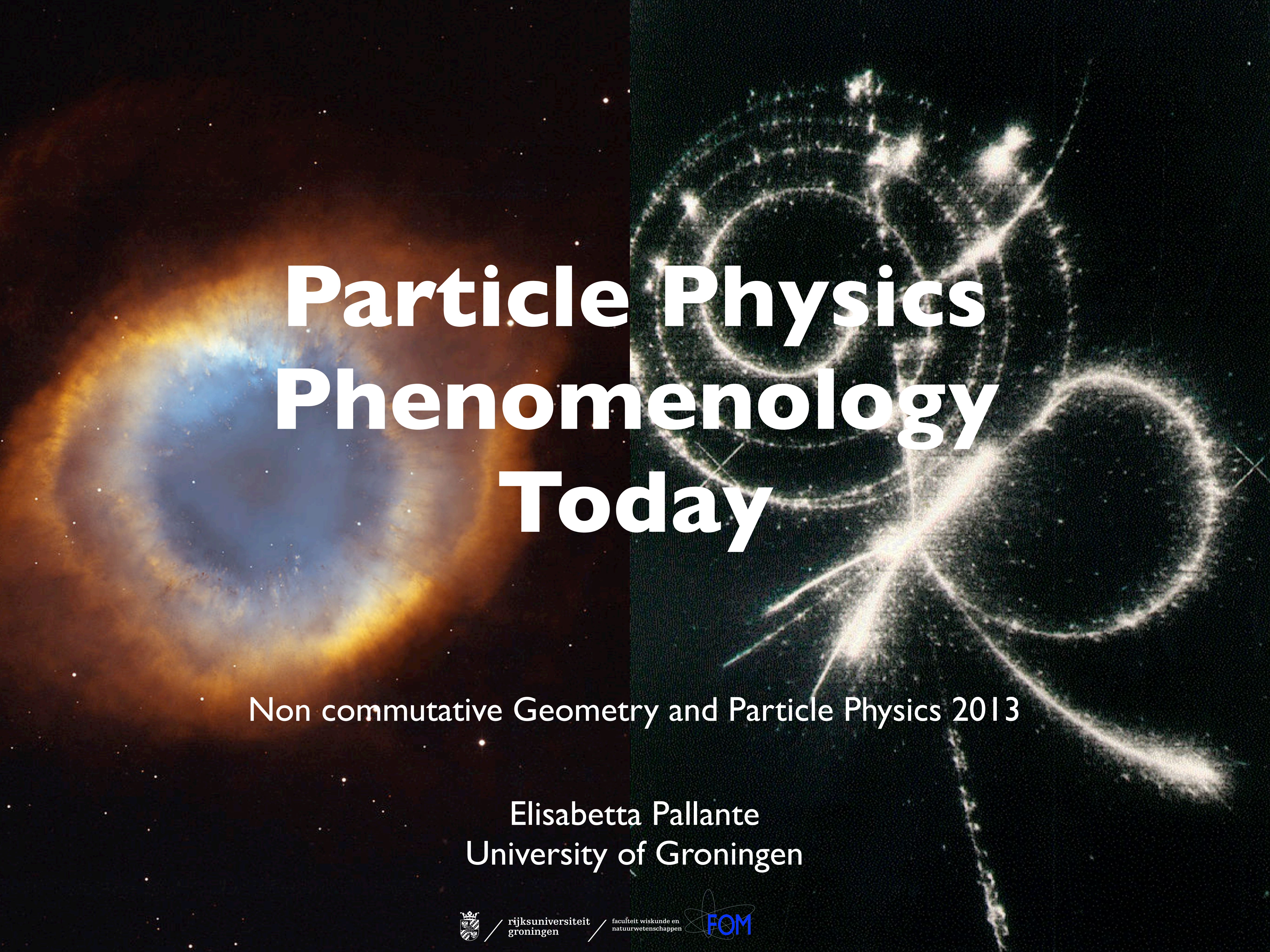

Particle Physics Phenomenology Today

Non commutative Geometry and Particle Physics 2013

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University of Groningen

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Outline

- Snapshot of the desert from Higgs to Planck: Vacuum, scalar fields, hierarchy, unification

- Filling the desert: new scales and new physics supersymmetry and compositeness

- Role of conformal symmetry

- Flavour physics and BSM

- After the LHC

Disparate Scales

1 10^3 10^{19} GeV

confinement ElectroWeak Planck

Is the LHC announcing a desert up to the Planck scale?

Standard Model of
electroweak and strong forces

Gravity

It cannot be a desert

Dark energy (the cosmological constant problem)

Dark matter

Baryon Asymmetry

Neutrinos: Majorana and Dirac

Muon g-2

Electric Dipole Moments (EDMs)

. . .

Cosmology
& Astronomy

Particle Physics

Can one scalar (Higgs) field and some massive neutrinos explain it all ?

i.e. the evolution of our Universe

Find an answer to the following questions:

Stability of the EW vacuum

Renormalization of scalar masses (naturalness)

Hierarchy of scales (gauge hierarchy problem)

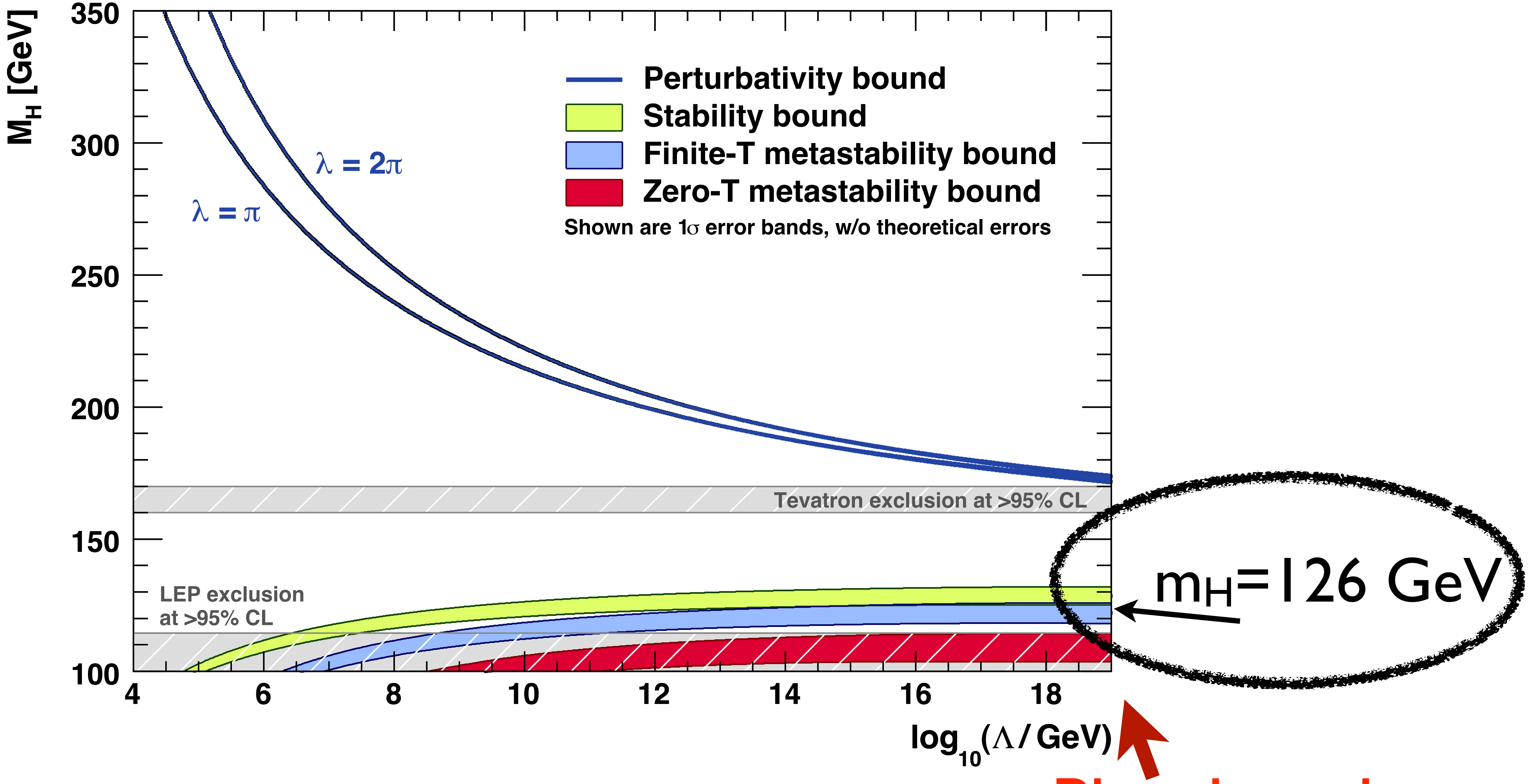
Unification

Stability of the EW vacuum

⇒ triviality and radiative corrections   Cortese Petronzio EP '92

⇒ vacuum stability   Isidori Ridolfi Strumia '01

Ellis et al. '09



m_H=126 GeV

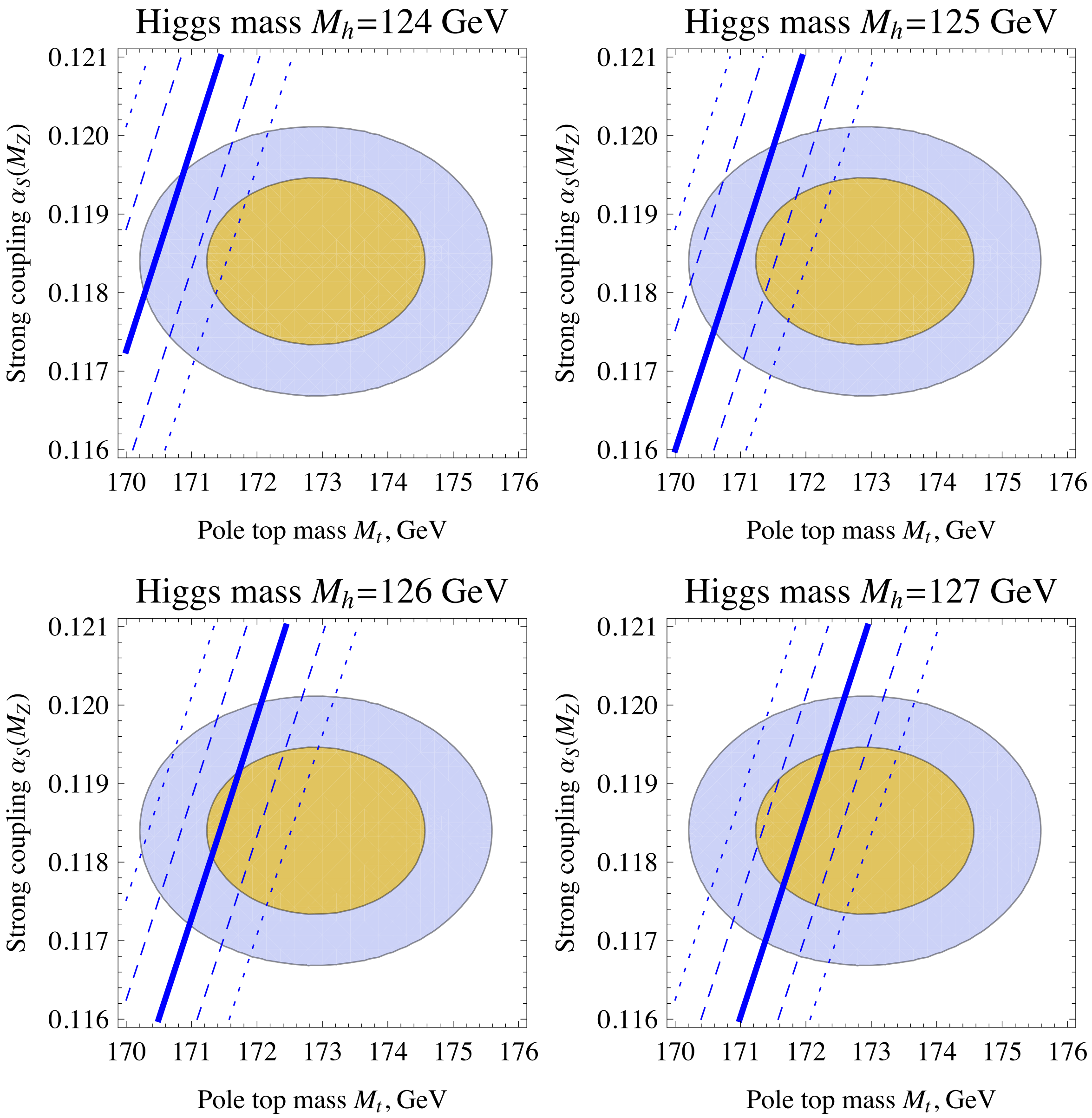
Planck scale

The SM may be a valid EFT up to the Planck scale

Updated stability bound

Bezrukov, Kalmykov, Kniehl, Shaposhnikov 2012

$$M_{\text{min}} = \left[128.95 + \frac{M_t - 172.9\,\text{GeV}}{1.1\,\text{GeV}} \times 2.2 - \frac{\alpha_s - 0.1184}{0.0007} \times 0.56\right] \text{GeV}$$



Present uncertainties do not allow to conclude if M_H=124 -127 GeV indicates stability or metastability of the SM vacuum

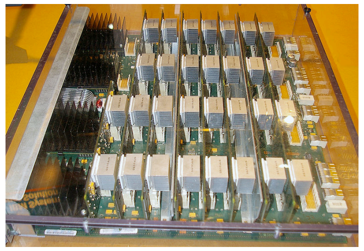
Higgs & the Evolving Universe

LEP and LHC tell us that $M_H > M_{metastability}$: we live in a vacuum with lifetime at least larger than the age of the Universe ⇒ NP is not needed to stabilise the SM vacuum

A numerical coincidence ?
UV stability scale predicted by SM parameters is about the Planck scale

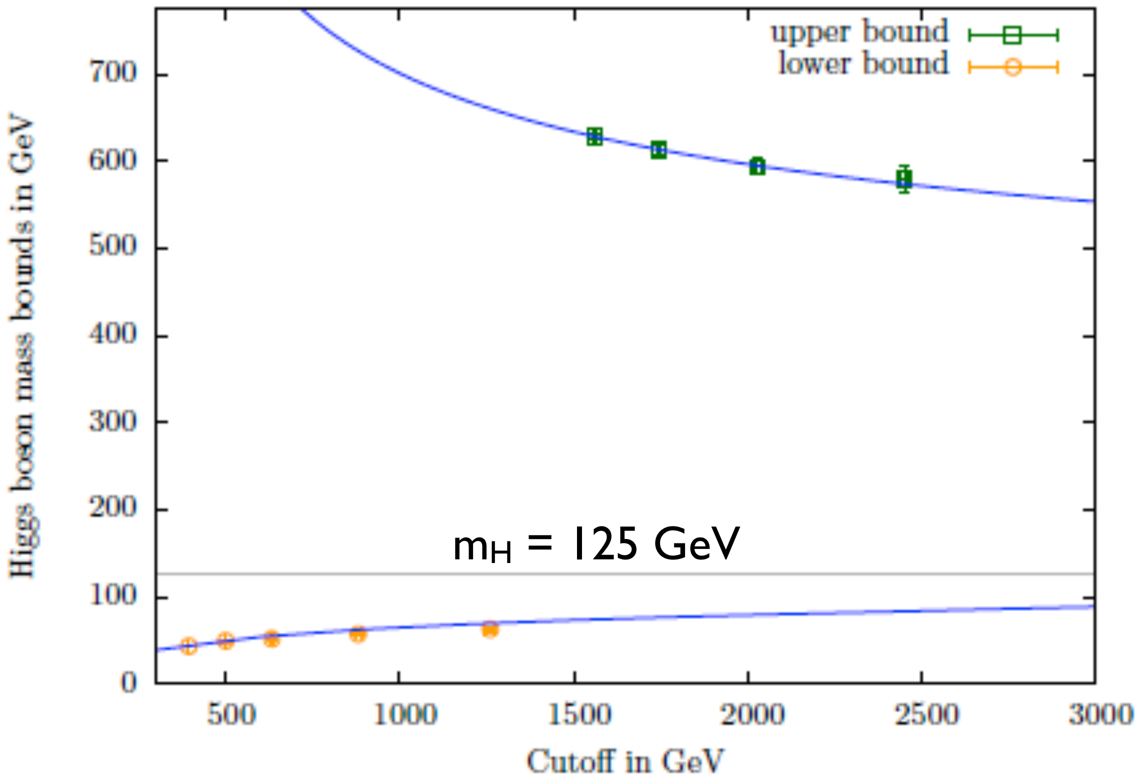
Lattice stability bound

Hedge et al. Adv. High Energy Phys. 2013 (2013) 875612



$$\mathcal{L}_{F+Y}[\bar{\psi},\psi,\phi] = \bar{\psi} D_{ov} \psi + y_b\,(\bar{t},\bar{b})_L \phi b_R + y_t\,(\bar{t},\bar{b})_L \tilde{\phi} t_R + h.c.$$

Overlap fermions with exact $SU(2)_L$ x $U(1)_R$ chiral symmetry



↑ N_f

Λ=1/a $\Lambda \sim 10^{10}$ GeV inaccessible

4th fermion generation excluded
($m_{t'}$> 350 GeV exp. constraint)

Renormalization of scalar masses (naturalness)

Q: Well posed question or inappropriate use of regularization?

