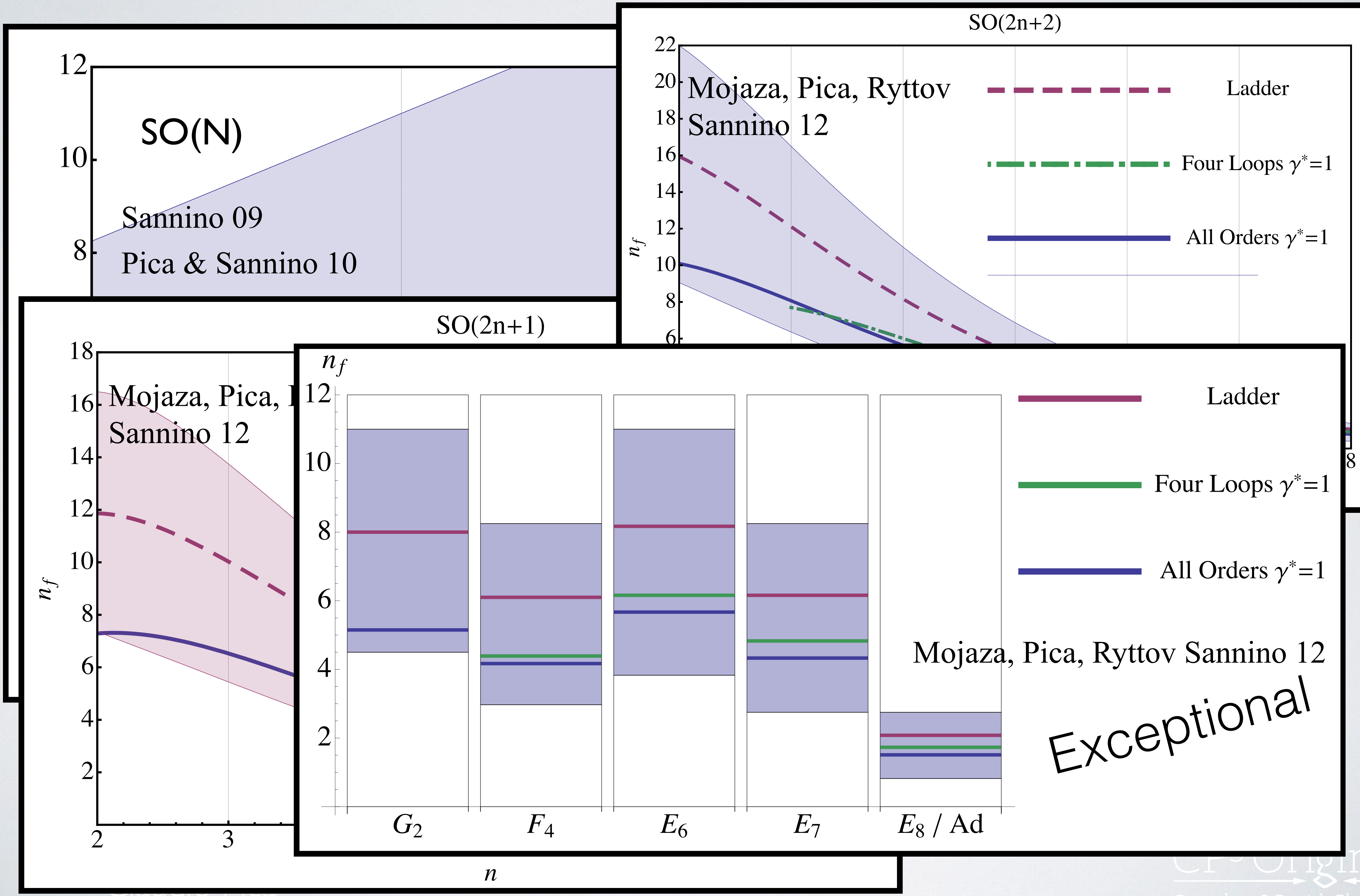
SU(N)