SM scalar mass

$$\delta m_h^2 = -4 \sum_f m_f^2 \frac{\Lambda^2}{v^2} + \left(2m_W^2 + m_Z^2 + m_h^2\right) \frac{\Lambda^2}{v^2}$$

conformal symmetry broken

SM fermion mass

$$\delta m_f = A\, m_f \ln \frac{\Lambda}{v} \qquad A > 0$$

chiral symmetry protection

Rescued by scale invariance (conformal symmetry)

$$\boxed{T^{\mu}_{\mu} \sim \sum_i \beta_i(\{g\},\{\lambda\}) \cdot O_i^{(d=4)} + \text{mass terms}}$$

$$\begin{aligned} T^{\mu}_{\mu\, classical} &= 2m_h^2\, h^\dagger h \\ T^{\mu}_{\mu\, one\ loop} &= 2\delta m_h^2\, h^\dagger h + \sum_i \beta_i(\{g\},\{\lambda\}) \cdot O_i^{(d=4)} \end{aligned}$$

$\delta m_h^2 \sim \Lambda^2$ $\longrightarrow$ explicit breaking of conformal symmetry

$\delta m_h^2 \sim m_h^2$ $\longrightarrow$ spontaneous breaking of conformal symmetry

Introduce a dilaton field

Exercise: classical scalar theory

[S. Coleman 'Aspects of symmetry']

$$\mathcal{L}_m = -\frac{1}{2}m^2\phi^2 \to -\frac{1}{2}m^2\phi^2\, e^{2f\sigma} \qquad \chi(x) = \frac{1}{f}e^{f\sigma(x)}$$

dilaton field
=
Goldstone boson of scale
(conformal) invariance

$$\int d^4x\, \delta\mathcal{L}_m = 0$$

Realize PCDC by adding a mass term for the dilaton

$$\mathcal{L}_B = -\frac{1}{2}m_\sigma^2\sigma^2 + O(\sigma^3) \Longrightarrow \partial_\mu s^\mu = T^\mu_\mu = -\frac{m_\sigma^2}{f}\,\sigma$$

Extend to the quantized theory

Open questions: unitarity, uniqueness, which SM sectors?

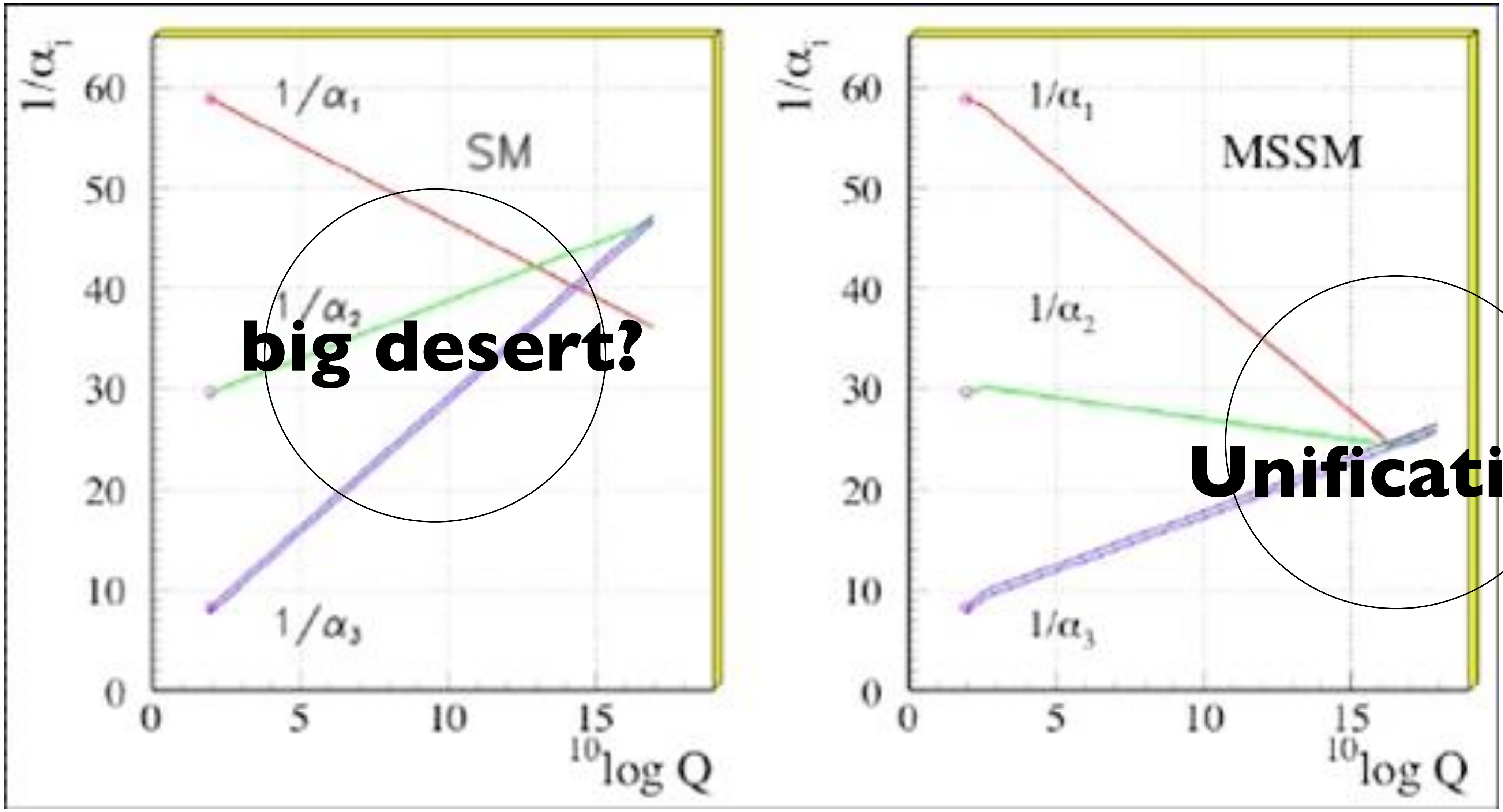
[see e.g. Shaposhnikov, Zenhausern arXiv:0809.3406]

scalar sector: $\frac{1}{2}m_{Higgs}^2 H^2 \to \frac{1}{2}\partial_\mu\chi\partial^\mu\chi - \lambda(H^2 - \zeta^2\chi^2)^2$

Hierarchy of scales and unification of forces

Q: Are there new relevant scales between Higgs/Fermi and Planck?

Two known scenarios



big desert?

Unification?

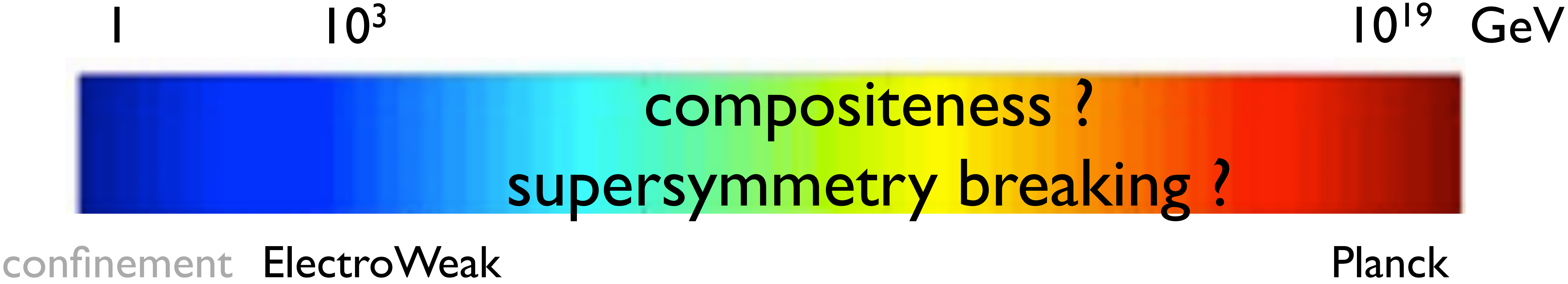
Two avenues

Add new scales
⇔ new particles

e.g.
(weakly coupled) supersymmetry
(strongly coupled) compositeness

No new scale
⇔ minimal particle content

e.g.
Conformal symmetry at Planck
Need to break it spontaneously



1 10^3 10^{19} GeV

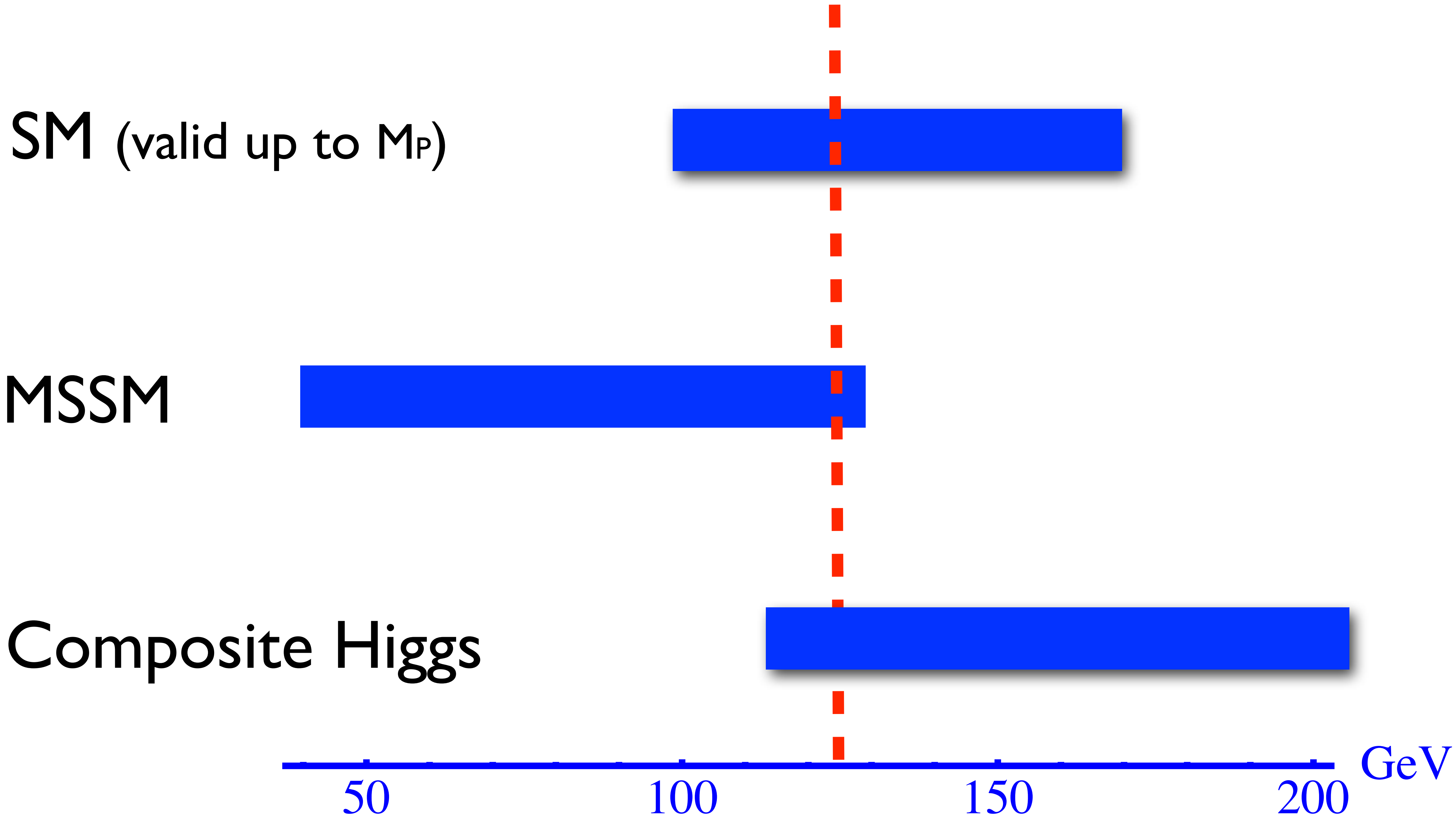
compositeness ?

supersymmetry breaking ?

confinement ElectroWeak Planck

Higgs mass range

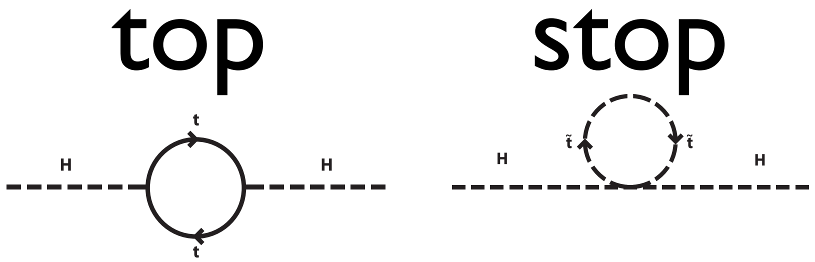
Pomarol @ICHEP12



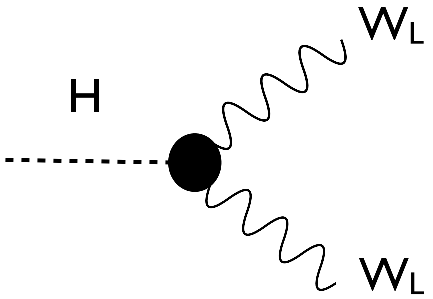
m_H = 125 GeV

Main stream solutions have invoked the criterion of naturalness (along with unification of gauge forces) for the last 40 years

SUPERSYMMETRY Djouadi 08



COMPOSITENESS Bhattacharyya 11



without or with extra spatial dimensions (RS, ADD, etc)

Compositeness

Superconductivity	Confinement
Cooper pairs <ee>	quark condensate <qq>
weakly coupled	strongly coupled

Postulate strong dynamics BSM (no decoupling of h.o. operators)
→ light composite Higgs

The Higgs boson can be the pNGB of an extended global symmetry or the dilaton of a spontaneously broken CFT ⇒ SM couplings modified

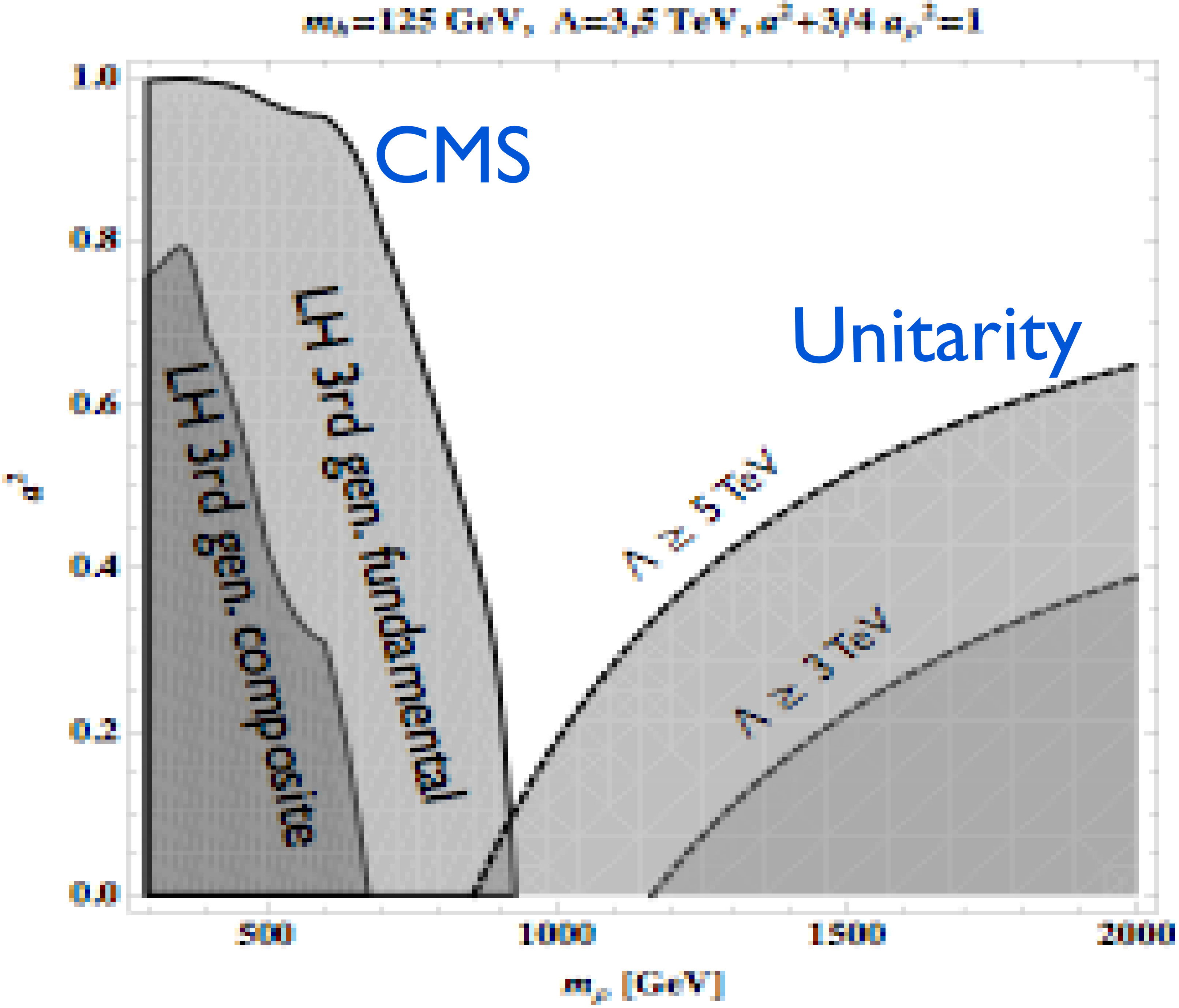
LHC data constrain the compositeness scale and the spectrum

The more the couplings deviate from the SM, the lighter the new composites (resonances) must be to ensure unitarity up to the compositeness scale Λ

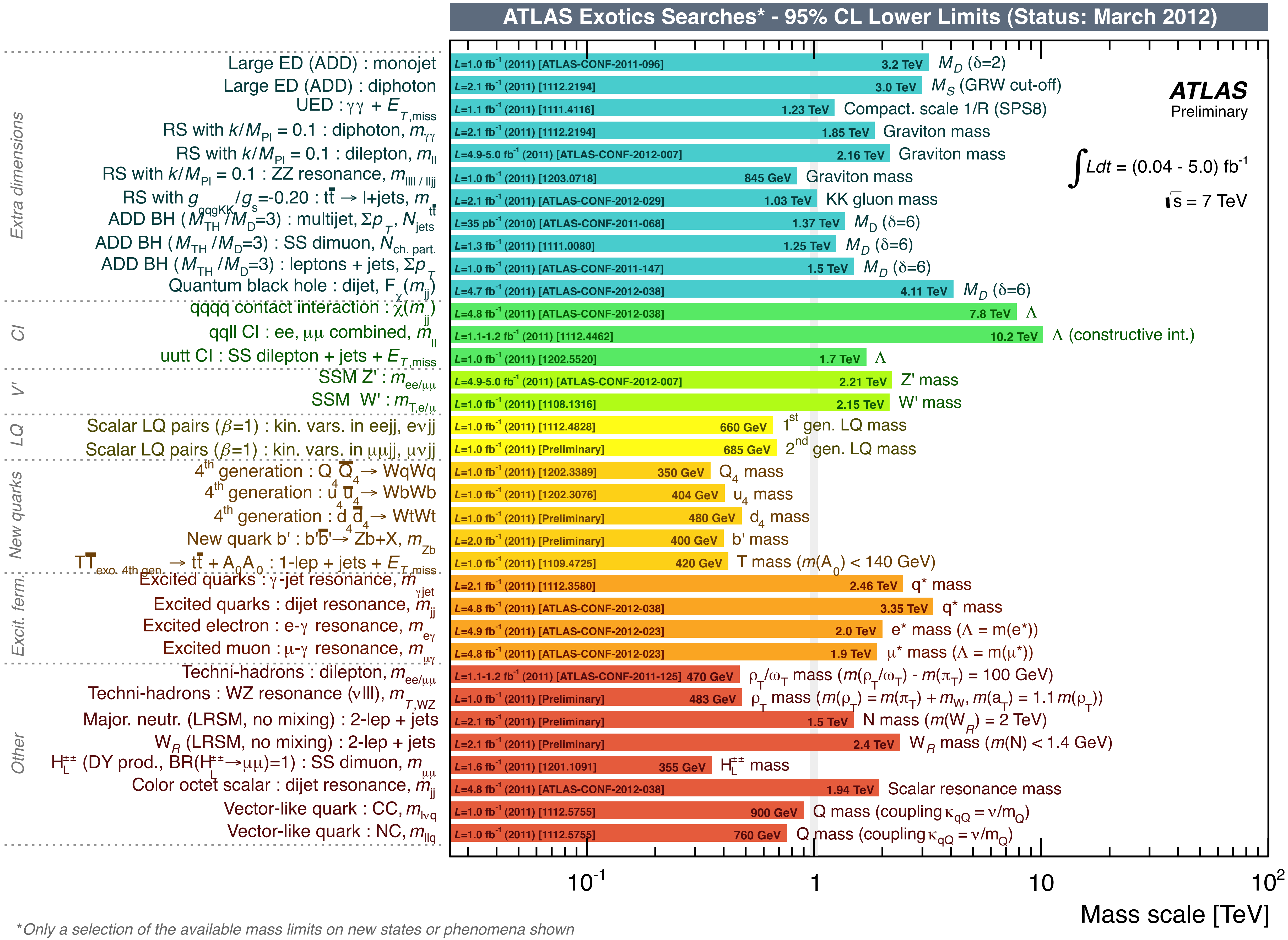
The Higgs postpones the onset of the vector resonance to higher masses w.r.t. to Higgsless models ⇒ improve compatibility with LHC constraints

Strongest direct constraints on the ρ come from di-boson searches at LHC $\rho^{\pm} \rightarrow W^{\pm} Z \rightarrow 3\, l + \nu$.

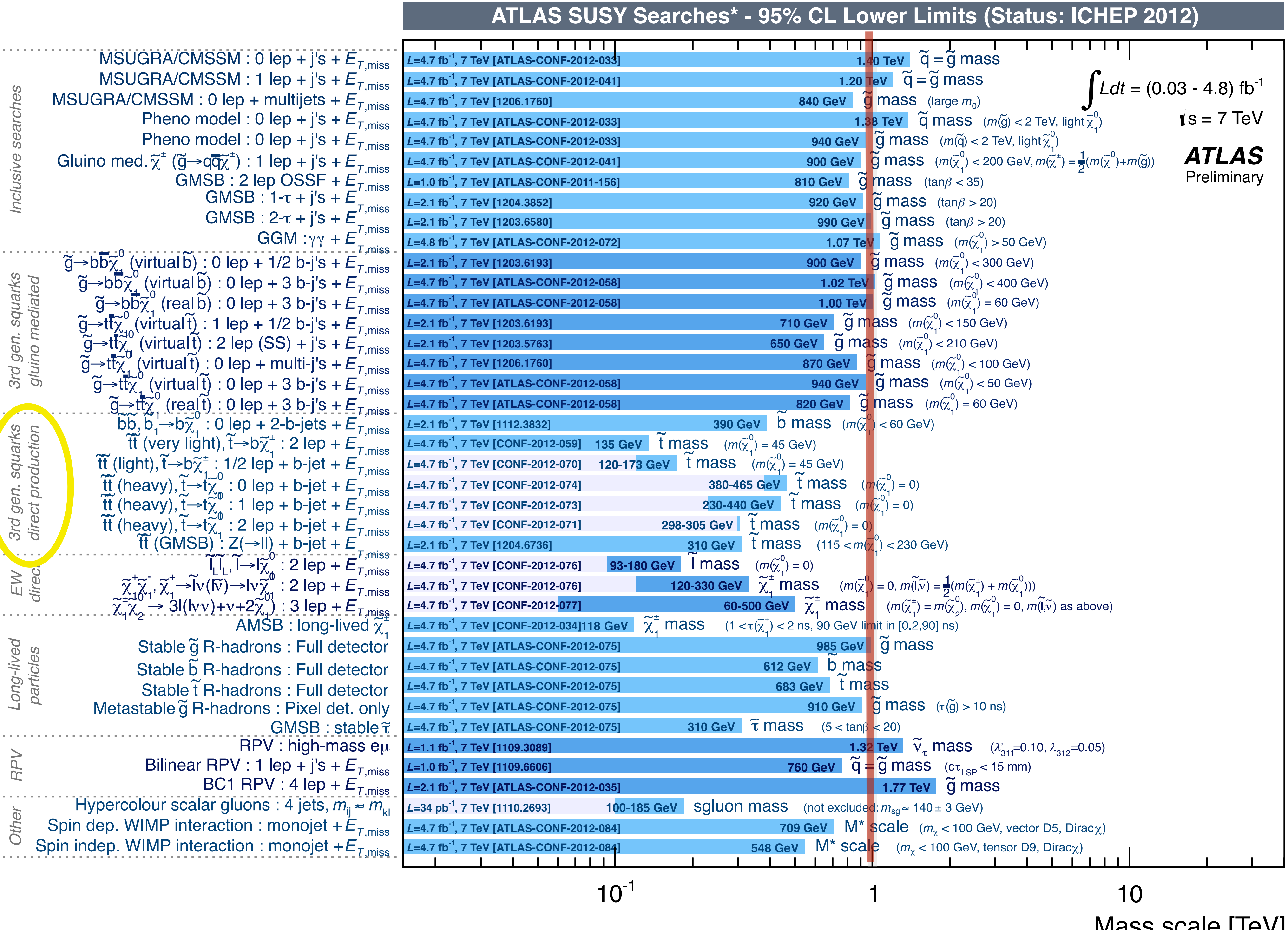
Bellazzini, Csaki, Hubisz, Serra, Terning 2012