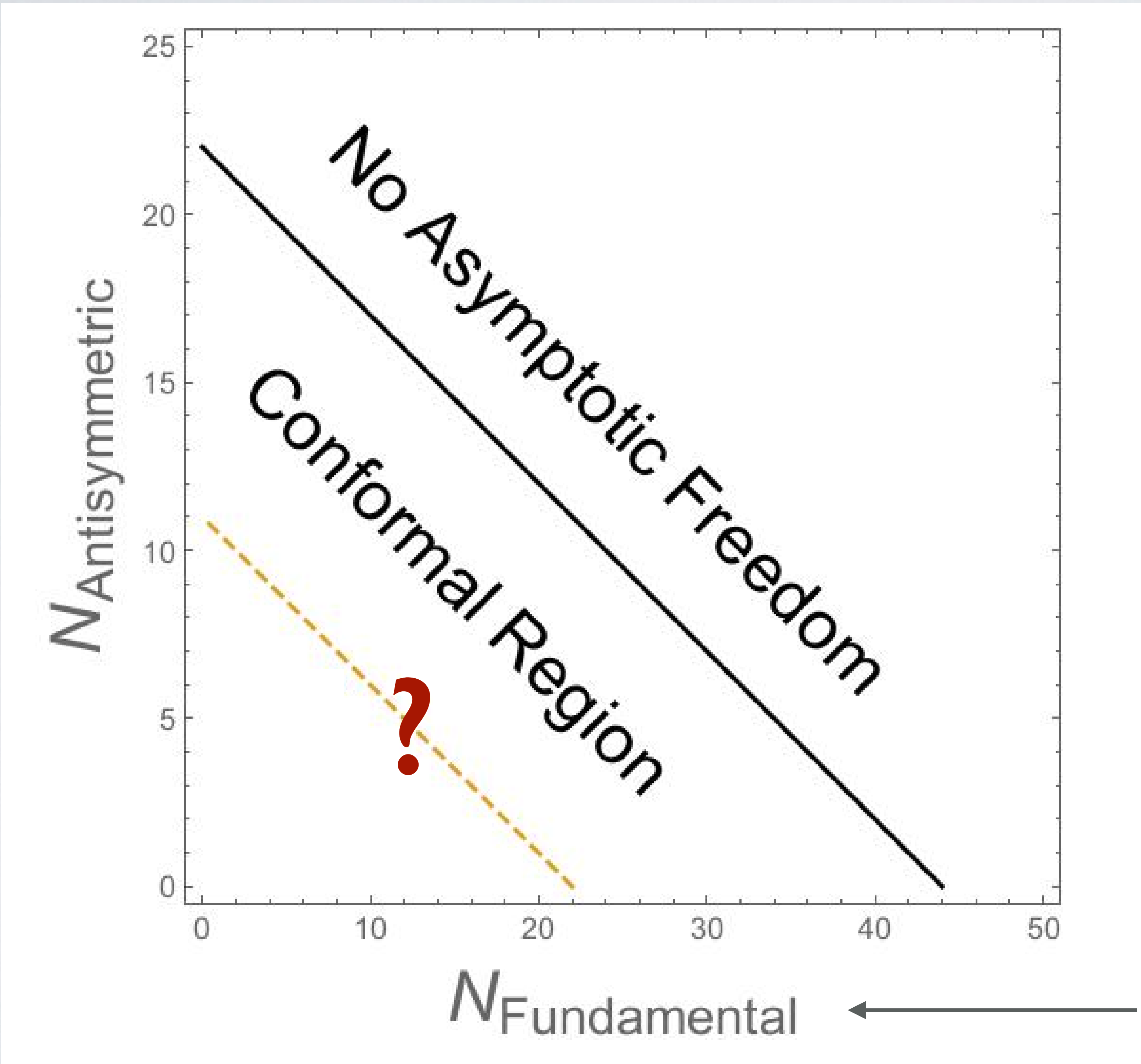


Other methods to estimate the lower boundary available: Schwinger–Dyson eq, counting of thermal d.o.f.,
not all in agreement → **NEED non-perturbative Lattice determination**