From CMS results the interesting range 700 GeV < m_ρ < 2 TeV is allowed



*Only a selection of the available mass limits on new states or phenomena shown

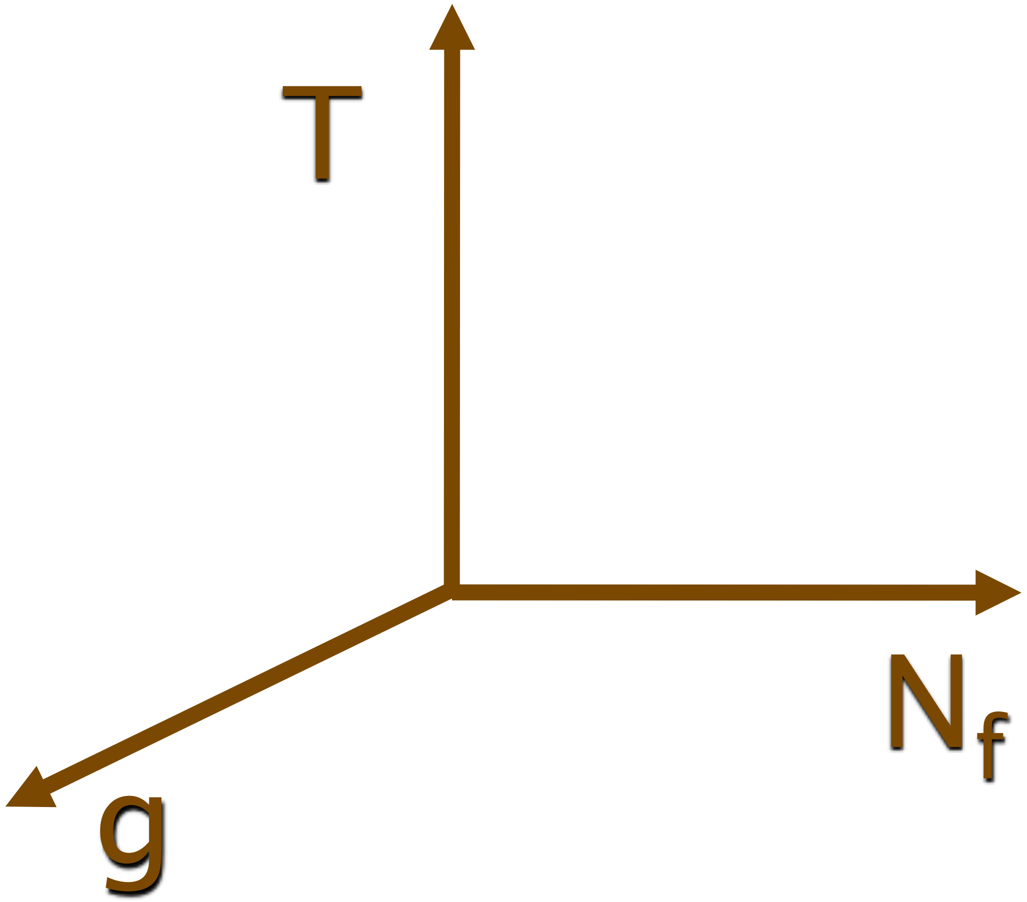


*Only a selection of the available mass limits on new states or phenomena shown

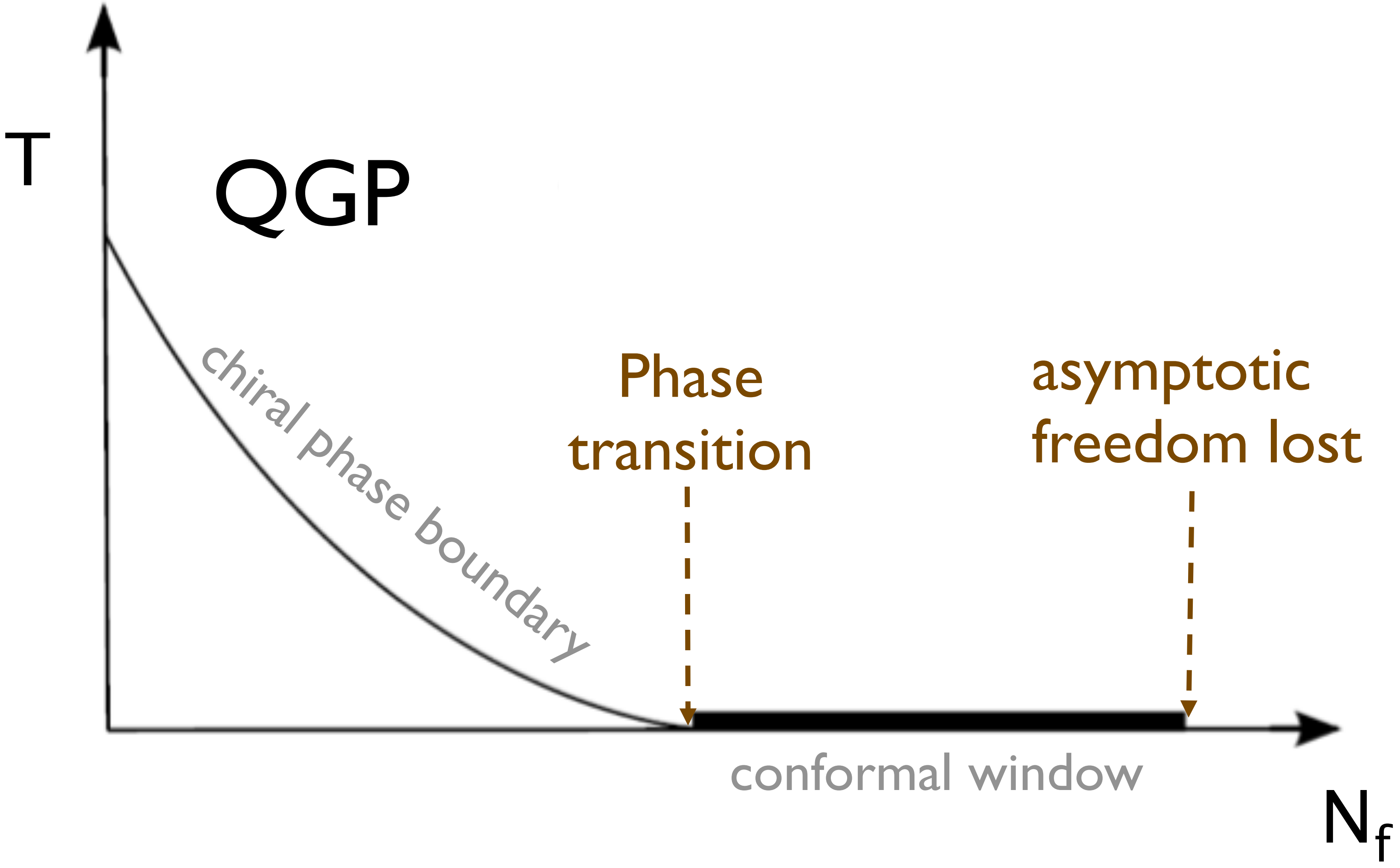
More on the role of Conformal Symmetry

A pedagogical example
What is the fixed point structure of fundamental forces?

The phase diagram of SU(N) gauge theories



QCD: fundamental fermions



Physics of:

✓quark gluon plasma (QGP): high T - low Nf
✓preconformal regime (T=0, low T - high Nf)
✓conformal regime (T=0)

Less flavour for larger Casimir

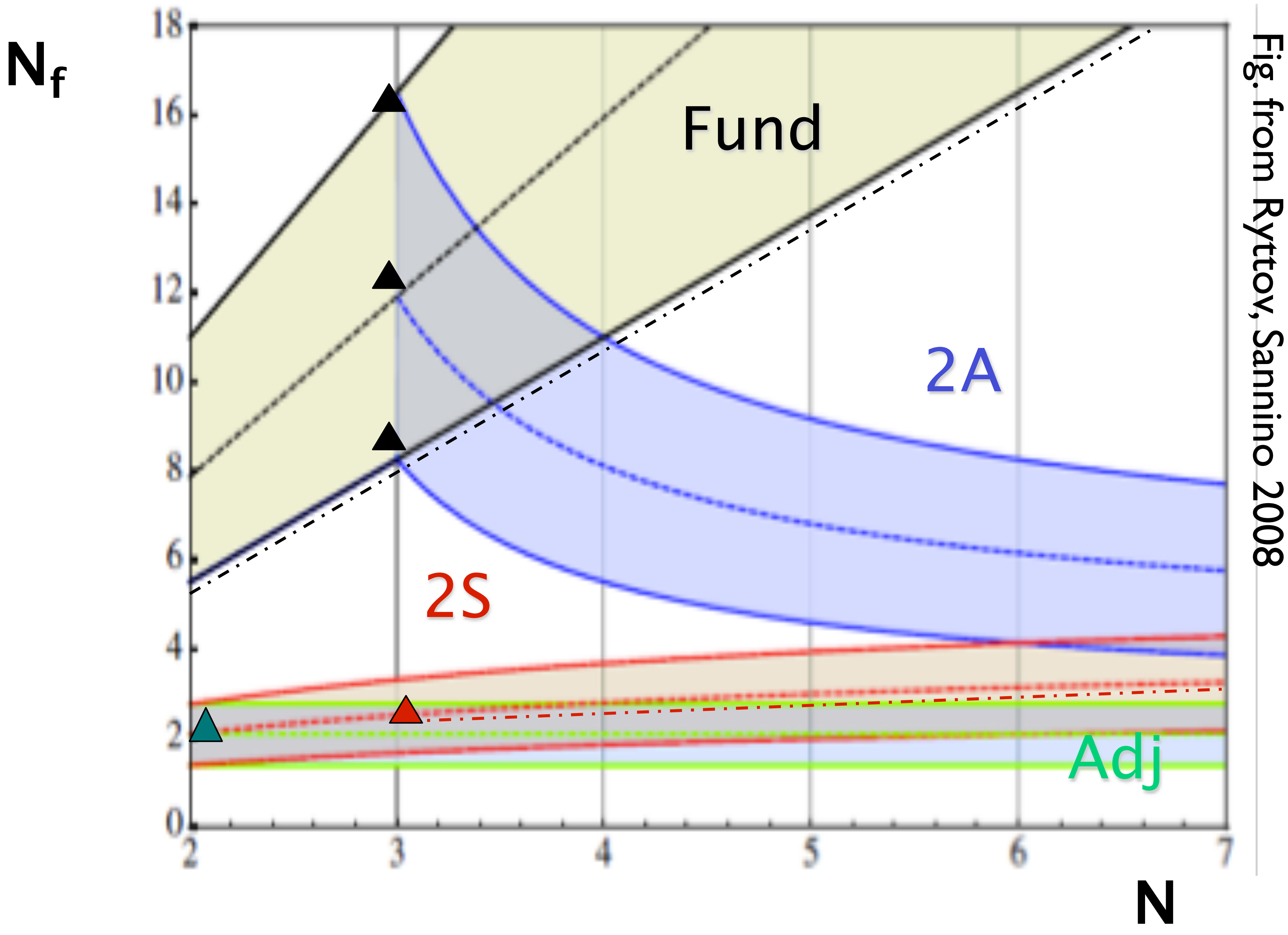


Fig. from Ryttov, Sannino 2008

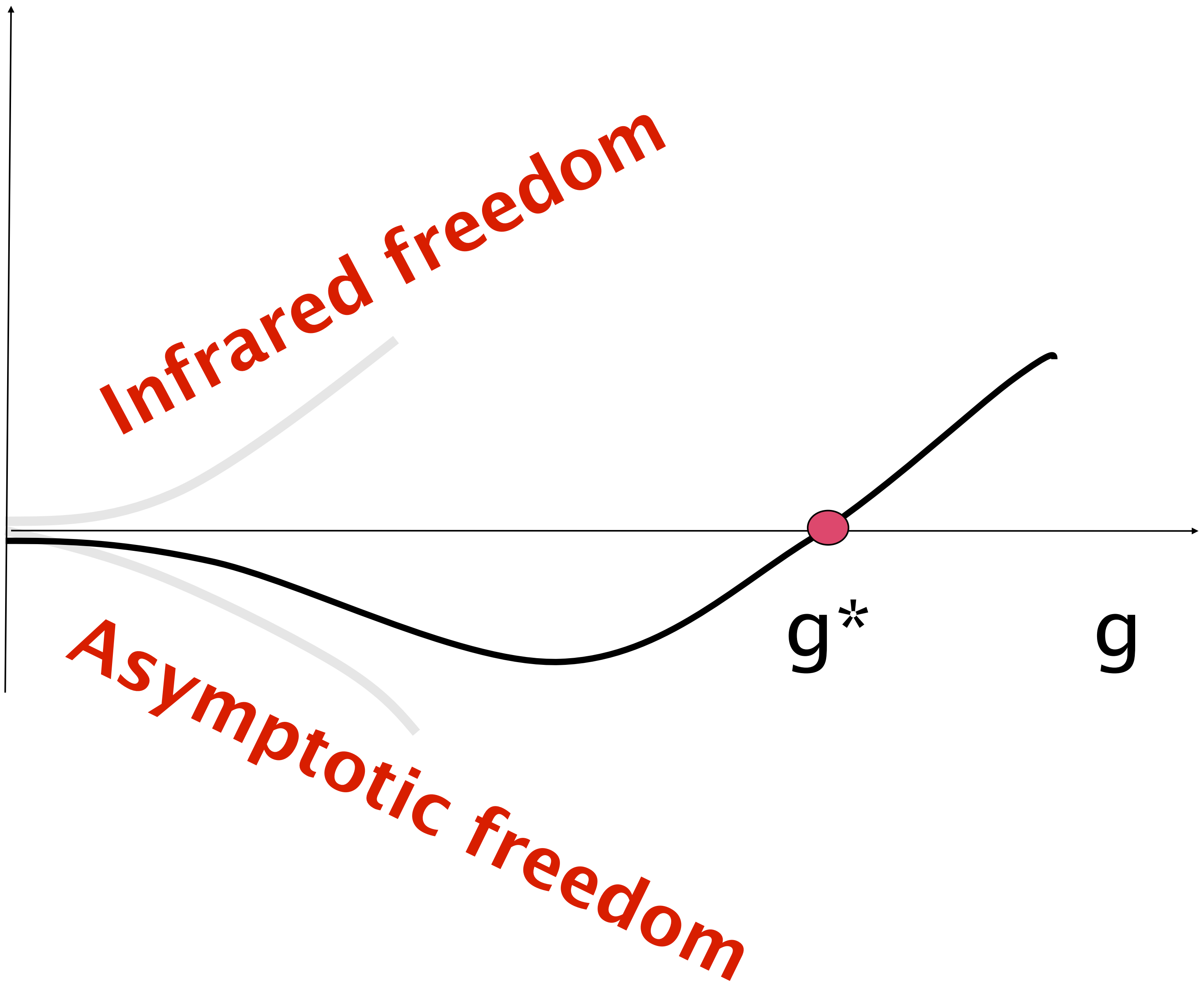
$$\beta(g) = -b_0 g^3 \; - \; b_1 g^5 \; + \ldots$$

The first two (universal) coefficients change sign by varying flavours

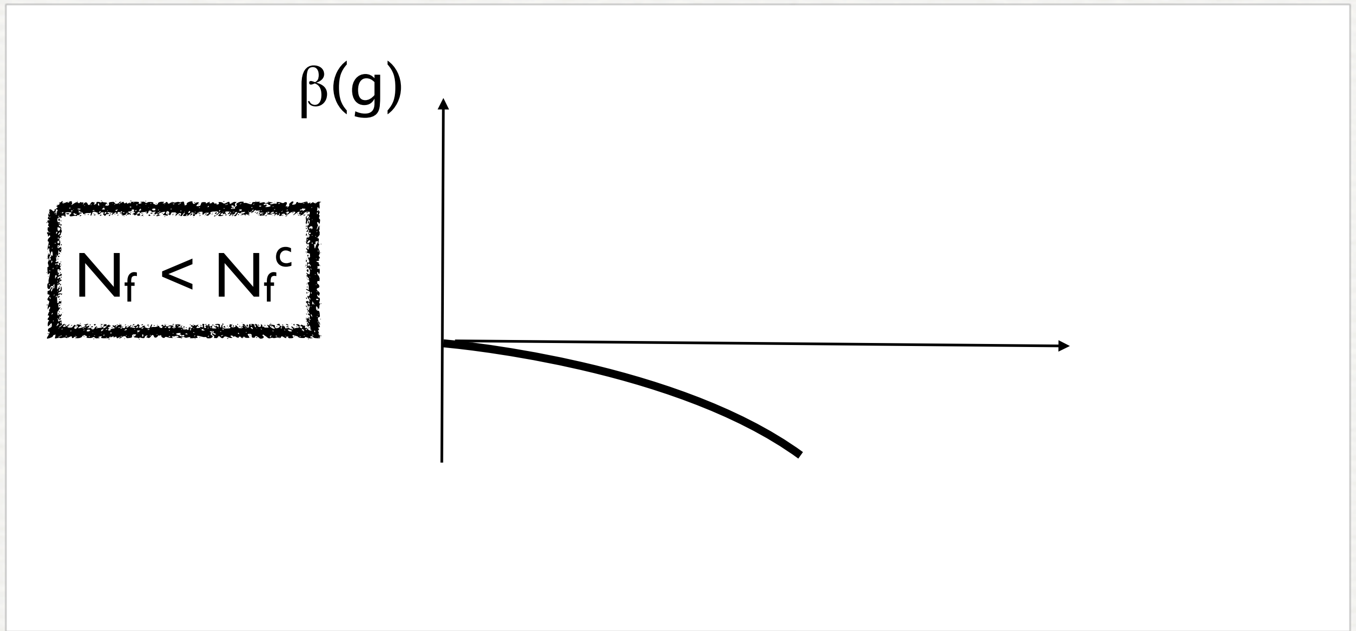
Caswell 1974
Banks,Zaks 1982

$$b_0 = \tfrac{1}{16\pi^2}\left(\underset{\substack{\uparrow \\ \text{N=3}}}{11} - \tfrac{2}{3}N_f\right) \qquad b_1 = \tfrac{1}{(16\pi^2)^2}\left(\underset{\substack{\uparrow \\ \text{N=3}}}{102} - \tfrac{38}{3}N_f\right)$$

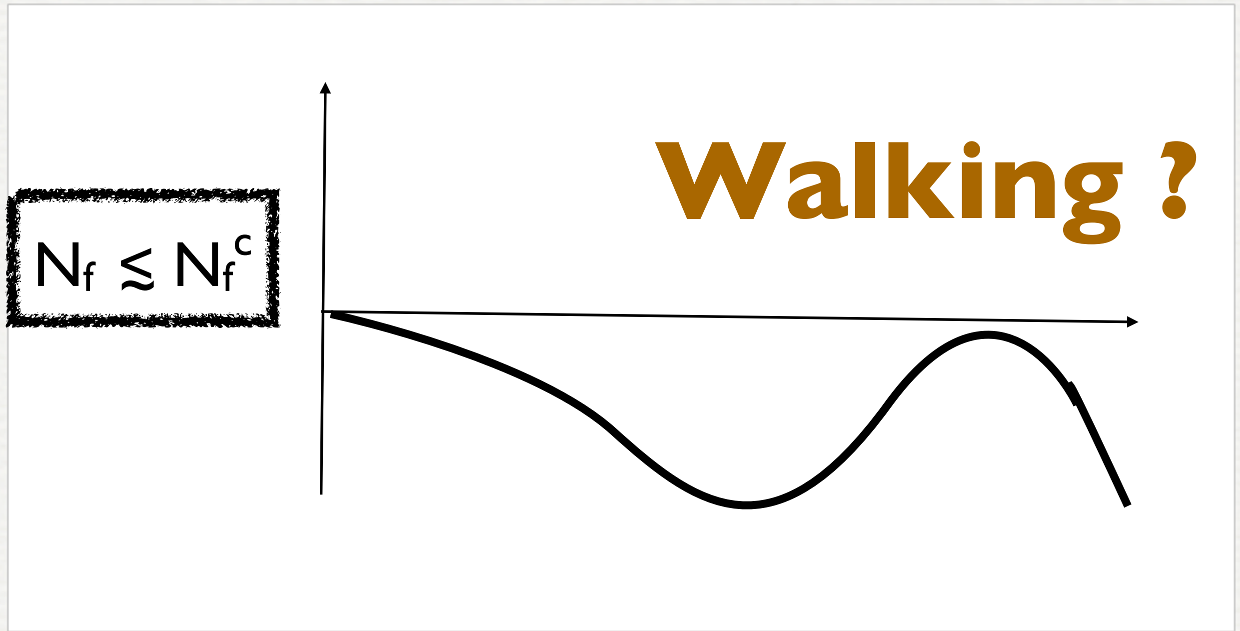
$$\beta(g)=\mu\ dg/d\mu$$



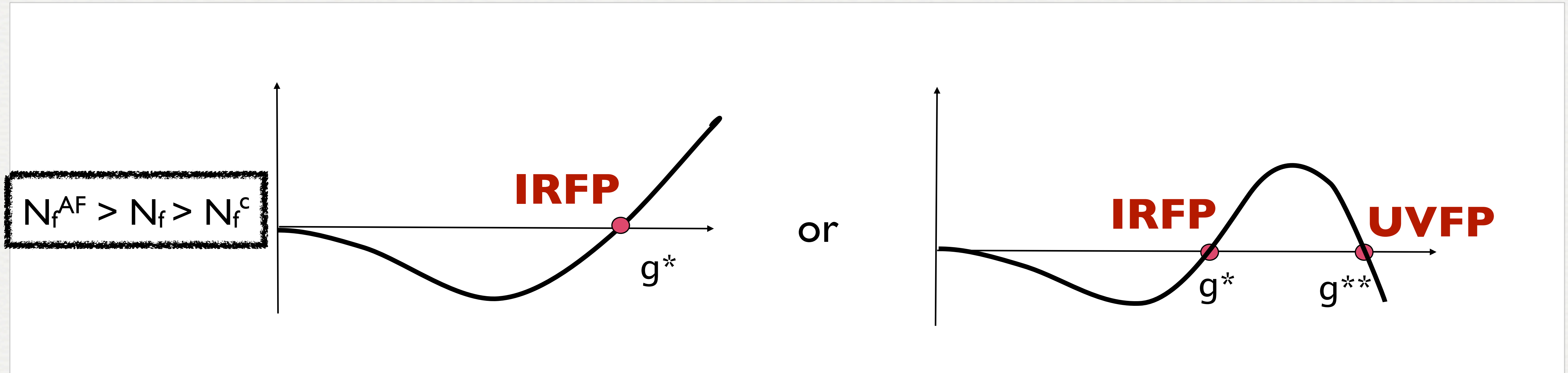
The 4D theory is conformal at g* with anomalous dimensions



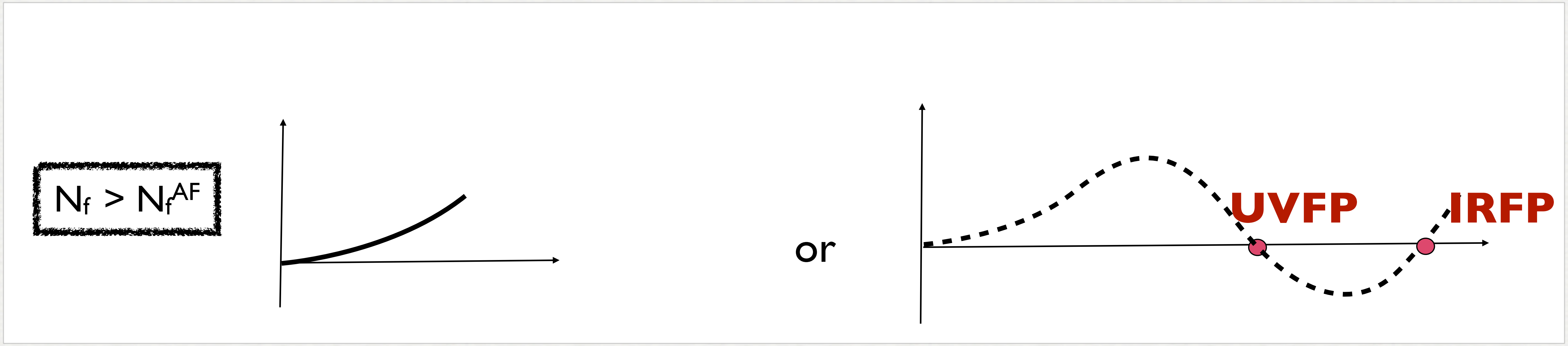
$N_f < N_f^c$



$N_f \lesssim N_f^c$

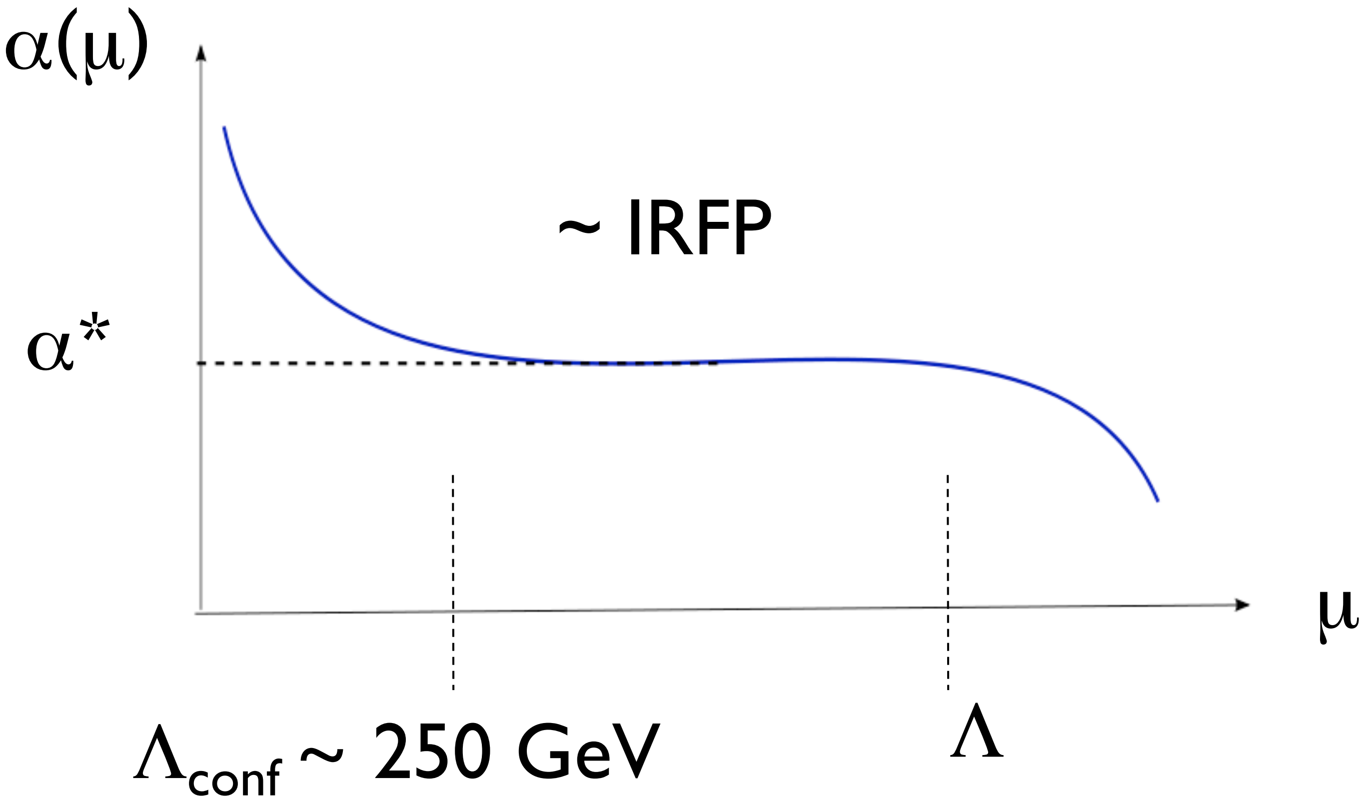


$N_f^{AF} > N_f > N_f^c$



$N_f > N_f^{AF}$

Walking regime



Large and slowly running anomalous dimensions

$$\langle\bar{\psi}\psi\rangle_{\Lambda'} = \langle\bar{\psi}\psi\rangle_{\Lambda}\, e^{\int_{\Lambda}^{\Lambda'} \frac{d\mu}{\mu}\,\gamma(\mu)} \simeq \langle\bar{\psi}\psi\rangle_{\Lambda} \left(\frac{\Lambda'}{\Lambda}\right)^{\gamma}$$

produce a large hierarchy of condensates

The ultraviolet fate of the Standard Model

IR

$g_{SU(3)}$ confinement

UV

$g_{U(1)}$ Landau pole

Before the top discovery [Pendleton, Ross 1981]

i) y_t and λ share AF and develop an IRFP if only gauge coupling $g_{SU(3)}$

ii) running of light quark masses and charged leptons unaffected by y_t, light down quark masses receive small contributions

iii) RG running of m_b/m_τ dominated by y_t

iv) gauge couplings unaffected by y_t at one loop

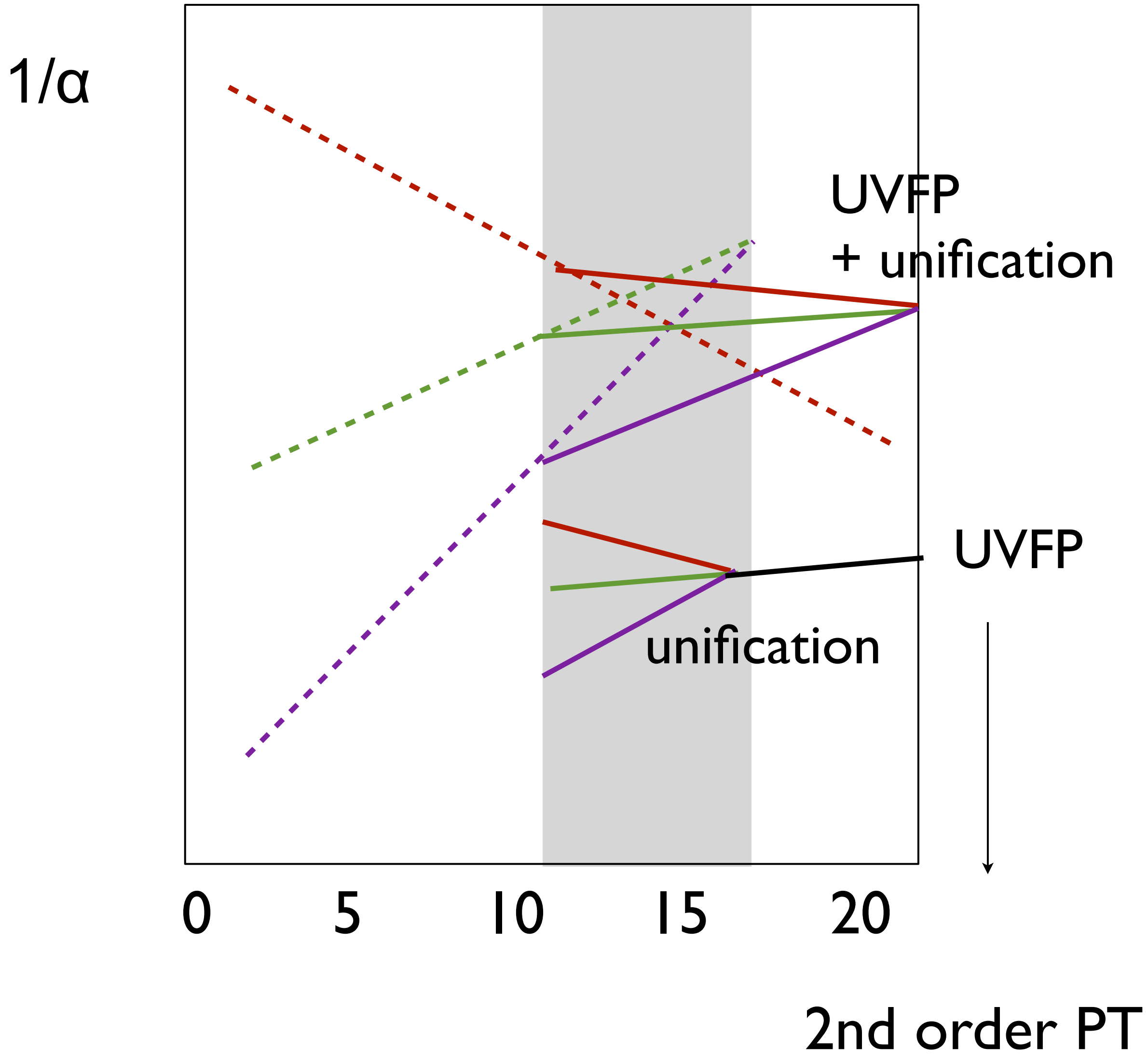
v) CKM mixing angles and phase seem to slowly approach an IRFP at zero