Other Gauge Groups



Multiple Representations

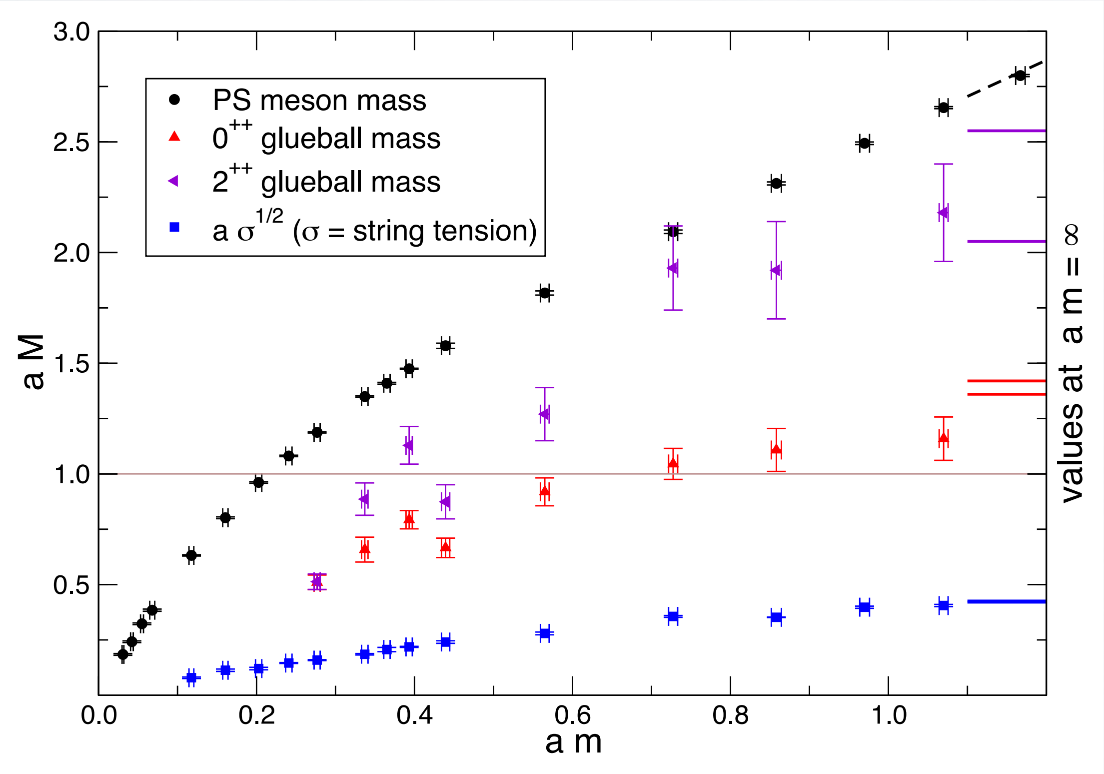


Weyl fermions

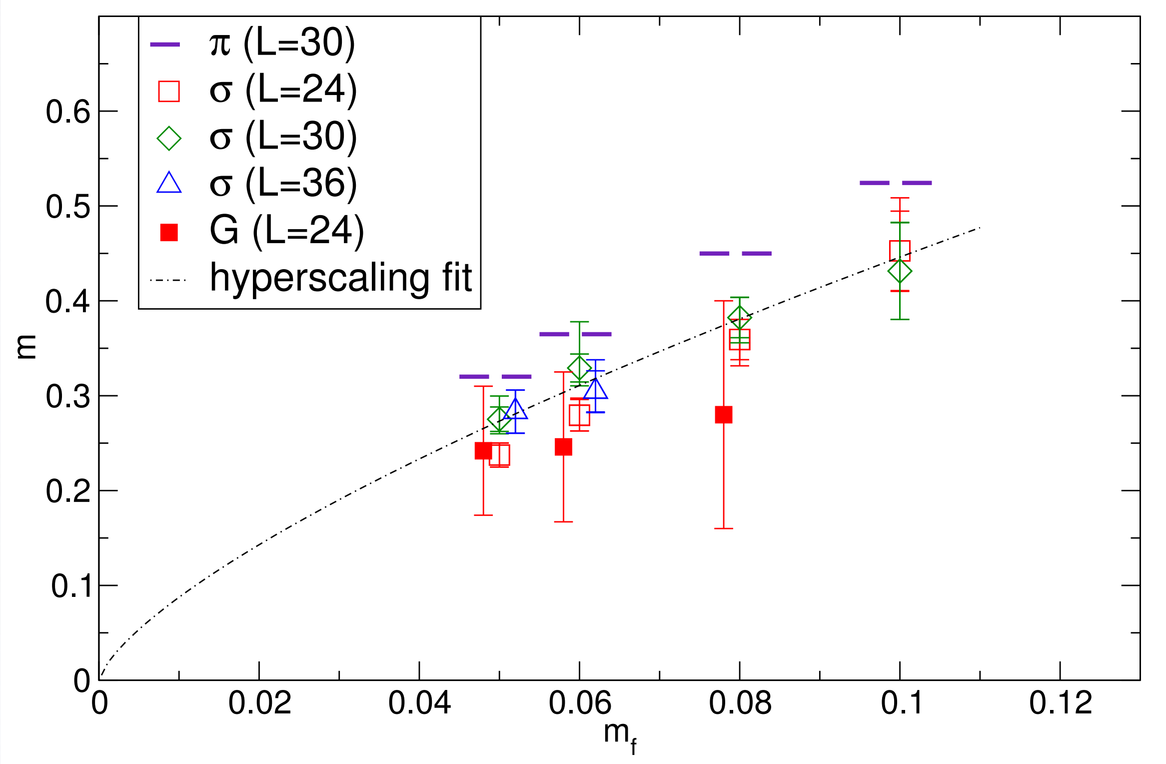
For an estimate of the conformal window, see also:
Ryttov, Sannino, Int.J.Mod.Phys. A25 (2010) 4603-4621 [0906.0307]

Light Scalars in Mass deformed Models

SU(2) Adj Nf=2
Phys. Rev. D 82, 014510 (2010)



SU(3) Fund Nf=12
Phys. Rev. Lett. 111, 162001 (2013)



Are light scalar states a generic feature of mass deformed (weakly coupled?) IR models?

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