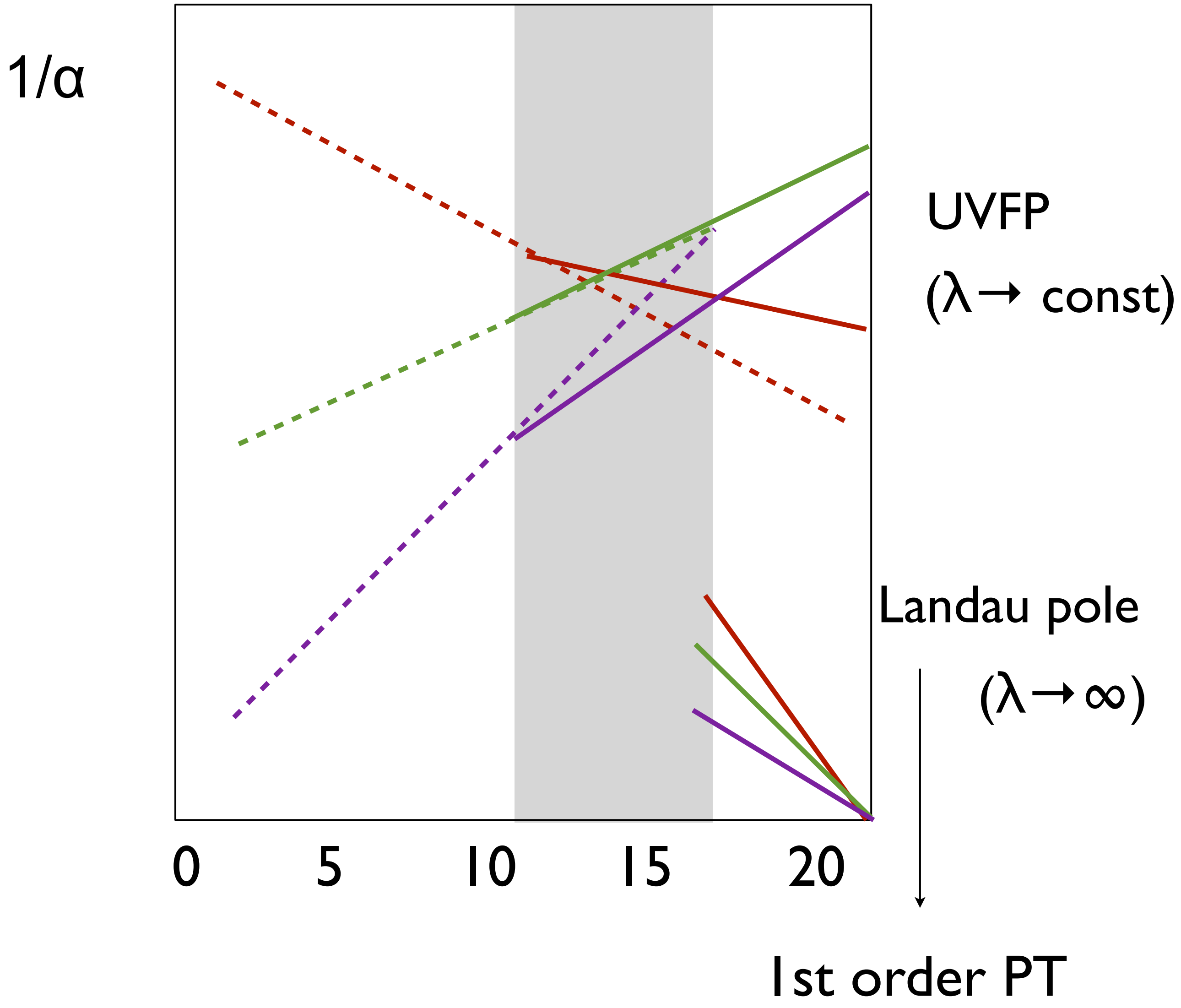
Scenarios at the Planck scale

Ingredients
New particle thresholds
New symmetries
Walking (near-conformal)

Caveats
Failure of e.g. SU(5)
$g_{1,2,3}$ enter strong coupling
⇒ no pert theory

$y_t \to 0$ for $\Lambda \to \Lambda_{\mathrm{Planck}}$ plausible ?
$\lambda \to 0$ or $\lambda \to \infty$ or $\lambda \to$ const (asymptotic safety)

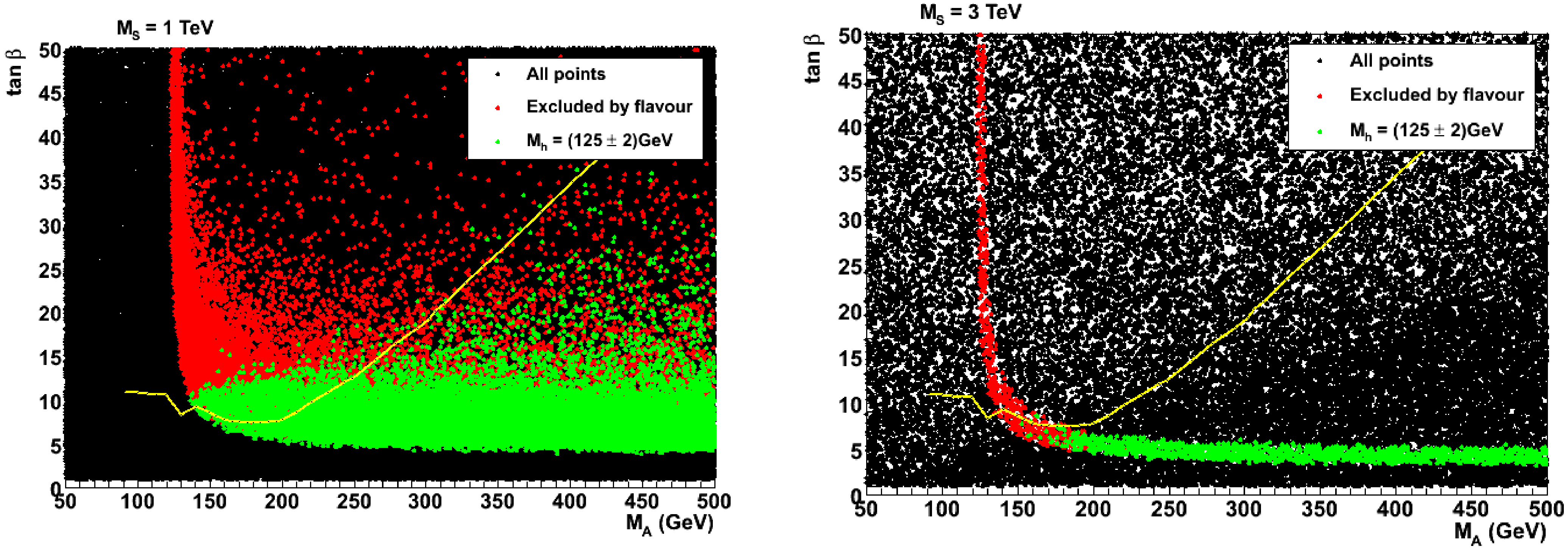




Flavour physics

Flavor@LHC and new physics

SUSY example: pMSSM maximal mixing scenario (N. Mahmoudi, Moriond 2012)



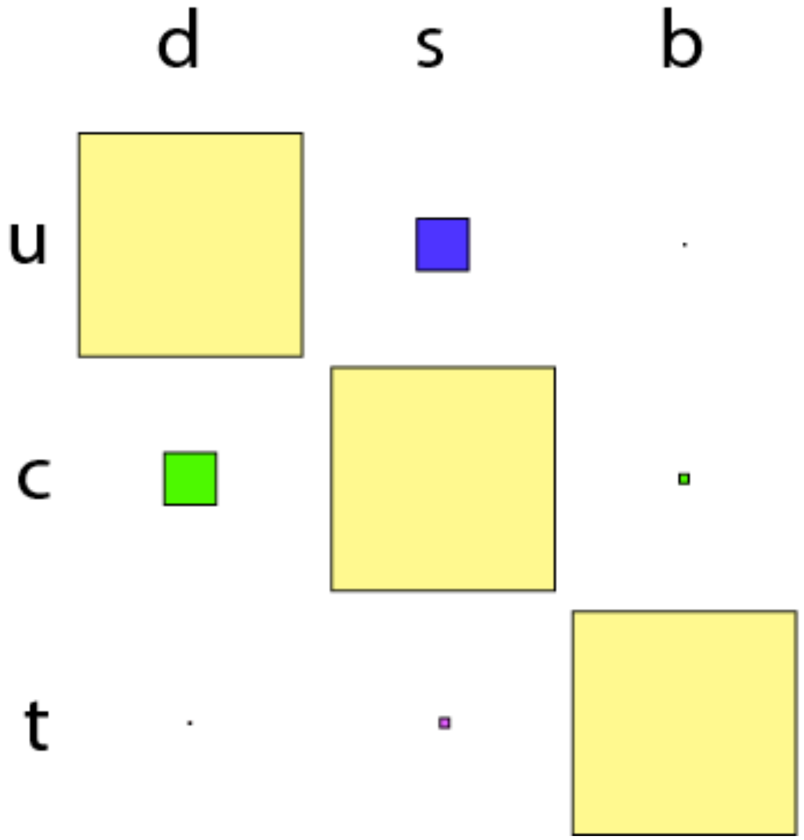
yellow line: CMS limit with 4.6/fb

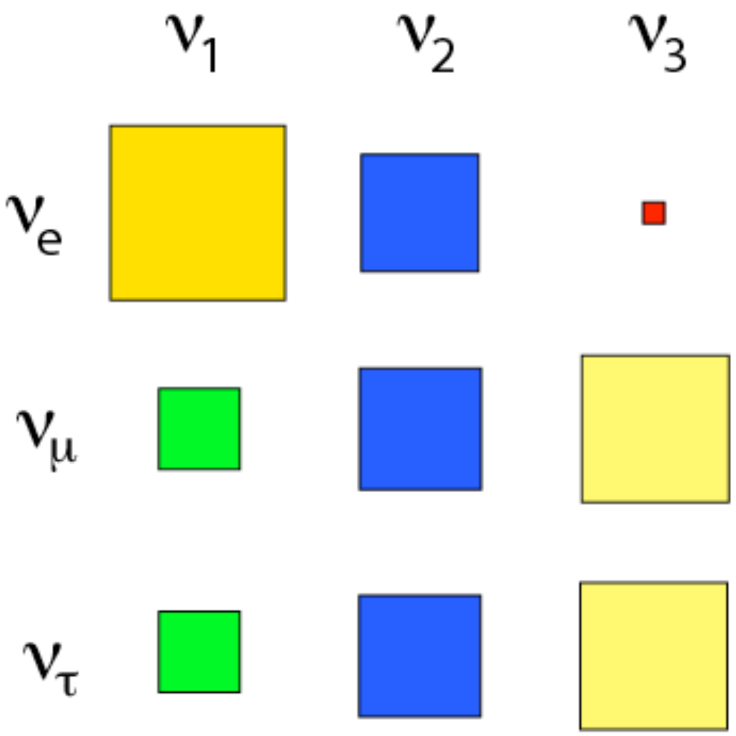
Flavor constraints from: $b \to s\gamma$, $B \to \tau\nu$ and new LHCb limit on $B_s \to \mu^+\mu^-$

Assumed discovery of Higgs at (125 ± 2) GeV

Mass & mixing patterns for quarks and leptons

Experimental mixing patterns





$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = V_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$V_{CKM} = \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \ldots$$

$$|V_{PMNS}|^2 = \begin{pmatrix} \frac{2}{3} & \frac{1}{3} & 0 \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2} \end{pmatrix} + \ldots$$

CKM matrix almost unity

PMNS matrix almost tribimaximal

Neutrinos
A pedagogical mystery

Mass & mixing matrices

DOUBLE-CHOOZ, DAYA-BAY, RENO

$$7.15\times 10^{-5}\,eV^2 \leq \Delta m^2_{solar} \leq 8.00\times 10^{-5}\,eV^2$$
$$2.27\times 10^{-3}\,eV^2 \leq \Delta m^2_{atm} \leq 2.55\times 10^{-3}\,eV^2$$

$$r = \frac{\Delta m^2_{solar}}{\Delta m^2_{atm}} \simeq \frac{1}{30}$$

$$0.275 \leq \sin^2\theta_{12} \leq 0.342$$
$$0.348 \leq \sin^2\theta_{23} \leq 0.448$$
$$0.0193 \leq \sin^2\theta_{13} \leq 0.0290$$

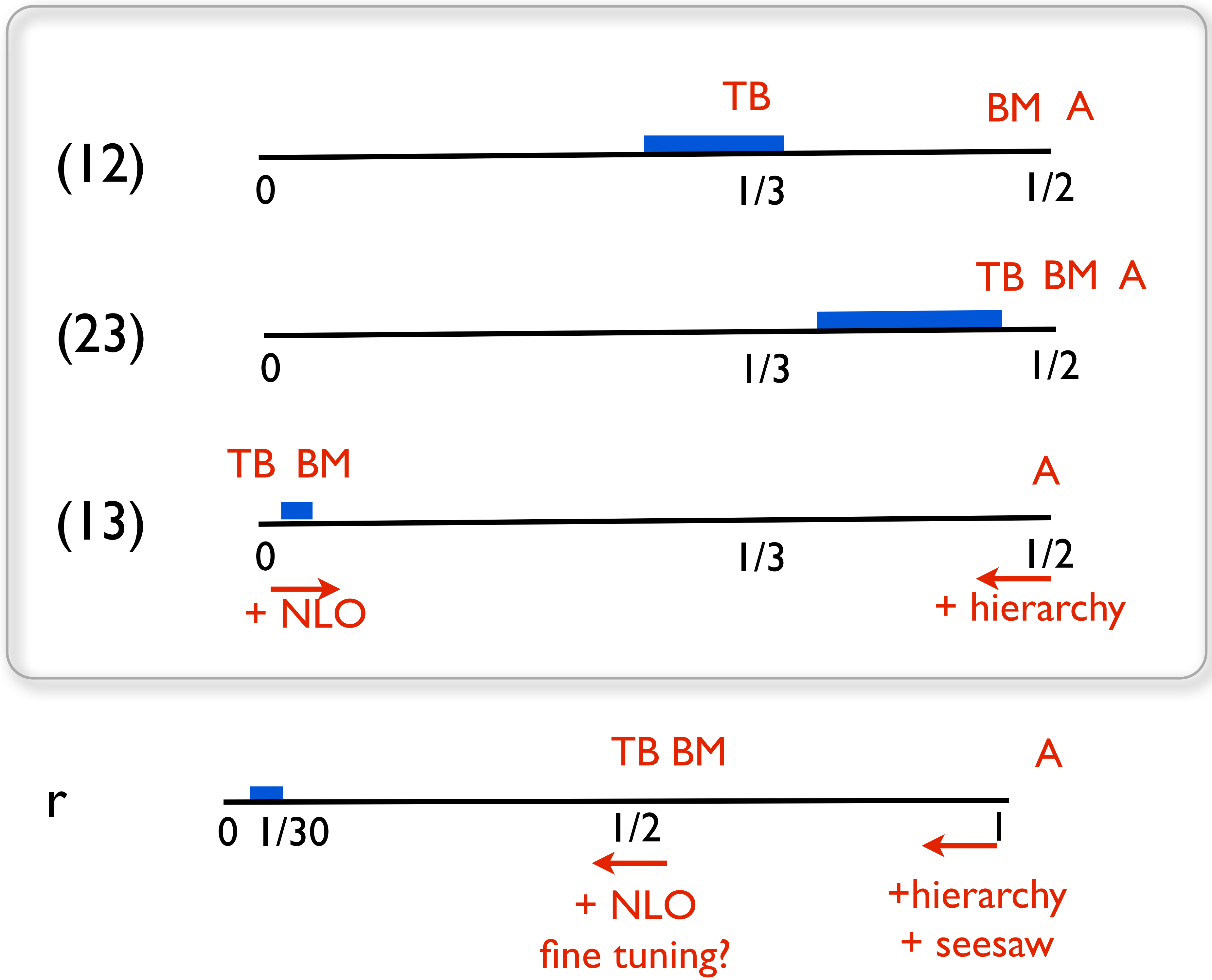
Pattern of mixing angles

$$\sin^2\theta_{12} \simeq \frac{1}{3}$$
$$\sin^2\theta_{23} \lesssim \frac{1}{2}$$
$$\sin^2\theta_{13} > 0$$

$$O(\lambda_C^2) < \sin\theta_{13} < O(\lambda_C) \qquad \lambda_C = \sin\theta_C$$

→ quark mixing

Anarchy versus Hierarchy
chaos and order

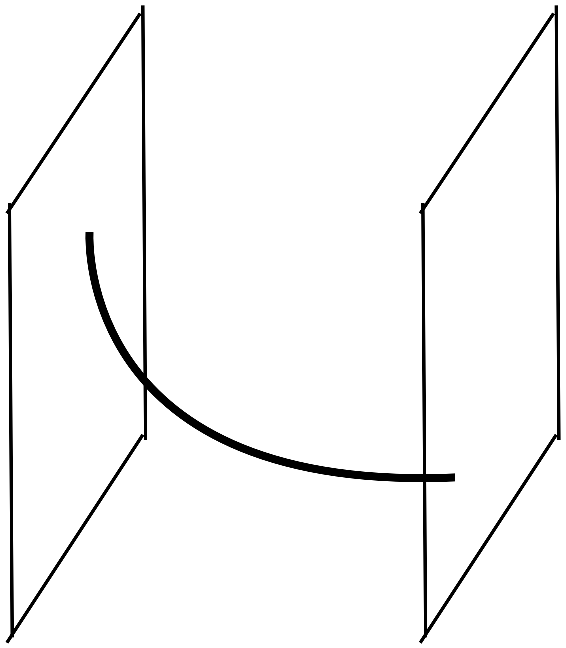


see e.g. Altarelli, Feruglio, Merlo, Stamou 2012

Is there a unified description for quarks & leptons?

Many attempts to a unified description: w and w/o extra dimensions

[e.g. RS-A4 Kadosh EP 2011]

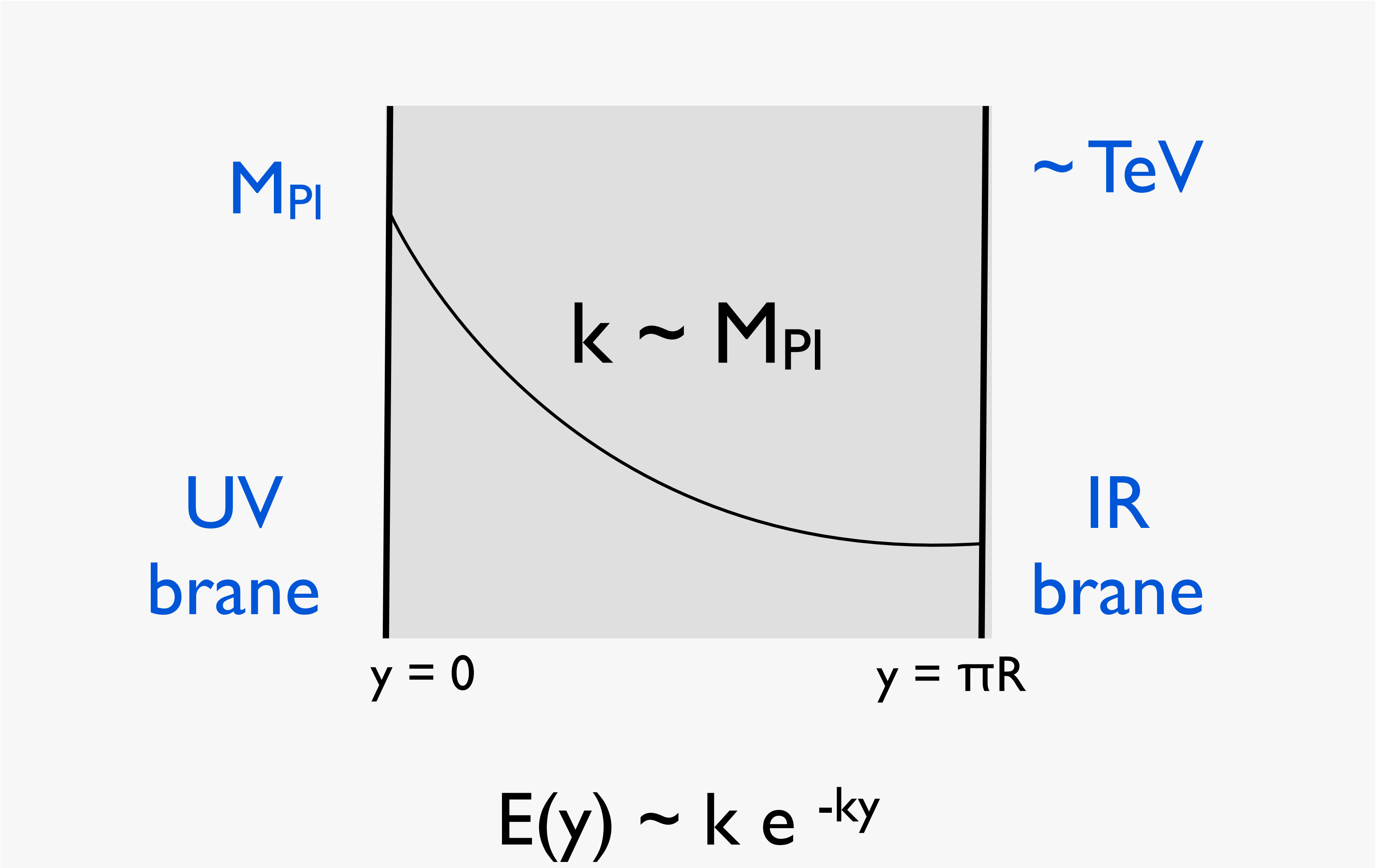


partial compositeness is natural

Powerful discriminators:
EWP parameters S,T - FCNC processes - CP violation - EDMs - LFV

⇒ High precision flavour physics

AdS_5 (S_1/Z_2)



$E(y) \sim k\, e^{-ky}$

Two scales: $k_{UV} \equiv k \sim M_{Pl}$

$k_{IR} \equiv k\, e^{-\pi k R}$ $kR \cong 11$ [KK scale]

All particles in the bulk ⇒ play with particle localization and symmetries

Zero mode fermions peaked at different points in the bulk ⇒ exponential hierarchy of quarks and charged lepton masses explained by tiny hierarchy of bulk masses and O(1) 5D Yukawas

Anarchy ? or Hierarchy ?

No underlying flavor symmetry to constrain the pattern of 5D Yukawa couplings and bulk mass parameters (non-degeneracy)

Large FCNC and CP violation
(little CP problem)

Custodial symmetry augmented with PLR to bring down the KK scale to a few TeV

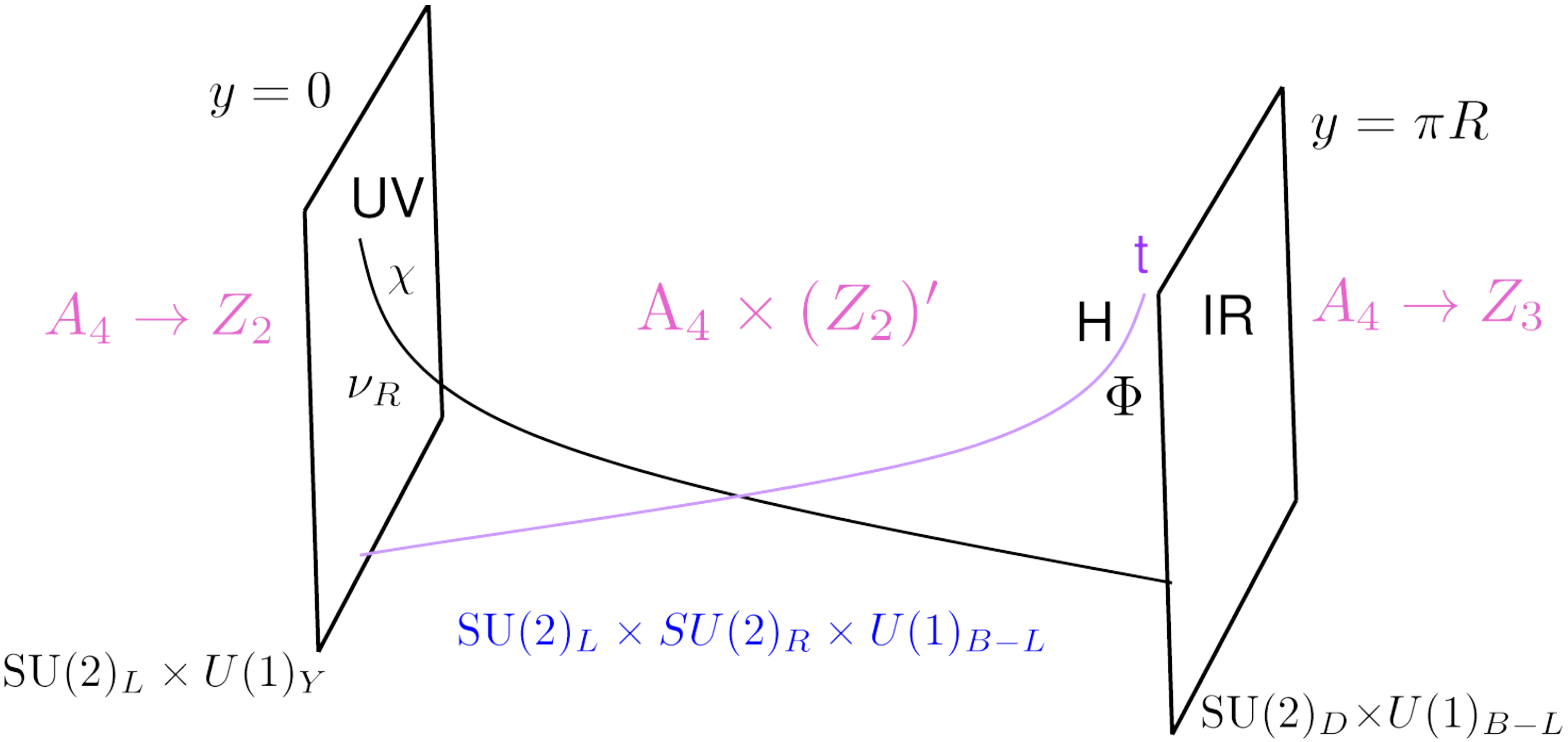
Underlying bulk flavor symmetry
5D MFV

Alignment of Yukawas and masses
Absence of tree level FCNC

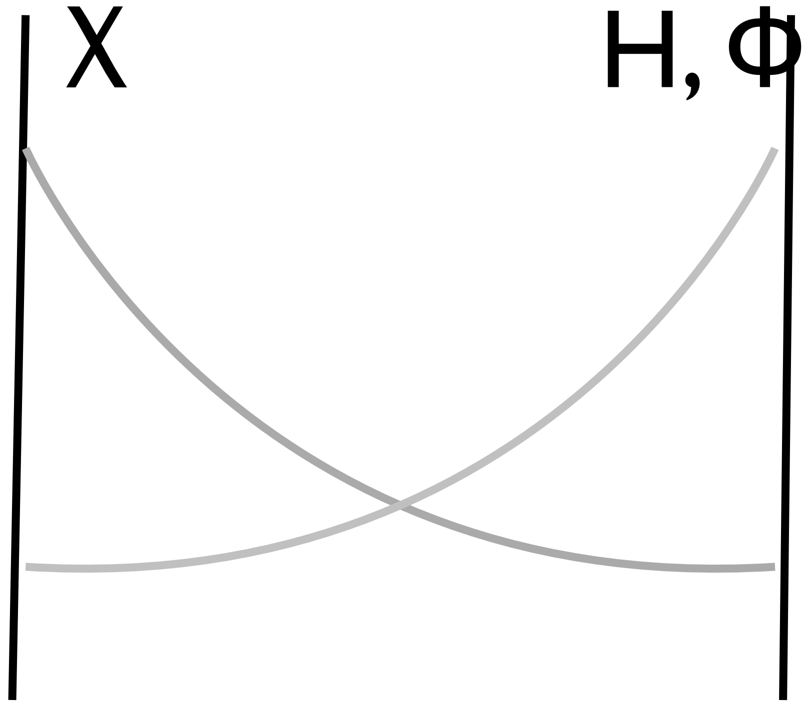
Naturally low KK scale and milder little CP problem

Kadosh EP 2010, 2011

The RS-A4 model



Masses and mixings at Leading Order



$\mathrm{A}_4 \rightarrow Z_2$

$\chi(y) = (0, \chi_0, 0)\ \left(1 - e^{4(k|y| - \pi k R)}\right)$

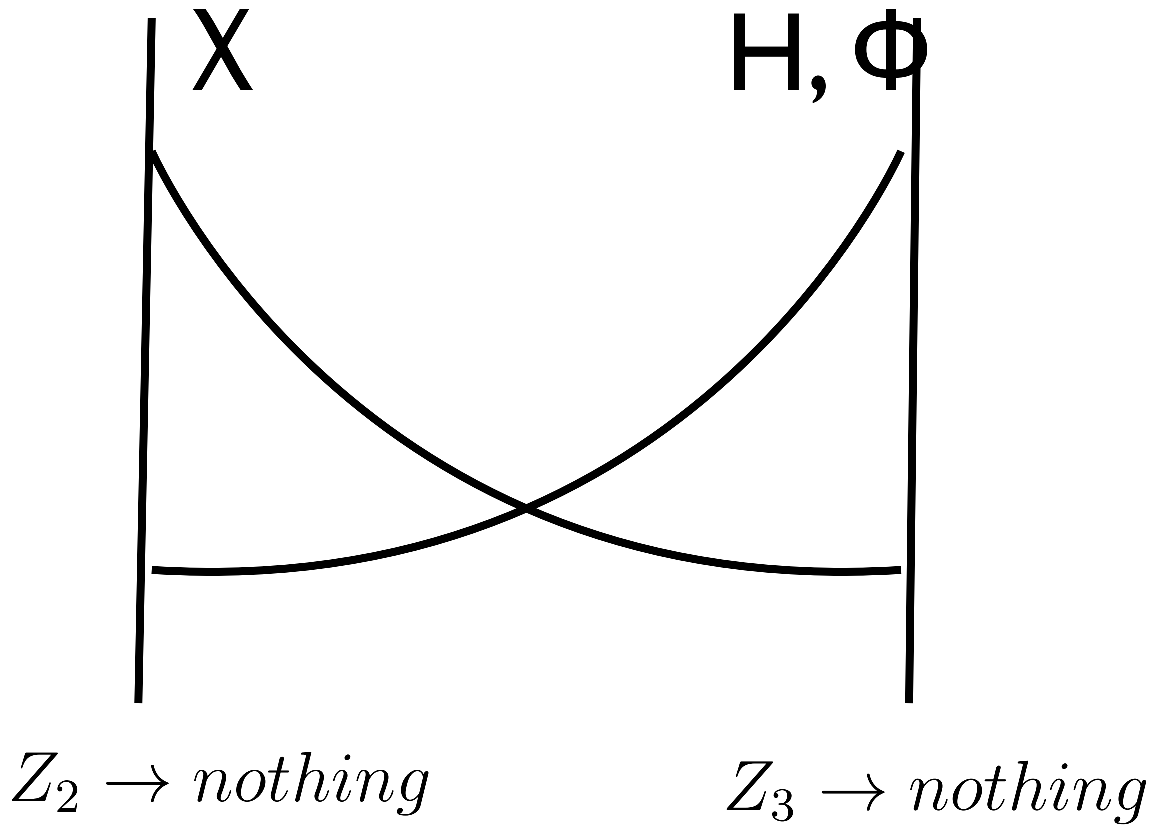
$\mathrm{A}_4 \rightarrow Z_3$

$\Phi(y) = (\Phi_0, \Phi_0, \Phi_0)\, e^{4(k|y| - \pi k R)}$

neutrino sector

charged fermion sector

CKM from cross-talk



cross-brane flavon interactions induce cross-talk
between neutrino and charged sector

⇒ CKM ≠ 1
and deviations from tribimaximal form

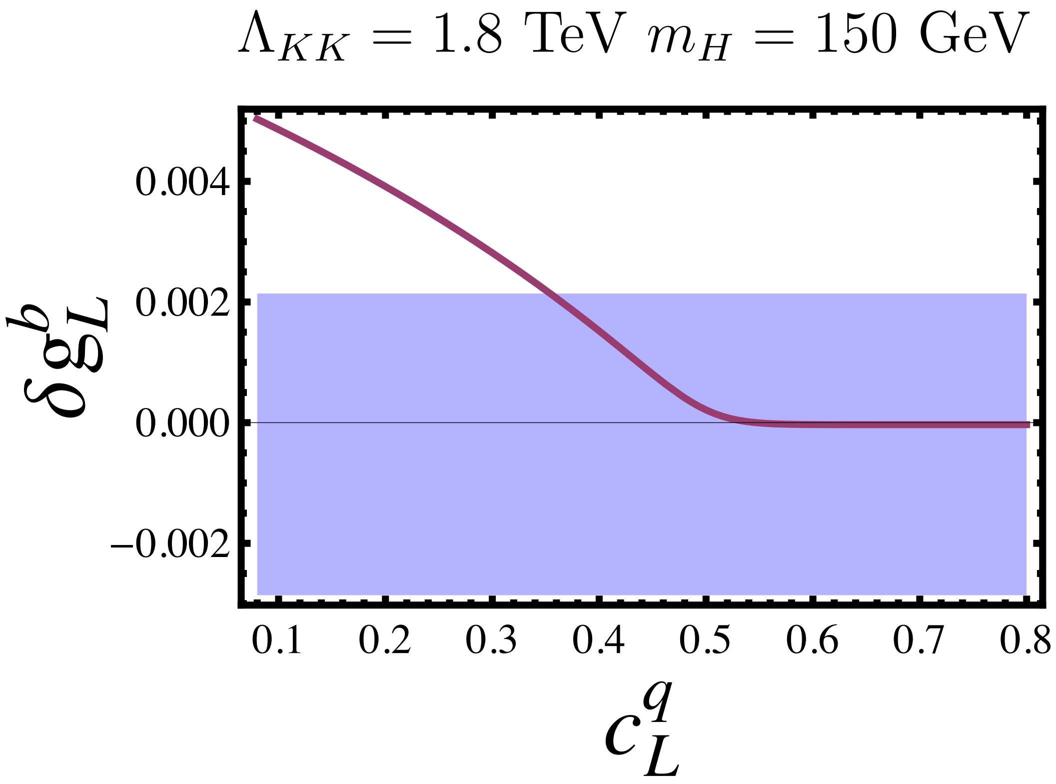
Phenomenology of RS-A4

Degenerate c_L

Zbb constraint

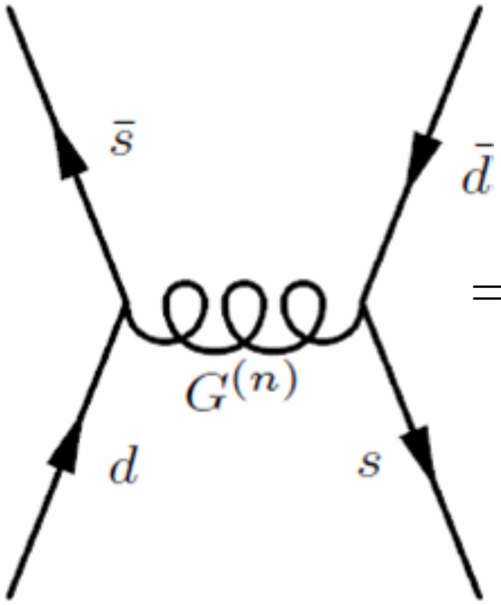
Lower c_L ↔ higher Λ_{KK}

Reduced window for lighter Higgs



Absence of tree level FCNC

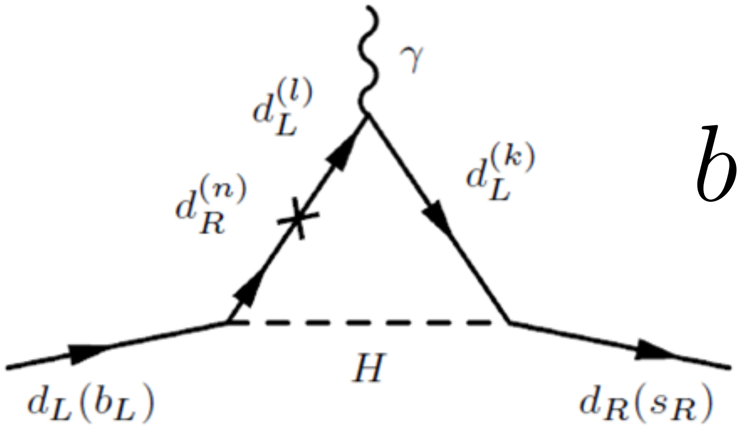
e.g. $\epsilon_K^{NP} = 0$



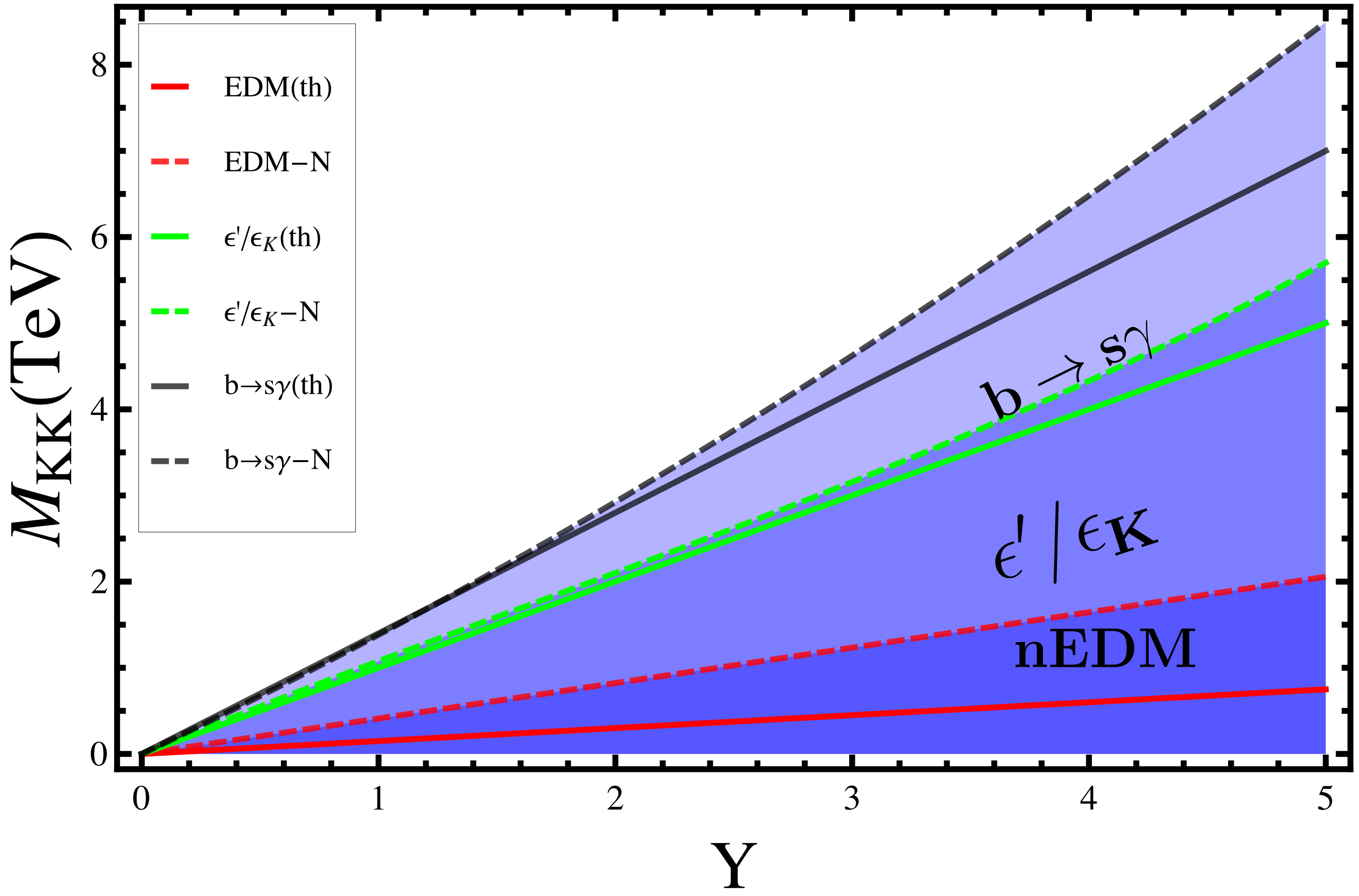
$\Longrightarrow \Lambda_{KK} \gtrsim 10$ TeV (no P_{LR})

(Flavor anarchy)

Dipole operators for FCNC

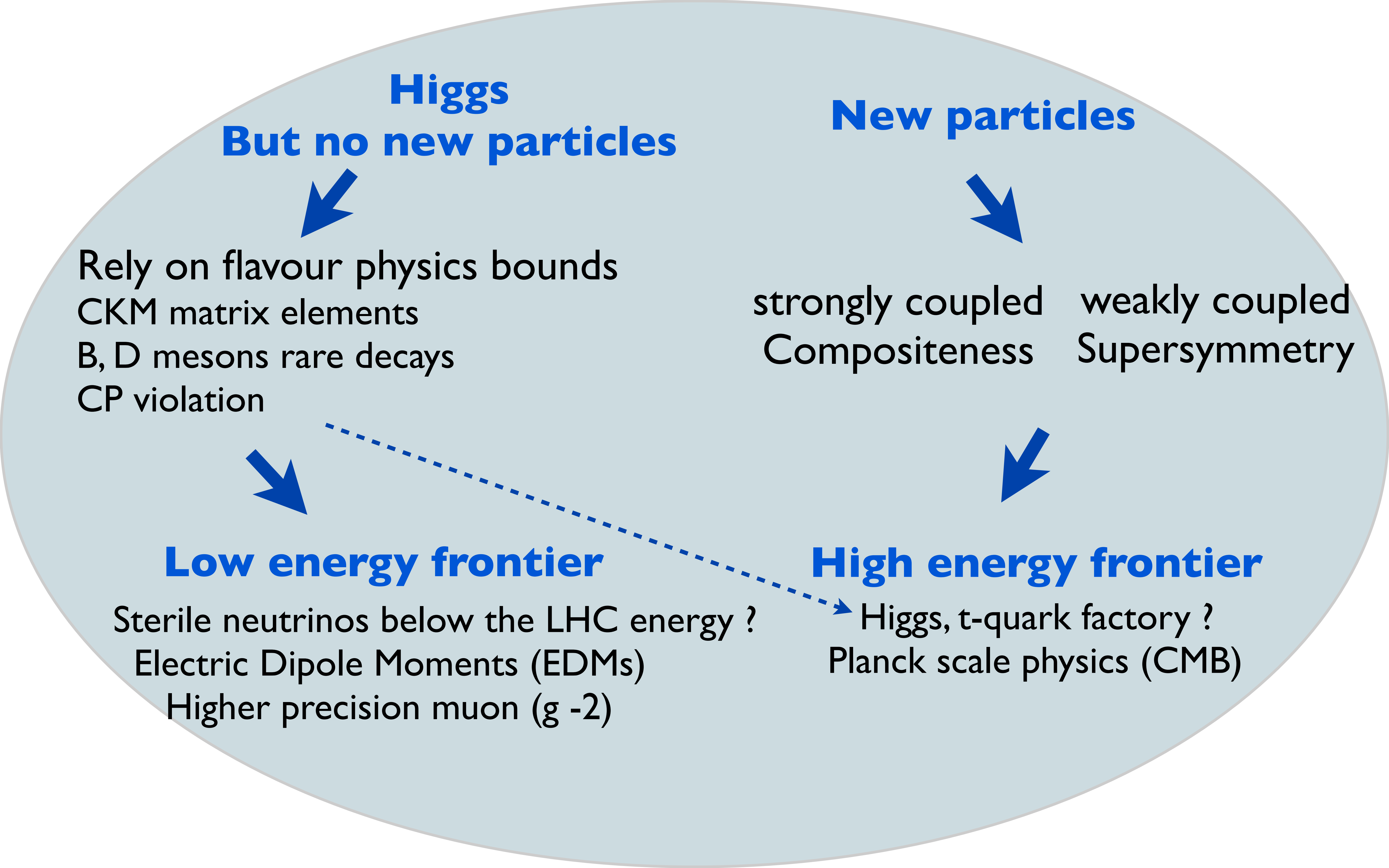


$$b \to s\gamma,\ \epsilon'/\epsilon_K,\ \text{nEDM}$$



d_n ~ 40 x d_n^{exp} !
flavor anarchy

After the LHC



Higgs
But no new particles

Rely on flavour physics bounds
CKM matrix elements
B, D mesons rare decays
CP violation

Low energy frontier

Sterile neutrinos below the LHC energy ?
Electric Dipole Moments (EDMs)
Higher precision muon (g -2)

New particles

strongly coupled
Compositeness

weakly coupled
Supersymmetry

High energy frontier

Higgs, t-quark factory ?
Planck scale physics (CMB)